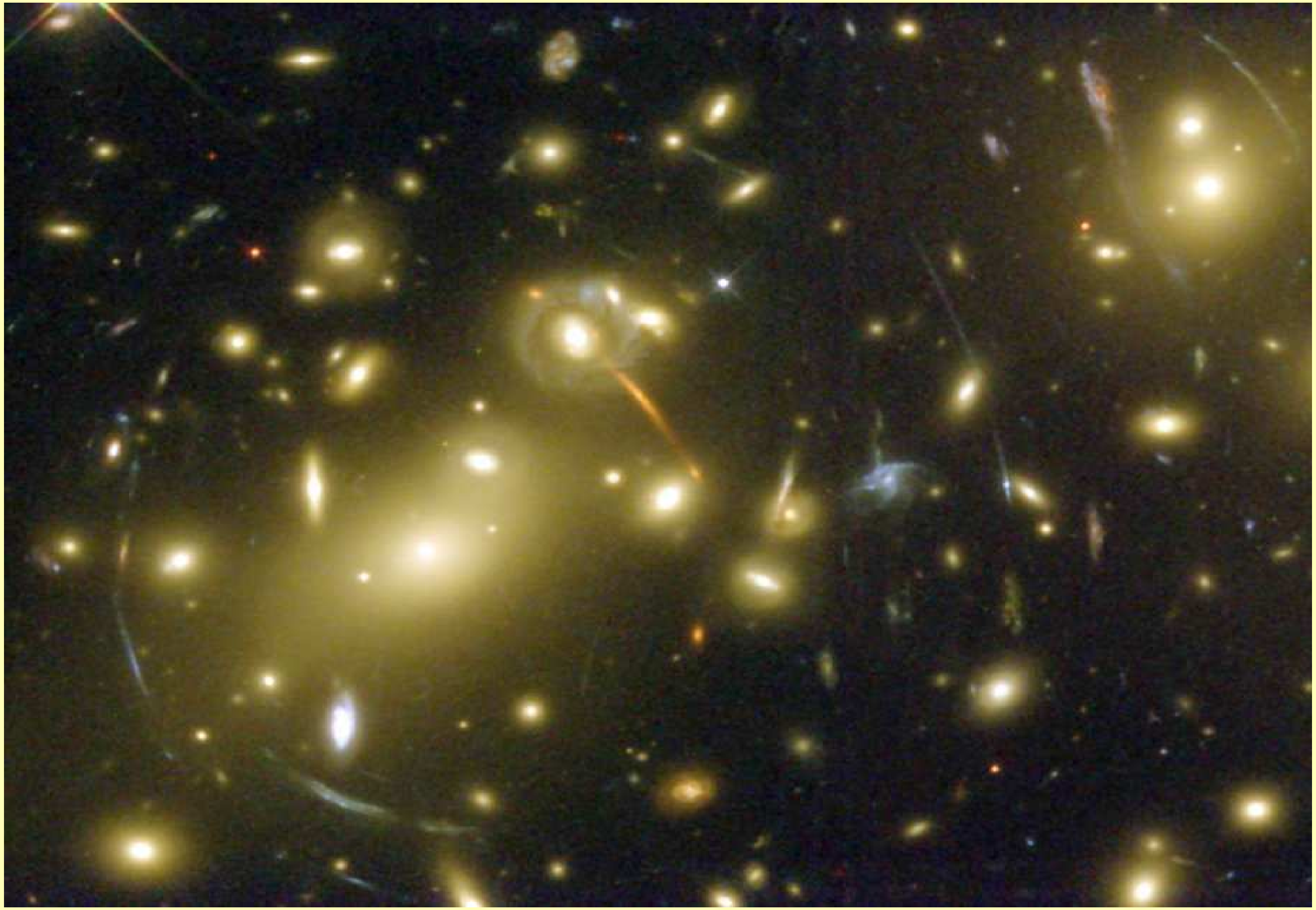
Dark Matter in cosmology



John Peacock Zuoz School August 2004

Outline

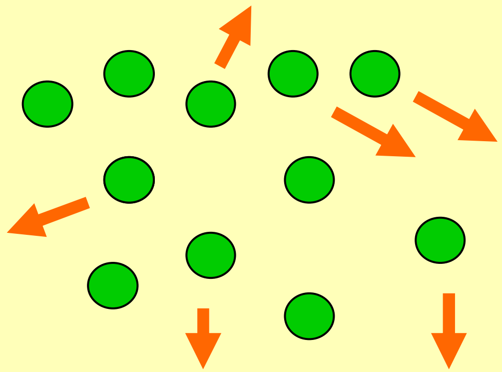
- Measuring masses in cosmology
  - Dynamics
  - Gravitational lensing
- Relic candidates for dark matter
  - Abundances, masses, ‘hot’ vs ‘cold’
- Dark matter & structure formation
  - The standard model
  - Limits on the nature of dark matter

Cosmology: jargon and notation

- **Expanding universe scale factor R(t)**
- **Hubble: $D \propto R(t) \Rightarrow v = (d \ln R / dt)\, D = H\, D$**
- **Friedmann equation** $$\dot{R}^2 - \frac{8\pi G}{3}\rho R^2 = -kc^2$$
- **Critical density for k=0**
- **Density parameter Ω = density / critical**
- **Ω for baryons, dark matter, radiation, vacuum**
- **$\Omega_m = \Omega_{baryons} + \Omega_{dark}$ (= 0.26 ± 15%)**
- **Inflation $\Rightarrow$ k=0 $\Rightarrow \Omega_m + \Omega_v = 1$**
- **$h = H_0 / 100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ (=0.72 ± 5%)**

Dynamical masses

- $v^2 = GM / r$
- Zwicky (1933): Coma cluster of galaxies contains >10x more mass than in the visible stars

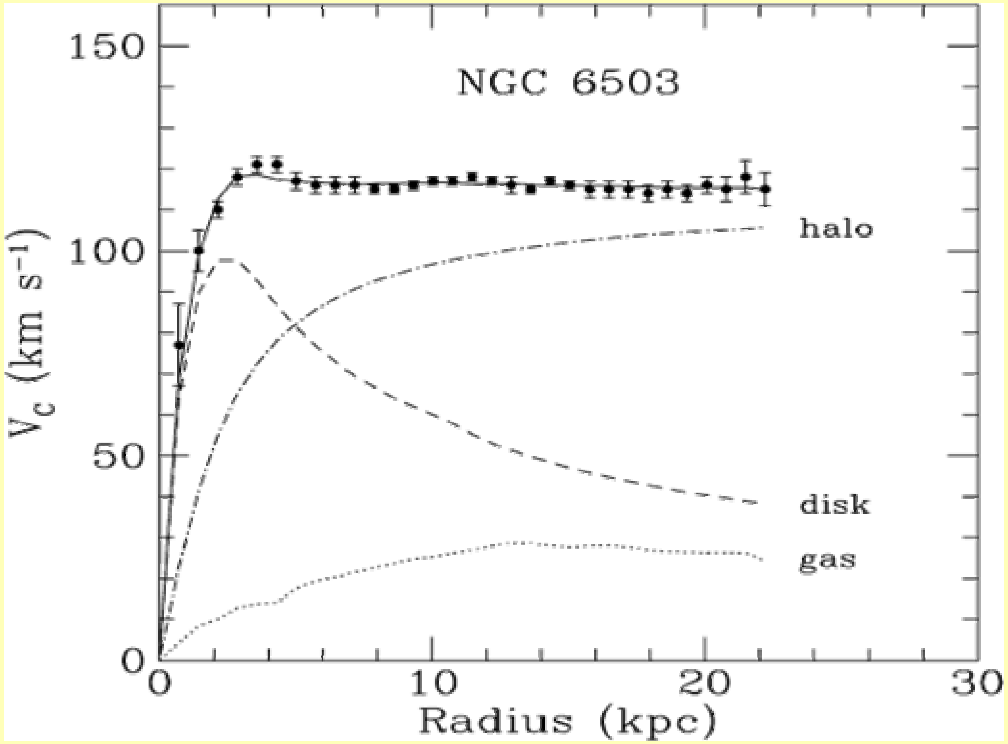


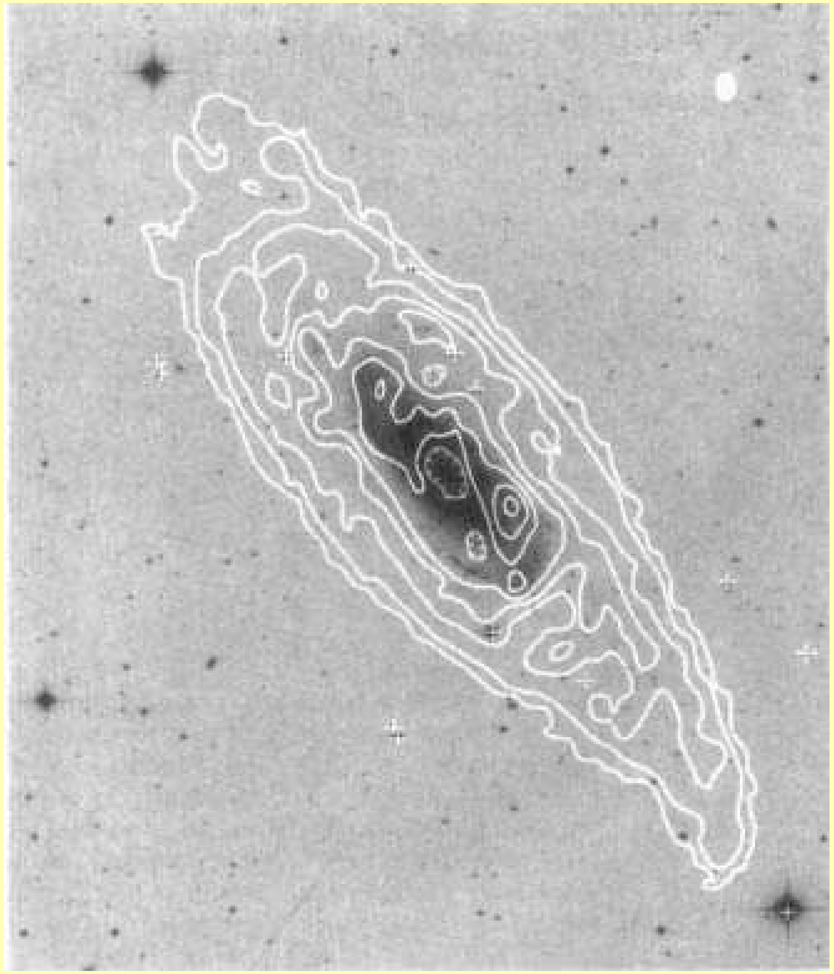
line-of-sight v from Doppler

- Quantify by mass-to-light ratio, where Sun = 1 (so typical stellar systems have M/L = 5 – 10). Best number for Coma is now about 300h

70s/80s: Galaxy Dark Matter haloes

- Observe flat galaxy rotation curve using Doppler shifts in 21 cm line from hyperfine splitting
- Halo: $M(<r) \propto r \Rightarrow \rho(r) \propto 1/r^2$
- M/L > 1000 in outer parts



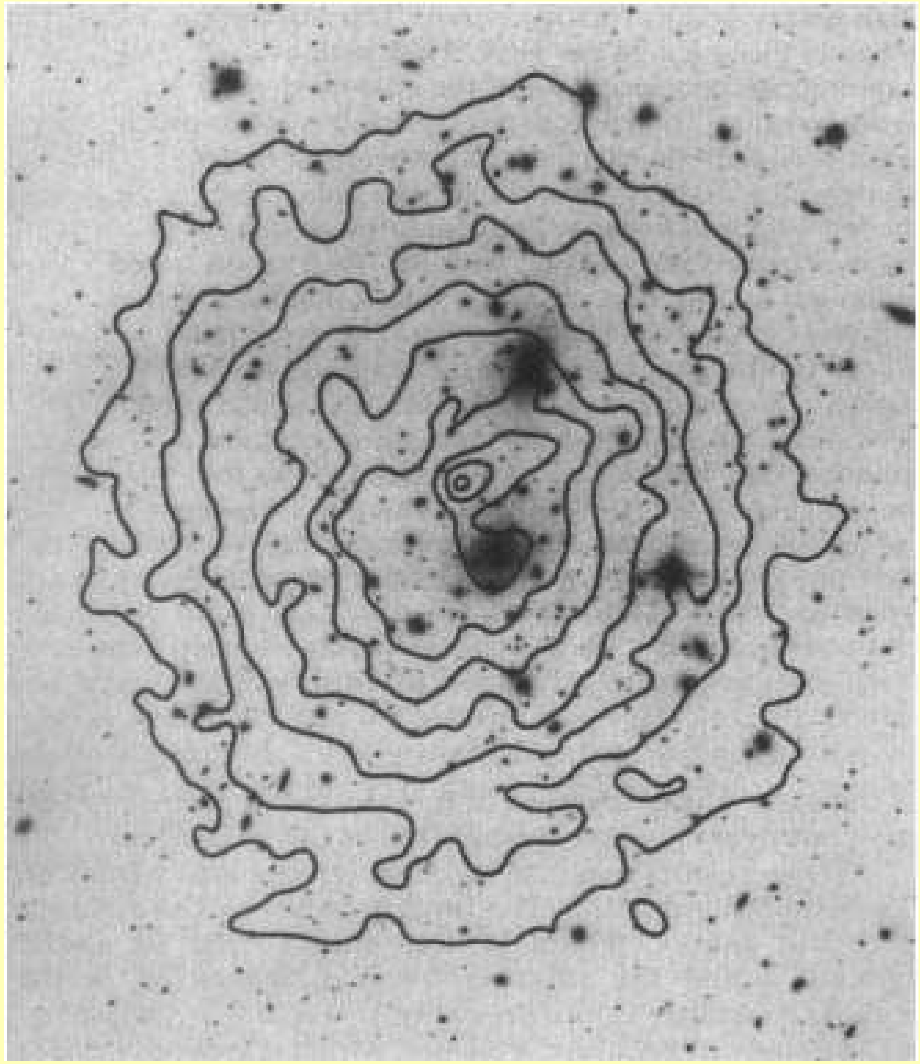


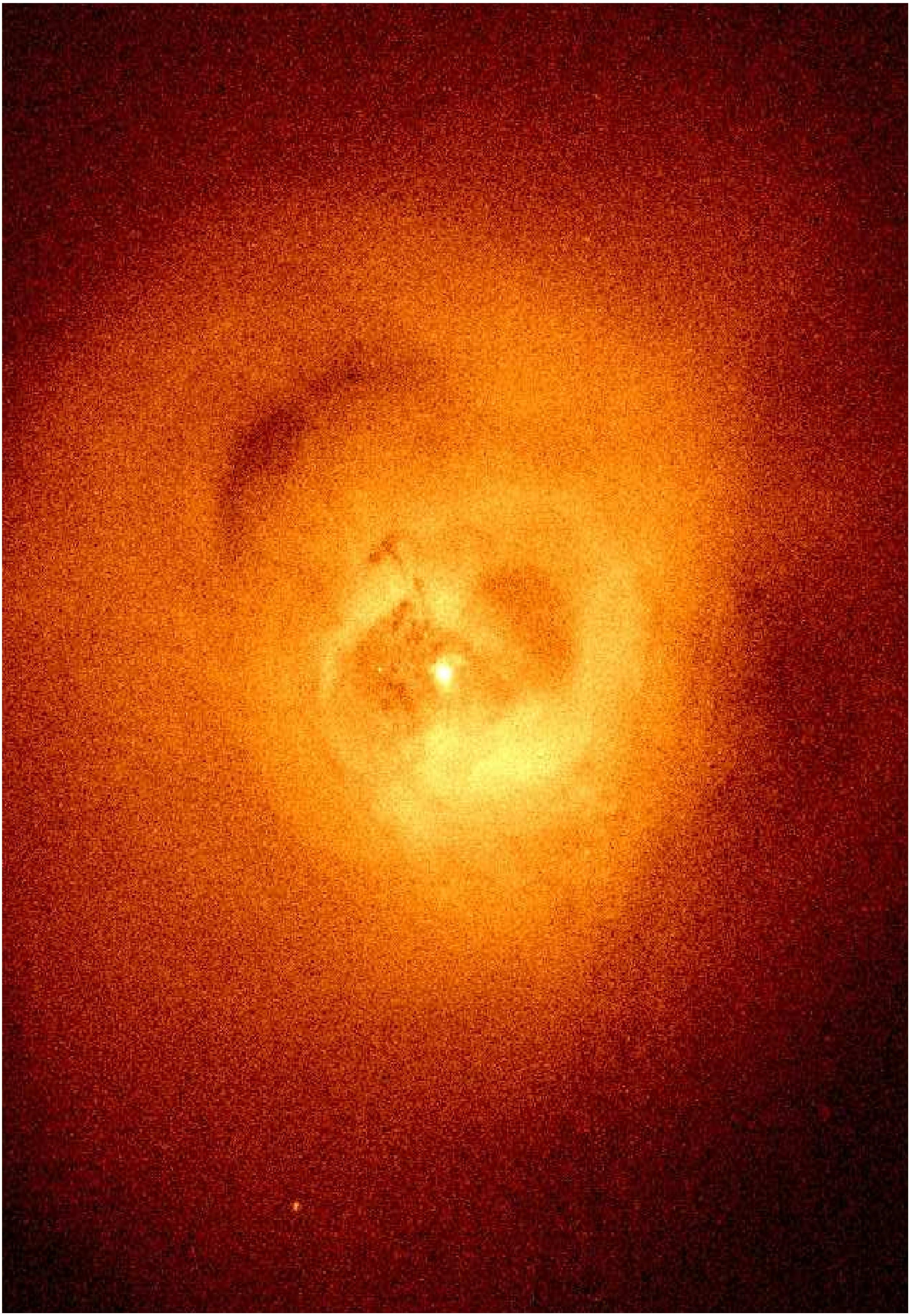
80s: Dark Matter in Galaxy Clusters from X-rays

- Intergalactic gas in deep potential is hot: X-rays
- Assume hydrostatic equilibrium gas confined by gravity
- Hence total mass: agrees with dynamics. M/L = 300h
- Can determine baryon fraction of the cluster

