Australian National University

ASTR2013 – *Foundations of Astrophysics*

Week 8: Structure and Dynamics of the Milky Way

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Jean's Mass

- Assume there is a cloud of ideal, non-relativistic gas of uniform temperature and density.
- The *Jean's Mass* is the mass as a function of radius (or density) that is unstable to gravitational collapse:

$$M_J = \frac{3k_B T}{G\bar{m}} r = \frac{3c_s^2}{G} r$$

Phases of ISM and Strömgren Spheres

- The Interstellar Medium (ISM) has a range of temperatures and densities, and a several stable phases.
- The transition between ionized gas around a hot star and surrounding neutral as is called the Strömgren sphere.
- For a rate of ionizing photons Q_*, a number density *n* and a recombination rate per unit volume α, the sphere radius is:

$$r_{\mathrm{strom}} = \left(\frac{3Q_*}{4\pi \alpha n^2} \right)^{1/3}$$

Week 8 Summary

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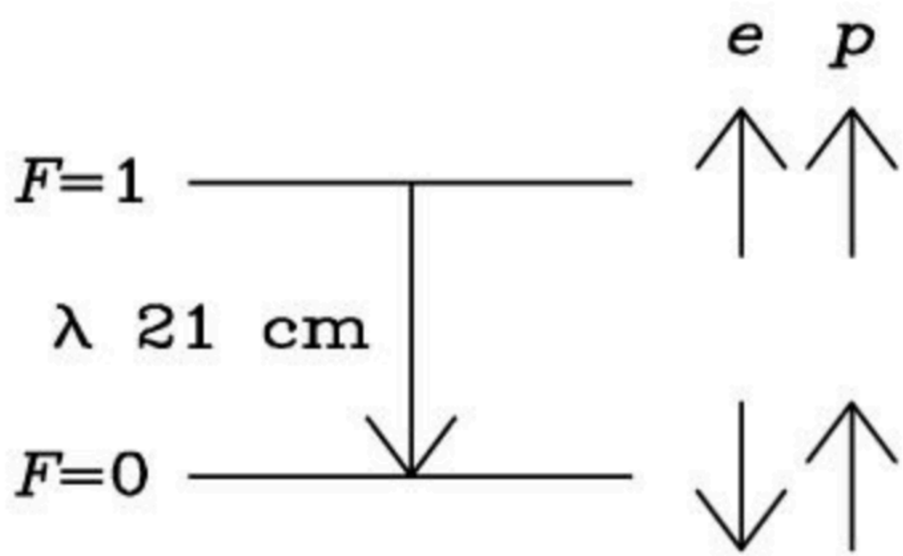
- HI radio emission at 21cm probes the mass of a key ISM component and structure of the Galaxy.
- The Galaxy has a Disk (young and old), Halo (old, metal poor), Bulge and bar.
- At the center is a 4 million solar mass black hole, which is relatively quiescent.
- The Galactic rotation curve is nearly flat at the location of the sun. Mass is dominated by dark matter – WIMPS not MACHOs.

