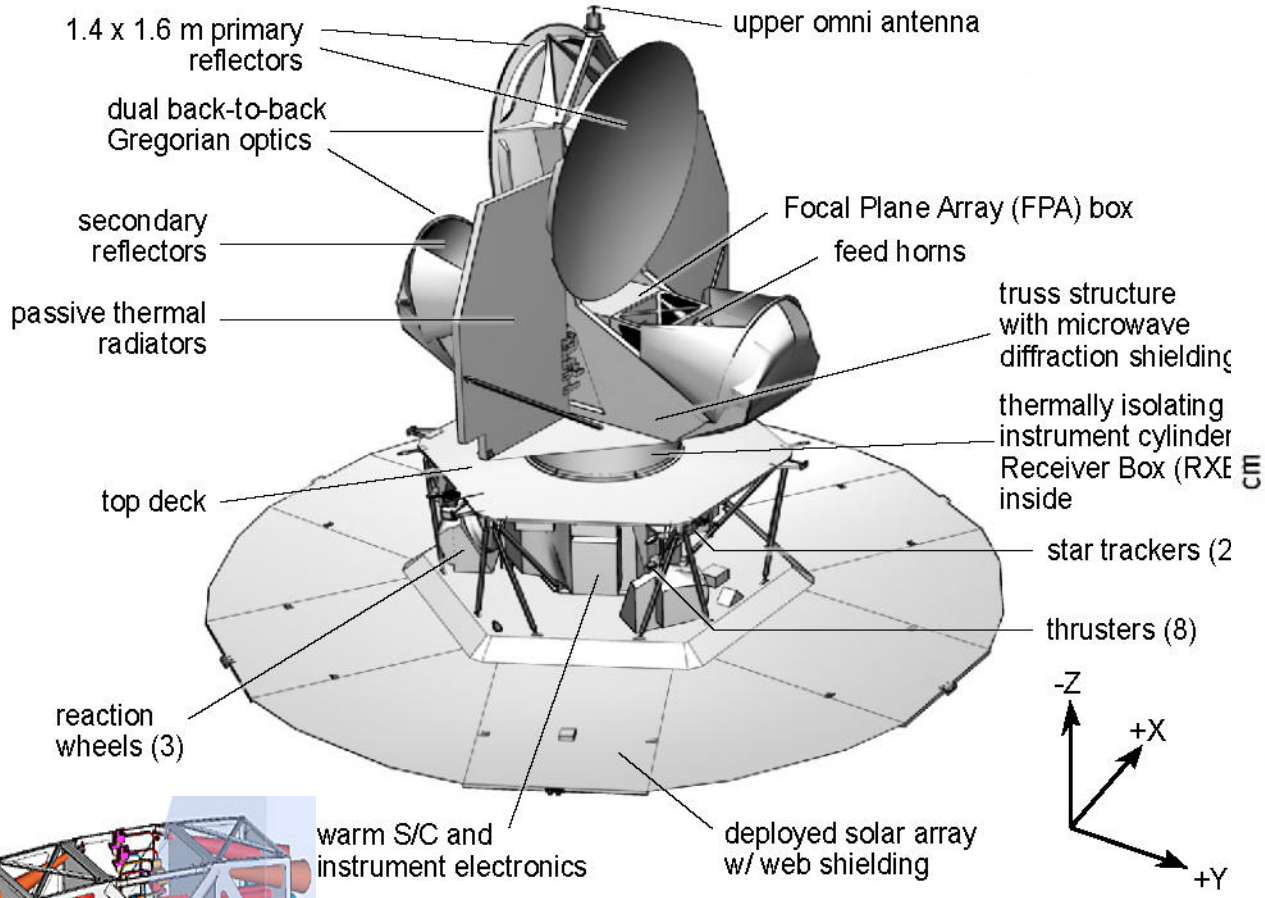
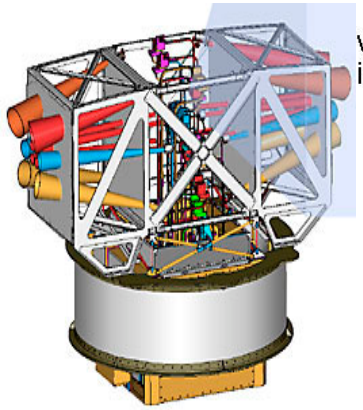
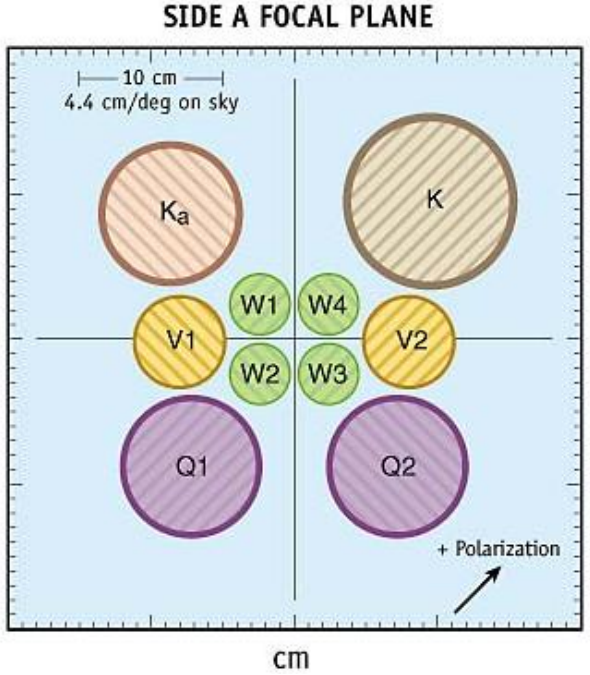
The WMAP satellite

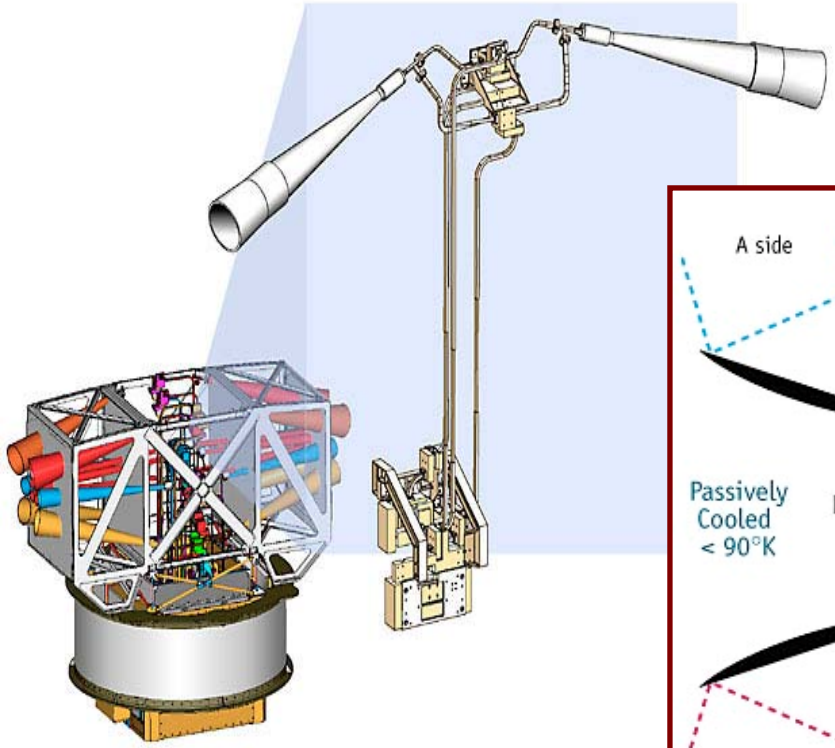


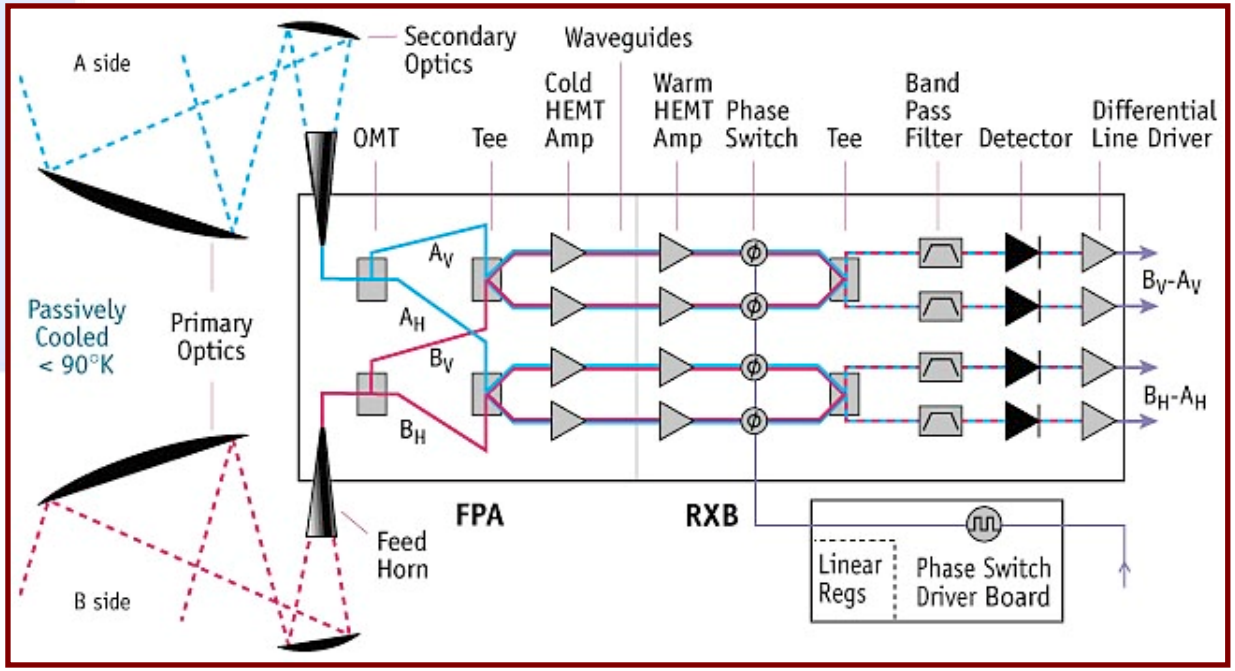




Frequency (GHz)	22 K	30 K_a	40 Q	60 V	90 W
FWHM, degrees	0.93	0.68	0.53	0.35	<0.23

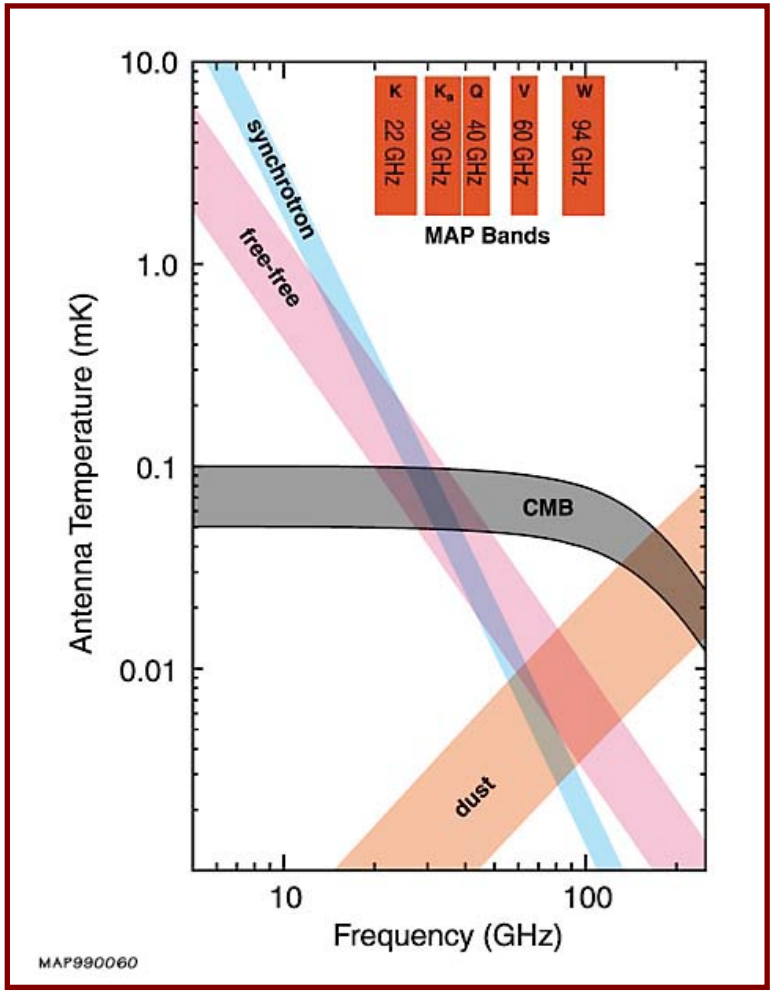
WMAP Receivers





Output: $V/s = (A^2 - B^2)g_1(t)g_2(t) = (T_A - T_B)\, g_1(t)g_2(t)$

Frequency Coverage



Frequency range:

$\nu < 22$ GHz can be observed from ground

$\nu > 100$ GHz foregr. from dust too high

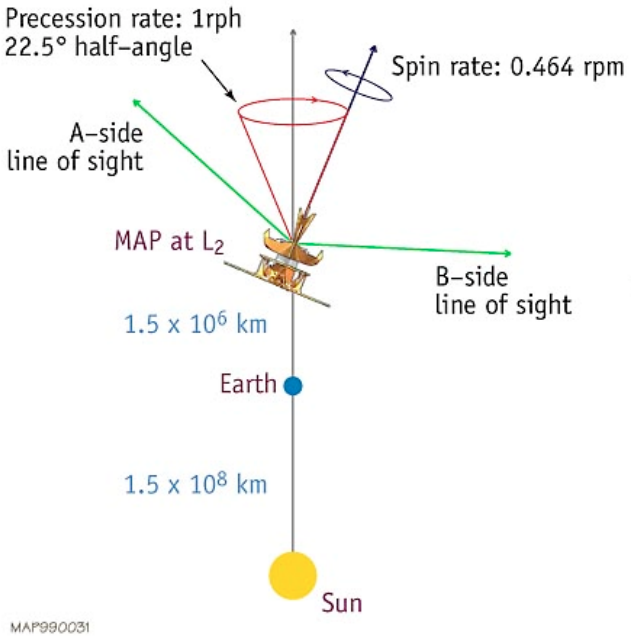
Foreground removal techniques

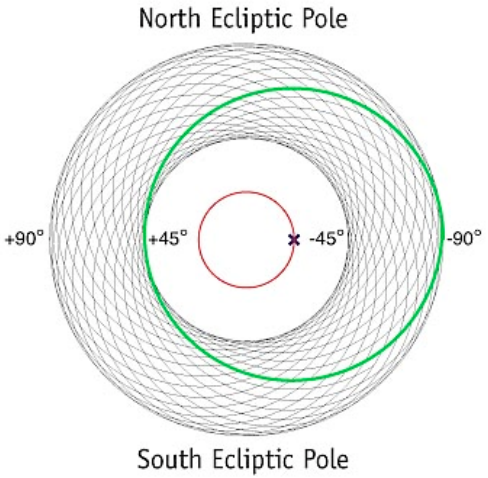
Technique 1: Template maps from other experiments (radio, infrared)

Technique 2: Take spectrum of each (= 4) source from theory and combine data from several frequencies

