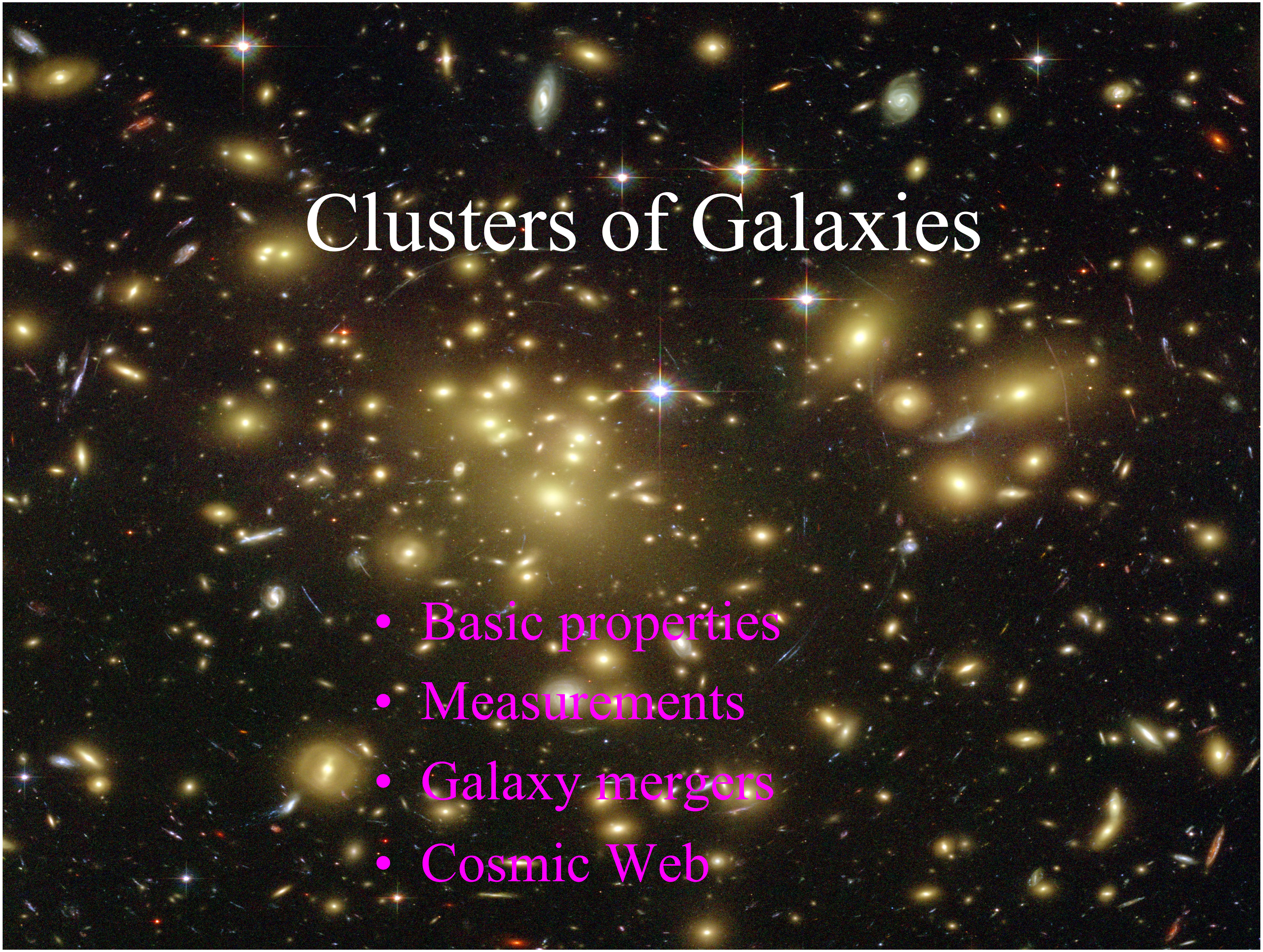


Clusters of Galaxies

- Basic properties
- Measurements
- Galaxy mergers
- Cosmic Web

Hierarchical Structure of the Universe

- Stars ($<150\ M_{\odot}$)
- Star clusters ($\sim 10^2$-$10^6\ M_{\odot}$)
- Galaxies ($\sim 10^6$-$10^{14}\ M_{\odot}$)
- Cluster of galaxies ($\sim 10^{12}$-$10^{15}\ M_{\odot}$)
- Superclusters ($>10^{15}\ M_{\odot}$) and voids

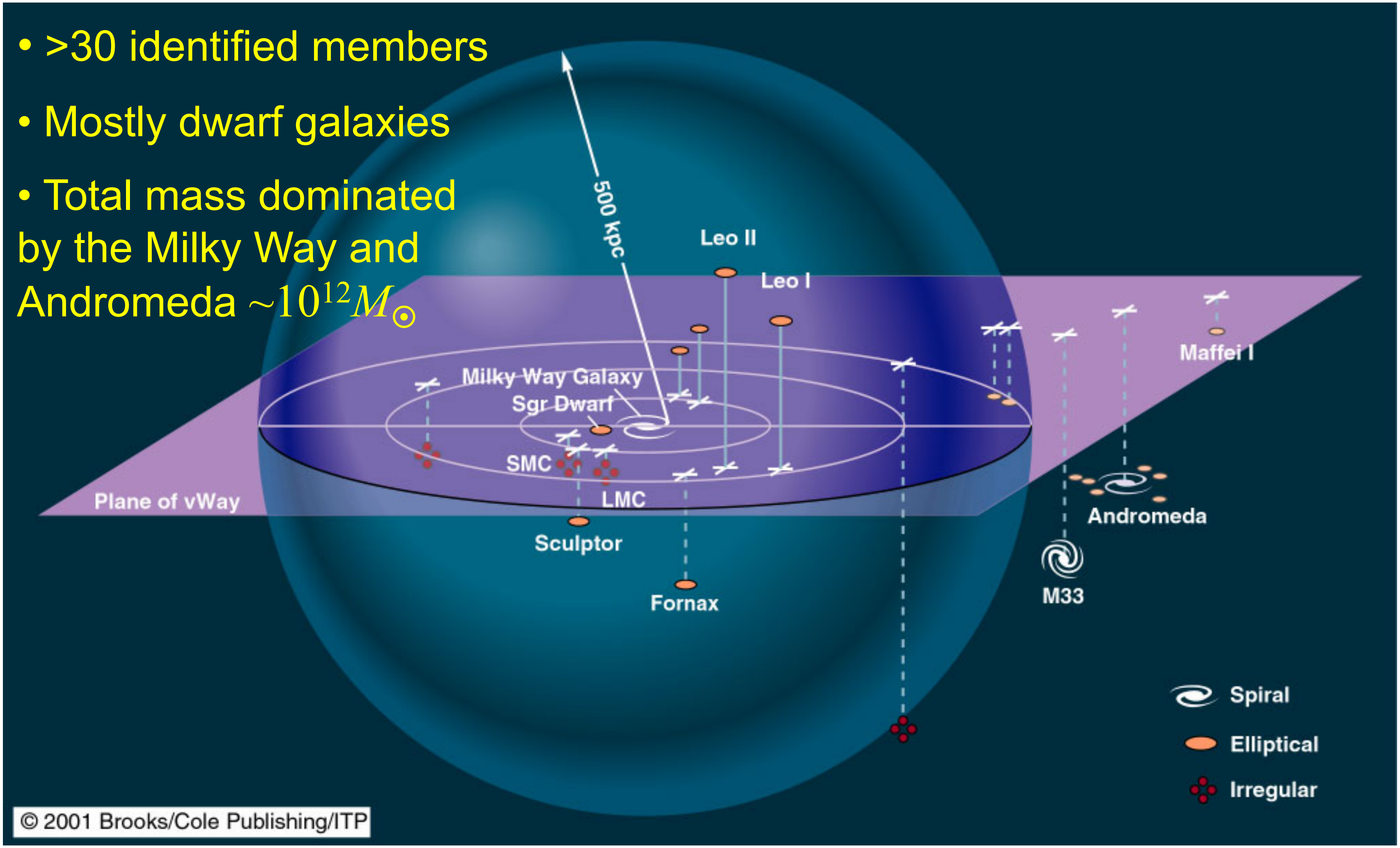
Clusters of galaxies

Galaxies are not distributed randomly in space, usually found in clusters

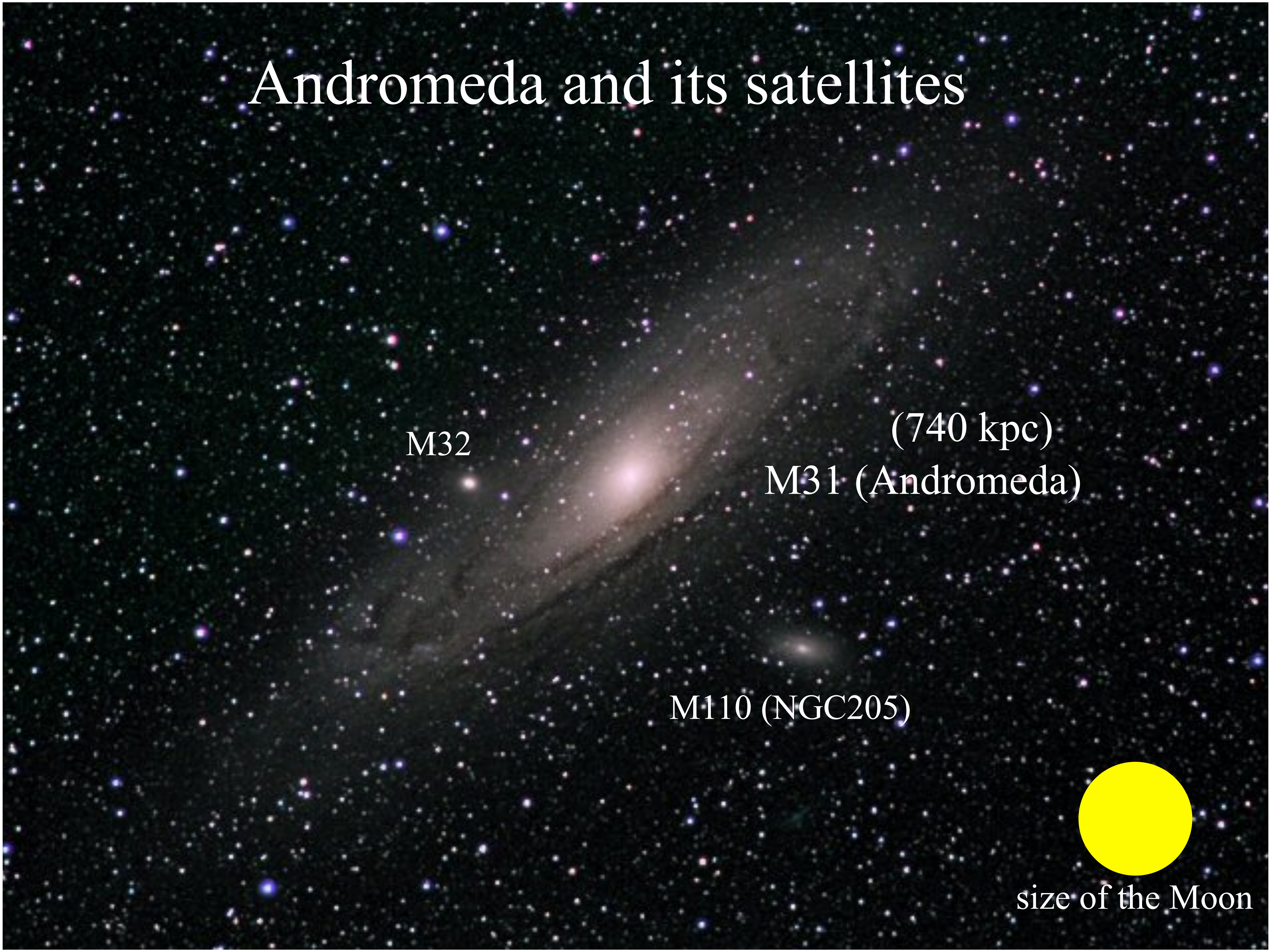
- *Poor cluster* (or *Group*) – 10's of galaxies, ~ 1 Mpc across
- *Rich cluster* – 1000's of galaxies, several Mpc across

