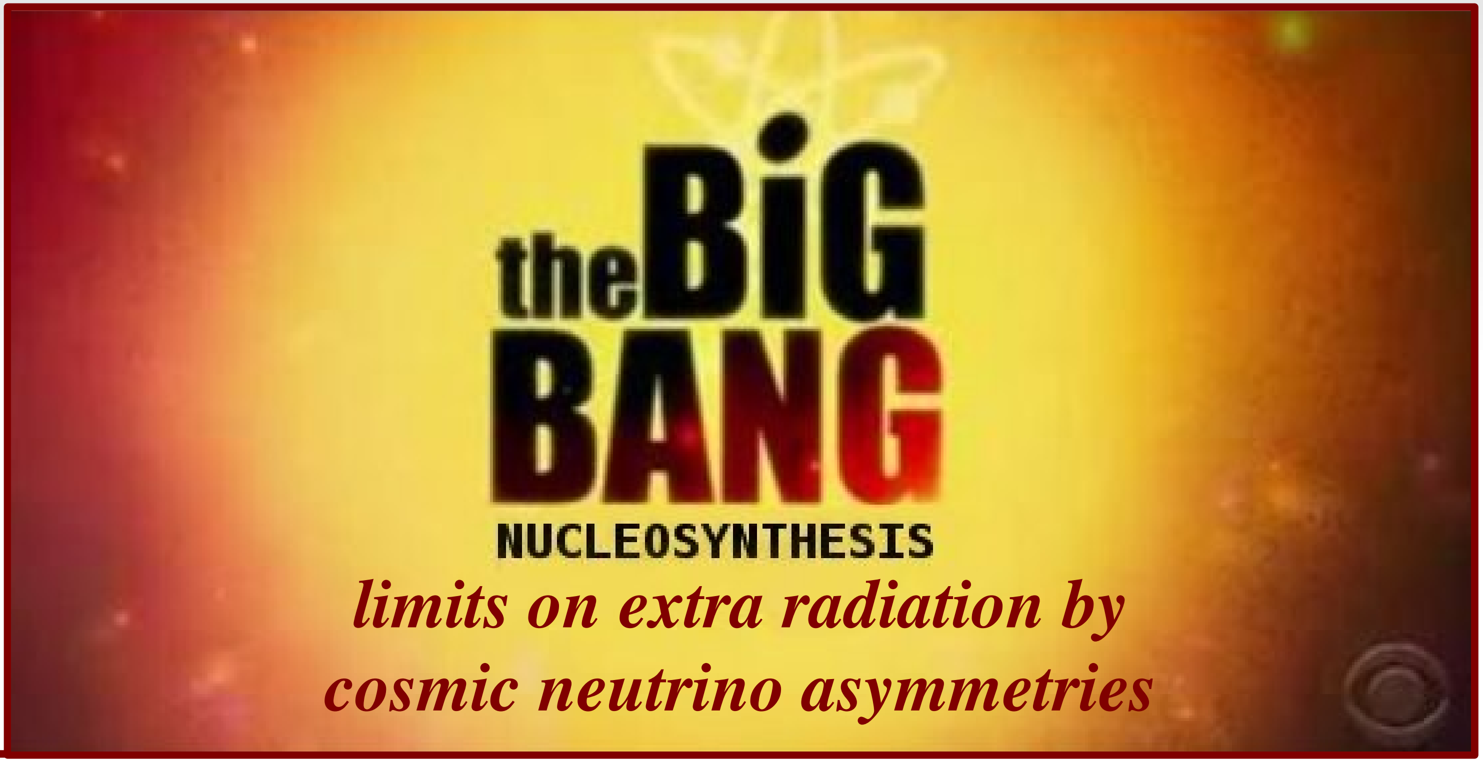
INFN Naples Astroparticle Physics Group
Università di Napoli ”Federico II”



limits on extra radiation by cosmic neutrino asymmetries

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Max Planck Institut für Physik, 25th Nov. 2010

Outline:

- Physics of Neutrino Oscillations
- BBN as a way of constraining cosmology
- Role of Neutrinos in BBN
- Our Work

Neutrinos

- Neutrinos in thermal equilibrium are described by a FD distribution with a chemical potential:

$$f_{\rm FD}(y) = \frac{1}{1+e^{y-\xi_\nu}}\ , \ y = \frac{p}{T}$$

- Asymmetry of neutrinos normalized to photon density is in close relation with neutrino chemical potential*:

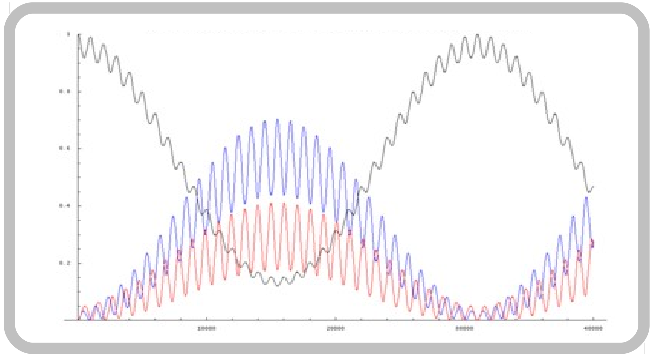
$$\eta_{\nu_\alpha} = \frac{n_{\nu_\alpha} - \bar{n}_{\nu_\alpha}}{n_\gamma} = \frac{\pi^2}{12\,\zeta(3)}\left(\xi + \frac{\xi^3}{\pi^2}\right)$$

**before e⁻ - e⁺ annihilation*

For small chemical potential (almost always), they are ***linearly proportional*** and of the ***same order of magnitude***!

("asymmetry" = "chemical potential" = "degeneracy parameter")

- Neutrinos oscillatate in flavours



$$\Delta m^2_{12} = 7.59^{+0.44}_{-0.37} \times 10^{-5}\ {\rm eV}^2 \quad \sin^2\theta_{12} = 0.32^{+0.04}_{-0.03}$$
$$|\Delta m^2_{23}| = 2.40^{+0.24}_{-0.22} \times 10^{-3}\ {\rm eV}^2 \quad \sin^2\theta_{23} = 0.50^{+0.13}_{-0.11}$$
$$\Delta m^2_{13} \approx \Delta m^2_{23} \quad \sin^2\theta_{13} \leq 0.053\ (3\sigma)$$

- But, it is for a neutrino with a definite energy! What about an ensemble?

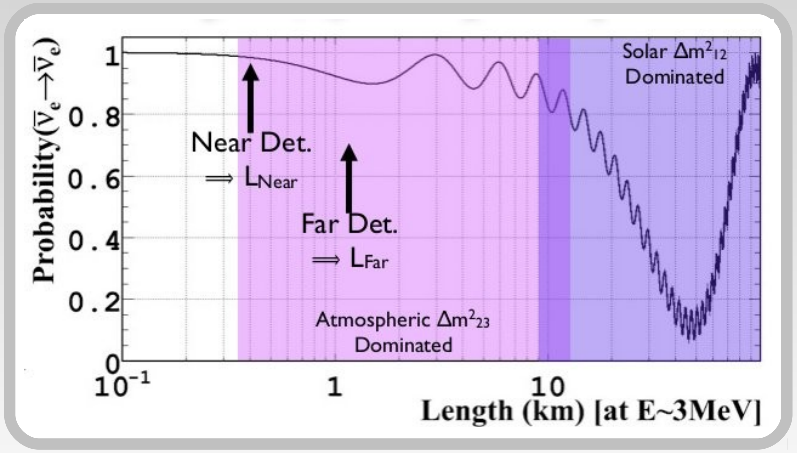
Quantum Statistical Physics!

Measuring θ_{13}

- **Reactor experiments** – look for disappearance of $\overline{\nu}_e$

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu}$$

  - relativly clean θ_{13} measurement

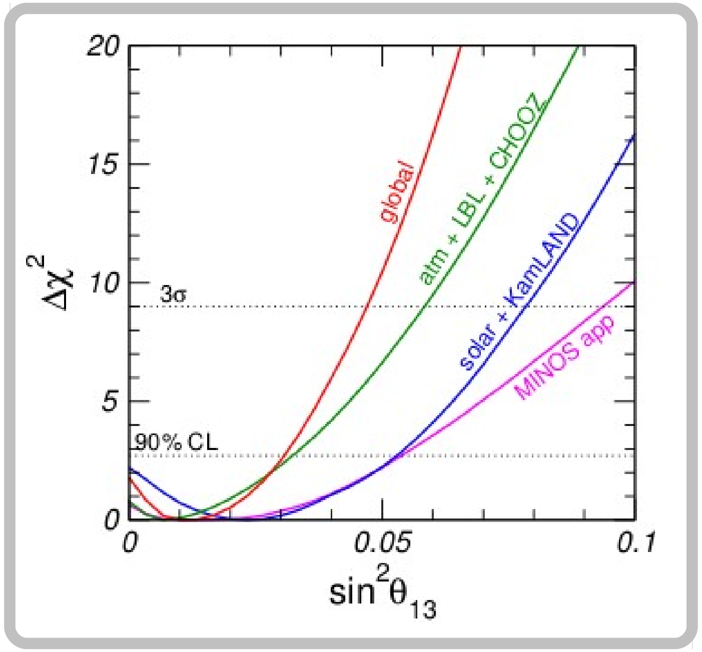


- **Beam experiments** – look for the appearance of (anti)neutrinos in beams $\nu_\mu \to \nu_e$
  - contamination of the beam
  - correlation with all other mixing parameters (esp. Dirac CP-violating phase)

- Mild preferance to non zero mixing angle.

$$\Delta\chi^2(\theta_{13}=0) = \begin{cases} 2.2 & (1.5\sigma) & \text{solar+KamLAND} \\ 0.8 & (0.9\sigma) & \text{CHOOZ+atm+K2K+MINOS} \\ 0.6 & (0.7\sigma) & \text{MINOS } \nu_e \text{ appearance} \\ 1.8 & (1.3\sigma) & \text{global data} \end{cases}$$

- Present status:

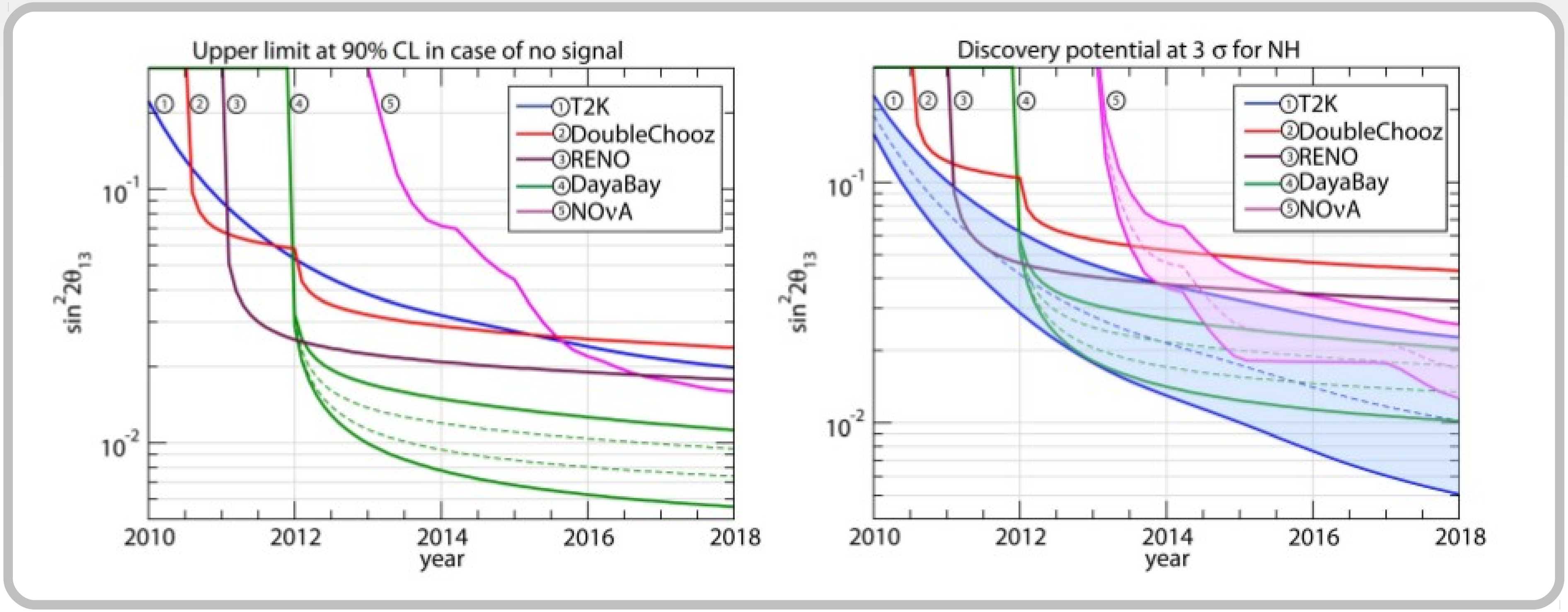


Measuring θ_{13}

future prospects

- Double Chooz
- RENO
- Daya Bay

- T2K
- NOvA



Neutrino Oscillations

- Def: 3 x 3 matrix in the flavour space: $$\rho(p,t) = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

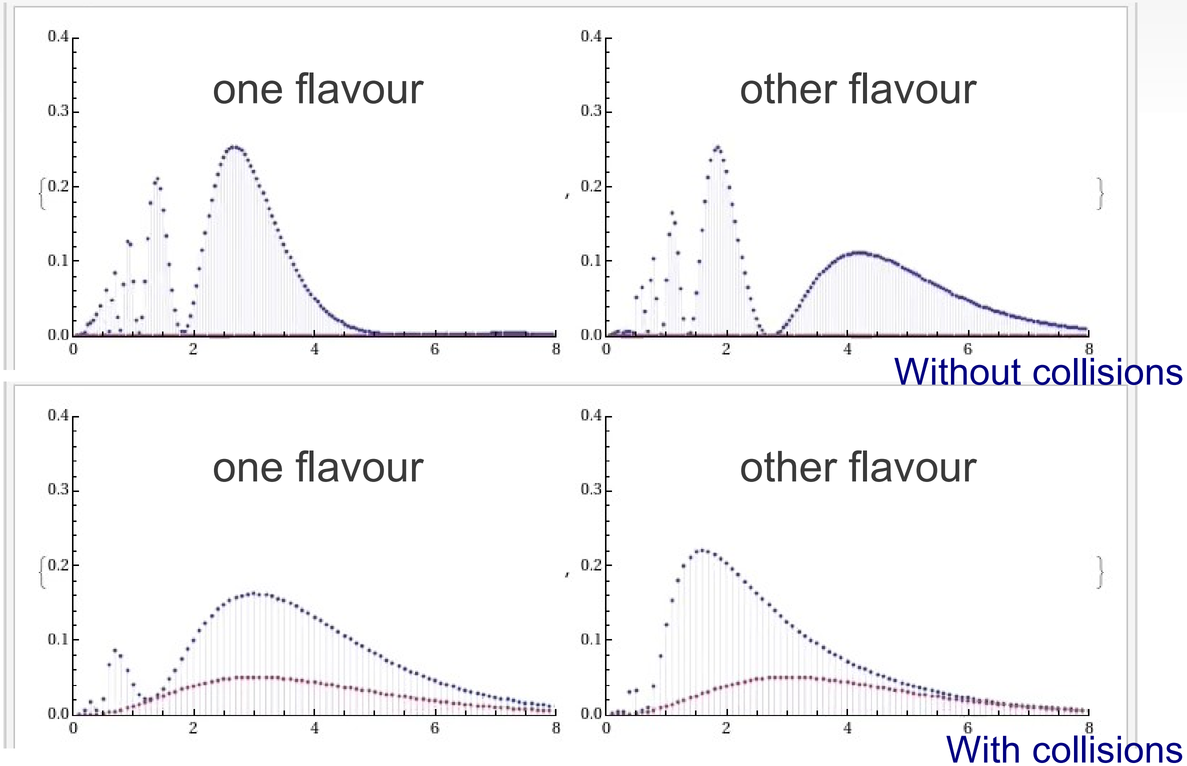
flavour transitions

distributions
(F.D. in equilibrium)

- For off-equilibrium problems one must write down Boltzmann kinetic equation (KE)
- Oscillation in flavours $\rightarrow$ Mixing of the flavours

Without collisions

With collisions



Neutrino Mixing

- In the Early Universe at energies between ~ 100 MeV and ~ 1 MeV, KE must account for:
  - effects of the background plasma;
  - effects of the neutrino background (self-interaction);
  - collisions;
  - vacuum oscillations.

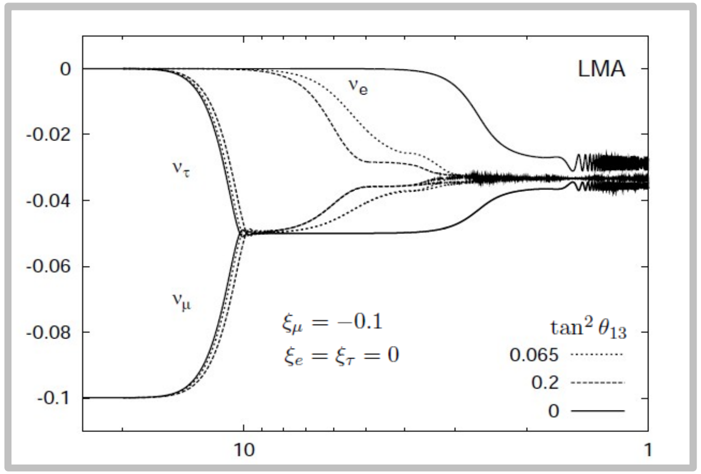
$$i\,\frac{d\varrho_{\mathbf{p}}}{dt} = \left[\frac{\mathsf{M}^2}{2p}, \varrho_{\mathbf{p}}\right] + \sqrt{2}\,G_{\mathrm{F}}\left[-\frac{8p}{3m_{\mathrm{W}}^2}\,\mathsf{E} + (\varrho - \bar{\varrho}), \varrho_{\mathbf{p}}\right] + C(\varrho_{\mathbf{p}}, \bar{\varrho}_{\mathbf{p}})$$

$$\frac{d}{dt} = \partial_t - p\,H\,\partial_p$$

at **2-3 MeV**
– the freeze-out!

- Non trivial dynamics of neutrino asymmetries in Early Universe. e.g:

" We conclude that in the LMA region the neutrino flavors essentially ***equilibrate long before n/p freeze out****, even when θ_{13} is vanishingly small"*

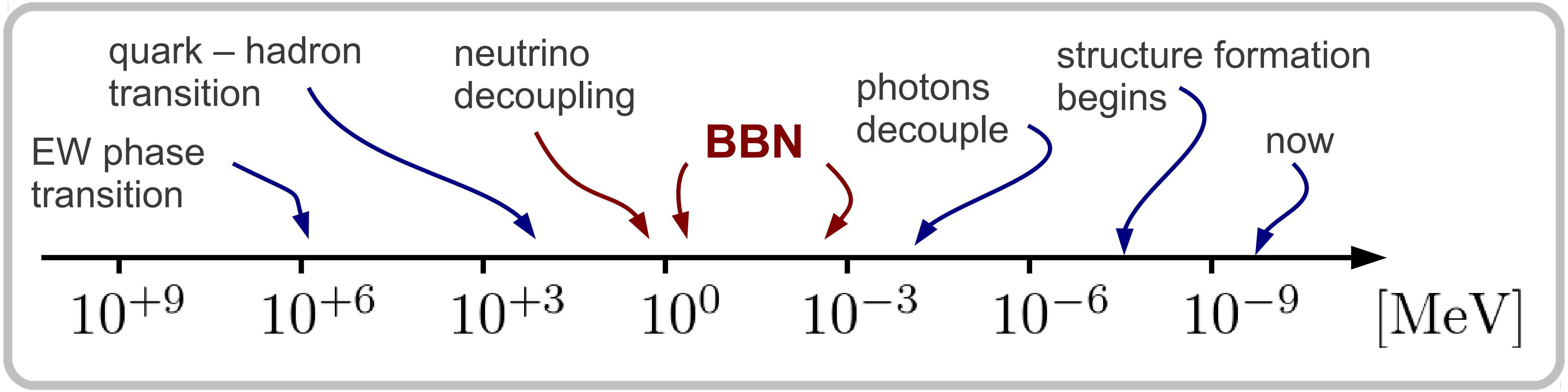


A. D. Dolgov et al., Nucl.Phys. B **632** (2002) 363

Primordial Nucleosynthesis

- Lemaitre (1931): ”hypothesis of the primeval atom” – Big Bang!
- Gamow (1946): Big Bang provides a feasable framework for the production of all chemical elements starting from protons and neutrons only.
- Alpher – Bethe – Gamow paper (1948): first quantitative indication of the right way...
  (later to be proved only for Helium and Hydrogen)
- Standard Cosmology:

  BBN is an epoch of evolution of the Universe:



Primordial Nucleosynthesis
Energy Budget

Electromagnetic plasma:
- photons γ
- electrons e

* In equilibrium until ~ 0.1 eV

- baryons (p $\leftrightarrow$ n)

* In equilibrium until ~ 0.1 MeV

$$\boxed{\rho_\gamma = \frac{\pi^2}{15} T_\gamma^4}$$

Neutrinos:

- 3 flavours ν_e , ν_μ , ν_τ

* In equilibrium until ~ 1 MeV

$$\boxed{\rho_\nu = 3\,\frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma}$$

Extra d.o.f.
- sterile neutrinos?
- DM particles?
- quintessence?

