Galaxies

1920: The Shapley-Curtis Debate on the Nature of the Spiral Nebulae

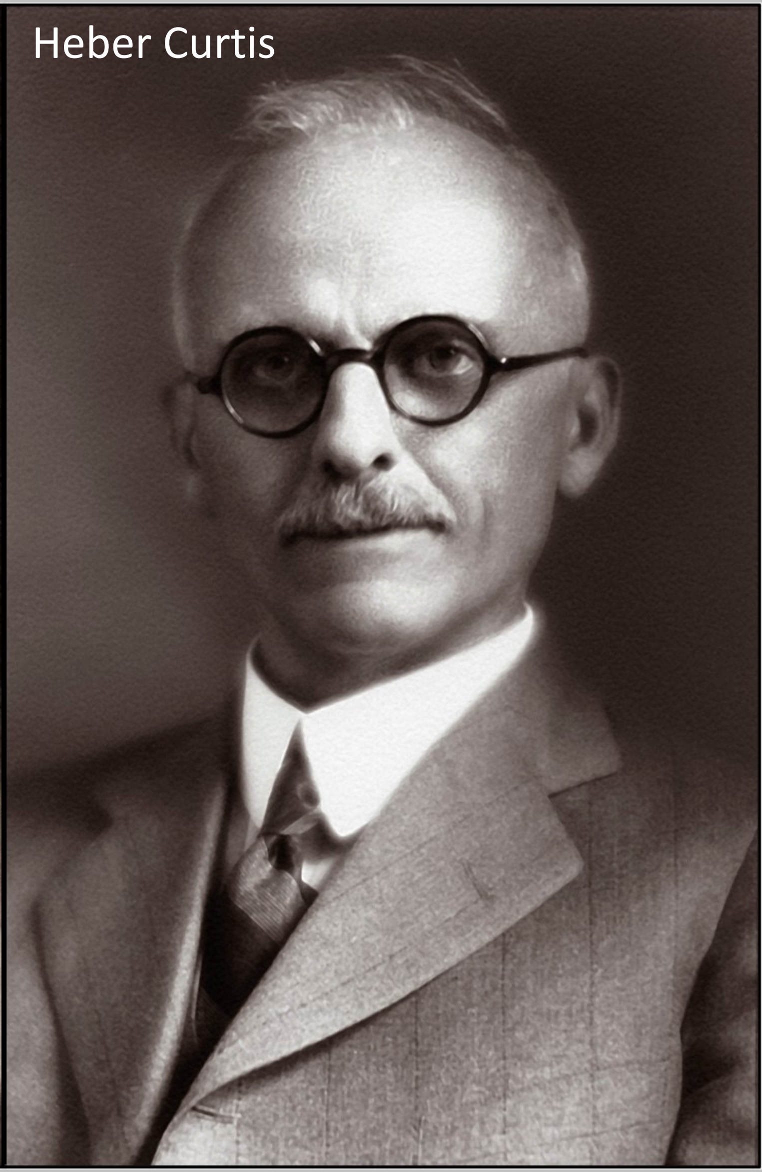
During the early part of the twentieth century, there was much argument about the nature of the "spiral nebulae."

Some astronomers believed they were nearby objects, within our own Galaxy.

Others believed they were galaxies in their own right, very large and very distant.

The controversy led to the "Great Debate" in 1920 at the National Academy of Science in Washington, DC.

Harlow Shapley



Heber Curtis

Harlow Shapley

The spiral nebulae are nearby objects inside the Milky Way Galaxy.

Argument 1: Novae

Novae had been seen in the Andromeda Nebula. Given Andromeda’s angular size, if it was a galaxy as big as the Milky Way, it would be very distant and so those novae would have to be so much luminous than novae in the Milky Way to be seen at that distance.

Argument 2: The Rotation of M101

Adrian van Maanen had observed proper motion of stars in the outskirts of M101, and calculated that M101 rotated once every 85,000 years. If M101 was a distant galaxy, its stars would be moving faster than the speed of light!

Heber Curtis

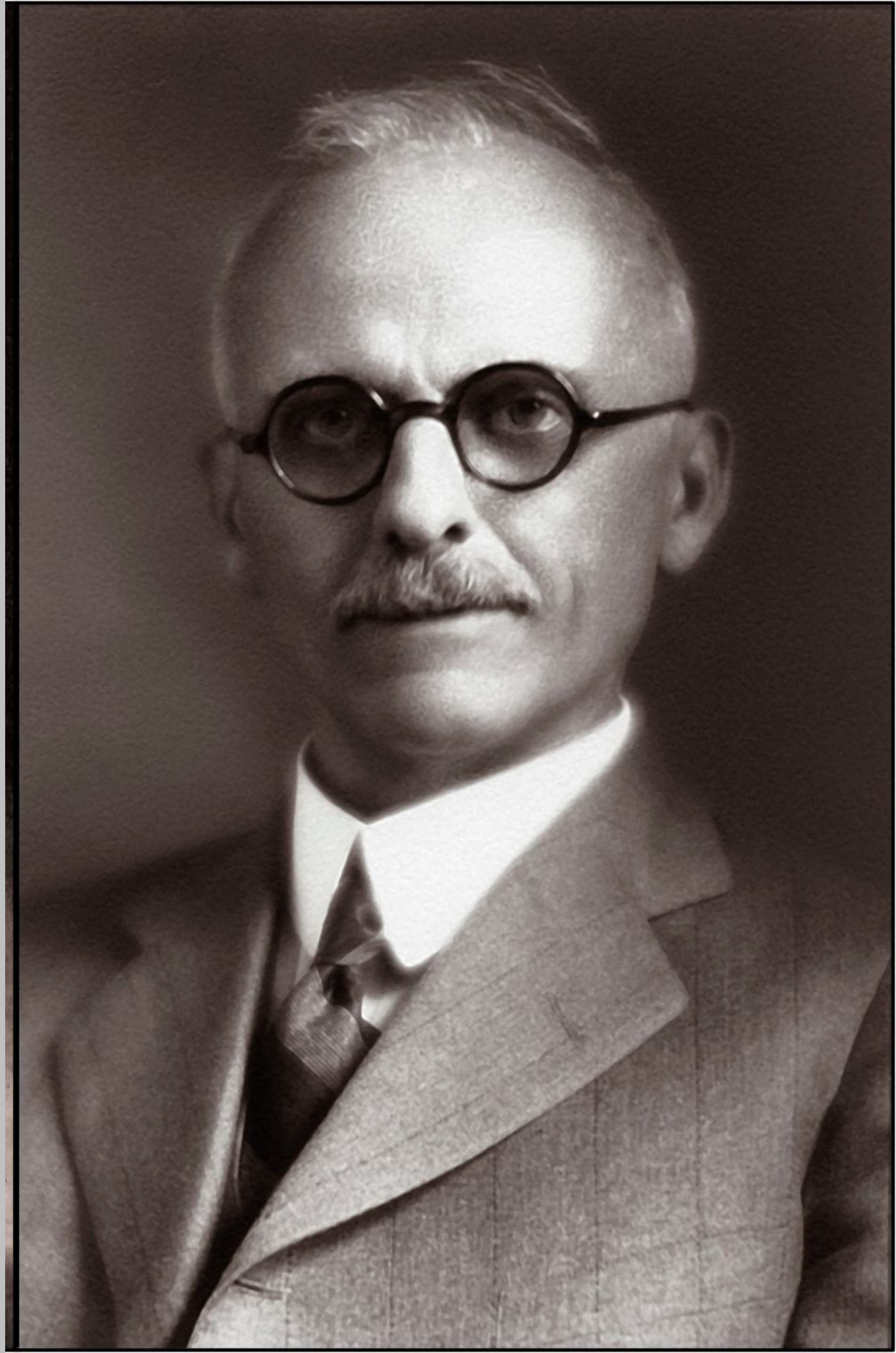
The spiral nebulae are distant galaxies similar to the Milky Way.

Argument 1: Novae

Novae in the Andromeda Nebula are very faint. If Andromeda was actually inside the Milky Way, those novae would be extremely underluminous compared to other Milky Way novae. *(Except for one really bright one....)*

Argument 2: Radial Velocities

Most spiral nebulae have radial velocities > 1000 km/s. No stars move this fast. If spiral nebulae move that fast, they wouldn't be gravitationally bound to the Milky Way! And if they are moving that fast, we should see proper motion of the nebulae themselves, and we don't! *(But why are they all moving away?)*



1920: The Shapley-Curtis Debate on the Nature of the Spiral Nebulae

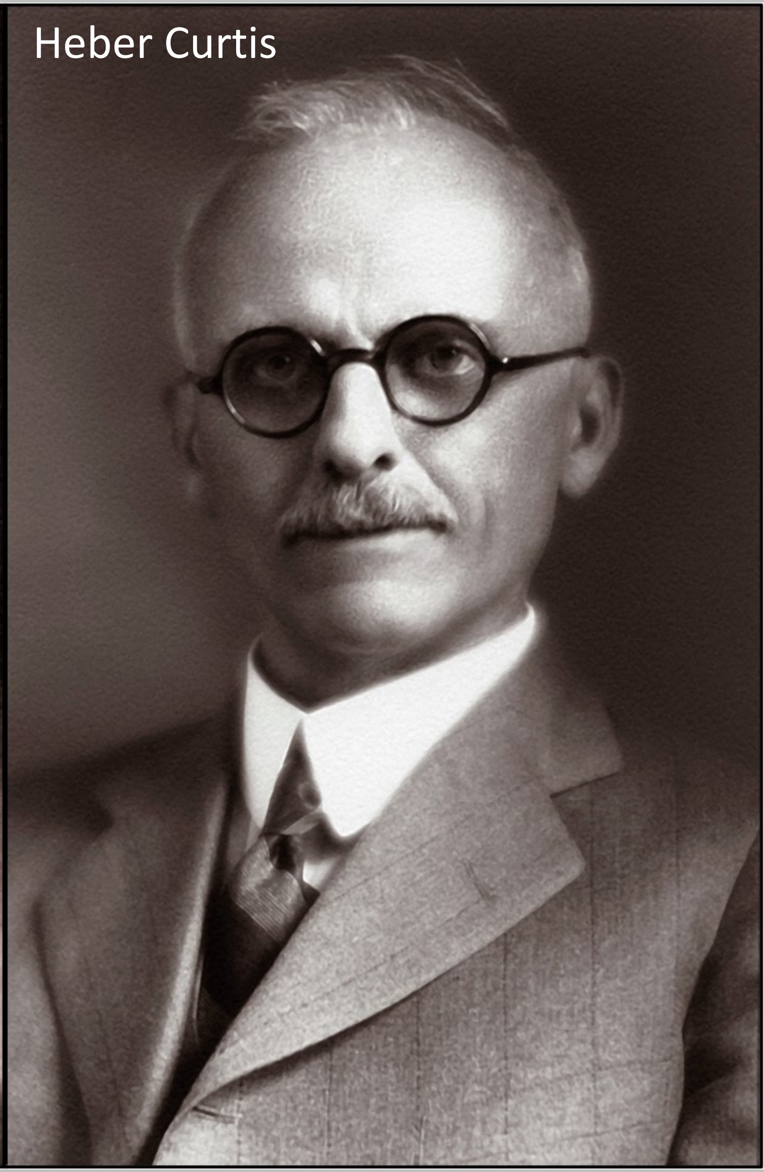
During the early part of the twentieth century, there was much argument about the nature of the "spiral nebulae."

Some astronomers believed they were nearby objects, within our own Galaxy.

Others believed they were galaxies in their own right, very large and very distant.

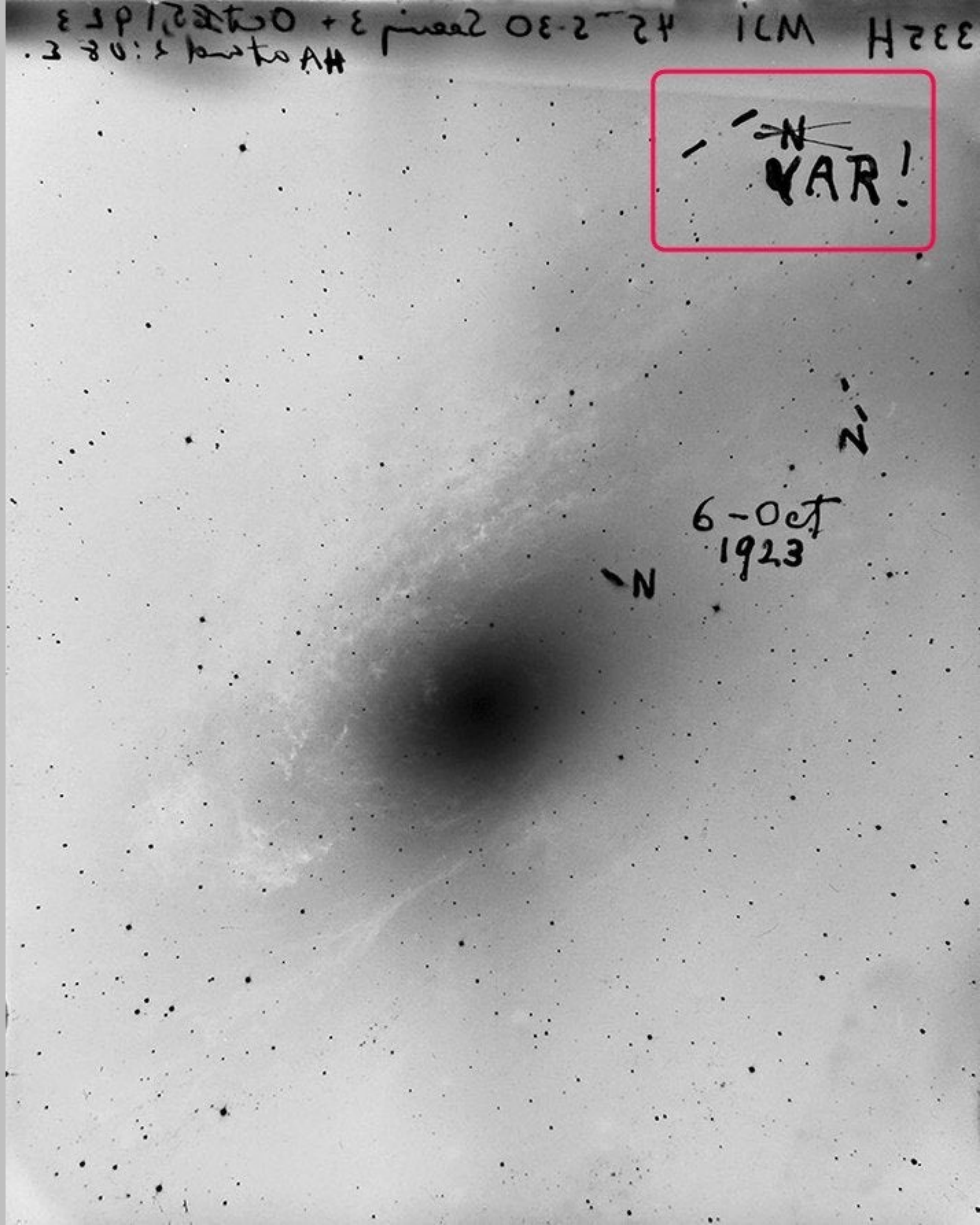
The controversy led to the Great Debate in 1920 at the National Academy of Science in Washington, DC.

Neither side won.



1923: Edwin Hubble finds variable stars in Andromeda

Mt Wilson 100” telescope

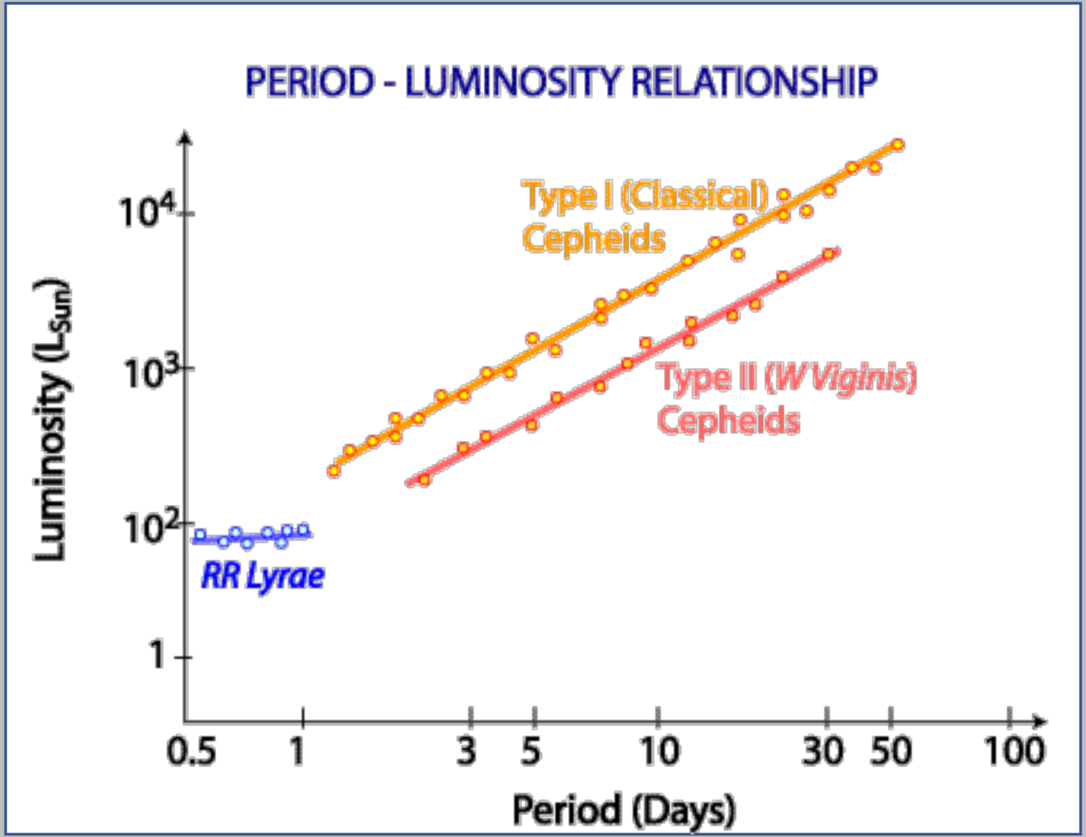


Hubble's Distance to Andromeda

Hubble uses the Cepheid period-luminosity relationship to calculate the distance to Andromeda.

Distance: 285 kpc. Not part of the Milky Way!

Our whole view of the Universe changes.



And actually Hubble got the distance wrong! He was using a P-L relationship calibrated on fainter, metal-poor Cepheids (W Virginis stars), but he was looking at regular Cepheids.

Since he thought his variable were intrinsically faint, he got a distance that is erroneously small. The actual distance to Andromeda is 780 pc.

Harlow Shapley

The spiral nebulae are nearby objects inside the Milky Way Galaxy.

Argument 1: Novae

Novae had been seen in the Andromeda Nebula. Given Andromeda's angular size, if it was a galaxy as big as the Milky Way, it would be very distant and so those novae would have to be so much luminous than novae in the Milky Way to be seen at that distance.

Mistake: Shapley had overestimated the Milky Way's size, and thus overestimated Andromeda's distance if it was that big. A too-distant Andromeda ***would*** *need overly-luminous novae. But it's* ***not*** *that far away.*

Argument 2: The Rotation of M101

Adrian van Maanen had observed proper motion of stars in the outskirts of M101, and calculated that M101 rotated once every 85,000 years. If M101 was a distant galaxy, its stars would be moving faster than the speed of light!

Mistake: van Maanen's observations were ***wrong****.*

Heber Curtis

The spiral nebulae are distant galaxies similar to the Milky Way.

Argument 1: Novae

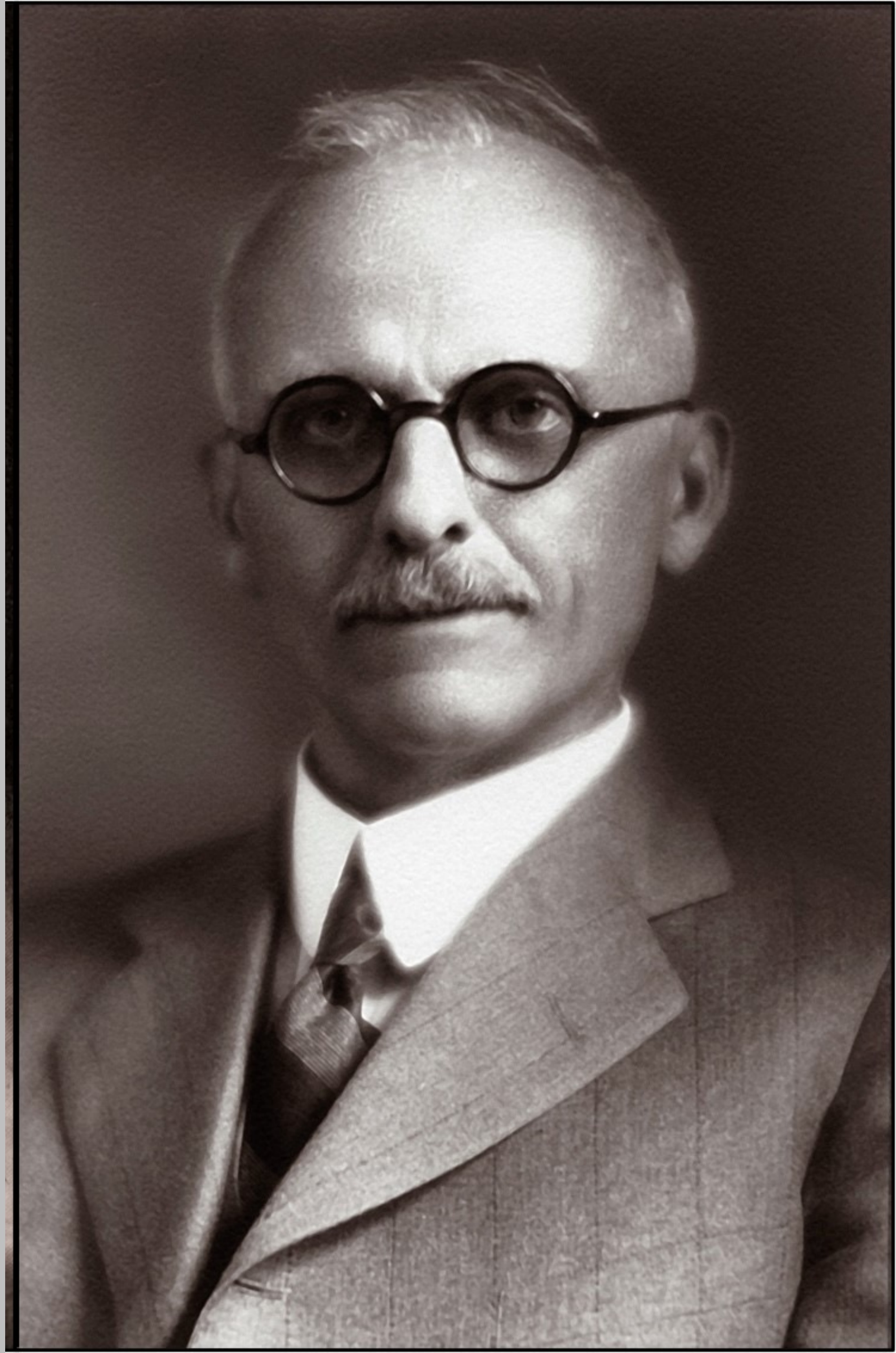
Novae in the Andromeda Nebula are very faint. If Andromeda was actually inside the Milky Way, those novae would be extremely underluminous compared to other Milky Way novae. *(Except for one really bright one....)*

*The really bright one was actually a **supernova**.*

Argument 2: Radial Velocities

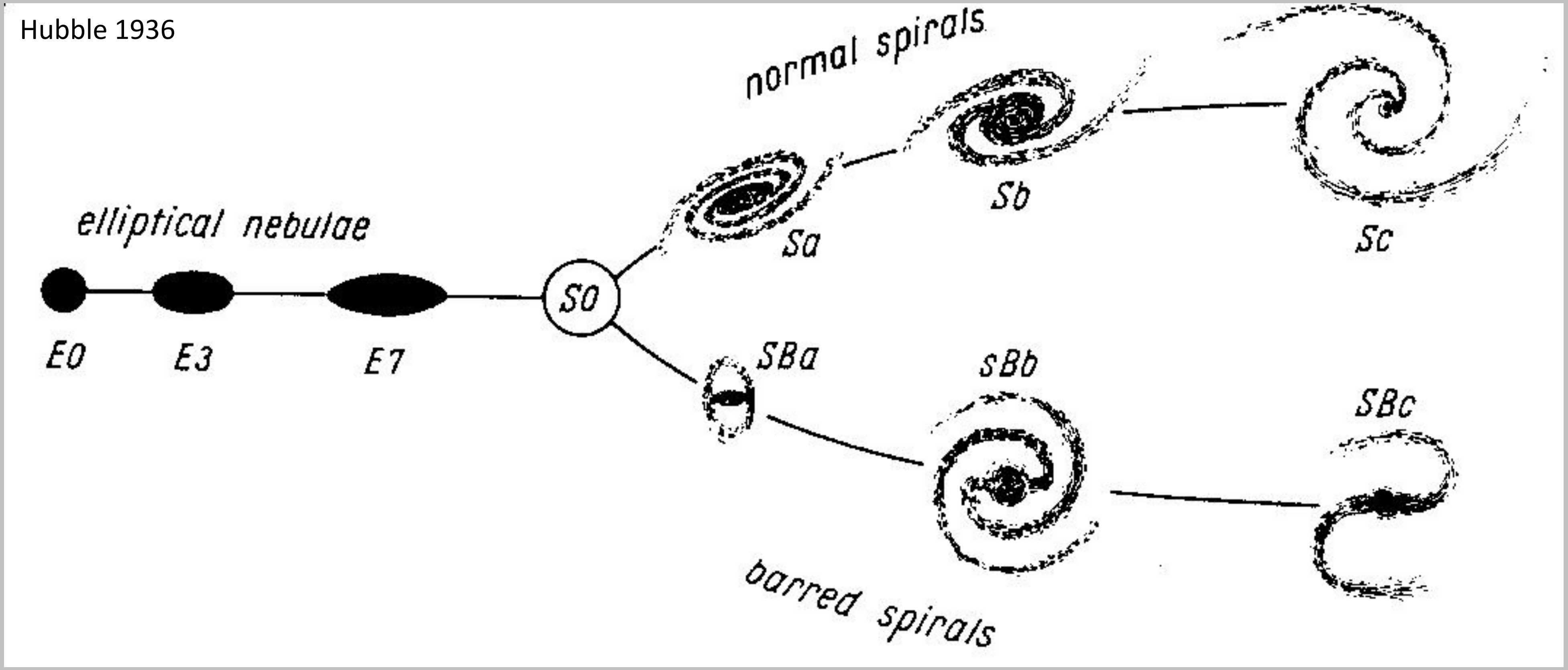
Most spiral nebulae have radial velocities > 1000 km/s. No stars move this fast. If spiral nebulae move that fast, they wouldn't be gravitationally bound to the Milky Way! And if they are moving that fast, we should see proper motion of the nebulae themselves, and we don't! *(But why are they all moving away?)*

***Nobody** could explain why the nebulae were all moving away.*



Galaxies: Types and Properties

Hubble Sequence ("The Tuning Fork"): The most basic of classification schemes: visual morphology.



Ellipticals: EN

$$N = 10\left(1 - \frac{b}{a}\right)$$

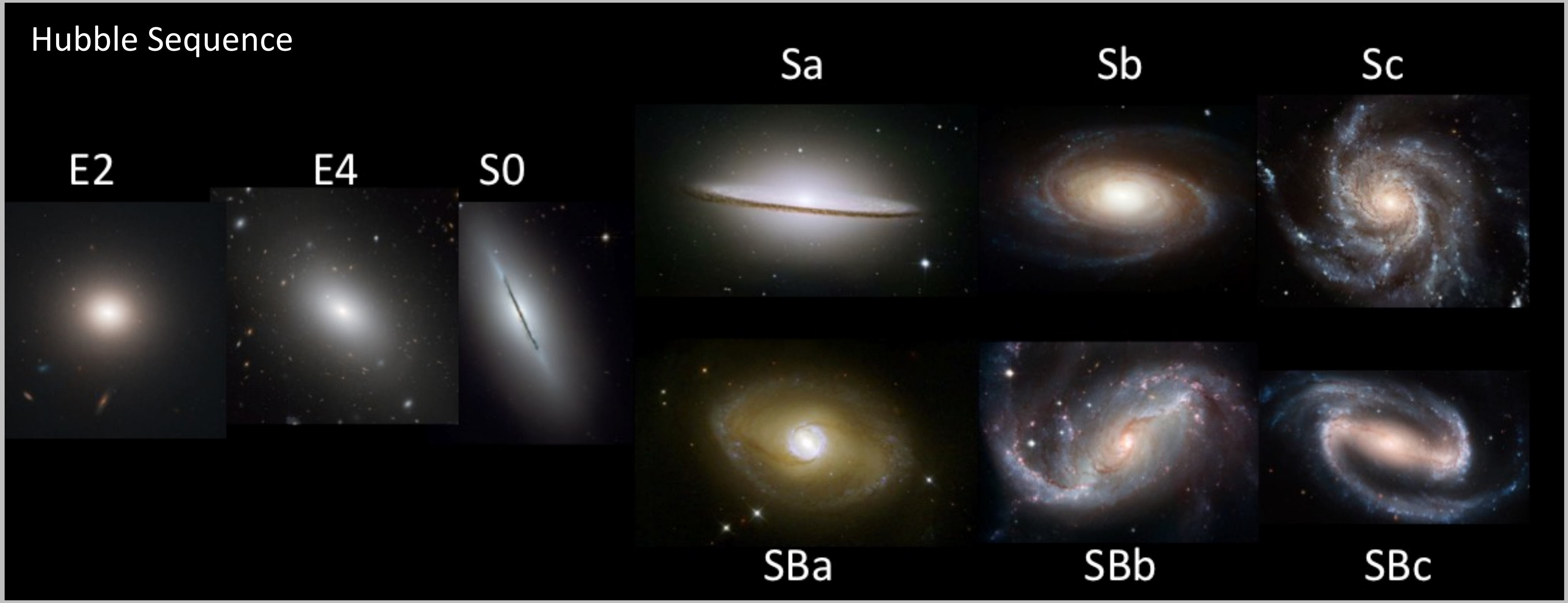
S0 ("Lenticulars")
transitional type
disky but smooth

Spirals: Sa,Sb,Sc
tightness of spiral
prominence of bulge

Barred Spirals: SBa, SBb, SBc
presence of central bar
otherwise like Spiral

Galaxies: Types and Properties

Hubble Sequence ("The Tuning Fork"): The most basic of classification schemes: visual morphology.



Extensions to the Hubble Sequence:

Sd
(diffuse spiral)

Sm
(irregular spiral)

Irr
(very irregular)

Ellipticals: EN

$$N = 10\left(1 - \frac{b}{a}\right)$$

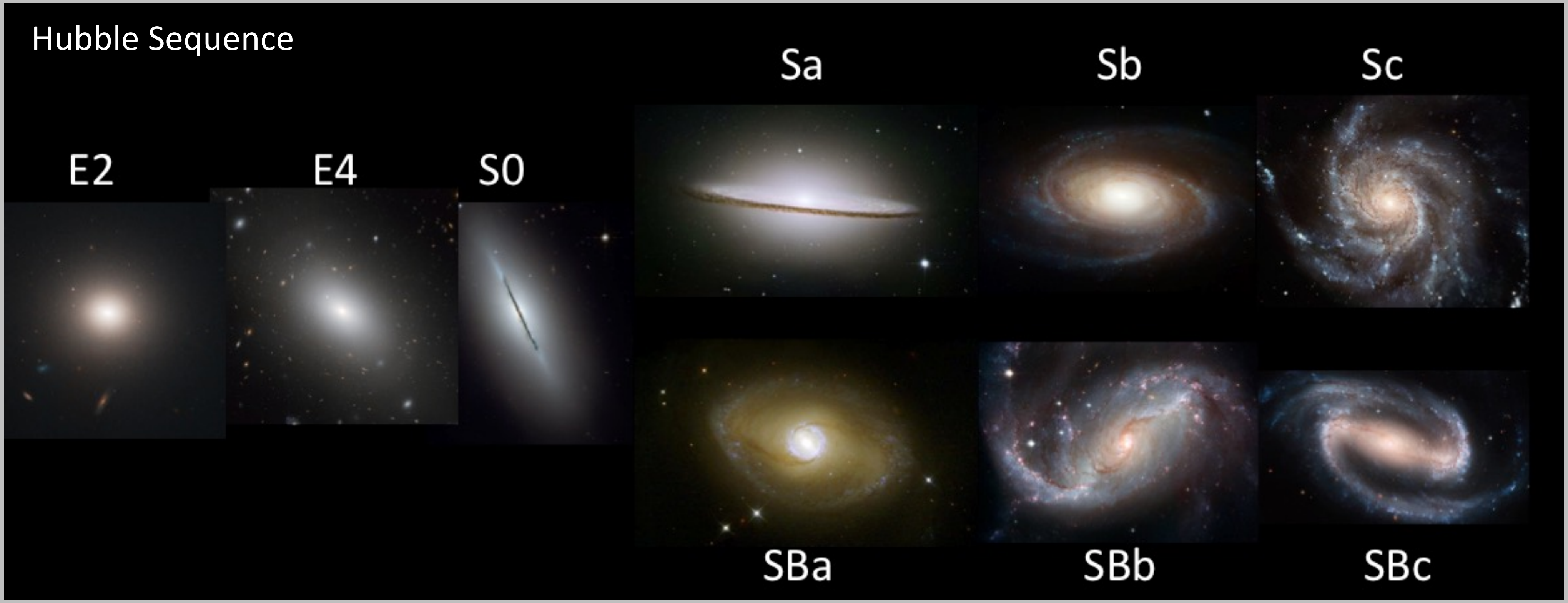
S0 ("Lenticulars")
transitional type
disky but smooth

Spirals: Sa,Sb,Sc
tightness of spiral
prominence of bulge

Barred Spirals: SBa, SBb, SBc
presence of central bar
otherwise like Spiral

Galaxies: Types and Properties

Hubble Sequence (“The Tuning Fork”): The most basic of classification schemes: visual morphology.



Extensions to the Hubble Sequence:

Sd
(diffuse spiral)

Sm
(irregular spiral)

Irr
(very irregular)

“Early” → “Late”

***Important**: The nomenclature of “Early” and ”Late” type galaxies is historical and misleading. Galaxies do not evolve from early to late types, and early types did not necessarily form before late types!*

Galaxy Properties (a thumbnail sketch)

Spiral Galaxies

- About ¾ of big galaxies are spiral galaxies.
- Scale lengths from from < 1 kpc (dwarfs) to > 10 kpc.
- Absolute magnitudes range from –16 to –23 (a factor of 1000 in luminosity!)
- Masses range from 10^9 – few x 10^{12} $\mathcal{M}_\odot$

On this scale, the Milky Way is a large spiral galaxy, but not the most extreme.

Milky Way *(very rough numbers)*:

- Radial scale length: $h \approx 3$ kpc
- Blue luminosity: $L_B \approx 1.5\times10^{10} L_\odot$
- Absolute B magnitude: $M_B \approx -20.7$
- Total mass: $\mathcal{M}_{tot} \approx 10^{12} \mathcal{M}_\odot$

Galaxy Properties (a thumbnail sketch)

Elliptical Galaxies

- About 10−20% of big galaxies are ellipticals, except in galaxy clusters where ellipticals dominate.

- Ellipticals have a wide range of properties:
  - Normal ellipticals
  - cD galaxies: massive E's at the center of a galaxy cluster
  - dE's: dwarf ellipticals

- Size is measured by the effective radius (r_e), which is the radius containing half the total light. Sometimes called the half-light radius.

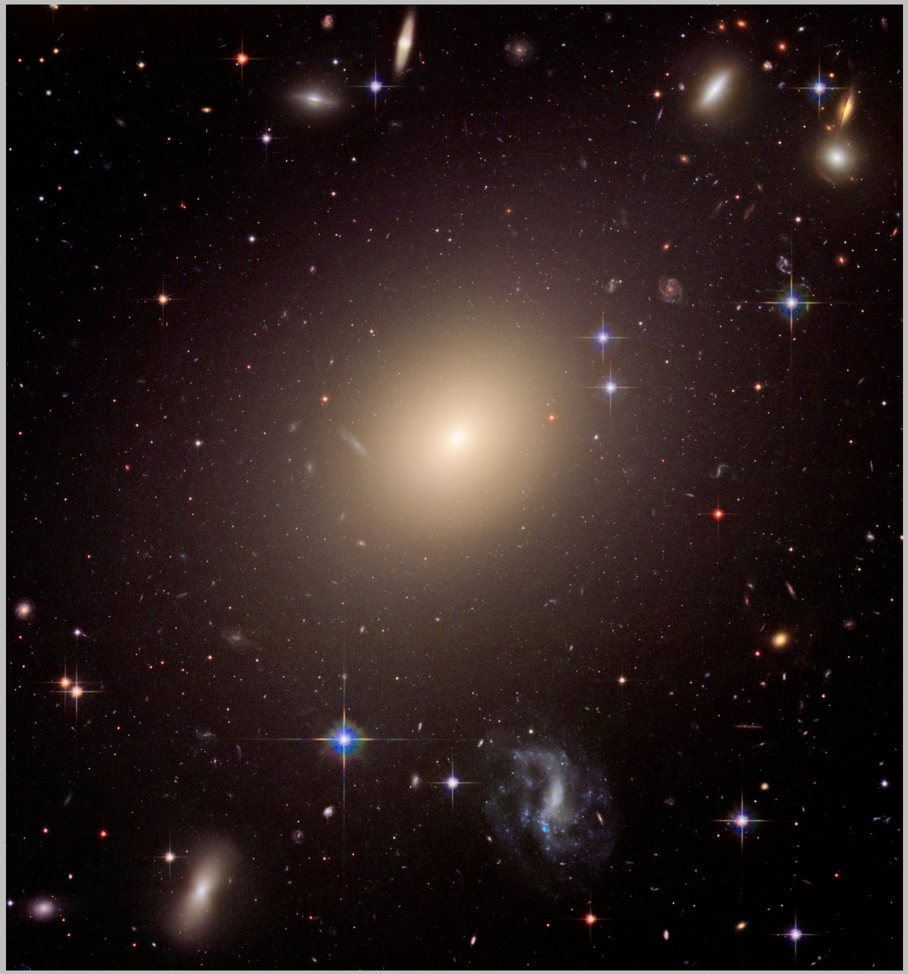
- Sizes: r_e ranges from < 1 kpc (dE's) to 10s of kpc (cD's)

- Absolute magnitudes: −10 to −25 (a factor of a million in luminosity!)

- Masses range from 10^7 – few x 10^{13} $\mathcal{M}_\odot$

Milky Way *(very rough numbers)*:

- Radial scale length: $h \approx 3$ kpc
- Blue luminosity: $L_B \approx 1.5{\times}10^{10} L_\odot$
- Absolute B magnitude: $M_B \approx -20.7$
- Total mass: $\mathcal{M}_{tot} \approx 10^{12} \mathcal{M}_\odot$



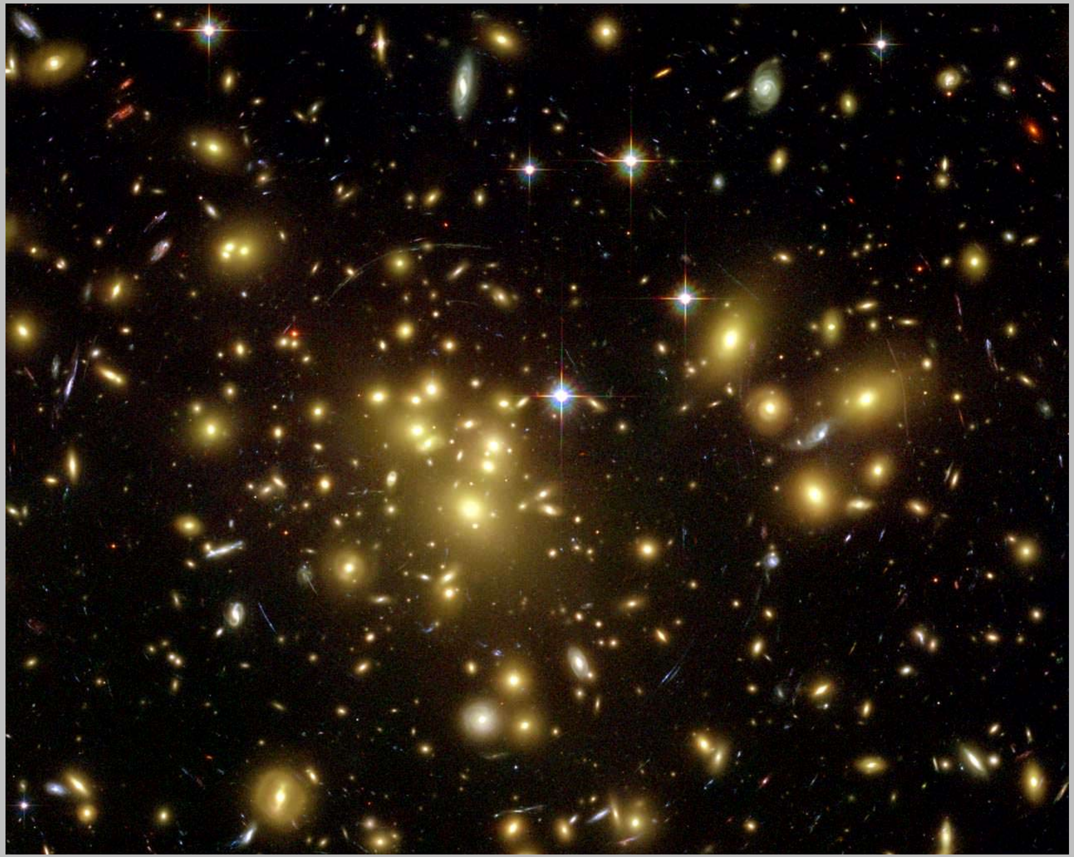
Galaxies: Morphology-Density Relationship

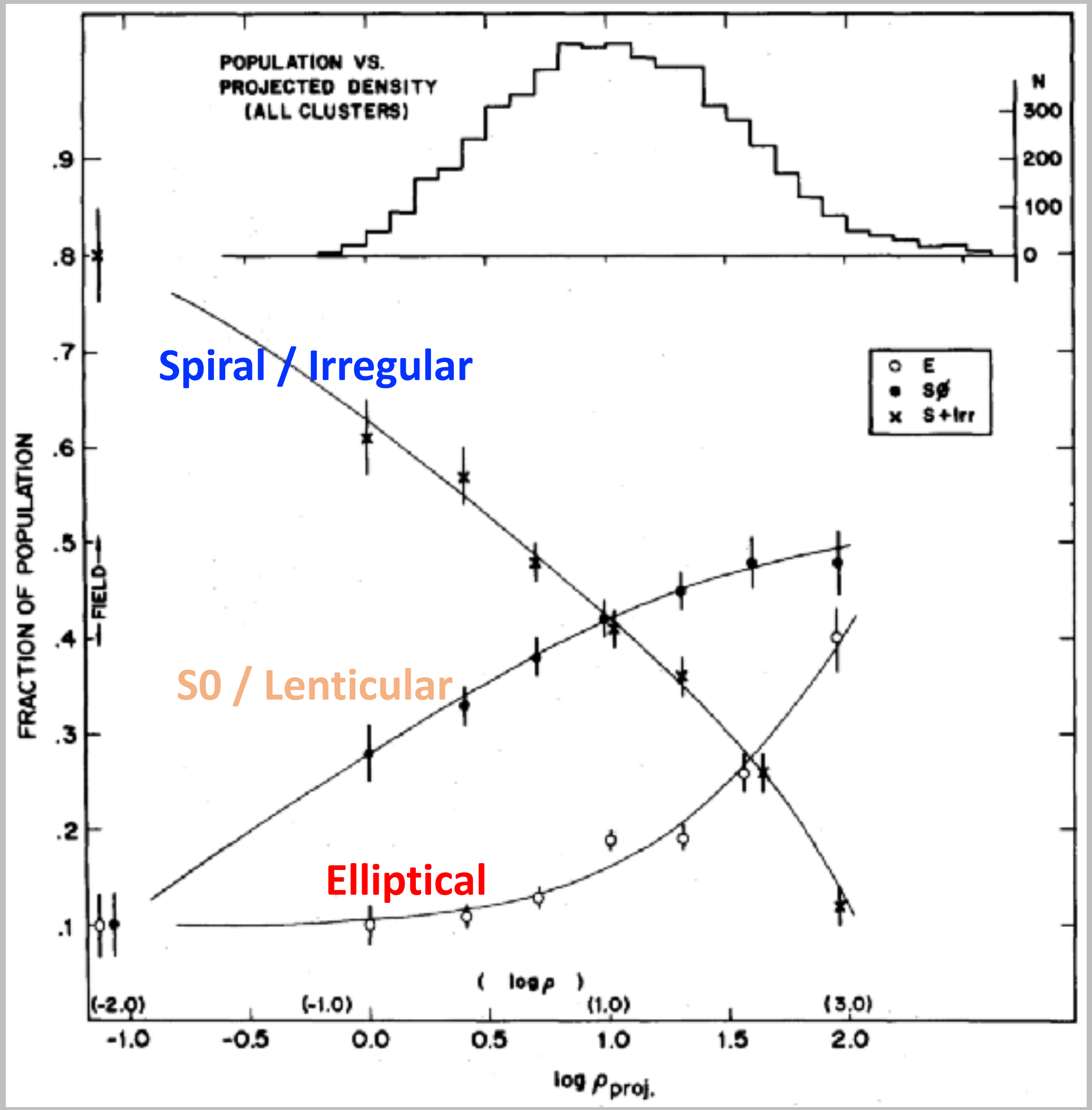
Dressler 1980

In the local universe, the fraction of galaxy types is a strong function of local environment.

Spirals/Irregulars dominate the in the field environment.

S0's and E's dominate in galaxy clusters.





Projected Number Density of Galaxies
log(# per Mpc^2)

Galaxies: Luminosities

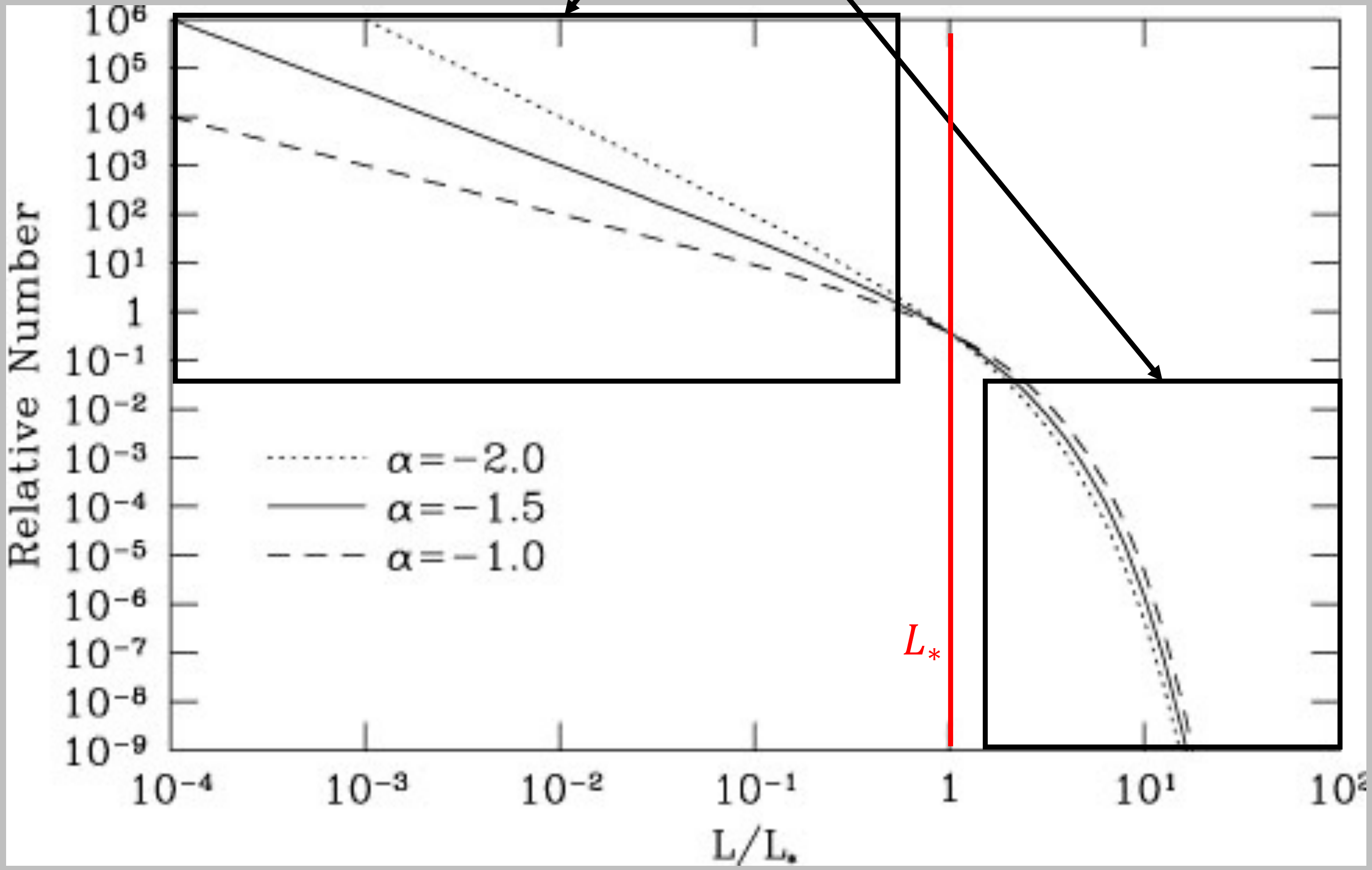
Luminosity function: number of galaxies (per unit volume) in a luminosity range L ⇒ L + dL

Common parameterization is the **Schechter Function**: $\Phi(L)dL = \Phi_* \boxed{\left(\frac{L}{L_*}\right)^{\alpha}} \boxed{e^{(-L/L_*)}} dL$

$\mathbf{\Phi_*}$: overall density (units = #/Mpc^3)

L_*: characteristic luminosity, the "knee" of the luminosity function

α: faint end power law slope



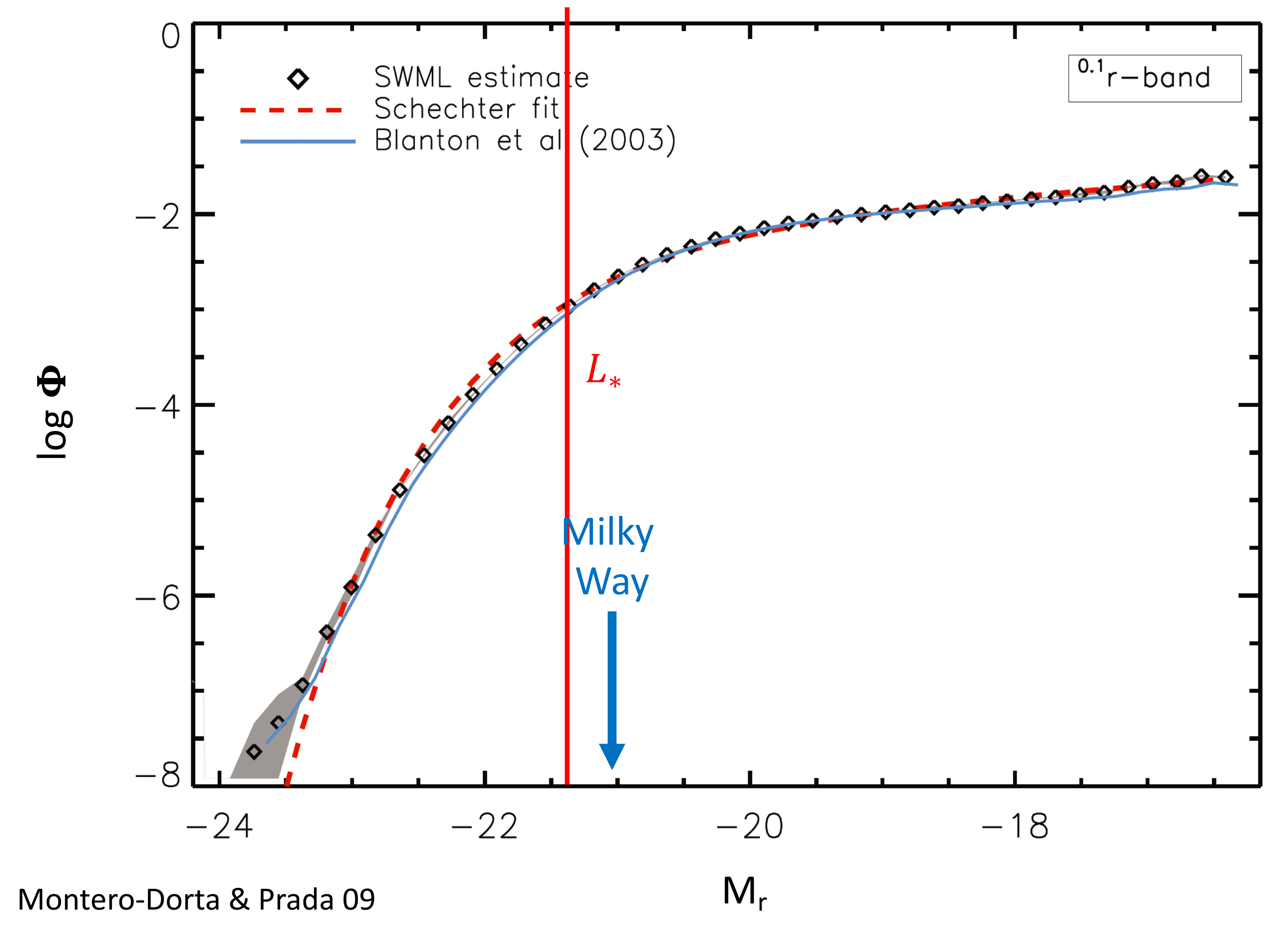
Luminosity Increases ⟹

Galaxies: Luminosities (expressed as absolute magnitudes)

$$\Phi(M)dM = \Phi_0 10^{-0.4(\alpha+1)M} e^{-10^{0.4(M_*-M)}} dM$$

Galaxy luminosity function from Sloan Digital Sky Survey:

$$M_{*,r} = -21.4$$
$$\alpha = -1.26$$



⟸ Luminosity Increases

Galaxy luminosity function: Very strong dependence on galaxy type and environment

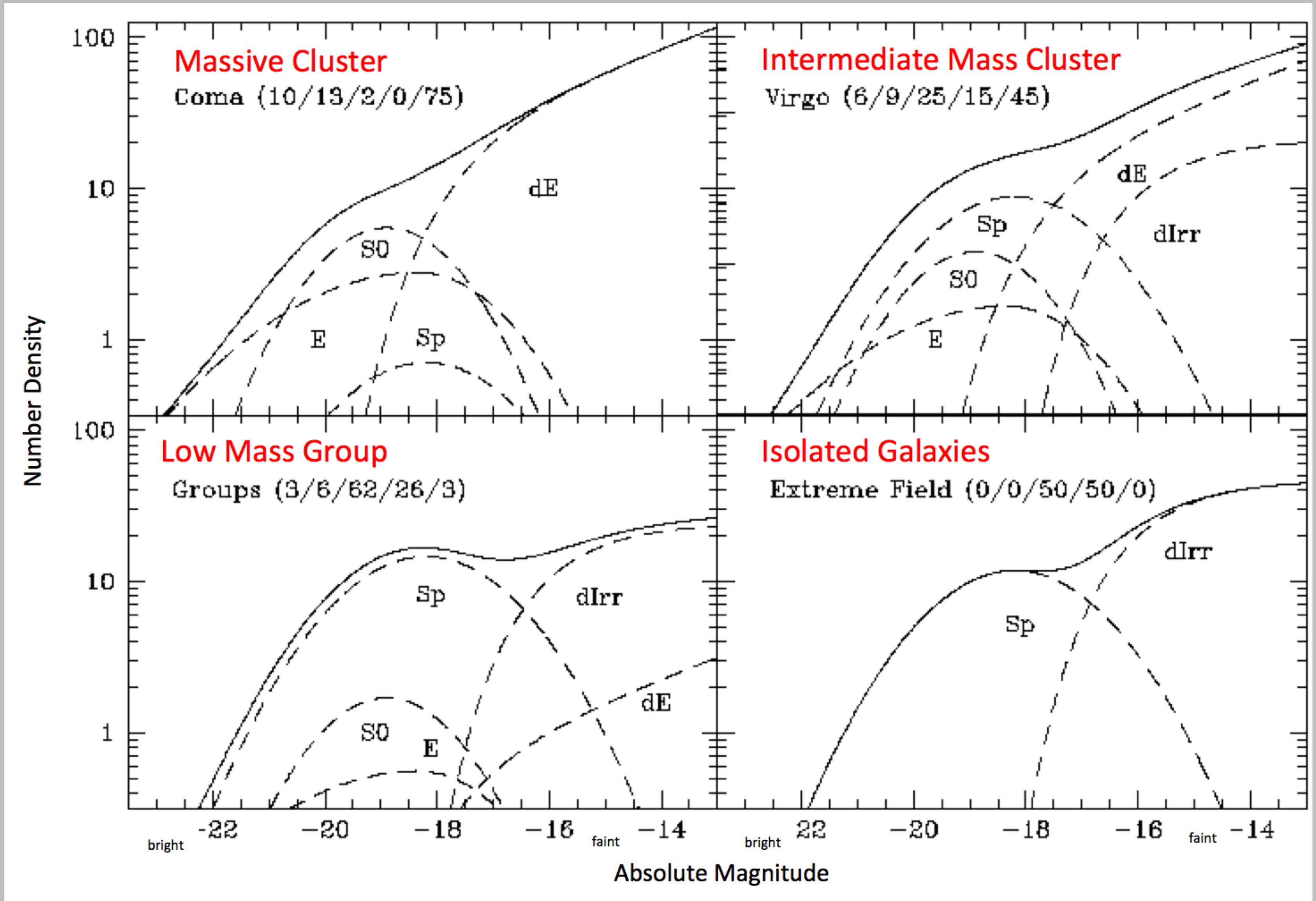
These are schematic LFs, not real

Inside big galaxy clusters:

- E/S0 dominate
- faint end mostly red things (dE's)

In groups and field:

- Spirals dominate
- faint end mostly blue things (dIrr's)



Stellar Populations

The mix of stars for a given star formation history and metallicity distribution.

Think of the color-magnitude diagram (CMD) for different types of star clusters.

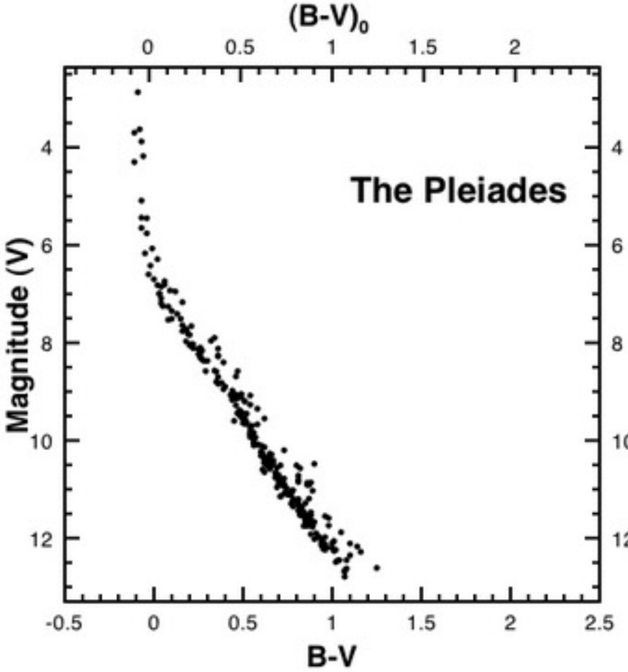
CMD reveals information about age and metallicity of the stellar populations.

These are “simple stellar populations”, meaning all the stars have the same age and metallicity.

Galaxies form stars over time, and the metallicity of each generation of stars can increase with time.

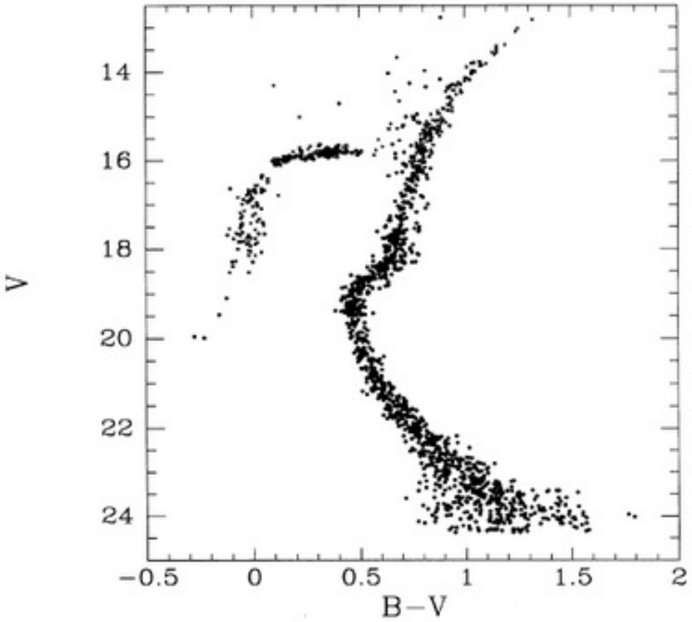
So a galaxy CMD is a mix of stars with different ages and metallicities.

Open Clusters



young, metal-rich open cluster

Globular Clusters



old, metal-poor globular cluster

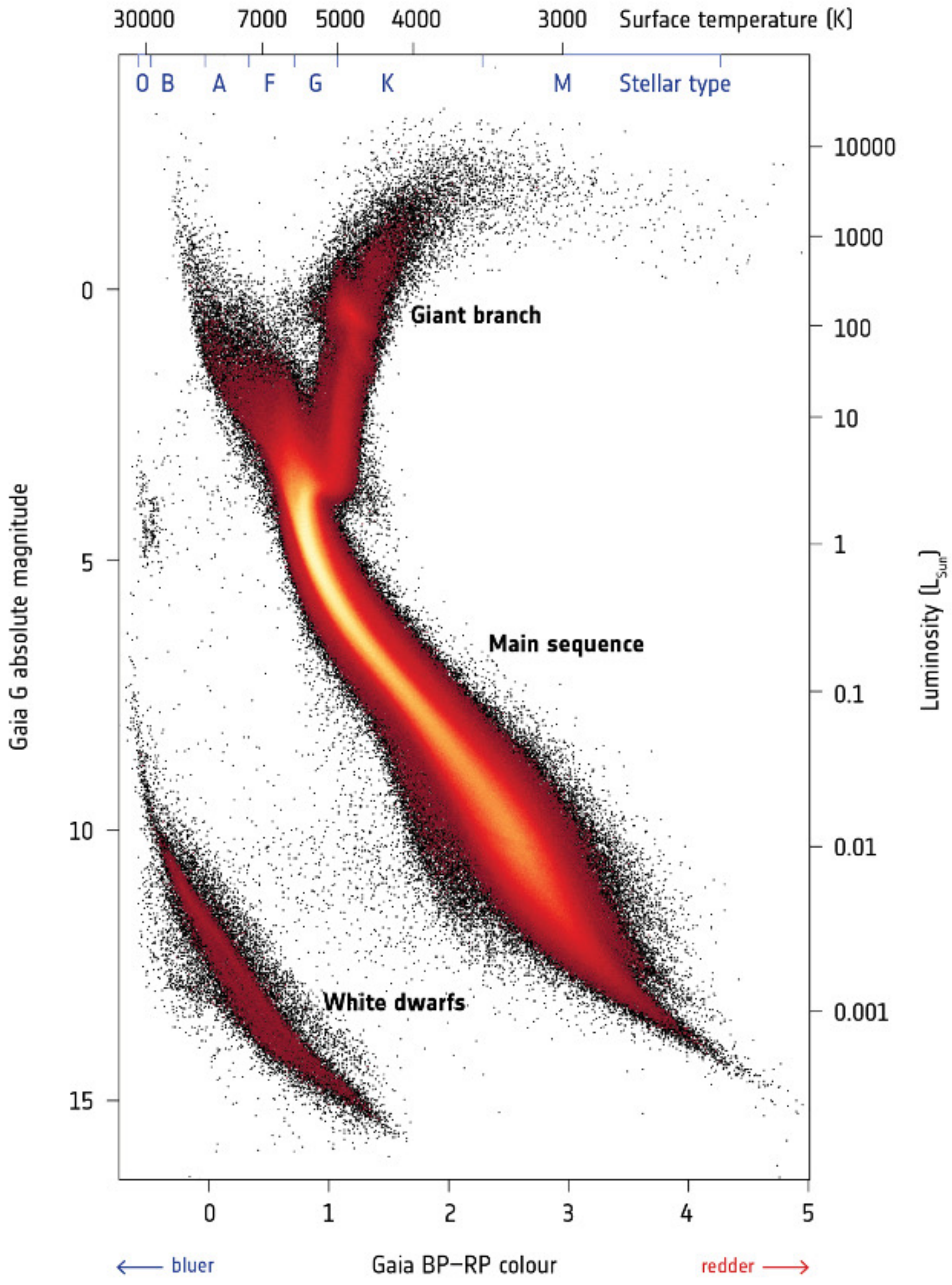
The color-magnitude diagram for the Milky Way's disk

Age information:

- The upper main sequence: young massive stars
- The lower main sequence: stars of a wide range of ages
- The giant branch and white dwarf sequence: old evolved stars

Metallicity information (see also notes from Jan 22):

- Main sequence: higher metallicity results in more metal absorption lines in the blue part of a star's spectrum ("line blanketing"), so metal-rich stars are slightly redder than low metallicity stars.
- Red giants: higher metallicity means more absorption by the stellar envelope, which makes it swell up more and become cooler. Metal-rich red giants are redder than metal-poor ones.

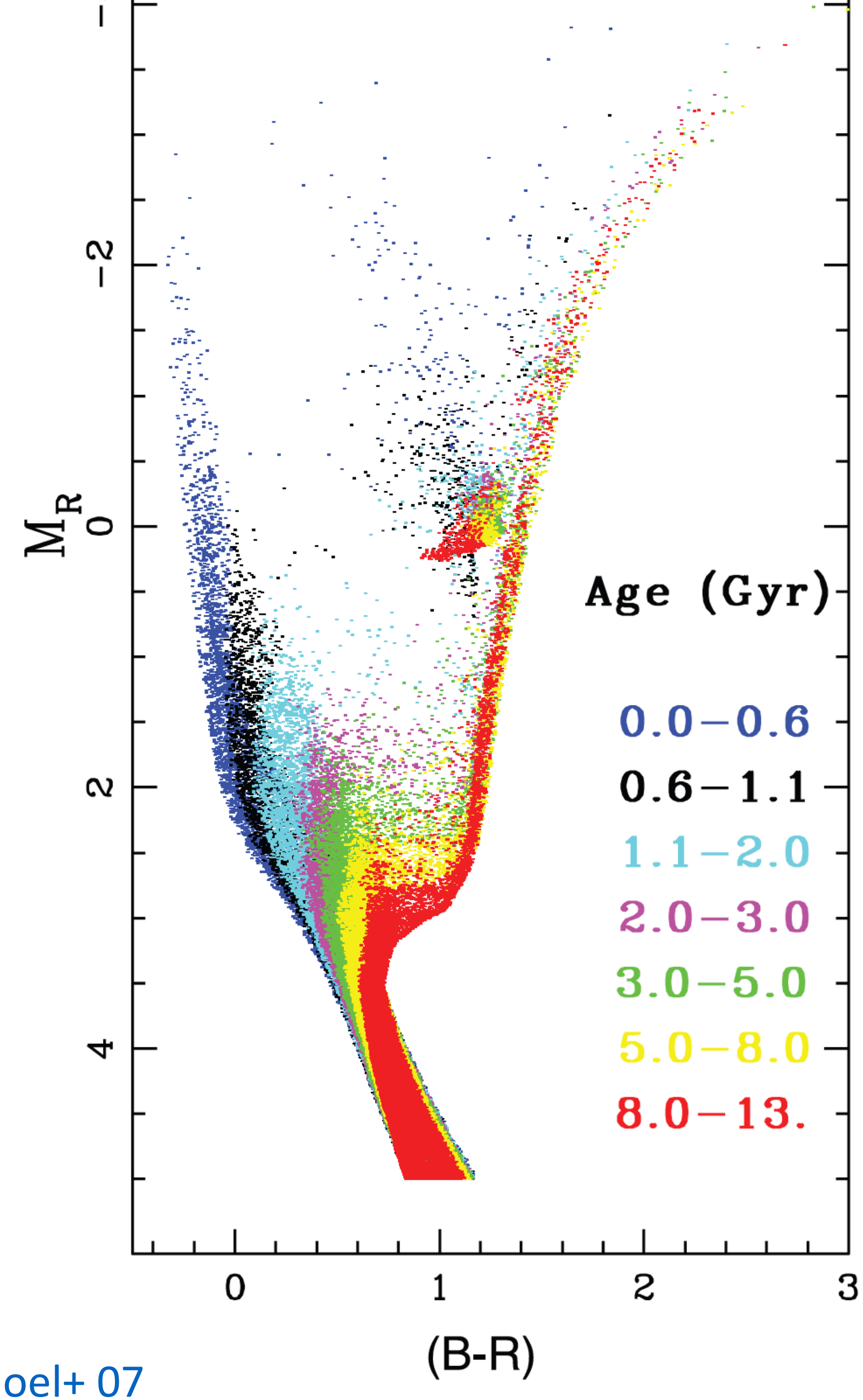


A synthetic color magnitude diagram (CMD)

Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

Milky Way satellite galaxies are close enough that we see this full CMD, including the faint main sequence turn off stars. Very good information on the age and metallicity distribution of stars in these galaxies.