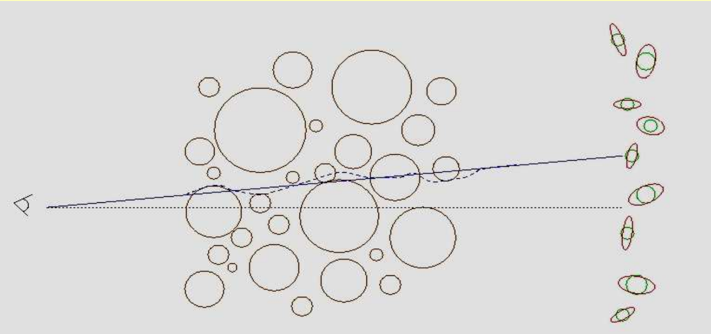
$$f_B h^{3/2} = 0.056 \pm 0.014$$

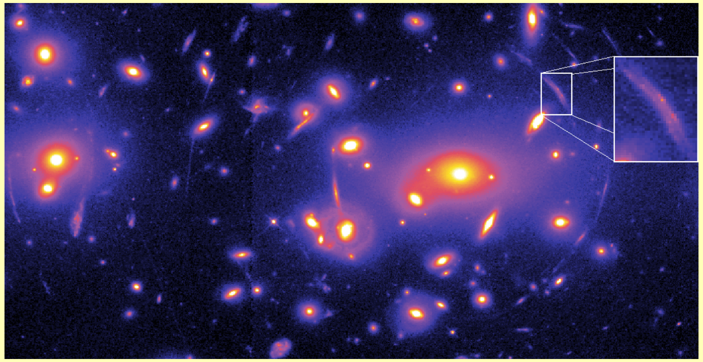
- Roughly DM : gas : stars = 100:10:1



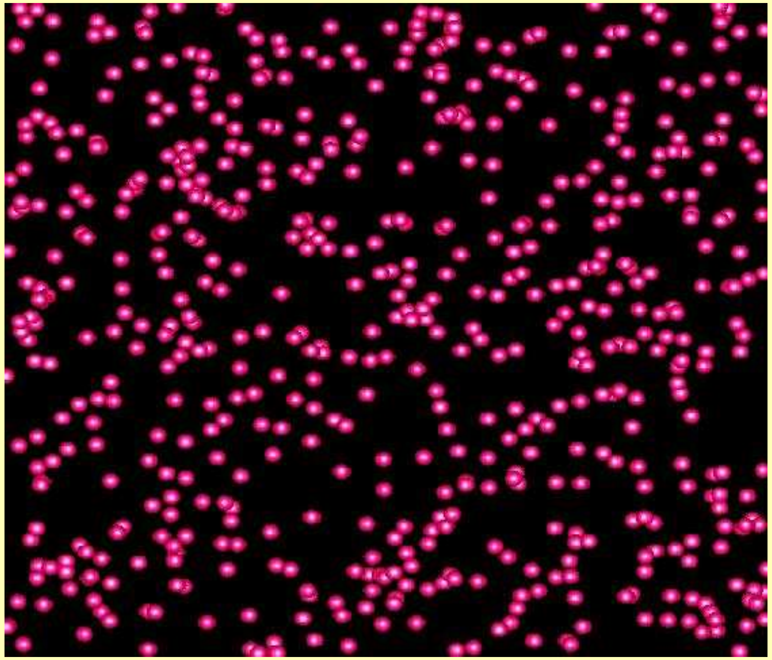


90s: Gravitational Lensing

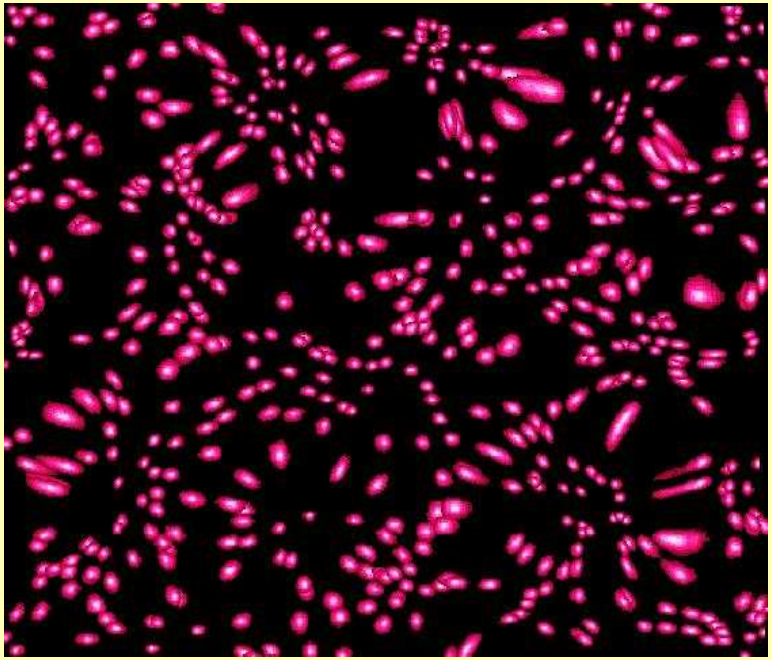




Distortion of background images by foreground matter

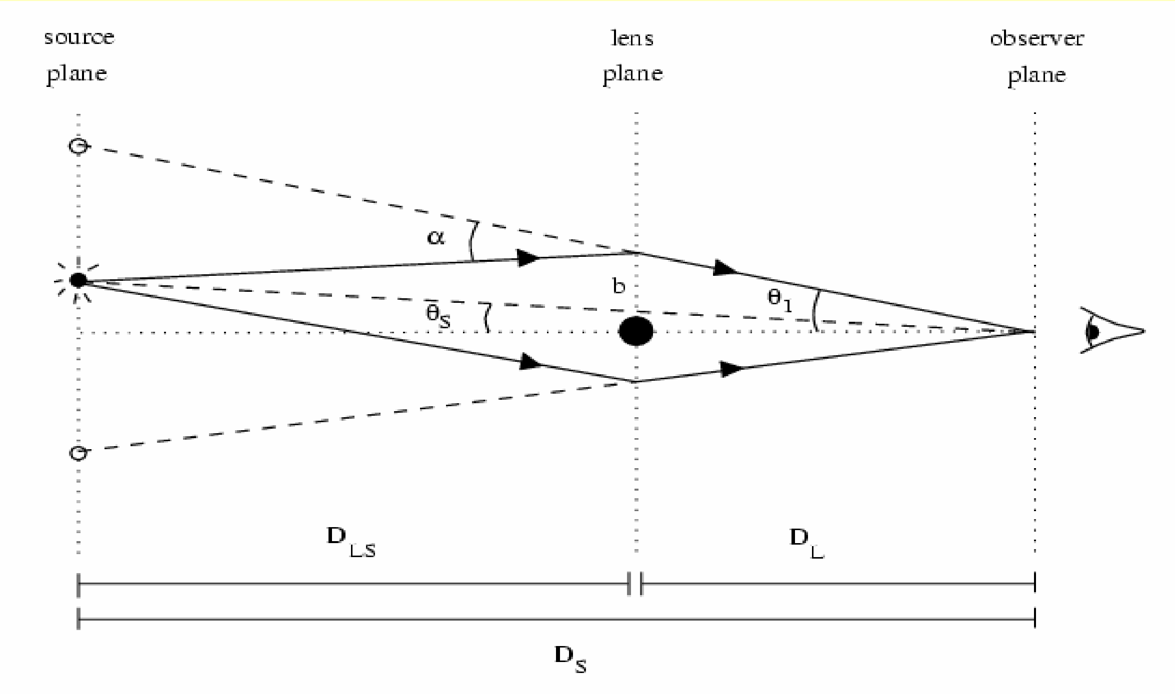


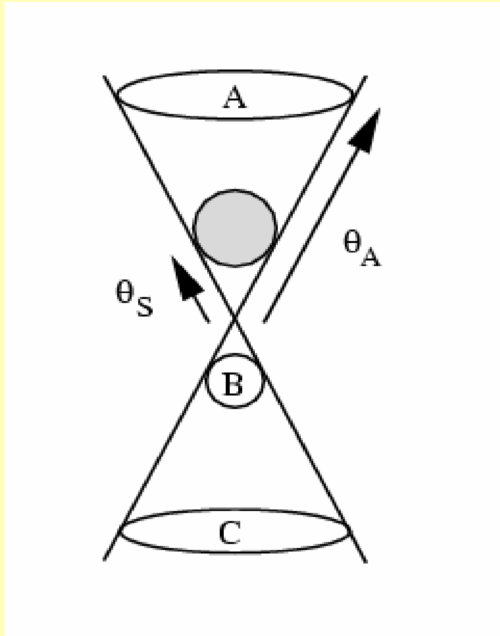
Unlensed



Lensed

Gravitational Lensing





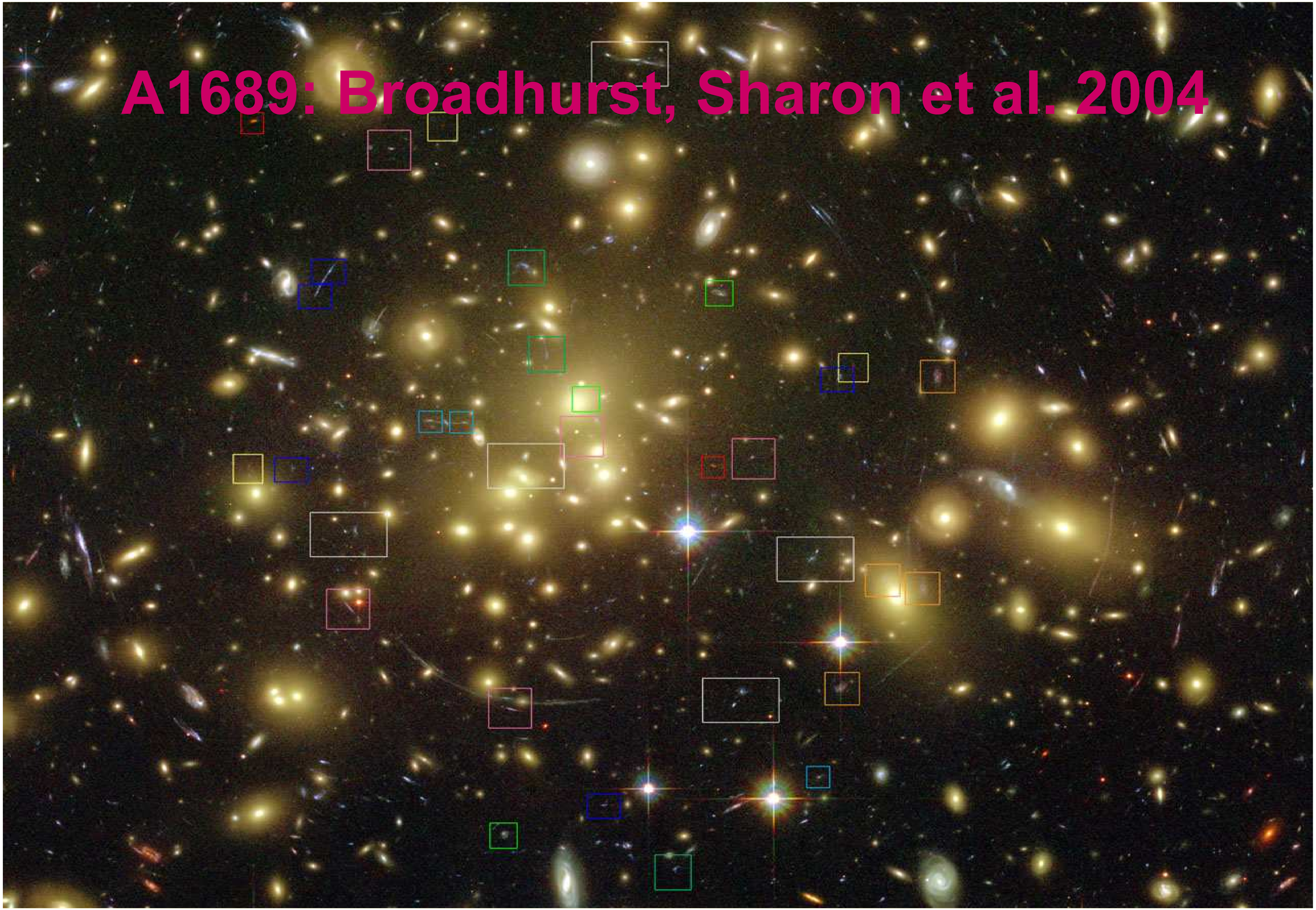
Relativistic factor 2 in deflection angle

$$\alpha = \frac{2}{c^2}\int a_\perp \, d\ell .$$

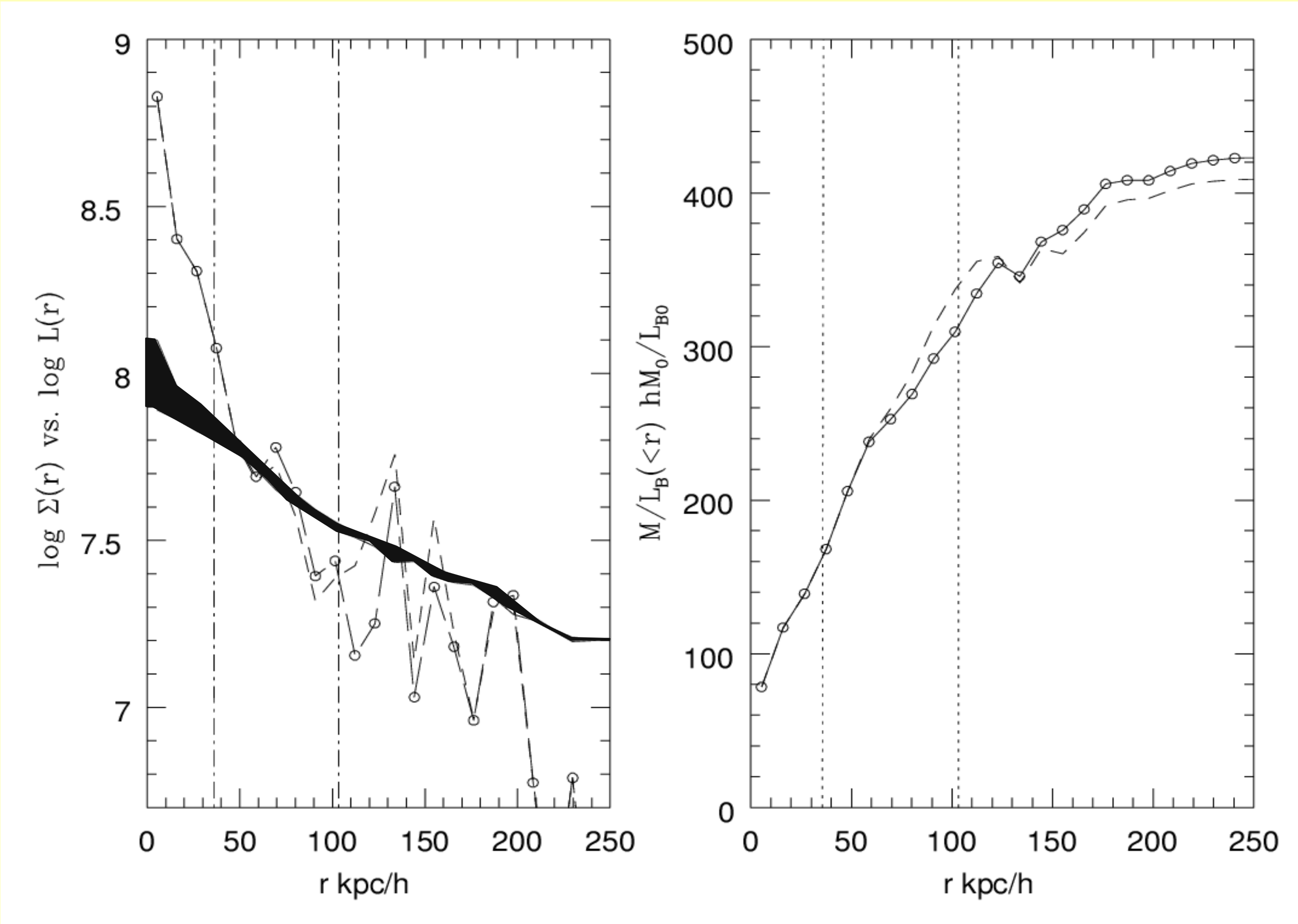
Einstein ring radius gives robust measure of mass inside ring

$$\theta_E = \left(\frac{4GM}{c^2}\,\frac{D_{LS}}{D_L D_S}\right)^{1/2}$$

$$= \left(\frac{M}{10^{11.09} M_\odot}\right)^{1/2} \left(\frac{D_L D_S / D_{LS}}{\mathrm{Gpc}}\right)^{-1/2} \quad \text{arcsec.}$$


A1689: Broadhurst, Sharon et al. 2004

Comparison of Mass and Light



- Light profile steeper than mass
- Mass profile hardly affected by galaxy contribution even in centre
- Total M/L rises to ~400 h $(M/L)_\odot$
- Consistent with dynamical masses, but needs relativistic factor 2

Weighing the universe - I

L X M/L = M

Luminosity density X M/L = mass density

- Suggested Ω_m = 0.2 since 1970s
- but stellar populations in clusters will differ from elsewhere, so not watertight
- gave rise to term 'missing mass', i.e. apparently less than critical density
- But cluster stellar populations differ from average (redder galaxies)

Nature of Galactic Dark Matter

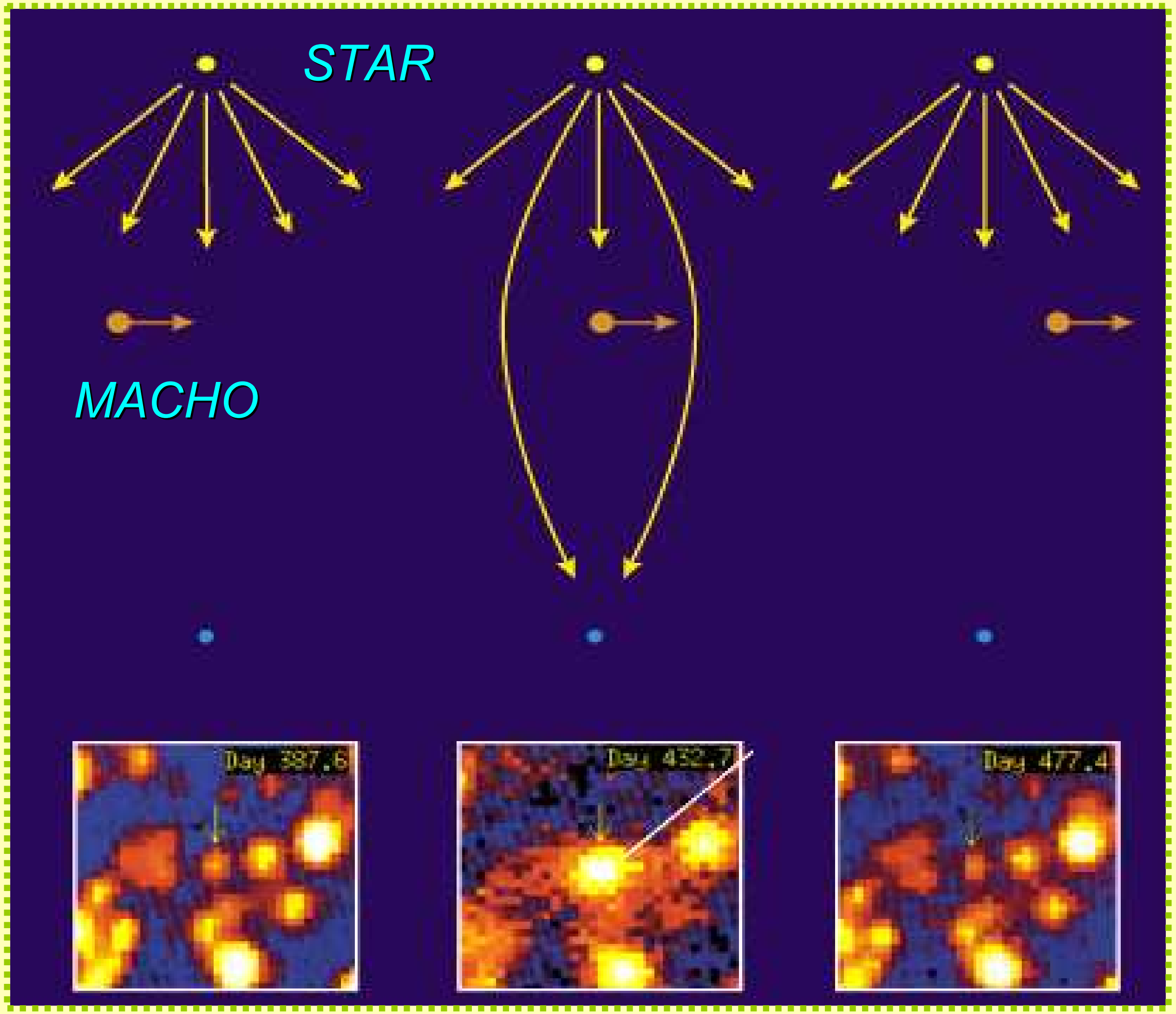
- Luminous matter (stars)

  $\Omega_{lum}h = 0.002 - 0.006$
- Non-luminous matter

  $\Omega_{gal} > 0.02 - 0.05$
- Lower bound because we don't know where the galaxy halos stop
- Could in principle be baryons
- Jupiters? Brown dwarfs?

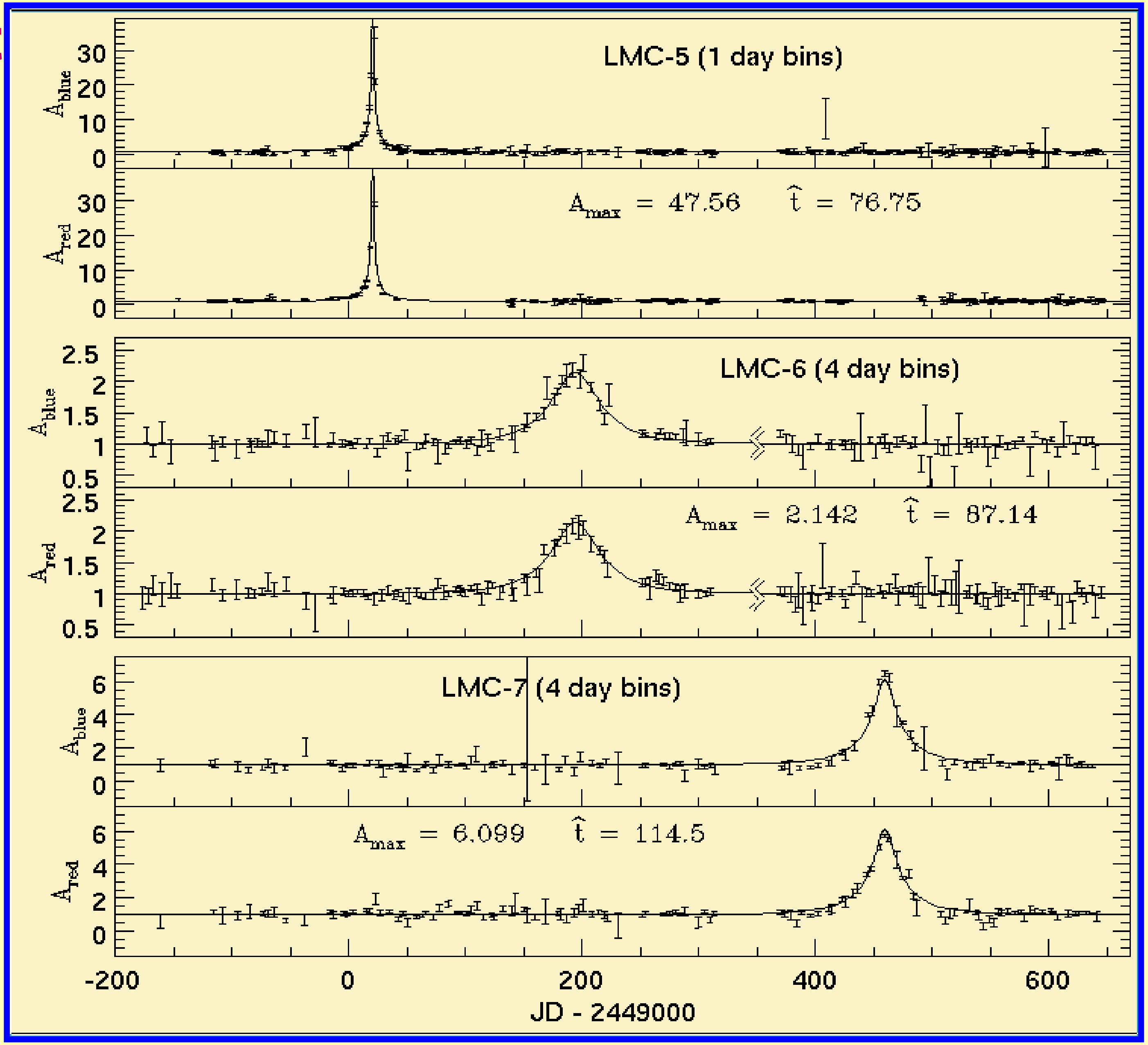
Massive Astrophysical Compact Halo Objects (MACHOs) and microlensing

- Use gravitational lensing
- When a MACHO moves in front of a star, gravitational focusing amplifies flux

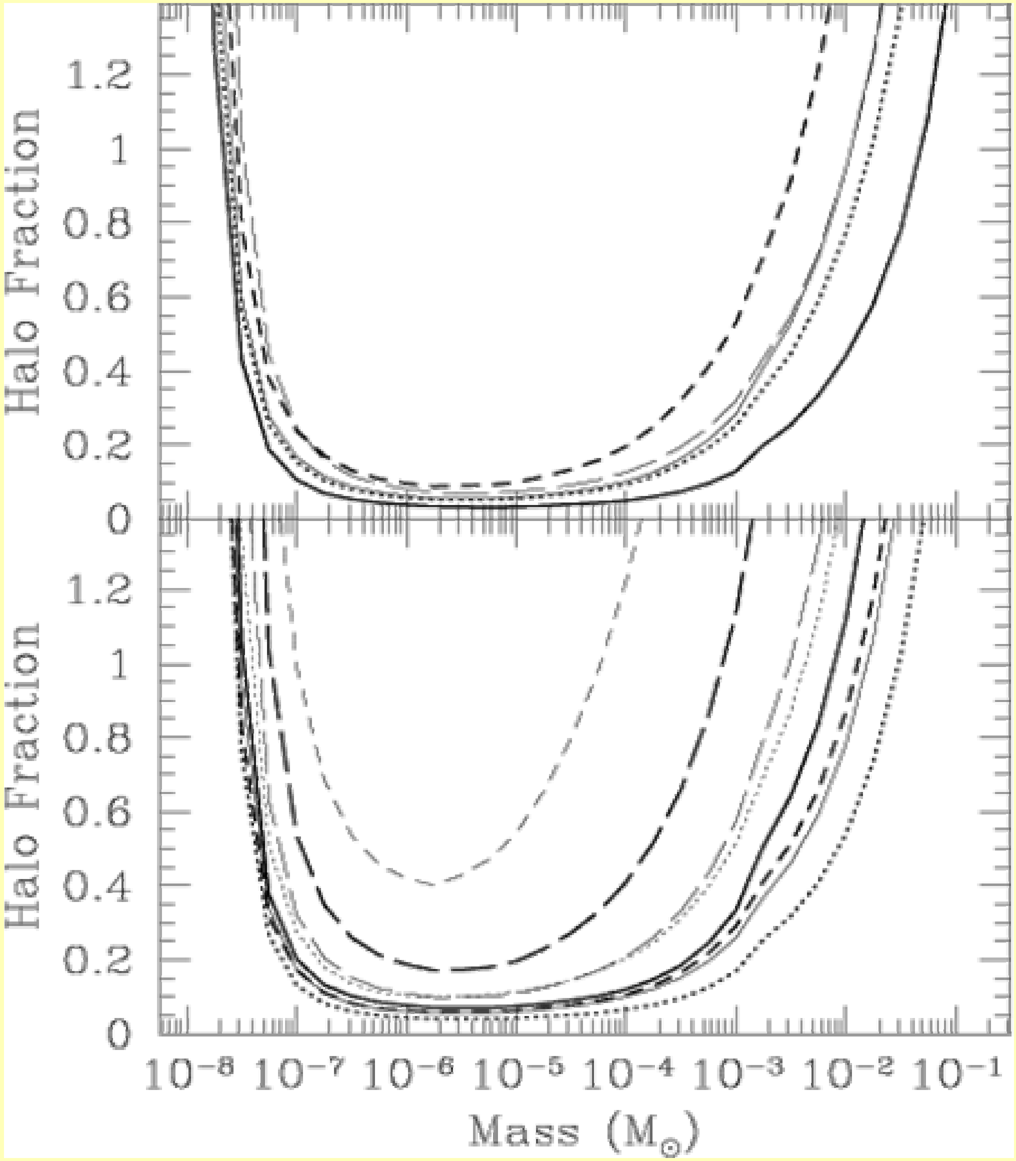


IACHO hunt result 2004

- MACHOs are detected
- But not enough to explain all dark matter



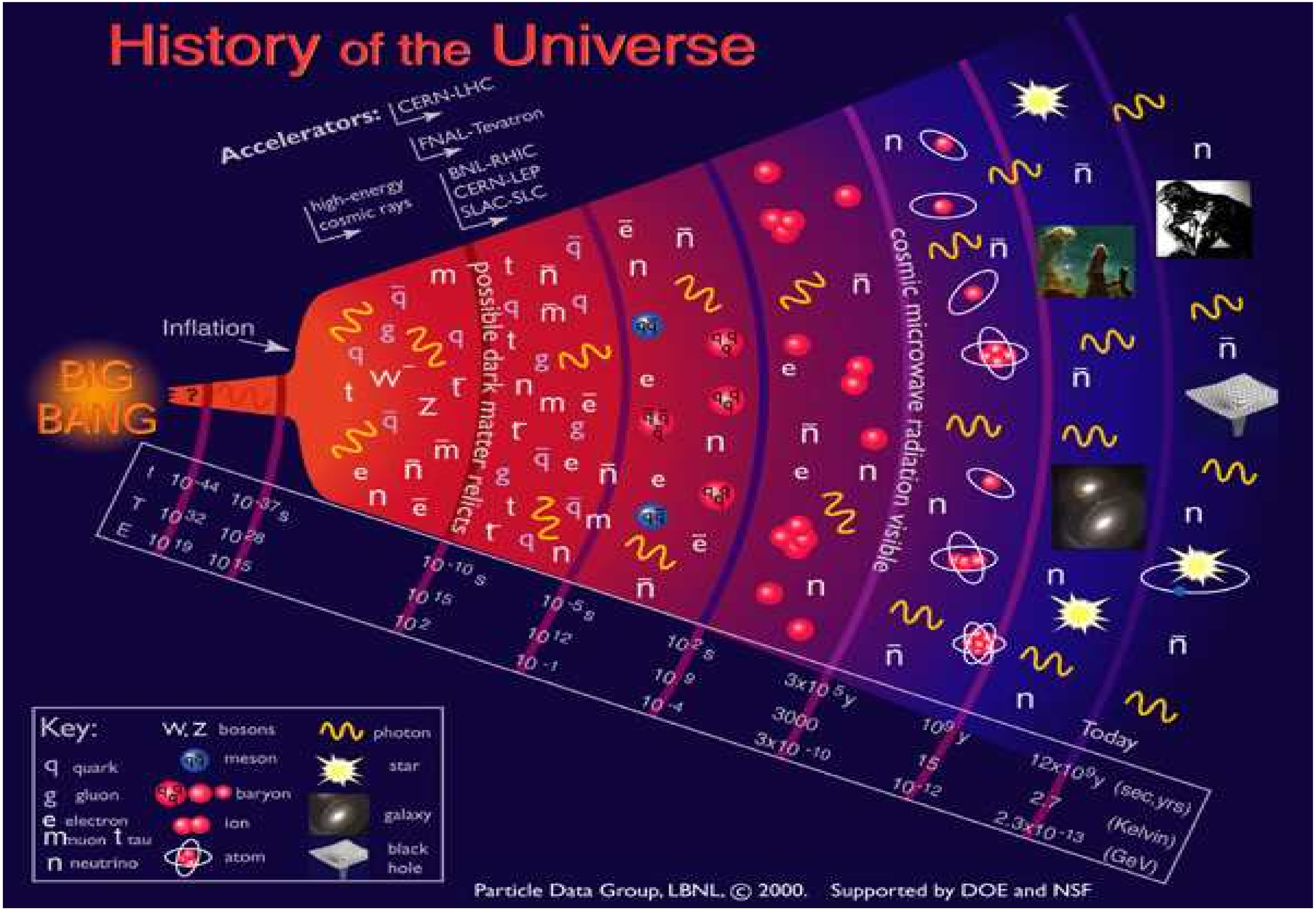
MACHO exclusion limits



Baryonic halo ruled out unless machos are of sub-planetary scale

Makes sense: the estimate of Ω_m = 0.2 is higher than the estimate of the primordial baryon density (see later)

