The Matter Content in the Universe

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April 9th, 2024

Quiz

- What is the parametrisation of the equation of state of Dark Energy?
- What is the normalised Hubble parameter?
- What is its equation as a function of redshift?
- What is the surface brightness dimming?
- What is the flatness problem?
- What is the Horizon problem? What is inflation?
- What are the (new) cosmological tests?

How to measure the Matter Content in the Universe

- **Mass on galaxy scale**
  - Rotation curve of disk galaxies
    - Viral theorem and velocity dispersion
- **Mass on Cluster scale**
- **Gravitational Lensing #8,9,10 (galaxies, clusters, LSS)**

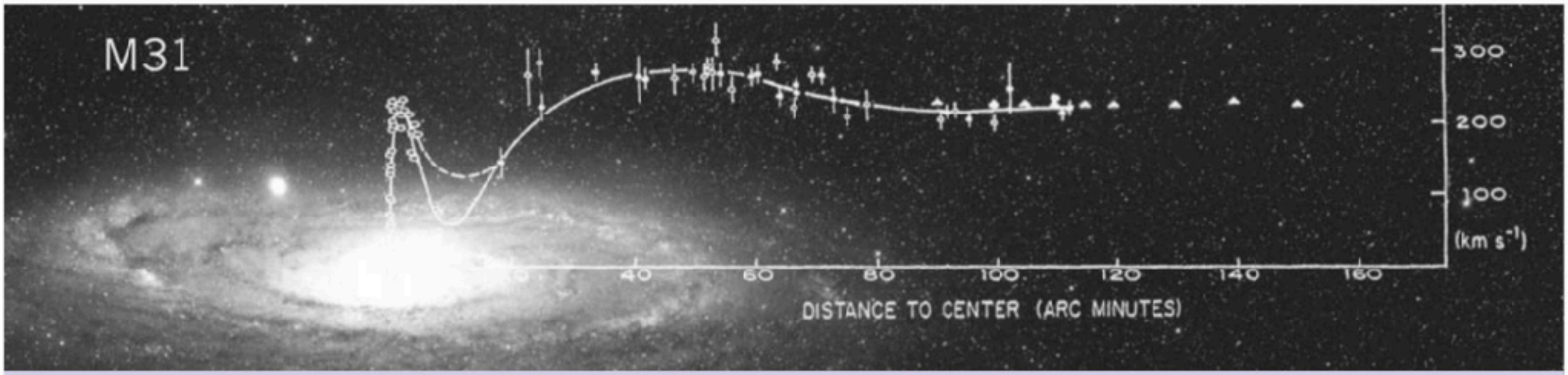
Galaxy Mass

- A galaxy is a gravitationally *bound system* of: Stars, Stellar Remnants (BHs), Interstellar Gas, Dust, SMBH, and **Dark Matter**.

- Galaxies range in size from **dwarfs** with just a few thousand (10^3) stars to **giants** with up to hundred trillion (10^{14}) stars

Key equations

- **Check Astro-IV course on stellar and galaxy dynamics**
- Assumptions: spherical/disk symmetry
- Dynamical equilibrium:
  - Rotation (rotation curve) => from Newton
  - Random motion (velocity dispersion) => Jeans equation
- Virial Theorem

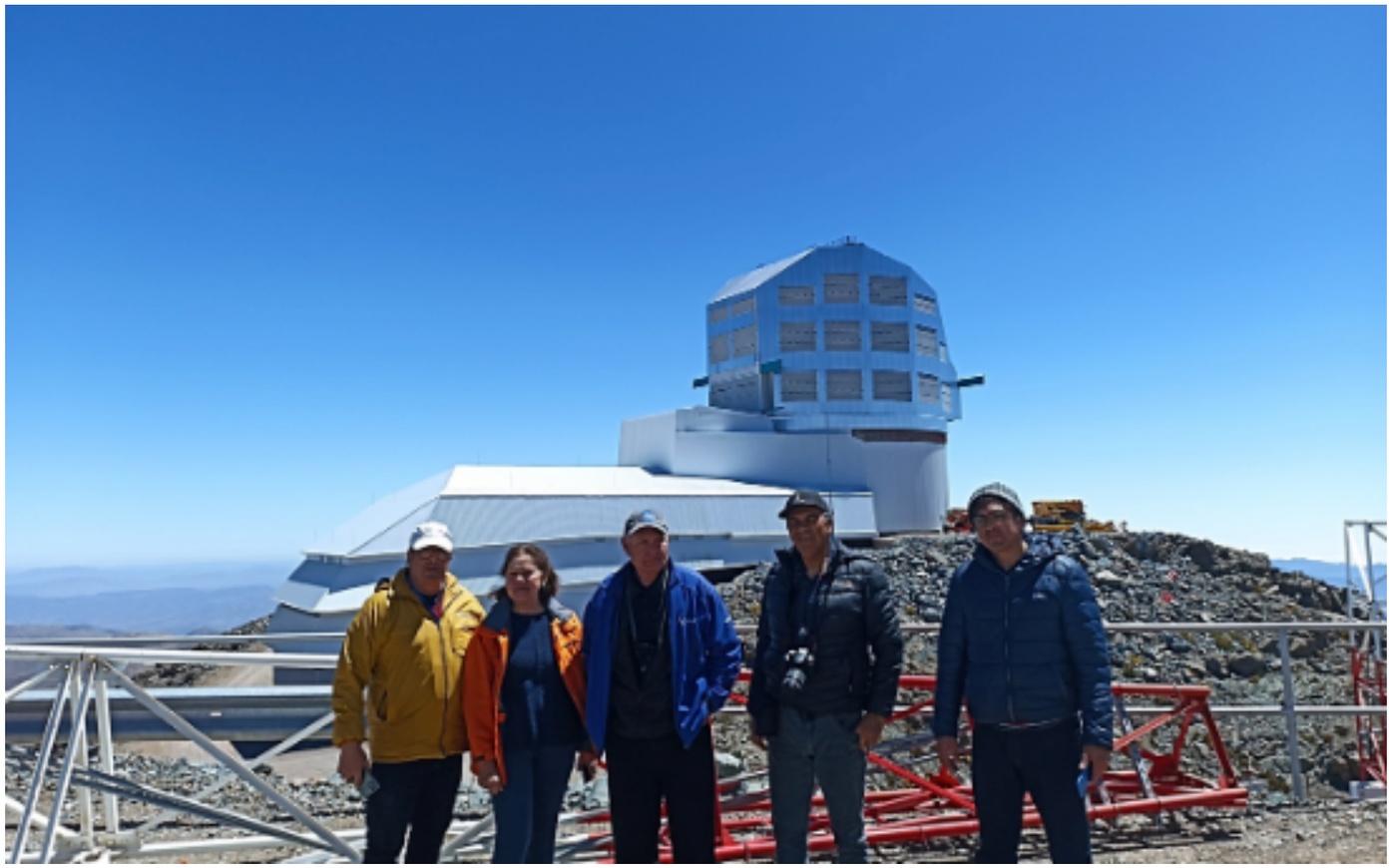


The M31 major axis mean optical radial velocities and the rotation curve,[4] $r < 120$ arcmin, superposed on the M31 image from the Palomar Sky Survey. Velocities from radio observations[5] are indicated by triangles, $90 < r < 150$ arcmin. Rotation velocities remain flat well beyond the optical galaxy, implying that the M31 cumulative mass rises linearly with radius. (Image by Rubin and Janice Dunlap.)

Vera Rubin pioneered measurements of galaxy rotation curves. Starting with her Rubin & Kent (1970) paper on the rotation curve of M31, her work provided compelling evidence for extended halos of dark matter around galaxies.

Vera Rubin Observatory

https://www.lsst.org/about



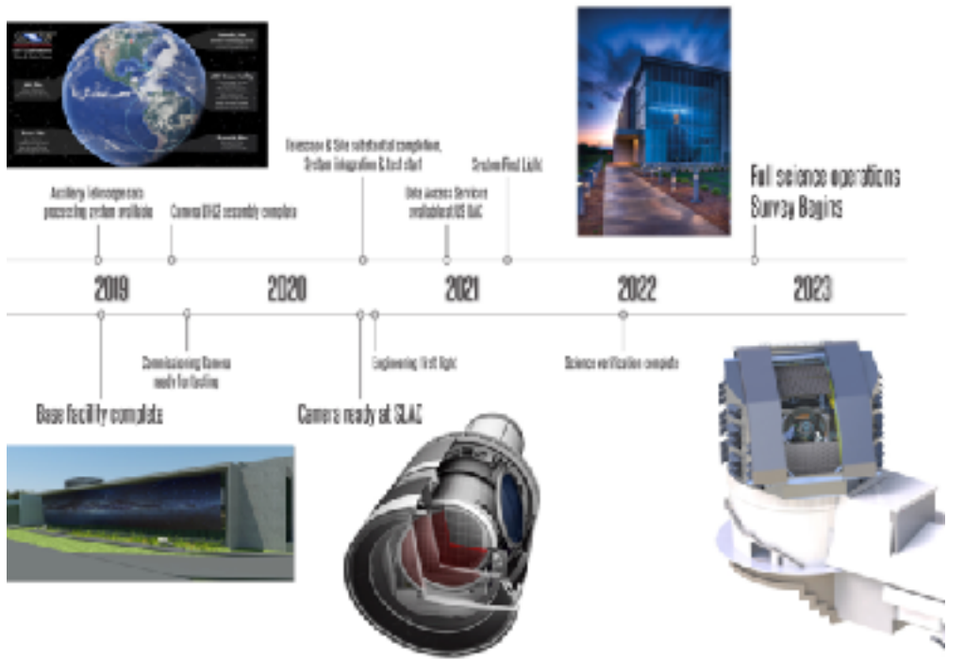
The 8.4-meter Simonyi Survey Telescope uses a special 3-mirror design, which creates an exceptionally wide field of view, and *has the ability to survey the entire sky in only three nights.*

Will conduct a 10-year Legacy Survey of Space and Time (LSST).

Will deliver a 500 petabyte set of images and data products.

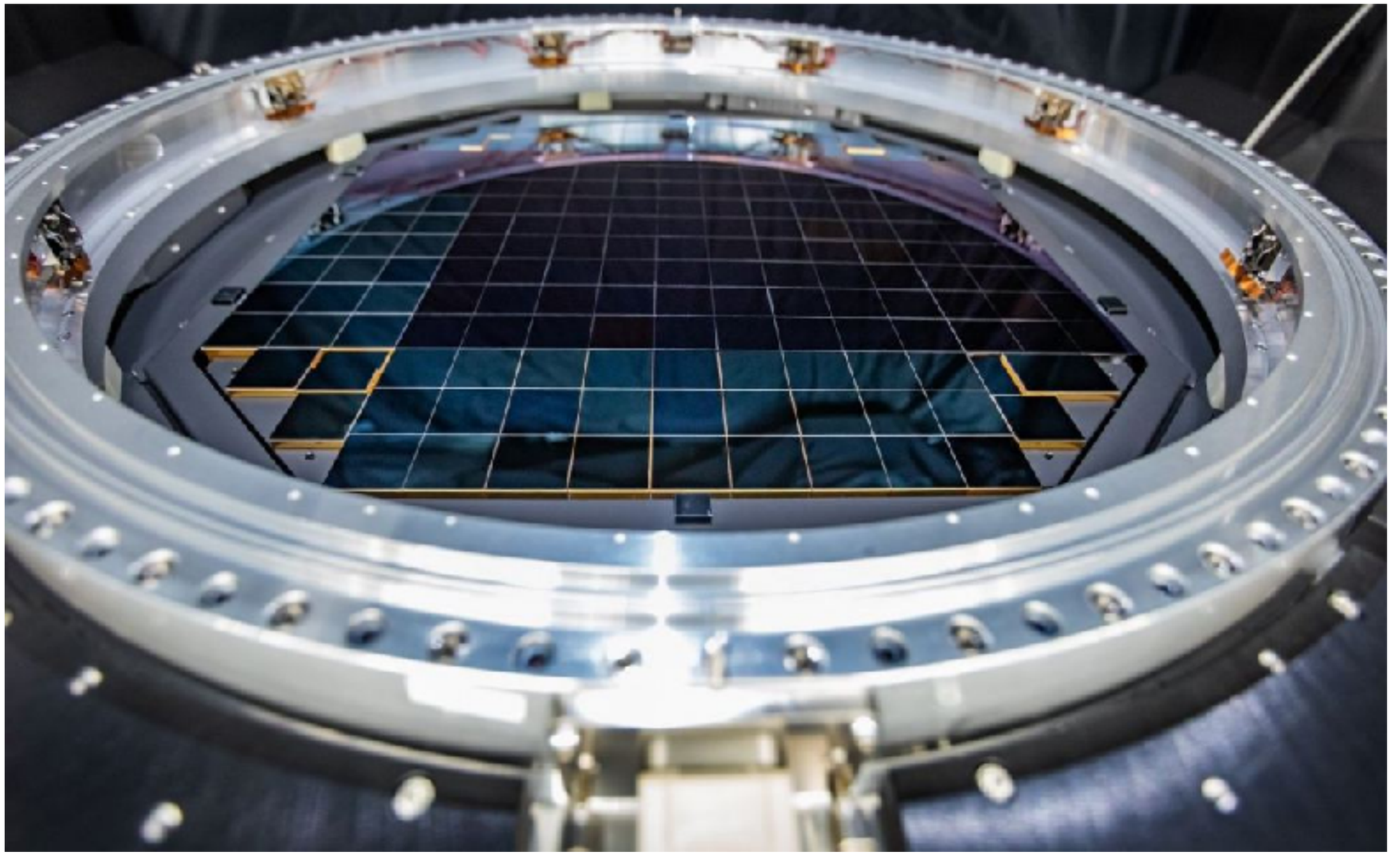
The Rubin Observatory LSST is designed to address 4 science areas:

- Probing dark energy and dark matter.
- Taking an inventory of the solar system.
- Exploring the transient optical sky.
- Mapping the Milky Way.



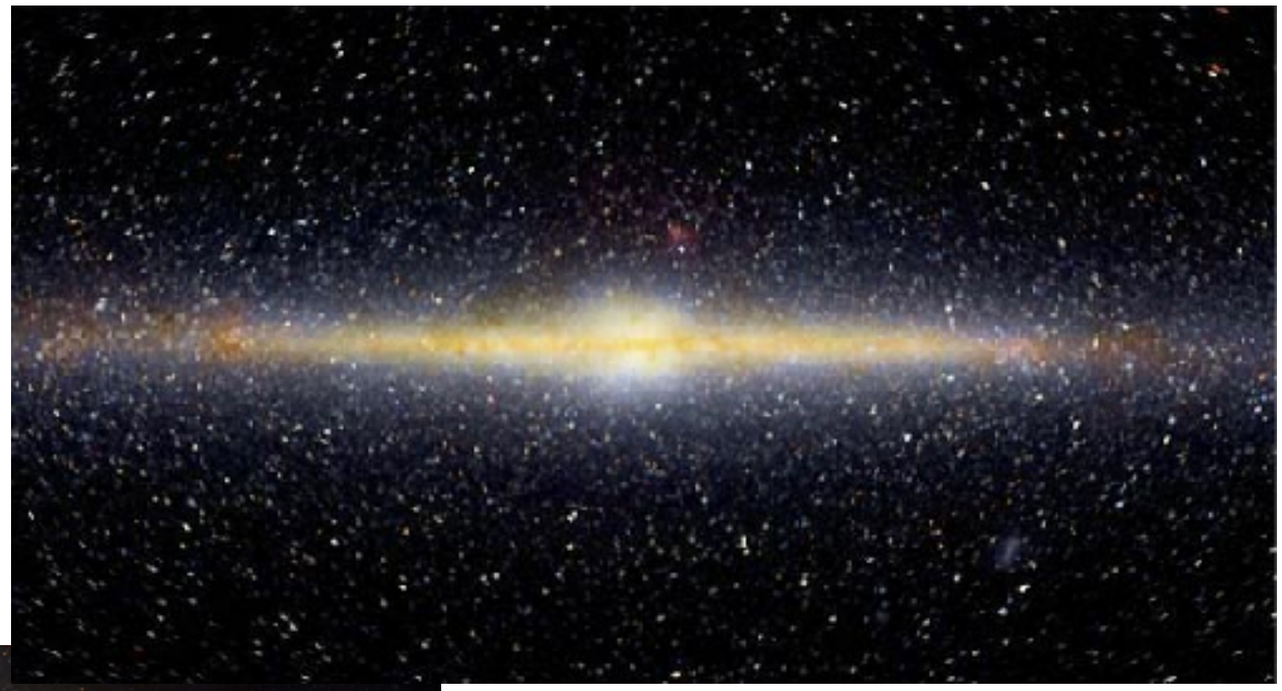
V. Rubin Focal Plane

189 CCD detectors to produce images of 3’200 megapixels.
Can map the full observable sky (at a given time) every 3 nights.
Will revolutionise the study of transient objects !