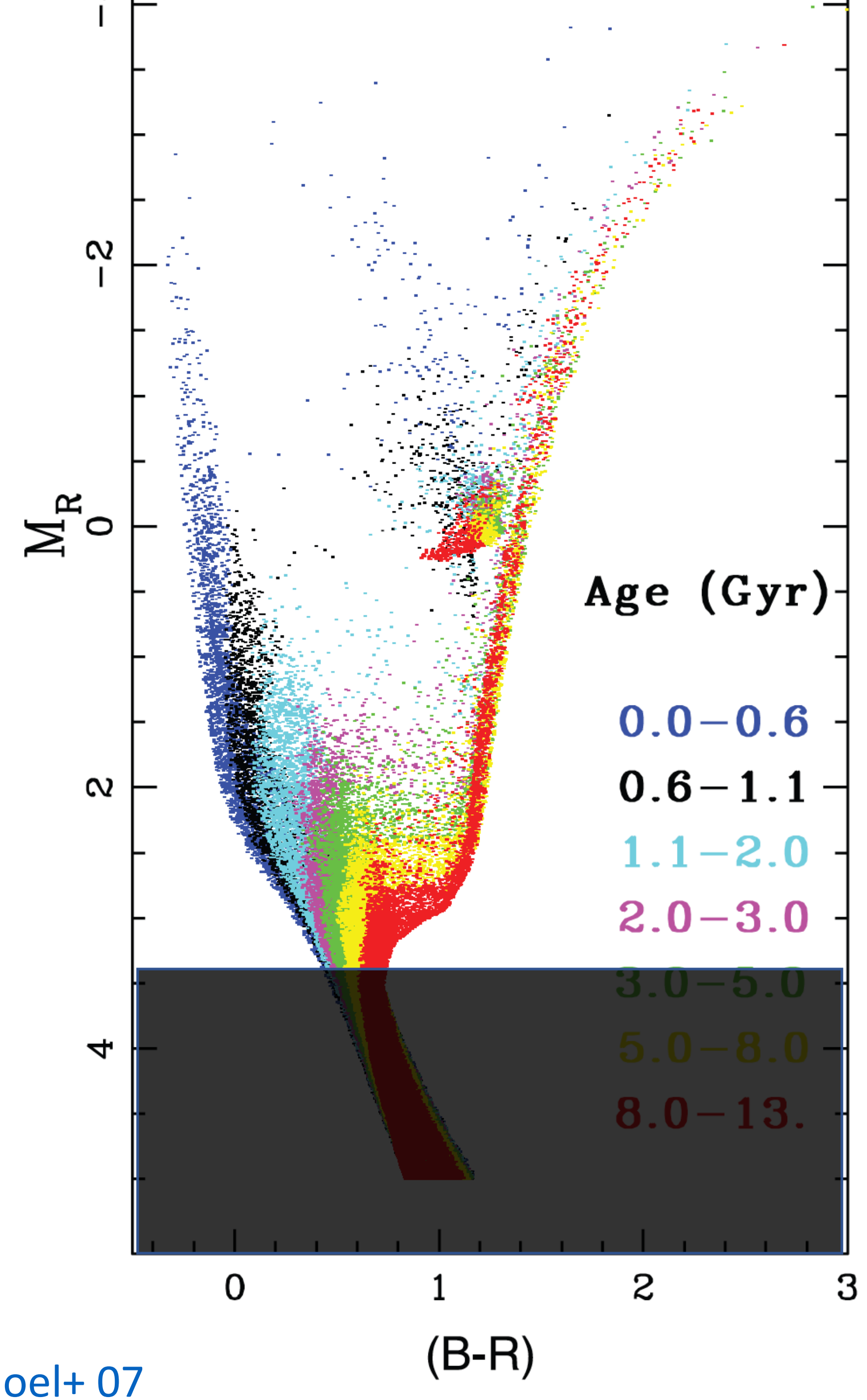
Noel+ 07

A synthetic color magnitude diagram

Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

For Andromeda (750 kpc away), we can only see down just past the main sequence turnoff. Fainter stars are not seen individually, but contribute to the overall brightness of the galaxy.



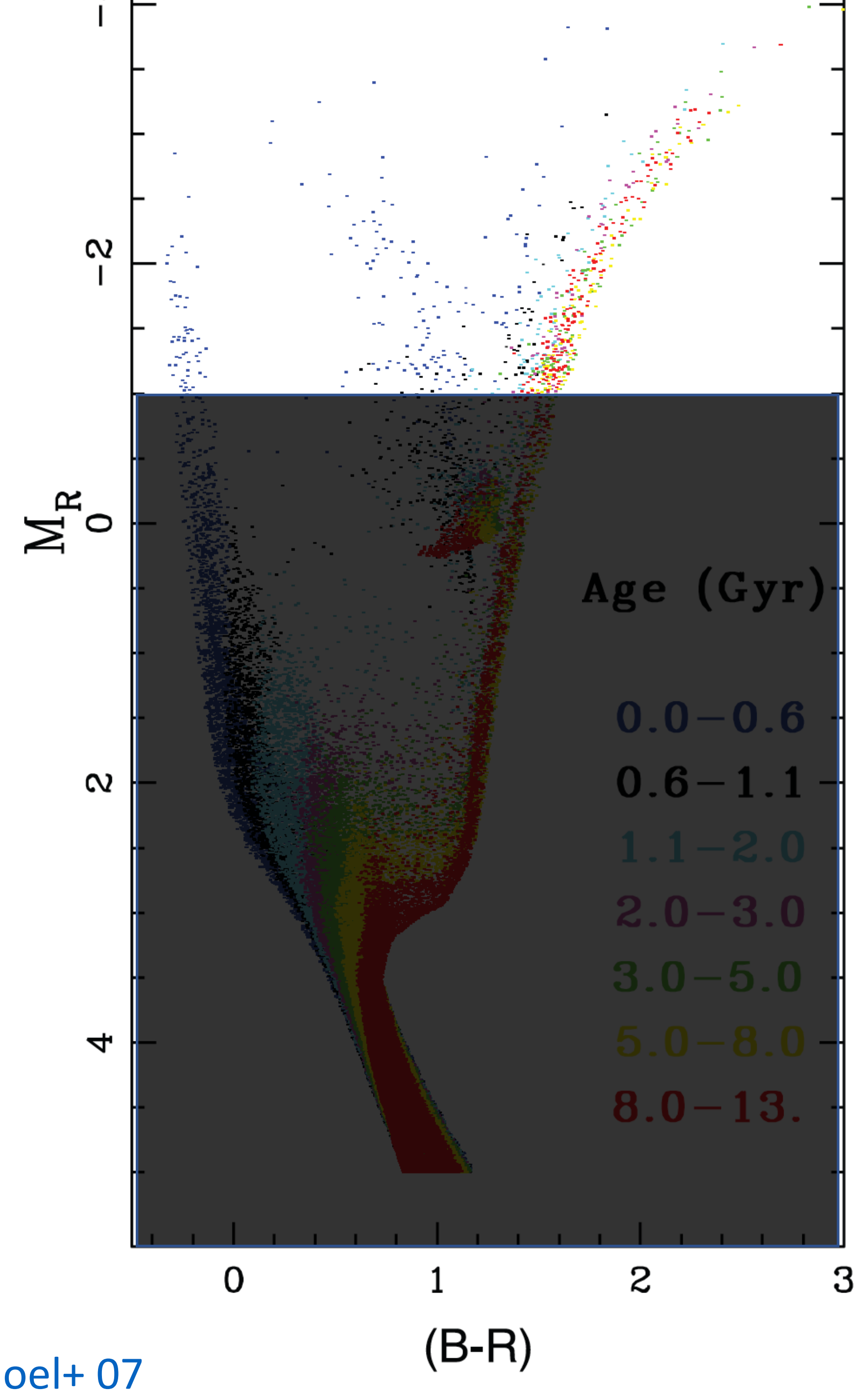
Noel+ 07

A synthetic color magnitude diagram

Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

For galaxies further away, we start to lose all but the very brightest (youngest) stars on the main sequence, and old stars on the red giant and asymptotic giant branches. (M101, 7 Mpc away)



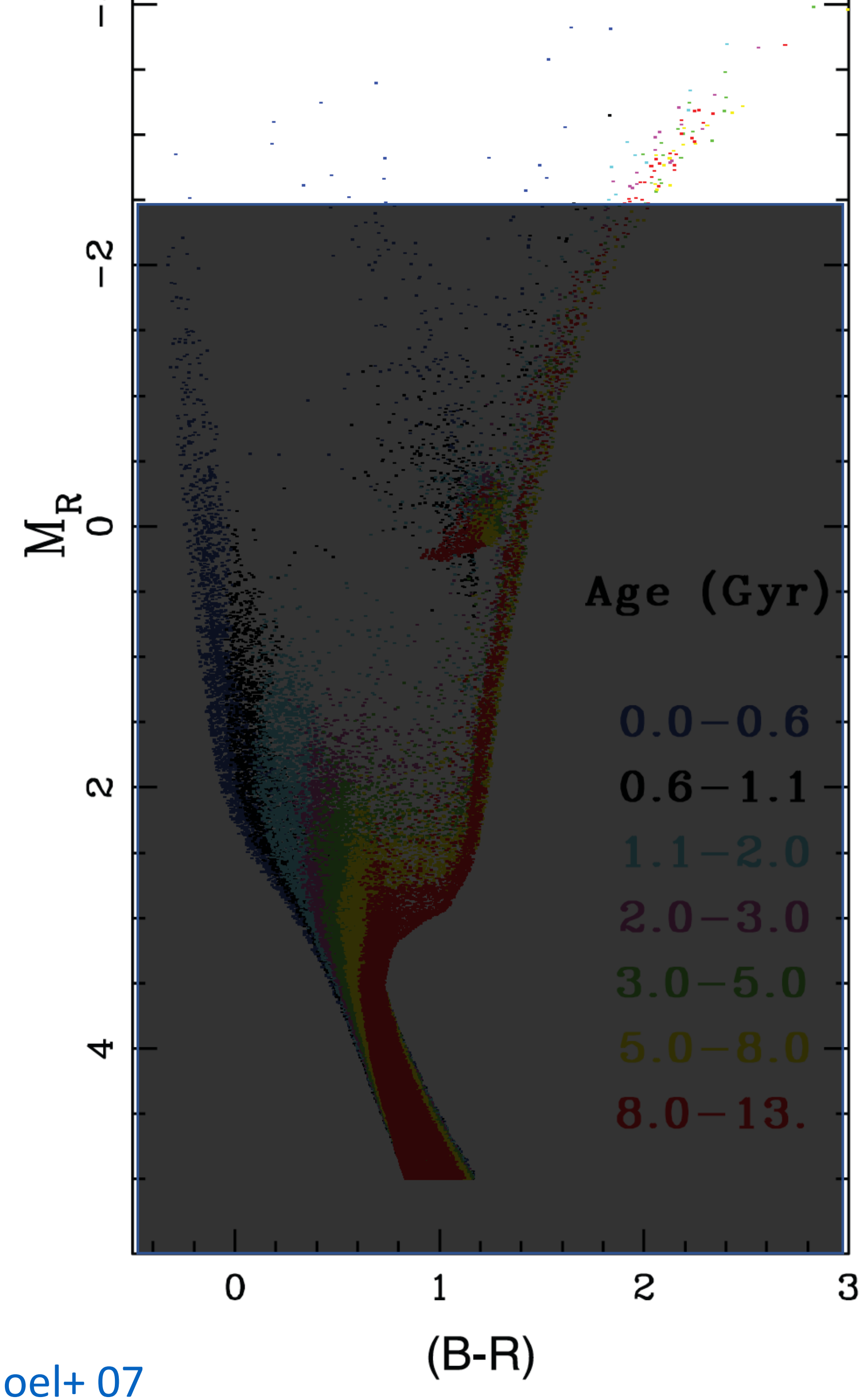
Noel+ 07

A synthetic color magnitude diagram

Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

At the distance of the Virgo cluster (16 Mpc), it's difficult to get anything but the very brightest stars. And at even larger distances, information about individual stars is pretty much lost completely.



Noel+ 07

Integrated Light and Surface Brightness

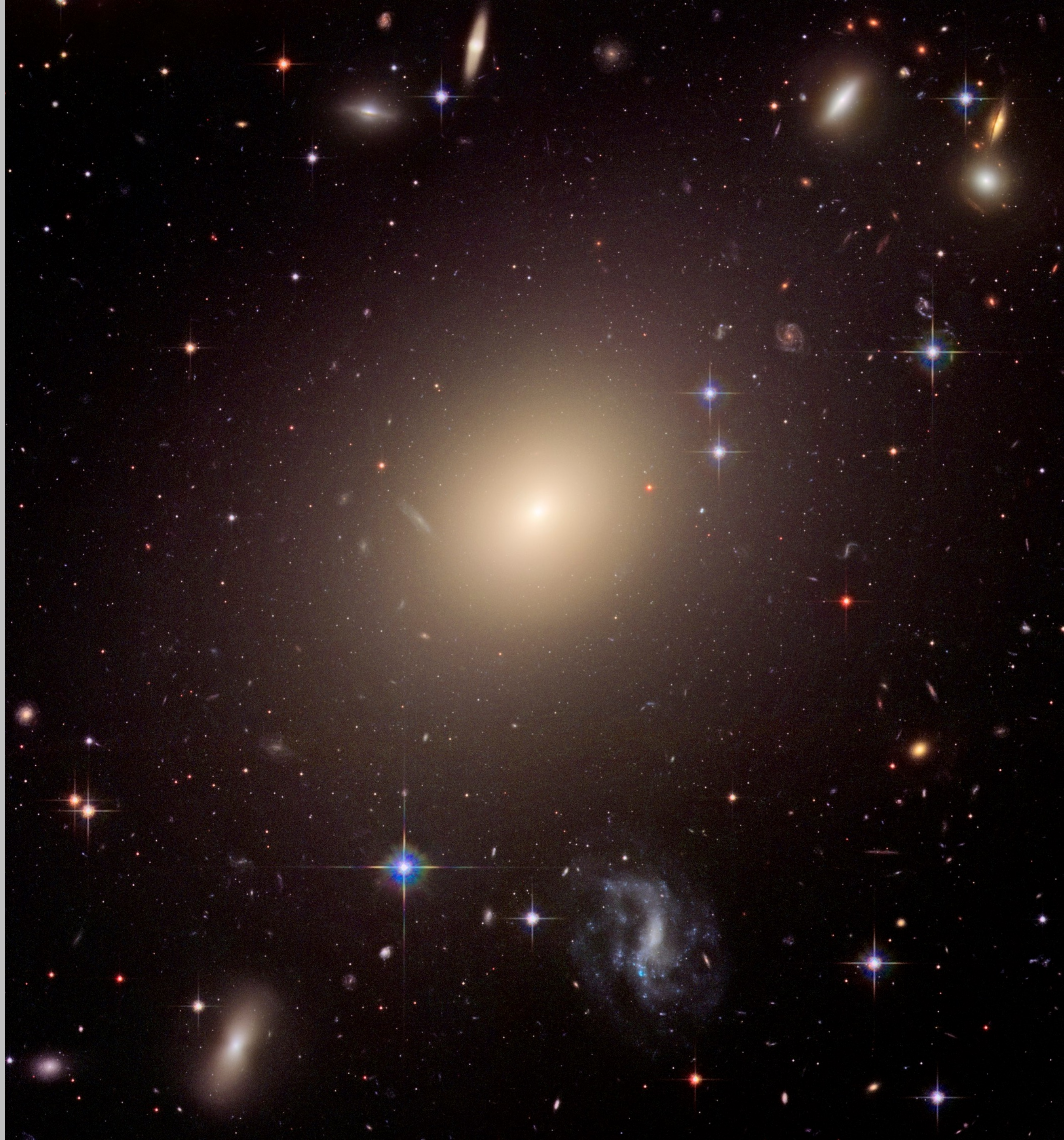
Most galaxies are too distant to see their individual stars. Stars are too faint, and they are also crowded too closely together. Instead, we see the "integrated light" of all those stars mixed together.

When the flux from all the stars is spread over a galaxy, we talk about galaxy's flux per area (f/A), or surface brightness (μ).

Surface brightness is a logarithmic measure of flux per area, just like magnitudes are a logarithmic measure of flux.

$$\begin{aligned}\mu &= -2.5\log(f/A) + C \\ &= -2.5\log f + 2.5\log A + C \\ &= m + 2.5\log A\end{aligned}$$

The units are typically given as "magnitudes per square arcsecond", but **be careful**: $\mu \neq m/A$



Integrated Light and Surface Brightness

Example surface brightness calculation.

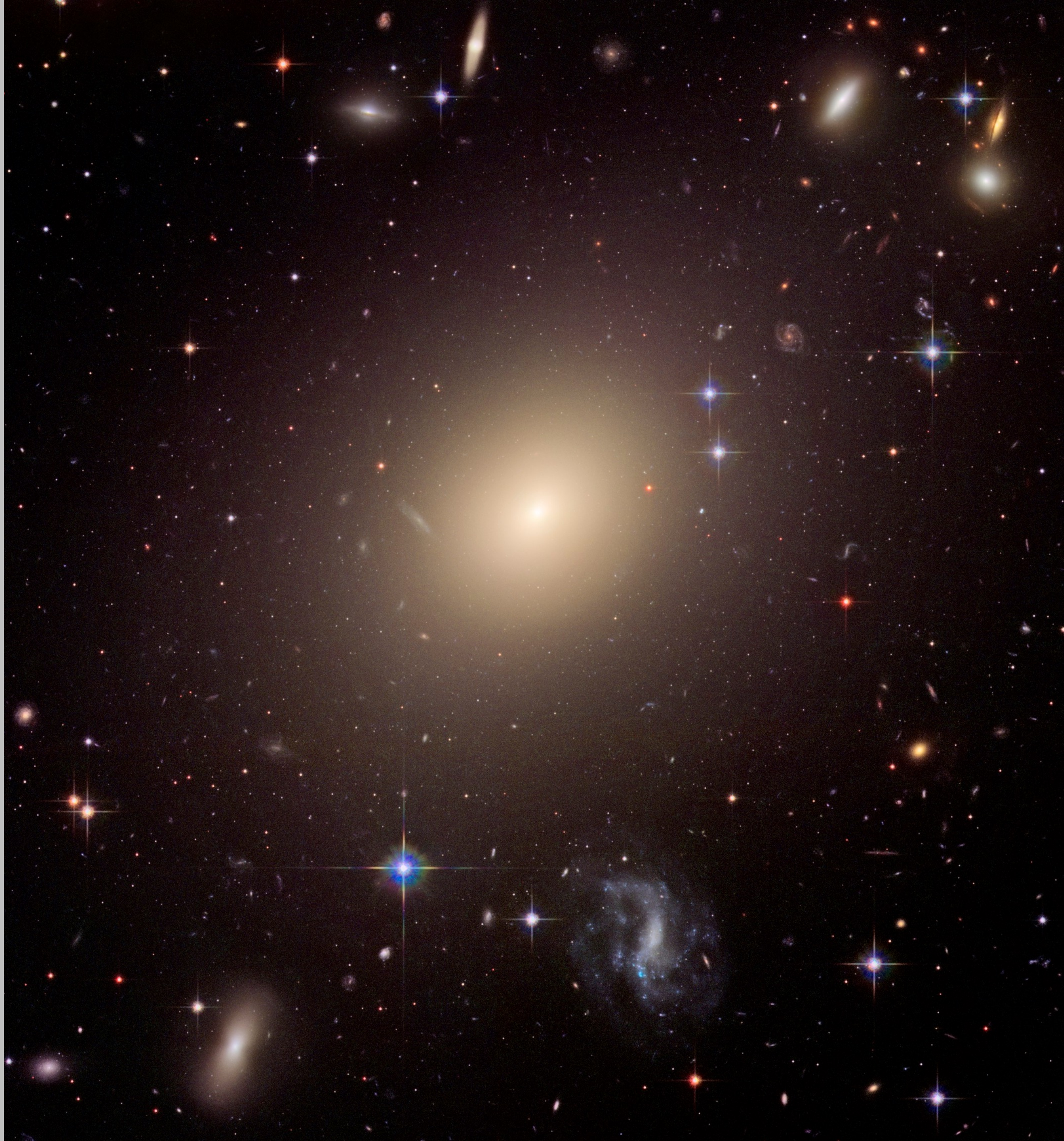
An elliptical galaxy has an integrated, total apparent magnitude (all its stars put together) of $m_{V,tot} = 12.0$ and a half-light radius of $r_e = 30$ arcseconds. What is its average surface brightness inside the effective radius?

$$\begin{aligned} m_{V,1/2} - m_{V,tot} &= -2.5\log\left(L_{1/2}/L_{tot}\right) \\ &= -2.5\log(1/2) \\ &= 0.75 \end{aligned}$$

So $m_{V,1/2} = m_{V,tot} + 0.75 = 12.75$

Then the galaxy's average surface brightness inside that radius is:

$$\begin{aligned} \langle\mu\rangle &= m_{V,1/2} + 2.5\log(\pi r_e^2) \\ &= 12.75 + 2.5\log(\pi 30^2) \\ &= 21.38 \text{ mag/arcsec}^2 \end{aligned}$$



Surface Brightness and Luminosity Density

Think about flux per area will change if you move a galaxy to twice its distance.

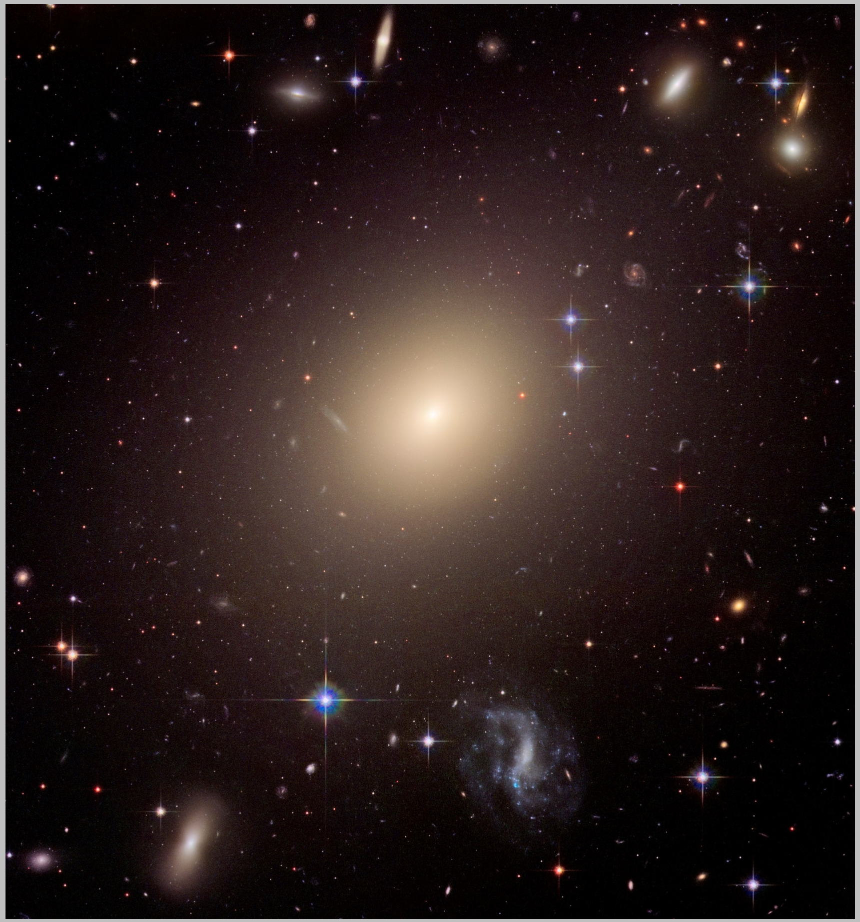
Flux drops by $1/r^2 = 1/4$
Size drops by $1/r$, so area drops by $1/r^2 = 1/4$

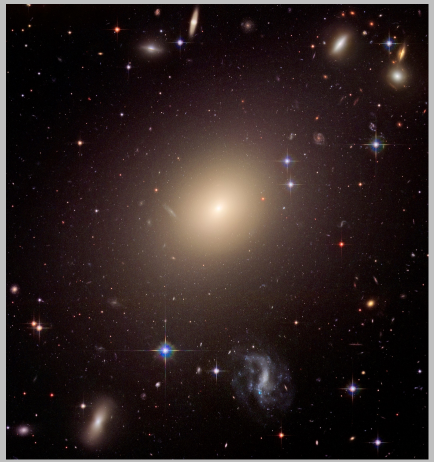
So flux per area stays constant.

The observed surface brightness of a galaxy does not depend on distance! It is an ***intrinsic property*** of the galaxy.

The surface brightness can be converted to a luminosity surface density of the galaxy.

Surface brightness: flux/area (logarithmic mag/arcsec^2)
Luminosity density: luminosity/physical area ($L_\odot$/pc^2)





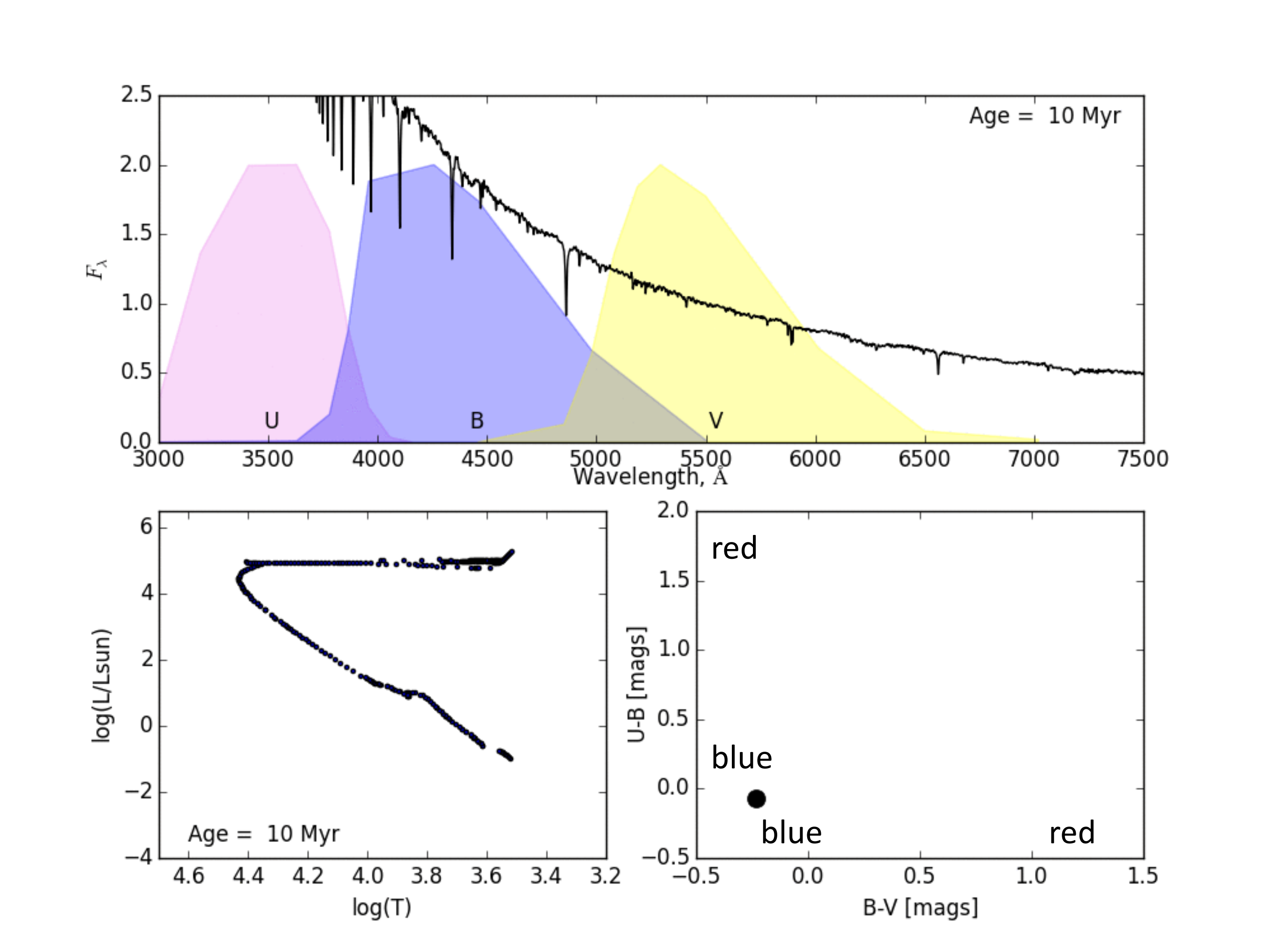
Back to Stellar Populations

We can measure the colors of galaxies and take spectra of galaxies, but when we do that we are measuring the integrated light of all its populations put together. A galaxy spectrum (or color) is different from a star spectrum (or color).

Look at a simple stellar population (SSP):
A single burst of star formation, whose stars then just evolve and die over time.

Look at how the spectrum changes.
Look at how the CMD changes
Look at how the U-B and B-V colors change.

Time evolution of an evolving SSP ⇒



Stellar Populations with different star formation histories

The properties of the integrated light depend on the mix of stellar populations, which depends on the star formation history of a galaxy.

Imagine a star formation rate that follows an exponential decline with time:

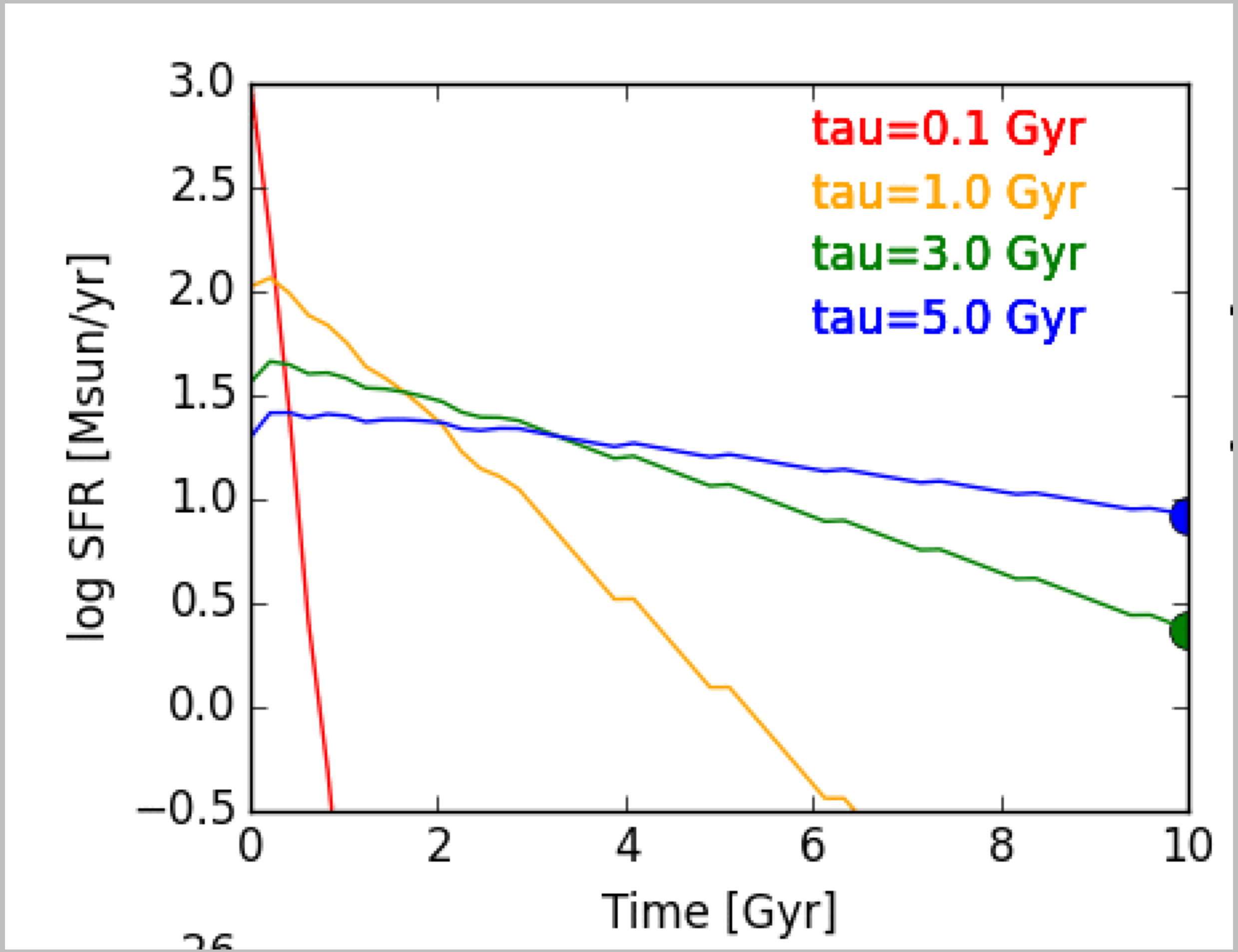
$$SFR(t) = Ce^{-t/\tau}$$

where τ is a characteristic time scale.

$\tau = 0.1$ Gyr: rapid burst, quickly dies out
$\tau = 5.0$ Gyr: very gradual decline in SFR

Look at four different τ models, each of which has made a total amount of 10^{11} $M_{\odot}$ worth of stars after 10 Gyr.

How does the color change with time?



Stellar Populations with different star formation histories

The properties of the integrated light depend on the mix of stellar populations, which depends on the star formation history of a galaxy.

Imagine a star formation rate that follows an exponential decline with time:

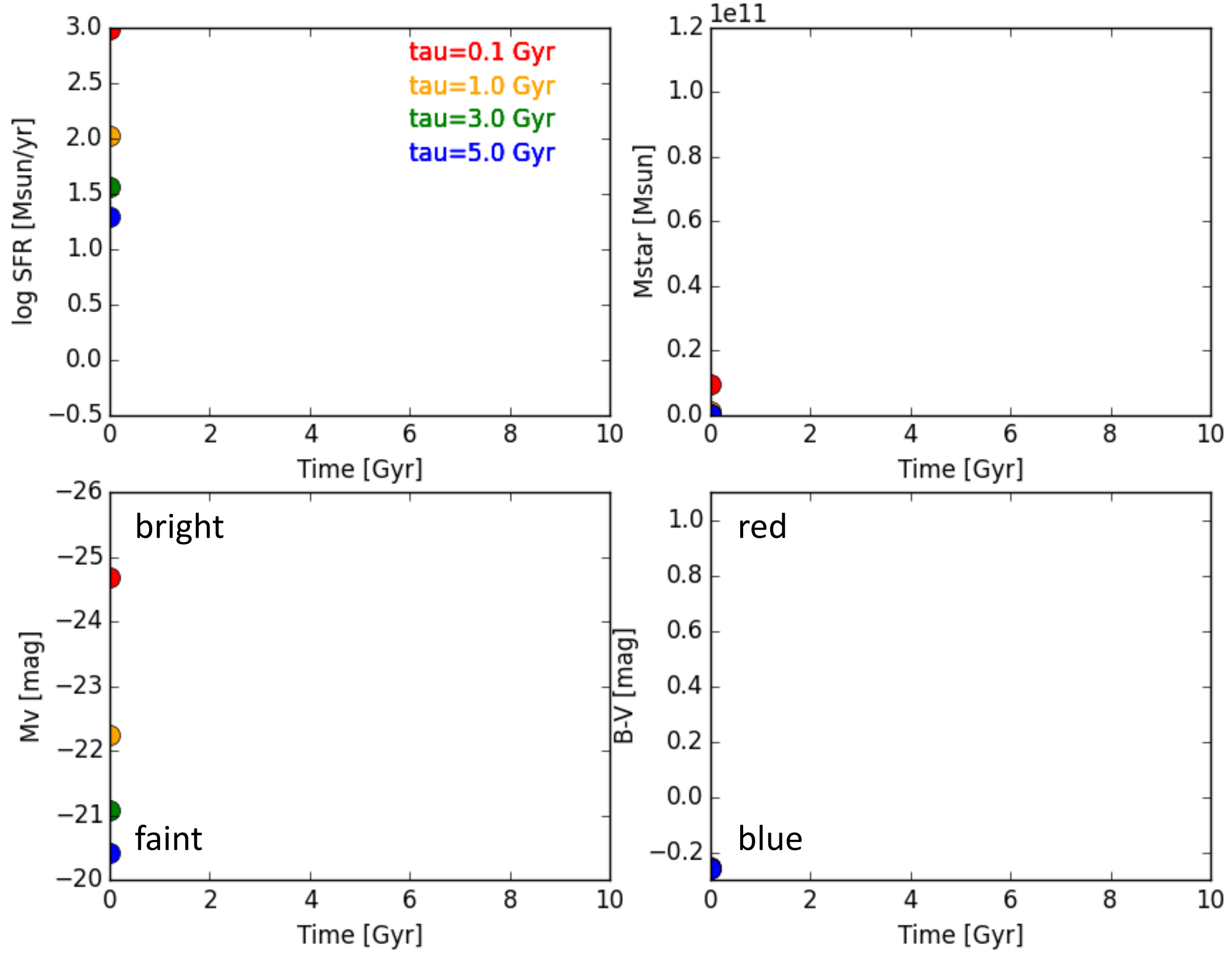
$$SFR(t) = Ce^{-t/\tau}$$

where τ is a characteristic time scale.

$\tau = 0.1$ Gyr: rapid burst, quickly dies out
$\tau = 5.0$ Gyr: very gradual decline in SFR

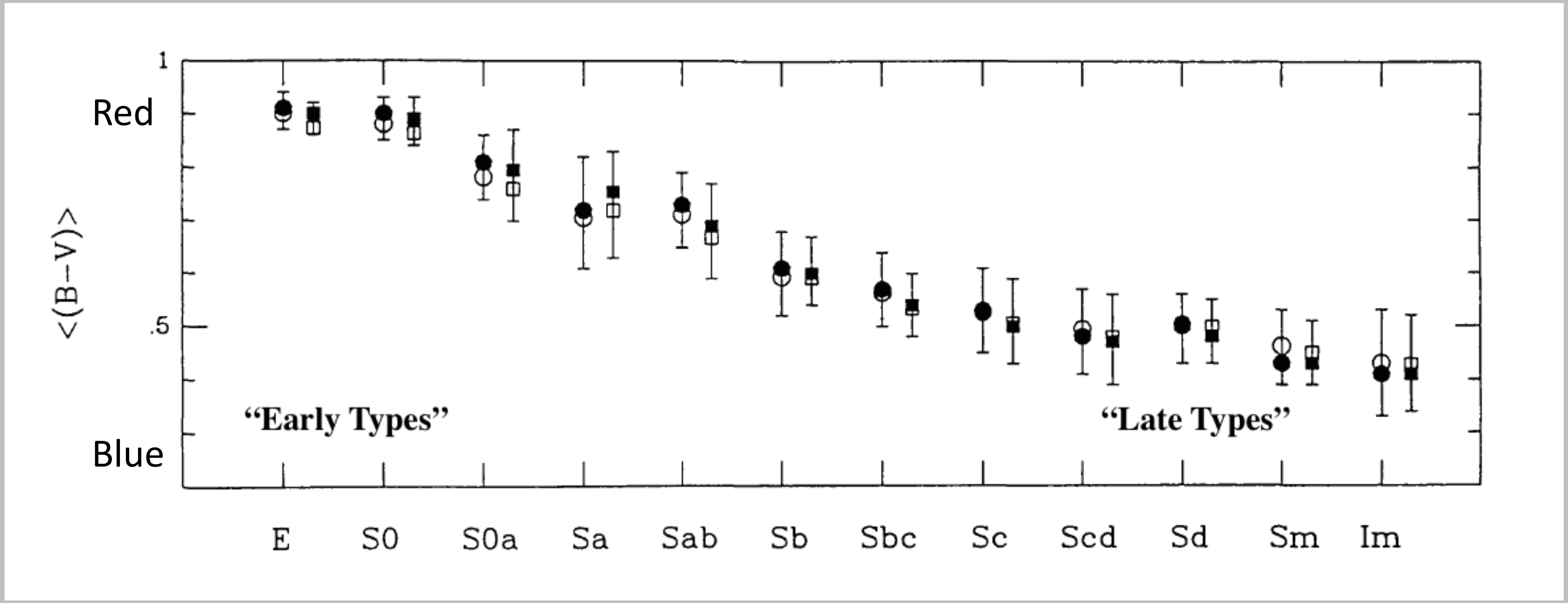
Look at four different τ models, each of which has made a total amount of 10^{11} $M_\odot$ worth of stars after 10 Gyr.

How does the color change with time?



Integrated colors of galaxies

Look at how the average B−V color of galaxies changes across different galaxy types.



Early type galaxies (E/S0) have redder colors than late type galaxies (Sc/Sm/Im). This is largely a difference in stellar population age. Stars in early type galaxies are, on average, older than those in late type galaxies.

But even late type galaxies have lots of old stars.

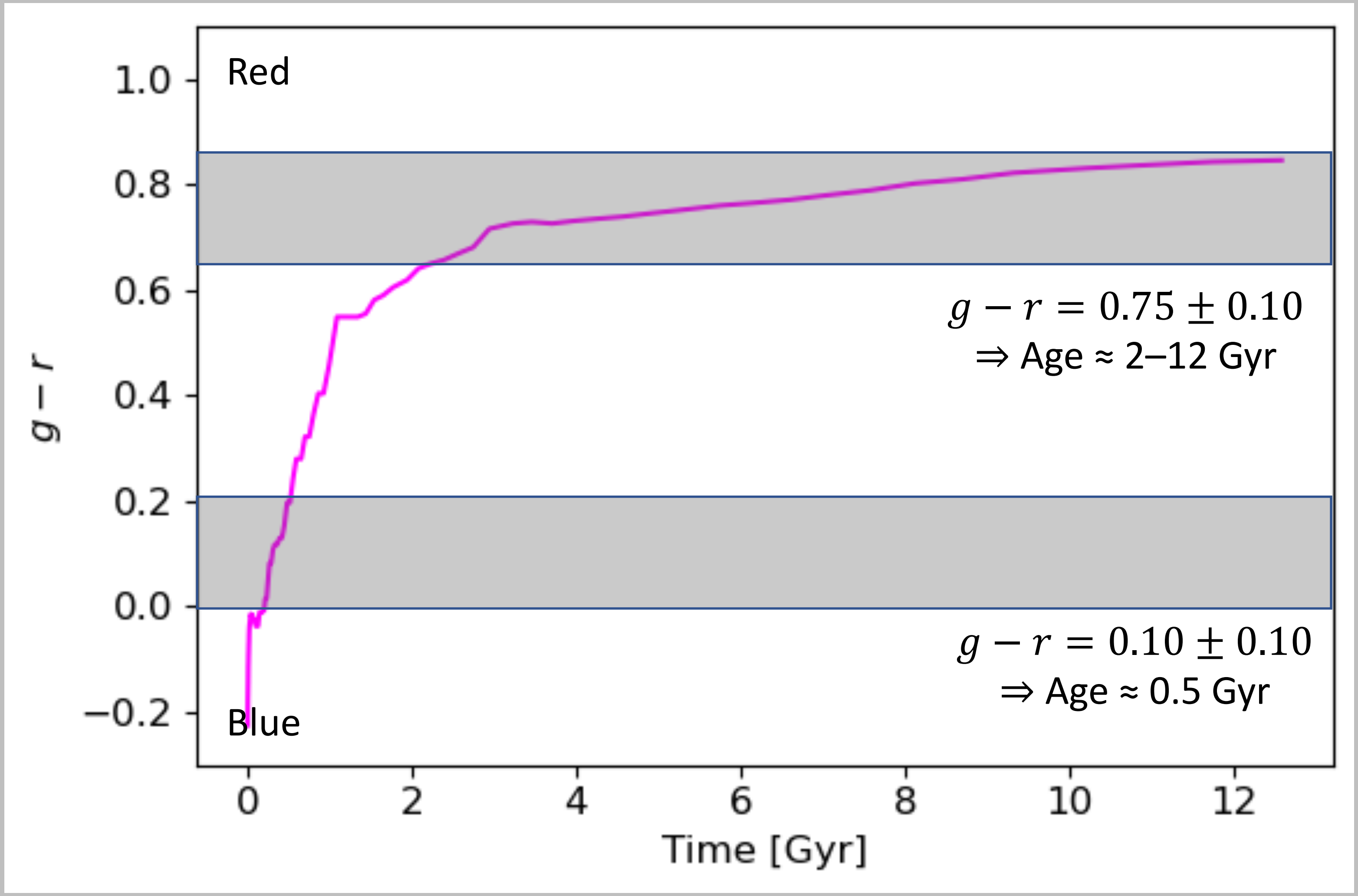
And even a small amount of new star formation can turn a galaxy blue, due to the brightness of massive young stars.

Colors, ages, and metallicity

Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

Color evolution for a single burst stellar population with solar metallicity.

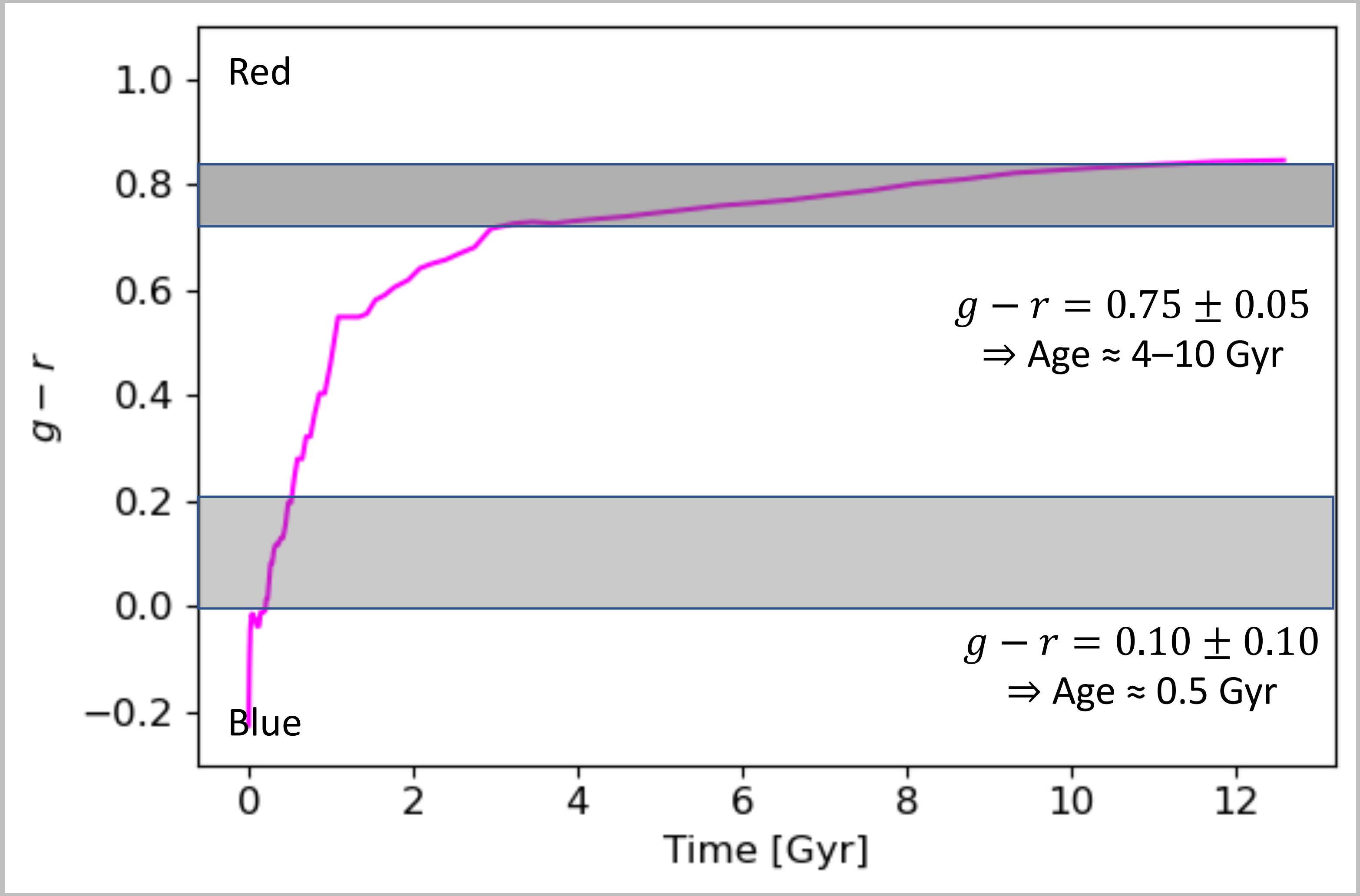


Colors, ages, and metallicity

Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

Color evolution for a single burst stellar population with solar metallicity.



Banana analogy
courtesy of Mia de los Reyes (Caltech)

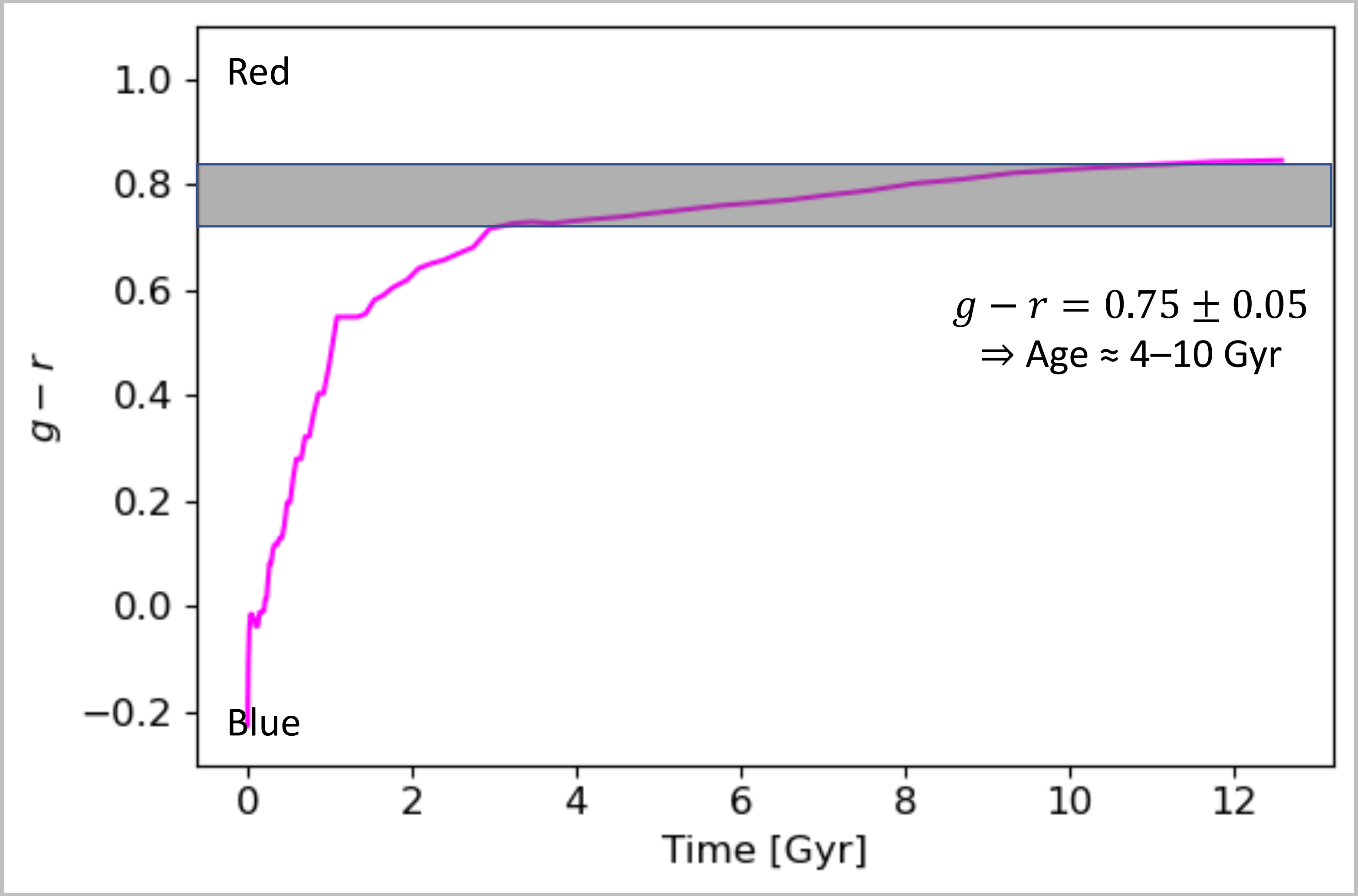
Banana analogy
courtesy of Mia de los Reyes (Caltech)

Colors, ages, and metallicity

Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

Color evolution for a single burst stellar population with solar metallicity.



Colors, ages, and metallicity

Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

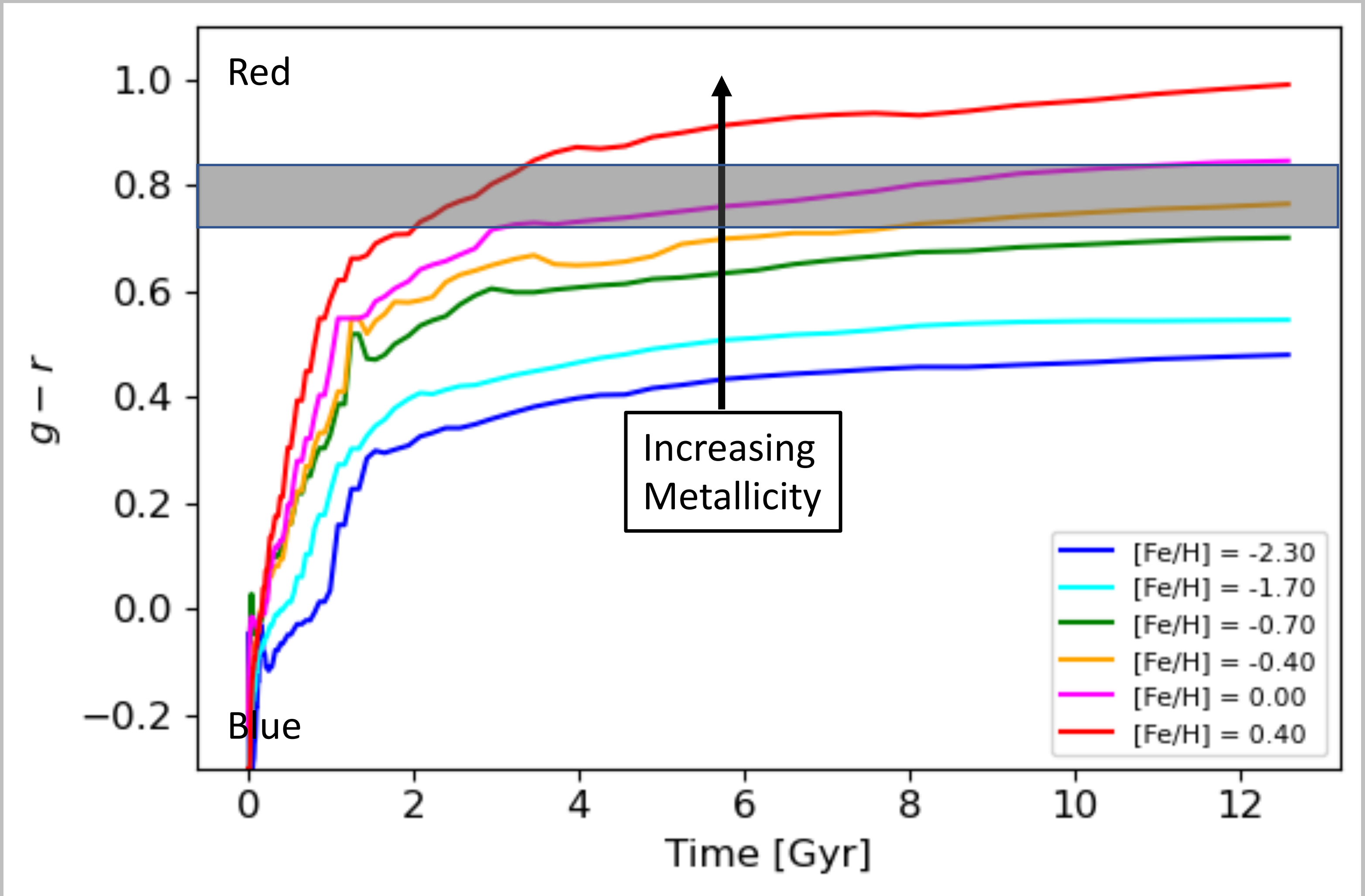
Age-metallicity degeneracy: Metallicity effects makes this even harder: red populations can be younger and metal-rich, or older and metal-poor.

Dust and different star formation histories further complicate things!

Solutions (both time-consuming):

- Many different filters / wavelengths.
- Spectroscopy.

Color evolution for a single burst stellar population with varying metallicity.



Stellar mass-to-light ratio: $(\mathcal{M}/L)_*$

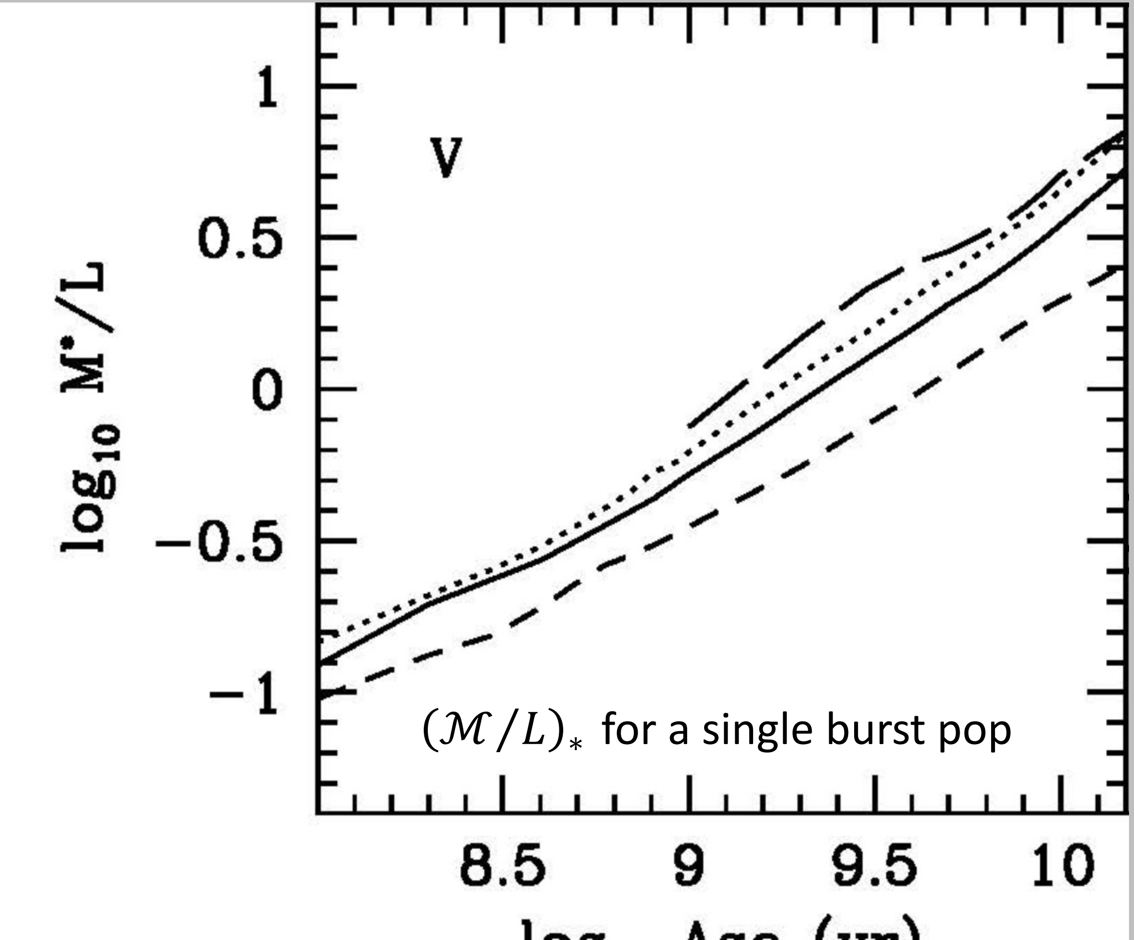
We measure a galaxy's integrated light, but we would like to convert that to a stellar mass. How much stellar mass does it take to get a given amount of light? What is the ratio of mass to light **for stars**?

Star	Mass ($\mathcal{M}_\odot$)	Luminosity ($L_{\odot\,V}$)	$(\mathcal{M}/L)_{*,V}$ (solar units)
Sun	1	1	1.000
O star	20	6000	0.003
M dwarf	0.4	0.006	67
Red Giant	1	25	0.04

For a galaxy, it depends on the mix of stars in the galaxy. In general, $(\mathcal{M}/L)_*$ increases as age increases. $\Rightarrow$

It is also very sensitive to which wavelength you are observing. $(\mathcal{M}/L)_*$ changes quickly with age at blue wavelengths, much less at red/infrared wavelengths.

Generally $(\mathcal{M}/L)_*$ must be inferred by modeling the population.



Courteau+ 14

END OF MATERIAL FOR MIDTERM #1

MIDTERM #1: Monday, Feb 24 -- in class

Study using your notes, the online course notes, and the HW assignments and solutions. Arguments and explanations you make in your answers must be based on material covered in class or on HW sets.

When answering questions, try to address both "what" and "why" in your answer. That is, both describe/define whatever is being asked about (that's the "what") and also give an explanation for how or why something works (the "why").

Sketches are useful, but if you are sketching a plot you should always have axes labeled (i.e., "Time", "Apparent Magnitude", etc). It's also a good idea to indicate which direction the values increase (i.e., "the Y-axis is magnitude, with brighter objects to the top").

When calculating something, if your answer doesn't make sense, say so! ("I got a size for the Sun of 10 meters, which is crazy small -- I must have done something wrong!"). Otherwise I would worry that you don't really understand how big the Sun really is...

Also on calculations, SHOW YOUR WORK and EXPLAIN YOUR STEPS. Without that information, if you make a mistake, it is very difficult to see where you went wrong and award proper partial credit. Wrong answers with no explanations will get zero points.

If you are absolutely stuck on a calculation and don't know how to finish (or even start), if you can at least make a qualitative estimate for what you expect the answer to be, and why, that can help with partial points.

Make sure to always have units attached to your numbers.