HI Emission

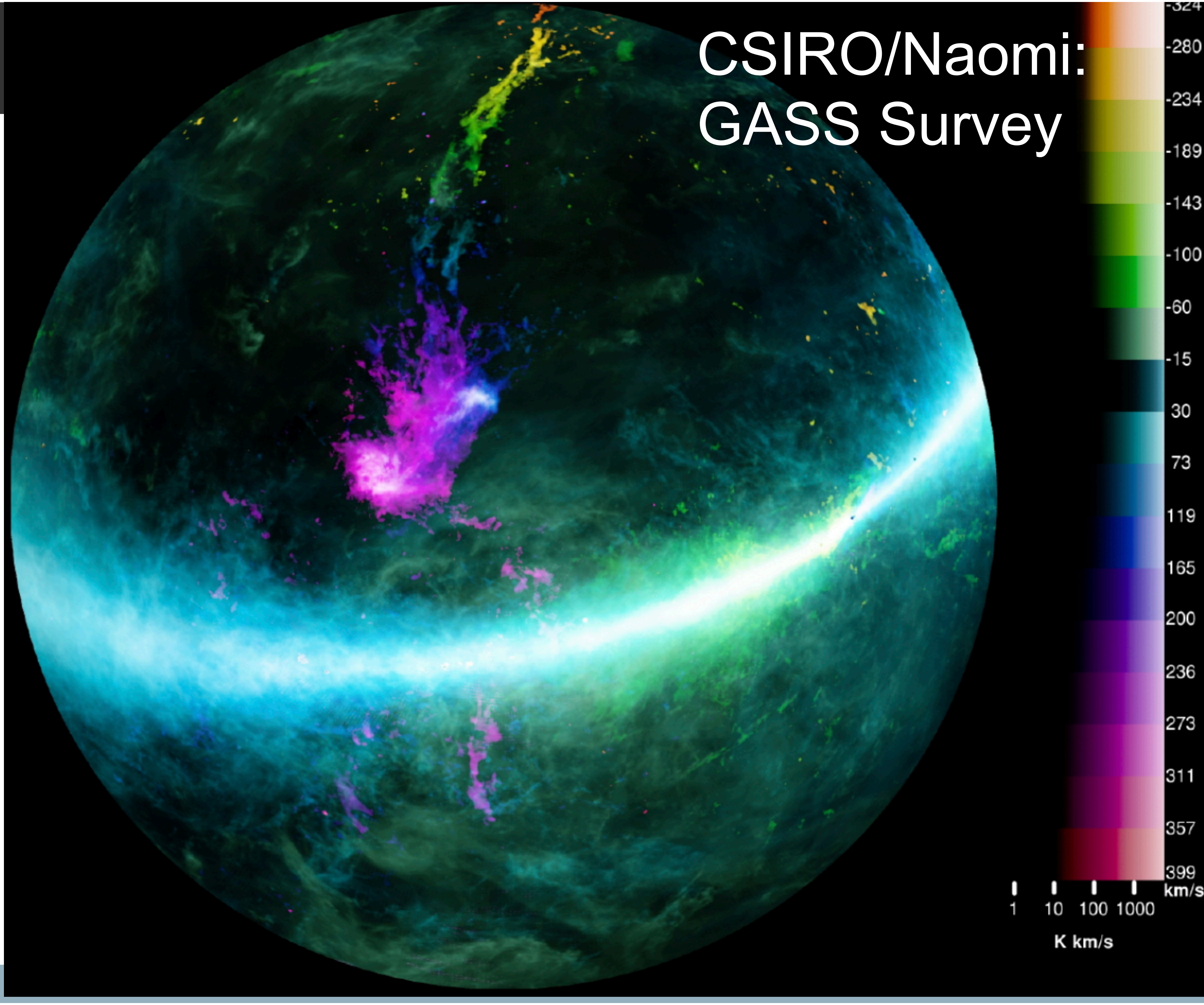
- Atomic transitions are *allowed* if e.g. electron spin doesn't change and angular momentum is conserved.
- Spin-orbit coupling splits energy levels, regarded as *fine* structure. E.g. The Sodium Doublet, or transitions between ground state level of neutral Carbon THz/sub-mm line of CI at 370μm.
- *Hyperfine* structure refers to transitions where the nuclear and electron spins are aligned or anti-aligned.
- Key examples are the Cs atomic clock transition at 9.19 GHz, and the 21cm line (1.42GHz) of H.



HI Emission

- HI is so important because all neutral hydrogen emits at this wavelength. Ionised and molecular hydrogen can be difficult to detect.
- The transition rate is 3 x 10^{-15} Hz from upper to lower energy level – i.e. 10^7 years on average to emit a photon.
- Fraction of HI in upper level depends on collision excitation only.
- Even at 30K, $k_B T$ is ~400 times lower than $h\nu$., so very close to 50% of H is always in upper state – *emission measures mass.*

CSIRO/Naomi: GASS Survey



Milky Way as a Spiral Galaxy

- We can see the disk-like nature of our Galaxy on a dark night in Coonabarabran.
- The spiral structure is most easily inferred by looking at other, otherwise similar Galaxies…

M51
(Textbook – NASA, ESA and Hubble Heritage team)

