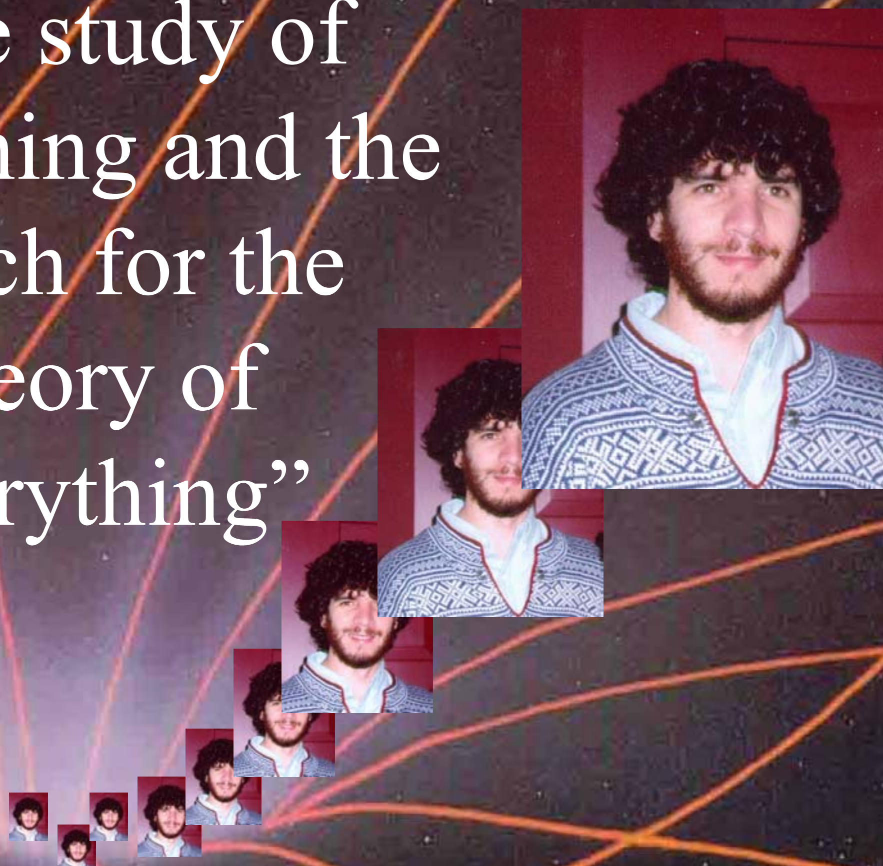
CIAR The Canadian Institute for Advanced Research

Cosmology and Gravity Program

“The study of everything and the search for the theory of everything”



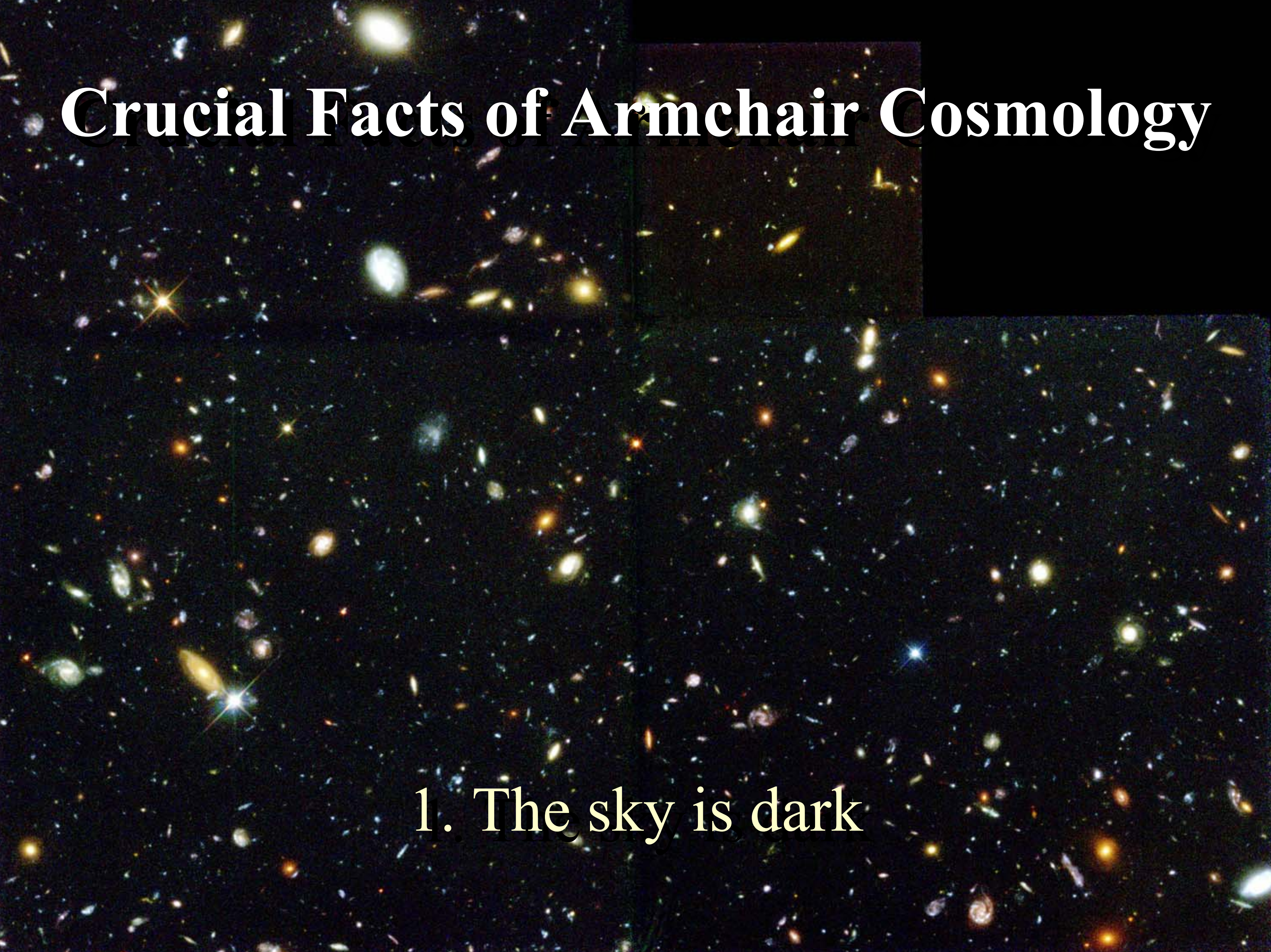
Julio F. Navarro
Julio F. Navarro

UVic

Lecture Plan

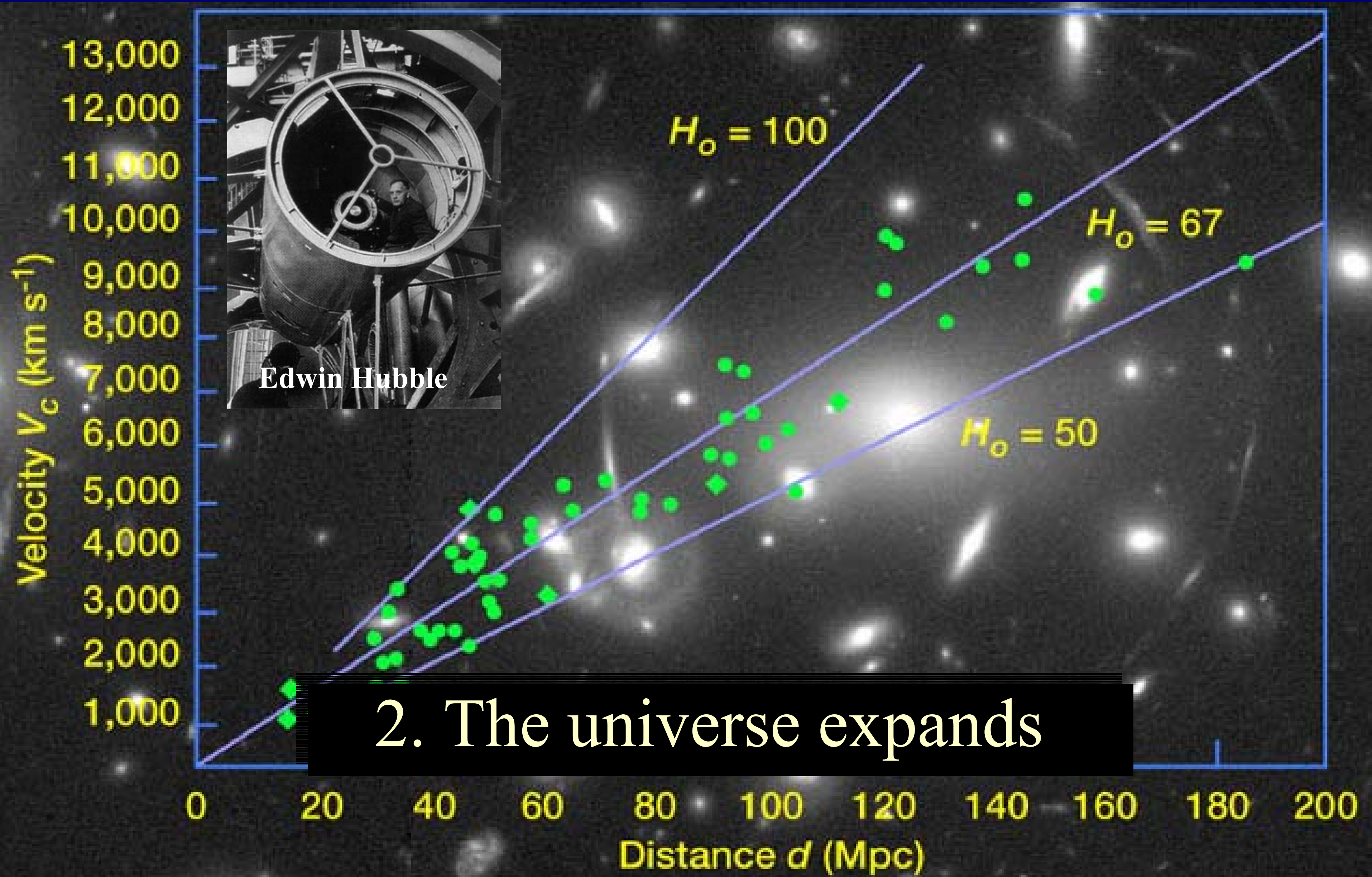
- **Lecture 1:**
  - The Unperturbed Universe: A Cosmology Primer
- **Lecture 2:**
  - The Perturbed Universe: Statistics of Hierarchical Clustering
- **Lecture 3:**
  - The Dark Universe: Dark Matter Halos, Structure and Substructure
- **Lecture 4:**
  - The Local Universe: The Milky Way and its Cosmological Context

Crucial Facts of Armchair Cosmology



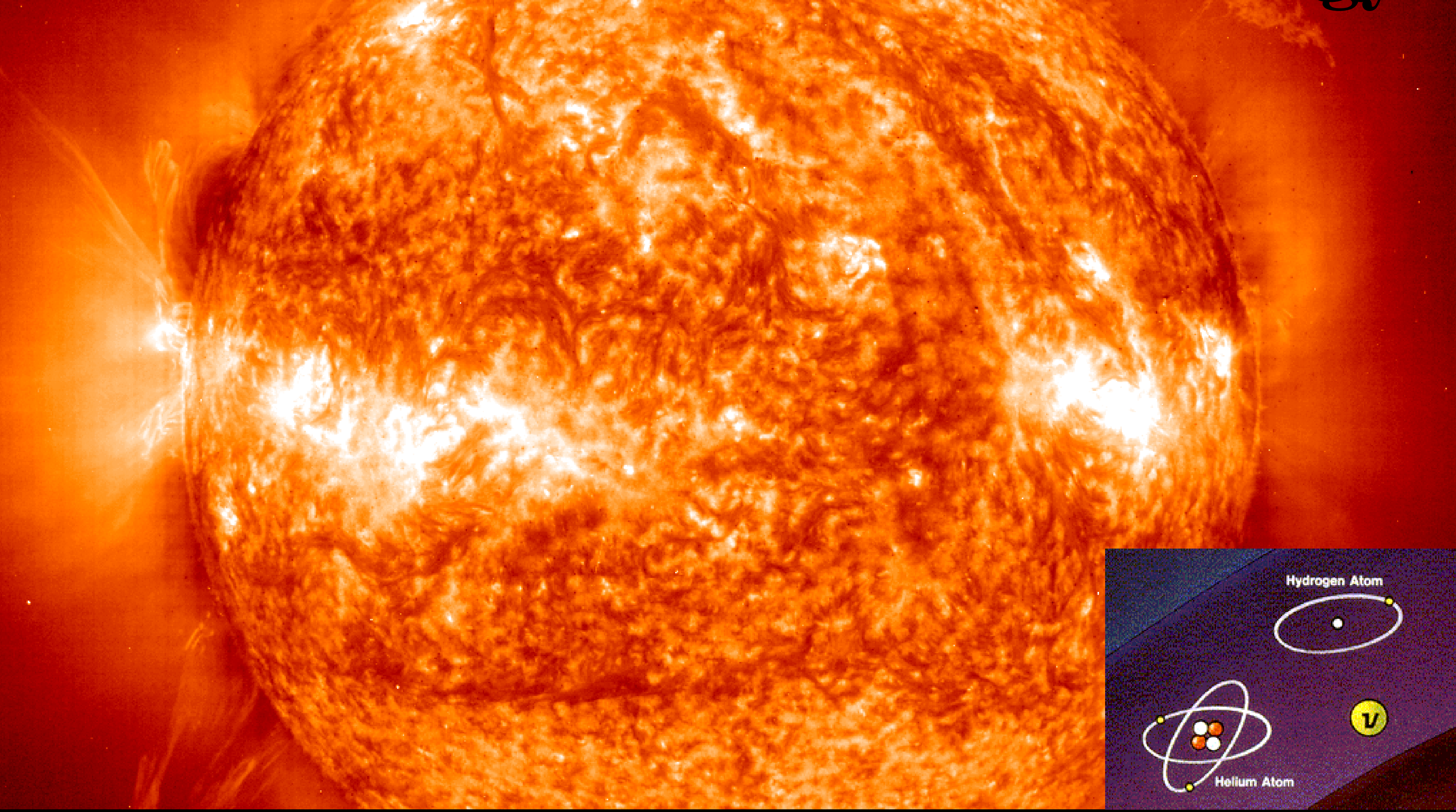
1. The sky is dark

Crucial Facts of Armchair Cosmology



2. The universe expands

Crucial Facts of Armchair Cosmology



3. Most of the luminous matter is hydrogen

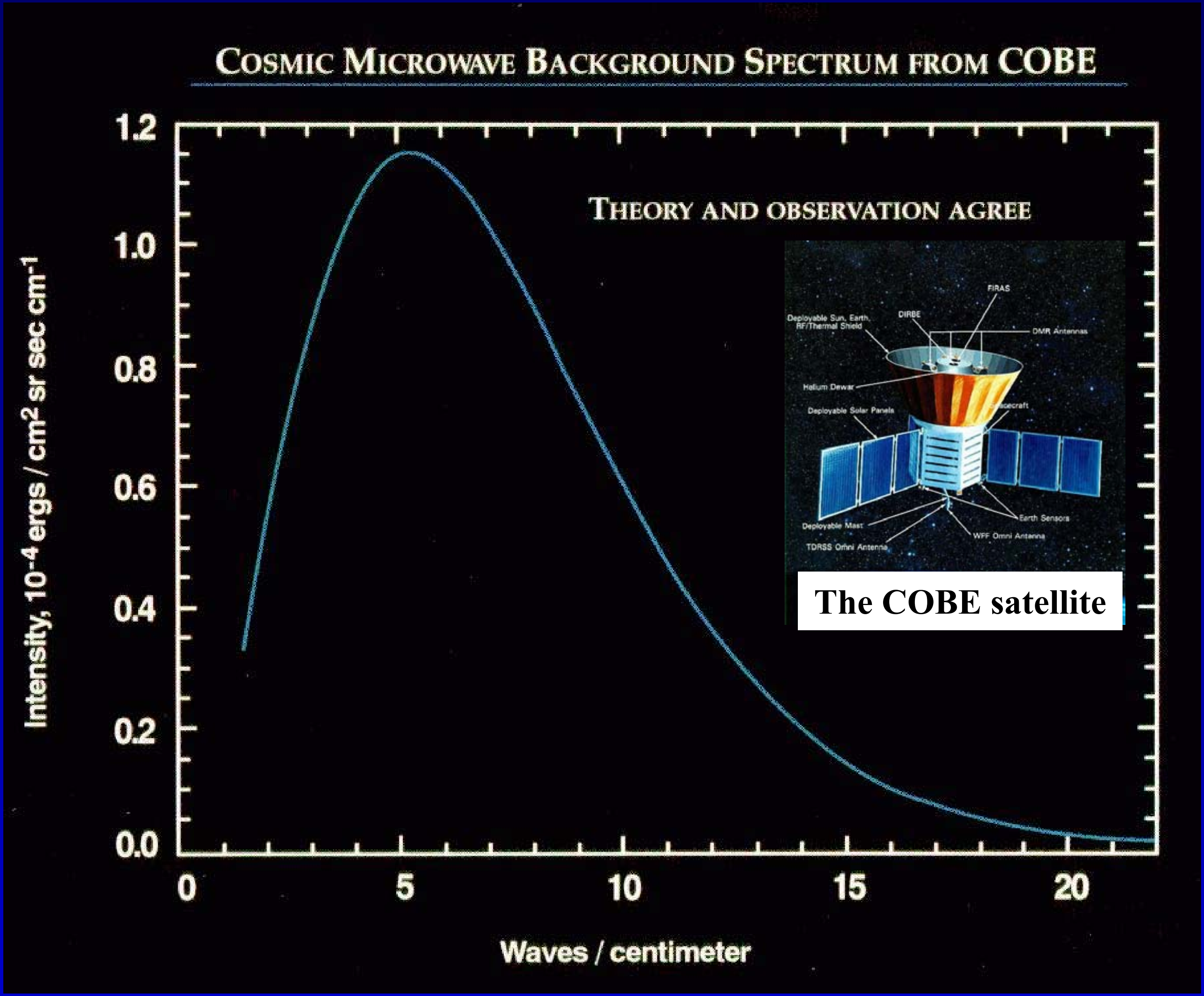
The Consequences

- The observable universe is finite
- The universe was once much denser and hotter than today
- The universe is filled with light: a background of photons left over from the Big Bang
  - The Cosmic Microwave Background

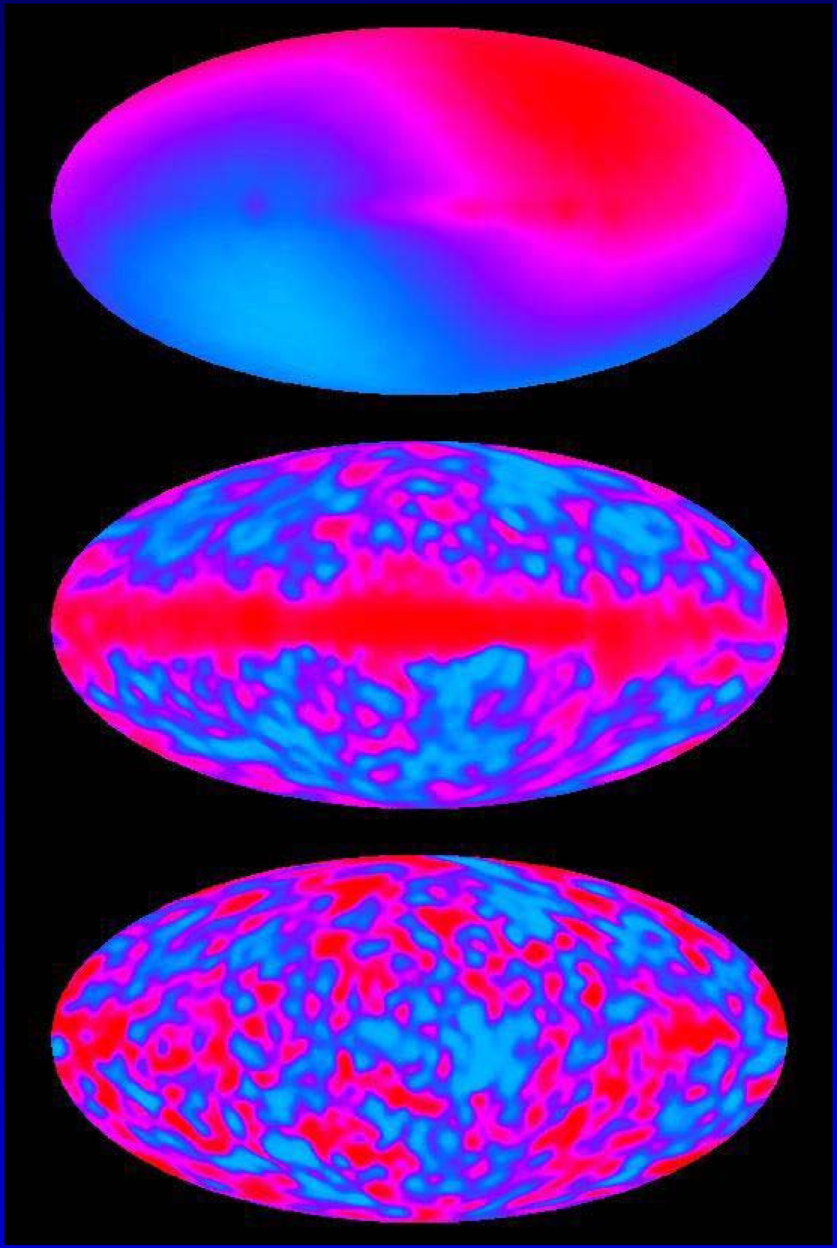
The Echo of the Big Bang

- In 1964, Arno Penzias and Robert Wilson were carrying out experiments using a microwave antenna for satellite communications.
- As they pointed the antenna towards the sky, their receiver registered a faint ‘hiss’ coming from all directions that would not go away.

The Perfect Black Body



COBE Maps -- Light from the farthest frontier

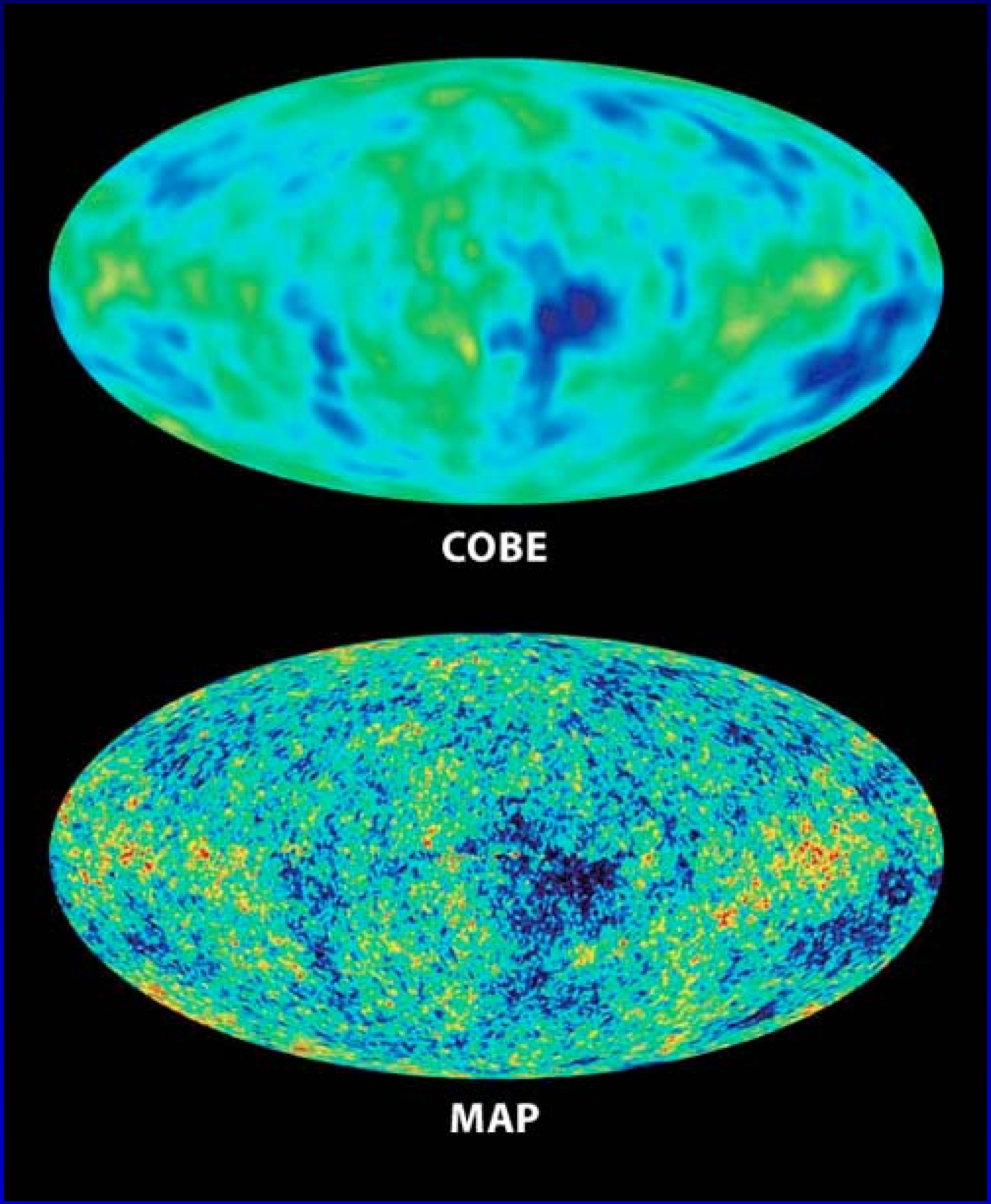


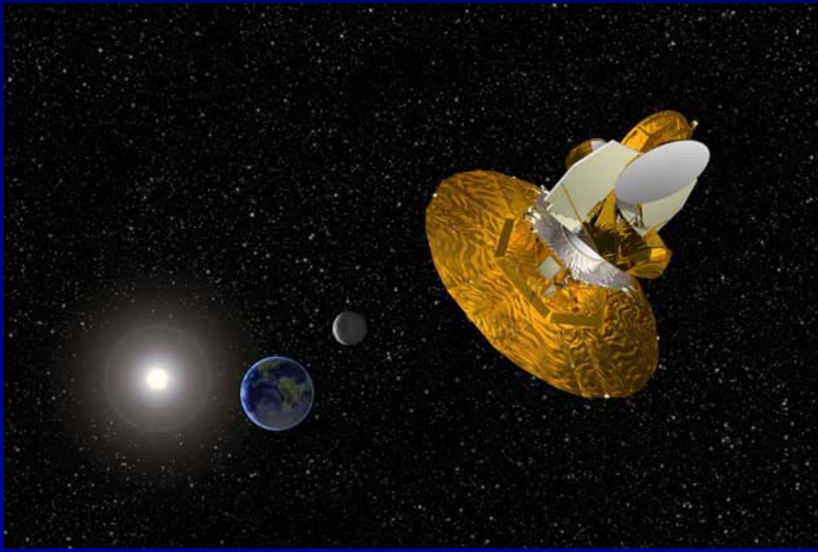
Our motion
through the universe

Dust in our own
Galaxy

Primordial Fluctuations

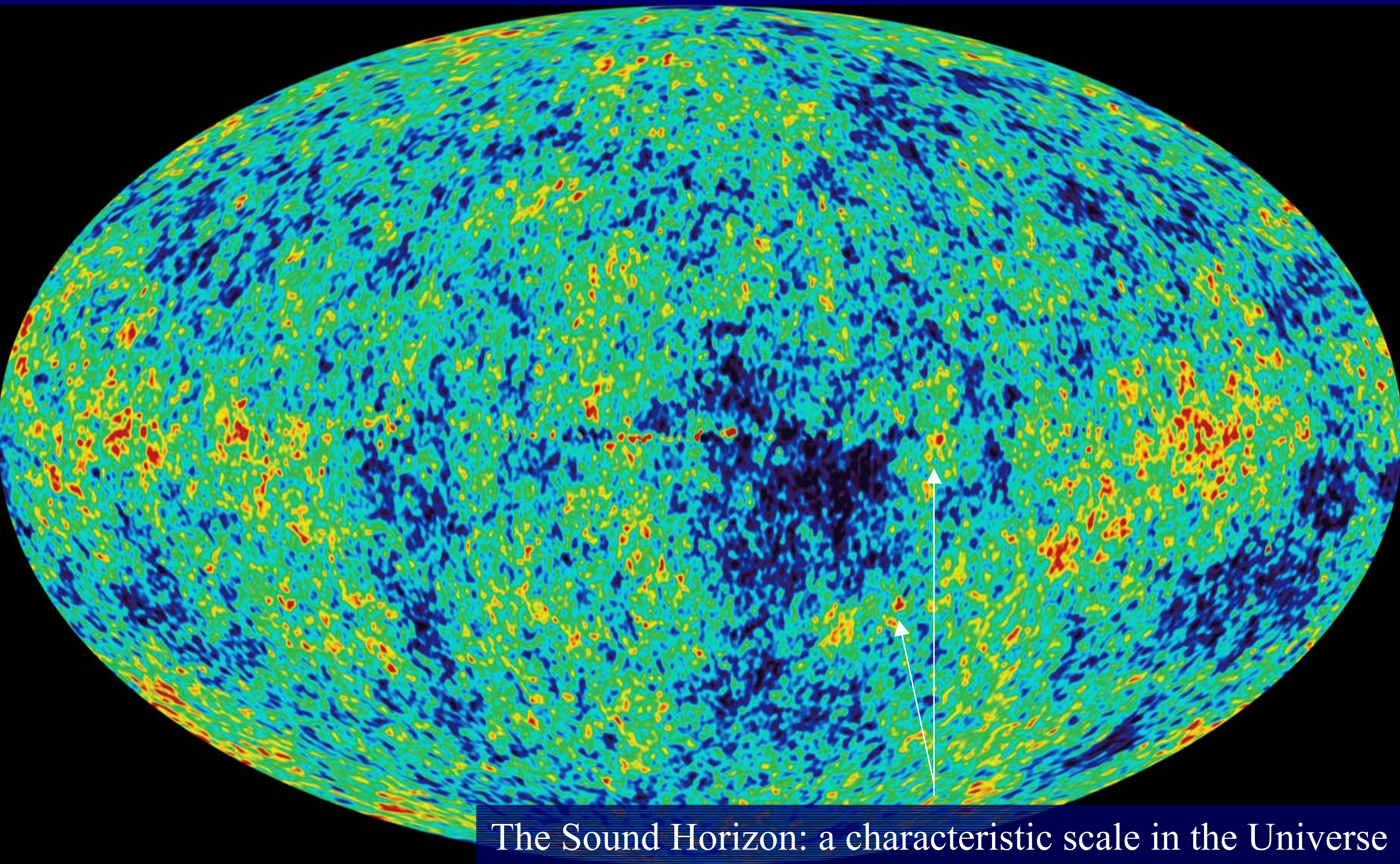
A sonogram of the baby universe





- Emitted when the Universe was 300,000 years old
- The most convincing proof that the Universe was not born uniform!

Light from the farthest frontier



The Sound Horizon: a characteristic scale in the Universe

CMB Angular Power Spectrum

- Statistical way to characterize the spatial structure in a 2-dimensional image or map

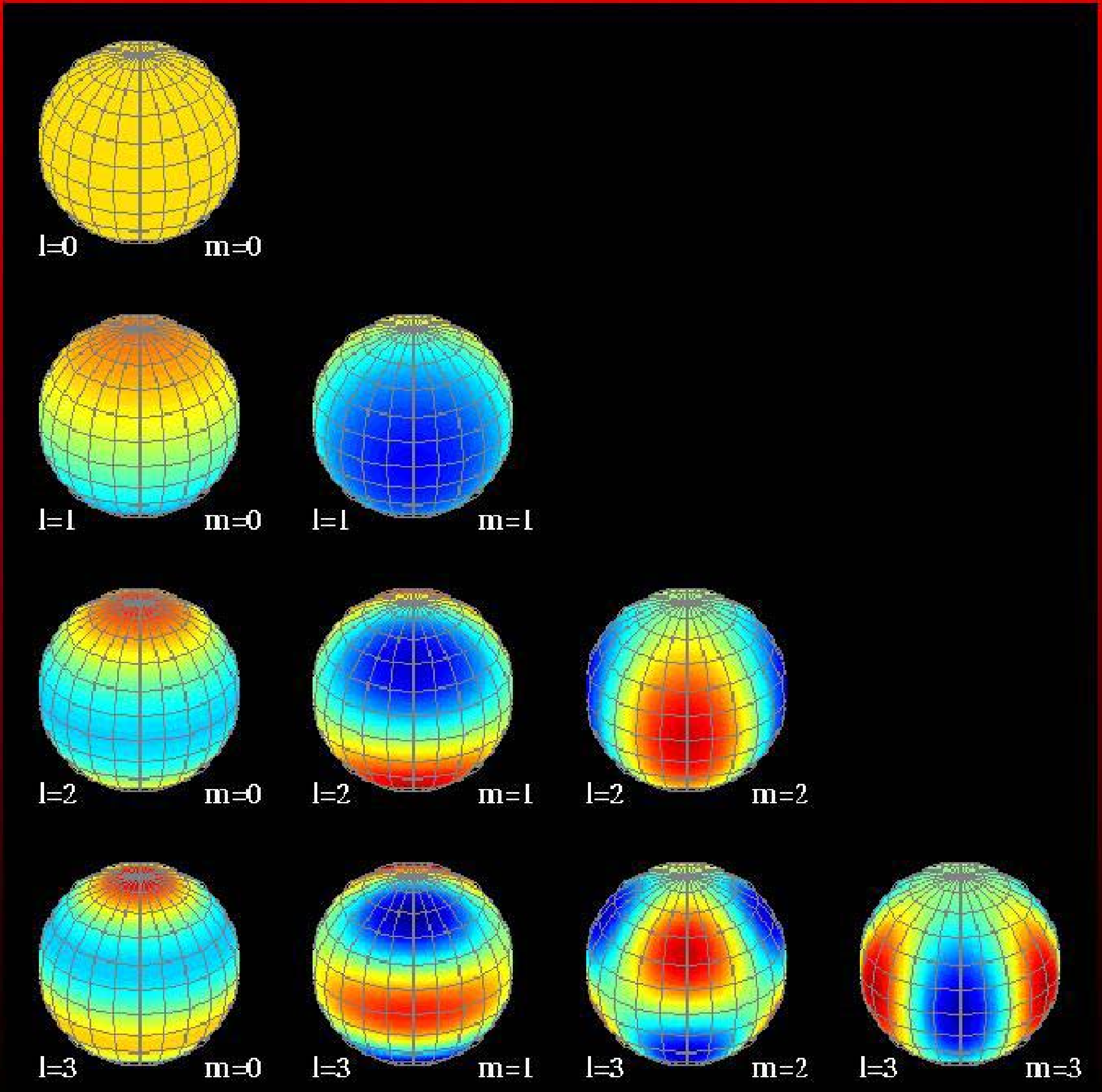
$$\Delta T/T = \Sigma\, a_{lm}\, Y_{lm}(\vartheta,\Phi)$$

$$C_l = \langle |a_{lm}|^2 \rangle$$

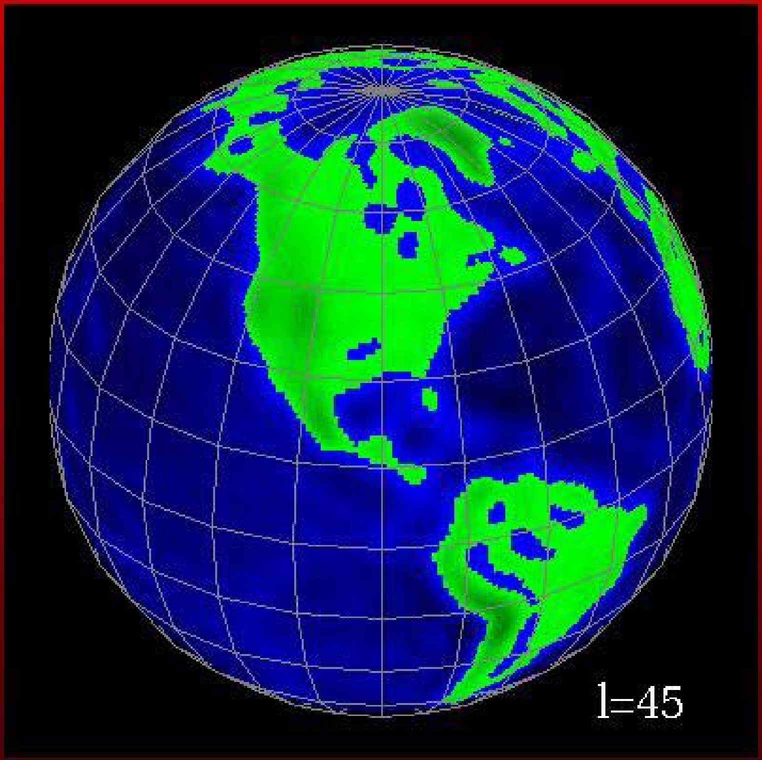
Power spectrum

•Power spectrum contains all the information if the image is Gaussian

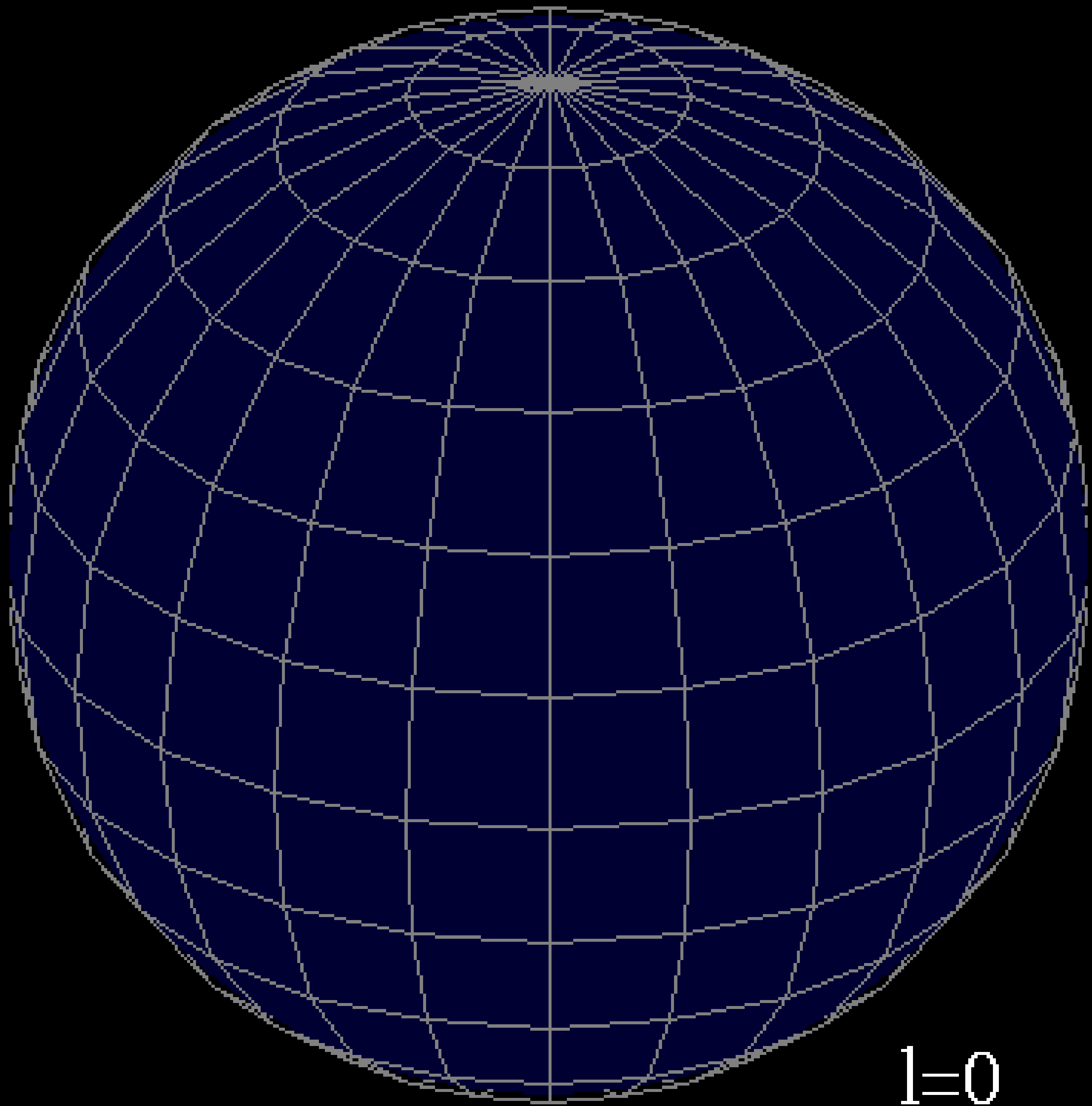
Spherical Multipoles



Topographic Map of the Earth



By adding up multipole patterns we can make any map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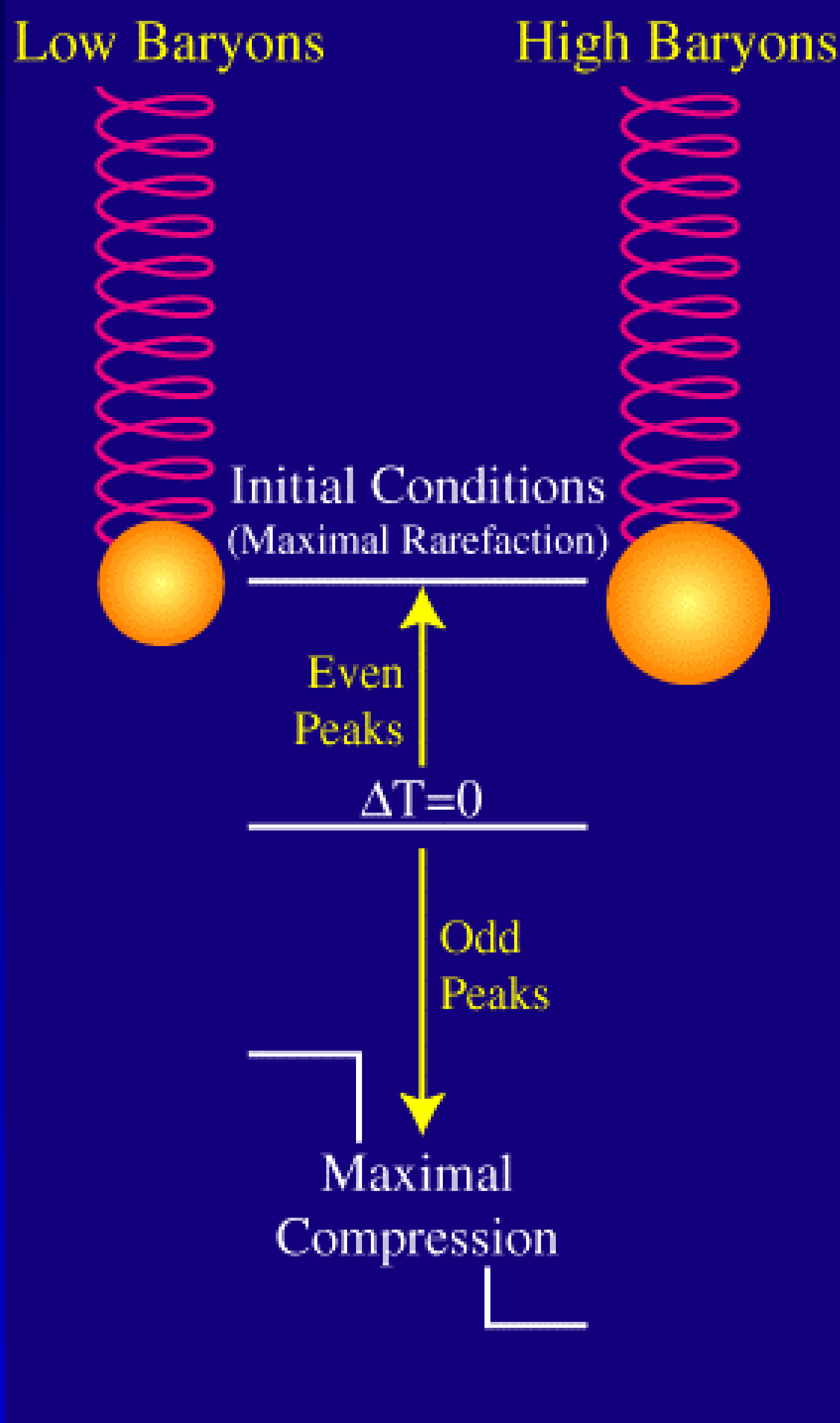
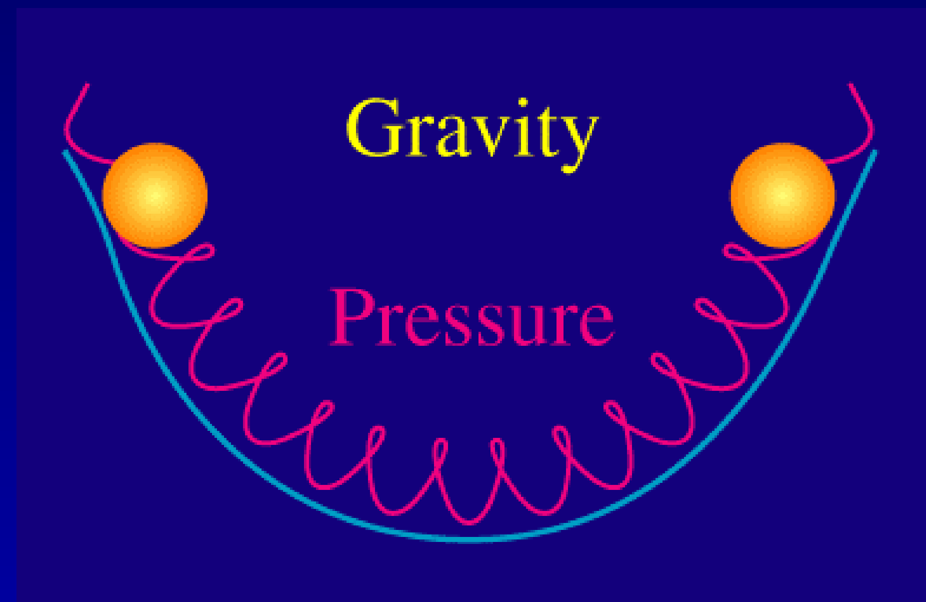
Physics of CMB Anisotropy



