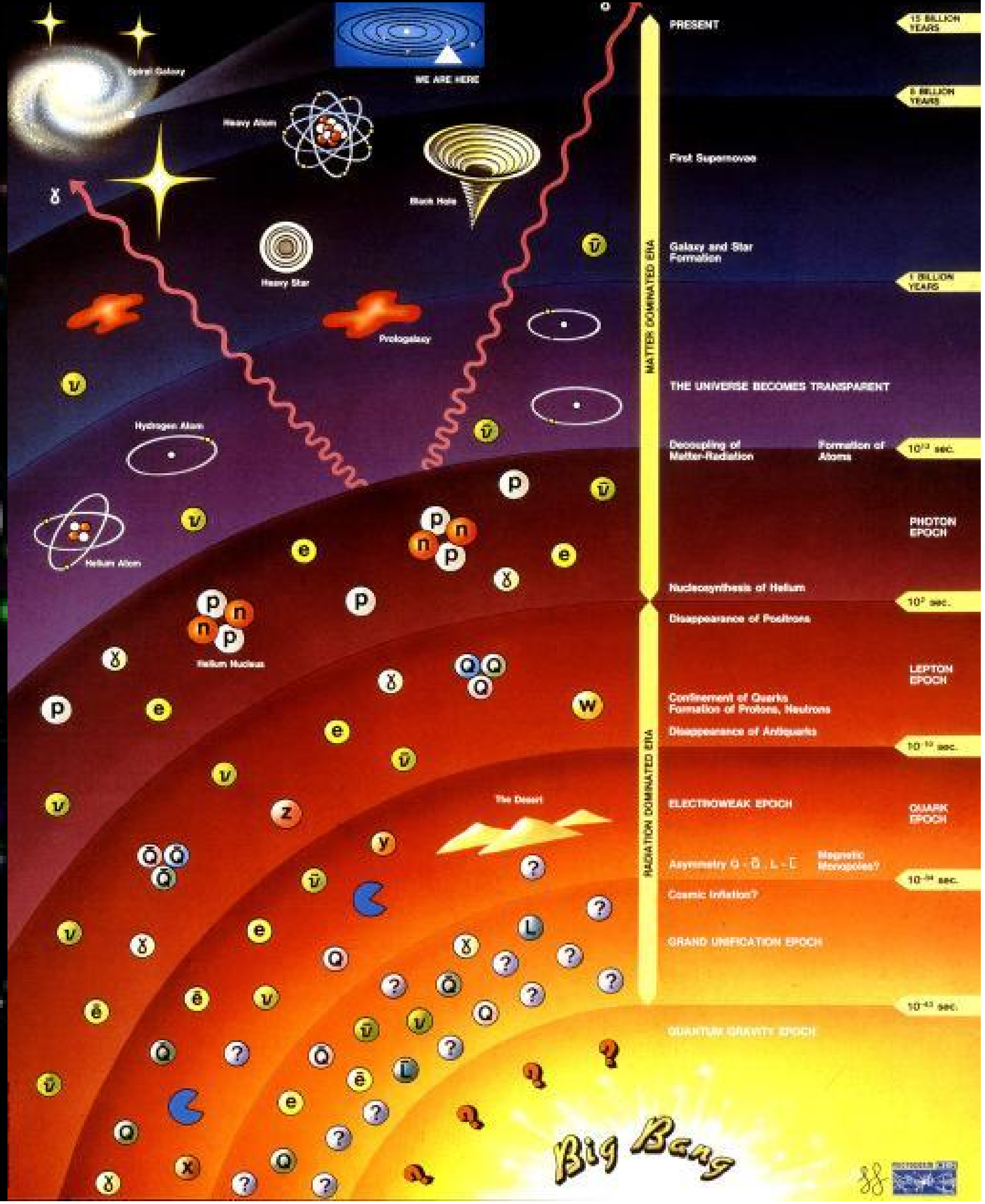
Neutrino Mass and Cosmology

- History of the Universe
- The Universe according to WMAP 5
- The Big Questions:
  - Origin of the Universe
  - Origin of Dark Energy
  - Origin of Dark Matter
  - Origin of Atoms

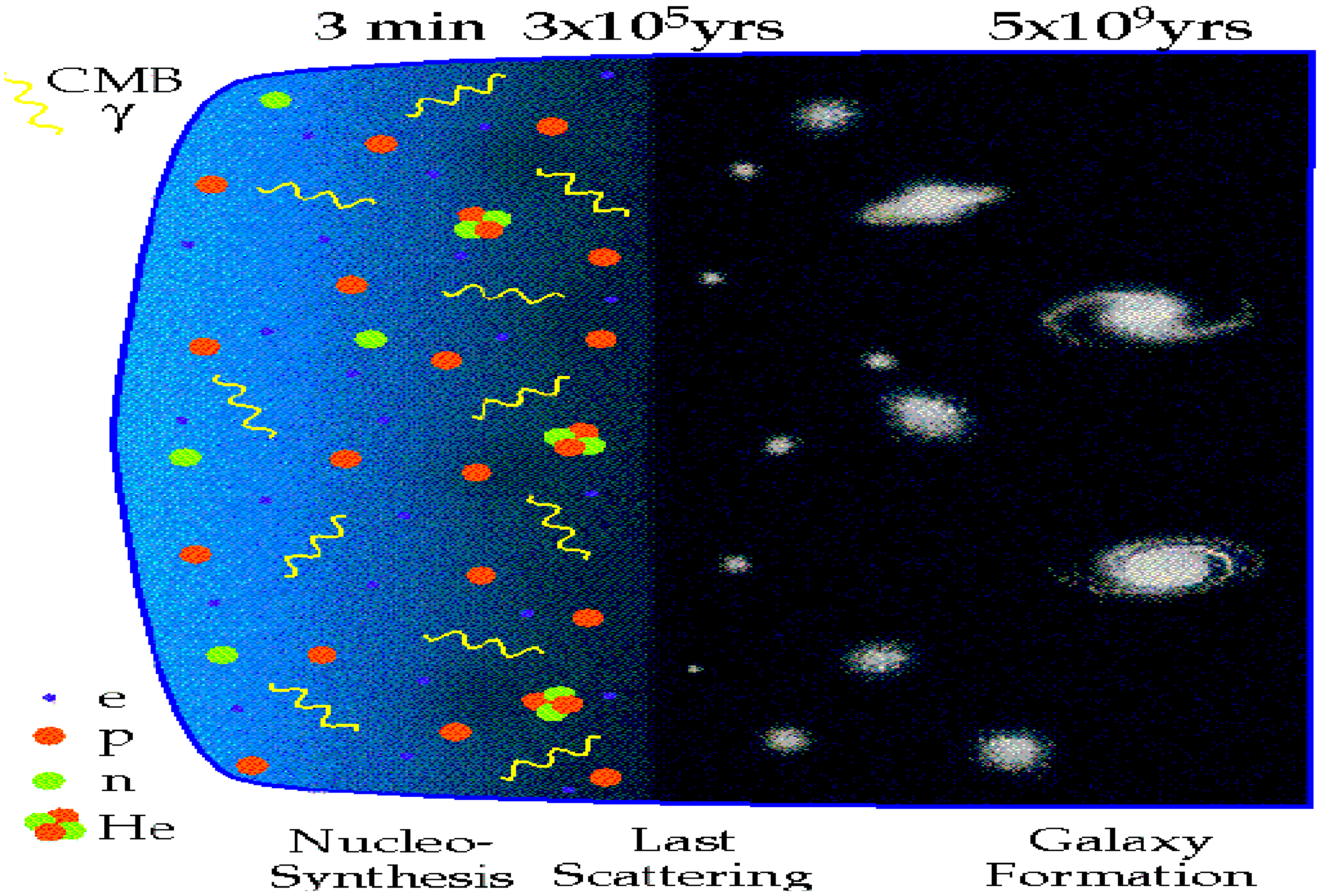
Steve King, UK HEP Forum Neutrino Horizons,
Coseners House, Abingdon, 18th April, 2008

UNIVERSITY OF Southampton
School of Physics and Astronomy

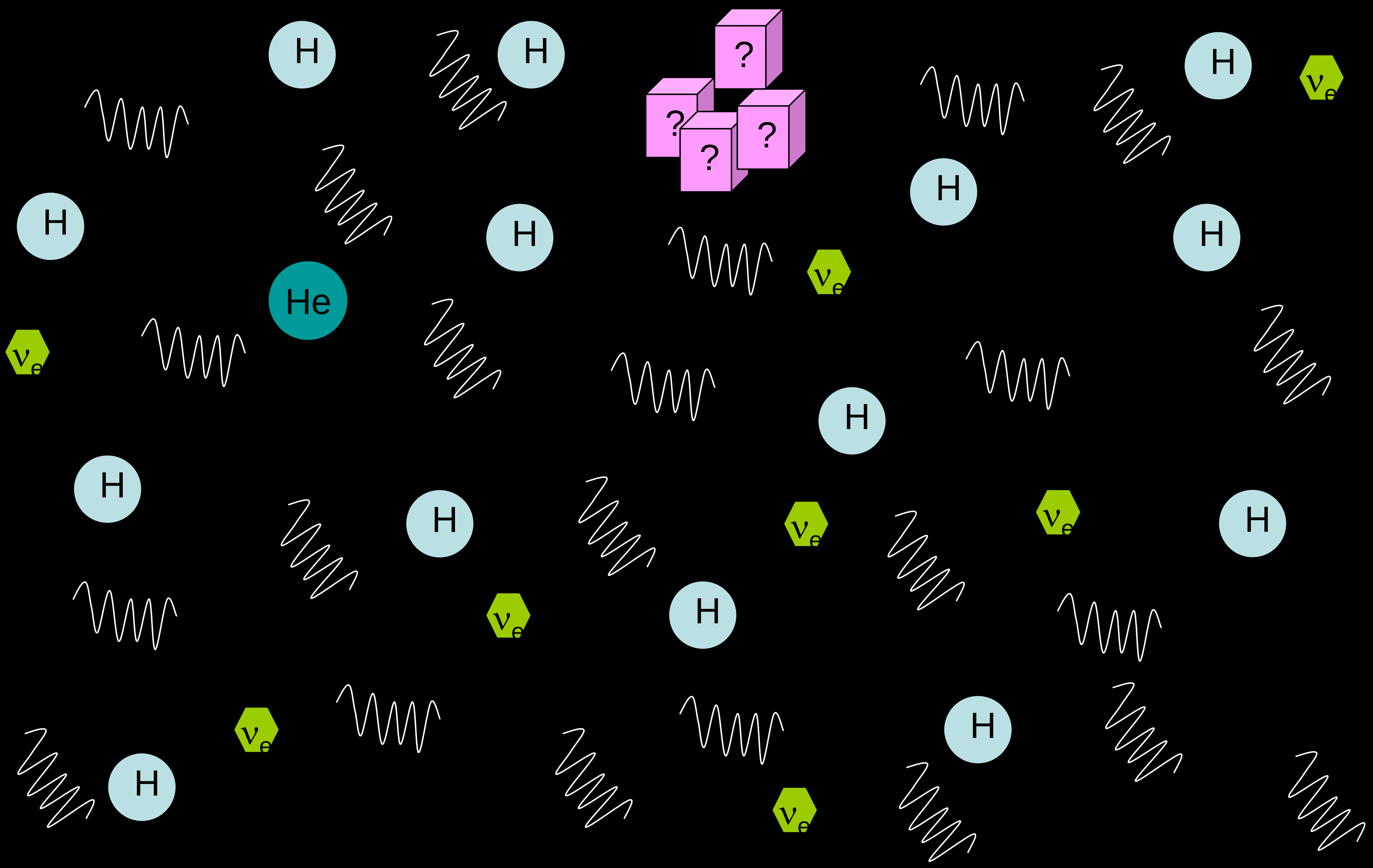
The History of the Universe



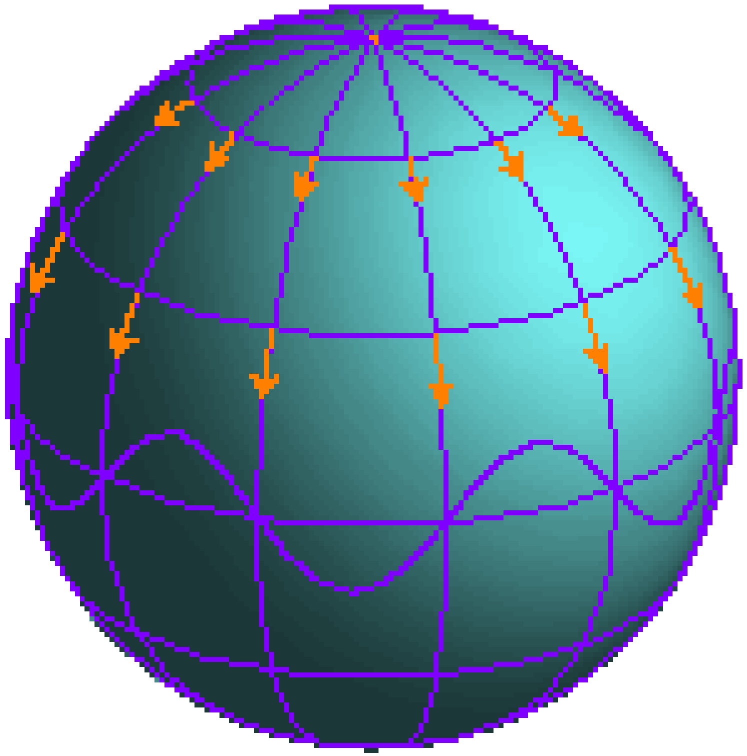
(Very) Brief History



The Universe Age 380,000 years just after the atoms were formed and the Universe becomes transparent -- henceforth these Big Bang photons travel unhindered through the Universe

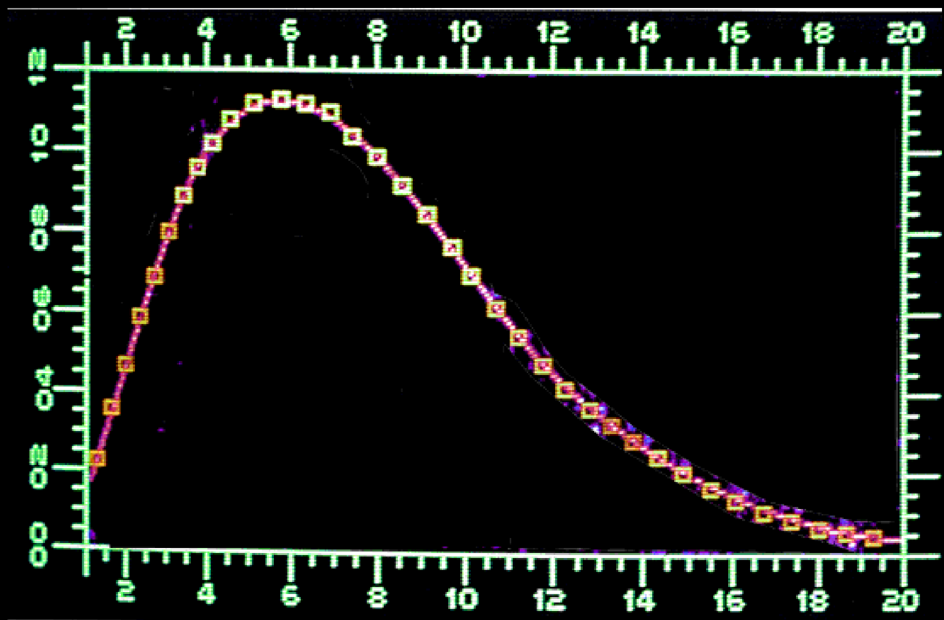


As the Universe expands, the Big Bang photons in the visible spectrum get redshifted into microwave photons

