

Reflections on the baryon asymmetry

Reflections, not thoughts or ideas

(Certainly not a summary!)

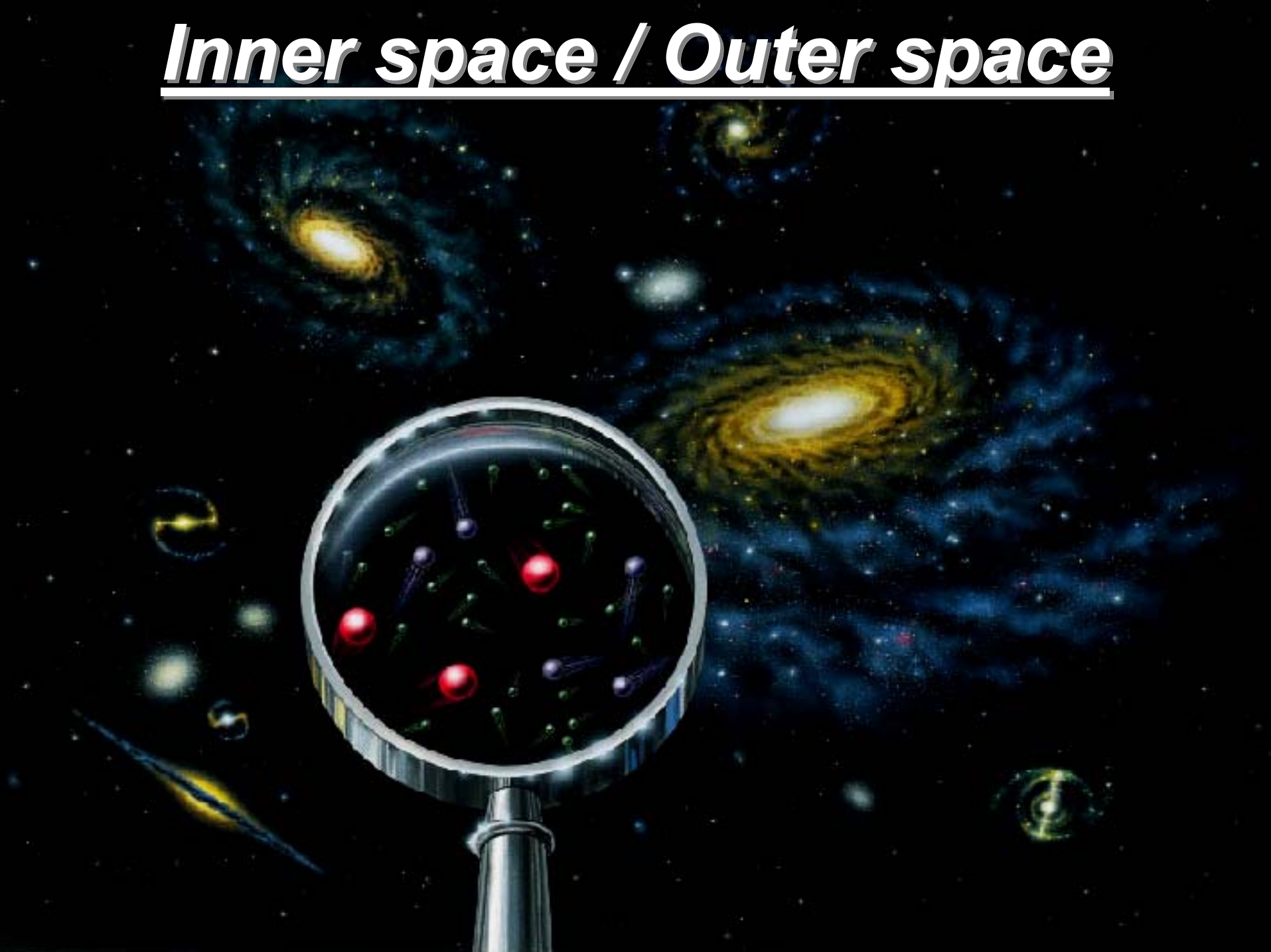
VIIIth Rencontres de Blois June 2002

Matter—Antimatter Asymmetry

Rocky Kolb

Fermilab, University of Chicago, & CERN

Inner space / Outer space



Baryon asymmetry symbols?



Salamander (Francois I)



Ermine (Claude of France)



Porcupine (Loius XII)



Flying Squirrel (Rocky of US)

The baryon asymmetry *is like a salamander*



- Born in the fire of the big bang
- Denotes constancy

* I will ~~not~~ ~~be~~ ~~and~~ extinguish

Cosmological parameters

- **Cosmological parameters:**

H_0 → Hubble's constant

q_0 → deceleration parameter

Ω_i → the cosmic food chain

(Ω_{TOTAL} , Ω_M , Ω_B , Ω_Λ , Ω_γ , Ω_ν ,)

t_0 → age of the universe

T_0 → temperature of the universe

- **Power spectrum of large-scale structure:**

$P(k)$

- **Anisotropy of CMB:**

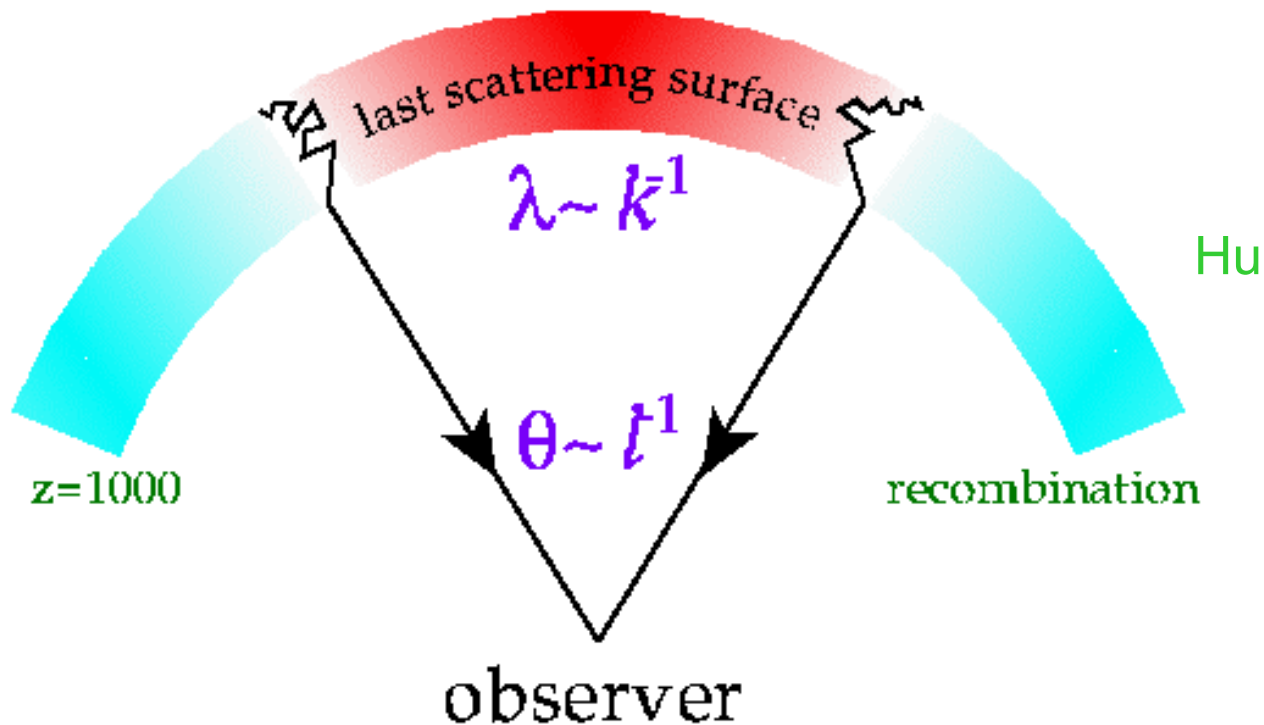
C_l

Cosmological parameters

... are just numbers

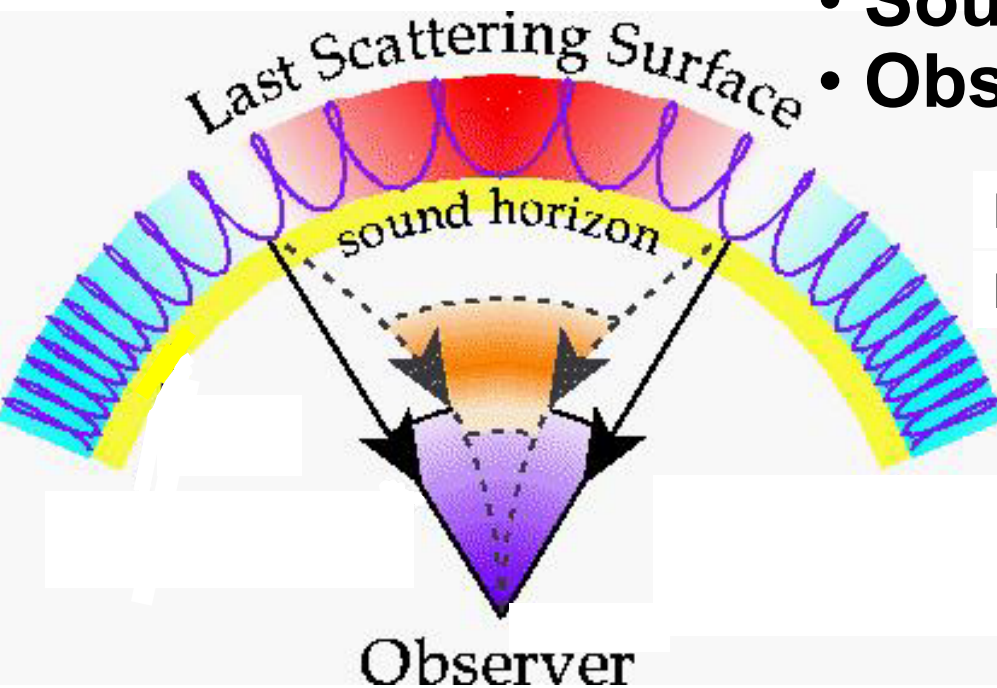
Acoustic peaks $\Omega_{TOTAL}=1$

- At recombination, baryon–photon fluid undergoes “acoustic oscillations” $A \cos kt + B \sin kt$
- Compressions and rarefactions change T_γ
- Peaks in ΔT_γ correspond to extrema of compressions and rarefactions



