Galaxy Formation

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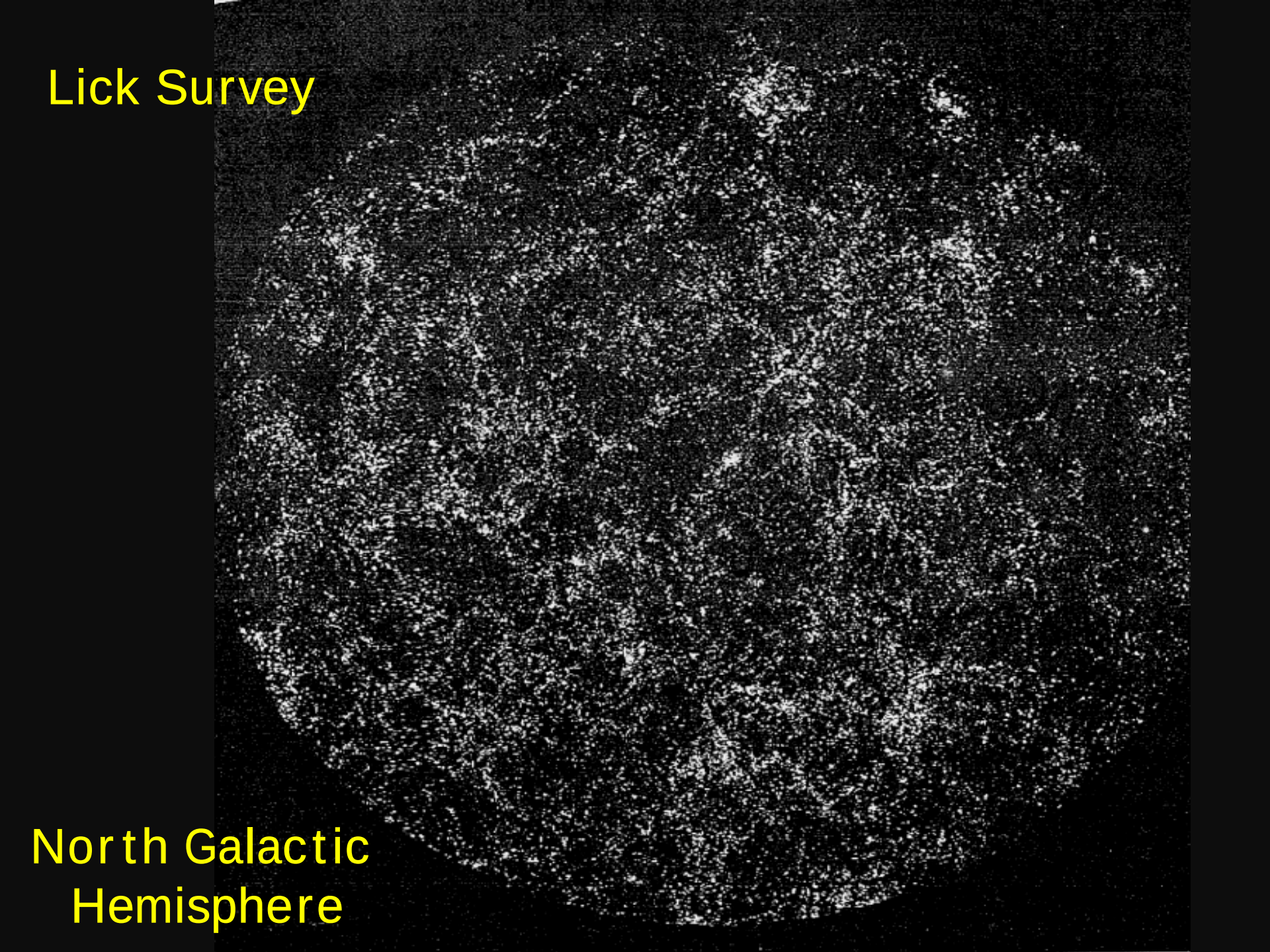
SLAC, summer 2003

Outline

1. large-scale structure
2. dark halos: collapse & mergers
3. luminous galaxies in dark halos
4. puzzles in galaxy formation

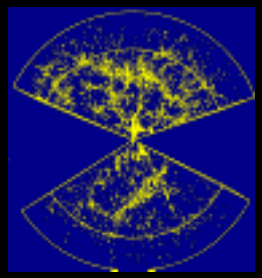
1. Large-Scale Structure


Lick Survey
North Galactic
Hemisphere

2dF Galaxy Redshift Survey
¼ M galaxies 2003

1/4 of the horizon

CFA Survey
1980



The Cosmological Model

Nearly flat: $\Omega_{\text{tot}} = 1.02 \pm 0.02$

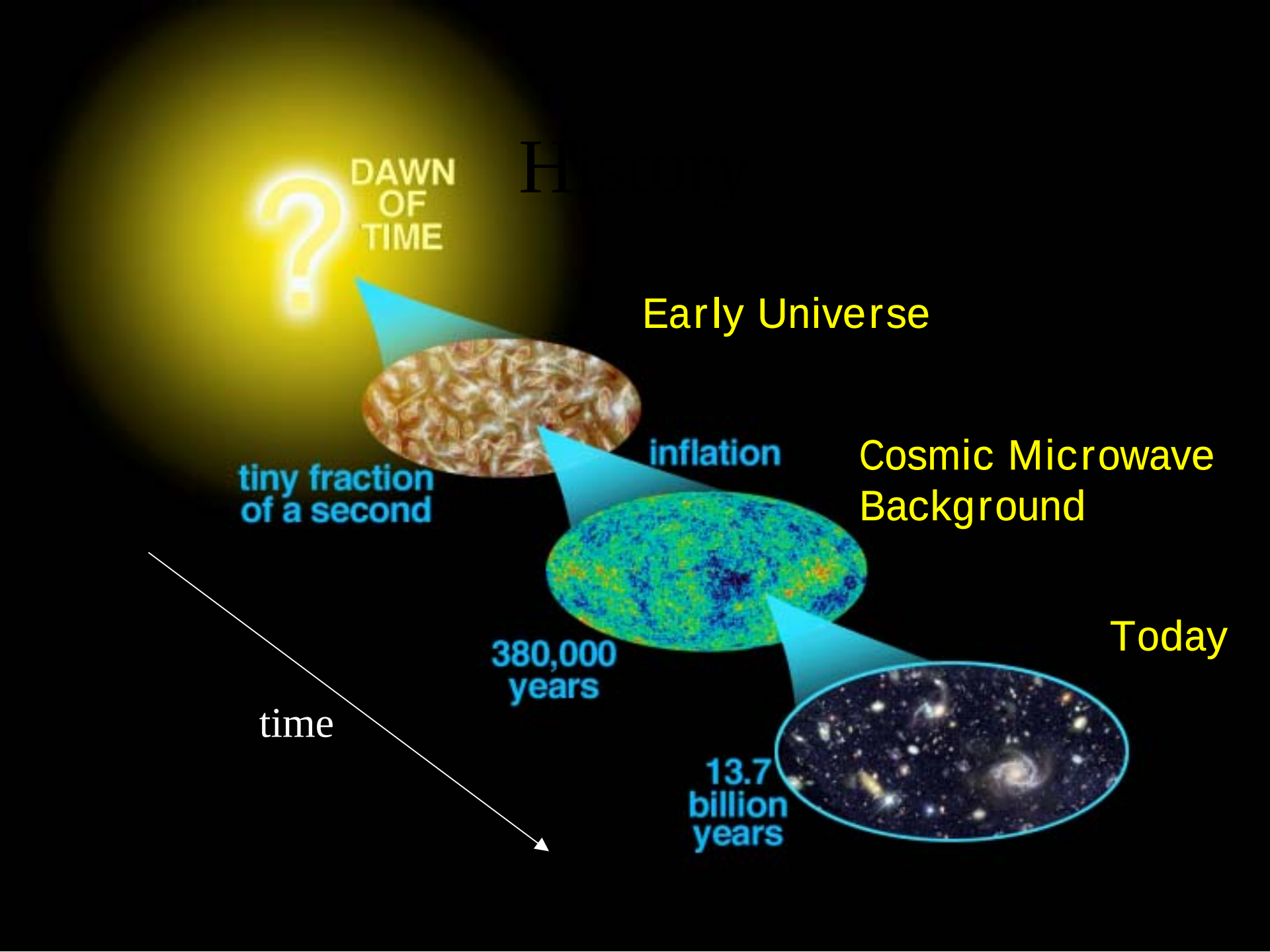
but a bizzare mixture:

$$\Omega_{\text{luminous}} \approx 0.01$$

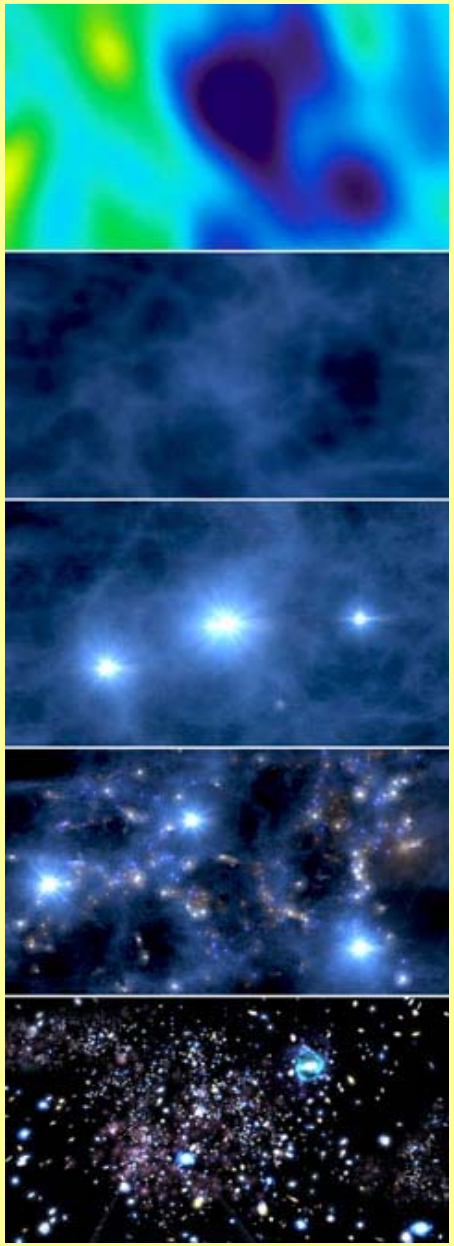
$$\Omega_{\text{baryons}} = 0.044 \pm 0.004$$

$$\Omega_{\text{mass}} = 0.30 \pm 0.05$$

$$\Omega_{\Lambda} = 0.70 \pm 0.05$$


DAWN
OF
TIME
Early Universe
inflation
tiny fraction
of a second
Cosmic Microwave
Background
380,000
years
Today
time
13.7
billion
years

Late Cosmological Epochs



380 kyr z~1000

recombination
last scattering

dark ages

180 Myr z~20

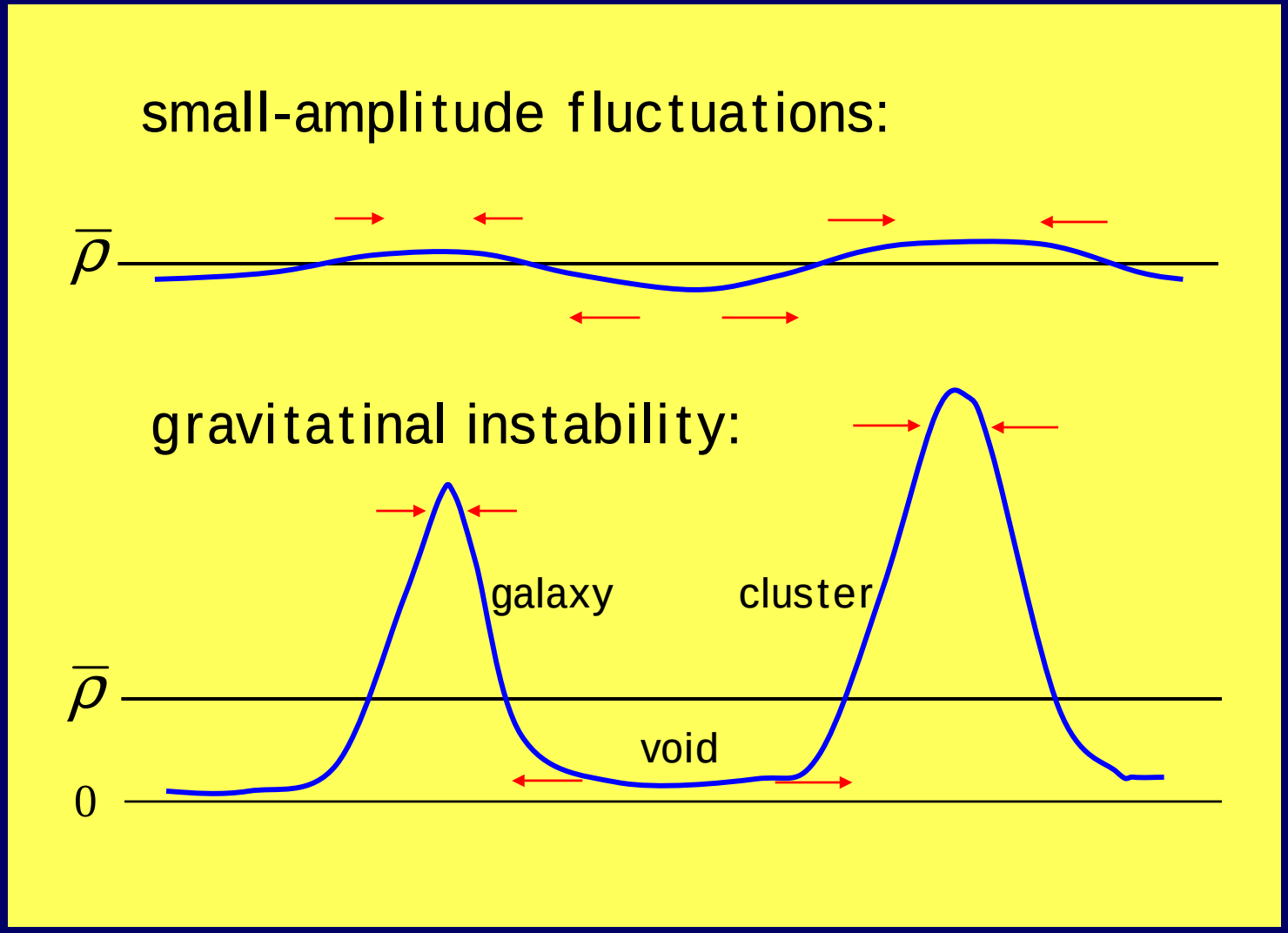
first stars
reionization

galaxy formation

13.7 Gyr z=0

today

Gravitational instability



Gravitational Instability

Small fluctuations: $\delta, v, \varphi \quad (x,t)$ comoving coordinates

$r = a(t)x$ etc.