Disk Galaxies

Density of stars in the Milky Way's disk: $\rho(R, z) = \rho_0 e^{-|z|/z_0} e^{-R/h}$

Let's integrate over all z to get the surface density of the disk:

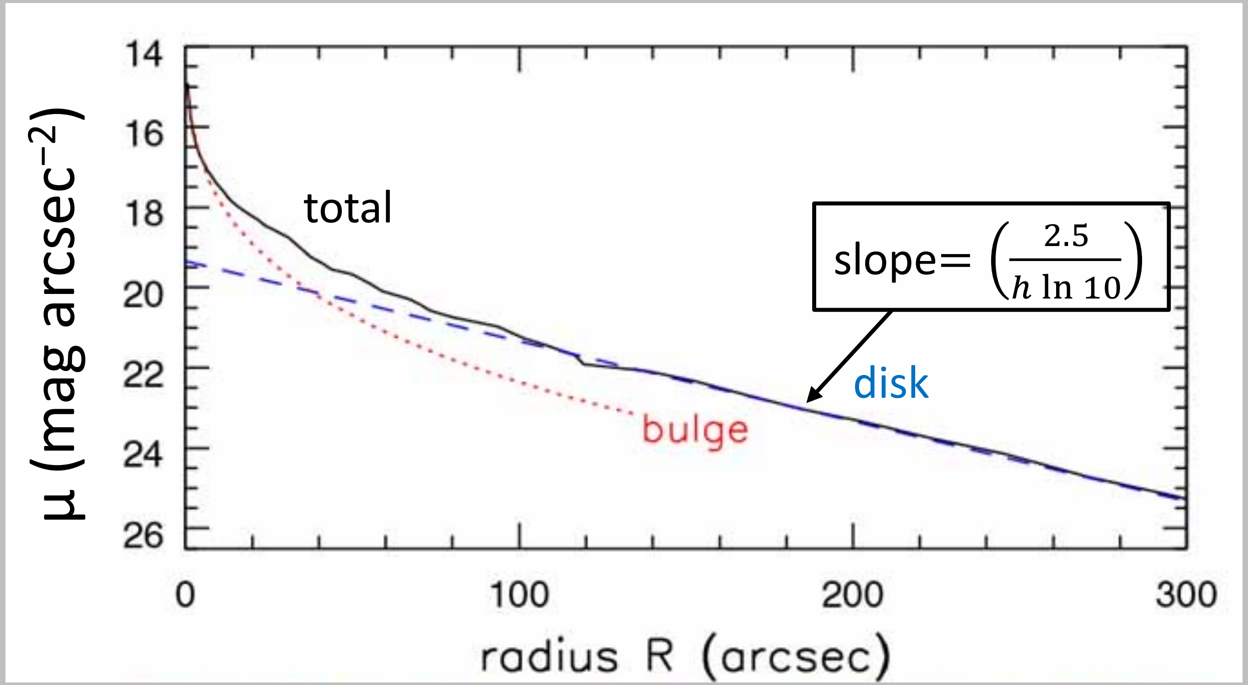
$$\Sigma(R) = \rho_0 e^{-R/h} \int_{-\infty}^{+\infty} e^{-|z|/z_0}\, dz = 2z_0 \rho_0 e^{-R/h}$$

So the stars are distributed exponentially with radius, which means the luminosity density of the disk will drop exponentially with radius:

$$I(R) = I_0 e^{-R/h}$$

Expressed as **surface brightness profile** in mag/arcsec^2:

$$\begin{aligned}
\mu(R) &= -2.5 \log I(R) + C \\
&= -2.5 \log\left(I_0 e^{-R/h}\right) + C \\
&= -2.5 \log I_0 + \frac{2.5}{\ln 10} \frac{R}{h} + C \\
&= \mu_0 + \frac{2.5}{\ln 10} \frac{R}{h}
\end{aligned}$$



Disk Galaxies and Surface Brightness

First, remember surface brightness is an intrinsic property of a galaxy, tracing the **luminosity density** of the disk.

surface brightness	luminosity density
μ_B = 27 mag/arcsec^2	I_B = 1.0 L_B/pc^2
μ_B = 22 mag/arcsec^2	I_B = 100.0 L_B/pc^2

surface brightness works just like magnitudes:

$$\mu_1 - \mu_2 = -2.5 \log\left(\frac{I_1}{I_2}\right)$$

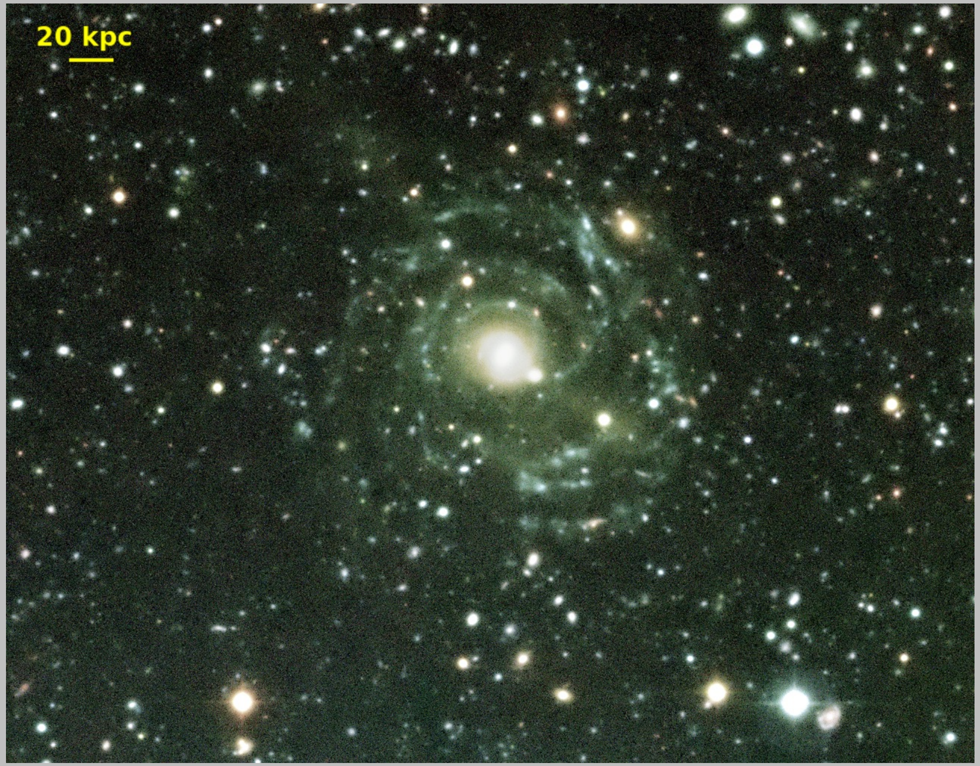
Galaxies show a **wide range** of surface brightnesses

⇐ **M101** (High surface brightness galaxy)

Malin 1 (Low surface brightness galaxy) ⇒

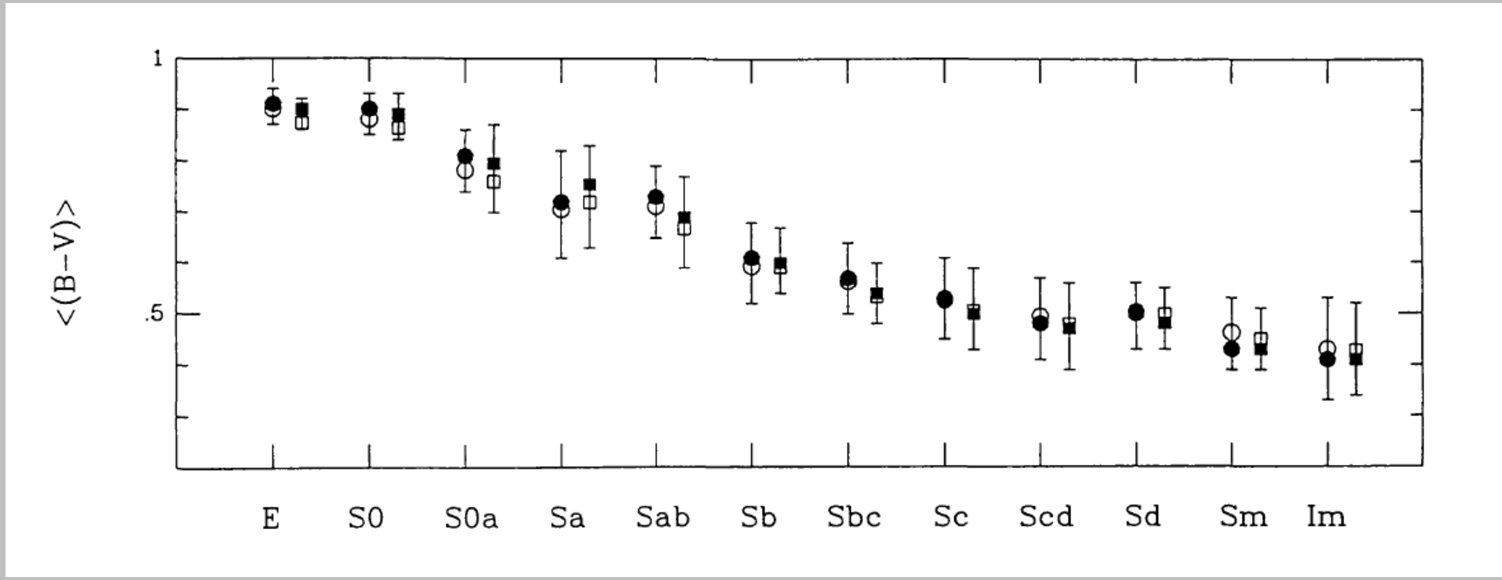
Both galaxies have the *similar total luminosity,* but Malin 1 has a *much lower luminosity density* and is also much bigger (larger physical scale length).

Boissier+16



Disk Galaxies, Star Formation, and Colors

The color of a galaxy depends on its stellar populations (and dust....). Remember the sequence of colors across the range of Hubble types.



M101 (Sc galaxy)

Disk galaxies are more gas-rich and have younger stars (on average) as you move across the Hubble sequence.

For big spirals like the Milky Way:

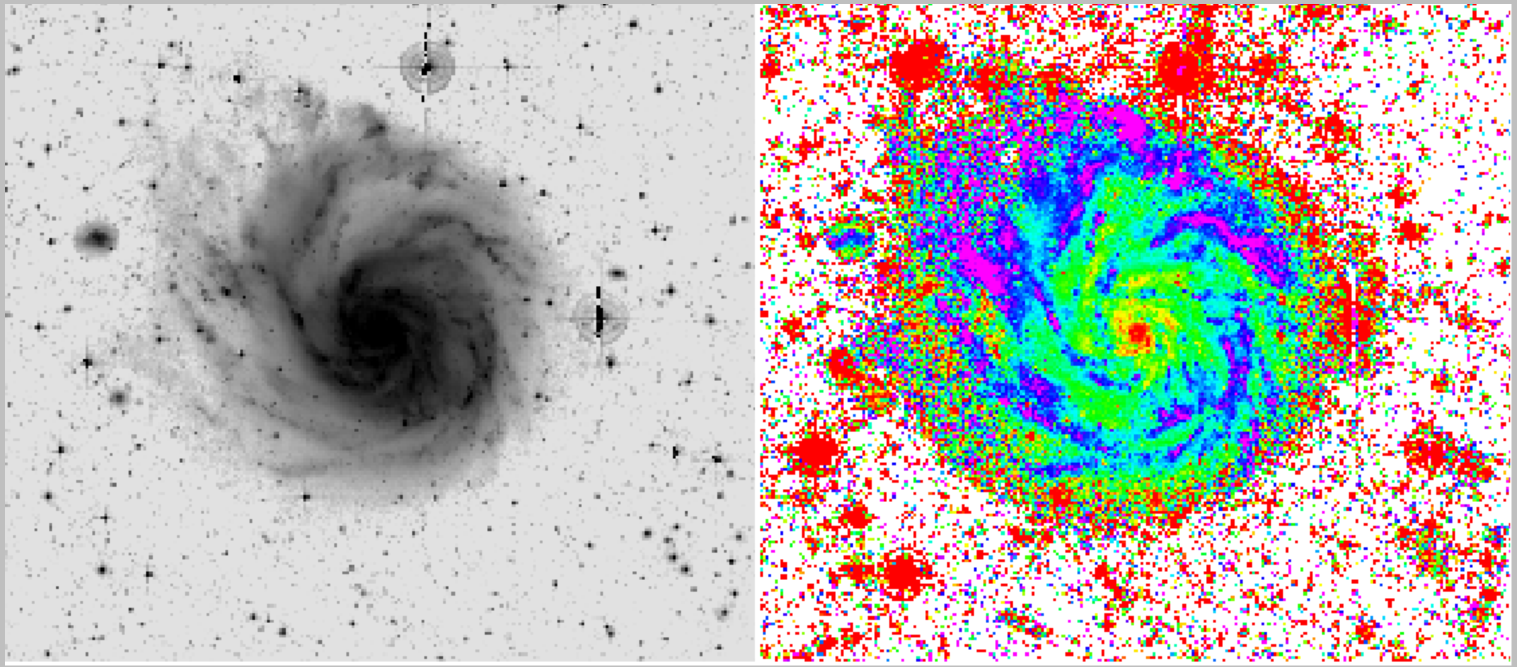
- Gas mass ~ few x $10^9\ \mathcal{M}_\odot$
- Star formation rates ~ a few $\mathcal{M}_\odot$/yr

Star formation converts gas to stars. How long can galaxies keep this up?

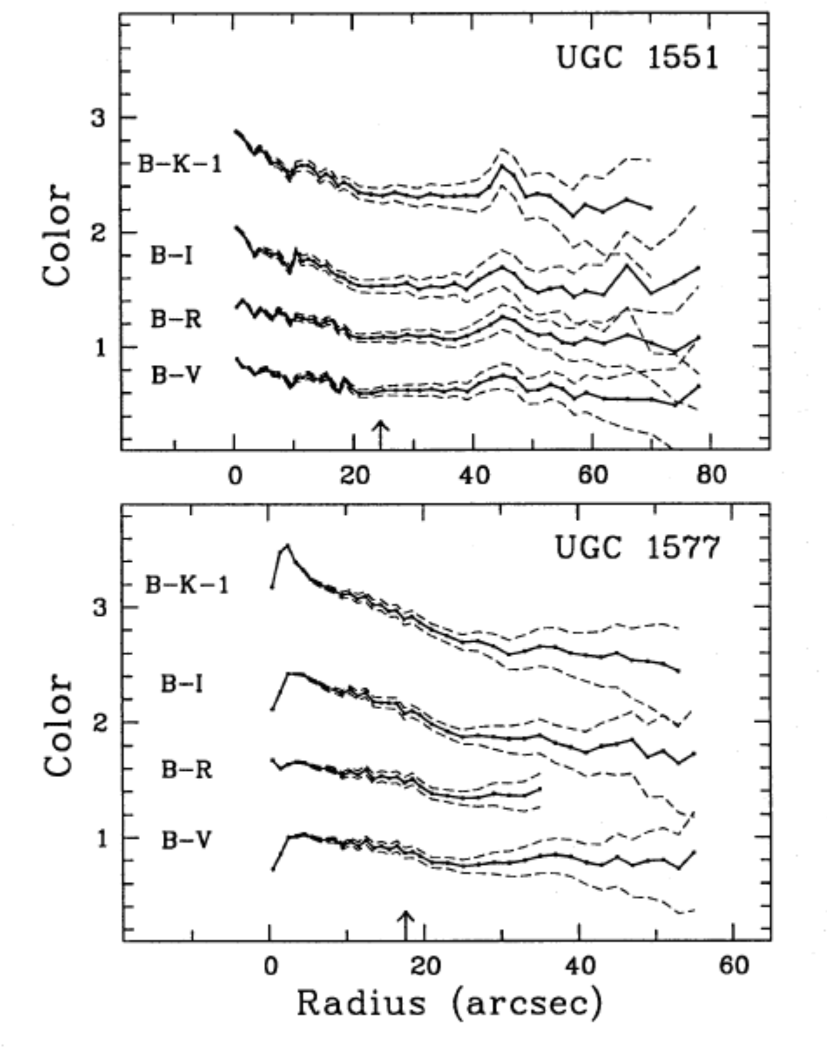
Gas depletion time: $t = \mathcal{M}_{gas}/SFR\ \sim$ few $\times\ 10^9$ yr

Disk Galaxies and Color Gradients

Disk galaxies also often show color gradients: a systematic change in color with radius. Disks typically get bluer in their outskirts:



M101 colormap (exaggerated!)
[Mihos+ 2013](#)

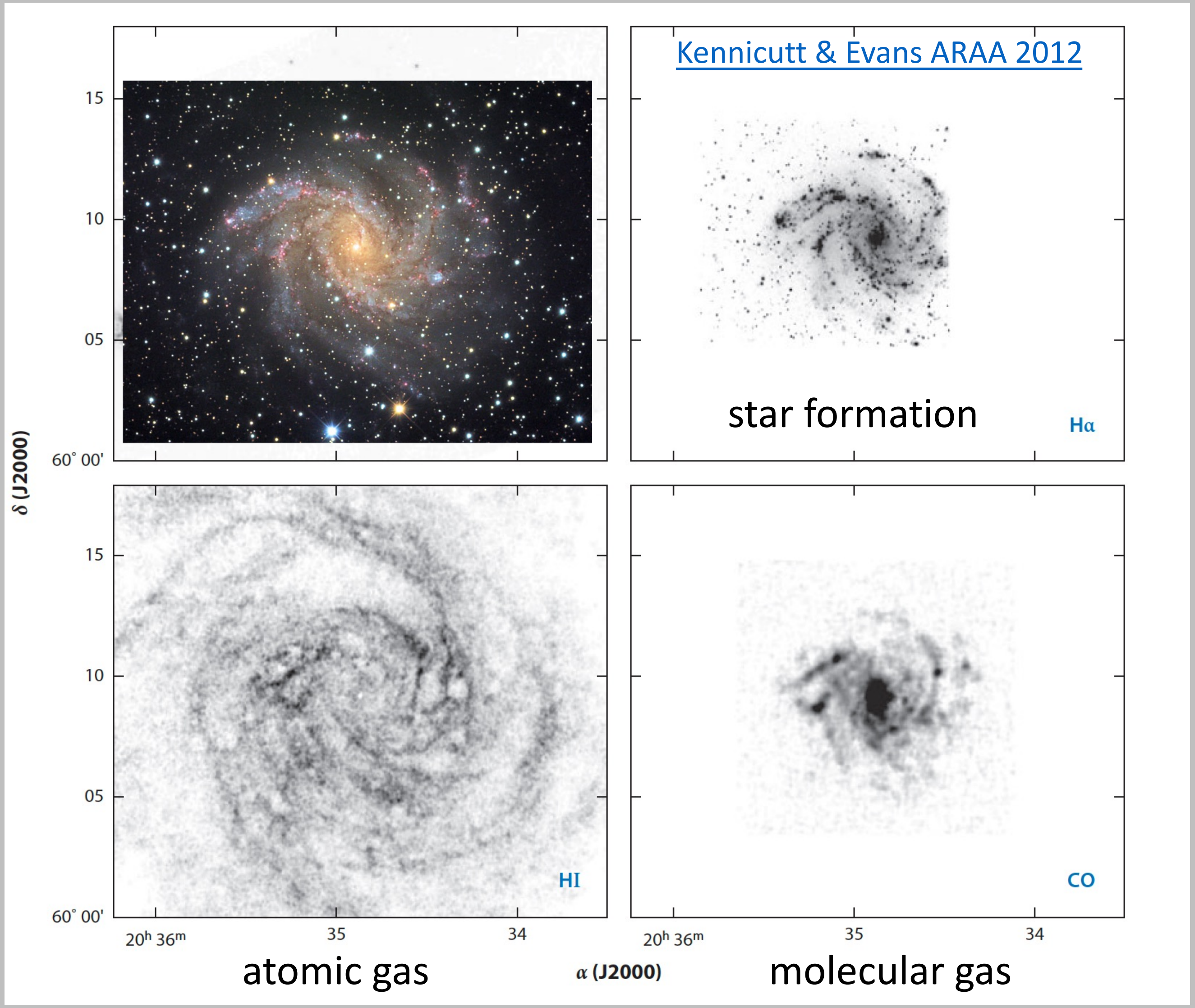


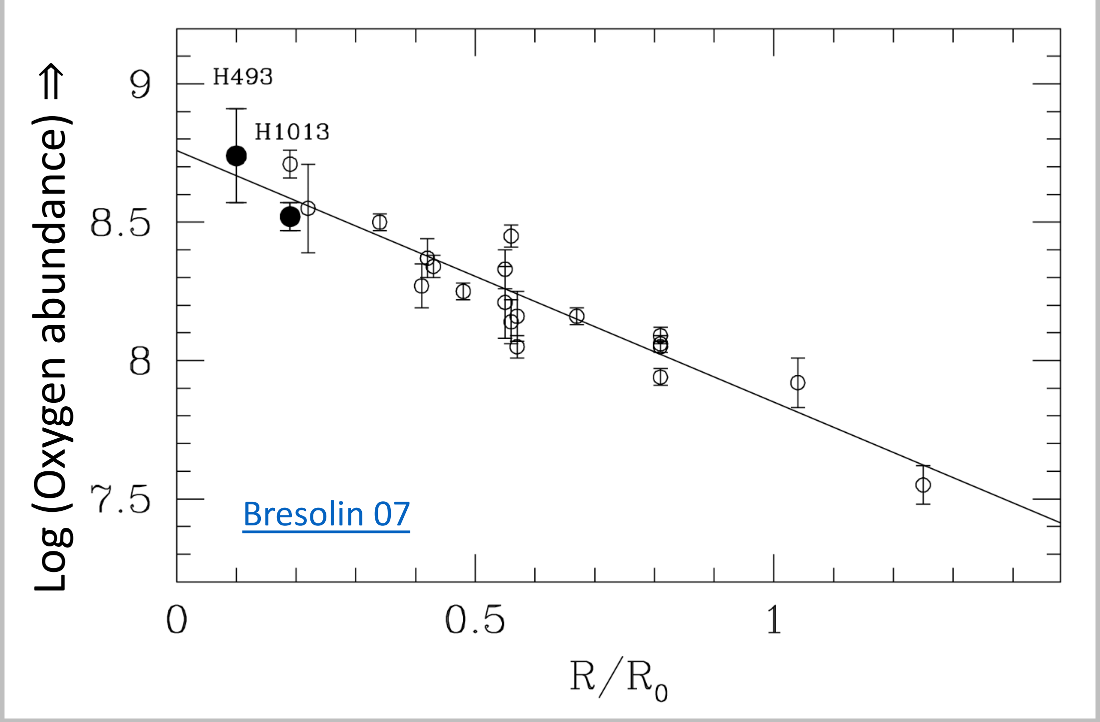
Color gradients in disks
[de Jong 1996](#)

Some of this bluing is likely due to lower metallicity and less dust in the outskirts, but most of it is a difference in mean age. Disk galaxy outskirts are younger on average than their inner parts.

Disk Galaxies and other radial trends

The gas fraction $\mathcal{M}_{gas}/(\mathcal{M}_{stars} + \mathcal{M}_{gas})$ also goes up as you go outwards. Disk have a lot of extended atomic hydrogen gas. ⇒





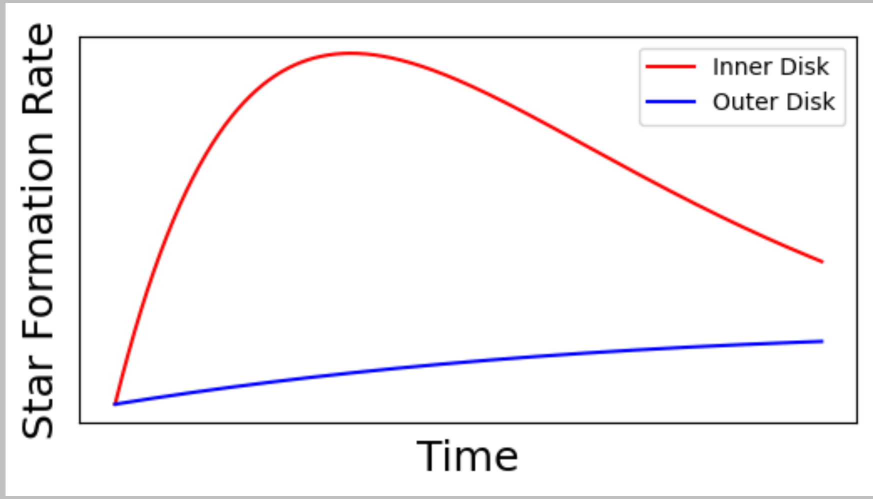
Disks typically show **metallicity gradients** as well. Outskirts have lower metallicity than inner parts.

⇐ M101 metallicity gradient

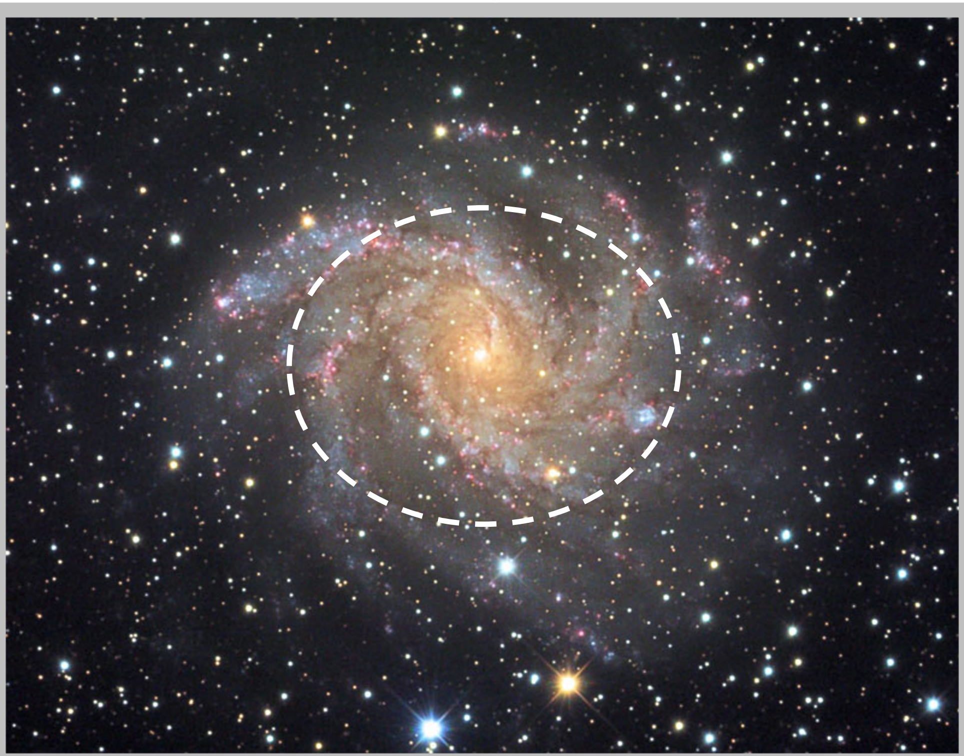
Disk Galaxies: Inner vs Outer Disk

In general, the differences between the inner and outer disk regions suggest different evolutionary paths.

Inside-out galaxy formation: inner regions formed stars earlier and at a faster pace, outer regions form stars later and more gradually. Probably driven by density differences: Things happen faster in denser regions.



Inner Disk	Outer Disk
High density of stars	Low density
Active star formation	Weaker star formation
Redder colors	Bluer colors
Older mean stellar age	Younger mean ages
Lower gas fraction	Higher gas fractions
Shorter gas depletion times	Long gas depletion times
More metal-rich	More metal-poor



Important caveats:

- This is a cartoon sketch, real SFRs arent smooth like this
- There is no hard division between inner and outer disk
- Not all spirals show this behavior, galaxies are individual creatures!

Rotation Curves of Spiral Galaxies: Systematic Trends

1) More luminous galaxies rotate faster

⇒ "Tully-Fisher Relation"

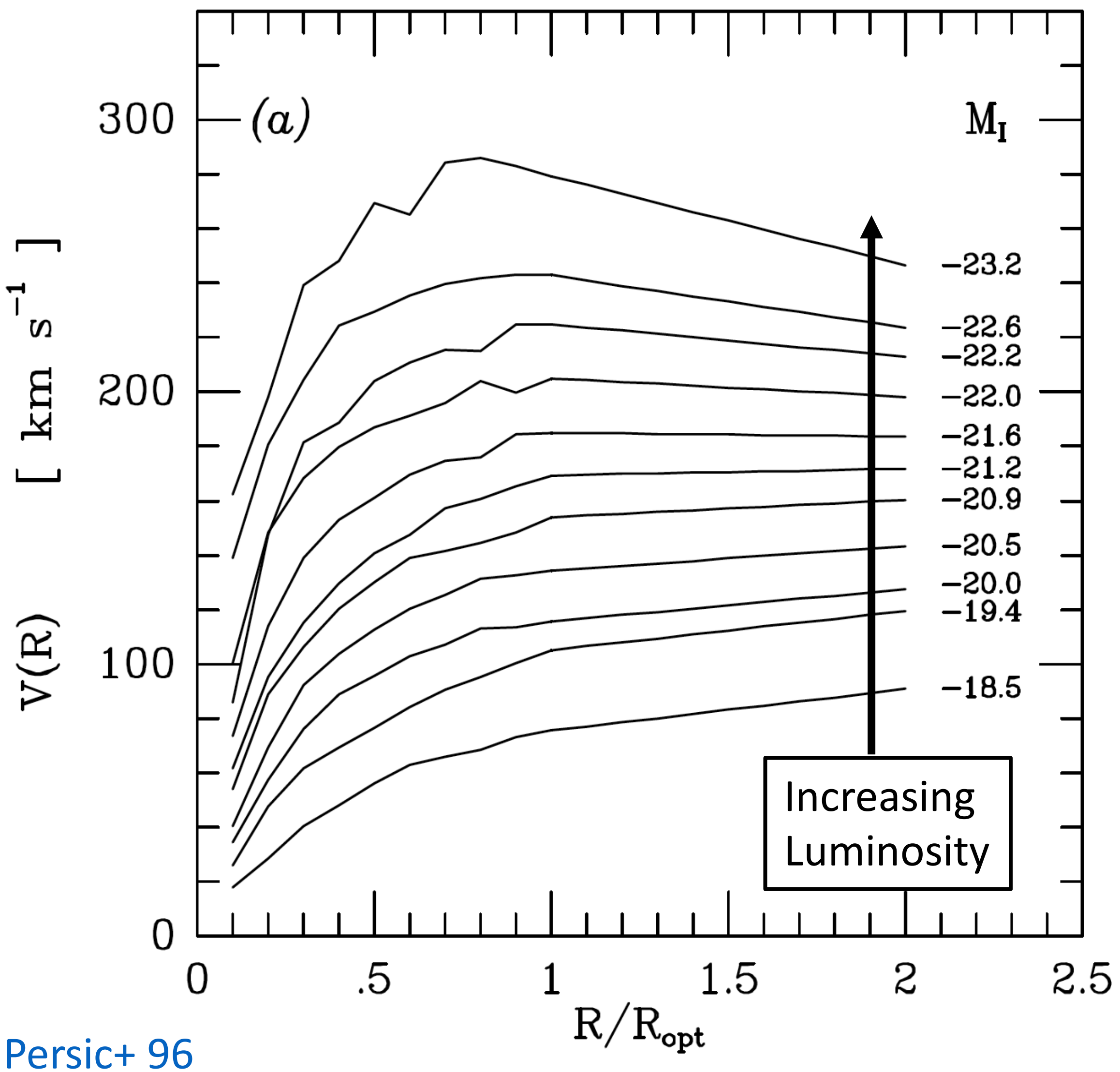
2) Rotation curves are generally flat in their outskirts

Falling rotation curves almost always due to

- Bright inner disk/bulge (high stellar density)
- Disturbances in outer disk (non-rotational motion)

3) The outskirts of disk galaxies rotate too fast for their total stellar mass

⇒ dark matter (or modified gravity?).



Persic+ 96

The Tully-Fisher Relationship

More luminous galaxies rotate faster.
Parameterize this as a power law involving galaxy luminosity (L) and circular velocity (V_c):

$$L \sim V_c^{\alpha}$$

Note: "~" means "scales as" or "is proportional to"

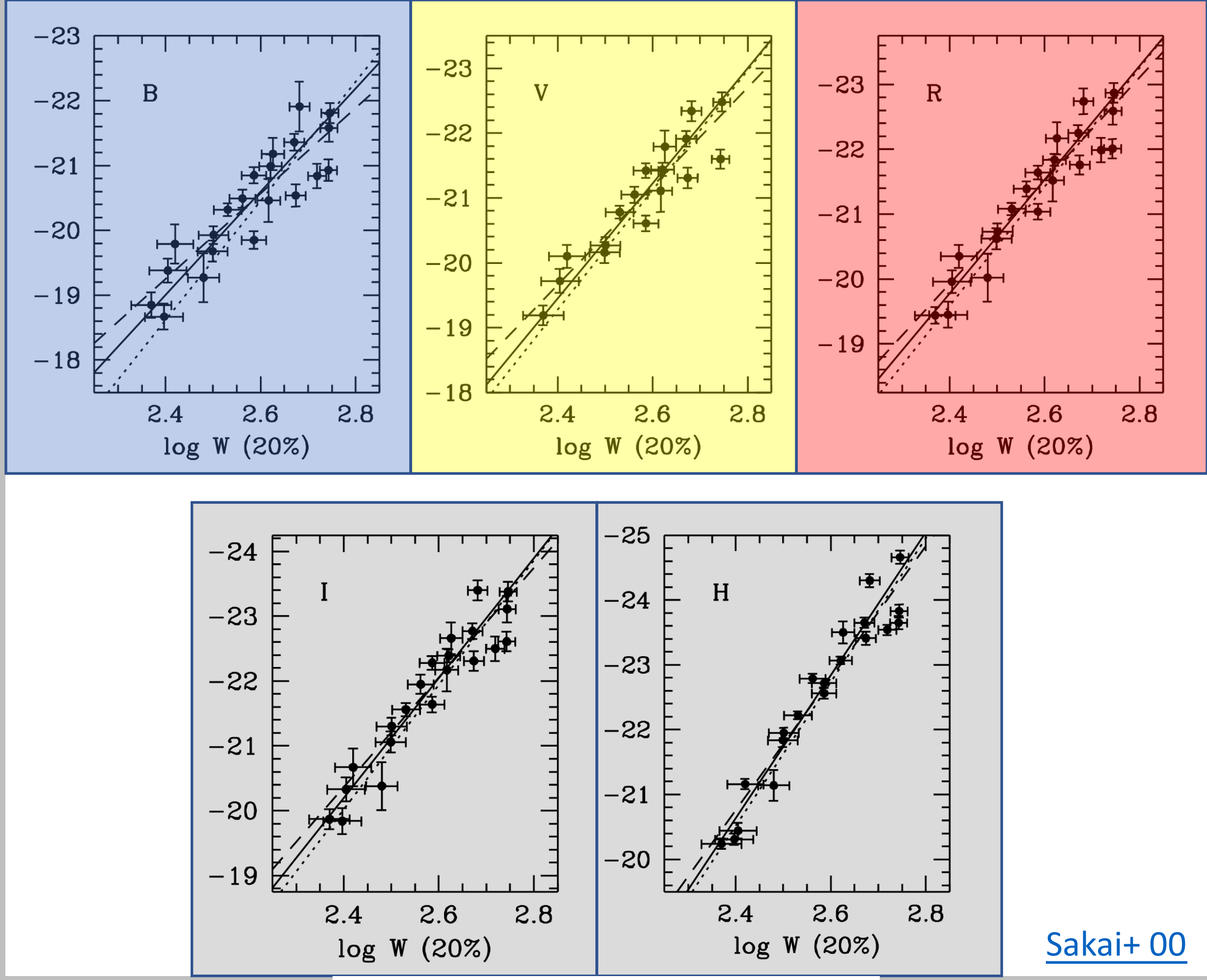
or if we turn this into absolute magnitudes:

$$\begin{aligned} M &\sim -2.5 \log L \\ &\sim -2.5 \log(V_c^{\alpha}) \\ &\sim -2.5\alpha \log(V_c) \end{aligned}$$

So a plot of absolute magnitude vs $\log(V_c)$ should be linear with a slope = -2.5α

Optical ⇒

Near IR ⇒



Sakai+ 00

W = "Velocity width" $\approx 2V_c$

Tully-Fisher relation is best measured at near-IR wavelengths:

- No obscuration by dust inside the galaxies: clean measure of luminosity
- The near-IR luminosity is the best measure of stellar mass, less sensitive to recent SFR changes.

The near-IR Tully Fisher relationship has very low scatter and a slope of ≈ -10 or so. This means $\alpha \approx 4$.

The Tully-Fisher Relationship: Physical Interpretation

What does it mean? Think of what these parameters are measuring

- Circular speed: measure of total mass (gas+stars+dark)
- Luminosity: measure of stellar light

How do we connect these things?

1. First work out scaling between mass, size, circular velocity: $V_c^2 = G\mathcal{M}_{tot}/R \implies \mathcal{M}_{tot} \sim RV_c^2$

2. Now connect that to luminosity by adopting a total mass-to-light ratio: $\mathcal{M}_{tot} = L(\mathcal{M}/L)_{tot}$

3. Equate our two expressions for total mass: $RV_c^2 \sim L(\mathcal{M}/L)_{tot}$

4. How do we get rid of R? Bring in luminosity density: $I = L/(\pi R^2) \implies R \sim \sqrt{L/I}$

5. Insert $R \sim \sqrt{L/I}$ to get $\sqrt{L/I}\, V_c^2 \sim L(\mathcal{M}/L)_{tot}$

6. Solve for luminosity: $L \sim \dfrac{V_c^4}{I(\mathcal{M}/L)_{tot}^2}$

This "scaling argument" works to explain the observed $\alpha \approx 4$, but only if $I(\mathcal{M}/L)_{tot}^2 =$ constant.

This means that the dark matter (dominating $\mathcal{M}_{tot}$) and the luminosity density of starlight (I) must be very tightly linked. We don't understand why this is!

The Baryonic Tully-Fisher Relation (McGaugh 05, etc)

Baryonic matter: normal matter (stars, gas, etc: made from protons and neutrons
Dark matter: not baryonic!

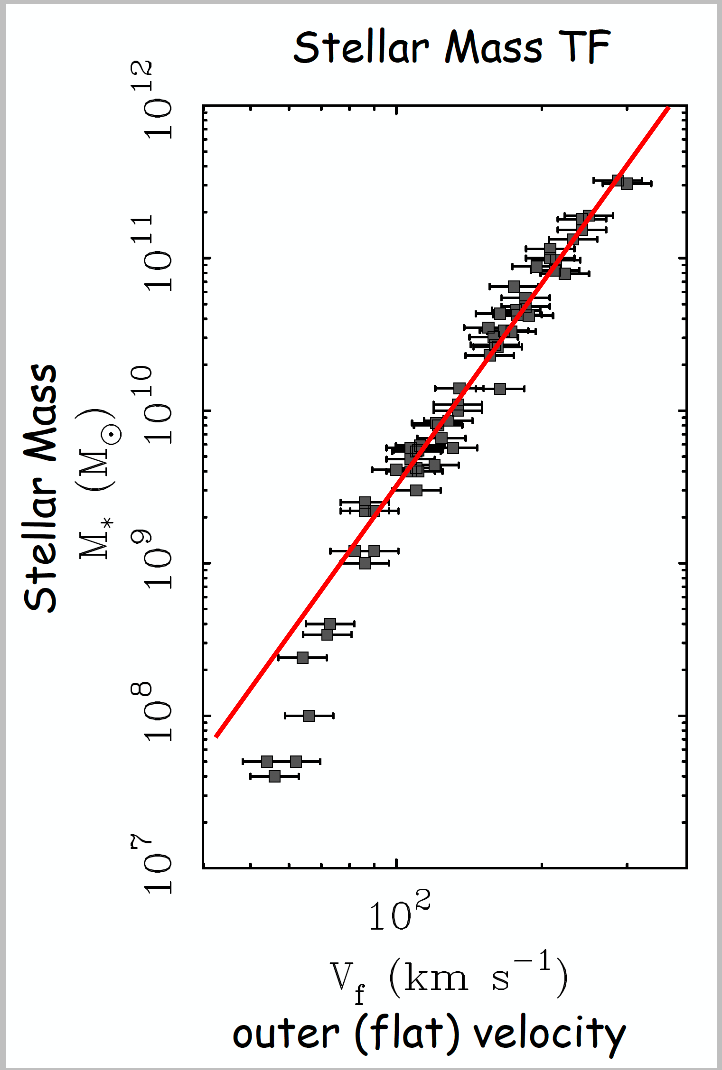
Instead of correlations between light and velocity, look at the connection between baryonic mass and velocity.

Convert light to stellar mass using stellar population models 👉

$$\mathcal{M}_* = (\mathcal{M}/L)_* \times L$$

Low luminosity disk galaxies deviate from TF, they have too little stellar mass.

But low luminosity spirals also tend to be very gas rich….



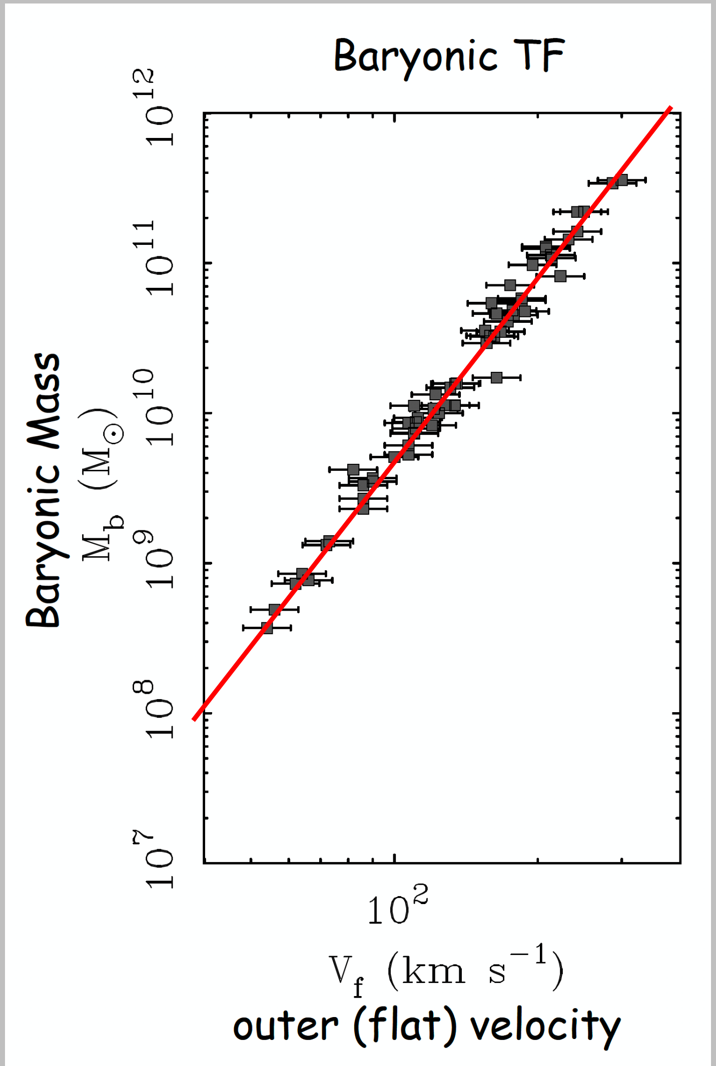
Add in gas mass 👉

$$\mathcal{M}_b = \mathcal{M}_* + \mathcal{M}_{gas}$$

Wow.

slope= 3.94 ± 0.08

scatter consistent with pure observational uncertainties.



The Baryonic Tully-Fisher Relationship: Physical Interpretation

The circular velocity of a galaxy is predictable *solely* from the baryonic content of a galaxy – the normal stuff. No need to know anything about the dark matter to work out the rotation speed.

Suggests that rotation speed is determined by baryonic mass. But, Newton's Law says that in that case, rotation curves should decline, and they don't. So dark matter must somehow arrange itself to give a baryonic relationship.

Modified Gravity

Example: Modified Newtonian Gravity (MOND)

Gravitational force law acts like R^{-2} at high acceleration but R^{-1} at acceleration below an acceleration $a_0 \approx 10^{-10}$ m/s^2.

These low accelerations only achieved far from galaxy centers, and would give a rotation curve that looks like

$$\frac{V^2}{R} = a_{MOND} \sim \frac{1}{R}$$

or

$$V(R) = const$$

HW #3, Problem 1: Steps to calculate luminosities and colors for the model galaxies.

1. Work out the B and V absolute magnitude of each type of star: $M_B = M_V + (B - V)$.
2. Calculate the B and V luminosities (in $L_{B,\odot}$ and $L_{V,\odot}$) of each star type using the absolute magnitudes of the Sun:
$$M_{B,*} - M_{B,\odot} = -2.5\log\left(L_{B,*}/L_{B,\odot}\right)$$
$$M_{V,*} - M_{V,\odot} = -2.5\log\left(L_{V,*}/L_{V,\odot}\right)$$
3. Given $L_{V,tot}$ for the galaxy, and the fraction of V light coming from each type of star ($f_{V,*}$), figure out how much total V light each star type is contributing: $L_{V,tot,*} = f_{V,*} \times L_{V,tot}$
4. Knowing the individual V luminosity of each star type, you can work out how many stars of that type you need:
$$N_* = L_{V,tot,*}/L_{V,*}$$
5. Work out the total stellar mass by adding up all the mass: $\mathcal{M}_{*,tot} = \sum N_* \times \mathcal{M}_*$, then use that to calculate the V-band mass-to-light ratio:$(\mathcal{M}/L)_{*,tot,V} = \mathcal{M}_{*,tot}/L_{V,tot}$.
6. Knowing how many of each type of star you have, you can also work out the amount of total B light they are putting out:
$$L_{B,tot,*} = N_* \times L_{B,*}$$
7. Add up all the $L_{B,tot,*}$ for each type of star to get the total B luminosity of the galaxy:
$$L_{B,tot} = \sum L_{B,tot,*}$$
8. Work out the total absolute B and V mags of the galaxy using
$$M_{B,tot} - M_{B,\odot} = -2.5\log\left(L_{B,tot}/L_{B,\odot}\right)$$
$$M_{V,tot} - M_{V,\odot} = -2.5\log\left(L_{V,tot}/L_{V,\odot}\right)$$
9. Work out the galaxy's total color from the absolute magnitudes:
$$(B-V)_{tot} = M_{B,tot} - M_{V,tot}$$

Important:
Never mix B and V mags and luminosities in one equation! In other words, ***don't do anything that looks like this****:*

$$M_B - M_V = -2.5\,log(L_B/L_V)$$

☠️😱😡💩❌🤮😵‍💫😩

Spiral structure in disks

Types of spirals:

Grand design: 2 well-defined, symmetric spiral arms.

Flocculent: spiral arm “fragments”, not continuous

Multiple arms: 3, 4, etc

Barred spirals

M81 (Adam Block)

Spiral structure in disks

Types of spirals:

Grand design: 2 well-defined, symmetric spiral arms.

Flocculent: spiral arm “fragments”, not continuous

Multiple arms: 3, 4, etc

Barred spirals

Spiral structure in disks

Types of spirals:

Grand design: 2 well-defined, symmetric spiral arms.

Flocculent: spiral arm “fragments”, not continuous

Multiple arms: 3, 4, etc

Barred spirals

Spiral structure in disks

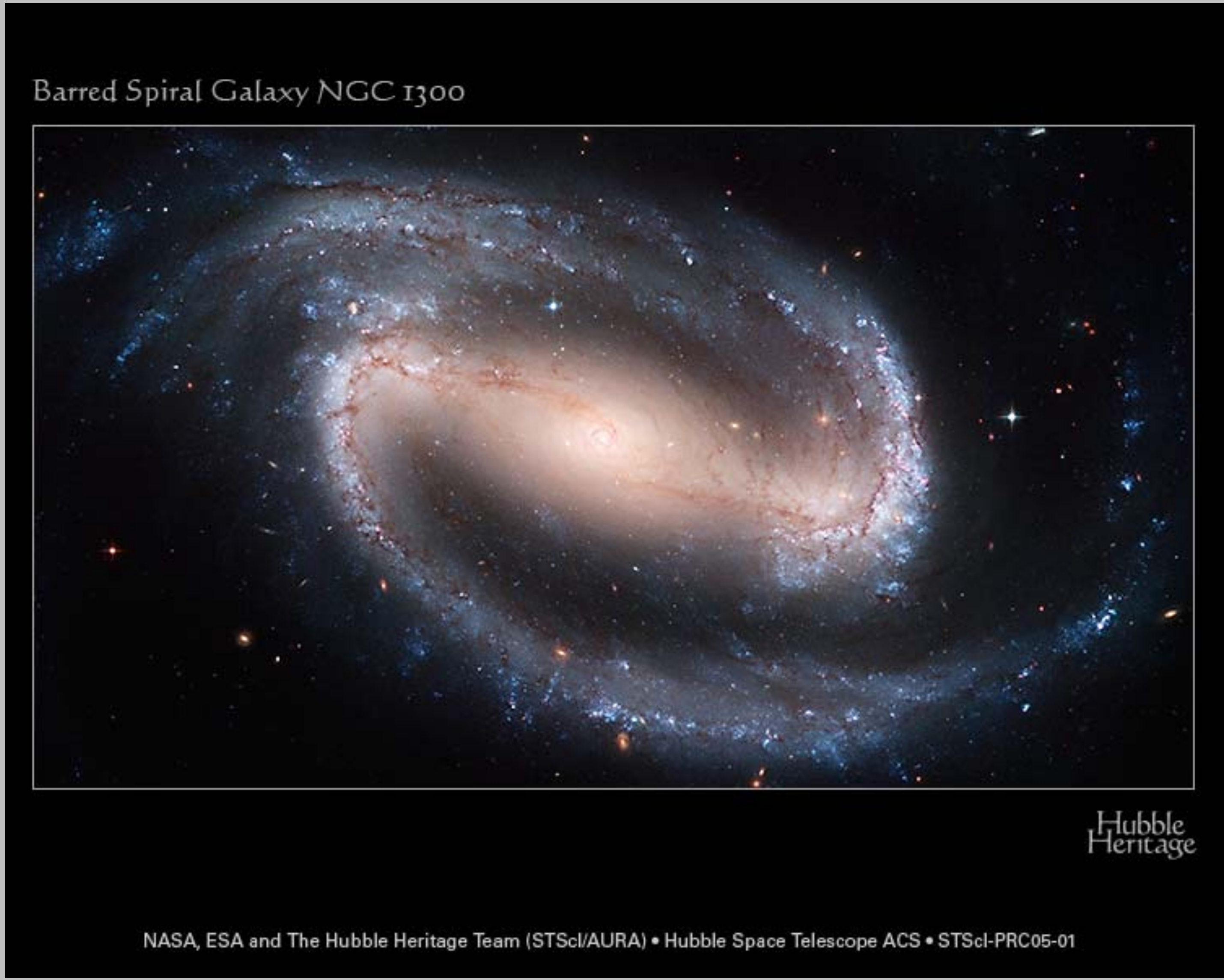
Types of spirals:

Grand design: 2 well-defined, symmetric spiral arms.

Flocculent: spiral arm “fragments”, not continuous

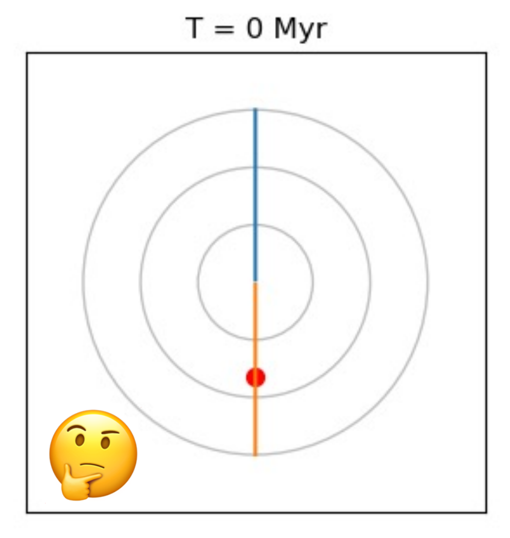
Multiple arms: 3, 4, etc

Barred spirals: arms coming off a central bar



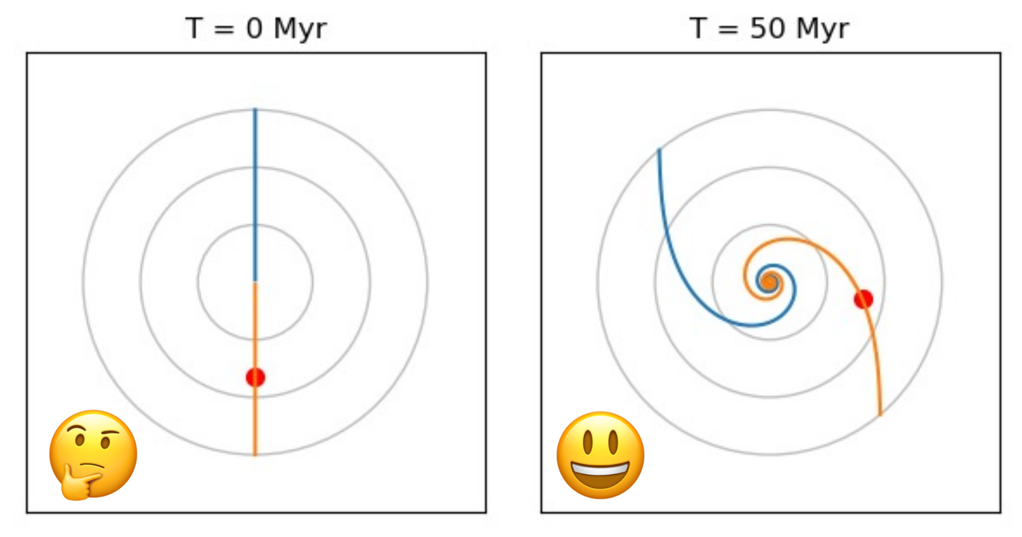
Making spiral arms

Imagine making a linear “ridge” of stars and letting it orbit around the galaxy. What happens over time?



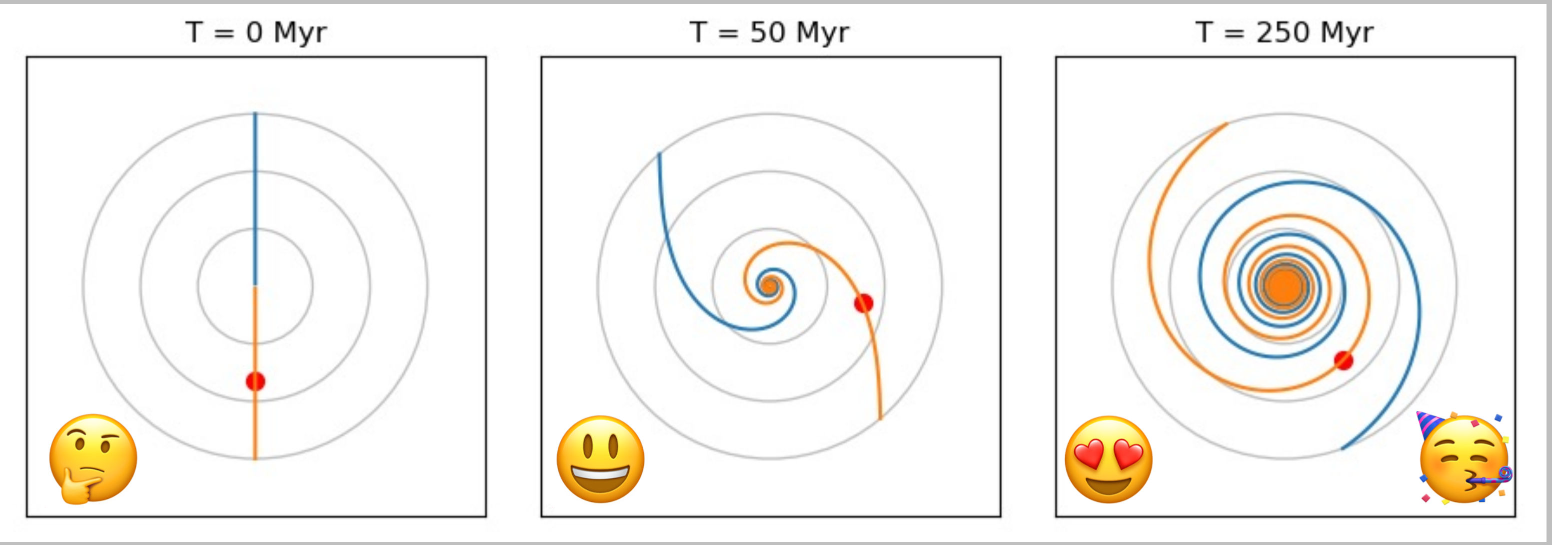
Making spiral arms

Imagine making a linear “ridge” of stars and letting it orbit around the galaxy. What happens over time?



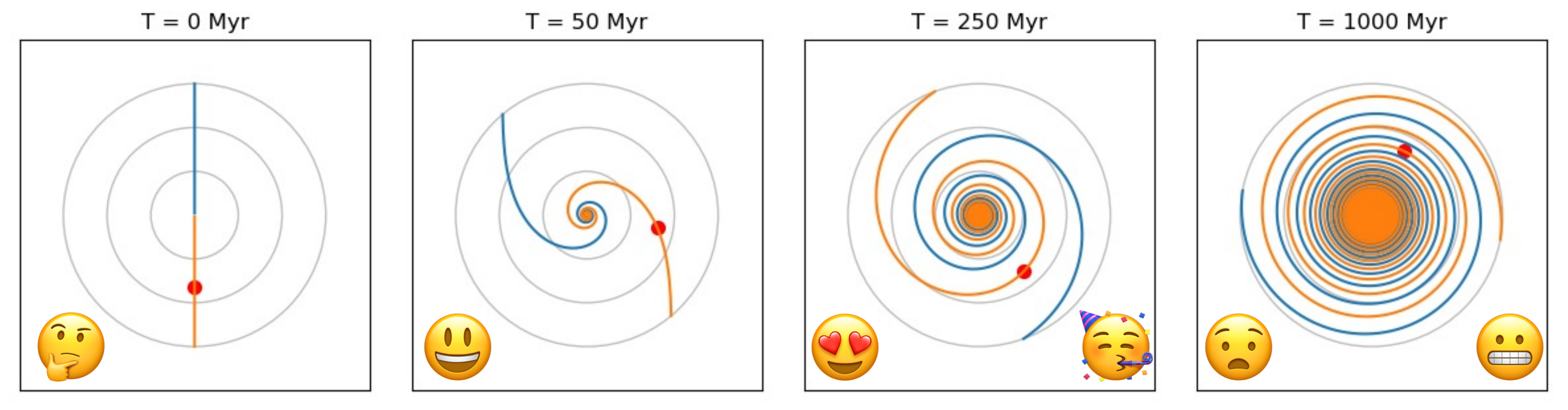
Making spiral arms

Imagine making a linear “ridge” of stars and letting it orbit around the galaxy. What happens over time?



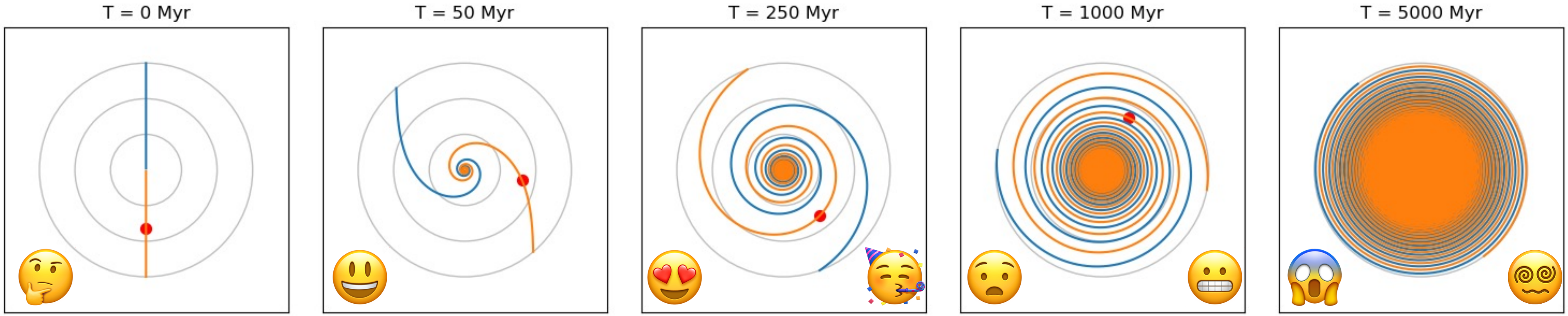
Making spiral arms

Imagine making a linear "ridge" of stars and letting it orbit around the galaxy. What happens over time?



Making spiral arms

Imagine making a linear "ridge" of stars and letting it orbit around the galaxy. What happens over time?



The winding problem

Galaxies do not rotate like a solid object – since $V_c(R)$ is roughly constant with radius , the orbital time is short in the inner disk and long in the outer disk. This means any physical structure will wind up very quickly and be sheared away.

What would the rotation curve have to look like for this not to be a problem?

Orbital time is $T = \frac{2\pi R}{V_c(R)}$ so if the orbital time needs to be the same at all radius, then $V_c(R) = \frac{2\pi R}{T} \sim R$

"Solid Body Rotation"
Not what galaxies do!

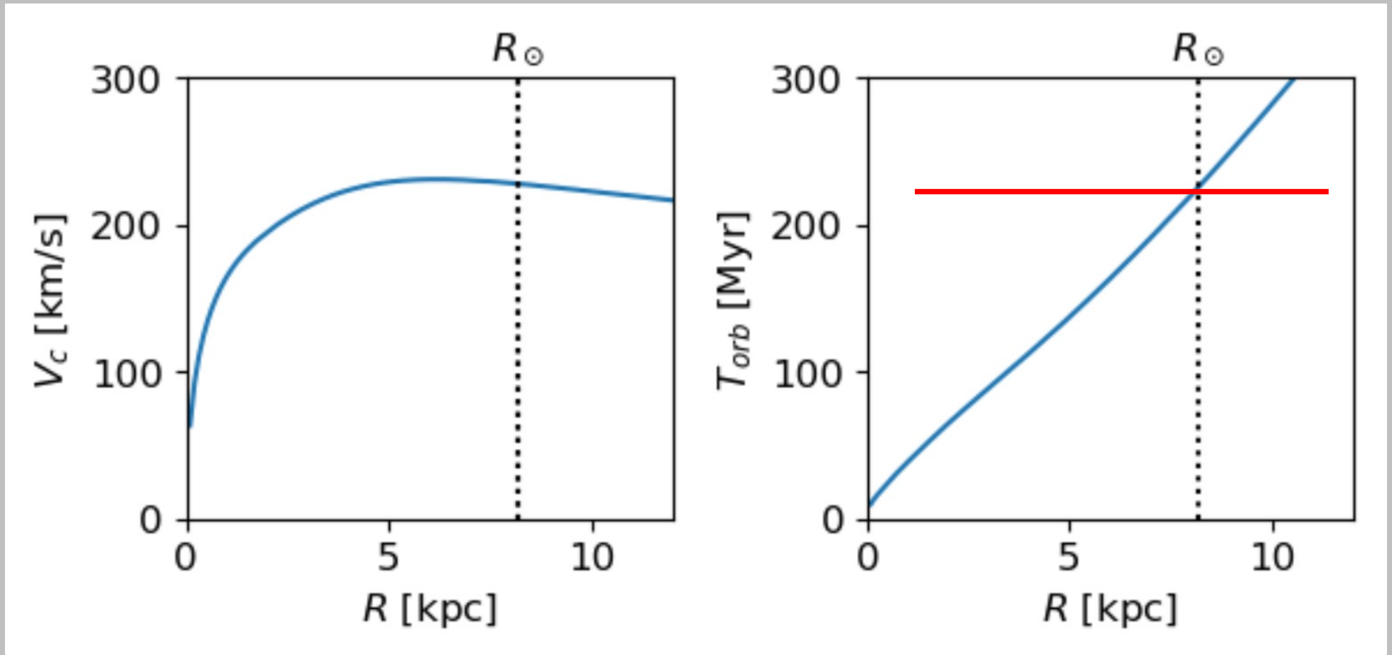
Spiral Density Waves

Spirals cannot be physical structures orbiting coherently for long timescales. Instead, they are density waves moving through the disk. What is a density wave?

A traffic jam is an example of a density wave. Cars move in and out of the jam at a different speed than the jam itself moves.

Spiral Density Waves in Disk Galaxies

In a galaxy a density wave is moving compression of gas and stars that travels with a fixed *angular* rate that is different from the circular velocity. This gives it an orbital time that doesn't change with radius. Look at the Milky Way's rotation:



Co-rotation is where the stars and spiral wave move at the same velocity, and is very close to the Sun's orbital radius.

⇒ Inside co-rotation, stars orbit faster than the wave and "catch up" to the spiral arms.

⇒ Outside co-rotation, stars orbit more slowly than the wave, and the arms "sweep past" them.

Spiral Density Waves in Disk Galaxies

Think of a star orbiting inside co-rotation. As it nears the arm, the extra mass of the arm pulls it forward into the arm, speeding the star up.

As it leave the arm, the extra mass of the arm pulls back on the star, slowing it down.

So the star spends more time in the arm, adding to the arm's mass and density. The spiral wave is sustained by this "self-gravity" as it moves through the disk.

But stars can easily move in and out of arms. What happens to the interstellar gas in the disk?

- **Collisions**: unlike stars, gas collides together in arms and is shocked, compressing the gas and driving star formation.

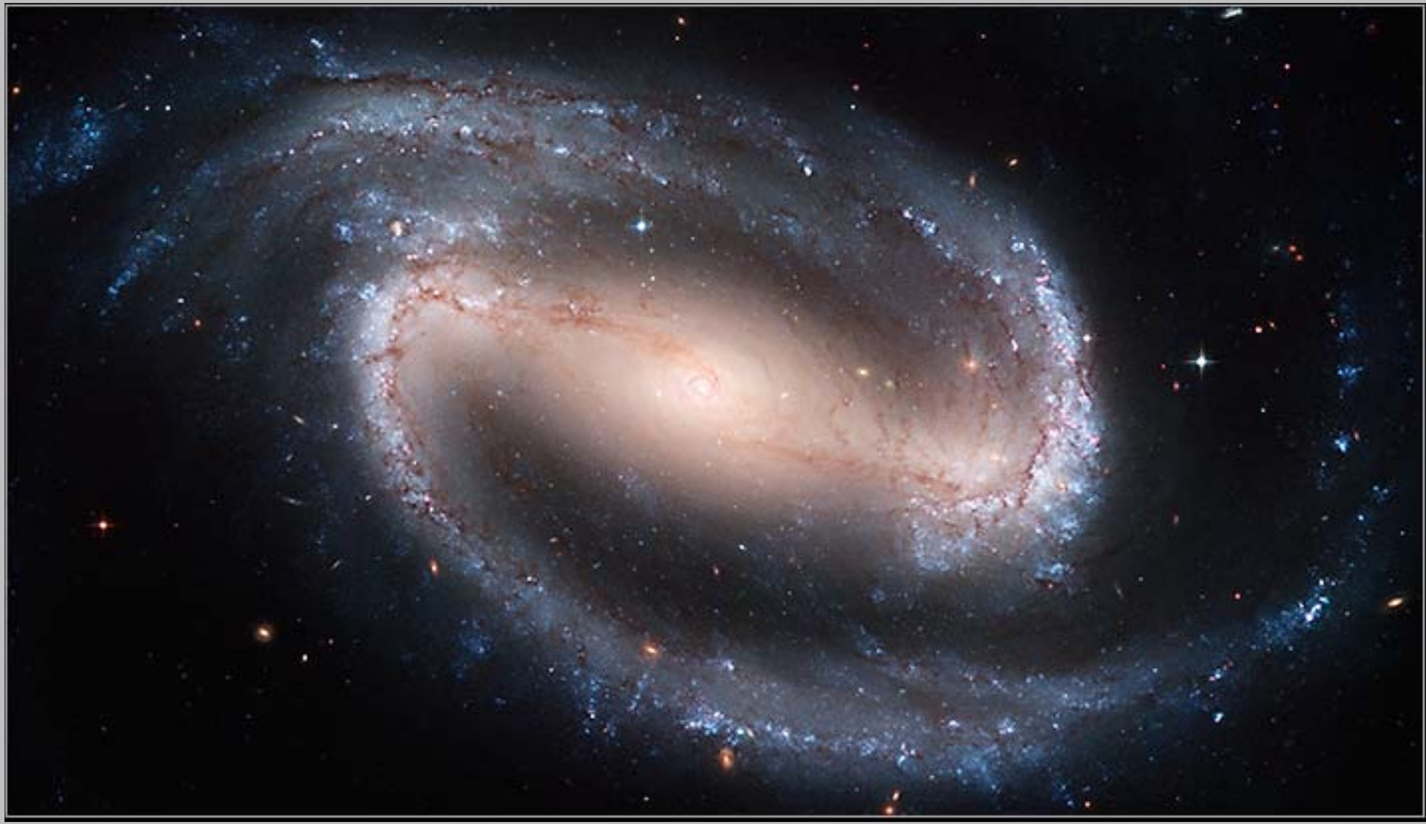
- **Ambient density**: the overall mass density inside arms is greater than outside them, so clouds are closer to gravitational collapse and can form stars.

⇒ ***Increased efficiency of star formation in spiral arms!***

Barred spirals

If the conditions are right, the self-gravity of the disk can be so strong that the galaxy forms a bar.

The density wave perturbation is so strong that it “traps” stars inside the wave. Stars begin to move radially along the wave rather moving on circular orbits. ⇒ linear bar structure



What are those conditions?

1. High disk surface density

If the overall density of the disk is high, its self-gravity is very strong and the density of the wave grows very quickly. A bar forms and strengthens.

2. Slowly rising rotation curve

A slowly rising rotation curve mimics solid body rotation:
$V_c(R) \sim R$

In this case, the wave and the stars rotate at the same speed so stars can get more easily “trapped” inside the wave, strengthening it.

Both these conditions can happen in the inner disks of bright galaxies!

But what starts the spiral density wave to begin with?

Any kind of non-axisymmetric perturbation can seed a wave, after which the disk self-gravity can amplify it into spiral arms.

- Galaxy interactions?
- Galaxy bars?
- Irregular lumps of mass in the disk?

Elliptical galaxies

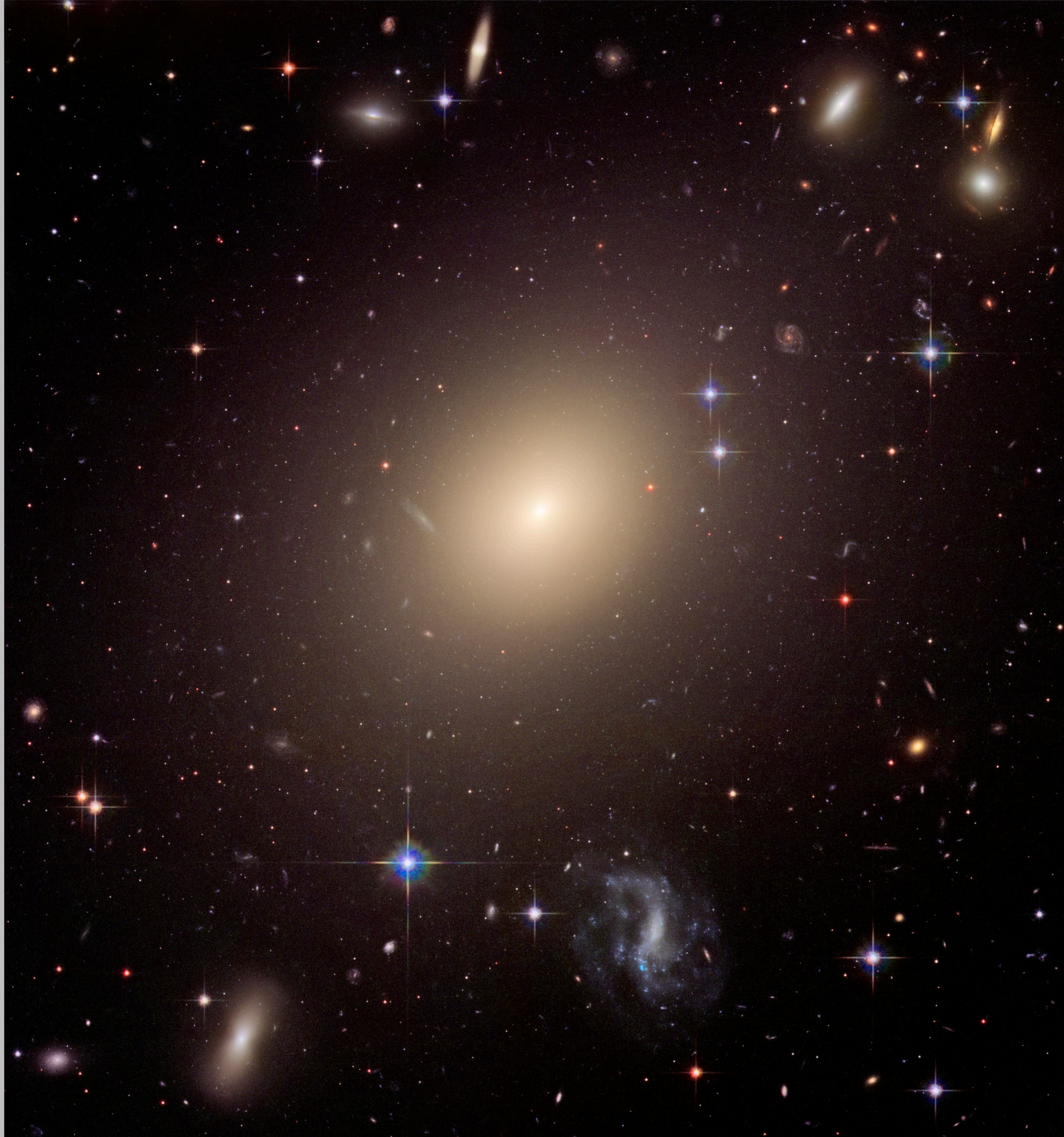
E's span a wide range of luminosity and have a correspondingly wide range of structural properties.

