Distance Measurement

- Light echo

$$D = c\,\Delta t$$

- Standard ruler

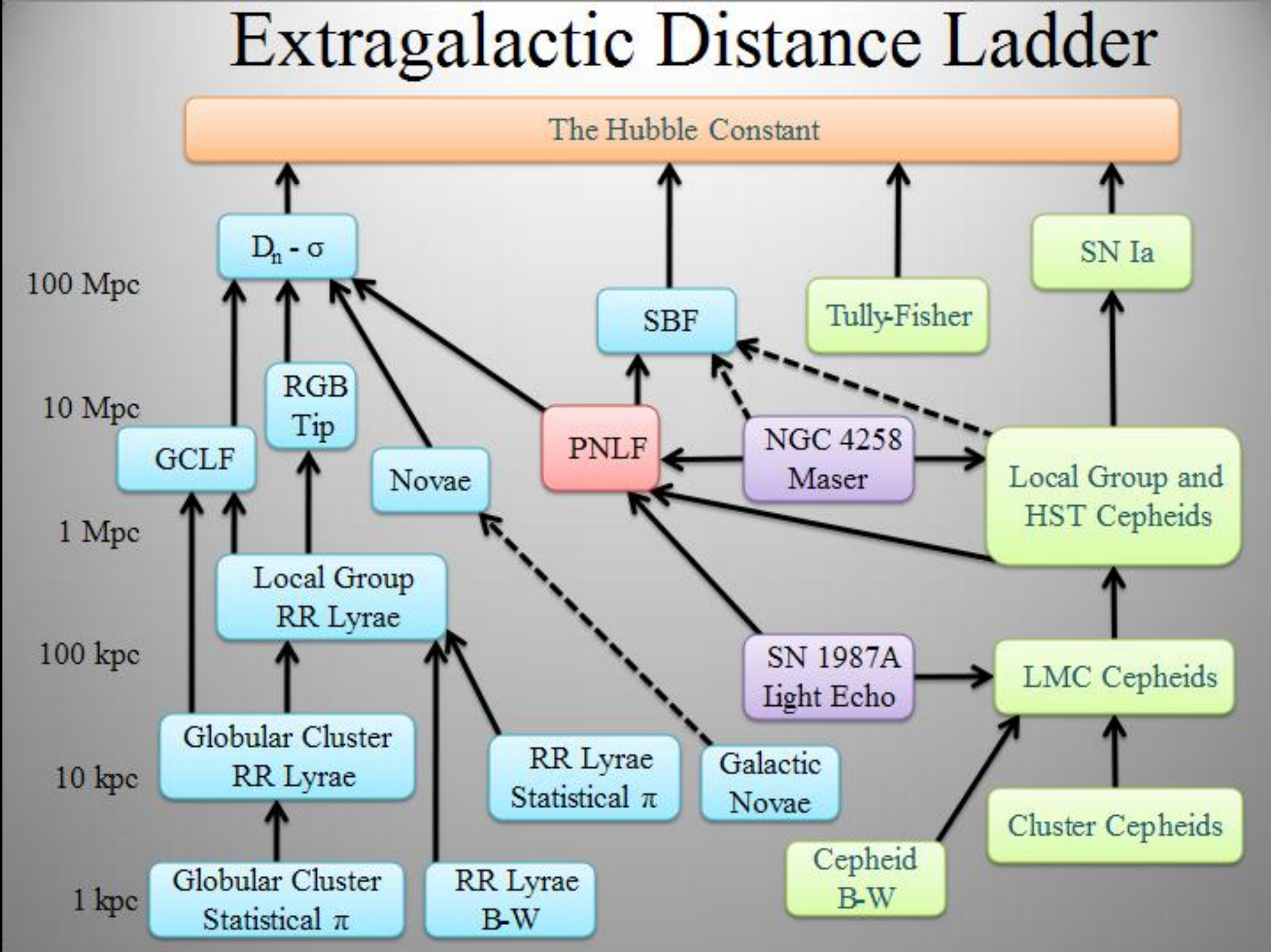
$$D = L / \theta$$

- Standard candle

$$D = \sqrt{\frac{L}{4\pi f}}$$

- Hubble expansion

$$D = \Delta v / H_0$$


Extragalactic Distance Ladder
The Hubble Constant
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
$D_n - \sigma$
SBF
Tully-Fisher
SN Ia
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

Distance Measurement

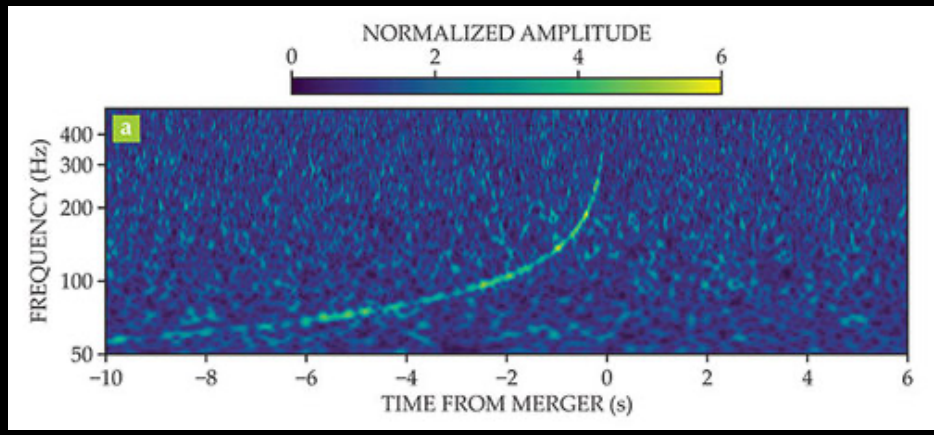
- Standard siren
  - GW “chirp” signal

$$\frac{d\Omega}{dt} = \frac{96}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{\frac{5}{3}}\Omega^{11/3}$$

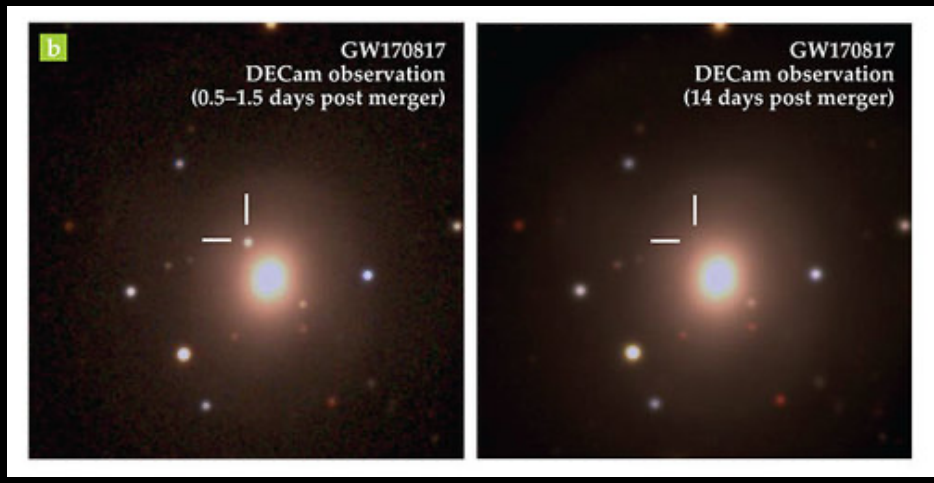
$$h_\times = \frac{4c}{D}\left(\frac{G\mathcal{M}}{c^3}\right)^{\frac{5}{3}}\Omega^{11/3}\cos i \sin 2\Phi(t)$$

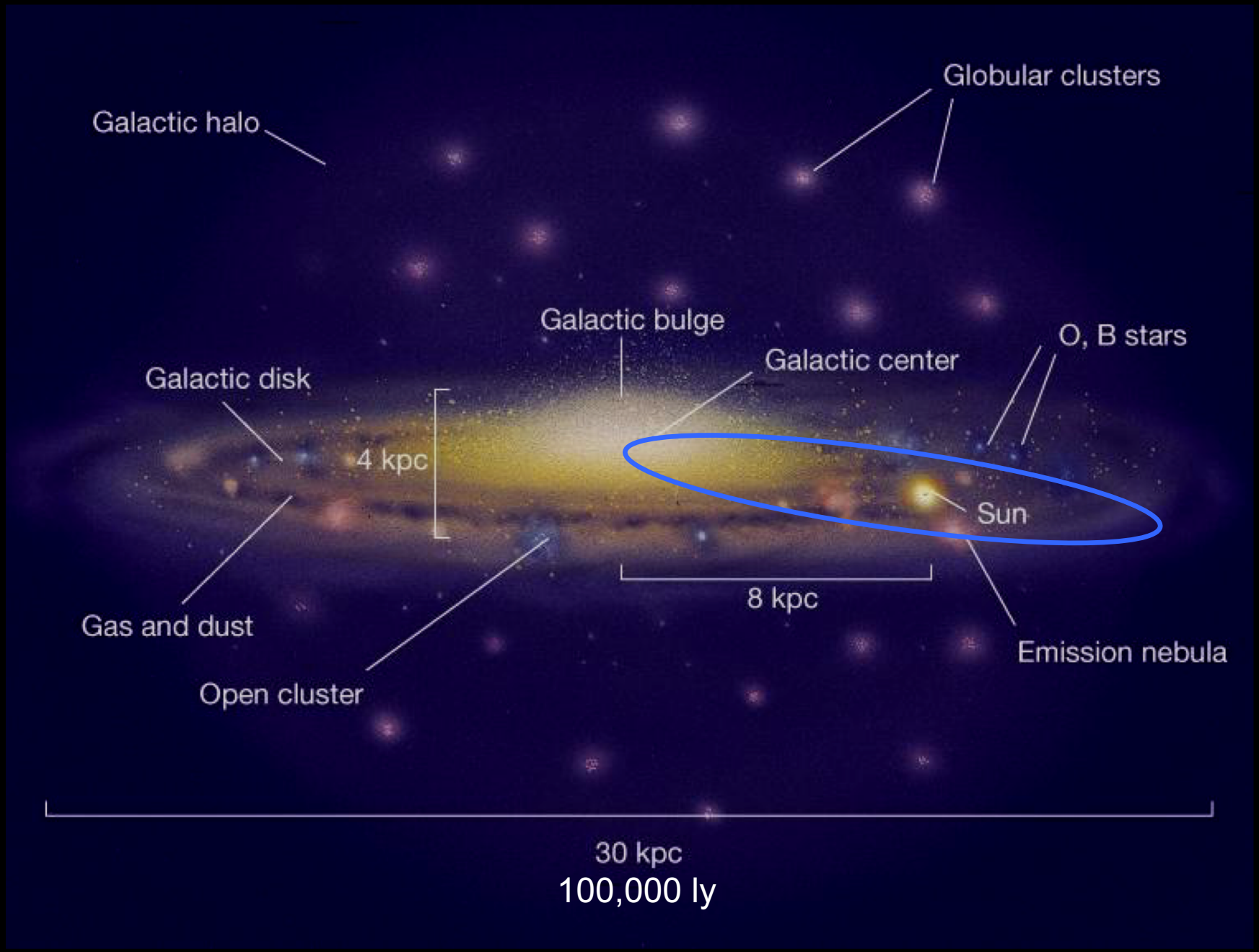
  - measure $\mathcal{M}$, h ⇒ distance D directly

