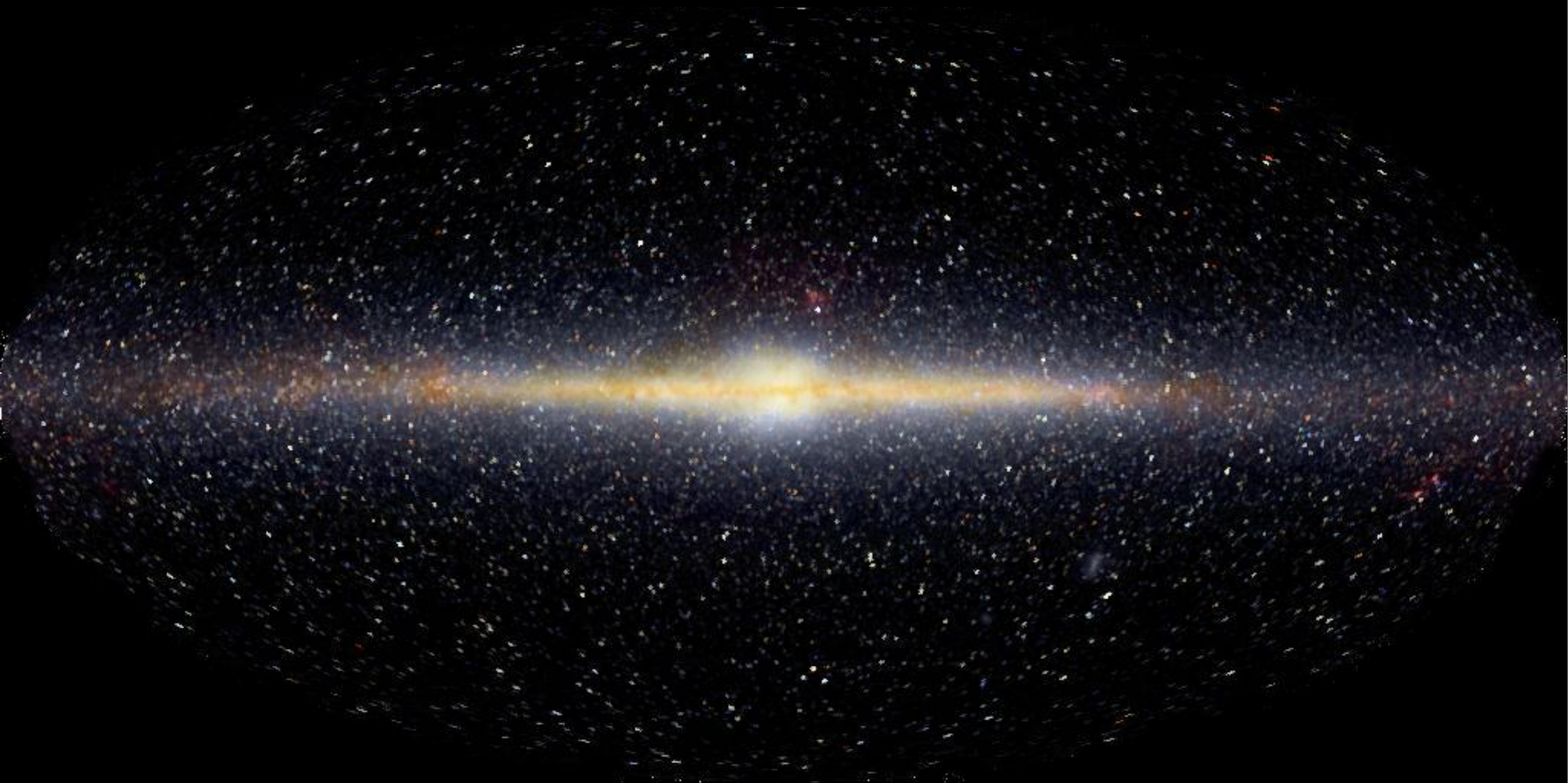
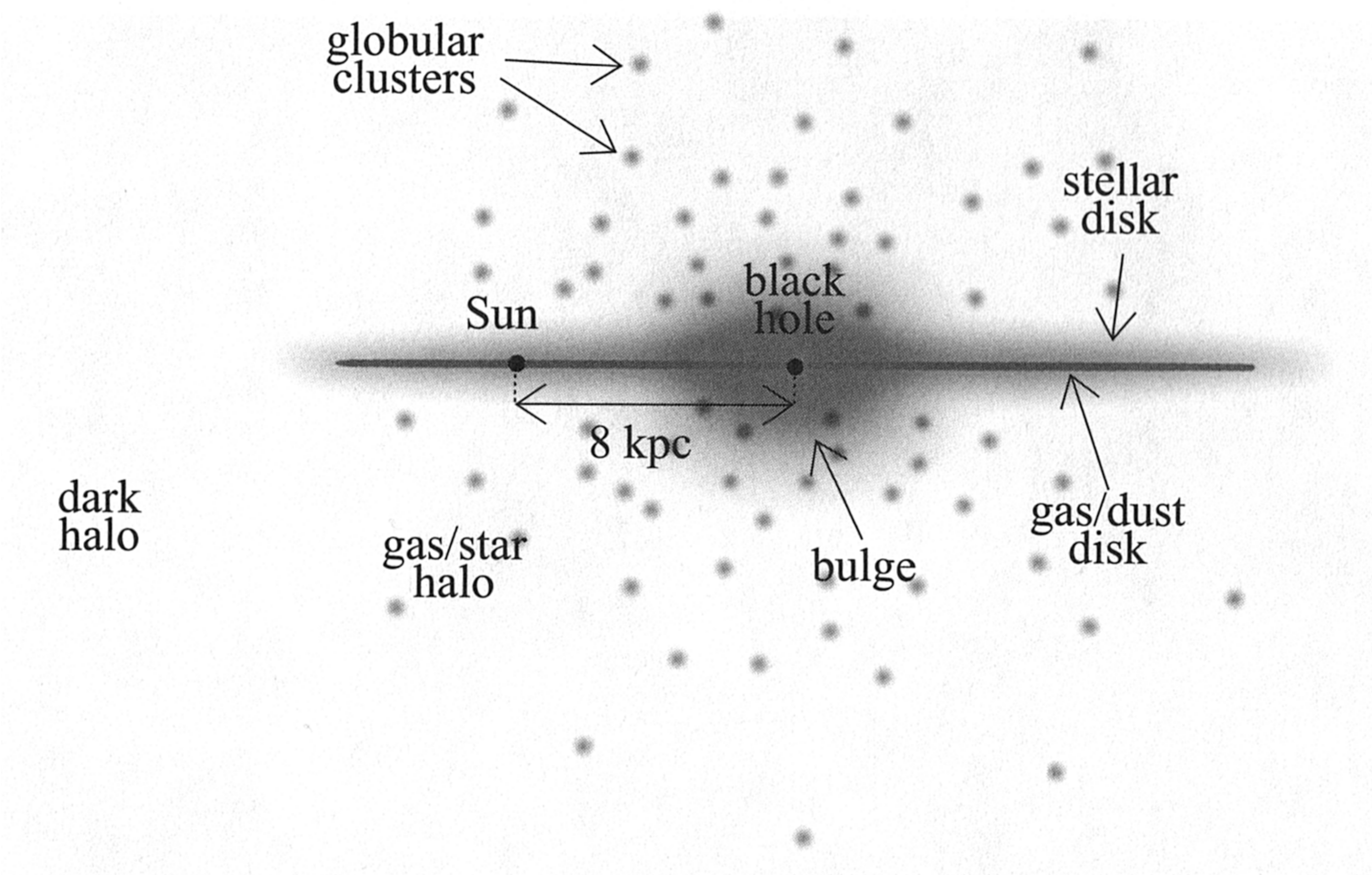


Structure of the Milky Way

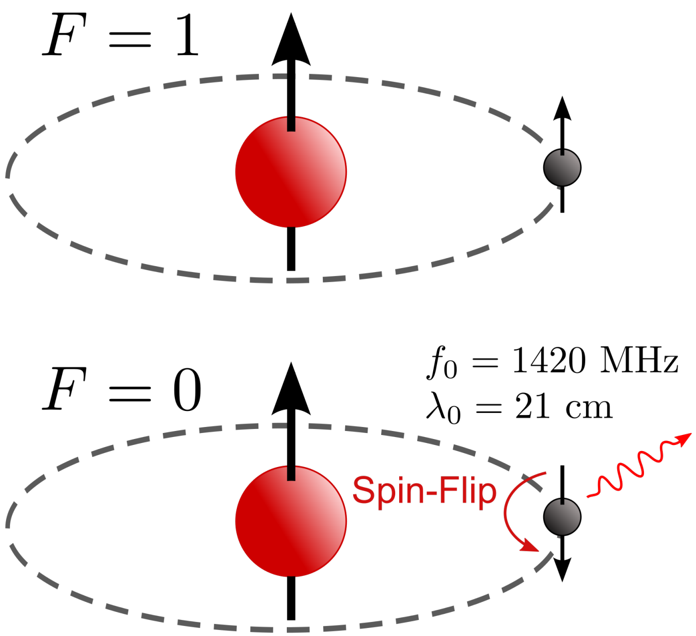


21-cm Radiation

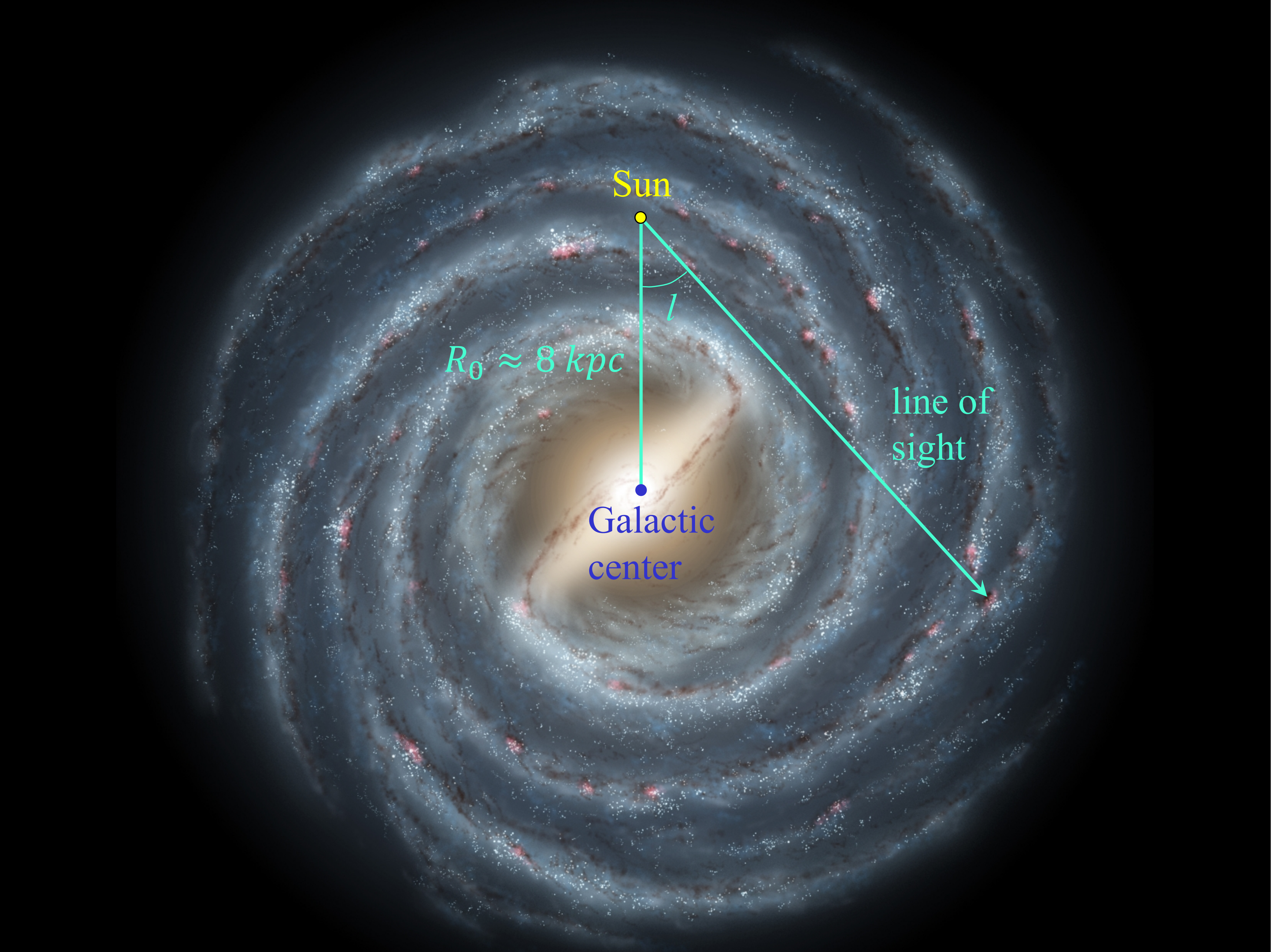
- Hyperfine splitting in the ground state of hydrogen
- parallel state has slightly higher energy than the antiparallel state
- energy difference

  $= 5.9\times10^{-6}$ eV
- frequency 1420 MHz

  wavelength 21 cm



can see almost the entire Milky Way disk!