$\Rightarrow$ **Nonbaryonic DM**


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

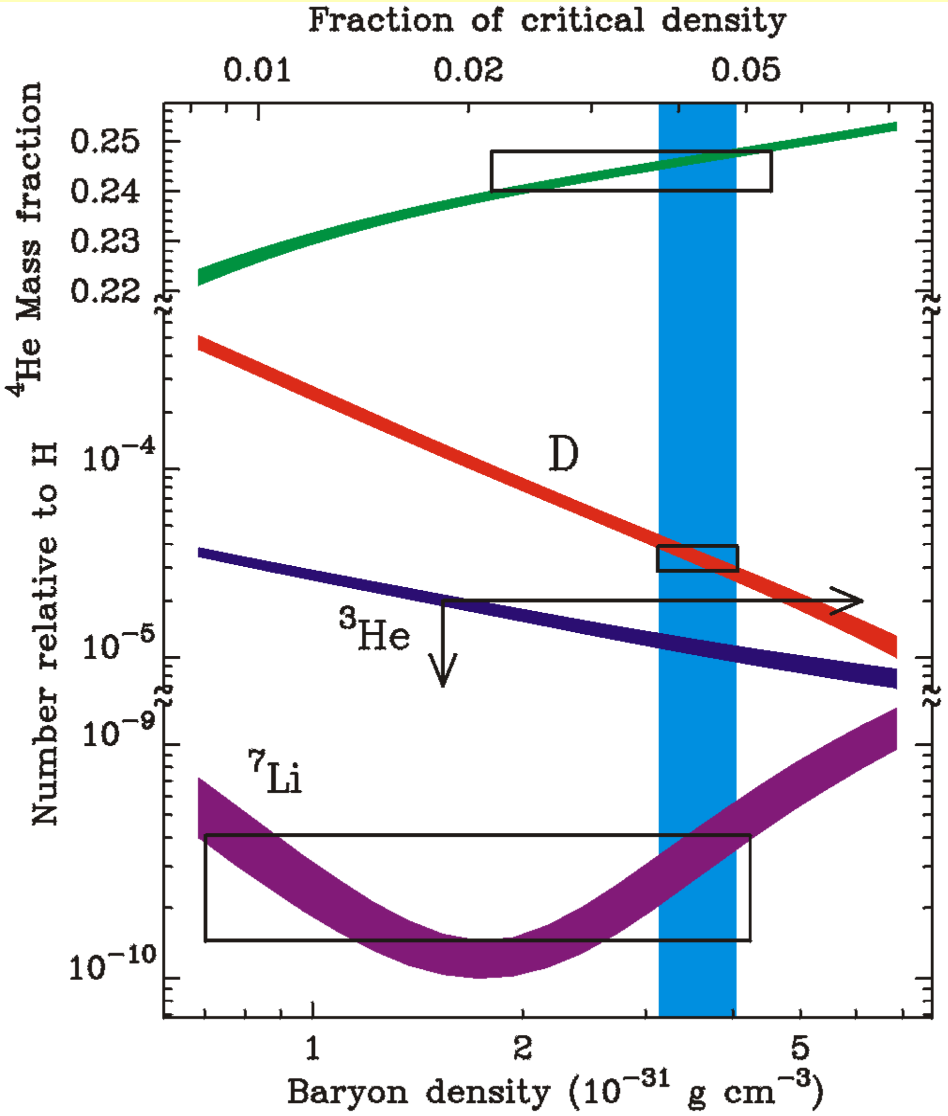
The thermal history of the universe

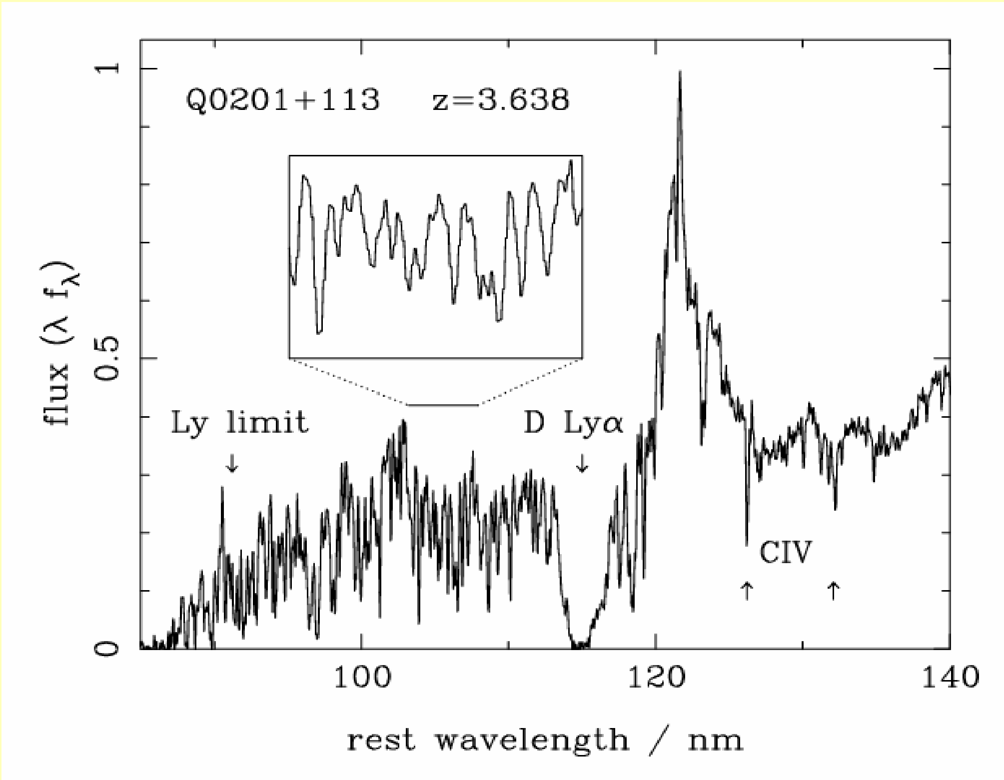
Event	T	redshift	time	size of today's universe
Now	2.73 K	0	13 Gyr	13×10^9 light-years
Distant galaxy	16 K	5	1 Gyr	7×10^9 light-years
Recombination	3000 K	1100	$10^{5.6}$ years	11×10^6 light-years
Radiation domination	9500 K	3500	$10^{4.7}$ years	4×10^6 light-years
Electron pair threshold	$10^{9.7}$ K	$10^{9.5}$	3 s	4 light-years
Nucleosynthesis	10^{10} K	10^{10}	1 s	1.3 light-years
Nucleon pair threshold	10^{13} K	10^{13}	$10^{-6.6}$ s	0.5 light-day
Electroweak unification	$10^{15.5}$ K	10^{15}	10^{-12} s	0.1 light-hour
Grand unification	10^{28} K	10^{28}	10^{-36} s	10^{-2} m
Quantum gravity	10^{32} K	10^{32}	10^{-43} s	10^{-6} m

At high enough T, pairs of particles & anti-particles exist in equilibrium

Note: still just a classical object at the highest energies we can imagine

Nucleosynthesis





Abundances set at t ~ 1 min

Measure D/H in intergalactic medium ⇒ $\Omega_b h^2$ = 0.022 ±10%

Thermal relics

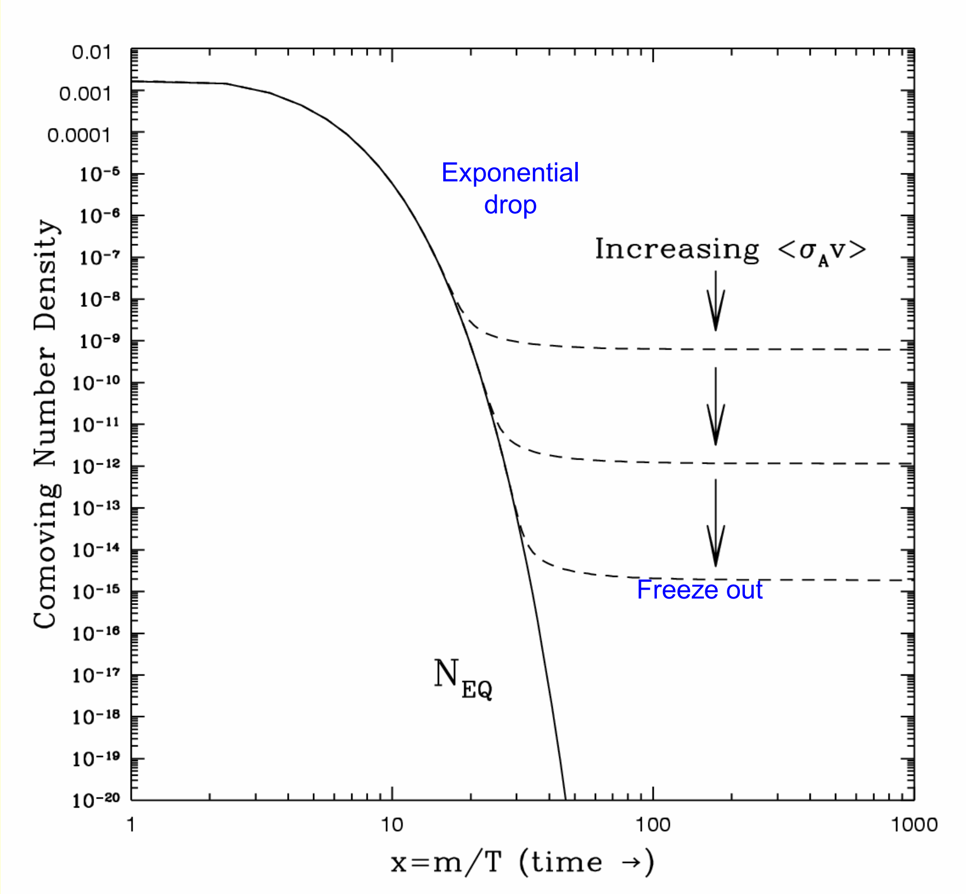
$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_T^2)$$

Boltzmann rate equation tries to maintain thermal equilibrium – but fails when reaction timescale exceeds 1/H: **Freezeout**

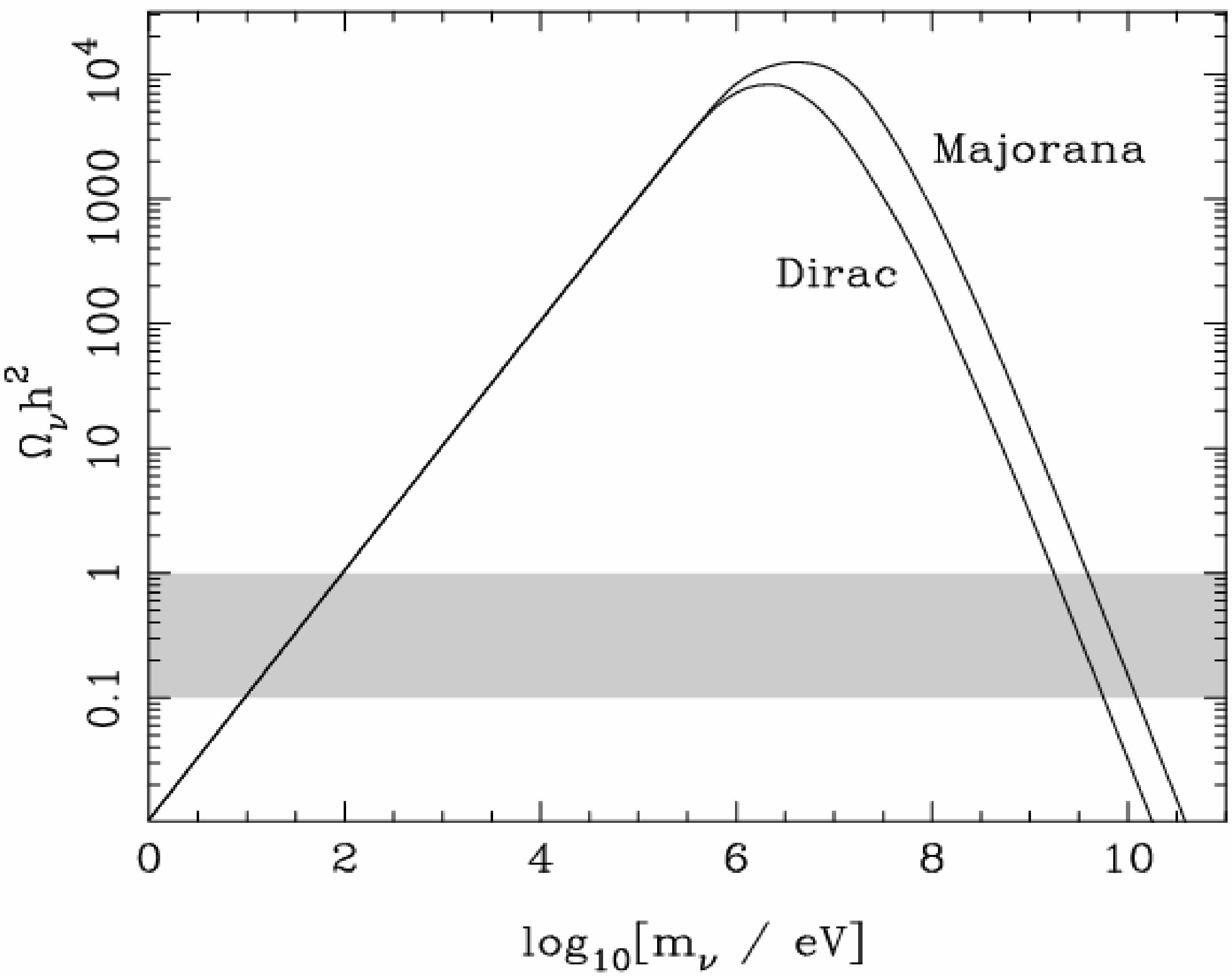
Two generic possibilities for when freezeout happens:

(1) relativistic: number density today ~ photon density)

(2) nonrelativistic: rarer than photons by $\exp(-mc^2/kT)$



Weakly Interacting Massive Particles (WIMPs)



(1) Hot Dark Matter (~10 eV) if neutrino

(2) Warm Dark Matter (~ keV) if freezeout very early

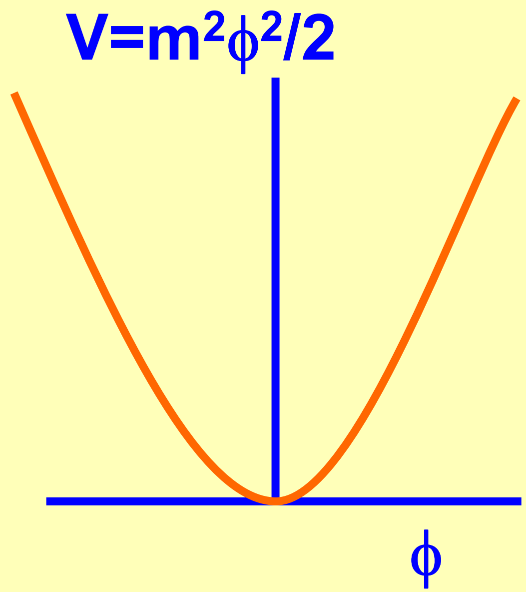
(3) Cold Dark Matter (~10 GeV) if nonrelativistic neutrino

(4) Or SUSY CDM with m ~ 1 TeV

hot to cold $\Rightarrow$ declining thermal velocities (important for structure formation)

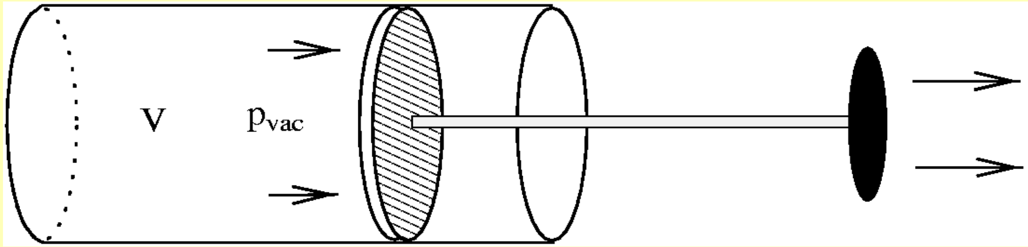
Or scalar-field condensate CDM?

$$\ddot{\phi} + m^2\phi = 0$$
$$\rho = \dot{\phi}^2/2 + V$$
$$P = \dot{\phi}^2/2 - V$$
$$\Rightarrow \langle P \rangle = 0$$



m can be anything until Compton length h/mc gets bigger than a galaxy (m > 10^{-22} eV)

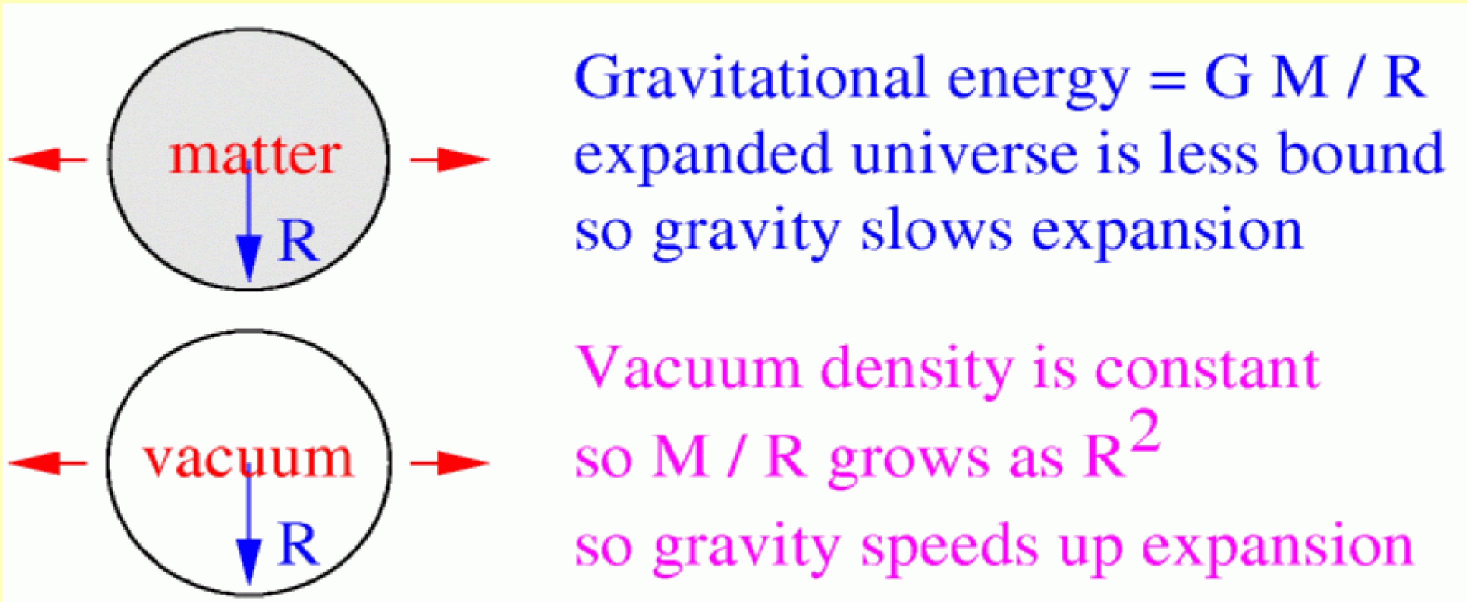
The missing ingredient: vacuum energy



Einstein: vacuum can have density if it has negative pressure:

Energy ρ c^2 V balances work - P V

This **'Dark Energy'** would cause the expansion of the universe to accelerate



Evidence for vacuum energy from distant supernovae

- SNe Ia look like stars superimposed on distant galaxies
- Very similar intrinsic properties, so get relative distances from apparent brightness

SN94D observed on a ground based telescope and with the Hubble Space Telescope.

SN Ia Hubble Diagram

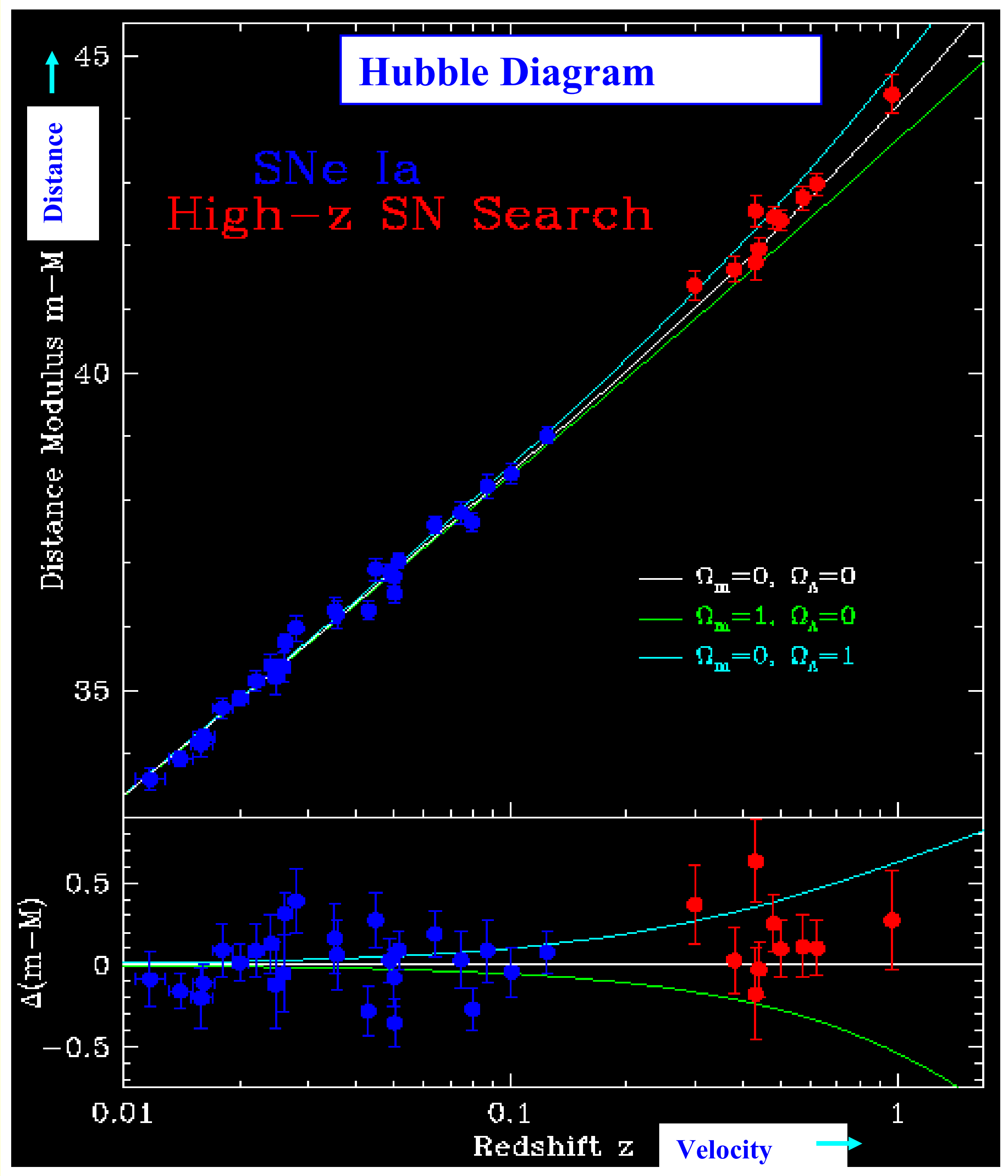
Distant supernovae are fainter than expected if the universe just contained normal matter:

The expansion must be accelerating, not slowing down

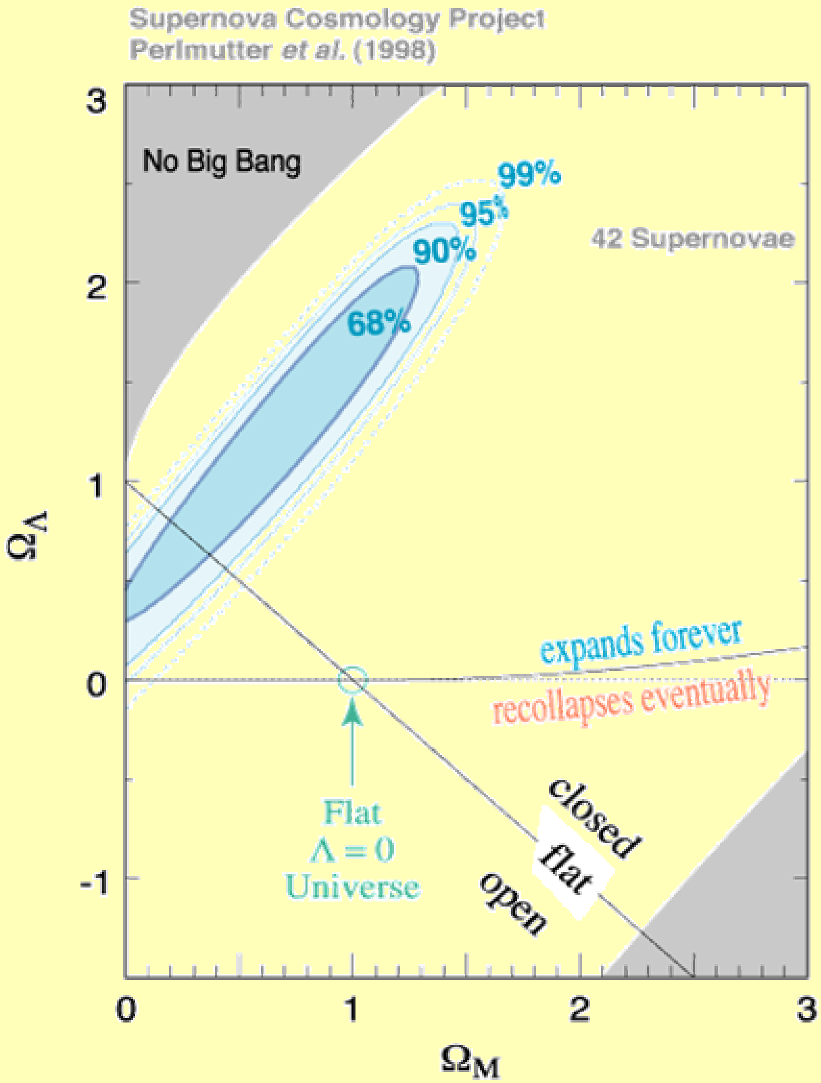
A flat vacuum-dominated universe:

$\Omega_{matter} = 0.3$

$\Omega_{vacuum} = 0.7$



Type IA Supernovae results



- Clear indication for “cosmological constant”
- Ω_m = 0.3 if flat
- Can in principle be something else with negative pressure
- With w = –P /ρ,
- Often generically called “Dark Energy”

$$\boxed{\rho \propto R^{-3(1+w)}, R \propto t^{2/3(1+w)}}$$

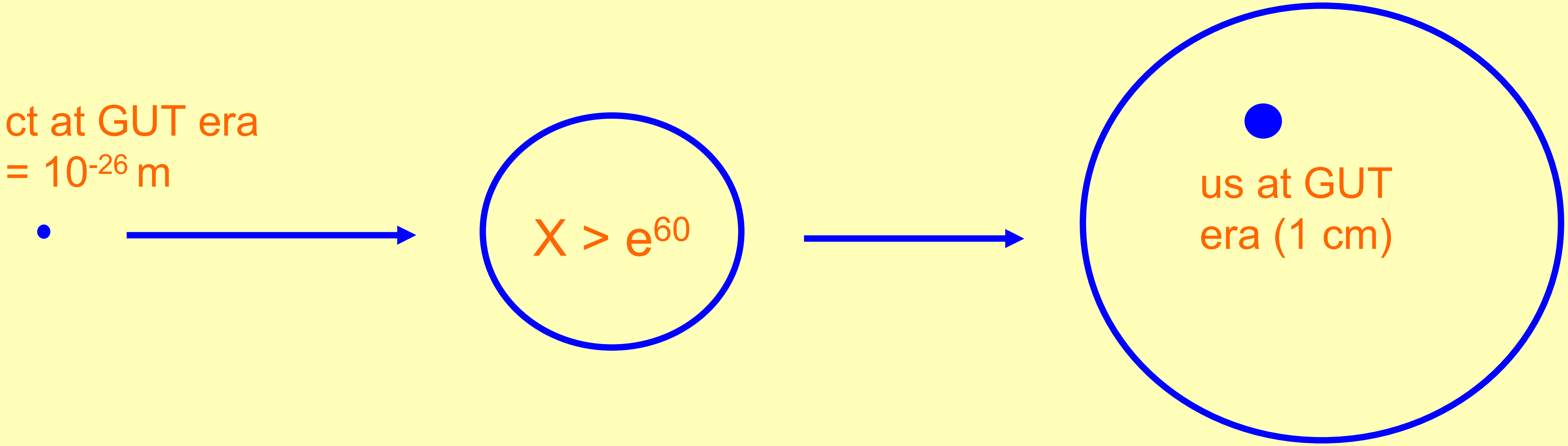
Alan Guth (1947 -)

The Inflationary universe (1981: long before vacuum energy was proved to exist today)

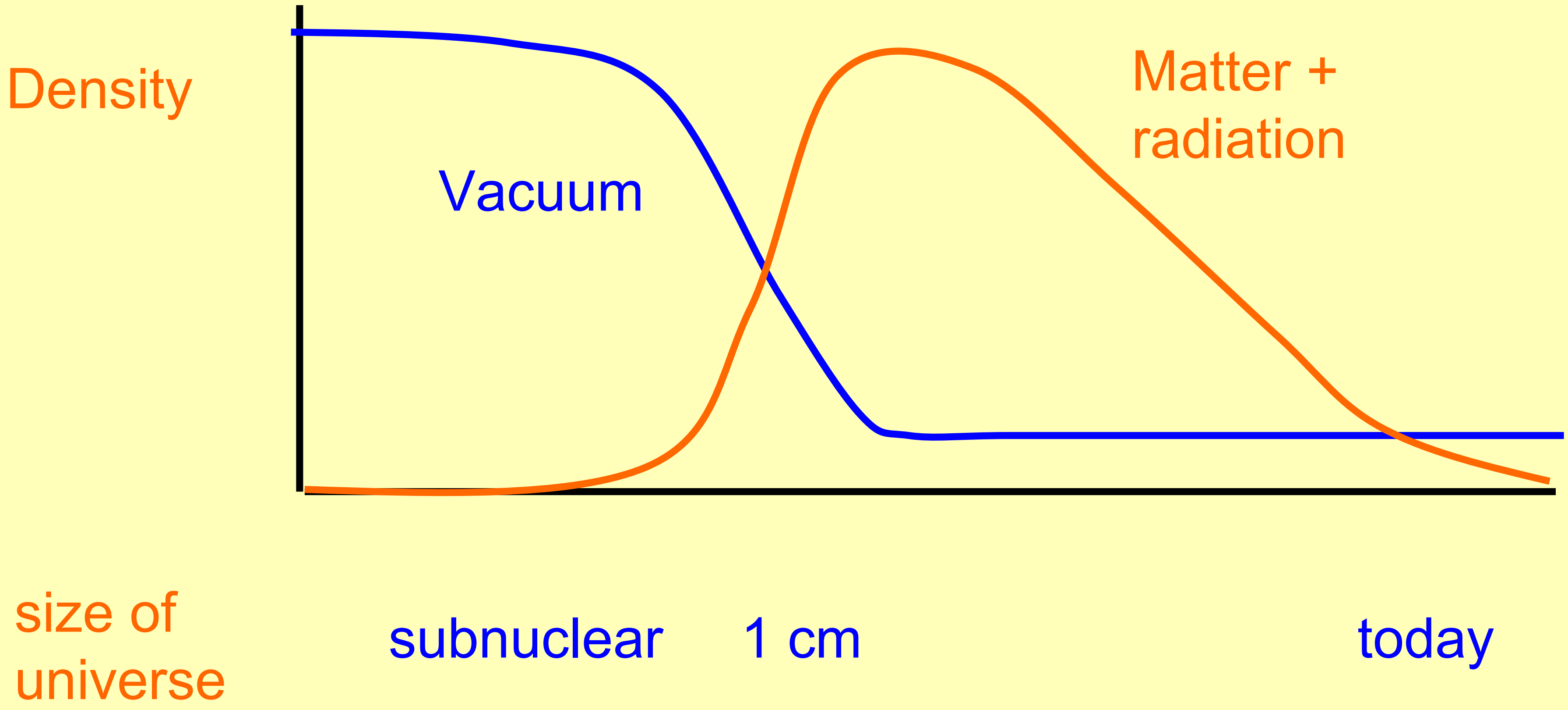
What if the vacuum density was much higher in the past?

(needs 10^{80} kg m^{-3} to dominate at the GUT era (10^{-26} today)

Antigravity can blow a big bubble from a subatomic patch



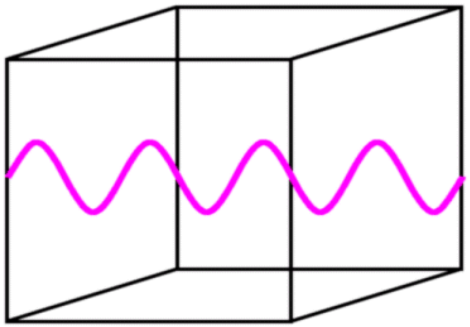
The History of the vacuum?



variable vacuum from a new scalar field?

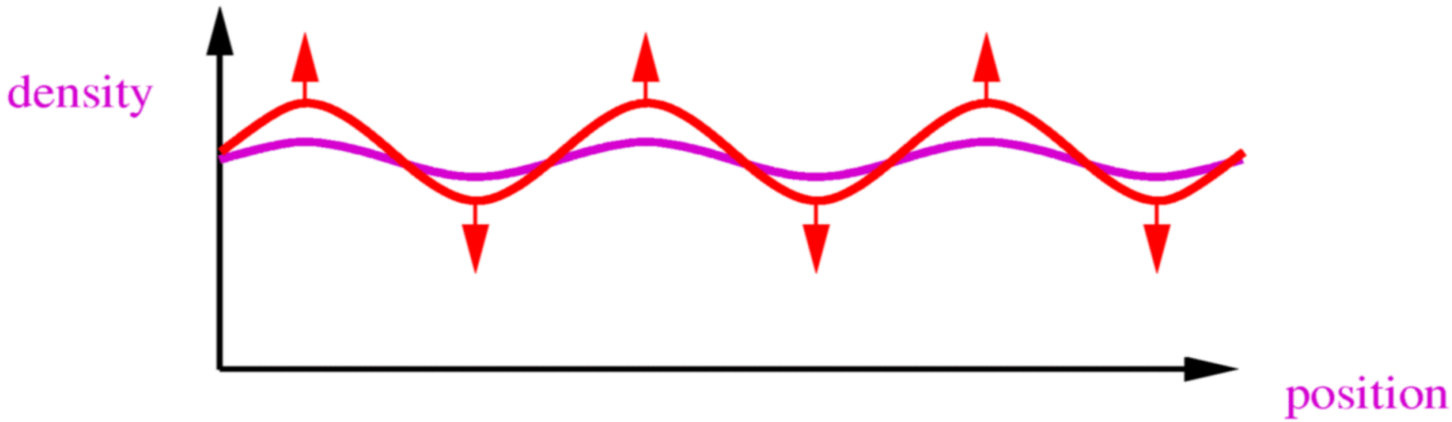
Quantum fluctuations and cosmic structure

The presently visible universe was once of subatomic size

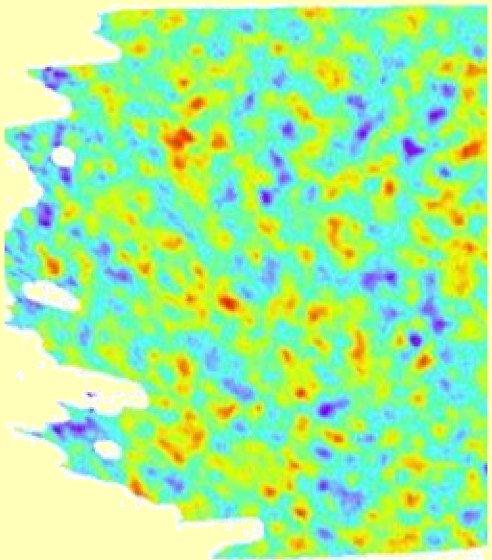


Quantum fluctuations
leave ‘ripples’ in the universe
when it is very small

These are then amplified by gravity to make structure



Measuring the energy content with cosmological fluctuations



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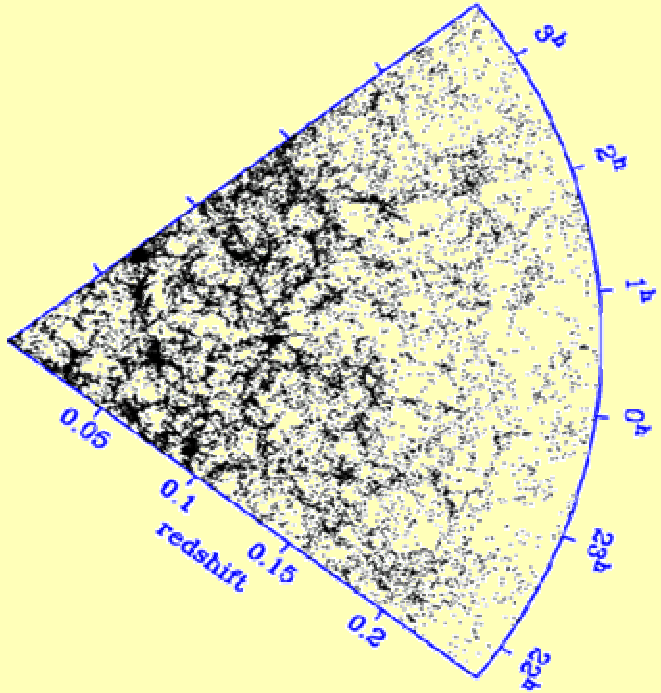


=

Ω_m

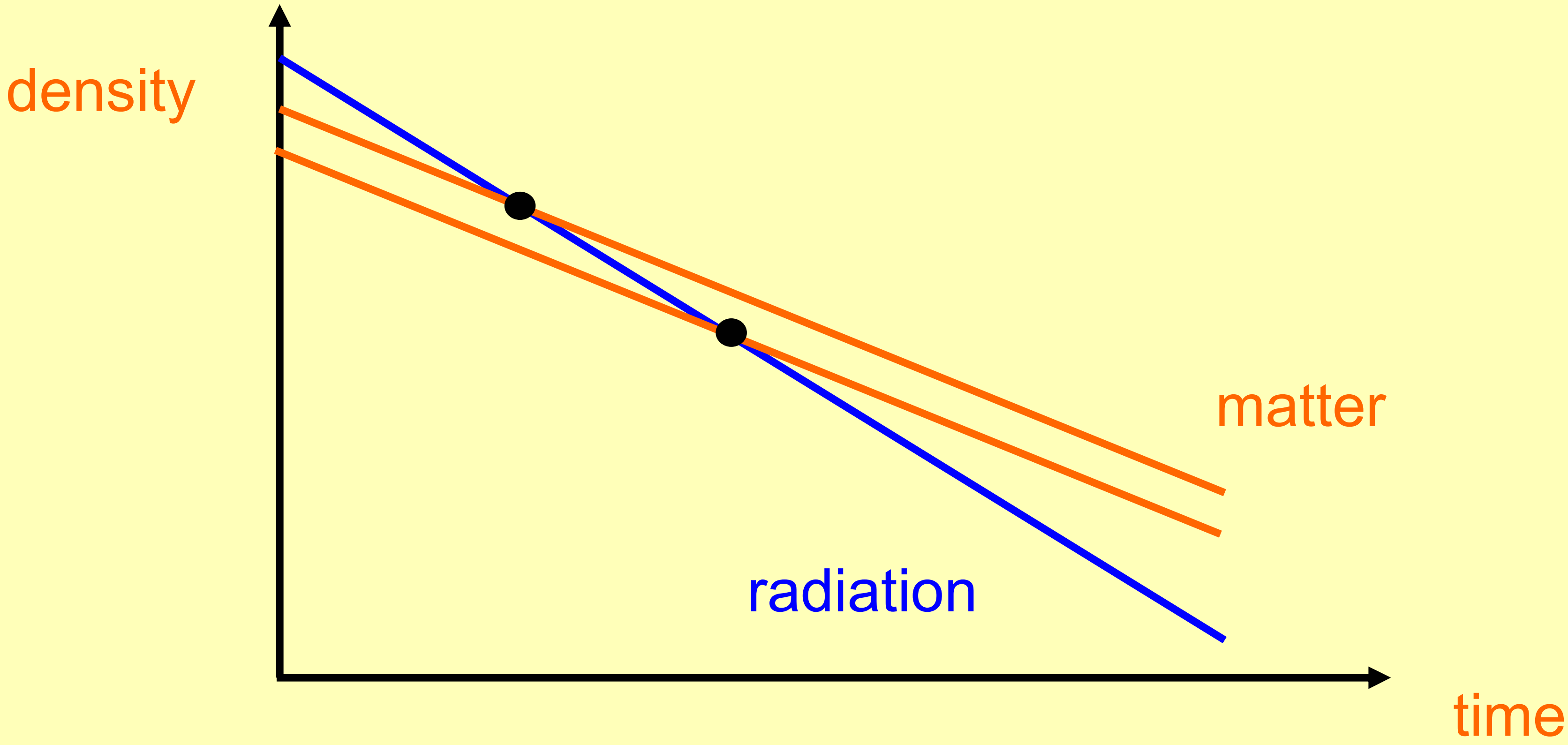
Ω_b

h

n

r

Weighing the universe - II

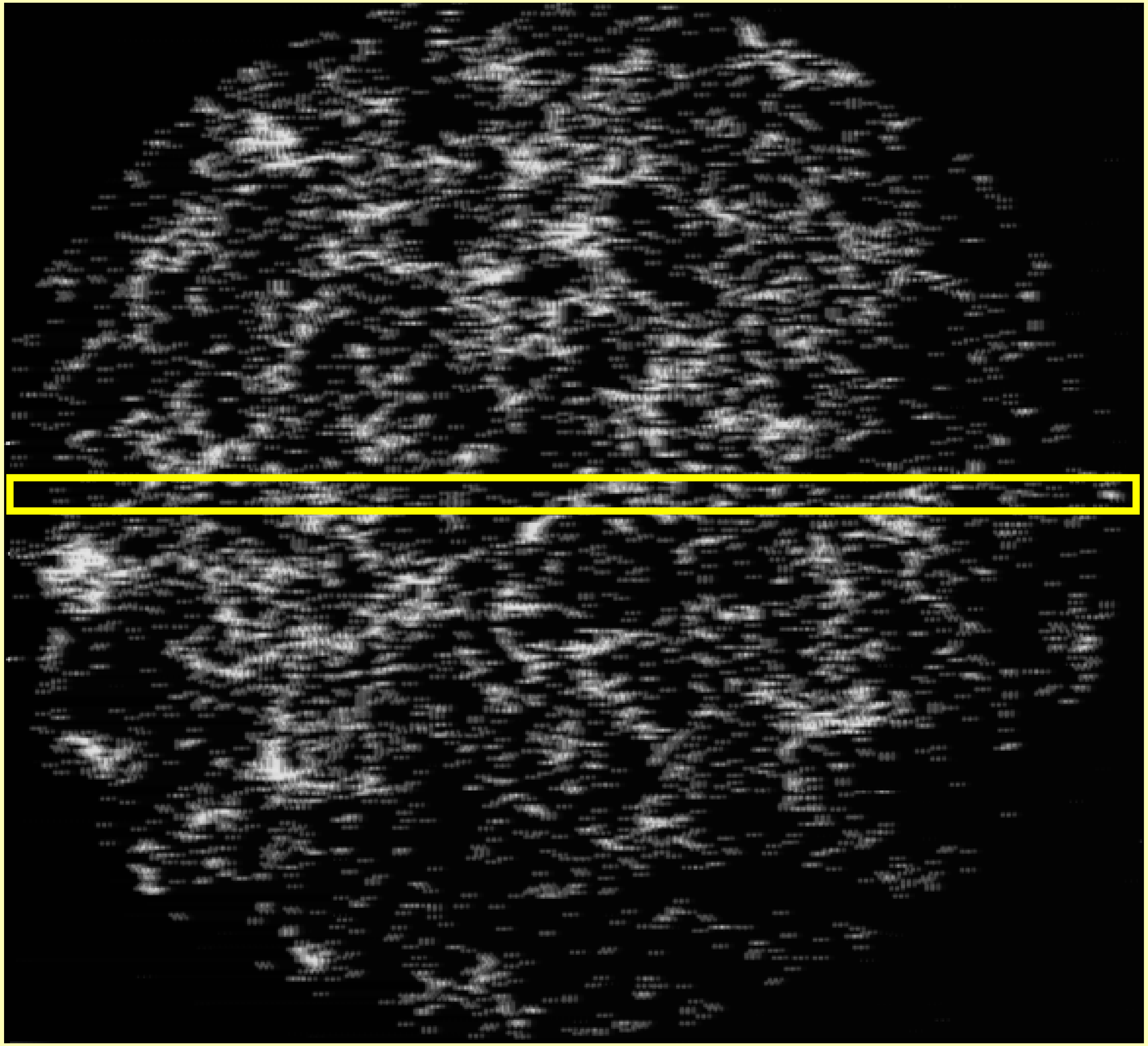


Now: background radiation 'weighs' 1 / 3000 of matter

t < 100,000 years (depending on matter density):

radiation weighs more - affects growth of structure

The distribution of the galaxies



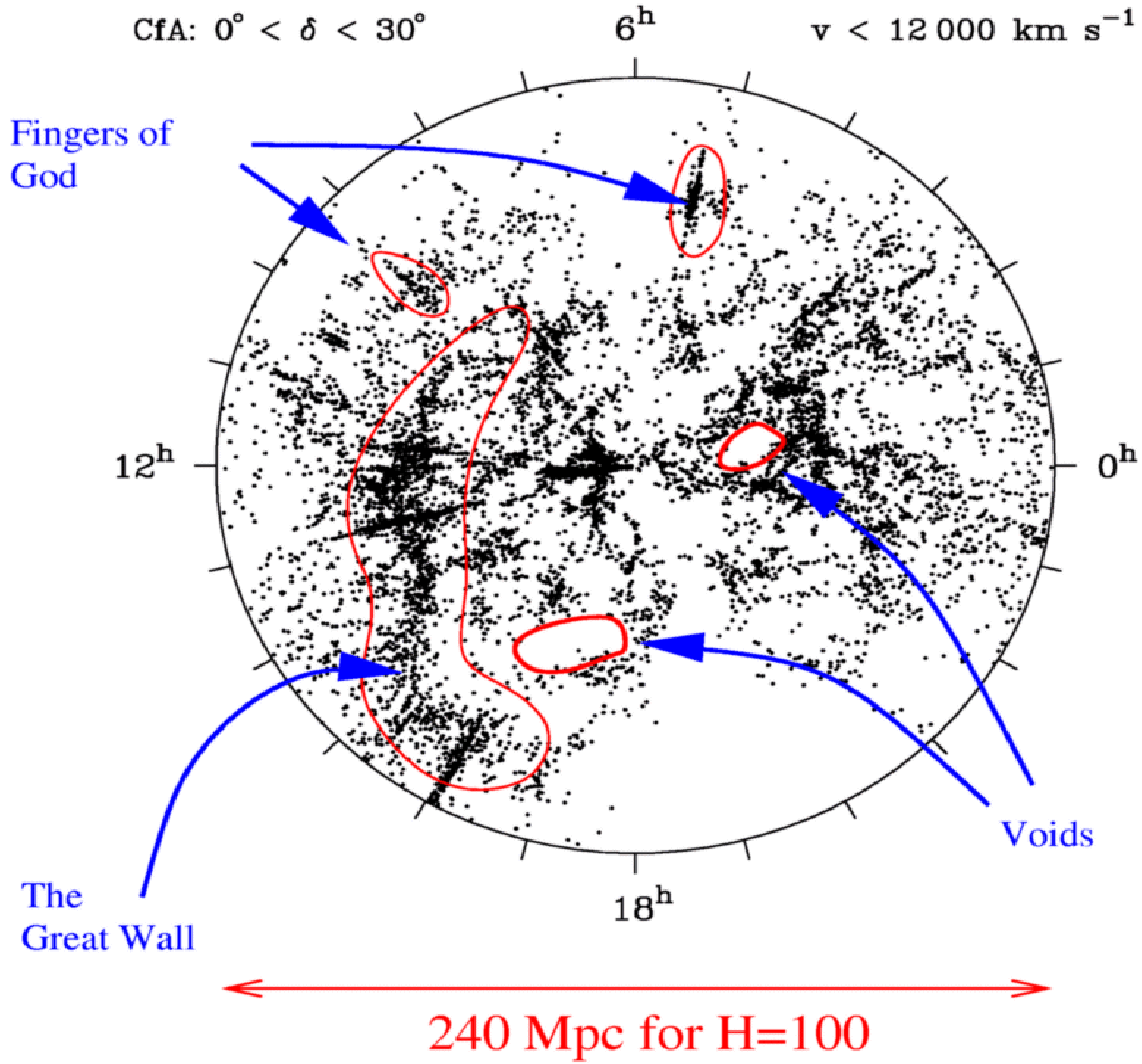
1950s:

Shane & Wirtanen spend 10 years counting 1,000,000 galaxies by eye

- filamentary patterns?

1980s:

Take a strip and get redshifts



Redshift surveys (mid-1980s)

Inverting v = cz = HD gives an approximate distance.

