Stellar mass-to-light ratio: $(M/L)_*$

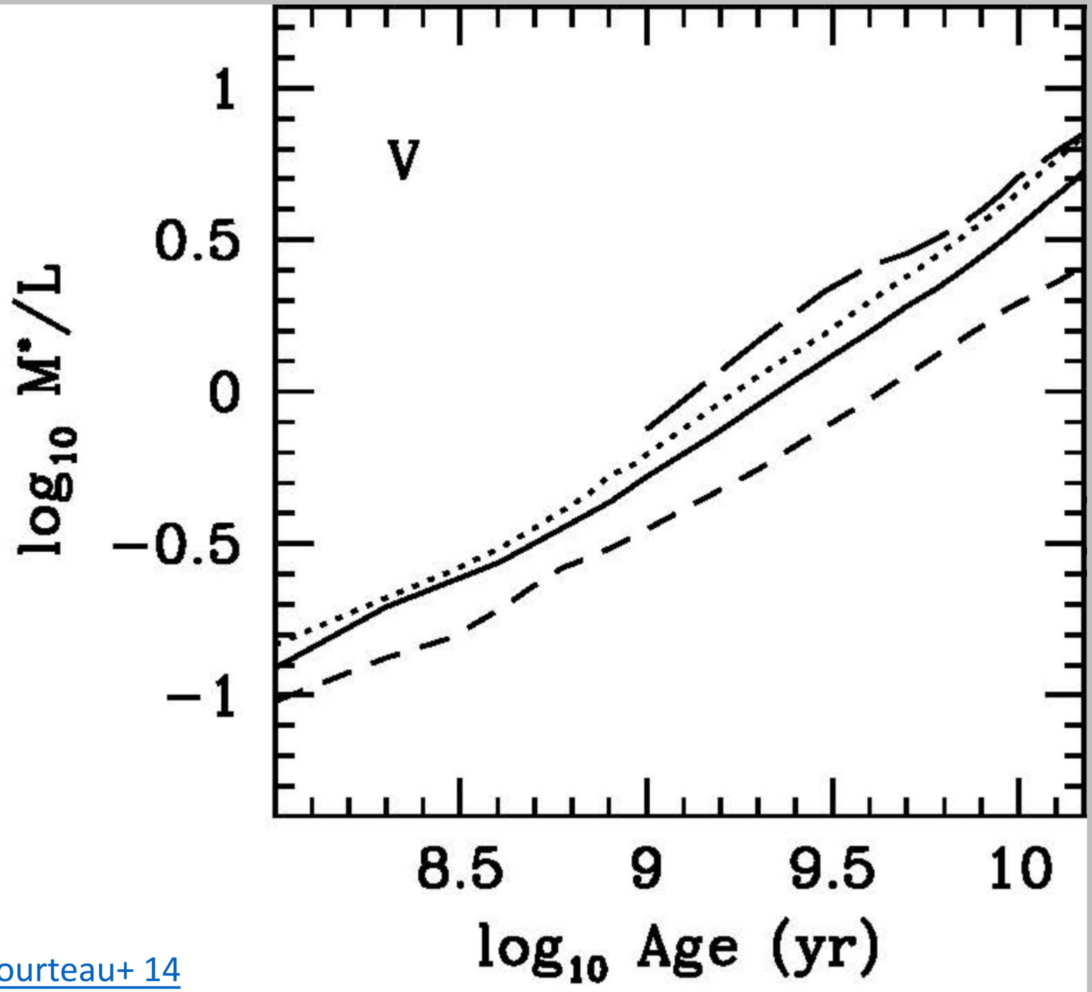
We measure a galaxy's integrated light, but we would like to convert that to a stellar mass. How much stellar mass does it take to get a given amount of light? What is the ratio of mass to light **for stars**?

Star	Mass ($M_\odot$)	Luminosity ($L_{\odot,V}$)	$(M/L)_{*,V}$ (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, $(M/L)_*$ increases as age increases. ⇒

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

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



Courteau+ 14

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:

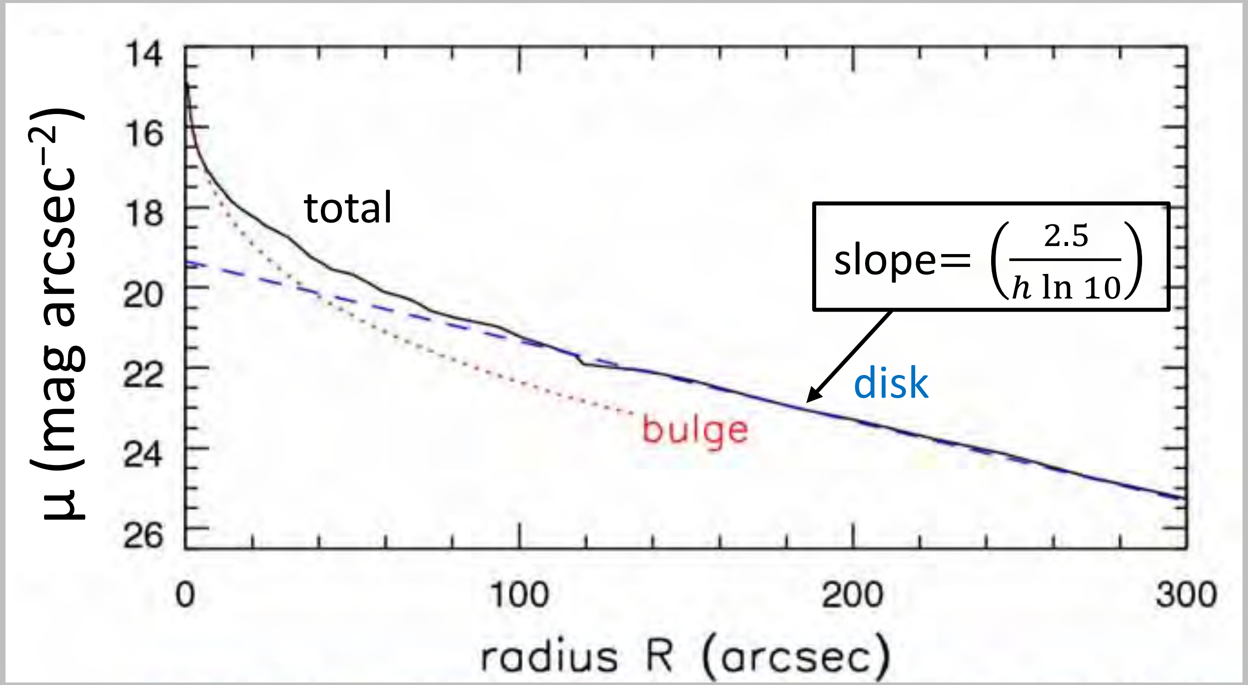
$$\Sigma(R) = \rho_0 e^{-R/h} \int_{-\infty}^{+\infty} e^{-|z|/z_0}\, dz = 2 z_0 \rho_0 e^{-R/h}$$

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:

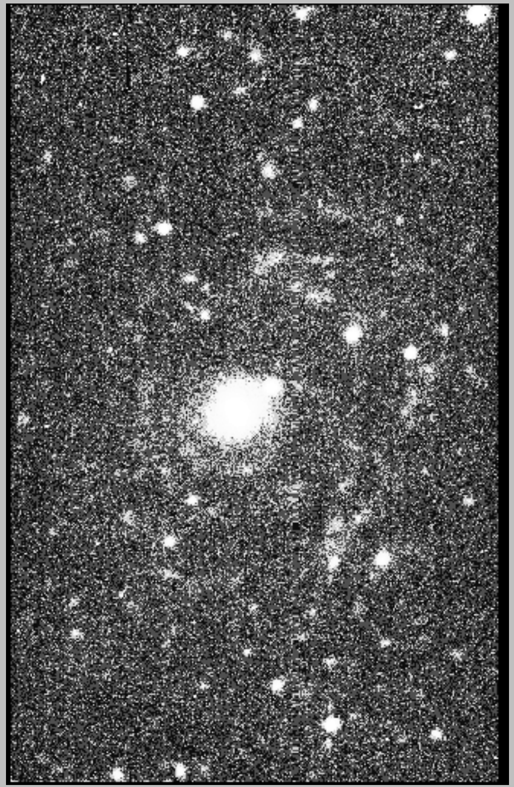
$$\mu_1 - \mu_2 = -2.5 \log\left(\frac{I_1}{I_2}\right)$$

