Topics in Neutrino Cosmology

Бруно Понтекорво

VII *International Pontecorvo Neutrino Physics School*

Prague, August 20-31 2017

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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?)

Summary

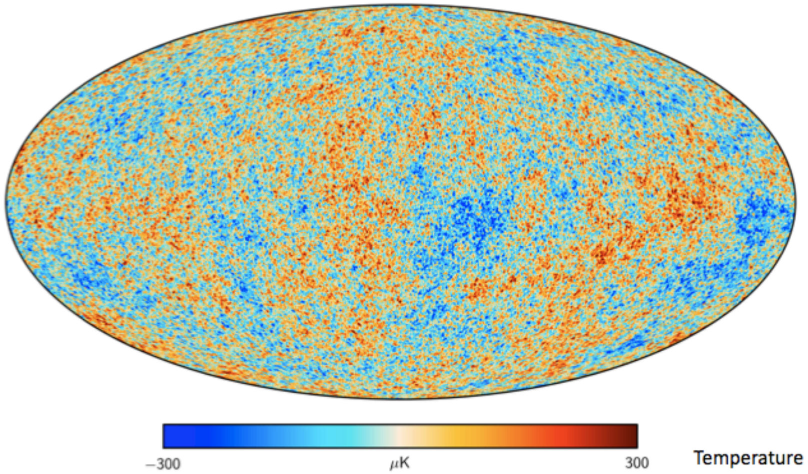
- review of neutrino properties and interactions (very brief)
- cosmology and statistical mechanics in an expanding universe (brief)
- ν distribution and mixing in the early universe (CNB=Cosmic Neutrino Background)
- CNB chemical potentials (asymmetries)
- BBN and neutrinos: ν asymmetries, extra radiation and N_{eff}
- sterile neutrinos
- exotic scenarios for sterile neutrinos

Summary

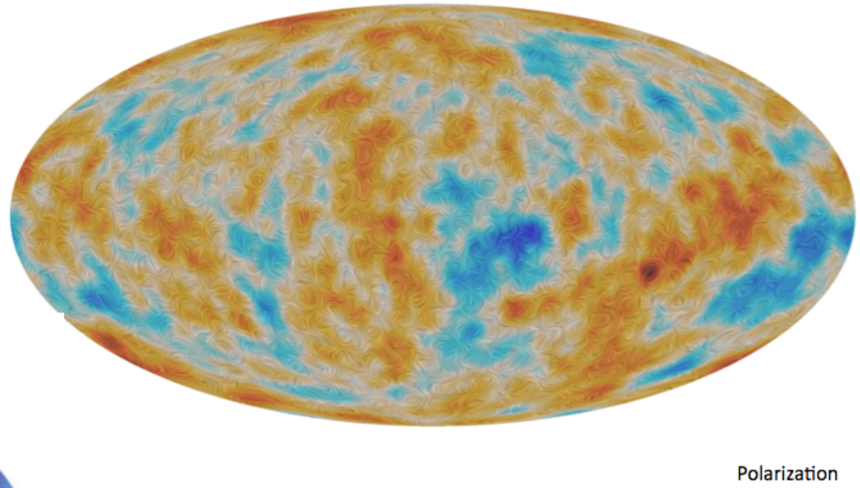
- ν non standard interactions
- ν properties from CMB anisotropies and LSS
- (keV) sterile neutrinos as warm dark matter
- ν background today and detection perspectives. Tritium decay and ν capture

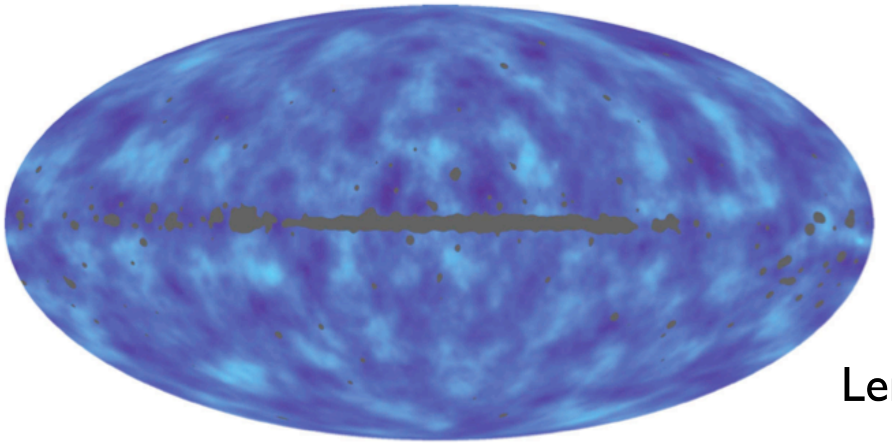
Planck 2015

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)

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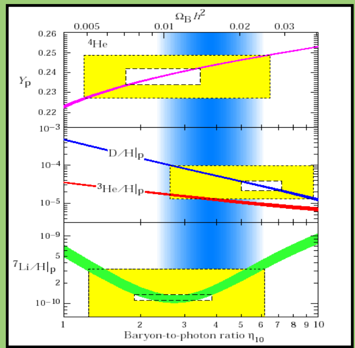
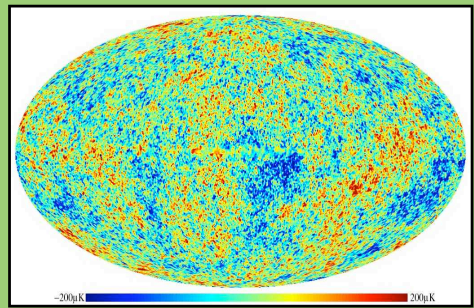
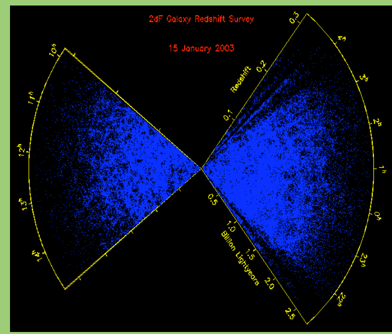
<tr><td></td><td></td><td></td></tr>
<tr><td>Primordial Nucleosynthesis
BBN</td><td>Cosmic Microwave Background
CMB</td><td>Formation of Large Scale Structures
LSS</td></tr>
<tr><td>T ~ MeV</td><td colspan="2">T < eV</td></tr>
<tr><td>ν_e versus $\nu_{\mu,\tau}$ N_{eff}</td><td colspan="2">No flavour sensitivity N_{eff} & m_ν</td></tr>
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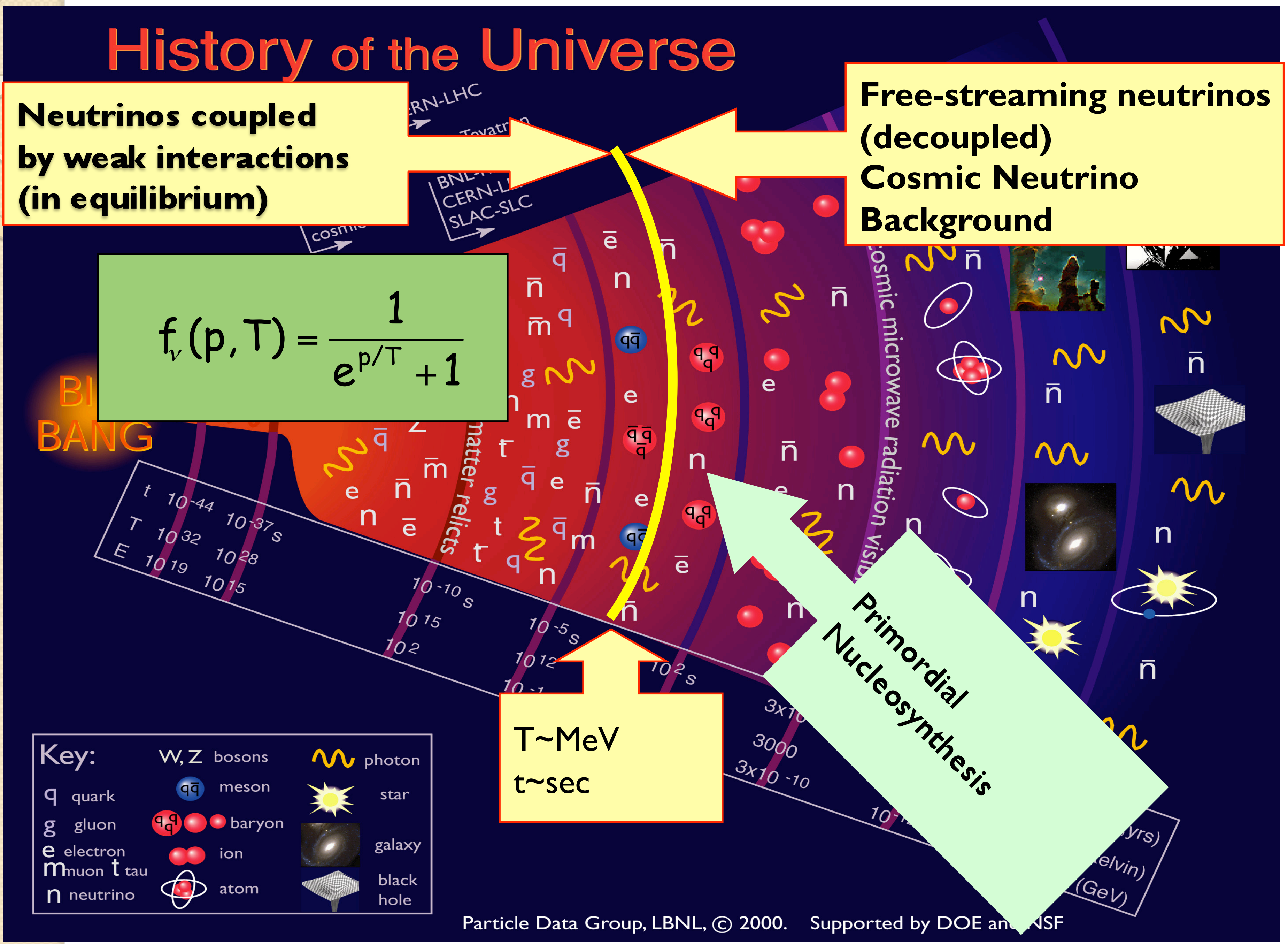
History of the Universe



Neutrinos coupled by weak interactions (in equilibrium)

Free-streaming neutrinos (decoupled) Cosmic Neutrino Background

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

T~MeV
t~sec

Primordial Nucleosynthesis

Suggested References

Books

The Early Universe, E. Kolb & M. Turner (Addison-Wesley, 1990)

Modern Cosmology, S. Dodelson (Academic Press, 2003)

Kinetic theory in the expanding Universe, J. Bernstein
(Cambridge U., 1988)

Neutrino Cosmology, J. Lesgourgues, G.M, G. Miele & S. Pastor
(Cambridge U., 2013)

Reviews

Neutrino Cosmology,
A.D. Dolgov*, Phys. Rept. 370 (2002) [hep-ph/0202122]*

Massive neutrinos and cosmology,
J. Lesgourgues & S. Pastor*, Phys. Rep. 429 (2006) [astro-ph/0603494]*

Primordial Nucleosynthesis: from precision cosmology to fundamental physics,
F. Iocco et al, *Phys. Rept. 472 (2009) arXiv:0809.0631 [astro-ph]*

Review of neutrino properties and interactions

three active weakly interacting states (LEP, N=2.984 ± 0.008)

$$L^{\text{int}} = -\frac{g}{2\sqrt{2}} J_W^\mu W_\mu - \frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu + h.c.$$

$$J_W^\mu \supset 2\bar{\nu}_{iL}\gamma^\mu l_L^i$$

$$J_Z^\mu \supset 2g_{\nu L}\bar{\nu}_{iL}\gamma^\mu \nu_L^i + 2g_{lL}\bar{l}_{iL}\gamma^\mu l_L^i + 2g_{lR}\bar{l}_{iR}\gamma^\mu l_R^i$$

with couplings:

$$g_{aL} = T_{3a} - Q_a \sin^2\theta_W, \quad g_{aR} = -Q_a \sin^2\theta_W$$

Notice: fields are not in general mass eigenstates but flavour eigenstates (oscillations!)

Similarly for quarks.

Diagonalizing mass terms in the Higgs sector, charged (not neutral ones!!) currents in mass eigenstates become

$$J_W^{\mu} = 2\overline{\nu}_{iL}\gamma^{\mu}U_{j}^{PMNS,i}l_L^{j} + 2\overline{u}_{iL}\gamma^{\mu}U_{j}^{CKM,i}d_L^{j}$$

flavour oscillations!

In the following, low energy regime of neutrino interactions (well below W and Z mass scale) and the tree level process amplitudes can be described in terms of contact (Fermi) interactions

$$L_{eff}^{CC} = -\frac{G_F}{\sqrt{2}} J_W^{\mu+} J_{\mu W}$$

$$J_Z^{\mu} = -\frac{G_F}{\sqrt{2}} \frac{M_W^2}{M_Z^2 \cos\theta_W^2} J_Z^{\mu+} J_{\mu Z}$$

examples:

- lepton scatterings

Process $1+2 \longrightarrow 3+4$	$3\pi G_F^{-2}\, \sigma_{12\to 34}$
$\nu_e + \overline{\nu}_e \longrightarrow \nu_e + \overline{\nu}_e$	s
$\nu_e + \nu_e \longrightarrow \nu_e + \nu_e$	$\frac{3}{2}\, s$
$\nu_e + \overline{\nu}_e \longrightarrow \nu_{\mu(\tau)} + \overline{\nu}_{\mu(\tau)}$	$\frac{1}{4} s$
$\nu_e + \overline{\nu}_{\mu(\tau)} \longrightarrow \nu_e + \overline{\nu}_{\mu(\tau)}$	$\frac{1}{4} s$
$\nu_e + \nu_{\mu(\tau)} \longrightarrow \nu_e + \nu_{\mu(\tau)}$	$\frac{3}{4}\, s$
$\nu_e + \overline{\nu}_e \longrightarrow e^+ + e^-$	$\frac{4}{\sqrt{s}}\sqrt{s-4m_e^2}[(s-m_e^2)(\tilde{g}_L^{l2} + g_R^{l2}) + 6m_e^2 \tilde{g}_L^l g_R^l]$
$e^+ + e^- \longrightarrow \nu_e + \overline{\nu}_e$	$\frac{\sqrt{s}}{2\sqrt{s-4m_e^2}}[(s-m_e^2)(\tilde{g}_L^{l2} + g_R^{l2}) + 6m_e^2 \tilde{g}_L^l g_R^l]$
$\nu_e + e^- \longrightarrow \nu_e + e^-$	$(3\, s\, \tilde{g}_L^{l2} + s\, g_R^{l2} - 3\, m_e^2\, \tilde{g}_L^l\, g_R^l)$
$\overline{\nu}_e + e^- \longrightarrow \overline{\nu}_e + e^-$	$(3\, s\, g_R^{l2} + s\, \tilde{g}_L^{l2} - 3\, m_e^2\, \tilde{g}_L^l\, g_R^l)$

-neutron β decay and n-p charged current processes. Crucial to set the final value of neutron to proton density ratio at the onset of Big Bang Nucleosynthesis. At tree level and in the infinite nucleon mass (C_V=0.97425, C_A/C_V=-1.2701)

$$\cos\theta_C \langle p|\overline{u}\gamma^\mu(1-\gamma_5)d|n\rangle \approx \overline{u}_p\gamma^\mu(C_V - C_A\gamma_5)u_n$$

EXERCISE 1

Compute the neutron lifetime in the infinite nucleon mass limit (but with fixed $Q=M_n-M_P$, at tree level (Born amplitude). Verify that:

$$\tau_n^{-1} = \frac{G_F^2 (C_V^2 + 3C_A^2)}{2\pi^3} \int_1^{Q/m_e} x\, dx \left(x - \frac{Q}{m_e} \right)^2 \left(x^2 - 1 \right)^{1/2}$$

which using the values of C_V, C_A and $Q=M_n- M_P= 1.29$ MeV, gives a value 10% off with respect with the experimental value,

$\tau_n \approx 880.1$ sec.

What is wrong then?

Review of neutrino properties and interactions

Oscillations in vacuum

$$|\nu_a\rangle(t) = U^*_{ai}|\nu_i\rangle\ e^{-iE_i t}$$

a flavour eigenstates (production and detection)

i mass eigenstates (evolution)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

for relativistic states, $E_i(p) \approx p + m_i^2/2p$

oscillation/survival probabilities

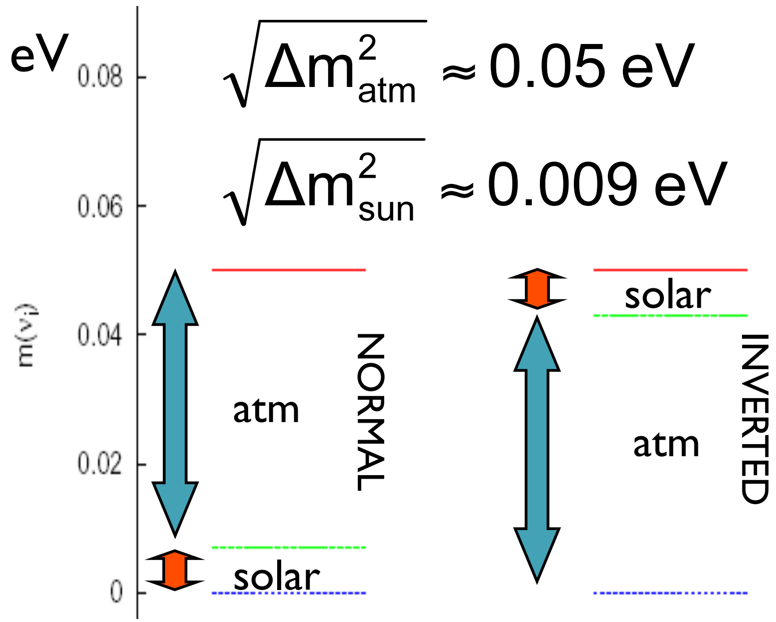
$$P(\nu_a \rightarrow \nu_b) = U^*_{ai}U_{bi}U_{aj}U^*_{bj}\exp(-i\ \Delta m^2_{ij}\ \mathrm{L}/2\mathrm{p})$$

"solar" $\delta m^2 \approx 7\ 10^{-5}\ eV^2$ $\sin^2\theta_{12} \approx 0.3$

"atmospheric" $\Delta m^2 \approx 2\ 10^{-3}\ eV^2$ $\sin^2\theta_{23} \approx 0.5$ (?)

"absolute" ?? $M_\beta < 2$ eV (^3H decay) $\sin^2\theta_{13} \approx 0.02$

hierarchy ??



Oscillations in matter

$$H_a^{eff} = \overline{\nu}_a \gamma^\mu (1-\gamma_5)\nu_a Tr(\rho_f J_{f,\mu})$$

$$\rho_f = \int \frac{d^3p}{2E(p)} \sum_h f(p,h) \left| f(p,h) \right\rangle \left\langle f(p,h) \right|$$

$J_{f,\mu}$ charged/neutral current of fermions in the medium (leptons, baryons)

Ex. only (unpolarized) electrons and baryons (Sun)

$$Tr(\rho_f J_{f,\mu}) = \int \frac{d^3p}{2E(p)} f(p) Tr[(p+m_f)\gamma_\mu (g'_V - g'_A \gamma_5)] = 4g'_{V,f} \left\langle p_\mu \right\rangle$$

$g'_{V,f}$ = 1(CC) + $g_{V,f}$ (NC)

matter potential

$V_{CC+NC}(\nu_e) = \sqrt{2}\, G_F\, (n_e - n_n/2)$ $V_{NC}(\nu_{\mu,\tau}) = -\sqrt{2}\, G_F\, n_n/2$

$$i\frac{d}{dL}\left|\nu_a\right\rangle = (U^*_{ai}E_iU_{ib} + V_a\delta_{ab})\left|\nu_b\right\rangle$$

In the early universe, at the MeV epoch (neutrino decoupling) baryons and almost the same number of electrons and positrons (from BBN, CMB and charge neutrality we know that $n_{e-} - n_{e+} \approx 10^{-9}\, n_\gamma$, so the two contribution of opposite sign almost cancel!)

More relevant the contribution expanding W propagator at second order

$$D_{\mu\nu}(p) = \frac{g_{\mu\nu}}{M_W^2} + \frac{1}{M_W^4}(g_{\mu\nu}p^2 - p_\mu p_\nu)$$

$$\Rightarrow V_{CC} = \sqrt{2}G_F\left(n_{e-} - n_{e+} + \frac{8p}{3M_W^2}(\rho_{e-} + \rho_{e+})\right)$$

Resonance in matter (MSW)

removing the diagonal neutral current contribution via a phase redefinition, in a two flavour scheme we have (atmospheric or solar)

$$\mathcal{H}_F = \frac{1}{4|\vec{p}|}(\Delta m^2 + 2|\vec{p}|V_{CC})\mathbb{I} + \frac{1}{4|\vec{p}|}\begin{pmatrix} -\Delta m^2\cos(2\theta) + 2|\vec{p}|V_{CC} & \Delta m^2\sin(2\theta) \\ \Delta m^2\sin(2\theta) & \Delta m^2\cos(2\theta) - 2|\vec{p}|V_{CC} \end{pmatrix}$$

resonance condition: first term is diagonal, second term diagonal via an orthogonal trasformation

$$\tan 2\theta_M = \tan 2\theta \left[1 - \frac{2|\vec{p}|V_{CC}}{\Delta m^2\cos 2\theta}\right]^{-1}$$

$$\Delta m^2_M = \sqrt{(\Delta m^2\cos 2\theta - 2|\vec{p}|V_{CC})^2 + (\Delta m^2\sin 2\theta)^2}$$

$$n_e^{res} = \frac{\Delta m^2\cos 2\theta}{2\sqrt{2}G_F p}$$

Cosmology and statistical mechanics in an expanding universe

The FLRW Model describes the evolution of the isotropic and homogeneous expanding Universe

$$\boxed{ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right)}$$

a(t) **is the scale factor and** *k=-1,0,+1* **the curvature**

Einstein eqs $\rightarrow$ $\boxed{G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}}$

Energy-momentum tensor of a perfect fluid $\rightarrow$ $\boxed{T_a^b = (\rho + P)u_a u^b + P\delta_a^b}$

Cosmological constant $\rightarrow$ $\boxed{\Lambda}$

Eqs in the SM of Cosmology

00 component (Friedmann eq) ➡

$$\boxed{H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{k}{a^2}}}$$

H(t) **is the Hubble parameter**

$$H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$1 + z = a(today)/a$ redshift

$$\boxed{\frac{k}{H(t)^2 a^2} = \Omega - 1}$$

$\Omega = \rho/\rho_{crit}$

$$\boxed{\dot{\rho} = \frac{d\rho}{dt} = -3H(p+p)}$$

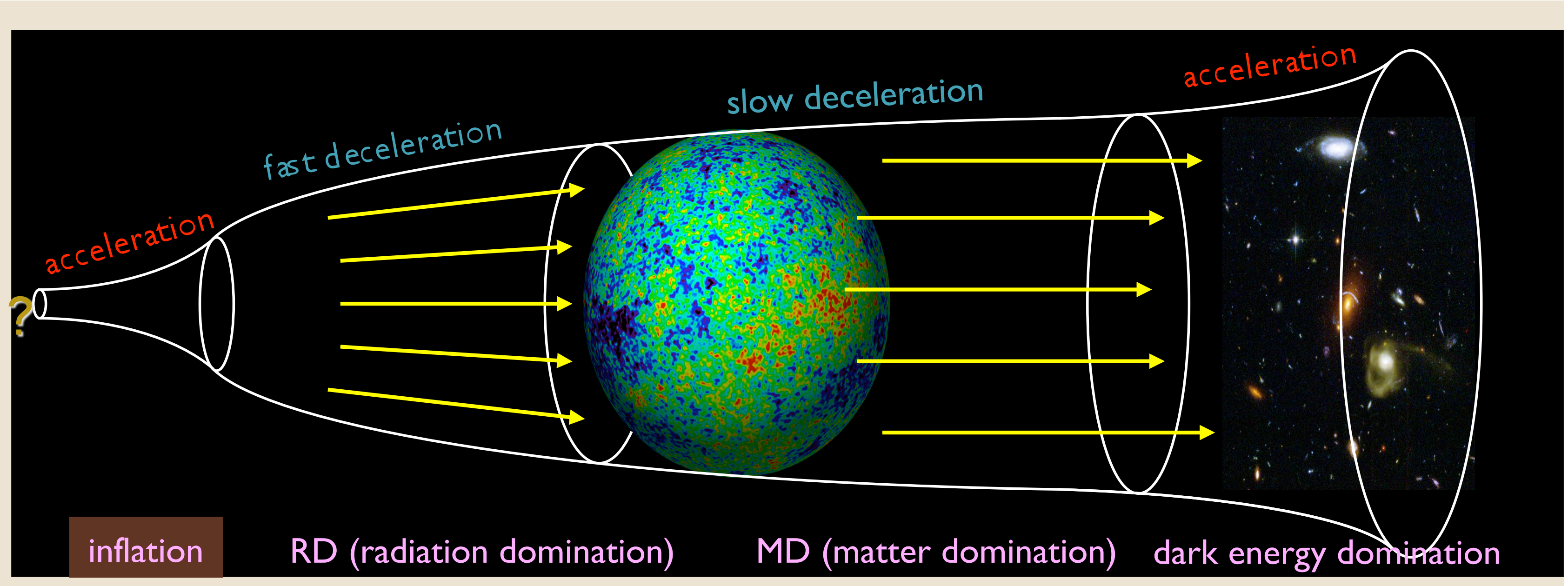
$\rho_{crit} = 3H^2/8\pi G$ **is the critical density**

Eq of state p=αρ ➡ $\rho = \text{const } a^{-3(1+\alpha)}$

Radiation α=1/3	Matter α=0	Cosmological constant α=-1
$\rho_R \sim 1/a^4$	$\rho_M \sim 1/a^3$	$\rho_\Lambda \sim$ const

Evolution of the Universe

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



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

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

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

definition of momentum

$$P^a = \frac{dx^a}{ds}, \qquad \frac{dP^a}{ds} = -\Gamma^a_{bc} P^b P^c \qquad \Gamma^c_{ab} = \frac{1}{2} g^{cd} \left(\partial_a g_{db} + \partial_b g_{ad} - \partial_d g_{ab} \right)$$

$$g_{ab} P^a P^b = -m^2$$

EXERCISE II

Compute the Levi Civita connection for a spatially flat (k=0) FLRW universe and show that P^i decreases as a^{-2}

comoving momentum: $p_a = g_{ab} P^b$, $y = \Sigma_i \, p_i^2$ y = constant

"physical momentum": rate of change in physical distances:
$p = a(t)\, P$, $-E^2 + p^2 = -m^2$ p behaves as $1/a$

current density n_a and $T^a{}_b$

macroscopic approach: perfect fluid (no viscosity)

$T^a{}_b=(\rho+P)u^a u_b + P\,\delta^a{}_b$

$n_a=N\,u_a$ (N = number density in the fluid comoving frame, $u^a=(1,0,0,0)$)

microscopic description

$$T_a^b = g\int \frac{d^4P}{(2\pi)^4}(-g)^{1/2}P^a P_b 2(2\pi)\ \theta(P_0)\delta(P_c P^c + m^2) f(P,t)$$

$$n_a = g\int \frac{d^4P}{(2\pi)^4}(-g)^{1/2}P_a 2(2\pi)\ \theta(P_0)\delta(P_c P^c + m^2) f(P,t)$$

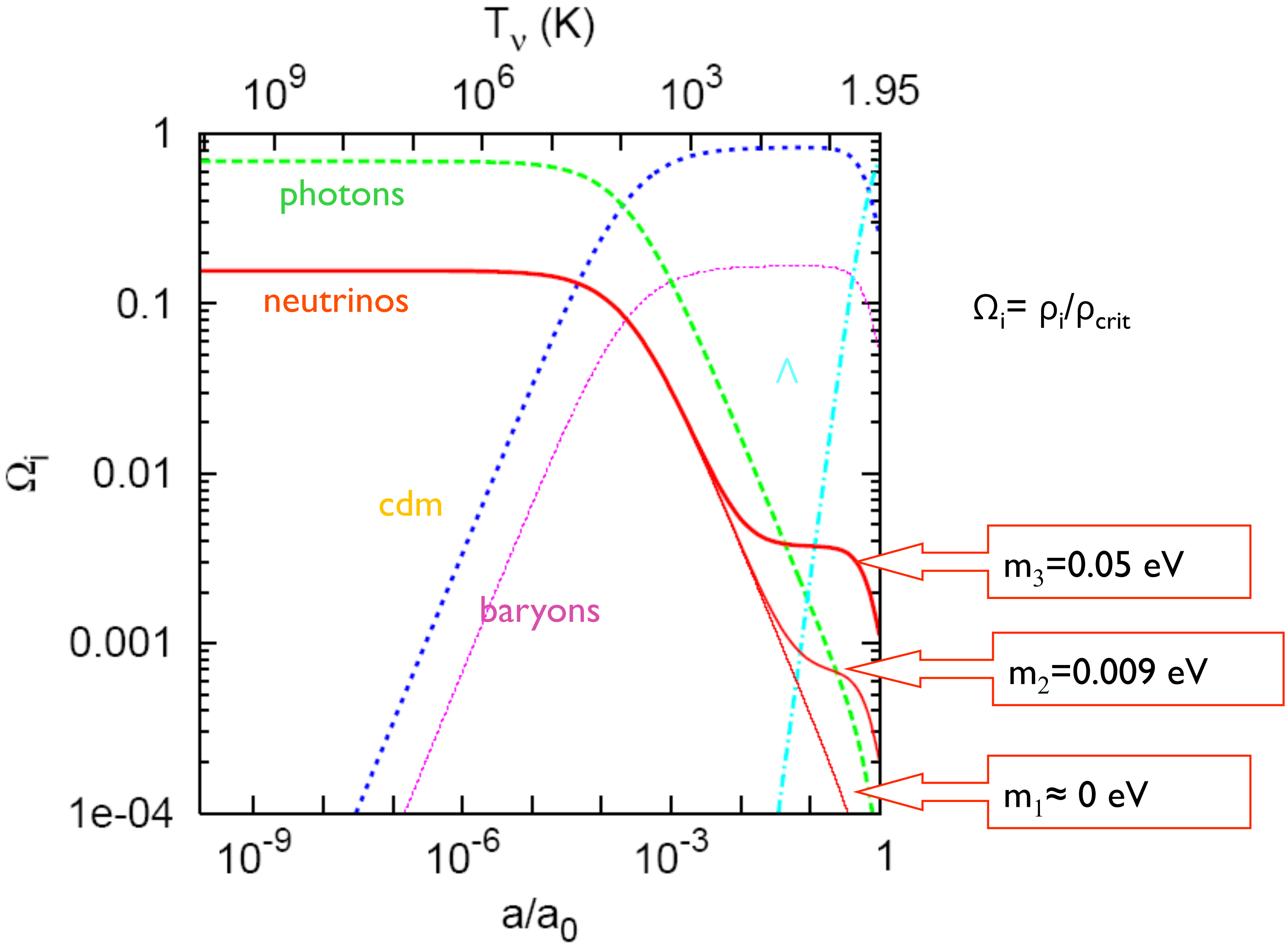
or in physical momentum

$$T_0^0 = -g\int \frac{d^3p}{(2\pi)^3} E(p) f(p,t) = -\rho$$

$$T_j^i = g\delta_j^i \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{3E(p)} f(p,t) = \delta_j^i P$$

for equilibrium distribution we can define a temperature parameter T. For relativistic species and covariant conservation of $T^b_{\ a}$

$$\nabla_a T_b^a = 0 = \partial_a T_b^a + \Gamma_{ac}^a T_b^c - \Gamma_{ab}^c T_c^a \Rightarrow Ta = const$$



$\Omega_i = \rho_i/\rho_{crit}$

definition of comoving particle horizon

$$\chi = \int_{a_{em}}^{a} \frac{da'}{a'^2 H} = \int_{z}^{z_{em}} \frac{dz}{H}$$ massless particles

$$d\chi = \frac{p}{aE} dt$$ particle with mass m

$$\chi = \int_{a_{em}}^{a} \frac{y\, da'}{a'^2 H(a') \sqrt{y^2 + m^2 a'^2}}$$

EXERCISE III

The last scattering surfaces of photons and neutrinos are at redshifts ≈10^3 and ≈10^9 respectively. Compute the comoving distances from earth of these surfaces for a neutrino mass of 1 eV

Equilibrium vs kinetic theory

Along the history of the universe many phases are characterized by equilibrium conditions.