We can measure surface brightness profile, 2D shape, integrated colors:

- spheroids, not thin exponential disks
- round to moderately flattened ($b/a \approx 0.5 - 1.0$)
- typically red ($B - V \ \approx 0.7 - 1.1$)
- generally smooth and "featureless": no internal substructure
- not much cold atomic or molecular gas
- old stellar populations, little on-going star formation.

⇒ "red and dead" *(maybe....?)*

Here we will mostly be talking about regular/giant ellipticals. Dwarf ellipticals (dE's) and dwarf spheroidals (dSph's) are different animals entirely!



Elliptical Galaxies: Ellipticity

Typically defined by $\epsilon = 1 - b/a$, where a, b are the major and minor axis lengths.

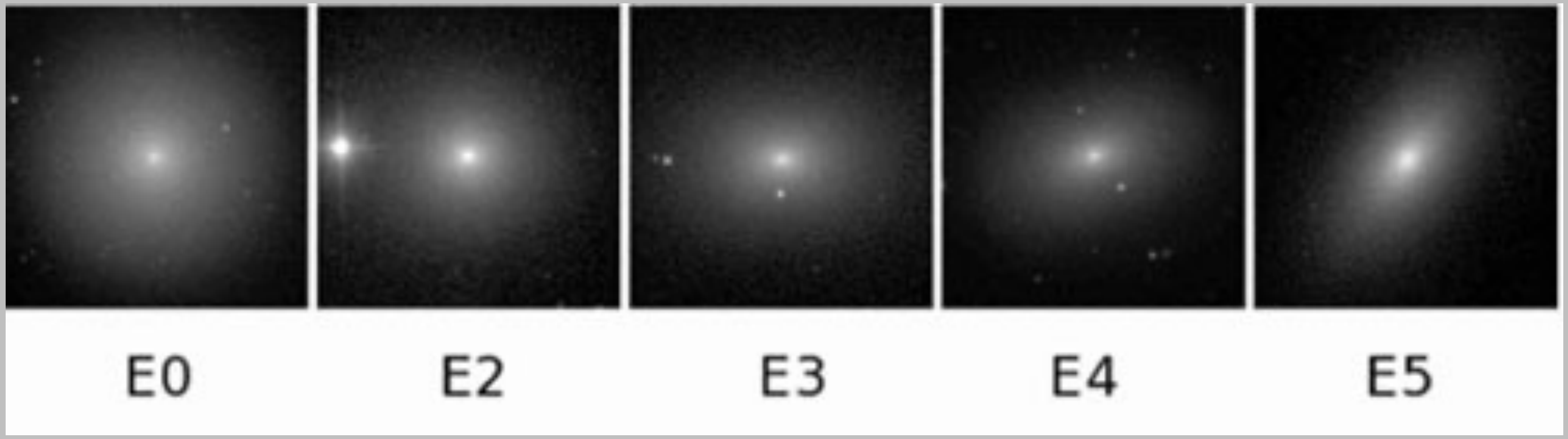
Hubble scheme EN, where $N = 10\epsilon$

*Beware: **observed** axis ratio not the same as the **true** axis ratio.*

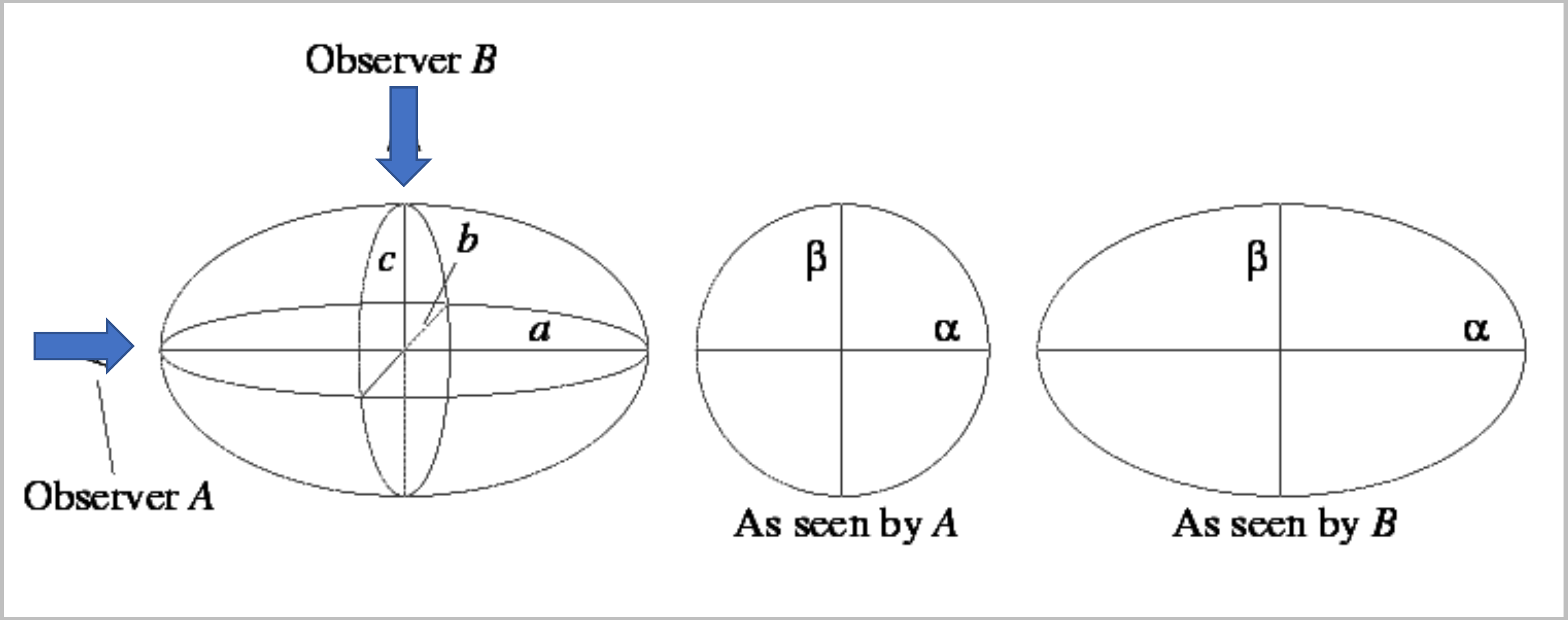
Observed axis ratio is a projected version of the underlying 3D axis ratio.

3D geometry:

- ⚽ Spherical: $a = b = c$
- 🏈 Prolate: $a > b = c$
- 🍔 Oblate: $a = b > c$
- 🚲 Triaxial: $a > b > c$



$b/a = 1$ $b/a = 0.8$ $b/a = 0.7$ $b/a = 0.6$ $b/a = 0.5$



Elliptical Galaxies: Luminosity Profiles

First, remember **disk galaxies**: Exponential luminosity profiles ($I = I_0 e^{-R/h}$) which turn into linear profiles ($\mu(R) \sim R$) when plotted as logarithmic surface brightness. But ellipticals are not exponential.

Elliptical galaxies: Originally defined by Gerard deVaucouleurs to have profiles that behave like $\mu(R) \sim R^{1/4}$. Known as an "R-to-the-quarter law" or a "deVaucouleurs profile".

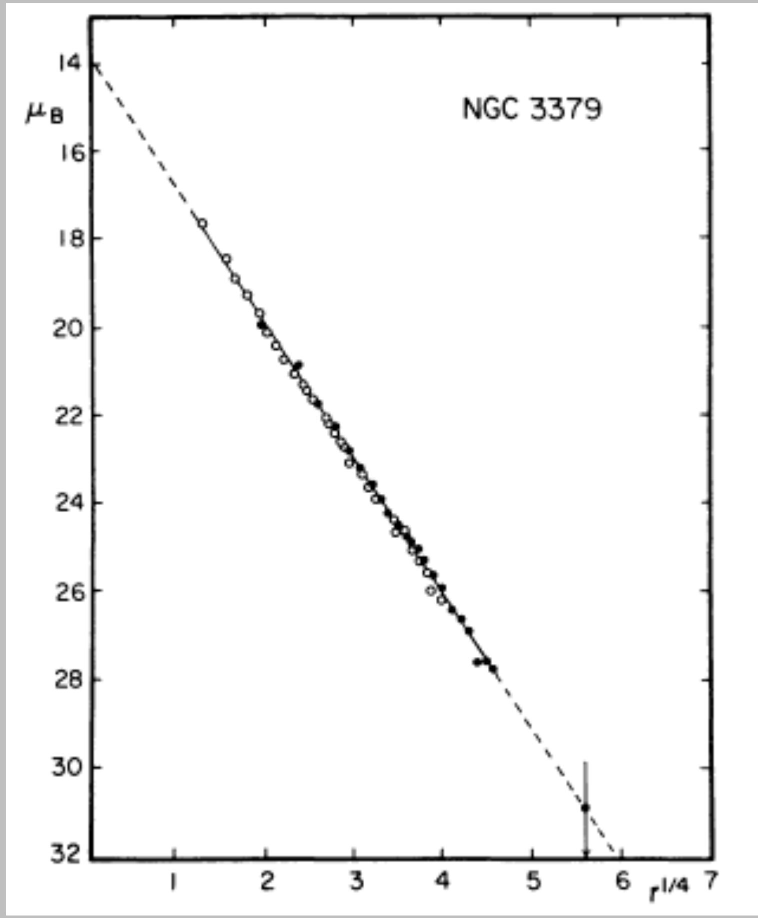
Since $R^{1/4}$ laws don't have a natural radial scale length like exponential profiles do, we characterize the size of an elliptical by the radius containing half the total light of the galaxy.

This is known as the half-light radius or effective radius (R_e).

And instead of a central surface brightness, we talk about the average surface brightness within the effective radius: $\langle \mu \rangle_e$ or $\langle I \rangle_e$

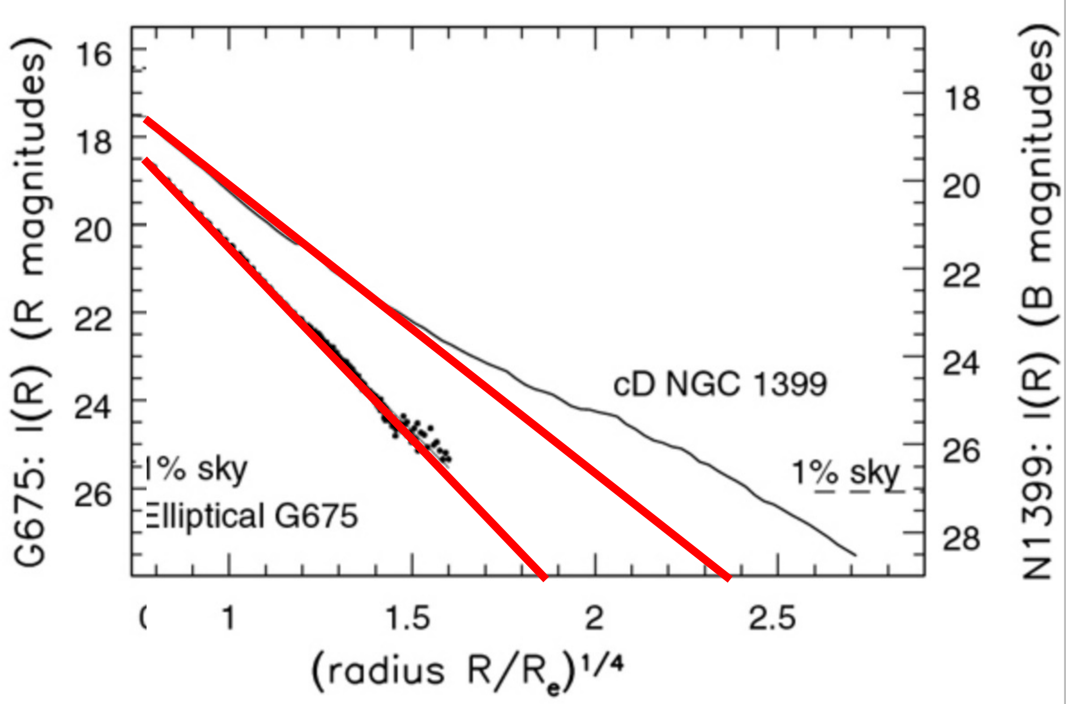
mag/arcsec^2

$L_\odot$/pc^2



Elliptical Galaxies and the Sersic profile

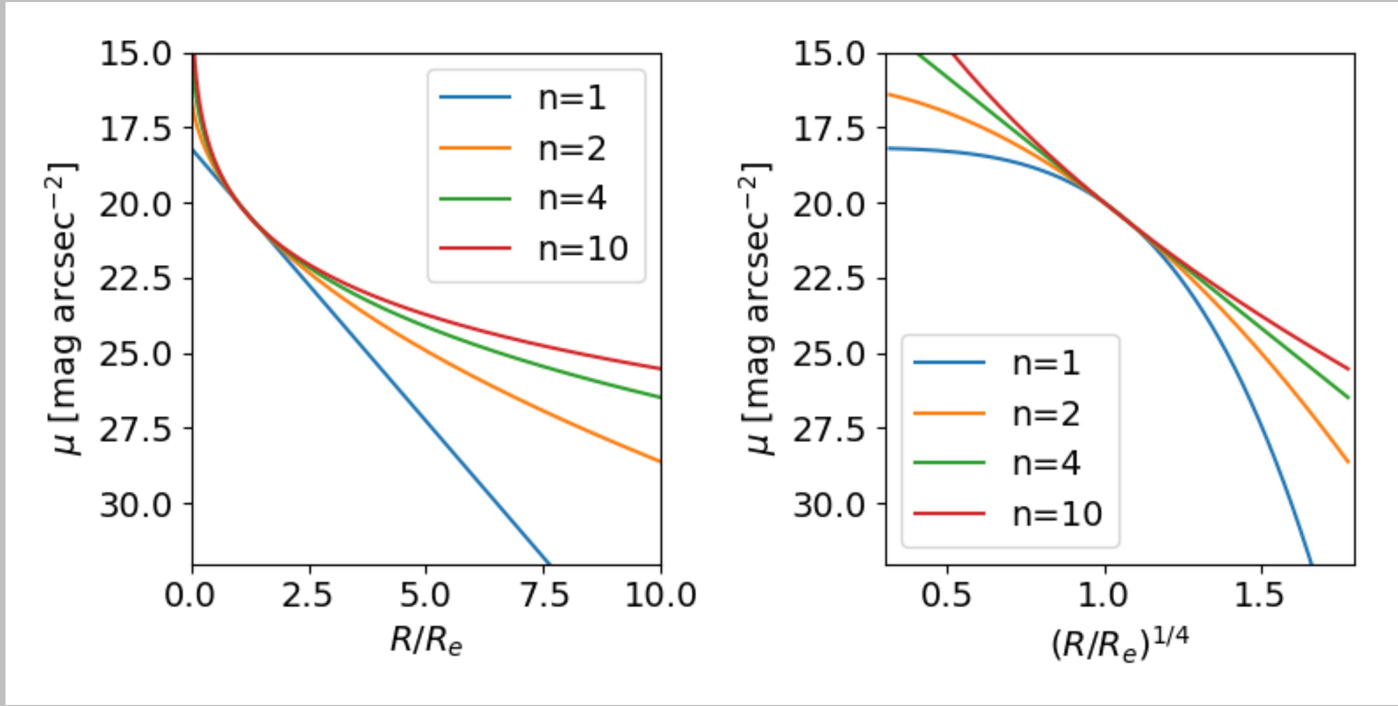
But elliptical galaxies show a range of profile types, not always $R^{1/4}$ $\Rightarrow$



This has led to the definition of a more general profile shape, called a Sersic profile of index n:

$$\mu(R) \sim R^{1/n}$$

- $n = 1$: pure exponential, $\mu(R) \sim R$
- $n = 4$: de Vaucouleur law, $\mu(R) \sim R^{1/4}$
- Ellipticals a wide range of n values



Compared to disk galaxies, ellipticals typically have more light at both large and small radius.

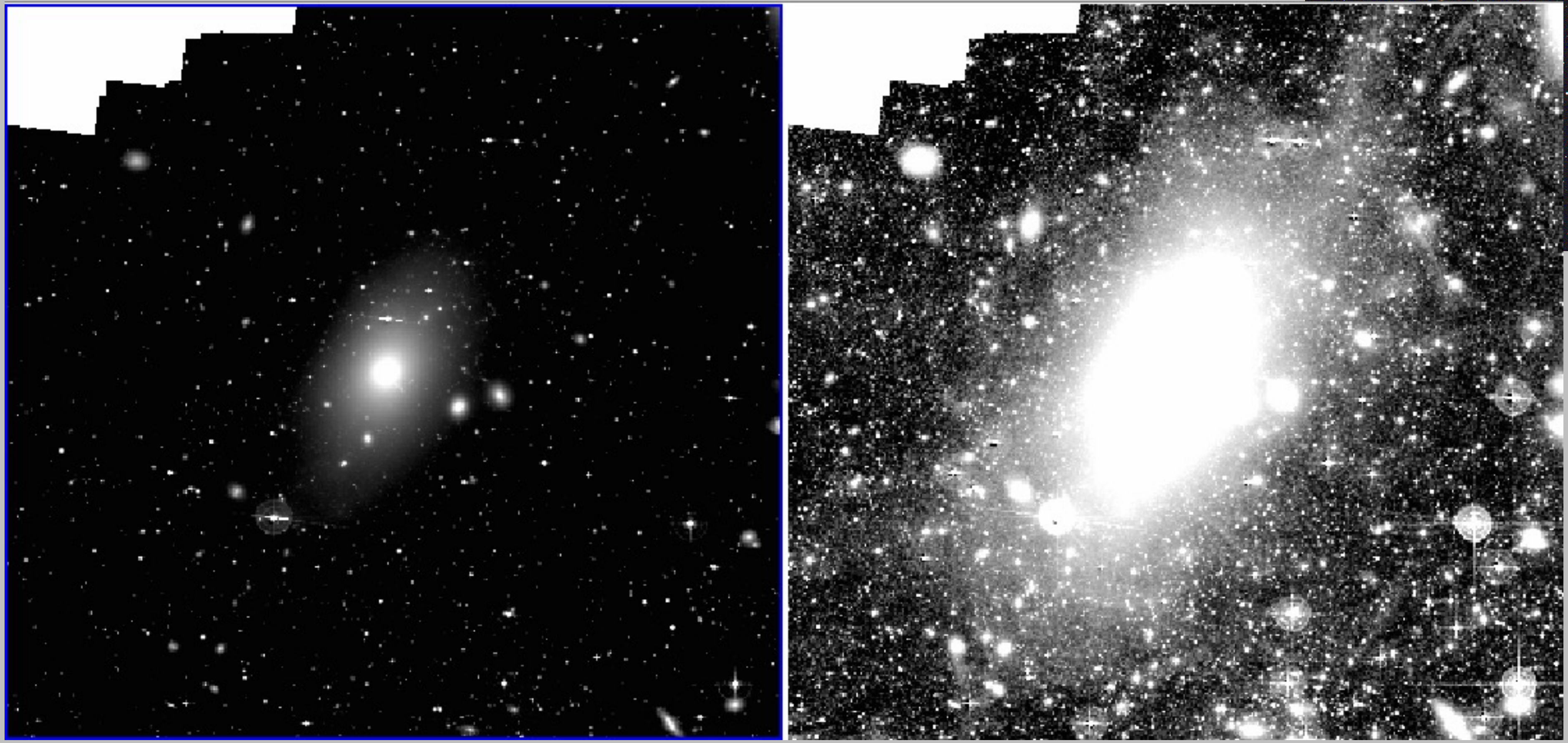
Sersic n roughly correlates with luminosity:
Luminous ellipticals ($L \approx 10^9 - 10^{10}\ L_\odot$) : $n \approx 4$
Massive cD ellipticals ($L >$ few $\times 10^{10}\ L_\odot$): $n > 4$
Dwarf ellipticals ($L \lesssim 10^9\ L_\odot$) : $n \approx 1$

exponential, but not disks!

Ellipticals at low and high luminosity

NGC 205
dwarf elliptical
$n \approx 1$
(John Chumack)

M87
Giant cD galaxy
$n \approx 10$
(Mihos+17)



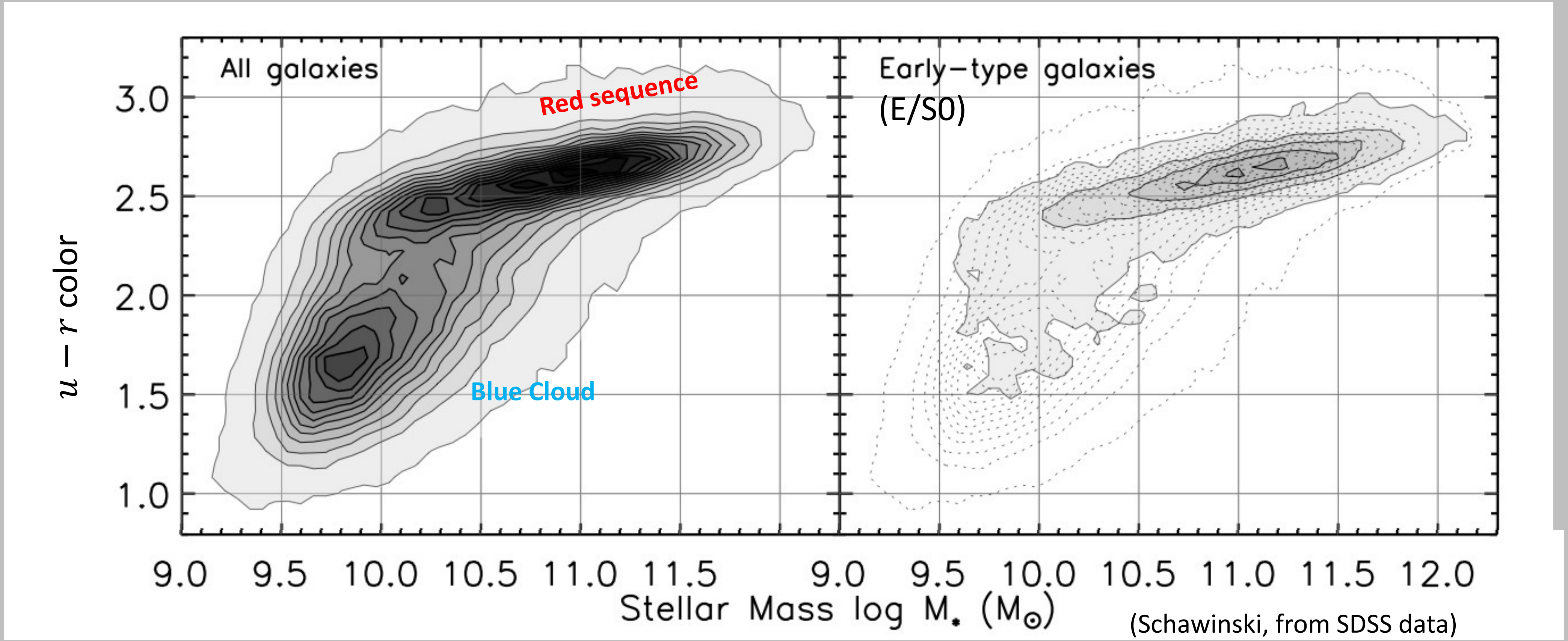
Elliptical Galaxies: Colors and stellar populations

Galaxies tend to segregate into two color groups:

- **red sequence** (old ellipticals and S0s)
- **blue cloud** (star forming disks and irregulars)

Three important take-aways:

1. The most massive galaxies are ellipticals.
2. Ellipticals are red: generally old stellar populations
3. Ellipticals follow a mass-color relationship: massive ellipticals are redder, lower mass ellipticals are (slightly) bluer.



(Schawinski, from SDSS data)

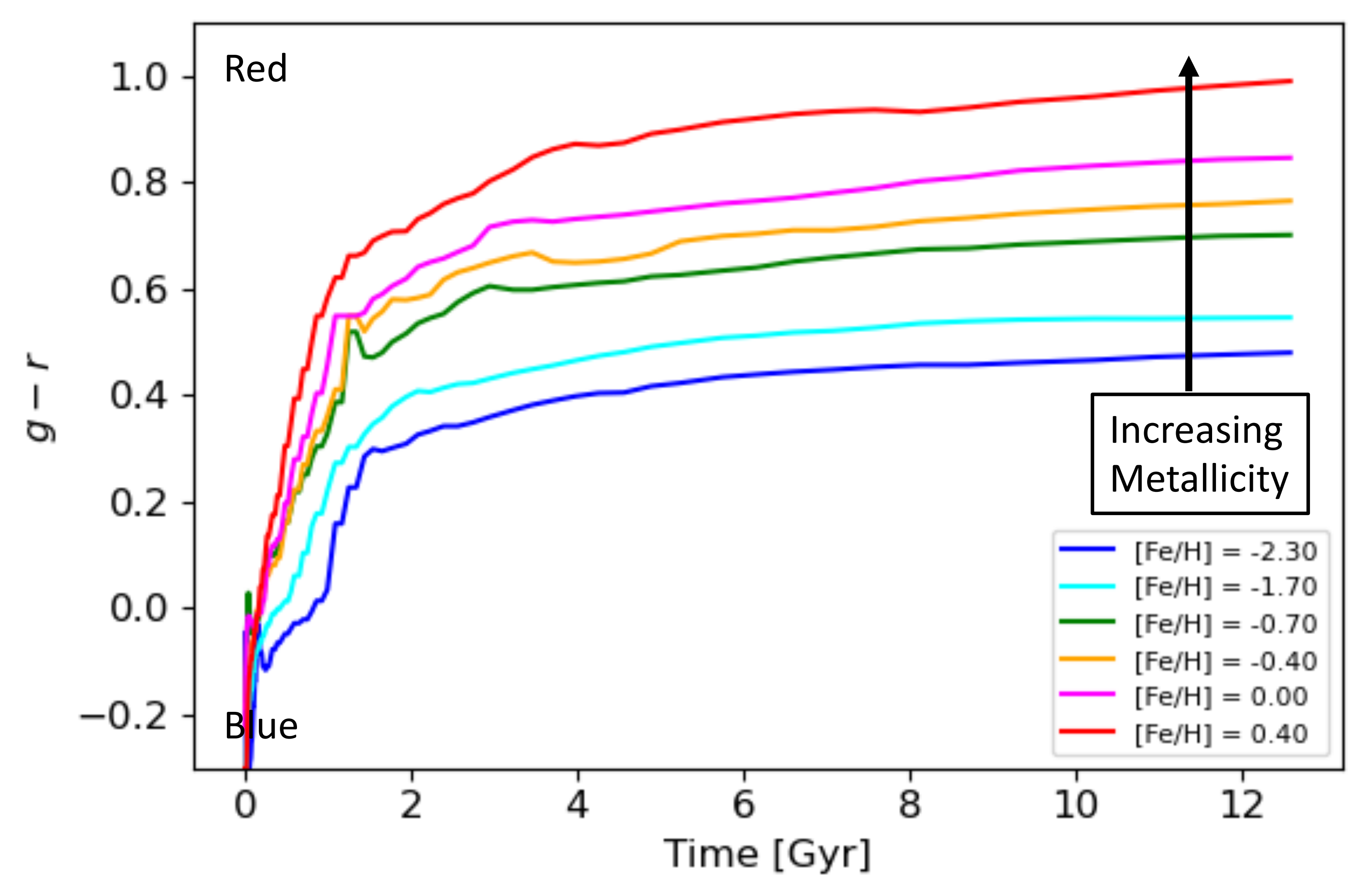
Elliptical Galaxies: Colors and stellar populations

Remember that for old stellar ages, color is much more sensitive to metallicity differences than age differences.

The color spread along the red sequence would imply an age spread of 2 – 15 billion years, which is nonsense.

Instead we are seeing a metallicity sequence: **the mass-metallicity relationship**. More massive ellipticals have more metal-rich stellar populations (and are thus redder).

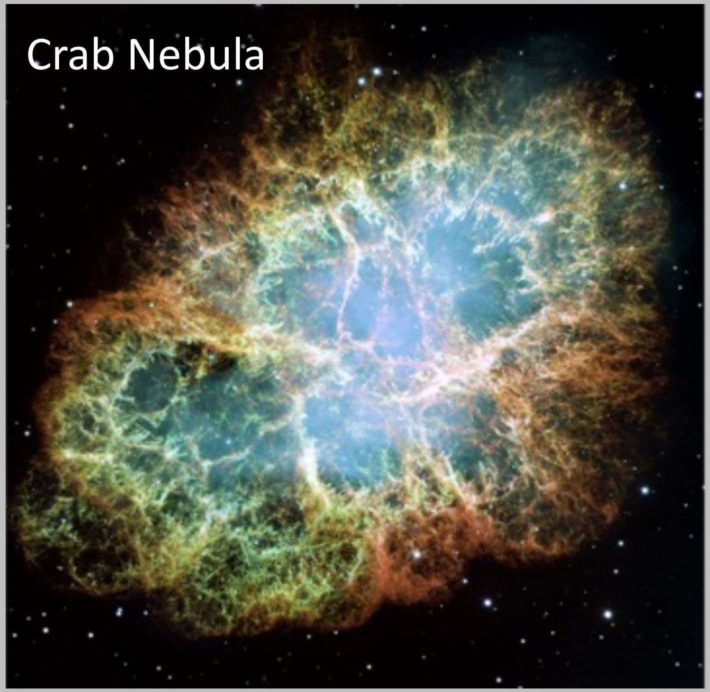
This is confirmed by spectroscopic studies of elliptical galaxies which show stronger absorption lines due to metal-rich stars.



What drives the mass-metallicity relationship

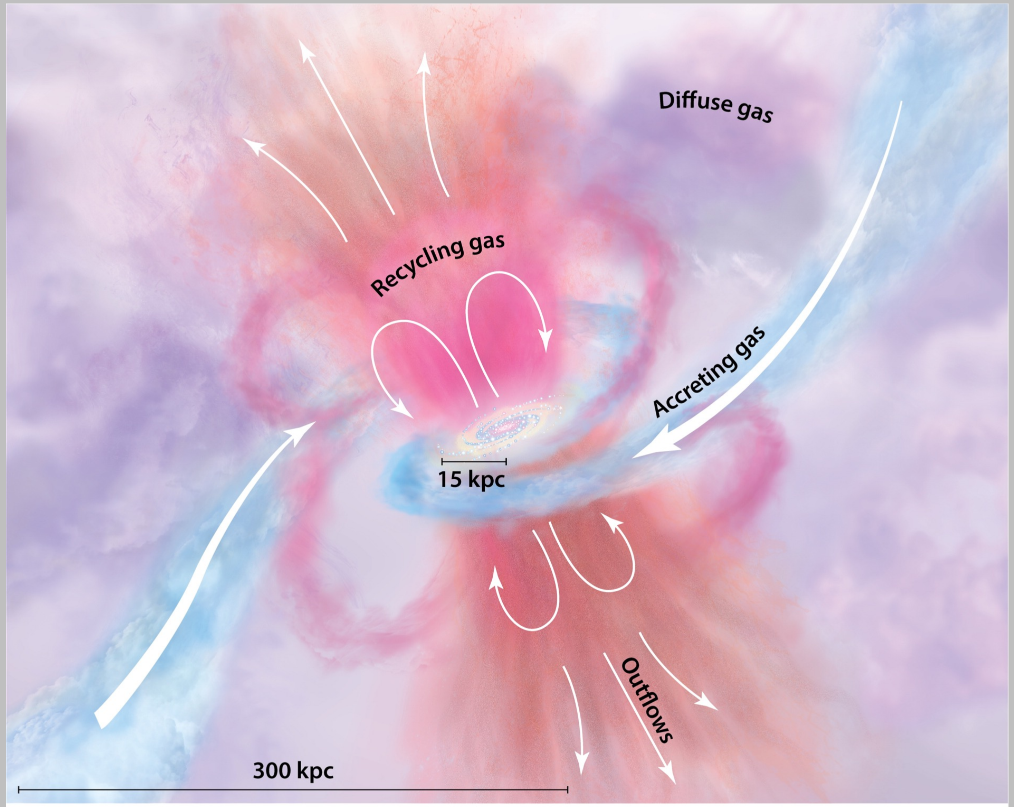
Remember **chemical evolution**: stars make heavy elements ("metals") in their cores and then eject them into the surrounding gas for subsequent star formation to create more metal-rich stars.

These metals are often ejected at high speed during supernovae events.



One possibility is that if the ejection speed exceeds the escape velocity for a galaxy, those metals will be lost to intergalactic space and won't be incorporated into subsequent generations of stars.

It's easier to escape from low mass galaxies than massive galaxies, so only more massive galaxies could build up stars with high metallicity.

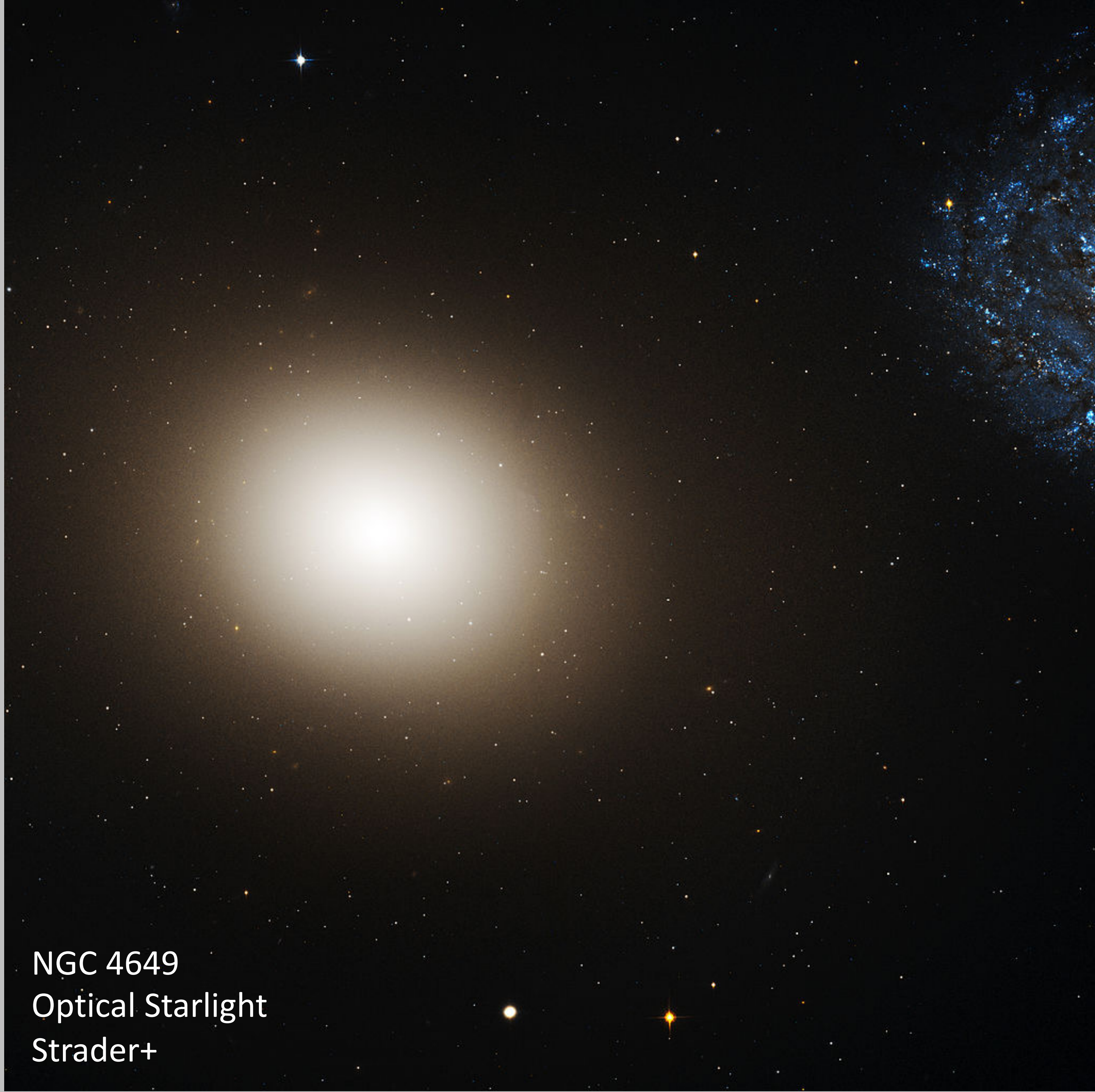


Tumlinson J, et al. 2017.
Annu. Rev. Astron. Astrophys. 55:389–432

Sounds plausible,
but is far from proven!

Hot gas in elliptical galaxies

Ellipticals generally have very little cold atomic or molecular gas. But if we look in X-rays....



Hot gas in elliptical galaxies

Ellipticals generally have very little cold atomic or molecular gas. But if we look in X-rays....

... we see lots of diffuse X-ray emission: free-free (Bremsstrahlung) emission from ionized gas.

How hot is this gas? Set the X-ray photon energy equal to the thermal energy:

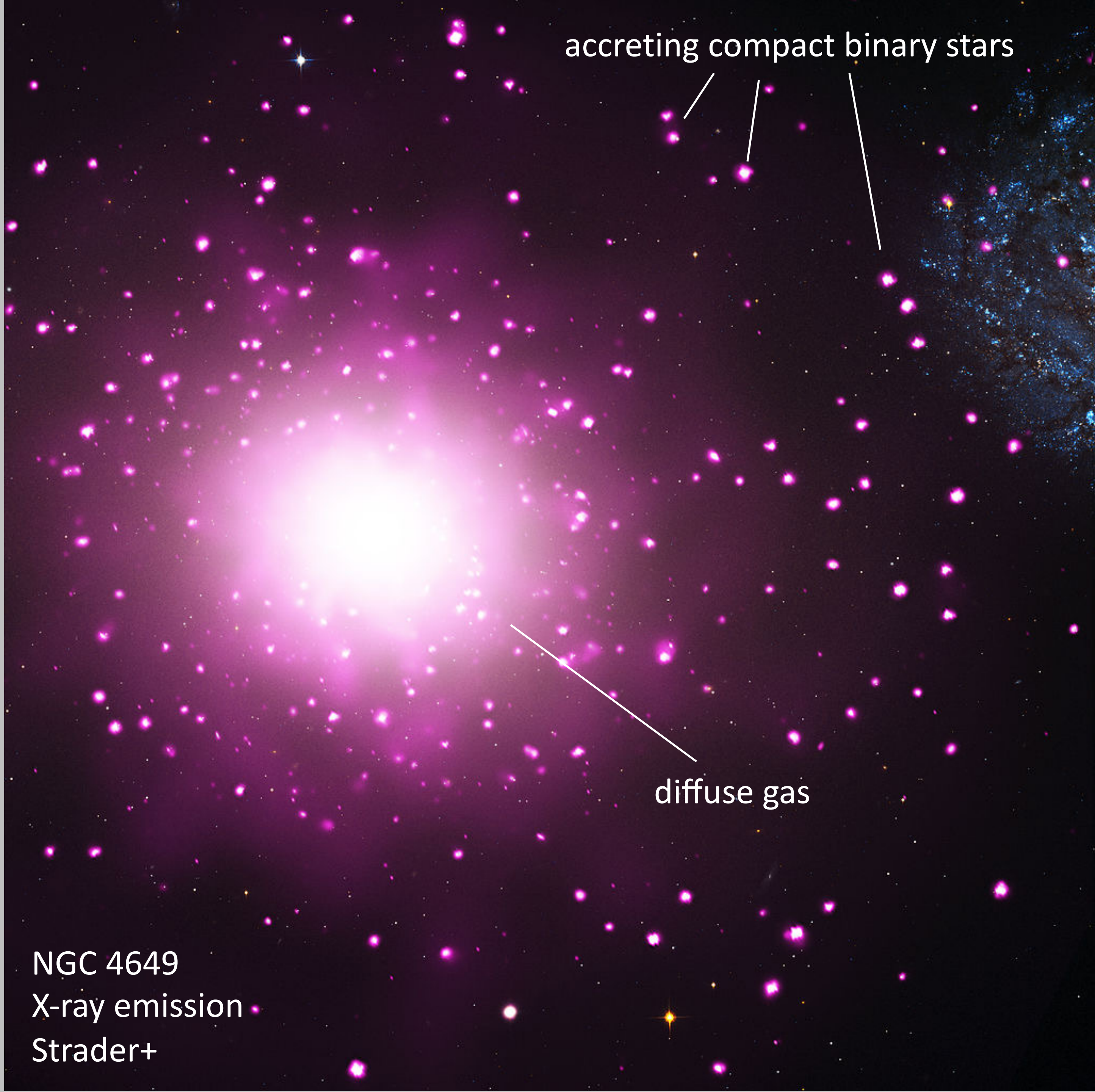
$$h\nu \approx kT$$

and solve for temperature: $T \approx h\nu/k \approx 10^6$ K

The gas is hot and diffuse and cannot form stars. But there's a fair bit of it! $\mathcal{M}_{gas} \approx 10^8 - 10^9 \mathcal{M}_\odot$.

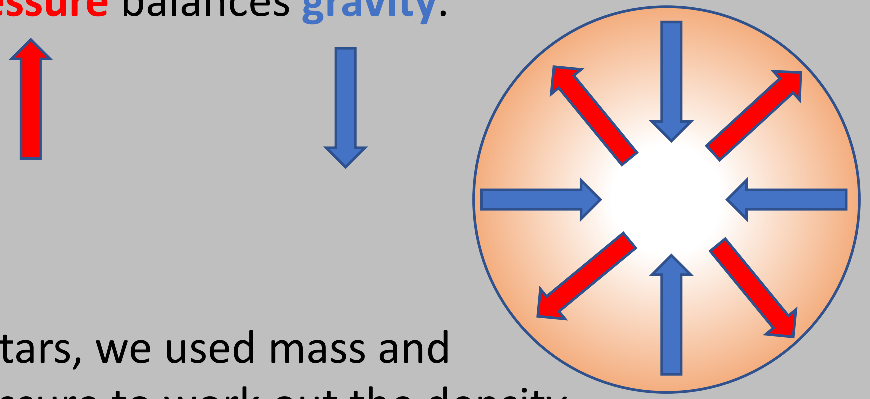
Metallicity is low, about 1/3 solar.

What's going on?



Hot gas in elliptical galaxies

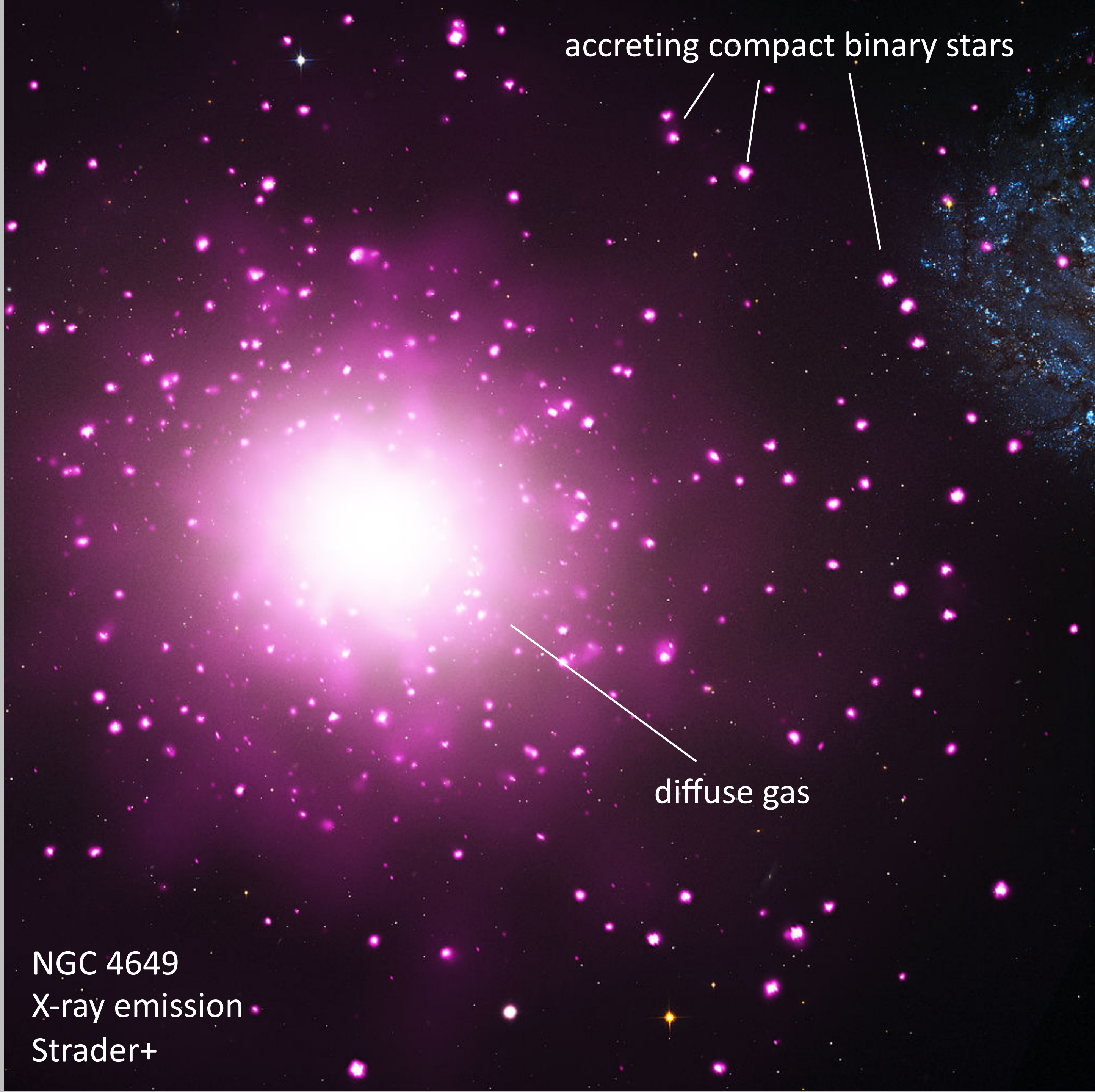
Remember hydrostatic equilibrium.
Pressure balances **gravity**.



In stars, we used mass and pressure to work out the density and temperature structure of the star.

Here, we can measure density and temperature of the gas and work out the mass of the galaxy.

A big elliptical might have a mass of $\approx 10^{12}\mathcal{M}_\odot$, much more than gas+star mass. $\Rightarrow$ ***Dark matter!***

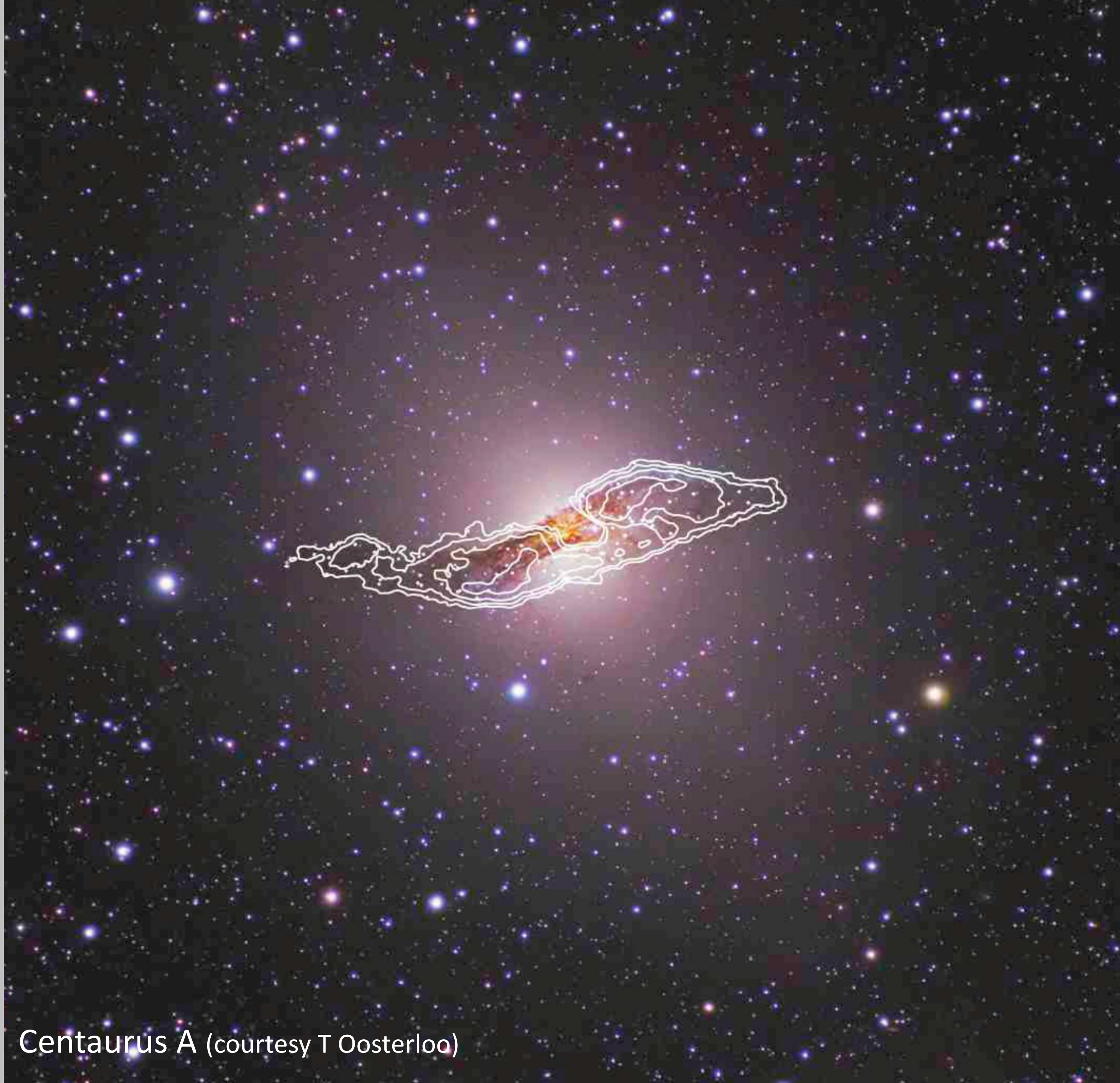


Cold gas in elliptical galaxies

Some ellipticals have a bit of cold neutral hydrogen gas.

Typically morphologically peculiar ellipticals like Centaurus A.

Color image: Visible starlight
Contours: 21-cm HI emission



Centaurus A (courtesy T Oosterloo)

Cold gas in elliptical galaxies

Some ellipticals have a bit of cold neutral hydrogen gas.

Typically morphologically peculiar ellipticals like Centaurus A.

Color image: Visible starlight
Contours: 21-cm HI emission
Overlay: mid-IR dust emission

Centaurus A (courtesy T Oosterloo)

Kinematics: Spiral Galaxies vs Elliptical Galaxies

Spiral Galaxies: Lots of cold gas and star formation.

We can use emission lines from HII regions or 21-cm emission from neutral hydrogen gas to get Doppler shifts and velocities, and measure rotation curves.

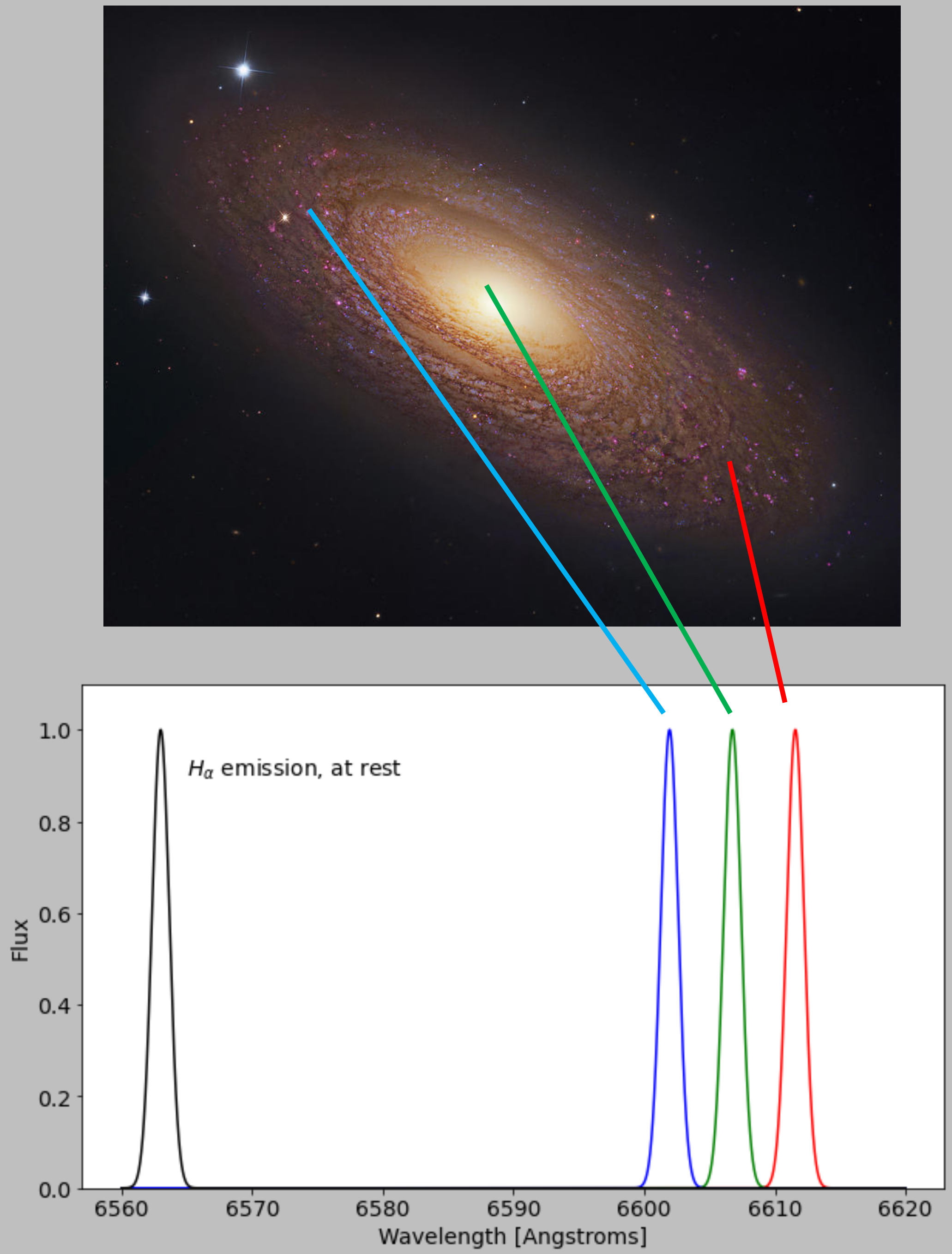
Emission line wavelengths:

- Galaxy center: shifted due to the overall motion of the galaxy towards or away from us
- Edges: shifted relative to center, showing rotation

Compare circular motion (V_c) to velocity dispersion (σ). For the Milky Way typical values give

$$\frac{V_c}{\sigma} = \frac{220}{30} \approx 7$$

So most of the galaxy's motion is bulk motion (rotation) not random motion (dispersion). We call this a **dynamically cold** galaxy.

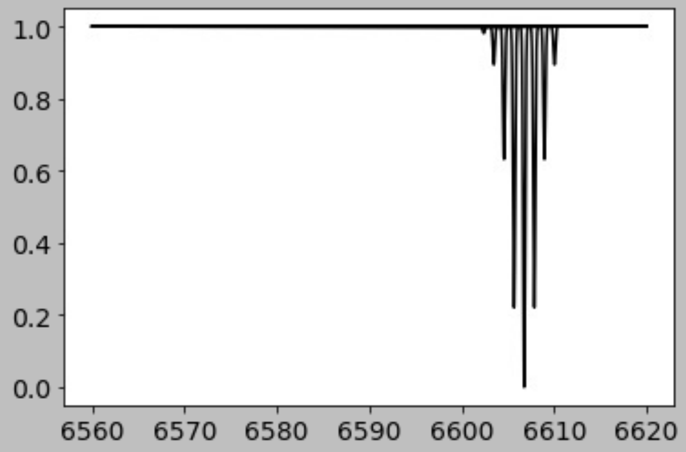


Kinematics: Spiral Galaxies vs Elliptical Galaxies

Elliptical Galaxies: Very little cold gas and star formation.

We use absorption lines in the integrated spectra to show us the distribution of stellar velocities. Along any line of sight through the galaxies, the spread in velocities broadens the absorption lines.

Individual stars

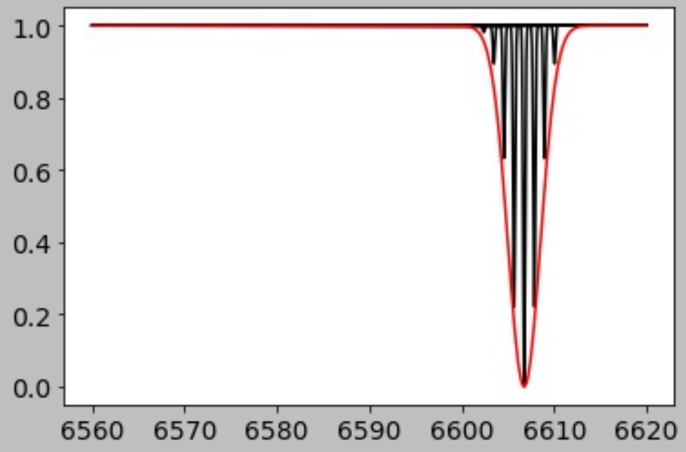


Kinematics: Spiral Galaxies vs Elliptical Galaxies

Elliptical Galaxies: Very little cold gas and star formation.

We use absorption lines in the integrated spectra to show us the distribution of stellar velocities. Along any line of sight through the galaxies, the spread in velocities broadens the absorption lines.

Individual stars…
blend together…



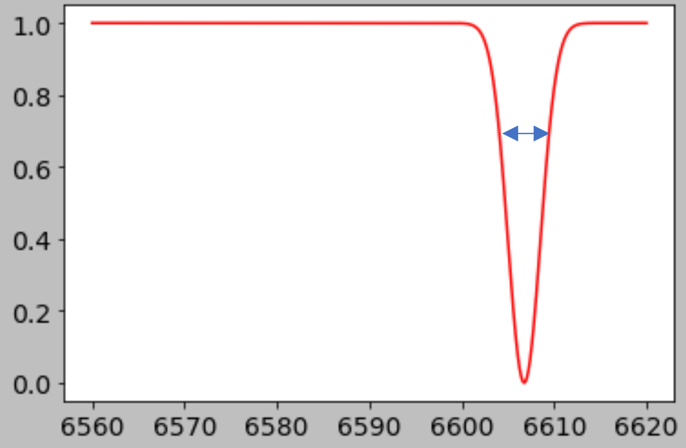
Kinematics: Spiral Galaxies vs Elliptical Galaxies

Elliptical Galaxies: Very little cold gas and star formation.

We use absorption lines in the integrated spectra to show us the distribution of stellar velocities. Along any line of sight through the galaxies, the spread in velocities broadens the absorption lines.

Individual stars…
blend together…
to make broader absorption lines.

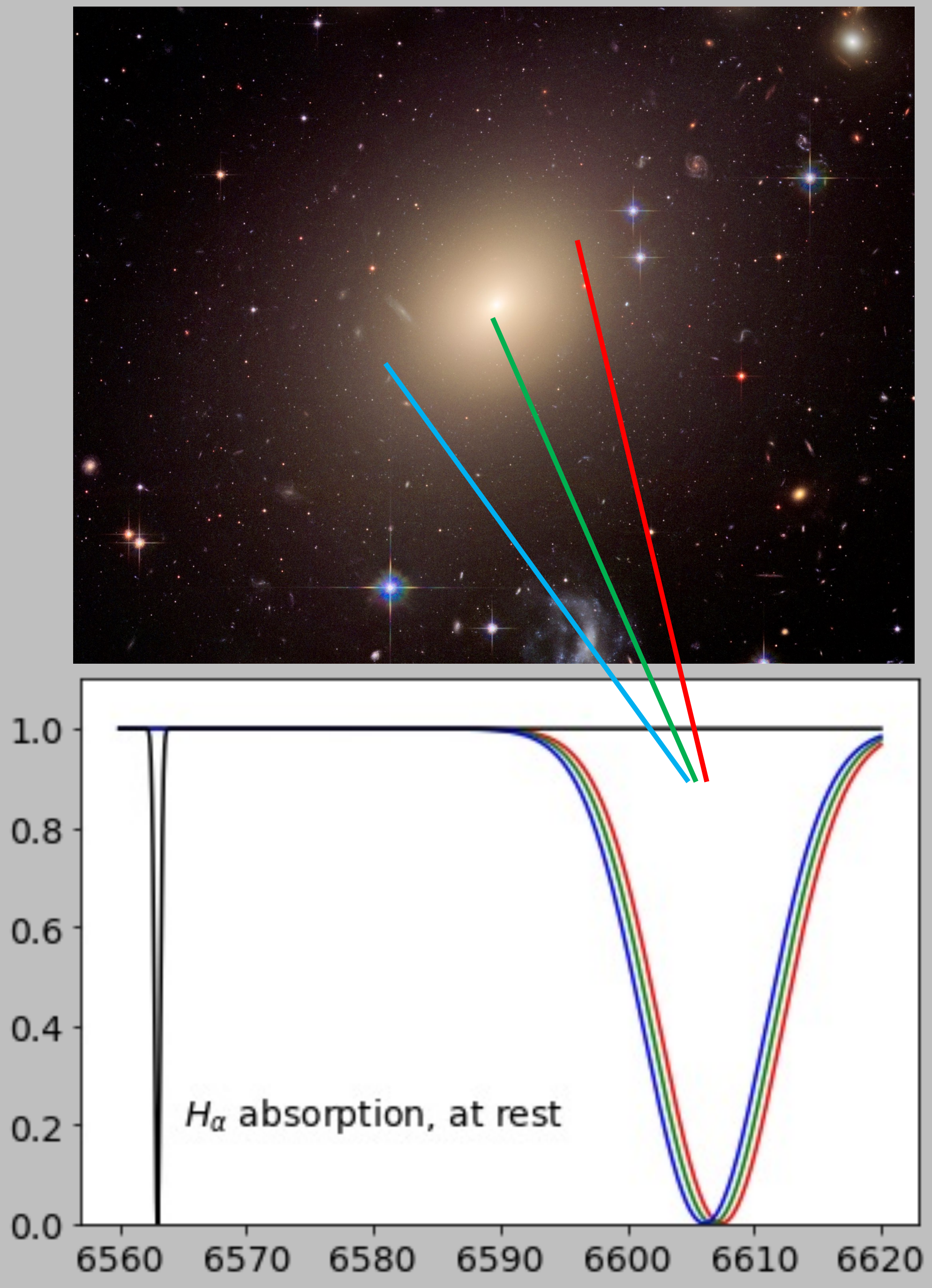
Width shows velocity dispersion.



Ellipticals typically large velocity dispersion and low rotation:

$$\frac{V_c}{\sigma} = \frac{35}{350} \approx 0.1$$

So most of the galaxy's motion is random motion (dispersion) not bulk rotation. We call this a **dynamically hot** galaxy.



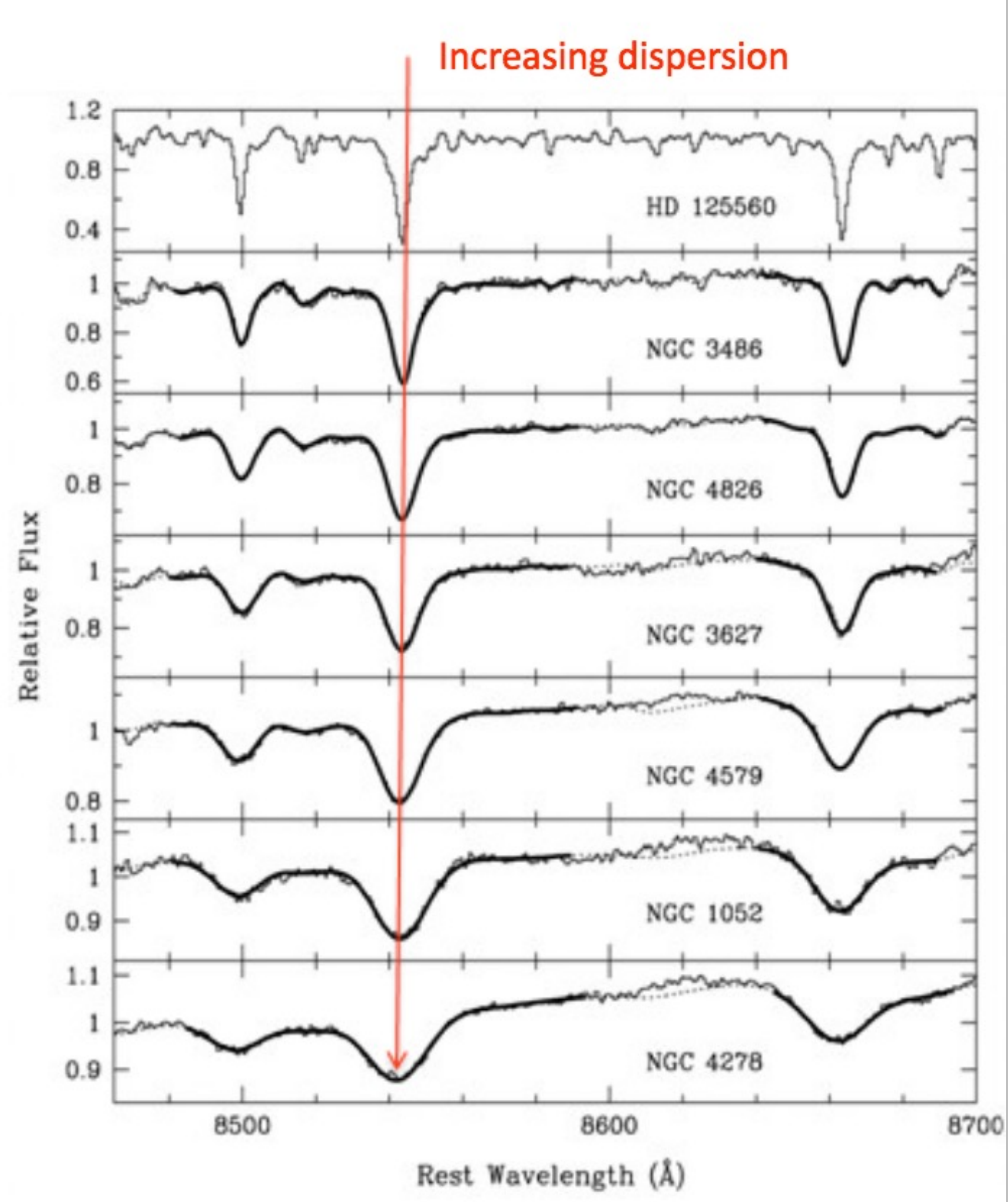
Broadening and velocity dispersion

Individual Red Giant Star

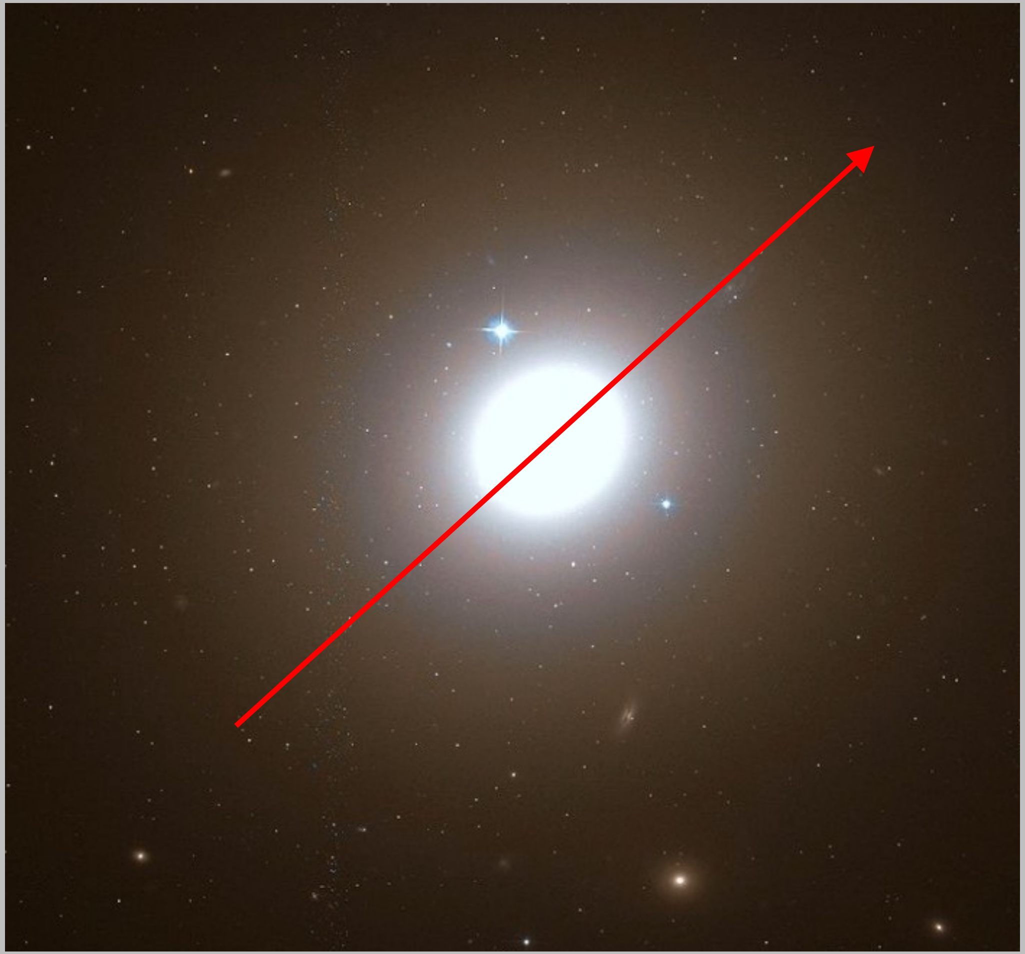
Absorption lines are broadened in wavelength, showing that ellipticals typically have low rotation (V_c) and large velocity dispersion (σ).

