Formation & evolution of galaxies & supermassive black holes

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Outline of lectures

1. Structure formation & assembly of dark halos
2. Gas cooling & angular momentum
3. Star formation & feedback
4. Galaxy mergers & morphologies
5. Cosmic evolution of galaxies
6. Formation of black holes
7. BH binaries & spin
8. Co-evolution of galaxies & AGN

Further reading for lectures 1-5

- Galaxy Formation and Evolution by Houjun Mo, Frank van den Bosch and Simon White
  - the best textbook on galaxy formation, very comprehensive & up-to-date
- Galaxy formation theory by Andrew Benson (Physics Reports vol 495, p33, 2010)
  - a useful recent review article
- A primer on hierarchical galaxy formation: the semi-analytical approach by Carlton Baugh (Reports on Progress in Physics, vol 69, p3101, 2006)
  - another useful review, good overview, less technical

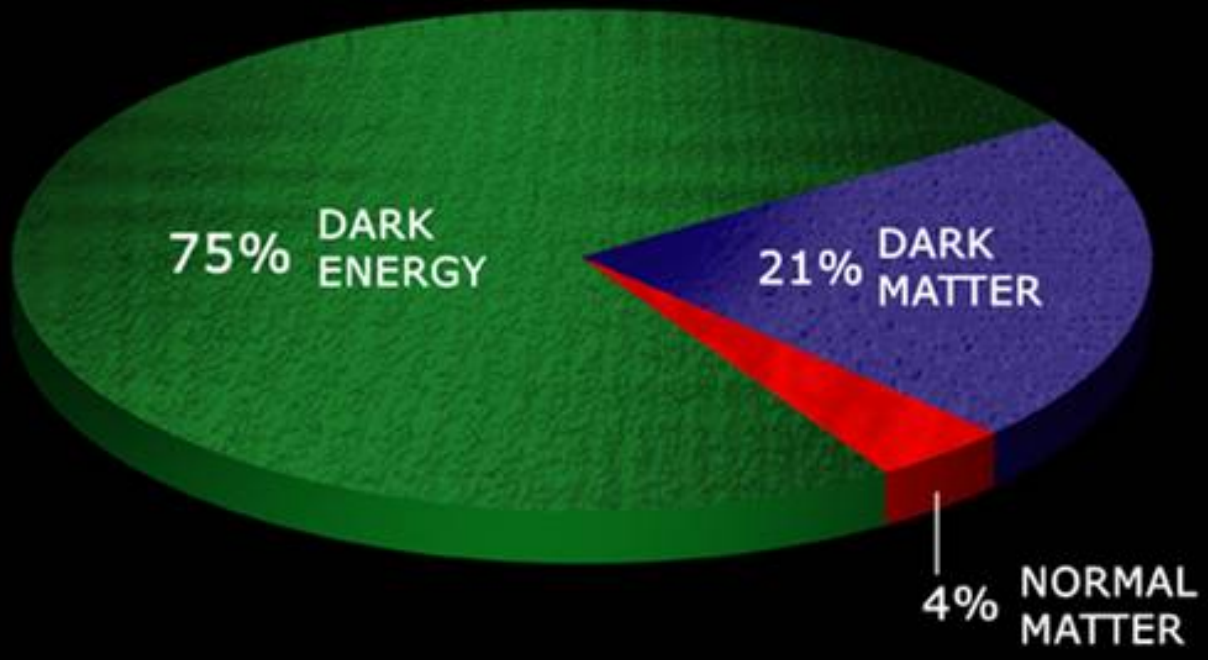
Lecture 1:
Structure formation & dark matter halos

Lecture 1 outline

- Contents of universe
- Outline of structure formation
- Non-linear evolution of structure in dark matter - N-body simulation results
- Analytical approaches to assembly of dark matter halos & halo mass function
- Halo density profiles

Constituents of universe

Contents of the universe



- dark energy = mysterious form of energy which opposes gravity
- dark matter = invisible form of matter which interacts only via gravity

Dark Matter – observational evidence

- Dynamics of galaxy clusters
- Galaxy rotation curves
- Gravitational lensing

Non-baryonic dark matter candidates

Type	candidate	mass
hot	neutrino	a few eV
warm	?	a few keV
cold	axion neutralino	10^{-5}eV ->100 GeV

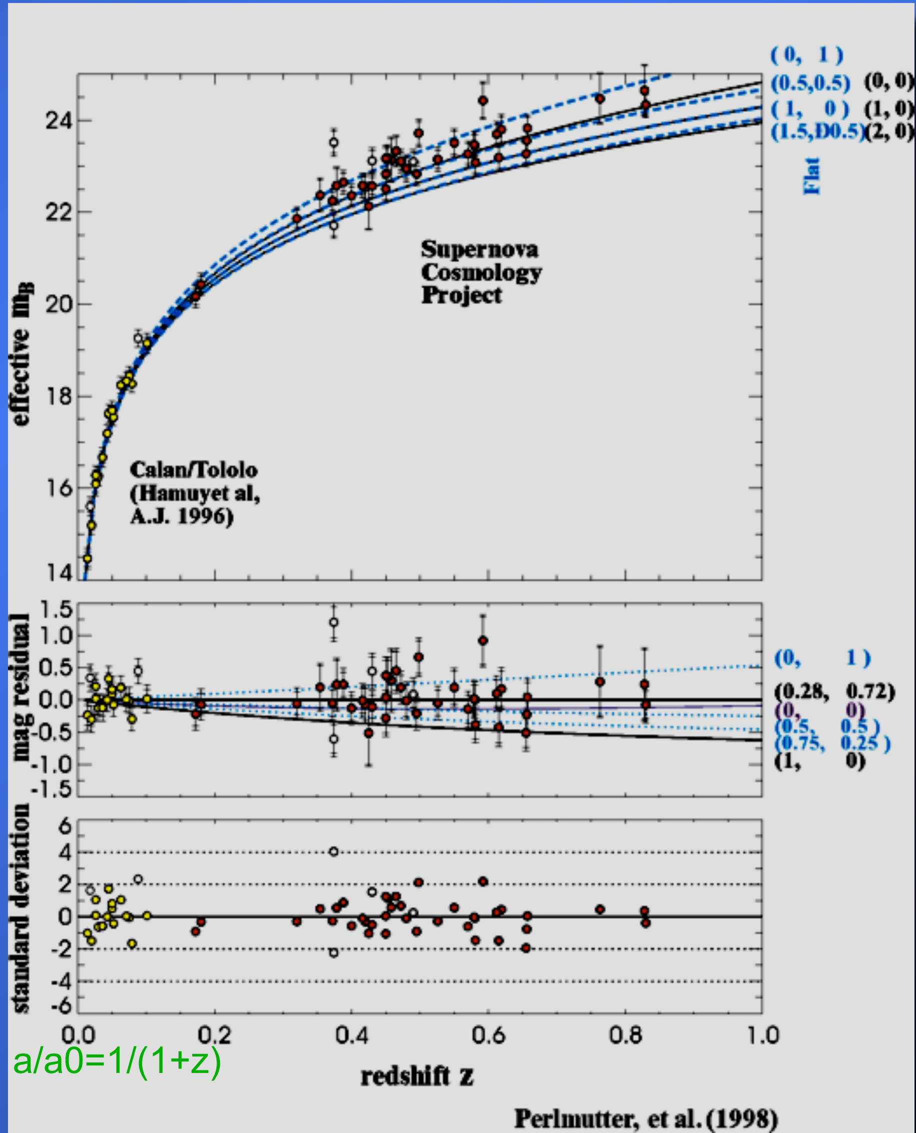
Standard model is Cold Dark Matter (CDM)

Dark energy – observational evidence

Expansion of universe from high-z supernovae:
- SNIa (standard candles) at z~0.5-1 are fainter than expected even if universe were empty

=> cosmic expansion must have been accelerating since light was emitted

Standard model for dark energy is cosmological constant (Λ)



Origin of structure in the universe

Standard model for structure formation

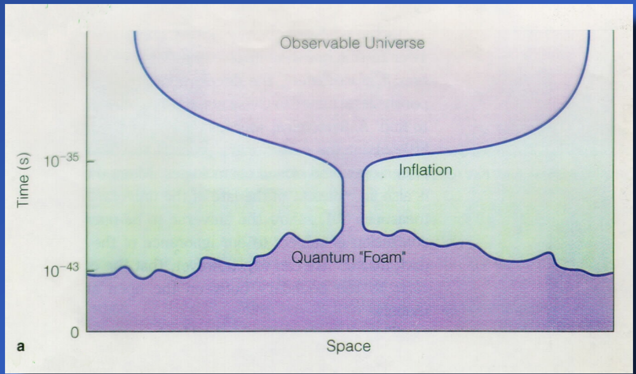
- Universe today contains:

~70% dark energy, ~25% dark matter, ~4% baryons

- Inflation made universe spatially flat
- Also generated spectrum of adiabatic density fluctuations
- Density fluctuations grew by gravitational instability to produce present-day structure

The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)



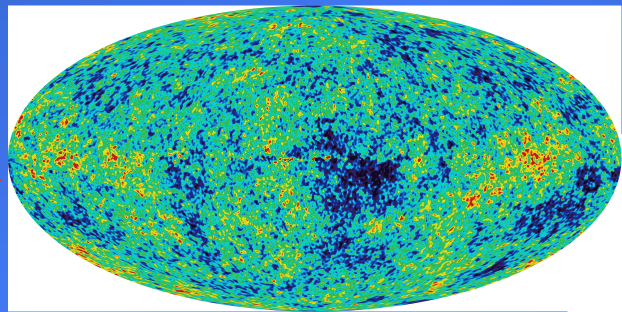
1. FLAT GEOMETRY: $$\Omega + \frac{\Lambda}{3H^2} = 1$$