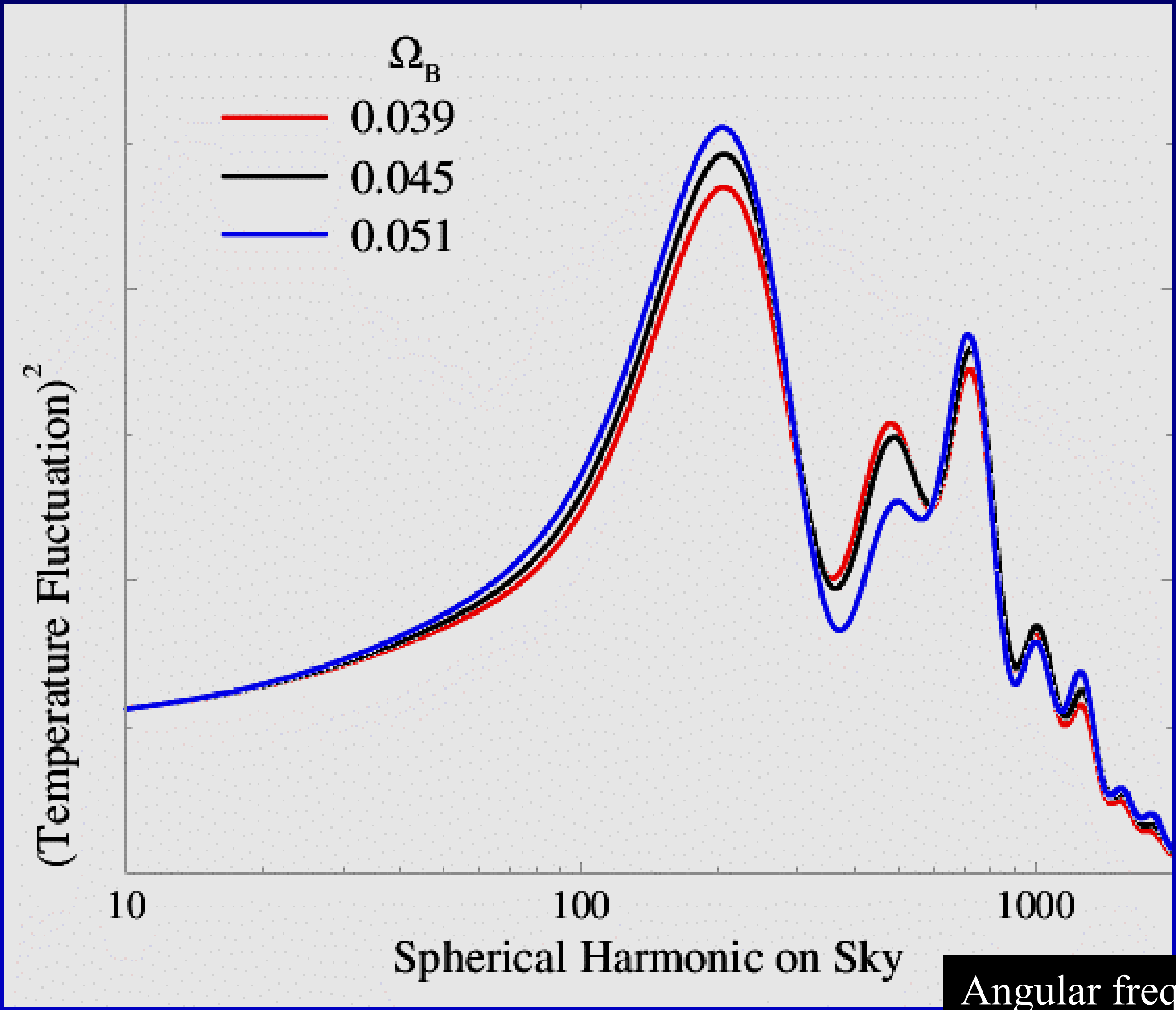


Acoustic oscillations of the Photon-baryon fluid when the Universe was 400,000 yrs old

→ Imprint on the Microwave sky

From Wayne Hu

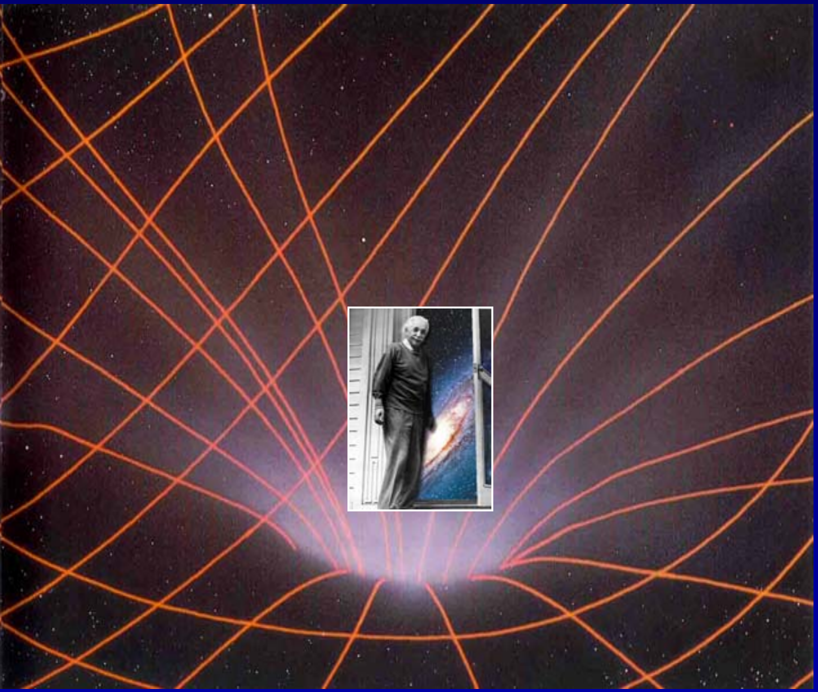
Theoretical dependence of CMB anisotropy on the baryon density

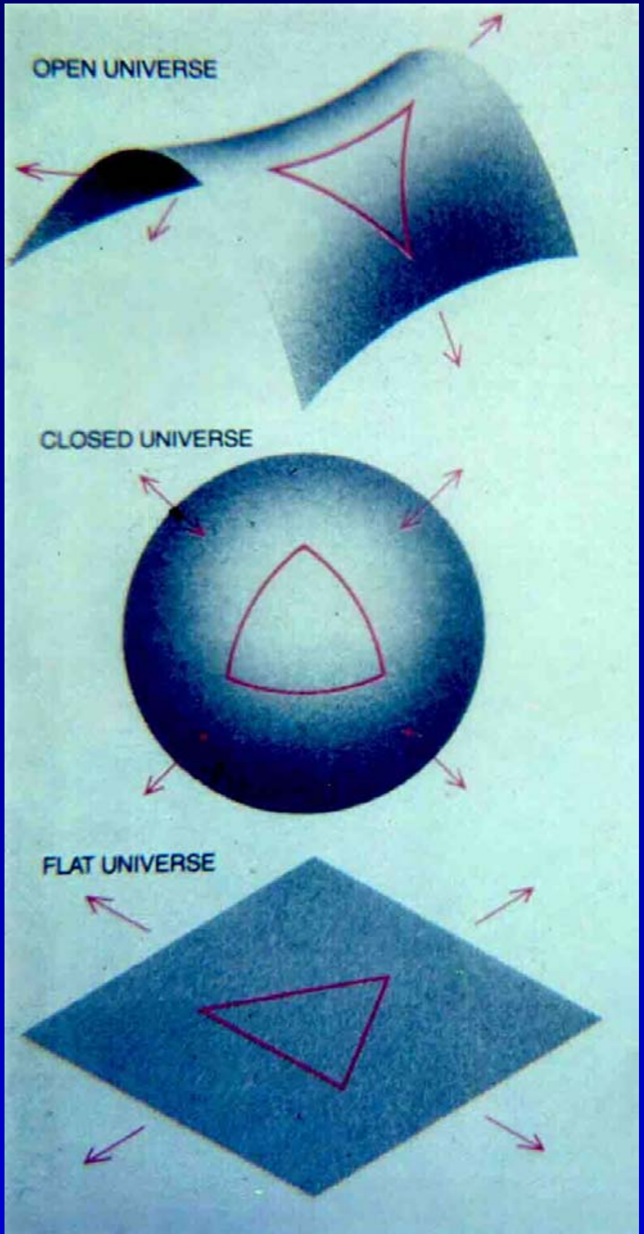


Angular frequency

Angular separation on the sky

Mass-Energy Content and Geometry of the Universe





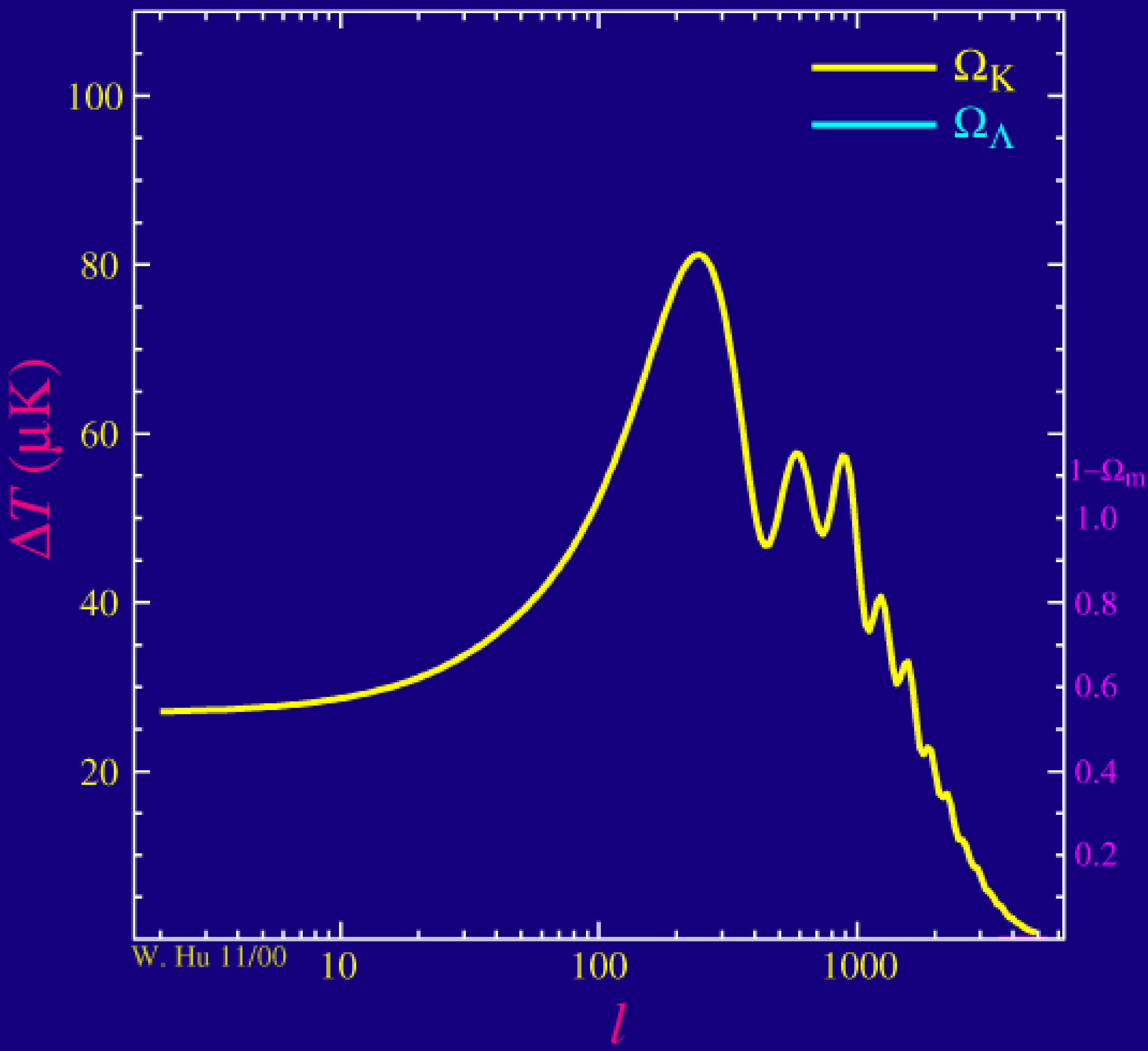
Too little matter & energy…

Too much…

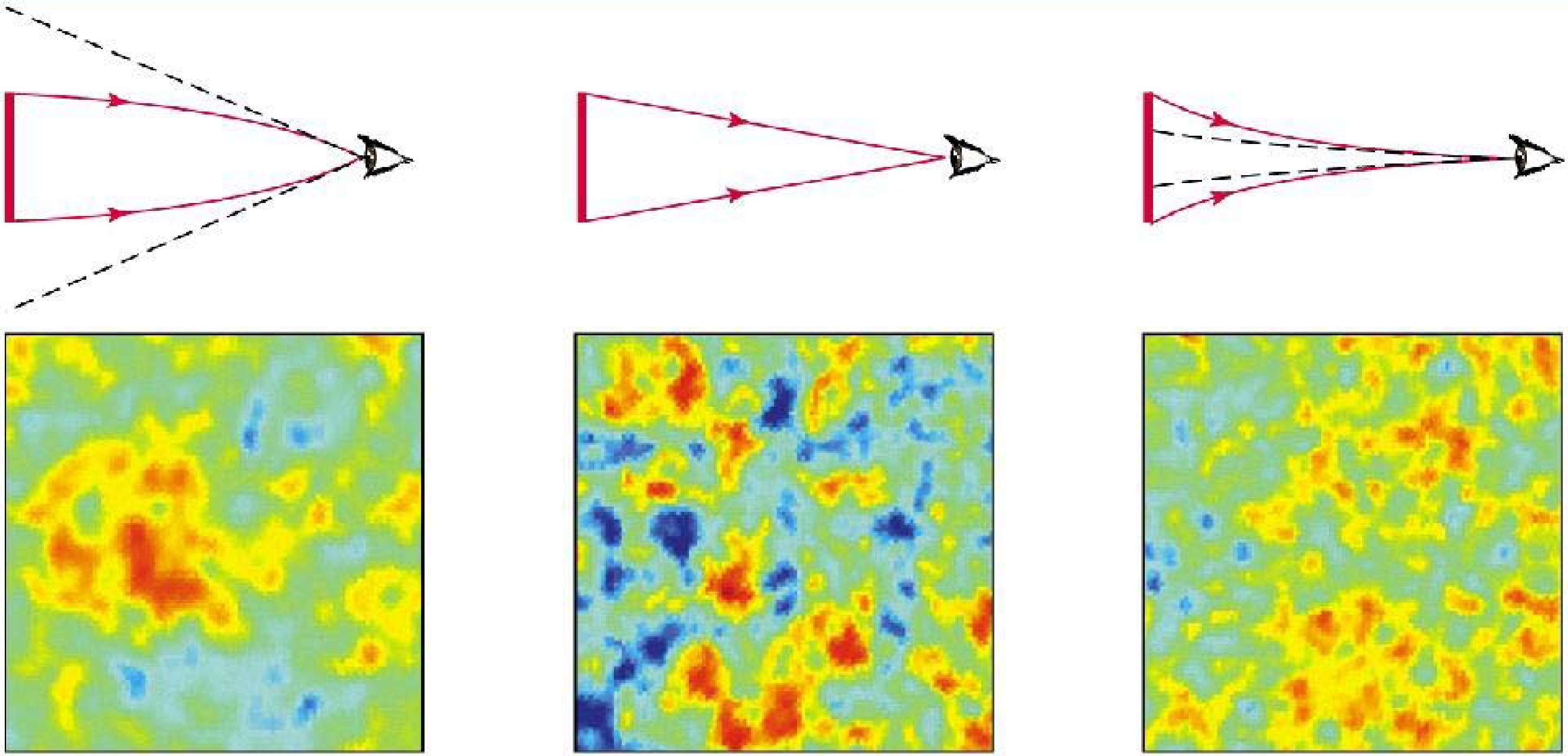
Just about right…

- Matter and Energy curve space!

Position of first Peak probes the spatial Curvature of the Universe



Seeing the Sound Horizon



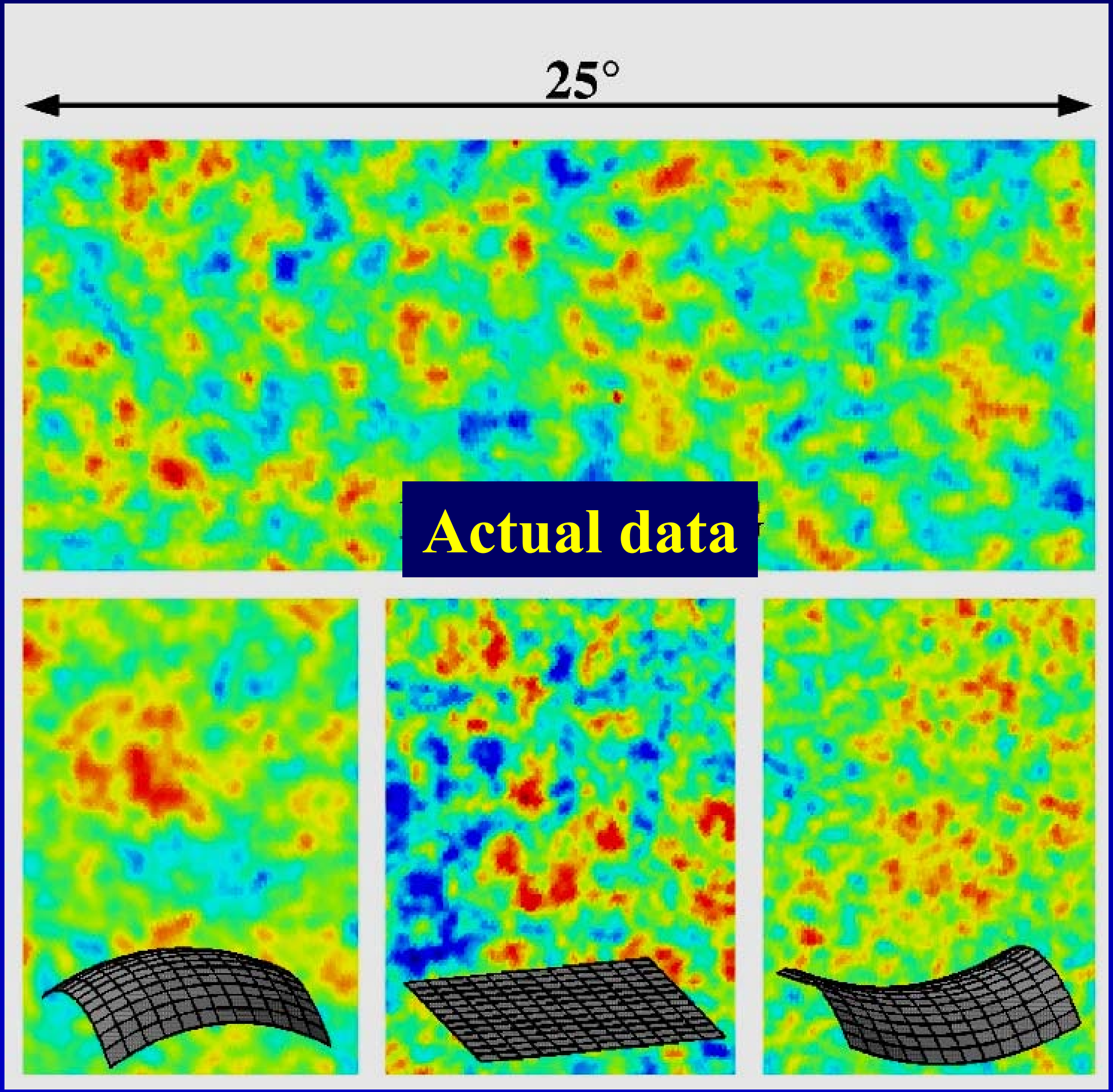
a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

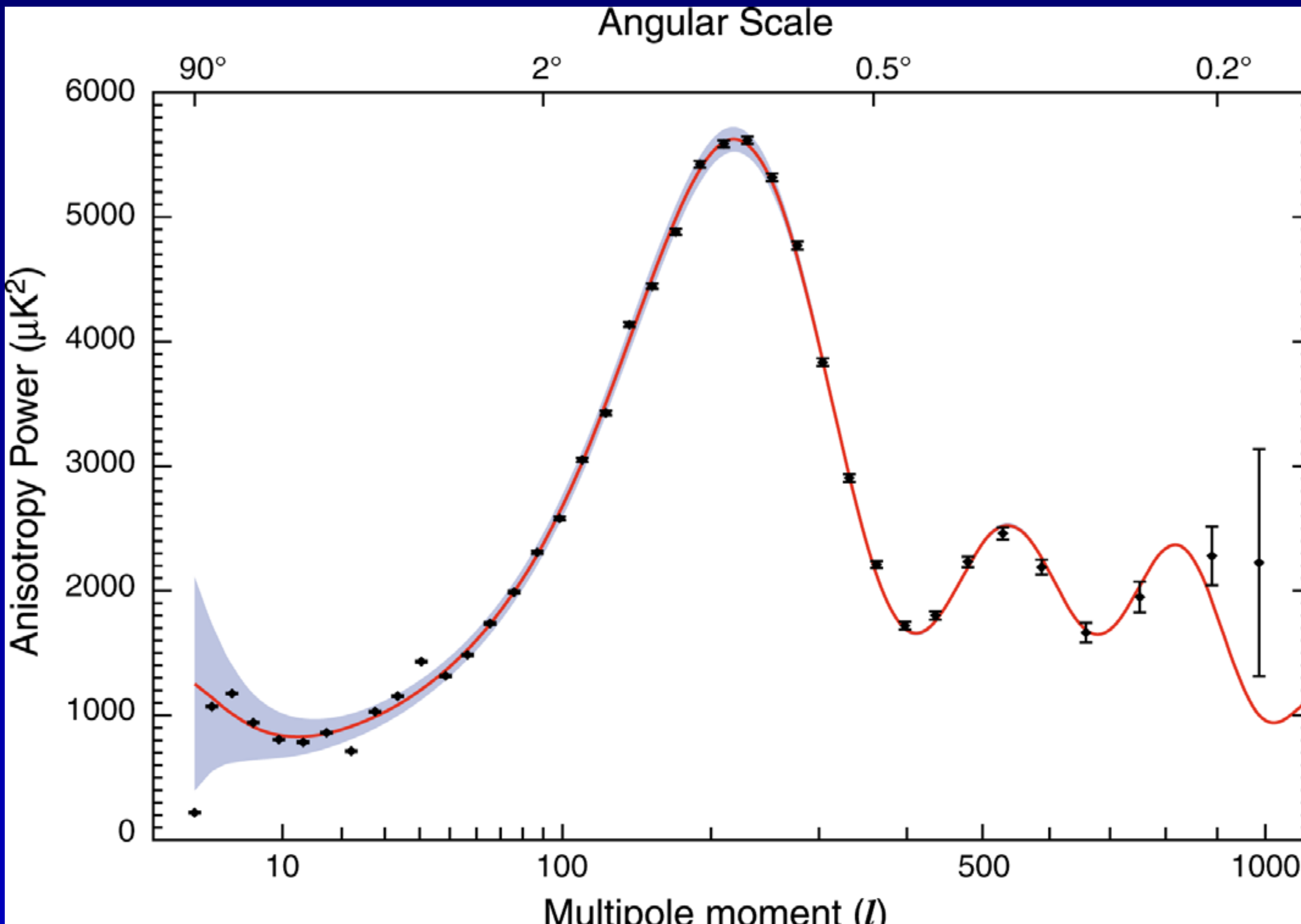
Sound horizon length = speed of light * age of the universe

The Flat Universe



$\Omega > 1$ $\Omega = 1$ $\Omega < 1$

The Latest from WMAP



Ω_m=0.238
Ω_b=0.042
Ω_k=0.0
h=0.73
Flat geometry

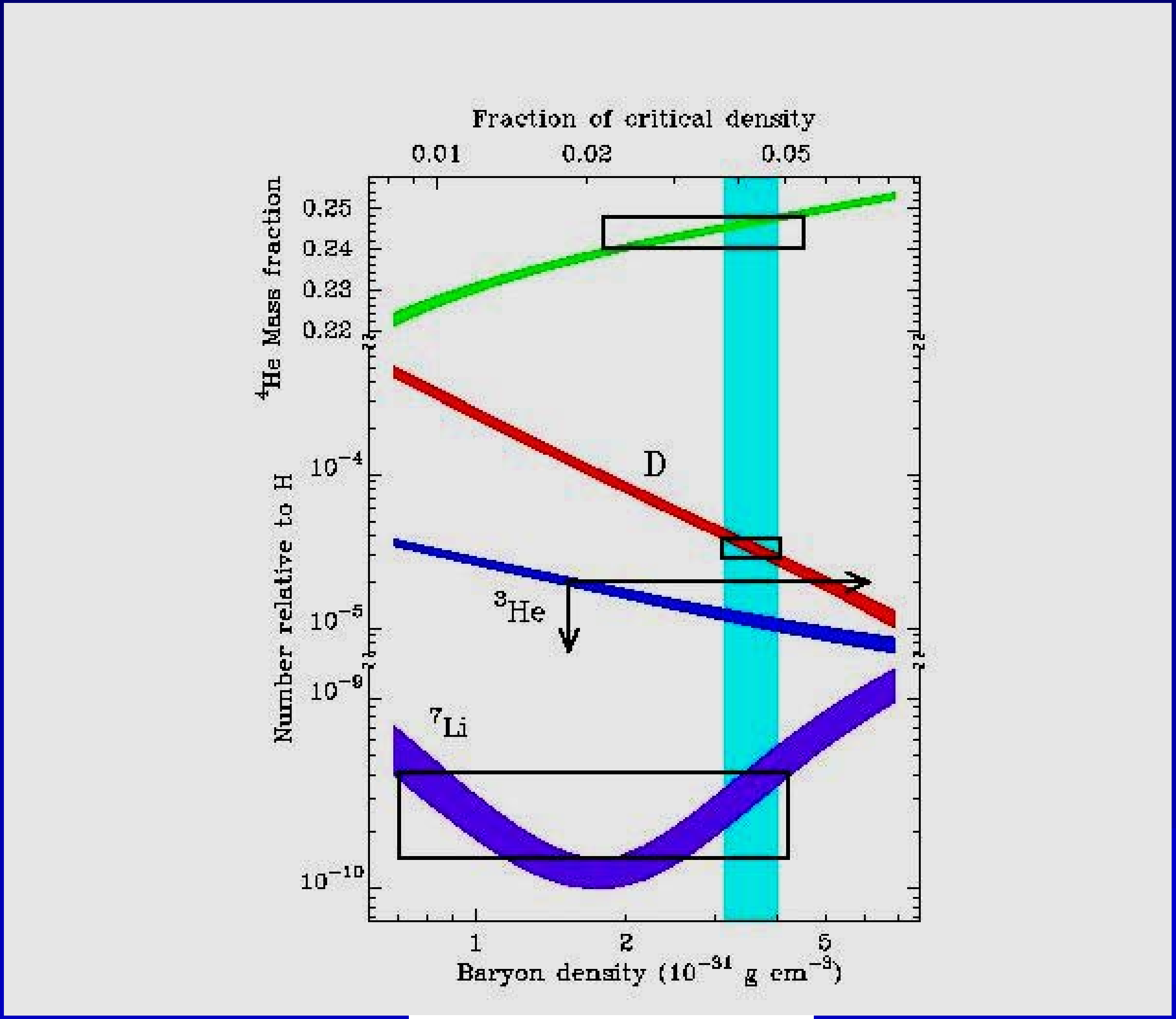
The "Concordance" Model (I)

- The geometry of the Universe is flat ($\Omega_{tot}=1$).
  - This puts strong constraints on the overall mass-energy density of the Universe.
  - What form does this mass energy-density take? (baryonic matter, photons, neutrinos, etc?)

The "Concordance" Model

- The geometry of the Universe is flat ($\Omega_{tot}=1$).
- Big Bang nucleosynthesis requires that ordinary matter (baryons) contribute less than about 4% ($\Omega_b \sim 0.04$) of the energy density required for this.

Big Bang Nucleosynthesis of the Light Elements…



$\Omega_b h^2 = 0.019$

The “Concordance” Model

- The geometry of the Universe is flat ($\Omega_{tot}=1$).
- Big Bang nucleosynthesis requires that ordinary matter (baryons) contribute less than about 4% ($\Omega_b \sim 0.04$) of the energy density required for this.
  - One can make further progress by looking at the expansion history of the universe. The “potential energy” depends on size as
    - (a) $\rho_{matter} \sim (\text{size})^{-3}$ (particle number density)
    - (b) $\rho_{photons} \sim (\text{size})^{-4}$ (number density + redshift)
    - (c) $\rho_{vacuum} \sim (\text{size})^{-0}$ (cosmological constant)

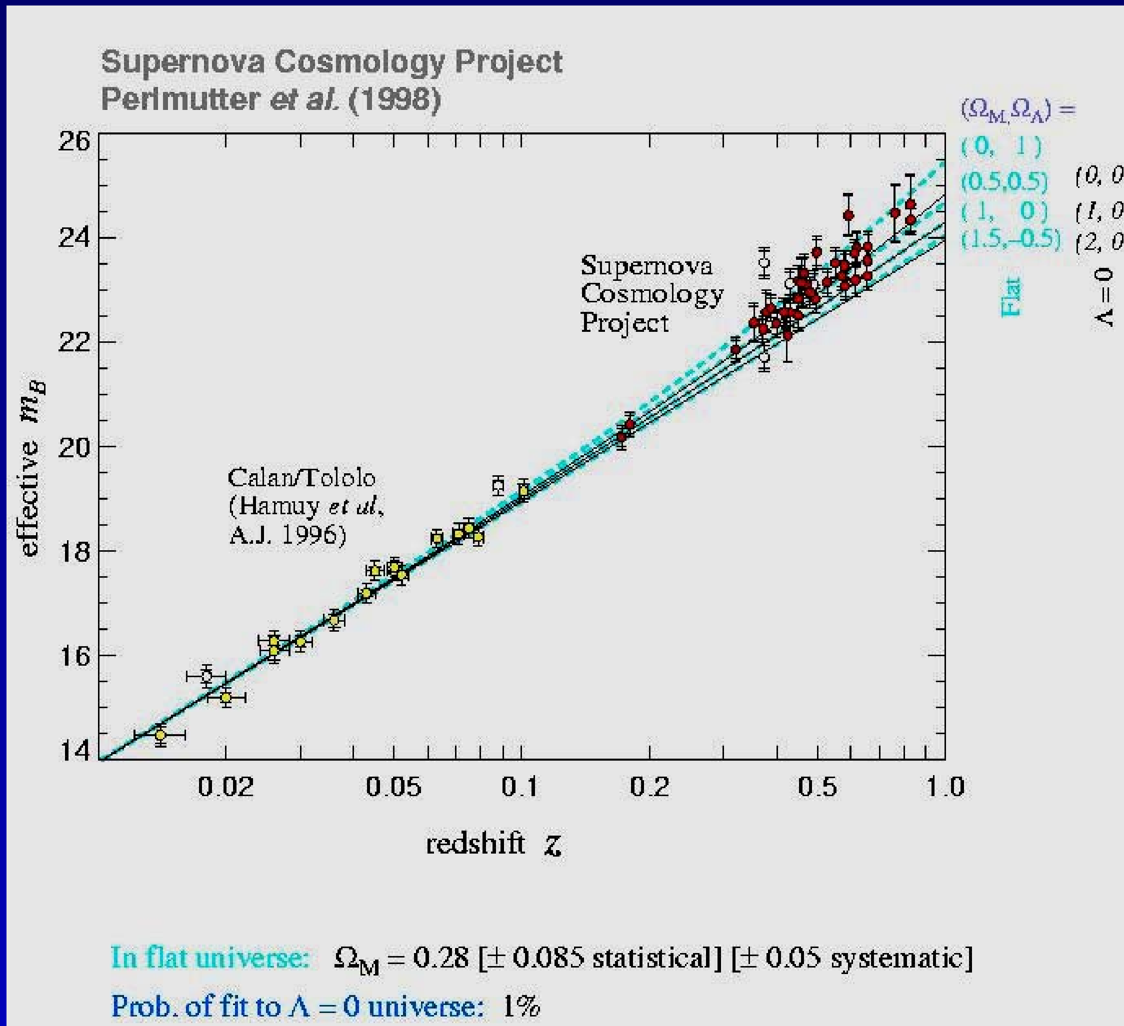
    - Expansion (the “kinetic energy”) will decelerate for (a) and (b) but will accelerate for (c), since the total vacuum energy will grow with size!
  - We need measurements that tell us the time it has taken the universe to, say, double in size.

Supernovae as standard candles

fainter→

Apparent Brightness

←brighter



The "size" of the universes measured by the stretching of the light frequency

•Standard candles--objects of fixed intrinsic luminosity--will appear fainter the faster the Universe expands (light must travel "farther" to reach us)

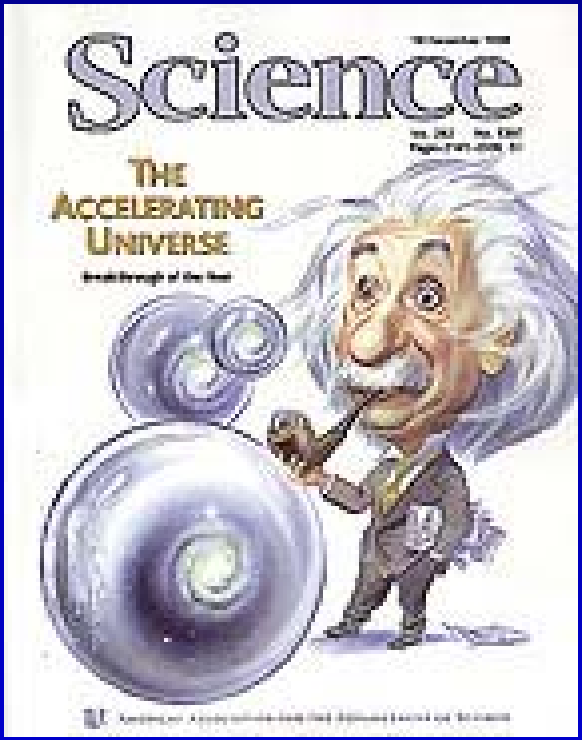
•One can use this to deduce the expansion history of the Universe!

The accelerating Universe

•Distant supernova are too faint, implying that their light has travelled farther than expected

➔ the cosmic expansion has been accelerating since the light was emitted.

(not slowing down as we used to think!)



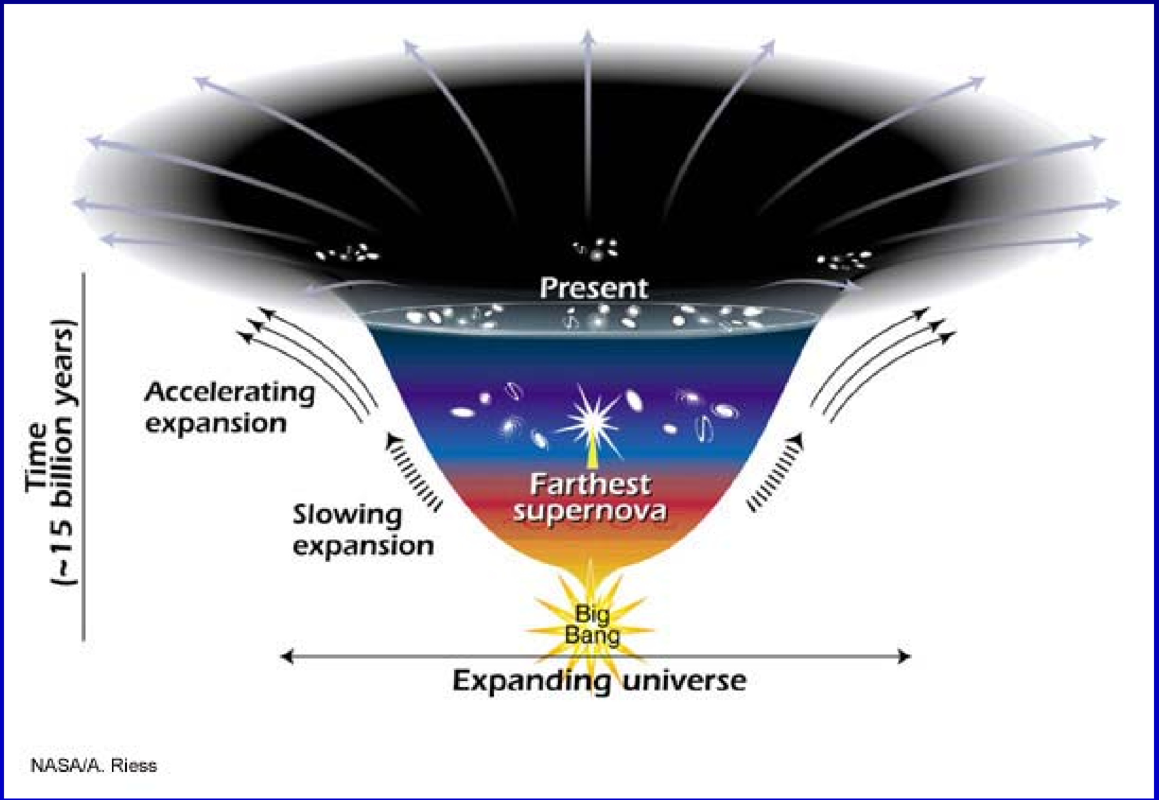
•But the expansion can only accelerate if there is a “repulsive force”; for lack of a better term this is referred to as

”Dark Energy”

The decelerating-accelerating Universe

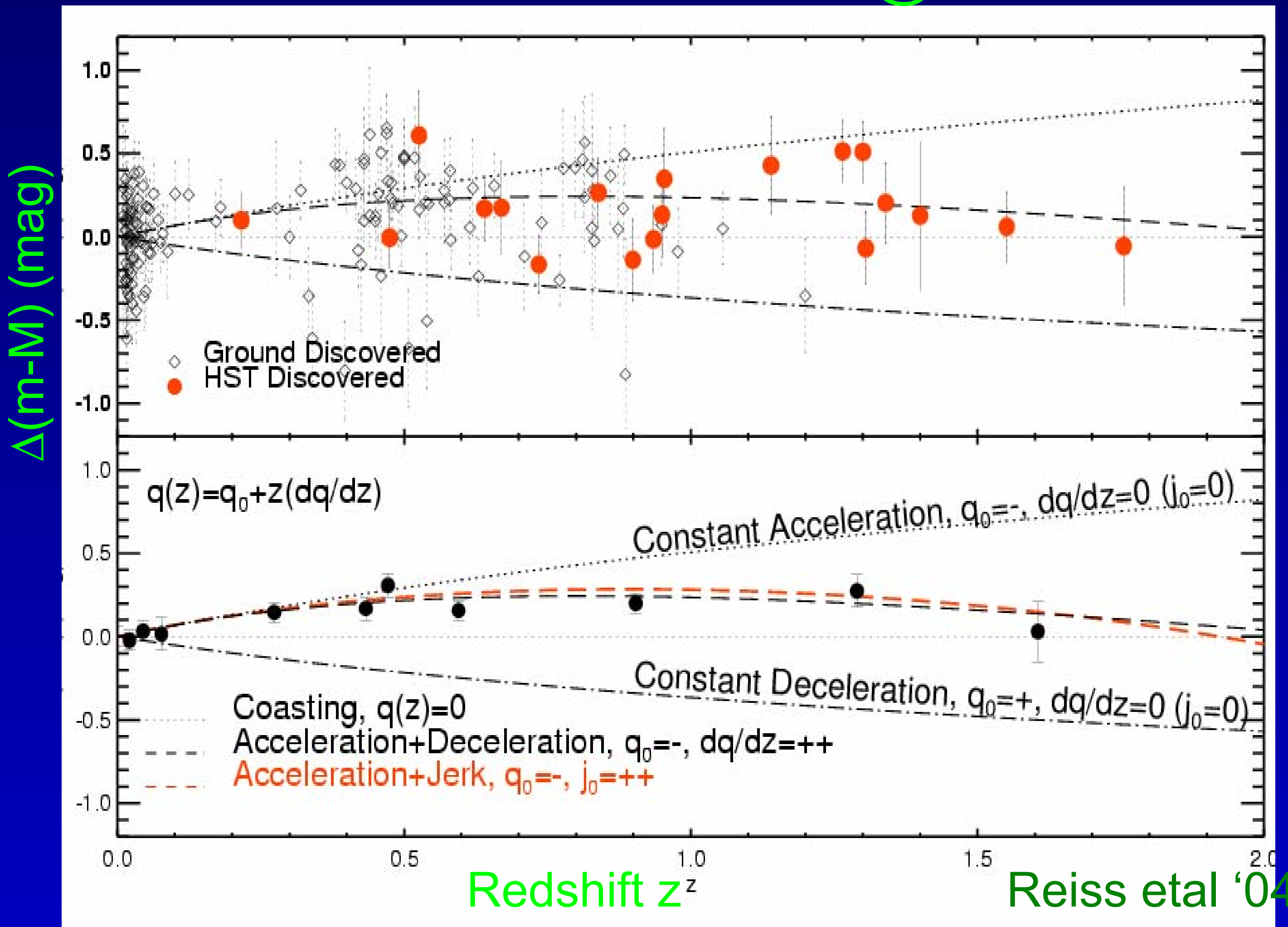
- Initially, gravity was able to slow the expansion of the Universe.
- But as the Universe expanded the repulsive force of the Dark Energy overcame gravity, causing the Universe to expand at an ever faster rate.

