
Other Galaxies!

Galaxies

- A galaxy is a gravitationally bound collection of stars, gas and dust
  - e.g. our Galaxy contains of order 10^{11} stars
- Usually isolated in space, although can interact with near neighbours
- The main visible component of the Universe

Galaxy Types

- Galaxies are seen in three major types
  - Spirals
  - Ellipticals
  - Irregulars

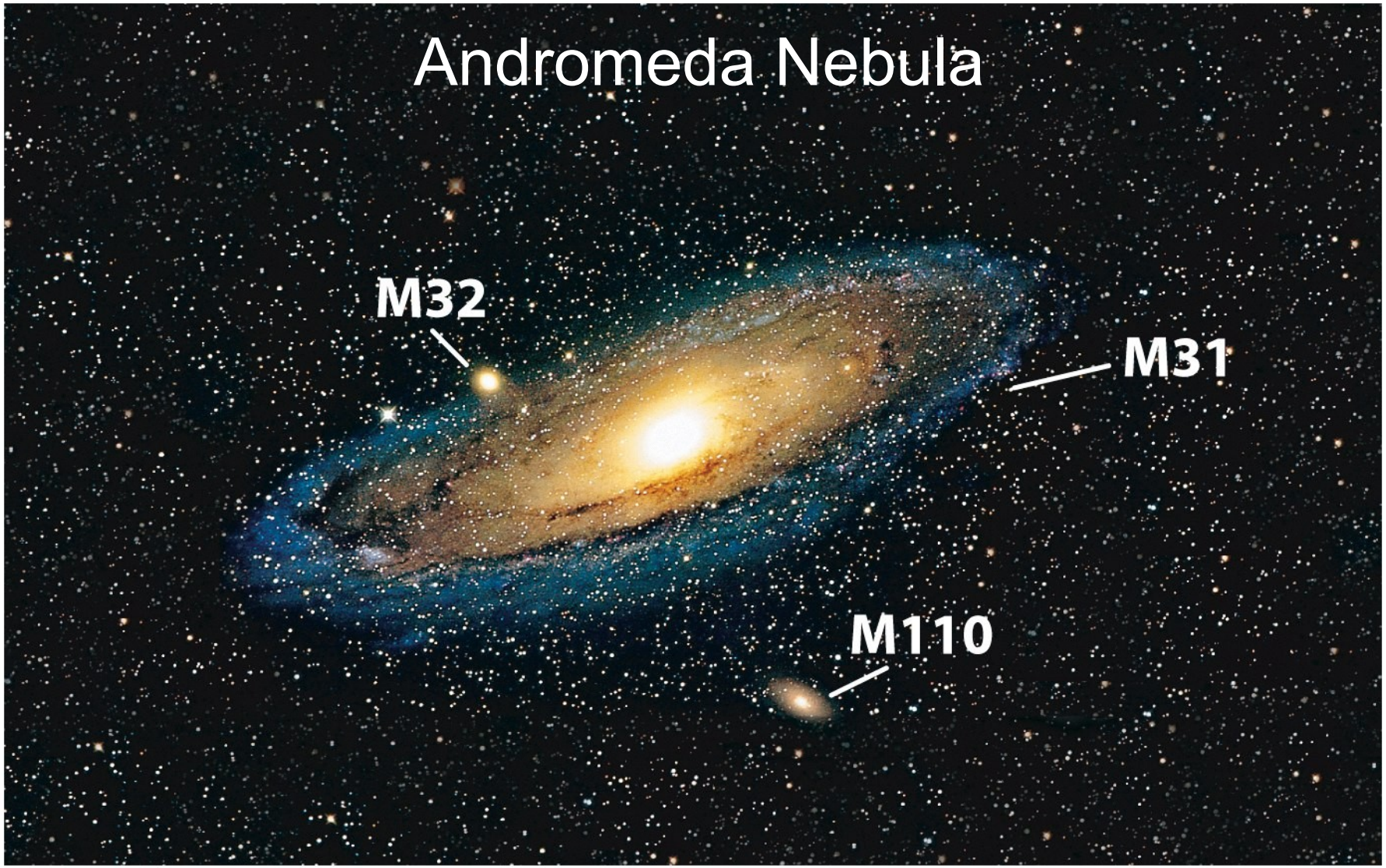
Spiral Galaxies

- Rotating *disc* dominated by spiral arms
- Spiral Arms are
  - rich in young, hot, blue stars, i.e. Population I
  - rich in gas and dust
  - where formation of new stars takes place

Credit: Gemini Observatory, GMOS Team

- Also come in *barred* form where the two arms originate from the ends of a central linear feature of bulge-like stars

Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



Elliptical Galaxies

- Elliptical collections of red stars – Population II and old Population I
- Smooth variation in intensity
- Very little gas & dust
- Little organized rotation
- Come in both giant and dwarf forms

Leo I

Dwarf
Elliptical

Irregular Galaxies

- No regular structure
- Contain plenty of gas and dust and blue stars
- Mixture of Population I and II
- Usually relatively small

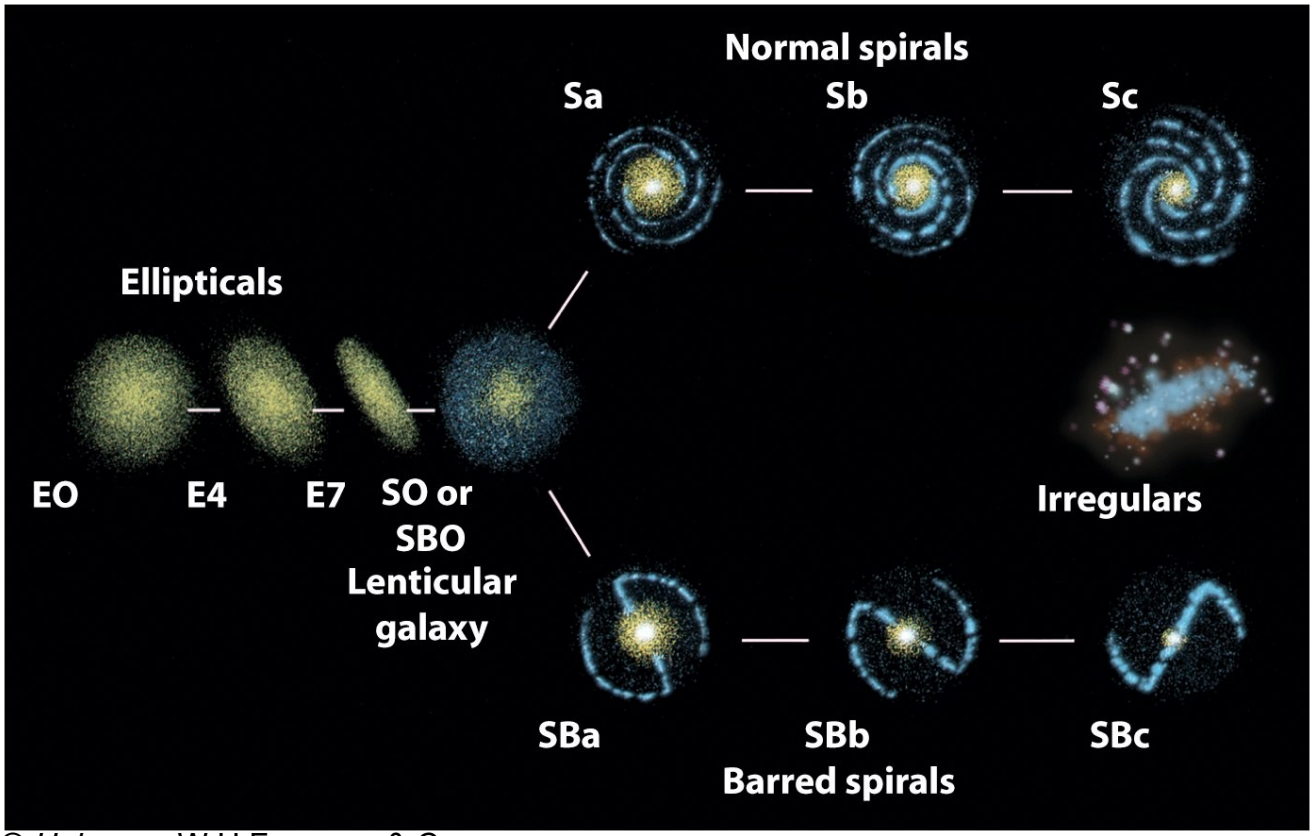
IC10: credit line: Adam Block/NOAO/AURA/NSF

Irregular galaxy NGC 4214. Credit NASA HST

Galaxy Morphological Classification

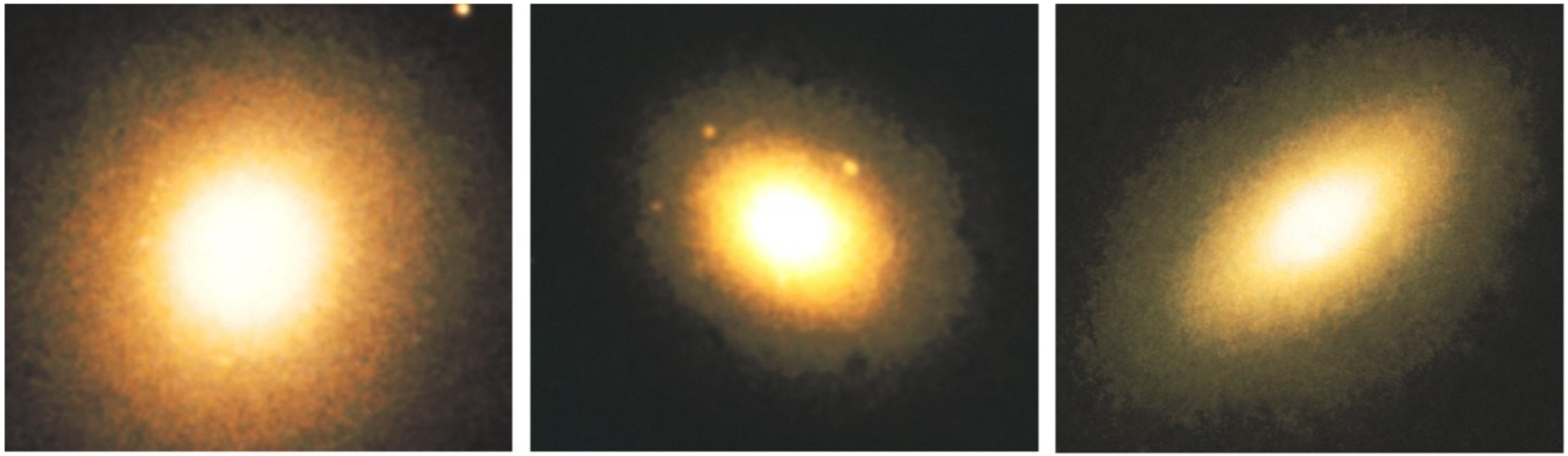
- Galaxies are classified according to Hubble's tuning fork diagram (Hubble sequence)

"Early"



"Late"