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

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

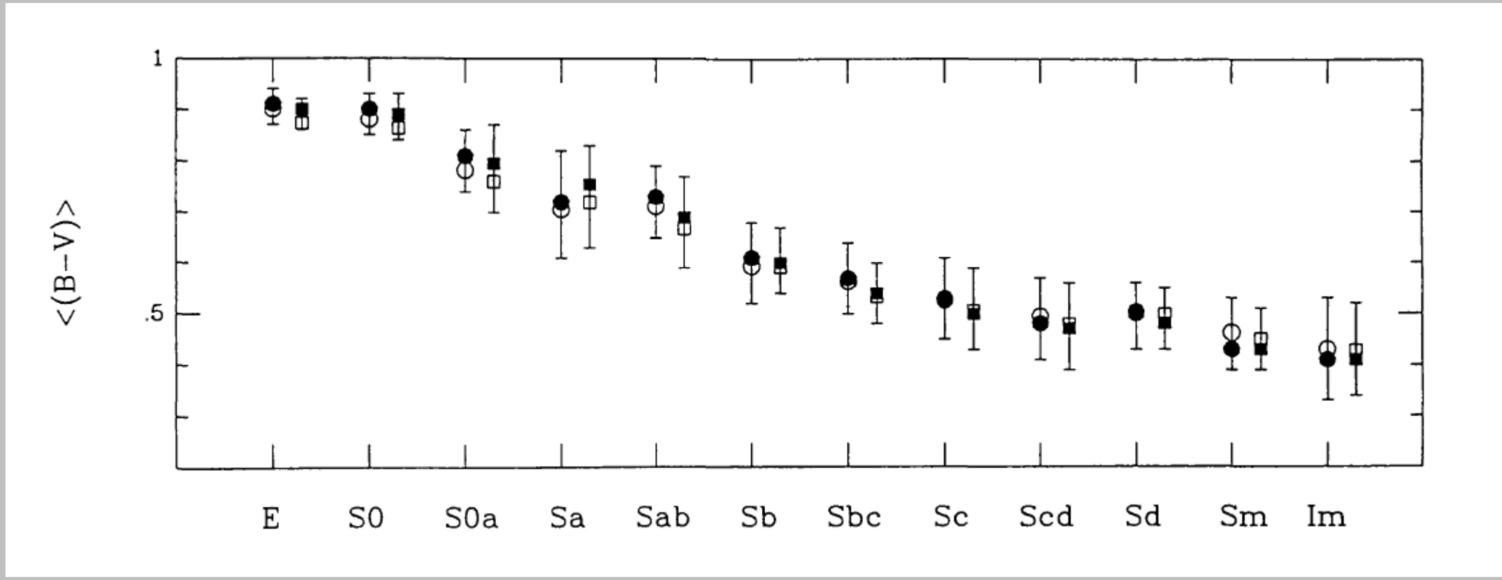
Malin 1 (Low surface brightness galaxy) ⇒

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).



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:

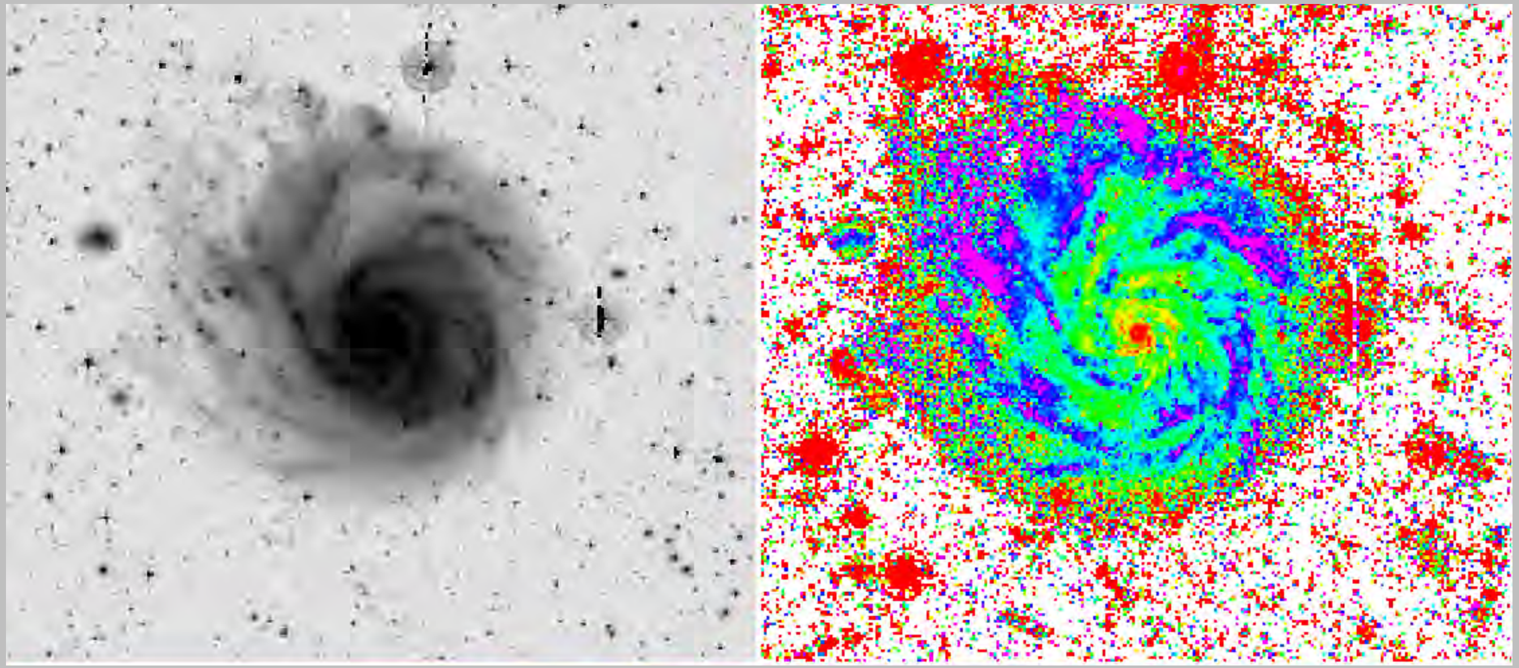
- Gas mass ~ few x 10^9 $M_\odot$
- Star formation rates ~ a few $M_\odot$/yr