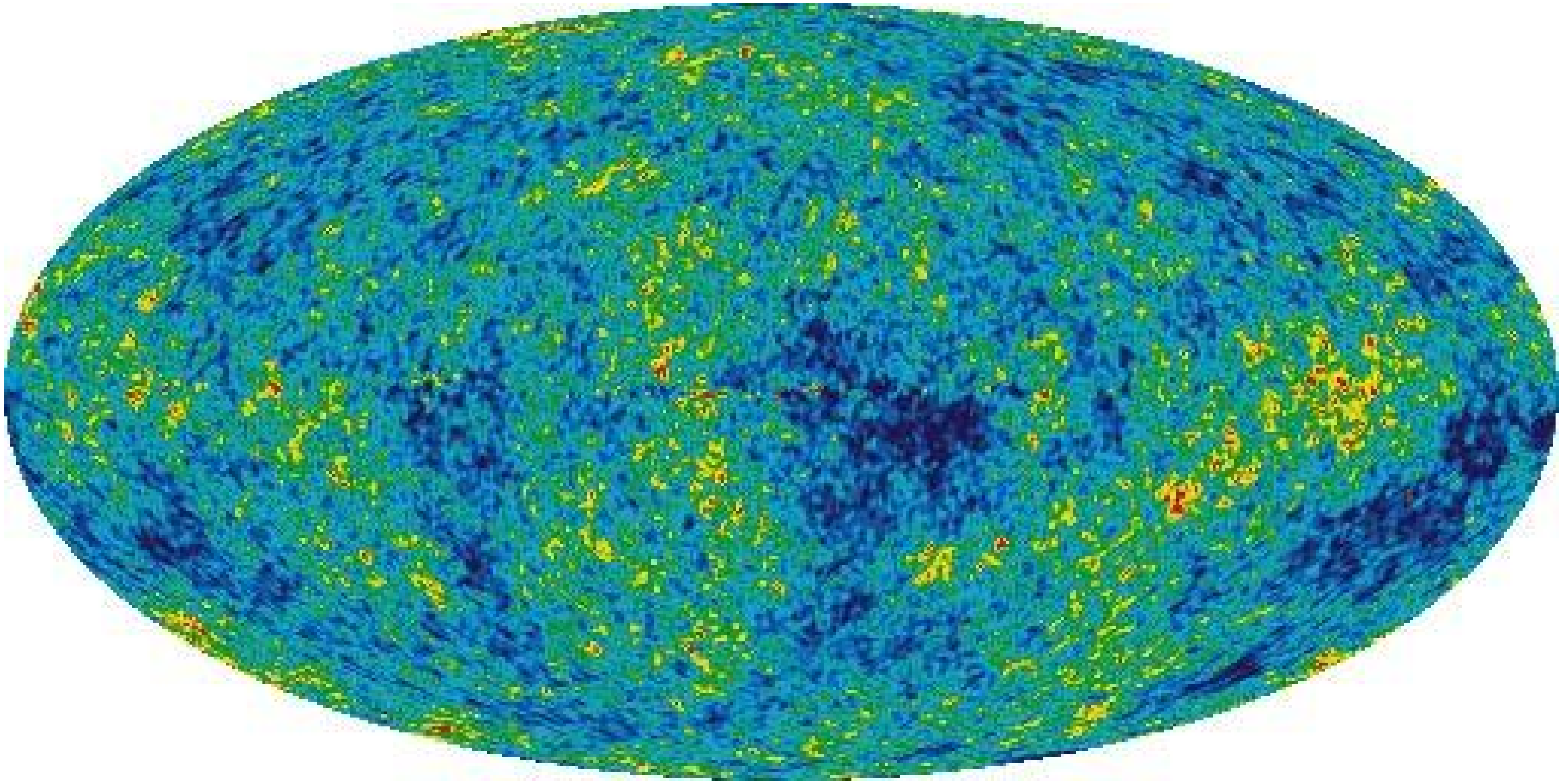


Cosmic microwave background

The Big Bang photons from the time of atom formation (380,000 yrs) are observed as microwave background radiation, with a Black Body spectrum corresponding to a temperature of about 3 K = -270º C
(redshifted from a temperature of about 3,000 K)

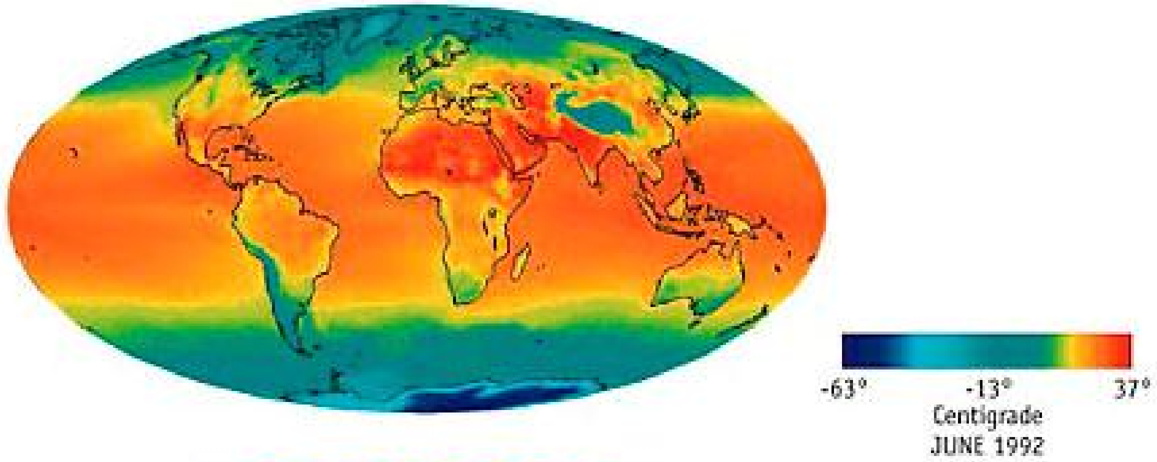


The Universe according to WMAP5

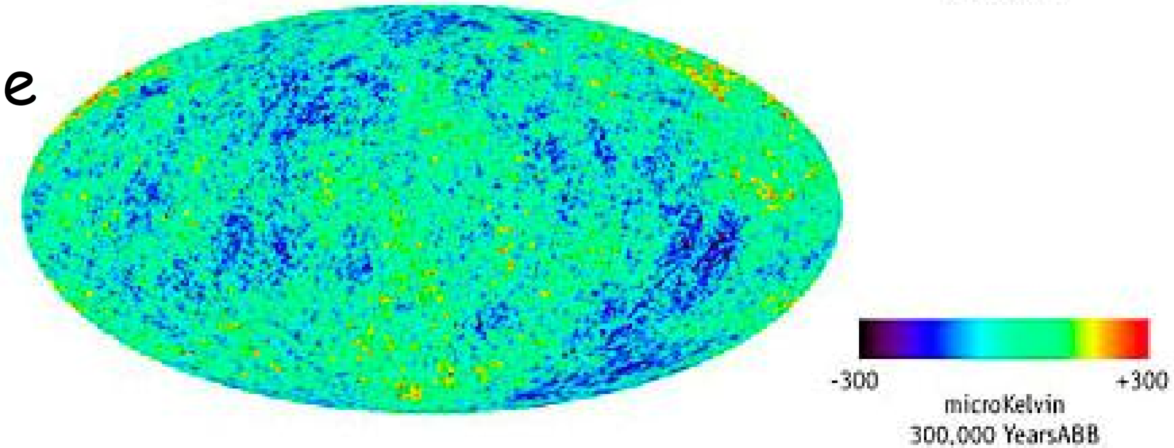


Temperature Maps

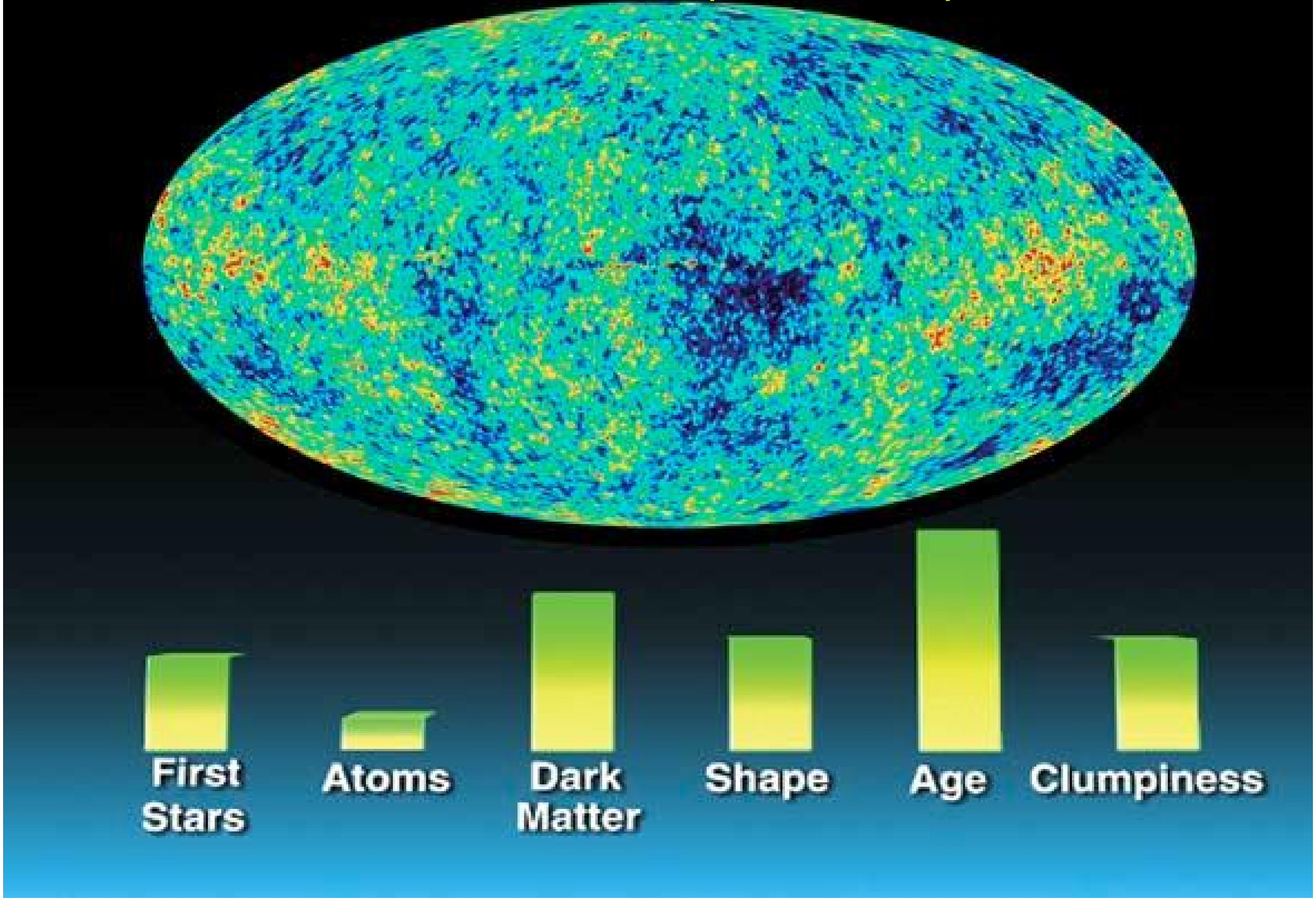
Earth



Universe

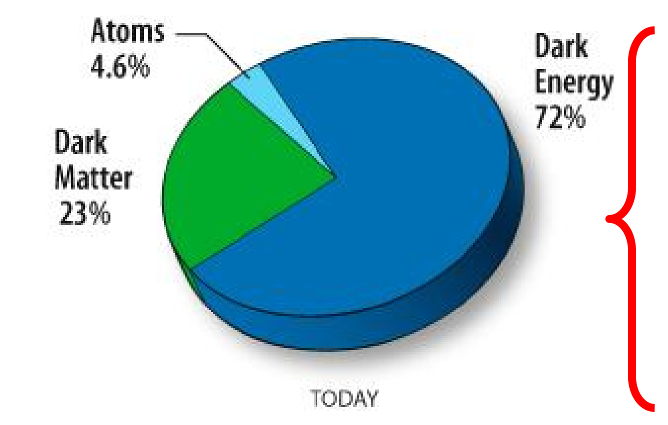


We can learn a lot from these temperature maps



The Standard ΛCDM Model

- Flat Universe
- Dark Energy
- Dark Matter



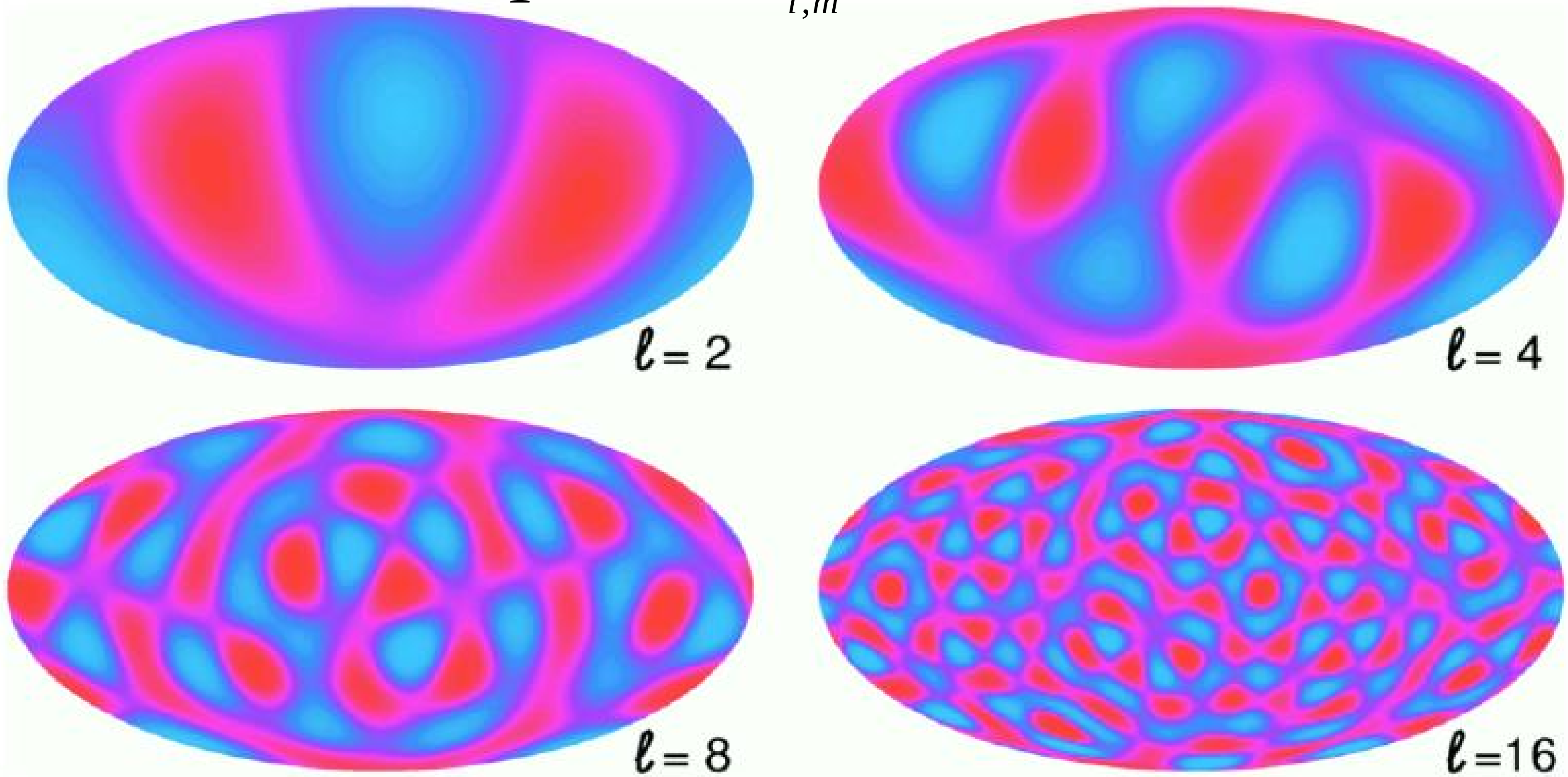
Parameter	Value	Description
Basic parameters		
H_0	70.1 ± 1.3 km/s Mpc^{-1}	Hubble parameter
Ω_b	0.0462 ± 0.0015	Baryon density
Ω_c	0.233 ± 0.013	**Dark matter density**
Derived parameters		
Ω_Λ	0.721 ± 0.015	Dark energy density
t_0	13.73 ± 0.12 Gyr	Age of the universe
n_s	$0.960^{+0.014}_{-0.013}$	**Scalar spectral index**

How solid is this paradigm?