Disk Galaxies

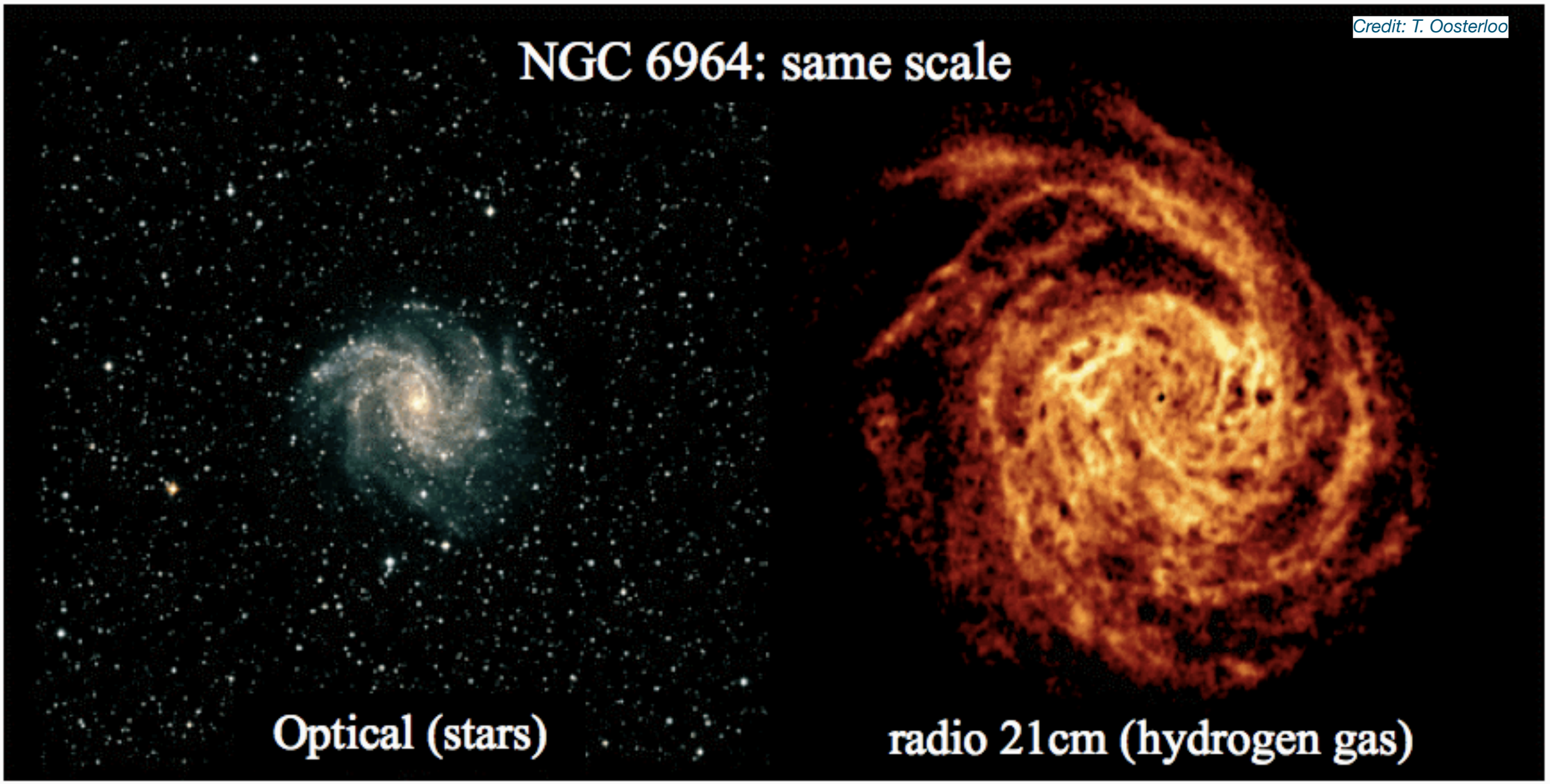
Sombrero



Milky Way

Messier 101

Galaxy Extension



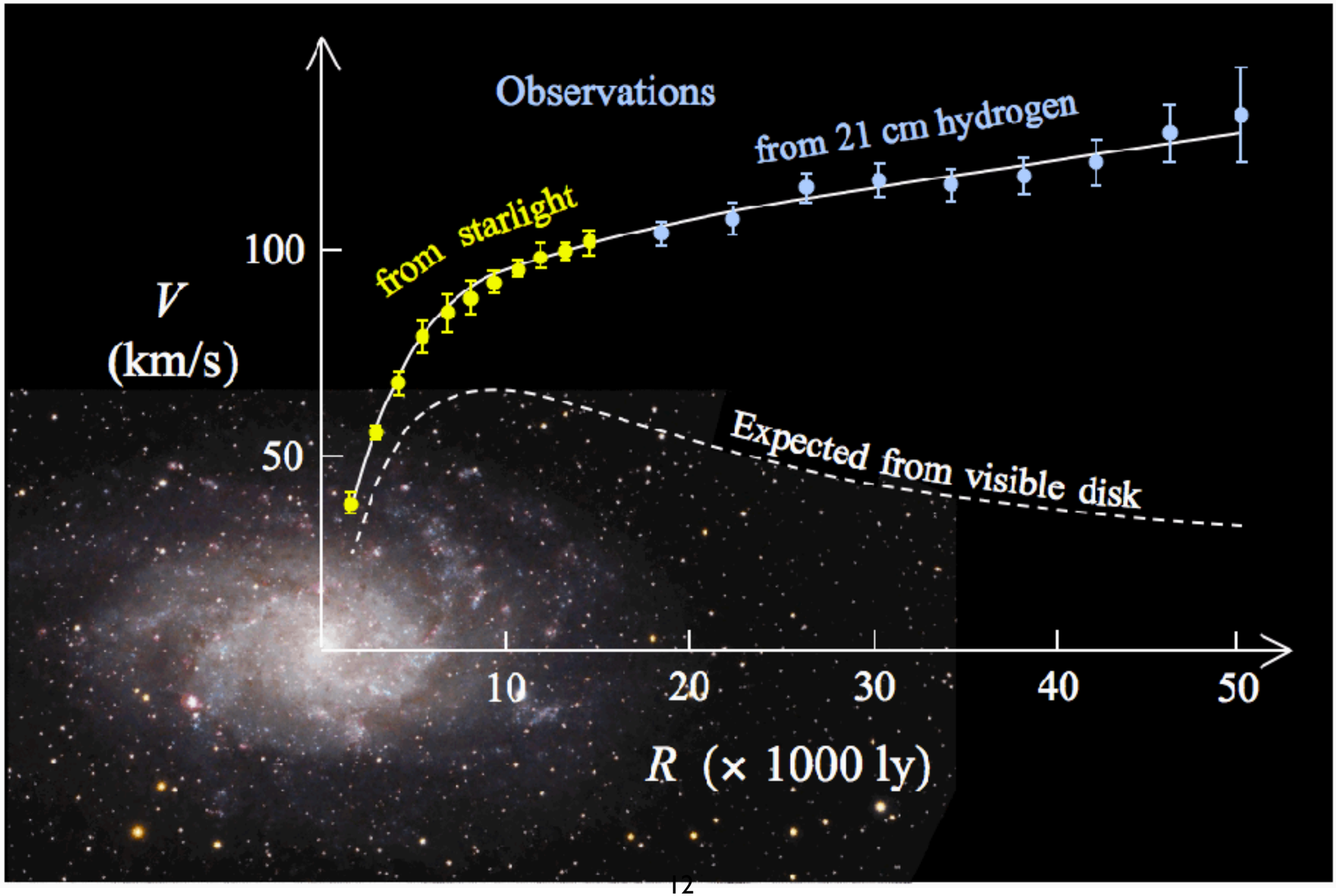
Rotation Curve

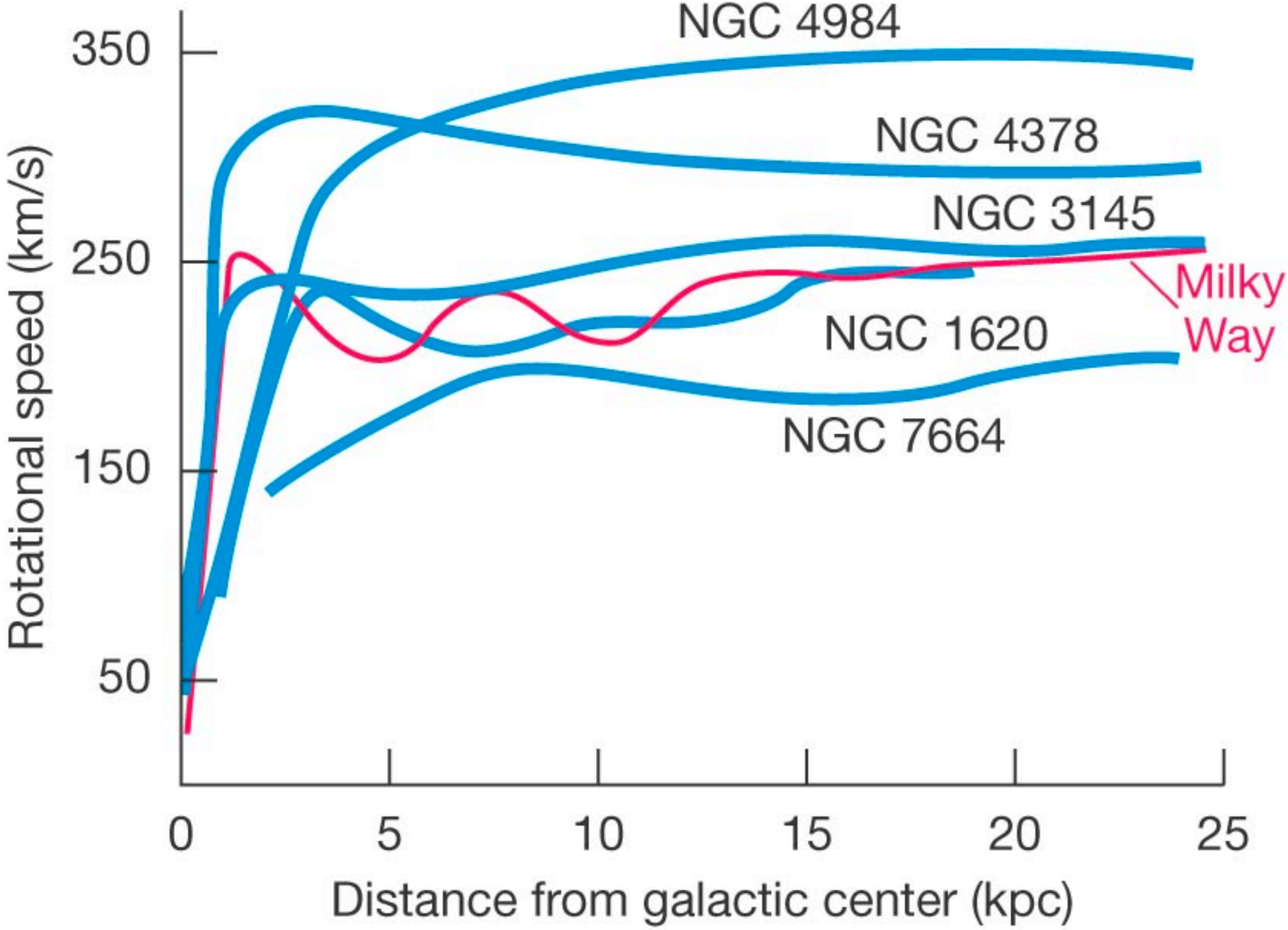
- Assuming Newtonian Gravity, the rotational velocity *(of any tracers like stars or gaz)* $v(r)$ is related to the **total Mass** $M(r)$ within radius r by the equation:

$$v(r)=\sqrt{\frac{GM(r)}{r}} \qquad M(r)=r\frac{v^2(r)}{G}$$

$$M(r)=2.3\ 10^{10}\left(\frac{r}{10kpc}\right)\left(\frac{v}{100km/s}\right)^2 M_\odot$$

Rotation Curve





(b)

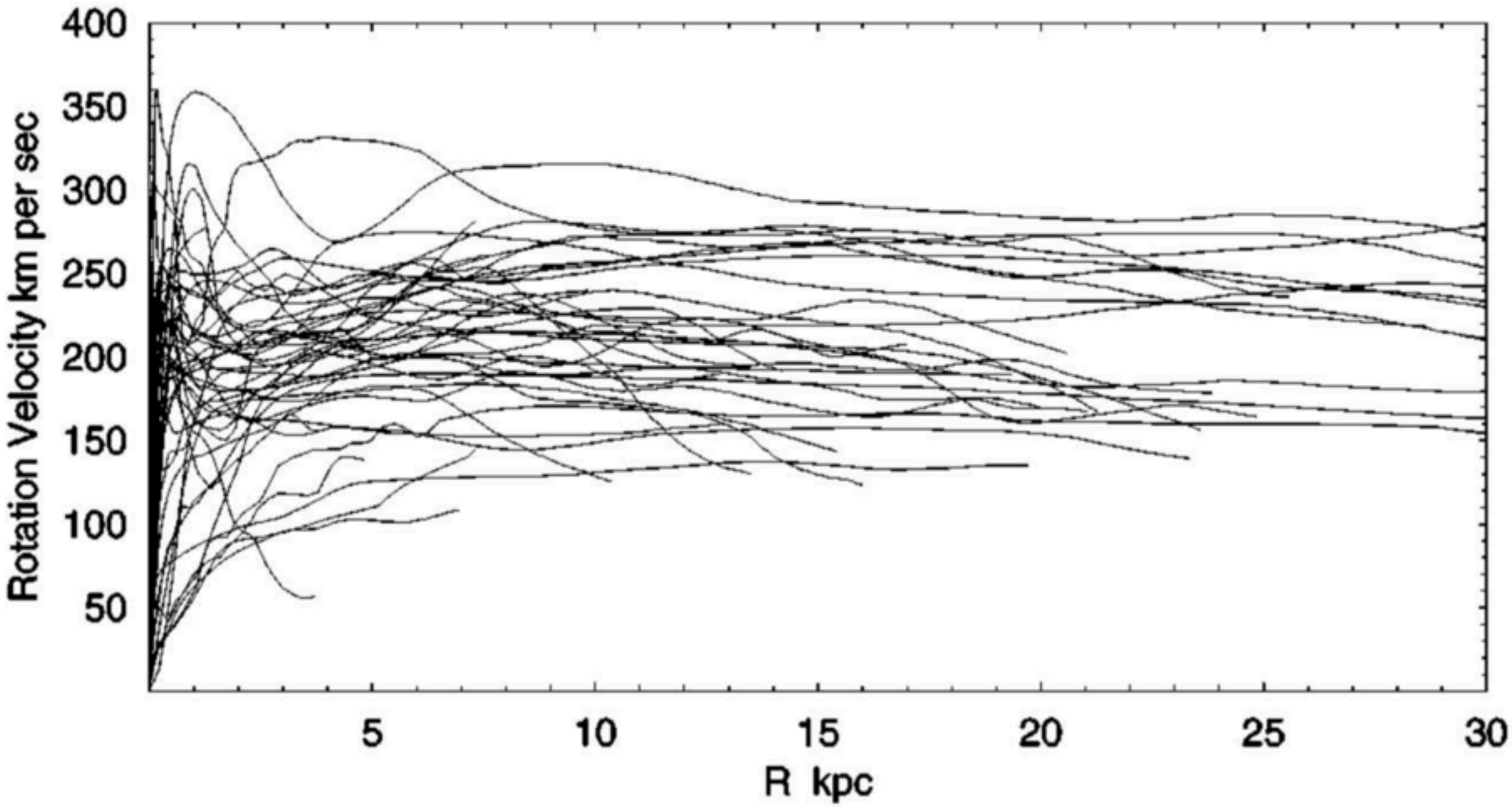
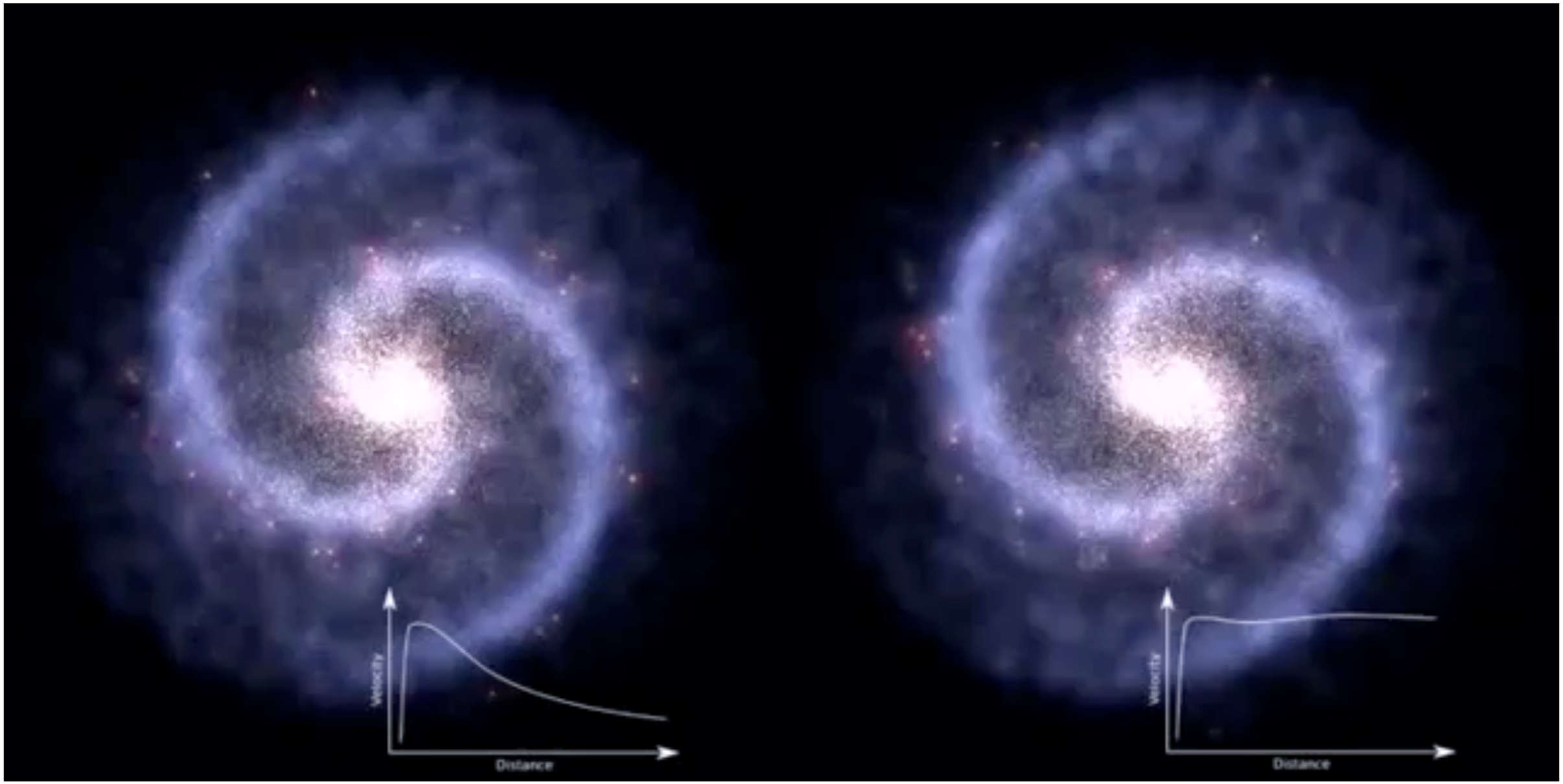


