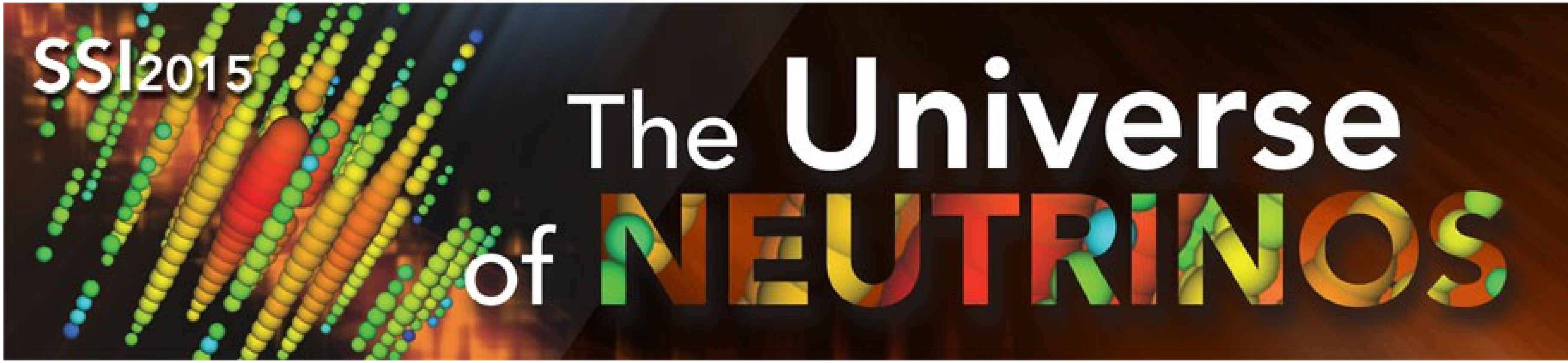


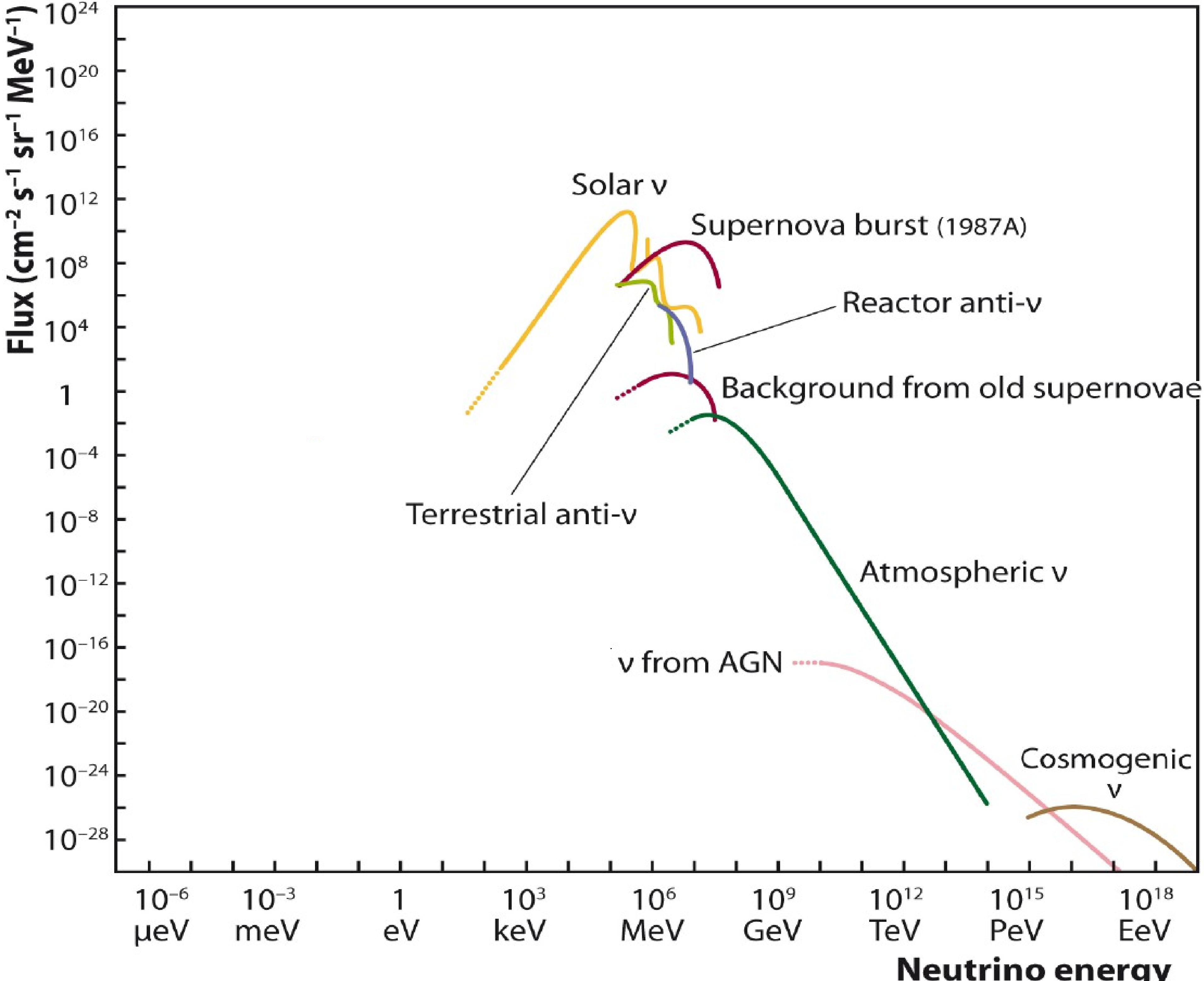
Neutrino Cosmology (I)

Stanford, August 11th 2015

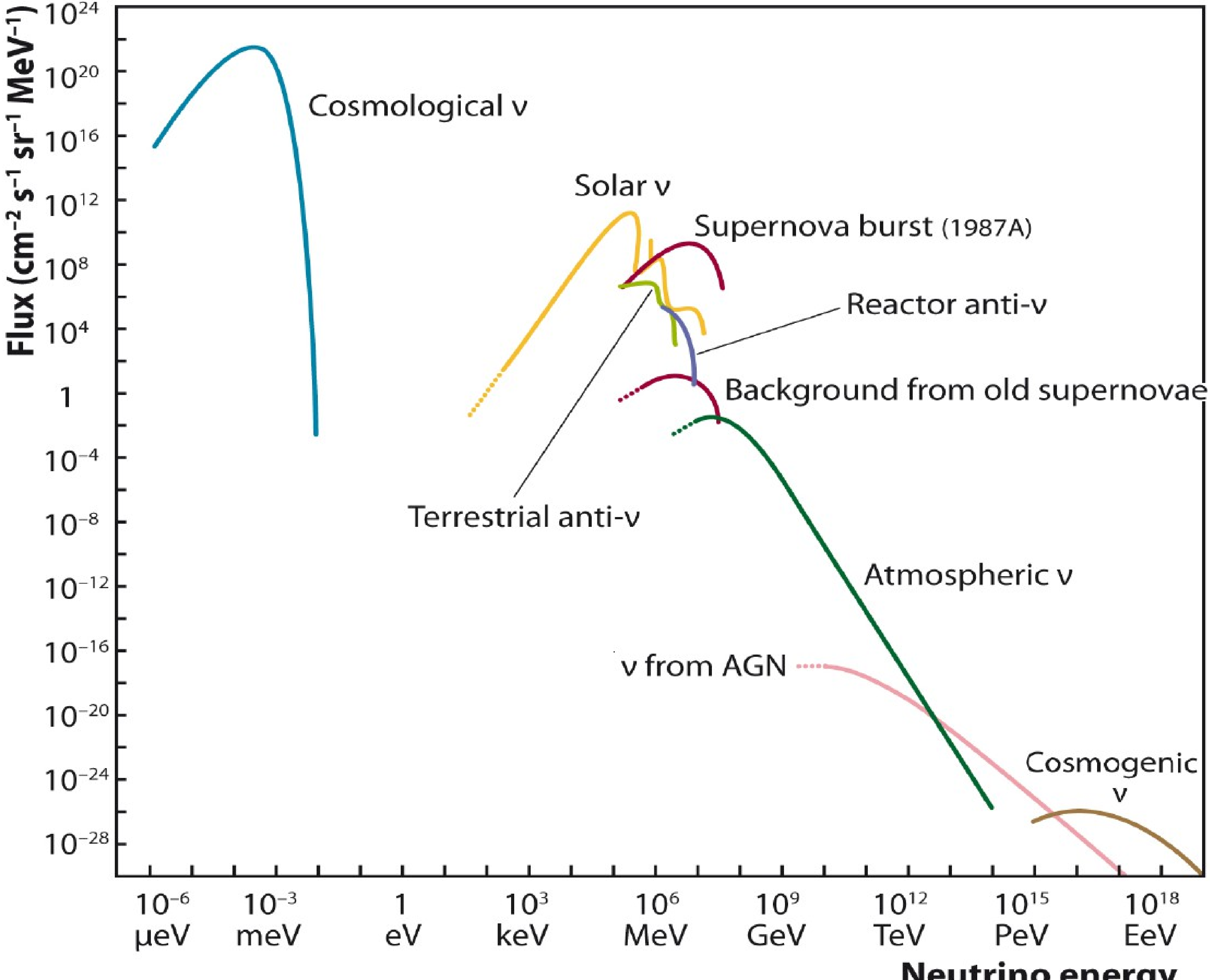
Alessandro Melchiorri

University of Rome “La Sapienza”

(Disclaimer: many thanks to Eleonora Di Valentino and Sergio Pastor for some of the slides)



Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Cosmology: Basics

Isotropic and homogeneous expansion of the Universe (at zeroth order) determined by the scale factor a(t), that just depends on time.
The scale factor solves the Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi G}{3}\left(\rho_R + \rho_M + \rho_\Lambda\right)$$

We have just 3 types of Energy components !

Energy density in RADIATION (as CMB photons) scales as:

$$\rho_R = \frac{\rho_R^0}{a^4} \longrightarrow a(t) = \sqrt{\frac{t}{t_0}}$$

Energy density in MATTER (CDM and baryons) scales as:

$$\rho_M = \frac{\rho_M^0}{a^3} \longrightarrow a(t) = \left(\frac{t}{t_0}\right)^{2/3}$$

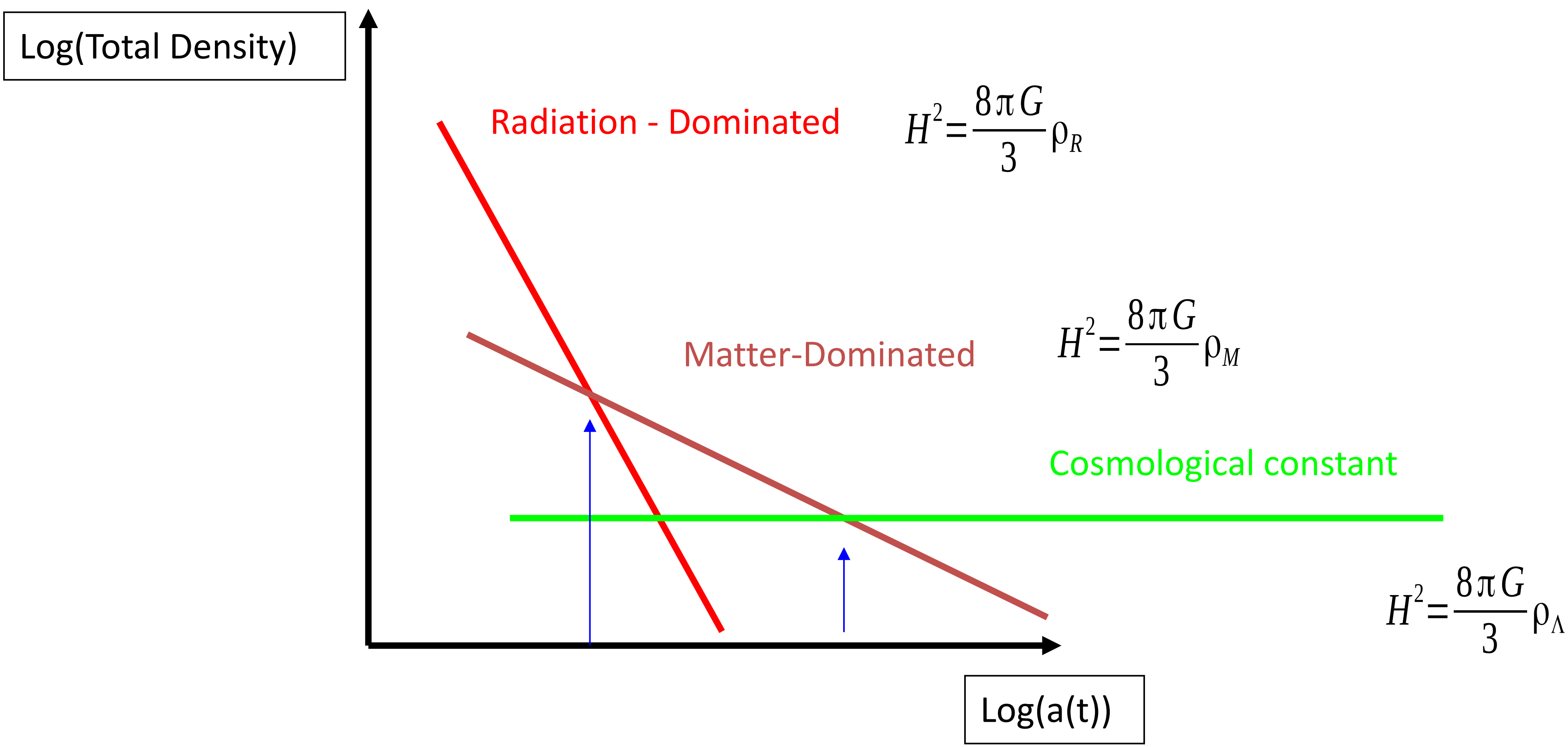
Energy density in cosmological constant scales as:

$$\rho_\Lambda = \rho_\Lambda^0 \longrightarrow a(t) = \mathrm{e}^{(H_0(t-t_0))}$$

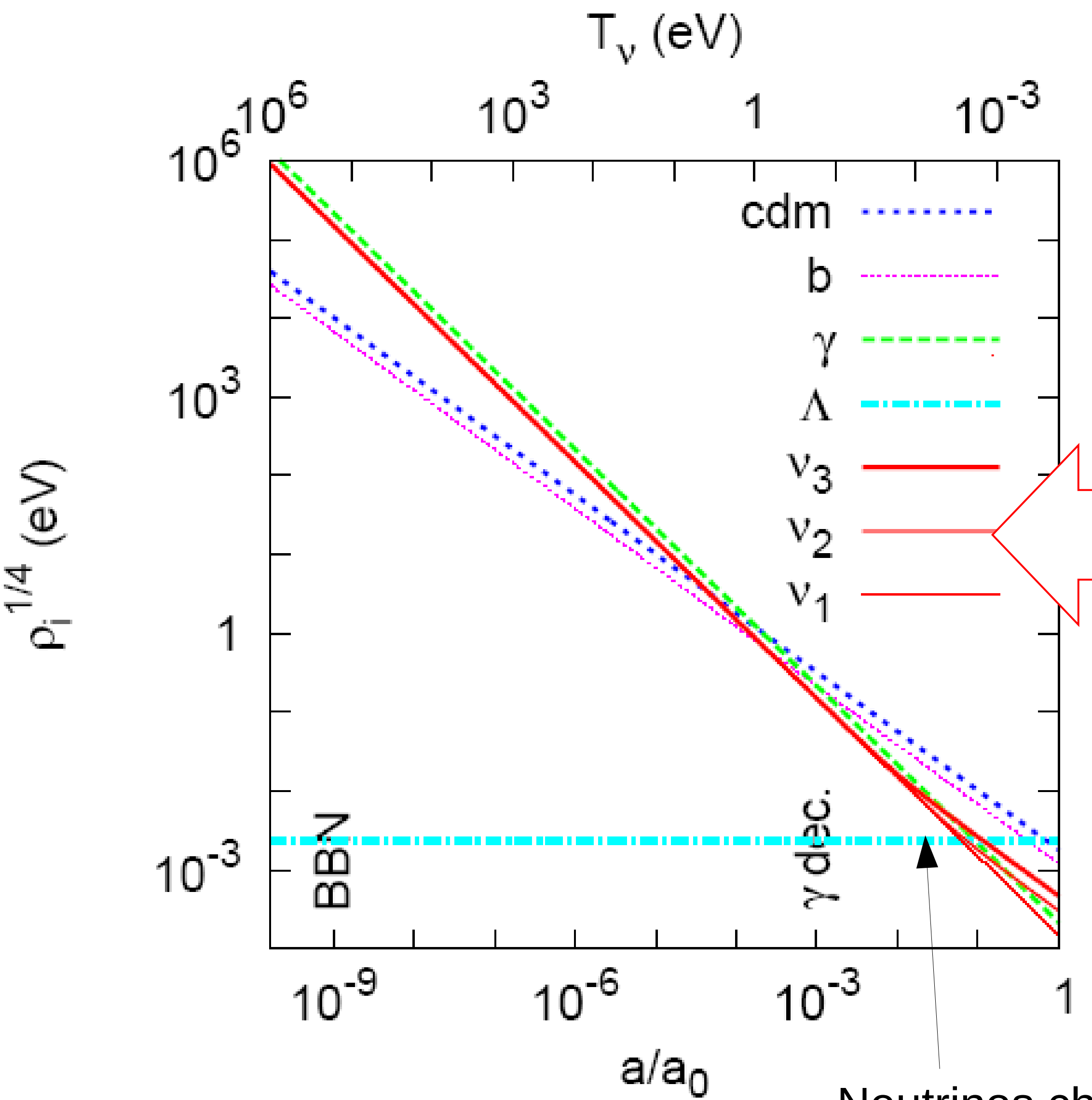
Neutrinos are the only particle in the standard cosmological model that change status: they move from radiation to matter during the evolution of the universe !

Multiple-Component Universe

If the different components do not interact between themselves then each energy component evolves independently
Thus the total energy density of the Universe is dominated by each component at different epochs: radiation (early universe), matter (late universe), c.c. (today).



Evolution of the background densities: 1 MeV → now



3 neutrino species with different masses

Neutrinos change from relativistic to non-relativistic !

Multiple-Component Universe

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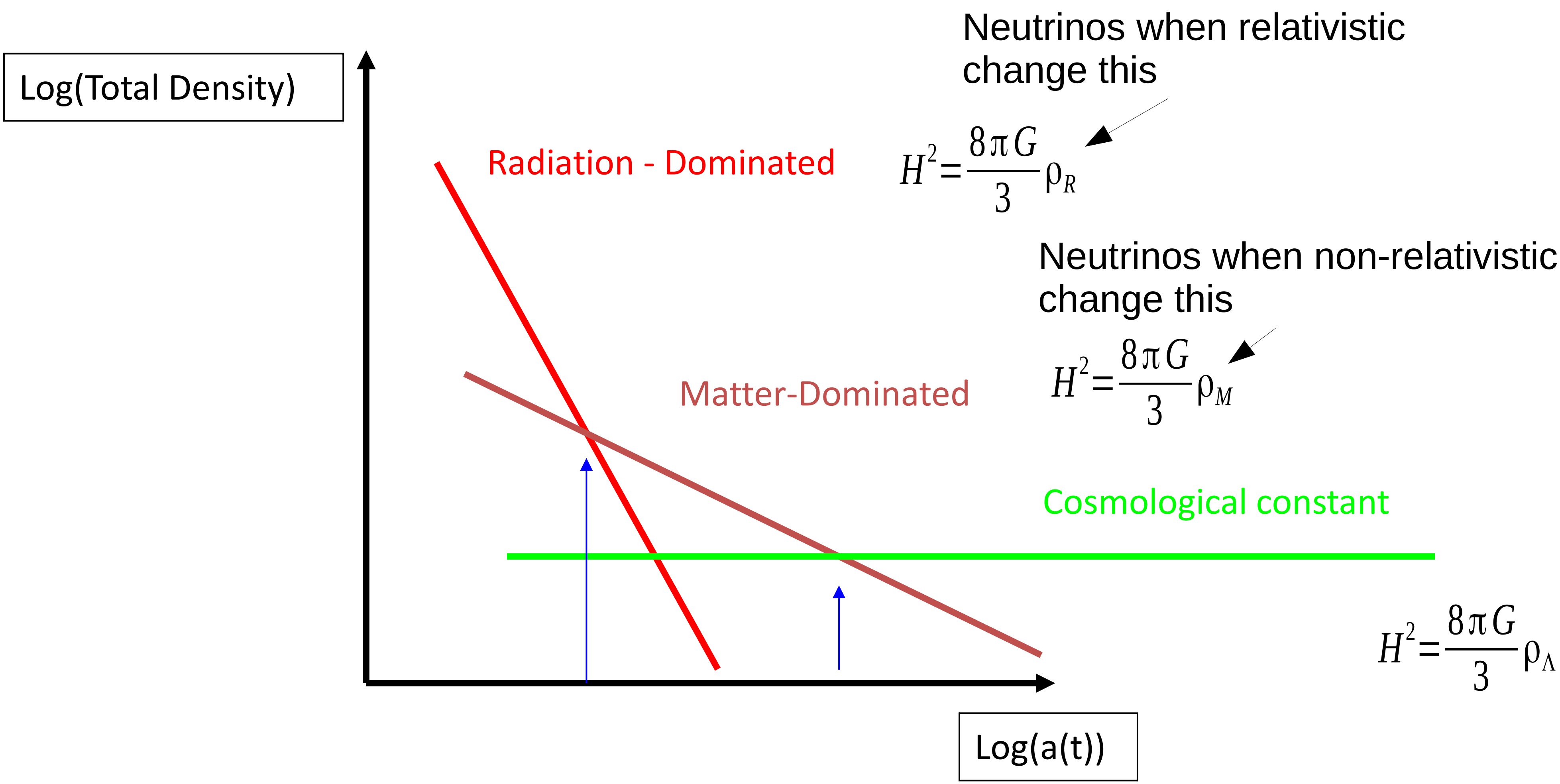


Relativistic Neutrinos $T >> m_\nu$

Neutrinos in the Early Universe

- Neutrinos at temperature T > 1 Mev are in equilibrium with the primordial plasma made by photons, electrons and positrons through weak interactions. Neutrinos follow a Fermi-Dirac distribution with the same temperature T of the plasma.

$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$

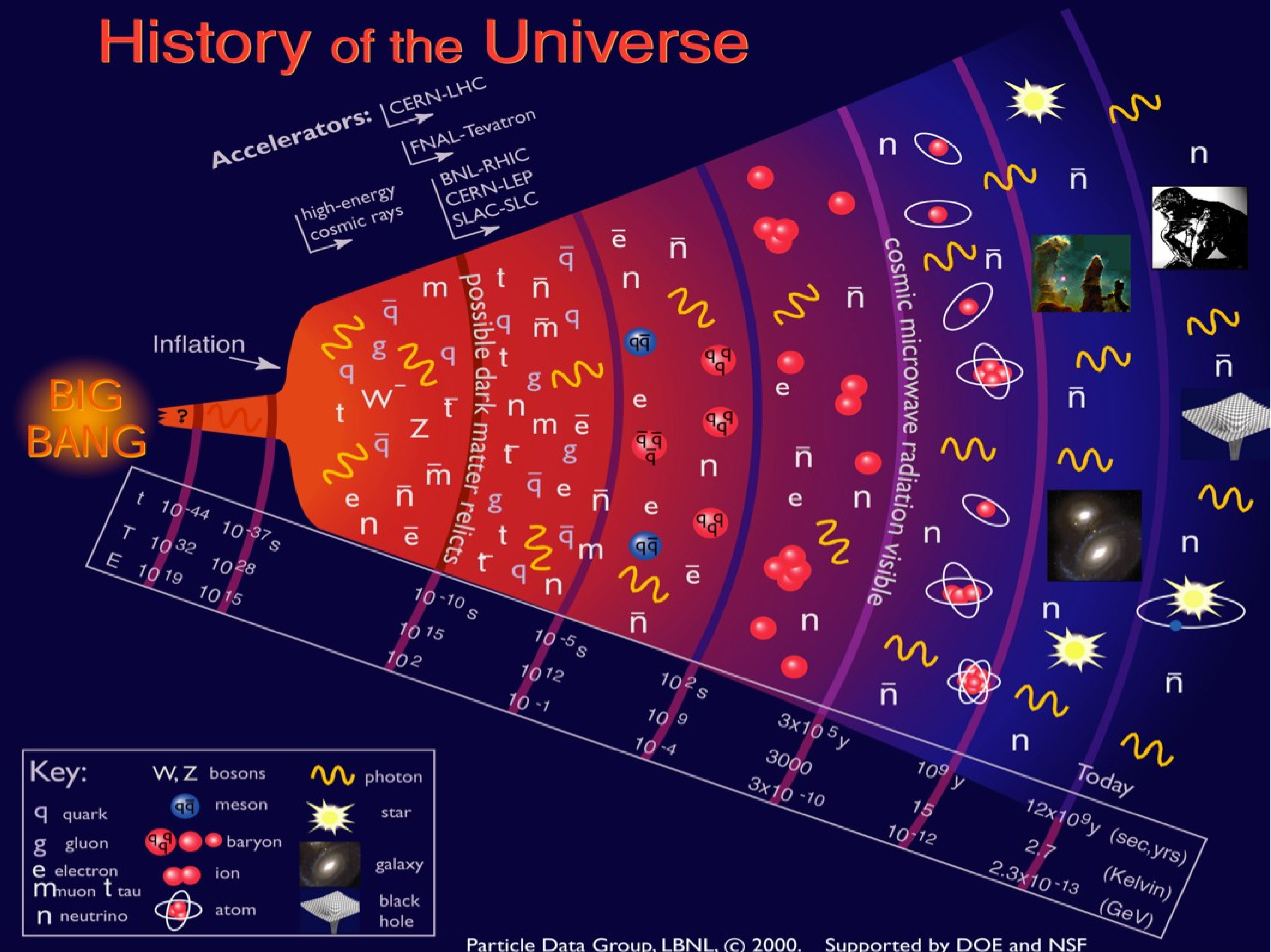
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$

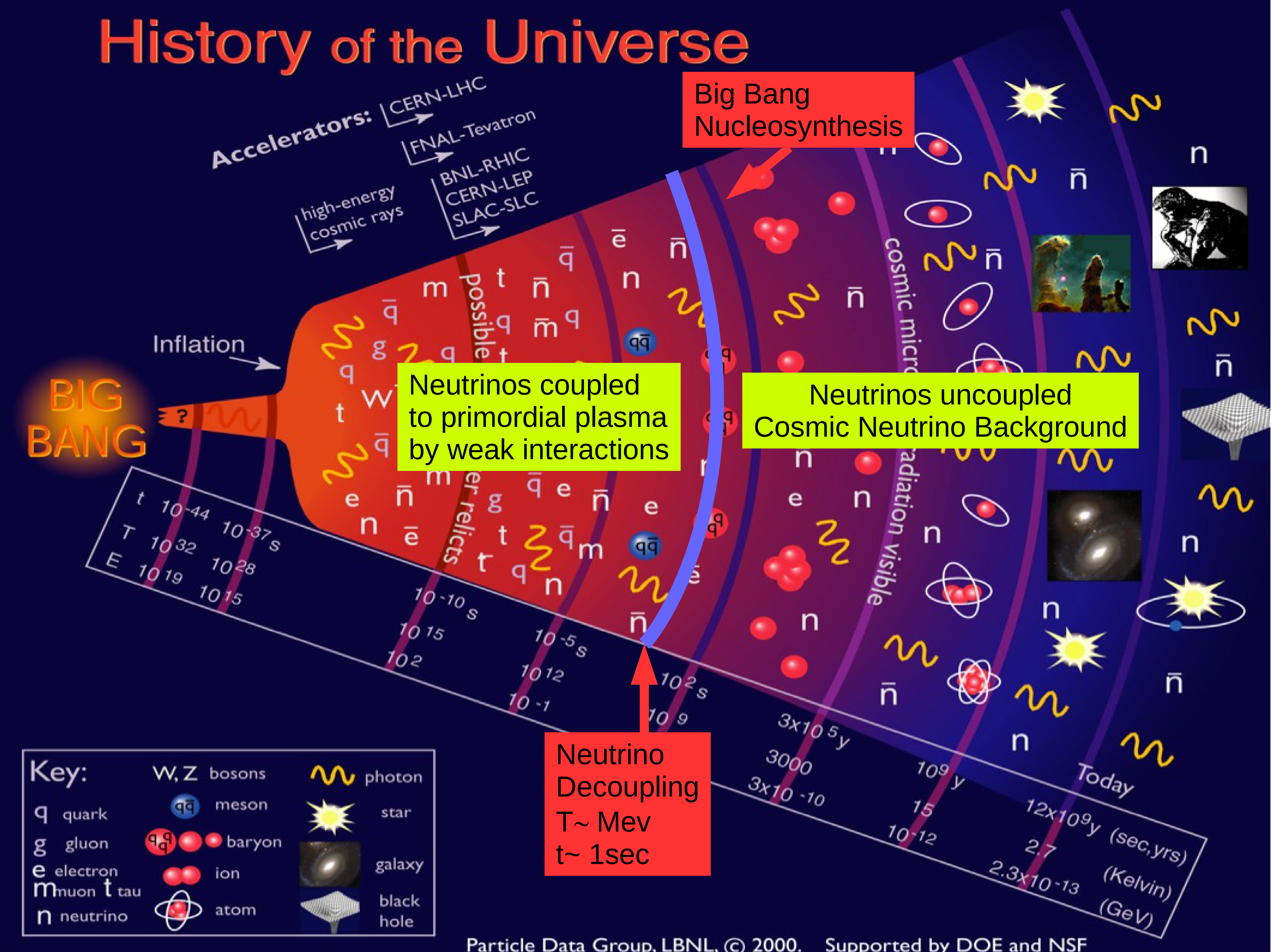
$$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$$

$$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$$

$$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$$

- At those temperatures neutrino are relativistic !


