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Galaxy Formation

Carlos Frenk

Institute of Computational Cosmology
University of Durham

Goal: understand origin and evolution of cosmic structures

- Review of standard Big Bang model
- Growth of small fluctuations (linear theory)
- Fluctuations in the microwave background radiation
- The formation of galaxies and clusters

Connection to three outstanding problems in 21st Physics:

- The identity of the dark matter
- The nature of the dark energy
- Origin of cosmic structure

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Galaxy Formation

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You should be familiar with:

- Basic concepts in Big Bang theory
- The contents of the Universe
- The expansion properties of the Universe

Books:

Cole & Lucchin: Cosmology -- about the right level

Peacock: Galaxy Formation -- advanced

Liddle: Cosmology -- basic background

http://star-www.dur.ac.uk/~csf/homepage/GalForm_lectures

The Big Bang Theory

What it is:

- Theory that the Universe as we know it began 10 – 15 billion years ago
- Initial state was a hot, dense, uniform sea of particles that filled space uniformly and was expanding

What it describes:

- How the universe expands and cools
- How the light chemical elements formed
- How matter congealed to form stars and galaxies

What it does not describe:

- What caused the expansion (*expanding initial state assumed*)
- Where did matter come from (*energy assumed to be there from start*)

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Empirical evidence for the Big Bang

1. The expansion of the universe of galaxies

- galaxies are receding from us with speed proportional to their distance
- expansion is the same for all observers

2. The microwave background radiation

- heat left over from Big Bang explosion
- comes from everywhere in space (homogeneous and isotropic)
- it was emitted when the universe was 300000 years old

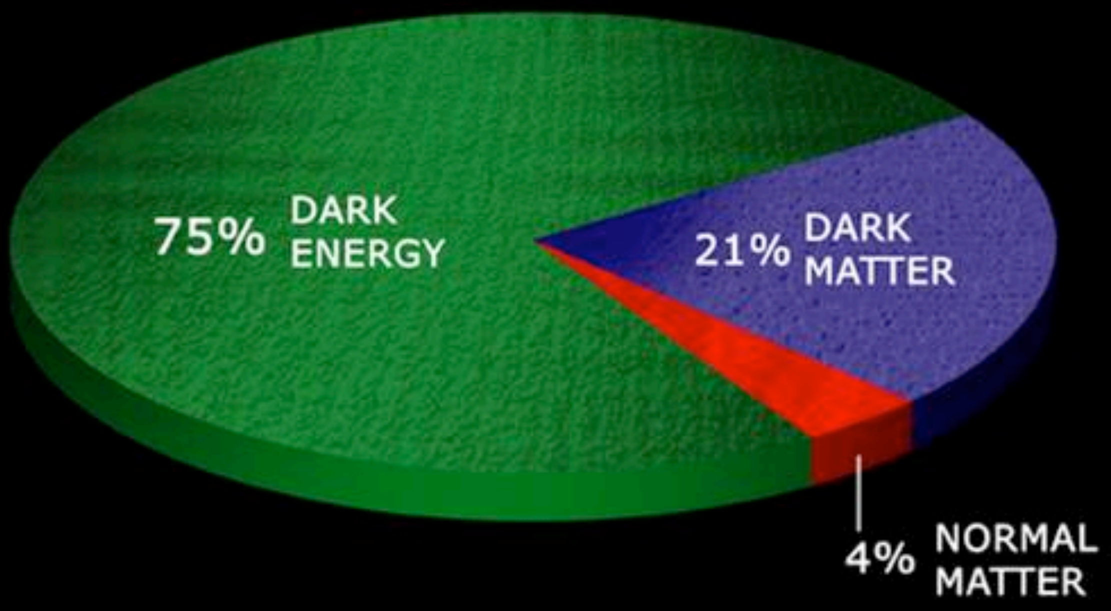
3. The abundance of the light elements

- BB theory predicts that 75% of mass is hydrogen, 24% is helium and 1% is the rest
- These are precisely the abundances observed in distant gas clouds!

(nb: elements heavier than H and ^{4}He were produced billions of years later inside stars)

What is the Universe made of?

The content of our universe



Dark matter ≡ matter that does not emit light at any wavelength

What is the universe made of?

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$$\Omega = \frac{\text{density}}{\text{critical density}} \qquad \rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

critical density = density that makes univ. flat: (Ω = 1 for a flat univ.)

- Radiation (*CMB, T=2.726±0.005* ^{o}K) — $\Omega_r = 4.7 \times 10^{-5}$
- Massless neutrinos — $\Omega_\nu = 3 \times 10^{-5}$
- Massive neutrinos — $\Omega_\nu = 6 \times 10^{-2}$ ($<m_\nu>$/ev)
- Baryons — $\Omega_b = 0.037 \pm 0.009$
  (of which stars) — $\Omega_s = 0.0023 \pm 0.0003$
- Dark matter (cold dark matter) — $\Omega_{dm} \cong 0.26$
- Dark energy (cosm. const. Λ) — $\Omega_\Lambda \cong 0.7$

$$\longrightarrow \Omega = \Omega_b + \Omega_{dm} + \Omega_\Lambda \cong 1$$

(assuming Hubble parameter h=0.7)

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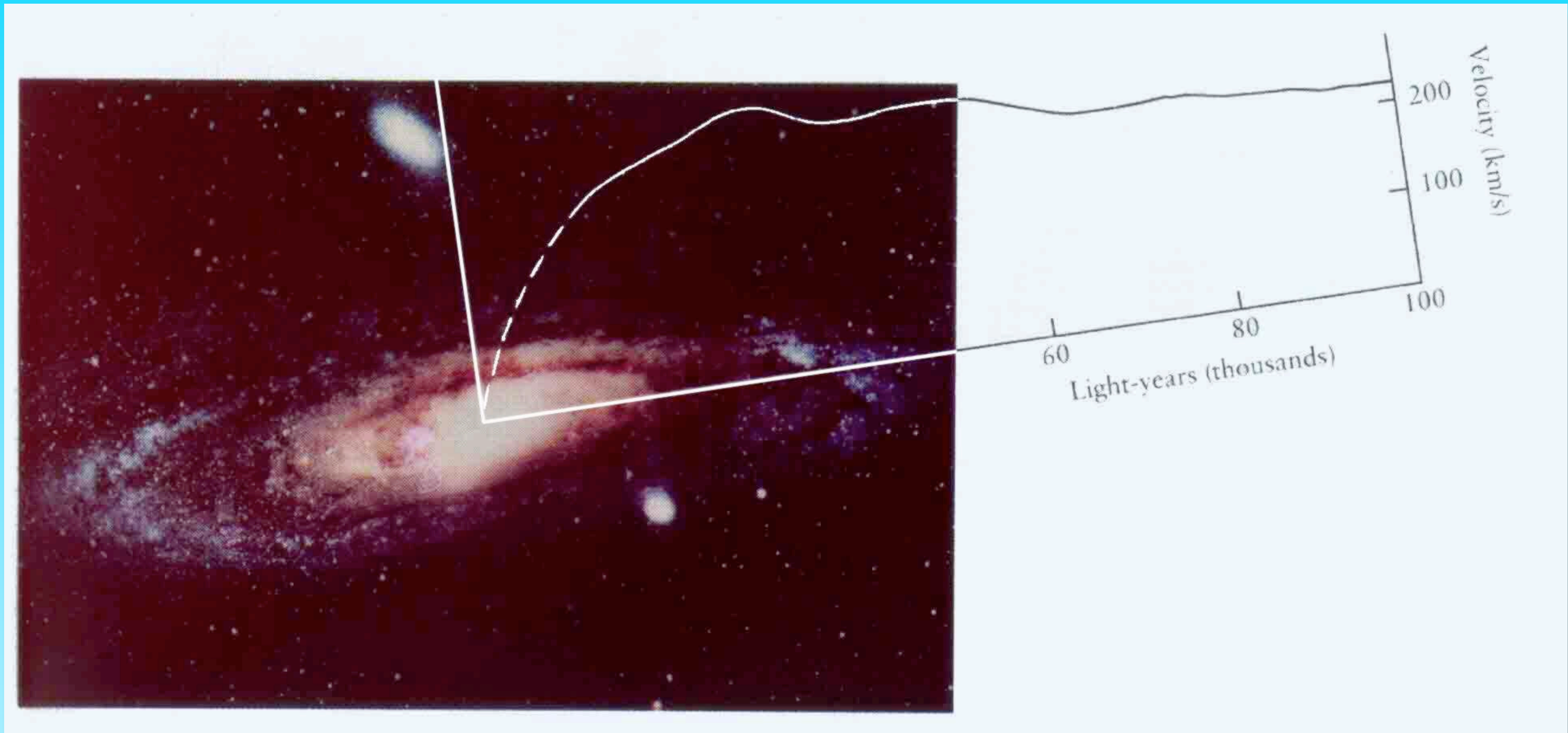
Galaxy rotation curves



Flat V_c → $M(<r) \propto r$

⇒ **dark halos around galaxy**

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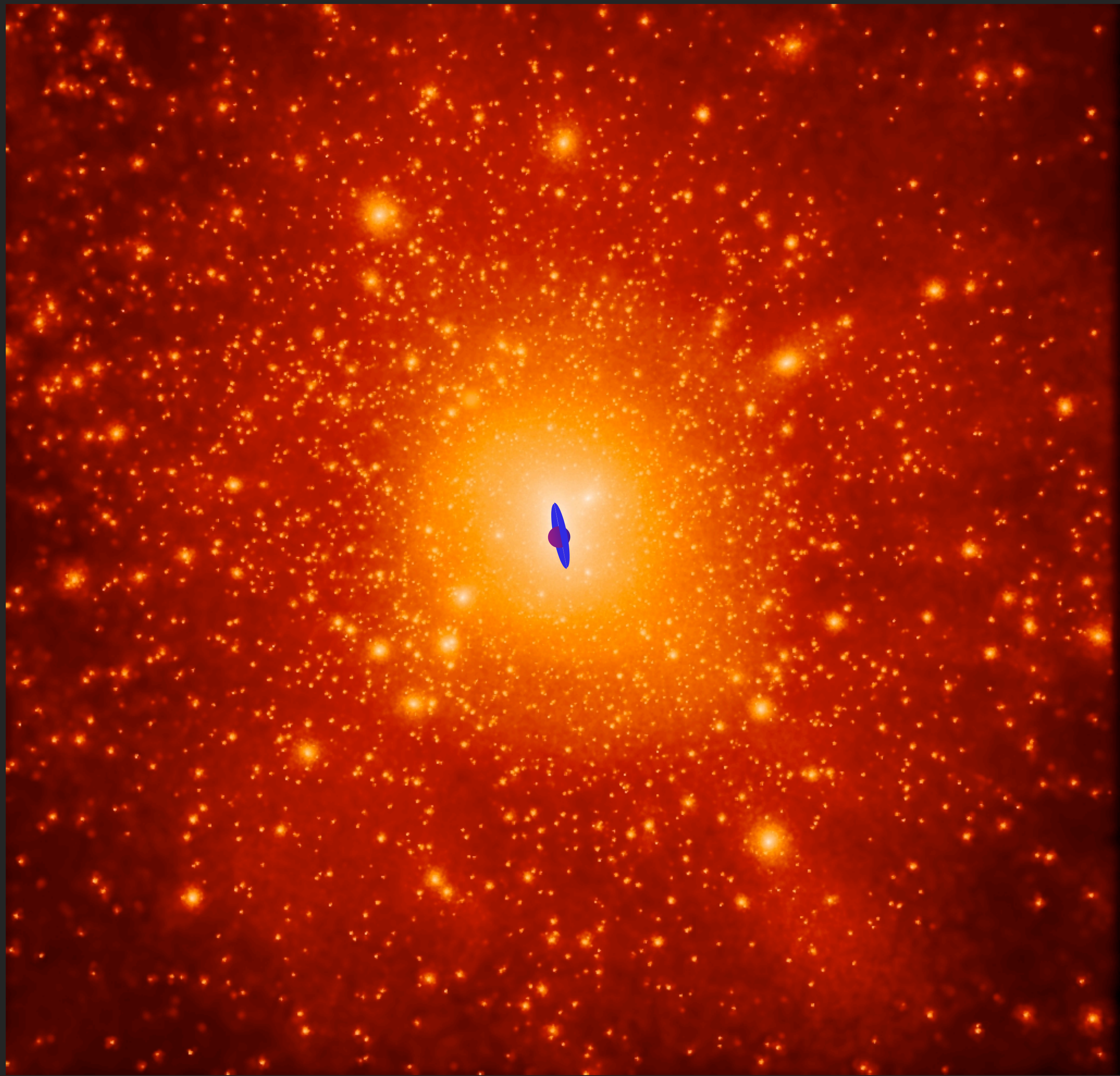
Computer simulation of galaxy halo



0.5 Mpc/h

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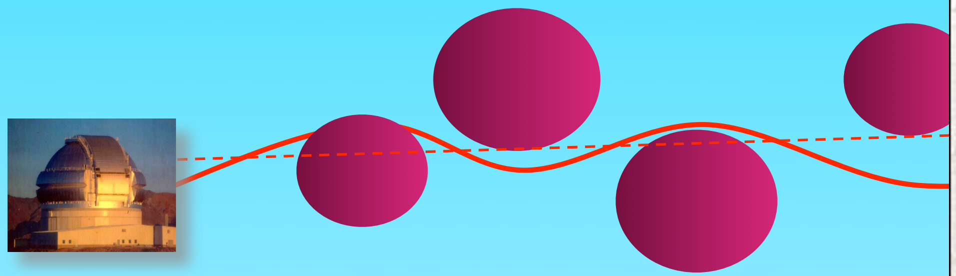
Mapping the dark matter

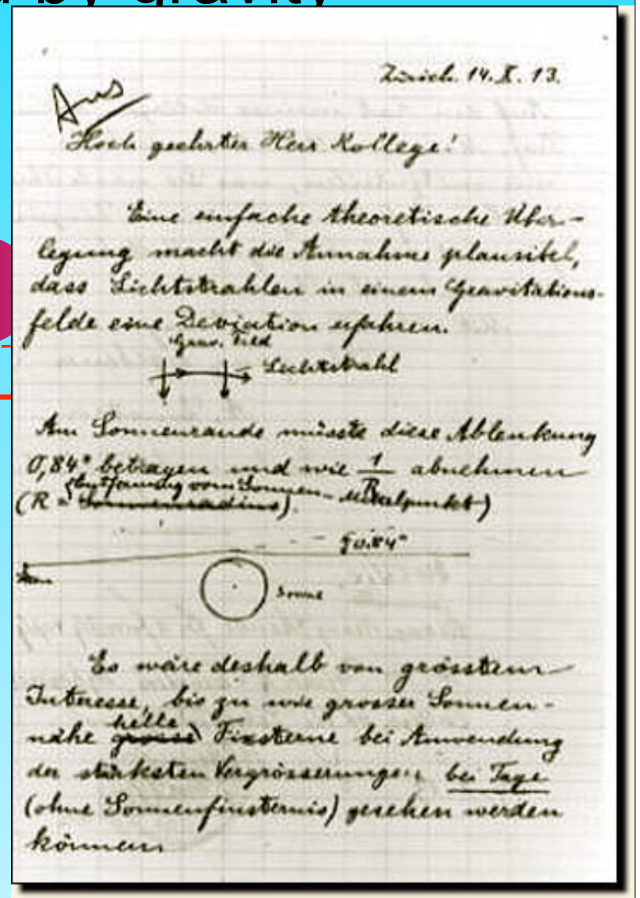
Light rays are deflected by gravity

($E=mc^2$)



Observer

Galaxy clusters
(Gravitational lens)



Zürich 14. X. 13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld
Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = Abstand vom Sonnenmittelpunkt).

0,84"
Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

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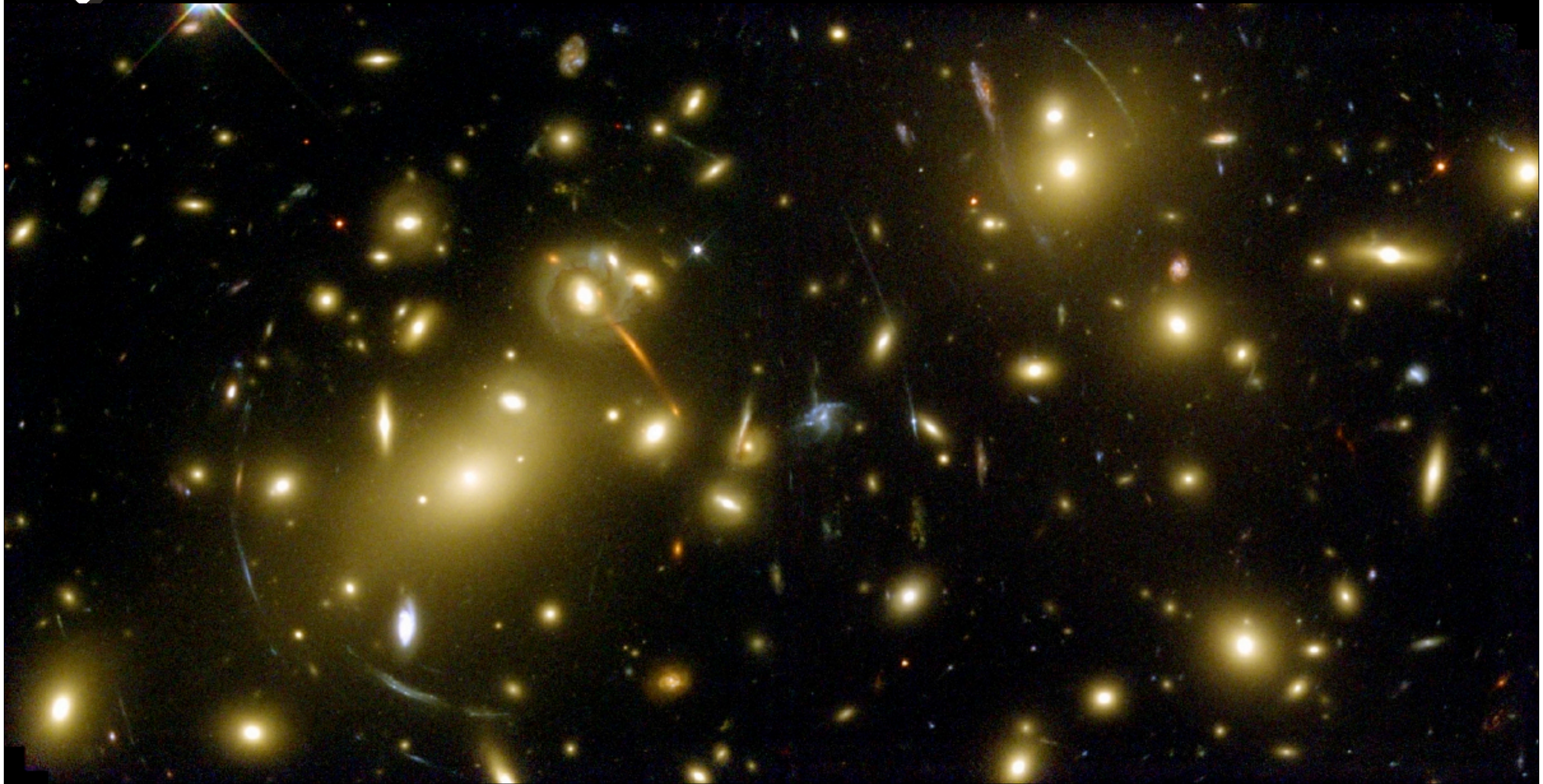
Gravitational lensing



Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs

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The visible and dark sides of the universe

- There is ~5 times more dark matter than there is ordinary (baryonic) matter

(~90% of the mass of the Universe is dark matter)

→

® Most of the dark matter is NOT ordinary (baryonic) matter

® **Weakly interacting massive particles (WIMPS)**

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Non-baryonic dark matter candidates

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

Looking for WIMPS

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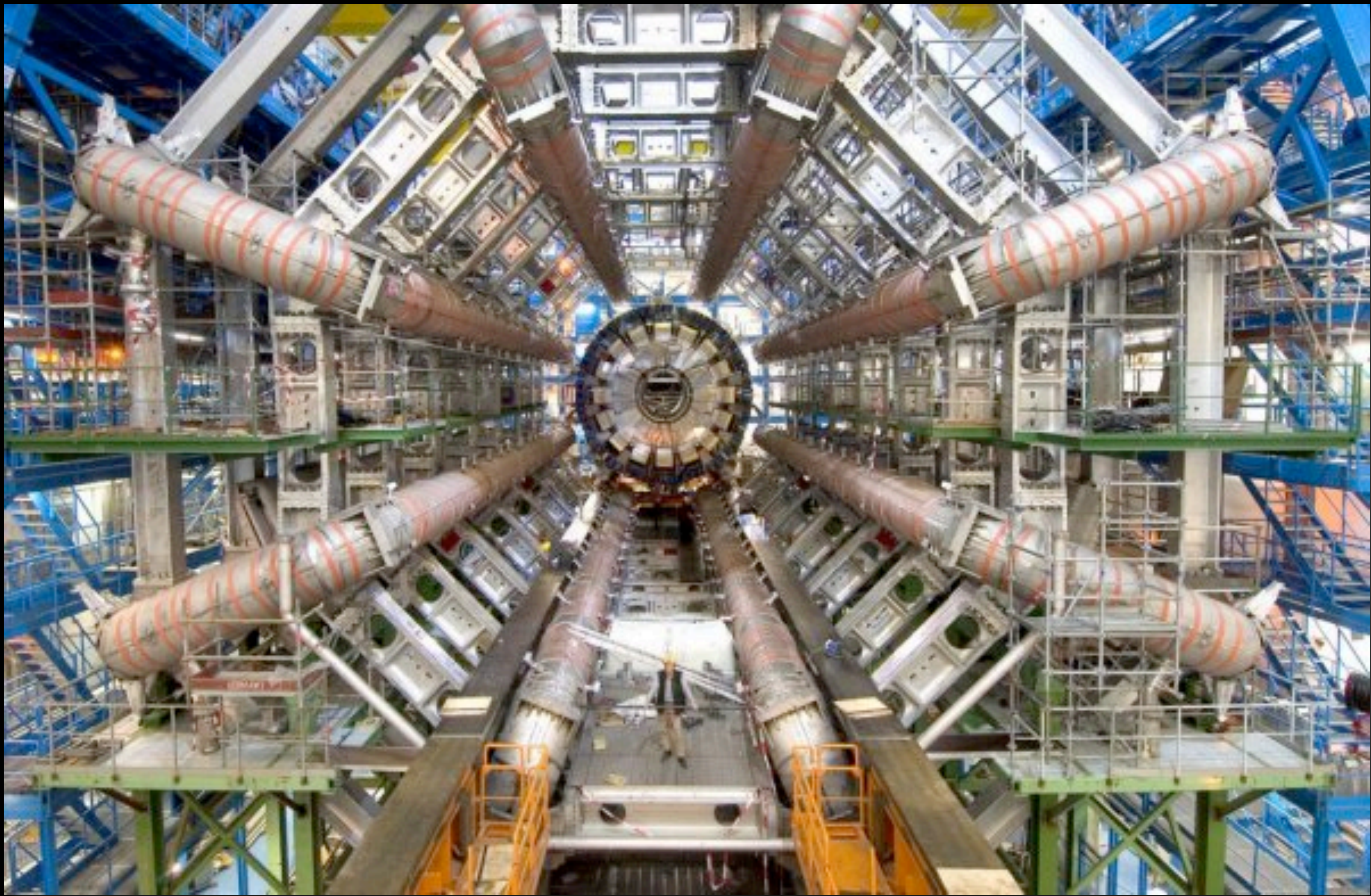
CERN

Geneva

The search for dark matter



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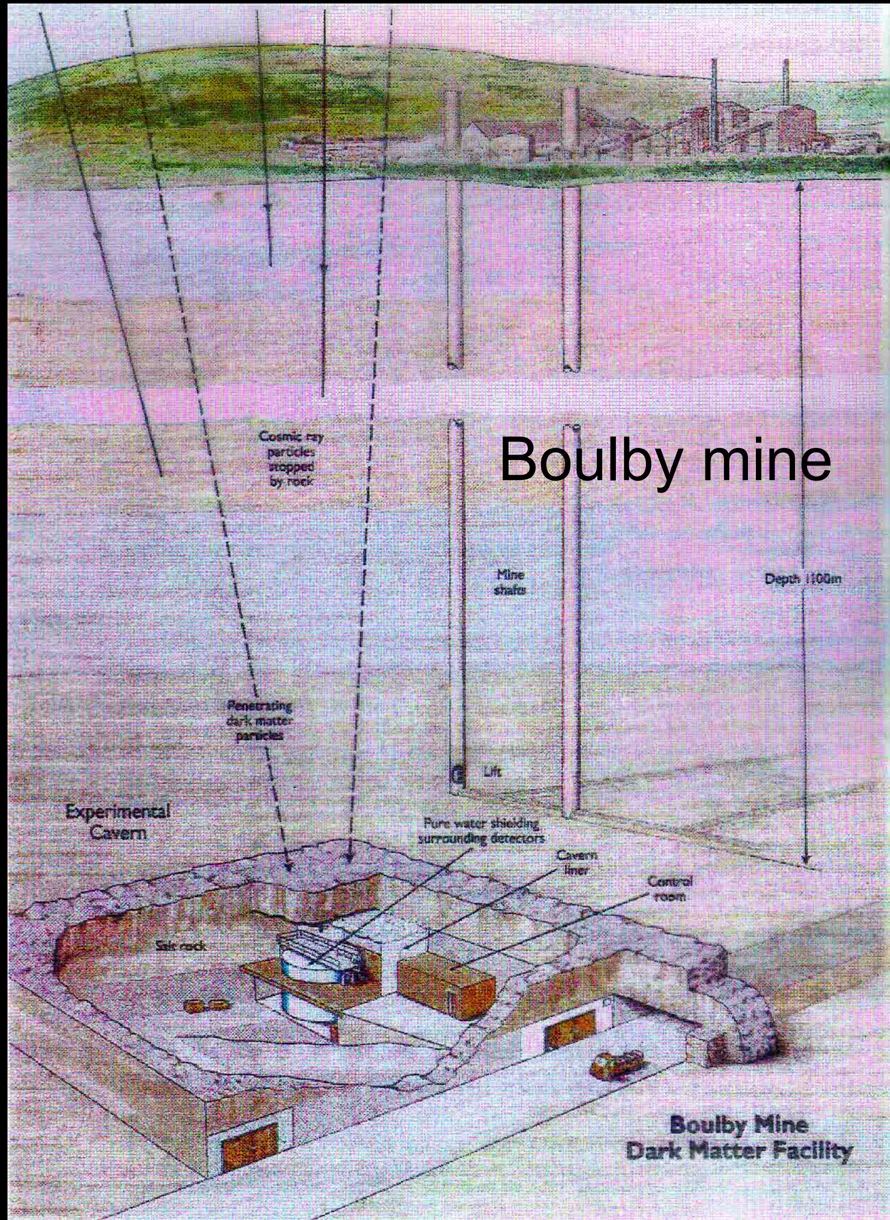
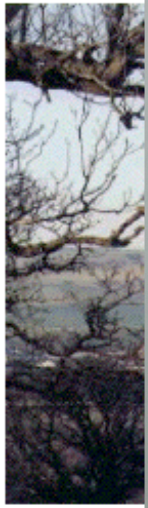


Looking for dark matter … down the mine

(where cosmic rays can't penetrate)



Look

dow

(wh

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What is the universe made of?

So, the Universe contains:

- Ordinary matter (Ω_b=0.04)
- Dark matter (Ω_{dm}= 0.21)

Anything else?

Yes! Dark energy

Dark energy is a property of space itself.

It has the opposite effect to gravity

Evidence for Λ from high-z supernovae

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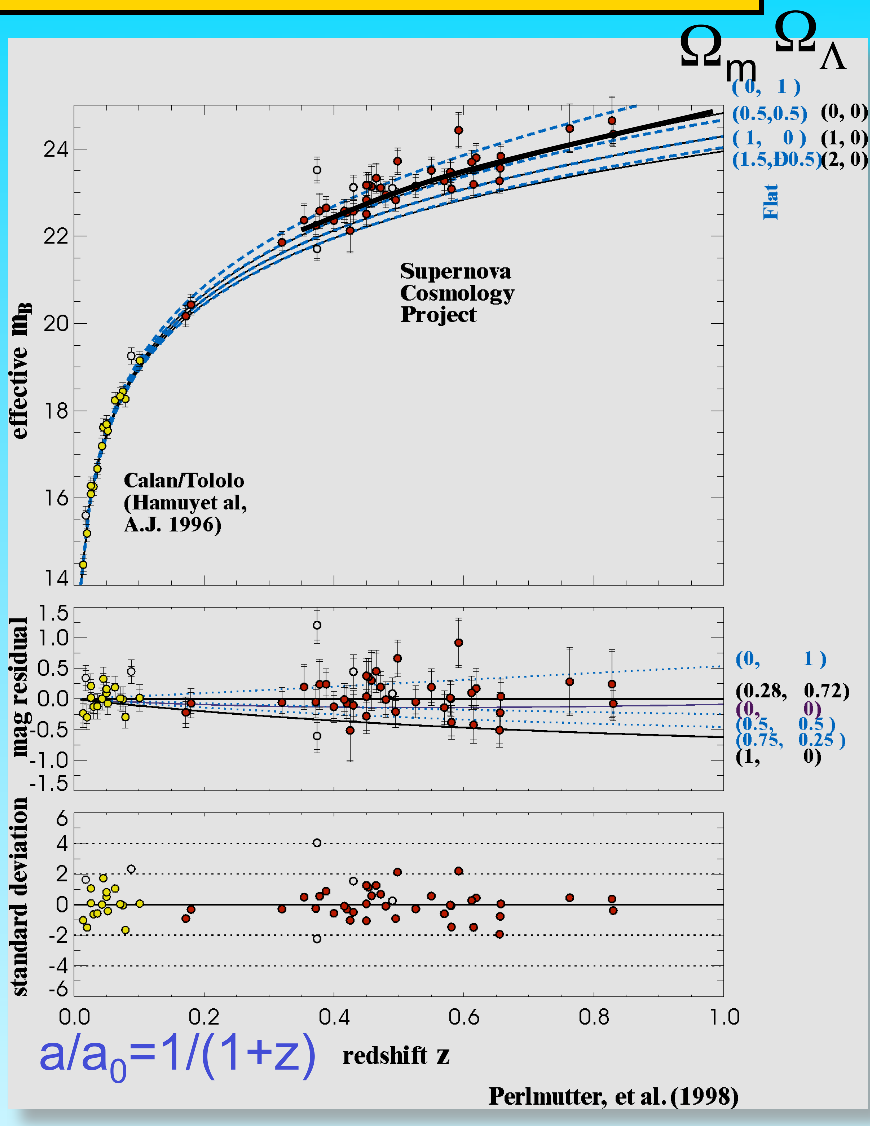
SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

flux

Þ The cosmic expansion must have been accelerating since the light was emitted



$a/a_0=1/(1+z)$

Perlmutter et al '98

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Friedmann equations

$$\ddot{a} = -\frac{4\pi}{3} G\rho a(3w+1)$$

$$c^2 a \frac{d\rho}{da} = -3(p + \rho c^2)$$

$$\rho_{tot} = \underbrace{\rho_{mass}}_{a^{-3}} + \underbrace{\rho_{rel}}_{a^{-4}} + \underbrace{\rho_{vac}}_{const?}$$

where $p = w\rho c^2$

$\Rightarrow 3w + 1 < 0 \quad \Rightarrow \ddot{a} > 0 \quad \Rightarrow$ expansion accelerates

If $\rho = \rho_{vac} = \text{const}$, $\frac{d\rho}{da} = 0 \Rightarrow p = -\rho c^2 \Rightarrow w = -1$

cosmological constant

If $\rho_{vac} = \rho_{vac}(z, \mathbf{x})$ and $w < -\frac{1}{3}$ $\Rightarrow$ quintessence

Evolution of Cosmic Scale Factor in FRW Model

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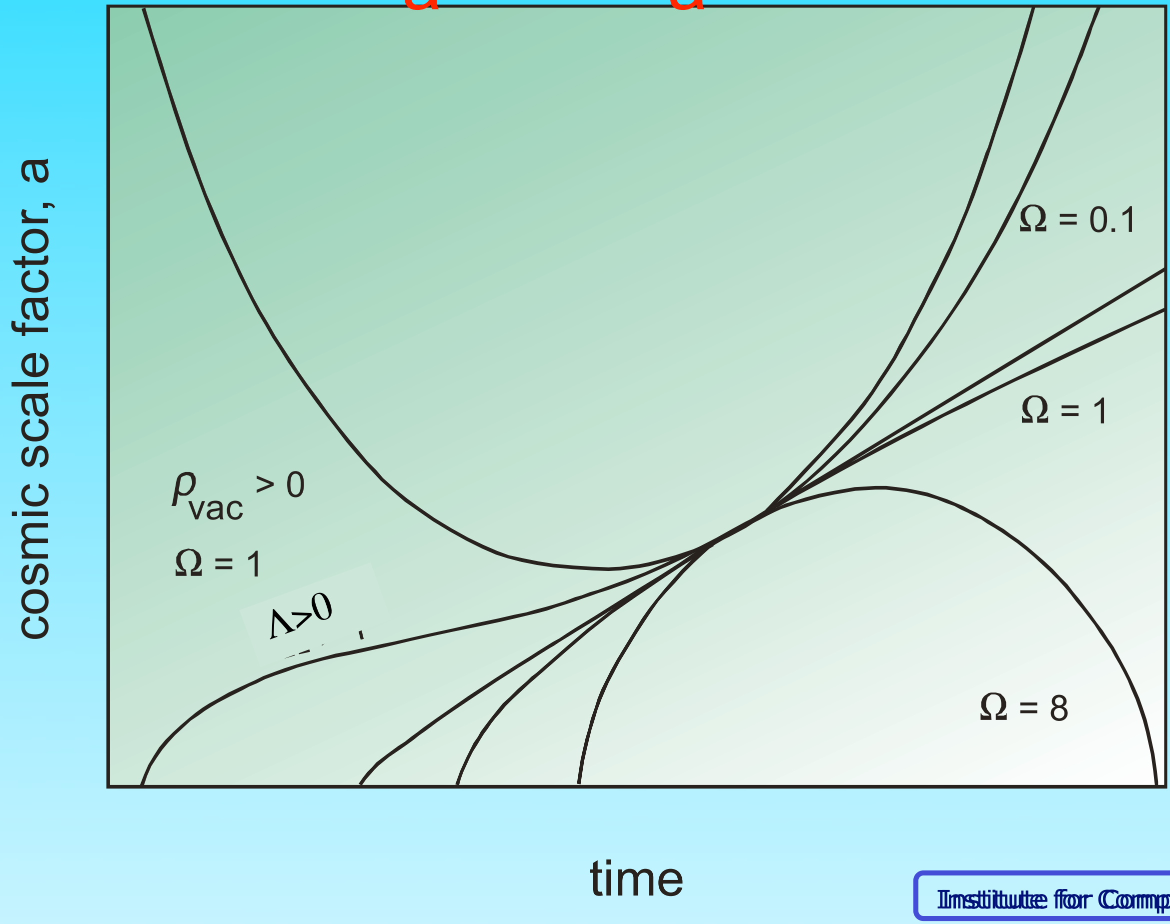
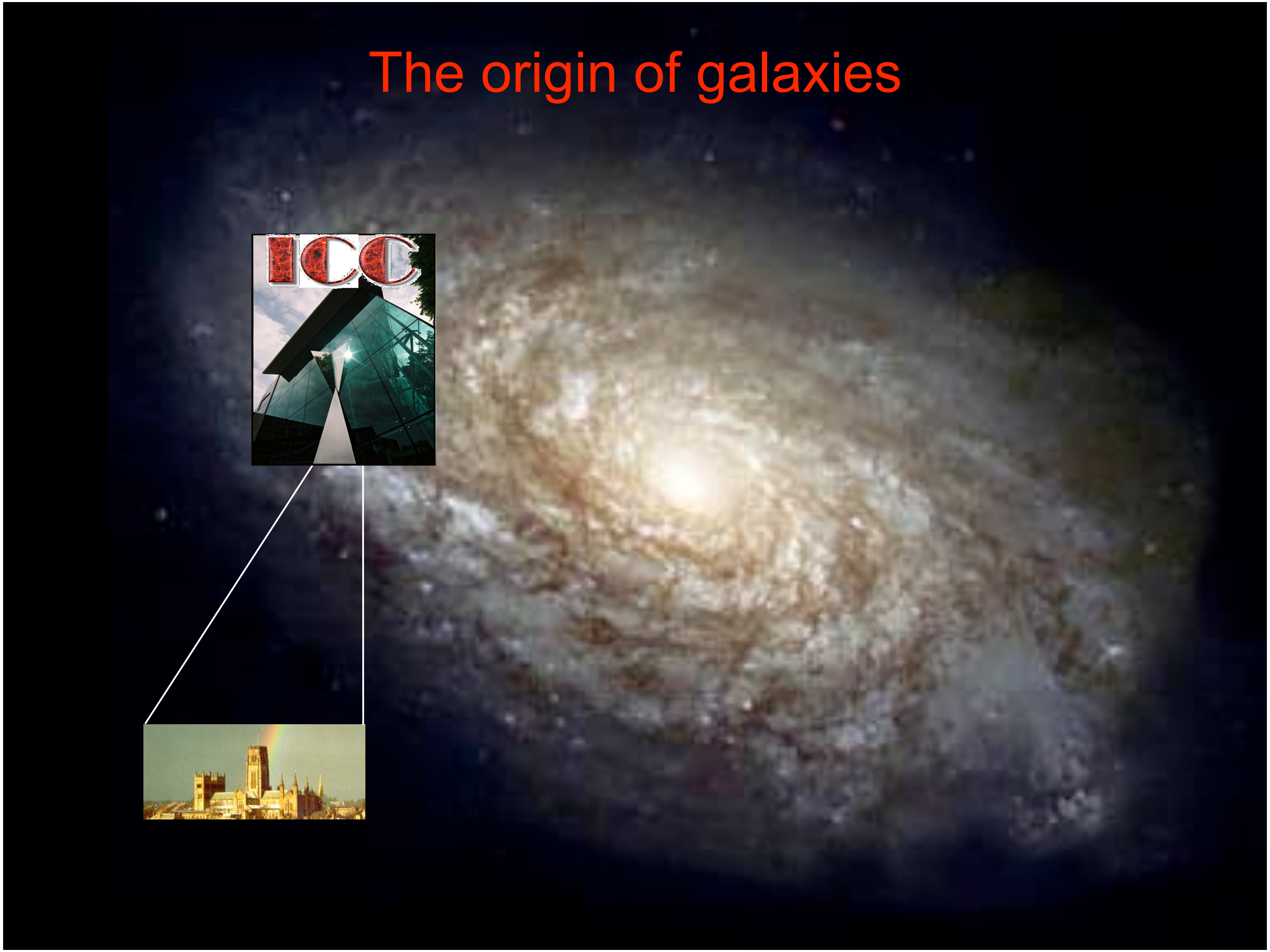
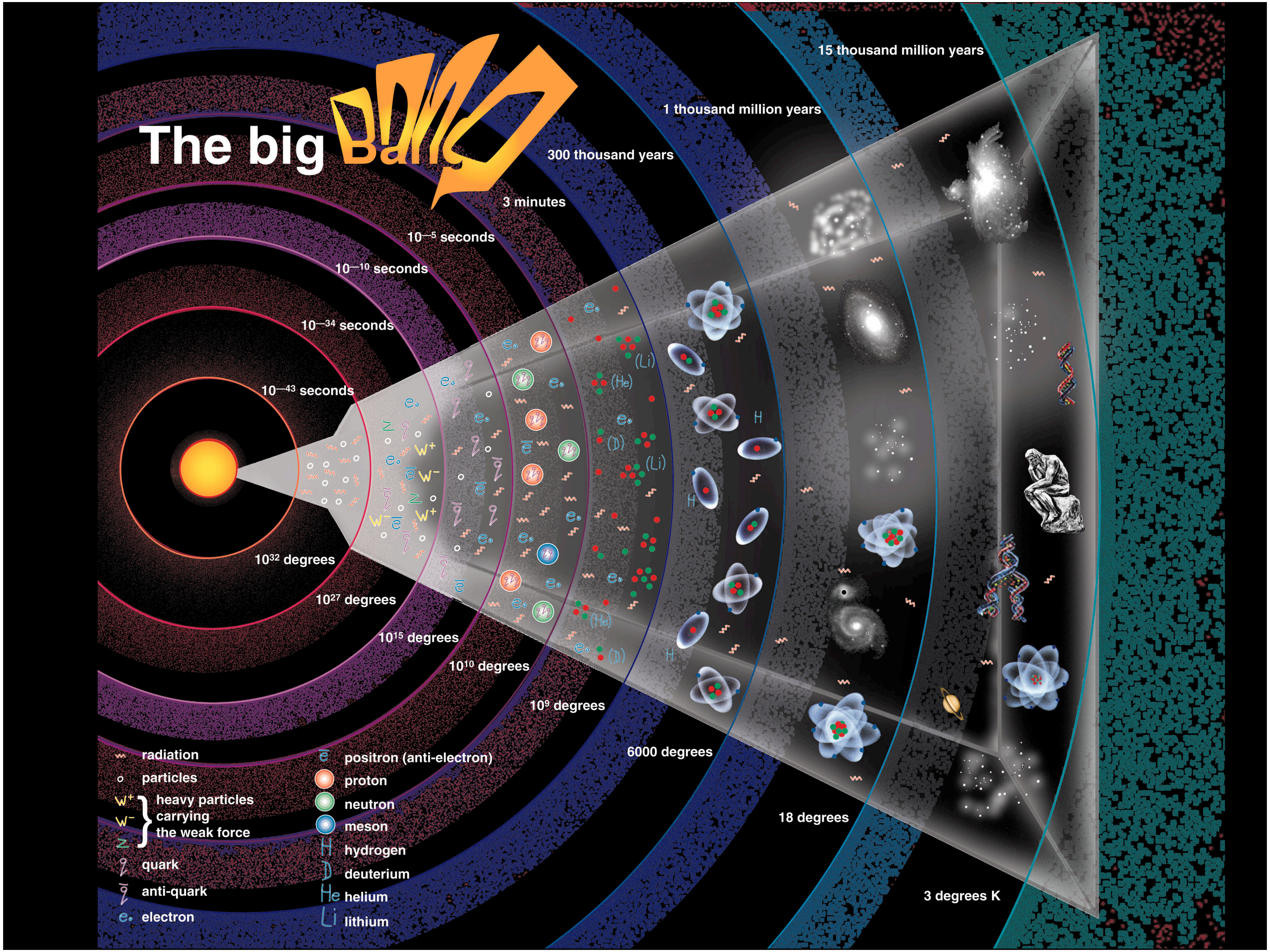
$$\rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