Elliptical galaxies



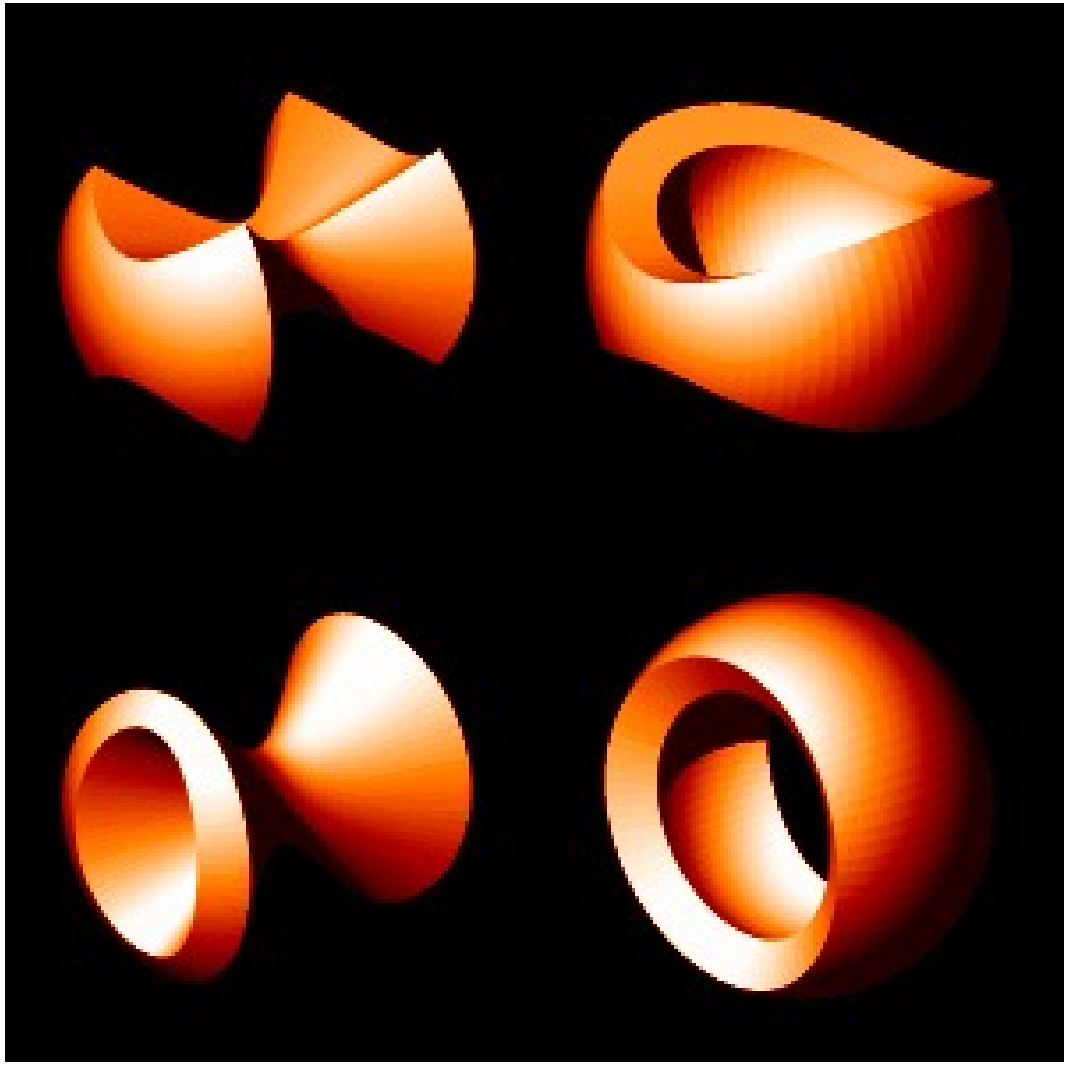
(a) E0 (M105) (b) E3 (NGC 4365) (c) E6 (NGC 3377)

Ellipticity e=1-b/a , a=semi-major axis, b=semi-minor axis
e=0.7 denoted by E7

- Ellipticals are not oblate, rotationally flattened objects
- Slowly rotating bodies, with shape maintained by structure of orbits of individual stars, (anisotropic velocity dispersion)
- Visible part ~ all stars, visible to dark ratio ~5-10
- Contain hot, x-ray emitting gas
- Surface brightness empirically ~ exp-$kR^{1/4}$

(deVaucouleurs law)

Stellar orbits in elliptical galaxies



Masses of elliptical galaxies

- The Virial theorem
  - Gravitationally bound - in dynamic equilibrium under gravity
  - Gravitational PE of system Ω related to KE U
    - $U=1/2|\Omega|$
    - Assuming velocity dispersion isotropic
    - Total KE $=(1/2)\Sigma_i m_i v_i^2 = 3/2\ M_{total}\langle v_{radial}^2 \rangle$
    - $|\Omega|=GM_{total}^2/R_{cluster}$
    - So $M=3\langle V_{radial}^2 \rangle R_{cluster}/G$
  - **Total** mass, visible plus dark matter

Spectrum of Elliptical galaxy

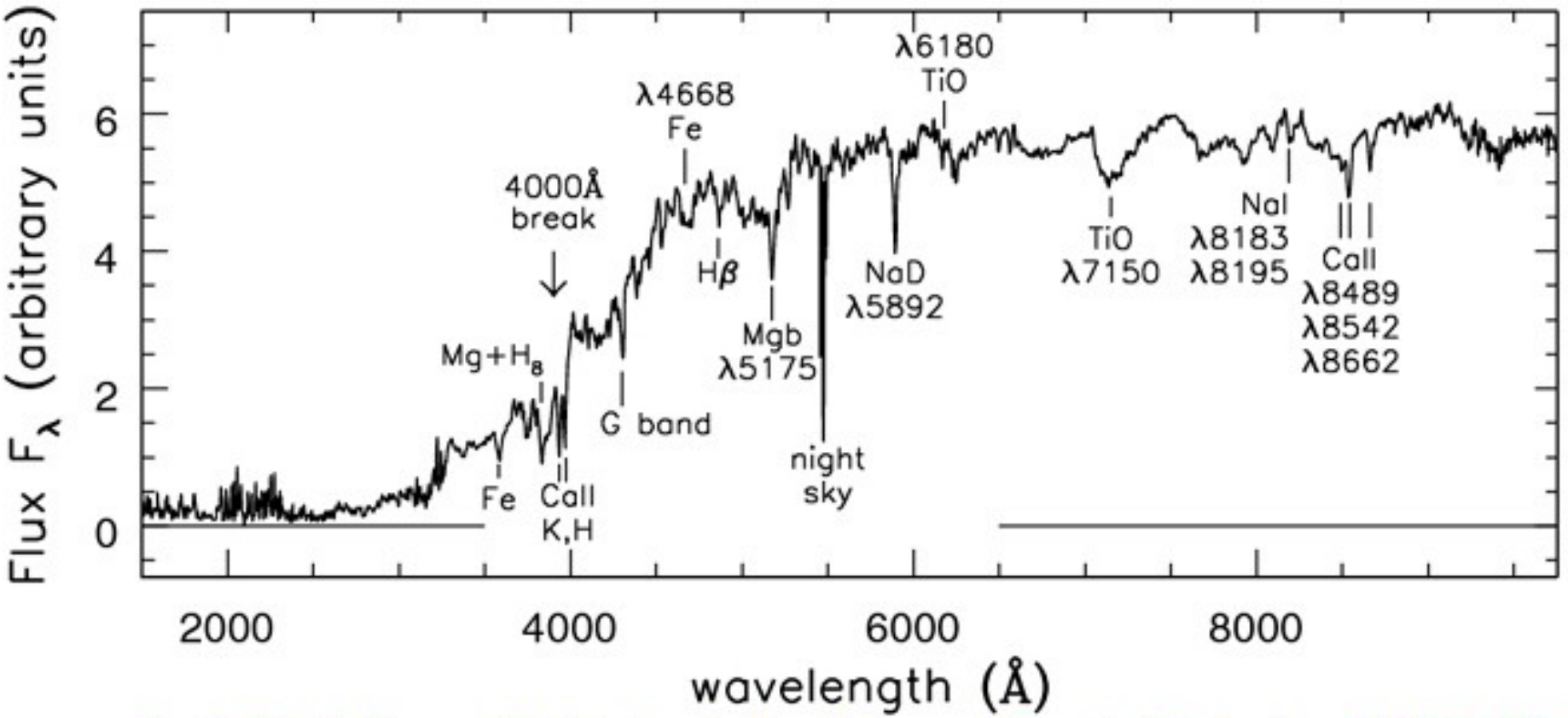
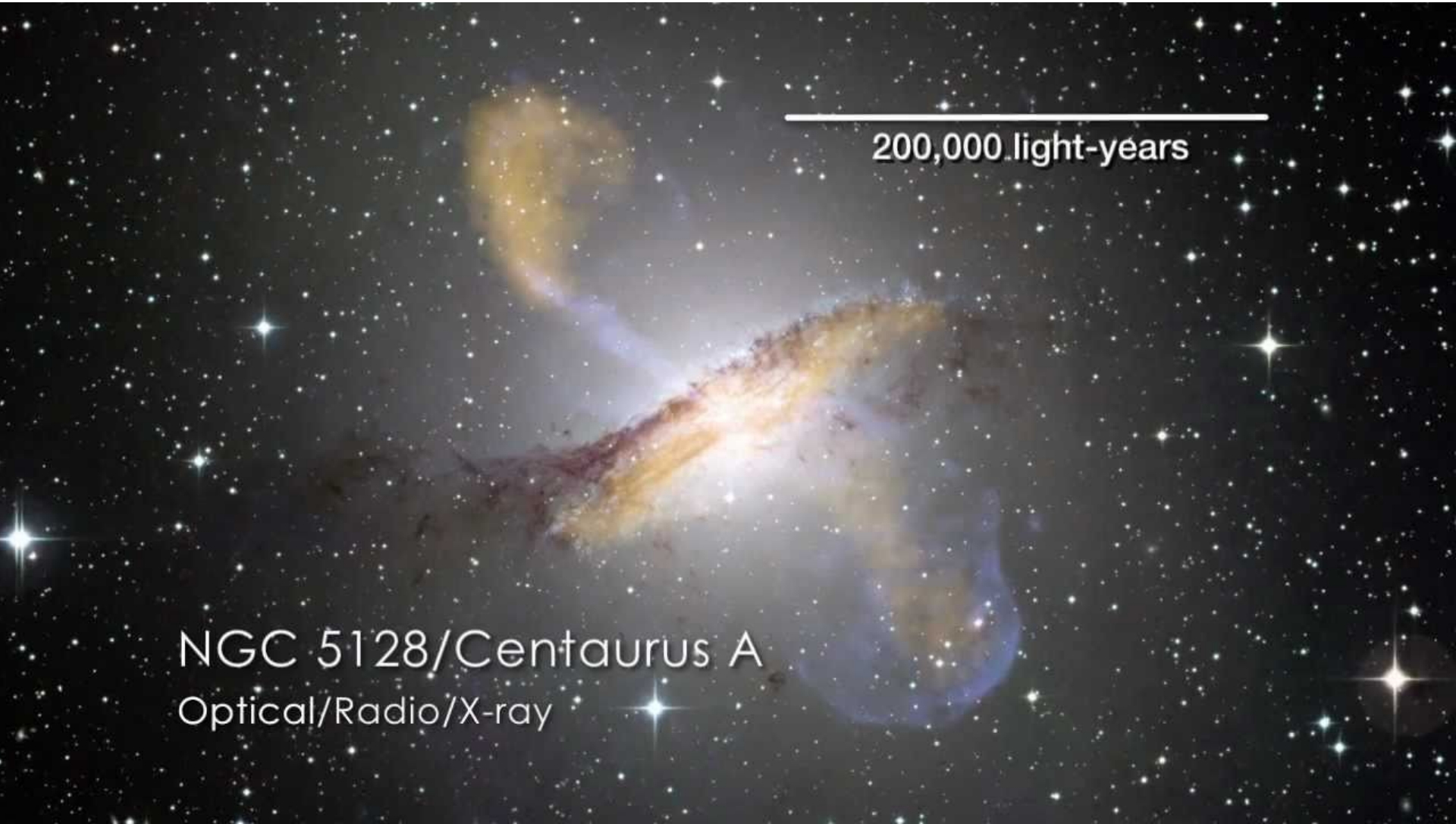


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Elliptical galaxies can be complicated!



