Topics in Neutrino Cosmology

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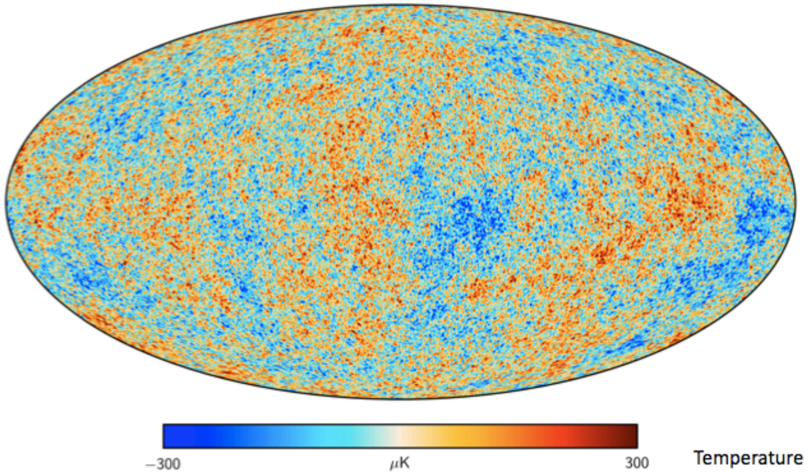
Two approaches:

1. Ask what cosmology can do for neutrinos! (particle physicists?)

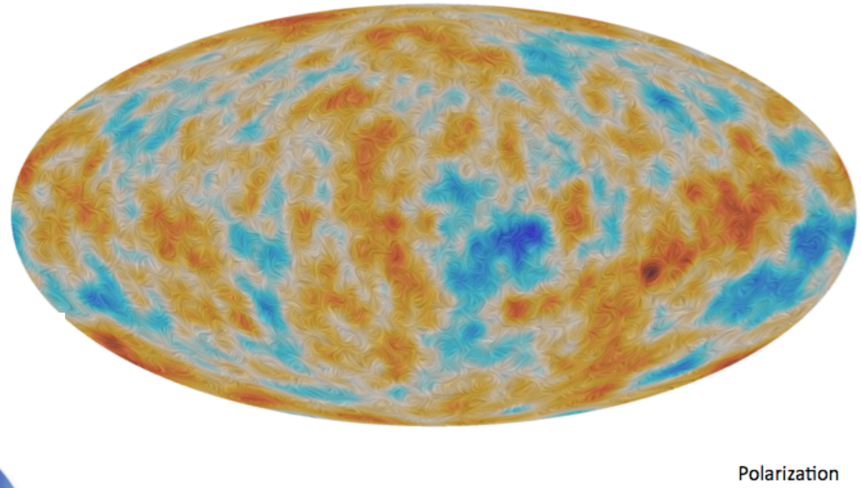
2. Ask what neutrinos can do for cosmology! (cosmologists?)

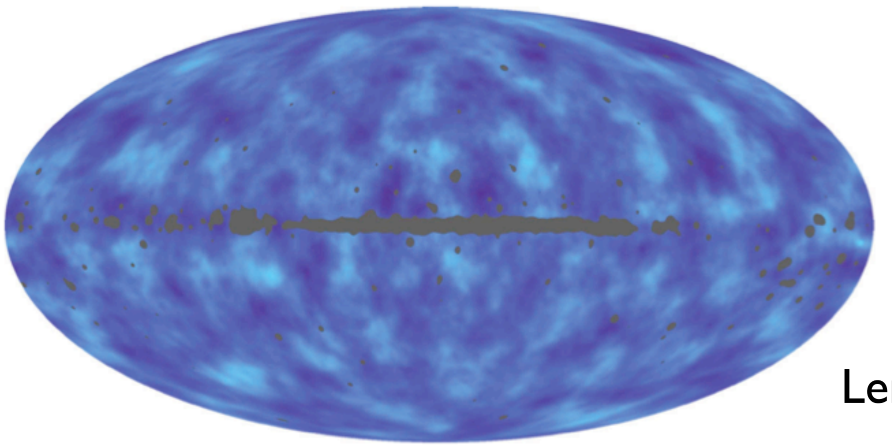
Planck 2015

Temperature



Polarization





Lensing Potential

Neutrino properties from cosmology: overview

Neutrinos impact expansion history:

Extremely high T regime (above EW scale) (Leptogenesis)
Majorana vs. Dirac, see-saw mechanism, high scale physics (Leptogenesis)

High T regime (≈ MeV):
weak + gravitational effects (BBN)
observables: phase space density (in particular ν_e distribution), non standard interactions, chemical potentials, number of species (active, sterile)

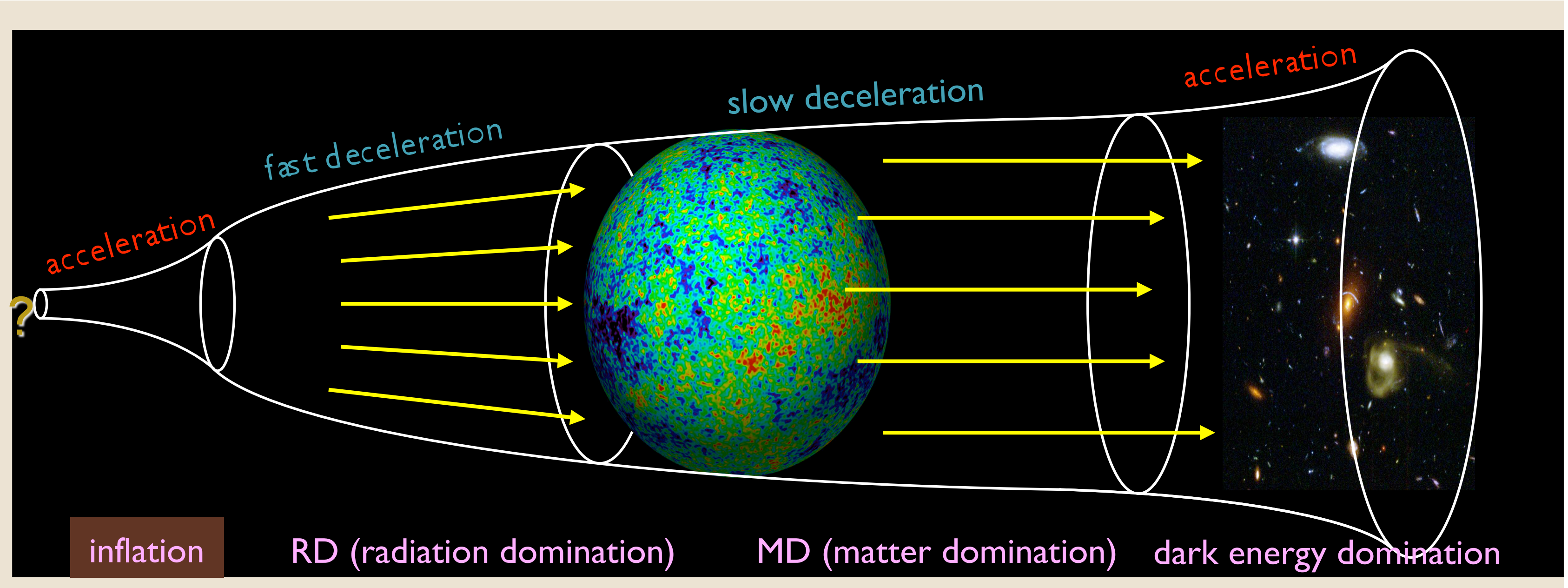
Intermediate T regime (eV):
gravitational effects including perturbations (CMB)
observables: phase space density, non standard interactions, mass scale, number of species

Low T regime (< eV):
gravitational effects including perturbations (LSS)
observables: phase space density, non standard interactions, mass scale

Extremely low T regime (today): mass scale, local density (CNB direct detection)

Evolution of the Universe

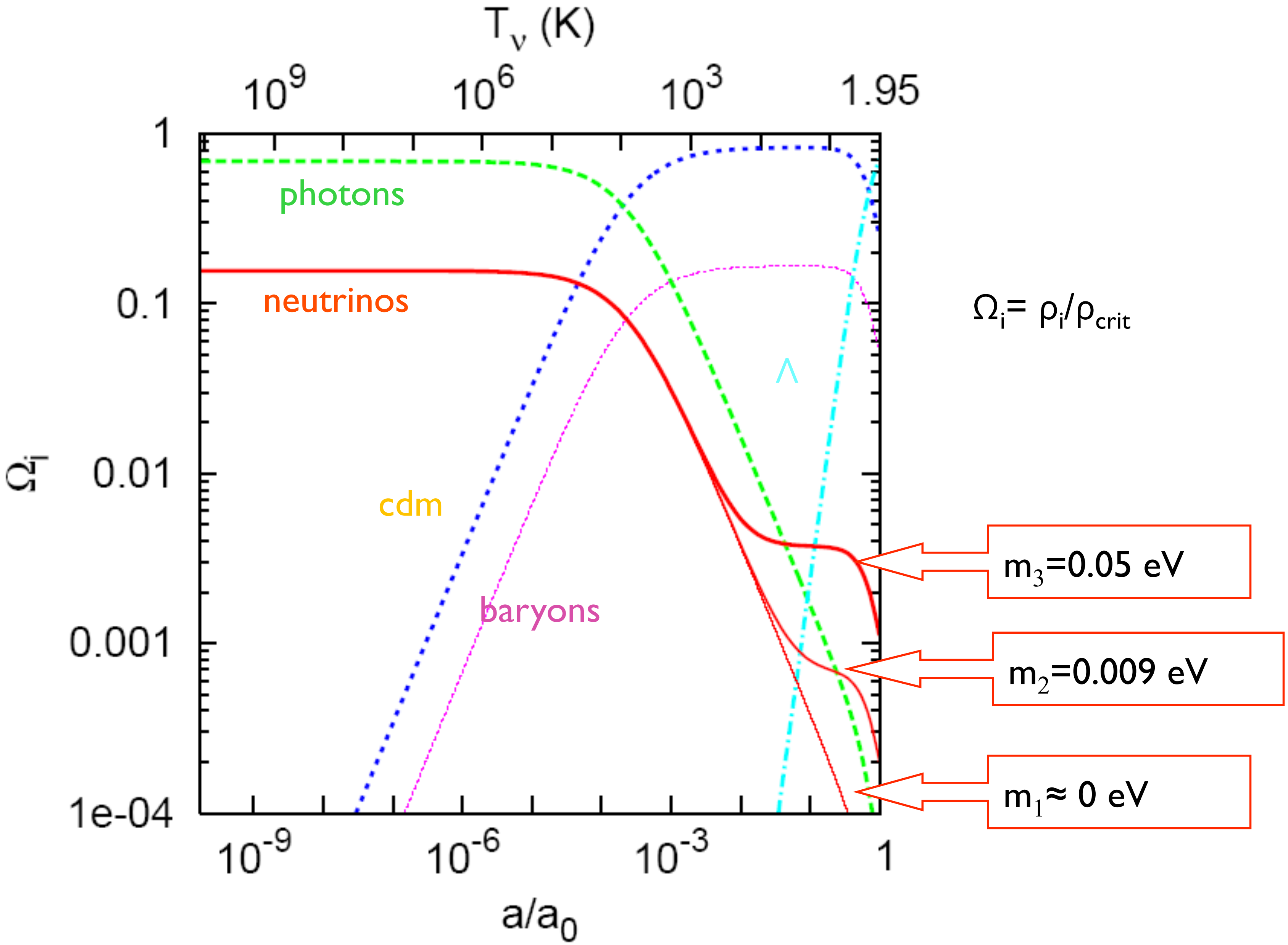
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$



$a(t) \sim e^{Ht}$

$a(t) \sim t^{1/2}$

$a(t) \sim t^{2/3}$



T_ν (K)
10^9
10^6
10^3
1.95
1
0.1
0.01
0.001
1e-04
Ω_i
photons
neutrinos
cdm
baryons
Λ
10^{-9}
10^{-6}
10^{-3}
1
a/a_0
$\Omega_i = \rho_i/\rho_{crit}$
m_3=0.05 eV
m_2=0.009 eV
$m_1 \approx$ 0 eV

The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

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

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3 \quad \approx 112 \text{ cm}^{-3}$$

$$\rho_{\nu_i} = \int \sqrt{p^2 + m_{\nu_i}^2} \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \rightarrow \begin{cases} \dfrac{7\pi^2}{120}\left(\dfrac{4}{11}\right)^{4/3} T_{CMB}^4 & \Omega_\nu h^2 = 1.7\times 10^{-5} \\ m_{\nu_i} n_\nu & \Omega_\nu h^2 = \dfrac{\sum_i m_i}{94.1 \text{ eV}} \end{cases}$$

Massless

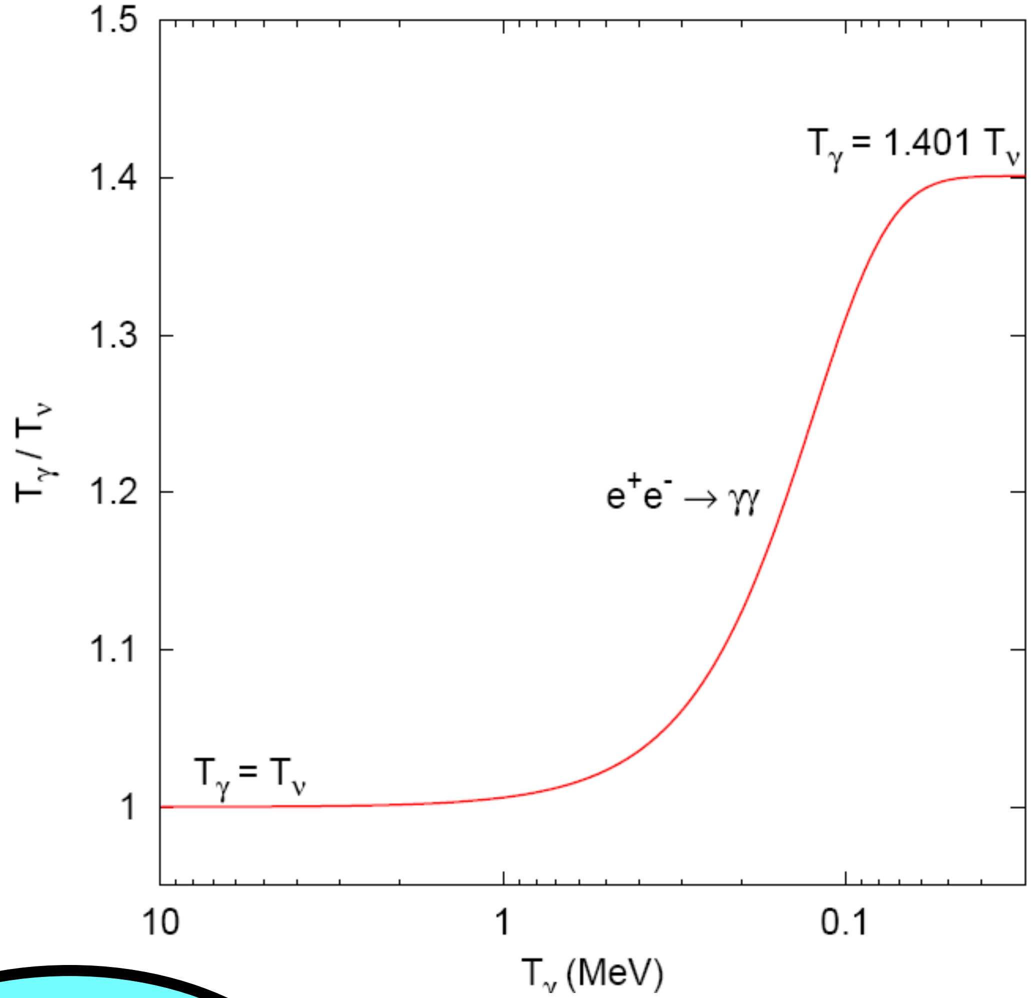
Massive $m_\nu >> T$

Neutrino and Photon (CMB) temperatures

At $T \sim m_e$, electron-positron pairs annihilate

$$e^+e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos



from entropy conservation

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

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

Relativistic particles in the Universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T_\gamma^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T_\nu^4 = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3\right] \rho_\gamma$$