$H \equiv \dot{a}/a, \quad \Omega(t)$

matter era

Continuity: $\dot{\delta} + \nabla \cdot v + \nabla \cdot (v\delta) = 0$

Euler: $\dot{v} + 2Hv + (v \cdot \nabla)v = -\nabla\varphi$

Poisson: $\nabla^2 \varphi = (3/2)H^2 \Omega \delta$

Linear approximation: $\ddot{\delta} + 2H\dot{\delta} = (3/2)H^2 \Omega \delta$

growing mode: $\delta \propto D(t) = t^{2/3} \xrightarrow[\Omega_m \to 0]{} t^0$

$\delta = -\nabla \cdot v / [Hf(\Omega)]$ $\quad f(\Omega) \equiv \dot{D}/(HD) \approx \Omega^{0.6}$

irrotational, potential flow: $\nabla \times v = 0 \quad v = -\nabla \varphi_v$

The Initial Fluctuations

At Inflation: Gaussian, adiabatic

Fourier transform:

$$\delta(\vec{x}) = \sum_{\vec{k}} \delta_{\vec{k}}\ e^{i\vec{k}\cdot\vec{x}}$$

Power Spectrum:

$$P(k) \equiv <|\ \tilde{\delta}(\vec{k})\ |^2> \ \propto k^n$$

rms perturbation:

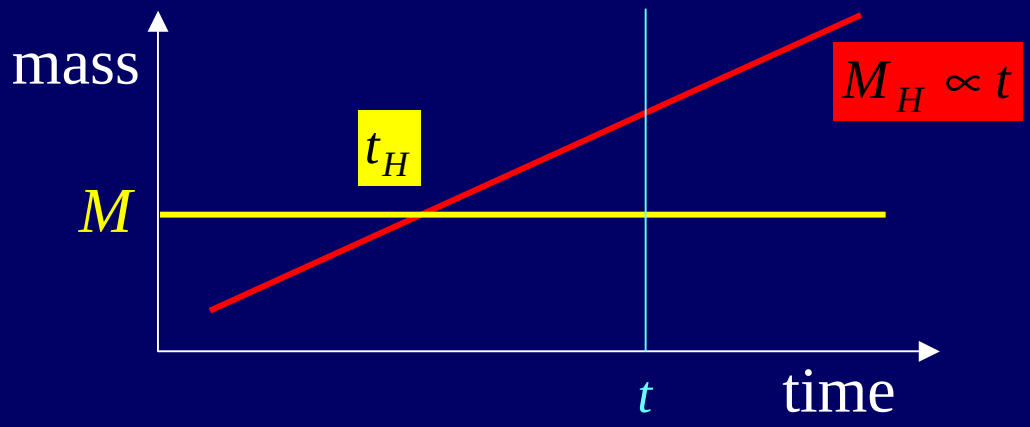
$$\delta_{rms} = <\delta^2>^{1/2} \propto \int_{k=0}^{k_{\max}} P_k\ d^3k \quad \propto M^{-(n+3)/6}$$

Correlation function:

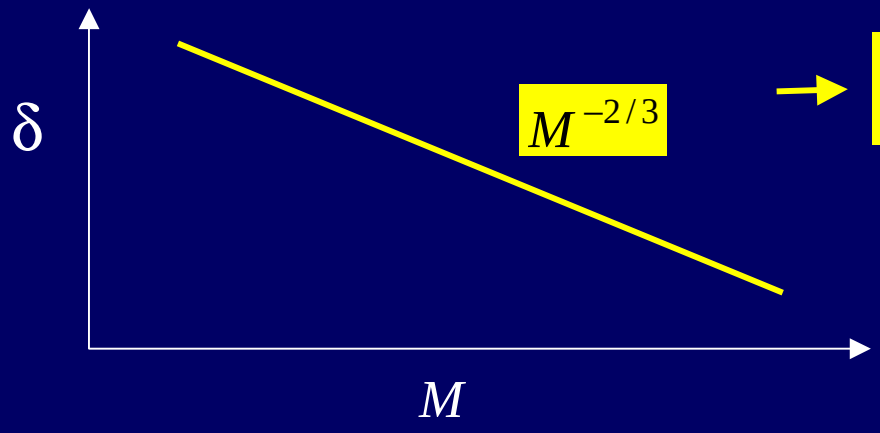
$$\xi(r) \equiv <\delta(\vec{x})\delta(\vec{x}+\vec{r})> \ \propto \int |\ \tilde{\delta}(\vec{k})\ |^2\ e^{-i\vec{k}\cdot\vec{r}}\, d^3k \ \propto r^{-(n+3)}$$

$$dP = [1+\xi(r)]\, n\, dV$$

Scale-Invariant Spectrum (Harrison-Zel'dovich)

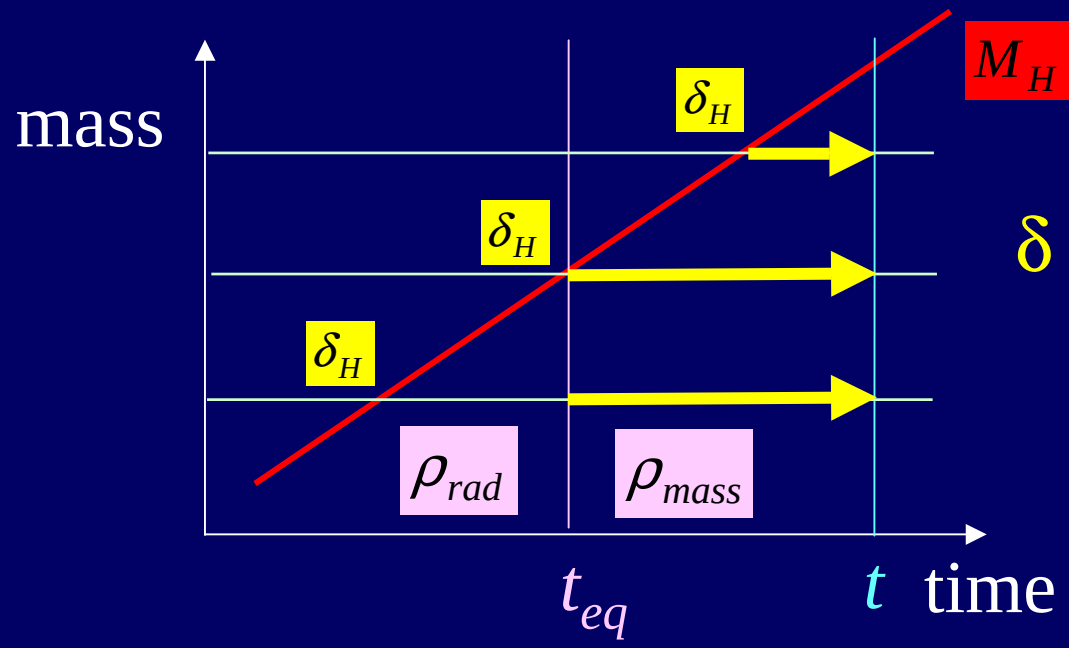


$$\delta(M,t) = \delta_H \left(\frac{t}{t_H(M)} \right)^{2/3} \propto M^{-2/3} t^{2/3}$$

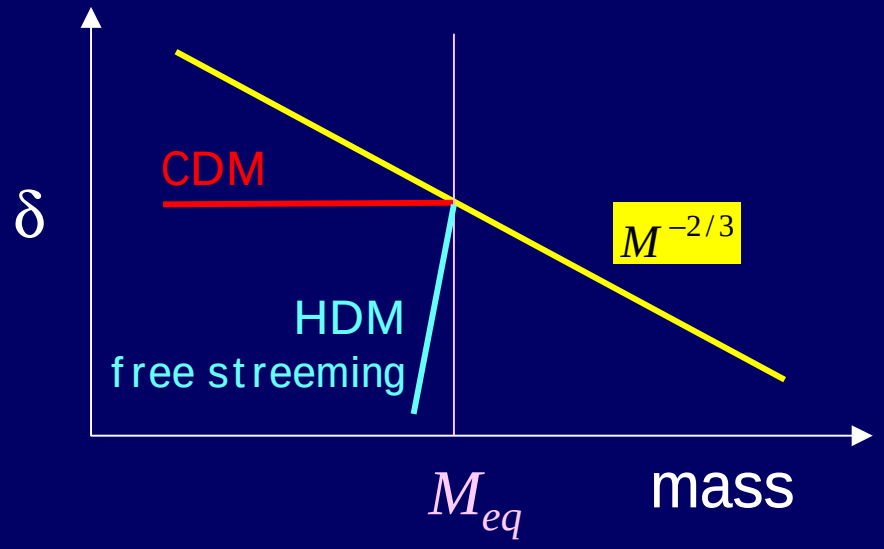


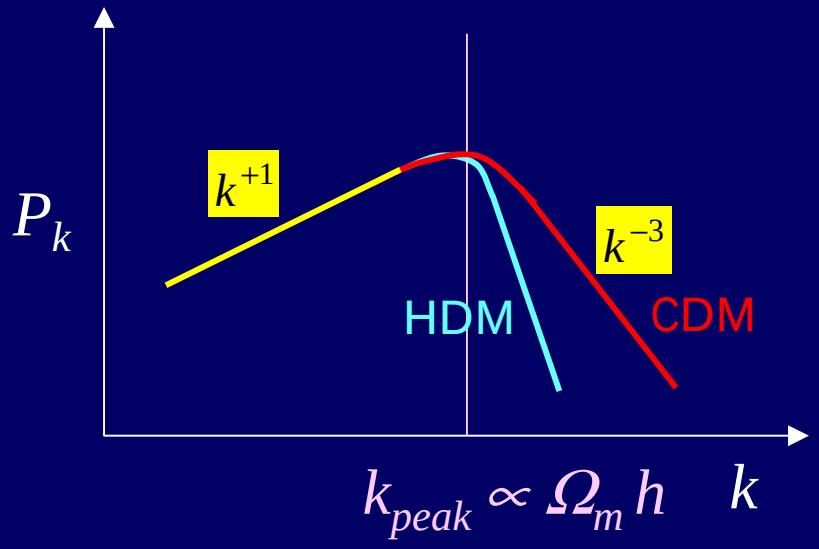
$$\rightarrow \quad n = +1 \quad P_k \propto k$$

CDM Power Spectrum



δ Growth when matter is self-gravitating

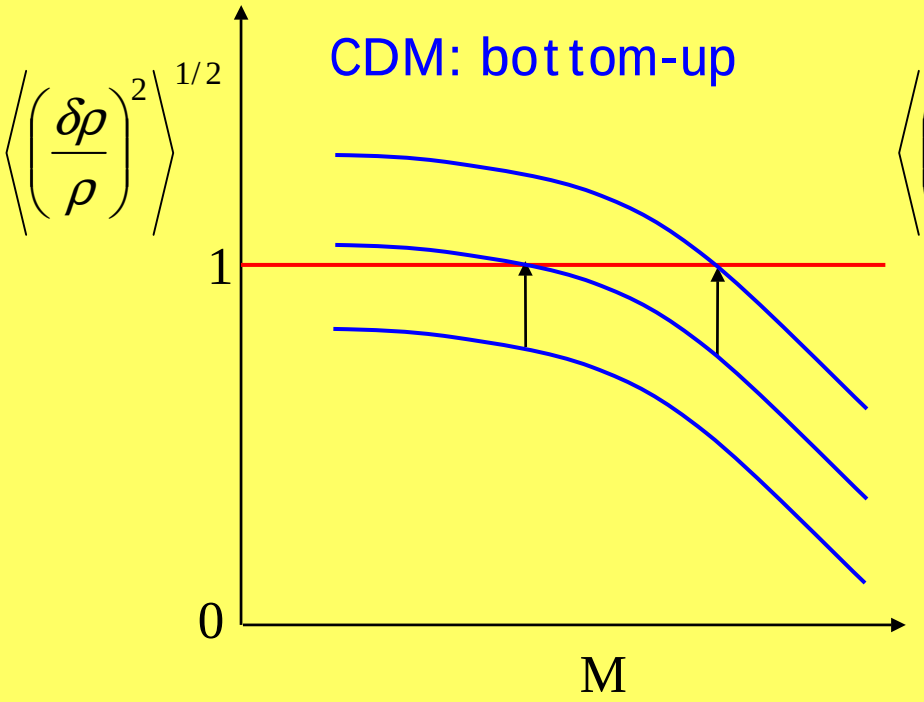


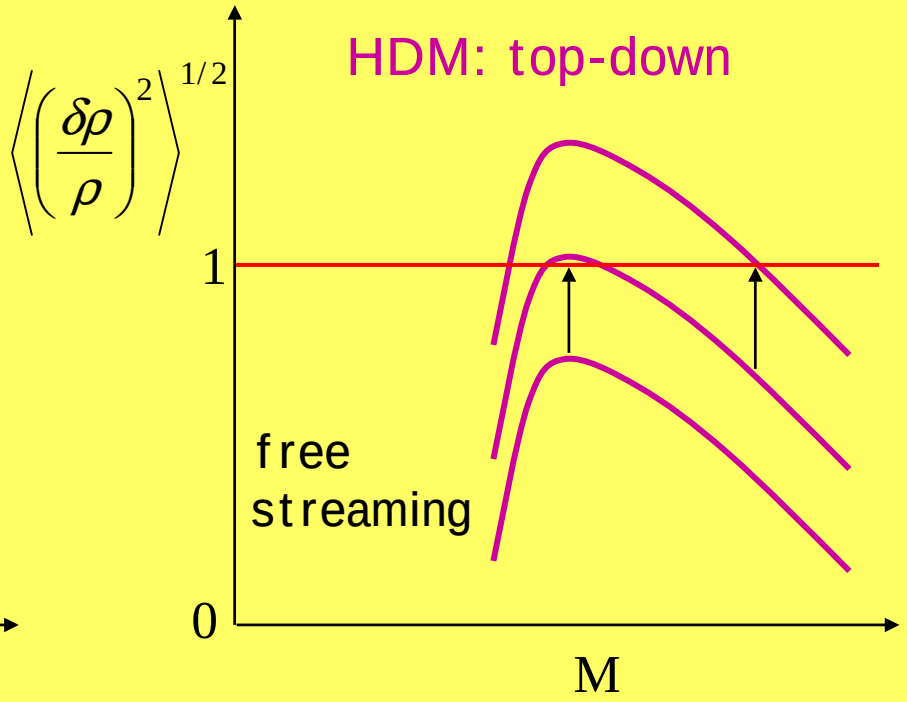


Formation of Large-Scale Structure

Fluctuation growth in the linear regime: $\delta << 1 \quad \rightarrow \quad \delta \propto t^{2/3}$

rms fluctuation at mass scale M: $\delta \propto M^{-\alpha} \quad 0 < \alpha \leq 2/3$