$$\rho_{mass} \propto a^{-3}, \quad \rho_{rel} \propto a^{-4}, \quad \rho_{vac} \propto const$$



The origin of galaxies

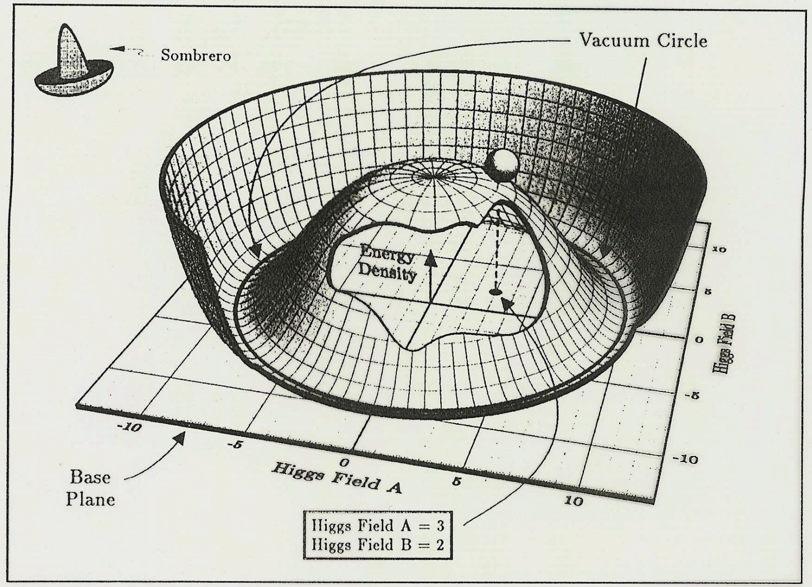




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Inflation

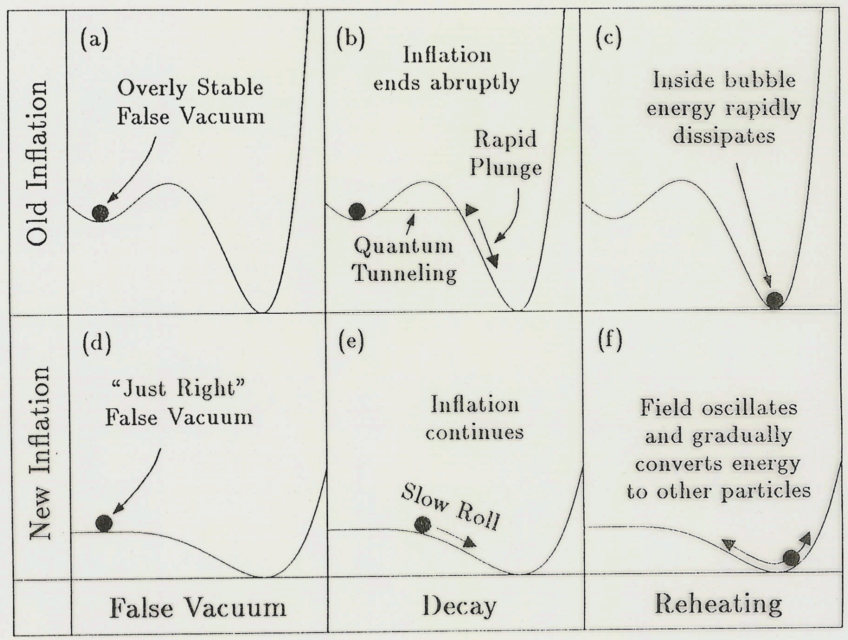
Initially, Universe is trapped in false vacuum



Scalar field Φ

Universe decays to true vacuum keeping ρ_v~ const

Universe oscillates converting energy into particles



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Friedmann equations

$$\dot{a}^2 + kc^2 = \frac{8\pi}{3} G\rho a^2$$

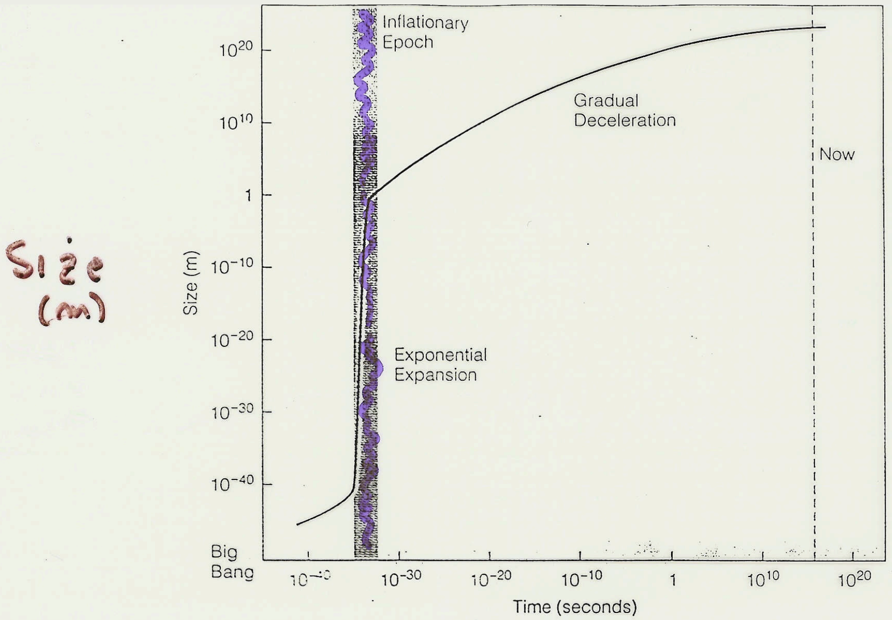
If $k = 0$ and $\rho = \rho_{vac} = const \quad (w = -1)$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho$$

$$\Rightarrow \quad a \propto e^{\frac{t}{\tau}} \qquad \tau = \left(\frac{3}{8\pi G\rho}\right)^{1/2}$$

$\Rightarrow$ Universe expands exponentially

Inflation



INFLATION SOLVES 4 MAJOR COSMOLOGICAL PROBLEMS

1. FLATNESS: $\frac{\Omega_{PL}^{-1}-1}{\Omega_0^{-1}-1} = \frac{T_0}{T_{eq}}\left(\frac{T_{eq}}{T_{PL}}\right)^2 \simeq 10^{-57}$ & $\Omega_0^{-1}-1 < 100$

SO, AT T_{PL} UNIVERSE FLAT TO 1 PART IN 10^{55} !

2. HORIZON: $R_H(z_{ls}) = 3ct_{ls} \simeq 10^{-1}\, r_{ls}$

horizon at "last scattering" — radius of "last scattering" surface

BUT $\Delta T/T \simeq 10^{-5}$!

3. MONOPOLE: GUT PRODUCES ~1 MAGNETIC MONOPOLE PER HORIZON VOL. AT t_{GUT} $\Rightarrow$ $\Omega_M \simeq 10^{16}$!

4. STRUCTURE: GENERATION OF $\delta\rho/\rho$?

Cosmic Inflation

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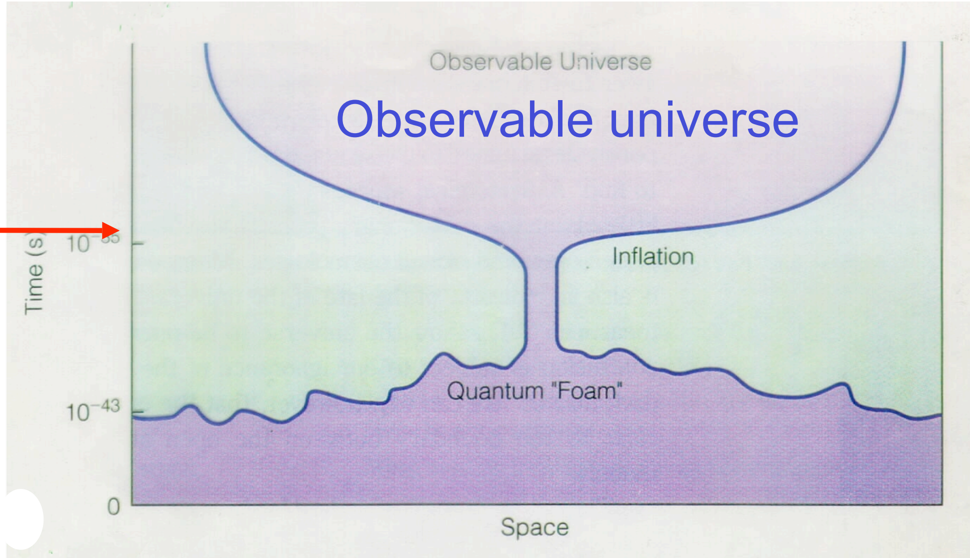
$t=10^{-35}$ s



Inflation theory predicts:

1. Flat geometry (Ω =1) √

   (eternal expansion)

2. Small ripples in mass distribution

Generation of primordial fluctuations

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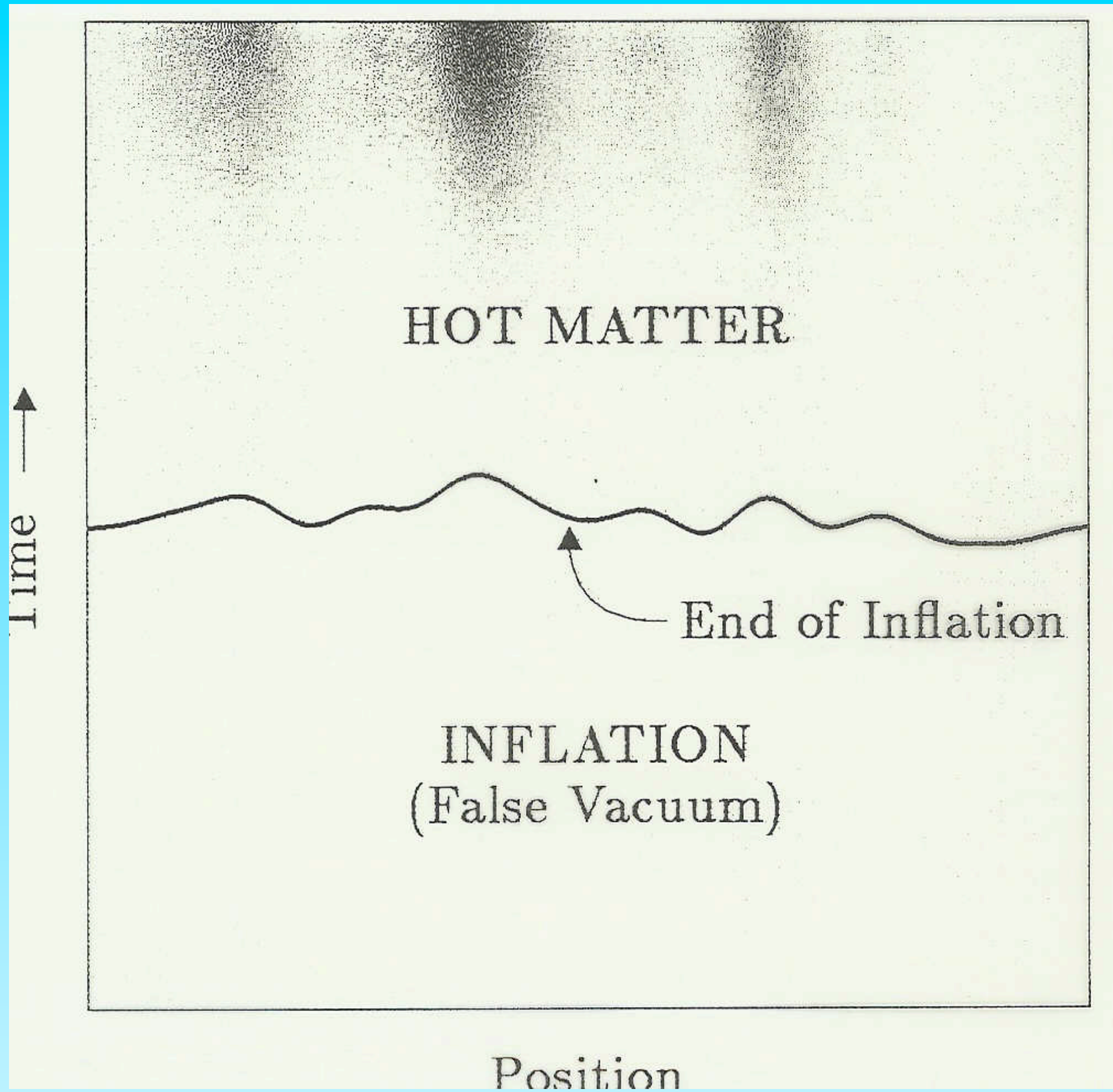
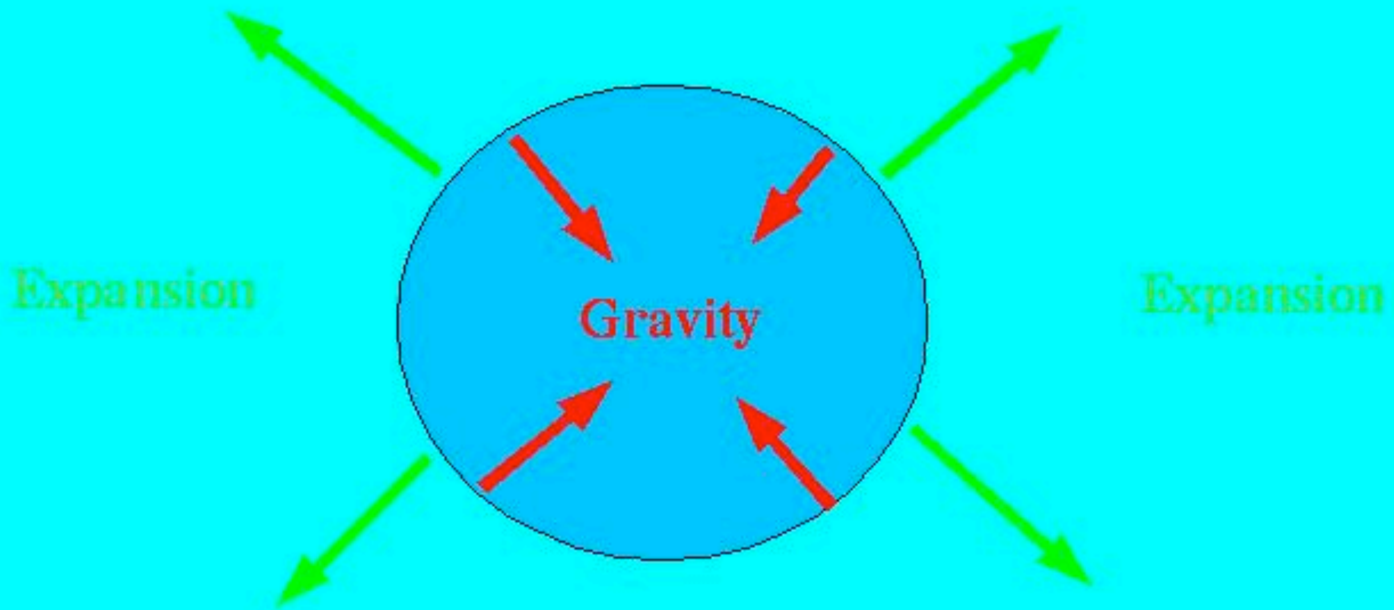
Quantum fluctuations are blown up to macroscopic scales during inflation