* In equilibrium ?

$$\boxed{\rho_X = ?}$$

Primordial Nucleosynthesis
Energy Budget

Electromagnetic plasma:
- photons γ
- electrons e

* In equilibrium until ~ 0.1 eV

- baryons (p ↔ n)

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Extra d.o.f.
- sterile neutrinos?
- DM particles?
- quintessence?

* In equilibrium ?

$$\boxed{\rho_X = ?}$$

- total energy after electron-positron annihilation: $$\boxed{\rho = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)}$$

Effective number of neutrinos

- we expect N_{eff} = 3
- extra ν-like degrees of freedom, N_{eff} = 4, 5...
- non instantaneous decoupling effects: N_{eff} = 3.046
- non standard neutrino physics...

- e.g: with neutrinos asymmetries:

$$\Delta N_{\rm eff} \simeq \frac{30}{7}\left(\frac{\xi_\nu}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_\nu}{\pi}\right)^4$$

Primordial Nucleosynthesis
Role of Neutrinos

- Neutrinos enter in two ways:

  1. *indirectly:* contributing to energy budget
  $\rightarrow$ governing the expansion rate:
  crucial parameter: effective number of neutrinos N_{eff}

$$H = \sqrt{\frac{8\pi G_N}{3}\,\rho}$$

  2. *directly* *(only electronic)**:*** in weak interactions
  converting p ⇌ n :
  $\rightarrow$ governing the neutron to proton ratio
  $\rightarrow$ dictating the abundance of heavier nuclides!

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

  - Crucial parameter – chemical potential:
    - $\xi > 0 \;\rightarrow\; \eta > 0 \;\rightarrow$ more ν than $\bar{\nu}$ $\rightarrow$ less neutrons $\rightarrow$ less He-4
    - $\xi < 0 \;\rightarrow\; \eta < 0 \;\rightarrow$ less ν than $\bar{\nu}$ $\rightarrow$ more neutrons $\rightarrow$ more He-4

    raises also N_{eff} !

Primordial Nucleosynthesis Calculation

INPUTS

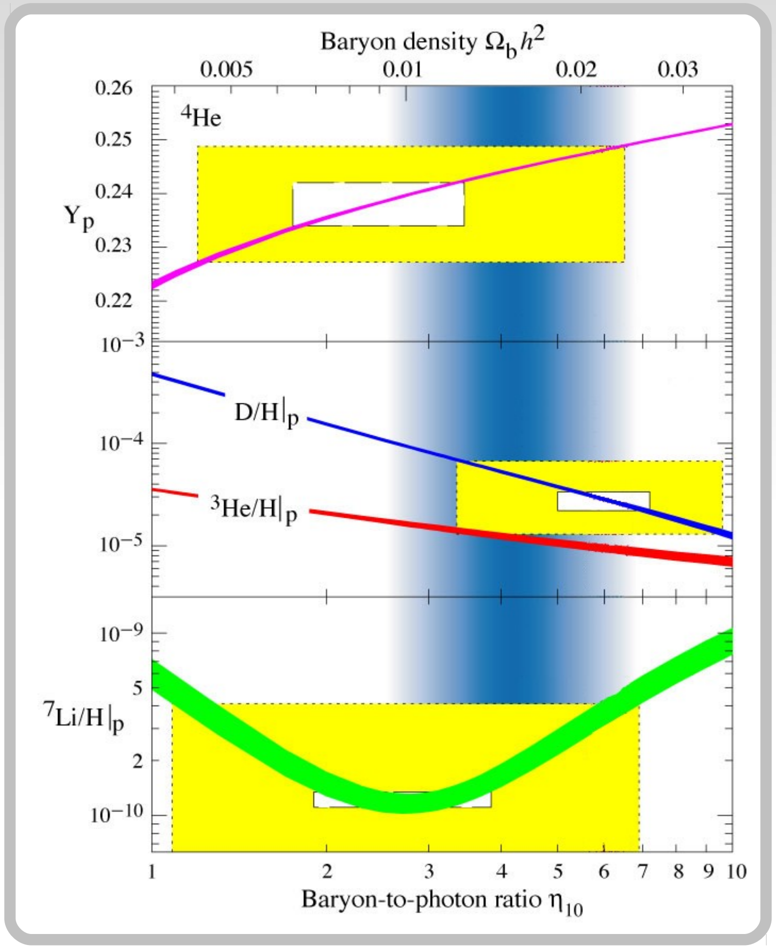
- baryon asymmetry η_b
- neutrino asymmetry ξ
- energy density in rel. d.o.f., N_{eff}
- cosmological constant...

CODE
PArthENoPE

- Make prediction on abundances.

Astrophysical data

- Compare predictions with measurements (**He-4**, **D**, He-3, Li-7)



PDG

Primordial Nucleosynthesis Calculation

INPUTS → CODE PArthENoPE

- baryon asymmetry η_b
- neutrino asymmetry ξ
- energy density in rel. d.o.f., N_{eff}
- cosmological constant...

- Make prediction on abundances.

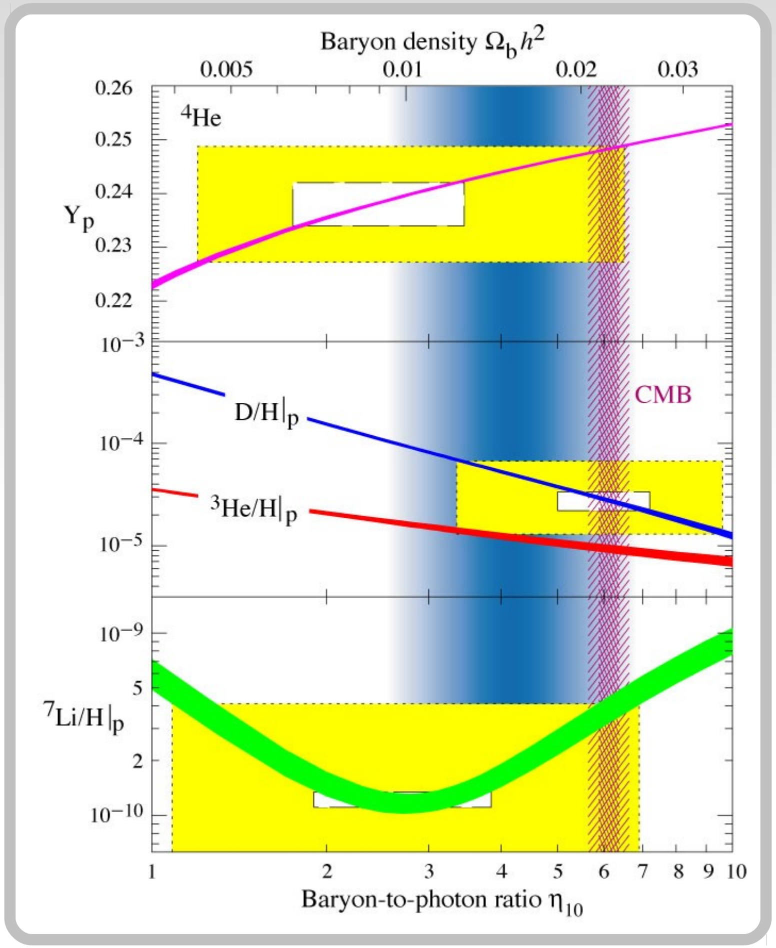
Astrophysical data

- Compare predictions with measurements (**He-4**, **D**, He-3, Li-7)

- Use them as INPUT

e.g: WMAP pinned down the baryon content to high precision:

$$\boxed{\eta_b = 6.19(14) \times 10^{-10}}$$



PDG

Primordial Nucleosynthesis Data

Astrophysical data

F. Iocco et al, Phys. Rep. 472 (2009) 1–76

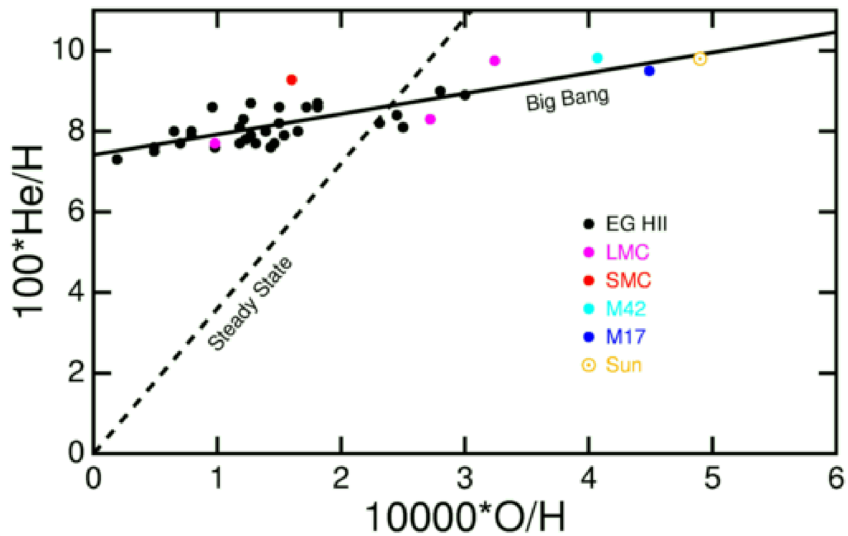
$$Y_p = 0.250 \pm 0.003$$
$$^2\mathrm{H}/\mathrm{H} = (2.87 \pm 0.22) \times 10^{-5}$$