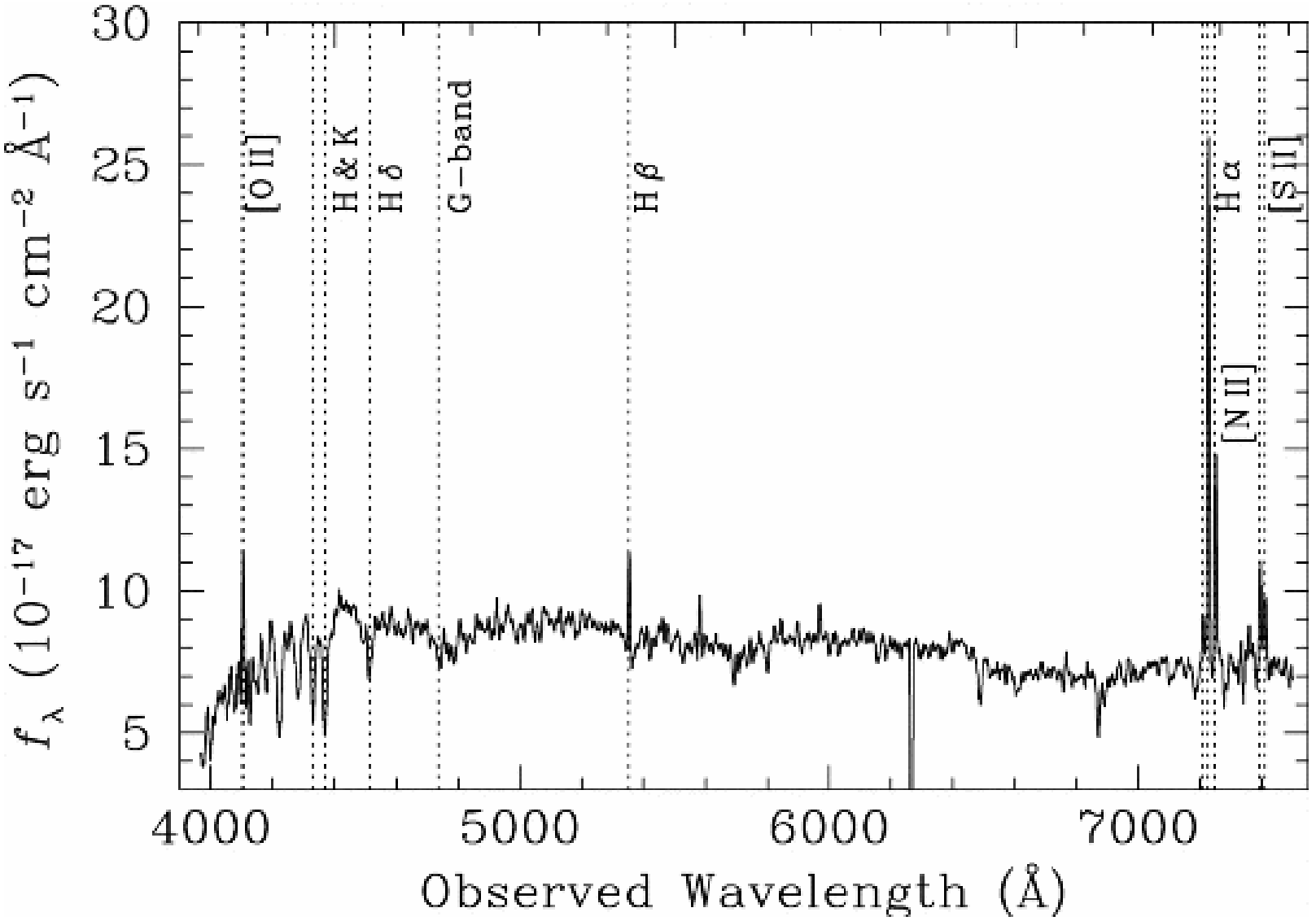
Spiral galaxies

Sombrero Galaxy M104 Sa

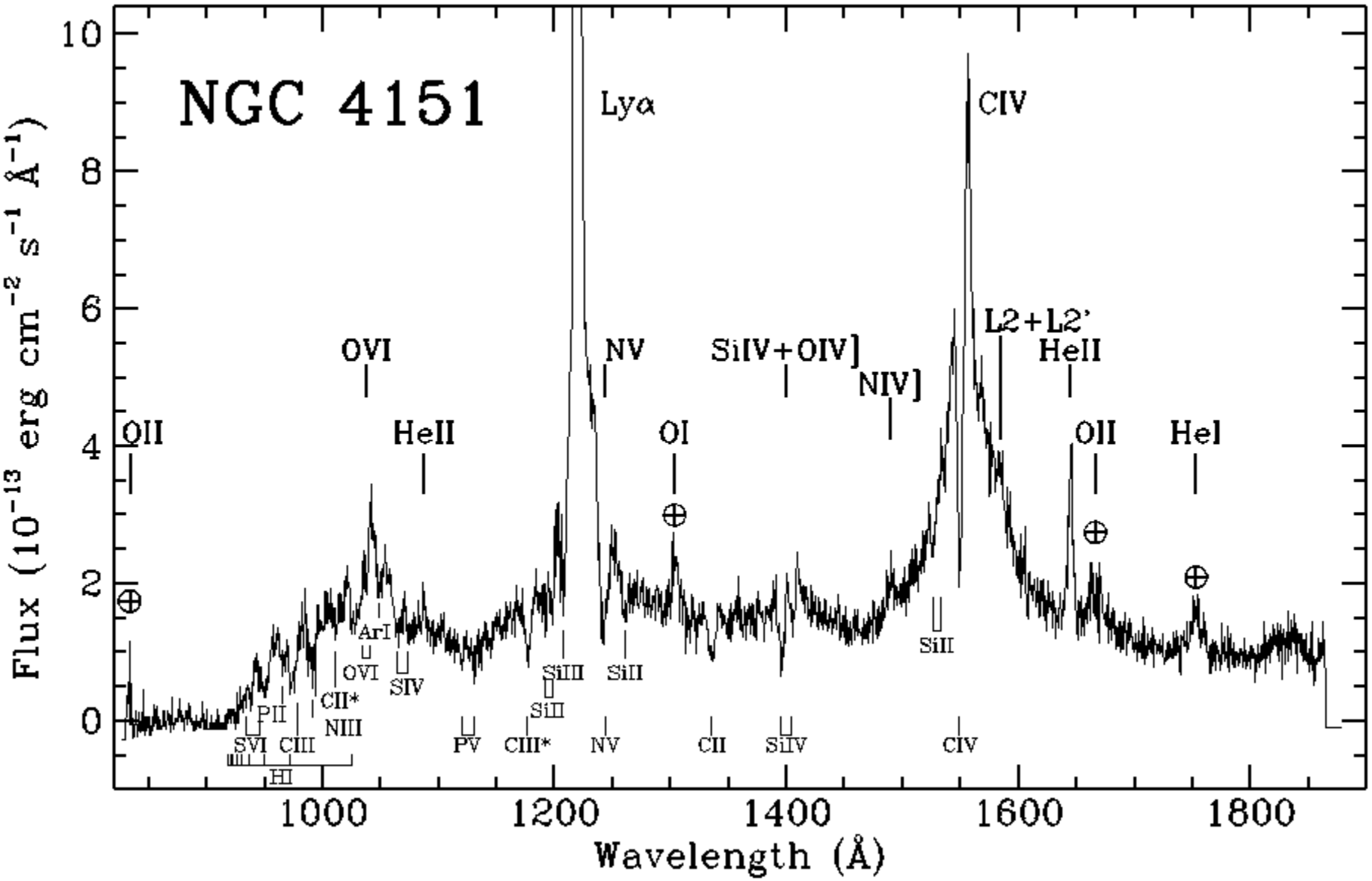

M81 Sb

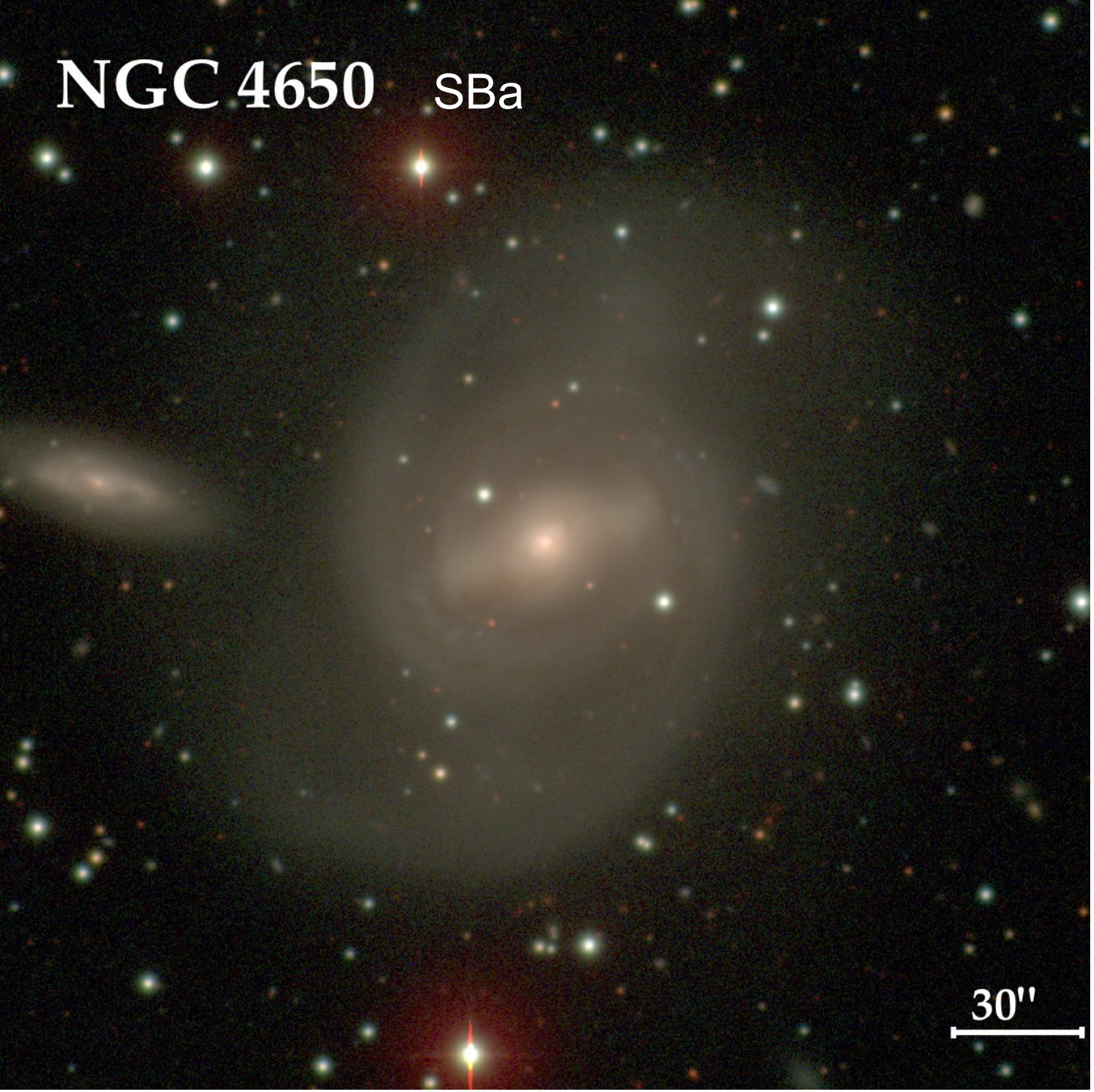

M100 NGC 4321 Sc

Spectrum of a spiral galaxy



Spectrum of an active galaxy





Barred
Spiral
Galaxies

M58
SBb
Intermediate
barred spiral


NGC 1365 SBc

Lenticular galaxy M102: Credit: AURA/NOAO/NSF

Light distribution

- Light distribution in spiral and lenticular galaxies
  - Bulge - de Vaucouleurs $r^{1/4}$ law
  - Disk – exponential $I(r)=I_0 exp(-r/h)$, where h is the disk scale length (~3kpc for our galaxy) and I_0 is the central surface brightness
  - These two can be combined to give disk or bulge dominated profiles