- The dark energy makes up the remaining 70% of the matter-energy content of a flat universe.



Supernovae Ia and dark energy

16 new Sn Ia -- 6 @ z>1.25

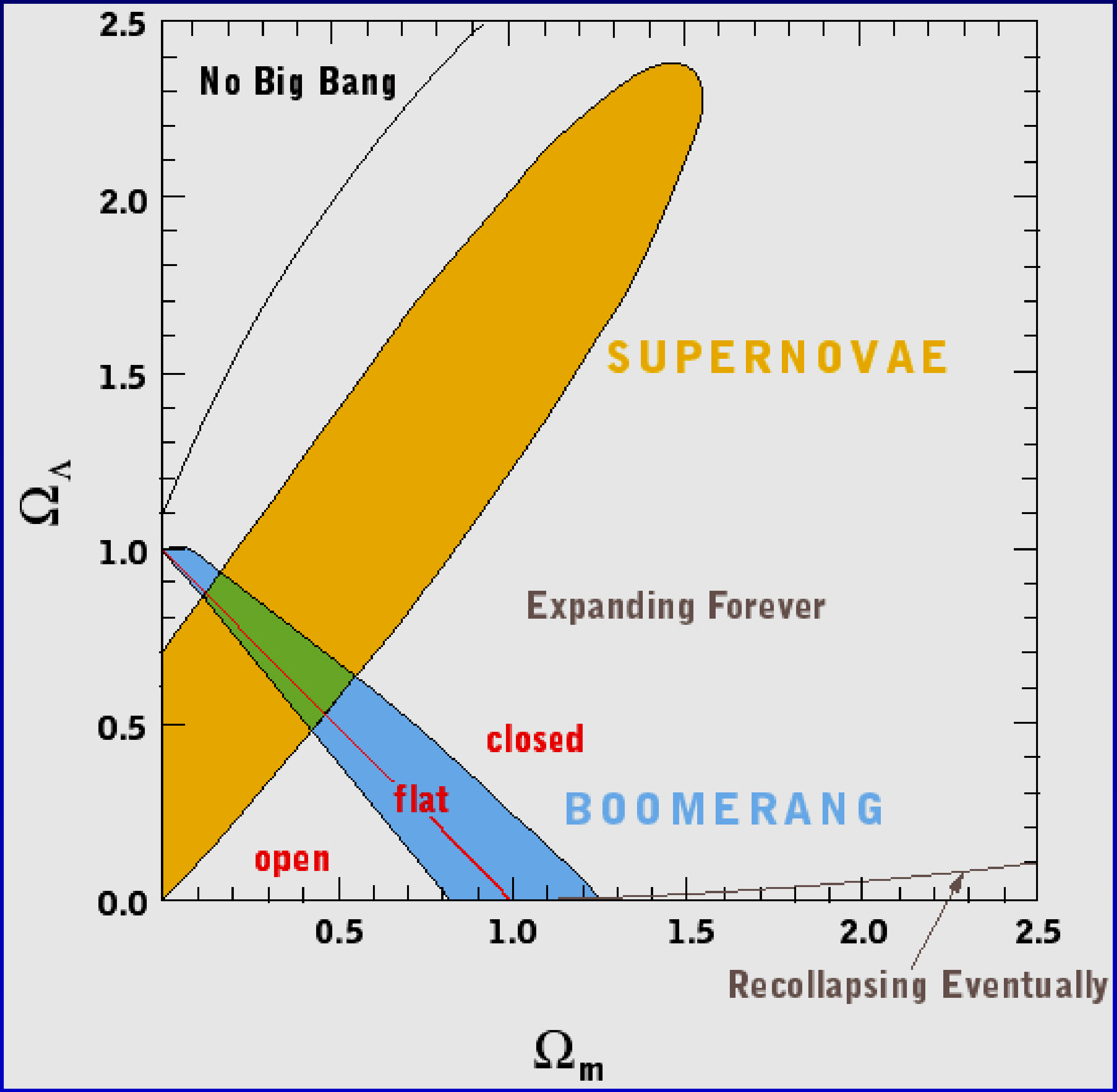


Transition from decelerated to accelerated expansion at ~0.5

The "Concordance" Model

- The geometry of the Universe is flat ($\Omega_{tot}=1$).
- Big Bang nucleosynthesis requires that ordinary matter (baryons) contribute less than about 4% ($\Omega_b \sim 0.04$) of the energy density required for this.
- Most of the energy content of the universe comes from some sort of "dark energy" (a cosmological constant?) which accelerates the expansion of the universe at present.

CMB and SUPERNOVAE



Cosmological Constant = Vacuum Energy

Matter Density

The "Concordance" Model

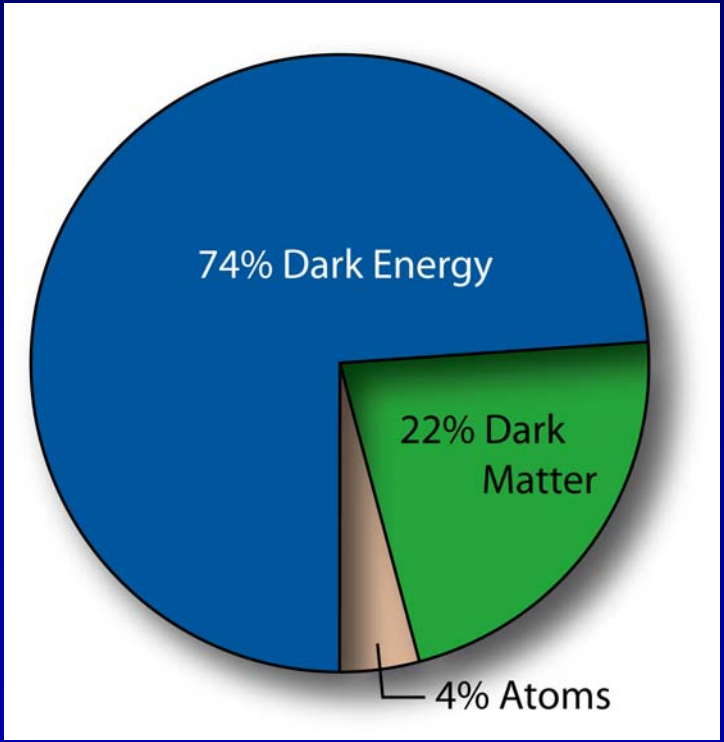
- The geometry of the Universe is flat ($\Omega_{tot}=1$).
- Big Bang nucleosynthesis requires that ordinary matter (baryons) contribute less than about 4% ($\Omega_b \sim 0.04$) of the energy density required for this.
- Most of the energy content of the universe (~70%) ($\Omega_\Lambda \sim 0.7$) comes from some sort of "dark energy" (a cosmological constant?) which accelerates the expansion of the universe at present.
- "Dark matter" contributes about 26% ($\Omega_{DM} \sim 0.26$). This dark matter is thought to be contributed by some WIMP, and behaves as a cold, collisionless fluid.

Summary of the Paradigm

"Our universe is expanding
From a hot big bang
In which the light elements were synthesized.
There was a period of inflation
Which led to a flat universe today.
Structure was seeded by Gaussian irregularities
Which are the relics of quantum fluctuations
And the large –scale dynamics is dominated by Cold Dark Matter"

Martin Rees.-

The Challenge



"The Pie of Ignorance"
our current inventory of the matter-energy content of the Universe

- The recent progress in our understanding of the matter-energy content and the expansion history of the Universe has challenged the very foundations of our physical understanding of Nature.
  - **What is the dark matter?**
  - **What is the dark energy?**
  - **What is the eventual fate of the Universe?**
  - **How did galaxies like our own Milky Way form in such Universe?**
- These are the questions being addressed by cosmologists today

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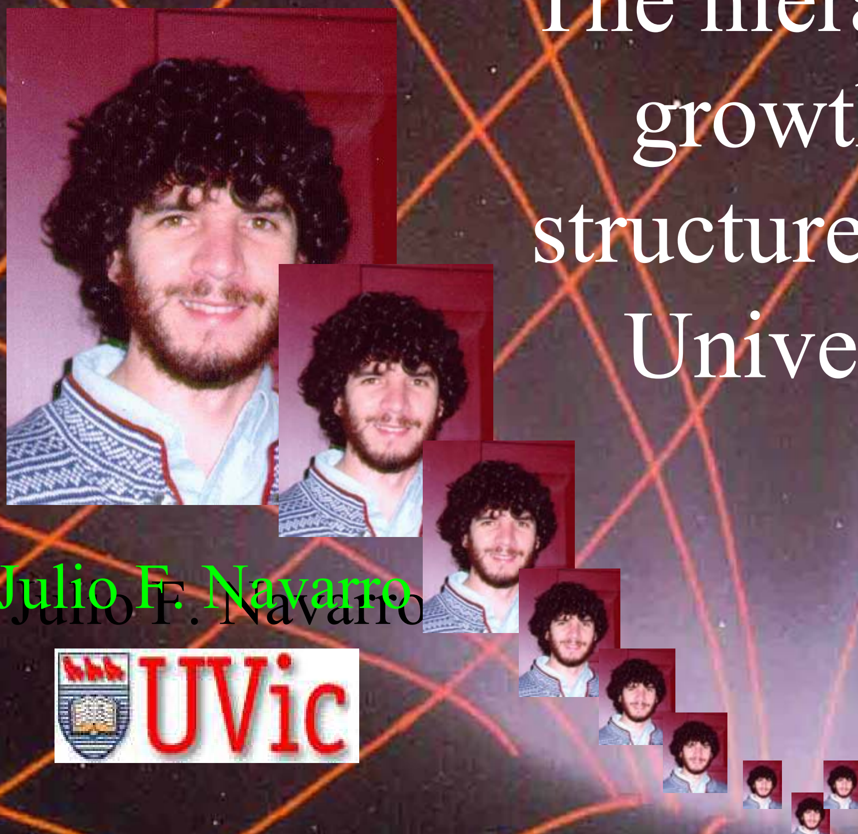
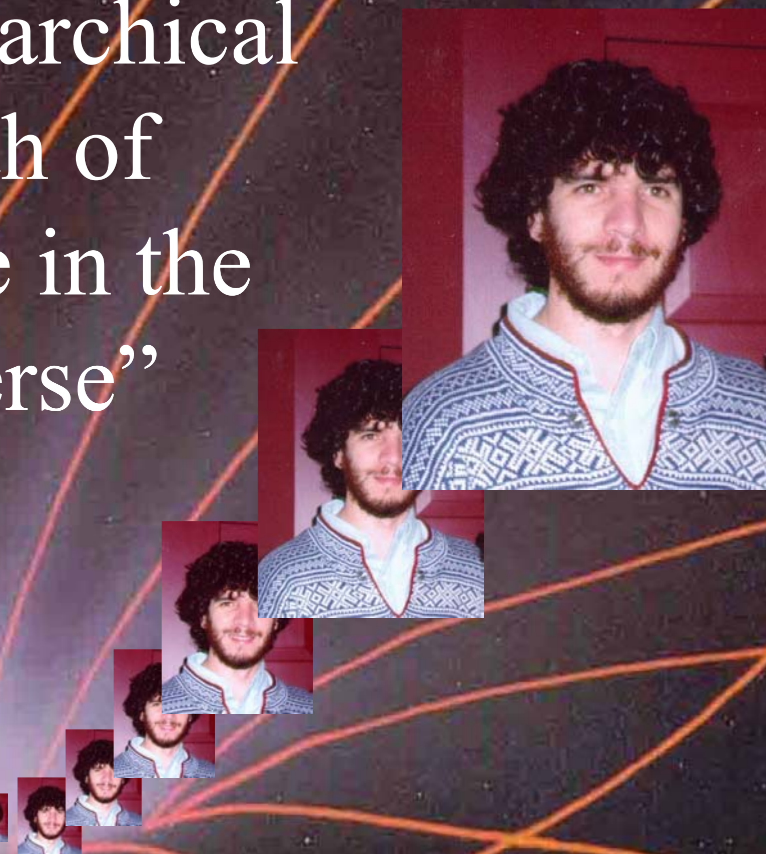
"The hierarchical growth of structure in the Universe"





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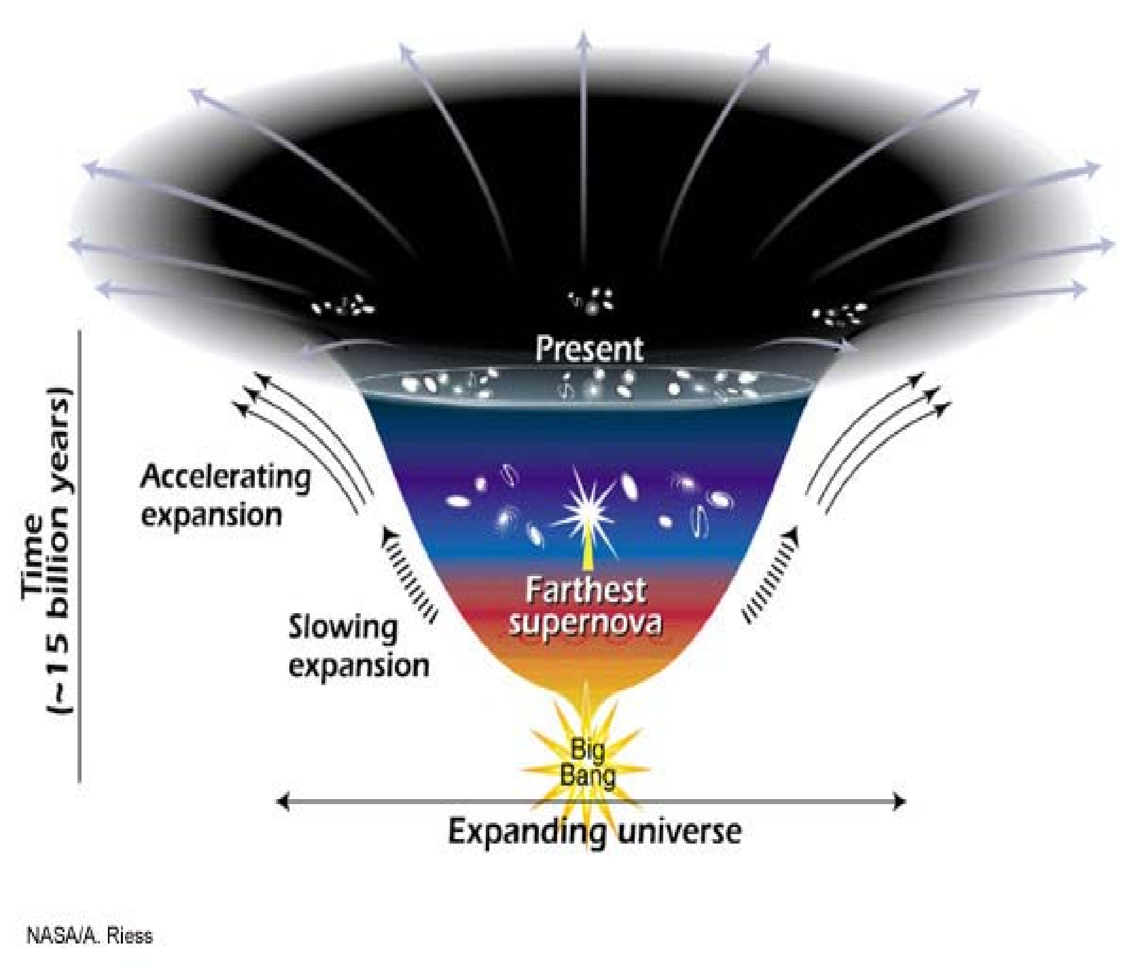
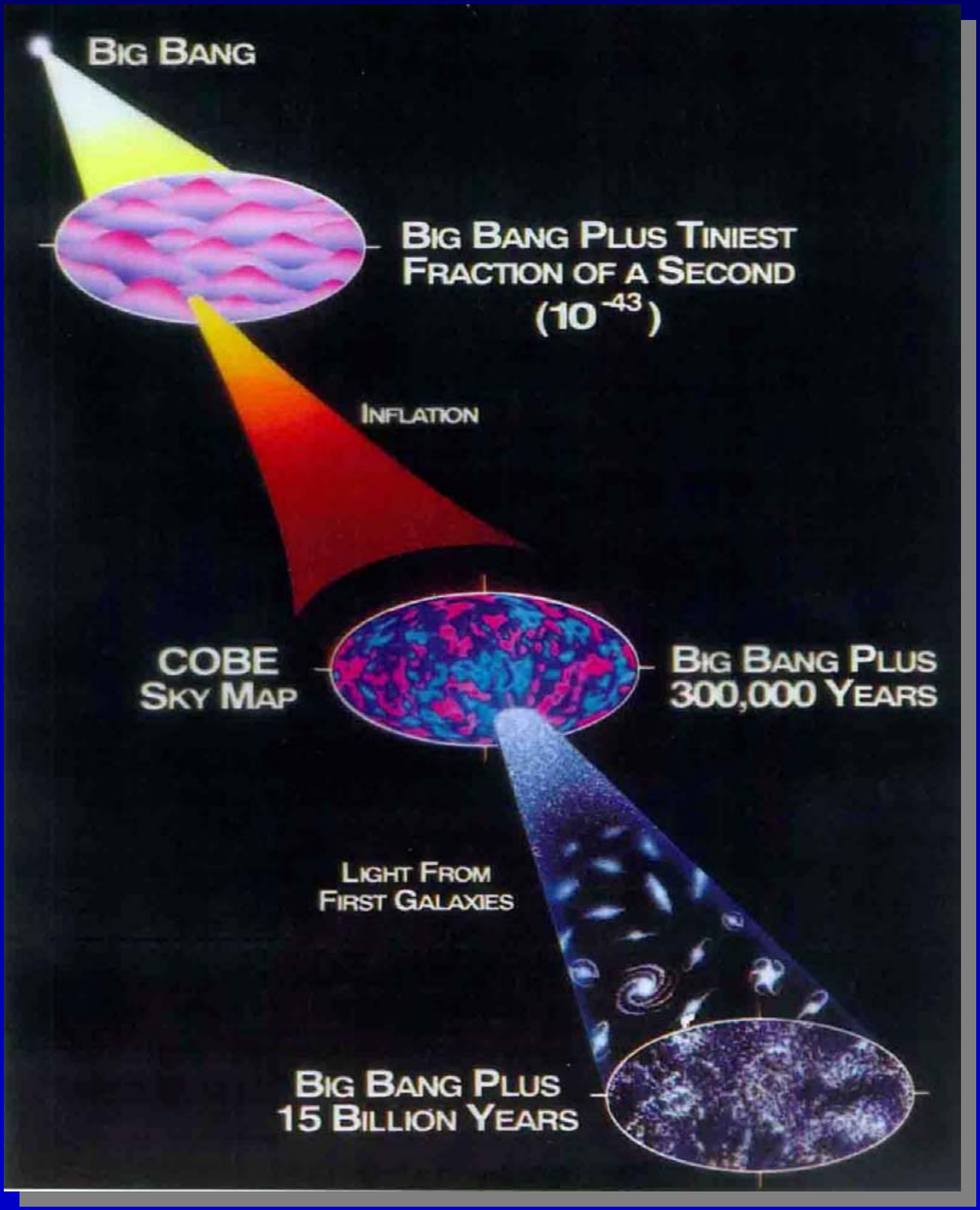
The expansion history of the Universe

The expansion history of the universe is characterized by several epochs:

- (a) radiation domination:
  $\rho_{radiation} \sim (\text{size})^{-4}$
  (number density + redshift)
- (b) matter domination:
  $\rho_{matter} \sim (\text{size})^{-3}$
  (number density)
- (c) Vacuum domination:
  $\rho_{vacuum} \sim (\text{size})^{-0}$
  (cosmological constant)



The Origin of Structure

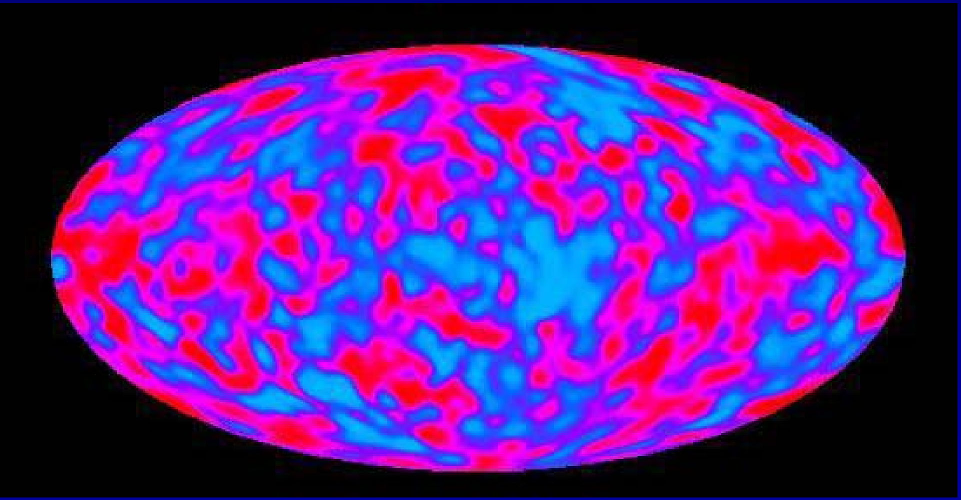


Structure in the Universe originates in minute quantum fluctuations amplified to macroscopic levels by inflation.

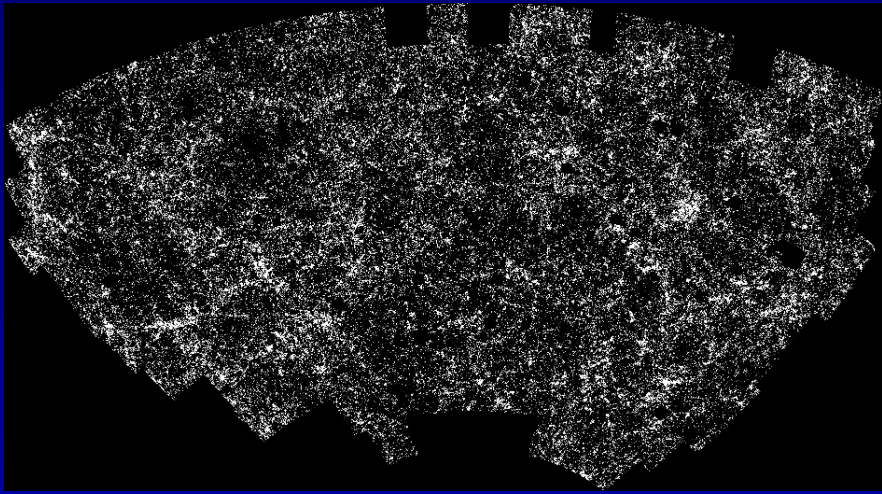
This explains why vast objects such as galaxy clusters have potential wells as deep as $\phi/c^2 \sim 10^{-4}$

This is still rather smooth…

How do we get from the smooth universe of yesteryear to the highly structured universe of today?



COBE map, z~1000, $\delta \sim 10^{-5}$



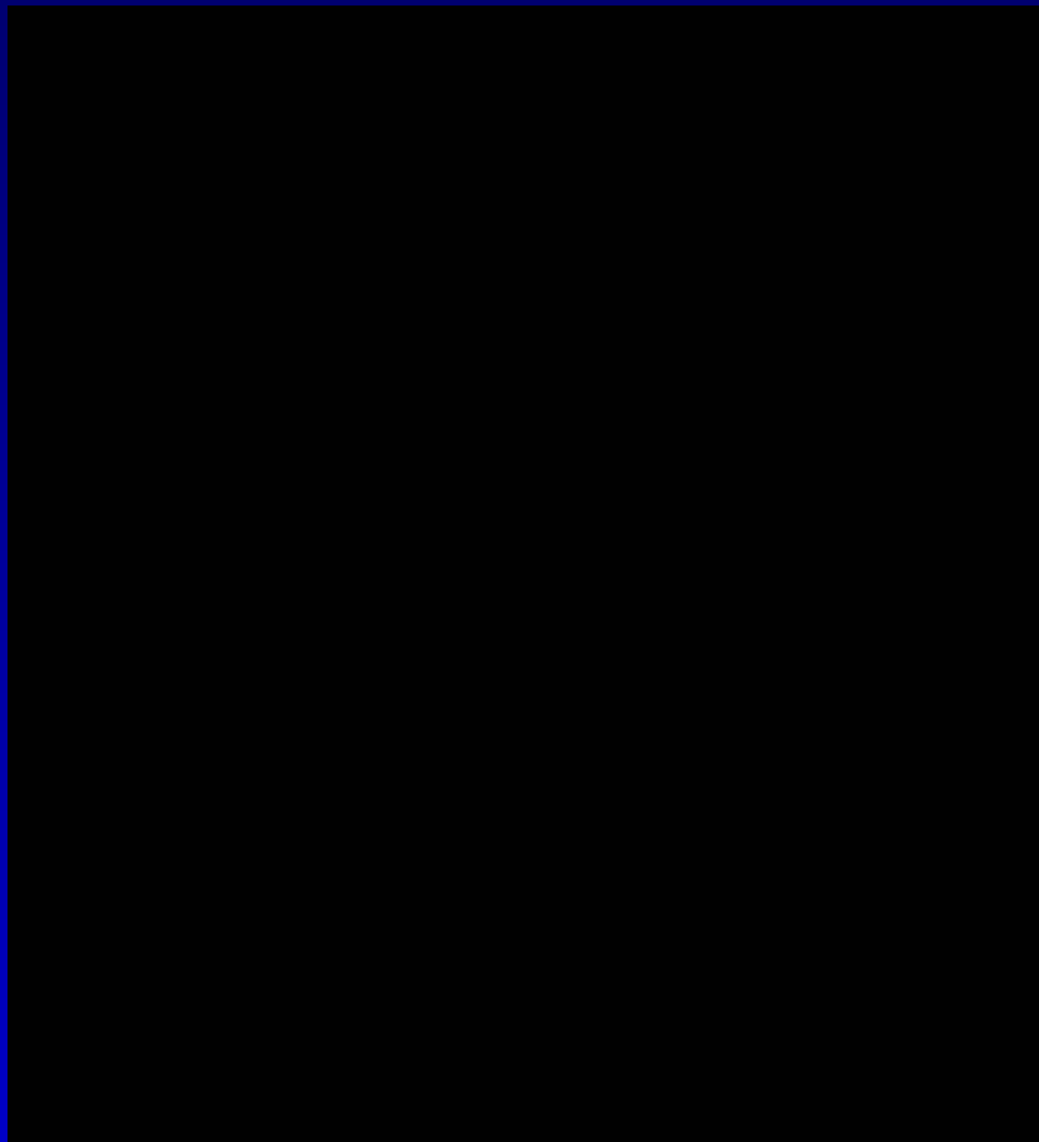
APM map z=0, $\delta \sim 1$

Answer: Gravitational Instability

- Overdense regions get more and more overdense as the universe expands
- Underdense regions get more and more underdense as the universe expands.

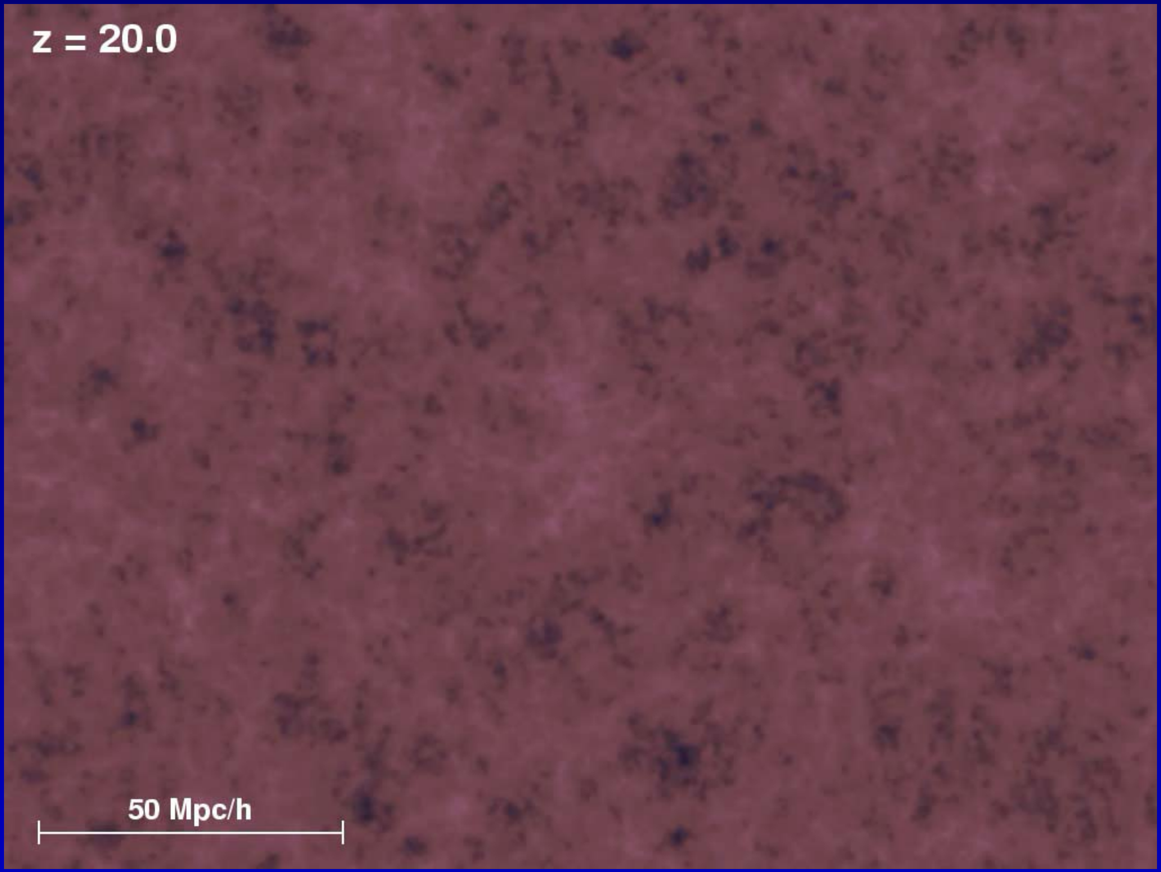
This seems to defy the usual thermodynamical intuition that systems should tend to become more uniform with time?

A simulation of structure formation



One can estimate fairly reliably the abundance of photons and baryons in the local universe, and simulate the evolution of structure in an expanding universe…

The Origin of Structure



Need dark matter to reconcile the highly structured z=0 universe with the small fluctuations seen in the photon-baryon fluid at the time of recombination.

Evidence suggests that dark matter is non-baryonic, most likely some kind of Weakly Interacting Massive Particle (WIMP)

Evolution of Dark Matter Fluctuations

- Linear theory allows us to calculate accurately the evolution of small perturbations in an expanding universe.
- Expressing the density field as

$$\rho(\mathbf{x})=\rho_0[1+\delta(\mathbf{x})],$$

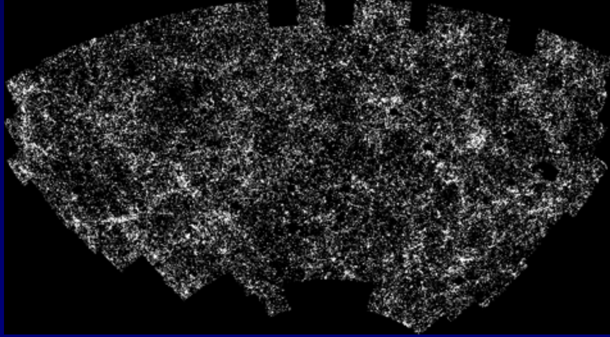
one can find the rate of growth of the fluctuations $\delta(\mathbf{x})$, and relate linear perturbations on a given scale at various times:

$$\delta(\mathbf{x},t)=D(t)\ \delta_0(\mathbf{x}),$$

where $D(t)$ is a function of the expansion rate of the Universe:

- the faster the expansion the slower the growth
- $D(t) \sim a(t)$, the scale factor, after matter domination and before dark energy domination

Spatial Correlations: the Power Spectrum



- It is also important to characterize how fluctuations on different spatial scales are correlated.
  - The power spectrum characterizes fully linear Gaussian fluctuations
  - For power-law spectra, $P(k) \propto k^n$, $n>-3$ implies a hierarchy of collapsed structures, from small to large: "hierarchical clustering"
  - $n=0$ is "white noise", that obtained by throwing particles at random.

Taking a Fourier transform:

$$\delta_k = \frac{1}{V} \int d^3x \, \delta(\vec{x}) \, e^{i\vec{k}\cdot\vec{x}}$$

We define the power spectrum, which fully characterizes linear Gaussian fluctuations:

$$P(k) = |\delta_k|^2$$

Averaged on a particular mass scale, $M \propto \rho k^{-3}$

$$\Delta^2 \sim \left(\frac{\delta M}{M}\right)^2 \sim k^3 P(k)$$

For $P(k) \propto k^n$ $\qquad \frac{\delta M}{M} \propto M^{-\frac{1}{6}(3+n)}$

The Scale-Invariant Spectrum

- The associated gravitational potential perturbations are:

$$\delta\Phi \propto \frac{\delta M}{R} \propto M^{\frac{1}{6}(1-n)}$$

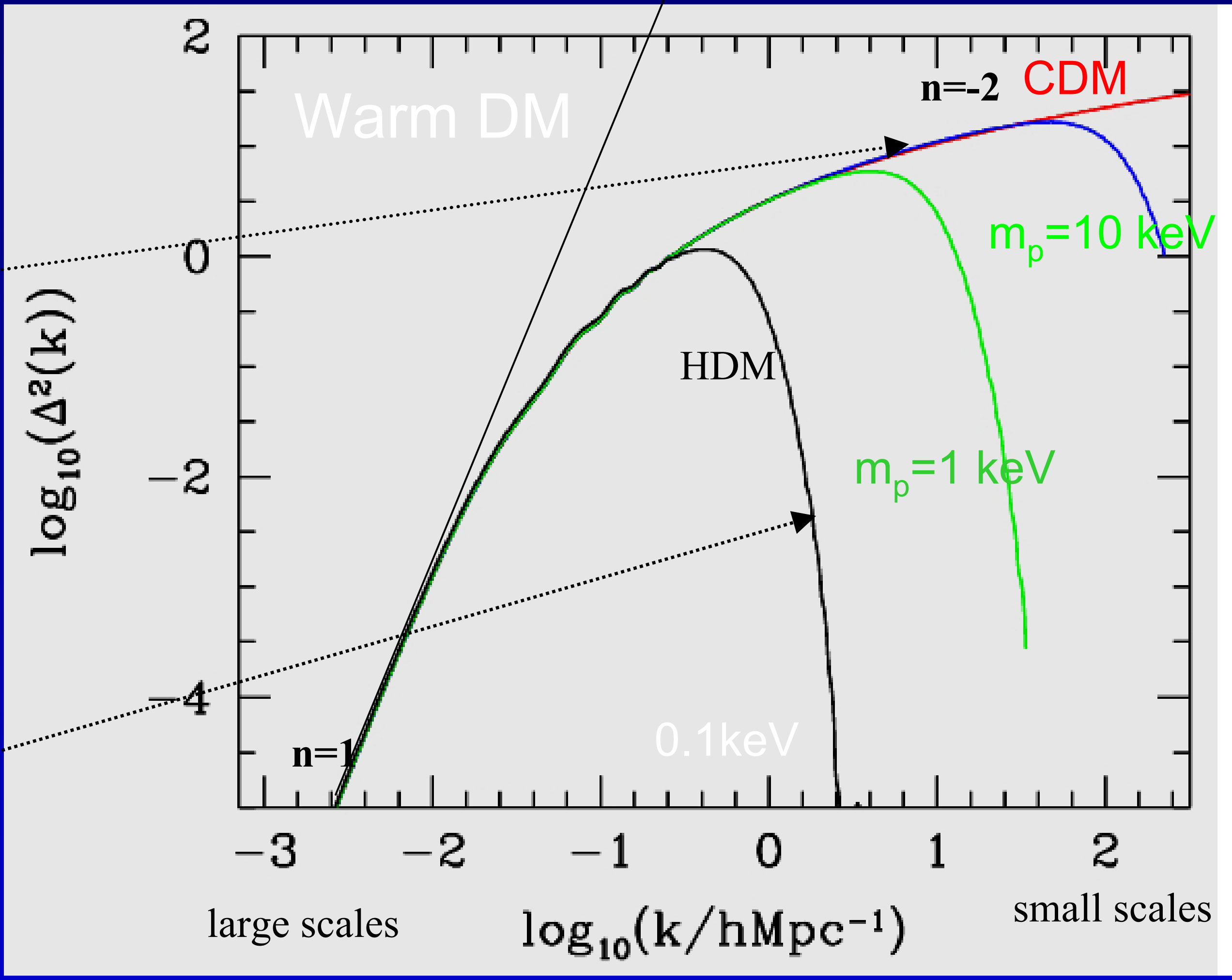
  - For n=1 all mass scales have similar characteristic escape velocities
  - No divergence on small or large scales
  - This is the "Harrison-Zeldovich" spectrum
    - Predicted by inflation
    - Not applicable to the observed universe on the scale of galaxies!
    - Need $n<1$ to explain why galaxy clusters and groups have higher velocity dispersions than galaxies.