2. QUANTUM FLUCTUATIONS:

adiabatic

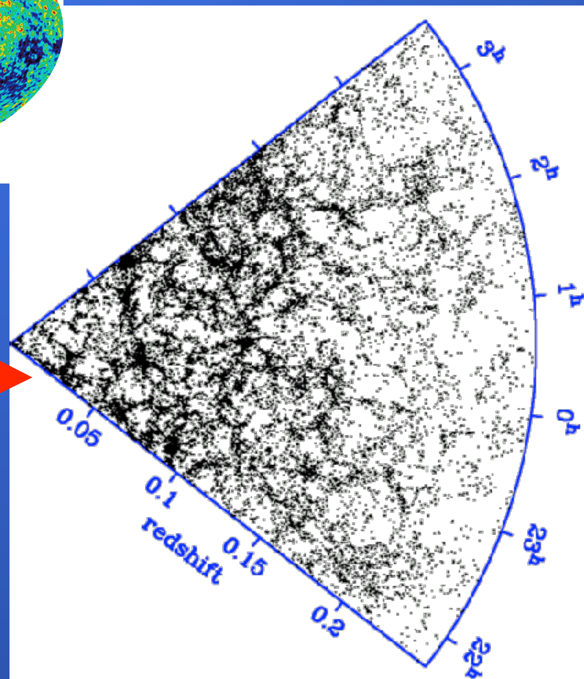
$$\left\{ \begin{array}{l} |\delta_k|^2 \propto k^n \quad n = 1 \\ \text{Gaussian amplitudes} \end{array} \right.$$

CMB ($t \sim 3\times10^{5}$ yrs)



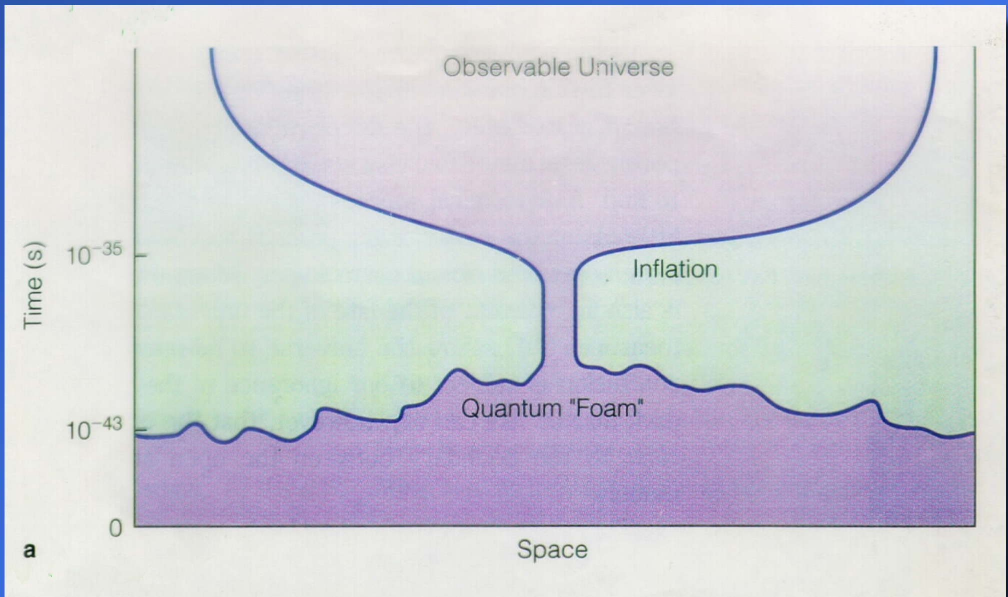
Structure ($t \sim 13\times10^{9}$ yrs)

Dark matter



Cosmic Inflation

Inflation - period of exponential expansion driven by scalar field



Standard inflation predicts:

1. **FLAT GEOMETRY:**

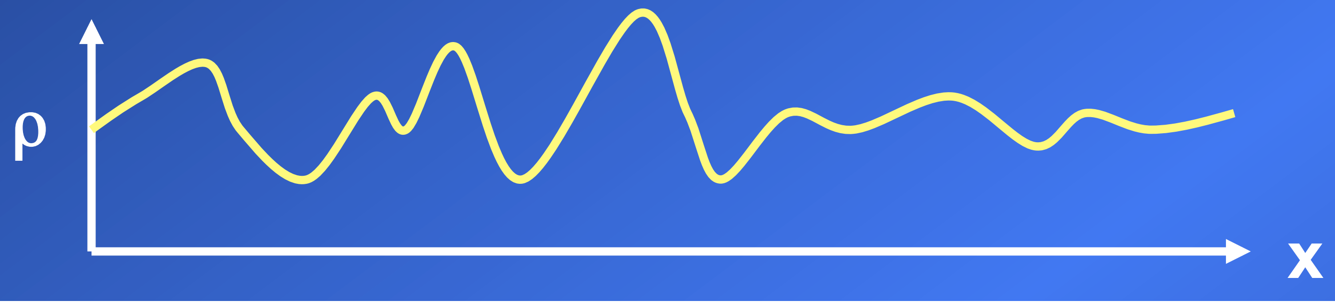
$$\Omega_m + \frac{\Lambda}{3H^2} = 1$$

2. $$\left(\frac{\delta\rho}{\rho}\right)^2 \sim k^3 |\delta_k|^2$$

$|\delta_k|^2 \alpha\, k^n \quad n = 1$

Gaussian amplitudes

Spectrum of inhomogeneities



Fourier decomposition of density field

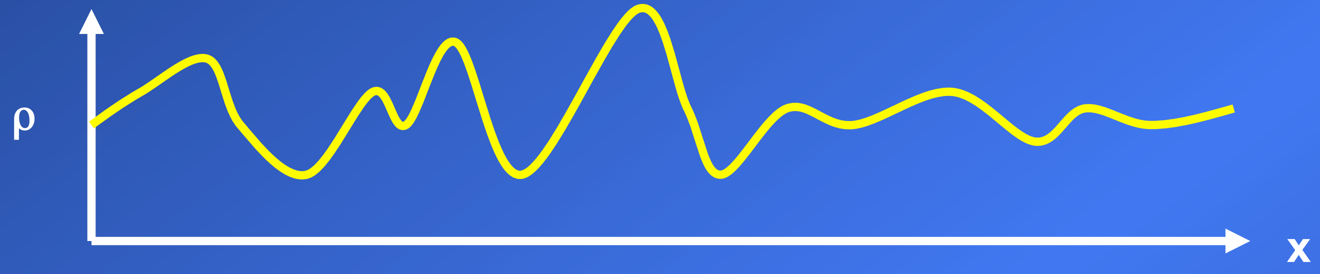
$$\delta(\mathbf{r}) \equiv \frac{\delta\rho}{\rho} = \sum_k \delta_k \, e^{-i\mathbf{k}\cdot\mathbf{r}}$$

Dimensionless power

$$\Delta^2(k) \equiv \frac{d\sigma^2}{d\ln k} \propto k^3 \, |\delta_k|^2$$

- power spectrum $P(k) = |\delta_k|^2$
- $\Delta^2(k) \sim k^3 \, |\delta_k|^2$ = average $(\delta\rho/\rho)^2$ on length scale $\lambda \sim 1/k$

Spectrum of inhomogeneities



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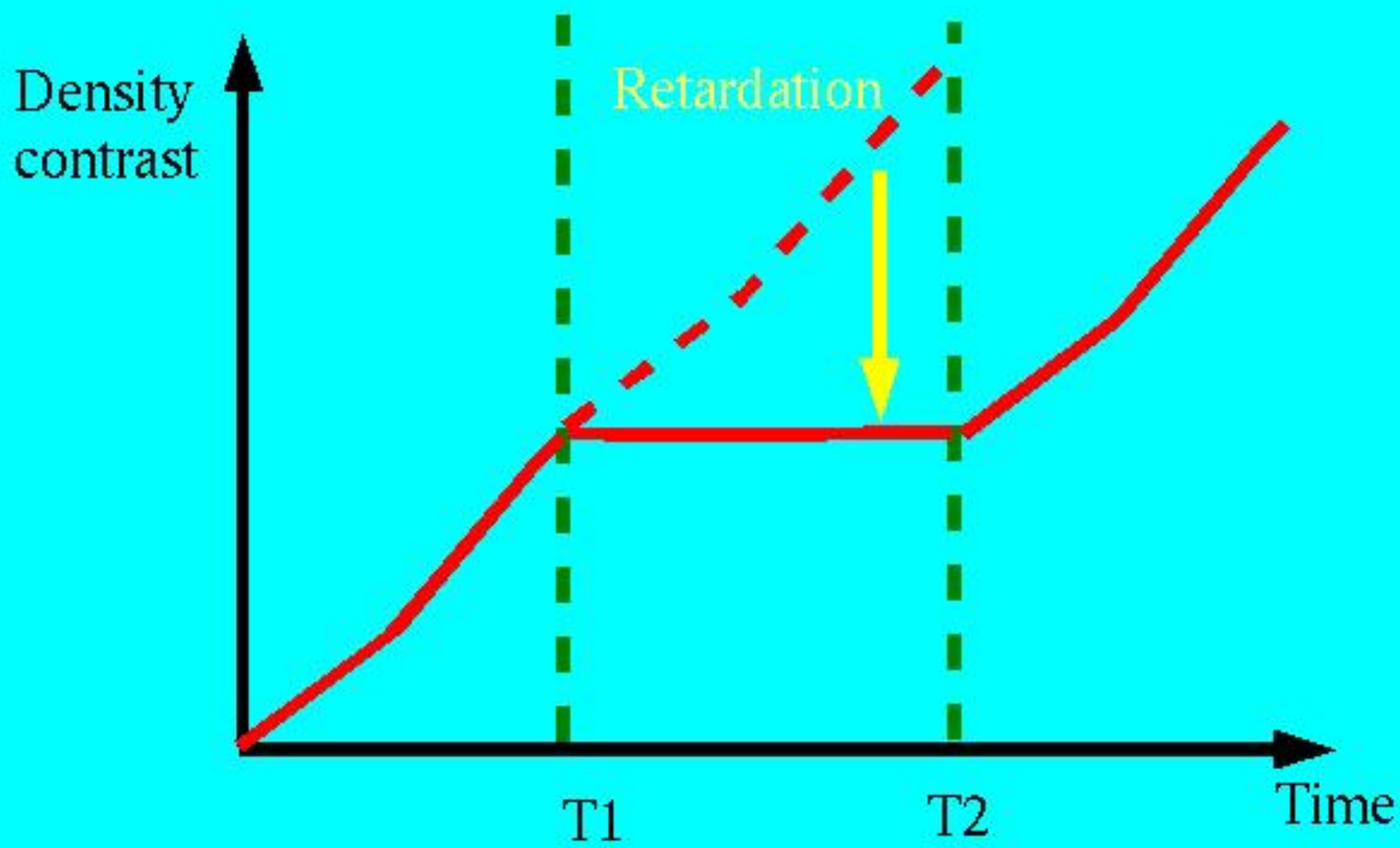
Dimensionless power