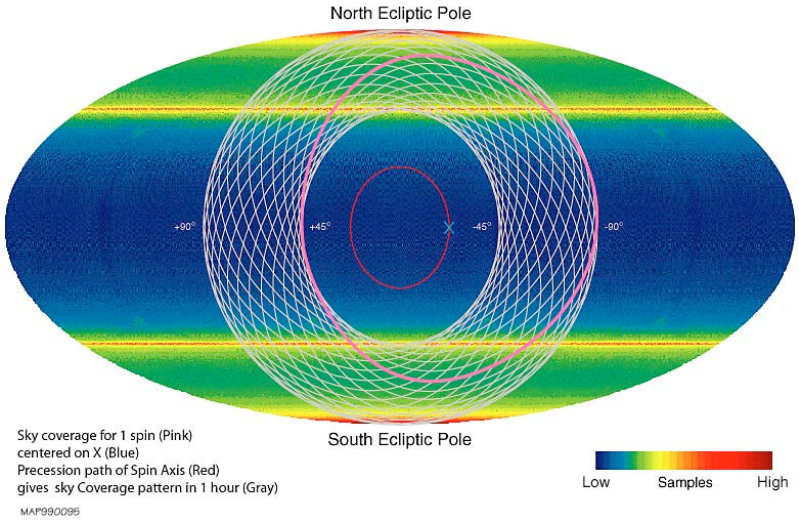
Technique 3: Combine 1 and 2

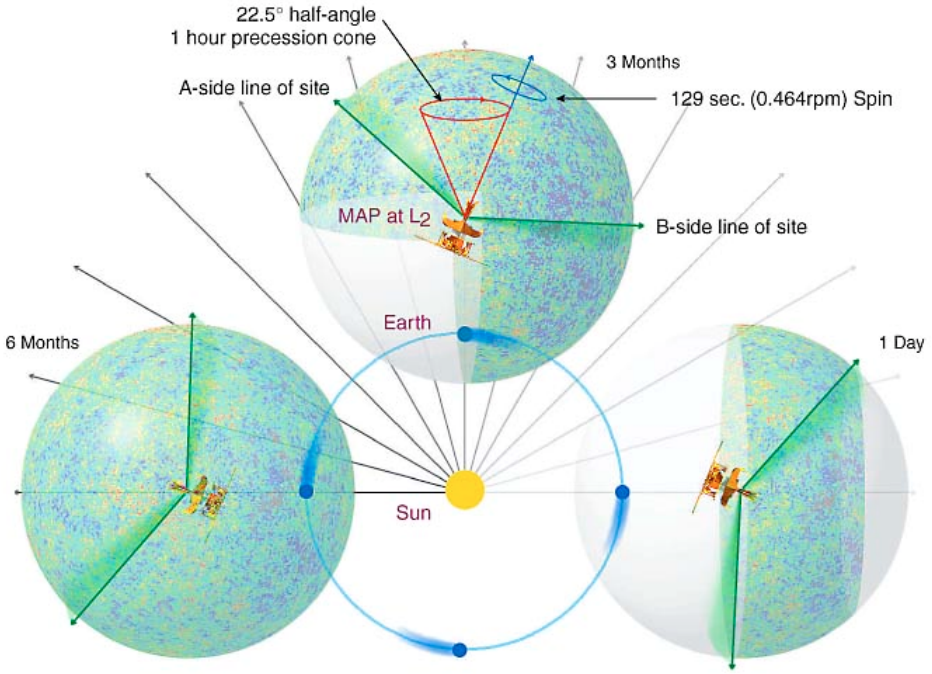
Scan Strategy



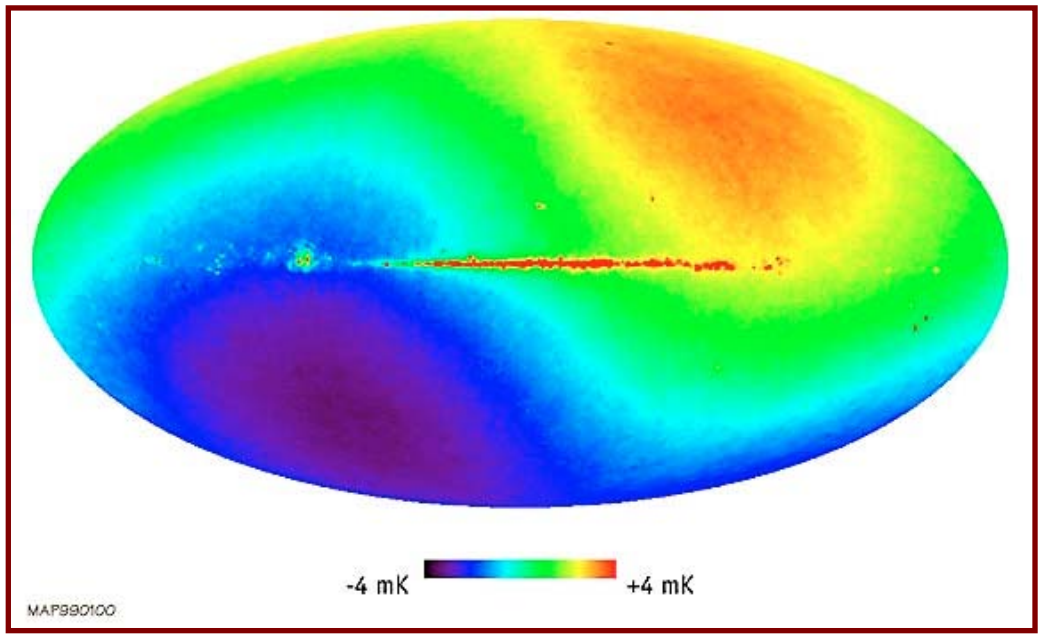


- 30% of sky per day
- Full sky after 6 months





Calibration



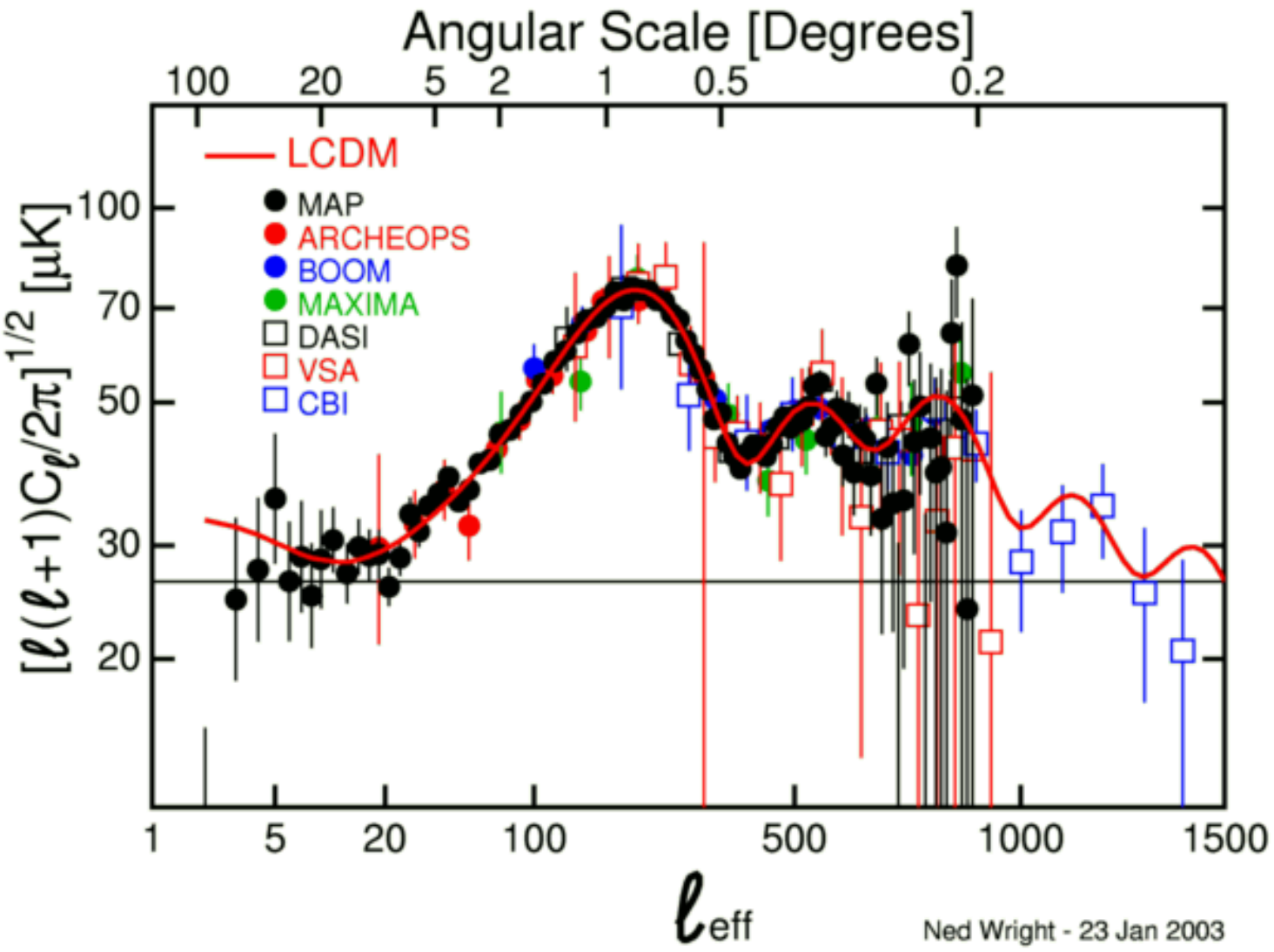
- Dipole measured by COBE
- Use dipole modulation due to motion of WMAP with respect to the Sun

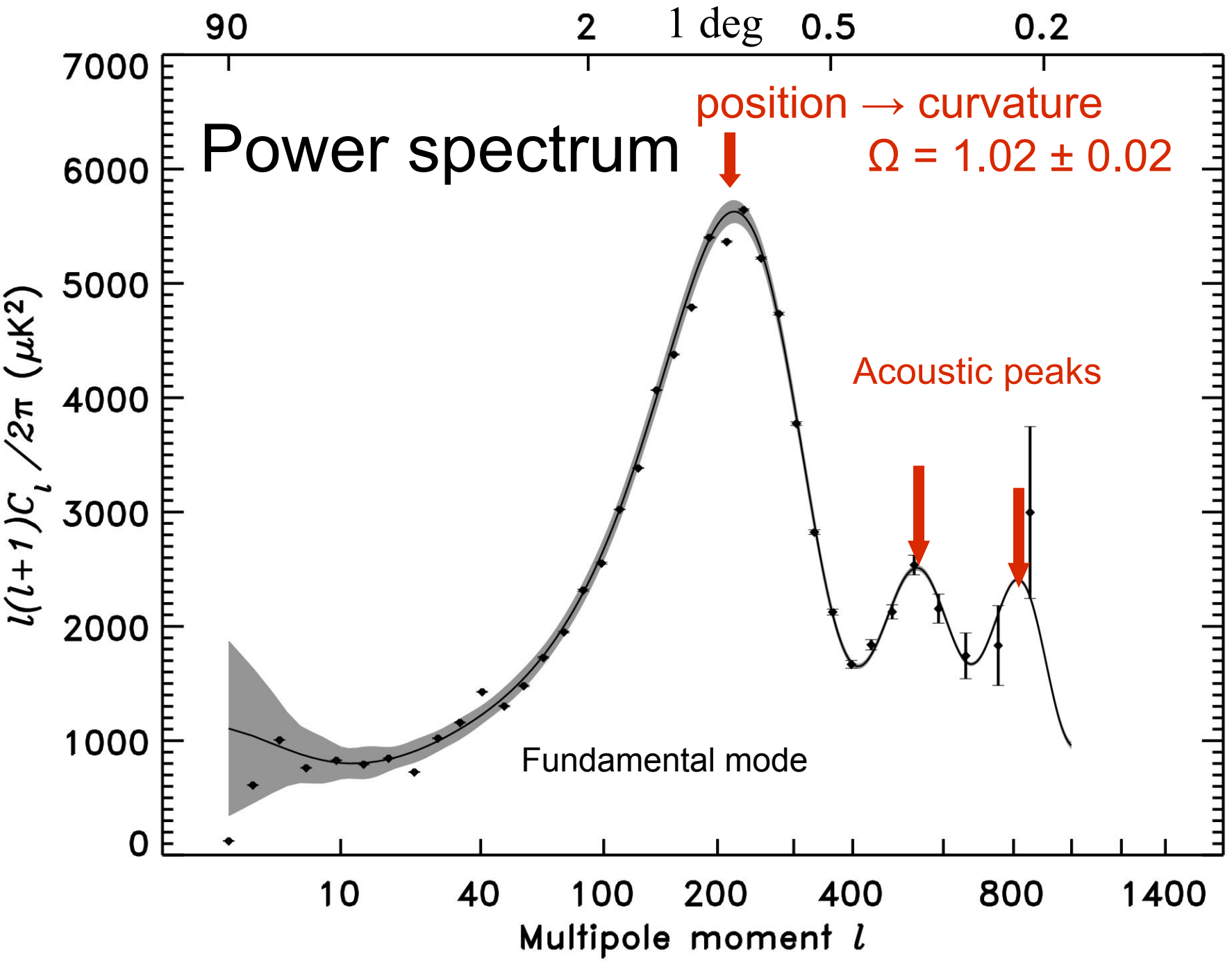
CBI

radio telescope
at 5040 m
in the Andes (Chile)

Boomerang

More Measurements



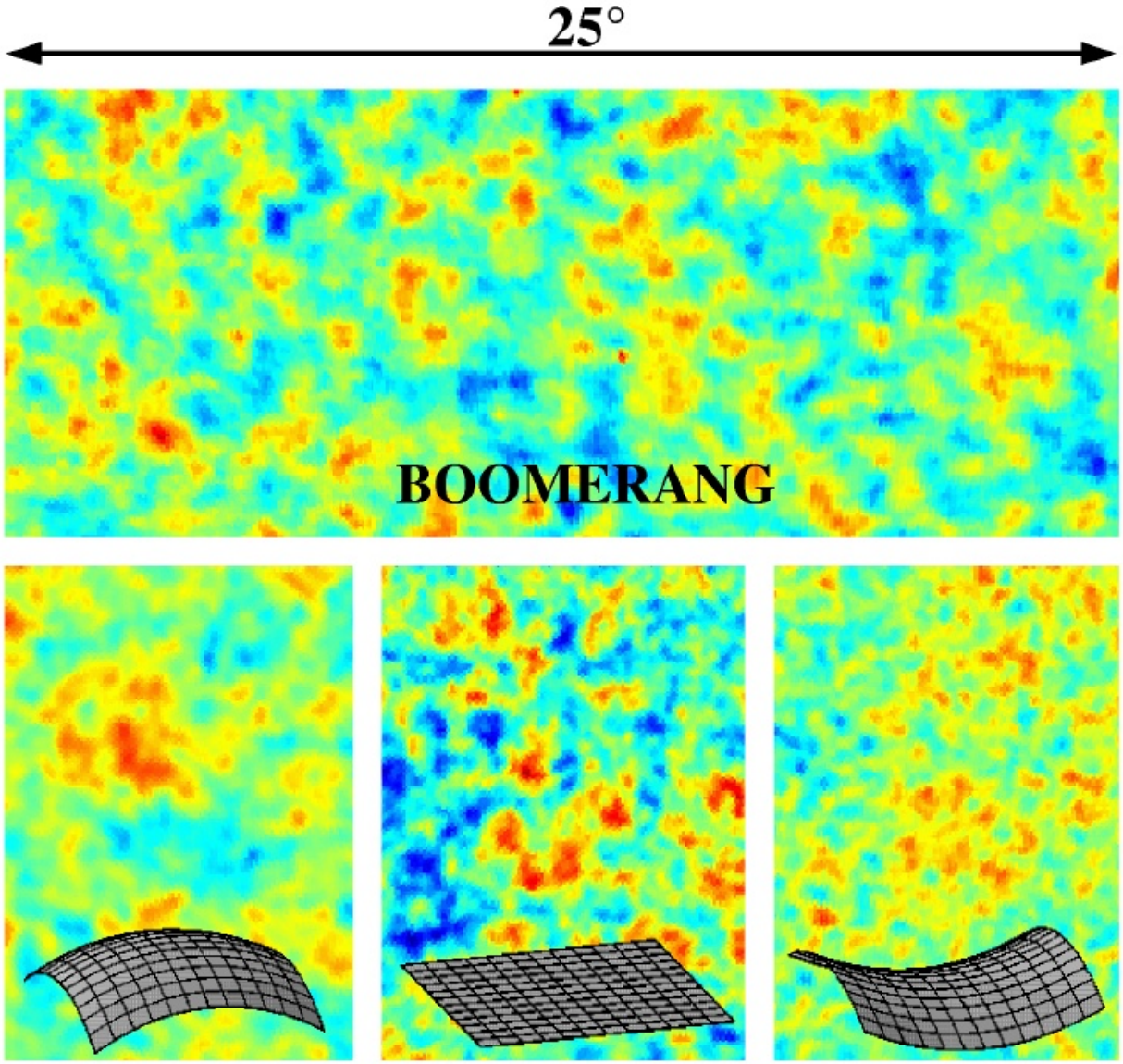

90
2
1 deg
0.5
0.2
Power spectrum
position → curvature
Ω = 1.02 ± 0.02
Acoustic peaks
Fundamental mode
7000
6000
5000
4000
3000
2000
1000
0
l(l+1)C_l /2π (μK²)
10
40
100
200
400
800
1400
Multipole moment l

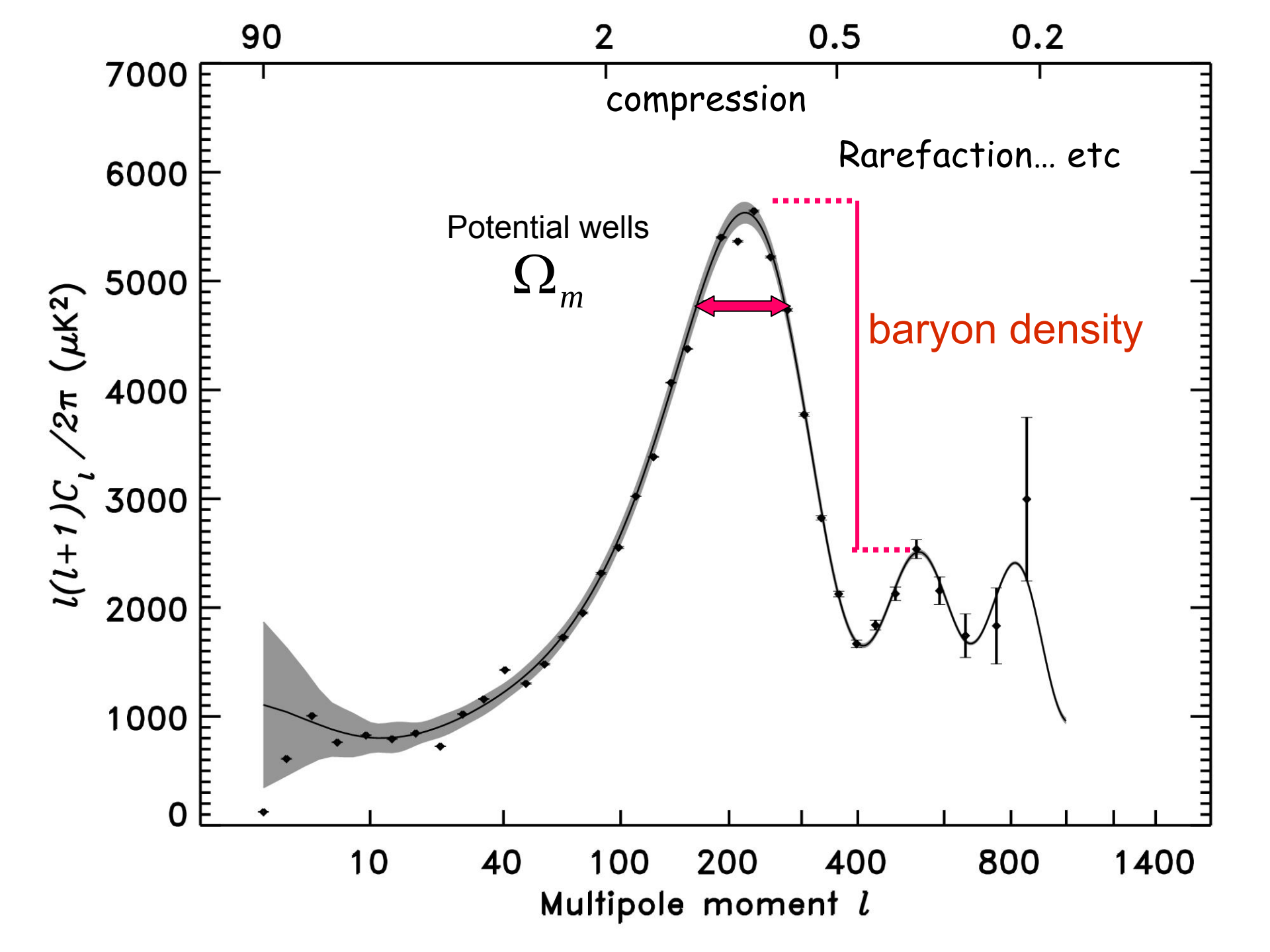
Interpretation

position of first peak = size of sound horizon at recombination (plasma $\rightarrow$ neutral atoms)
$l \sim 200 \Rightarrow \Omega_{tot} = 1.02 \pm 0.02$

The universe is flat!

Curvature Model Calculations




90
2
0.5
0.2
compression
Rarefaction… etc
Potential wells
Ω_m
baryon density
$l(l+1)C_l/2\pi$ (μK^2)
7000
6000
5000
4000
3000
2000
1000
0
10
40
100
200
400
800
1400
Multipole moment l

Interpretation

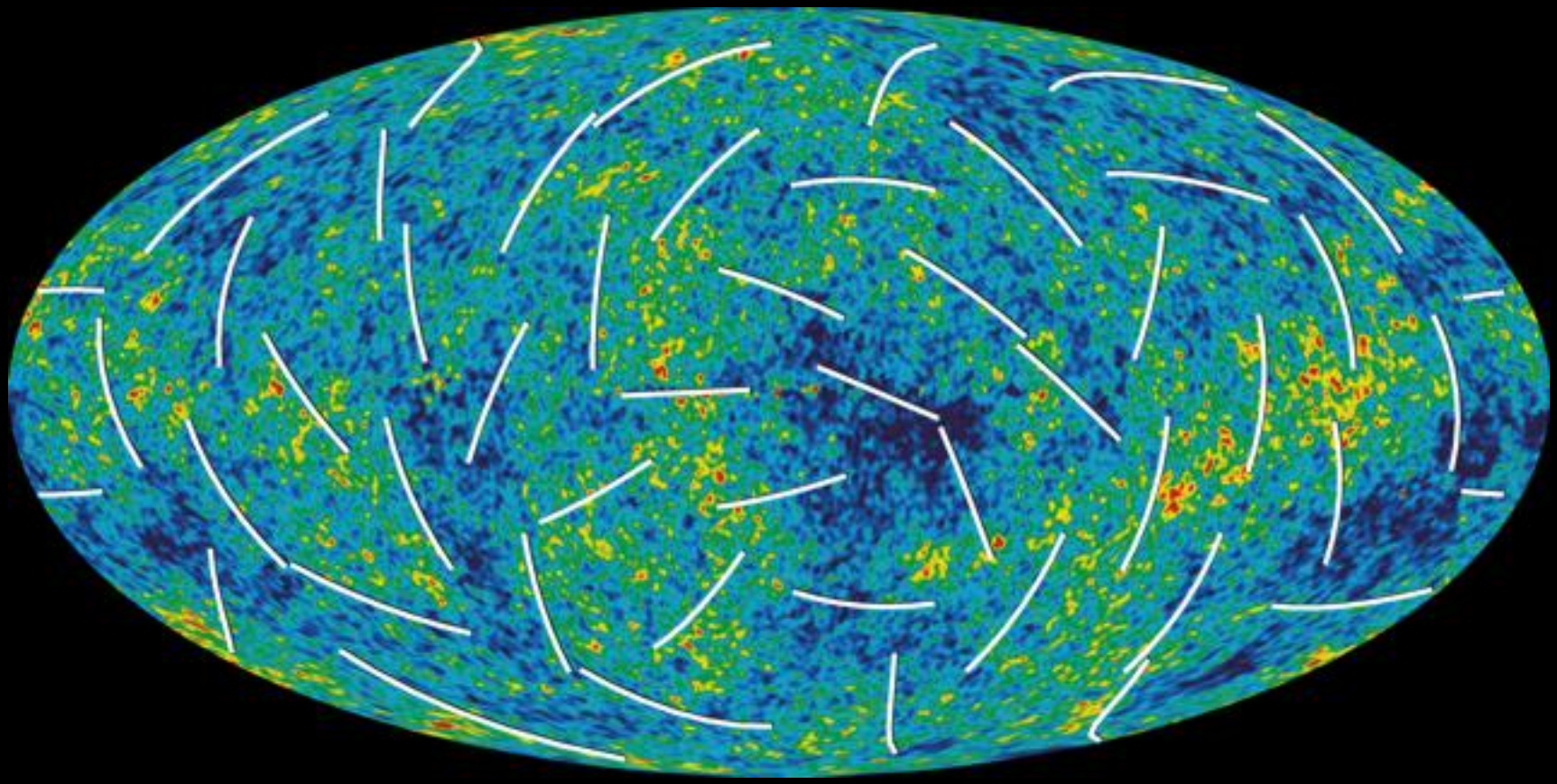
Baryon to photon ratio:
baryons (i.e. nuclei, mostly protons and ^{4}He)
increase effective mass of fluid, i.e. change balance between pressure and gravity

increase baryon density
→ greater compression in gravity potential well
→ compressions are enhanced over rarefactions
→ relative height of peaks measure compression : rarefaction ratio, so the baryon density