Simple criterium:

interaction rate (Γ) >> expansion rate (H)

Ex. two body scattering ($a+b \rightarrow c+d$) $\Gamma = \sigma\ v\ n_a$

$$\sigma\ v\ n_a > (8\pi G_N \rho /3)^{1/2}$$

Equilibrium thermodynamics

$$f(p,T) = \frac{1}{\exp(p/T) \pm 1}$$

T~1/a(t)

VARIABLE	RELATIVISTIC		NON RELATIVISTIC
	BOSE	FERMI	
n	$\frac{\zeta(3)}{\pi^2} g T^3$	$\frac{3}{4}\frac{\zeta(3)}{\pi^2} g T^3$	$g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$
ρ	$\frac{\pi^2}{30} g T^4$	$\frac{7}{8}\frac{\pi^2}{30} g T^4$	mn
p	$\frac{\rho}{3}$		$nT \ll \rho$
$\langle E \rangle$	$2{,}701T$	$3{,}151T$	$m + \frac{3}{2}T$

$$n = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, f_i(p,T) \qquad \rho = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, E_i\; f_i(p,T)$$

$$p = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, \frac{p^2}{3E_i} f_i(p,T) \qquad \langle E \rangle = \rho/n$$

Kinetic theory

Boltzmann (Stosszahlansatz: no correlations among different momenta)

$\mathcal{L}\, f(p,t) = C(f(p,t))$

$\mathcal{L}$ Liouville operator (evolution in phase space of particle distribution)

C collisional integral (change of momentum and/or particle species)

In a spatially flat FLRW universe

$$\left(\frac{d}{dt} - Hp\frac{d}{dp}\right) f_\nu(p,t) = C(f_\nu(p,t))$$

1+2 ➔ 3+4

Statistical Factor

$$\boxed{\frac{1}{2E_1}\int\prod_{i=2}^{4}\left(\frac{d^3p_i}{(2\pi)^3 2E_i}\right)}\boxed{(2\pi)^4\delta^4(P_1+P_2-P_3-P_4)}\boxed{|M|^2}\boxed{F}$$

9-dim Phase Space

ΣP_i conservation

Process

$$F = f_3 f_4[1+f_1][1-f_2] - f_1 f_2[1+f_3][1-f_4]$$

Notice: collisional integral can be zero either because interactions are **very efficient** or **too weak**!

EXERCISE IV

Show that for example, for a 2-2 scattering process collisional integral vanishes for kinetic equilibrium distribution and for chemical equilibrium

$$\mu_a + \mu_b = \mu_c + \mu_d$$

ν distribution and mixing in the early universe

1 MeV ≤ **T** ≤ m_μ

$T_\nu = T_e = T_\gamma$

$\nu\,\nu \leftrightarrow \nu\,\nu$

$\nu\,\bar{\nu} \leftrightarrow \nu\,\bar{\nu}$

$\nu\, e^- \leftrightarrow \nu\, e^-$

$\nu\,\bar{\nu} \leftrightarrow e^+ e^-$

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

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

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

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

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

Since ν_e have both CC and NC interactions with $e^{\pm}$

$T_{dec}(\nu_e)$ ~ 2 MeV

$T_{dec}(\nu_{\mu,\tau})$ ~ 3 MeV

EXERCISE V

Prove that for a relativistic specie, any function of the comoving momentum y is a solution of the collisionless Boltzmann equation. Use this to show that if neutrino decoupling is assumed to be instantaneous neutrino distribution keeps a Fermi-Dirac shape after decoupling (like photon keep a almost perfect black body distribution after last scattering) with a temperature falling as 1/a

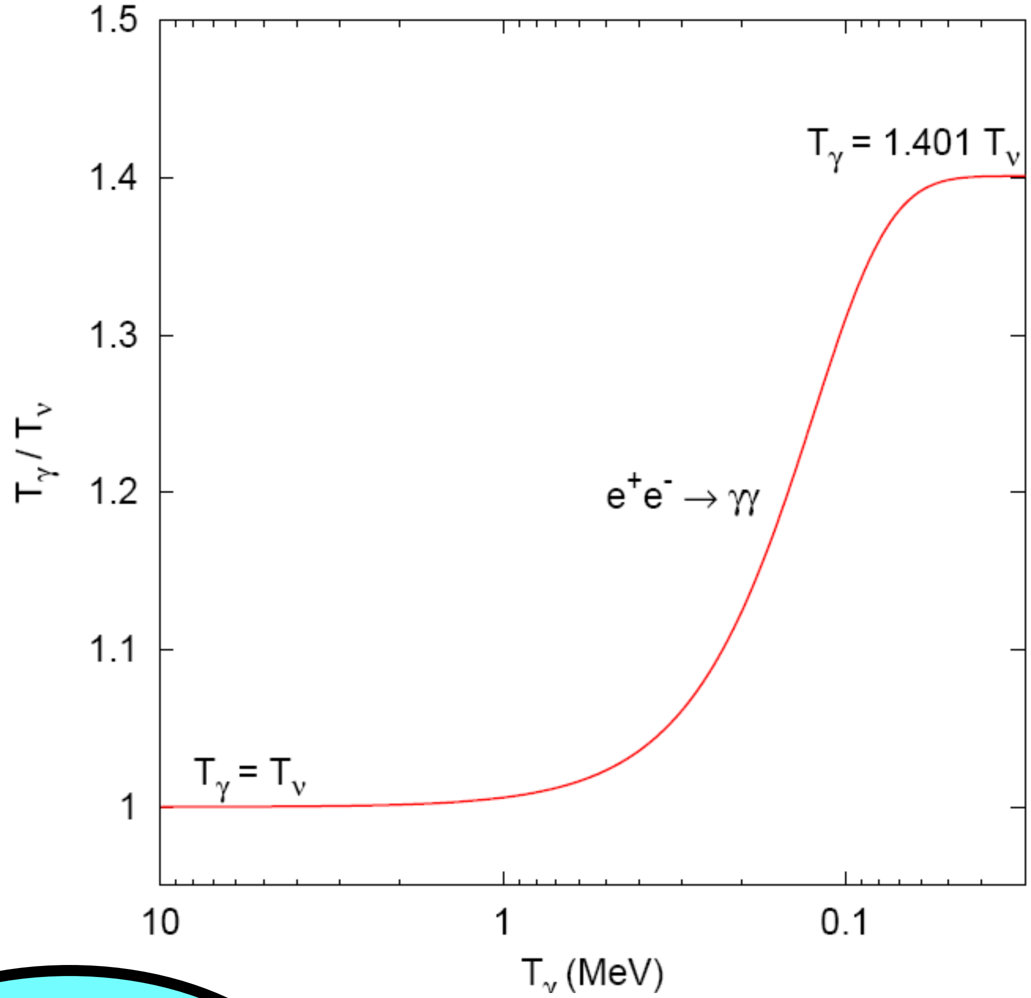
Discuss then the case of a very massive particle (see Bernstein book)

Neutrino and Photon (CMB) temperatures

At T~m_e, electron-positron pairs annihilate

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

heating photons but not the decoupled neutrinos



from entropy conservation

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

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

The Cosmic Neutrino Background

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

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

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

Massless

$$\rho_{\nu_i} = \int \sqrt{p^2 + m_{\nu_i}^2} \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \rightarrow \begin{cases} \dfrac{7\pi^2}{120}\left(\dfrac{4}{11}\right)^{4/3} T_{CMB}^4 & \Omega_\nu h^2 = 1.7\times10^{-5} \\ m_{\nu_i} n_\nu & \Omega_\nu h^2 = \dfrac{\sum_i m_i}{94.1\ \mathrm{eV}} \end{cases}$$

Massive m_ν >>T

Relativistic particles in the Universe

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

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

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

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

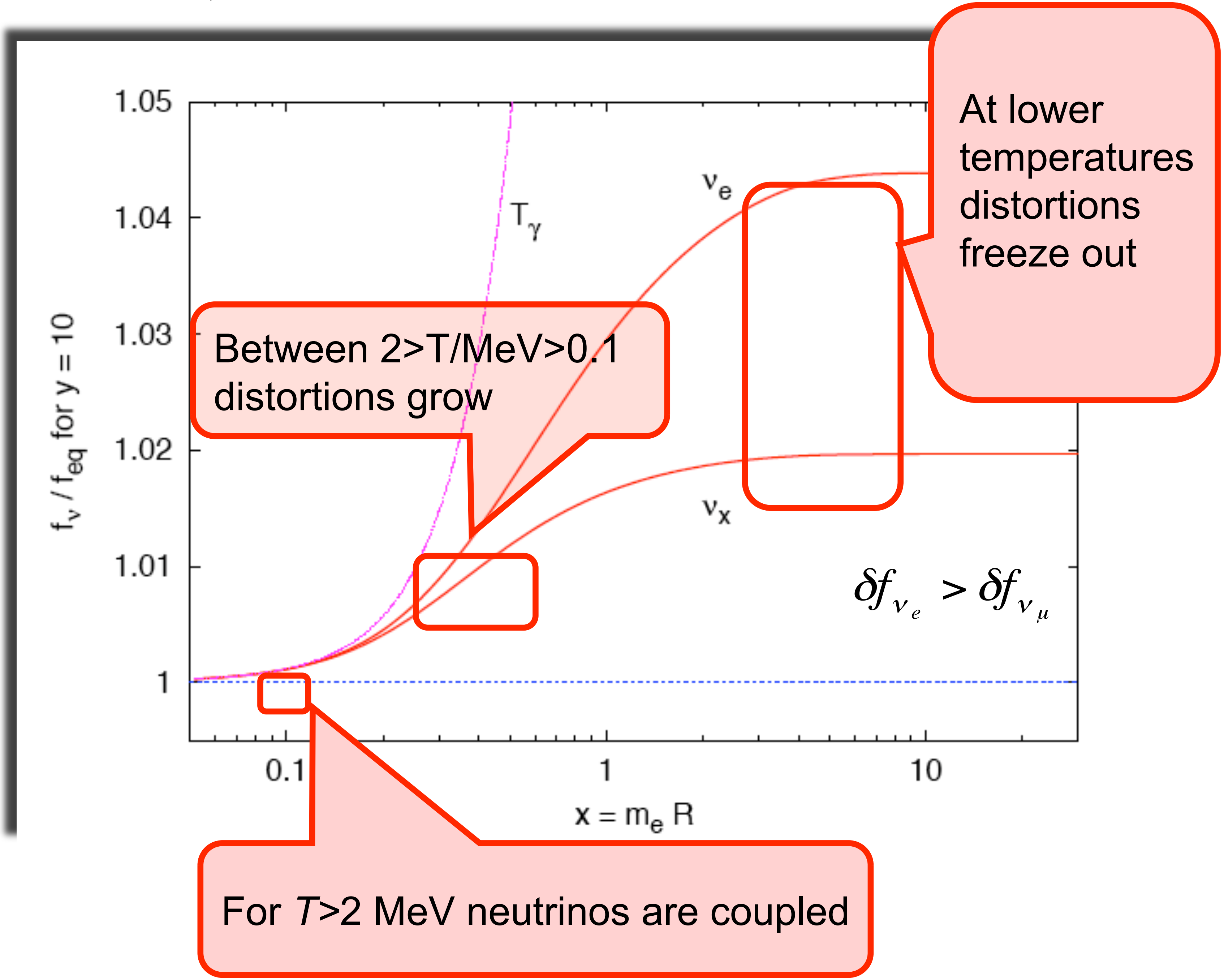
At $T \sim m_e$, e^+e^- pairs annihilate heating photons

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

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

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

Evolution of f_ν for a particular momentum p=10T



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

EXERCISE VI

Recalling that:

1. vacuum oscillation term goes like $\Delta m^2 \cos 2\theta / 2p$
2. neutrino momentum redshift as the photon temperature T
3. the energy density of electrons/positrons in the non relativistic regime scales as T^3

draw the evolution of vacuum and matter terms in the neutrino equation of motion versus T. Consider the two cases of atmospheric and solar square mass difference and mixing angle θ. Find the two corresponding resonance temperatures

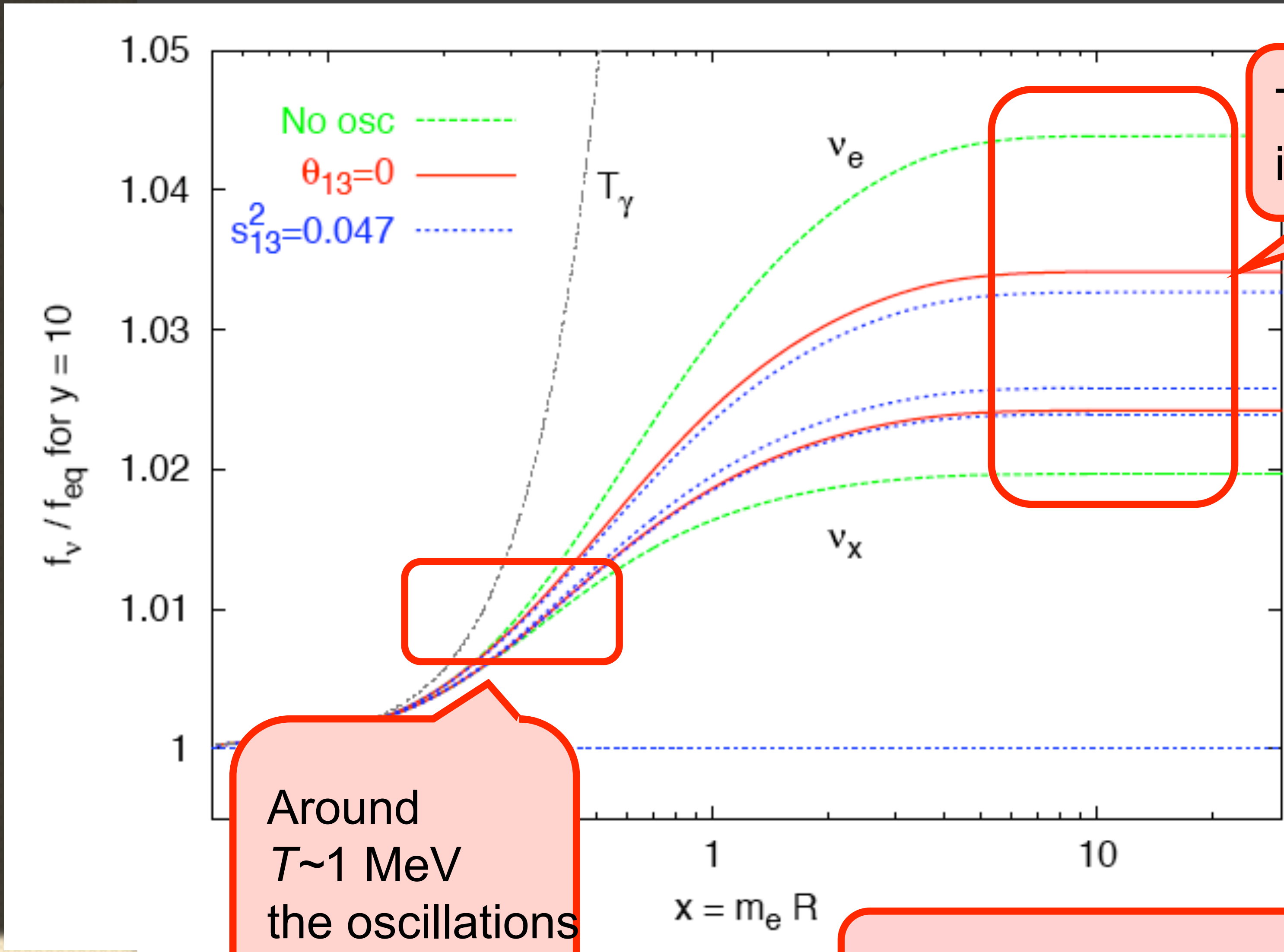
Standard case: all neutrino flavours equally populated

→ oscillations are effective below a few MeV, but have no effect (except for mixing the small distortions δf_ν)

Cosmology is insensitive to neutrino flavour after decoupling!

Non-zero neutrino asymmetries: flavour oscillations lead to (almost) equilibrium for all μ_ν

Effects of flavour neutrino oscillations on the spectral distortions



The variation is larger for ν_e

Around T~1 MeV the oscillations start to modify the distortion

Oscillations smooth the flavour dependence of the distortion

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

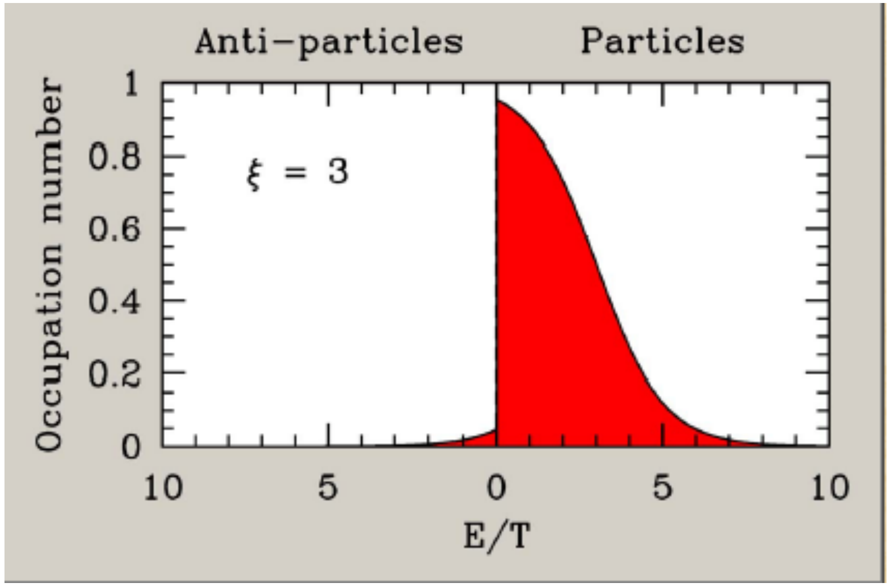
$$\sum_a \eta_a = \sum_a \frac{n_a - n_{\bar{a}}}{n_\gamma} = \sum_a \frac{1}{12\zeta(3)}\left(\pi^2 \xi_a + \xi_a^3\right) \approx \frac{n_B}{n_\gamma}\eta_B = 6\times 10^{-10}$$

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!



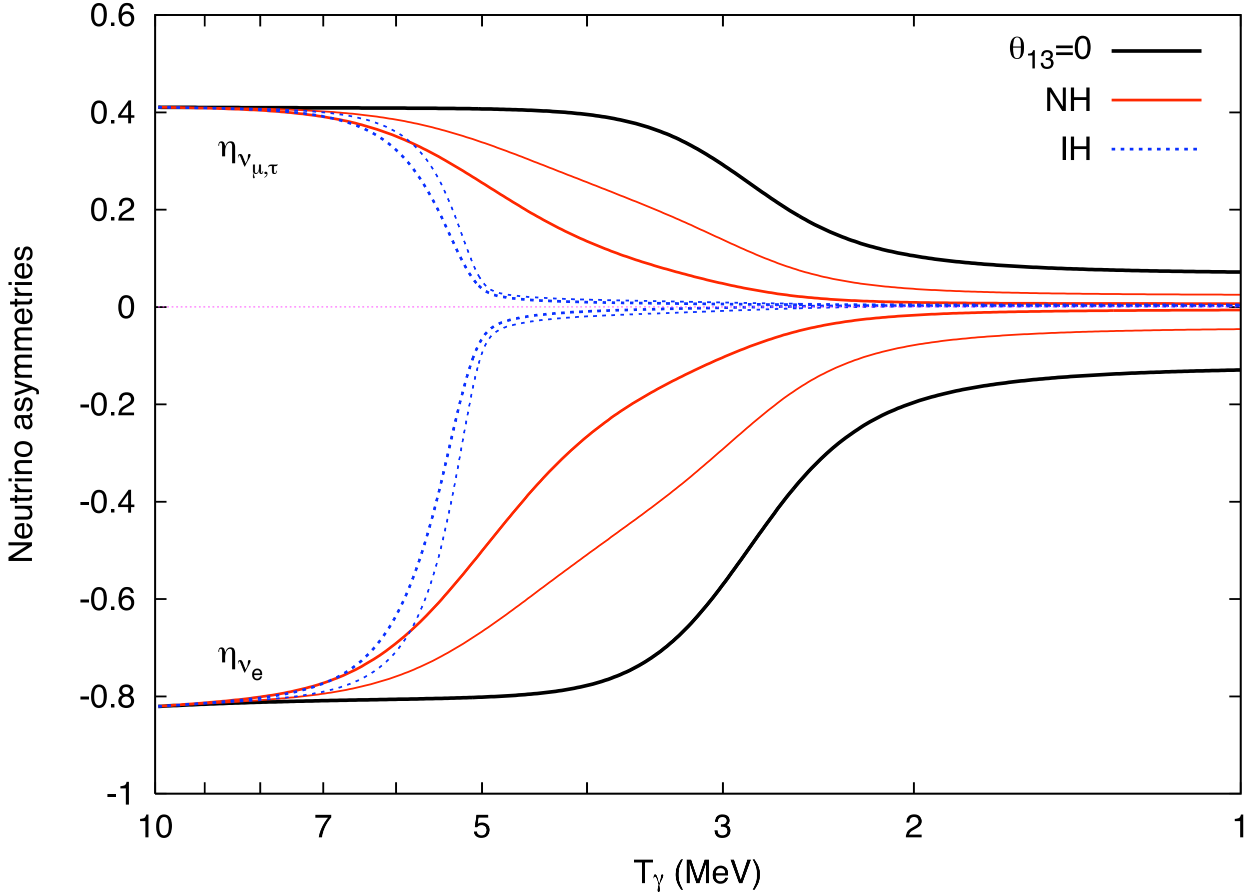
The presence of ν chemical potential

- shift the n-p chemical equilibrium and thus BBN (see later)
- change the neutrino energy density (N_{eff})

$$\boxed{\Delta N_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]}$$

Oscillations and neutrino asymmetries

The value of θ_{13} is crucial (and to a minor extent the mass hierarchy)



BBN and neutrinos

- **BBN: almost seventy years after $\alpha\beta\gamma$ seminal paper(Alpher, Bethe & Gamow 1948)**

  - Theory reasonably under control (per mille level for ^4He (neutron lifetime), 1-2 % for ^2H);
  - Increased precision in nuclear reaction cross sections at low energy (underground lab's);
  - $\Omega_b h^2$ (baryon density). measured by WMAP/Planck with high precision (1% level).

    crucial parameter! $\eta = n_B/n_\gamma \approx 274\, \Omega_b h^2\ 10^{-10} = 6\ 10^{-10}$
  - Still some systematics on ^4He, ^2H fixes $\Omega_b h^2$ value in good agreement with CMB data, ^7Li not understood, ^6Li too small, yet some claim.

BBN: Creation of light elements

Range of temperatures: from few to 0.01 MeV

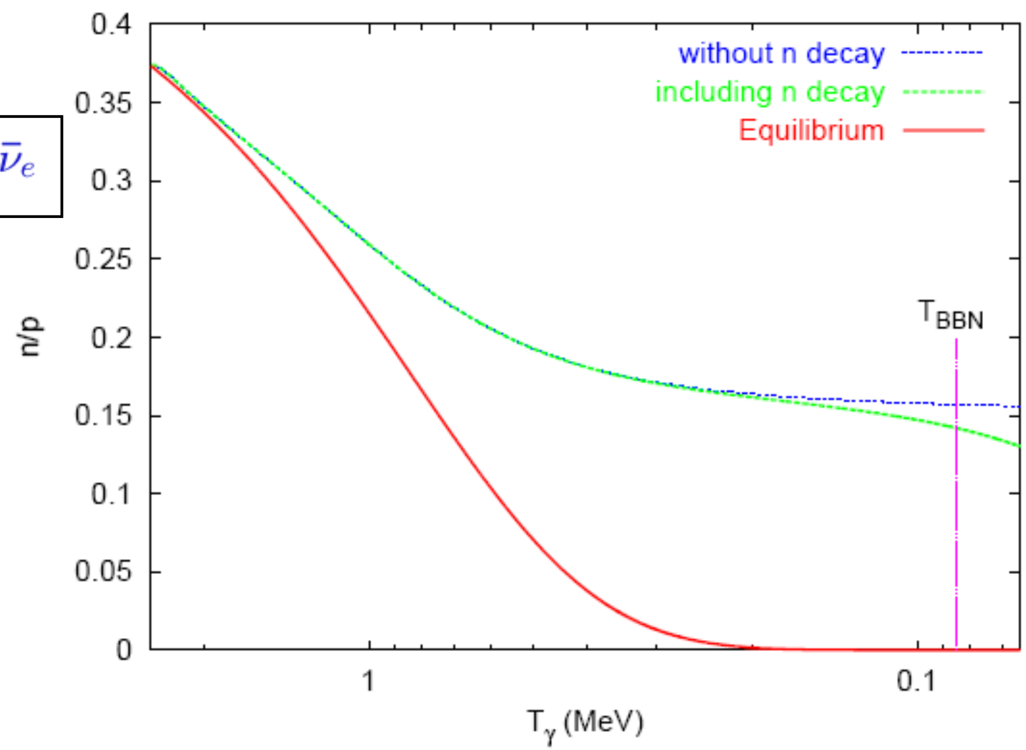
$$t \simeq 0{,}74 \left(\frac{\text{MeV}}{T}\right)^2 \ \text{sec}$$

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

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

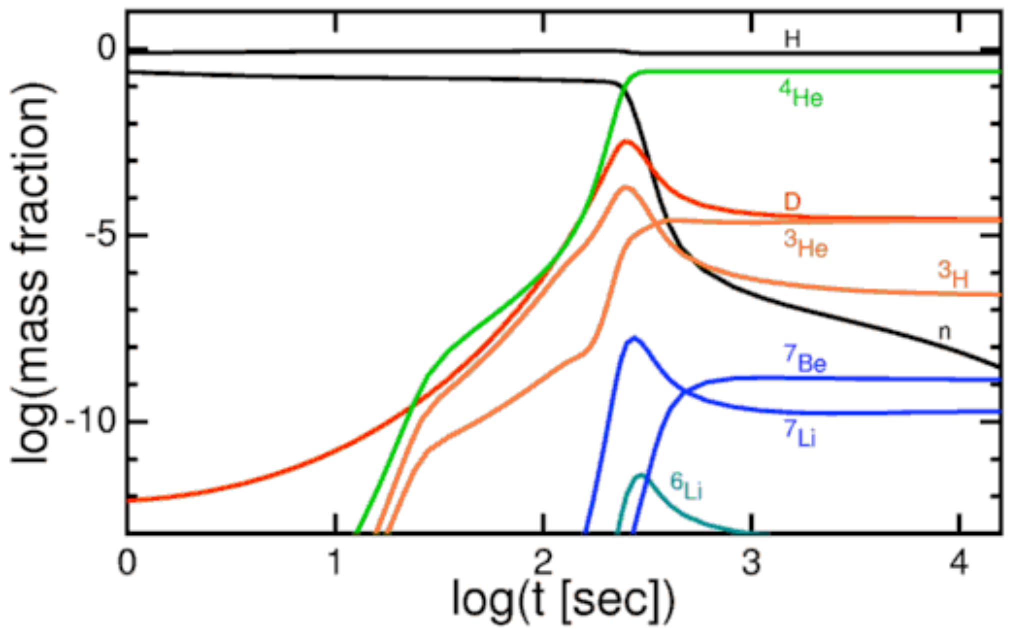
$n/p = \exp[(-M_n - M_p)/T_{fr}]\ \exp[-(t(T_D) - t(T_{fr}))/\tau_n] \approx 1/7$

EXERCISE VII

How the freezing temperature changes as function of G_N? What would be the ratio n/p if at the MeV epoch the Newton constant was a 10% larger than today?

