Some cosmological implications of "MiniBoone"

Pasquale Dario Serpico

LAPTh Annecy-le-Vieux

RPP Clermont-Ferrand 14/01/2011

Status of neutrino mixing, circa 2010

mismatch between flavour and mass basis expressed via mixing matrix U

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{lk} \equiv \text{Sin}\, \theta_{lk}$, $c_{lk} \equiv \text{Cos}\, \theta_{lk}$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}.$$

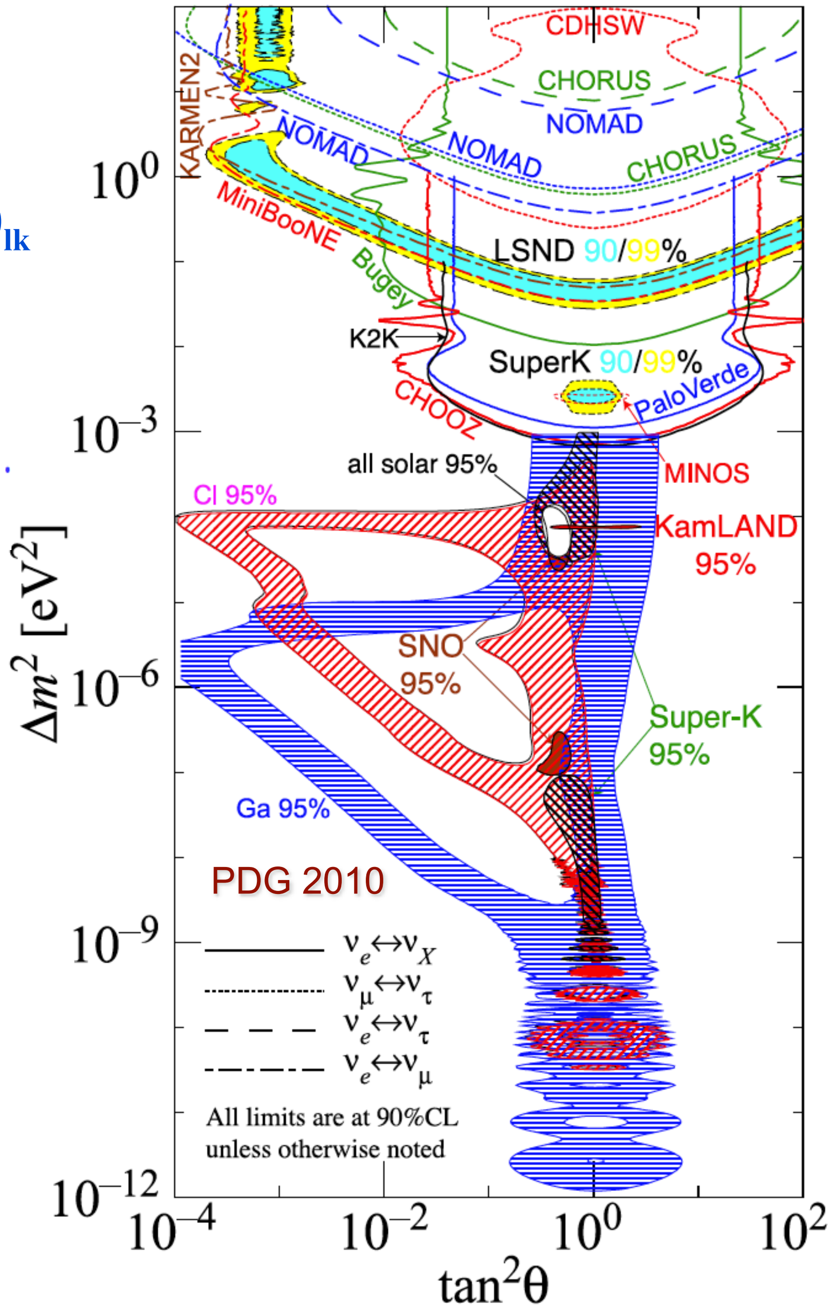
$$(\Delta m^2_{21})_{BF} = 7.65 \times 10^{-5}\ \text{eV}^2,$$
$$7.05 \times 10^{-5}\ \text{eV}^2 \le \Delta m^2_{21} \le 8.34 \times 10^{-5}\ \text{eV}^2,$$

$$(\sin^2\theta_{12})_{BF} = 0.304, \qquad 0.25 \le \sin^2\theta_{12} \le 0.37,$$

$$(|\Delta m^2_{31}|)_{BF} = 2.40 \times 10^{-3}\ \text{eV}^2,$$
$$2.07 \times 10^{-3}\ \text{eV}^2 \le |\Delta m^2_{31}| \le 2.75 \times 10^{-3}\ \text{eV}^2,$$

$$(\sin^2\theta_{23})_{BF} = 0.5, \qquad 0.36 \le \sin^2\theta_{23} \le 0.67.$$

$$\sin^2\theta_{13} < 0.035\ (0.056) \quad \text{at } 90\%\ (99.73\%)\ \text{C.L.}$$



Preamble: What does MiniBoone(*) claim?

In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events. (This is the region of maximal sensitivity if the LSND signal is L/E and CPT invariant.)

In a ν_μ beam below 475 MeV, we see a 3σ excess (128 ± 43) of ν_e signal candidates that don't fit well to a 2ν mixing hypothesis.

In a anti-ν_μ beam below 475 MeV, we see a small excess (18 ± 14).
It rules out some explanations of the ν_μ beam low-E excess. In a anti-ν_μ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2-ν fit prefers an LSND-like signal at 99.4% CL.

(*) a dedicated experiment to test the LSND claim of anti-ν_μ → anti-ν_e appearance

from a Talk by Chris Polly (FNAL) @ NOW, 09/2010

It does not fit in SM+3 massive ν: Interpretations?

- "Background" issue? E.g. something wrong with fluxes and σ's estimated?
- Of course, one may solve the discrepancy by a radical departure from known physics (e.g. CPT violation, getting rid of QFT as we know it...)
- Less radical alternatives invoked include either (3+2) with CP, or 3+1 with NSI, but no real good fit/explanation of all the data is on the market!

With the addition of the new MiniBooNE data sets, **there are clear incompatibilities between neutrino and antineutrino experiments under a (3+1) oscillation hypothesis**. **A better description** of all short-baseline data over a (3+1) is **provided by a (3+2)** oscillation hypothesis **with CP violation**. **However, we still find large incompatibilities among appearance and disappearance experiments**, consistent with previous analyses, as well as incompatibilities between neutrino and antineutrino experiments.

Karagiorgi et al. 0906.1997v3

We have compared the quality of the (3+1) NSI fits to an updated fit in the (3+2) oscillation scheme[...] **Similarly to (3+1) NSI, in (3+2) the appearance experiments can be described very well**. However, we confirm previous results that **for (3+2) oscillations significant tension remains in the global fit between appearance and disappearance** experiments. [...] Let us mention also that in **none of the scenarios considered here we can explain the MiniBooNE low energy excess of events** when disappearance data are taken into account.

E. Akhmedov and T. Schwetz. JHEP 1010, 115 (2010)

Purpose of the present talk

- To argue that even the most “conservative” BSM interpretations of these data have significant cosmological consequences.
- My main goal is to illustrate the basic physics through which new ν states affect observables in BBN, CMB, LSS mostly via “extra radiation” and “extra mass”
- I will first review how the standard scenario goes... and also briefly address why adding NSI does not have a major impact.
- I will quickly present the present constraints on sterile ν’s and rather stress the power of forthcoming data (PLANCK & co.)

The Birth of cosmological ν's

T>> 1 MeV
Neutrinos in equilibrium

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

Above ~MeV-scale temperatures, $e^\pm$ pairs can be created "Boltzmann unsuppressed". ν's are populated (& reach a thermal distribution) via reactions of the kind

$$\nu_a \nu_b \leftrightarrow \nu_a \nu_b$$

$$\nu_a \bar{\nu}_a \leftrightarrow \nu_b \bar{\nu}_b$$

$$\nu_a \bar{\nu}_a \leftrightarrow e^+ e^-$$

$$\nu_a e^- \leftrightarrow \nu_a e^-$$

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They decouple from the plasma at T~O(1) MeV

Rate of weak processes

$$\Gamma_w \approx n\,\sigma\,c \approx g\,a^{-3}\,G_F^2 E^2 \approx g\,G_F^2 T^5$$

Hubble expansion rate

$$H \approx \sqrt{G_N \rho} \approx \sqrt{g\,G_N} T^2$$

$$\frac{\Gamma_w}{H} \approx \left(\frac{T}{\text{MeV}}\right)^3$$

After this epoch (~O(1) s after Big Bang) ν's evolve only due to gravity

"Detection" of the CνB

- Pseudo-thermal distribution: $T_\nu = 1.95$ K
- Number density ($\nu + \overline{\nu}$): 112 cm^{-3}/flavour
- Mean kinetic energy: << meV

lower than 2.7 K of CMB due to later
$e^+ e^- \rightarrow \gamma\gamma$
(heating of photons)

Direct searches hopeless?