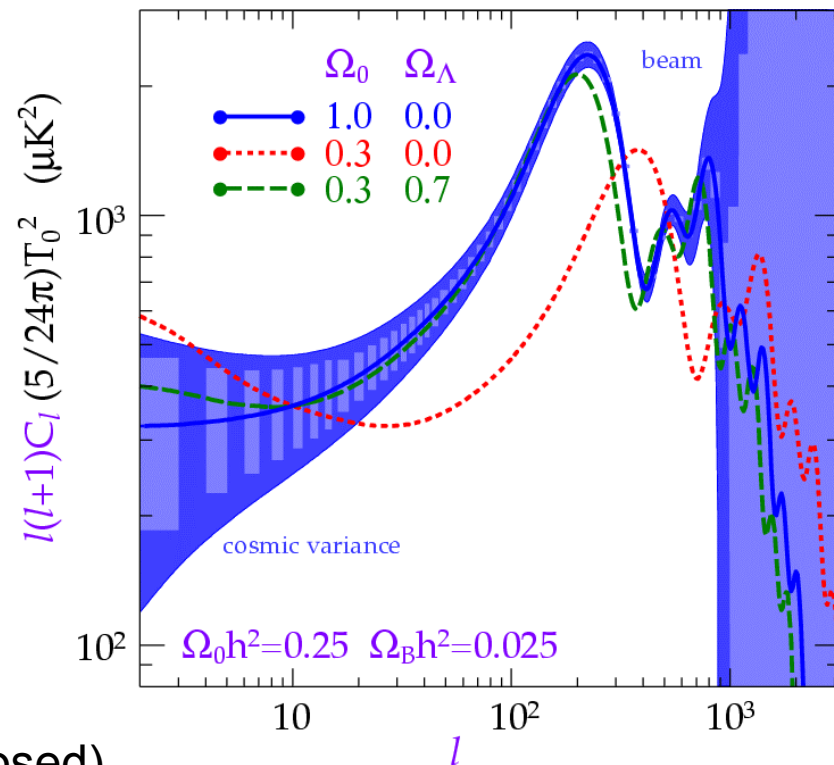
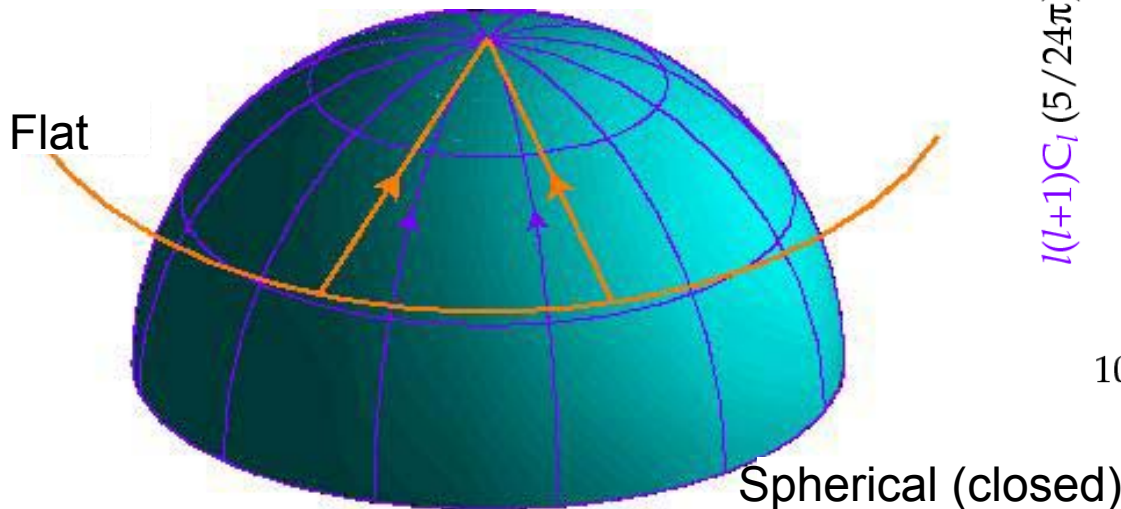
Acoustic peaks $\Omega_{TOTAL}=1$

- Sound travel distance known
- Observed $l_{peak} \rightarrow$ geometry

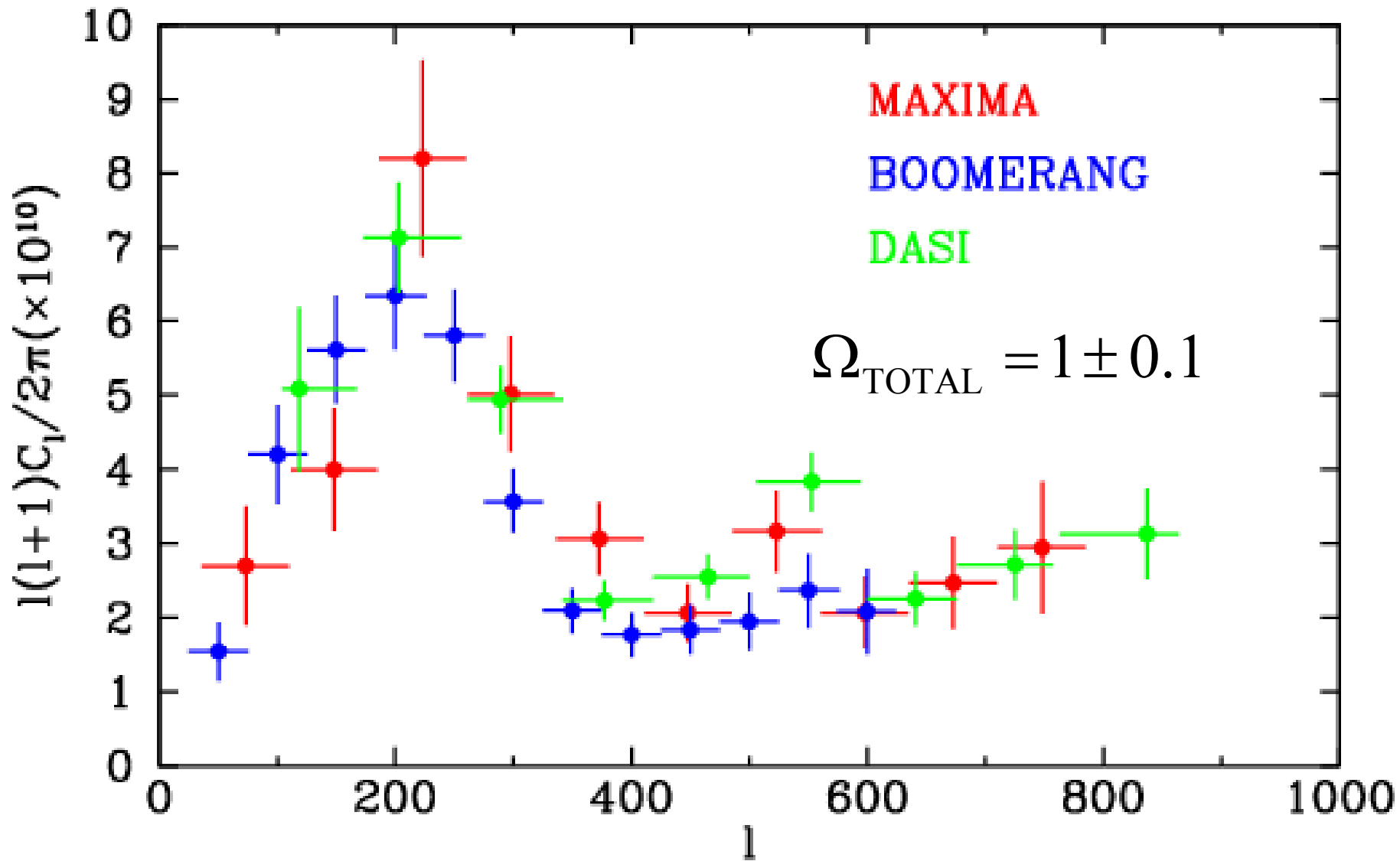


Flat (Euclidean) —————

Hyperbolic (open)