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

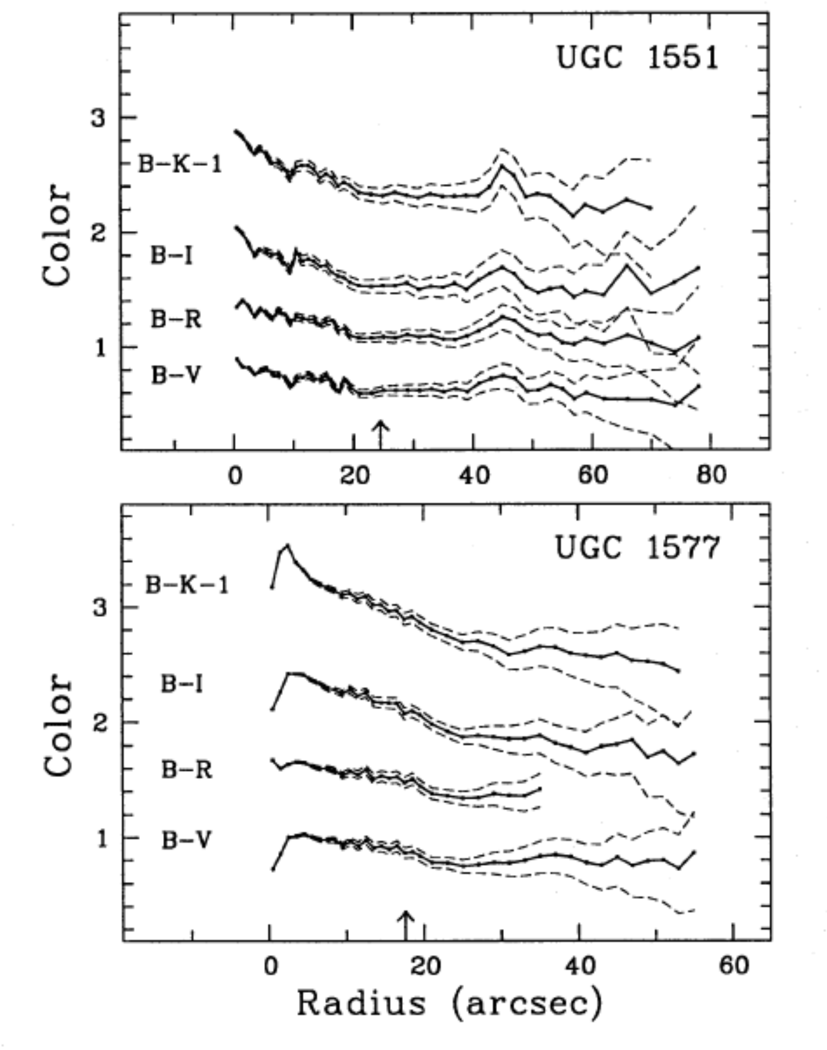
Gas depletion time: $t = M_{gas}/SFR \sim \text{few} \times 10^9$ yr