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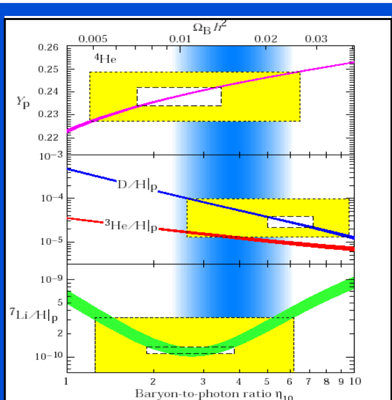
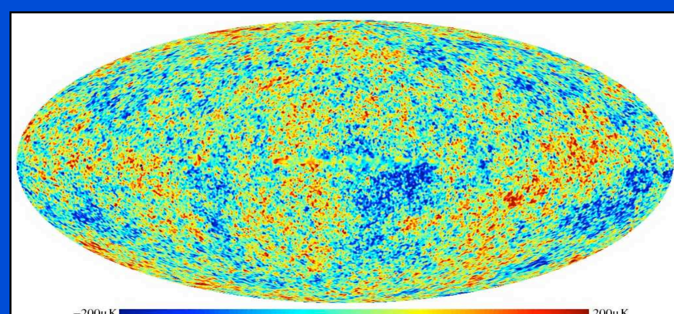
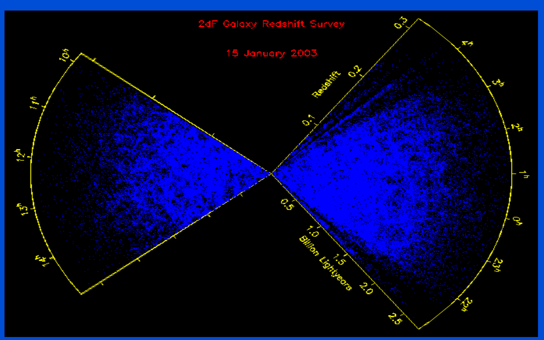
Indirect searches: Cosmological observables







BBN	CMB	LSS
T ~ MeV	T ~ eV	
ν_e vs. $\nu_{\mu,\tau}$ N_{eff}	Gravity only (no flavor discr.) N_{eff} & m_ν	

Neutrinos & BBN: How do ν's enter the game?

Hubble Expansion Law

Gravity only, mostly integral quantity, extra relativistic species

$$H=\frac{\dot{a}}{a}=\left(\frac{8\pi G_N}{3}\right)^{1/2}(\rho_\gamma+\rho_e+\rho_b+\rho_\nu+\rho_X)^{1/2}$$

$$\rho_\nu+\rho_X \rightarrow \frac{7}{8}\,\frac{4^{1/3}}{11^{1/3}}\,N_{eff}\,\rho_\gamma$$

$N_{eff}=3$
(SM only & instantaneous decoupling)

For a review, see e.g. F. Iocco et al.
"Primordial Nucleosynthesis: from Precision Cosmology to fundamental physics"
Phys. Rept. 472, 1 (2009) [arXiv:0809.0631]

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Weak Rates: p↔n equilibrium

Very sensitive to weak interactions (only e-flavour matters), energy spectrum.

$$\nu_e + n \leftrightarrow e^- + p$$

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

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

Final n/p (& hence ^{4}He, where most neutrons are ultimately locked) depends on "when" $\Gamma_w=H$

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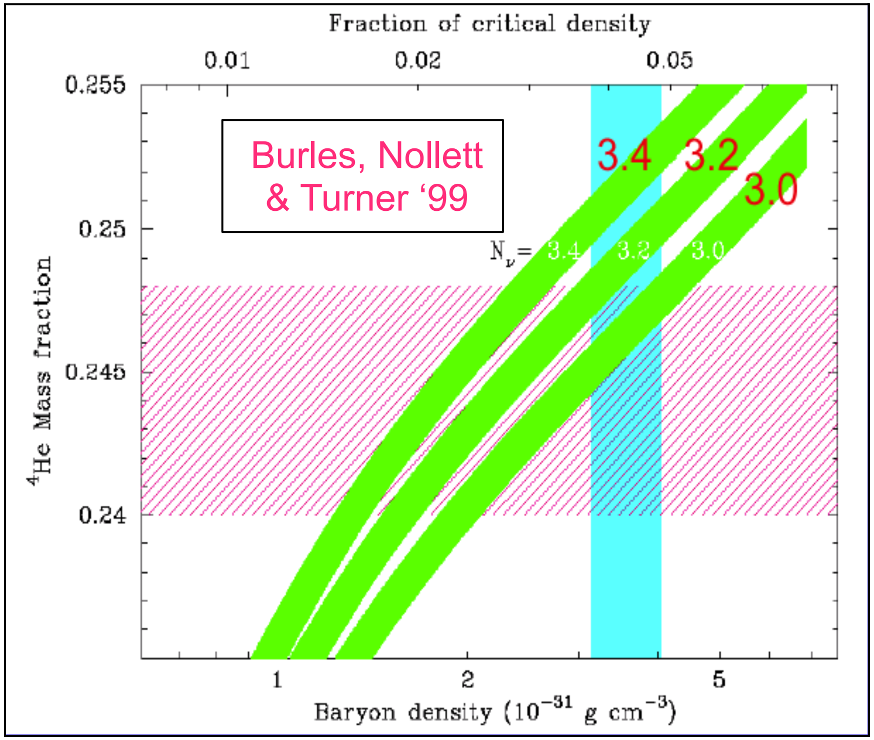
Estimating ^{4}He response to parameter changes

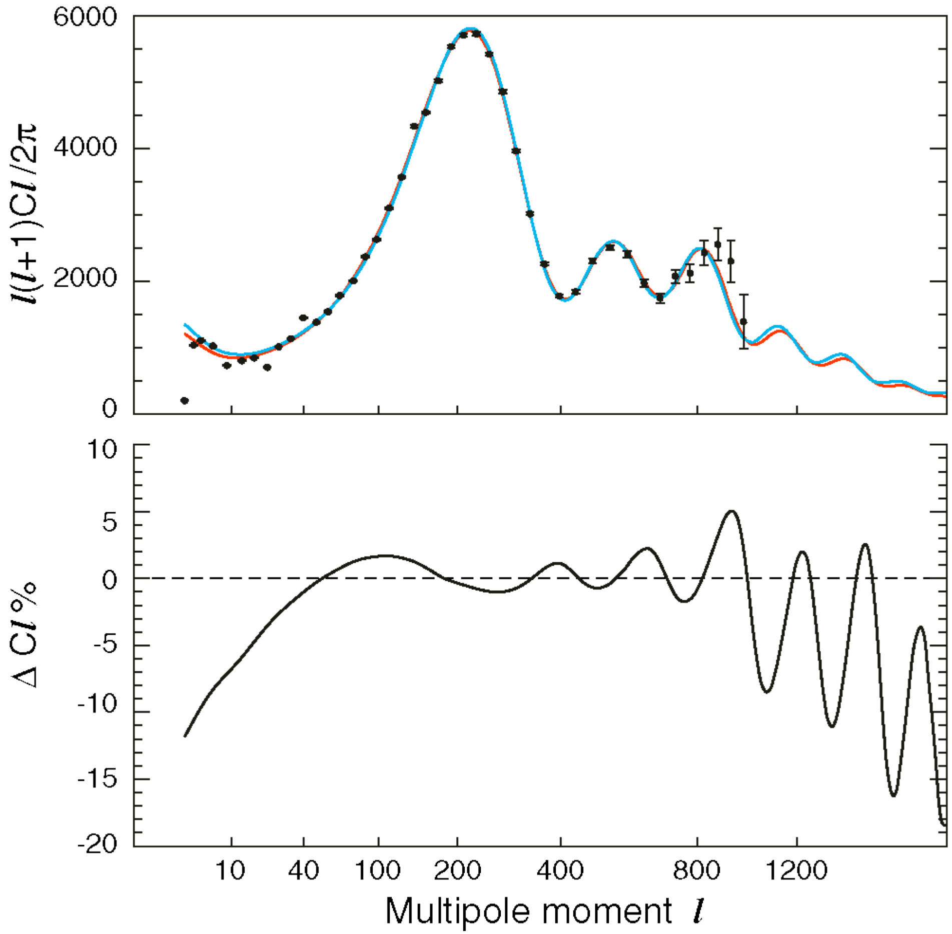


- High N_{eff} → High H → early freeze out ($\Gamma_{pn} \sim H$ at high T) → high n/p → high Y_p
- $\nu_e > \bar{\nu}_e$ → $\nu_e\, n \to e^-\, p$ favored over $\bar{\nu}_e\, p \to e^+\, n$ → low n/p at fr.out → low Y_p (chemical potential $\mu_{\nu e} > 0$)
- ...

Neutrinos & CMB

We know that neutrinos are light (eV-scale at most); for this range, both m_ν and N_{eff} mostly affect the time of matter-radiation equality. All the rest fixed:

- Raising N_{eff} means more radiation, hence delayed equality.
- Raising m_ν means that part of the total that we call now (dark) matter was behaving as ~radiation at CMB formation, hence delayed equality.



