Plan for lectures on Galaxy Formation

- **Lecture 1: Introduction to galaxy formation**
  - * The growth of structure via gravitational instability
  - * Baryons and dark matter; baryon cooling within DM halos
  - * Introduction to properties of galaxies: the Hubble sequence
  - * The sketch of a galaxy formation theory

- **Lecture 2: Disk galaxies over the last half of cosmic time**
  - * Structure of dark halos
  - * Structural properties of disk galaxies
  - * Evolution of disk galaxies since $z = 1$

Plan for lectures on Galaxy Formation, cont'd

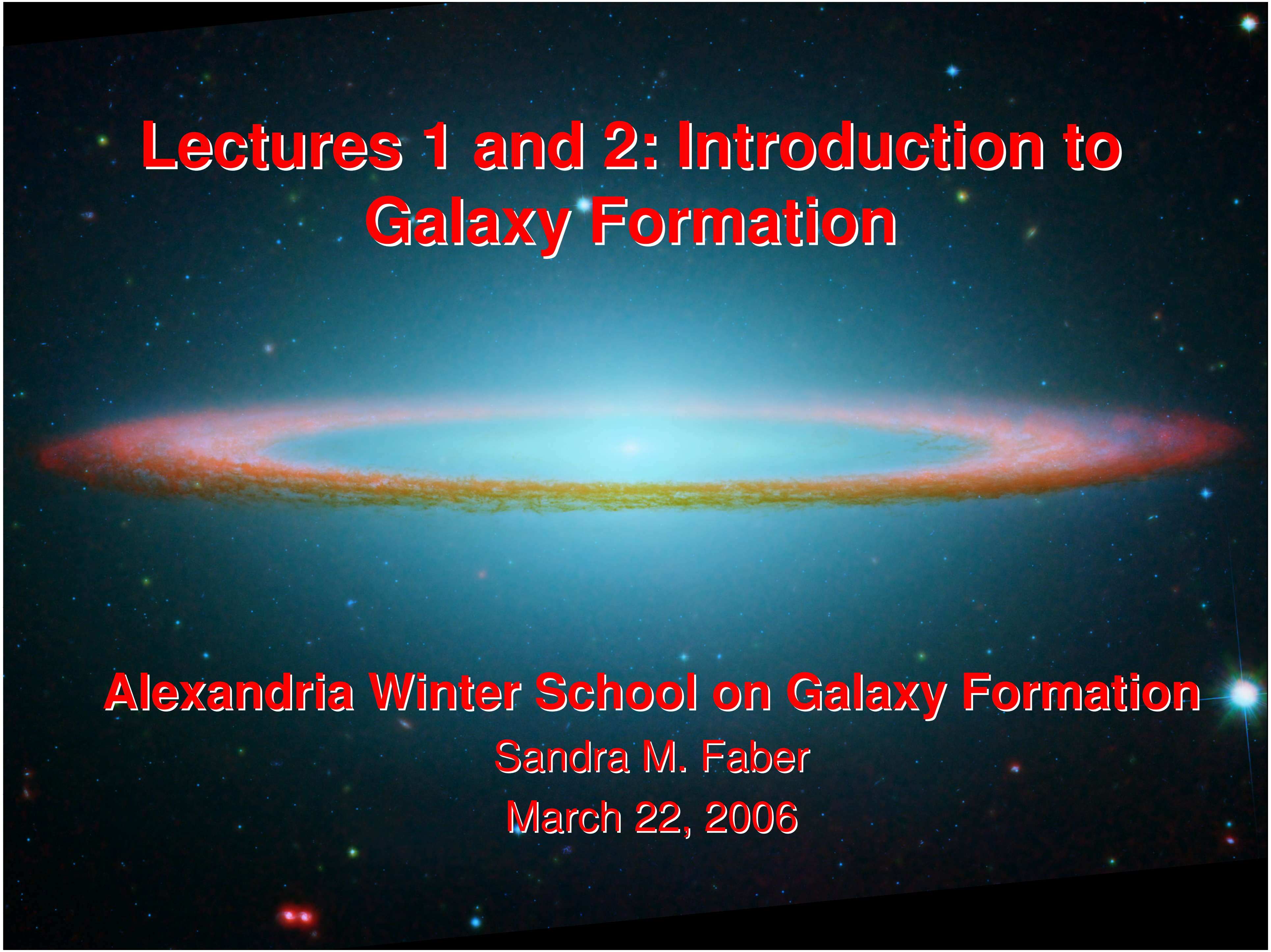
- **Lecture 3: Spheroidal galaxies over the last half of cosmic time**

  * Structural properties of spheroidal galaxies

  * Formation theories: monolithic collapse versus mergers

  * Evolution of spheroidal galaxies since $z = 1$

  * The possible role of central black holes in spheroid evolution



Lectures 1 and 2: Introduction to Galaxy Formation

Alexandria Winter School on Galaxy Formation

Sandra M. Faber

March 22, 2006

z = “redshift,” a measure of the expansion of the Universe.

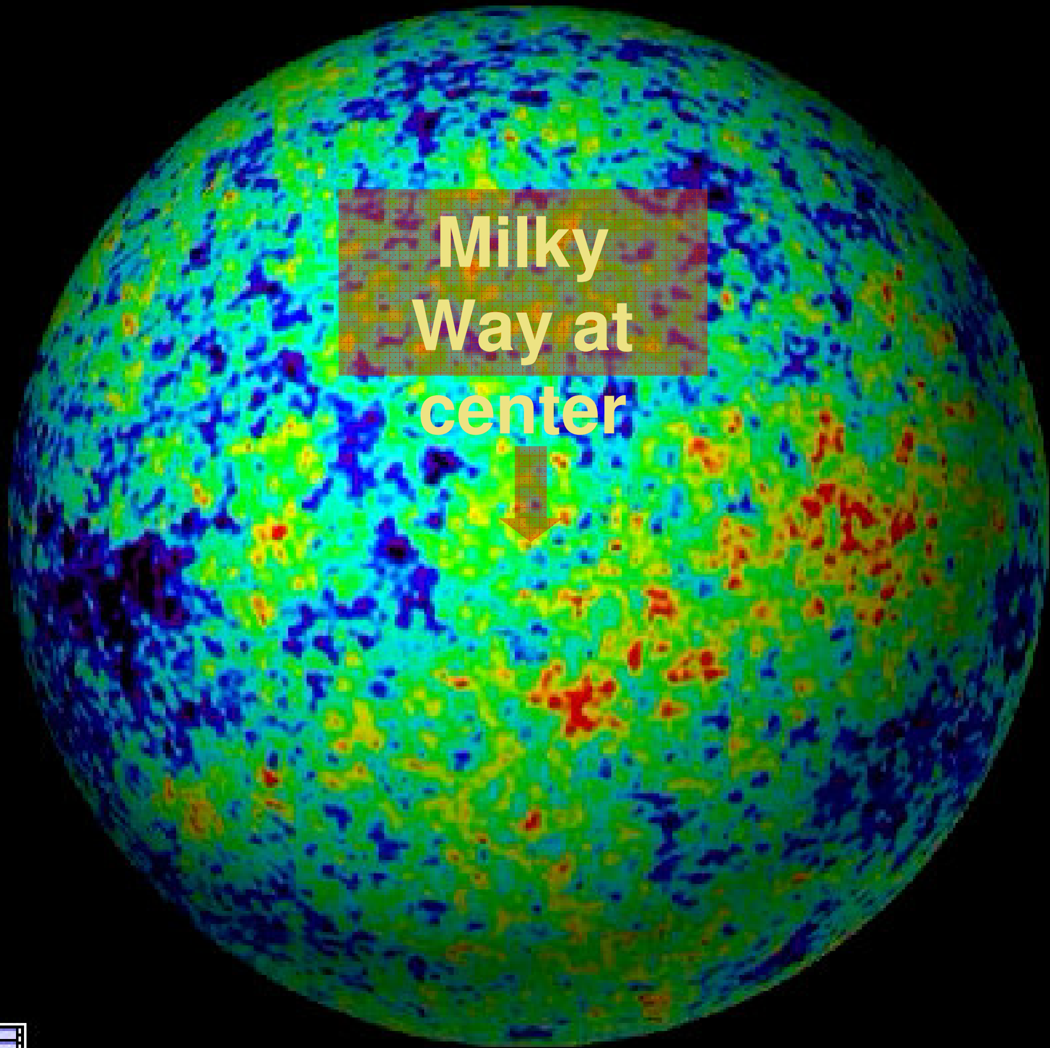
The ratio of the size now to size then is (1 + z).

Cosmic structure forms via gravitational instability

Simulation courtesy of Springel, White, and Hernquist

[redacted]

The latest CMB map, from the **WMAP** satellite



Ripples in the CMB intensity on the celestial sphere, as mapped with the WMAP satellite.

The celestial sphere as portrayed from outside. **The Milky Way is at the center of the sphere.**

The latest CMB map, from the **WMAP** satellite

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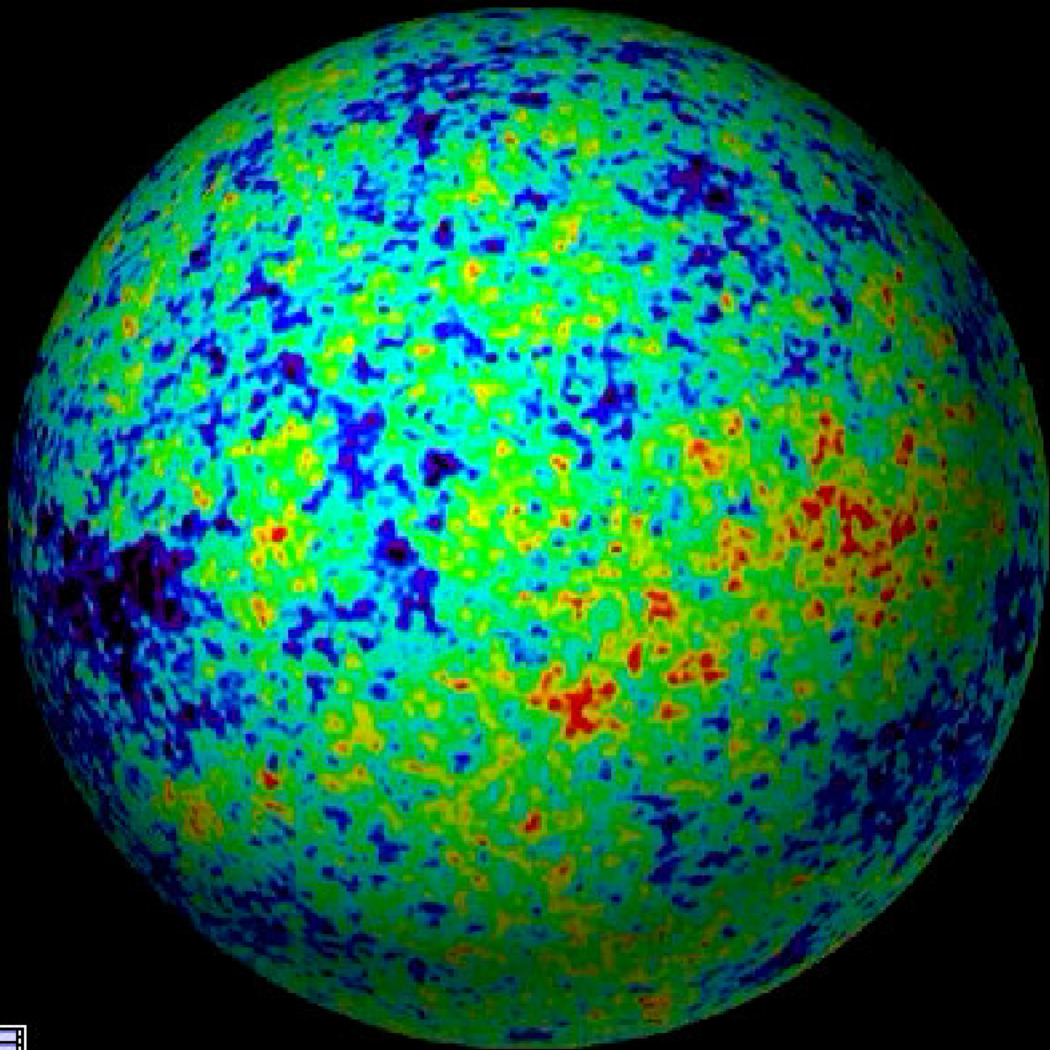

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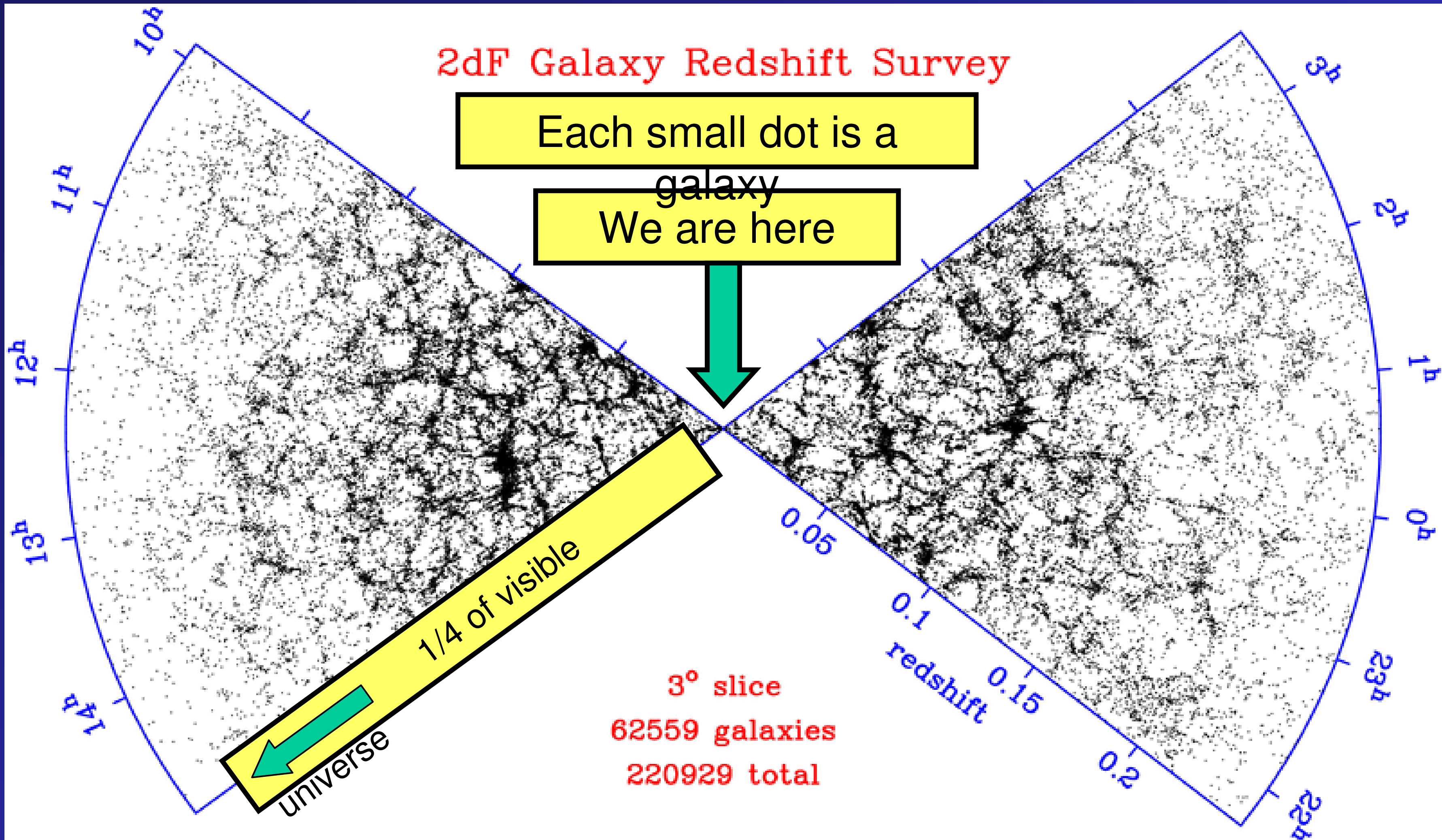
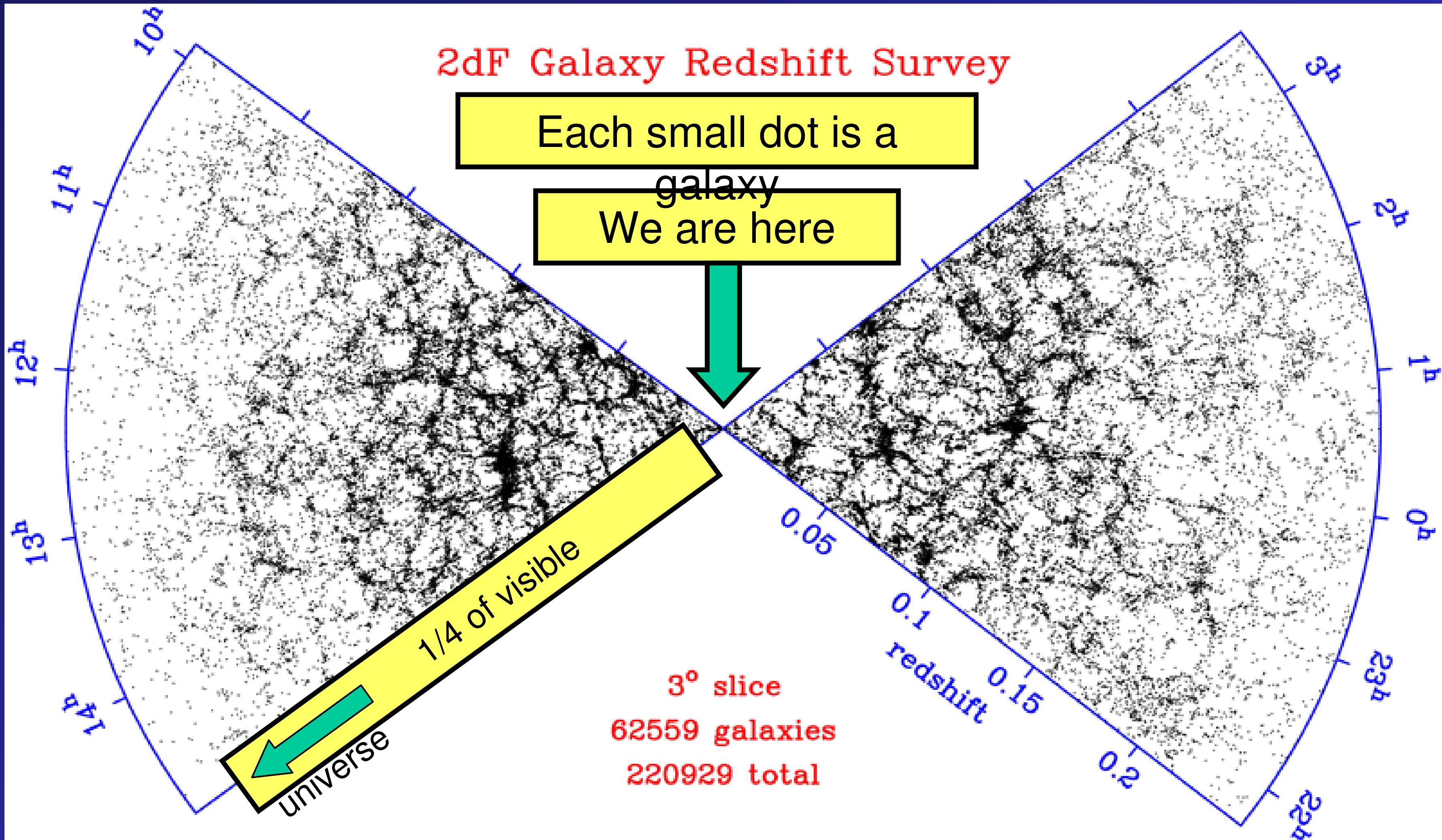
The celestial sphere as portrayed from outside. **The Milky Way is at the center of the sphere.**