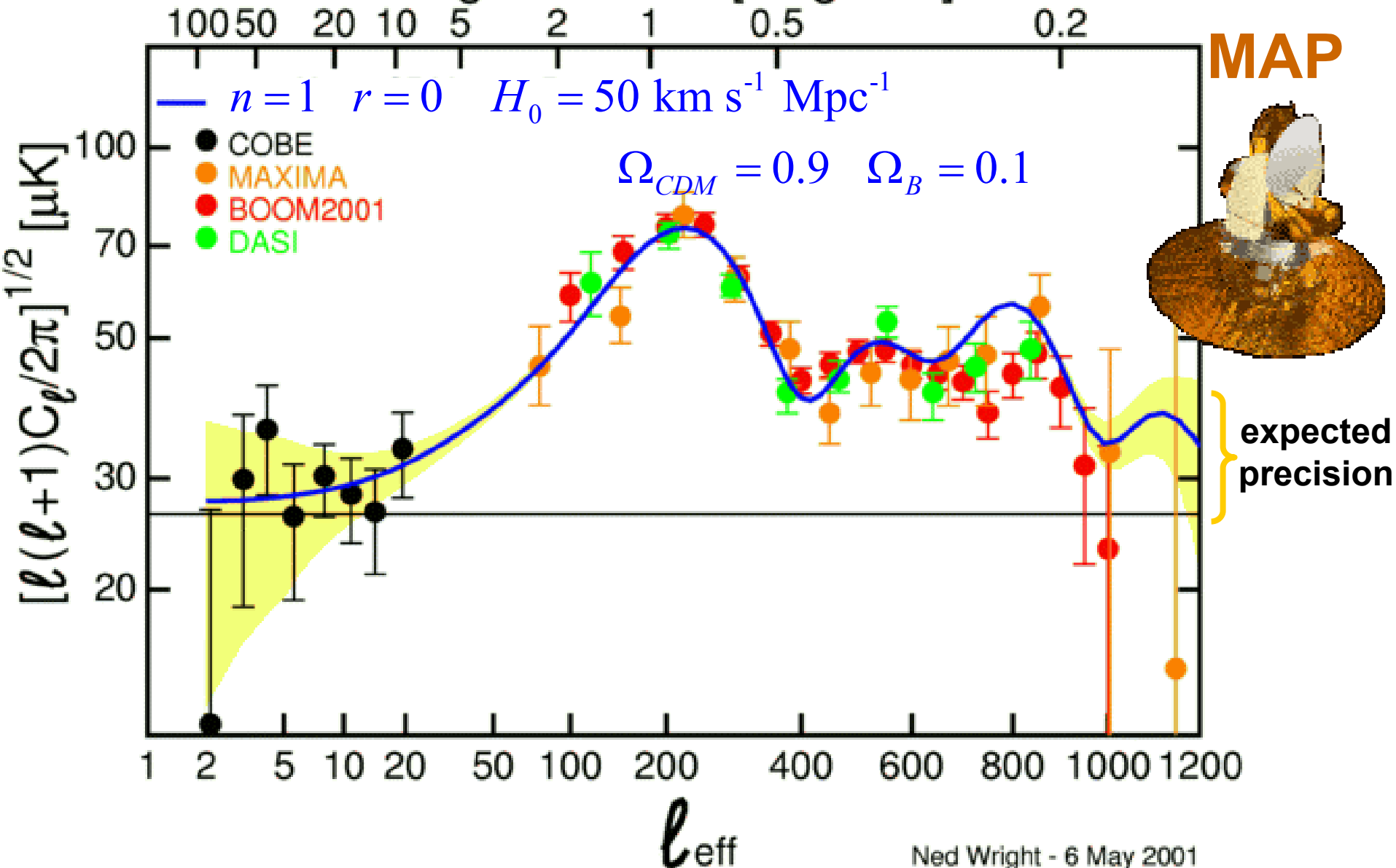


Acoustic peaks $\Omega_{TOTAL}=1$

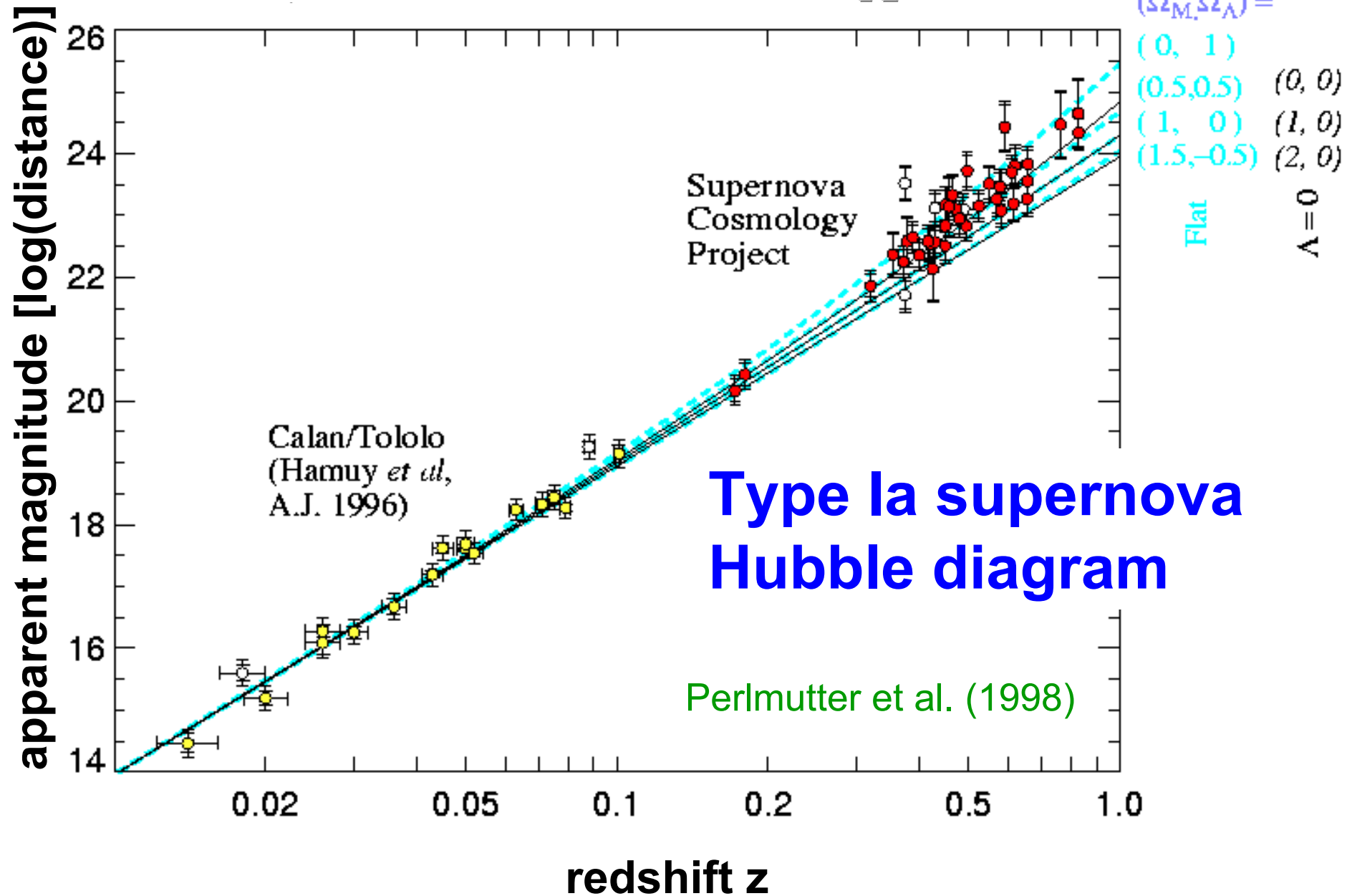


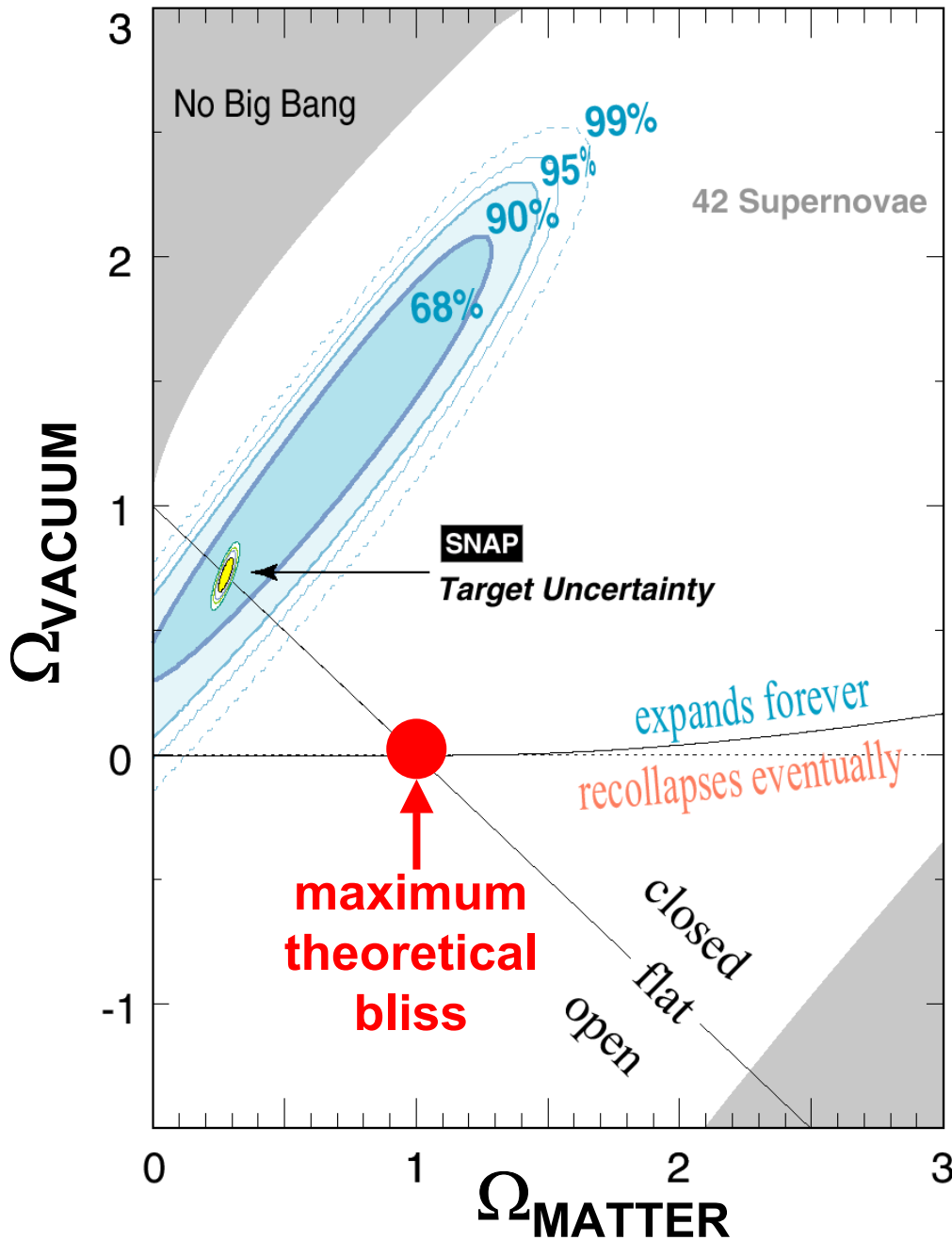
Acoustic peaks $\Omega_{TOTAL}=1$

Angular Scale [Degrees]



Dark energy $\Omega_\Lambda=0.7$





cosmological constant,
...some changing non-zero vacuum energy,
... or some unknown systematic effect(s)

Cosmo-illogical constant

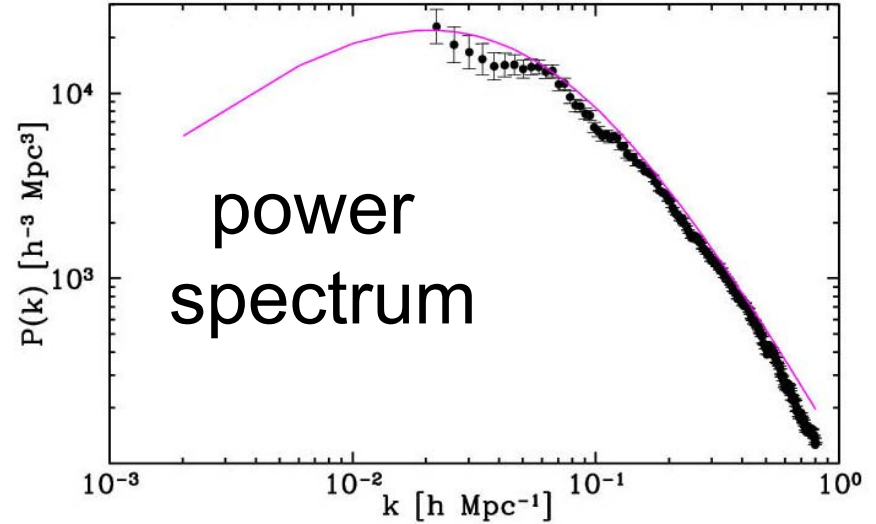
Mass density of space:

$$\rho \simeq 10^{-30} \text{ g cm}^{-3}$$

The unbearable lightness of nothing!

