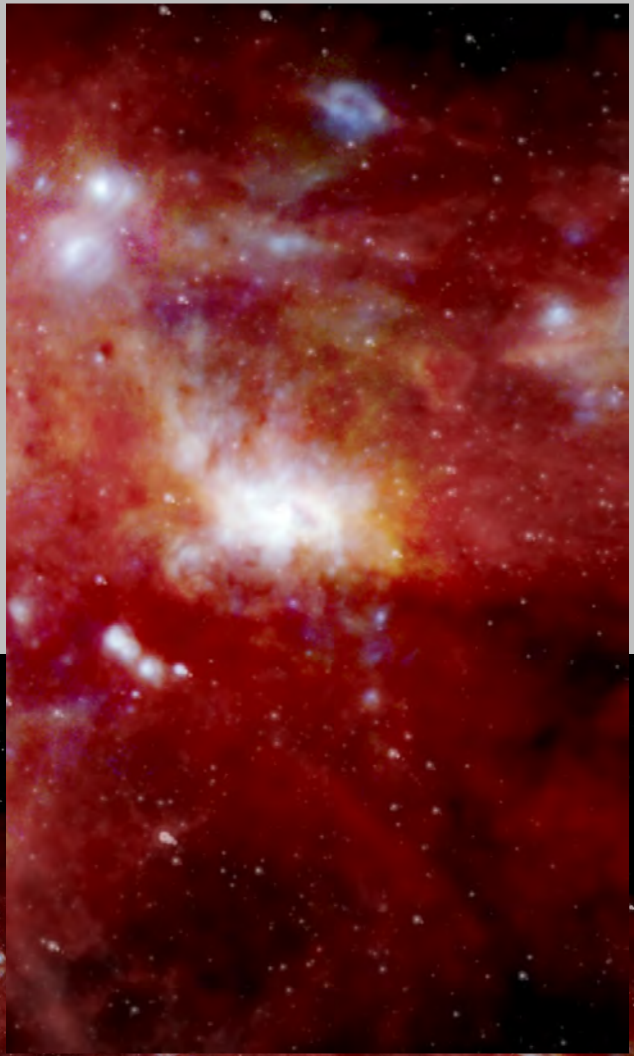
Studying the Galactic Center

Can’t be done optically: 28 magnitudes of dust obscuration

Infrared light

- much less obscured
- old red giants are bright in the near-infrared
- dust emits in the mid infrared

In the inner few parsecs, the density of stars rises as $\sim r^{-2}$: very dense, lots of old stars AND massive young stars (recent star formation), very high energy density.



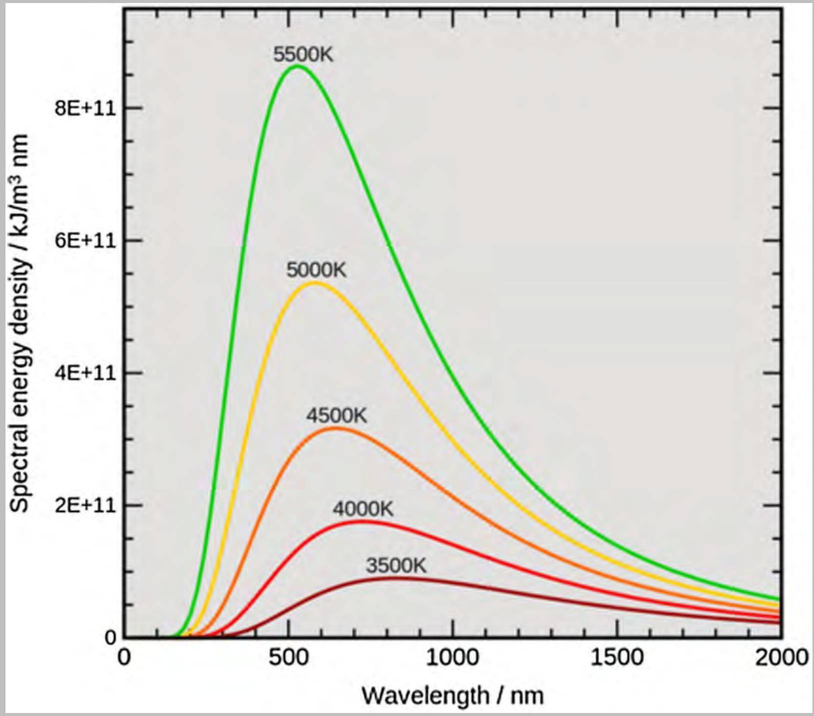
Radio emission

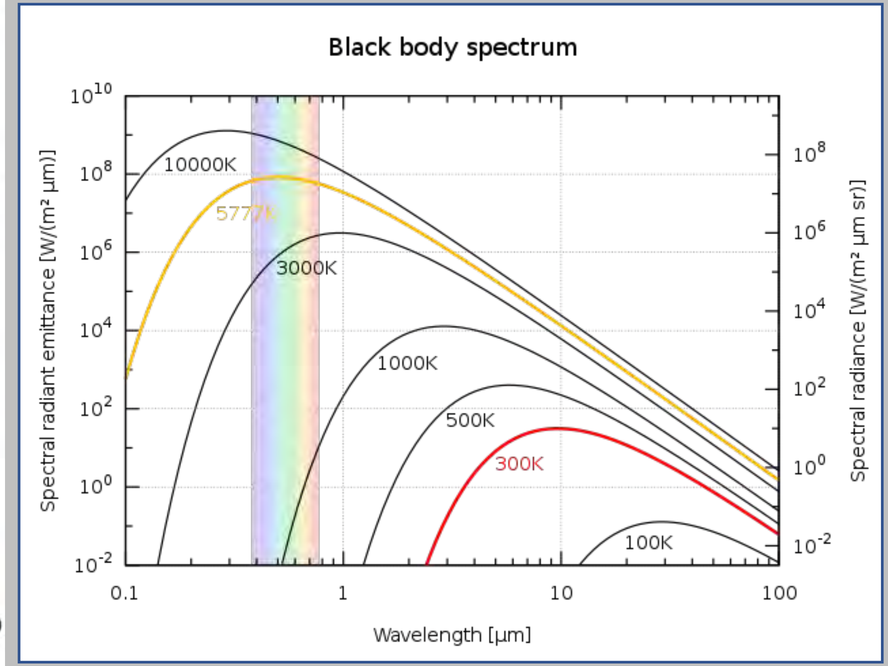
Remember Kirchoff's laws from optical spectra:

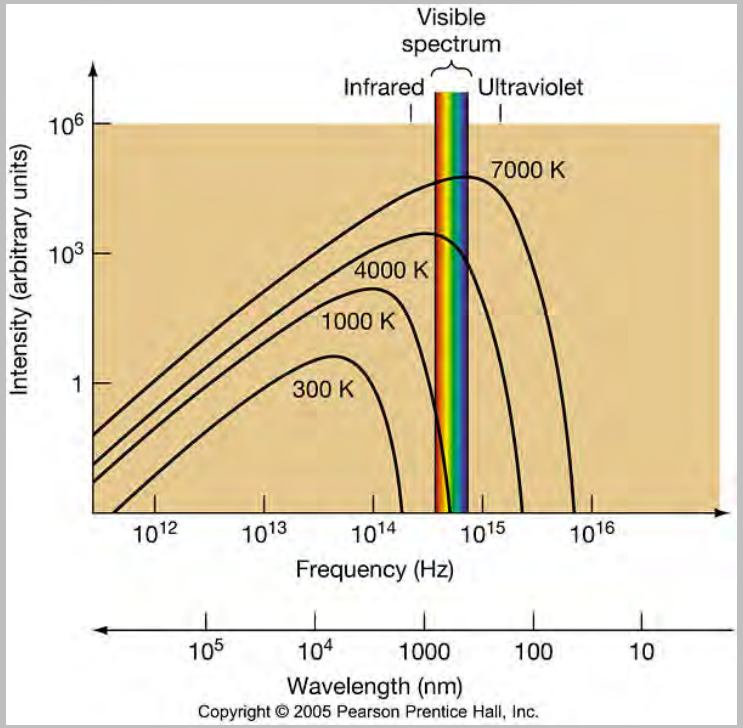
"bound-bound emission"

- Hot dense gas or solid emits **continuous spectrum**: black body
- Low density gas shows an **emission line spectrum** when electrons jump down in energy level
- Low density gas in front of a continuum source shows an **absorption line spectrum** when electrons absorb light and jump up in energy level

Blackbody spectra plotted different ways. At long wavelengths (Rayleigh-Jeans tail), the spectrum is a power law.