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

$n\ p \rightarrow d\ \gamma$



EXERCISE VIII

Consider a two body interaction process a+b ➔c+d. Writing for simplicity the particle distribution in the Boltzmann limit

$$n_i = \exp(\mu_i / T) \int \frac{d^3 p}{(2\pi)^3} e^{-E_i / T}$$

show that chemical equilibrium, i.e.

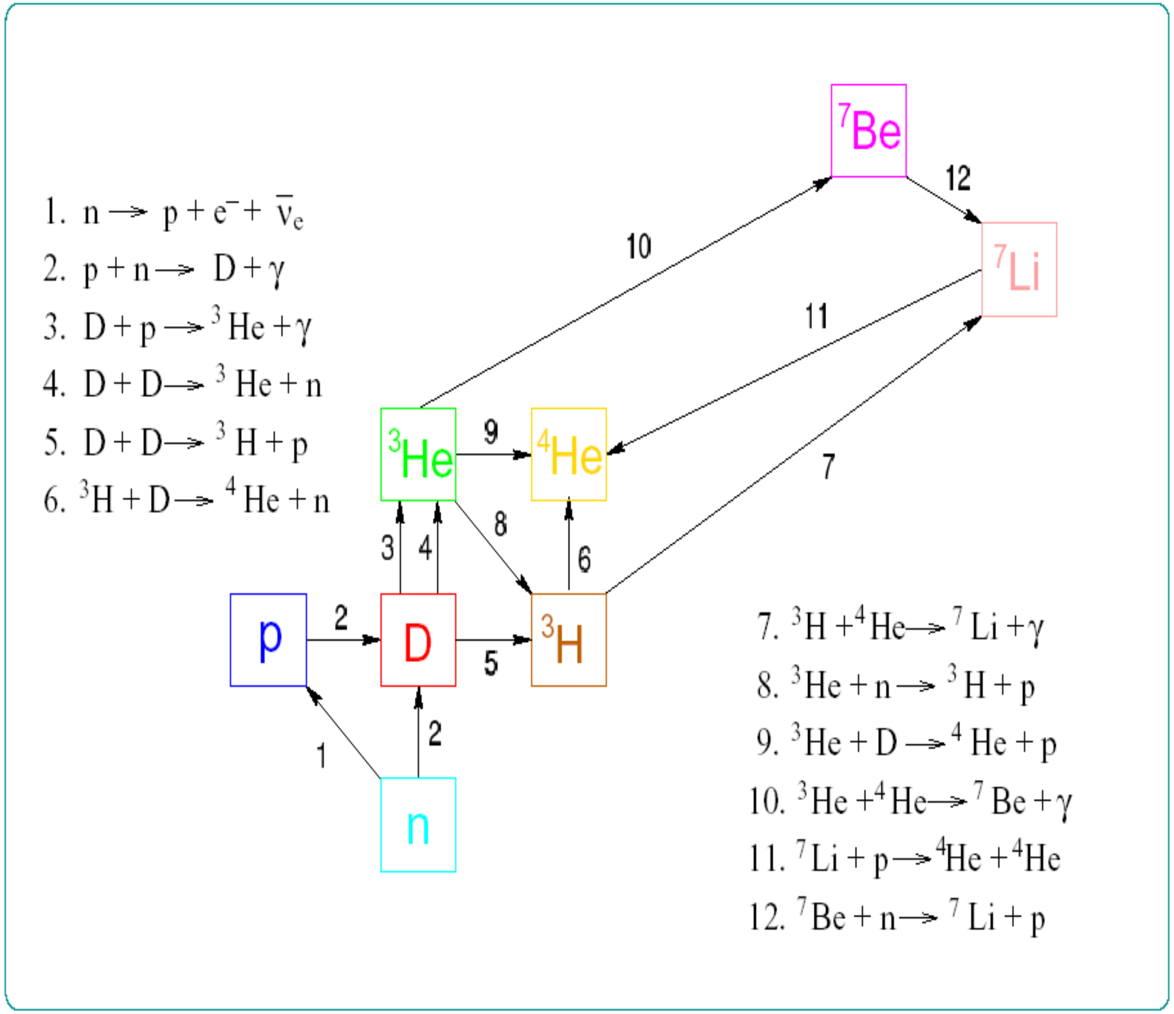
$$\mu_a + \mu_b = \mu_c + \mu_d$$

gives the "Saha" equation

$$\frac{n_c n_d}{n_a n_b} = \frac{\int d^3 p \ \exp(-E_c / T) \int d^3 p \ \exp(-E_d / T)}{\int d^3 p \ \exp(-E_a / T) \int d^3 p \ \exp(-E_b / T)}$$

Use this result to get the order of magnitude of deuterium formation i.e. when $n_D \approx n_B$

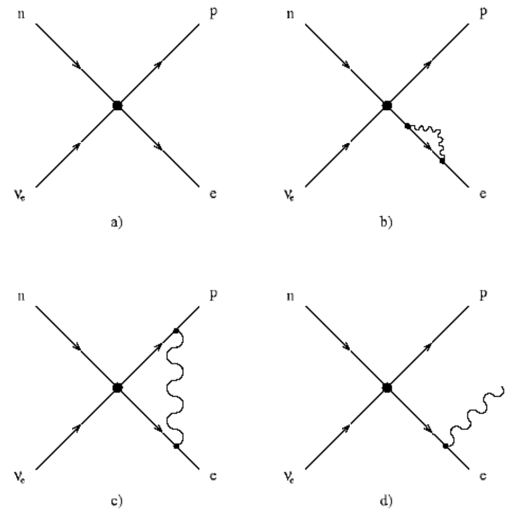
Phase III: 700 - 30 keV
Formation of light nuclei
starting from D



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



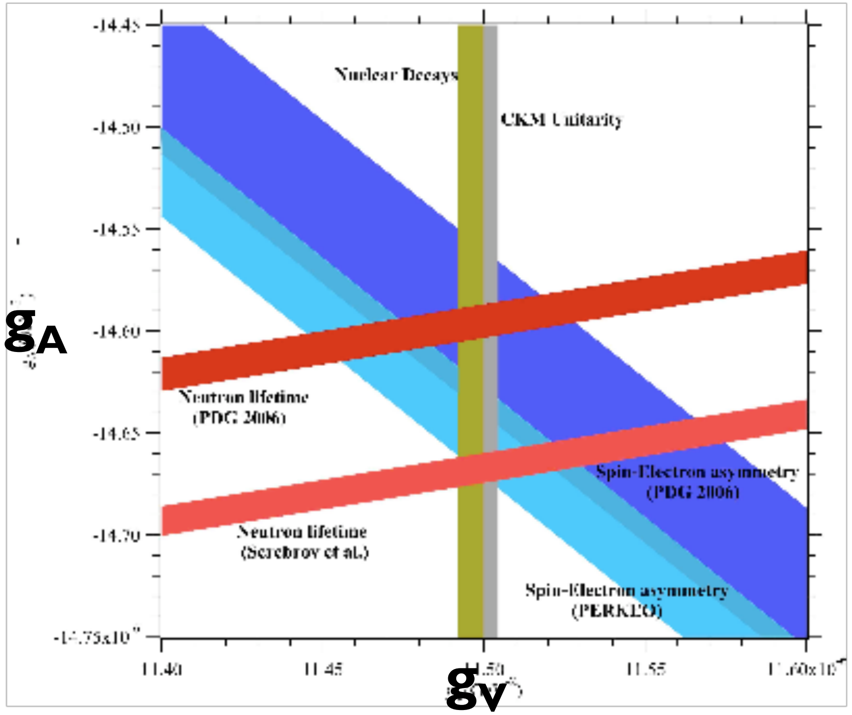
Main uncertainty: neutron lifetime
τ_n= 885.6 ± 0.8 sec (old PDG mean)
τ_n= 878.5 ± 0.8 sec (Serebrov et al 2005)

Presently:

τ_n=880.2 ± 1.0 sec (PDG)

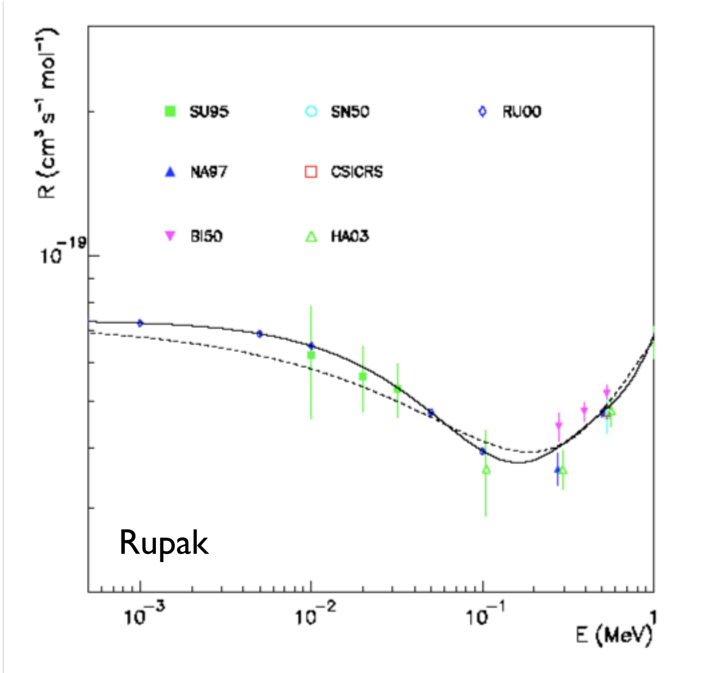
^{4}He mass fraction Y_P linearly increases with τ_n: 0.246 - 0.249

Nico & Snow 2006

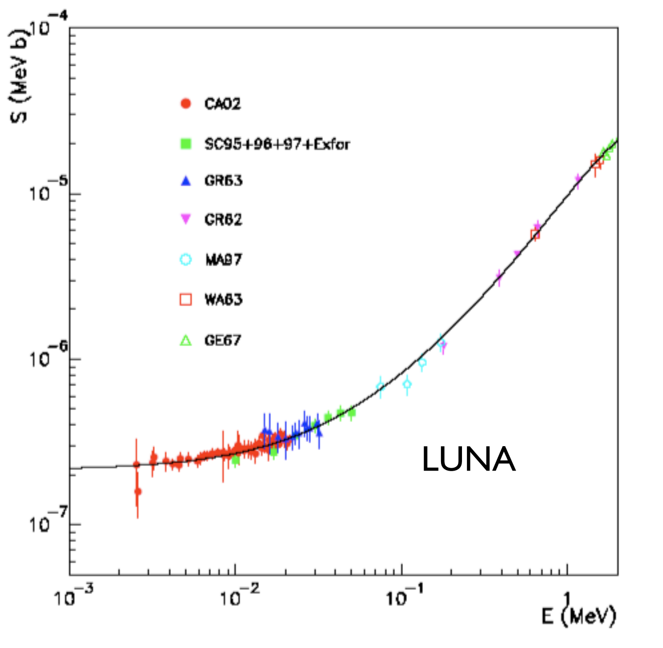


Nuclear rates:

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

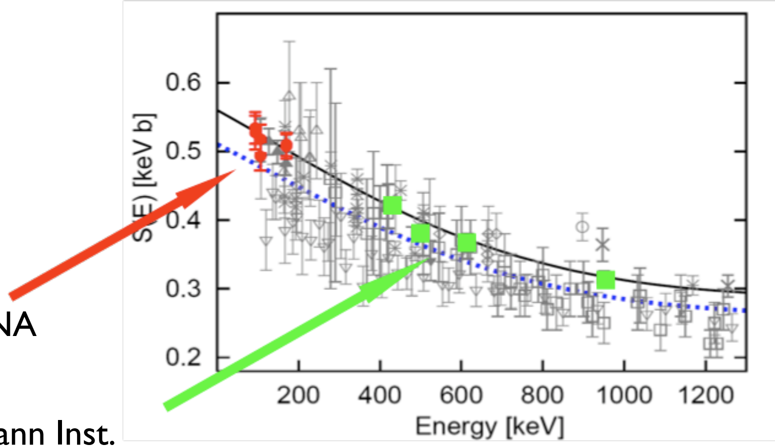


$n(p,\gamma)^2H$



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

LUNA



Weitzmann Inst.

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

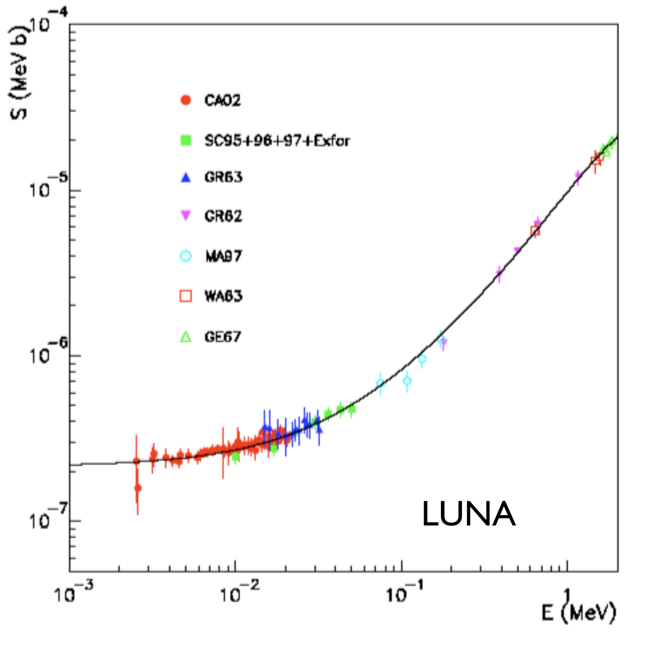
Nuclear rate error budget:

^4He $\tau_n \approx 100\%$ (0.0003)

$^2H/H$ $d(p,\gamma)^3He$ 78% (0.06)
$d(d,n)^3He$ 19% (0.02)
$d(d,p)^3H$ 3% (0.013)

^6Li $d(\alpha,\gamma)\,^6Li$ (almost 100%)

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

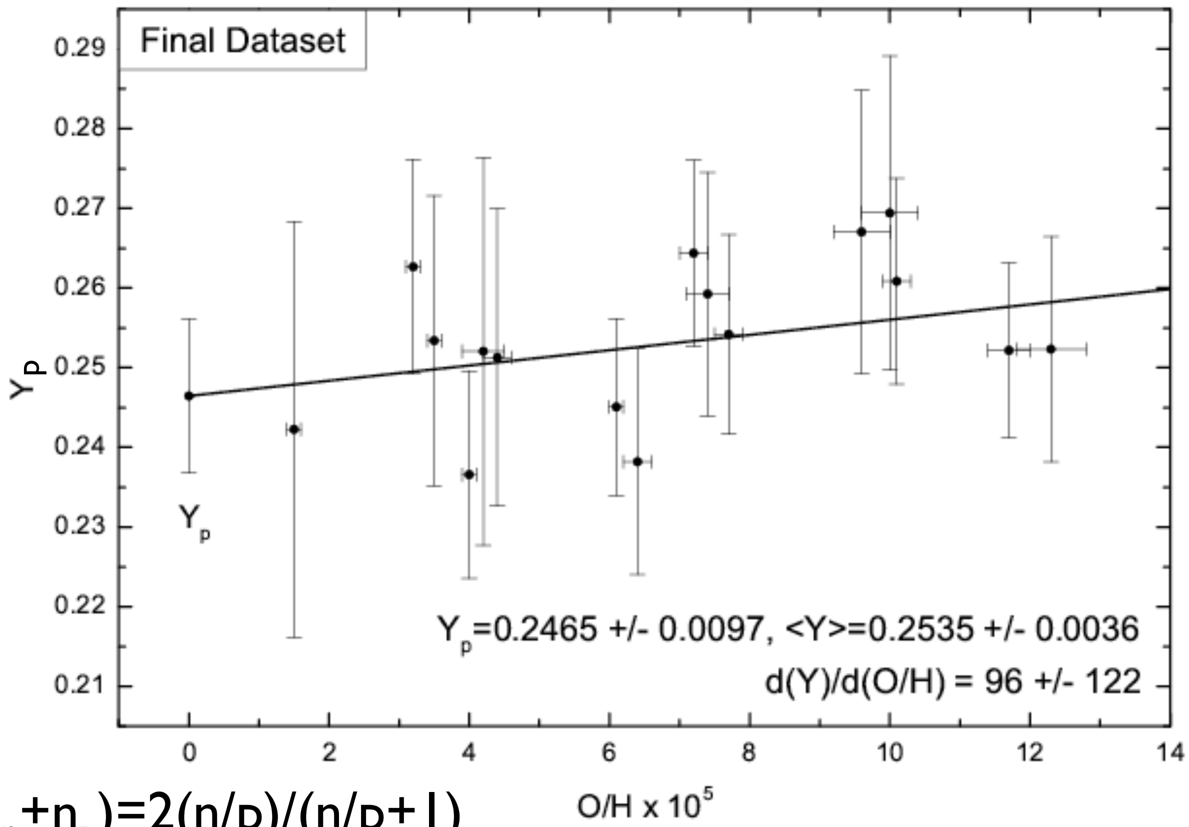
The quest for primordiality

- 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



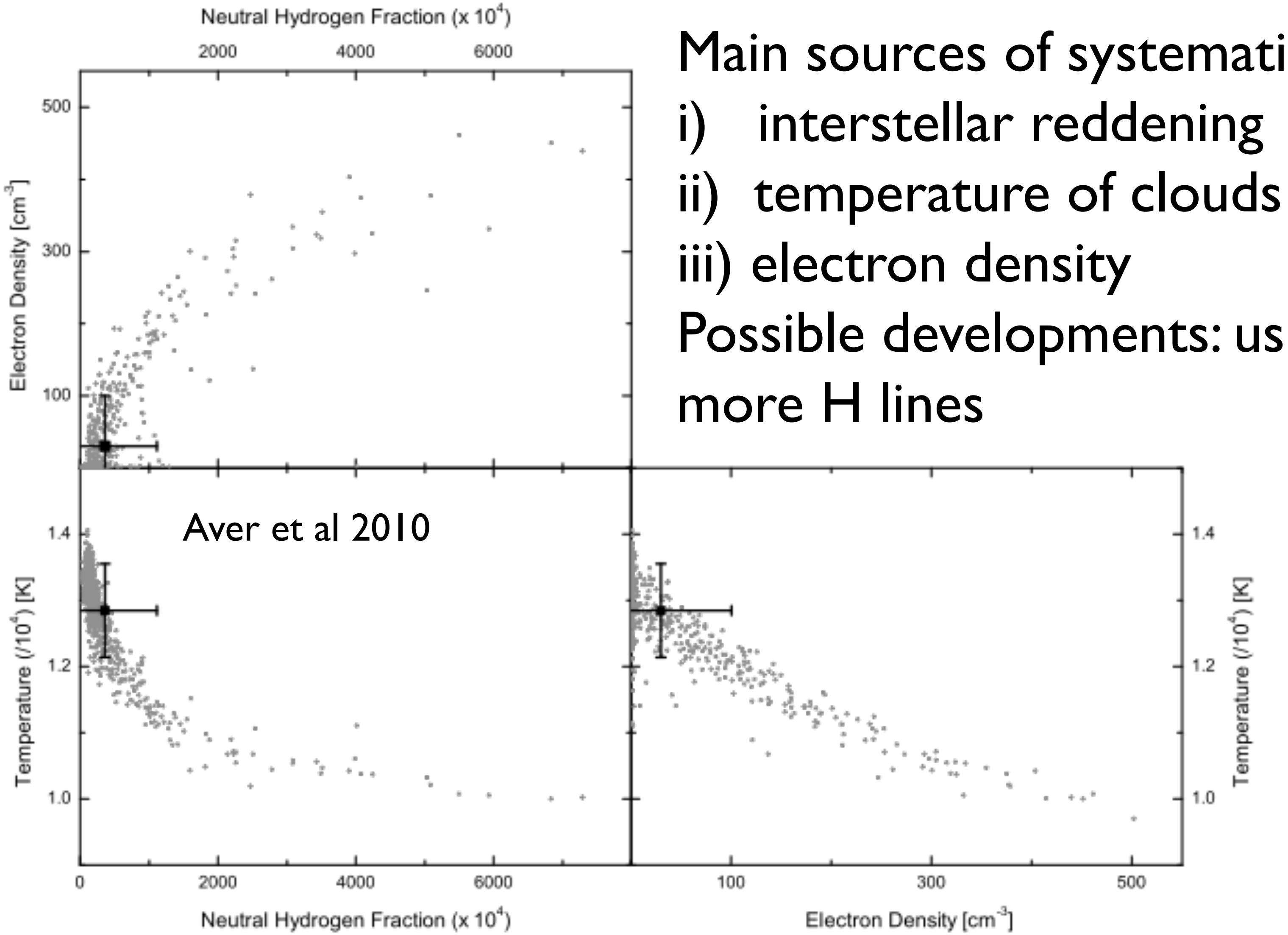
$Y_p = 4\, n_{4He}/n_B \approx 2n_n/(n_n+n_p)=2(n/p)/(n/p+1)$

Aver, Olive & Skillmann 2015

Main sources of systematics:

i) interstellar reddening
ii) temperature of clouds
iii) electron density

Possible developments: using more H lines



New recent analysis
use also the infrared I $\lambda 10830$

$Y_p = 0.2551 \pm 0.0022$ Izotov et al 2014

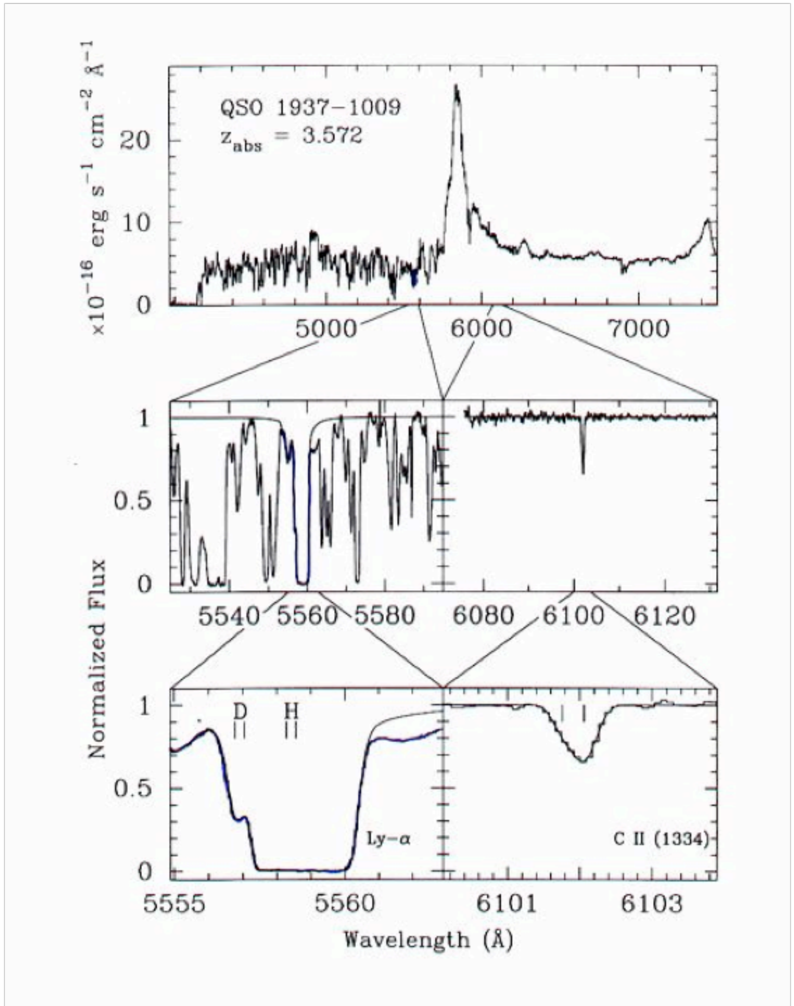
$Y_p = 0.2449 \pm 0.0040$ Aver et al 2015

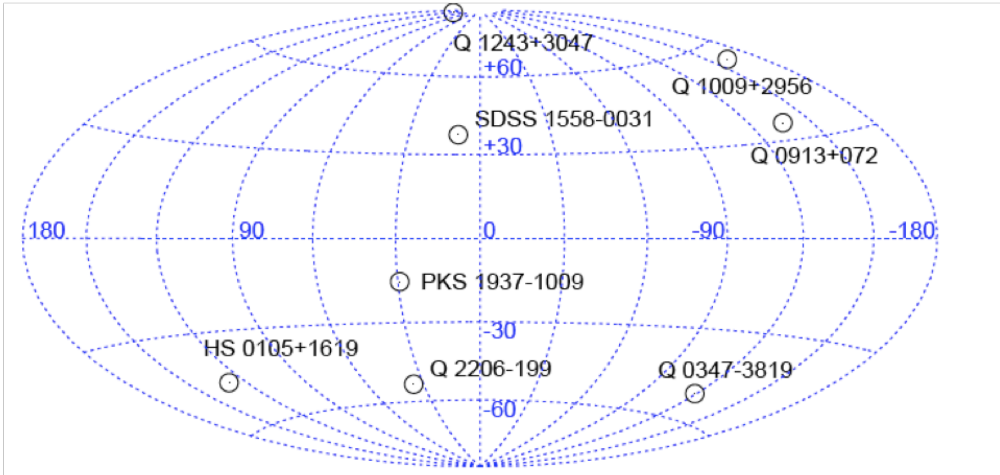
$Y_p = 0.245 \pm 0.0040$ PDG 2016

^{2}H 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





$^2H/H(10^{-5})=2.53\pm0.04$ Cooke et al, 2014, ApJ

$^2H/H(10^{-5})=2.55\pm0.03$ Riemer-Sorensenet al, 2017, MNRAS

^3He

observed on Earth (nuclear weapons)

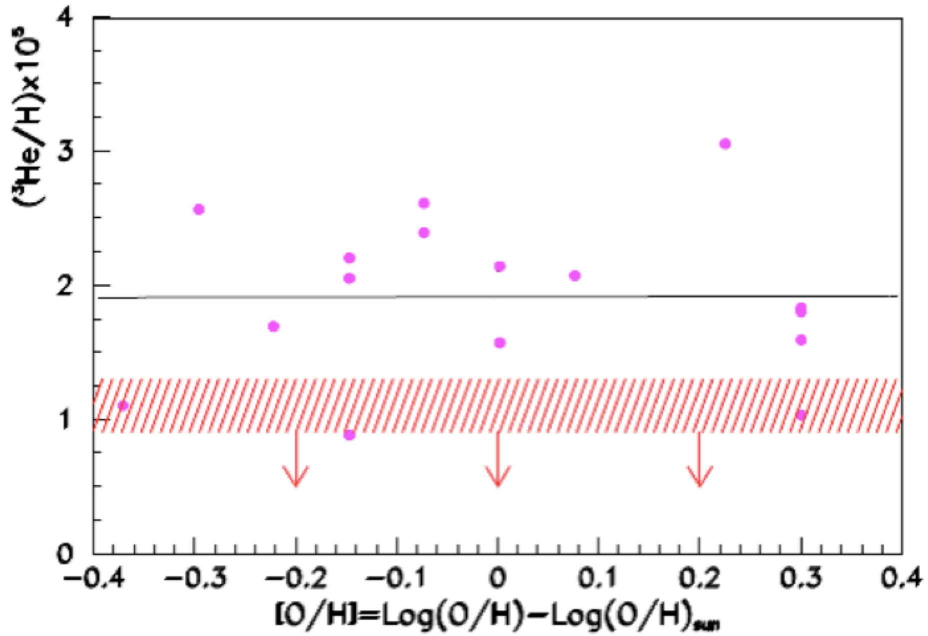
observed in the Solar System (Sun): $^2H \Rightarrow {}^3He$

observed in the ISM $^3He/H= 0.1$

observed in planetary nebulae and H_{II} regions outside the solar system ($^3He^+$ spin flip 3.46 cm wavelength band)