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

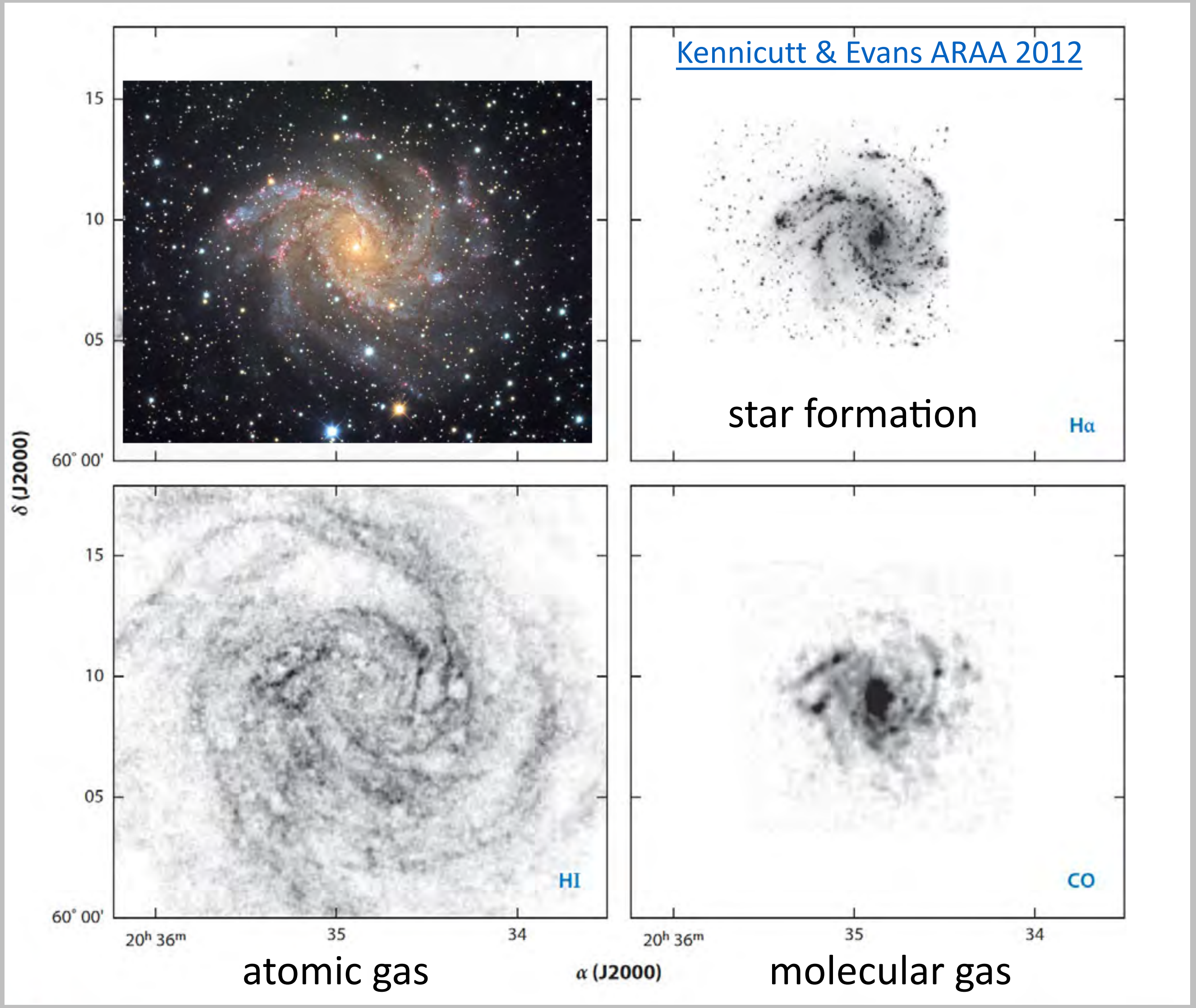


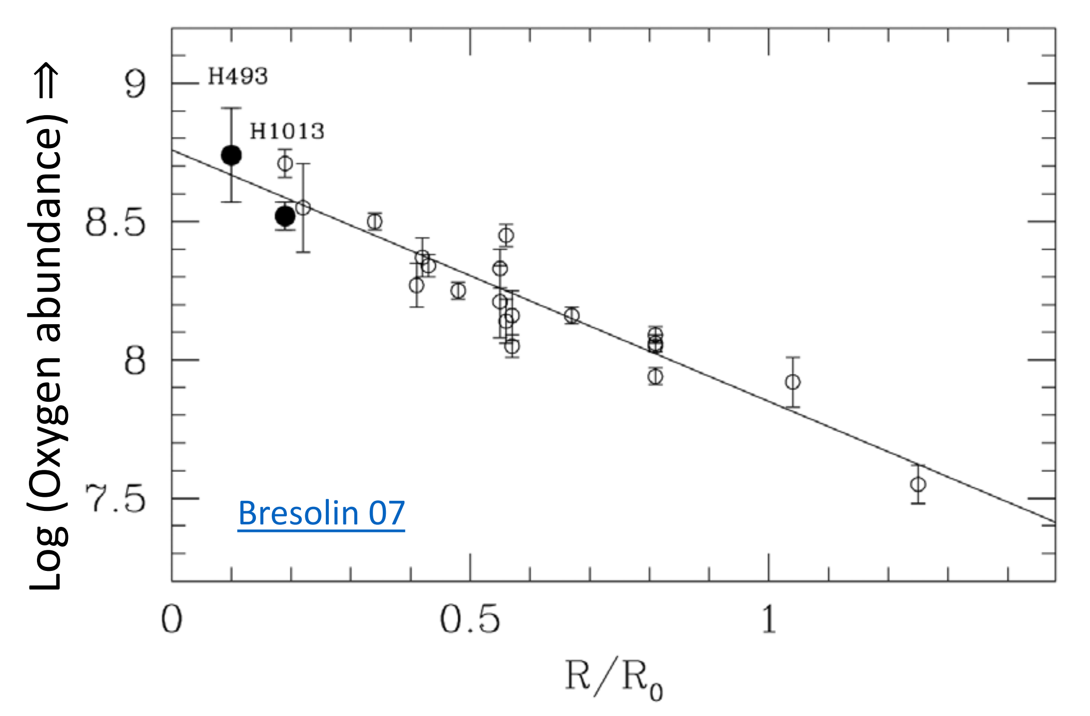
Color gradients in disks
de Jong 1996

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 $M_{gas}/(M_{stars} + M_{gas})$ also goes up as you go outwards. Disk have a lot of extended atomic hydrogen gas. ⇒