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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Inflation
BIG BANG
Neutrinos coupled to primordial plasma by weak interactions
Neutrinos uncoupled Cosmic Neutrino Background
possible super relics
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 3x10-10 10-12 2.3x10-13 (GeV)
Today
Neutrino Decoupling
T~ Mev
t~ 1sec
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

Neutrino Decoupling

As the Universe expands, particle densities are diluted and temperatures fall. Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma

Rough, but quite accurate estimate of the decoupling temperature

Rate of weak processes ~ Hubble expansion rate

$$\Gamma_w \approx \sigma_w |\mathrm{v}| n \, , \; H^2 = \frac{8\pi\rho_R}{3M_p^2} \rightarrow G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_R}{3M_p^2}} \rightarrow T_{dec}^{\nu} \approx 1 \; MeV$$

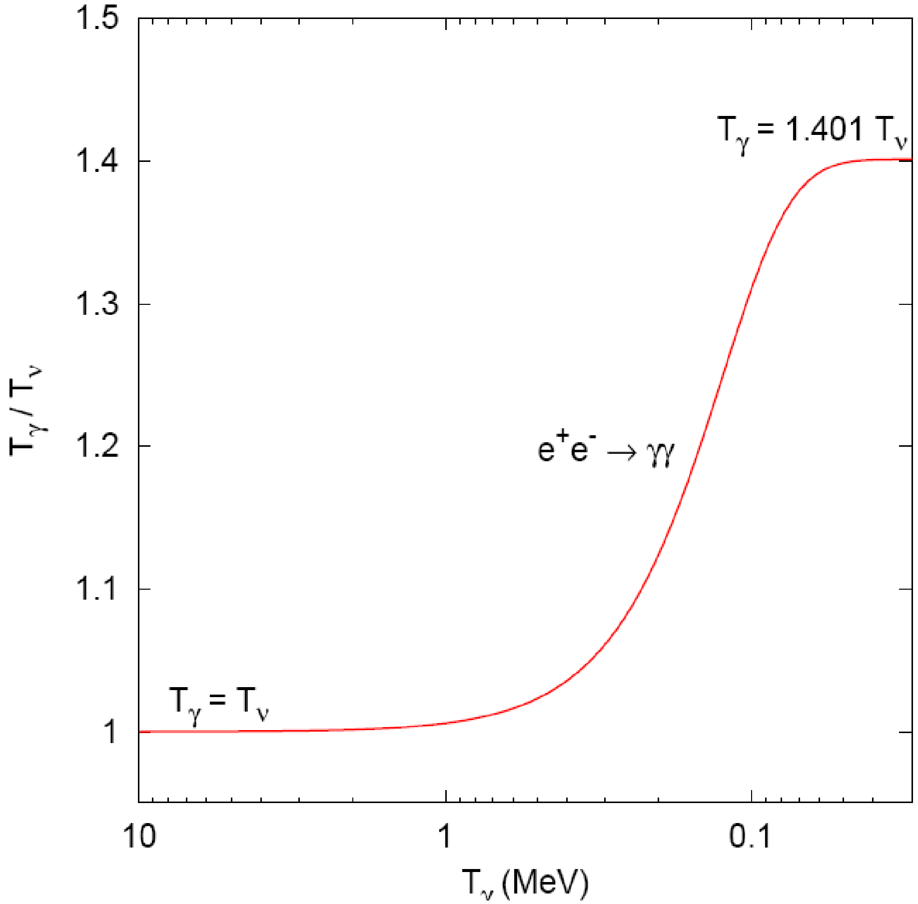
Neutrino Decoupling

- After decoupling, neutrinos keep the Fermi-Dirac distribution with temperature scaling as 1/a(t).
- Since also the e.m. plasma temperature scales as 1/a(t), e.m. plasma and the neutrino background share the same temperature even if they are decoupled.
- However at $T \sim m_e$ electron-positron pairs annihilate heating photons but not the decoupled neutrinos.

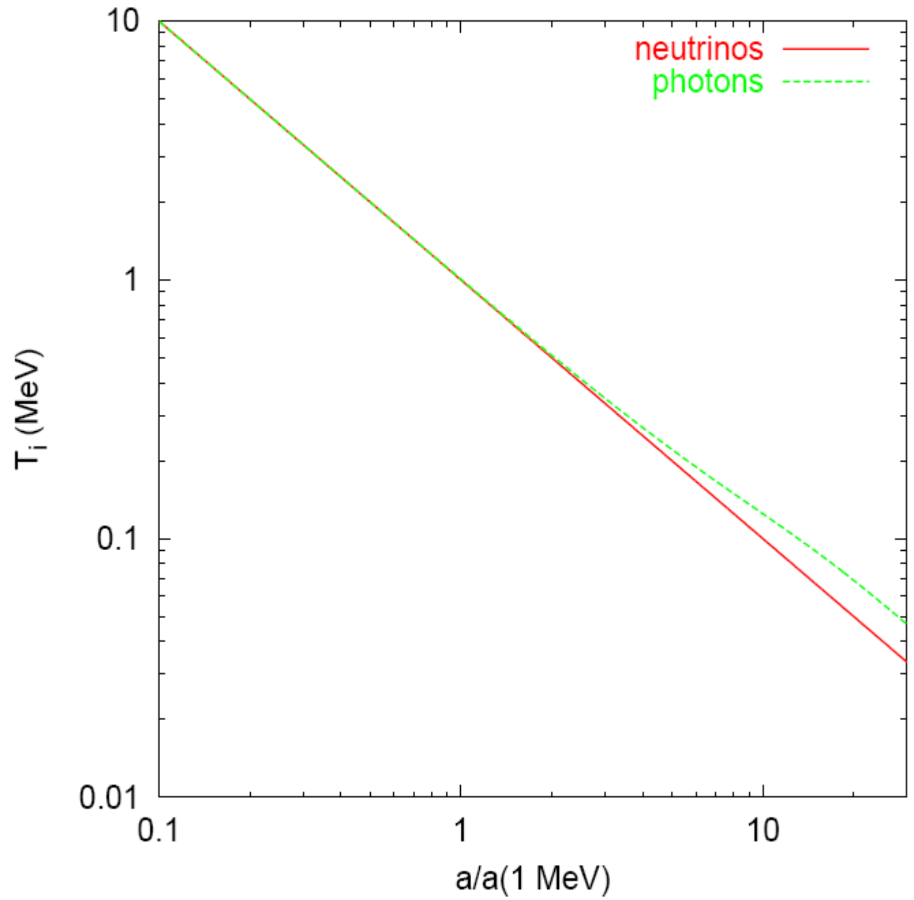
$$e^+ e^- \to \gamma\gamma$$

CMB and CNB temperatures

The photon temperature increases respect to neutrino temperature.



The photon temperature falls slower than 1/a(t).



CMB and CNB temperatures

- A classic result that assumes instantaneous neutrino decoupling (see, for example, Dodelson Modern Cosmology) gives:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

- Since for a relativistic gas of fermions and bosons we have:

$$\rho_\nu = \frac{7}{8}\frac{\pi^2}{30} g_\nu T_\nu^4 \qquad \rho_\gamma = \frac{\pi^2}{30} g_\gamma T_\gamma^4$$

- and, since $g_\nu = 2 * N_\nu$, we have:

$$\rho_{rad} = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right]\rho_\gamma$$

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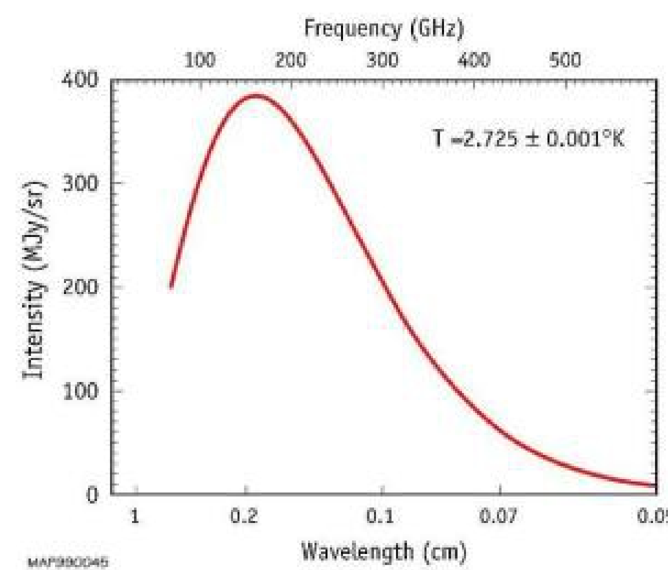
We know this !

The Cosmic Microwave Background

Discovered By Penzias and Wilson in 1965.

It is an image of the universe at the time of recombination (near baryon-photons decoupling), when the universe was just a few thousand years old ($z \sim 1000$).

The CMB frequency spectrum is a perfect blackbody at T=2.726 K: this is an outstanding confirmation of the hot big bang model.



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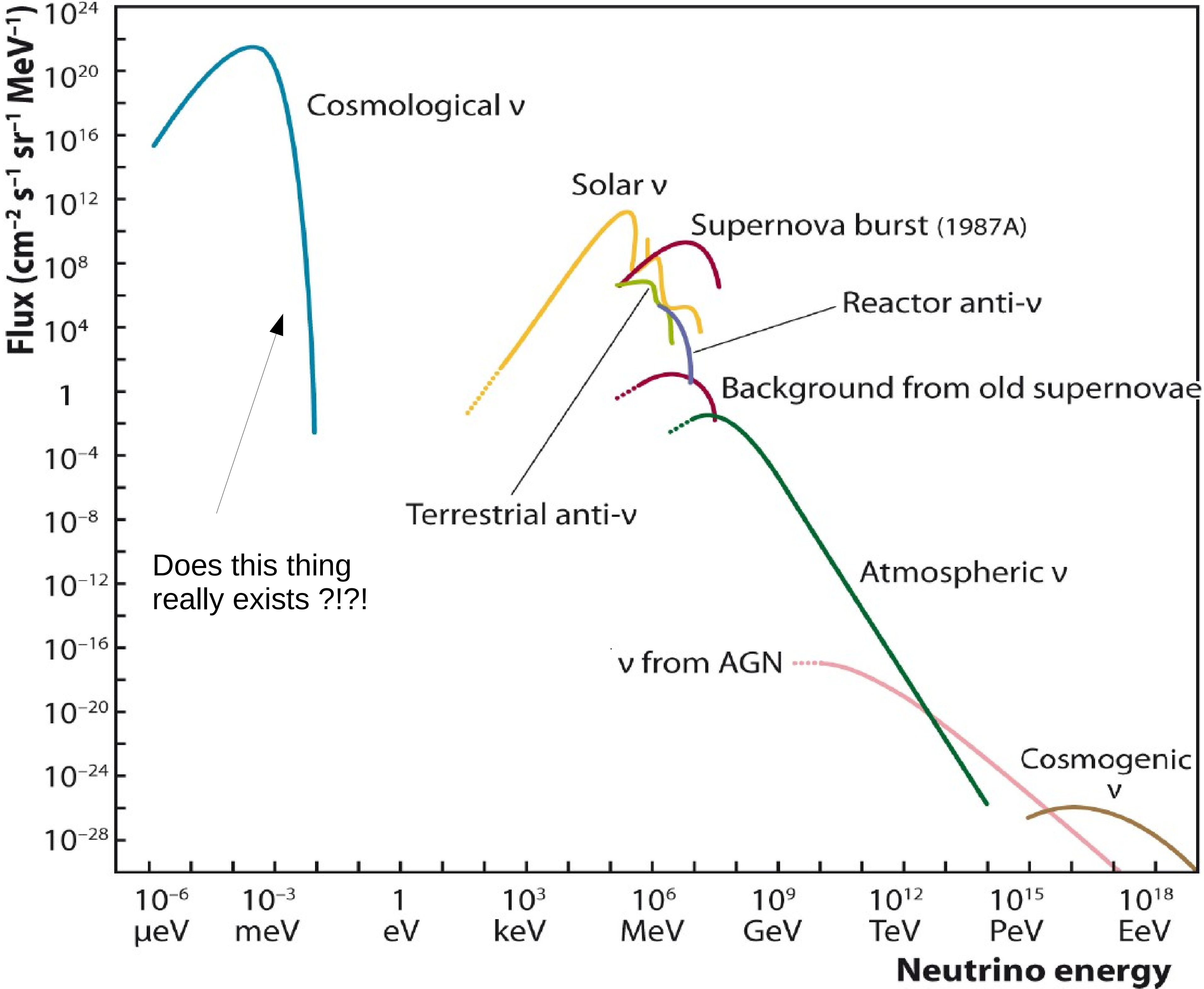
We know this !

Neutrino number, if zero NO CNB


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Neutrino energy
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Does this thing really exists ?!?!

Neutrinos and Hubble rate

Neutrinos change the Hubble rate during the radiation dominated epoch (or when the radiation component is still not negligible respect to matter):

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right]\rho_\gamma$$

NO CNB means smaller Hubble rate,
more neutrinos means larger Hubble rate.
This has important implications:

- If we change N_ν during BBN we change the Hubble rate and the final (post-BBN) abundance of primordial nuclides.

- If we change N_ν at CMB, the relativistic component is non-negligible, we change the Hubble rate and two important scales to the creation of CMB anisotropies: the sound horizon and the damping scales.

- Moreover, if we change N_ν we change the epoch of matter-radiation equality and structure formation.

Caveat

- Neutrino decoupling is, in reality, non-instantaneous.

  a more correct formula is given by:

$$\rho_{rad} = \rho_{\gamma} + \rho_{\nu} = [1 + \frac{7}{8}(\frac{46}{125})^{4/3} N_{\nu}]\rho_{\gamma}$$

- But since cosmologists are conservative we assume the standard equation:

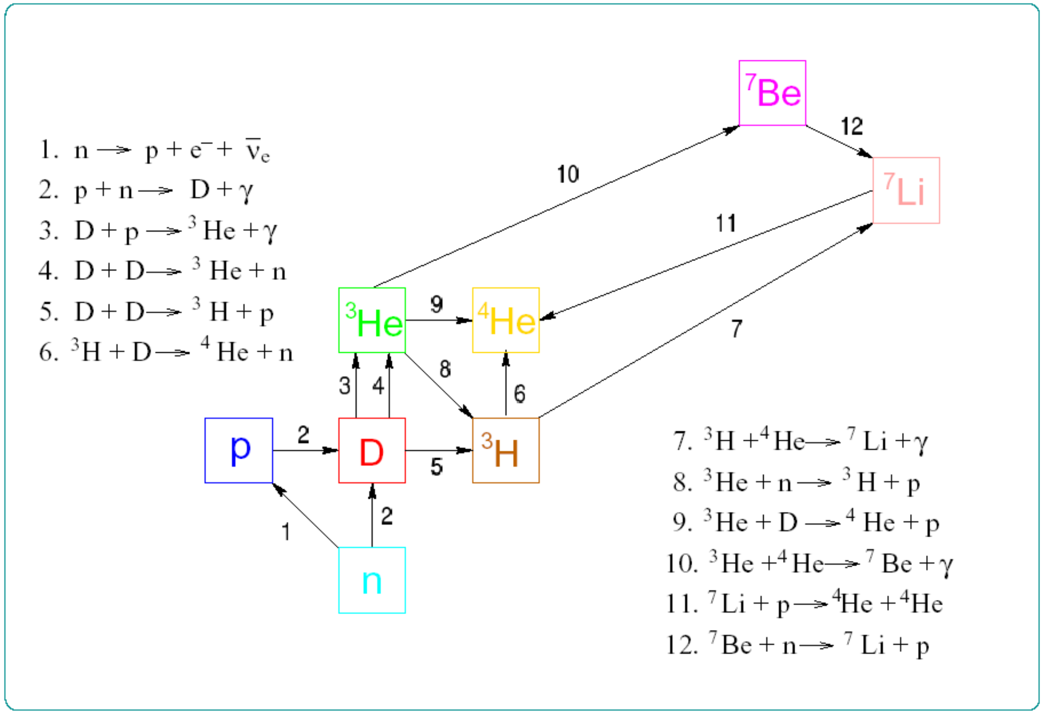
$$\rho_{rad} = \rho_{\gamma} + \rho_{\nu} = [1 + \frac{7}{8}(\frac{4}{11})^{4/3} N_{eff}]\rho_{\gamma}$$

- But where, for the standard 3 neutrinos framework, we have:

$$N_{eff} = 3.046$$

Testing N_{eff} with cosmology

Big Bang Nucleosynthesis

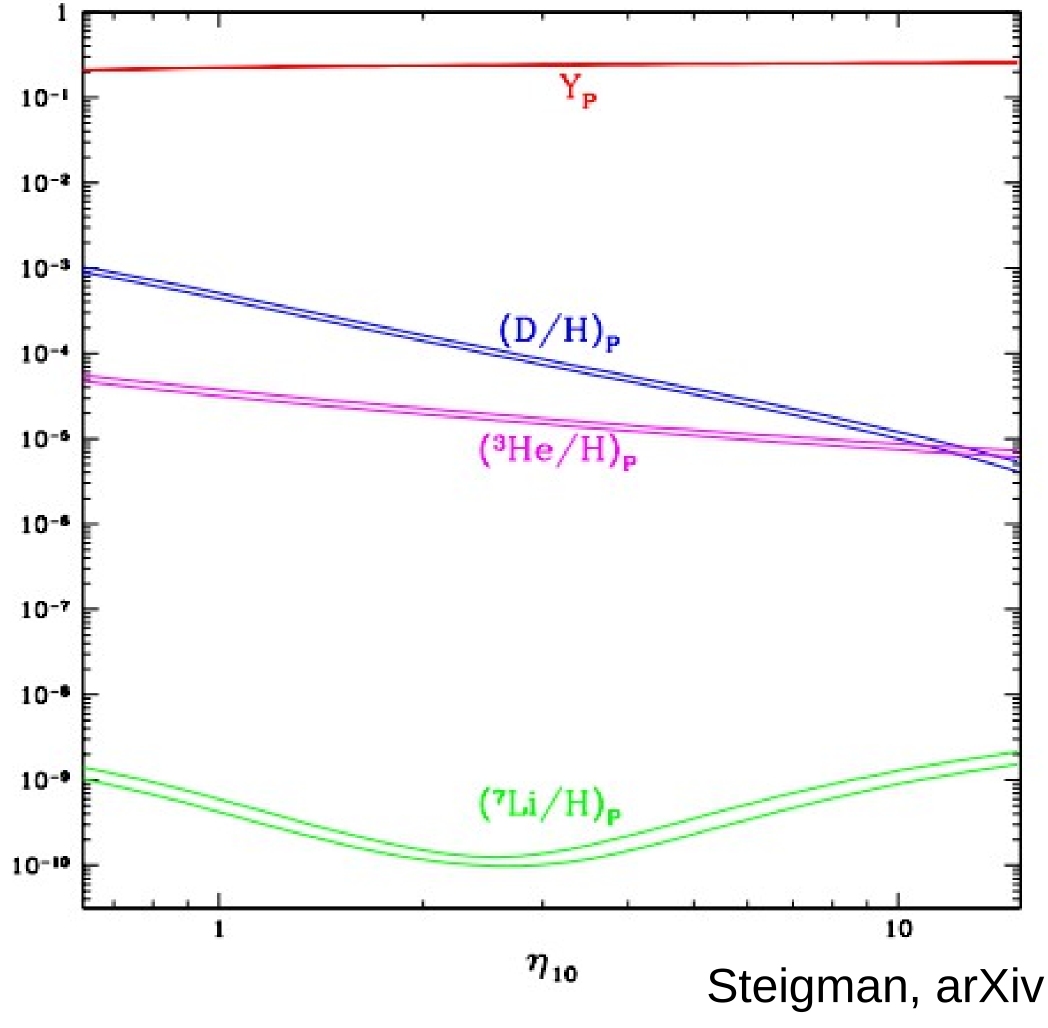


Produced elements: D, ^{3}He, ^{4}He, ^{7}Li and small abundances of others

Theoretical inputs:

- τ_n, the neutron lifetime;
- G_N, the Newton gravitational constant;
- η, the baryon to photon number density ratio;
- the nuclear rates.

Big Bang Nucleosynthesis



$$\eta \equiv \frac{N_b}{N_\gamma} \simeq 2.75 \times 10^{-8}\ \Omega_b h^2$$

Steigman, arXiv:astro-ph/0307244

In the standard 3 neutrinos framework Big Bang Nucleosynthesis essentially relates the primordial abundance of light elements to the baryon density parameter ω_b .

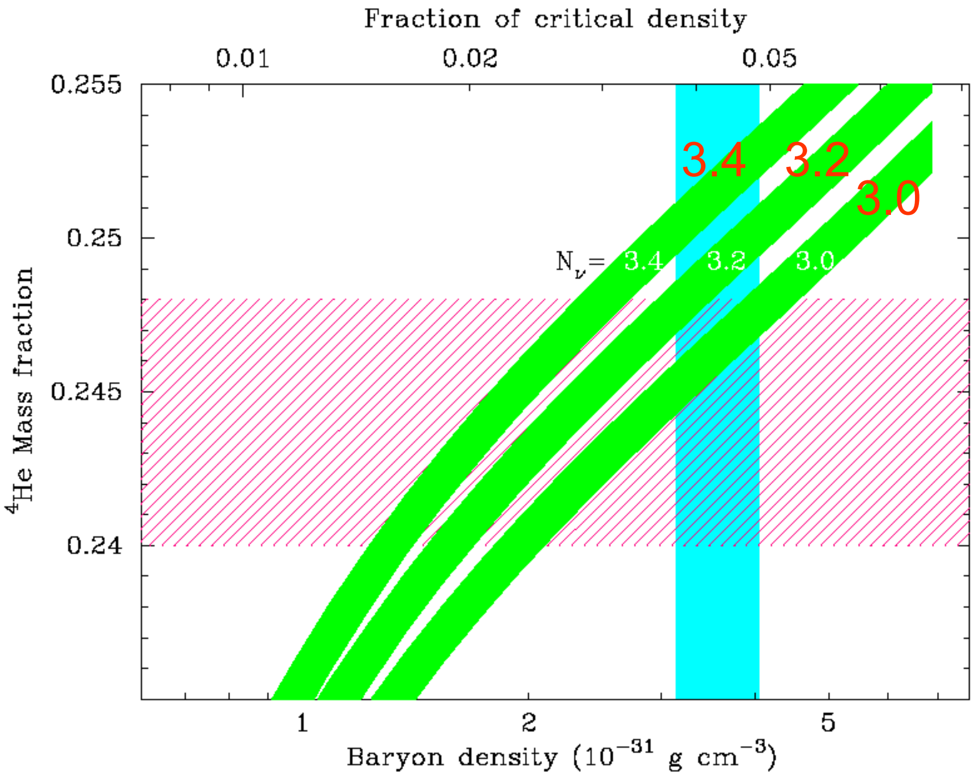
Constraining N_{eff} with BBN

1. N_{eff} fixes the expansion rate during BBN

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$

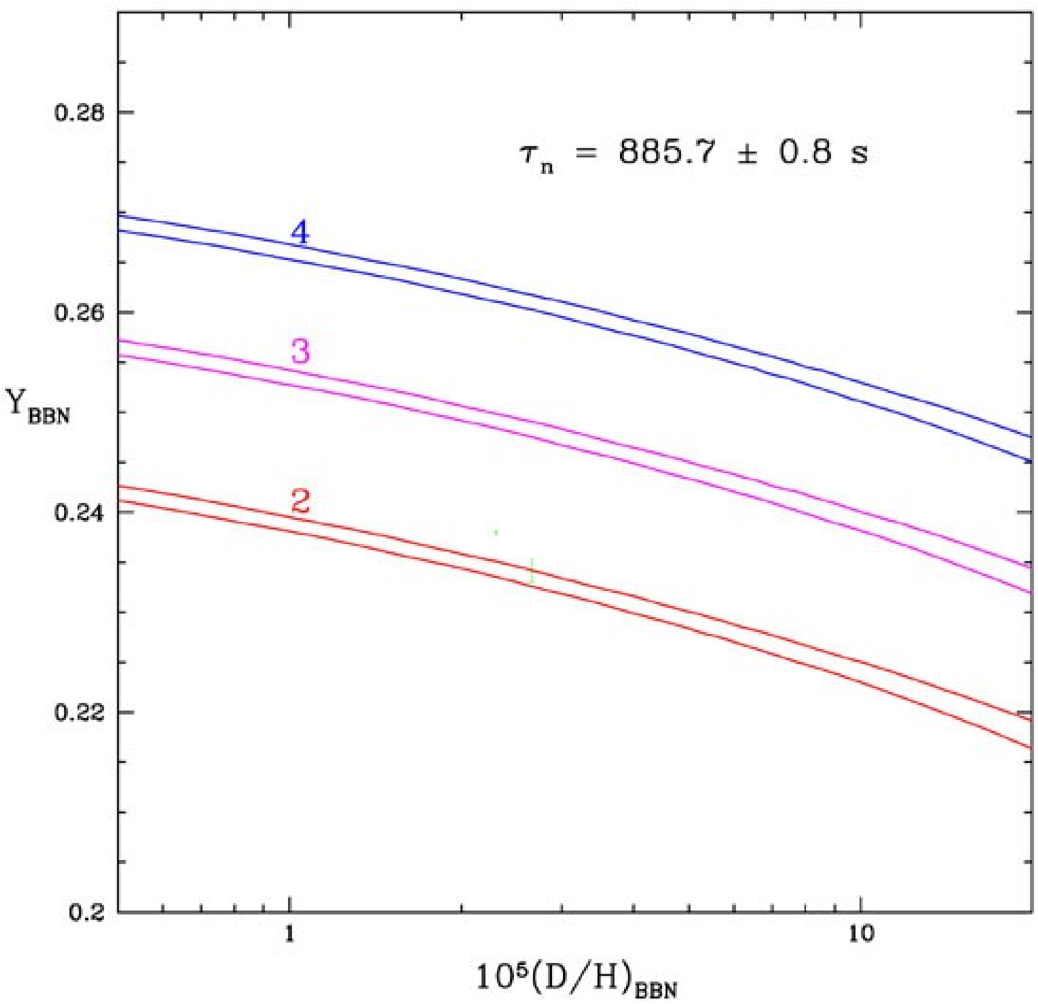
$\rho(N_{eff}) > \rho_0 \;\rightarrow\; \uparrow {}^4He$

Burles, Nollett & Turner 1999



For the same value of the baryon abundance, increasing the effective neutrino number increases the Helium abundance.