Sun
l
$R_0 \approx 8\ kpc$
line of sight
Galactic center

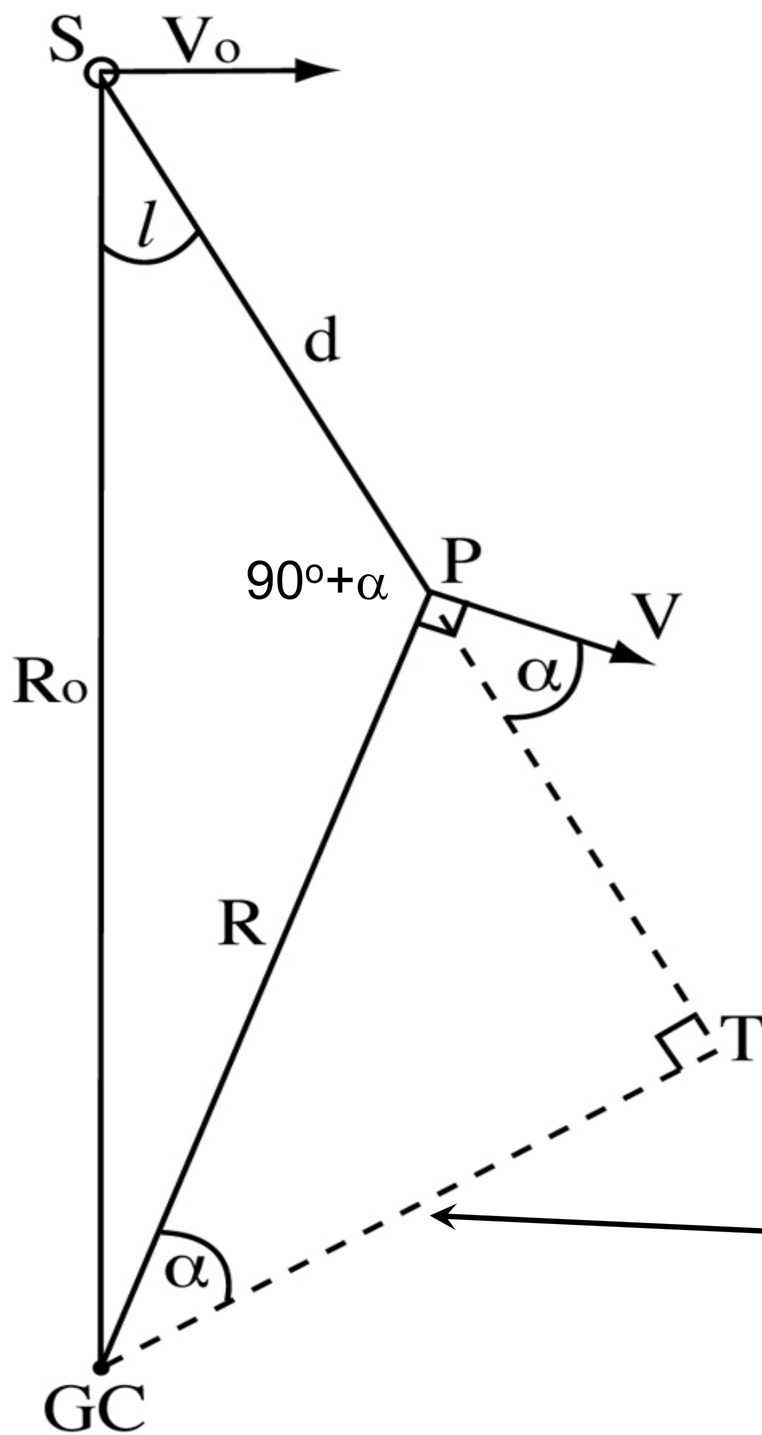


Fig 2.19 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$$V_r = V\cos\alpha - V_0\sin l$$

$$V = \Omega(R)R$$

$$\frac{\sin l}{R} = \frac{\cos\alpha}{R_0}$$

$$V_r = R_0\,[\Omega(R) - \Omega(R_0)]$$

maximum V_r occurs at T, where R is smallest:

$$R = R_0\sin l$$

Weighing the Galaxy

- studies of "nearby" stars and 21-cm HI line reveal

$$V_0 \approx 220 - 240 \text{ km/s}$$

$$\Longrightarrow \quad \tau \approx \frac{2\pi R_0}{V_0} = 2.0 - 2.2 \times 10^8 \text{ yr}$$

$$M(R_0) \approx \frac{R_0 V_0^2}{G} = 1.1 \times 10^{11} M_\odot$$

- most of the mass is in the form of stars (~10% gas)

Galactic Rotation Curve

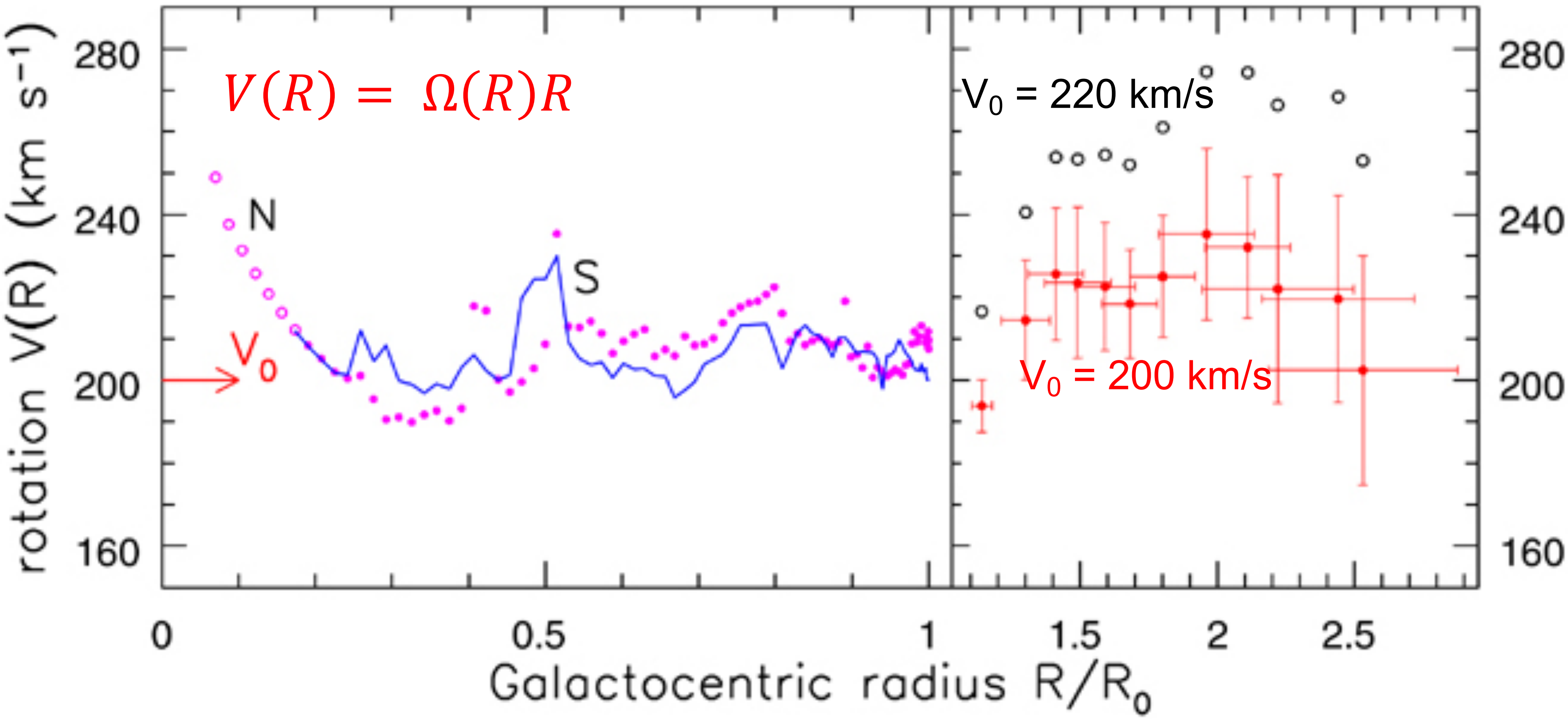


Fig 2.21 (Burton, Honma) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Galactic Rotation Curve

- studies of "nearby" stars and 21-cm gas line also find

  angular speed $\Omega(R) \downarrow$ as $R \uparrow$

  $$\Omega \sim R^{-1}$$

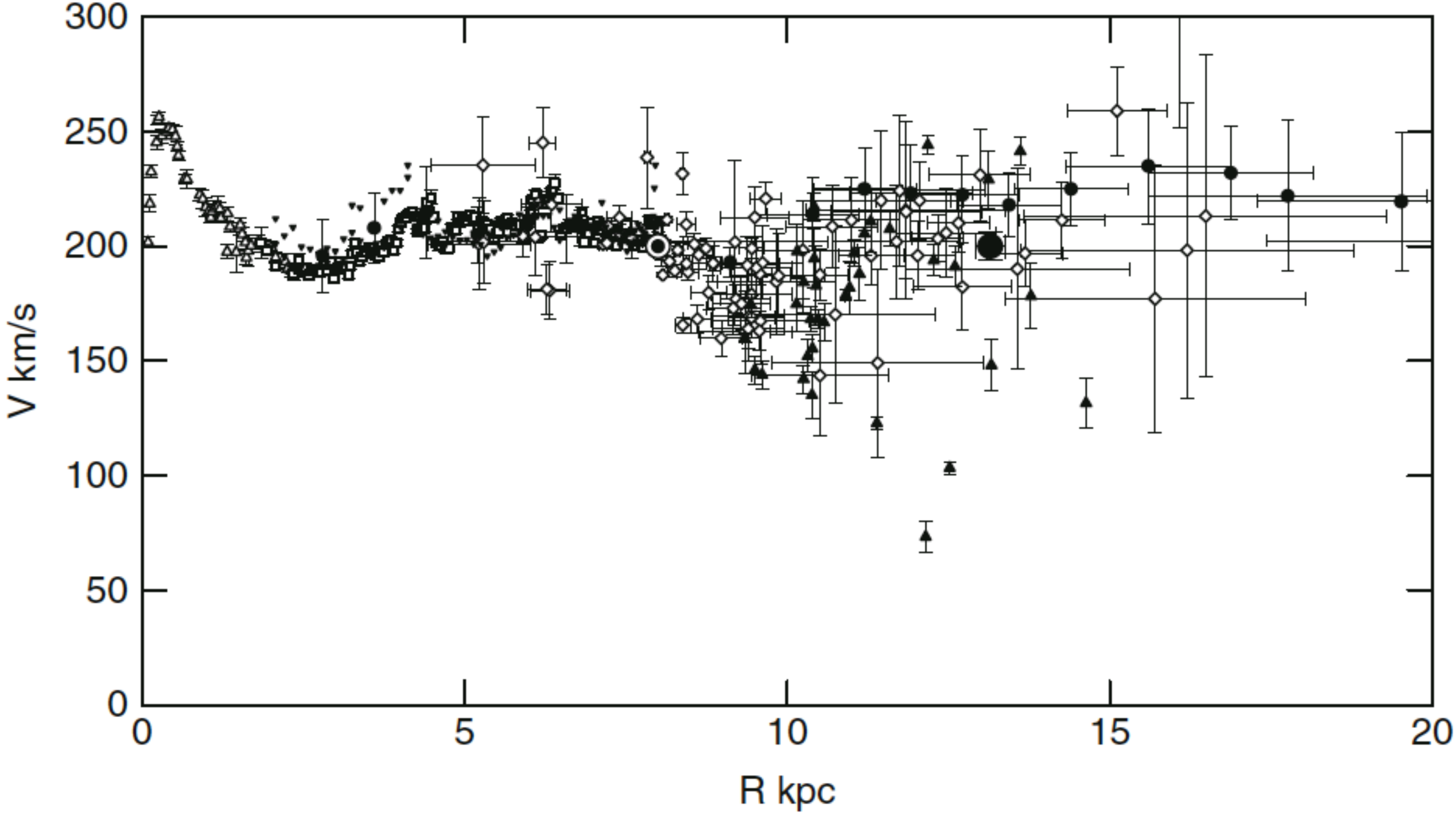
  $$\Longrightarrow \quad V(R) \approx \text{constant}$$