Elliptical galaxies are “dynamically hot” galaxies, with $V_c/\sigma < 1$.

Galaxies



Elliptical Galaxies: Major Axis Kinematics



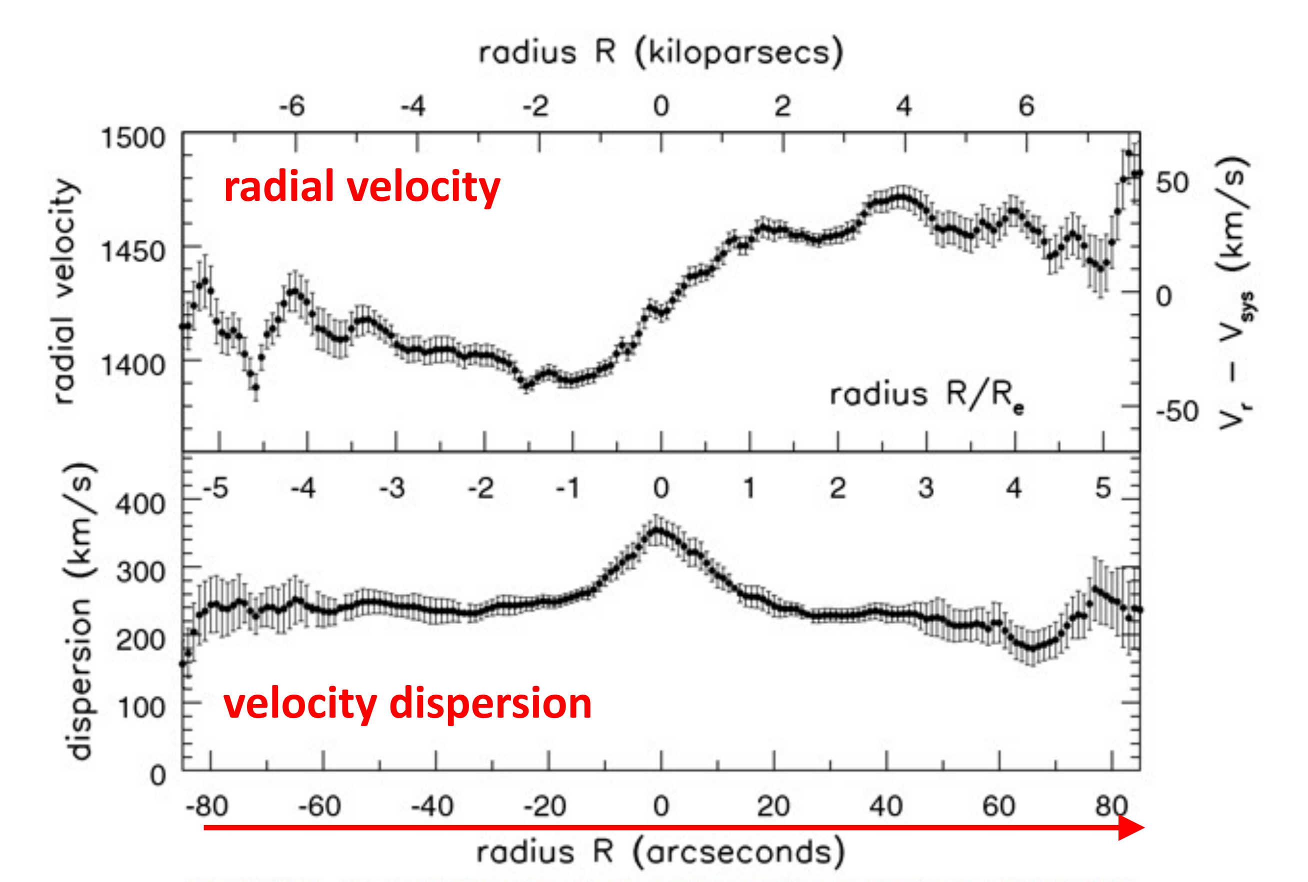


Fig 6.12 (A. Graham) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

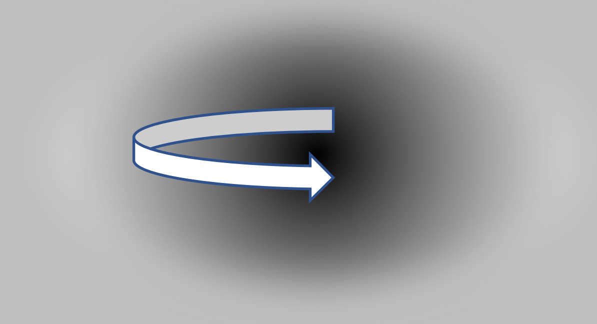
NGC 1399: $\sigma \approx 350$ km/s, $V_c \approx 35$ km/s, $V_c/\sigma \approx 0.1$

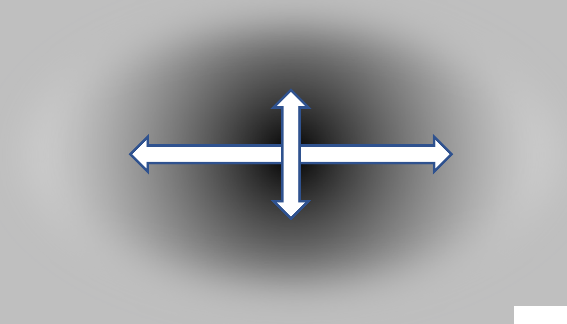
(Compare to Milky Way disk: $\sigma \approx 30$ km/s, $V_c \approx 220$ km/s, $V_c/\sigma \approx 7.3$)

Elliptical Galaxies: Rotation vs Dispersion

Why are ellipticals flattened? Two possibilities:

- **Rotational support**: ellipticals are flattened due to relatively large spin (higher V_c/σ)
- **Pressure support**: ellipticals have higher velocity dispersion along one (or more) axes: $\sigma_x > \sigma_y$

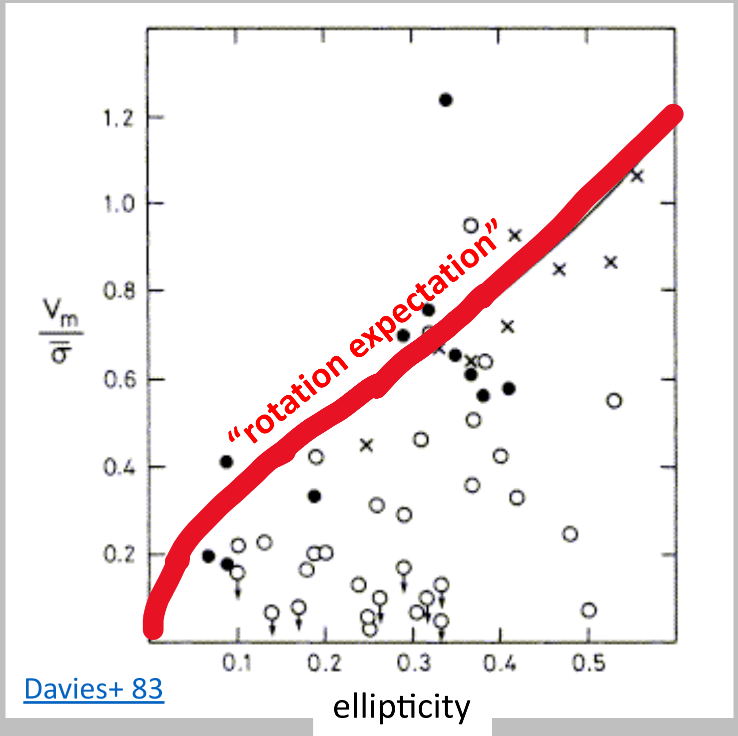




You can calculate the amount of rotation you'd need to flatten an elliptical to a certain flatness. If flattening is due to rotation, flatter ellipticals should have higher value of V_c/σ.

This works for low luminosity ellipticals (black dots), but not for luminous ellipticals (open circles), which fall below the "rotation expectation" line. ⇒

So we say low luminosity ellipticals are more likely to be "rotationally supported", while luminous ellipticals are "pressure supported".



Davies+ 83

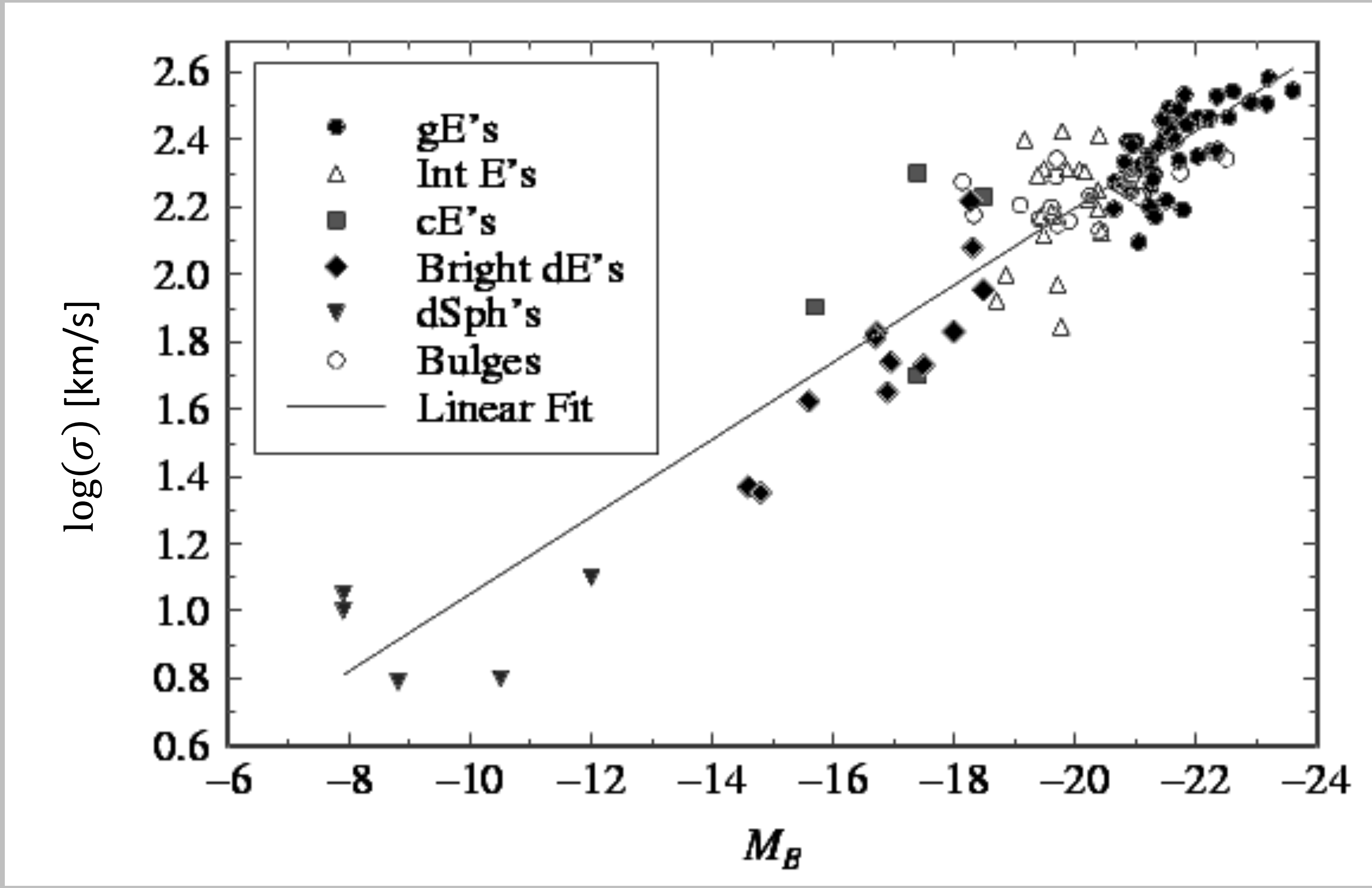
Elliptical Galaxies: Kinematic Scaling Relationships

Remember the Tully-Fisher relation for spiral galaxies: $L \sim V_c^\alpha$ where $\alpha \approx 3-4$.

Is there a similar relationship for elliptical galaxies using the velocity dispersion (σ)?

Yes, for ellipticals, the **Faber-Jackson relation** correlates velocity dispersion with absolute magnitude ⇒

But the scatter around the F-J relation (about 1 magnitude) is much larger than in T-F (a few tenths of a mag). *Why?*



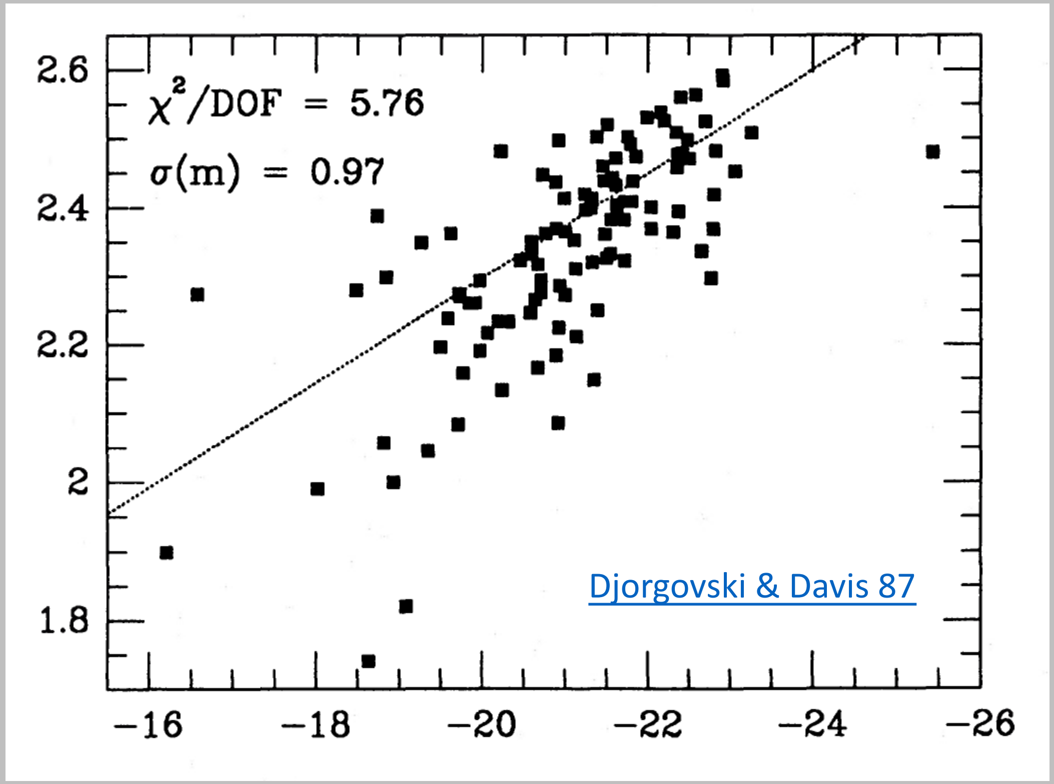
Elliptical Galaxies: Kinematic Scaling Relationships

Think about the observables you can measure for ellipticals:

- Luminosity (or absolute magnitude, M)
- Size (half-light radius, r_e)
- Average surface brightness μ or luminosity density I inside r_e: $\langle \mu \rangle_e$ or $\langle I \rangle_e$
- Velocity dispersion (σ)

Since $\langle I \rangle_e = L/\pi r_e^2$, if you measure two of L, $\langle I \rangle_e$, and r_e, you can calculate the third. So we say that **only two of those properties are independent of each other**. If we add velocity dispersion to the list, we have three independent observables.

Do any of these independent properties correlate with each other?



$\log \sigma$ [km/s] (y-axis) vs M_B (x-axis)
(This is Faber-Jackson)

Correlation yes, but a lot of scatter! 😒

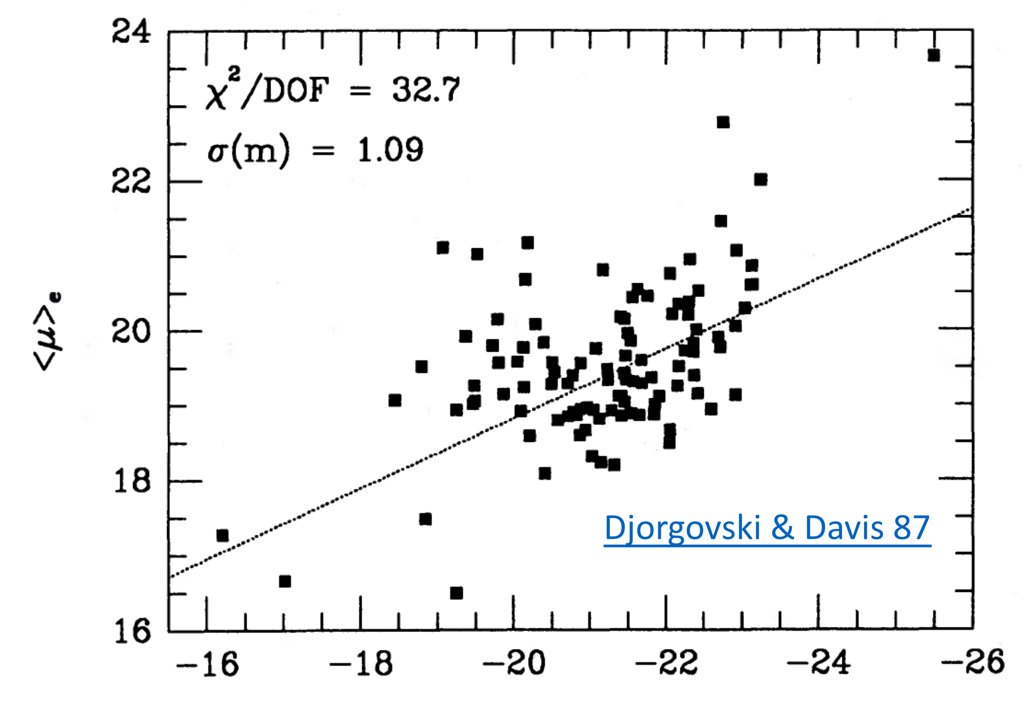
Elliptical Galaxies: Kinematic Scaling Relationships

Think about the observables you can measure for ellipticals:

- Luminosity (or absolute magnitude, M)
- Size (half-light radius, r_e)
- Average surface brightness μ or luminosity density I inside r_e: $\langle\mu\rangle_e$ or $\langle I\rangle_e$
- Velocity dispersion (σ)

Since $\langle I\rangle_e = L/\pi r_e^2$, if you measure two of L, $\langle I\rangle_e$, and r_e, you can calculate the third. So we say that **only two of those properties are independent of each other**. If we add velocity dispersion to the list, we have three independent observables.

Do any of these independent properties correlate with each other?



Djorgovski & Davis 87

$\langle\mu\rangle_e$[B-mags/arcsec^2] (y-axis) vs M_B (x-axis)

Blurgh, no correlation 🤮

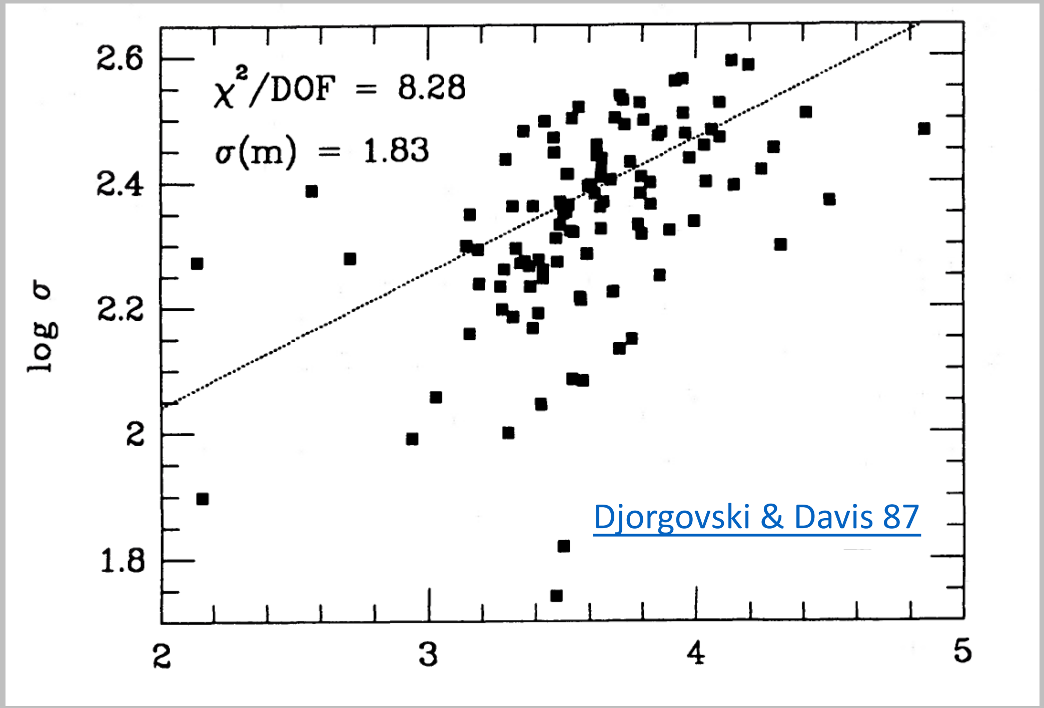
Elliptical Galaxies: Kinematic Scaling Relationships

Think about the observables you can measure for ellipticals:

- Luminosity (or absolute magnitude, M)
- Size (half-light radius, r_e)
- Average surface brightness μ or luminosity density I inside r_e: $\langle \mu \rangle_e$ or $\langle I \rangle_e$
- Velocity dispersion (σ)

Since $\langle I \rangle_e = L/\pi r_e^2$, if you measure two of L, $\langle I \rangle_e$, and r_e, you can calculate the third. So we say that **only two of those properties are independent of each other**. If we add velocity dispersion to the list, we have three independent observables.

Do any of these independent properties correlate with each other?



$\log \sigma$ [km/s] (y-axis) vs $\log r_e$ [pc] (x-axis)

Ugh, also not great 😢

What now? How about a combination of all three?

Elliptical Galaxies: The Fundamental Plane

Fundamental Plane: a tight correlation between physical size (r_e in pc or kpc) and a combination of velocity dispersion and luminosity density (σ in km/s, $\langle I \rangle_e$ in $L_{\odot}/\mathrm{pc}^2$):

$$\log r_e = 1.24 \log \sigma - 0.82 \log\langle I \rangle_e + \mathrm{C}$$

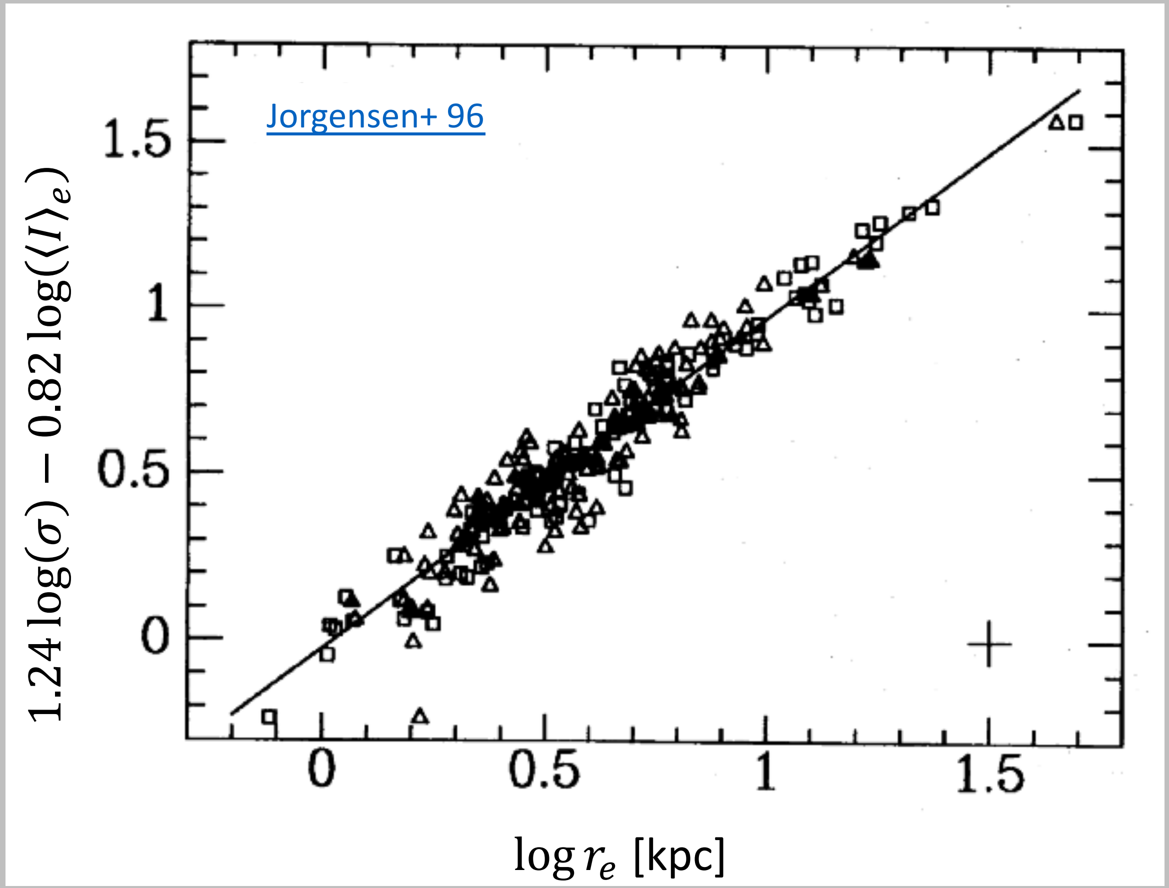
or

$$r_e \sim \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

Why is it called the Fundamental *Plane*?

A correlation between two variables (x and y) is a **line**.
A correlation between three variables (x, y, and z) is a **plane**.

Plotting one parameter against a combination of the other two means that we are projecting the 3D plane onto a 2D plot.



The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ **They give us ways to derive distances to galaxies**

Note that one axis is always physical (TF: absolute magnitude; FP: physical size) and the other is pure observable (TF: circular velocity, FP: combination of velocity dispersion and surface brightness).

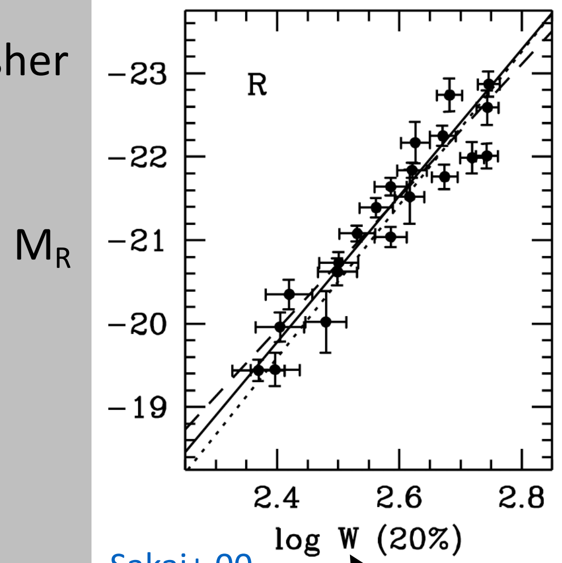
Tully-Fisher: measure circular speed (V_c), get ***absolute*** magnitude (M). Then measure apparent magnitude (m), and get galaxy distance from

$$m - M = 5 \log D - 5.$$

Fundamental Plane: measure velocity dispersion (σ) and surface brightness ($\langle \mu \rangle_e$ or $\langle I \rangle_e$), get ***physical*** size ($r_{e,phys}$, in kpc). Then measure angular size ($r_{e,obs}$ in arcsec) and get distance from

$$r_{e,phys} = \frac{r_{e,obs} D}{206265}$$

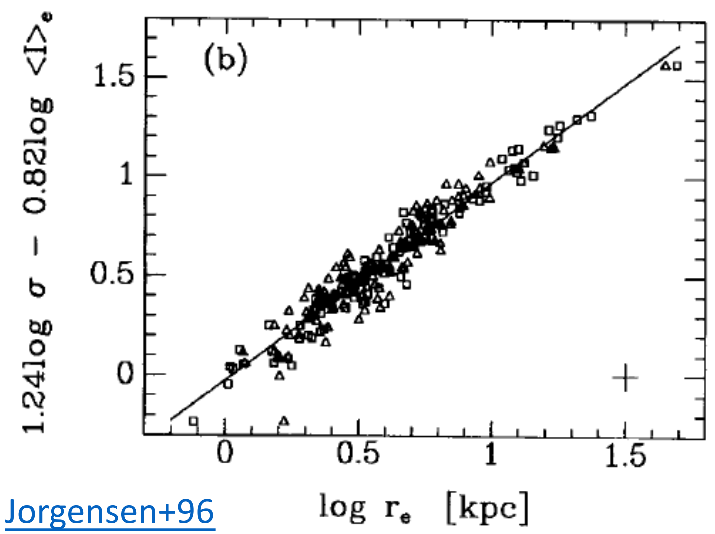
Spirals:
Tully-Fisher



Sakai+ 00

$W \approx 2V_c$

Ellipticals:
Fundamental Plane



Jorgensen+96

The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ **They give us ways to derive distances to galaxies**

⇒ **They tell us about dark matter and stellar populations in galaxies**

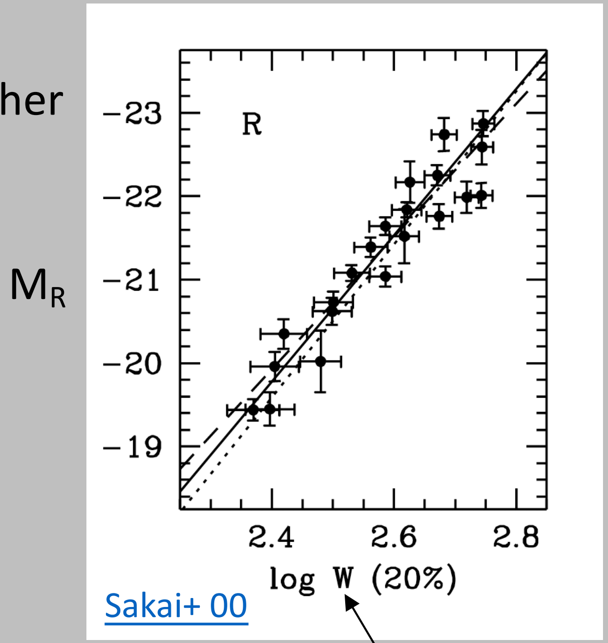
One term involves dynamical motion (V_c or σ), which depends on total mass (incuding dark matter), while the others depend only on the stars.

So you can look at how these relationships differ between galaxies of different types, for example:

- Does the TF relation behave differently for Sa vs Sc galaxies?
- Is the FP relation different for ellipticals in galaxy clusters?
- Do these relationships change over time (by comparing nearby galaxies to very distant galaxies)?

Differences in these relationships tell you how stars and dark matter are distributed differently (or change) in galaxies.

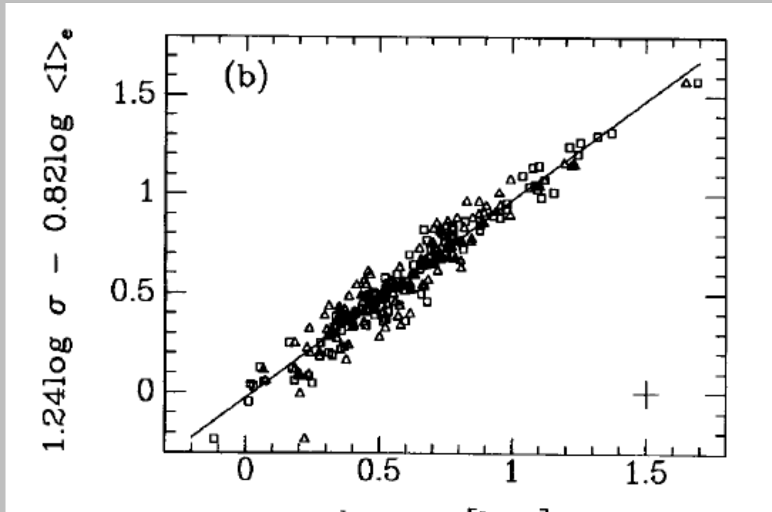
Spirals:
Tully-Fisher



Sakai+ 00

$W \approx 2V_c$

Ellipticals:
Fundamental Plane



Jorgensen+96

The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ **They give us ways to derive distances to galaxies**

⇒ **They tell us about dark matter and stellar populations in galaxies**

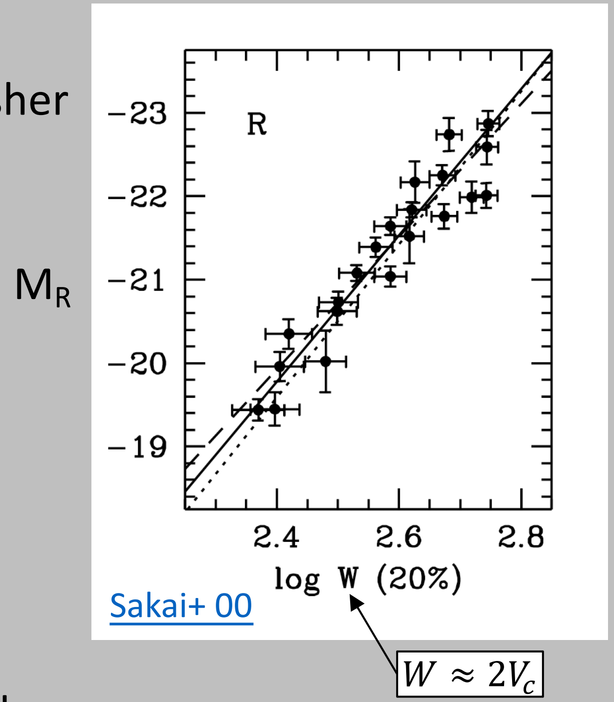
⇒ **They tell us something fundamental about how galaxies form**

Why do galaxies follow these relationships? Many different physical process are involved in forming galaxies (dark matter, regular baryonic matter, gravity, star formation, gas physics, etc, etc), so how do all these processes work together to form such tight relationships?

We don't know!

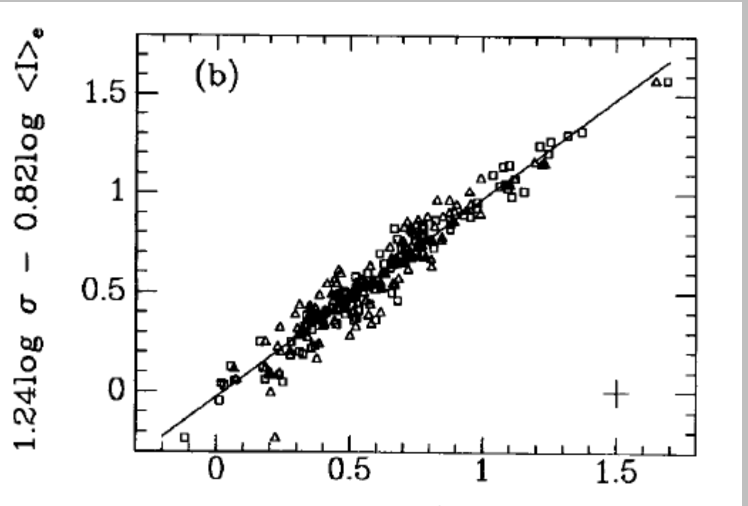
With all these questions, the scatter around the relationship is very important. How much of that is real, how much is observational uncertainty? Lots of work going into these questions.....

Spirals:
Tully-Fisher



Sakai+ 00

Ellipticals:
Fundamental Plane

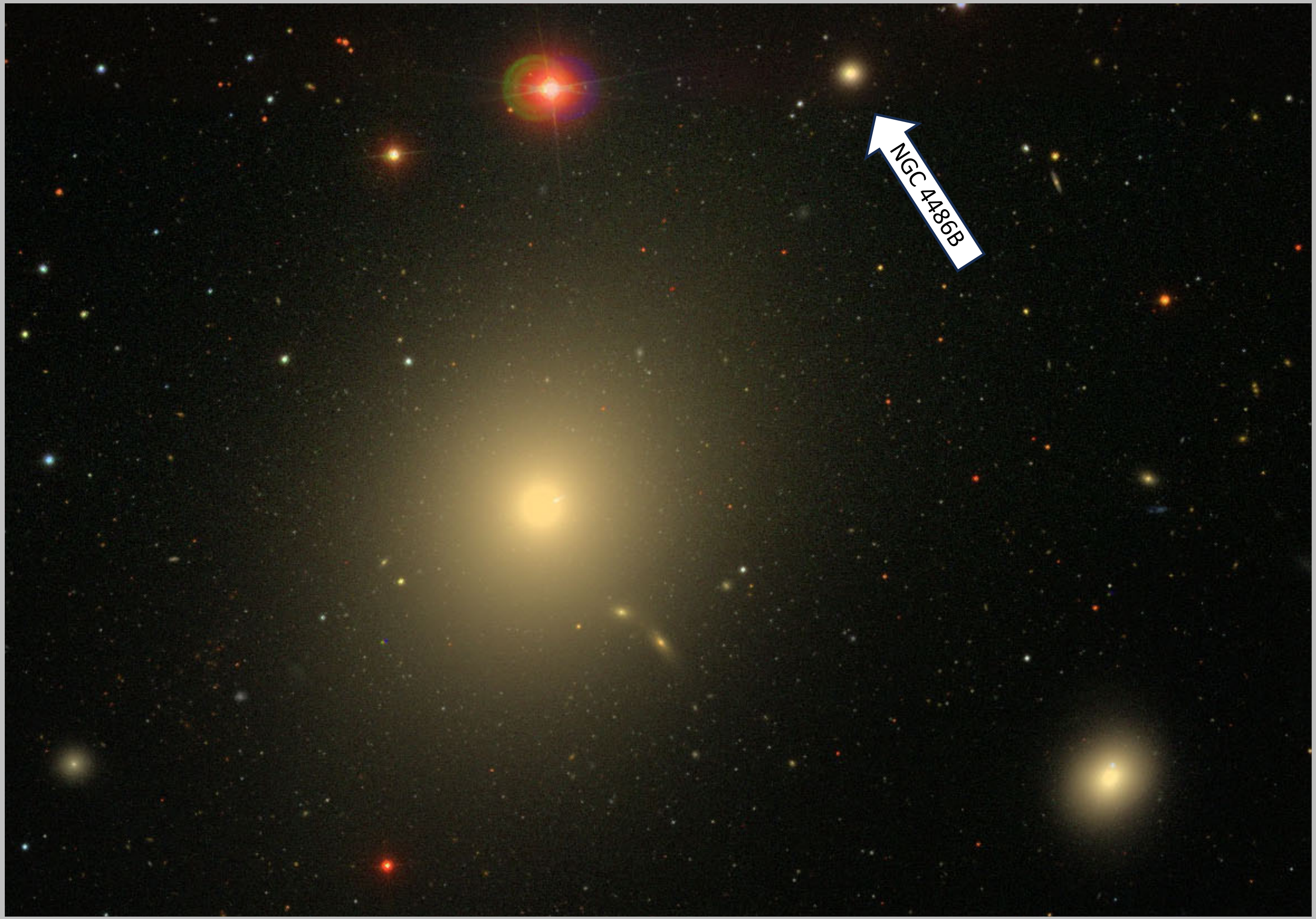


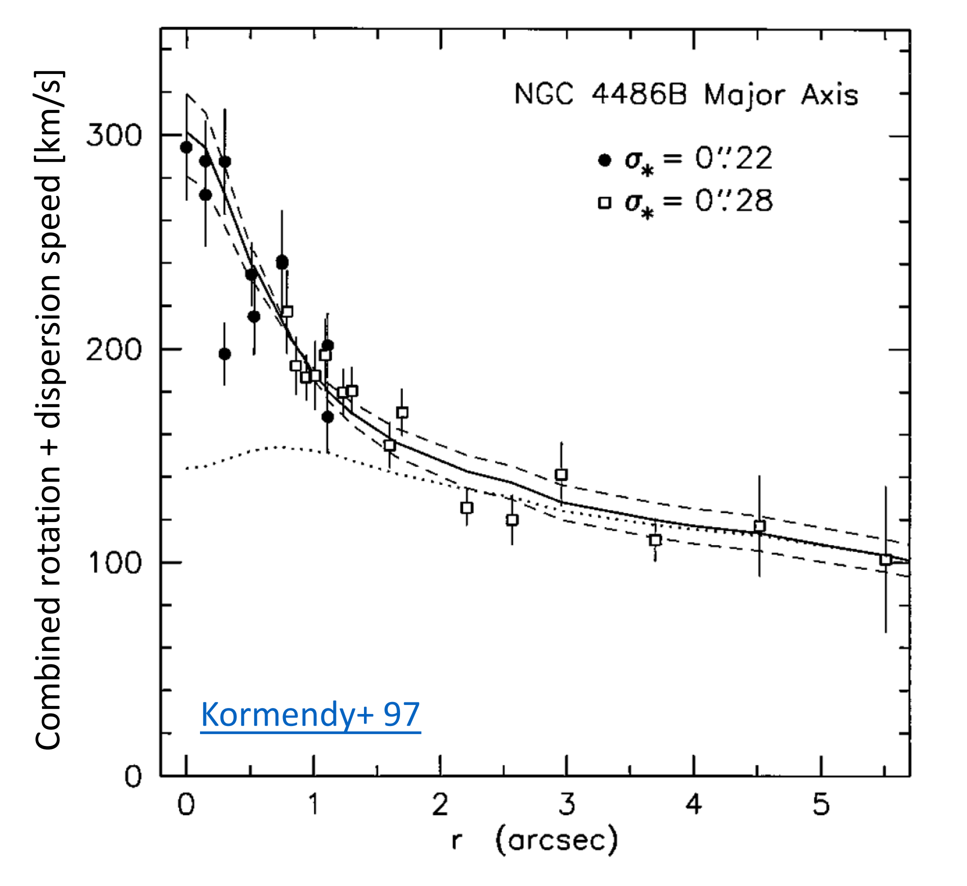
Jorgensen+96

Supermassive Black Holes

Many ellipticals have been found to host supermassive black holes in the nuclei.

Look at the motions of stars near the center of NGC 4486B.





Dotted line: No black hole expectation, gravity just based on stars.

Solid/dashed lines: Model based on stars + supermassive black hole with mass:

$$M_{BH} = 9{\times}10^8\ M_{\odot}$$

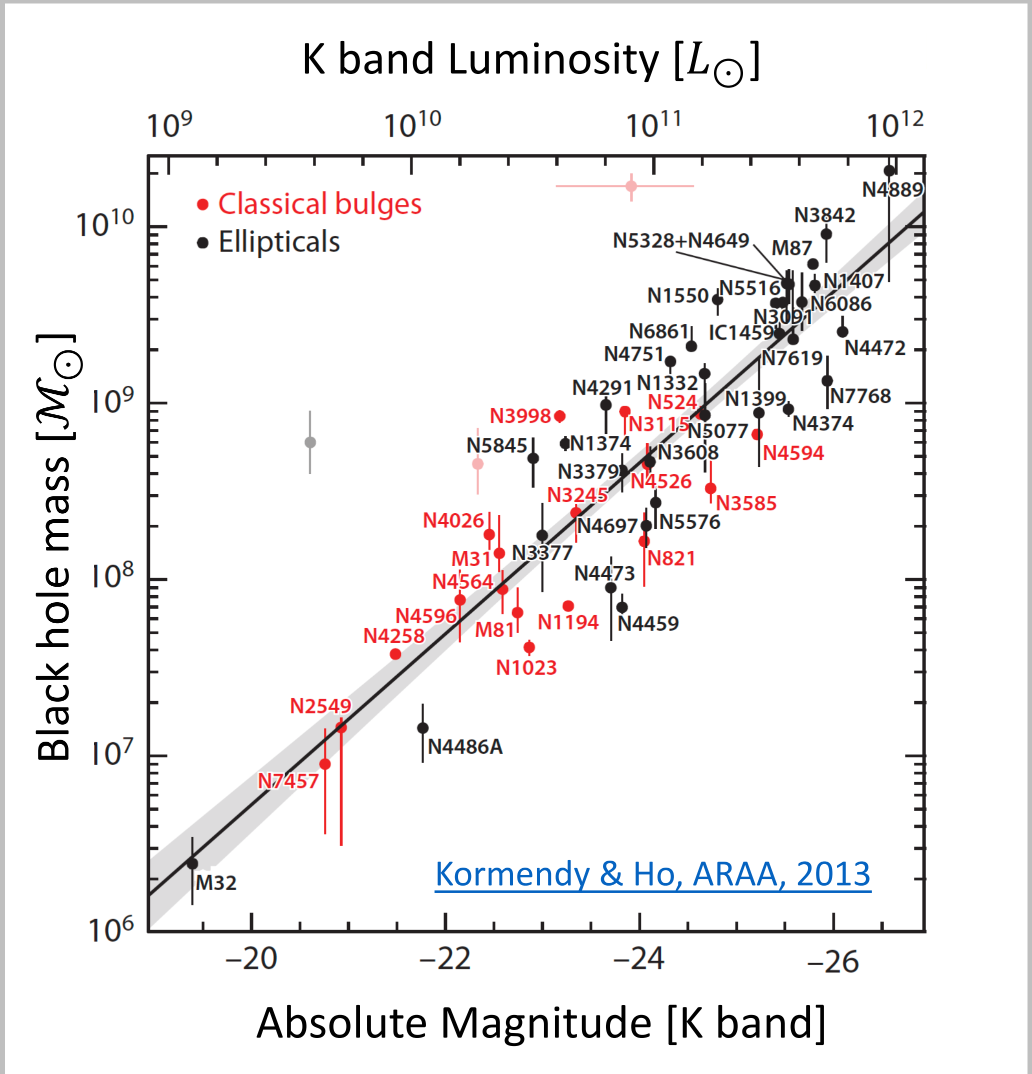
Supermassive Black Holes

Do this for many galaxies, plotting black hole mass versus galaxy absolute magnitude (or luminosity).

Black points: Elliptical galaxies
Red points: Bulges of spiral galaxies (ignoring their disk)

Strong correlation between black hole mass and *spheroid* luminosity (i.e., elliptical galaxy stars or spiral galaxy bulge stars).

And in spirals, no correlation at all between black hole mass and stellar mass of the *disk*.



Black holes have masses that are ≈ 0.1 % – 1% of the stellar mass of the entire spheroid.

Not enough to affect the dynamics of the galaxy as a whole, but does affect dynamics of the inner ≈ 50 – 100 pc.....

Peculiar Galaxies: Starbursts and Interactions

M82 – *NASA/ESA*

The Antennae – *Rolf Olsen*

The “Star-forming Main Sequence” of Galaxies

Alternatively, think about **gas depletion time**: how long can galaxies maintain their current rate of star formation?

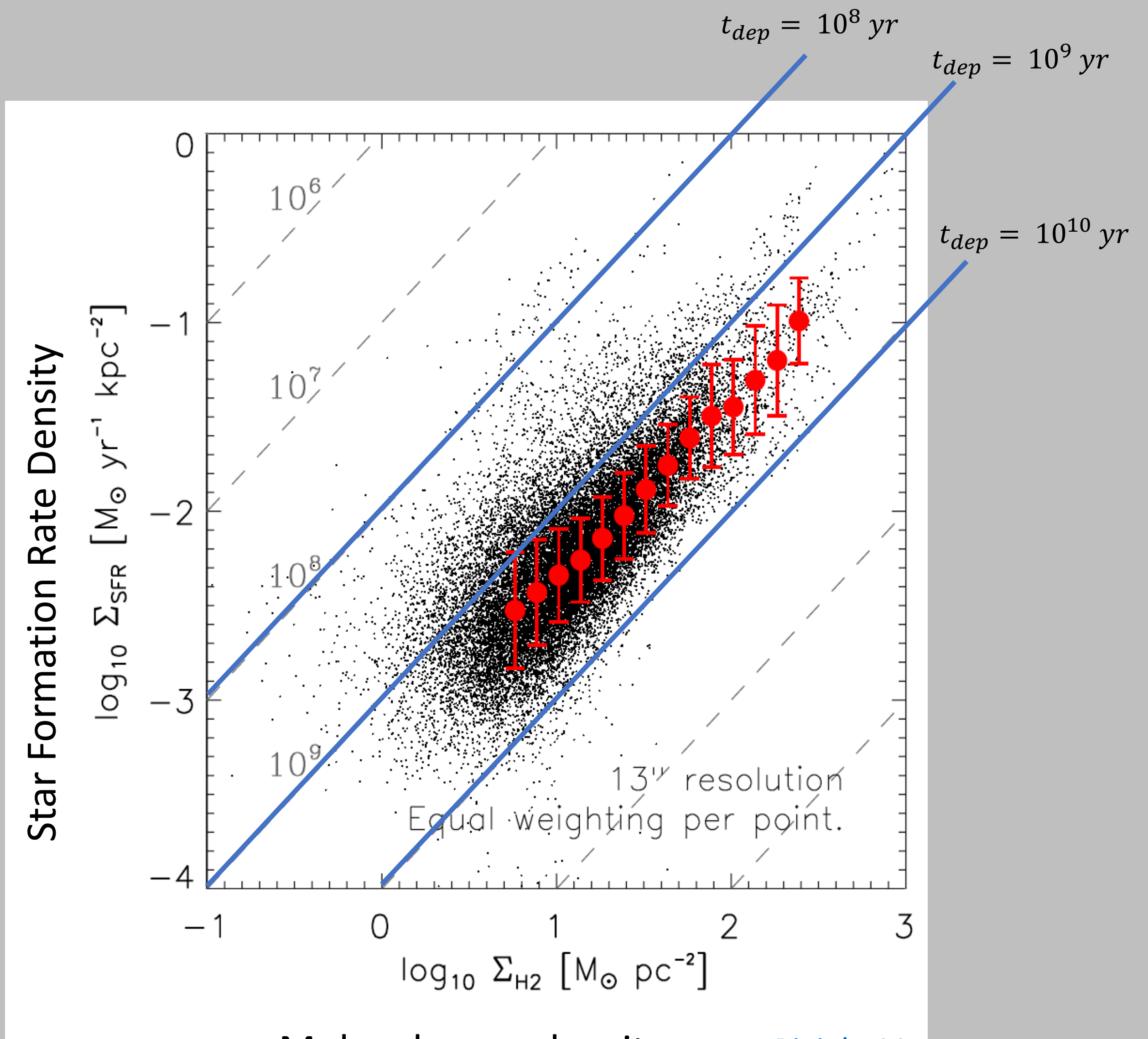
Depends on how much gas they have, and how fast they are using it:

$$t_{dep} = \mathcal{M}_{gas}/SFR$$

For most star-forming galaxies, $t_{dep} \approx 1 - 10$ billion years.

Outliers: some galaxies have $t_{dep} < 100$ million years.

Starburst galaxies: Galaxies that are forming stars at a furiously high and unsustainable rate.



Bigiel+ 11

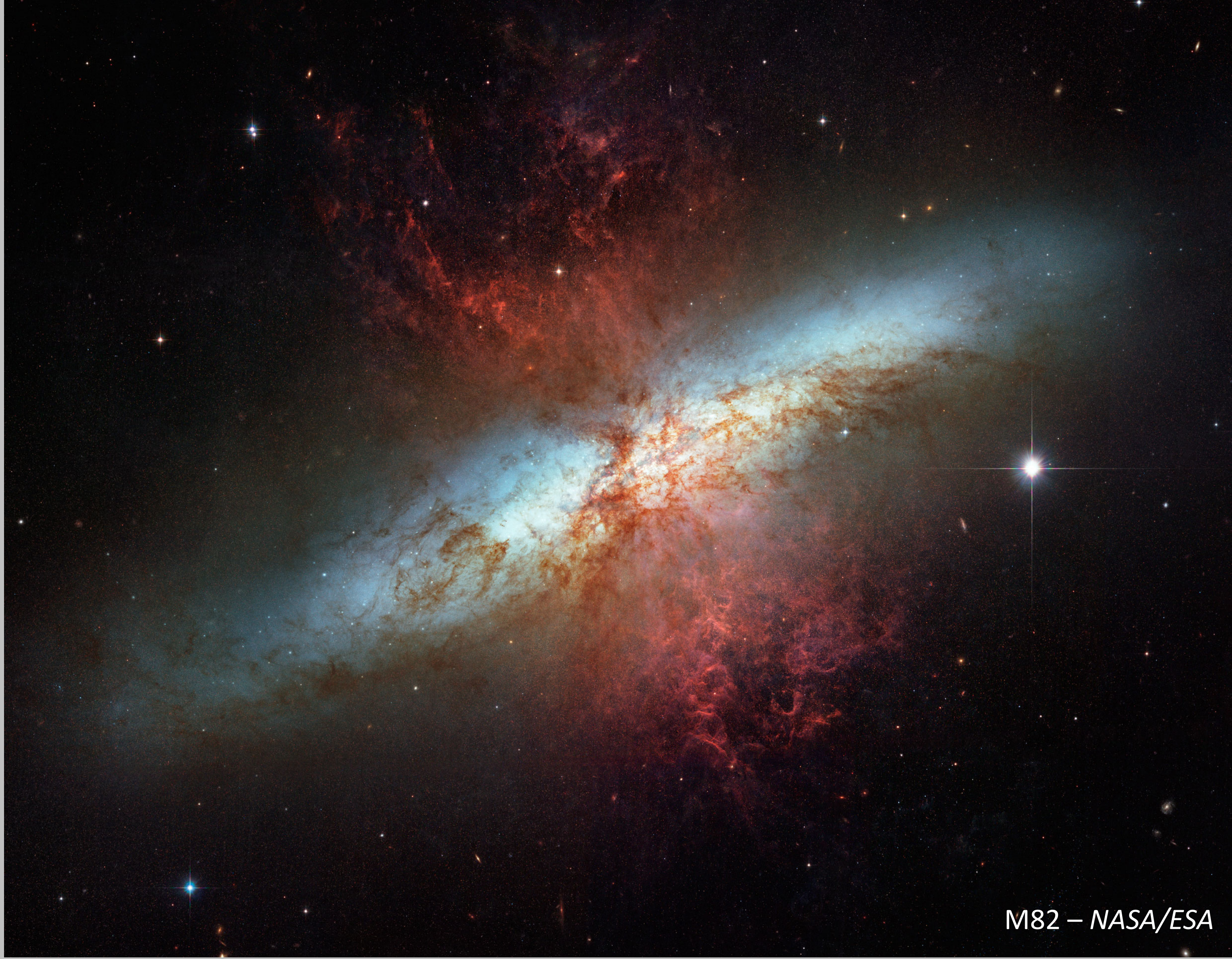
Starburst galaxy M82 (distance ≈ 3.5 Mpc)

Edge on disk, with giant filaments of Hα emission: ionized gas.

Gas is moving at high velocity: racing outwards

Star formation rate (SFR) ≈ few $M_\odot$/yr

Many supernovae seen (via radio emission) embedded in its dusty core.

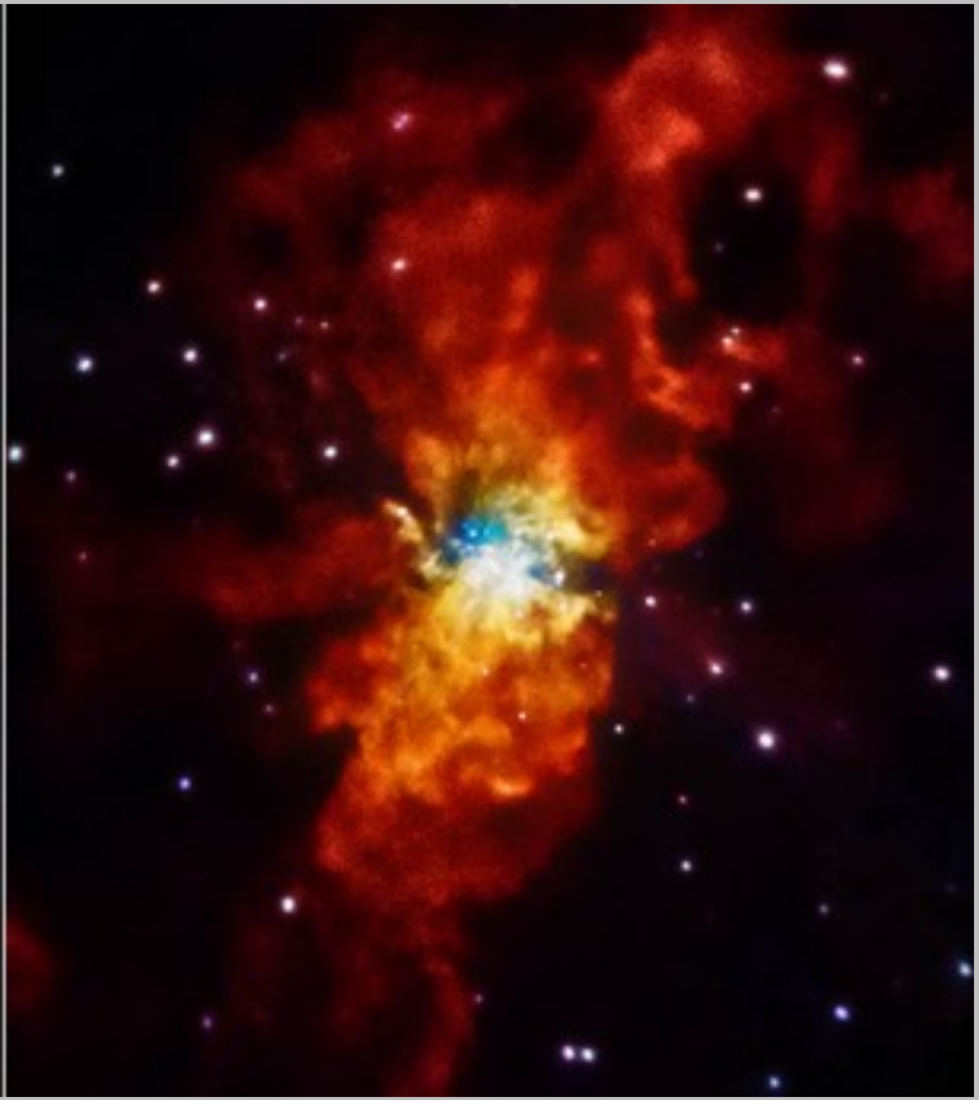


Blueish-white: optical starlight
Reddish filaments: Hα emission

M101 and M82 have similar star formation rates, but M82 is much smaller, less massive, and has a very short gas depletion time. That makes M82 a starburst galaxy.

Starburst winds: Massive star outflows and supernovae combine together to deposit a lot of energy in the surrounding gas, heating it up and blowing it outwards: **starburst winds**.

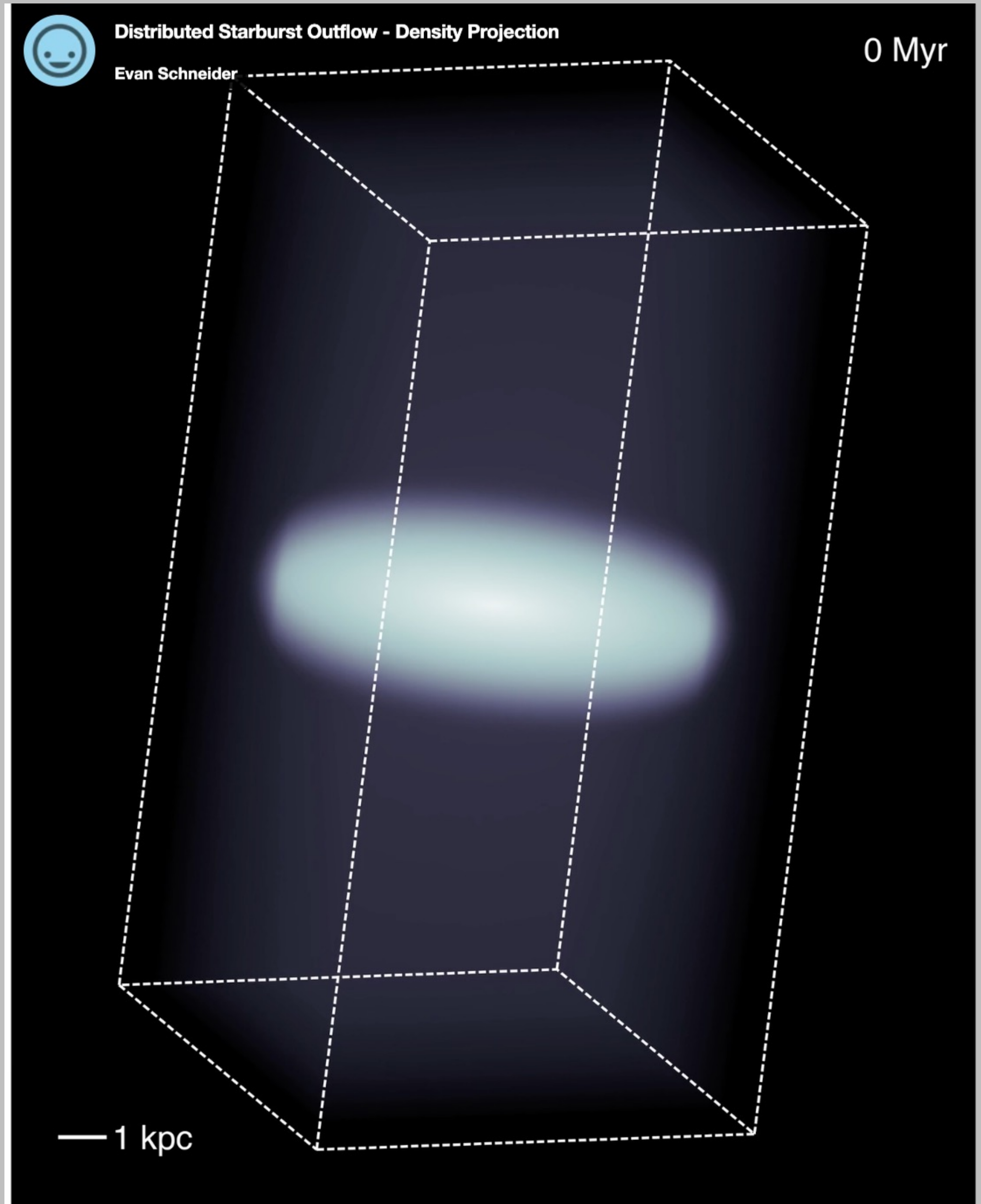
M82: starlight + ionized gas (Hα)



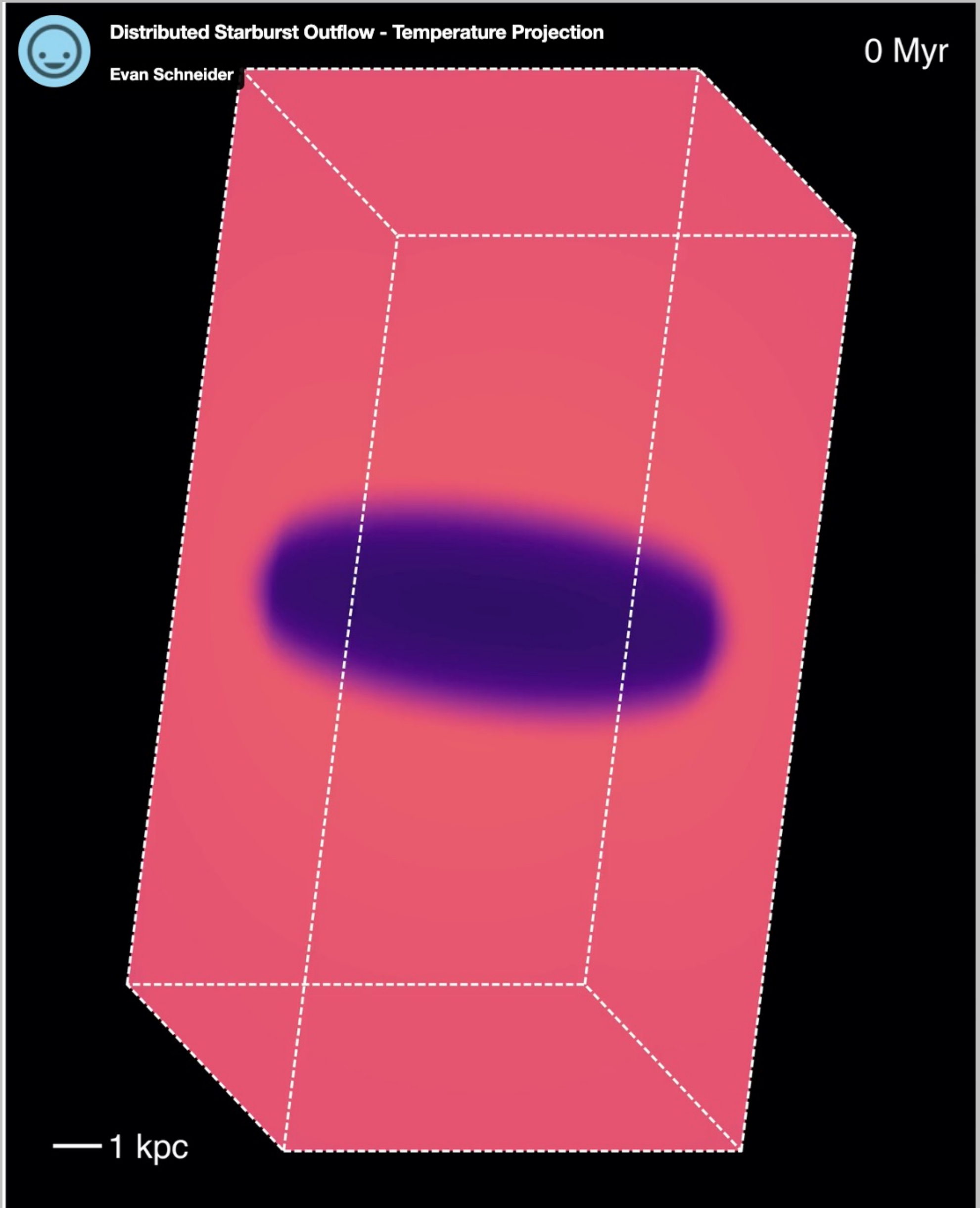
M82: very hot X-ray emitting gas

Starburst wind videos (Evan Schneider, Pittsburgh):

Gas density



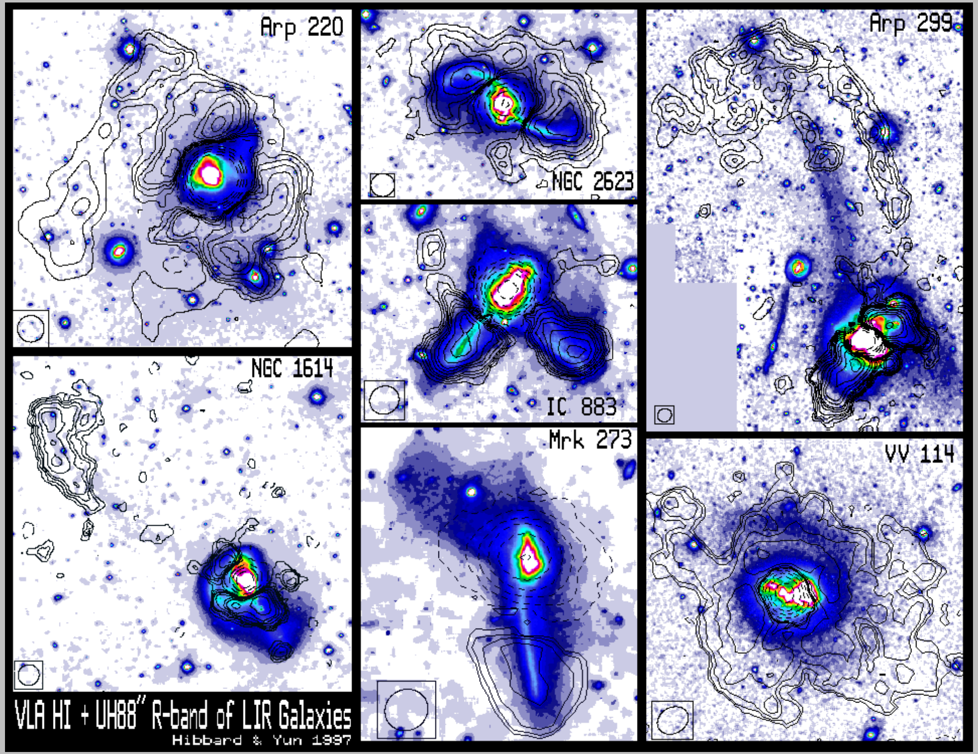
Gas temperature



Starbursts and Luminous Infrared Galaxies

Starburst galaxies are generally gas-rich, with lots of dust. This dust absorbs a lot of the light from the young stars, masking them from our view.