The Milky Way is in a poor cluster – the Local Group

- >30 identified members
- Mostly dwarf galaxies
- Total mass dominated by the Milky Way and Andromeda $\sim 10^{12} M_{\odot}$

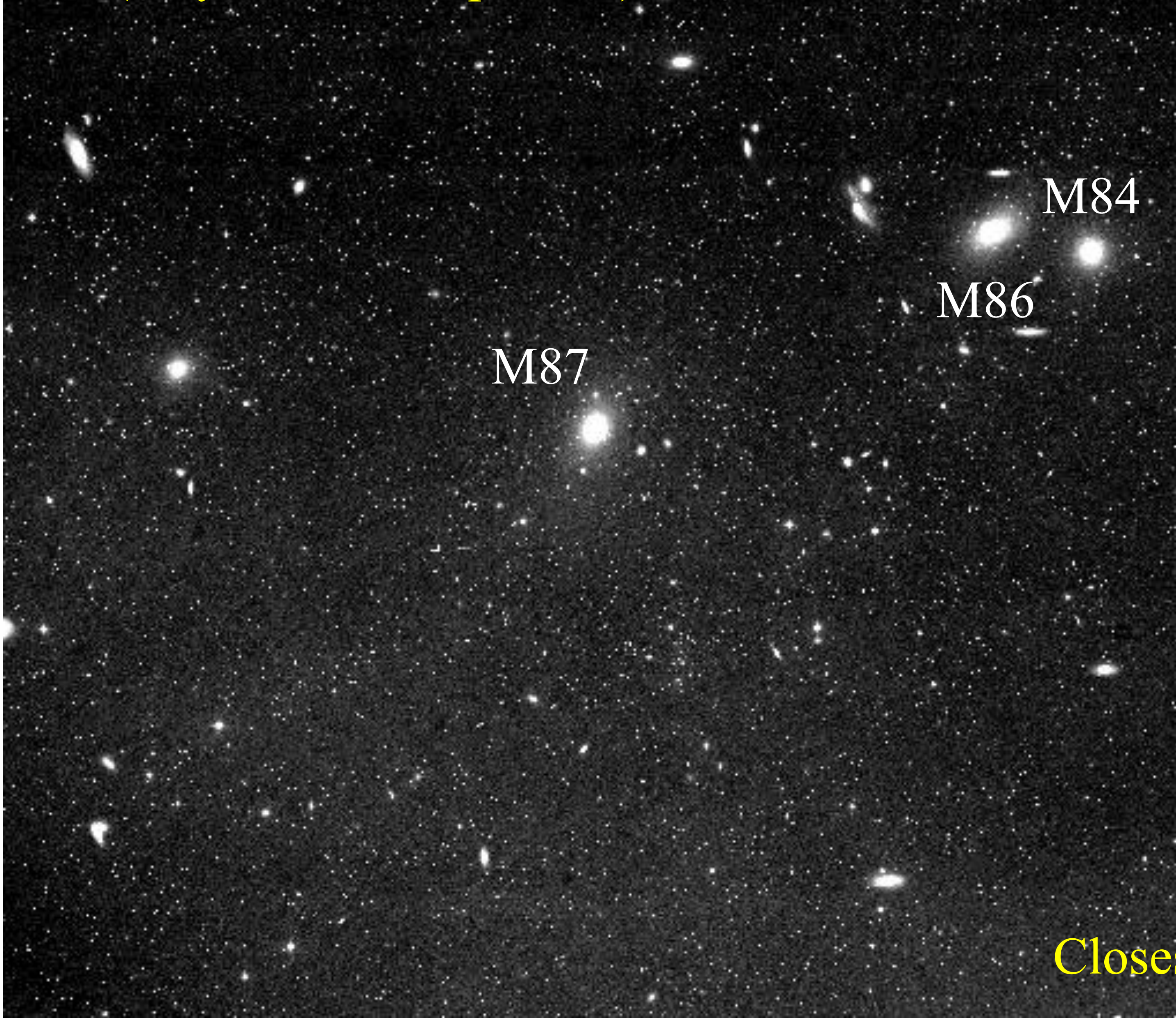


Andromeda and its satellites



The Virgo cluster – a rich cluster of galaxies

(only the central portion)



Distance: 16 Mpc

Radius: ~2 Mpc

>1000 members

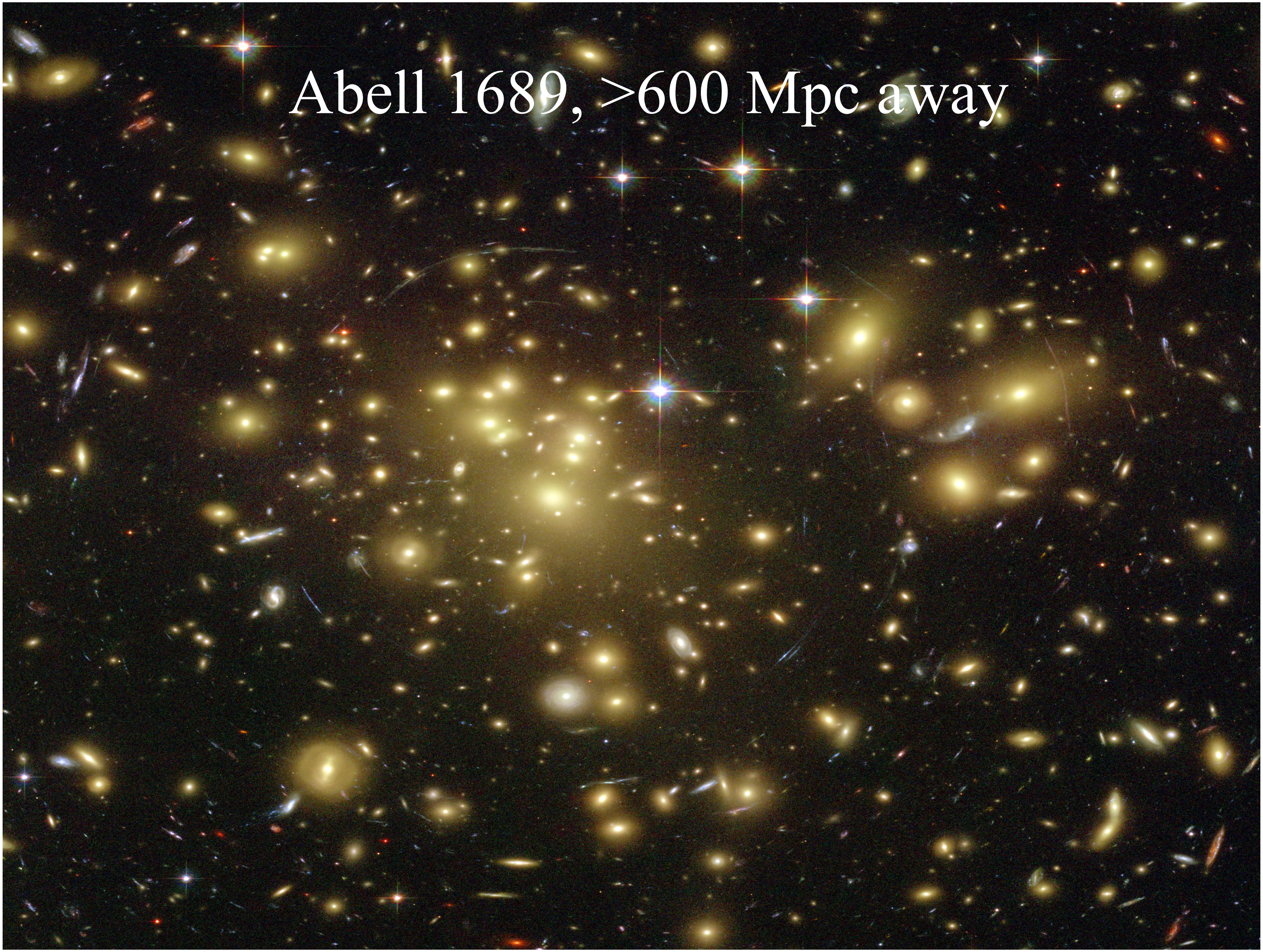
Mass: $\sim 10^{15} M_{\odot}$

Covers large area in the sky

Closest rich cluster to us

The Coma cluster – another nearby rich cluster

Distance: 100 Mpc


Abell 1689, >600 Mpc away

Measurement: distance

Distance measurement based on Hubble's Law:

$$d = V_r / H$$

H is usually parameterized by $H = 100\ h$ km s^{-1} Mpc^{-1}

Current estimate: $h \cong 0.7$

- Contamination from random velocity ~1000 km s^{-1}
- Distance to individual galaxies not well constrained (known as redshift distortion)
- Distance to the cluster obtained by averaging over all members.