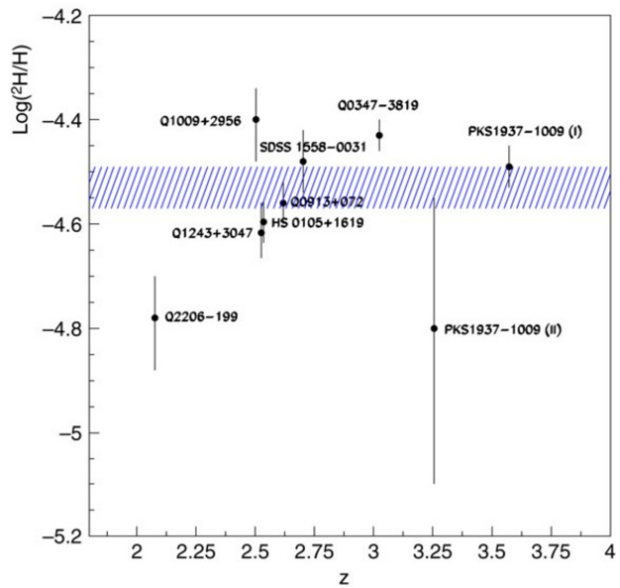
Aver et al: astro-ph/1001.5218

$$Y_p = 0.2561 \pm 0.0108$$

Izotov, Thuan, AJL 710 (2010) L67-L71

$$Y_p = 0.2565 \pm 0.0010(\mathrm{stat.}) \pm 0.0050(\mathrm{syst.})$$



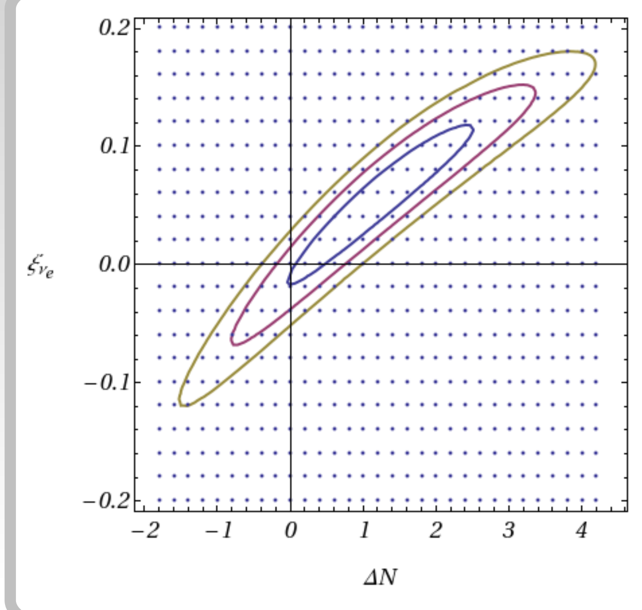


BBN and Neutrinos

an example

– varying 2 parameters:

electronic neutrino chemical potential
vs
effective number of neutrinos



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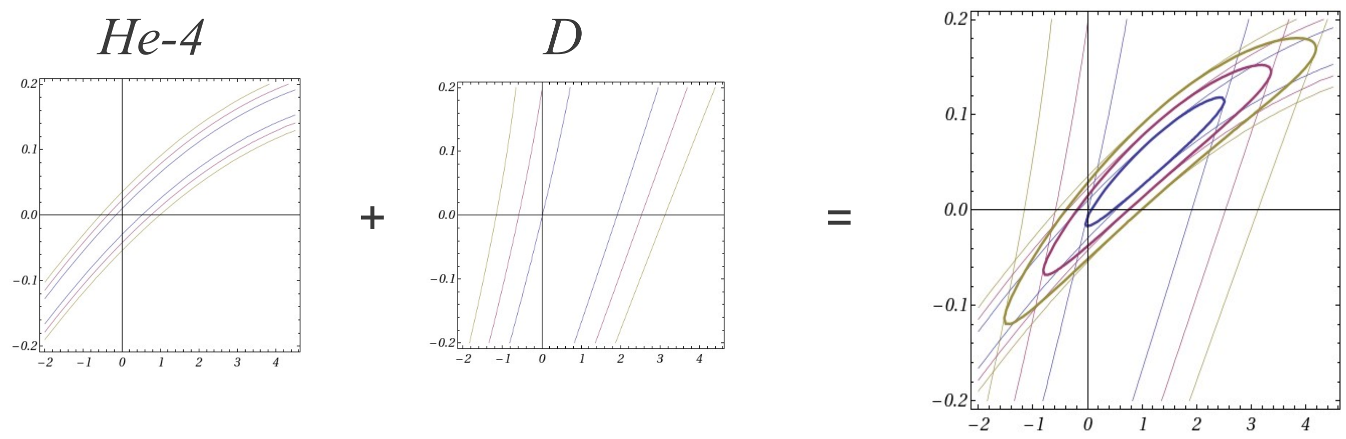

BBN and Neutrinos

Izotov & Thuan 2010

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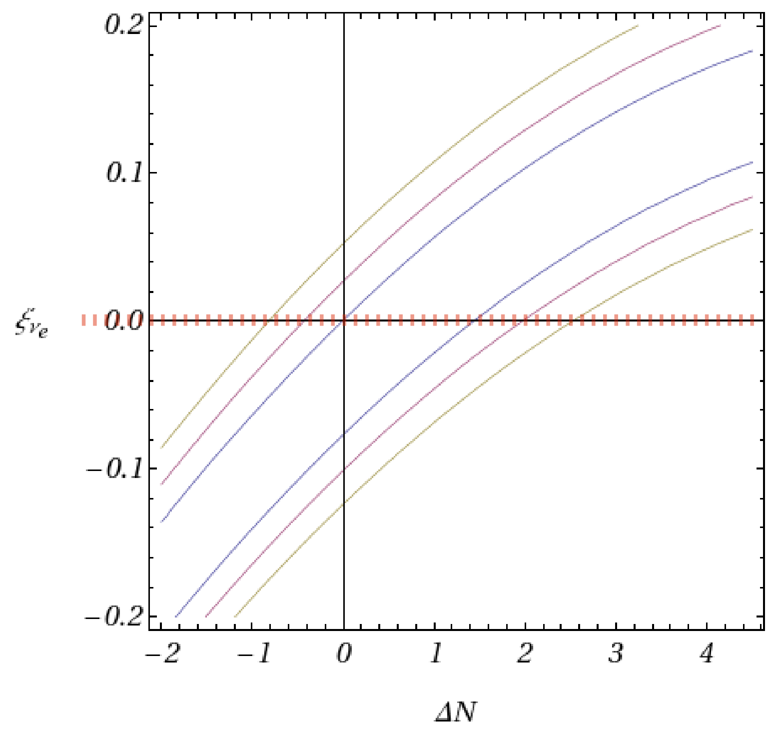