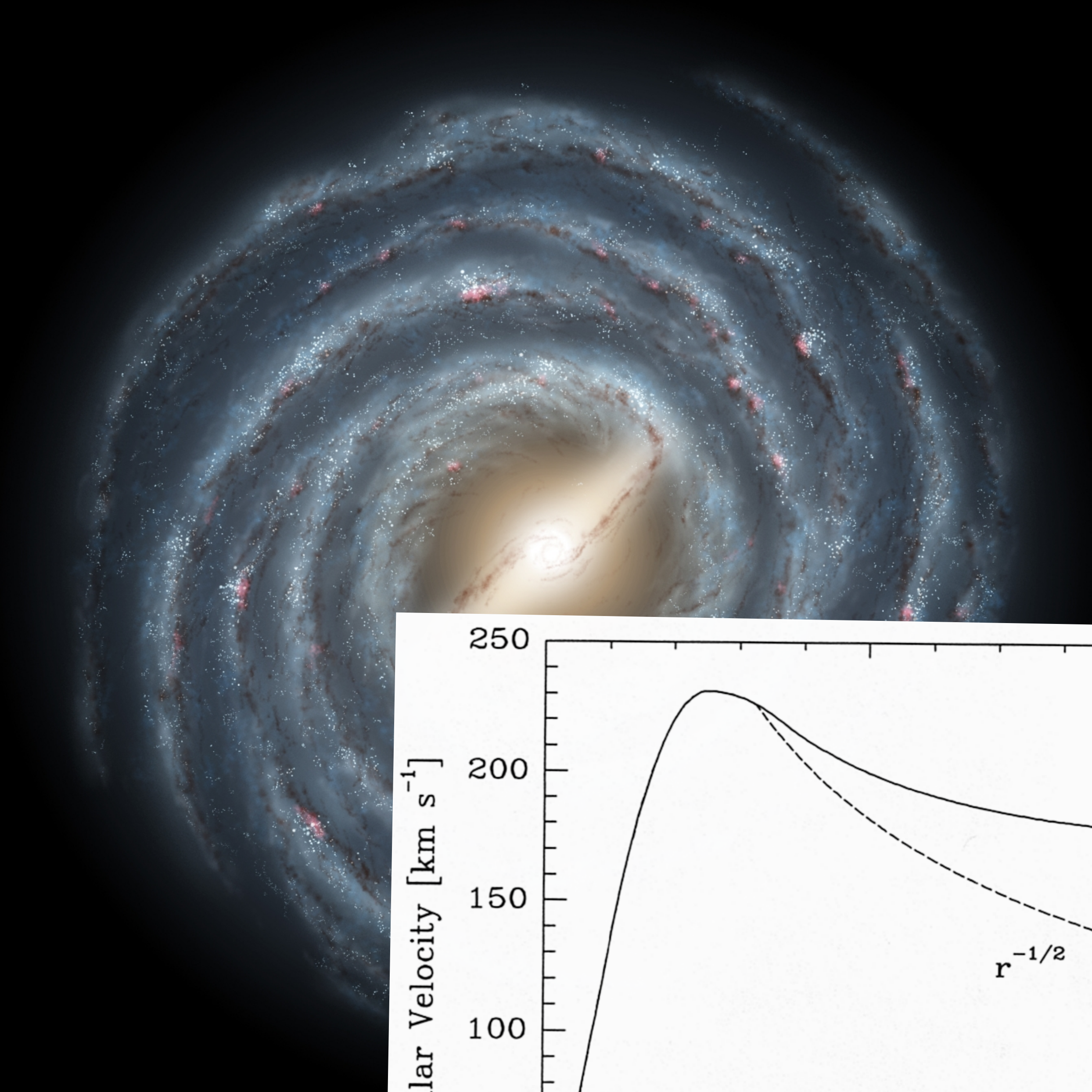
  $$\Longrightarrow \quad M(R) \approx \frac{RV^2}{G} \propto R$$

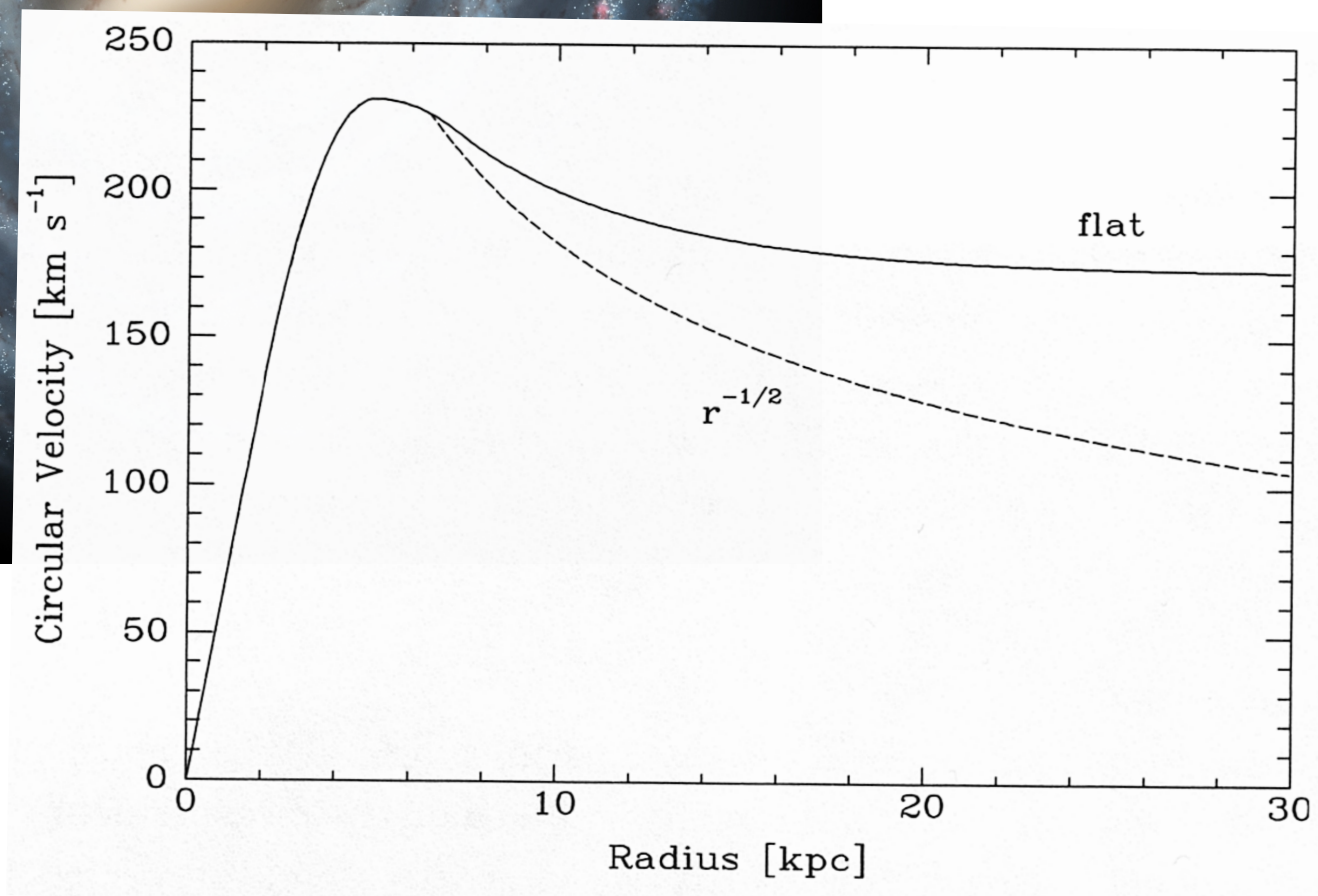
  <u>inconsistent</u> with observed luminous matter

Galactic Rotation Curve

Sofue et al. (2008)

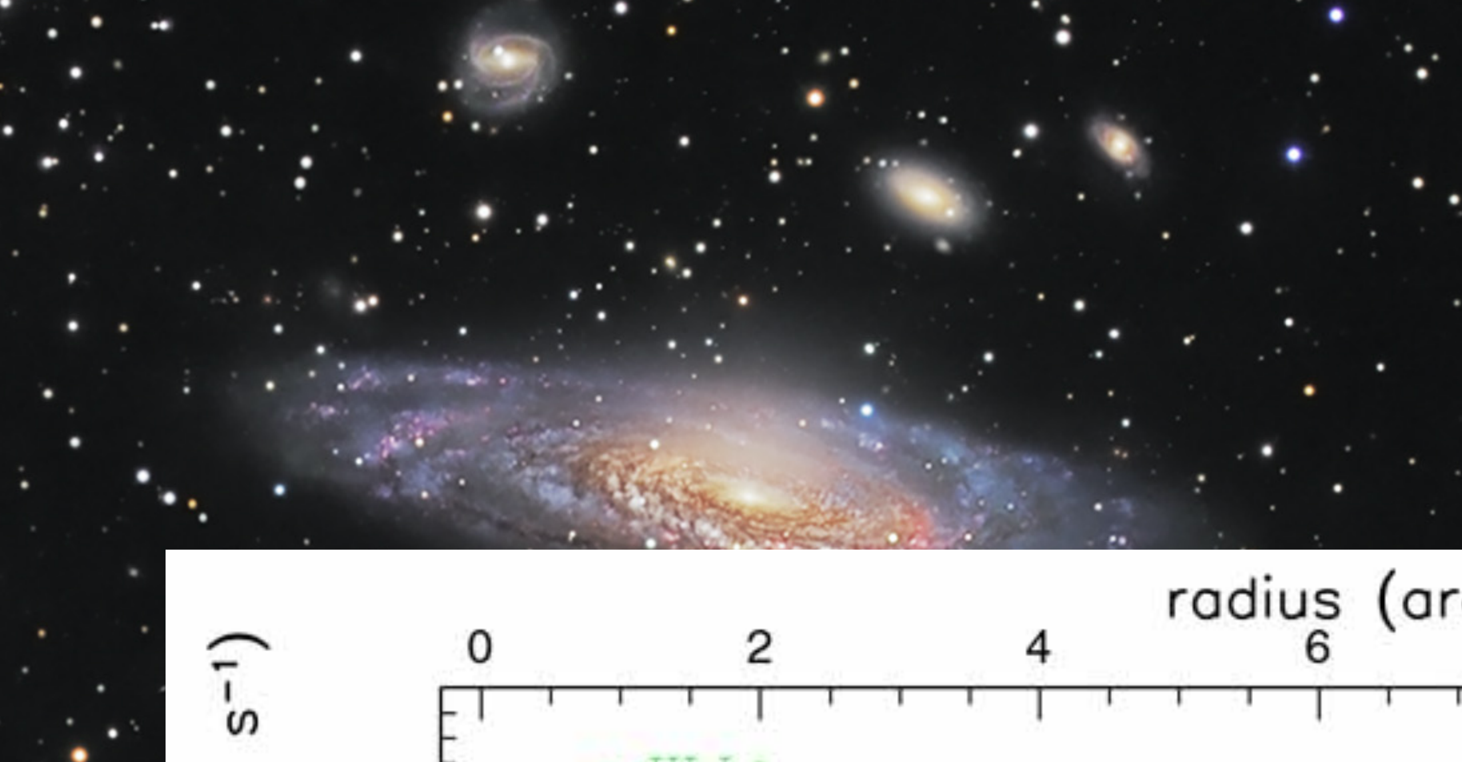


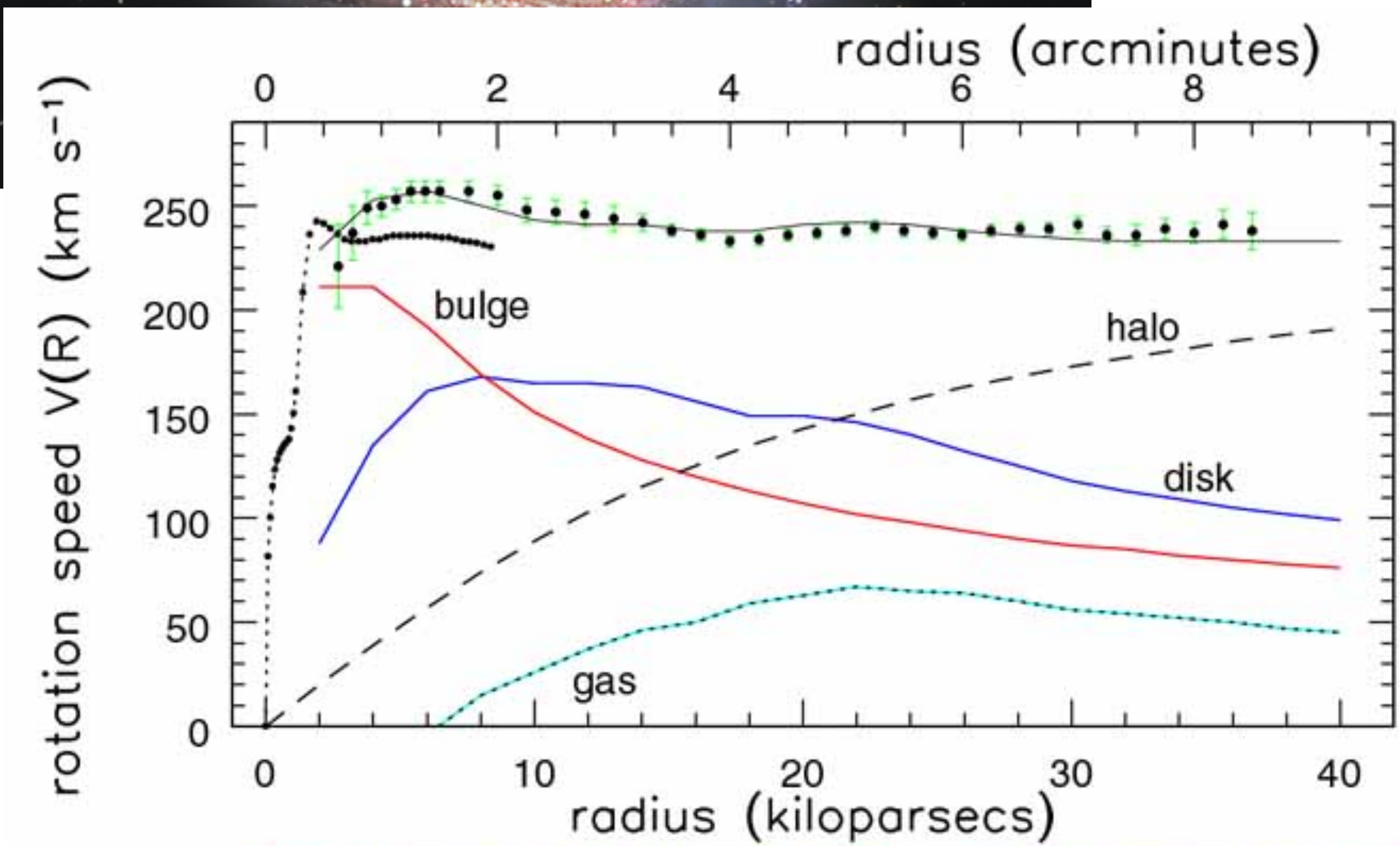




Circular Velocity [km s^{-1}]
Radius [kpc]
250
200
150
100
50
0
0
10
20
30
flat
$r^{-1/2}$