N_{eff}=3.046

N_{eff}=0

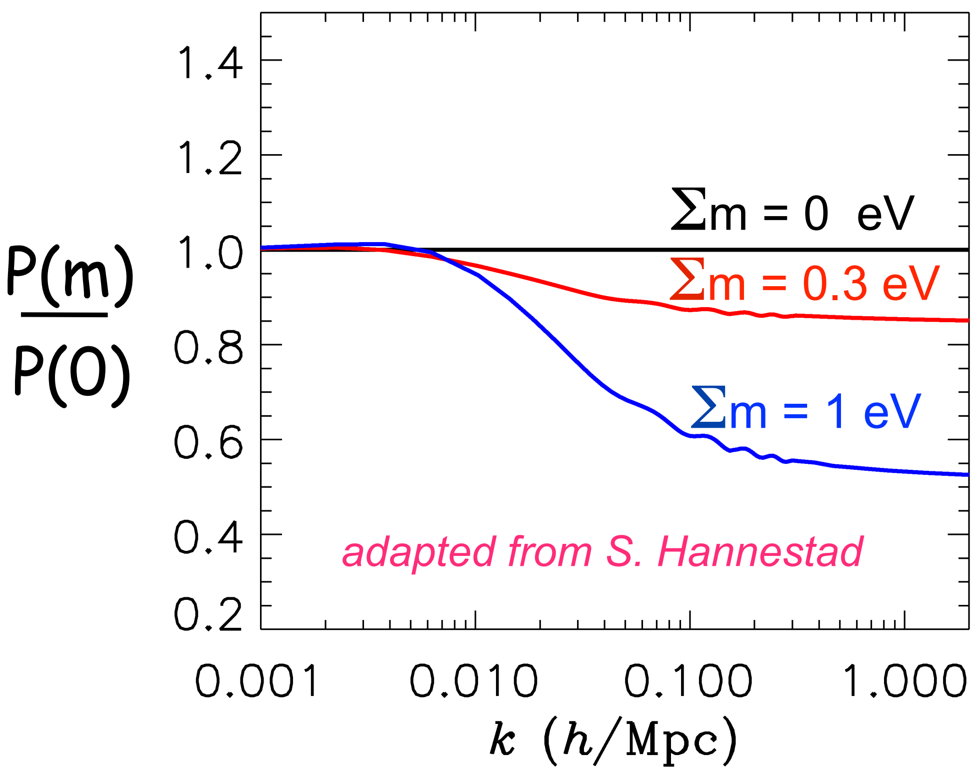
WMAP-7
Dunkley, et al., 2009, ApJS, 180, 306-329

Suppression of power-spectrum due to Neutrinos

ν's do not contribute to gravitational clustering below the free-streaming scale, but they do contribute to the homogeneous expansion. This "unbalance" introduces a peculiar spectral suppression. In linear theory one finds

$$\frac{\Delta P}{P} \approx -8 \frac{\Omega_\nu}{\Omega_m} \approx -0.8 \frac{\Sigma m_i}{1\ \mathrm{eV}} \frac{0.1}{\Omega_m h^2}$$

$@\ k > k_{NR} \approx 0.015\ (\Sigma m_{eV} \times \Omega_m h^2)^{1/2}\ \mathrm{Mpc}^{-1}$



This is the key effect used to derive bounds on massive neutrinos from LSS

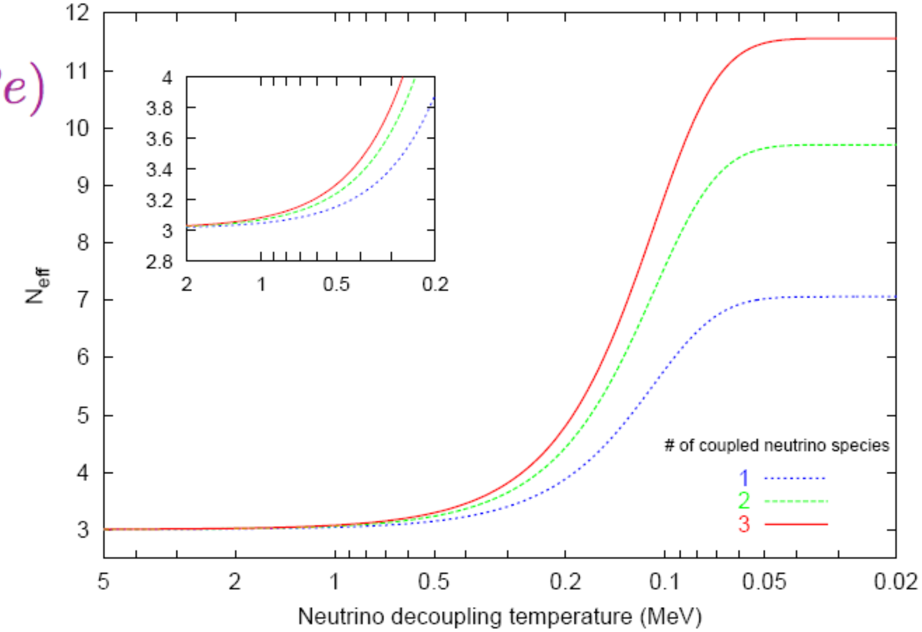
Alteration in presence of NSI

“Altered Decoupling”: Non-Standard Interactions

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

❖ If FCNC or non-universal 4f Fermi-like operators present, ν decoupling might change (typically delayed) : ν's get more energy from e^+-e^- annihilations;
Both **collisional** and **refractive** terms affected!

G. Mangano et al.
Nucl.Phys. B 756, 100 (2006)



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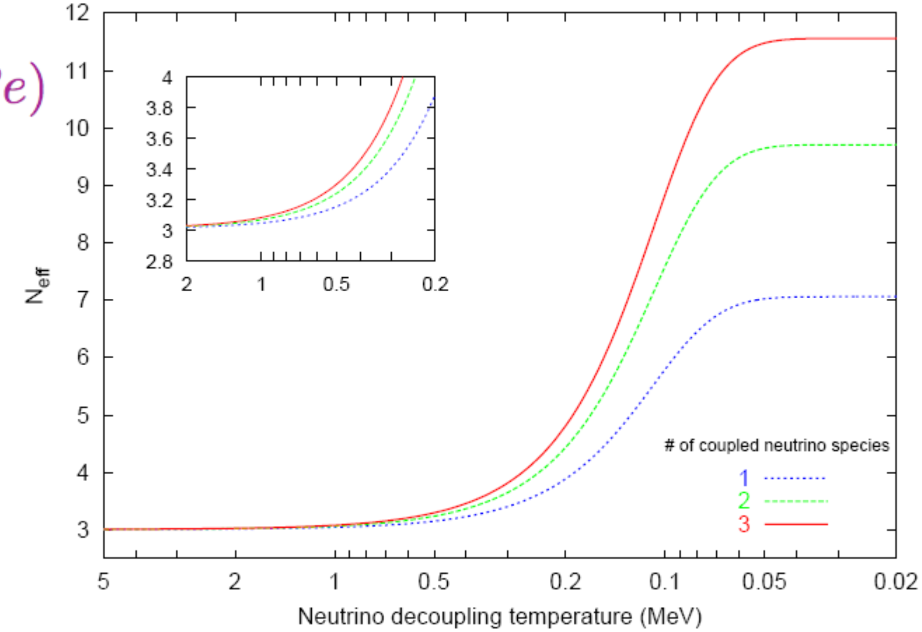


❖ We found that no more than ΔN_{eff} =O(0.1) (but anyway ΔY_p=0.001 due to cancellations) might be obtained for current upper bounds, for ε's~O(1). Likely, improvements in the ν_τ sector bounds (e.g. from OPERA) will exclude these cases.

NSI of O(0.01) required to fit Miniboone, see e.g. *E. Akhmedov and T. Schwetz, JHEP 1010, 115 (2010)* have at most a sub-leading effect in the early universe

Adding sterile states...

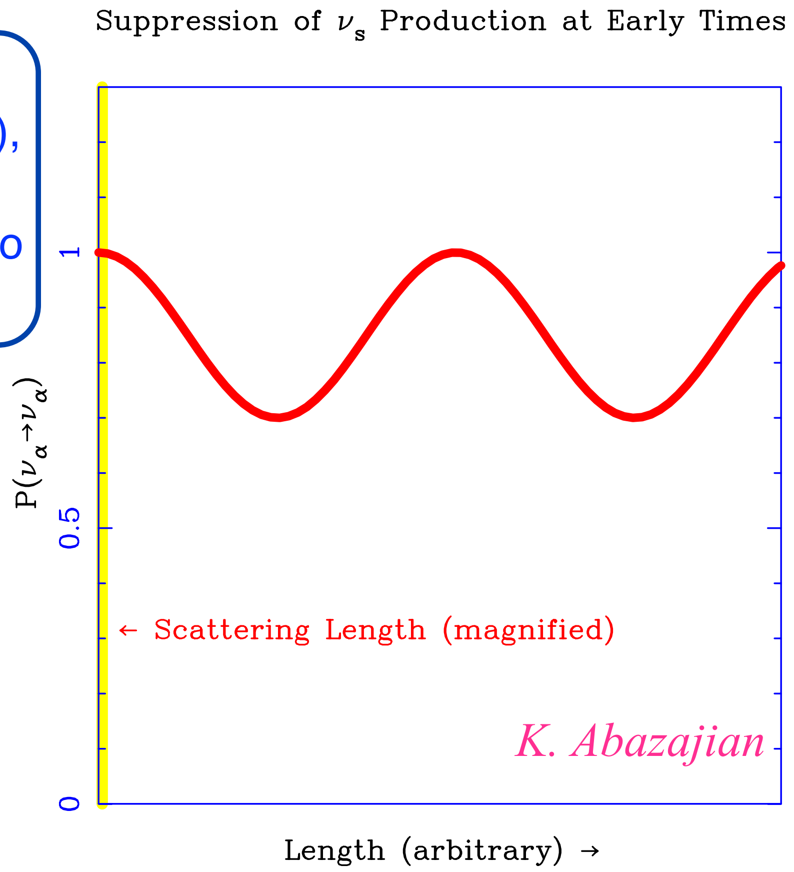
The Quantum Zeno effect (for production via osc.)