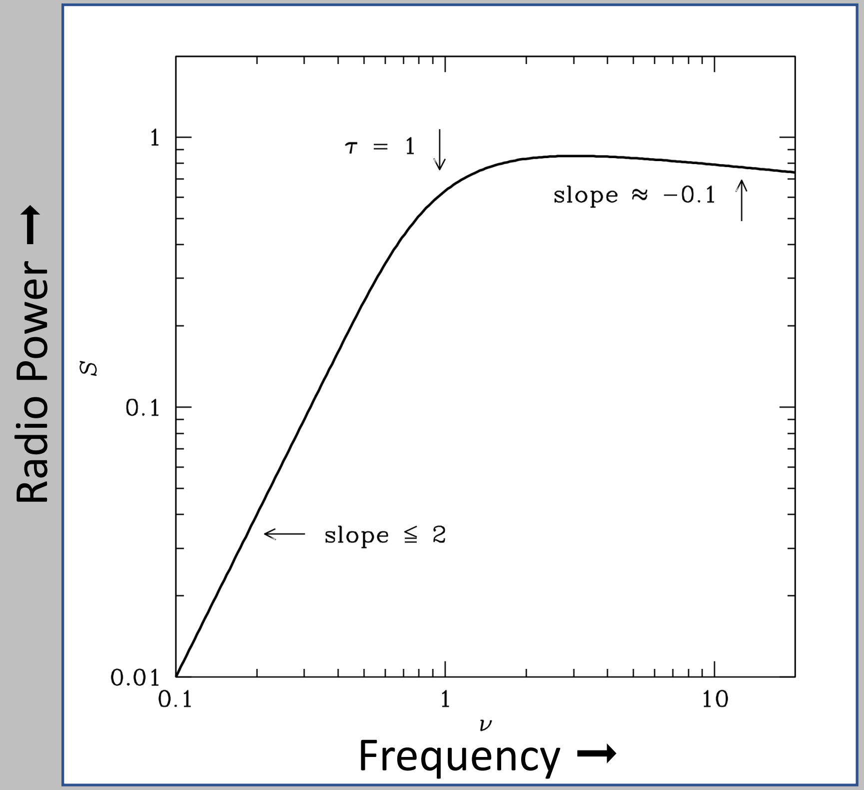


Radio emission

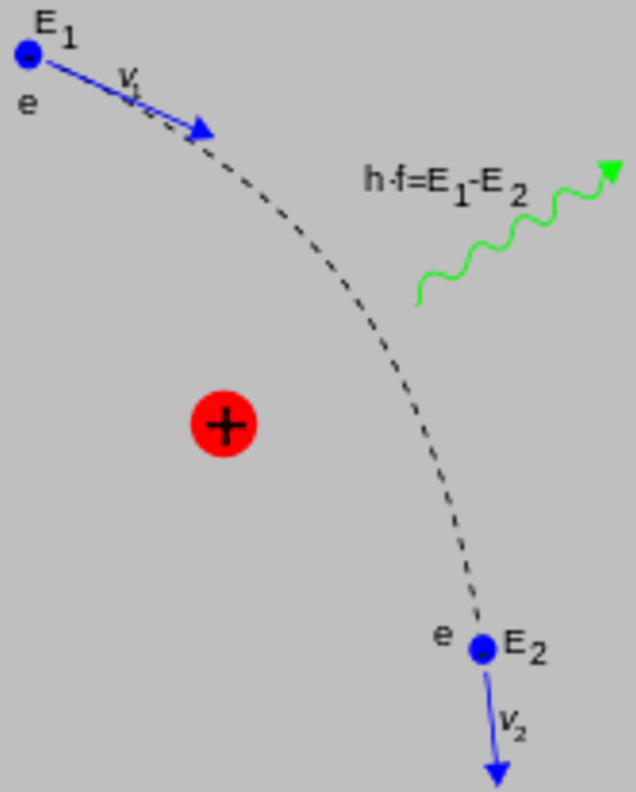
Free-free ("Bremsstrahlung") emission:

Charged particles in ionized gas interact with one another electrostatically, which accelerates them. Accelerated charged particles emit energy (photons). Most important is electrons interacting with ions.

At low frequencies (radio), the emitting gas is opaque and emits like a blackbody, with a power law spectrum: $S \propto \nu^2$



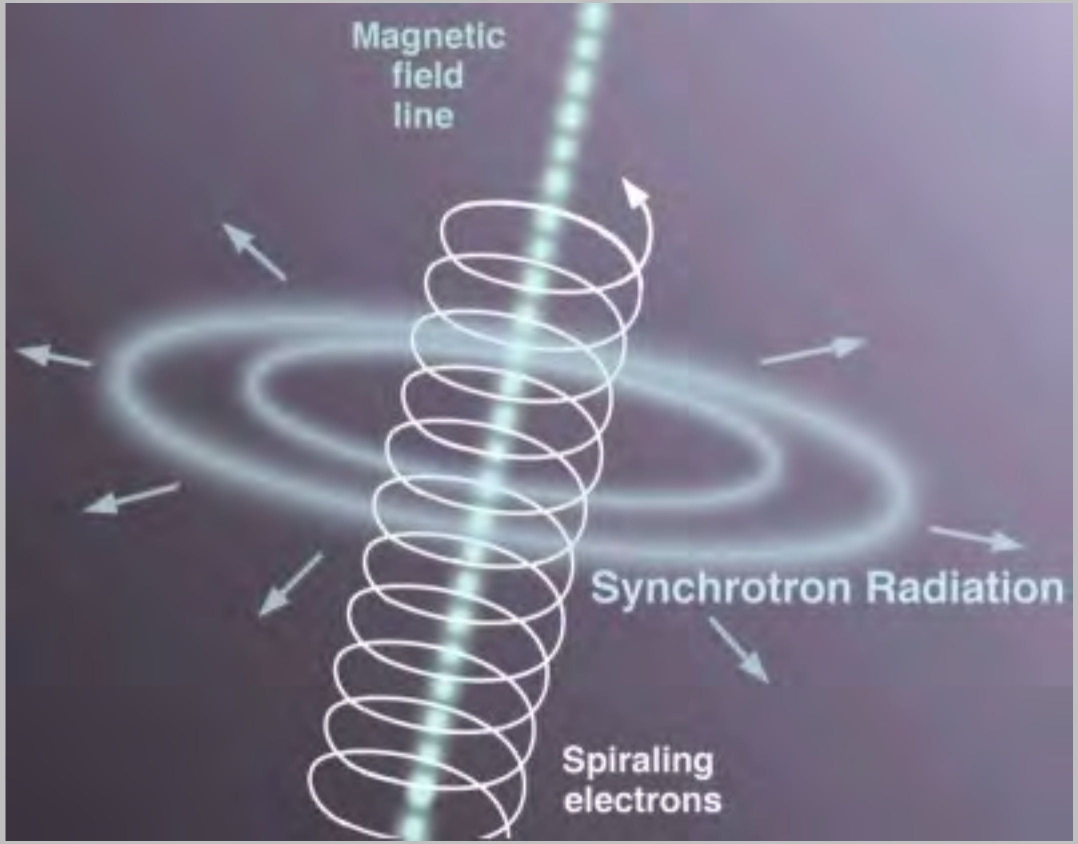
details and figure courtesy Scott Ransom



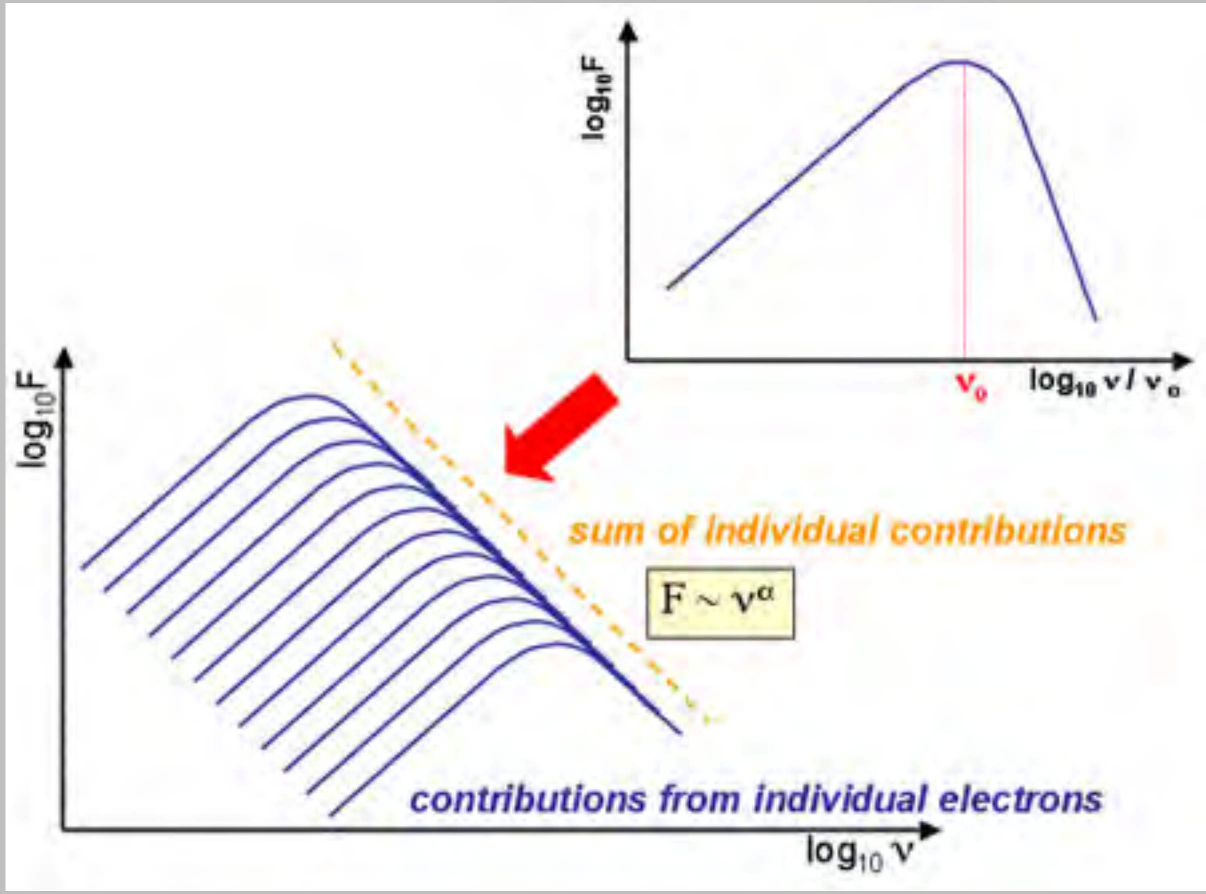
Radio emission

Synchrotron Emission

Relativistic electrons are accelerated by magnetic fields, spiral along magnetic field lines, and emit synchroton radiation.