But absorbing all that energy makes the dust heat up to ≈ 40 – 60 K, emitting far infrared (blackbody) radiation. So dusty starburst galaxies are bright in the far infrared, with luminosities $L_{FIR} = 10^{11} - 10^{12}\ L_{\odot}$. Which would need SFR ≈ 10 – 100 $M_{\odot}$/yr!



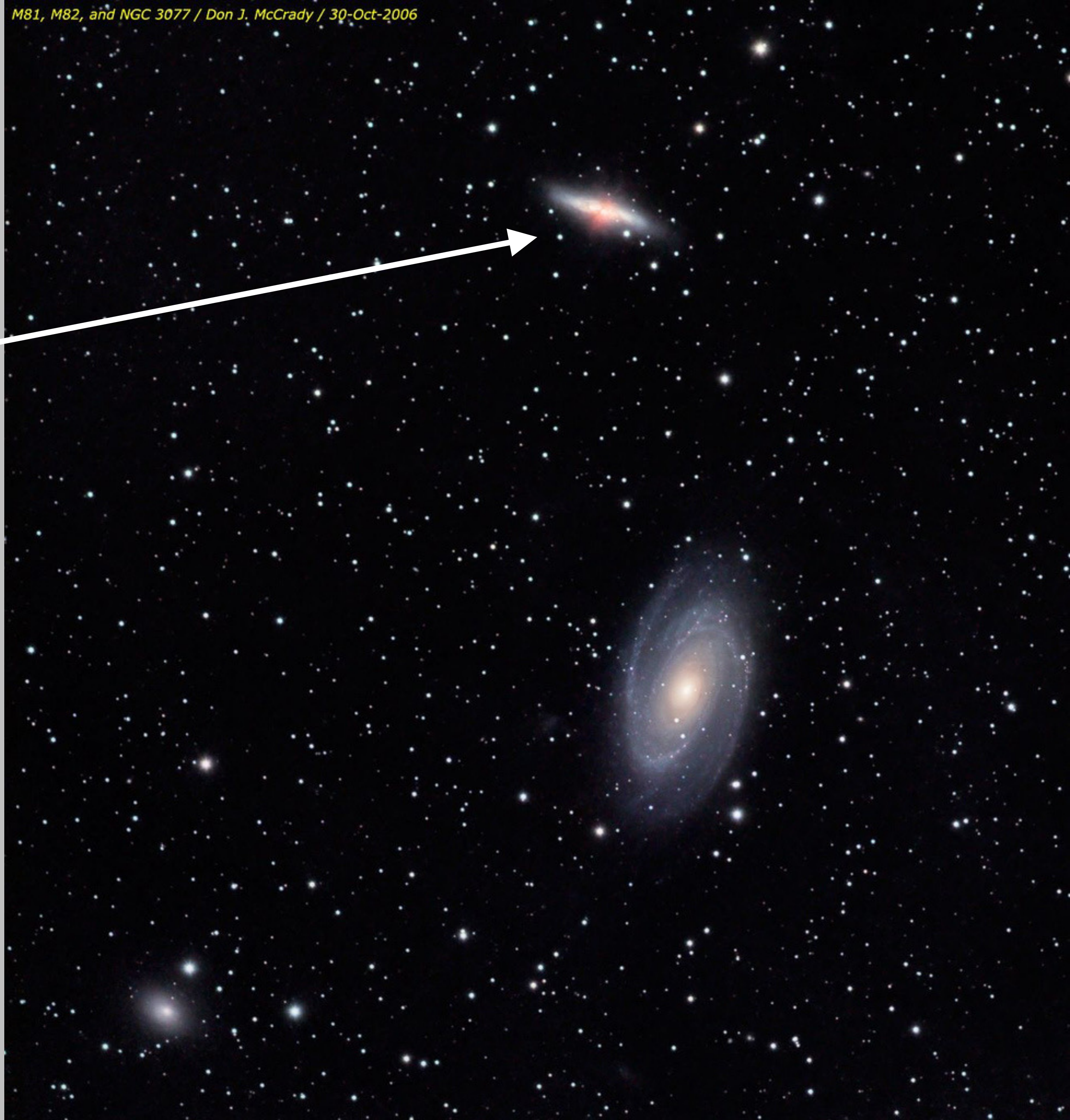
late 1980s: The Infrared Astronomy Satellite (IRAS) began detecting large numbers of luminous infrared galaxies: starbursts.

Followup optical imaging showed many of them to have very peculiar morphologies: interacting and merging galaxies.

⇐ Optical images of LIRGs (color shows surface brightness; contours show gas density). From Hibbard and Yun 1998.

What about M82? Is it interacting?

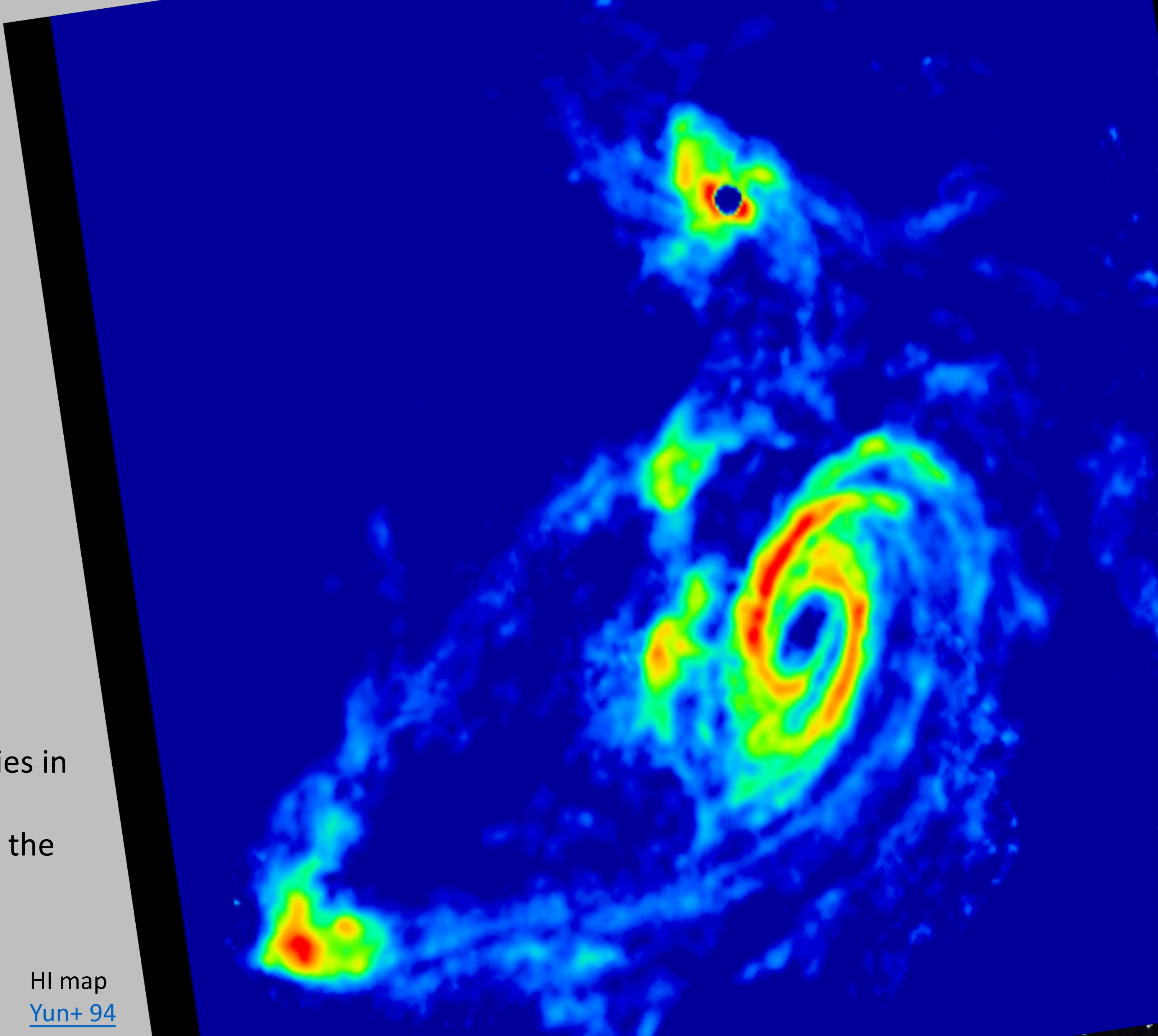
M82 is part of the M81 galaxy group....



What about M82? Is it interacting?

M82 is part of the M81 galaxy group....

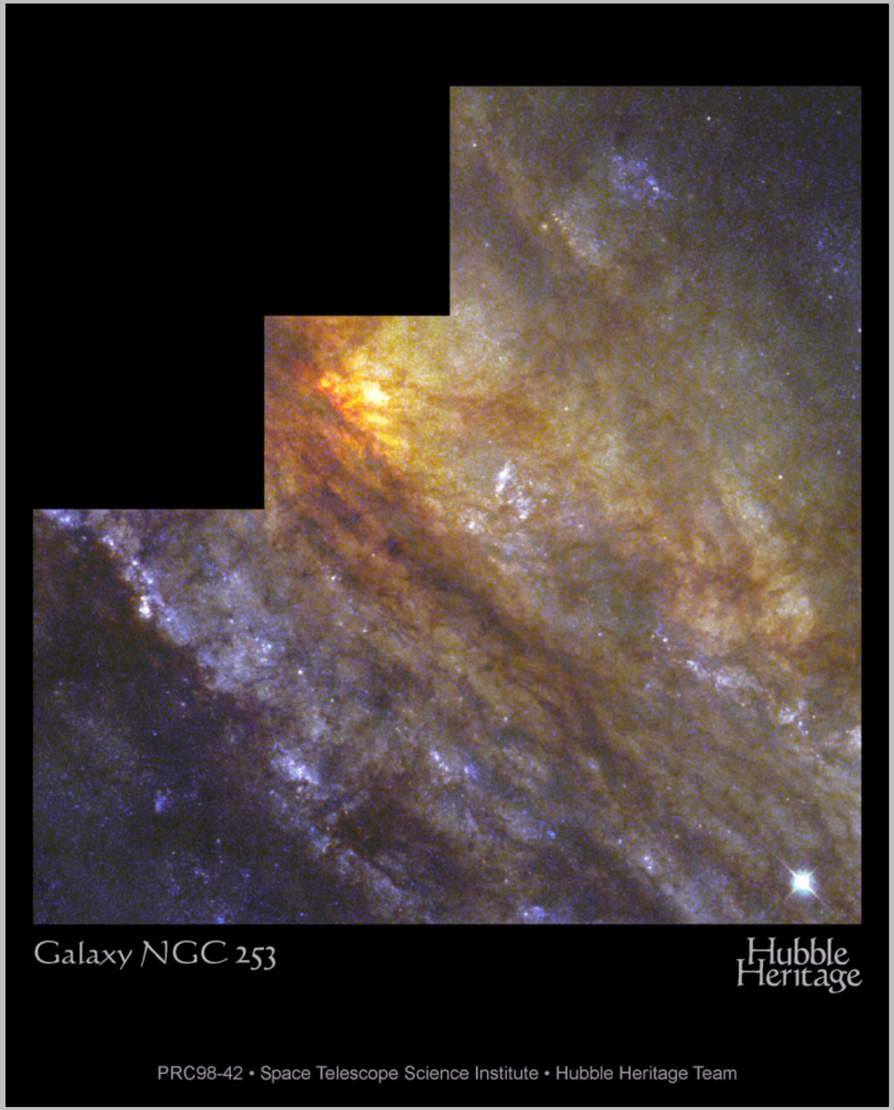
....and 21-cm HI observations show the galaxies in the group all connected by filaments of gas, probably pulled out by gravitational forces as the galaxies have interacted with each other!



HI map
[Yun+ 94]

But not every starburst galaxy is interacting!

NGC 253 (D=3.5 Mpc)




Arp 87
NASA/STScI
Galaxy Interactions

Galaxy Interactions: Timescales

Think of two galaxies passing by one another. How long does this take?

Let's say "passing" means moving 4x their diameter, so:

$$t_{pass} \approx \frac{4 \times D}{V_{rel}}$$

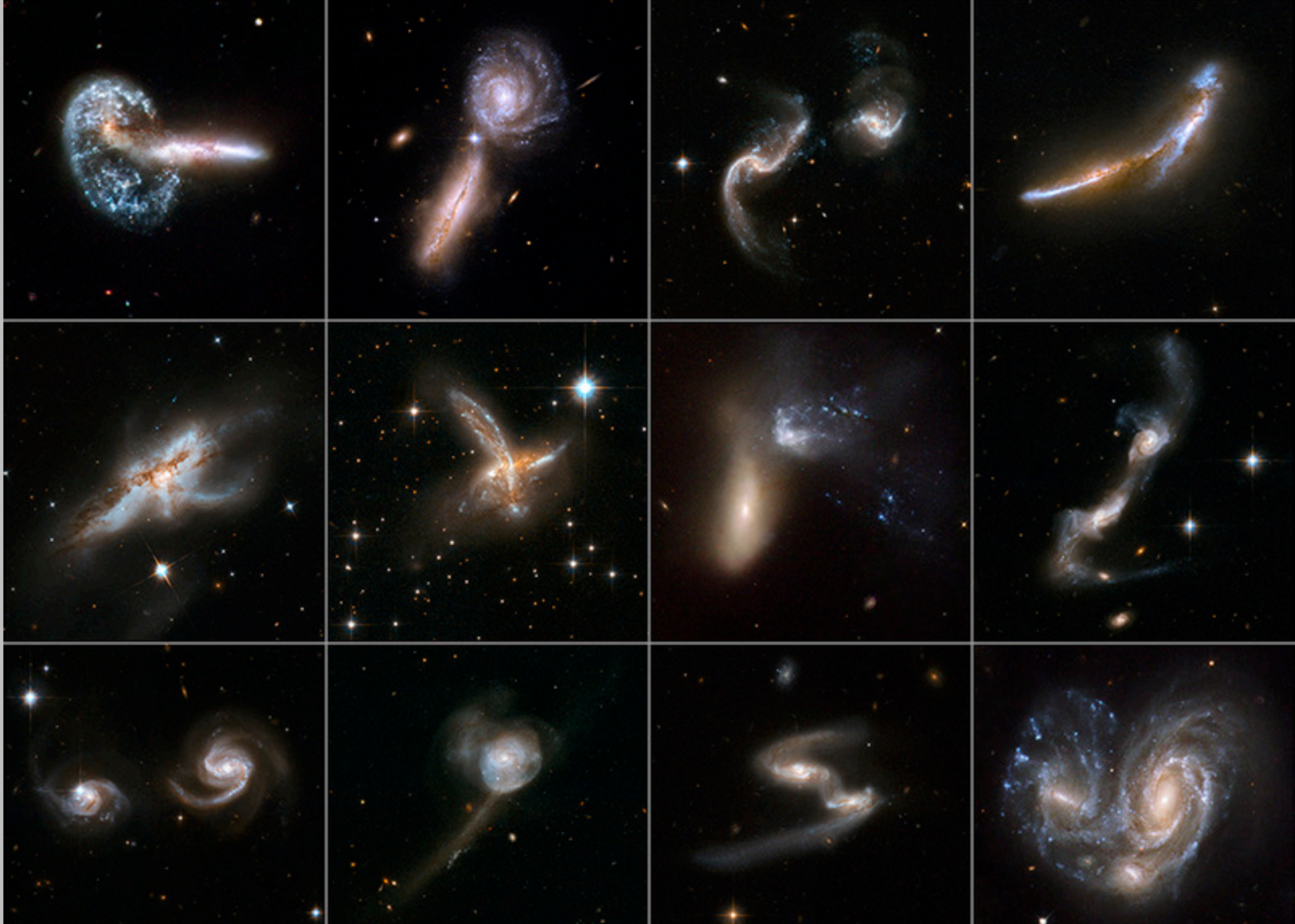
Using typical numbers:

$$D \approx 30\ kpc$$
$$V_{rel} \approx 200\ km/s$$

we get:

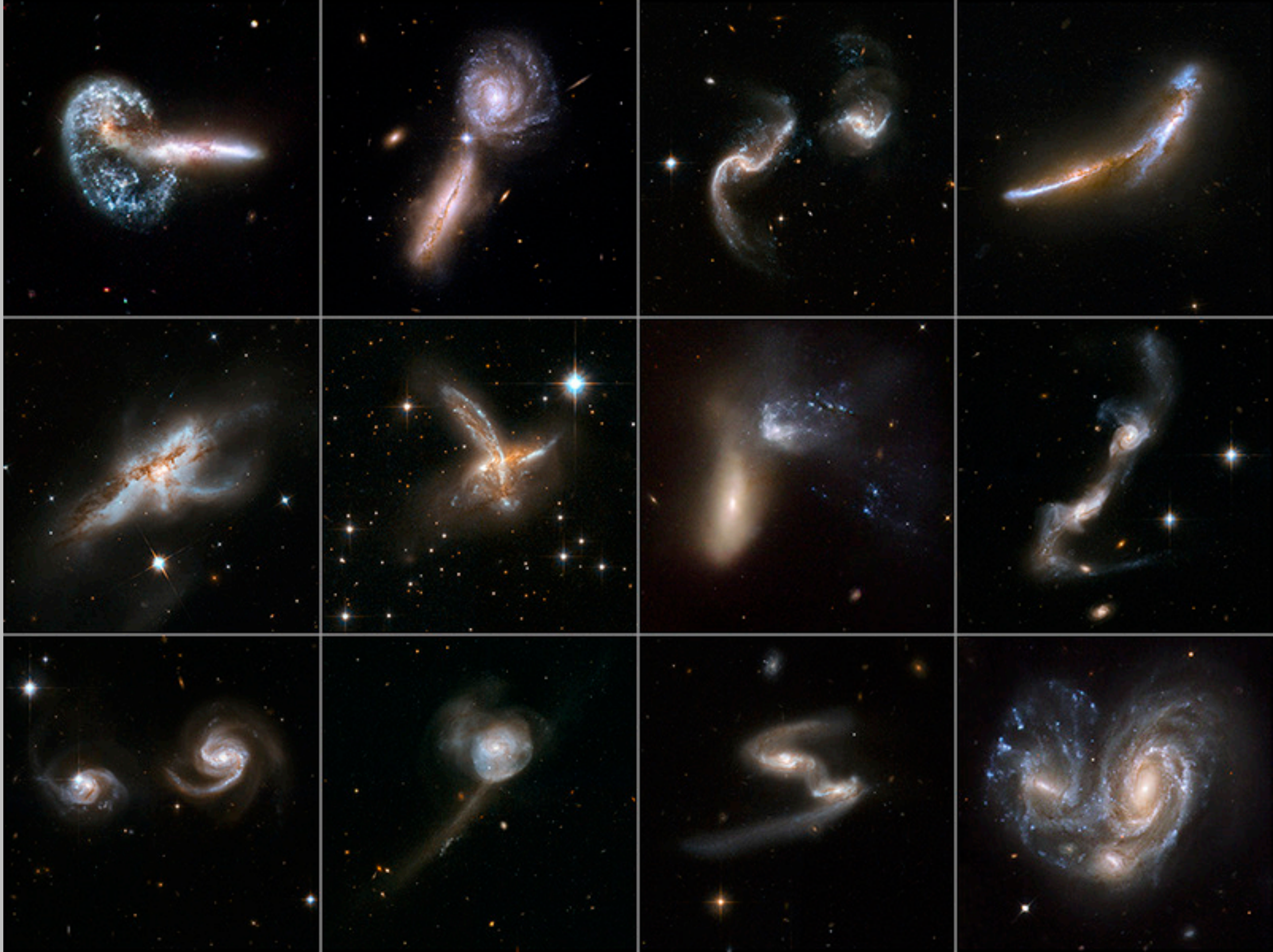
$$t_{pass} \approx \frac{4 \times 30000\ pc}{200\ pc/Myr}$$

$$\approx 480\ Myr$$



Interacting galaxy montage from Hubble Space Telescope

From snapshots in time...



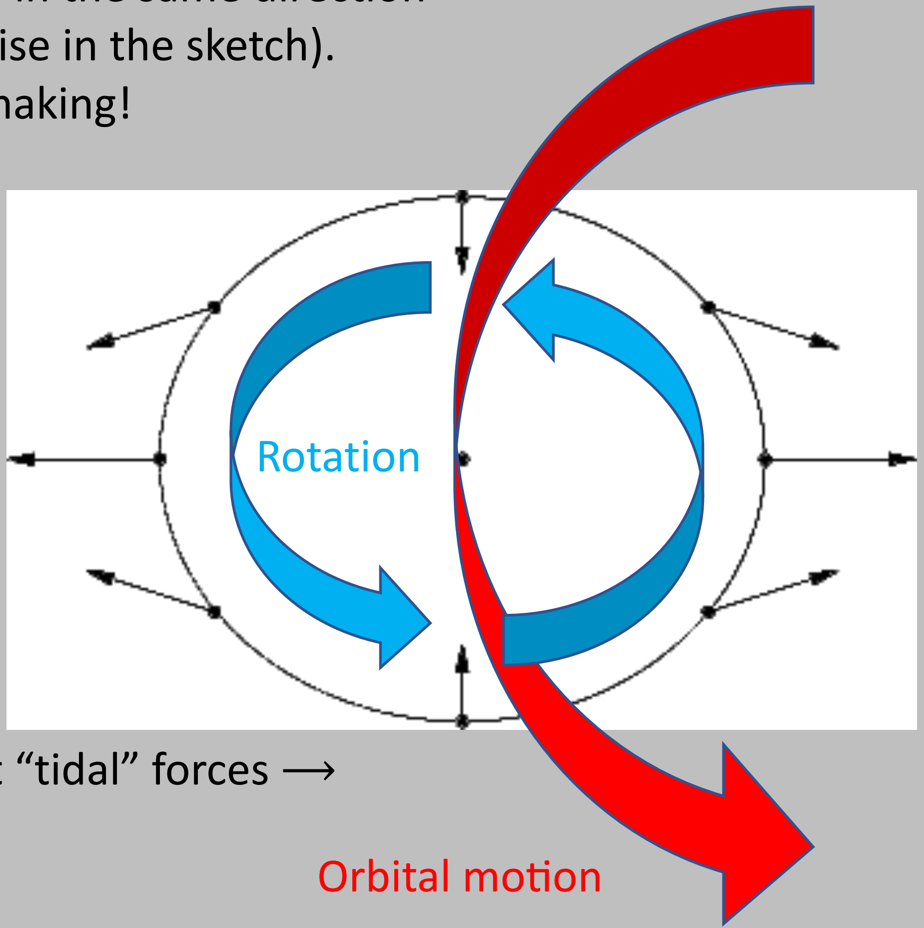
...to physical understanding

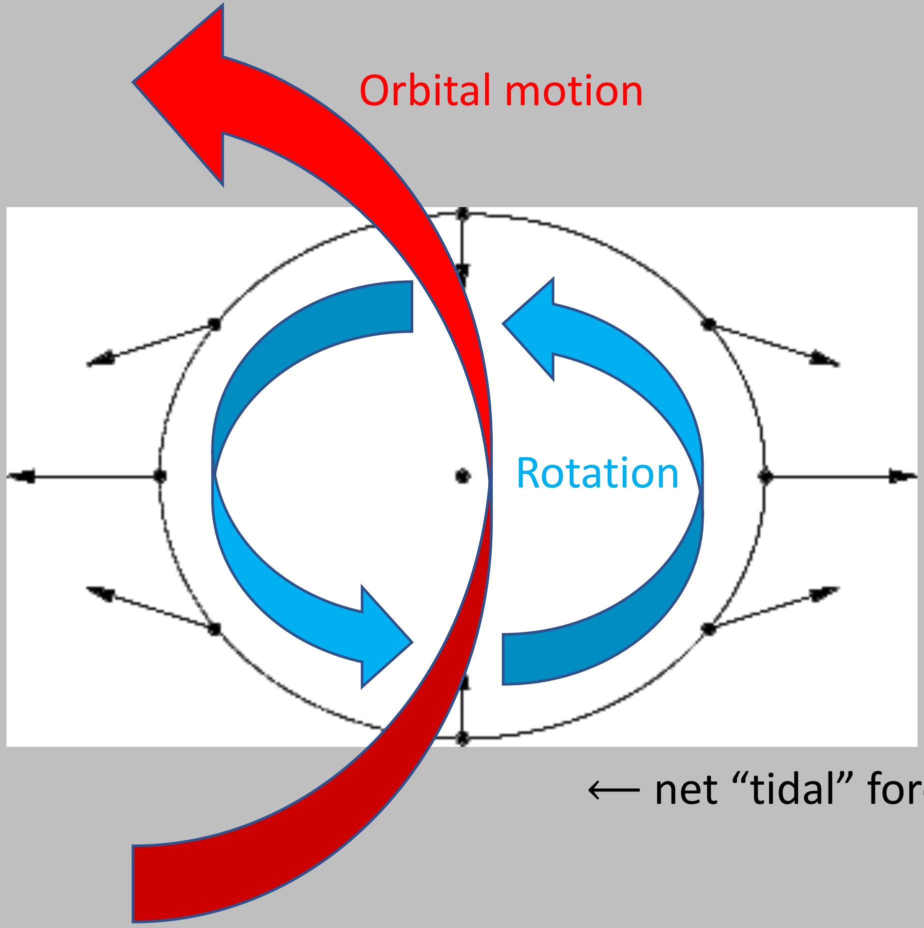
Simulation: Mihos & Hernquist
Visualization: Summers

Interaction Dynamics: Tidal Forces, Tails, and Bridges

Tidal forces from each galaxy's gravity stretches the other one, stripping stars off both the near side and the far side. The coupling of orbital motion and rotation acts to strip stars out in long tidal tails and (sometimes) "bridges".

Prograde encounter: Orbital motion and **rotation** are in the same direction (counter-clockwise in the sketch). Maximizes tail-making!

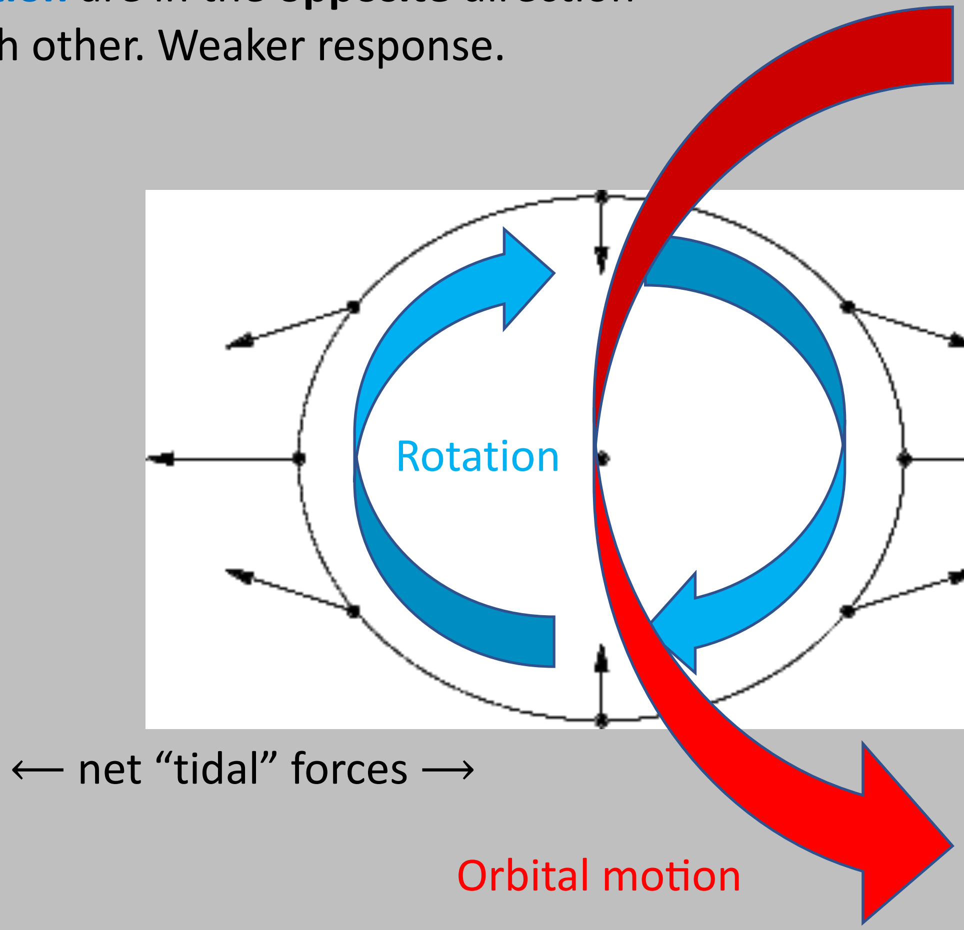


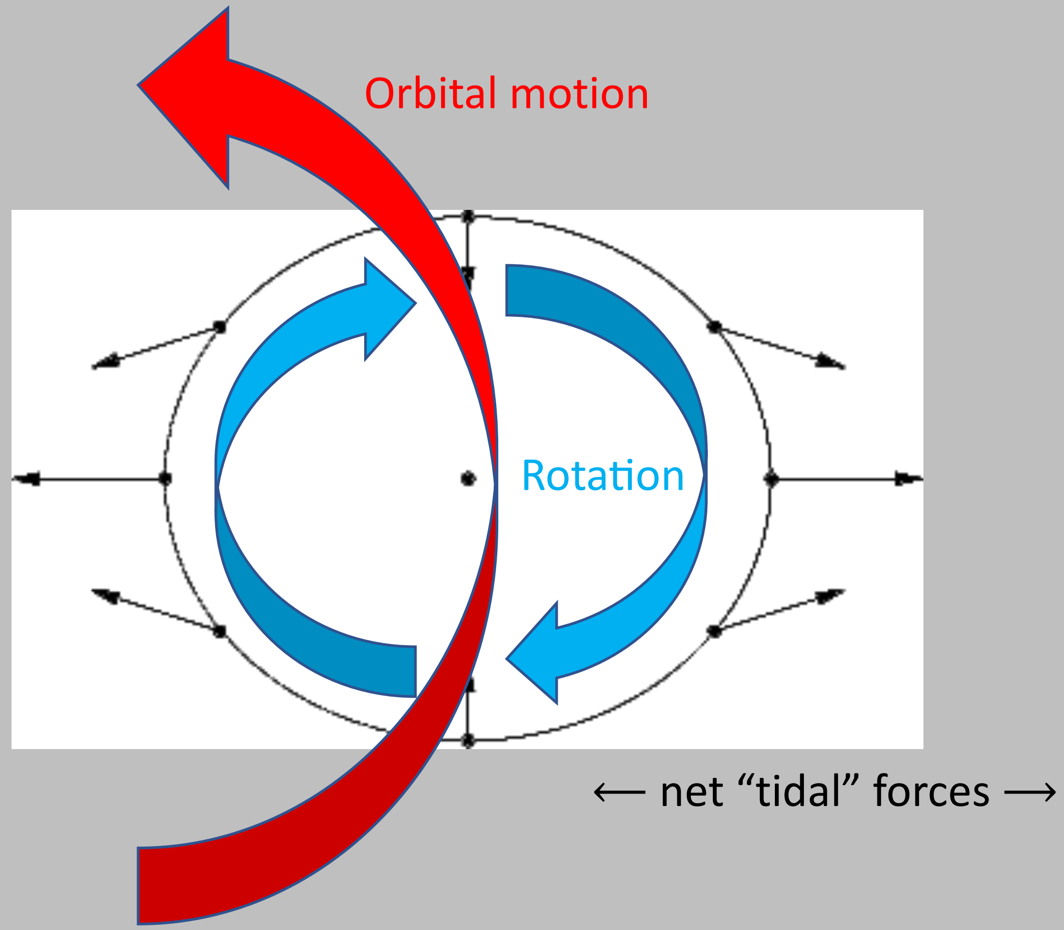


Interaction Dynamics: Tidal Forces, Tails, and Bridges

Tidal forces from each galaxy's gravity stretches the other one, stripping stars off both the near side and the far side. The coupling of orbital motion and rotation acts to strip stars out in long tidal tails and (sometimes) "bridges".

Retrograde encounter: **Orbital motion** and **rotation** are in the **opposite** direction from each other. Weaker response.

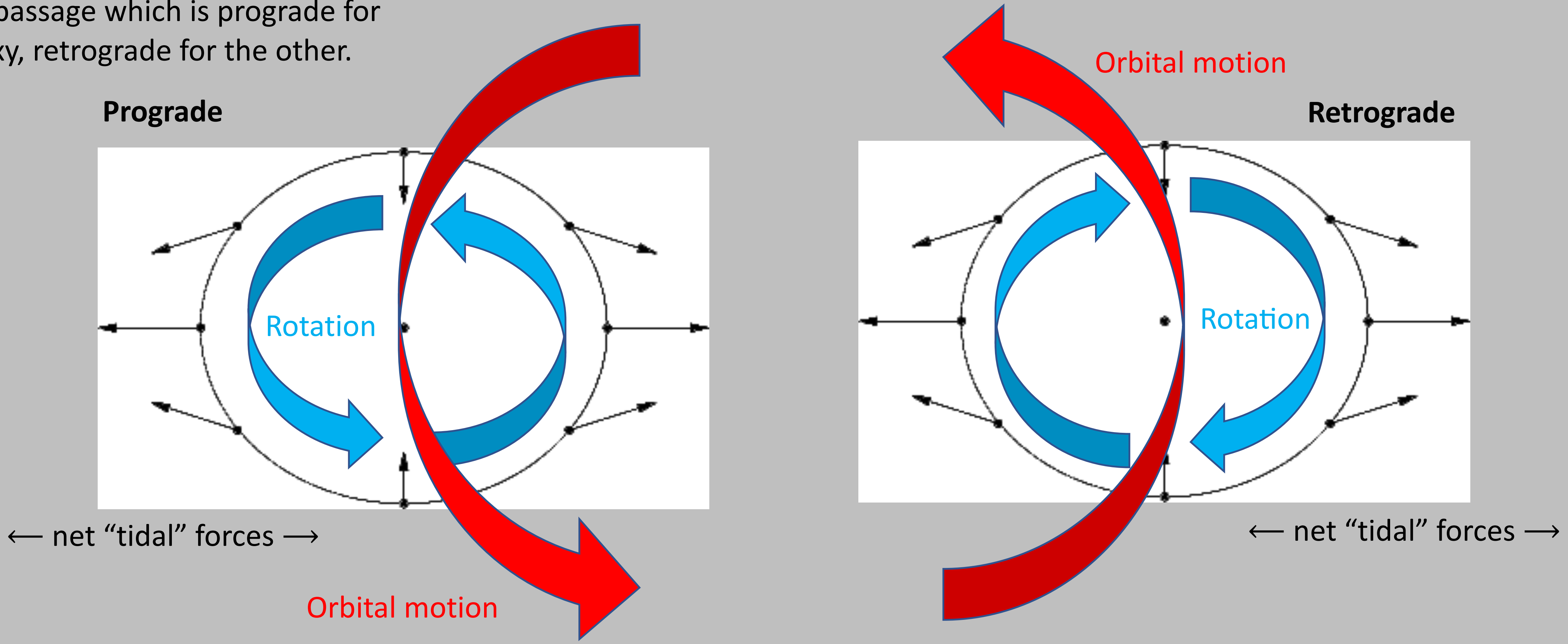




Interaction Dynamics: Tidal Forces, Tails, and Bridges

Tidal forces from each galaxy's gravity stretches the other one, stripping stars off both the near side and the far side. The coupling of orbital motion and rotation acts to strip stars out in long tidal tails and (sometimes) "bridges".

Orientation is specific to each galaxy:
Here's a passage which is prograde for one galaxy, retrograde for the other.



Interaction Dynamics: Tidal Forces, Tails, and Bridges

Tidal forces from each galaxy's gravity stretches the other one, stripping stars off both the near side and the far side. The coupling of orbital motion and rotation acts to strip stars out in long tidal tails and (sometimes) "bridges".

But there is a huge diversity in the outcome of a galaxy interactions, due to many factors.

Geometry: Encounters are rarely "pure prograde" or "pure retrograde": the orbital plane and disk planes can be tilted in different ways, creating complex geometries.

Mass: Tidal forces scale as $\boldsymbol{\mathcal{M}}/\boldsymbol{R}^{\mathbf{3}}$. A bigger galaxy does more damage to a little galaxy than the other way around.

Distance: Tidal forces scale as $\boldsymbol{\mathcal{M}}/\boldsymbol{R}^{\mathbf{3}}$. A closer encounter does more damage than a distant encounter.

Velocity: Slow encounters do more damage than fast encounters; the galaxies feel tidal forces for a longer time.

Galaxy Type:

- Spirals have ordered rotation, ellipticals do not -- tidal features in ellipticals are much more diffuse ("plumes").
- Spirals have cold gas, ellipticals generally do not – spirals have a strong star forming response.

Viewing angle: Tails, plumes, etc can look very different from different angles.

Time: The view changes with time as the galaxies collide and reshape each other.

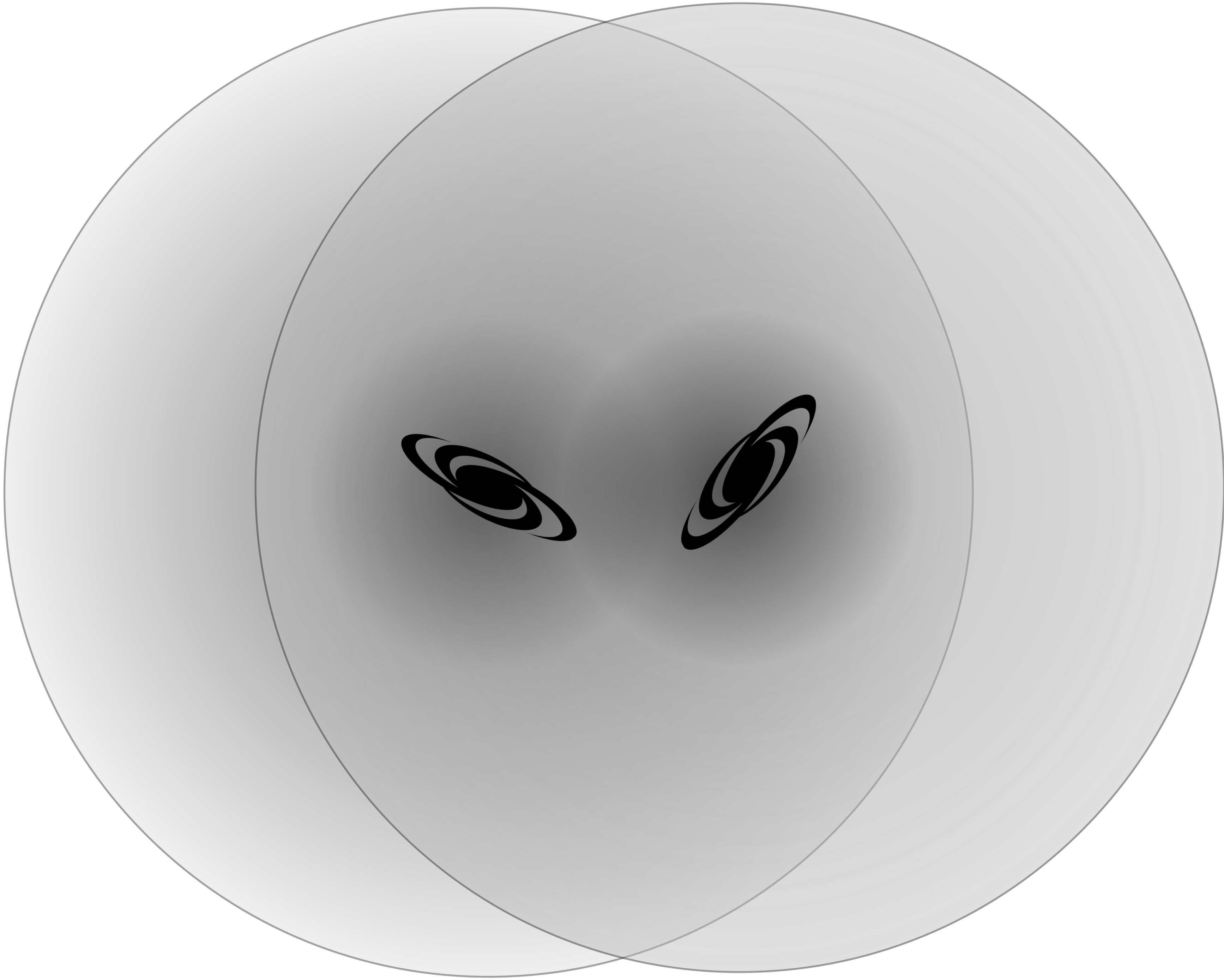
Galaxy Mergers

The overlapping dark halos means that dynamical friction is important. This causes the orbit to decay and the galaxies to merge.

This is a purely gravitational process, there are virtually no direct collisions of stars.

Violent relaxation: the rapidly changing gravitational field as the galaxies merge scatters the orbits of stars wildly.

Rotating disks are destroyed, high velocity dispersion spheroids are created.



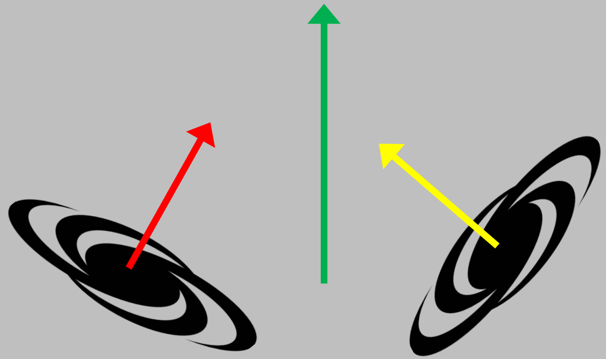
Galaxy Mergers and conservation laws

Remember that total energy and total angular momentum are conserved quantities and do not change over time. Break up energy (E) and angular momentum (L) in terms of internal and orbital terms:

$$\vec{L}_{tot} = \vec{L}_{spin,1} + \vec{L}_{spin,2} + \vec{L}_{orb}$$

and

$$E_{tot} = E_{kin,1} + E_{kin,2} + E_{orb} + \boldsymbol{\Phi}_{grav}$$



After galaxies have merged, $\vec{L}_{orb} = 0$ and $E_{orb} = 0$. But $\vec{L}_{tot}$ and E_{tot} ***couldn't*** have changed – they are conserved. So where did that orbital energy and angular momentum go?

Some went into the stars kicked out in the tidal tails.

But most went into the energy and angular momentum of the dark halos: they expanded a little bit, and they gained a bit of rotation.

Dark halos are good "dynamical sponges"!

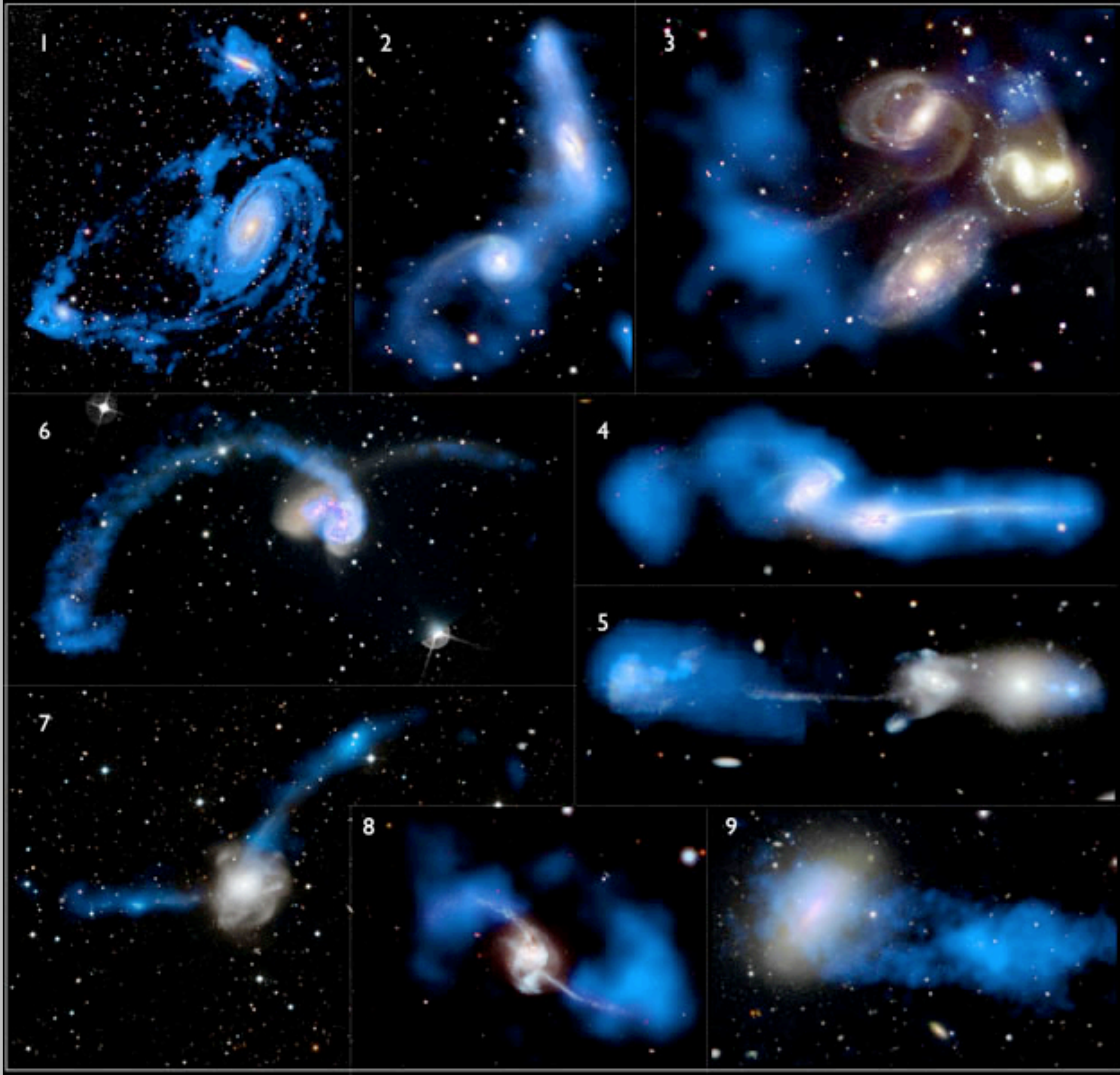
Interactions, Mergers, and Gas Dynamics

Gas Ejection: Lots of gas in the outskirts of colliding galaxies can be ejected in the tidal tails.
(Neutral hydrogen gas shown in blue, from Duc & Renaud 11)

Gas Inflows: While stars don't collide, gas clouds do. These cloud collisions are "sticky", and compress and heat the gas. This converts kinetic energy to heat, so the clouds lose kinetic energy and start to flow towards the center.

Starburst activity: Compressed gas triggers star formation throughout the galaxy and often in centrally-concentrated starbursts.

Colliding galaxy images, with neutral hydrogen gas shown in blue ⇒
(from Duc & Renaud 11)



The Antennae Galaxies

Mergers and Galaxy Transformations: A galaxy evolution story

Spiral Galaxies
Thin disks of stars
High rotation, low dispersion (kinematically cold; $V_c/\sigma \gg 1$)
Lots of cold neutral and molecular gas
Very little hot gas
Ongoing-star formation, with a mix of stellar ages

Mergers and Galaxy Transformations: A galaxy evolution story

Spiral Galaxies	Merger Effects
Thin disks of stars	Disks destroyed, spheroids formed
High rotation, low dispersion (kinematically cold; $V_c/\sigma \gg 1$)	Stars scattered, orbits randomized
Lots of cold neutral and molecular gas	Gas ejected in tails, or driven inwards to form nuclear starbursts
Very little hot gas	Starbursts drive "winds" of hot gas outwards
Ongoing-star formation, with a mix of stellar ages	Gas used up or ejected, star formation ceases

Mergers and Galaxy Transformations: A galaxy evolution story

Spiral Galaxies	Merger Effects	Elliptical Galaxies
Thin disks of stars	Disks destroyed, spheroids formed	Spheroidal shapes
High rotation, low dispersion (kinematically cold; $V_c/\sigma \gg 1$)	Stars scattered, orbits randomized	Very little rotation, mostly random motion (kinematically hot $V_c/\sigma \ll 1$)
Lots of cold neutral and molecular gas	Gas ejected in tails, or driven inwards to form nuclear starbursts	Very little cold gas
Very little hot gas	Starbursts drive "winds" of hot gas outwards	Hot gaseous halos
Ongoing-star formation, with a mix of stellar ages	Gas used up or ejected, star formation ceases	Very little star formation, old stellar populations

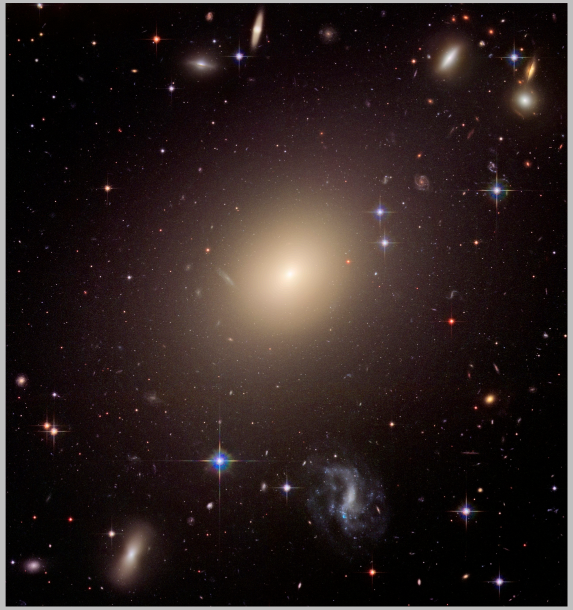
Getting Distances to Galaxies

Galaxies are all way way too far away for parallax, so what can we do?

Nearby galaxies (< 20 Mpc)

- spirals: Cepheid variables (evolving massive young stars, period-luminosity relationship)
- ellipticals: RR Lyrae variables (evolving low mass old stars, (different) period-luminosity relationship)
- all types: Luminous red giant stars (TRGB: “tip of the red giant branch”)

More distant galaxies (> 20 Mpc)



- spirals: Tully-Fisher relationship (connecting circular speed and luminosity/absolute-mag)
- ellipticals: Fundamental plane (connecting physical size with velocity dispersion and surface brightness)
- Type Ia supernovae (known luminosity, get distance from apparent magnitude)

But...

- These methods don’t work on all galaxies, so what else can we use?
- And these are data-intensive methods requiring a lot of work. Are there simpler methods?

Hubble's Law

1920—1930s: After demonstrating that the spiral nebulae are distant galaxies, he finds another amazing result: a correlation between a galaxy's distance from the Milky Way and its radial velocity:

Hubble realized this meant the Universe must be expanding, and that galaxies are being carried away from us in all directions by this expansion. 😲🤯😵‍💫

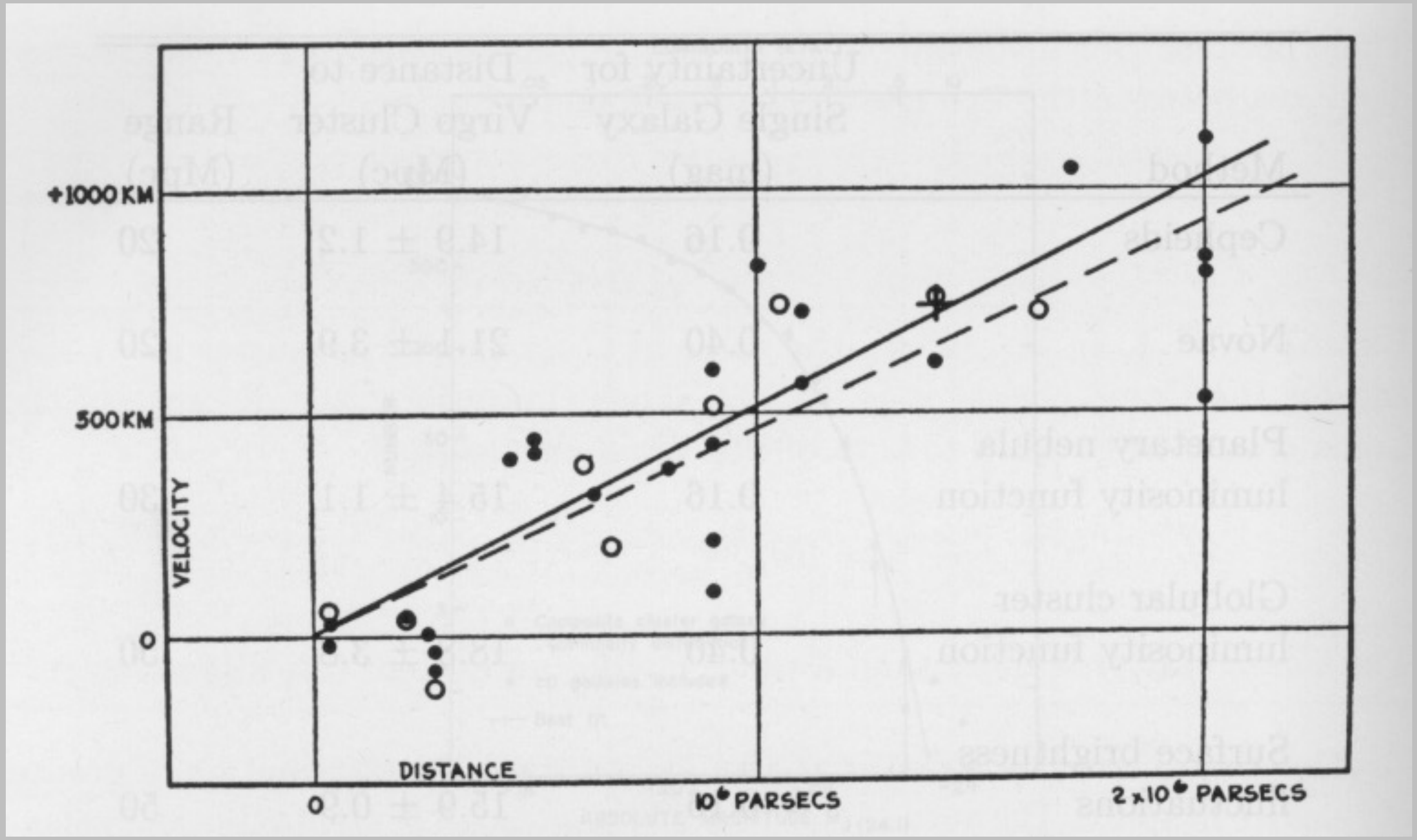
More distant galaxies are moving away faster. This is now called Hubble's Law:

$$v = H_0 D$$

H_0 is referred to as Hubble's constant and has a value of $H_0 \approx 72$ km/s/Mpc.

Can easily measure a velocity from an emission line, then instantly have a distance from $D = v/H_0$. Yay! 🥳🤩

(Hubble 1936)



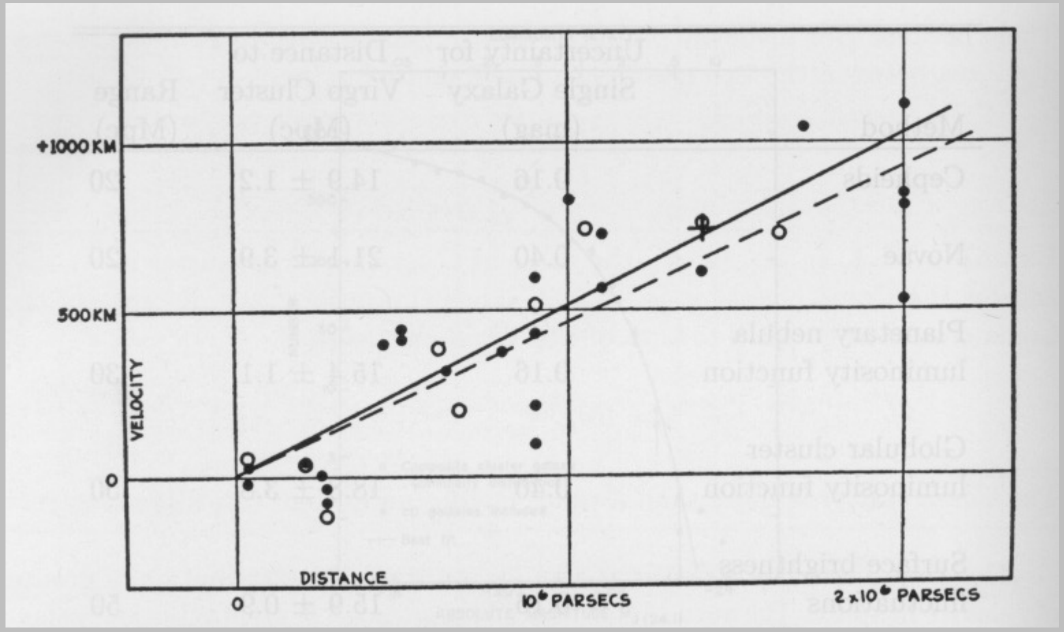
Since we get the distance from redshifted emission or absorption lines ("redshifts") and Hubble's law, these are referred to as "Hubble distances".

Complications using Hubble's Law

1. Not all motion is due to the expansion of the universe.

Galaxies also have motions due to the effect of gravity. Think about interacting galaxies, for example. $v = v_{Hubble} + v_{grav}$

And we live near a very massive galaxy cluster (Virgo, $D = 16$ Mpc) whose gravity alters the velocities of nearby galaxies. So Hubble distances are pretty untrustworthy in the local universe.

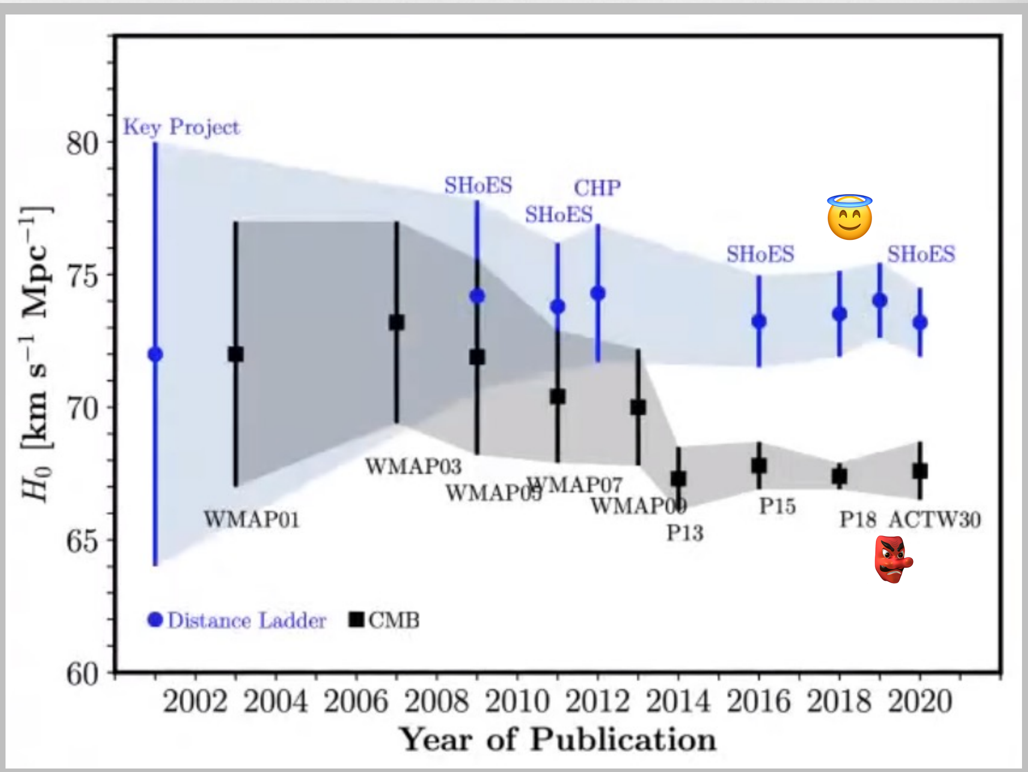


2. Uncertainties in the Hubble constant (H_0)

To work out the value of H_0 we need very accurate distances using some other technique, and that's hard!

Also, different techniques to determine H_0 give different answers.

Distance measures (astronomers 😇): $H_0 = 73 \pm$ a few km/s/Mpc
Cosmological measures (physicists 👺): $H_0 = 68 \pm$ a few km/s/Mpc



Hubble's Law

Galaxies at greater distances are moving away from us more quickly:

$$v = H_0 D$$

where the Hubble constant $H_0 \approx 72$ km/s/Mpc.

The Doppler shift

Light from objects moving toward or away from is shifted in wavelength by:

$$\frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda_{rest}} = \frac{v}{c}$$

Redshift vs Doppler shift

The redshift is defined as $z = \Delta\lambda/\lambda_{rest}$. ***This is an observable.***

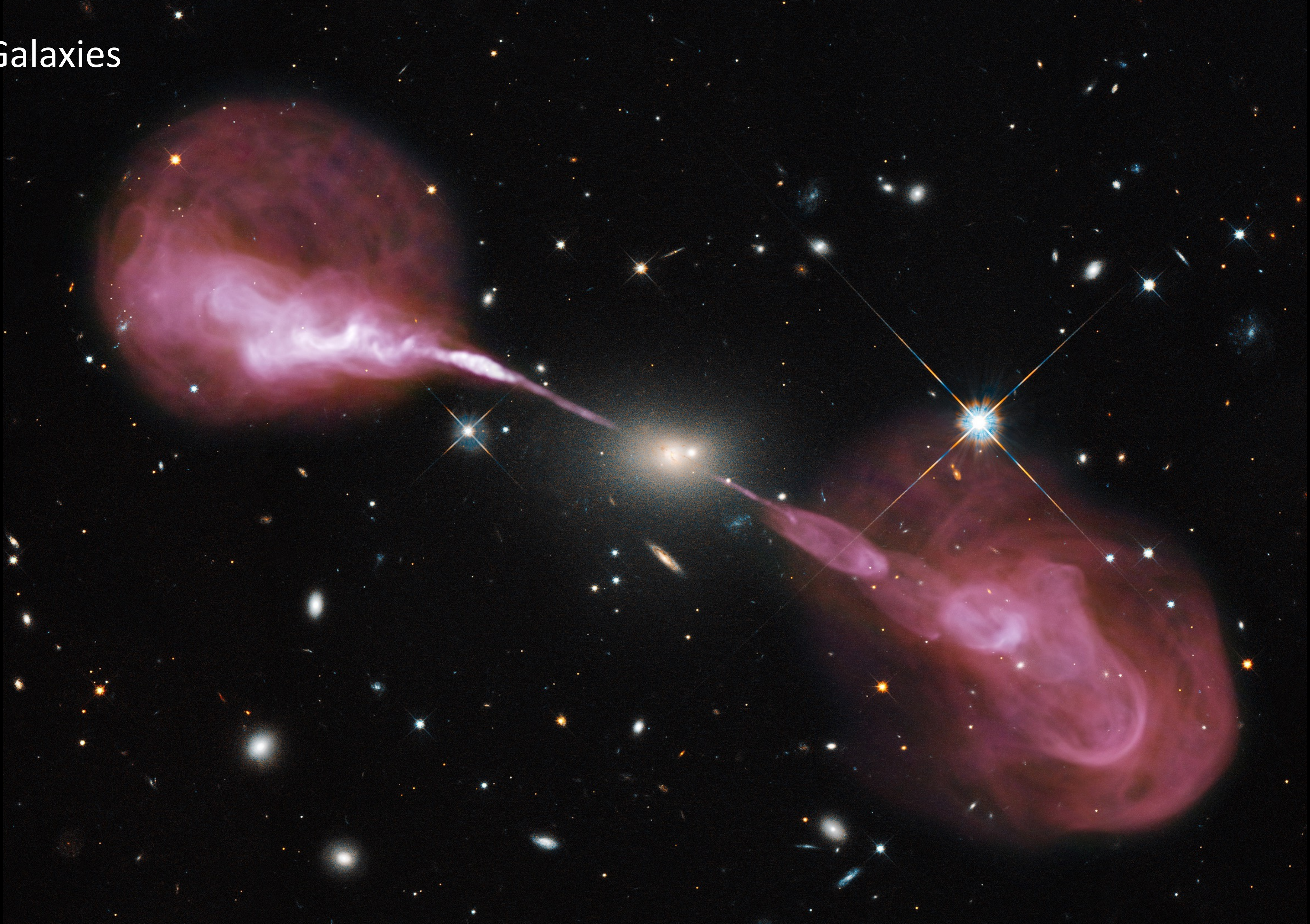
We often talk about redshifts in the local universe in terms of velocities, using the language of Doppler shift: "That galaxy has a redshift of 1500 km/s" meaning its redshift is $\mathrm{z} = v/c = 0.005$, so that it has a Hubble distance of

$$D = v/H_0 = cz/H_0 = 21\ Mpc$$

But the "Hubble law" redshift of a galaxy is not a Doppler shift, and at greater distances ($D \gtrsim 100$ Mpc, or $z \gtrsim 0.02$), the use of both Hubble's law ***and*** the Doppler analogy is very wrong.