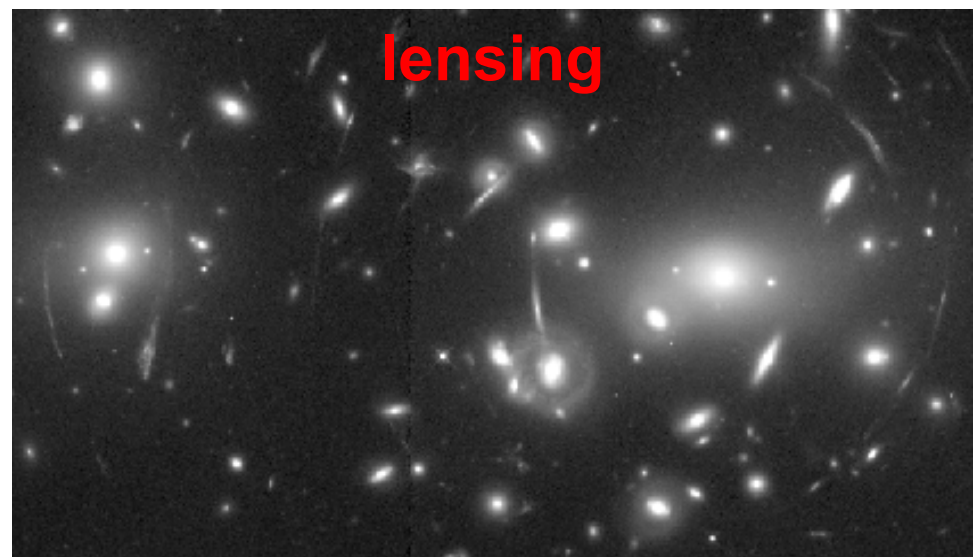
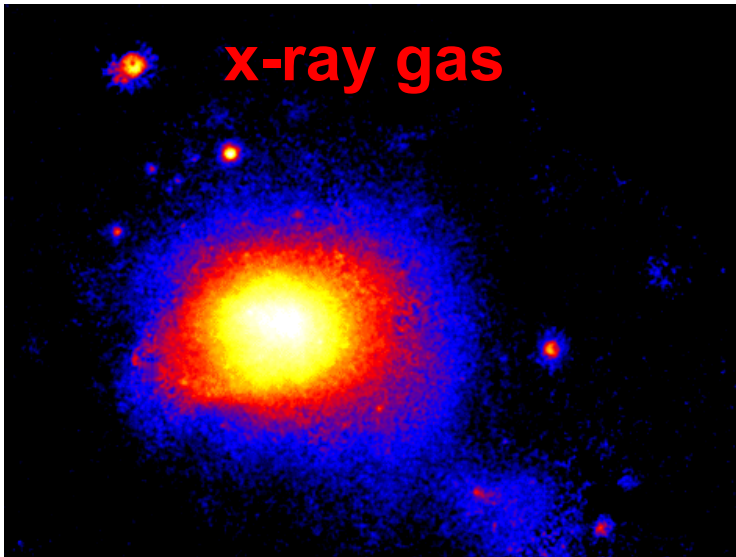
Dark Energy: aether of the 21st century

Matter $\Omega_M \sim 0.3$



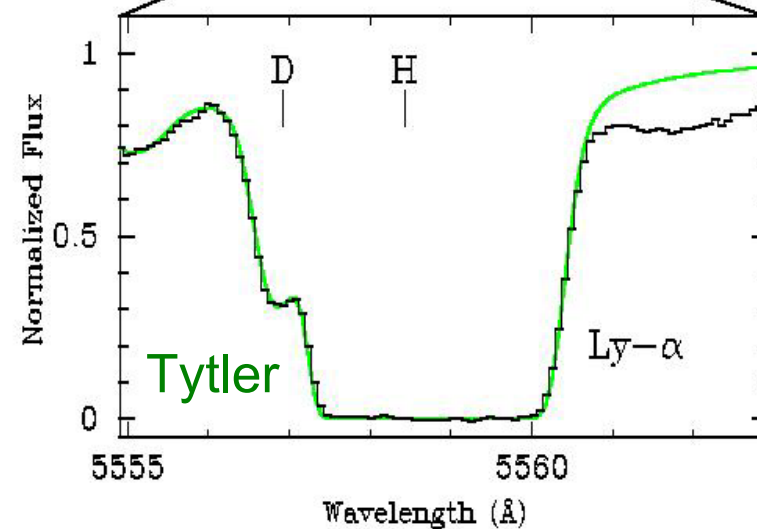
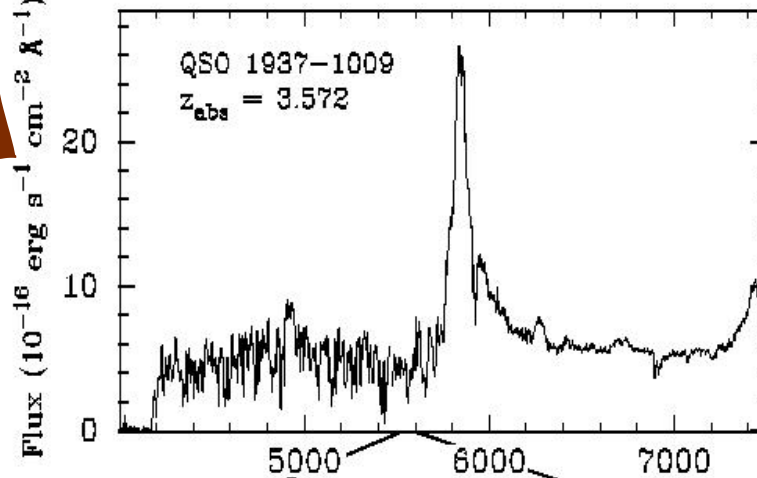
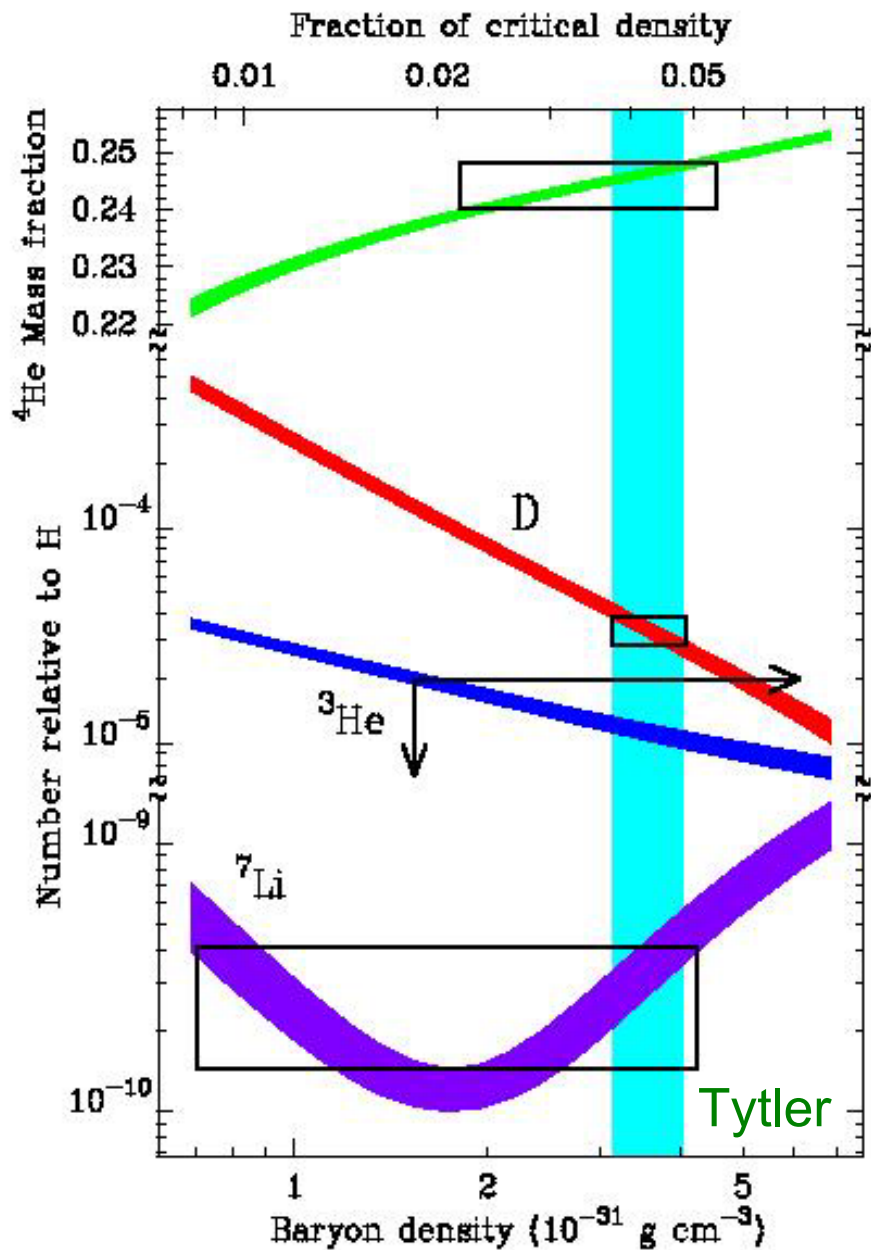
$$\Omega_0 = 1, \quad \Omega_M = 0.3$$

$$1 - 0.3 = 0.7$$



Baryons $\Omega_B h^2 \sim 0.02$ QSO 1937-1009

Ly- α



The cosmic food chain ($\Omega_{TOTAL}=1$)

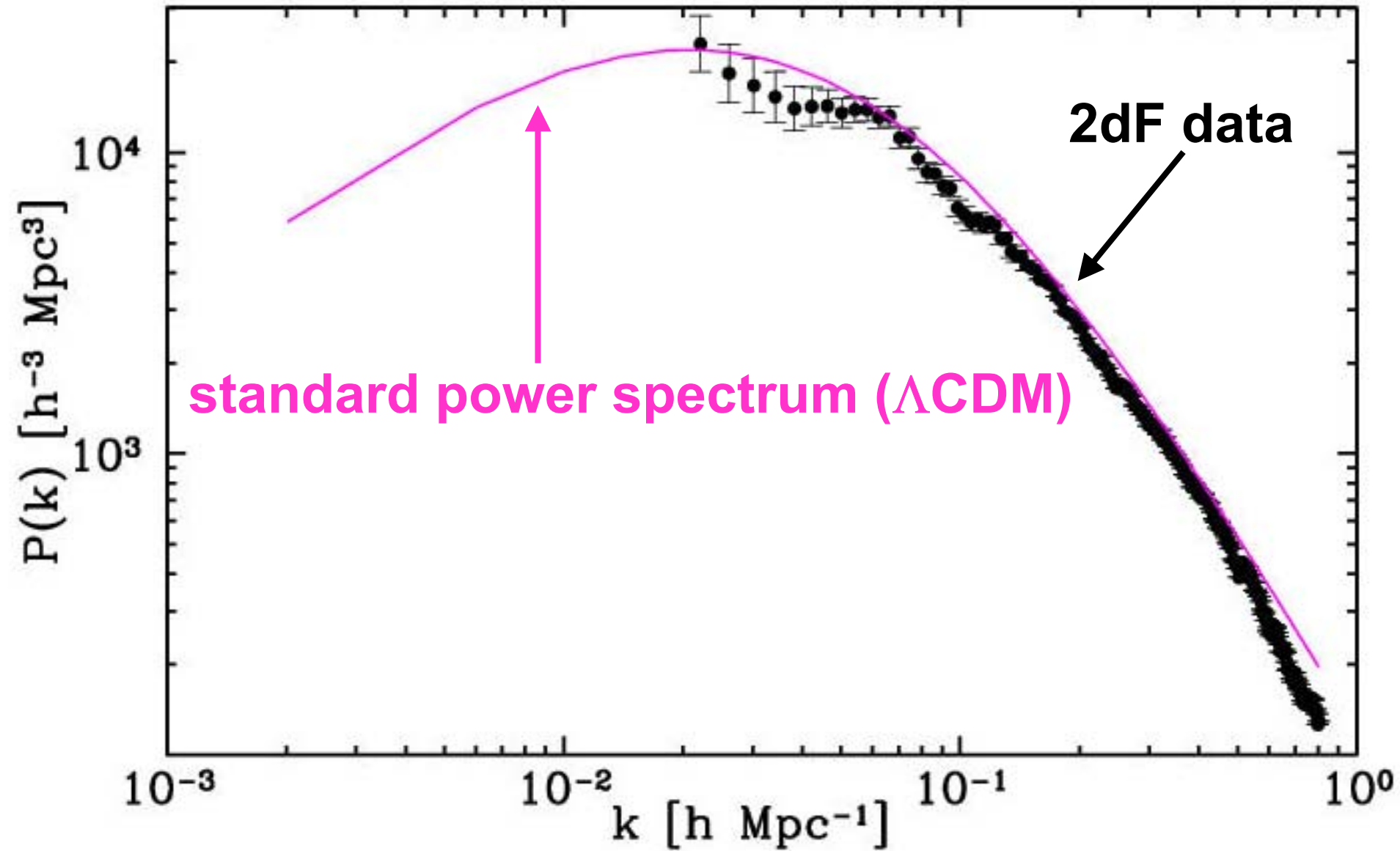
Dark energy:	66%
Dark matter:	30%
Dark neutrons & protons:	3.78%
Visible matter:	0.1%
Massive neutrinos:	0.1%
Radiation:	0.02%