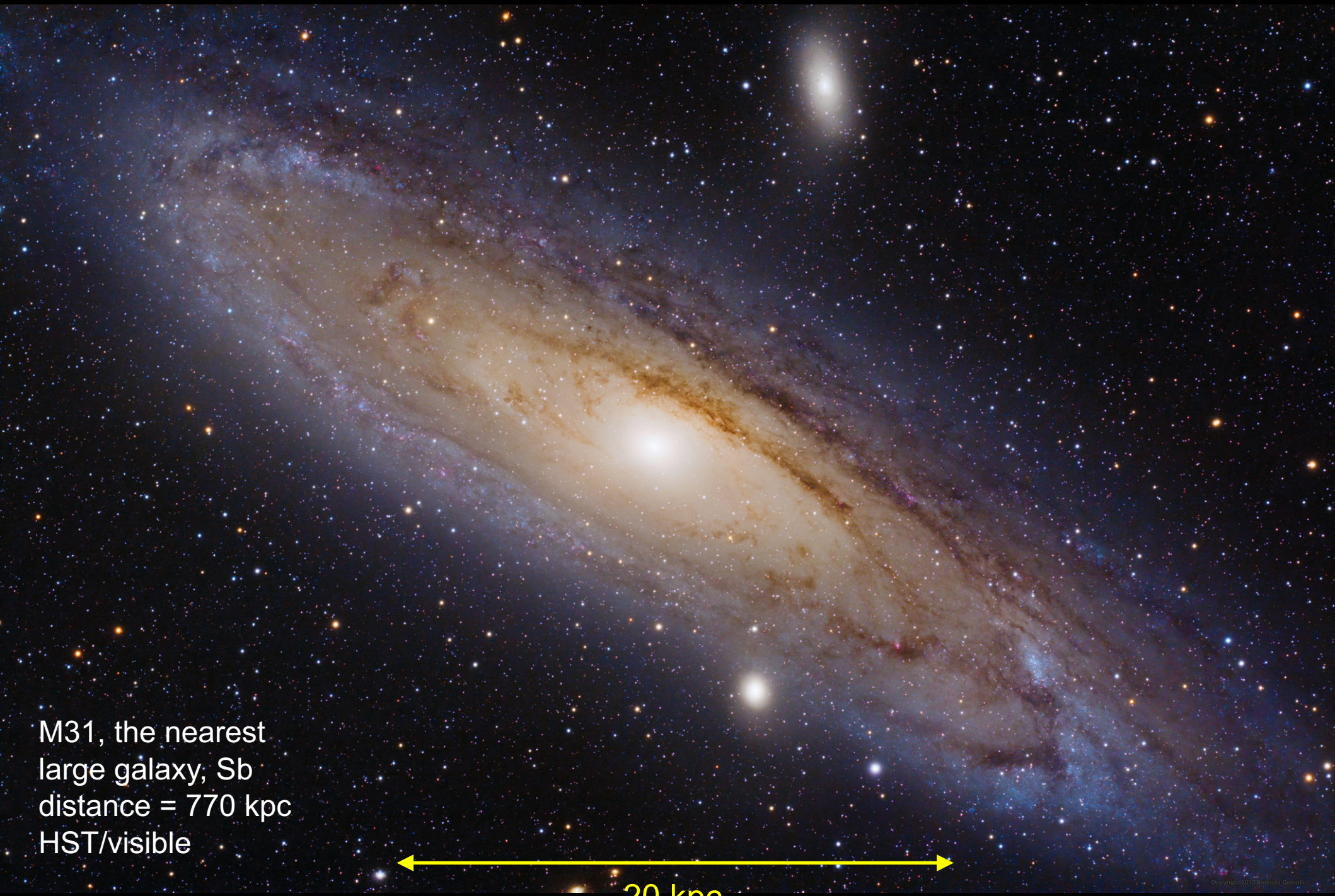
$$\mathcal{M} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}}$$