Modulation of the Power Spectrum

The shape of the power spectrum evolves mainly due to two factors:

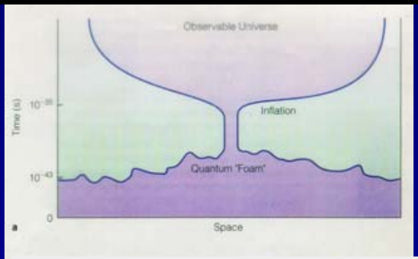
•The stunted growth of fluctuations on small scales, which enter the horizon earlier before the universe becomes matter dominated

•The washing out of perturbations on scales smaller than the free streaming scale of the dark matter particle



The origin of cosmic structure

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



QUANTUM FLUCTUATIONS:

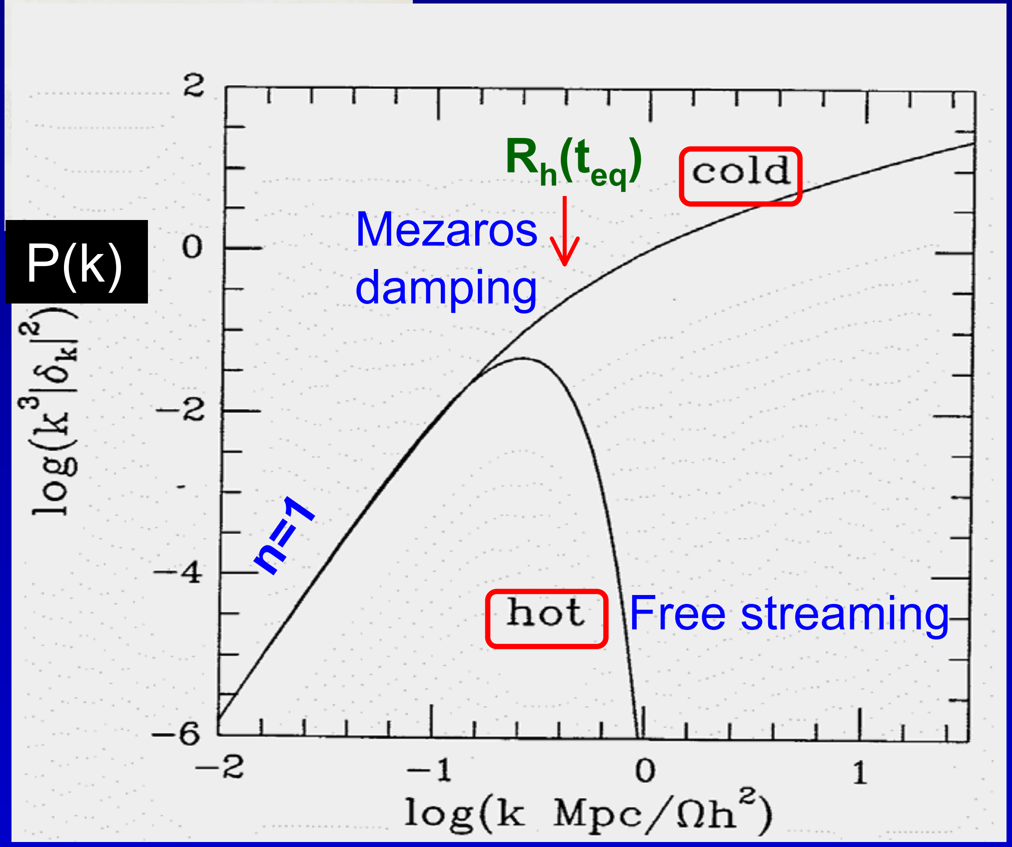
$$\begin{cases} |\delta_k|^2 \propto k^n \qquad n = 1 \\ \text{Gaussian amplitudes} \end{cases}$$

+

Damping (nature of dark matter)

$P(k) = A k^n \, T^2(k,t)$

→ Transfer function



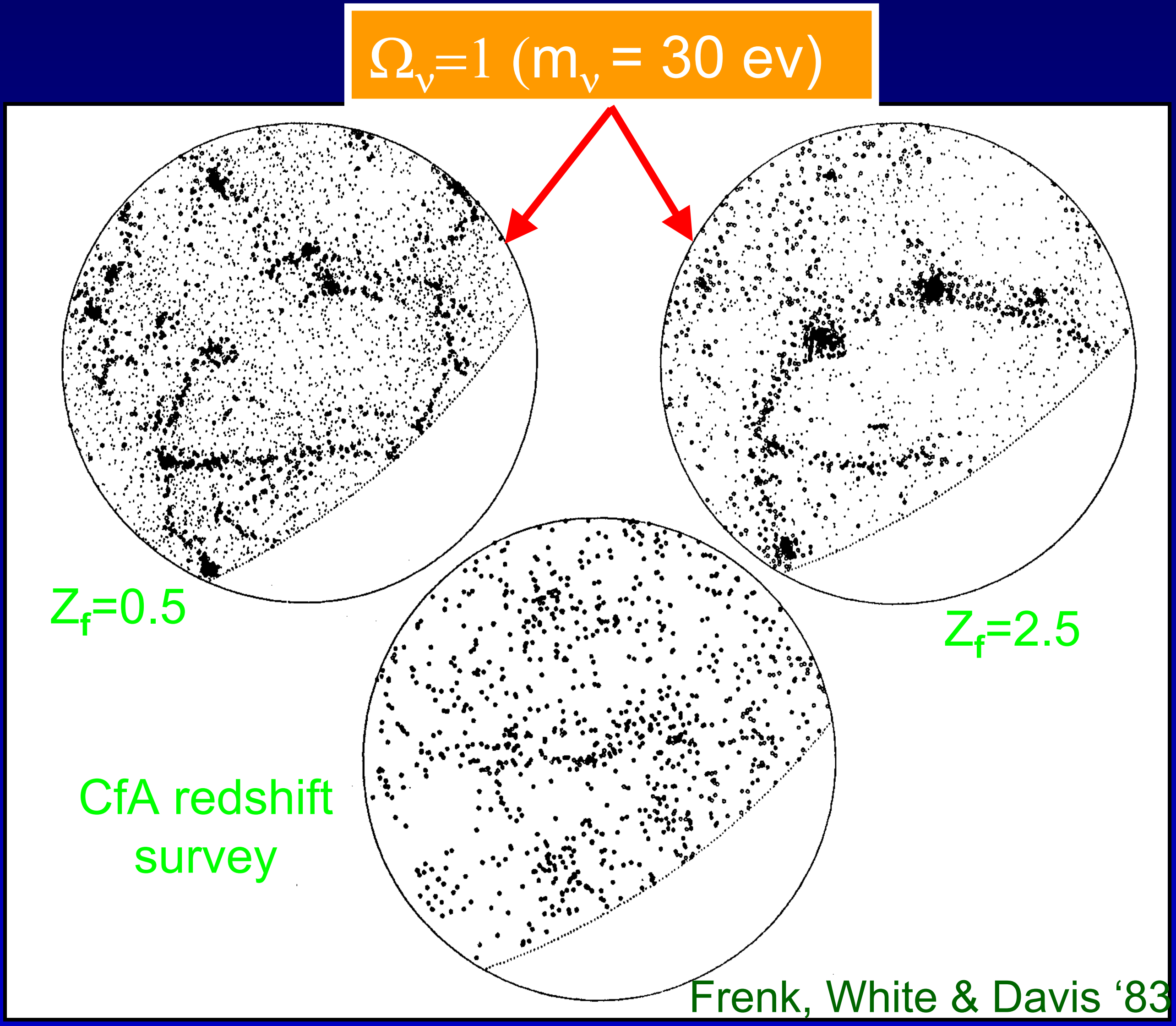
- Hot DM (eg ~30 eV neutrino)
  - Top-down formation
- Cold DM (eg ~neutralino)
  - Bottom-up (hierarchical)

Neutrino (hot) dark matter

Free-streaming length so large that superclusters form first and galaxies are too young

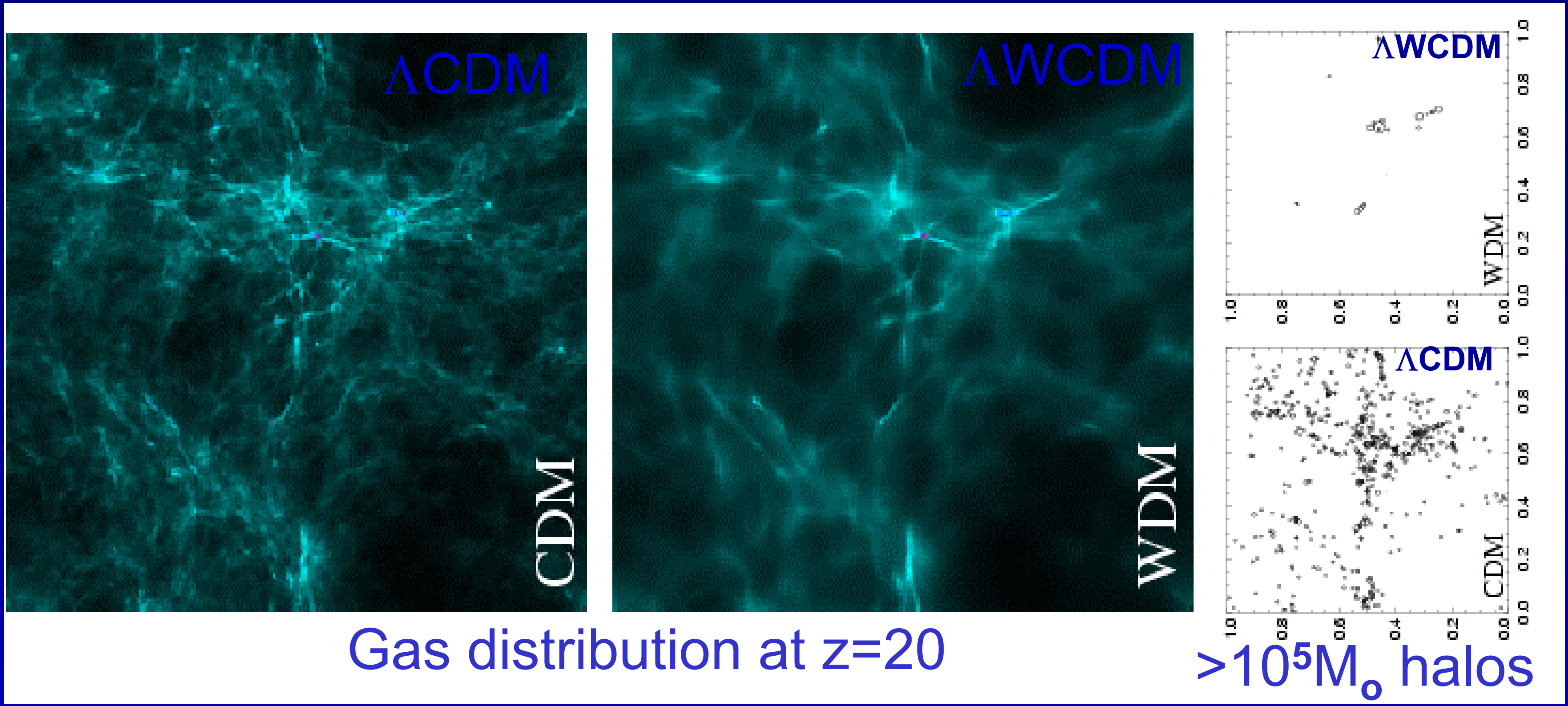
⇨

Neutrinos cannot make an appreciable contribution to Ω and $m_\nu << 30$ eV



A warm dark matter Universe?

OK, if we cannot have it HOT, can we at least have it WARM?



Yoshida etal '03

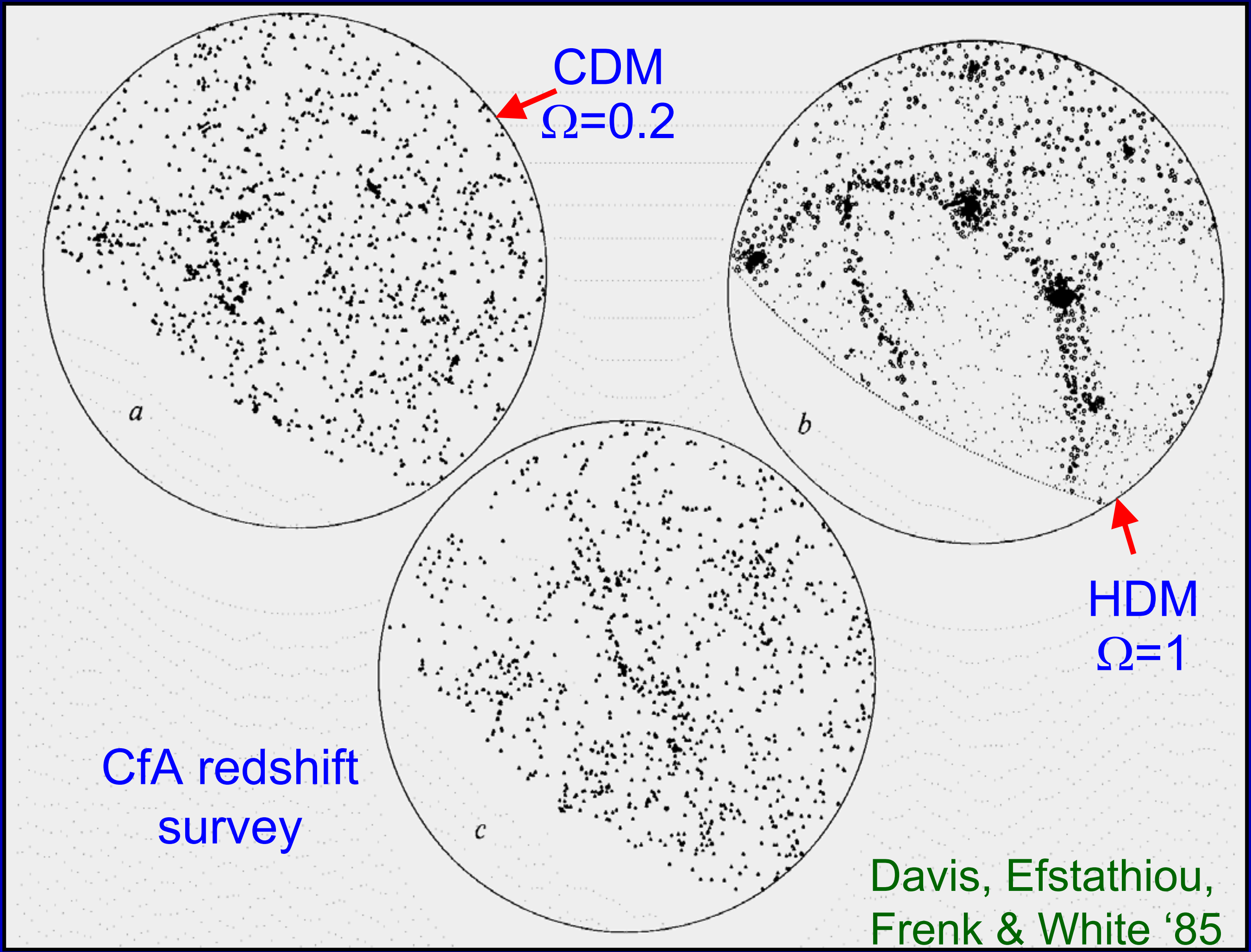
Not enough small halos at high redshift to make galaxies and reionize the Universe at high redshift even for m_x=10 keV

(cf Ly-α forest requires m_x> 0.75keV -Narayanan 00)

Cold dark matter

In CDM structure forms hierarchically

Early CDM N-body simulations gave promising results



The Initial Power Spectrum of Mass Fluctuations

The shape of the power spectrum evolves mainly due to two factors:

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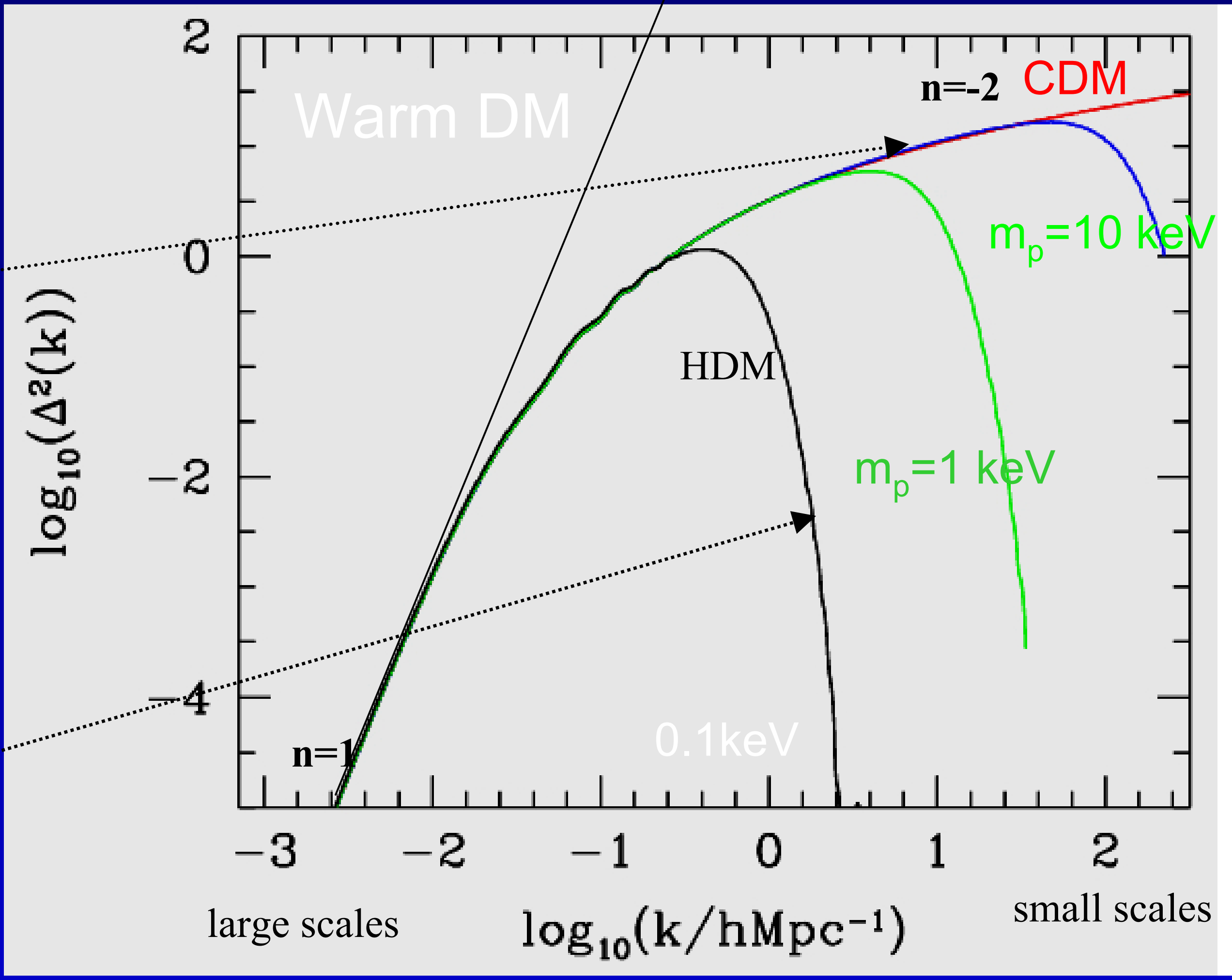
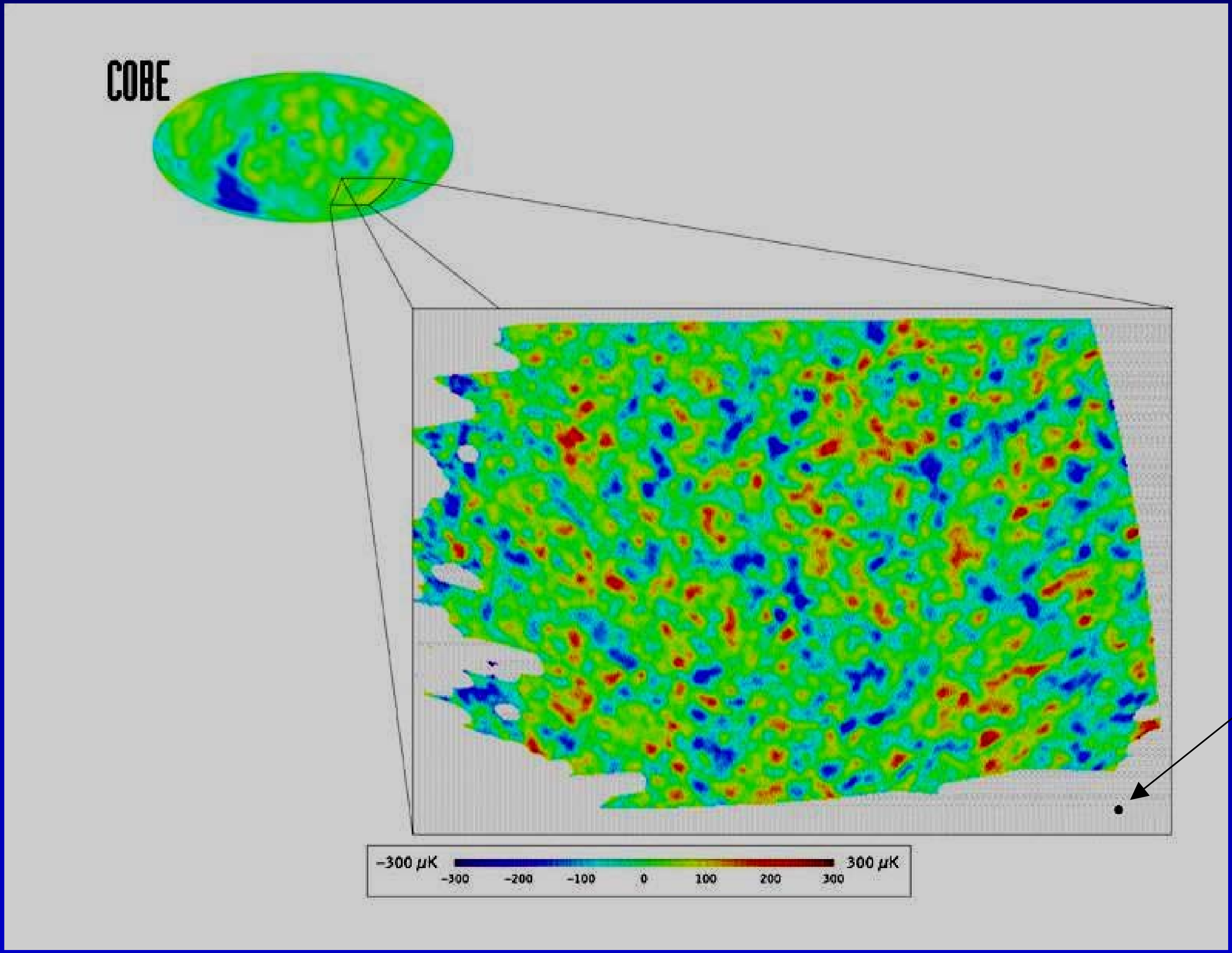


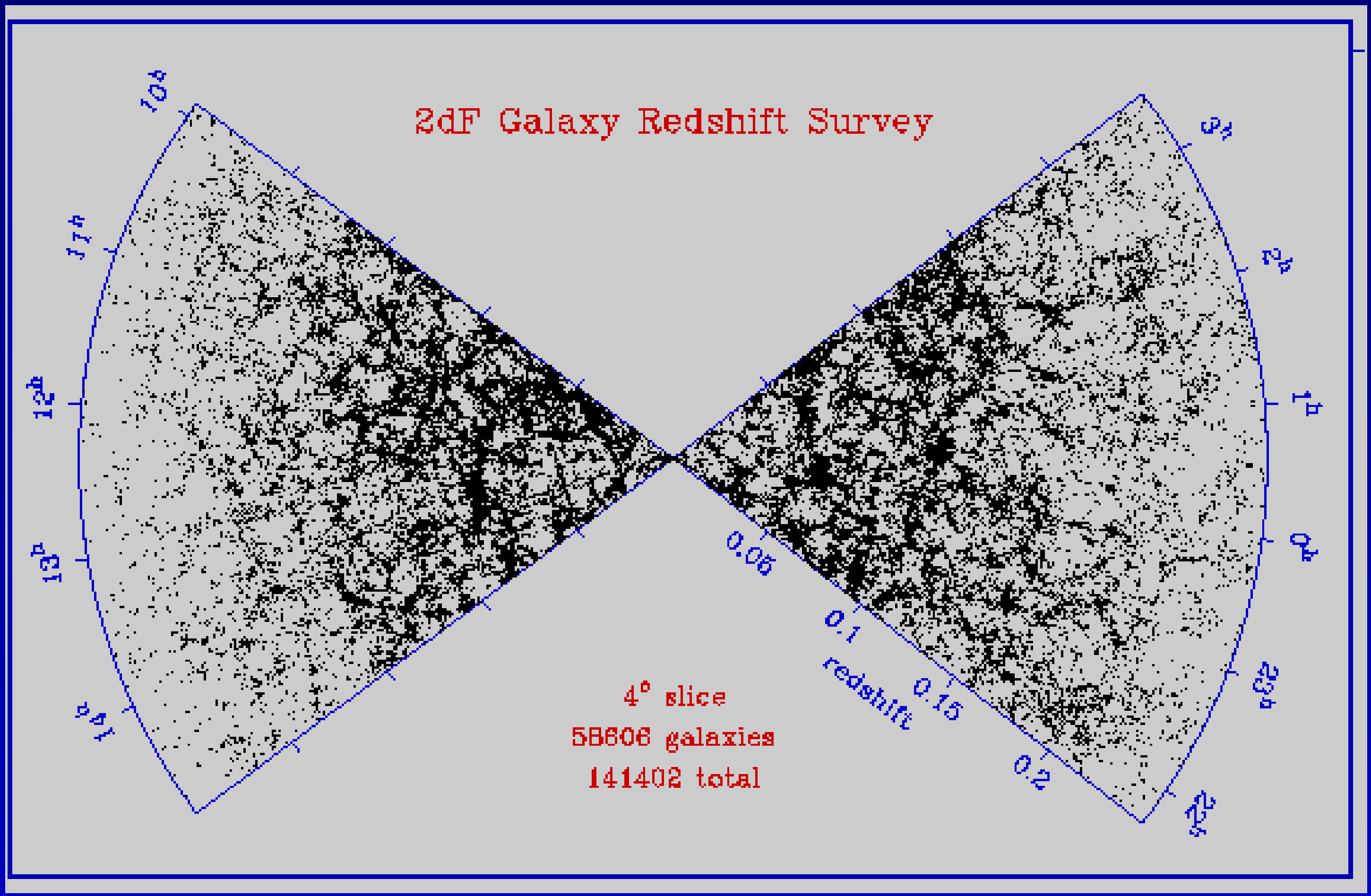
Probing the CDM Spectrum:CMB Fluctuations



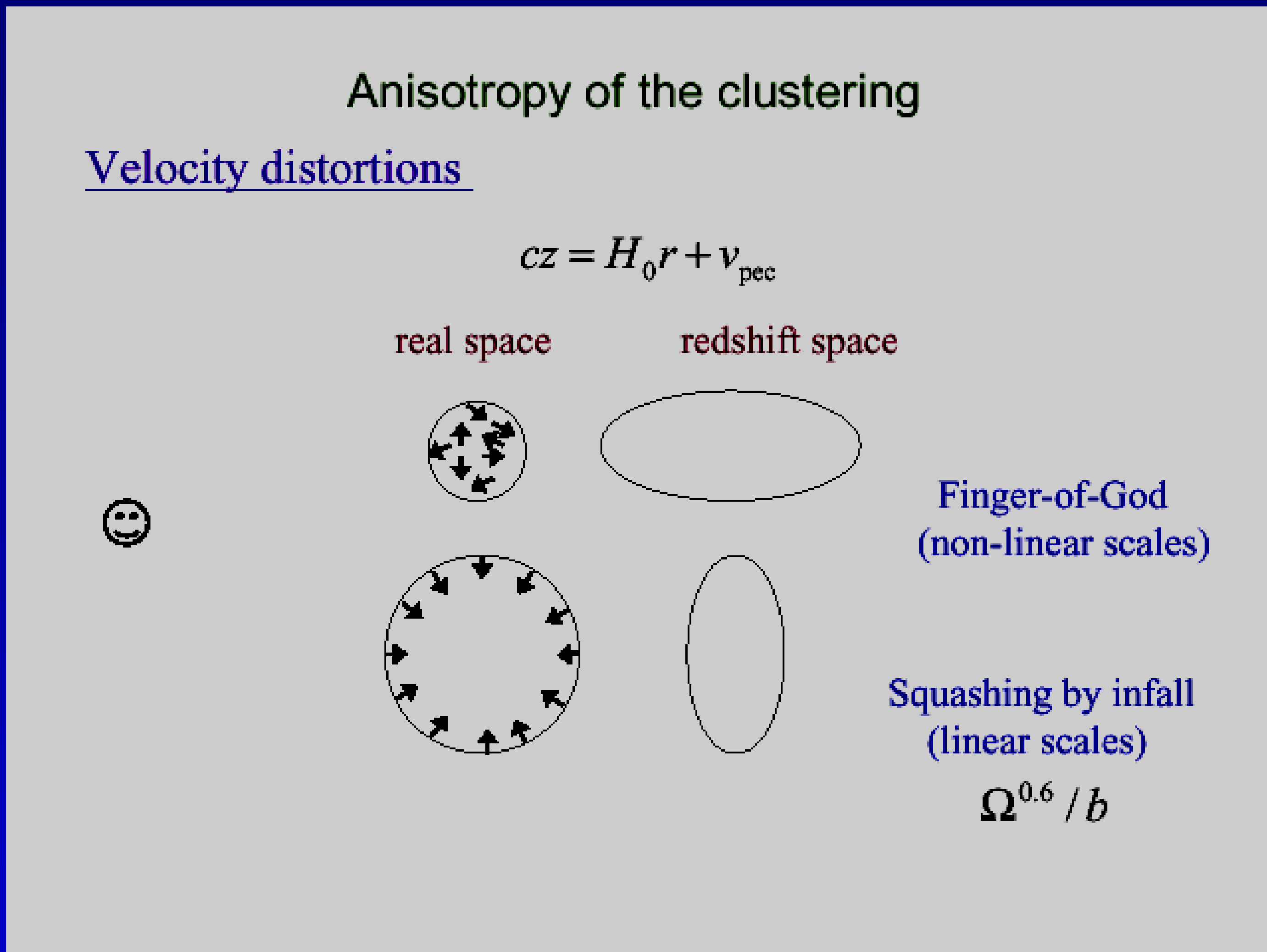
The seeds of structure formation (z~1000)

Beam size subtends the mass of a rich galaxy cluster

Probing the CDM Spectrum: Galaxy Redshift Surveys (z~0)



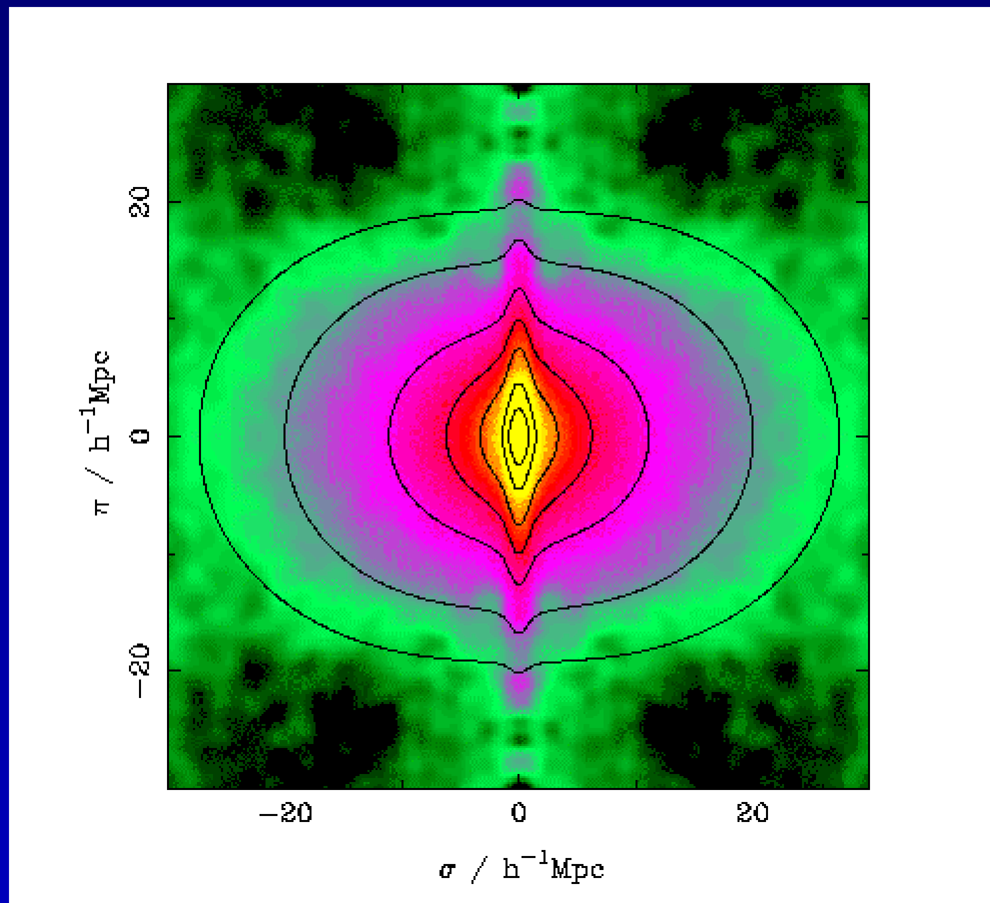
How do we know it is gravity?



from Josh Frieman

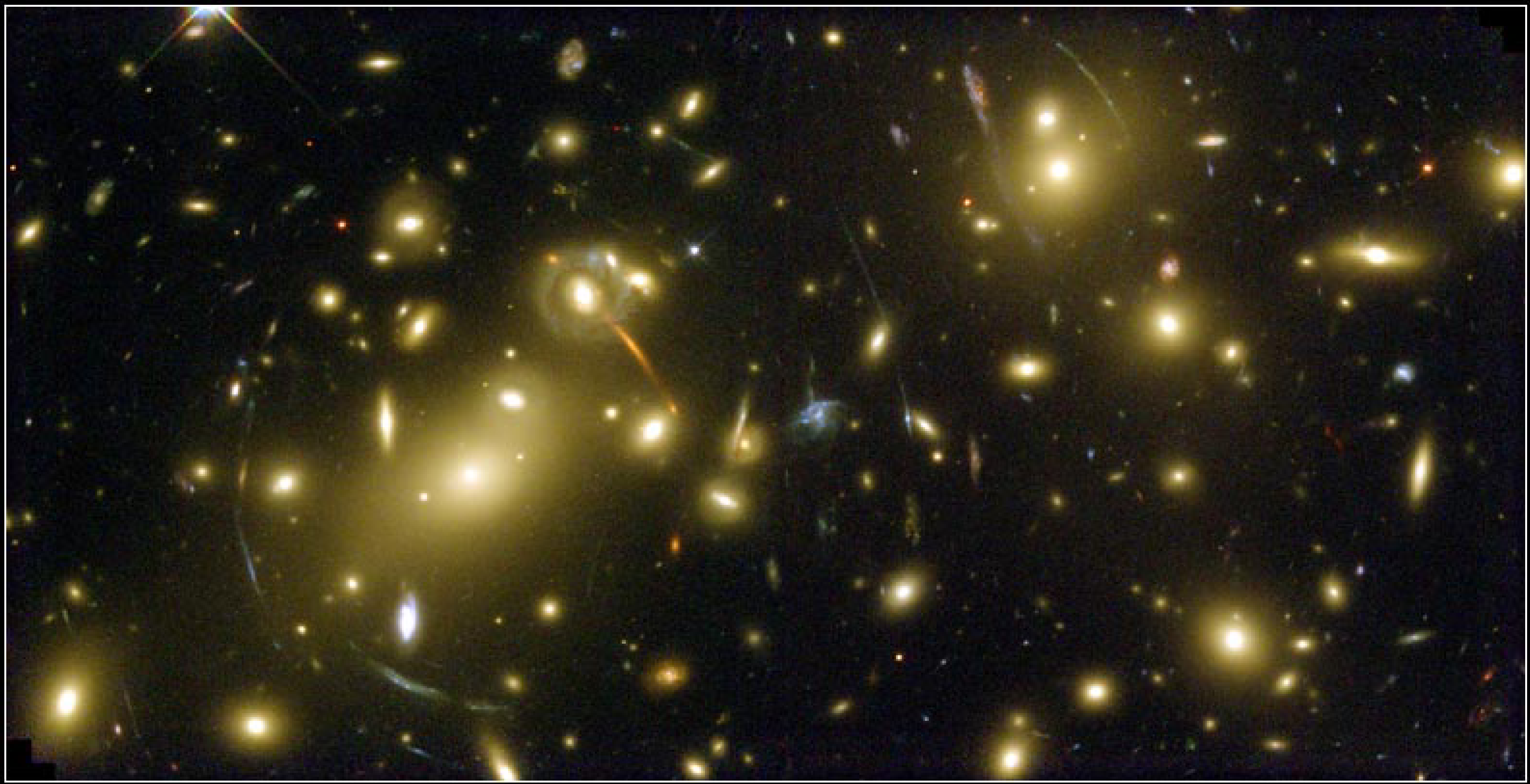
Gravitational Instability from 2dFGRS

Redshift



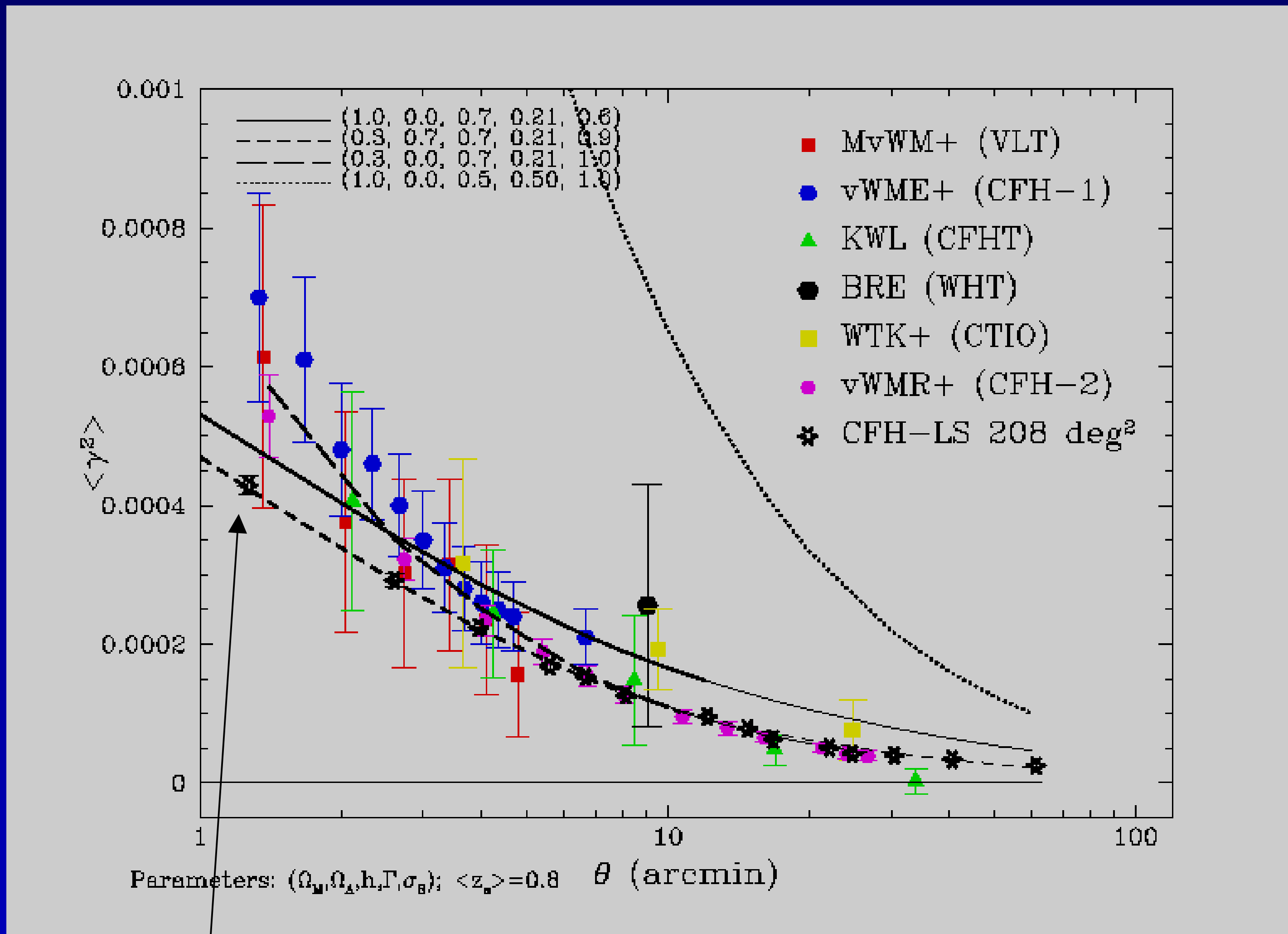
Angular distance

Probing the CDM Spectrum: Gravitational Lensing



Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

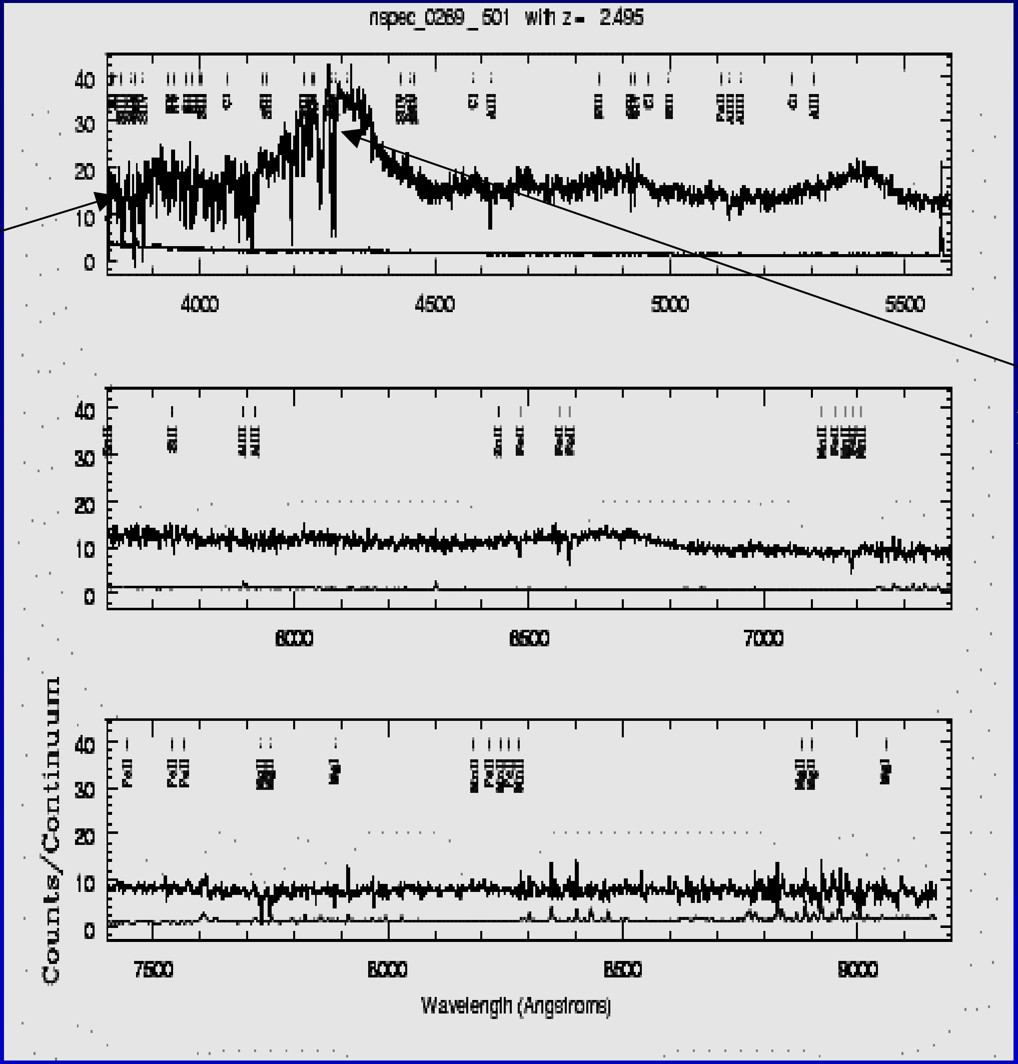
Cosmic Shear: Power Spectrum from Weak Lensing



Signal on small scales
dominated by
small galaxy groups at
moderate z

van Waerbeke et al

Probing the CDM Spectrum: "typical" QSO spectrum (SDSS)



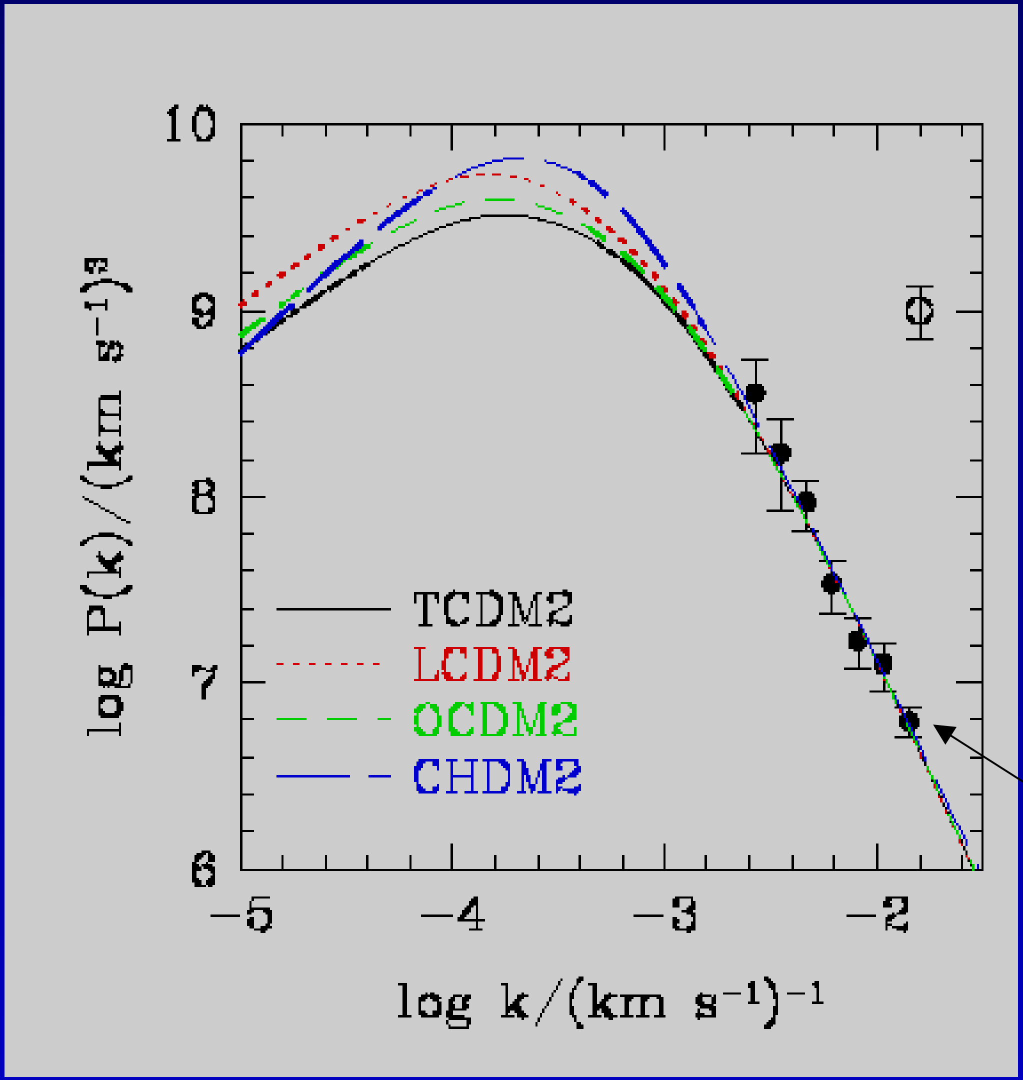
Ly-alpha forest

Redshifted Ly-alpha

Wavelength

z~3 Power Spectrum from the Ly-α forest

Power



Smallest scale probed by 2dfGRS at z=0

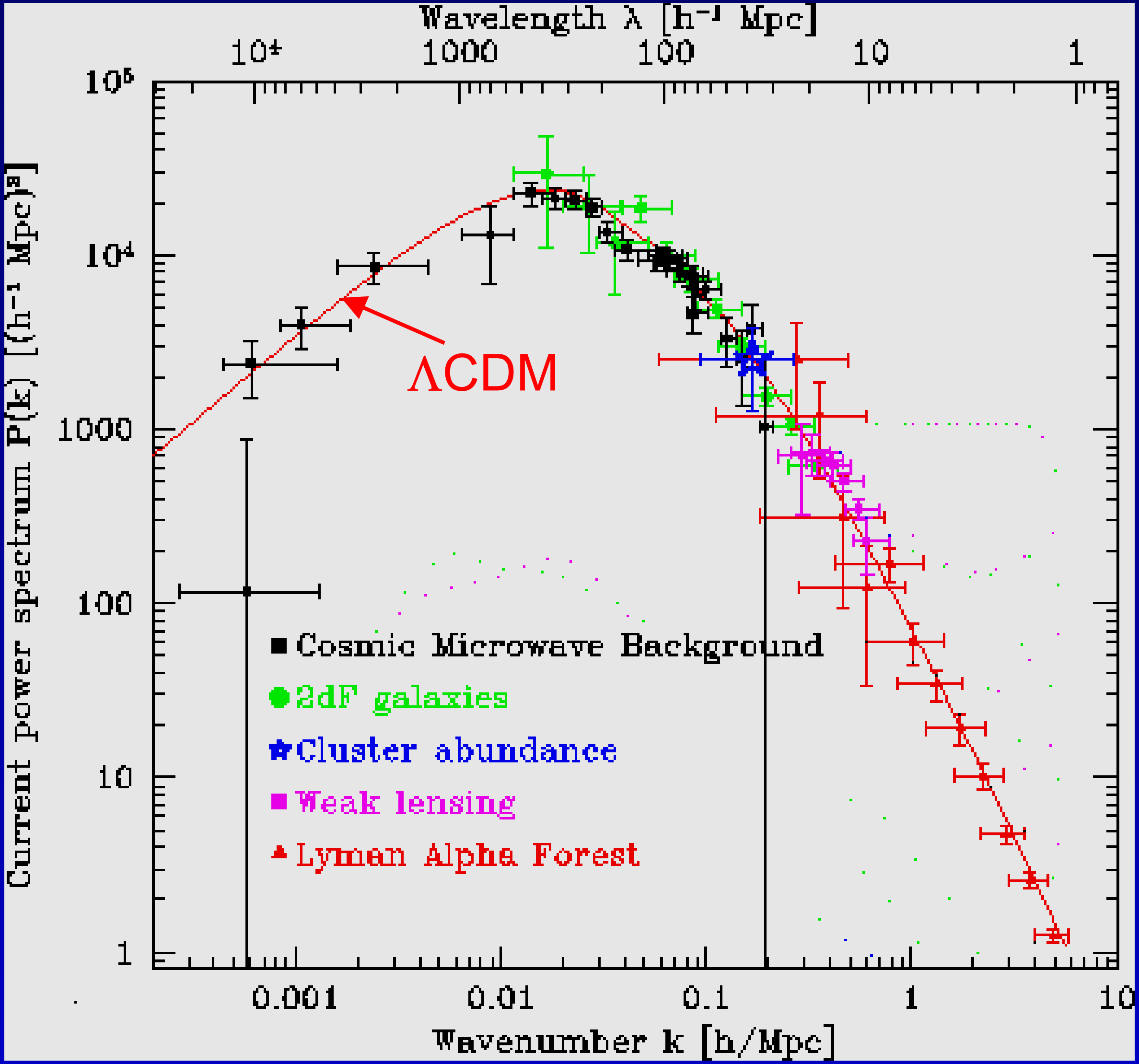
Wavenumber (size^{-1})

Croft et al

Linear power spectrum of density fluctuations

CMB fluctuations (z ~ 1000) agree well with Ly-alpha forest measurements at z~3 and with clustering of galaxies at z~0.