The evolution of density fluctuations



If the universe expands rapidly, difficult for fluctuations to collapse

Or if pressure forces dominate inside the perturbation

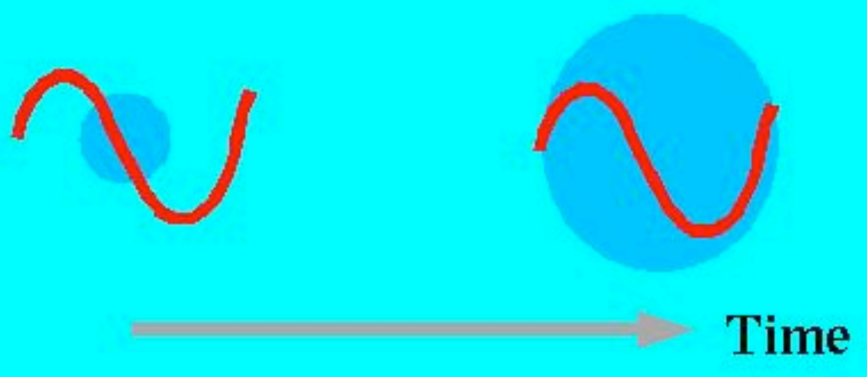
How fluctuations evolve

Key time: epoch of matter/radiation equality

Radiation dominated: $\delta \sim a^2$

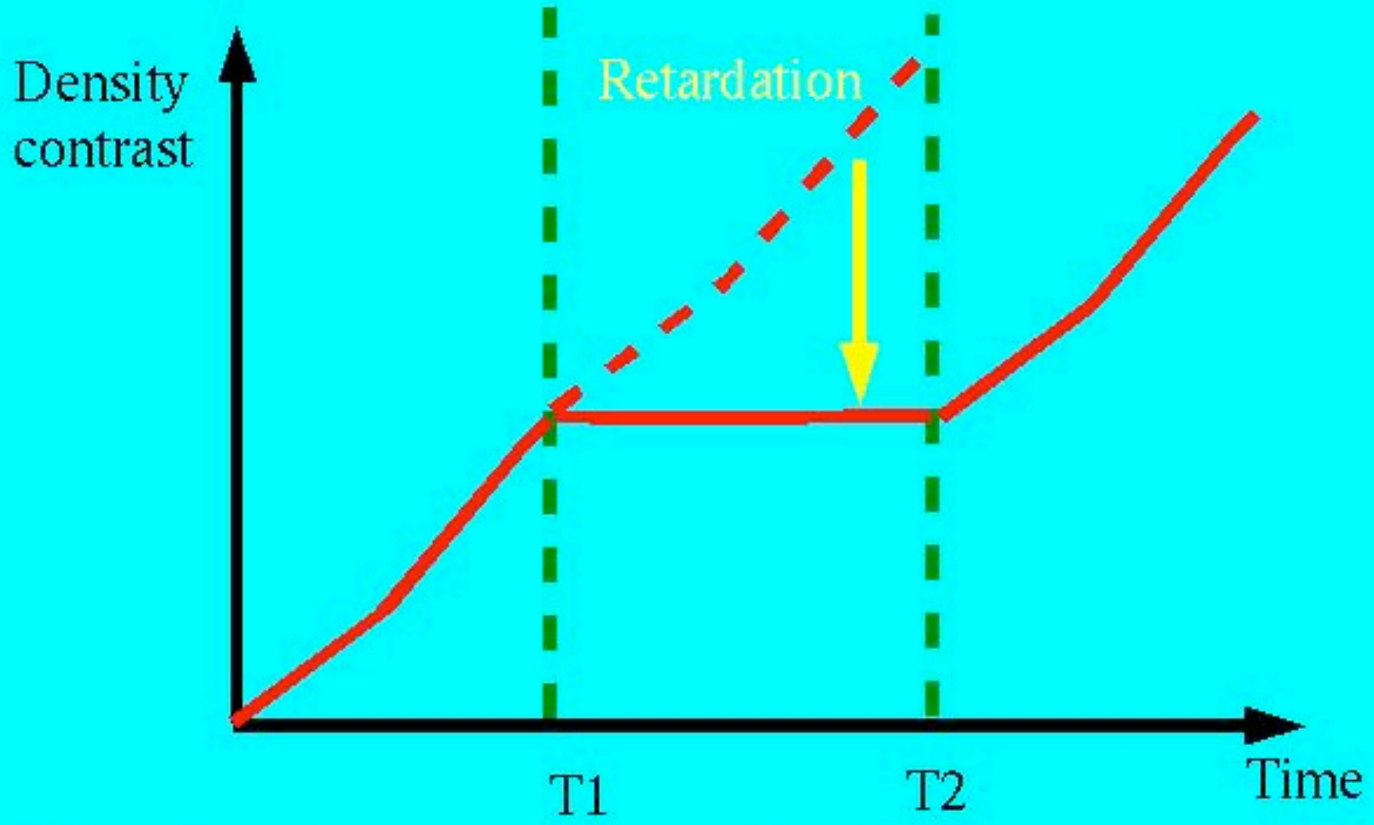
Matter dominated: $\delta \sim a$

Key concept: is the fluctuation inside the horizon?



Inside horizon scale: DAMPING

Evolution of a density perturbation (dark matter)

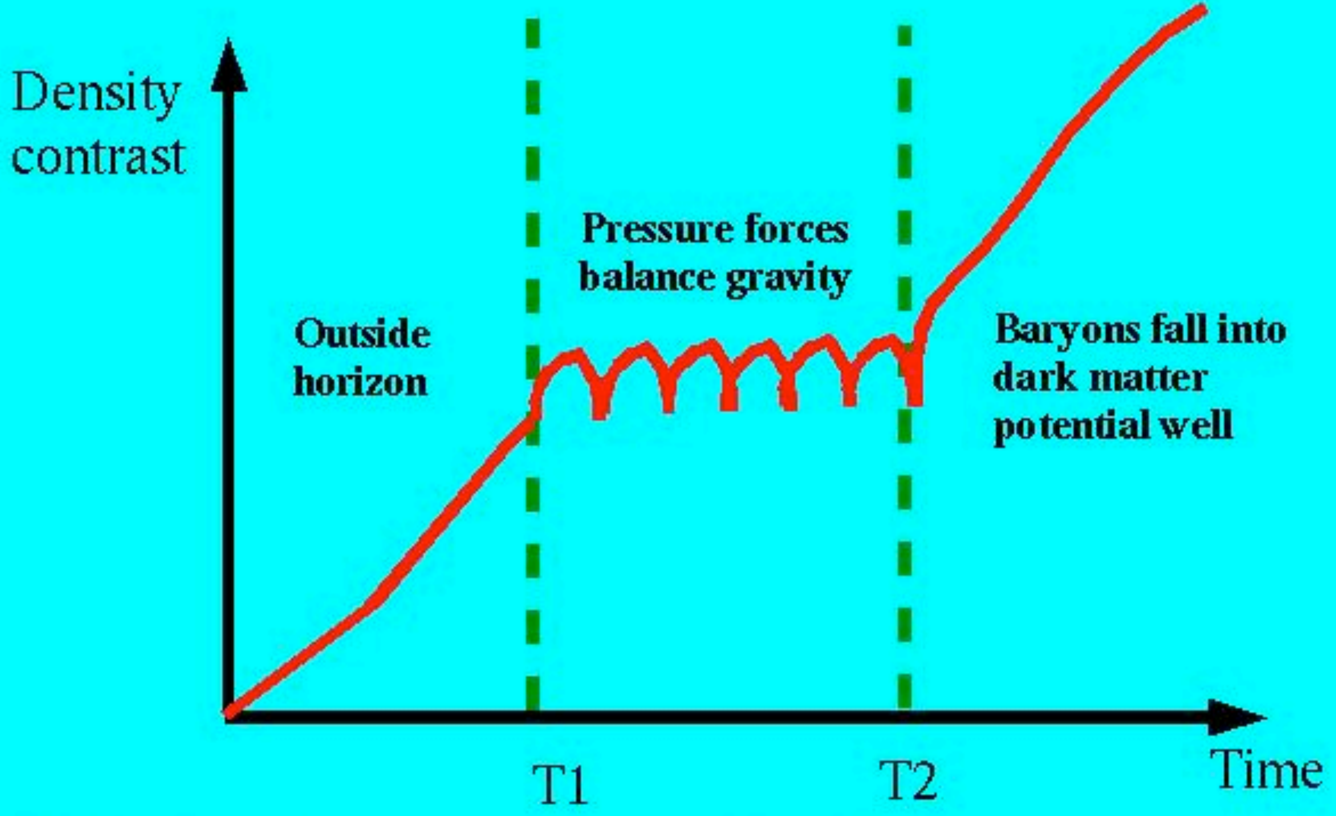


T1: horizon has expanded to enclose fluc'n

T2: epoch of matter-radiation equality

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

Evolution of a density perturbation (baryons)



T1: horizon has expanded to enclose fluc'n

T2: epoch of recombination: atoms form, photon pressure drops

EVOLUTION OF AN ADIABATIC PERTURBATION IN A CDM UNIVERSE

$M = 10^{15}\ M_\odot$ $\Omega = 1$ $h = 0.5$

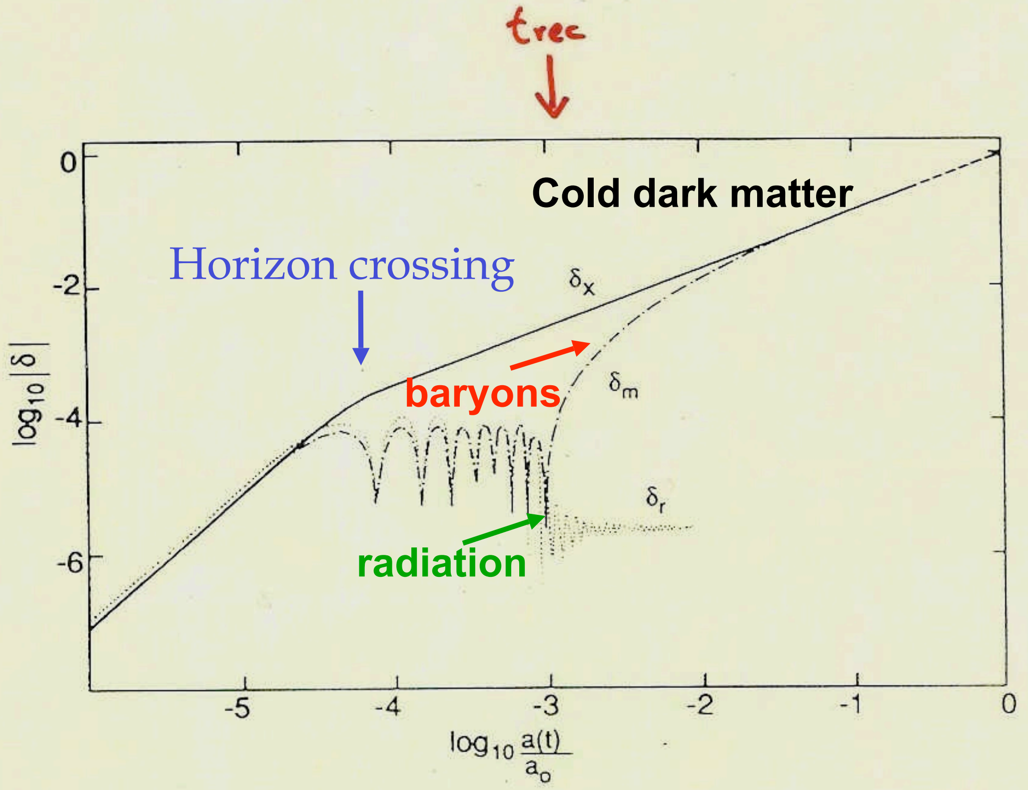


Figure 13.3 Evolution of perturbations on a scale $M \simeq 10^{15}\ M_\odot$ for the cold component δ_X, baryonic component δ_m and photons δ_r in a model dominated by CDM ($\Omega = 1$, $h = 0.5$)

The origin of cosmic structure

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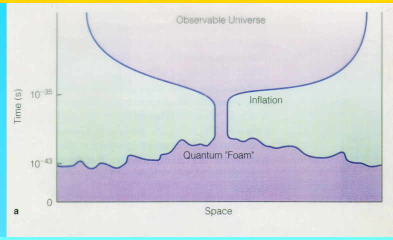
Inflation ($t \sim 10^{-35}$ s)



QUANTUM FLUCTUATIONS:

$|\delta_k|^2 \propto k^n \quad n = 1$

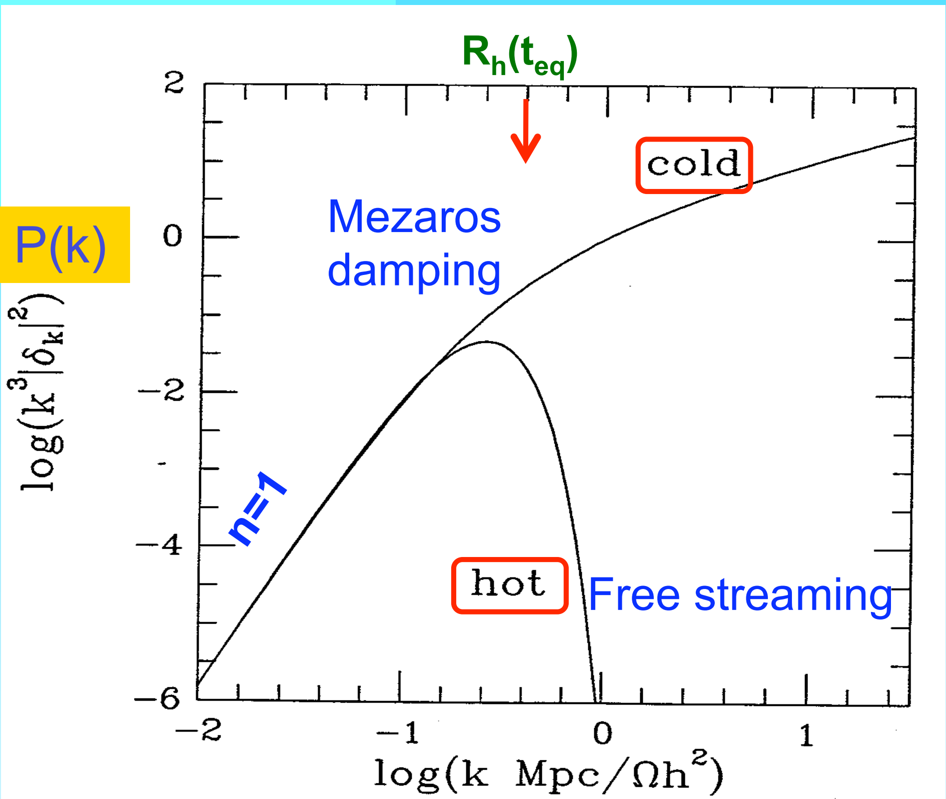
Gaussian amplitudes

+

Damping (nature of dark matter)

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

→ Transfer function



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

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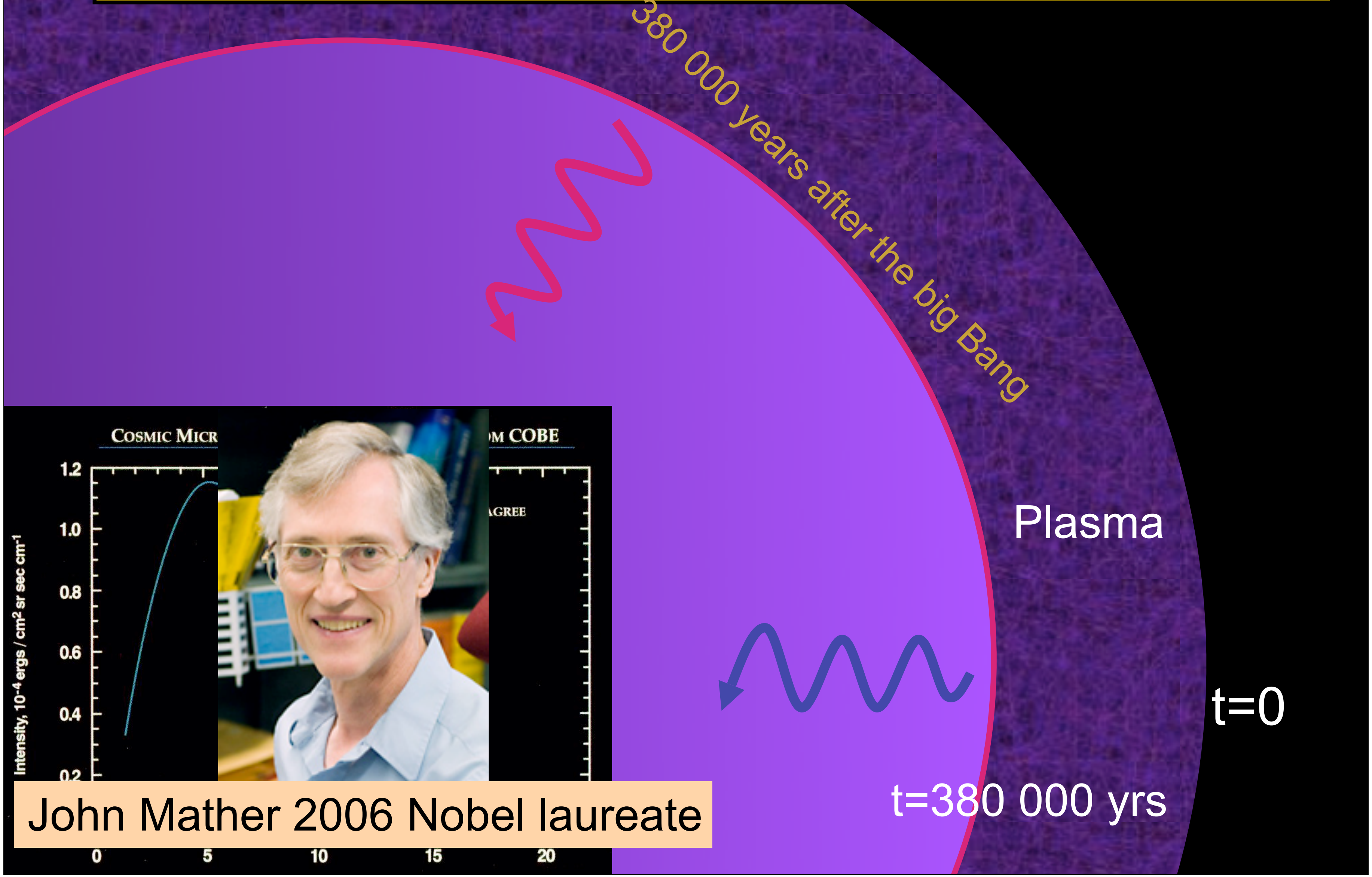
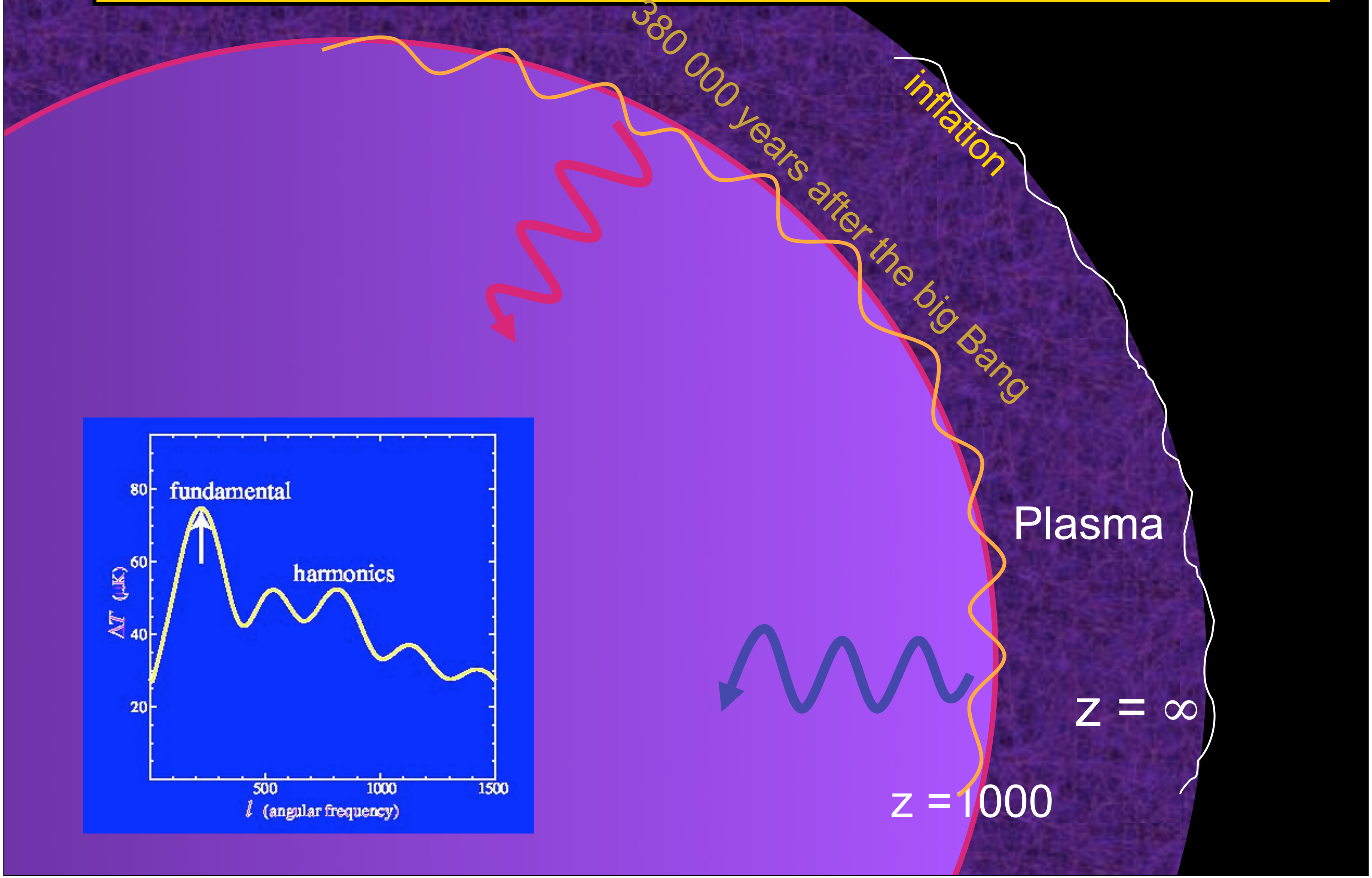
The microwave background radiation