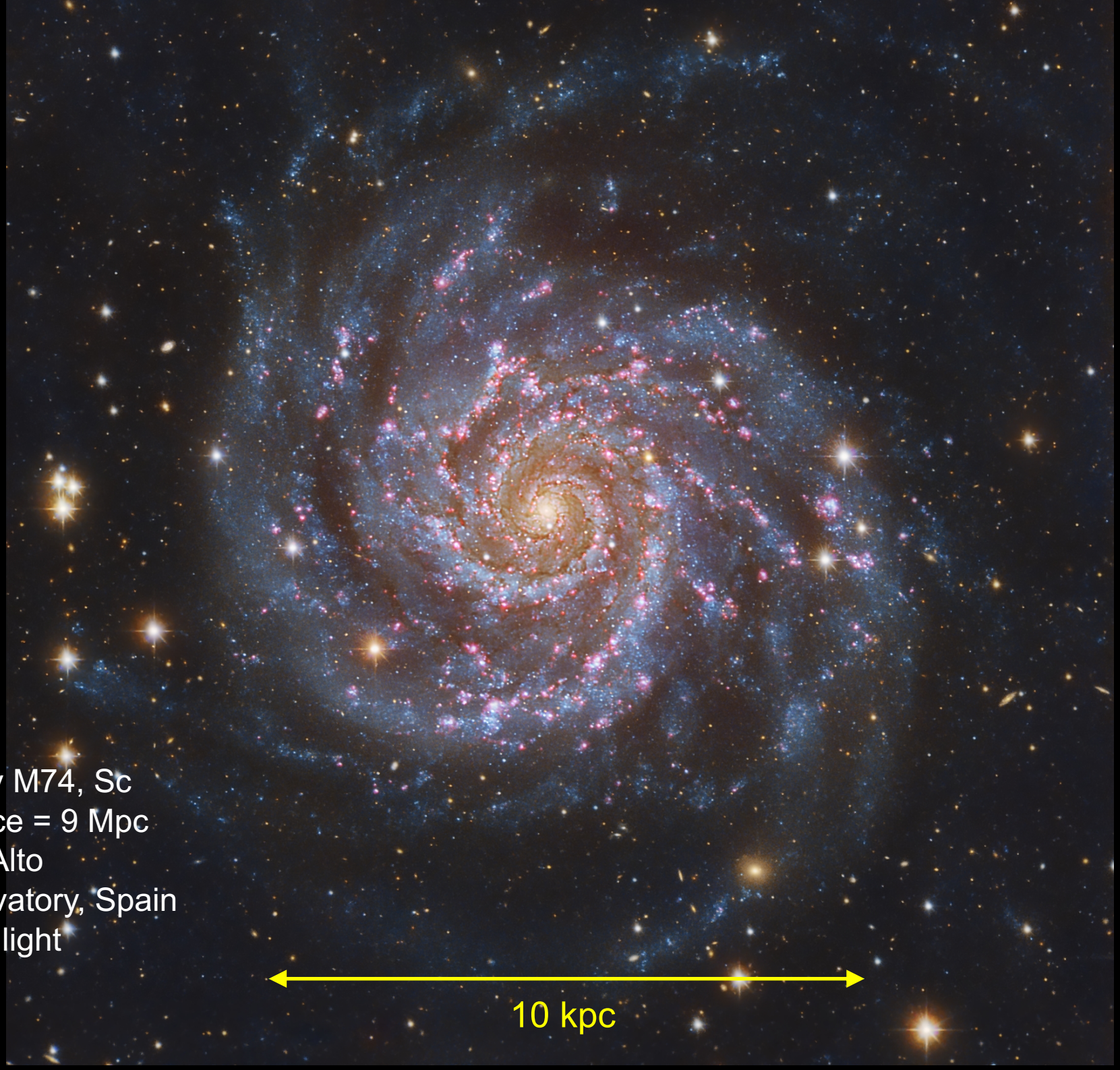


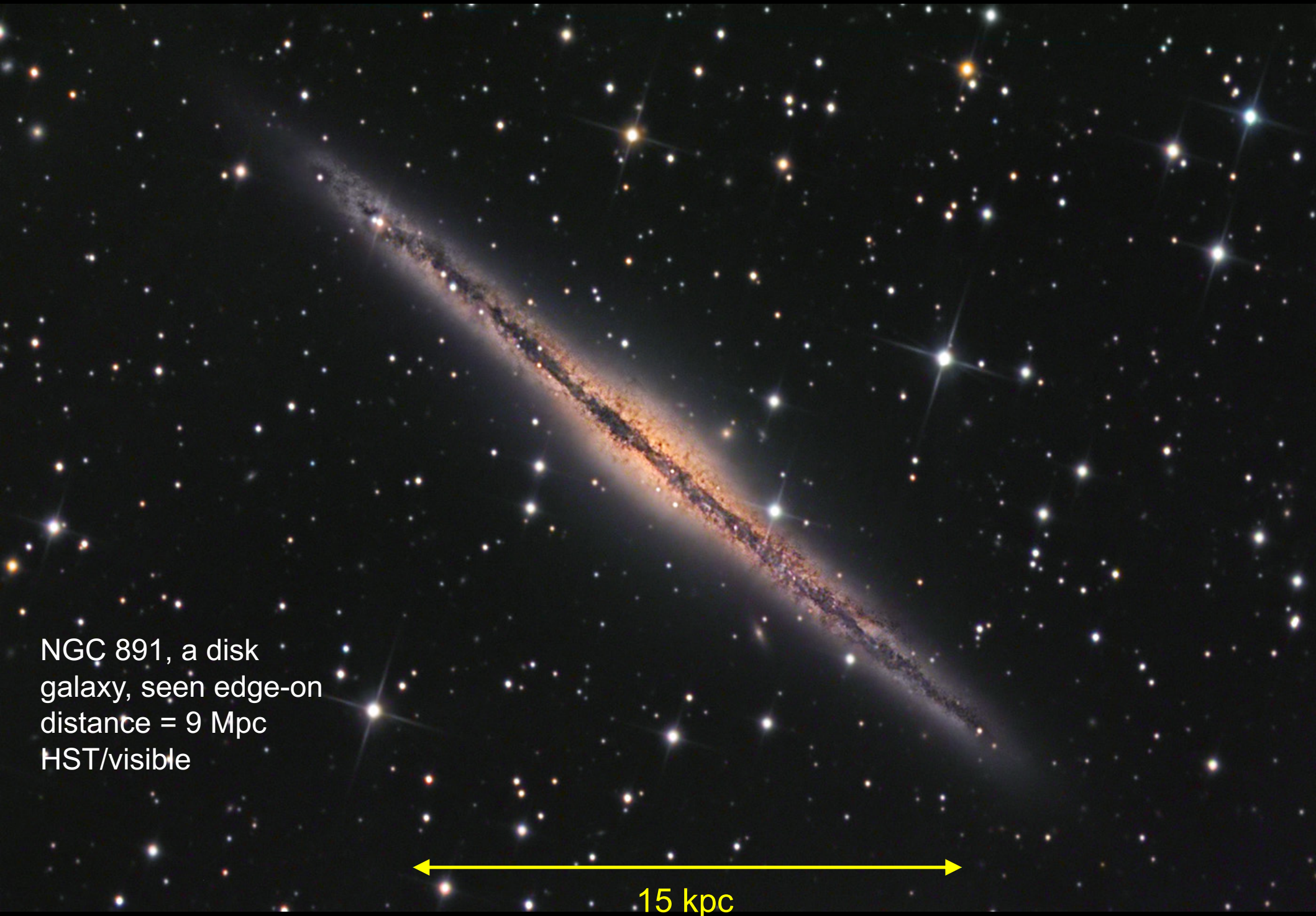
- multi-messenger astronomy
  - GW170817 (NS merger) had an <u>electromagnetic</u> counterpart
    ⇒ redshift measurement
    ⇒ measurement of H_0




Globular clusters
Galactic halo
Galactic bulge
O, B stars
Galactic center
Galactic disk
4 kpc
Sun
8 kpc
Gas and dust
Emission nebula
Open cluster
30 kpc
100,000 ly


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


Galaxy M74, Sc
distance = 9 Mpc
Calar Alto
Observatory, Spain
visible light
10 kpc

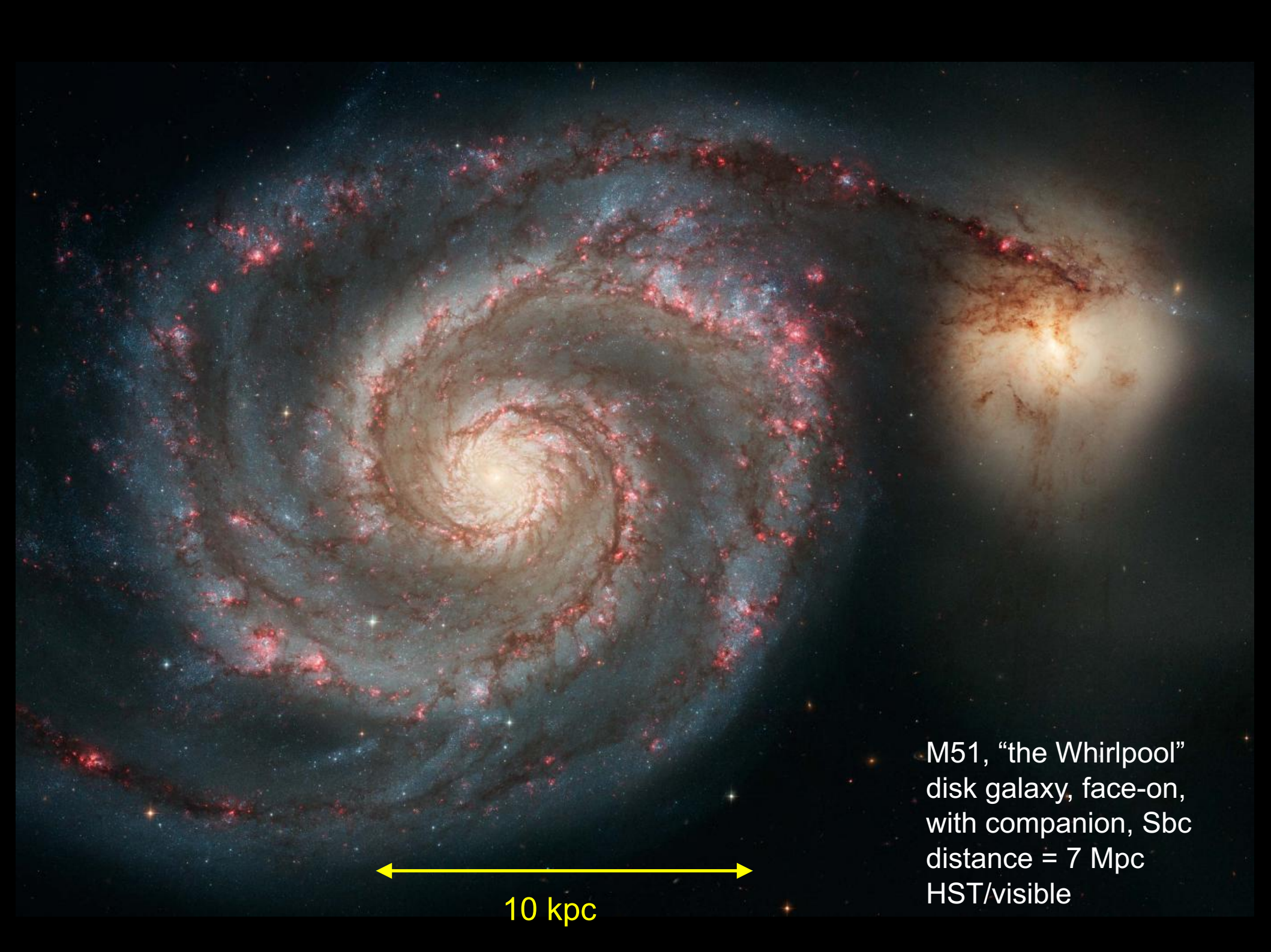

NGC 891, a disk
galaxy, seen edge-on
distance = 9 Mpc
HST/visible
15 kpc

Sombrero Galaxy • M104

NGC 4594, a disk galaxy, seen almost edge-on, Sa
distance = 9 Mpc
HST/visible

Hubble Heritage

10 kpc



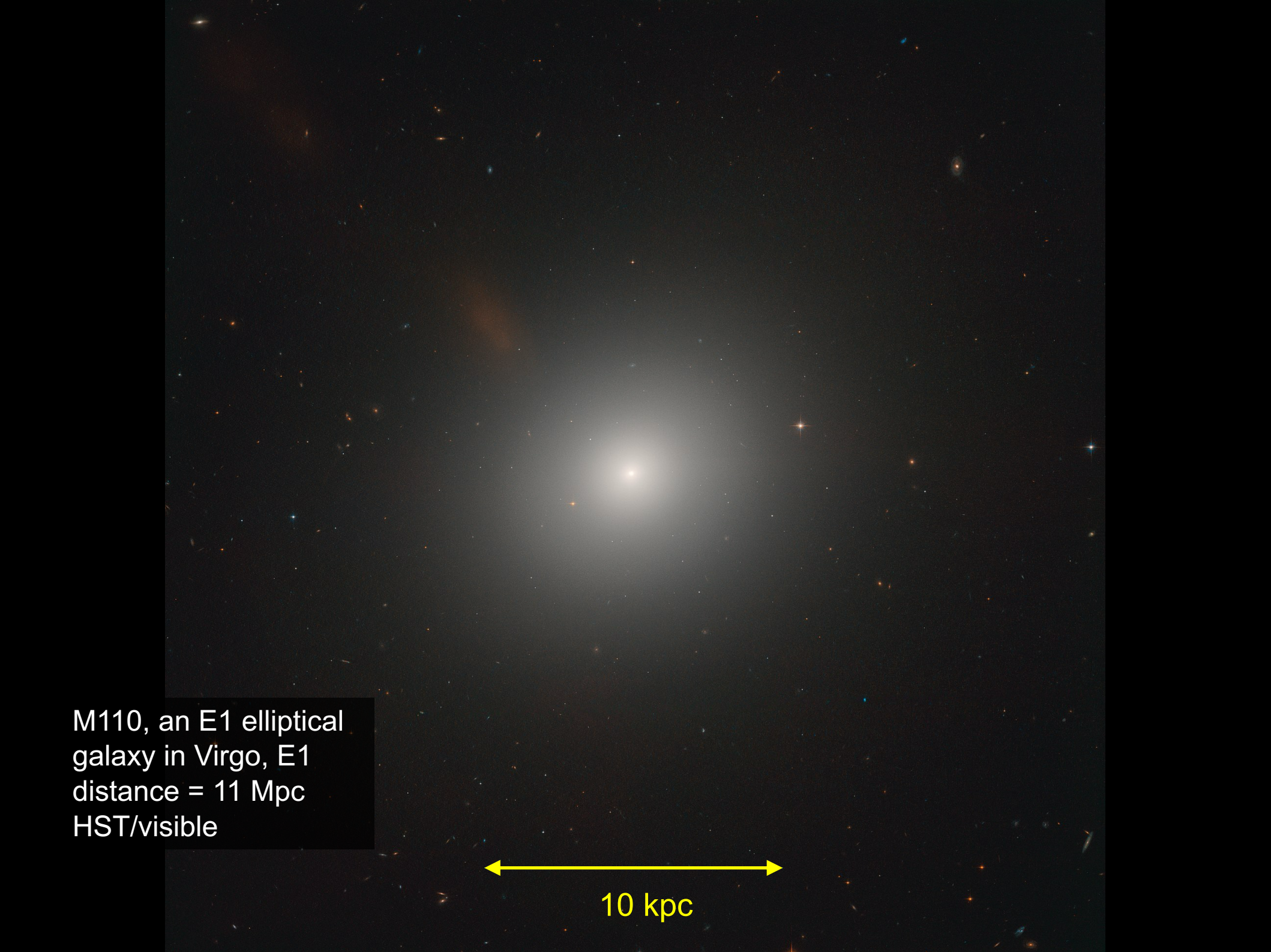
M51, “the Whirlpool”
disk galaxy, face-on,
with companion, Sbc
distance = 7 Mpc
HST/visible