A redshift survey: 220,000 galaxies

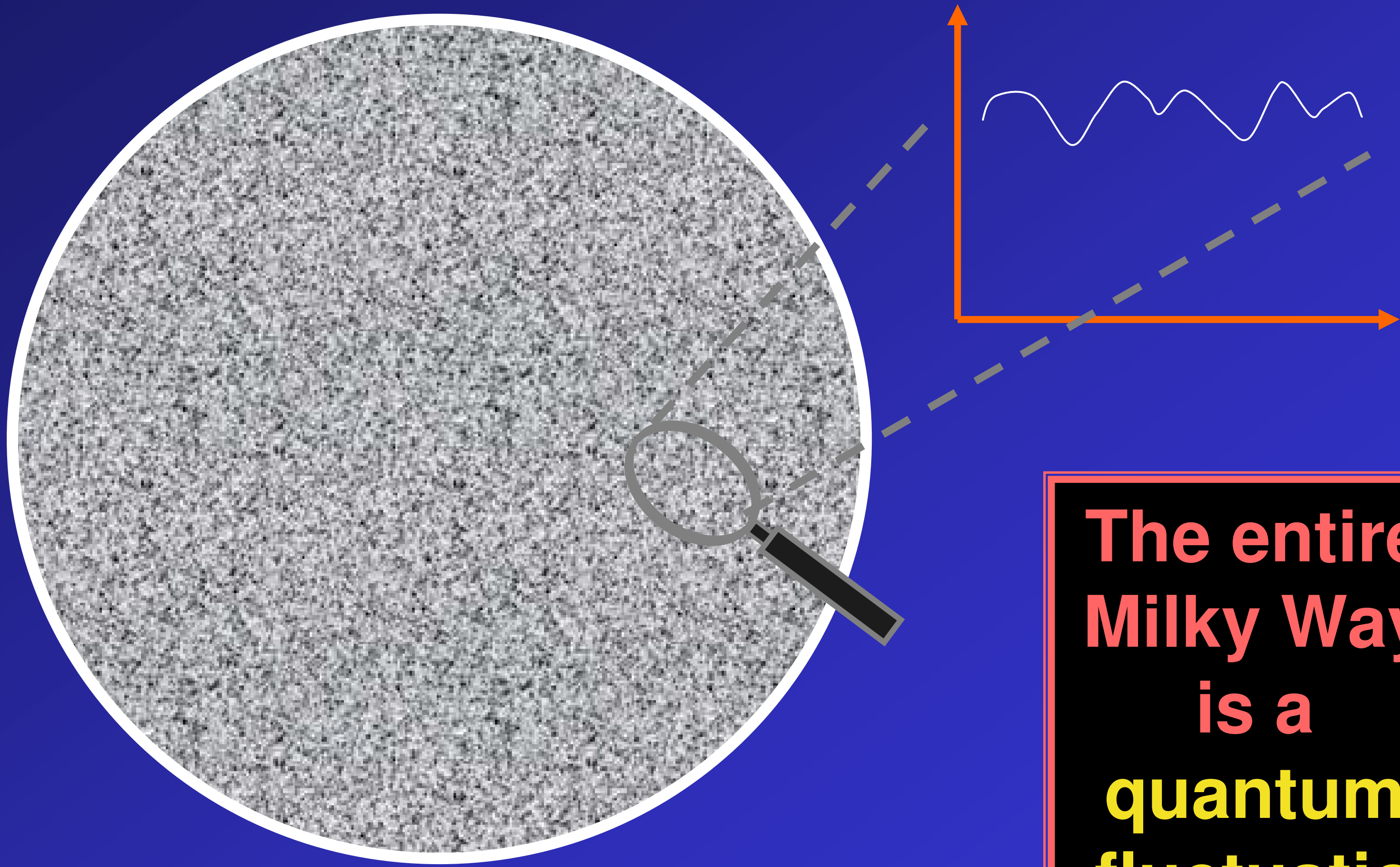


Large waves make the large-scale structure



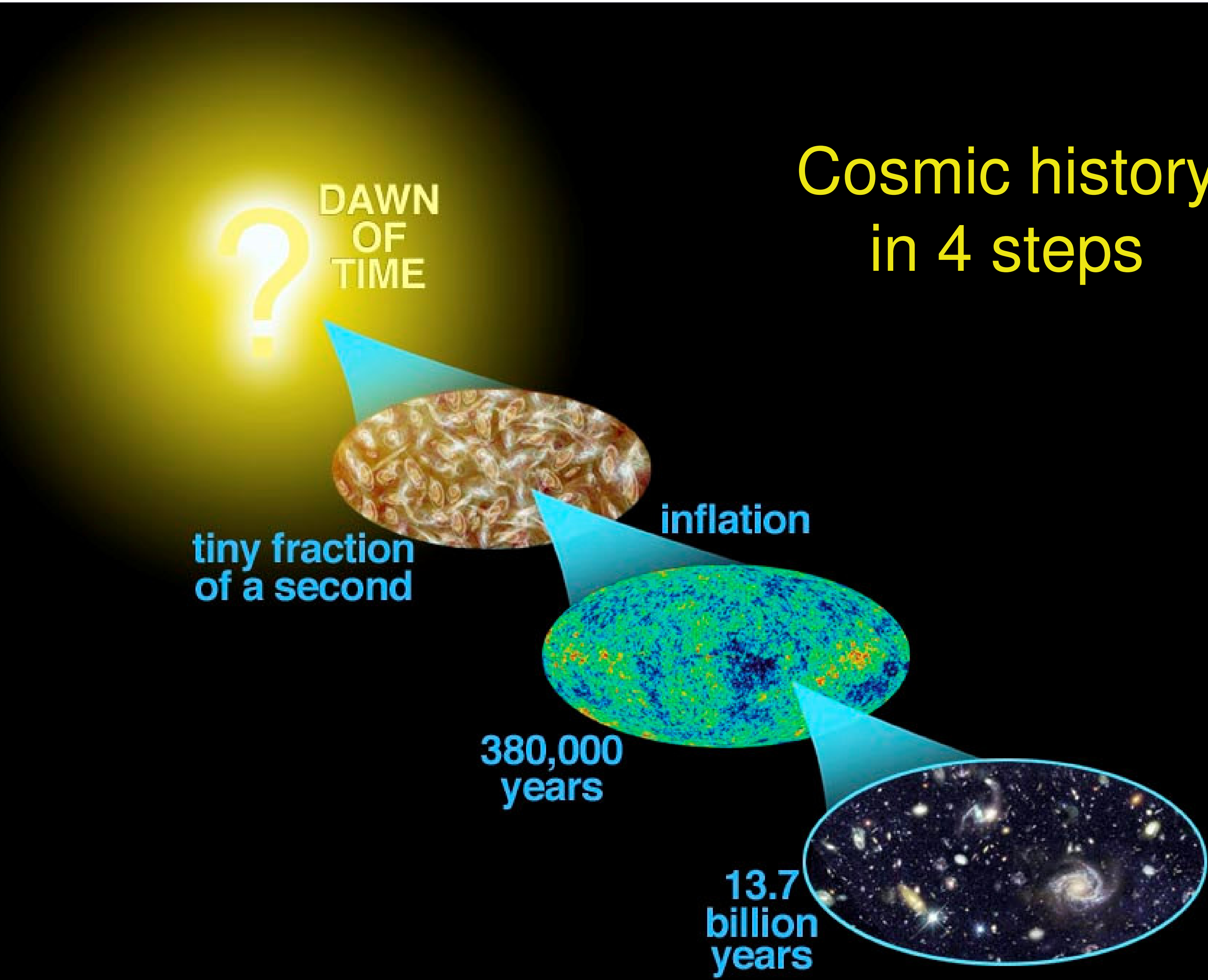
Small wavelets make the individual galaxies

The ripples were born during **INFLATION,** from **QUANTUM NOISE** at 10^{-32} seconds after the Big Bang



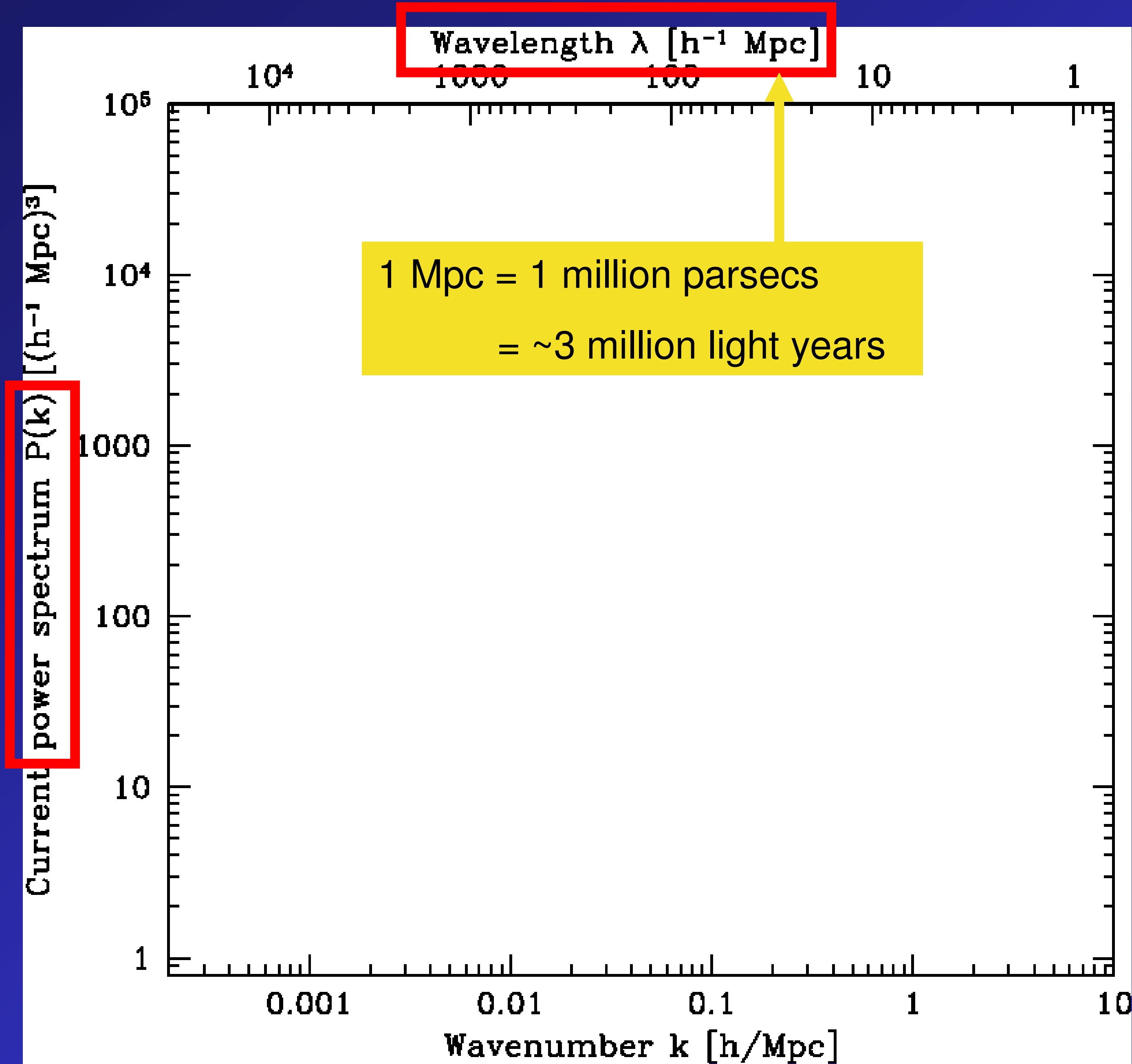
The entire Milky Way is a quantum fluctuatio n