$\Omega_b = 0.047 \pm 0.006$

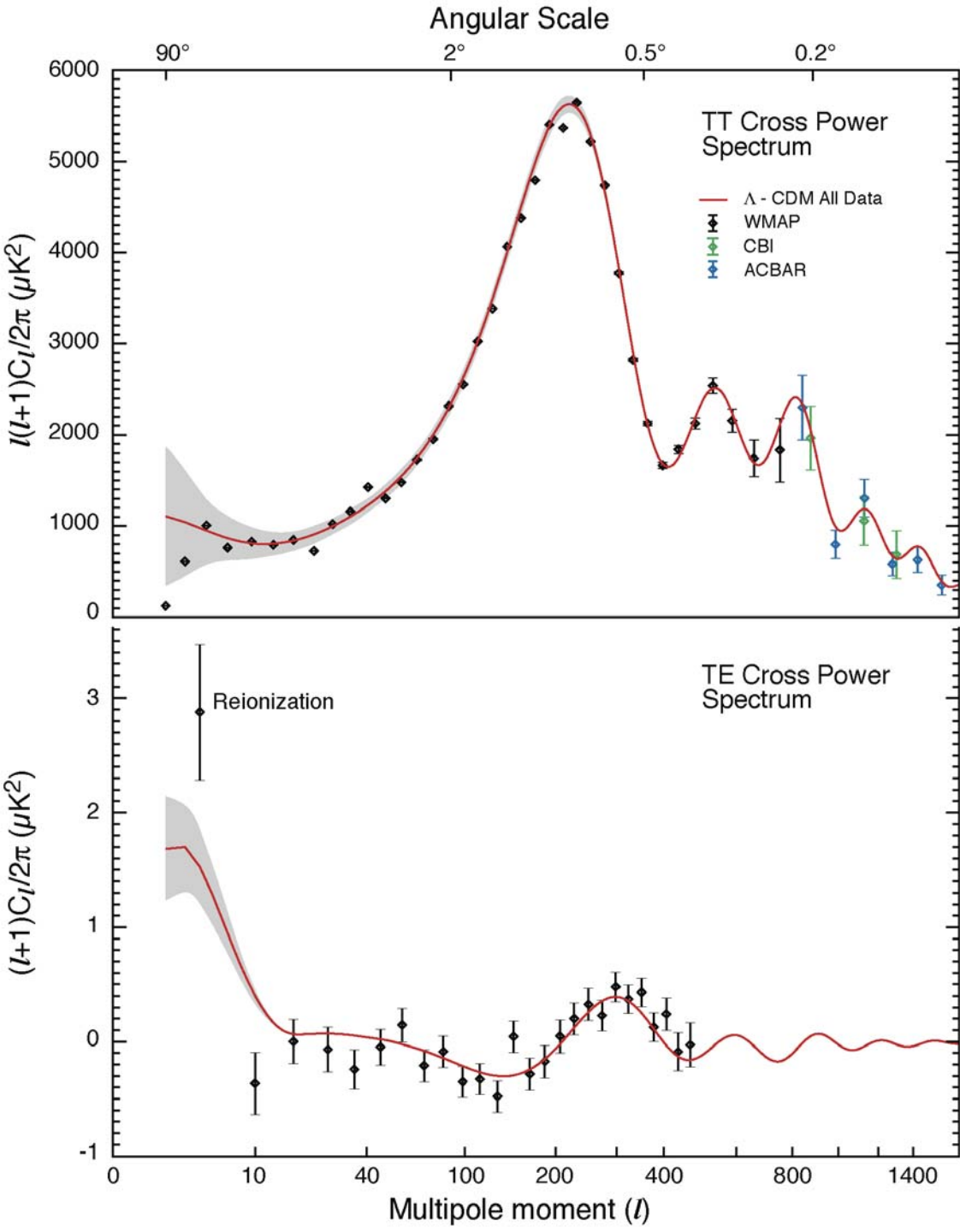
Ordinary matter only 5% of energy density of universe!

Polarisation Measurements

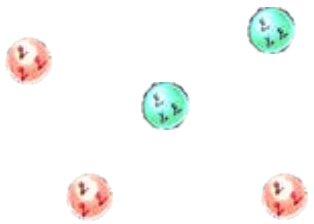


from polarisation correlations:

- optical depth (correction!)
- spectral index
  n = 0.95±0.02 (→ Inflation)



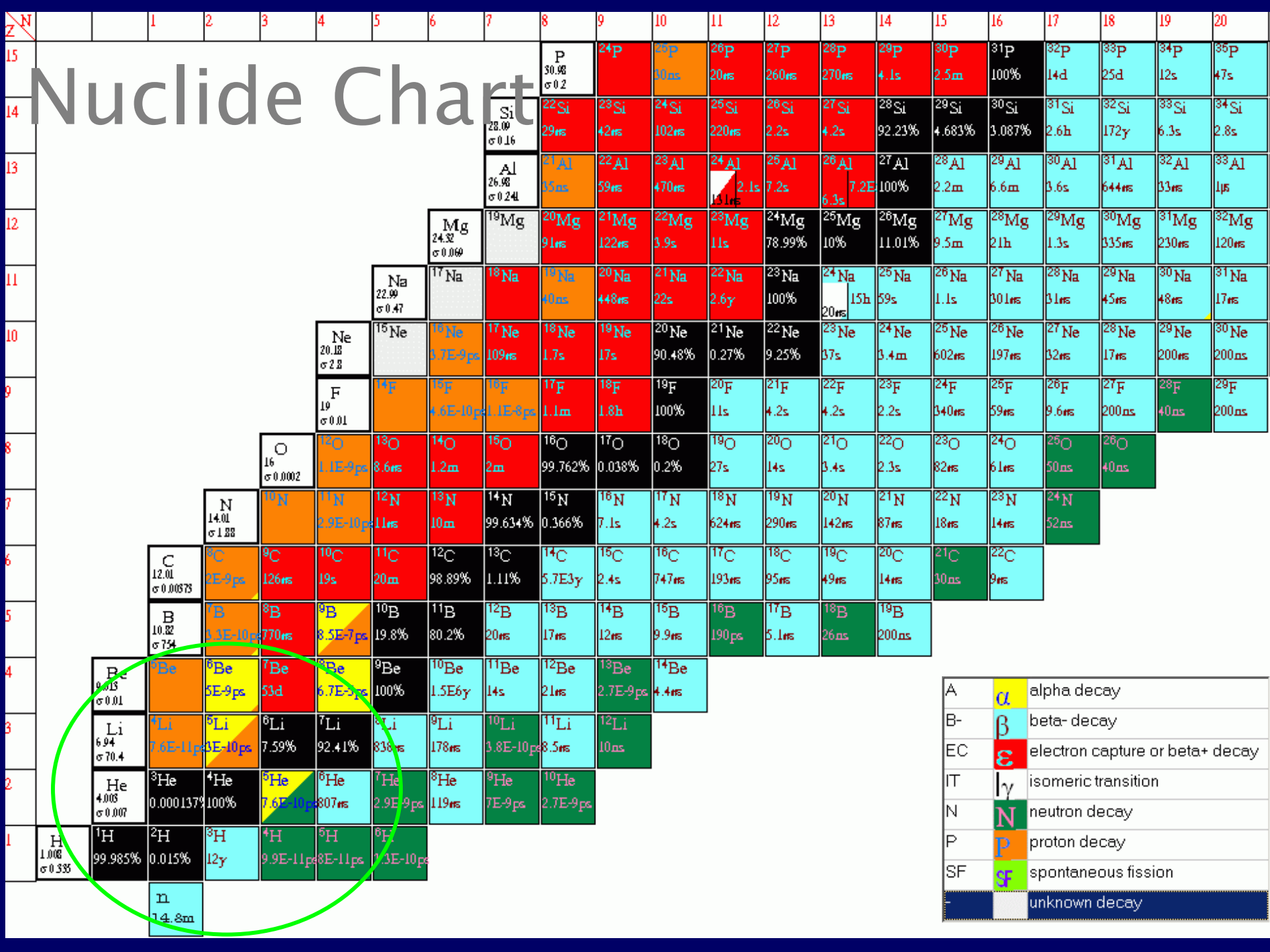
more physics: nucleosynthesis



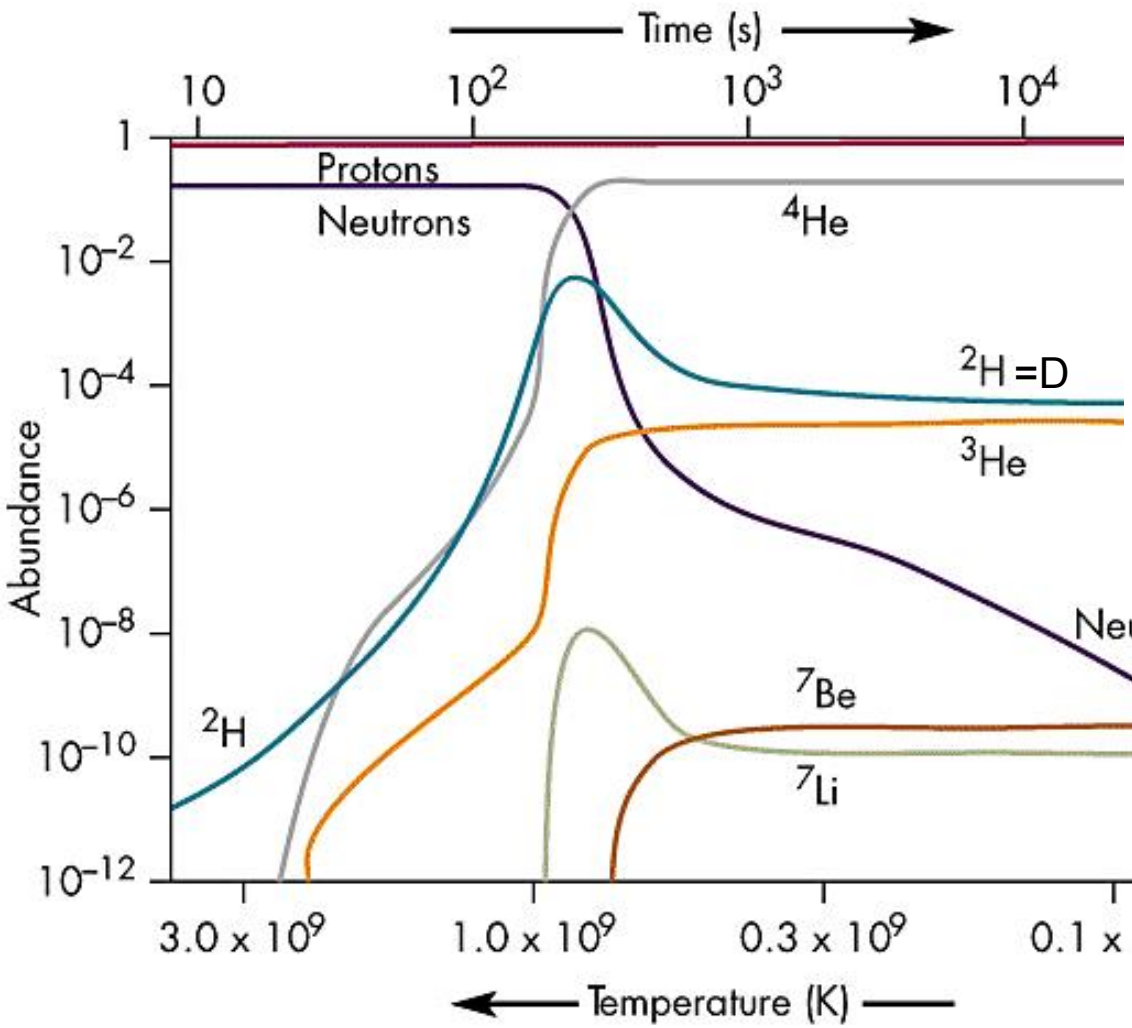
p + n → nuclei

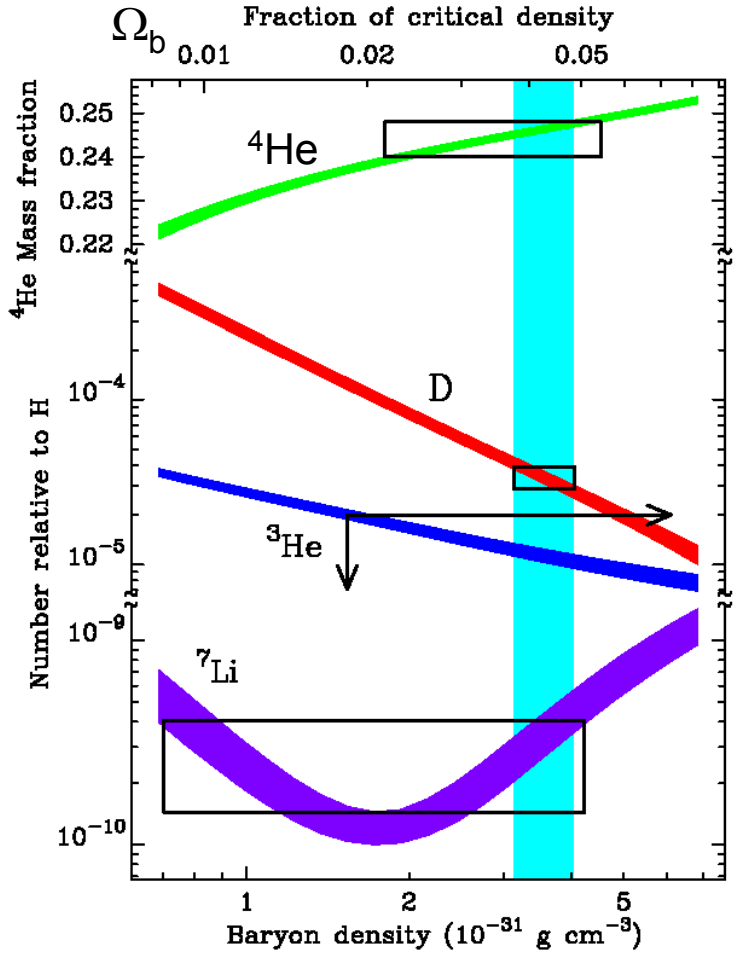
production rate depends

- on nucleon : photon ratio
  (early deuterium D production avoids n loss via decay, i.e. less H remaining)
- high density = effective D + D → ^{4}He means less remaining D


Nuclide Chart
N
Z
P 30.98 σ 0.2
Si 28.09 σ 0.16
Al 26.98 σ 0.241
Mg 24.32 σ 0.069
Na 22.99 σ 0.47
Ne 20.18 σ 2.8
F 19 σ 0.01
O 16 σ 0.0002
N 14.01 σ 1.88
C 12.01 σ 0.00575
B 10.82 σ 754
Be 9.013 σ 0.01
Li 6.94 σ 70.4
He 4.003 σ 0.007
H 1.008 σ 0.333
n 14.8m
A alpha decay
B- beta- decay
EC electron capture or beta+ decay
IT isomeric transition
N neutron decay
P proton decay
SF spontaneous fission
unknown decay