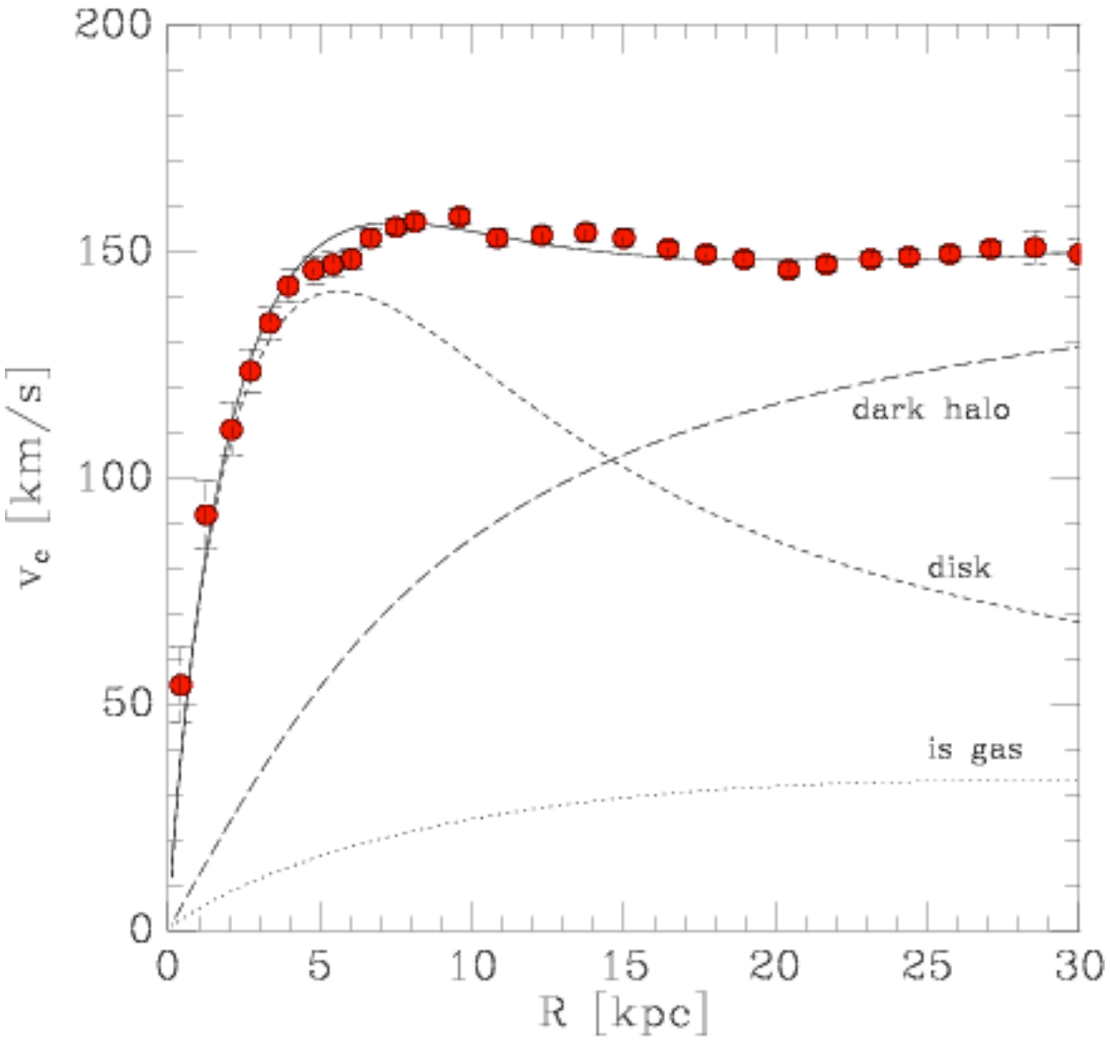
Figure 4 Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999a).

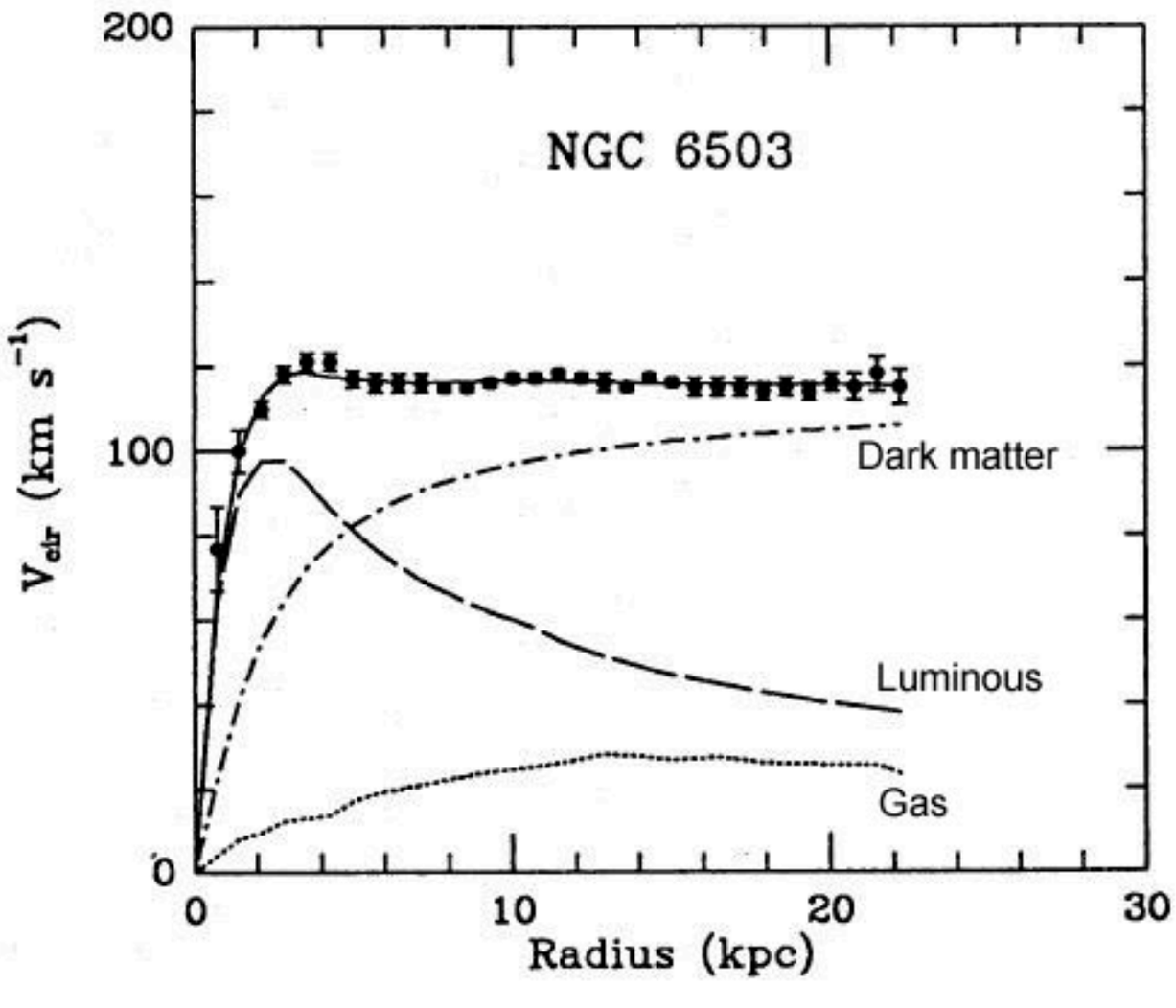
Review by: Sofue & Rubin 2001
https://www.annualreviews.org/doi/pdf/10.1146/annurev.astro.39.1.137

Rotation Curve without and with DM



Example of rotation curves & interpretation

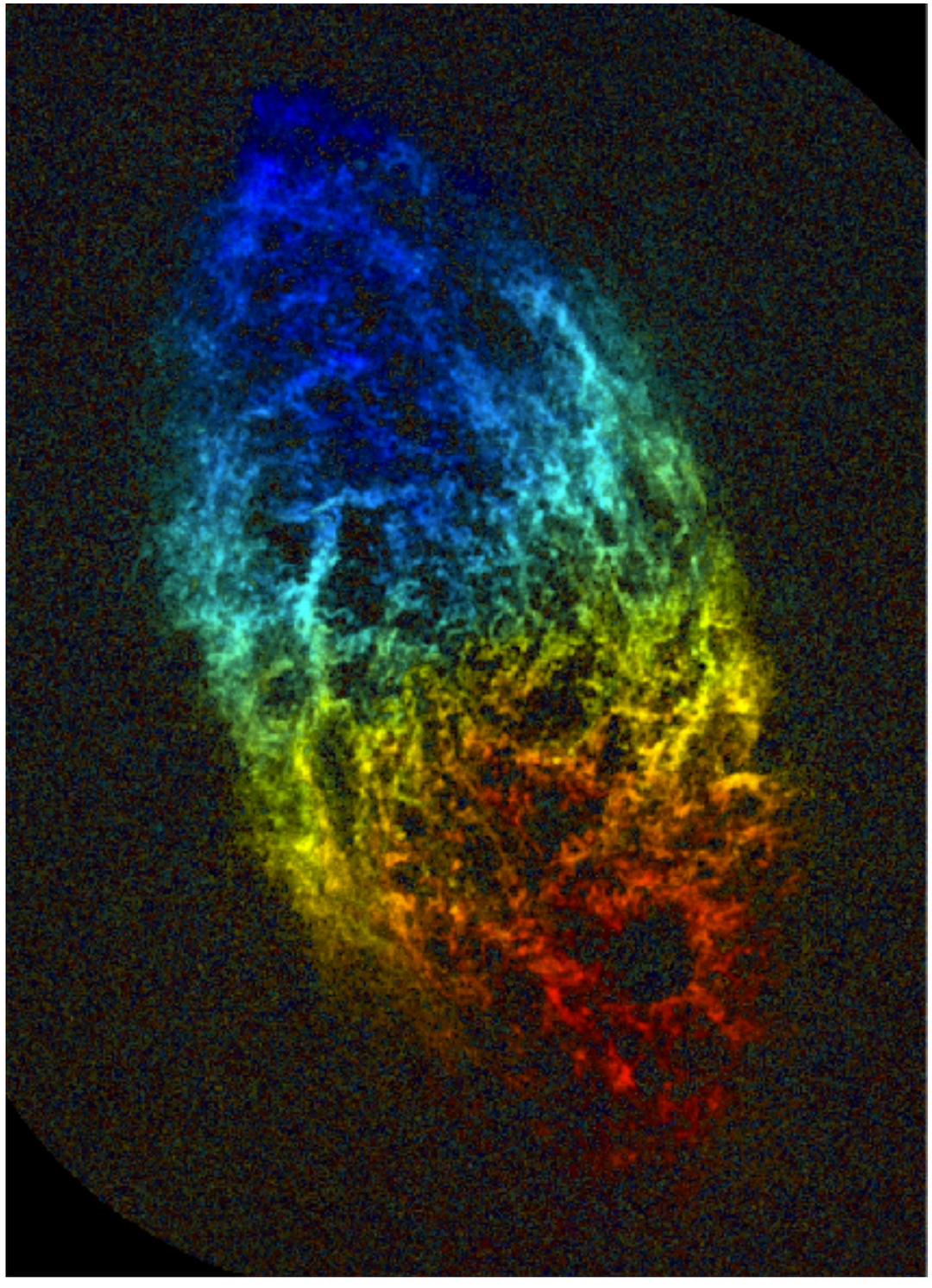




Galaxy Velocity Field

The HI radial velocity field of the nearby spiral galaxy M33 is shown here by colors corresponding to Doppler redshifts and blueshifts relative to the center of mass.

Brightness in this image is proportional to HI column density



Mass from a Galaxy velocity field

- Inclination is given by (assuming a disk galaxy):

$$\cos(i) = \frac{b}{a}$$

- radial velocity observed is given by:

$$v_r(r) = v(r)\sin(i)$$

- derived mass:

$$M(r) = r\frac{v^2(r)}{G}$$

Mass from velocity field order of magnitude

- Expressing the mass relation in typical units:

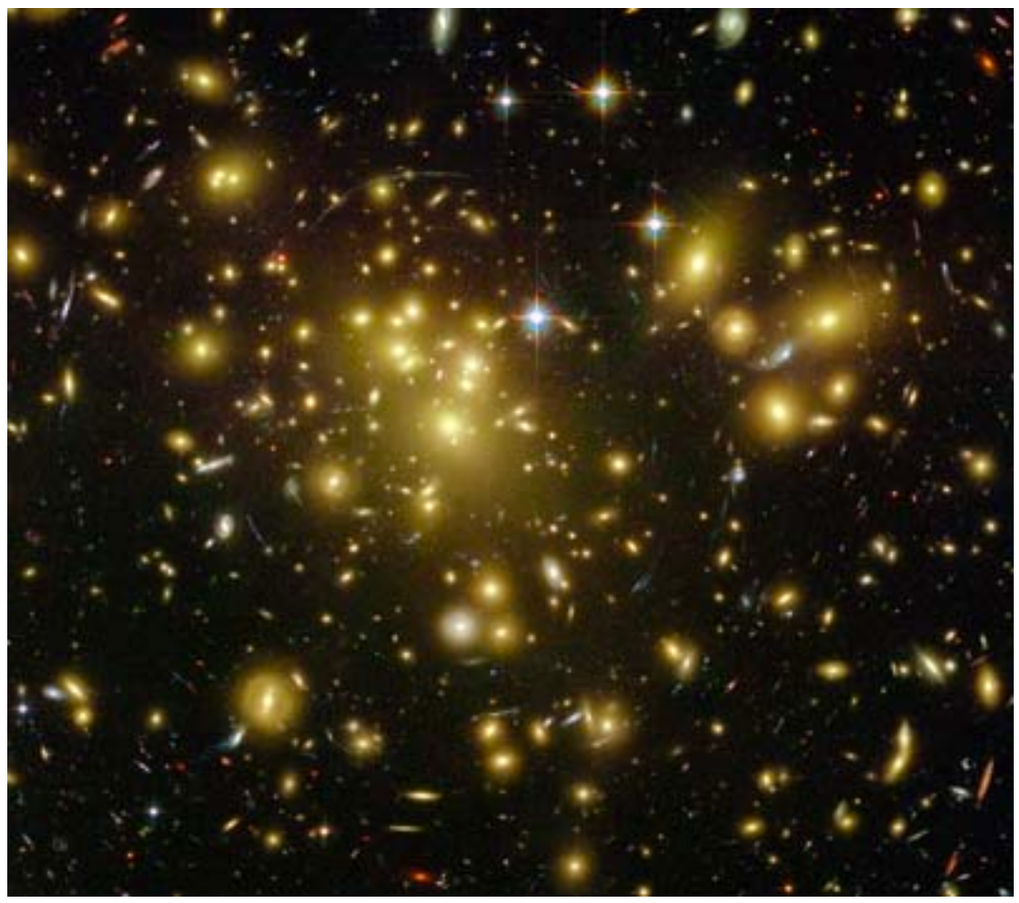
$$M(r) \sim 2.3 \times 10^{10} \left(\frac{v(r)}{100 km/s} \right)^2 \left(\frac{r}{10 kpc} \right) \; M_\odot$$

- **Milky Way:**
  - Dynamical mass: v~254 km/s, r~80 kpc leading to M~10^{12} solar masses
  - Mass of stars in the MW ~5.10^{10} solar masses
  - **M/M*~20**