Cosmic history in 4 steps



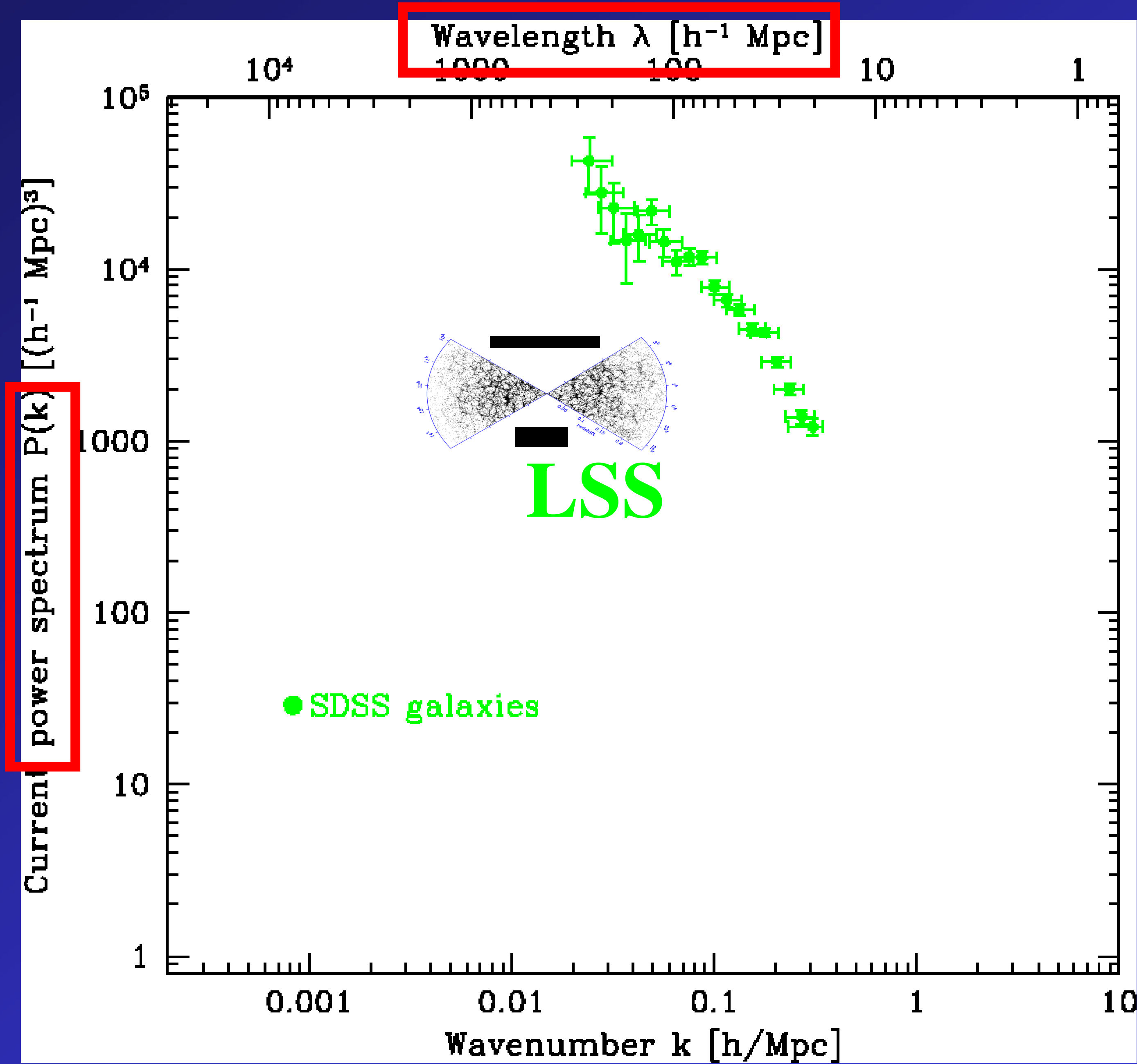
Graphics from WMAP team

Power spectrum of *initial density fluctuations*



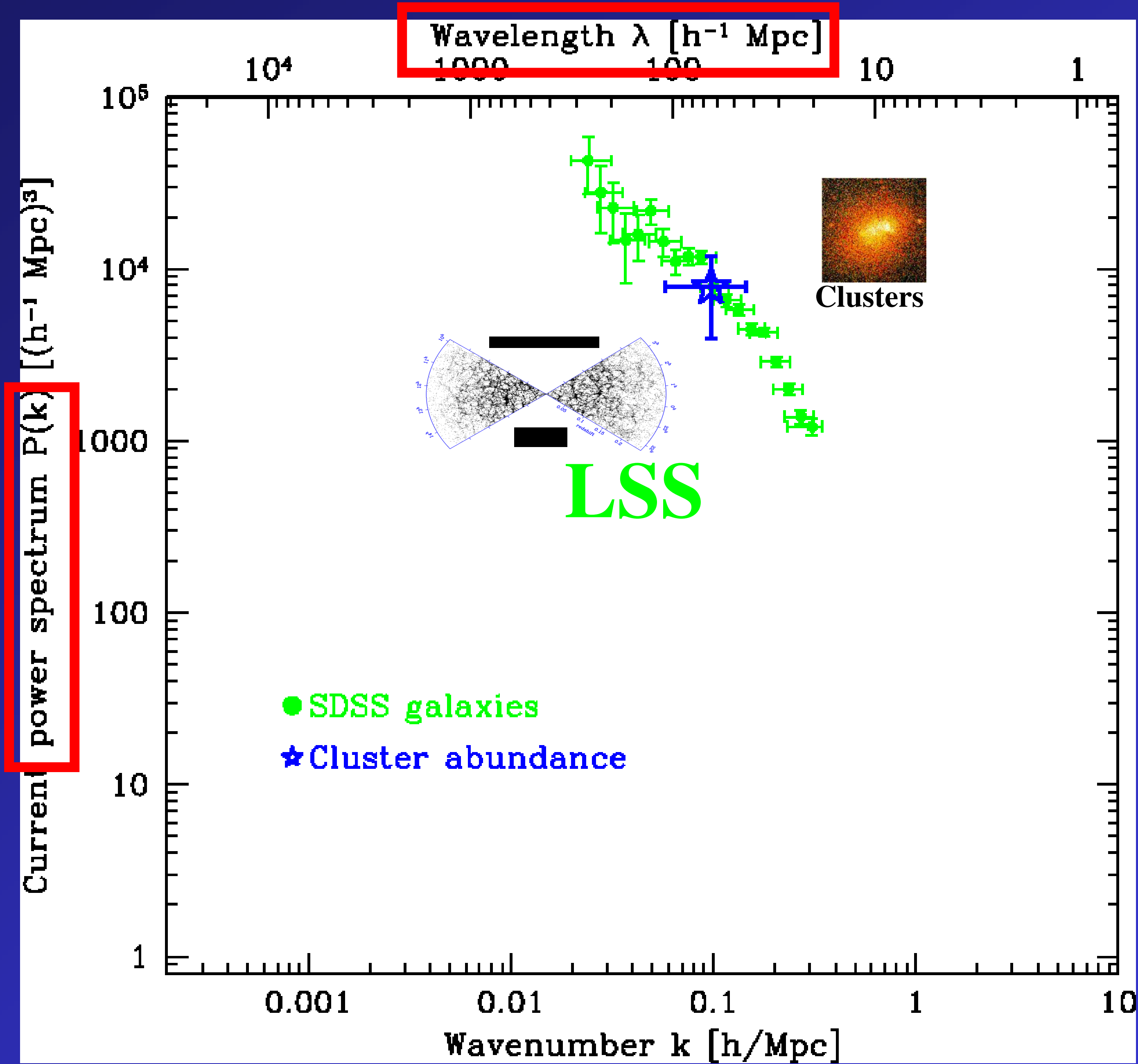
Courtesy Max Tegmark

Power spectrum of *initial density fluctuations*



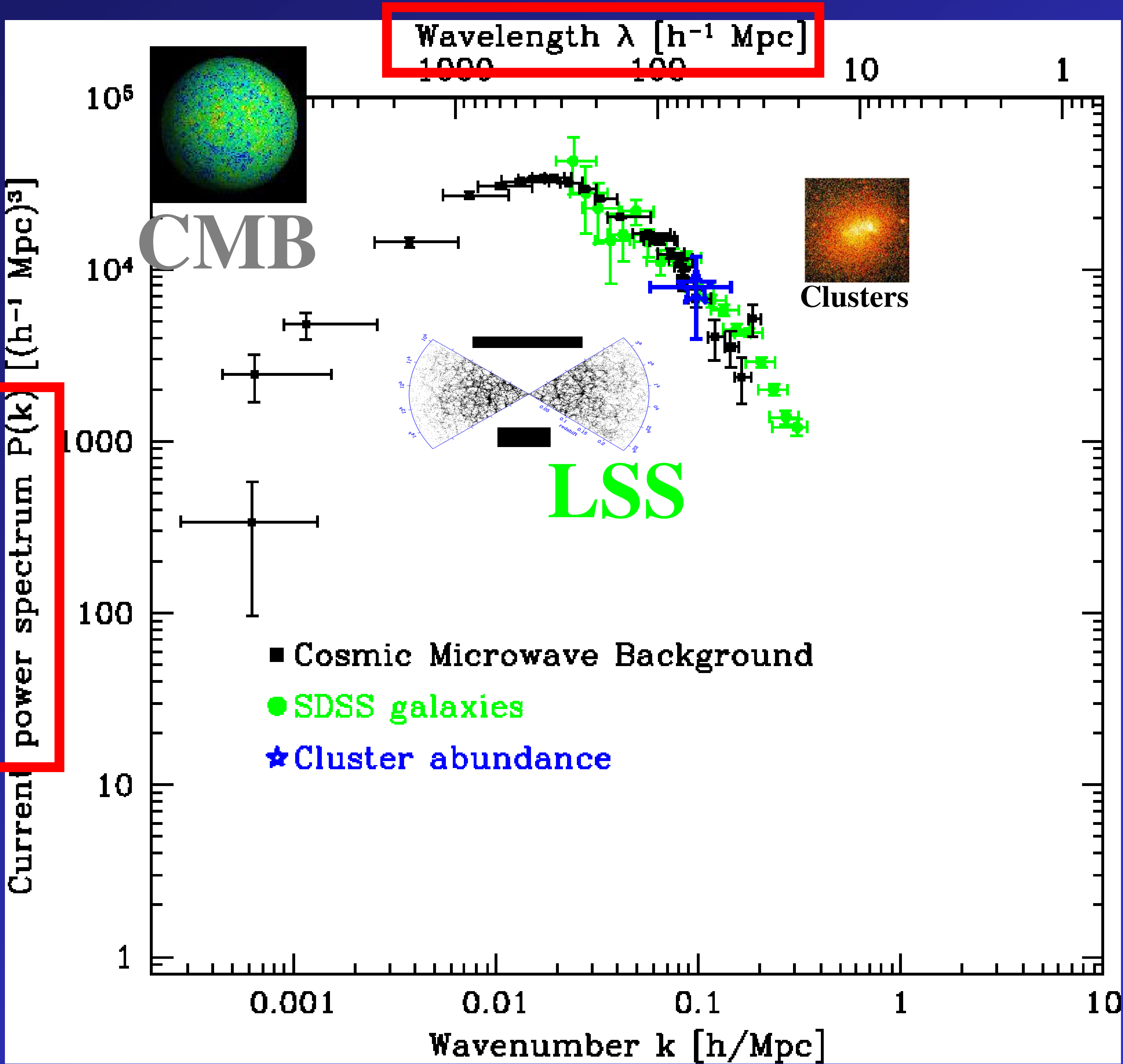
Courtesy Max Tegmark

Power spectrum of *initial density fluctuations*



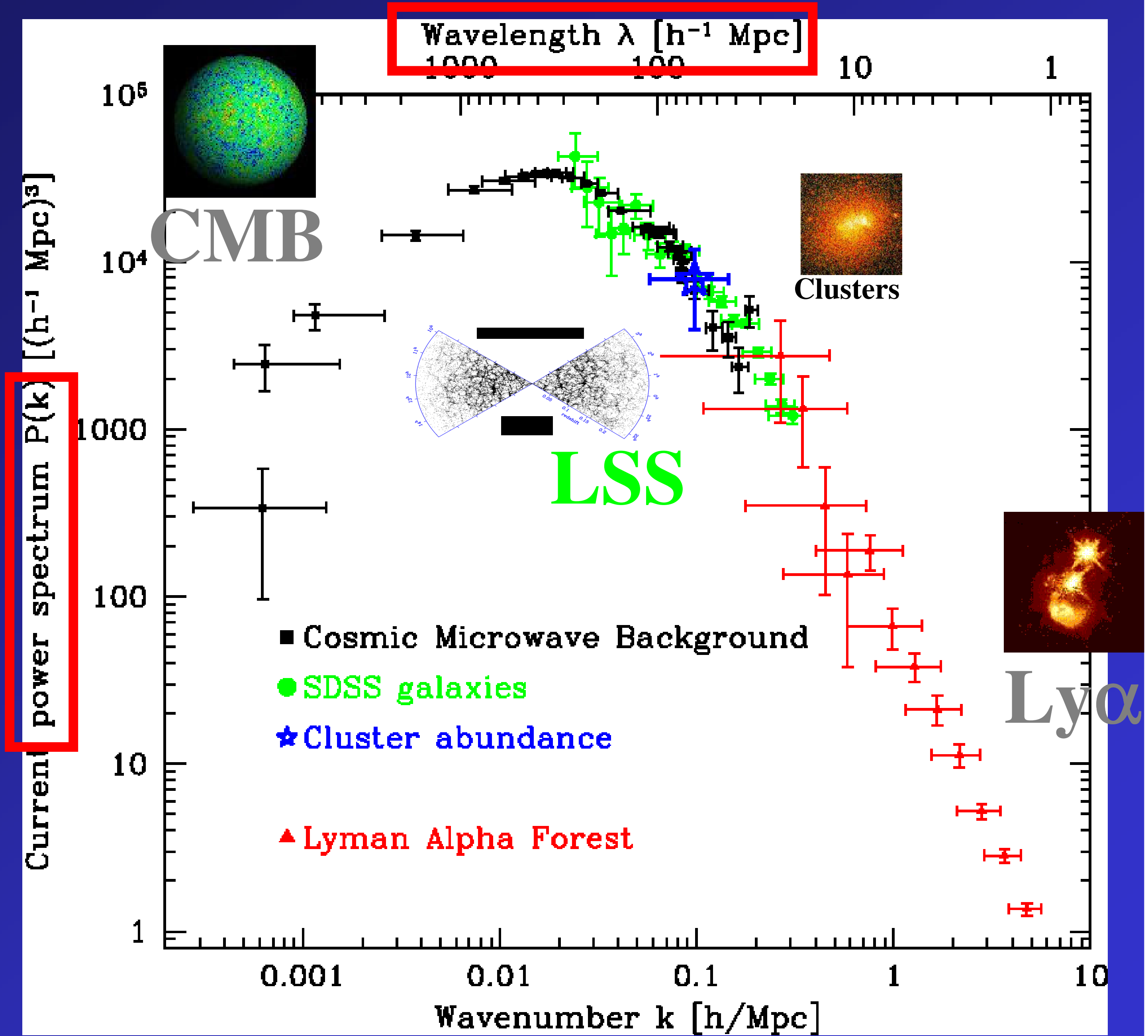
Courtesy Max Tegmark

Power spectrum of *initial density fluctuations*



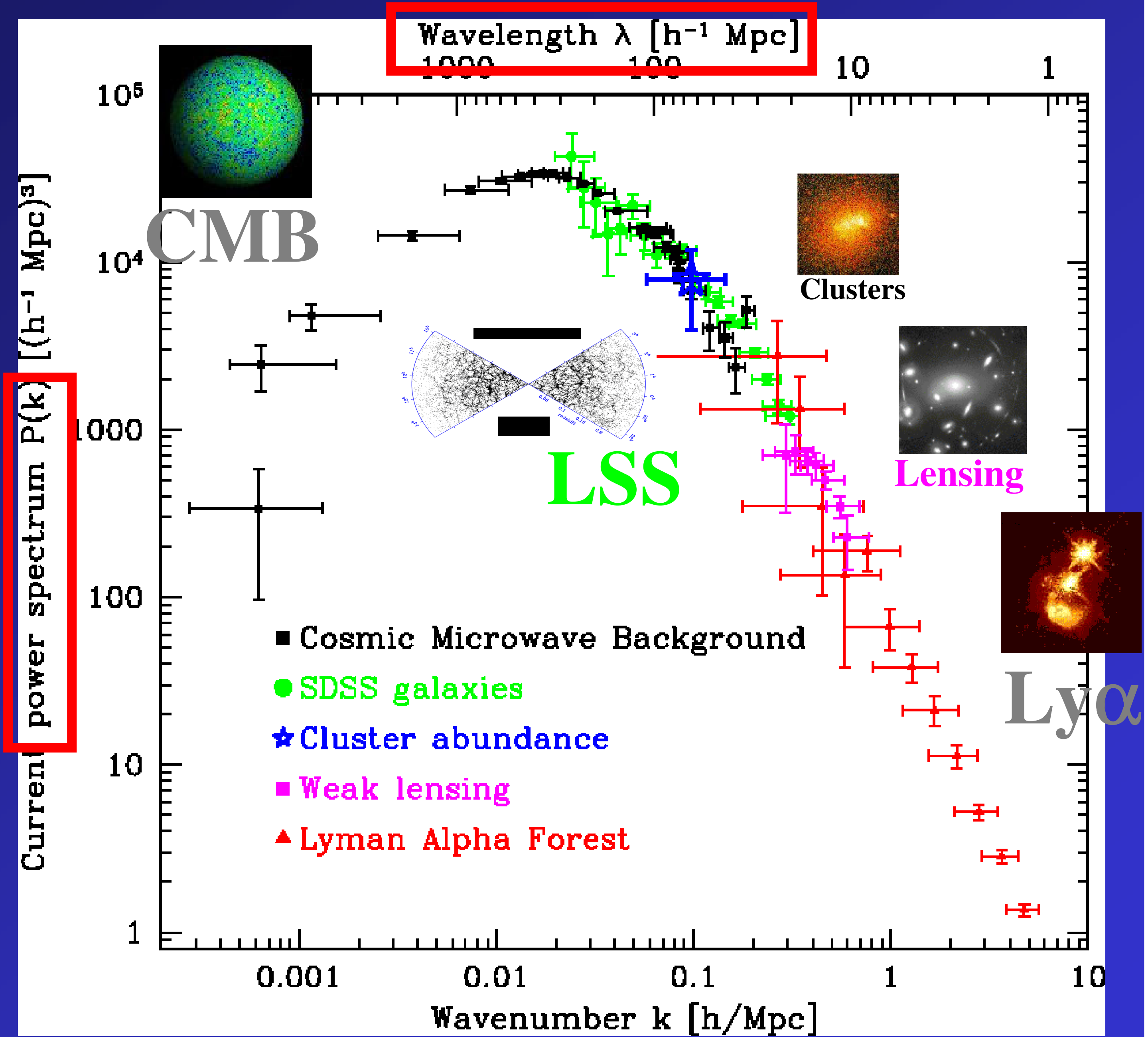
Courtesy Max Tegmark

Power spectrum of ***initial density fluctuations***



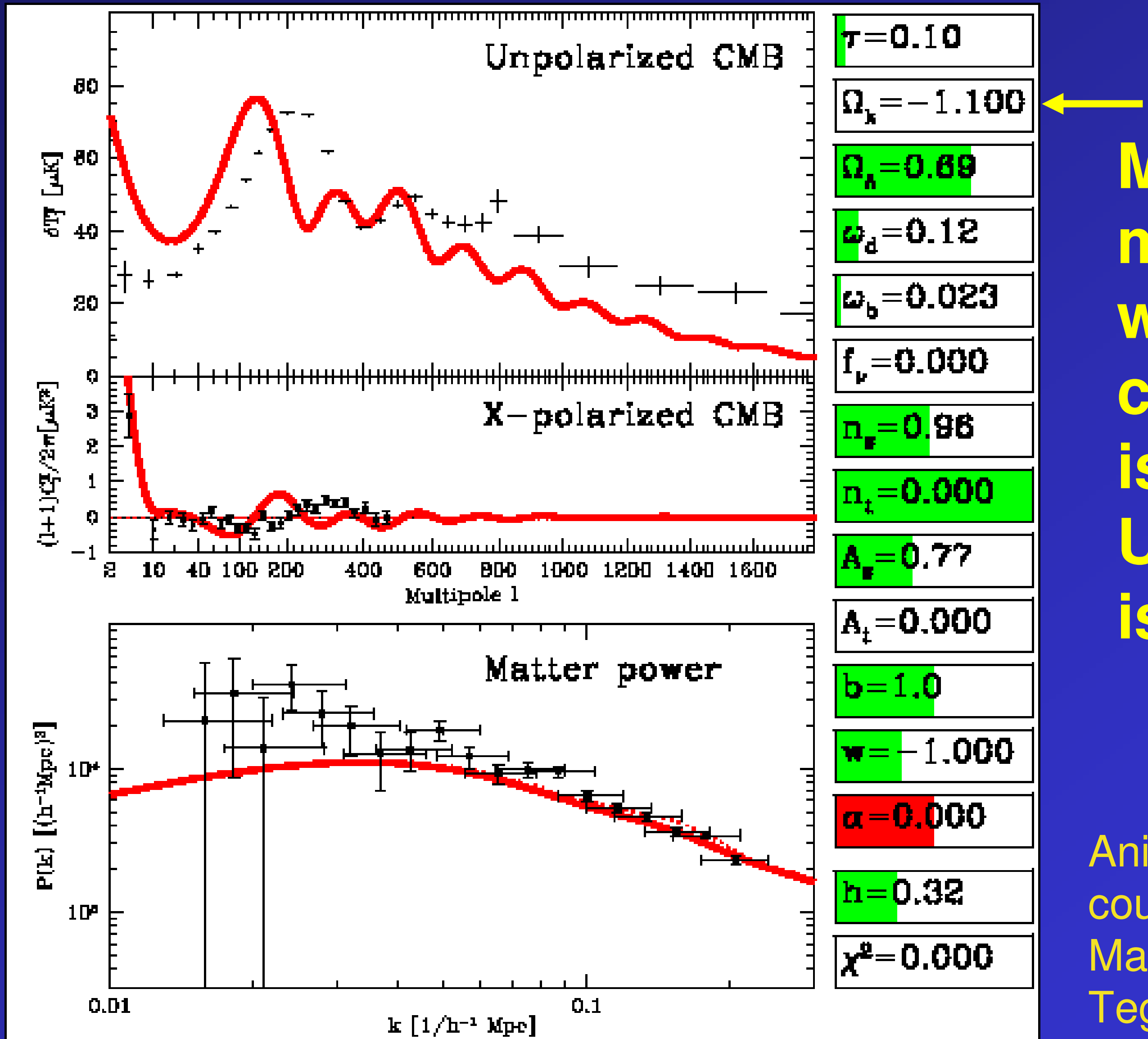
Courtesy Max Tegmark

Power spectrum of *initial density fluctuations*



Courtesy Max Tegmark

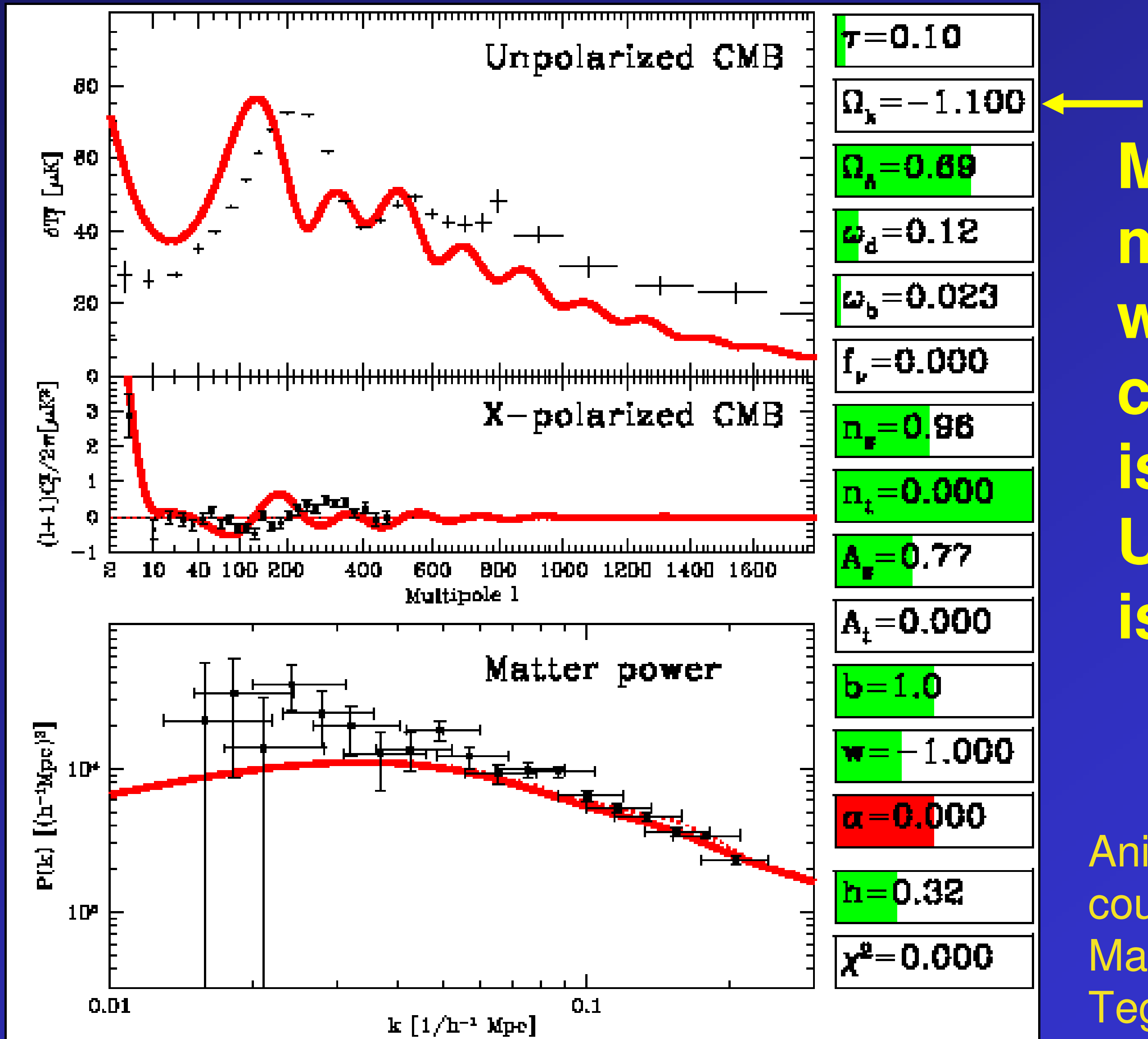
Predictions to fantastic accuracy



Measles match when curvature is zero; Universe is flat!

Animation courtesy of Max Tegmark

For example…showing that the *curvature is flat*



Measles match when curvature is zero; Universe is flat!

Animation courtesy of Max Tegmark

Spergel et al., ApJS, 148, 175, 2003: WMAP cosmic parameters

Table 2. Derived Cosmological Parameters

Parameter	Mean (68% confidence range)
Amplitude of Galaxy Fluctuations	$\sigma_8 = 0.9 \pm 0.1$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.44 \pm 0.10$
Baryon Density/Critical Density	$\Omega_b = 0.047 \pm 0.006$
Matter Density/Critical Density	$\Omega_m = 0.29 \pm 0.07$
Age of the Universe	$t_0 = 13.4 \pm 0.3$ Gyr
Redshift of Reionization[b]	$z_r = 17 \pm 5$
Redshift at Decoupling	$z_{dec} = 1088^{+1}_{-2}$
Age of the Universe at Decoupling	$t_{dec} = 372 \pm 14$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 194 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 115 \pm 5$ kyr
Redshift at Matter/Radiation Equality	$z_{eq} = 3454^{+385}_{-392}$
Sound Horizon at Decoupling	$r_s = 144 \pm 4$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 13.7 \pm 0.5$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 299 \pm 2$
Current Density of Baryons	$n_b = (2.7 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/Photon Ratio	$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

[a]Fit to the *WMAP* data only

[b]Assumes ionization fraction, $x_e = 1$

[c] $l_A = \pi d_C / r_s$

The mass-energy budget of the Universe: *definitions*

Contribution to the mass-energy density from component i:

$$\Omega_i \equiv \rho_i / \rho_{crit} \quad \text{where}$$

$$\rho_{crit} = 3(H_0)^2 / 8\pi G \qquad \text{“critical density”}$$

Total matter = sum of dark matter and baryons:

$$\rho_{mat} = \rho_{DM} + \rho_{bary}$$

$$\therefore \ \Omega_{mat} = \Omega_{DM} + \Omega_{bary}$$

There is also a mass-energy density from ***dark energy*** **=** Ω_Λ

In a flat Universe, the Ω_I’s sum to 1: thus…

$$\Omega_{DM} + \Omega_{bary} + \Omega_\Lambda = 1$$

The mass-energy budget of the Universe: *current data*

	WMAP: Spergel et al. 03	D/H: Tytler et al. 04
Ω_Λ (dark energy)	0.71±0.07	0.69±0.04
Ω_{mat} (matter)	0.29±0.07	-------
Ω_{bary}	0.047±0.006	0.042±0.002
Ω_{DM}	0.24±0.07	-------

Mass densities for $H_0 = 70$:

ρ_{crit} = 1420 x $10^8\ M_\odot$ / Mpc^3

ρ_{mat} = 411 x $10^8\ M_\odot$ / Mpc^3

ρ_{bary} = 67 x $10^8\ M_\odot$ / Mpc^3

ρ_{DM} = 344 x $10^8\ M_\odot$ / Mpc^3

$\rho_{*,gal}$ = 5.6 x $10^8\ M_\odot$ / Mpc^3 (Cole et al 01)

CONCLUSIONS

- Dark matter is **84%** of all matter.
- Baryons are **16%** of all matter.
- Only **10%** of baryons have fallen into galaxies. **Where are the other baryons??**

The *missing baryons* are partly inside halos and partly between halos

Matter budget for Milky Way: Klypin, Zhao & Somerville 2001

Total mass of MW: $1 \times 10^{12}\ M_\odot$

Total mass of stars and gas: $5 \times 10^{10}\ M_\odot$ (5%)

Expected mass of stars and gas: $16 \times 10^{10}\ M_\odot$ (16%)

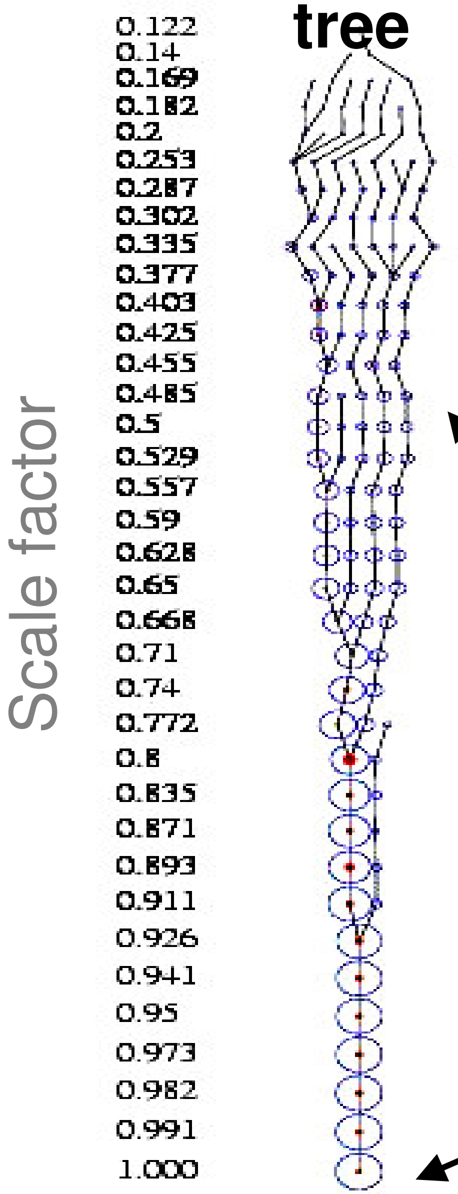
$\therefore$ Fraction of collapsed baryons: 5%/16% = ~1/3

Baryon collapse in spirals is inefficient; only 1/3-1/2 of baryons in spiral dark halos have fallen in; reasons are inefficient cooling and long dynamical time in outer parts.

But 1/3 ≠1/10. Still need another factor of 3. Thus, only ~1/3 of baryons are to be found in spiral halos.