Spectrum of an individual particle is continuous and peaks at a frequency that corresponds to its kinetic energy.



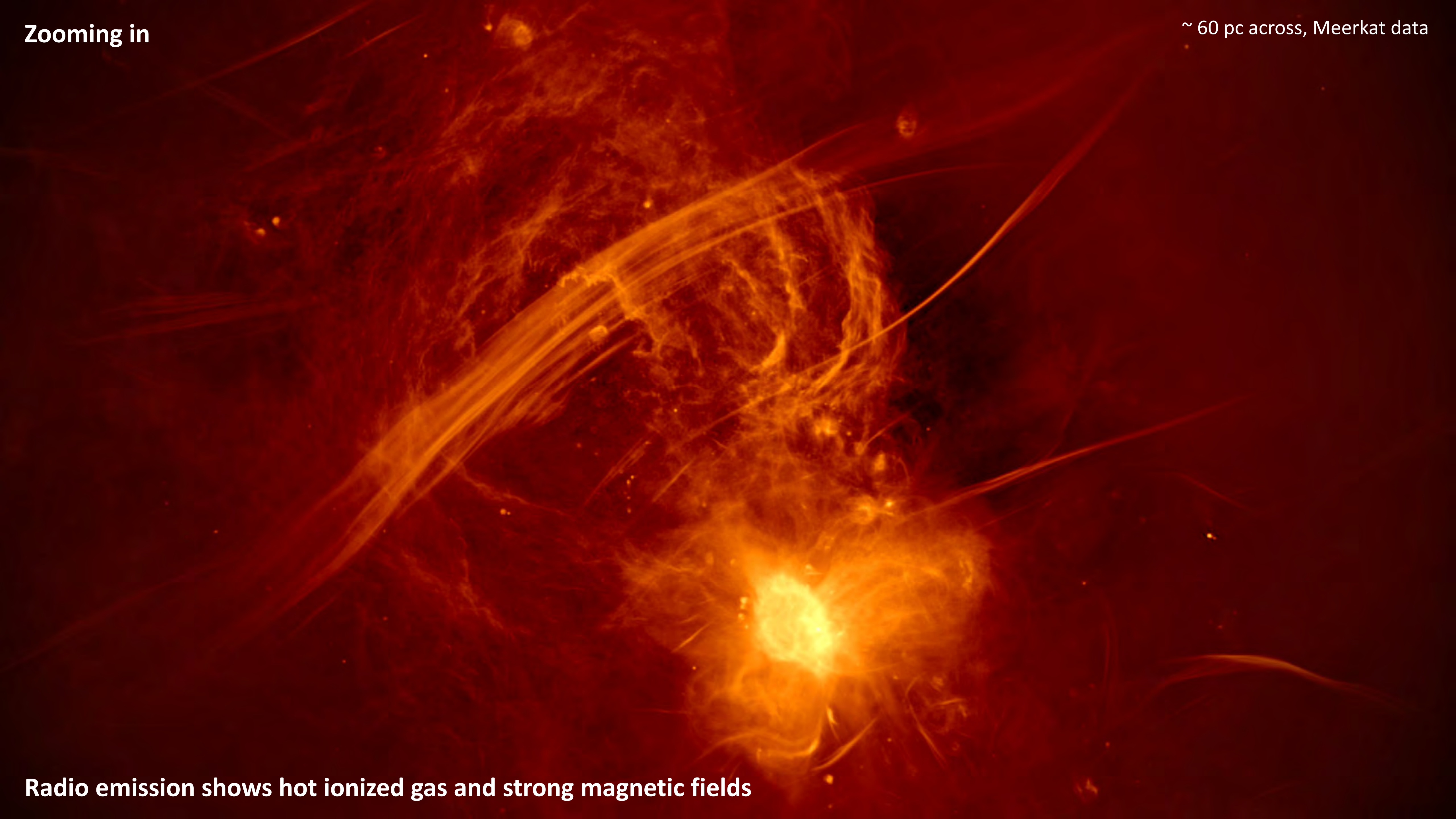
Adding up the spectra from all particles together, gives an overall power law spectrum.

The Galactic Center in Radio Emission

~ few hundred pc across, Meerkat data

- unobscured, not stellar emission
- synchrotron emission: charged particles spiraling in magnetic fields
- free-free emission: charged particles interacting with each other

Zooming in



Radio emission shows hot ionized gas and strong magnetic fields

At the center

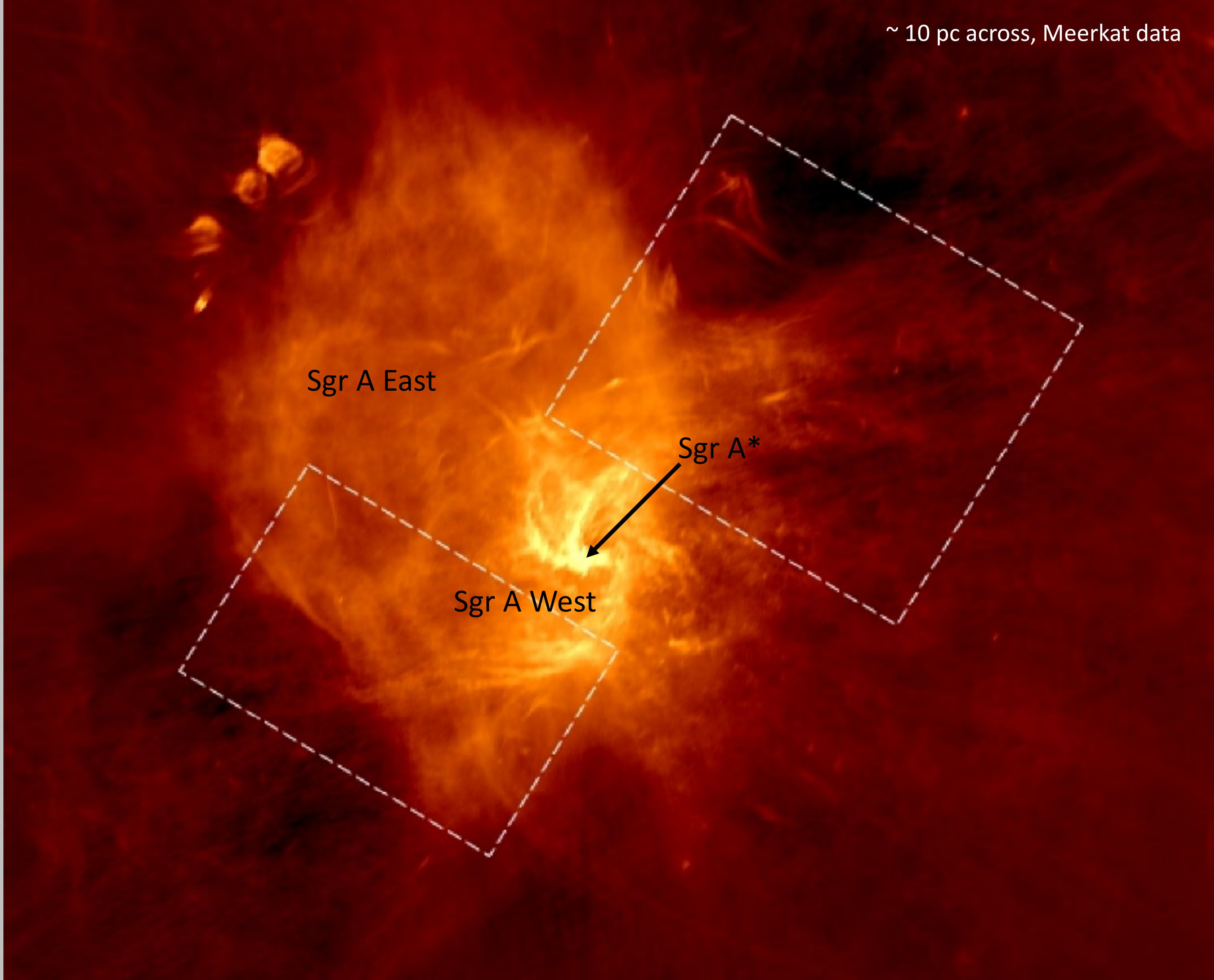
Sgr = Sagittarius

Sgr A East: hot gas, possible supernovae remnant

Sgr A West: ionized gas, spiral shaped.

Sgr A*: bright, very compact radio source at the center.

What's going on??



The central object: Sgr A*

Sgr A* is also an **X-ray source**, with luminosity $L_X \approx 10^5\ L_{\odot}$.