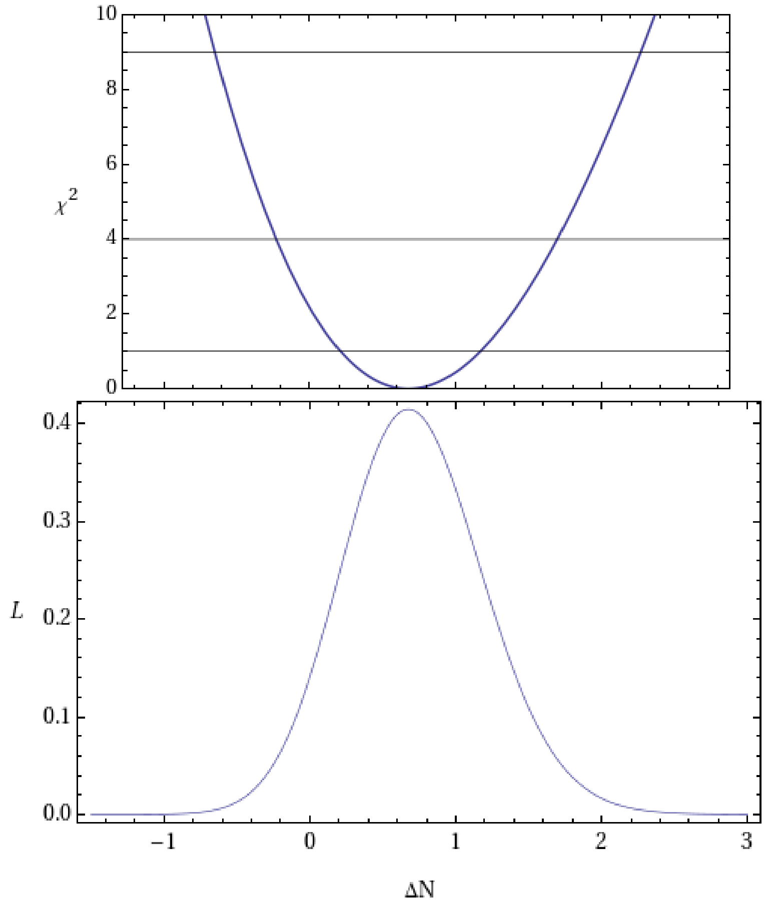

– set chemical potential to zero

BBN and Neutrinos

Izotov & Thuan 2010

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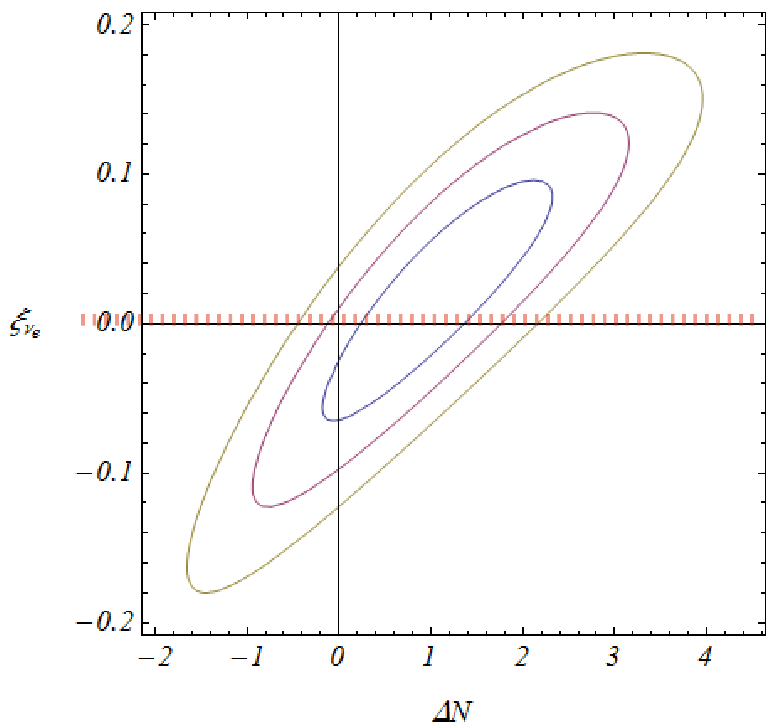
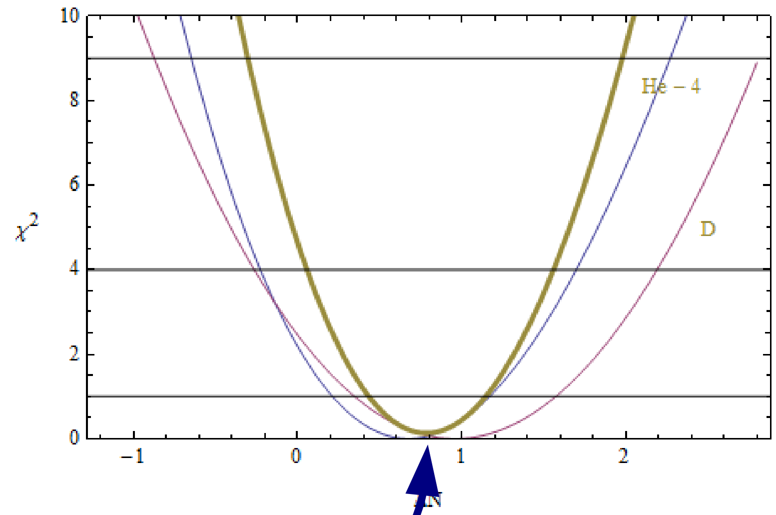
$$^2\mathrm{H/H} = (2.87 \pm 0.22) \times 10^{-5}$$



– set chemical potential to zero

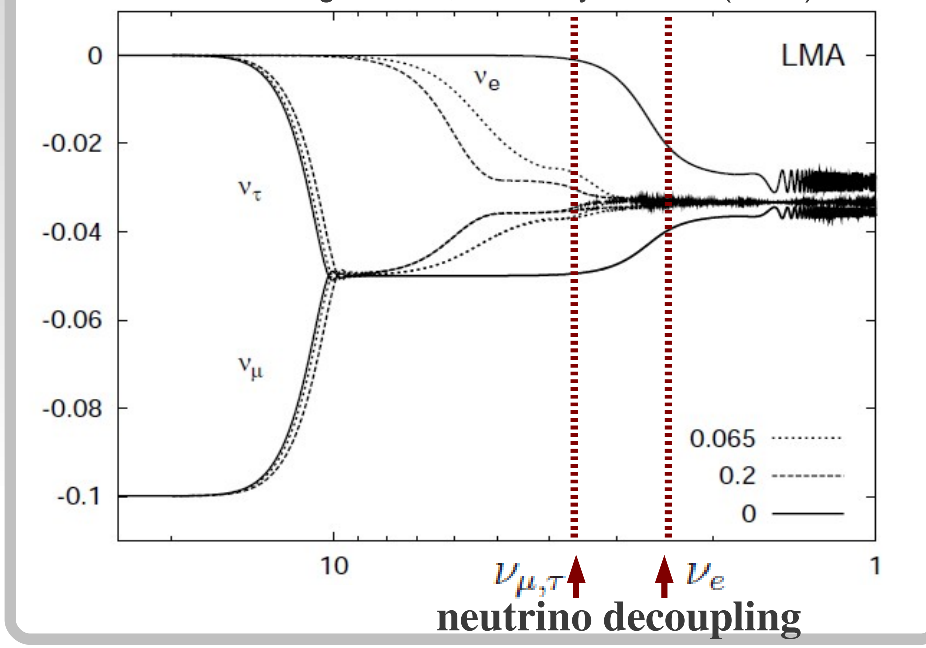


Sign of extra d.o.f?
sterile?
axion?

What is the maximal contribution of neutrinos to energy density?

Understanding the neutrino dynamics

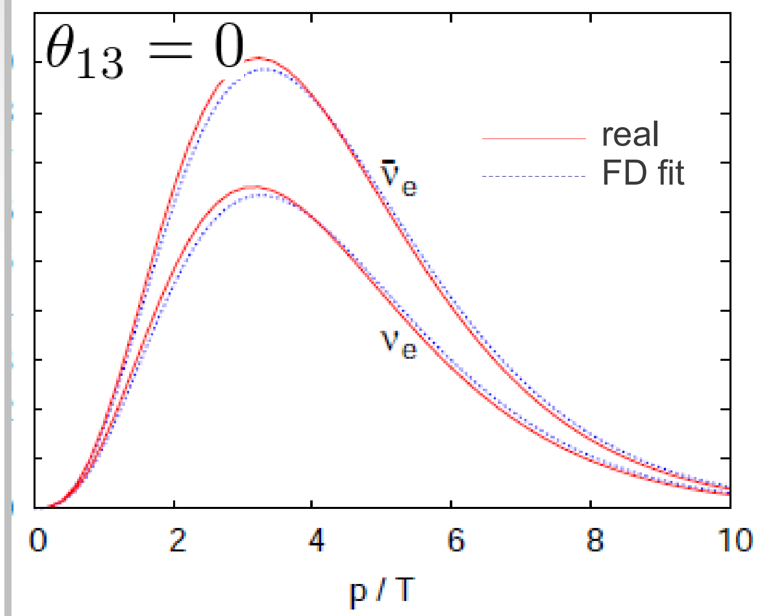
A. D. Dolgov et al., Nucl.Phys. B **632** (2002) 363



S.Pastor, T.Pinto and G.G.Raffelt, Phys.Rev.Lett. **102**(2009)

After decoupling flavour mixing continues, but ***there is no process driving them to kinetic and chemical equilibrium!***

- So, we are dealing with non equillibrium distributions.
- They need to be obtained from KE!
- Neutrinos are a bit hotter $\rightarrow \Delta N \uparrow$



We fit to a FD with two ***effective parameters*** T_ν^{eff} and ξ_ν^{eff} .

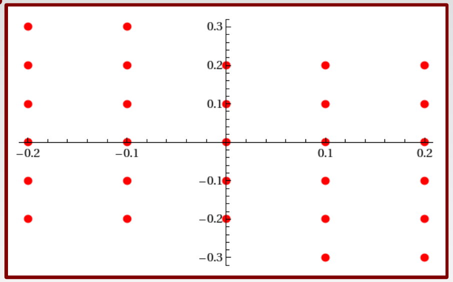
An average of two equilibrium Fermi-Dirac distributions is ***not necessarily a FD distribution!***

Method

Choose a point in ($L_{\nu_e}^{init}$, L^{tot}) plane

Solve KE for neutrinos

Neutrino evolution files

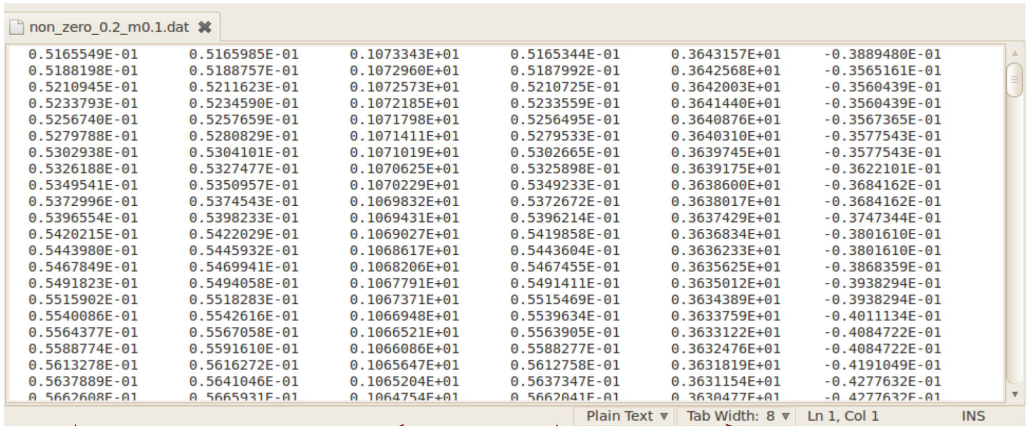


Run ParthENoPE
(calculate the abbundances)