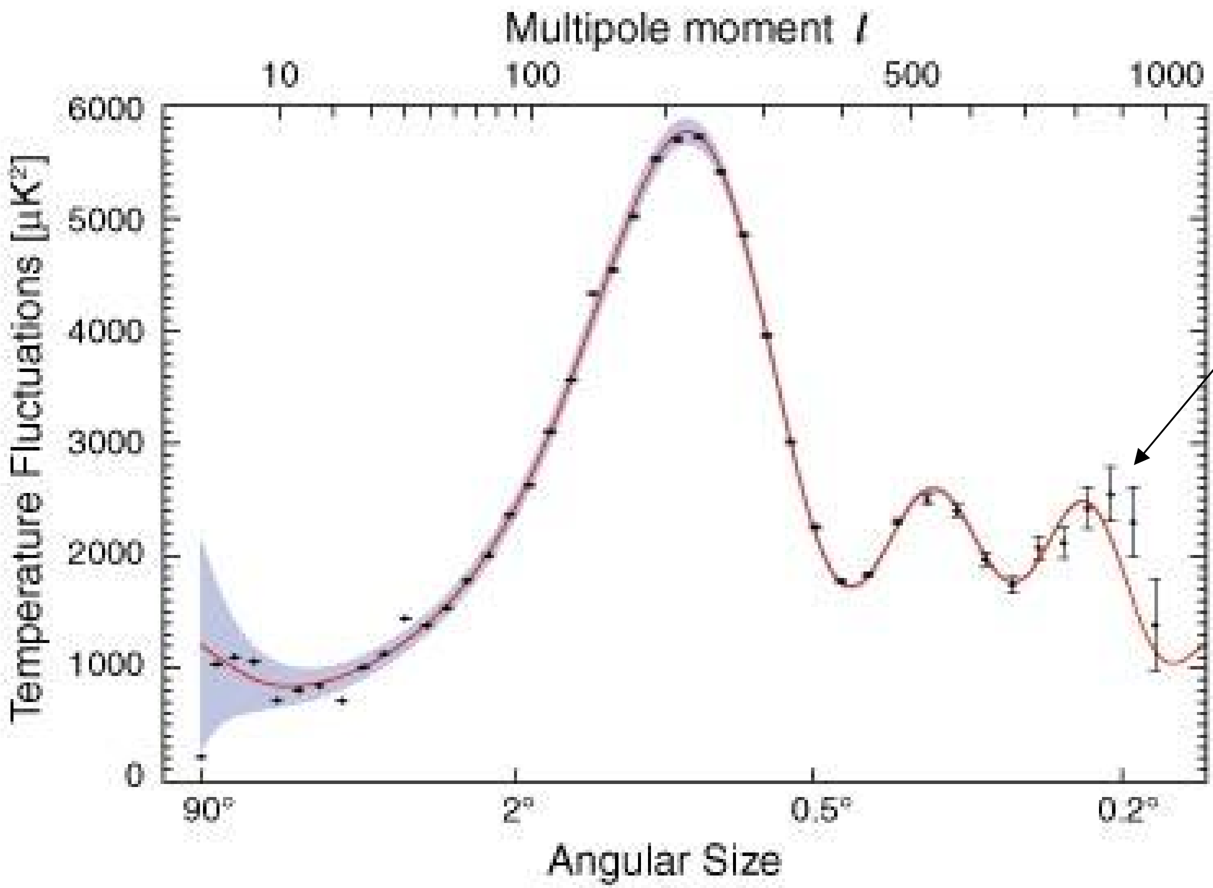
Sarkar

Spherical Harmonic Decomposition

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta,\phi)$$



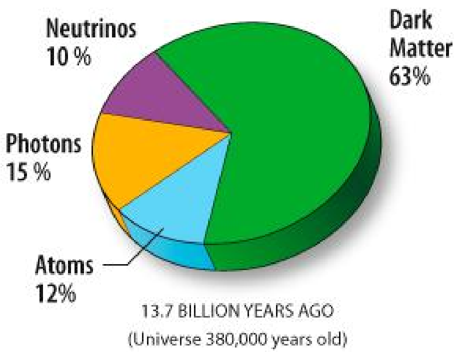
Angular Power Spectrum from WMAP5



NEW RESULT

Third peak measures dark matter density and provides indirect evidence for the neutrino cosmic background at 95% C.L.

The Universe at the decoupling time 380,000 years after big bang



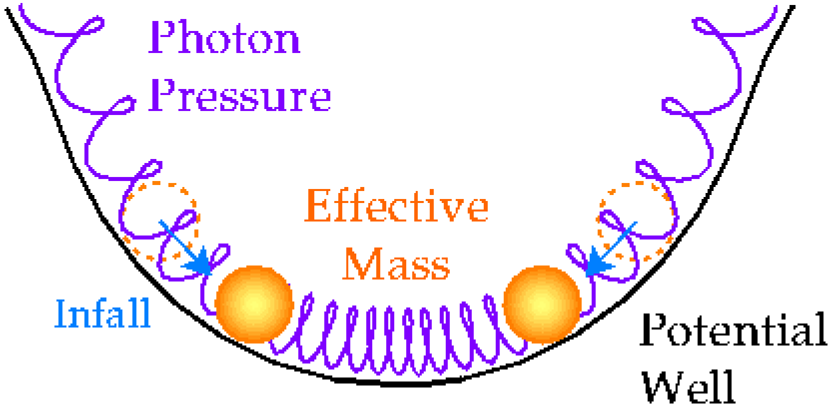
Dark energy is insignificant

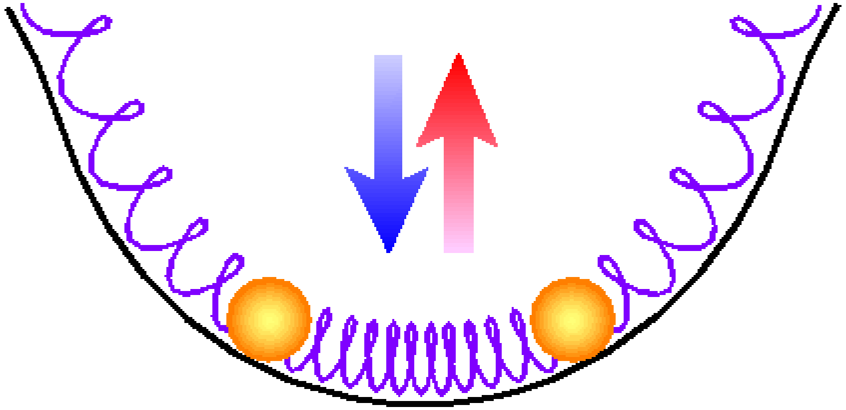
- Most of the mass is dark matter
  - 63% of the density
  - Zero pressure
  - Sound speed is zero
- The baryon-photon fluid
  - baryons are protons & neutrons = all ordinary matter **makes up 12%**
  - energy density of the photons is **15% of total**

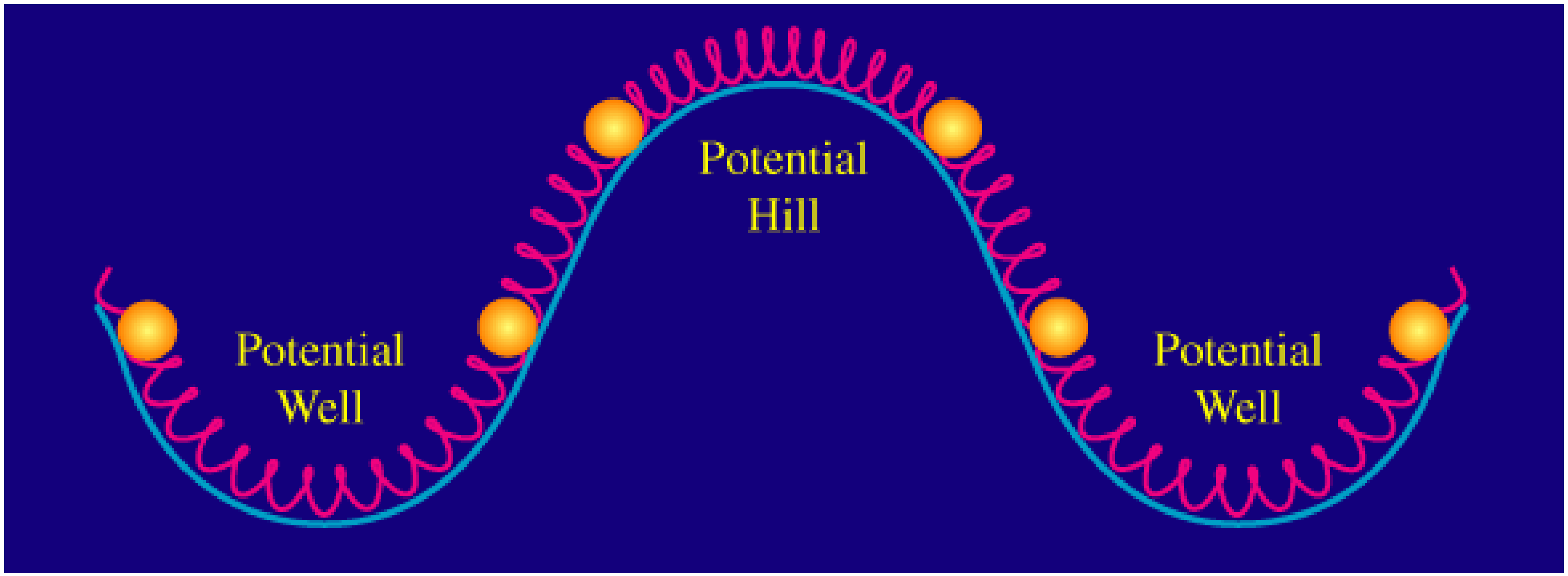
  - since Ω =1 it is deduced that the energy density of neutrinos must make up 10 %

  - Pressure of photons = u/3 = $(1/3)\rho c^2$
  - Sound speed is about $c/\sqrt{3}$ = 170,000 km/sec