Galaxies in galaxy clusters

Just as there are much more low-mass stars than massive stars, most galaxies in galaxy clusters are dwarf galaxies:

- Low luminosity and surface brightness
- Extremely difficult to identify
- Currently known members are only a small fraction of all

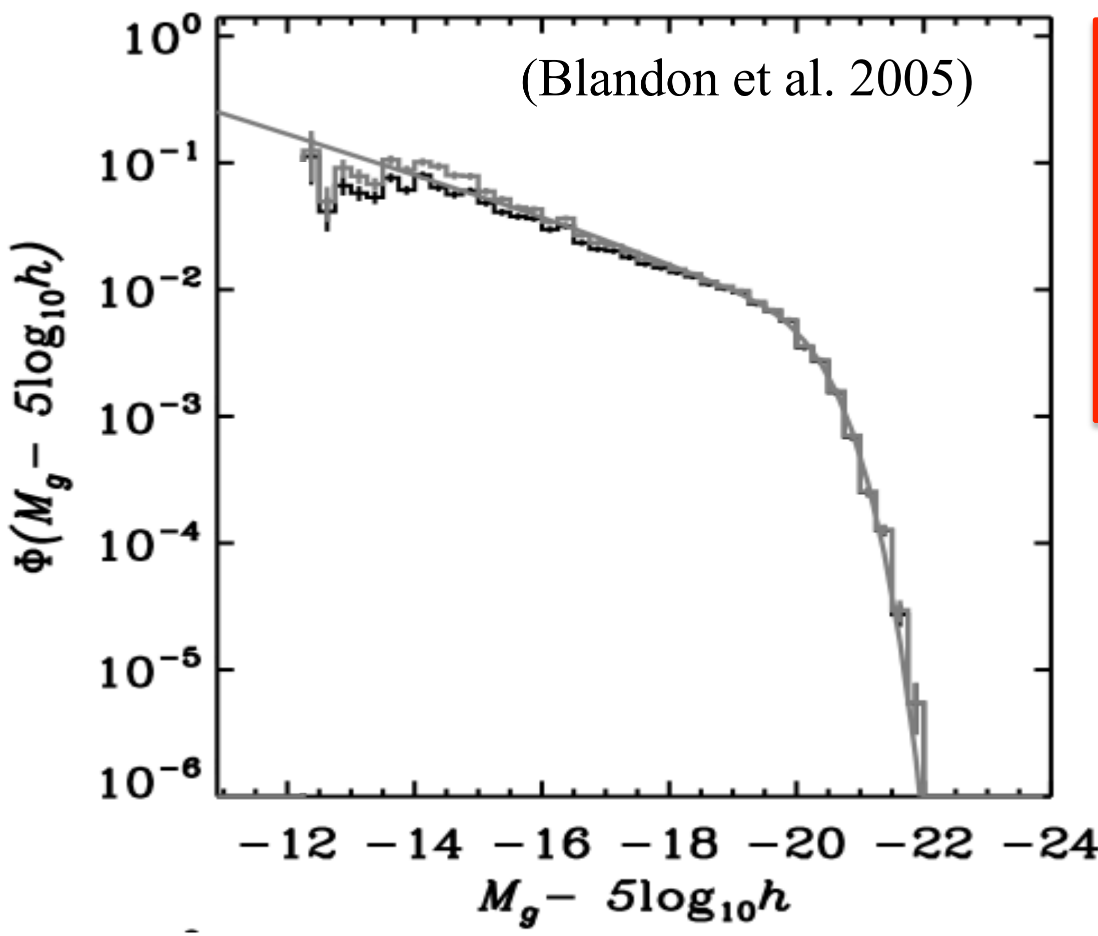
Faint galaxies dominate in number

Bright galaxies dominate the total luminosity

Galaxy Luminosity Function

Schecter function:

$$\Phi(L)dL = \Phi_* \left(\frac{L}{L_*}\right)^{\alpha} \exp\left(-\frac{L}{L_*}\right)\frac{dL}{L_*}$$



$\Phi(L)dL$:

number of galaxies per volume with luminosity between L and $L+dL$

Fitting with data:

$$L_* \sim L_{\rm MW}$$

$$\alpha \lesssim -1$$

Probing the mass distribution in clusters

Use the velocity dispersion of galaxies in the cluster, assuming *Virial equilibrium* with the gravitational potential:

$$\frac{GM}{2R} \approx \frac{3}{2}\sigma_r^2$$

Similar to measuring the mass of elliptical galaxies using stellar velocity dispersion.

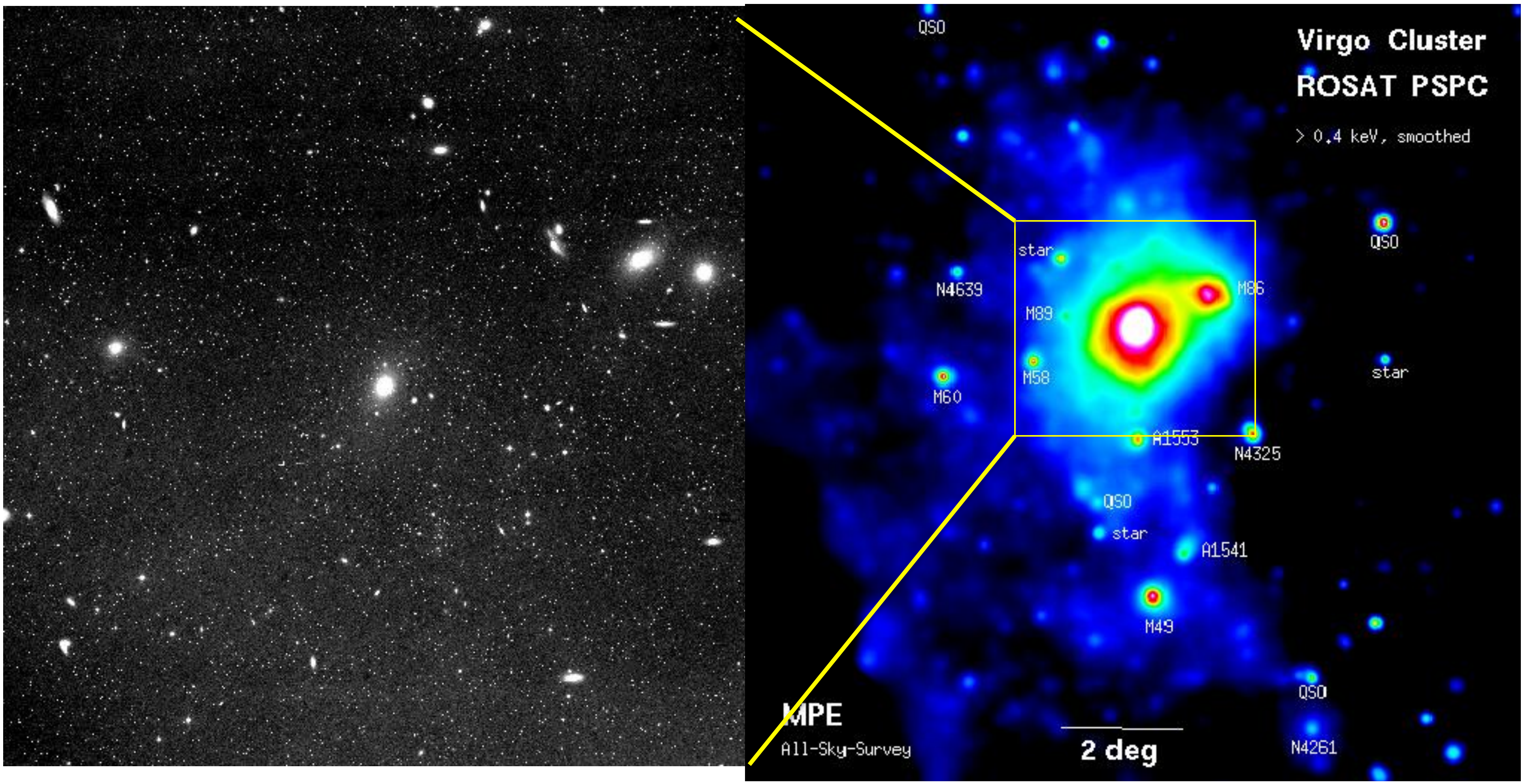
For a typical rich cluster:

$$\sigma_r \sim 1000 \text{ km s}^{-1} \text{ , } R \sim 2 \text{ Mpc} \ \Rightarrow \ M \sim 10^{15} M_\odot$$

For a typical poor cluster (group):

$$\sigma_r \sim 350 \text{ km s}^{-1} \text{ , } R \sim 0.5 \text{ Mpc} \ \Rightarrow \ M \sim 4 \times 10^{13} M_\odot$$

Virgo cluster: optical and X-ray



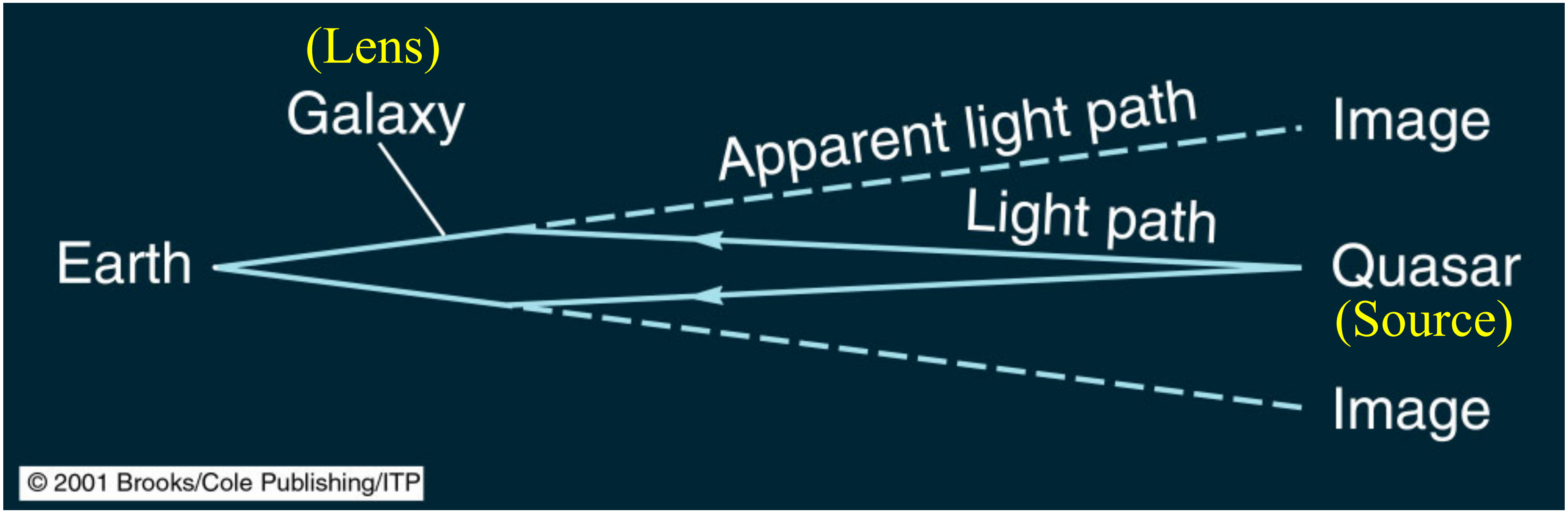
Hot gas in galaxy clusters

- Galaxy clusters and groups contain large amount of hot gas with temperature up to 10^8 K => $kT \approx 10$ keV
- Strong X-ray emission due to thermal Bremsstrahlung
- Most baryons in galaxy clusters reside in the hot gas (rather than in the galaxies!)
- Density and temperature distribution of the hot gas probes the gravitational potential of the galaxy cluster

$$kT \sim m_H v_H^2 \Rightarrow v_H \sim 1000 \text{ km s}^{-1} \text{ (for } T=10^8 \text{ K)}$$