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

Extra relativistic particles

- Extra radiation can be:

scalars, pseudoscalars, sterile neutrinos (totally or partially thermalized, bulk), neutrinos in very low-energy reheating scenarios, relativistic decay products of heavy particles…

- Particular cases: relic neutrino asymmetries, sterile ν's

Actually N_{eff} is slightly larger than 3 for standard active neutrinos

Non-instantaneous neutrino decoupling

At $T \sim m_e$, e^+e^- pairs annihilate heating photons

$$e^+e^- \rightarrow \gamma\gamma$$

But, since $\mathbf{T_{dec}(\nu)}$ is close to $\mathbf{m_e}$, neutrinos share a small part of the entropy release

$$\mathbf{f_\nu = f_{FD}(p, T_\nu)[1 + \delta f(p)]}$$

Neutrino oscillations in the Early Universe

Neutrino oscillations are effective when medium effects get small enough

Compare oscillation term with effective potentials (see Exercise VI) and neglecting large neutrino asymmetries (see later)

$$\left(i\partial_t - Hp\partial_p\right)\rho = \left[\frac{M^2}{p} - \frac{8\sqrt{2}G_F}{M_W{}^2}p\rho_{e\pm} + \frac{\sqrt{2}G_F}{3M_Z{}^2}(\rho_\nu - \overline{\rho}_\nu) - \frac{8\sqrt{2}G_F}{M_Z{}^2}p\rho_{\nu,\bar{\nu}}, \rho\right] + C(\rho)$$

with ρ the neutrino density matrix (similarly for antineutrinos)

$$\left\langle a_b^+(p)a_a(p')\right\rangle = \left(2\pi\right)^3\delta^3(p-p')\rho_{ab}$$

ρ description to account for scatterings AND oscillations

Results

	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}$(%)	$\delta\rho_{\nu\mu}$ (%)	$\delta\rho_{\nu\tau}$(%)	**N_{eff}**
Instantaneous decoupling	1.40102	0	0	0	3
SM	1.3978	0.94	0.43	0.43	3.045
+3ν mixing (θ_{13}=0)	1.3978	0.73	0.52	0.52	3.045
+3ν mixing ($\sin^2\theta_{13}$=0.02)	1.3978	0.72	0.54	0.52	3.045

Neutrino asymmetries

neutrino distribution with a flavour dependent chemical potential

$$f_a(p,T) = \frac{1}{e^{p/T_\nu - \xi_a} + 1}$$

Total lepton asymmetry expected quite small in (standard) leptogenesis

$$\sum_a \eta_a = \sum_a \frac{n_a - n_{\bar{a}}}{n_\gamma} = \sum_a \frac{1}{12\zeta(3)}\left(\pi^2 \xi_a + \xi_a^3\right) \approx \frac{n_B}{n_\gamma}\eta_B = 6\times 10^{-10}$$

unless leptogenesis takes place well below the EW breaking scale

$$\exp\left(-M_W(T)/g^2 T\right) << 1$$

but for each flavour in principle they could be large!

The role of oscillation!

BBN: Creation of light elements

Range of temperatures: from few to 0.01 MeV

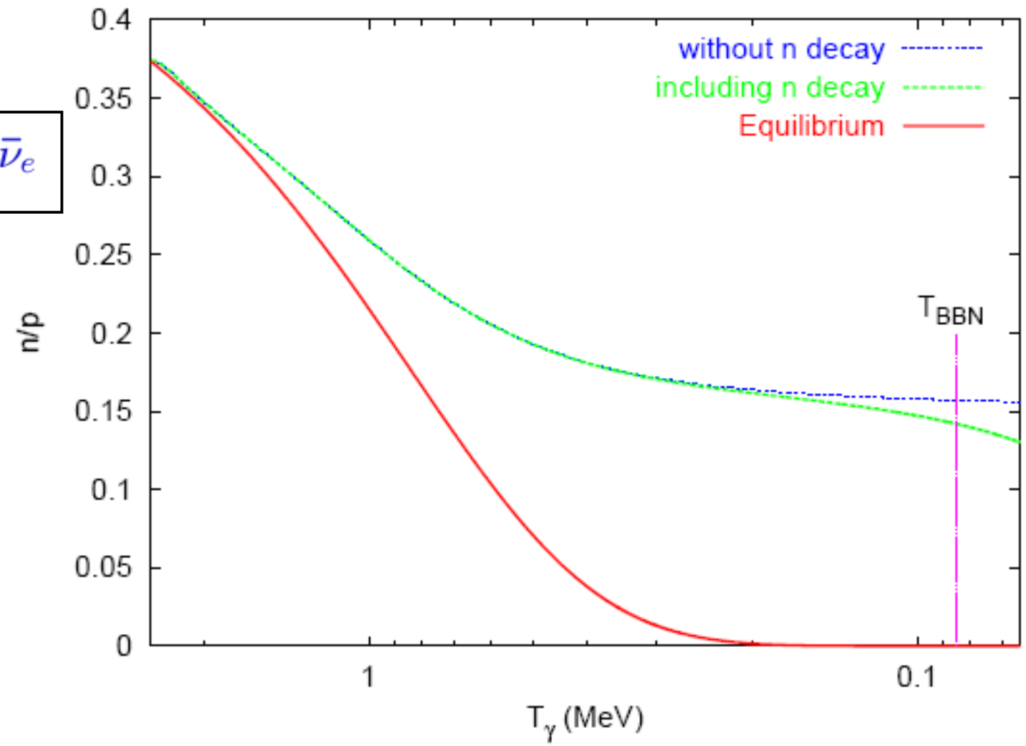
$$t \simeq 0{,}74 \left(\frac{\text{MeV}}{T}\right)^2 \text{ sec}$$

Phase I: few – 0.8 MeV
n-p reactions

$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

n/p freezing and
neutron decay

$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$



$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293 \text{ MeV}}{T_\gamma}\right)$$

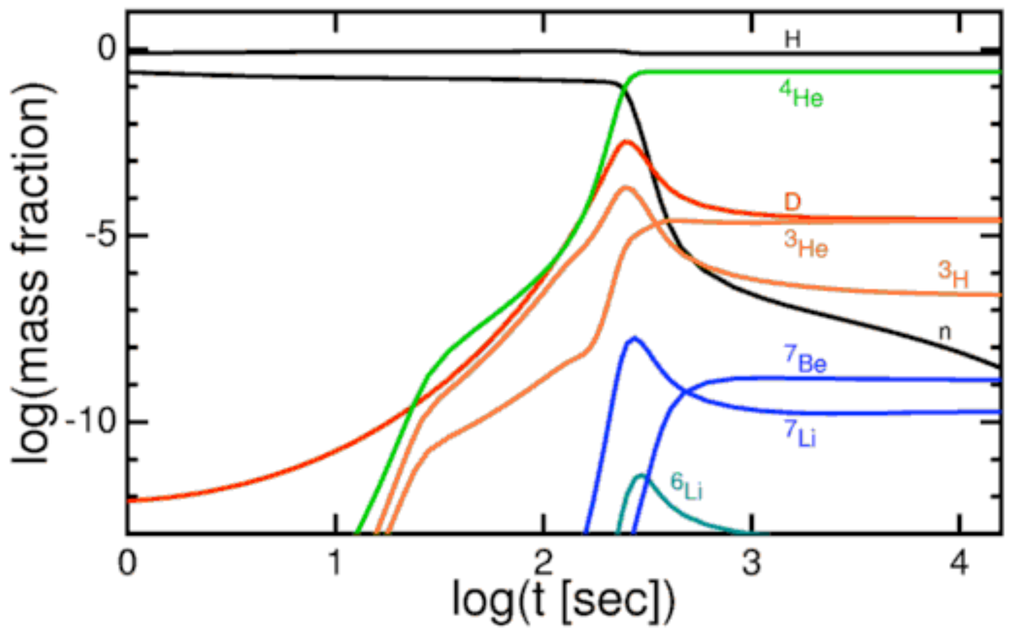
Freezing of weak rates and so of n/p ratio

$G_F^2 T_{fr}^5 = H(T_{fr}) \approx (8 \pi G_N g T^4_{fr}/3)^{1/2}$

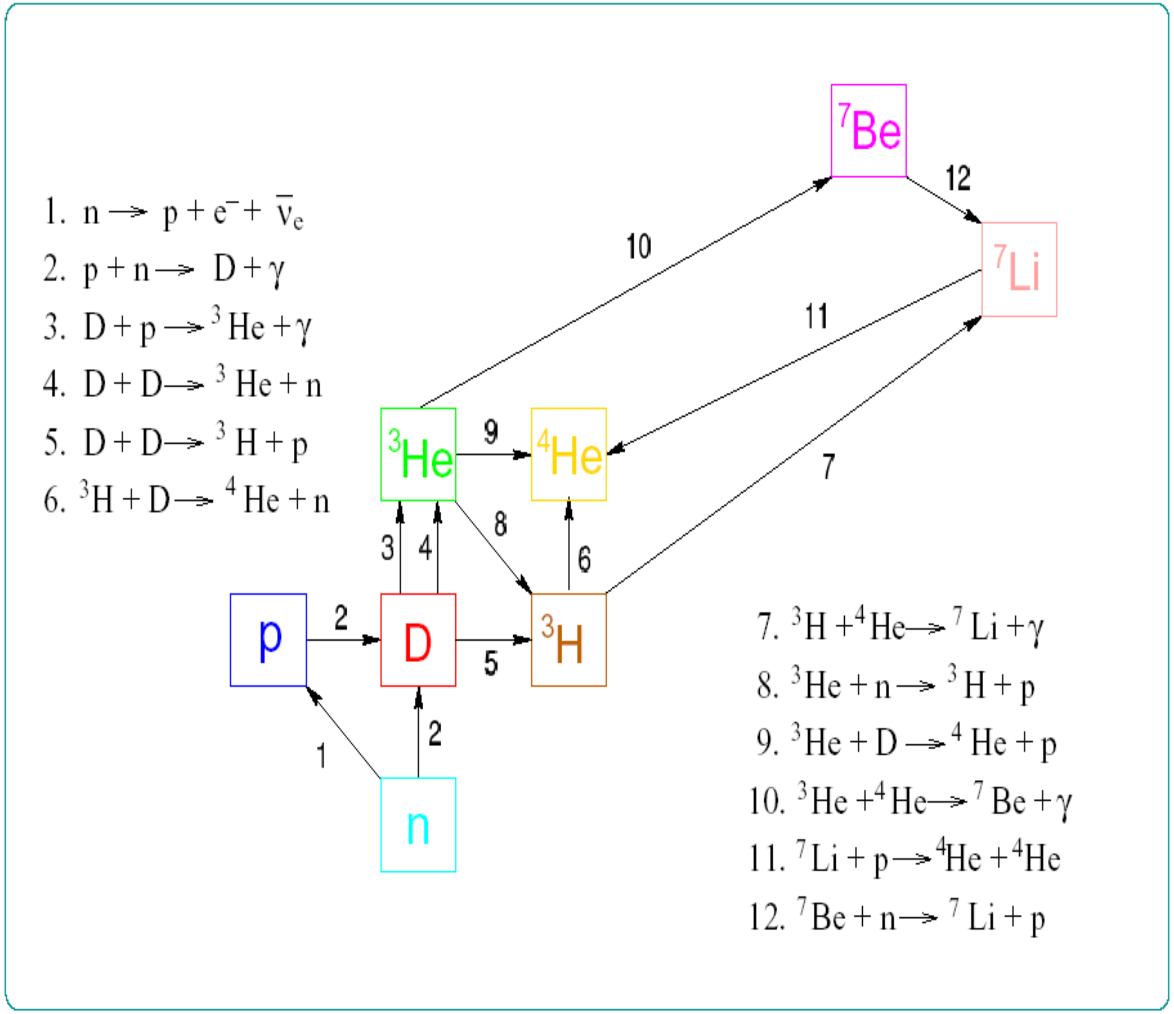
$n/p = \exp[(-M_n - M_p)/T_{fr}] \exp[-(t(T_D)-t(T_{fr}))/\tau_n] \approx 1/7$

phase II ^2H forms at $T_D \sim 0.08$ MeV;
Photodisintegration prevents
earlier formation for
temperatures closer
to nuclear binding energies

$n\ p \rightarrow d\ \gamma$



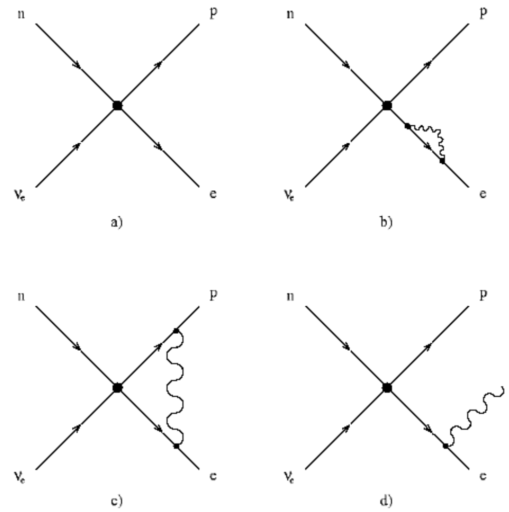
Phase III: 700 - 30 keV
Formation of light nuclei
starting from D



Weak rates:

radiative corrections $O(\alpha)$
finite nucleon mass $O(T/M_N)$
plasma effects $O(\alpha T/m_e)$
neutrino decoupling $O(G_F^2\, T^3\, m_{Pl})$

N_{eff}=3.045



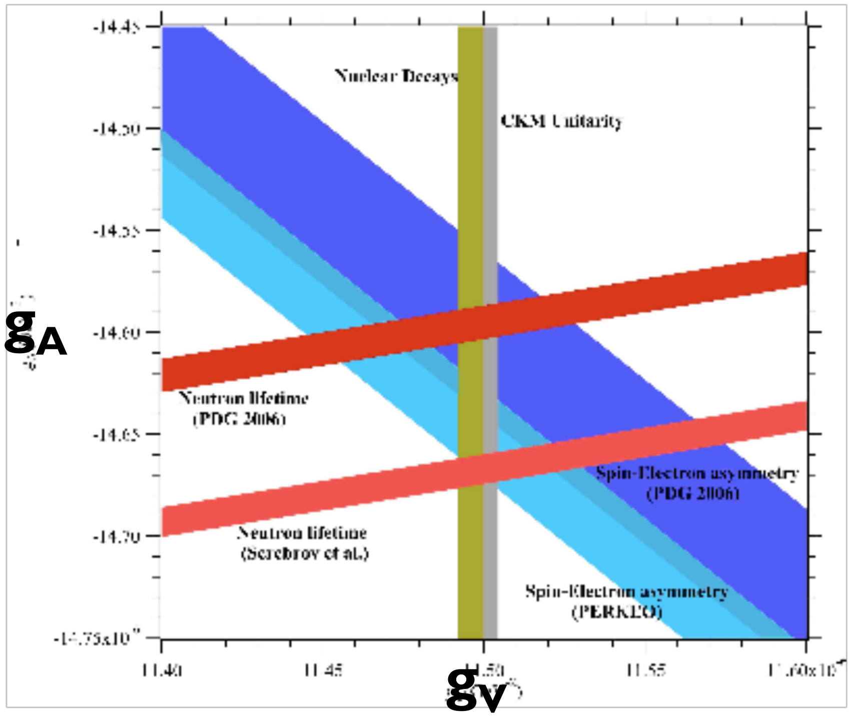
Main uncertainty: neutron lifetime
τ_n= 885.6 ± 0.8 sec (old PDG mean)
τ_n= 878.5 ± 0.8 sec (Serebrov et al 2005)