$$\Delta^2(k) \equiv \frac{d\sigma^2}{d\ln k} \propto k^3 \, |\delta_k|^2 \propto k^{3+n} \, T_k^2$$

Primordial power-law spectrum (n=1?)

Transfer function $T_k(k,z)$
- describes growth of density perturbations in linear regime after inflation

Evolution of a density perturbation (dark matter)

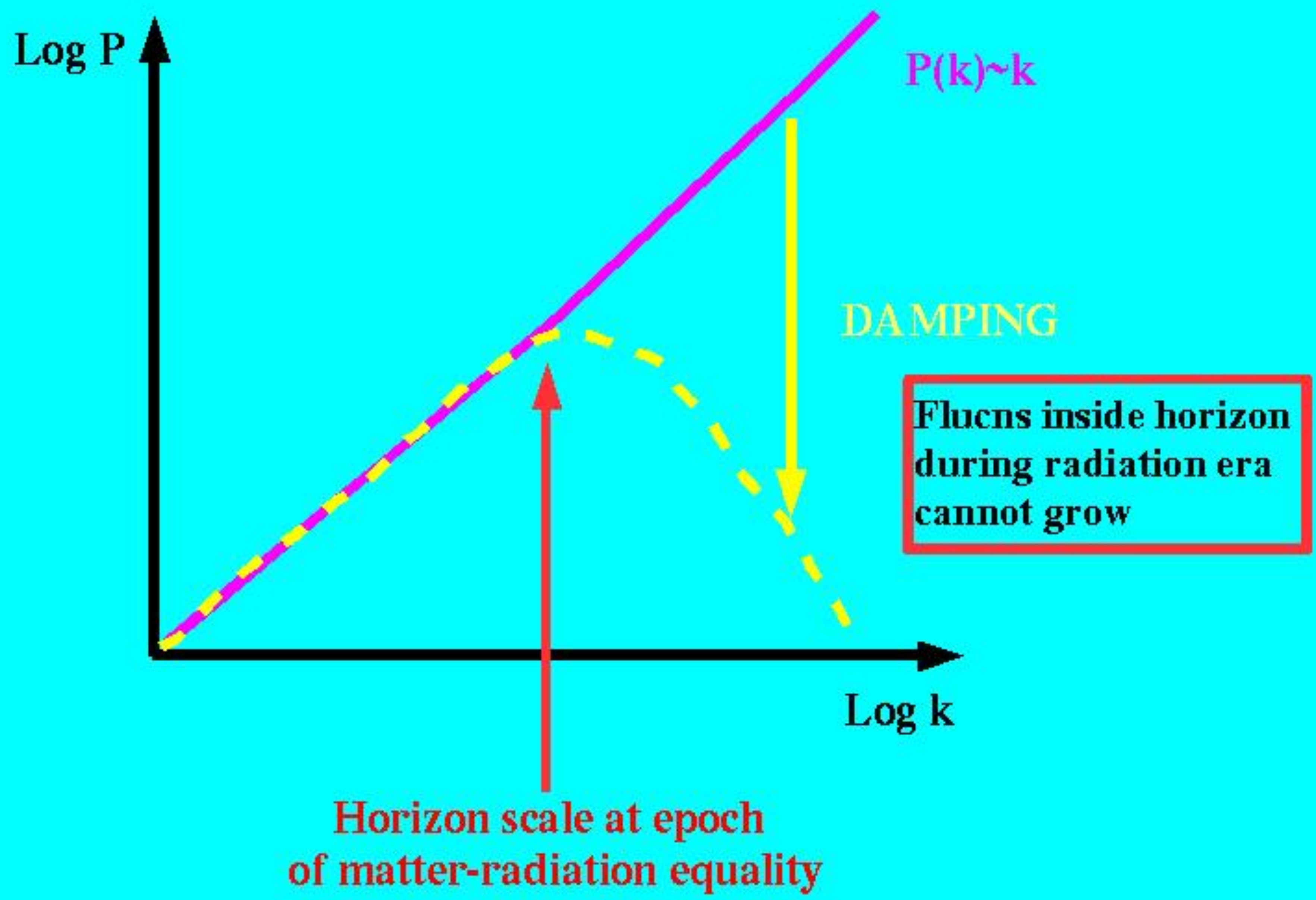


T1: horizon has expanded to enclose fluc'n

T2: epoch of matter-radiation equality

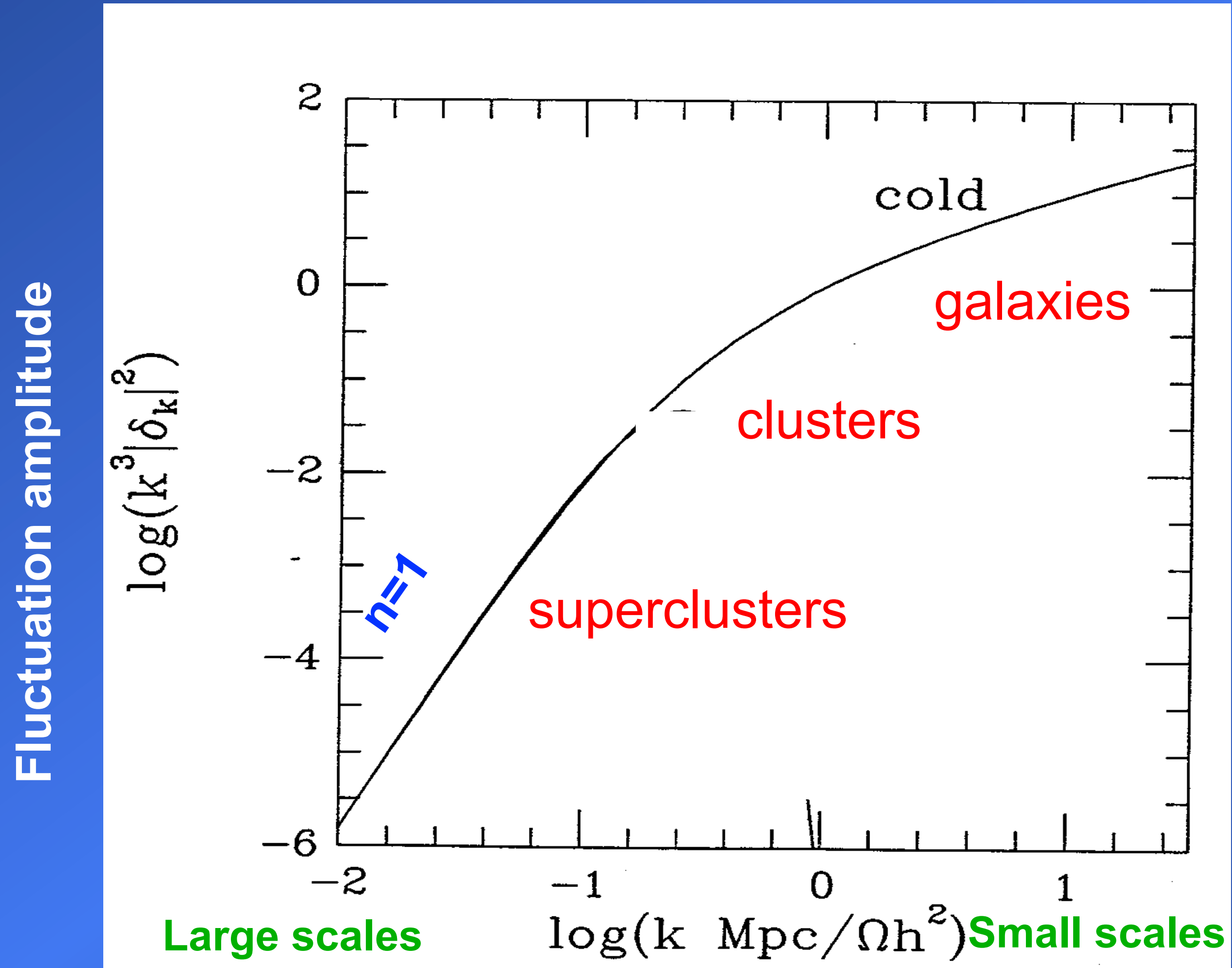
T1<t<T2 fluc'ns in radiation density and expansion of universe stop growth of density contrast