Strong gravity needed to confine the hot gas

Gravitational lensing

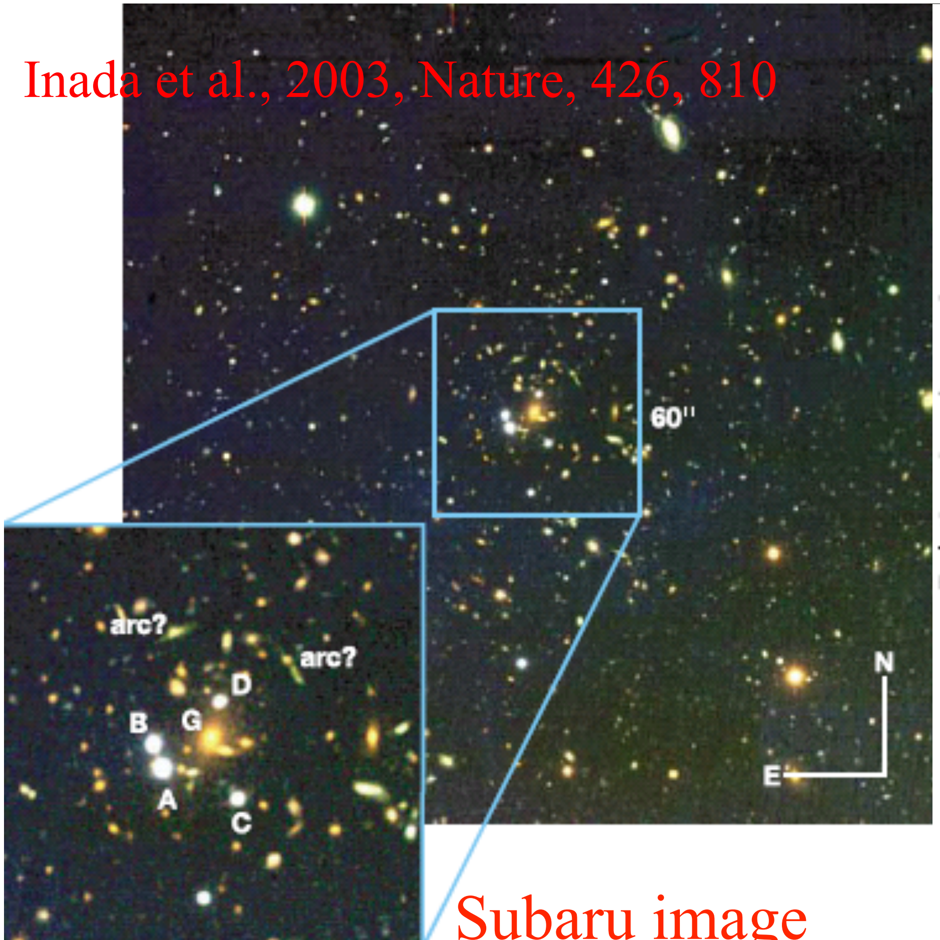


- Strong lensing: Highly distorted image of distant galaxies by galaxies and clusters
- Weak lensing: Subtle distortion of background galaxy shapes by extended foreground masses
- Independent probe of mass distribution of the lens object

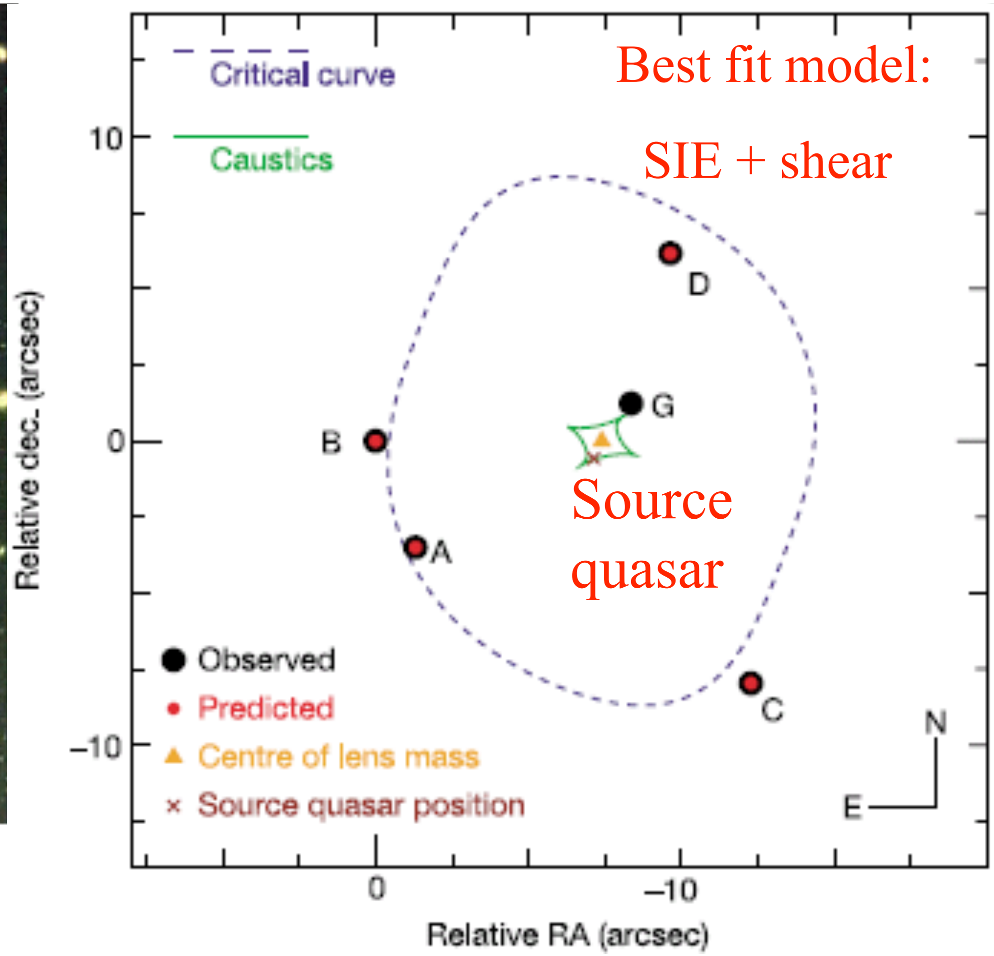
Gravitational lensing by a cluster

An example: SDSS J1004+4112

Inada et al., 2003, Nature, 426, 810



Subaru image



Maximum separation: 14.62”

Source quasar: z=1.732

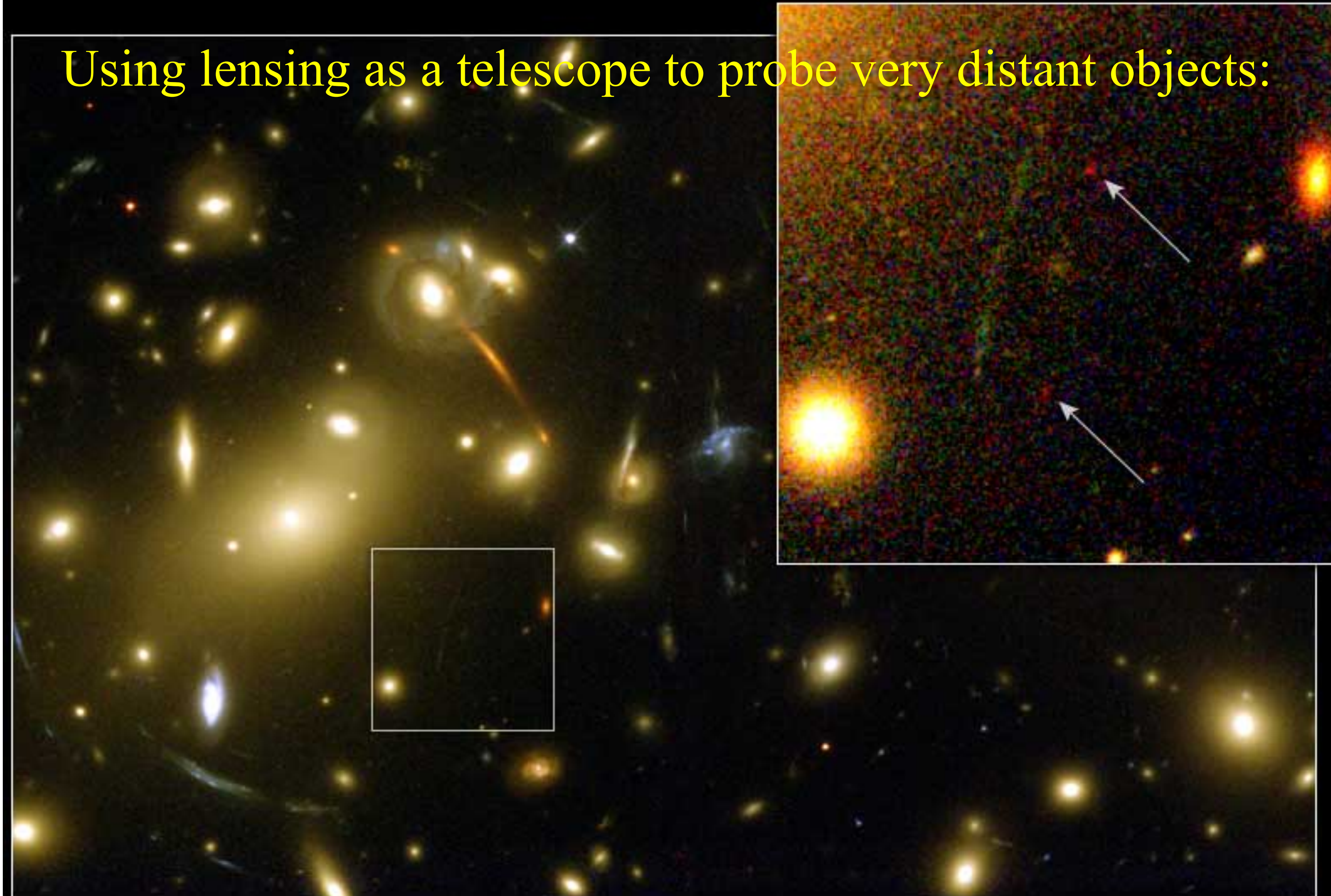
Lens group of galaxies: z=0.68

Model result:

Velocity dispersion: ~700km/s => mass

Total magnification: ~56

Using lensing as a telescope to probe very distant objects:



Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

Evidence for Dark Matter

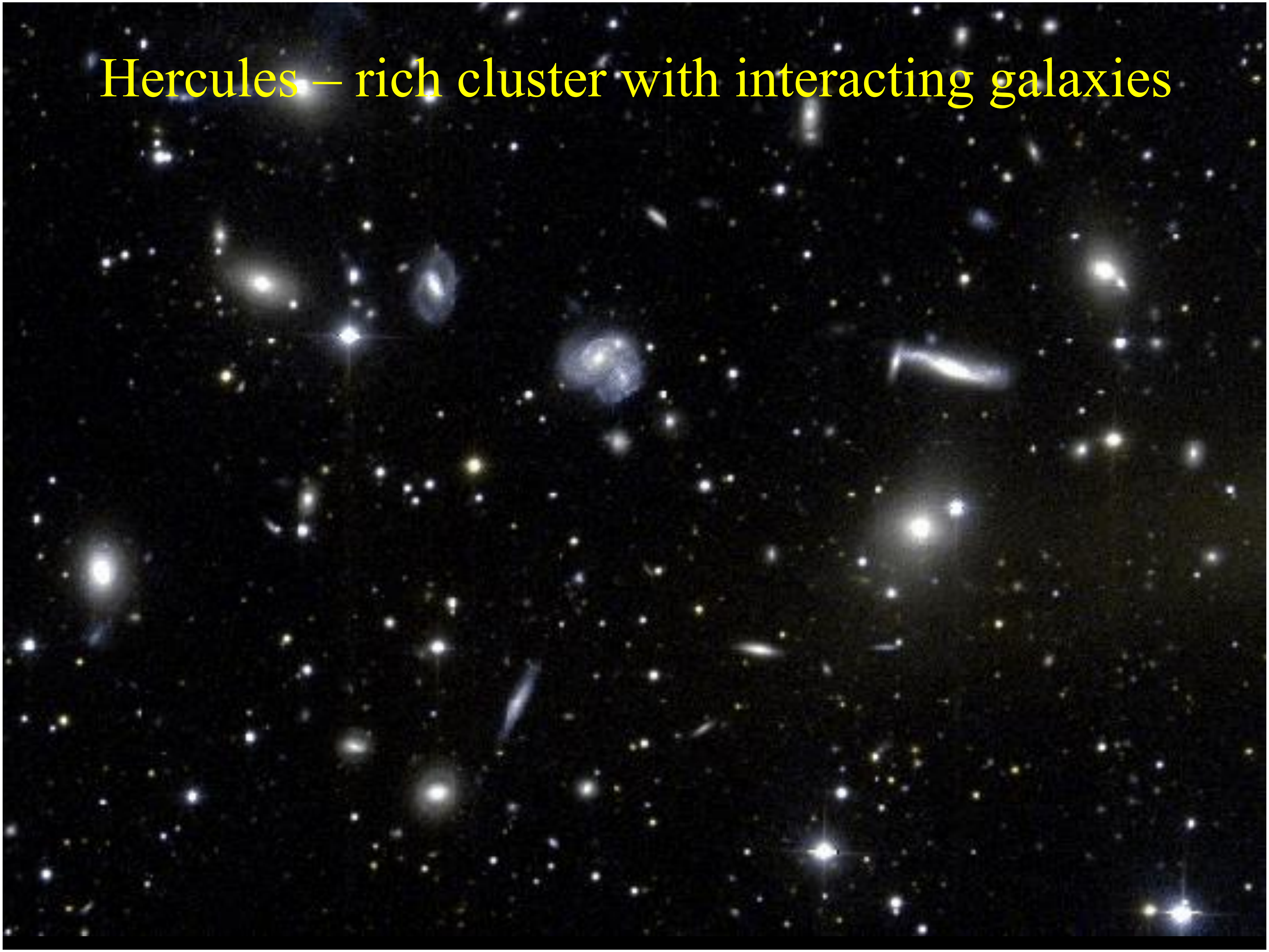
For a typical galaxy cluster with $M=10^{15}M_\odot$,

- Mass in the hot gas: ~11%
- Mass in stars: ~2%

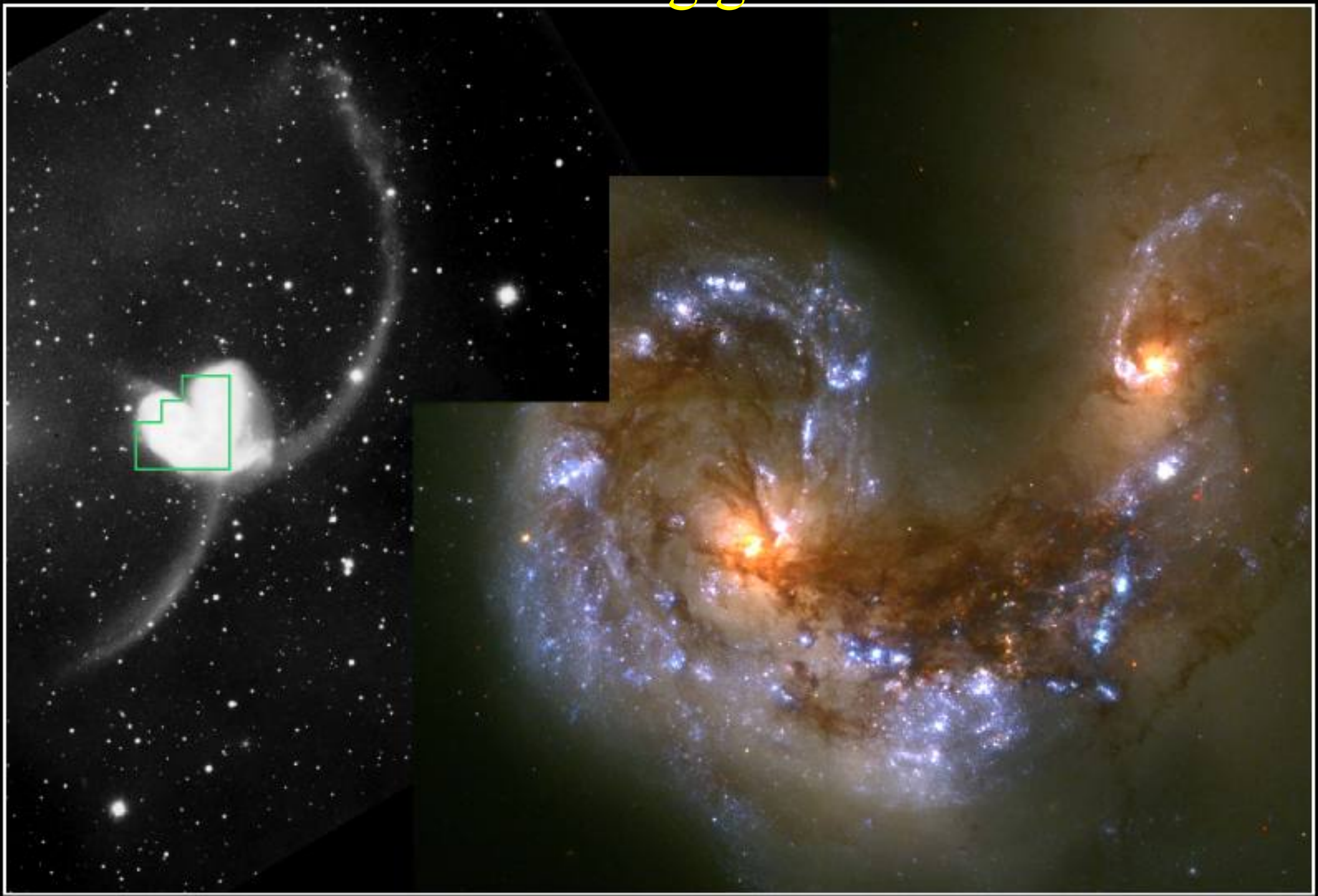
The rest of the mass is dark!

Mass to light ratio ($\gamma=M/L$, unit is $\gamma_\odot=M_\odot/L_\odot$):

System	Sun	Stellar System	Milky Way	Galaxy Cluster	The Universe
$\gamma/\gamma_\odot$	1	1-10	~70	200±50	900±300


Hercules – rich cluster with interacting galaxies

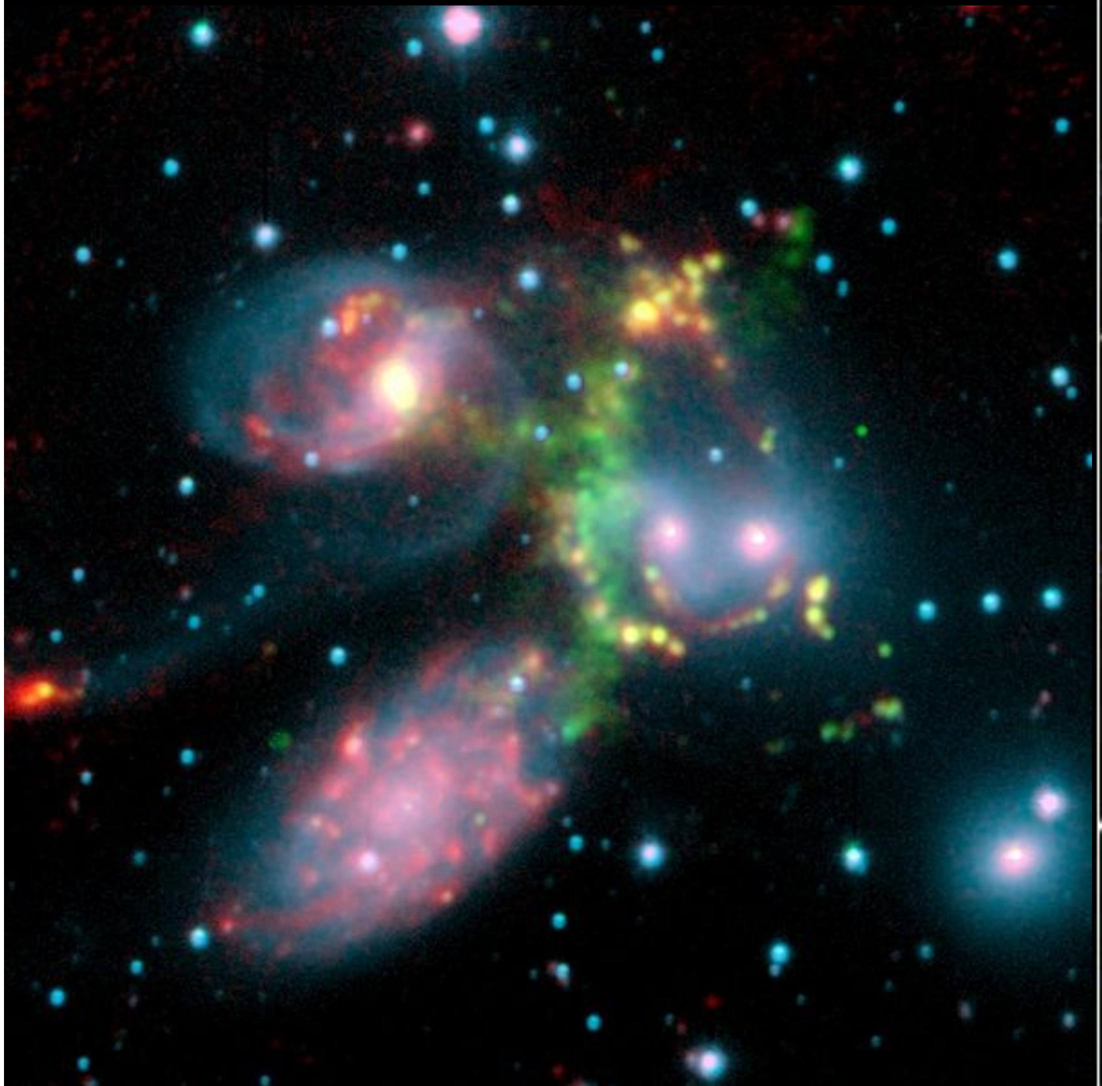
The most famous interacting galaxies – The Antennae