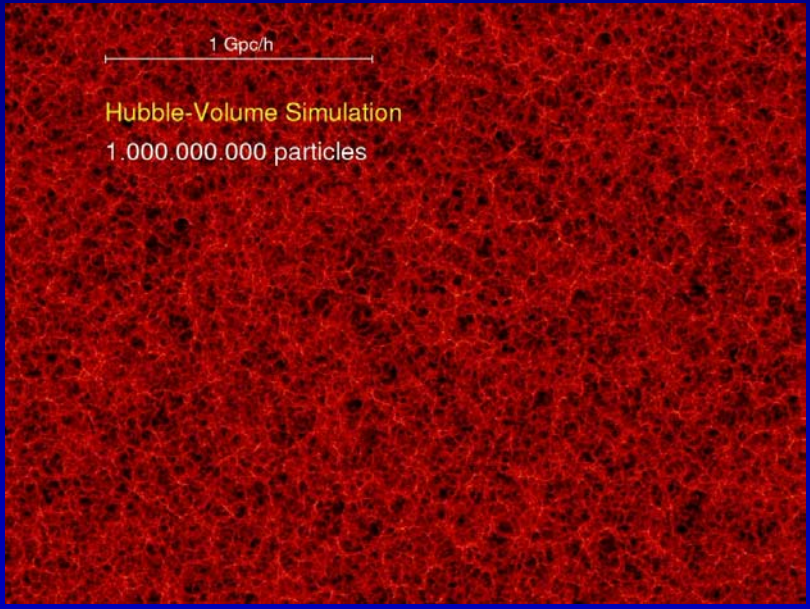
This is remarkable!



Tegmark & Zaldarriaga '03

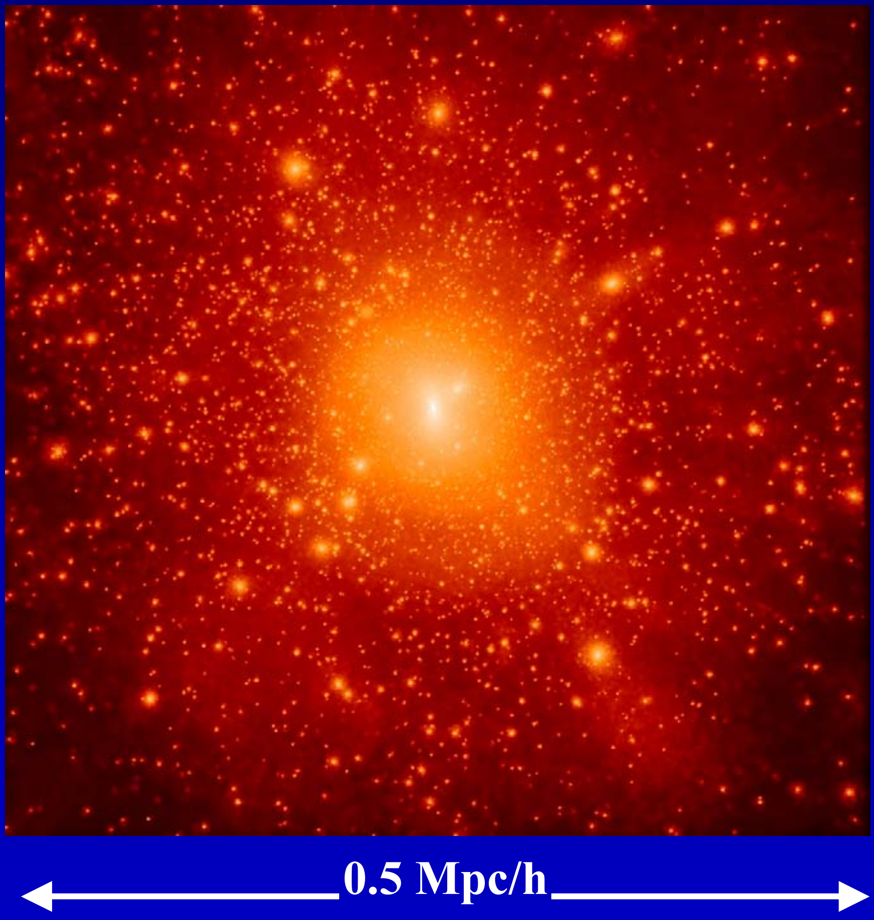
The non-linear Universe: the small scale structure of Cold Dark Matter

- All parameters of CDM fixed by the properties of the large-scale structure, where linear theory applies.
- CDM is a fully predictive theory for the dark matter component, once the particle candidate is specified
- Small, highly non-linear scales scales (e.g., individual galaxies or centers of galaxy clusters) may be used to falsify or validate the theory.
- Need numerical simulations.
- The Millennium Run: the largest N-body cosmological simulation so far.



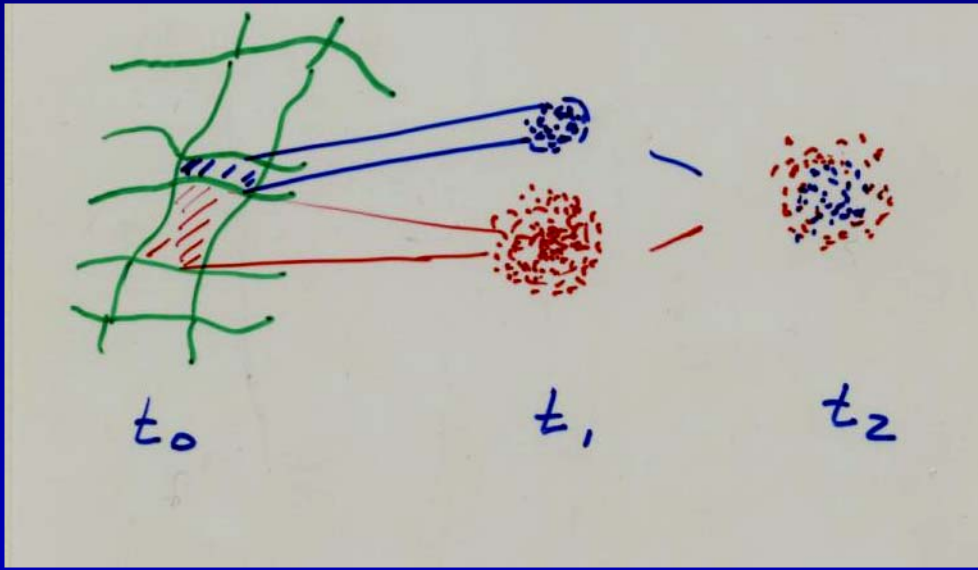
The Non-Linear Universe

- Most of the mass in the Universe is in collapsed, non-linear structures (dark matter halos)
- What is the abundance of structures as a function of mass and time?
- What is the internal structure (and substructure) of dark matter halos?



Statistics of Hierarchical Clustering

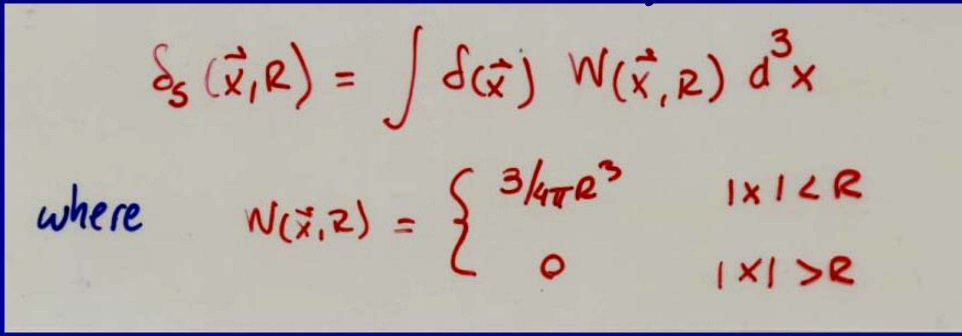
- Given $\delta(\mathbf{x})$, we want to devise a way to assign different mass elements to collapsed systems at different times so as to:
  - construct mass functions
  - compute formation times
  - follow merging histories
  - understand the internal structure and spatial correlations of halos

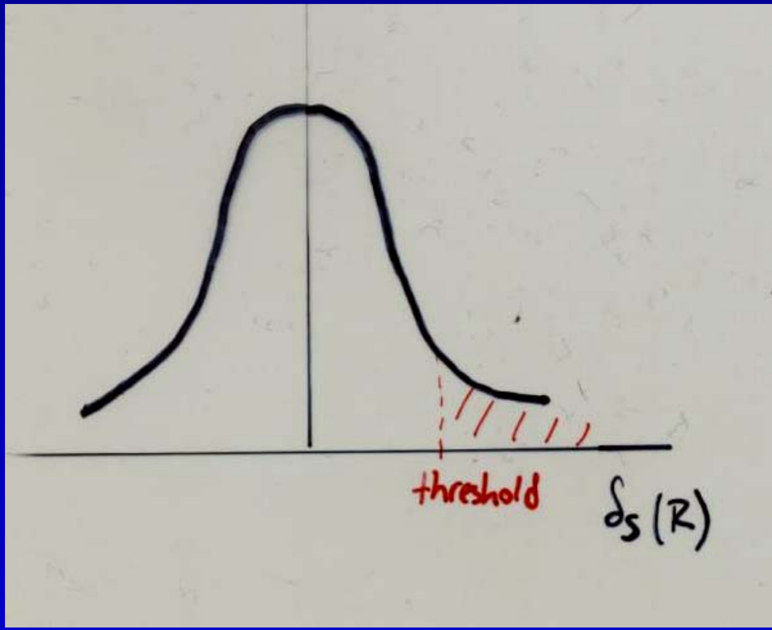


Peak Theory

- Clumps of a given mass $M \propto \rho R^3$ form at the locations where the smoothed density field, $\delta_s(\mathbf{x},M)$, has peaks exceeding a given threshold

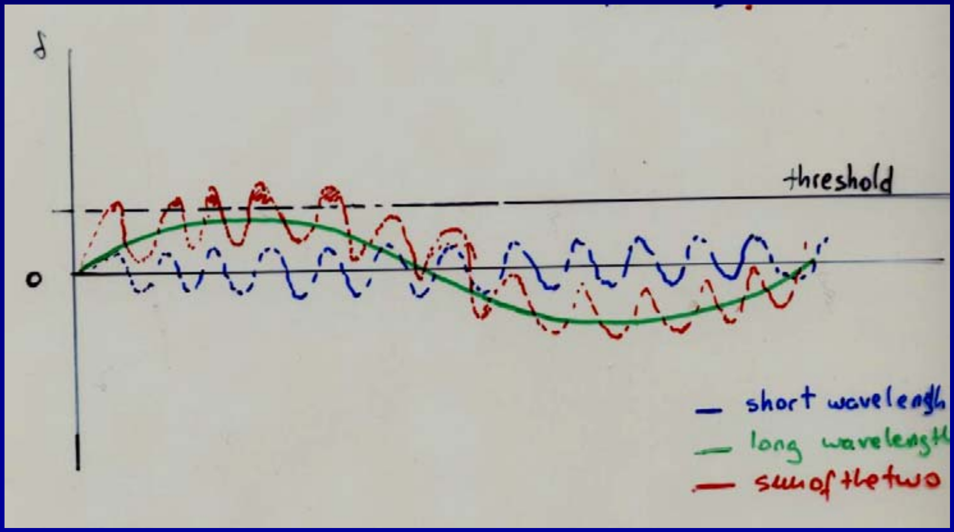
Smoothed Density Field

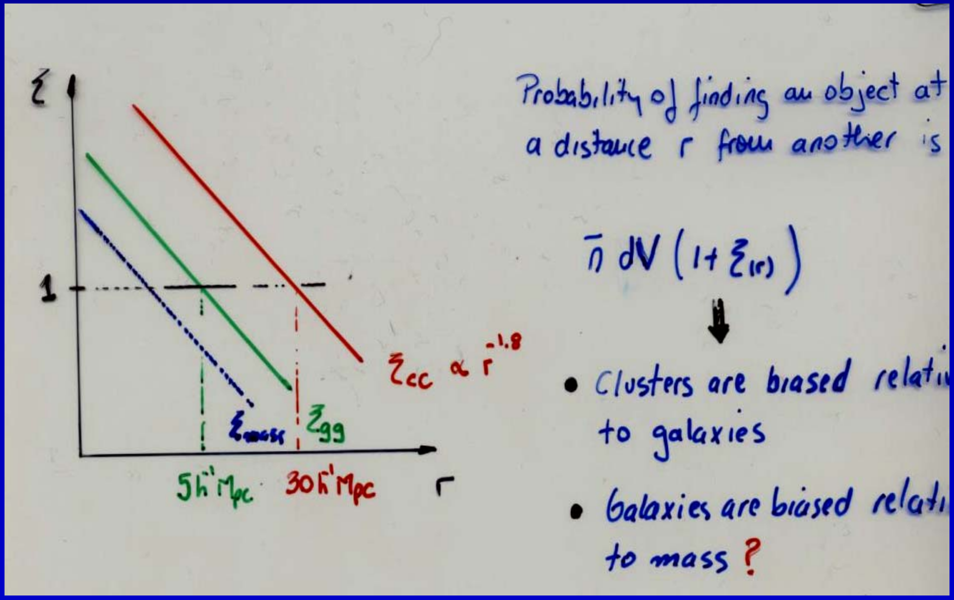




Peak Theory

- Good:
  - δ_s is Gaussian, so mathematics is relatively simple: abundance and clustering can be computed as a function of height, shape, etc.
  - Reasonable agreement with N-body simulations for large masses, high thresholds (rare peaks).
  - Provides a “natural” explanation for why larger masses are more highly correlated spatially

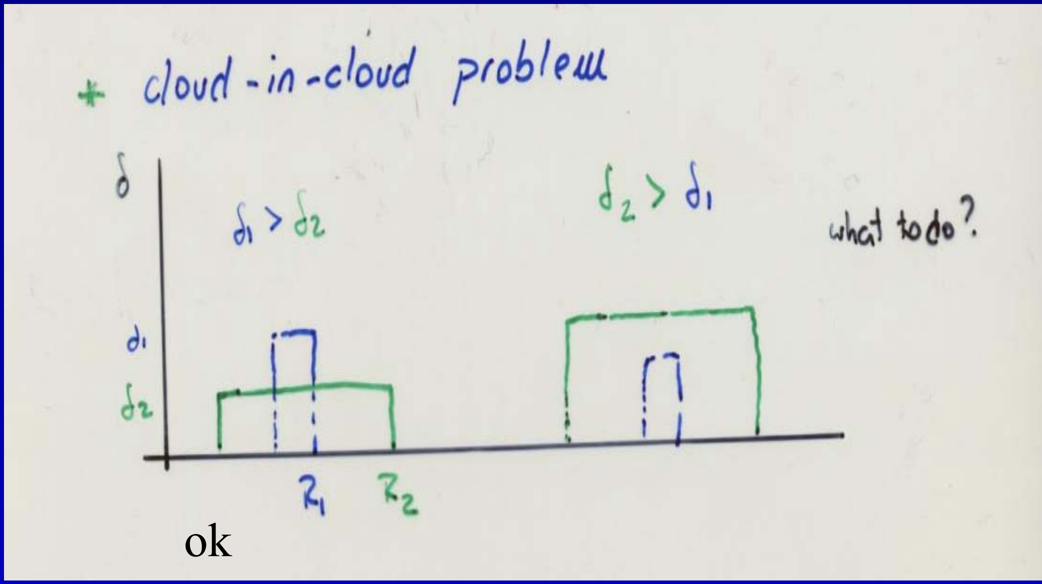




Peak Theory

- Bad:
  - No obvious way to construct a mass function, or to follow it from one time to another
  - Cloud-in-cloud problem: what if the same region of space satisfies the peak condition for different mass scales?

Smoothed Density Field



The Goal

What is really required is a method for partitioning the initial density field $\delta(\vec{x})$ into a set of disjoint regions each of which will form a single non linear object at some later time t, and a way of computing the statistical properties of this partition.

The Press-Schechter Theory

Smoothed Density Field

$$\delta_s(\vec{x}, z) = \int \delta(\vec{x})\, W(\vec{x}, z)\, d^3x$$

- Take the same $\delta_s(M,z)$, but use a different *ansatz:*
  - Fraction of volume where $\delta_s(M,z)$ exceeds a given threshold = fraction of mass in clumps of mass exceeding M.

Since δ_s is gaussian, this is simple to compute

$$F(z) = \int_{\delta_c}^{\infty} d\delta \, \frac{1}{\sqrt{2\pi}\, \Delta(z)}\, e^{-\delta^2/2\Delta^2(z)} \quad , \quad \Delta^2(z) = \langle \delta_s^2(z$$

One problem is that, as $M \to 0$, $F \to 1/2$, so a fudge factor = 2 was introduced, so that all the mass in the universe is in clumps of one size or another.

Press-Schechter (continued)

- This gives immediately a mass function.
- This looks like the galaxy luminosity function, but it is not: $M_* >> M(L_*)$
- Power spectrum enters only through $\Delta(M_*)$
- Time enters only through $M^*(t)$
- Mergers are the way to go, as most of the mass is always in clumps.

$$n(M)\,dM = -\sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\,\frac{\delta_c}{\Delta^2}\,\frac{d\Delta}{dM}\,e^{-\delta_c^2/2\Delta^2}\,dM$$

For a power-law spectrum, $P(k) \propto k^n$

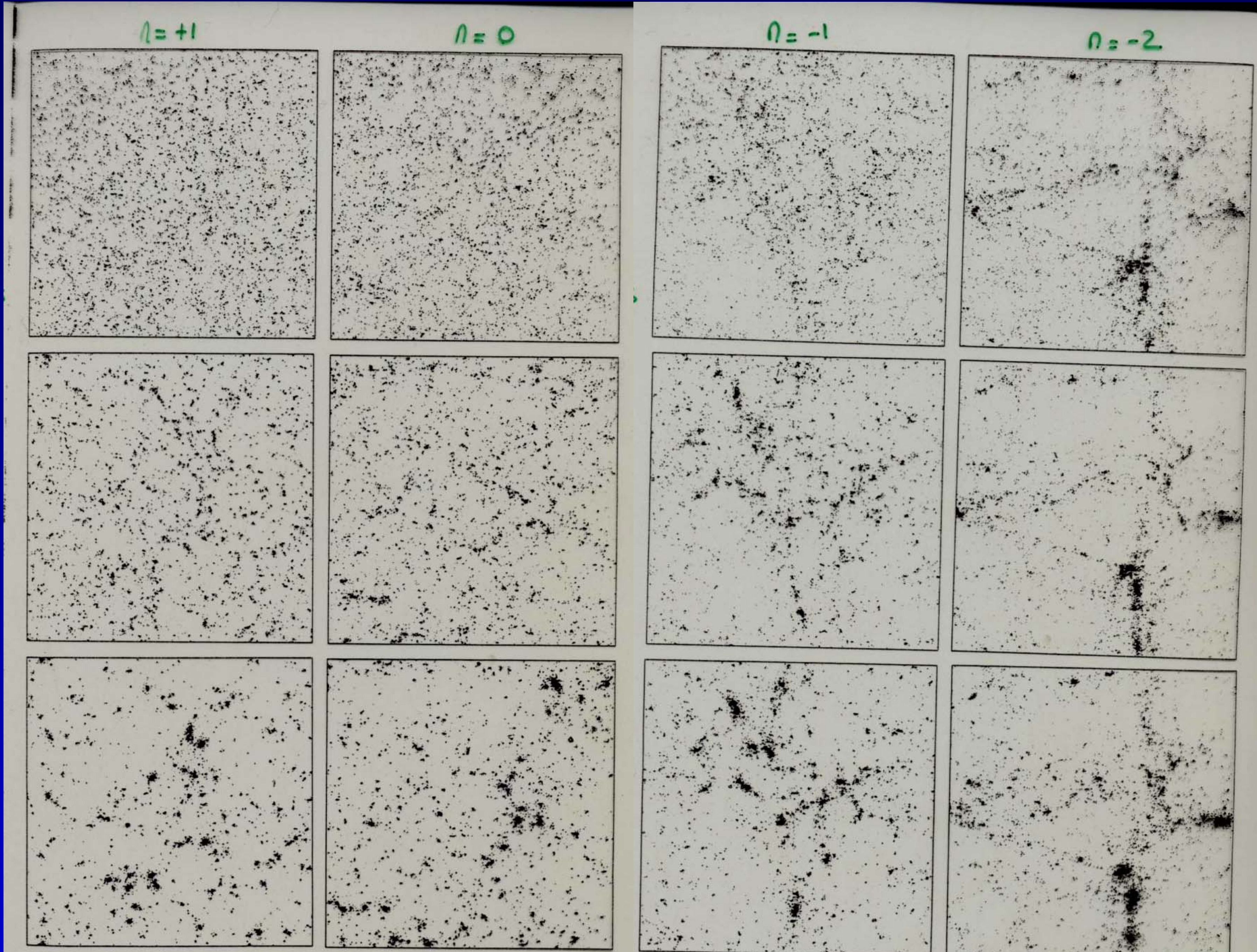
$$n(M)\,dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\left(1+\frac{n}{3}\right)\left(\frac{M}{M_*}\right)^{\frac{3+n}{6}} e^{-\frac{1}{2}\left(M/M_*\right)^{\frac{3+n}{3}}}\,\frac{dM}{M}$$

power-law

exponential cutoff

M_* is defined by $\Delta(M_*) = \delta_c$

Scale-Free Gravitational Clustering (Ω=1)



M* doubles in each frame, time runs downwards (Efstathiou et al 1988)

Scale-Free Halo Mass Function

Efst. et al 1988

Mass functions scaled to $M_*(t)$

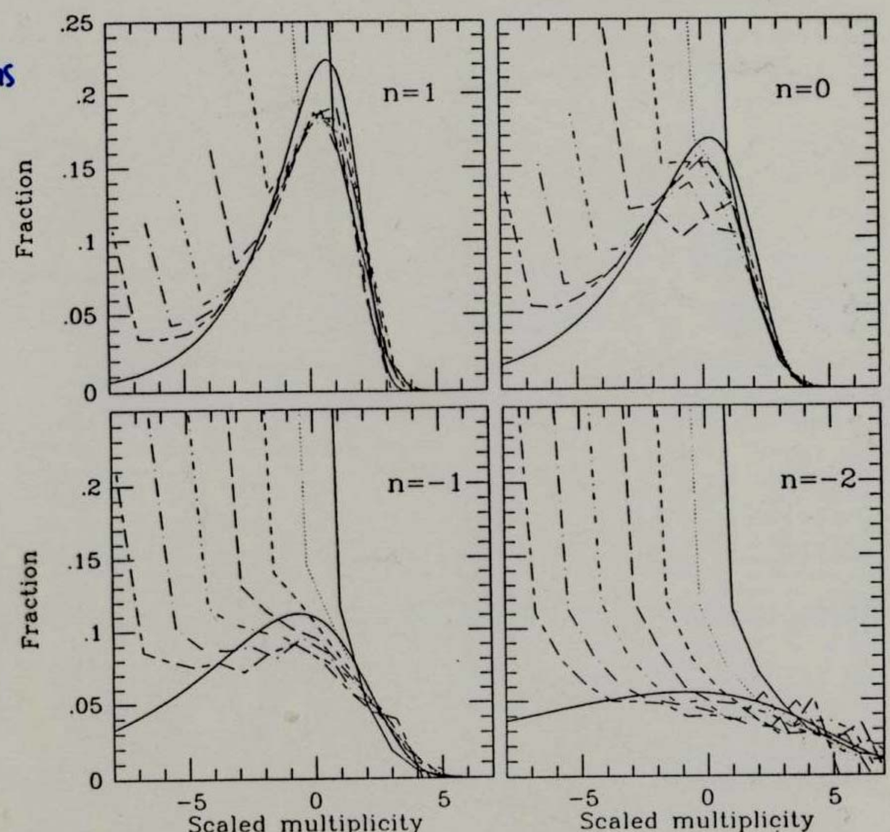


Figure 9. The multiplicity functions of Fig. 8 scaled to $a=1$ according to self-similarity. The smooth curves show the Press–Schechter model (equation 14).

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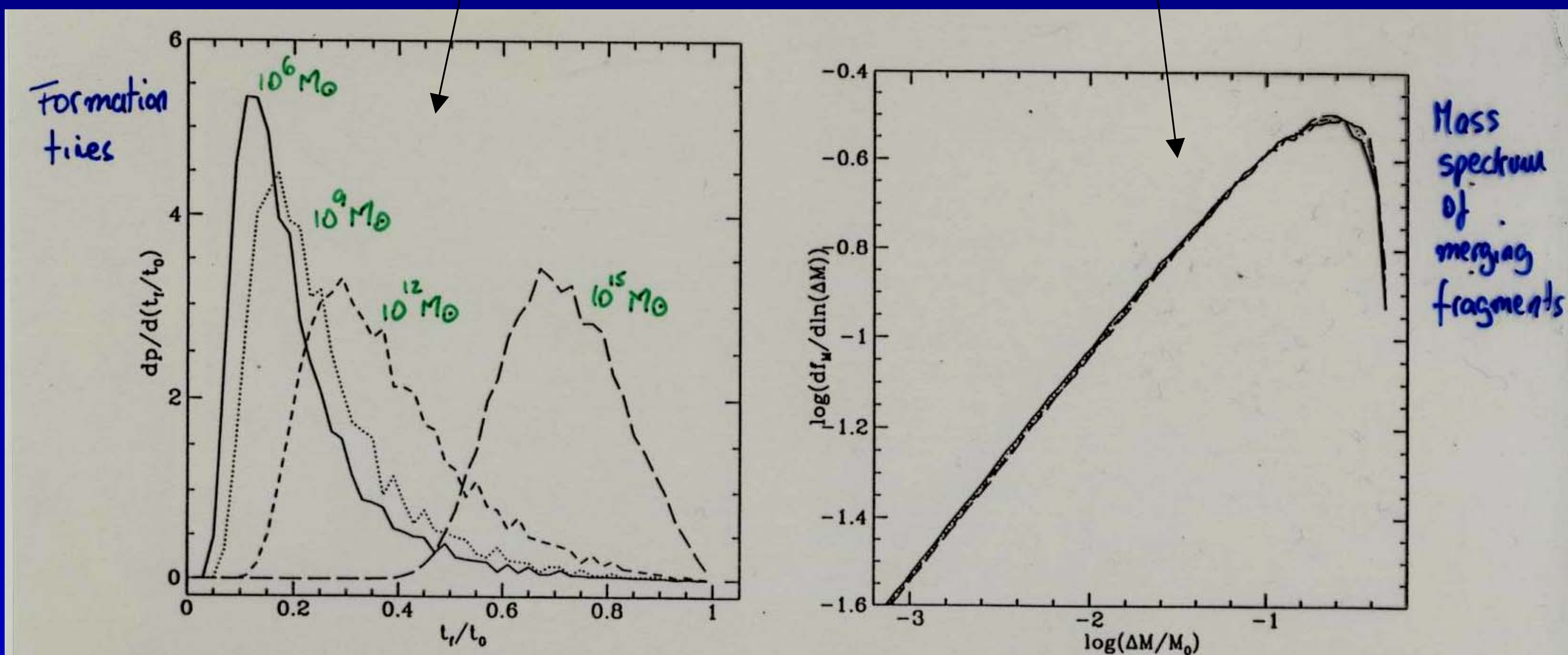
Formation Times

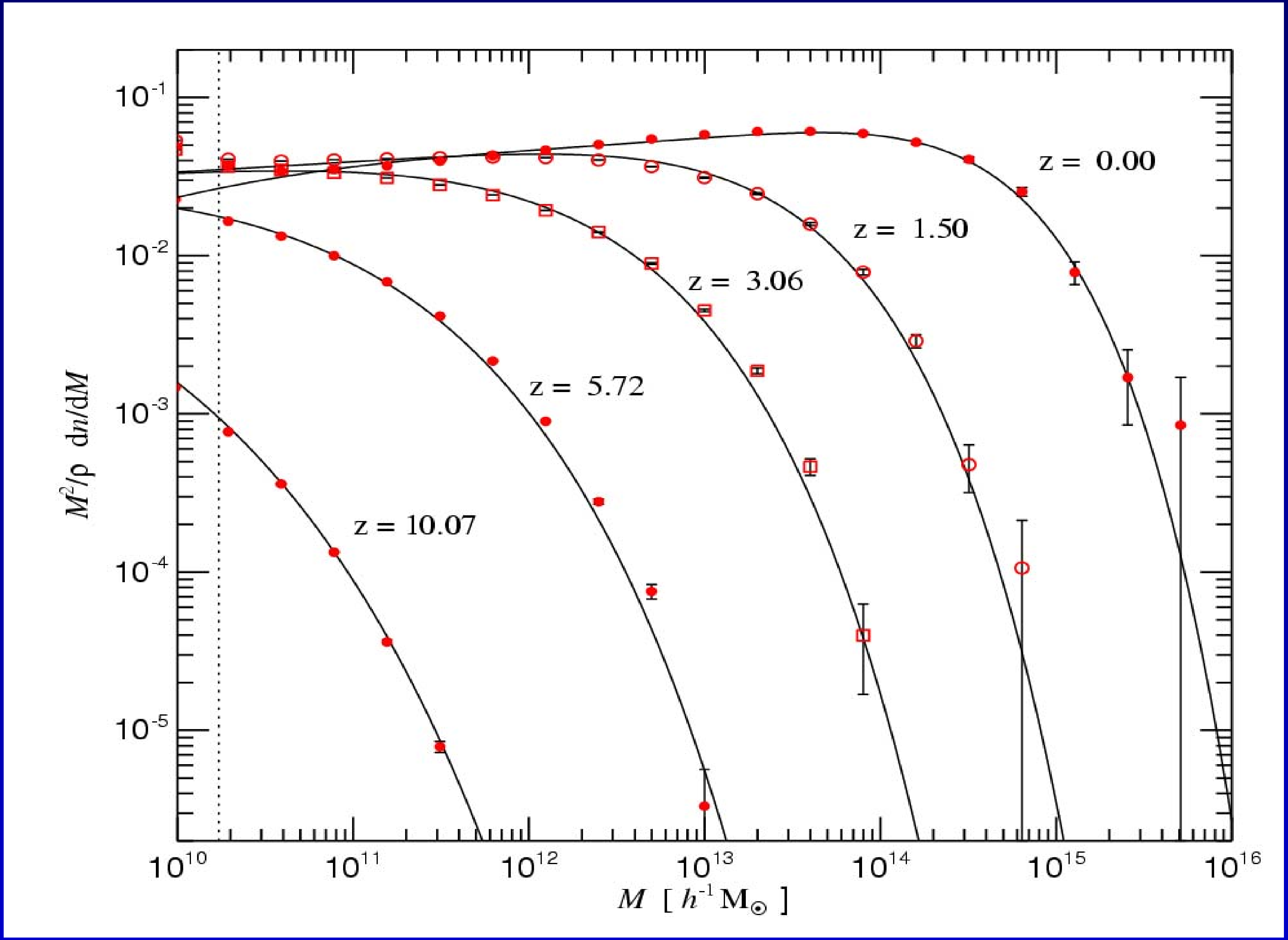
Using extensions of the Press-Schechter theory one may compute the distribution of formation times, or the mass spectrum of merging fragments.



Low mass halos assemble early, most of the mass is accreted in one or two major events

The CDM halo mass function is very well fit by the model of Jenkins et al. (2001), an improvement over the original PS formula.

MASS MULTIPLICITY FUNCTION IN THE MILLENNIUM RUN



(First halo with 23 particles at z=18.24, Springel et al 2004)

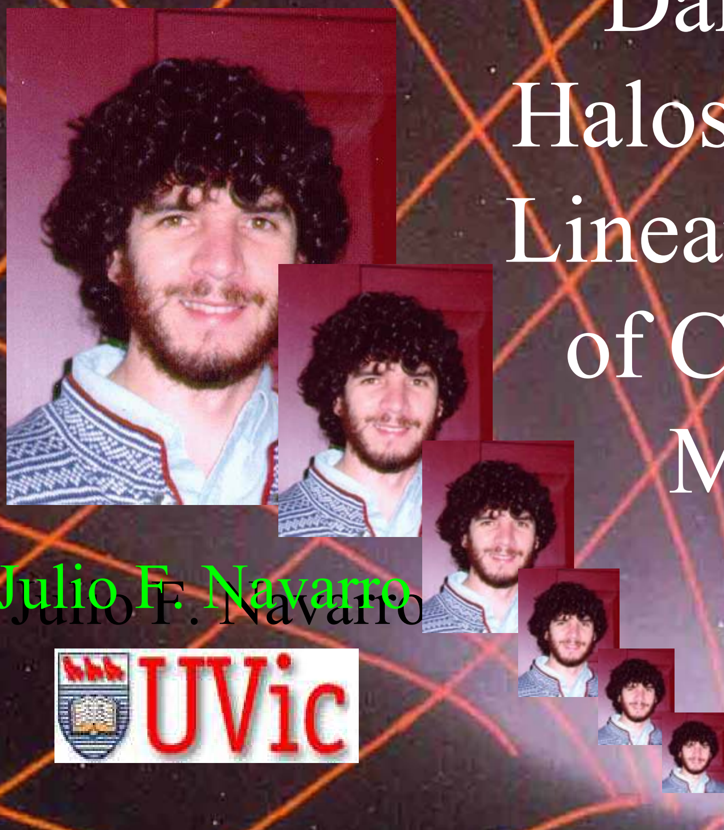
Things to remember

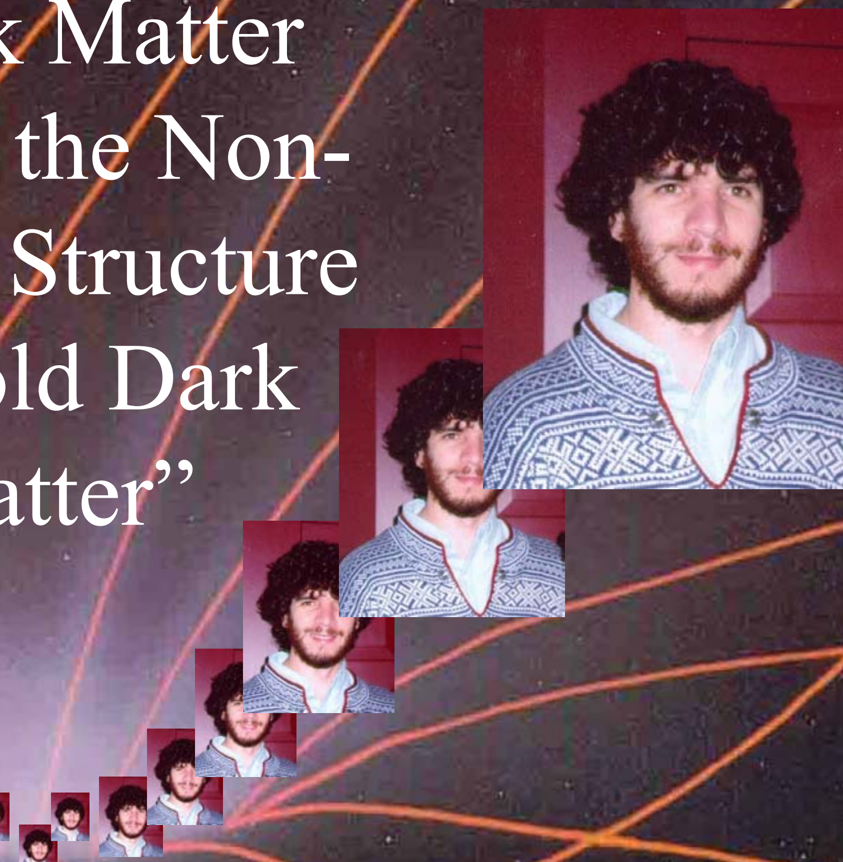
- The linear evolution of density perturbations is well understood. The predictions of the ΛCDM scenario are in very good agreement with observations on large scales.
- Structure in a ΛCDM universe progresses hierarchically, as small systems merge into larger ones. The statistics of this process are also well understood via extensions of the Press-Schechter theory.
- Most of the mass of the universe is in clumps of some mass, the evolution is hierarchical as clumps merge and accrete to transform into larger systems.