The matter power spectrum



Spectrum of linear density fluctuations for CDM

$(\delta\rho/\rho)^2$

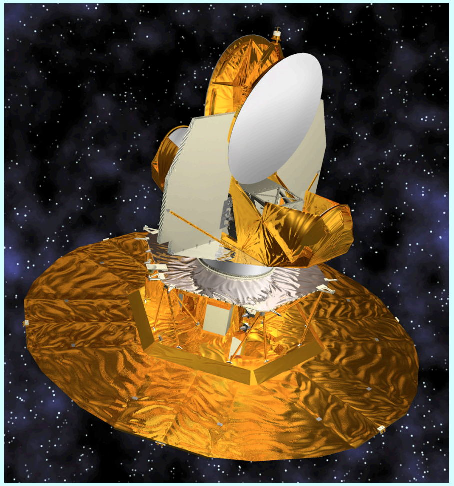


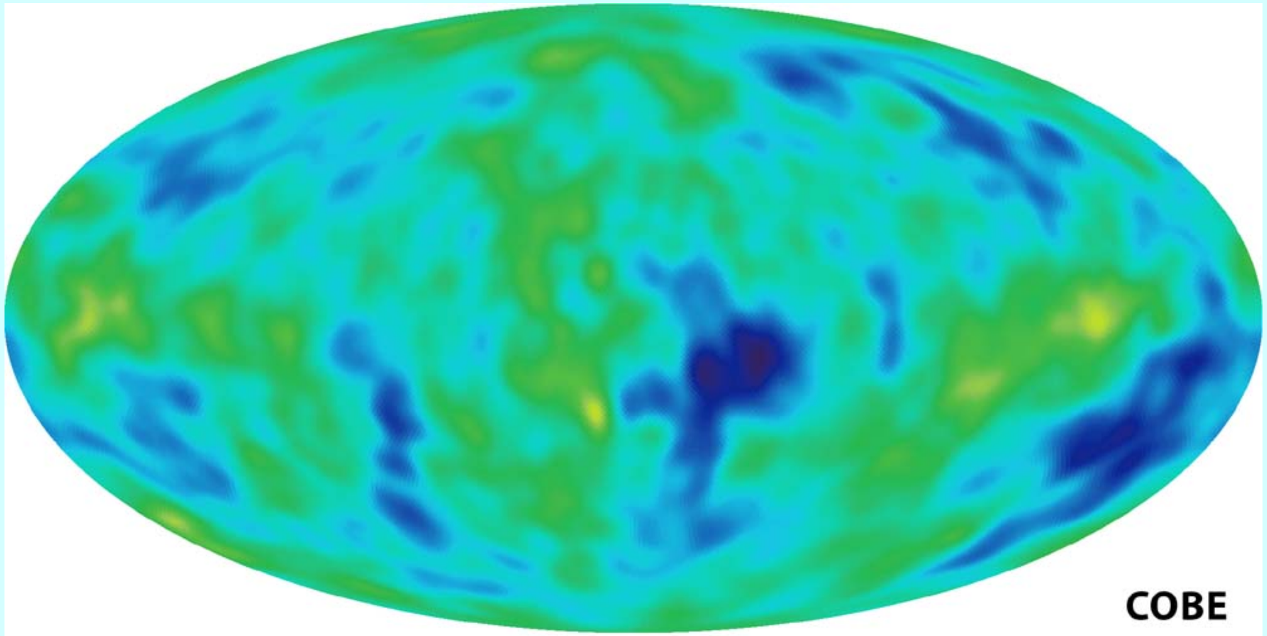
$k^3\,|\delta_k|^2$ = average $(\delta\rho/\rho)^2$ on length scale $\lambda \sim 1/k$ according to linear perturbation theory at z=0