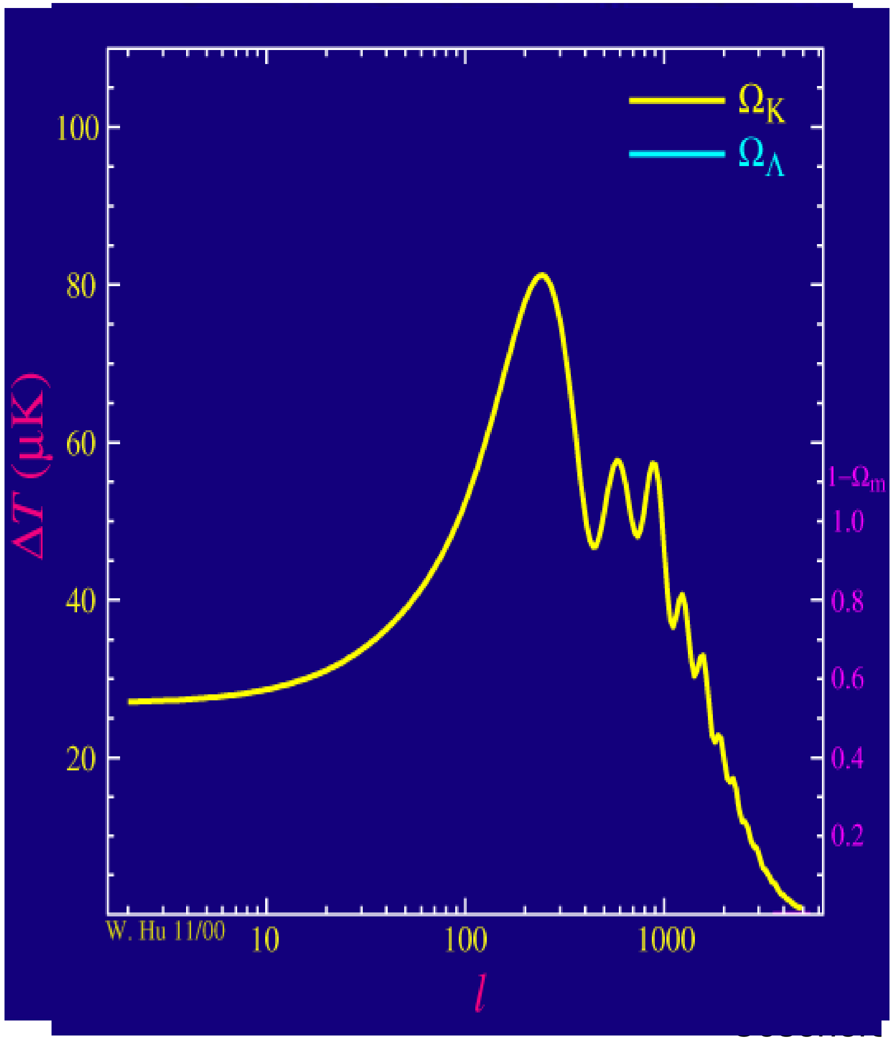
Seeing Sound

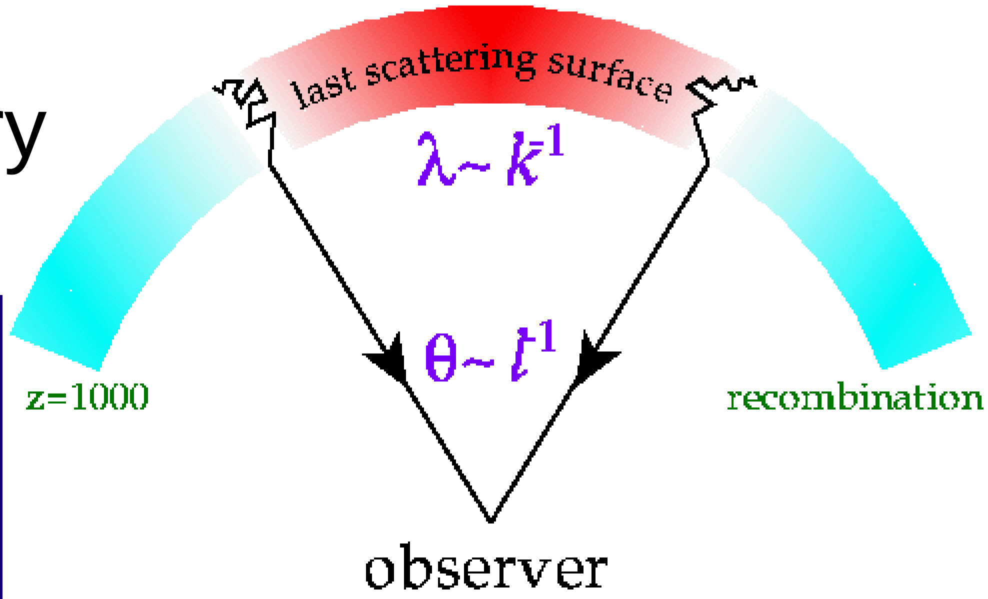


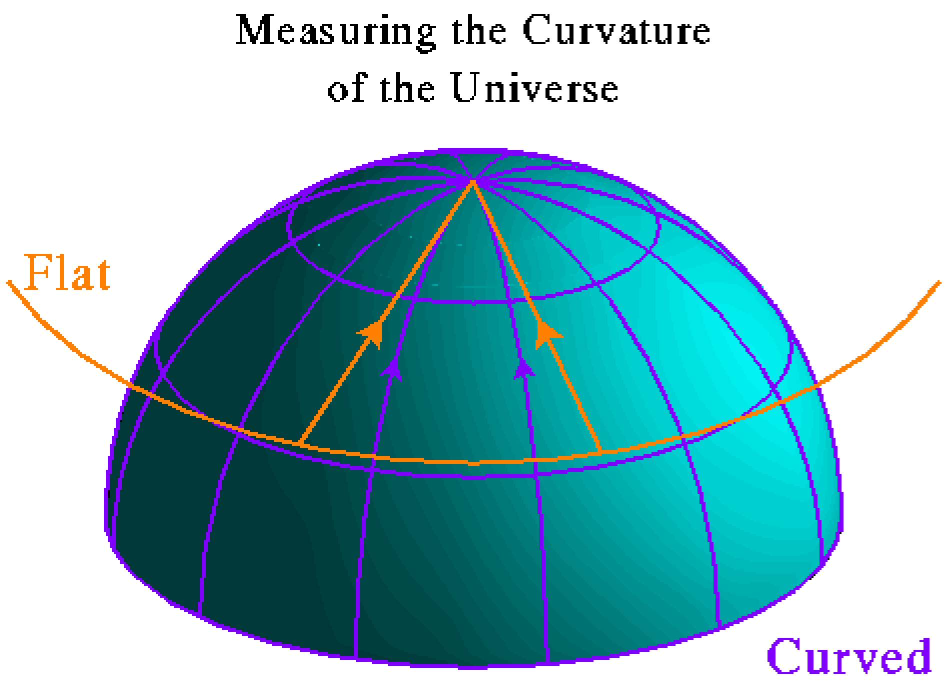




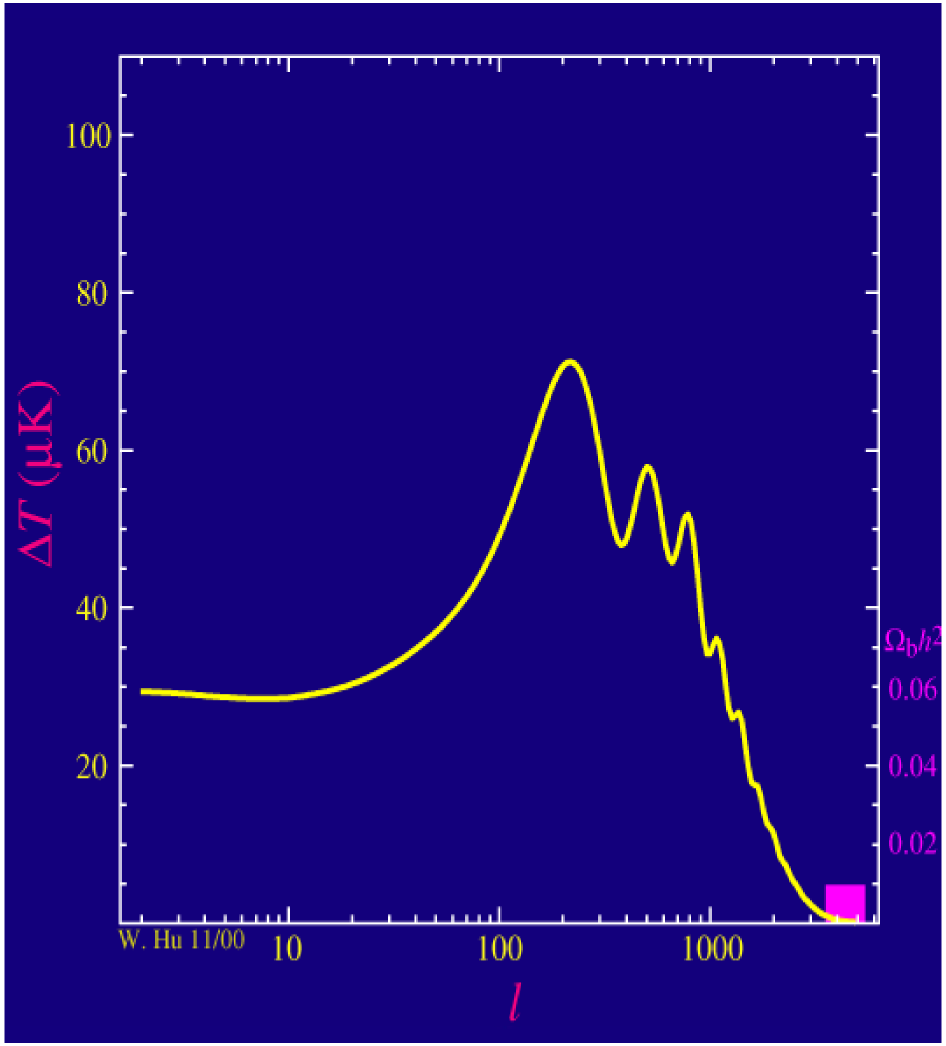
Position of First Peak Measures the Geometry of the Universe

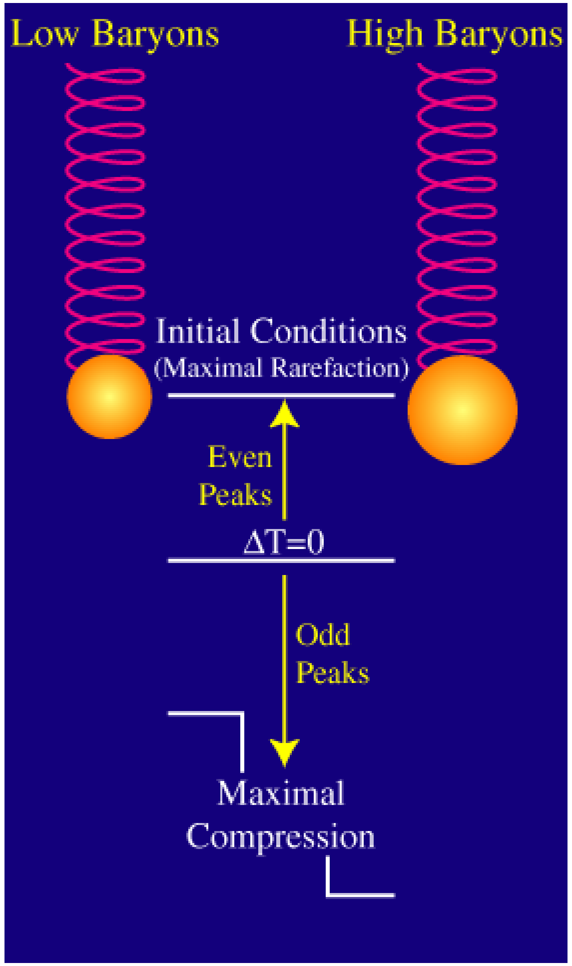




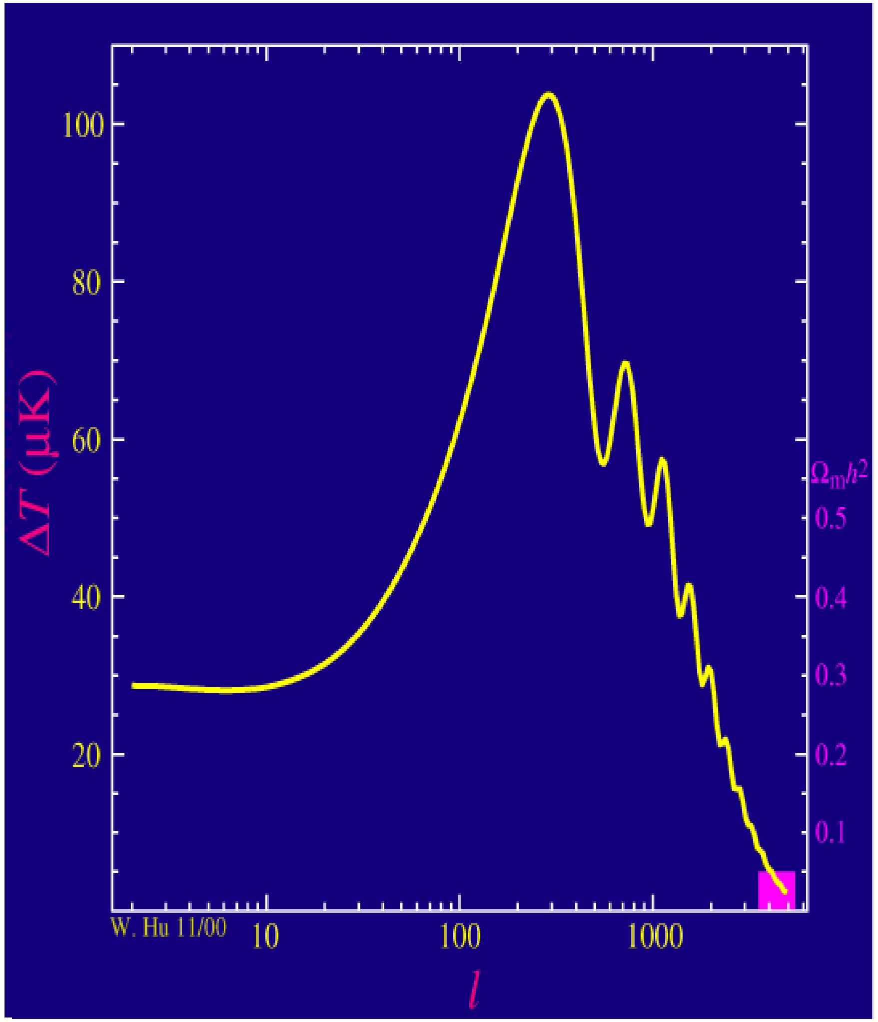


The Relative Height of Second Peak Measures the Density of Baryons

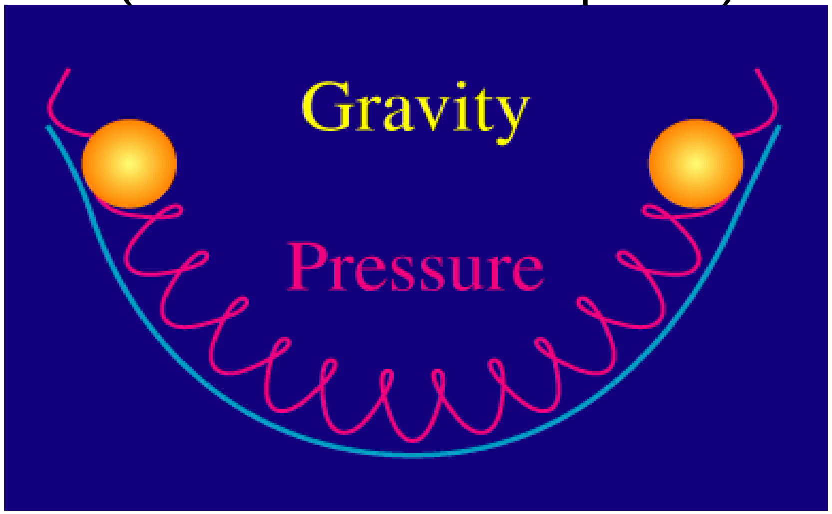




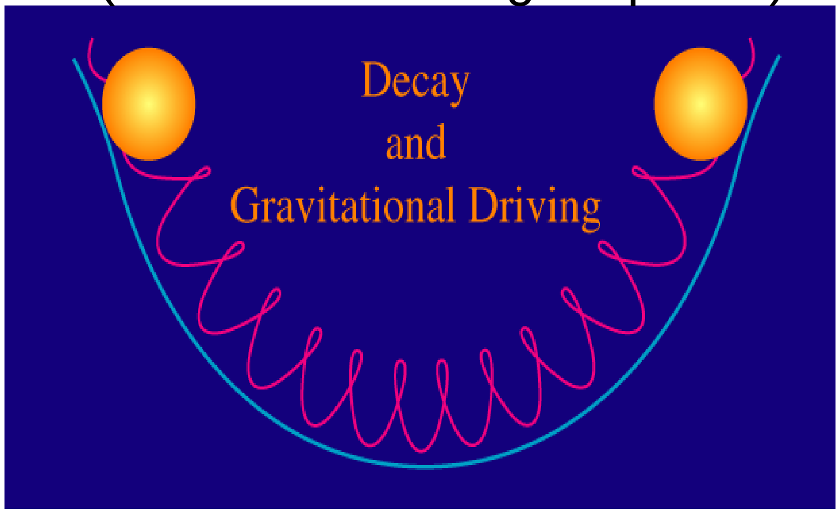
The Relative Height of Third Peak Measures the Density of Dark Matter



Dark Matter Domination
(later times – lower peaks)



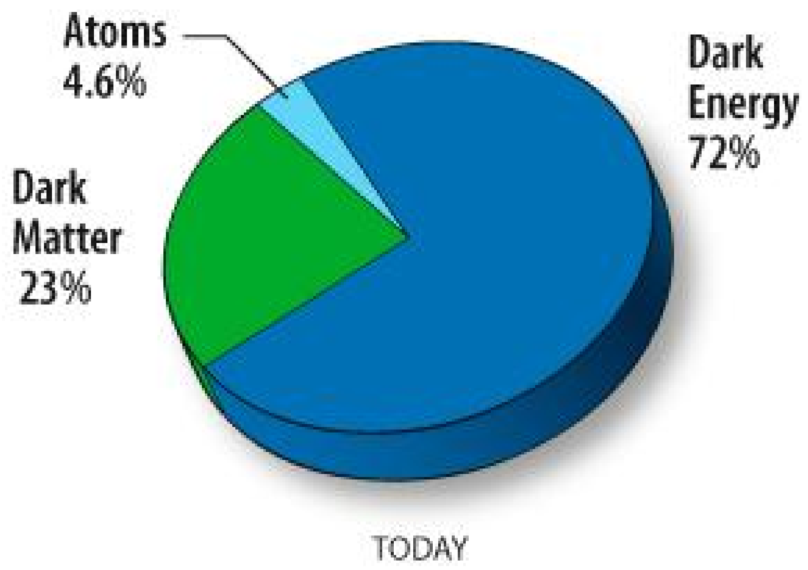
Photon Domination
(earlier times – higher peaks)



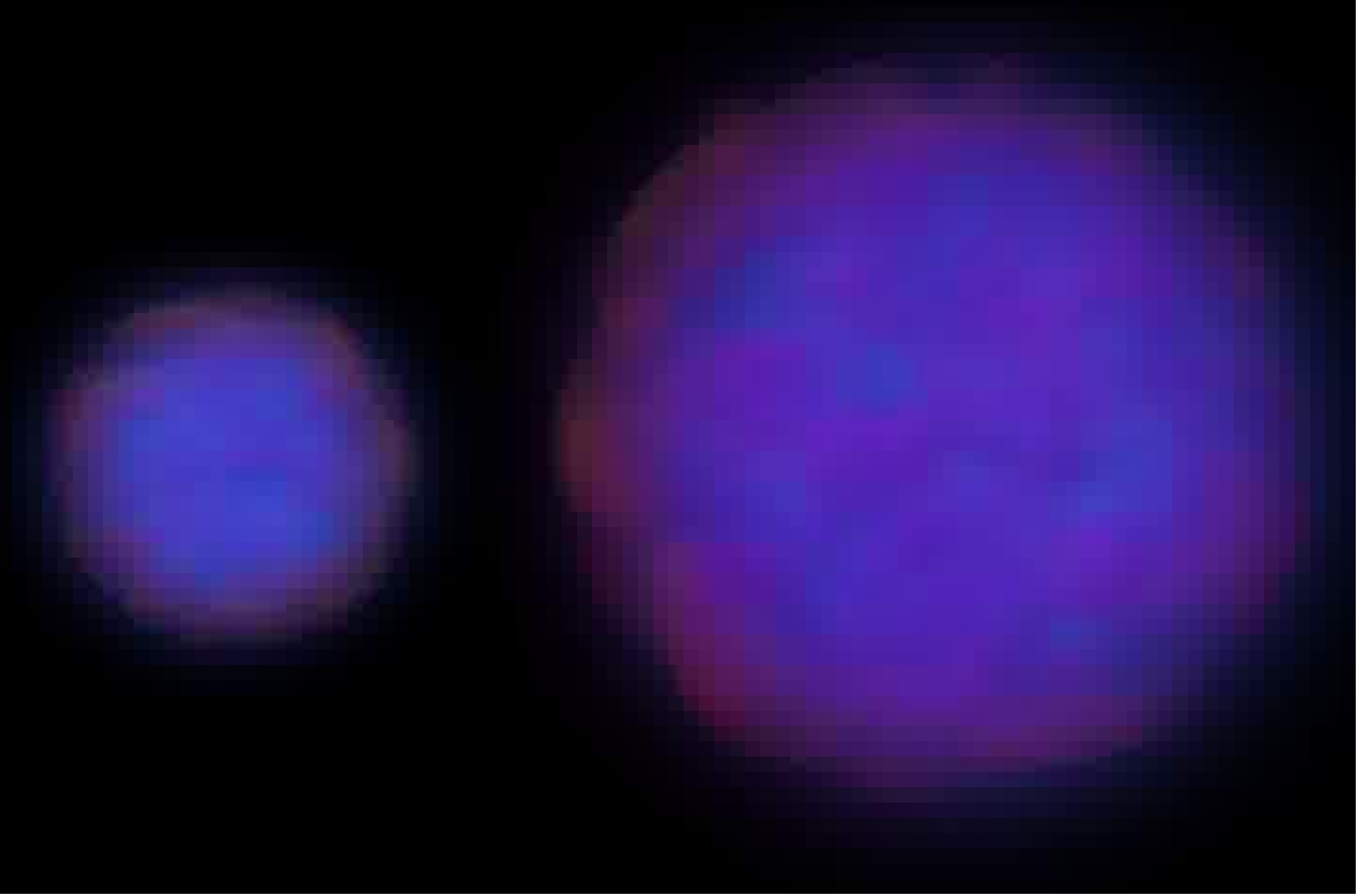
The Big Questions and Neutrino Mass

What is the origin of the Universe and its constituent parts?