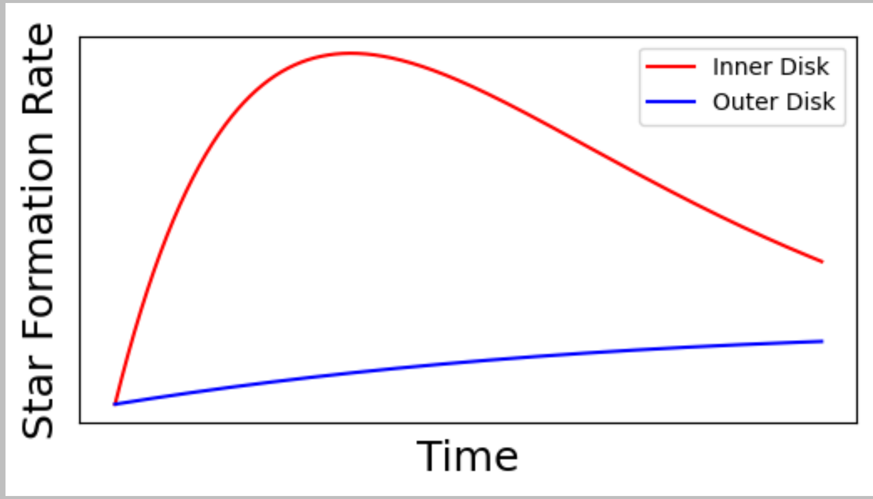
Disks typically show **metallicity gradients** as well. Outskirts have lower metallicity than inner parts.

⇐ M101 metallicity gradient

Disk Galaxies: Inner vs Outer Disk

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

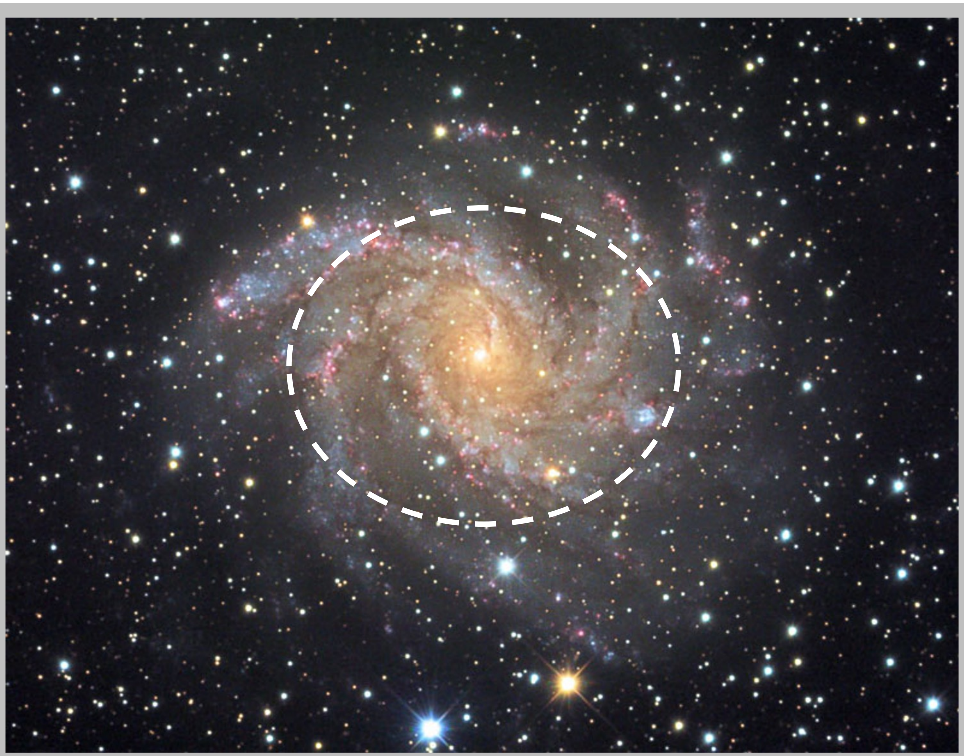
Inside-out galaxy formation: inner regions formed stars earlier and at a faster pace, outer regions form stars later and more gradually. Probably driven by density differences: Things happen faster in denser regions.



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!

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



Rotation Curves of Spiral Galaxies: Systematic Trends

1) More luminous galaxies rotate faster

⇒ "Tully-Fisher Relation"