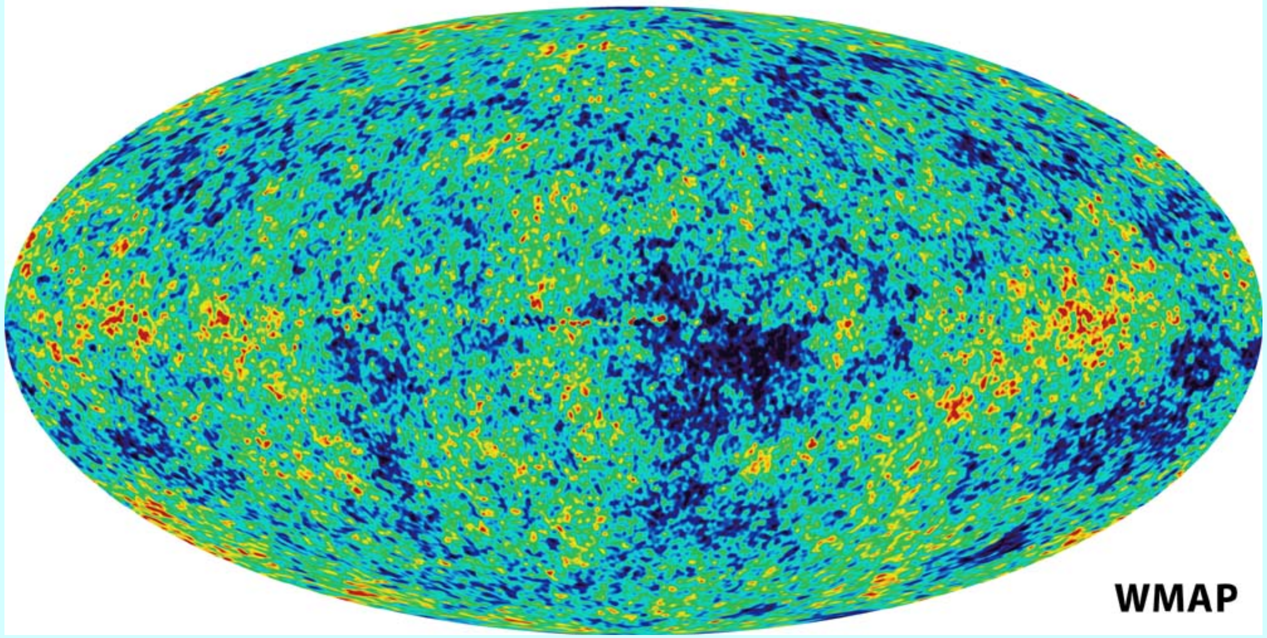
The CMB

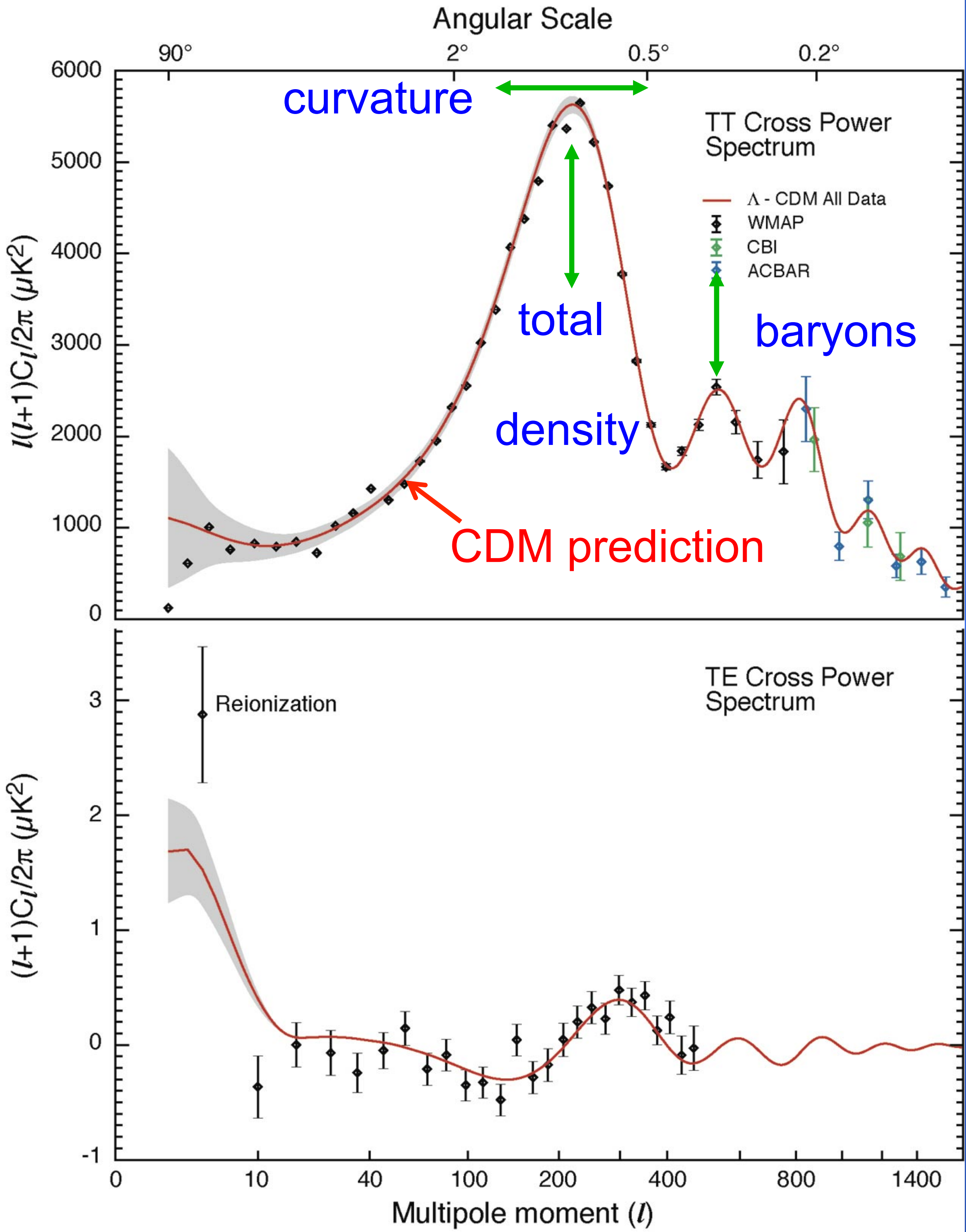
1992

2003

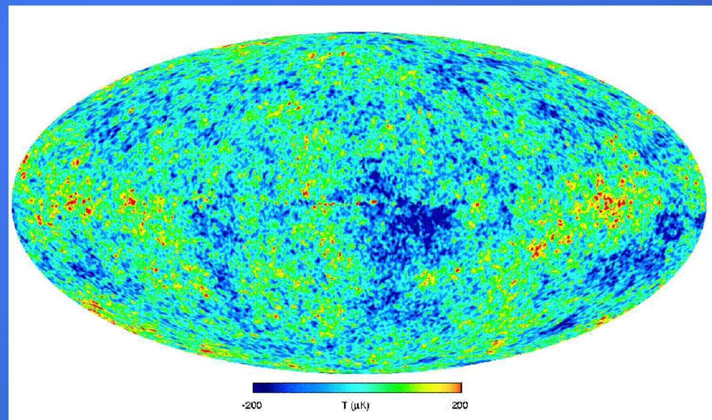






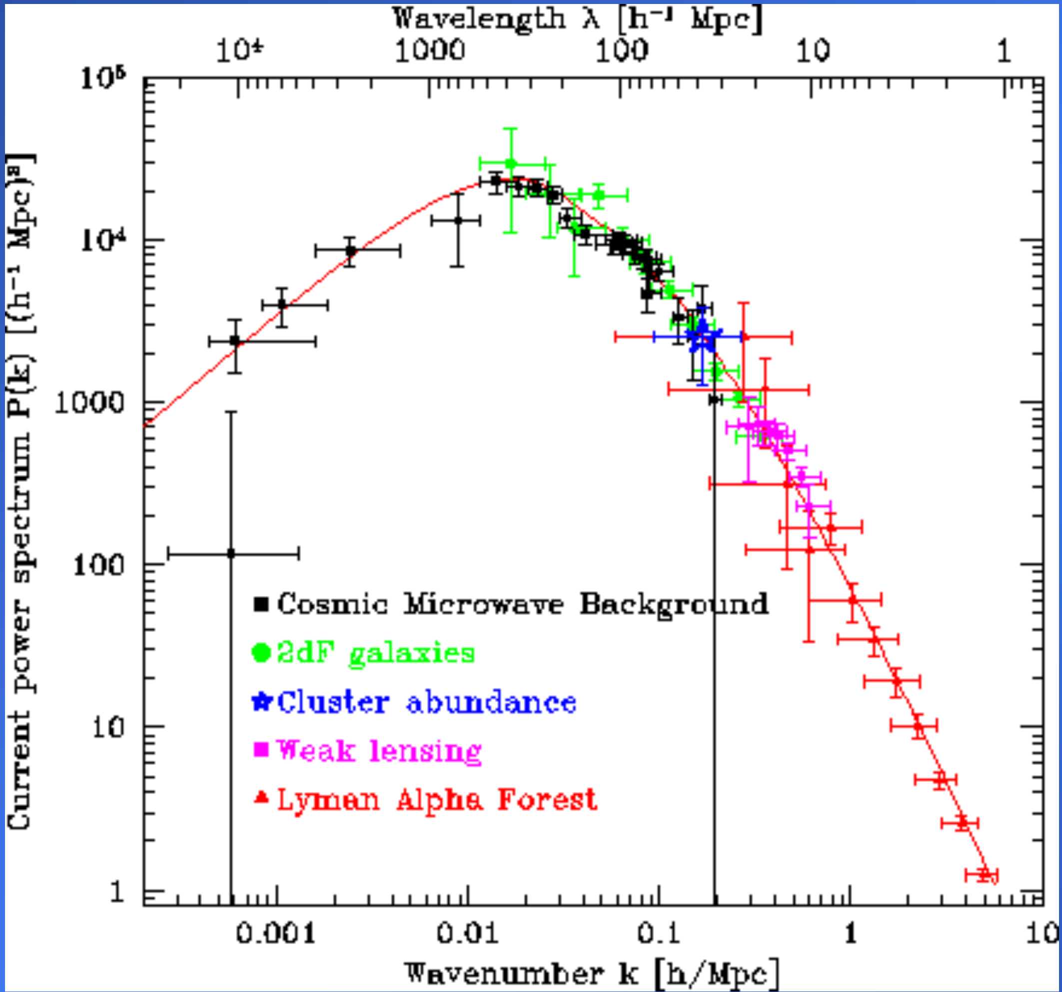


Cosmic Initial Conditions: observational constraints from CMB fluctuations



CMB temperature fluctuations confirm ΛCDM density fluctns & give most precise constraints on cosmological params

Observed power spectrum of linear density fluctuations



Obs measures of P(k) from:

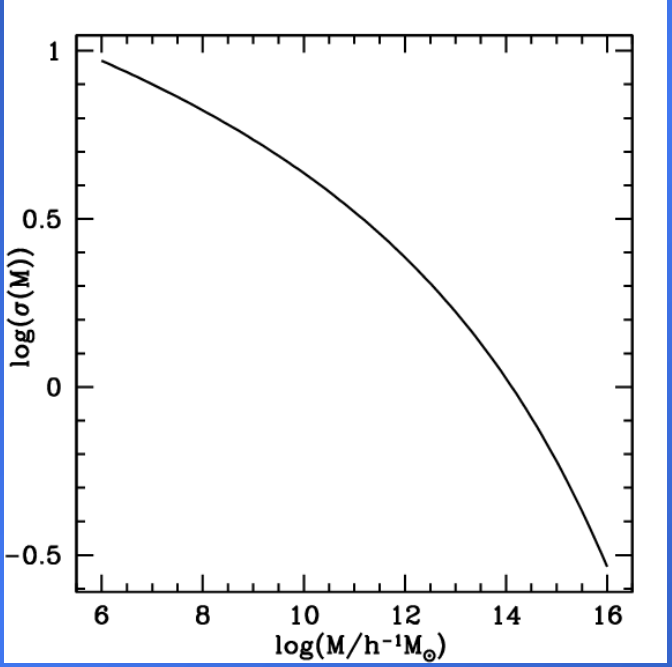
- CMB
- galaxy clustering
- weak lensing
- Lyα forest

- confirm ΛCDM

Hierarchical structure formation

- in linear regime ($\delta\rho/\rho \ll 1$), perturbations on all scales grow as $\delta\rho/\rho \propto a(t) = 1/(1+z)$ after recombination
- perturbations collapse to gravitationally bound objects when $\delta\rho/\rho \sim 1$ according to linear theory
  => perturbations with larger $(\delta\rho/\rho)_{init}$ collapse earlier

$(\delta\rho/\rho)$

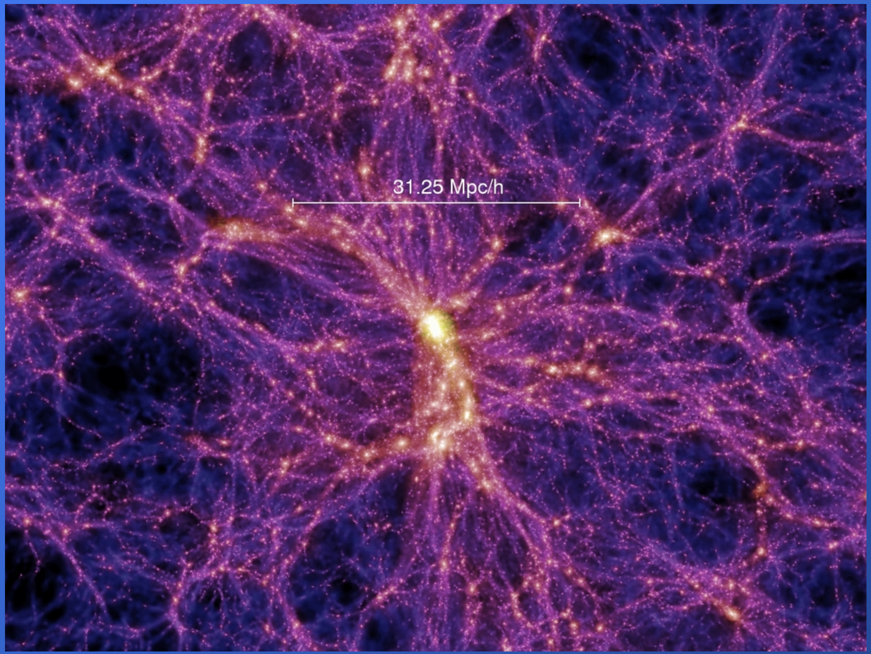


- in CDM, typical $\delta\rho/\rho$ increases monotonically with decreasing mass scale
  => small objects collapse first, larger objects later
- HIERARCHICAL or bottom-up structure formation