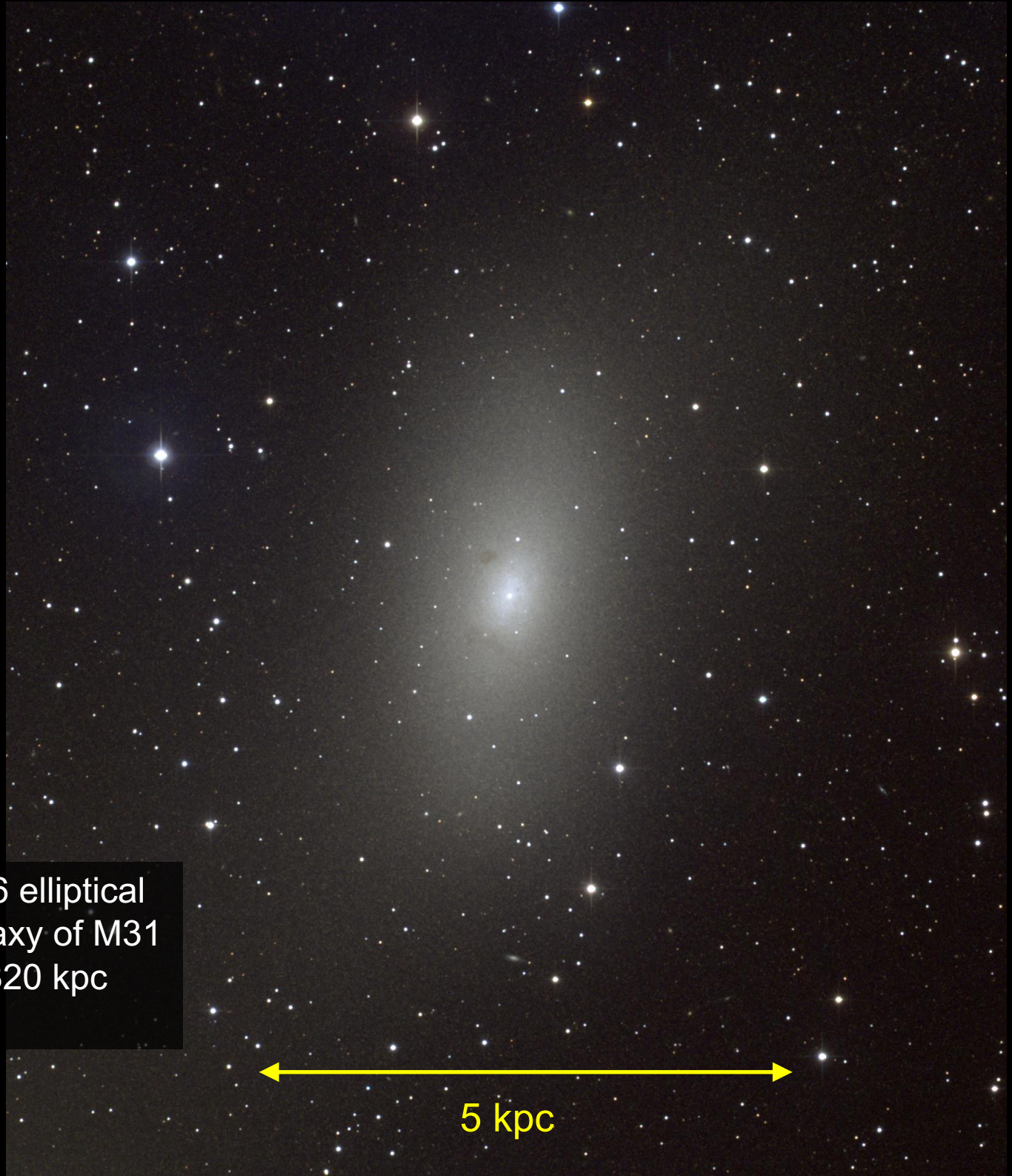
Barred Spiral Galaxy NGC 1300

NGC 1300, a barred-spiral galaxy, seen almost face-on, SBc
distance = 19 Mpc
HST/visible