Filamentary Structure: Zel'dovich Approximation

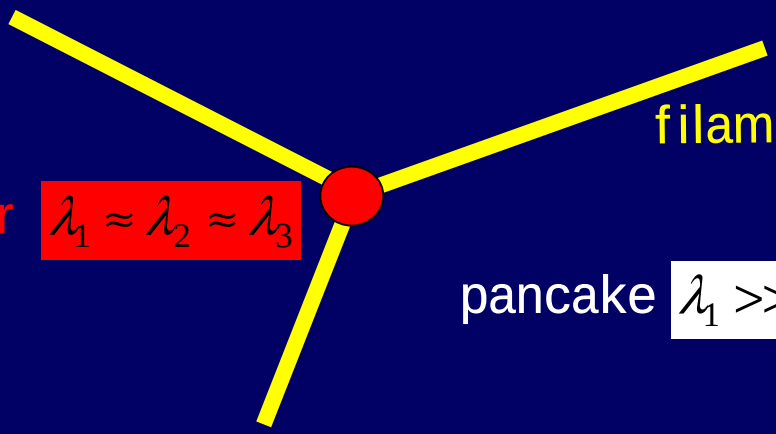
displacement from initial position: $x(q,t) = q - D(t)\,\nabla\phi(q)$

continuity: $\rho(x,t)\,d^3x = \rho_q d^3q \quad \rightarrow$

$$\rightarrow \rho(x,t) = \rho_q \,/\, \| \partial\vec{x} / \partial\vec{q} \,\|$$

$$= \frac{\rho_q}{(1-D(t)\lambda_1)(1-D(t)\lambda_2)(1-D(t)\lambda_3)}$$

eigenvalues of deformation tensor: $\lambda_i \equiv \frac{\partial^2\phi}{\partial^2 q_i}, \quad \lambda_1 \geq \lambda_2 \geq \lambda_3$