Constraining N_{eff} with BBN



Clearly, measuring Helium abundance alone is not enough to determine Neff since we have to also determine the baryon abundance.

We can however combine with Deuterium measurement and have a BBN only determination.

Steigman, arXiv:astro-ph/0307244

BBN: Measurements of Primordial Abundances

Difficult task: search in astrophysical systems with chemical evolution as small as possible

Deuterium: destroyed in stars. Any observed abundance of D is a *lower* limit to the primordial abundance. Data from high-z, low metallicity QSO absorption line systems

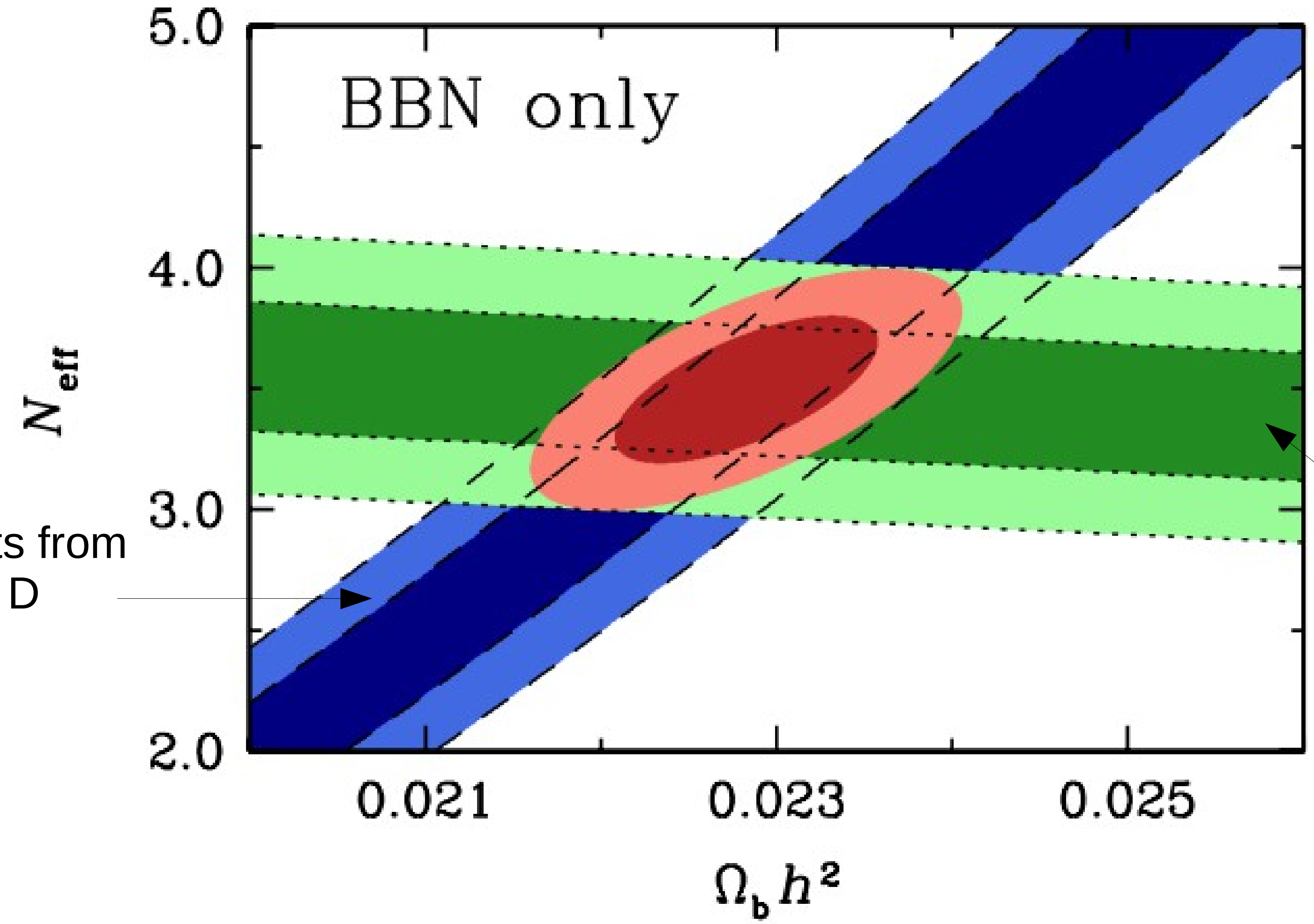
Helium-3: produced and destroyed in stars (complicated evolution) Data from solar system and galaxies but not used in BBN analysis

Helium-4: primordial abundance increased by H burning in stars. Data from low metallicity, extragalatic HII regions

Lithium-7: destroyed in stars, produced in cosmic ray reactions. Data from oldest, most metal-poor stars in the Galaxy

Current Constraints from BBN only

Constraints from primordial D



Constraints from primordial He

Neutrino Background needed at about 17 sigmas !

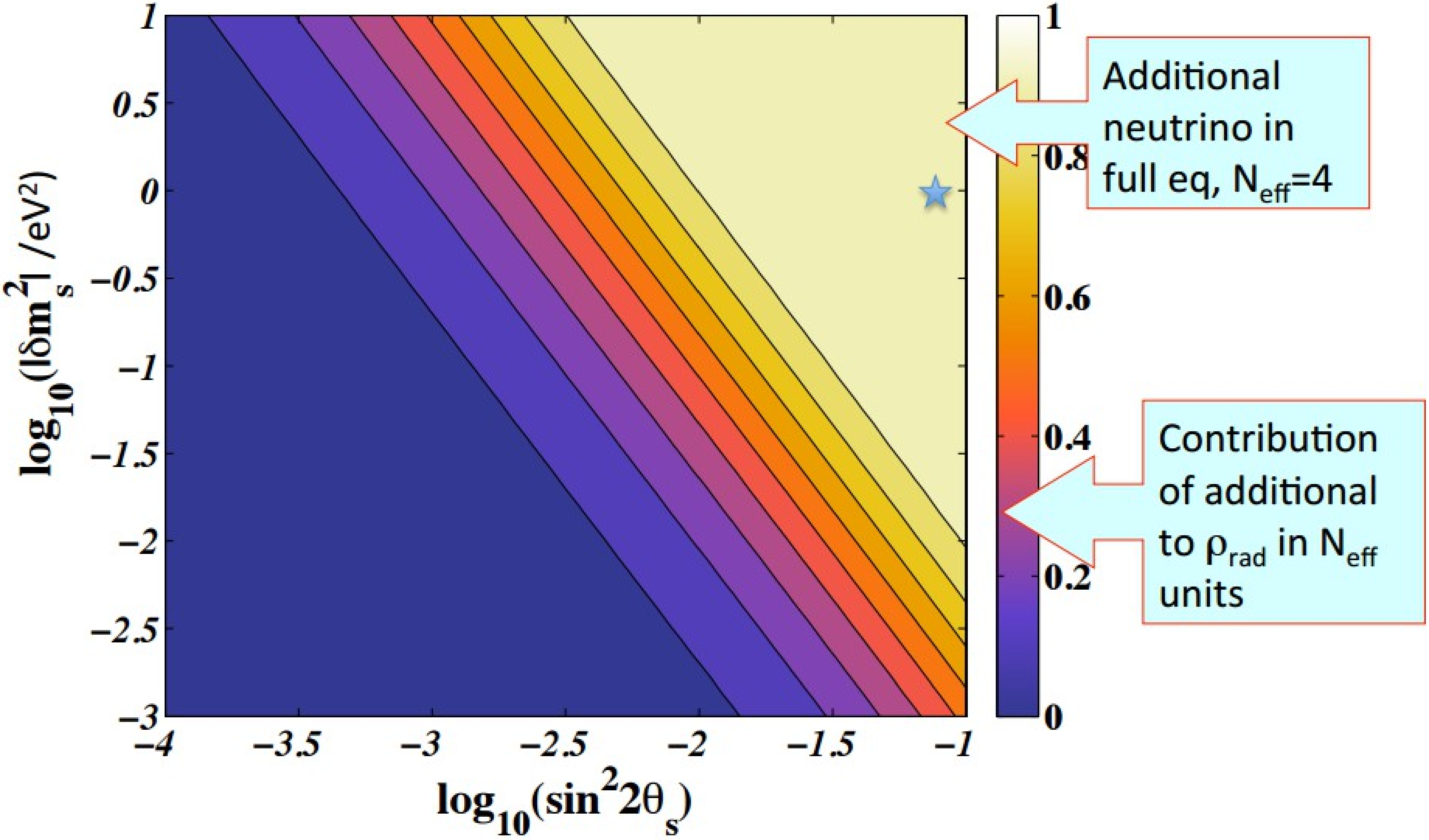
$$100\,\Omega_{b,0}\,h^2 = 2.28 \pm 0.05$$

$$N_{eff} = 3.50 \pm 0.20\,.$$

Mild indication for $N_{eff} > 3.046$

Cooke et al., arXiv:1308.3240

Can this be an extra sterile neutrino ?



Hannestad, Tamborra & Tram, JCAP 07 (2012) 025

Star: preferred sterile neutrino model from:
C. Giunti and M. Laveder, Phys.Lett. B706 (2011) 200–207, arXiv:1111.1069

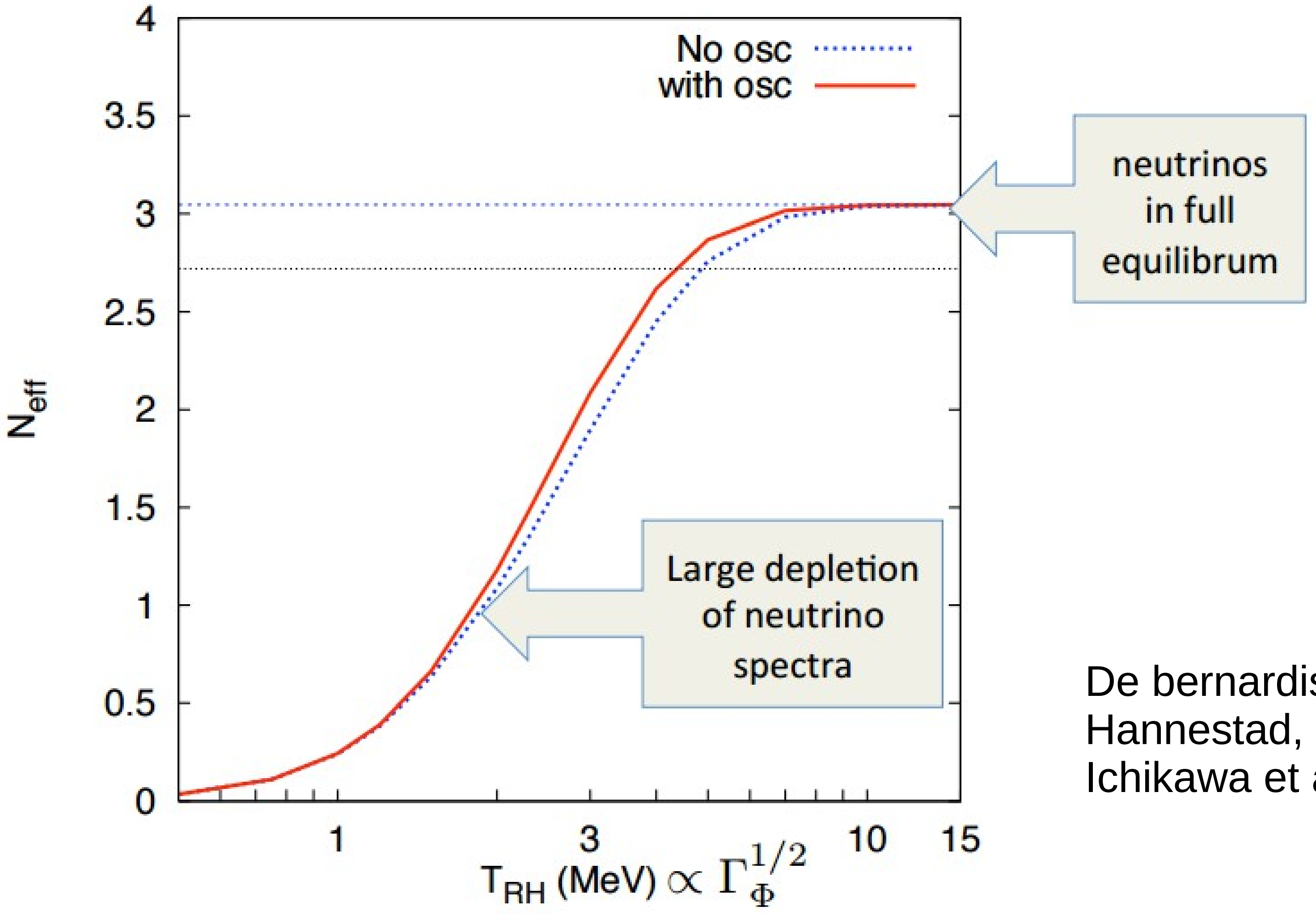
Mechanisms for having $N_{eff}>3.046$

- Non-standard decoupling (Mangano et al. 2006)

  $N_{eff}\sim 3.04$-3.1
- Thermal axions (see eg. Di Valentino et al. 2015)
- Gravitational waves (Smith et al., 2006)
- Extra dimensions
- ….

Mechanisms for having $N_{eff} < 3.046$

- Inflationary reheating temperature at ~MeV scales.

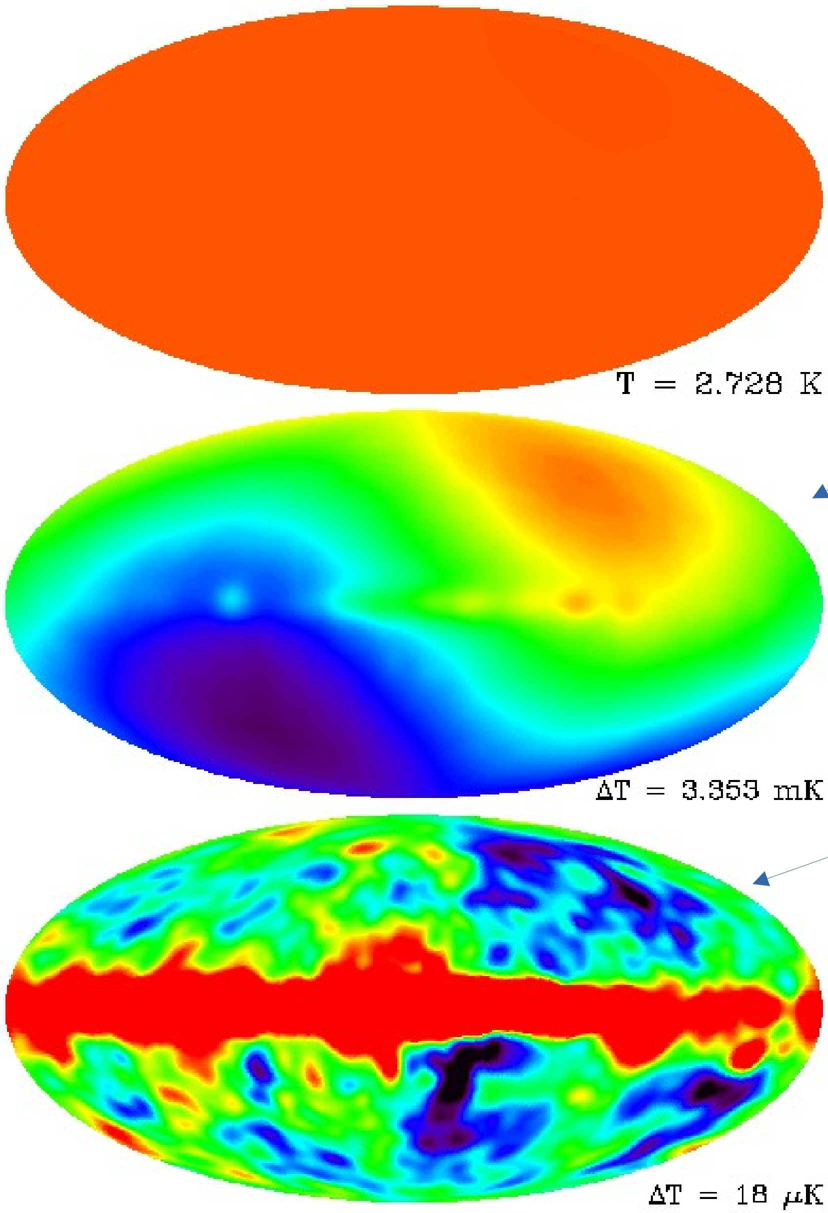


De bernardis et al., 2008
Hannestad, 2005
Ichikawa et al, 2004

Testing Neff with CMB anisotropies

The Microwave Sky

COBE (circa 1995) @90GHz

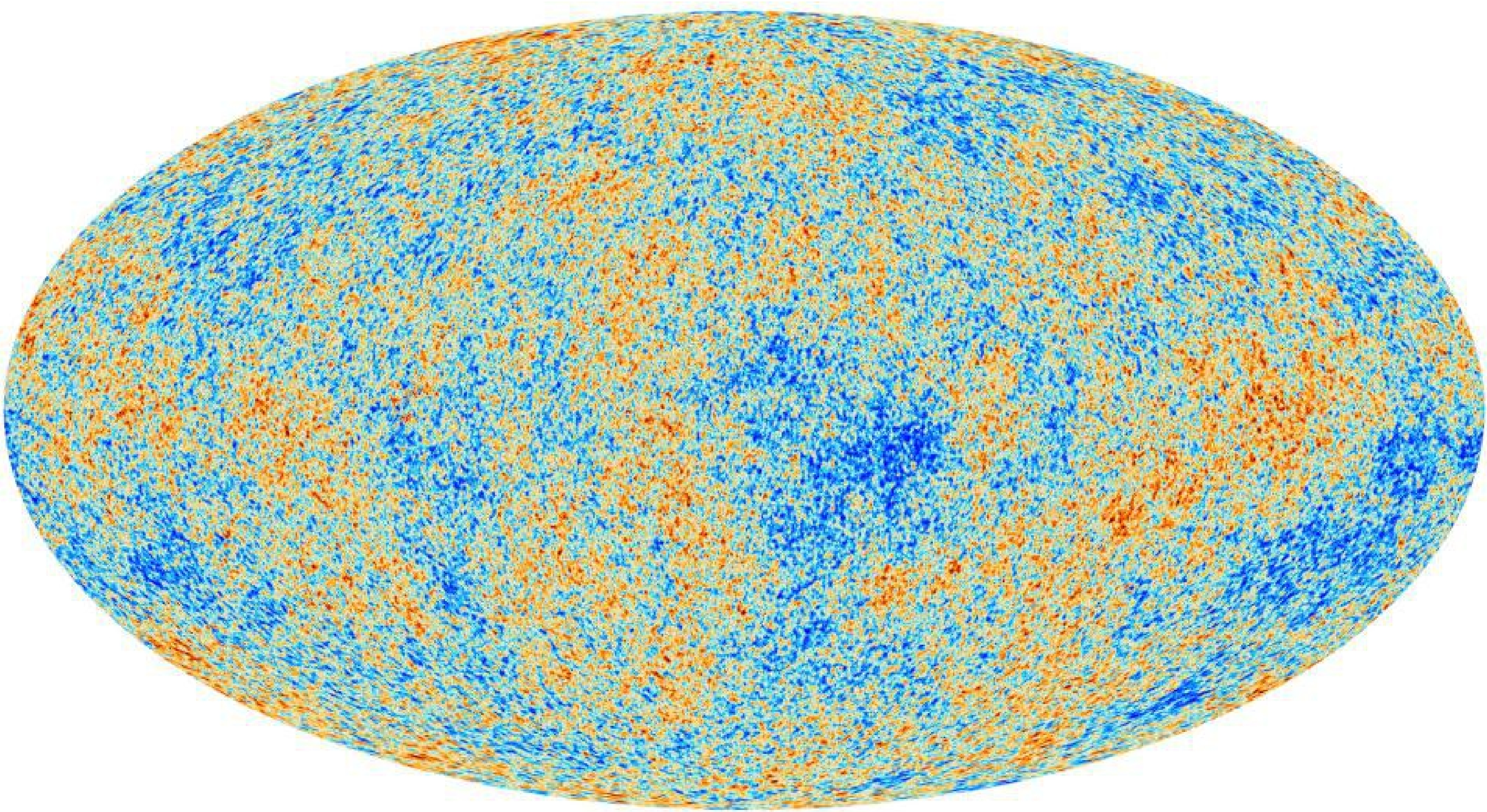


Uniform…

First Anisotropy we see is a Dipole anisotropy:
Implies solar-system barycenter has velocity v/c~0.00123 relative to 'rest-frame' of CMB.

If we remove the Dipole anisotropy and the Galactic emission, we see anisotropies at the level of $(\Delta T/T)_{rms}$~ 20 μK (smoothed on ~7° scale).
These anisotropies are the imprint left by primordial tiny density inhomogeneities (z~1000)..

Planck 2013 CMB Map

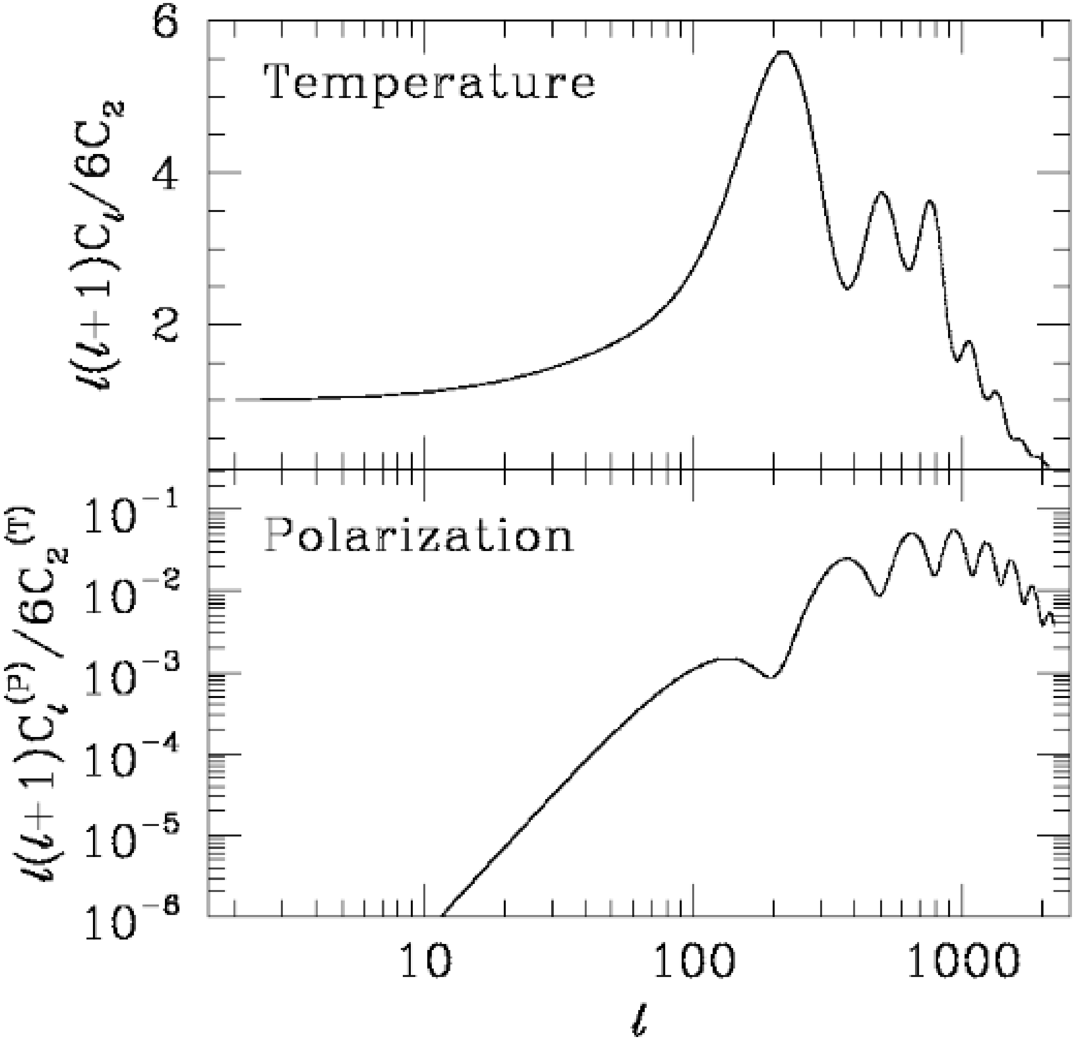


The CMB Angular Power Spectrum

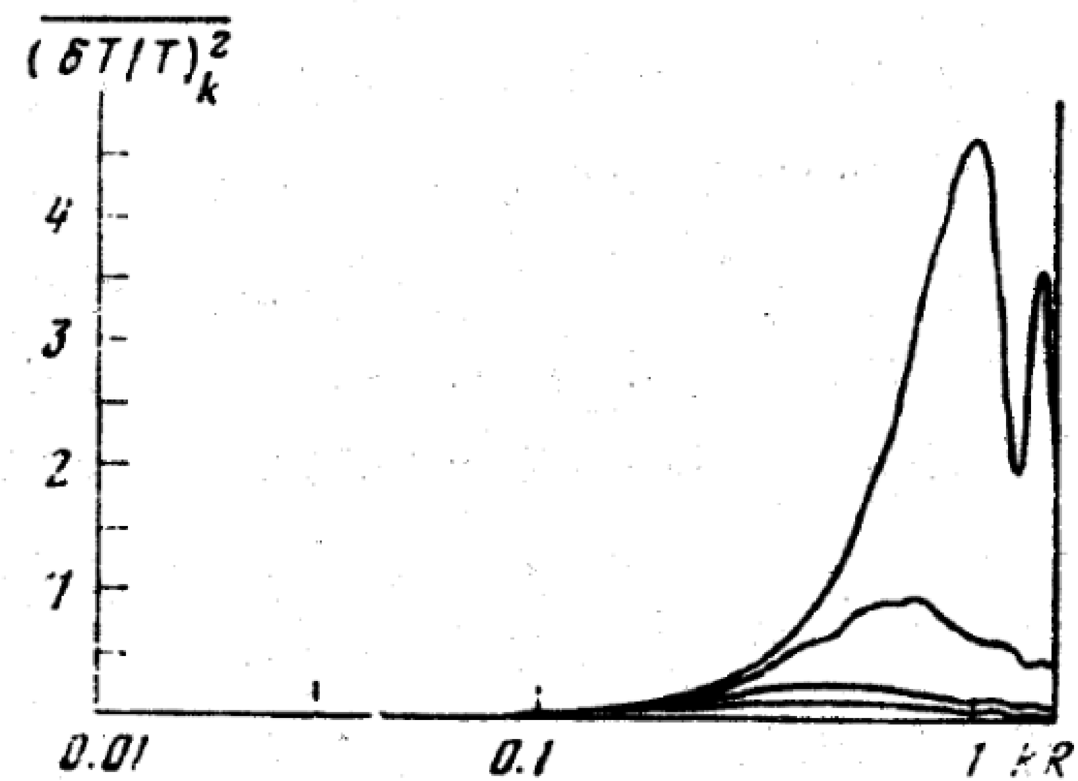
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)\,C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

R.m.s. of $\Delta T / T$ has $l(l+1)C_l / 2\pi$ power per decade in l:

$$\left\langle (\Delta T/T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$



A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Doroshkevich, A. G.; Zel'Dovich, Ya. B.; Syunyaev, R. A.