Elliptical Galaxies

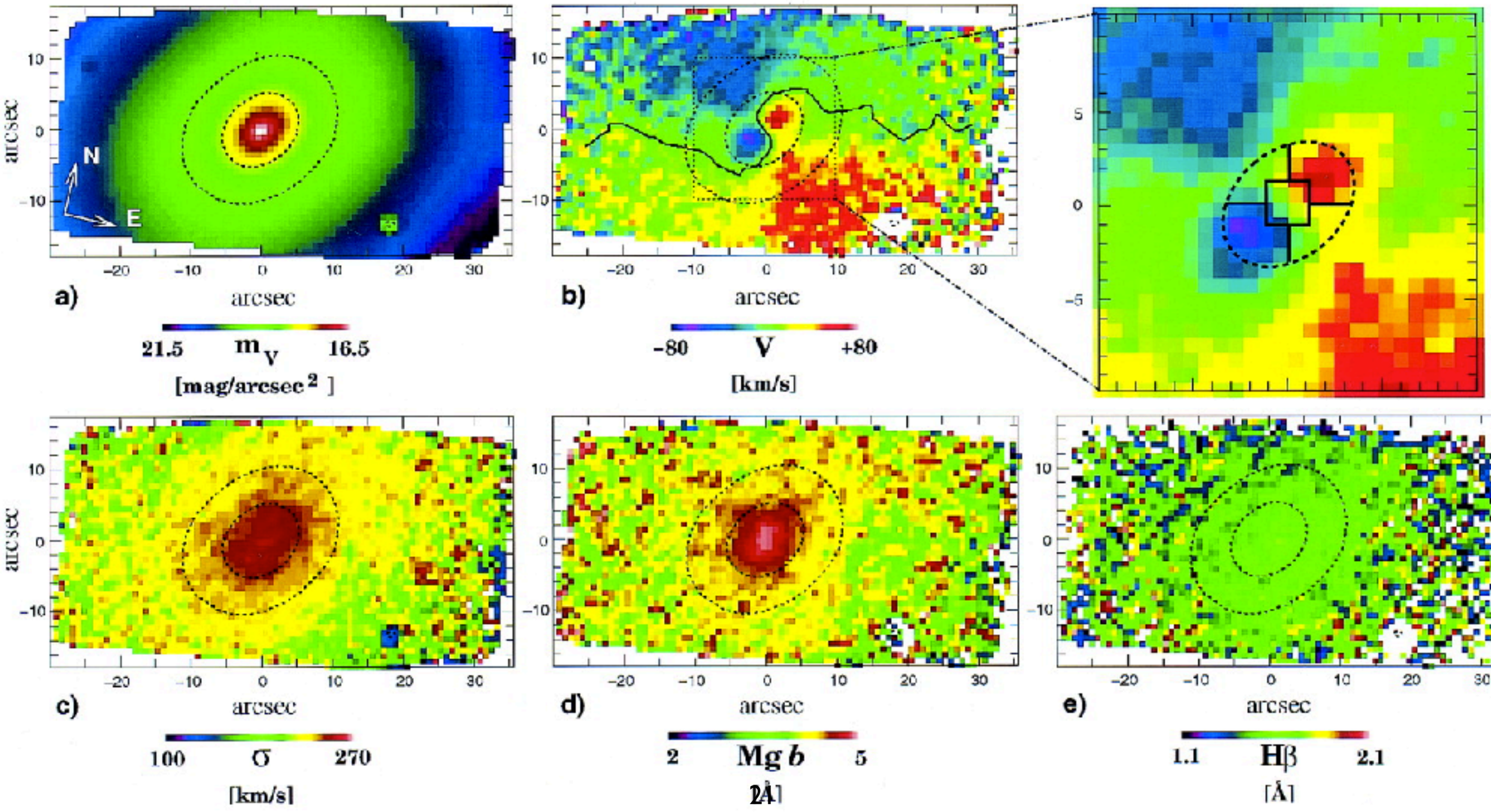
Messier 87

Classification

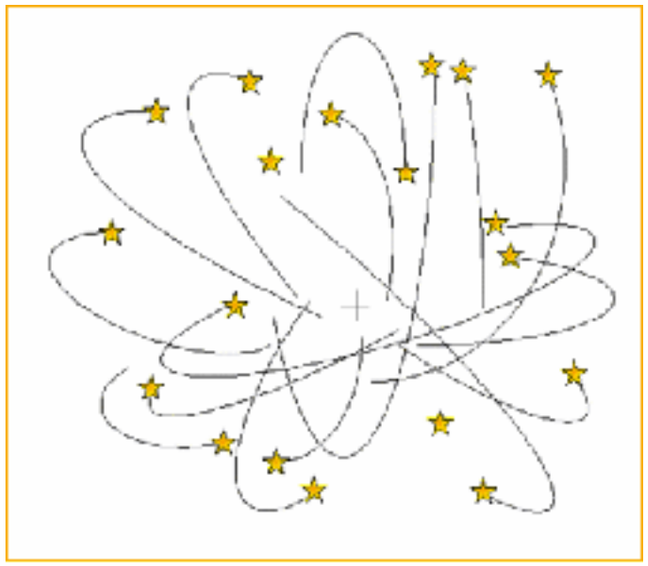


Abell 1689
Many E galaxy
in the core

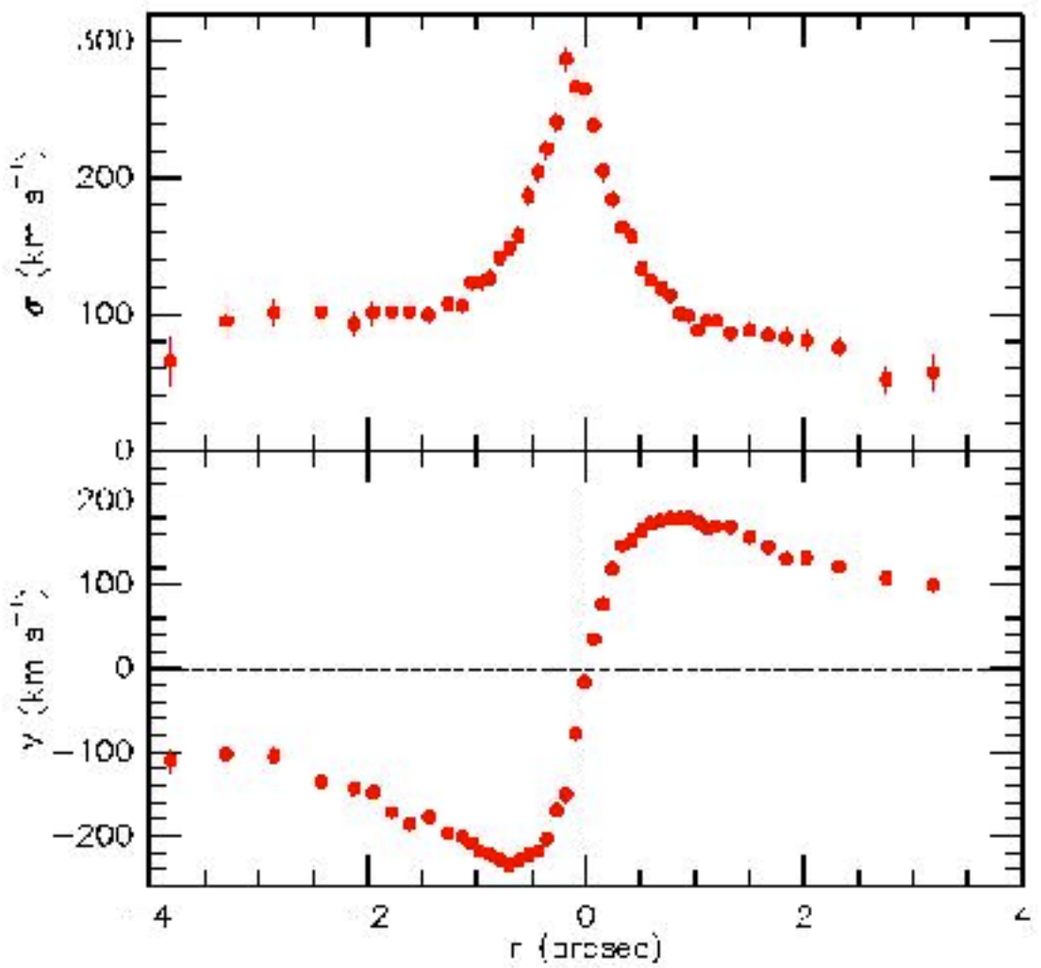
Velocity map



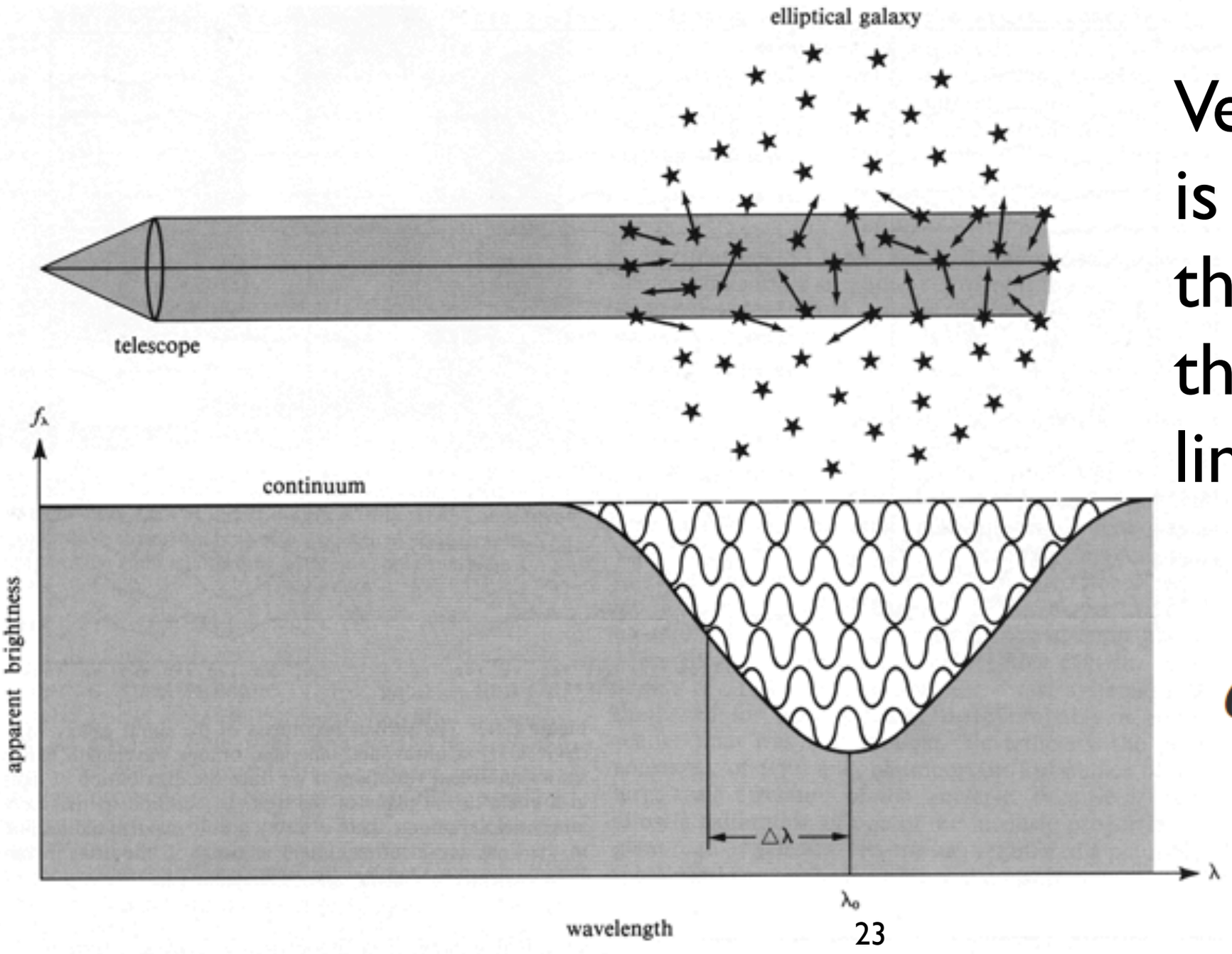
Velocity map



- Velocity dispersion from random motion of stars
- Rotational velocity map (as in disk galaxy)



Velocity dispersion measurement



Velocity dispersion is proportional to the broadening of the absorption line width

$$\sigma \sim \frac{\Delta\lambda}{\lambda_0} c$$

Viral Theorem

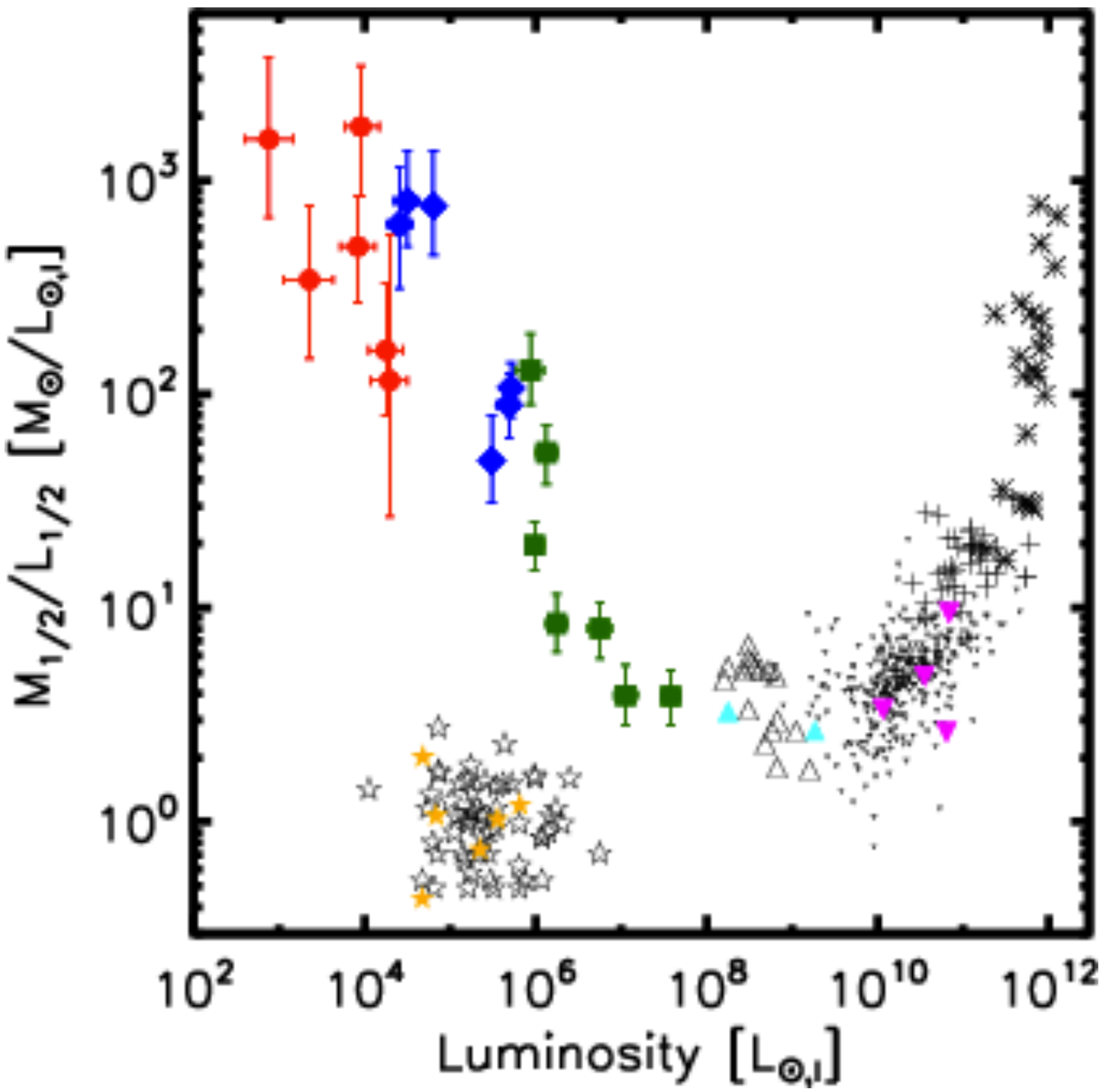
- The total mass of an isolated spherical system in a steady state can be expressed as (Binney and Tremaine, 2008):