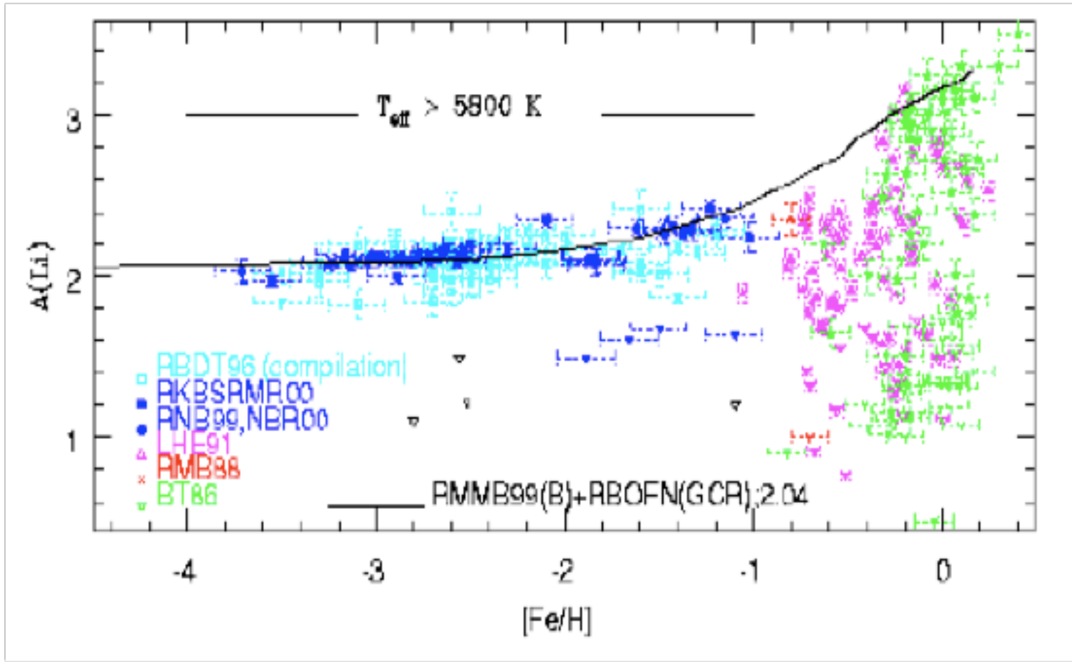
No clear evidence for dependence upon metallicity

Bania et al 2002



$^3He/H<(1.1\pm0.2)\ 10^{-5}$

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



$[^7Li/H] = 12 + \log_{10}(^7Li/H)$

(Bonifacio et al. 97) $[^7Li/H] = 2.24 \pm 0.01$

(Ryan et al. 99, 00) $[^7Li/H] = 2.09^{+0.19}_{-0.13}$

(Bonifacio et al. 02) $[^7Li/H] = 2.34 \pm 0.06$

(Melendez et al. 04) $[^7Li/H] = 2.37 \pm 0.05$

(Charbonnel et al. 05) $[^7Li/H] = 2.21 \pm 0.09$

(Asplund et al. 06) $[^7Li/H] = 2.095 \pm 0.055$

(Korn et al. 06) $[^7Li/H] = 2.54 \pm 0.10$

A factor 2 or more below BBN prediction, trusting ^2H +PLANCK 2015 baryon density and ^3He upper bound

- Nuclear rates under control ($^3He(\alpha,\gamma)^7Be$ & $^7Be(d,p)2\,\alpha$)
- Systematics in measurements?
- Non standard BBN (catalyzed BBN)?
- Observed values NOT primordial

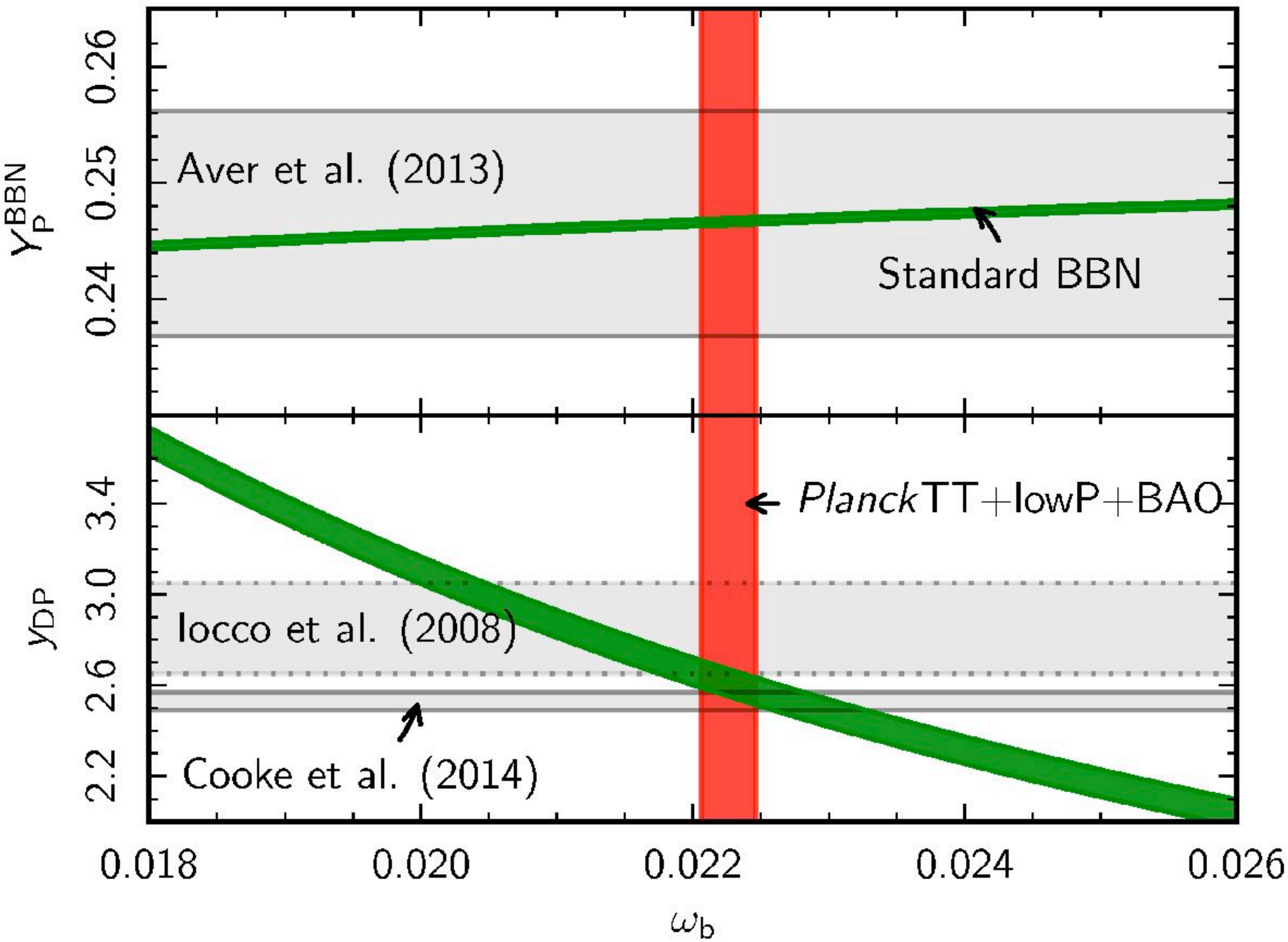
$^6Li/^7Li = 0.05$ (Asplund et al 2006), expected much smaller!!
Convective motions might generate asymmetries in the line shape and mimic the presence of ^6Li

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:
$Y_p = 0.2551 \pm 0.0022$!!!
$Y_p = 0.2449 \pm 0.0040$!
$^2H/H(10^{-5}) = 2.55 \pm 0.03$!!



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

PLANCK 2015

Discrepancies at worst 2 σ:

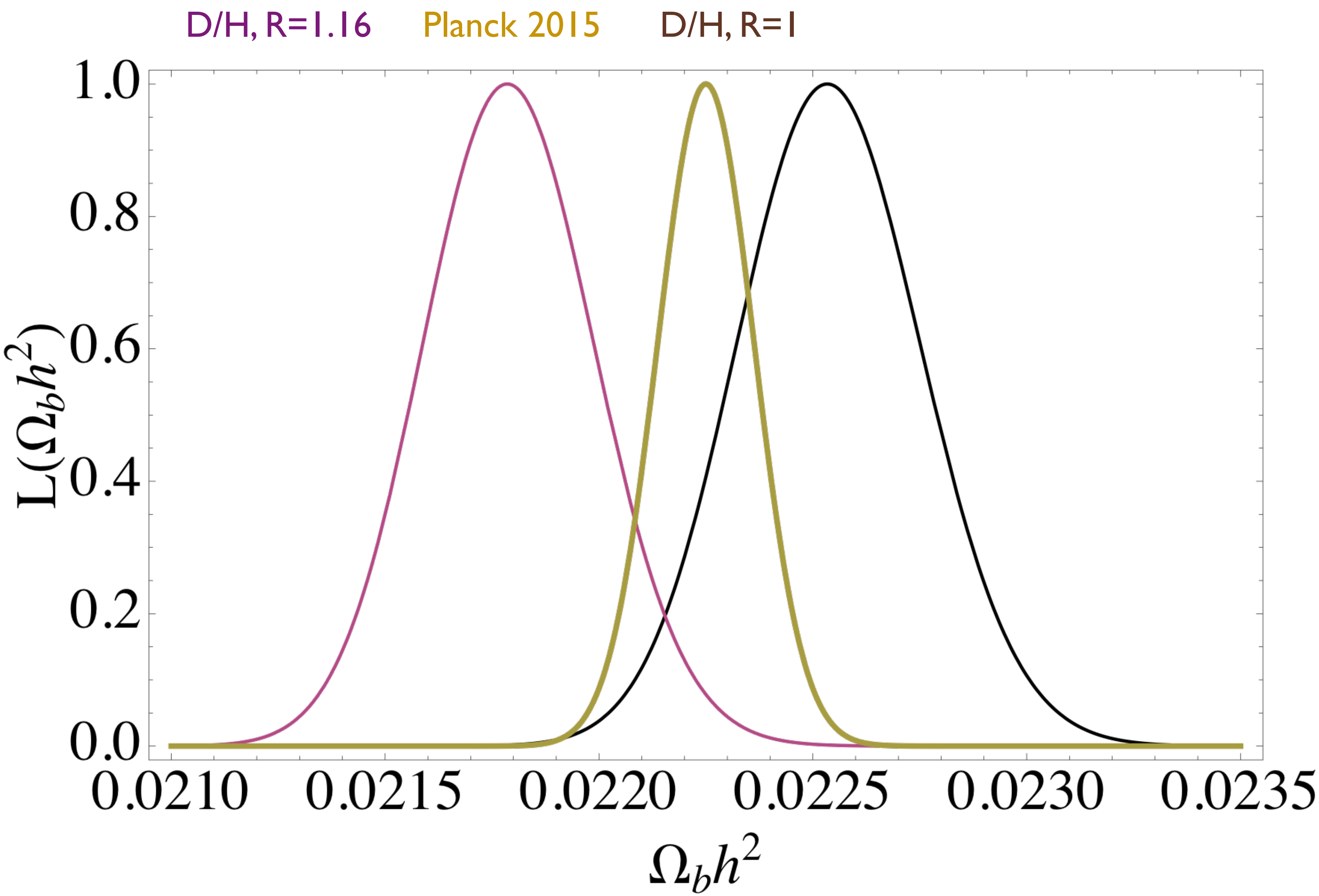
- ✓ New physics?
- ✓ systematics/uncertainties

Example: increasing $d(p,\gamma)^3He$ (as from by ab initio calculations) deuterium decreases, better agreement with Planck $\Omega_b h^2$

$$R = \Gamma(d(p,\gamma)^3He)/\Gamma(d(p,\gamma)^3He)_{exp}$$

PAUSA

Using D/H


D/H, R=1.16
Planck 2015
D/H, R=1
1.0
0.8
0.6
0.4
0.2
0.0
$L(\Omega_b h^2)$
0.0210
0.0215
0.0220
0.0225
0.0230
0.0235
$\Omega_b h^2$

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!

Room for extra light particles?

^{4}He grows with N_{eff}

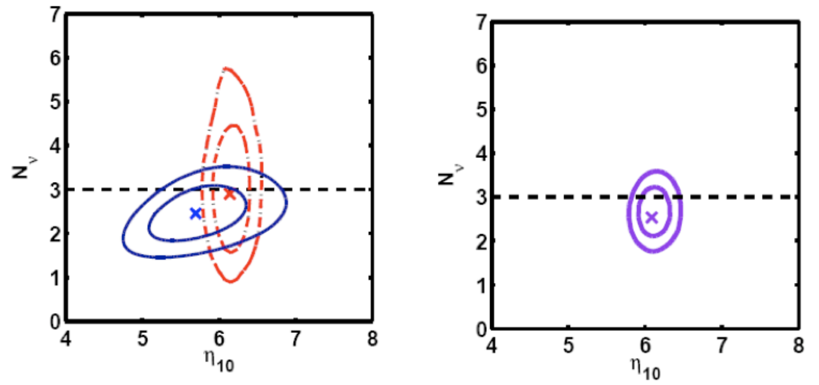


Figure 4:
(Left) In blue (solid), the 68% and 95% contours in the N_ν - η_{10} plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and ^{4}He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small scale CMB data, SNIa, and the HST Key Project prior on H_0 along with the LSS matter power spectrum data. (Right) The 68% and 95% joint BBN-CMB-LSS contours in the $N_\nu - \eta_{10}$ plane.

Steigman 2008

2-3 σ claim ! (Izotov & Thuan 2010,2014)

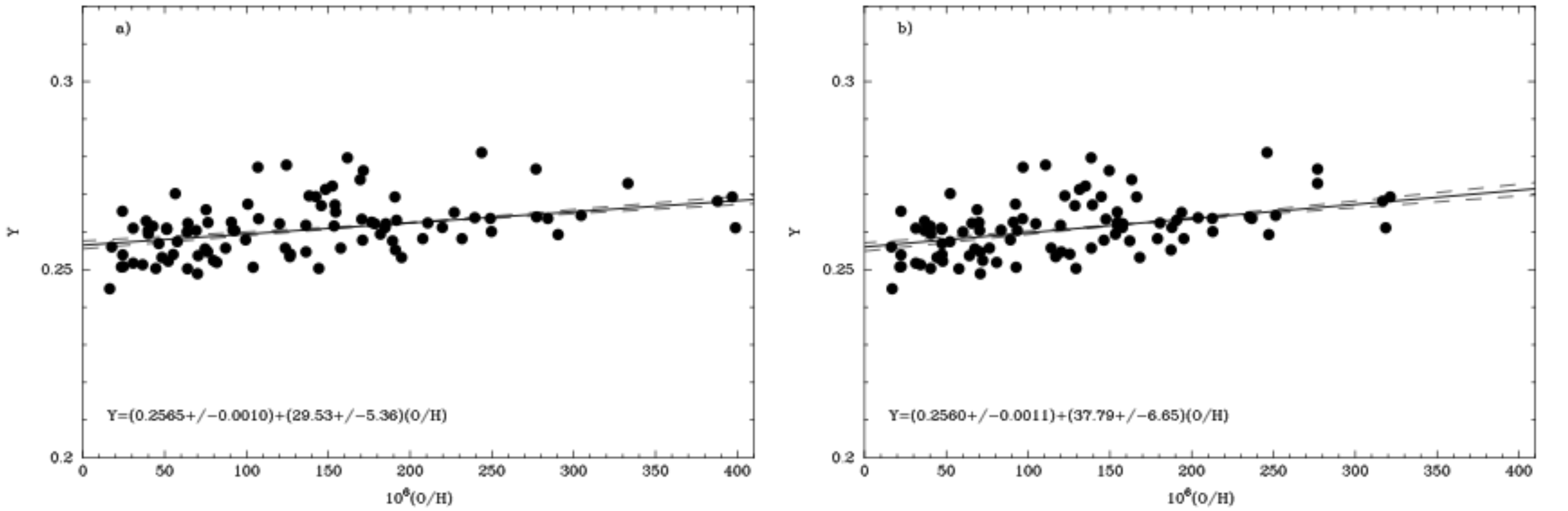
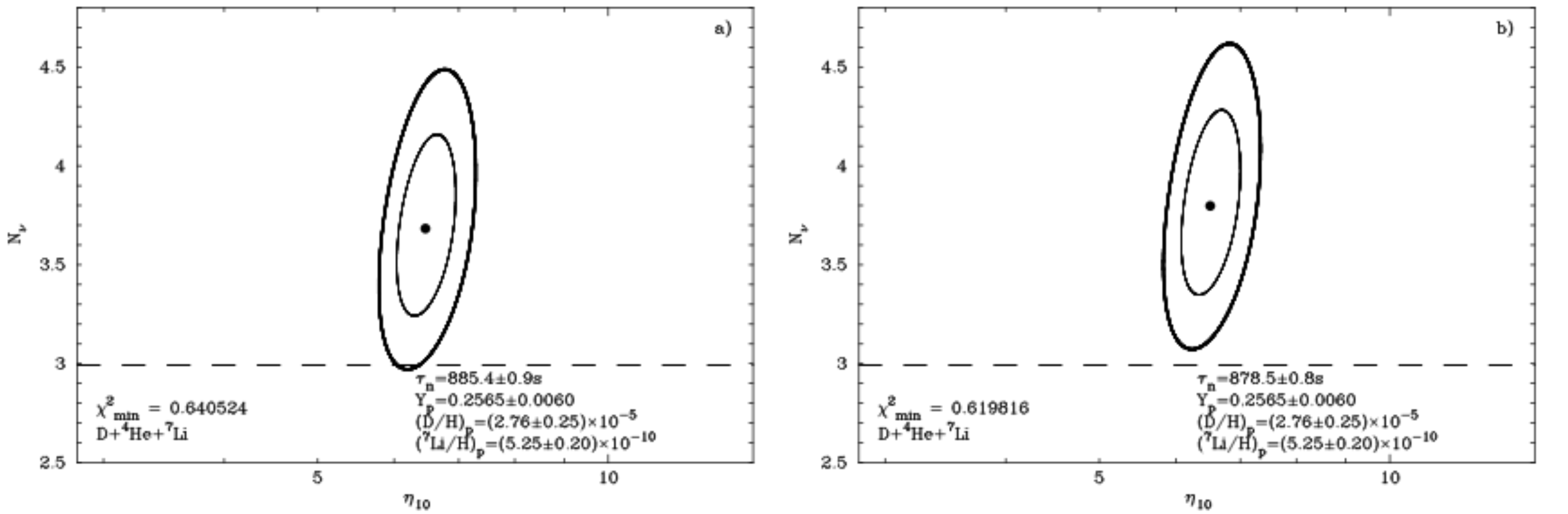


FIG. 1.— Linear regressions of the helium mass fraction Y vs. oxygen abundance for H II regions in the HeBCD sample. The Ys are derived with the He I emissivities from Porter et al. (2005). The electron temperature $T_e(\mathrm{He}^+)$ is varied in the range $(0.95-1)\times T_e$(O III). The oxygen abundance is derived adopting an electron temperature equal to $T_e(\mathrm{He}^+)$ in a) and to T_e(O III) in b).



Izotov et al 2014

N_{eff} = 3.7 ±0.2

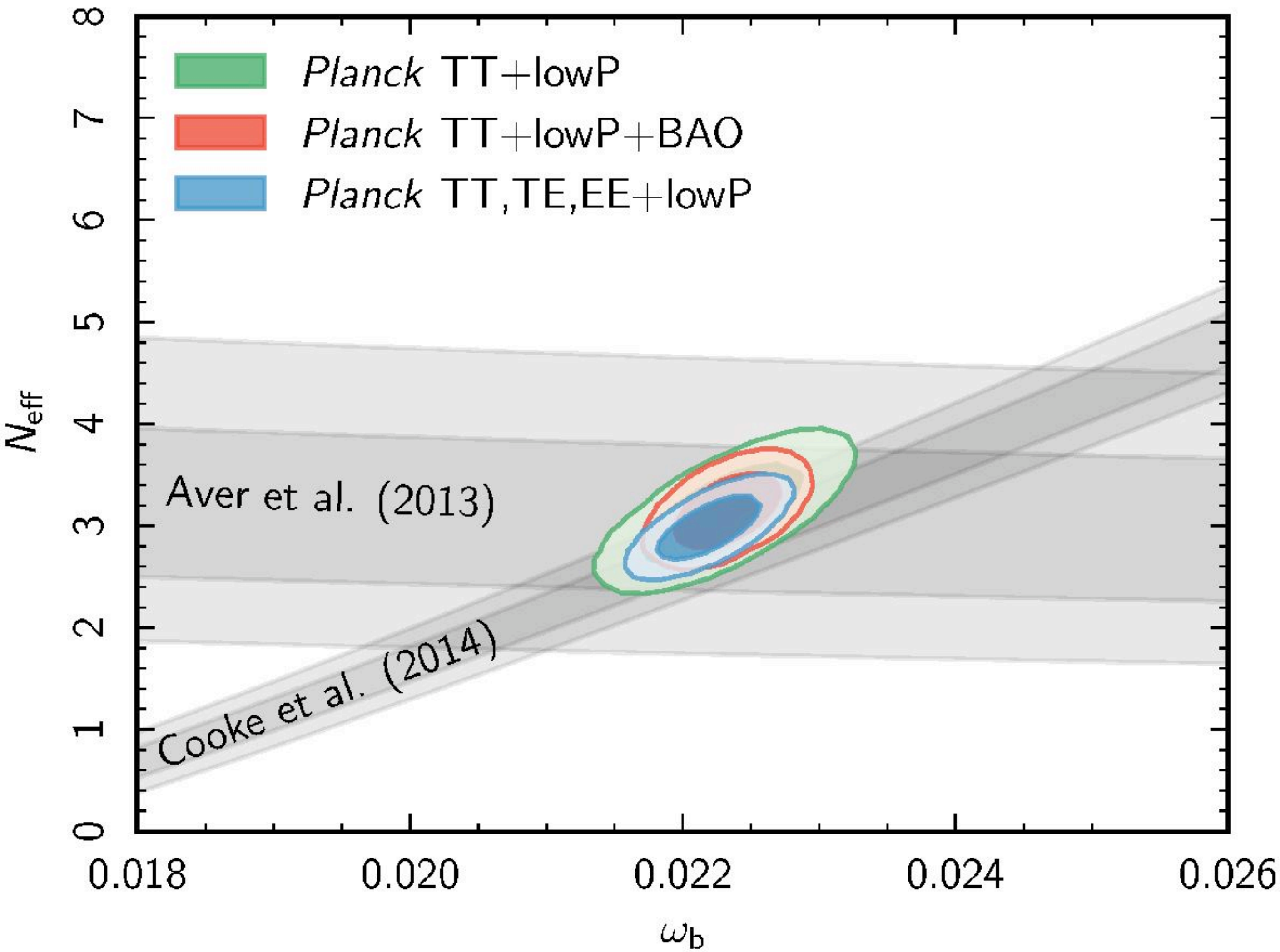
But using Aver et al. 2015 (larger error)

N_{eff} = 2.9 ±0.3

Planck 2015: N_{eff} = 3.04 ±0.18 !!

Remember: CMB and BBN scrutinize different "mass" scales!

Planck 2015

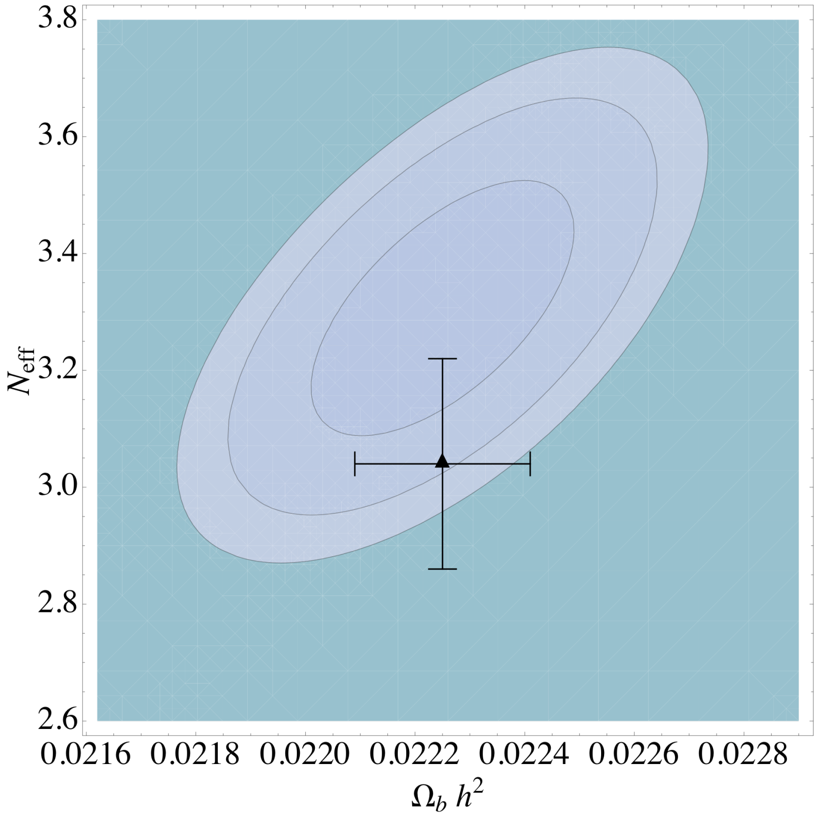


Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
Aver et al. (2013)
Cooke et al. (2014)
$N_{\rm eff}$
$\omega_{\rm b}$
0
1
2
3
4
5
6
7
8
0.018
0.020
0.022
0.024
0.026

Deuterium constraint: crucial the $d(p,\gamma)^3He$!

Present data fit (Adelberger et al) leads to a slightly deuterium overproduction which might be compensated by a smaller expansion rate (N_{eff}=2.84)

Ab initio calculation gives a larger cross section and lower deuterium yield!
In this case better a larger expansion rate (N_{eff}=3.2)



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.