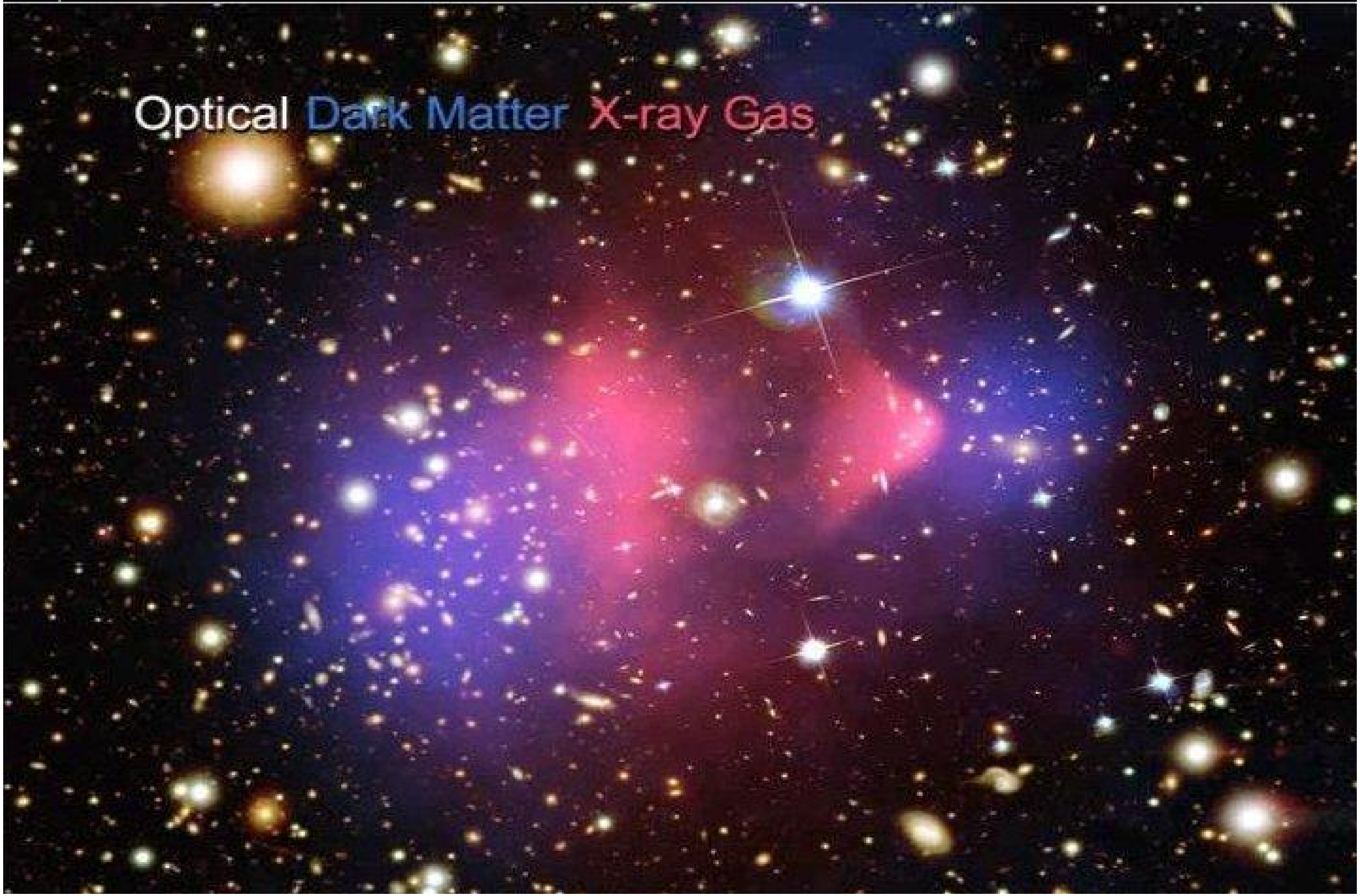
- Origin of the Universe
  Sneutrino inflation
- Origin of dark energy
  Neutrino dark energy $\Lambda \sim m_\nu^4$
- Origin of dark matter
  Neutrino limits
- Origin of atoms
  Types of leptogenesis



Origin of Dark Matter



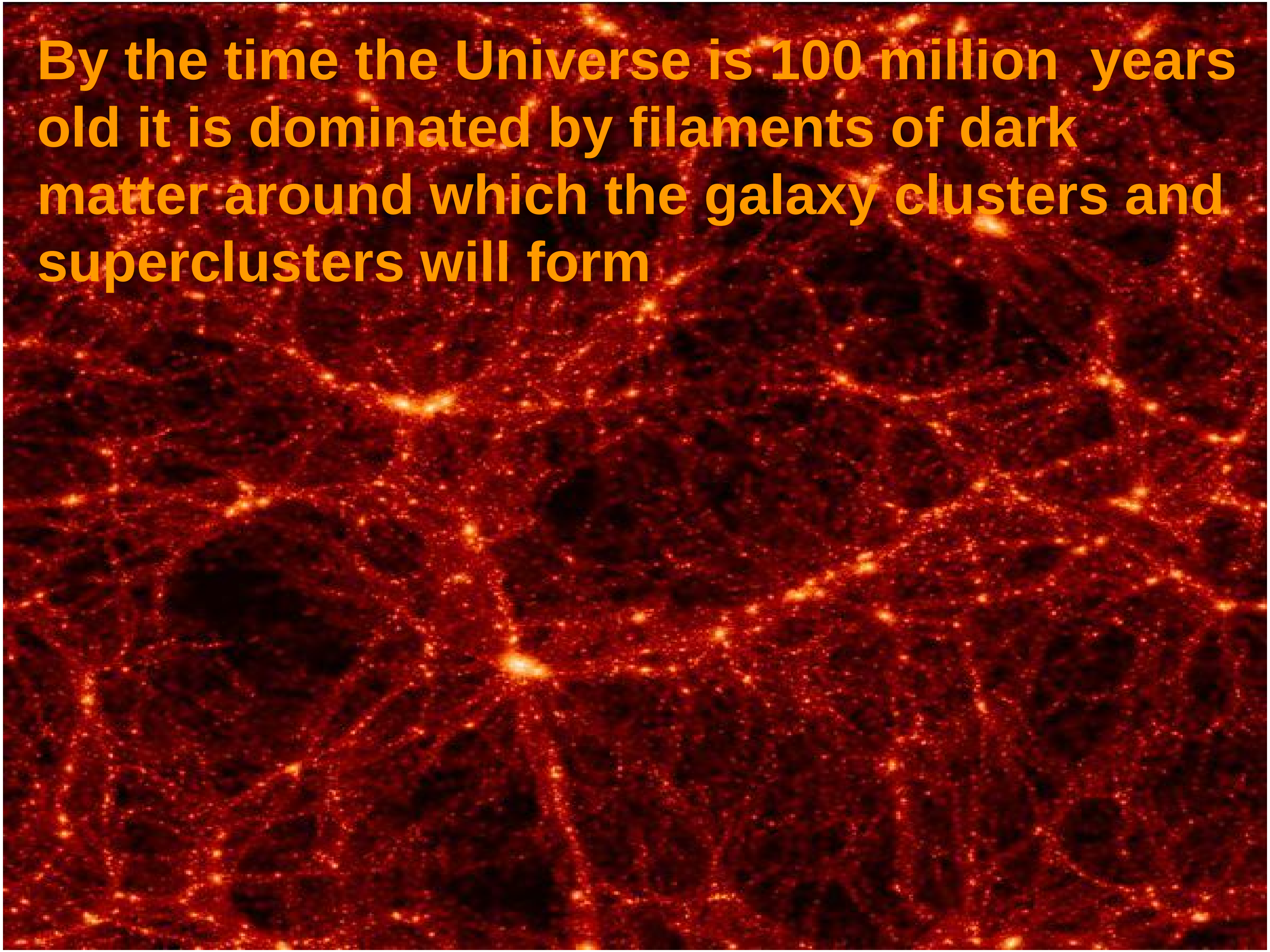
The Bullet Cluster of Galaxies



How Dark Matter Evolves

This computer simulation takes the CMB temperature fluctuations as seeds of density fluctuations which evolve in time to give long filaments of dark matter

By the time the Universe is 100 million years old it is dominated by filaments of dark matter around which the galaxy clusters and superclusters will form



Who is the dark matter particle?

Likely suspects

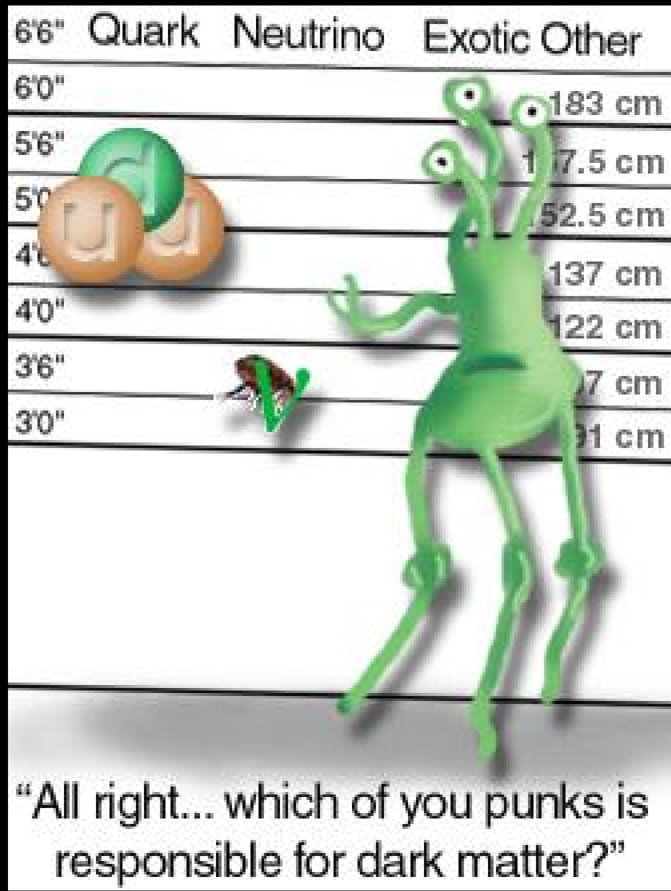
- Neutralino
- Singlino
- Gravitino

} ΛCDM

- Neutrino → Hot or Warm

Standard neutrinos give hot dark matter – disfavoured

(keV neutrinos can give warm dark matter – not discussed here)