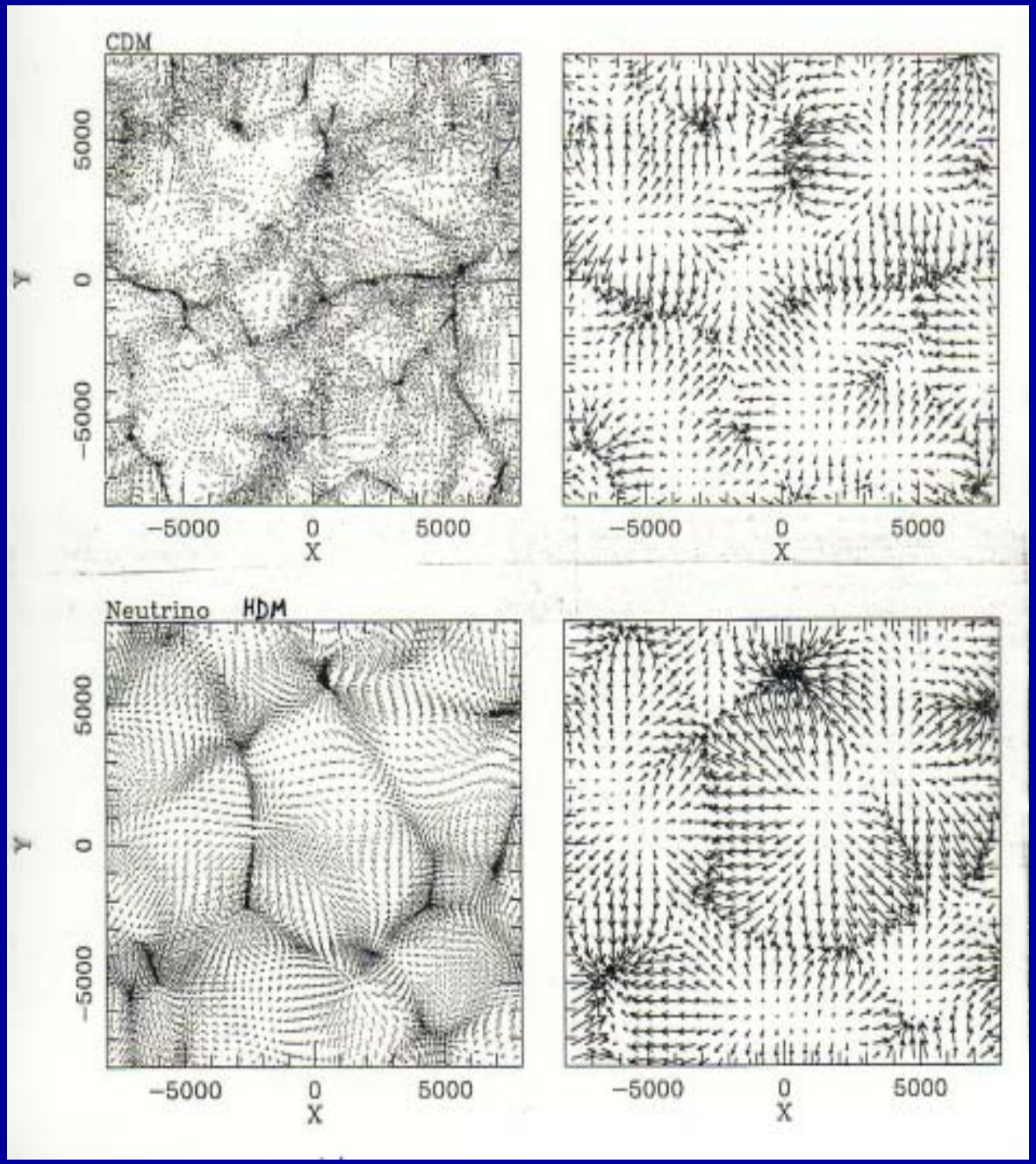


Micro-Macro Connection

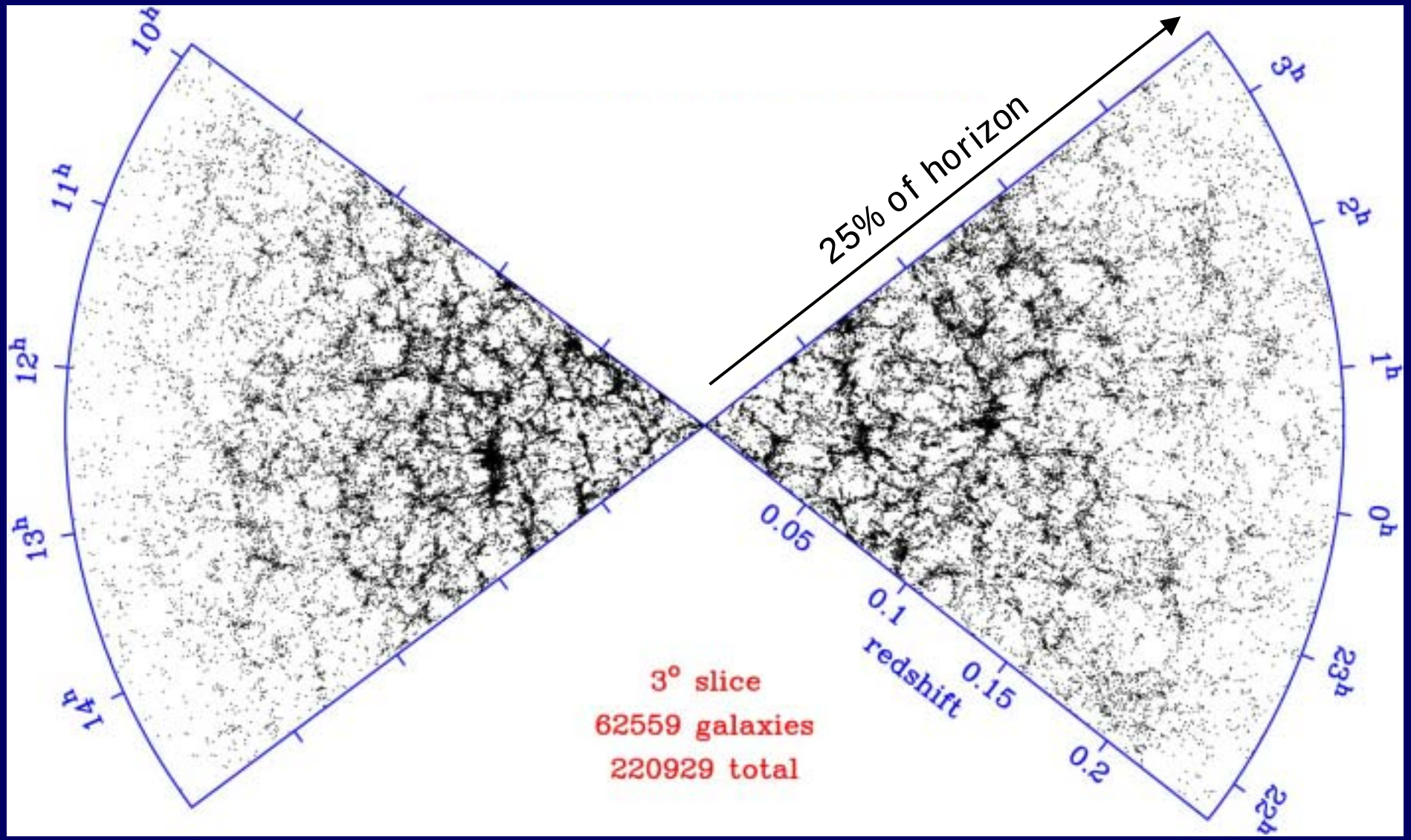
Cold Dark Matter

Hot Dark Matter

ν

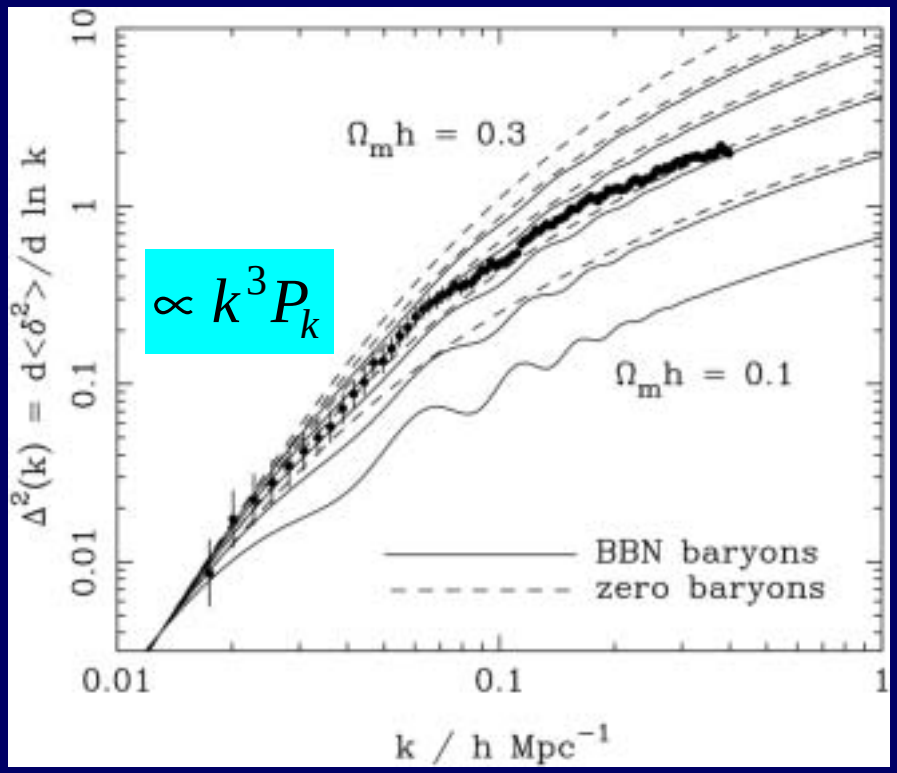


2dF redshift survey



Measuring Ω_m from the 2dF Survey

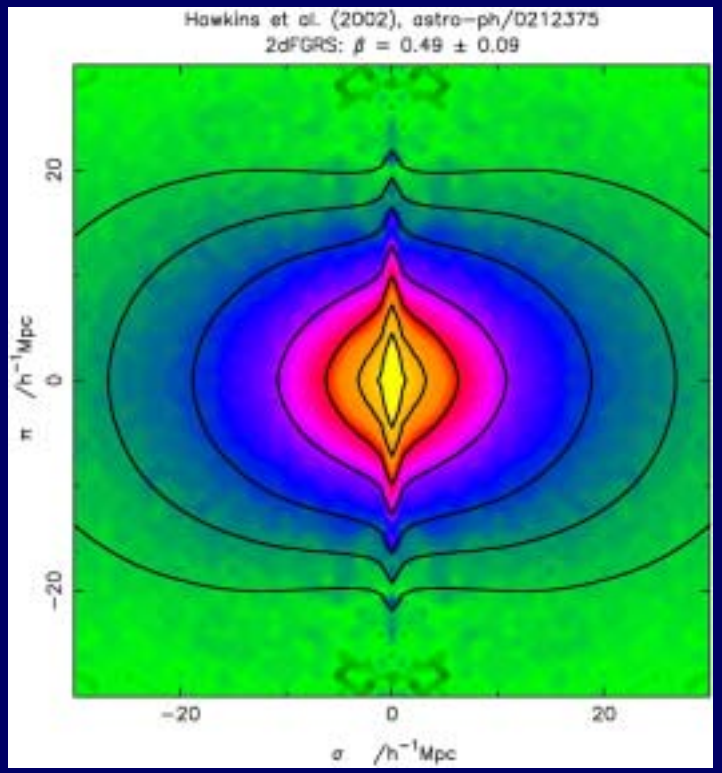
power spectrum



$\propto k^3 P_k$

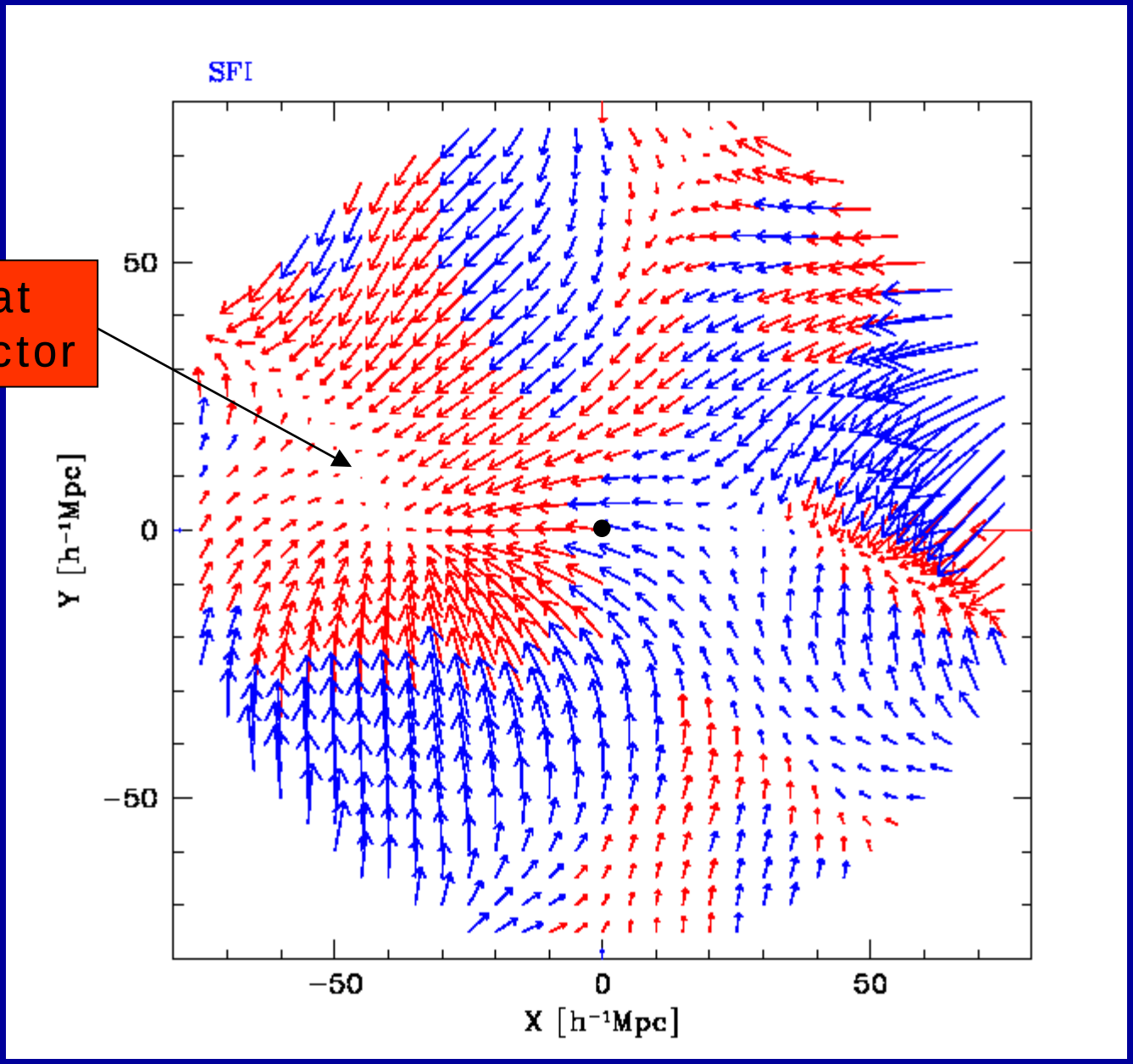
$\Omega_m h \approx 0.2 \quad \rightarrow \Omega_m \approx 0.3$

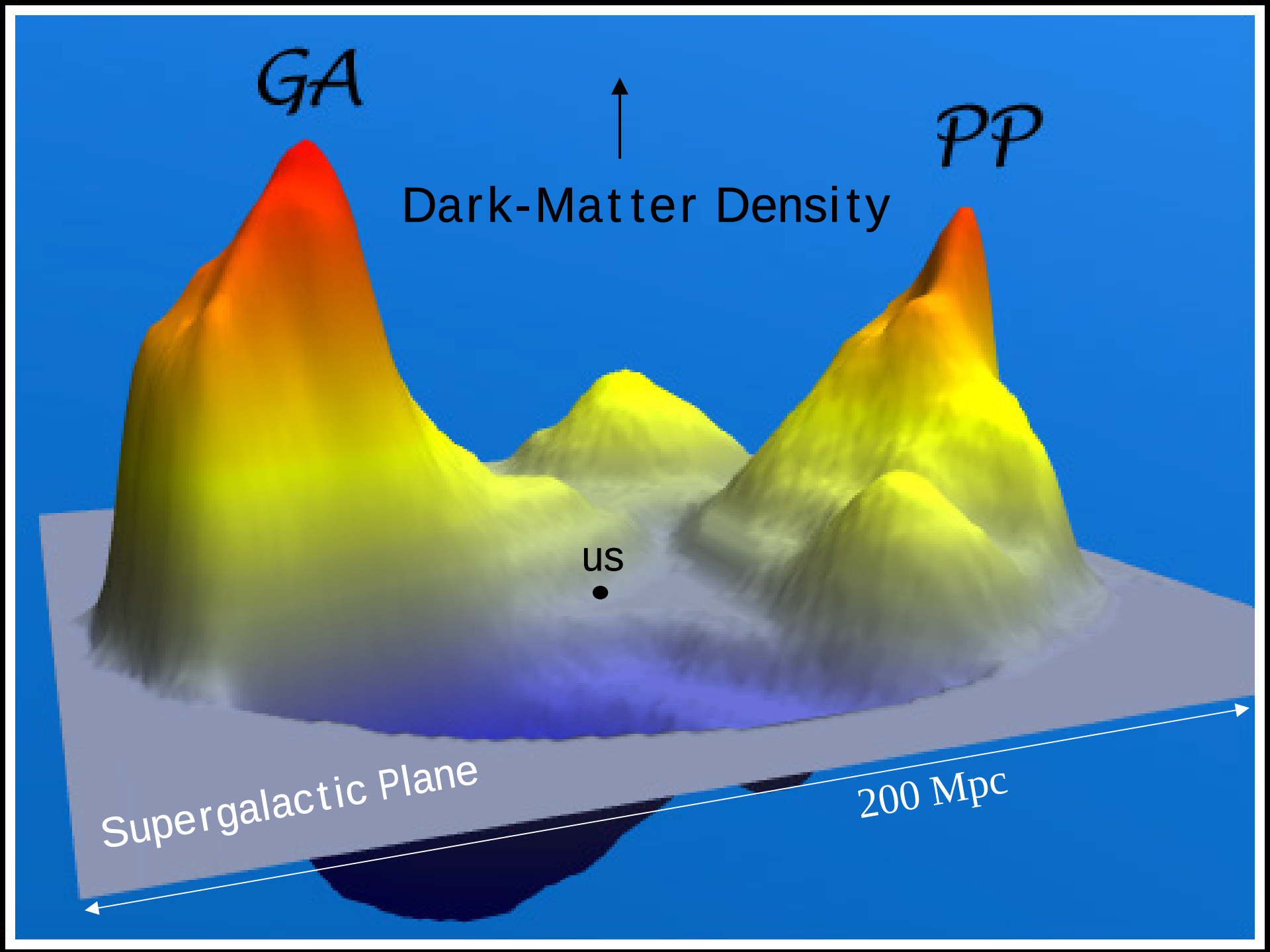
2D correlation function anisotropy in z-space



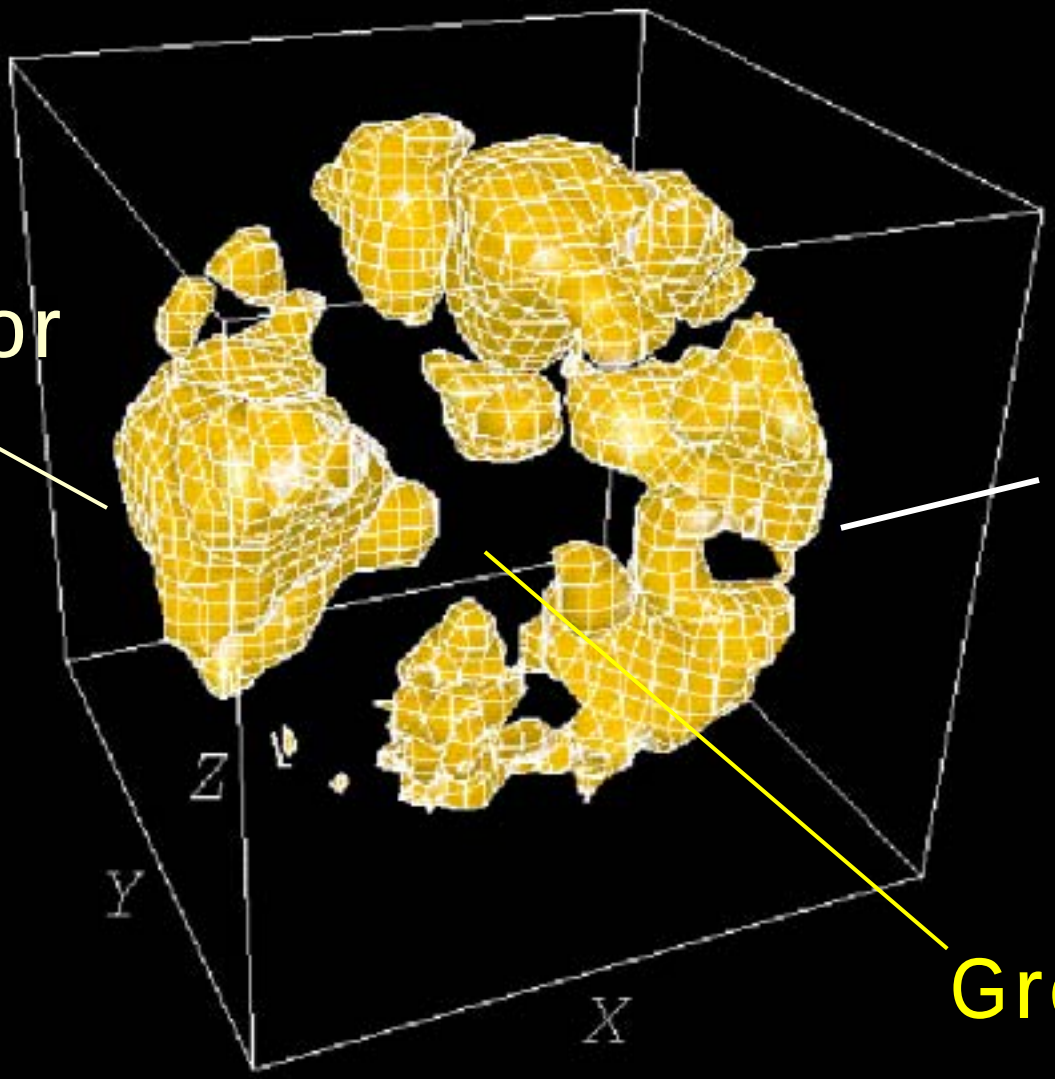
$\Omega_m^{0.6} \approx 0.5 \pm 0.1 \quad \rightarrow \Omega_m \approx 0.3$