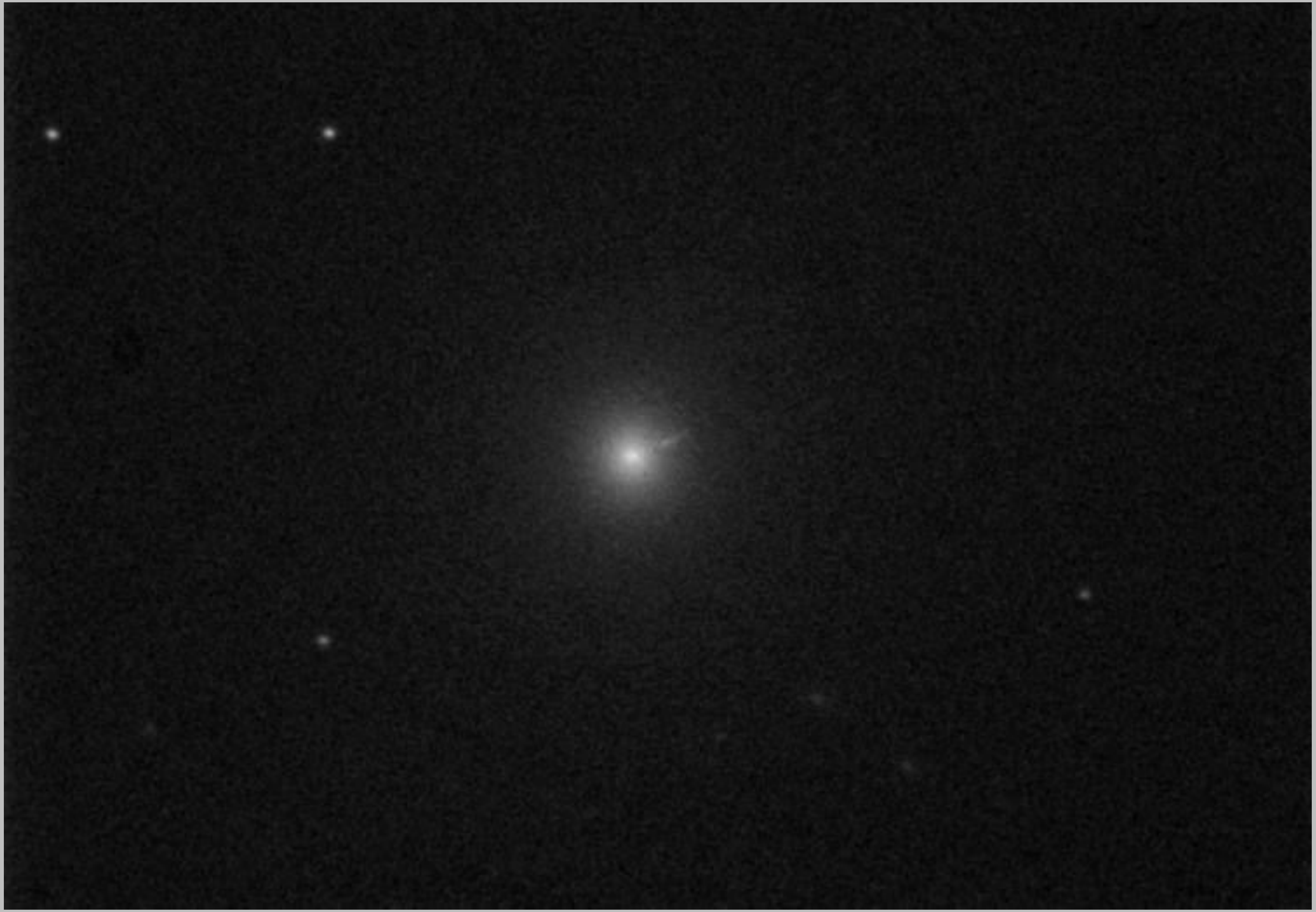
Therefore at greater distances / higher redshifts we refer to the redshift itself (z) and not the velocity.

Active Galaxies



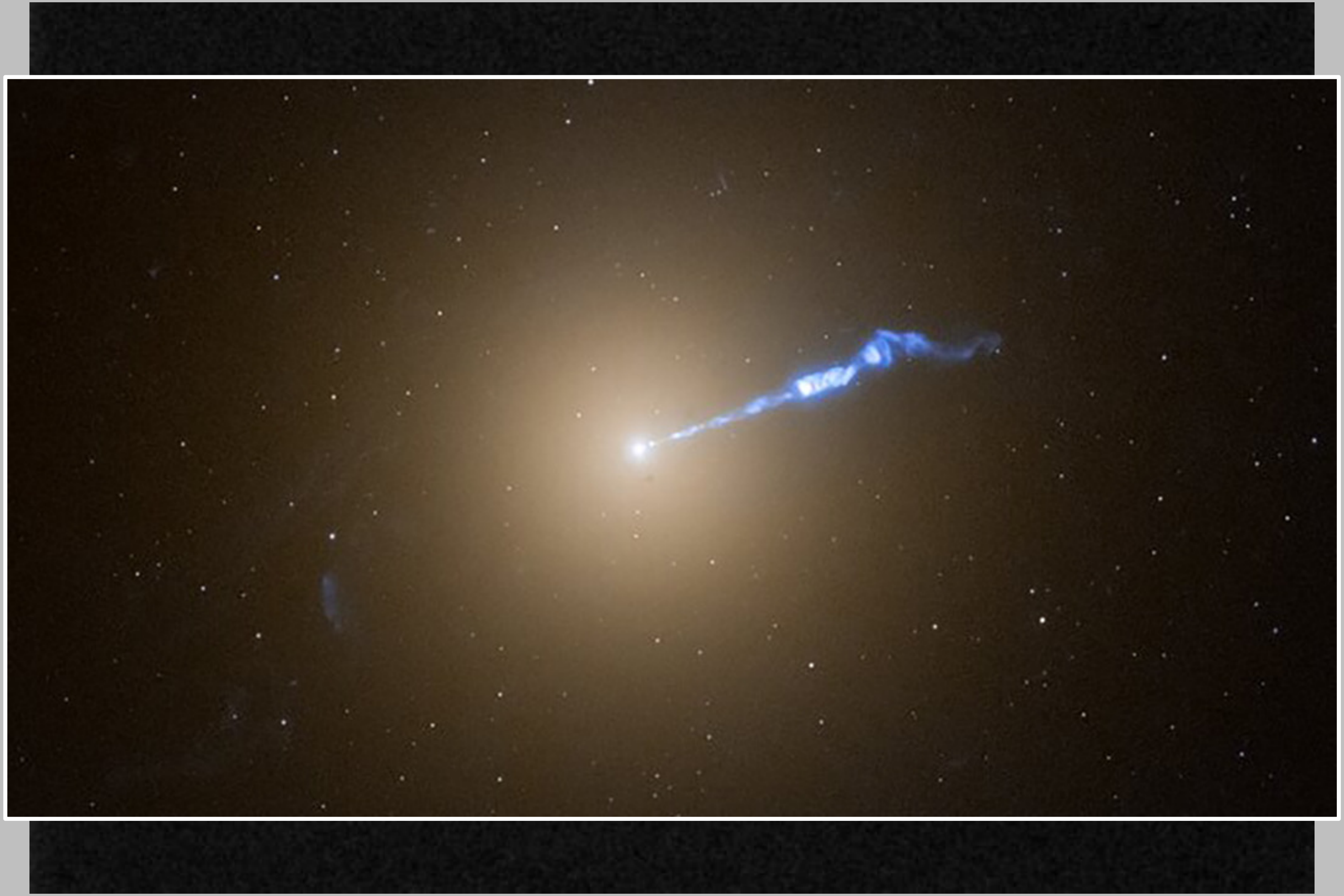
The Discovery of Active Galaxies: M87

1918: Heber Curtis notices a “curious straight ray” emanating from the center of the Virgo elliptical “nebula” M87.



The Discovery of Active Galaxies: M87

1918: Heber Curtis notices a “curious straight ray” emanating from the center of the Virgo elliptical “nebula” M87.

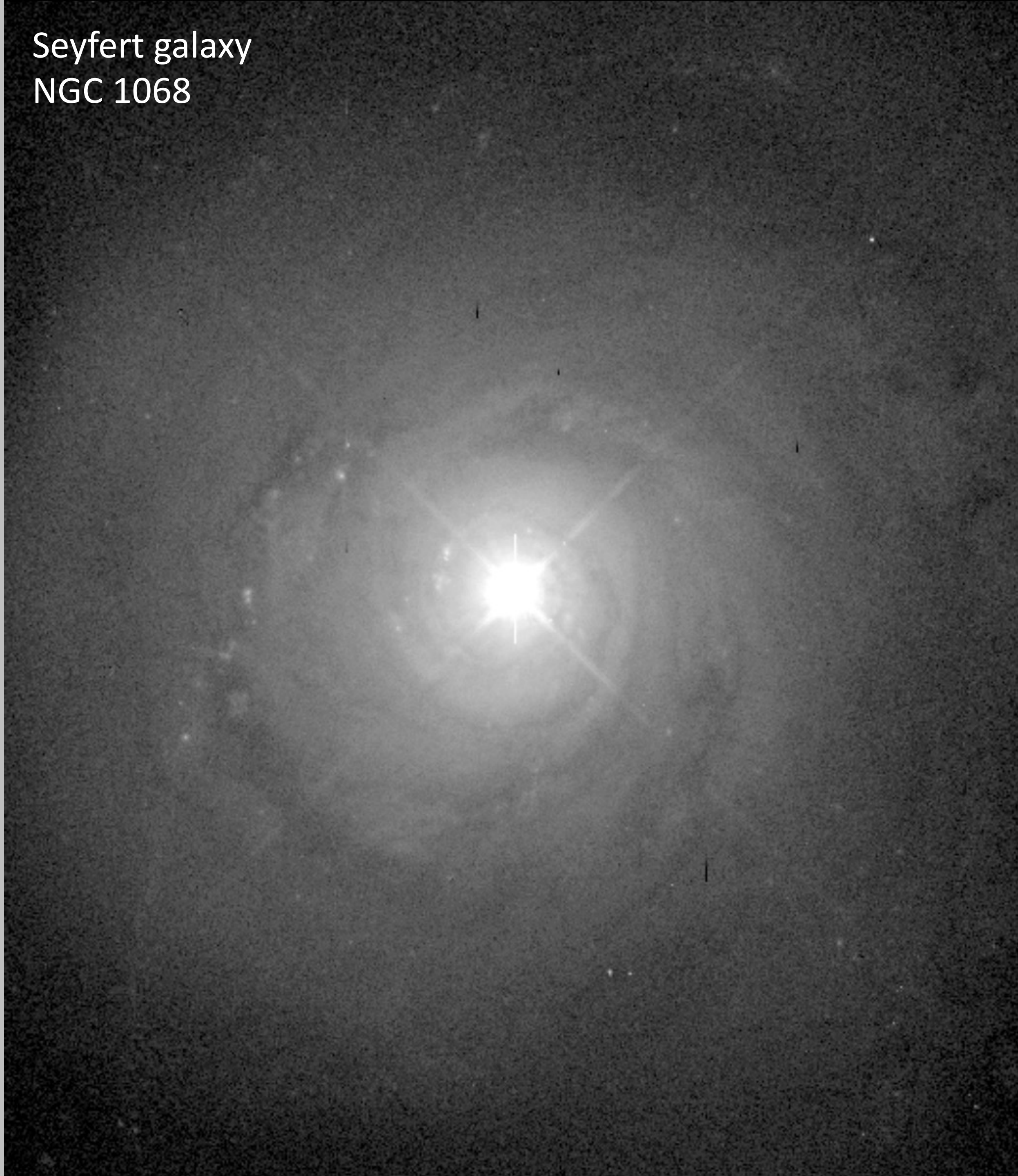


The Discovery of Active Galaxies: Seyfert Galaxies

1940s: Karl Seyfert catalogs spiral galaxies with “point source” (star-like) nuclei.

But the nuclei show very strange spectra, not like stars and not like star forming regions or starburst galaxies.

Karl Seyfert and Jason Nassau at CWRU’s Burrell Schmidt telescope

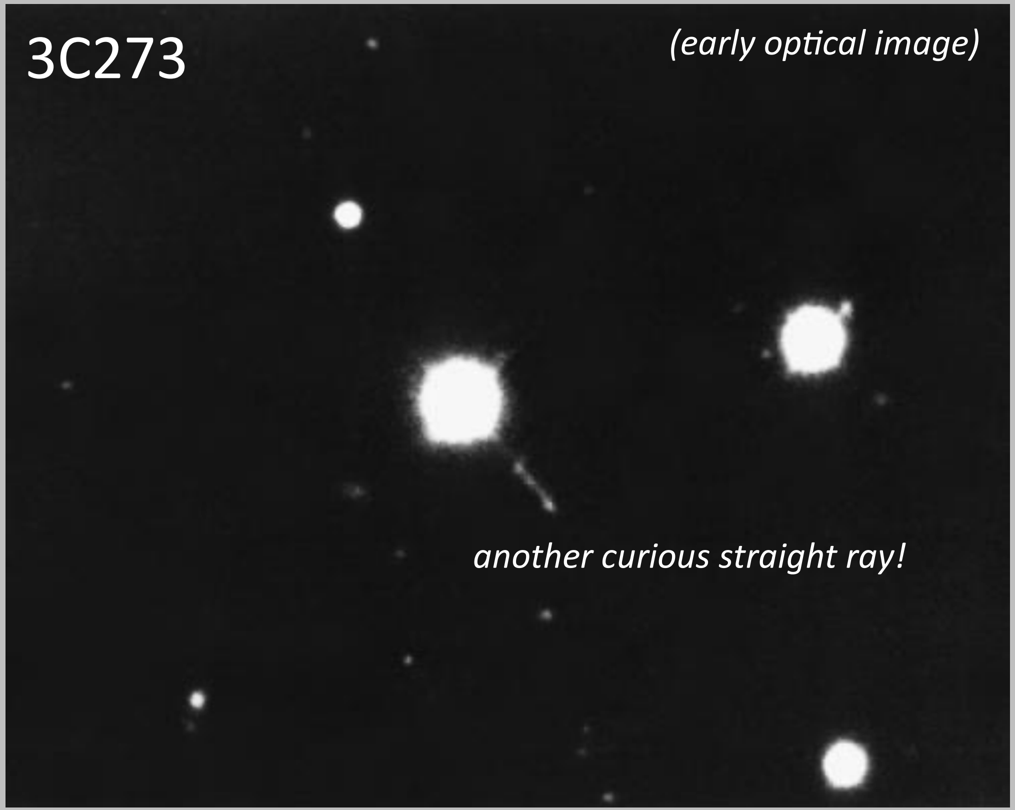


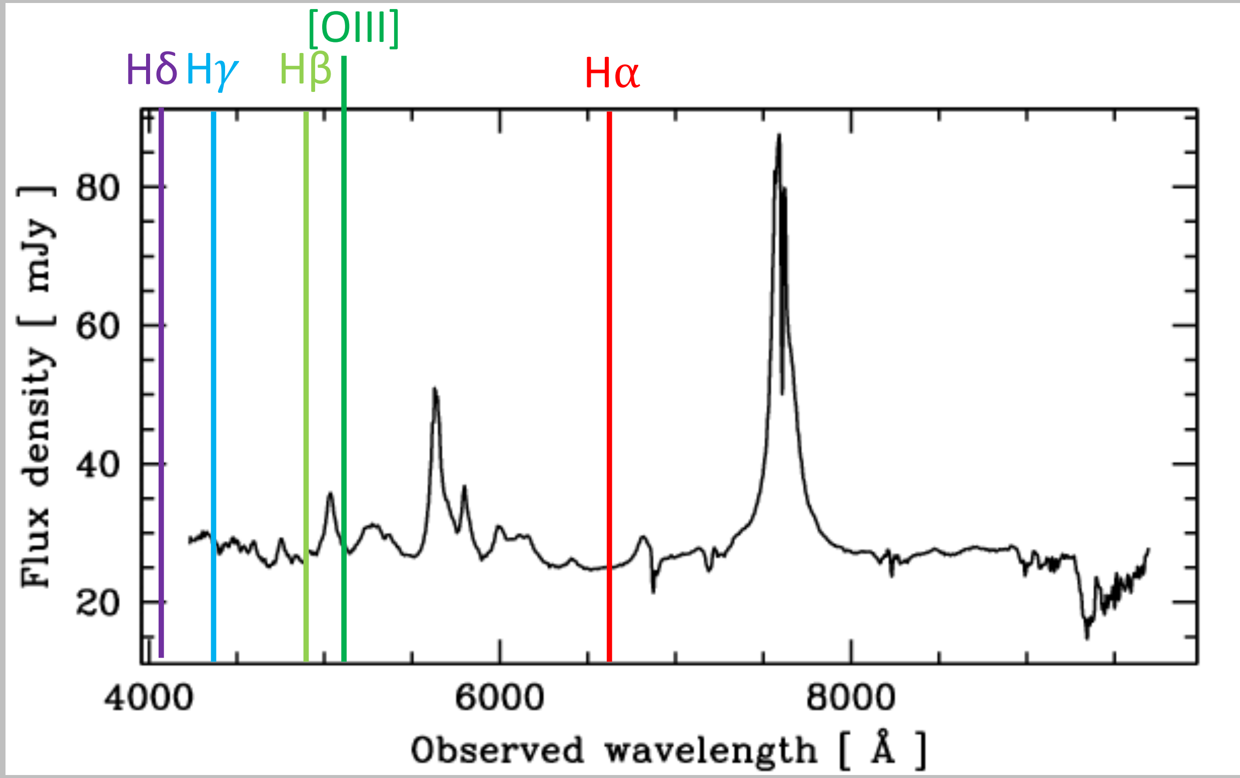
The Discovery of Active Galaxies: Quasars

1950s: Radio telescopes began find bright radio sources, but optical telescopes showed only a faint star-like object.

These were called "quasi-stellar radio sources", or quasars.

Their spectra were bizarre, showing never-before seen emission lines, as well as missing emission lines.





The Discovery of Active Galaxies: Quasars

1950s: Radio telescopes began find bright radio sources, but optical telescopes showed only a faint star-like object.

These were called “quasi-stellar radio sources”, or quasars.

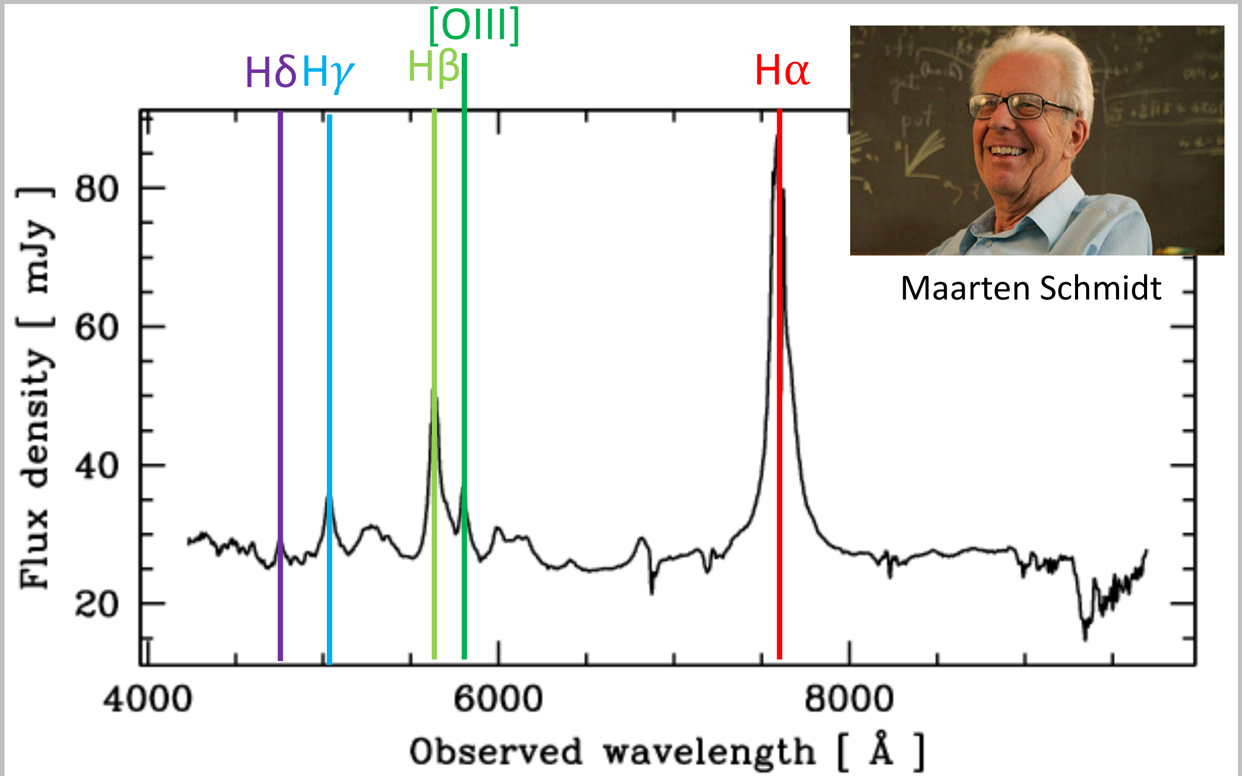
Their spectra were bizarre, showing never-before seen emission lines, as well as missing emission lines.

1964: Maarten Schmidt figures out these are regular emission lines, just redshifted much further than had ever been seen.

The quasar 3C273 has a redshift of z=0.152, putting it at a distance of about 650 Mpc.

Shortly thereafter another quasar 3C48 was found with a redshift of z=0.367 ⇒ 1,500 Mpc away!

At these huge distances the objects must be very luminous: ≈ 1,000x more luminous than the Milky Way! And yet small and point-like in appearance. *What are these things?*



Remember, at these high redshifts don’t use Doppler shift / Hubble Law!

For 3C48 (z=0.367), Doppler shift / Hubble Law would say

- Doppler shift velocity: 45,600 km/s
- Hubble distance: $D = v/H_0 = 633$ Mpc

and both of those things are wrong (conceptually and quantitatively). To do the calculation right, we have to consider cosmological effects.

Quasar Properties

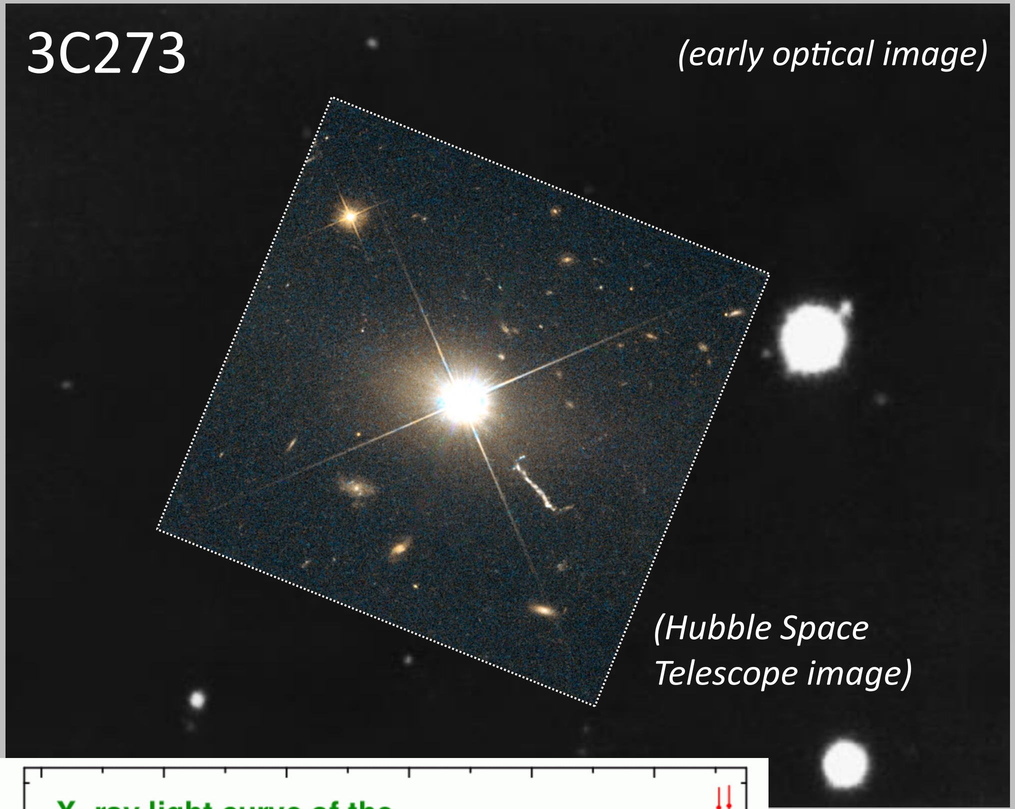
We now know quasars to be the bright nuclei of galaxies: an active galactic nucleus (AGN). The nucleus outshines the host galaxy by a factor of 1000. But what are they?

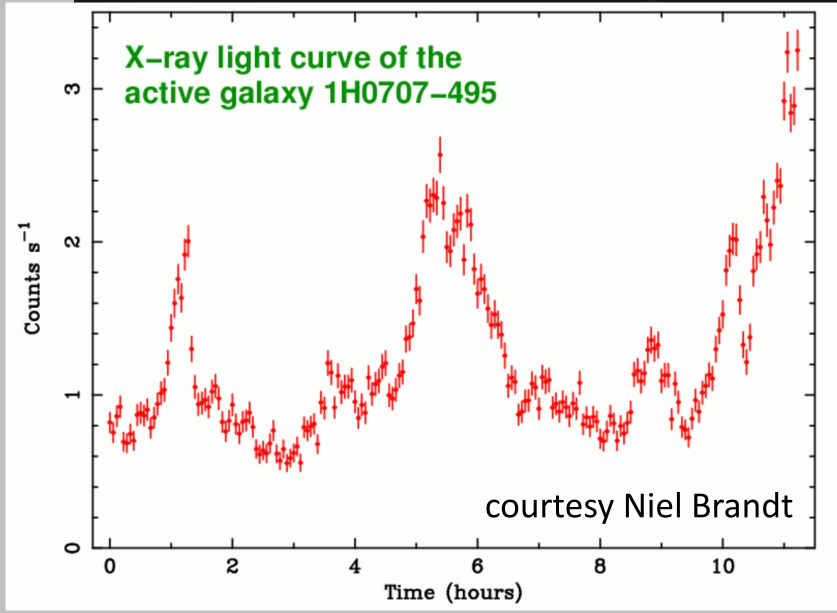
Clue #1: They have high luminosities: $L \approx 10^{13} L_\odot$

Clue #2: They have emission lines that show ***very*** highly ionized gas, so the energy source must be much hotter than even hot young stars.

Clue #3: They often vary significantly in brightness, over timescales of days or even hours. Remember causality: if an object varies in brightness over a timescale of Δt, it must be smaller than the light travel time: $R < c\Delta t$. That means sizes < 10 AU.

Thats 1000 Milky Way galaxies' worth of high energy radiation packed into an area the size of our solar system!

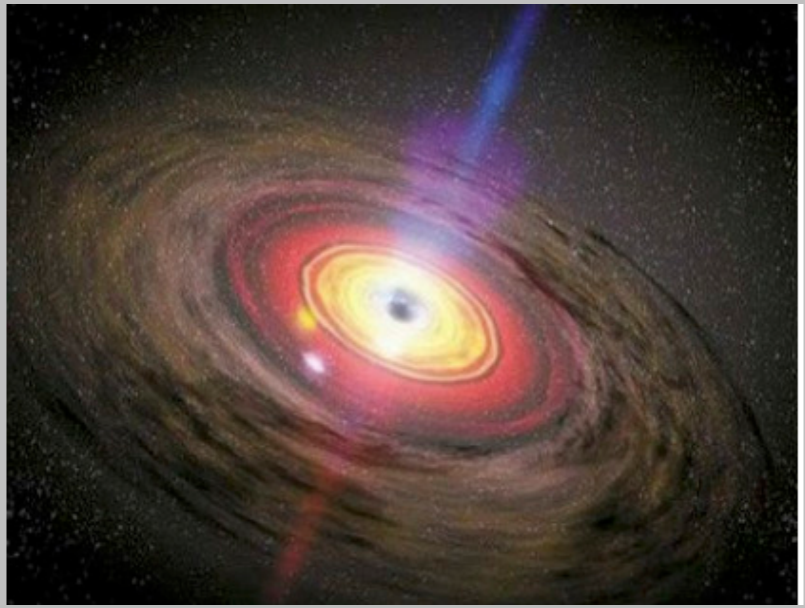




Active Galactic Nuclei: The central engines

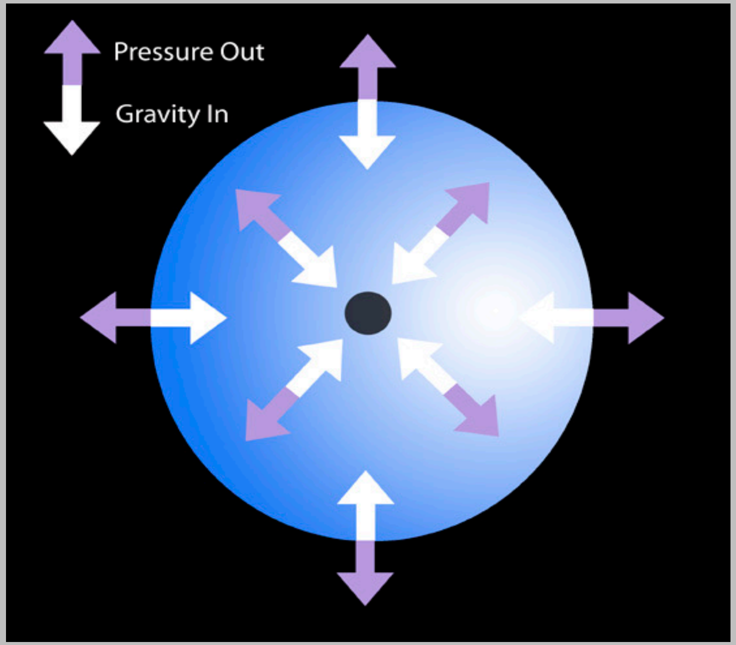
The only thing we know of that can produce that much energy in a small region of space is a rapidly accreting super-massive black hole.

As gas falls inwards toward the black hole, it settles into a hot accretion disk. As the gas swirls around, friction heats it up to $10^5 - 10^7$ K, causing it to emit UV light, X-rays, and γ-rays, highly ionizing the gas all around it.



How massive is the black hole?

Let's balance radiation pressure and gravity to find out.



Photons produce an outward pressure on nearby particles given by:

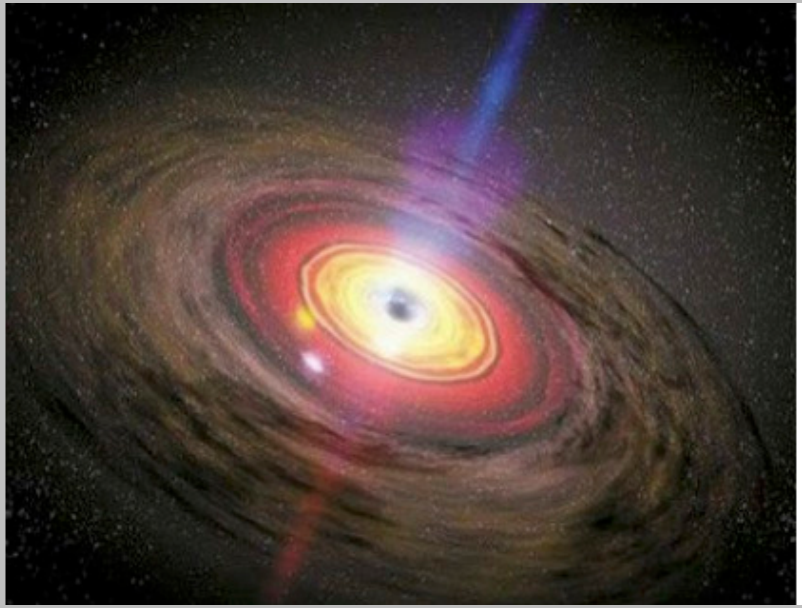
$$P_{rad} = \frac{L}{4\pi R^2 c}$$

An electron feels this pressure as a force pushing it away from the nucleus:

$$F_{rad} = \sigma_T P_{rad} = \frac{\sigma_T L}{4\pi R^2 c}$$

where σ_T is the Thomson cross-section for the interaction between electrons and photons.

Active Galactic Nuclei: The central engines



While photon pressure pushes out, gravity pulls in. In a ionized gas where protons (p) and electrons (e) are coupled by electrostatic forces,

$$F_{grav} = -\frac{G\mathcal{M}\left(m_p + m_e\right)}{R^2} \approx -\frac{G\mathcal{M}m_p}{R^2}$$

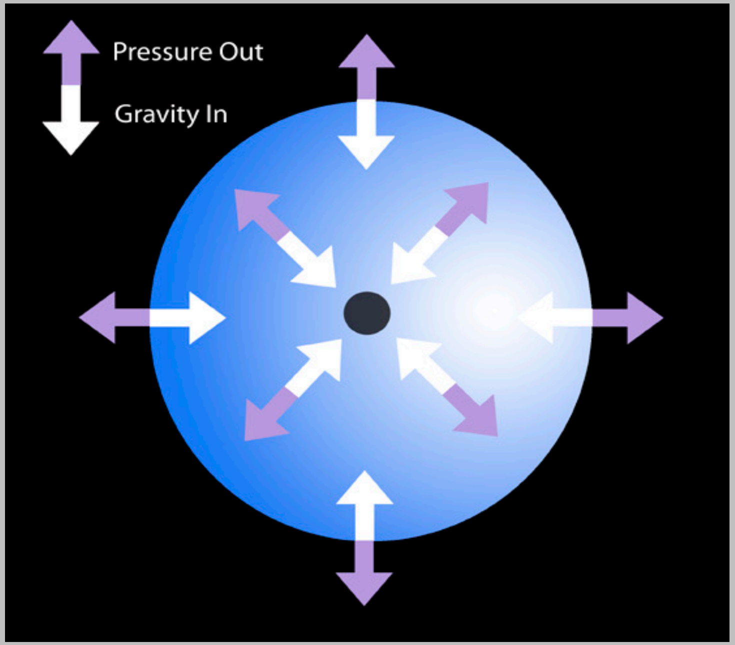
For the whole thing to remain bound together, $F_{grav} > F_{rad}$, or:

$$\frac{G\mathcal{M}m_p}{R^2} \geq \frac{\sigma_T L}{4\pi R^2 c}$$

Important Notes:

1. The R's canceled out. Handy!

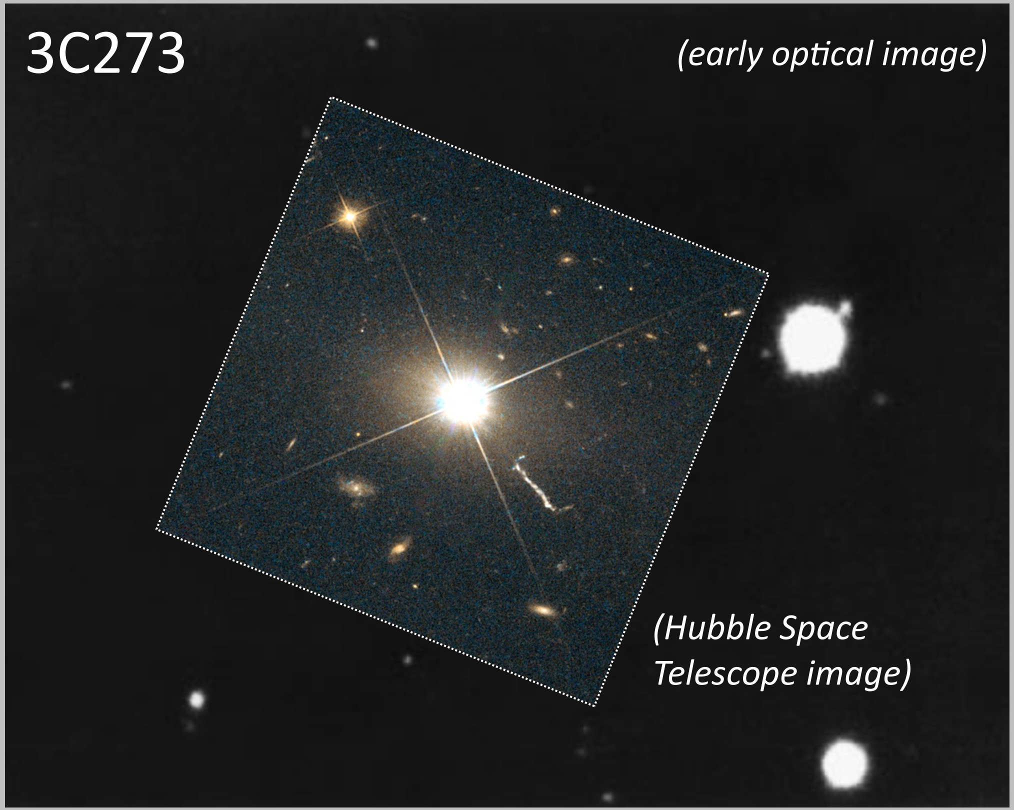
2. Nowhere did the calculation assume a black hole. This works for any luminous object, even individual stars!



Solving for mass, we get the ***Eddington mass***

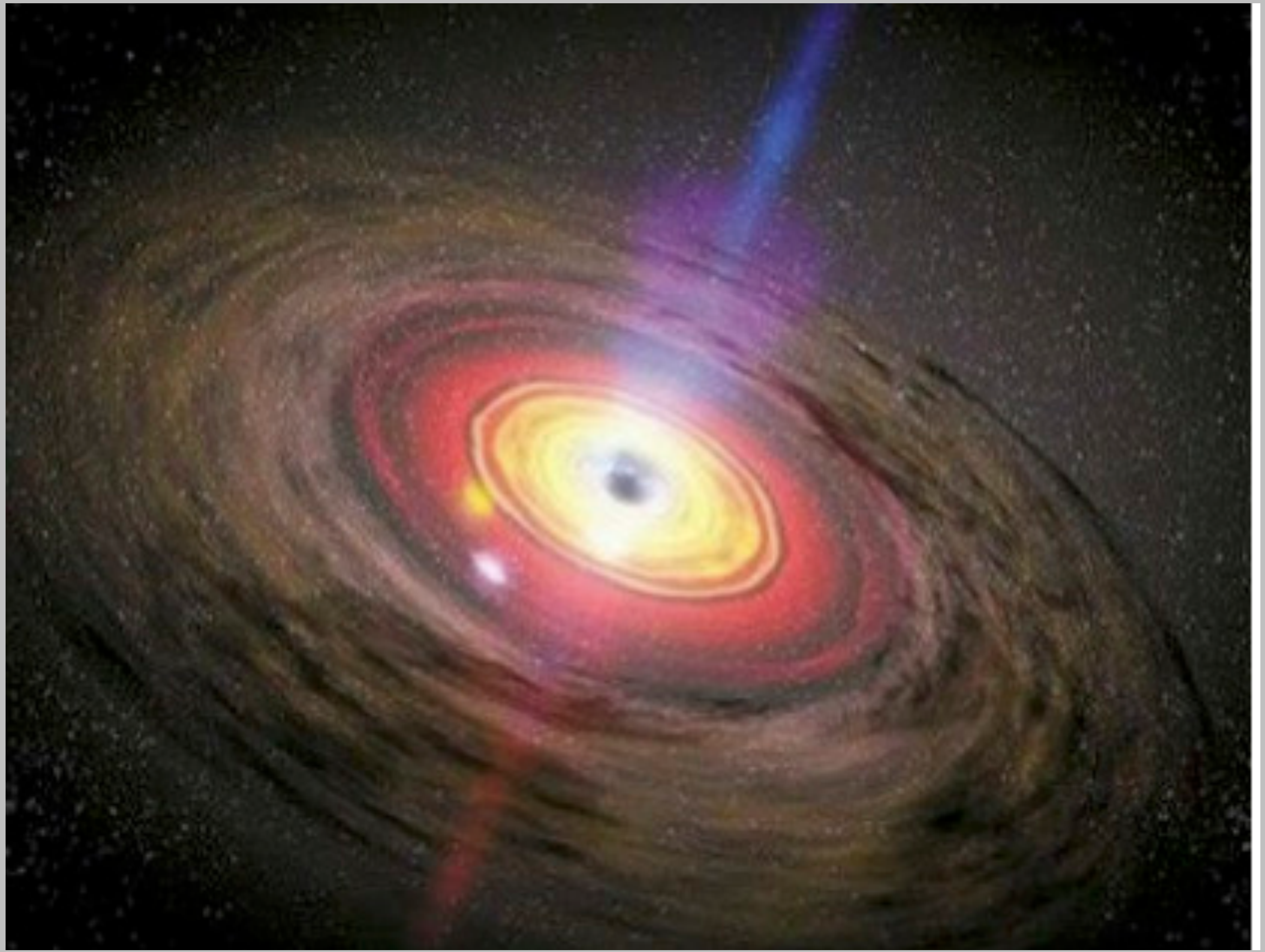
$$\mathcal{M}_{Edd} = \frac{\sigma_T L}{4\pi G m_p c} = 3.1\times10^{-5}\left(\frac{L}{L_\odot}\right)\mathcal{M}_\odot$$

The black hole must be at least this massive, or radiation pressure will blow the whole thing apart. For a $10^{13}L_\odot$ AGN, the Eddington mass is $\approx 3\times10^{8}\mathcal{M}_\odot$.



⇐ Galaxy scale view

Nucleus view (solar system scale!) ⇒



The AGN Zoo: Type 1 and Type 2 Seyfert Galaxies

Seyfert galaxies are spirals, and come in two types characterized by their spectra.

Type 1 Seyferts:

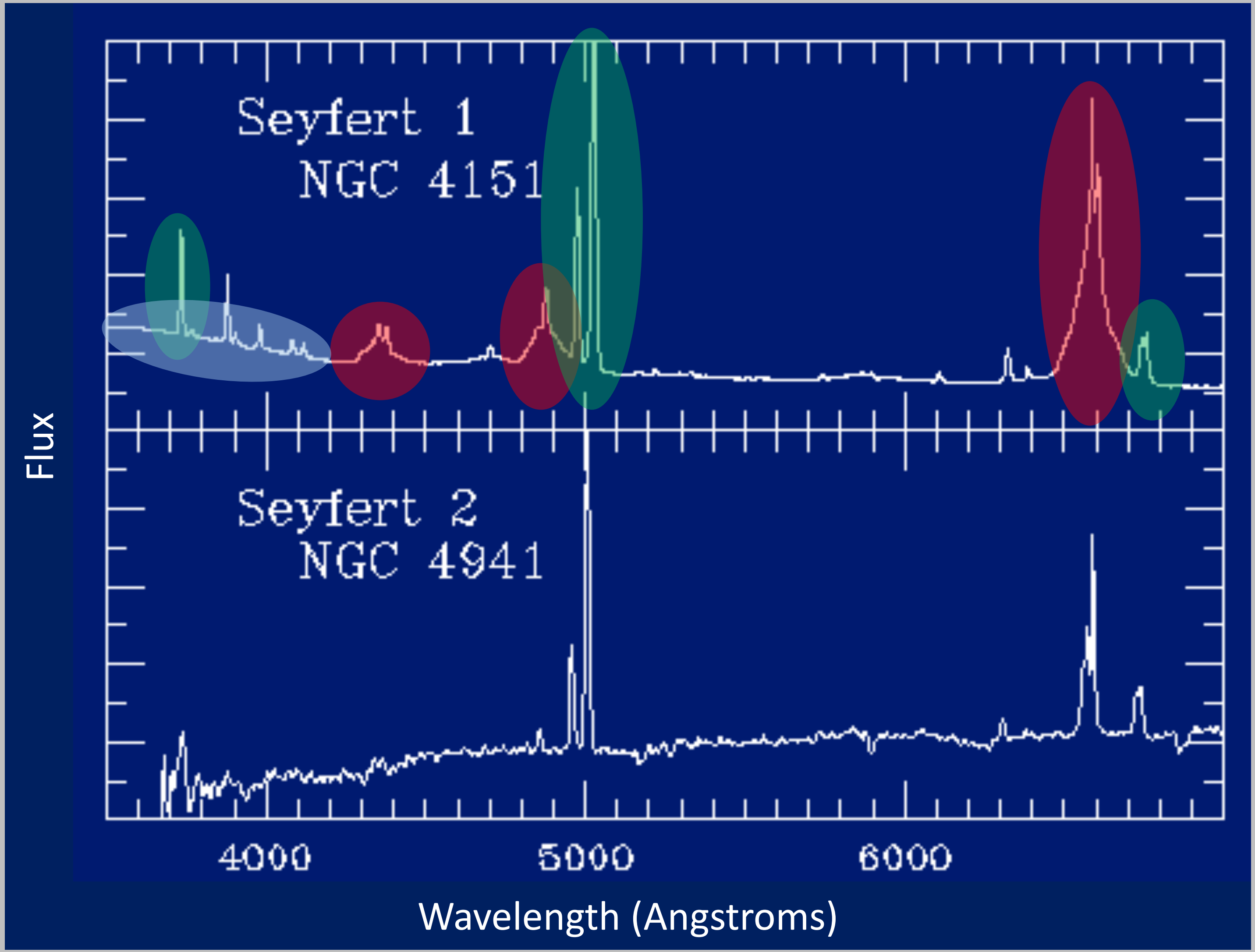
- Broad emission lines with a Doppler width of 1000 – 5000 km/s.
- Narrow emission lines ≈ 500 km/s.
- Spectrum rising in the blue

Type 2 Seyferts:

- Lines are all narrow
- No broad lines
- Spectrum flat or falling in the blue.

Quasars show similar types (1 and 2) as well.

courtesy Bill Keel

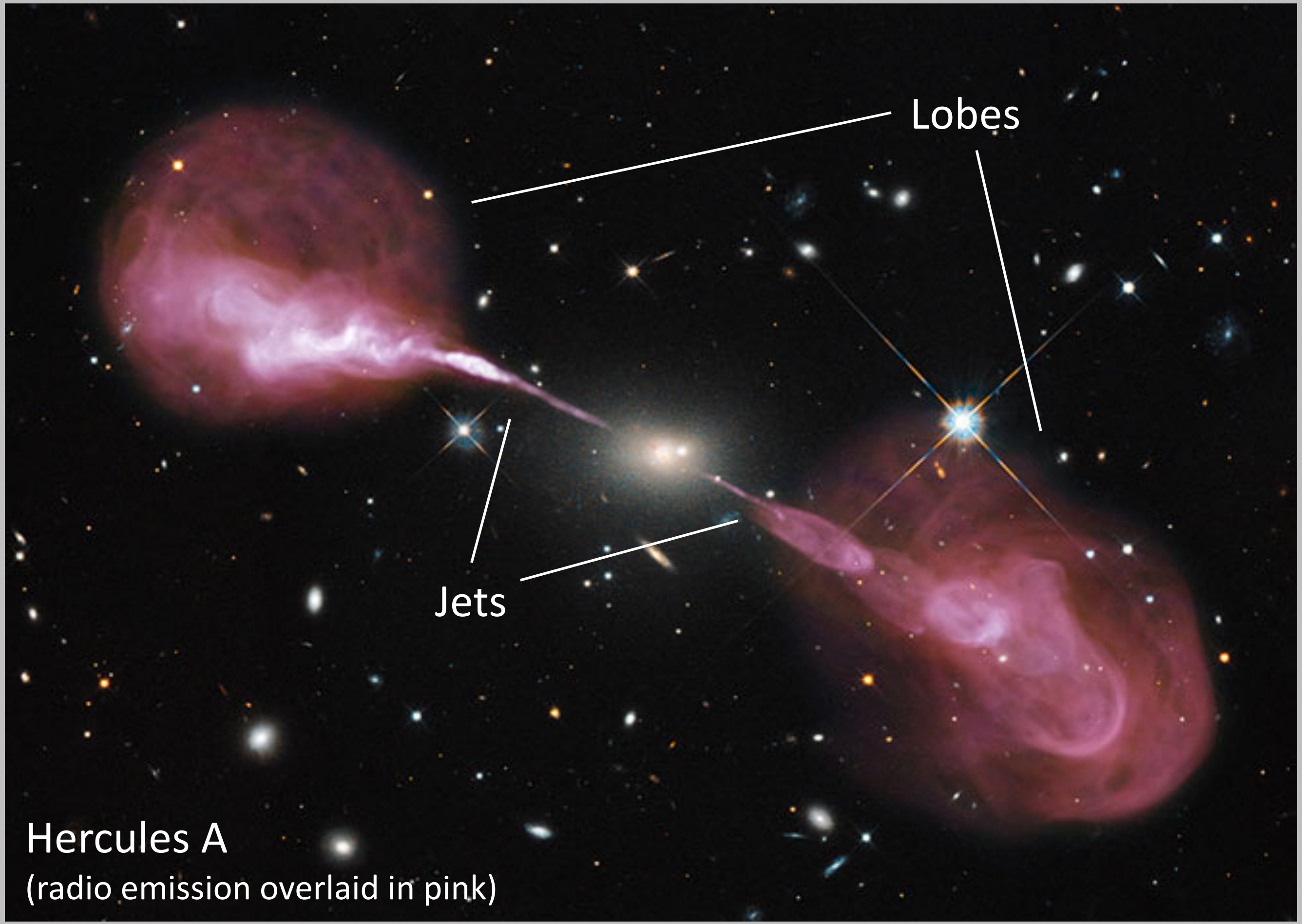


The AGN Zoo: Radio galaxies

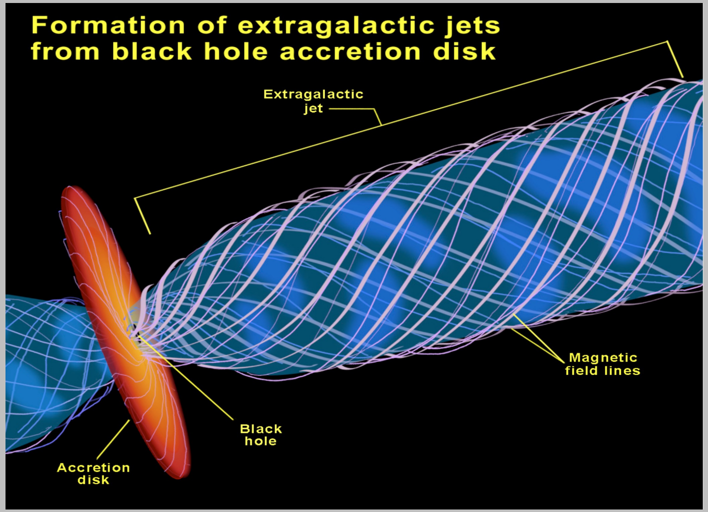
Some AGN put out lots of radio emission as well. These "radio galaxies" are usually ellipticals and often have radio jets and lobes.

Hercules A

- $z=0.155$ (distance ≈ 650 Mpc)
- radio lobes span ≈ 250 kpc
- radio luminosity ≈ 10^{45} erg/s ($10^6 \times$ typical galaxy)
- Jets show **synchroton** radio emission (electrons spiraling around magnetic fields)
- Lobes show **free-free** radio (interactions between charged particles)



Hercules A
(radio emission overlaid in pink)



AGN jets

The black hole + accretion disk has wound up the magnetic fields and launched a collimated jet of relativistic charged particles. (synchroton jet)

When the particles get out far enough they diffuse to form the broad radio lobes

The "Unified Model" for AGN: how to describe these various types of AGN with one basic model?

Central black hole: $\mathcal{M} \approx 10^7 - 10^9\, \mathcal{M}_\odot$, accreting mass at $\approx 1 - 10\, \mathcal{M}_\odot$/yr.

Accretion disk: hot, luminous gas accreting onto the black hole, ≈ solar system sized.

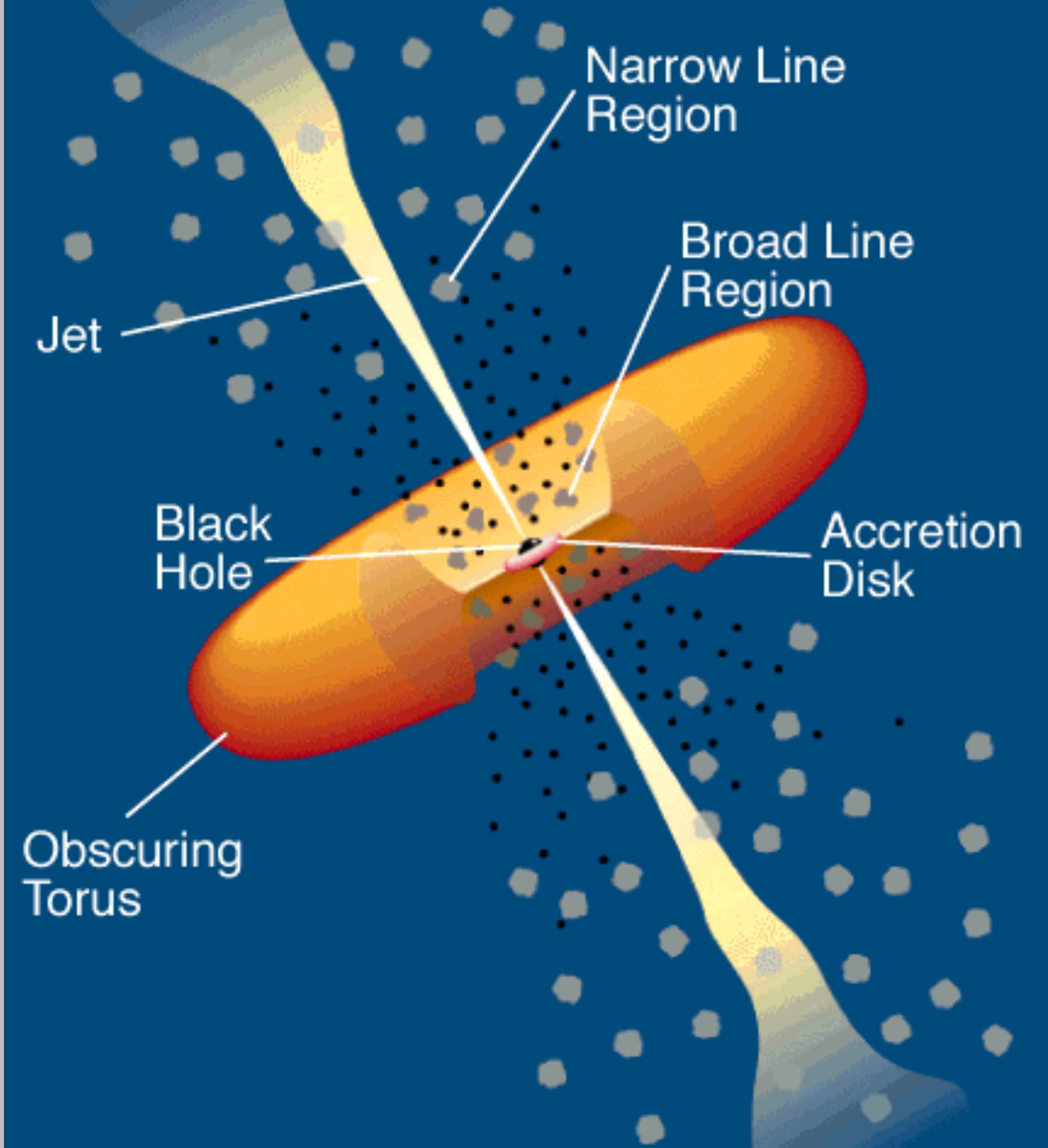
Jets: charged particles moving at relativistic speeds out of the nucleus

Broad-line region: Gas clouds near the accretion disk, turbulent motions at high speed.

Dusty torus: a ring of denser gas and dust surrounding the nucleus. ≈ 0.1 pc in size.

Narrow-line clouds: Gas clouds further out, moving more slowly.

Important: This is all happening on size scales too small to be resolved at the distances of most AGN.

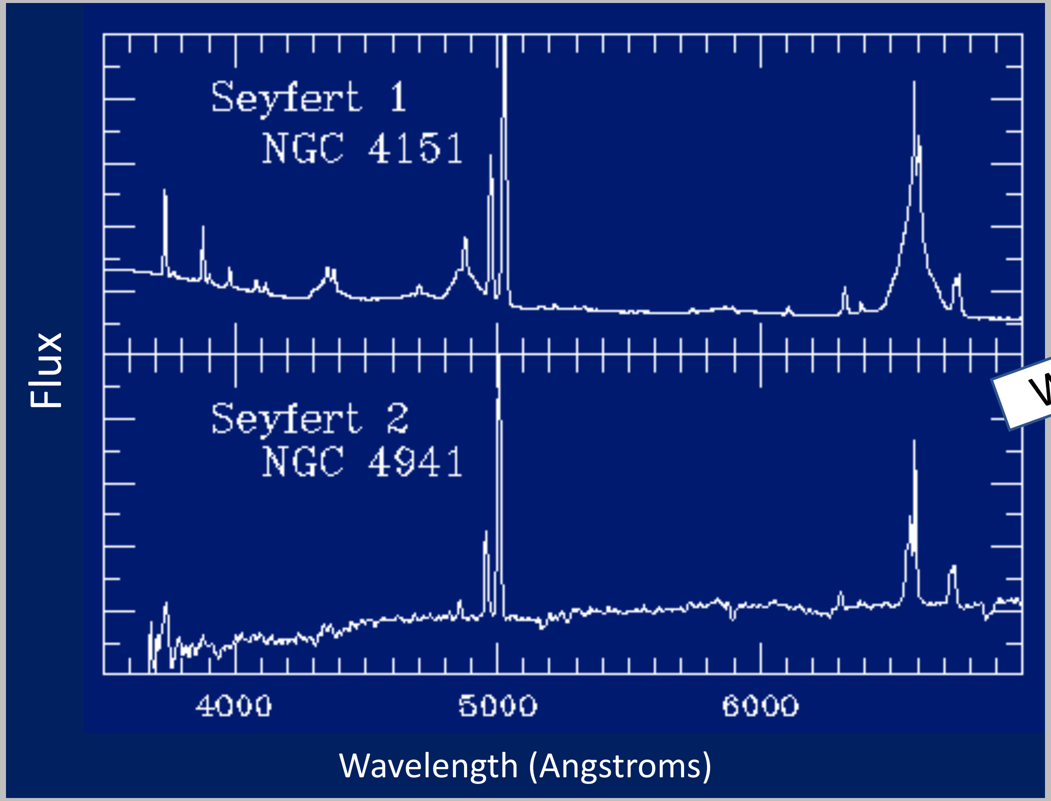


How does this "unify" the different kinds of AGN?

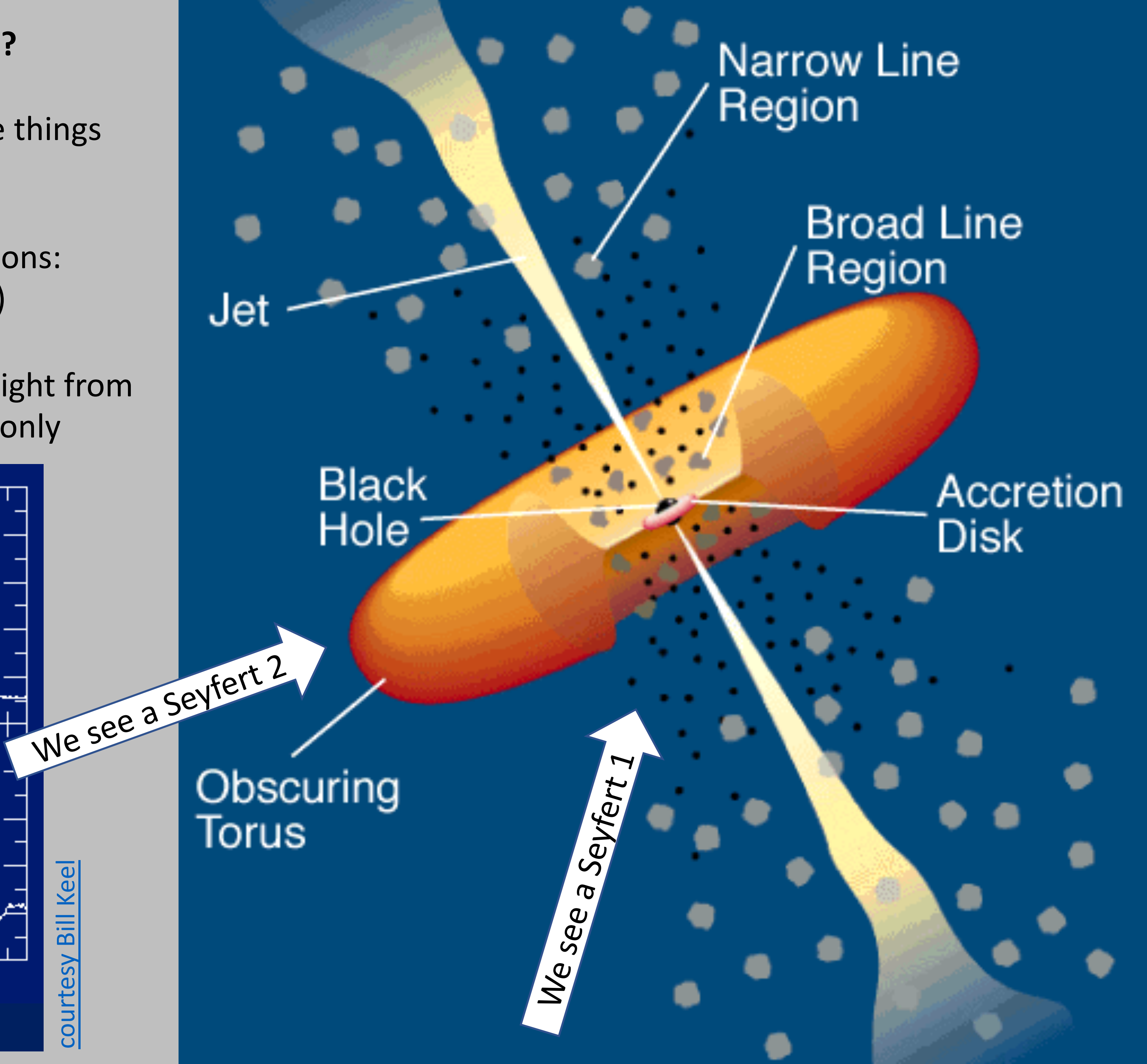
Seyfert (and other) Type 1 and Type 2 AGN: same things seen from different angles.

Type 1: we see light from the inner and outer regions: broad lines, narrow lines, hot accretion disk (blue)

Type 2: we see only the light from outer regions, light from the inner regions is blocked by dust: narrow lines only



courtesy Bill Keel



How does this "unify" the different kinds of AGN?

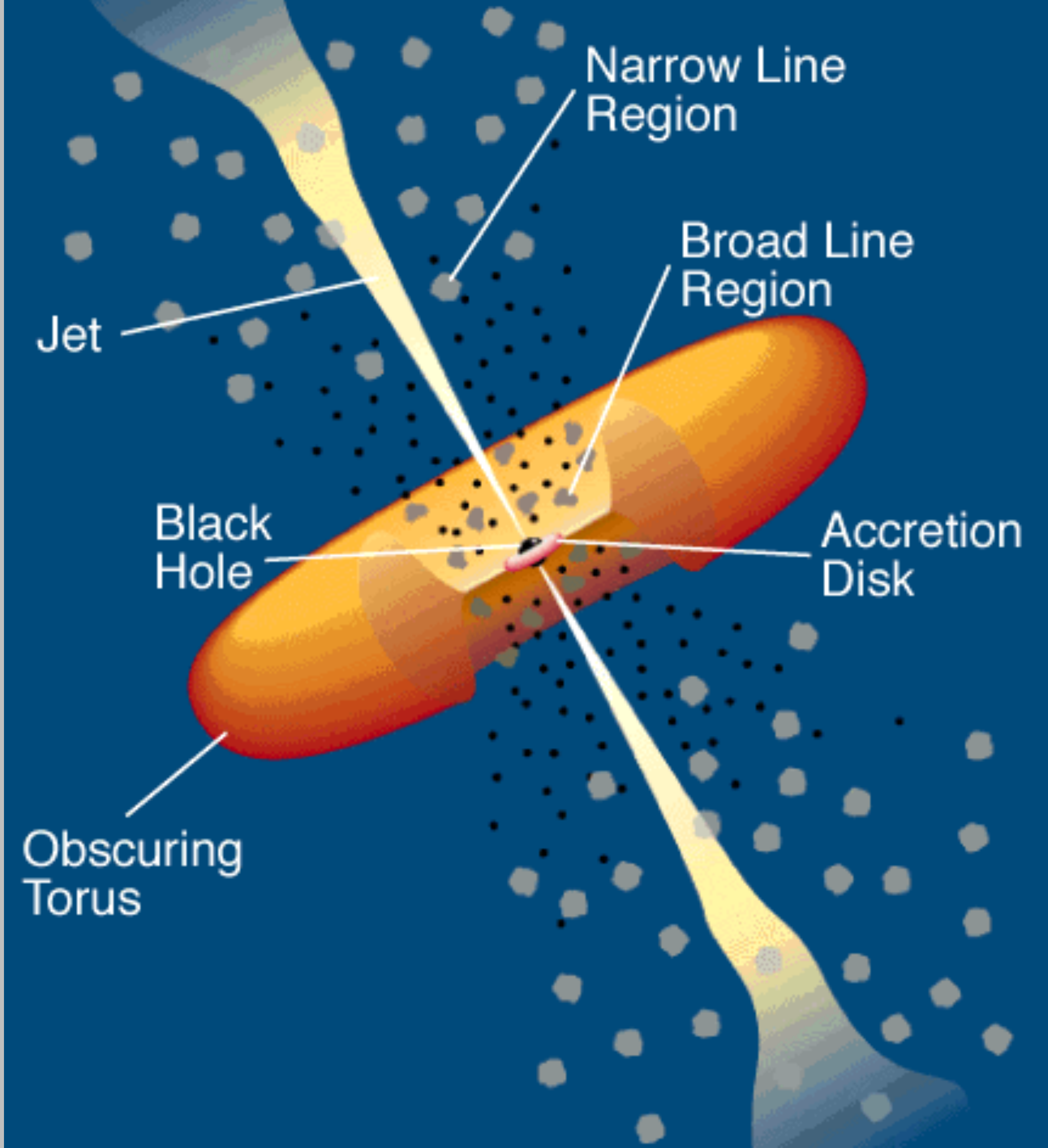
"Radio loud" vs "radio quiet" AGN: Maybe the jet hasn't turned on, or has been choked off somehow?

> *One possibility:* Radio galaxies tend to be ellipticals, spirals are generally not radio loud. Maybe the dense gas in the disks of spiral galaxies blocks the jets from getting out? Ellipticals don't have dense gas, so the jets can expand outwards unimpeded.

Luminous Quasars vs lower luminosity AGN: different amounts of power from "central engine"

> Lower accretion rates: Not as much gas falling in on low luminosity AGN?
>
> Lower mass black hole in low luminosity AGN?

Unified model: Physical differences in detail, but not really physically different mechanisms.



Timescale and Triggering of AGN activity

In the local universe, AGN are rare:

- 1 in a million galaxies host luminous quasars
- ≈ 5% of galaxies host bright Seyfert nuclei.

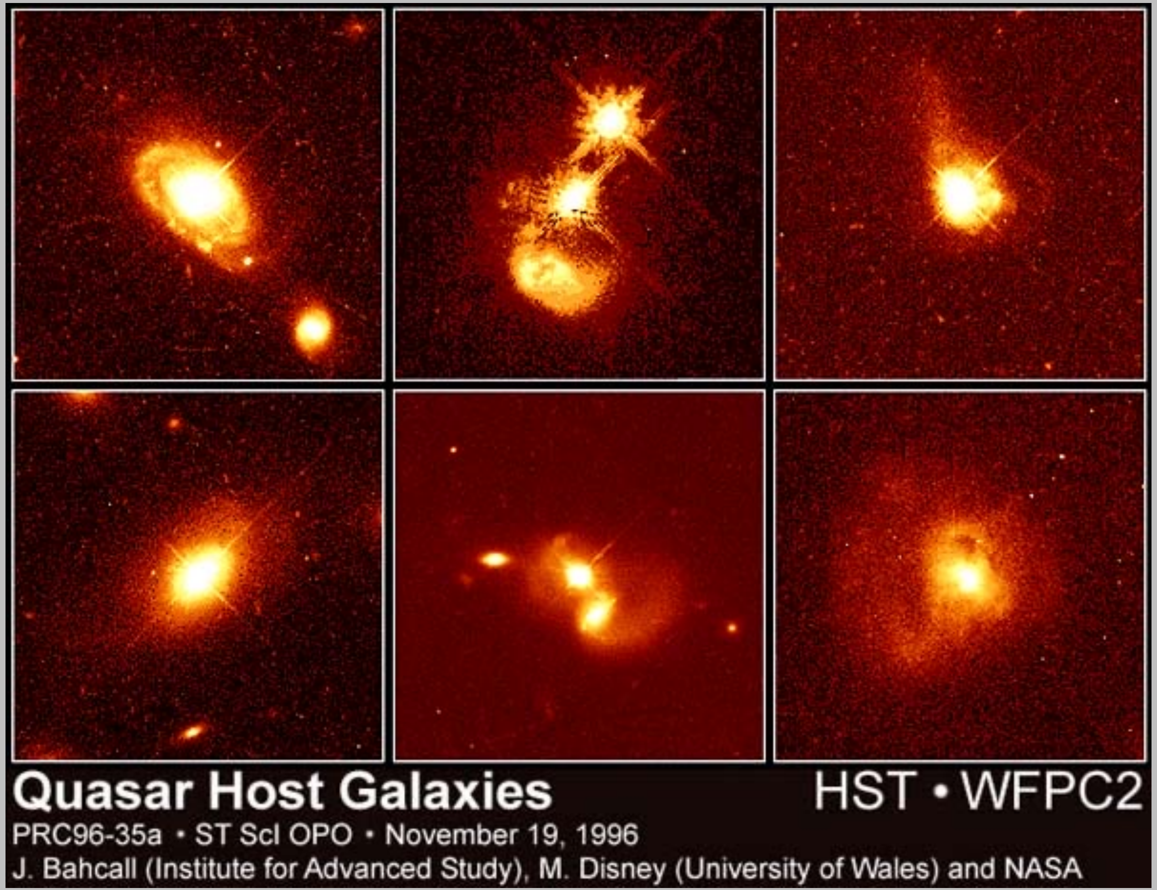
But **most** bright galaxies have black holes.