CIAR The Canadian Institute for Advanced Research

Cosmology and Gravity Program

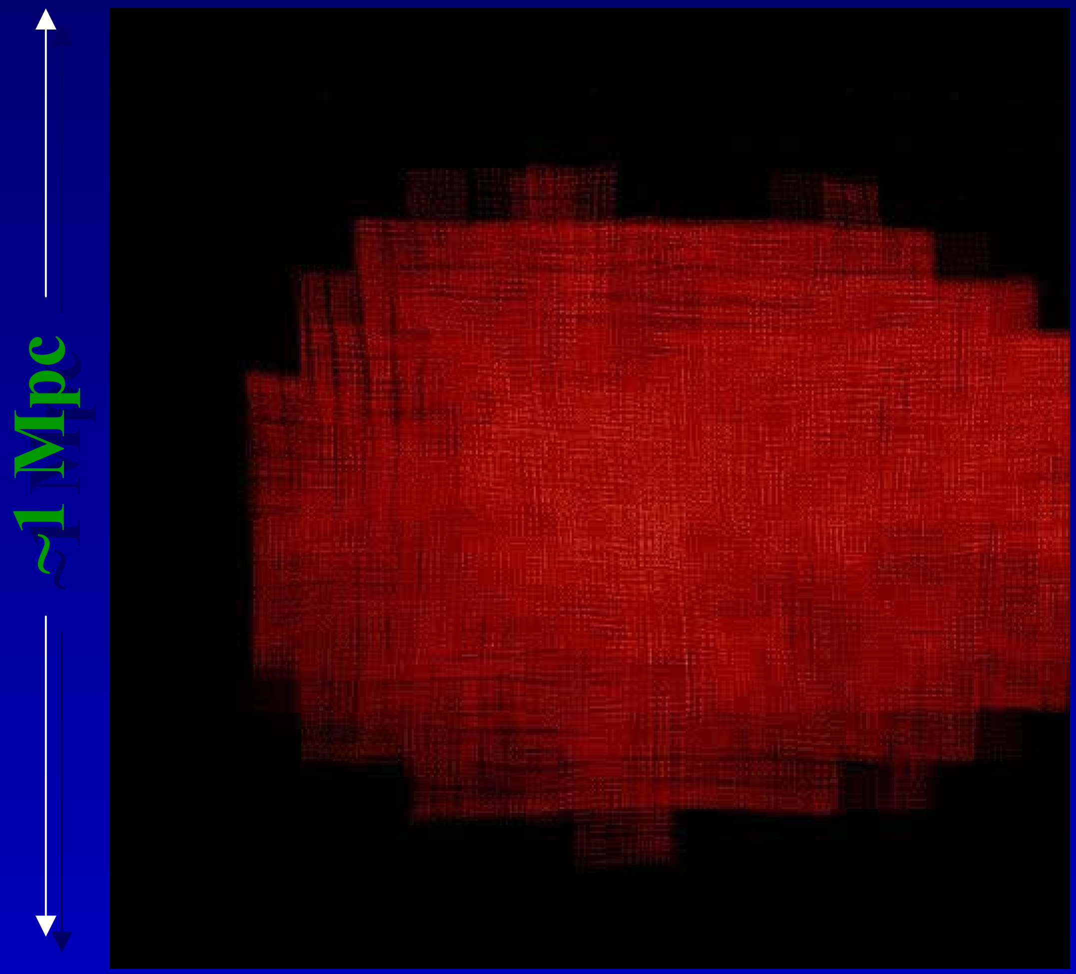
"Dark Matter Halos: the Non-Linear Structure of Cold Dark Matter"





Julio F. Navarro
UVic
Julio F. Navarro

Dark Matter Halos:
The Hosts of Galaxy Systems in CDM Universes



Dark Matter only

•Structure is formed from the bottom-up (i.e. small, dense halos collapse first)
•A substantial fraction of the mass is accreted through mergers.
•A significant amount of substructure remains in the halo at z~0.

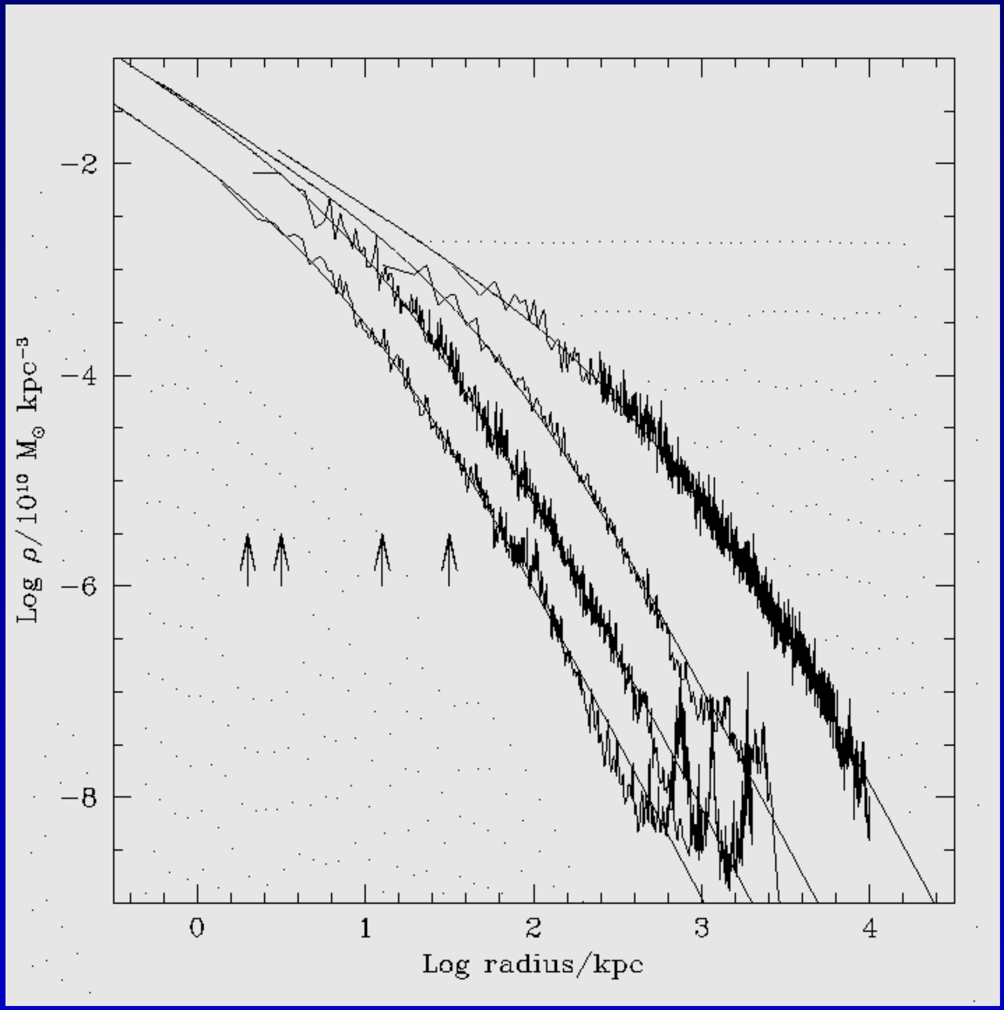
Steinmetz & Navarro 2000

Simulated CDM halos: Main results

- CDM mass profiles are "universal":
  - their shape is independent of mass and cosmological parameters.
- CDM density profiles are "cuspy":
  - density increases inward down to the innermost resolved radius. No evidence for an asymptotic power-law behaviour near the center.
- CDM halos are "clumpy":
  - Roughly 5-10% of the mass is in the form of self-bound clumps; the cores of accreted satellites that have so far survived full tidal disruption.

Mass Profile of Cold Dark Matter halos

Density



Radius

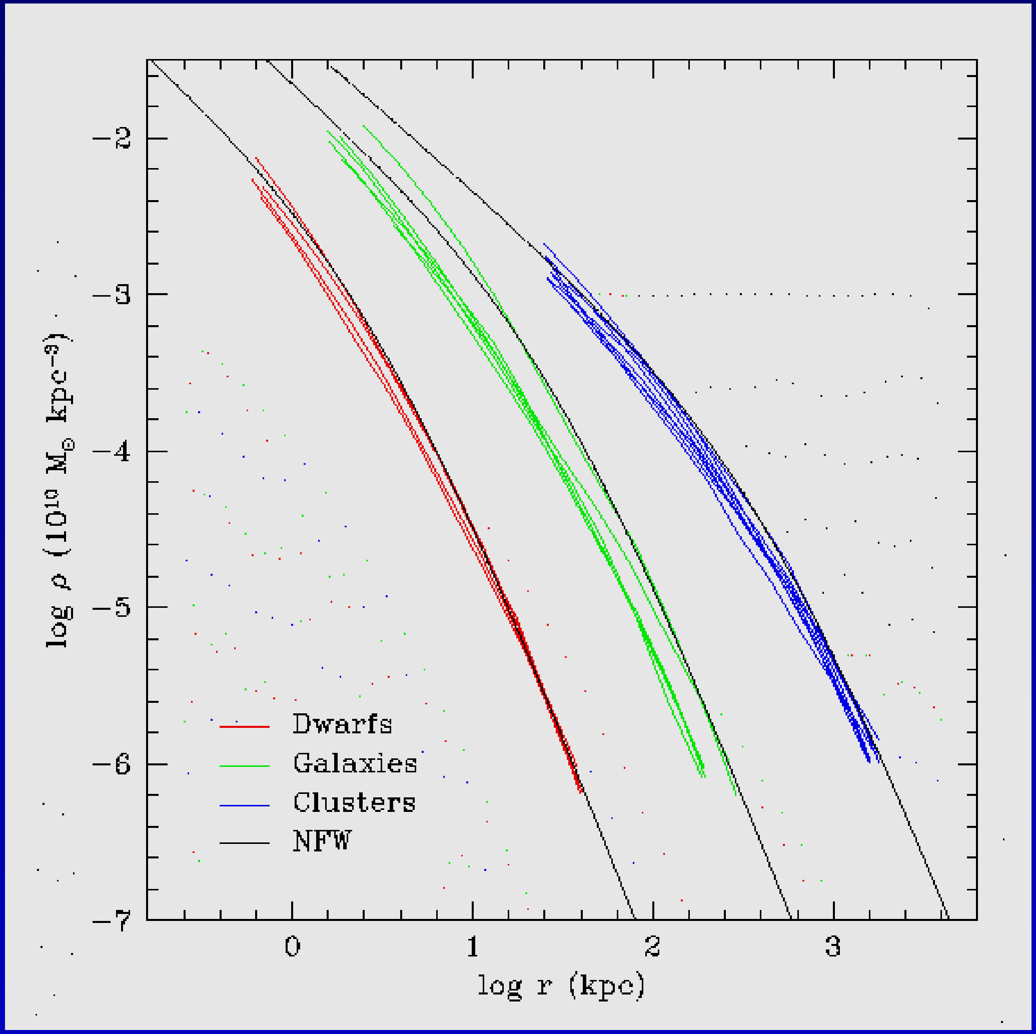
- Density profiles clearly differ from power laws
- The profile is shallower than isothermal near the center and steeper than isothermal in the outer regions
- There is no obvious density 'plateau' or 'core' near the the center

- Mass profiles of dark halos are independent of halo mass and cosmological parameters (Navarro, Frenk & White 1996, 1997)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

ΛCDM halo structure: mass dependence

Density



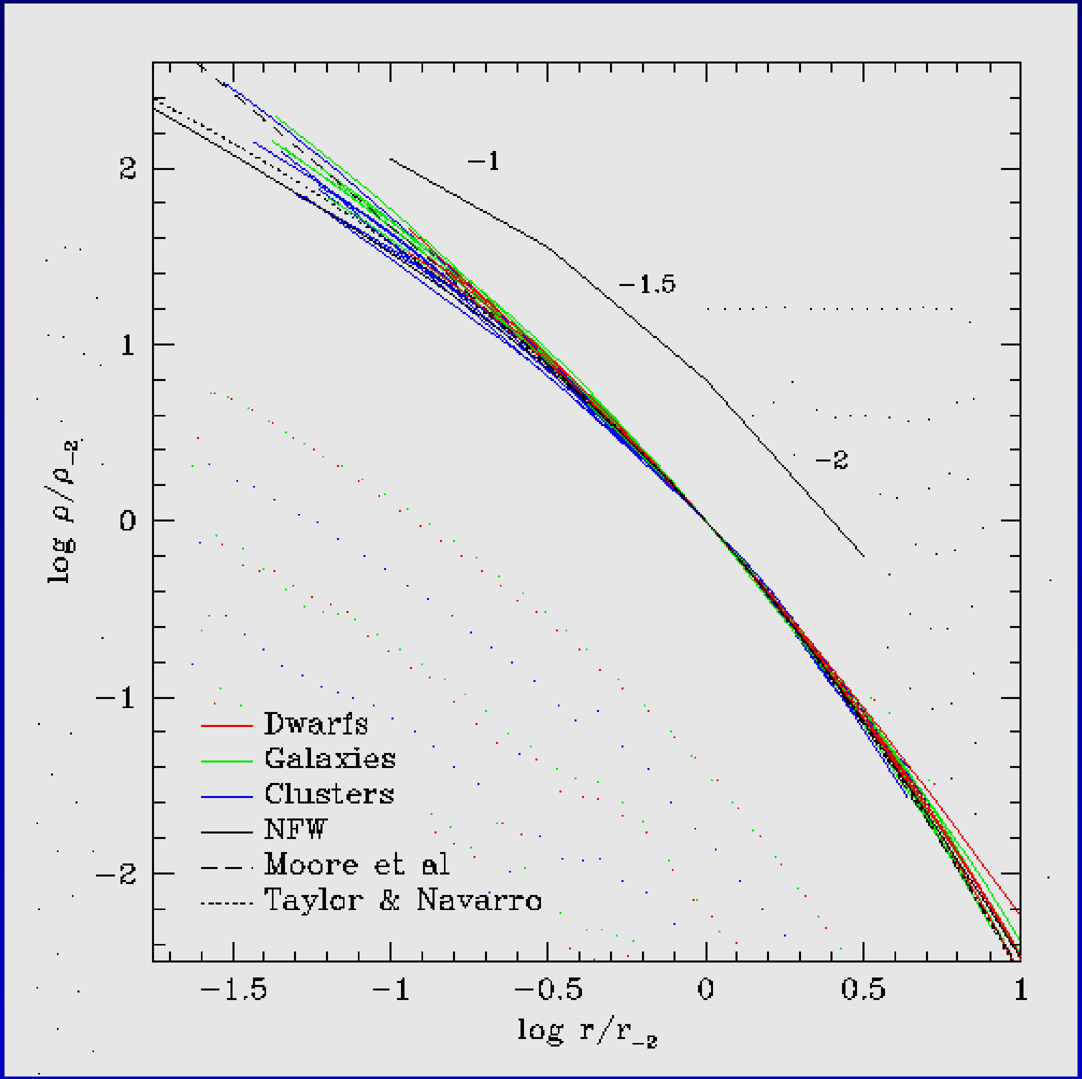
Radius

- Simulations span ~6 decades in halo mass, from dwarf galaxies (V_c~ 50 km/s) to galaxy clusters (V_c~1000 km/s)
- Characteristic density is a weak function of mass
- More massive halos are denser than less massive ones at all radii

Navarro, Frenk, White, Hayashi, Jenkins, Power, Springel, Quinn, Stadel

Universality of ΛCDM halo density profile

Scaled Density



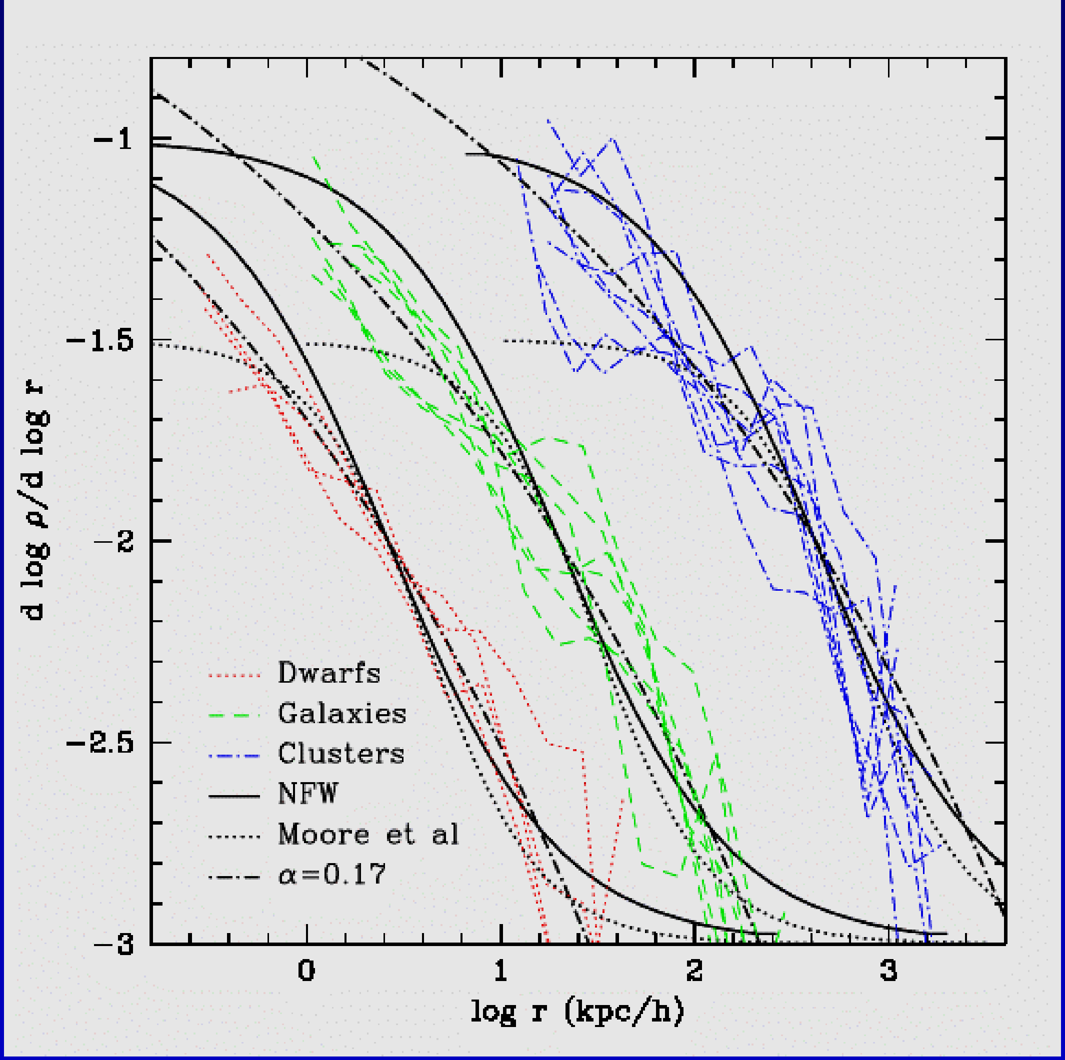
Scaled Radius

Properly scaled, all halos look alike: CDM halo structure appears to be approximately "universal"

Navarro, Frenk, White, Hayashi, Jenkins, Power, Springel, Quinn, Stadel

Logarithmic slope of halo density profile

Logarithmic Slope



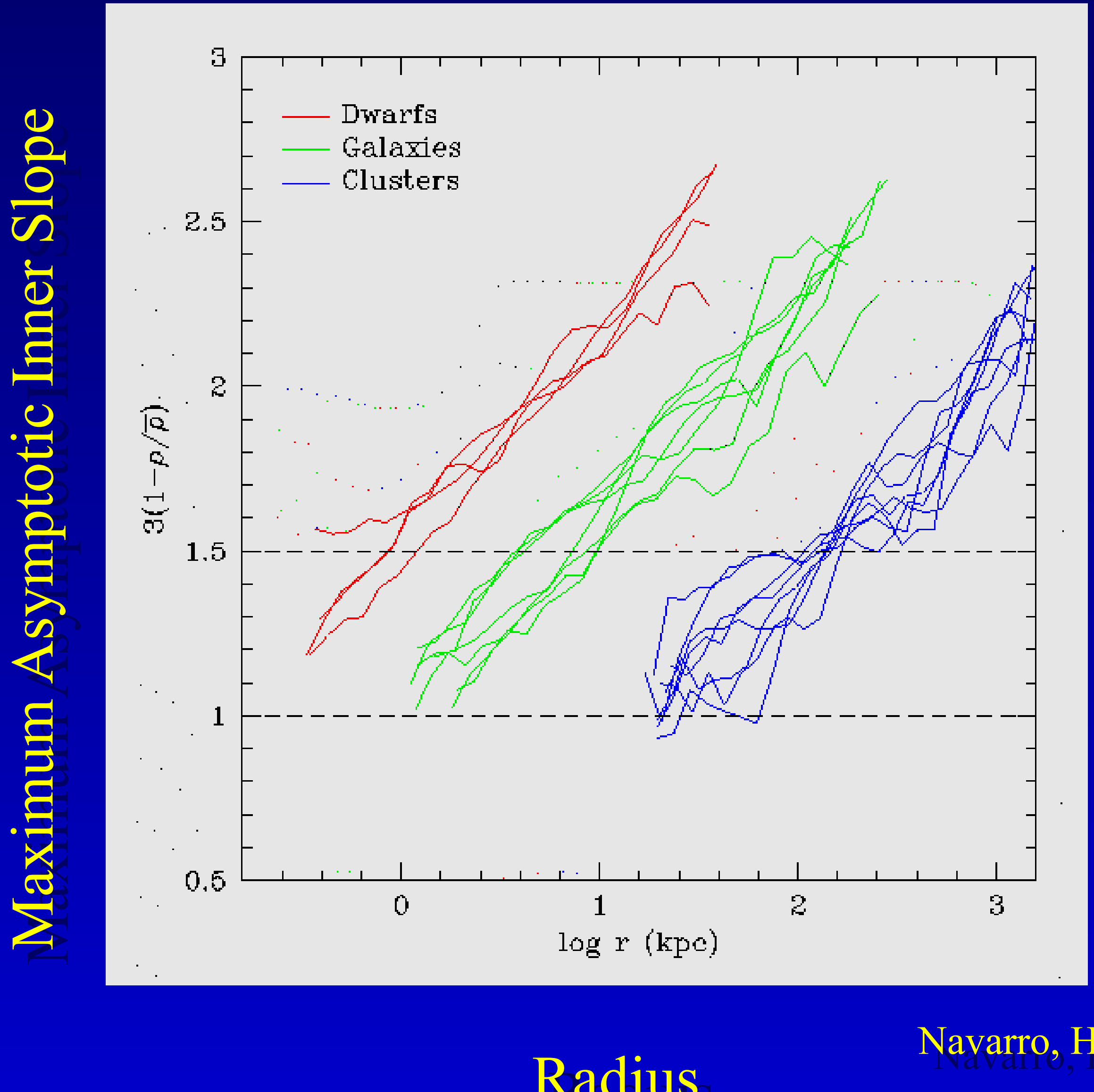
Radius

- No obvious convergence to a power law: profiles get shallower all the way in.
- Innermost slopes are shallower than –1.5
- Slope scales approximately as a power-law of radius:

$$\frac{d \log \rho_\alpha}{d \log r} = -2\left(\frac{r}{r_{-2}}\right)^{\alpha}$$

Navarro, Frenk, White, Hayashi, Jenkins, Power, Springel, Quinn, Stadel

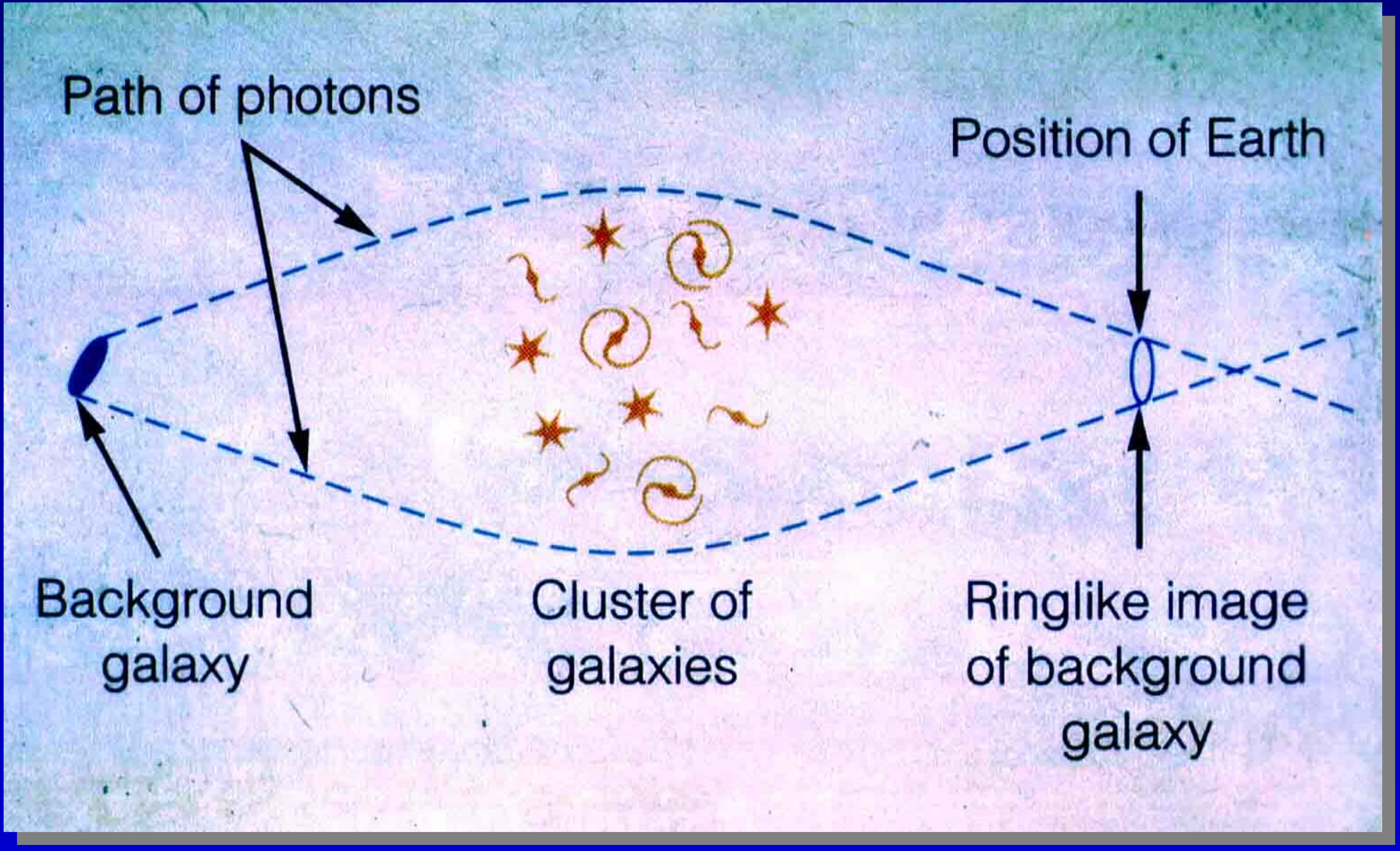
Central slope of ΛCDM halo density profile



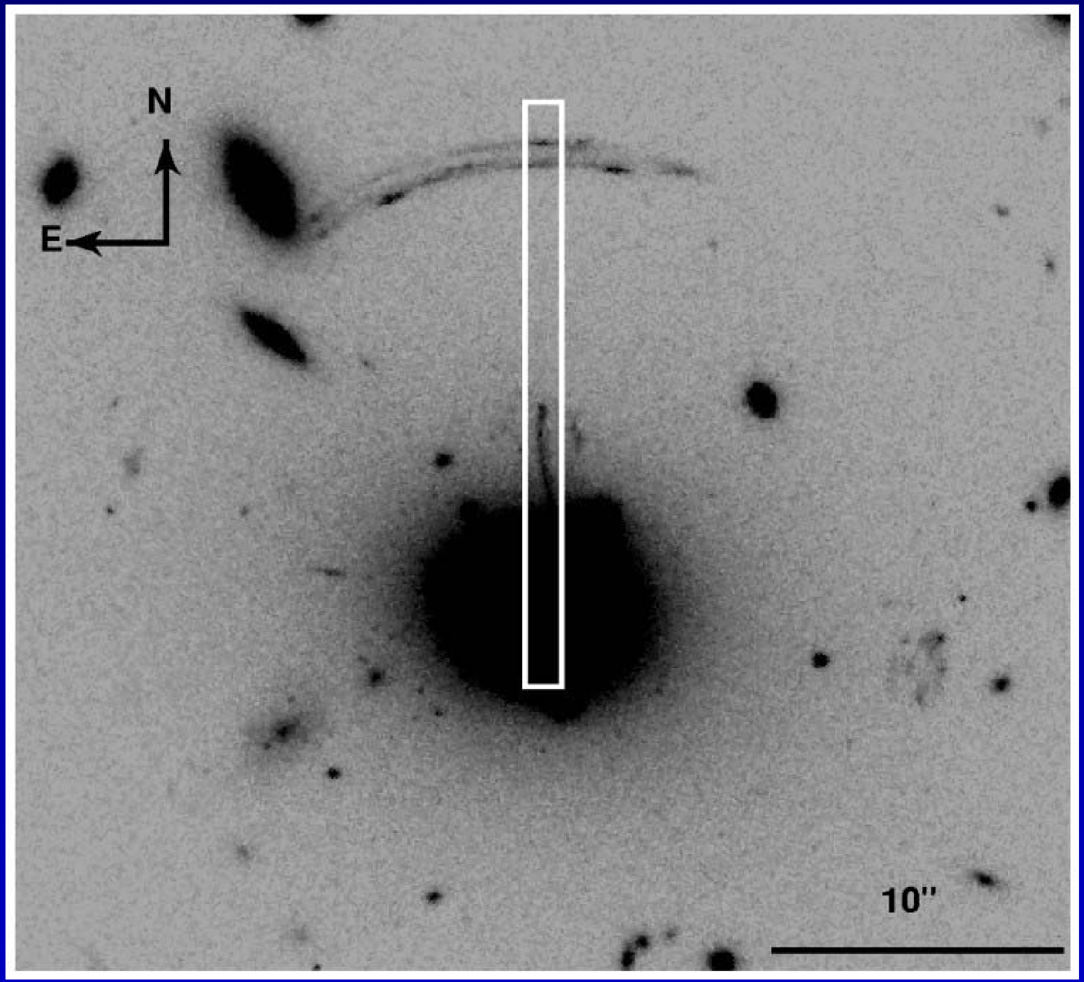
- The total mass enclosed within a given radius is robustly measured in the simulations.
- Combined with the local density, it may be used to derive an upper limit to the inner asymptotic logarithmic slope
- There is not enough mass in the inner regions to sustain a power-law profile as steep as $\rho \sim r^{-1.5}$

Navarro, Hayashi, Frenk, Jenkins, White, Power, Springel, Quinn, Stadel

CDM Halo Structure and Gravitational Lensing



Why do we care?: "shallow" density profiles and lensing



- CDM halos must be shallower than isothermal near the center: the velocity dispersions of central cluster galaxies is lower than that of the cluster as a whole.

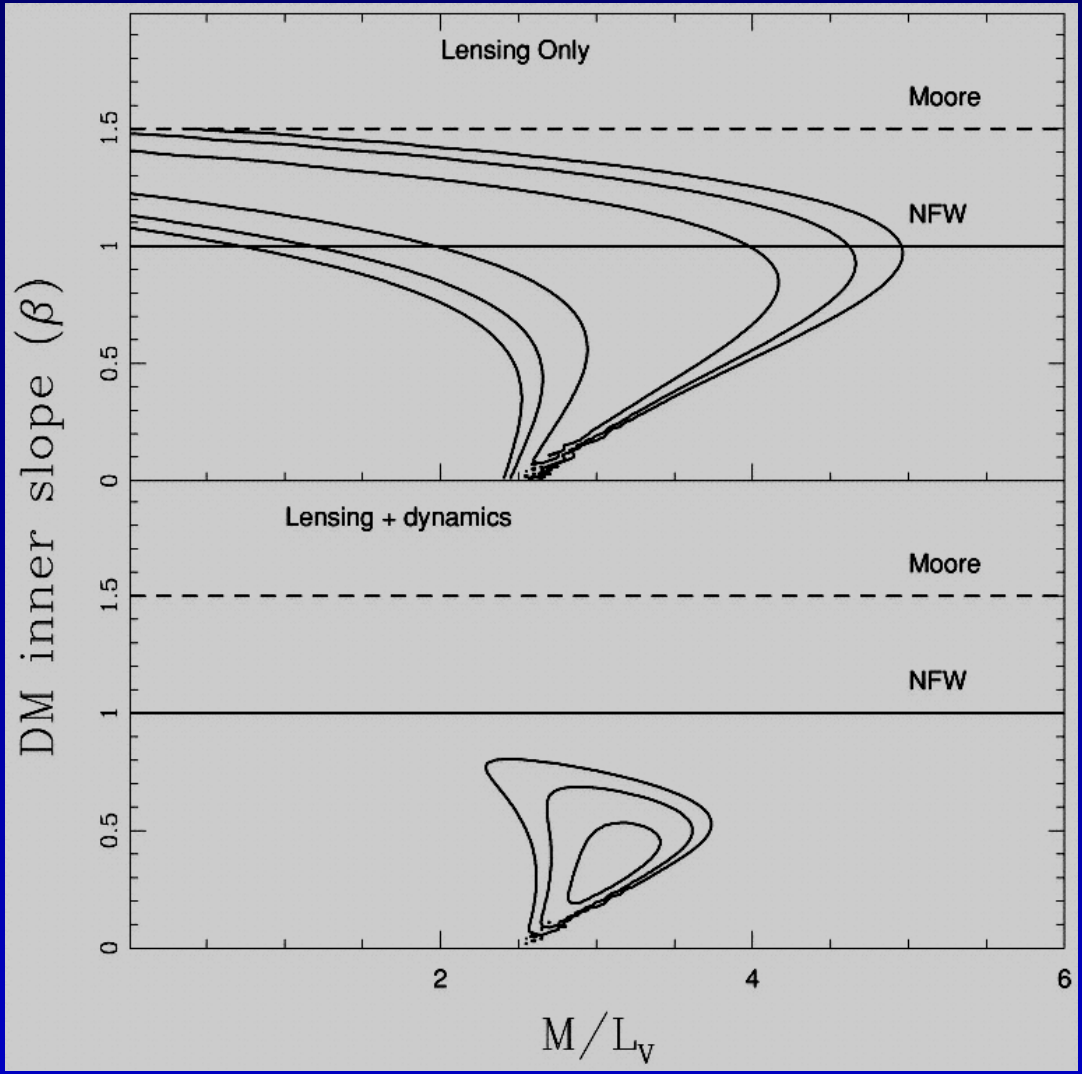
- CDM halos do not make great lenses: arcs are expected to be thick and close to the center—unless their lensing power is boosted by a central galaxy

- Shallow inner profiles allow the formation of "radial arcs".

Sand et al 2002

“Shallow” density profiles and lensing

Maximum Asymptotic Inner Slope



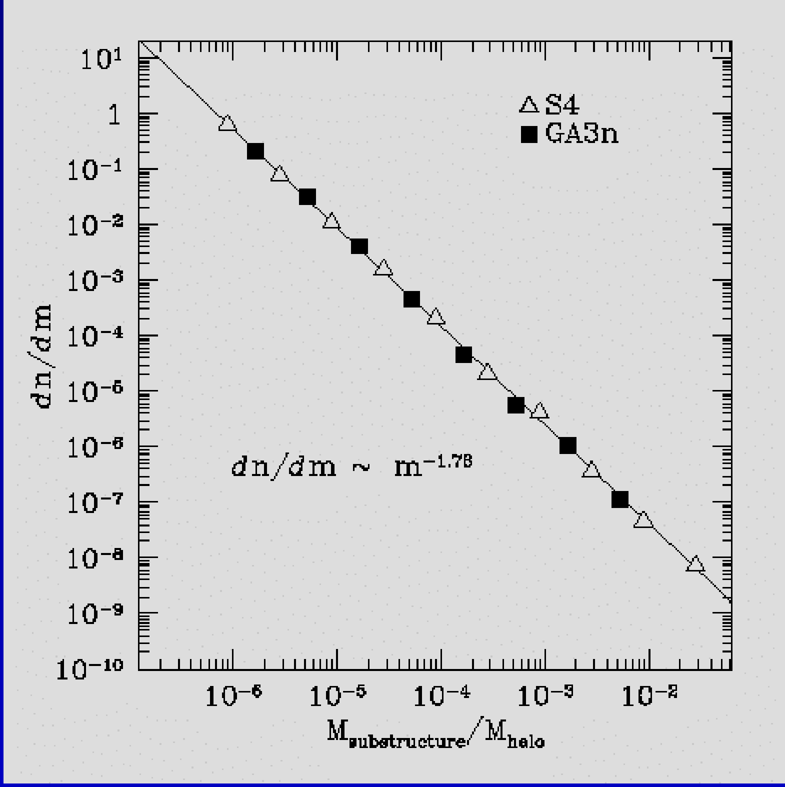
Radius

•Spatially resolved measurements of the velocity dispersion of stars in the central galaxy, together with the position of the arcs allow for constraints to be placed on the inner slope of the dark matter density profile: **shallow halos are favoured by the data.**

Sand et al 2002

Implications of CDM halo structure

- **Shallow inner central slopes ($\rho \sim r^{-1}$ or shallower) :**
  - ➔ relatively little mass at the center
  - ➔ cores are not "self-bound"
  - ➔ halos may fully disrupt in the tidal field of other halos
  - ➔ more massive halos are denser
  - ➔ tidal disruption is very efficient
  - ➔ little mass (5-10%) is attached to bound substructures: this is a robust result, the mass function of substructures is well established



Implications for dark matter direct detection experiments

- Signal recovery and interpretation depends critically on the local distribution of dark matter particles
- DM in the solar vicinity is expected to be uniformly distributed and with approximately Gaussian velocity distribution

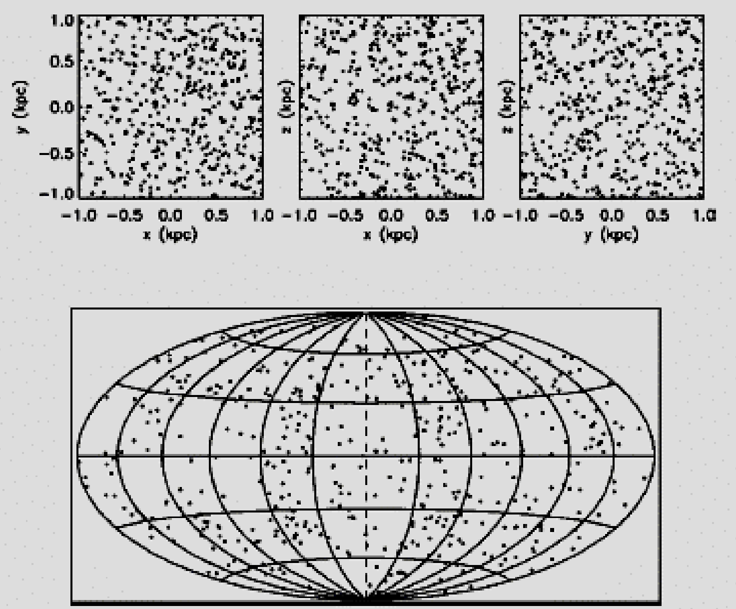
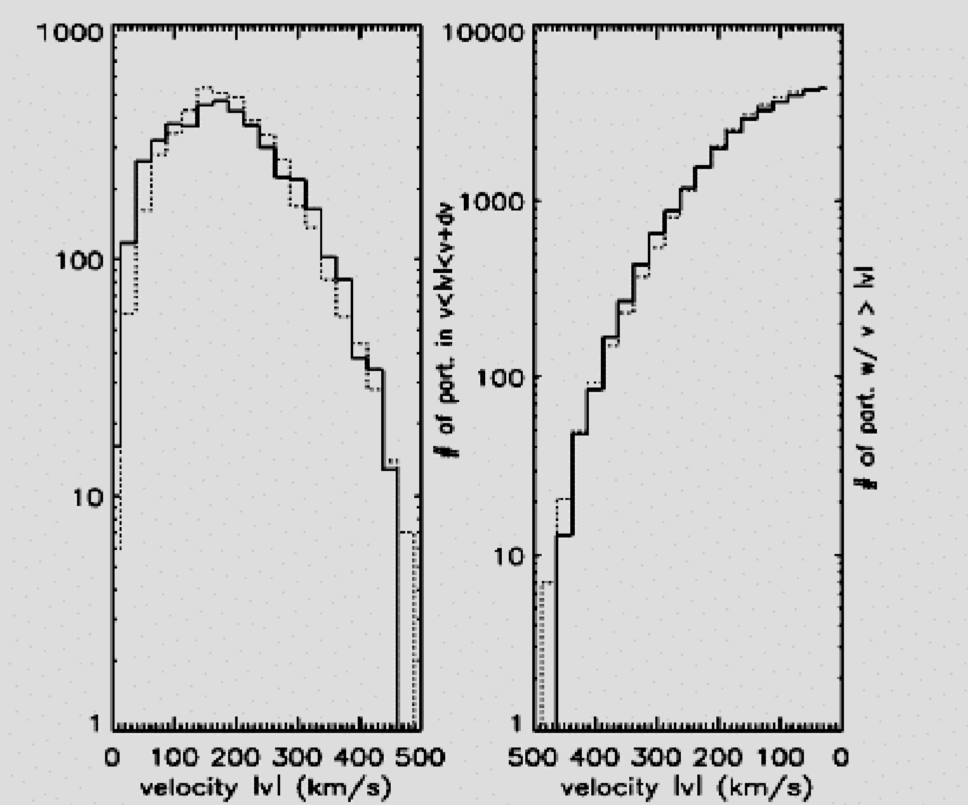


FIG. 5. The top panels show the spatial distribution of particles inside a 2 kpc on a side volume located at 8 kpc from the galaxy center, i.e., this volume is centered on the "Sun." There are 474 particles in this box. The bottom panel shows their distribution on the sky.