Presently:

τ_n=880.2 ± 1.0 sec (PDG)

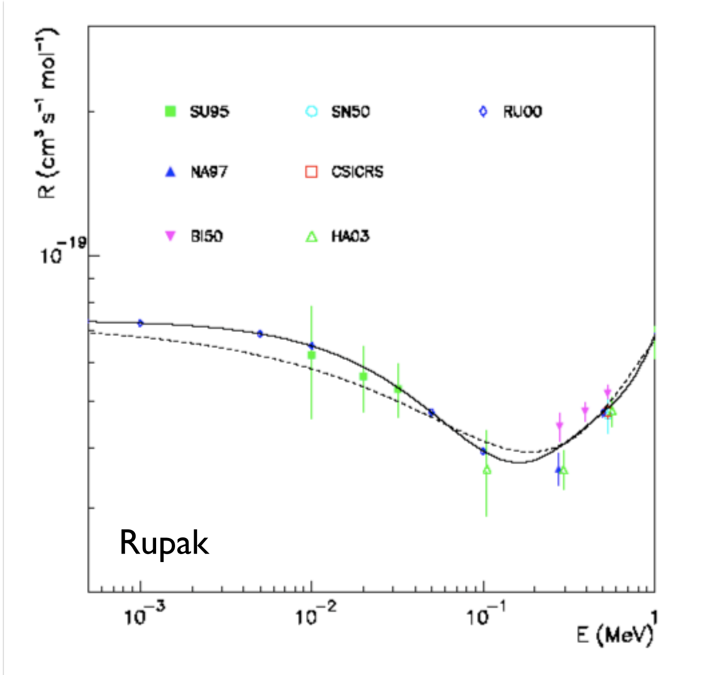
^{4}He mass fraction Y_P linearly increases with τ_n: 0.246 - 0.249

Nico & Snow 2006

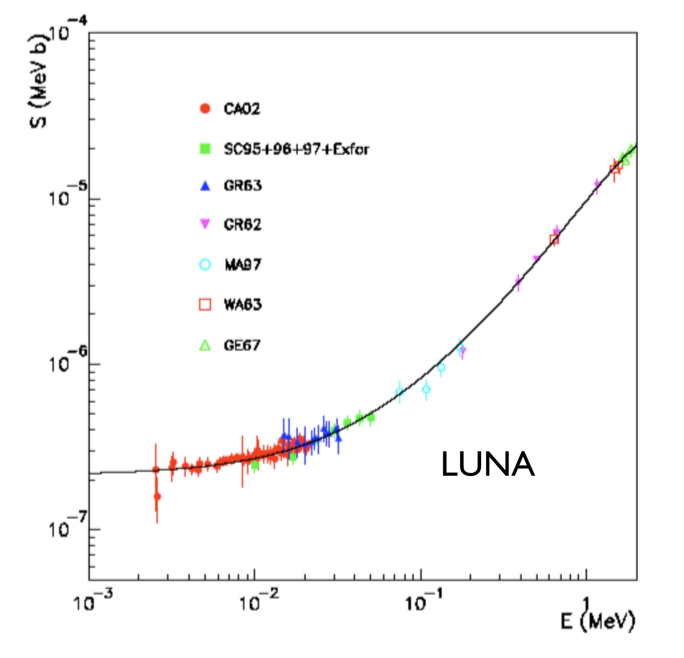


Nuclear rates:

main input from experiments
low energy range (10^2 KeV)
major improvement: underground measurements (e.g. LUNA at LNGS)

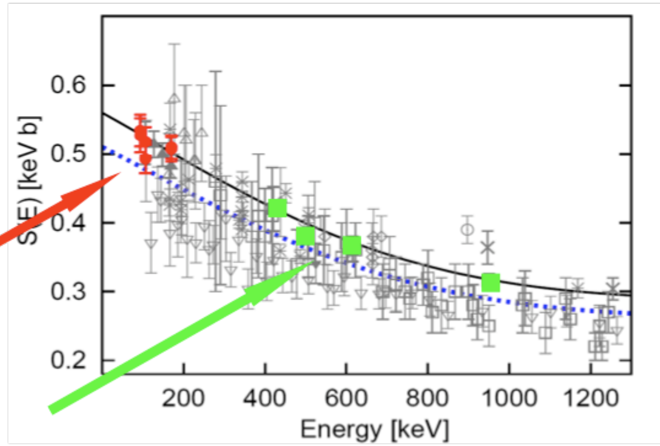


$n(p,\gamma)^2H$



$^2H(p,\gamma)^3He$

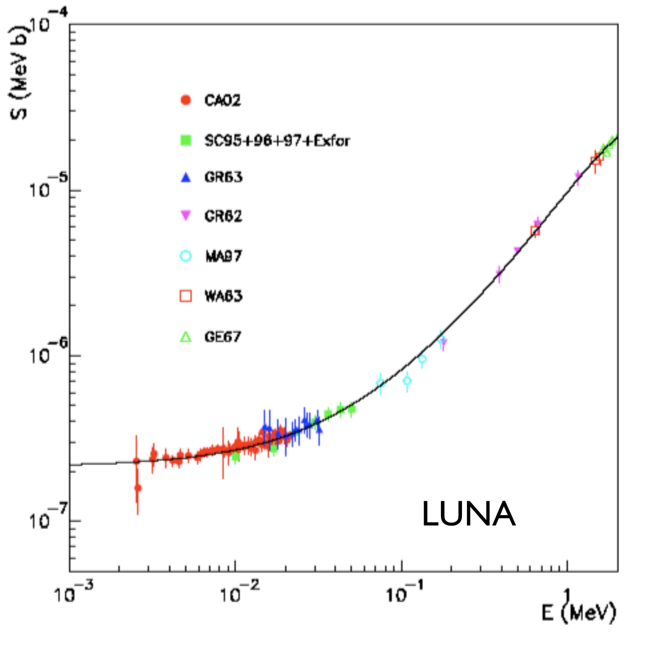
LUNA



Weitzmann Inst.

$^3He(\alpha,\gamma)^7Be$

Nuclear rates: for d(p,γ) ^{3}He also available ab initio calculations (Viviani et al 2000 PRC, Marcucci et al 2005 PRC, …,Marcucci et al 2016 PRL)



^{2}H(p,γ)^{3}He

Larger cross section than present data fit (Adelberger et al, 2011, Rev. Mod. Phys.)

$R = \langle S \rangle_{TH} / \langle S \rangle_{exp} > 1!$

Important to check experimentally this result!
LUNA 2018?

d(α,γ) ^{6}Li crucial for ^{6}Li production, see later non minimal models:

extra radiation $g = 5.5 + 7 N_{eff}/4$

boosts the expansion rate H

$\xi_i = \mu_i/T$ $i = e, \mu, \tau$

boosts the expansion rate H

change chemical equilibrium of n/p (ν_e)

DATA

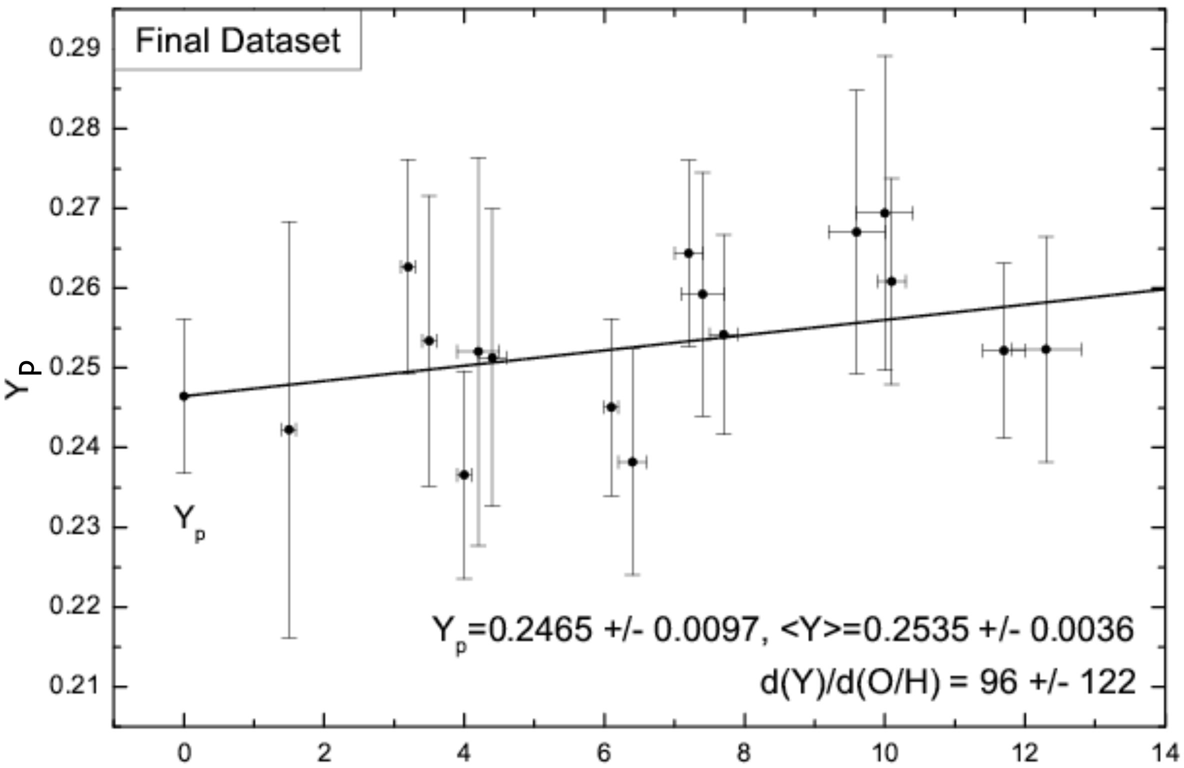
The quest for primordiality

- Observations in systems negligibly contaminated by stellar evolution (e.g. high redshift);
- Careful account for galactic chemical evolution.

He recombination lines in ionized H_{II} regions in BCG & regression to zero metallicity. Small statistical error but large systematics

Recent analyses:

Izotov & Thuan 2014
Aver, Olive
& Skillmann 2015



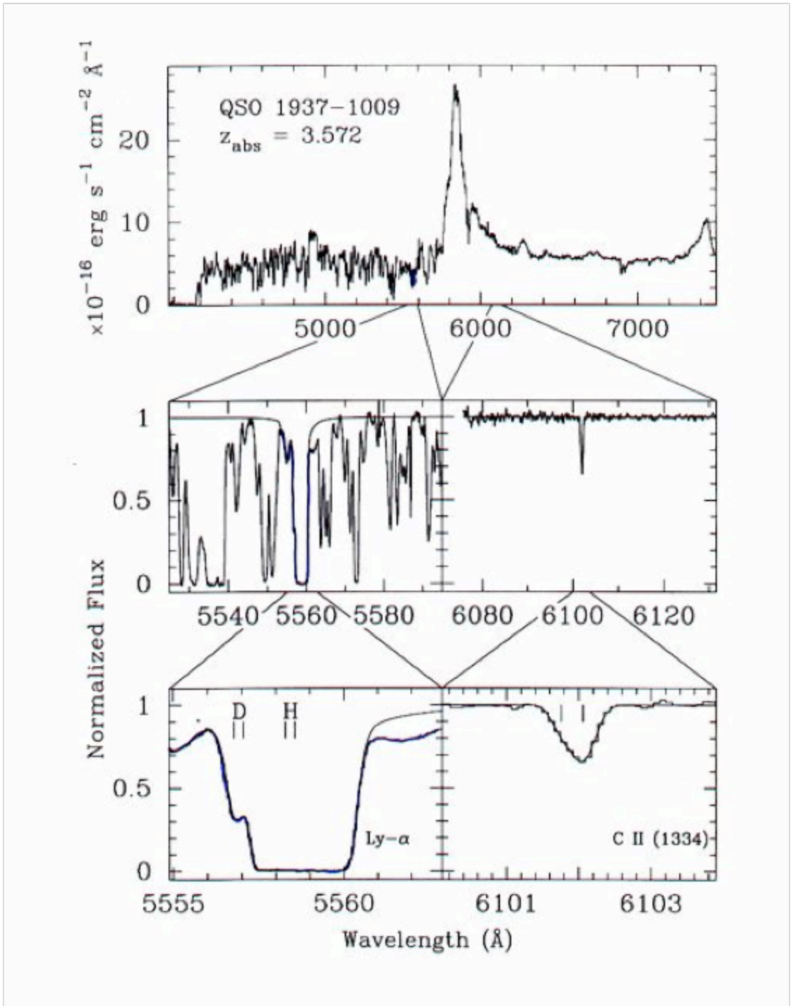
$Y_p = 4\ n_{4He}/n_B \approx 2n_n/(n_n+n_p)=2(n/p)/(n/p+1)$

Aver, Olive & Skillmann 2015

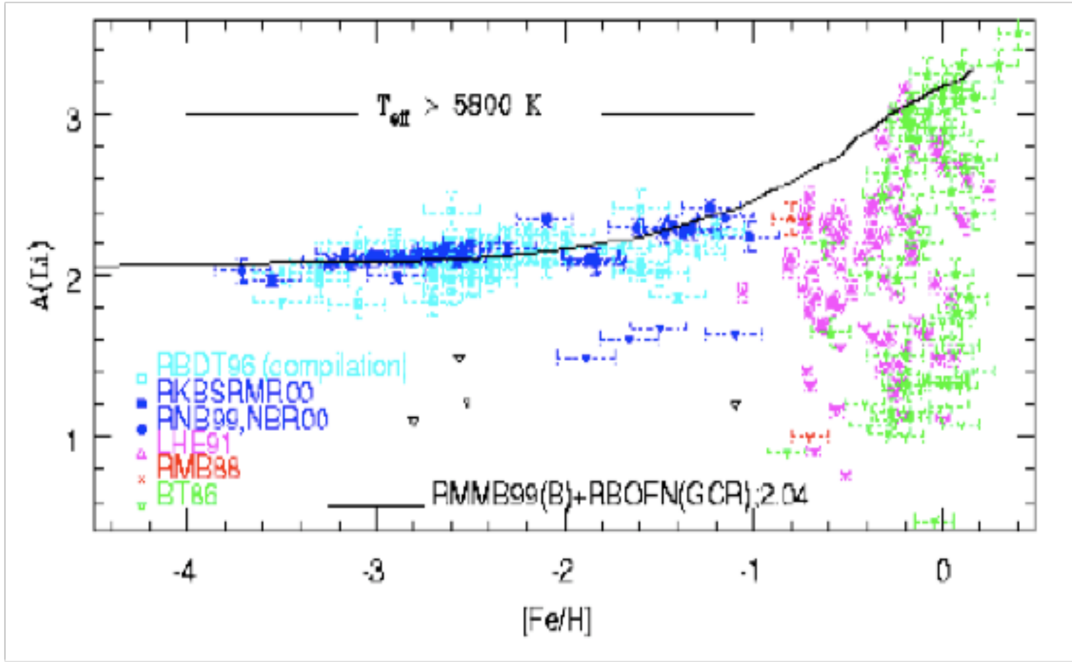
^2H measures baryon fraction. Quite good agreement with Planck determination:

$$\Omega_b h^2 = 0.02225 \pm 0.00032$$

Observations: absorption lines in clouds of light from high redshift background QSO



^{7}Li (and ^{6}Li) still a puzzle.
Spite plateau in metal poor dwarfs questioned



MINIMAL SCENARIO: ALL FIXED!