The X-ray luminosity varies on timescales of a few months. This puts a limit on its size, due to **causality**.

Variability is caused by some disturbance in the object, and the fastest any disturbance can travel is the speed of light. So causality says that the size must be less than:

$$R < c\Delta t$$

So the size of the central object must be less than a few light-months, which corresponds to < 0.1 pc.

At **radio wavelengths** Sgr A* is also unresolved down to a few milliarcseconds, meaning it must be smaller than 20 AU.

So that's $10^5\ L_{\odot}$ worth of energy packed into a size comparable to the size of our solar system!

The central object: Stellar kinematics

Look at the velocity dispersion of stars in the inner few parsecs.

What would we expect to see? Balance kinetic energy of motion (σ_v^2) with gravitational potential:

$$\sigma_v^2 \propto \frac{GM(r)}{r}$$

The mass should just be density times volume, so:

$$\sigma_v^2 \propto \frac{G\rho(r)}{r}\frac{4\pi r^3}{3}$$

We said earlier that the density of stars rises towards the center: $\rho(r) \propto r^{-2}$, so

$$\sigma_v^2 \propto \frac{Gr^{-2}}{r}\frac{4\pi r^3}{3}$$

The r terms all cancel, so **the velocity dispersion should be constant with r** – it should not change as we near the galactic center.

What we actually see!

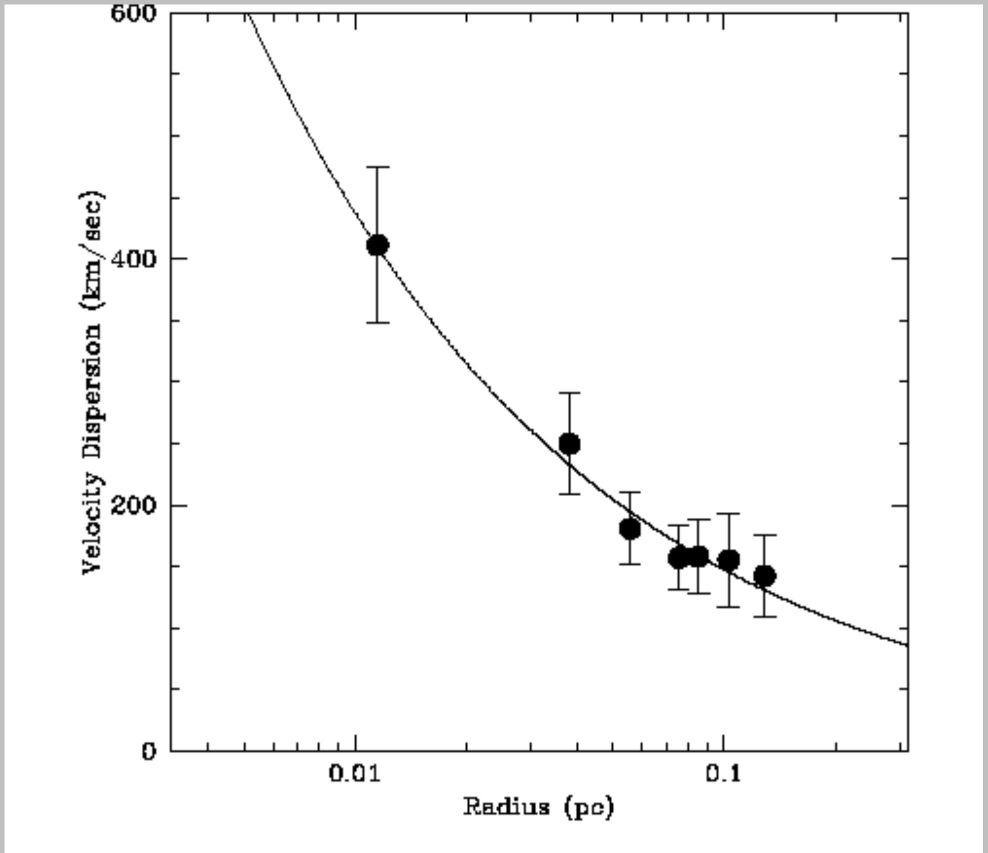


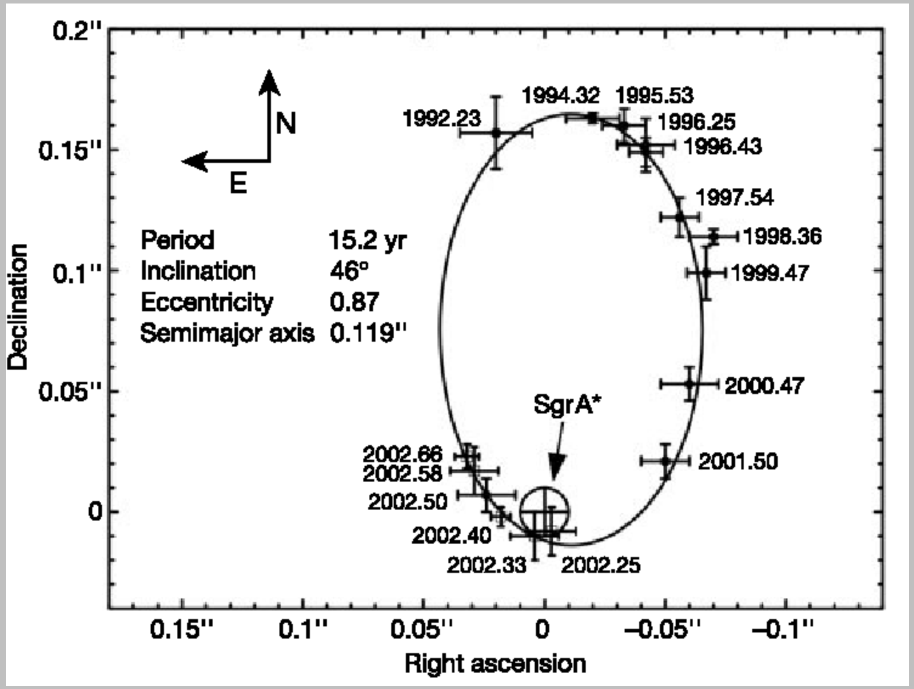
FIG. 5.—Projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies the gravitational field is dominated by mass within 0.1 pc.

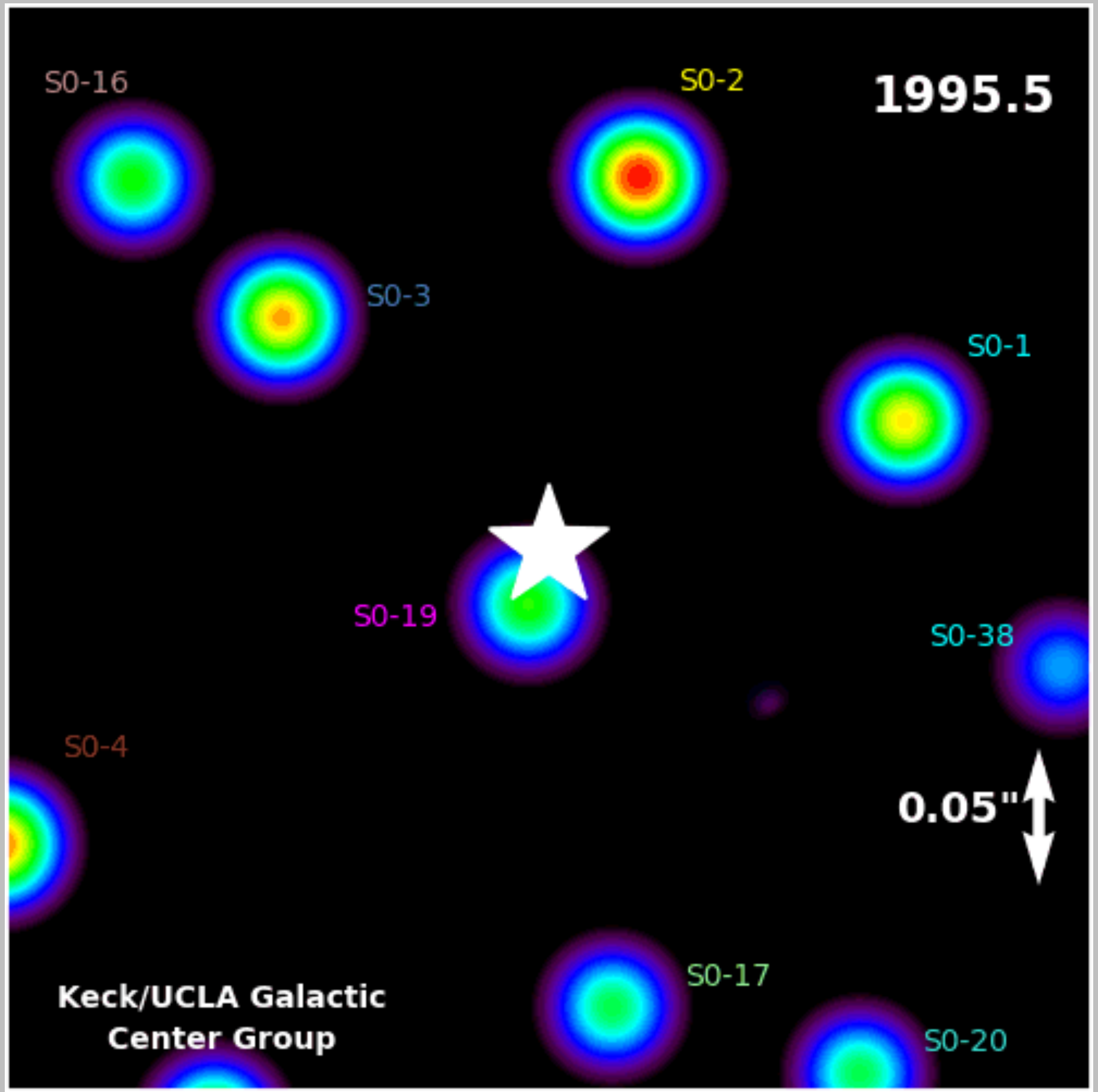
The kinematics are dominated by a massive object at the center no larger than 0.1 parsecs in size.