Positions

Velocities

Helmi et al 2003

Dark Matter annihilation signal

- If dark matter particle is Majorana, it may self-annihilate in high density regions and give rise to a detectable signal

$$F = \frac{N_\gamma \langle \sigma v \rangle}{2 m_{\rm DM}^2} \int_V \frac{\rho_{\rm DM}^2(\mathbf{x})}{4\pi d^2(\mathbf{x})} \, \mathrm{d}^3 x,$$

$$F = \frac{N_\gamma \langle \sigma v \rangle}{2 d^2 m_{\rm DM}^2} \int_0^{r_{200}} \rho_{\rm DM}^2(r) r^2 \, \mathrm{d}r,$$

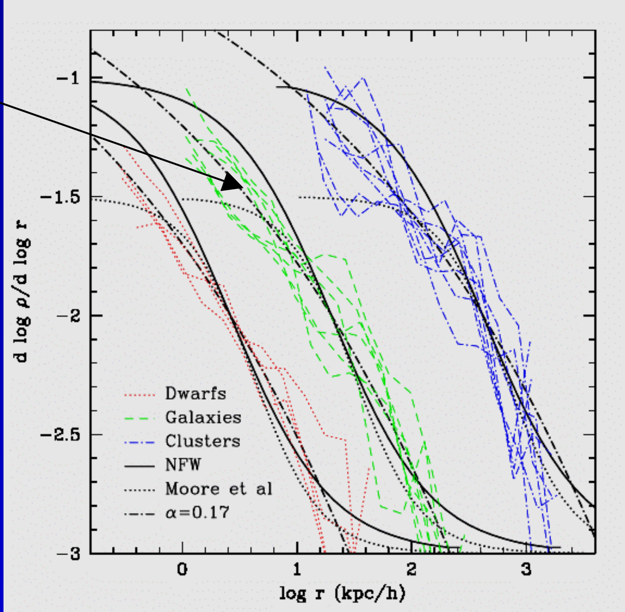
➔ this collision-driven process is highly dependent on the central properties of the halo

➔ for a smooth halo, most of the flux will come from the region where $\rho \sim r^{-1.5}$ (indeed, it formally diverges for cusps this steep)

➔ for galactic halos, this happens at moderately large radius (~3-5 kpc)

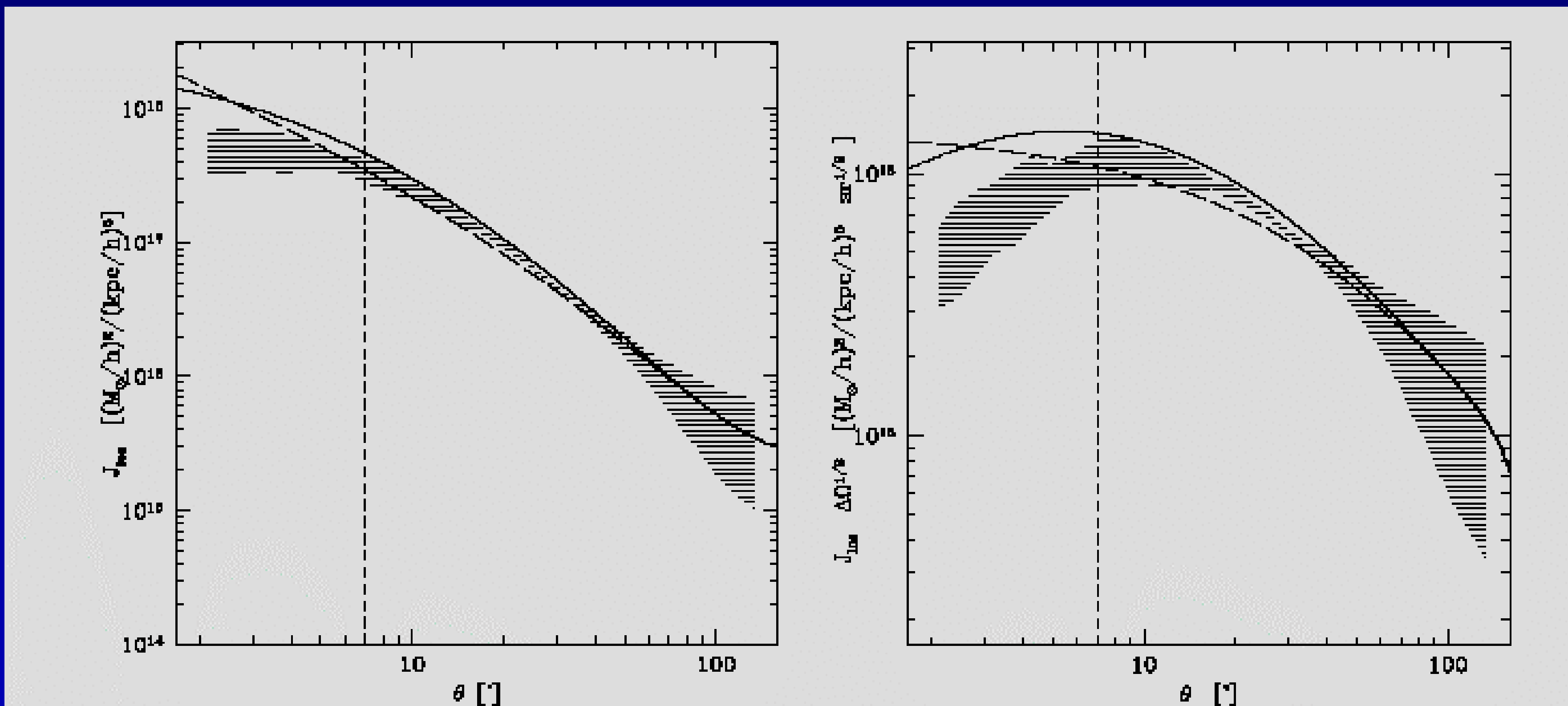
➔ This implies that annihilation signal is predicted be extended, and not point-like

➔ It should have a sharp upper energy cutoff: the rest-mass energy of the particle



Dark Matter annihilation signal

- Annihilation signal is expected to be significantly extended



Flux vs angular distance from the Galactic Center

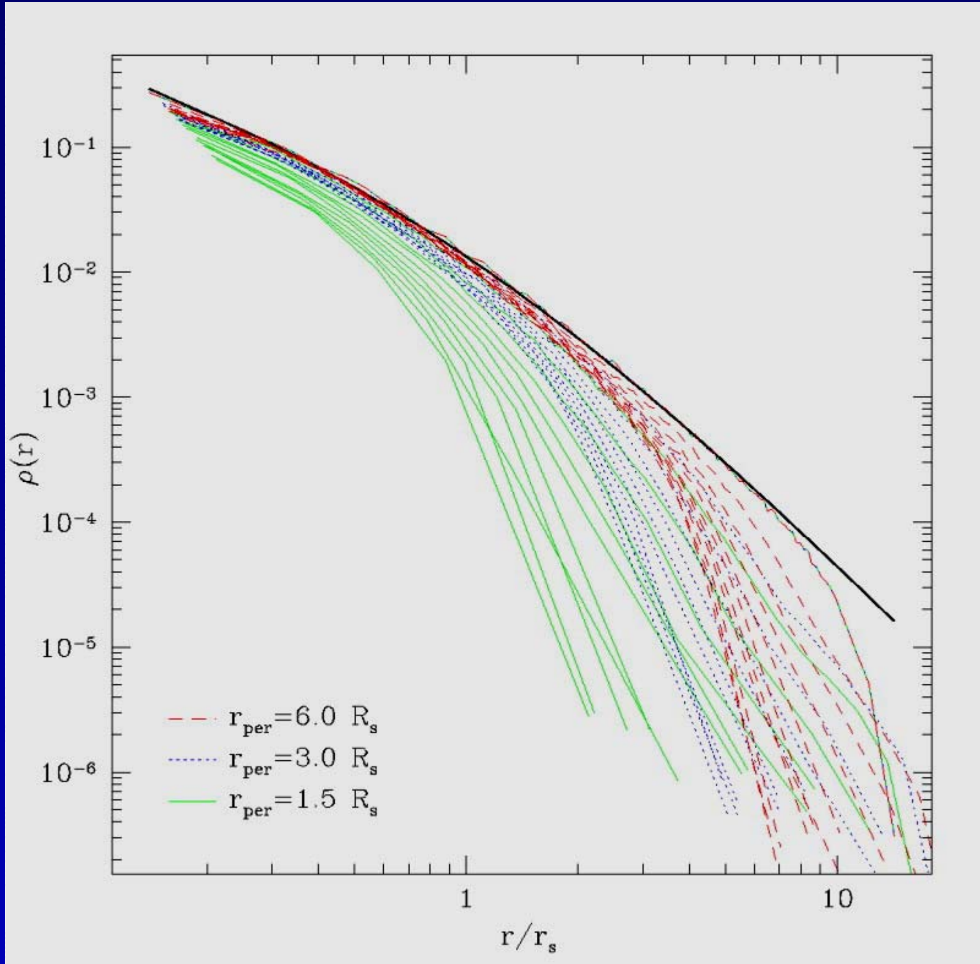
Signal-to-noise (for a uniform background)

Stoehr et al 2003

Dark Matter annihilation signal

- Substructure halos are expected to contribute little to the overall annihilation flux

  - ➔ Tidal losses lower significantly the central density of substructure halos
  - ➔ Most of the flux is expected to come from around the Galactic center
  - ➔ It may deviate significantly from spherical symmetry

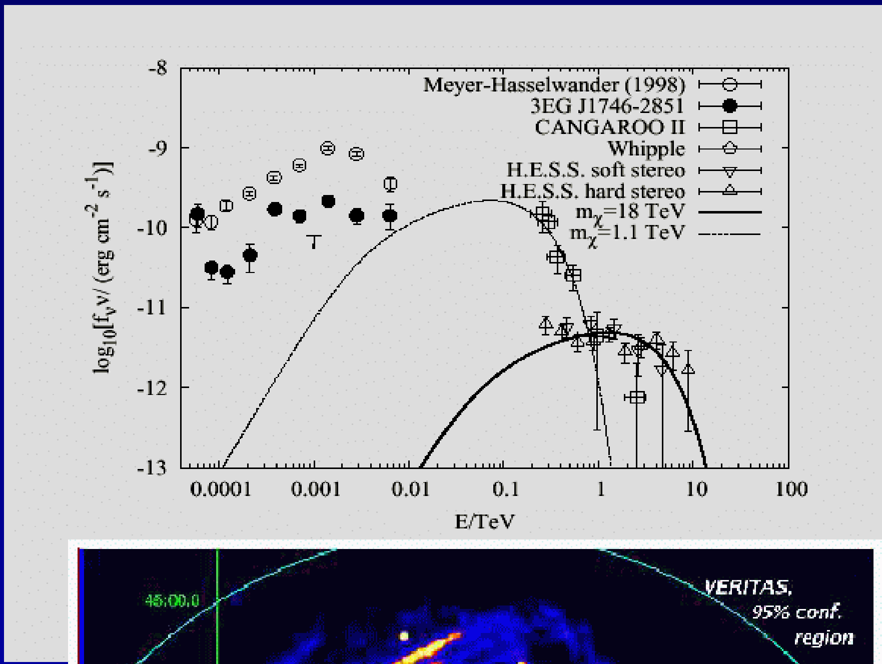


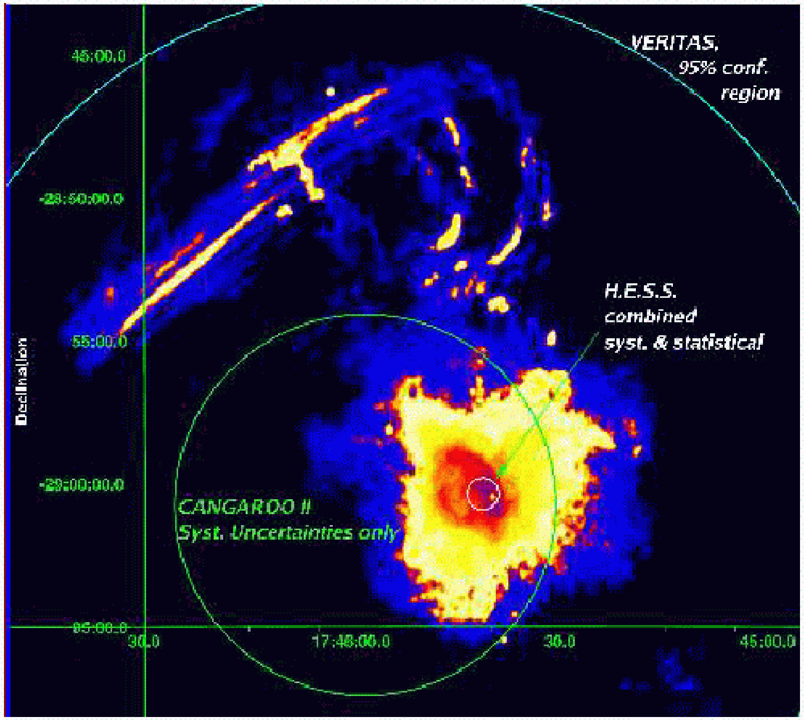
GA3n. The region displayed is a cube of side 270 kpc, i.e. 1 times r_{200}. Each particle is weighted by its local density so that the picture represents an image in annihilation radiation. The main image has a logarithmic intensity scale, whereas the small image reproduces the centre on a linear intensity scale. This figure is available in colour in the online version of the journal on *Synergy*.

Stoehr et al 2003

Dark Matter annihilation

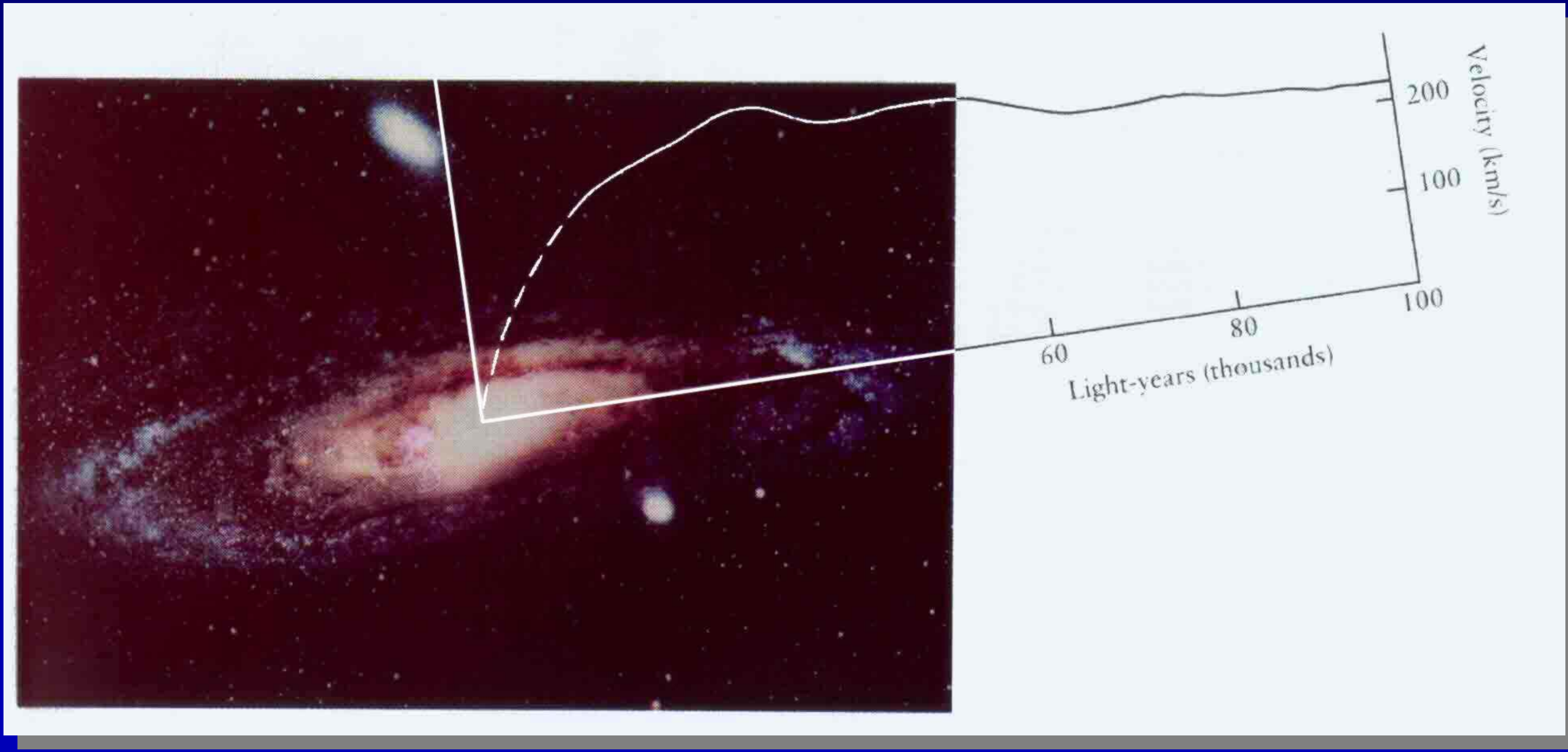
- Has this been already observed?
  - ➔ Excess of gamma-ray flux above 1 TeV over expected background
  - ➔ But point-mass like
  - ➔ Also implies a much larger mass than traditional predictions for thermal relics
  - ➔ There are ways around this, but…





Boer et al 2004, Horns 2004

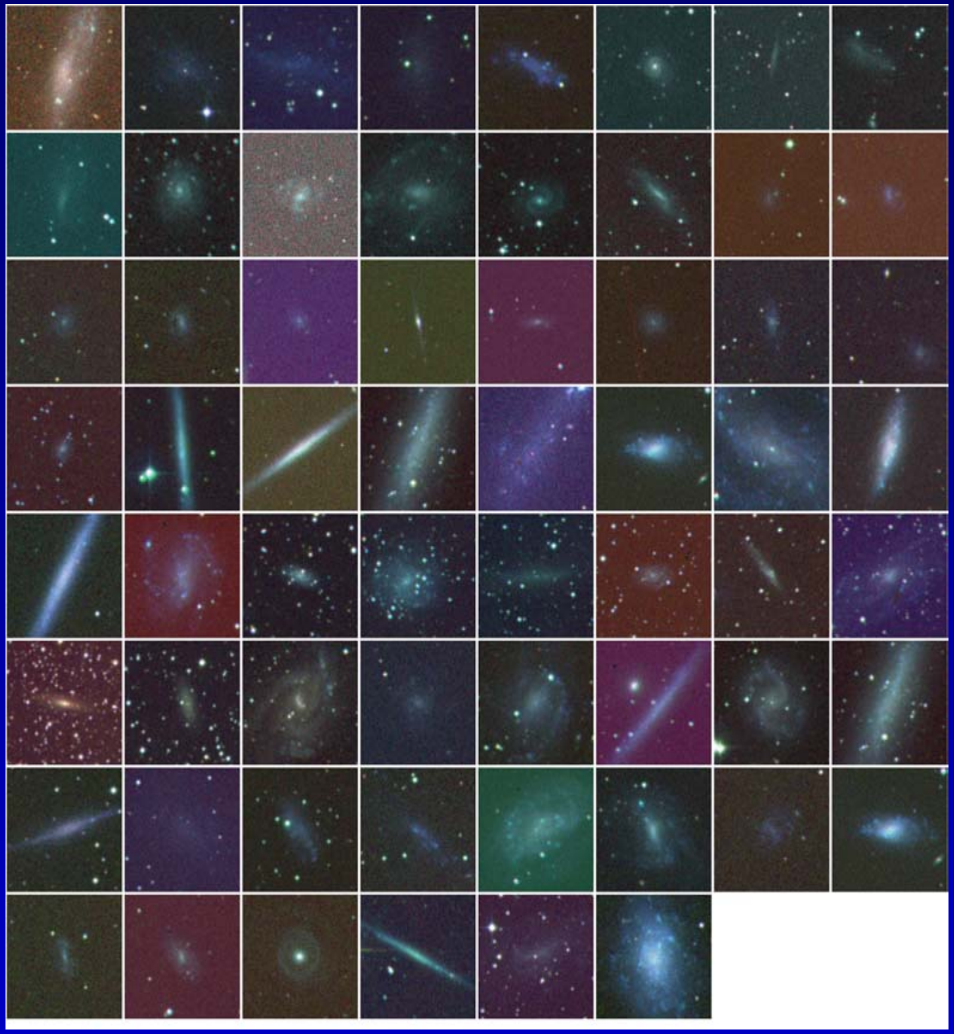
CDM Halo Structure and Disk Galaxy Rotation Curves



Flat $V_c \rightarrow$ $M(<r) \propto r$

$\Rightarrow$ **dark massive halo around galaxy**

CDM halo cusps and rotation curves



- Compare dwarf- and galaxy-sized halo circular velocity (V_C) profiles with rotation curves of dark matter-dominated LSB galaxies

- Relies on the assumption that rotational velocity is directly proportional to circular velocity

- Rotation curve datasets of
de Blok et al (2001) (B01),
de Blok & Bosma (2002) (B02), and
Swaters et al (2003) (S03)

- Peak velocities range from 25 km/s to 270 km/s

Most disk galaxy rotation curves are consistent with “cuspy” CDM halos

ROTATION CURVE FITS

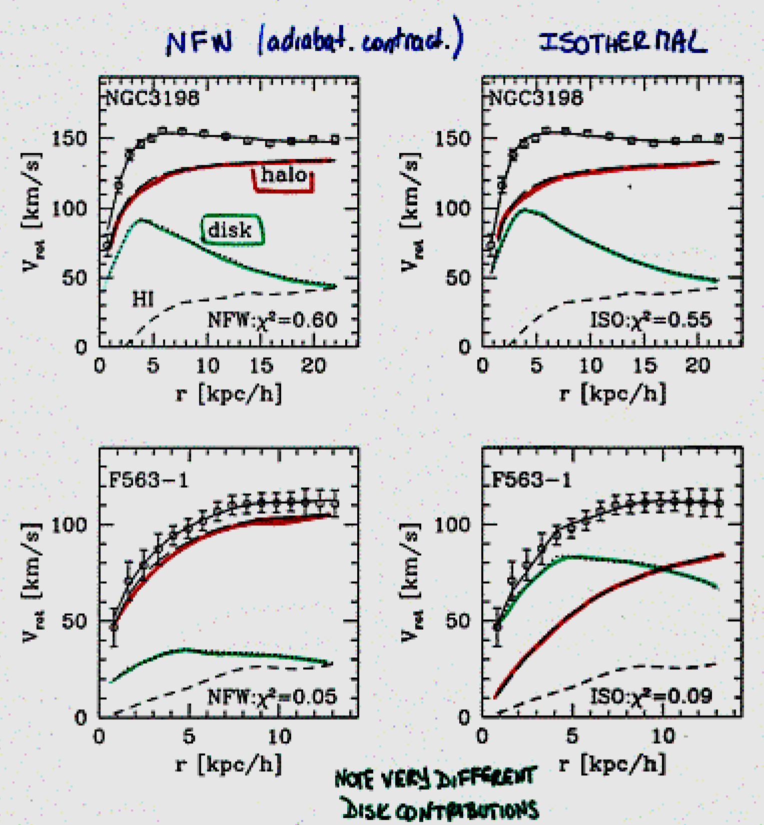


Fig. 2.— Rotation curve fits using the NFW and the ISO halo models shown for a high-surface brightness galaxy (NGC 3198, Begeman 1988) and a low-surface brightness galaxy (F563-1, de Blok 1997). Note that either halo model produces acceptable fits, although they may require different contributions of the disk.

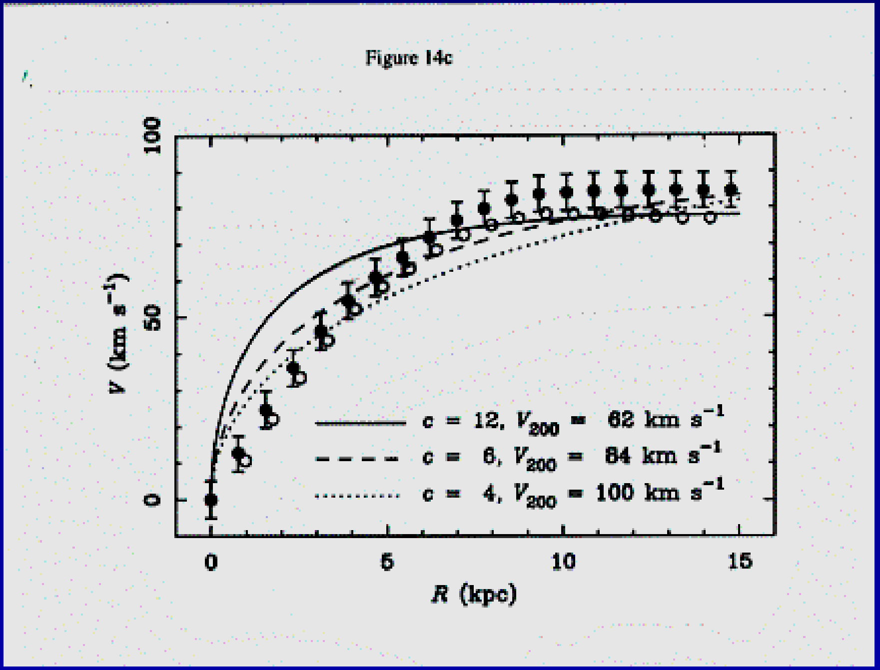
NFW + ISOTHERMAL DO ≈ EQUALLY WELL

EXCEPT FOR A FEW LSBs

LSB rotation curves and CDM halos

- Let us split the problem in two:
  - –The shape of LSB galaxy rotation curves is inconsistent with the circular velocity curves of CDM halos.
  - –The concentration of dark matter halos is inconsistent with rotation curve data:

    there is too much dark matter in the inner regions of LSB galaxies.



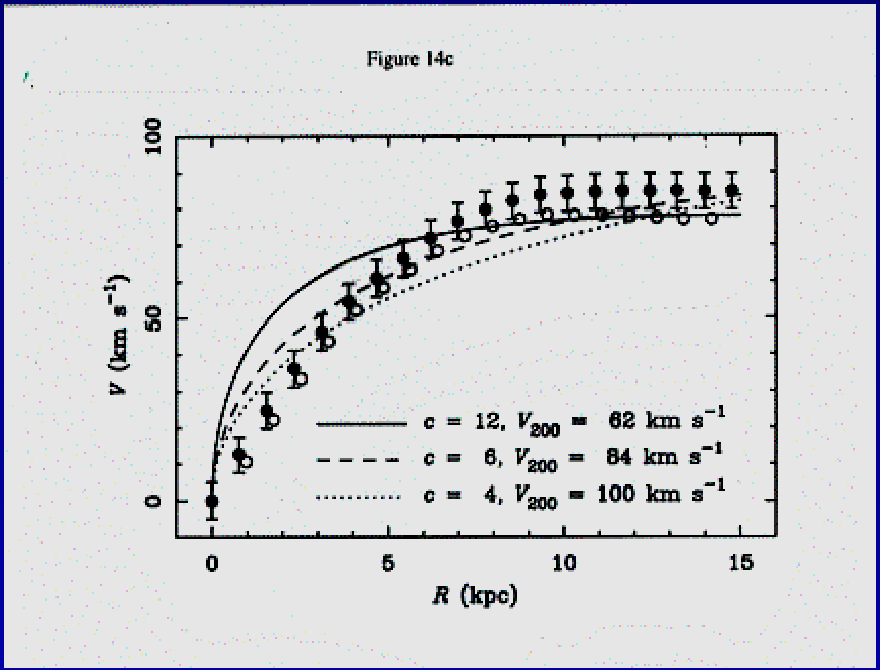
McGaugh & de Block 1998
see also Moore 1994
Flores & Primack 1994

LSB rotation curves vs cusps

•Some caveats:

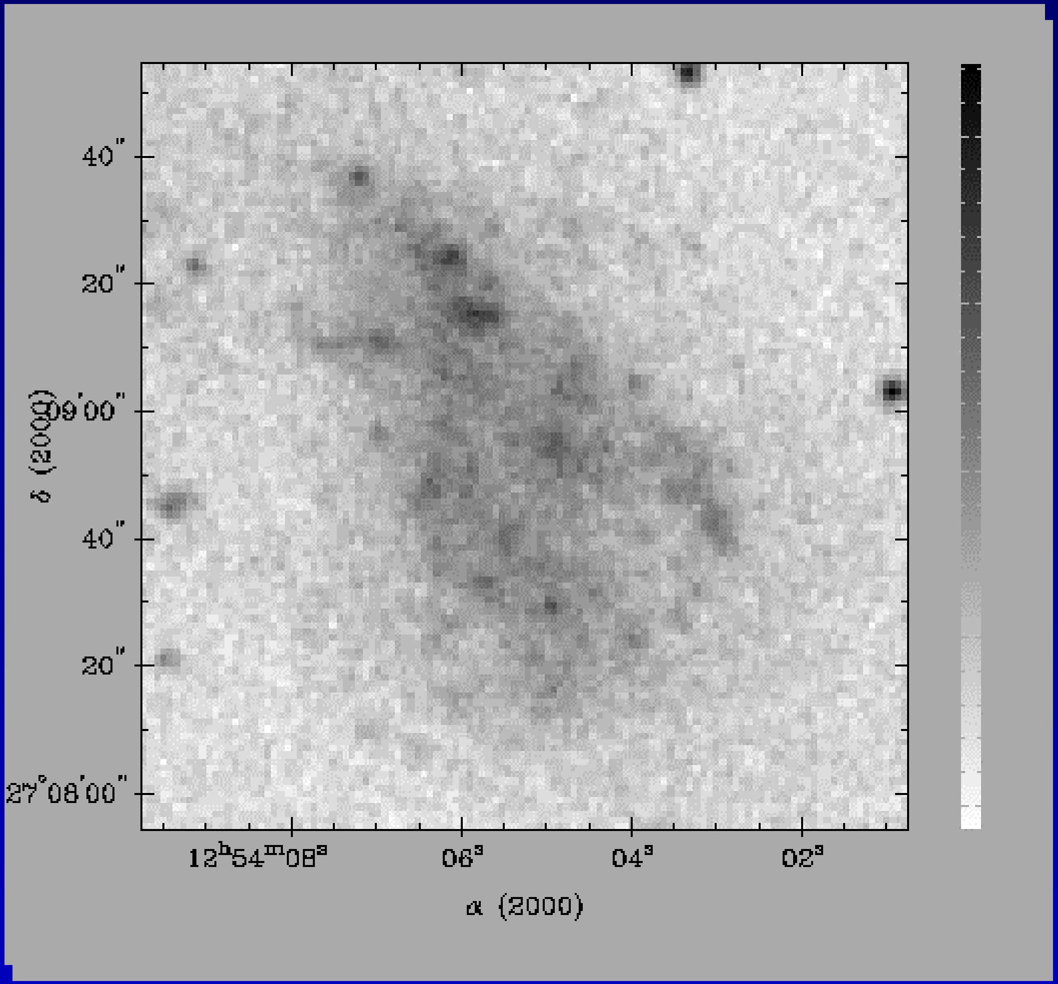
–The disagreement reported so far is with fitting formulae, not with the actual structure of simulated CDM halos. Why? Because simulating dwarfs at high resolution is hard.

–Strictly, the disagreement is between gas rotation speeds and halo circular velocities. These two may be different if halo is not spherical, or if velocity dispersion of the gas is important, etc.



McGaugh & de Block 1998
see also Moore 1994
Flores & Primack 1994

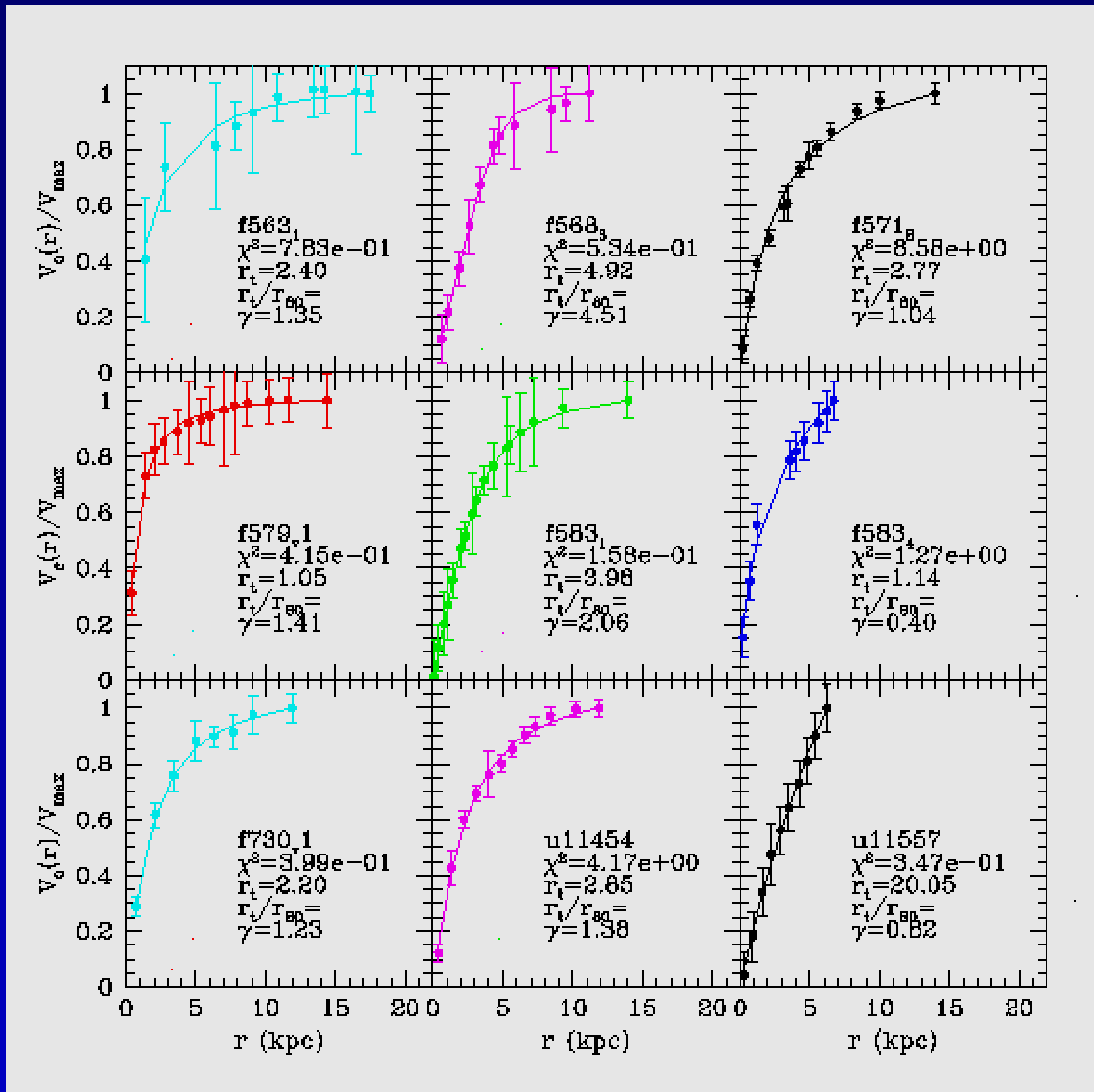
These measurements are hard!



DDO154 (a dwarf LSB)

LSB rotation curves (McGaugh et al sample)

Rotation Speed



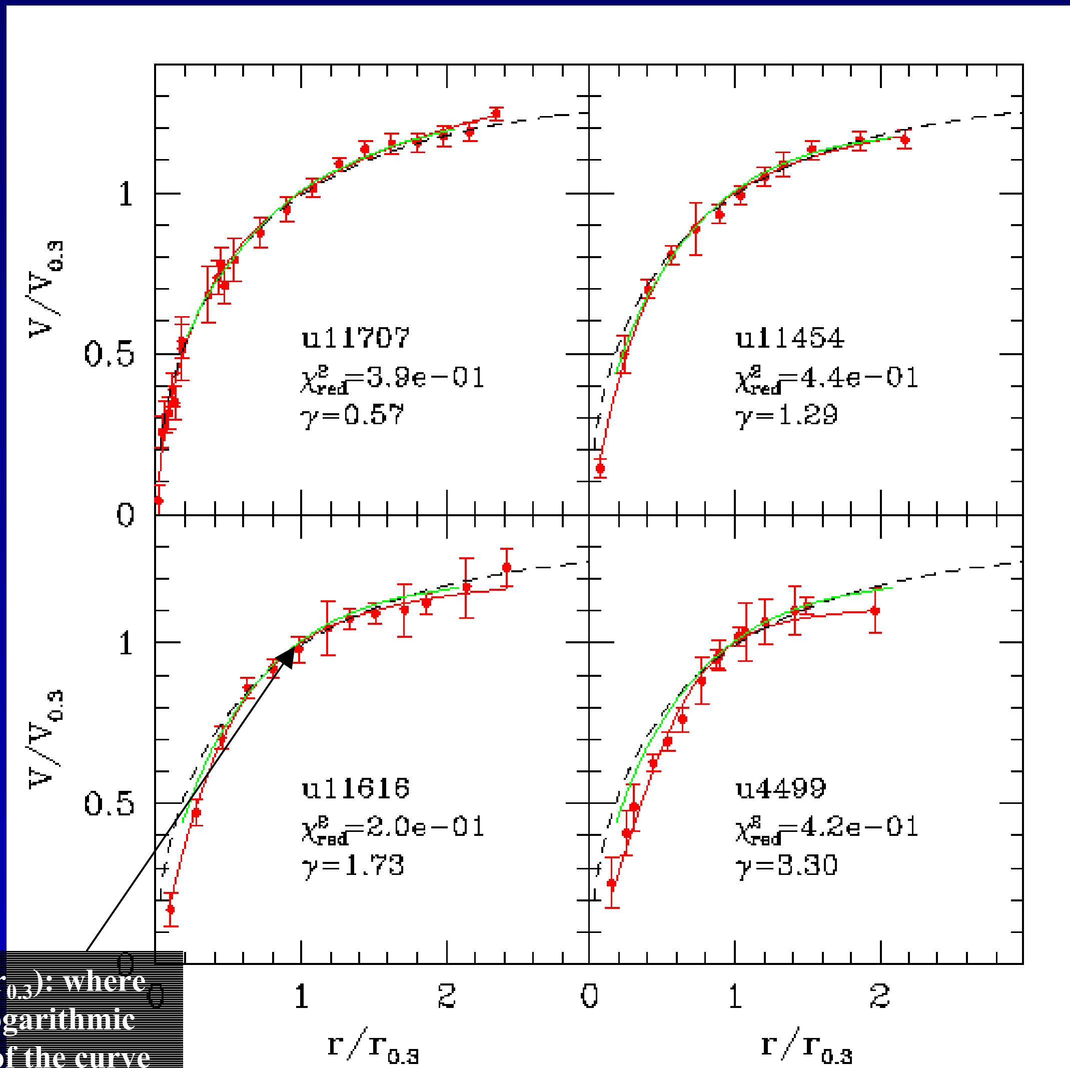
Radius

- The shape of the rotation curves varies significantly from galaxy to galaxy
- Let us characterize them with a simple formula: $V_c(r)=V_0\,(1+(r/r_t)^{-\gamma})^{-1/\gamma}$
- The parameter γ is a good indicator of the shape of the rotation curve

Hayashi et al 2003

Scaled LSB rotation curves: a representative sample

Rotation Speed



($V_{0.3}$,$r_{0.3}$): where the logarithmic slope of the curve is 0.3

Radius

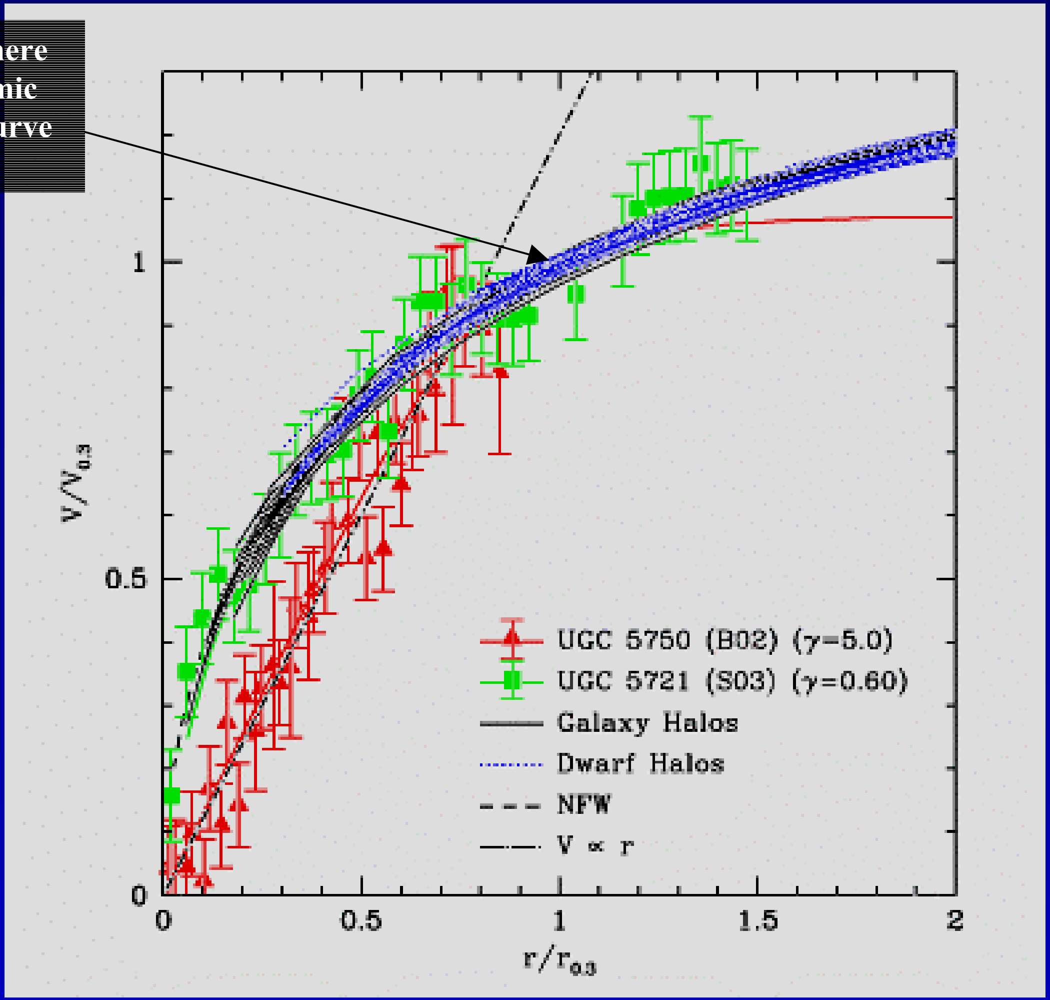
- More than 3/4 of LSB rotation curves have $0.5<\gamma<2$ (these are reasonably well fitted by CDM halos)
- The rest (~6 galaxies) have $\gamma>>2$ (in disagreement with CDM halos)