$\Omega_b h^2 = 0.0223 \pm 0.0002$

$Y_p = 0.2467 \pm 0.0001 \pm 0.0003$

$^2H/H = 2.60 \pm 0.03 \pm 0.07$

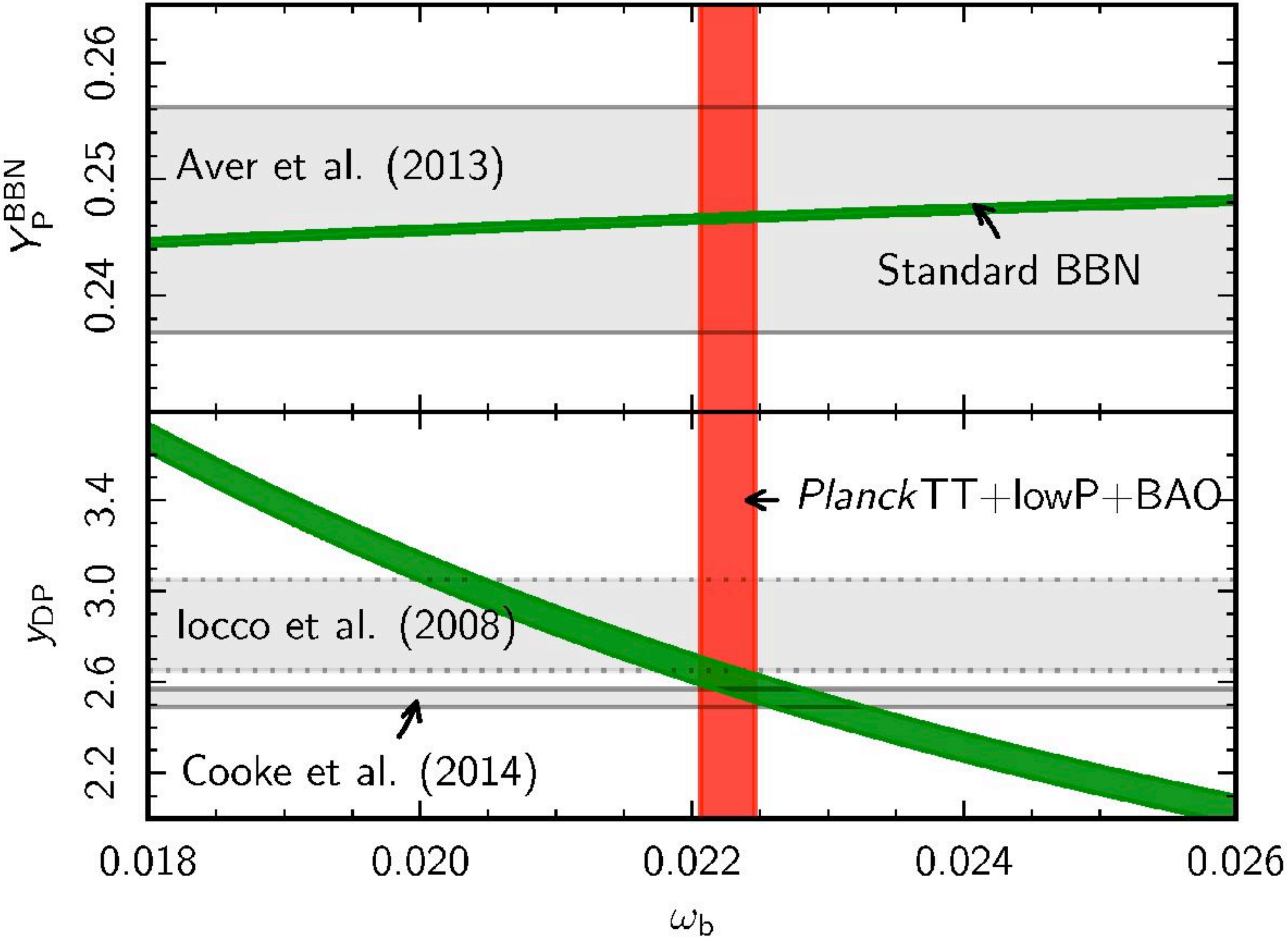
PLANCK 2015

EXP:

$Y_p = 0.2551 \pm 0.0022$!!!

$Y_p = 0.2449 \pm 0.0040$!

$^2H/H (10^{-5}) = 2.55 \pm 0.03$!!



Aver et al. (2013)
Standard BBN
Y_P^{BBN}
0.24
0.25
0.26
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
y_{DP}
2.2
2.6
3.0
3.4
0.018
0.020
0.022
0.024
0.026
ω_b

PLANCK 2015

Extra neutrinos

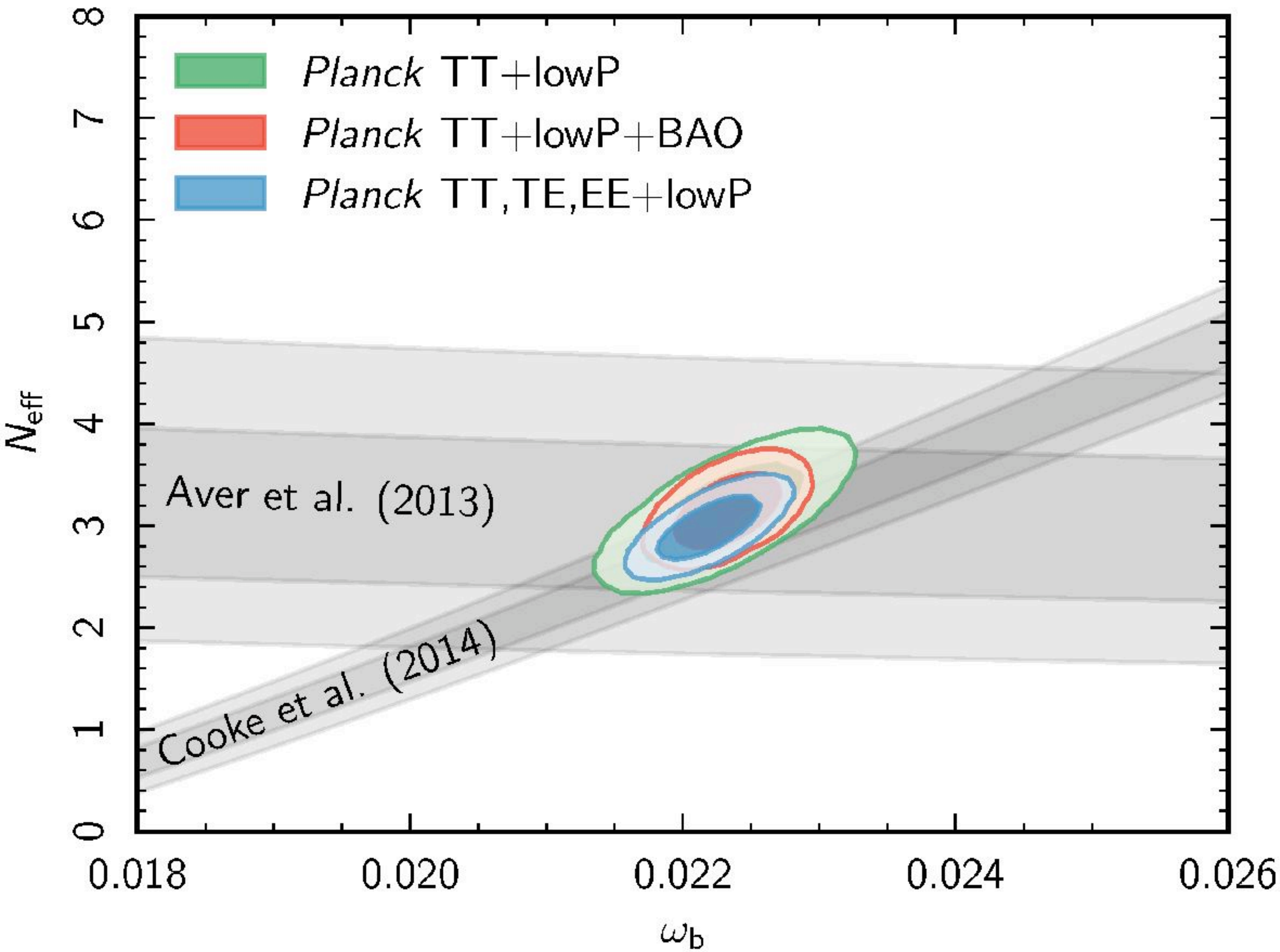
For several cosmological observables, all in a single parameter

$$\rho_{rad} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)\frac{\pi^2}{15} T_\gamma^{\ 4}$$

Instantaneous ν decoupling value for T_ν / T_γ

CMB and BBN scrutinize different "mass" scales!

Planck 2015



Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
Aver et al. (2013)
Cooke et al. (2014)
$N_{\rm eff}$
0
1
2
3
4
5
6
7
8
0.018
0.020
0.022
0.024
0.026
$\omega_{\rm b}$

What could it be this putative extra radiation?

Sterile neutrinos?

Succesfull picture of 3-active neutrino mixing in terms of 2 mass differences and 3 mixing angles.

Few parameters describe a lot of data: solar ν flux, atmospheric ν's, accelerator ν beams!

Yet, few anomalies (2-3 σ) :

1) LSND-MiniBooNE (short baseline exp's);
2) Reactor anomaly;
3) Gallium anomaly.

For large mixing angles sterile neutrino too much produced (N_{eff} = 1)

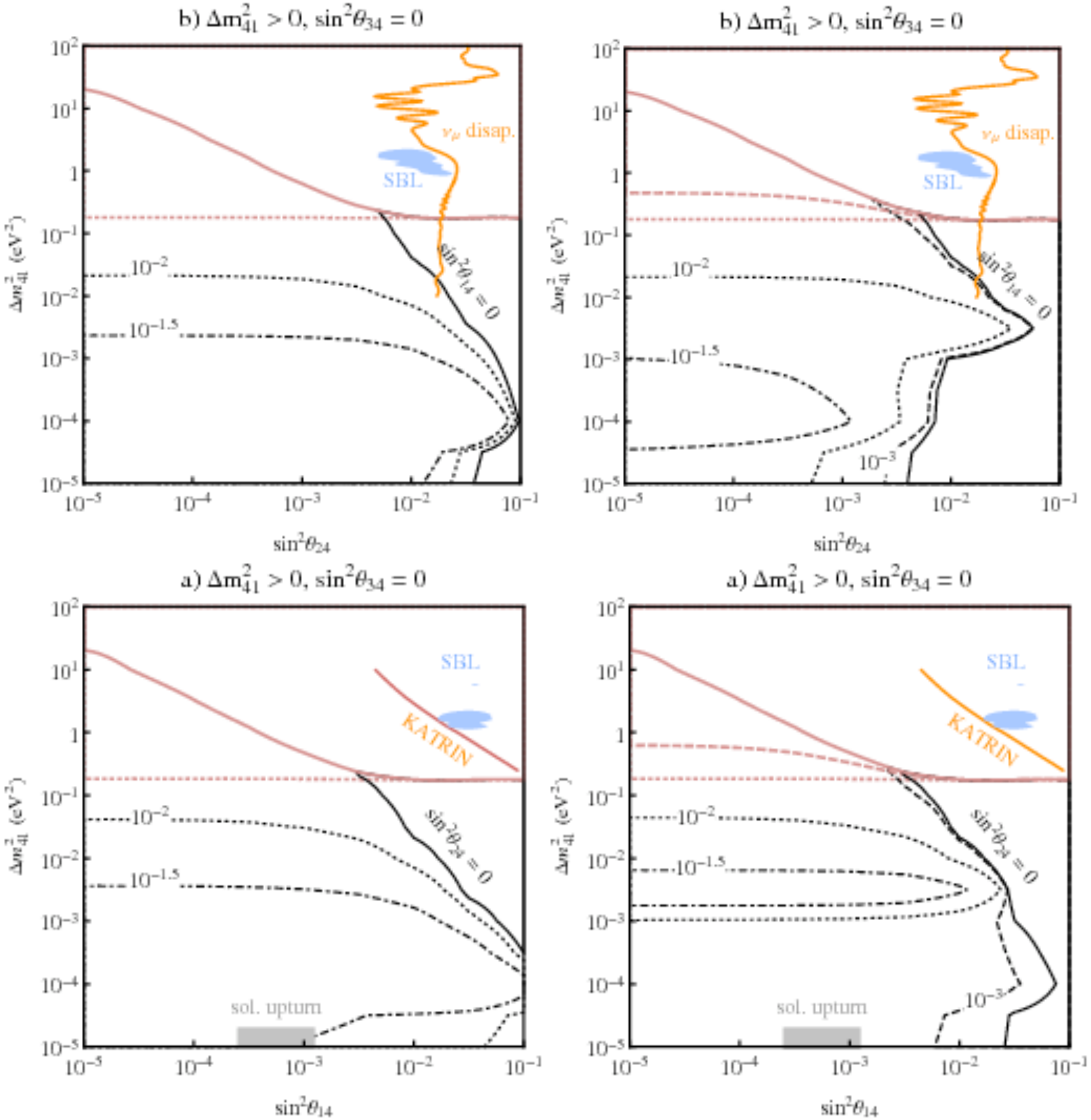
The standard case, after Planck 2013

$N_{eff} < 3.30 \pm 0.27$
$m_s < 0.38$ eV

New Planck analysis 2015 even stronger!