The central object: Stellar orbits

Using infrared data, we can follow the motion of individual stars passing within a hundred AU of Sgr A*. The orbits are Keplerian!

Use the orbits to derive a mass for Sgr A* of $\approx 4{\times}10^6\,M_\odot$



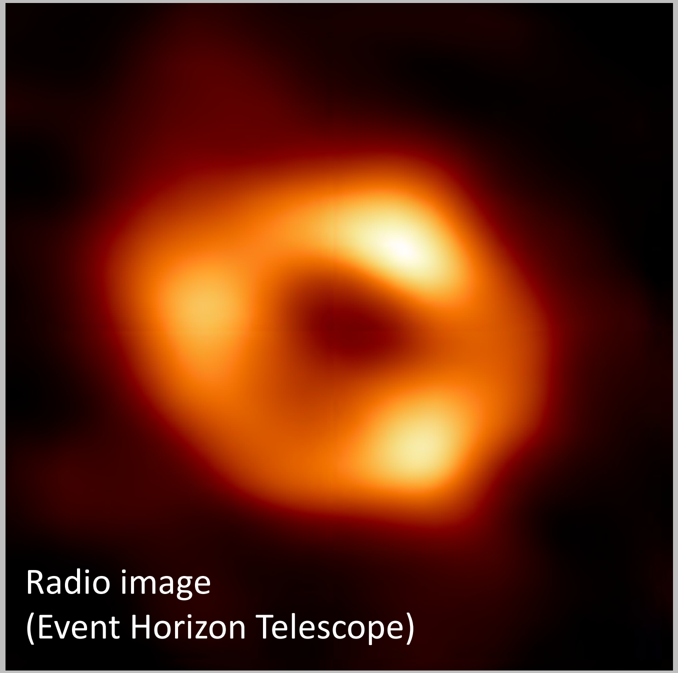


The Milky Way's supermassive black hole

At the heart of Sgr A* is a $\approx 4\times10^6\, M_\odot$ supermassive black hole.

Surrounding the black hole is an accretion disk of infalling hot gas which emits the X-rays.

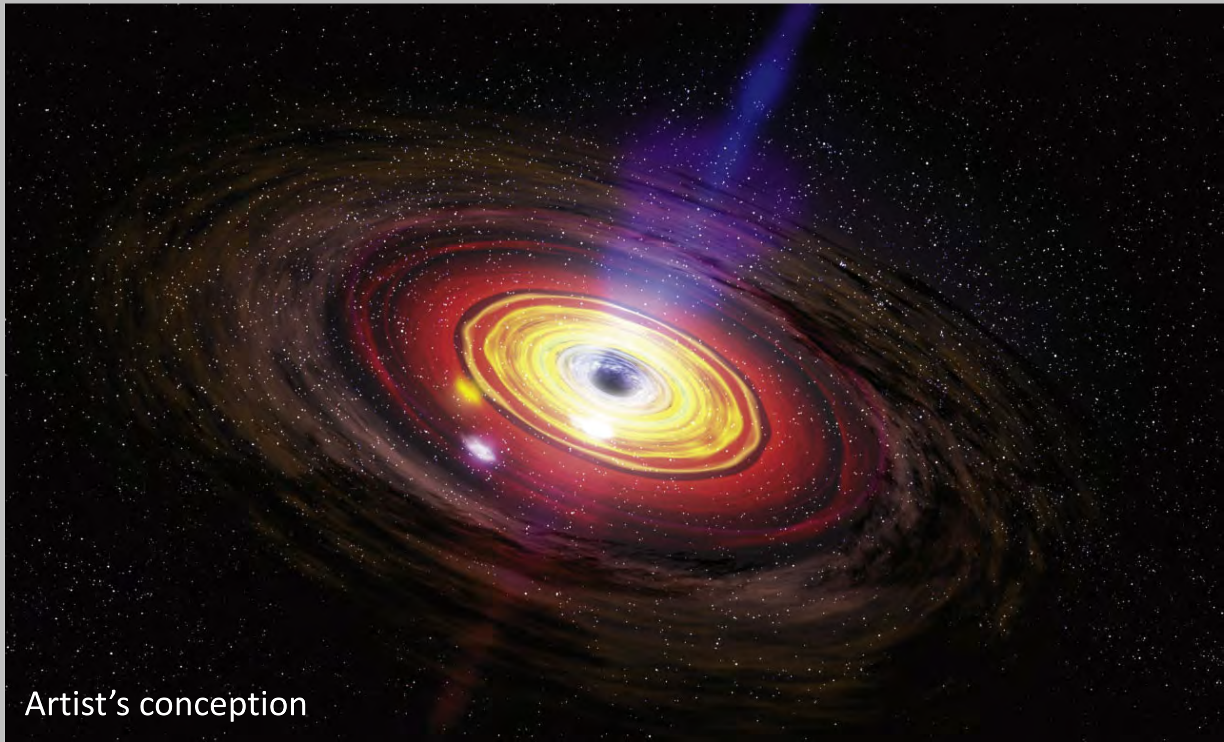
The energy ionizes the surrounding gas, creating the radio emission.



Radio image
(Event Horizon Telescope)

Outstanding Questions:

- *How did it form? How did it grow?*
- *How has it affected the galactic center?*
- *It's fairly quiet now, but what happens when it feeds?*
- *Is there one of these at the center of every galaxy?*



Artist's conception

The Milky Way's Environment: Satellite Galaxies

The Milky Way is orbited by a host of small satellite galaxies at a distances of 10-100 kpc.

Brightest two are the **Large and Small Magellanic Clouds**, two gas-rich irregular dwarf galaxies.

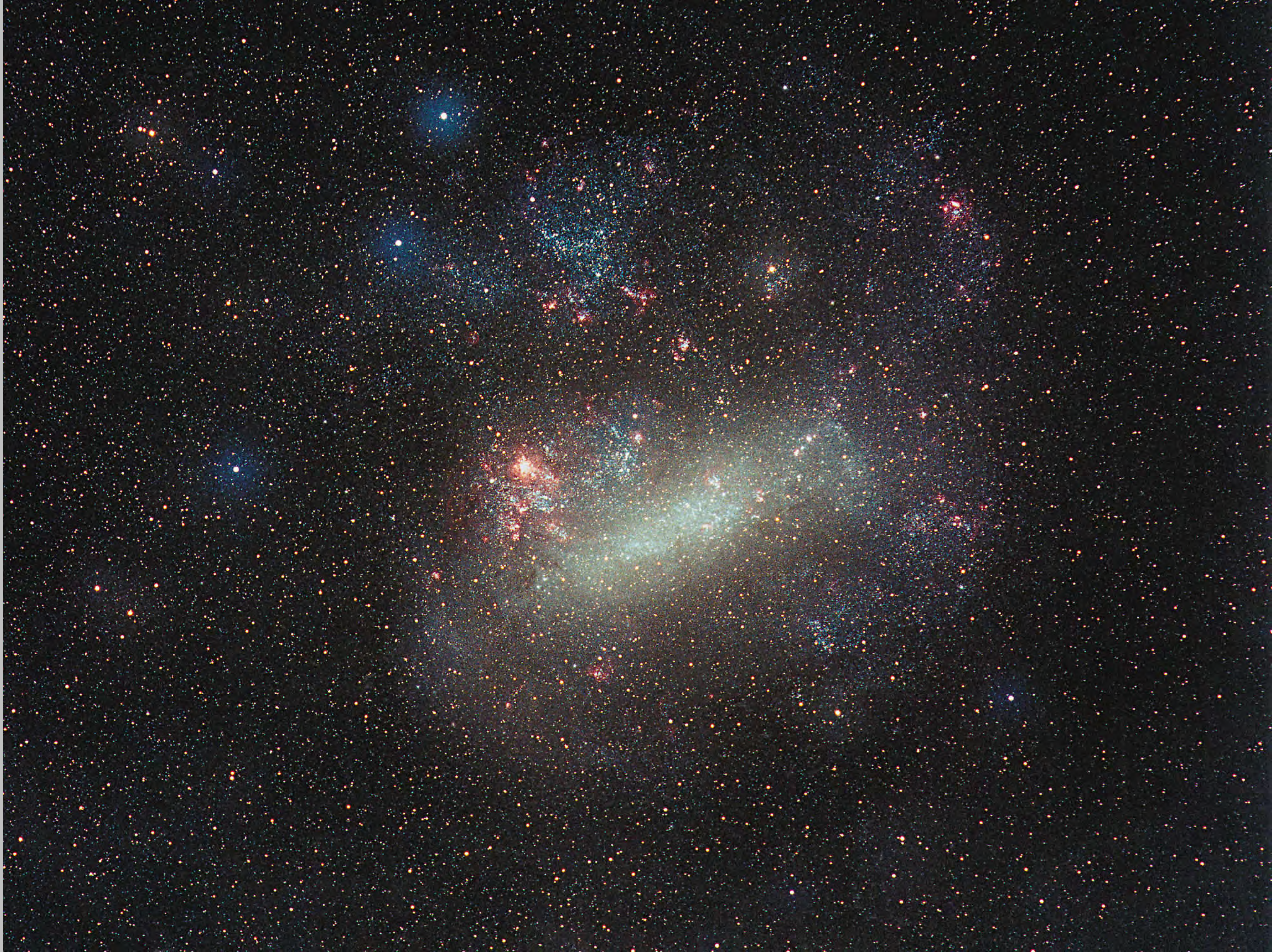
LMC and SMC are visible as naked eye objects in the southern hemisphere.