Face-on Spiral Galaxy

Note – our galaxy is a barred spiral… clearest evidence only in last 18 months

Milky Way as a Spiral Galaxy

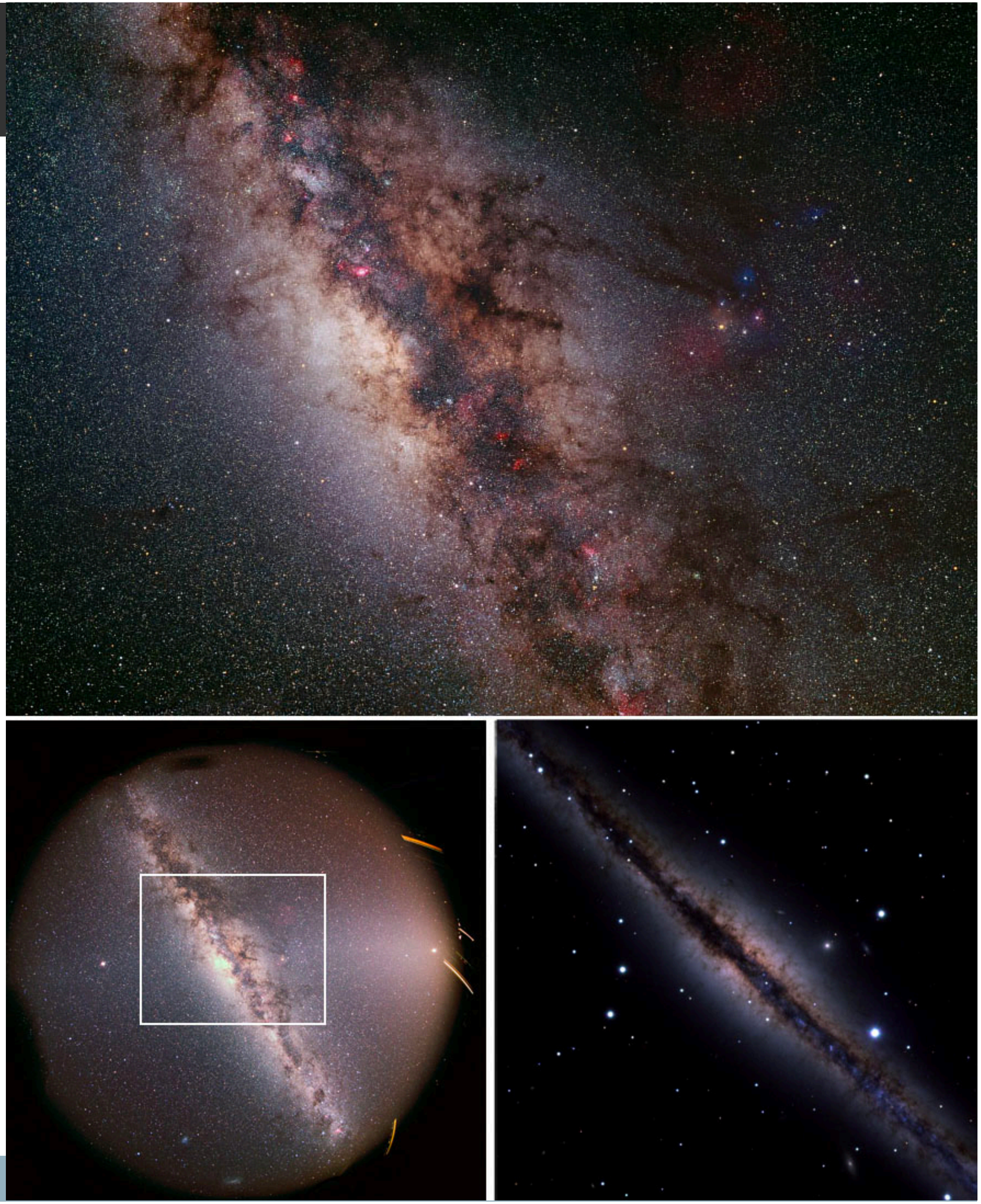
NGC 3370
(Textbook – NASA, ESA
and Hubble Heritage team)