Cosmic Flows - POTENT




GA
PP
Dark-Matter Density
us
Supergalactic Plane
200 Mpc

Mass Density in 3D



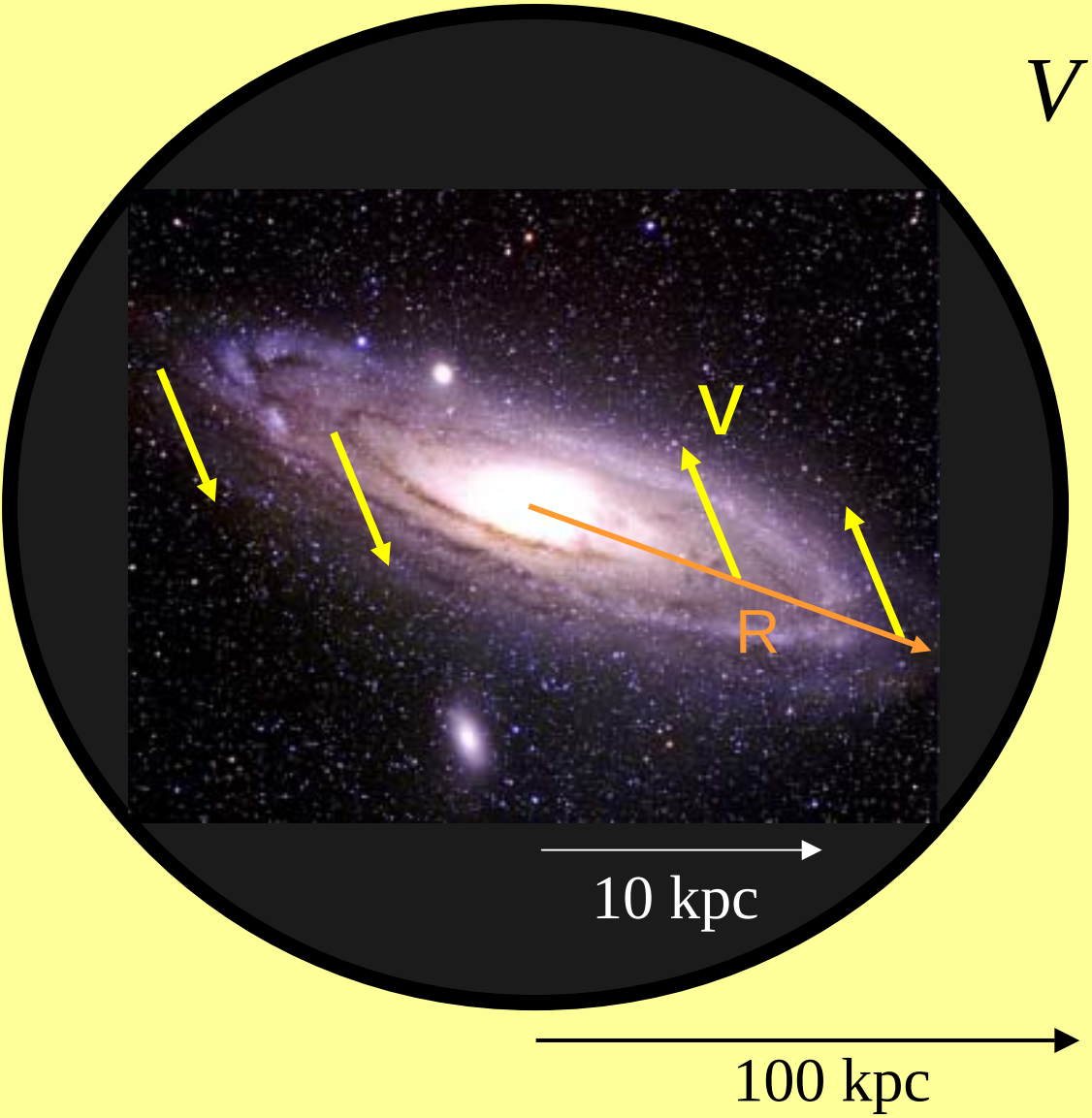
Great Attractor

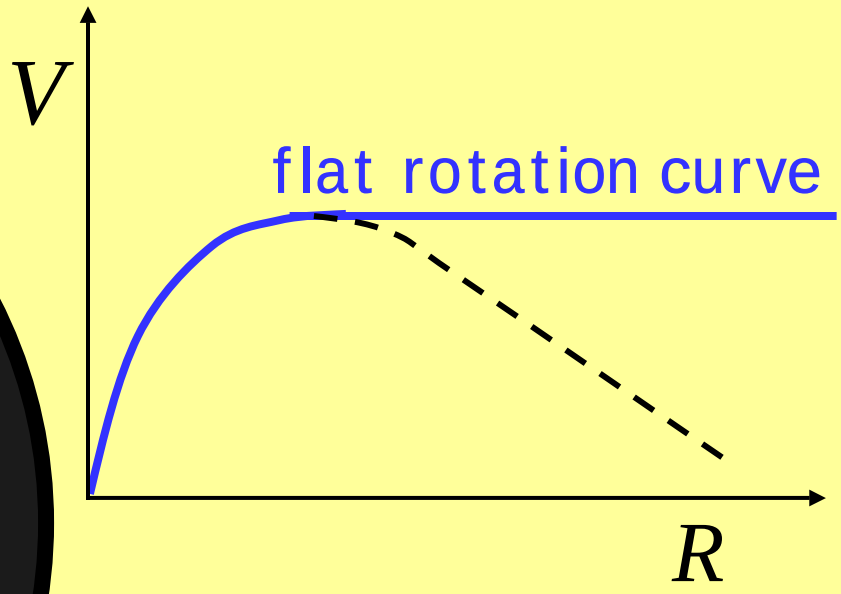
Perseus Pisces

Great Void

2. Dark Halos: Collapse & Mergers

Dark Halos

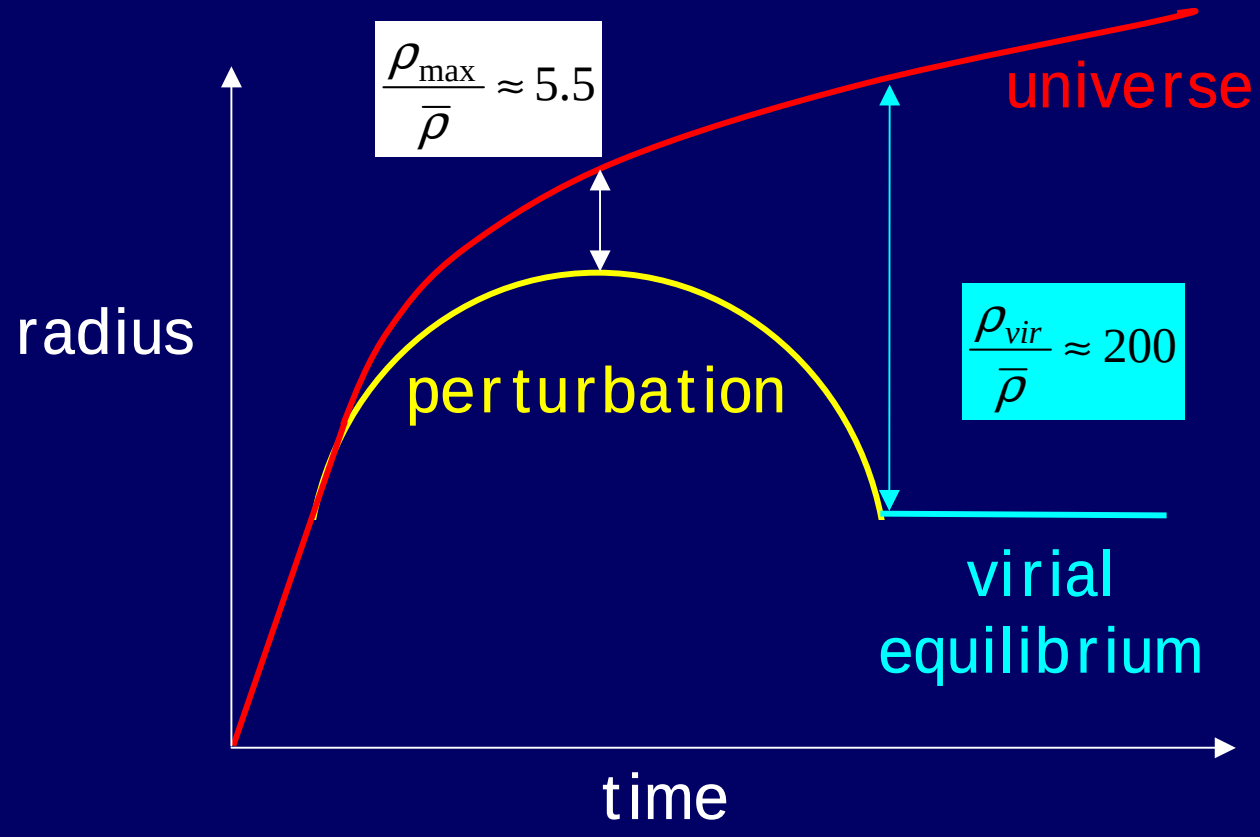




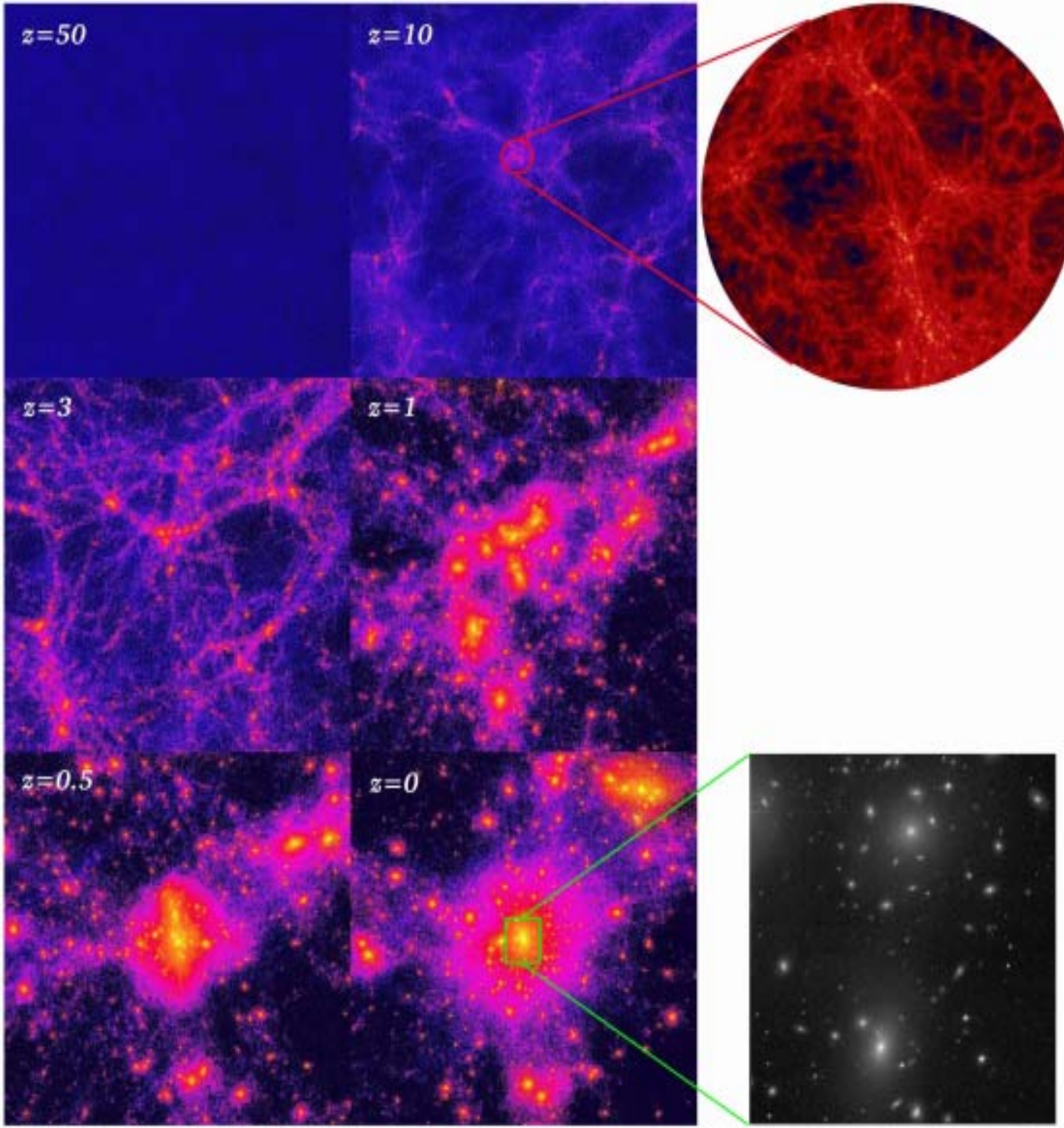
$$V^2 = \frac{GM}{R}$$

$$M(R) \propto R$$