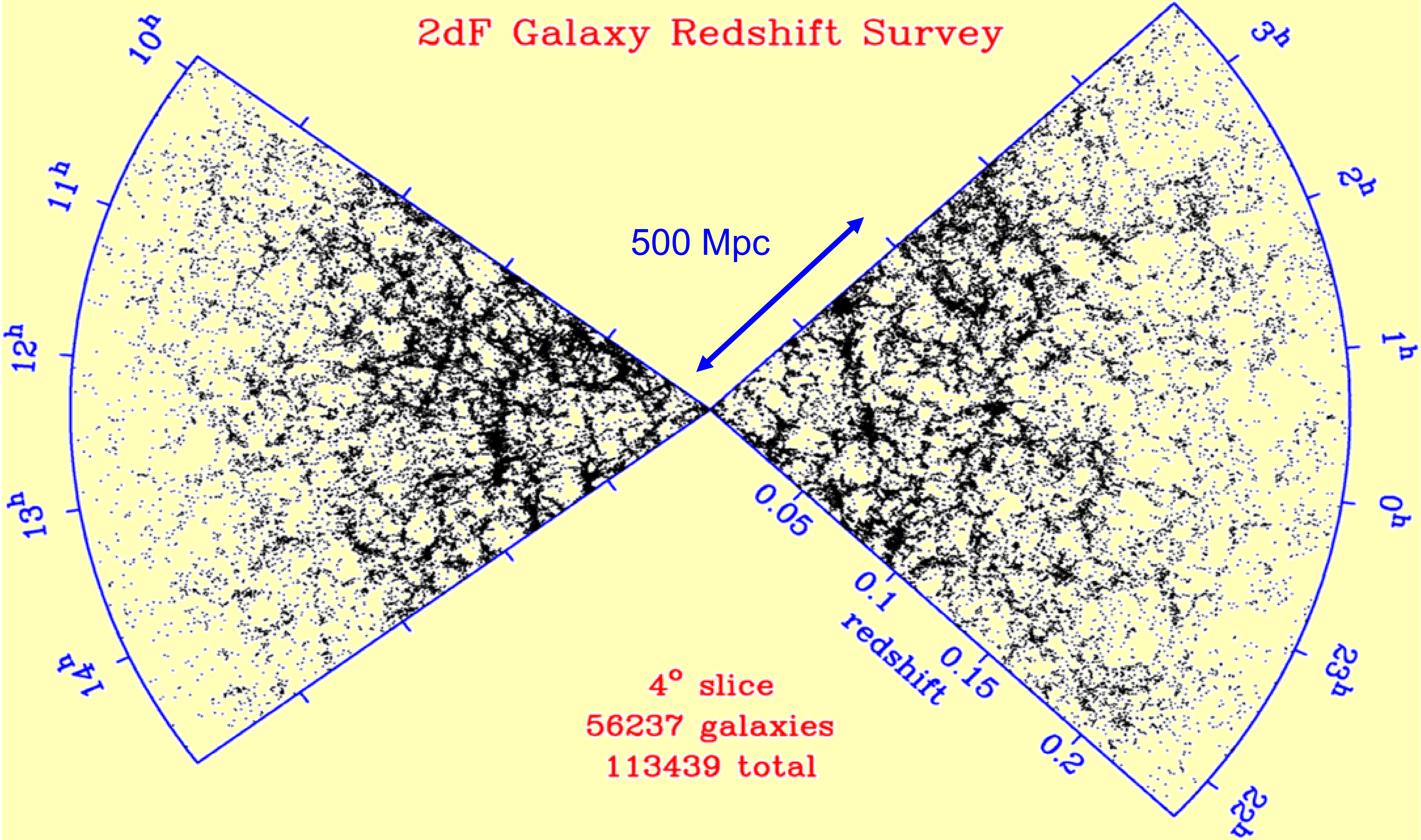
Applied to galaxies on a strip on the sky, gives a ‘slice of the universe’

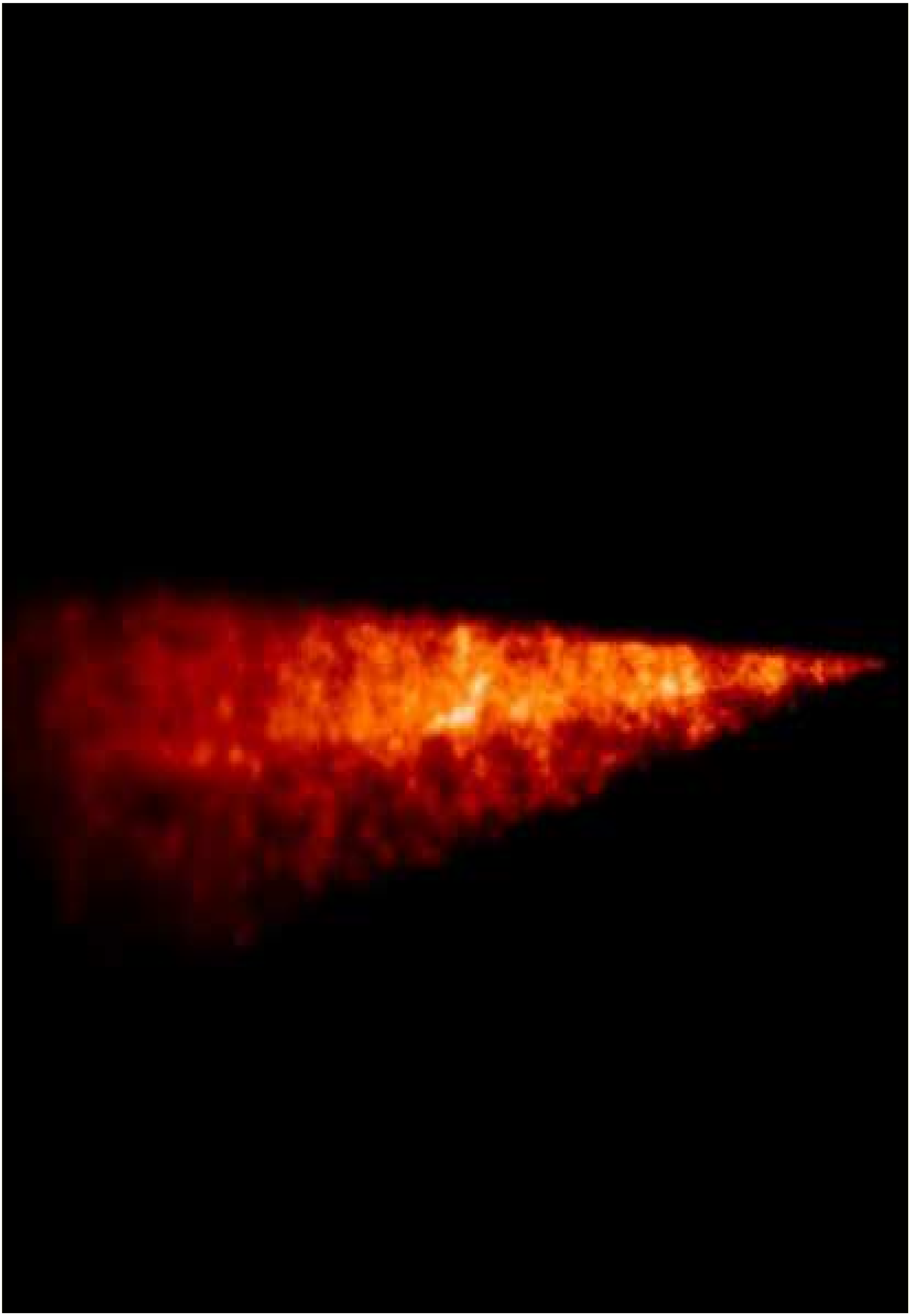
The 2dF Galaxy Redshift Survey

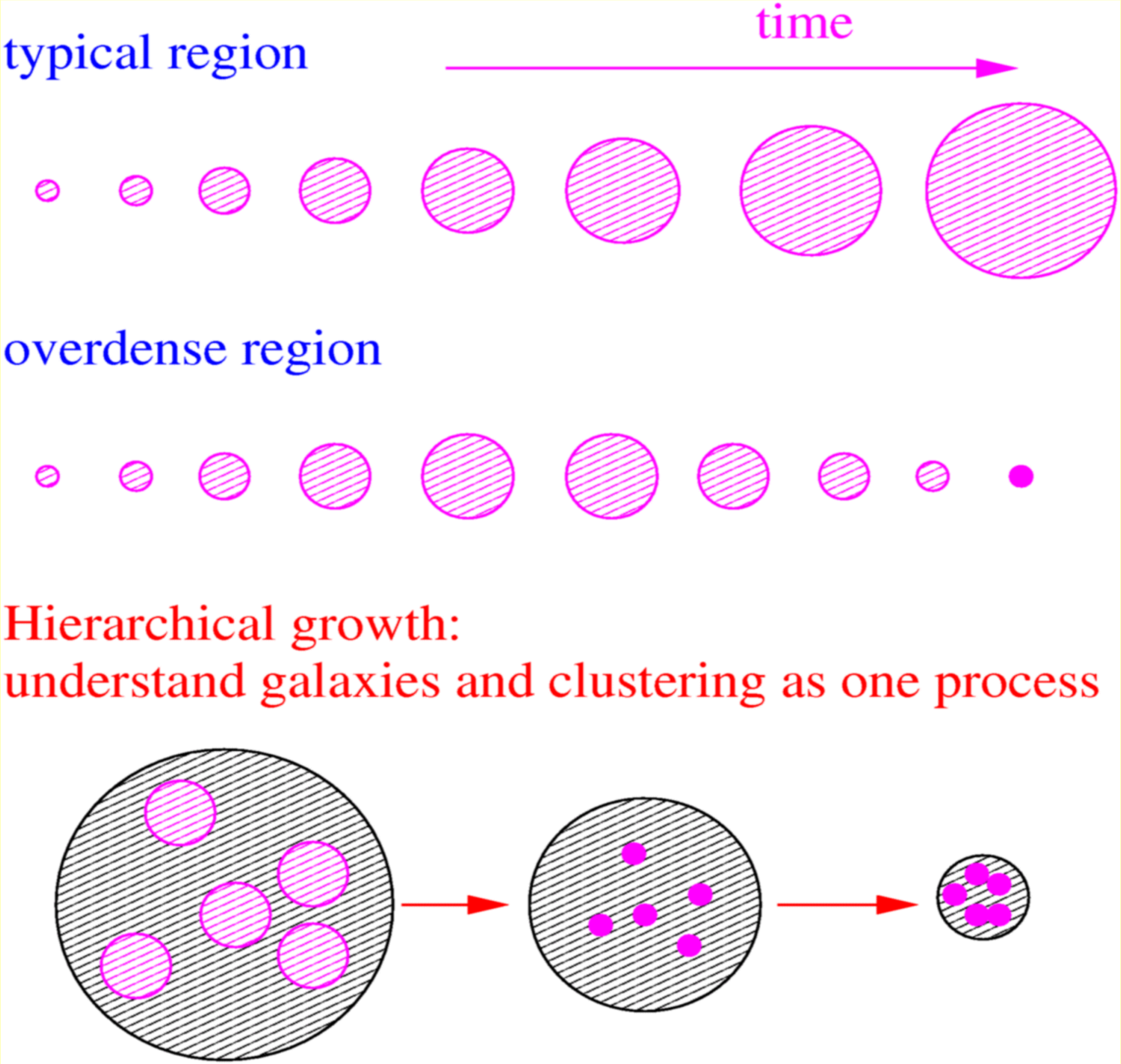
A UK / Australian project to map the positions of 250,000 galaxies:

ten times the largest previous survey

The state of the art in galaxy clustering



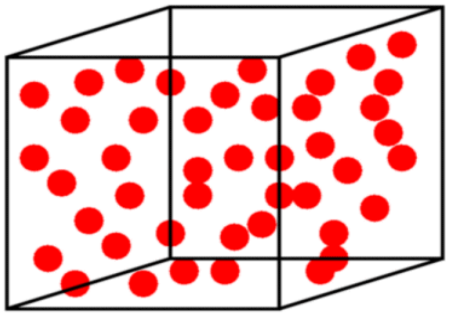




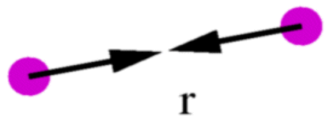
Gravitational instability:

hierarchical collapse generates ever larger structures

Simulating structure formation

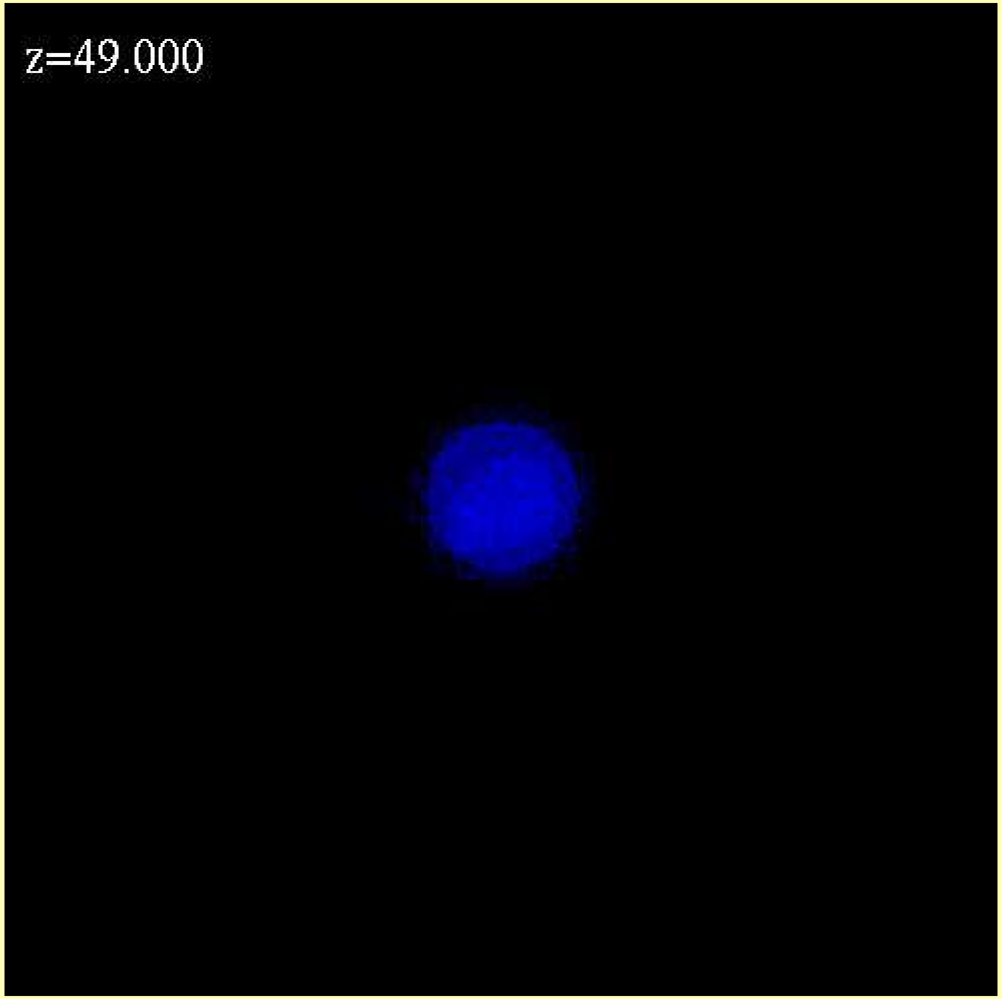


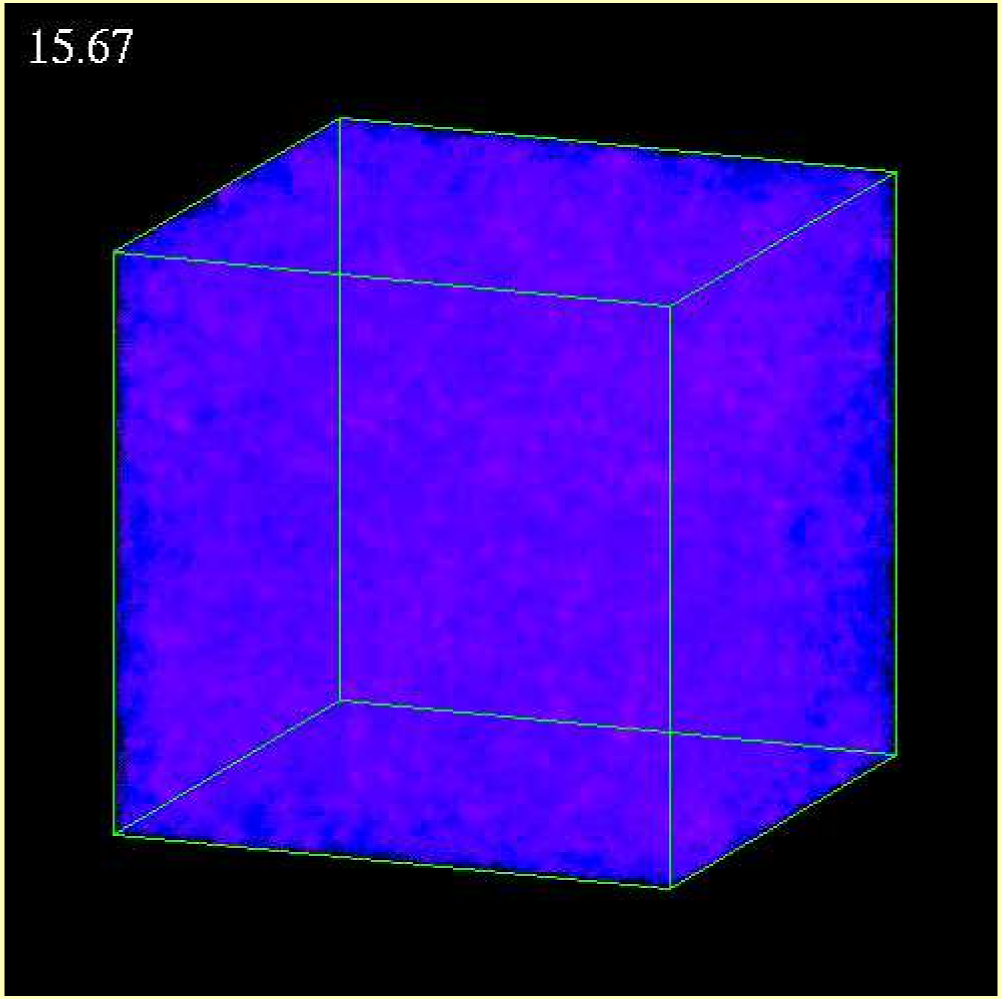
Use a supercomputer to follow the trajectories of 10 million - 1 billion imaginary particles

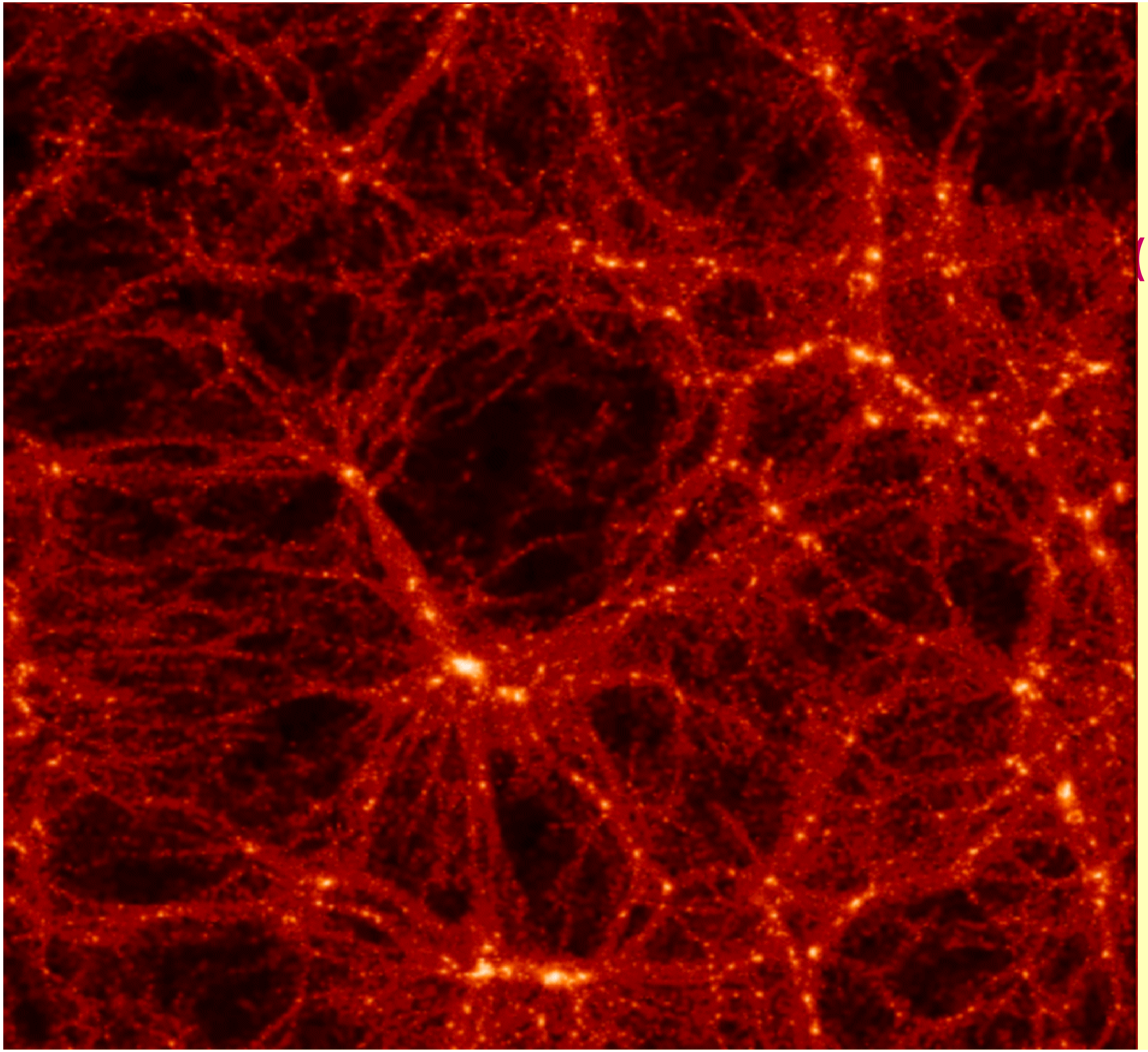


$$F = \frac{G\,m\,m}{r^2}$$

The Virgo consortium uses Cray and IBM supercomputers (up to 512 processors) in Edinburgh & Munich to simulate the growth of cosmological structure


z=49.000


15.67



Forming superclusters (comoving view)

redshift z=3

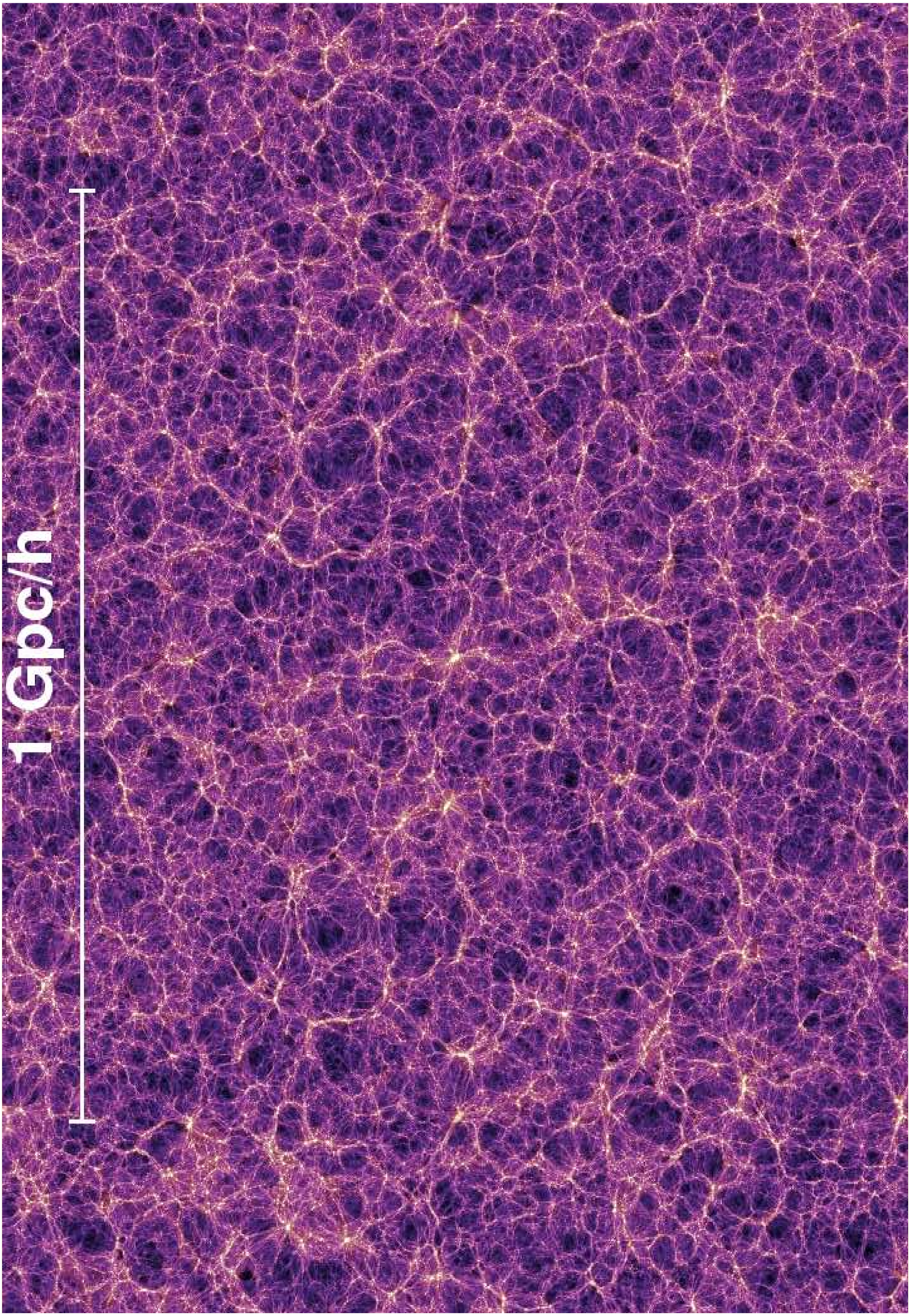
(1/4 present size)