LSND+ MiniBooNE: evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

MiniBooNE: excess of $\nu_\mu \rightarrow \nu_e$

Interpretation: order 1 eV massive extra sterile neutrino with large mixing angle

$\Delta m^2 \approx eV^2$

$\sin^2 2\theta \approx 10^{-3} - 1$

$P_{e\mu} = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L/E)$

(L in meters, E in MeV)

sterile-active oscillations

consider 1 active + 1 sterile

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix}$$

$$\left(i\partial_t - Hp\partial_p\right)\rho = [\frac{M^2}{2p} + V, \rho] + C(\rho)$$

$$V = (V_{CC} + V_{NC} + V_{asym})\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + V_{st}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

$$C(\rho) = \begin{pmatrix} C(G_F^2) & 0 \\ 0 & C(G_X^2) \end{pmatrix}$$

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

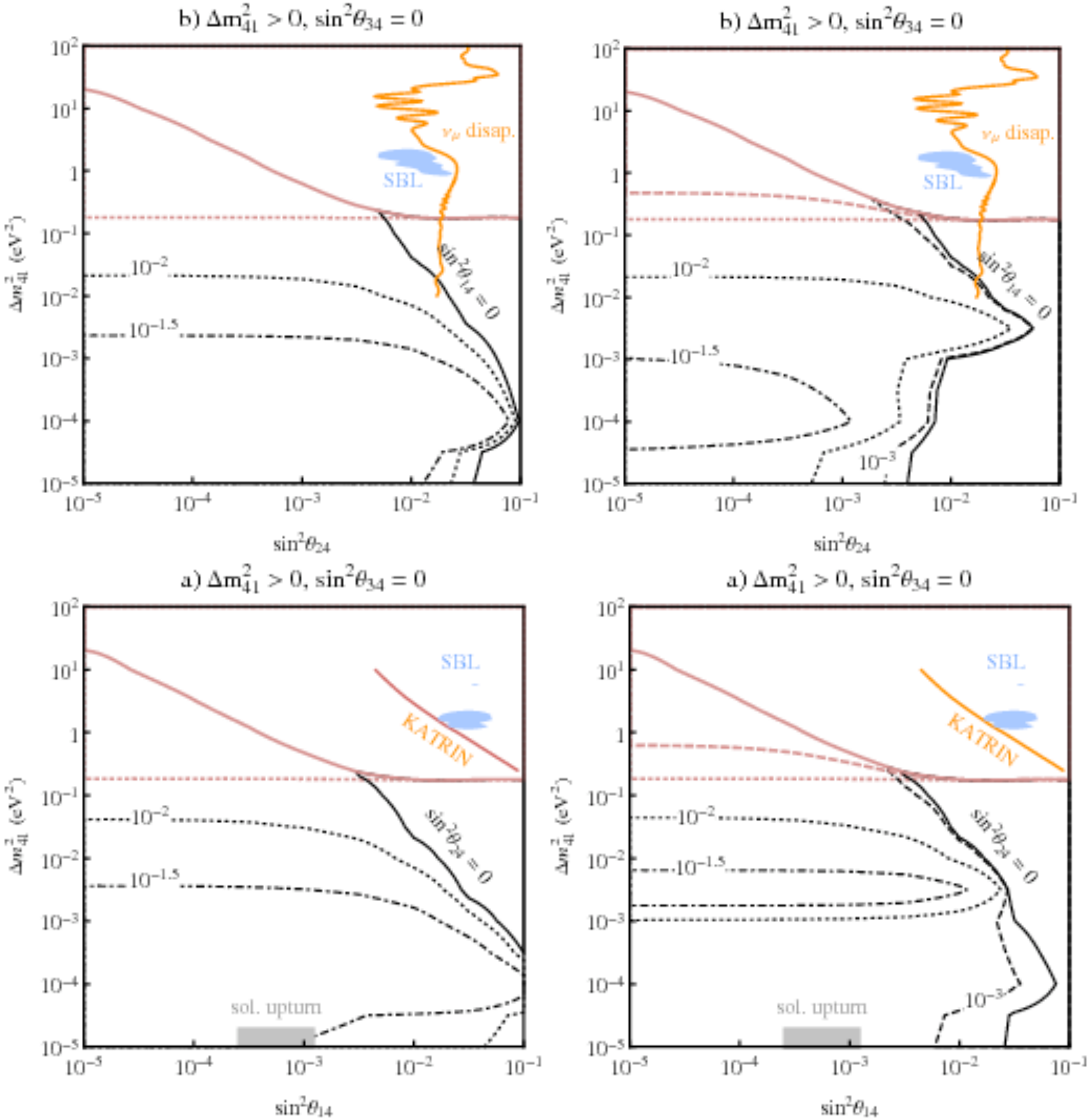
The standard case, after Planck 2013

N_{eff} < 3.30±0.27
m_s< 0.38 eV

New Planck analysis 2015 even stronger!

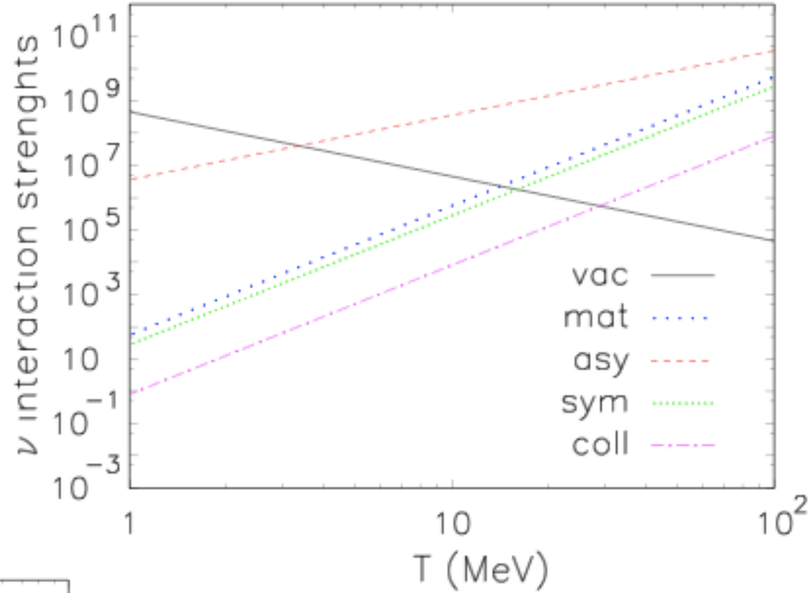
(Planck XIII 2015)

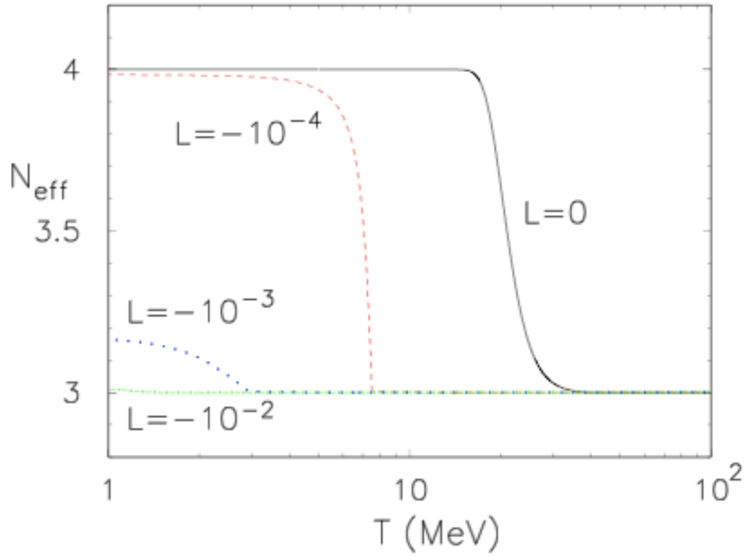
N_{eff} = 3.04±0.22
m_s< 0.38 eV



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" ?

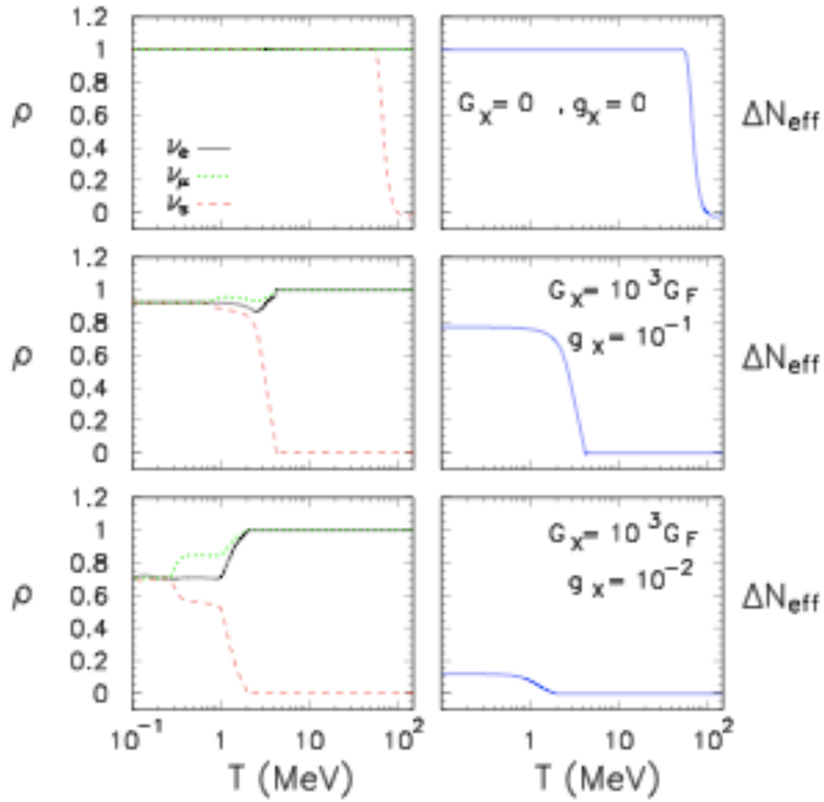
$$g_X \bar{\nu}_s \gamma^\mu X_\mu \nu_s$$

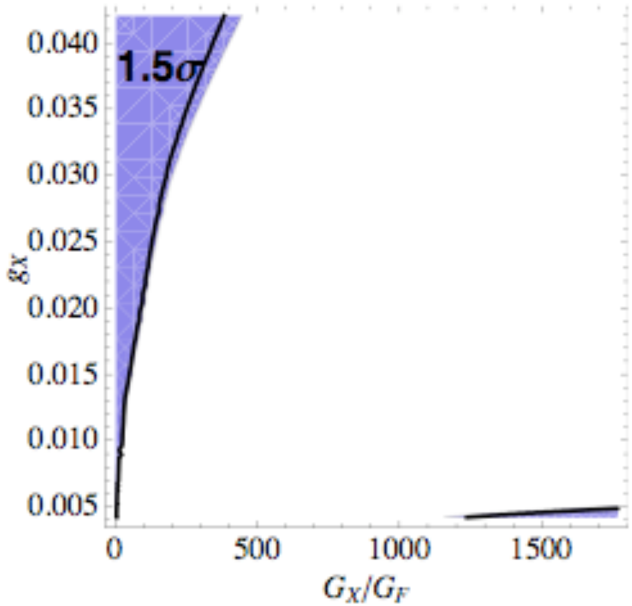
Fermi type lagrangian term with coupling G_X^2 and a sterile potential term linear in G_X

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

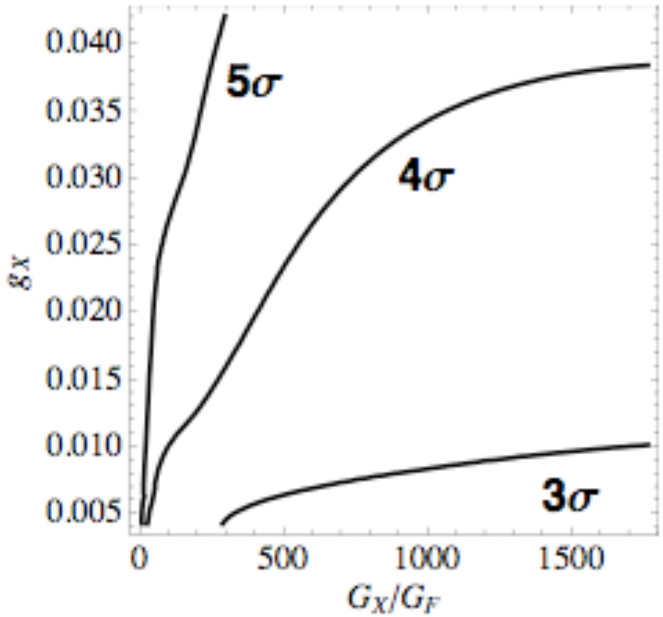
"small" G_X ($<10^4 G_F$) problem with BBN
"large" G_X ($>10^5\ G_F$) problem with N_{eff} (smaller than 3 and neutrino mass bounds from CMB)

BBN sensitive to ν_e distribution




1.5σ
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
g_X
0
500
1000
1500
G_X/G_F

Y_p


5σ
4σ
3σ
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
g_X
0
500
1000
1500
G_X/G_F

$^2H/H$

Degenerate Big Bang Nucleosynthesis

If $\xi_\nu \neq 0$, for any flavor

$$\boxed{\Delta N_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]}$$

$\rho(\xi_\nu) > \rho(0) \rightarrow \uparrow {}^4He$

Plus the direct effect on $n \leftrightarrow p$ if $\xi(\nu_e) \neq 0$

$$\boxed{\left(\frac{n}{p}\right)_{eq} = \exp\left(-\frac{m_n - m_p}{T} - \xi_e\right)}$$

$\xi_e > 0 \rightarrow \downarrow {}^4He$

Pairs $(\xi_e, \Delta N_\nu)$ that produce the same observed abundances for **larger** η_B

Kang & Steigman 1992

oscillations and ν decoupling almost at the same temperature scale

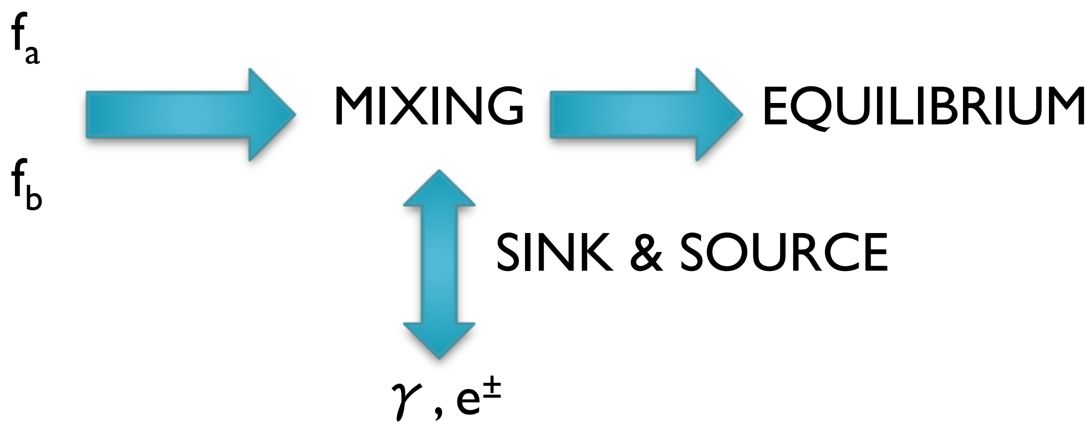
Example: $\xi_a = -\xi_b = \xi$

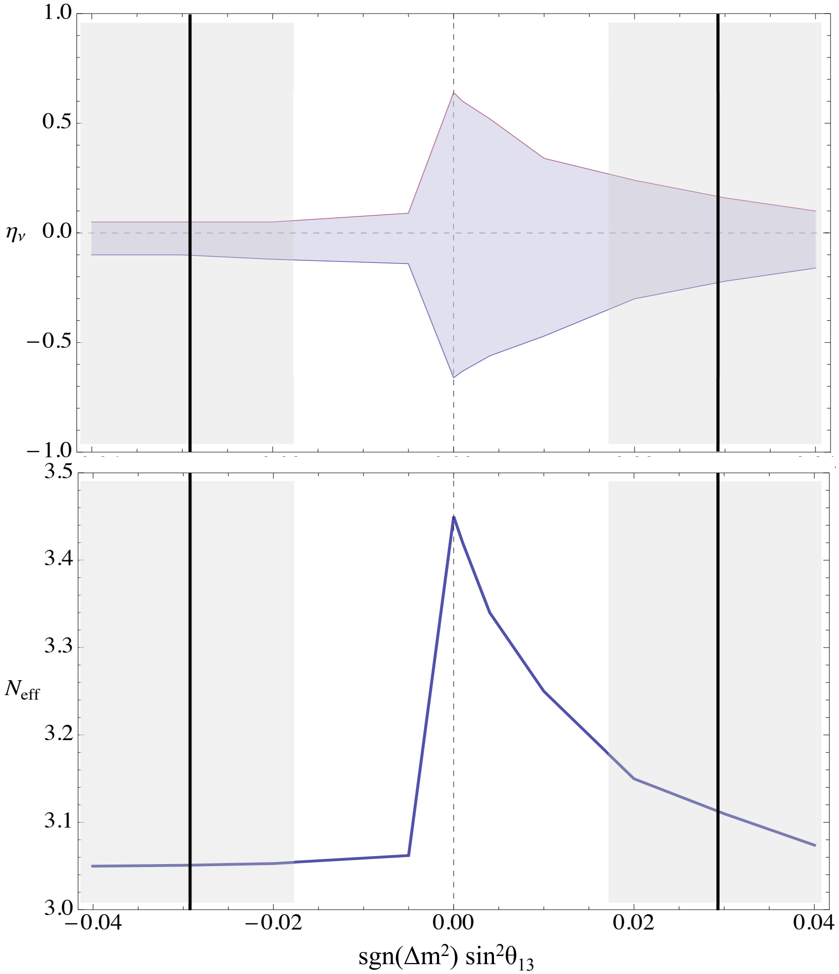
$T_{mix} >> T_{dec}$ $$f_a = f_b = \frac{1}{e^{p/T}+1}$$ $N_{eff} = 3.045$

$T_{mix} << T_{dec}$ $$f_a = f_b = \cos^2\theta \frac{1}{e^{p/T-\xi}+1} + \sin^2\theta \frac{1}{e^{p/T+\xi}+1}$$

$N_{eff} > 3$

unless $\xi = 0$





the bounds:

scanning all asymmetries compatible with BBN

$N_{\rm eff} < 3.2$

$-0.2\ (-0.1) \leq \eta_\nu \leq 0.15\ (0.05)$

- $N_{eff} \leq 3.2$ still compatible with slightly degenerate neutrinos
- $N_{eff} \geq 3.2$ some extra "dark" radiation required or highly non-thermal neutrino distribution, or both

Planck 2015: a (large) neutrino asymmetry is still viable and can saturate the N_{eff} (68 % C.L.) upper bound

Bounds on non standard neutrino interactions

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

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

New effective interactions between electron and neutrinos

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

$$\boxed{P = L,\, R = (1 \mp \gamma_5)/2} \qquad \boxed{g_L = -\tfrac{1}{2} + \sin^2\theta_W \text{ and } g_R = \sin^2\theta_W}$$

Electron-Neutrino NSI

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

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

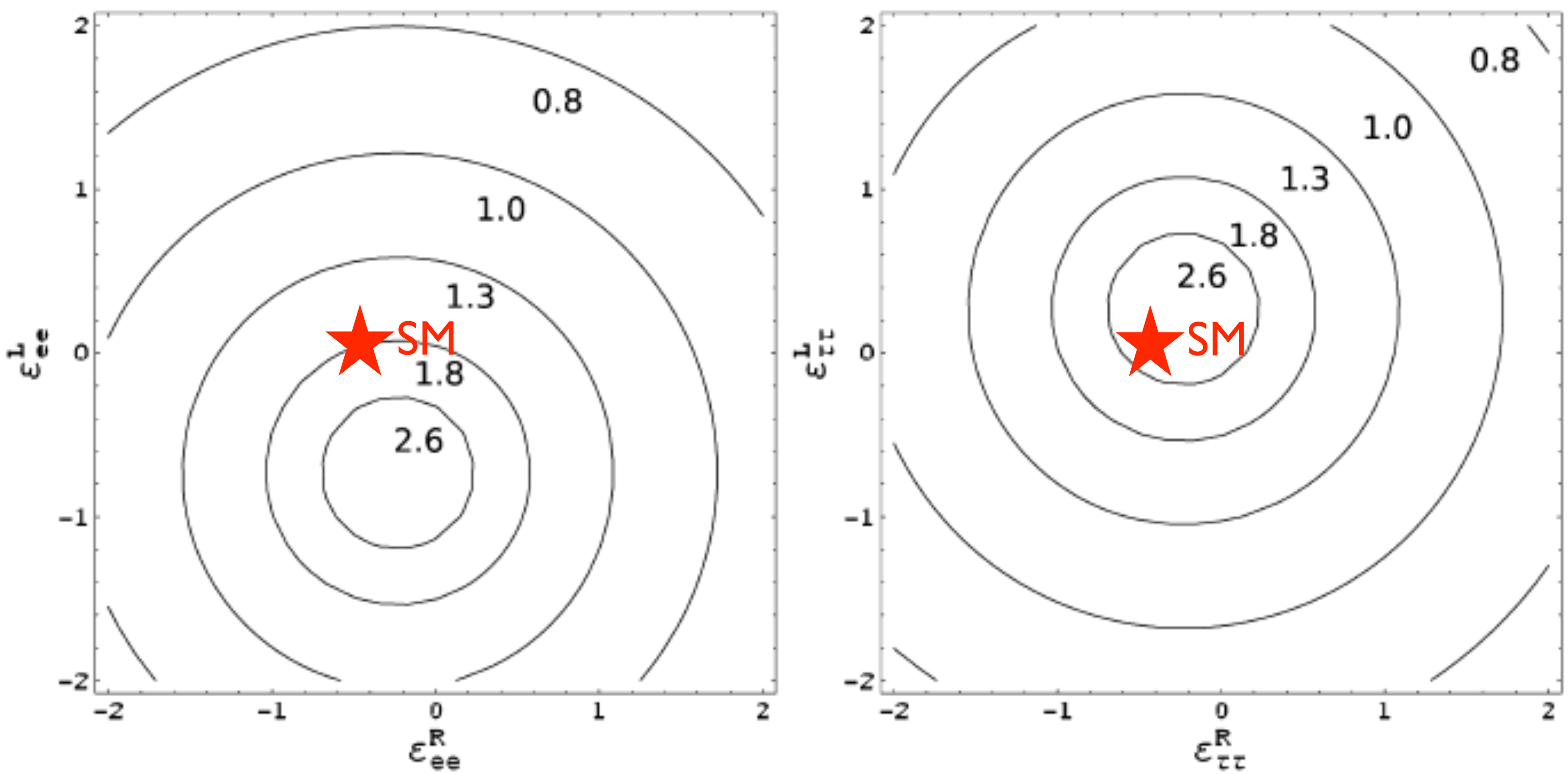
Breaking of Lepton universality ($\alpha=\beta$)

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

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

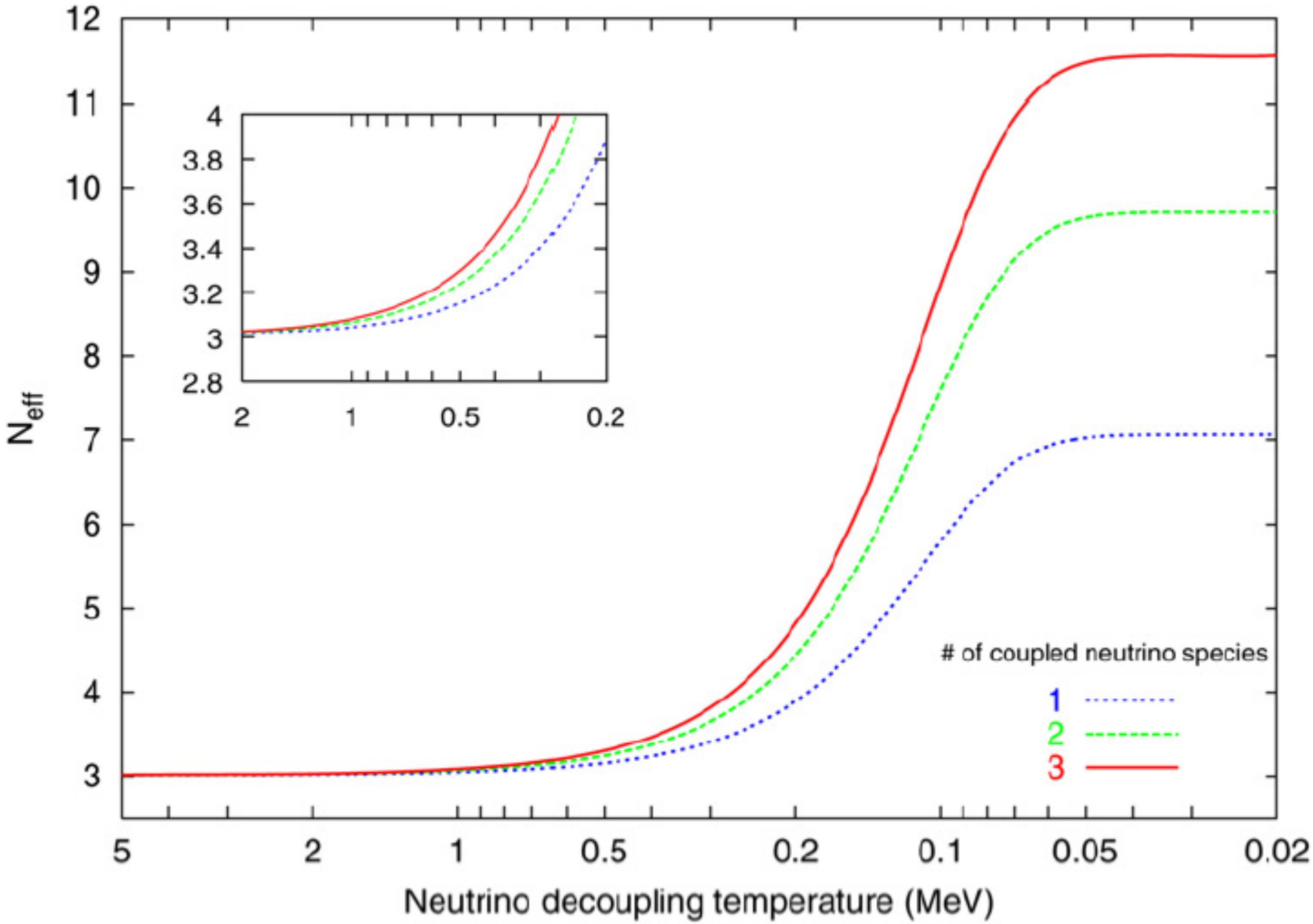
Limits from scattering experiments,
LEP data, solar vs Kamland data…

Analytical calculation of T_{dec} in presence of NSI

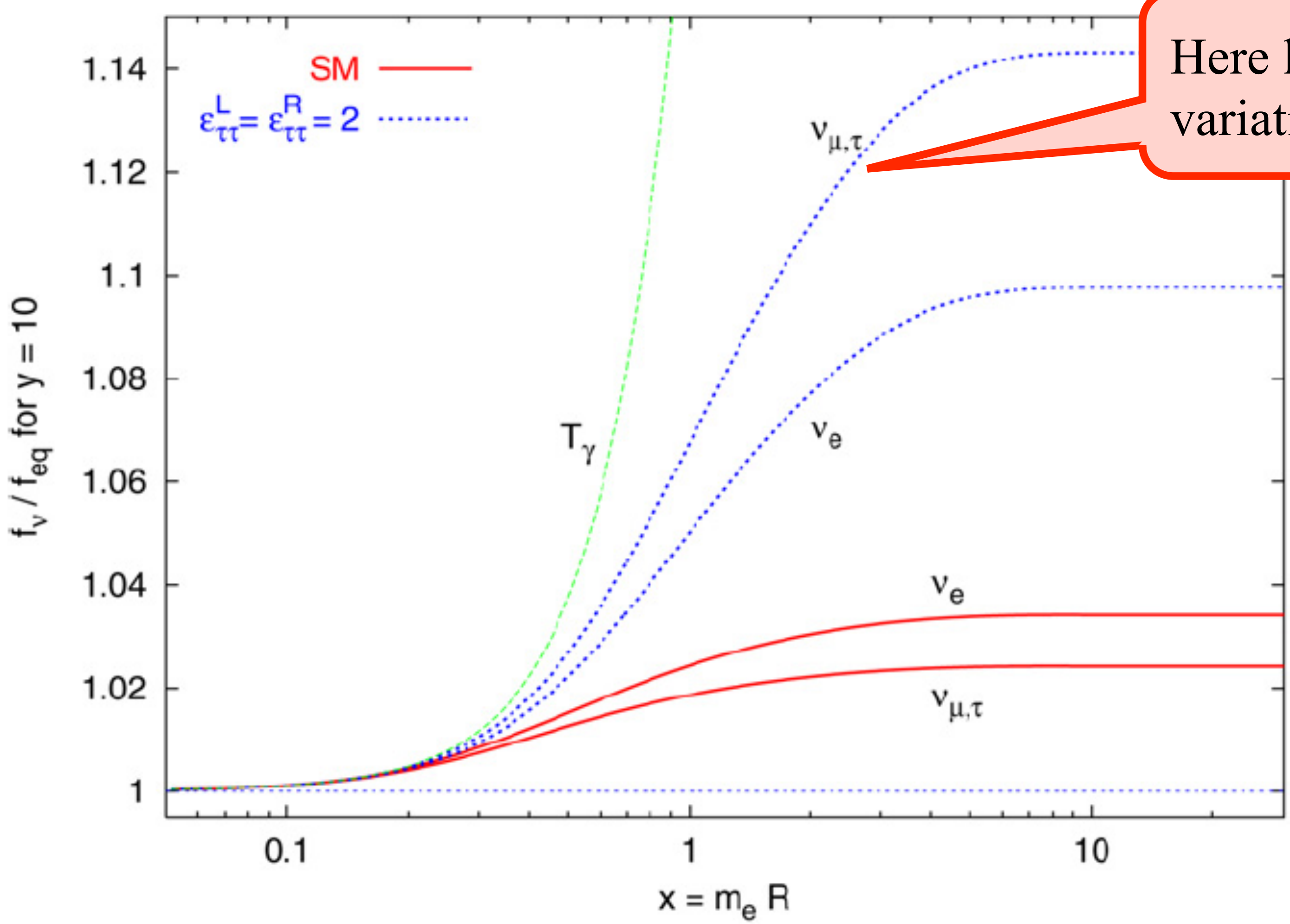


Contours of equal T_{dec} in MeV with diagonal NSI parameters

N_{eff} varying the neutrino decoupling temperature



Effects of NSI on the neutrino spectral distortions



Here larger variation for $\nu_{\mu,\tau}$

Neutrinos keep thermal contact with e-γ until smaller temperatures

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
ε^{L}_{ee}= 4.0 ε^{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)

EXERCISE IX

Compute the comoving neutrino free streaming length as function of neutrino mass

$$d_{FS} = \int_{t_{in}}^{t} c_{\nu}(t')\frac{dt}{a(t')} = \int_{a_{in}}^{a} c_{\nu}(a')\frac{da'}{a'^2 H(a')}$$