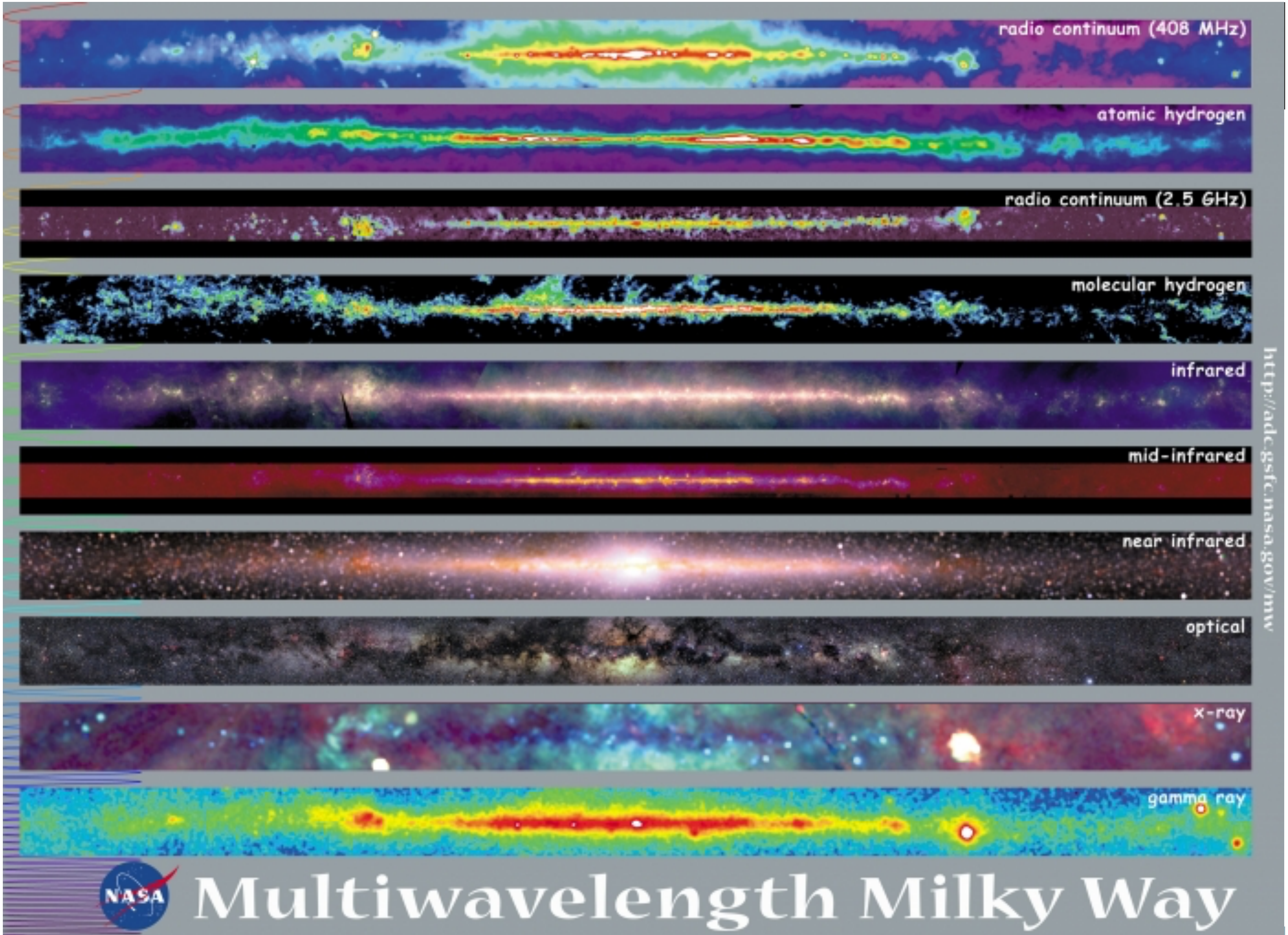
Moderately Inclined Galaxy

Milky Way as a Spiral Galaxy

NGC 4594 *Near Edge On Galaxy*
(Textbook – NASA, ESA and Hubble Heritage team)