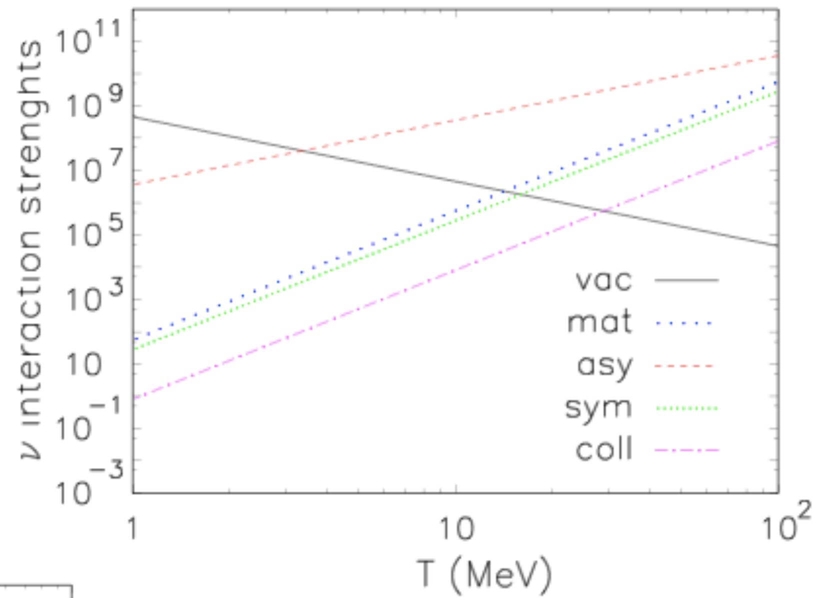
(Planck XIII 2015)

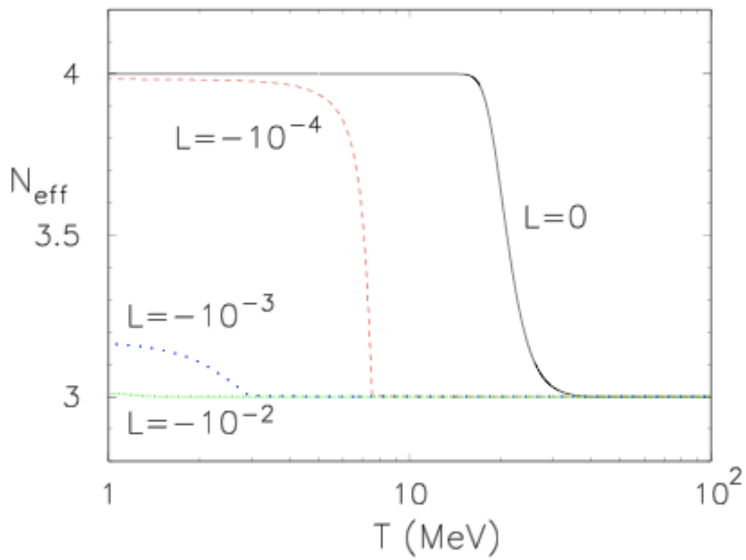
$N_{eff} = 3.04 \pm 0.22$
$m_s < 0.38$ eV



Lepton asymmetry suppresses sterile production

$V = \sqrt{2}\, G_F\, L_\nu$





Possible way out?
active neutrino large (> 10^{-3}) chemical potential, but then ν_e distortion

sterile neutrino "secret interactions" ?

$$g_X \bar{\nu}_s \gamma^\mu X_\mu \nu_s$$

Fermi type lagrangian term with coupling G_X^2 and a sterile potential term linear in G_X

$$V_S = -\sqrt{2} G_X \frac{8p}{3M_X^2} \rho_s$$

"small" G_X ($<10^4 G_F$) problem with BBN
"large" G_X ($>10^5$ G_F) problem with N_{eff} (smaller than 3 and neutrino mass bounds from CMB)

Bounds on non standard neutrino interactions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{\alpha,\beta} \mathcal{L}_{\rm NSI}^{\alpha\beta}$$

$$\mathcal{L}_{\rm NSI}^{\alpha\beta} = -2\sqrt{2} G_F \sum_P \varepsilon_{\alpha\beta}^P (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{e}\gamma_\mu P e)$$

New effective interactions between electron and neutrinos

$$\mathcal{L}_{\rm SM} = -2\sqrt{2} G_F \left\{ (\bar{\nu}_e \gamma^\mu L \nu_e)(\bar{e}\gamma_\mu L e) + \sum_{P,\alpha} g_P (\bar{\nu}_\alpha \gamma^\mu L \nu_\alpha)(\bar{e}\gamma_\mu P e) \right\}$$

$P = L,\, R = (1 \mp \gamma_5)/2$

$g_L = -\frac{1}{2} + \sin^2\theta_W$ and $g_R = \sin^2\theta_W$

Electron-Neutrino NSI

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\alpha,\beta} \mathcal{L}_{\text{NSI}}^{\alpha\beta}$$

$$\mathcal{L}_{\text{NSI}}^{\alpha\beta} = -2\sqrt{2} G_F \sum_P \varepsilon_{\alpha\beta}^{P} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{e} \gamma_\mu P e)$$

Breaking of Lepton universality ($\alpha=\beta$)

Flavour-changing ($\alpha \neq \beta$)

$$\varepsilon_{\alpha\beta}^{L,R}$$

Limits from scattering experiments,
LEP data, solar vs Kamland data…

Results

	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}(\%)$	$\delta\rho_{\nu\mu}(\%)$	$\delta\rho_{\nu\tau}(\%)$	N_{eff}
Instantaneous decoupling	1.40102	0	0	0	3
$\varepsilon^{L}_{ee} = 4.0$ $\varepsilon^{R}_{ee} = 4.0$	1.3812	9.47	3.83	3.83	3.357

Very large NSI parameters,
FAR from allowed regions

Results

	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}(\%)$	$\delta\rho_{\nu\mu}(\%)$	$\delta\rho_{\nu\tau}(\%)$	N_{eff}
Instantaneous decoupling	1.40102	0	0	0	3
$\varepsilon^{L}_{ee} = 0.12$ $\varepsilon^{R}_{ee} = -1.58$ $\varepsilon^{L}_{\tau\tau} = -0.5$ $\varepsilon^{R}_{\tau\tau} = 0.5$ $\varepsilon^{L}_{e\tau} = -0.85$ $\varepsilon^{R}_{e\tau} = 0.38$	1.3937	2.21	1.66	0.52	3.120

Large NSI parameters, still allowed by present lab data

Neutrino properties from CMB and LSS

LSS: neutrino mass scale (free streaming and suppression of perturbation growth on scales smaller than free streaming length

CMB: N_{eff} and neutrino mass scale (gravitational lensing)

Direct laboratory bounds on m$_\nu$

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

m(ν_e) < 2.2 eV (95% CL) Mainz

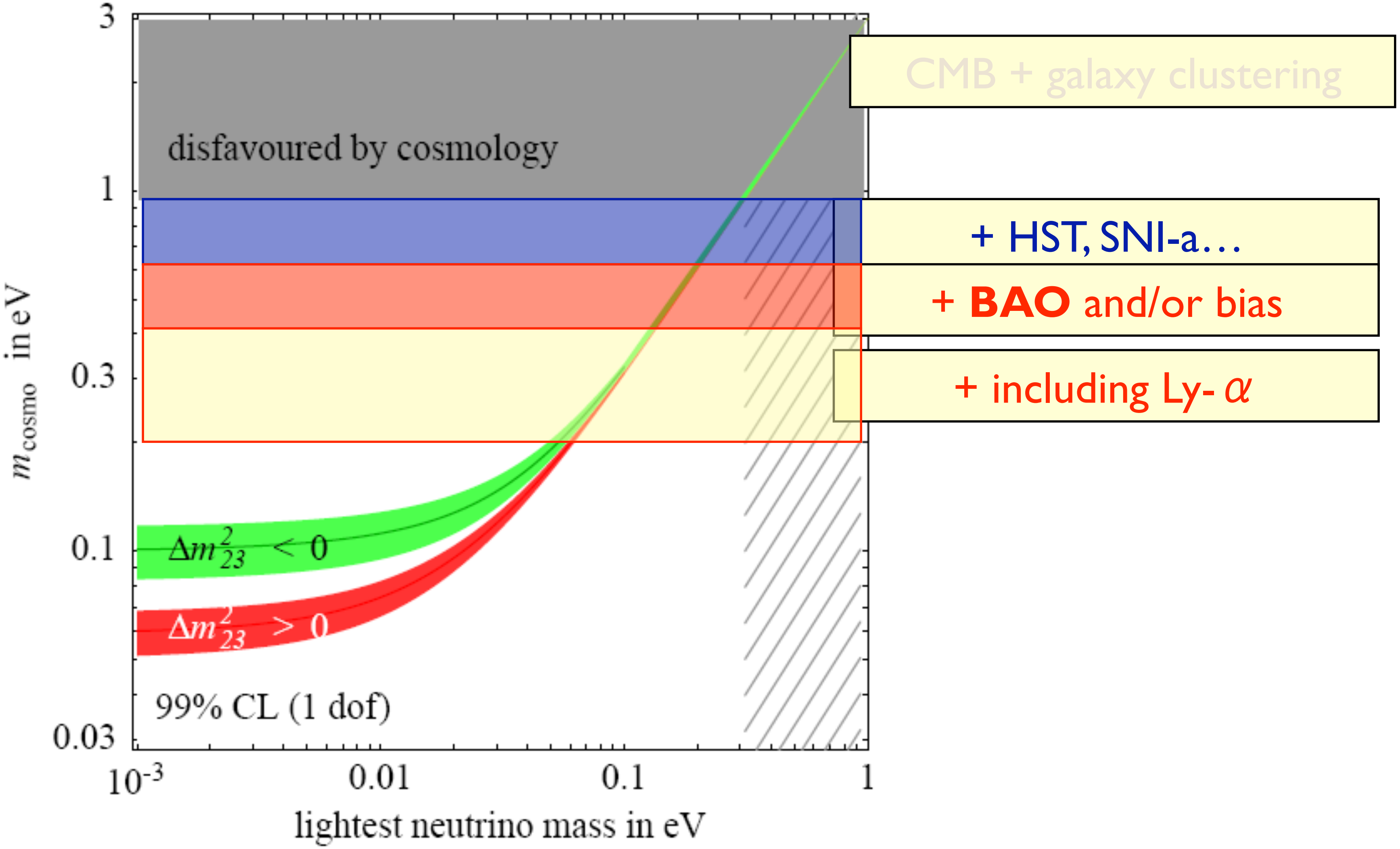
Future experiments (KATRIN) m(ν_e) ~ 0.2-0.3 eV

- Neutrinoless double beta decay: if Majorana neutrinos

$$(A,Z) \to (A,Z+2) + 2e^-$$

experiments with ^{76}Ge and other isotopes: $|m_{ee}| < 0.4 h_N$ eV

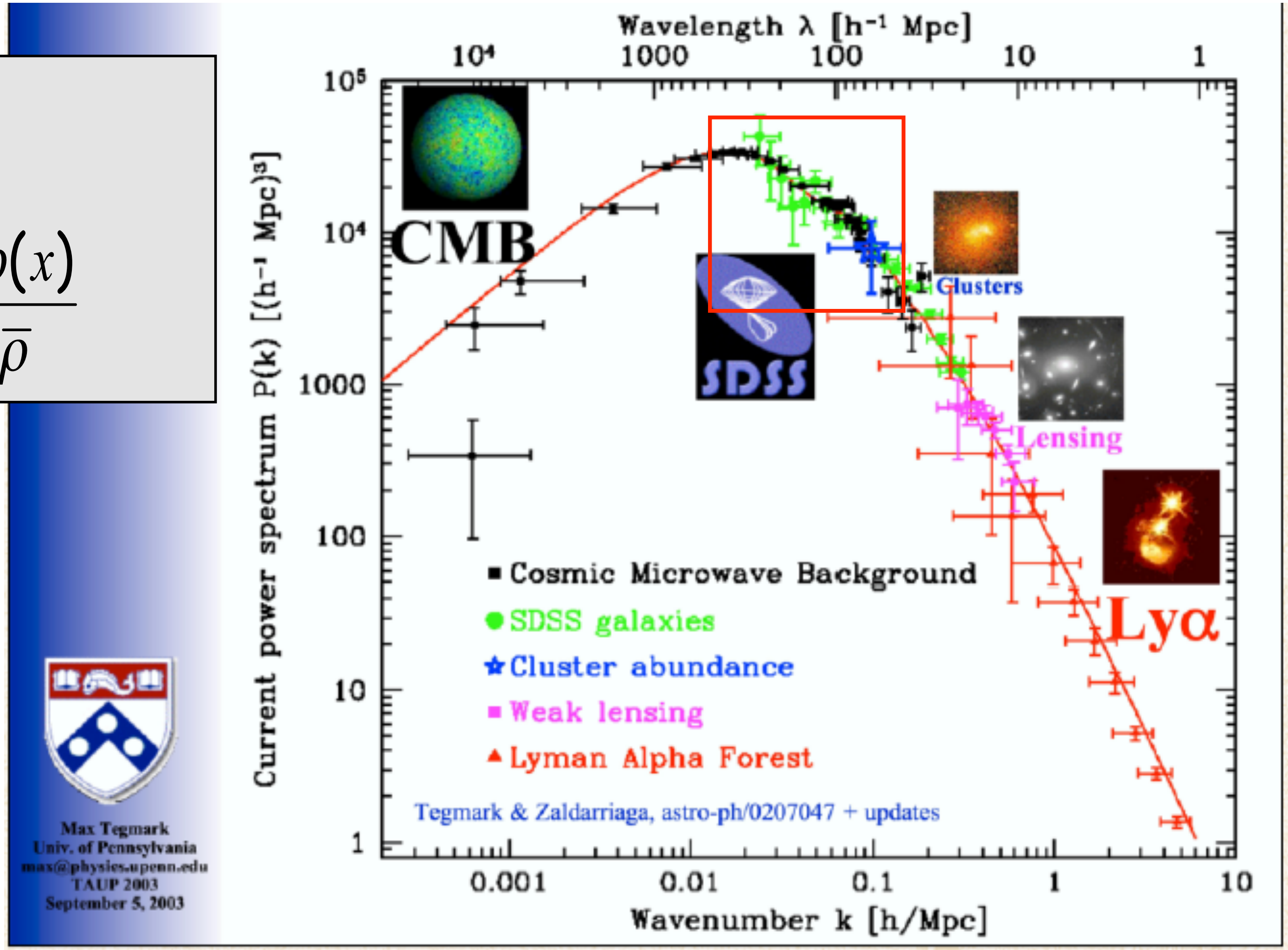
Neutrino masses in 3-neutrino schemes



Power Spectrum of density fluctuations

Field of density
Fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$



Neutrinos as Hot Dark Matter

Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

- Effect of Massive Neutrinos: suppression of Power at small scales

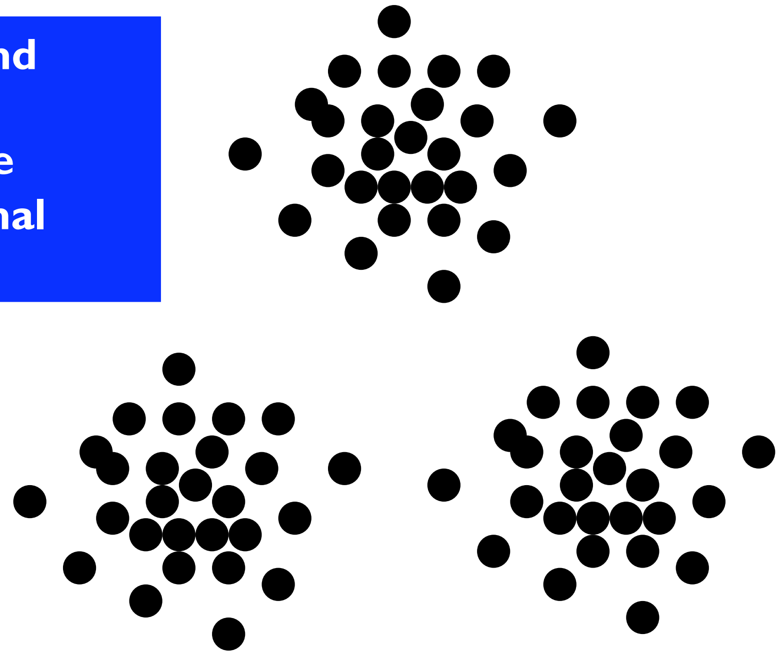
The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