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Infrared

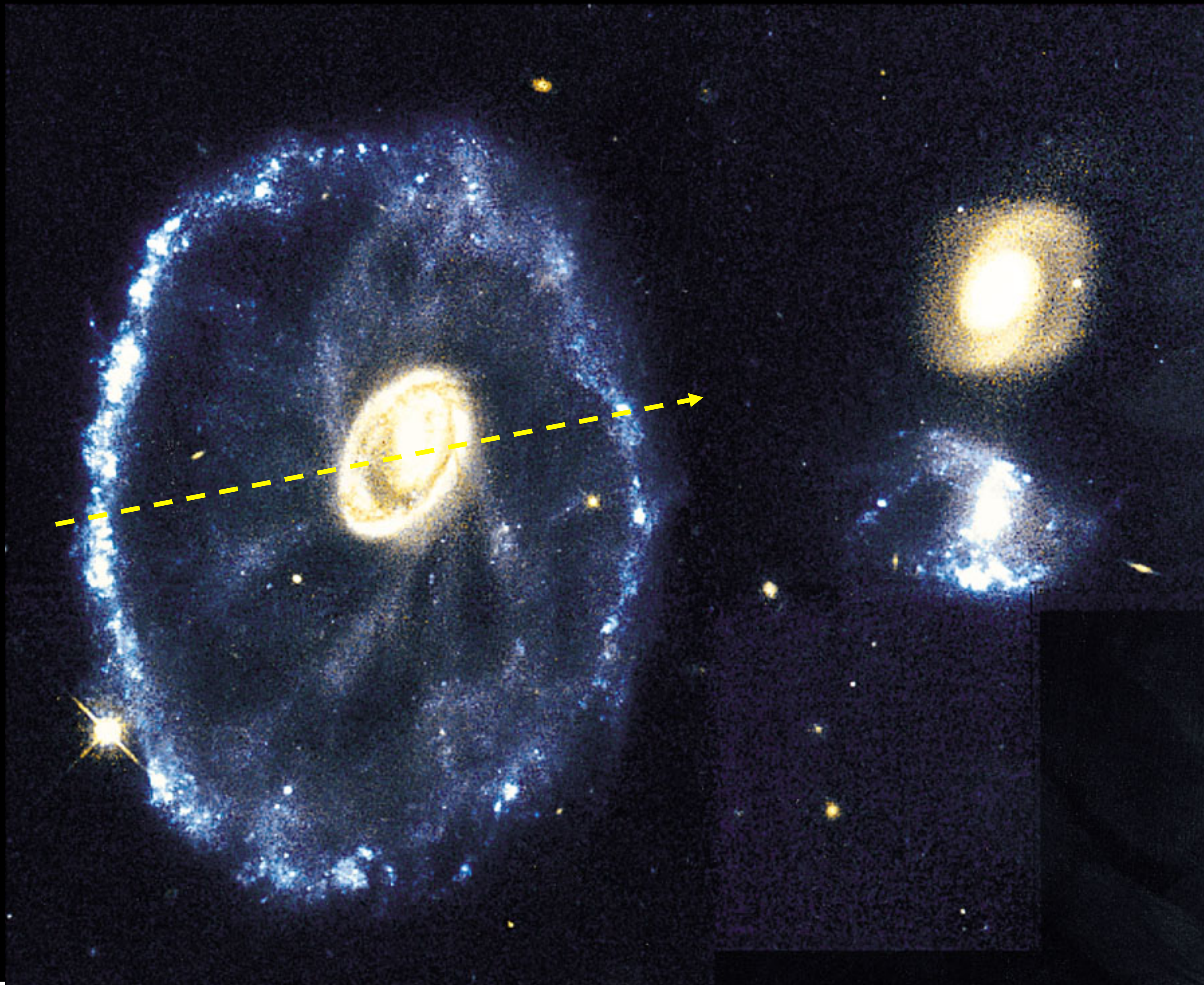


Stephan's Quintet **HST** • WFPC2
NASA and S. Gallagher (Penn State University)
STScI-PRC01-22

Galaxies in clusters can interact

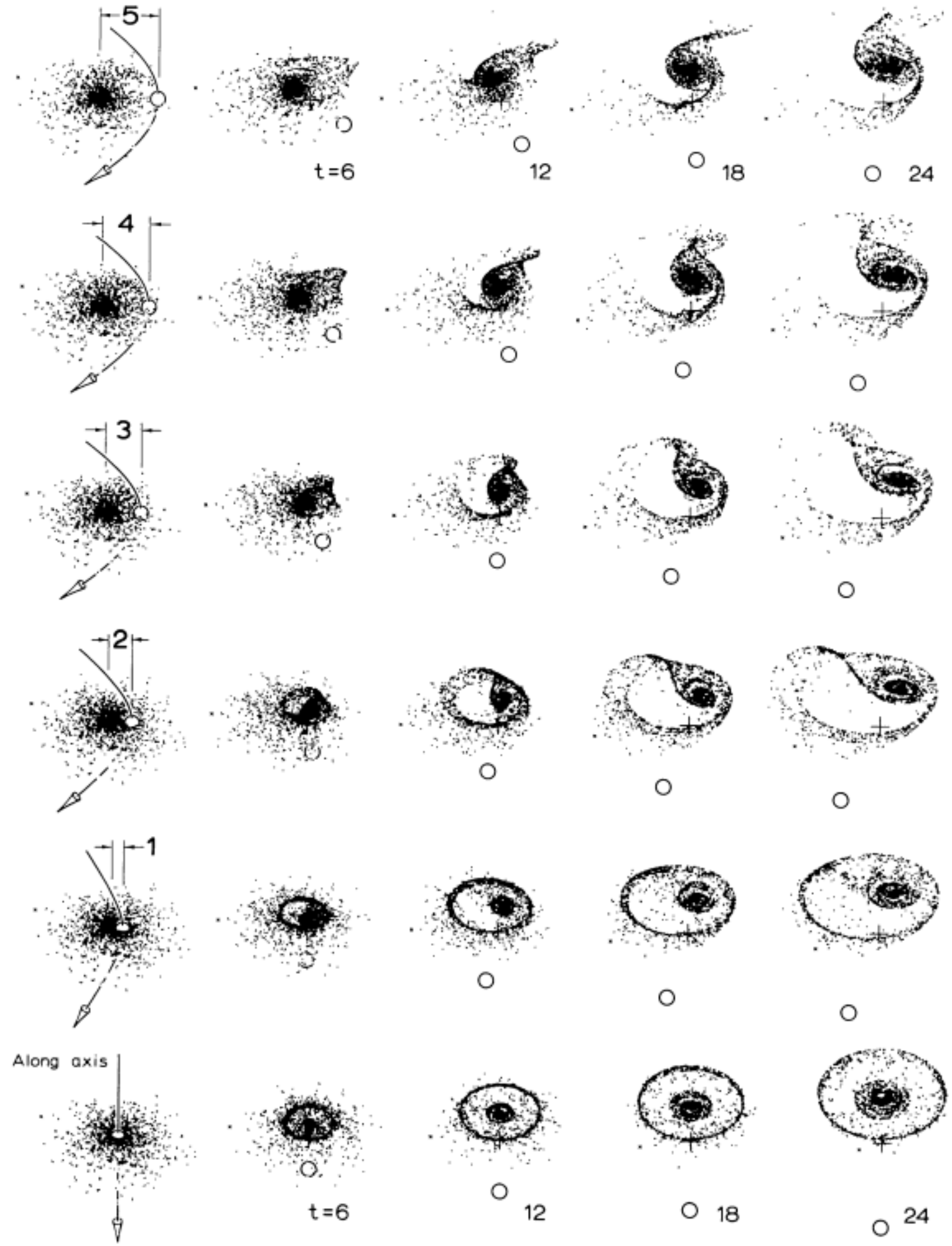
Tadpole galaxy

The Cartwheel Galaxy – spiral hit face on by another spiral



Galaxy Collision: Scenarios

Strong tidal interaction leads to tails, streams, rings, shells, …



Galaxies – distance between is small compared to size

Distance = 25 times size

Stars – distance between is large compared to size

Distance = 50,000,000 times size

So *galaxies* collide, but *stars* do not.

When *galaxies* collide, *stars* do not collide

Density of stars in the solar neighborhood:

$$n \sim 0.1 \text{ pc}^{-3}$$

Typical size of a (big) galaxy:

$$l \sim 10 \text{ kpc}$$

Cross section of a star:

$$\sigma \sim \pi R_{\odot}^{2} \sim 10^{18} \text{ m}^{2}$$

Chance of collision:

$$p \approx n\sigma l \approx 10^{-10}$$

Galaxy Collision: Consequences

• Two comparable-sized galaxies merge into one larger galaxy, or a small galaxy is engulfed by the large galaxy.

Stars don't collide, but why do galaxies merge rather than separate after the collision?

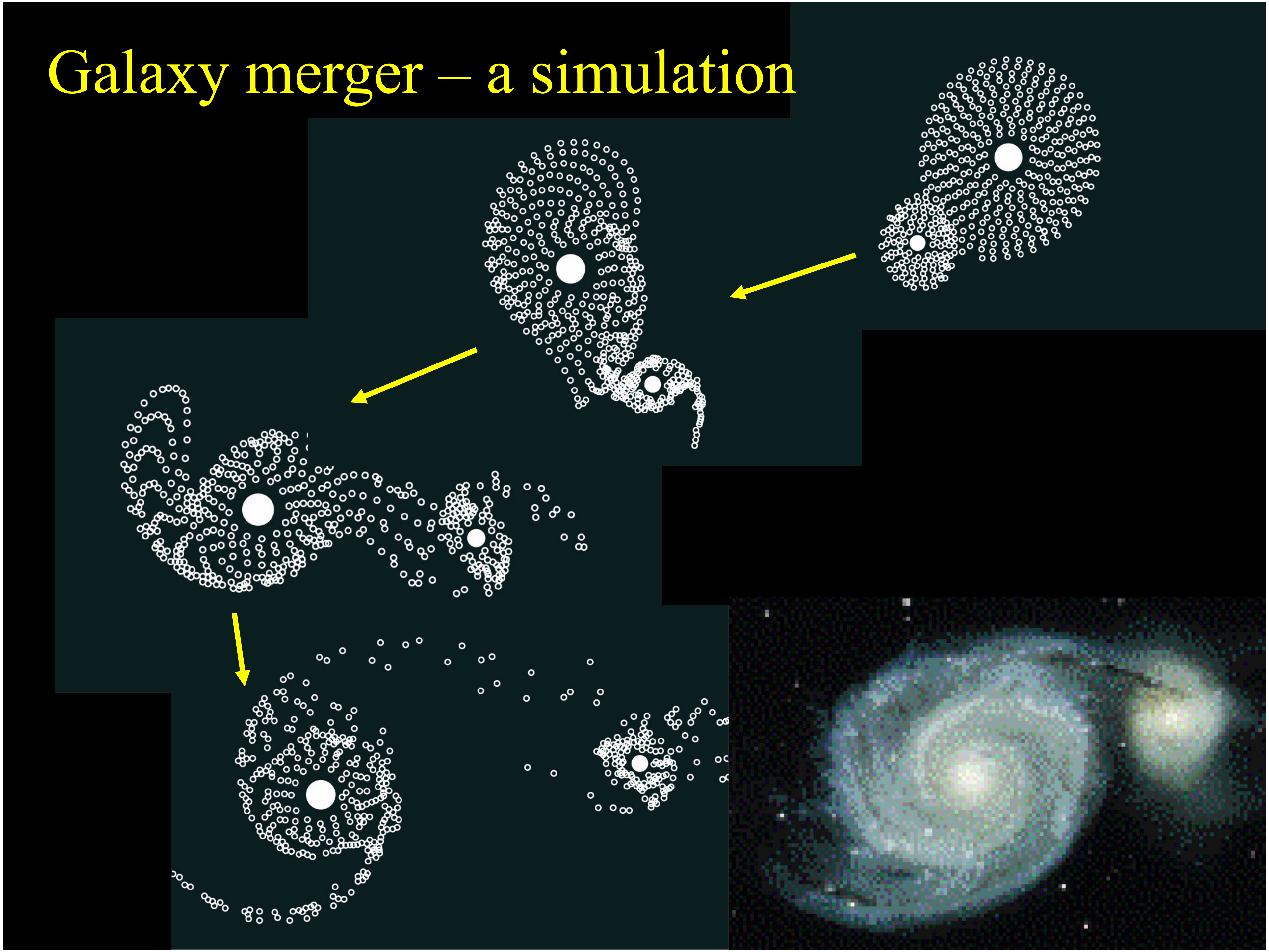
Energy is converted to the increase the random velocity of the stellar system, i.e., "heating".