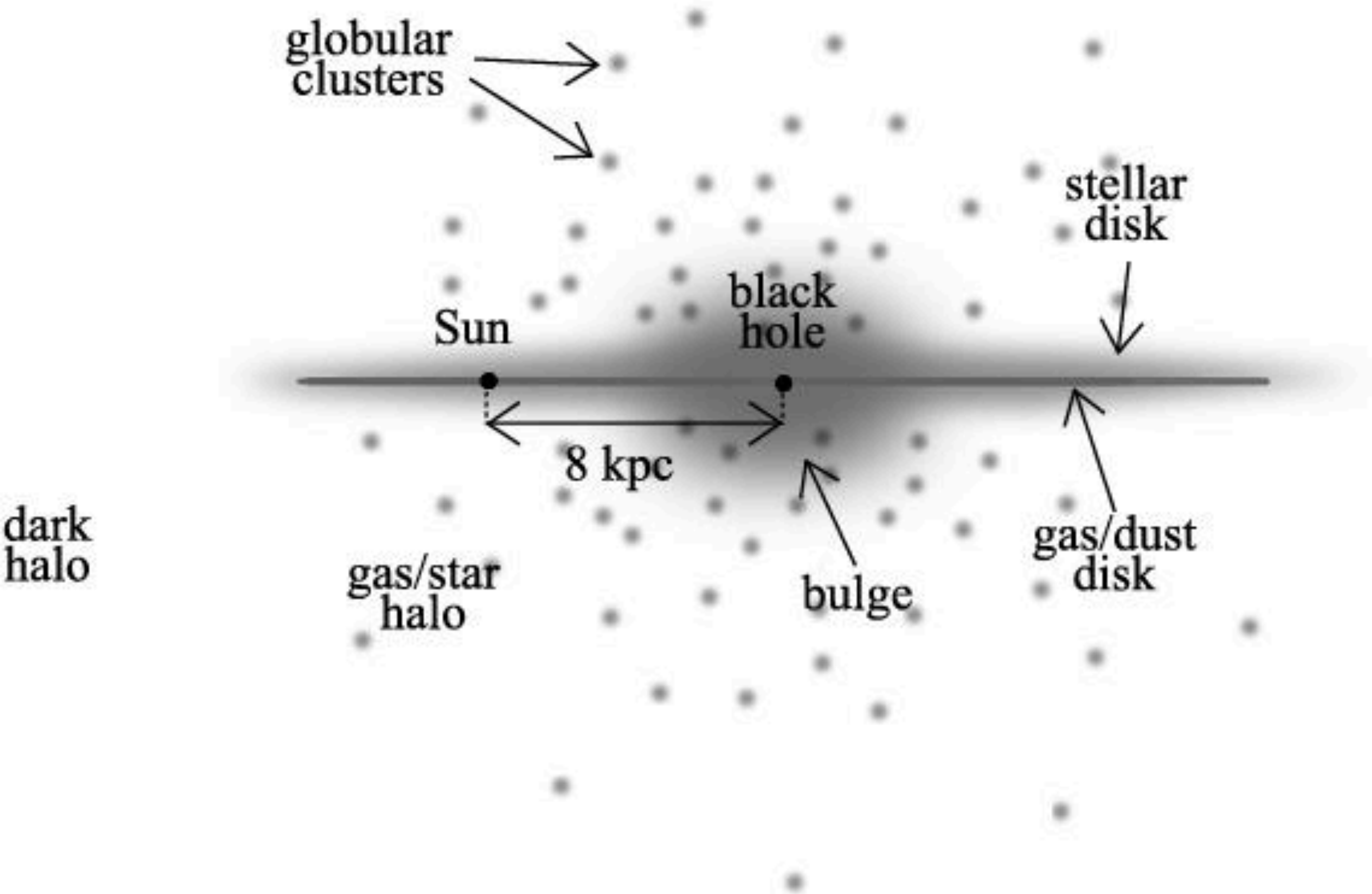
- Our view of the Galaxy in optical light (top and bottom-right)
- NGC 891 – an edge on spiral




radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Other Key Galactic Observations

- Even without parallax measurements, star counts (histogram of the number of stars of a given brightness as a function of angle) historically informed our Galactic structure models.
- Velocity measurements of stars (radial velocity or proper motion) and gas (radial velocity only) enable the Galactic potential to be modelled and statistical structures of stars to be found.
- For example, stars that have a similar spatial and velocity distribution to gas are likely young stars.


globular clusters
stellar disk
black hole
Sun
8 kpc
dark halo
gas/star halo
bulge
gas/dust disk

Key Galactic Parameters

- Distance to Galactic Center 8.18 +/- 0.03 kpc (star orbiting black hole , https://arxiv.org/abs/1904.05721)
- Circular rotational velocity at our Galactocentric radius: 234 +/- 3 km/s (https://arxiv.org/abs/1810.02131), which results in an orbital period of 2 x 10^8 years.
- For circular orbits, gravitational acceleration balances centripetal acceleration:

$$\frac{GM(M_\odot)}{R_\odot^2} = \frac{v_{\mathrm{circ}}^2}{R_\odot}$$

- This gives a mass of 1.1 x 10^{11} M_{sun}.

The Galactic Disks

- The density of various components of the Galactic disk approximately follows an exponential in radius and height in cylindrical coordinates.

$$\rho(r,z) = \rho_0 \left[\exp\left(-\frac{r}{r_d}\right)\right] \left[\exp\left(-\frac{|z|}{h_d}\right)\right]$$

- The scale height is 130 to 400pc for young to old stars in the thin disk, and ~1kpc for theso-called *thick* disk.
- The cold gas (HI, molecular clouds) has the same scale height as the young stars.