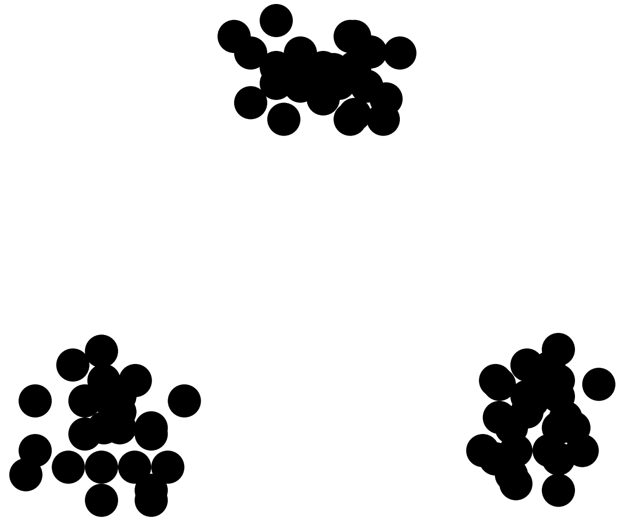
f_ν

Structure formation after equality

baryons and CDM experience gravitational clustering



baryons and CDM experience gravitational clustering

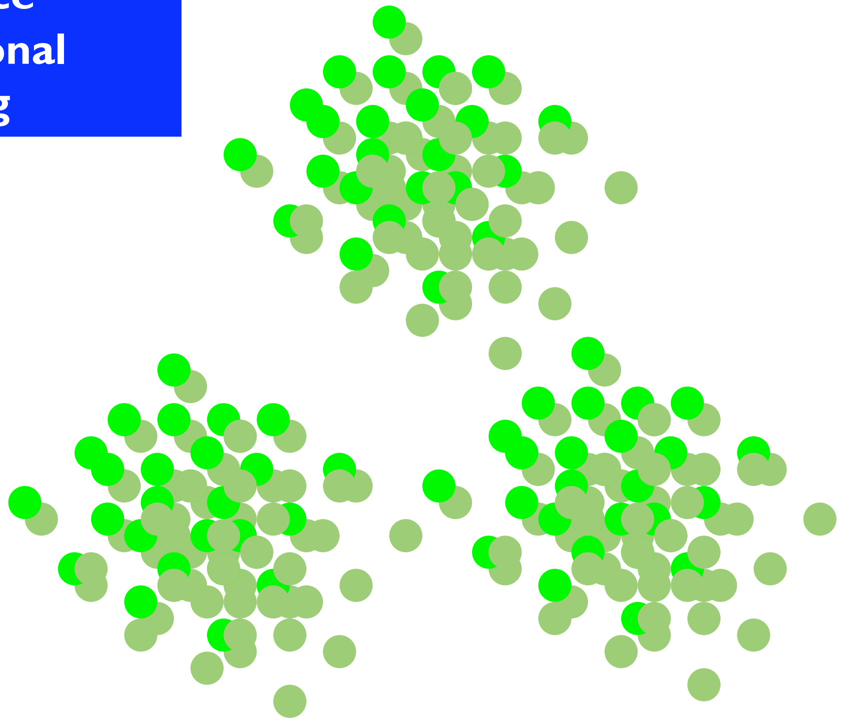


growth of $\delta\rho/\rho$ (k,t) fixed by

« gravity vs. expansion » balance

⇨ $\delta\rho/\rho \propto \mathbf{a}$

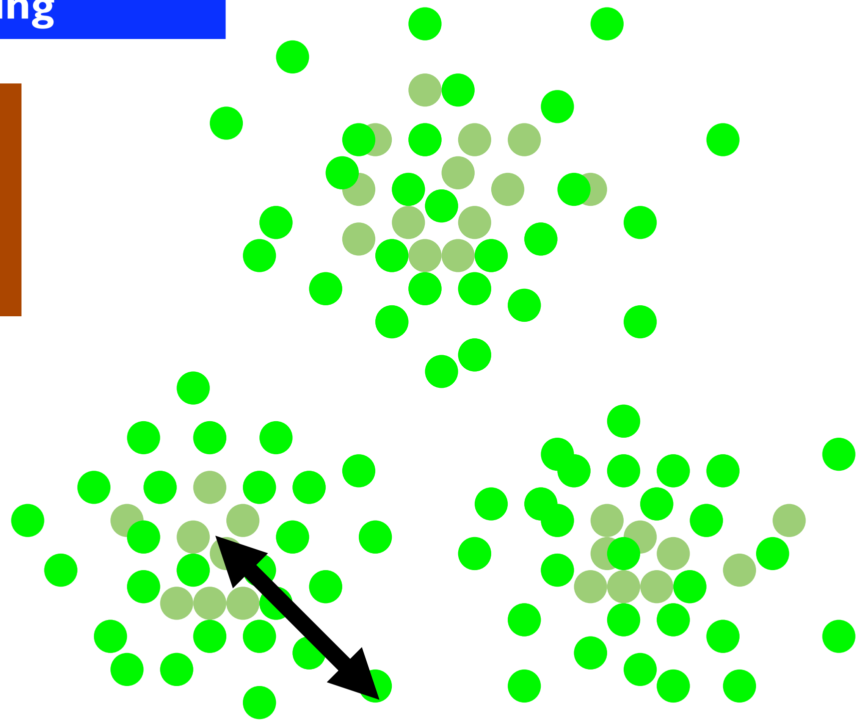
baryons and
CDM
experience
gravitational
clustering



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

baryons and CDM experience gravitational clustering

baryon and CDM experience gravitational clustering



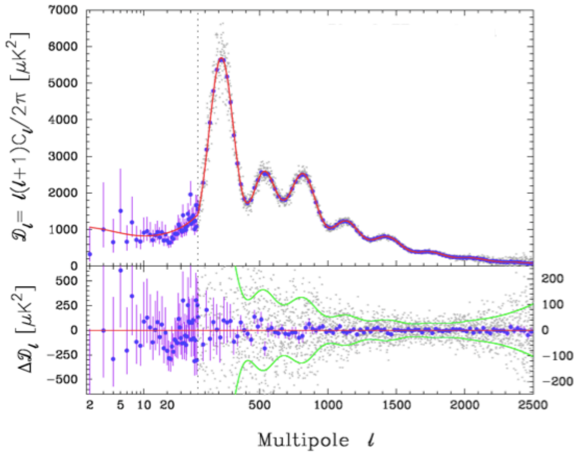
neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

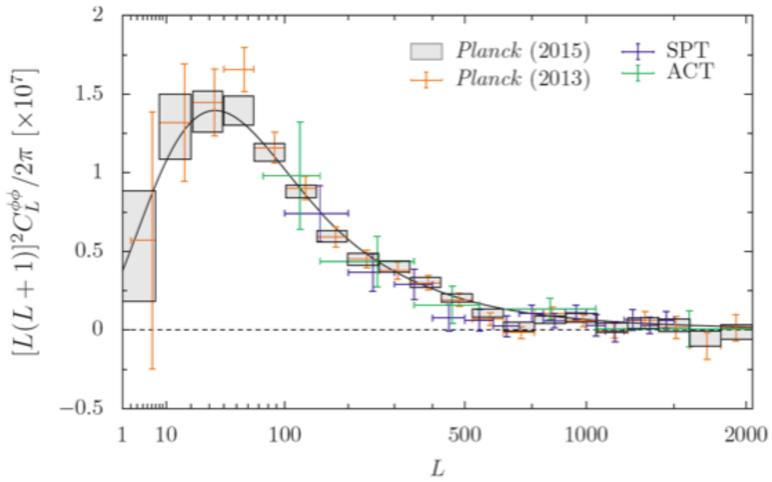
neutrinos cannot cluster below their diffusion length

$$\lambda = \int v \, dt/a \quad < \int c \, dt/a$$

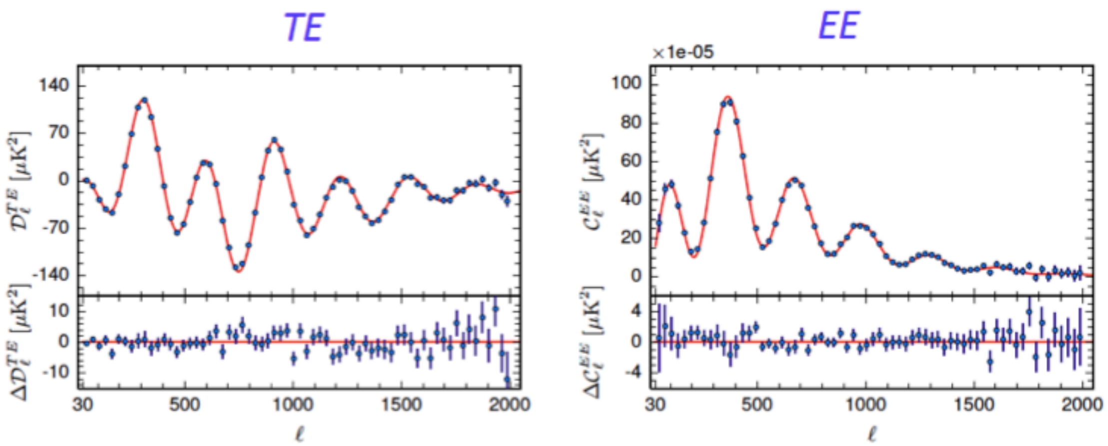
Planck 2015

Planck 2015 TT-spectrum





Planck 2015

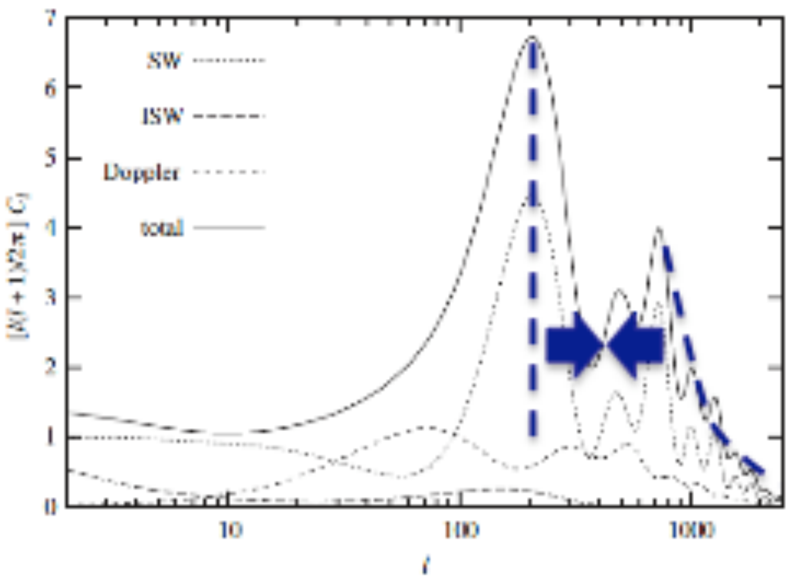


Are there neutrinos in the universe?

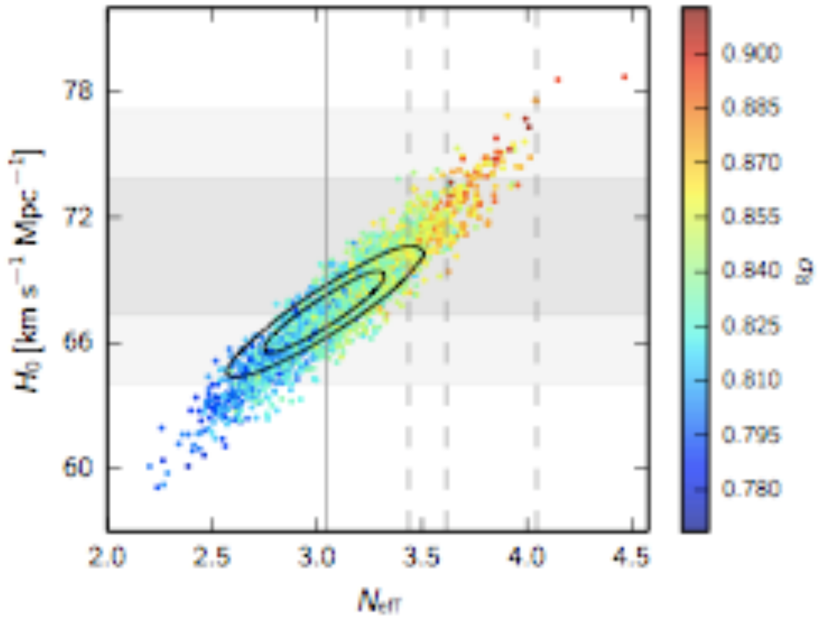
CMB
fixing the angular scale of acoustic peaks and
z_{eq} , a larger amount of dark radiation (and a larger H_0)
gives a higher expansion speed, a shorter age of the
universe T at recombination.

Diffusion length ≈ √T
(Brownian motion)

Sound horizon ≈ T



J. Lesgourgues, Planck 2014, Ferrara

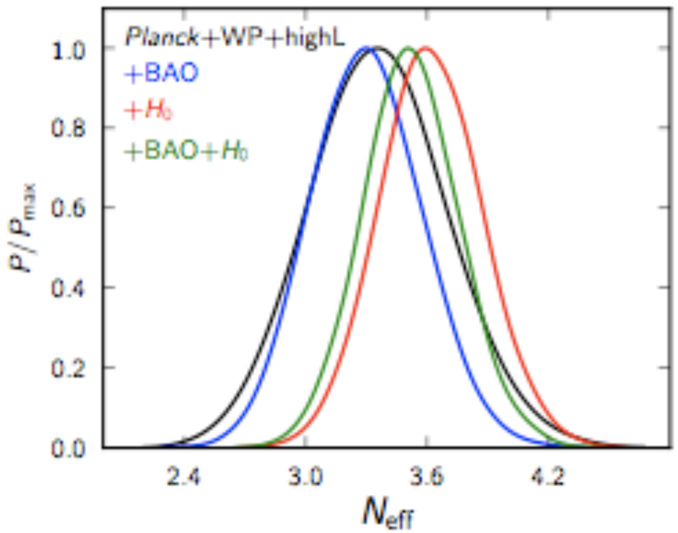


Planck 2015 results, XIII

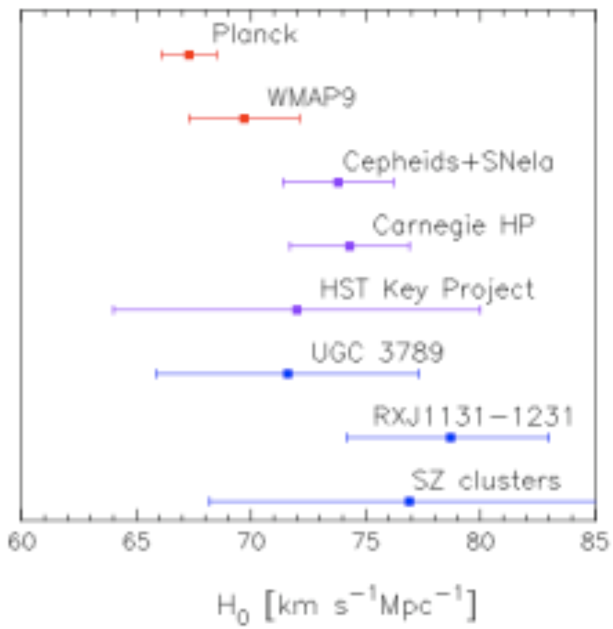
$N_{eff} > 0$ at 10 σ

How many of them? (the long tale of N_{eff})

Planck 2013 : a narrower 95 % C.L. range for N_{eff}, but still inconclusive. H_0 problem:



3.4±0.7
3.3±0.5
3.6±0.5
3.5±0.5



Ade et al. 2013
(Planck XVI)

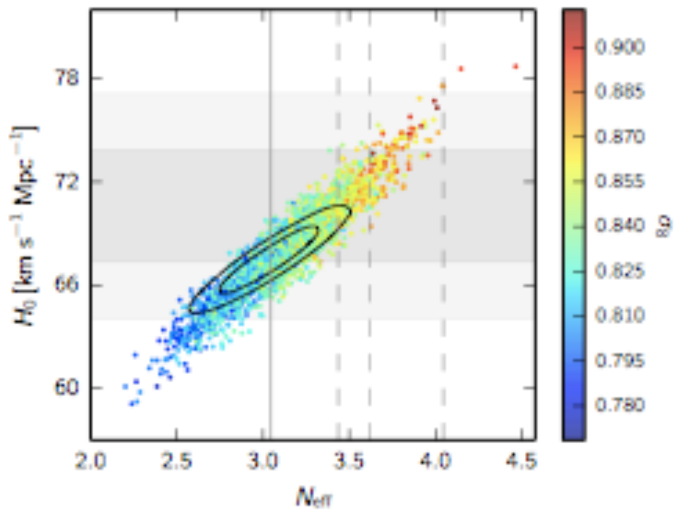
Planck 2015 :

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP};$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO};$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT,TE,EE+lowP};$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}.$$