The microwave background radiation



The microwave background radiation



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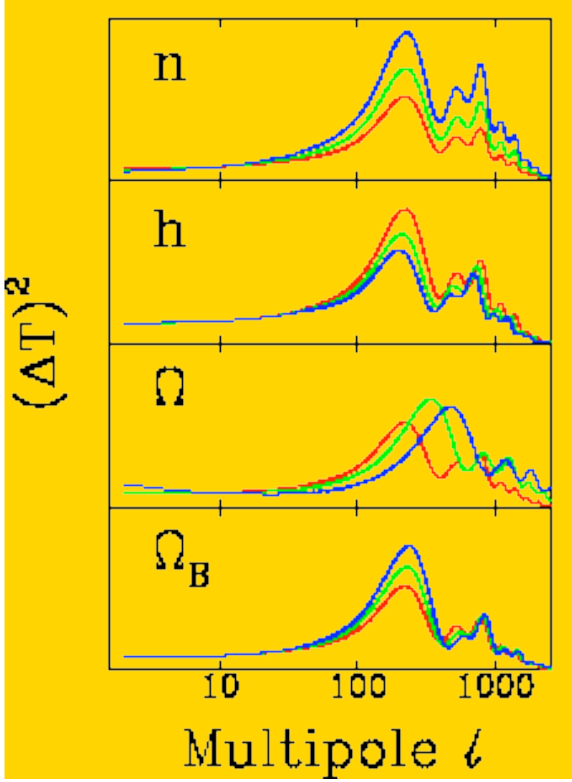
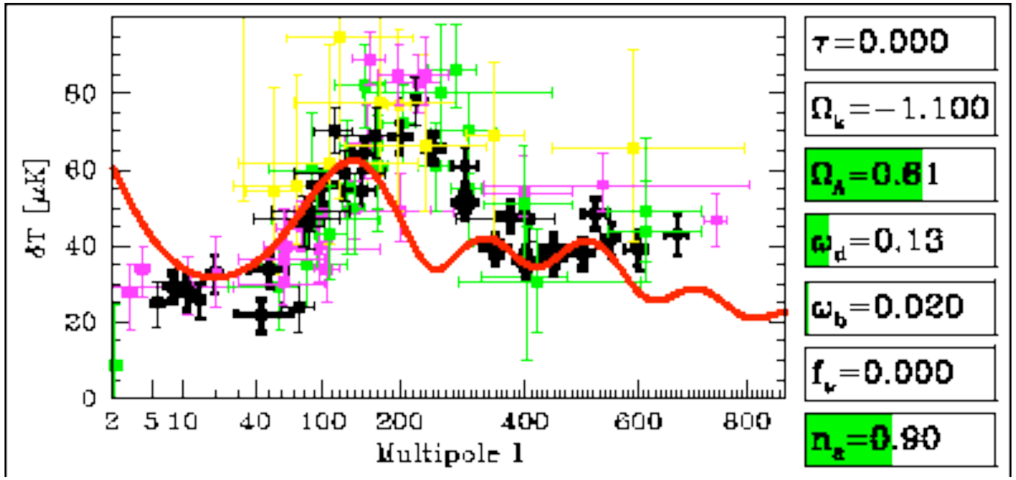
Dependence of ΔT/T on cosmological params

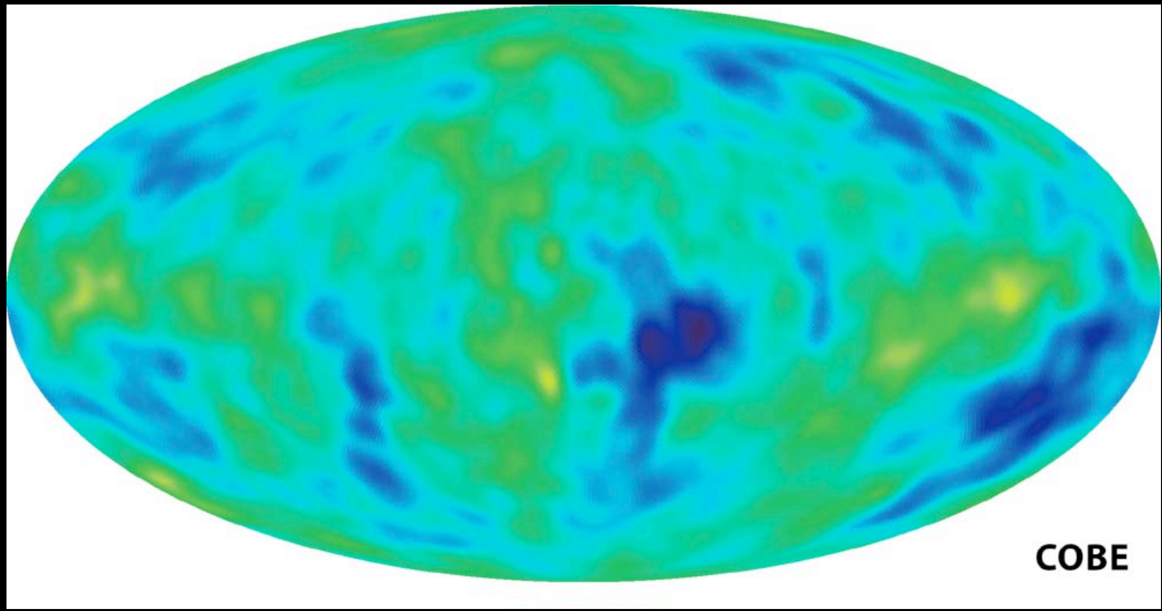




Max Tegmark

The CMB

1992

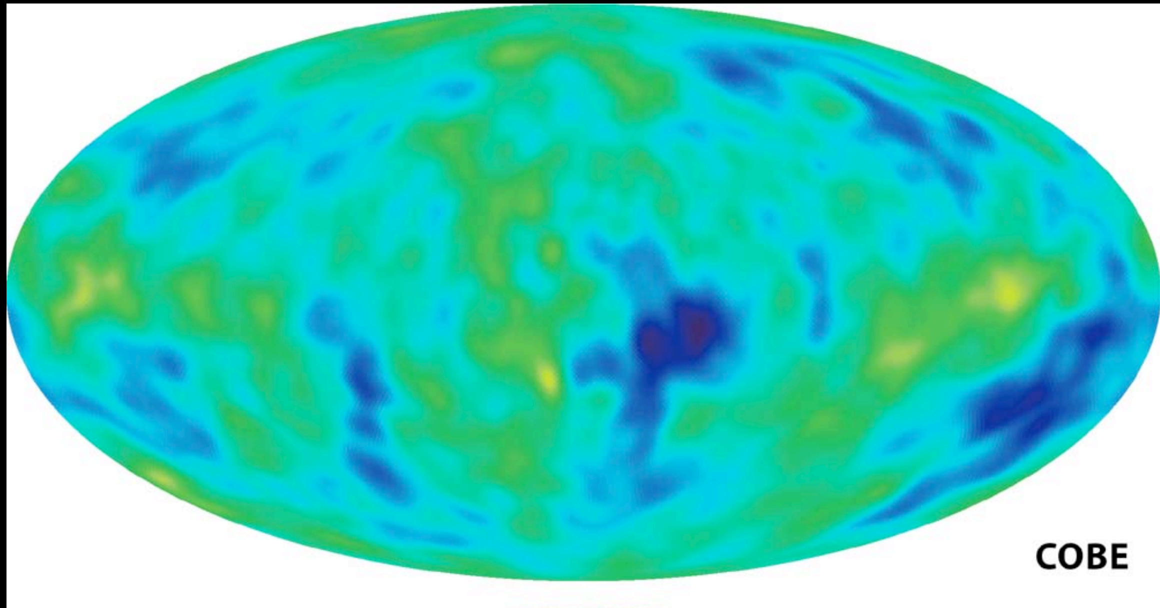


The cosmic microwave background radiation (CMB) provides a window to the universe at t~3x10^5 yrs

In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions

The CMB

1992



George Smoot - Nobel Prize 2006

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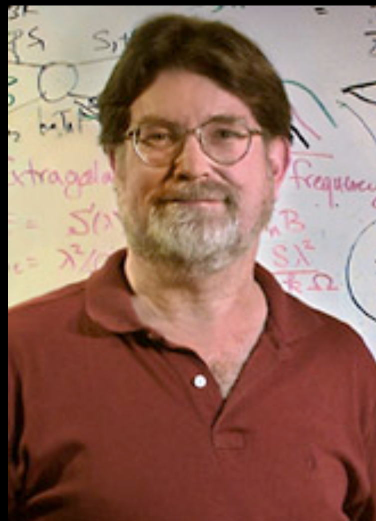
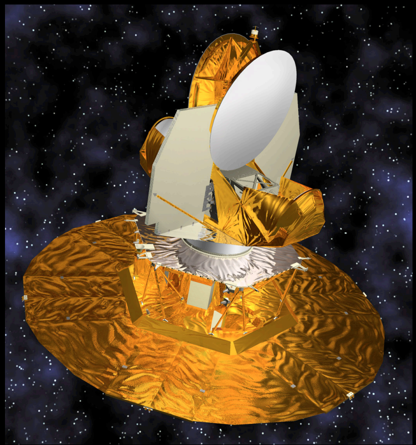
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

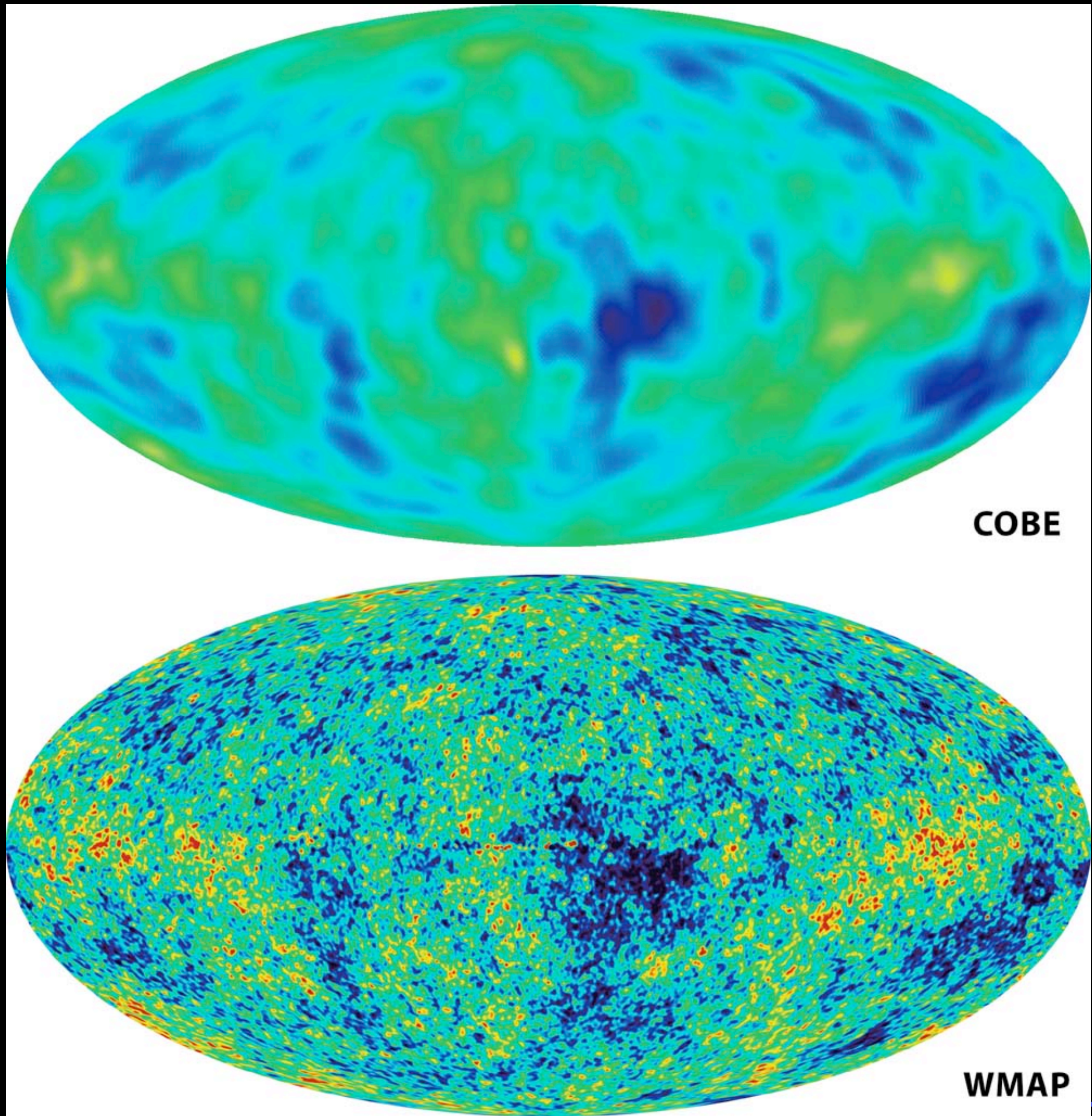


The CMB

1992

2003





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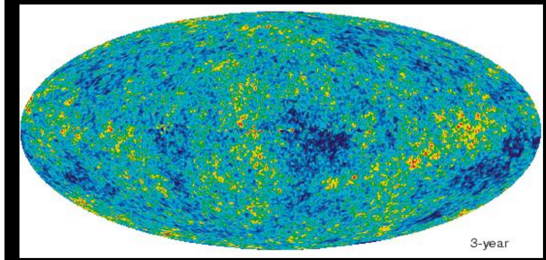
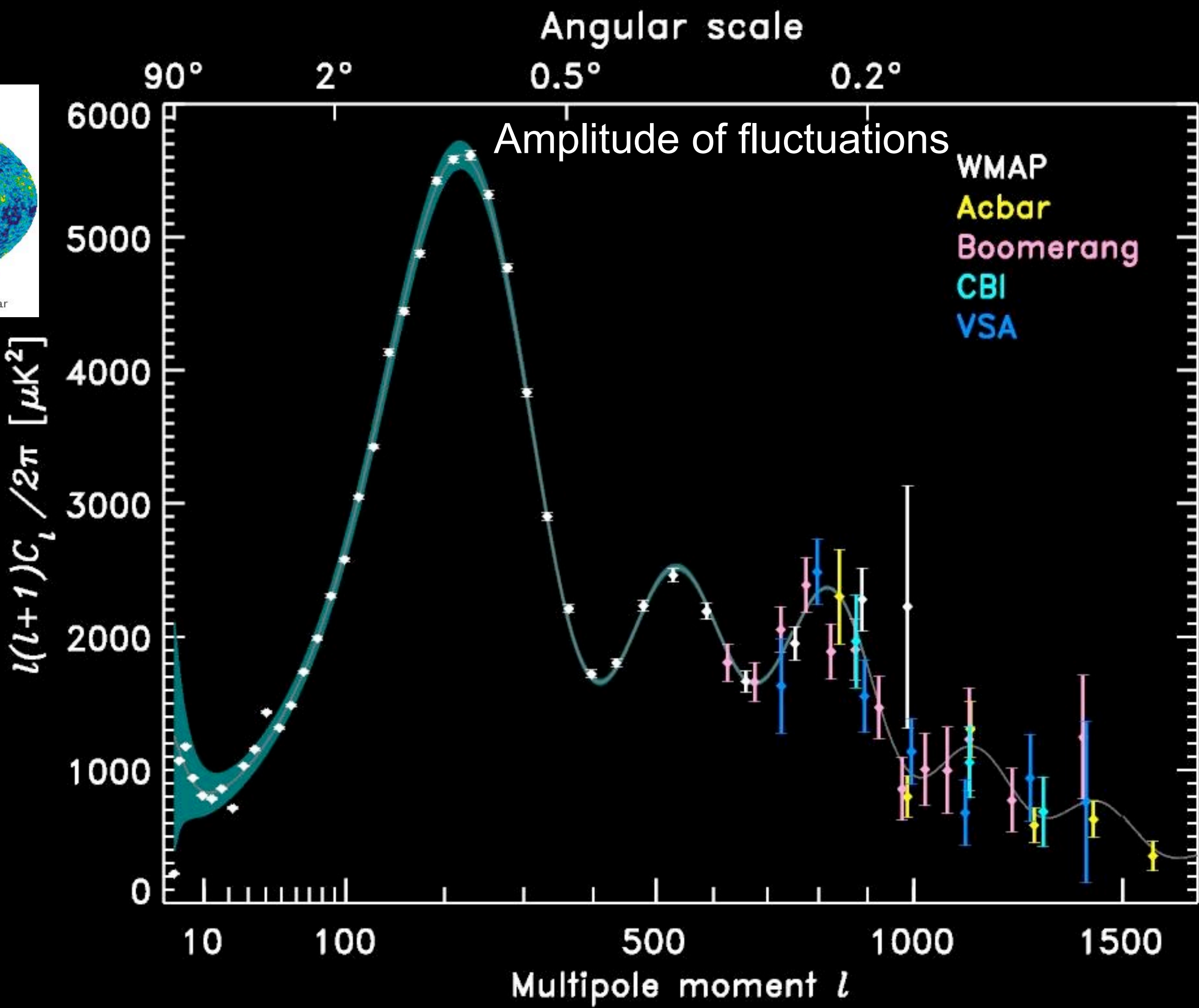
WMAP temp anisotropies in CMB