• If the merging galaxies contain gas, merger leads to starburst.

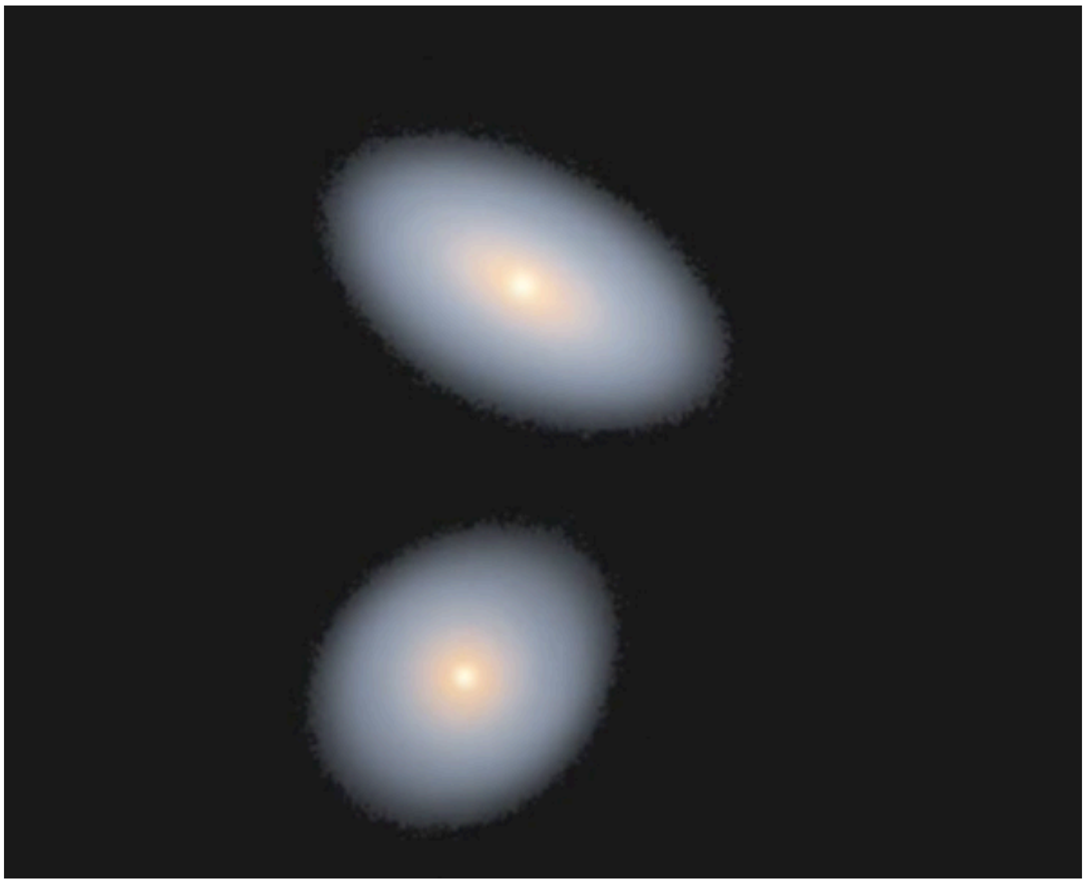
• Galaxy encounter may lead to grand-design spiral arms

• Galaxy encounter is responsible for the appearance of most peculiar galaxies

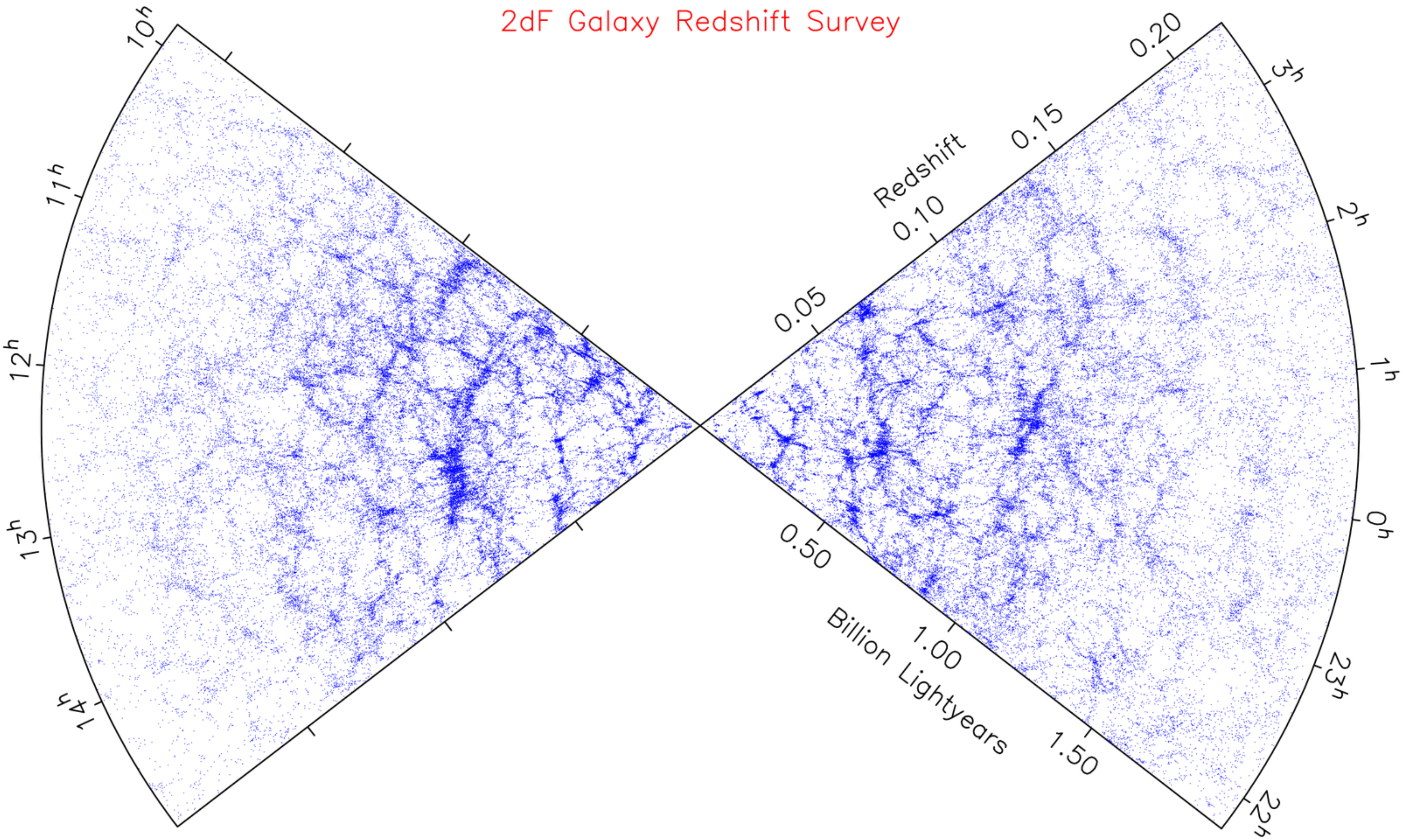
Galaxy merger – a simulation



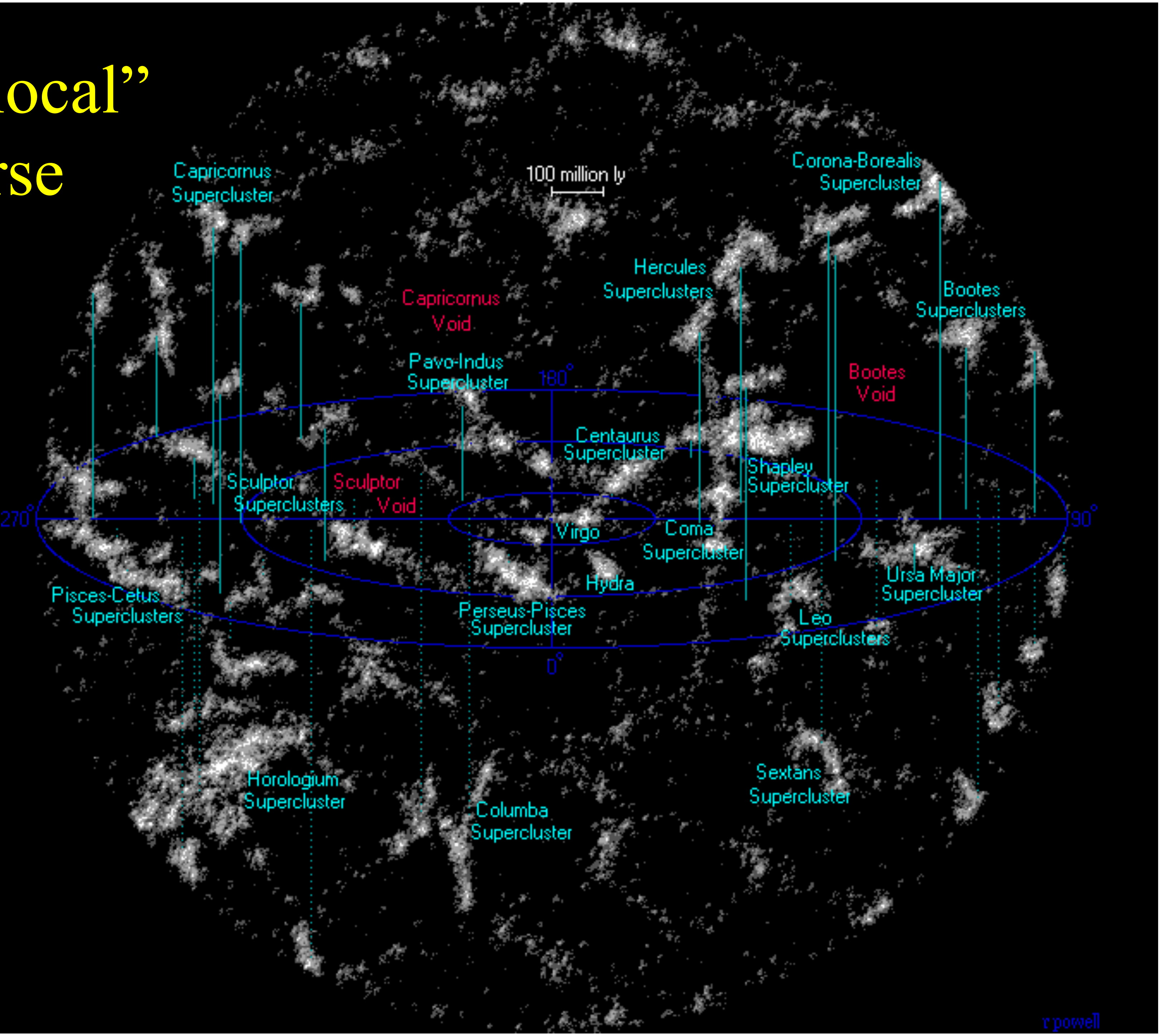
In 2 billion years, MW and Andromeda will merge.
Computer simulations of that merger….