Stellar Interactions and Collisions

- As the disk consists of the highest densities of stars, we can ask the question: *how often to stars collide?*
- Like any group of particles, all we need to know is the number density *n*, the particle velocities *v* and the cross-section σ to result in a collisional time of:

$$\tau_{\rm coll} = \frac{l}{v_{\rm ran}} = \frac{1}{\bar{n}\sigma_{\rm geom} v_{\rm ran}}$$

- This is 10^{19} years with a naieve stellar cross-section, or 10^{16} years once gravitational focusing is taken into account (see textbook for details).
- On the other hand, stars do collide with outer planetary systems – a 50au radius planetary system is disrupted by a stellar collision every ~200 Gyr.

The Bulge and Halo

- The spherical distribution of stars in the Galaxy consists of the bulge (~1kpc in size) and the halo. The textbook has:

$$\rho \propto r^{-3}$$

- Other references, e.g. the often used Besançon model (Robin et al 2003) has:

$$\rho \propto r^{-2.44}$$

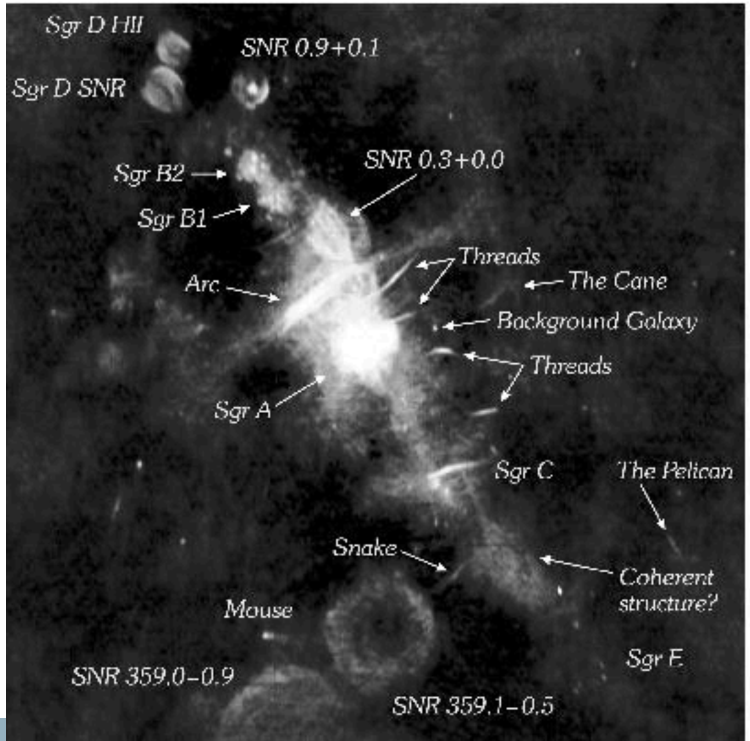
- The halo/spheroid consists of old, metal poor stars.

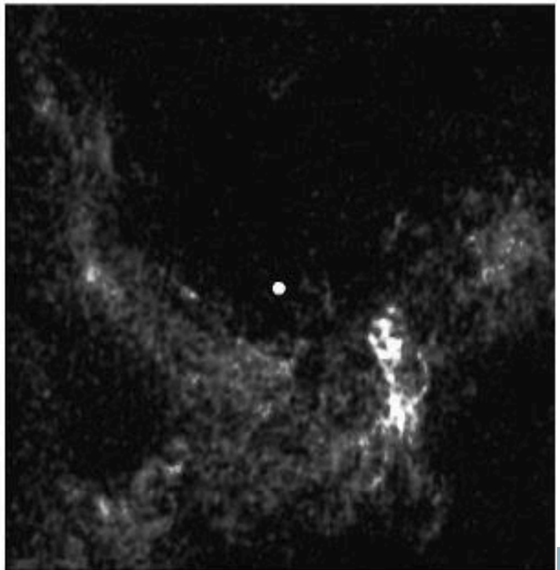
$$\frac{[\mathrm{Fe/H}]}{[\mathrm{Fe/H}]_\odot} = 10^{-4.5} \text{ to } 10^{-0.5}.$$

Galactic Center

- Sgr A (and Sgr A* for the very central source) was a radio source detected at the center of the Galaxy in the 1930s.
- X-ray variability and orbits of stars around the center both measured approximately 20 years ago made the identification as a supermassive black hole secure – $M=4 \times 10^6\ M_{sun}$