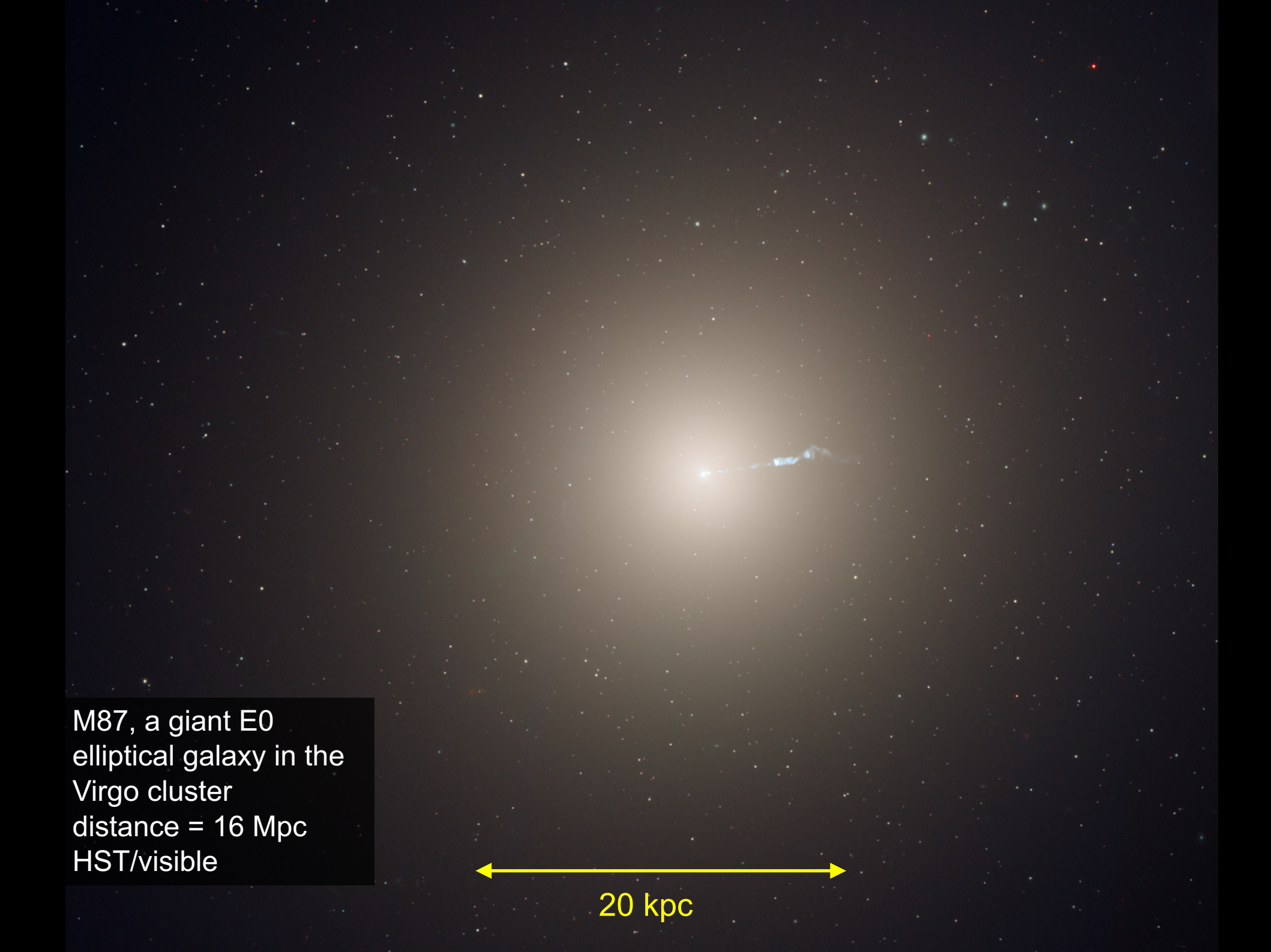
10 kpc

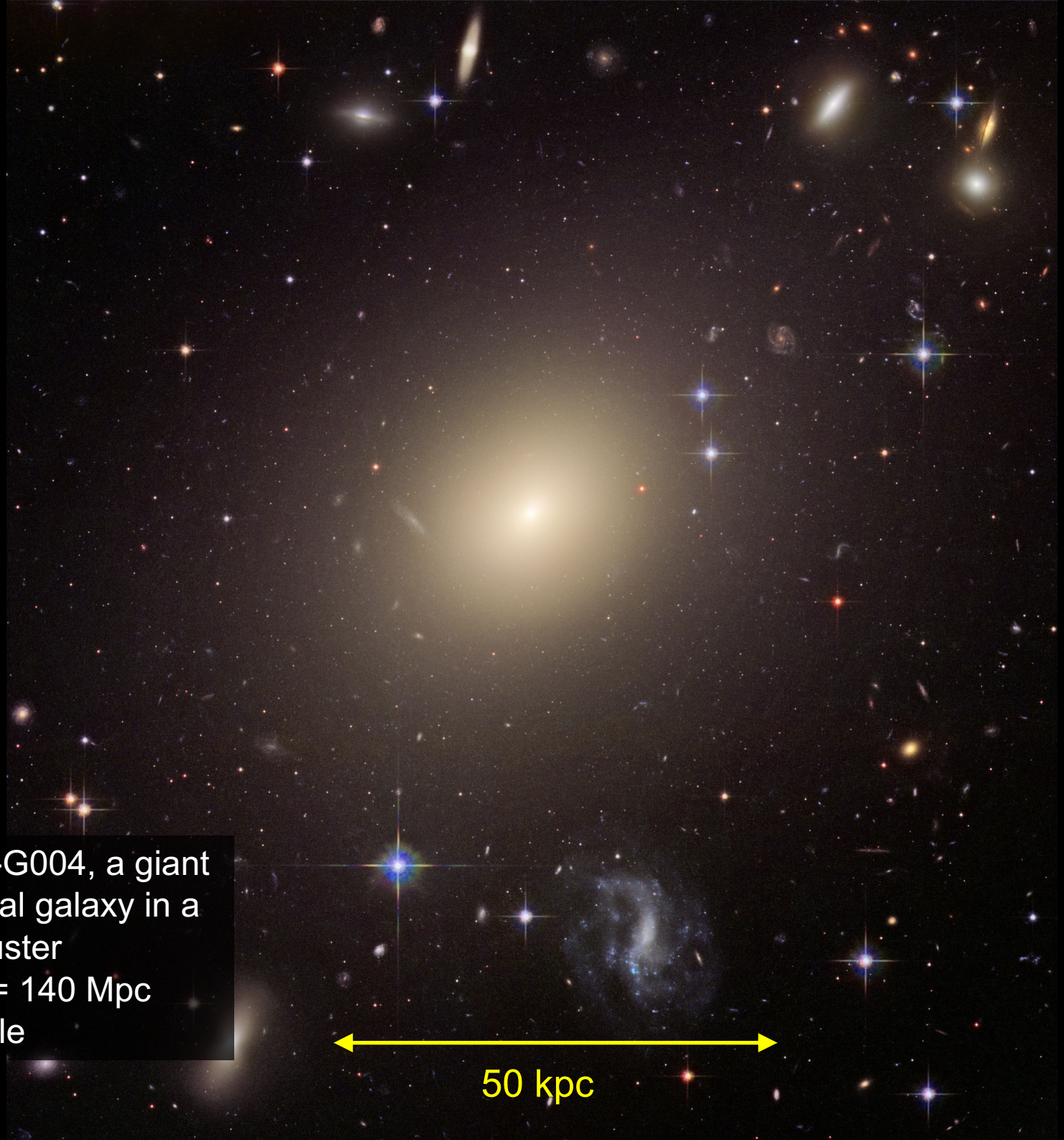
Hubble Heritage


M110, an E1 elliptical
galaxy in Virgo, E1
distance = 11 Mpc
HST/visible
10 kpc

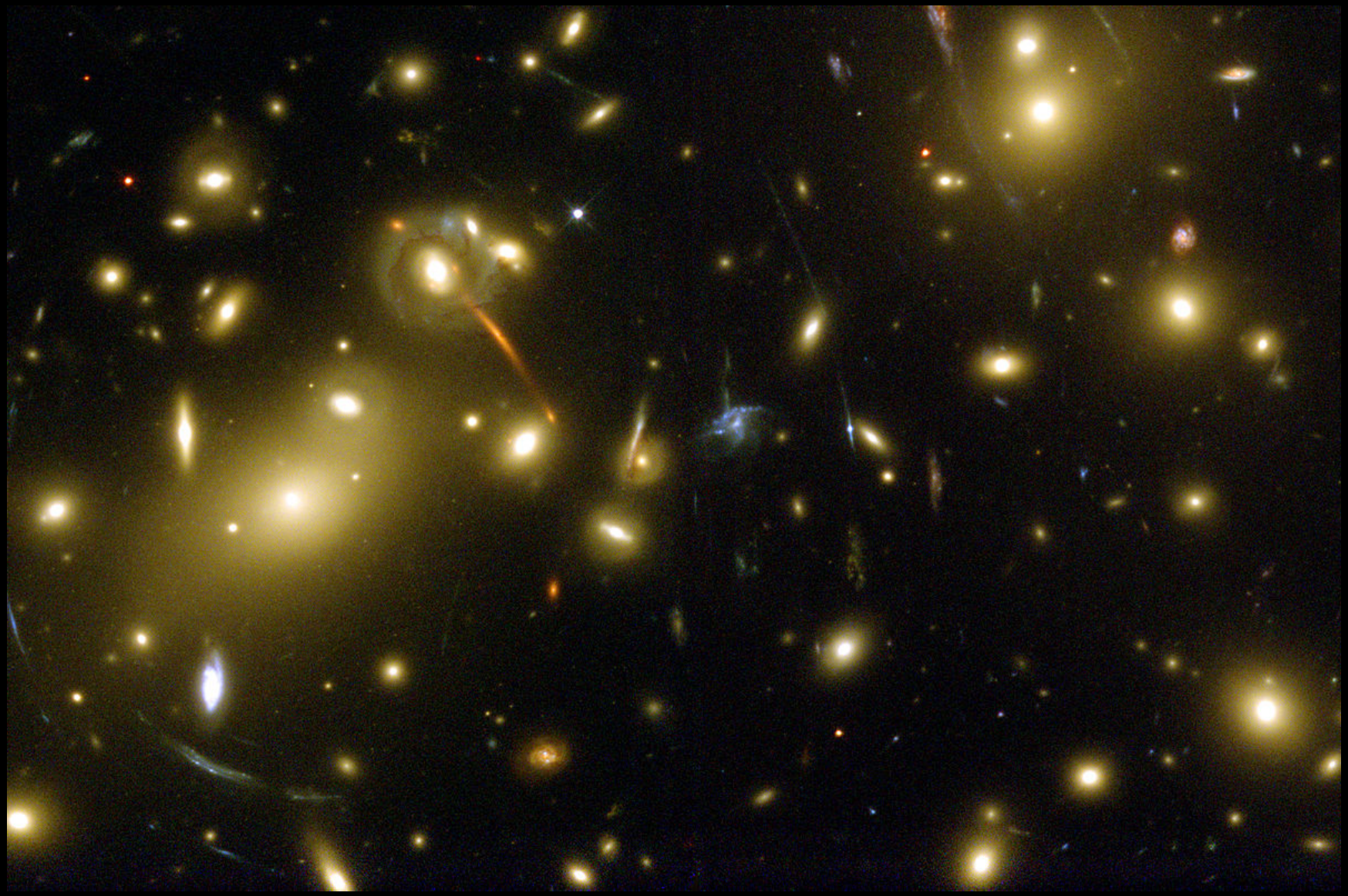


M110, an E6 elliptical
satellite galaxy of M31
distance = 820 kpc
HST/visible


M87, a giant E0
elliptical galaxy in the
Virgo cluster
distance = 16 Mpc
HST/visible
20 kpc