Large Magellanic Cloud (LMC)

distance ≈ 50 kpc

diameter ≈ 15 kpc

mass $\approx 2 - 3 \times 10^{10}\ M_{\odot}$
(few % of MW mass)



Small Magellanic Cloud (SMC)

distance ≈ 60 kpc

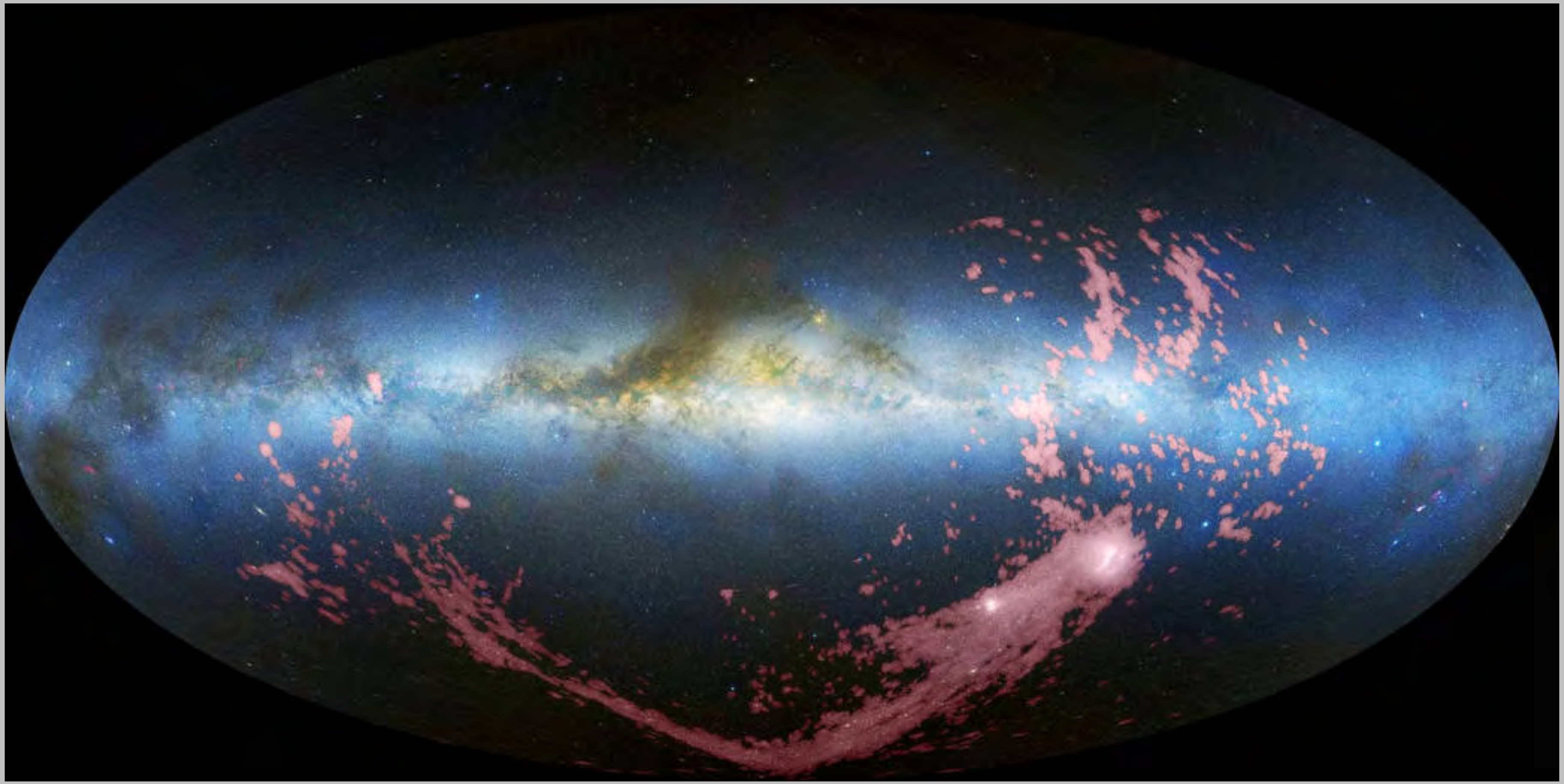
diameter ≈ 5 kpc

mass ≈ $3 - 5 \times 10^9\ M_\odot$
(< 1% of MW mass)

The Magellanic Clouds

The Clouds orbit each other as they orbit the Milky Way. The combined interaction has pulled a long stream of neutral hydrogen (HI) gas out of the galaxies and spread it across the sky: **The Magellanic Stream**. (HI overlaid in pink, below)

Dynamics of the system suggest the clouds orbit the MW with semimajor axis a ≈ 125 kpc and T ≈ few billion years, *but these numbers are very uncertain.*



Dwarf Spheroidal Galaxies (dSph)

low mass: $10^6 - 10^8\ M_\odot$

small ($\leq$ kpc)

low density

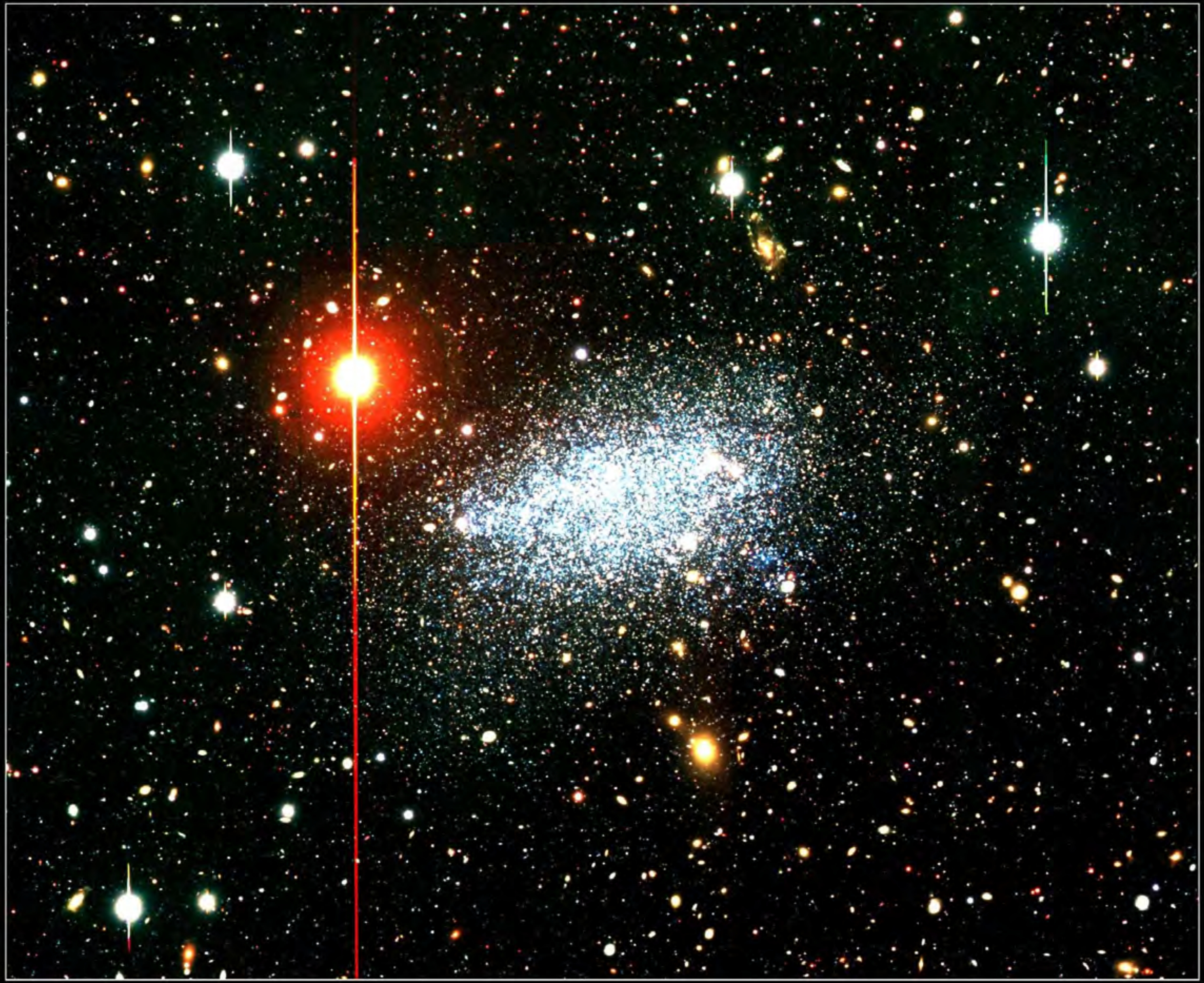
gas poor, no ongoing star formation

Leo I dSph

Dwarf Irregular Galaxies (dIrr)

Similarly low in mass and size to dSph galaxies, but brighter, and gas-rich with active star formation.