Parse outputs

$^4He, D$

Compare to exp. values
(Draw likelihoods)


non_zero_0.2_m0.1.dat

0.5165549E-01	0.5165985E-01	0.1073343E+01	0.5165344E-01	0.3643157E+01	-0.3889480E-01
0.5188198E-01	0.5188757E-01	0.1072960E+01	0.5187992E-01	0.3642568E+01	-0.3565161E-01
0.5210945E-01	0.5211623E-01	0.1072573E+01	0.5210725E-01	0.3642003E+01	-0.3560439E-01
0.5233793E-01	0.5234590E-01	0.1072185E+01	0.5233559E-01	0.3641440E+01	-0.3560439E-01
0.5256740E-01	0.5257659E-01	0.1071798E+01	0.5256495E-01	0.3640876E+01	-0.3567365E-01
0.5279788E-01	0.5280829E-01	0.1071411E+01	0.5279533E-01	0.3640310E+01	-0.3577543E-01
0.5302938E-01	0.5304101E-01	0.1071019E+01	0.5302665E-01	0.3639745E+01	-0.3577543E-01
0.5326188E-01	0.5327477E-01	0.1070625E+01	0.5325898E-01	0.3639175E+01	-0.3622101E-01
0.5349541E-01	0.5350957E-01	0.1070229E+01	0.5349233E-01	0.3638600E+01	-0.3684162E-01
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0.5420215E-01	0.5422029E-01	0.1069027E+01	0.5419858E-01	0.3636834E+01	-0.3801610E-01
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0.5491823E-01	0.5494058E-01	0.1067791E+01	0.5491411E-01	0.3635012E+01	-0.3938294E-01
0.5515902E-01	0.5518283E-01	0.1067371E+01	0.5515469E-01	0.3634389E+01	-0.3938294E-01
0.5540086E-01	0.5542616E-01	0.1066948E+01	0.5539634E-01	0.3633759E+01	-0.4011134E-01
0.5564377E-01	0.5567058E-01	0.1066521E+01	0.5563905E-01	0.3633122E+01	-0.4084722E-01
0.5588774E-01	0.5591610E-01	0.1066086E+01	0.5588277E-01	0.3632476E+01	-0.4084722E-01
0.5613278E-01	0.5616272E-01	0.1065647E+01	0.5612758E-01	0.3631819E+01	-0.4191049E-01
0.5637889E-01	0.5641046E-01	0.1065204E+01	0.5637347E-01	0.3631154E+01	-0.4277632E-01
0.5662608E-01	0.5665931E-01	0.1064754E+01	0.5662041E-01	0.3630477E+01	-0.4277632E-01

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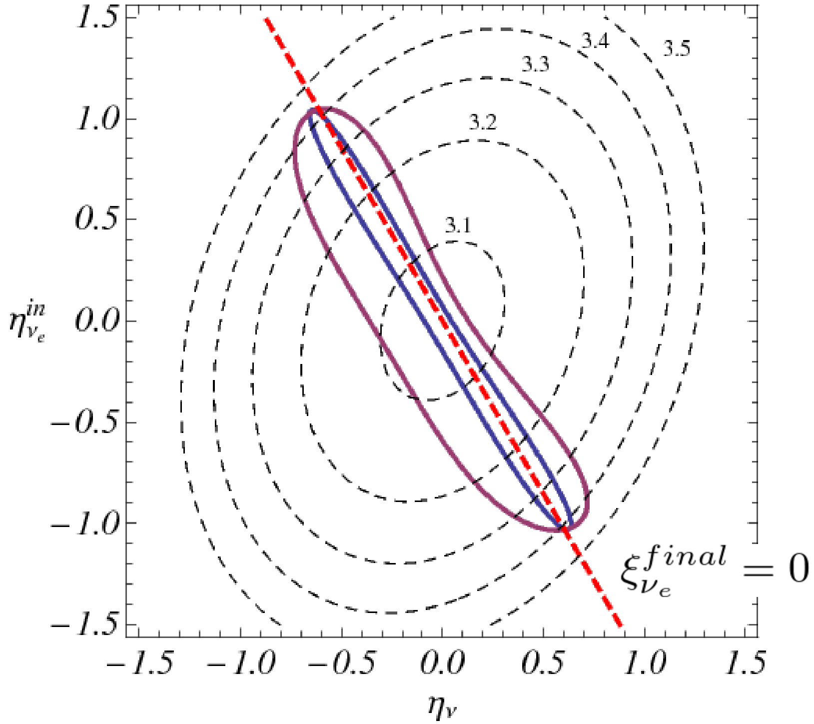
$$z = \frac{m_e}{T_\gamma} \qquad \xi_\nu^{eff} \qquad z_\nu = \frac{m_e}{T_\nu^{eff}} \qquad \frac{\rho_\nu}{\rho_\gamma}$$

Results

Constraints in the plane: Total ν asymmetry vs. Initial electronic ν asymmetry

$\theta_{13} = 0$



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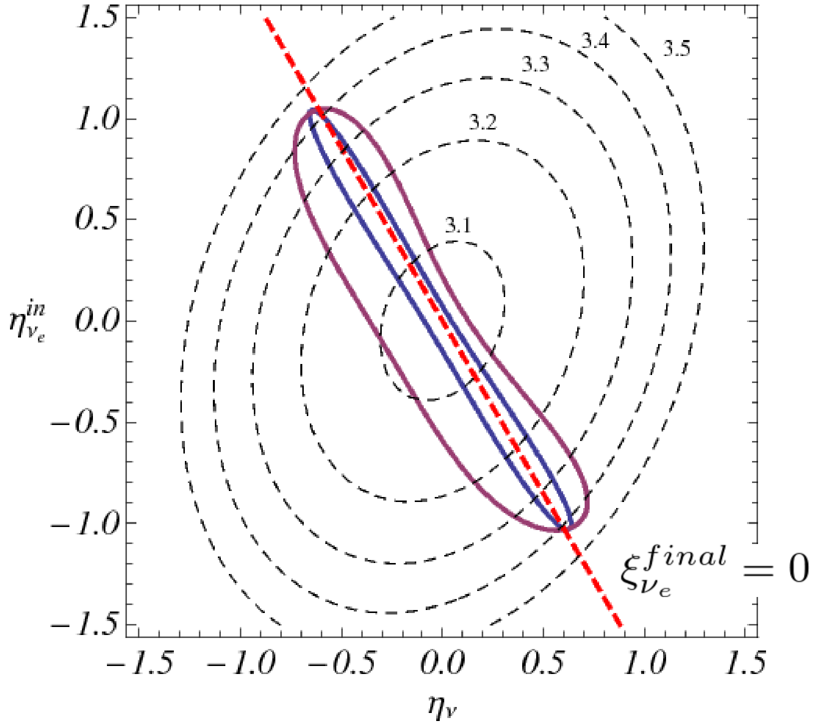


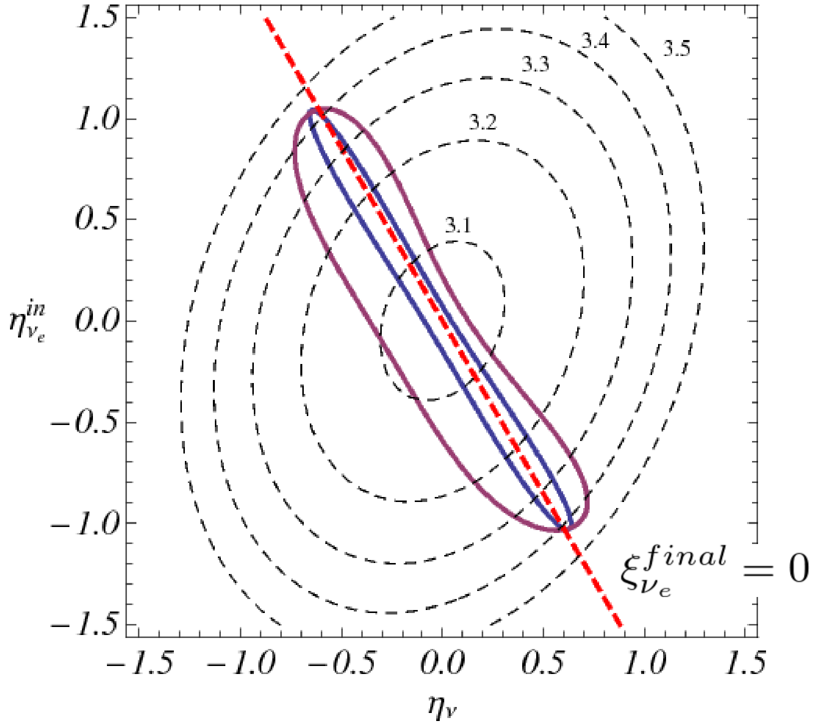
Results prefer $\xi_{\nu_e} \approx 0$.

Results

Constraints in the plane: Total ν asymmetry vs. Initial electronic ν asymmetry

$\theta_{13} = 0$

$\sin^2\theta_{13} = 0.04$



Results prefer $\xi_{\nu_e} \approx 0$.

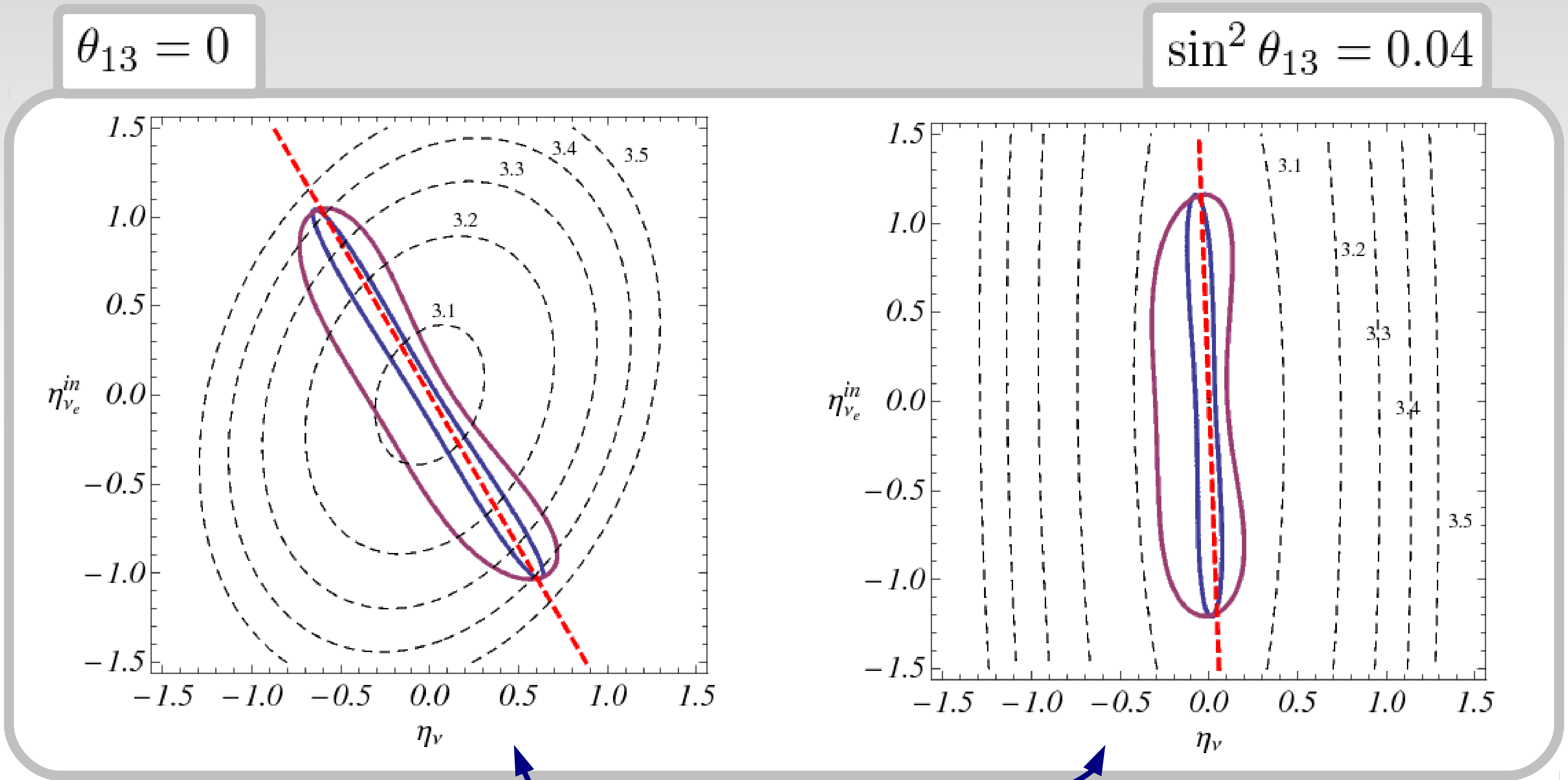
Neutrino chemical potentials have more time to equilibrate: $\xi_{\nu_e} \approx \xi_{\nu_x}$