Nucleosynthesis

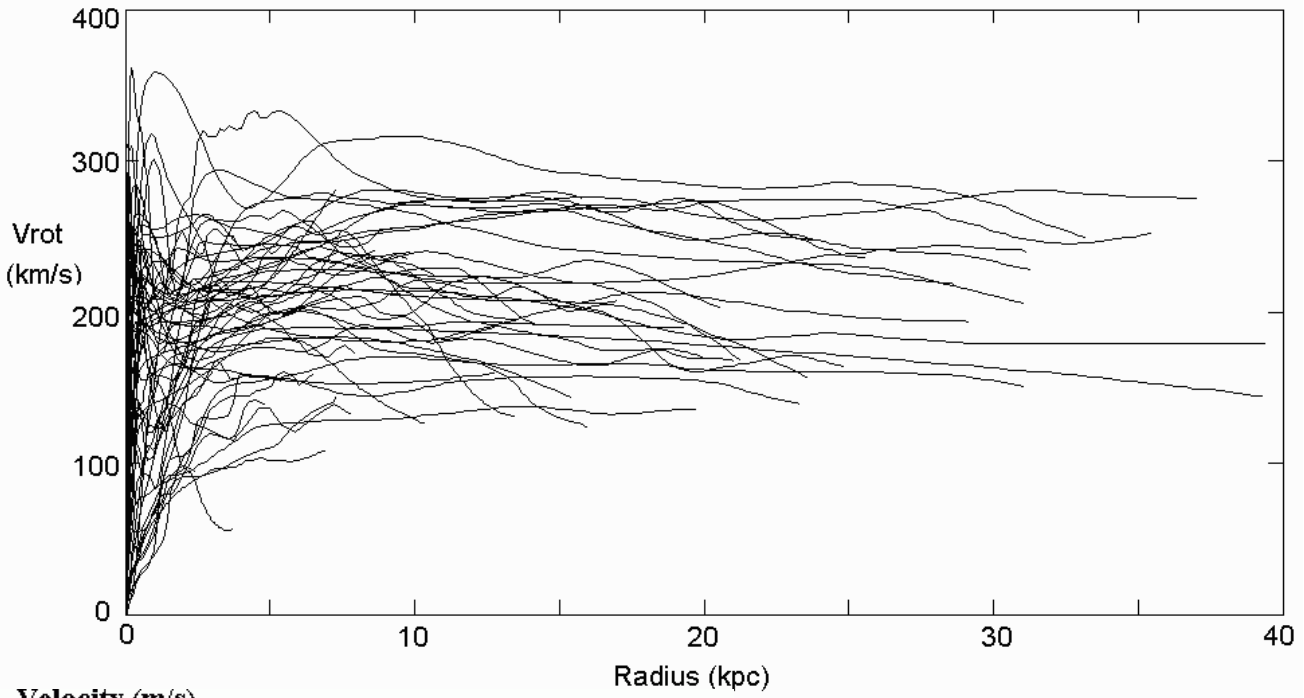


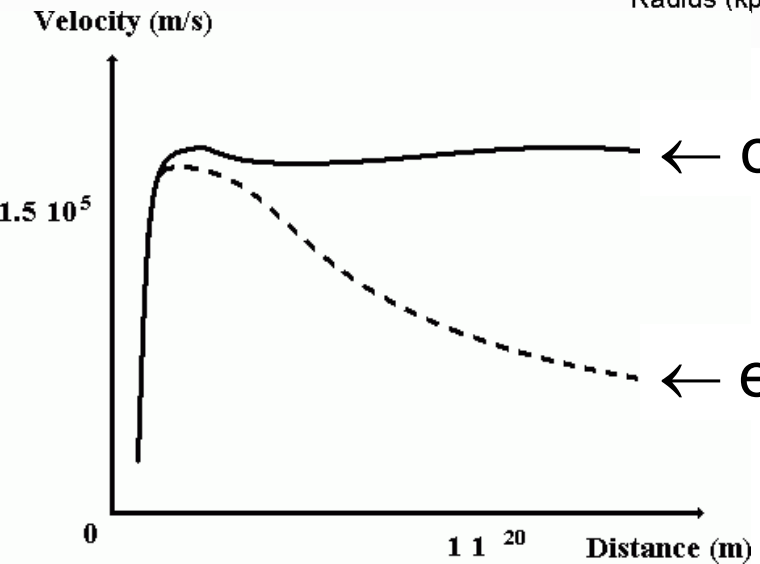


fraction determined by nucleon density

→ $\Omega_b \approx 0.04 \ldots 0.05$

Galaxy Rotation: Dark Matter

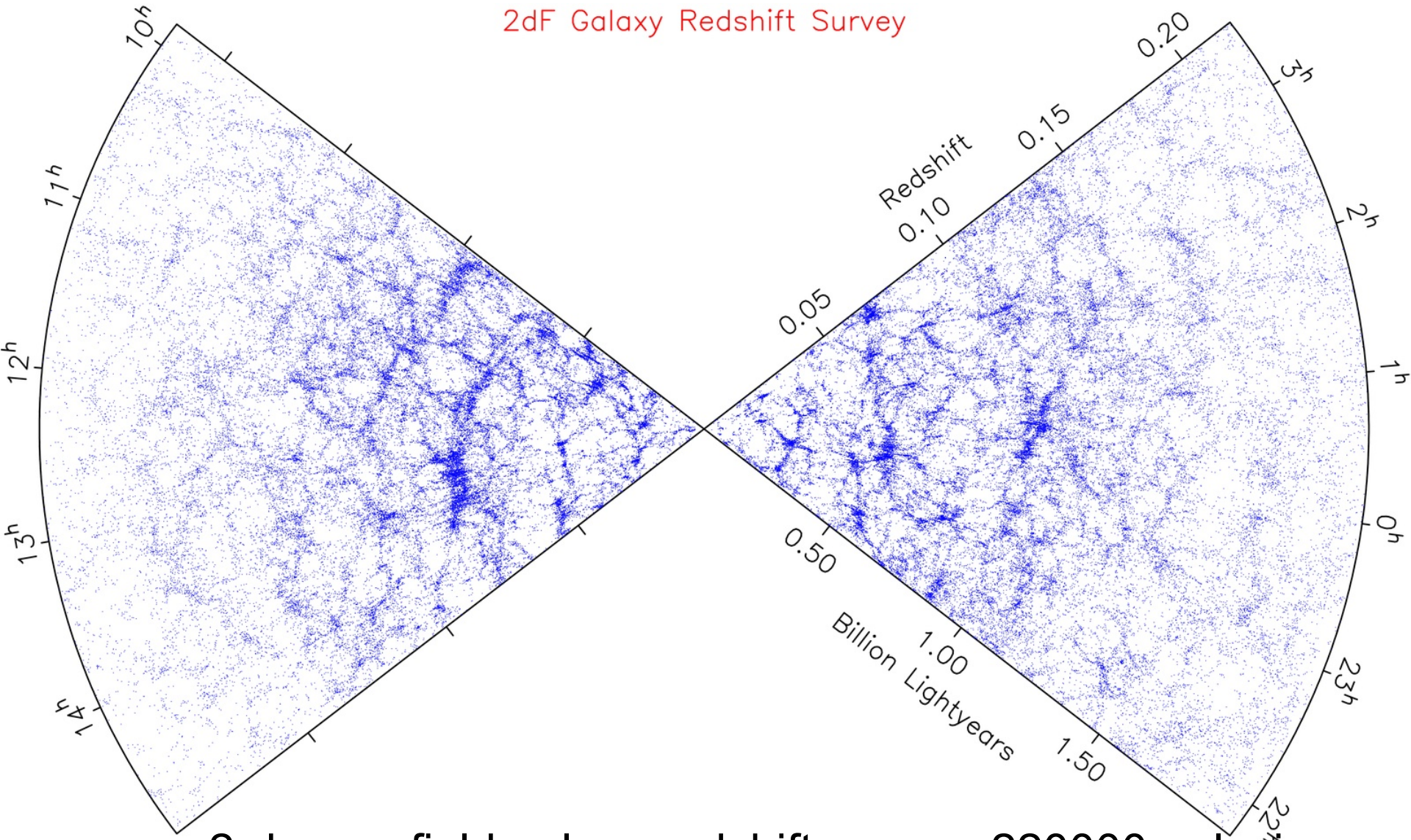




← observed

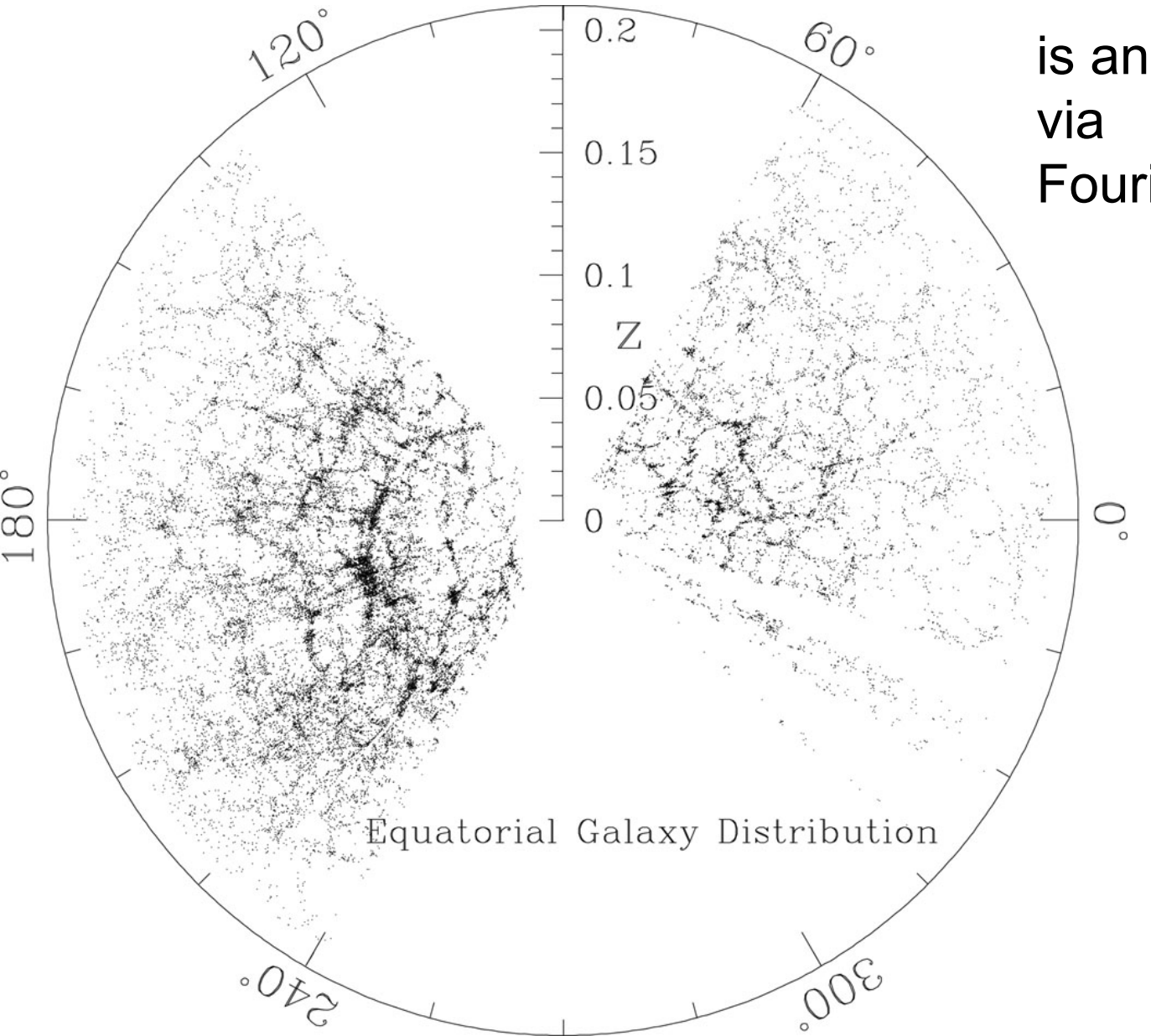
← expected (visible matter = stars)

Visible Matter Distribution



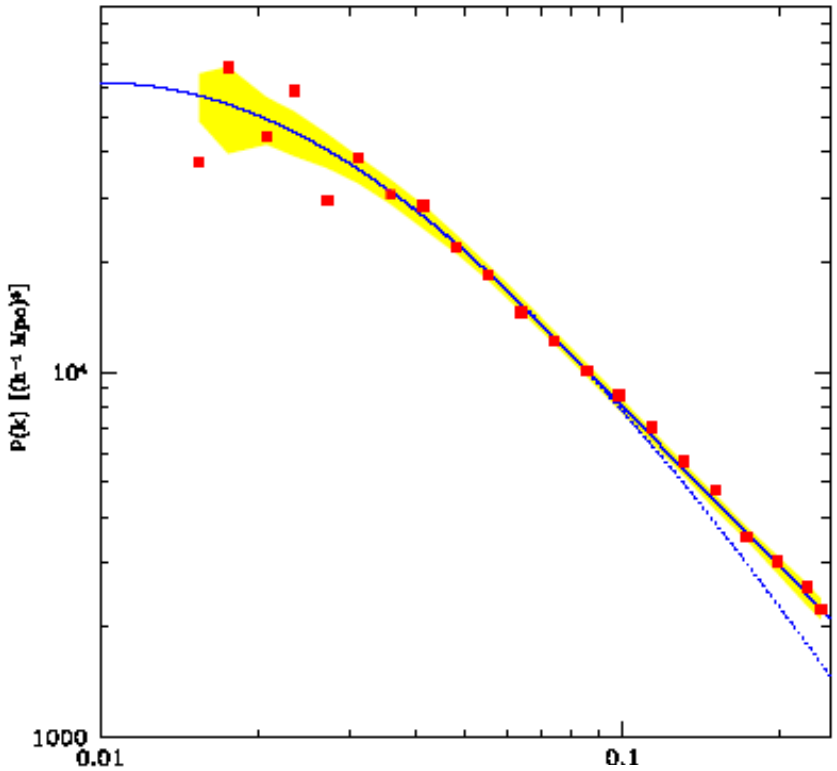
2-degree field galaxy redshift survey, 220000 galaxies

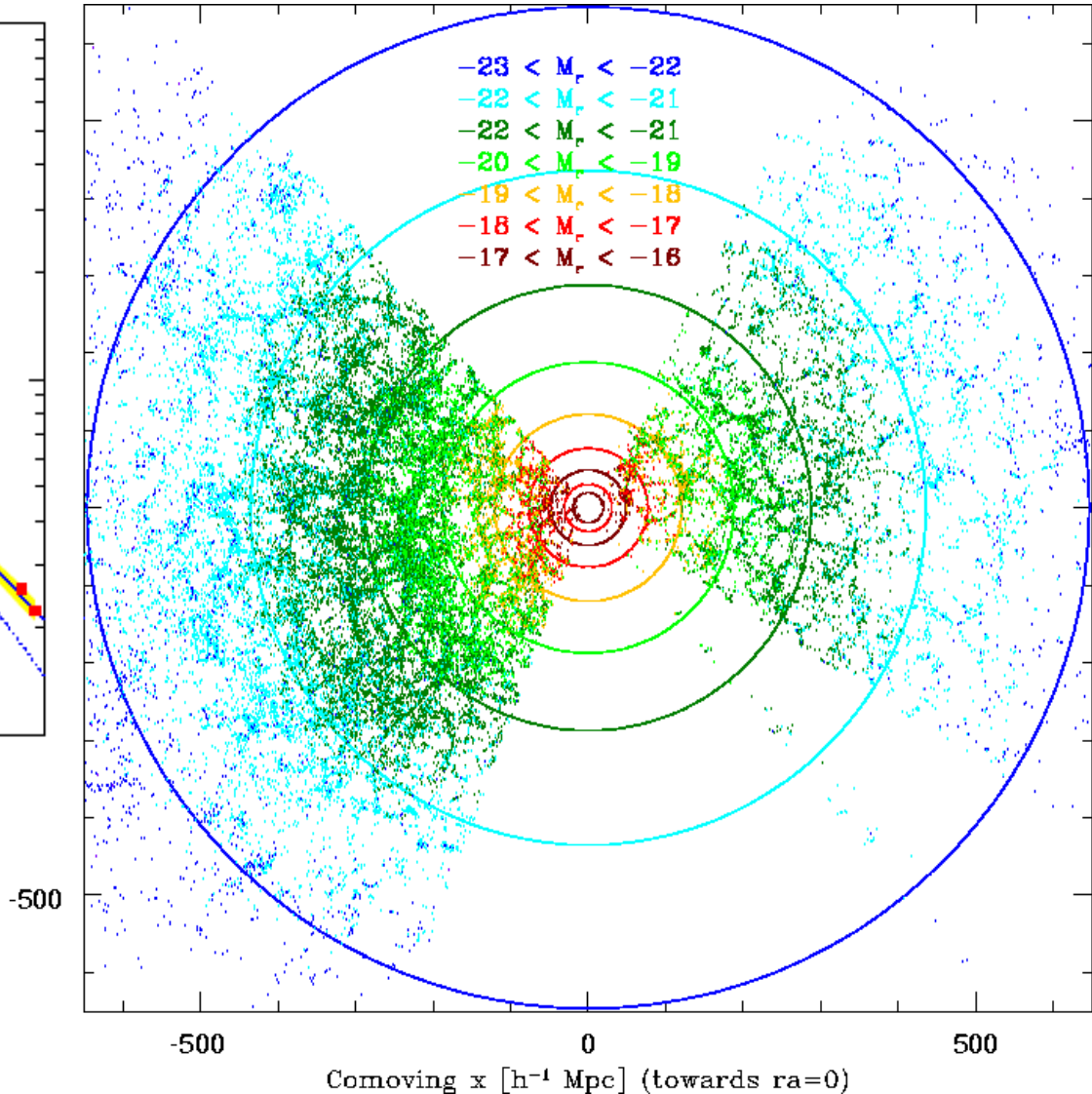
Visible Matter Distribution



is analysed
via
Fourier transformation

Sloan Digital Sky Survey (SDSS) Matter Power Spectrum

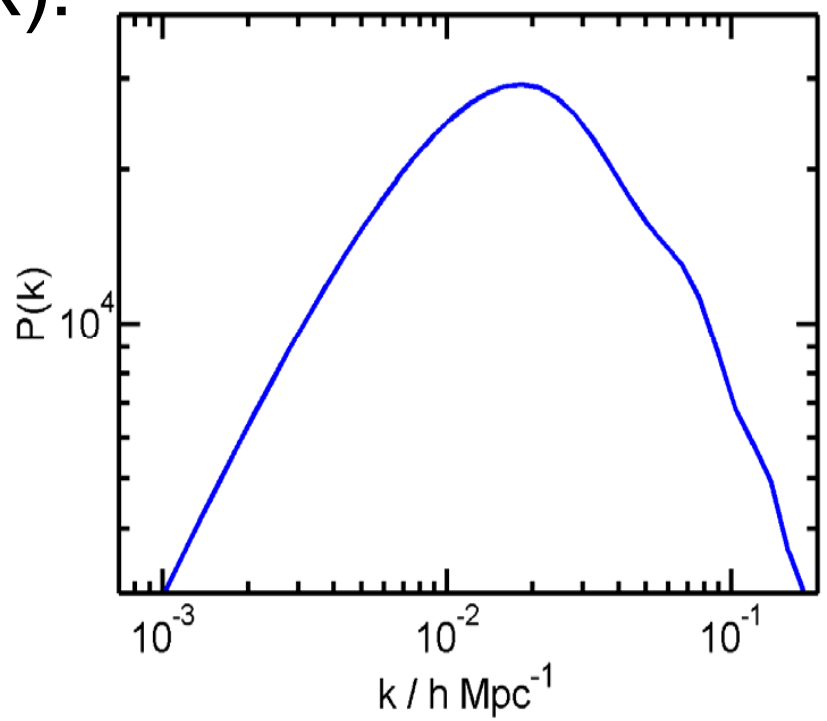




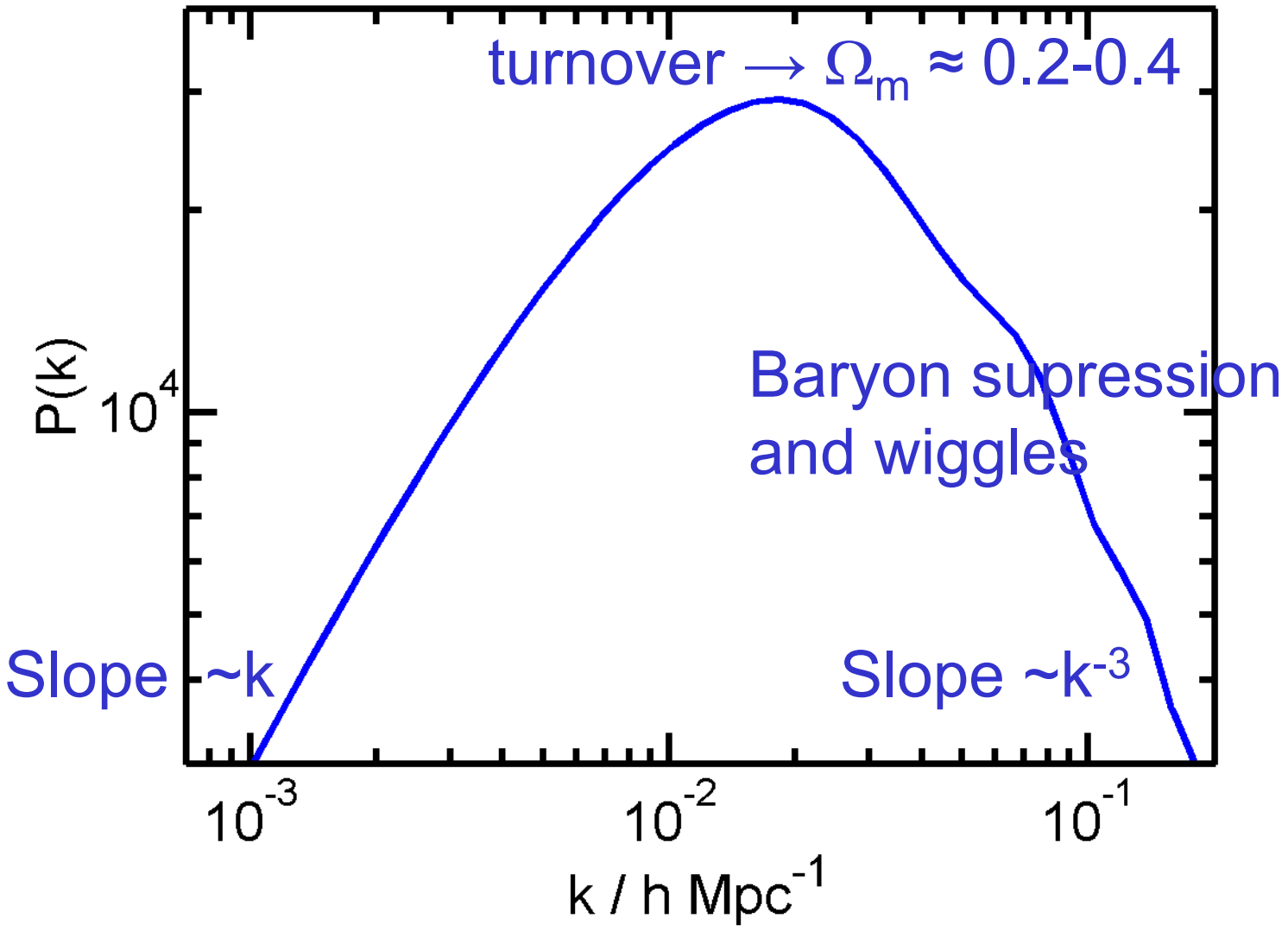
Power Spectrum P(k)

k = Fourier Transform of 3D matter distribution

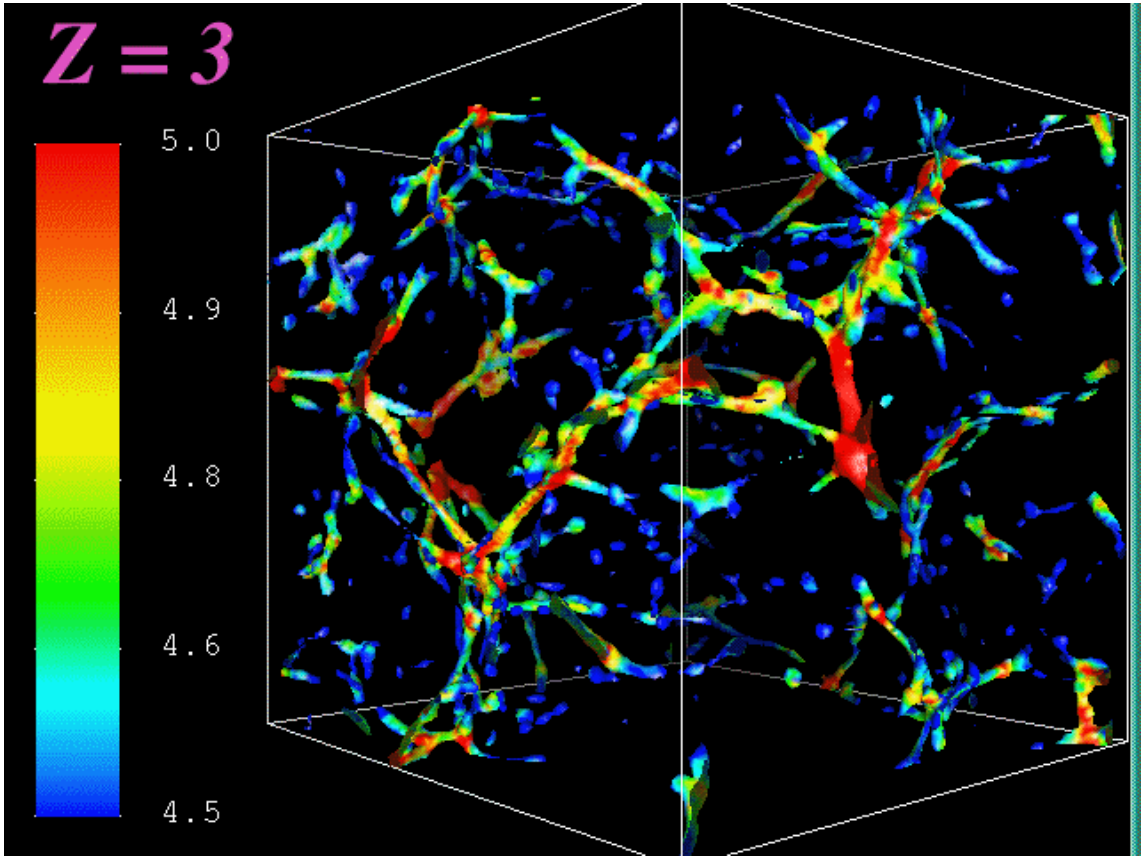
Present day universe P(k):