The brightest ones are the LMC and SMC, but there are more faint ones.



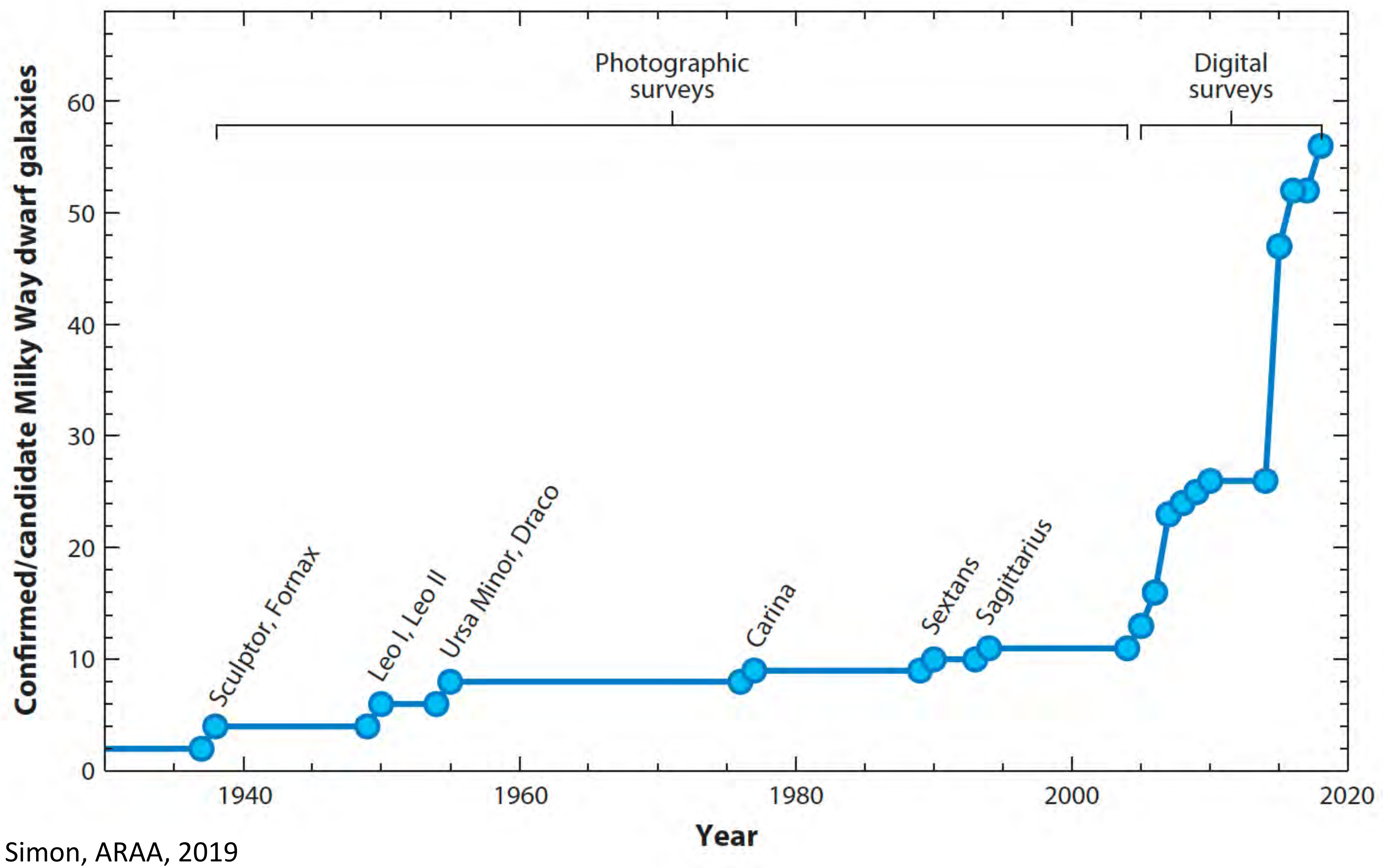
Dwarf Irregular Galaxy Leo A

Suprime-Cam (B, R, z')
August 5, 2004

Subaru Telescope, National Astronomical Observatory of Japan

Ultrafaint Dwarfs

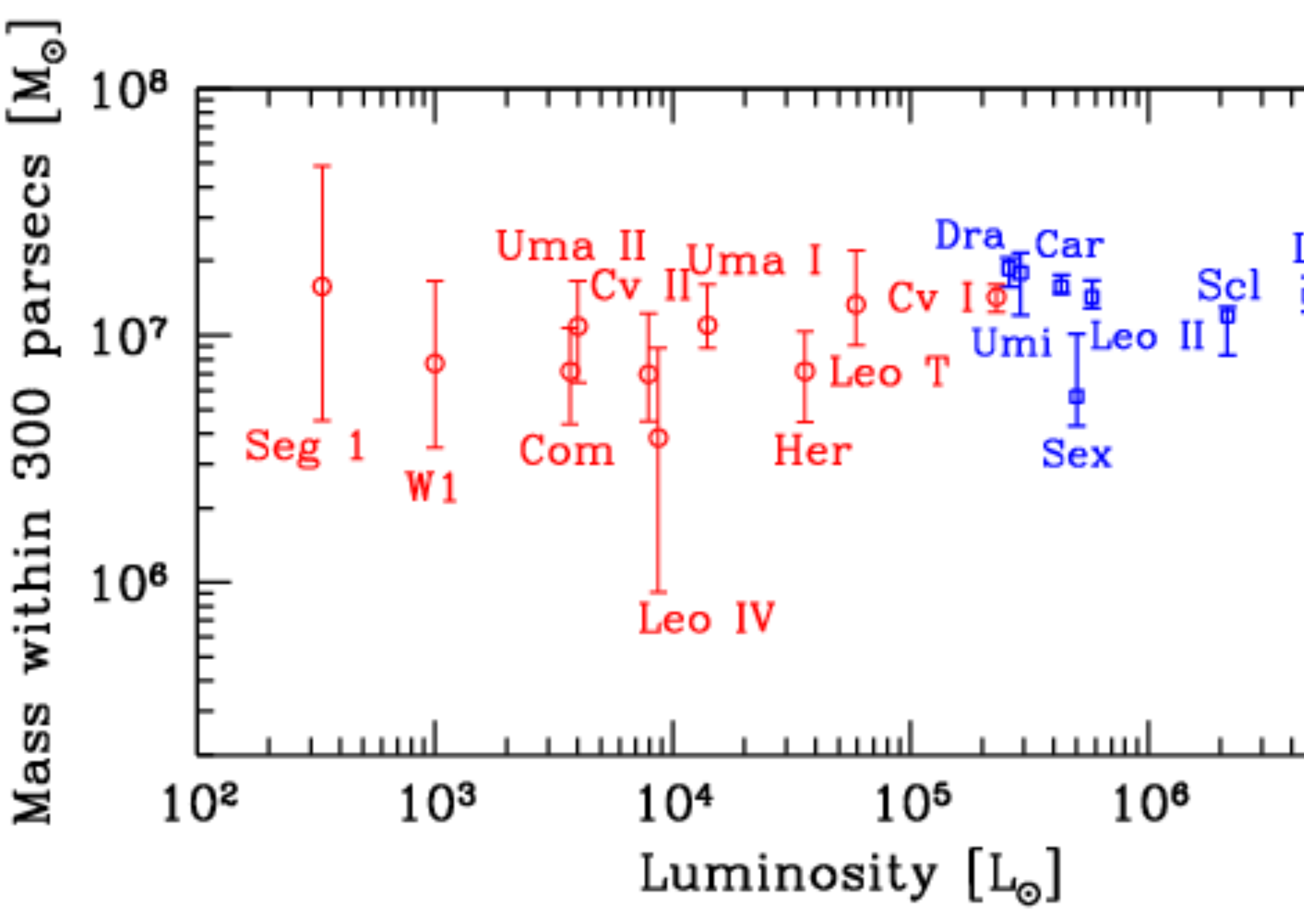
New deep imaging surveys are finding lots and lots of dwarf galaxies orbiting in the Milky Way's halo:



Simon, ARAA, 2019

Ultrafaint Dwarfs

These new galaxies are extremely low in luminosity ("ultrafaint"), but still show evidence for dark matter halos.