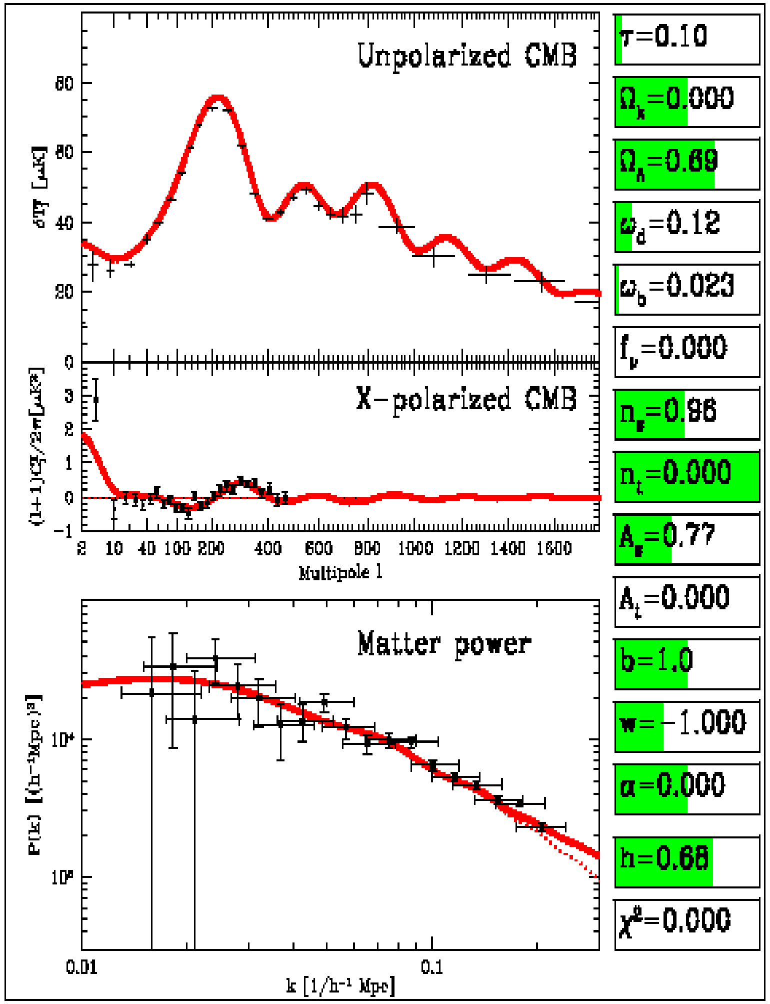


WMAP/LSS HDM limits on neutrino mass*

CMB power spectrum

Tegmark

Galaxy power spectrum



WMAP5 only

$$f_\nu = \Omega_\nu / \Omega_{matter}$$

$$f_\nu < 0.10$$

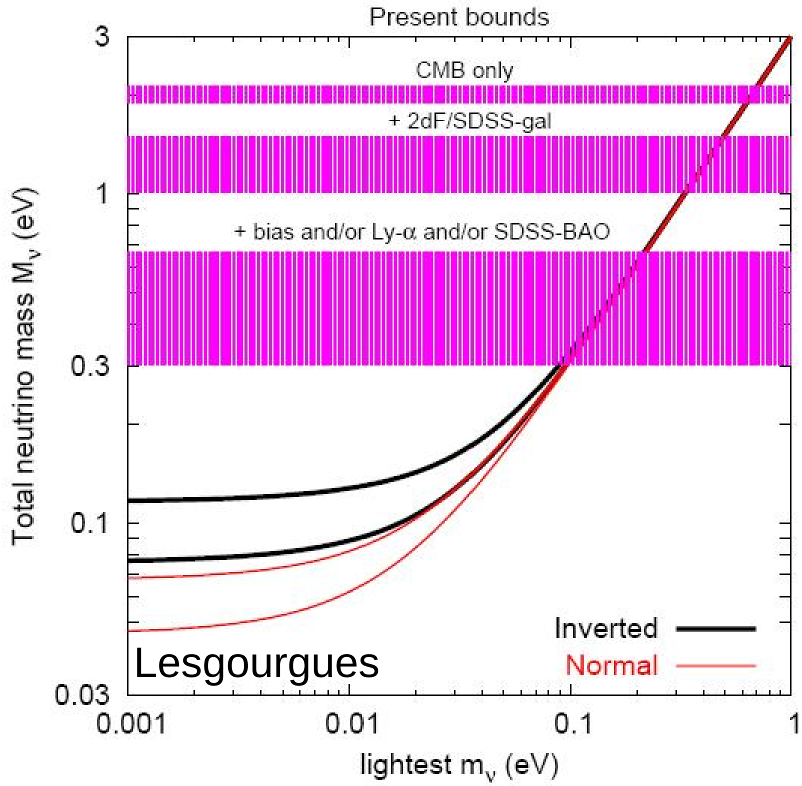
$$\sum m_i < 1.3\, eV$$

$$(95\% C.L.)$$

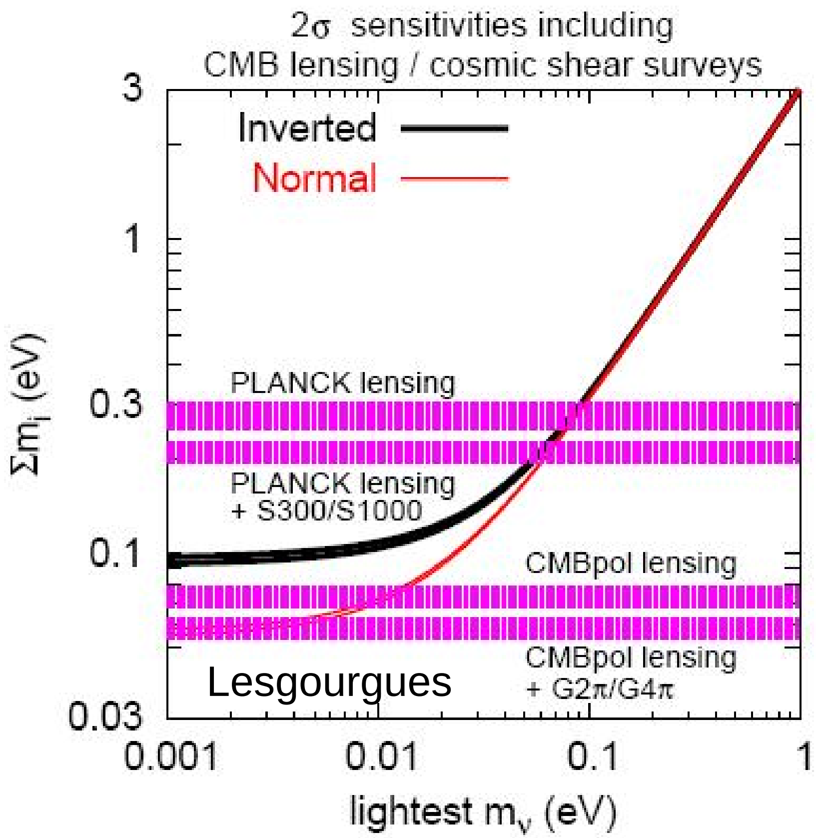
* Forget MaVaNs

Present and Future Cosmology limits on the sum of neutrino masses

Present



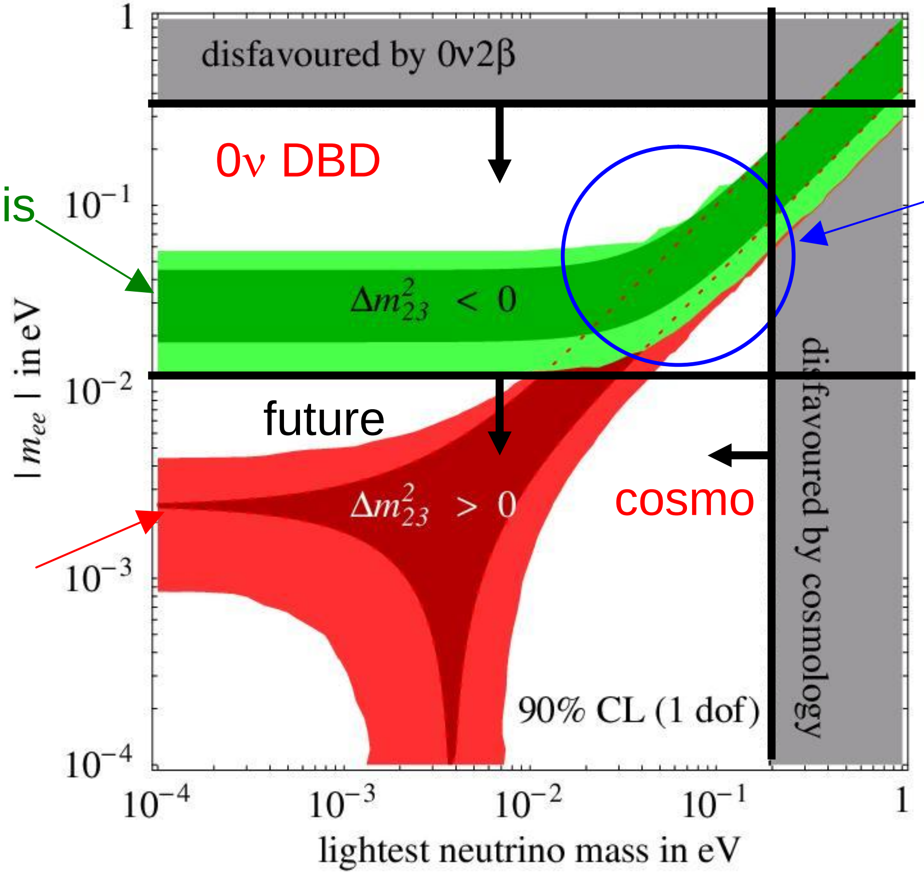
Future



Cosmology vs Neutrinoless DBD

Inverted hierarchy is TESTABLE

Normal hierarchy is NOT TESTABLE

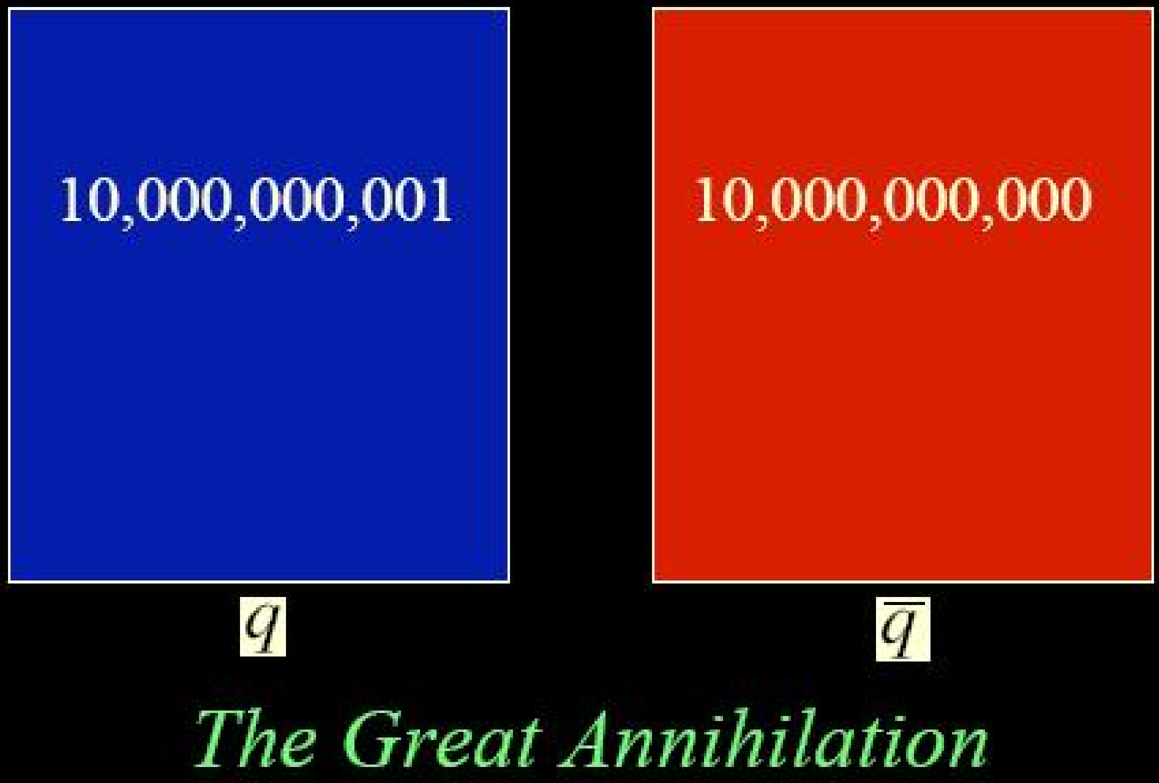


Approx. degeneracy is TESTABLE

from: F. Feruglio, A. Strumia, F. Vissani ('02)

Origin of atoms

Want to understand $\eta = \dfrac{n_b - n_{\bar{b}}}{n_\gamma} = (6.1 \pm 0.2) \times 10^{-10}$

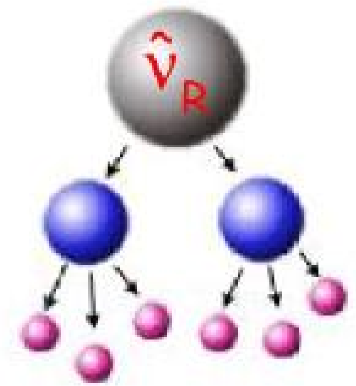


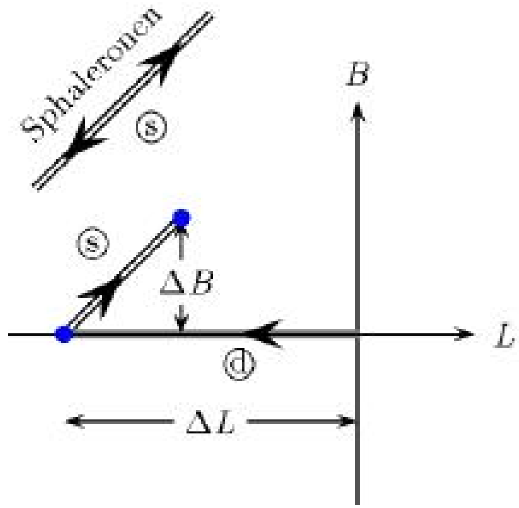
Murayama

Leptogenesis

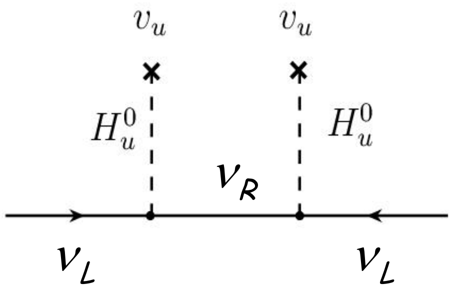
Fukugita,Yanagida
Silvia Pascoli talk

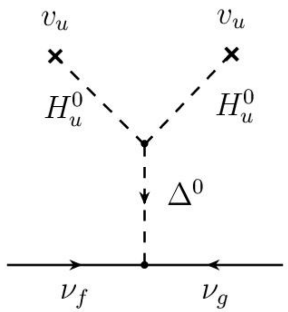
- Right-handed neutrinos are produced in early universe and decay out of equilibrium giving net lepton numbers L_e , L_μ , L_τ
- CP violation from complex Yukawa couplings
- Out of equilibrium Boltzmann eqs lead to L_e , L_μ , L_τ partial washouts
- Surviving L_e, L_μ , L_τ are processed into B via B-L conserving sphalerons



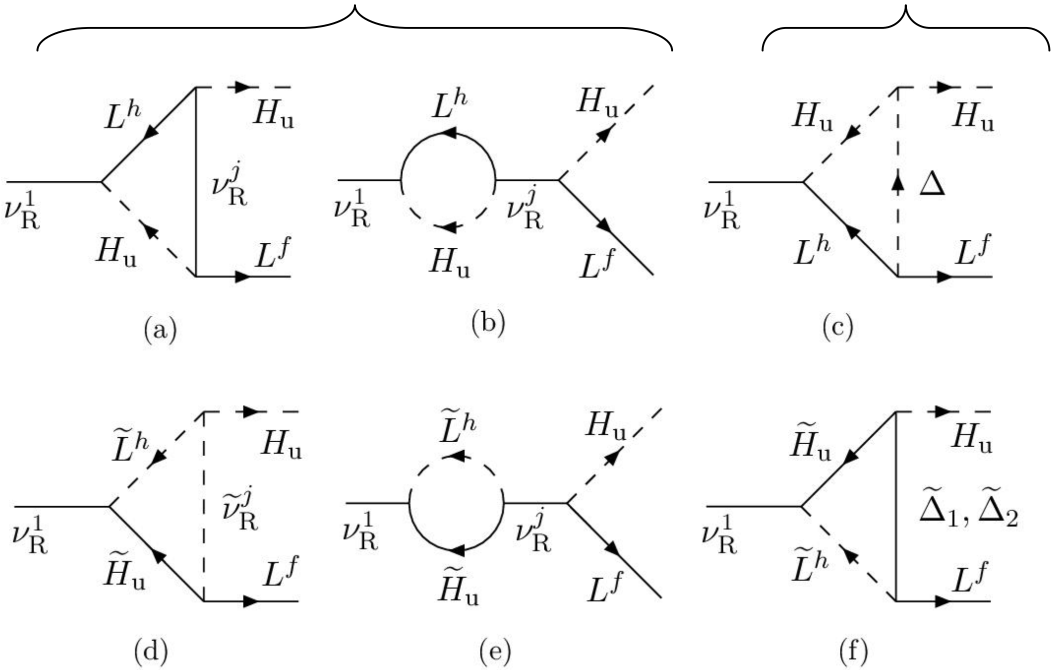


Type I and II leptogenesis

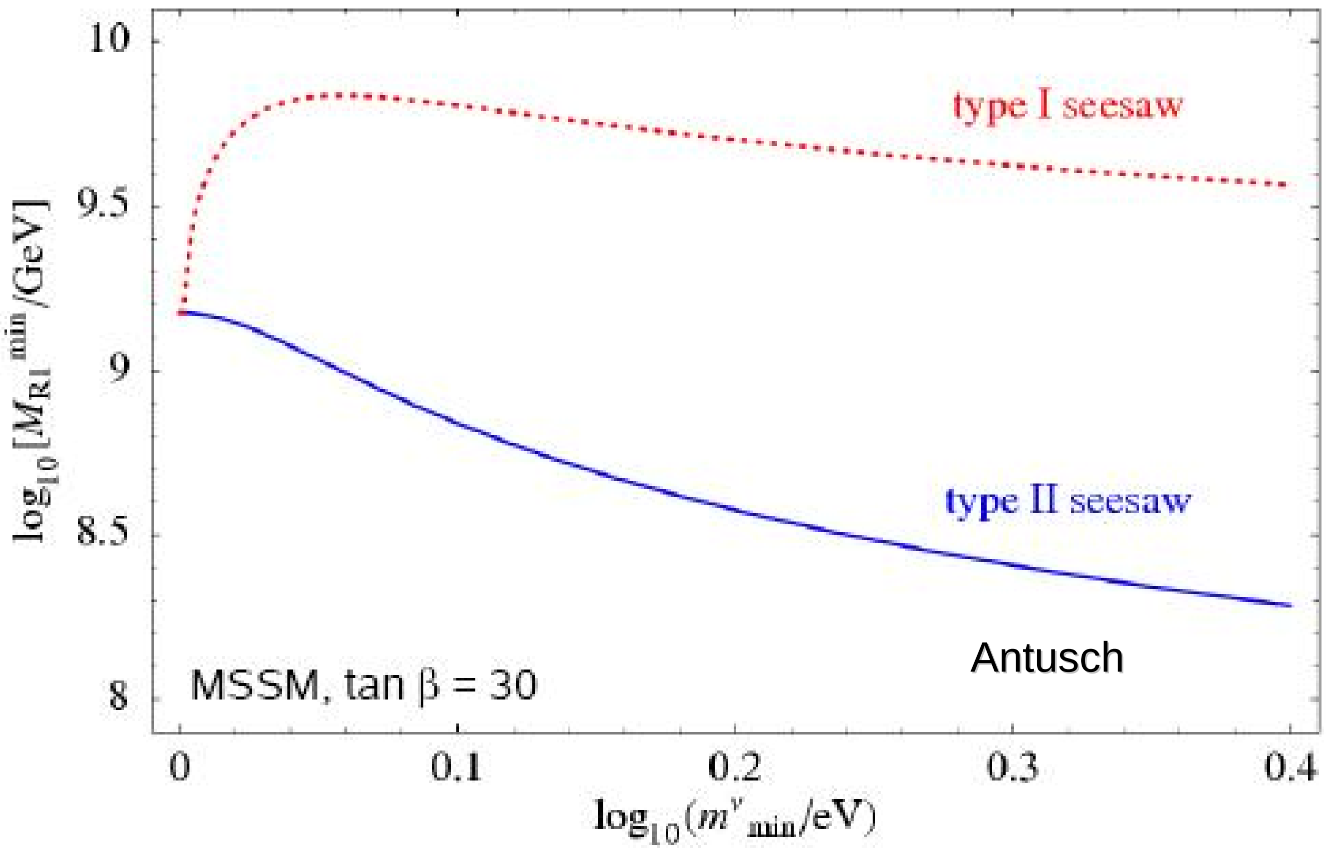




Covi,Roulet,Vissani **Type I** **Type II** Antusch,SFK



Thermal leptogenesis limits on m_ν and M_{R1}



M_{R1} can be as low as $\sim 10^8$ GeV for neutrino mass near the Klapdor claim

Can M_{R1} be reduced further?