Hayashi et al 2003

Scaled LSB rotation curves

$(V_{0.3}, r_{0.3})$: where the logarithmic slope of the curve is 0.3

Rotation Speed

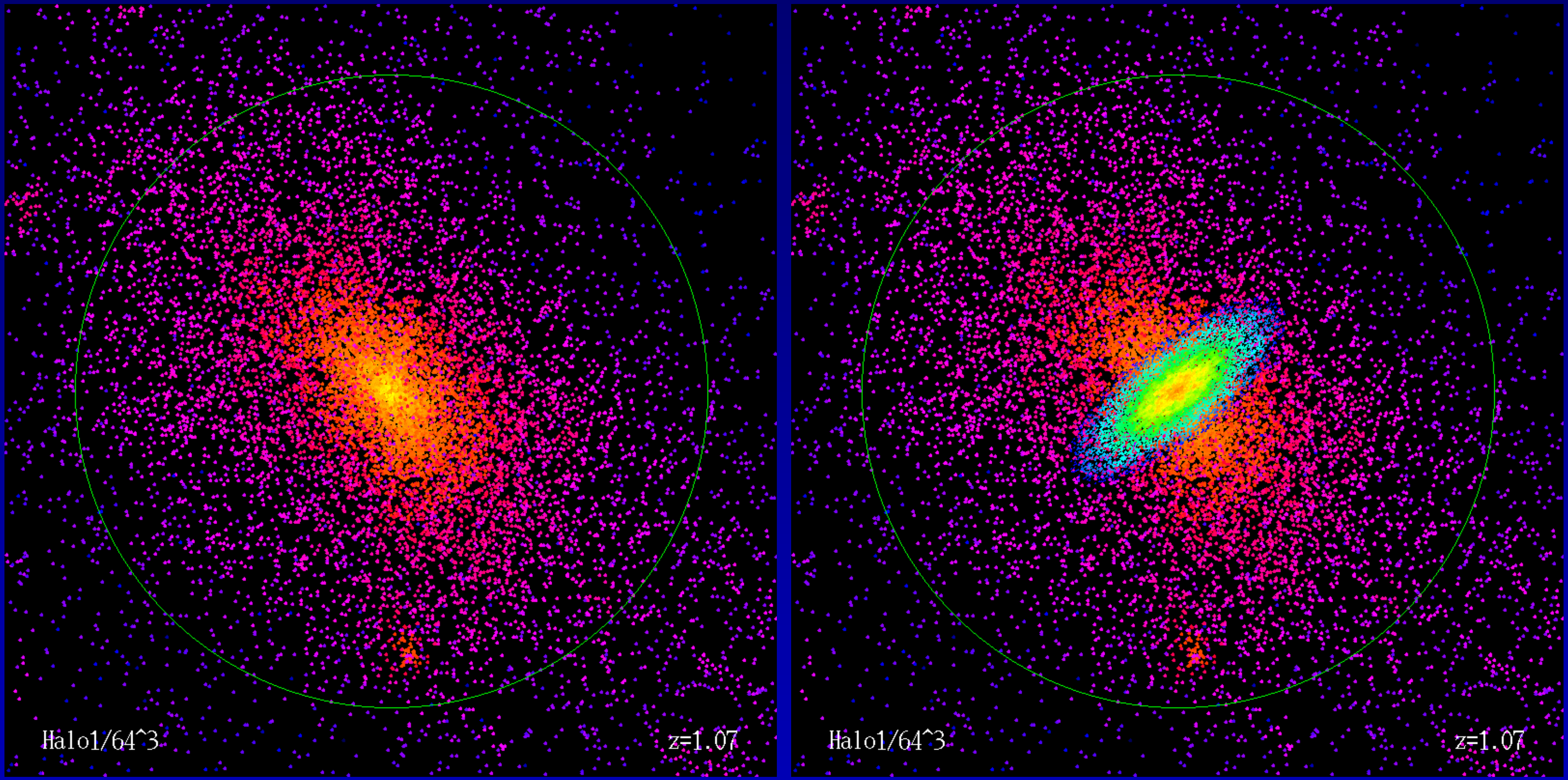


Radius

- More than 3/4 of LSB rotation curves have $0.5<\gamma<2$ (these are reasonably well fitted by CDM halos)
- The rest (~6 galaxies) have $\gamma>>2$ (not well fitted by CDM halos)

Hayashi et al 2003

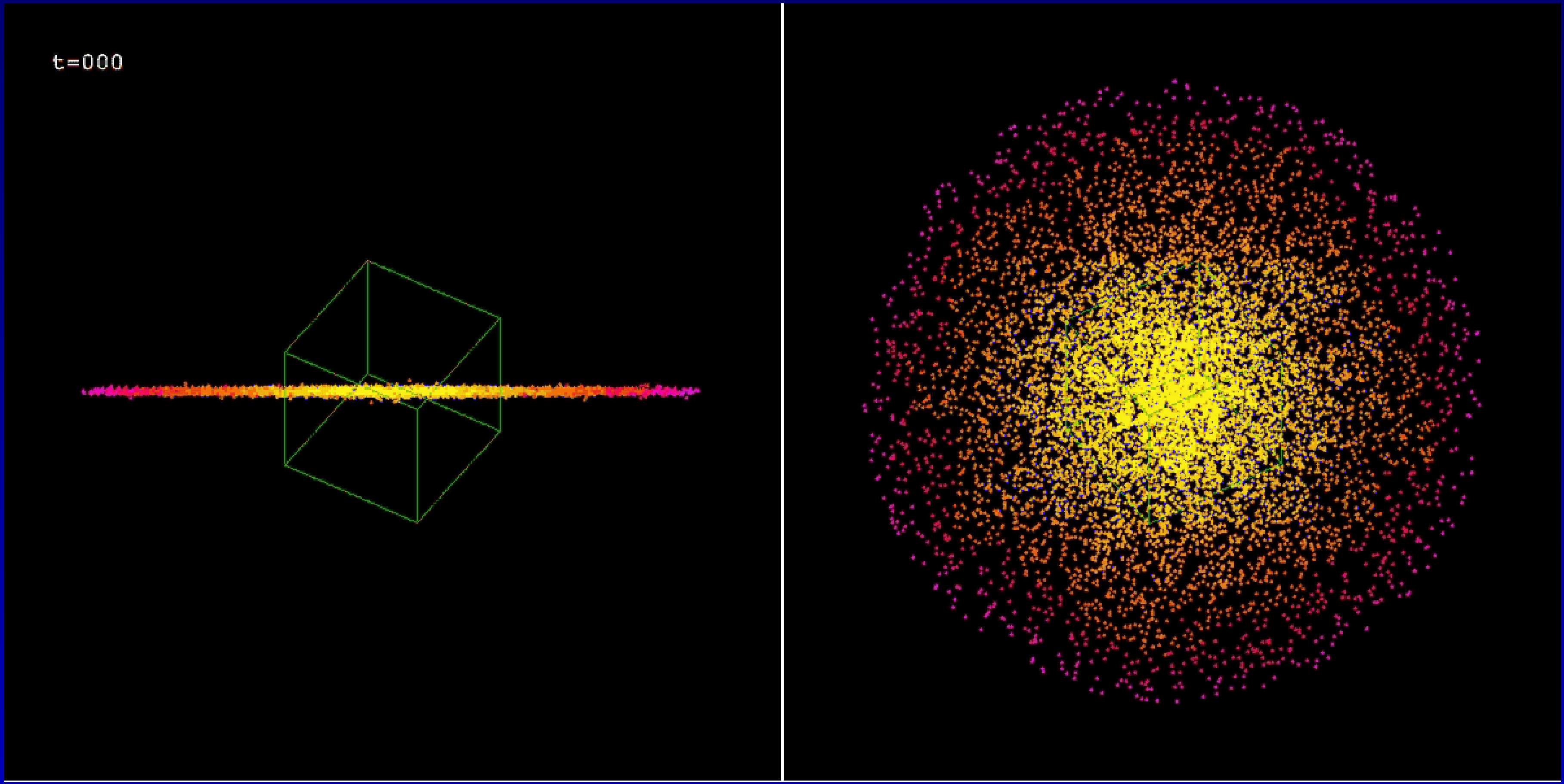
Disks in realistic dark matter halos



•Massless isothermal gaseous disk in the DM halo potential tracks the closed orbits within this non-spherical potential

Hayashi et al 2003

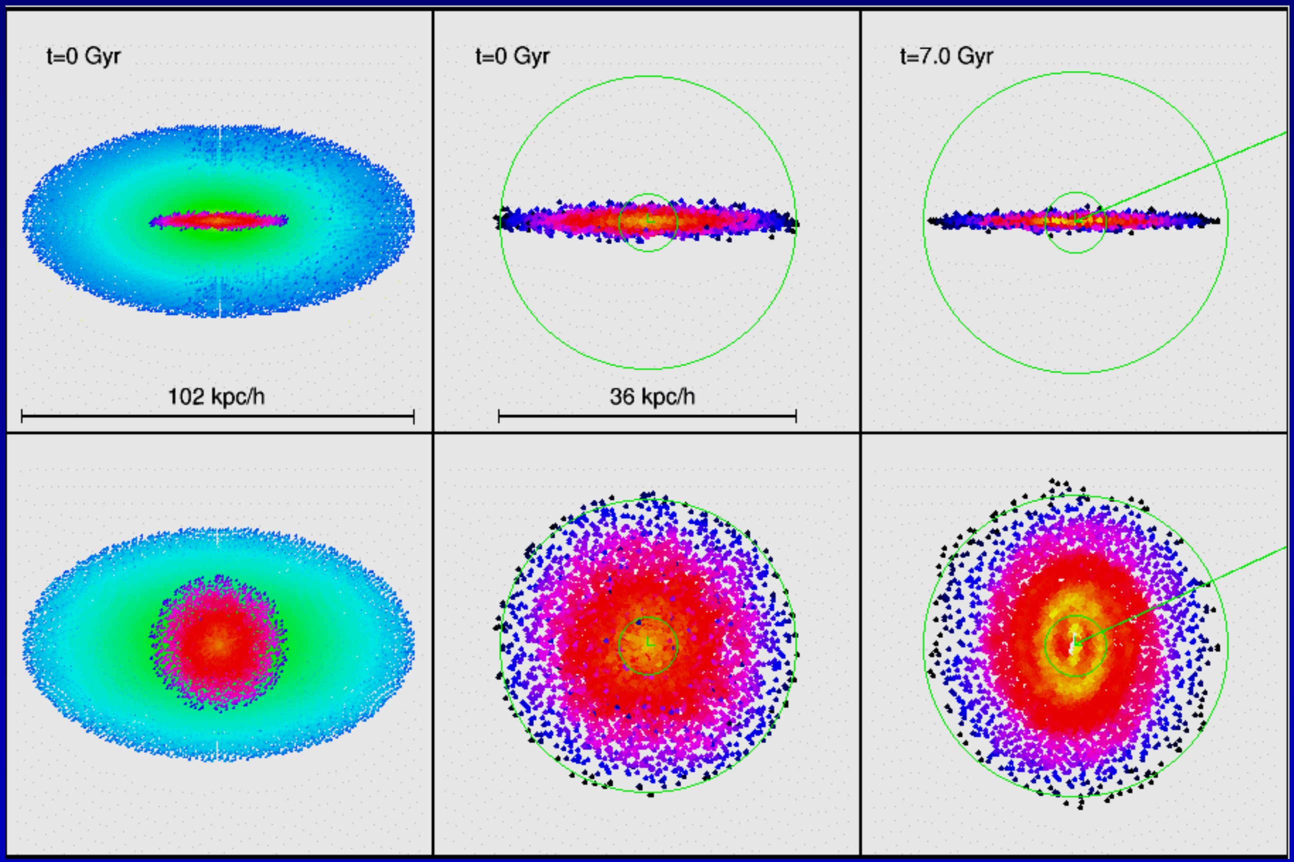
Disks in realistic dark matter halos



•Massless isothermal gaseous disk in the DM halo potential

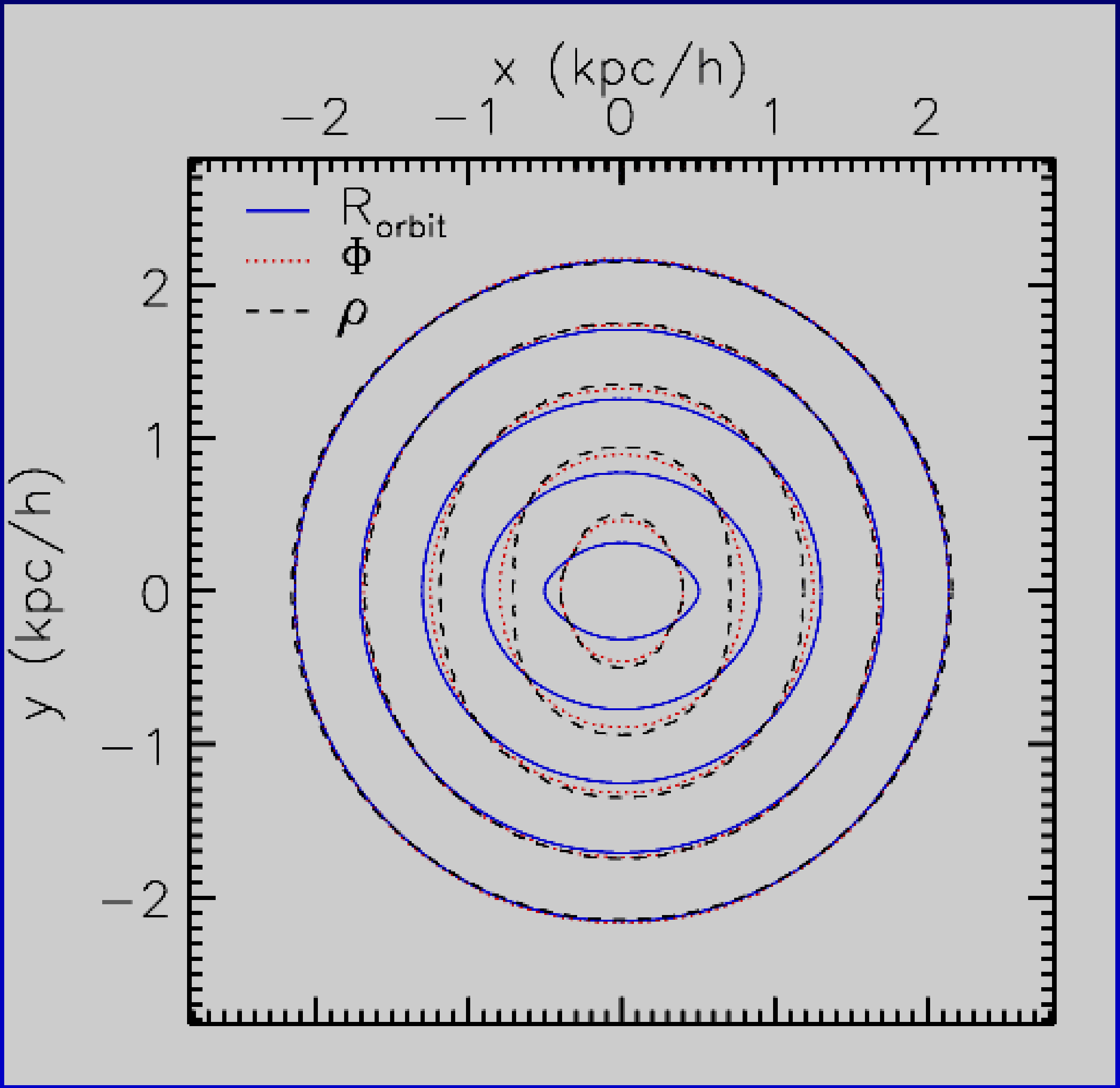
Hayashi et al 2003

Signatures of Halo Triaxiality: Elliptical Orbits



For disks situated in the symmetry plane of a triaxial halo, closed loop orbits may be to first order approximated by ellipses

Orbits in an m=2 perturbed NFW halo



For a perturbed potential of the form:

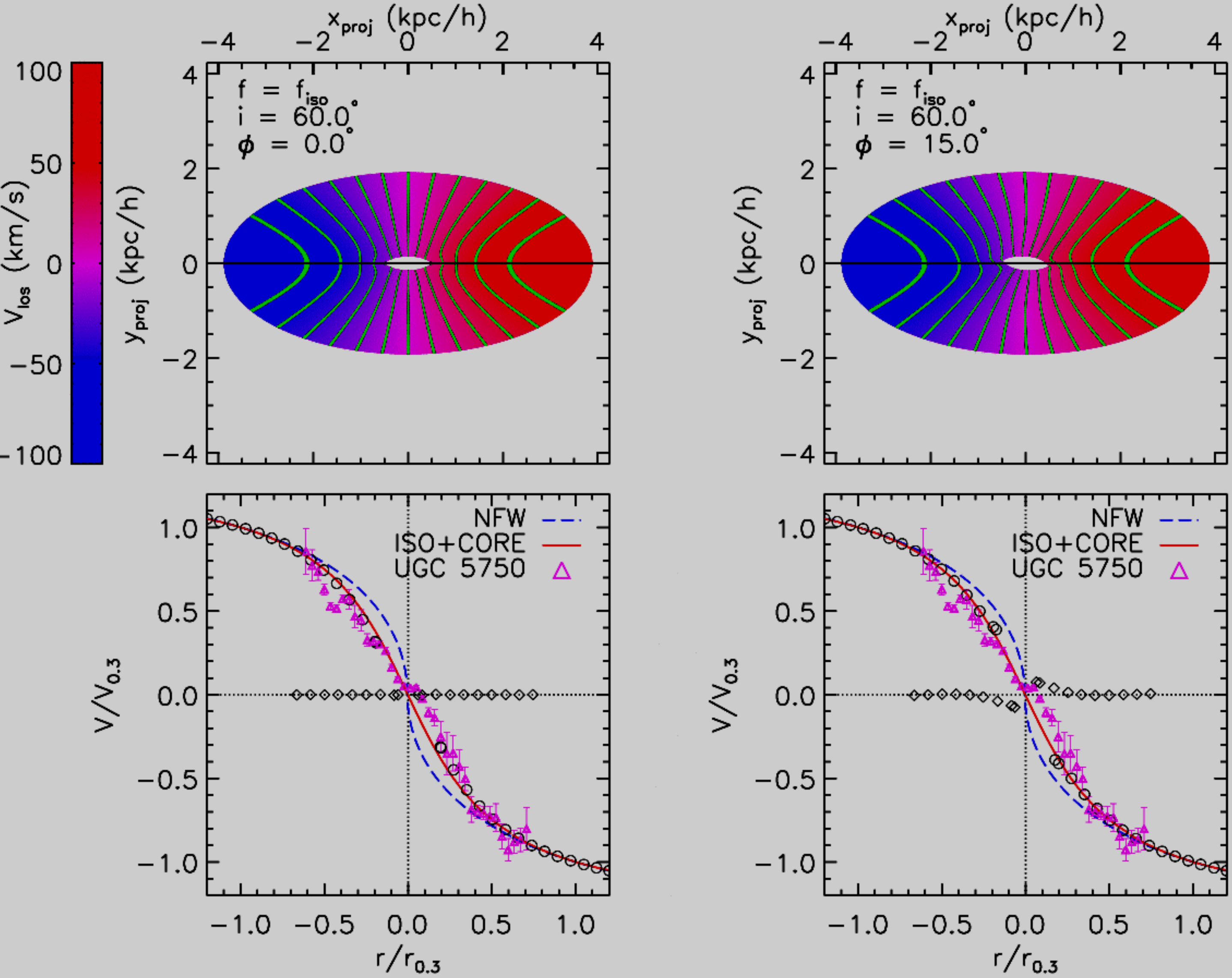
$$\Phi(r)= (1+f\cos 2\theta)\, \Phi_{NFW}(r),$$
$$(f<<1)$$

The ellipticity of the orbit is given by:

$$\varepsilon(r) \sim f\,(v_{esc}^{2}/v_{c}^{2}-1)$$

which increases toward the center for an NFW potential, so that large deviations from circularity may be obtained with small perturbations.

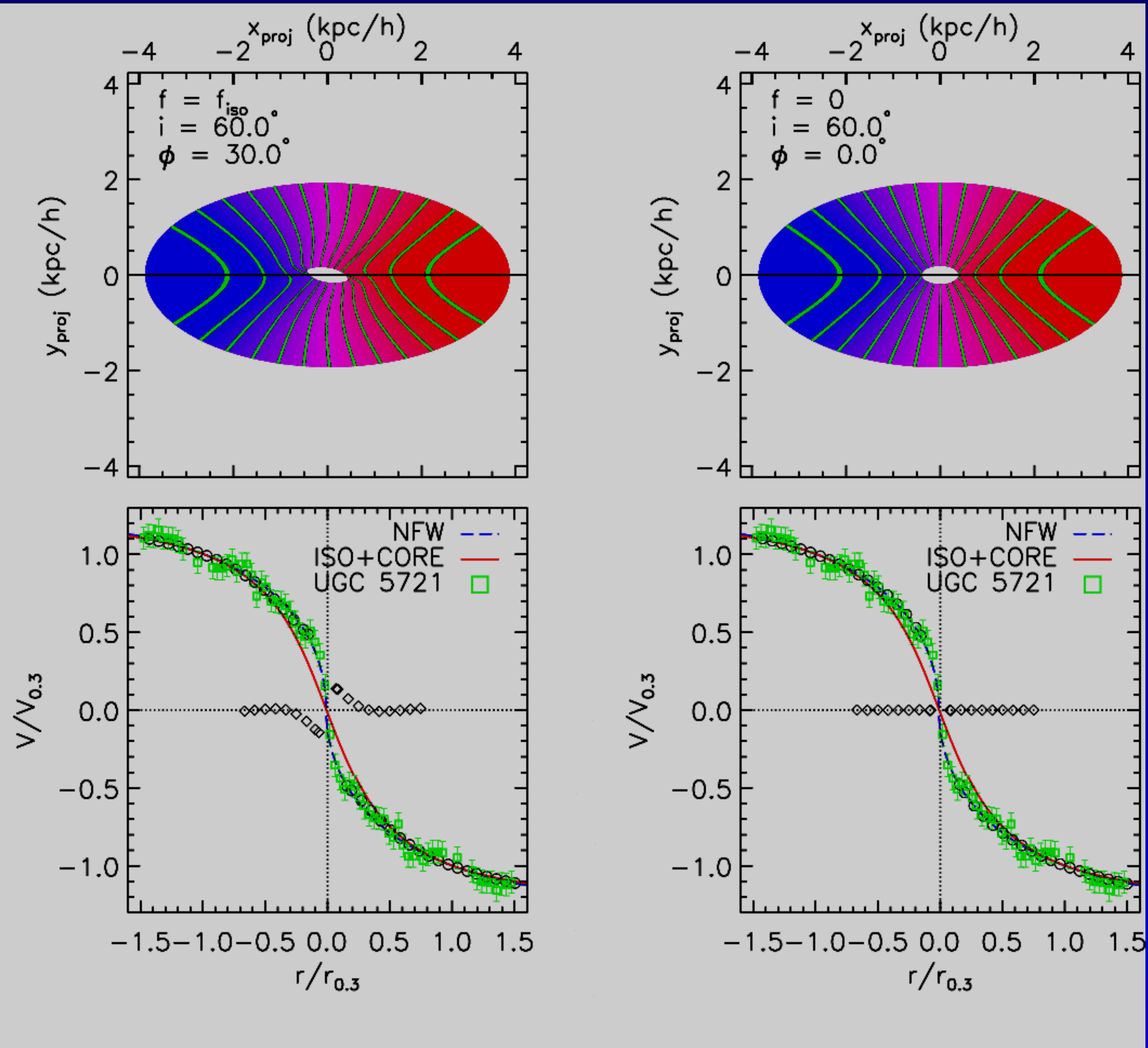
Long-slit rotation curves



- Along the long axis of symmetry of the orbits, the line-of-sight velocities are gradually reduced toward the center (relative to circular) so that the rotation curve looks "solid-body", mimicking the presence of a constant-density core.

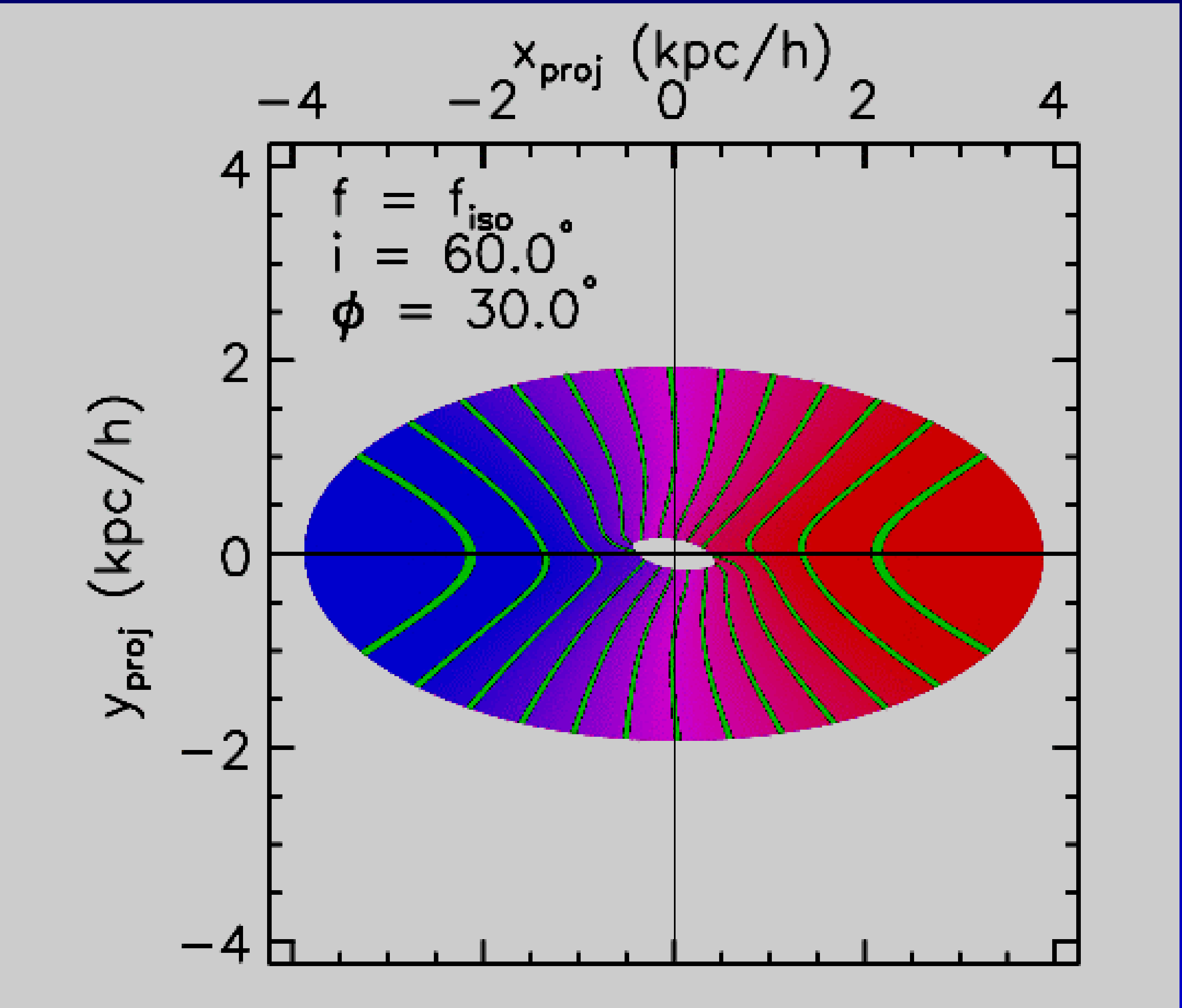
- For this configuration, the velocity field is symmetric and orbits are indistinguishable from circular.

Long-slit rotation curves



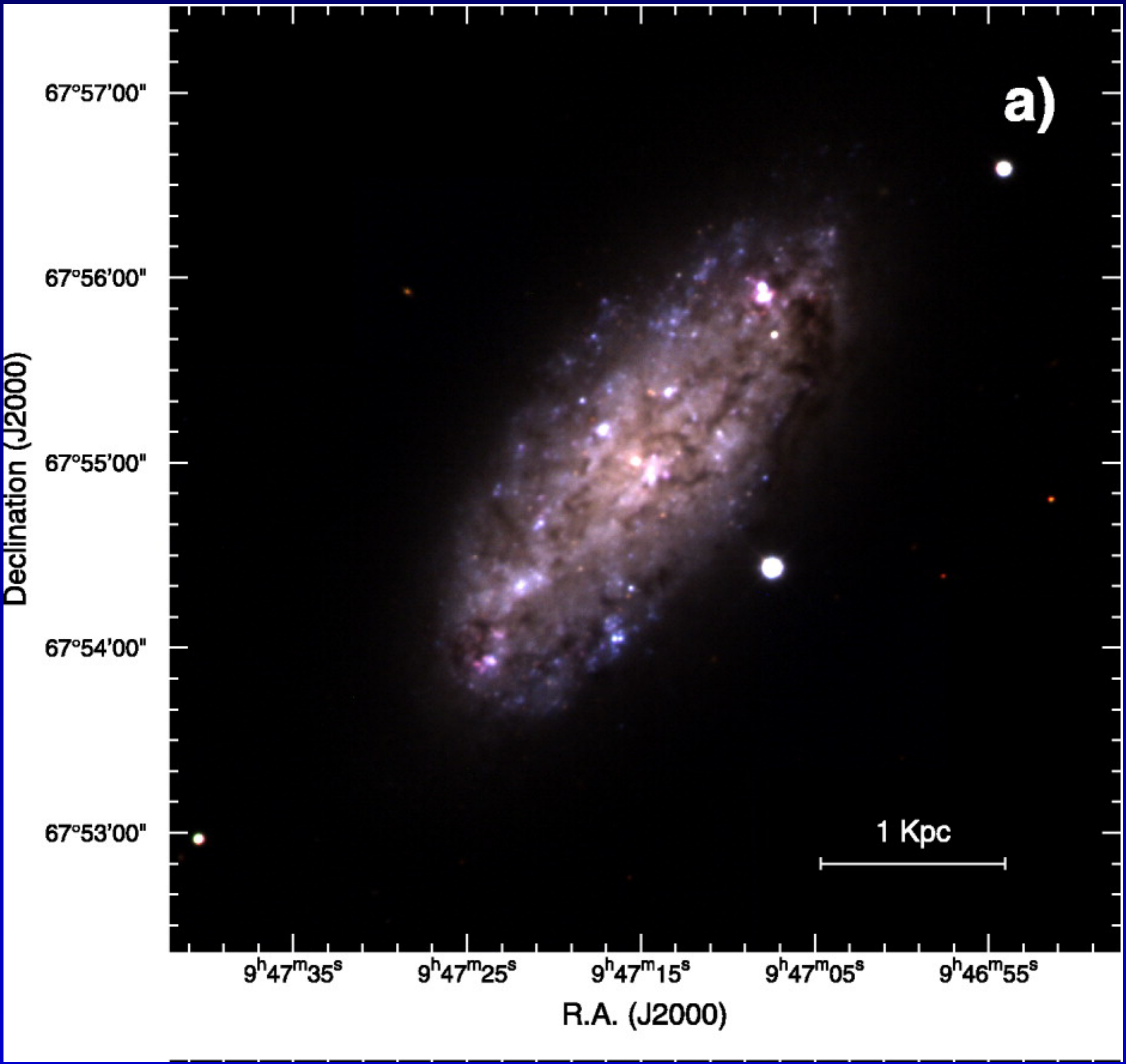
- For other viewing angles, the long-slit rotation curve is steeper and may resemble the circular velocity of the unperturbed NFW potential.
- "Rotation" may be present in this case along the minor axis.
- The velocity field tends to have strong asymmetries in that case.

The imprint of halo triaxiality on disk velocity fields



- Lines of constant speed are asymmetric, and show characteristic "kinks".
- Iso-velocity contours are (anti)symmetric in diagonally opposite quadrants, but differ in contiguous ones.
- The effect becomes gradually more pronounced toward the centre.

LSBs with 2D Velocity Field Data: NGC 2976

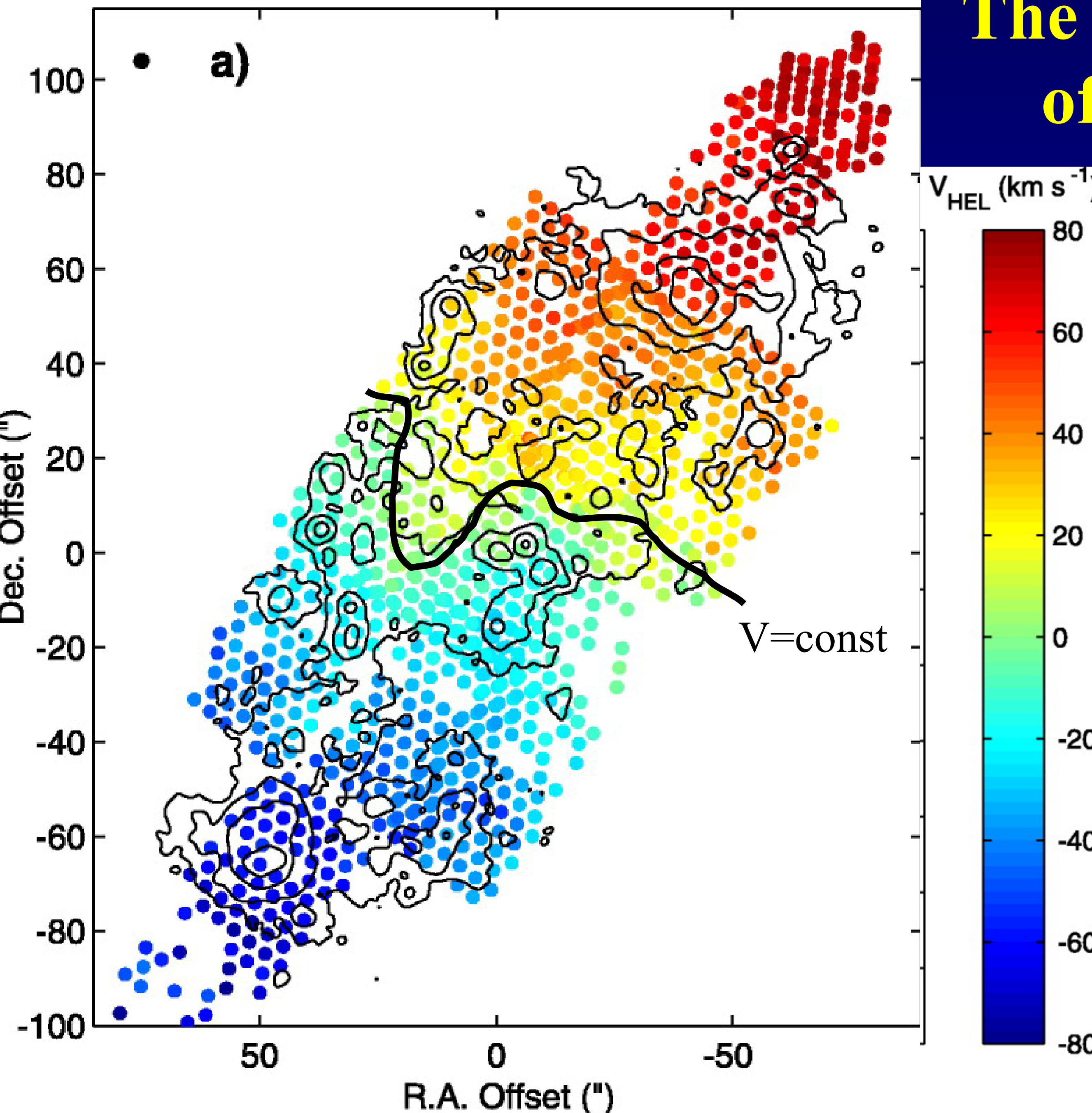


NGC 2976:
an LSB disk without obvious bulge or bar components.

"…independent of any assumptions about the stellar disk or the functional form of the density profile, NGC 2976 does not contain a cuspy dark matter halo"

Simon et al 2004

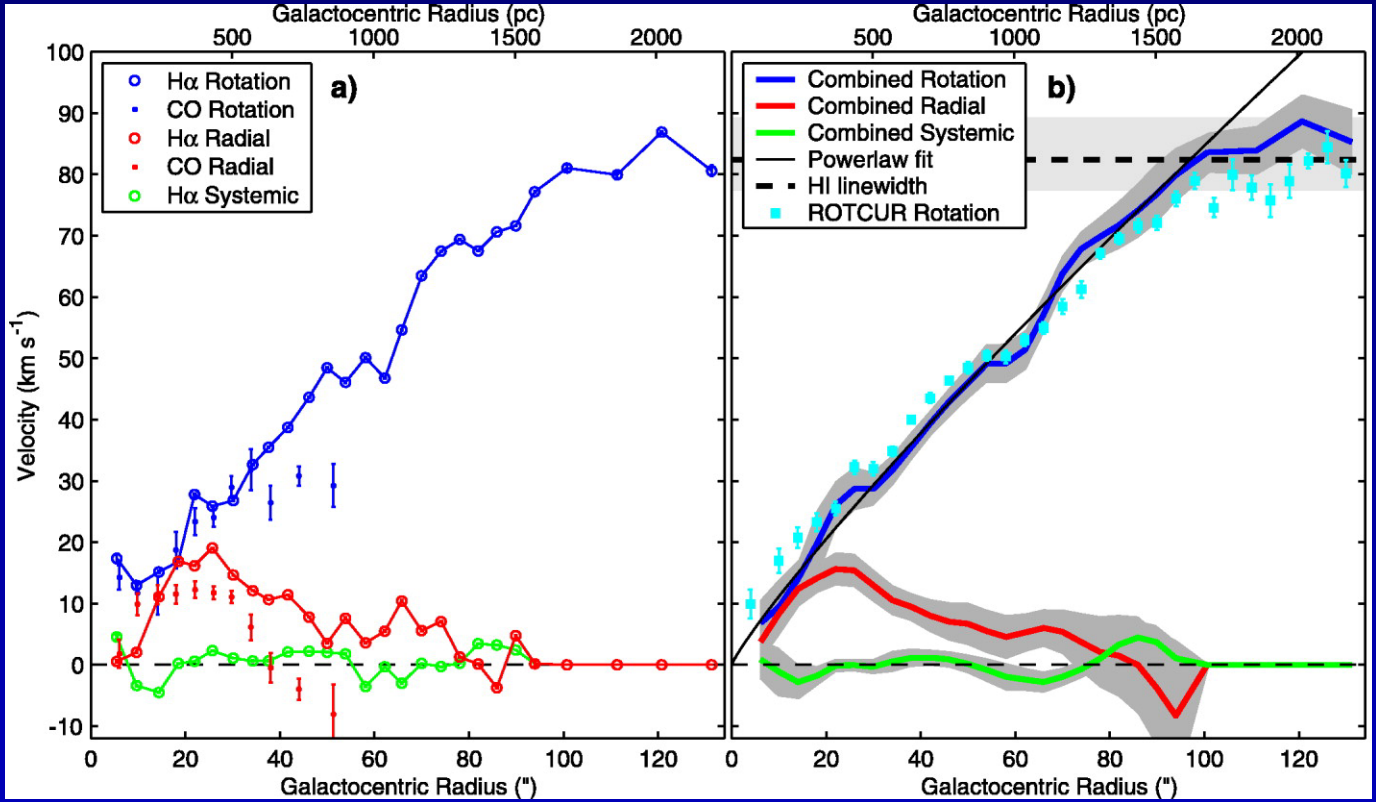
The Velocity Field of NGC 2976



Velocity field is quite asymmetric, with "kinks" similar to those seen in projection for disks in triaxial halos.

Simon et al 2004

Modeling of 2D Velocity Field Data: NGC 2976

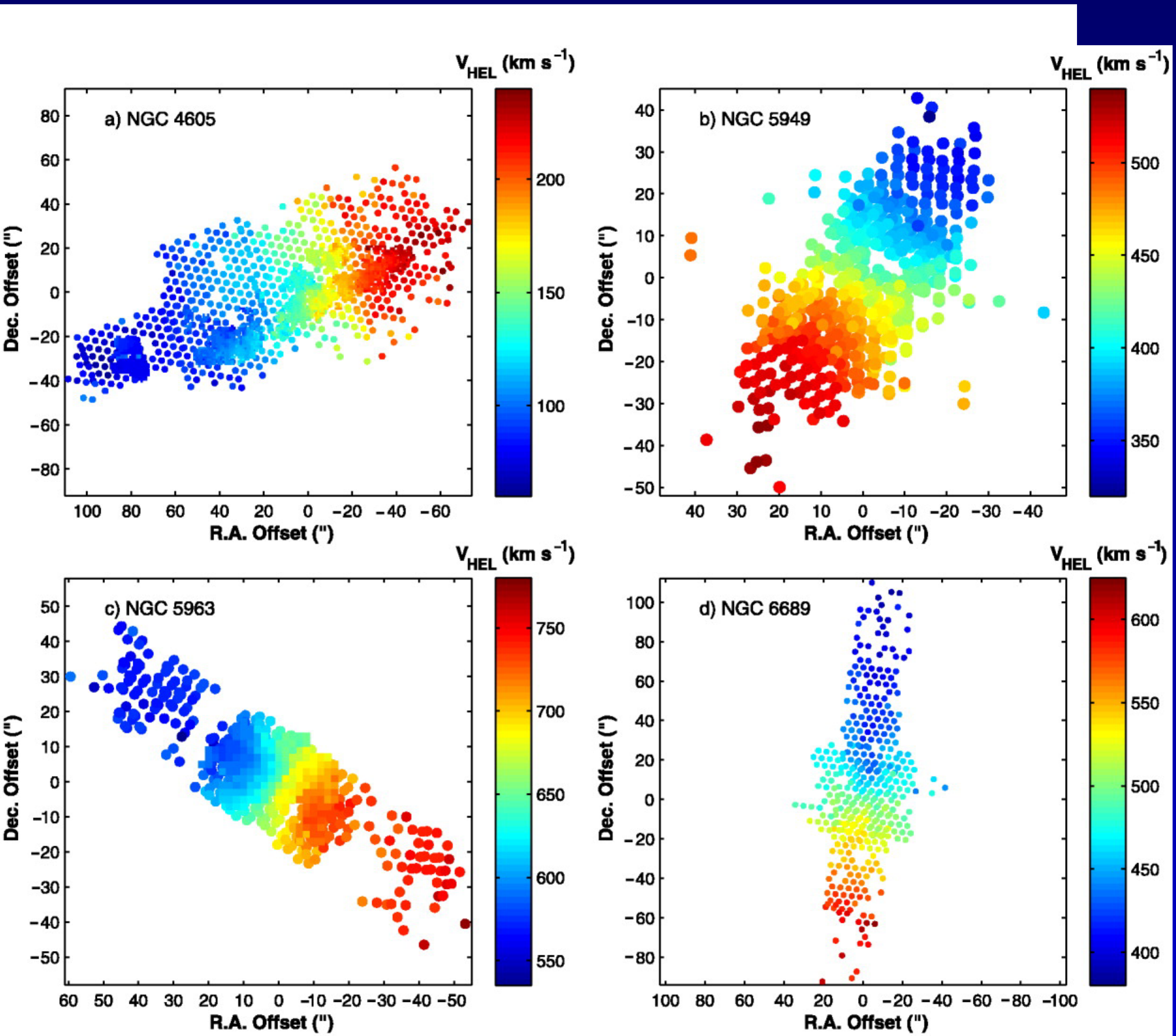


Simon et al (2004) choose to model such deviations by tilted concentric rings with rotation, as well as "radial" (i.e. expansion or contraction) velocities.

Good fits are obtained, but this treatment may mask the presence of elliptical motions and may hide a cusp.

Simon et al 2004

Other LSBs with 2D velocity data



•Inner regions of halos surrounding dwarfs show a variety of behaviors: some are consistent with cusps, others are not.

•Asymmetries in the velocity fields ("radial motions") are common

•Could this reflect various orientations of disks within halos of different triaxiality?

Simon et al 2005

The End

"Great PowerPoint, Kevin, but the answer is no."