Direct laboratory bounds on m$_\nu$

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

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

m(ν_e) < 2.2 eV (95% CL) Mainz

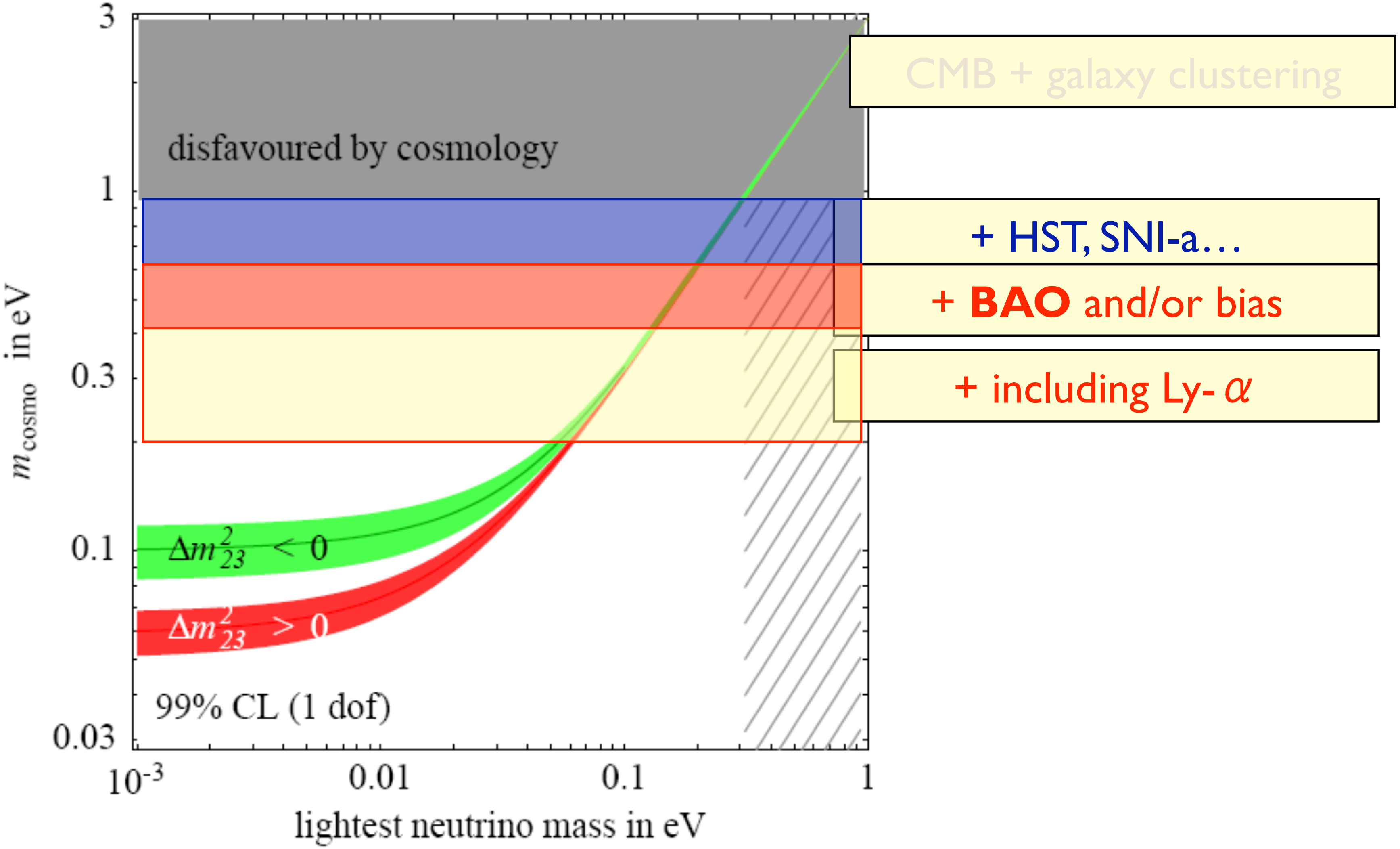
Future experiments (KATRIN) m(ν_e) ~ 0.2-0.3 eV

- Neutrinoless double beta decay: if Majorana neutrinos

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^-}$$

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

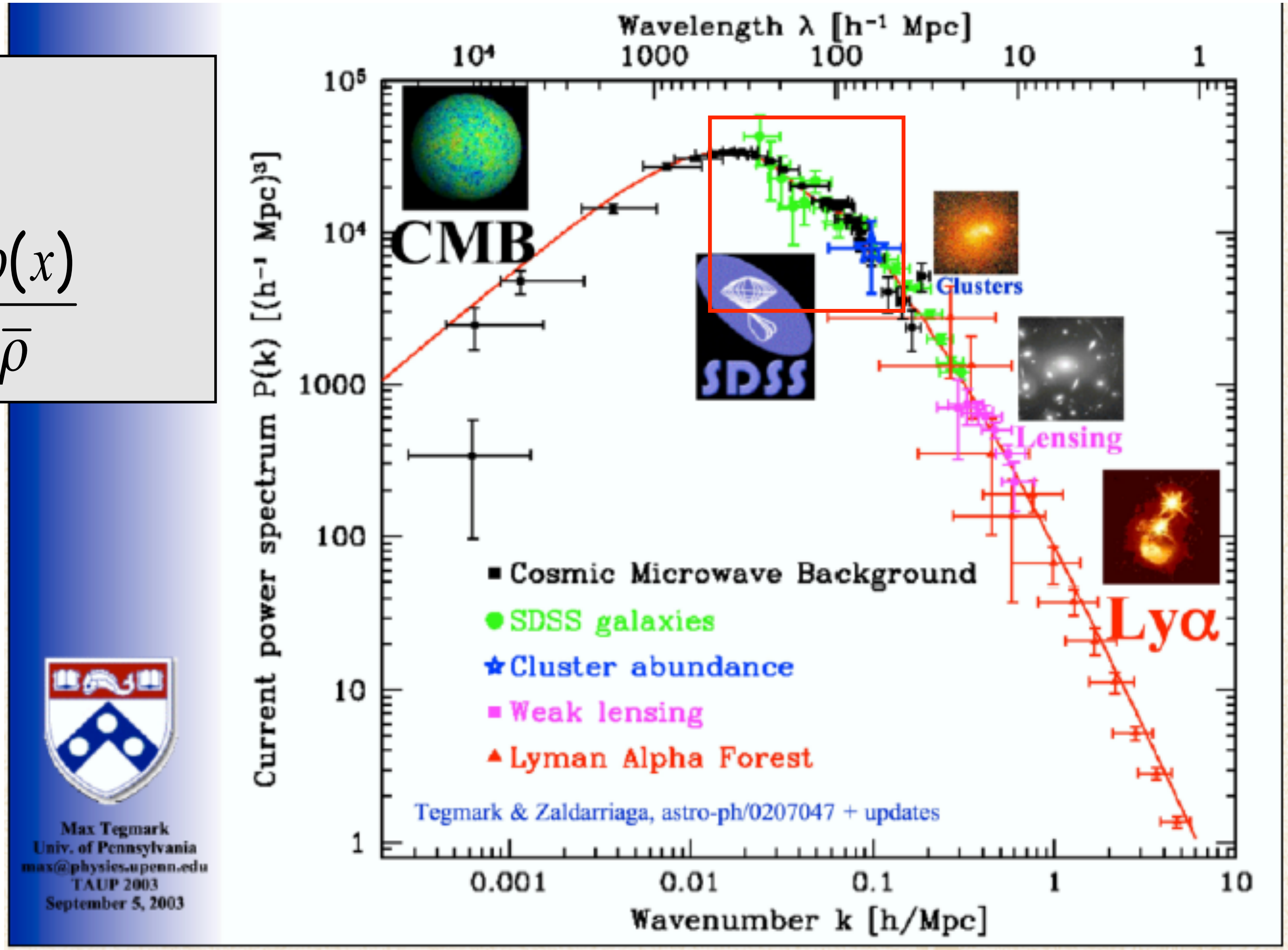
Neutrino masses in 3-neutrino schemes



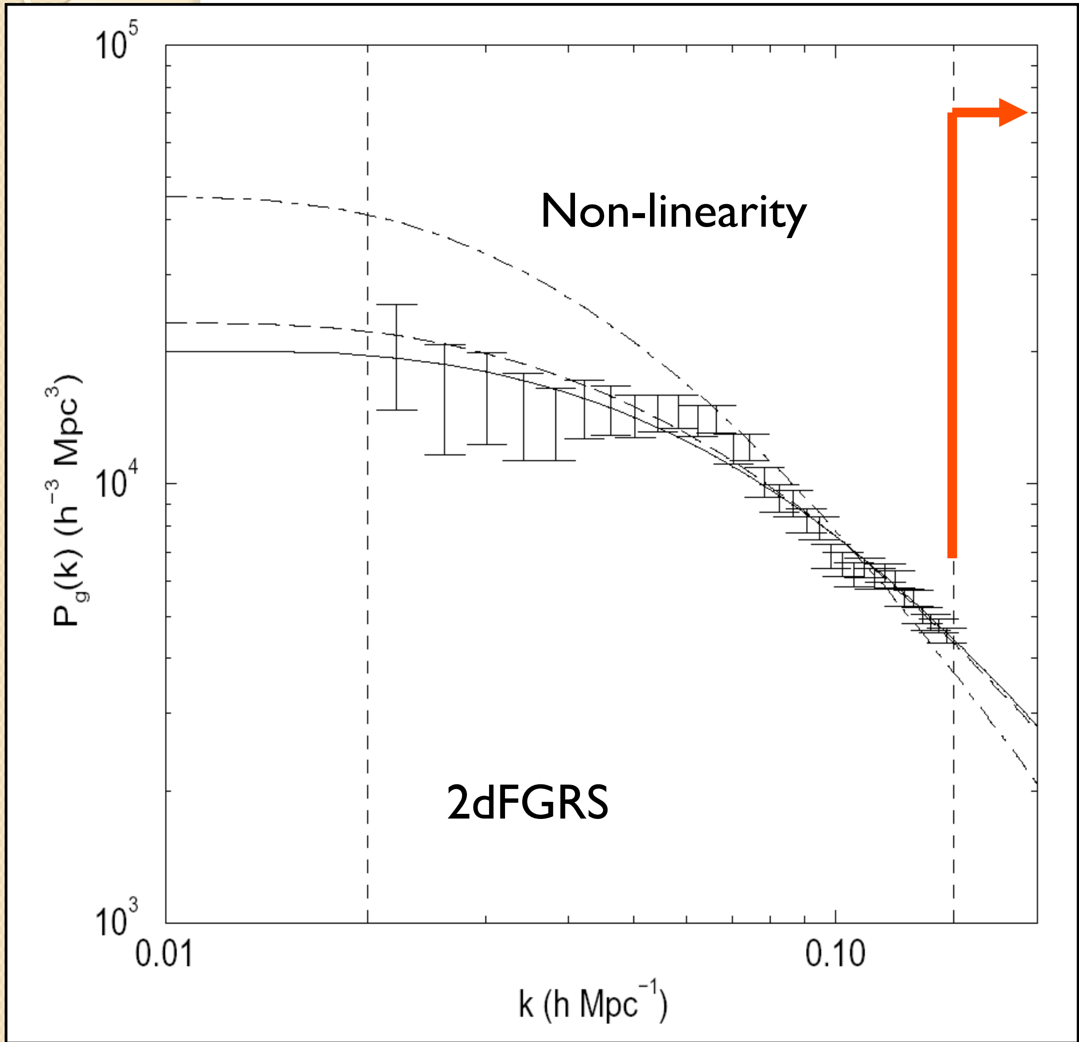
Power Spectrum of density fluctuations

Field of density
Fluctuations

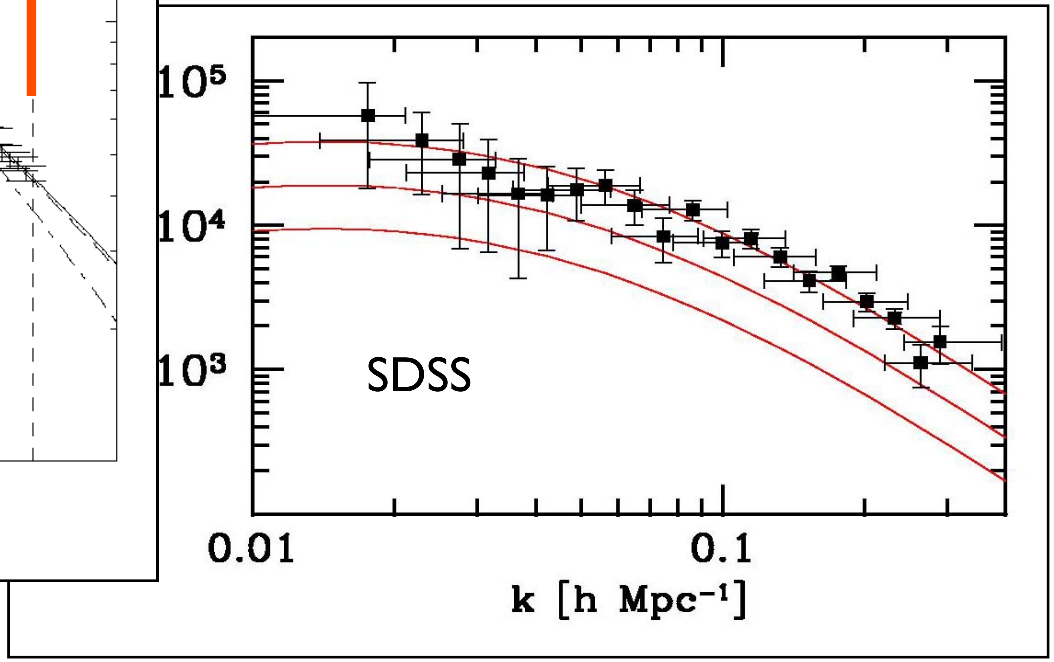
$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$



Power spectrum of density fluctuations



Bias $b^2(k)=P_g(k)/P_m(k)$



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

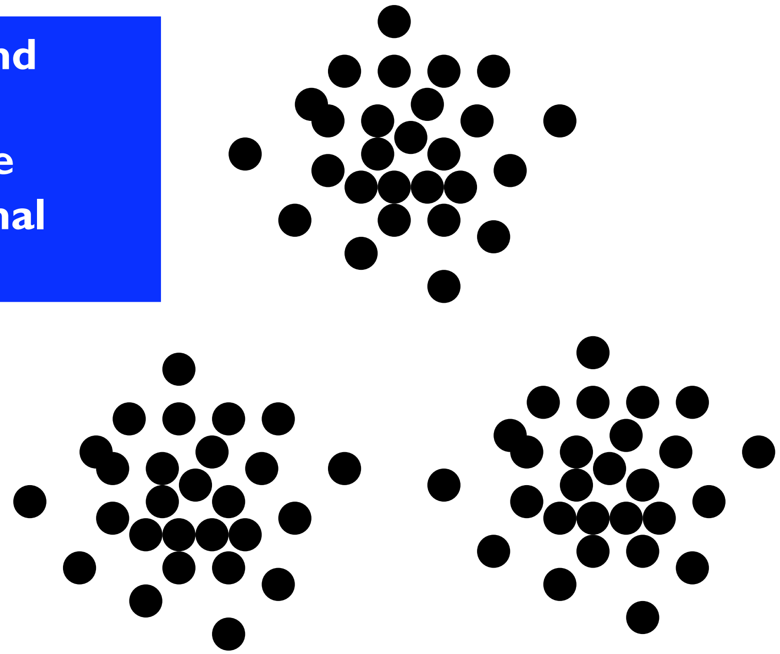
The small-scale suppression is given by

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

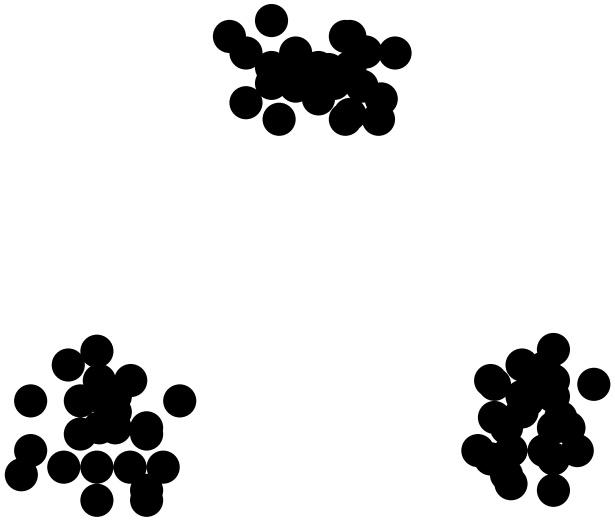
f_ν

Structure formation after equality

baryons and CDM experience gravitational clustering



baryons and CDM experience gravitational clustering

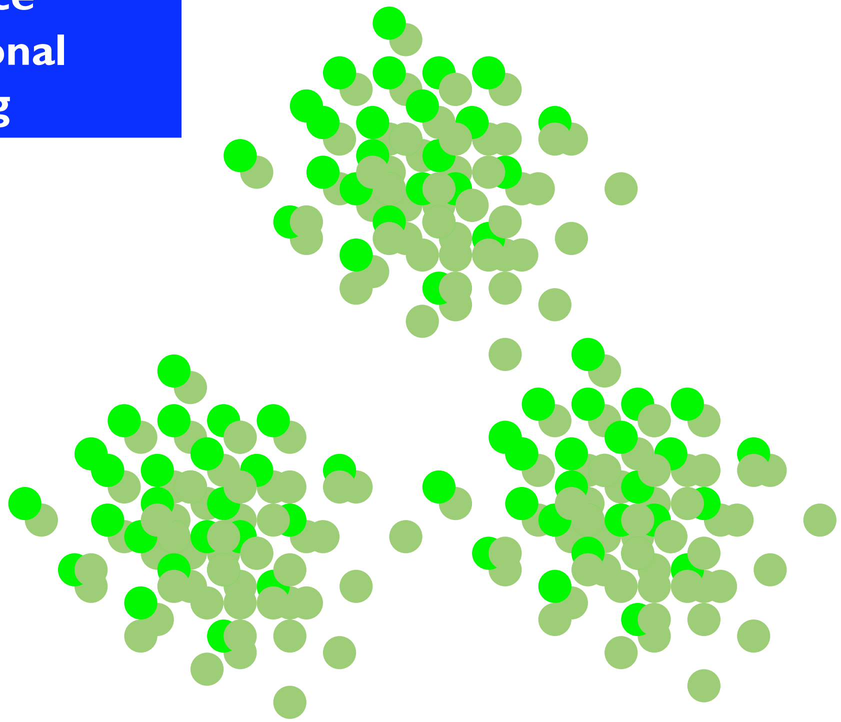


growth of $\delta\rho/\rho$ (k,t) fixed by

« gravity vs. expansion » balance

⇨ $\delta\rho/\rho \propto$ **a**

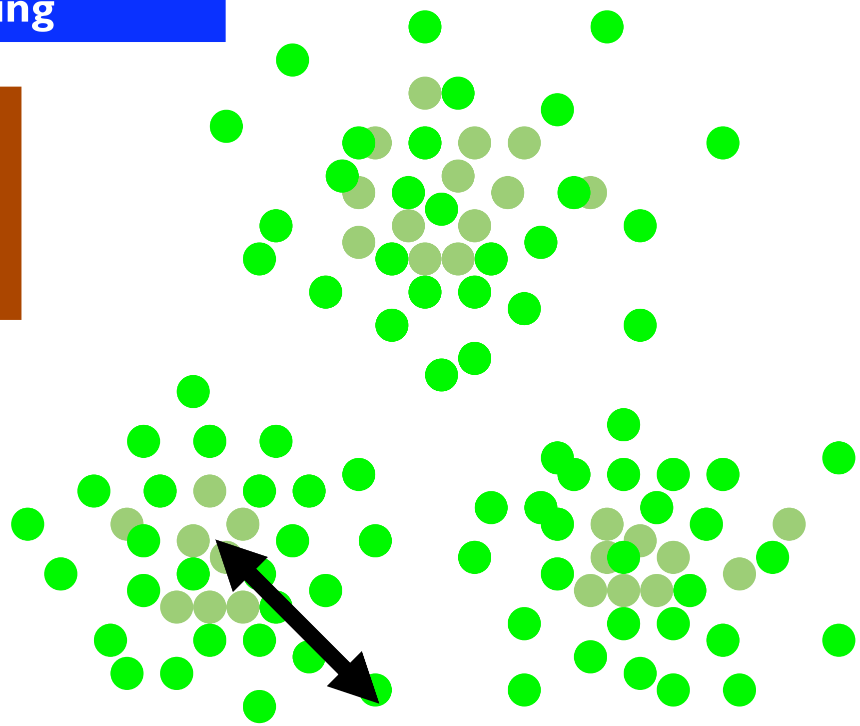
baryons and CDM experience gravitational clustering



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

baryons and CDM experience gravitational clustering

baryon and CDM experience gravitational clustering

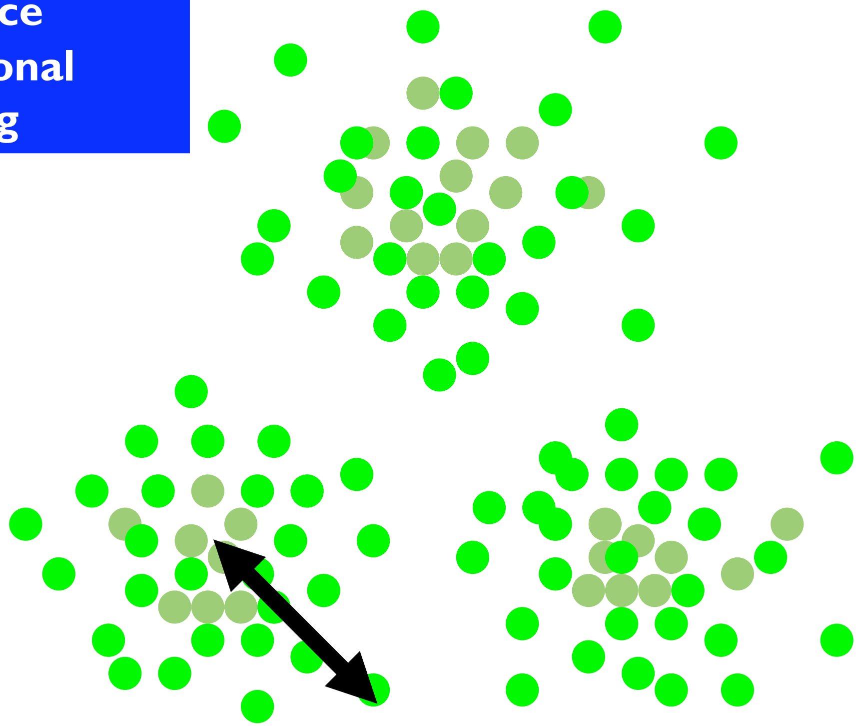


neutrinos experience free-streaming with v = c or <p>/m

neutrinos cannot cluster below their diffusion length

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

baryons and CDM experience gravitational clustering



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

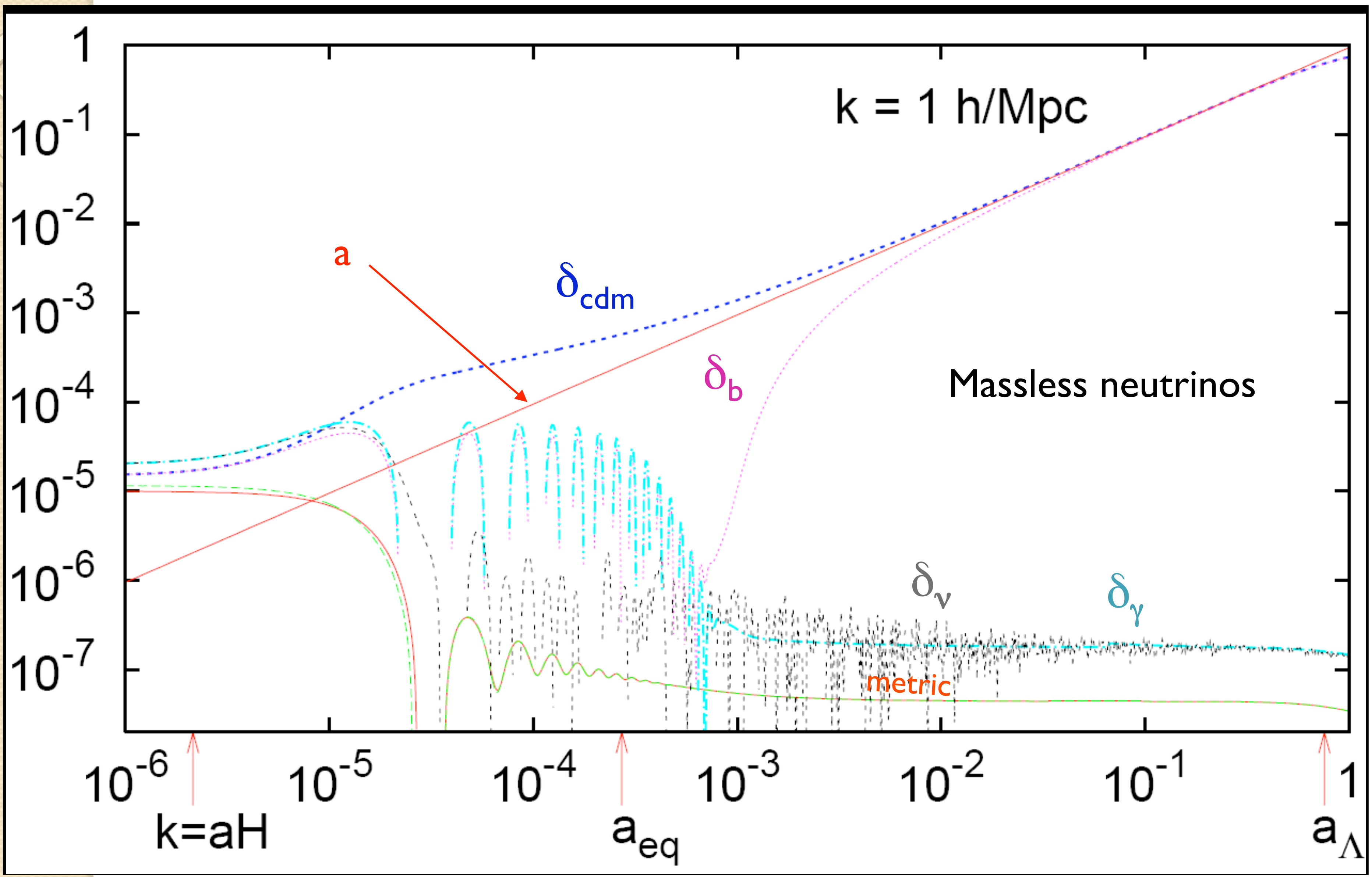
$$\ddot{\delta}_{\mathrm{cdm}} + \frac{2}{\tau}\dot{\delta}_{\mathrm{cdm}} - \frac{6}{\tau^2}(1-f_\nu)\,\delta_{\mathrm{cdm}} = 0\,.$$

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

free-streaming supresses growth of structures during MD

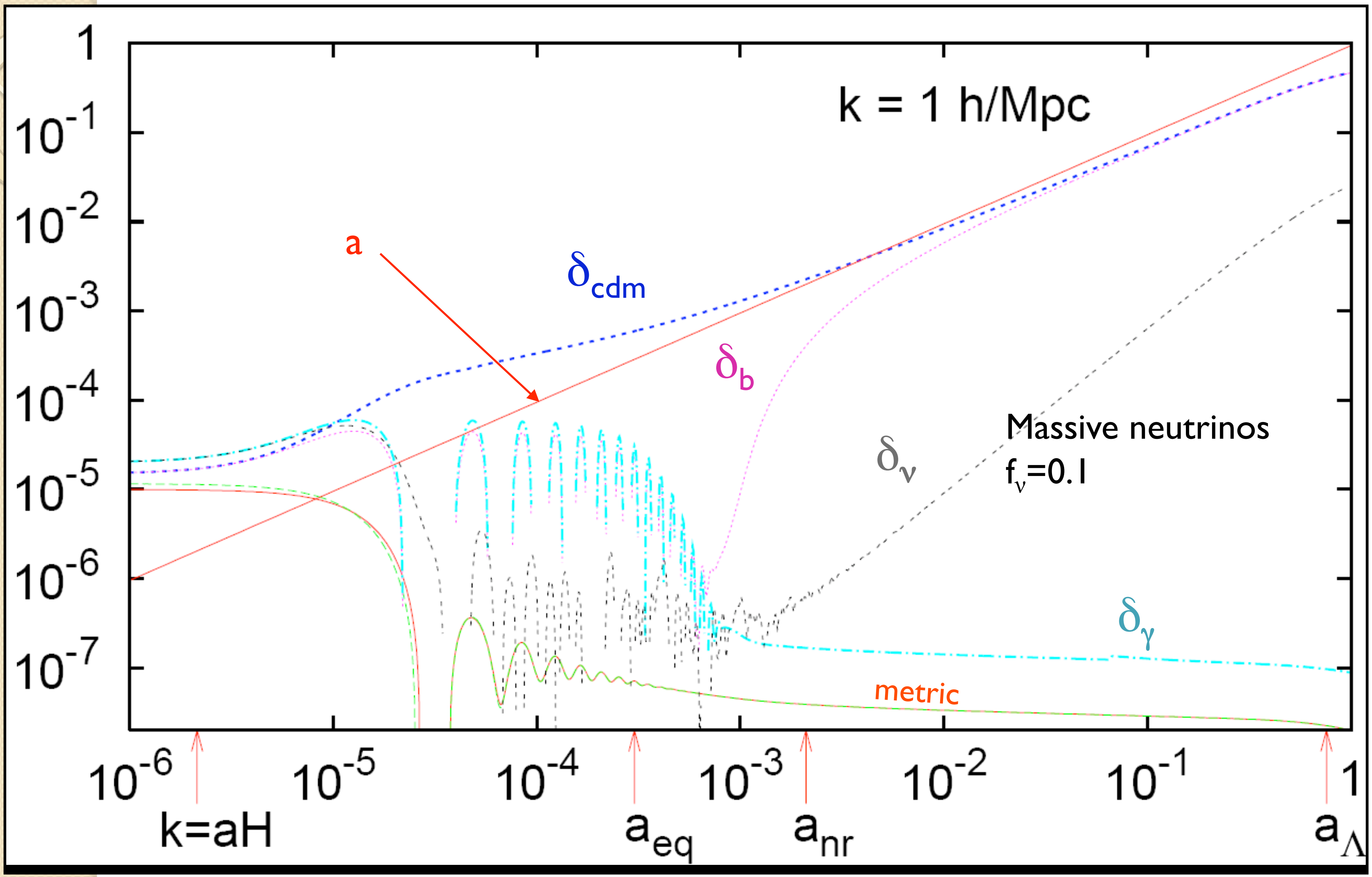
⇨ $\delta\rho/\rho \propto \mathbf{a}^{\mathbf{1-3/5\, f\nu}}$ with $f_\nu = \rho_\nu/\rho_m \approx (\Sigma m_\nu)/(15\ \mathrm{eV})$