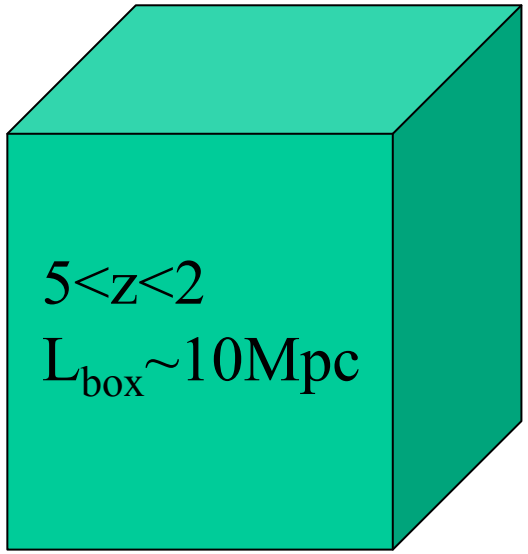


Key Features of Spectrum



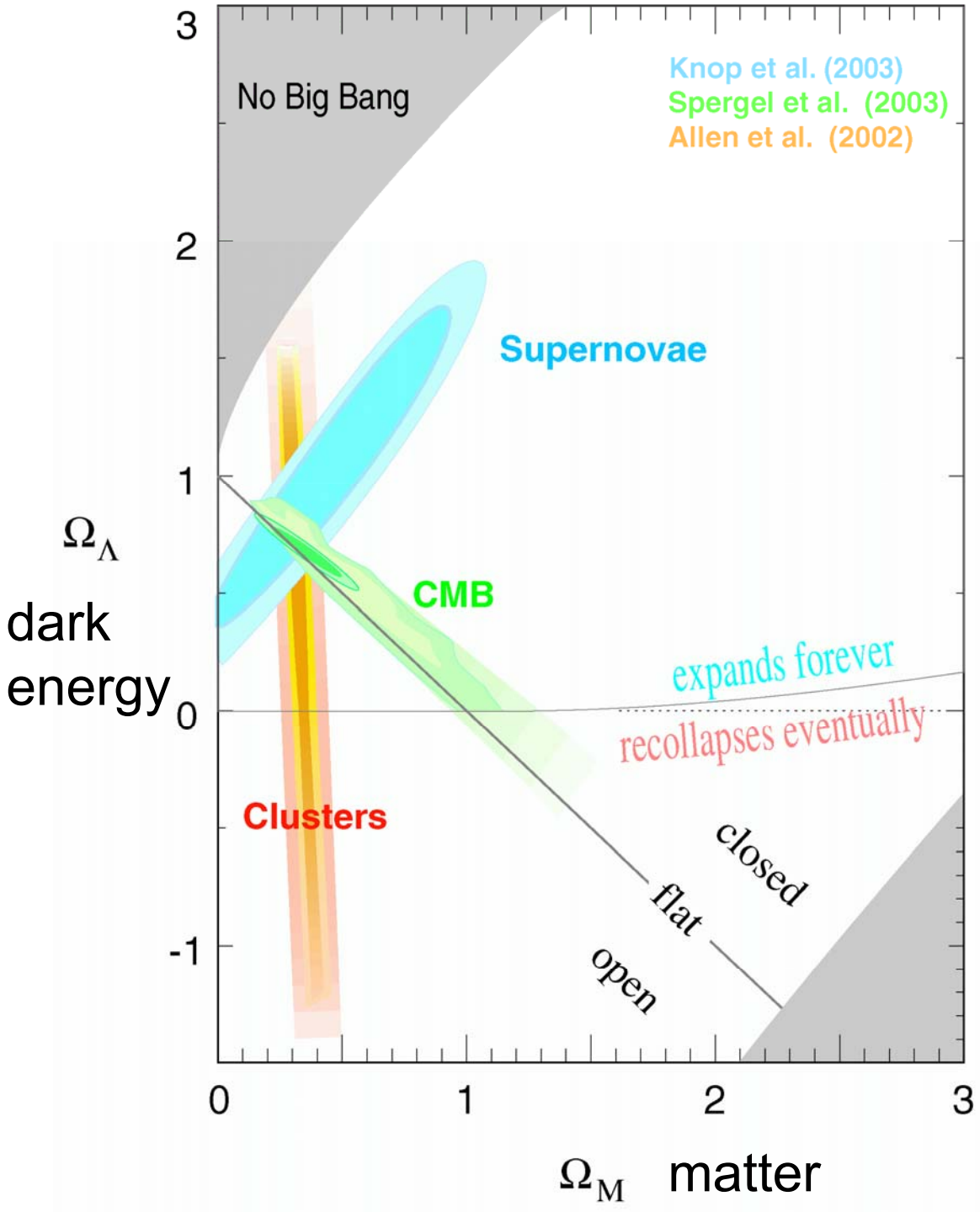
Structure at Large Distance: Hot Intergalactic Hydrogen



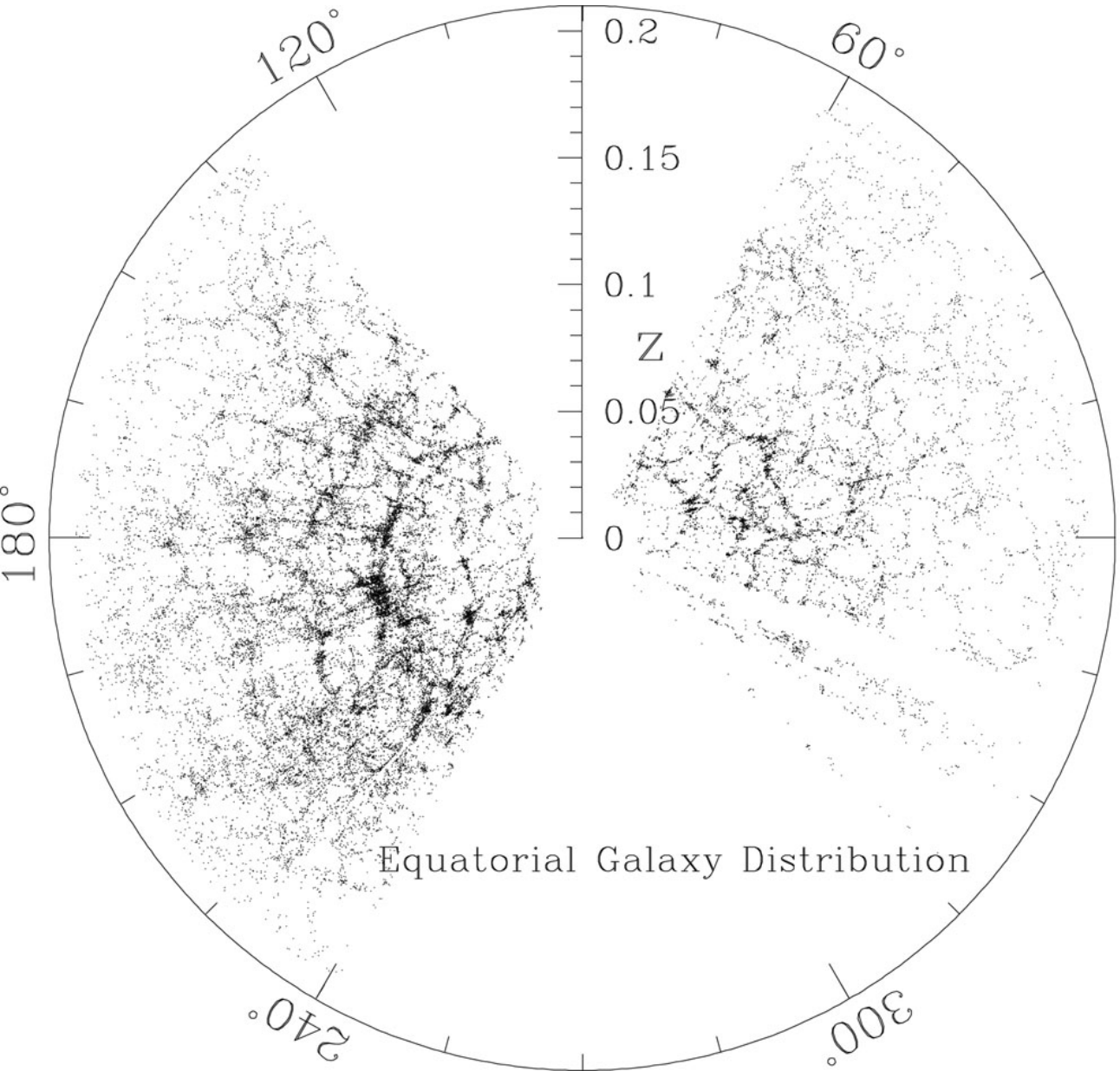


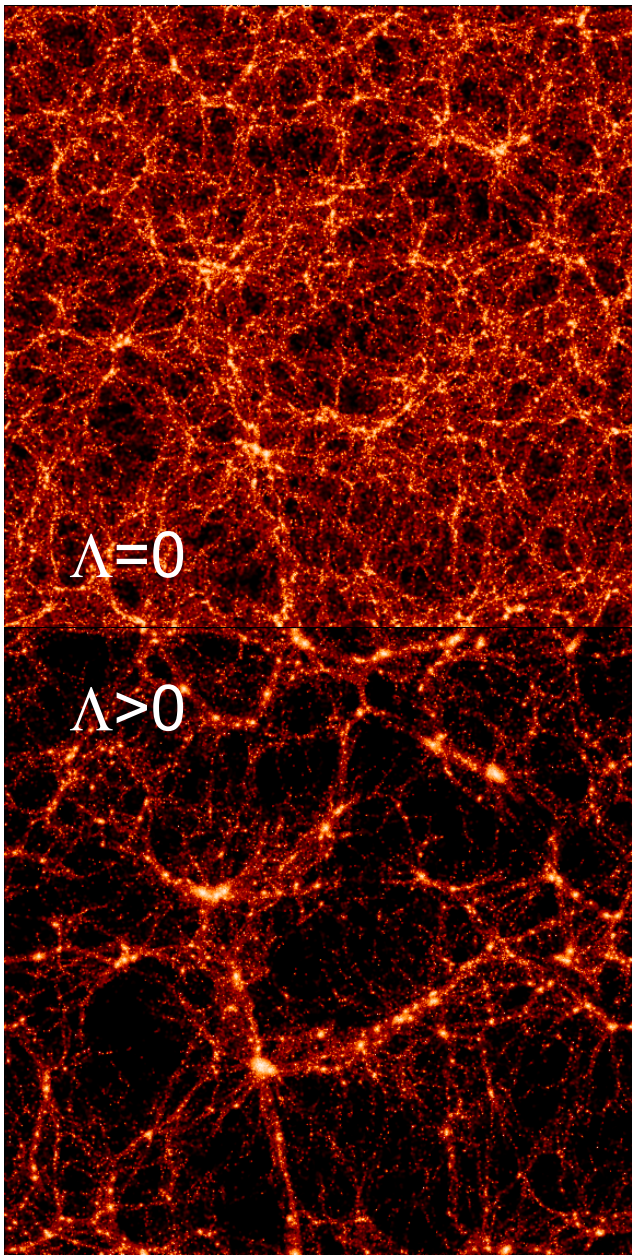
Intergalactic filaments at z=3
Zhang, Meiksin, Anninos & Norman (1998)