DARK MATTER!





radius (arcminutes)
0
2
4
6
8
rotation speed V(R) (km s⁻¹)
250
200
150
100
50
0
bulge
halo
disk
gas
0
10
20
30
40
radius (kiloparsecs)

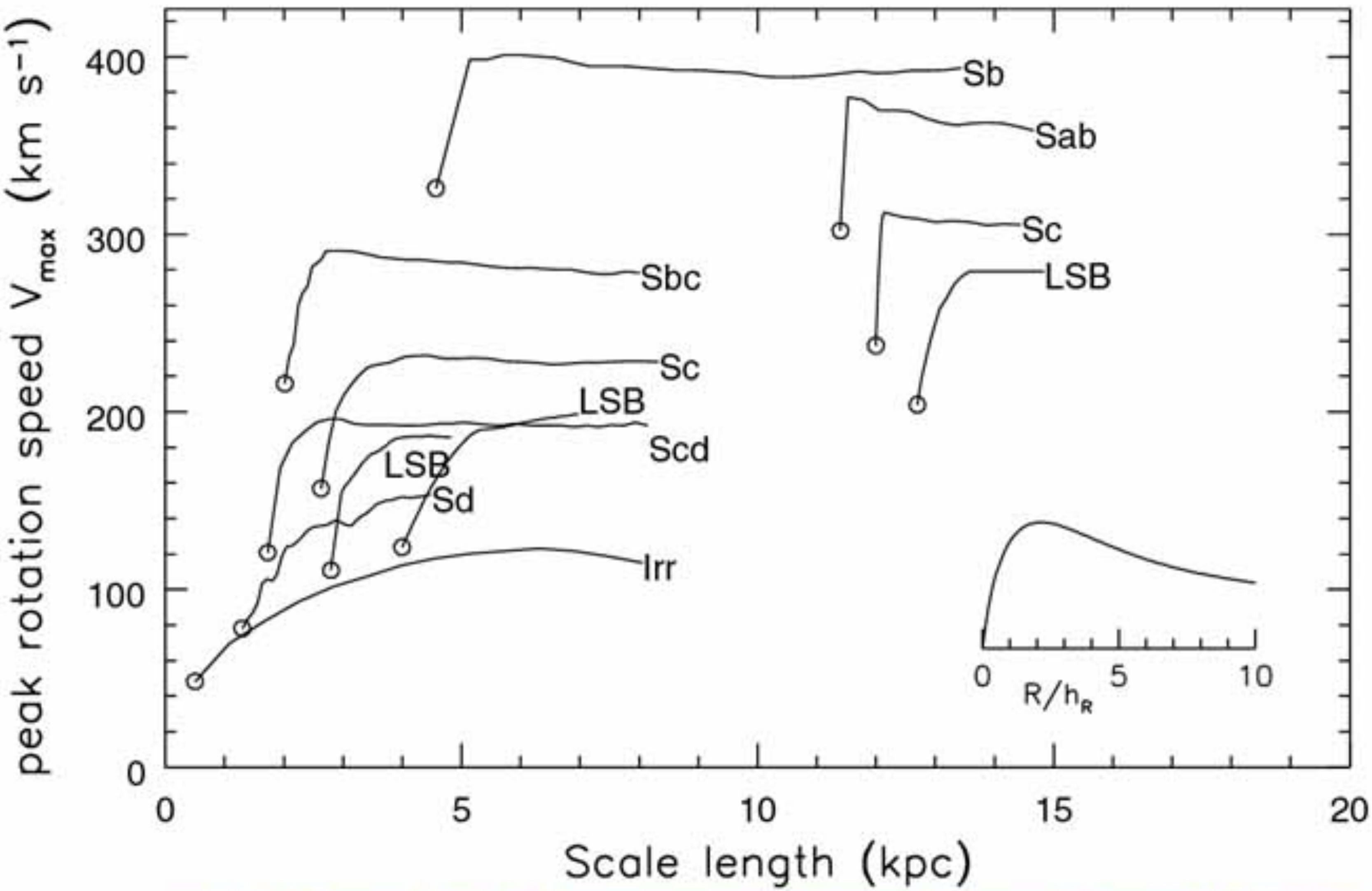


Fig 5.21 (Broeils & de Blok) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Dark Matter in the Galaxy

- mass inside solar circle (8 kpc)

$$M(R_0) \approx \frac{R_0 V_0^2}{G} = 1.1 \times 10^{11}\ M_\odot$$

- mass inside 80 kpc

$$M(10\ R_0) \approx\ 1.1 \times 10^{12}\ M_\odot$$

- dark matter <u>dominates</u> the mass of the Milky Way and other galaxies on large scales

What is Dark Matter?

gas?	would see E/M radiation
dust?	would see IR
stars?	too bright – visible
WD?	too much He, C, N, O, Ne
NS/BH?	too many heavy elements
brown dwarfs?	ruled out by microlensing

Dark matter is not baryonic (“normal”) matter

Dark Matter Candidates

- massive neutrinos
- cosmological problems, but not fully excluded
- weakly interacting massive particles
- non-electromagnetic

  axions

  supersymmetric relics

WIMPs are our best bet, but their nature is completely unknown

Modified Newtonian Dynamics?

- what if the calculation is wrong?
- suppose $F = ma$ is not correct for small a?
  - $a = 9.8 \text{ m s}^{-2}$ on Earth
  - $a = 6\times 10^{-3} \text{ m s}^{-2}$ for Earth's orbit
  - $a = 2\times 10^{-10} \text{ m s}^{-2}$ for Sun orbiting the Galaxy
- MoND (Milgrom, Berkenstein)
  - characteristic acceleration $a_0 \sim 10^{-10} \text{ m s}^{-2}$
  - for $a \ll a_0$, Newton II becomes

$$F = ma\left(\frac{a}{a_0}\right) = \frac{ma^2}{a_0} \qquad \text{e.g. } F = ma\left(1 + \frac{a_0}{a}\right)^{-1}$$

Modified Newtonian Dynamics?

- for a star orbiting the Galaxy

$$F = \frac{ma^2}{a_0} = \frac{m}{a_0}\left(\frac{V^2}{R}\right)^2 = \frac{GMm}{R_0^2}$$

$$\Longrightarrow V^4 = GMa_0$$

$$V = (GMa_0)^{1/4}$$

$$= 205 \text{ km s}^{-1}$$

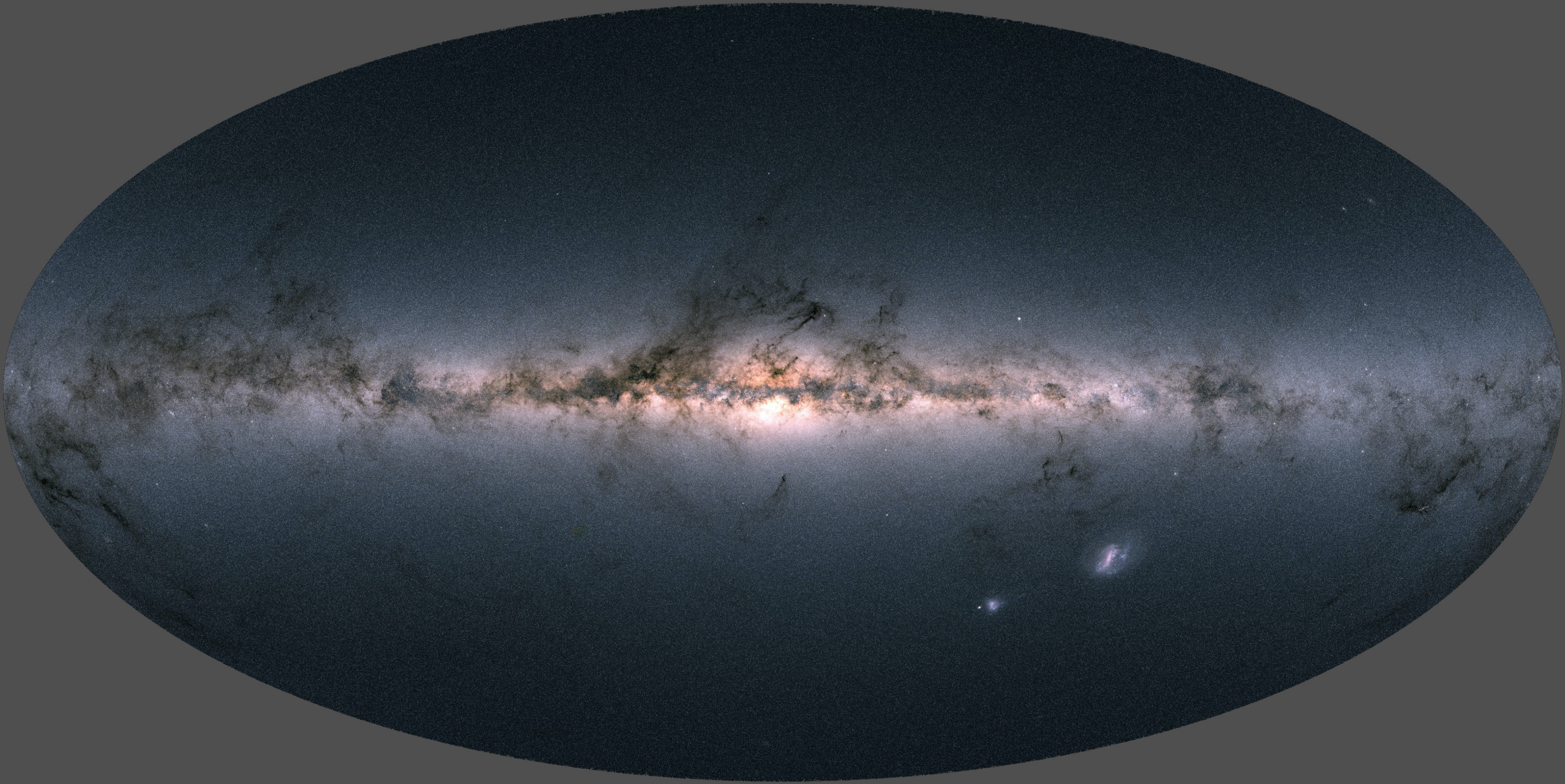
for $a_0 = 1.2\times10^{-10} \text{ m s}^{-2}$

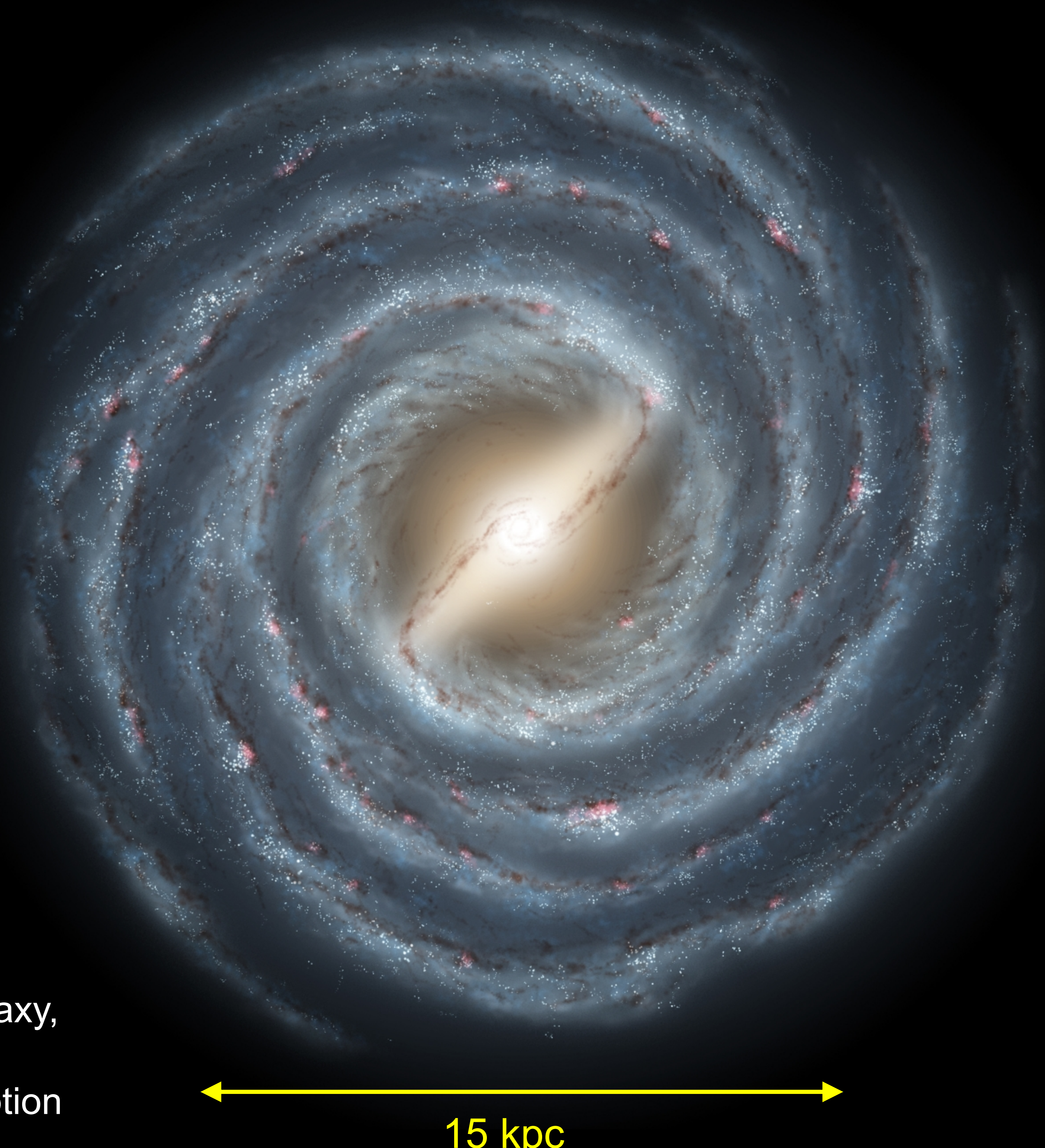
$$\text{M} = 1.1\times10^{11} M_\odot$$

constant!