Each CC scattering of a ν acts as a "measurement" of its flavor state. At high temperatures (say, T≥100 MeV), λ_{scatt} is extremely short compared to λ_{osc}
Therefore, a population of active ν's won't have time to evolve into sterile ν's, but in small amounts.

$$\lambda_{\rm scatt} = [\sigma\, n]^{-1} \sim E^{-2} T^{-3} \propto T^{-5}$$

$$\lambda_{\rm osc} = \frac{4\pi E}{\Delta m^2} (\text{in vacuo}) \propto T$$

$$P_{\alpha\alpha}(\lambda_{\rm scatt}) = 1 - \sin^2(2\theta) \sin^2\left(\pi \frac{\lambda_{\rm scatt}}{\lambda_{\rm osc}}\right)$$



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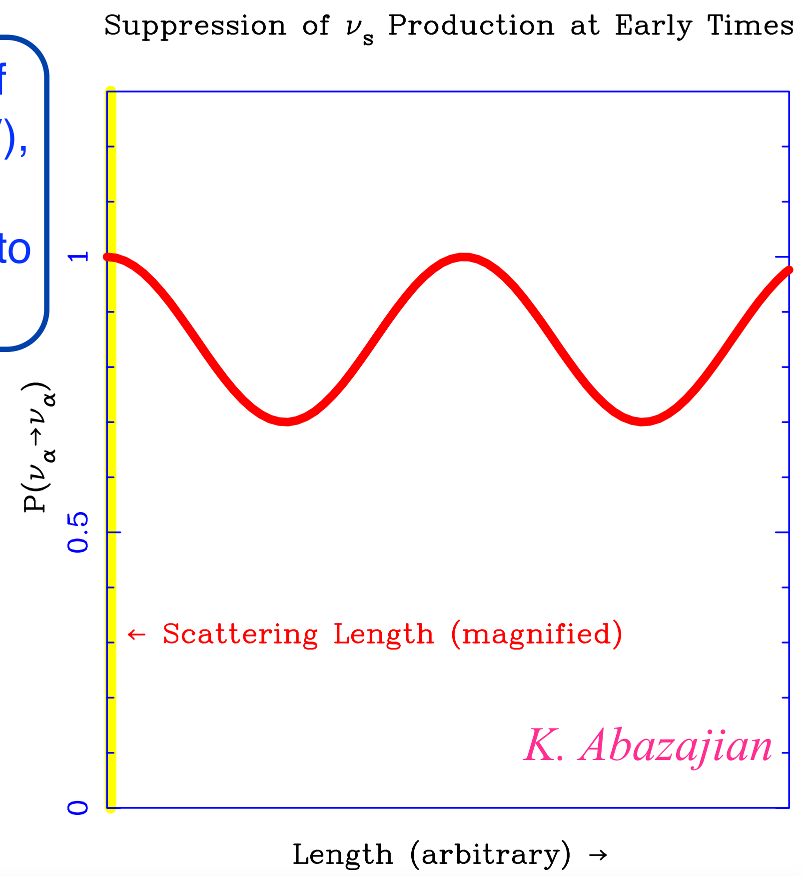


As the universe expands, cools & becomes less dense, λ_{scatt} ↗. Then, $P_{\alpha s}=(1-P_{\alpha\alpha})$ ↗

☞ The larger Δm^2, the faster ν's oscillate, the higher the conversion $P_{\alpha s}$

☞ Also, the larger θ^2, the larger $P_{\alpha s}$

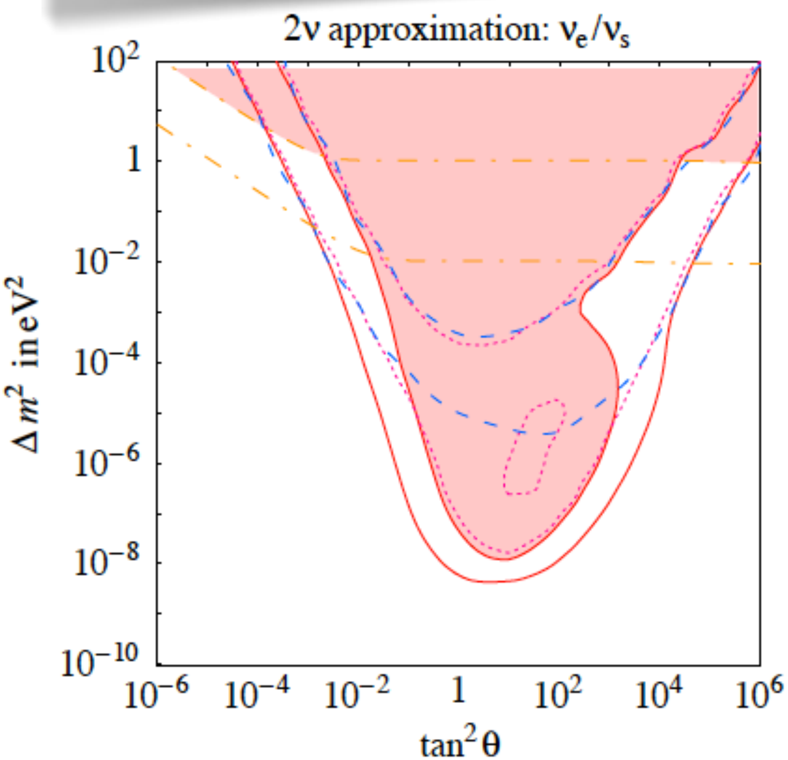
⇒ Oscillation constraints from Early Universe exclude upper-right portion in a θ^2-Δm^2 plot

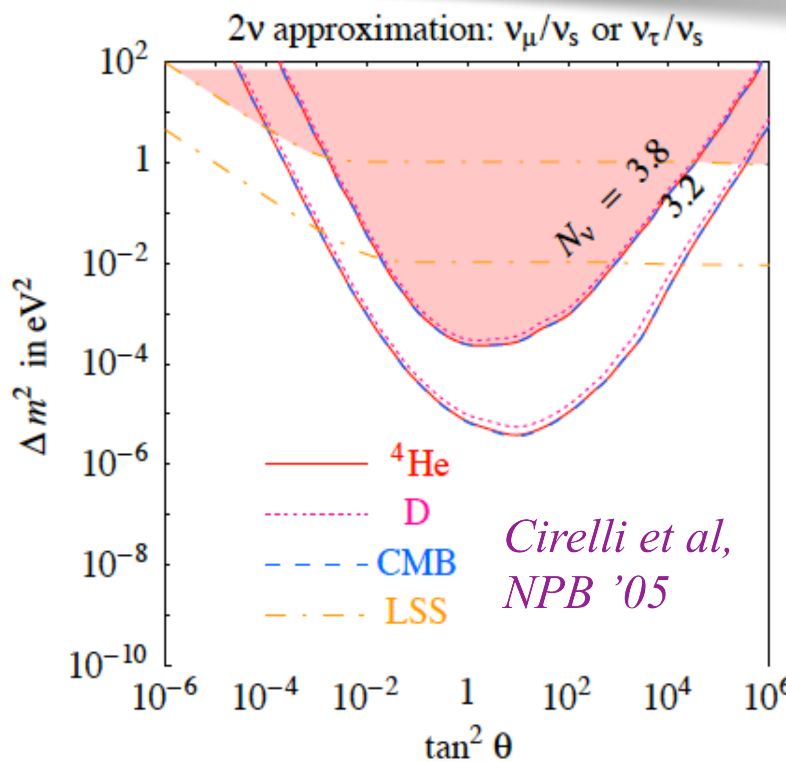
Sterile neutrinos are born

✻ If oscillations are effective before decoupling: the additional species can be brought into equilibrium: $N_{eff}=4$

✻ If oscillations are effective after decoupling: $N_{eff}=3$ but the spectrum of active neutrinos is distorted (direct effect on n/p equilibrium!)

Matter effects are responsible for the hierarchy dependence (resonant vs. non-resonant case) See e.g. Kirilova '03, Dolgov & Villante, NPB 679 (2004)...





“Realistic” 3+2 ν’s scenarios for LSND/MB

If multiple sterile states are present (as in 3+2 schemes) in general there is: i) partial thermalization ($4<N_{eff}<5$) ii) spectral *distortions* at BBN times
see e.g. Melchiorri et al. JCAP 01 (2009) 036

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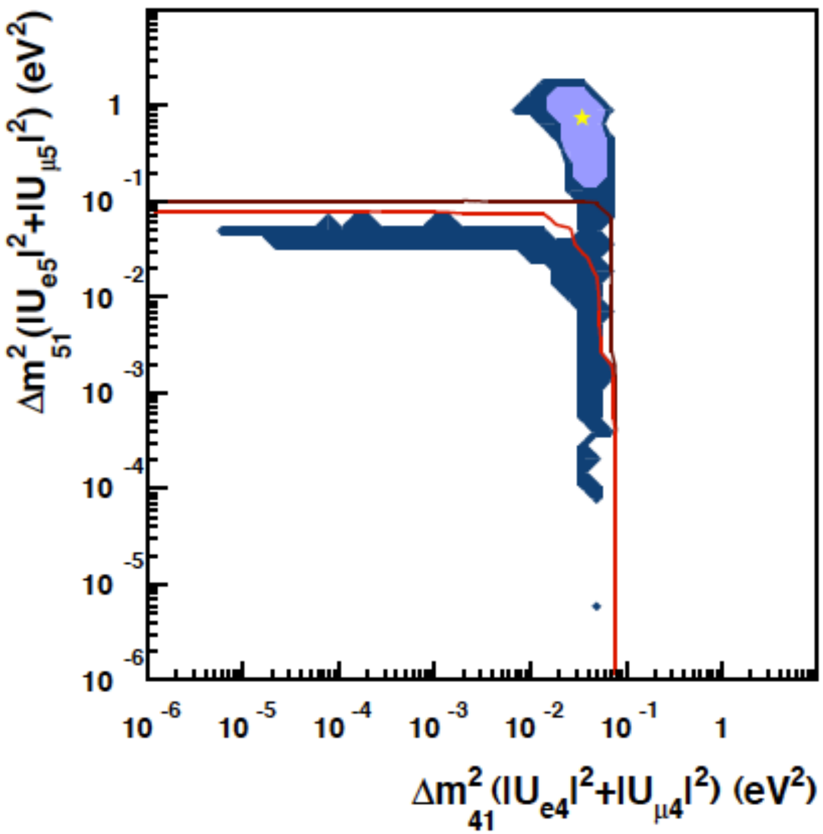
☞ Simultaneous fits are still possible (goodness of fit dominated by Lab exp.)