$$\langle \sigma_p^2 \rangle = \frac{GM}{3r_g}$$

r_g is the gravitational radius

$\langle \sigma_p^2 \rangle$ is the average line of sight velocity dispersion

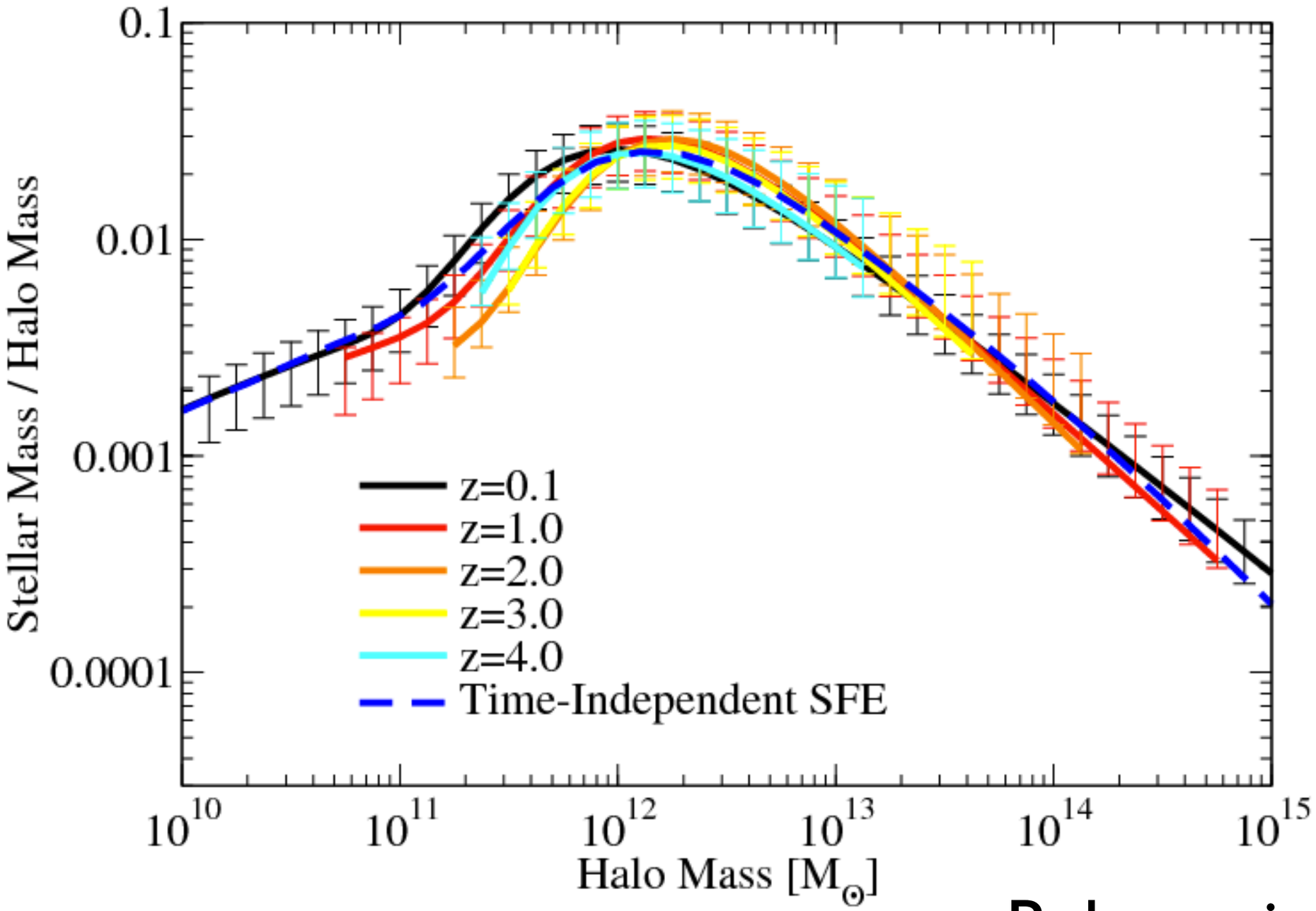
Mass to Light Ratio



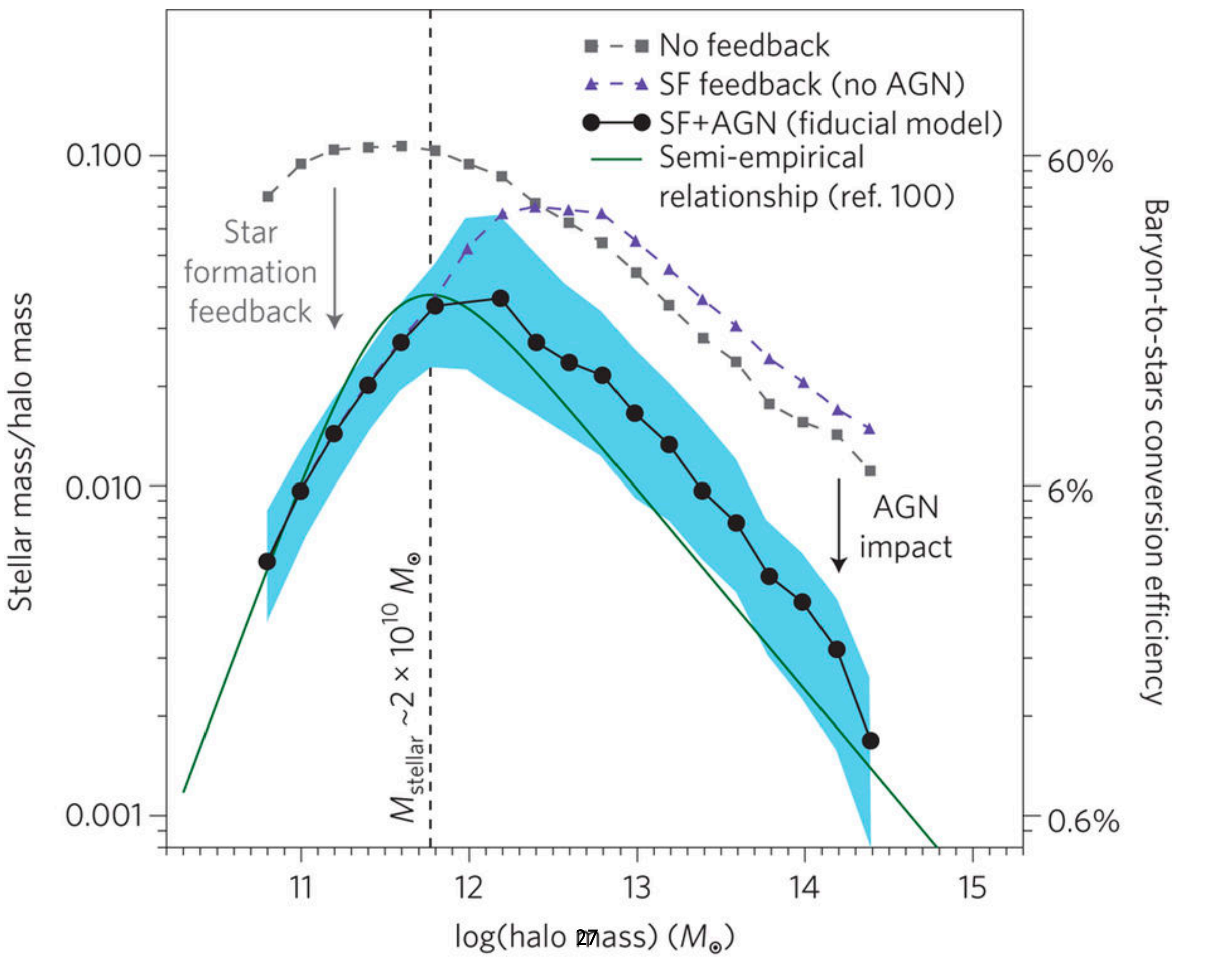
- Mass to Light ratio for a range of spheroidal galaxy systems (Mass measured at the half-light radius)
- Dwarfs to Giants
- Globular clusters

Wolf et al 2010

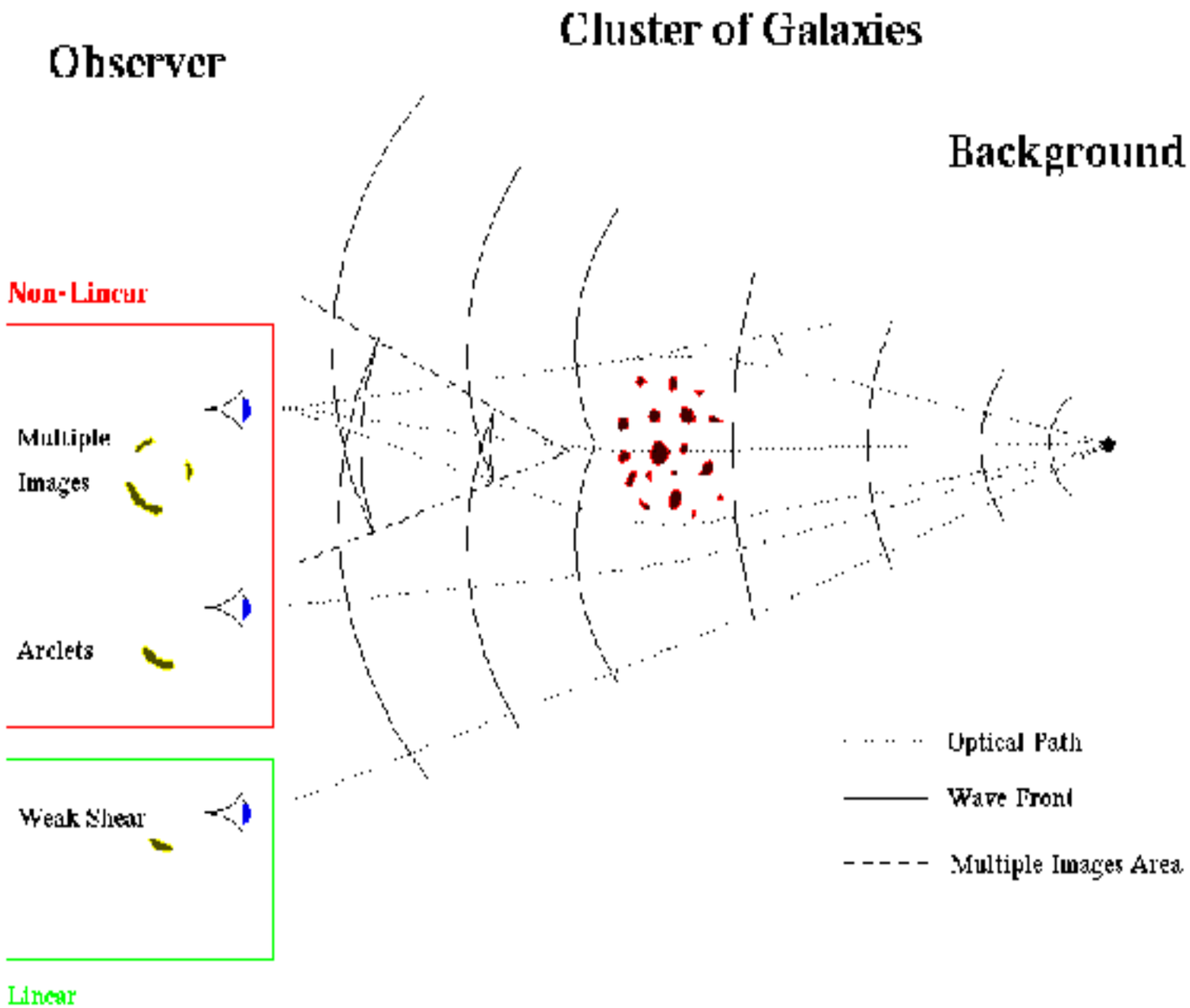
Stellar to dark halo mass ratio



Behroozi et al 2013


No feedback
SF feedback (no AGN)
SF+AGN (fiducial model)
Semi-empirical relationship (ref. 100)
Star formation feedback
AGN impact
$M_{stellar} \sim 2 \times 10^{10}\ M_\odot$
0.100
0.010
0.001
60%
6%
0.6%
11
12
13
14
15
log(halo mass) ($M_\odot$)
Stellar mass/halo mass
Baryon-to-stars conversion efficiency

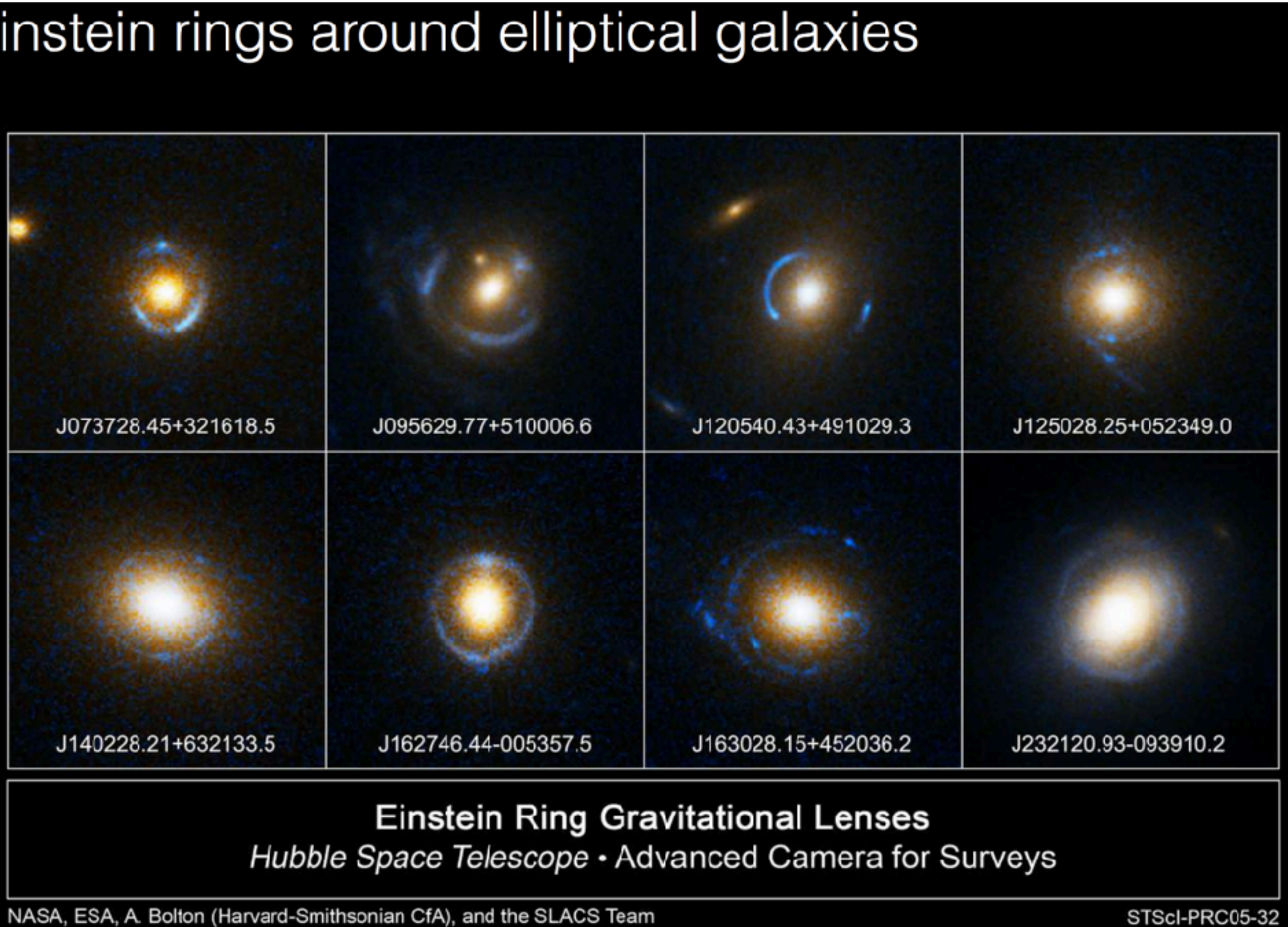
Gravitational Lensing to measure Galaxy mass



$$M(r_E) = \pi \Sigma_{crit} r_E^2$$

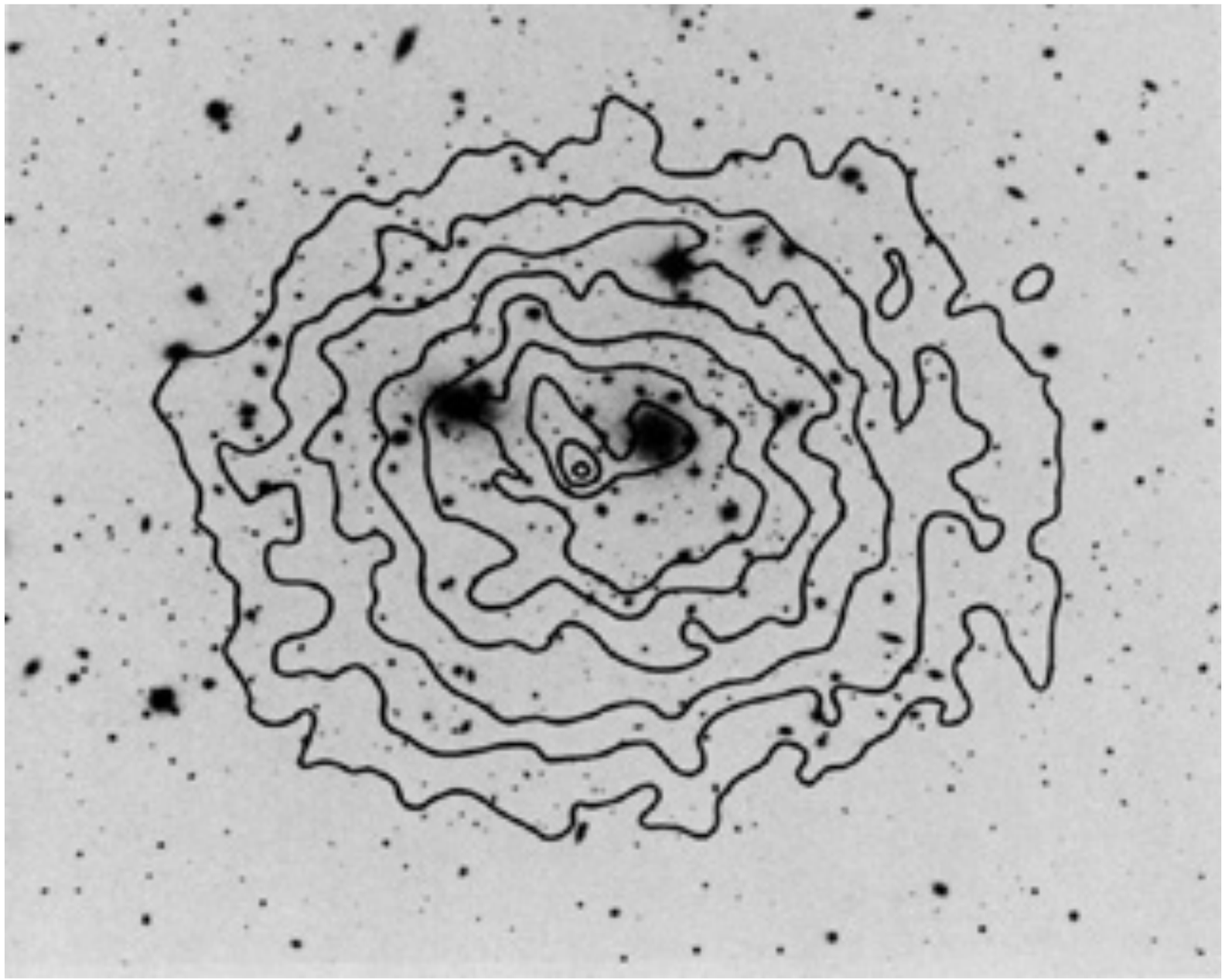
$$\approx 1.1 \times 10^{14}\, M_\odot \left(\frac{\theta_E}{30''}\right)^2 \left(\frac{D}{1\,\mathrm{Gpc}}\right)$$