➡ **~2/3 of baryons are outside of collapsed halos.**

Dark halo merger tree



Wechsler et al. 2002

Dark-halo merger tree for a Milky Way-type galaxy

Within the currently favored cosmology (Lambda Cold Dark Matter, LCDM) structure forms ***hierarchically,*** from the bottom-up. Dark matter halos (and possibly the galaxies they host) are built by a series of discrete merging events.

Z=2 *Major*

progenitor: 3.9 x 10^{11} $M_\odot$ *12*

distinct halos (> 2.2 x 10^{10} $M_\odot$)

Z=1

Major progenitor: 1.5 x 10^{12}

6 distinct halos (> 2.2 x 10^{10} $M_\odot$)

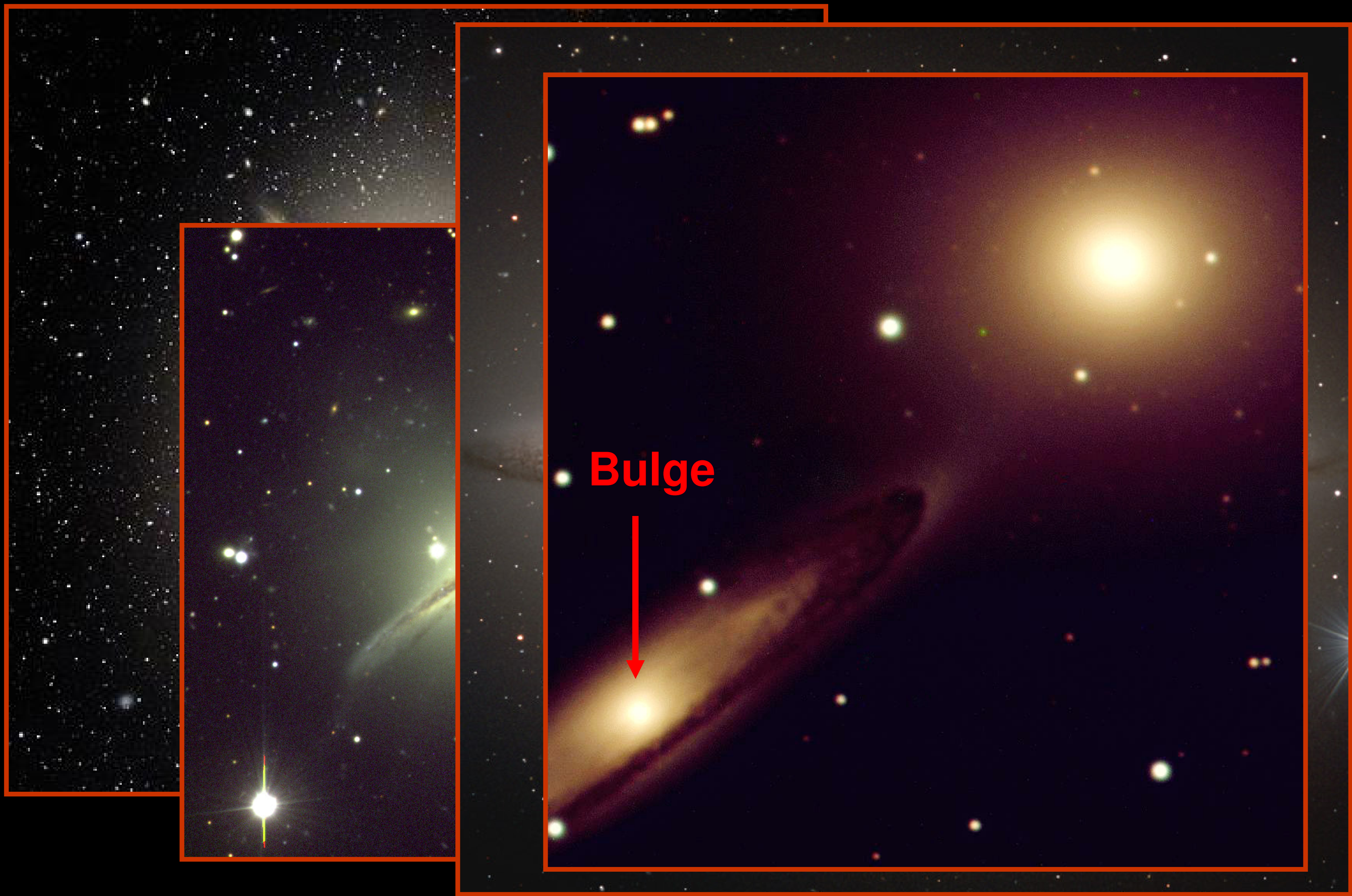
Z=0

One galaxy-sized halo roughly the size of the Milky Way, Mass=2.9 x 10^{12} $M_\odot$

Spiral galaxies are flattened, rotating disks seen at various inclinations

“Spheroidal” galaxies are oblate or prolate with low net rotation and high internal velocity dispersion

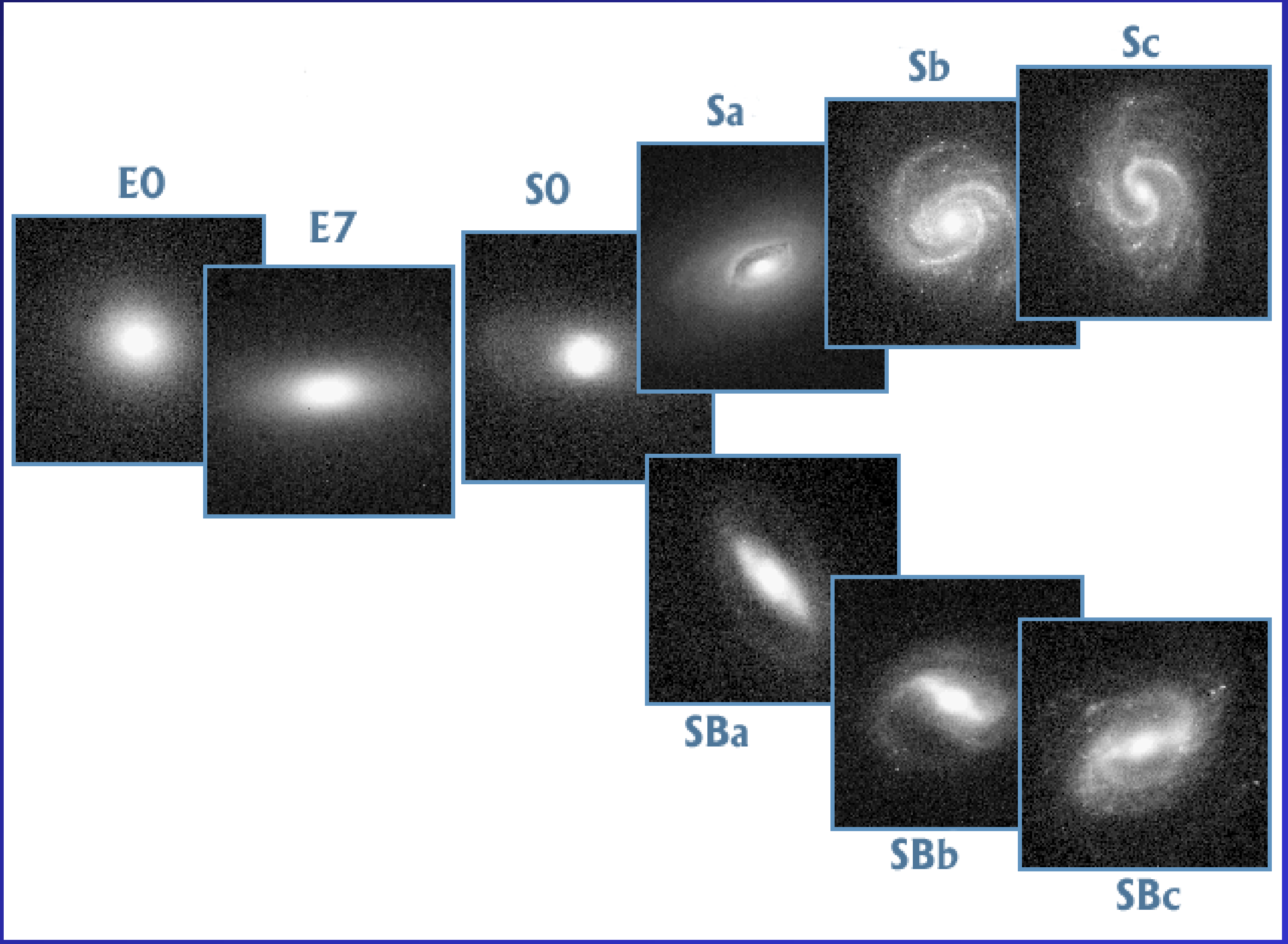
Spheroidal components inside disk galaxies are called *bulges*



Spheroidal galaxies populate *dense regions* such as clusters of galaxies

Galaxies can be classified by disk vs. bulge into *Hubble types*

This ordering is termed the *Hubble sequence*



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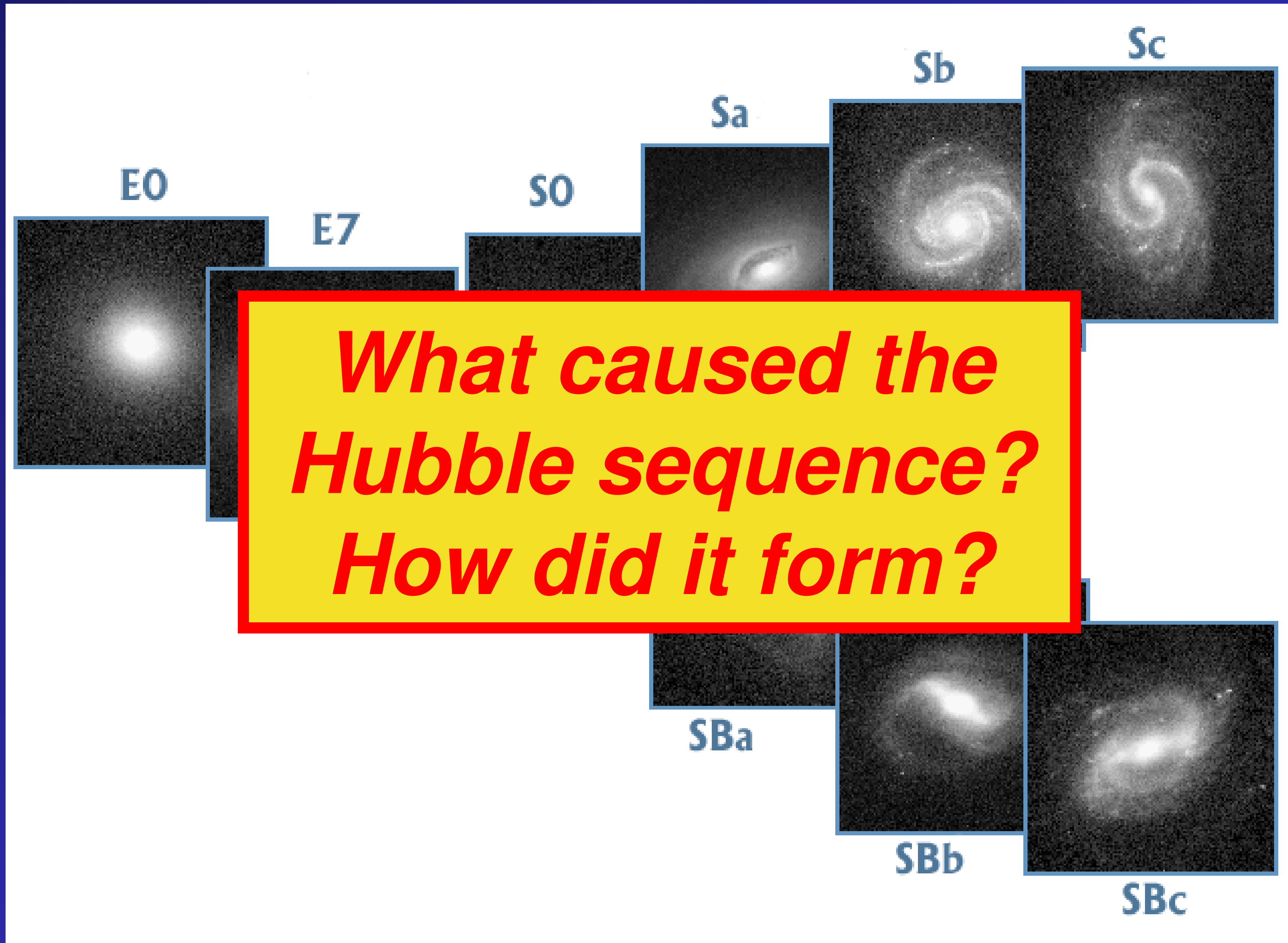
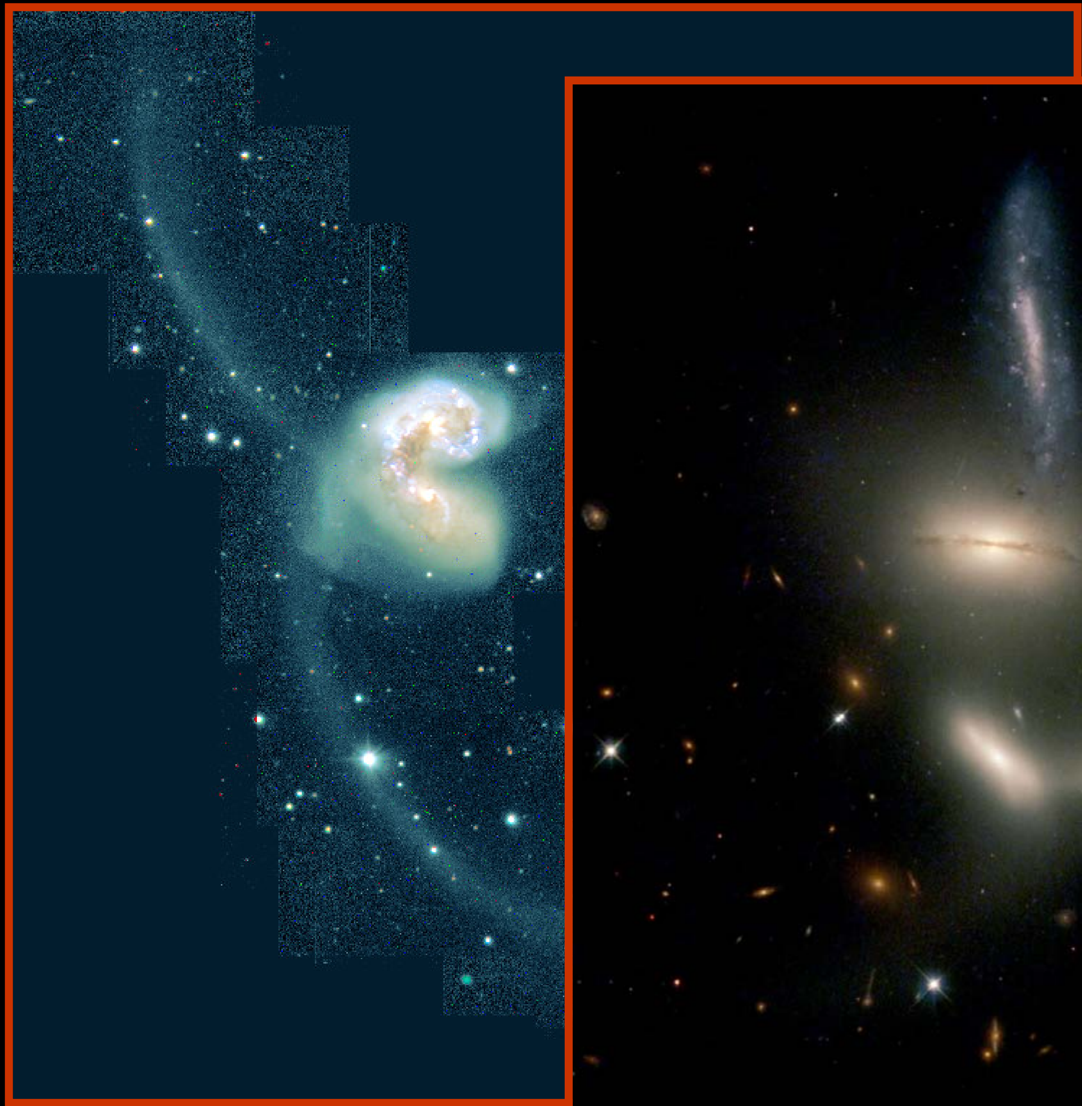
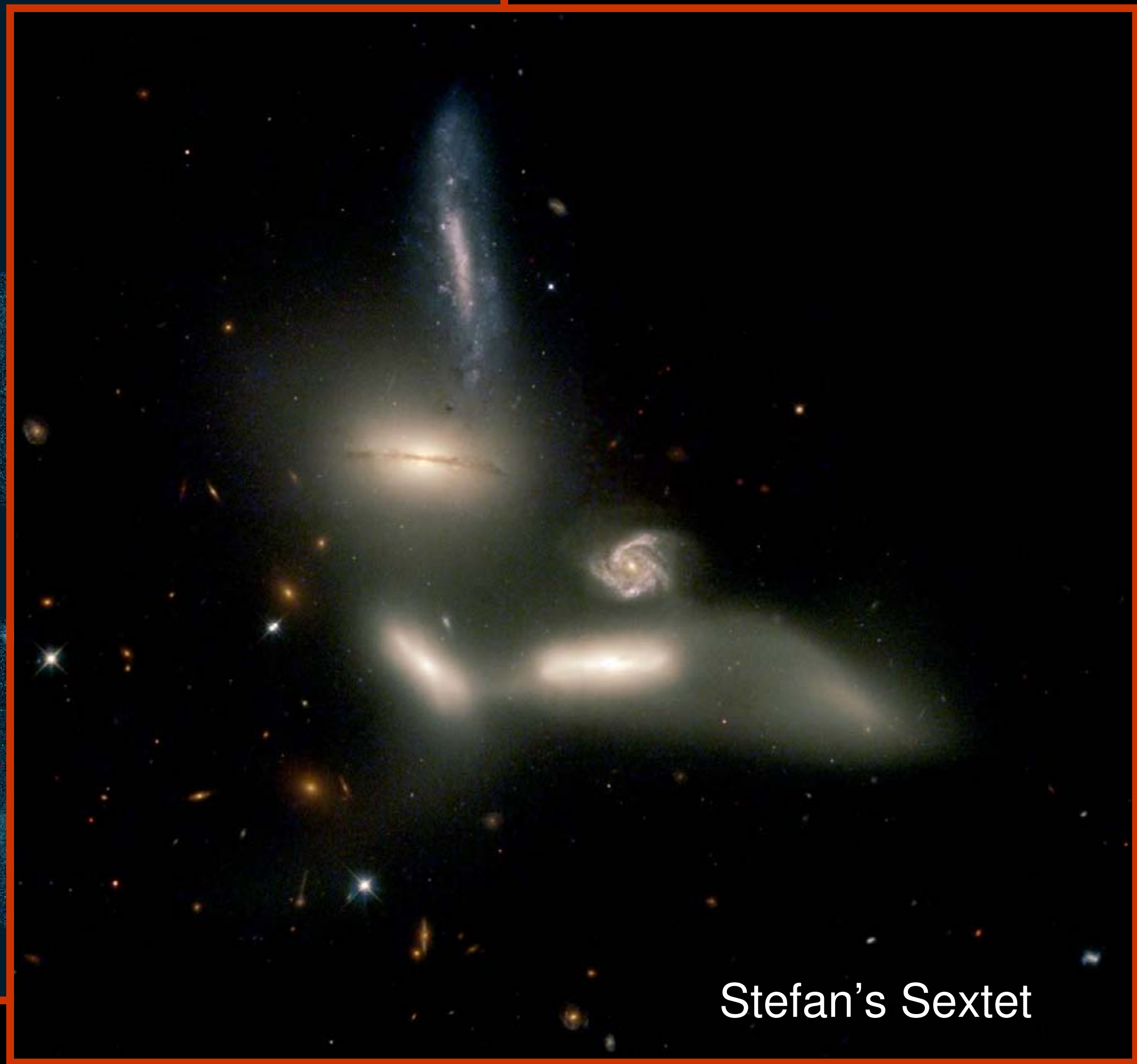


What caused the Hubble sequence? How did it form?