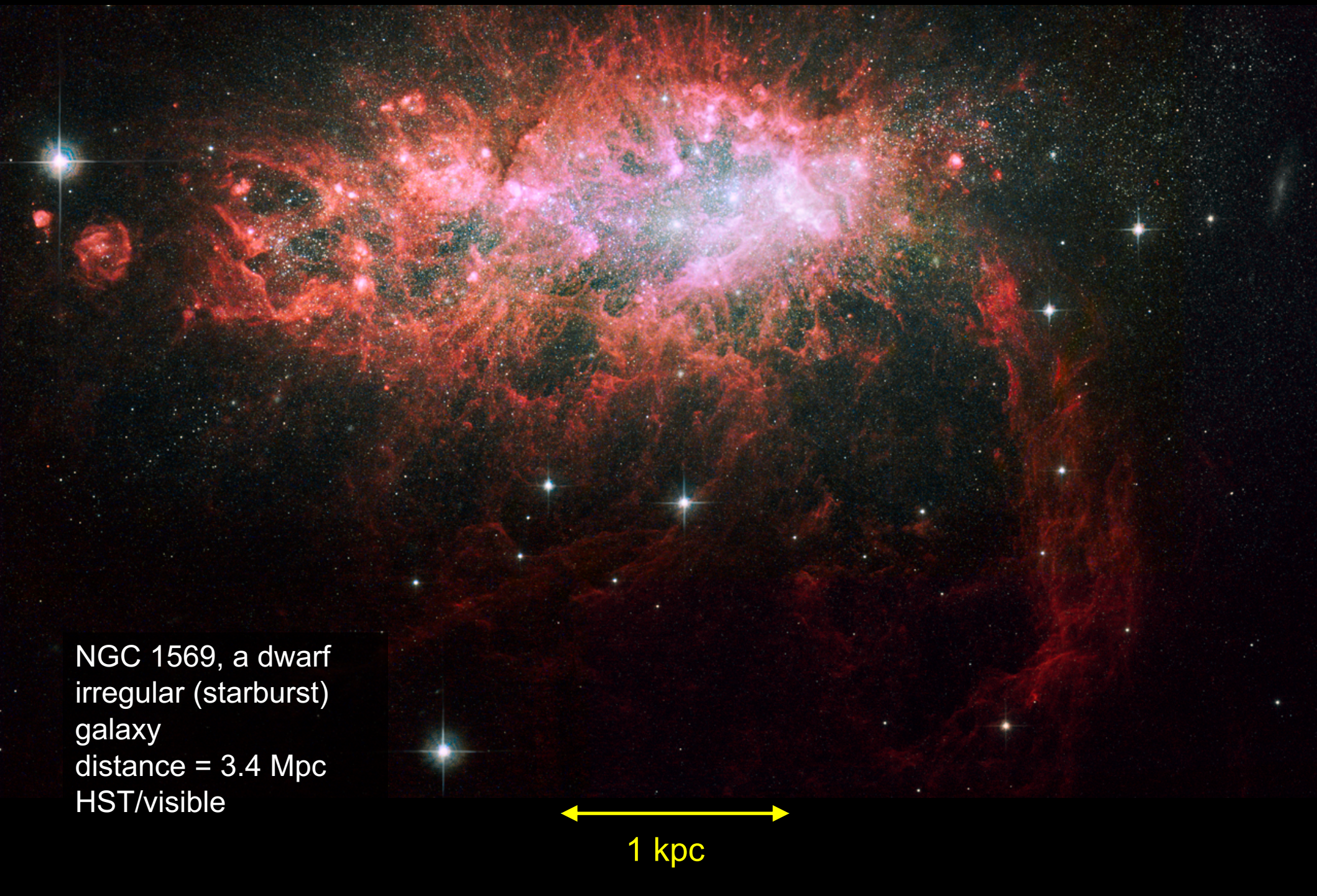


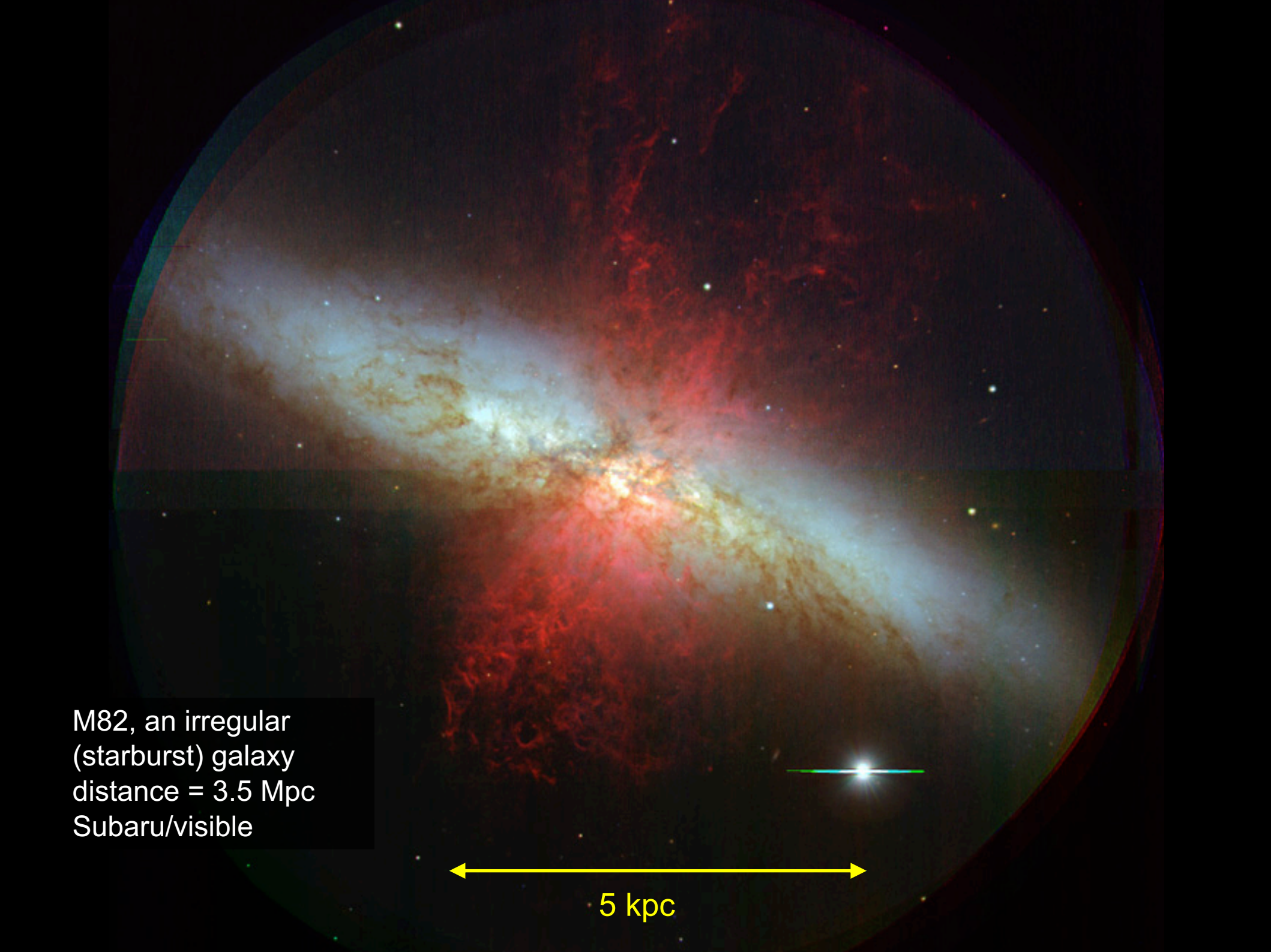
ESO 325-G004, a giant E2 elliptical galaxy in a galaxy cluster
distance = 140 Mpc
HST/visible



Abell 2218, a large
galaxy cluster
distance 700 Mpc
HST/visible

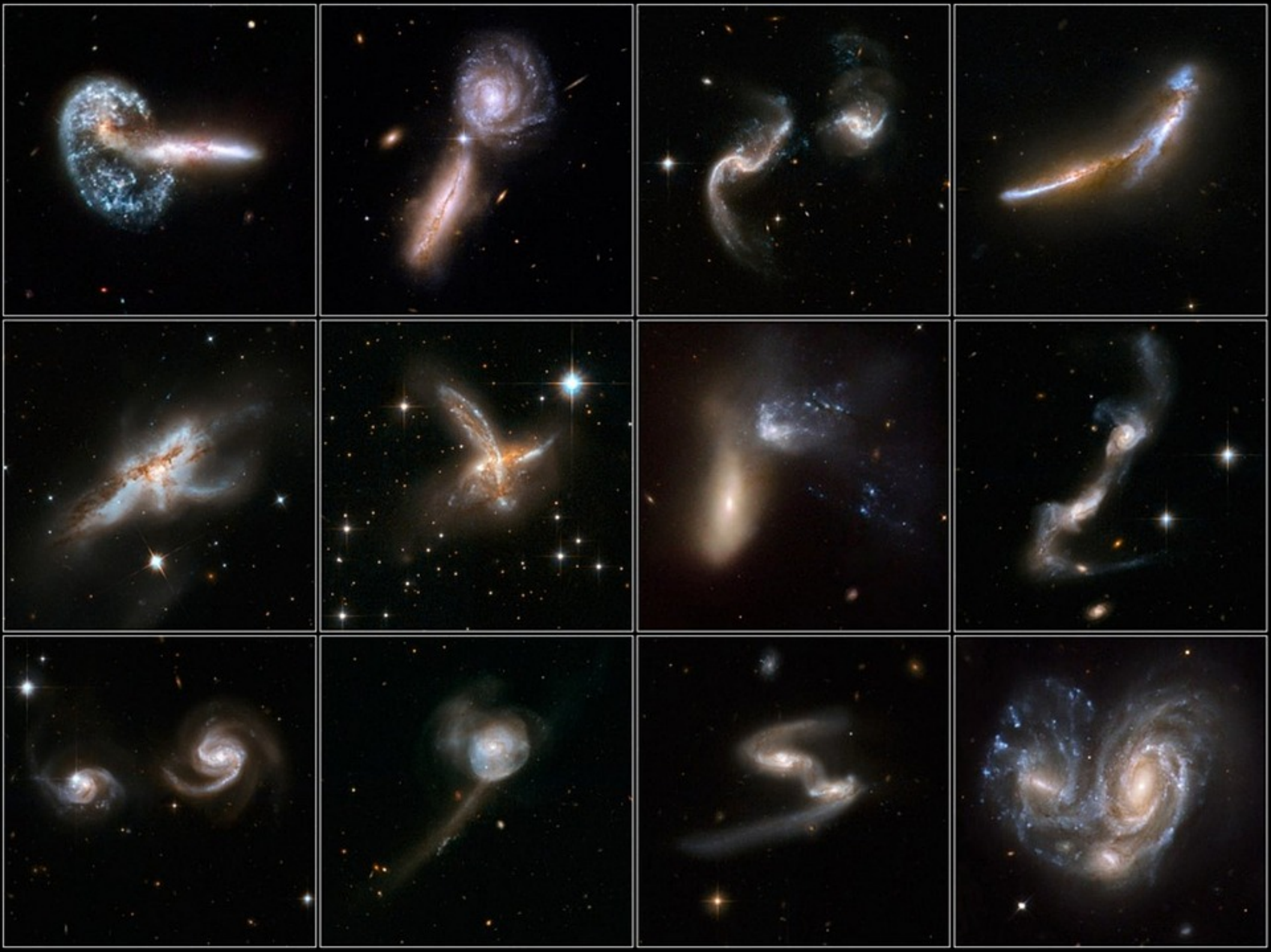
1 Mpc


NGC 1569, a dwarf irregular (starburst) galaxy
distance = 3.4 Mpc
HST/visible
1 kpc