Gravitational Lensing to measure Galaxy mass



Clusters of Galaxies

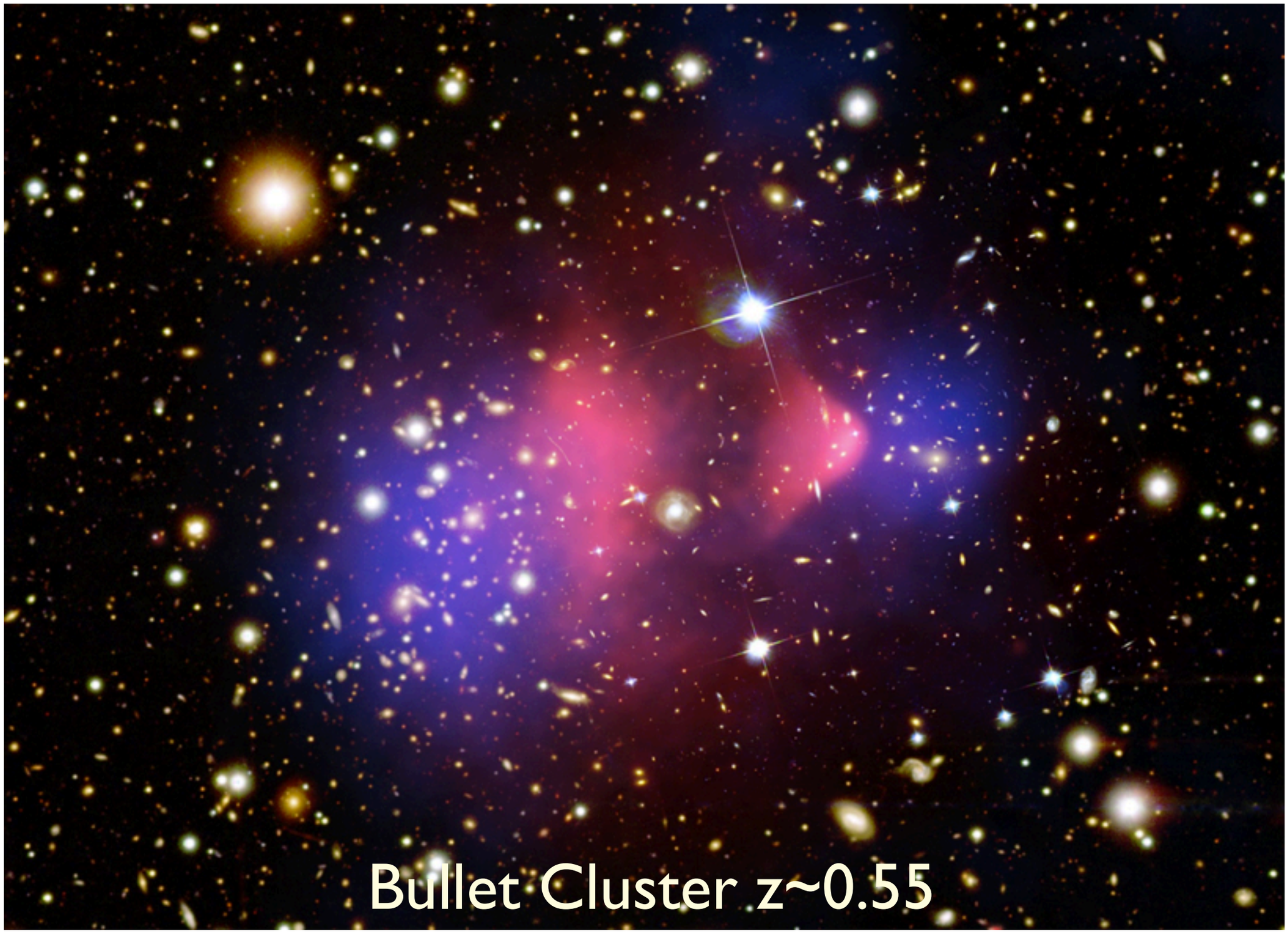
Cluster of Galaxies



- The Nearby Coma Cluster (z~0.02)
- X-ray detection detected by the Uhuru X-ray satellite in 1971

Cluster of Galaxies

Strong evidence of the existence of Dark Matter



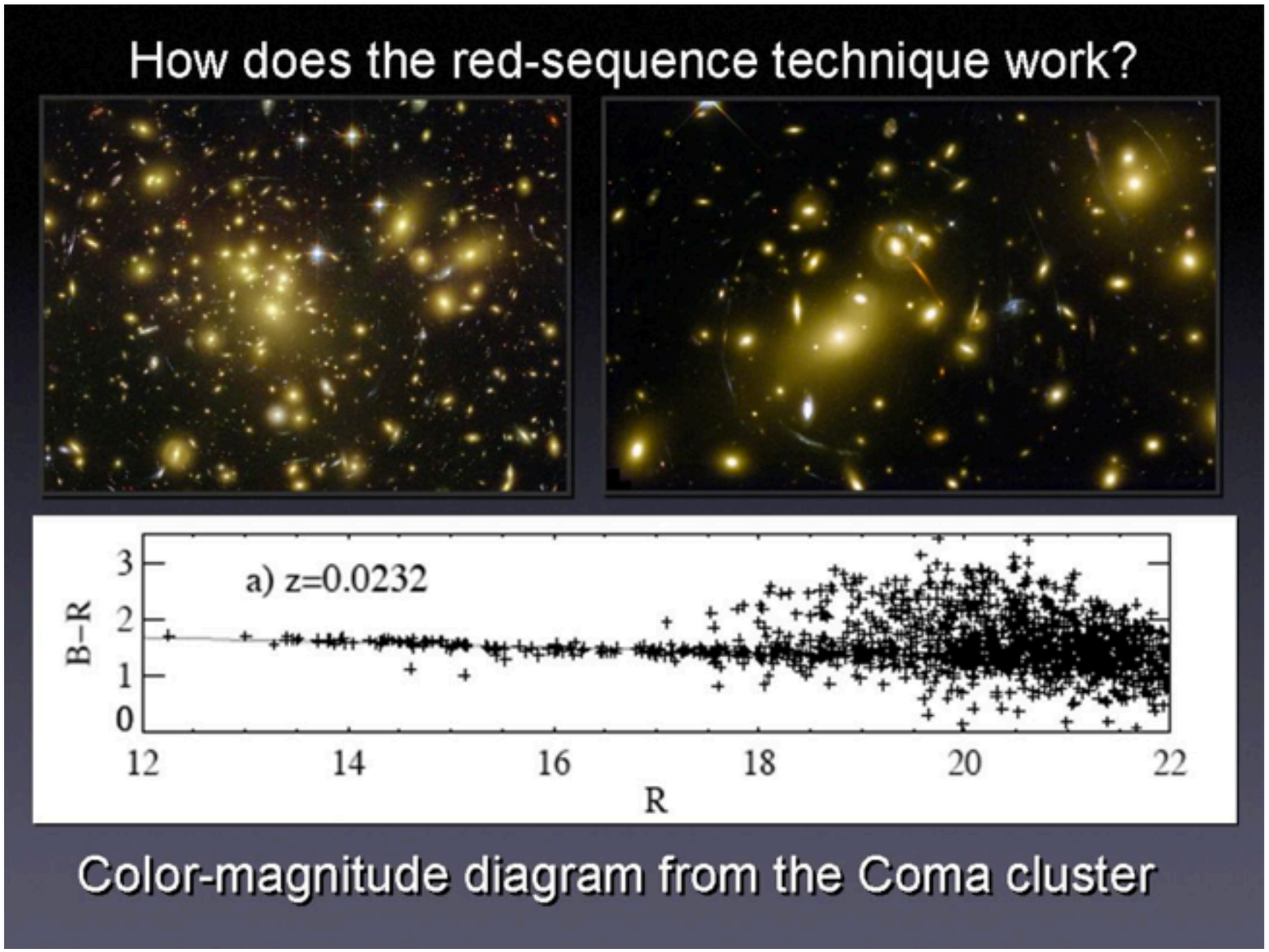
Cluster of Galaxies

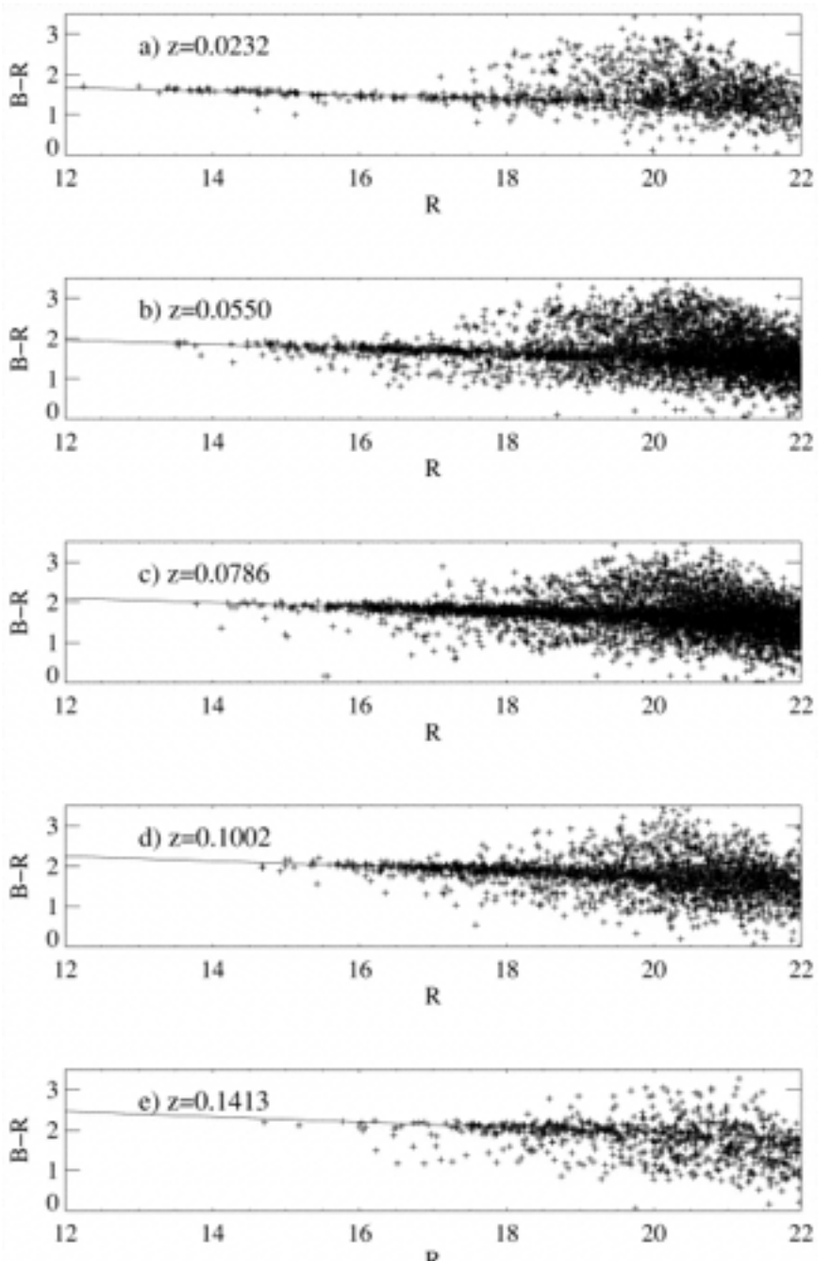
- **How to detect clusters of galaxies:**
  - Concentration of galaxies:
    - Abell catalogue (1958)
    - color-magnitude sequence http://risa.stanford.edu/redmapper/
  - X-ray emission from Bremsstrahlung
    - First X-ray satellite Uluru (1971)
    - Current: Chandra and XMM-Newton satellite
  - Sunayev-Zeldovich effect (SZ)
    - ground based telescopes (~1990)
    - Planck space mission (2013)
  - Gravitational Lensing

Stopped Here

Cluster of Galaxies

- Color Magnitude sequence
- Cluster galaxies formed ~about the same time





Cluster of Galaxies

- X-ray Bremsstrahlung

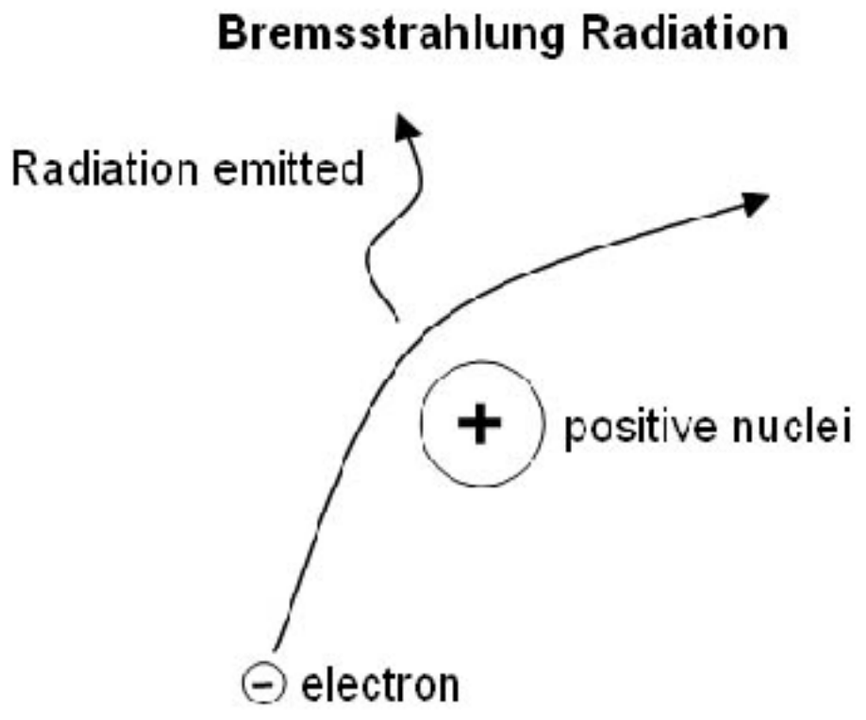
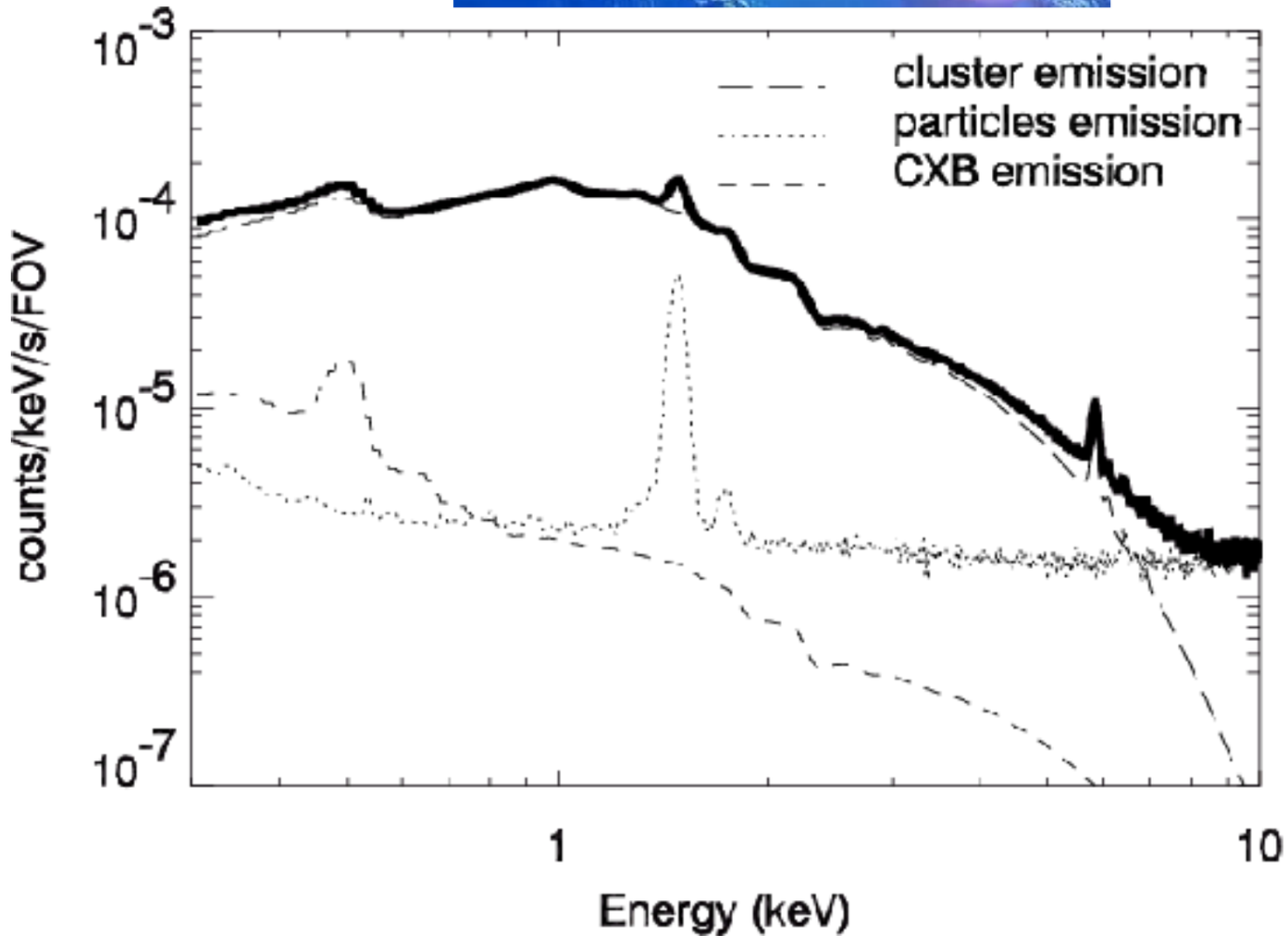
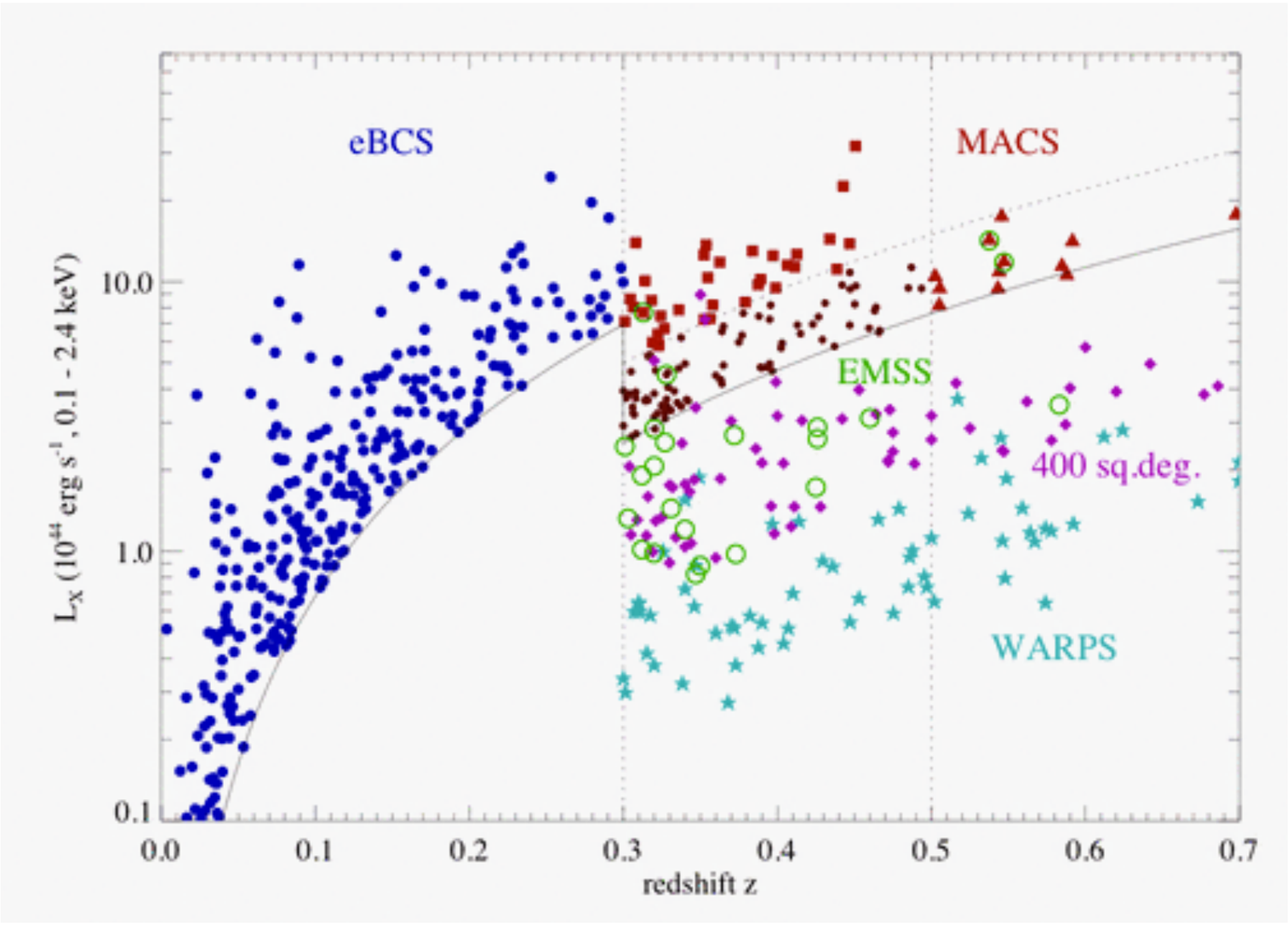