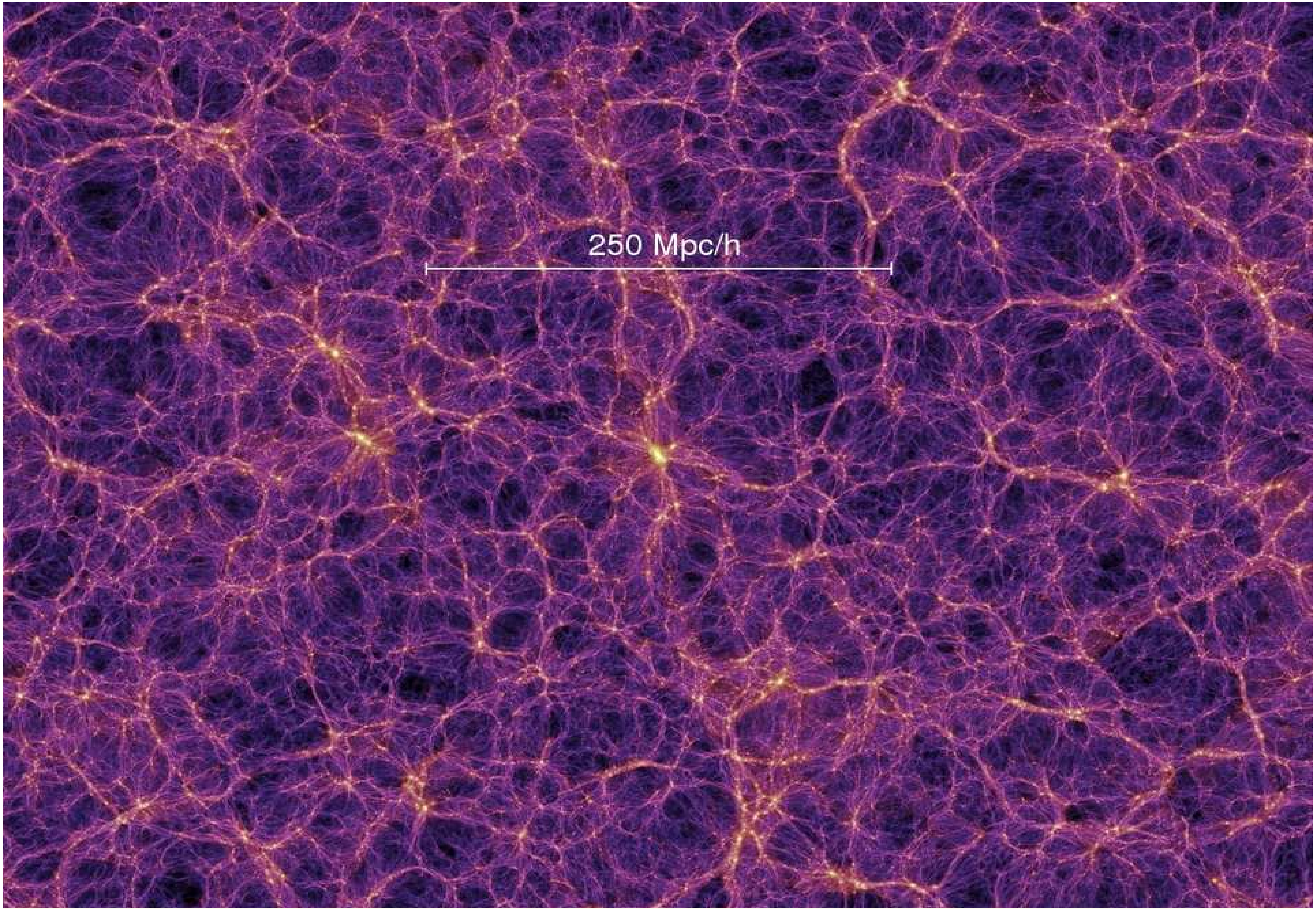
redshift z=1

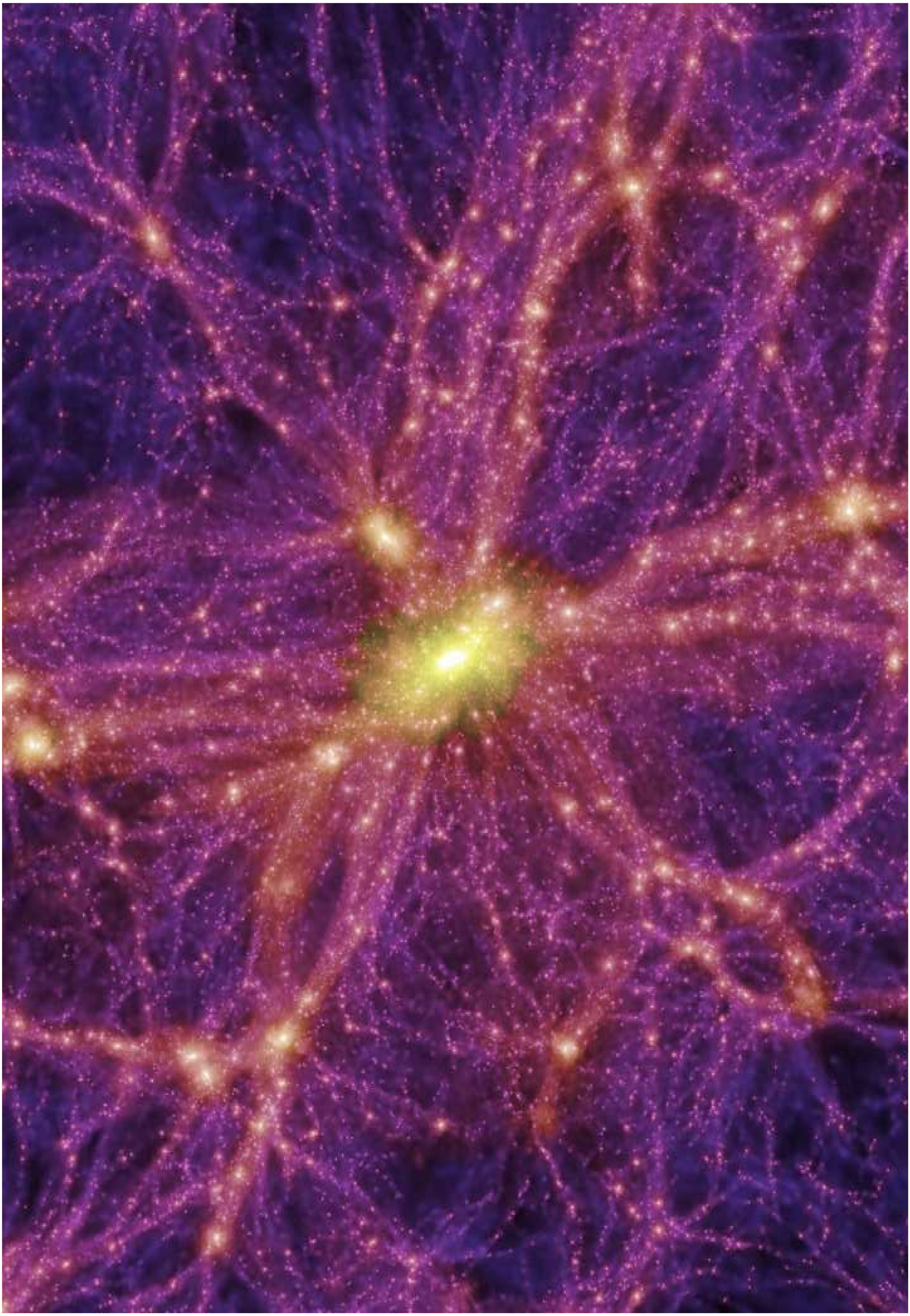
(1/2 present size)

Redshift z=0

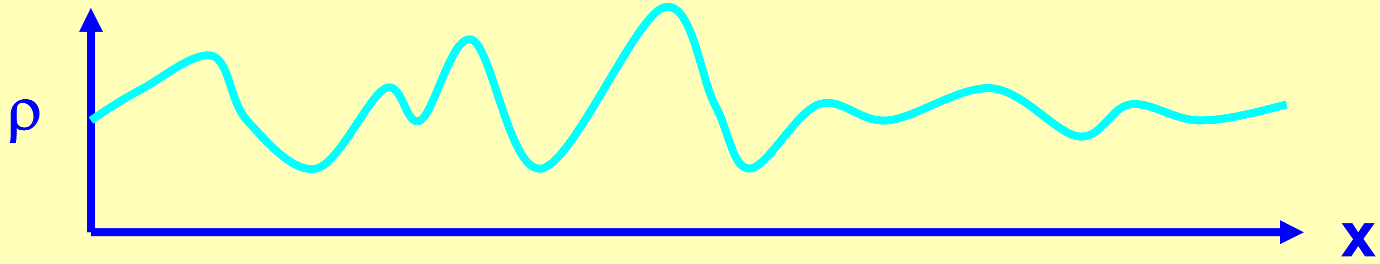
(today)


1 Gpc/h


250 Mpc/h



The 2dFGRS power spectrum



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

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

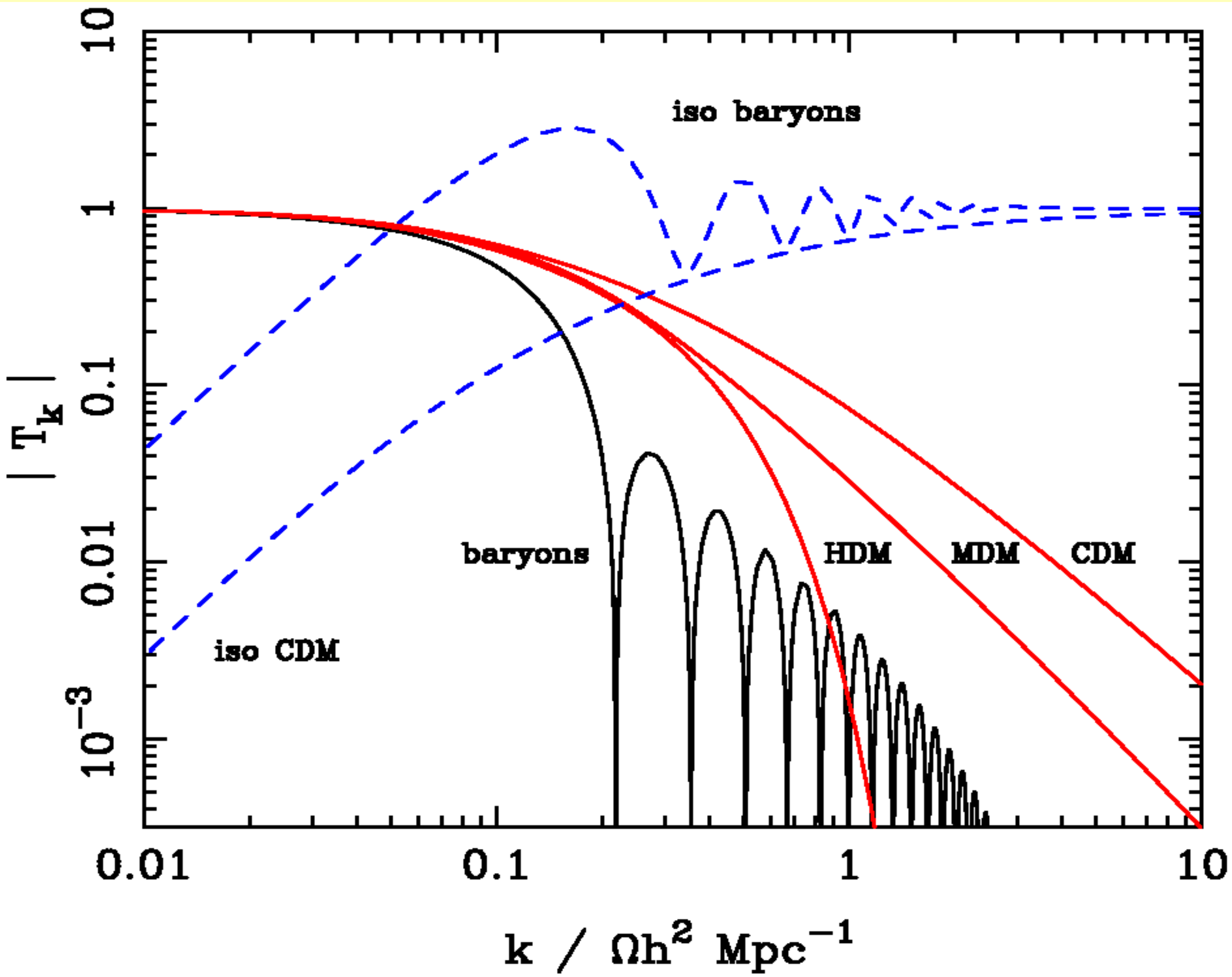
Primordial power-law spectrum (n=1?)

Transfer function

Transfer function: $P=k^nT^2(k)$

Parameters: Ω_d

Ω_b Ω_v $\Omega_{neutrino}$ h w n M



Key scales:

* Horizon (=ct) at z_{eq} :
16 $(\Omega_m h^2)^{-1}$ Mpc
(observe $\Omega_m h$)

* Free-stream length :
80 $(M/eV)^{-1}$ Mpc ($\Omega_m h^2$ = M / 93.5 eV)

* Acoustic horizon :
sound speed < $c/3^{1/2}$

* Silk damping

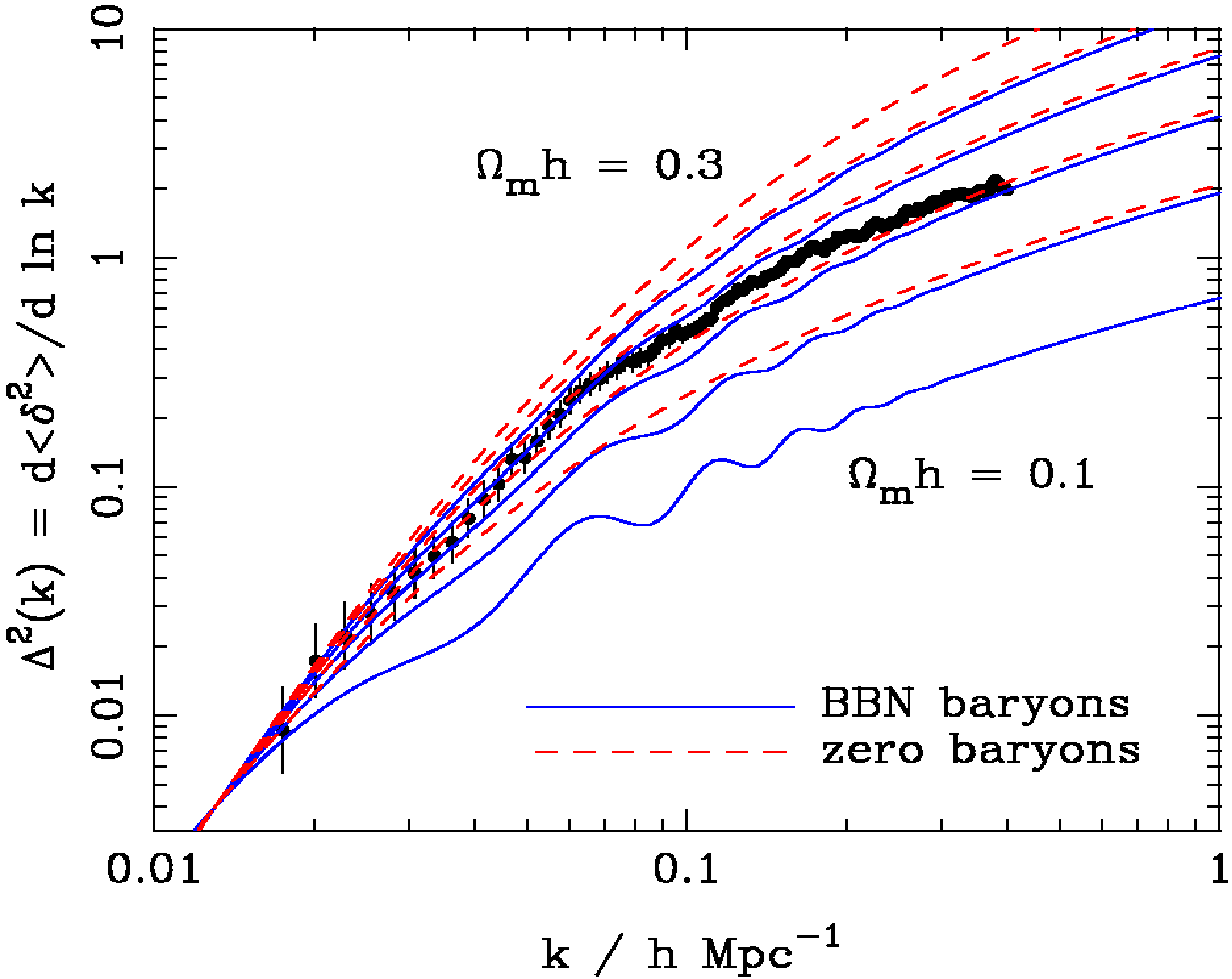
M sets damping scale - reduced power rather than cutoff if DM is mixed

Generally assume adiabatic

2dFGRS power-spectrum results

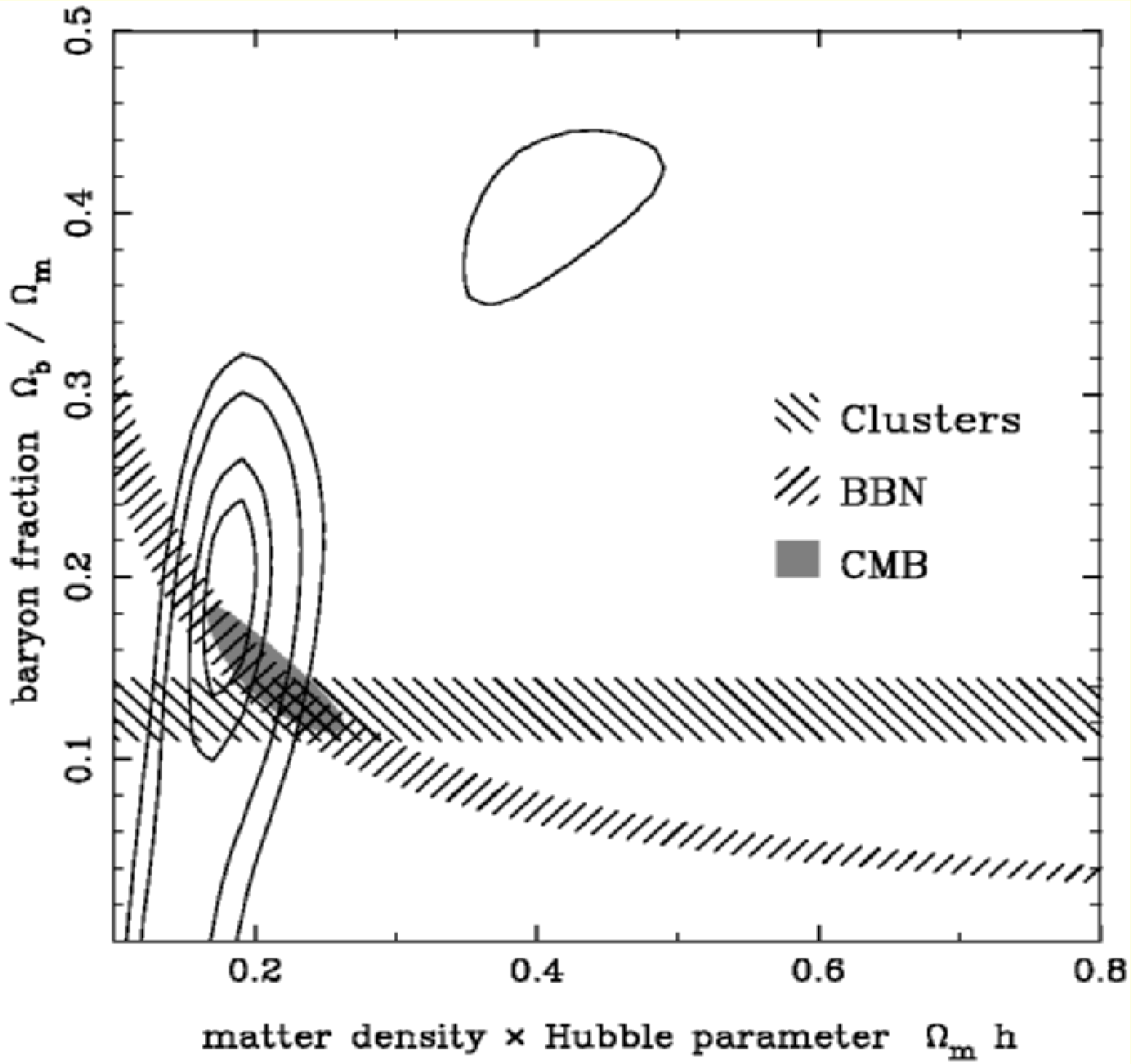
Dimensionless power:

d (fractional variance in density) / d ln k



Percival et al. MNRAS 327, 1279 (2001)

2dFGRS P(k) model fits: Feb 2001 vs 'final'



Ω_mh = 0.20 ± 0.03

Baryon fraction = 0.15 ± 0.07

Ω_mh = 0.17 ± 0.02

Baryon fraction = 0.17 ± 0.06

(if n = 1)

(Cole et al.)

Observing fluctuations from the early universe:

Furthest back we can see is the microwave background ($z = 1100$)

COBE Microwave Sky (1992)

- The sky temperature with range from 0 - 4 Kelvin
- Microwave background is very uniform at nearly 2.73 Kelvin

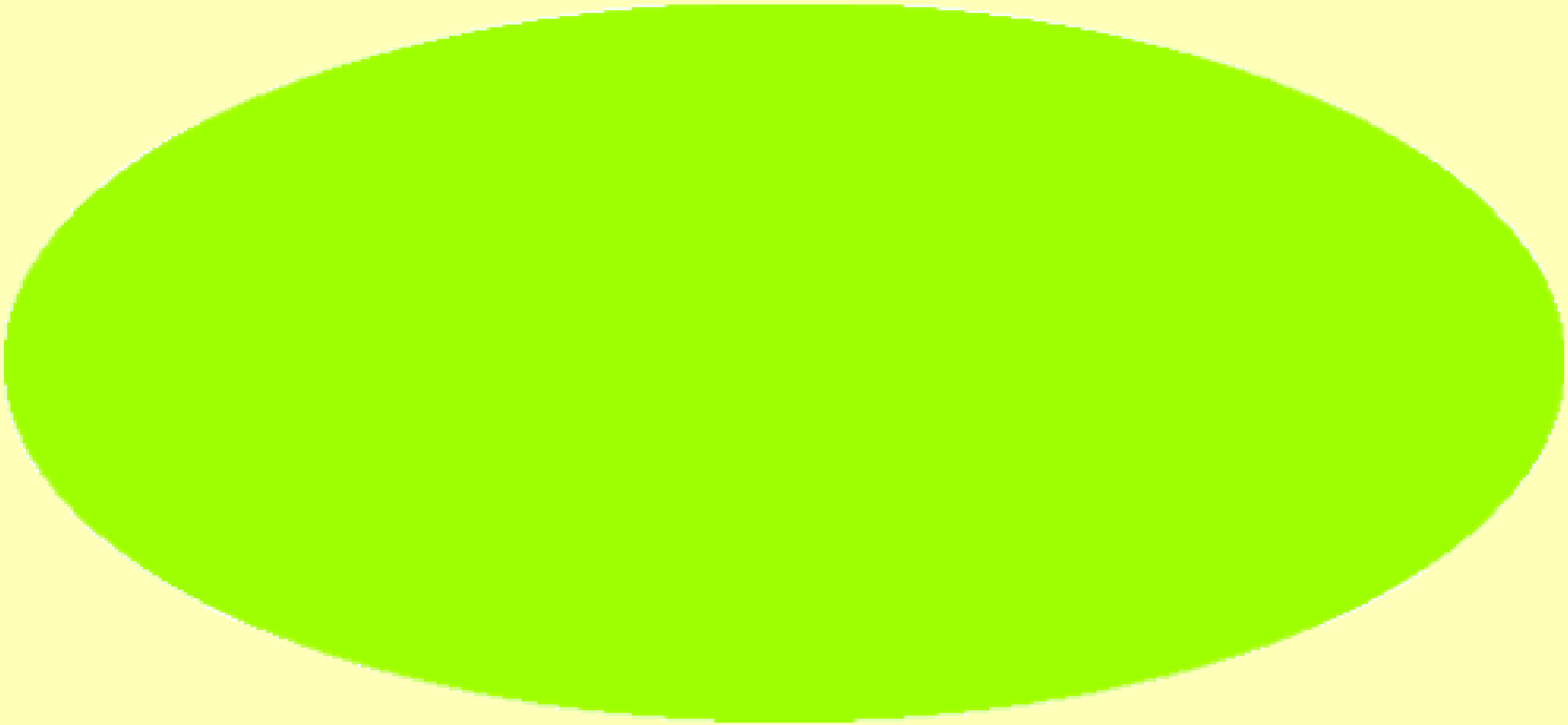


Image courtesy COBE homepage.