•Resonant leptogenesis – degenerate RH neutrinos

Pilaftsis et al

•Extended models – more Higgs, more leptons, leptoquarks

SFK,Luo,Miller,Nevzorov

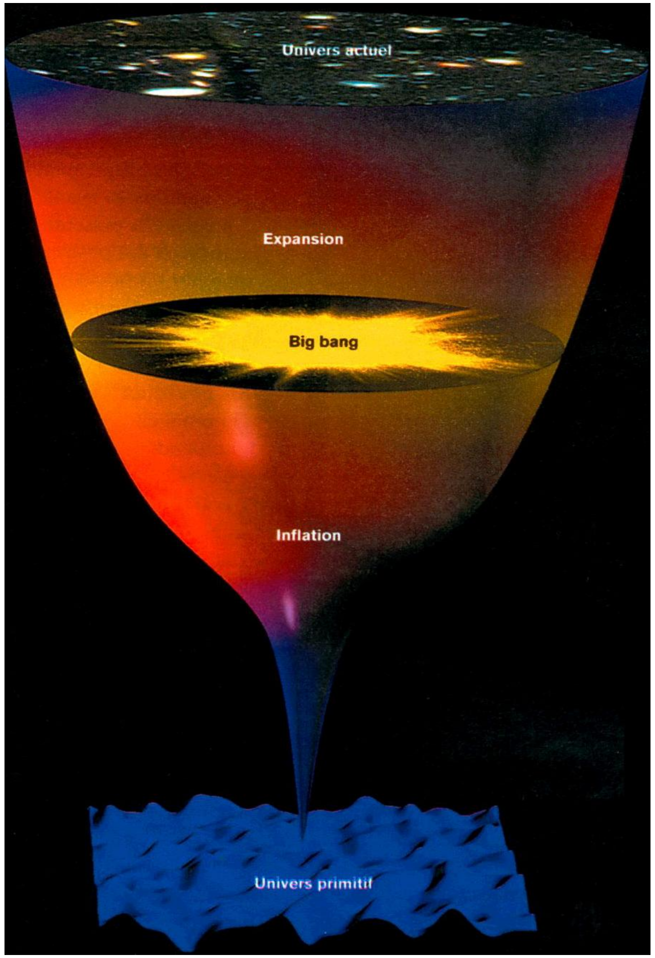
•Non-thermal leptogenesis – produce RH neutrinos directly from inflaton decay

Lazarides,Shafi

•Preheating of right-handed neutrinos – non-perturbative enhancement

Bastero-Gil,SFK

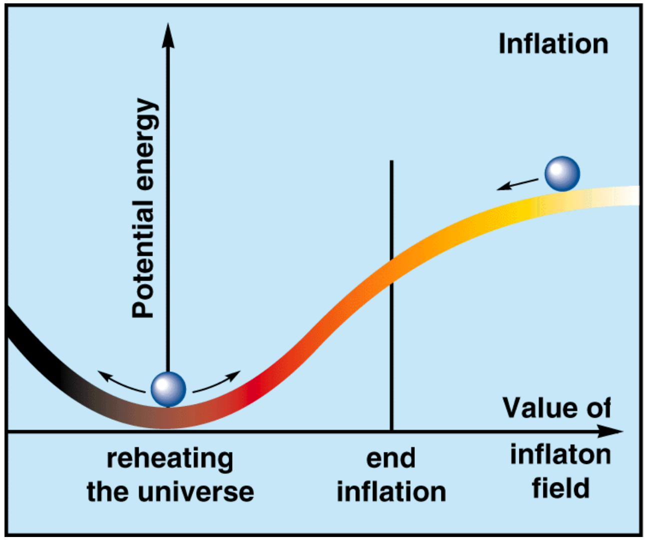
Origin of the Universe



Why is the Universe so big and flat?

What seeds the density perturbations?

-- Inflation!



Status of Inflation – looking good

Prediction	Observation
• Flatness $\Omega_0 = 1$	• Observed Flatness $\Omega_0 = 1.005 \pm 0.006$
• Density perturbations	• Observed perturbations
1. Acoustic peaks	1. 3 peaks observed
2. Gaussian	2. No evidence for non-Gauss
3. Spectral index $n_s \approx 1 \quad \left\| \frac{dn_s}{d \ln k} \right\| \ll 1$	3. Spectral Index $n_s = 0.960 \pm 0.014 \quad \frac{dn_s}{d \ln k} = -0.032 \pm 0.020$
• Gravity Waves $r = \frac{tensor}{scalar} < 1$	• Gravity waves not observed $r = \frac{tensor}{scalar} < 0.20\ (95\% C.L.)$

Could the inflaton be a sneutrino?

Murayama, Suzuki, Yanagida, Yokoyama

Chaotic inflation requires an inflaton with a simple potential $V = \frac{1}{2}m^2\phi^2$

Linde

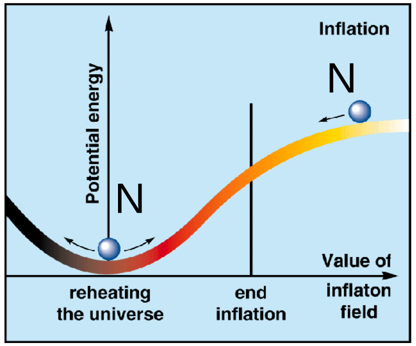
⇒ $n_s \approx 0.96$ Good! $r \approx 0.16$ Gravity waves soon

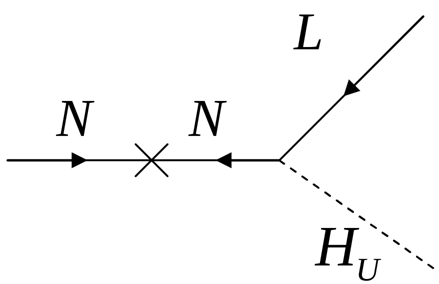
Could inflaton be SUSY partner of the right-handed neutrino?

Yes but no gauge interactions up to M_P (no SO(10) GUTs, etc.)

The mass scale is in the right range $m \simeq 2 \times 10^{13}$ GeV

Yukawa couplings allow reheating of the Universe $Y_\nu \, L \, H_u N$





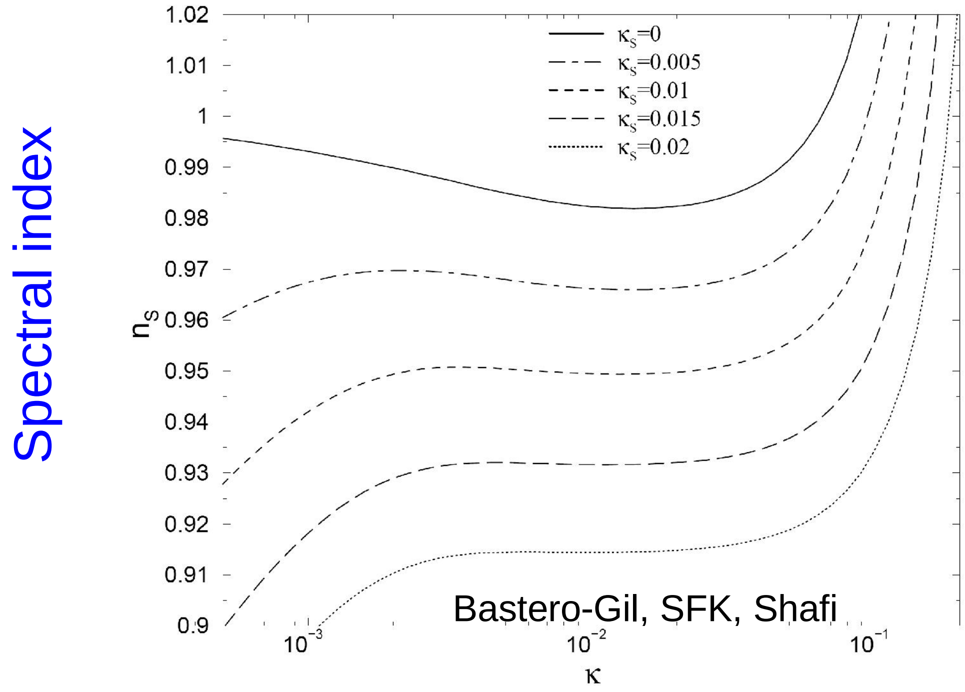
Alternative sneutrino inflation

Antusch, Bastero-Gil, SFK, Shafi

Hybrid inflation with potential $V = \kappa^2 M^4 \left(1 - \kappa_S \frac{N^2}{2 m_P^2} \right) + \Delta \mathcal{V}_{1\text{loop}}$

Right-handed neutrino mass generated after inflation

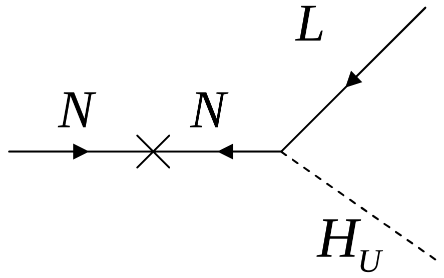
Radiative corrections important - have been calculated for similar model



No gravity waves!

$r \ll 1$

Reheating and non-thermal leptogenesis



$$\Gamma_N = (Y_\nu Y_\nu^\dagger) M_R / 4\pi \qquad T_{RH} \approx \sqrt{\Gamma_N M_P}$$

To avoid gravitino problem suppose $T_{RH} \approx 10^6 GeV$

Sneutrino chaotic inflation $\quad M_R \approx 10^{13} GeV \rightarrow Y_\nu \approx 10^{-10}$

Sneutrino hybrid inflation $\quad M_R \approx 10^{8} GeV \rightarrow Y_\nu \approx 10^{-6}$

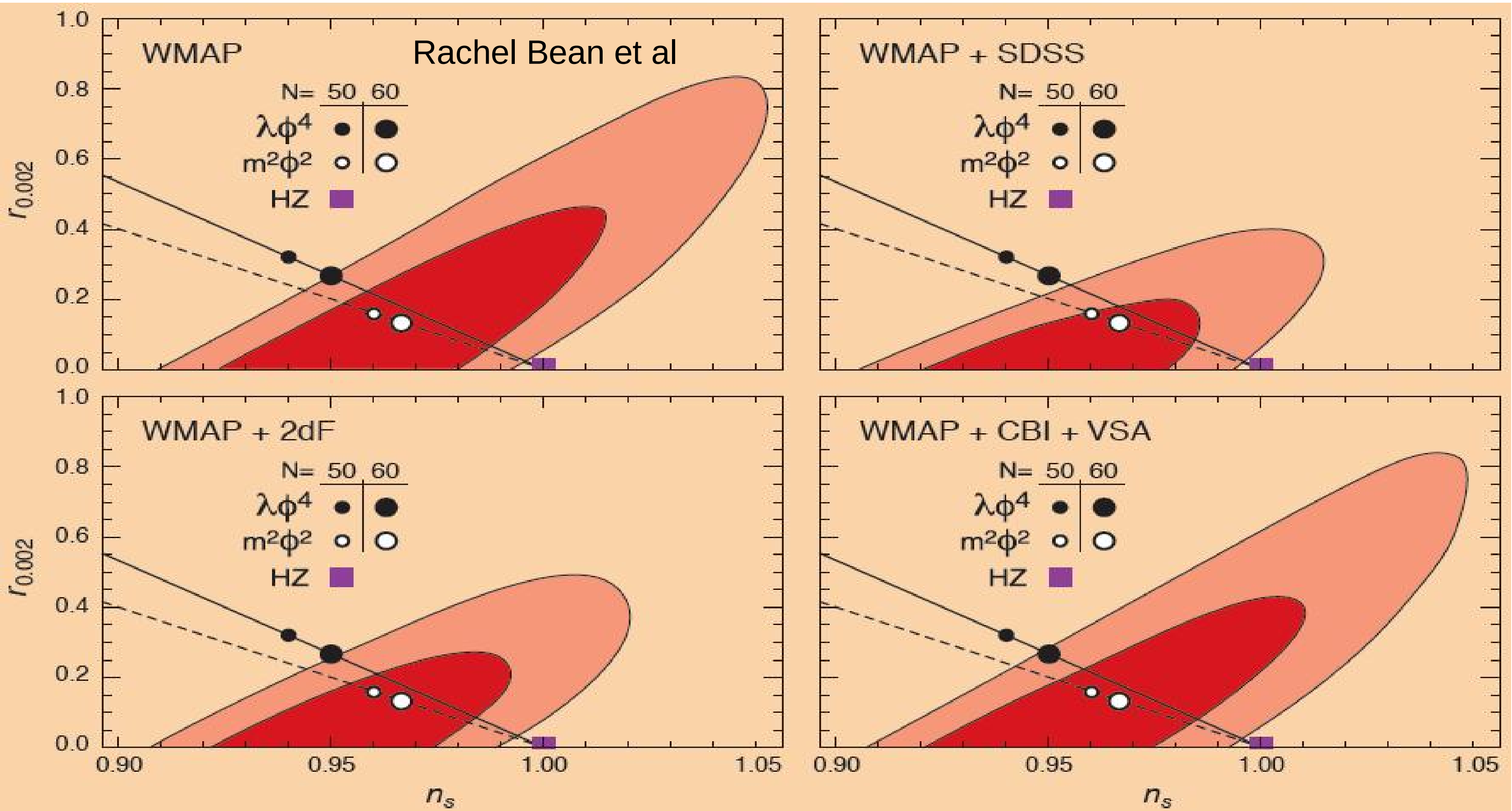
In both cases RH neutrino is decoupled from see-saw mechanism
c.f. sequential dominance → effective 2 RH neutrino models Ibarra, Ross

Lepton asymmetry may be produced via the cold (non-thermal) decays of the sneutrino