Soviet Astronomy, Vol. 22, p.523, 1978

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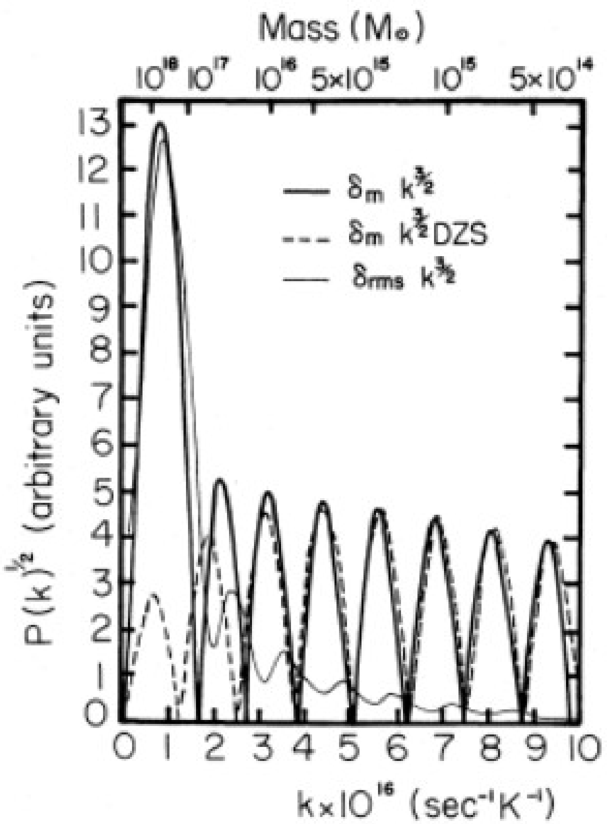

Wilson, M. L.; Silk, J., Astrophysical Journal, Part 1, vol. 243, Jan. 1, 1981, p. 14-25.
1981

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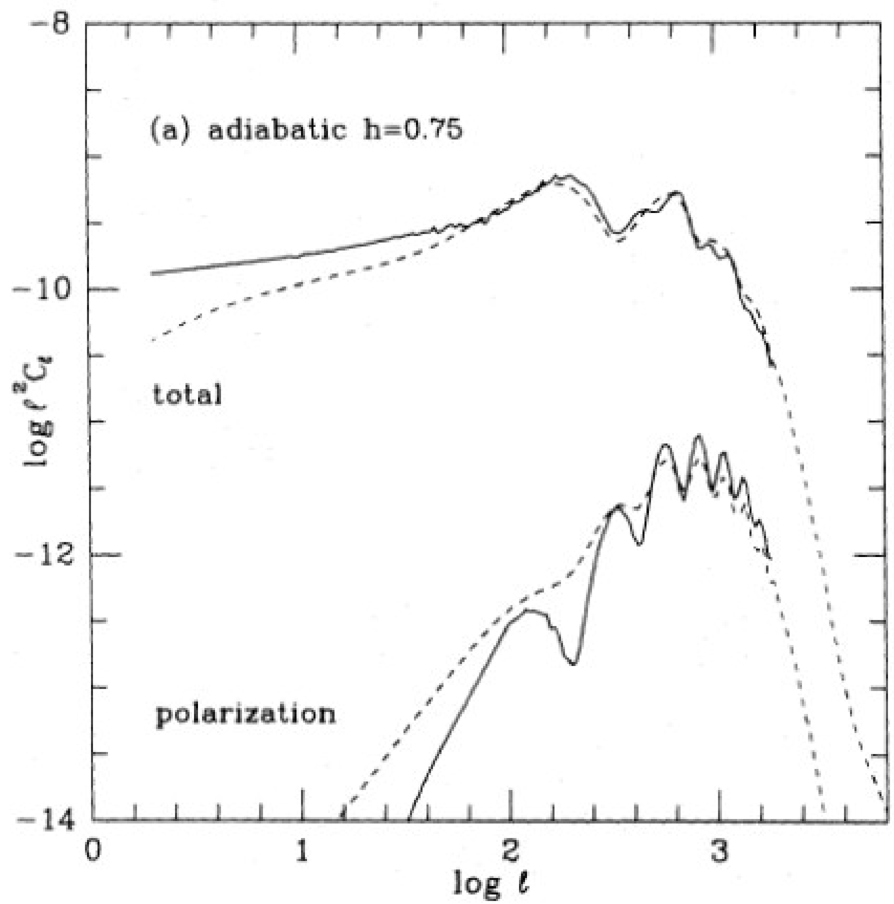

Bond, J. R.; Efstathiou, G.; Royal Astronomical Society, Monthly Notices (ISSN 0035-8711), vol. 226, June 1, 1987, p. 655-687, 1987

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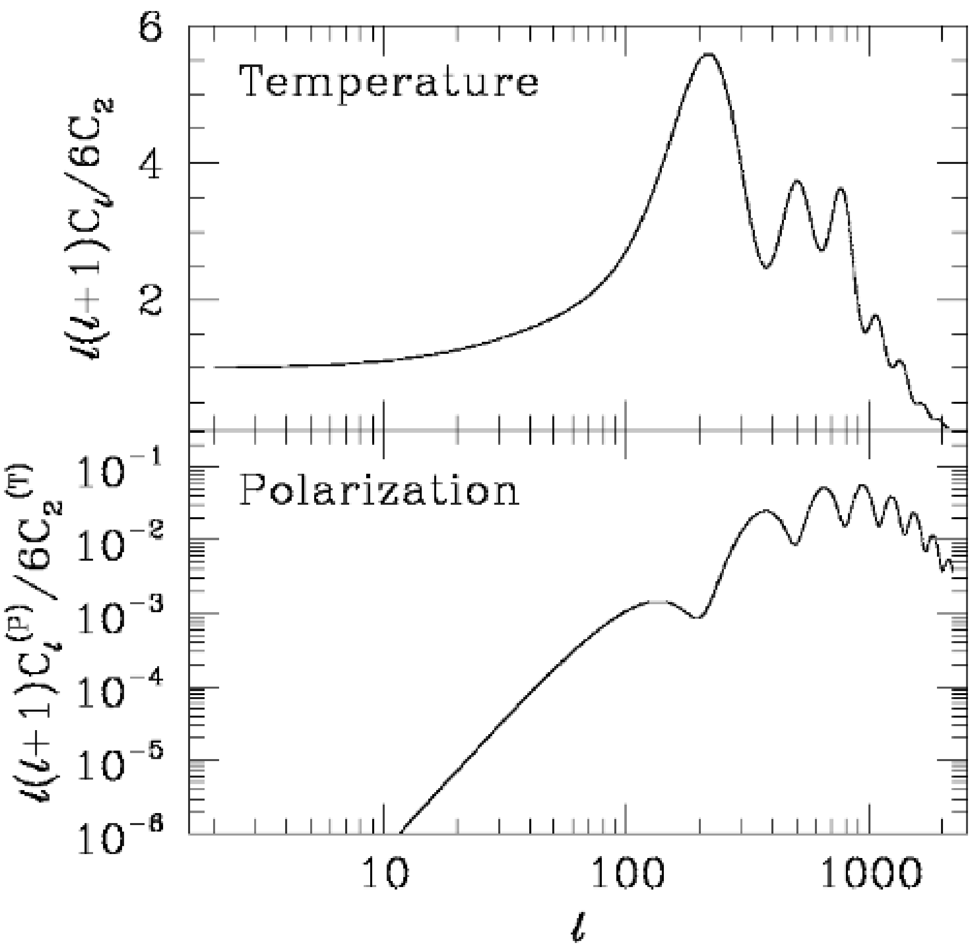
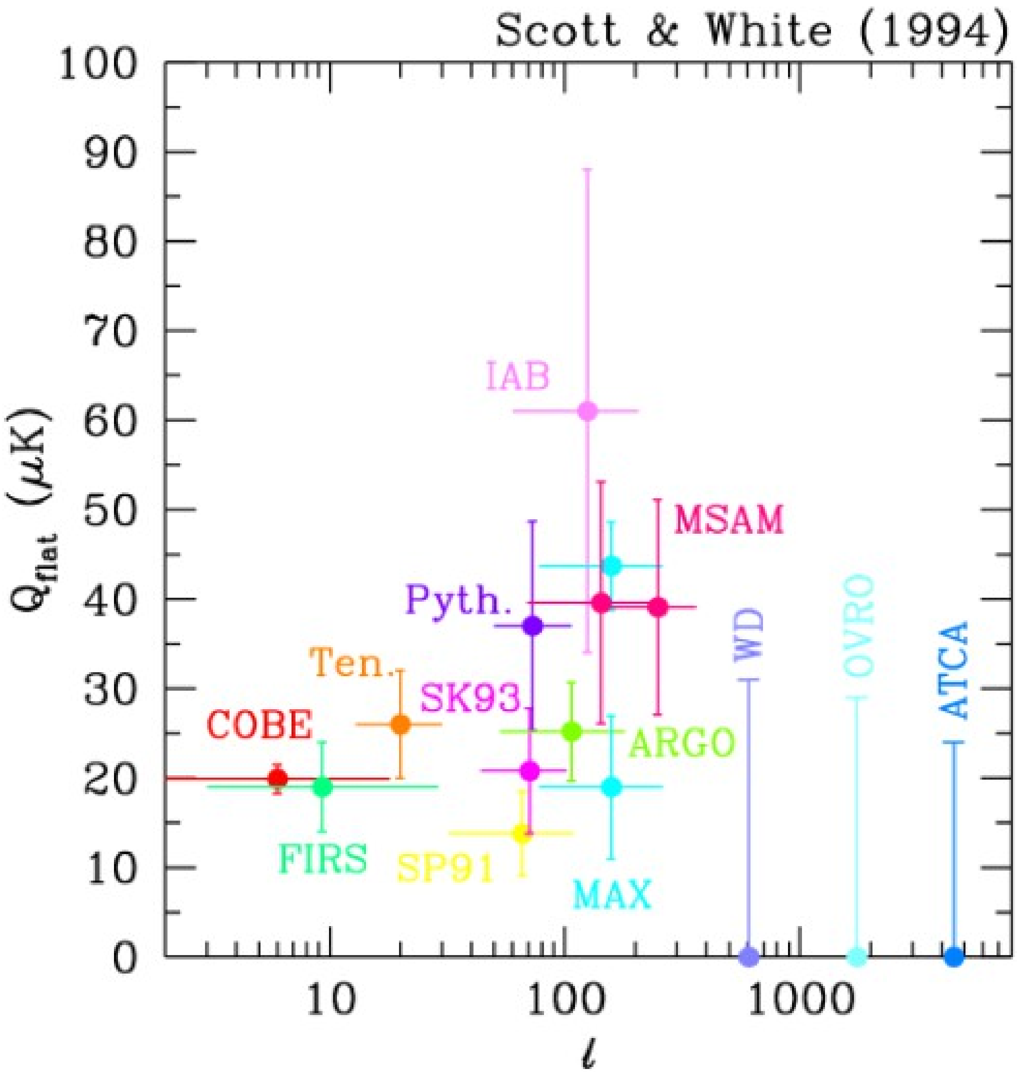


Hu, Wayne; Scott, Douglas; Sugiyama, Naoshi; White, Martin.
Physical Review D, Volume 52, Issue 10, 15 November 1995, pp.5498-5515

A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



In 1995 Big Bang Model was nearly dead…

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Big Bang not yet dead but in decline

John Maddox

The latest measurements of the Hubble constant make the Big Bang account of the origin of the Universe more dependent on the coincidence of numbers than it has so far been. But it remains the only theory in the field.

Top

Is there a crisis in cosmology, or is it that the latest measurement of the Hubble constant is yet another of those numeri-cal disagreements that plague the field from time to time? That is the question inevitably prompted by last week's article by N.

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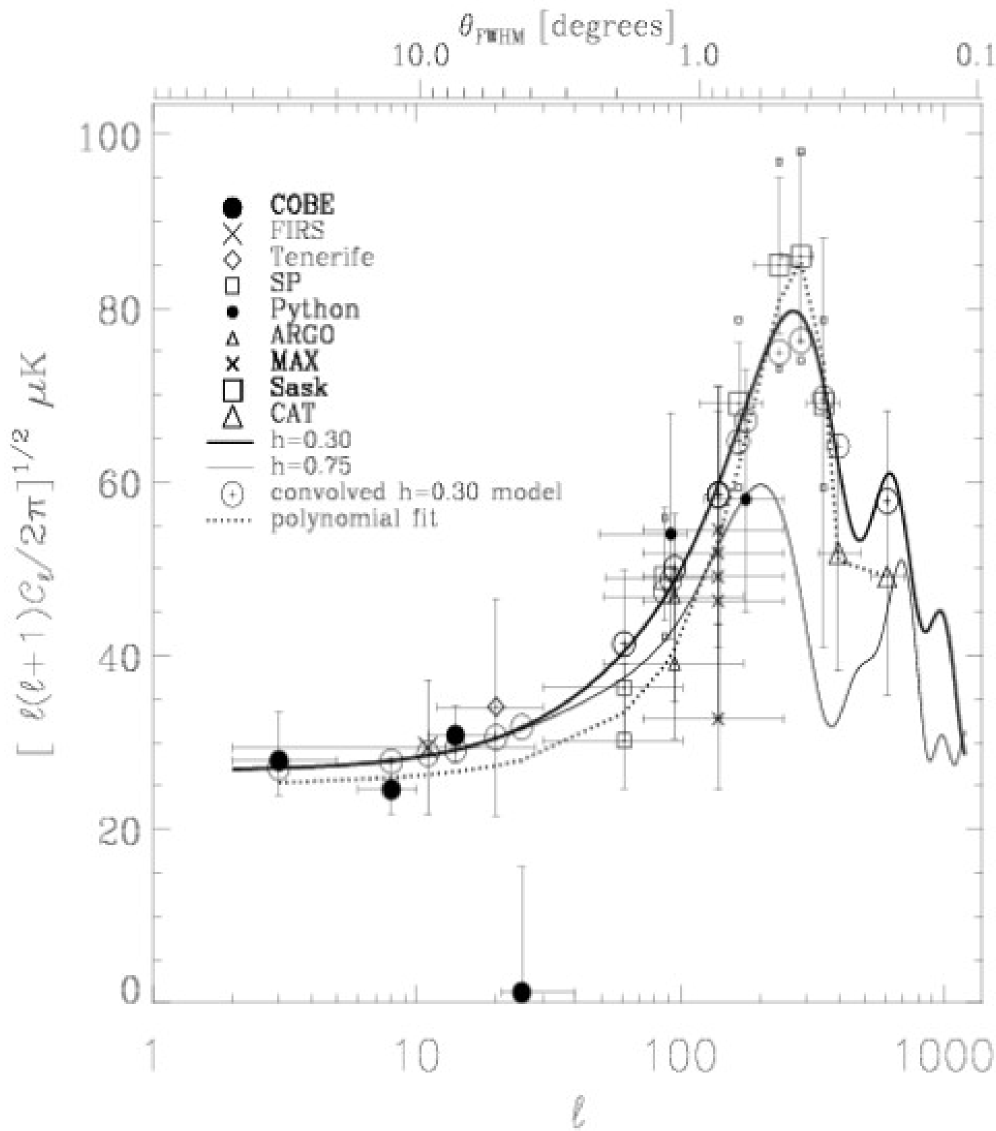
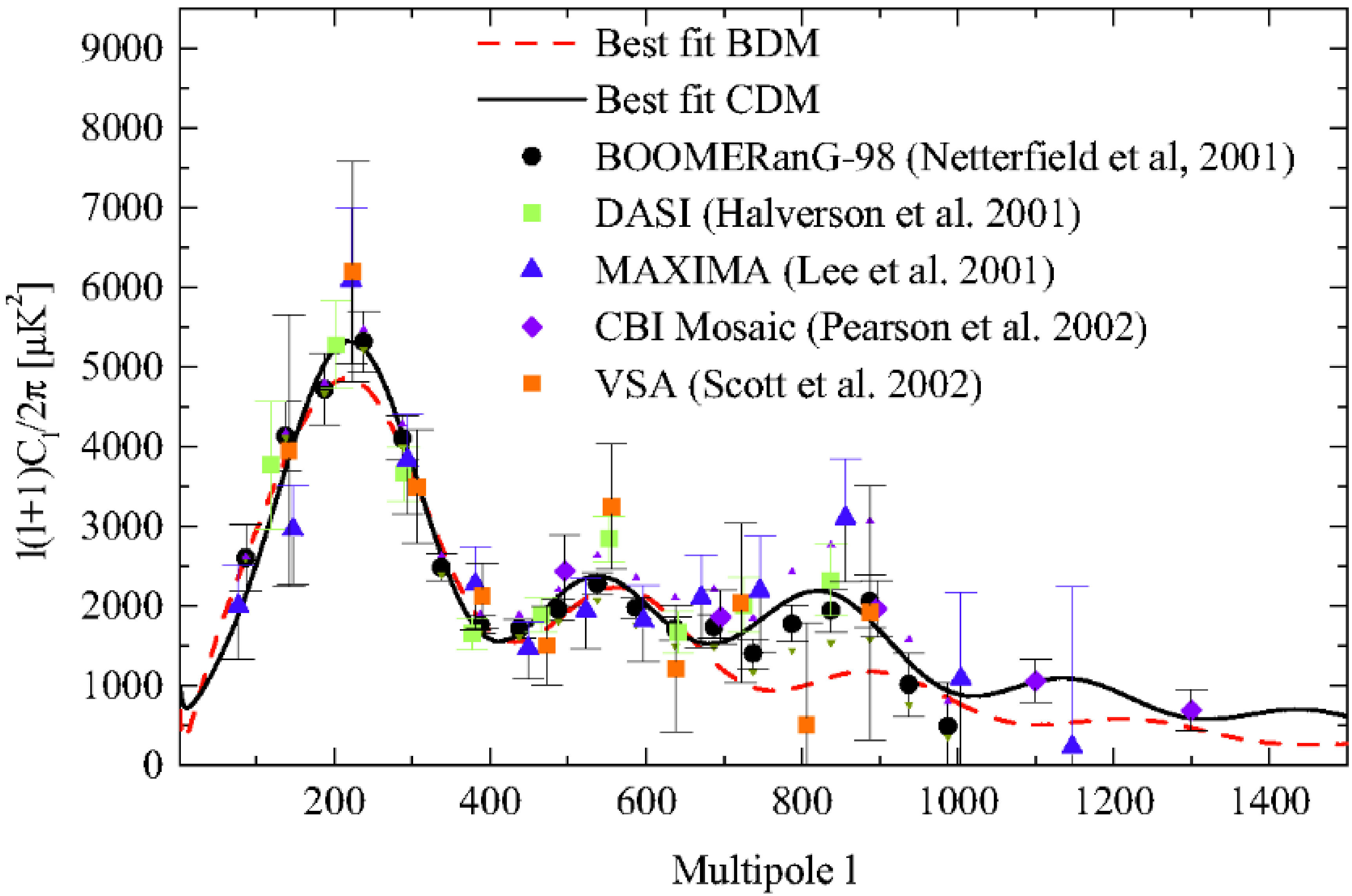
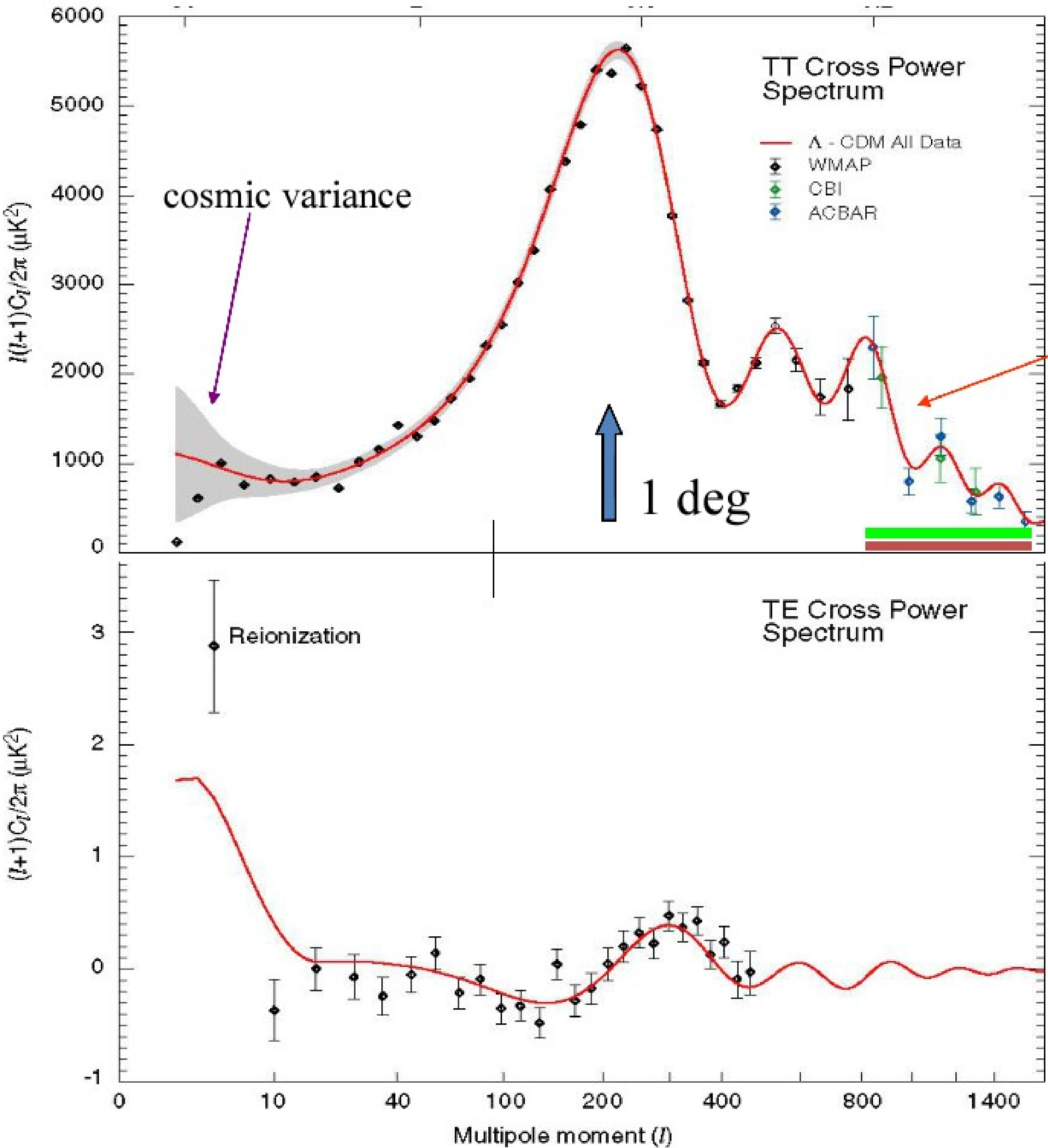
A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



Collection of CMB anisotropy data from C. Lineweaver et al., 1996

CMB anisotropies pre-WMAP (January 2003)





Temperature

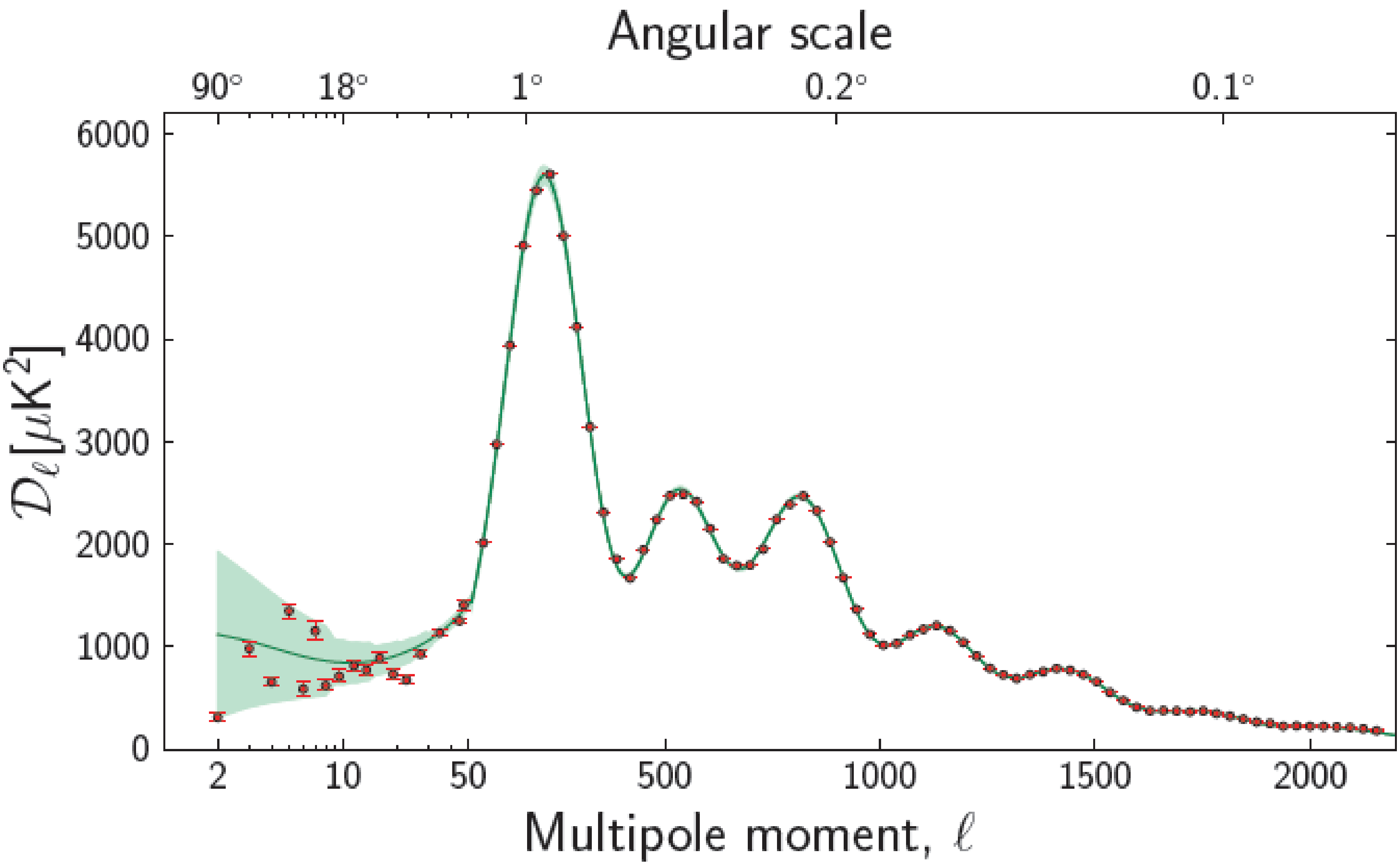
85% of sky

Best fit model

Spergel et al, 2003

Temperature-polarization

Planck 2013 TT angular spectrum



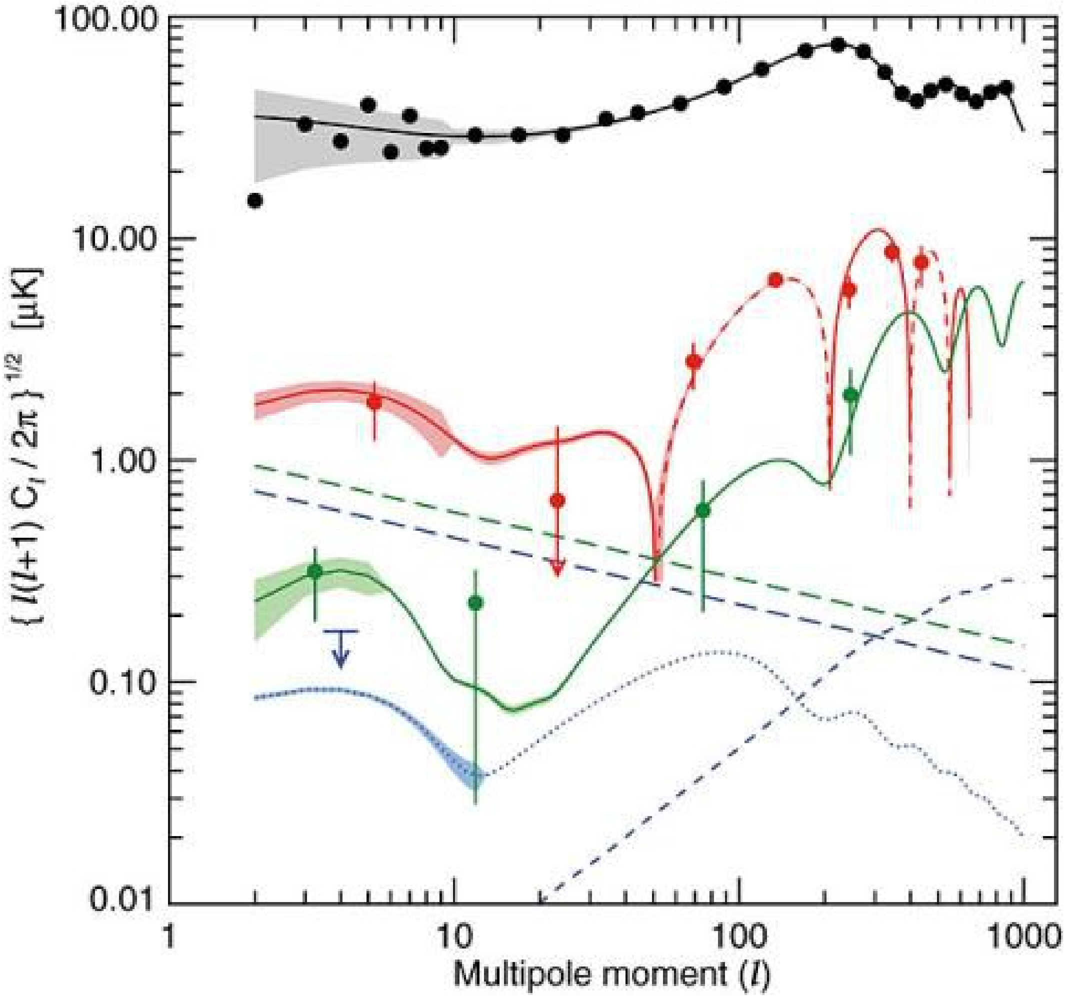
The CMB Angular Power Spectrum

R.m.s. of $\Delta T / T$ has power per decade in l: $l(l+1)C_l / 2\pi$

$$\left\langle \left(\Delta T / T\right)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$