The amplitude of the CMB ripples is exactly as predicted by inflationary cold dark matter theory

The position of the first peak

➔ FLAT UNIVERSE



Hinshaw etal '06

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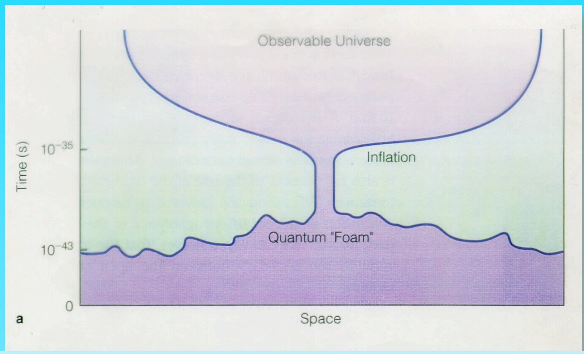
The origin of cosmic structure

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

2. QUANTUM FLUCTUATIONS: $|\delta_k|^2 \propto k^n \quad n = 1$

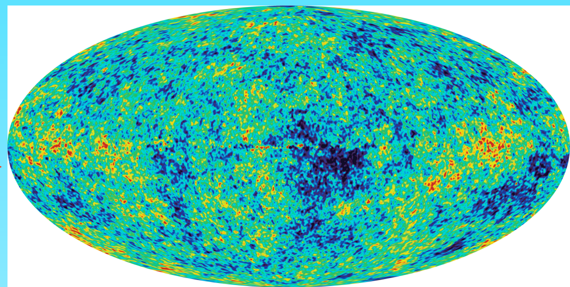
Gaussian amplitudes

Inflation (t~10^{-35} s)

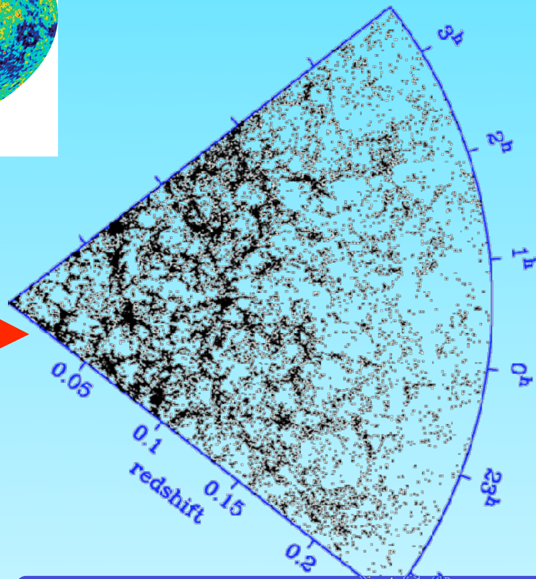


Cold dark matter

CMB (t~3×10^5 yrs)



Structure (t~13×10^9yrs)



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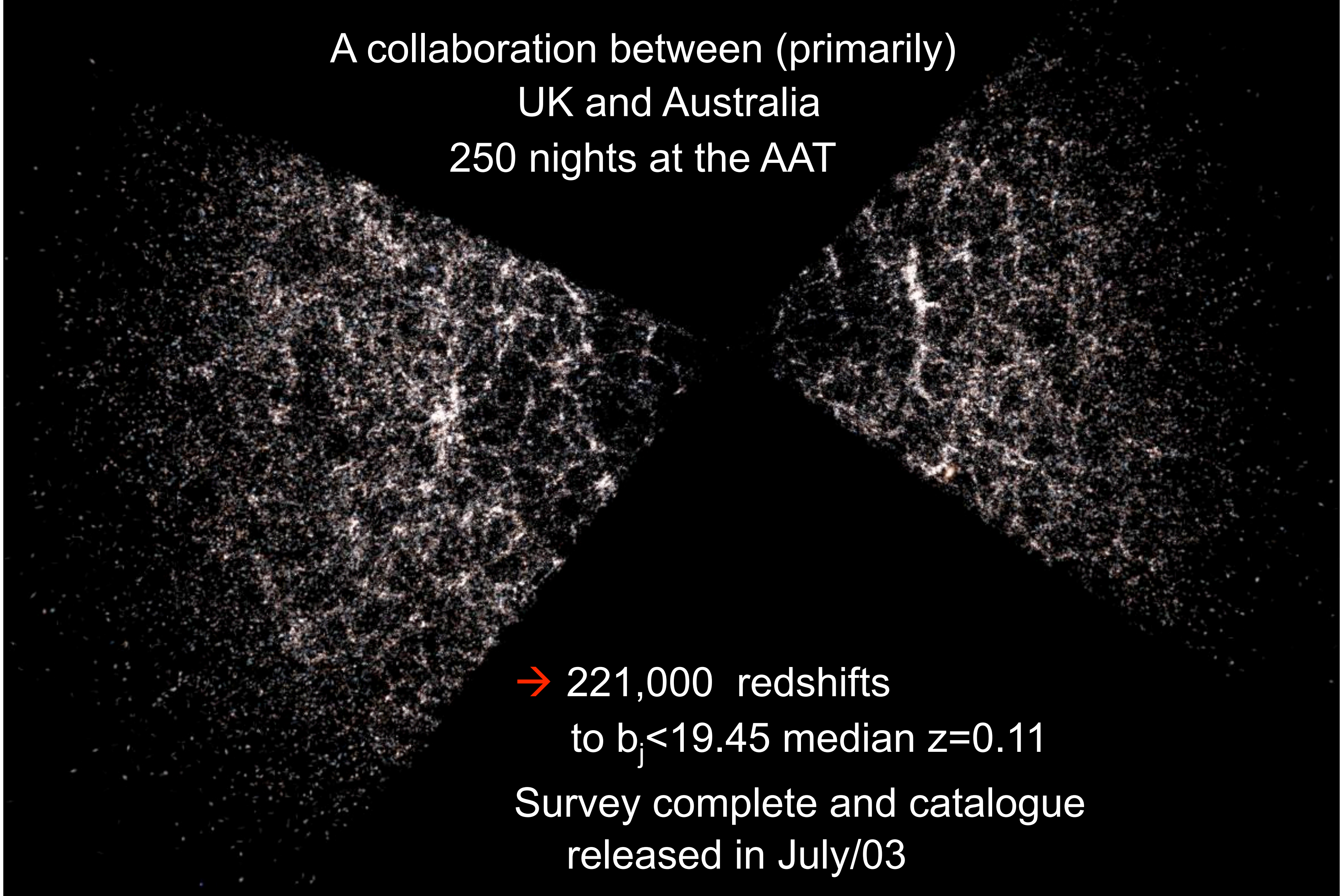
The 2dF Galaxy Redshift Survey

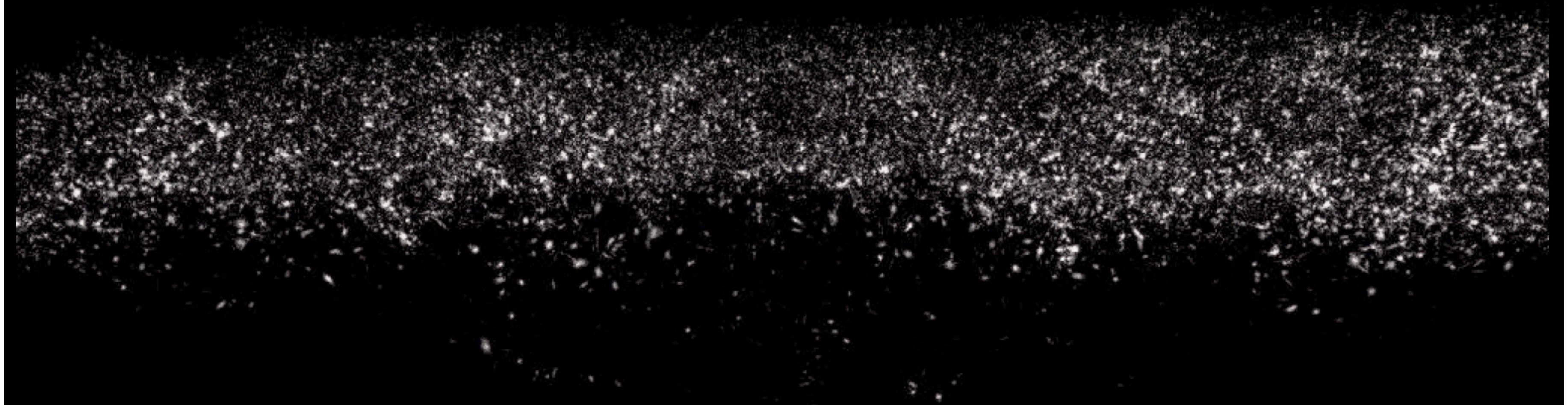
A collaboration between (primarily)
UK and Australia
250 nights at the AAT



→ 221,000 redshifts
to b_j<19.45 median z=0.11

Survey complete and catalogue
released in July/03

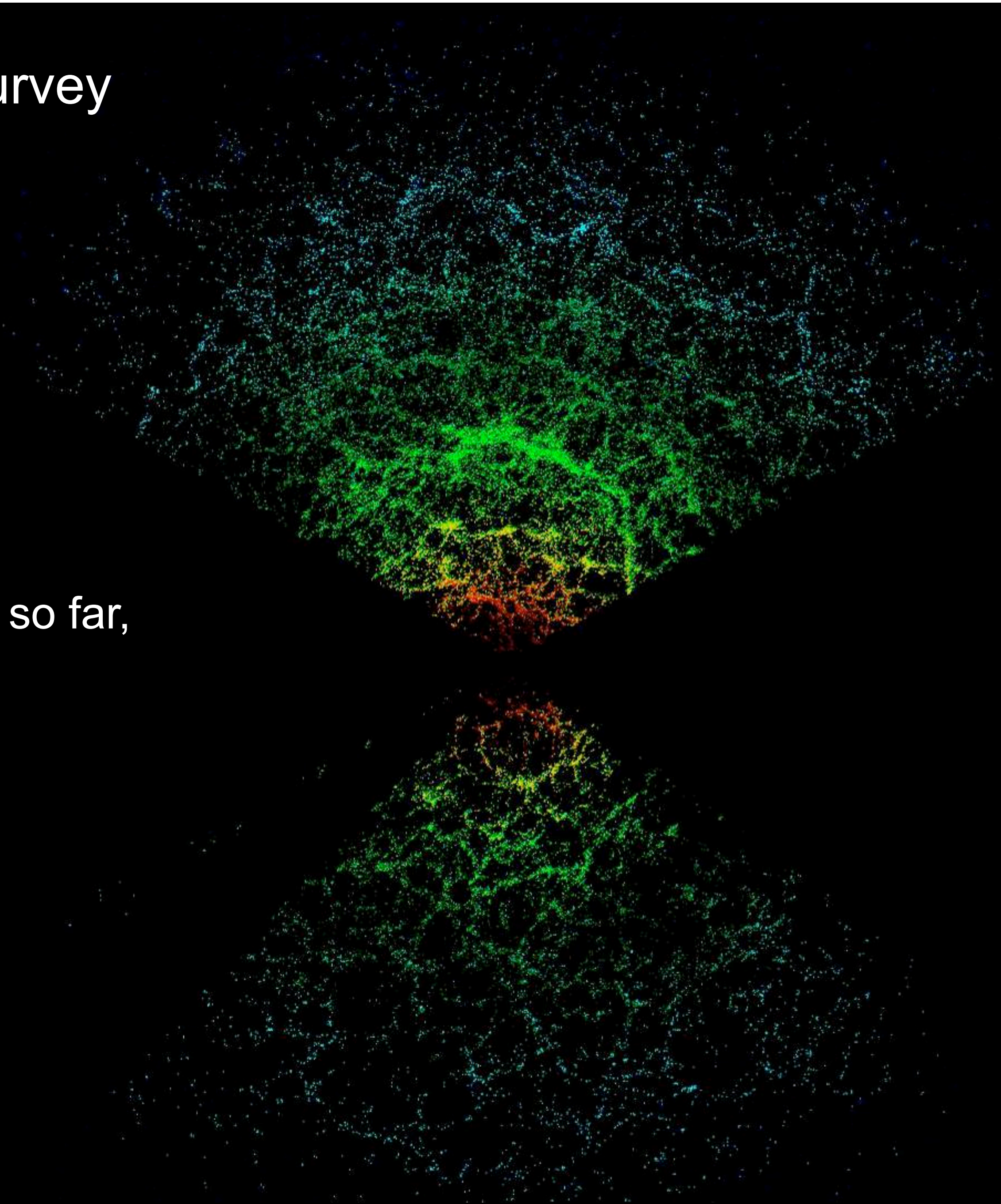
The 2dF galaxy redshift survey



→ 1997-2003: 250 nights at 4m AAT

→ 221,000 redshifts to b_j<19.45

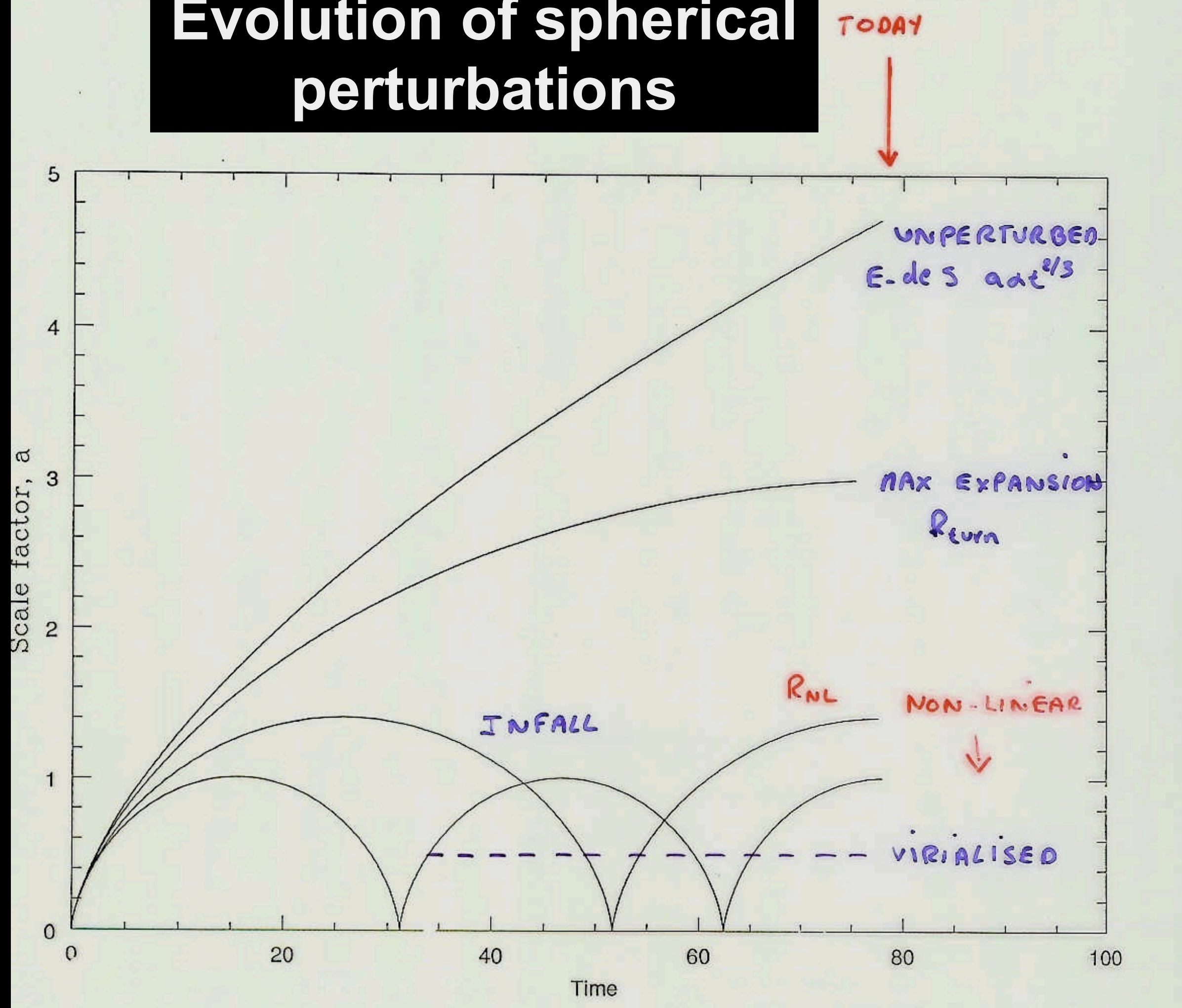
Sloan Digital Sky Survey



~300,000 galaxy redshifts so far,

500,000 eventually

Evolution of spherical perturbations



- R_{NL} SEPARATES UNMIXED, UNSHOCKED (PRIMORDIAL) MATERIAL FROM MIXED, SHOCKED, NON-LINEAR MATERIAL
- IN E-d-S, R_{NL} CORRESPONDS TO $\delta\rho/\rho \sim 100$