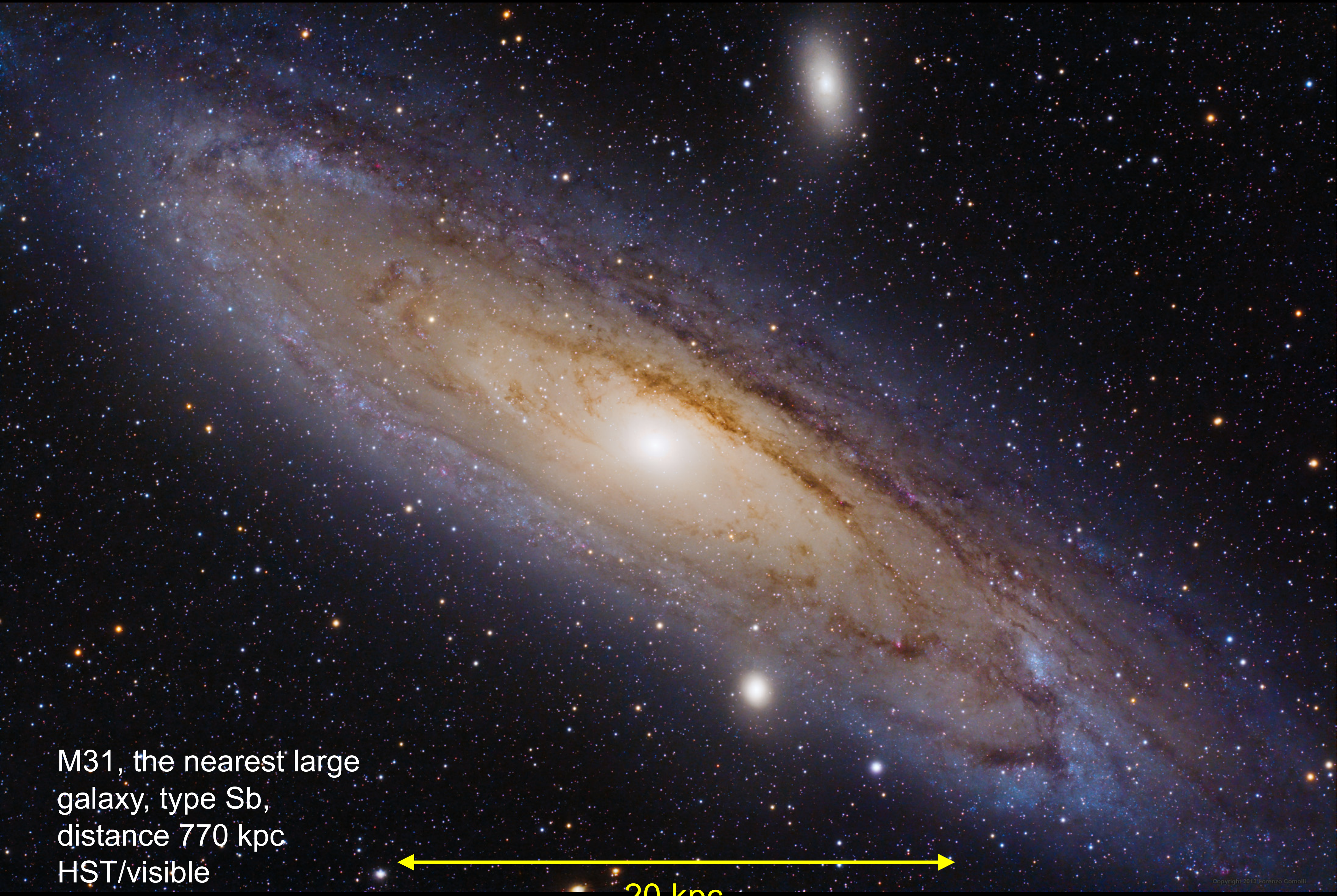
Modified Newtonian Dynamics?

- resolves the dark matter problem, but
  - changes a very fundamental equation (NII or gravity)
  - is not relativistically correct (in this form)
  - choice of a_0 works for rotation curves but not on other scales
  - consequences not fully explored
  - drives cosmologists crazy!