Irregular galaxies

NGC 4650a

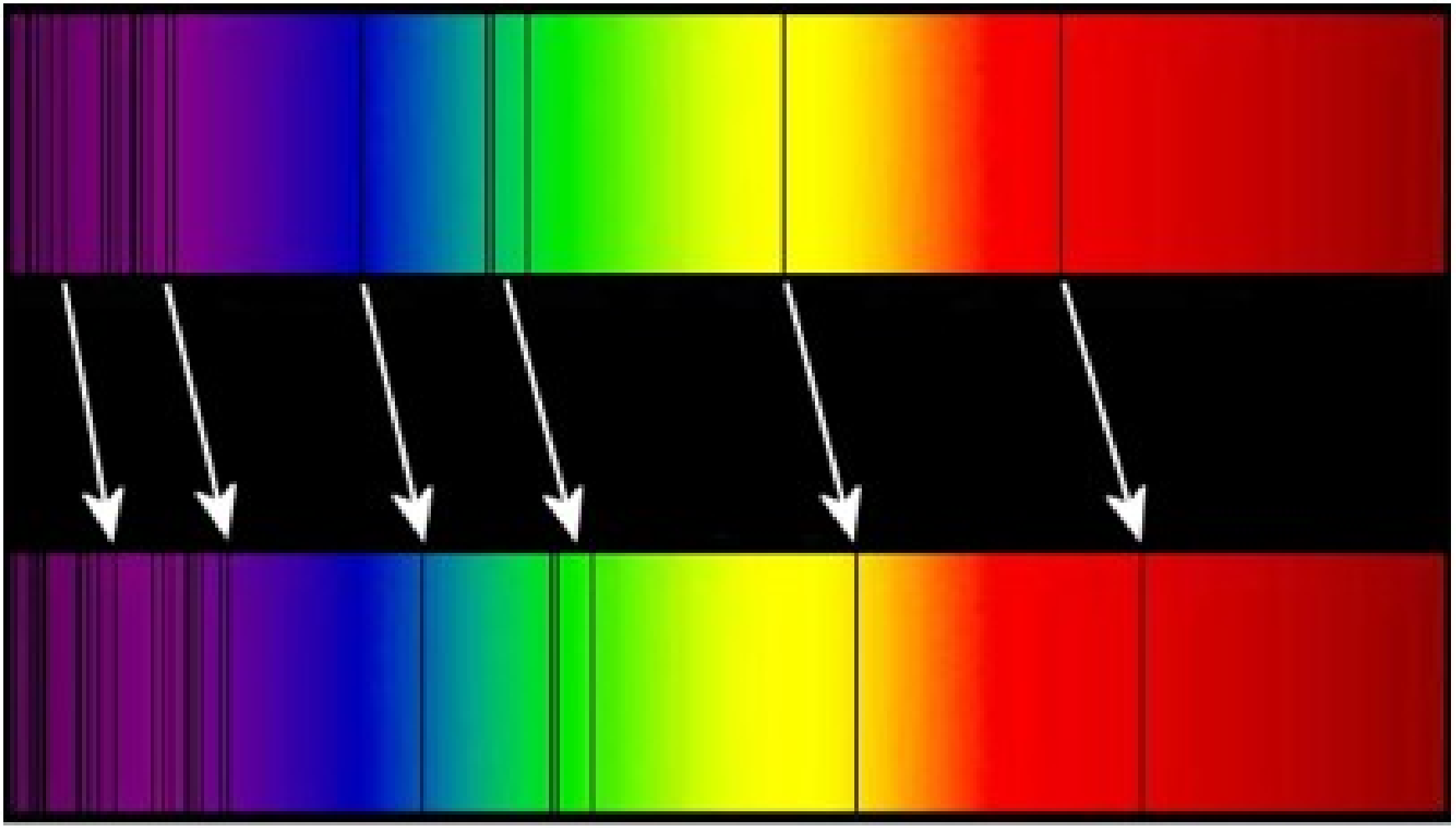
Evidence of a galaxy merger

Interacting galaxies NGC 4038 and NGC 4039

Shell galaxies
NGC 474


Shell galaxies can even contain colliding neutron stars!
NGC 4493

How we measure velocities

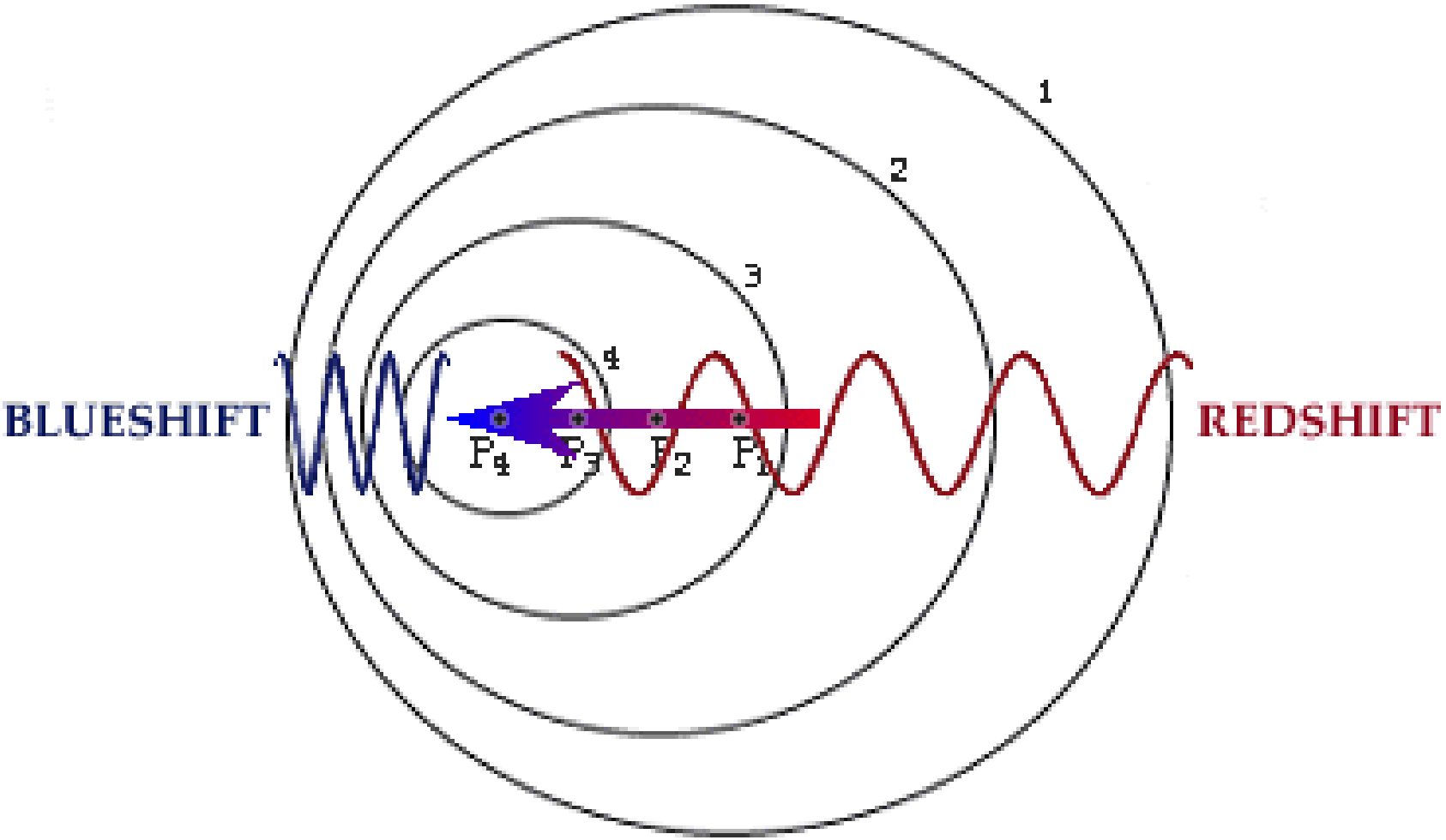


Redshift

- Doppler shift due to relative motion of source or observer
- $$z = \frac{\lambda\ observed - \lambda emitted}{\lambda emitted}$$
- $$1 + z = \frac{\lambda\ observed}{\lambda emitted} = \frac{femitted}{fobserved}$$

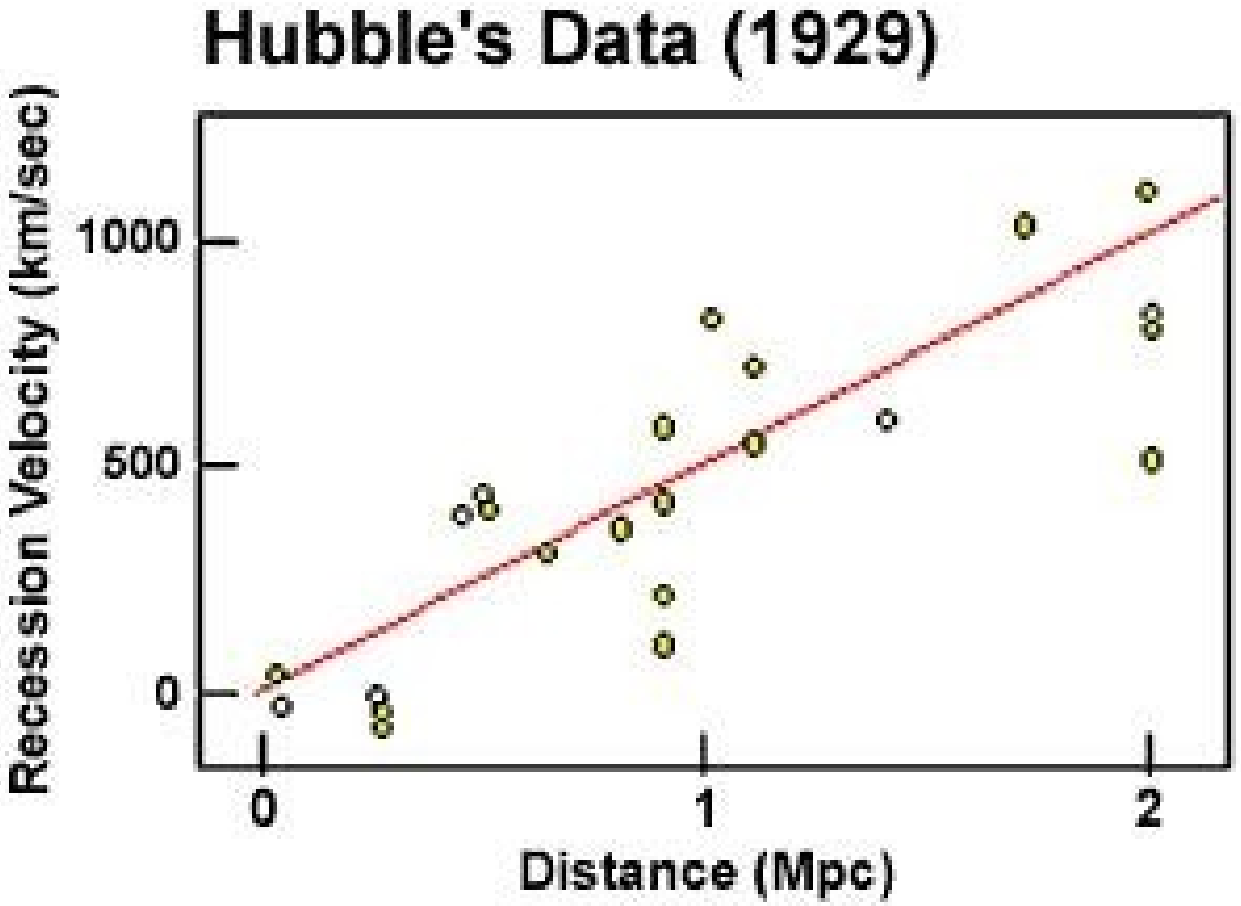
For small redshifts V(recession)=cz

Doppler shift



Distances - Recession of galaxies
Hubble's Law

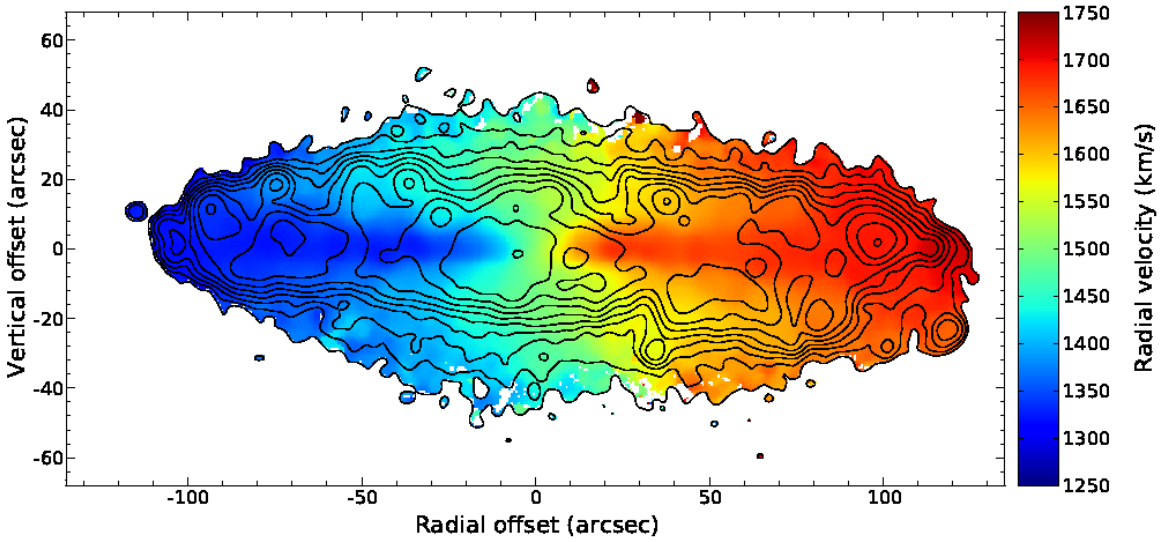
$V=H_0\ d$



Evidence for dark matter

- The rotation curves of spiral galaxies suggest an invisible dark halo
- Velocities within galaxy clusters suggest a lot more mass than we can see is needed to bind the galaxies together
- Velocity dispersions – broadening of spectral lines
- Mass/Light ratio (M/L) >1