Figure 1: Bremsstrahlung (or 'braking') radiation is emitted when the path of a charged particle such as an electron is deviated by another charged particle. The acceleration of the electron causes it to emit a photon of light with an energy indicative of the electrons kinetic energy.



Cluster of Galaxies

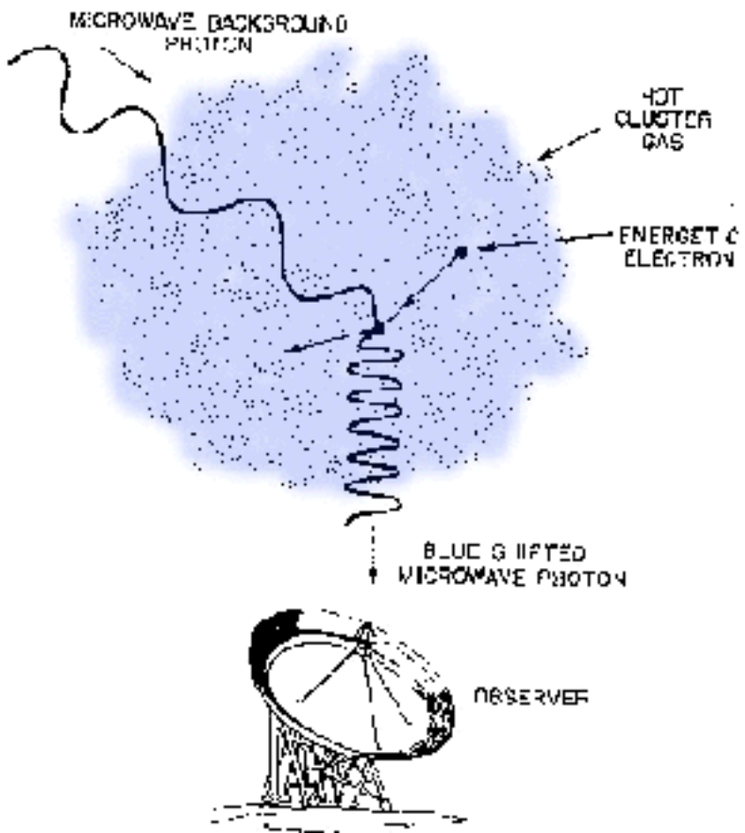
- X-ray cluster samples
- Based on the ROSAT All Sky Survey + Optical follow-up

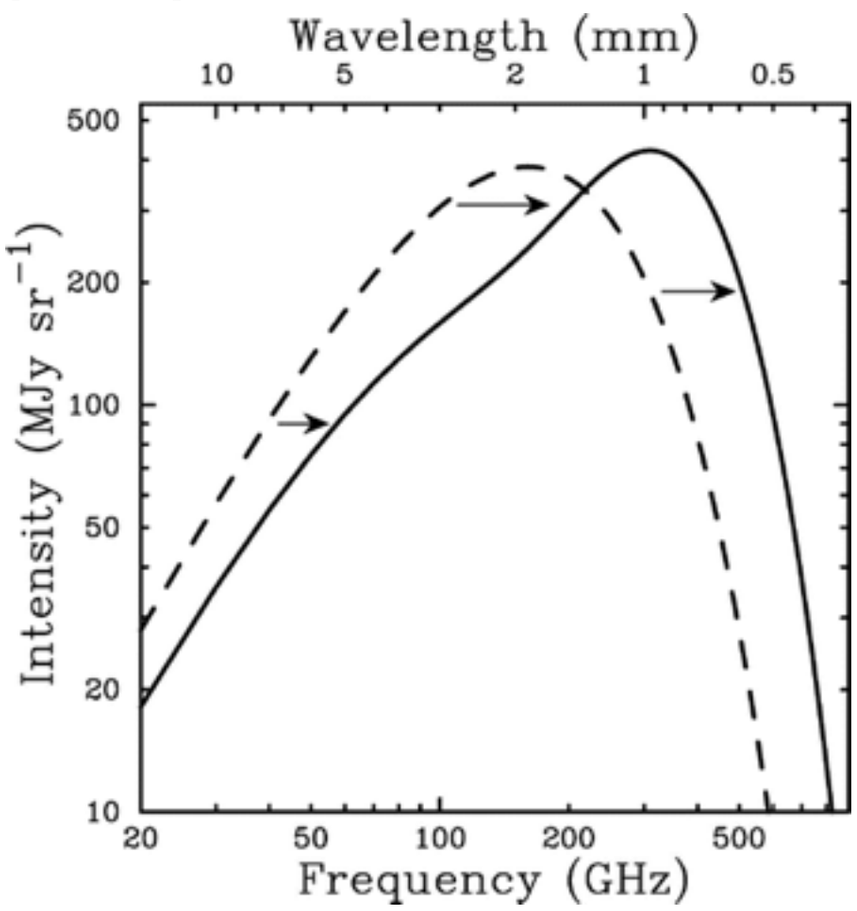


http://www.ifa.hawaii.edu/~ebeling/clusters/MACS.html

Cluster of Galaxies

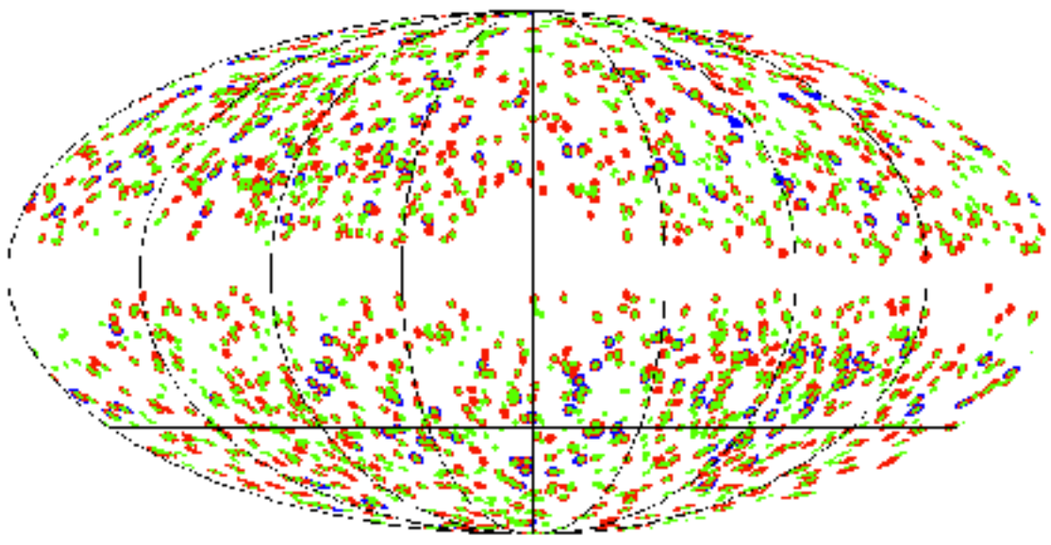
- Sunayev-Zeldovich (SZ) - effect:
  - CMB photons going through a massive cluster
  - collision with electrons: energy boost through inverse Compton scattering
  - CMB spectrum shifted to higher frequency



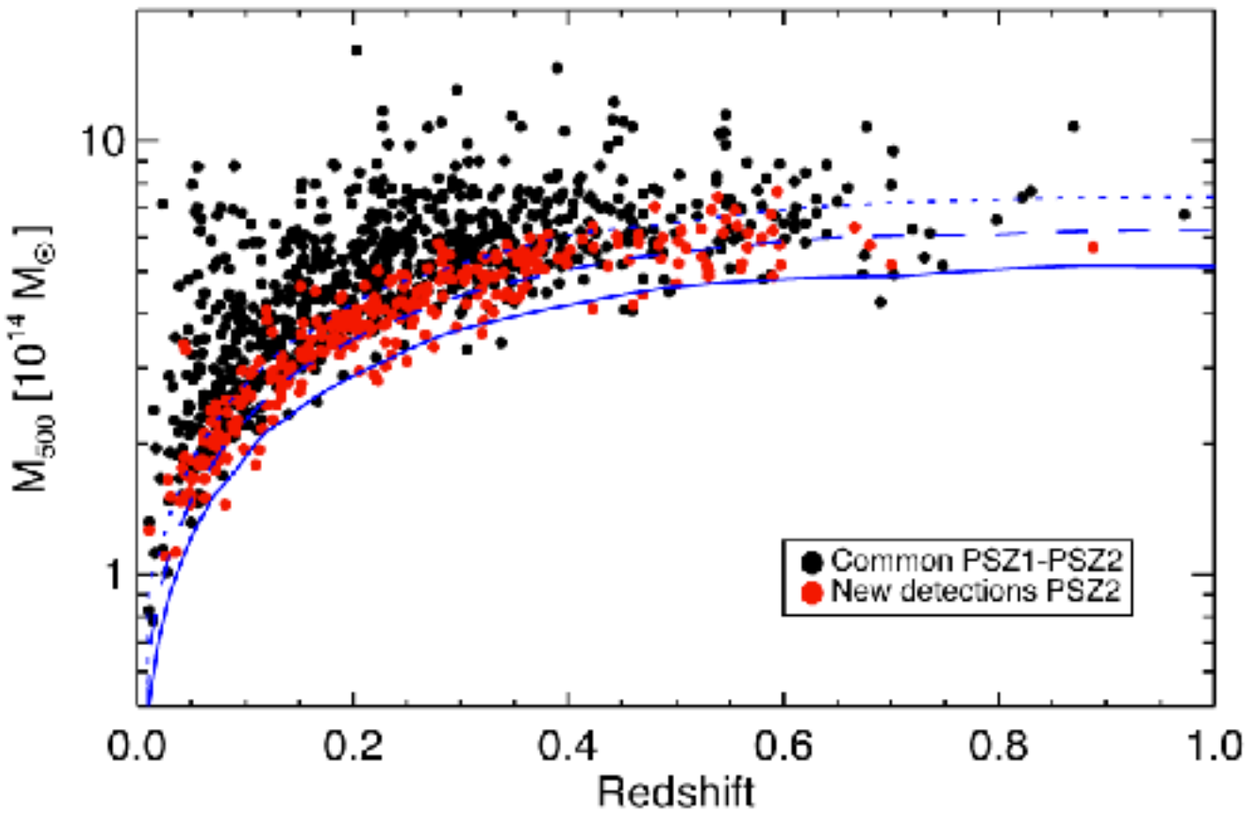


Cluster of Galaxies

- SZ detection of Clusters with the Planck mission
- ~1650 detections, ~1100 confirmed clusters