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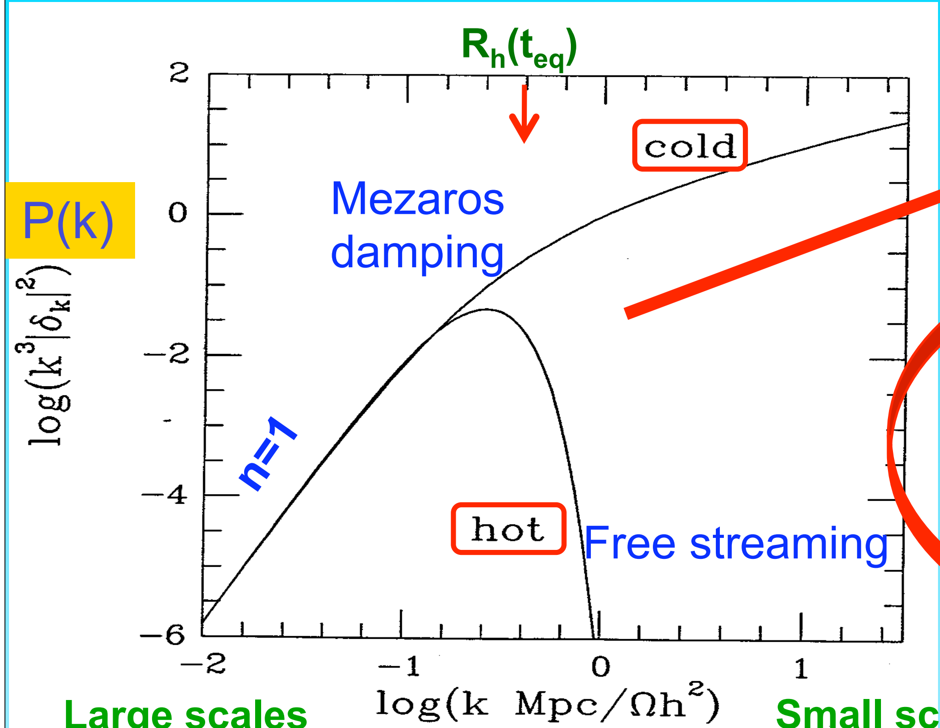
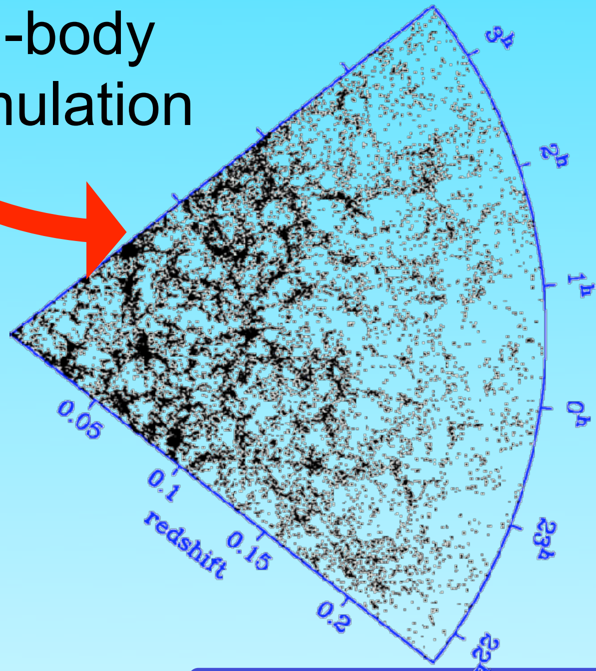
Calculating the evolution of cosmic structure



Large scales

Small scales

N-body simulation



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Non-baryonic dark matter candidates

	Candidate	*Mass*
Cold DM	Axions	10^{-5} eV
Hot DM	Neutrinos	30 eV
Cold DM	Neutralinos (SUSY)	>20 GeV
Cold DM	Primordial black holes	$>10^{15}$ g

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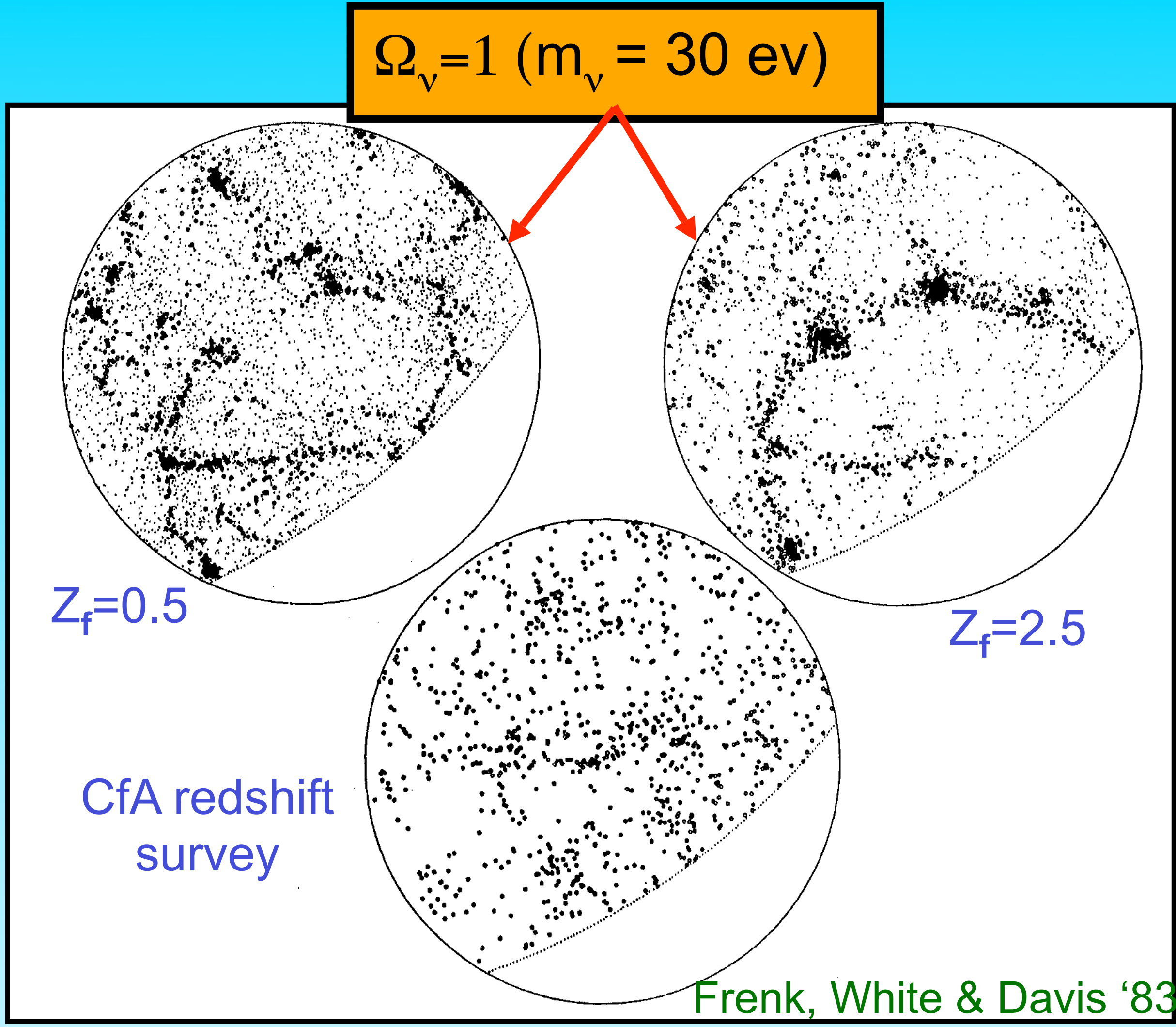
Neutrino (hot) dark matter

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

⇨

Neutrinos cannot make an appreciable contribution to Ω and m_ν<< 30 ev



Cold dark matter

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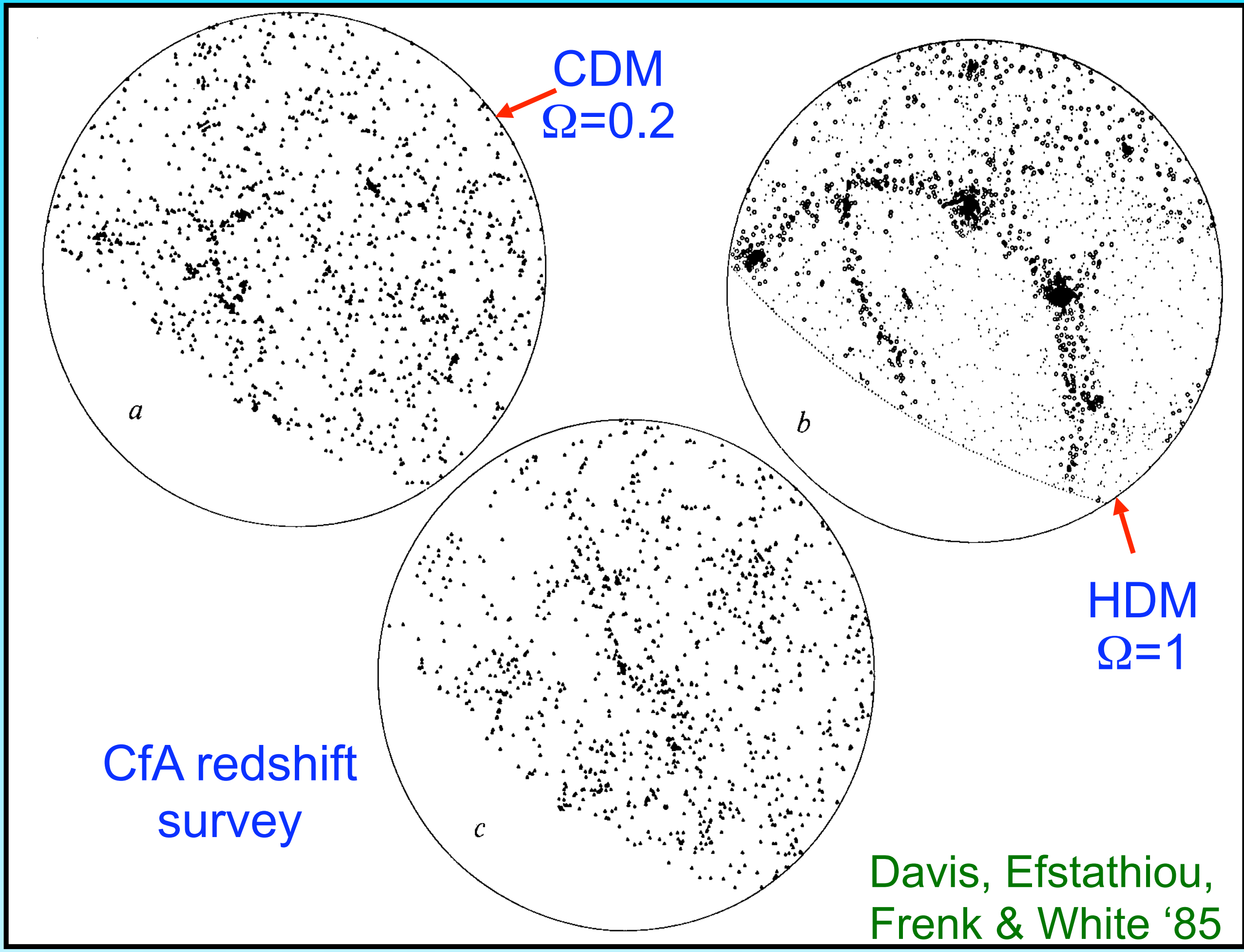
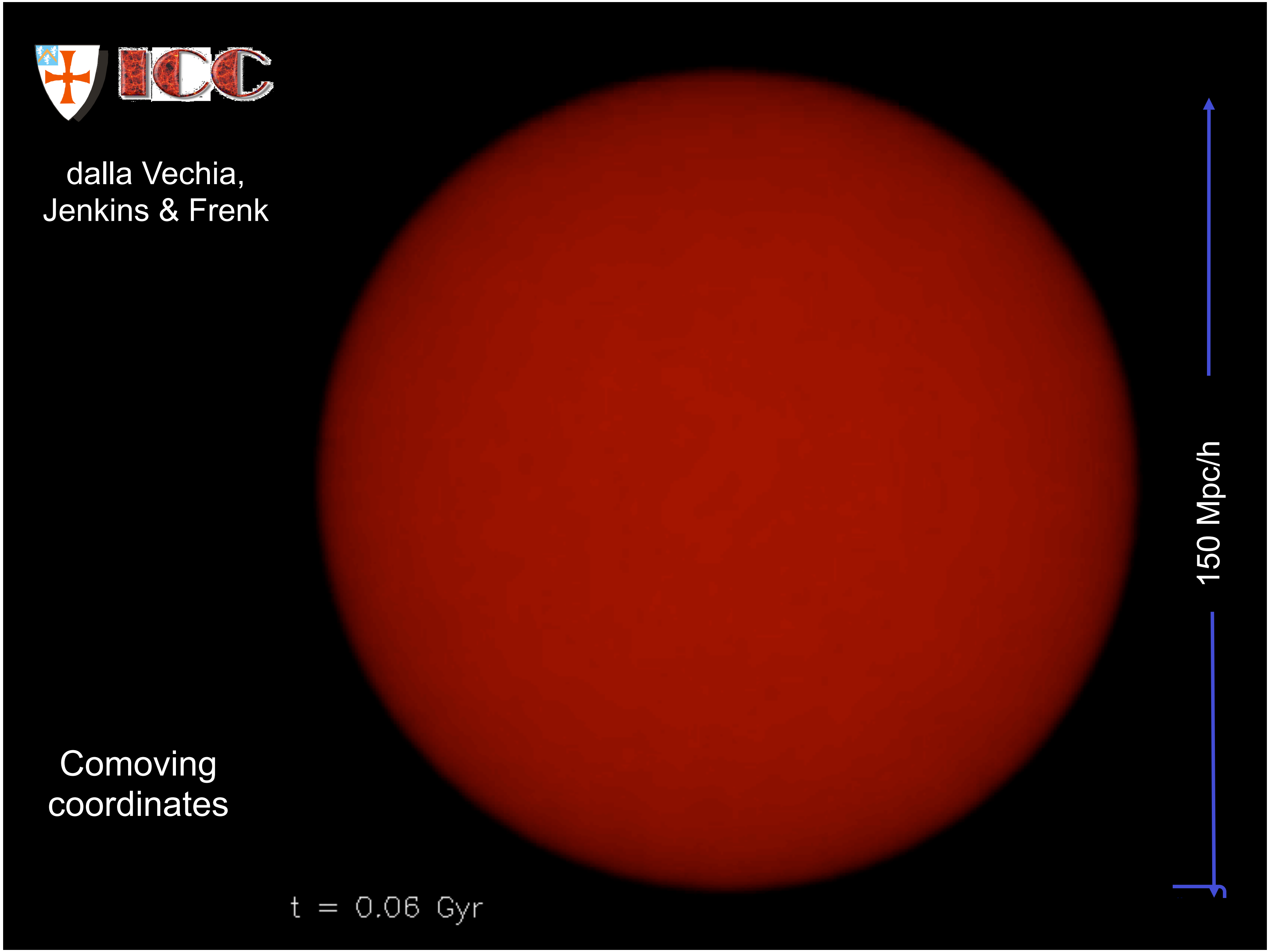
In CDM structure forms hierarchically

Early CDM N-body simulations gave promising results



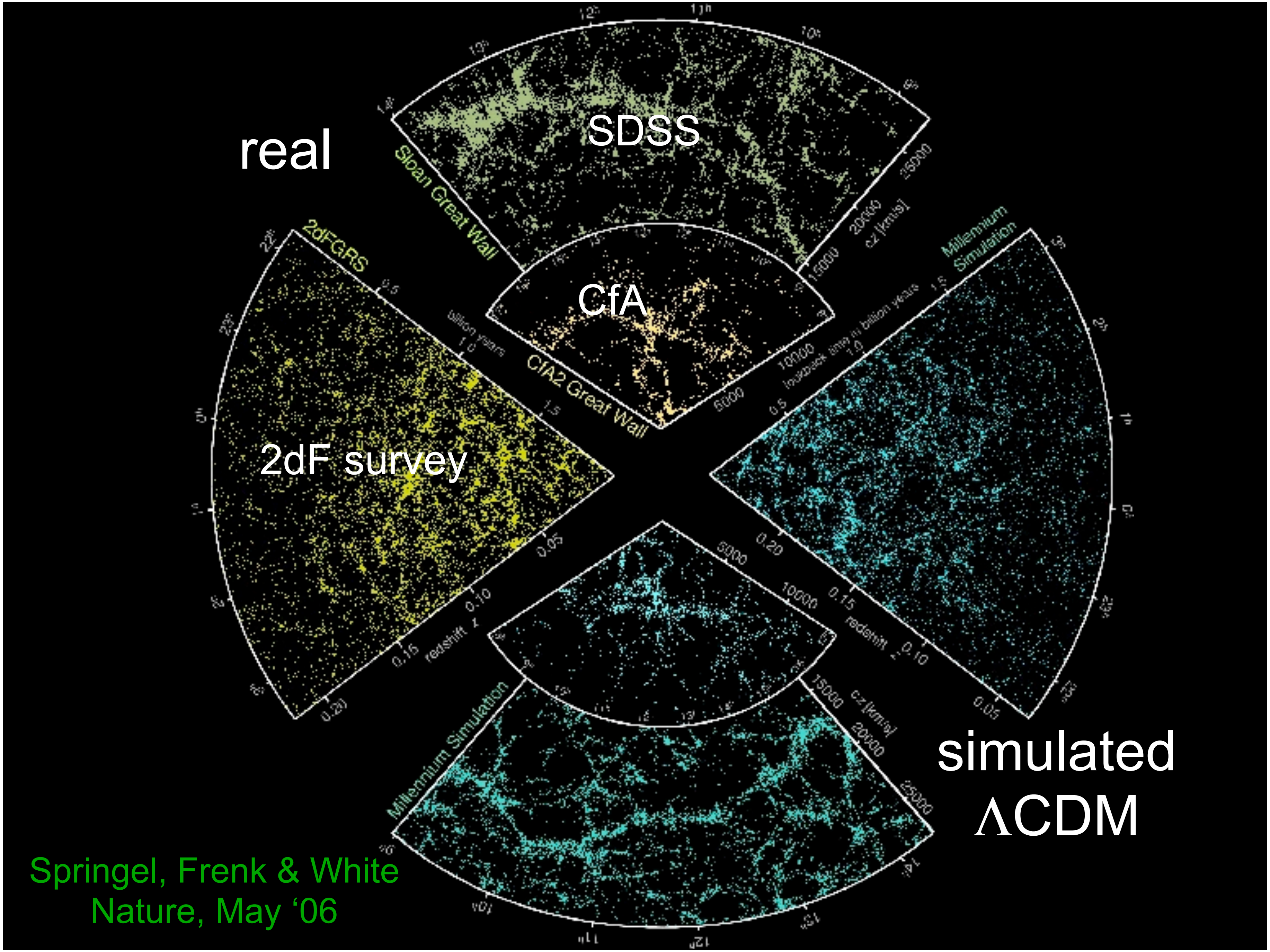

dalla Vechia,
Jenkins & Frenk
Comoving
coordinates
t = 0.06 Gyr
150 Mpc/h

QuickTime™ and a
3ivx D4 4.5.1 decompressor
are needed to see this picture.