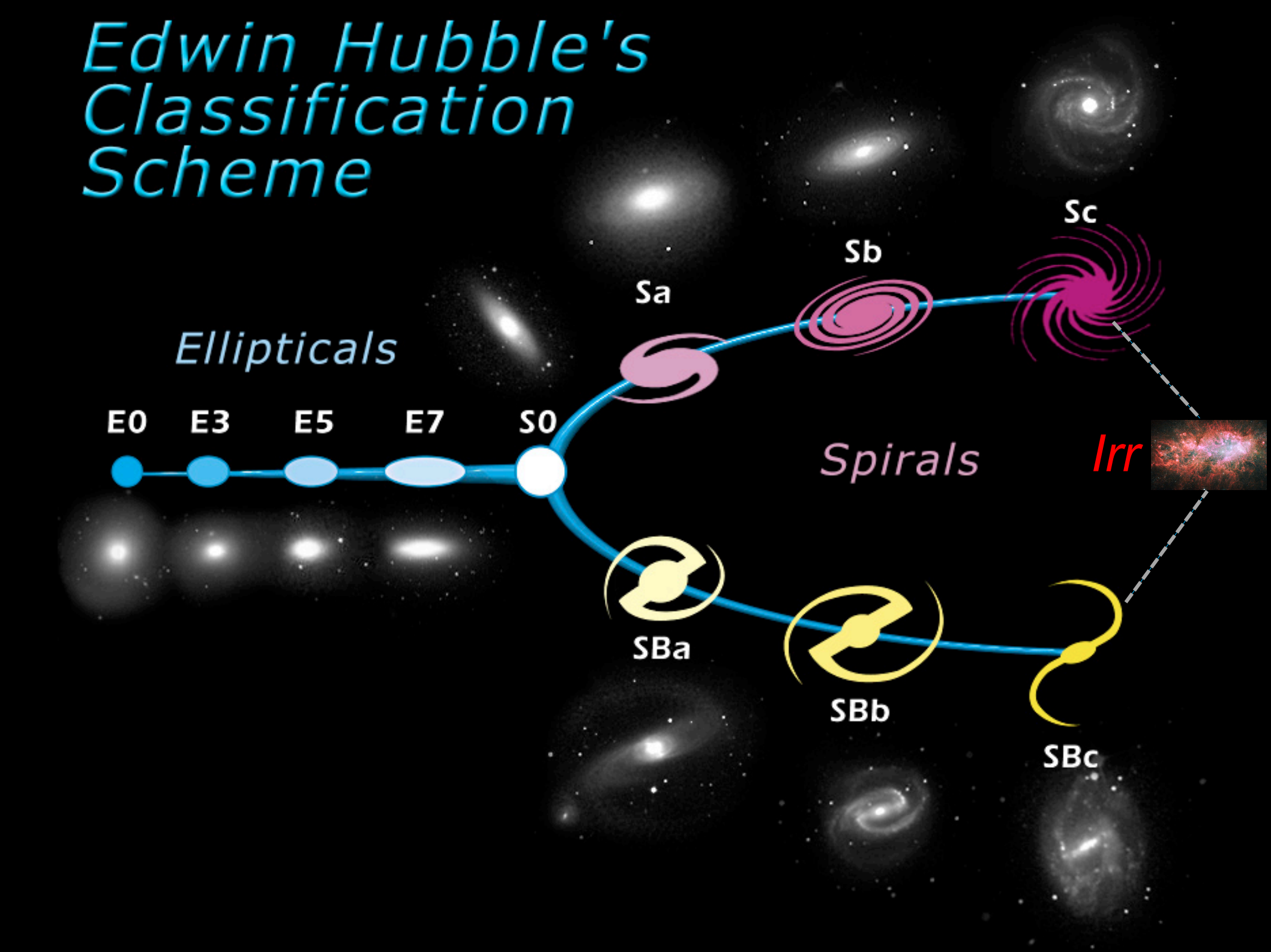

M82, an irregular
(starburst) galaxy
distance = 3.5 Mpc
Subaru/visible
5 kpc

M82 and M81 (Sab),
on a larger scale
distance ~ 10 Mpc
HST/visible

50 kpc



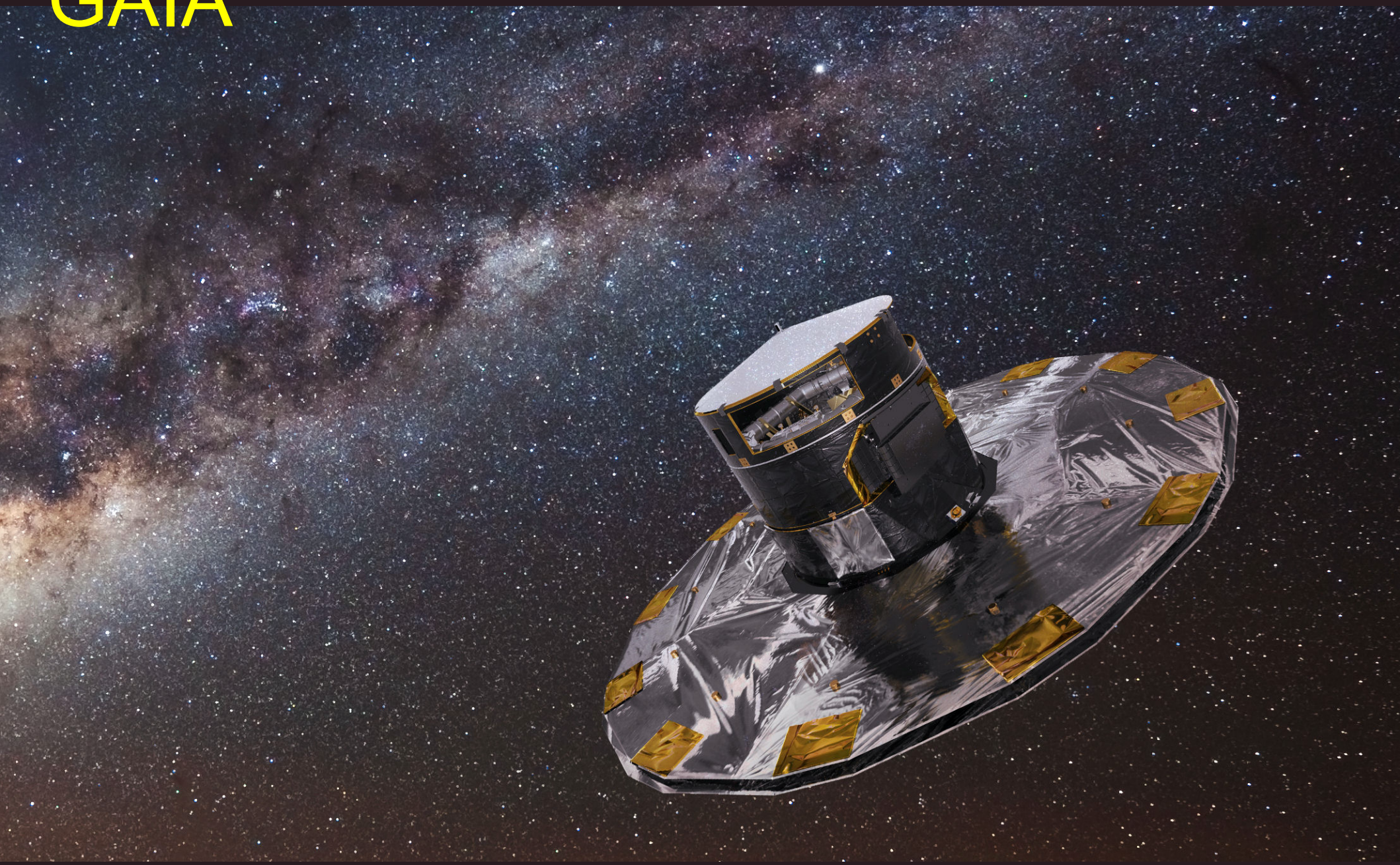
Edwin Hubble's Classification Scheme

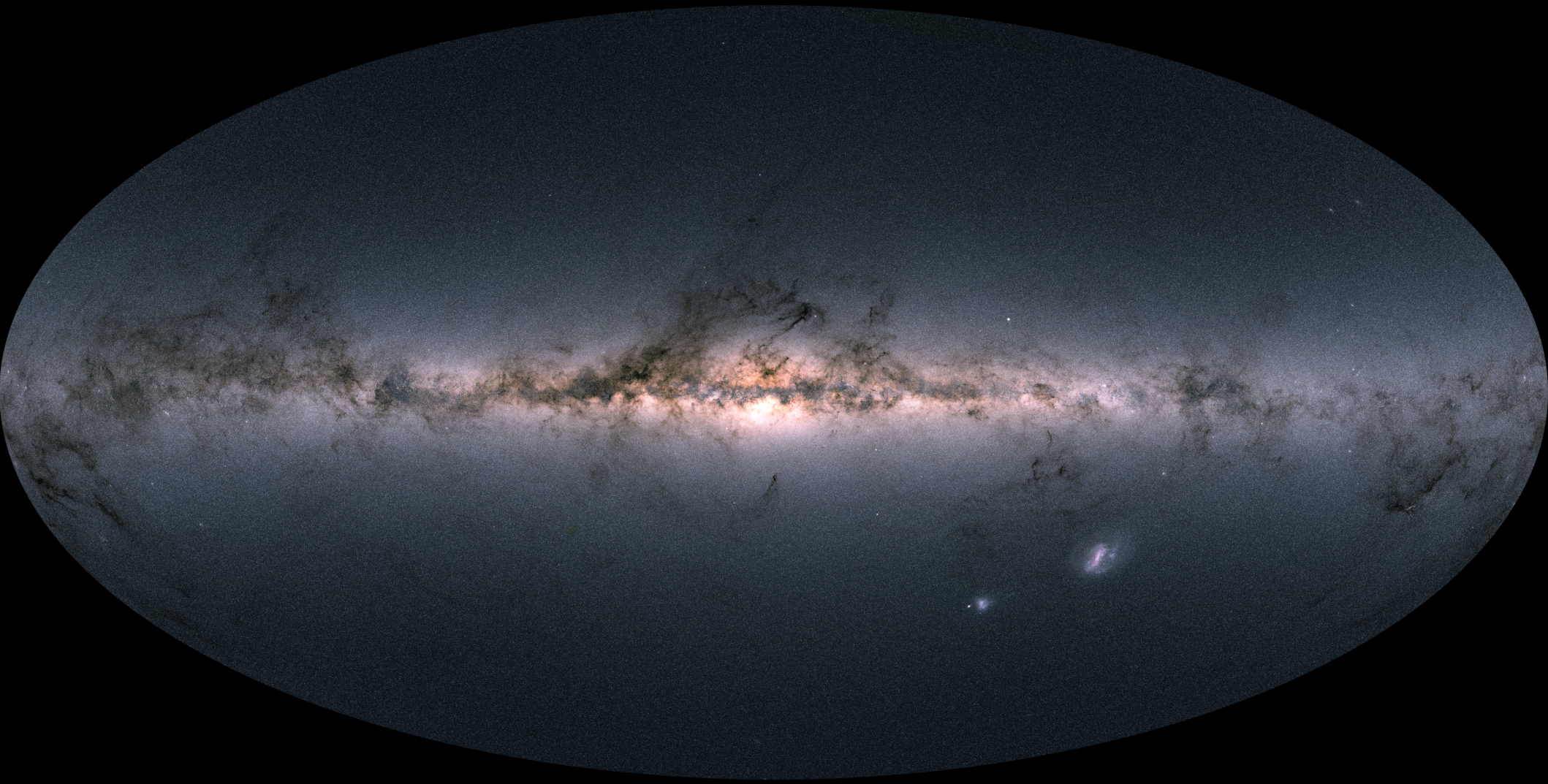


Stellar Properties

- positions and velocities – astrometry
  - parallax, proper motion, radial velocity
  - GAIA: 6D information on 3 billion stars to distances > 10 kpc