Combined Results

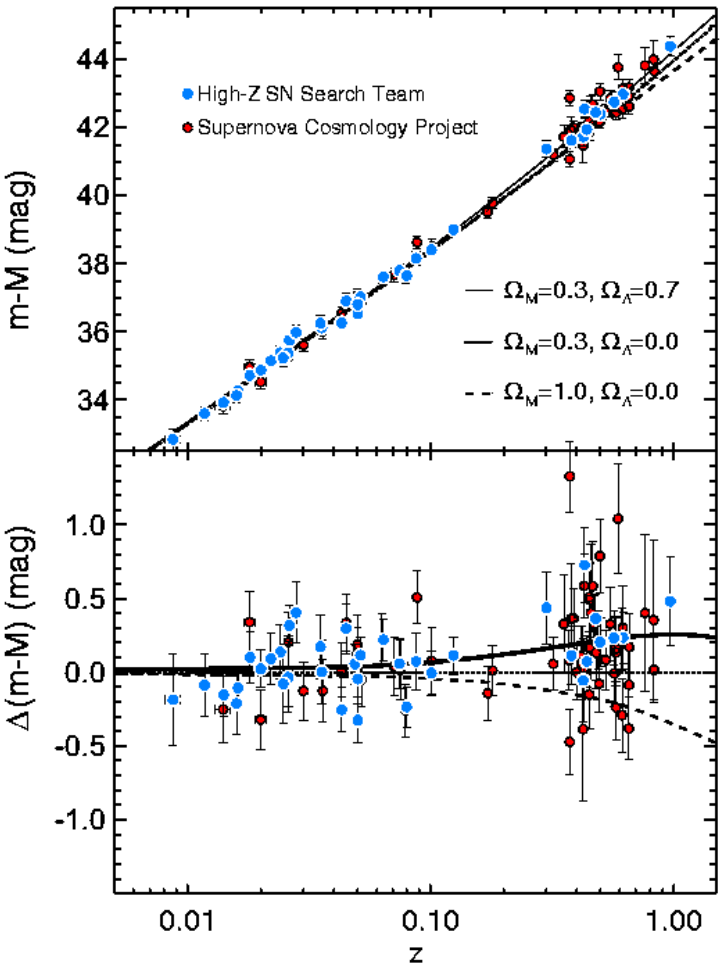


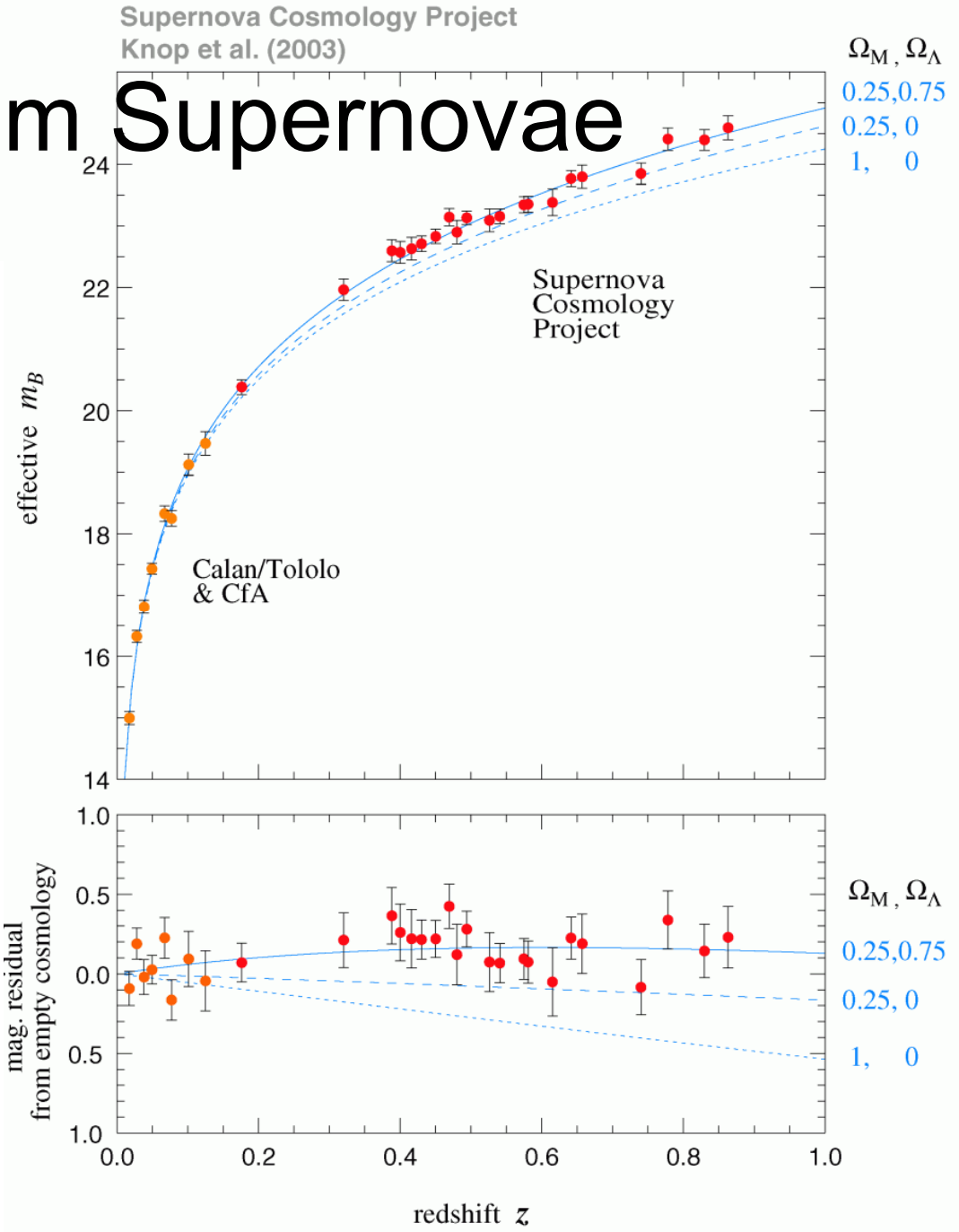
Comparison with Model Simulations



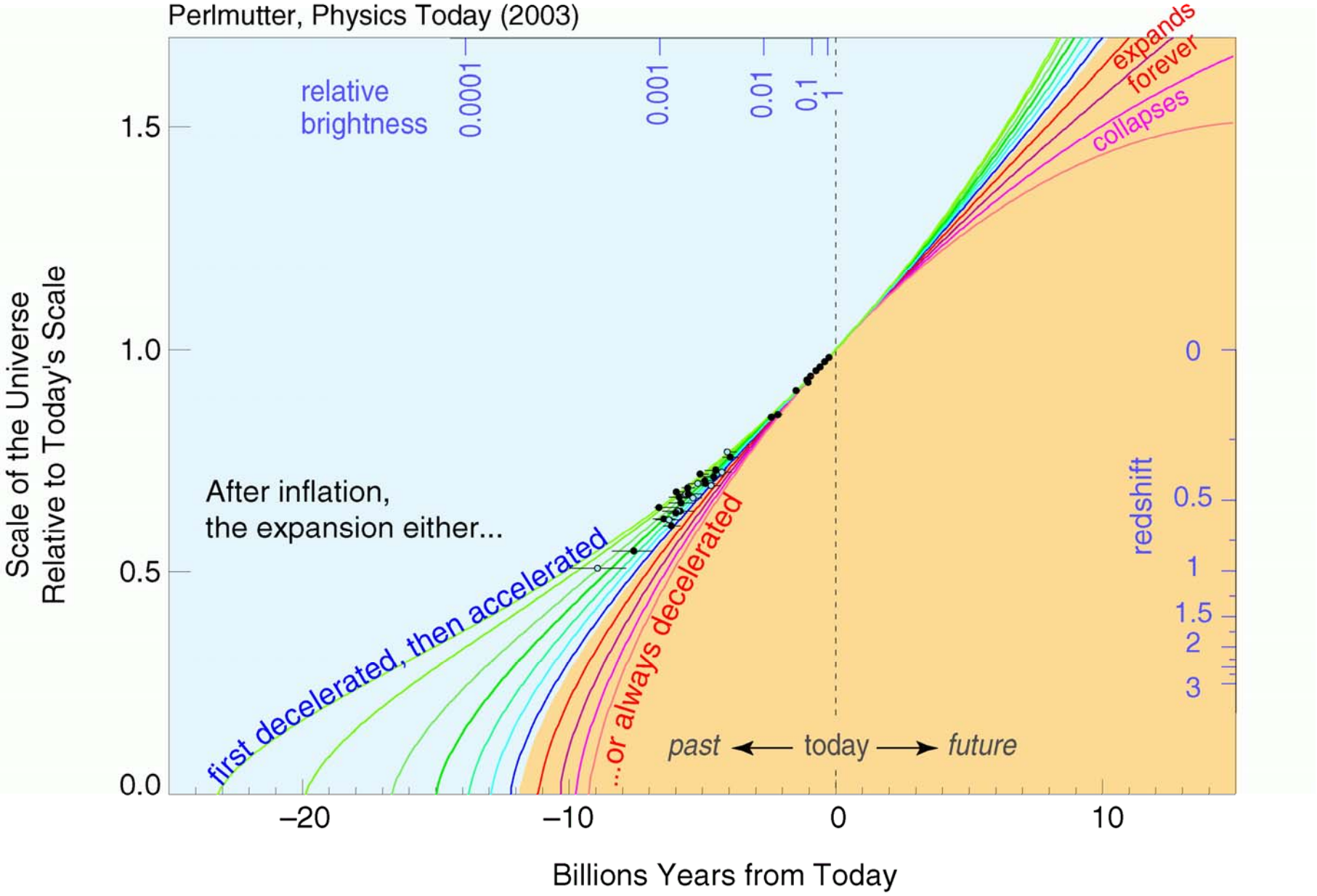


Hubble Plots from Supernovae

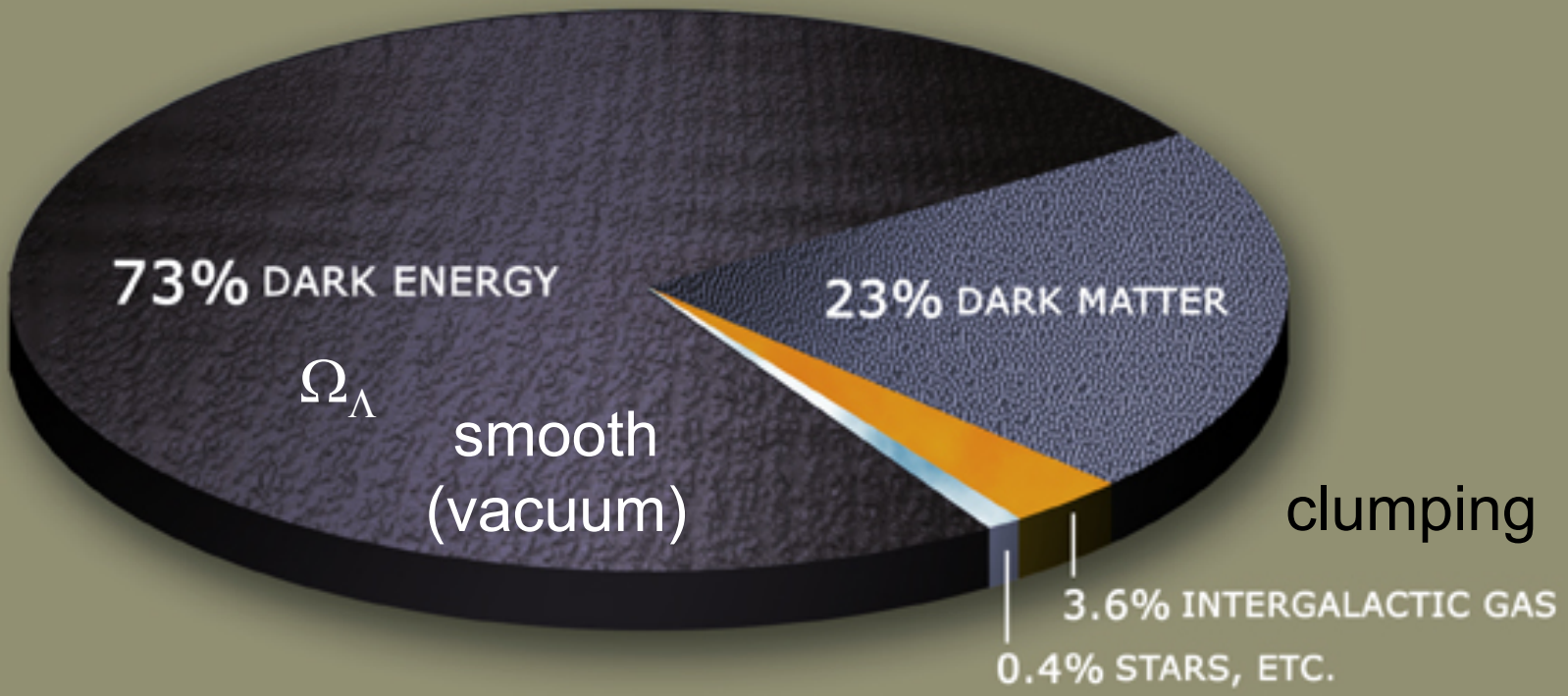




Expansion History of the Universe compared to SN Ia data



Mass (Energy) in the Universe:



Parameters of our Universe

present values

ΛCDM = Cosmological Constant + Cold Dark Matter

$H = (71 \pm 4)\,\mathrm{km/s/Mpc}$

$\Omega = 1.02 \pm 0.02$

$\Omega_m = 0.27 \pm 0.02$ incl. $\Omega_b = 0.044 \pm 0.004$ and $\Omega_\nu < 0.014$

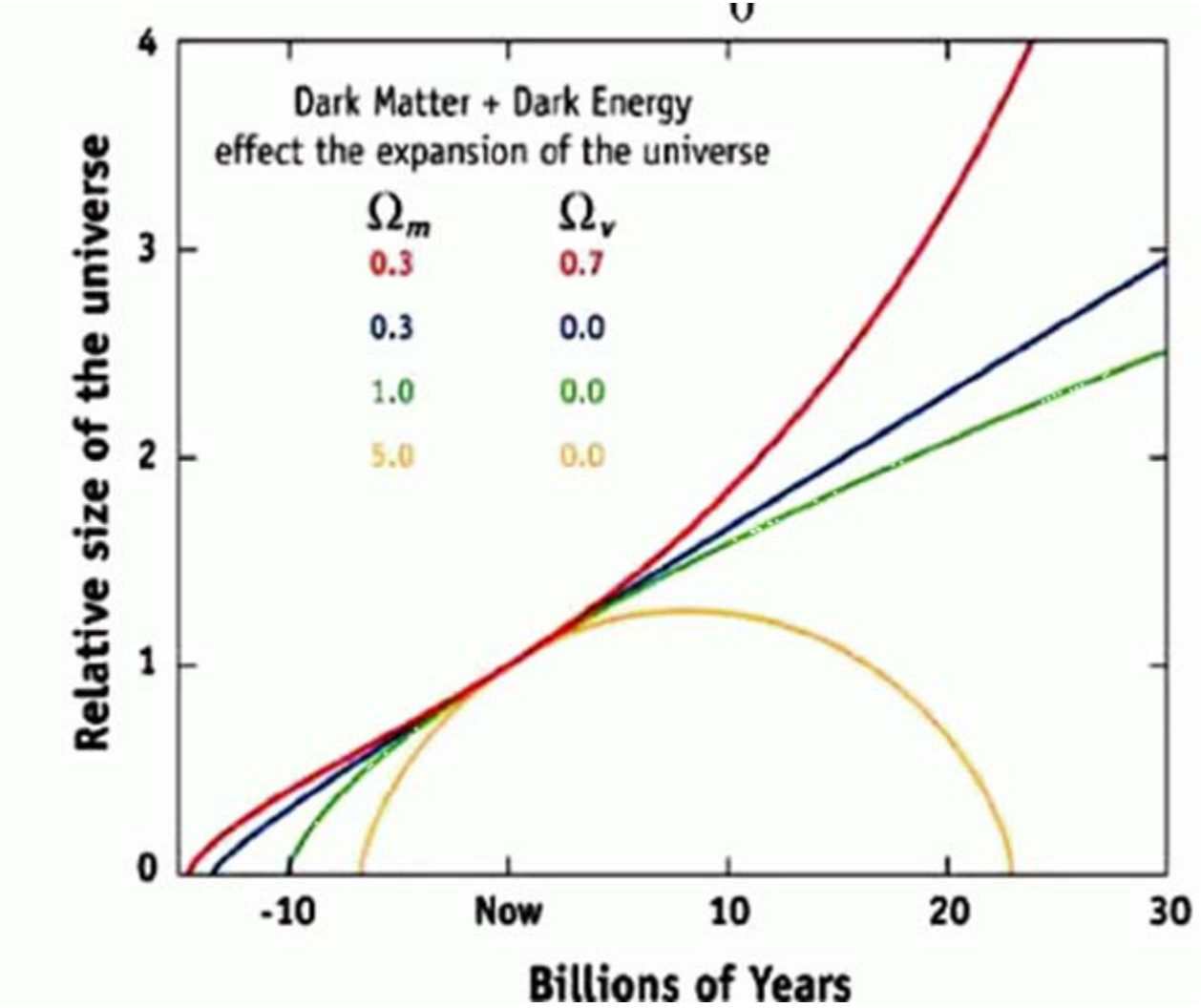
photons $\Omega_r = 4.9 \cdot 10^{-5}$

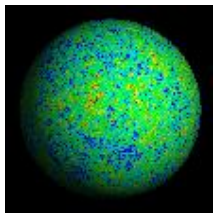
dark energy $\Omega_\Lambda = 0.75 \pm 0.02$

age $t = (13.7 \pm 0.2) \cdot 10^9$ a

(from Sep. 2005)

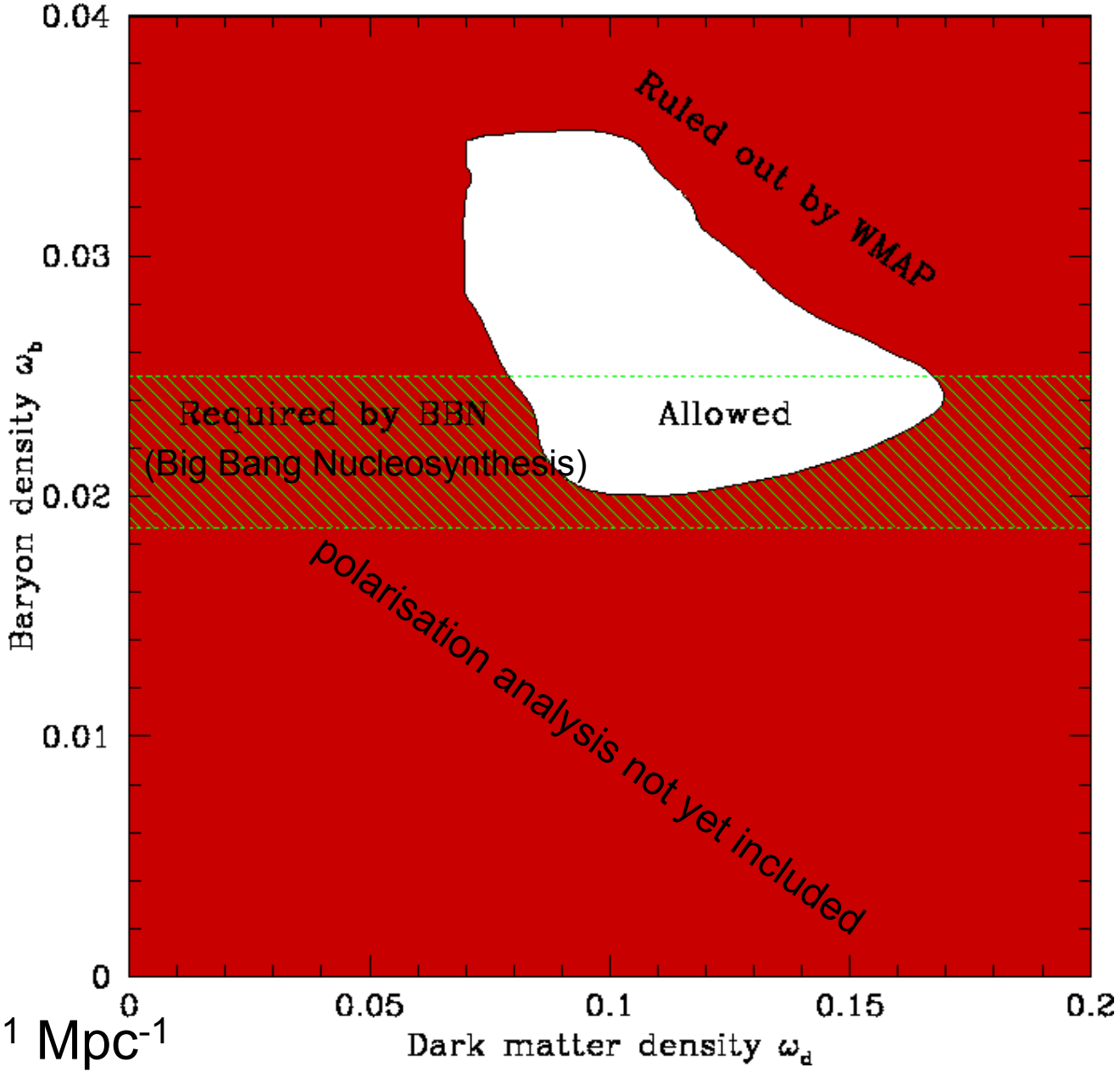
Cosmology: Evolution





CMB

How much dark matter is there?

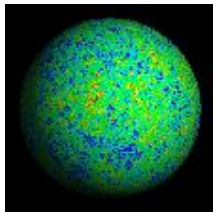


$\omega = \Omega h^2$

$h = H/100 km\ s^{-1}\ Mpc^{-1}$

$h^2 \approx 0.5$

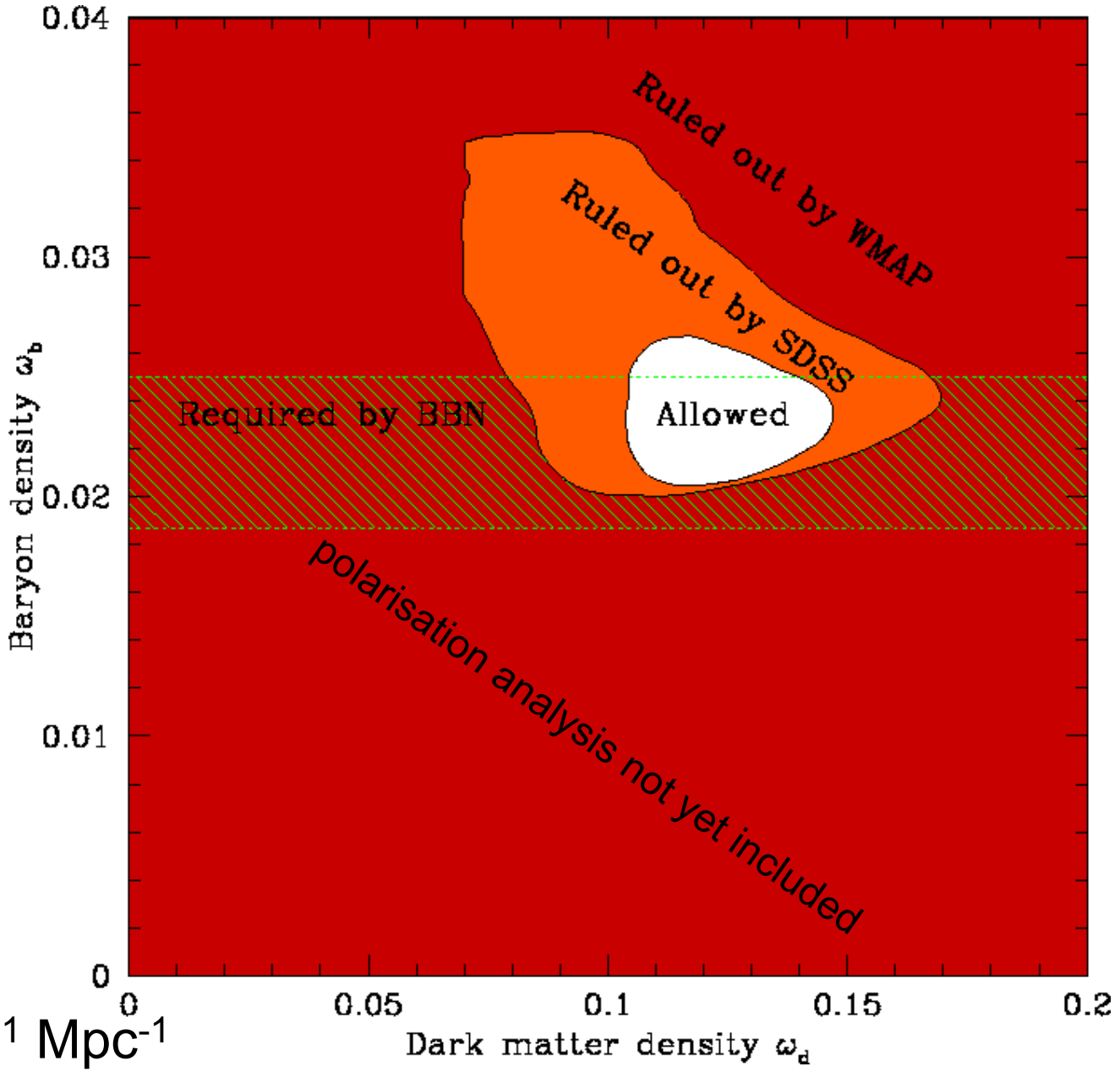
How much dark matter is there?