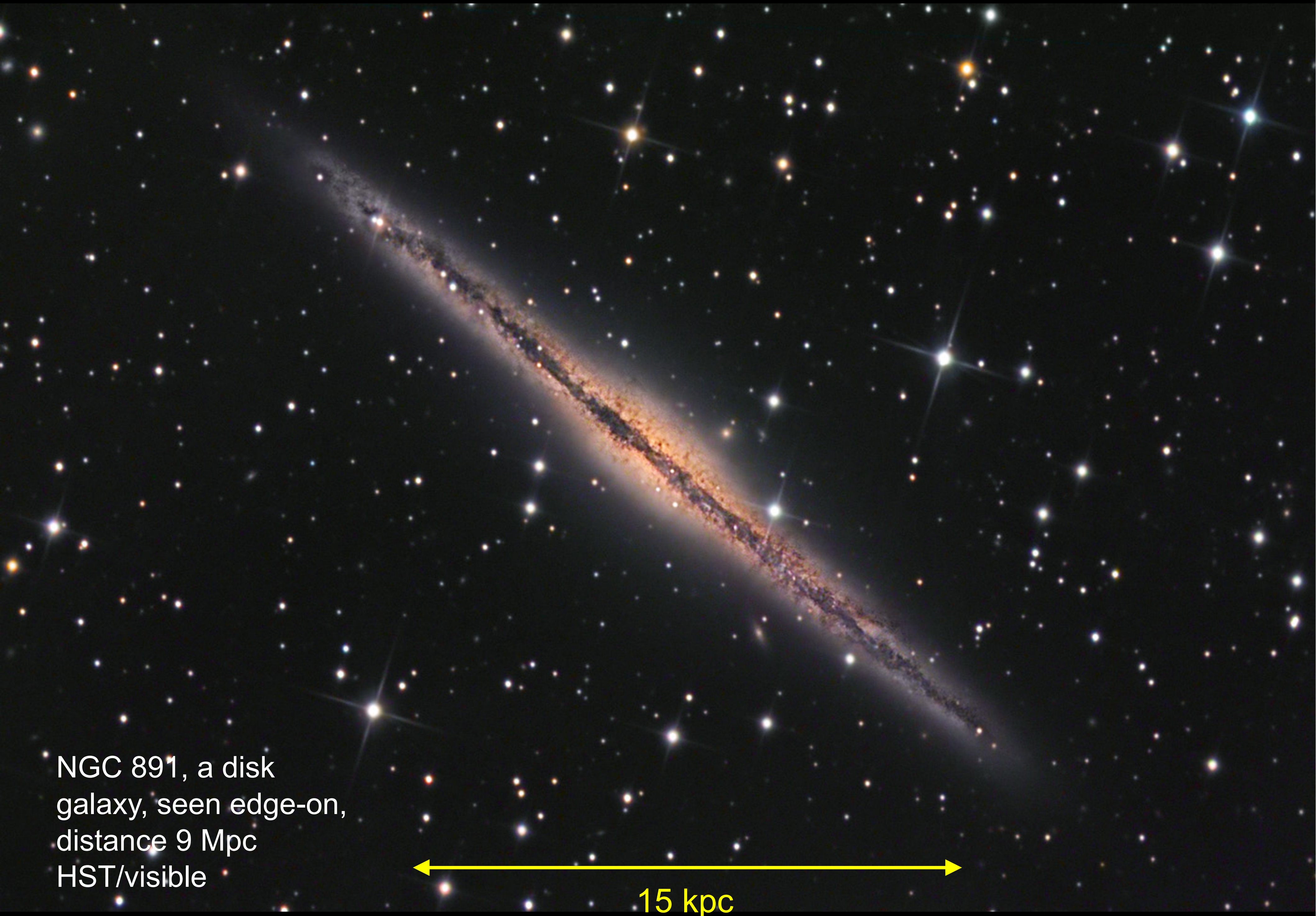


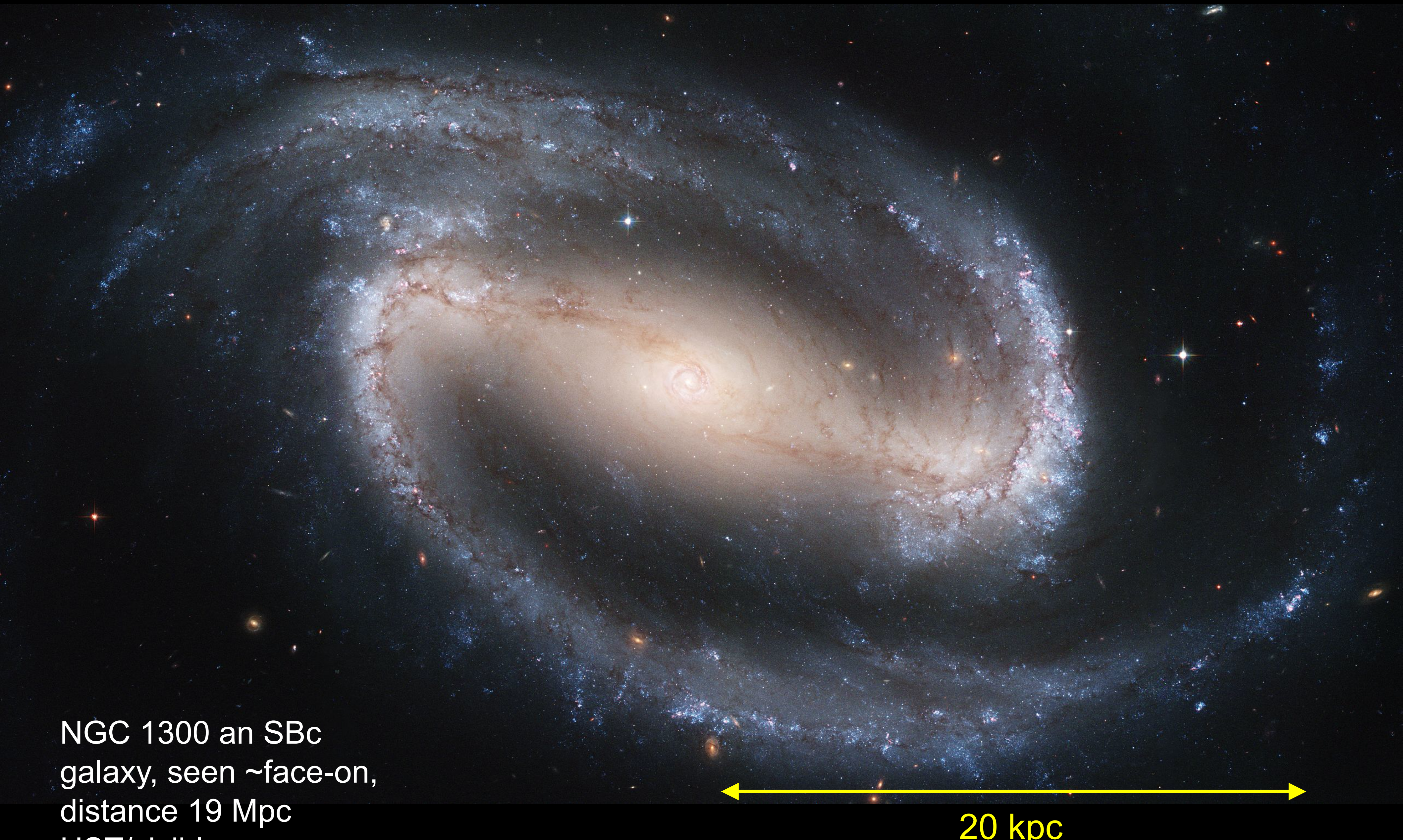


Milky Way galaxy,
type SBb,
artist's conception

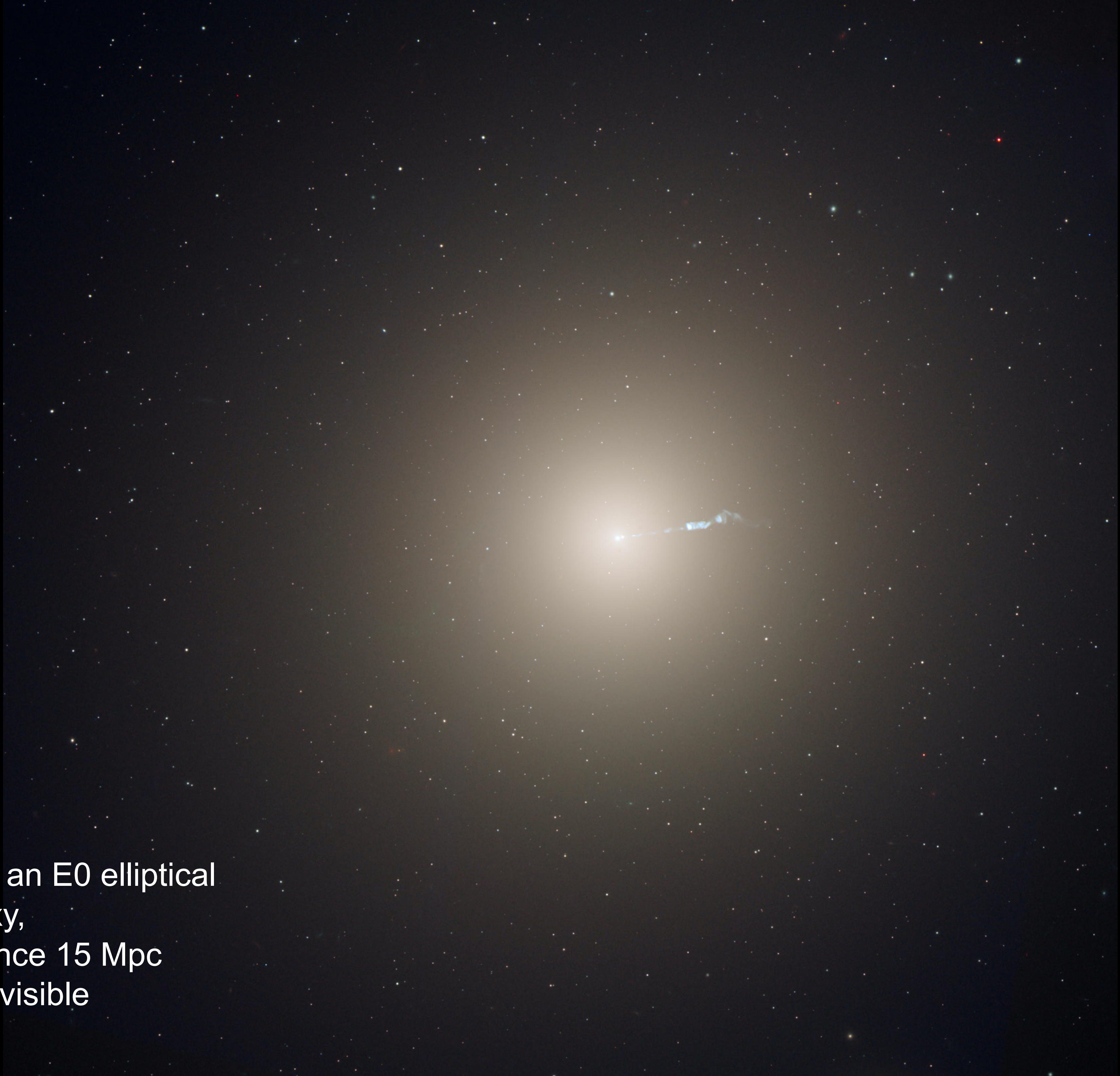

M31, the nearest large
galaxy, type Sb,
distance 770 kpc
HST/visible
20 kpc

M101, an Sc spiral galaxy,
distance 6 Mpc
HST/visible

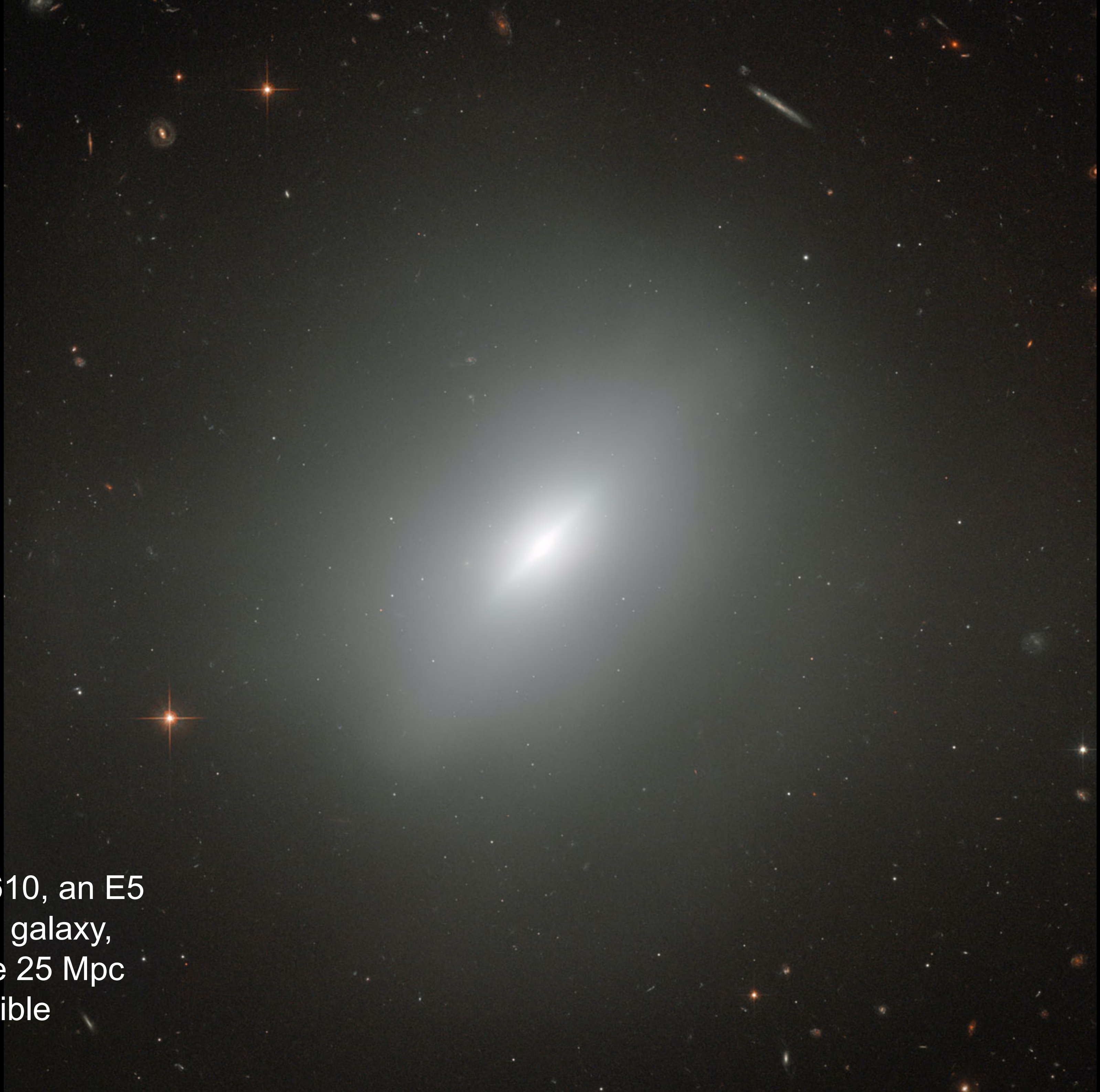

NGC 891, a disk galaxy, seen edge-on, distance 9 Mpc
HST/visible
15 kpc



NGC 1300 an SBc
galaxy, seen ~face-on,
distance 19 Mpc