Structure formation after equality



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

Structure formation after equality

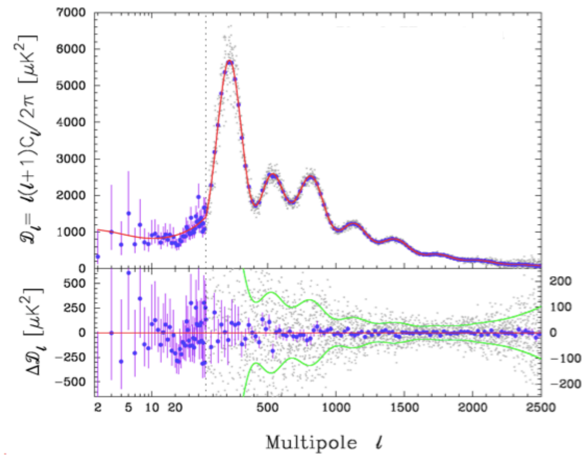


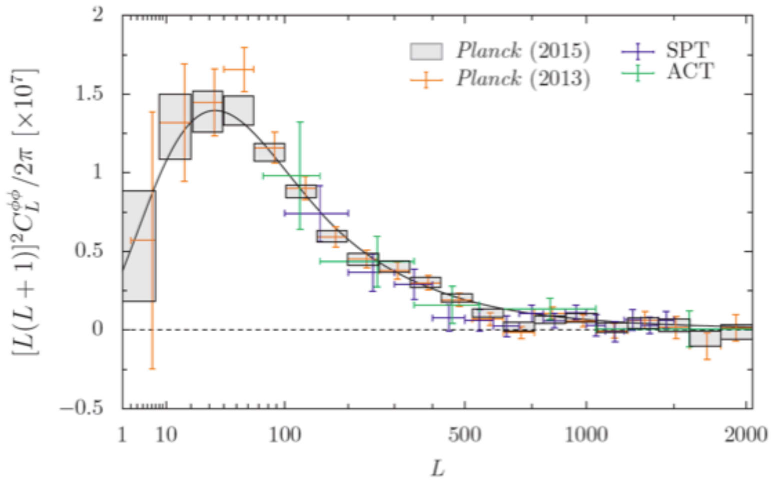
J.Lesgourgues & S. Pastor, Phys Rep 429 (2006) 307 [astro-ph/0603494]

CMB bounds

Planck 2015

Planck 2015 TT-spectrum

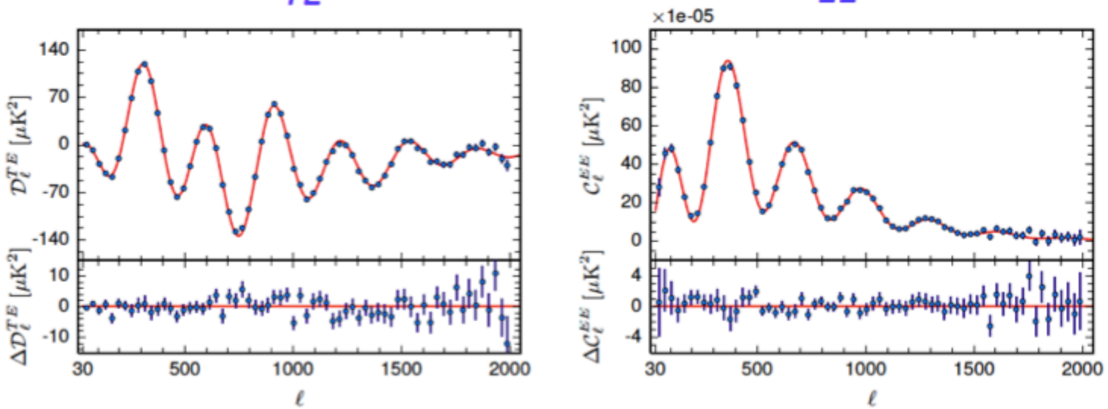




Planck 2015

TE

EE

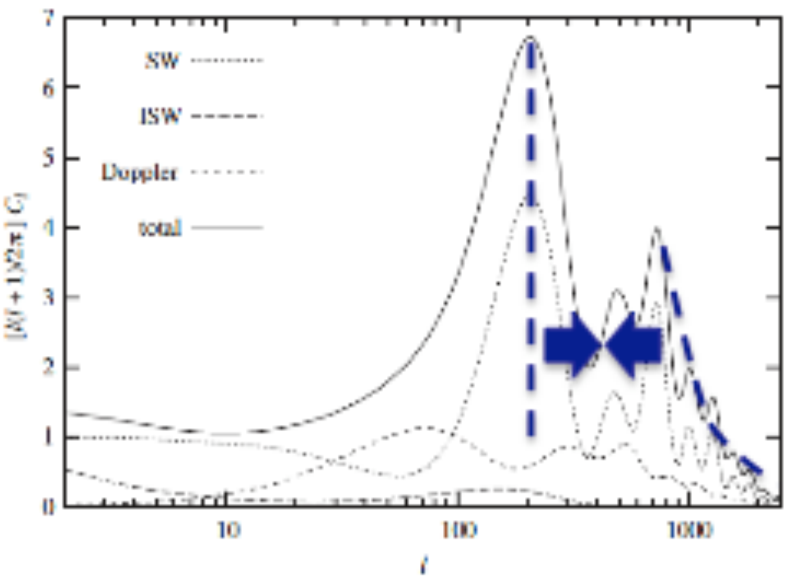


Are there neutrinos in the universe?

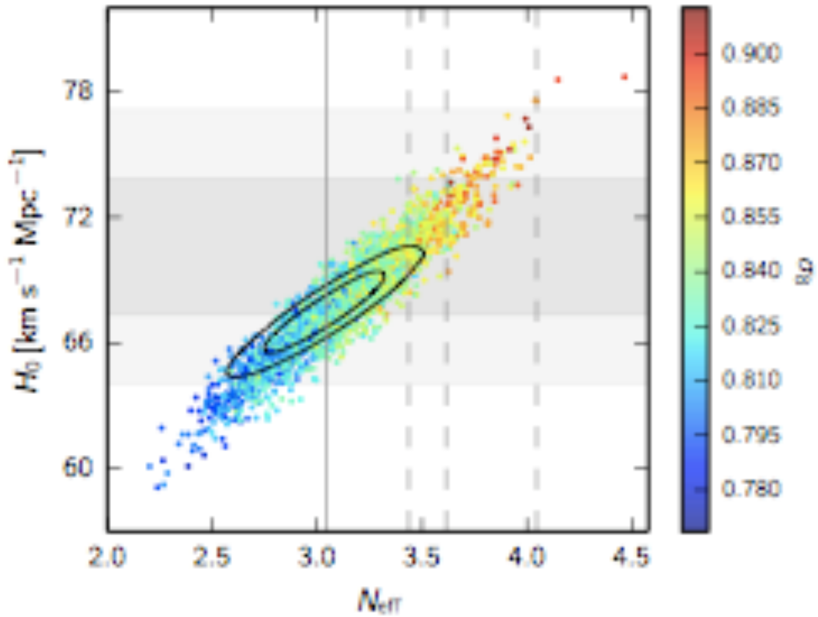
CMB
fixing the angular scale of acoustic peaks and
z_{eq} , a larger amount of dark radiation (and a larger H_0)
gives a higher expansion speed, a shorter age of the
universe T at recombination.

Diffusion length ≈ √T
(Brownian motion)

Sound horizon ≈ T



J. Lesgourgues, Planck 2014, Ferrara



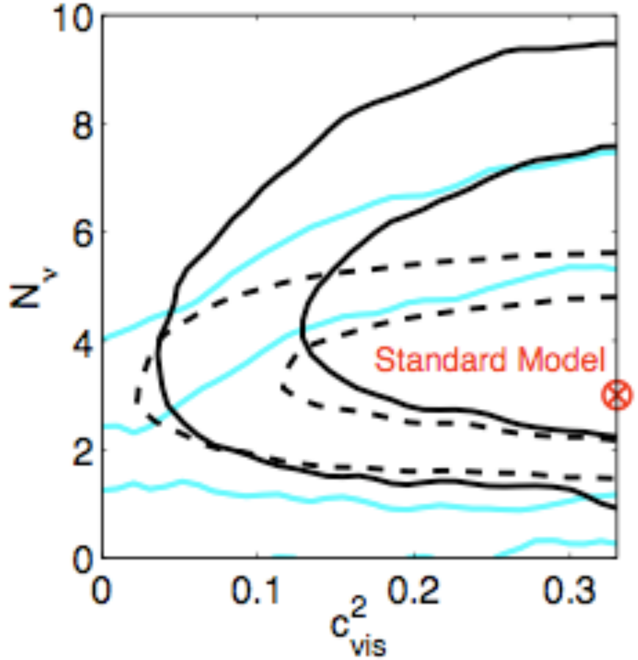
Planck 2015 results, XIII

$N_{eff} > 0$ at 10 σ

Perturbation effects:

- gravitational feedback of neutrino free streaming damping
- anisotropic stress contributions

c_{vis} :velocity/metric shear – anisotropic stress relation (Hu 1998)

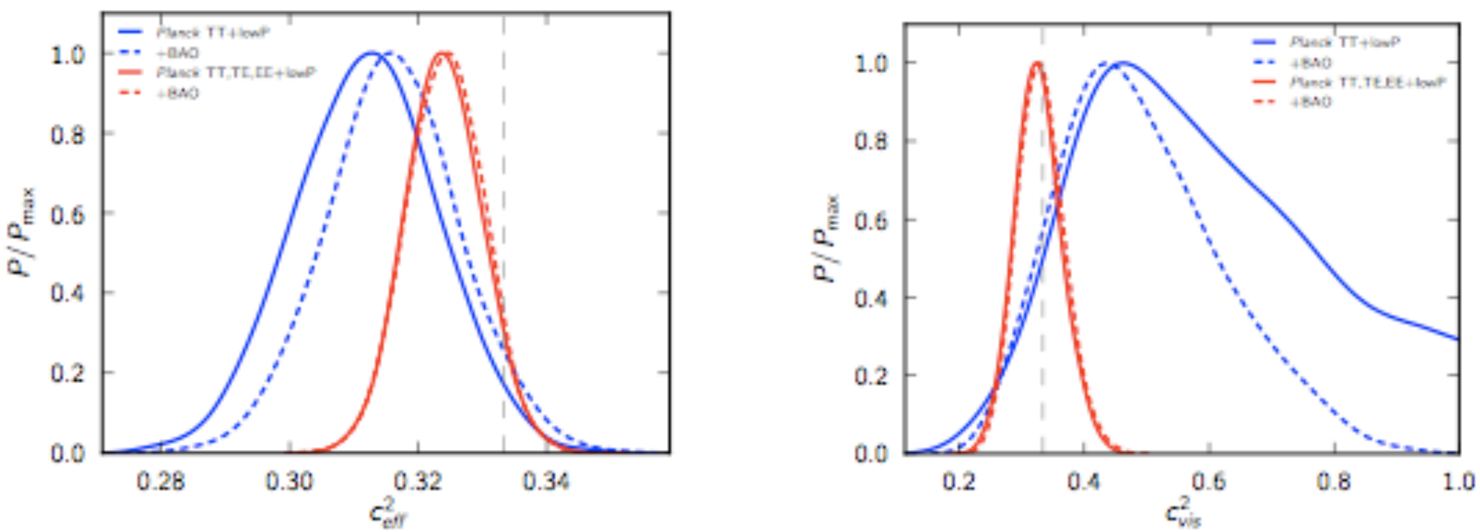


Trotta & Melchiorri 2005

Neutrino perturbations in terms of two phenomenological parameters:

$$\delta P = c_{eff}^2 \; \delta \rho \quad (1/3)$$

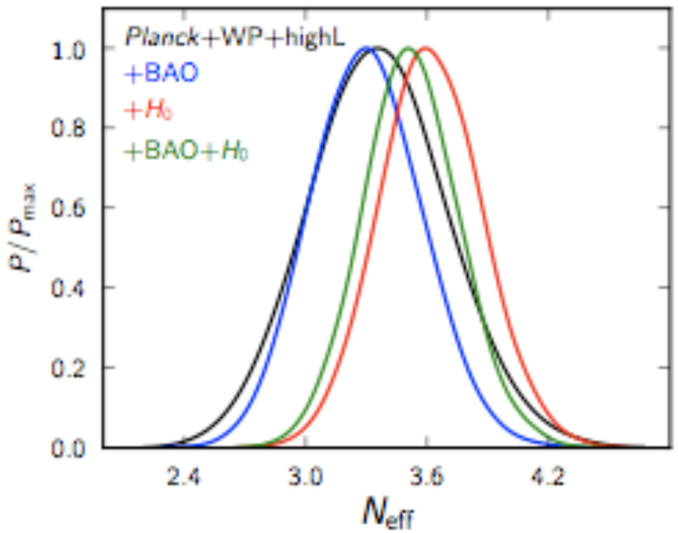
$$c_{vis}^2 \quad (1/3)$$



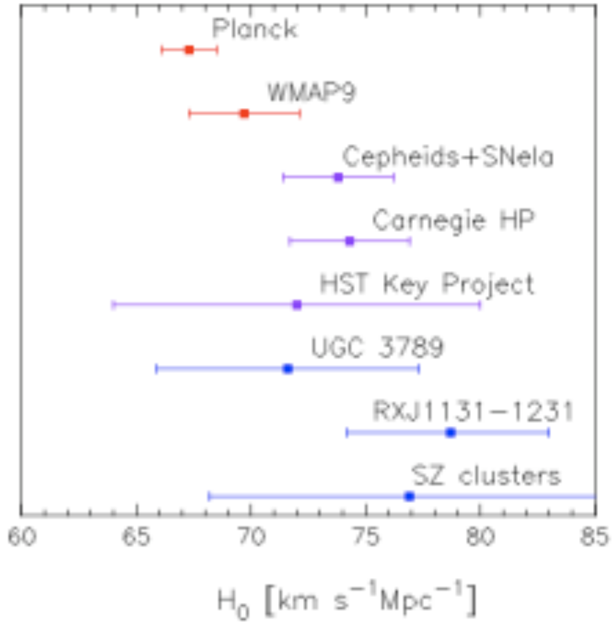
Planck 2015 results, XIII

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)

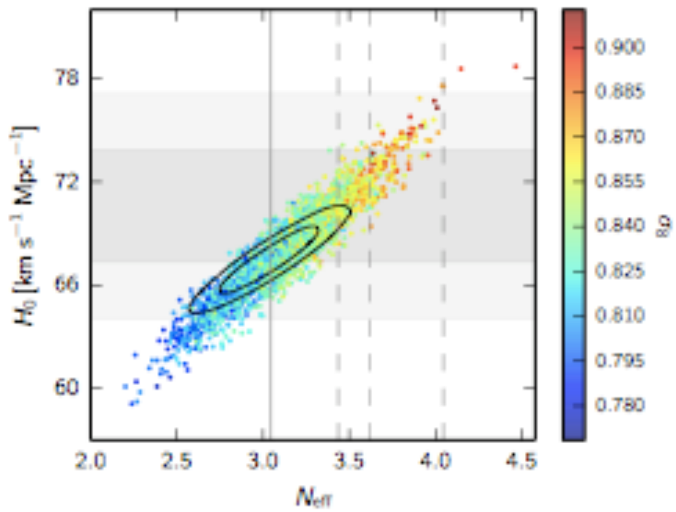
Planck 2015 :

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

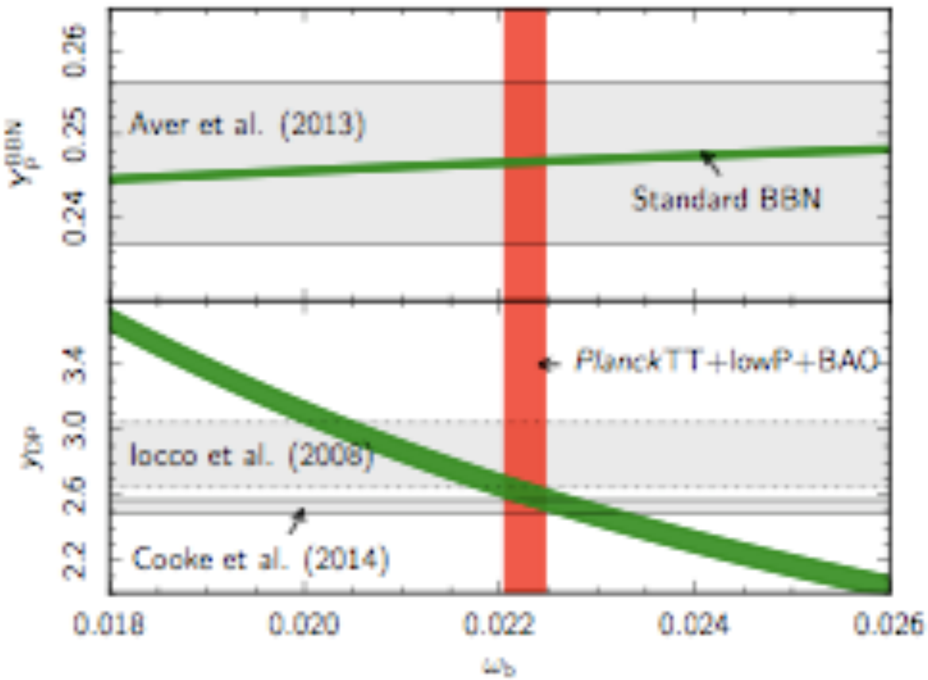
Standard expectation (3.045)

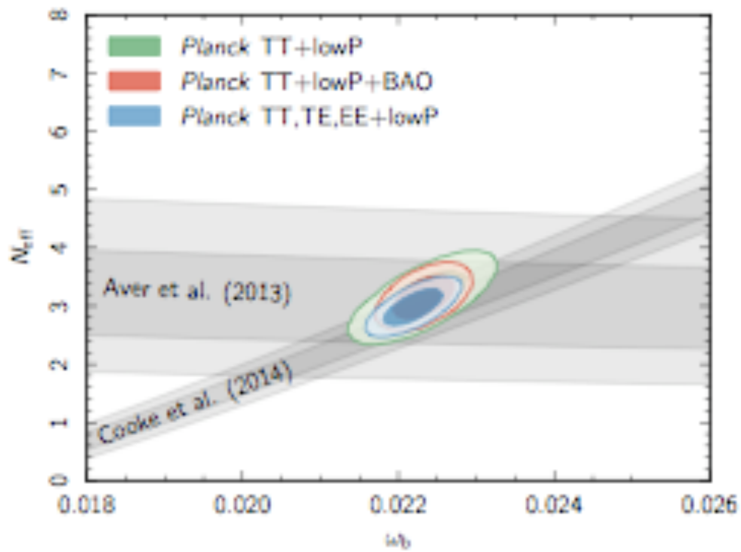
Caveat: discrepancy with SNIa value of H_0 at 2.2 σ level

$\sigma_8 \approx 0.83$



CMB and BBN are quite consistent





N_{eff} free

Planck 2015 results, XIII

Neutrino mass from CMB

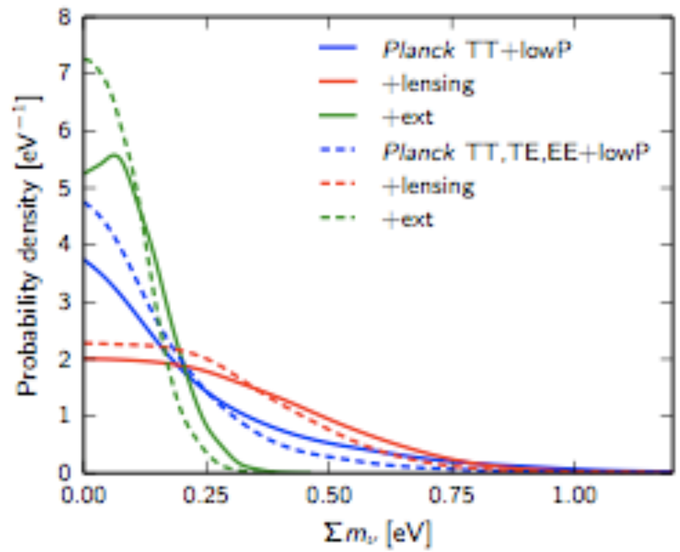
CMB:
For the expected mass range the main effect is around the first acoustic peak due to the early integrated Sachs-Wolfe (ISW) effect;

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

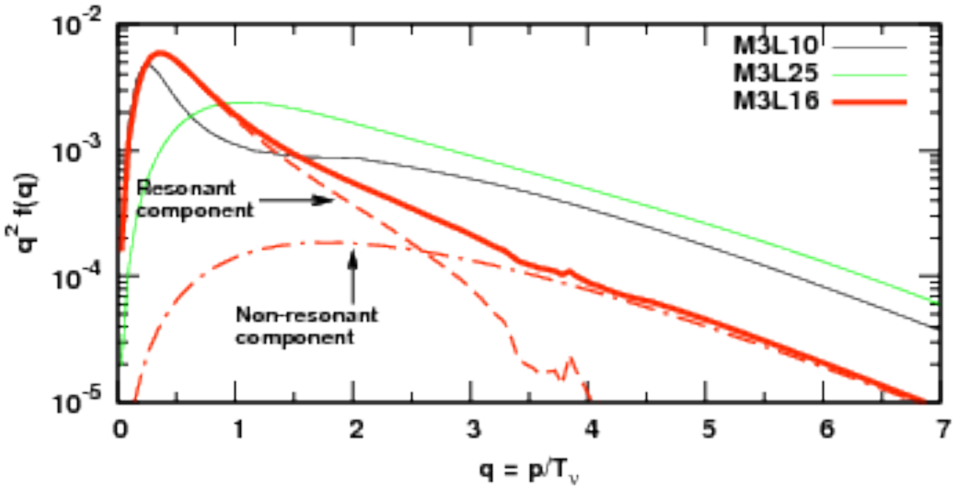
Non thermal production! Otherwise too much energy density!

$$\rho_S > 45 \text{ keV cm}^{-3}$$

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

Production via oscillations:

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

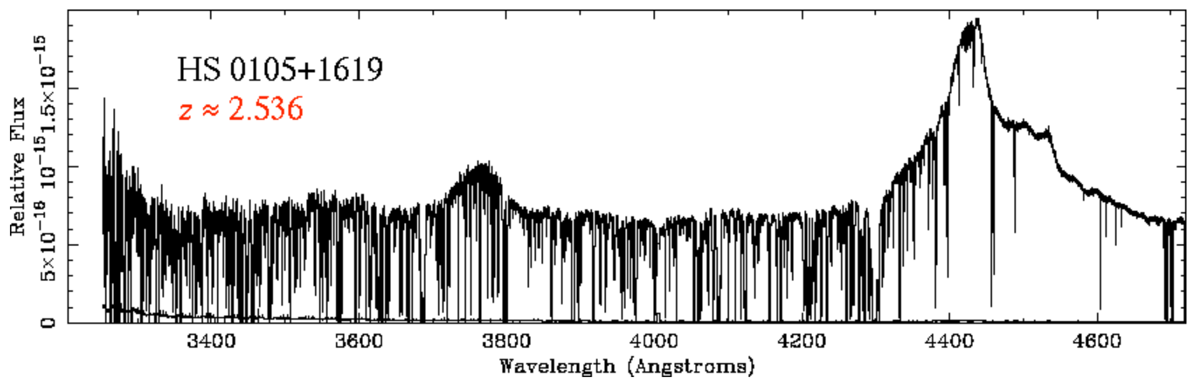


Non resonant mode:
lower sterile density.

2) X ray signal from $\nu_S \rightarrow \nu + \gamma$
m_S <50 keV

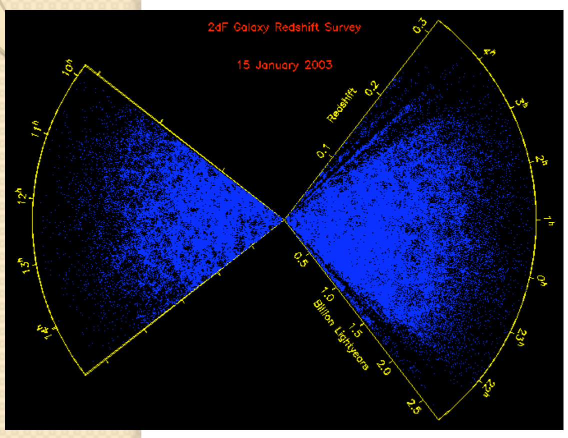
3) bounds from LSS. For warm dark matter the free streaming length is smaller: suppression of structure at a smaller scale with respect to hot dark matter: Ly α forest

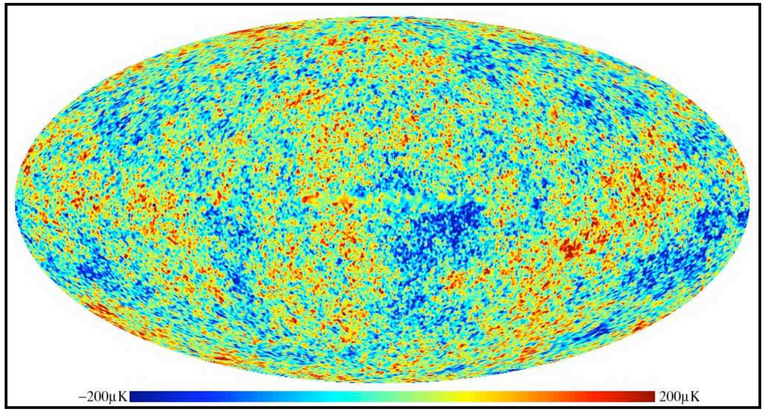
m_S > 2 keV

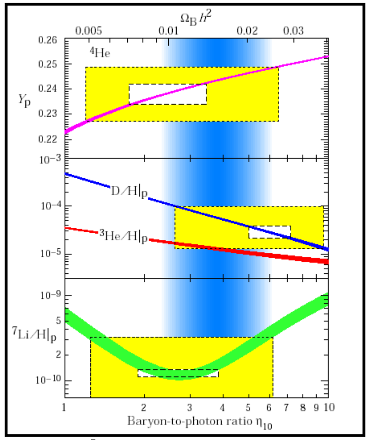


III International Pontecorvo Neutrino Physics School (2009)

Neutrinos in Cosmology







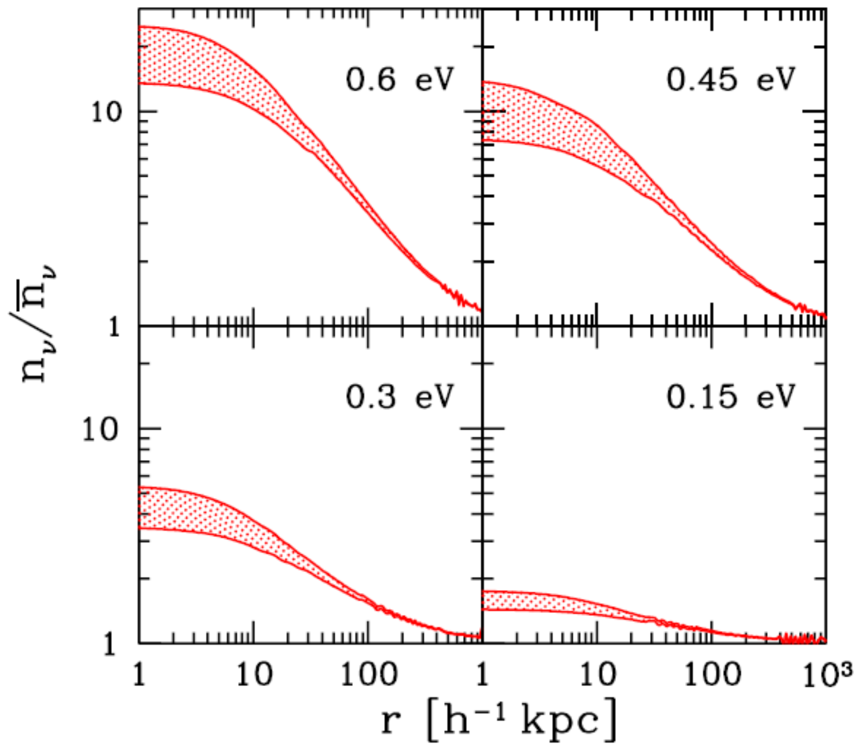
Several indirect effects of the neutrino background on cosmological observables

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

DIRECT OBSERVATION?