Intelligent design?

Baryons small fraction – **visible baryons even less**

- Baryons cannot be dominant form of matter!
- (Neither can neutrinos!)

The evolved spectrum



The evolved spectrum

1. Collisionless damping – free streaming

If dark matter is relativistic or semi-relativistic particles can stream out of overdense regions and smooth out inhomogeneities. The faster the particle the longer its free-streaming length.

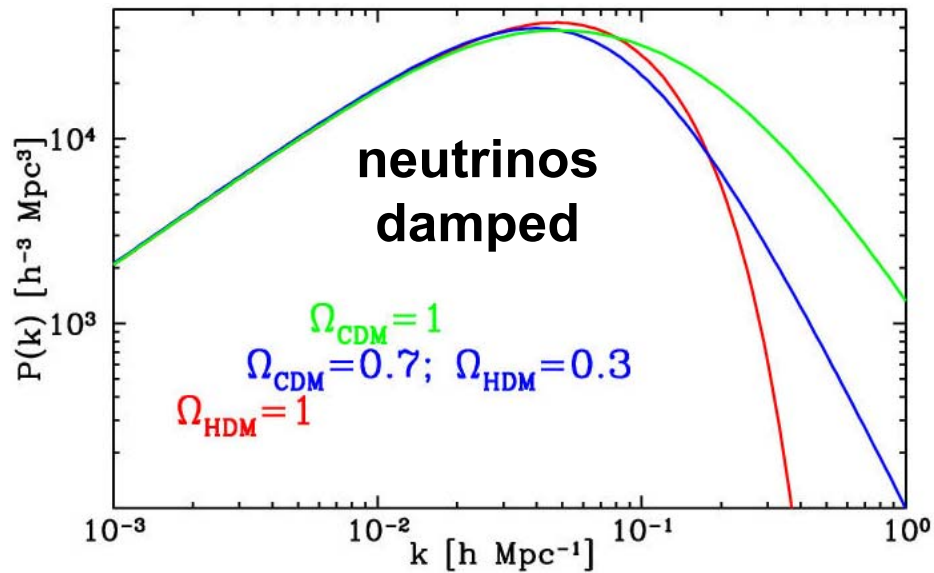
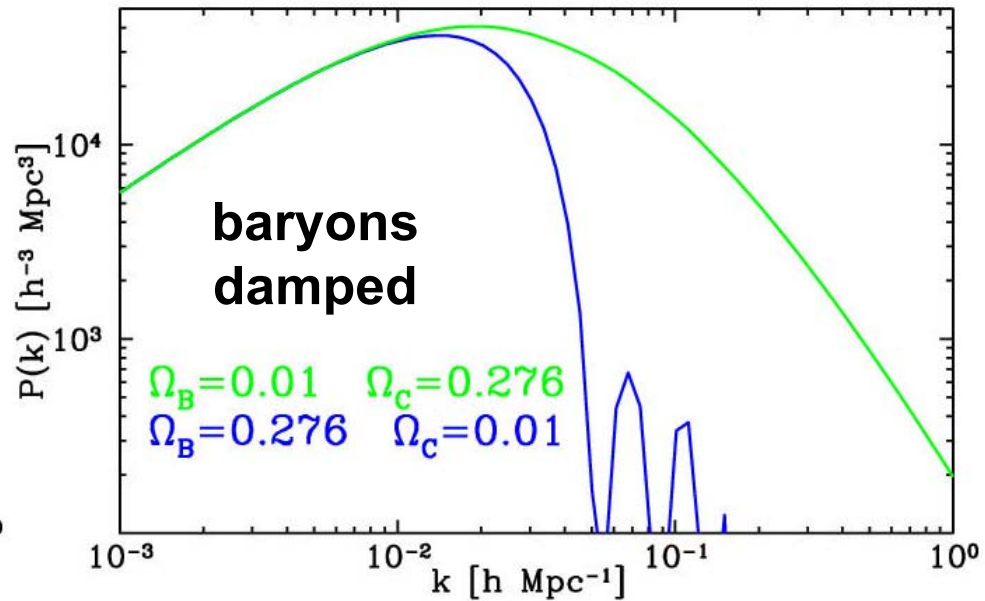
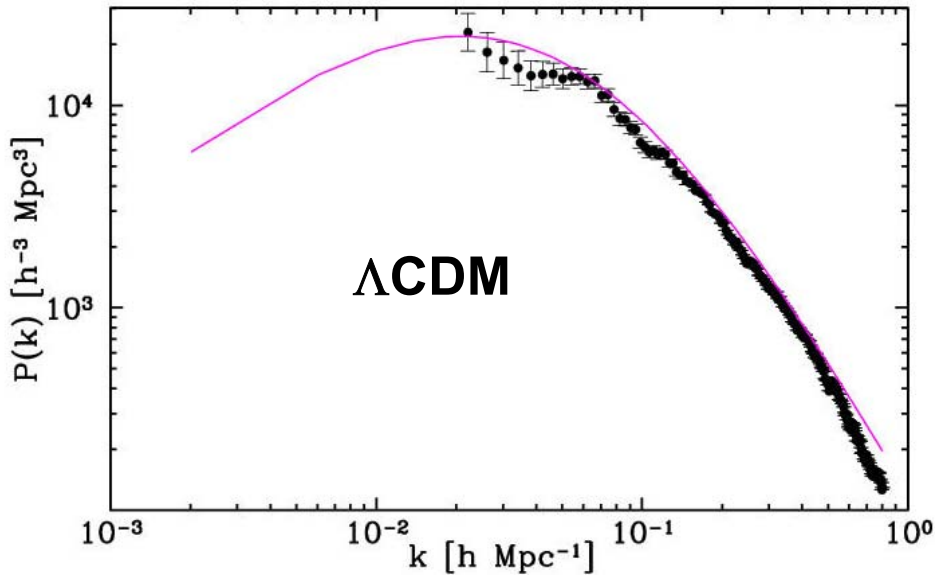
Quintessential example: eV-range neutrinos

2. Collisional damping – Silk damping

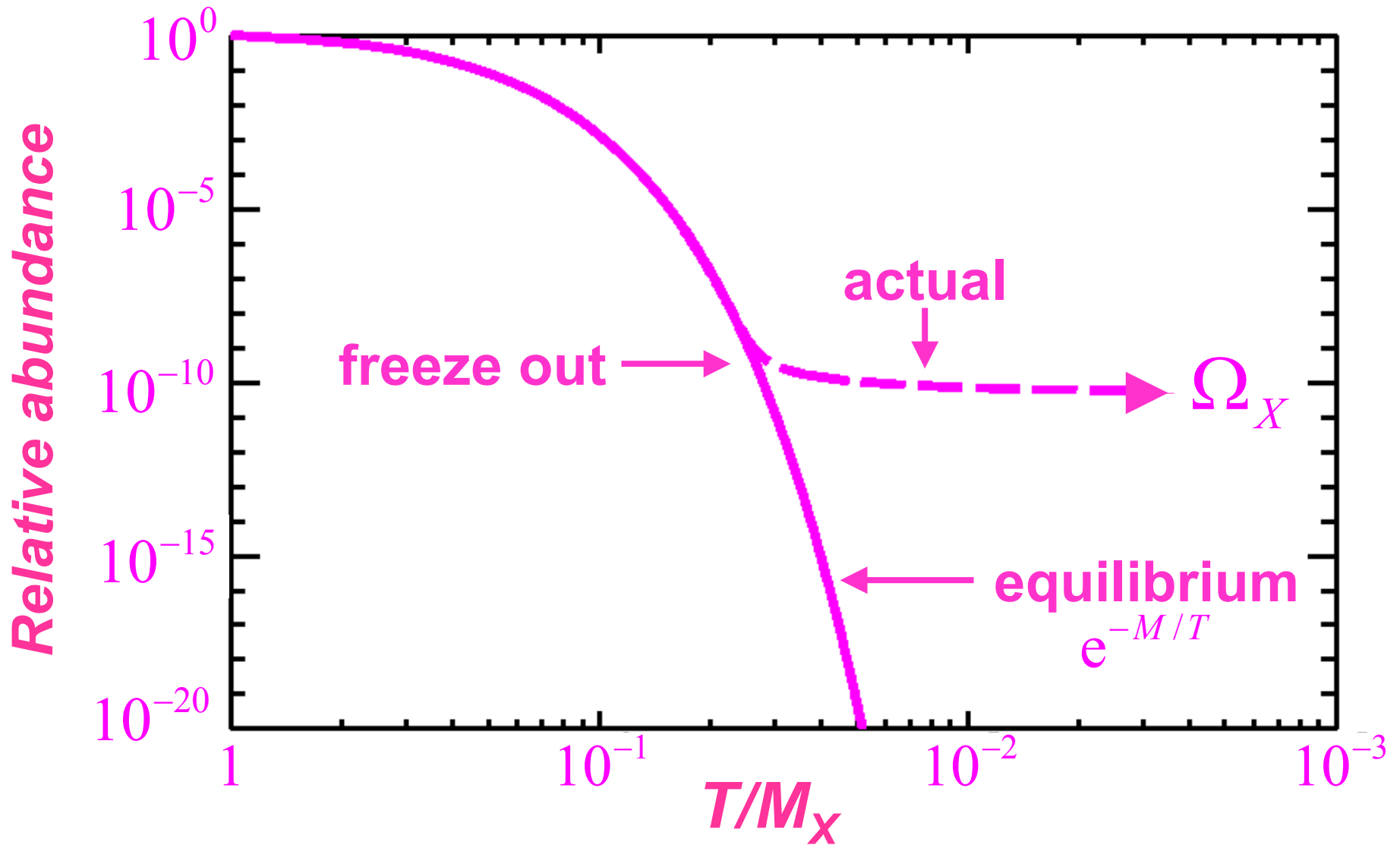
As baryons decouple from photons, the photon mean-free path becomes large. As photons escape from dense regions, they can drag baryons along, erasing baryon perturbations on small scales.