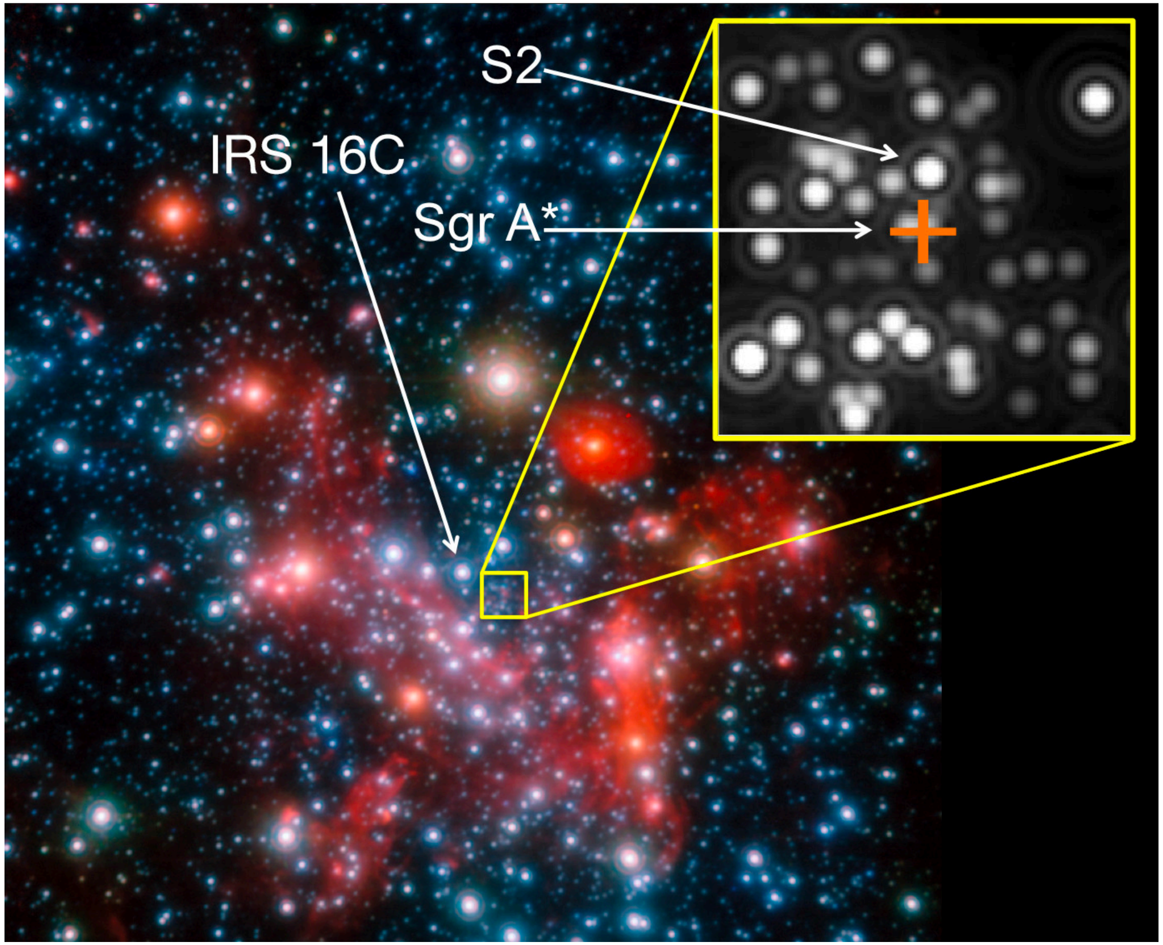
λ=90cm
1kpc





λ=1.3cm
1pc

Galactic Center



- Many bright sources near Sgr A* make stellar orbits complex
- US (Keck – Ghez/Lu textbook image) vs Europe (Genzel) competition.
- ESO's `Gravity' instrument (4x 8m telescopes) has best data now…