Spheroids are produced when *disks collide*





N-body merger simulations have now become quite realistic

The future Milky Way-Andromeda collision Credit: John Dubinski, CITA

This merger simulation includes gas and resulting star formation

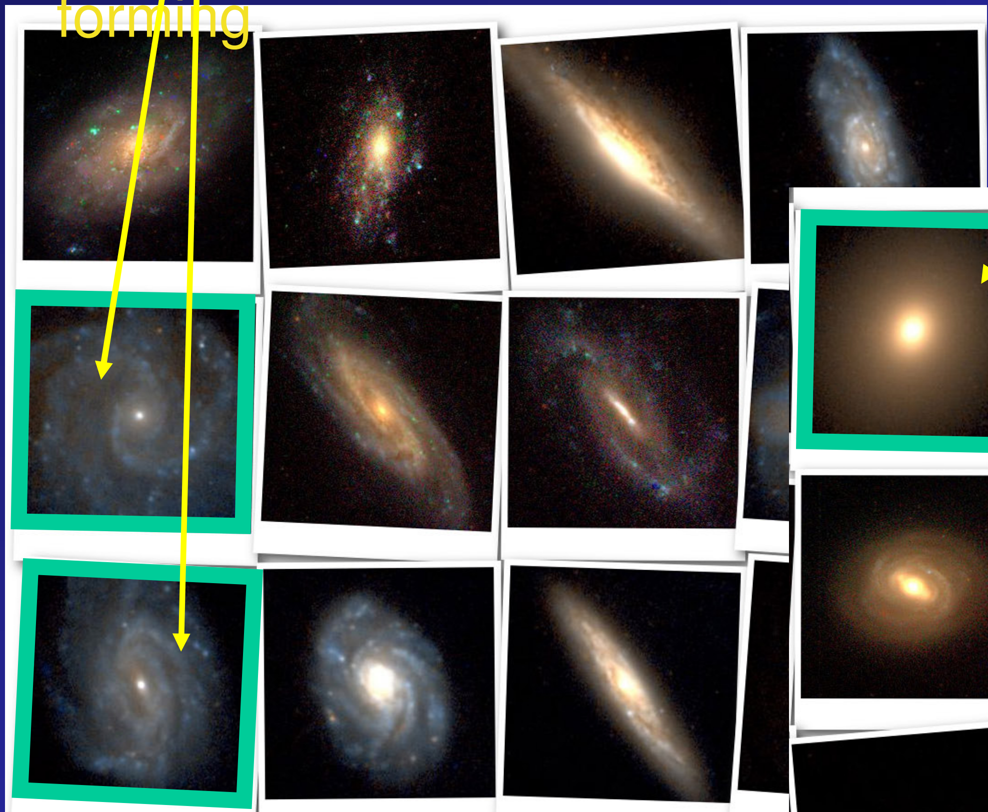
Merger simulation by Mihos and Hernquist, 1998

But to understand disks, we need to understand *dark matter…*

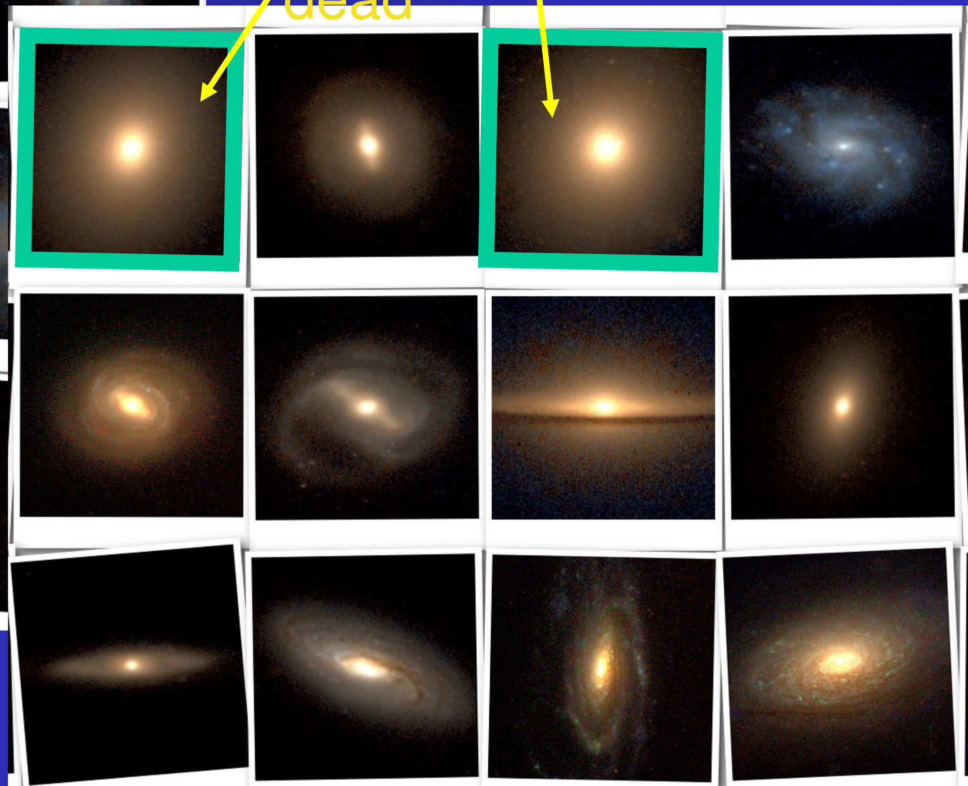
Color indicates different amounts of recent or ongoing star formation

Young stars are blue
Old stars are red

Disks are bluish--stars are forming

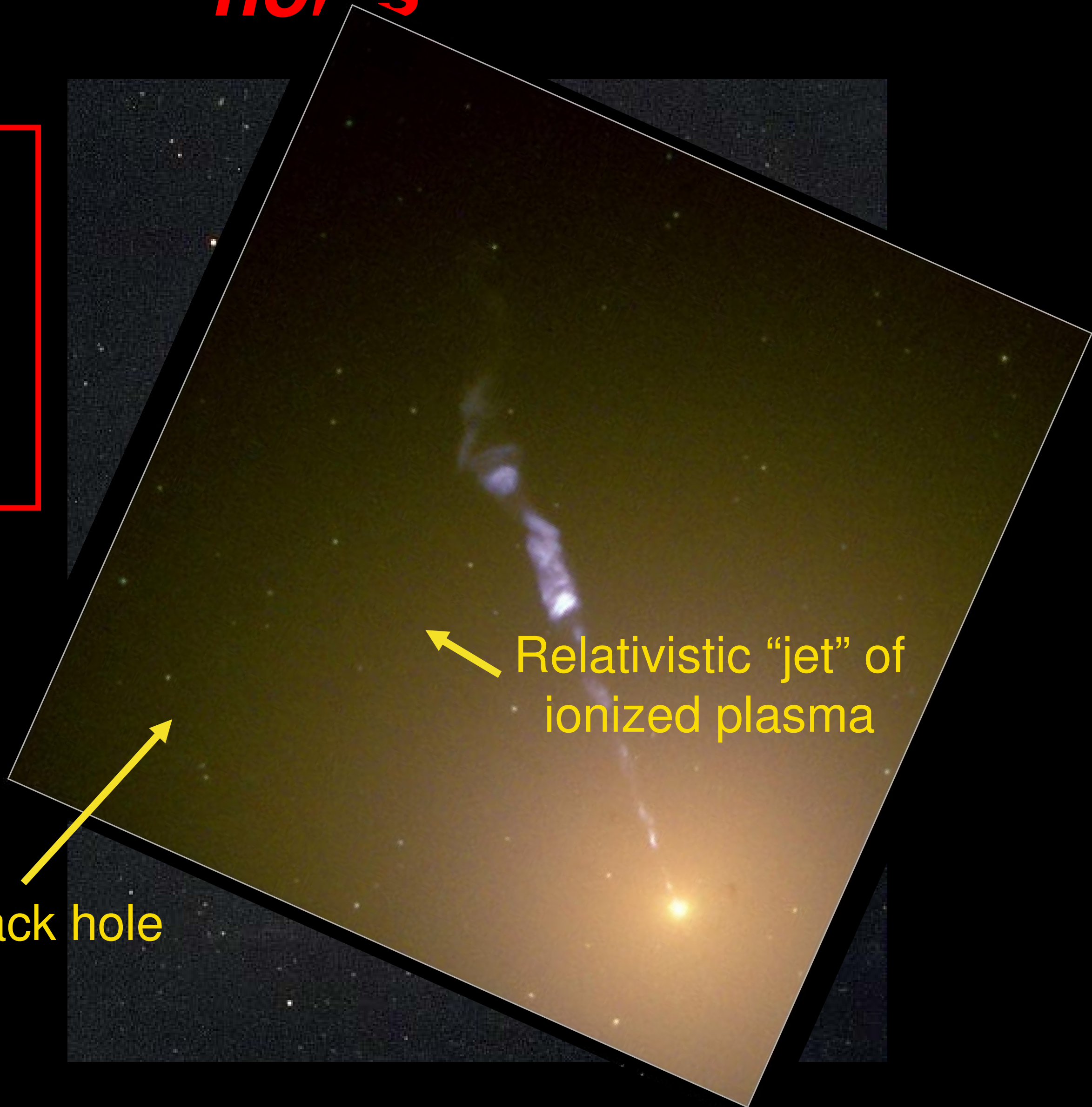


Spheroids are “red and dead”

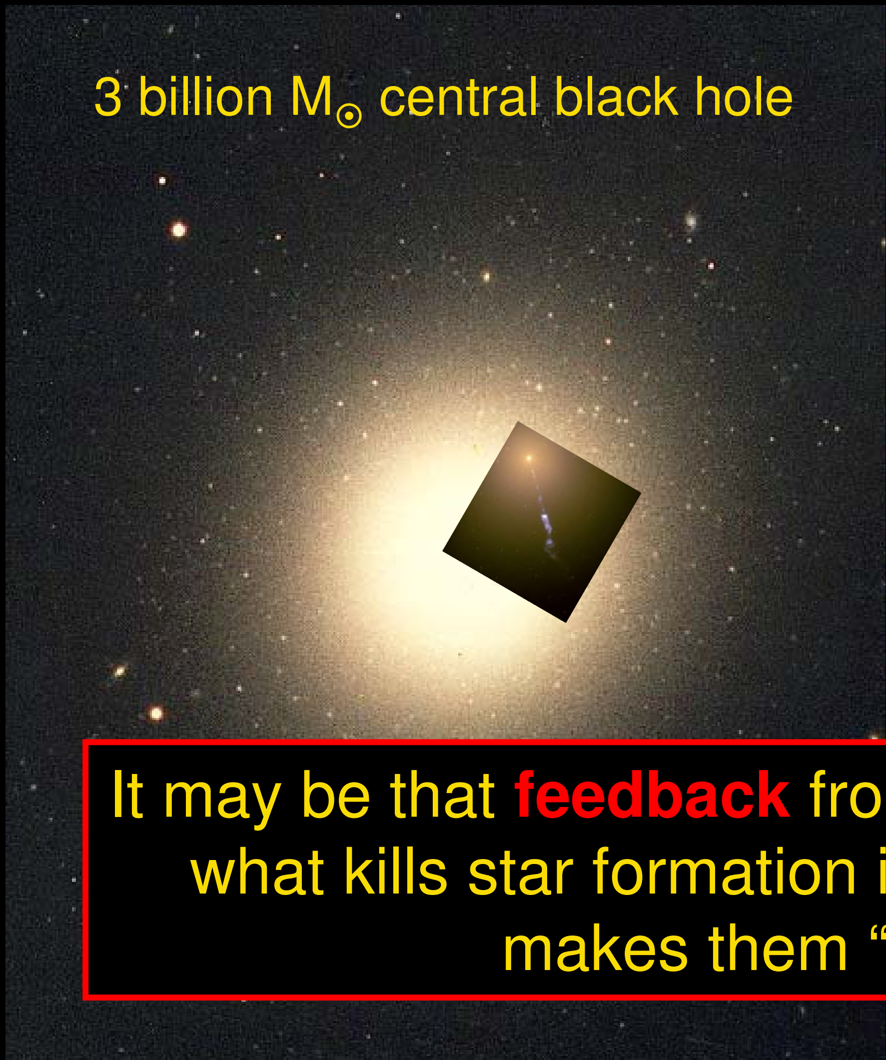


The centers of spheroids host ***massive black holes***

When gas falls onto BHs, they become **active galactic nuclei (AGN)** and **quasars (QSOs)**

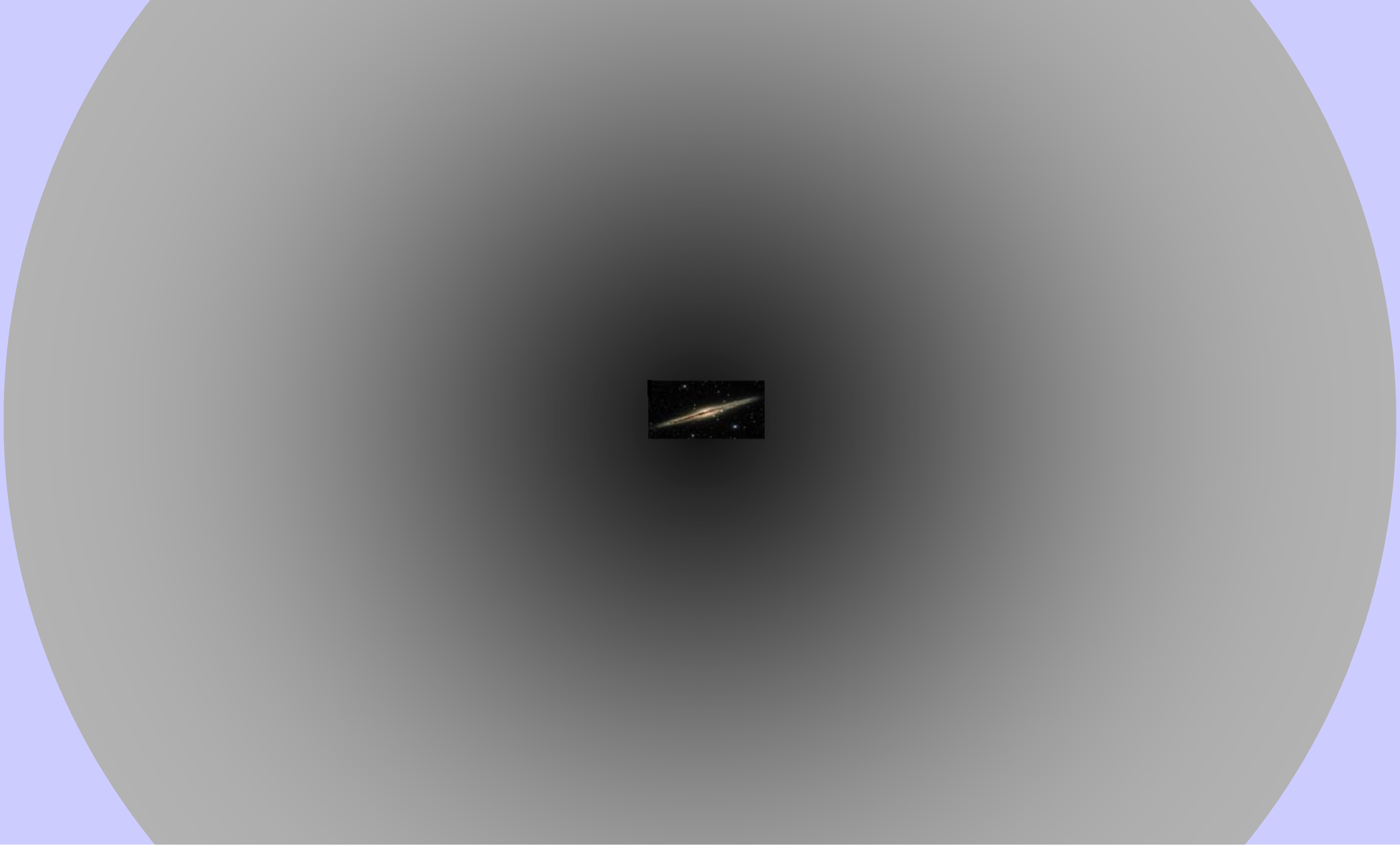


Energy emitted by the AGN heats the surrounding gas



It may be that **feedback** from these active black holes is what kills star formation in spheroidal galaxies and makes them “red and dead.”

Baryonic matter makes up only a small fraction of galactic mass. The remainder is in a ***halo of dark matter*** roughly 10 times as big and 10 times as massive.



Baryonic matter makes up only a small fraction of galactic mass. The remainder is in a ***halo of dark matter*** roughly 10 times as big and 10 times as massive.

Why is baryonic matter in the center and dark matter on the outside?

Formation of a cluster of galaxies: dark matter N-body simulation

Simulation courtesy of Stefan Gottloeber, AIP, Potsdam

Stephan's Quintet **is a famous small group of galaxies. It really has only four galaxies…the large spiral at lower left is in the foreground. The barred spiral near the middle is** ***falling into the group at high speed.***

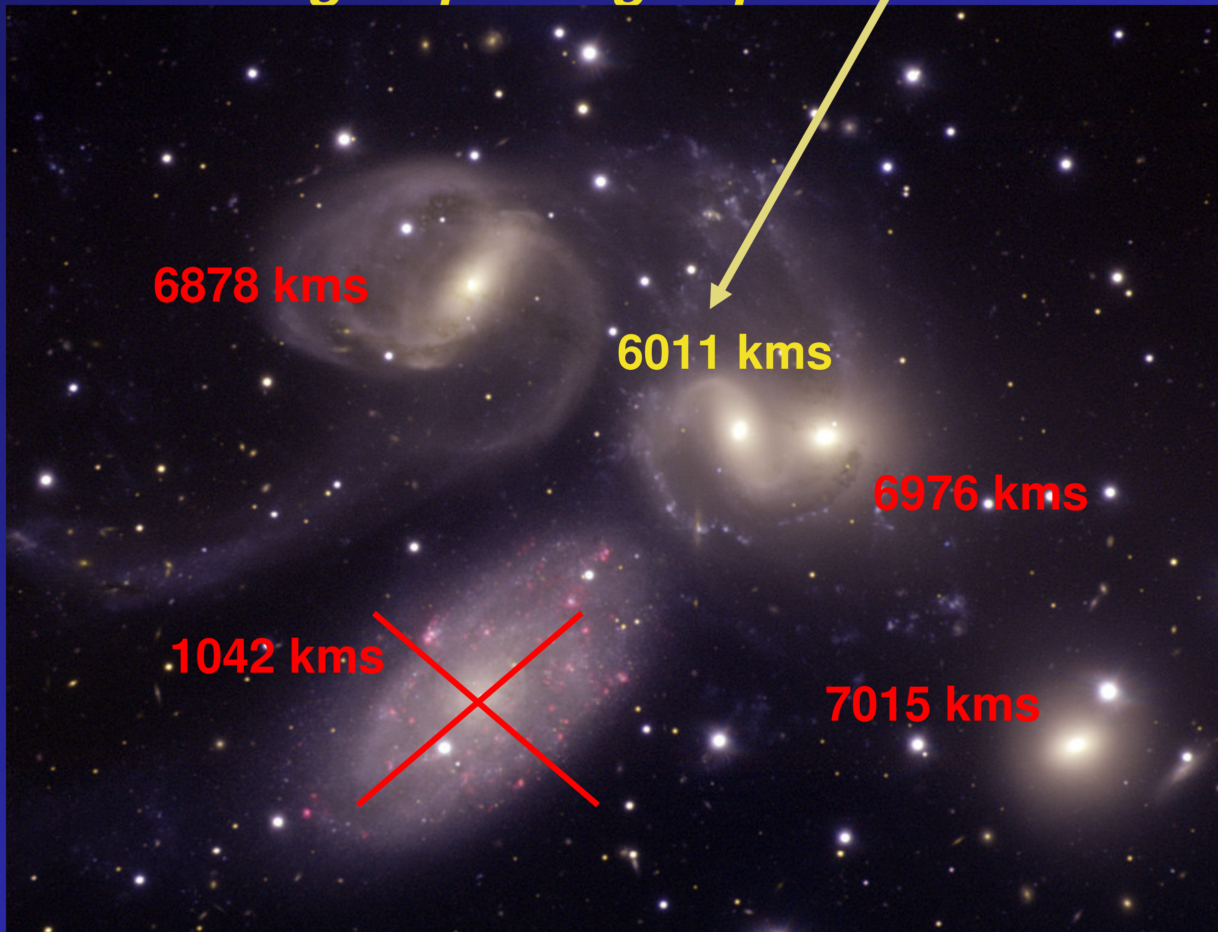
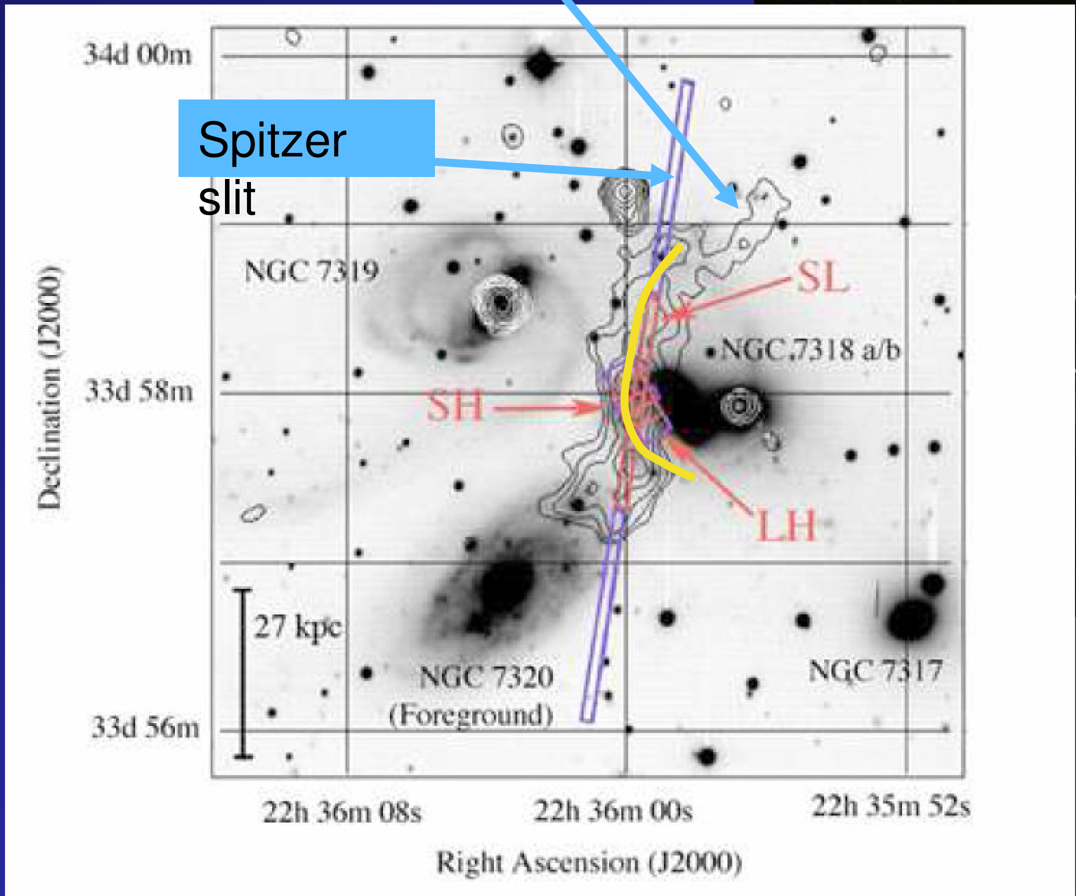


Photo NOAO

Baryon physics at work: a high-velocity collision in Stephan's Quintet brings a gas-rich galaxy into the group. _A shock forms_ at the boundary, molecular H_2 emission is produced, stars form in the shocked gas.