Cosmic Web: Superclusters and Voids



The "local" universe



Hierarchical structure formation

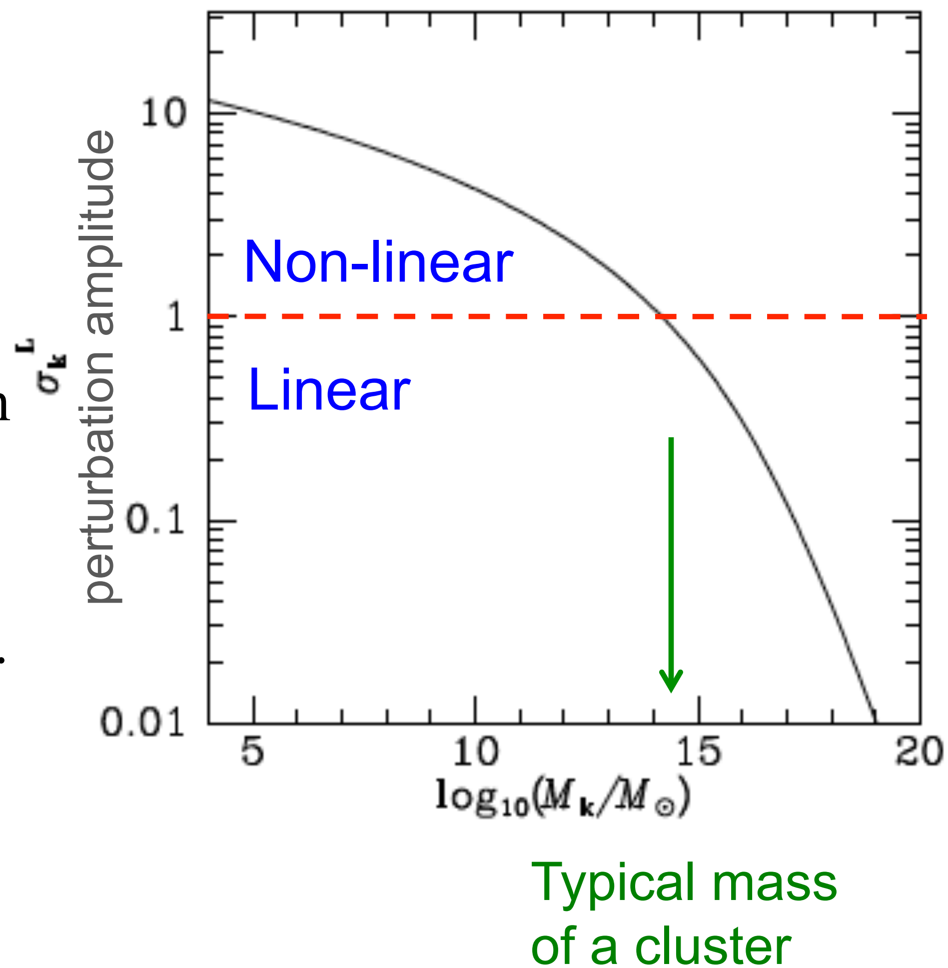
• The large scale structure today is seeded from the Big-Bang, and initial perturbations grow due to the gravity.

• Dark matter governs structure formation, while baryons fall into its gravitational potential well.

• The cosmic structure formation is “bottom-up”: smaller structures form before larger ones.

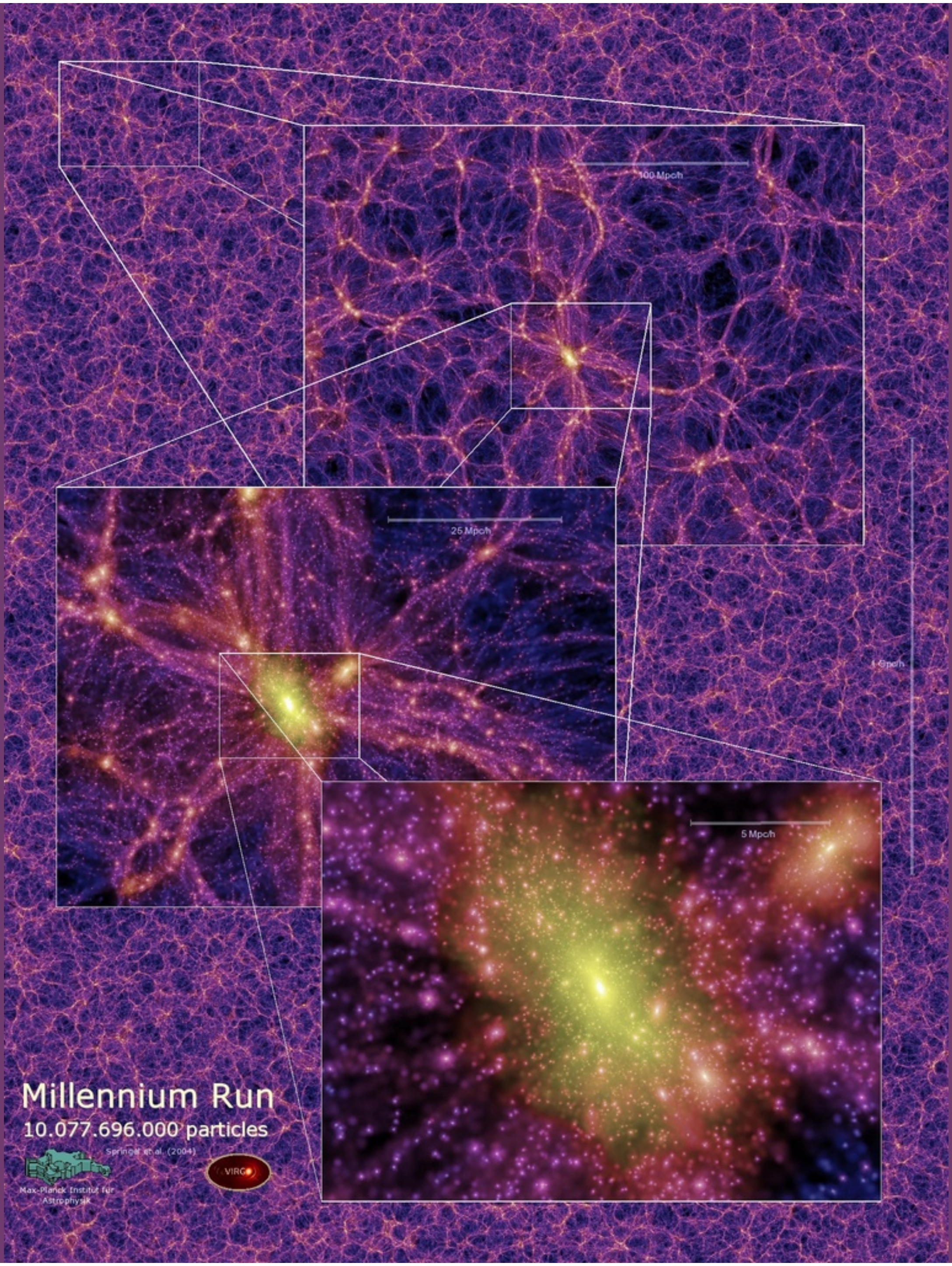
• Voids and filaments are natural consequence of non-linear evolution.

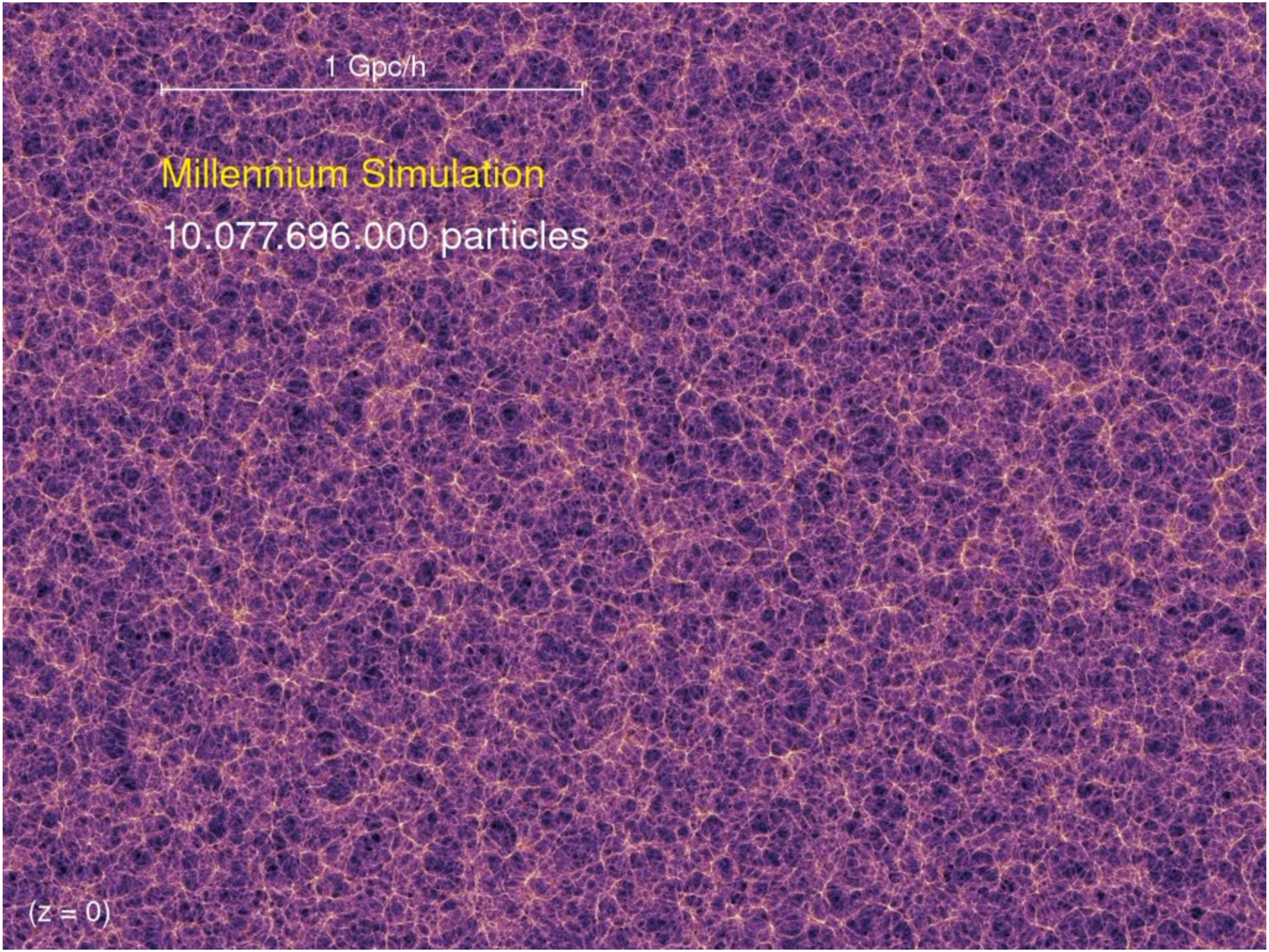
• Galaxy clusters form only recently, and they are dynamically young.



A toy movie of galaxy cluster formation

Cosmic-web from the computer




1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)