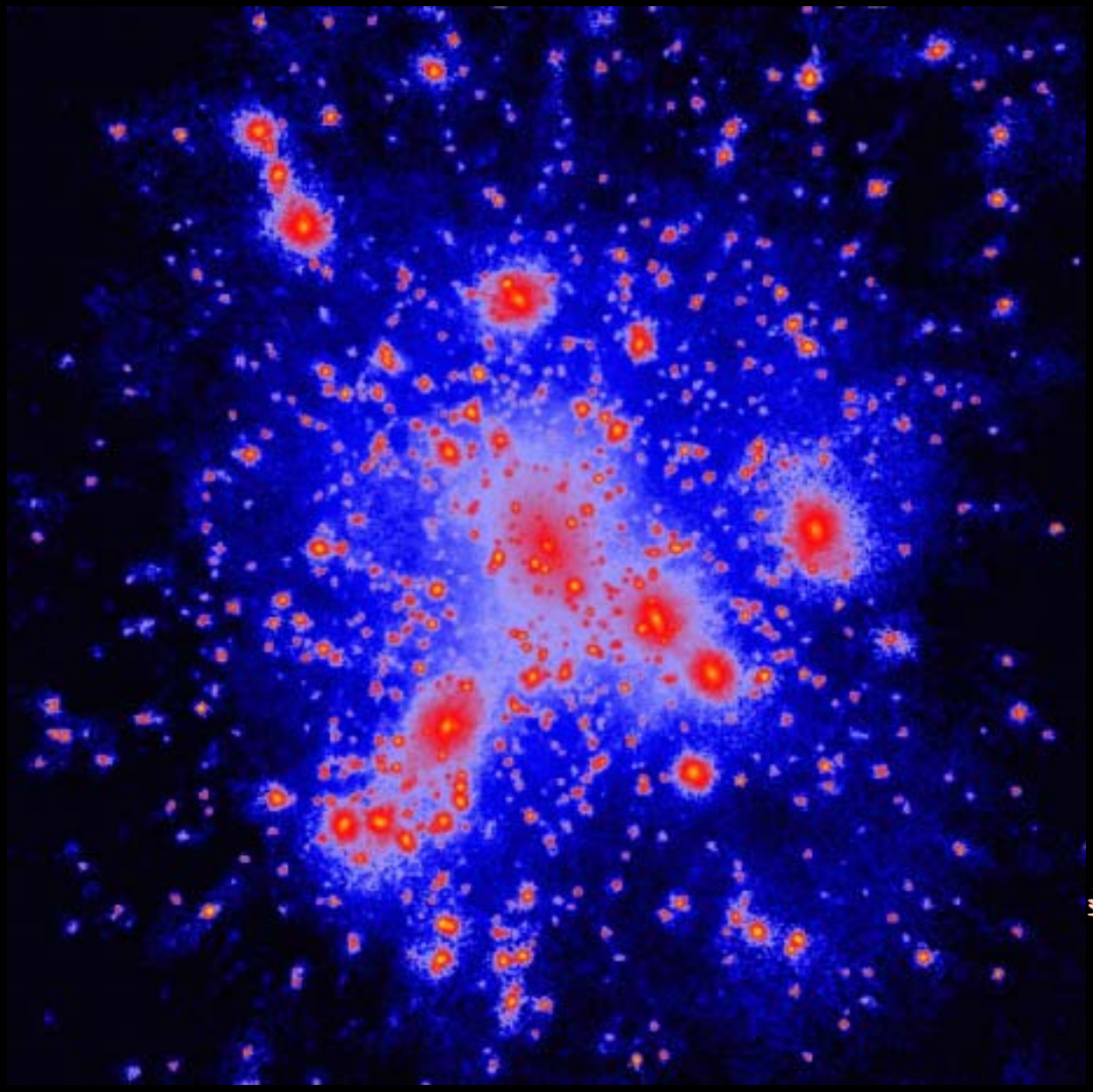
Spherical Collapse



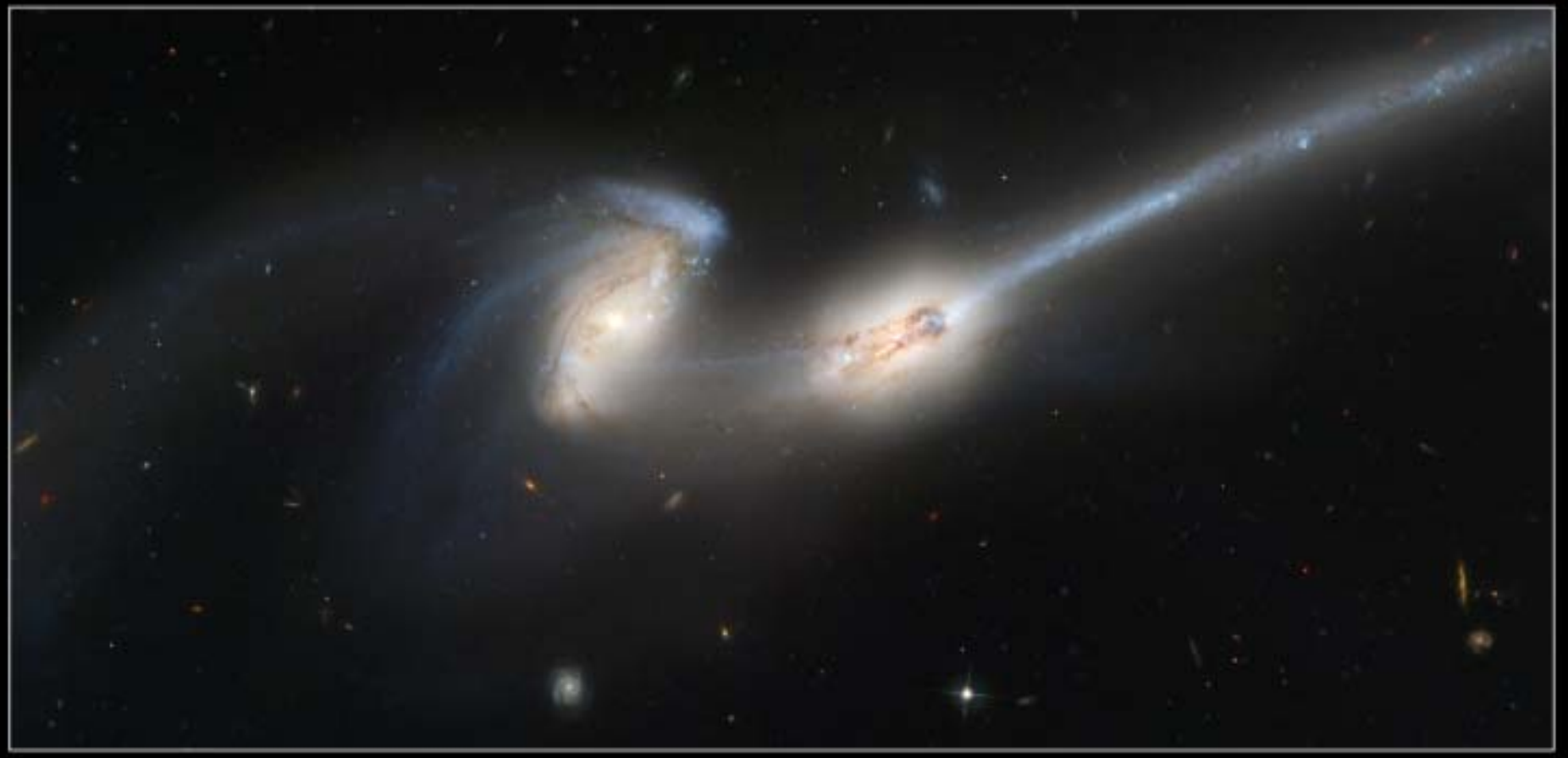
virial equilibrium: $E = -\frac{1}{2}\frac{GM}{R_{vir}} = -\frac{GM}{R_{\max}}$


z=50
z=10
z=3
z=1
z=0.5
z=0

N-body simulation of Structure Formation



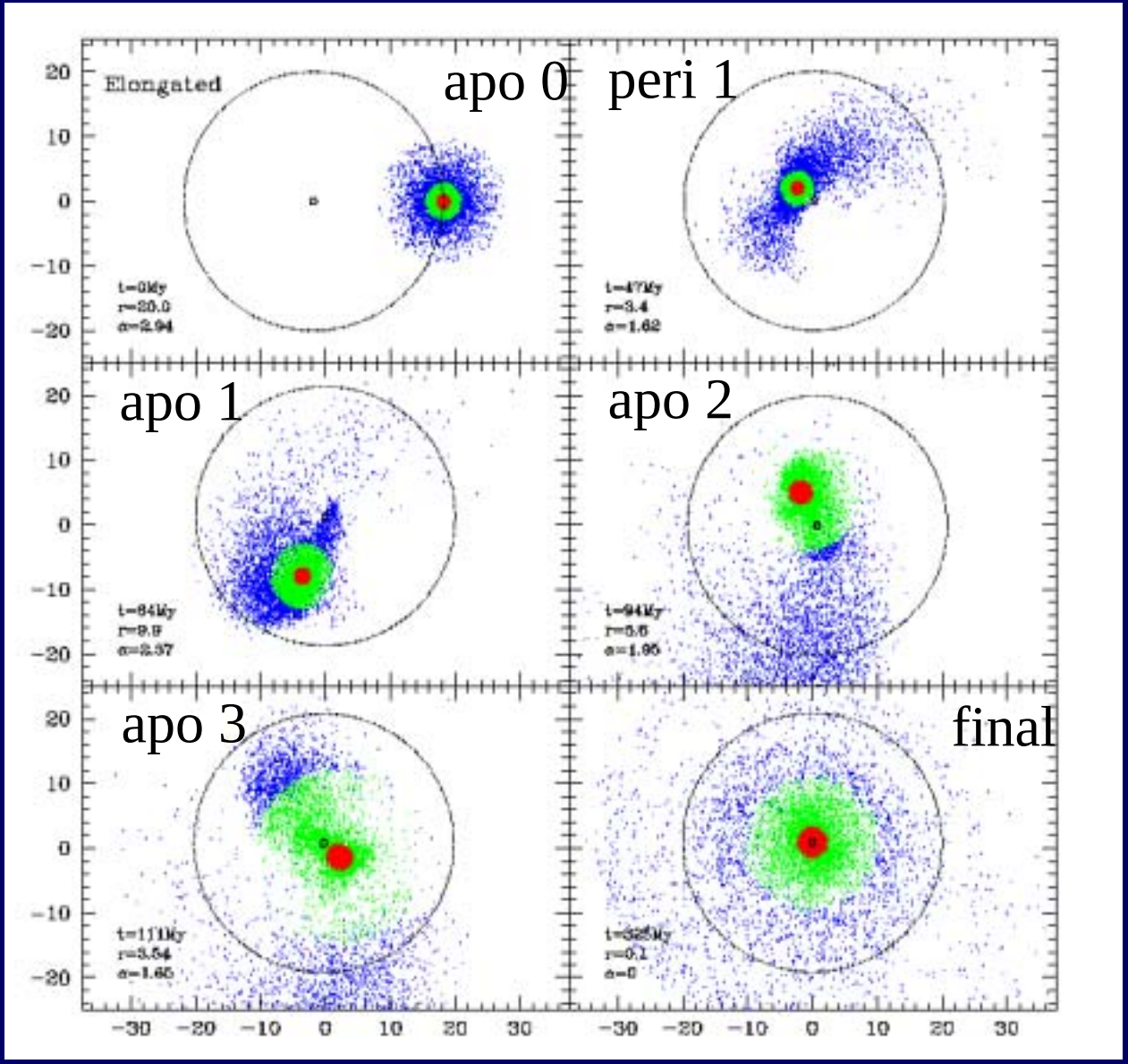
Tidal interaction & Merger



The Mice • Interacting Galaxies NGC 4676
Hubble Space Telescope • Advanced Camera for Surveys