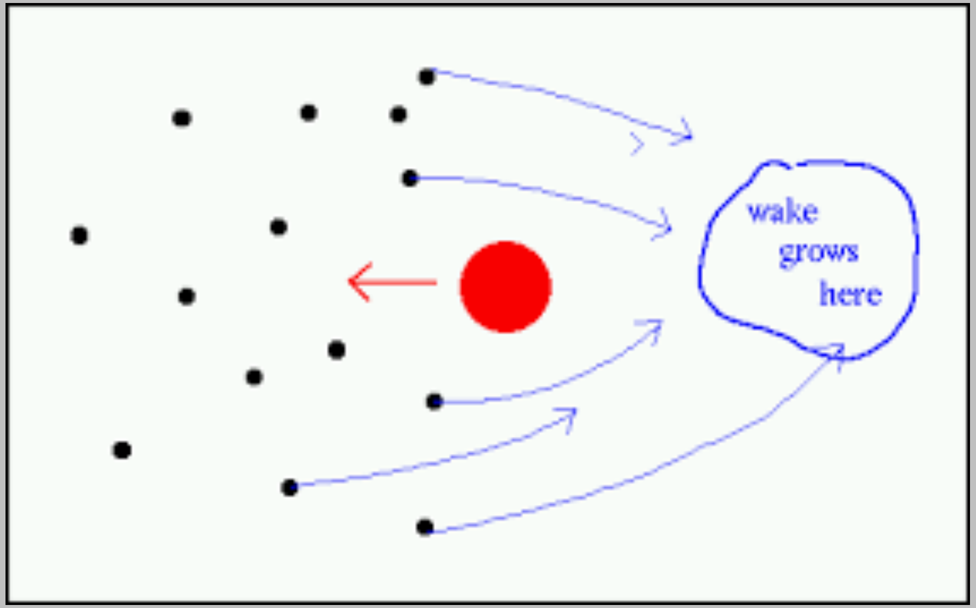
Bullock 2010

Dwarf Galaxies: Orbits, infall, and destruction

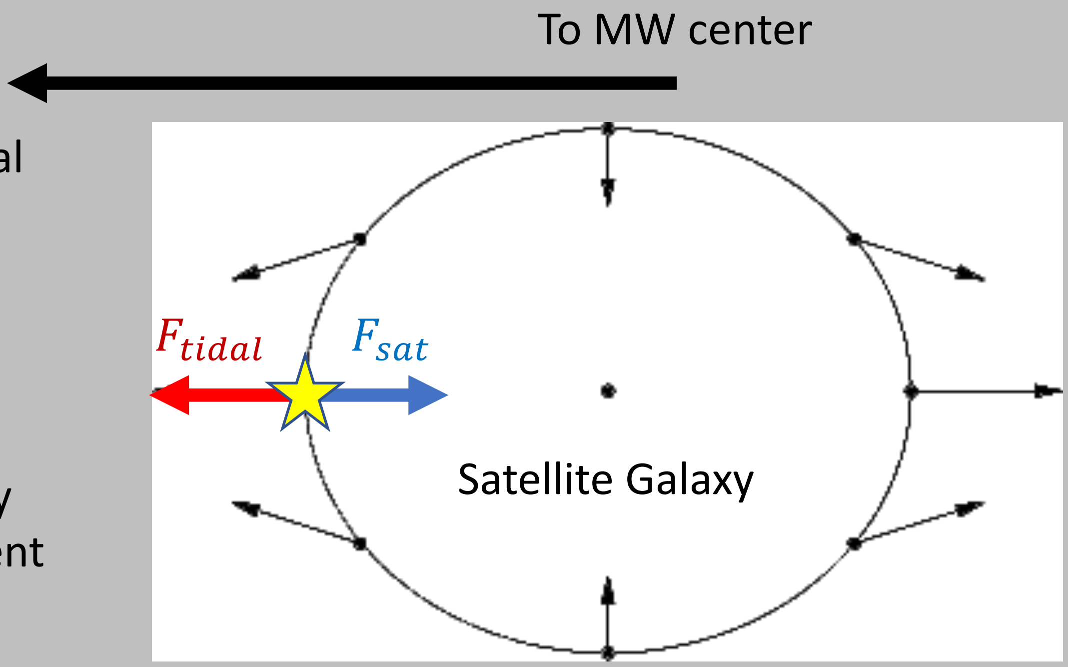
Imagine a massive object moving through a sea of low mass particles. As it moves through, it gravitational pull deflects the low mass particles into an overdense "wake" behind it.

This wake has mass and pulls backwards on the object, slowing its motion: **dynamical friction**.

This causes satellite galaxy orbits to decay with time, and the satellite slowly spirals inwards. The effect is stronger for massive satellites, and for satellites close to the Milky Way.



Dwarf Galaxies: Orbits, infall, and destruction



Imagine a star in the outskirts of a satellite galaxy. It feels a gravitational force holding it in its orbit around the satellite:

$$F_{sat} = \frac{GM_{sat}}{r^2}$$

But it also feels the tidal force from the Milky Way trying to pull it away from the satellite. Remember that the effective tidal force is the gradient of the Milky Way's gravitational force across the body of the satellite.

$$F_{tidal} = \left(\frac{\partial F_{MW}}{\partial R_{MW}}\right) r$$

$$= \frac{2GM_{MW}(< R_{MW})}{R_{MW}^3} r$$

If $F_{tidal} > F_{sat}$, the star will be stripped from the satellite and lost. This happpens at a critical tidal radius for the satellite given by:

$$r_{tidal} > R_{MW} \left(\frac{M_{sat}}{2M_{MW}(< R_{MW})}\right)^{1/3}$$

Stars outside this tidal radius will be stripped from the satellite.

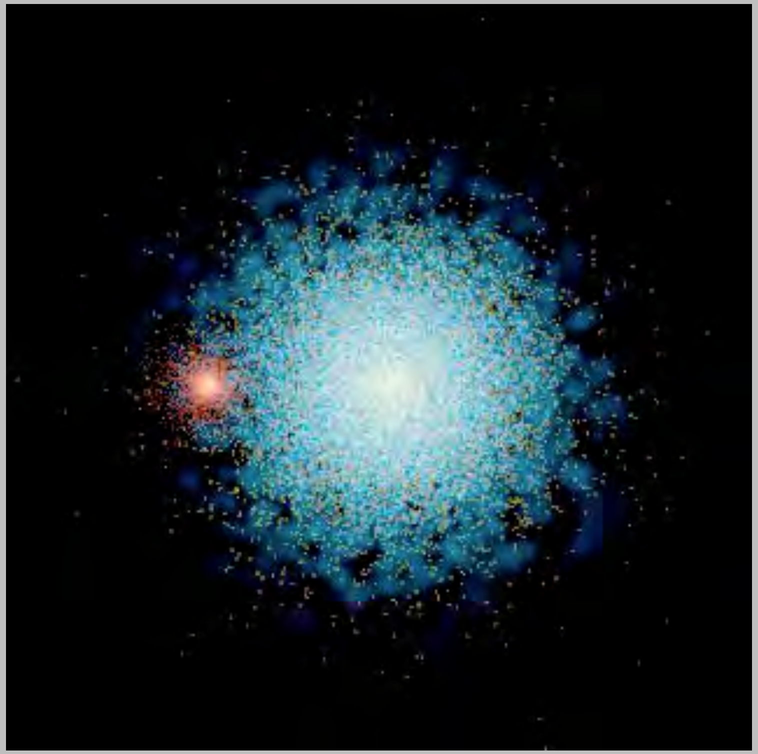
For the LMC, $r_{tidal} \approx 10$ kpc.

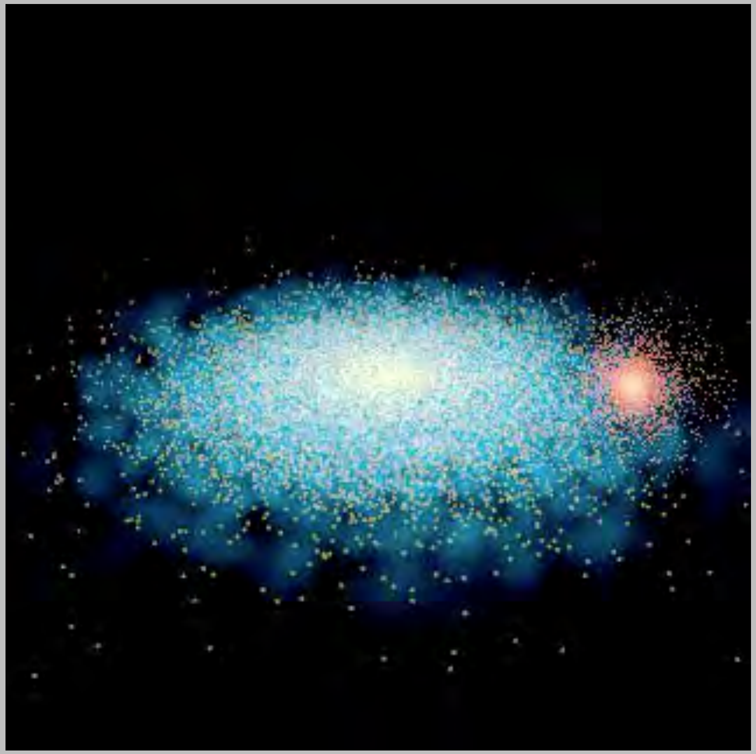
For smaller satellites, $r_{tidal} < 2$ kpc.

As stars are stripped, satellite loses mass. Satellite also moves inwards due to dynamical friction. Stripping gets stronger....

Dwarf Galaxies: Orbits, infall, and destruction

Putting it all together, its a race between dynamical friction and tidal stripping:





Massive and dense satellites can survive being completely stripped and will sink to the center.
Low mass, low density satellites have long sinking times and will be tidally disrupted in the halo.