$\xi_{\nu_e}^{final} = 0$ is closer to $\eta_\nu = 0$

Contours follow it!

Results

Constraints in the plane: Total ν asymmetry vs. Initial electronic ν asymmetry



- Constraints on total neutrino asymmetry depend on θ_{13}:

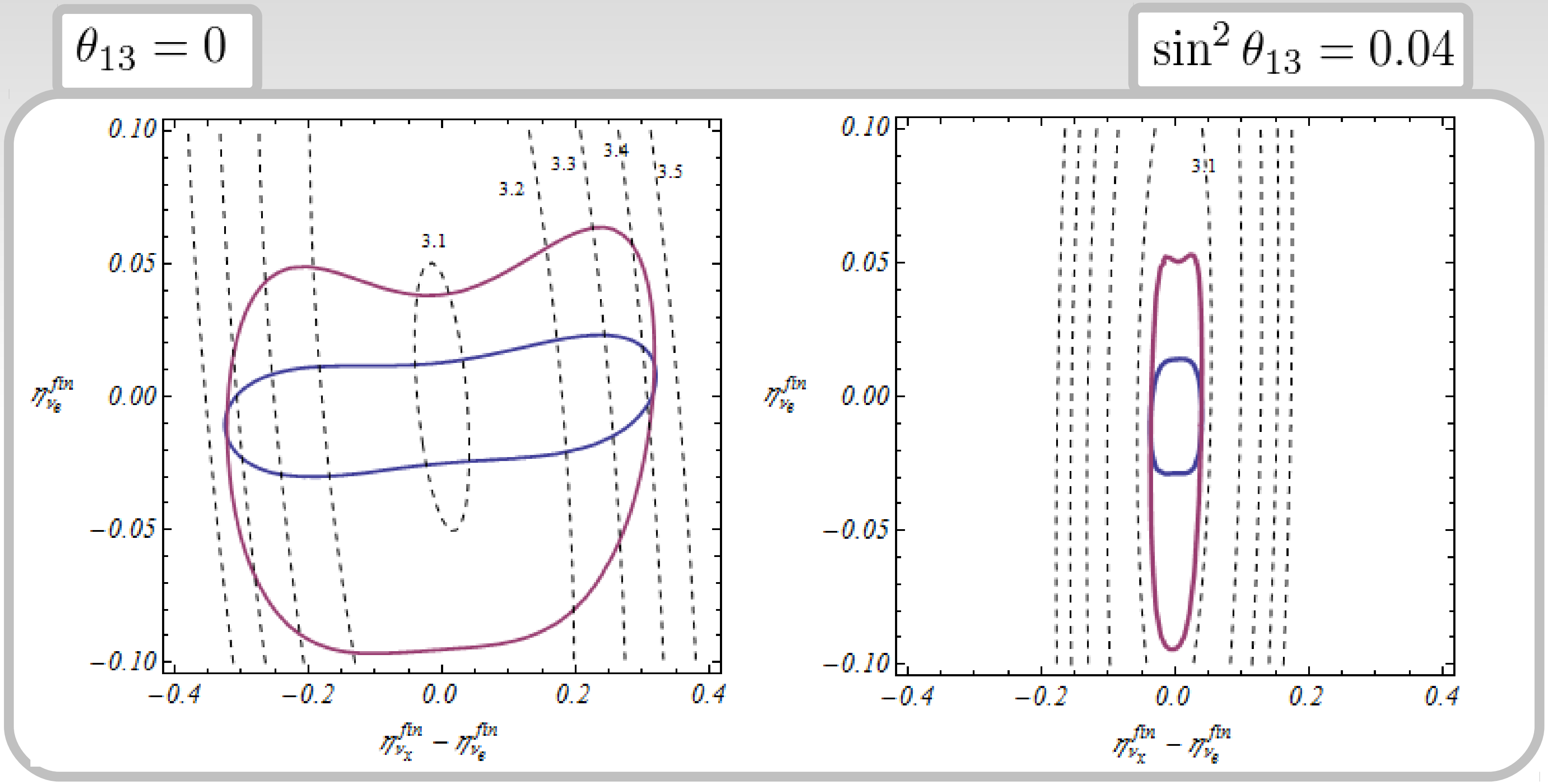
  - of the order of magnitute as previously thought;

  - as electronic with a clear anticorrellation.

- Constraints on ν_e asymmetry is order of magnitute looser in both cases!

Results

Constraints on the final degeneracies:

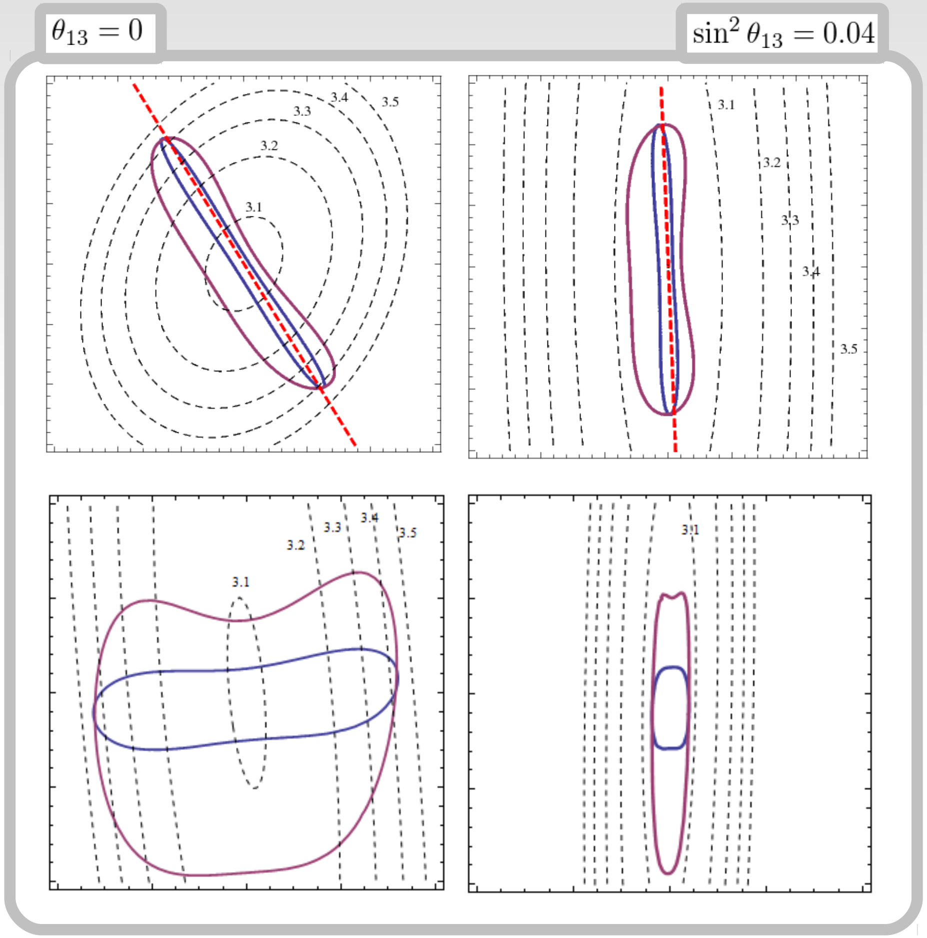


- Constraints on **final ν_e asymmetry** is virtually **indipendent** of mixing angle! (=> Dictated by He-4)
- **Difference** between final asymmetries **depends** on mixing angle. (as expected)

Results

Constraints on the residual N_{eff}:

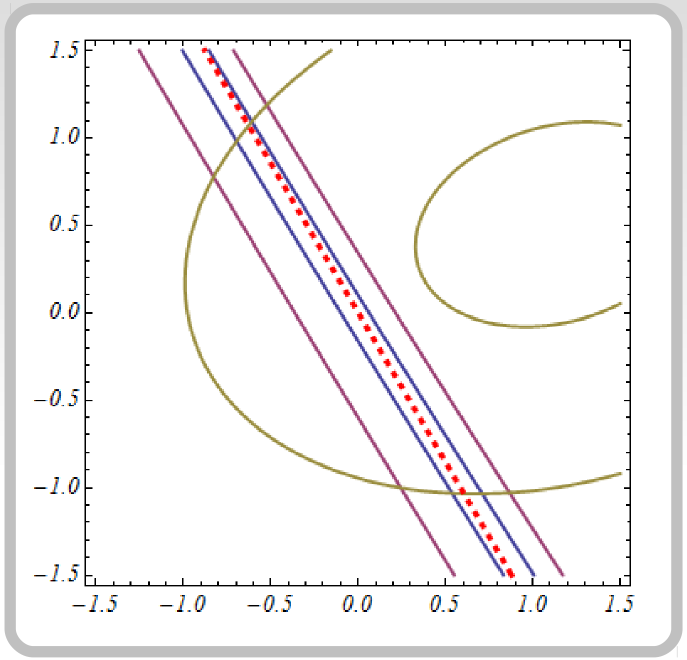
- Constraining the residual energy density N_{eff} < 3.4 max!