Shock front: VLA radio and X-ray emission



Spitzer H_2 spectra by Appleton et al., astro-ph/0602554

When gas clouds fall into dark halos, their kinetic energy of ordered motion is *converted into heat* via shocks.

Suppose a gas cloud is moving with velocity V and has the standard primordial abundance of H and He. If its energy of motion is converted into heat, the resultant temperature is

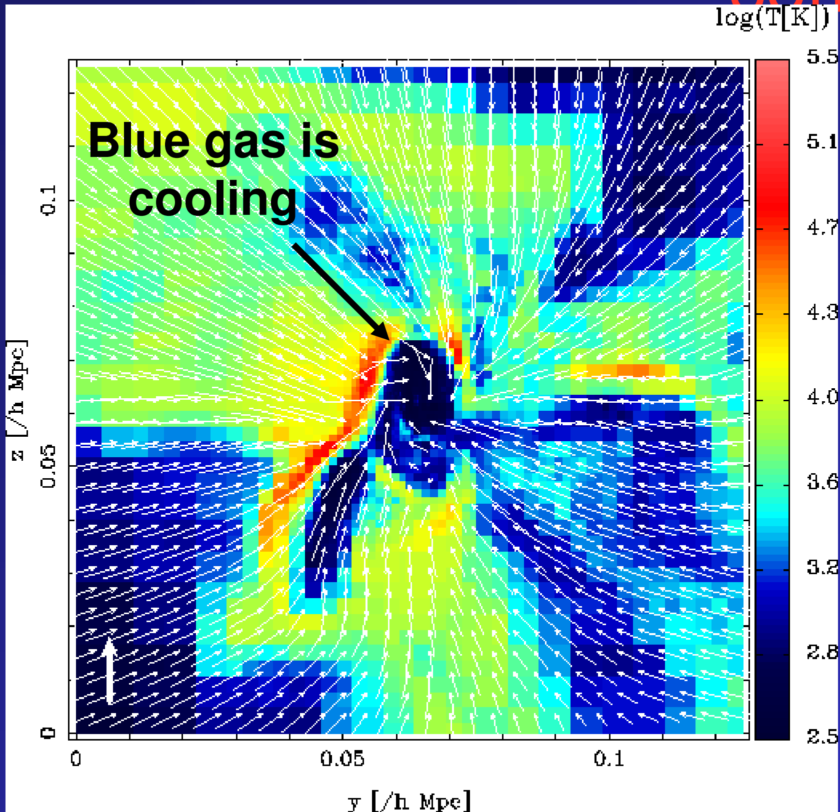
$$T \sim 24\ V^2,$$

where T is in degrees K and V is in km/s.

Galaxies have V ~ 300 km/s, so T ~ 2 million K. Clusters of galaxies have V ~ 1500 km/s, so T ~ 50 million K.

What does gas do at these temperatures?

Cooling is naturally slower in large dark halos because their gas is hotter and less dense…but this alone is not enough to quench the galaxy completely.



Red gas is not cooling

Small 10^{11} $M_\odot$ halo

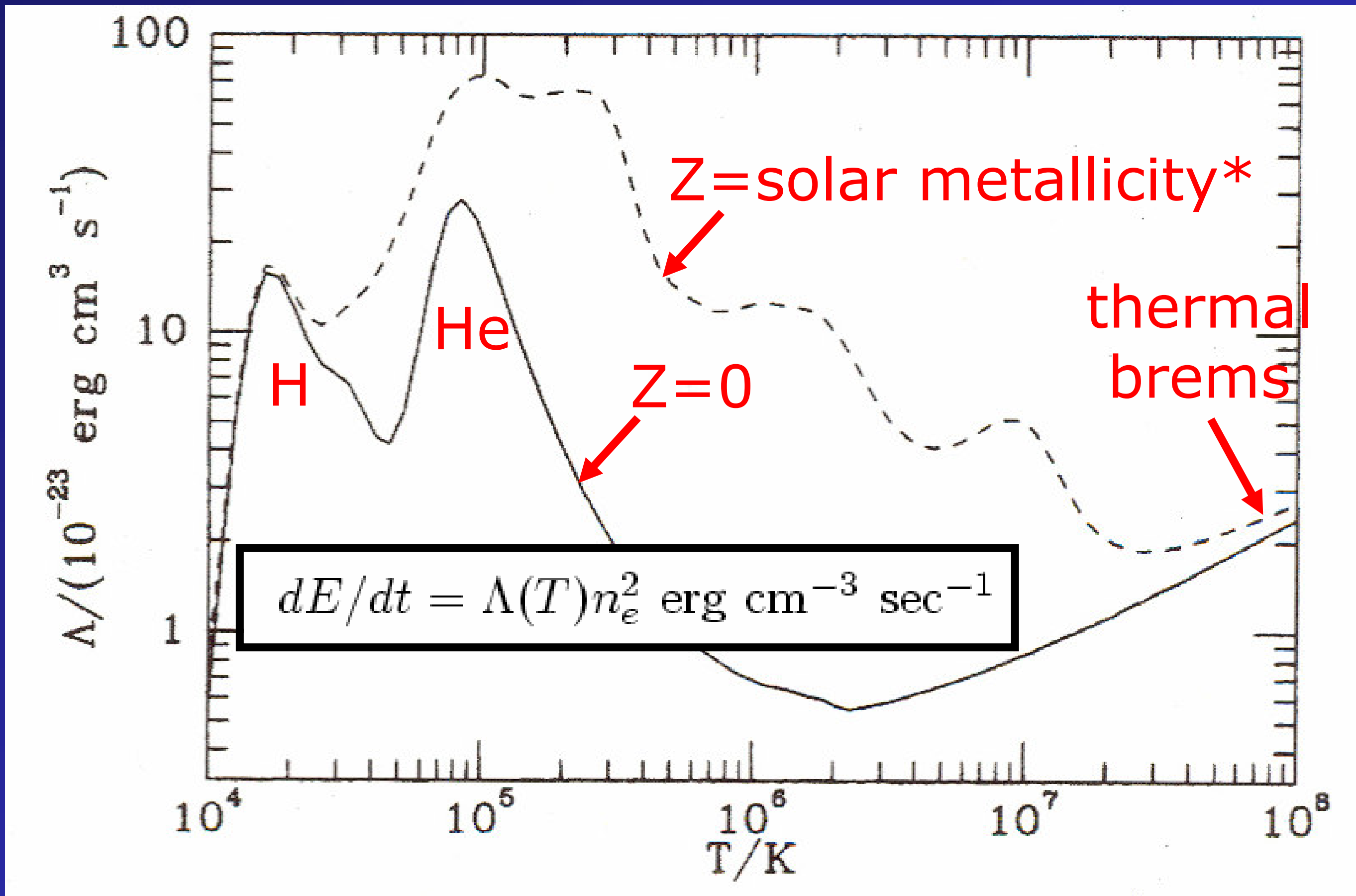
Large 10^{13} $M_\odot$ halo

Dekel & Birnboim 2005

Hydrodynamic simulations by Andrei Kravtsov

The *cooling curve* shows how fast energy is radiated by hot gas; depends on Z (metallicity)

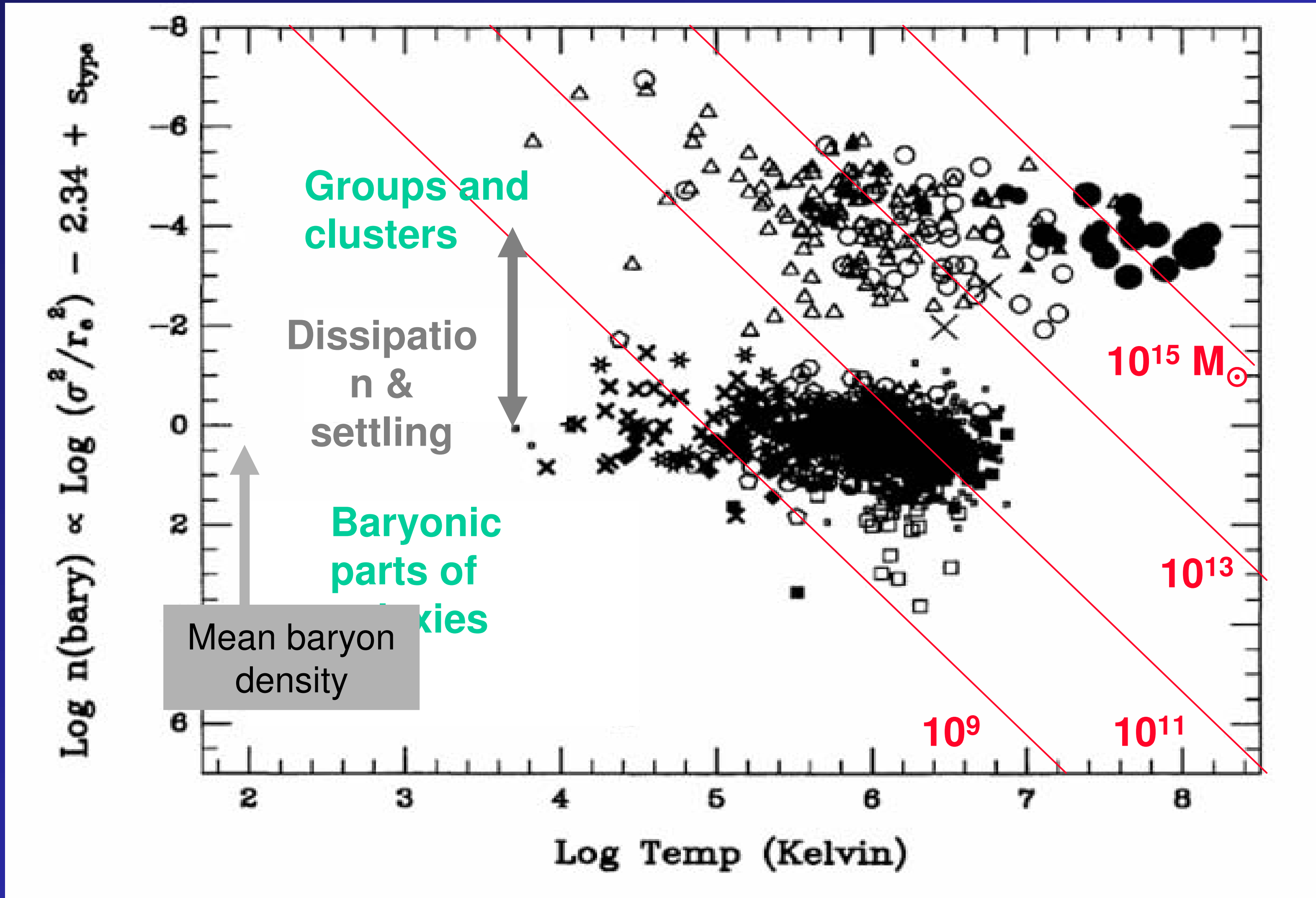
Rees & Ostriker 77, Silk 77, White & Rees 78, Blumenthal, Faber, Primack & Rees 84



* The fraction of heavy elements in the Sun is about 2% by mass.

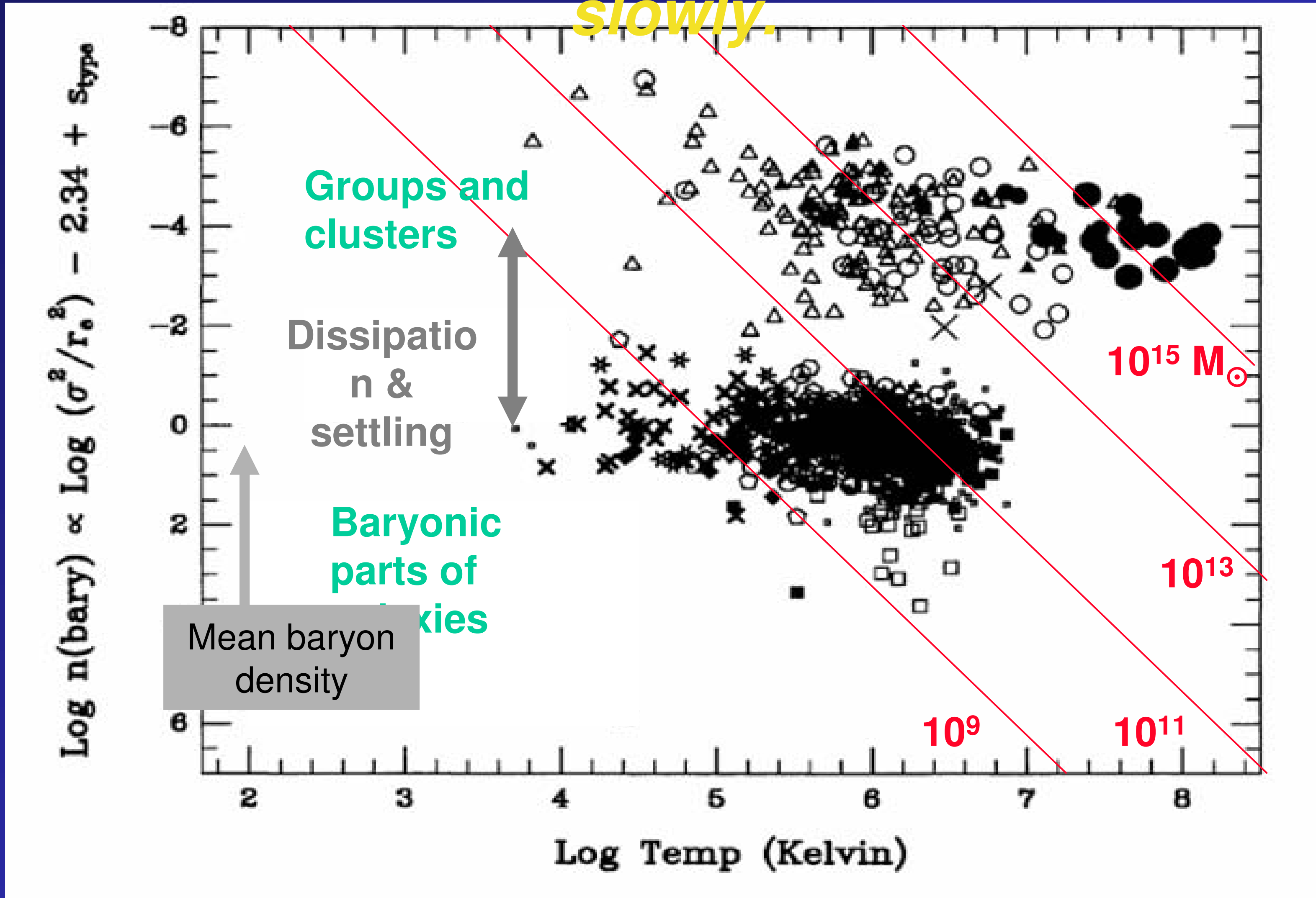
Figure from Binney and Tremaine 1988

Baryon densities inside galaxies are about *1000 times higher* than in groups and clusters



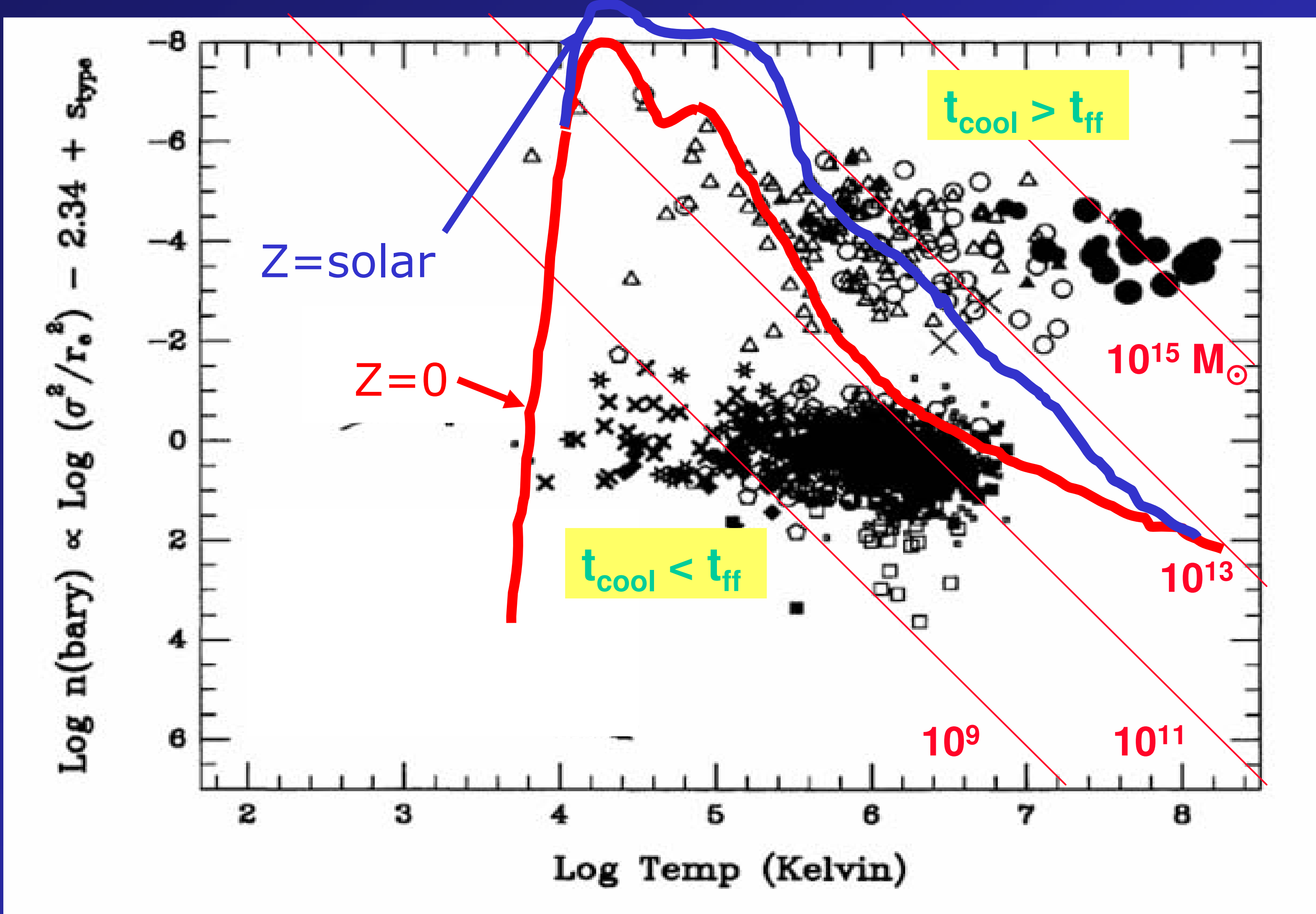
Burstein, Bender, Faber, and Nolthenius 1996

Galaxies are in halos where ***baryon cooling is efficient.*** In cluster-sized halos, ***baryons cool slowly.***



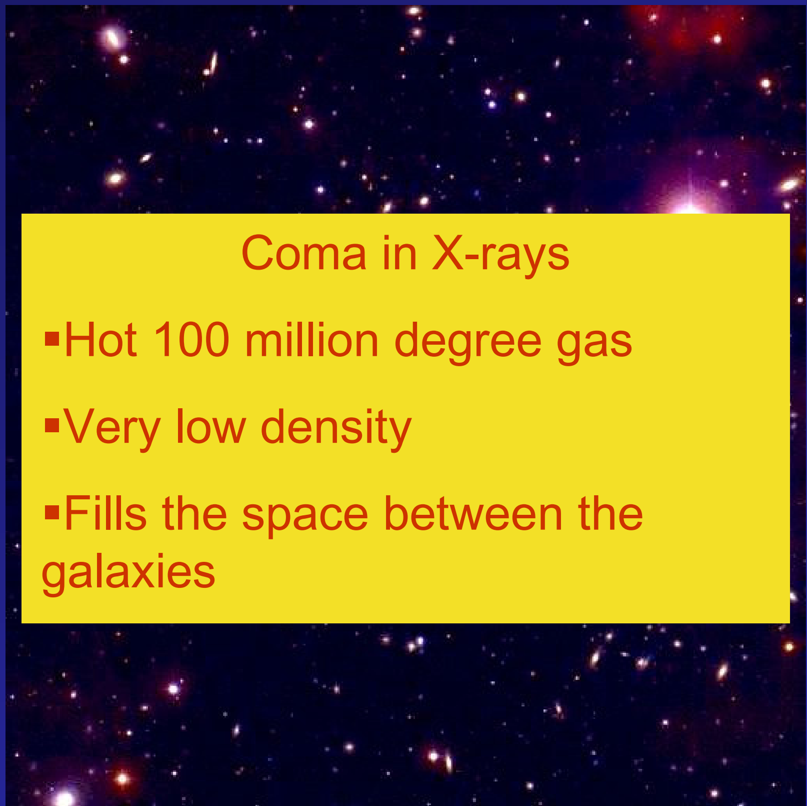
Burstein, Bender, Faber, and Nolthenius 1996

Baryon cooling is efficient when the *gas cools faster* than the free-fall time.