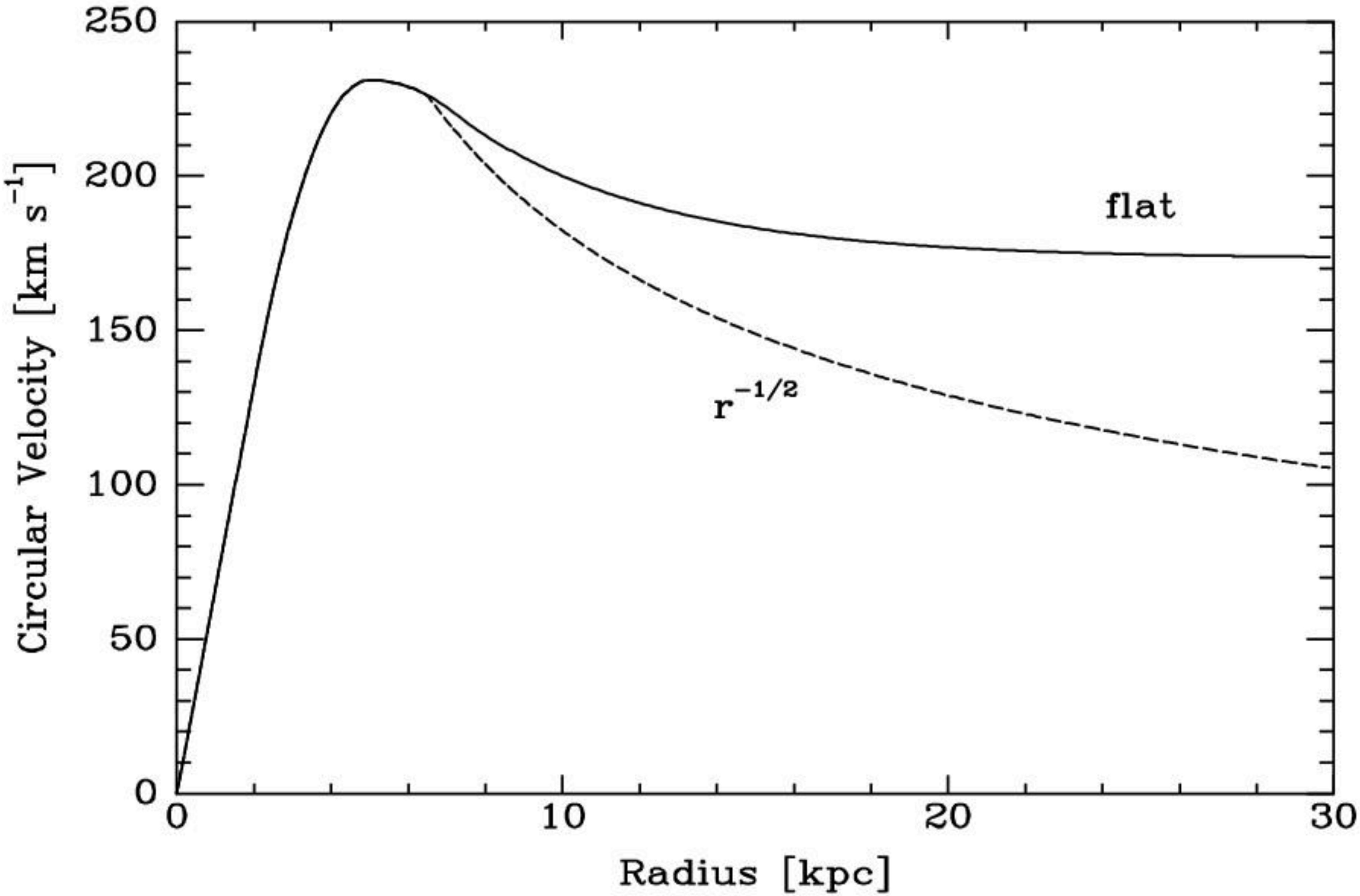
(https://arxiv.org/abs/1810.12641)

Galactic Center

ESO/MPE movie from NACO/VLT and Gravity
Discuss mass, flares, astrometric motion during flare

Dark Matter – the Dark Halo

- Locally, if we estimate the interior mass in the Galaxy (~10^{11} Msun), it is suspiciously higher (less than a factor of 2) than an estimate of the gas and stellar mass.
- However, most of the luminous stars are interior to the sun, so we'd naievely expect the rotation curve of the galaxy to approach Kepler's law.
- However, the rotation curve (measured from stars and HI) is flat – demonstrating there is unseen matter that dominates at the sun's radius and further out.


250
200
150
100
50
0
Circular Velocity [km s^{-1}]
0
10
20
30
Radius [kpc]
flat
$r^{-1/2}$

What is Dark Matter?

- 1970s to 1990s involved many attempts to find the source of dark matter.
- Best candidate: Cold dark matter consisting of massive particles that interact by gravity and nothing stronger than the electroweak force.
- The MACHO survey from Mt Stromlo eliminated massive objects due to the lack of gravitational lensing (many other microlensing surveys now, e.g. OGLE)
- Extremely cold molecular hydrogen clouds of just the right size not completely ruled out (as far as I’m aware), but there is no model of their formation.

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