Baryon-photon fluid suffers damped oscillations.

The evolved spectrum



Asymmetry needed



$$\Omega_X \propto \sigma_A^{-1} \quad (\text{independent of mass})$$

Baryon Symmetric (BS) models?



Baryon Symmetric (BS) models?

Require:

1. CP domains
2. Small amount of inflation after phase transition
3. Domains today separated by about
1 Gpc (Cohen *et al.*) 10 Mpc (Brown *et al.*)
[horizon $2H^{-1} = 6h^{-1}$ Gpc = 10 Gpc ($h=0.6$)]
4. No domain walls

**SIZE DOES
MATTER**

Models should be simple, *insofar as possible!*

“Despite temptations, I have remained chaste, *insofar as possible!*”

- Robert d'Arbrissel, Fontevrault Abbey, 1100

Experimental issue:

1. Annihilation radiation (background?)
2. Antinuclei in cosmic rays (do they get in our galaxy?)

Baryogenesis scenarios (BS)

Sakharov's Ingredients:

1. Baryon number violation
2. C & CP violation
3. Non-equilibrium conditions

How they are combined is important!

Dinner at a ★★ ★ :

1. Beef
2. Sauce
3. Potato

Dinner at McDonald's:

1. Beef
2. Sauce
3. Potato

Baryogenesis requires physics beyond the Standard Model*

- Standard Model EWK baryogenesis fails (M_H too large)
- Supersymmetric Standard Model problematic
- Sphalerons still operative, so need nonzero $B-L$

“Beyond the Standard Model”

does not mean

“Beyond Reason”

*Non-SM signals from baryon asymmetry, dark matter, astronomical neutrinos.

Baryogenesis scenarios (BS)

SU(5) Drift and decay*



SM Electroweak baryogenesis*



SUSY GUT nonzero B-L



Leptogenesis (decay of N)



Affleck—Dine



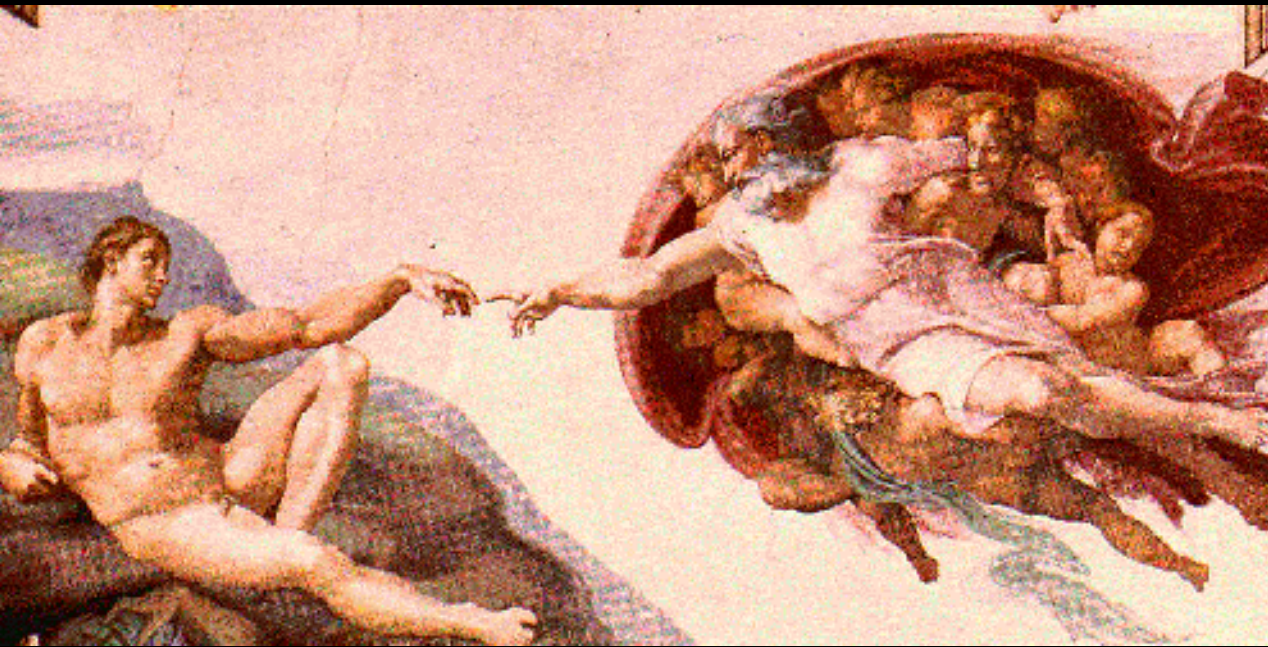
Spontaneous baryogenesis



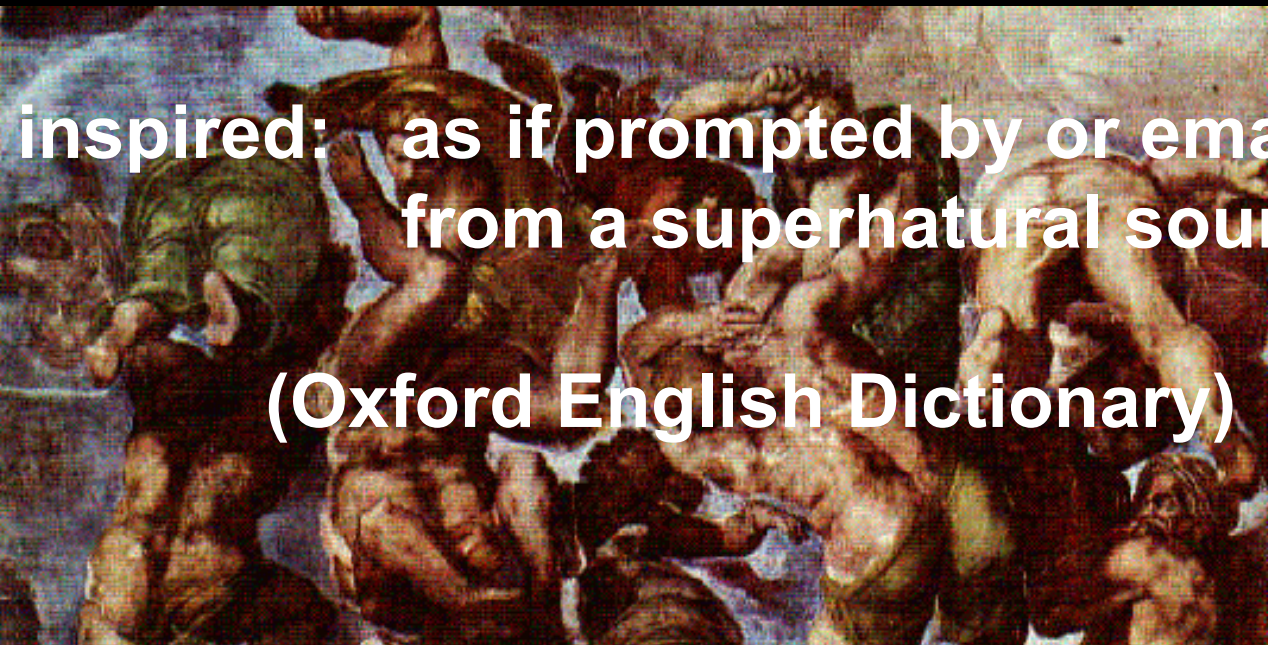
Brane scenarios



*See talk, “Six reasons I hate experimentalists.”



Top down
(superstring
inspired)



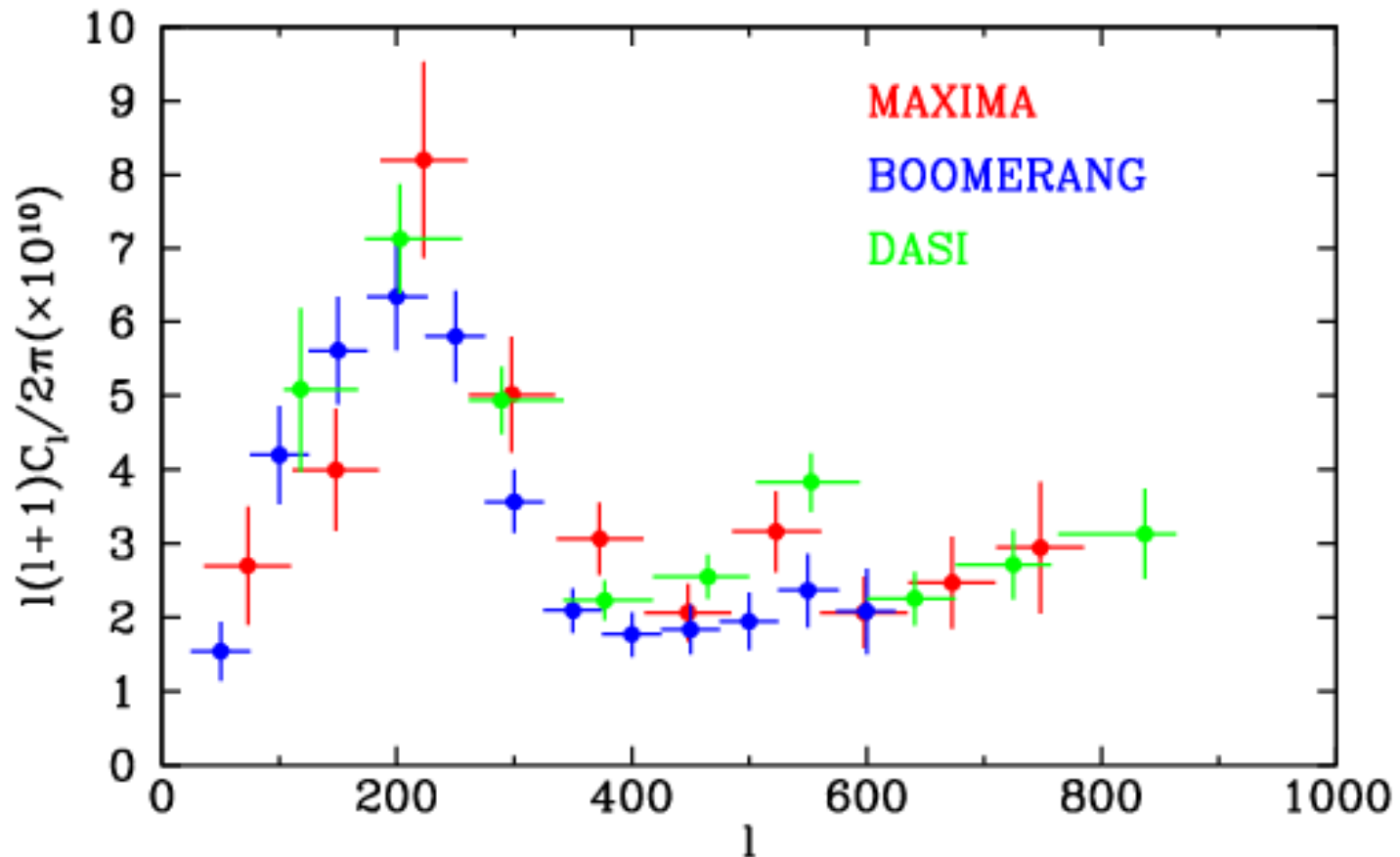
inspired: as if prompted by or emanating
from a superhatural source.