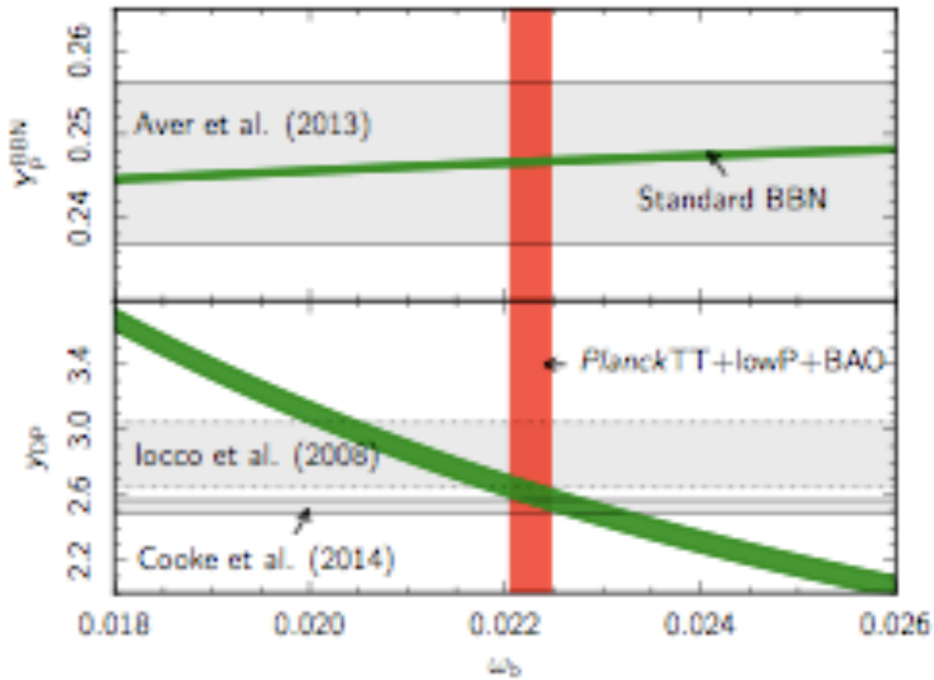
Standard expectation (3.045)

Caveat: discrepancy with SNIa value of H_0 at 2.2 σ level

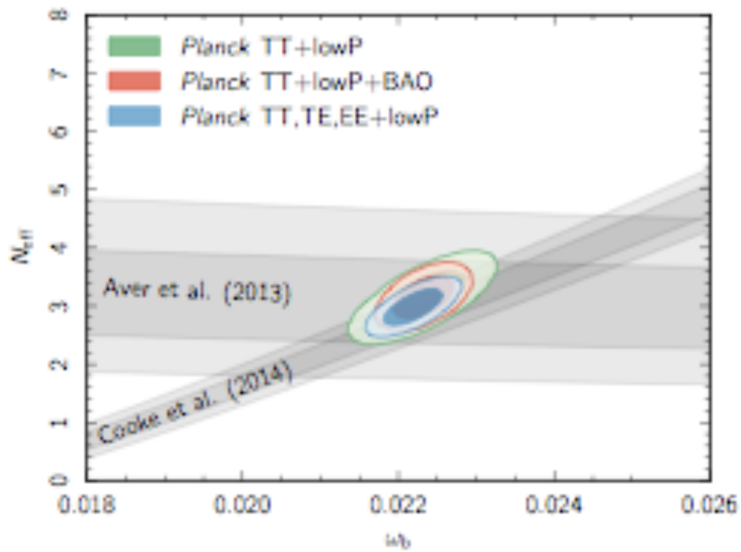
$\sigma_8 \approx 0.83$



CMB and BBN are quite consistent



Planck 2015 results, XIII



N_{eff} free

Neutrino mass from CMB

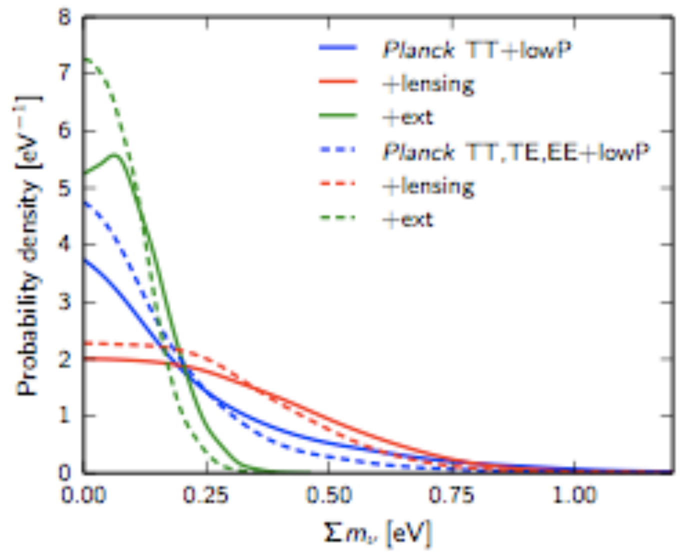
CMB:
For the expected mass range the main effect is around the first acoustic peak due to the early integrated Sachs-Wolfe (ISW) effect;

Planck: gravitational lensing. Increasing neutrino mass, increases the expansion rate at z **>** 1 and so suppresses clustering on scales smaller than the horizon size at the nonrelativistic transition (Kaplinghat et al. 2003 ; Lesgourgues et al. 2006). Suppression of the CMB lensing potential.

Total neutrino mass also affects the angular-diameter distance to last scattering, and can be constrained through the angular scale of the first acoustic peak. Degenerate with Ω_Λ (and so the derived H_0)

Including BAO constraint is much tighter:

$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$



Planck 2015 results, XIII

(keV) sterile neutrinos as warm dark matter

viable candidate as warm dark matter: not hot (decoupled when relativistic)neither cold (massive particles such as WIMP's).

Bounds

1) m_S > 0.4 keV (Tremain-Gunn): since they're fermions their local density cannot exceed the thermal Fermi degenerate gas density

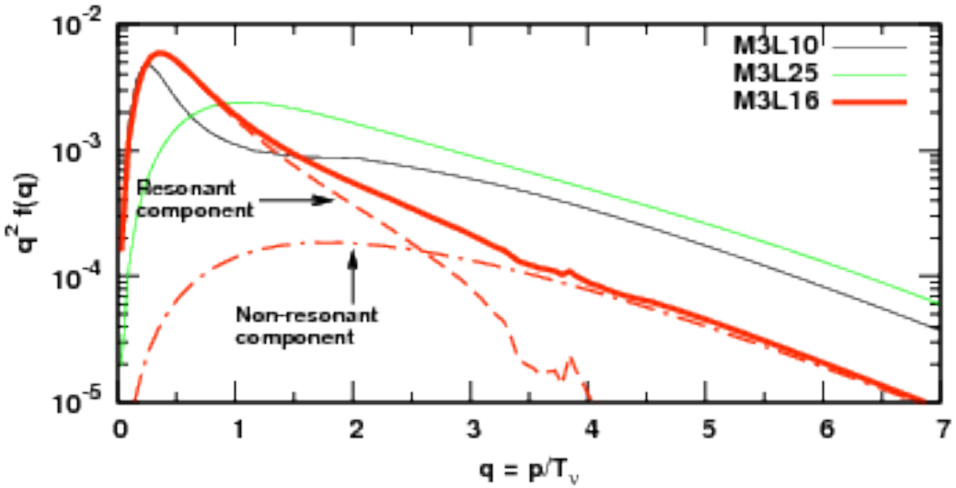
Non thermal production! Otherwise too much energy density!

$$\rho_S > 45 \text{ keV cm}^{-3}$$
$$\rho_{cr} = 10.5 \text{ h}^2 \text{ keV cm}^{-3}$$

Production via oscillations:

Resonant mode: a large active neutrino asymmetry can give a resonant matter effect

Non resonant mode:
lower sterile density.

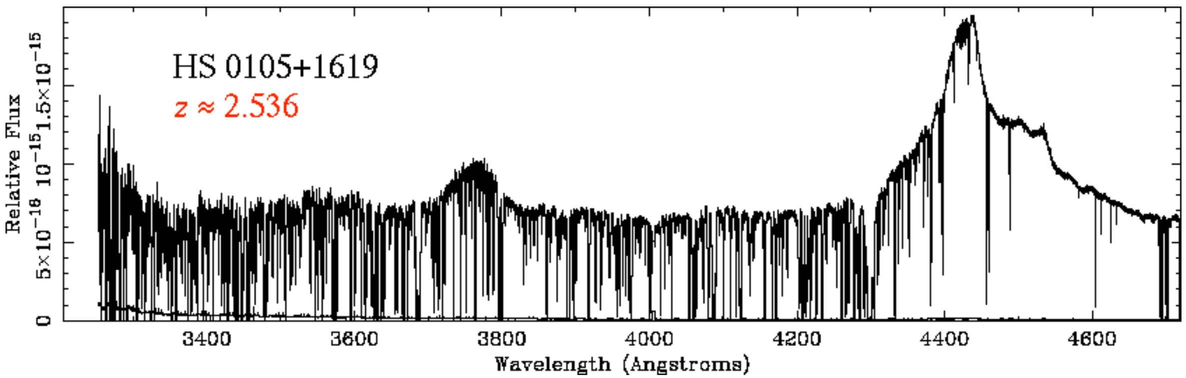


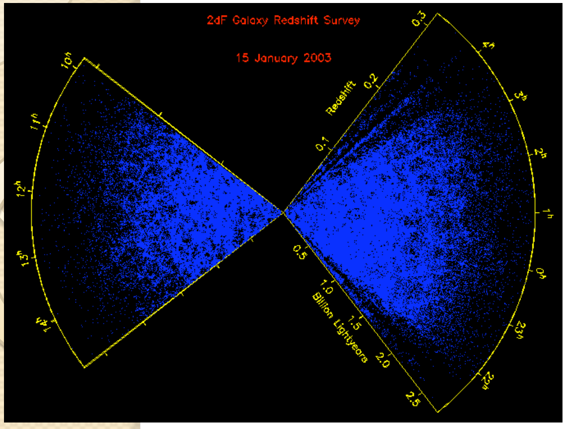
2) X ray signal from $\nu_S \rightarrow \nu + \gamma$

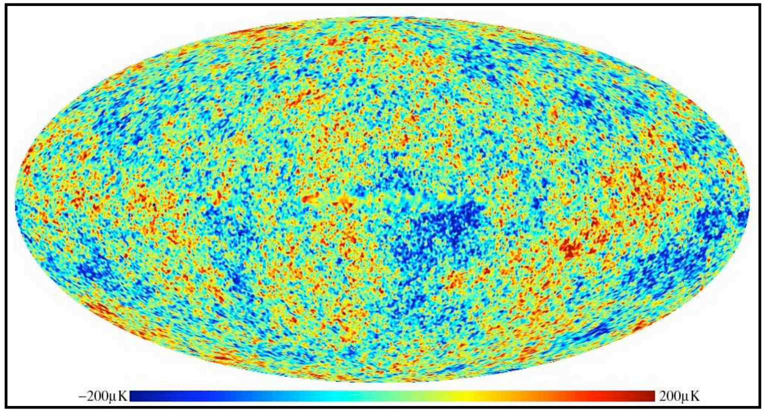
m_S <50 keV

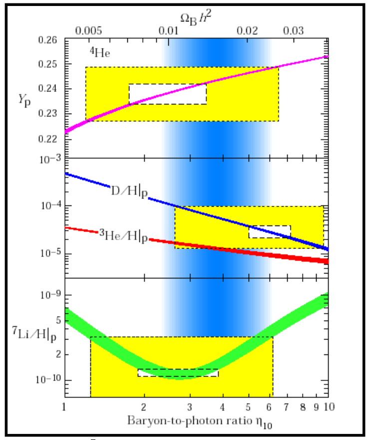
3) bounds from LSS. For warm dark matter the free streaming length is smaller: suppression of structure at a smaller scale with respect to hot dark matter: Ly α forest

m_S > 2 keV







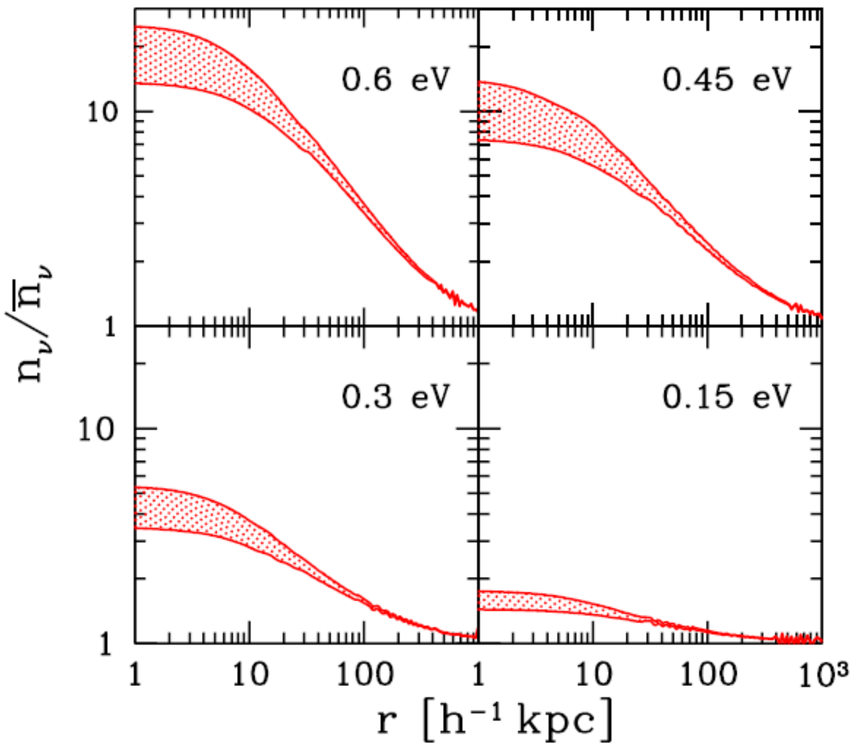


Several indirect effects of the neutrino background on cosmological observables

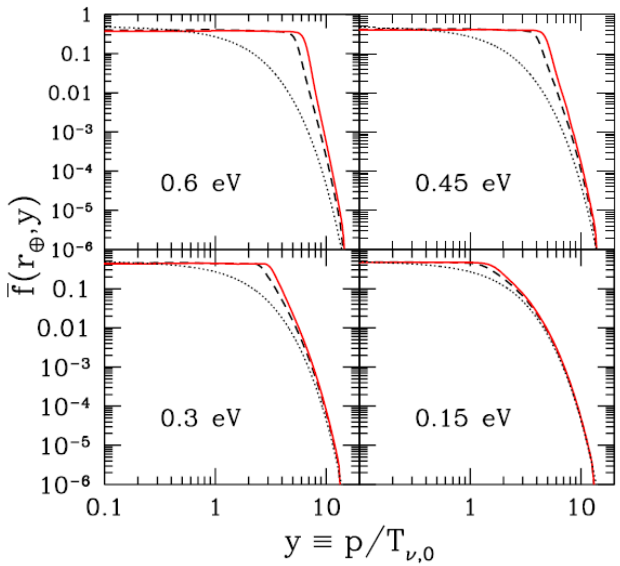
Informations on neutrino properties: mass oscillations, extra relativistic species, lifetime, magnetic moments,……

DIRECT OBSERVATION?