We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization
- Polarization type E (density fluctuations)
- Polarization type B (gravity waves)



CMB Anisotropies

Four mechanisms produce primary CMB anisotropies:

- Gravity (Sachs-Wolfe effect)
- Intrinsic (Adiabatic) Fluctuations
- Doppler effect
- Time-Varying Potentials (Integrated Sachs-Wolfe Effect)

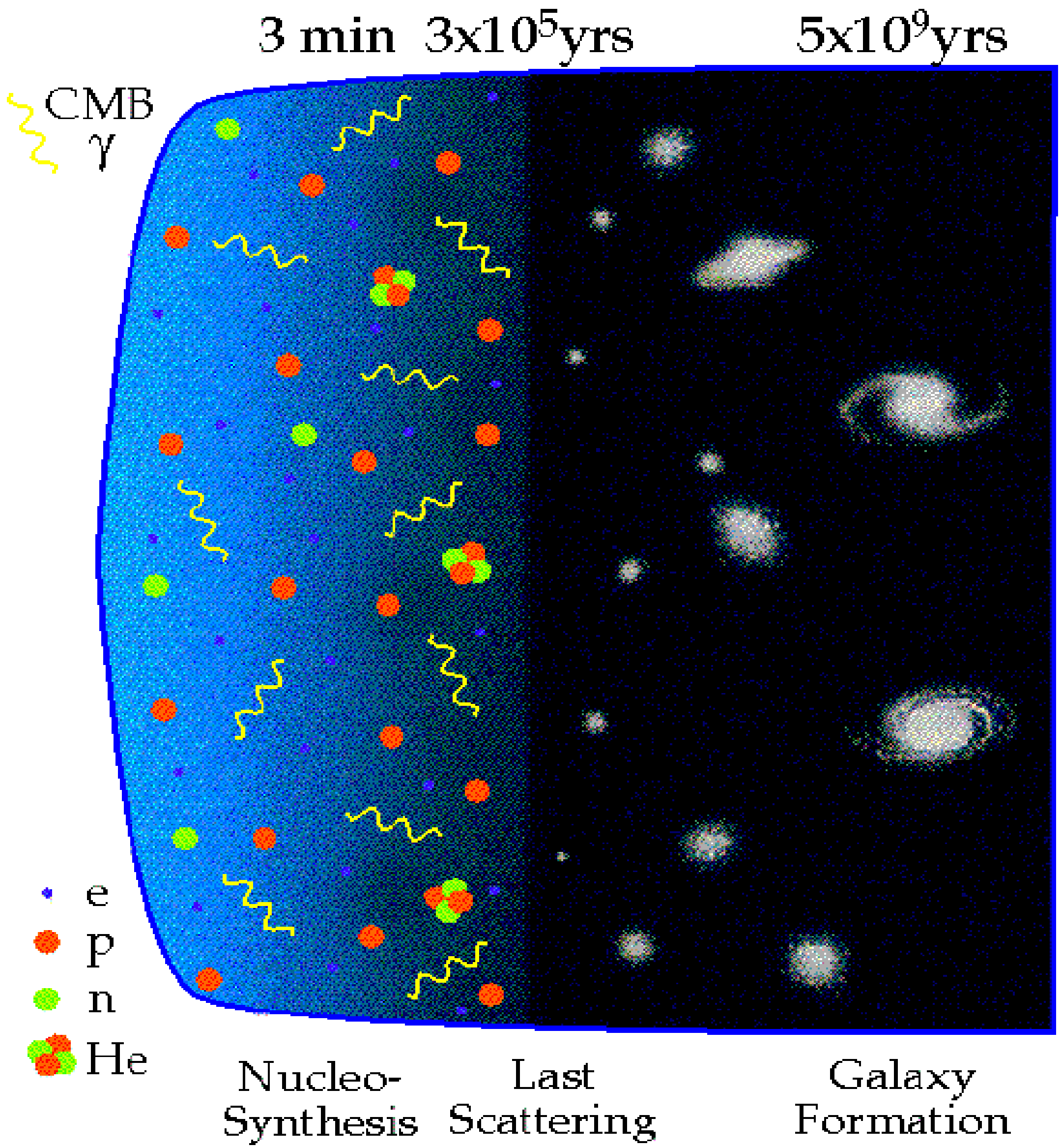
$$\frac{\Delta T}{T}\left(\vec{n}\right) \doteq \int_0^{\infty}\left[g(z)\left(\Psi + \Theta_0 + \vec{n}\cdot\vec{\mathrm{v}}_{\mathrm{b}}\right) + e^{-\tau}H^{-1}\dot{\Psi}\right]dz$$

Gravity Adiabatic Doppler ISW

(Very) Brief History

When T> 3000 K

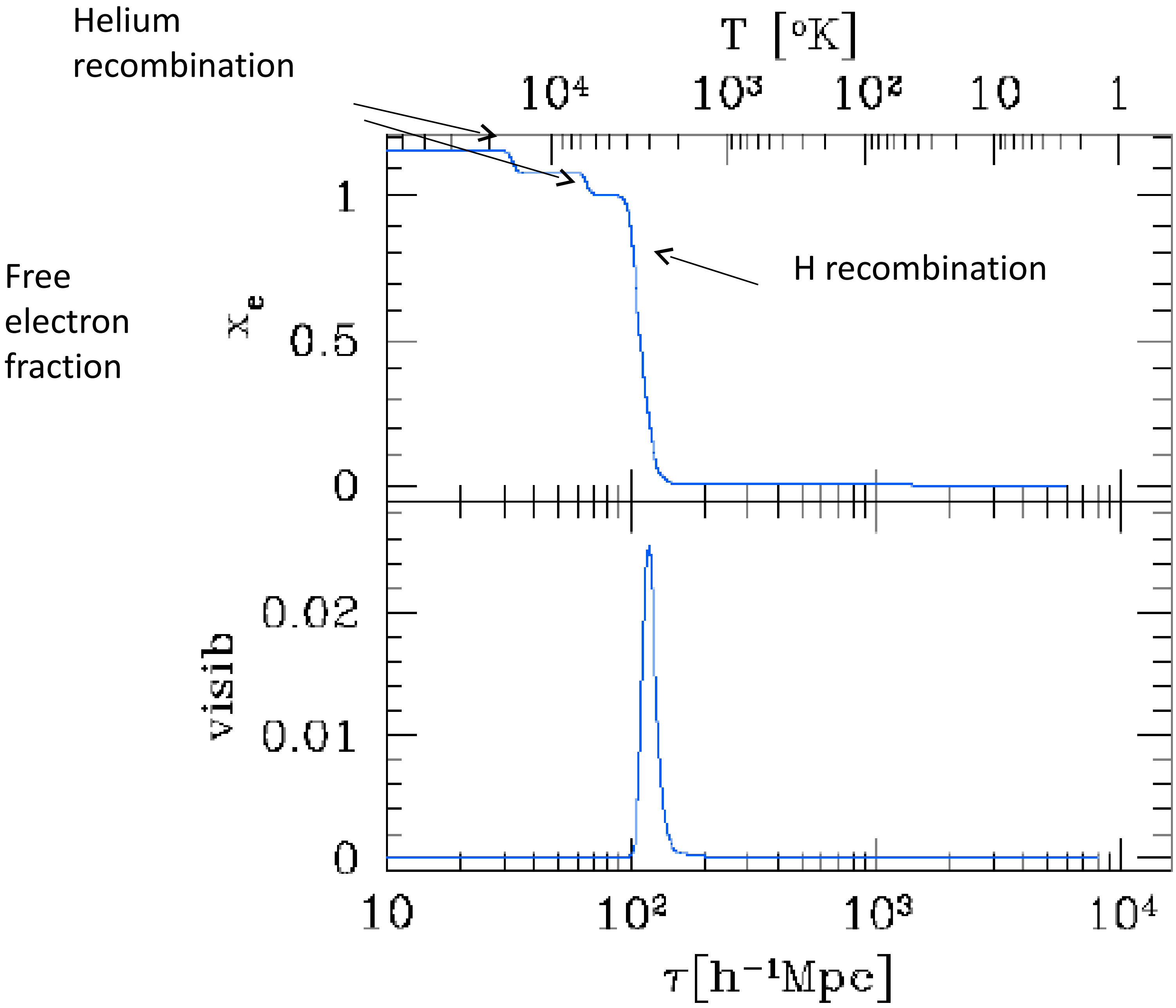
plenty of free electrons.
Photons are «trapped» in the primordial plasma.



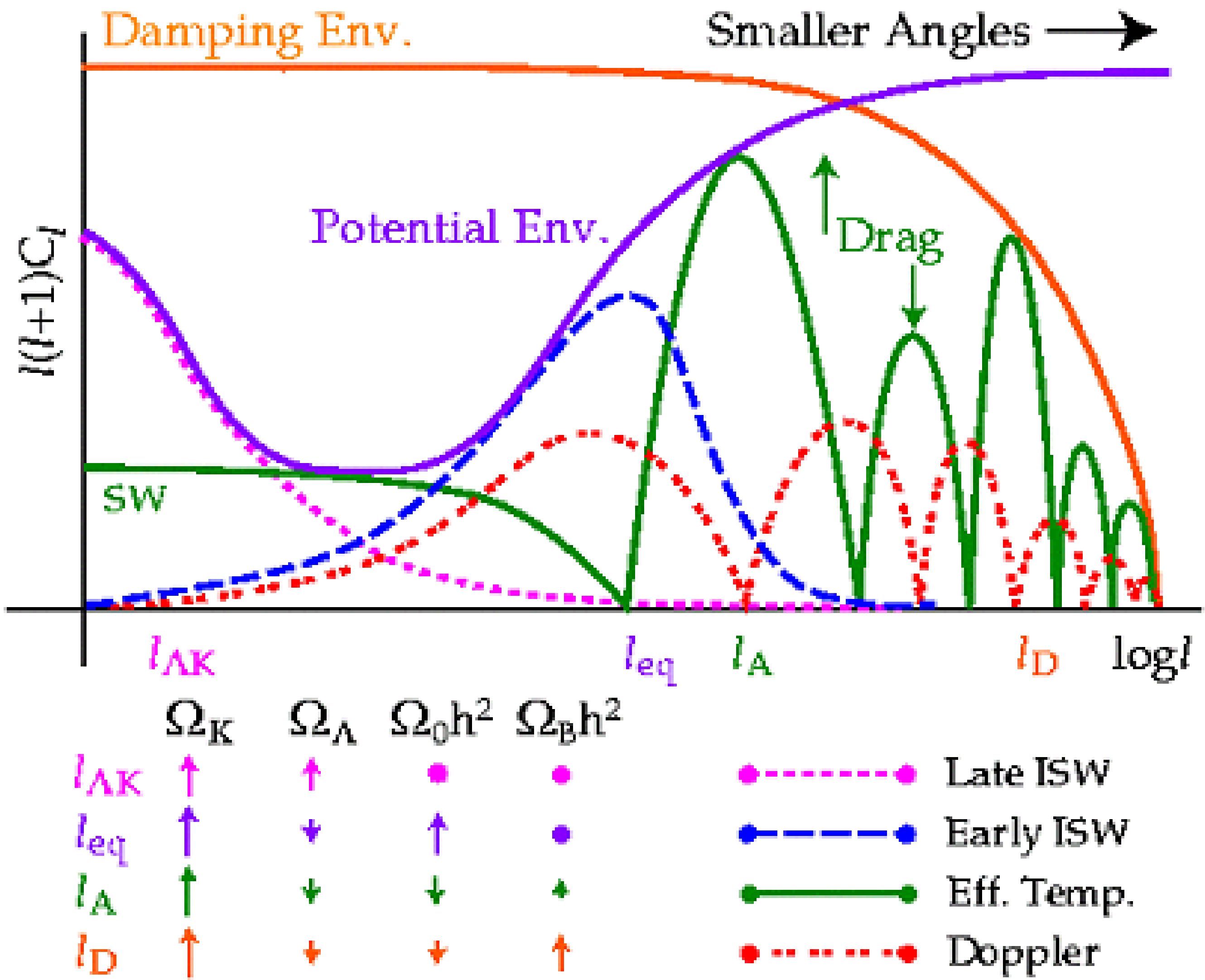
When T< 3000 K

All electrons are captured in neutral Hydrogen.
Photons can now travel freely and… reach us !

Recombination

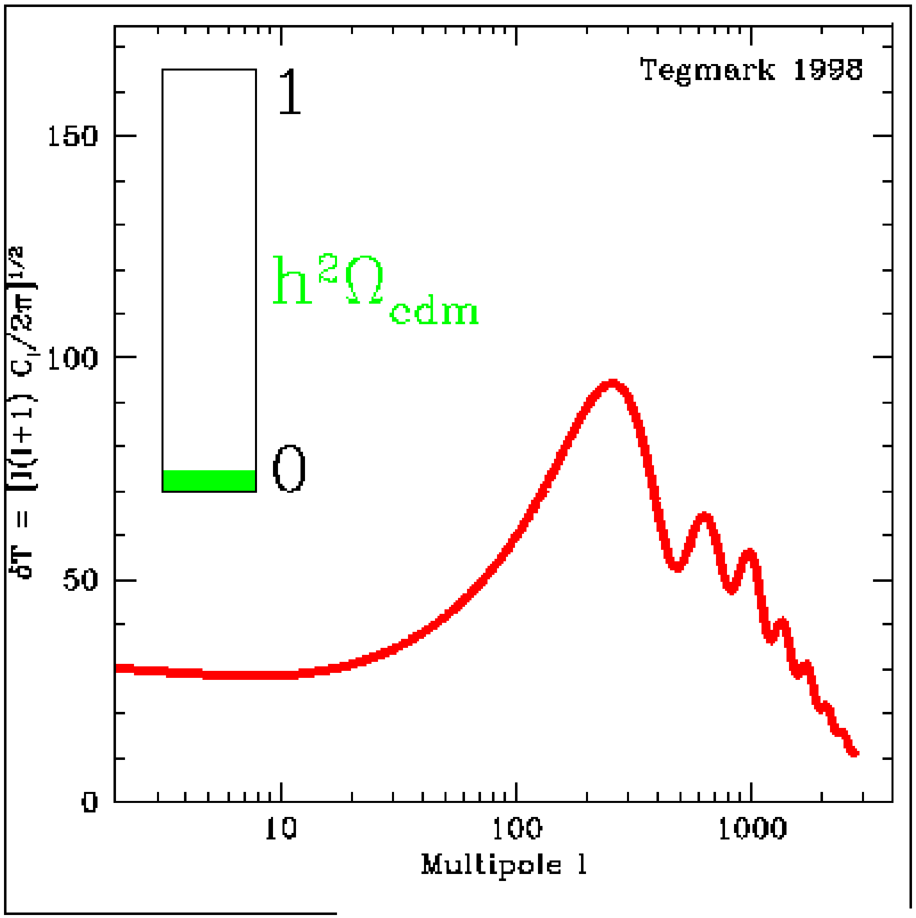


Hu, Sugiyama, Silk, Nature 1997, astro-ph/9604166

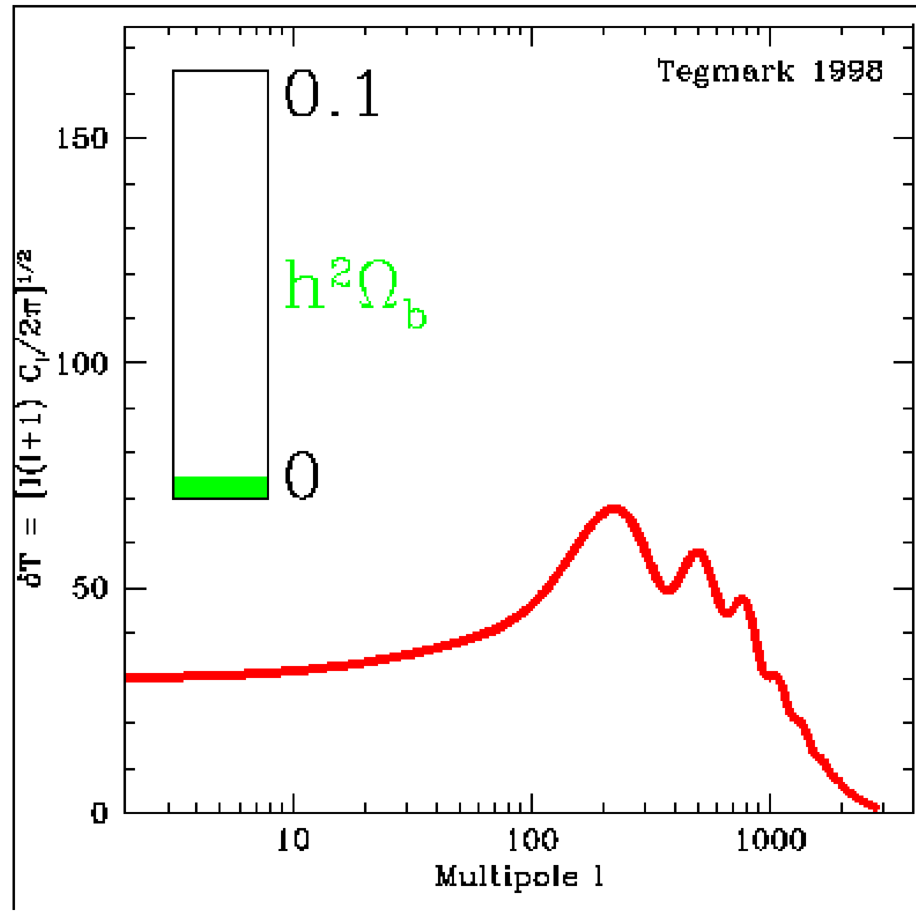


Constraining Cosmological Parameters with CMB

Cold Dark Matter Density

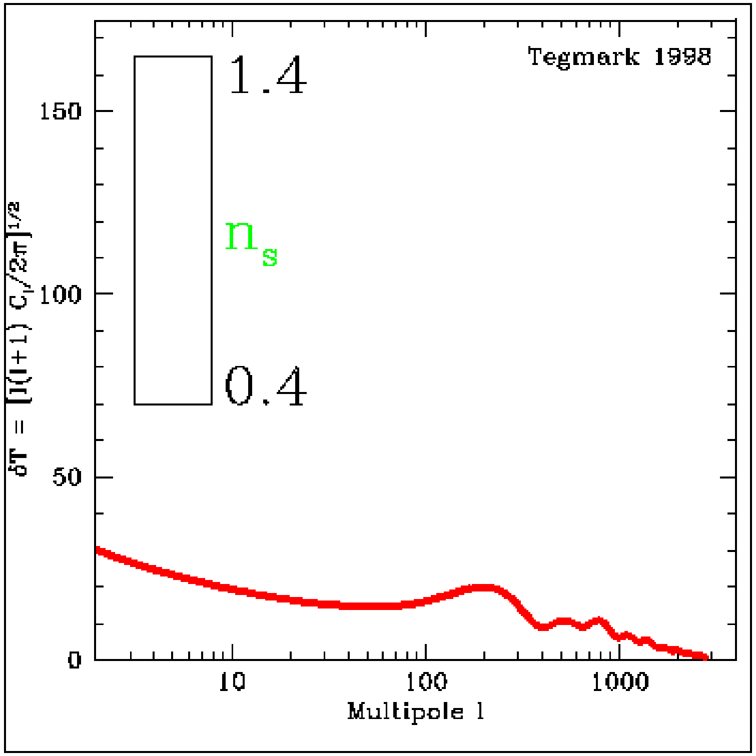


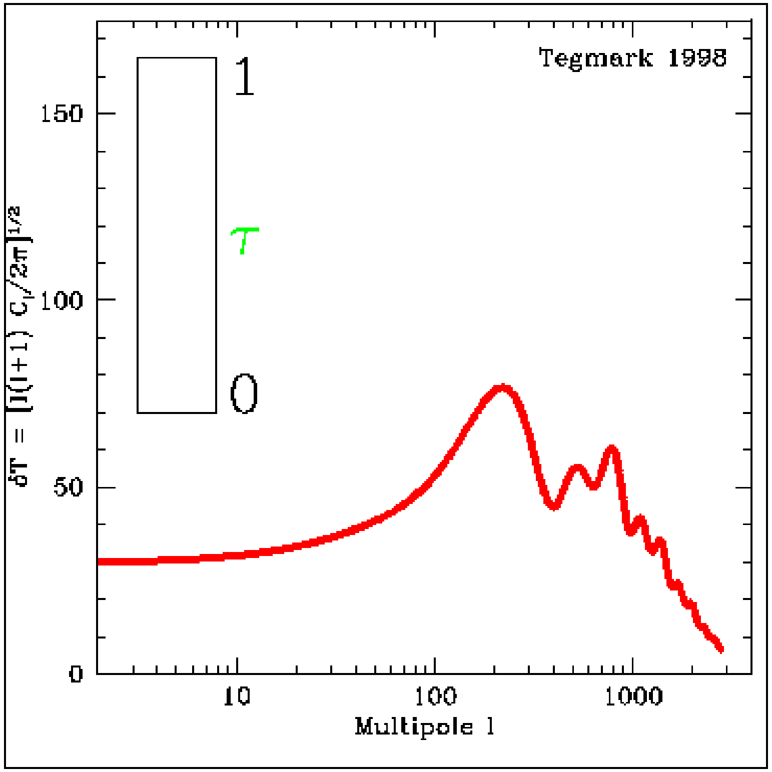
Baryon Density



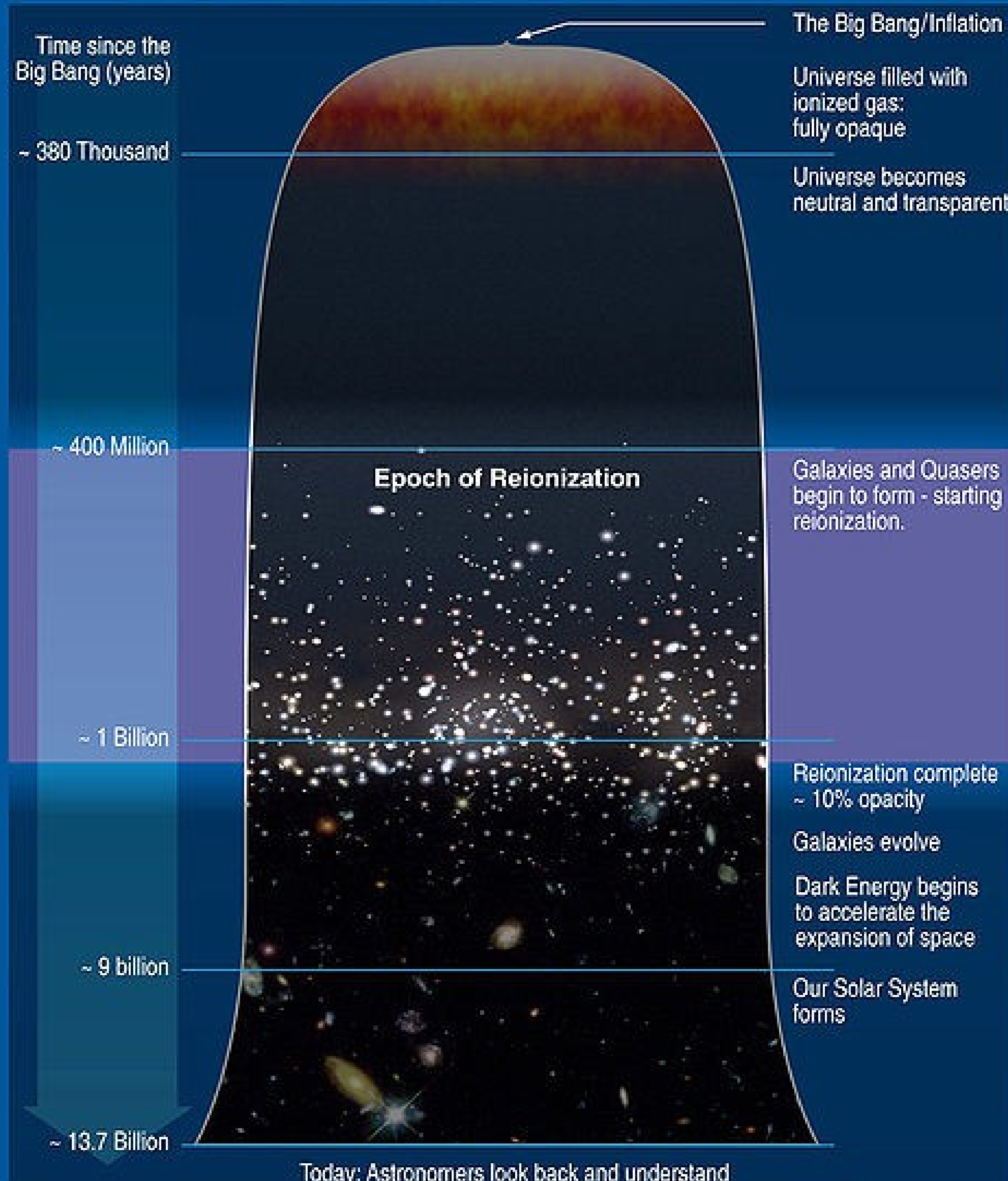
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015

Constraining Cosmological Parameters with CMB



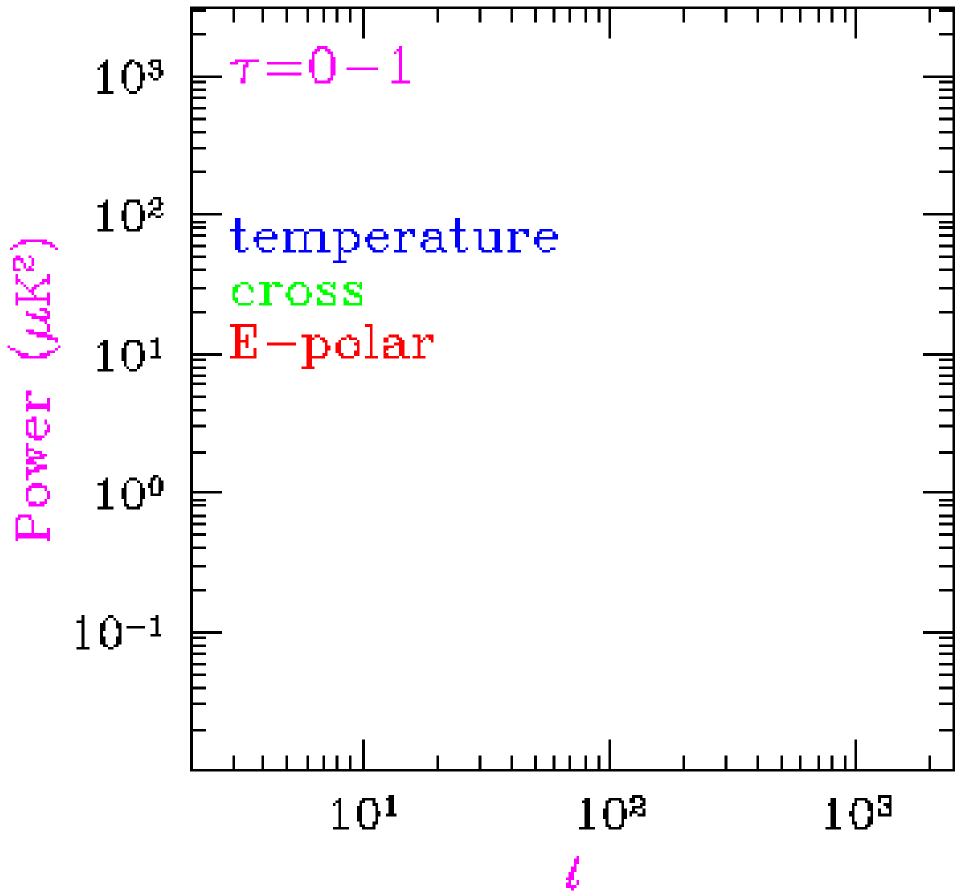


First Stars and Reionization Era



NASA/WMAP Science Team

Measuring large scale CMB polarization breaks this degeneracy.