COBE Microwave sky: 1,000 X stretch

- The sky temperature with range from 2.724 - 2.732 Kelvin
  - blue is 2.724 K and red is 2.732 K

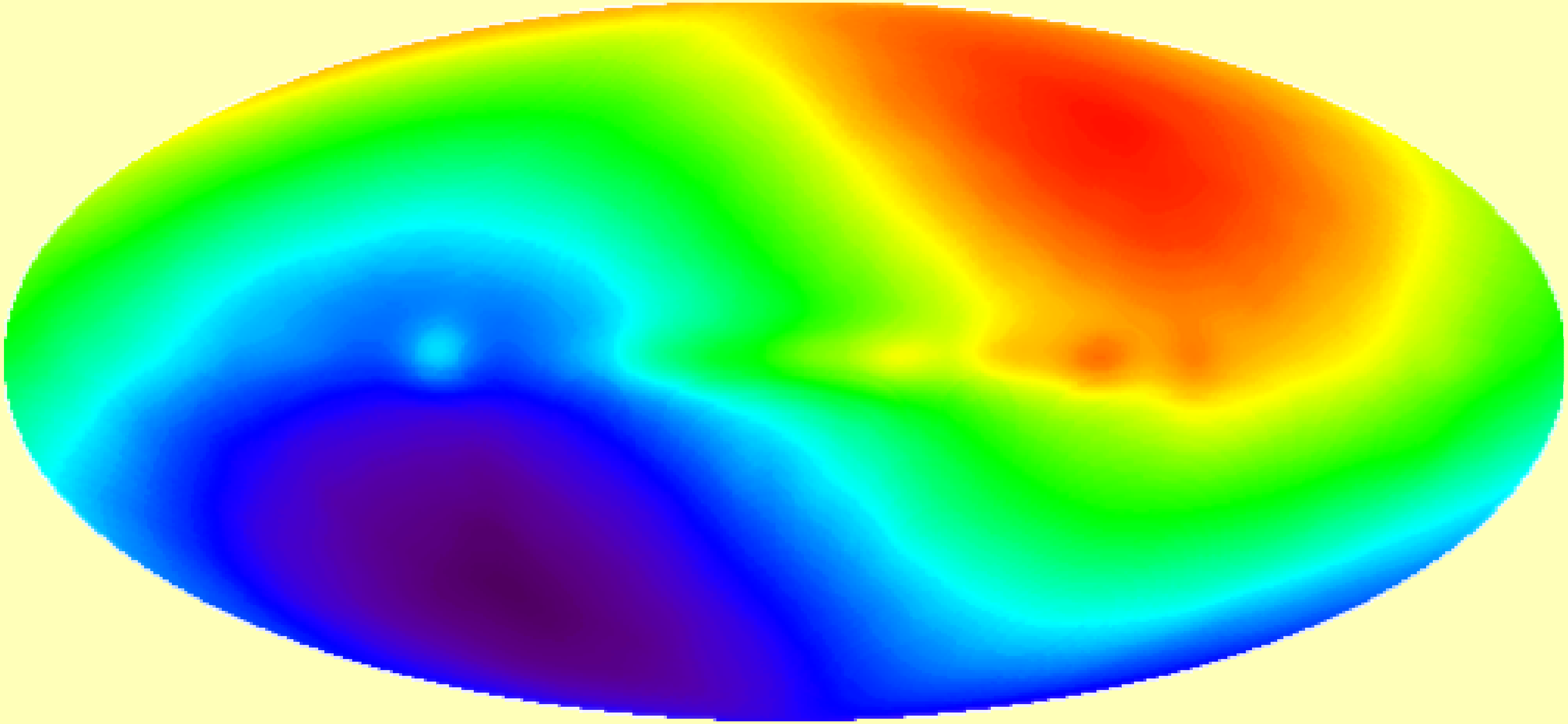


Image courtesy COBE homepage.

COBE microwave sky: 25,000 X stretch

The sky temperature ranging from 2.7279 to 2.7281 Kelvin

Real fluctuations in temperature away from Milky Way of 1 part in 100,000

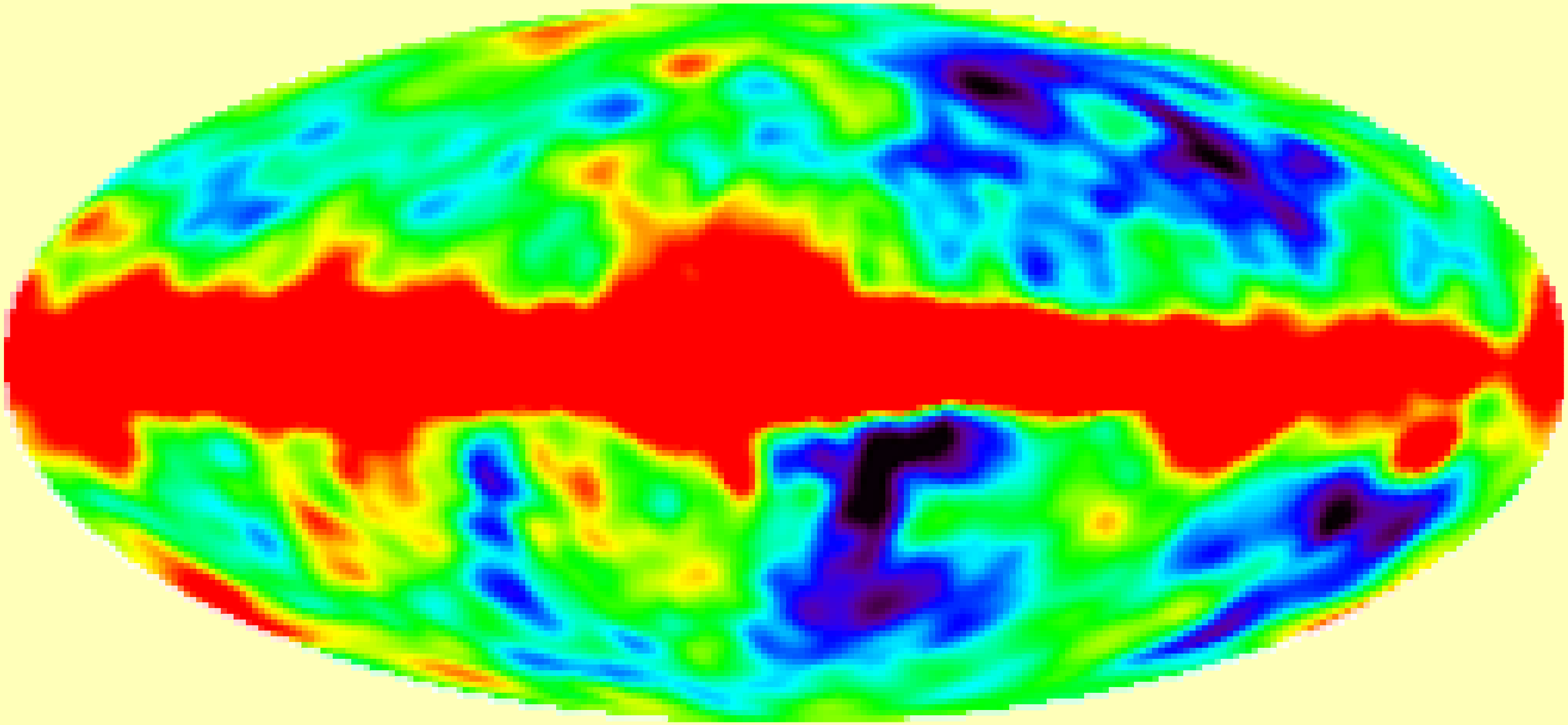
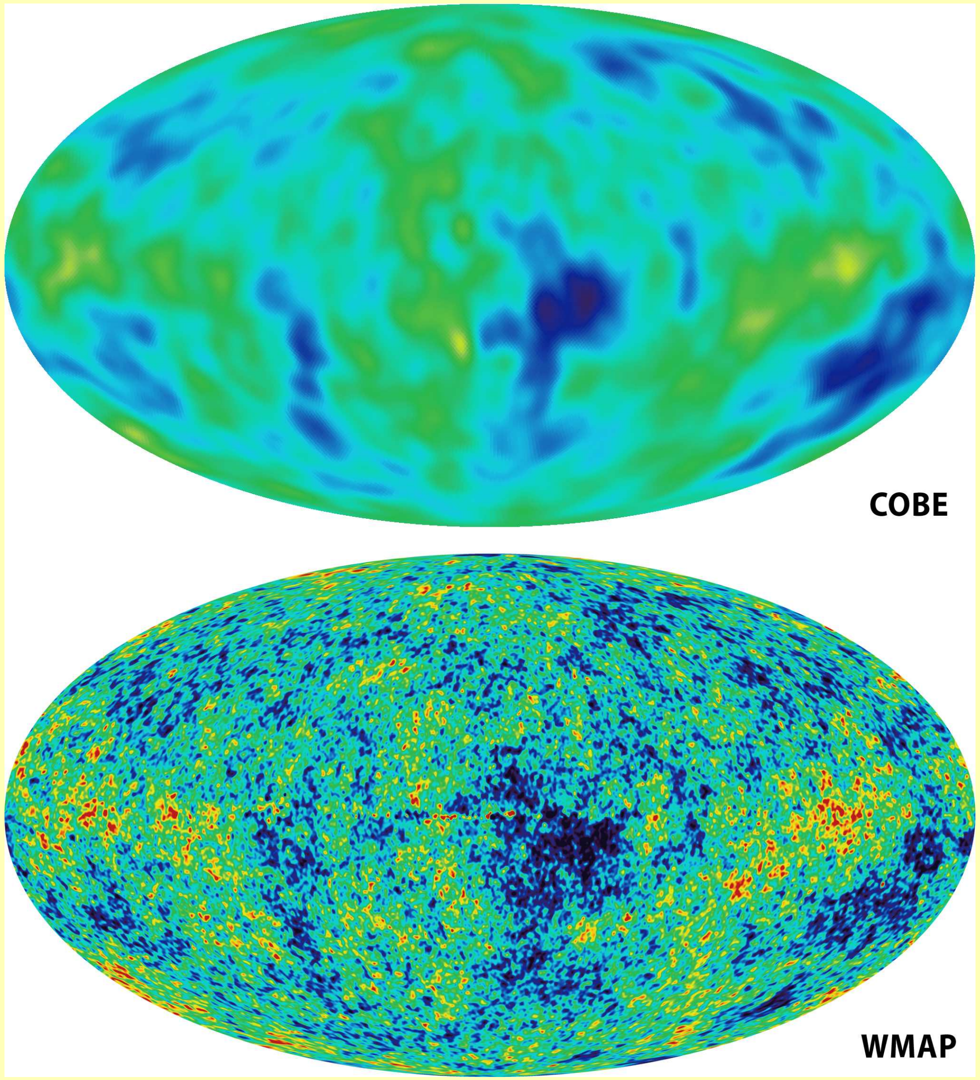
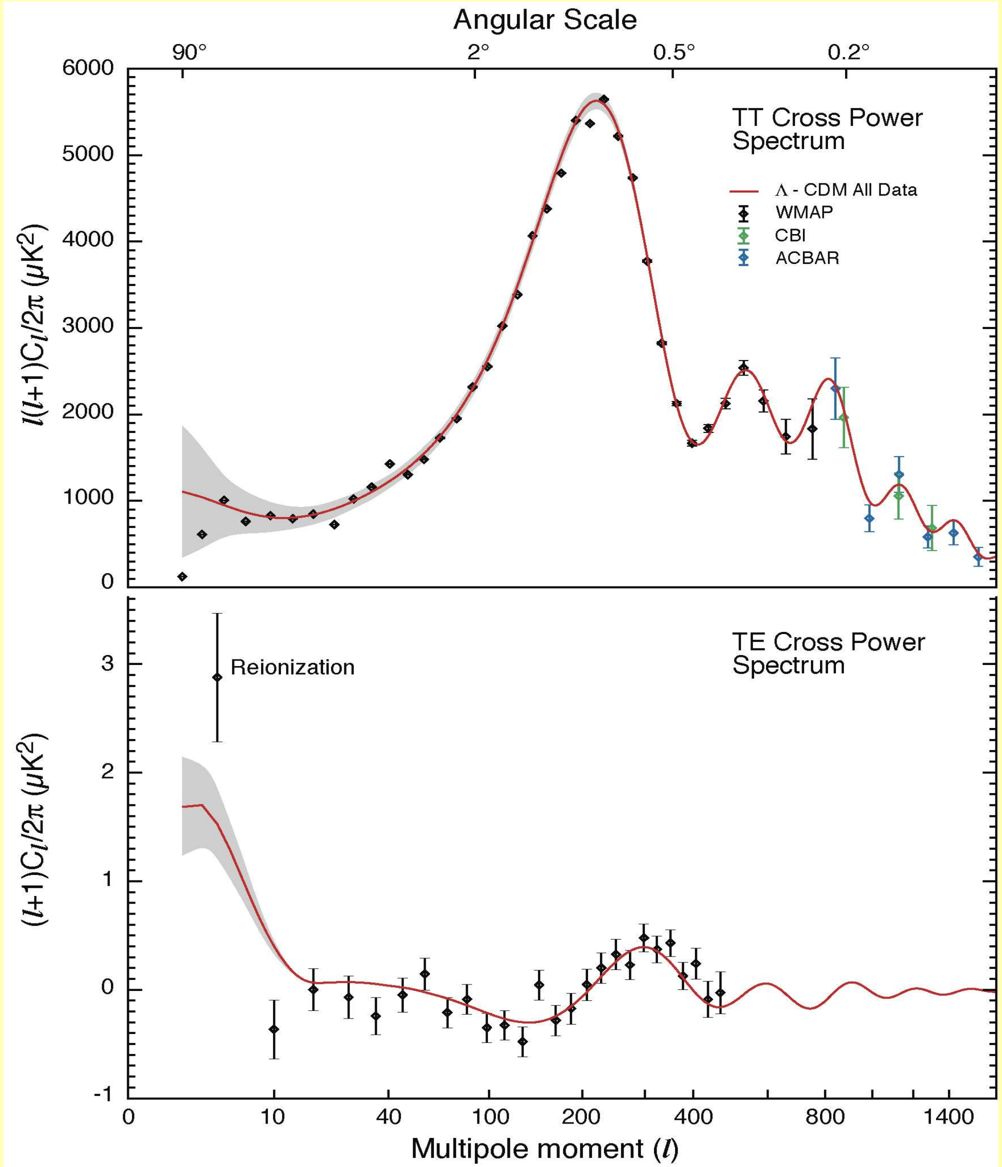
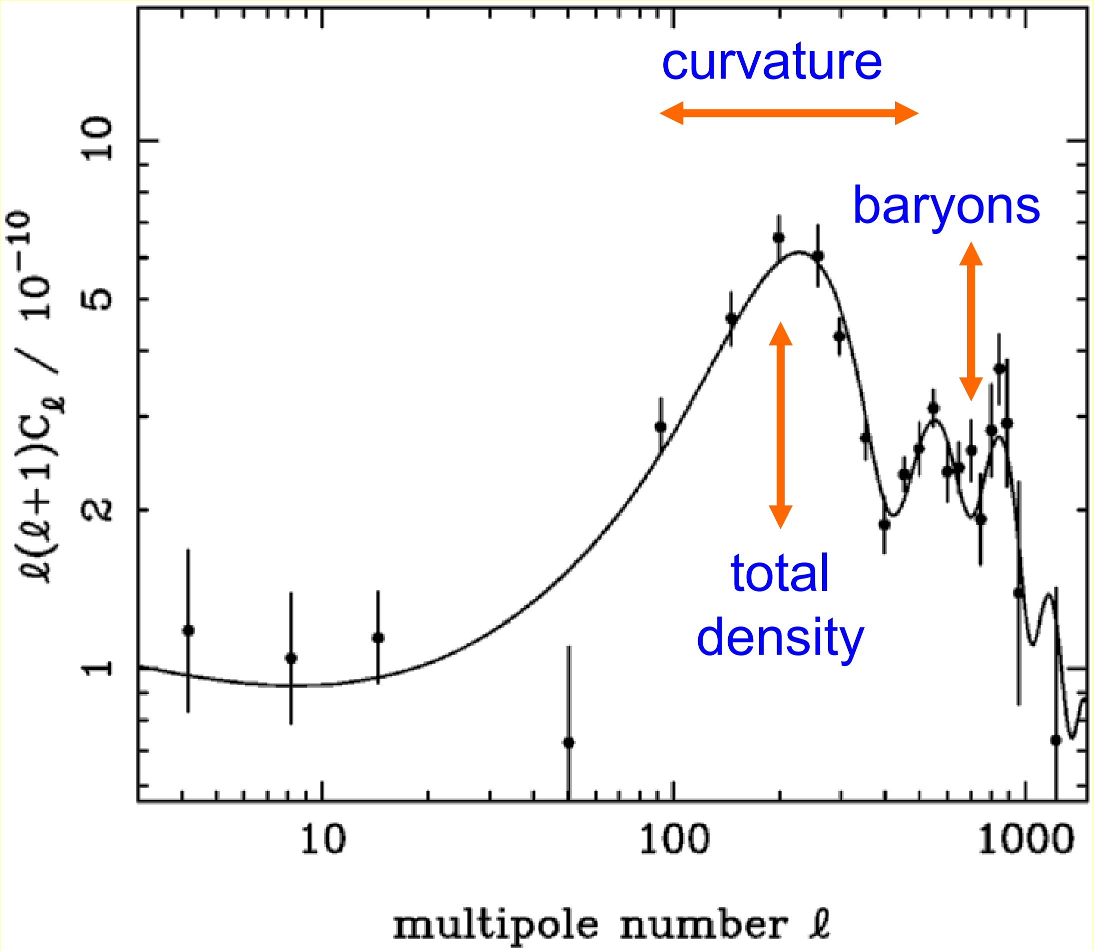


Image courtesy COBE homepage.

2003: WMAP


COBE
WMAP


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi\ (\mu K^2)$
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
3
2
1
0
-1
$(l+1)C_l/2\pi\ (\mu K^2)$
Reionization
TE Cross Power Spectrum
0
10
40
100
200
400
800
1400
Multipole moment (l)



Relation of LSS to CMB results

Combining LSS & CMB breaks degeneracies:

LSS measures $\Omega_m h$ only if power index n is known

CMB measures n and $\Omega_m h^3$ (only if curvature is known)

CMB degeneracies

Approx scaling of peak locations from angle subtended by horizon at last scattering:

$$\boxed{\theta_H \propto (\Omega_m h^{3.4})^{0.14} \ \Omega_{tot}^{1.4}}$$

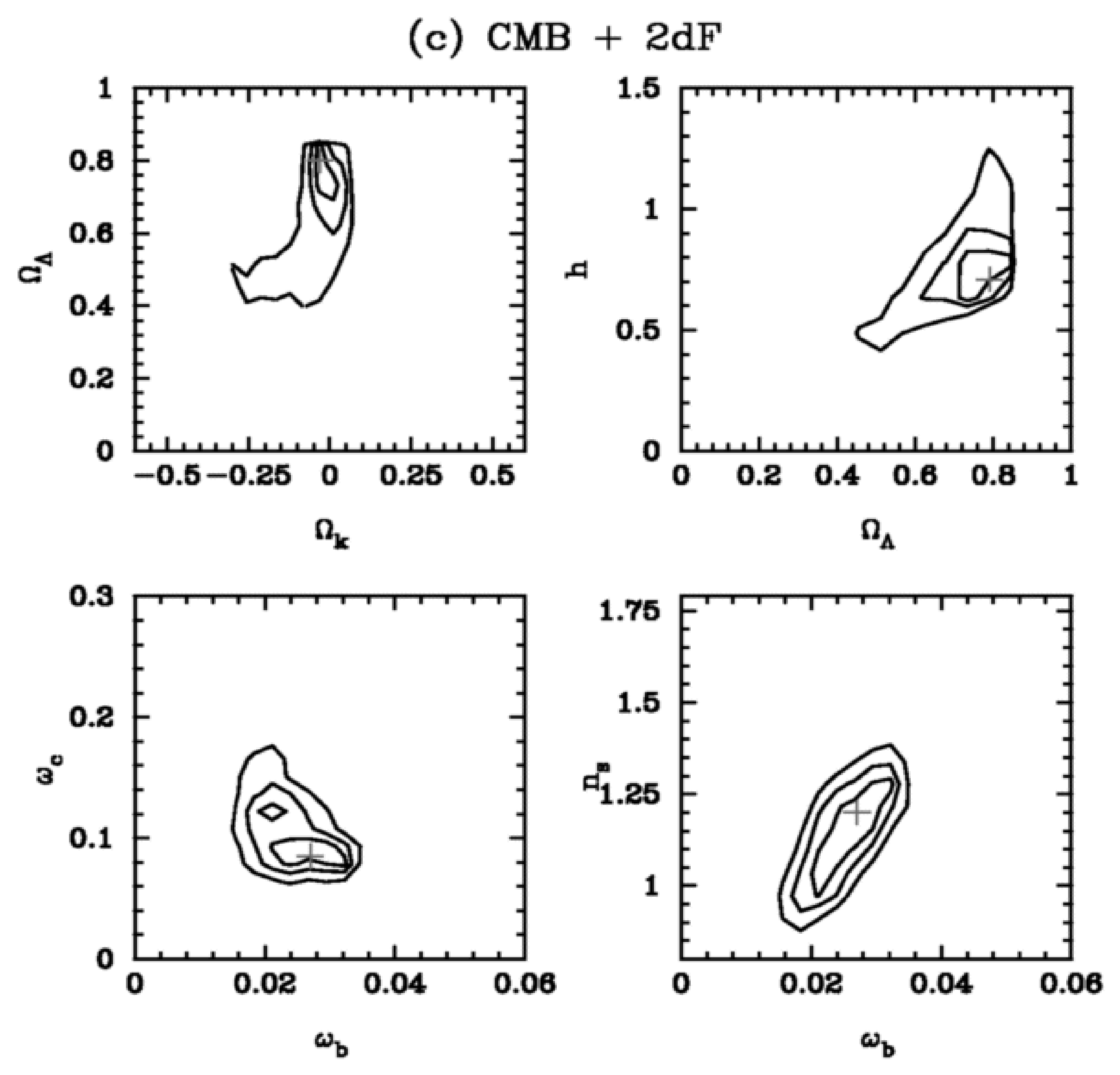
(1) CMB alone cannot prove flatness

(2) But LSS limits disallow strong curvature: $| 1 - \Omega_{tot} | < 0.04$

(3) Thus tend to assume flat (but should we?)

(4) If flat, still degeneracy in $\Omega_m - h$ space, but LSS breaks this

2dFGRS + CMB: Flatness



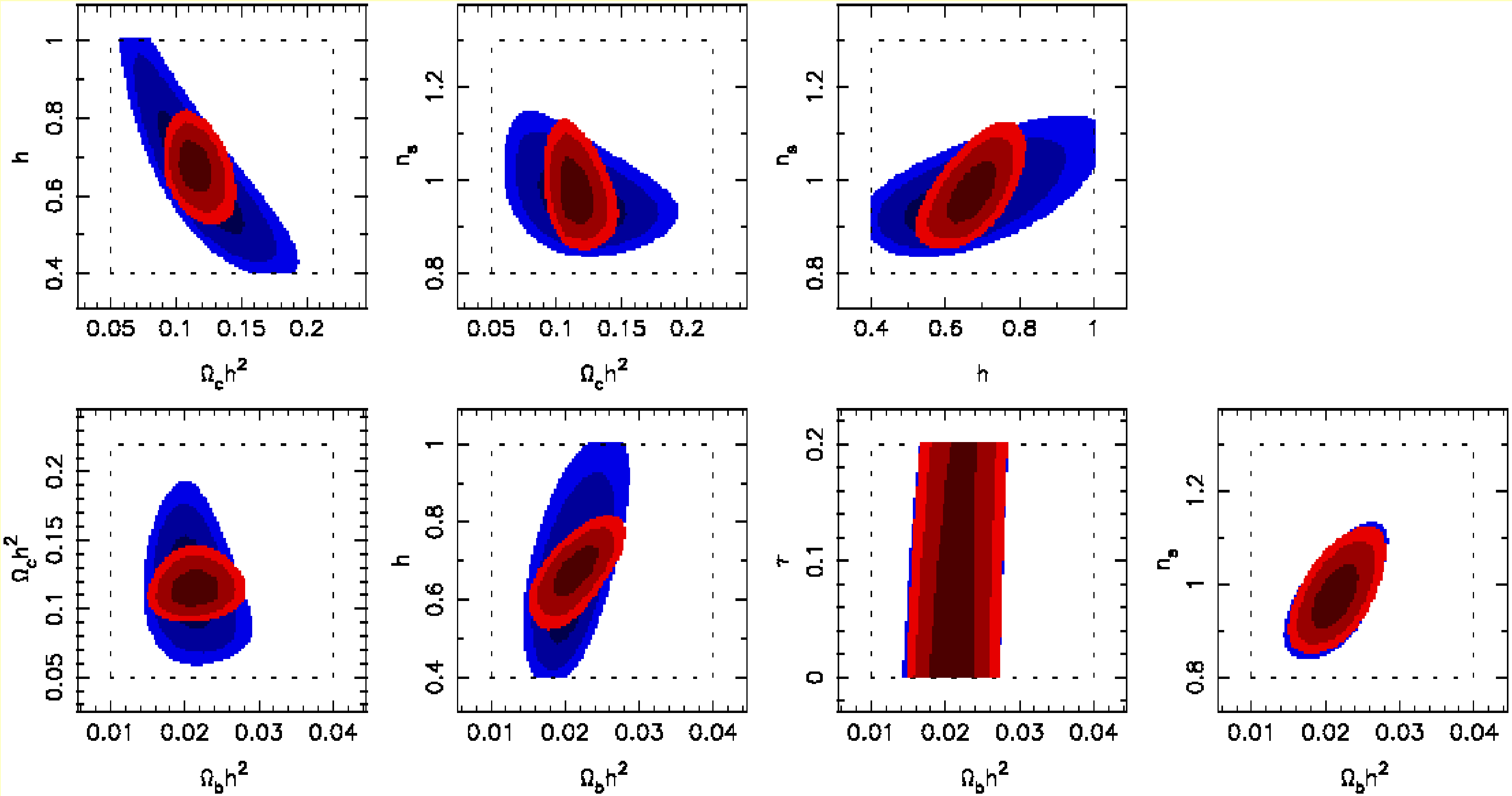
CMB alone has a geometrical degeneracy: large curvature is not ruled out