Tritium! See review of other approaches in S. Gariazzo talk



Ringwald and Wong '04



Milky Way (10^{12} M_{sun})

@ Earth

A ’62 paper by S. Weinberg and ν chemical potential

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

In the original idea a large neutrino chemical potential produces a distortion of the electron (positron) spectrum near the endpoint energy

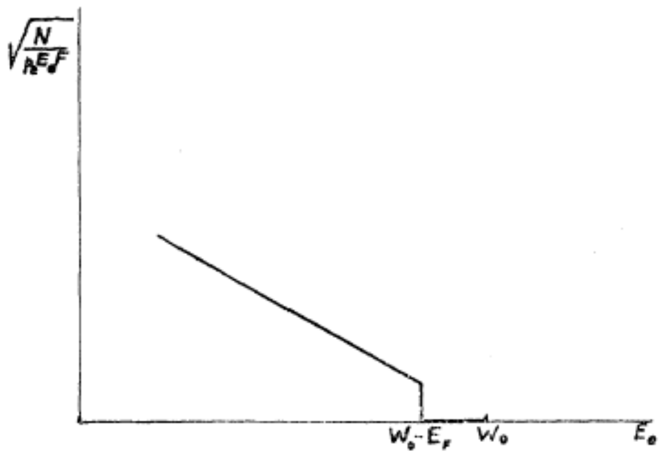


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

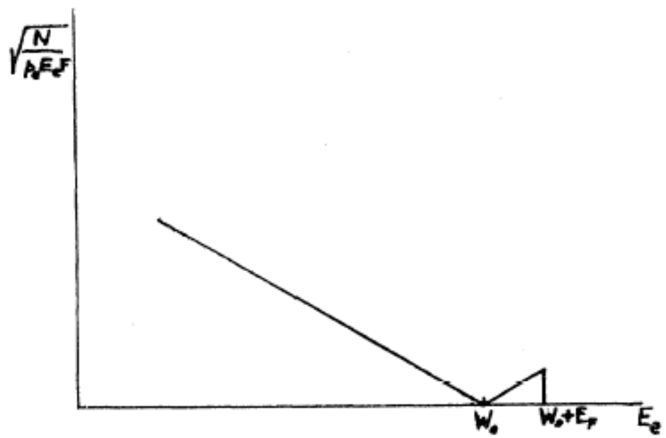
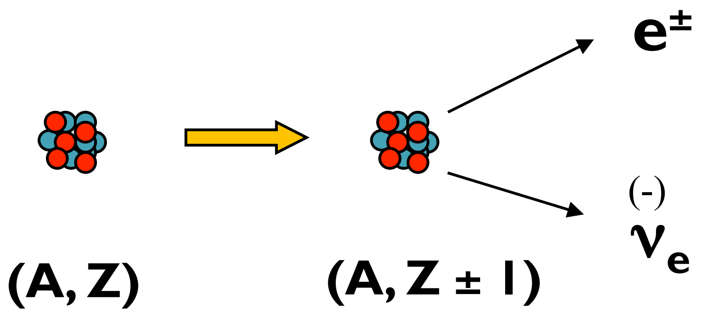


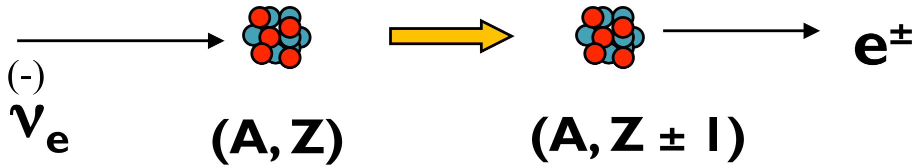
FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

Massive neutrinos and neutrino capture on beta decaying nuclei

Beta decay



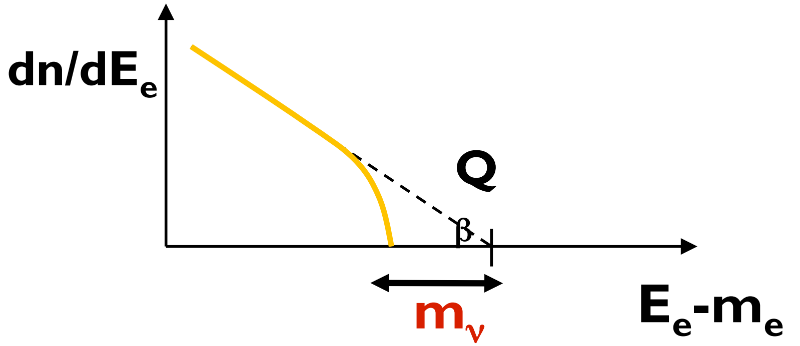
Neutrino Capture on a Beta Decaying Nucleus

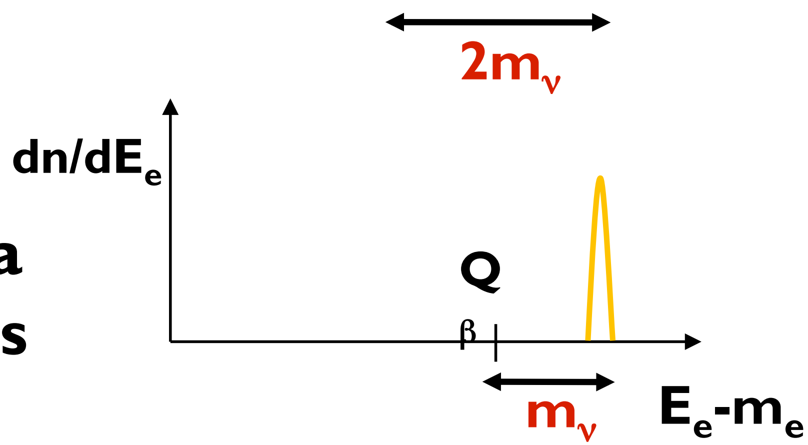


This process has no energy threshold !

Today we know that ν are NOT degenerate but are massive !!

Beta decay





Neutrino Capture on a Beta Decaying Nucleus

A 2 m_ν gap in the electron spectrum centered around Q_β

Two issues:

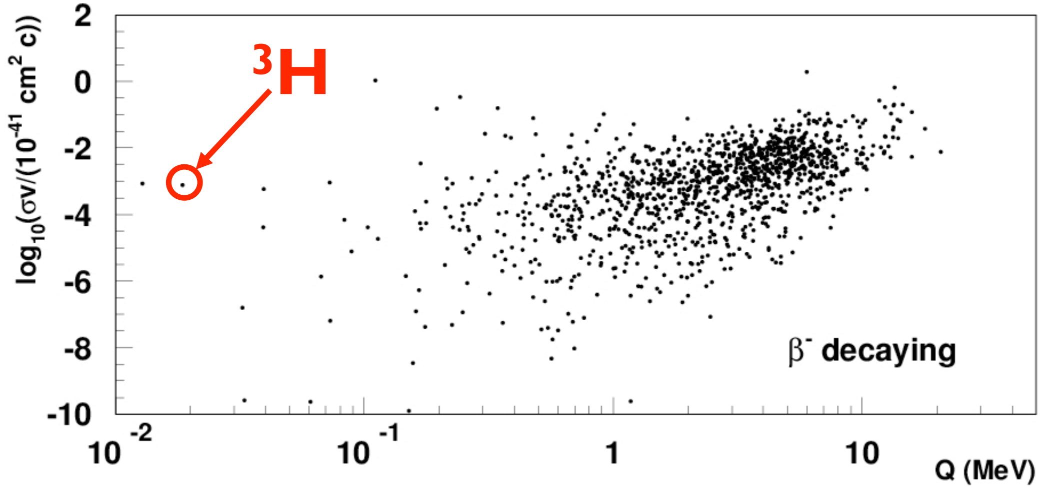
Rate

Background

NCB Cross Section Evaluation

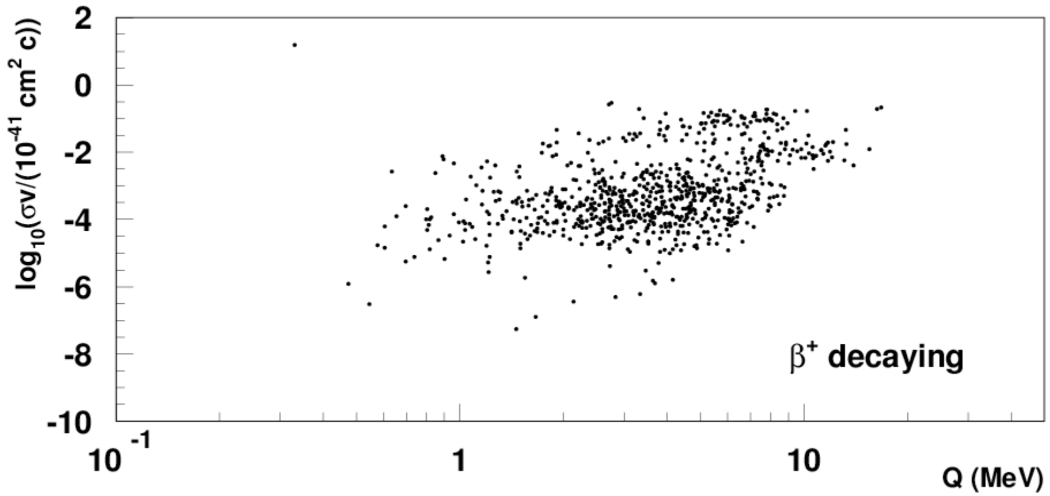
using measured values of Q_β and $t_{1/2}$

1272 β^- decays



A, Cocco et al, 2007

799 β^+ decays



Beta decaying nuclei having BR($\beta^\pm$) > 5 %
selected from 14543 decays listed in the ENSDF database

NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

Superallowed $0^+ \longrightarrow 0^+$ decays used for CVC hypotesis testing (very precise measure of Q_β and $t_{1/2}$)

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^{3}	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

Nuclei having the highest product $\sigma_{NCB}\, t_{1/2}$

The cosmological relic neutrino capture rate

$$\lambda_\nu = \int \sigma_{\rm NCB} v_\nu \, \frac{1}{\exp(p_\nu/T_\nu)+1} \, \frac{d^3 p_\nu}{(2\pi)^3}$$

$T_\nu = 1.7 \cdot 10^{-4}$ eV

$$2.85 \cdot 10^{-2} \, \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} \rm cm^2} \;\; \rm yr^{-1} \; mol^{-1}$$

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the previous expressions

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{\mathcal{A}}$$

In the case of Tritium:

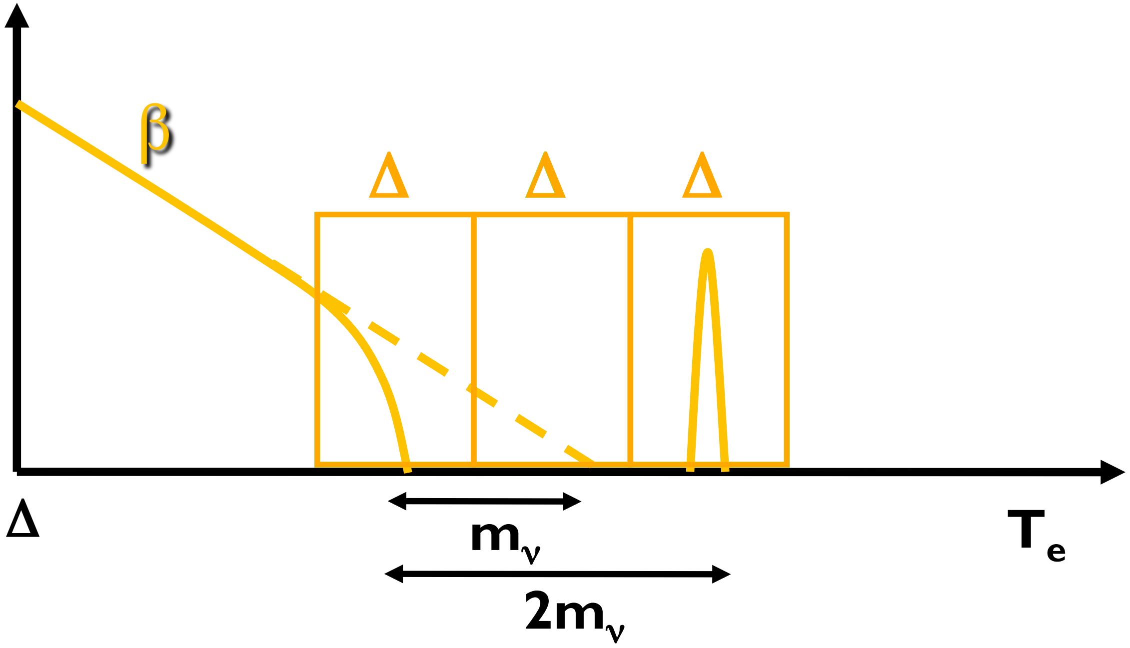
$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

Taking into account the beta decays occurring in the last bin of width Δ at the spectum end-point we have that

$$\frac{\lambda_\nu}{\lambda_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}} \sim 10^{-10}$$

signal to background ratio

Observing the last energy bins of width Δ



$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2}dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap

It works for $\Delta < m_\nu$

Discovery potential

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of 0.2 eV a signal to background ratio of 3 is obtained

In the case of 100 g mass target of Tritium it would take one and a half year to observe a 5σ effect

In case of neutrino gravitational clustering we expect a significant signal enhancement

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

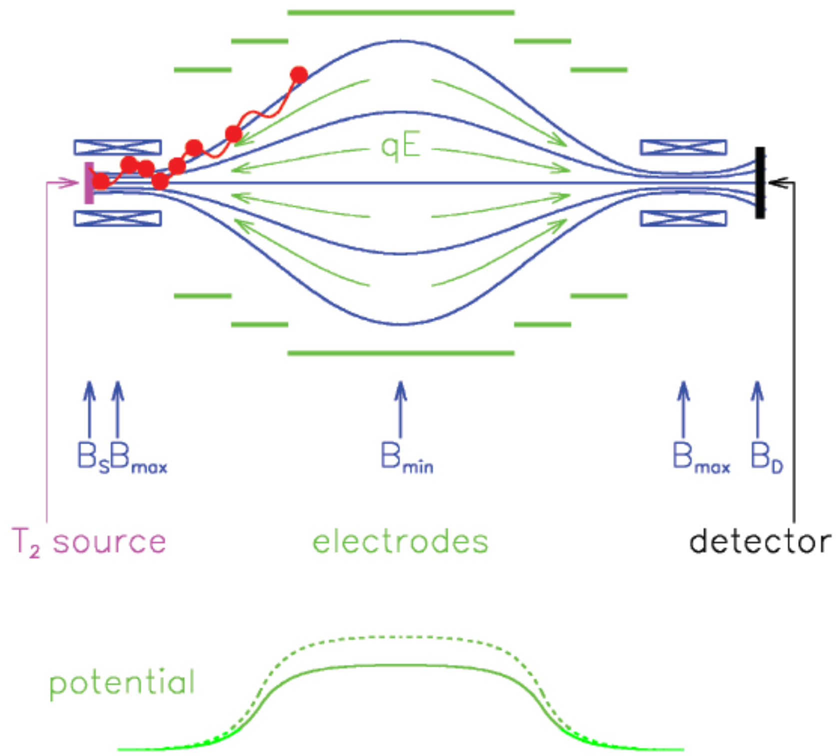
FD = Fermi-Dirac NFW= Navarro, Frenk and White MW=Milky Way (Ringwald, Wong)

KATRIN

Karlsruhe Tritium Neutrino Experiment

Aim at direct neutrino mass measurement through the study of the ^{3}H endpoint(Q_β =18.59 keV, $t_{1/2}$=12.32 years)

Phase I:
Energy resolution: 0.93 eV
Tritium mass: ~ 0.1 mg
Noise level 10 mHz
Sensitivity to ν_e mass: 0.2 eV



Magnetic Adiabatic Collimator + Electrostatic filter

PTOLEMY

Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], W. Sands[3], M. Schaefer[1], J. Taylor[1], C. G. Tully[3], R. Woolley[1], and A. Zwicker[1]