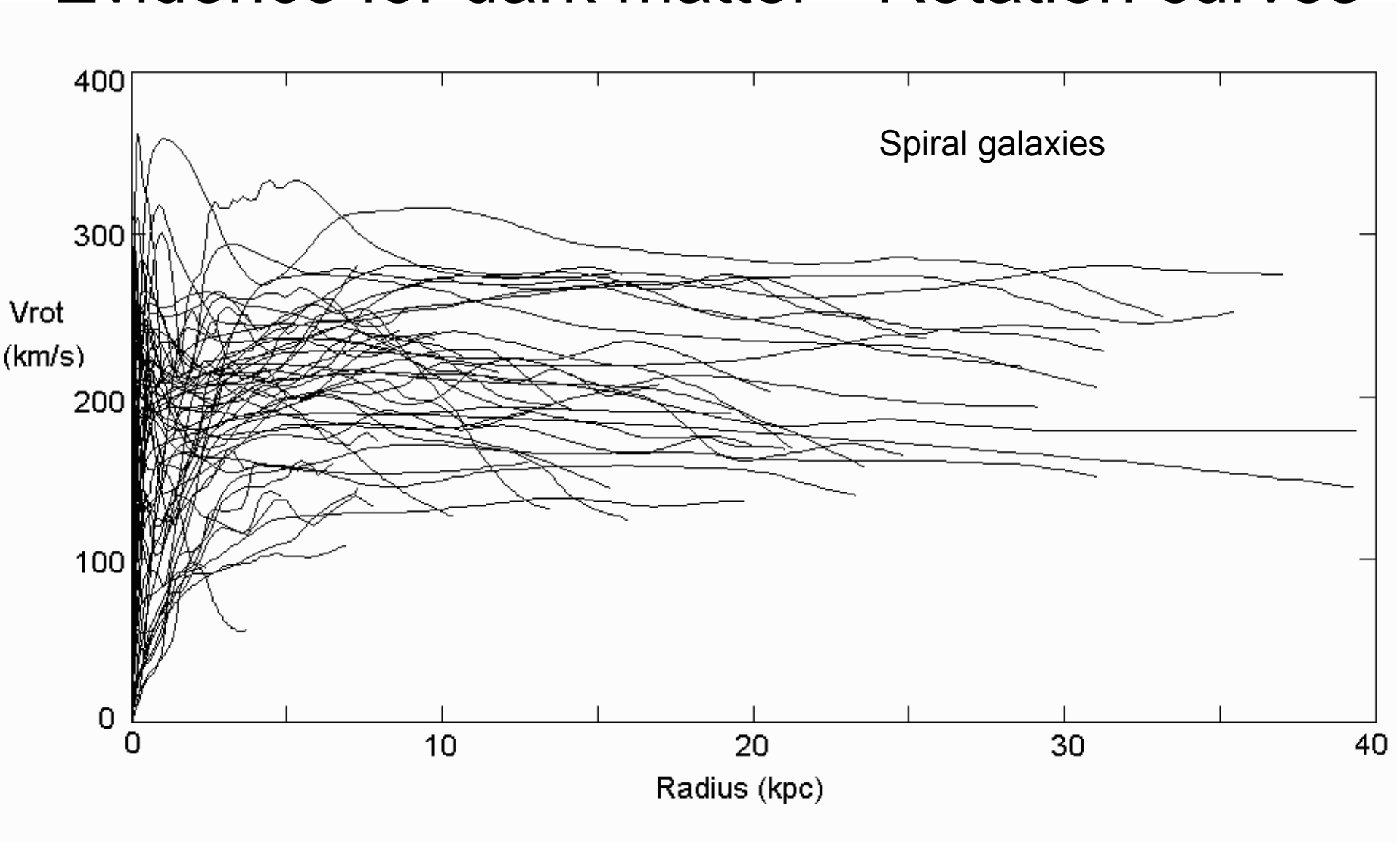
Velocity map



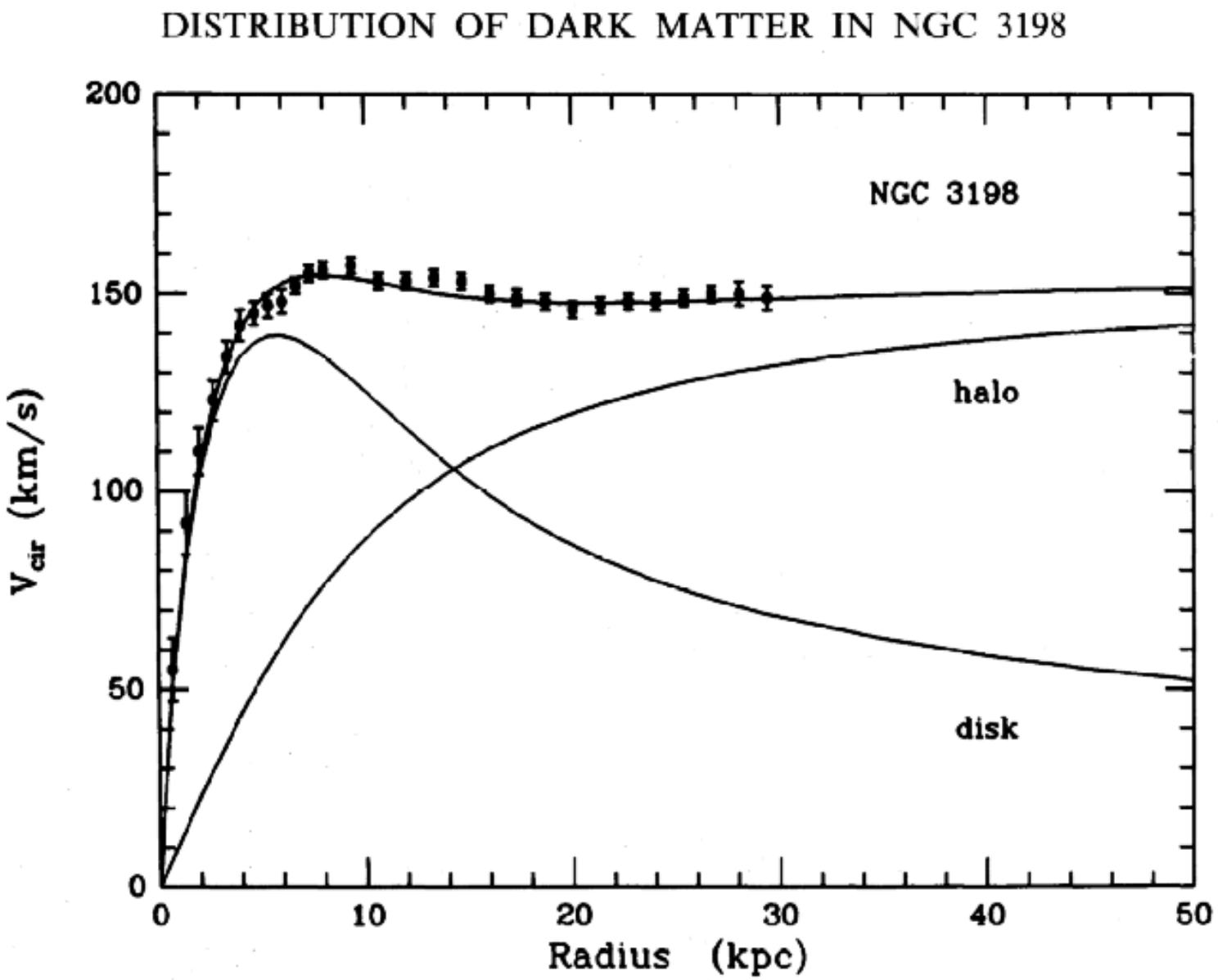
- Velocity map, ionized gas in NGC 4666
- Left hand side coming towards us, right away

Voigtländer, Pierre *et al.* Astron.Astrophys. 554 (2013)

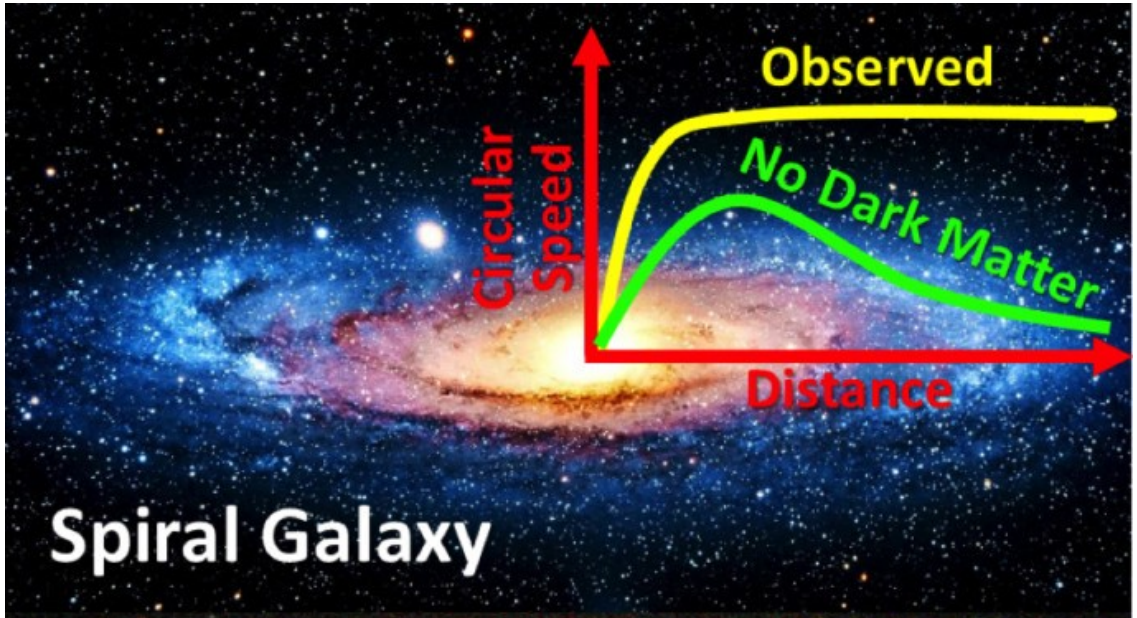
Evidence for dark matter - Rotation curves