The standard cosmological model

- Assumes General Relativity, Inflation, Adiabatic and Scalar Perturbations, flat universe.

- Friedmann-Robertson-Walker (or Friedmann-Lemaitre) metric. Hubble Constant (+1)

$$H_0 = 100h\ km/s/Mpc$$

- 3 Energy components: Baryons, Cold Dark Matter, Cosmological Constant (+3). Flat Universe (-1).

$$\omega_b = \Omega_b h^2 \quad \omega_{CDM} = \Omega_{CDM} h^2$$

- Initial conditions for perturbations given by Inflation: Adiabatic, nearly scale invariant initial power spectrum, only scalar perturbations. Two free parameters (+2): Amplitude and Spectral index.

$$P(k) \approx A_S \left(\frac{k}{k_0}\right)^{n_S}$$

Pivot scale is usually fixed to:

$$k_0 = 0.002\ \ hMpc^{-1}$$

- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

Total: 1+3-1+2+1= 6 parameters.

Probing the Neutrino Number with CMB

If we change the neutrino number we change the Hubble rate at recombination. This will change two important scales: the sound horizon and the damping scale:

$$r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s \, da}{a^2 H}.$$

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

If we measure the first peaks in the angular spectrum we fix the angular scale of the sound horizon given by:

$$\theta_s = \frac{r_s}{d_a(z_{dec})}$$

We can therefore write the angular damping scale as:

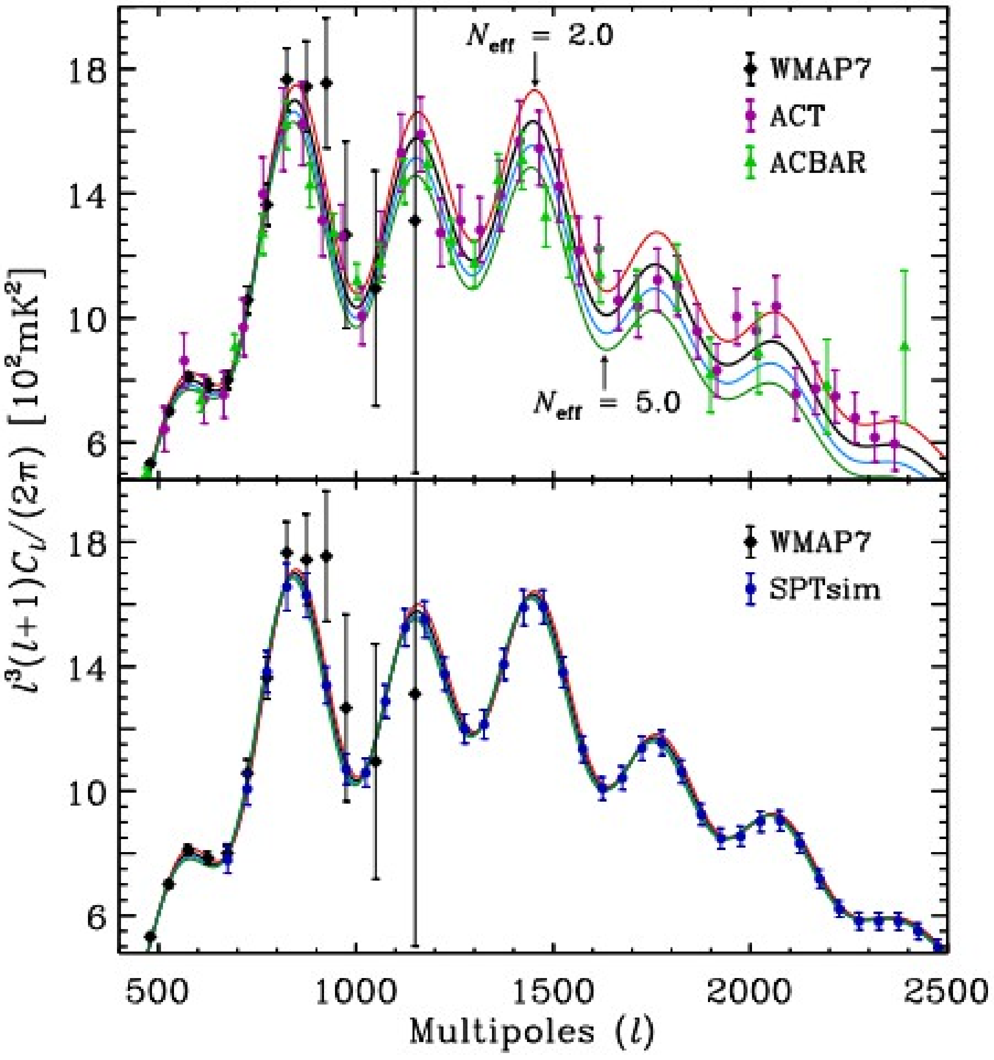
$$\theta_d = \frac{r_d}{d_a(z_{dec})} = \frac{r_d}{r_s} \theta_d \sim \sqrt{H}$$

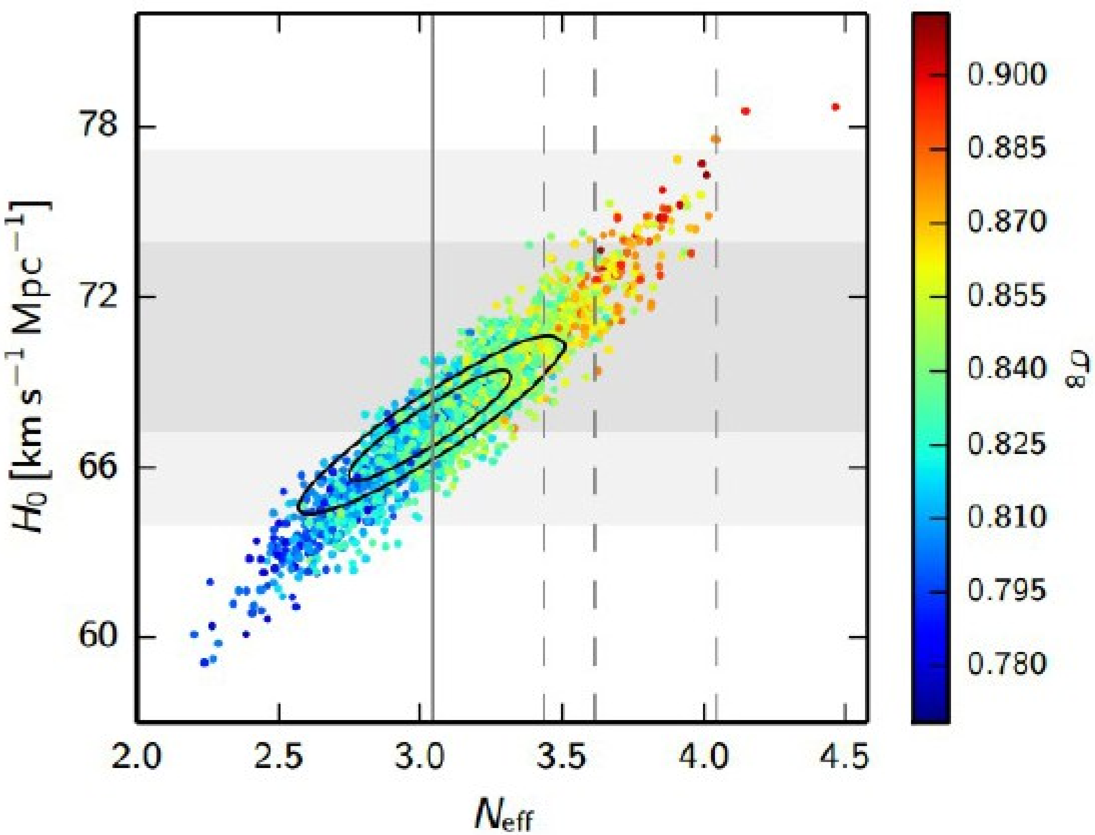
Therefore increasing the neutrino number increases the damping scale !

Probing the Neutrino Number with CMB

Larger Neutrino Number

Larger Damping of CMB anisotropies





$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;$$

$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$

$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP}\,;$$

$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}\,.$$

Probing the Neutrino Number with CMB

Parameter uncertainty	Planck	Planck+ACTPol		CMBPol	
$\sigma(\Omega_b h^2)$	0.00020	0.00013	(1.5)	0.000048	(4.1)
$\sigma(\Omega_c h^2)$	0.0025	0.0015	(1.7)	0.00058	(4.3)
$\sigma(\theta_s)$	0.00044	0.00024	(1.8)	0.000075	(5.9)
$\sigma(\tau)$	0.0043	0.0035	(1.2)	0.0023	(1.9)
$\sigma(n_s)$	0.0073	0.0049	(1.5)	0.0026	(2.8)
$\sigma(log[10^{10}A_s])$	0.019	0.013	(1.5)	0.0078	(2.4)
$\sigma(N_{eff})$	0.18	0.11	(1.6)	0.044	(4.1)

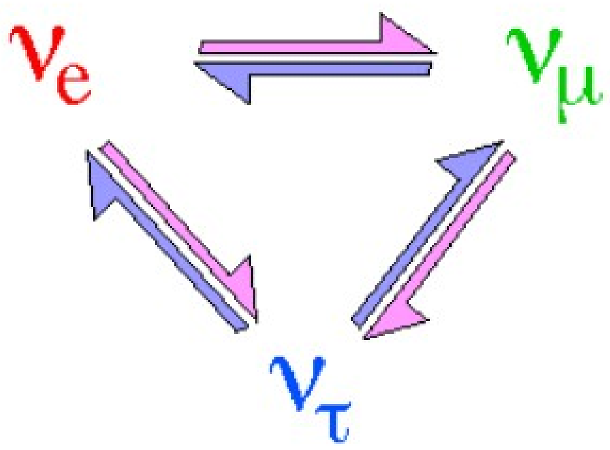
TABLE IV. 68% c.l. errors on cosmological parameters in the case of extra background of relativistic particles N_{eff}. The numbers in brackets show the improvement factor σ_{Planck}/σ respect to the Planck experiment.

Galli et al, Phys.Rev.D82:123504,2010

Neutrino Masses

We know that flavour neutrino oscillations exists

From present evidences of oscillations from experiments measuring atmospheric, solar, reactor and accelerator neutrinos

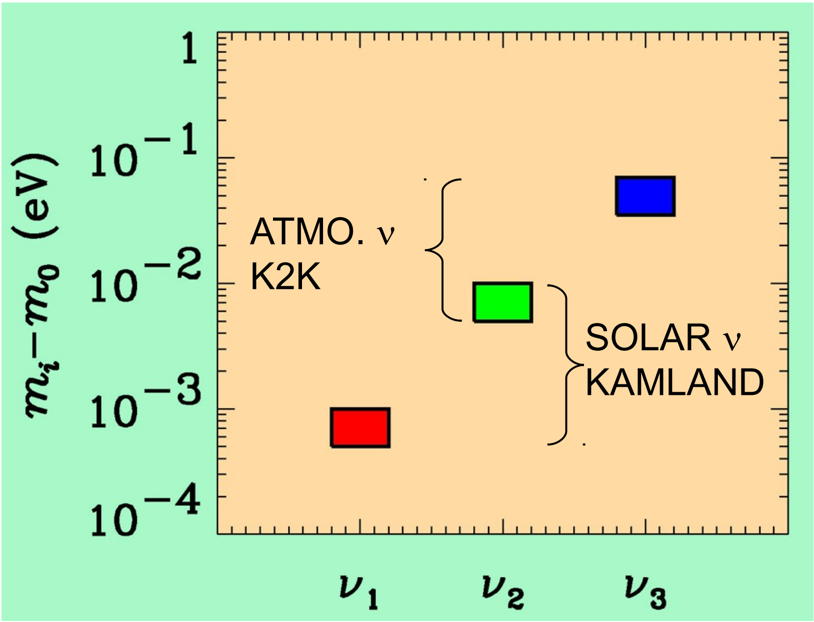


$$\boxed{(e,\mu,\tau) \leftrightarrow (\nu_1,\nu_2,\nu_3)}$$

$$\boxed{\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL}, \quad (\alpha = e,\mu,\tau)}$$

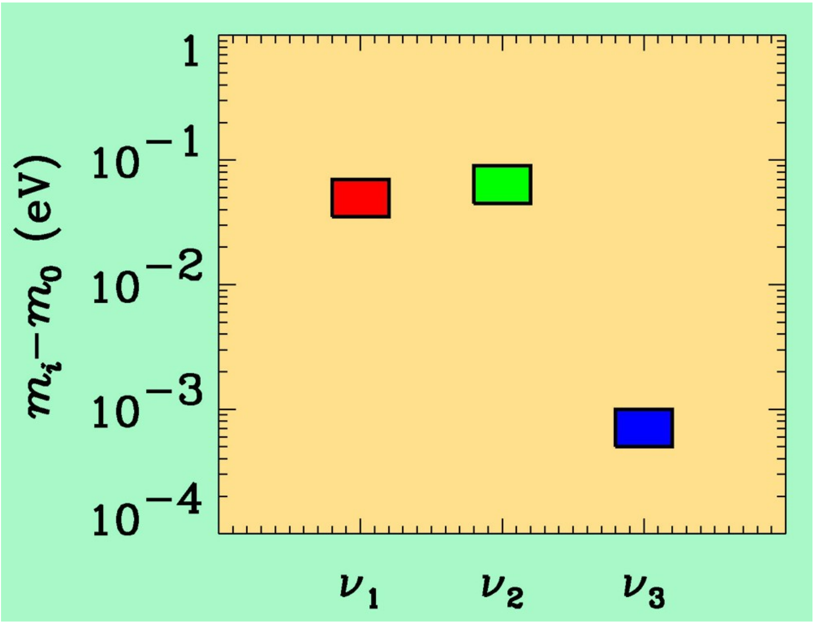
$$\begin{array}{cc} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} & \left[\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array}\right] \end{array}$$
$$\times\, \mathrm{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy

$$m_3 > m_2 > m_1$$



Inverted hierarchy

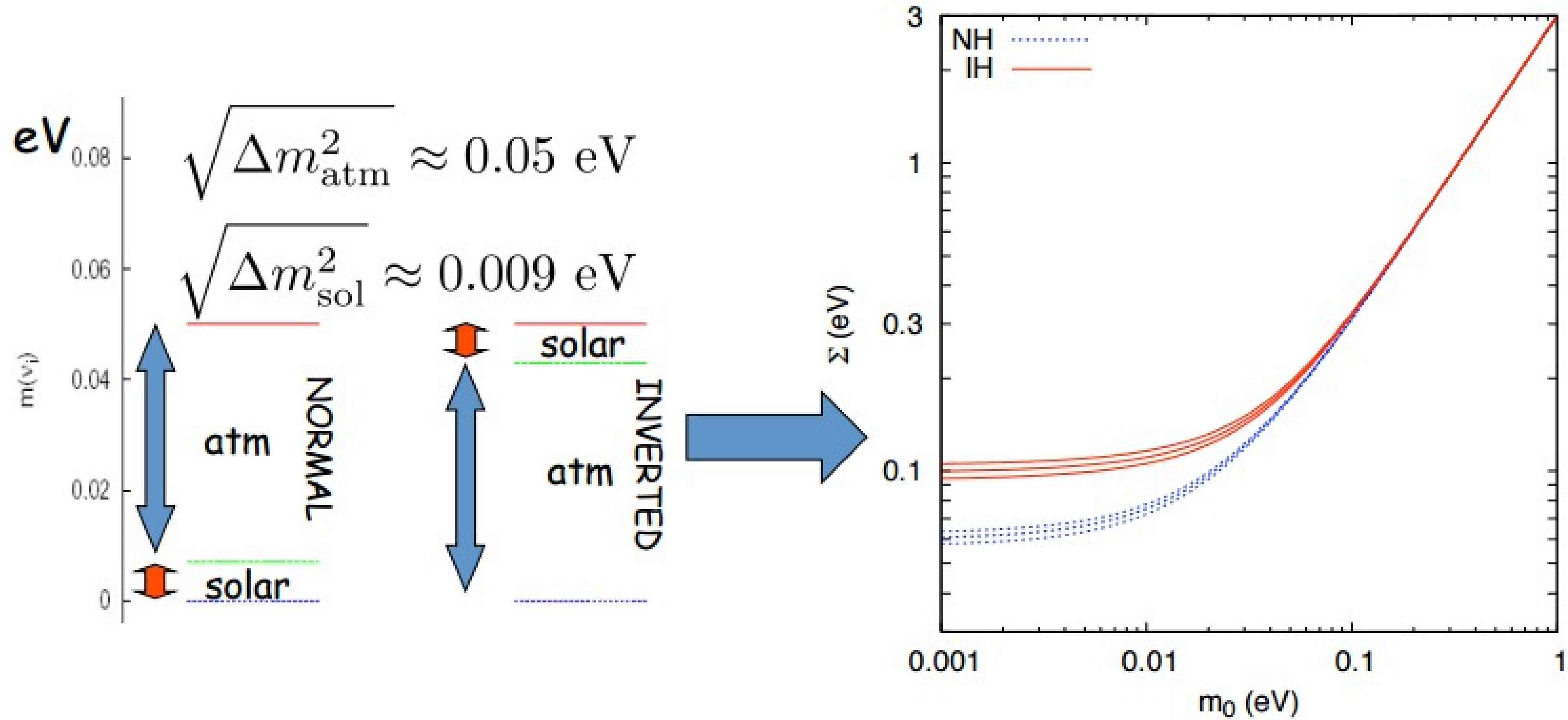
$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

$$\boxed{m_1, m_2, m_3 >> \delta m_{\text{atmospheric}}}$$

Neutrino Absolute Mass Scale

Oscillation data do not fix the absolute mass scale.



$$0.06(0.1)\,\mathrm{eV} \lesssim \sum_i m_i \lesssim 6\,\mathrm{eV}$$

A large range of values (about 2 orders of magnitude) is still allowed by current experiments !

Energy density from neutrinos (after decoupling)

If they are relativistic:

$$\rho_\nu = \frac{7\pi^2}{120} N_{eff} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

$$\Omega_\nu h^2 = \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{eff} \Omega_\gamma h^2$$

$$\Omega_\nu h^2 = 0.58 \times 10^{-5} N_{eff}$$

$(T_\gamma = 2.726\,K)$

If they are not relativistic:

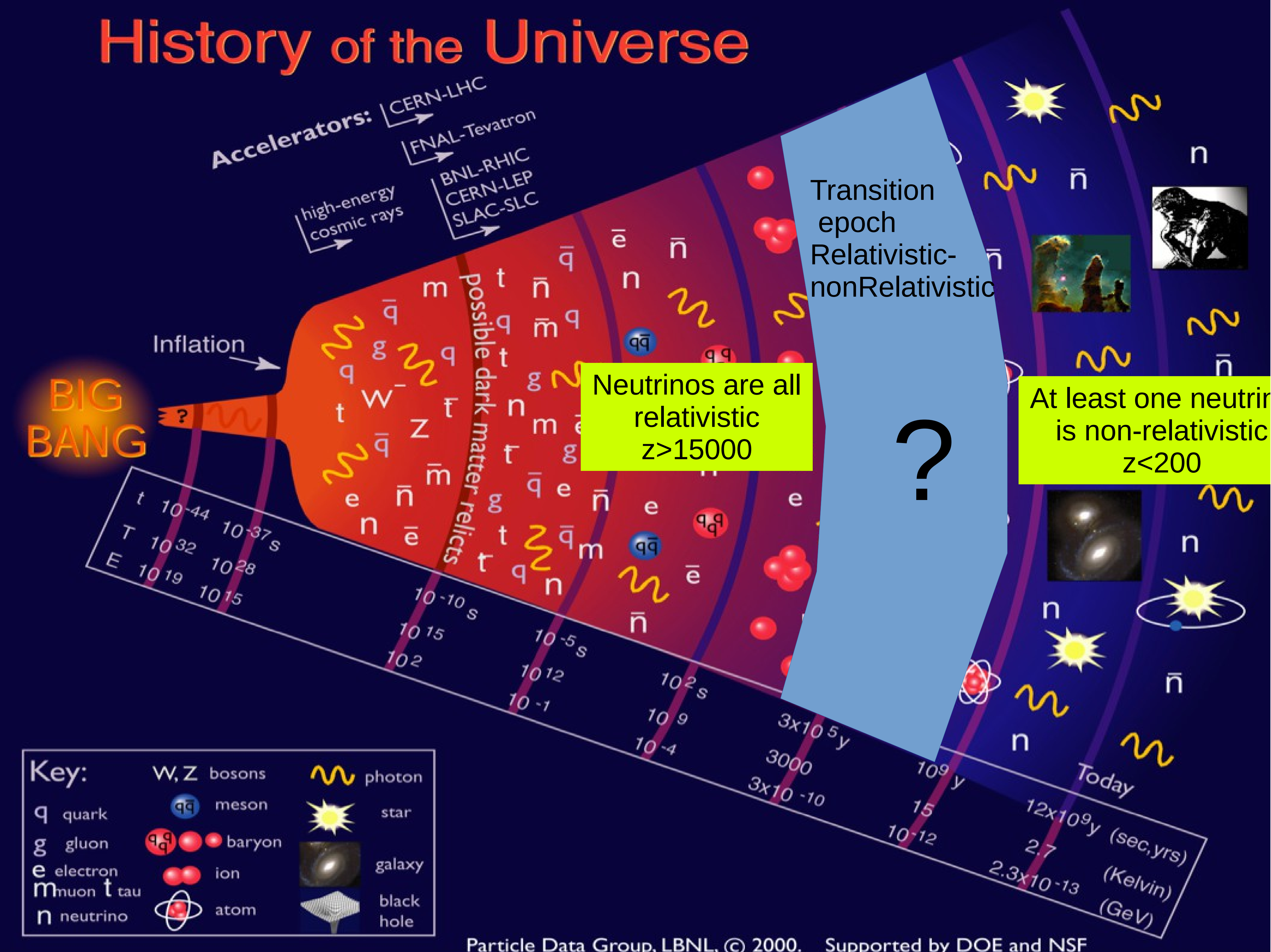
$$\rho_\nu = \sum n_i m_i$$

$$n_i = \frac{6\zeta(3)}{11\pi^2} T_\gamma^3$$

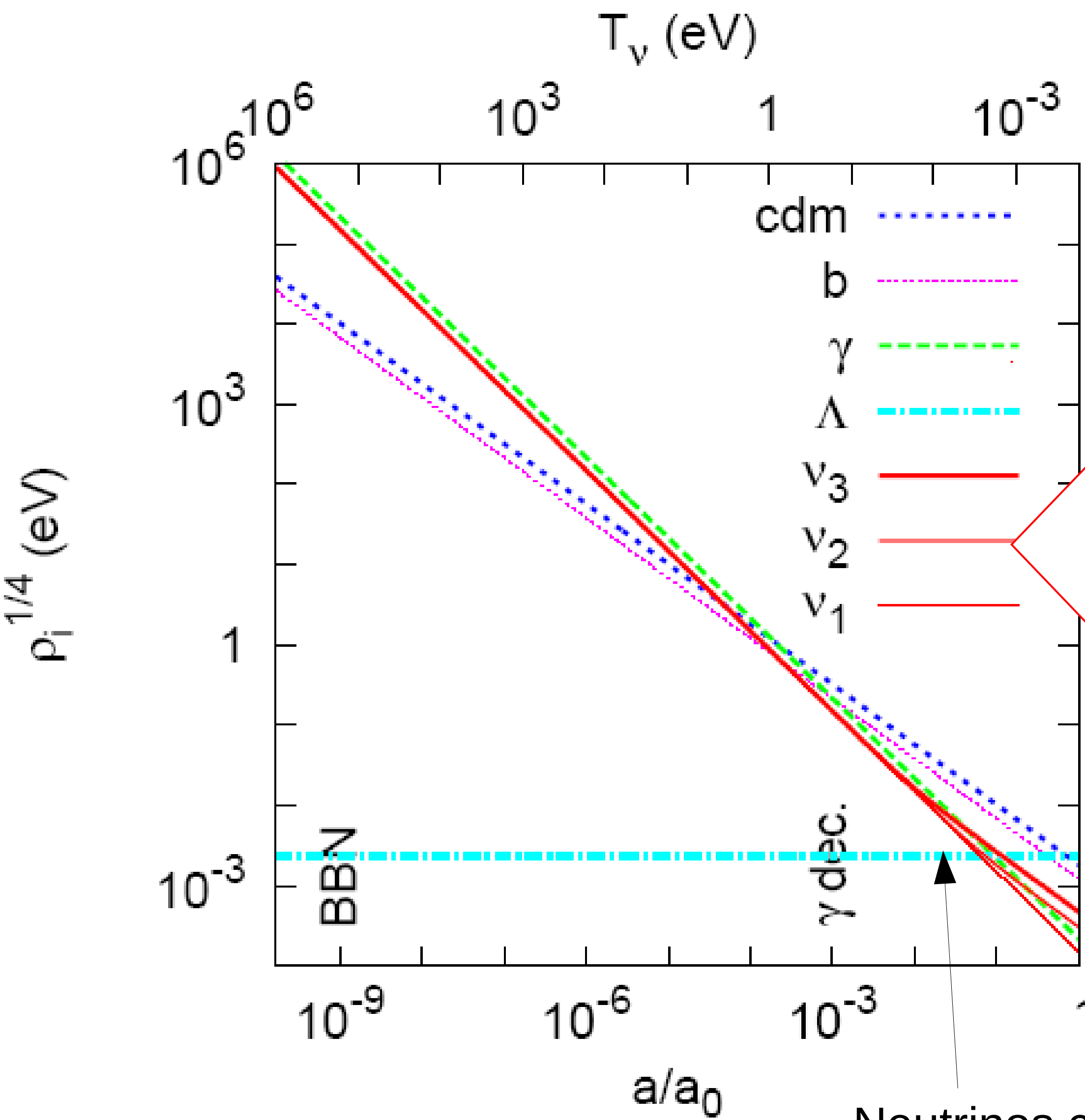
$$\longrightarrow$$

$$\Omega_\nu h^2 = \frac{\sum m_i}{93.2\,eV}$$

$(T_\gamma = 2.726\,K)$


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
Transition epoch
Relativistic-nonRelativistic
?
Neutrinos are all relativistic
z>15000
At least one neutrin
is non-relativistic
z<200
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