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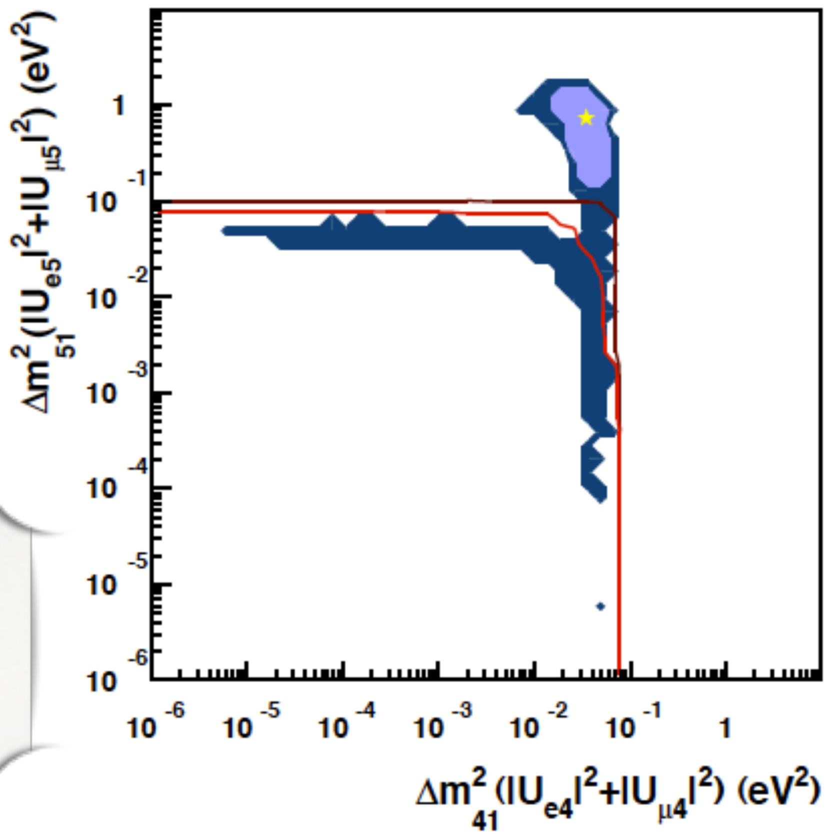


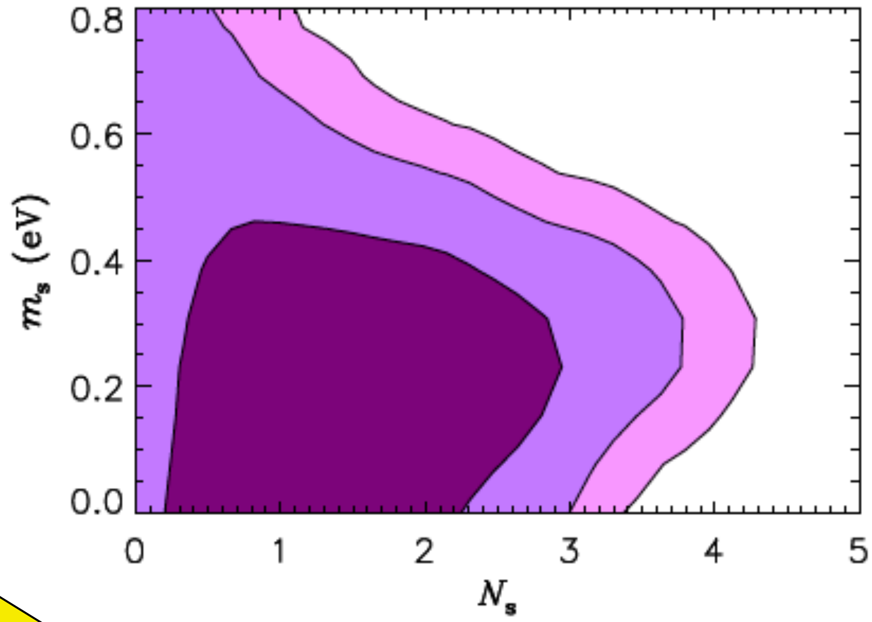
Note: the required CP-violation might further affect weak rates at BBN time (yet to be studied). A general-scan approach to the problem is numerically challenging (many scales involved...) and perhaps unjustified at present.

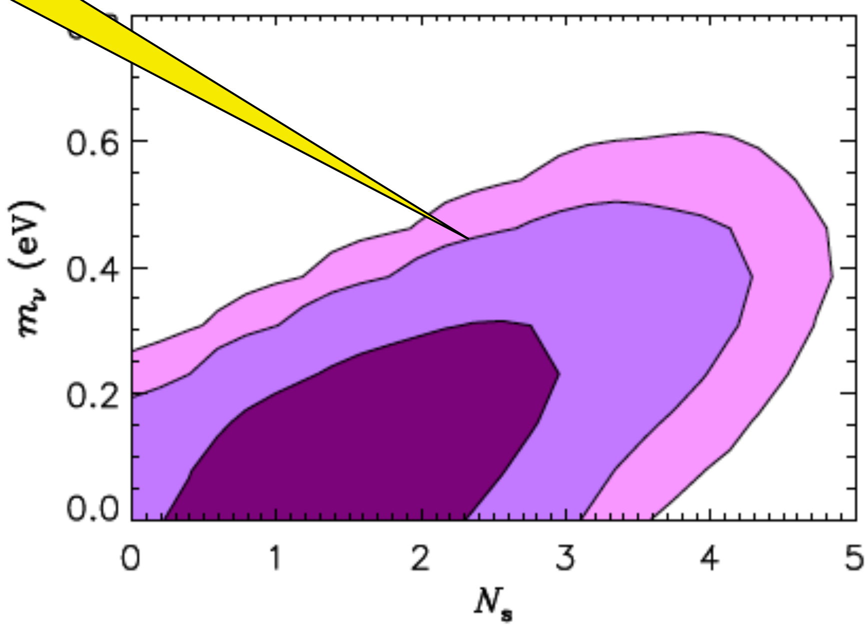
Present status on N_{eff}... and Σm_ν

From cosmology alone, all data are consistent with expectations within (less than) 2 σ

Not surprisingly, a m_ν - N_{eff} degeneracy is due to CMB sensitivity to the quantities