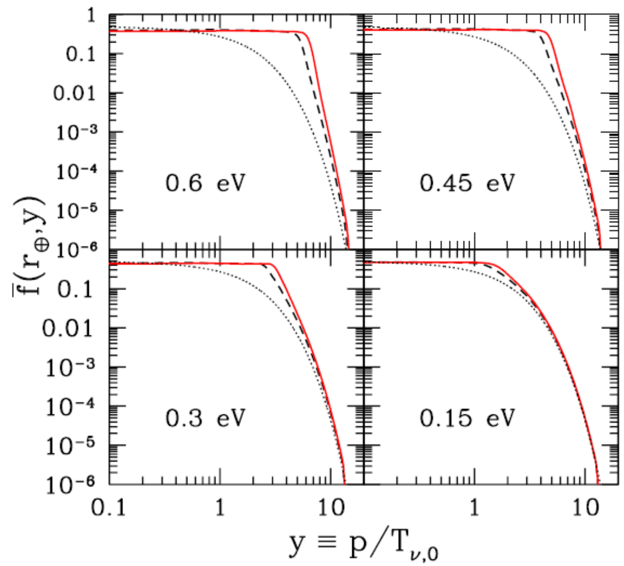
Pauli to his friend Baade:

“Today I did something a physicist should never do. I predicted something which will never be observed experimentally…”



Ringwald and Wong '04

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



@ Earth

Detection I: Stodolsky effect

Energy split of electron spin states in the ν background

Requires ν chemical potential (Dirac) or net helicity (Majorana)

Requires breaking of isotropy (Earth velocity)

Results depend on Dirac or Majorana, relativistic/non relativistic, clustered/unclustered

$$\Delta E \approx G_F \, g_A \vec{s} \cdot \vec{\beta}_{\oplus} (n_\nu - \bar{n}_\nu)$$

Duda et al '01

Torque on frozen magnetized macroscopic piece of material of dimension R

$$a \approx 10^{-27}\left(\frac{100}{A}\right)\left(\frac{cm}{R}\right)\left(\frac{\beta_\oplus}{10^{-3}}\right)\left(\frac{n_\nu - \bar{n}_\nu}{100\ cm^{-3}}\right) cm\ s^{-2}$$

Presently Cavendish torsion balances $a \approx 10^{-12}\ cm\ s^{-2}$

The only well established linear effect in G_F

Coherent interaction of large De Broglie wavelength

Energy (and angular momentum unless target is polarized and CNB has a net neutrino – antineutrino asymmetry) transfer at order G_F^2

Cabibbo and Maiani '82

Langacker et al '83

1. target is static

2. time average of incident neutrinos is spatially homogeneous over the detector size

Detection II: $G_F{}^2$

V-Nucleus collision: net momentum transfer due to Earth peculiar motion

$$\sigma_{\nu N} = G_F{}^2 E_\nu{}^2 \qquad a = n_\nu v_\nu \frac{N_A}{A} \sigma_{\nu N} \Delta p$$

$$\Delta p = \beta_\oplus E_\nu$$

$$\Delta p = \beta_\oplus m_\nu$$

$$\Delta p = \beta_\oplus T_\nu$$

$$a \approx (10^{-46} - 10^{54}) \frac{A}{100} cm\, s^{-2}$$

Coherence enhances

$$N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

$$\lambda_\nu \approx 1/T_\nu \quad - \quad 1/m_\nu \approx mm$$

Zeldovich and Khlopov '81

Smith and Lewin '83

Backgrounds: solar v + Dark matter (WIMPS)

Detection III

Accelerator: νN scattering hopeless

$$R \approx 10^{-8}\, yr^{-1}$$

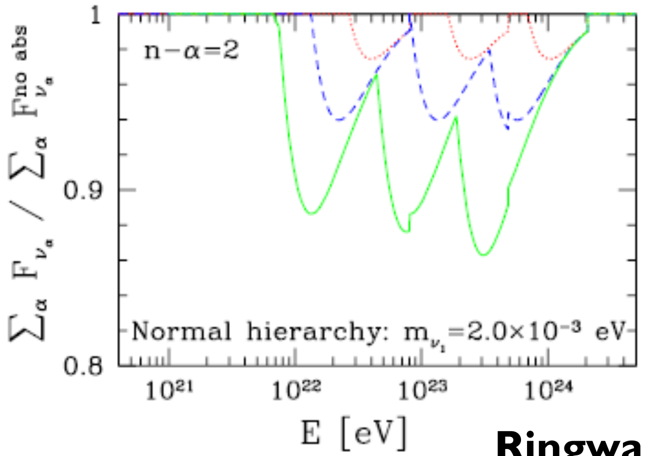
LHC

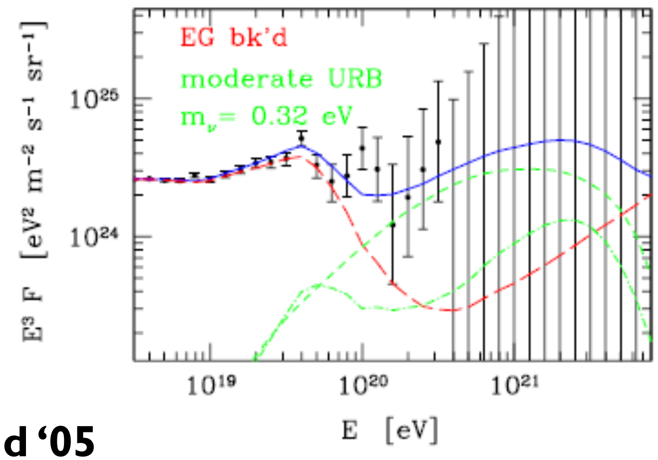
Cosmic Rays (indirect): resonant ν annihilation at m_Z

$$E = \frac{m_Z^2}{2m_\nu} \approx 4\ 10^{21} \left(\frac{eV}{m_\nu}\right) eV$$

Absorption dip (sensitive to high z)

Emission: Z burst above GZK (sensitive to GZK volume, (50 Mpc)^3)





Ringwald '05

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

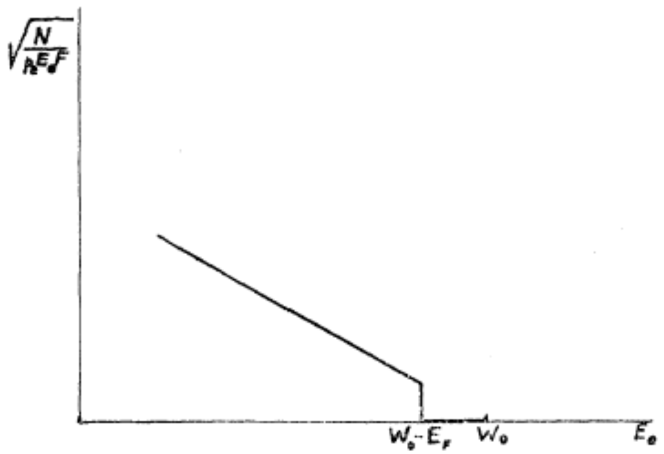


Fig. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

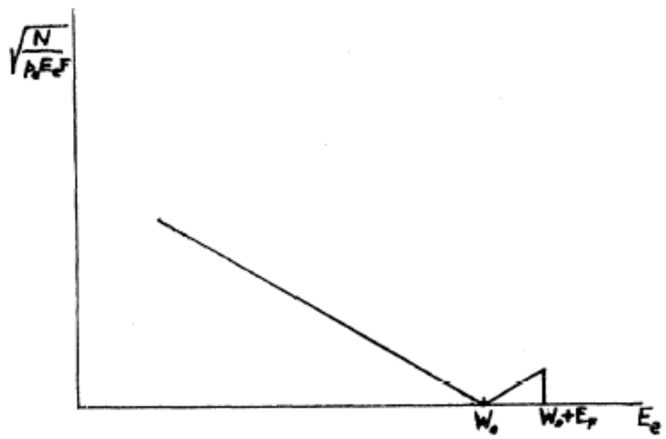
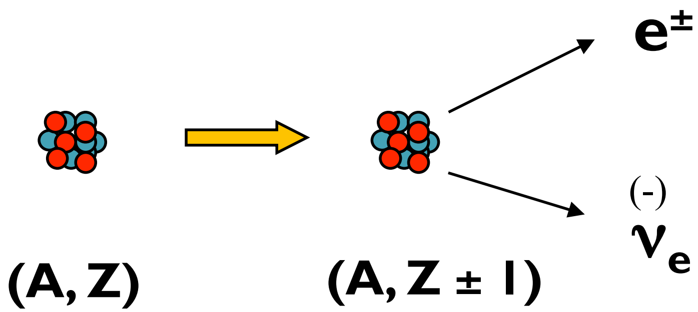


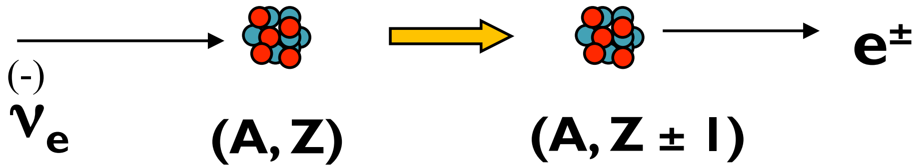
Fig. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

Massive neutrinos and neutrino capture on beta decaying nuclei

Beta decay



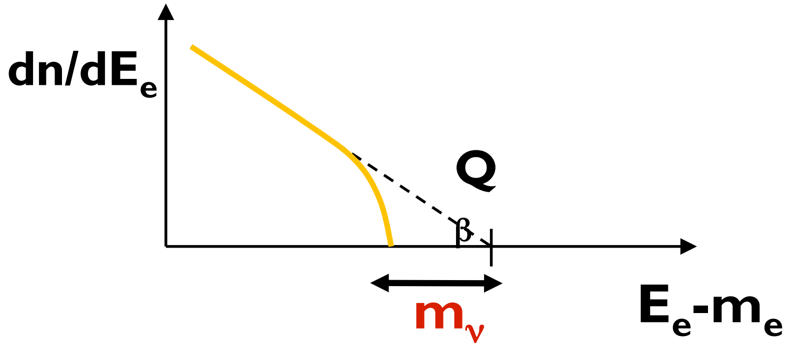
Neutrino Capture on a Beta Decaying Nucleus



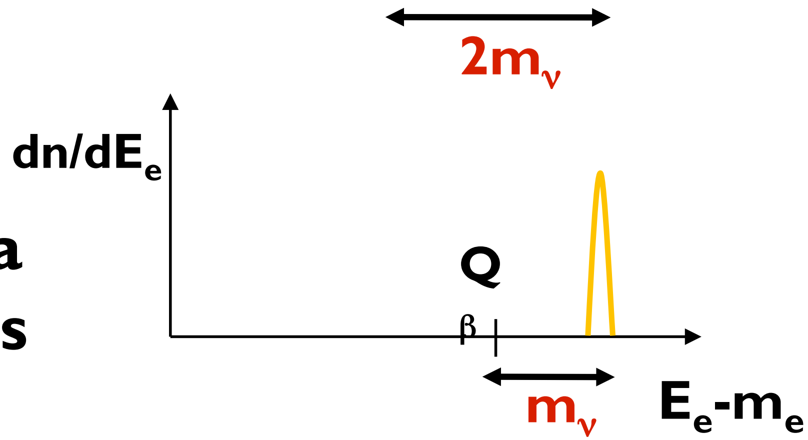
This process has no energy threshold !

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

Beta decay rate

$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3}\int_{m_e}^{W_o} p_e E_e F(Z,E_e) C(E_e,p_\nu)_\beta E_\nu p_\nu \, dE_e$$

NCB

$$\sigma_{\rm NCB} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z,E_e) C(E_e,p_\nu)_\nu$$

The nuclear shape factors C_β and C_ν both depend on the same nuclear matrix elements

Defining

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e,p'_\nu)_\beta}{C(E_e,p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e,Z)}{F(E_e,Z)} E'_\nu p'_\nu dE'_e$$

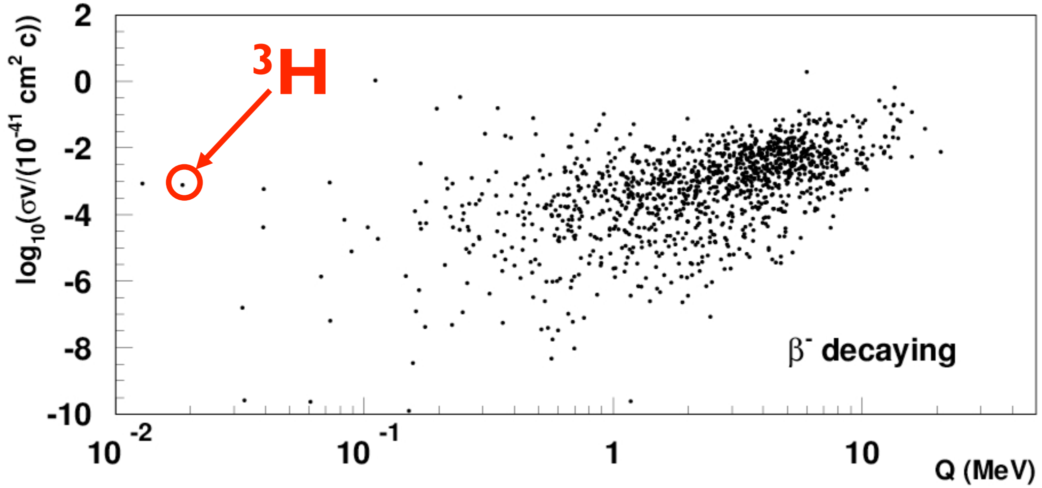
$$\boxed{\sigma_{\rm NCB} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}}$$

In a large number of cases A can be evaluated in an exact way and NCB cross section depends only on Q_β and $t_{1/2}$ (measurable)

NCB Cross Section Evaluation

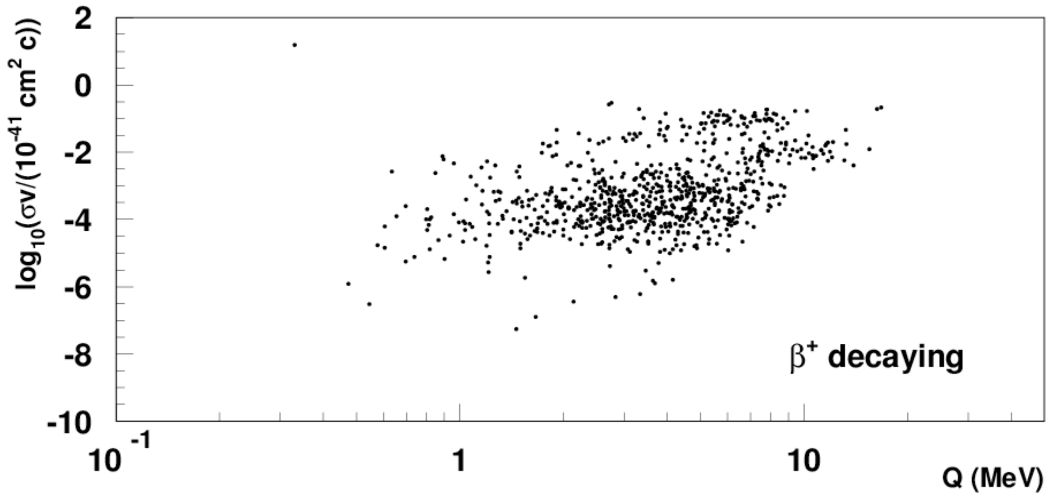
using measured values of Q_β and $t_{1/2}$

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

The case of Tritium

$$\boxed{\sigma_{\mathrm{NCB}} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu}$$

$$\boxed{\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c}} \underset{\lim \beta \to 0}{=} \boxed{(\ 7.7 \pm 0.2\ ) \times 10^{-45}\ \mathrm{cm}^2}$$

where the error is due to Fermi and Gamow-Teller matrix element uncertainties

---

Using shape factors ratio $\boxed{\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}}$

$$\boxed{\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c}} \underset{\lim \beta \to 0}{=} \boxed{(\ 7.84 \pm 0.03\ ) \times 10^{-45}\ \mathrm{cm}^2}$$

where the error is due only to uncertainties on Q_β and $t_{1/2}$

NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (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)	$\sigma_{\rm NCB}(v_\nu/c)$ (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 $\sigma_{\rm NCB}\, t_{1/2}$

The cosmological relic neutrino capture rate

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

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

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

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

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

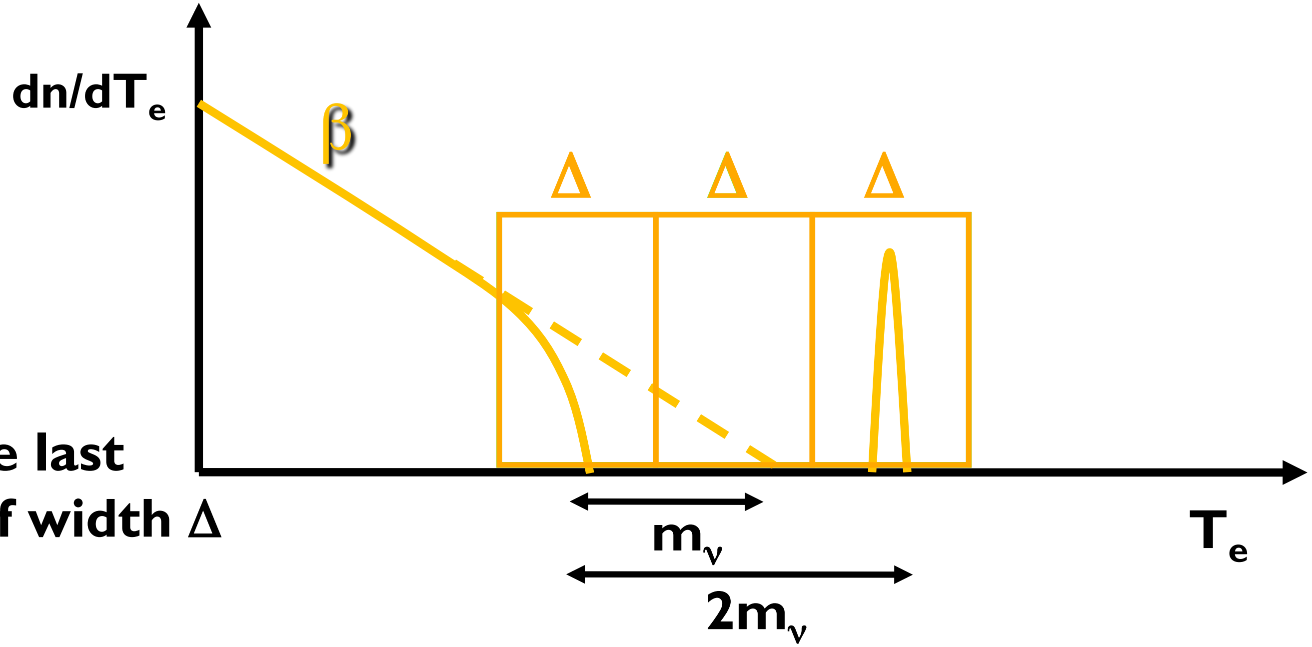
In the case of Tritium:

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

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

$$\frac{\lambda_\nu}{\lambda_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}$$ **~ 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 Δ<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

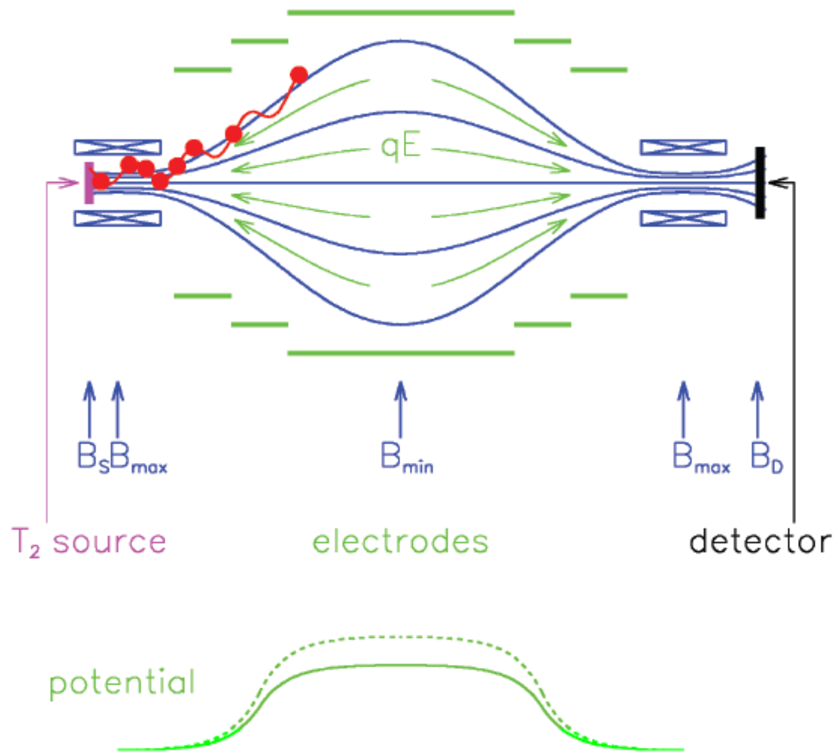
FD = Fermi-Dirac NFW= Navarro, Frenk and White MW=Milky Way (Ringwald, Wong)

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



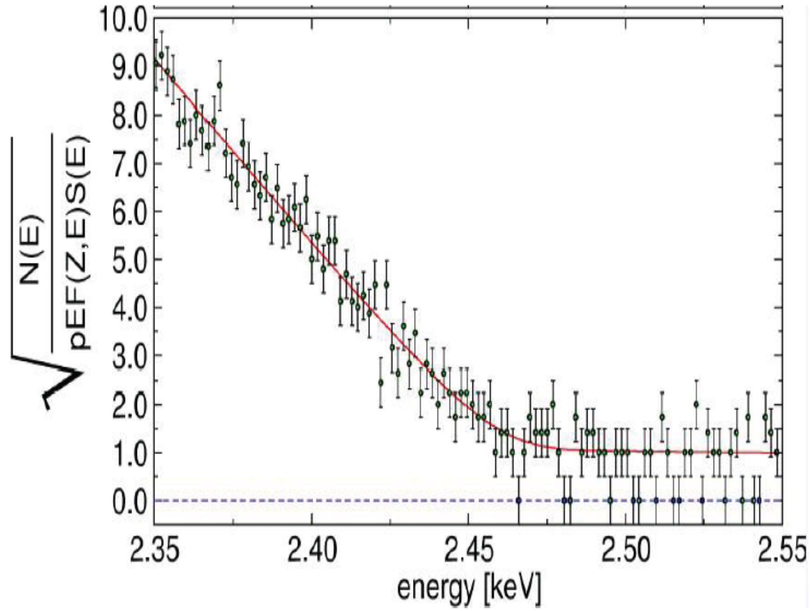
Magnetic Adiabatic Collimator + Electrostatic filter

MARE

Aim at direct neutrino mass measurement through the study of the ^{187}Re endpoint (Q_β =2.66 keV, $t_{1/2}$=4.3 x 10^{10} years)
Using TEs+micro-bolometers @ 10 mK temperature

Energy resolution: 2÷3 eV
Total ^{187}Re mass: ~ 100 g

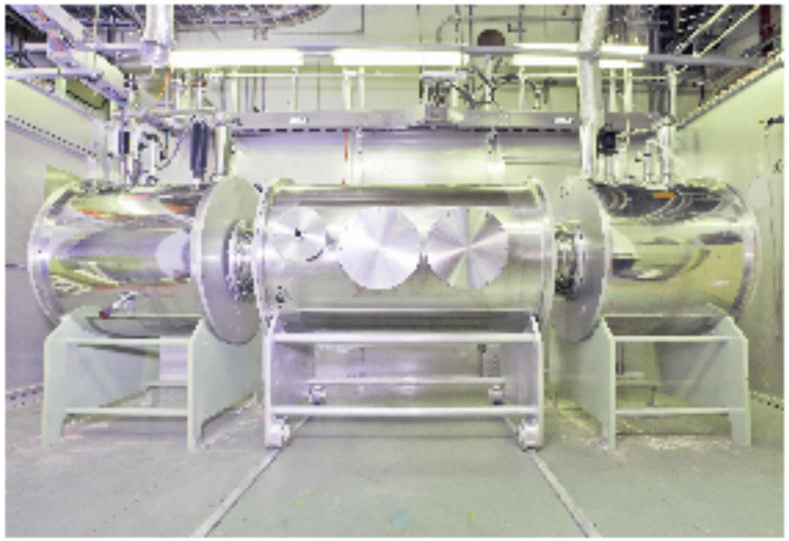
Phase II:
Energy resolution: < 1 eV



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]

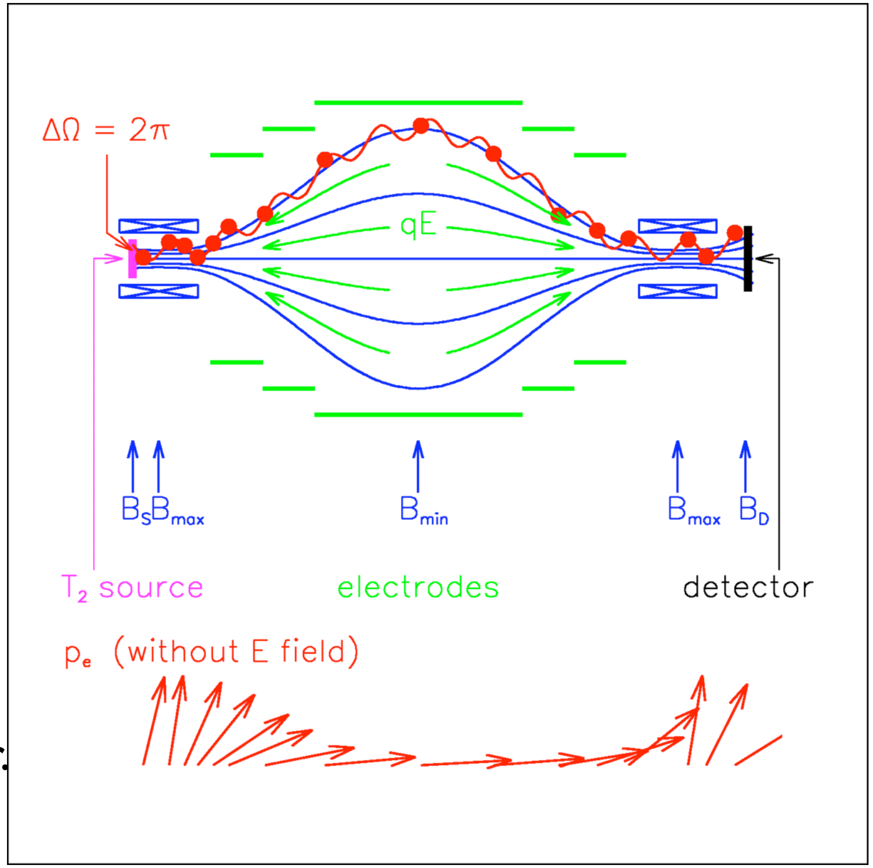


- A large area surface deposition target
- MAC-E filter
- RF signal from cyclotron electron motion in a magnetic field
- cryogenic calorimetry

MAC-E filter (magnetic adiabatic collimation combined with an electrostatic filter

used by Katrin exp.

The beta electrons, isotropically emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines (adiabatically). This parallel beam of electrons is running against an electrostatic potential formed by a system of cylindrical electrodes. All electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. Therefore the spectrometer acts as an integrating high-energy pass filter.



Conclusions I

- Cosmology can:

  constrain neutrino physics (optimistic)

  guide lab experiments to constrain neutrino physics (conservative)
- many other neutrino properties not discussed here (but quite weak bounds)

Conclusions II

- Neutrino physics can:

 constrain or give hints to understand unresolved problems of cosmology (ex. keV neutrinos as warm dark matter, leptogenesis if ν's are Majorana particles)