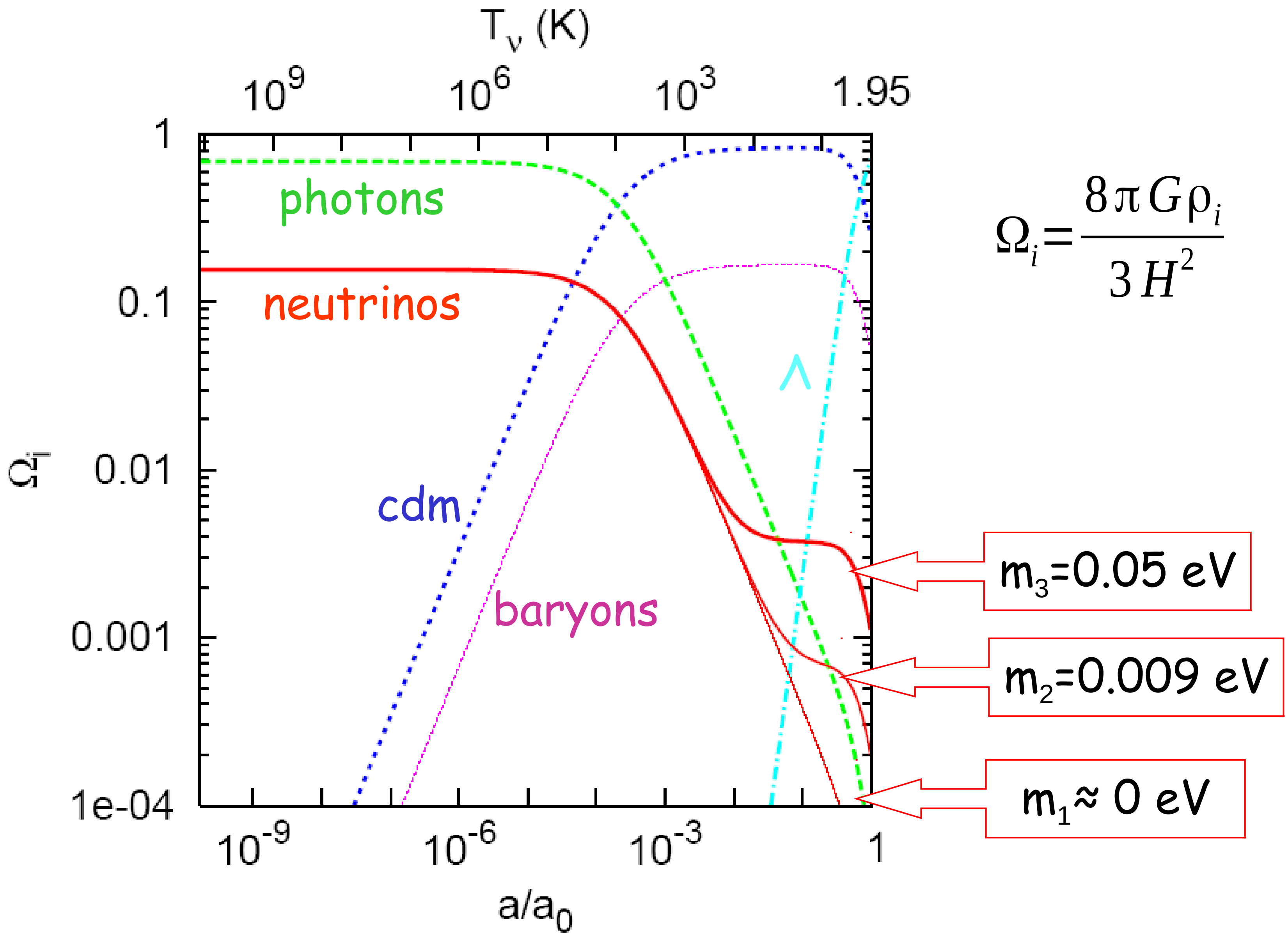
Evolution of the background densities: 1 MeV → now



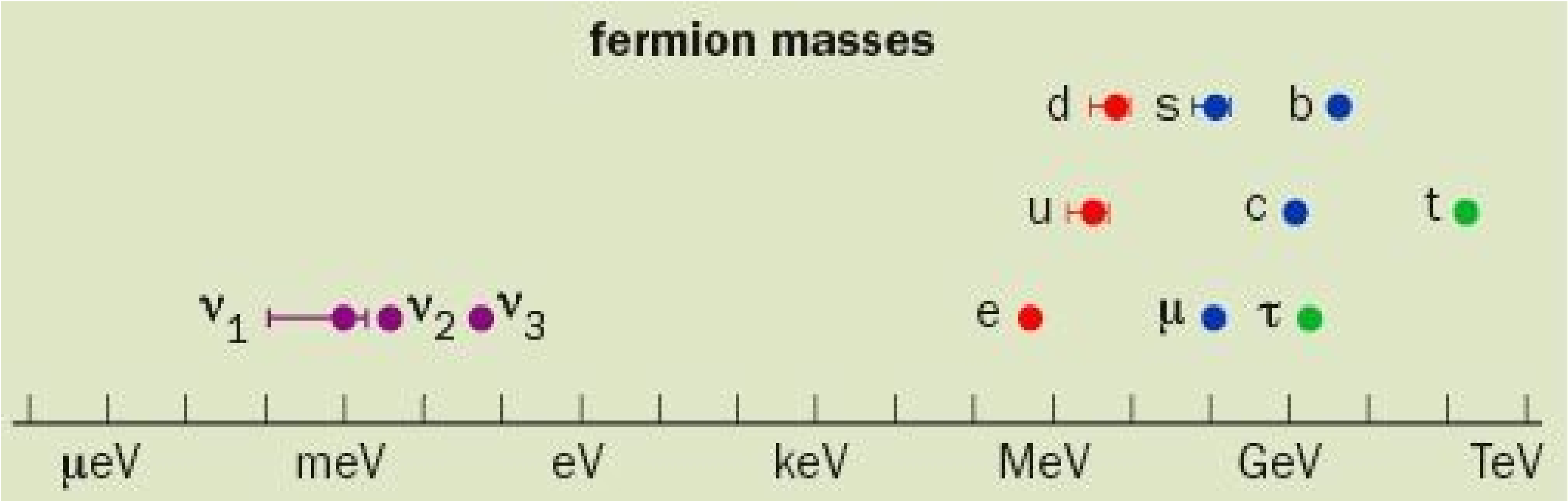
3 neutrino species with different masses

Neutrinos change from relativistic to non-relativistic

Evolution of the background densities: 1 MeV → now



$$\Omega_i = \frac{8\pi G \rho_i}{3H^2}$$

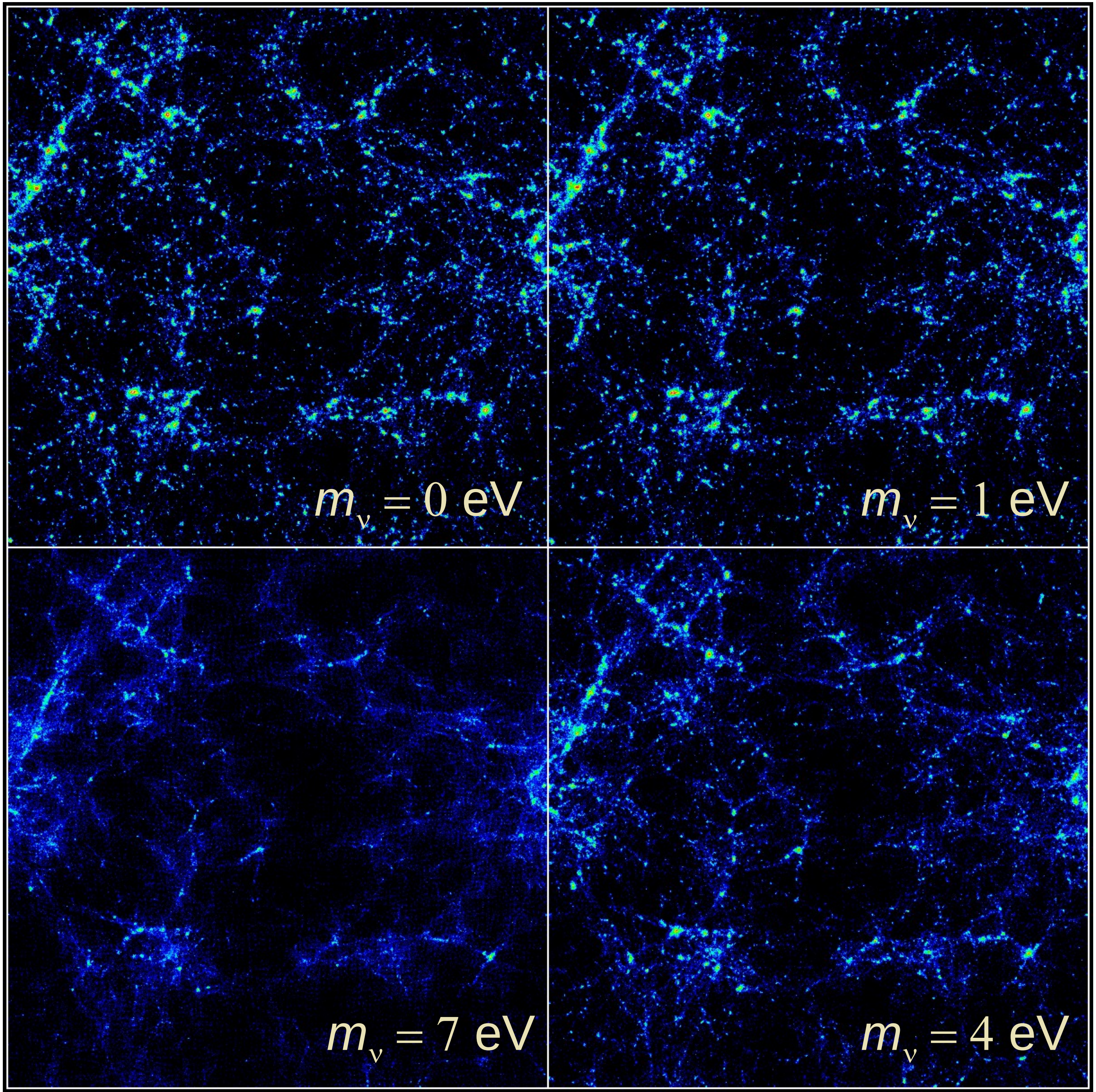

fermion masses
d
s
b
u
c
t
ν_1
ν_2
ν_3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

Massive Neutrinos affect large scale structure !

- We can relate the neutrino abundance in the universe to the total mass:

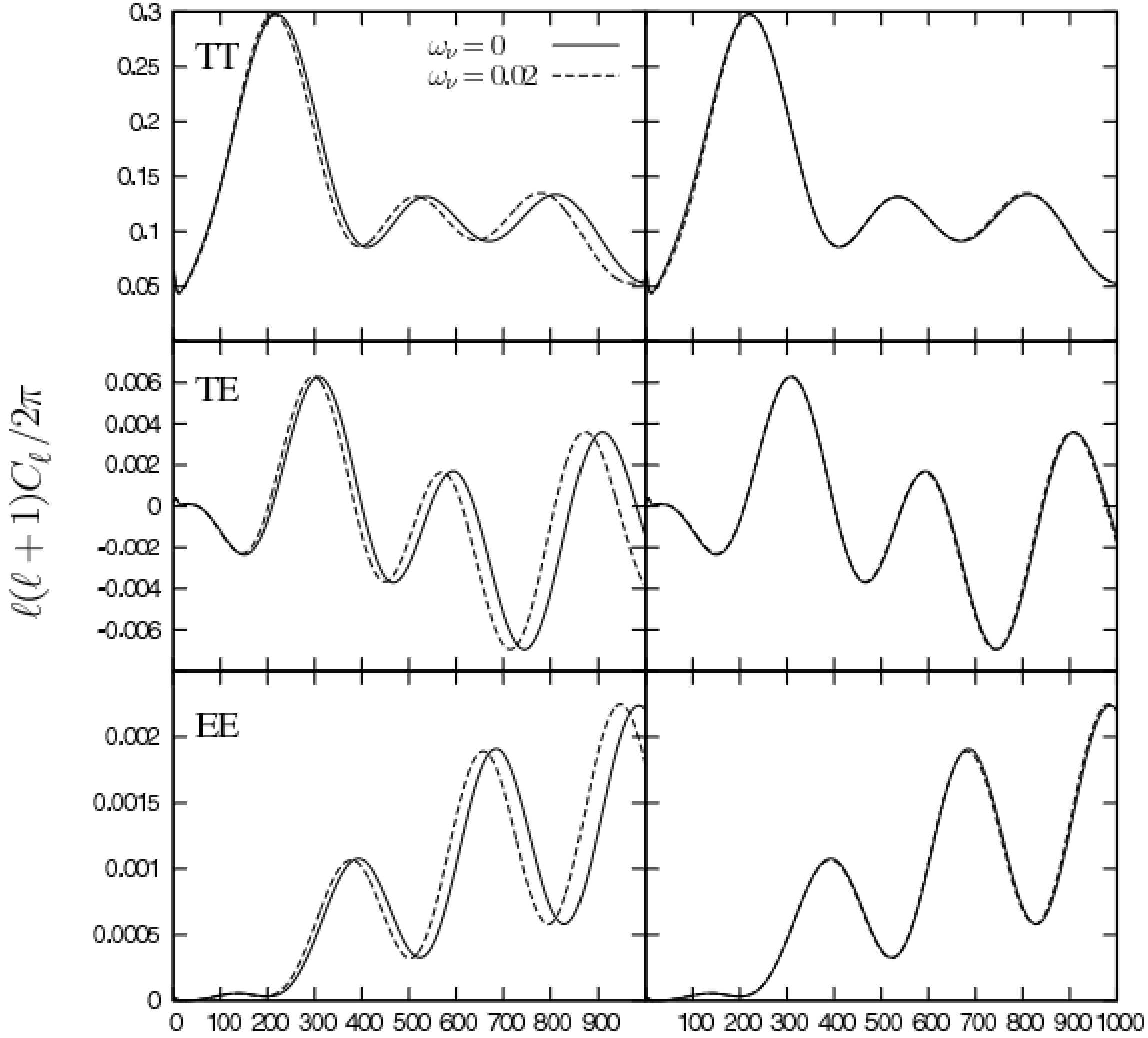
$$\Omega_{v} h^{2} = \frac{\Sigma m_{v}}{93.6\, eV}$$

- Less clustering in universe with massive neutrinos.



Ma '96

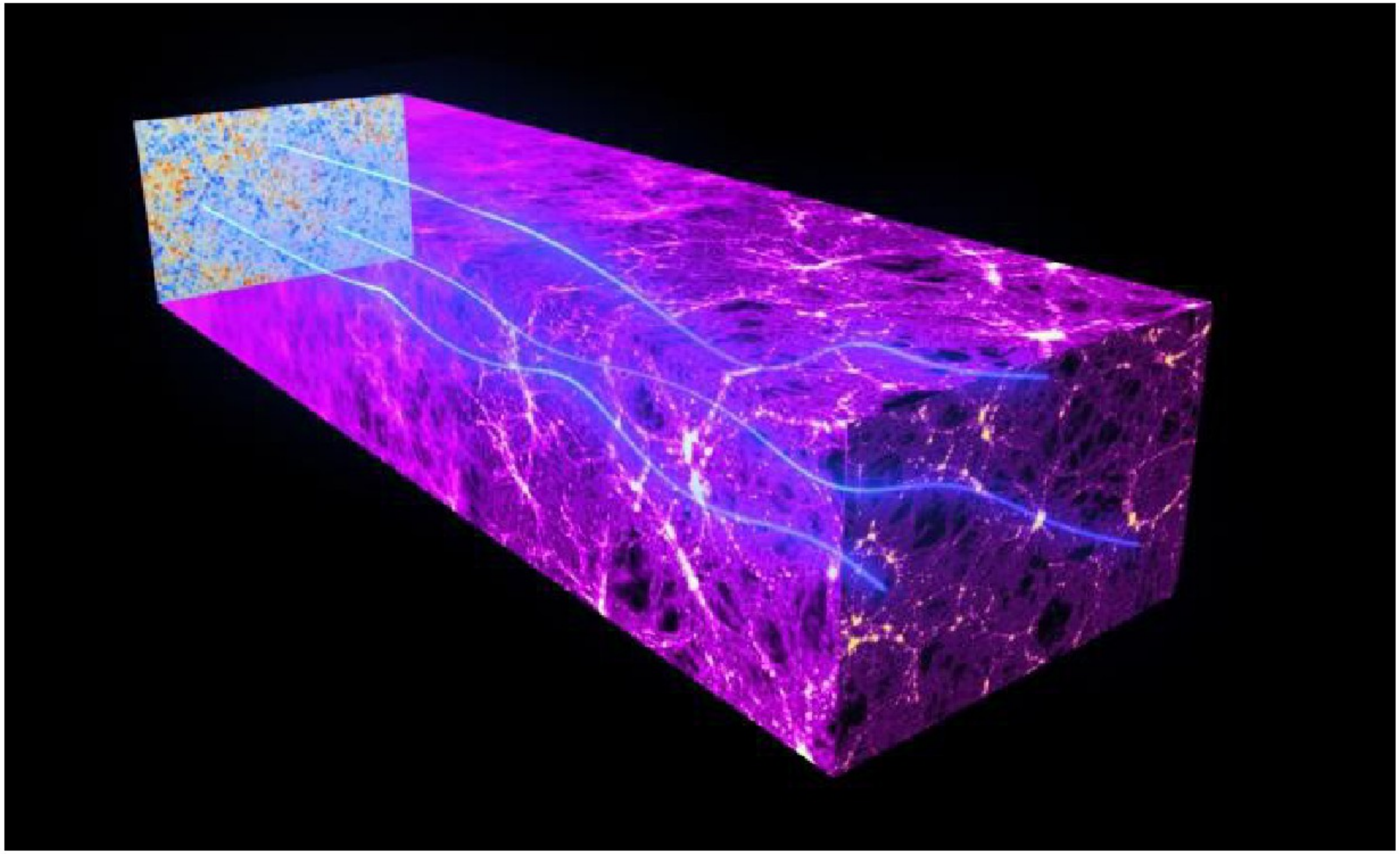
CMB bounds on neutrino masses



If neutrinos have a mass larger than m ~ 0.3 eV they are non-relativistic at recombination.
At this point, increasing their mass increases the dark matter component at recombination.
The change in the gravitational potential at early times with massive neutrinos leads to a slight changes in Cl below the first acoustic peak (see Ma & Bertshchinger 1998, Fukugita et al, 2006).
In principle, CMB should constrain neutrino masses to m < 2 eV but constraints are actually much better because of lensing.

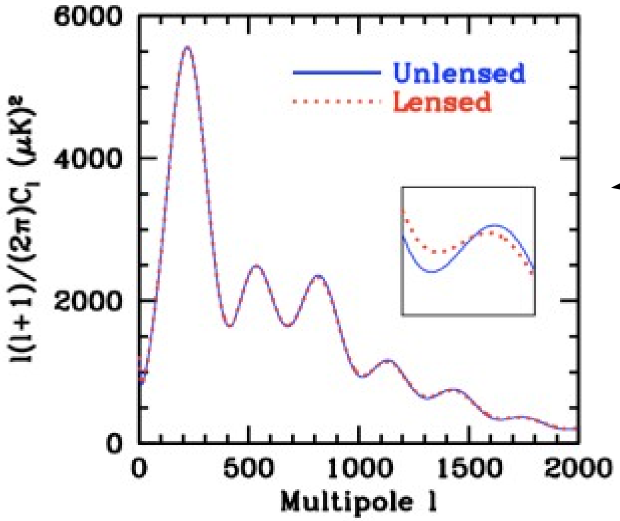
Gravitational Lensing

The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB

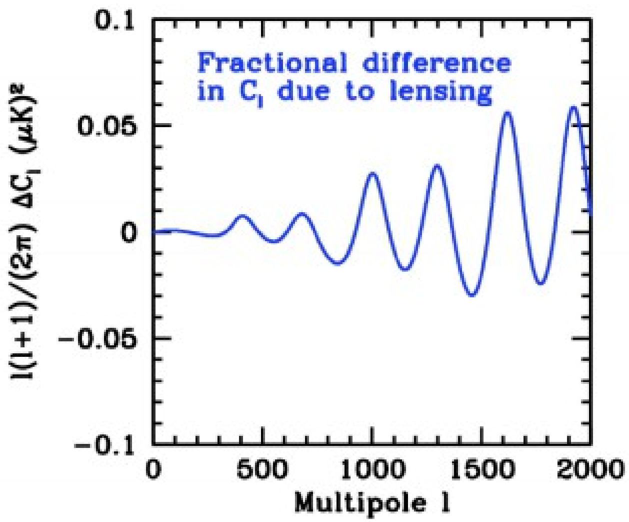


CMB anisotropy do not probe just recombination epoch !
CMB lensing probes structure formation around z~2 (broadly)

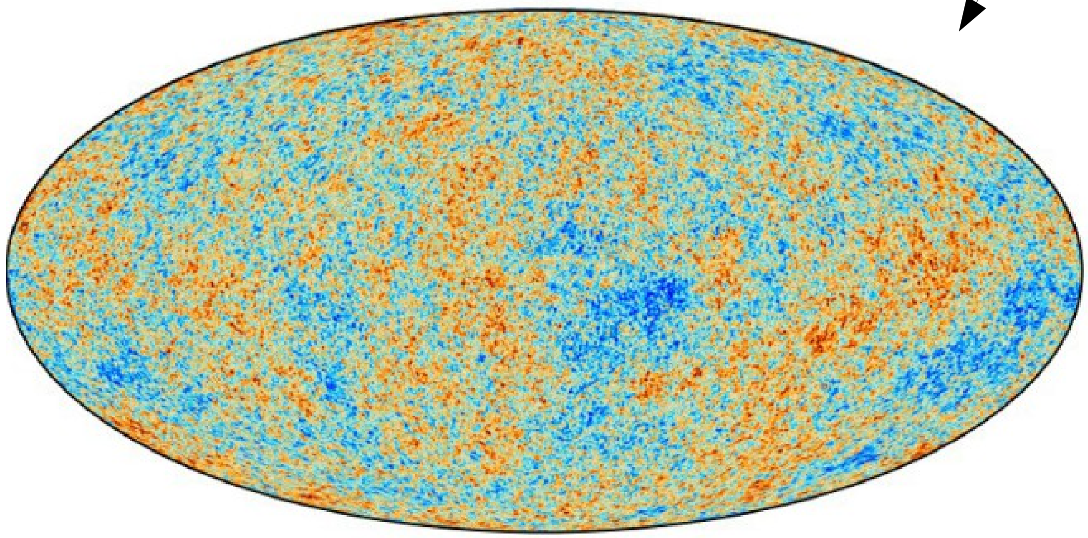
Extracting Lensing Signal from the CMB



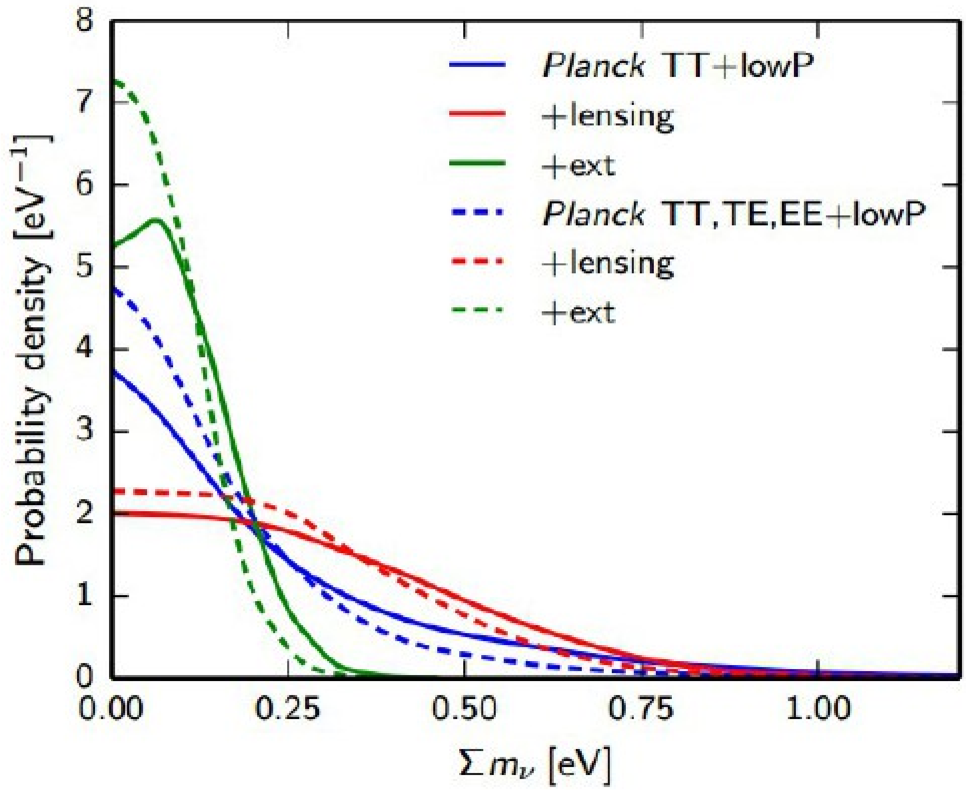
Extraction at Angular Spectrum Level
Effects on CMB angular spectrum.
More massive neutrinos → less lensing.



Extraction at map level.
Lensing introduce a correlation between Cl's.
This creates a non-zero trispectrum (4-point c.f.).



3 standard Massive Neutrinos



$$\left.\begin{array}{r}\sum m_\nu < 0.23\ \text{eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$

Constraining Neutrino Masses with CMB only (forecasts)

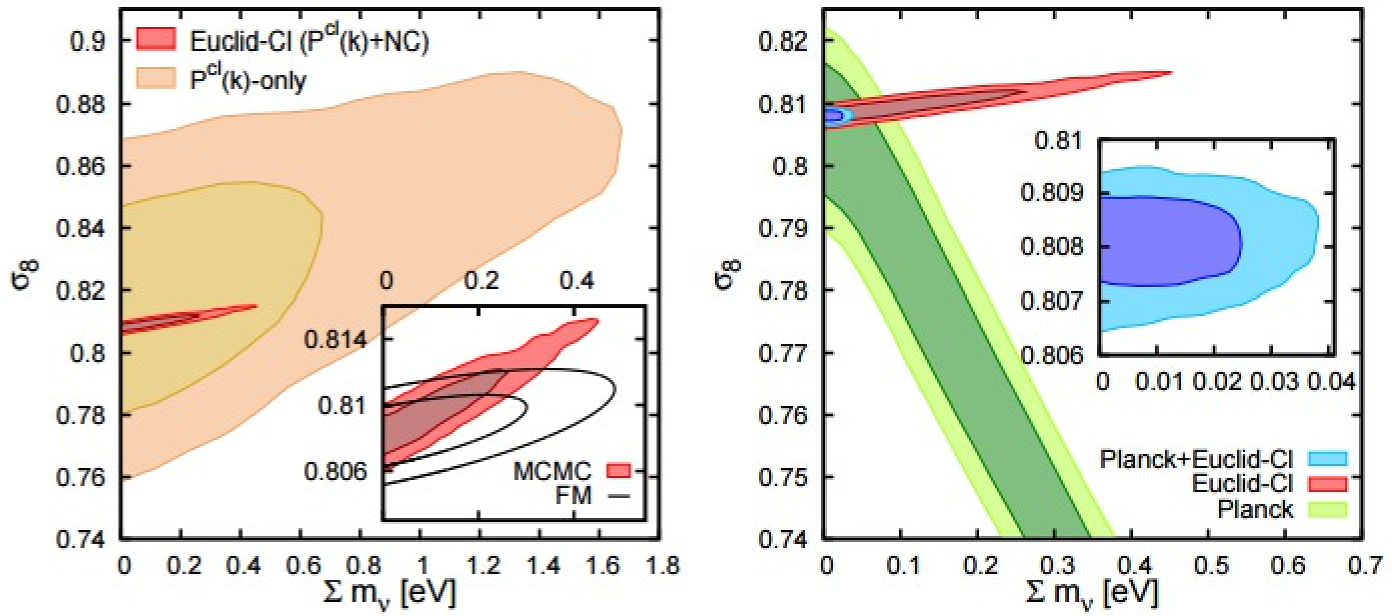
Parameter uncertainty	Planck	Planck+ACTPol		CMBPol	
$\sigma(\Omega_b h^2)$	0.00014	0.000081	(1.7)	0.000033	(4.2)
$\sigma(\Omega_c h^2)$	0.0017	0.0010	(1.7)	0.00071	(2.4)
$\sigma(\theta_S)$	0.00028	0.00016	(1.7)	0.000062	(4.5)
$\sigma(\tau)$	0.0042	0.0034	(1.2)	0.0023	(1.8)
$\sigma(n_S)$	0.0034	0.0022	(1.5)	0.0016	(2.1)
$\sigma(\log[10^{10} A_S])$	0.013	0.0094	(1.4)	0.0065	(2.0)
$\sigma(\sum m_\nu)$	< 0.16	< 0.08	(2.0)	< 0.05	(3.2)

(eV)

TABLE III. 68% c.l. errors on cosmological parameters in the case of massive neutrinos. The numbers in brackets show the improvement factor σ_{Planck}/σ respect to the Planck experiment.