Burstein, Bender, Faber, and Nolthenius
1996

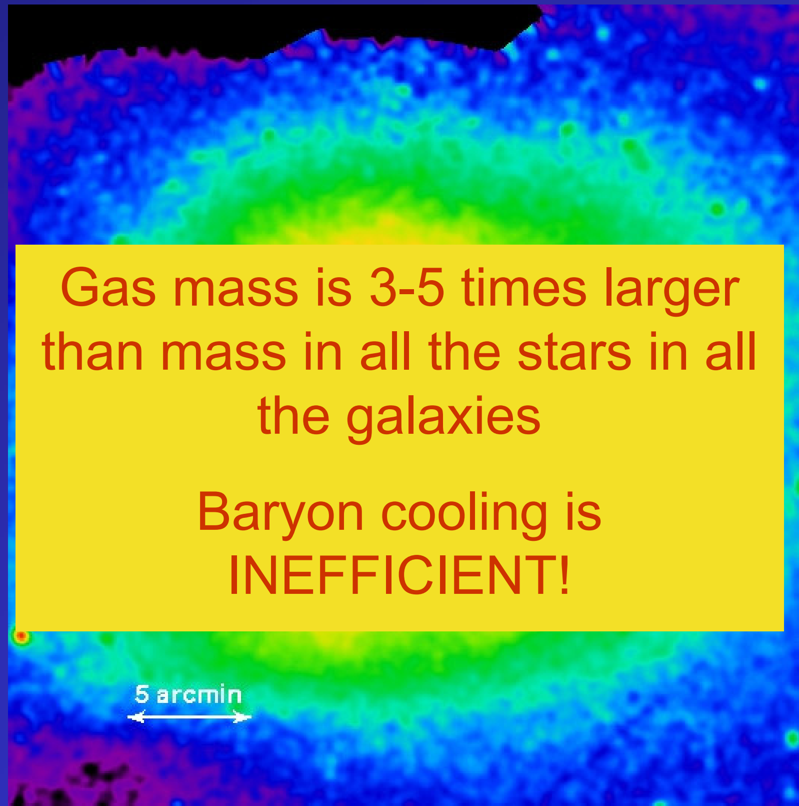
Leftover hot baryons fill the space between the galaxies



Coma in X-rays

- Hot 100 million degree gas
- Very low density
- Fills the space between the galaxies

Coma cluster in visible light



Gas mass is 3-5 times larger than mass in all the stars in all the galaxies

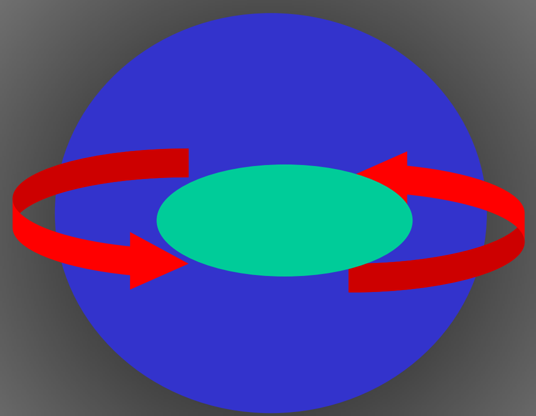
Baryon cooling is INEFFICIENT!

Coma cluster in X-rays

Formation of a cluster of galaxies

Simulation
courtesy of
Stefan
Gottloeber,
AIP,
Potsdam

As the baryons cool and fall in, their angular momentum causes them to settle into a *rotating disk.*



As the baryons cool and fall in, their angular momentum causes them to settle into a ***rotating disk.***

Though some technical details remain unclear, the angular momentum that galaxy baryons gain via hiearichal clustering is the ***right order of magnitude***.

Working hypothesis for the Hubble sequence

• ***Hierarchical clustering*** generates ***angular momentum*** as neighboring clumps of dark matter+baryons merge on elliptical orbits.

• In ***isolated halos*** that are undisturbed by mergers, baryons cool and sink to form ***rotating disks.*** Baryons with more angular momentum, settle at larger radii. ***The amount of angular momentum determines the radii of disks.***

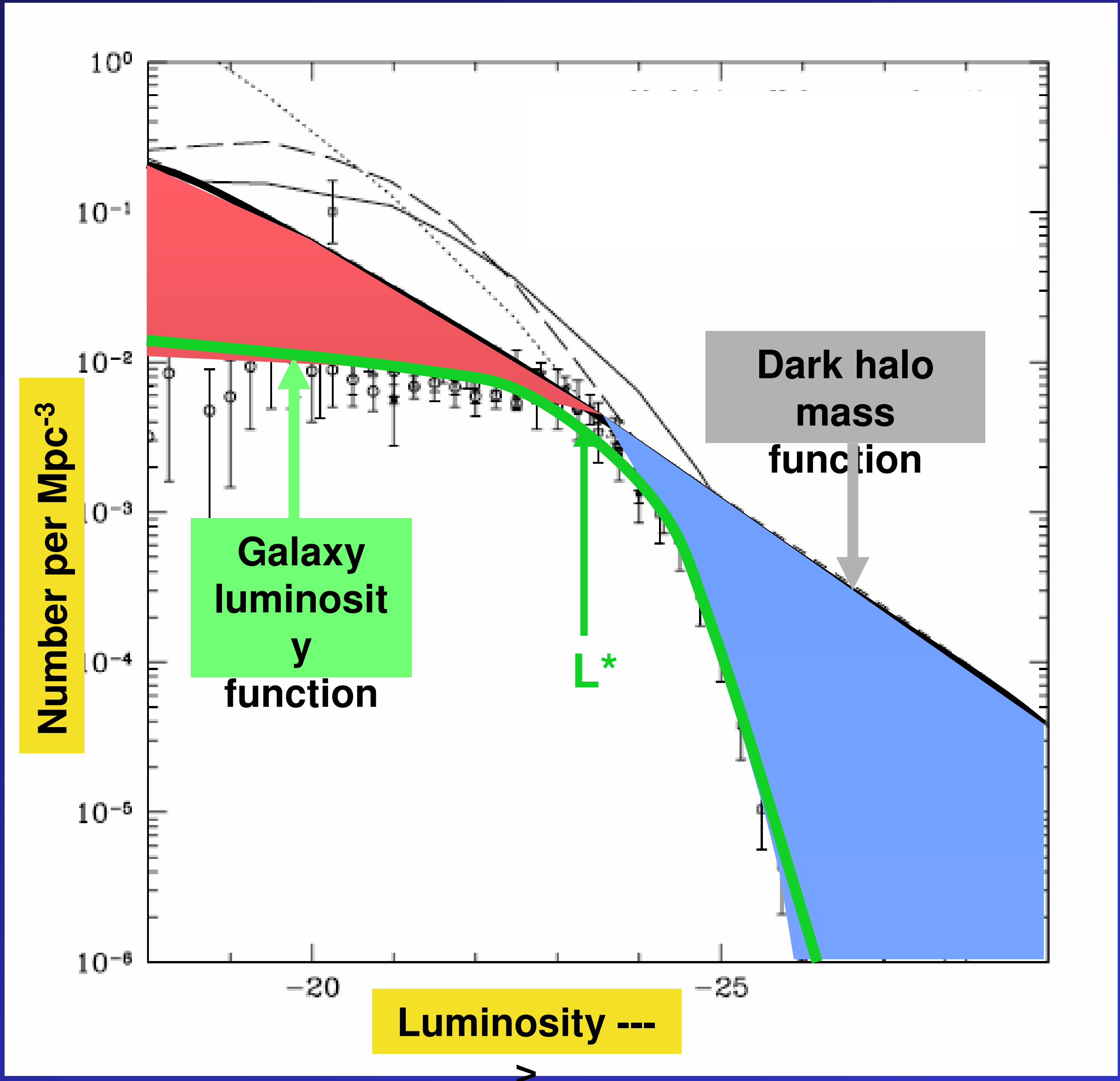
• ***Mergers scatter*** previously formed disk stars to form spheroids.

• The mass of the disk relative to the spheroid reflects ***when the last major merger occurred*** during the history of baryon infall. ***If early,*** most of the baryons fell in quiescently and the resulting galaxy has a ***big disk. If late,*** the previously formed stars were disrupted and the galaxy is ***mostly spheroid*** with little or no disk.

• This picture explains the fact that spheroidal galaxies are found in dense regions where mergers are more frequent, whereas disk galaxies are found in sparse regions where mergers are rare and baryons fall in quiescently.

Understanding galaxies means understanding how baryons fill dark halos.

The number of galaxies *does not match* the number of dark halos



Benson et al. 2003

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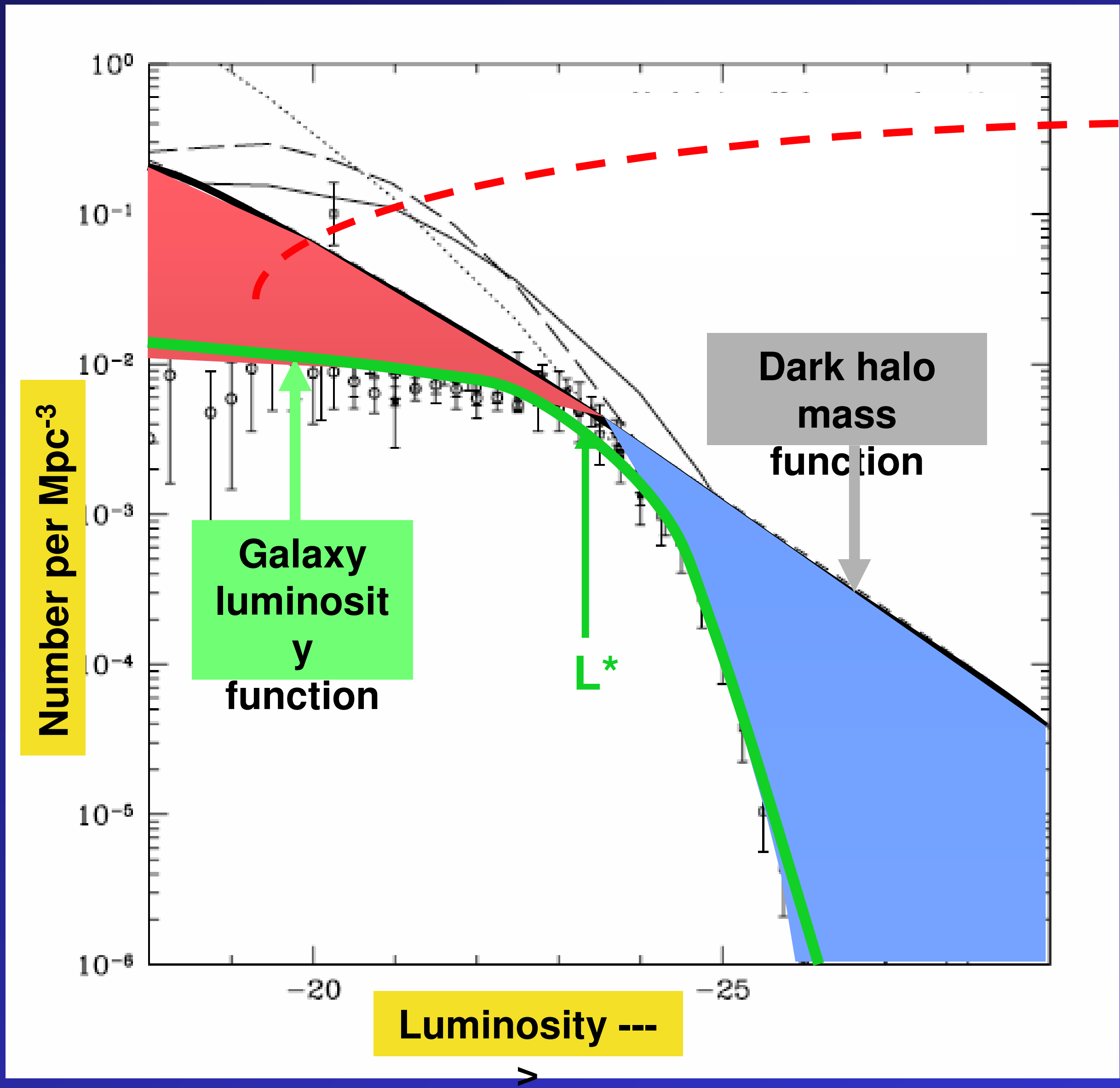


Missing dwarfs

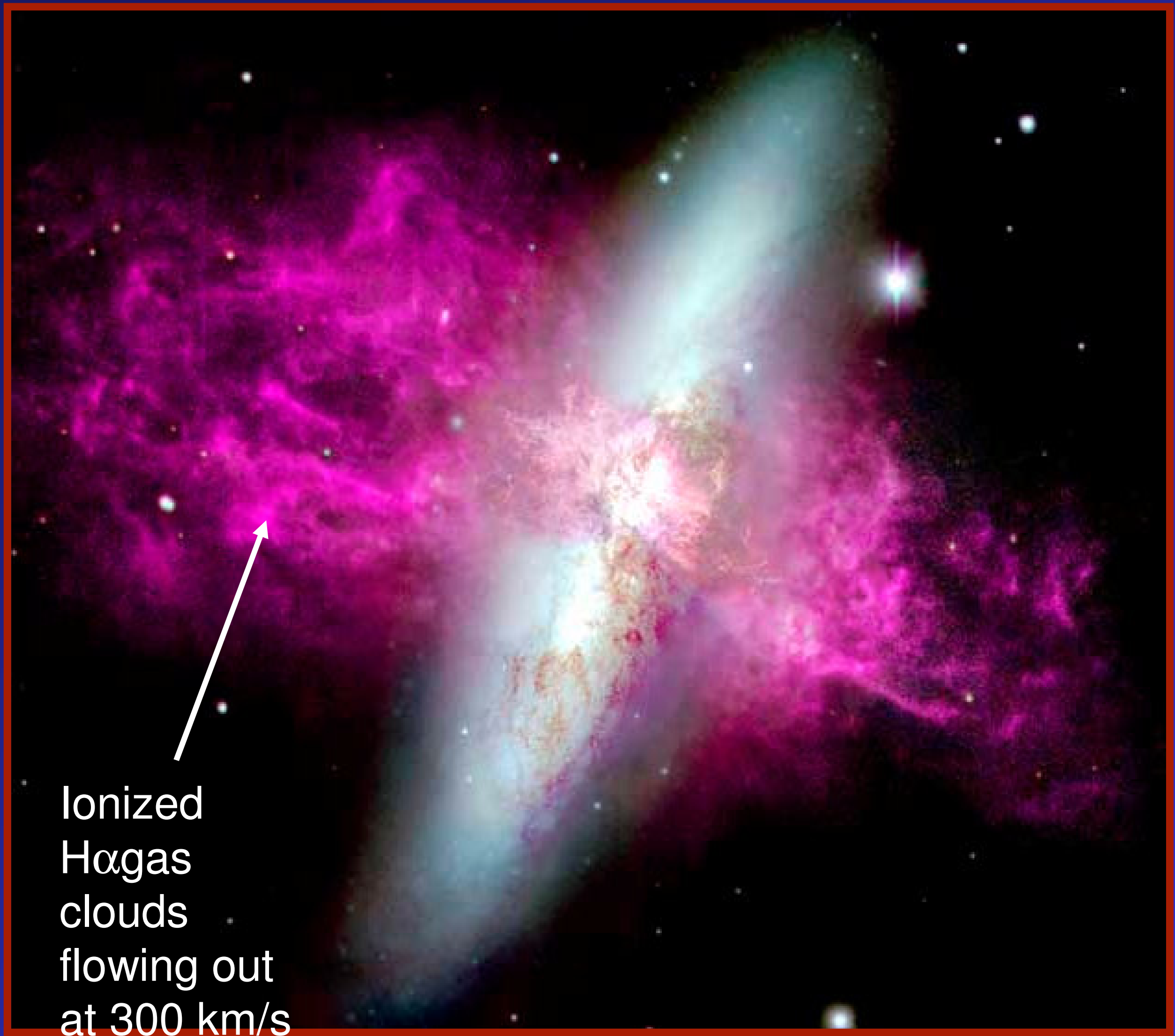
Benson et al. 2003

The predicted *swarm of small satellite galaxies* around the Milky Way

This N-body simulation of dark matter only predicts hundred of small satellite galaxies around large galaxies like the Milky Way. The actual number of galaxies is ***ten times fewer,*** suggesting that ***small dark halos have been swept clean of baryons.***

Kravtsov et al. 2004

Galactic winds can drive gas out of galaxies: an example of ***feedback***



Combined HST+ground-based image of the nearby ***starburst galaxy M82.*** The optical (stellar) galaxy is white. The purple clouds are the glow of Hα emitted by cool clouds near 10^4 K moving at ~300 km/sec.

Starbursts can expel gas from galaxies and perhaps prevent further baryon infall. This is ***easier in small galaxies,*** which have ***shallow potential wells.***

Jay Gallagher, WIYN Telescope, University of Wisconsin

Standard Picture of Infall to a Disc

Rees & Ostriker 77, Silk 77, White & Rees 78, …

Perturbed expansion

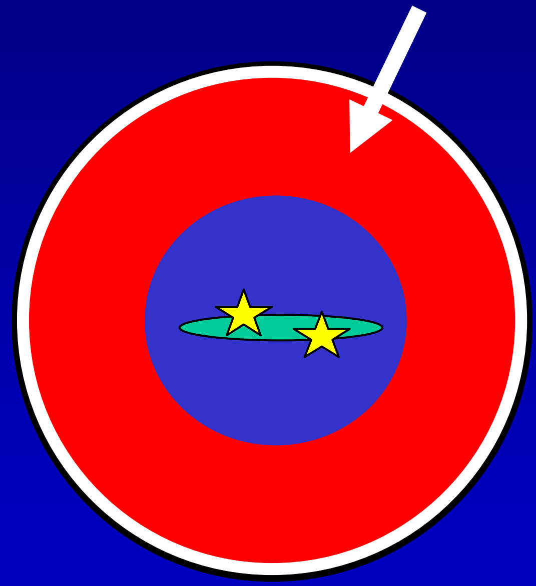
Halo virialization

Gas infall, shock heating at the virial radius

Radiative cooling

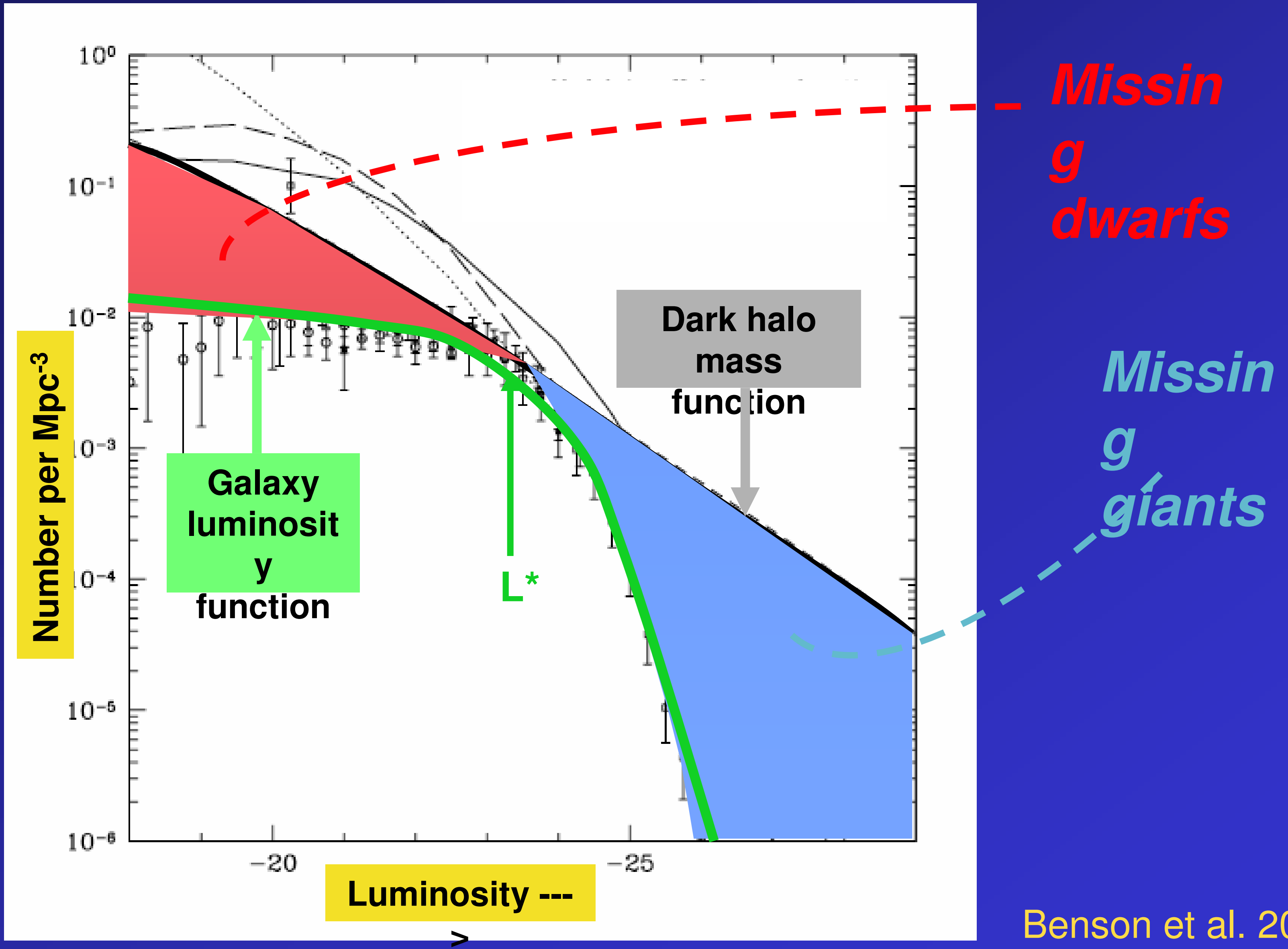
Accretion to disc if $t_{cool} < t_{ff}$