Helly & Frenk 06

1 Mpc


The Millennium simulation
Springel et al Nature June/05


real
SDSS
Sloan Great Wall
CfA
CfA2 Great Wall
2dFGRS
2dF survey
Millennium Simulation
Millennium Simulation
simulated
ΛCDM
Springel, Frenk & White
Nature, May '06

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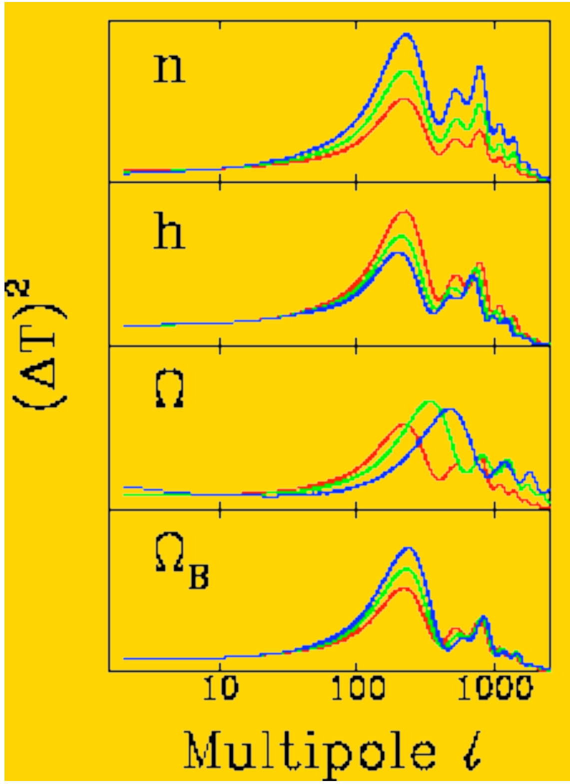
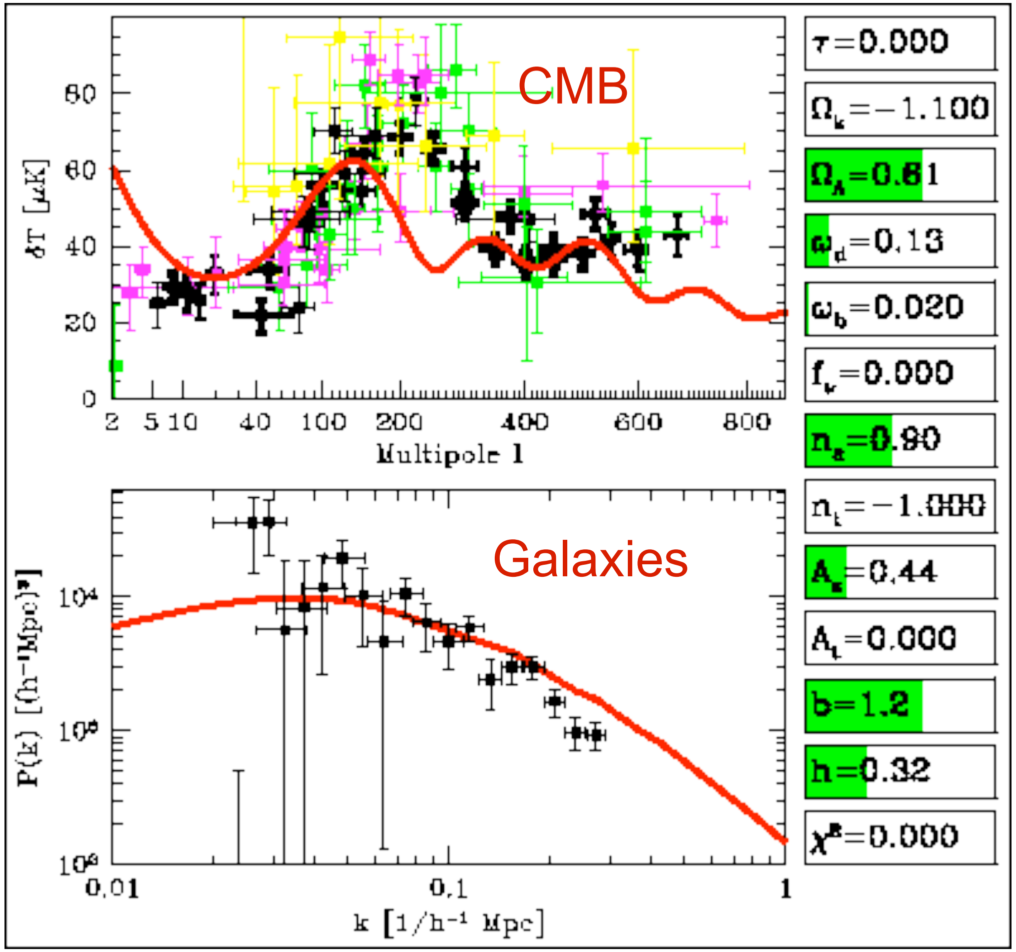
Dependence of ΔT/T on cosmological params





Max Tegmark

Cosmological parameters from WMAP+2dFGRS

Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$	$n_s = 0.93^{+0.03}_{-0.03}$
$w < -0.78$ (95% CL)	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$ Accelerated expansion	$r < 0.71$ (95% CL)
$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$	$z_{dec} = 1089^{+1}_{-1}$
$\Omega_b = 0.044^{+0.004}_{-0.004}$	$\Delta z_{dec} = 195^{+2}_{-2}$
$n_b = 2.5 \times 10^{-7}\,^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}	$h = 0.71^{+0.04}_{-0.03}$
$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$	$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr
$\Omega_m = 0.27^{+0.04}_{-0.04}$	$t_{dec} = 379^{+8}_{-7}$ kyr
$\Omega_\nu h^2 < 0.0076$ (95%CL)	$t_r = 180^{+220}_{-80}$ Myr (95% CL)
$m_\nu < 0.23$ eV (95% CL)	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K	$z_{eq} = 3233^{+194}_{-210}$
$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}	$\tau = 0.17^{+0.04}_{-0.04}$
$\eta = 6.1 \times 10^{-10}\,^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$	$z_r = 20^{+10}_{-9}$ (95% CL)
$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$	$\theta_A = 0^\circ.598^{+0.002}_{-0.002}$
$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$	$l_A = 301^{+1}_{-1}$
$A = 0.833^{+0.086}_{-0.083}$	$r_s = 147^{+2}_{-2}$ Mpc

Spergel etal '03

The cosmic power spectrum: from the CMB to the 2dFGRS

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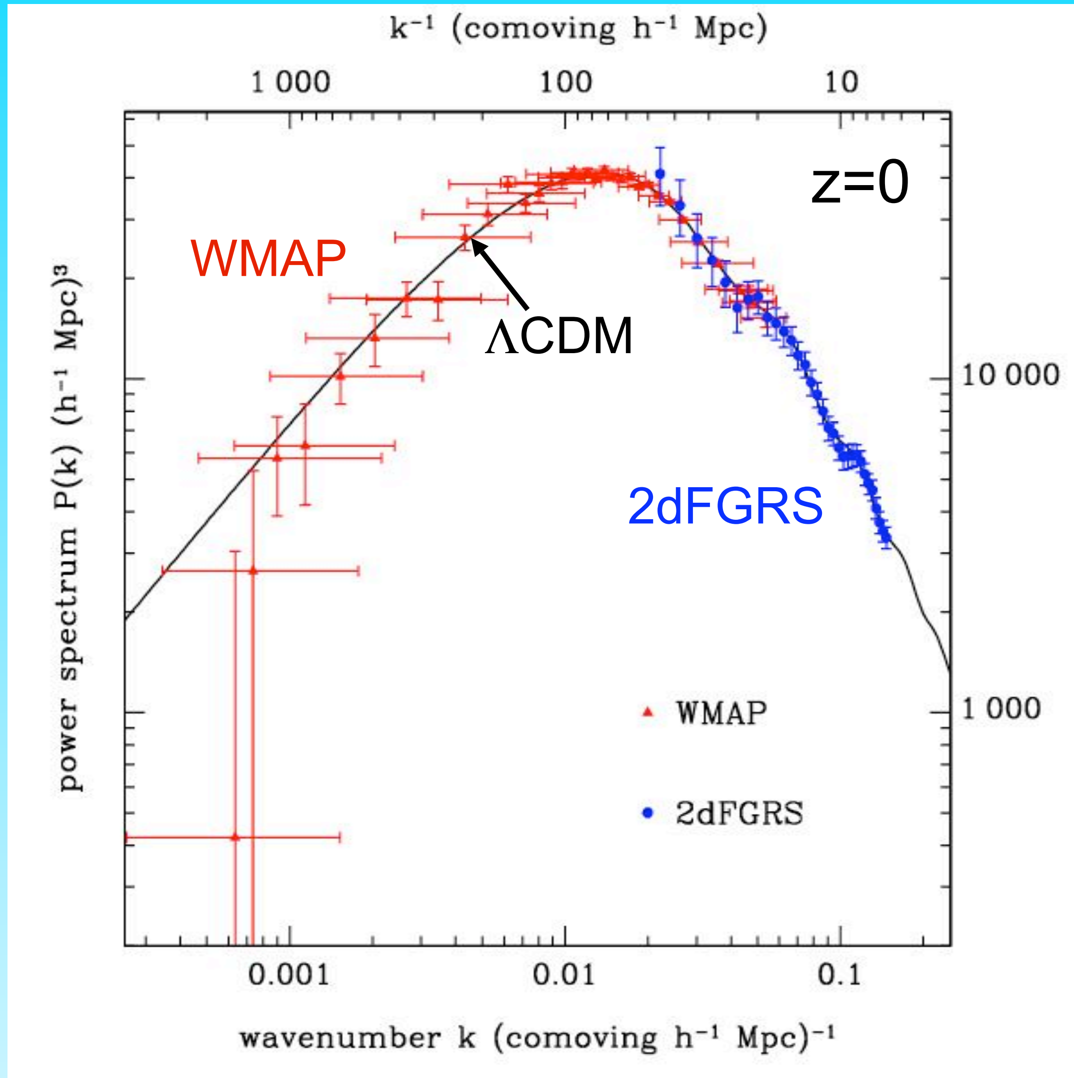
ΛCDM provides an excellent description of mass power spectrum from 10 -1000 Mpc

CMB:

- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory



Sanchez et al 06

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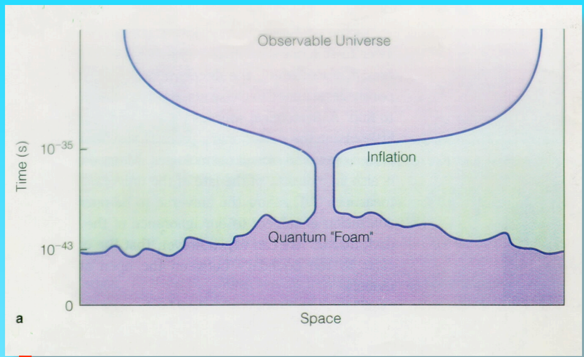
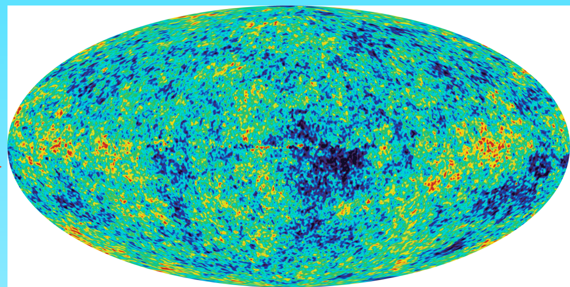
Conclusions
The origin of cosmic structure

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

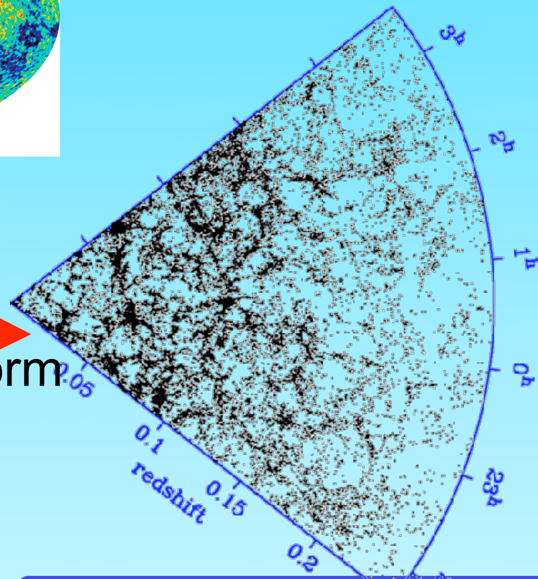


1. FLAT geometry:
2. Small (quantum) ripples

CMB ($t \sim 3 \times 10^5$ yrs)



Galaxies ($t \sim 13 \times 10^9$ yrs)



Cold dark matter

Ripples seen as hot & cold spots in cosmic radiation

Galaxies form

- Recent measurements of fluctuations in the temperature of the microwave background confirm this paradigm.

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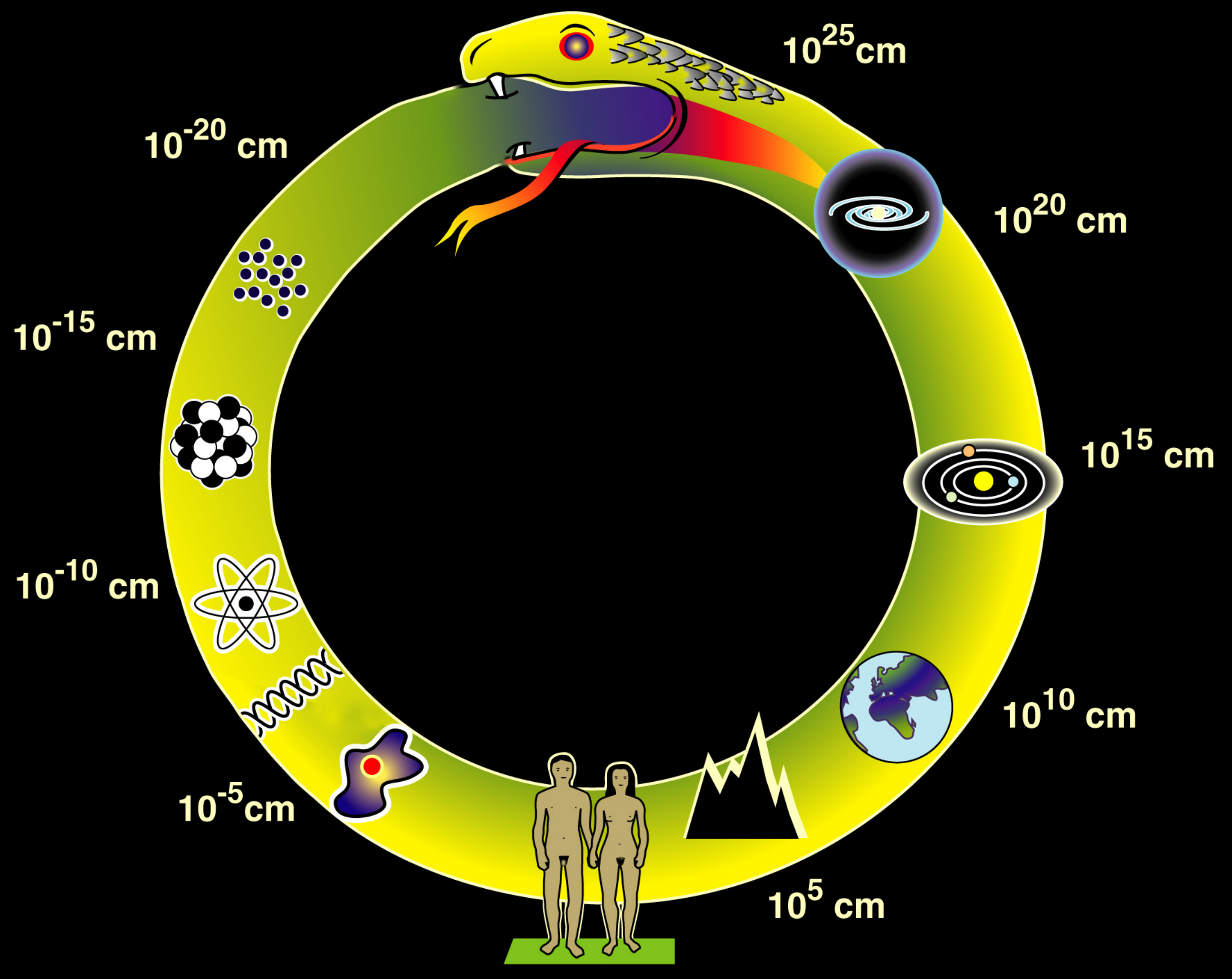

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Open questions

- What is the dark matter?
- What is the dark energy?
- What happened in the first 10^{-35}s after the Big Bang?
- How, in detail, did stars and galaxies form?
- How much farther will the simulations go?

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Open questions

Tools:

- Satellites to study the CMB & distant galaxies
- Large telescopes
- Direct dark matter searches
- Particle accelerators (CERN)
- Supercomputer simulations

Ideas:

- Theoretical physics & mathematics

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The paradigm of structure formation

ΛCDM

- Material content:
- Initial conditions:
- Growth processes:
- Parameters:

Cold dark matter, baryons, Λ

From quantum fluctuations during inflation: $|\delta_k|^2 \propto k$; Gaussian ampl.

Gravitational instability;
gas (cooling, star formation, etc)

$$\Omega_{CDM} = 0.26, \Omega_b = 0.04, h = 0.70,$$

$$\Lambda / 3H_0^2 = 0.7, \sigma_8 = 0.9$$

→ Galaxies form hierarchically

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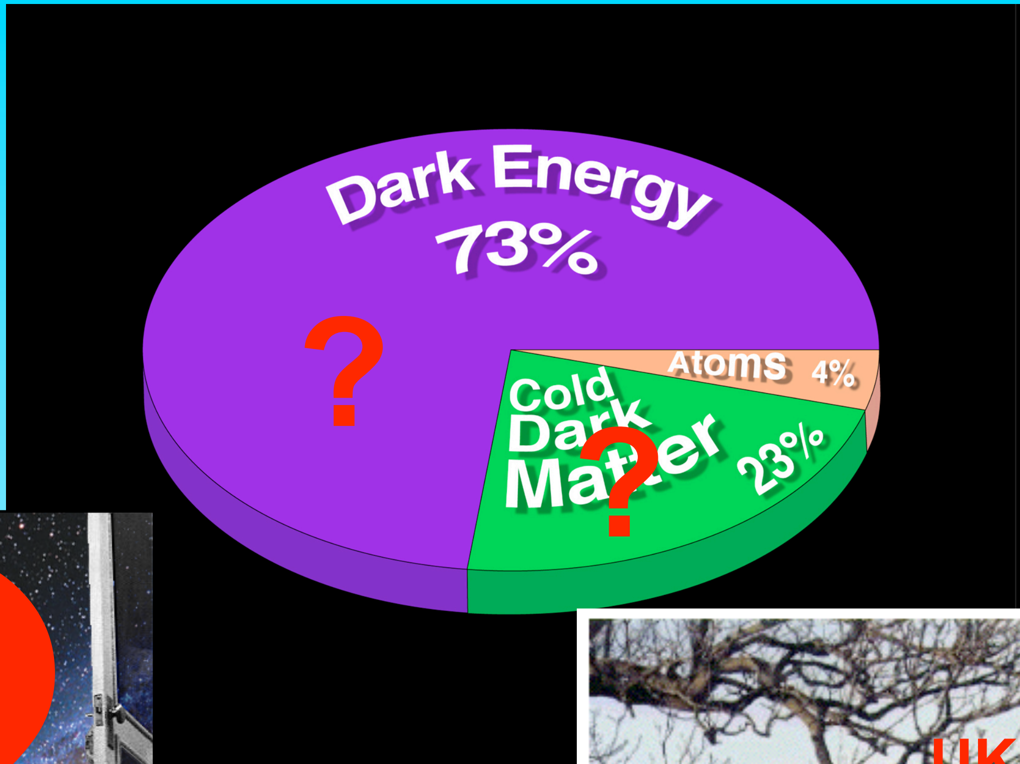
Conclusions: open questions



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The future of cosmology

Open questions:

➔ Detection (or manufacture) dark matter

➔ The origin of the dark energy ?

➔ The astrophysics of galaxy formation ?

- Direct searches for CDM (Boulby, CDMS, G Sasso)
- Constraints on w (high-z SN, lensing, high-z clustering)
- Surveys of galaxies at high-z (VLT, SIRTF, ALMA, NGST)
- Supercomputers simulations
- New ideas on w