Galli et al, Phys.Rev.D82:123504,2010

Thanks to lensing we can constrain neutrino masses using just CMB data !



Model		ΛCDM+m_ν			
Data		Planck	P^{cl}−only	Euclid-Cl	Euclid-Cl+Planck
$\sum m_\nu$ [eV]	68% CL	< 0.41	< 0.41	< 0.17	< 0.017
	95% CL	< 0.74	< 1.20	< 0.35	< 0.031

Costanzi et al, JCAP06(2013)020

Backup Slides

Caveats

- Current measurements of the neutron lifetime based on two different methods are disagreement by about ~8 s. Systematic errors for Helium production could be underestimated (see e.g. Salvati et al., arXiv:1507.07243).

$$\tau_n^{\mathrm{bottle}} = (879.6 \pm 0.8)\,[\mathrm{s}] \qquad \tau_n^{\mathrm{beam}} = (888.0 \pm 2.1)\,[\mathrm{s}]$$

- d(p,y)3He rate that enters in the calculation of D is not well measured (with most recent measurements dating 1998) and is about 10% smaller than what ab initio computations suggest. Again, systematics could be underestimated (see Di Valentino et al., Phys. Rev. D 90, 023543 (2014)).

Reaction	Rate Symbol	$\sigma_{^2\mathrm{H/H}} \cdot 10^5$
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062
$d(d,n)^3\mathrm{He}$	R_3	± 0.020
$d(d,p)^3\mathrm{H}$	R_4	± 0.013

2 pages Explanation

A classic result is that if all the matter contributing to the Cosmic density is able to cluster, the fluctuations grow as the Cosmic scale factor:

$$\delta \approx a$$

If only a fraction Ω_* can cluster the the equation is generalized to

$$\delta \approx a^p \qquad p \approx \Omega_*^{3/5}$$

In the radiation dominated era p=0 and so we don't have clustering.
In the recent Λ-dominated epoch again, p=0. Fluctuations grow only in the matter dominated epoch with a net growth of

$$\left(\frac{a_{\Lambda D}}{a_{MD}}\right)^p \approx 4700^p$$

Massive non relativistic neutrinos are unable to cluster on small scales because of their high velocities. Between matter domination and dark energy domination they constitute a roughly constant fraction of the matter density:

$$f_\nu = 1 - \Omega_\nu$$

Since the neutrino number density is determined by standard model neutrino Freezeout, the fraction is a function of the sum of the 3 neutrino masses:

$$f_\nu \approx \frac{M_\nu}{\Omega_* h^2 \times 92.5 eV}$$

The net fluctuation growth factor is therefore given by:

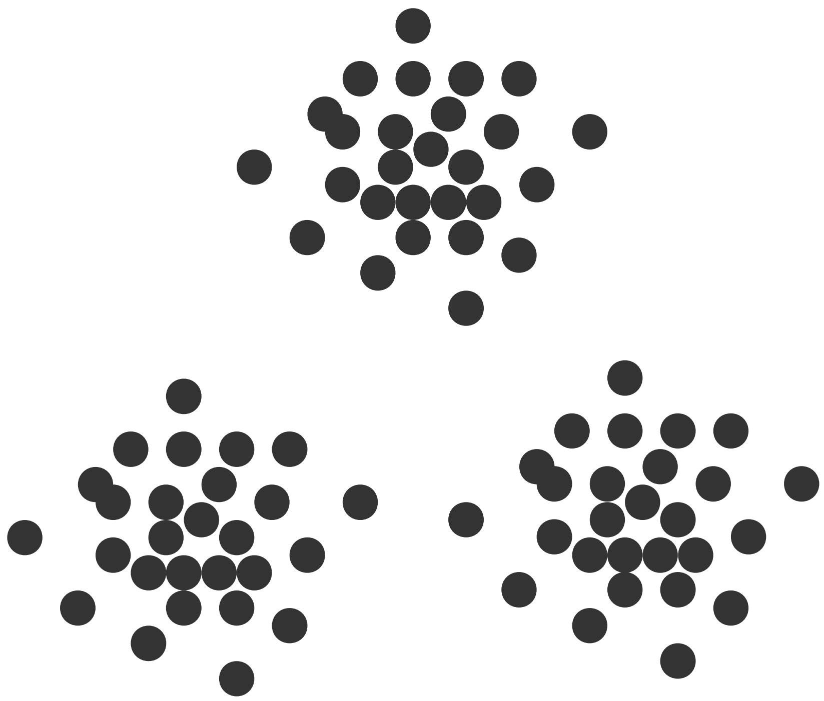
$$\left(\frac{a_{\Lambda D}}{a_{MD}}\right)^p \approx 4700^p \approx 4700^{(1-f_\nu)^{3/5}} \approx 4700 e^{-4 f_\nu}$$

The power spectrum is the variance of fluctuations in Fourier space, so Massive neutrinos suppress it by a factor:

$$P(k, f_\nu) \cong e^{-8 f_\nu} P(k,0)$$

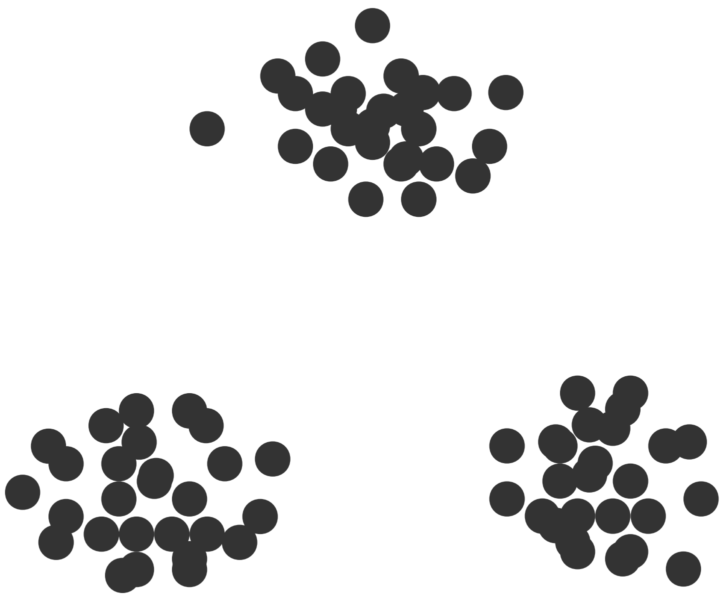
Structure formation after equality

baryons and CDM experience gravitational clustering



Structure formation after equality

baryons and CDM experience gravitational clustering



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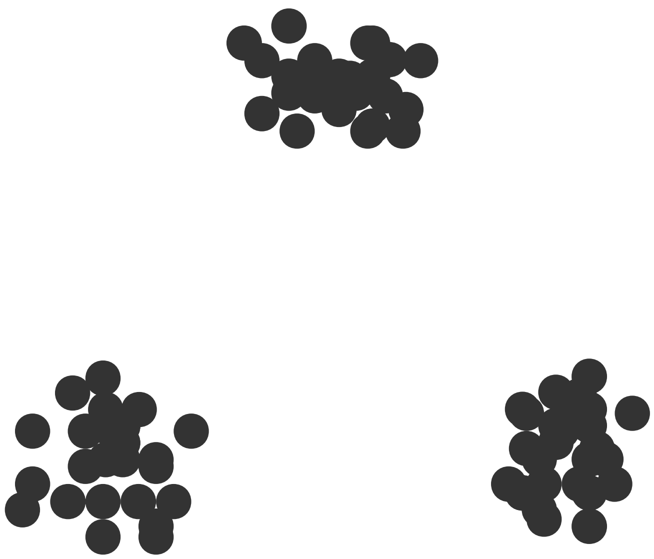

growth of $\delta\rho/\rho\ (k,t)$ fixed by

« gravity vs. expansion » balance

$$\delta\rho/\rho \propto a$$

Structure formation after equality

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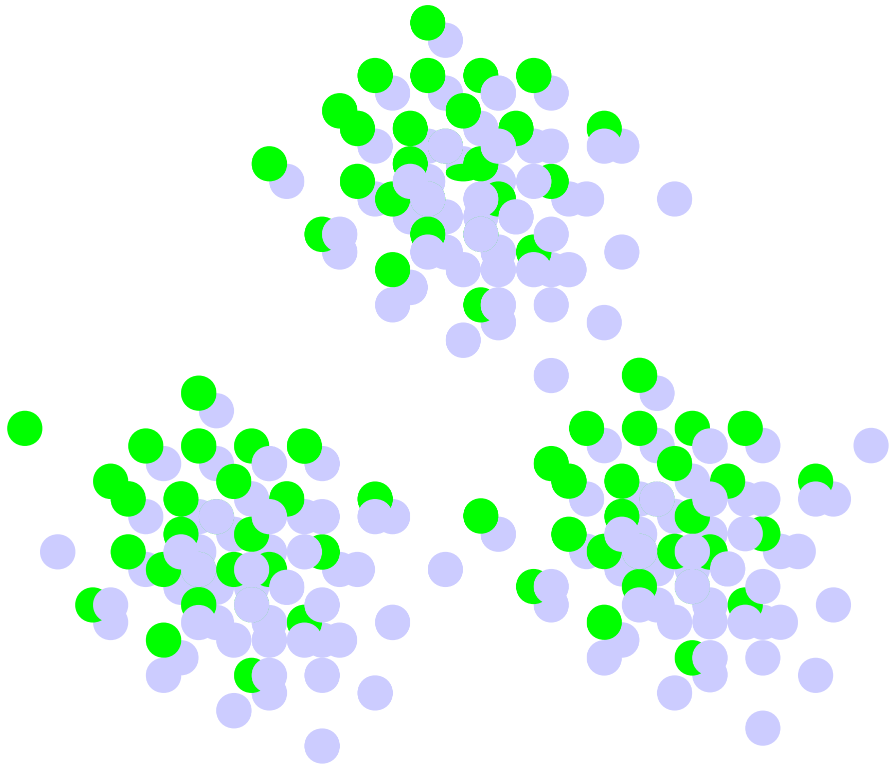
neutrinos experience free-streaming with v = c or <p>/m



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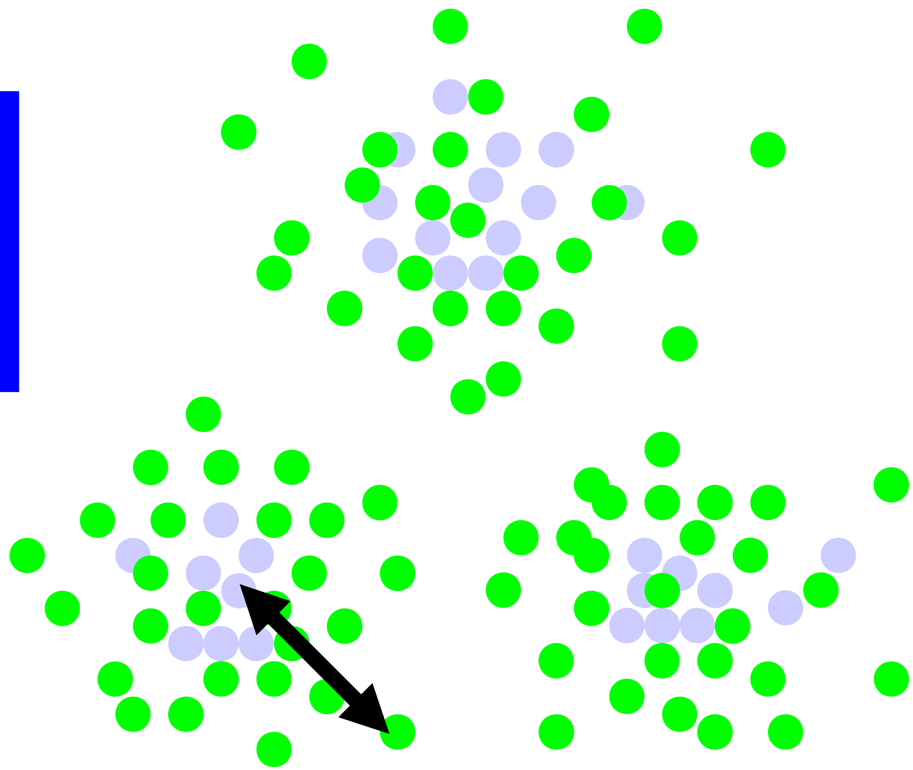
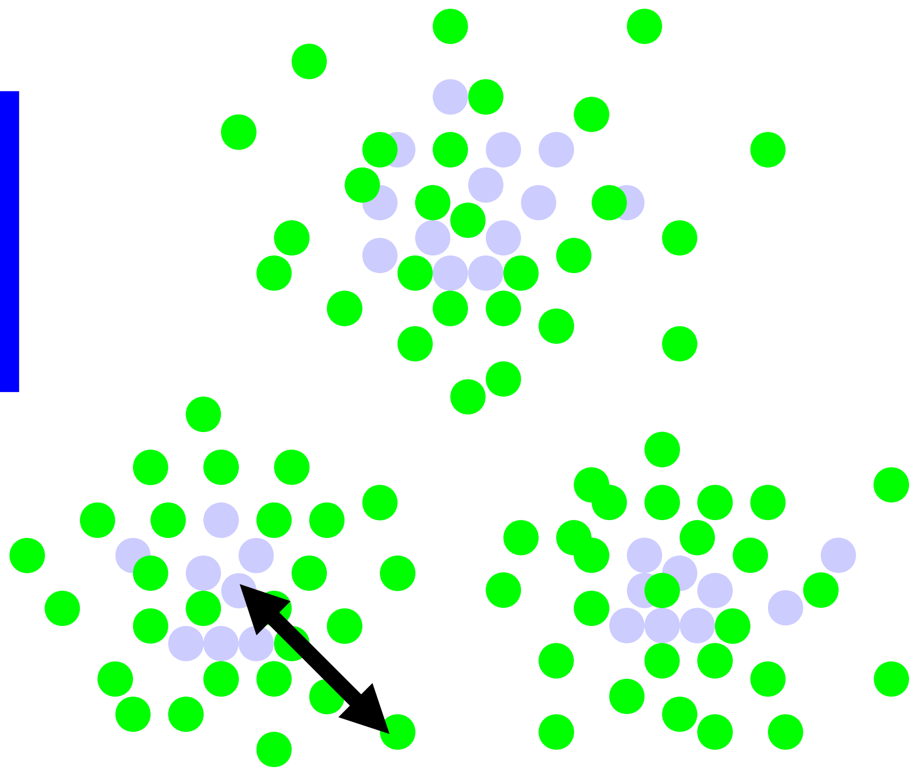


neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

neutrinos cannot cluster below a diffusion length

Structure formation after equality

baryons and CDM experience gravitational clustering



neutrinos experience free-streaming with v = c or <p>/m

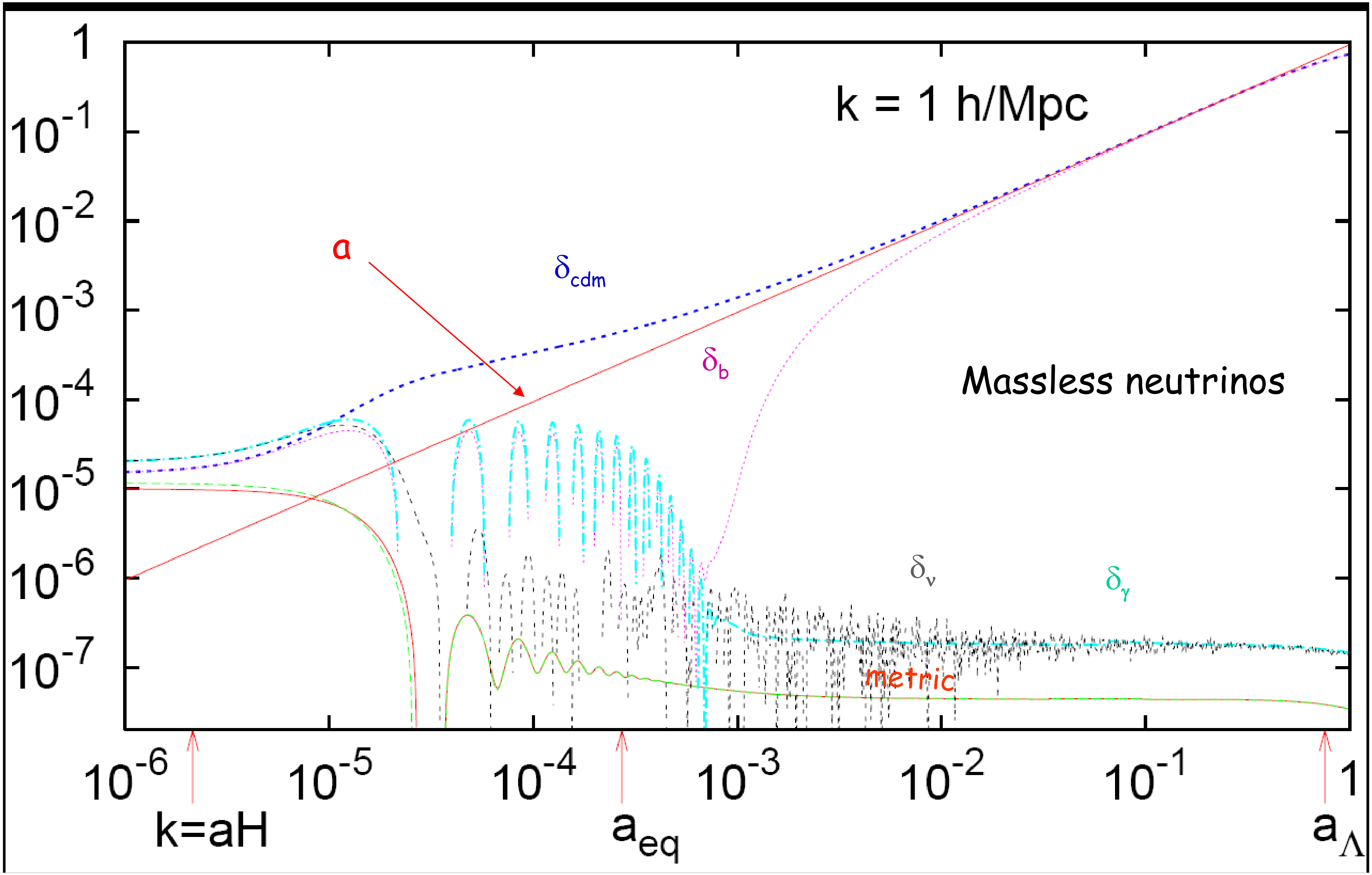
for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

$$\delta\rho/\rho \propto a^{1-3/5\, f_\nu}$$

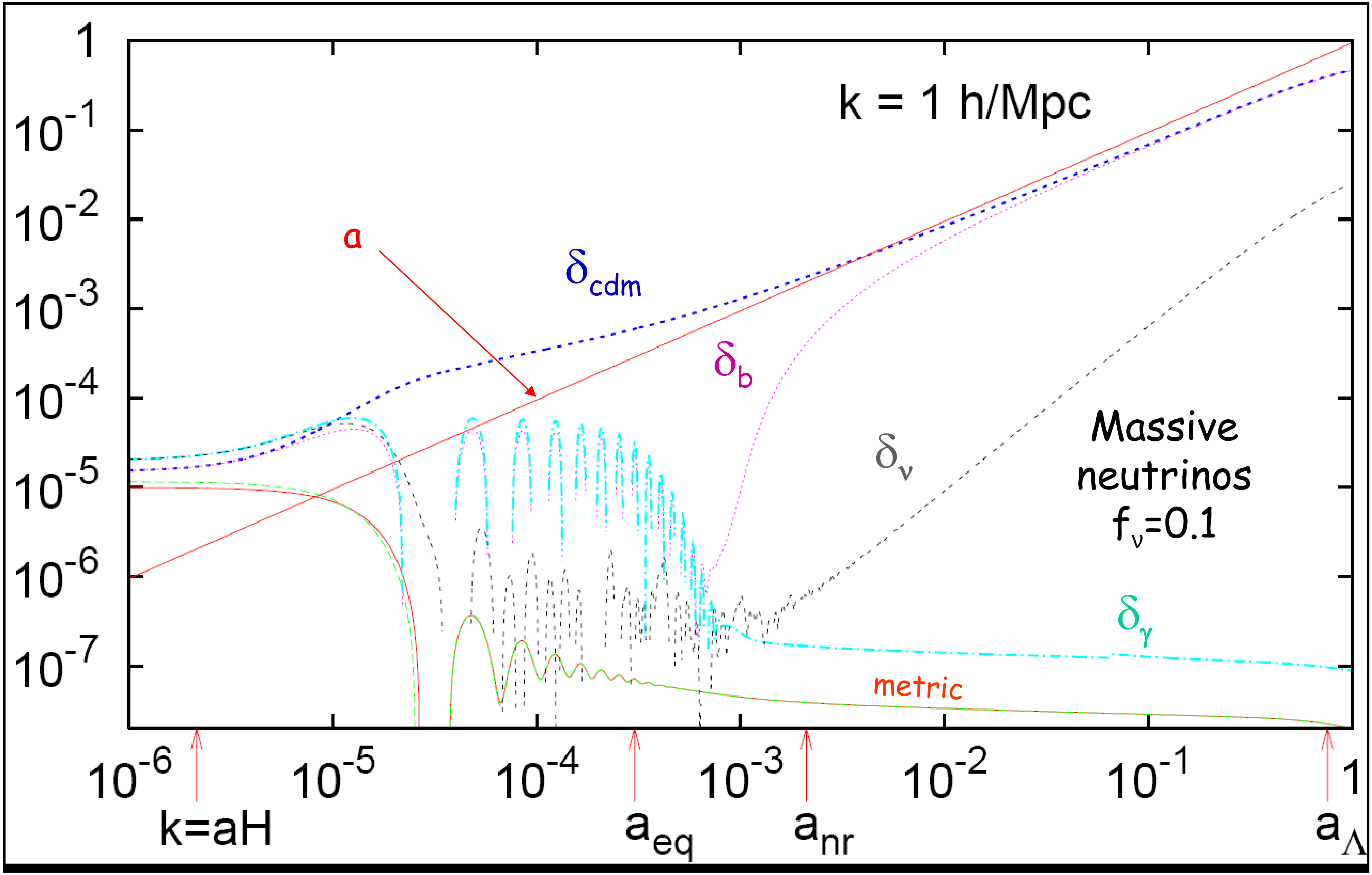
with $f_\nu = \rho_\nu/\rho_m \approx (\Sigma m_\nu)/(15\ \mathrm{eV})$

Structure formation after equality



J.Lesgourgues & Sergio Pastor, Phys Rep 429 (2006) 307 [astro-ph/0603494]

Structure formation after equality



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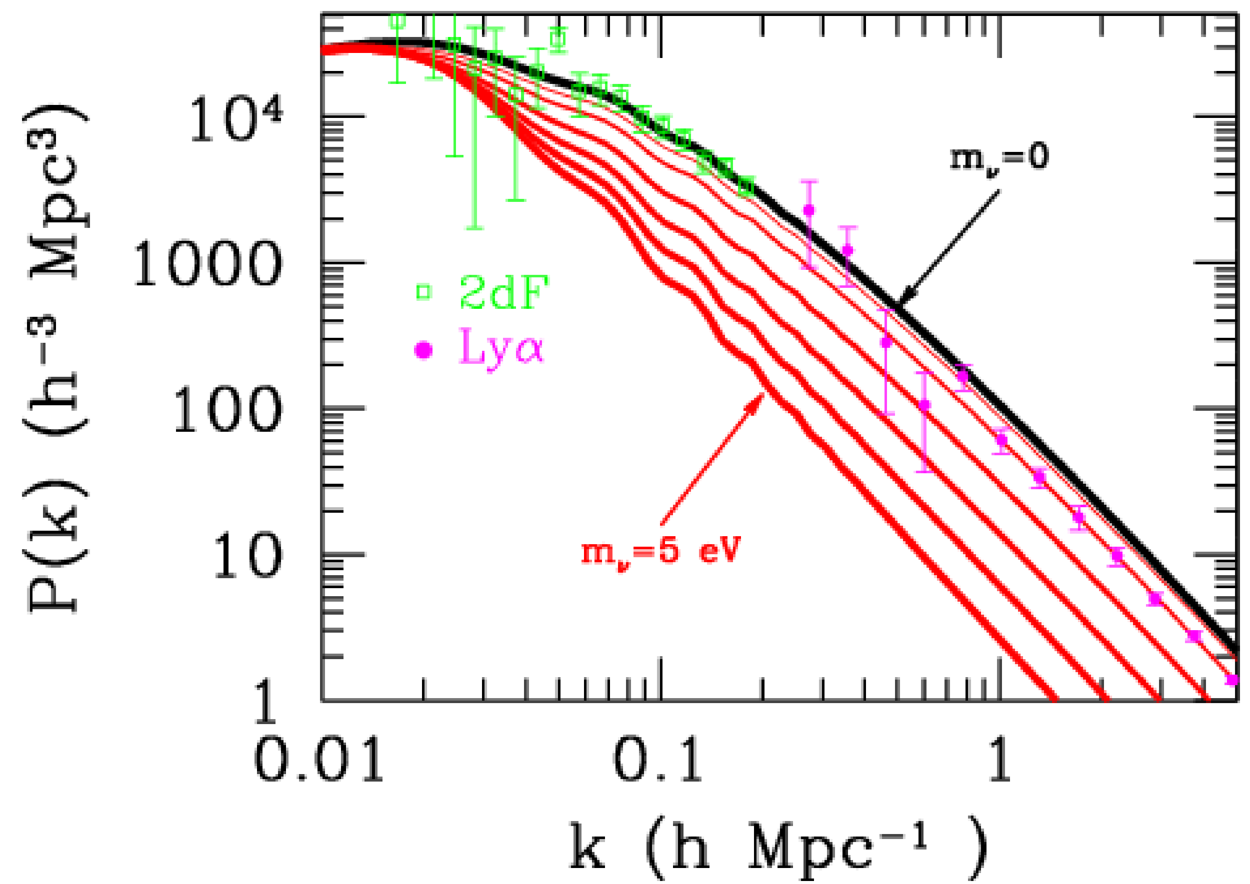

P(k) (h^-3 Mpc^3)
k (h Mpc^-1)
2dF
Lyα
m_ν=0
m_ν=5 eV

...but we have degeneracies...

- Lowering the matter density suppresses the power spectrum
- This is virtually degenerate with non-zero neutrino mass