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11d

Halo Bulidup by Mergers

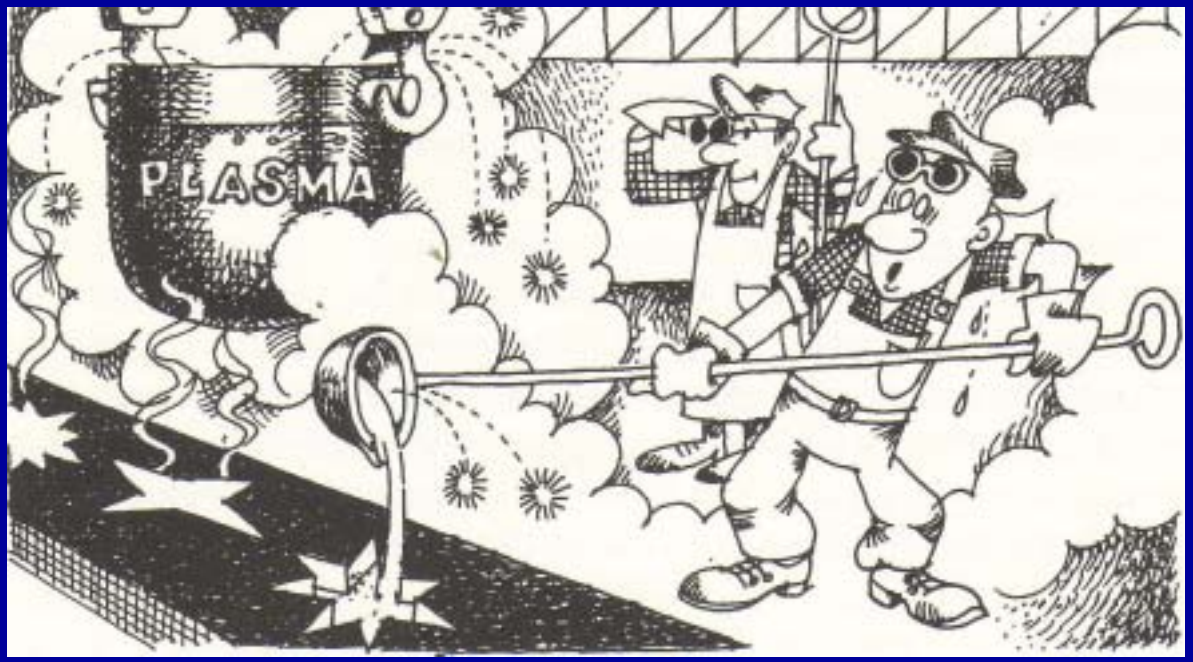


tidal stripping &

dynamical friction

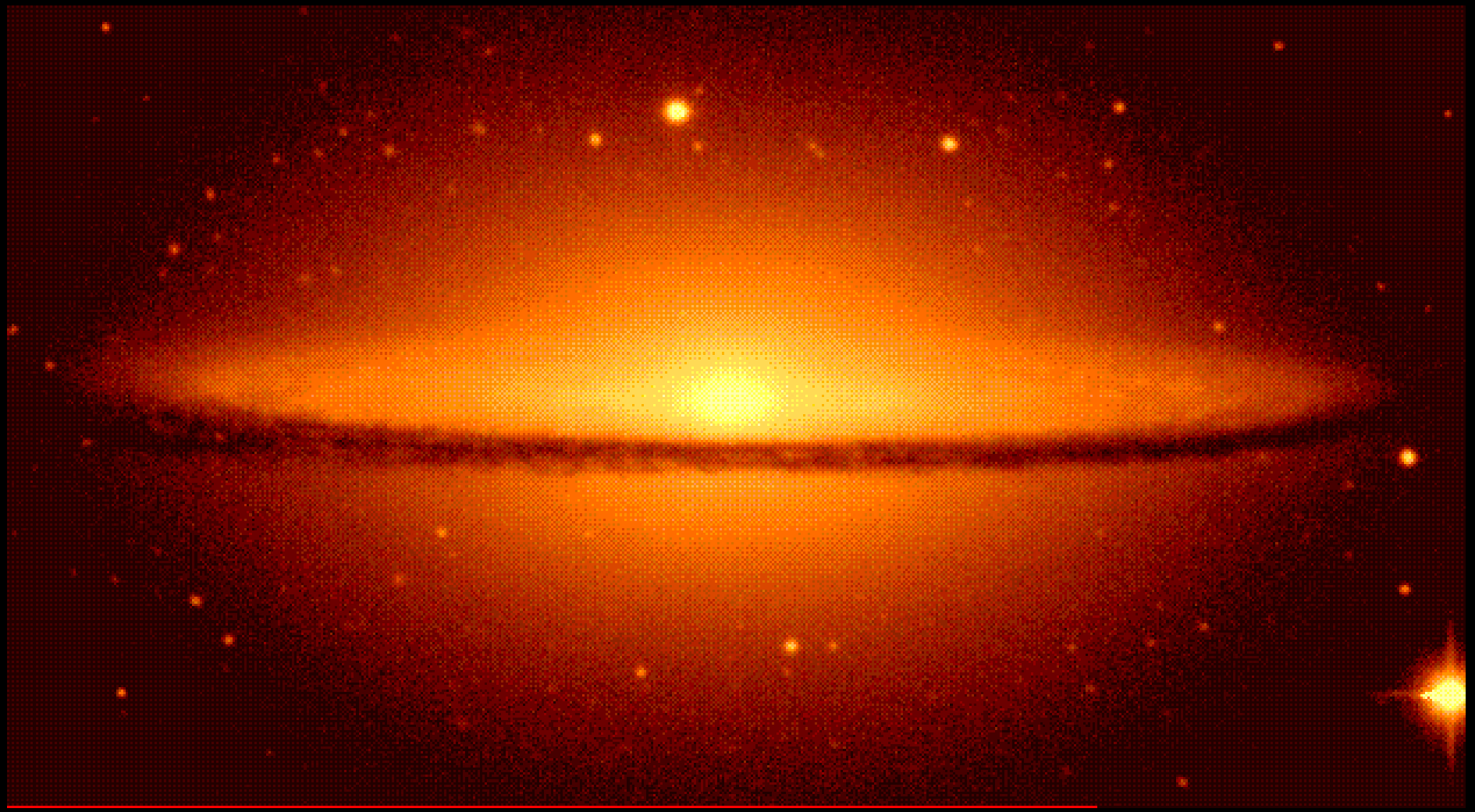
Dekel, Devor & Hetzroni 2003

3. Luminous Galaxies in Dark Halos



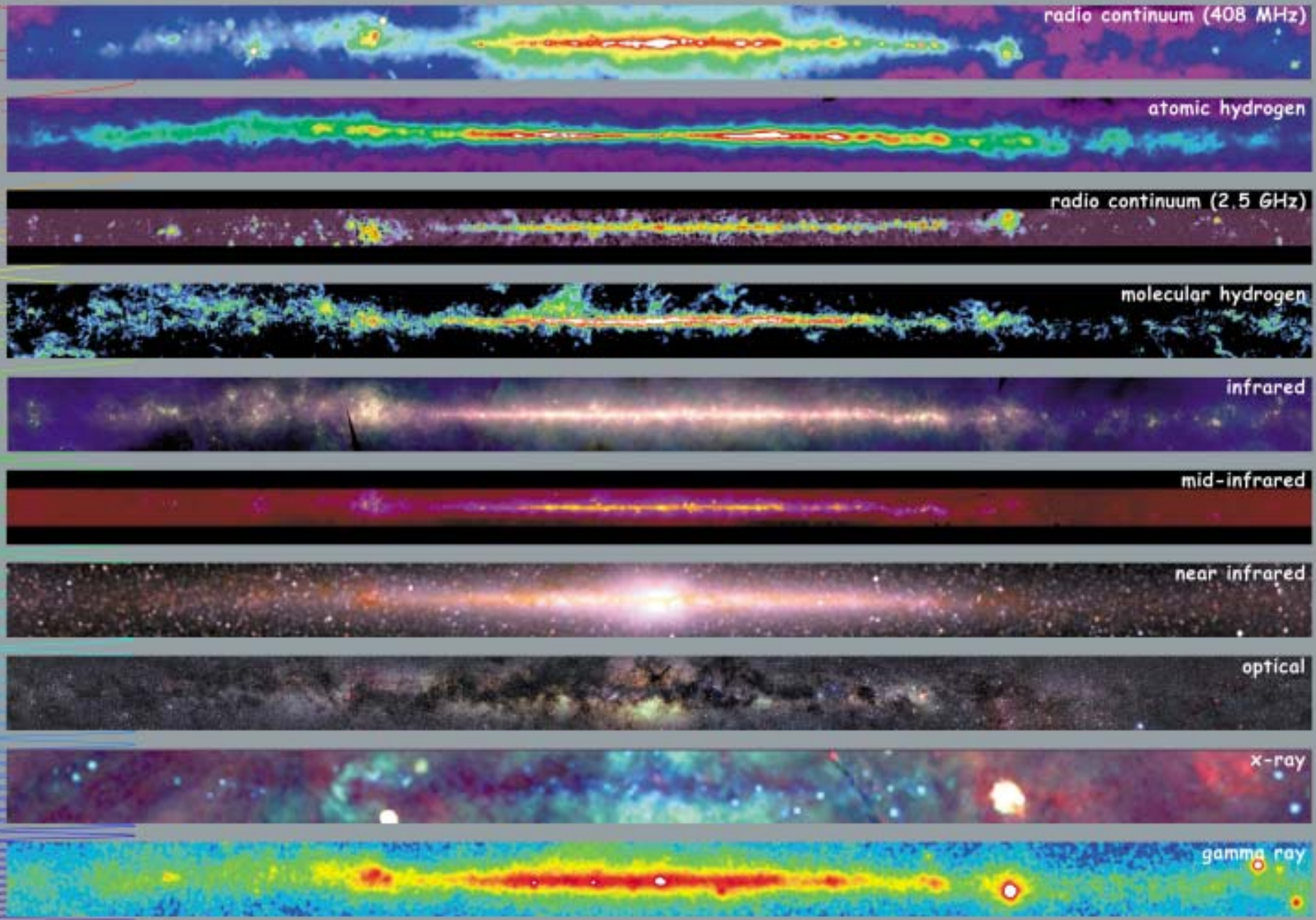
Spiral galaxy M74

The Sombrero M104



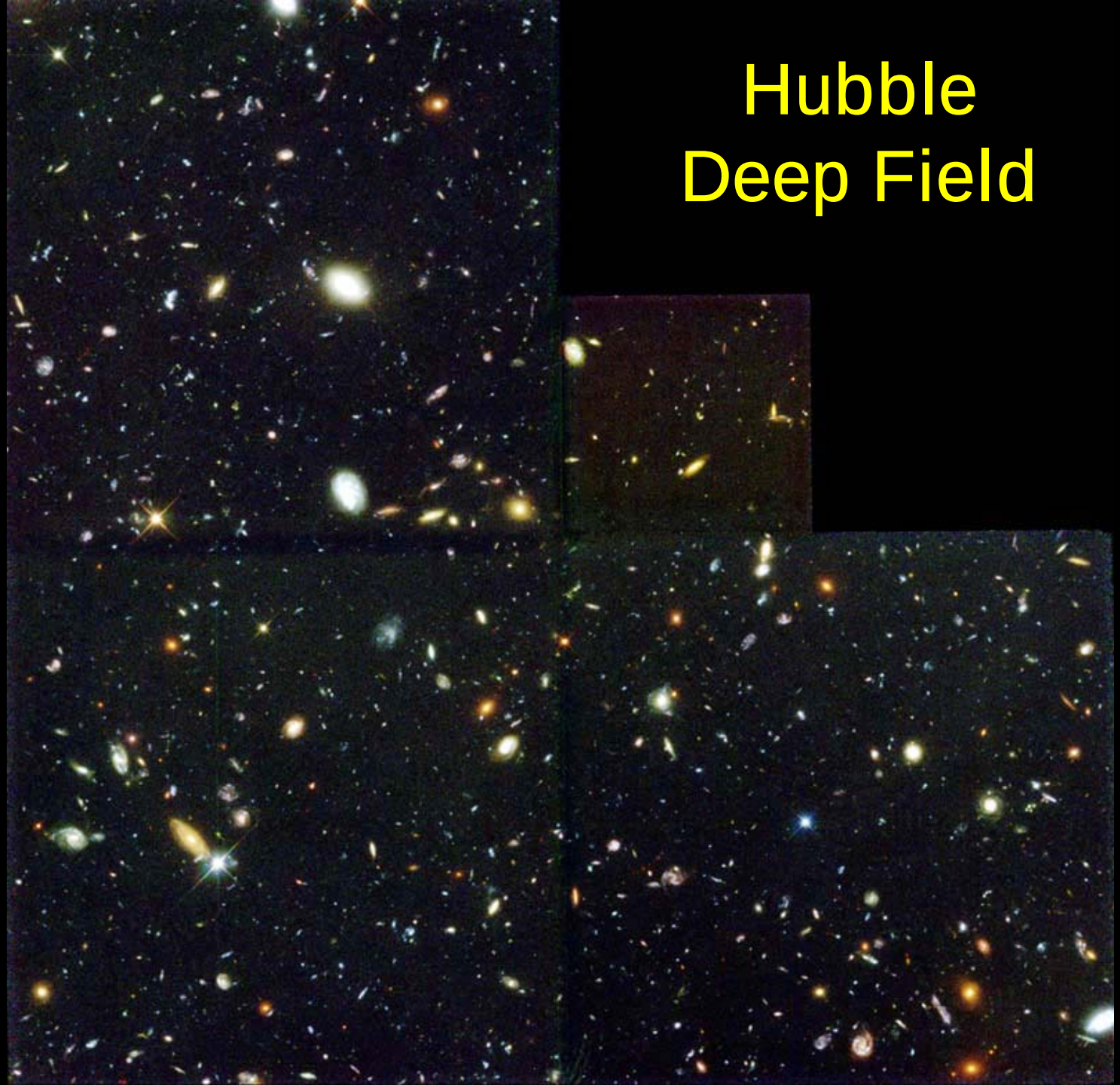
Elliptical galaxy M87

Low-Surface-Brightness & Dwarf Galaxies

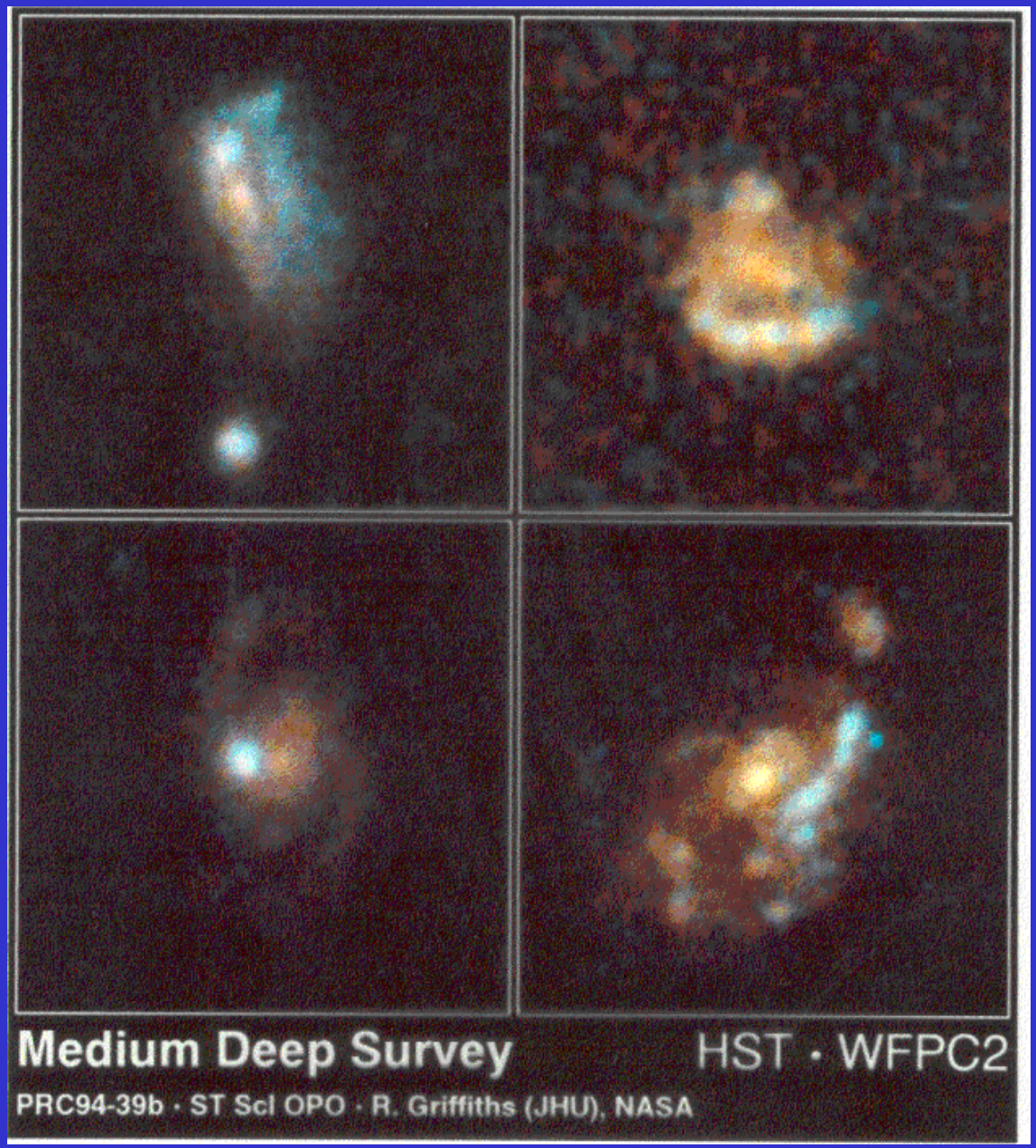


http://adc.gsfc.nasa.gov/mw/

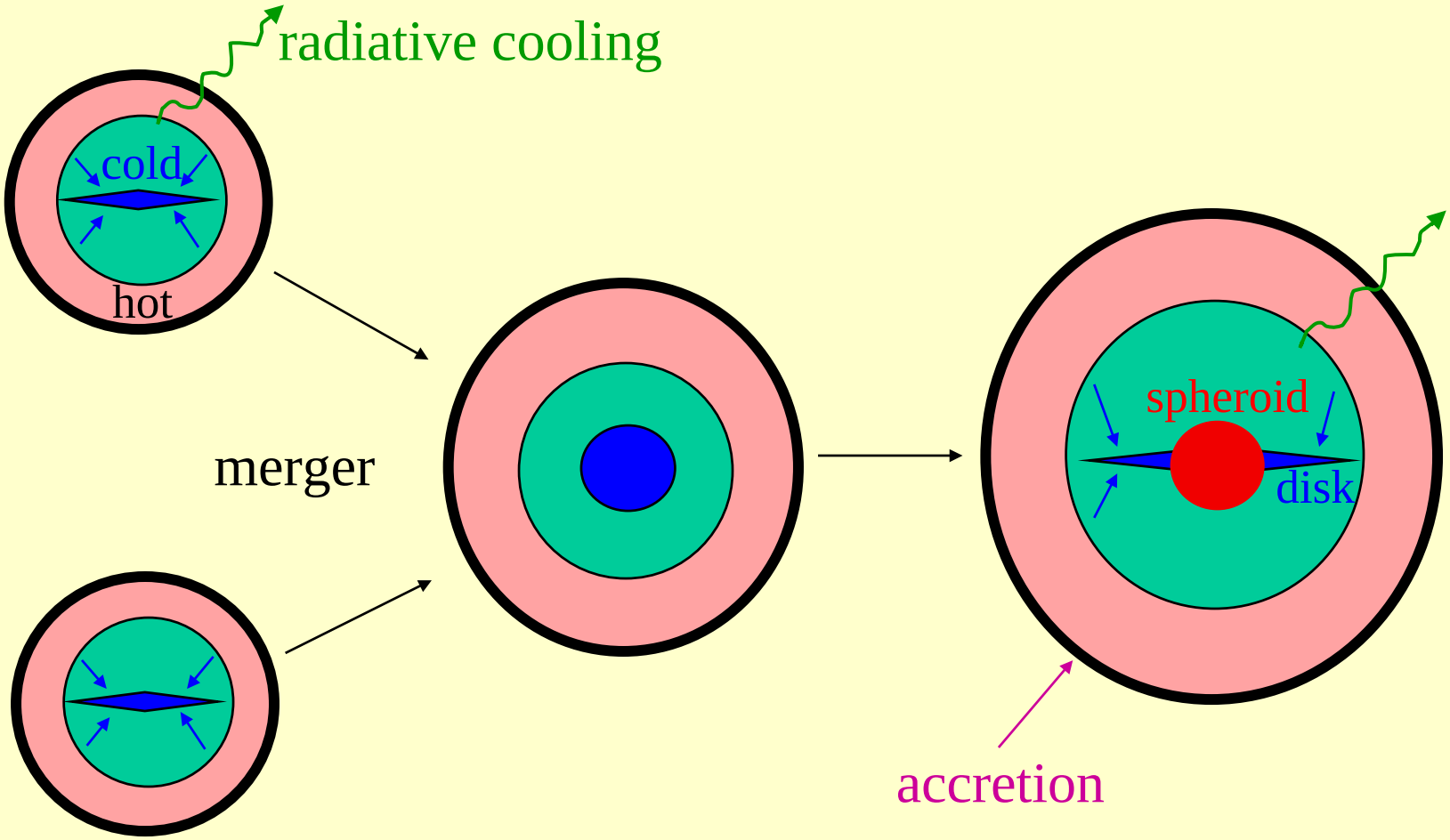
Multiwavelength Milky Way


Hubble
Deep Field

Baby galaxies in early universe



Galaxy Formation in halos

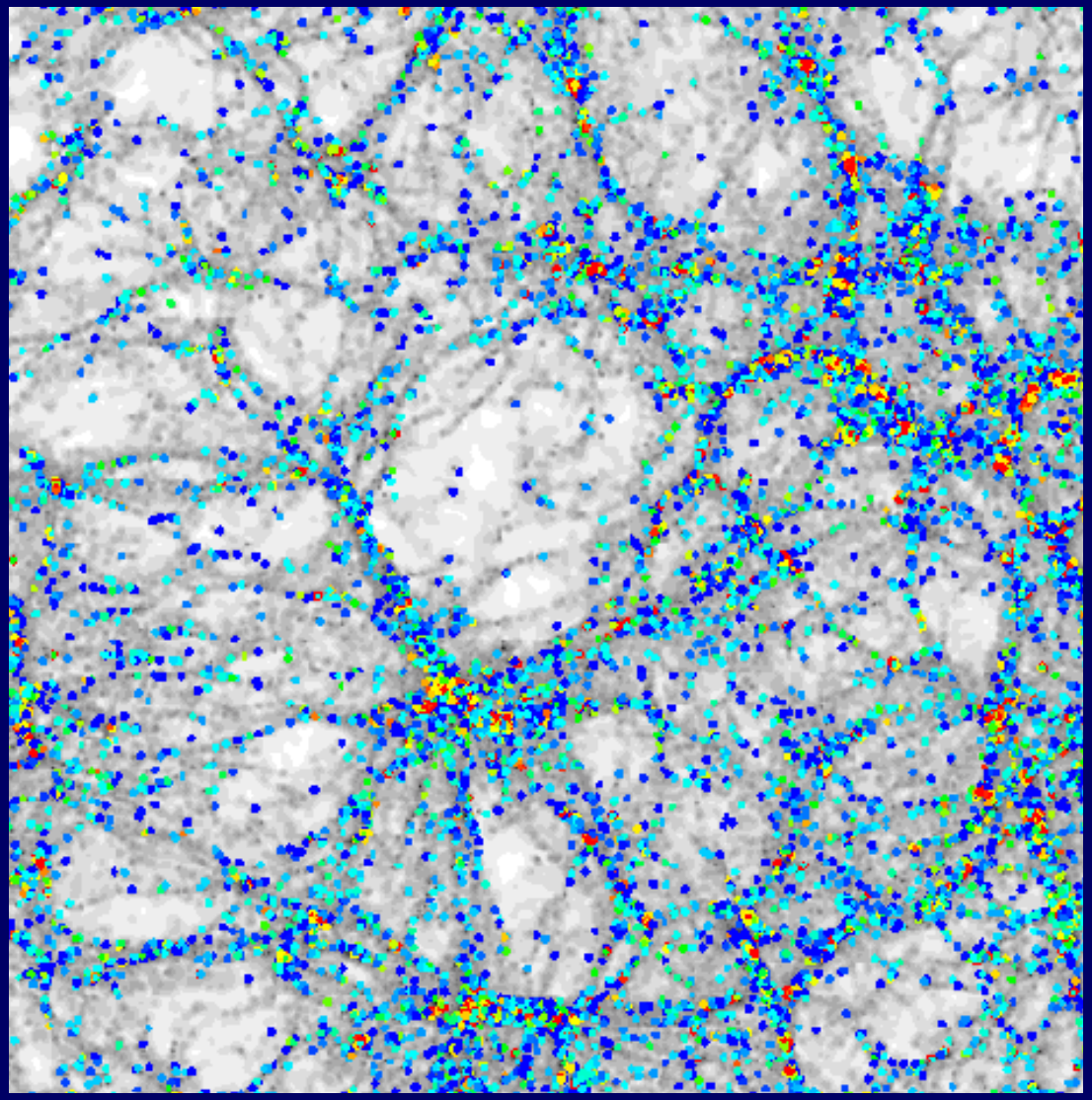


hhalos cold gas → young stars → old stars