Formation of dark matter halos

N-body simulations of structure formation in the dark matter

- most general method to calculate evolution of structure in dark matter (DM) in non-linear regime
- start from small density fluctuations with CDM power spectrum
- evolve collisionless DM particles under gravity only
- as first approximation, can ignore effects of baryons on DM

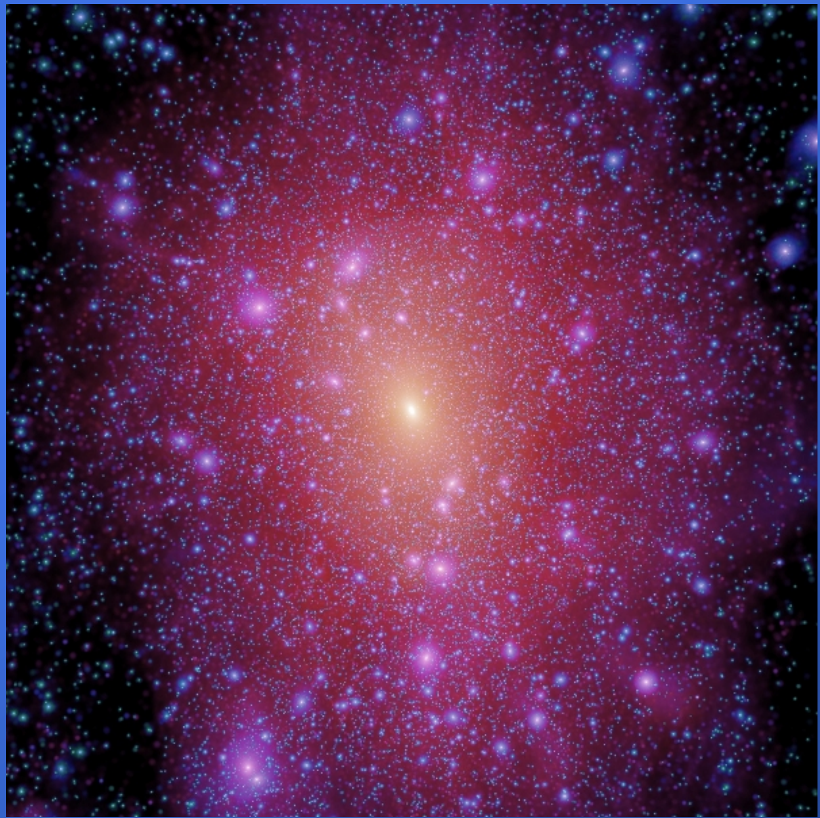


Growth of structure in DM from initial fluctuations

Movie of Millennium simulation (Springel et al 2005)

Formation of dark matter halos

- density fluctuations in the DM stop expanding with universe when $\delta\rho/\rho \sim 1$
- undergo collisionless gravitational collapse to objects in approximate dynamical equilibrium – DARK MATTER HALOS
- small halos typically form first
- large halos then assemble by MERGERS of smaller halos



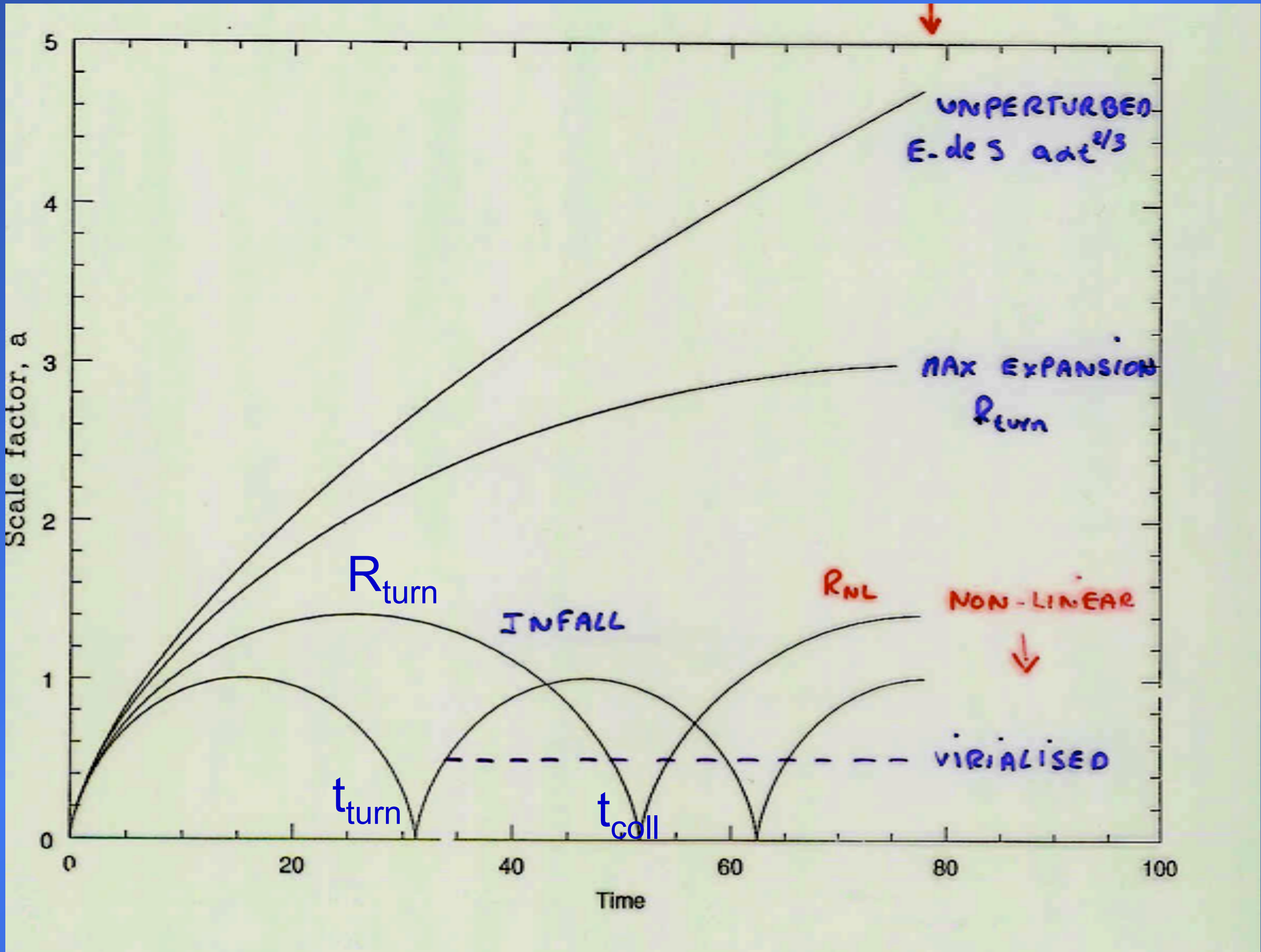
Formation of a single DM halo

Aquarius simulation of M ~ 10^{12} M_o halo

Spherical collapse model for dark halo formation

- uniform density spherical DM perturbation has exact analytical solution for evolution into non-linear regime
- provides useful guide to understand DM halo formation seen in N-body simulations
- even though real DM halos form through mergers of smaller objects - so clearly NOT spherical!

Evolution of radius of uniform spherical density perturbation



Collapse redshift for spherical perturbation

- Simplest for $\Omega=1$ cosmology:
- Collapse occurs when according to linear perturbn theory

  $\delta_{LIN}(t_{coll}) = (\delta\rho/\rho)_{LIN} = \delta_c = 1.69$
- V. similar result in ΛCDM cosmology
- So perturbn with initial amplitude δ_i at t_i collapses at time t_{coll} given by:

  $\delta_i D(t_{coll})/D(t_i) = \delta_c$

  where $D(t) \propto t^{2/3} \propto 1/(1+z)$ is growth factor in linear perturbn theory
- For $\Omega=1$, $t_{coll} = t_i (\delta_c/\delta_i)^{3/2}$ => $(1+z_{coll}) = \delta_{LIN}(t_0)/\delta_c$

Overdensity of just-collapsed halo in spherical collapse model

- Assume halo reaches virial equilibrium after collapse
- Energy conservation + Virial theorem =>