(Oxford English Dictionary)

Bottom up
(phenomenology
perspired)

Baryogenesis scenarios (BS)

- The baryon asymmetry is just one number
- cf. the microwave background

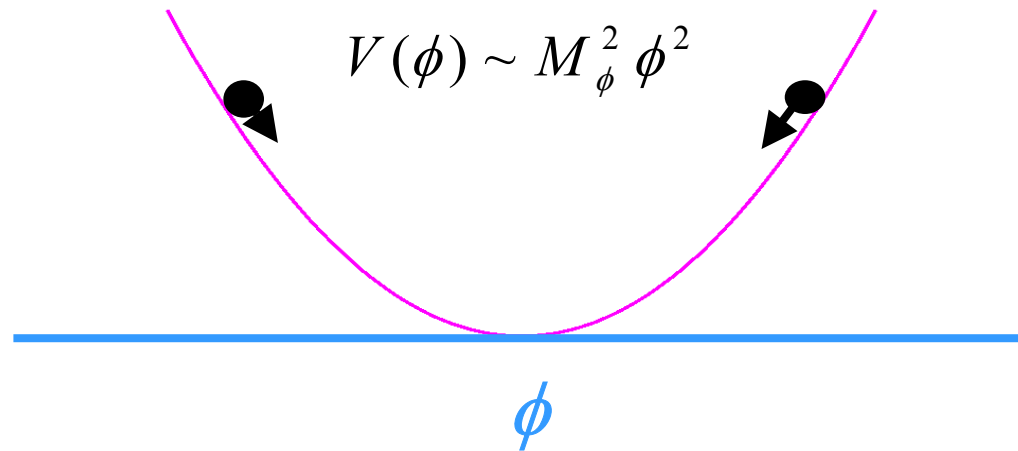


Baryogenesis after inflation

- Inflaton is light!
- Reheat temperature is low!
- Leptogenesis & SUSY GUT $\Delta(B-L)$ requires massive particles

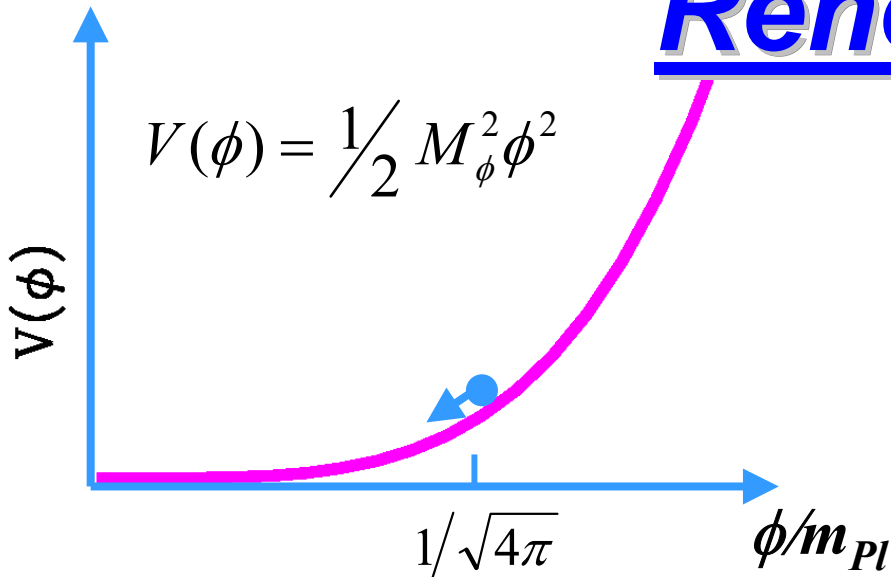
Defrosting

- generate ΔB after inflation
- after inflation the universe is frozen



- defrosting:
 - reheating (ca. early 80s)
incoherent, nonresonant, linear decay of inflaton
 - preheating (ca. mid 90s)
coherent, resonant, nonlinear particle production

Reheating



$$M_\phi = 10^{13} \text{ GeV}$$

$$\phi_{END} = m_{Pl} / \sqrt{4\pi}$$

- **coherent ϕ oscillations with decreasing amplitude**

$$\omega = M_\phi \quad \rho_\phi \propto a^{-3}$$

- **ϕ coupled to other fields**

$$\rho_\phi \text{ decays with width } \Gamma_\phi$$

- **decay produces massless degrees of freedom (γ)**

thermalize to temperature T

- **when “all” energy extracted from ϕ , $T = T_{RH}$**

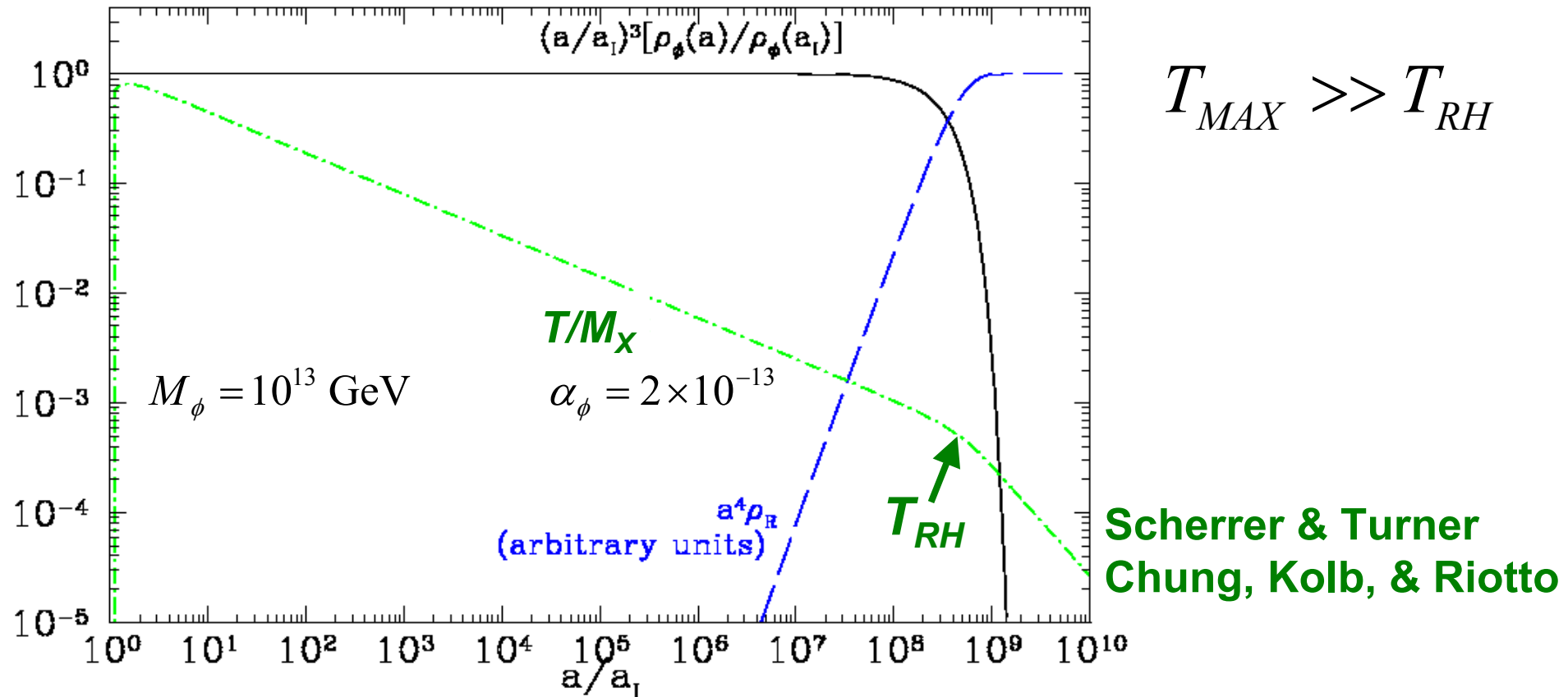
gravitino limit $T_{RH} < 10^9 \text{ GeV}$

Reheating

$$\phi = \text{inflaton} \quad \Gamma_\phi = \alpha_\phi M_\phi$$

$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi\rho_\phi = 0$$

$$\dot{\rho}_R + 4H\rho_R - \Gamma_\phi\rho_\phi = 0$$



Preheating

- Inflaton ϕ coupled to another scalar field χ :

$$V = \frac{1}{2} g^2 \phi^2 \chi^2$$

- Field equation:

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{\vec{k}^2}{a^2} + m_\chi^2 - \xi R + g^2 \phi^2 \right) \chi_k = 0$$