CMB

+

Survey

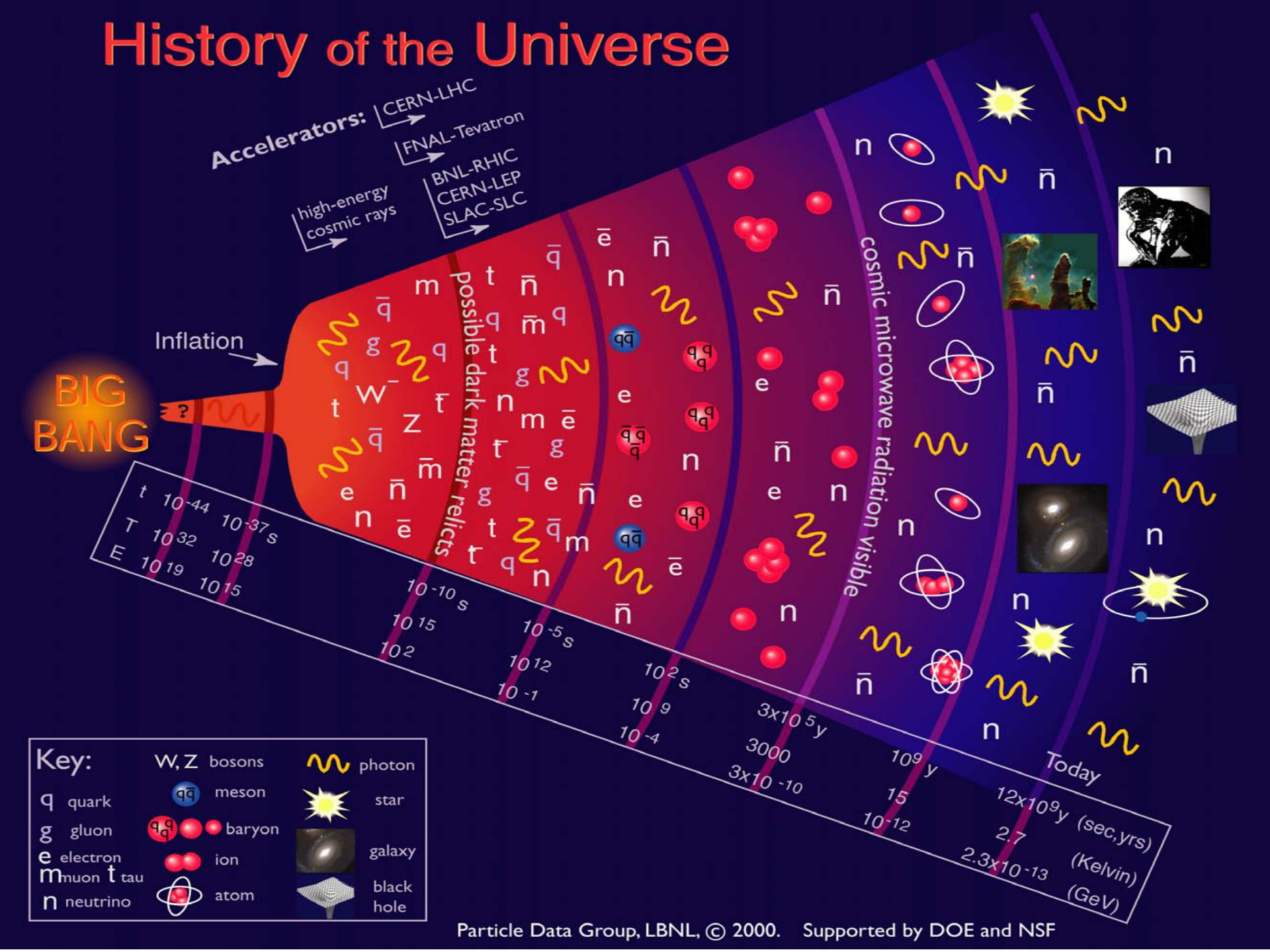


$\omega = \Omega h^2$

$h = H/100 km\ s^{-1}\ Mpc^{-1}$

$h^2 \approx 0.5$

History of the Universe



History of the Universe

Time	Size	Energy/part.	Temperature	Era
10^{-43} sec	10^{-33} cm	10^{19} GeV	10^{32} K	Planck
10^{-35} sec	10^{-27} cm	10^{15} GeV	10^{28} K	Grand Unification
10^{-31} sec	1 cm	10^{13} GeV	10^{26} K	Inflation >>
0.0001 μsec	10^{8} km	100 GeV	10^{15} K	Desert
1 μsec	10^{10} km	1 GeV	10^{13} K	Quarks + Leptons
0.1 msec	10^{11} km	100 MeV	10^{12} K	Hadrons
10 sec	0.1 ly	300 keV	$3 \cdot 10^{9}$ K	Leptons
15 min	1 ly	30 keV	$3 \cdot 10^{8}$ K	Nucleosynthesis
10 000 yr	10^{6} ly	2 eV	20 000 K	Radiation
300 000 yr	10^{7} ly	0.35 eV	3500 K	Plasma
10^{10} yr	10^{10} ly	10^{-4} eV	3 K	Matter

The Beginning of Time

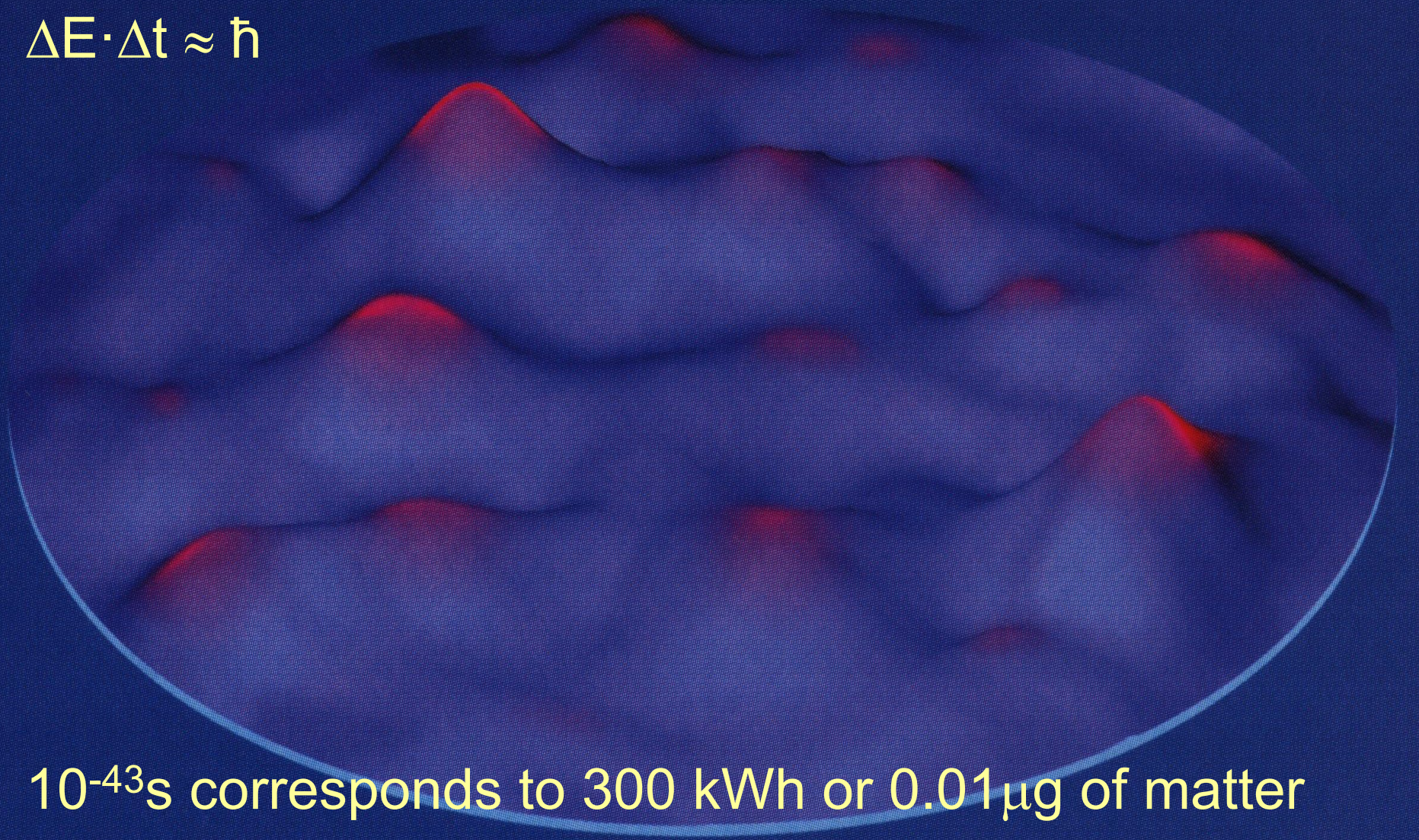
absolute starting point of every way north: the South Pole

absolute starting point of time: the Big Bang
$13.6 \cdot 10^{9}$ years ago

Planck time smallest meaningfull interval?
$t = 0.5 \cdot 10^{-43}$ s

Quantum Fluctuations

$\Delta E \cdot \Delta t \approx \hbar$



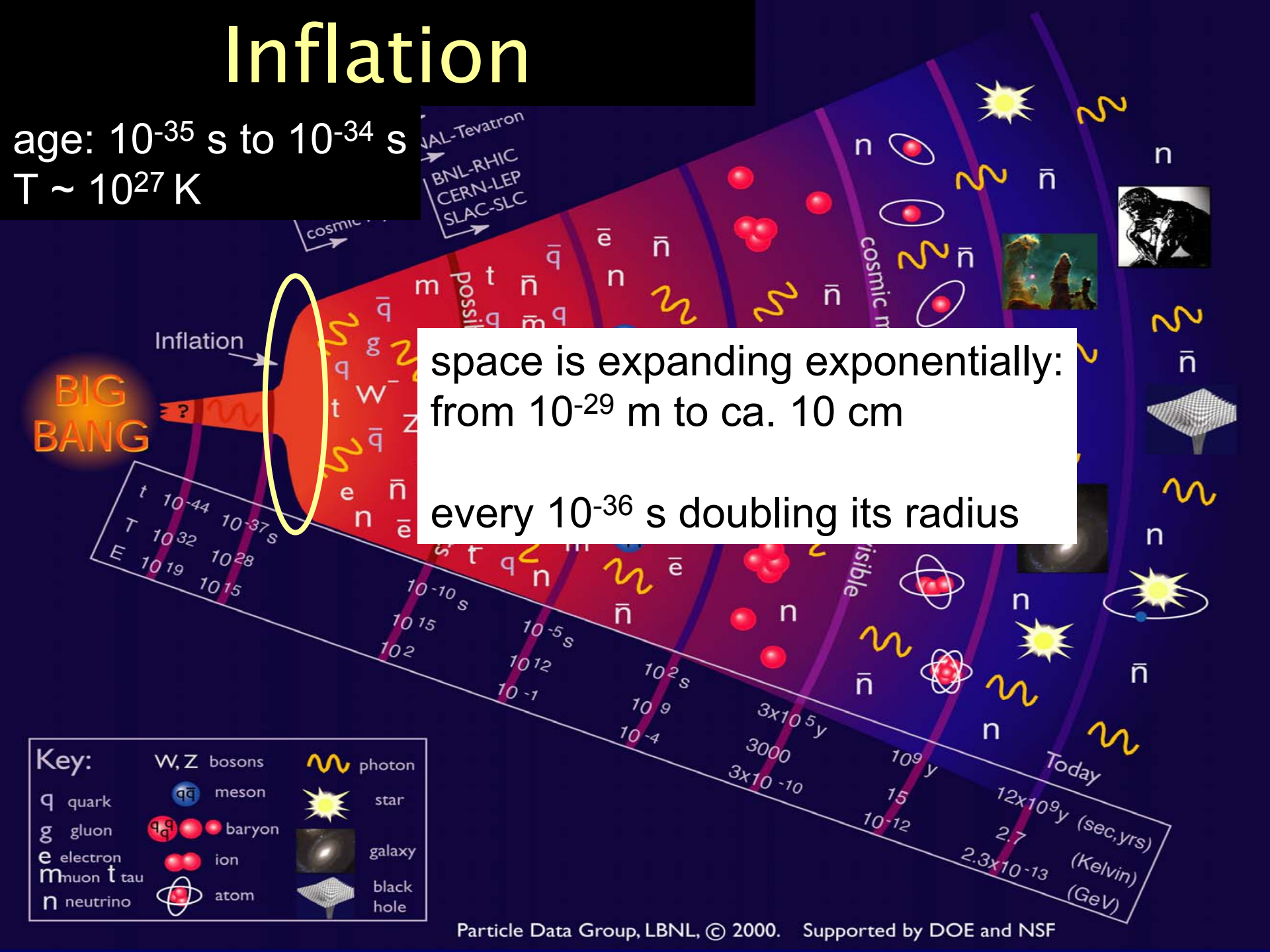
10^{-43}s corresponds to 300 kWh or 0.01μg of matter

History of the Universe

Time	Size	Energy/part.	Temperature	Era
10^{-43} sec	10^{-33} cm	10^{19} GeV	10^{32} K	Planck
10^{-35} sec	10^{-27} cm	10^{15} GeV	10^{28} K	Grand Unification
10^{-31} sec	1 cm	10^{13} GeV	10^{26} K	Inflation
0.0001 μsec	10^{8} km	100 GeV	10^{15} K	Desert
1 μsec	10^{10} km	1 GeV	10^{13} K	Quarks + Leptons
0.1 msec	10^{11} km	100 MeV	10^{12} K	Hadrons
10 sec	0.1 ly	300 keV	$3 \cdot 10^{9}$ K	Leptons
15 min	1 ly	30 keV	$3 \cdot 10^{8}$ K	Nucleosynthesis
10 000 yr	10^{6} ly	2 eV	20 000 K	Radiation
300 000 yr	10^{7} ly	0.35 eV	3500 K	Plasma
10^{10} yr	10^{10} ly	10^{-4} eV	3 K	Matter

Inflation

age: 10^{-35} s to 10^{-34} s
T ~ 10^{27} K



space is expanding exponentially: from 10^{-29} m to ca. 10 cm

every 10^{-36} s doubling its radius

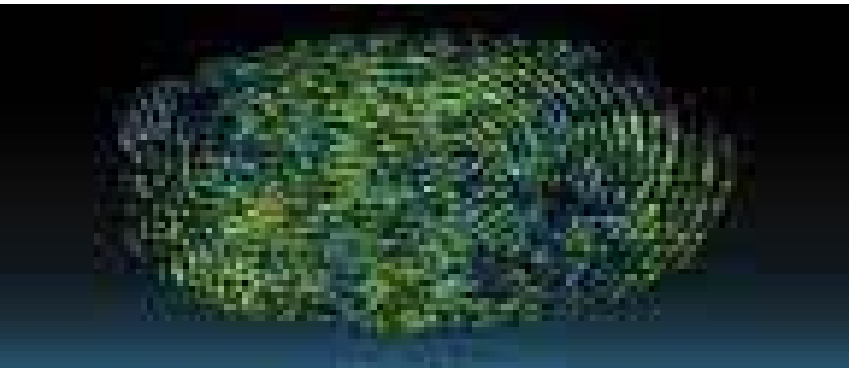
Inflation

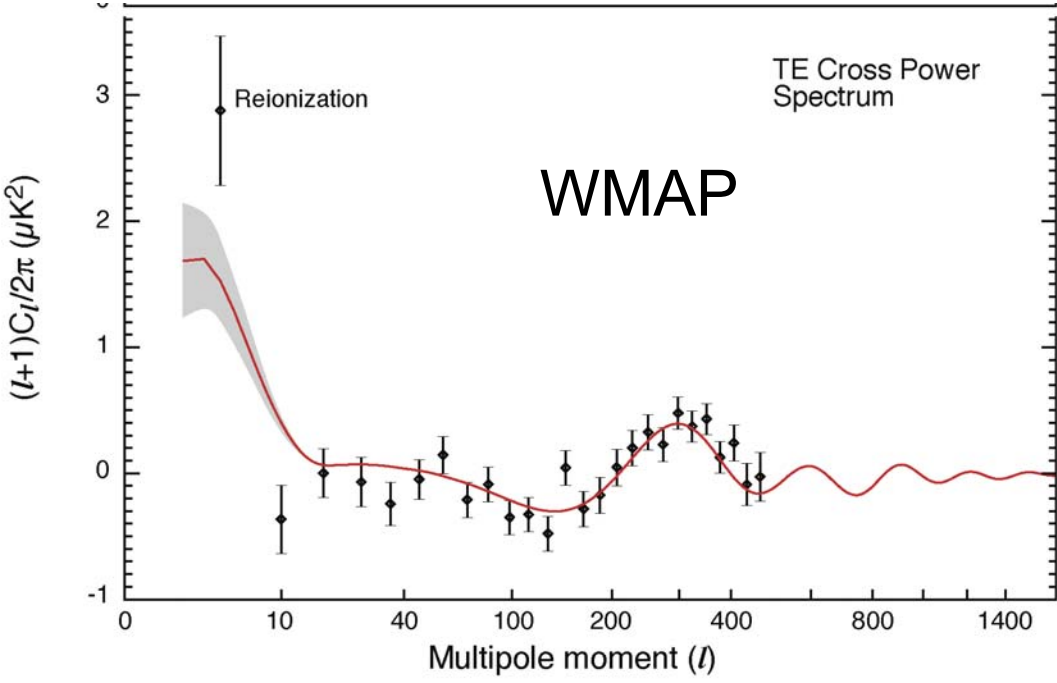
- proposed by Alan Guth 1981
- exponential growth of Universe $R \sim e^{Ht}$
- driven by negative pressure (Λ)
- regions separated by $v > c$ became causally disconnected
- structure of universe = expansion of microscopic initial fluctuations

Scale-Invariant Structure

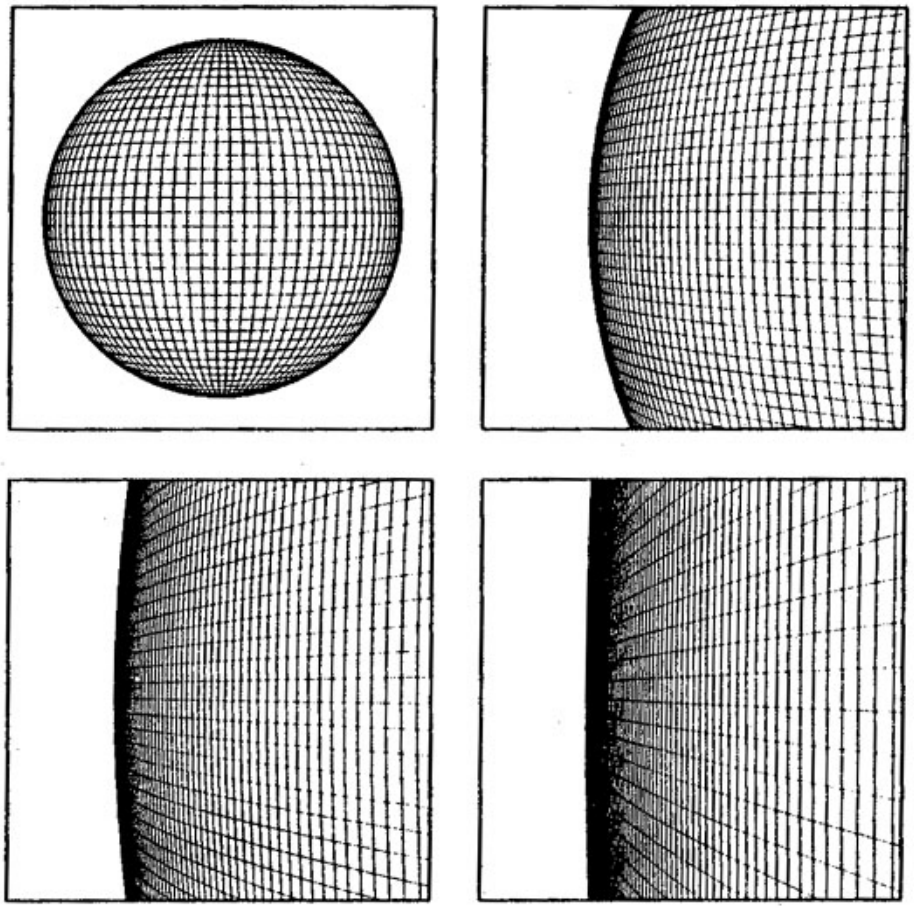
Spectrum $P(k) \sim k^{1-n}$
n = spectral index
scale invariance: n = 1 (white noise)
inflation models: n slightly below 1

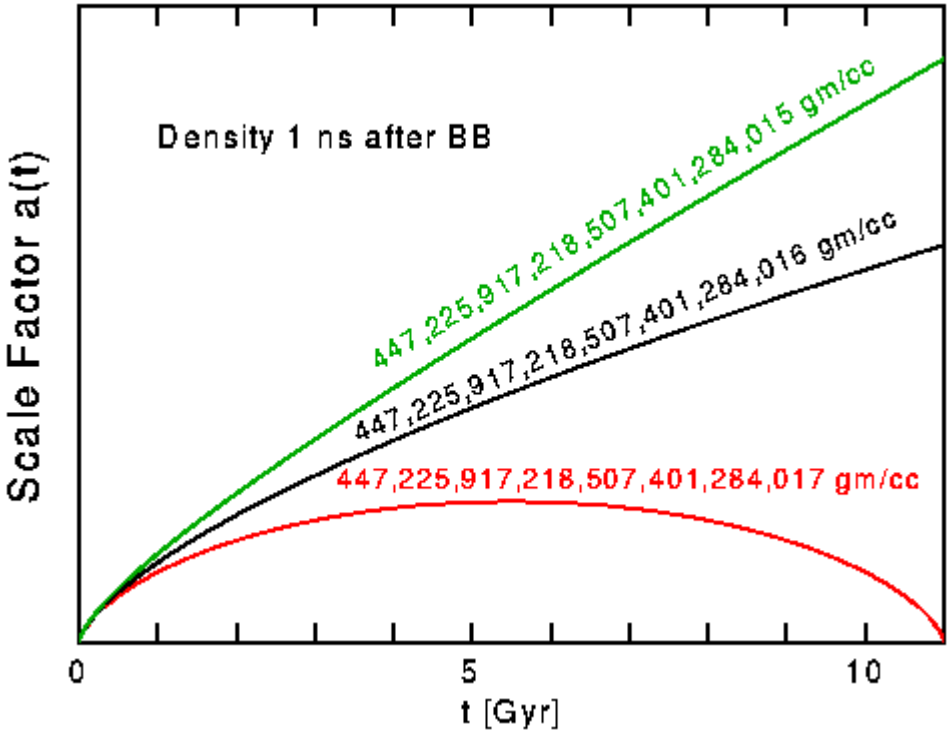
n = 0.95±0.02
can exclude
some specific models