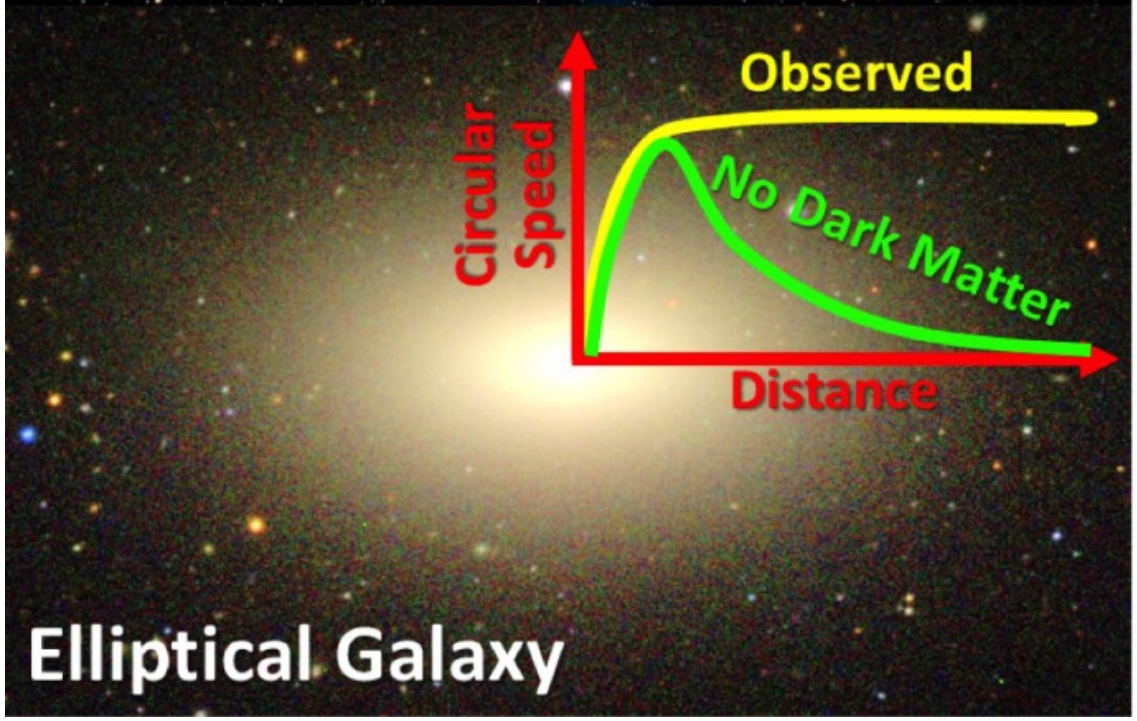


http://www.ioa.s.u-tokyo.ac.jp/~sofue/rotation/fig1/all-new.gif



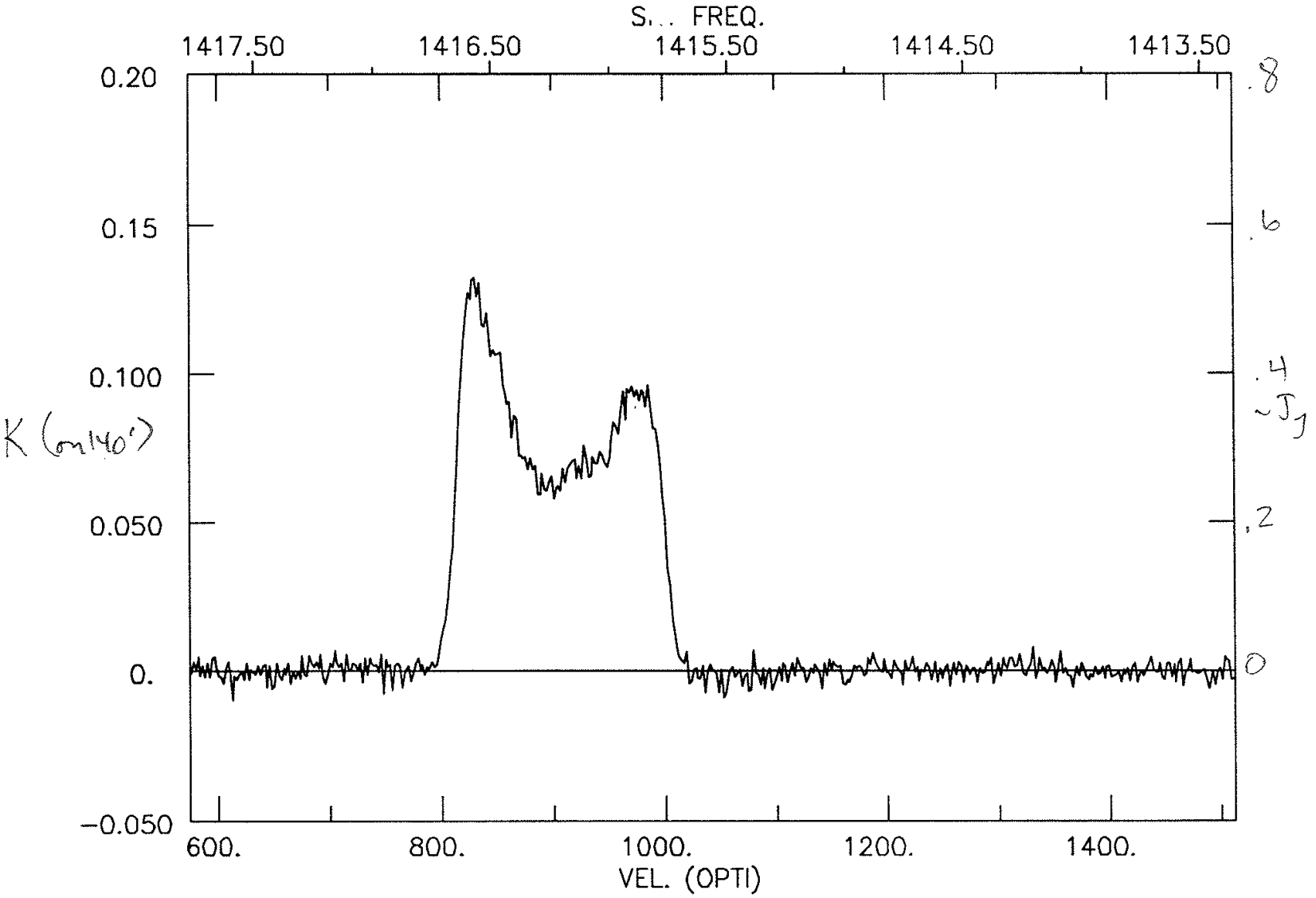
http://bustard.phys.nd.edu/Phys171/lectures/ngc3198_rc_big.gif





True for all galaxy types?

Masses of spiral galaxies – HI spectrum of UGC 11707 (NRAO 140 ft)



Kinematic measurement of the mass of a spiral galaxy

- Use $GMm/r^2 = mv^2/r$
- Hence $M=rv^2/G$
- Need to know rotation velocity v
  - Comes from HI spectrum of galaxy, corrected for inclination
- Need r, galaxy radius

  - comes from $r=d\theta$, where d=distance

  to galaxy and θ =size in arcsec
- Measures **total** mass

Statistical properties
Correlations along the Hubble sequence

- Elliptical galaxies red, spirals blue
  - Different types of star and rates of star formation in different galaxy types
- Ellipticals have little neutral hydrogen while spirals show a monotonic increase along the Hubble sequence
  - Spirals will have high star formation in future

Statistical properties
The Luminosity Function

- Frequency with which galaxies of different luminosity found in a given sample of galaxies
- $\phi(L)dL$ = space density of galaxies in luminosity range L to $L+dL$
- where flux density ($W/(m\ Hz)$)
- $L = 4\pi r^2 S \quad W/Hz$ where S = flux density (W/(m Hz)

Luminosity functions

- **Luminosity functions** are used to study the properties of large groups or classes of objects, such as the stars in clusters or the galaxies in the Local Group.
- Not totally general
- Varies with environment
- Brightest CD galaxies in clusters don’t fit
- SKA will do a “1 Billion galaxy” survey!

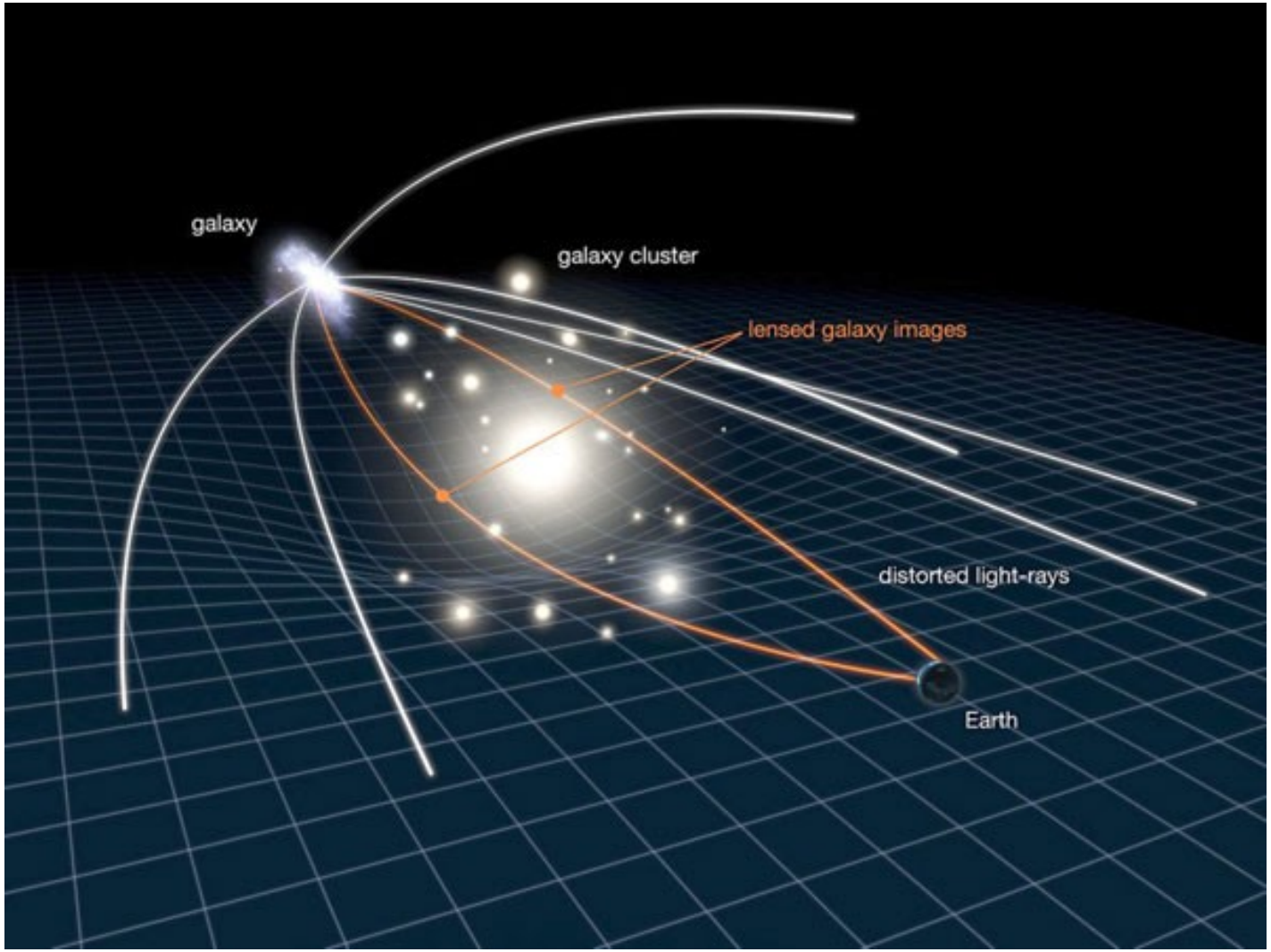
Statistical properties
Mass-to-light ratio

- How does the mass differ from that expected from the number of stars?
- Integrate luminosity function over a cluster
- Add up the masses of the various types of galaxies (spectral synthesis)
- M/L~5 in galaxies, M/L~100 virial mass ~100-500+ in clusters
- Universe ~ 1600, ie need more mass to close the universe.

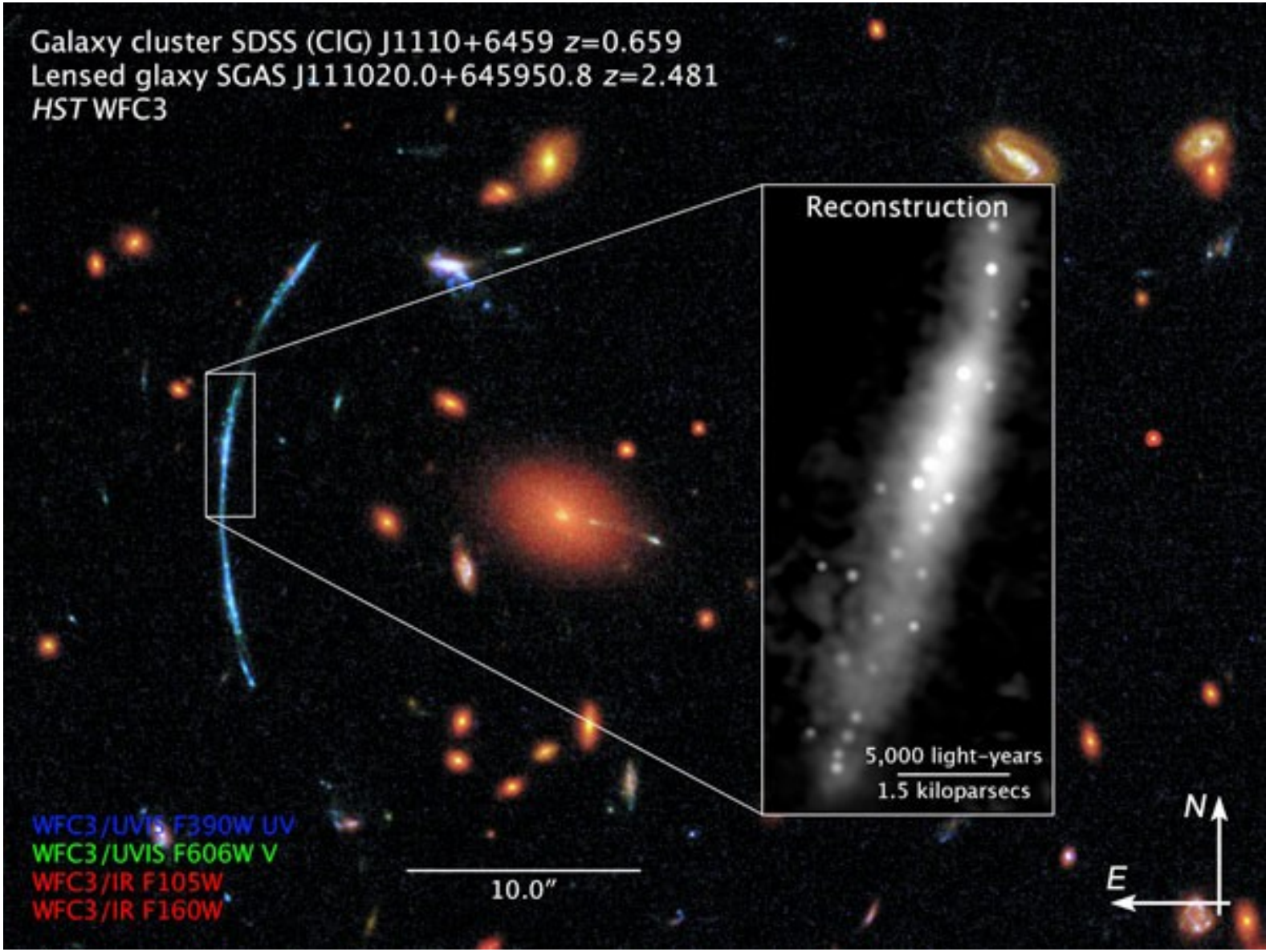
2017 Updates

- Using gravitational lensing to see very distant galaxies
  - Details in closer ones
  - Detecting more distant ones
- Which galaxies have black holes?