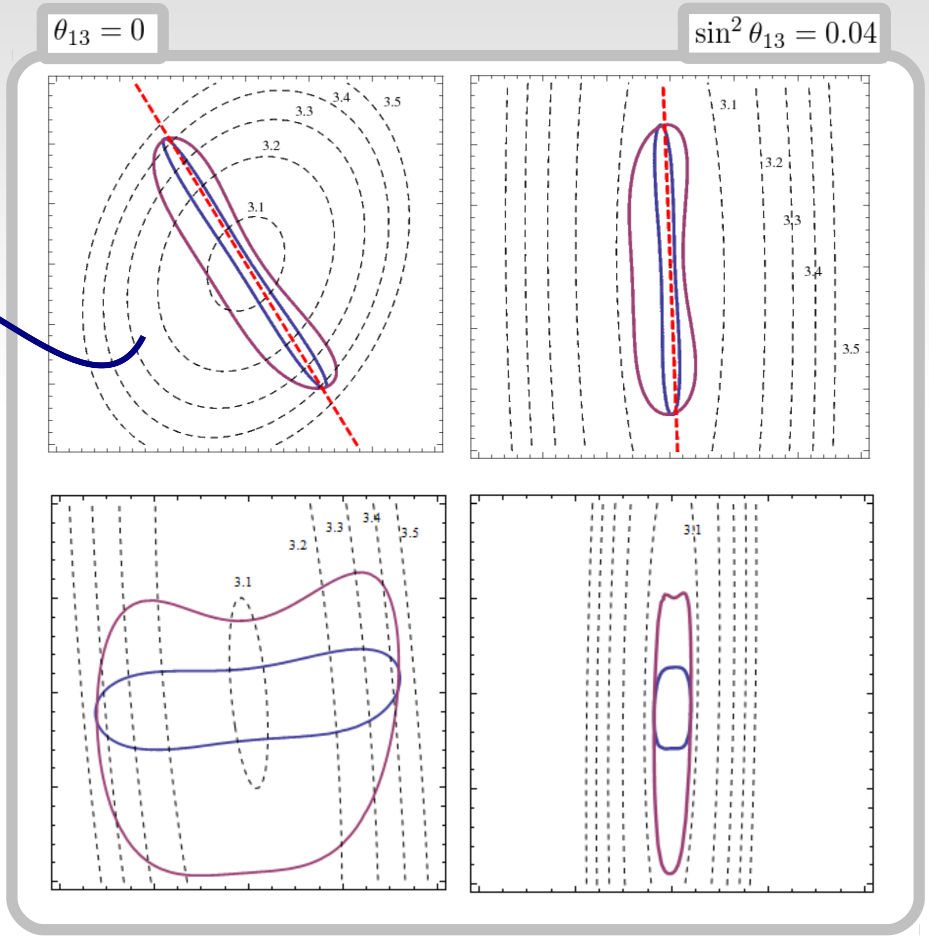


Results

Constraints on the residual $N_{\rm eff}$:

- Constraining the residual energy density N_{eff} < 3.4 max!

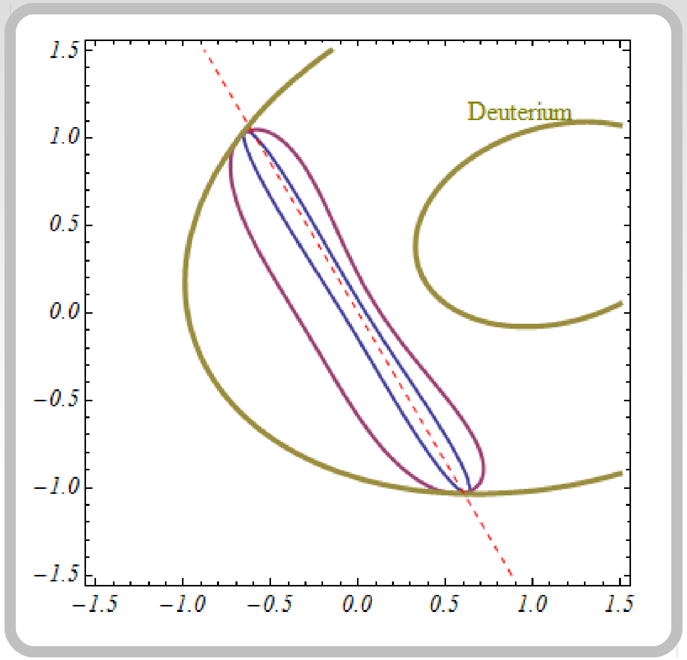


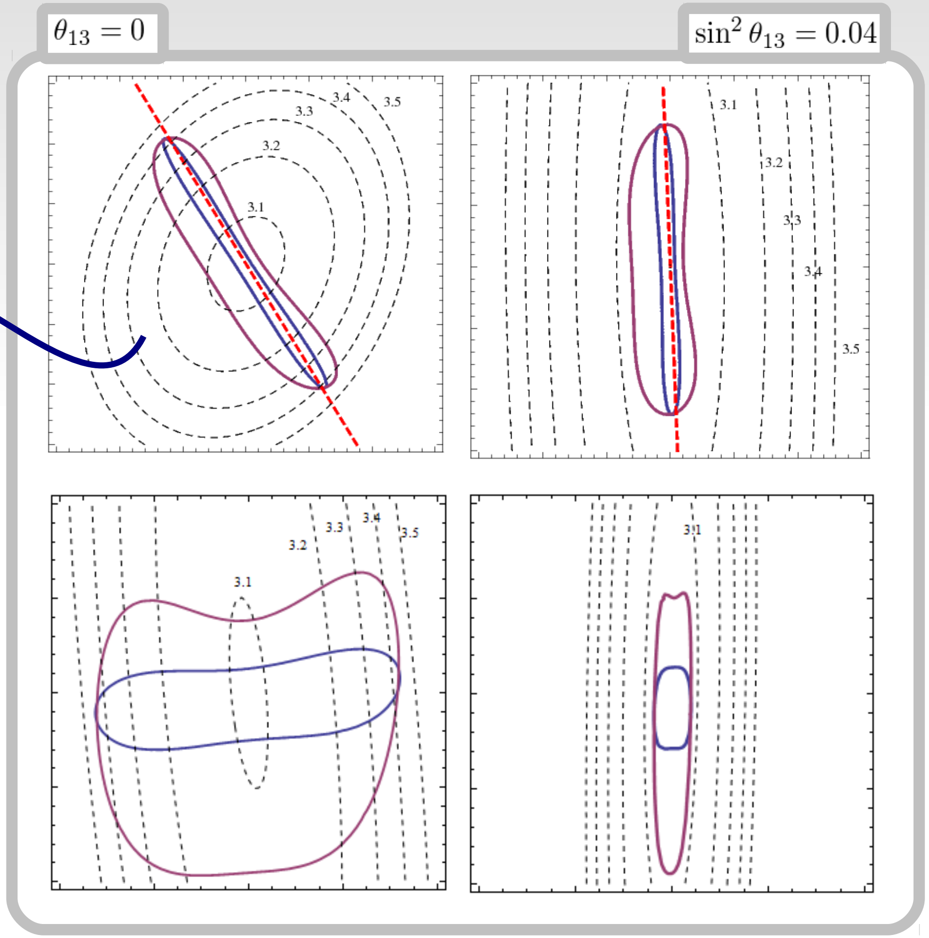


Results

Constraints on the residual N_{eff}:

- Constraining the residual energy density N_{eff} < 3.4 max!

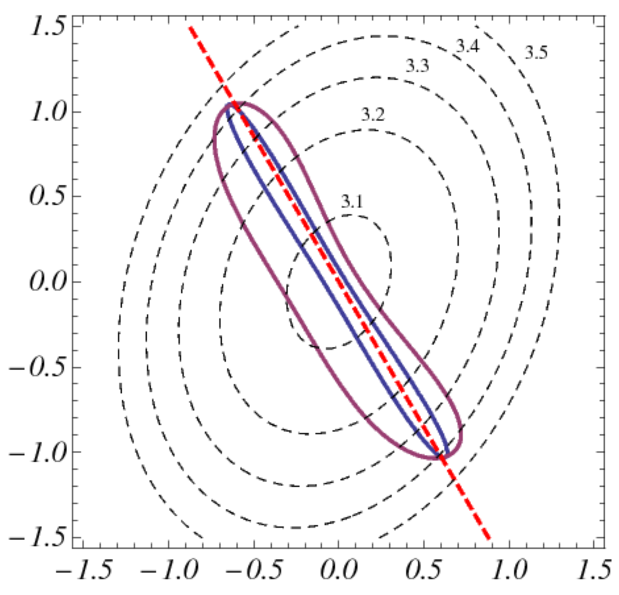




- Present bound on N_{eff} by WMAP is very loose:
  $N_{\text{eff}} < 6$
- The forecast on Planck sensitivity for N_{eff} ranges from ~0.6 to ~0.2.
- A proper BBN prior is crucial (dependence of Y_p on other parameters)!

Results

Constraints on the residual N_{eff}:



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- Constraining the residual energy density N_{eff} < 3.4 max!

  With the results from Planck, our results could complement experimental studies on neutrino physics and/or BSM physics:

- Suppose Planck measures $N_{eff} \simeq 3$
  ↳ No extra d.o.f. at the epoch of BBN;
  ↳ No conclusion on θ_{13} .

- Suppose Planck measures $N_{eff} \simeq 3.5$
  ↳ If we are to retain that the excess of energy content is due to neutrinos:
  ⇨ θ_{13} must be small ⇨ lab. exp.
  ⇨ Neutrinos are largely degenerate!
  or:
  ↳ Extra d.o.f ⇨ BSM.

- Suppose Planck measures $N_{eff} \gtrsim 4$
  ↳ energy excess ***cannot be explained in terms of (active) neutrino physics***
  ⇨ New physics BSM!