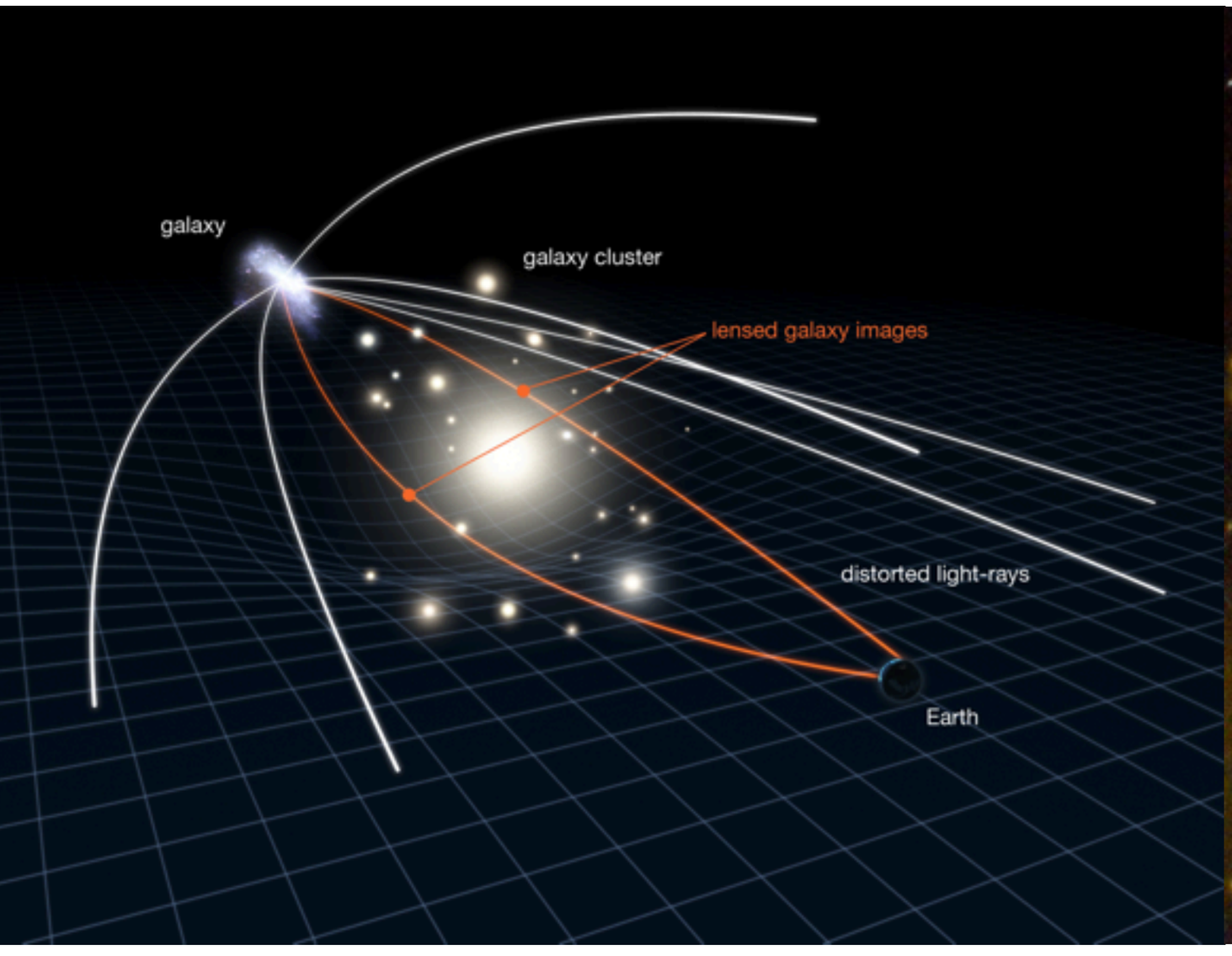


SZ Planck Clusters



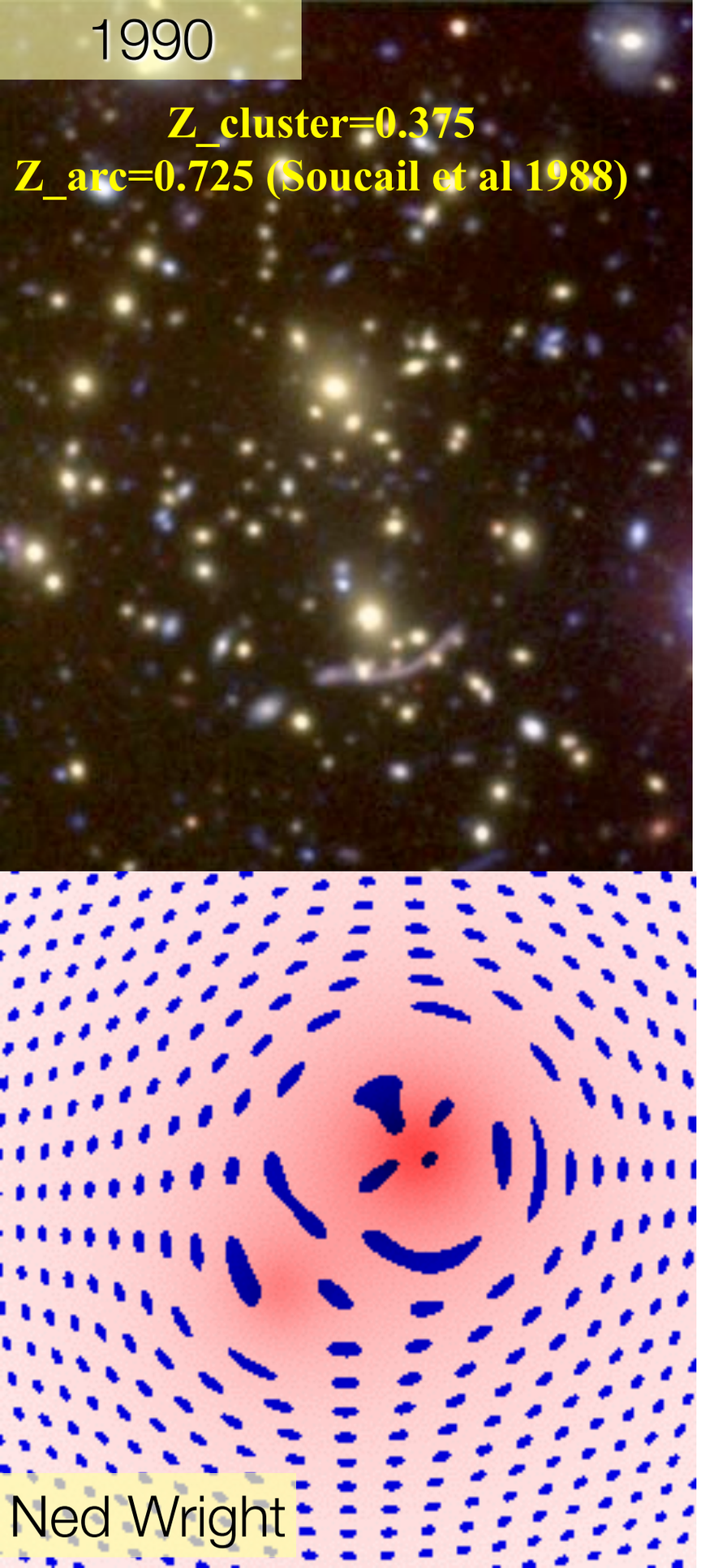
Cluster of Galaxies

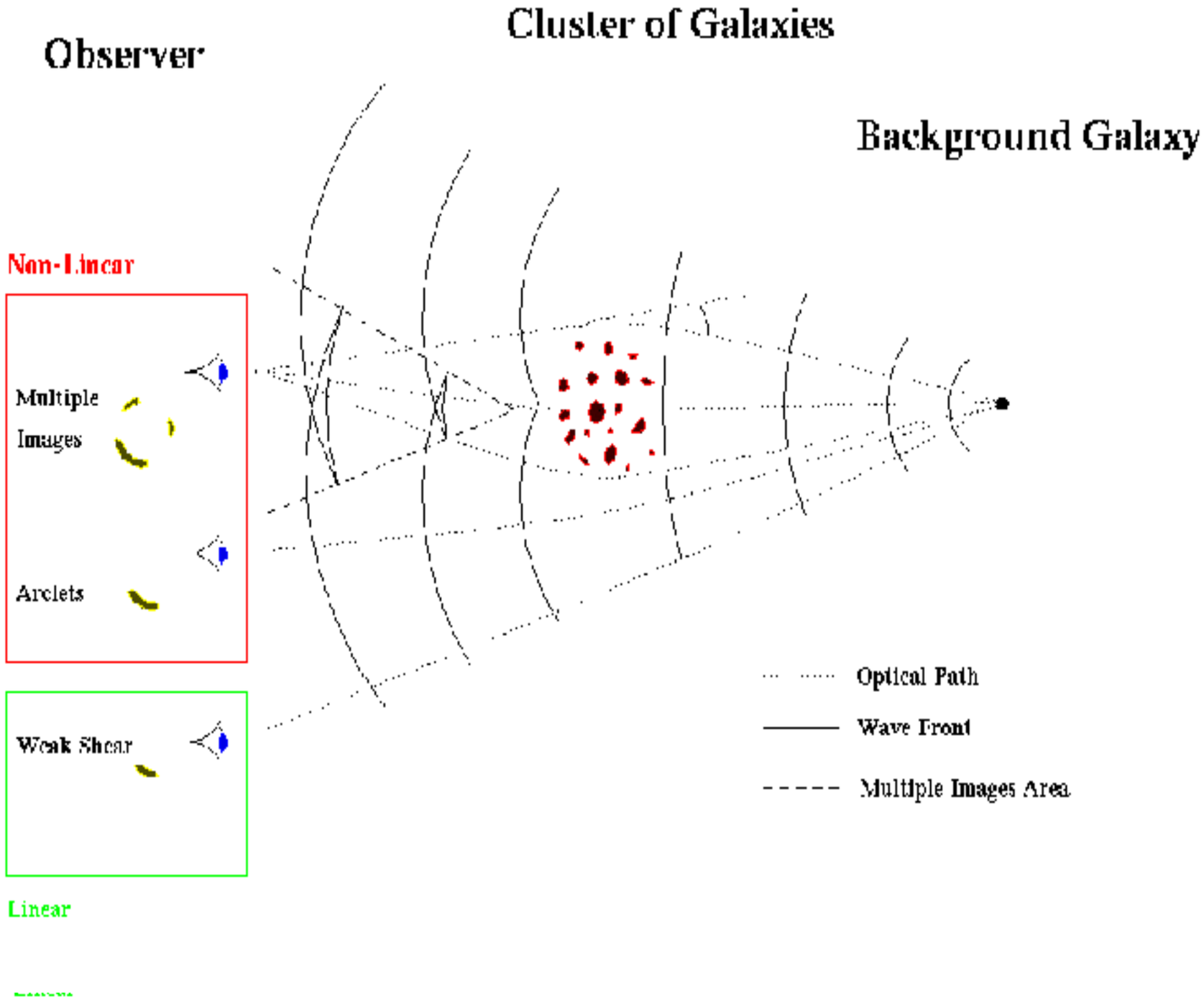
- Gravitational Lensing: distortion of Space-Time
- Deflection angle proportional to the cluster mass



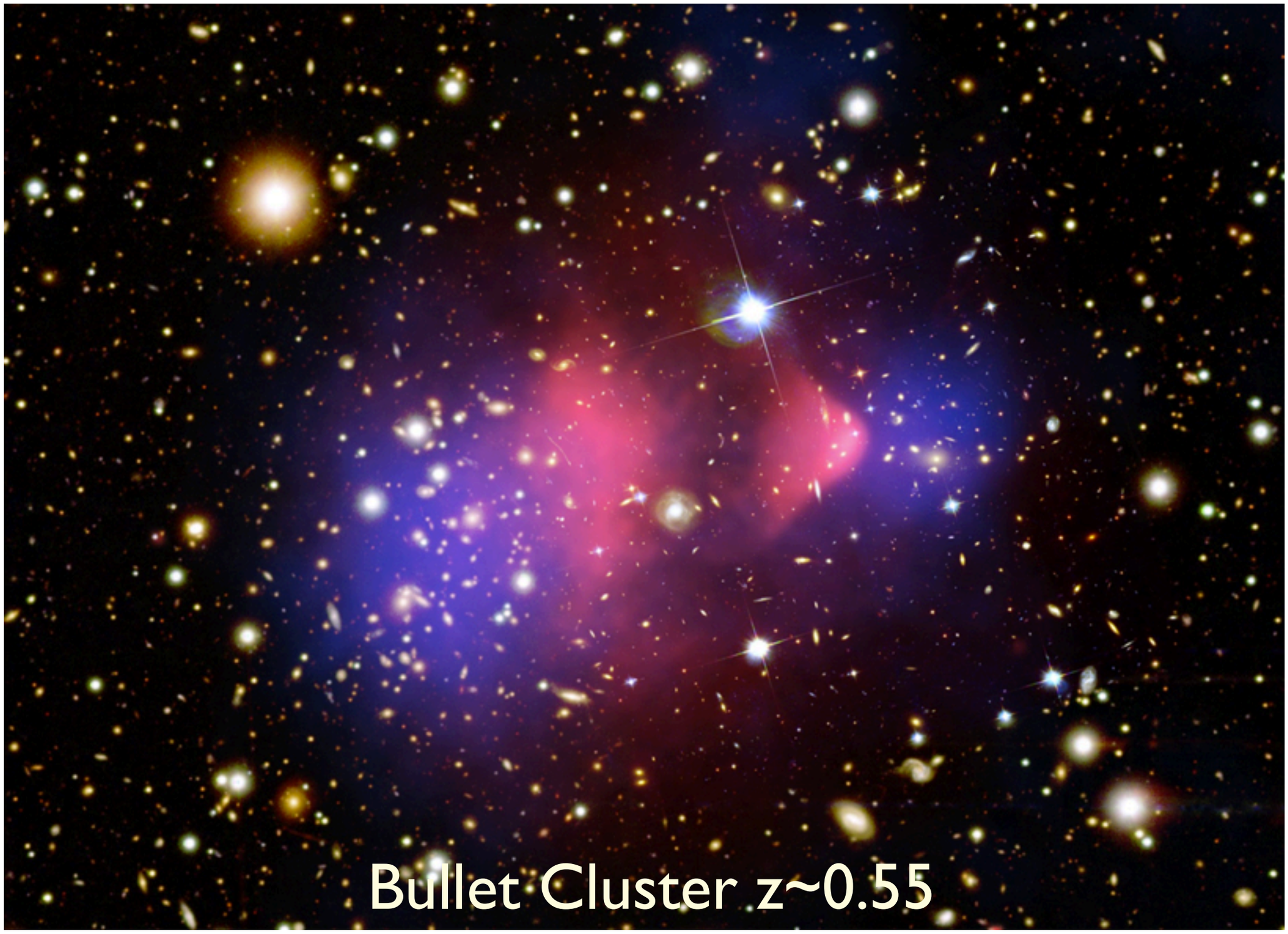
https://youtu.be/em2ypm33ulc

Cluster of Galaxies

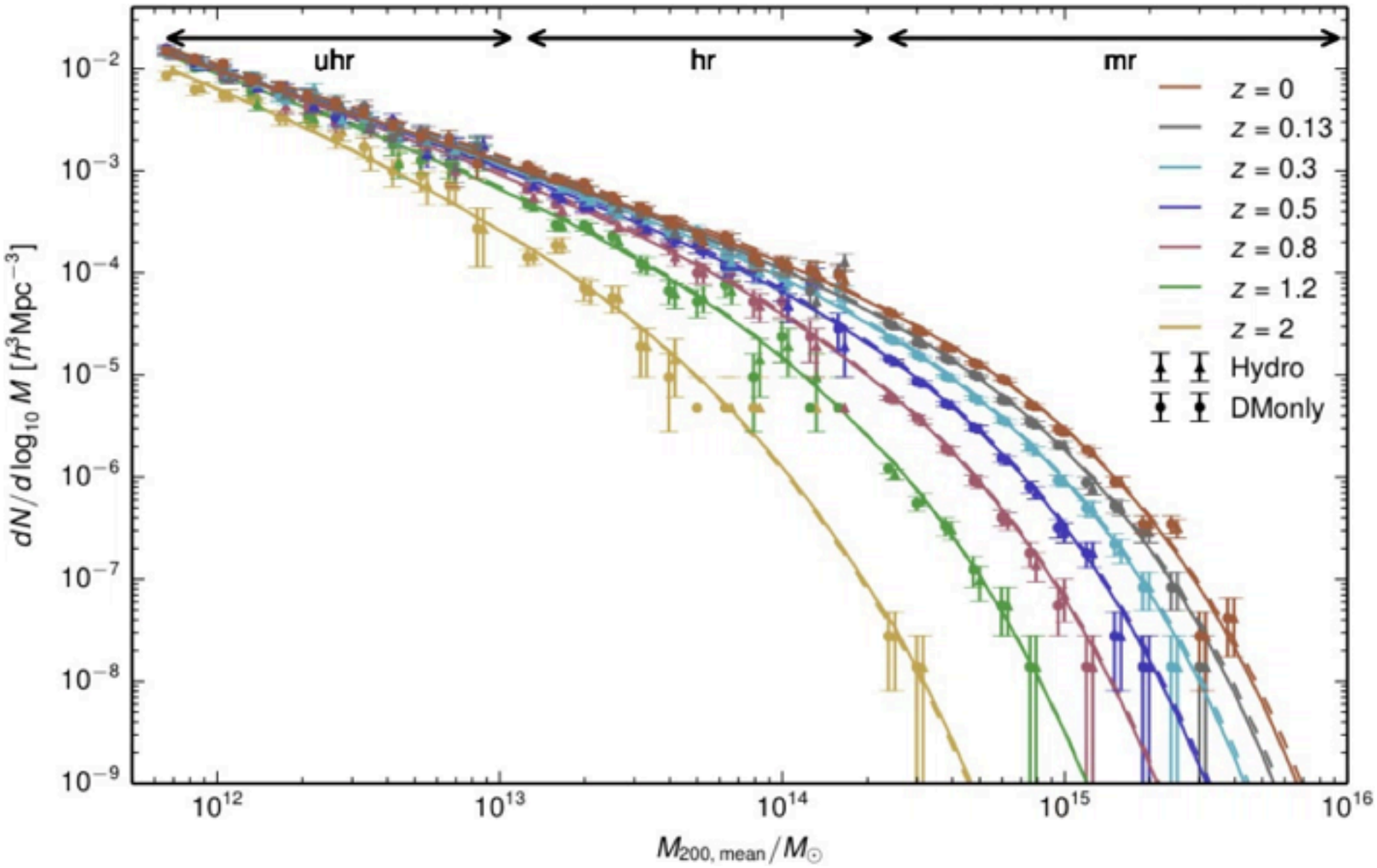




Cluster of Galaxies



Cluster of Galaxies



- Evolution of the cluster mass function with redshift from numerical simulations

Summary

~1/100 Stellar to Dark Matter ratios in galaxies

$\Omega_{\text{total-mass}} = 0.2\text{-}0.3$

$\Omega_{\text{stars}} = 0.002\text{-}0.003$

$\Omega_{\text{baryons}} = 0.04$ (from BBN=Big-Bang Nucleo-synthesis)
[this includes stars+gas]

Alternative Gravity Model

- MOND (Modified Newtonian Dynamics) theory (Milgrom 1983)

$$F_N = G\frac{m.M}{r^2} = m\mu\left(\frac{a}{a_0}\right)a \quad \text{With} \quad \mu\left(\frac{a}{a_0}\right) = \frac{1}{1+a_0/a}$$

Small acceleration $a_0 \sim 10^{-10}\ m/s^2$

$$\frac{GMm}{r^2} = m\frac{\left(\frac{v^2}{r}\right)^2}{a_0} \quad \Longrightarrow \quad v^4 = GMa_0$$

Velocity independant of radius (Flat rotation curve)

- TeVeS (Bekenstein 2004) - including relativistic effects