HST/visible

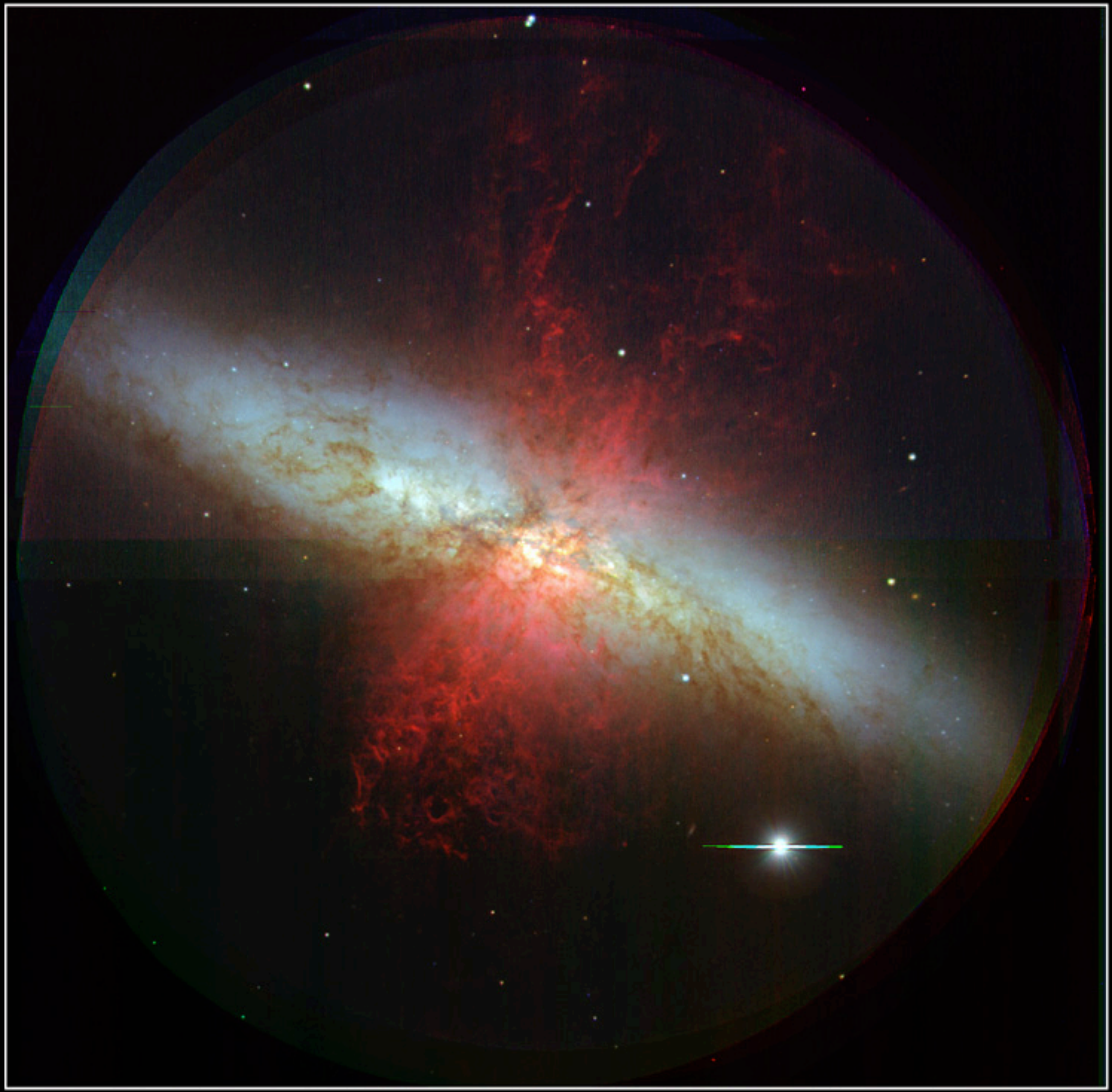


M87, an E0 elliptical
galaxy,
distance 15 Mpc
HST/visible



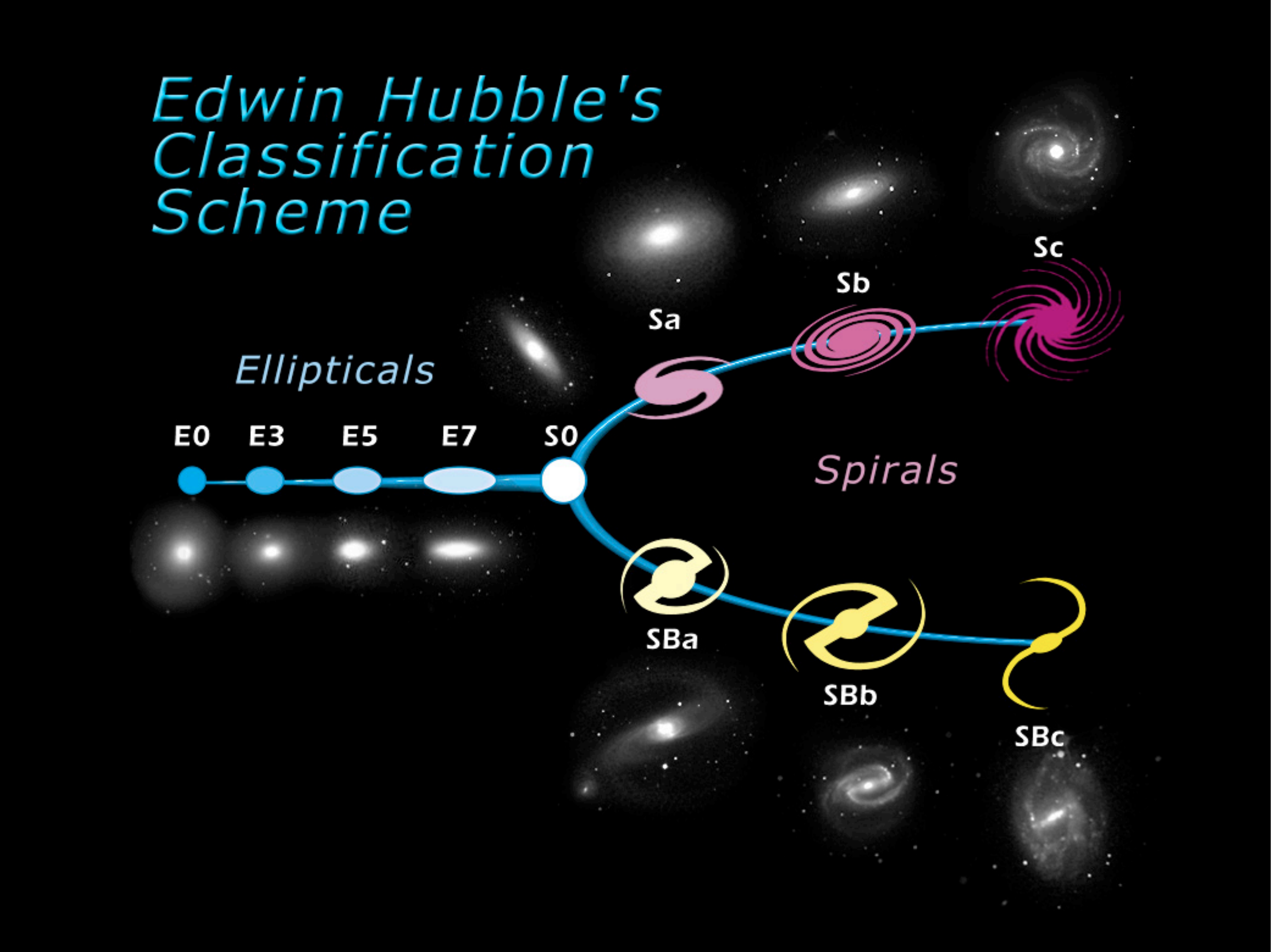
NGC 3610, an E5
elliptical galaxy,
distance 25 Mpc
HST/visible


E0
E3
E5
E7



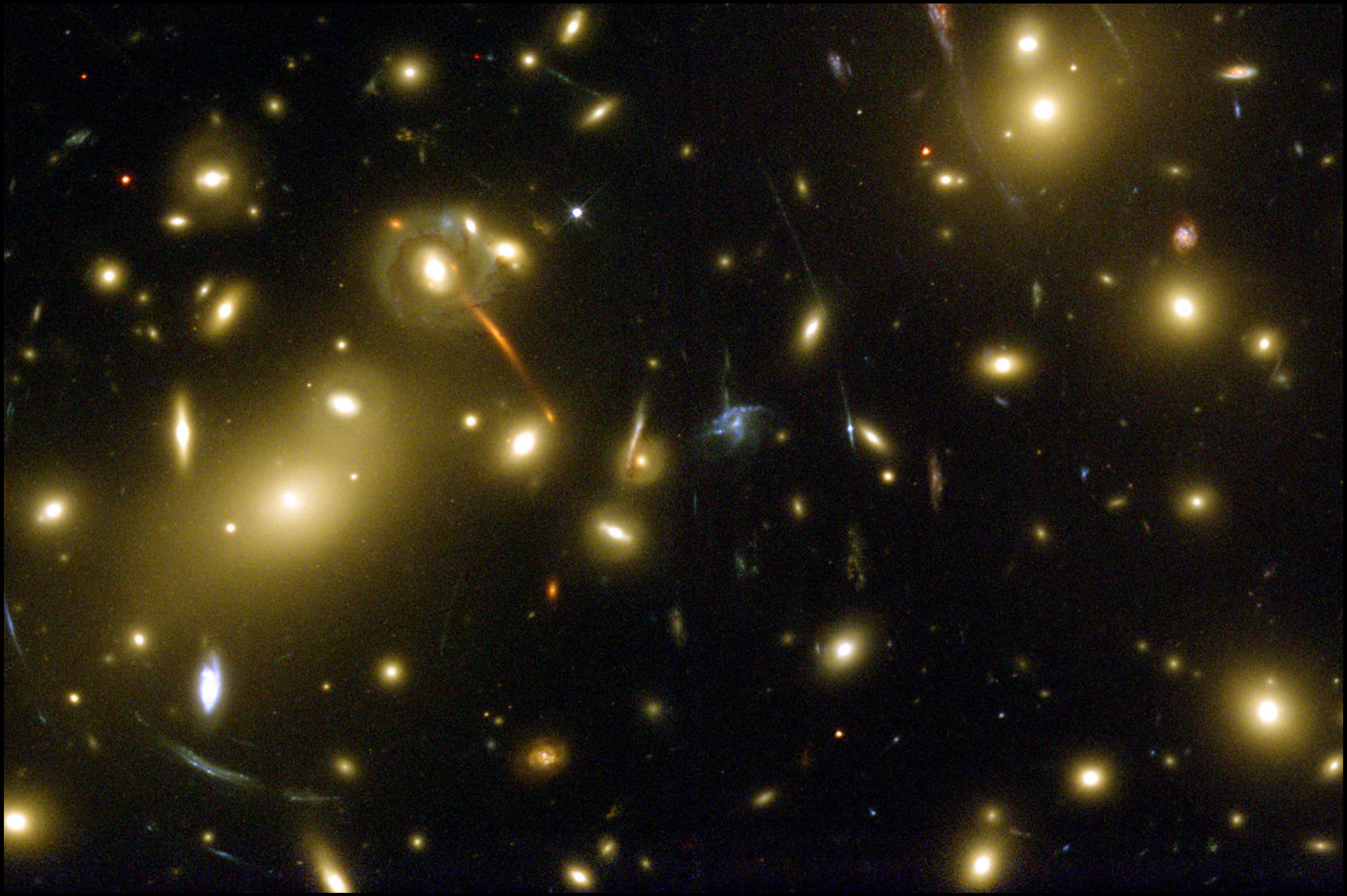
M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000


Edwin Hubble's
Classification
Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Virgo galaxy cluster, distance 15 Mpc visible