J. Hamann et al., PRL 105, 181301 (2010)





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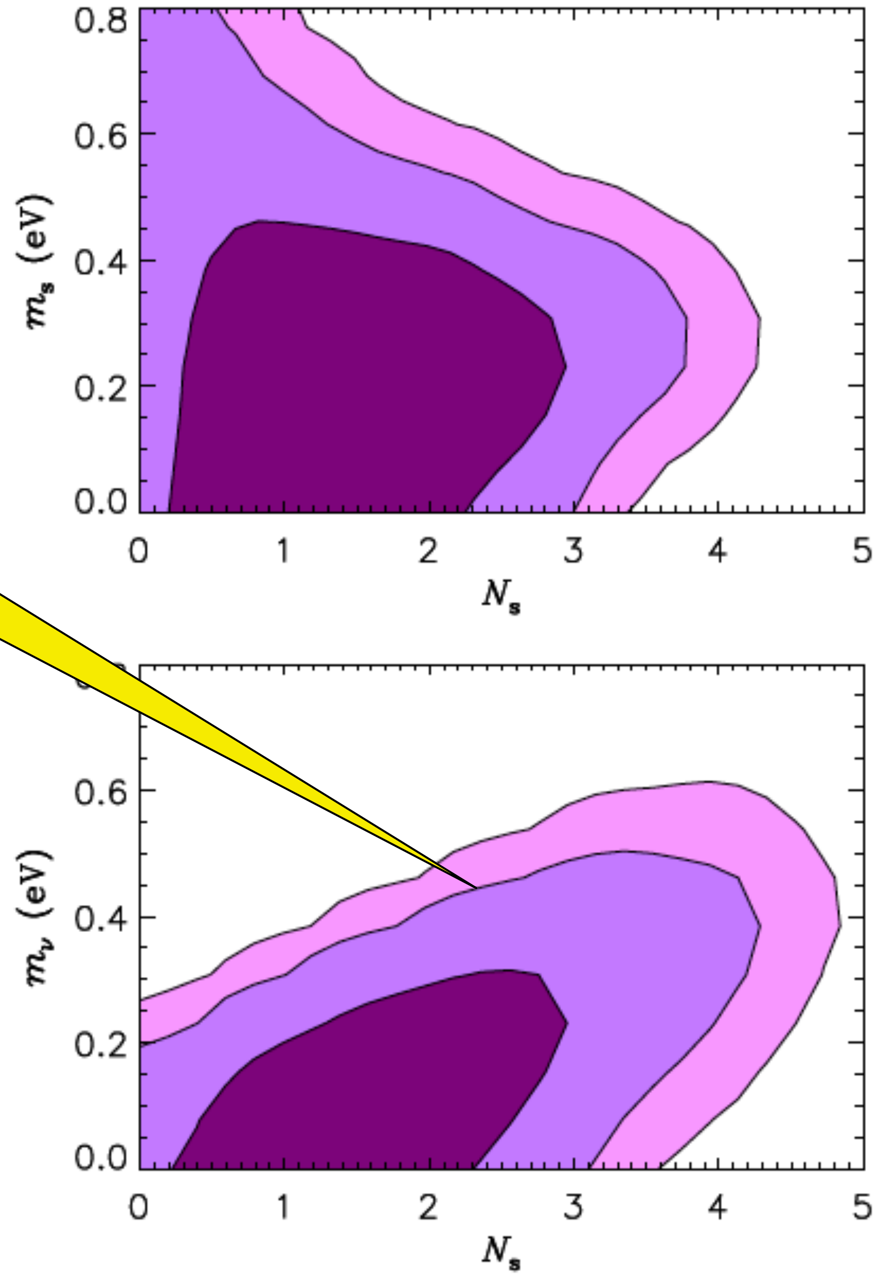
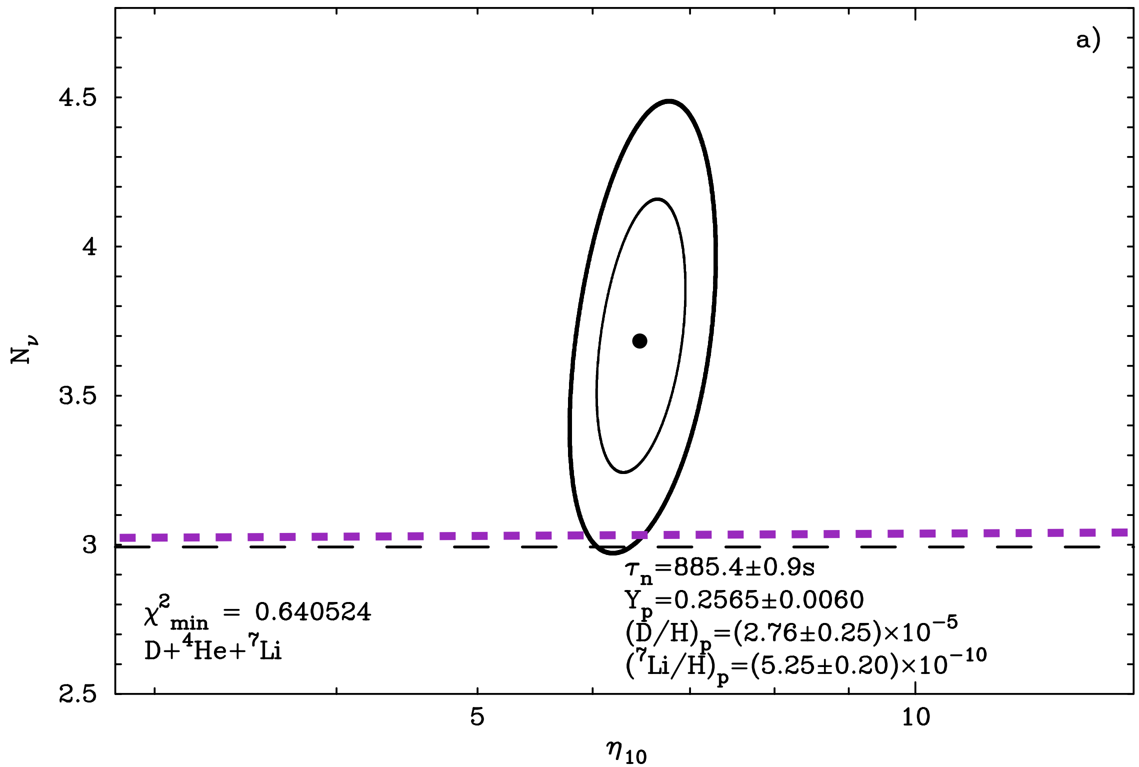


In the literature one finds also several (sometimes strong) claims about "hints for non-standard values".

I would call cosmological "discrepancies at 1 to 2 σ's" simply as "agreement"

A hint of a large N_{eff} from BBN?



Izotov and Thuan,
"The primordial abundance of ^{4}He: evidence for non-standard big bang nucleosynthesis,"
Astrophys. J. 710, L67 (2010)

Y_p=0.2565±0.0060

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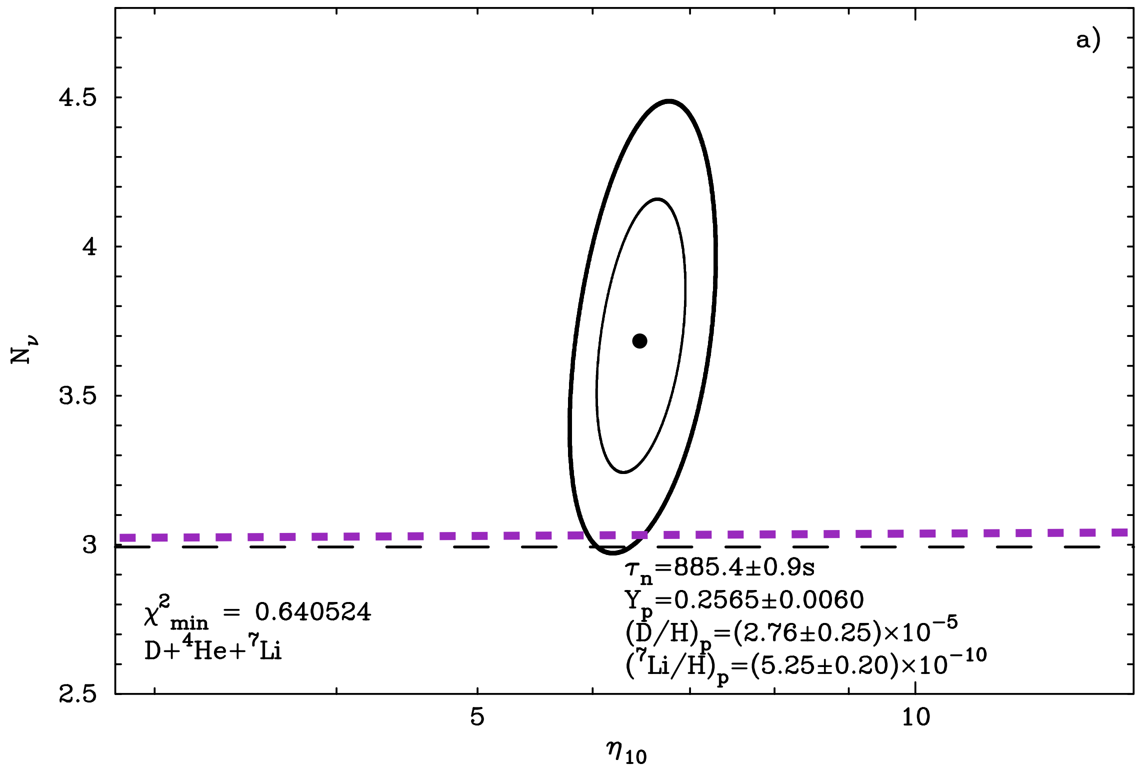

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Not surprisingly, in *Aver et al. JCAP 1004,029 (2010)* such an "evidence" is claimed to follow from underestimated systematics...

Forecast on future reach on N_{eff}...

It is very difficult to make accurate predictions, especially about the future (Niels Bohr)

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PLANCK CMB mission

Sensitivity ΔN_{eff}~0.05-0.1

Realistically (including degeneracies) ΔN_{eff}~0.2

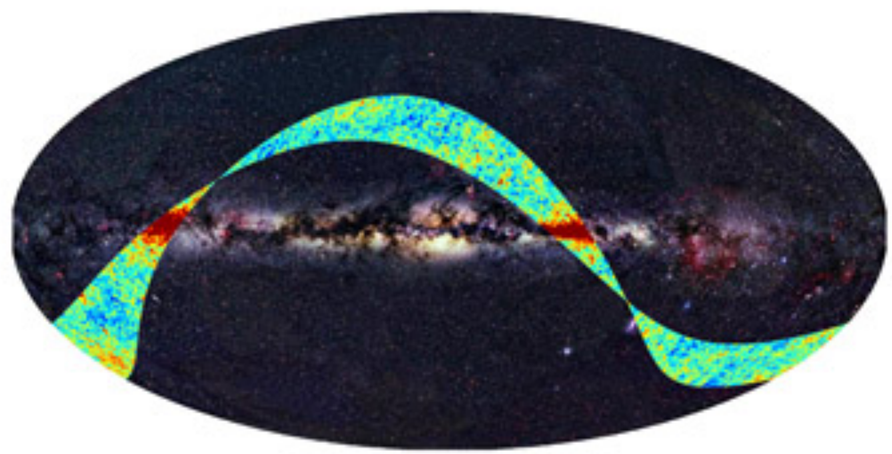
Lopez et al. PRL 82 3952 ‘99

Bowen et al., MNRAS 334 ‘02

Bashinsky & Seljak, PRD 69 ’04

Hamann et al JCAP 07 (2010) 022

In a few years we should know if there is any other major (>10%) component of light degrees of freedom (like axions, gravitinos, ν_R) in the “cosmic soup”



...and Σm_ν

	Planck	P+BAO	P+HPS	P+HST	P+HST+BAO	P+HST+HPS
$\omega_{\rm dm}$	0.22	0.24	0.20	0.21	0.21	0.19
$N_{\rm eff}$	0.21	0.21	0.22	0.21	0.21	0.22
$\sum m_\nu$	0.68	0.81	0.44	0.67	0.73	0.44
w	2.14	1.16	0.72	0.74	0.76	0.55
$n_{\rm S}$	0.46	0.48	0.49	0.46	0.48	0.48

Hamann et al JCAP 07 (2010) 022

Very likely, extra states would leave their imprints also due to their mass, if heavier that 0.3-0.5 eV...
In addition with future surveys, this number is going to improve even more!