So whatever triggers AGN activity must be relatively rare event, and the timescale for AGN activity is likely short ($10^7 - 10^8$ years?)

One good possibility: **galaxy interactions and mergers**

- Interactions are good at driving gas into the center of galaxies, where it can fuel an AGN

- Mergers scatter stars violently and grow galaxy spheroids. *If mergers fuel/grow black holes and also build spheroids, this might explain the correlation between black hole mass and spheroid mass.*

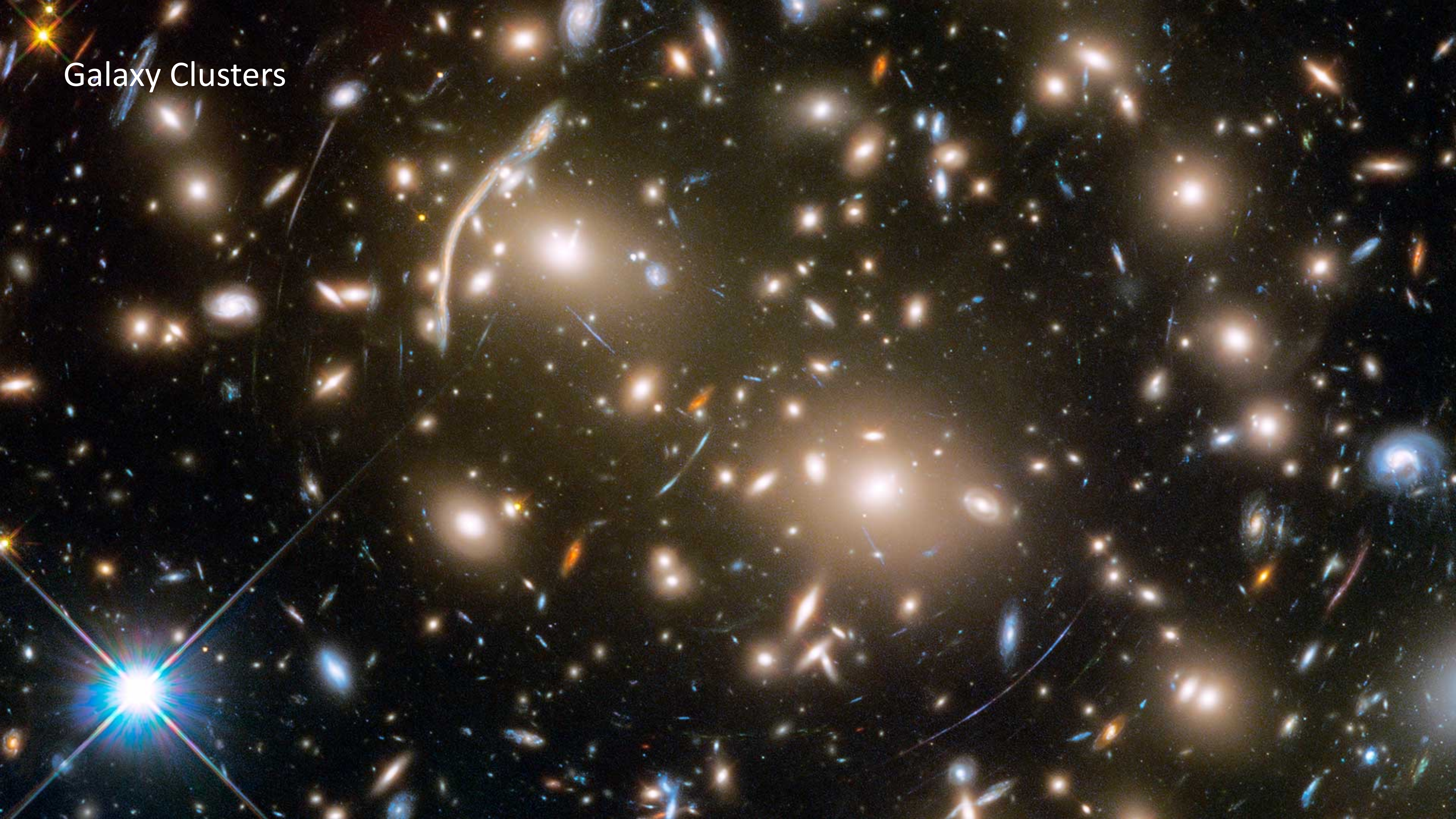


Many AGN are found in interacting or messy systems....
... but so are many non-AGN galaxies.

And also, many AGN are not in interacting systems.

So a direct connection between AGN activity and galaxy mergers *remains unclear*. 😩

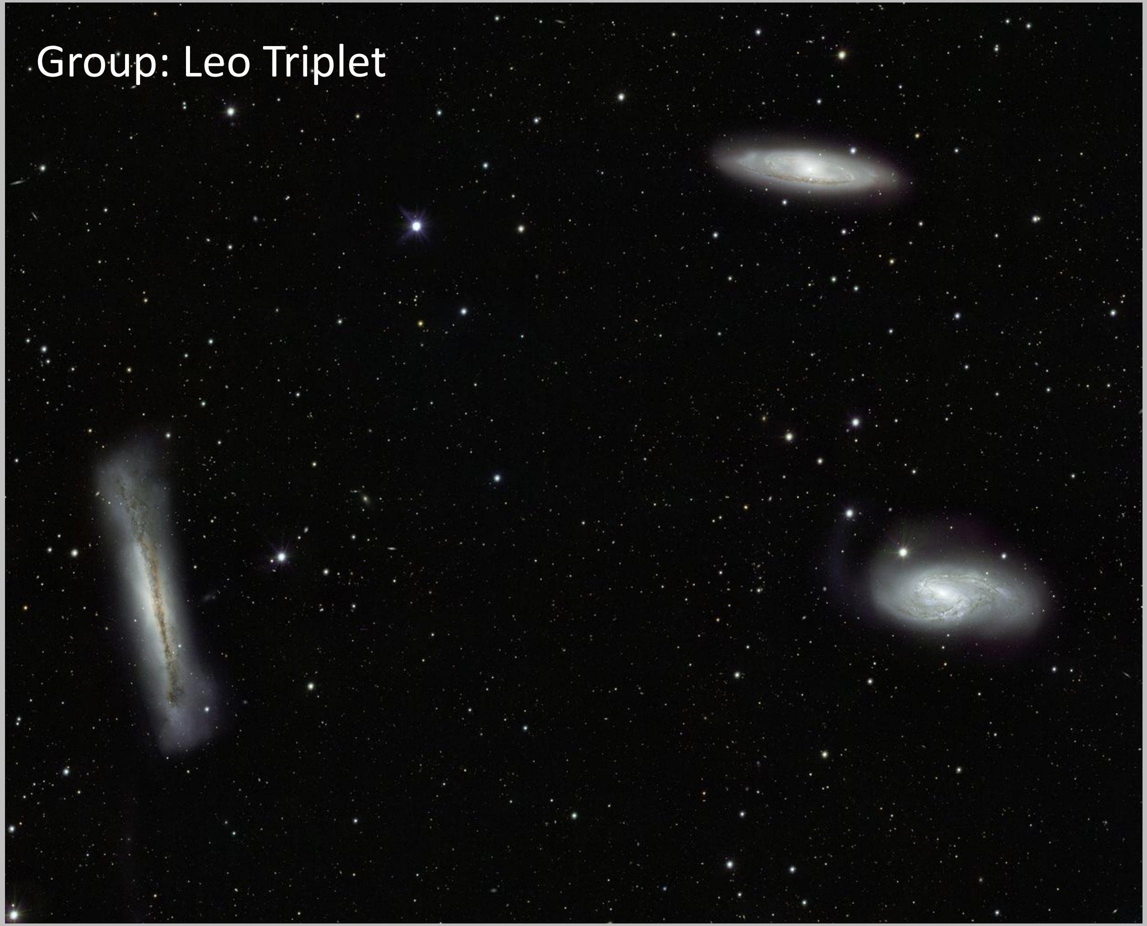
Galaxy Clusters

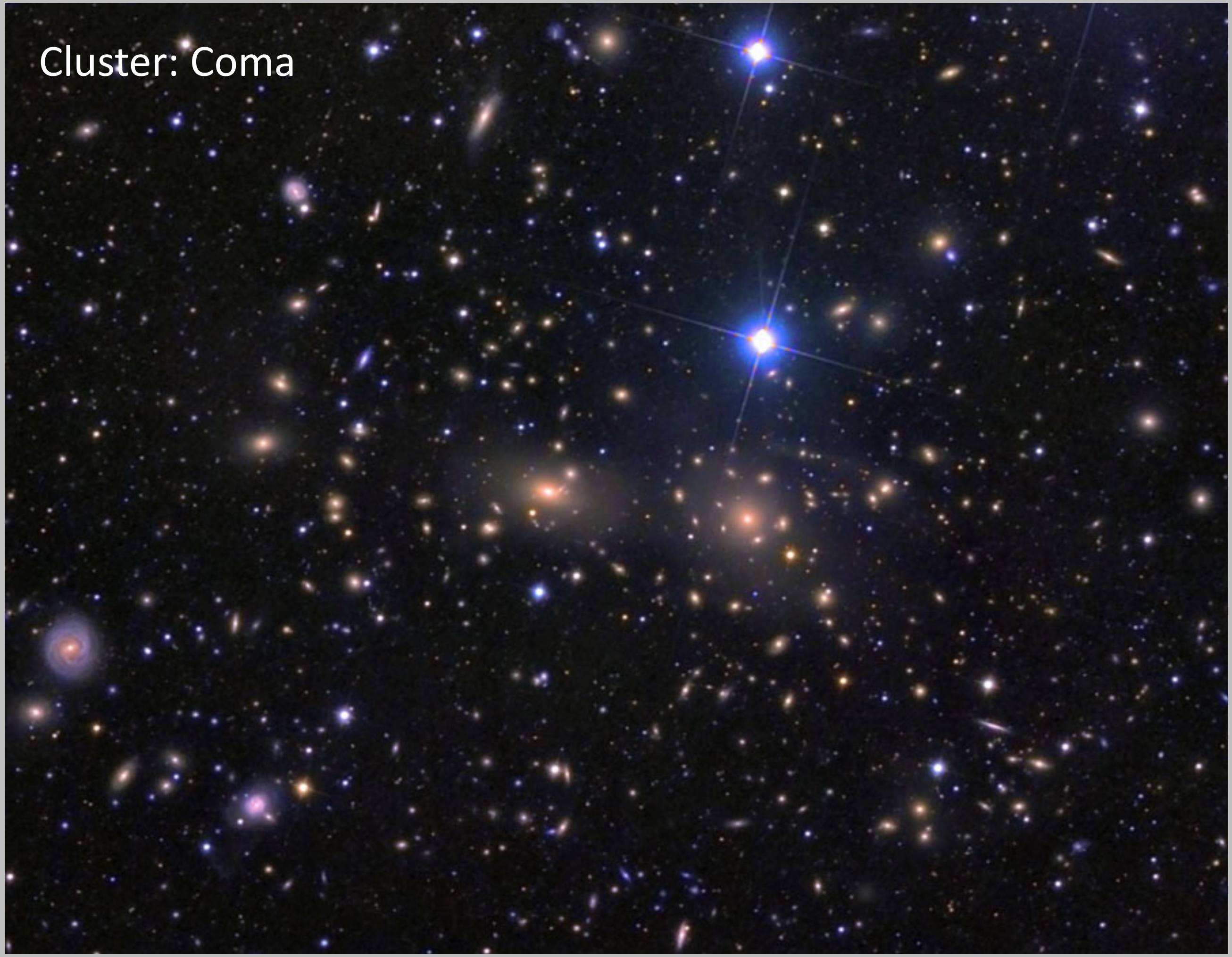


Galaxy Groups and Clusters

Galaxy groupings come in all sizes: no well-defined difference between groups and clusters.

Many big clusters contain smaller “subgroups”.





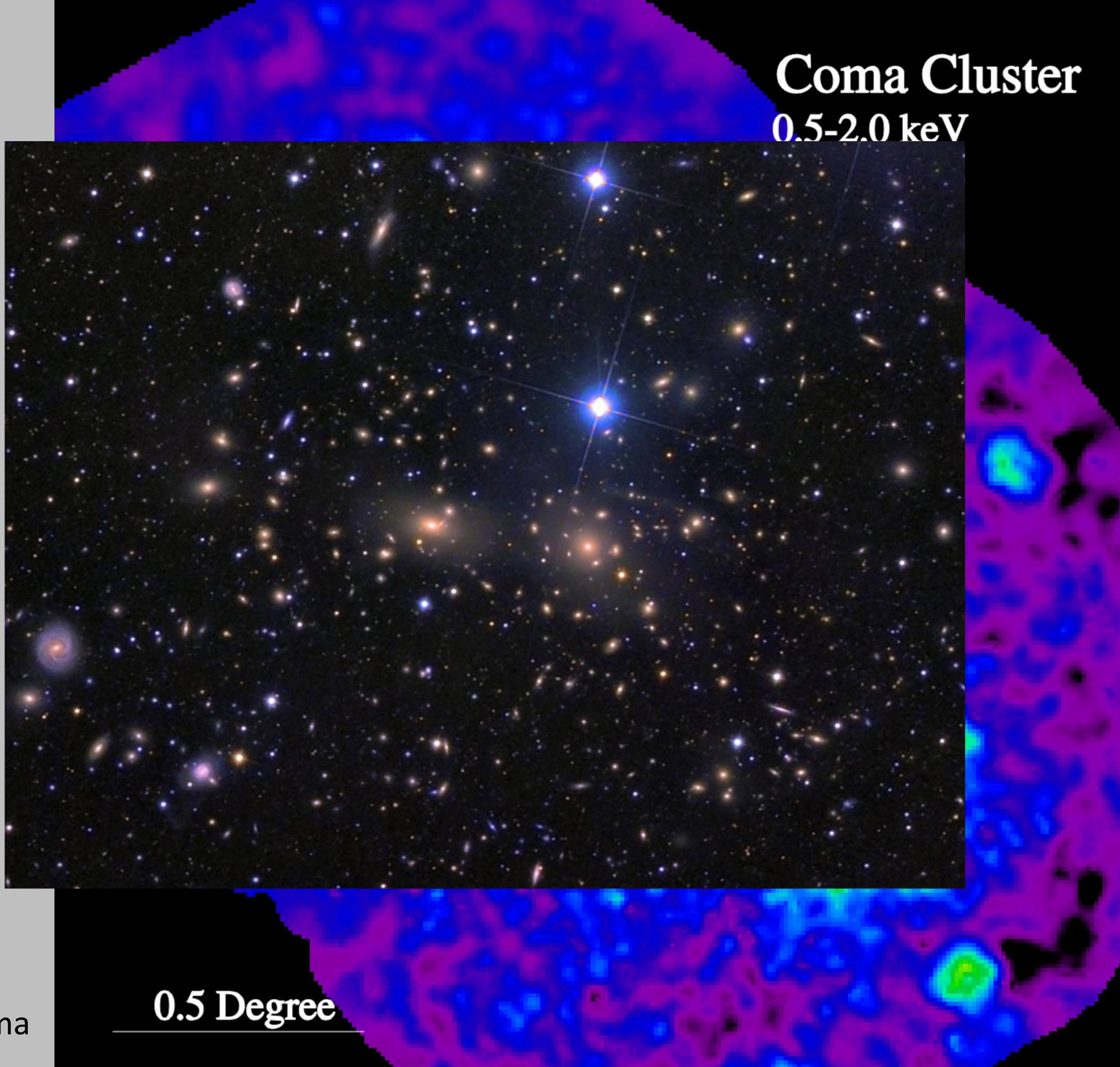
	Groups	Clusters
Galaxies	handful	100’s – 1000’s
Sizes	0.5 – 1 Mpc	few Mpc
Velocity Dispersion	≈ few 100 km/s	≈ 500 – 1000 km/s
Mass	$\approx 10^{13}\ M_\odot$	$\approx 10^{14} - 10^{15}\ M_\odot$

Hot gas in galaxy clusters

Massive galaxy clusters are filled with X-ray emission: free-free emission from hot, ionized $T \approx 10^7$ K gas.

The total amount of hot gas exceeds the total mass of the stars in all the galaxies combined!

Some of this gas may have been blown out from galaxies within the cluster, but most probably was primordial gas that never formed into stars to begin with.



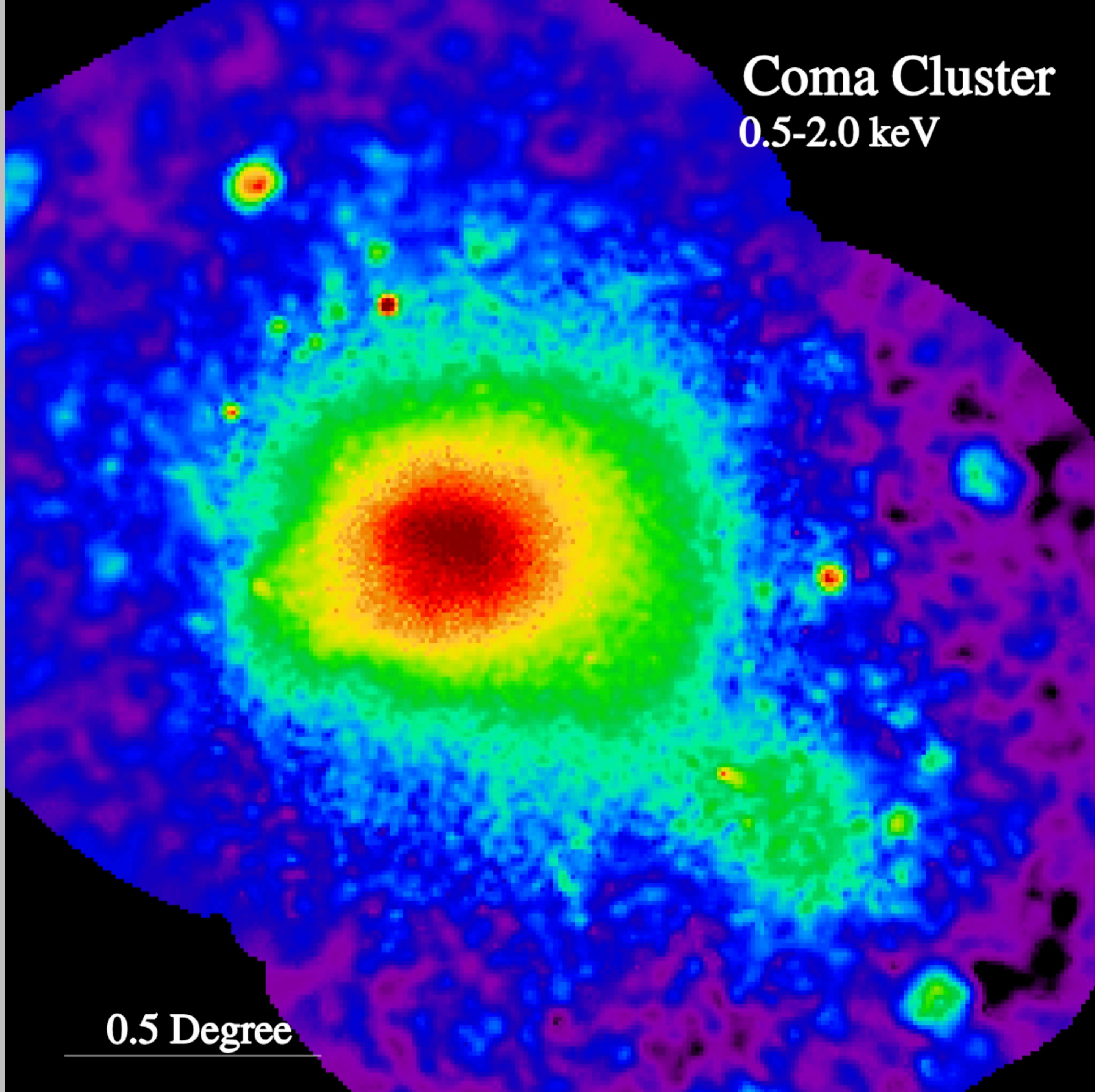
X-ray map of Coma

Hot gas in galaxy clusters

Massive galaxy clusters are filled with X-ray emission: free-free emission from hot, ionized $T \approx 10^7$ K gas.

The total amount of hot gas exceeds the total mass of the stars in all the galaxies combined!

Some of this gas may have been blown out from galaxies within the cluster, but most probably was primordial gas that never formed into stars to begin with.



X-ray map of Coma

Galaxy Cluster Masses (using galaxy velocities)

kinetic energy

gravitational potential energy

Start with the **virial theorem**: In a system in equilibrium, $2K + \Phi = 0$.

Let's check the virial theorem using circular orbits around a point mass:

Circular speed:

$$V_c^2 = \frac{G\mathcal{M}}{R}$$

Kinetic energy:

$$K = \frac{1}{2} m V_c^2 = \frac{G\mathcal{M}m}{2R}$$

Potential energy:

$$\Phi = -\frac{G\mathcal{M}m}{R}$$

Virial theorem:

$$2K + \Phi = 2\left(\frac{G\mathcal{M}m}{2R}\right) + \left(-\frac{G\mathcal{M}m}{R}\right) = \frac{G\mathcal{M}m}{R} - \frac{G\mathcal{M}m}{R} = 0$$ 🥳 👍

Galaxy Cluster Masses (using galaxy velocities)

Start with the **virial theorem**: In a system in equilibrium, $2K + \Phi = 0$.

Kinetic Energy

For galaxies in a galaxy cluster kinetic energy is approximately:

$$K = \sum_{i=1}^{N_{gal}} \frac{1}{2} m_i V_i^2 \approx \frac{1}{2} \mathcal{M} \langle V \rangle^2 \approx \frac{1}{2} \mathcal{M} (3\sigma^2) \approx \frac{3}{2} \mathcal{M} \sigma^2$$

adding up kinetic energy of each galaxy

M : total mass of galaxies
$\langle V \rangle$: their average 3D speed.

σ^2 : line of sight velocity dispersion, multiply by 3 to get 3D dispersion.

Potential Energy

If we treat the cluster as a ***uniform density sphere*** 😒, of mass $\mathcal{M}$ and size R, we can write the gravitational potential energy as:

$$\Phi = -\frac{3}{5} \frac{G\mathcal{M}^2}{R} \approx -\frac{3}{5} \frac{G\mathcal{M}^2}{\langle R \rangle}$$

Self-gravity of uniform sphere Derived(?) in PHYS 121, 310

$\langle R \rangle$: some characteristic measure of cluster size.

Galaxy Cluster Masses (using galaxy velocities)

Start with the **virial theorem**: In a system in equilibrium, $2K + \Phi = 0$.

Kinetic Energy

For galaxies in a galaxy cluster kinetic energy is approximately:

$$K = \sum_{i=1}^{N_{gal}} \frac{1}{2} m_i V_i^2 \approx \frac{1}{2}\mathcal{M}\langle V\rangle^2 \approx \frac{1}{2}\mathcal{M}(3\sigma^2) \approx \frac{3}{2}\mathcal{M}\sigma^2$$

Potential Energy

If we treat the cluster as a ***uniform density sphere*** 😒, of mass $\mathcal{M}$ and size R, we can write the gravitational potential energy as:

$$\Phi = -\frac{3}{5}\frac{G\mathcal{M}^2}{R} \approx -\frac{3}{5}\frac{G\mathcal{M}^2}{\langle R\rangle}$$

Virial Theorem

$$2K + \Phi \approx 2\left(\frac{3}{2}\mathcal{M}\sigma^2\right) + -\frac{3}{5}\frac{G\mathcal{M}^2}{\langle R\rangle} = 0$$

so solve for $\mathcal{M}$ to get:

$$\mathcal{M} \approx \frac{5\langle R\rangle\sigma^2}{G}$$

Galaxy Cluster Masses

Method 1) Using galaxy velocities to get **total mass**:

$$\mathcal{M} \approx \frac{5\langle R\rangle\sigma^2}{G}$$

Method 2) Using starlight to get **stellar mass**:

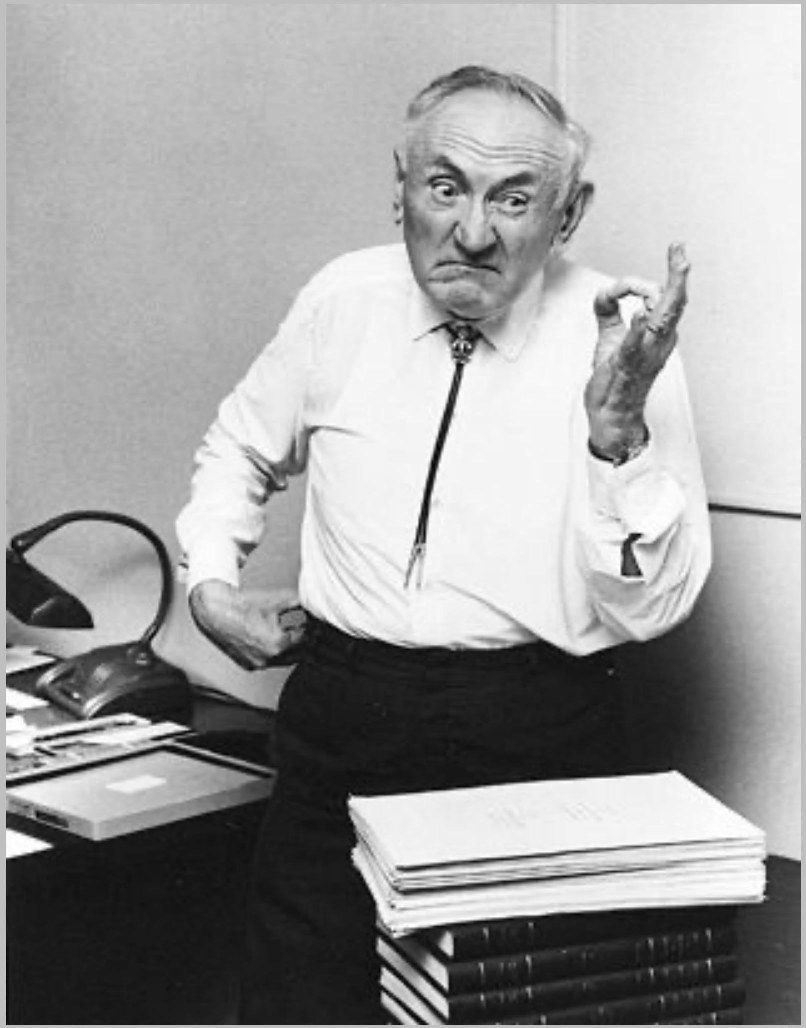
$$\mathcal{M}_* = \sum_{i=1}^{N_{gal}} L_i \left(\frac{\mathcal{M}}{L}\right)_{*,i} \approx L\left\langle\left(\frac{\mathcal{M}}{L}\right)_*\right\rangle$$

These methods do not agree!

There is far more total mass than stellar mass.
Much more than even stellar mass + gas mass.

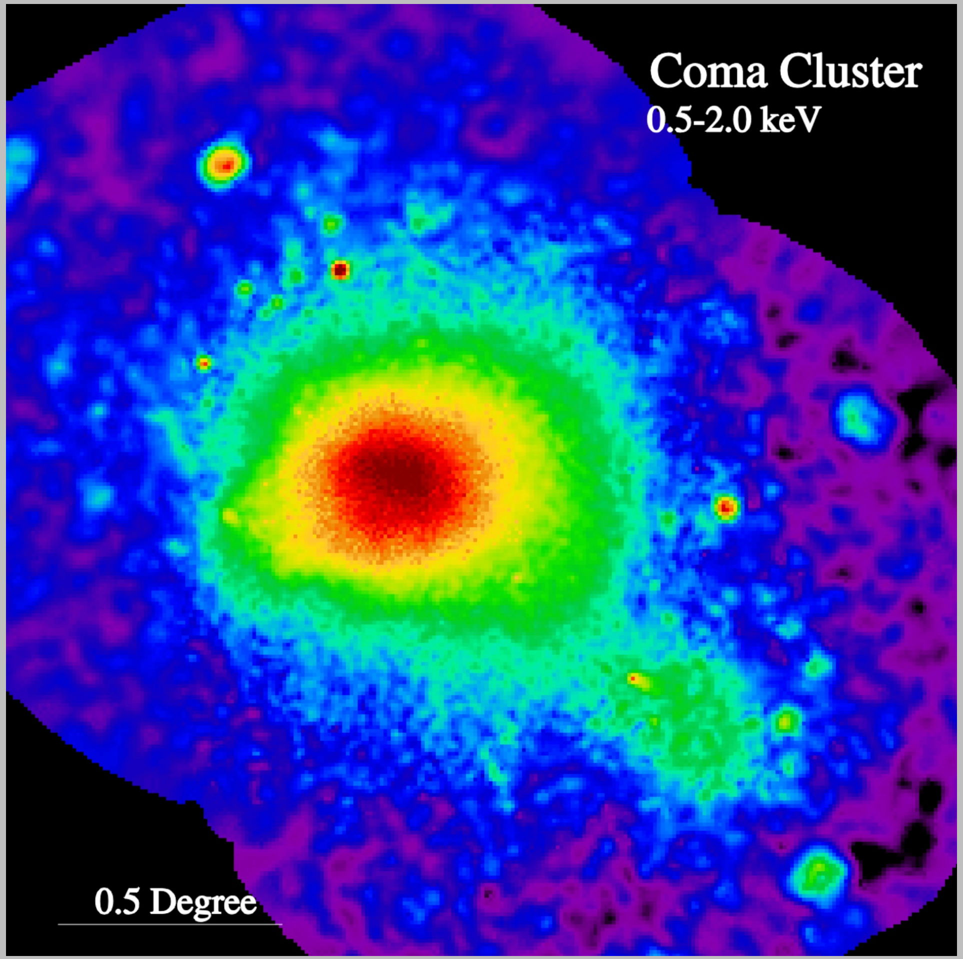
Fritz Zwicky (1933): realized that if the mass in stars was all there was, galaxies are moving way too fast for gravity to hold them together.

He hypothesized "*dunkle Materie*": dark matter.

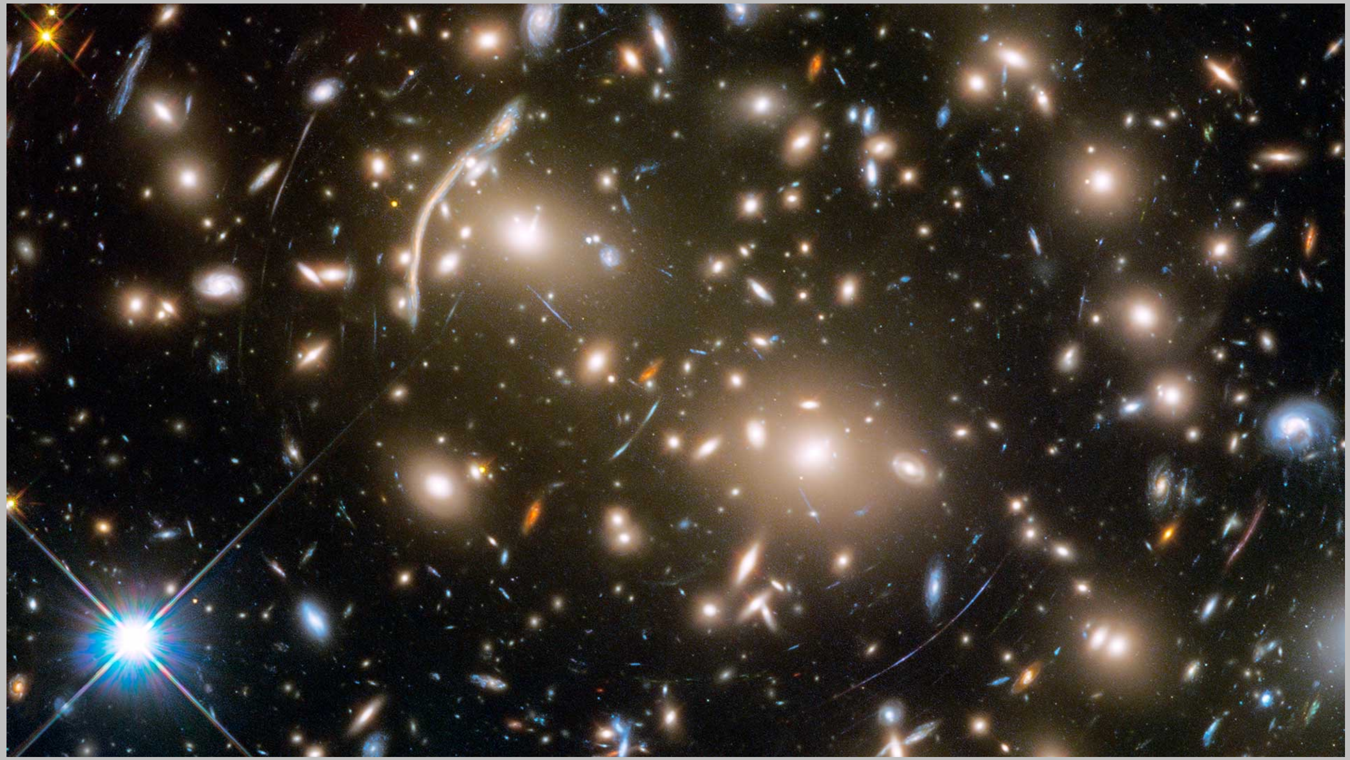


Galaxy Cluster Masses: Other (more recent) methods

Hydrostatic equilibrium: Balance thermal energy of hot X-ray gas with gravitational potential energy of cluster.



Gravitational lensing: the mass of the cluster bends the light from background galaxies, distorting their shapes. This can be modeled to get the cluster mass.



Galaxy cluster mass balance (rough numbers):

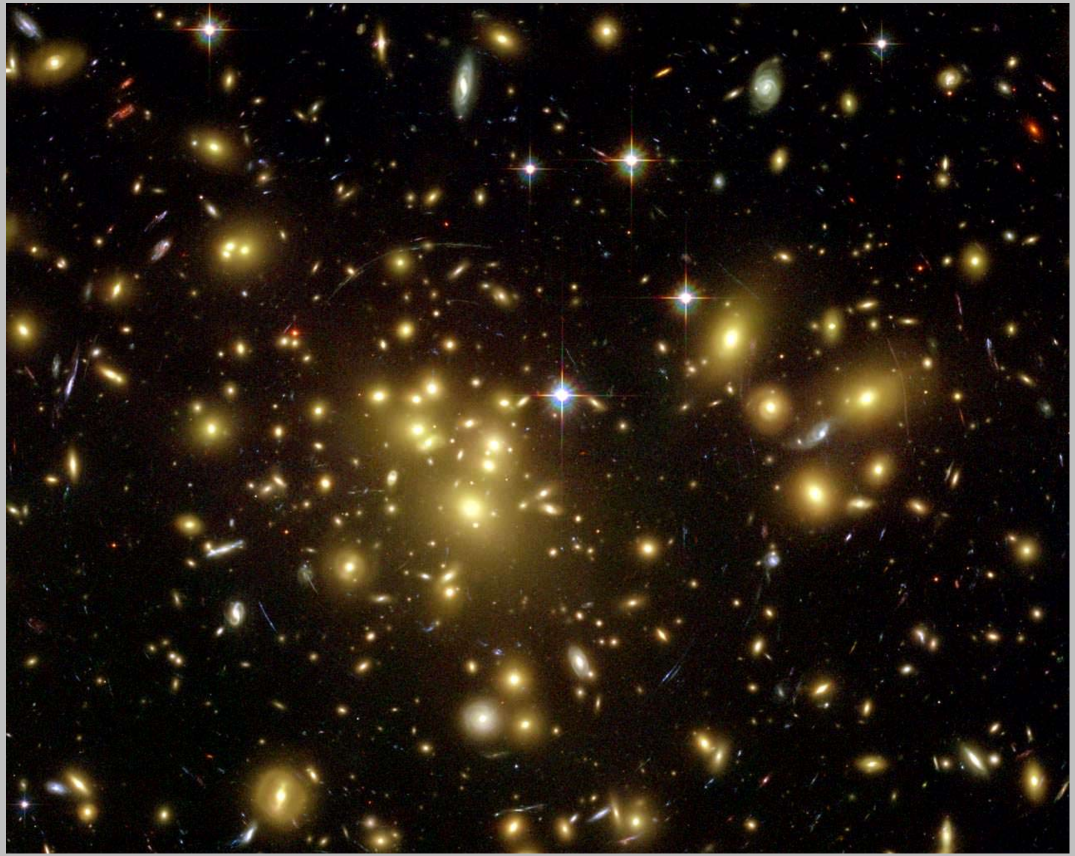
- ≈ few % of total mass is in stars
- ≈ 10% of total mass is in hot gas
- ≈ 85% of total mass is ”missing”: dark matter

Galaxies: Morphology-Density Relationship

In the local universe, the fraction of galaxy types is a strong function of local environment.

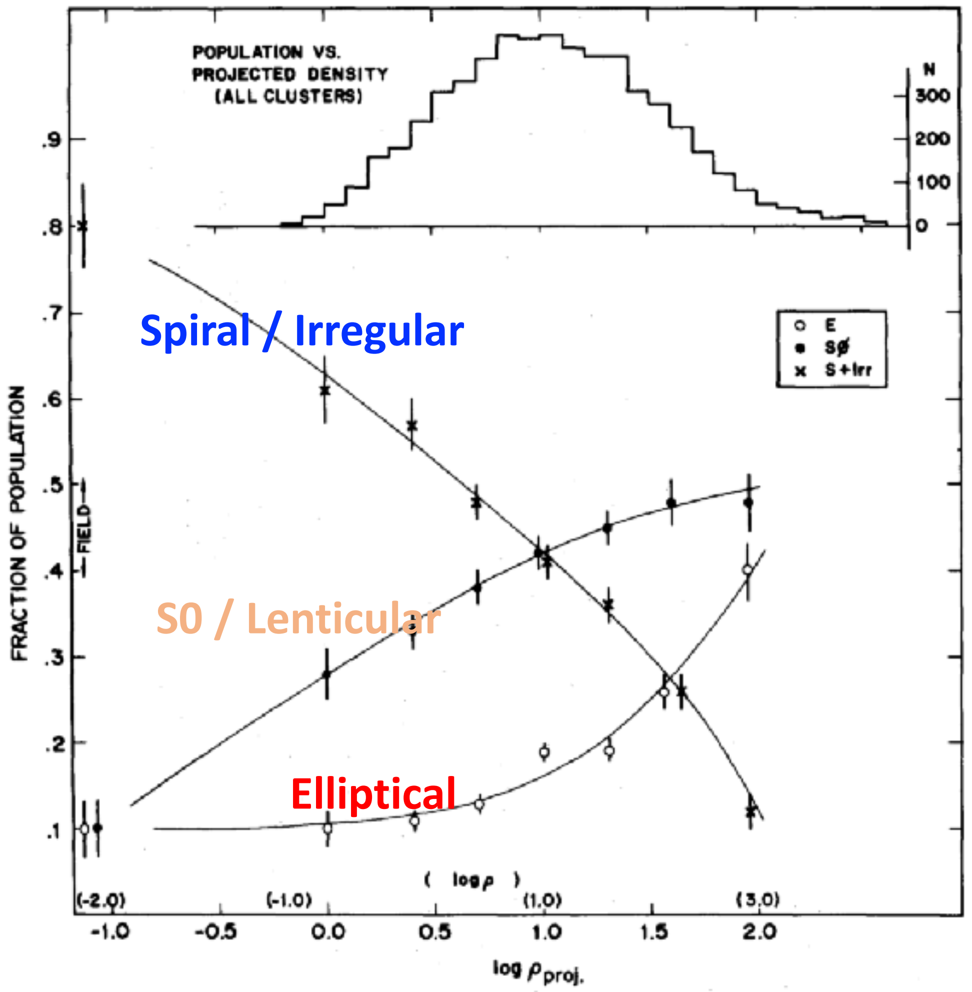
Spirals/Irregulars dominate the in the field environment.

S0's and E's dominate in galaxy clusters.



Dressler 1980

Galaxy Population Fraction



Projected Number Density of Galaxies
log(# per Mpc^2)

Evolution of Cluster Galaxies

Hubble Space Telescope (and now JWST) lets us look at galaxies in distant clusters, to see how things have changed with time.

Higher fraction of star-forming spiral galaxies in the past and a higher fraction of “red and dead” E and S0 galaxies today: galaxy evolution!

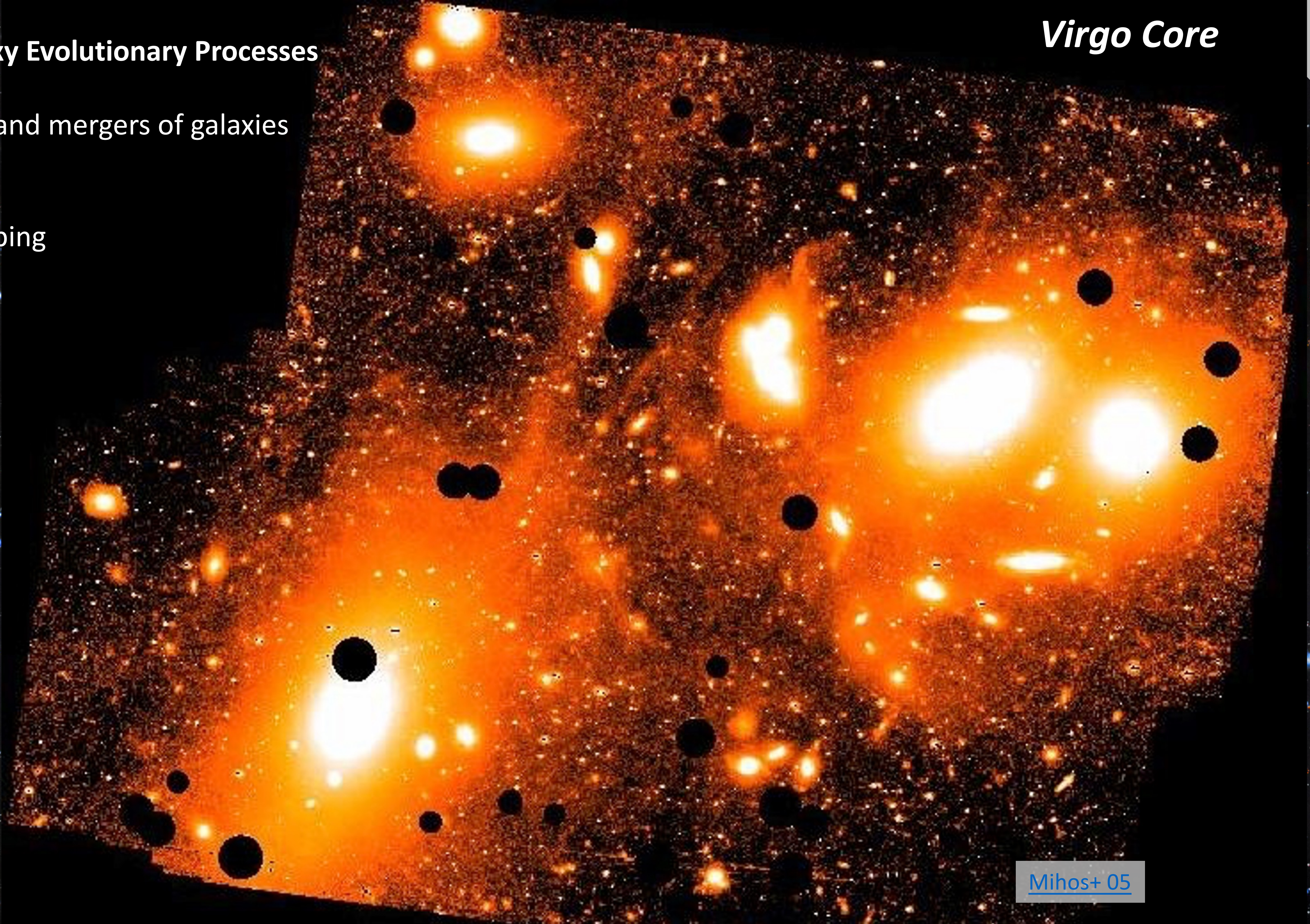
HST image of galaxy cluster MACS J0717+3745. Redshift $z = 0.55$, so we are looking back in time ≈ 5 billion years.

Cluster Galaxy Evolutionary Processes

1) Collisions and mergers of galaxies

2) Tidal stripping

Virgo Core



Mihos+ 05

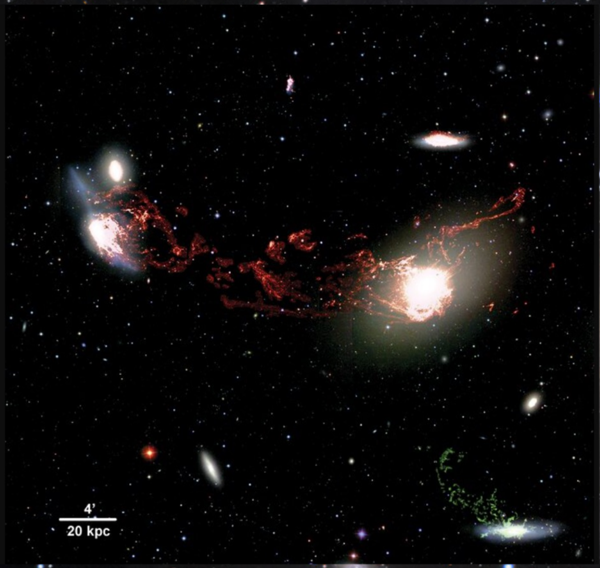
Virgo Core

Cluster Galaxy Evolutionary Processes

1) Collisions and mergers of galaxies

2) Tidal stripping

3) Ram pressure stripping



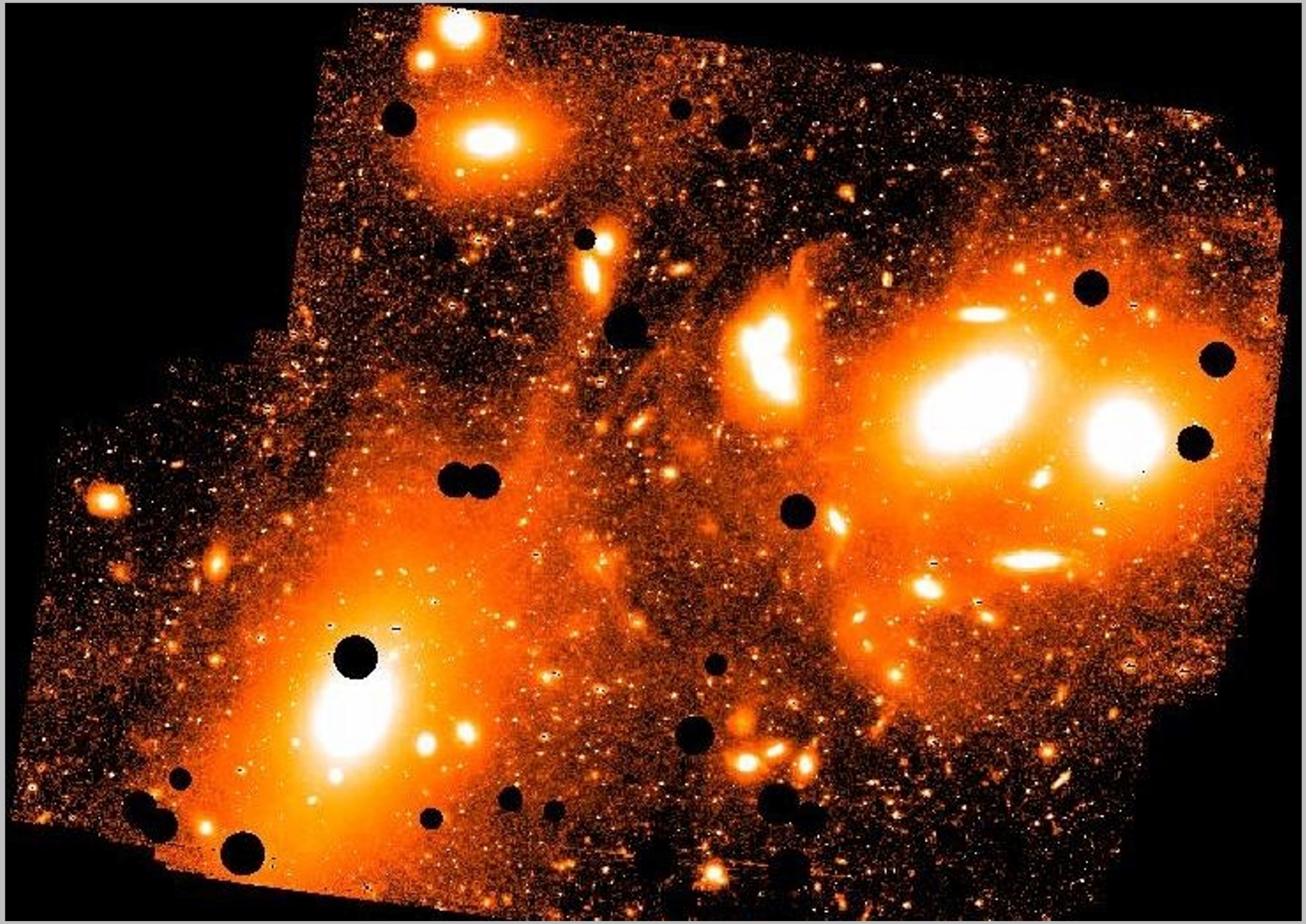
Cluster Galaxy Evolutionary Processes

1) **Collisions and mergers**: galaxies interact, collide, and sometimes even merge in group and cluster environments.

Cluster Galaxy Evolutionary Processes

1) **Collisions and mergers**: galaxies interact, collide, and sometimes even merge in group and cluster environments.

2) **Tidal stripping**: the tidal forces from the cluster's gravitational potential as a whole strips stars from galaxies and even completely shred smaller galaxies.



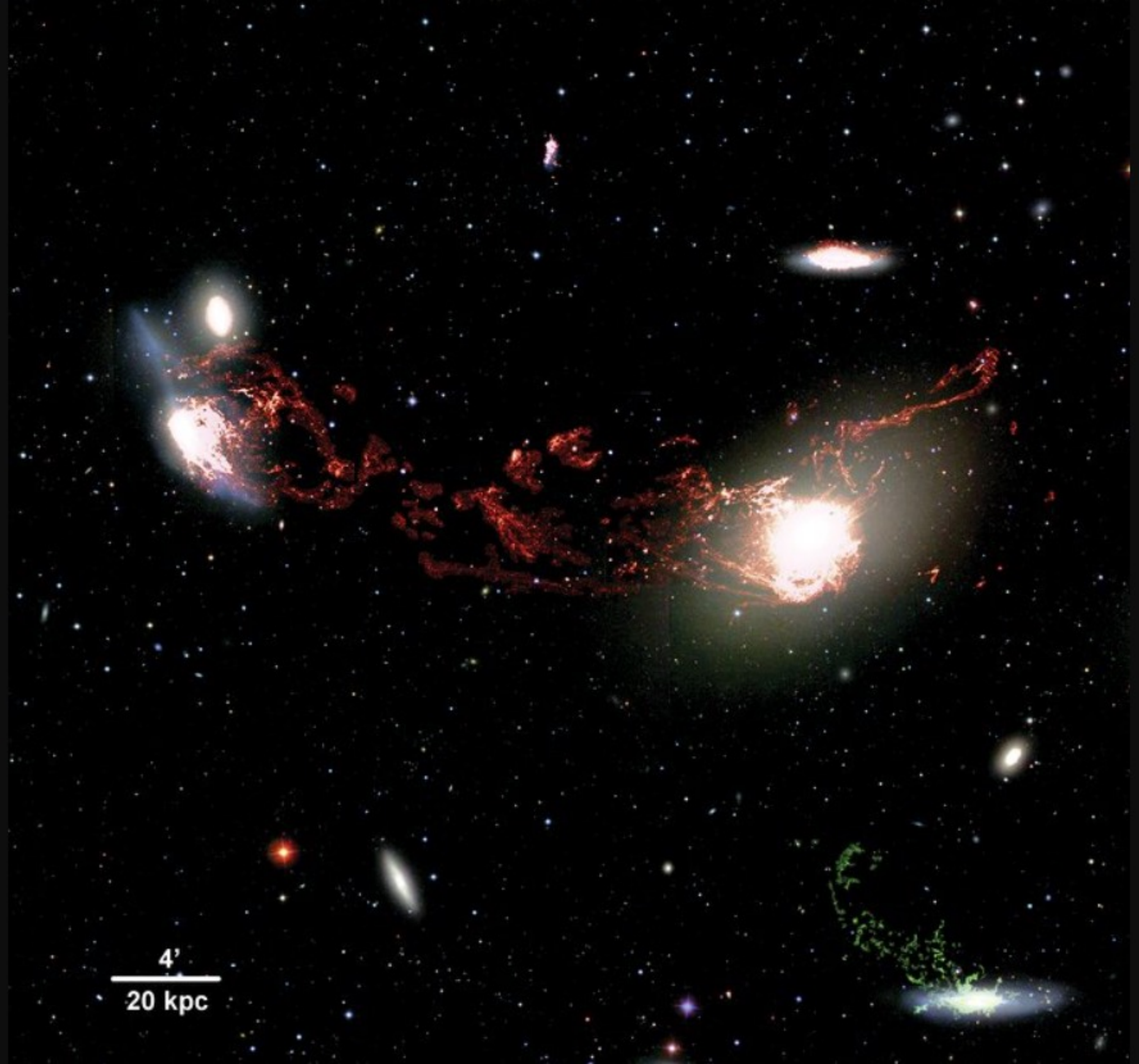
Tidal streams in the Virgo Cluster (Mihos+ 05)

Cluster Galaxy Evolutionary Processes

1) **Collisions and mergers**: galaxies interact, collide, and sometimes even merge in group and cluster environments.

2) **Tidal stripping**: the tidal forces from the cluster's gravitational potential as a whole strips stars from galaxies and even completely shred smaller galaxies.

3) **Ram pressure stripping**: In massive clusters, the gas pressure of the hot X-ray gas can completely strip cold star-forming gas out of spiral galaxies as they move through the cluster.



Red and green: filaments of gas stripped out of spiral galaxies in Virgo

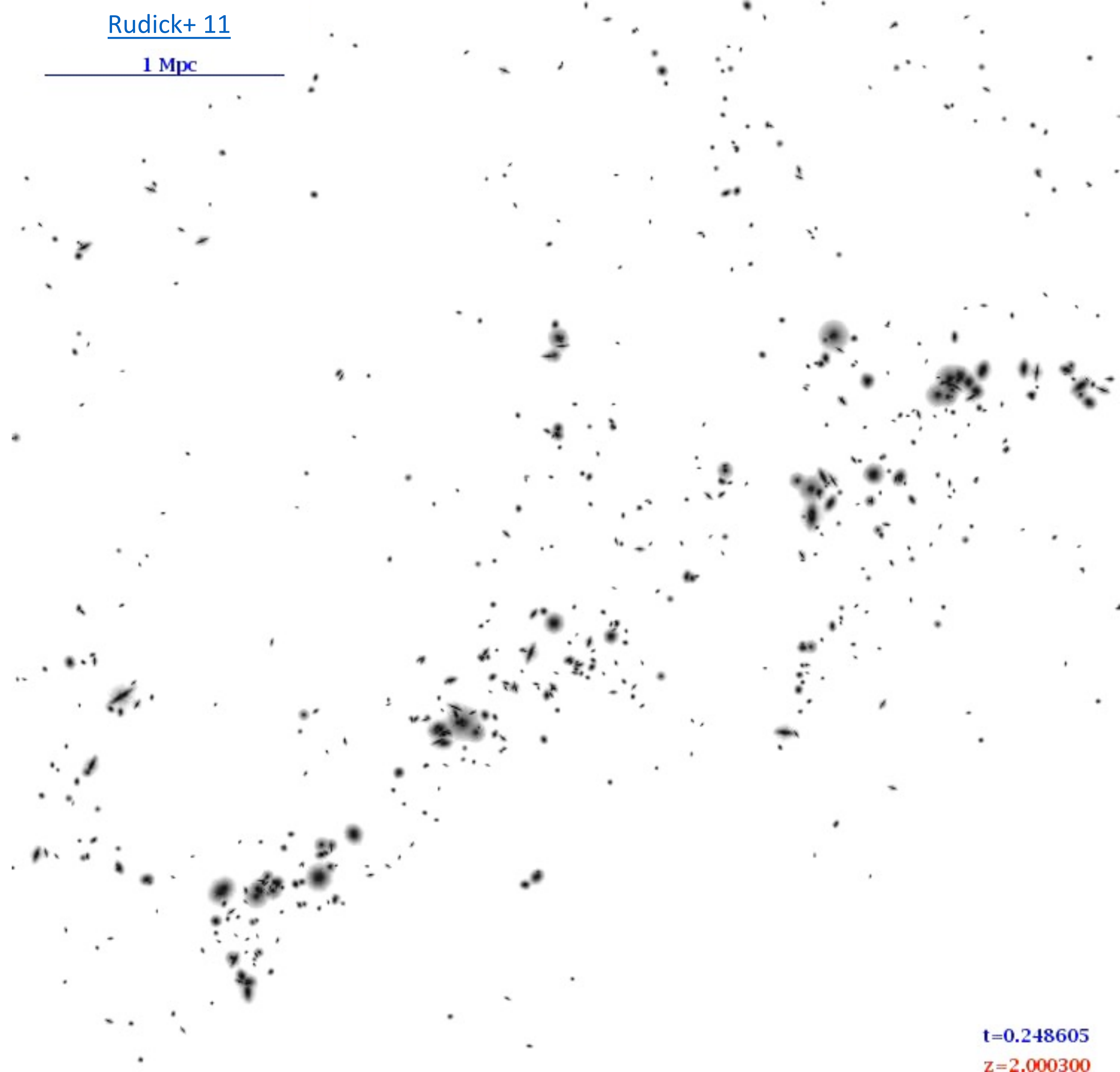
Kenney+ 08

Galaxy Cluster Formation

Clusters grow over time as gravity pulls galaxies together.

Hierarchical accretion: small groups form first, then groups of galaxies merge to form small clusters, then small clusters merge together to form big clusters.

Cluster formation is an *on-going process*.



Formation of a galaxy cluster over ≈ 10 billion years of time


500 kpc
z = 0.74
TNG50

Large Scale Structure

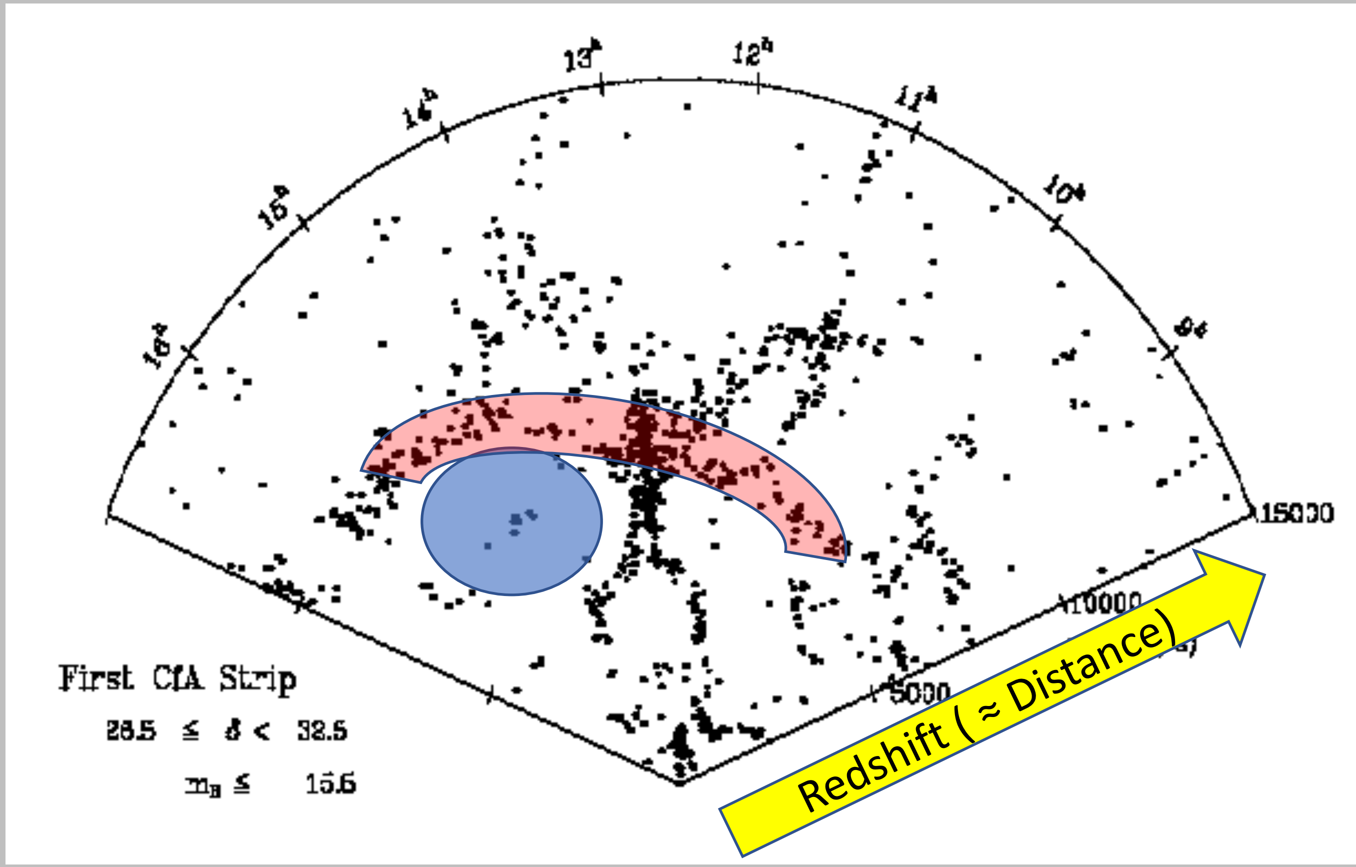
On scale of 100s of Mpc, galaxies are not spread completely randomly through space: they come in clusters, or strung out along "filaments", along with "voids": regions of very low galaxy density.

1985: The Stickman Cometh

The Harvard/Smithsonian Center for Astrophysics produces one of the first redshift surveys, mapping out redshifts for a large sample of galaxies to look at their spatial distribution ⇒

The Bootes Void: 100 Mpc away, 75 Mpc in diameter.
The Great Wall: 200 Mpc across, 10 Mpc thick

The CfA redshift survey: a polar plot of the galaxy distribution: redshift (distance) on the radial coordinate and angle across the sky on the angular coordinate.



Large Scale Structure

On scale of 100s of Mpc, galaxies are not spread completely randomly through space: they come in clusters, or strung out along “filaments”, along with “voids”: regions of very low galaxy density.

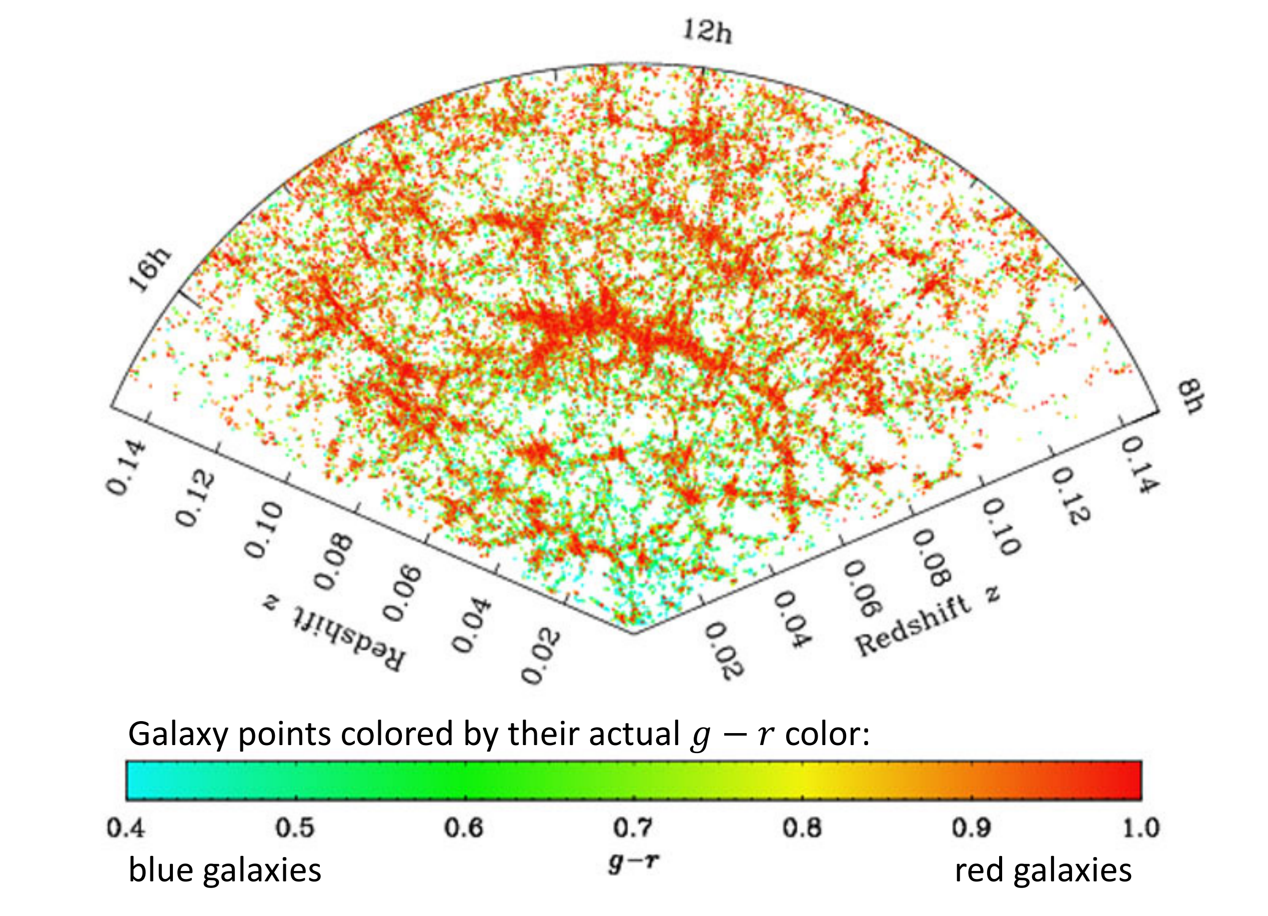
2000s: Sloan Digital Sky Survey

Many more galaxies, much deeper survey going to much larger distances.

The galaxy distribution shows lots of structure: think of cutting though a sponge.

Red galaxies more highly clustered than blue galaxies.

SDSS redshift survey: like the CfA survey, but much deeper and with many more galaxies. (Zehavi+ 11)



Large Scale Structure

2010s-2020s:
Bigger Surveys

SDSS/BOSS
Dark Energy Survey
Euclid

[SDSS/BOSS map]
~ 2 Gigaparsecs wide,
colored by redshift
(yellow → red)

What causes all this structure? 13.6 billion years of gravity acting on cosmic scales.

But to understand this....
it's time for cosmology.