3 Mpc



Galaxy cluster Abell 2218,
distance 700 Mpc
HST/visible

1 Mpc

Galaxy Cluster Masses

- galaxy cluster

  radius $r_{cl} \sim$ 1 Mpc

  rms velocity $\sigma \sim 1000 \text{ km s}^{-1}$

  $\Longrightarrow$ crossing time $\tau \sim r_{cl}/\sigma \sim 10^9$ yr

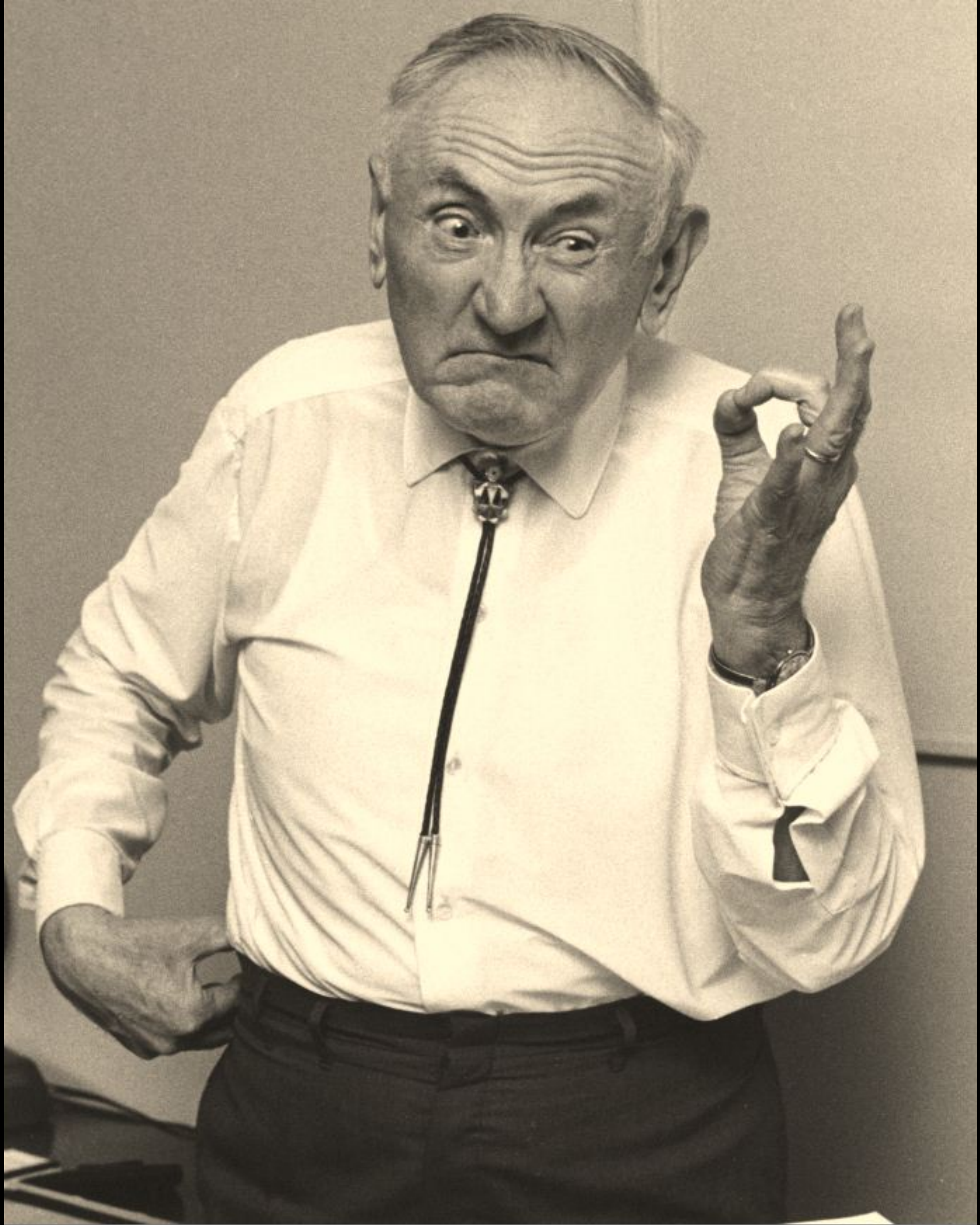
  $\ll$ cluster age

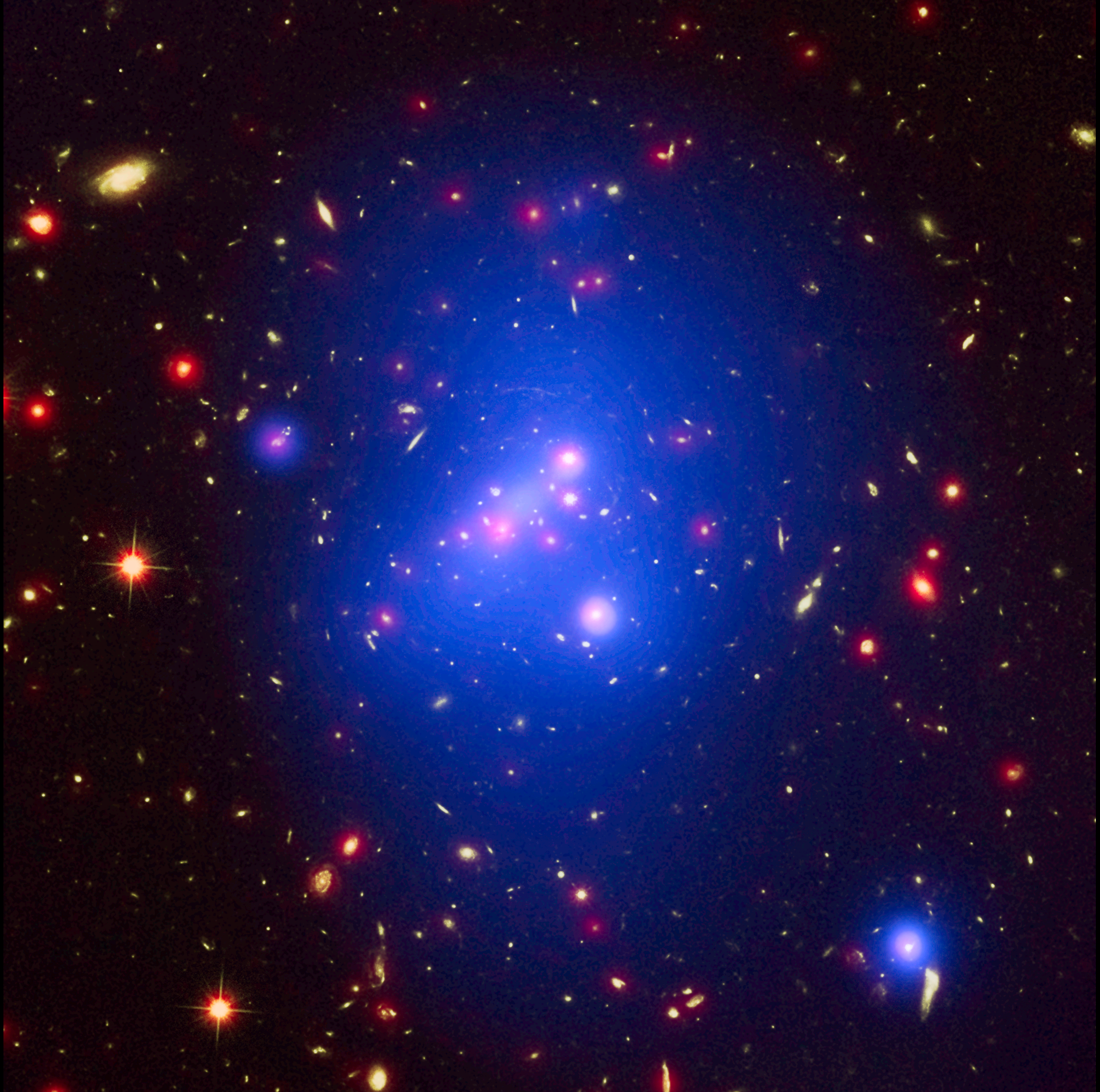
  $\Longrightarrow$ bound system

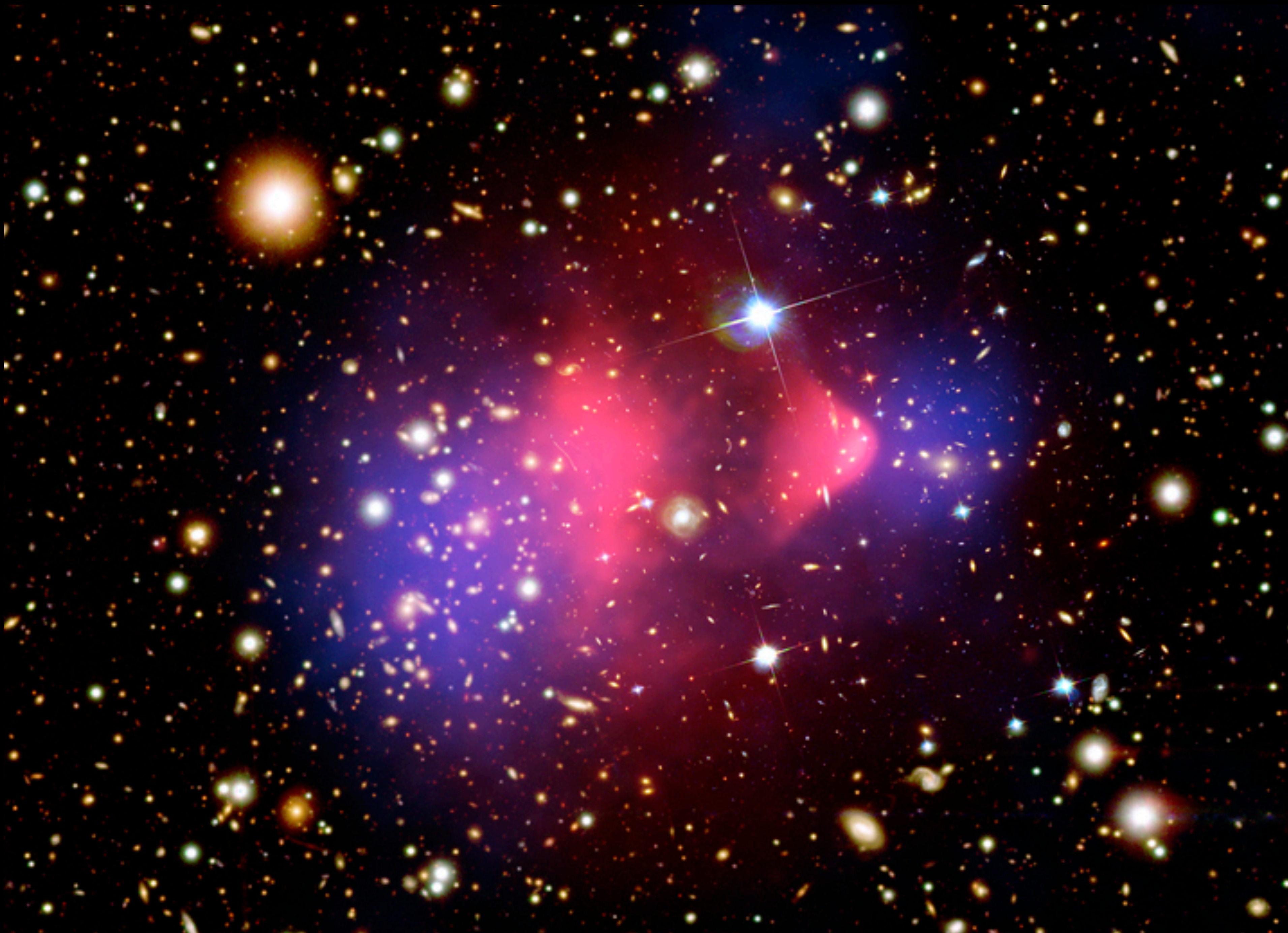
- estimate mass

$$M_{cl} \sim \frac{r_{cl}\sigma^2}{G} = 2\times 10^{14}\, M_\odot \quad \gg \quad M_{gal}$$

dark matter







Galaxy Collisions

- large galaxy cluster may have hundreds of galaxies within a radius of a few Mpc

$$\text{density} \quad n \sim 100 \text{ Mpc}^{-3}$$

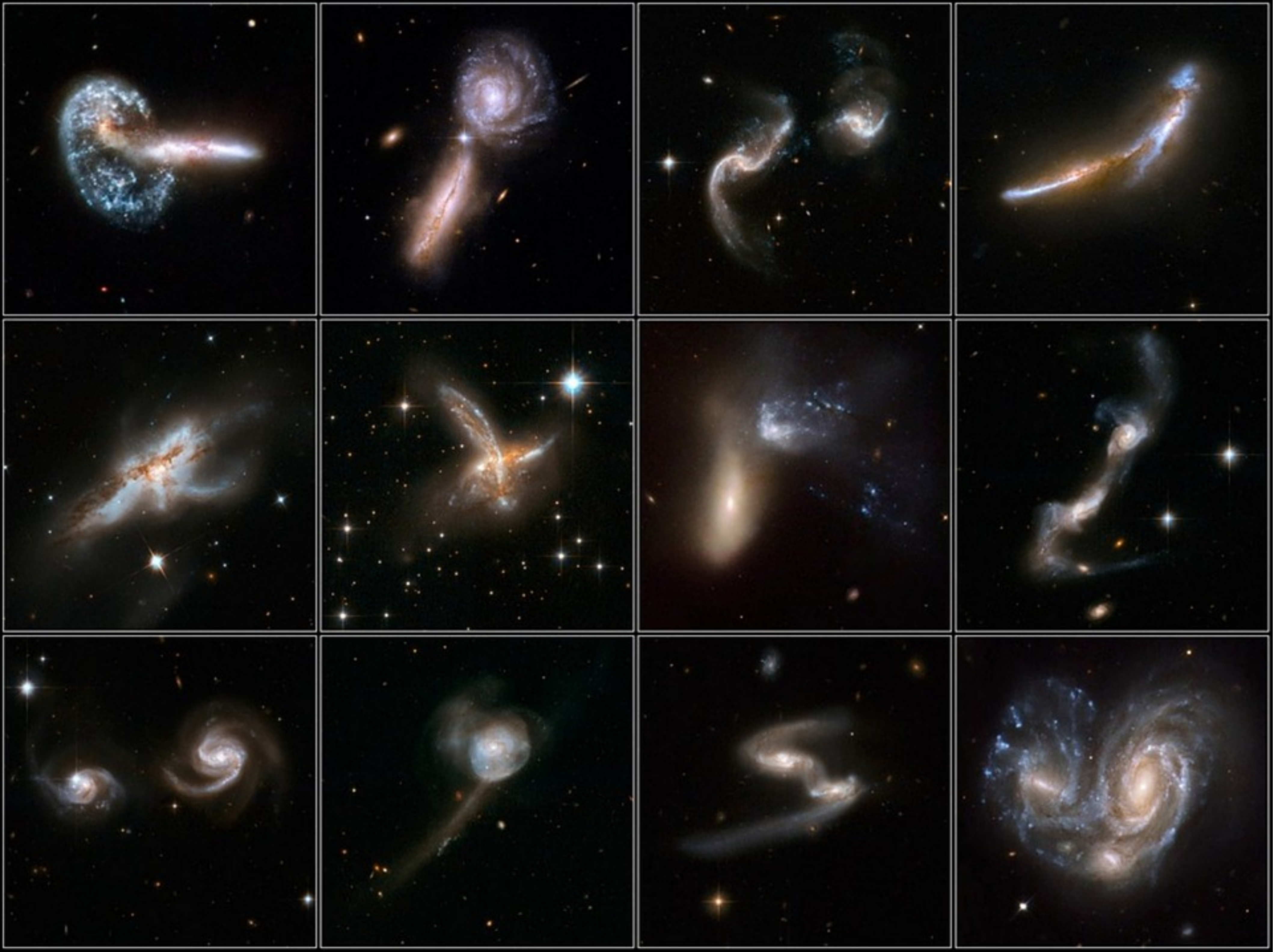
$$\text{velocity} \quad v \sim 1000 \text{ km s}^{-1}$$

- for a galaxies of effective radii $R \sim 50$ kpc, collision rate is

$$r \sim n \, \pi (2R)^2 \, v$$

$$\sim \frac{1}{300} \text{ Myr}^{-1}$$

galaxy collisions in clusters are <u>common</u>



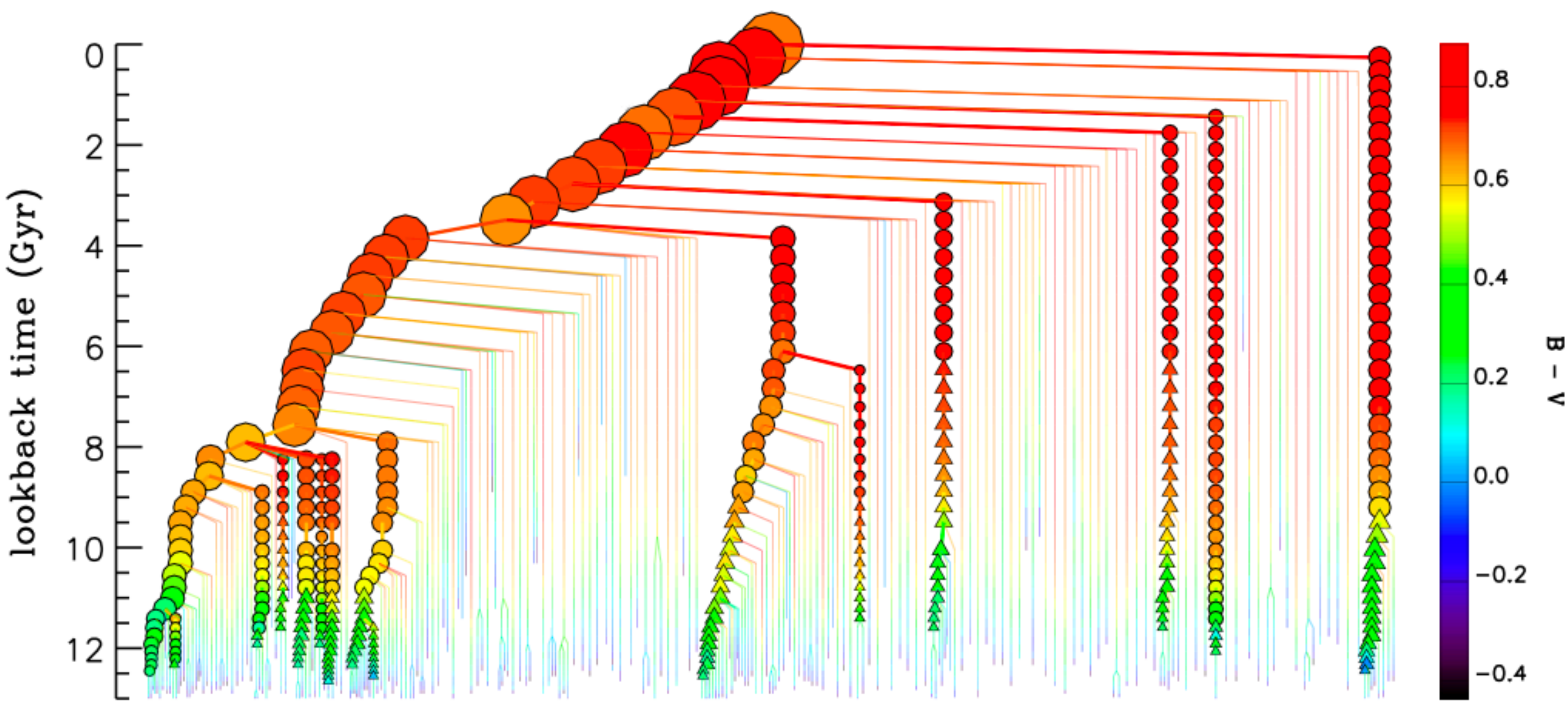
Barnes 1990


Seyfert's Sextet

Radio Galaxy MRC 1138-262 • **The Spiderweb Galaxy**
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, and G. Miley (Leiden Observatory)

STScI-PRC06-45


lookback time (Gyr)
0
2
4
6
8
10
12
B − V
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4