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w	2.14	1.16	0.72	0.74	0.76	0.55
n_S	0.46	0.48	0.49	0.46	0.48	0.48

Hamann et al JCAP 07 (2010) 022

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Mission/Method	Σm_i (eV)	$\sigma(\Sigma m_i)$ (eV)	Ref.
PLANCK + Weak Lensing surveys	0.07	0.04	Hannestad et al. '06
Inflation Probe with Lensing	0.00-0.05	0.035	Lesgourgues et al. '06
Galaxy Cluster surveys+other	0.00-0.05	~ 0.034	Wang '05
CMBpol, Lensing, Cosmic Shear	~ 0.05	~ 0.013	Song & Knox '04
CMB, SKA	~ 0.05	~ 0.015	Abdalla & Rawlings '07

Summary

✓ Extra physics in neutrinos (NSI, light sterile states, w or w/o CP violation...) is recurrently invoked to explain some Laboratory neutrino anomalies, like the long-standing LSND one (recently made more puzzling by MiniBoone results).

✓ The Standard Hot Big Bang model predicts the existence of a CνB. Although a direct detection seems unlikely, CνB effects on cosmological probes as CMB, BBN and LSS are significant

✓ At present, it is fair to say that cosmology is consistent with standard expectations, although the data allow (or marginally favour) a ΔN_{eff} =O(1)
Alone, $N_{eff} \neq 3$ does not necessarily indicate the presence of new ν dof: might be due to NS neutrino interactions (likely too small!) asymmetries (excluded but in fine-tuned circumstances), or dof unrelated to ν (like axions, ultralight gravitinos, etc.)

✓ If "LSND, MiniBoone ... anomalies" are due to sterile neutrinos, an interesting check will be allowed by forthcoming determination of N_{eff} (Planck) and a simultaneous imprint of "ν_s mass" in CMB/LSS (sterile ν's are not pure radiation!)

Extra slides

What do we know about ^{4}He?

Main problem

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HeII → HeI recombination lines in HII regions (about ~80 such regions known) of Blue Compact Dwarf Galaxies*

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Correct for chemical evolution

Extrapolate *linearly* to "zero metallicity" in Y_p vs O/H,N/H plots

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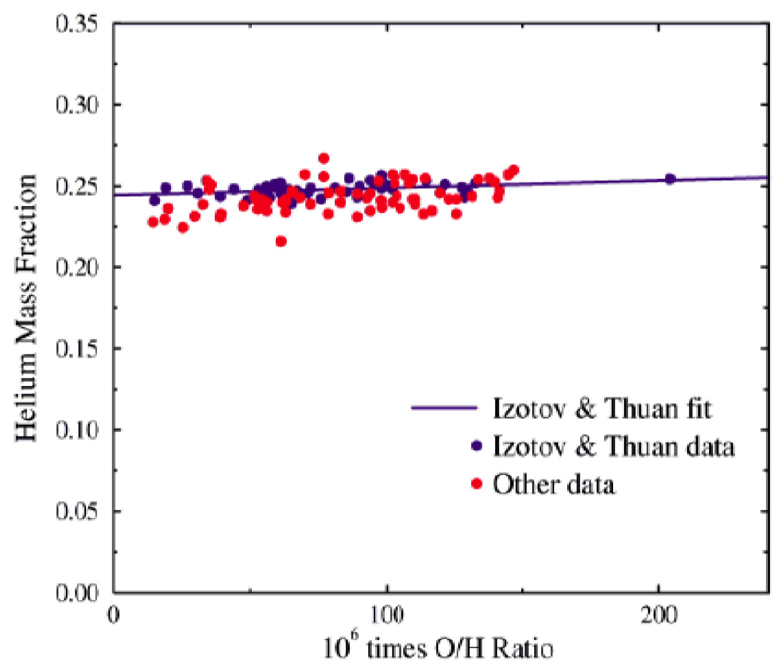


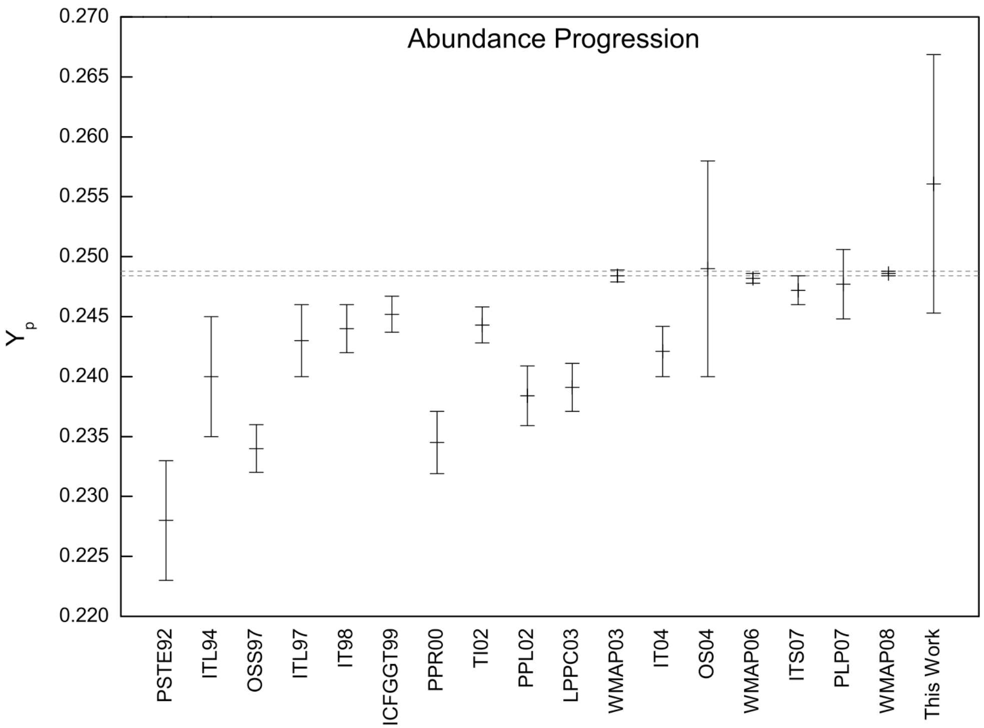
Observational Status over the last years

Not simple environment, systematics dominate!

Crucial to infer (consistently, if possible) the properties of the medium: photoionization, excitations, recombinations… must be modelled and fit!

✓ Izotov et al. '04, Y_p=0.2421±0.0021

✓ Olive et al '04, Y_p=0.249 ± 0.009
sample 7/82 of IT'04, conservative uncertainties



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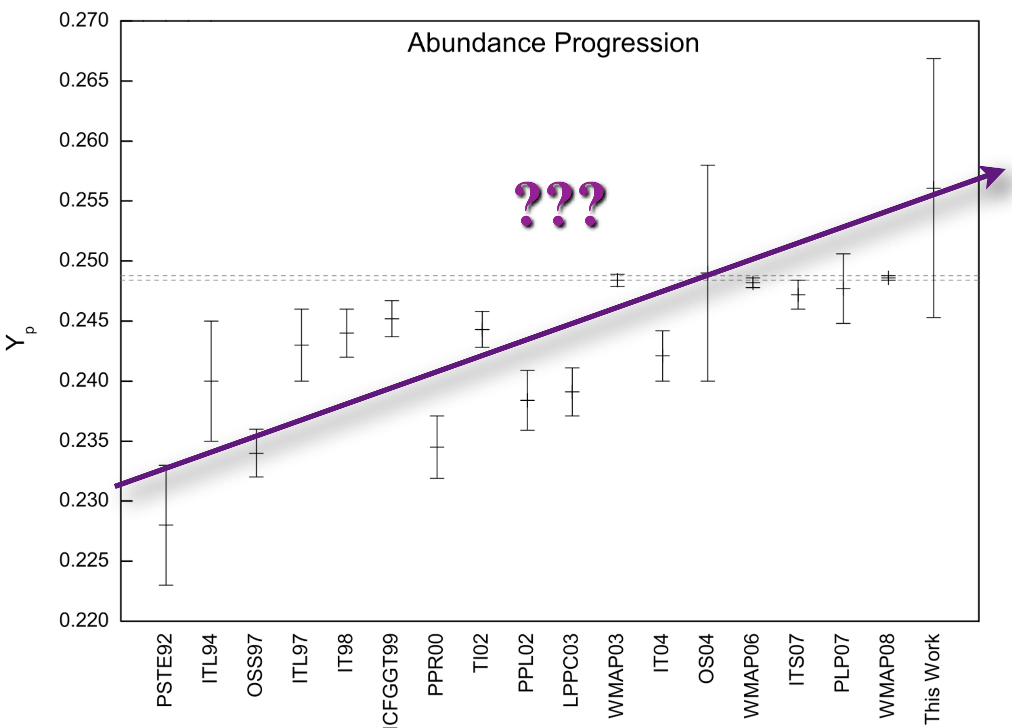