\vec{k} = comoving momentum $\phi(t) = \Phi(t) \sin mt$

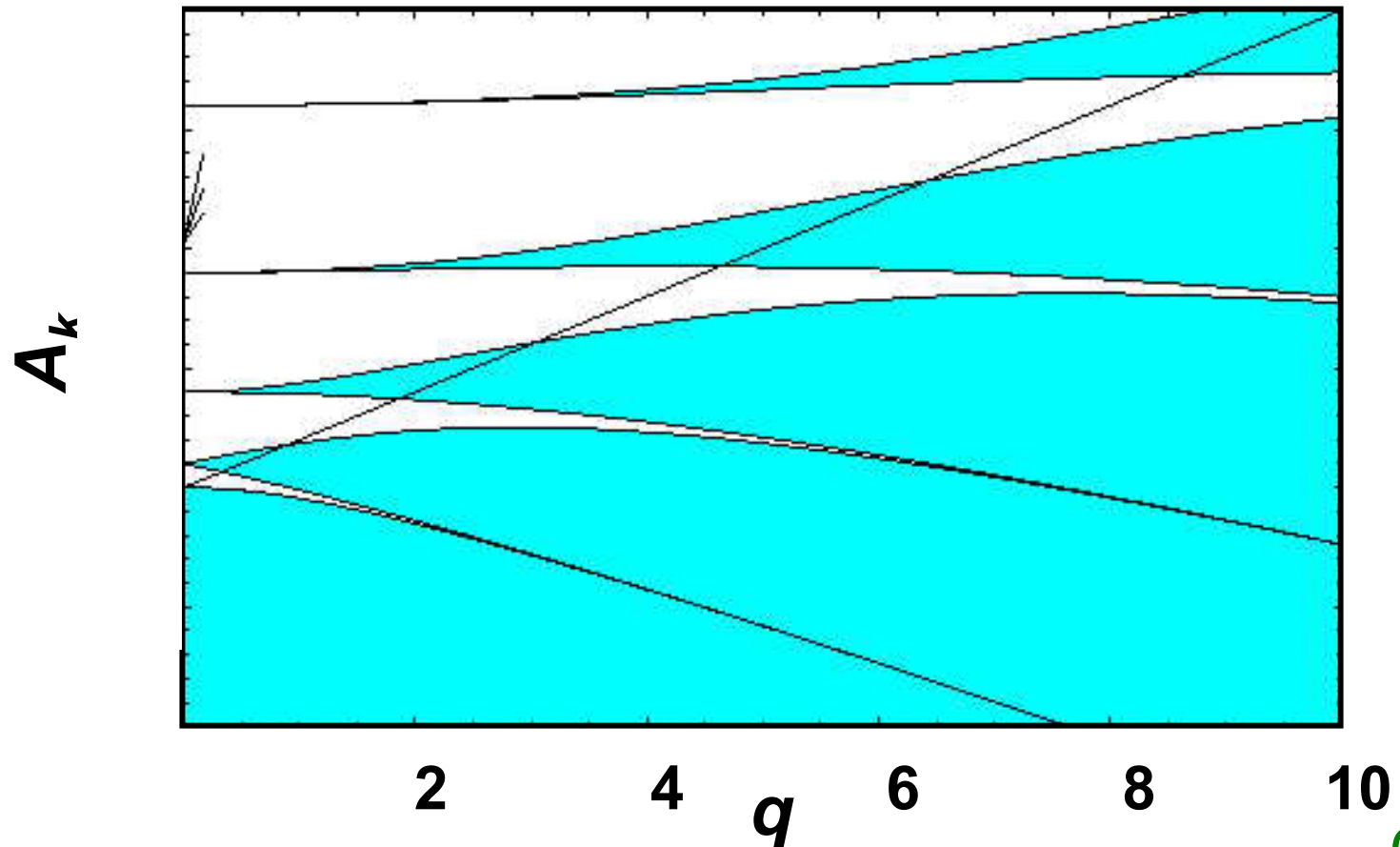
- Minkowski space Φ constant: Matheiu equation

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{\vec{k}^2}{a^2} + g^2 \Phi^2 \sin^2 mt \right) \chi_k = 0$$

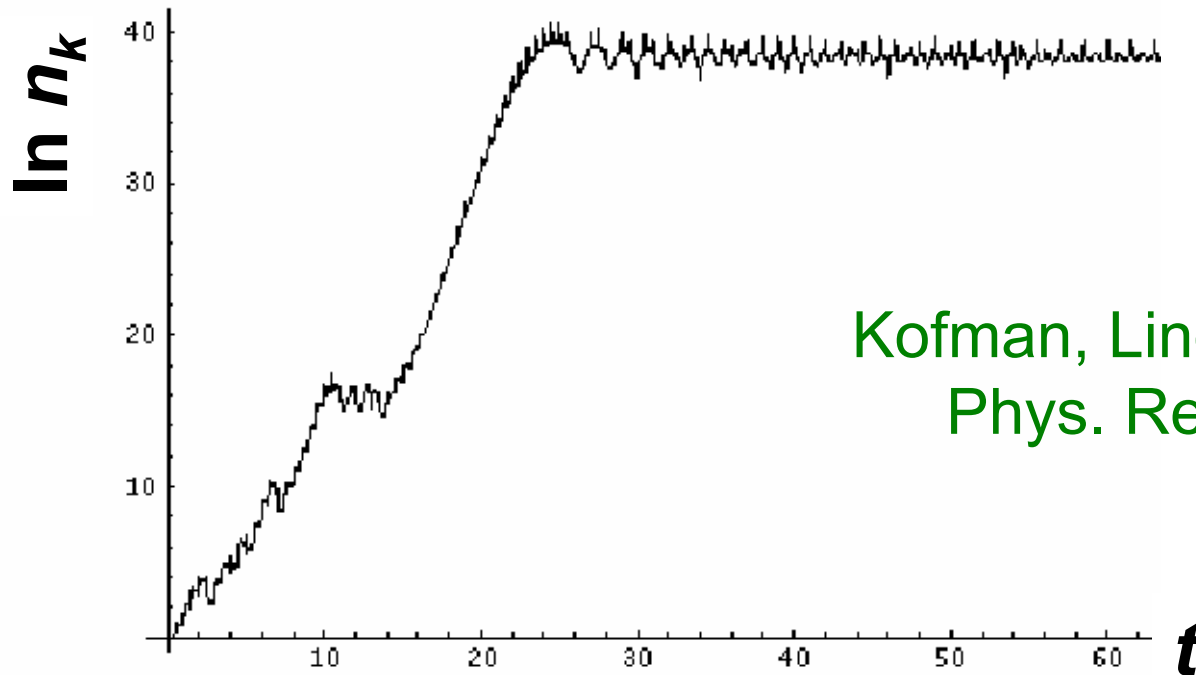
Instability regions of Matheiu Equation

$$q = \frac{g^2 \Phi^2}{4m^2} \simeq 10^{12} g^2$$

$$A_k = 2q + \frac{k^2}{m^2}$$



Preheating



Kofman, Linde, Starobinski
Phys. Rev. D (1997)

Conclusion: in a few dozen oscillation periods,
significant fraction of energy extracted

Note: inherently coherent process-
many inflaton quanta participate

Preheating

- Rethink symmetry restoration
(Khlebnikov, Kofman, Linde, Tkachev)
- Produce massive particles after inflation
(Kolb, Riotto, Tkachev)
- Naturally produce nonequilibrium conditions, massive particles for baryogenesis (assume CP violation)
(Kolb, Linde, Riotto)

Cosmological parameters

- **Cosmological parameters:**

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t_0 → age of the universe

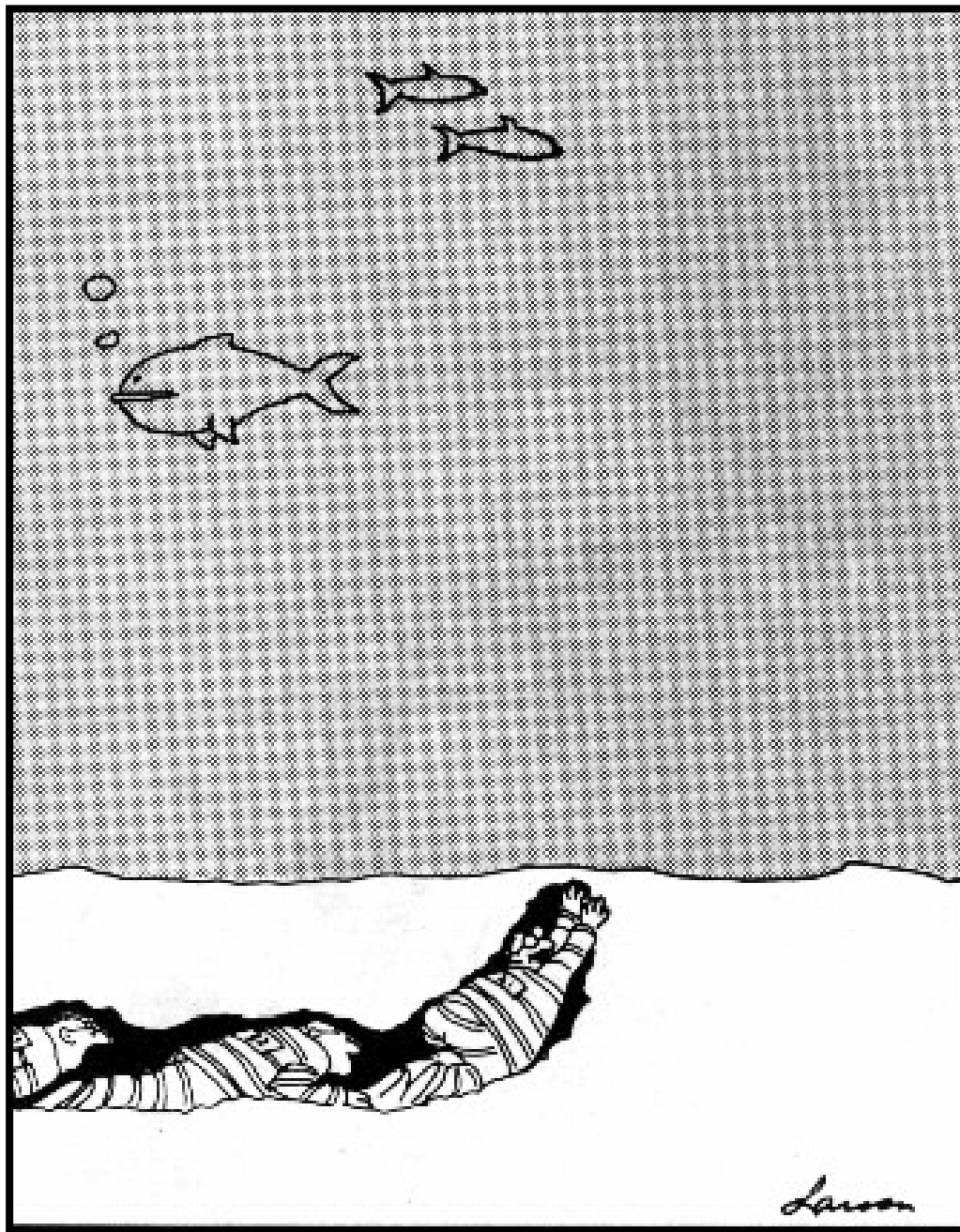
T_0 → temperature of the universe

- **Power spectrum of large-scale structure:**

$P(k)$

- **Anisotropy of CMB:**

C_l



We're almost free, I just felt the first drops of rain

What We “Know” *

The matter density is dominated by cold dark matter,
which we know nothing about!

The baryon asymmetry arises in the GUT or EWK era through B, CP, and equilibrium violation (Sakharov’s ingredients),
EWK doesn’t seem to work....GUT scenarios are not simple!

The perturbations arise from inflationary dynamics,
which depends on particle physics at high energies,
which we know nothing about!

The universe is dominated by a cosmological term
(dark energy, funny energy, quintessence, polenta,
cosmological constant, cosmoillogical constant,),
which we know less than nothing about!

***It ain’t what you don’t know, it’s what you know that ain’t so!**

Origin of baryon asymmetry:
a complex natural phenomenon

Sakharov's prescription:
*a simple, elegant, compelling
explanation*

**“For every complex natural phenomenon
there is a simple, elegant, compelling,
wrong explanation.”**

- Tommy Gold

**When one tugs at a
single thing in
nature, he finds it
hitched to the rest
of the universe.**

– John Muir