Adding 2dFGRS power spectrum forces flatness:

$$| 1 - \Omega_{tot} | < 0.04$$

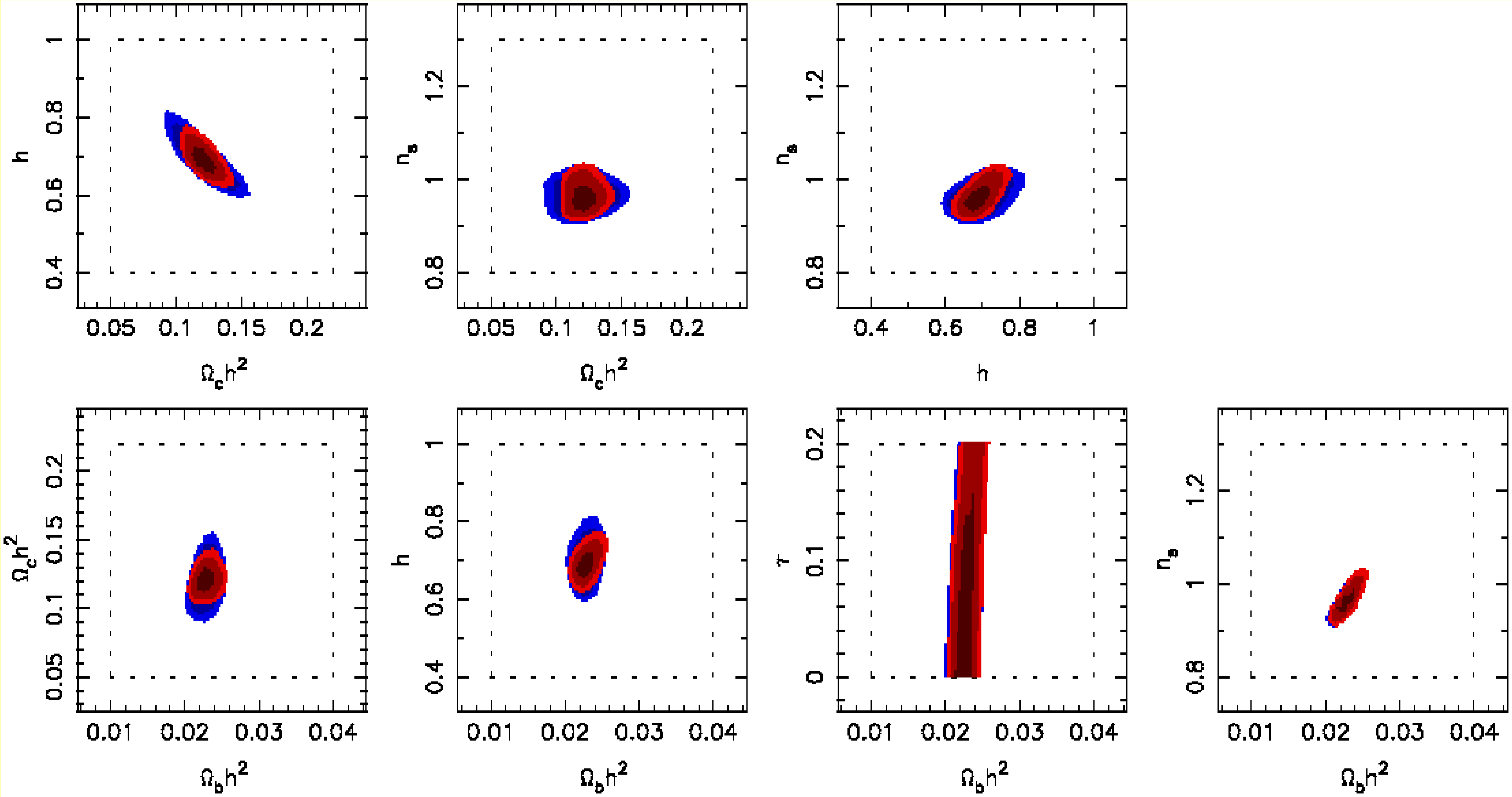
Efstathiou et al. MNRAS 330, L29 (2002)

likelihood contours pre-WMAP + 2dFGRS 147024 gals
scalar only, flat models



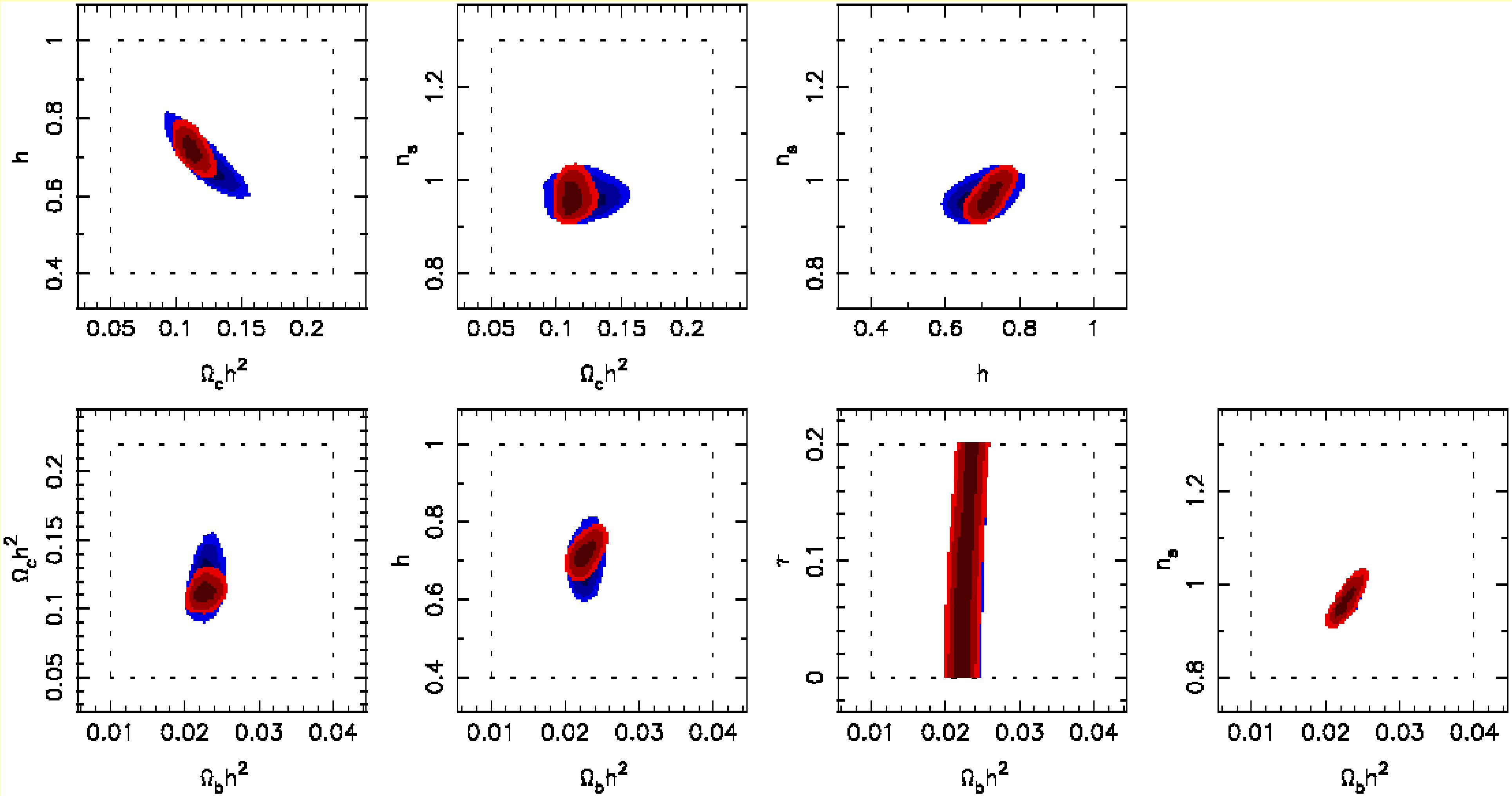
likelihood contours post-WMAP + 2dFGRS 147024 gals
scalar only, flat models

- WMAP's main achievement is confidence in CDM



likelihood contours post-WMAP + 2dFGRS 213947gals
scalar only, flat models

Ω_m = 0.25 +/- 15% h = 0.73 +/- 5%



The cosmological standard model

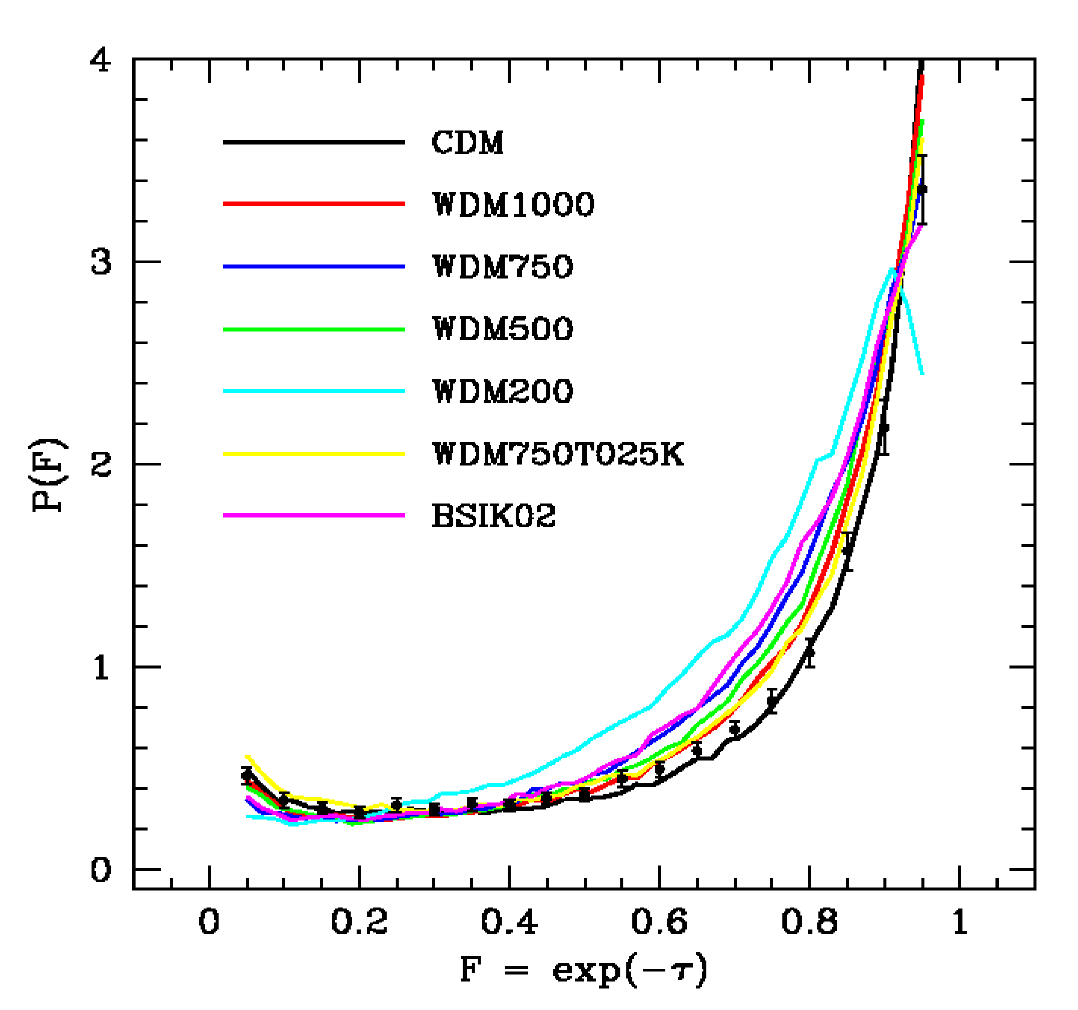
- Everything fits well with k=0 CDM model with Ω_m=0.25

But

- So far no test of inflation or other initial conditions
- We don't know if CDM is a wimp, nor its mass
- Is the vacuum energy a cosmological constant?

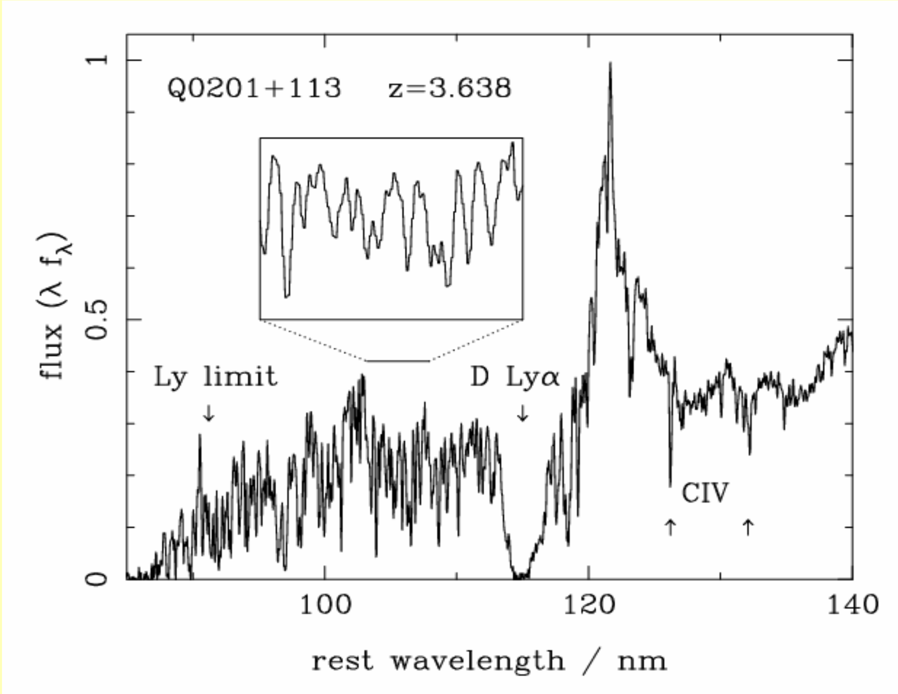
Limiting DM mass

Galaxies at z>6 need <100 kpc damping length

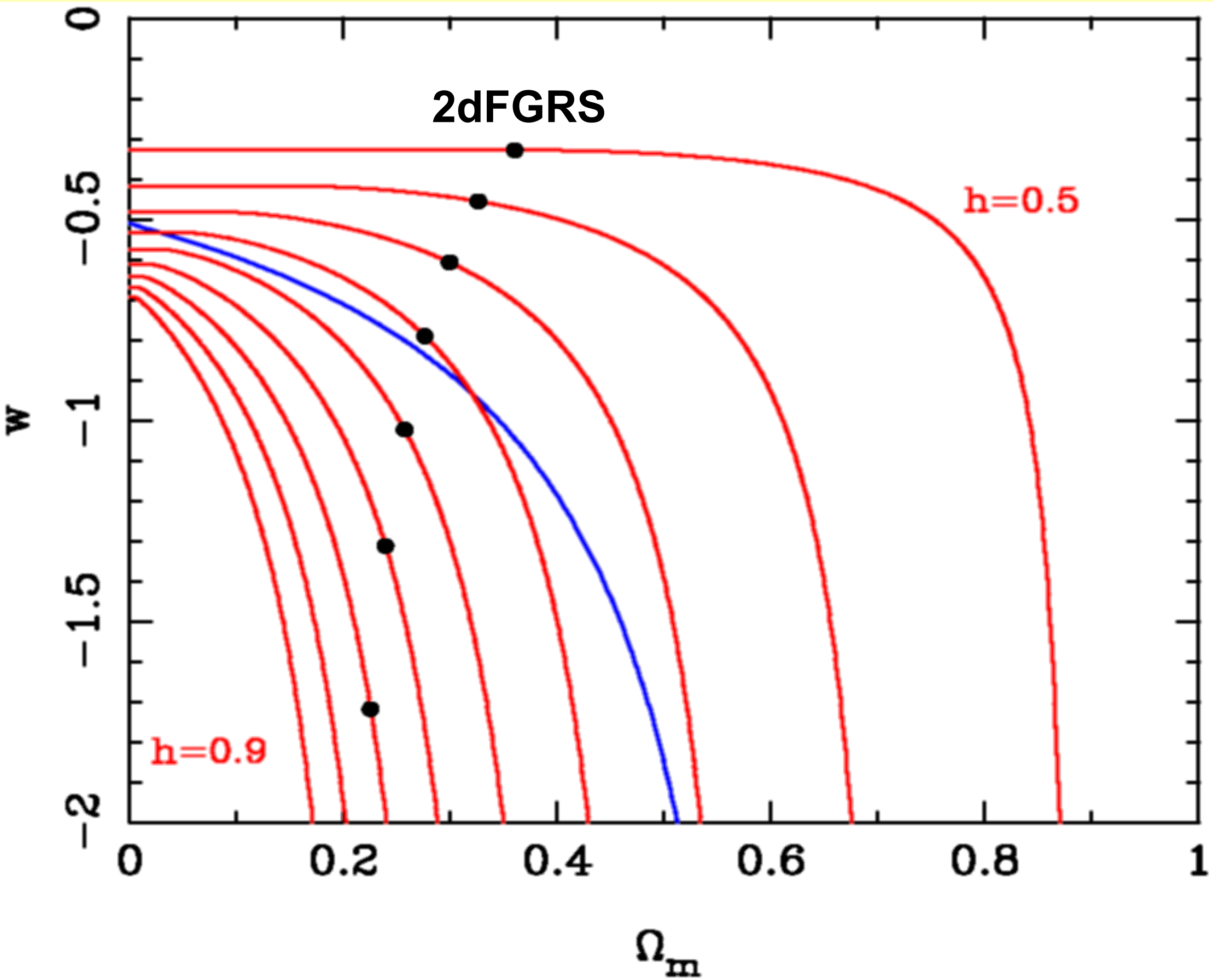


m > 0.75 keV from the Ly-alpha forest

(Narayanan et al. 2000)



Equation of state of vacuum (Dark tension): $P = w \rho c^2$

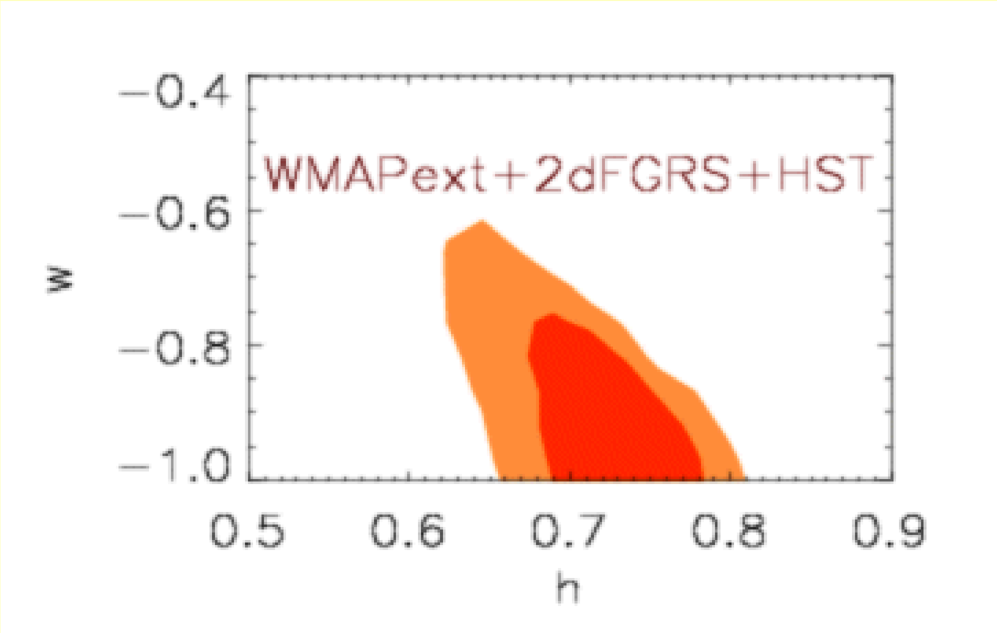


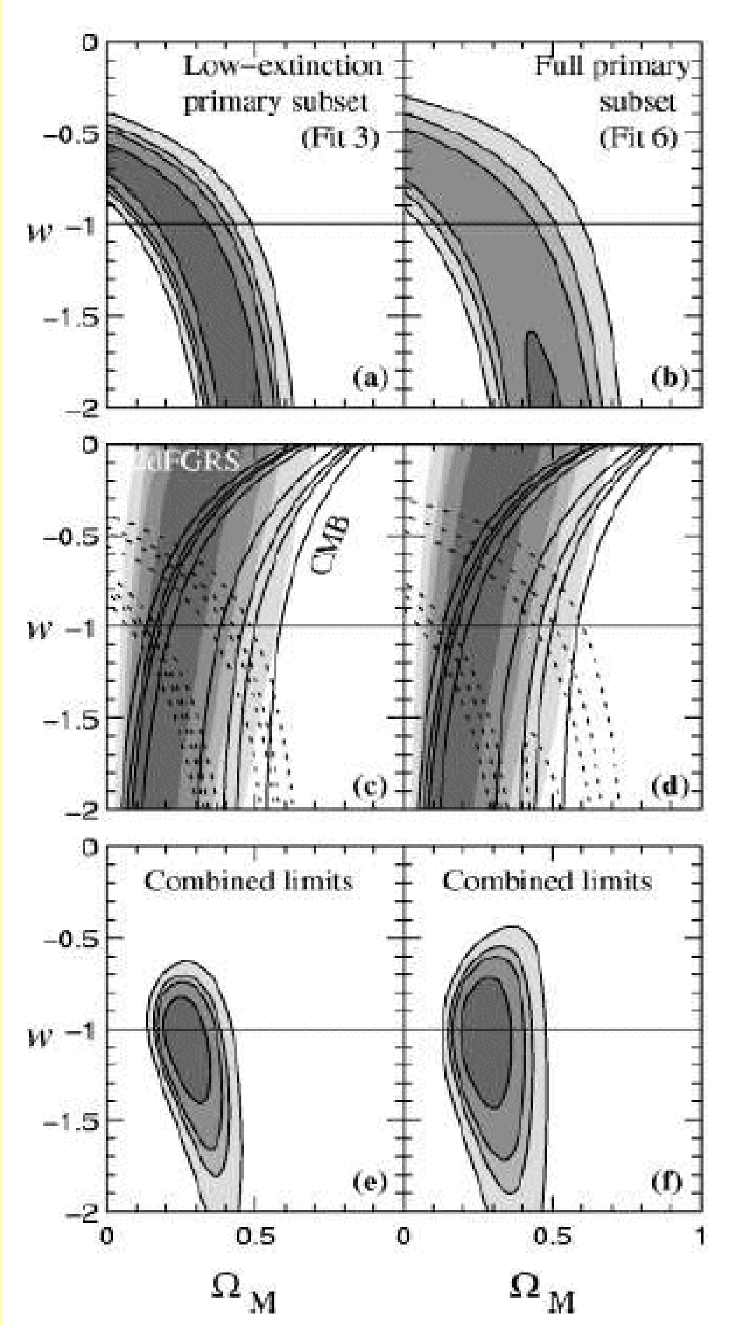
w shifts present horizon, so different Ω_m needed to keep CMB peak location for given h

$w < -0.54$

similar limit from Supernovae: $w < -0.8$ overall

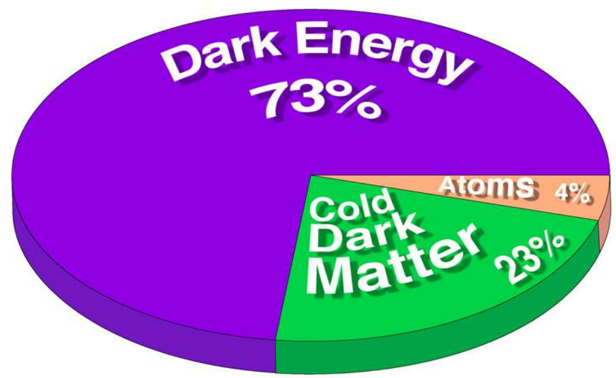
Consistent constraints from CMB/LSS and SNe



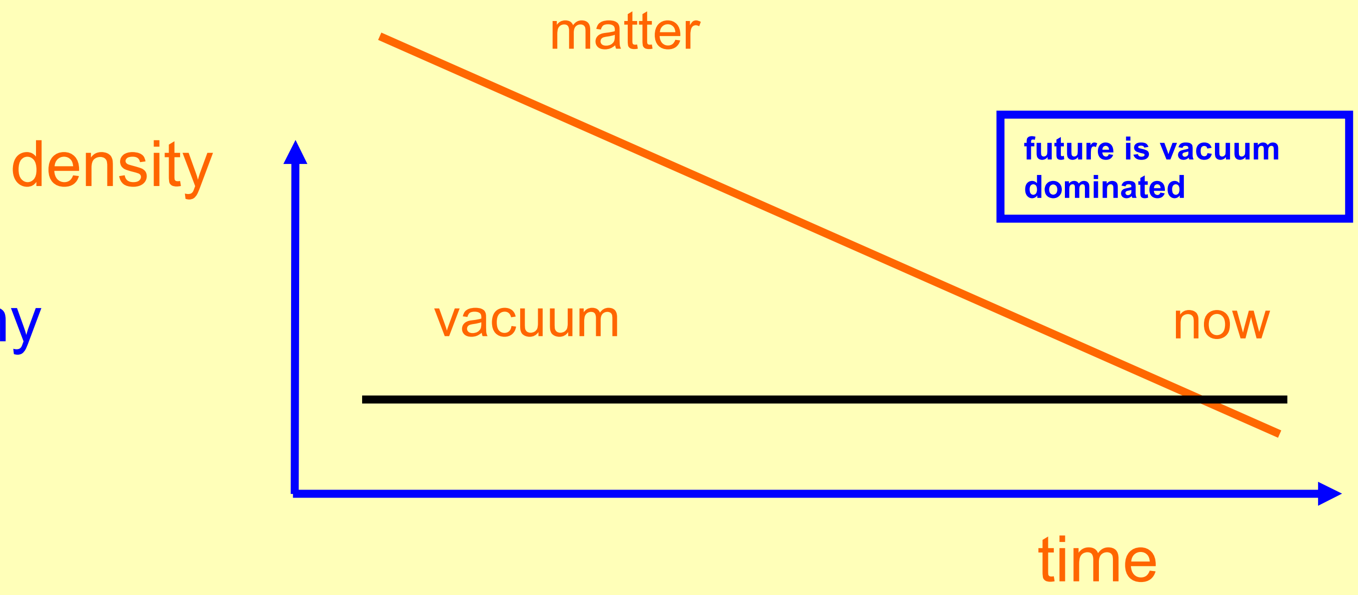


w = -1 ± 15%

The cosmic puzzle



Why so many constituents at similar level? If CDM is a WIMP, CDM/baryon equality is a coincidence



Vacuum energy: why now? Probably needs anthropic selection