How to see more in distant galaxies



http://hubblesite.org/news_release/news/2017-27



http://www.skyandtelescope.com/astronomy-news/incredible-resolution-reconstructed-galaxy-pushes-hubbles-limits

Behind Galaxy Cluster MACS 0416 z=0.397

167 galaxies, redshifts 5.3 to 8.8 (to 1.31×10^9 years ago!) *STScI / NASA / CATS Team / R. Livermore (UT Austin)*

http://www.skyandtelescope.com/astronomy-news/hubble-spies-faint-galaxies-bountiful-early-universe/

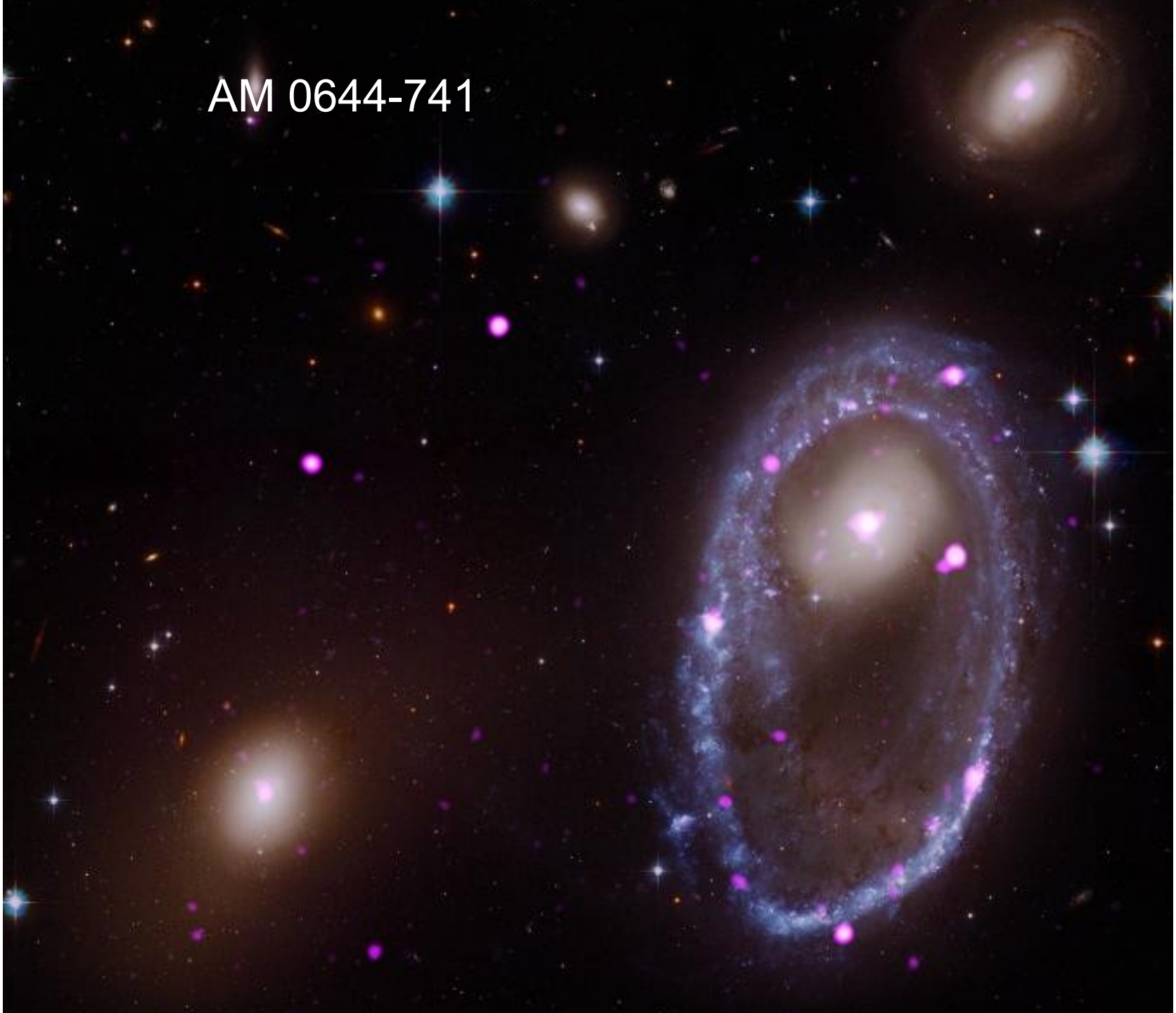
1,008 Black Holes in Deepest-Ever X-ray Image (Chandra composite)

- 7 million seconds observing over 17 years
- Hubble UDF in middle of this field

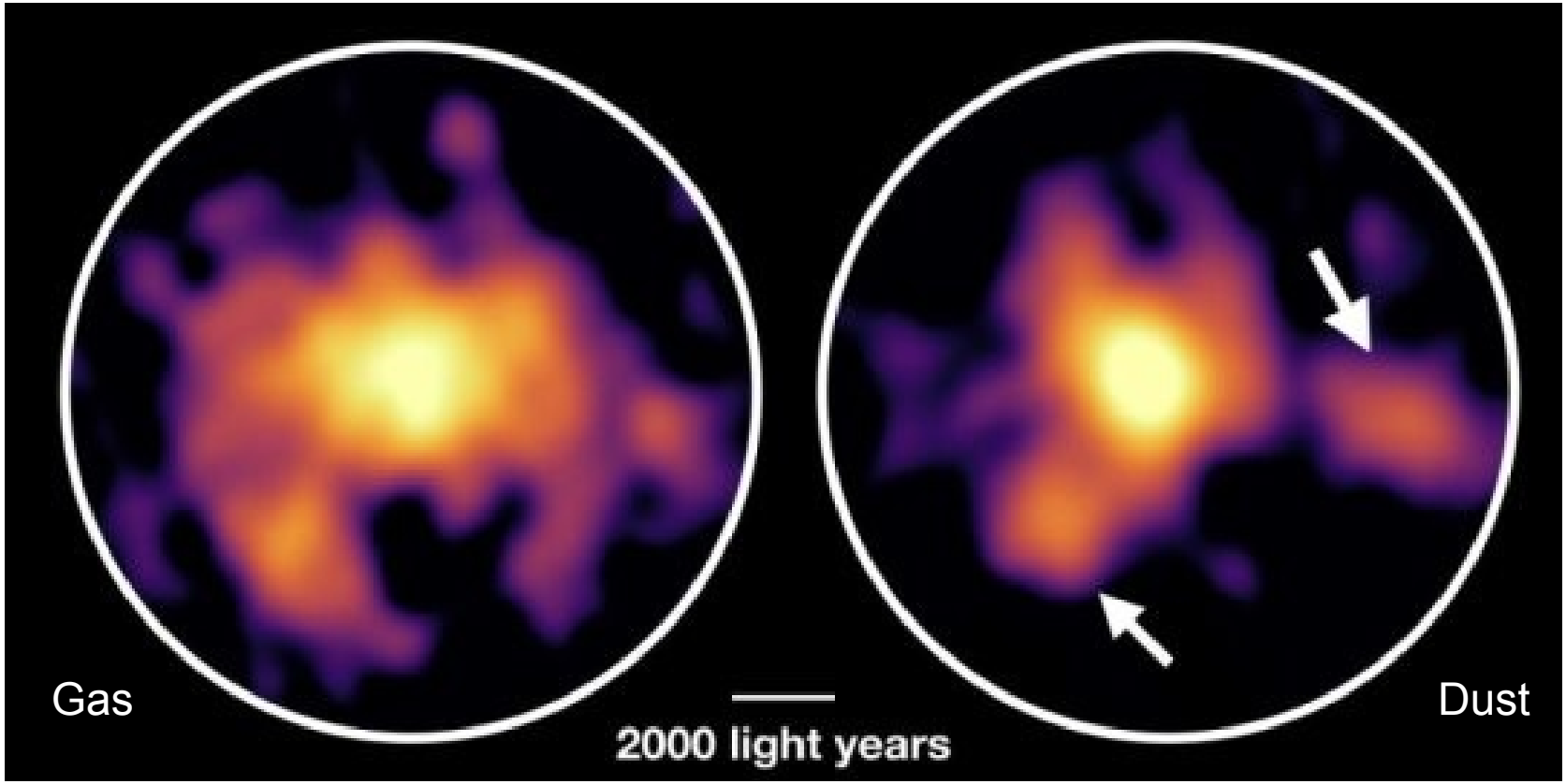
NASA / CXC / Penn State Univ. / B. Luo et al

2018 updates

- Galactic collisions can cause rings of black holes (CHANDRA)
- GAIA is radically altering our perception of galaxies – almost all show evidence of interaction if look carefully
- Forerunners of E galaxies found by ALMA?
- All distant galaxies surrounded by atomic hydrogen (Lyman α) (VLT+ MUSE)


AM 0644-741

Unstable molecular clouds in distant “monster” galaxy (ALMA)



- Monster galaxy 12.4 billion ly away
- Runaway star formation – E galaxy precursor

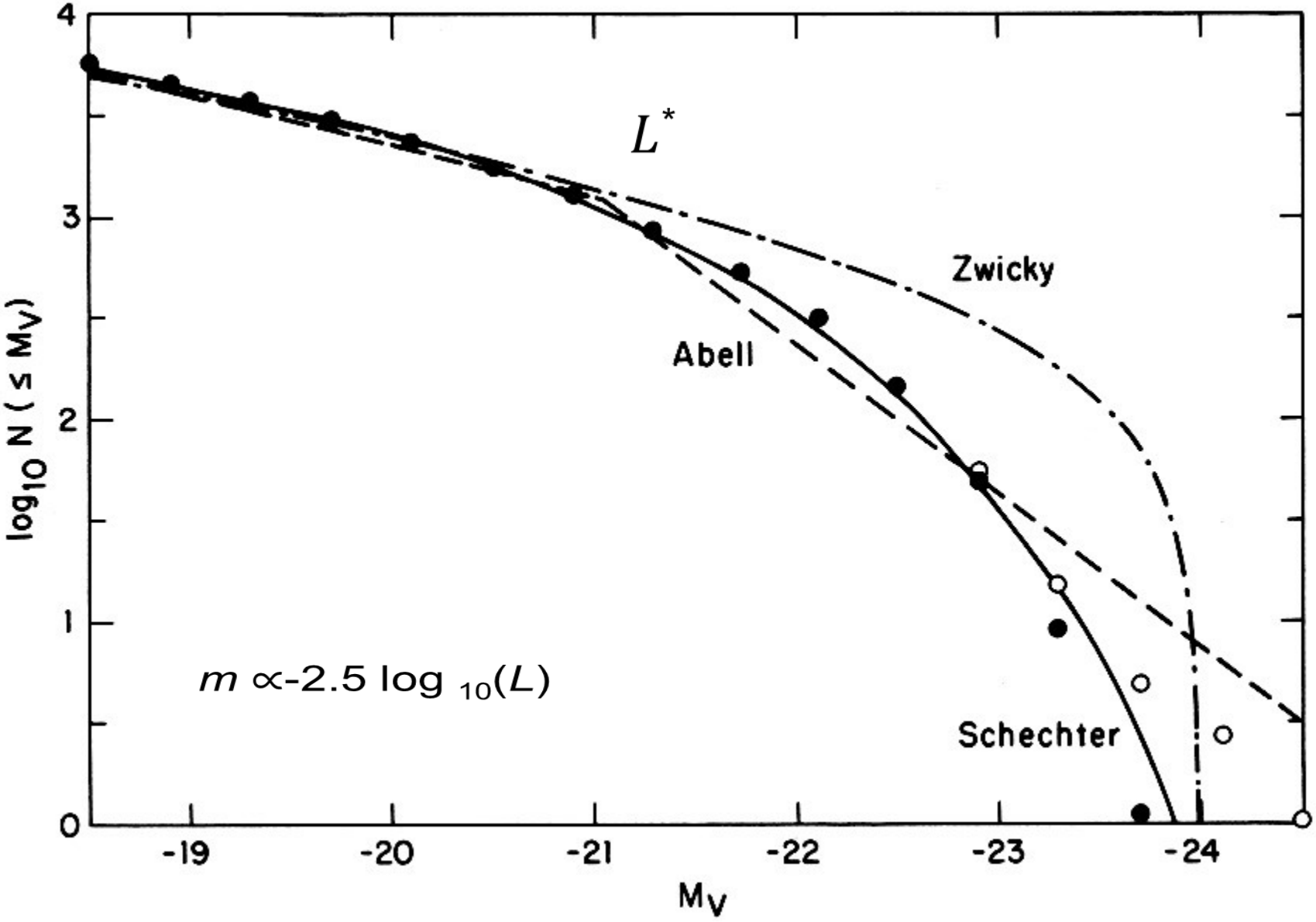
ESA/Hubble & NASA, ESO/Lutz Wisotzki et al.