  $GM/R_{turn} = GM/2R_{vir}$

  so $R_{vir} = R_{turn}/2$
- So for $\Omega=1$, mean overdensity is

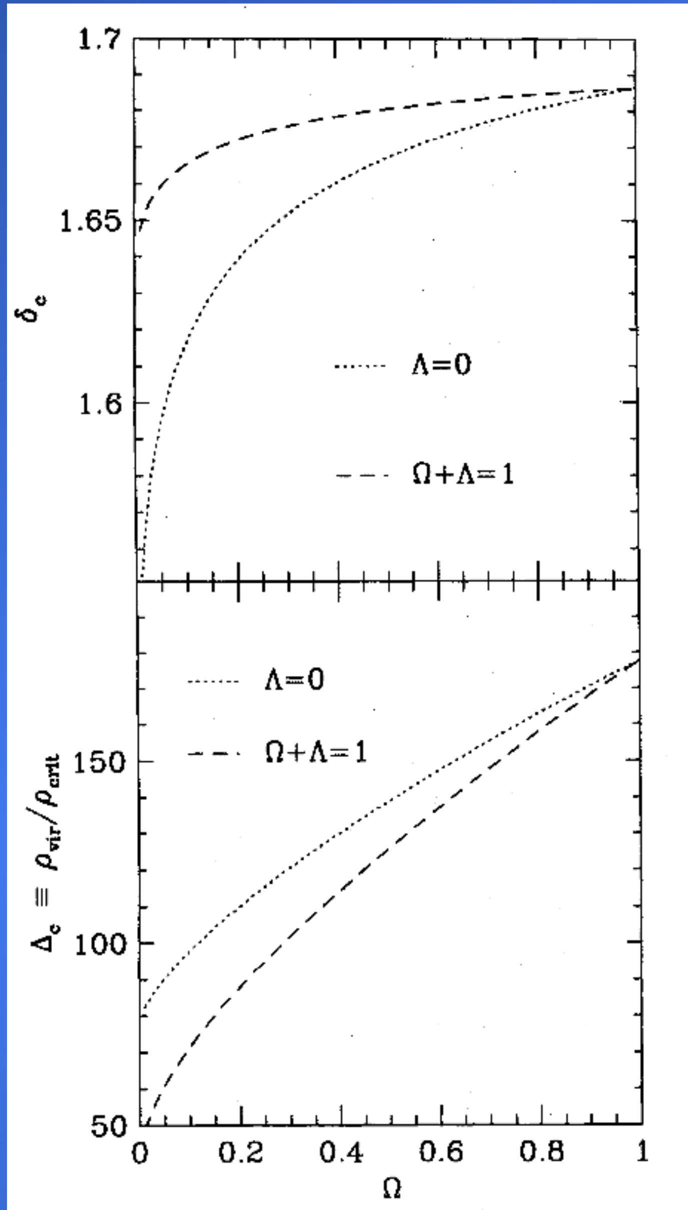
  $\rho(\text{halo})/\rho(\text{background}) = 18\pi^2 = 178$
- Similar for ΛCDM cosmology
- So halos at redshift z have mean density

  $\rho_{vir}(z) \sim 100\ \rho_{av}(z)\ \alpha\ (1+z)^3$

Results from spherical collapse model

For open & flat cosmologies

Eke et al 1996



Critical linear perturbn overdensity for collapse

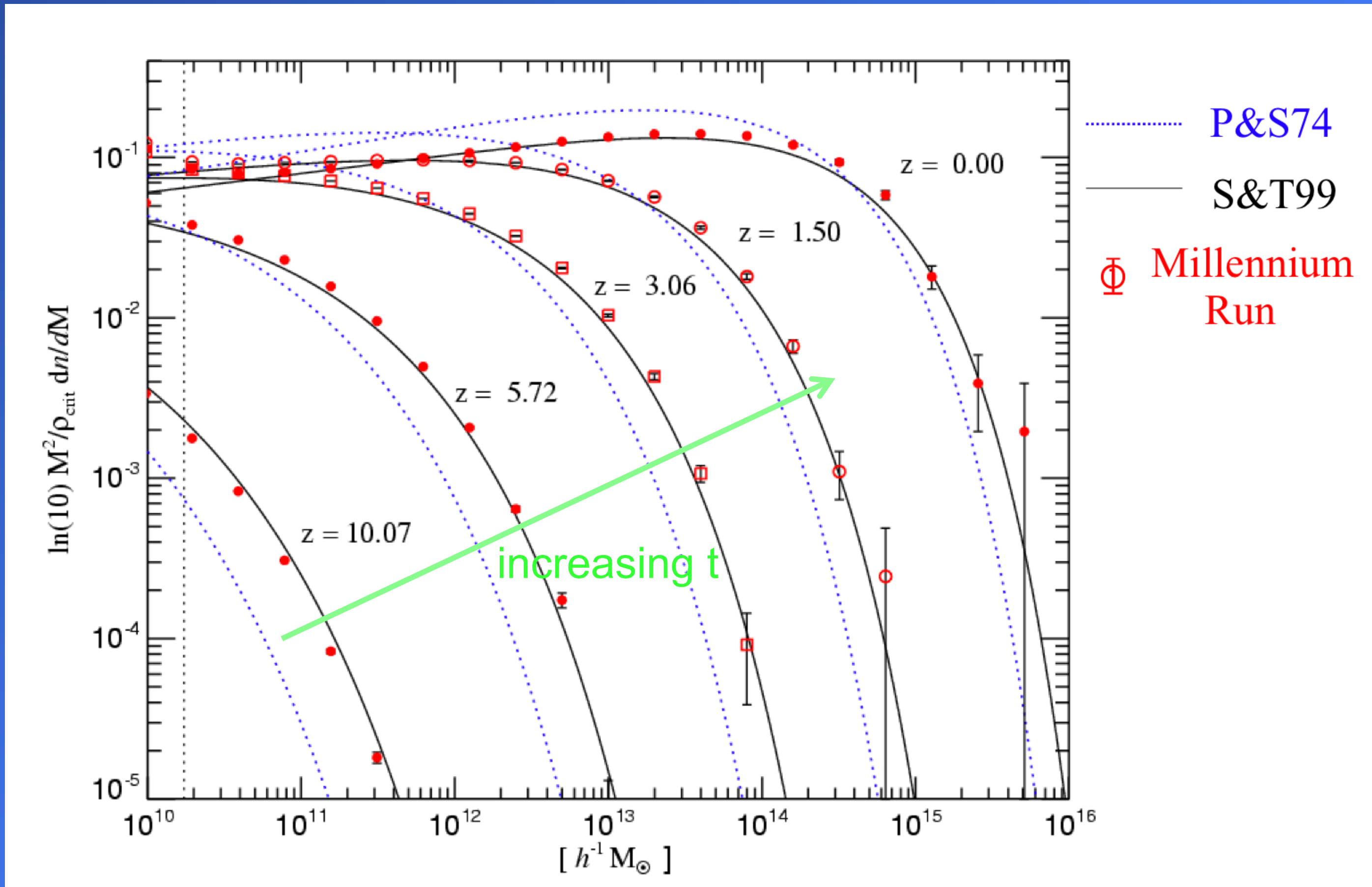
Mean overdensity (relative to critical) for just-virialized halos

Mass function of DM halos

dn/dM = number density of halos per unit halo mass M

$(M^2/\rho)\, dn/dM$ = fraction of total DM density in halos per $\ln M$

Halo mass function: simulations vs analytical models



- wide range of halo masses at any time
- characteristic mass increases with time due to hierarchical buildup of structure

y-axis gives fraction of total mass per log10 range in M

Press-Schechter mass function

(Press & Schecter 1974, Bond et al 1991)

- analytical model for halo mass function based on:
  - spherical collapse model for perturbns
  - Gaussian statistics for linear density perturbns
- predicts main features of halo mass function:
  - exponential cutoff at high-M
  - divergent power-law behaviour for dn/dM at low-M

$$\frac{dn}{dM} = n(M) = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M^2} \frac{\delta_c}{\sigma(M)} \left| \frac{d\ln\sigma}{d\ln M} \right| e^{-\left(\frac{\delta_c^2}{2\sigma^2(M)}\right)}$$

δ_c = collapse threshold, $\sigma(M)$ = r.m.s $(\delta\rho/\rho)_{LIN}$ in sphere of mass M

Sheth-Tormen mass function

(Sheth & Tormen 1999, Sheth et al 2001)

- Obtain even better fit to simulated halo MFs if allow for ellipsoidal collapse (instead of spherical collapse)

$$f(\sigma;\mathrm{S{-}T}) = A\sqrt{\frac{2a}{\pi}}\left[1+\left(\frac{\sigma^2}{a\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}\exp\left[-\frac{a\delta_c^2}{2\sigma^2}\right]$$

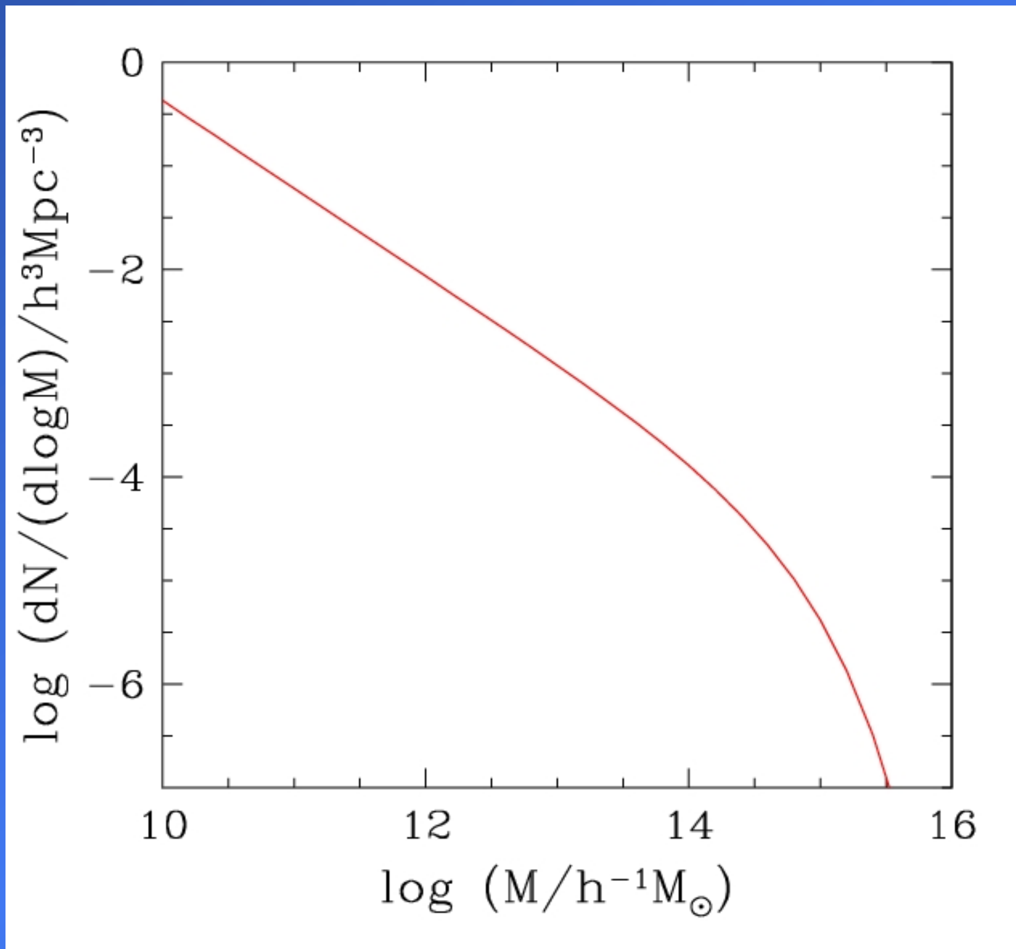
$$A = 0.3222,\ a = 0.707 \text{ and } p = 0.3$$