GAIA

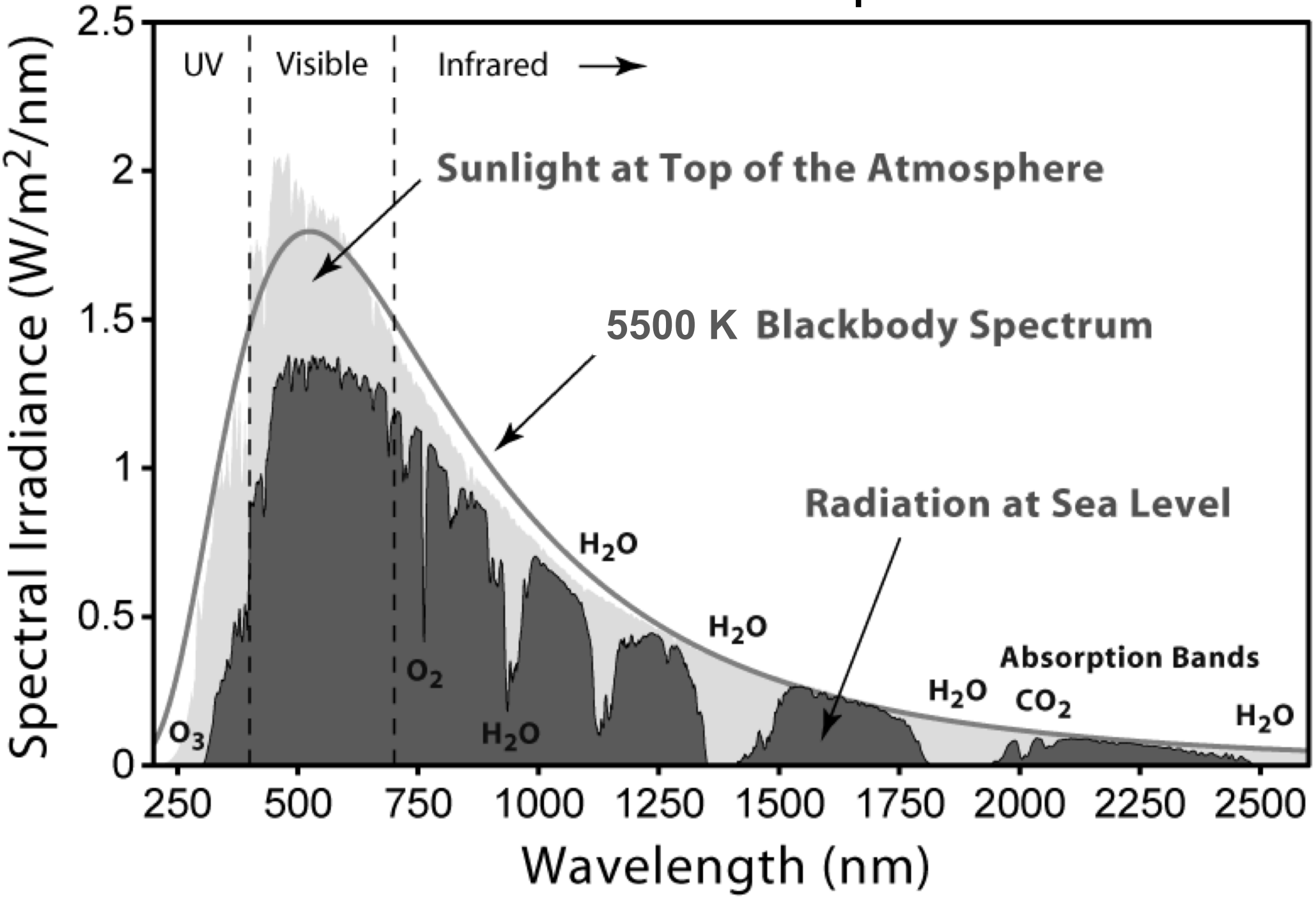




Stellar Properties

- positions and velocities – astrometry
- luminosities
  - inverse-square law
    - $f = \frac{L}{4\pi D^2}$

Solar Radiation Spectrum



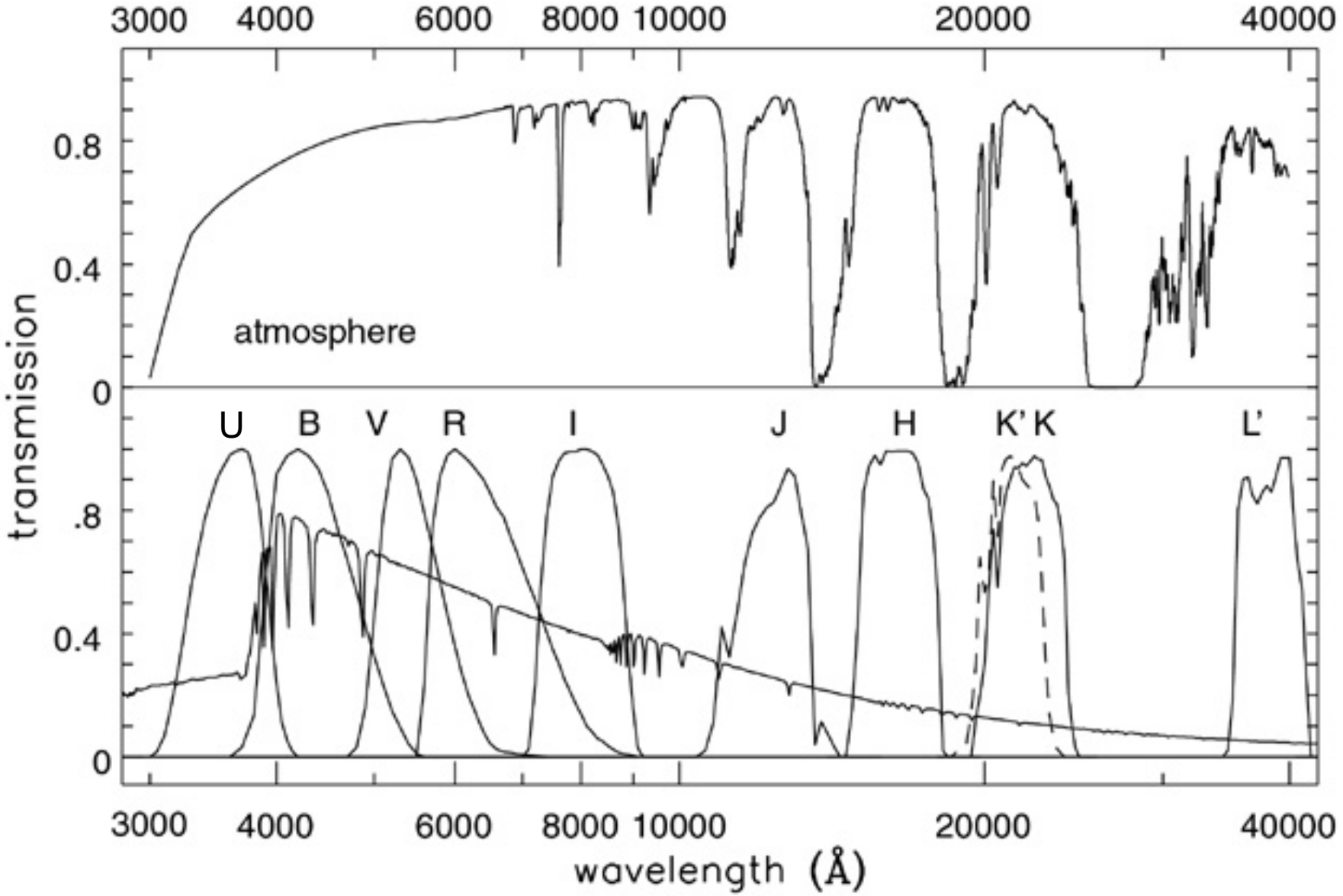


Fig 1.7 (M. Bessell) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Stellar Properties

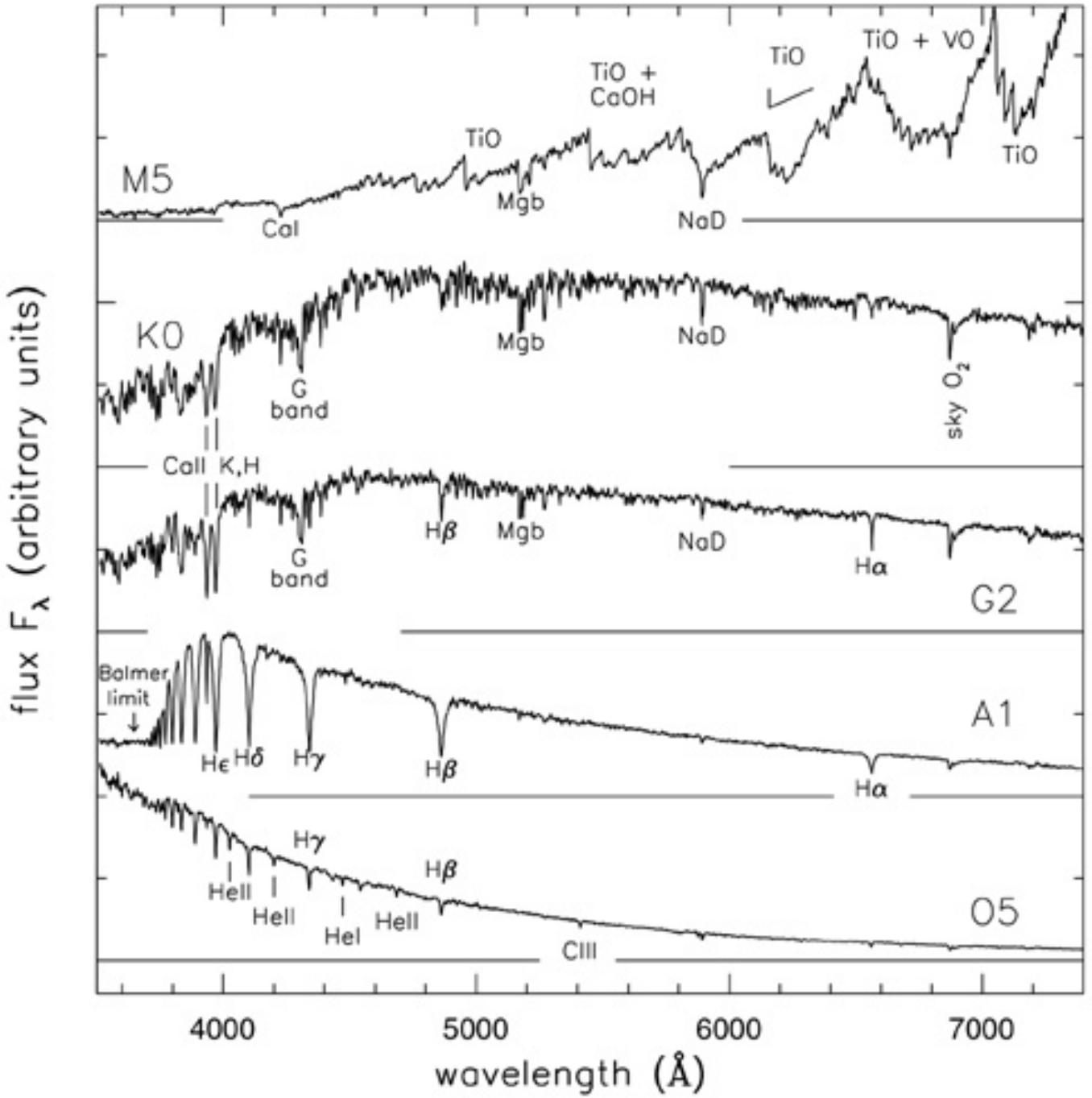
- positions and velocities – astrometry
- luminosities
  - inverse-square law
    - $f = \frac{L}{4\pi D^2}$
  - filters – photometry
    - $f_C = \int f(\lambda)\, t_C(\lambda)\, d\lambda$
  - the magnitude scale…

Stellar Properties

- positions and velocities – astrometry
- luminosities
  - inverse-square law
    - $f = \frac{L}{4\pi D^2}$
  - filters – photometry
    - $f_C = \int f(\lambda)\, t_C(\lambda)\, d\lambda$
  - the magnitude scale
    - $m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right) = 2.5 \log_{10}\left(\frac{f_2}{f_1}\right)$
    - $m - M = 5 \log_{10} D(\mathrm{pc}) - 5$
  - colors
    - $U - V \equiv m_U - m_V = 2.5 \log_{10}\left(\frac{f_V}{f_U}\right)$, etc.

Stellar Properties

- positions and velocities – astrometry
- luminosities
- temperatures
  - “effective” blackbody temperature
  - colors
  - spectra
- composition
- radii
- masses



3,300 K

5,200 K

5,800 K

9,100 K

41,000 K

Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007