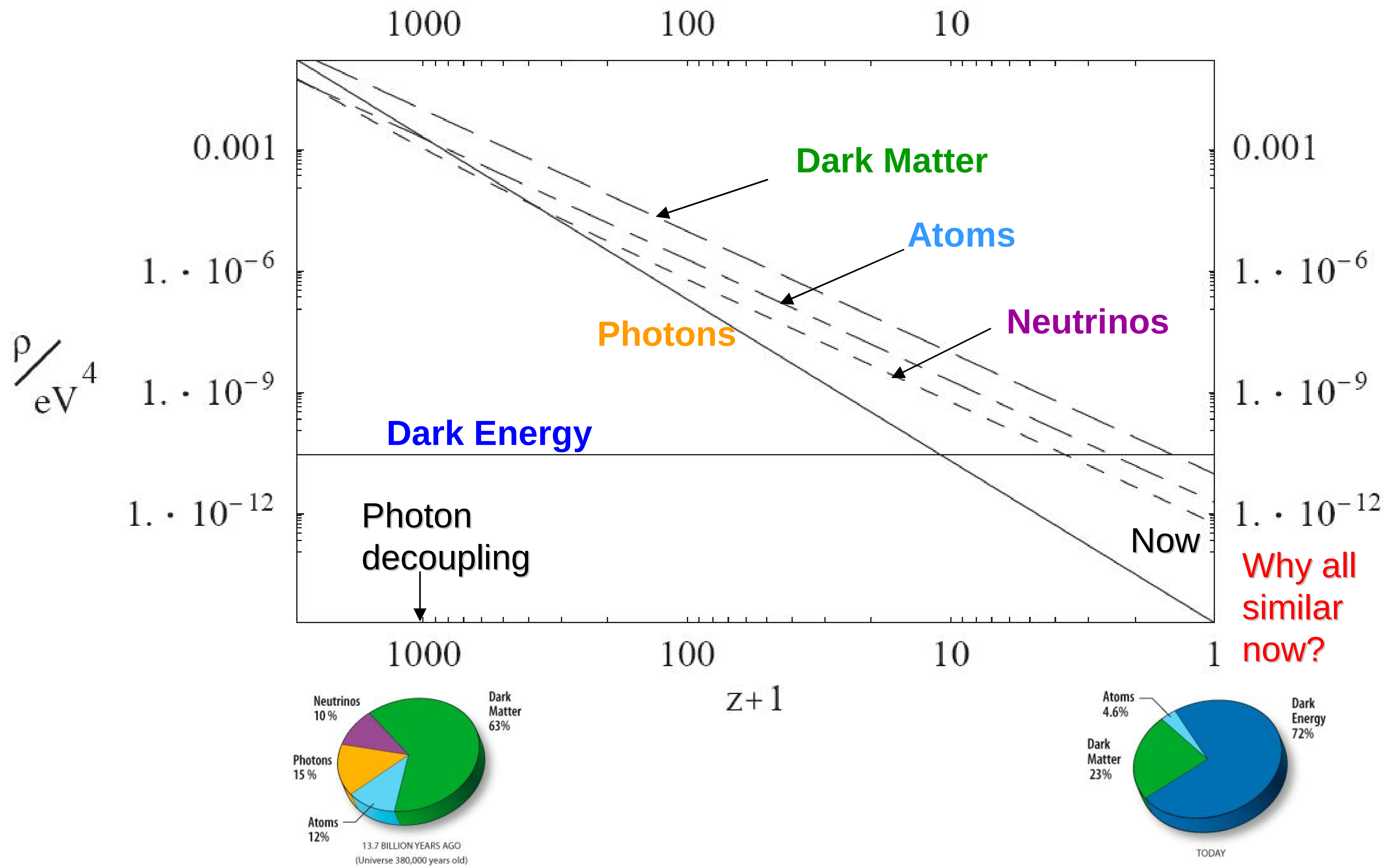
$$\frac{n_b}{n_\gamma} \approx \varepsilon \frac{T_{RH}}{M_{R1}} \approx 10^{-9} \quad \text{for} \quad M_R \approx 10^8 GeV, T_{RH} \approx 10^6 GeV, \varepsilon \approx 10^{-7}$$

Summary of sneutrino inflation

- Right-handed scalar neutrino as inflaton: $V=m^2\phi$ giving r=0.16, n_s=0.96 (Murayama,Suzuki,Yanagida,Yokoyama)
- Or sneutrino hybrid inflation r=0, $n_s\sim$ 0.9-1.0 (Antusch, Bastero-Gil, SFK, Shafi)



Origin of dark energy



Why all similar now?

Why is $\rho_{DE} \approx (3.10^{-3} eV)^4 \approx (m_\nu)^4$? Just a coincidence?

Mass Varying Neutrinos (MaVaNs)

Fardon,Nelson,Weiner

Assume that $m_\nu \propto 1/n_\nu$ where n_ν is background number density, so neutrino masses get smaller in early universe (up to local clustering)

This implies that $\rho_{DE} \sim \rho_\nu = m_\nu n_\nu$ always

To achieve such neutrino masses which depend on background neutrinos, new scalar forces between light neutrinos are invoked e.g.

$$\mathcal{L} = \frac{m_{lr}^2}{M(\mathcal{A})} \nu_l \nu_l + h.c. + \Lambda^4 \log(M(\mathcal{A})/\mu)$$

scalar acceleron field responsible for dark energy $\Lambda \sim 10^{-3}\ \mathrm{eV}$

But the new force causes neutrinos to clump into neutrino nuggets

→ The stability problem

Afshordi,Kohri,Zaldarriagra

Conclusion

- **Discovery of neutrino mass has profound implications for origin of matter and the Universe**
- **Origin of dark matter – HDM is not preferred → limit on neutrino mass of about 1 eV (will improve)**
- **Origin of atoms – leptogenesis has become the leading candidate: type I,II, resonant, non-thermal,…**
- **Origin of the Universe – the right-handed sneutrino is a good candidate for the inflaton, its decay gives efficient non-thermal leptogenesis**
- **Origin of dark energy – cosmic coincidence puzzle, with dark energy scale $\sim m_\nu$ is tantalizing but no convincing ideas yet in my opinion**

Inflation Formalism

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{a^2} \qquad \rho = V \longrightarrow \boxed{a \simeq a_I e^{Ht}} \qquad H = \sqrt{\frac{8\pi G_N}{3} V}$$

Universe inflates by factor of

$$e^N : N = \int H dt$$

Slow roll parameters – depend on shape of potential

$$\varepsilon \equiv \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv m_P^2 \frac{V''}{V} \ll 1 \qquad \xi \equiv m_P^4 \frac{V'V'''}{V^2} \ll 1$$

$$n_s = 1 - 6\epsilon + 2\eta \qquad r \equiv \frac{A_T}{A_S} = 16\epsilon \qquad n_T = -2\epsilon$$

$$\frac{dn_s}{d\ln k} = \frac{2}{3}\left[(n_s - 1)^2 - 4\eta^2\right] + 2\xi$$

Observables

Chaotic inflation $V = \frac{1}{2} m^2 \phi^2$

$$\epsilon = \frac{2M_P^2}{\phi_I^2}, \ \eta = \frac{2M_P^2}{\phi_I^2}, \ \xi = 0$$

Slow roll requires $\phi > M_P$!

$$\frac{\delta T}{T} \sim \frac{\delta \rho}{\rho} \sim 10^{-5} \longrightarrow \mu \equiv V^{1/4} = 0.027 M_P \times \epsilon^{\frac{1}{4}}$$

$$\longrightarrow m^{\frac{1}{2}} \phi_I = 0.038 \times M_P^{\frac{3}{2}}$$

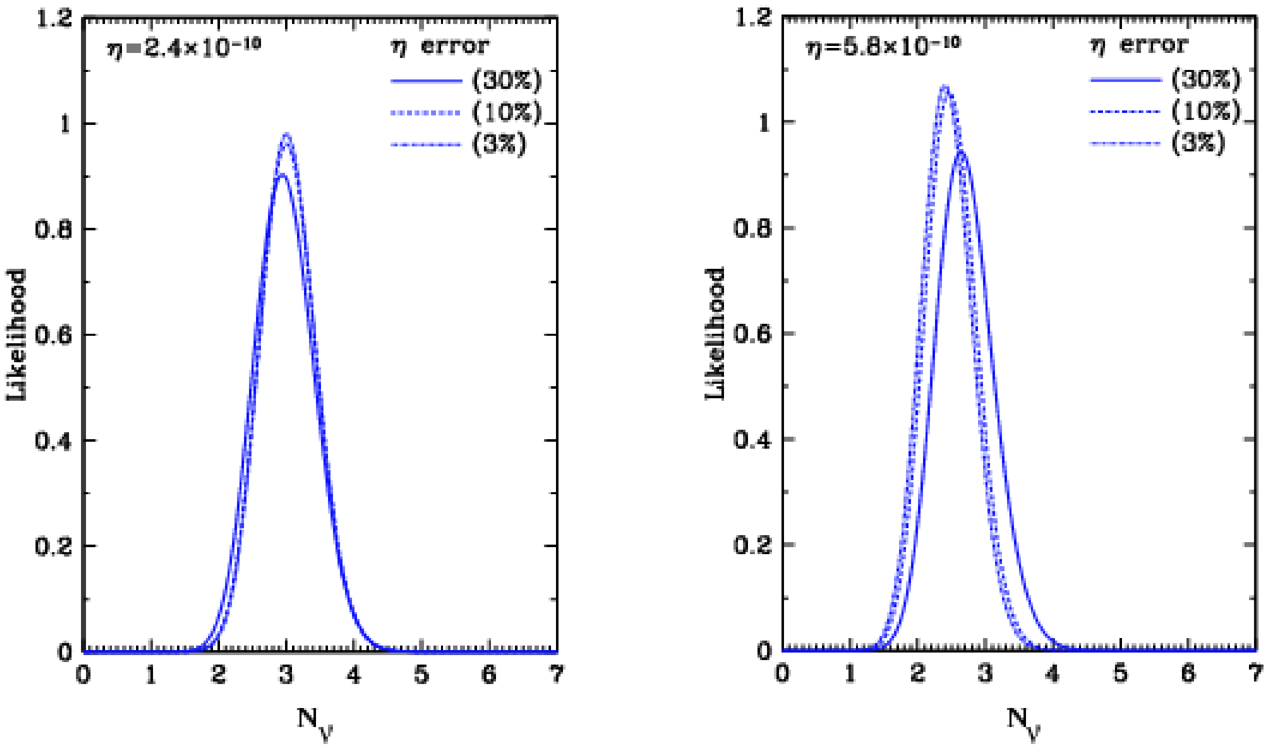
$$e^N \quad N = \frac{1}{4} \frac{\phi_I^2}{M_P^2} \simeq 50 \longrightarrow \phi_I^2 \simeq 200 \times M_P^2 \longrightarrow m \simeq 2 \times 10^{13} \text{ GeV}$$

$$n_s = 1 - \frac{8M_P^2}{\phi_I^2} \simeq 0.96 \qquad r = \frac{32 M_P^2}{\phi_I^2} \simeq 0.16 \qquad \frac{dn_s}{d\ln k} = \frac{32 M_P^4}{\phi_I^4} \simeq 8 \times 10^{-4}$$

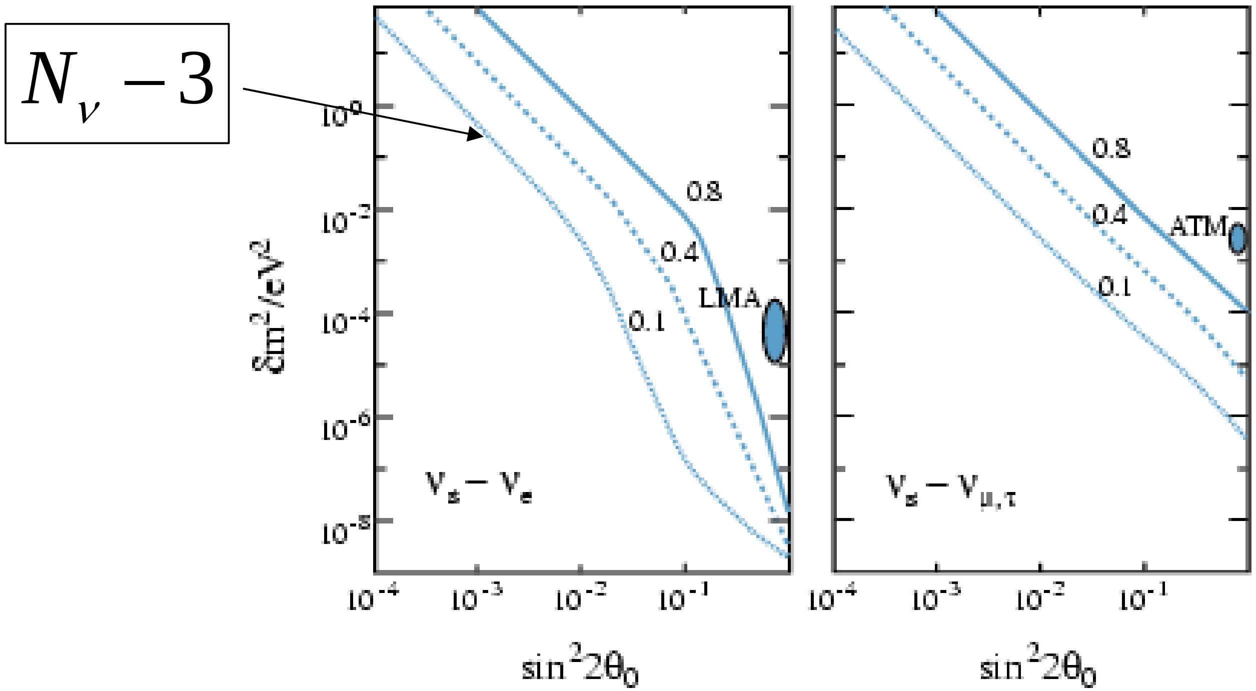
$$n_s = 0.960 \pm 0.014 \qquad r < 0.20 \ (95\% C.L.) \qquad \frac{dn_s}{d\ln k} = -0.032 \pm 0.020$$

Neutrinos and nucleosynthesis

The number of light "neutrino species" (or any light species) affects the freeze-out temperature of weak processes which determine n/p, and successful nucleosynthesis gives a constraint



What about sterile neutrinos? The limit on N_ν applies to them also, but they need to be produced during the time when nucleosynthesis was taking place, and the only way to produce them is via neutrino oscillations. This leads to strong limits on the sterile-active neutrino mixing angles which disfavour LSND – assuming the primordial lepton asymmetry is not anomalously large



Sakharov Conditions:

- Baryon number *B* violation
- C-symmetry and CP-symmetry violation
- Interactions out of thermal equilibrium

Standard Model satisfies all three (sphalerons violate B but conserve B-L) but the predicted value of η is too small

SUSY can help: MSSM, NMSSM, …

Traditionally GUTs are invoked (but B-L must be violated)

Alternatively the see-saw mechanism allows leptogenesis

Motivation to go beyond MSSM

Exceptional Supersymmetric Standard Model

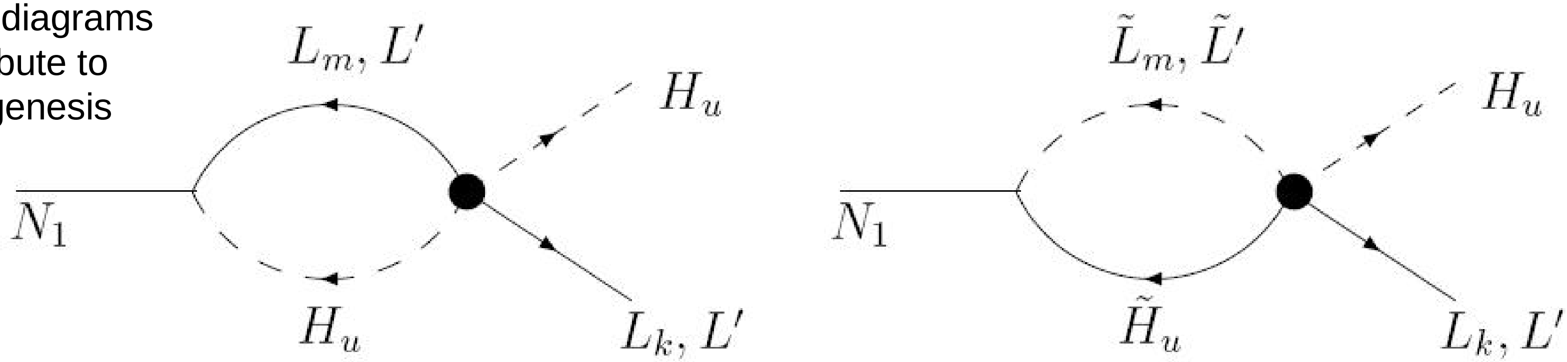
- Solves μ problem of MSSM

- Solves fine tuning problem of MSSM

- Predicts Z', exotic D quarks, exotic L' leptons at LHC

-Solves gravitino problem in leptogenesis (in progress)

Extra diagrams contribute to leptogenesis



SFK,Luo,Miller,Nevzorov