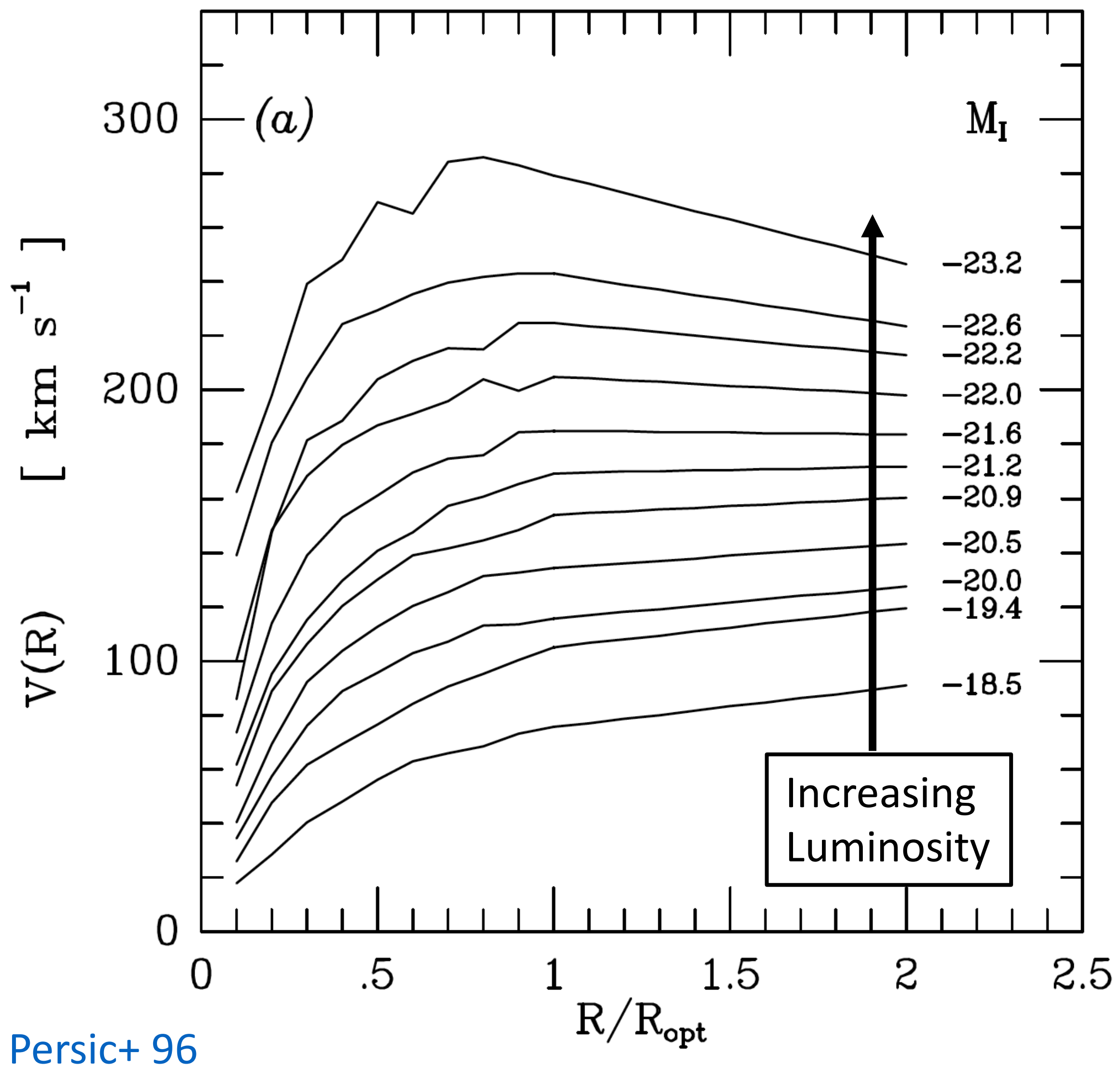
2) Rotation curves are generally flat in their outskirts

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?).



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The Tully-Fisher Relationship

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

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

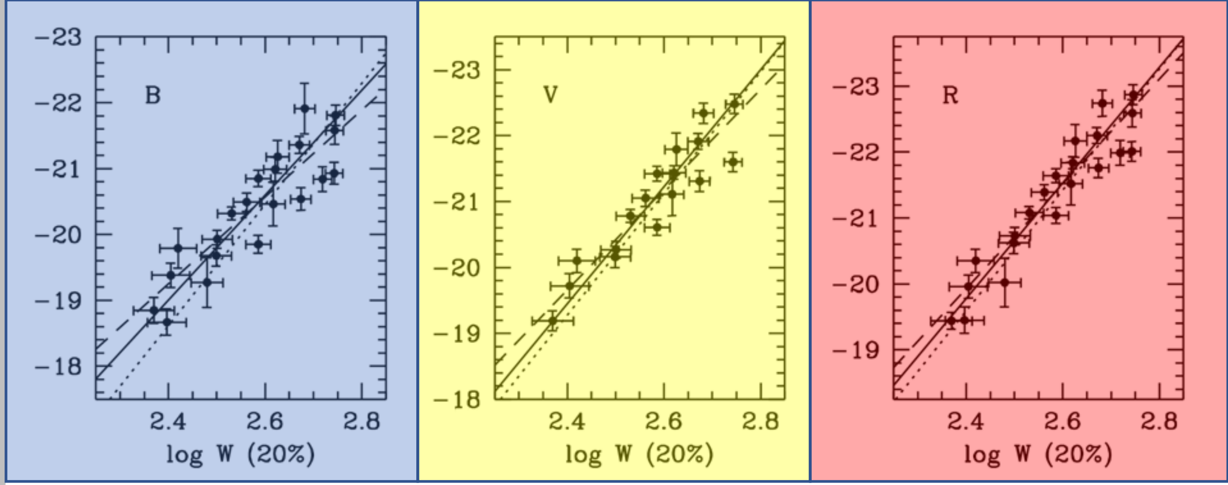
Note: "~" means "scales as" or "is proportional to"

or if we turn this into absolute magnitudes:

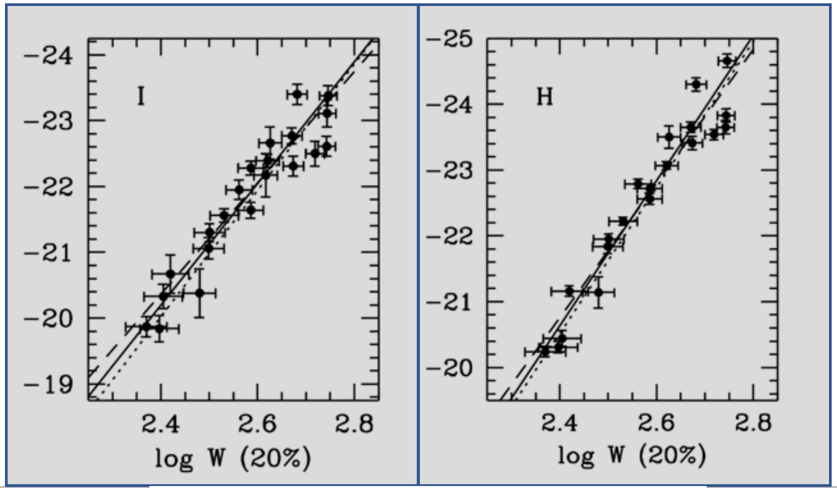
$$\begin{aligned} M &\sim -2.5 \log L \\ &\sim -2.5 \log(V_c{}^{\alpha}) \\ &\sim -2.5\alpha \log(V_c) \end{aligned}$$

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: $V_c^2 = \ G\mathcal{M}_{tot}/R \ \Longrightarrow \mathcal{M}_{tot} \sim RV_c^2$
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: $I = L/(\pi R^2) \ \Longrightarrow \ \ R \sim \sqrt{L/I}$
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 α ≈ 4, but only if $I(\mathcal{M}/L)_{tot}^2 =$ constant.

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

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

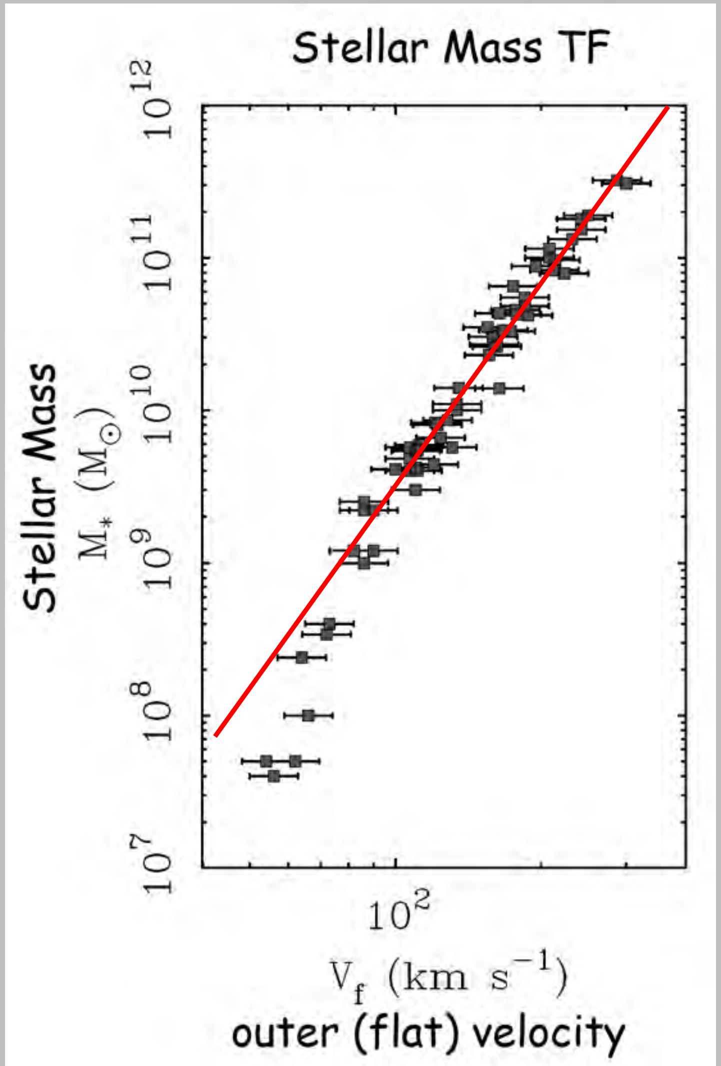
Baryons: normal matter (stars, gas, etc: made from protons, electrons, neutrons)
Dark matter: not baryonic!

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 👉

$$M_* = \left(\frac{M}{L}\right)_* L$$

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



Add in gas mass 👉

$$M_b = M_* + M_{gas}$$

Wow.

slope= 3.94 ± 0.08

scatter consistent with pure observational uncertainties.