Inflation explains flatness





$$\Omega \approx 1$$

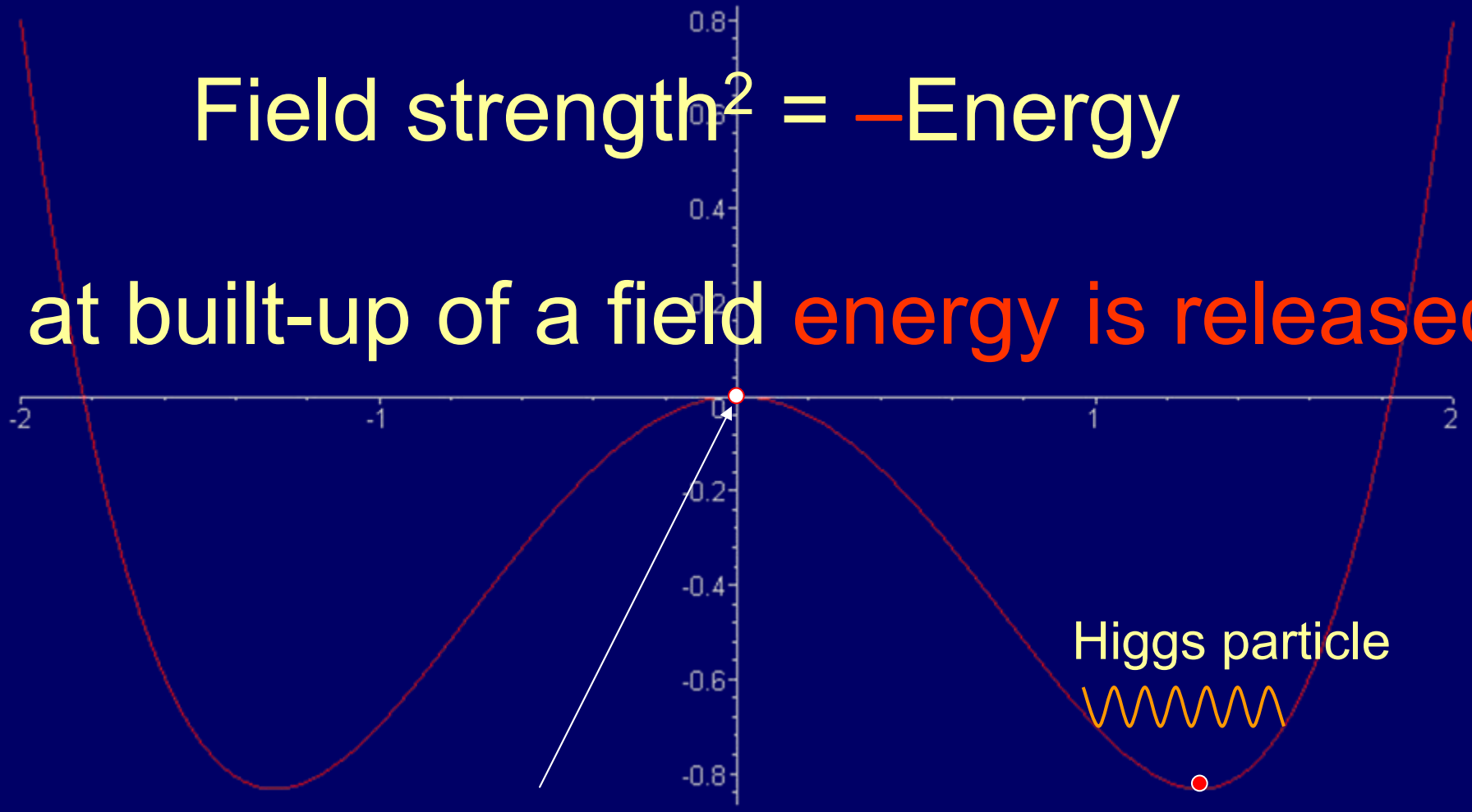
Inflation explains

- why our Universe is flat: small causally connected piece of possibly a large hypersphere
- size of structures of universe: was initially just quantum fluctuations
- but also its amazing homogeneity: inflation by dark energy is smooth without structure
- how energy comes out of Nothing: a small quantum fluctuation (Heisenberg's uncertainty) is amplified by inflation by a factor > 10^{75}

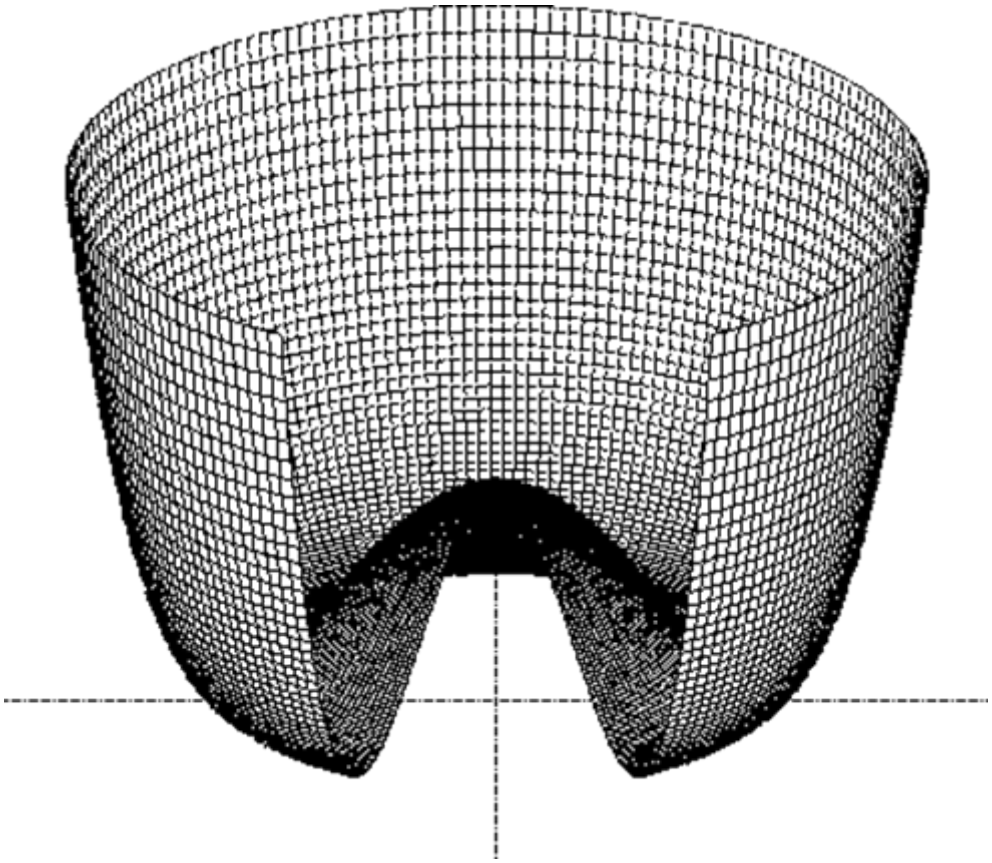
The Higgs-Field

Field strength^2 = –Energy

at built-up of a field energy is released!

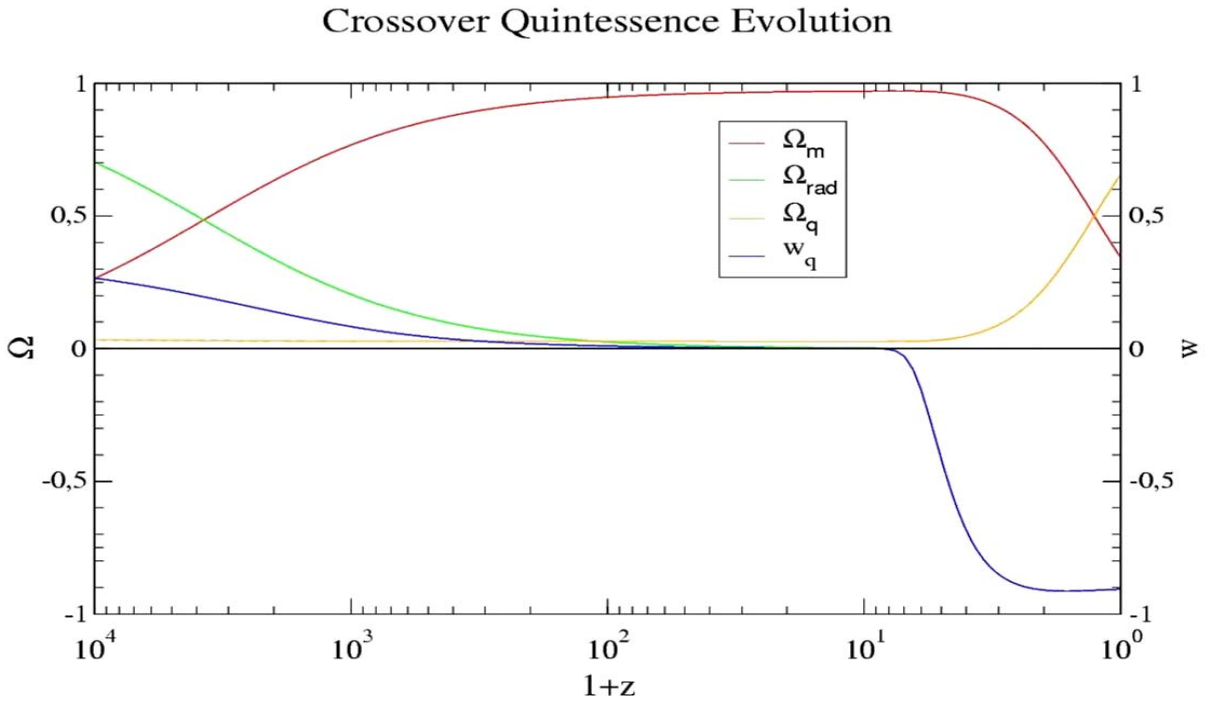


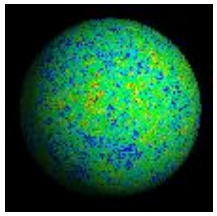
Spontaneous Symmetry Breaking



Quintessence, Kosmon, Inflaton

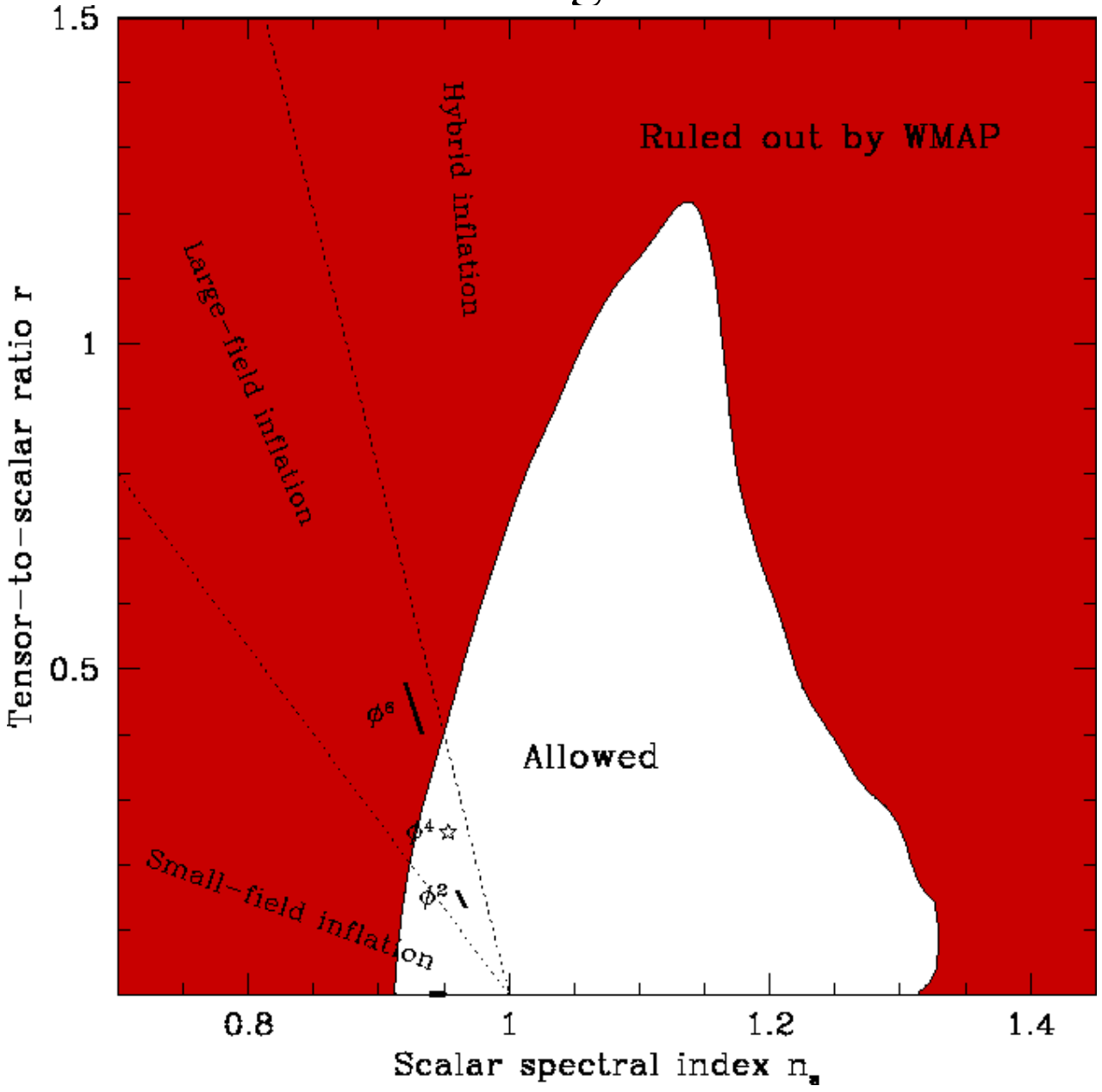
- is similar to but not identical to Higgs field
- produces energy to create matter
- produces negative pressure for inflation
- may still be the source called dark energy

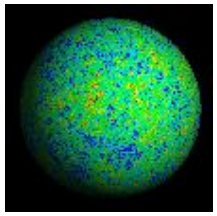




CMB

Testing inflation



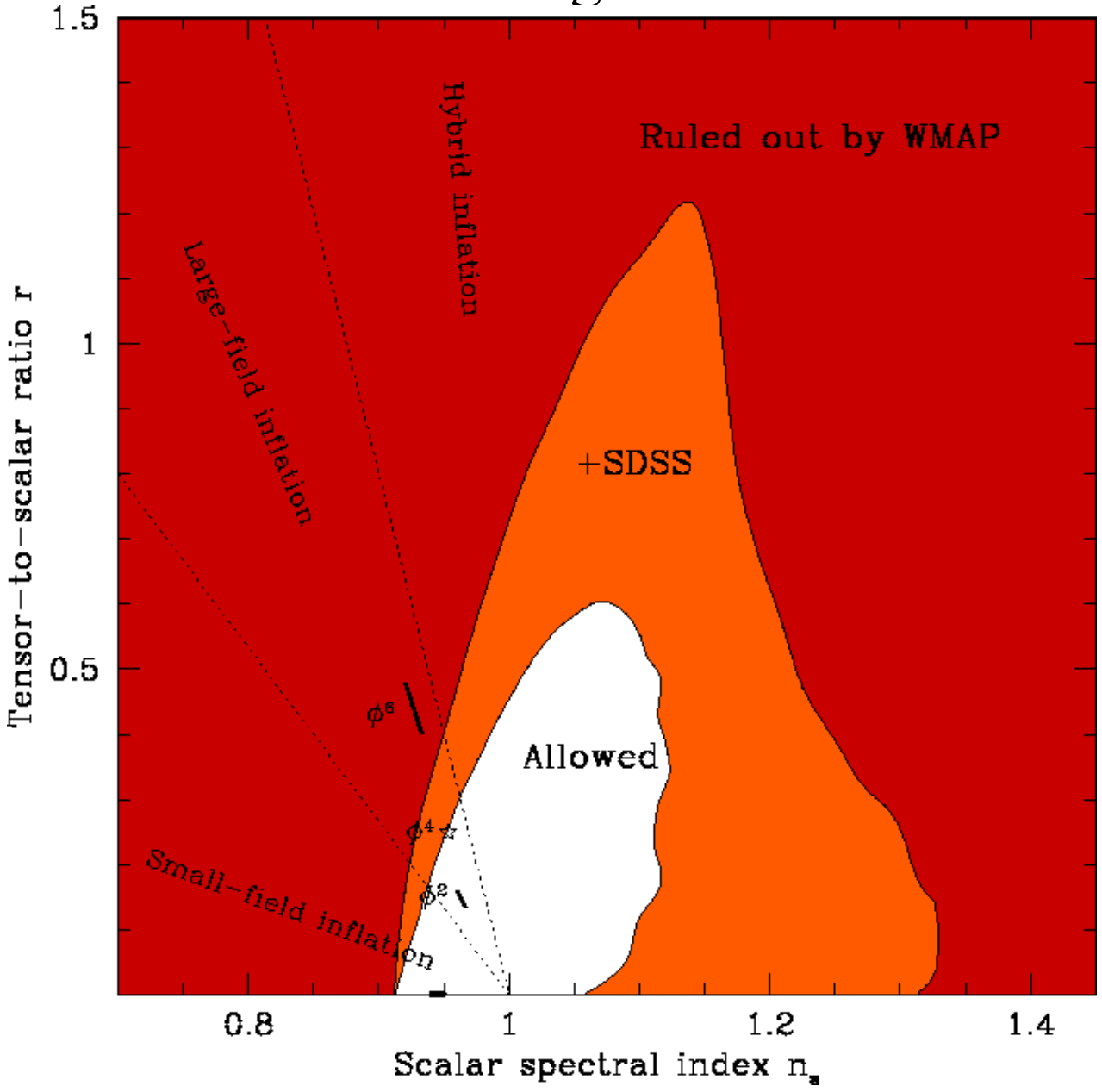


CMB

+

Survey

Testing inflation



History of the Universe

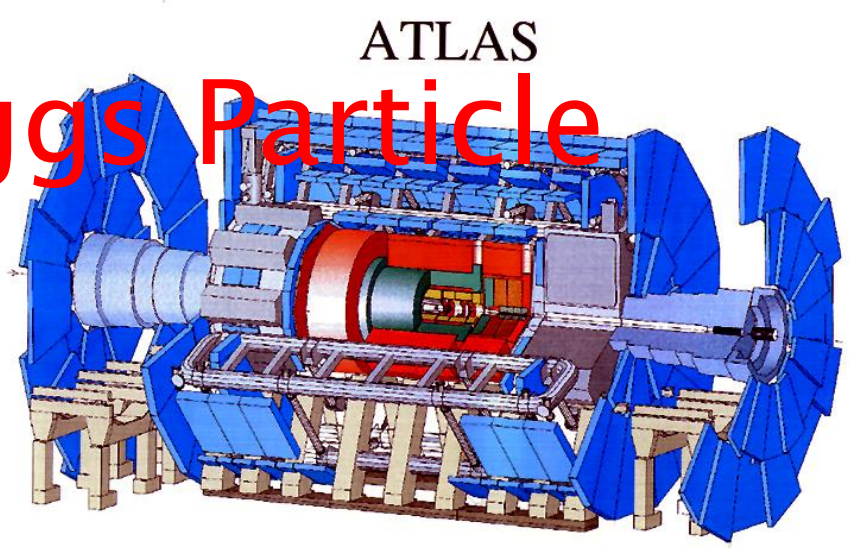
Time	Size	Energy/part.	Temperature	Era
10^{-43} sec	10^{-33} cm	10^{19} GeV	10^{32} K	Planck
10^{-35} sec	10^{-27} cm	10^{15} GeV	10^{28} K	Grand Unification
10^{-31} sec	1 cm	10^{13} GeV	10^{26} K	Inflation
0.0001 μsec	10^{8} km	100 GeV	10^{15} K	Desert
1 μsec	10^{10} km	1 GeV	10^{13} K	Quarks + Leptons
0.1 msec	10^{11} km	100 MeV	10^{12} K	Hadrons
10 sec	0.1 ly	300 keV	$3 \cdot 10^{9}$ K	Leptons
15 min	1 ly	30 keV	$3 \cdot 10^{8}$ K	Nucleosynthesis
10 000 yr	10^{6} ly	2 eV	20 000 K	Radiation
300 000 yr	10^{7} ly	0.35 eV	3500 K	Plasma
10^{10} yr	10^{10} ly	10^{-4} eV	3 K	Matter

Electroweak Symmetry Breaking

- by the Higgs field

- matter particles
  and weak-interaction bosons (W,Z)
  acquire a nonzero rest mass

Search for Higgs Particle



Genf

2008
CERN LHC

CERN