Stars & feedback



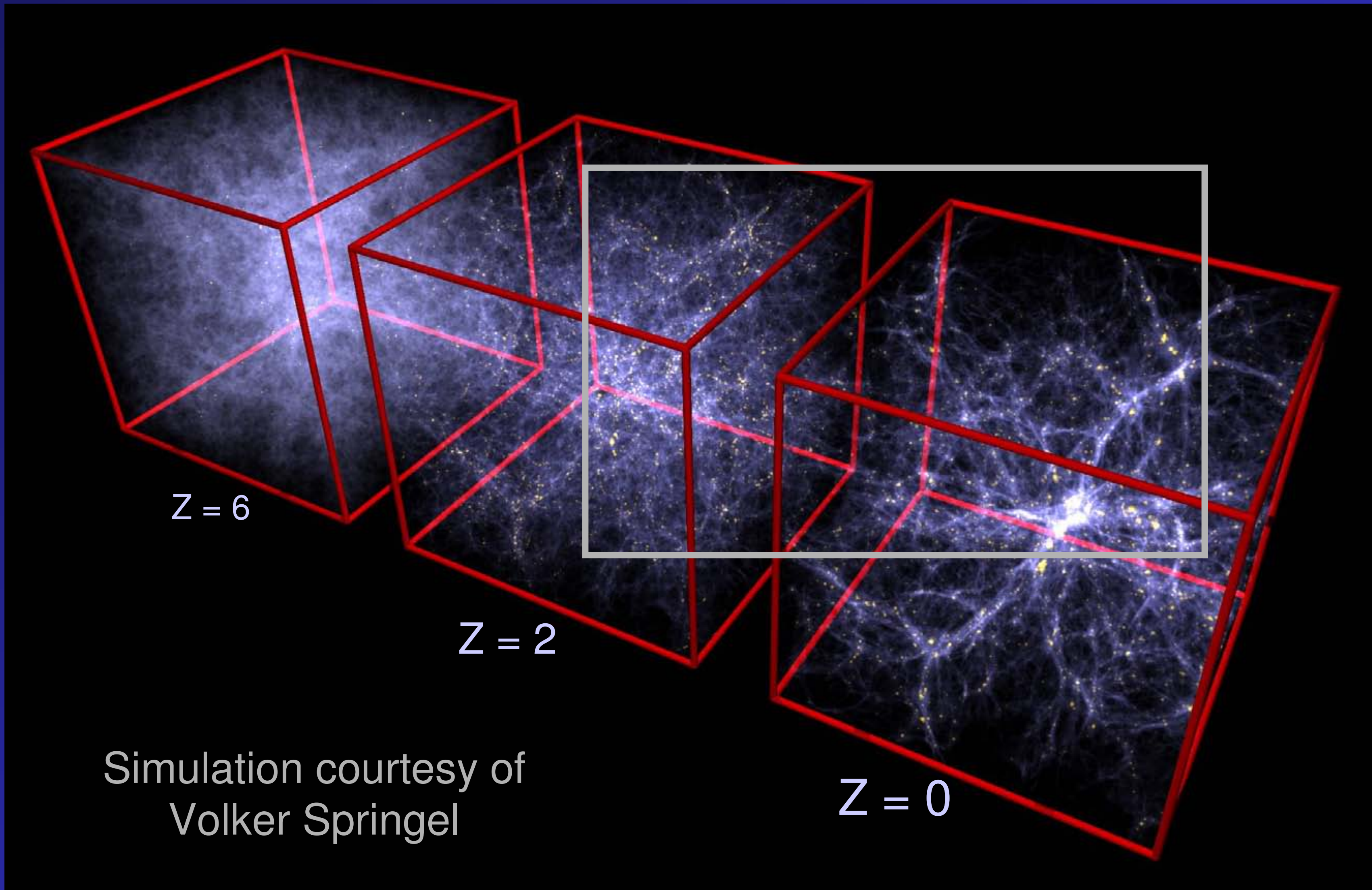
$M < M_{cool} \sim 10^{12-13} M_{\odot}$

The number of galaxies *does not match* the number of dark halos

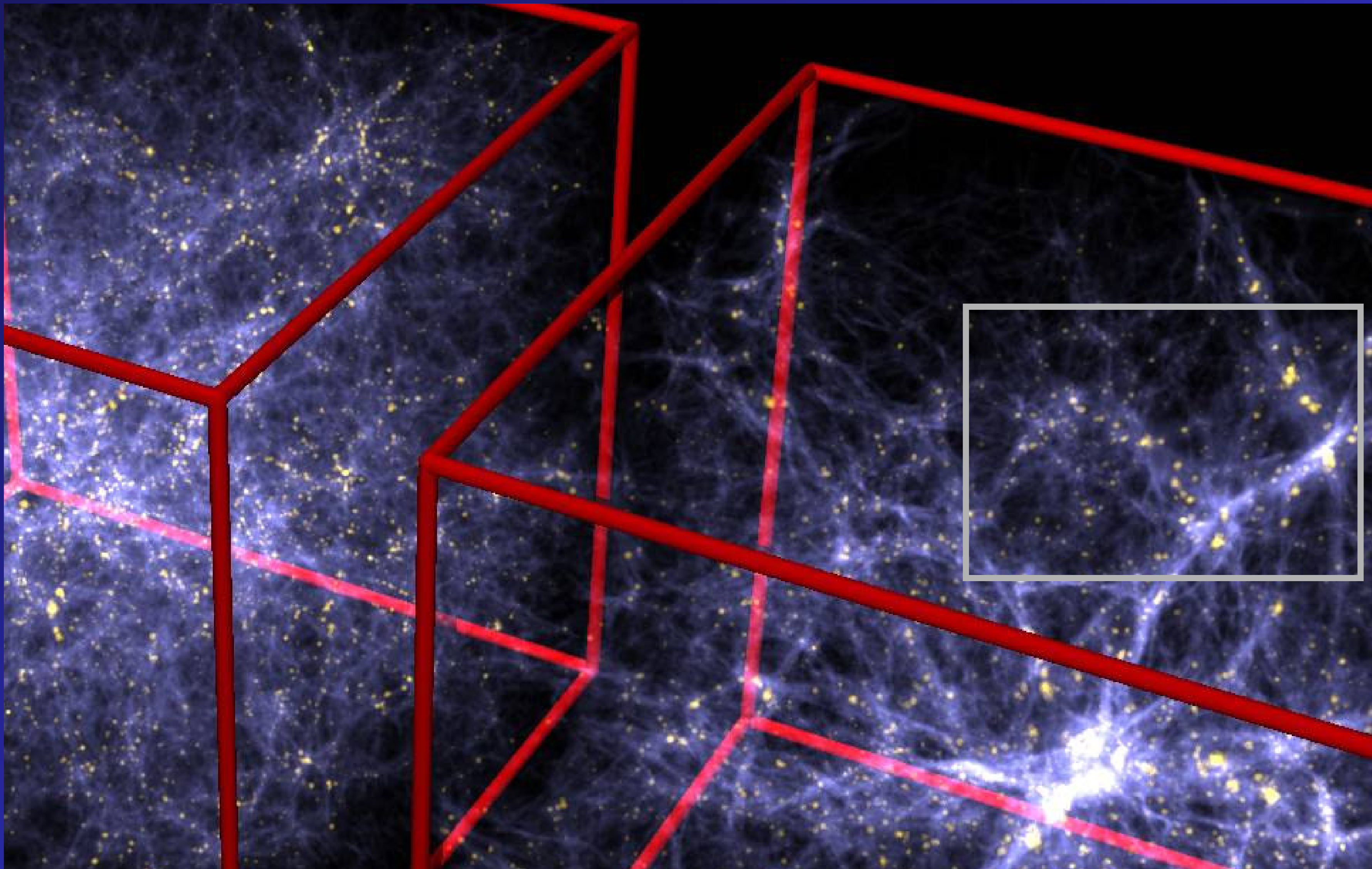


Benson et al. 2003

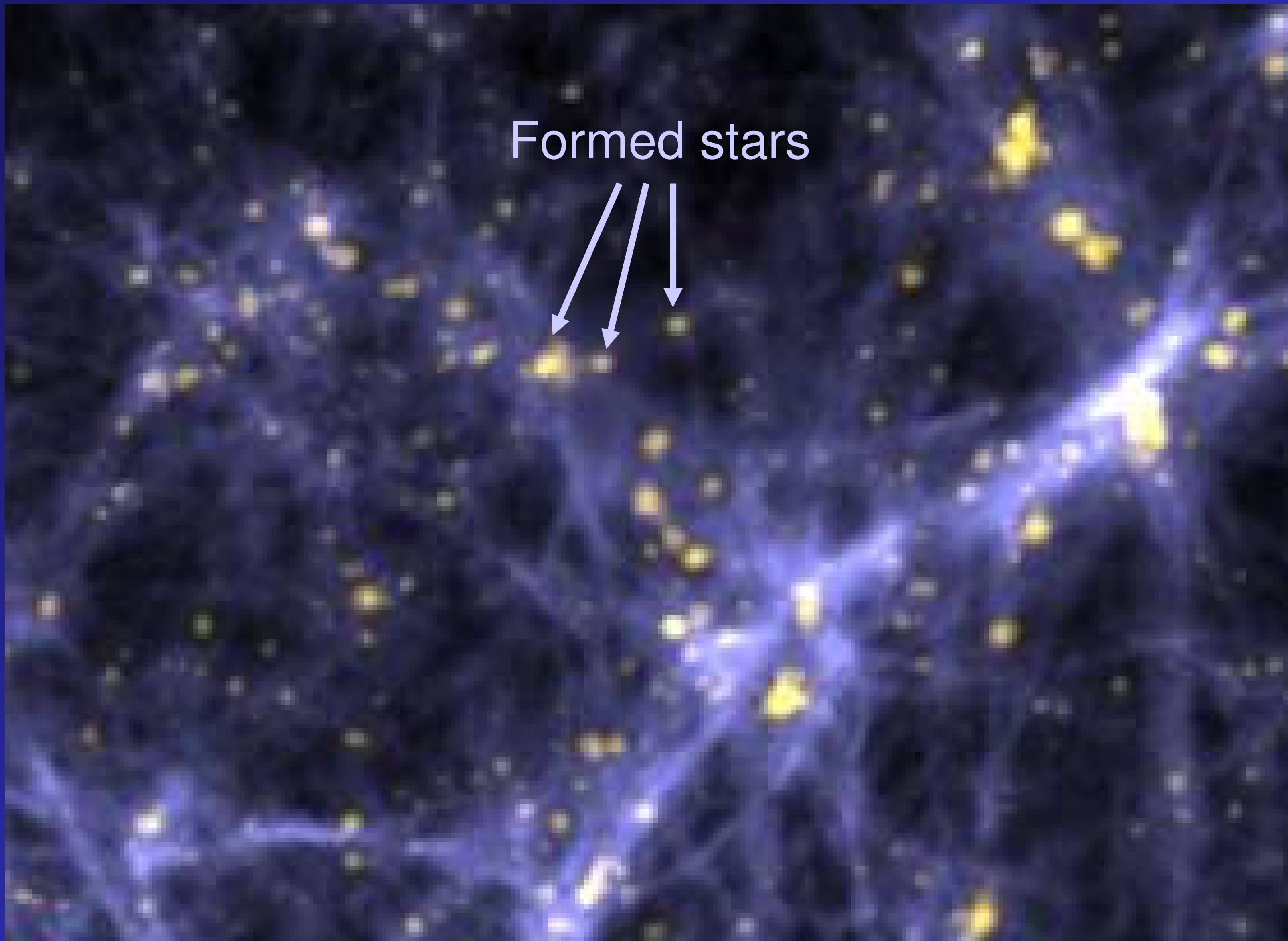
The Baryonic Web



The Baryonic Web



The Baryonic Web



The "lookback effect": an aid to studying galaxy formation

• The light of distant objects is redshifted owing to the expansion of the Universe. The light of farther objects is redshifted more. The ratio of the observed to emitted wavelength is given by:

$$\lambda_o/\lambda_e = (1 + z),$$

where the quantity **z** is termed the ***redshift.***

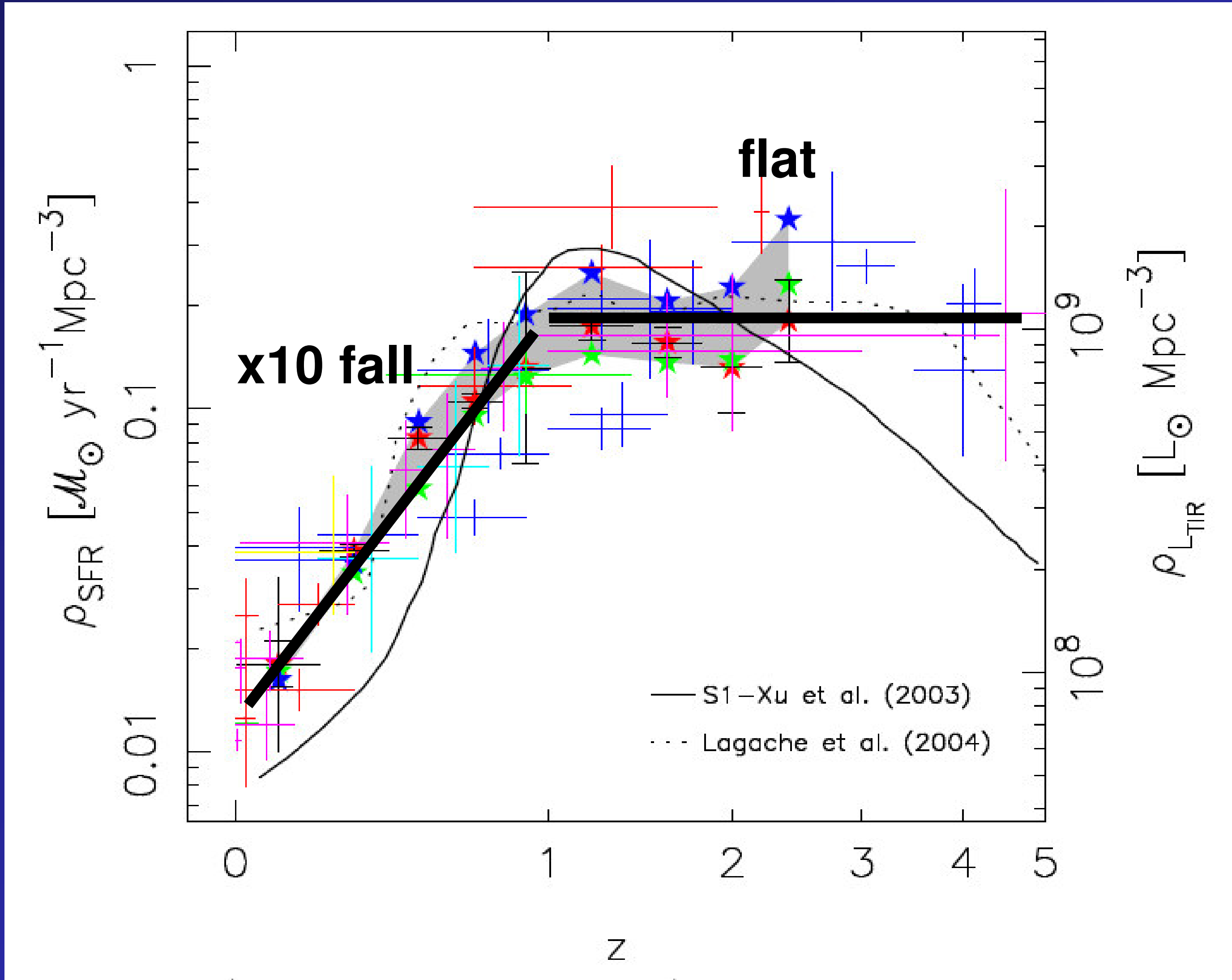
•The ***size of the Universe now*** compared to its size when the light was emitted is also ***(1+z)***.

• ***Redshift is a measure of lookback time,*** owing to the finite speed of light. Since the cosmological model is now tightly constrained, the relationship between redshift and epoch is well established (see Ned Wright's website http://www.astro.ucla/edu/~wright/CosmoCalc.html for a handy cosmology calculator). Here is a table of representative values, with times in Gyr:

z	time from Big Bang	lookback time
0.5	8.4	5.0
1.0	5.7	7.7
2.0	3.2	10.2
3.0	2.1	11.4
5.0	1.2	12.3
10.0	0.5	13.0

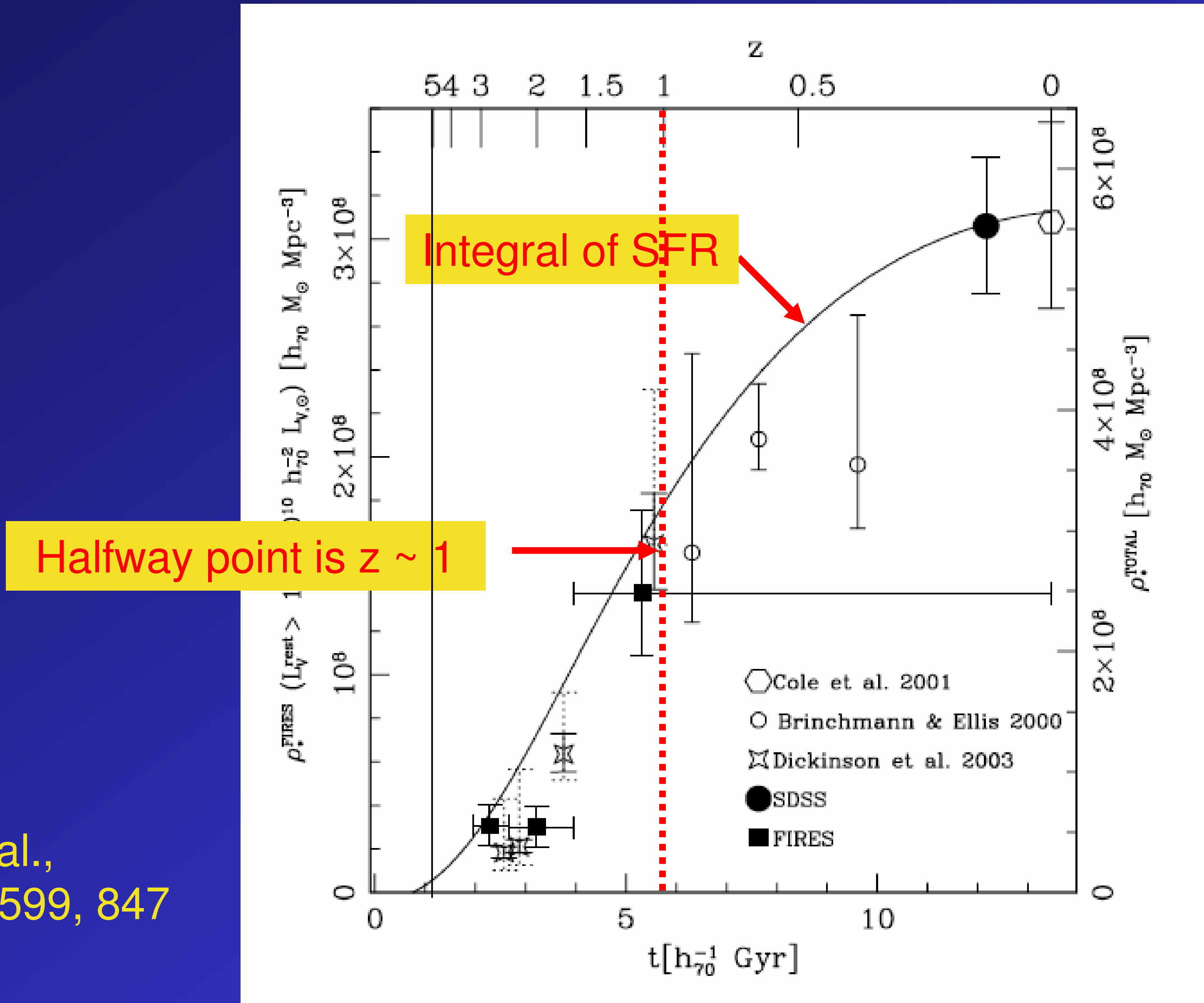
• Observing with large telescopes allows us to look far out in space, and therefore back in time. ***We can make a "cosmic movie" of the formation of structure in the Universe by combining snapshots of galaxies and other data at different epochs.*** When our theory of structure formation is correct, all snapshots will fit properly together. This is the ultimate test of theory.

The star-formation history of the Universe



Current version of the "Madau diagram" from Perez-Gonzalez et al. 2005

The build-up of stellar mass versus time



Rudnick et al.,
2003, ApJ, 599, 847