- where f(σ) = (M/ρ) dn/dlnσ
- value of p follows from ellipsoidal collapse

  a from fit to simulations

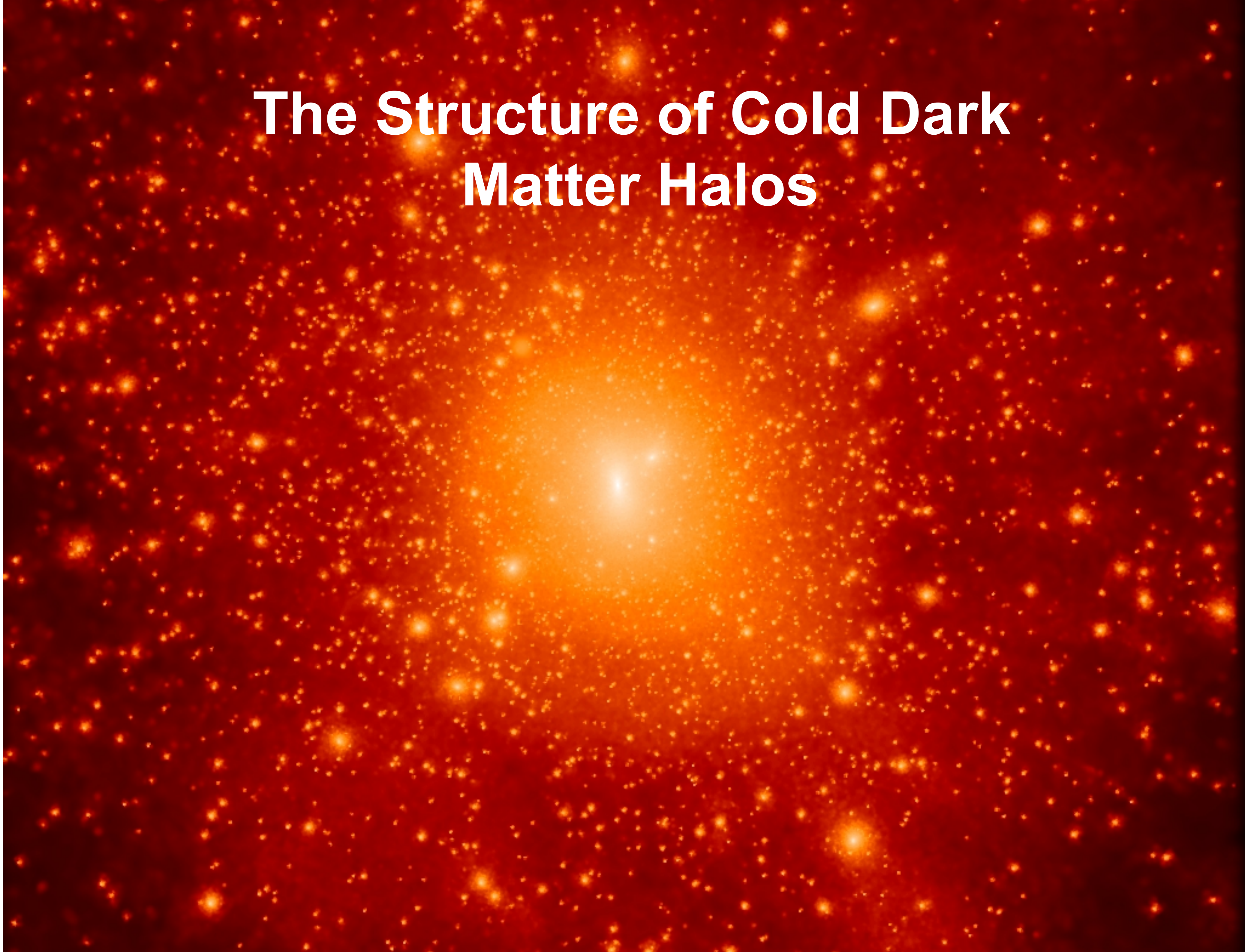
  A from normalization of MF

Sheth-Tormen halo mass function for CDM at z=0



- dn/dM α M^{-2} (approx) at low M
- exponential cutoff above $M \sim 10^{14}$ M_o

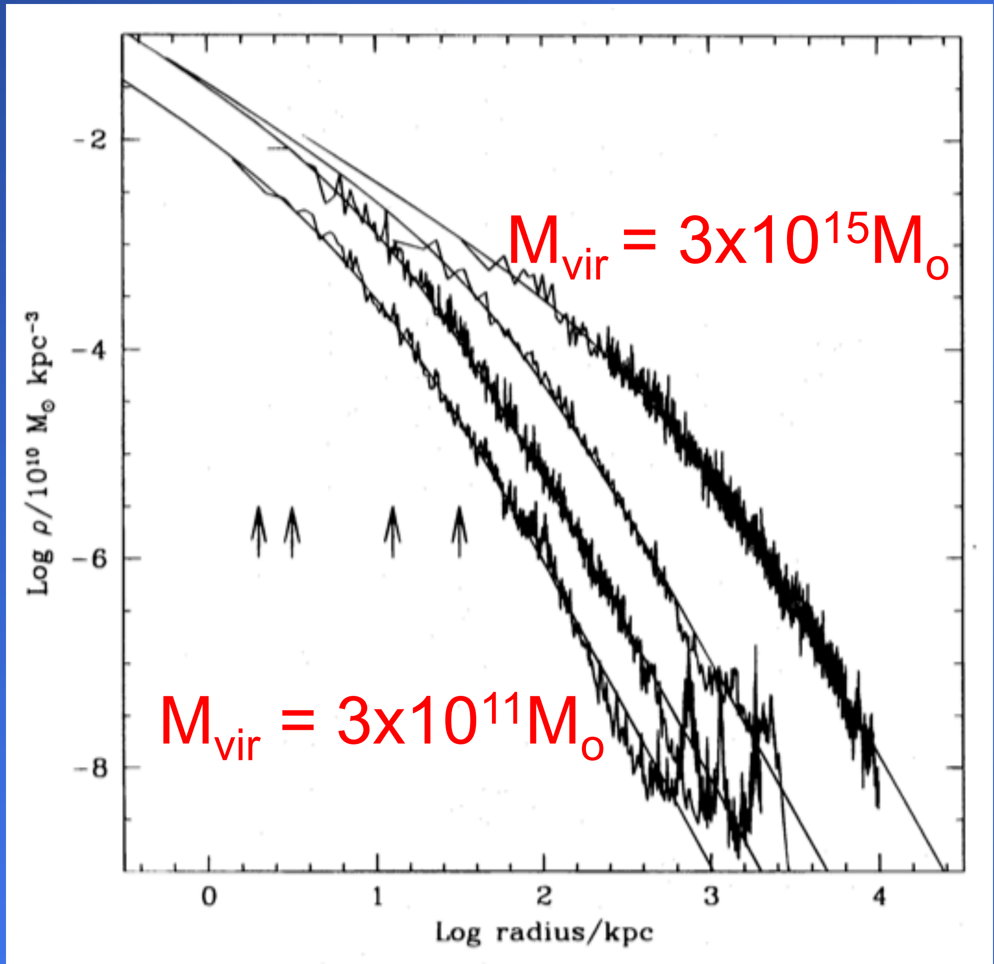
The Structure of Cold Dark Matter Halos



Structure of dark halos in CDM

- DM halos assemble by merging smaller objects
- however, tidal forces strip most of DM off halos as merge
- resulting halos have most (~90%) of DM in smooth, roughly spherical component
- only ~10% of DM remains in bound substructures orbiting in main halo
- halos are in approx dynamical equlibrium for $r<r_{vir}$, such that mean $\rho(<r_{vir}) \sim 100\rho_{av}$ (as predicted by spherical collapse model)

Halo density profiles



Navarro et al 1997 (NFW)

- halos of all masses have very similar density profiles:

$$\rho(r) \propto \frac{1}{r(1 + r/r_s)^2}$$

- $r_s = r_{vir}/c$, where concentration c ~ 5-20, weakly varying with M & z
- low-M halos (which form earlier) have larger c