Galaxies-review

- Galaxy Types
- Hubble's Tuning Fork Diagram
- Peculiar and interacting galaxies
- Light distributions
- Masses
- General (statistical) properties of galaxies
- The Luminosity function
- Mass-to-Light ratios

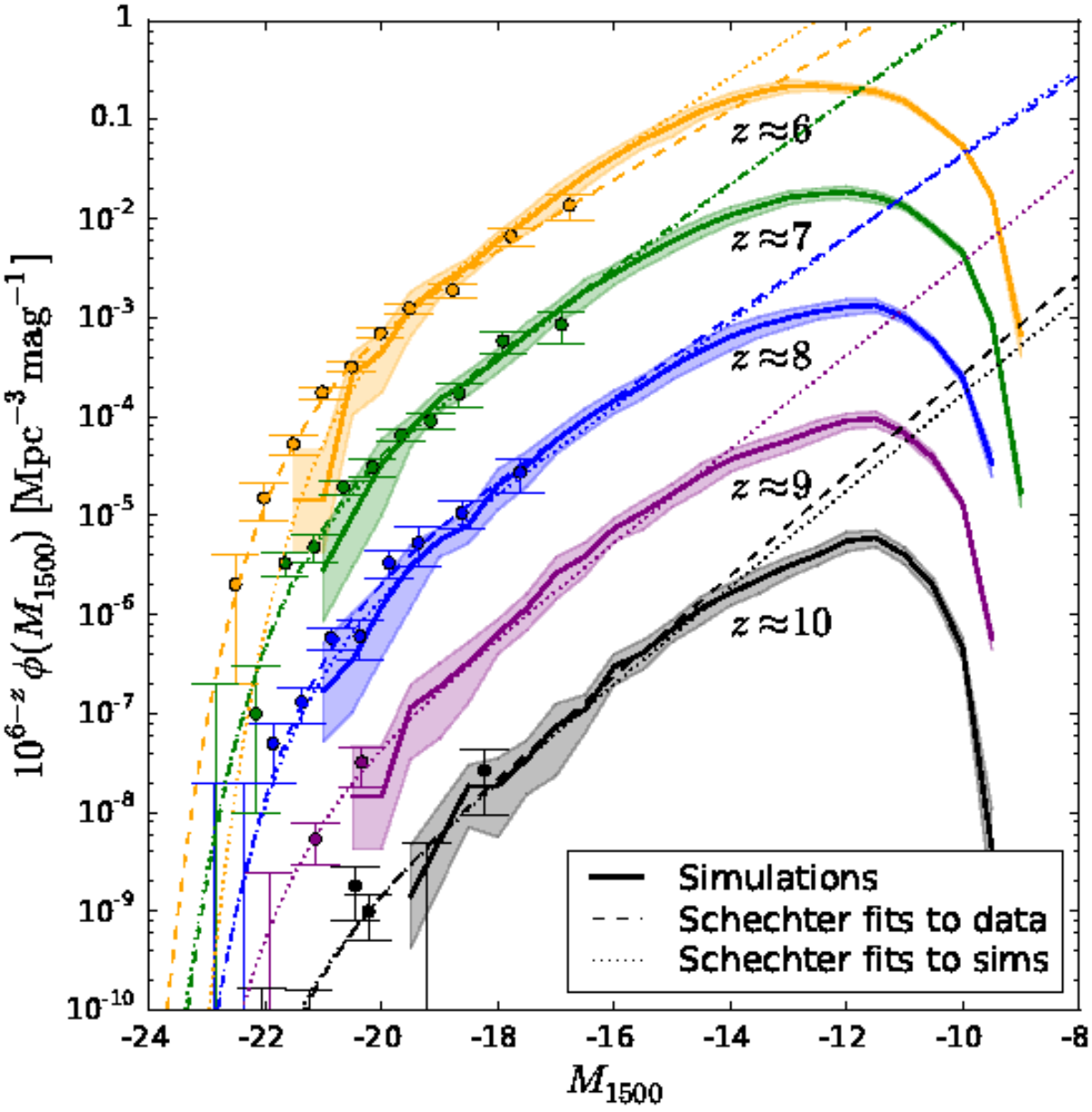
End

- Mstar-Msun=-2.5log10 (Lstar/Lsun)



https://ned.ipac.caltech.edu/level5/March02/Sarazin/Sarazin2_4.html

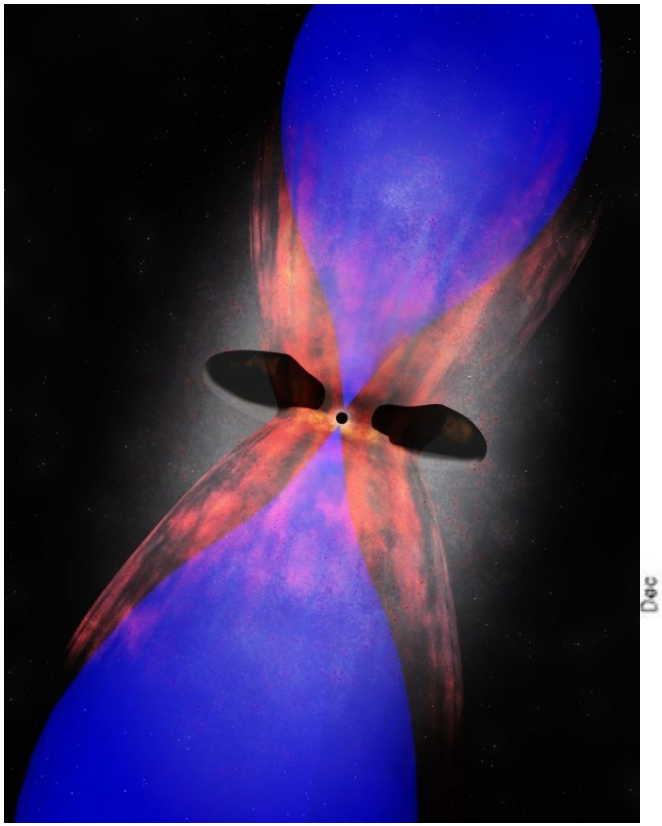
- Schecter law $\varphi(x)dx = \varphi^* x^\alpha e^{-x} dx$
  - $x = \frac{L}{L^*}$
  - Power law (slope α)
  - High luminosity exponential cutoff at L^*, "break



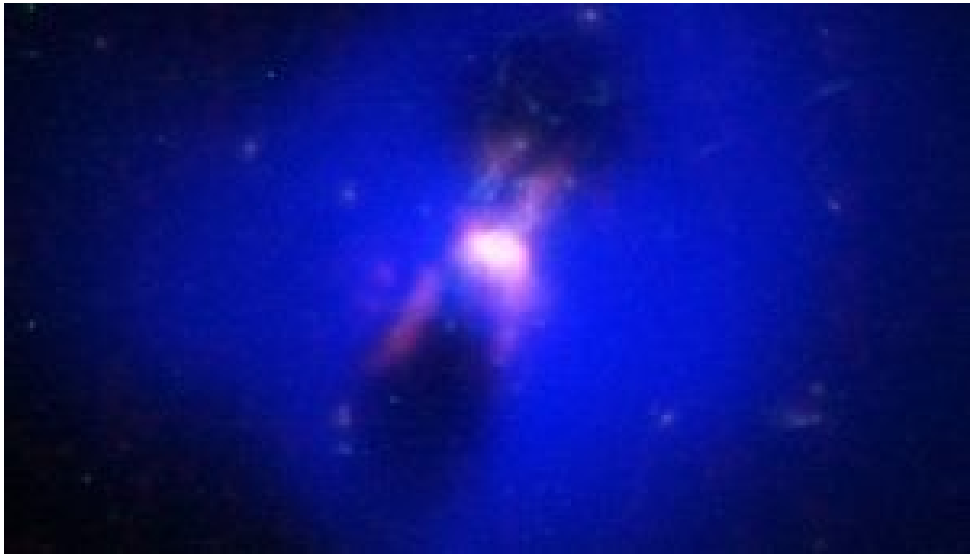
. - Gnedin, Nickolay Y. , Astrophys.J. 825 (2016) no.2, L17

Central galaxy, Phoenix cluster

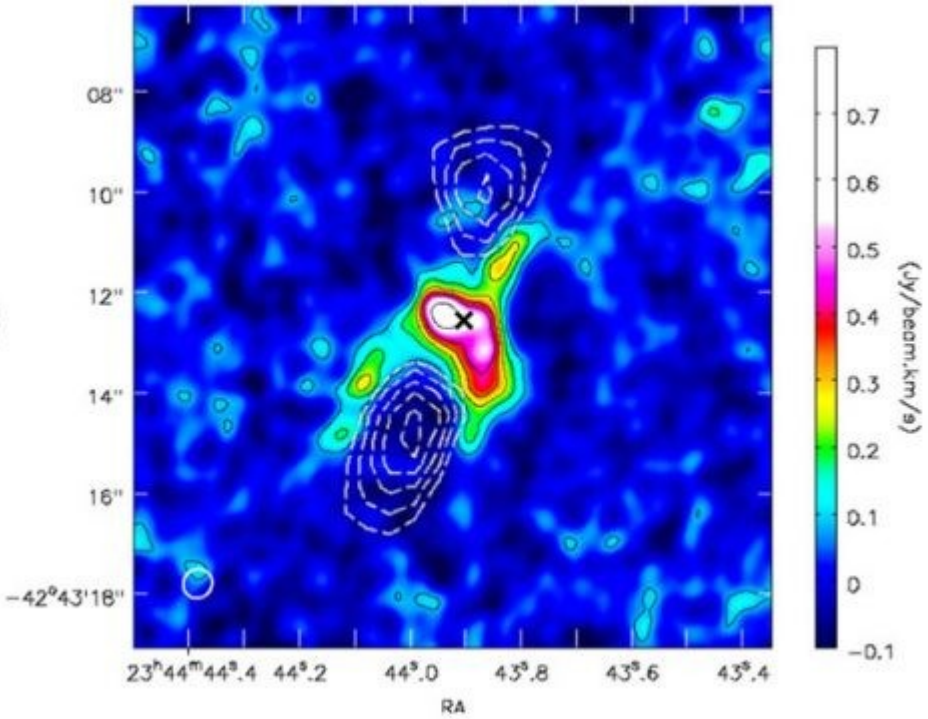
X-ray, ALMA (mm) and radio (VLA)



Not red and dead!



700 Solar masses per year!



- An elliptical concentration of stars at the centre is called the *bulge*
- Bulge is rich in red stars – Population II and old Population I

Barred spiral galaxies

(a) SBa (NGC 4650) (b) SBb (M83) (c) SBc (NGC 1365)