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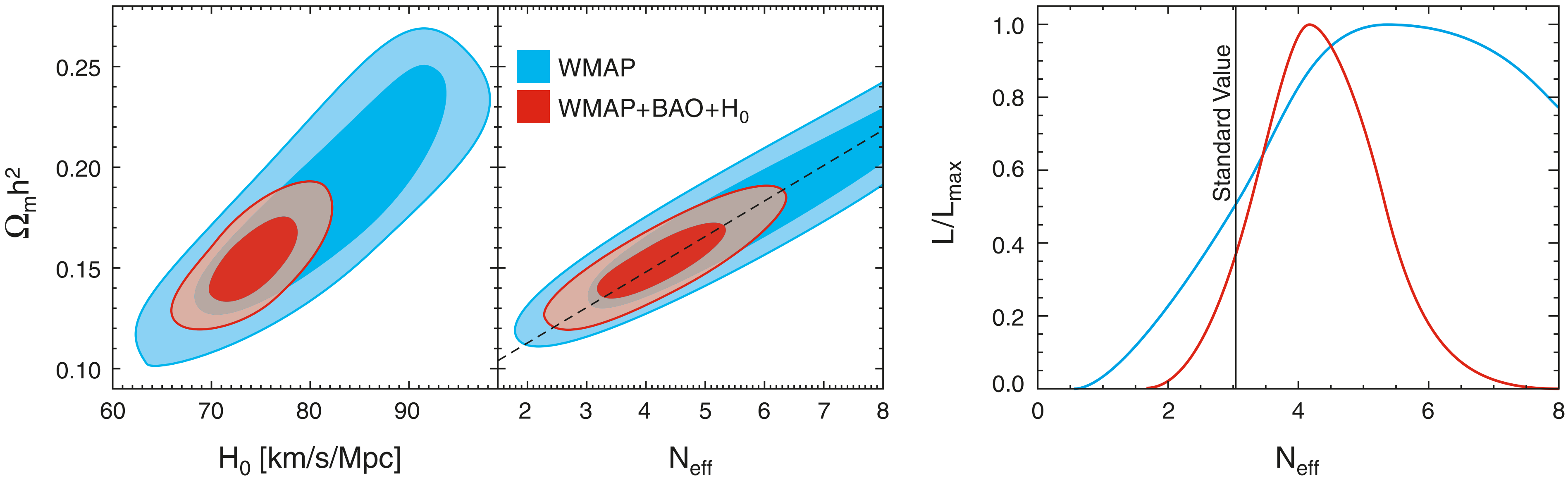
Despite this... some bold statements!

Izotov and Thuan, Astrophys. J. 710, L67 (2010)
"The primordial abundance of 4He: evidence for non-standard big bang nucleosynthesis,"

An independent hint from CMB+BAO+H_0?



WMAP [7-year], arXiv:1001.4538

Again consistent with expectations within $< 2\ \sigma$'s (in cosmology!):
you judge if one can really speak of “hints”!

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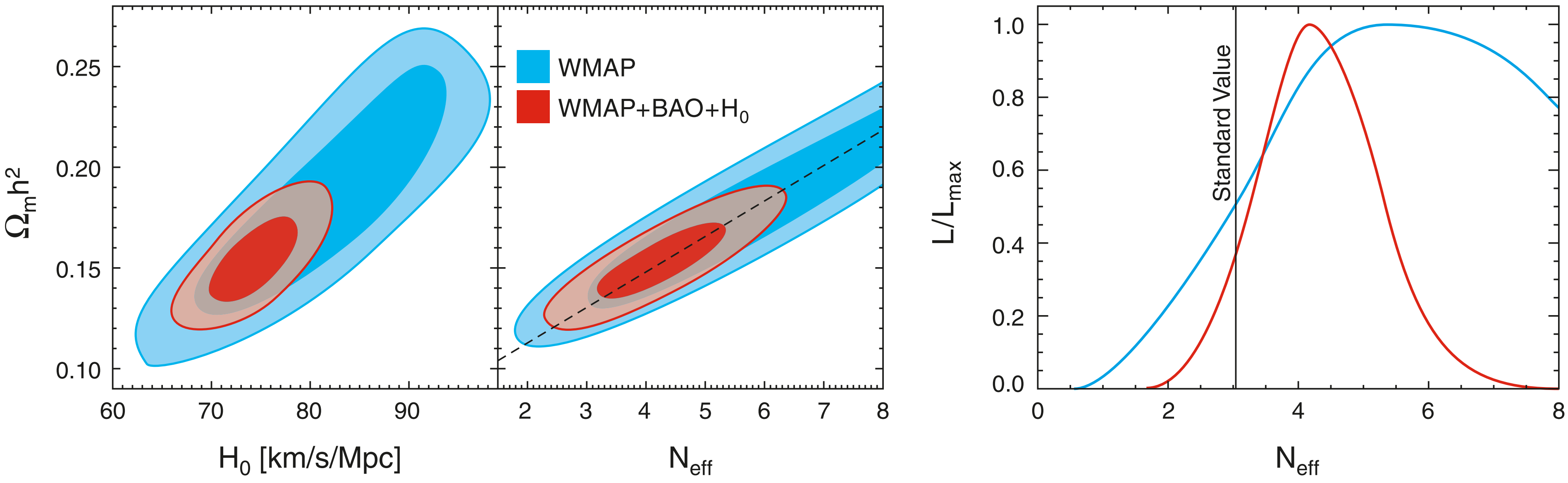

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Note that, on the other end, there is not yet evidence for massive neutrinos power spectrum suppression in LSS

EOM for ν evolution in the Early Universe

Effect of expanding universe

Refractive term due to e^--e^+ energy density

Self-refraction

Collisions

$$i\,(\partial_t - H p\,\partial_p)\,\varrho_p = \left[\left(\frac{U\,M_d^2 U^\dagger}{2p} - \frac{8\sqrt{2}G_{\rm F}\,p}{3m_{\rm W}^2}\mathcal{E} + \varrho - \bar{\varrho}\right), \varrho_p\right] + C[\varrho_p]\,,$$

additional refraction terms (e.g. FCNC)

barring cancellations, new collisional terms!

mismatch between flavour and mass basis expressed via mixing matrix U

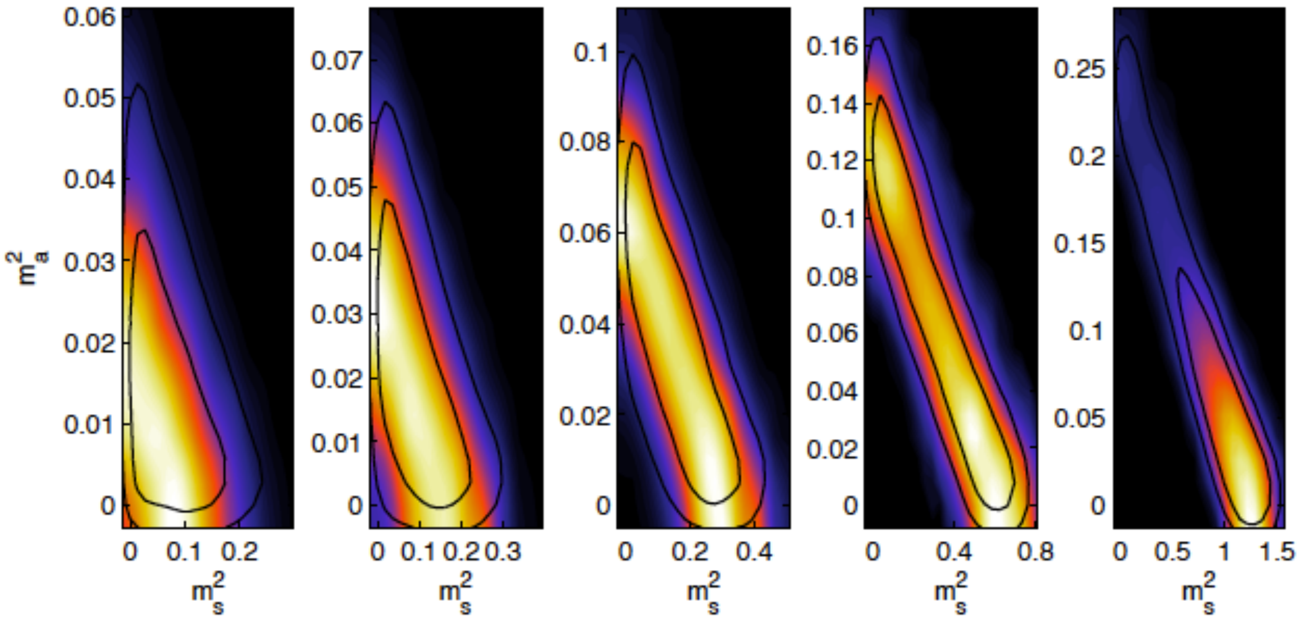
Diagonal mass matrix (i.e. in mass basis)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{lk} \equiv \sin\theta_{lk}$, $c_{lk} \equiv \cos\theta_{lk}$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}.$$

"Direct" detection?



m_s^2/eV^2= 0.0784 0.16 0.3136 0.64 1.2996

Sejersen Riis & Hannestad
arXiv:1008:1495

$|U_{es}|^2$=0.18

An ~eV scale "sterile" neutrino with a sufficiently large (O(0.1)) mixing with the "effective" ν_e may be detectable by the current experiment KATRIN as a distortion in the ^3H endpoint spectrum