Galaxy Formation

1. gravitational formation of dark halos via collapse & mergers
2. gas cooling $\rightarrow$ contraction to a disk, centrifugally supported
3. star formation in disks
4. feedback

Galaxies in large-scale structure



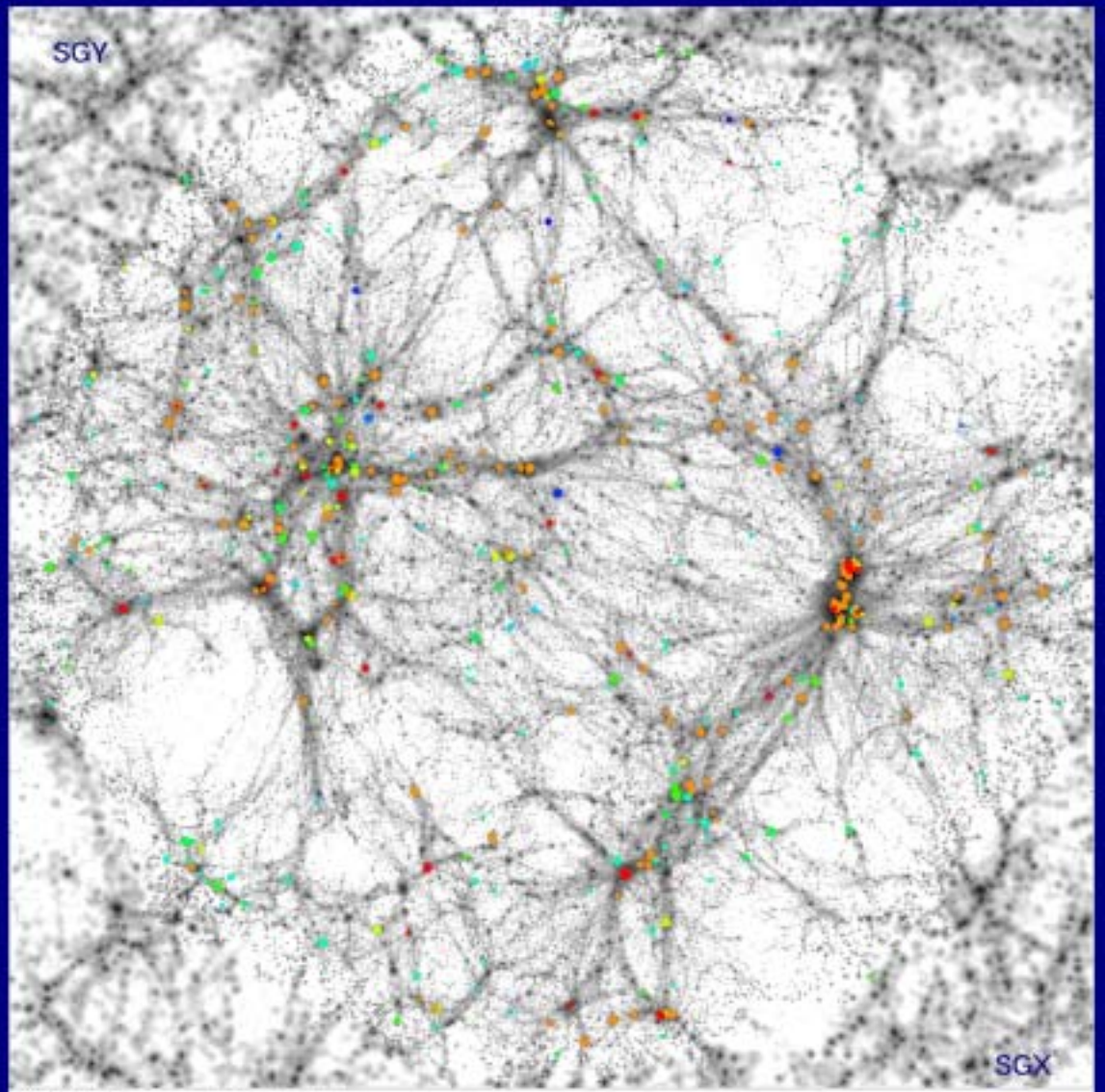
elliptical

elliptical

bulge+disk

disk

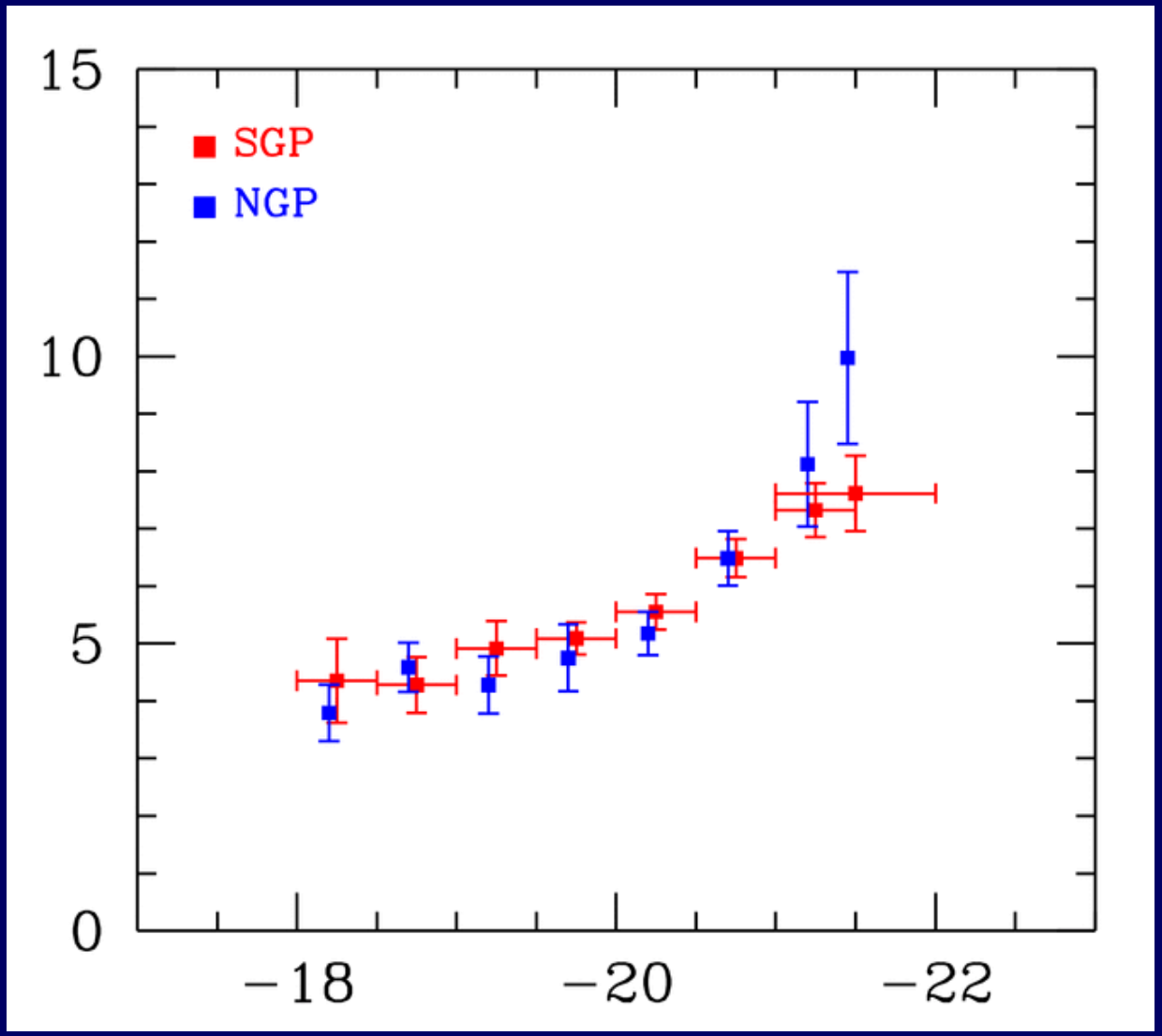
E galaxies in LSS (CR)



ΛCDM CR : E and S0 galaxies
Credits : Mathis, Lemson, Springel, Kauffmann, White and Dekel.

Luminosity Dependence of Galaxy Clustering

Correlation length (Mpc/h)



Luminosity ⟶

4. Puzzles in Galaxy Formation

Three Problems

- Halo profile: cusp - core
- Angular momentum
- Missing dwarf galaxies

Possible common solution:

feedback in small galaxies

To be continued…