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Active-sterile neutrino oscillations in the Early Universe with dynamical neutrino asymmetries

Ninetta Saviano
II Institut für Theoretische Physik, Universität Hamburg,
Dipartimento di Scienze Fisiche, Università di Napoli Federico II

Based on : *A. Mirizzi, N.S., G. Miele, P.D. Serpico*; *PRD 86, 053009 (2012)*

Experimental anomalies & sterile ν interpretation

Experimental data in tension with the standard 3ν scenario:

1. $\bar{\nu}_e$ appearance signals

- excess of $\bar{\nu}_e$ originated by initial $\bar{\nu}_\mu$: LSND/ MiniBooNE
  (but no ν_e excess signal from $\nu_\mu \to \nu_e$)

A. Aguilar et al., 2001

A. Aguilar et al., 2010

2. $\bar{\nu}_e$ and ν_e disappearance signals

- deficit in the $\bar{\nu}_e$ fluxes from nuclear reactors (at short distance)

Mention et al.2011

- reduced solar ν_e event rate in Gallium experiments

Acero, Giunti and Lavder, 2008

All these anomalies, if interpreted as oscillation signals, point towards the possible existence of ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(eV^2)$ and $\theta_s \sim O\,(0.1)$

Many analysis have been performed → 3+1, 3+2 schemes

Kopp, Maltoni & Schwetz 2011
Giunti and Laveder, 2012
Abazajian et al., 2012
(white paper)

Extra radiation

Sterile neutrinos can be produced via oscillations with active neutrinos in Early Universe

→ possible contribution to extra degrees of freedom ΔN

$$\varepsilon_\nu + \varepsilon_x = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 N_\nu^{eff} = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 \left(N_{SM}^{eff} + \Delta N\right) = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 \left(3.046 + \Delta N\right)$$

non-e.m. energy density

Mangano et al. 2005

Extra d.o.f. rebound on the cosmological observables :

- BBN (through the expansion rate H and the direct effect of ν_e and $\overline{\nu}_e$ on the n-p reactions)
- CMB & LSS (sound horizon, anisotropic stress, equality redshift, damping tail)

Cosmological hints for extra radiation

- Current precision cosmological data show a preference for extra relativistic d.o.f :

✓ **BBN** (standard) → $N_{eff} \leq 4$ (at 95% C.L)

Mangano and Serpico, 2011
Hamman et al., 2011
Pettini and Cooke, 2012

with only a small significance preference for N^{eff} > stand.value

✓ **CMB & LSS** → $N_{eff} > 3.046$ (at 98% C.L for ΛCDM + Neff)

WMAP7+ACT+ACBAR+H0+BAO
Hou, Keisler, Knox, et al. 2011

Many models → central value $N_{eff} \sim 4$

Exact numbers depend on the cosmological model and on the combination of data used

Extra radiation VS *lab* ν_s

The mass and mixing parameters preferred by experimental anomalies lead to the production and **thermalization** of ν_s (i.e., $\Delta N = 1, 2$) in the Early Universe via ν_a-ν_s oscillations + ν_a scatterings

Barbieri & Dolgov 1990, 1991
Di Bari, 2002
Melchiorri et al 2009

Problem:

not easy to link the extra radiation with the lab-sterile ν in the simplest scenarios

Indeed:

– 3+2: Too many for BBN (3+1 minimally accepted)

Hamman et al., 2010
Hamman et al., 2011

– 3+1, 3+2: Too heavy for CMB/LSS → $m_s < 0.48$ eV (at 95% C.L)

versus lab best-fit $m_s \sim 1\ eV$

It is possible to find an escape route to reconcile sterile ν's with cosmology?

A possible answer: primordial neutrino asymmetry

Foot and Volkas, 1995

Introducing $L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$ → *Suppress the thermalization of sterile neutrinos (Effective ν_a-ν_s mixing reduced by a large matter term $\propto L$)*

Caveat : L can also generate MSW-like resonant flavor conversions among active and sterile neutrinos enhancing their production

A lot of work has been done in this direction…..

Enqvist et al., 1990, 1991,1992; Foot, Thomson & Volkas, 1995; Bell, Volkas & Wong, 1998; Dolgov, Hansen, Pastor & Semikoz, 1999; Di Bari & Foot, 2000; Di Bari, Lipari and lusignoli , 2000; Kirilova & Chizhov, 2000; Di Bari, Foot, Volkas & Wong, 2001; Dolvgov & Villante, 2003; Abazajian, Bell, Fuller, Wong, 2005; Kishimoto, Fuller, Smith, 2006; Chu & Cirelli, 2006; Abazajian & Agrawal, 2008;

How large should be the value of L in order to have a significant reduction of the sterile neutrino abundance?

In Chu and Cirelli 2006, in a 3 +1 scenario, was found that $\mathbf{L \sim 10^{-4}}$ *is enough*

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WARNING:

- L taken constant during the flavor evolution

- equations of motion solved only for ν

- only a single a-s mixing angle considered

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- only a single a-s mixing angle considered → also the other flavors take part into oscillations

2 recent complementary papers on thermalization of ν_s

Hannestad, Tamborra and Tram, 2012

1+1, "multi-momenta"

Mirizzi, N.S., Miele and Serpico 2012

3+1, 2+1, "average momentum approx."

$$\langle p \rangle = 3.15T$$

Advantages

Hannestad, Tamborra and Tram:

- ✓ possibility to scan a broad range of ν_s mass-mixing parameters

$$\delta m_s^2 \approx [10^{-3}, 10]\, eV^2, \quad \sin^2 2\theta_s \approx [10^{-4}, 10^{-1}]$$

Mirizzi, N.S., Miele and Serpico:

- ✓ realistic account of the ν-ν coupling
- ✓ opportunity to explore several scenarios and effects:
  - different and opposite asymmetries
  - CP violation

Disadvantage

Hannestad, Tamborra and Tram:

- ✗ very simplified scenario: Not possible to incorporate effects due to the mixing of the ν_s with different ν_a

Mirizzi, N.S., Miele and Serpico:

- ✗ multi-momentum features (e.g. distortions of the ν distributions) cannot be revealed

Equations of Motion

- Describe the ν ensemble in terms of 4x4 density matrix $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$
- introduce the dimensionless variables $x \equiv ma,\ y \equiv pa,\ z \equiv T_\gamma a,$ with m = 1 eV,

  a= scale factor, $a(t)\rightarrow 1/T$
- denote the time derivative $d_t = \partial_t - Hp\partial_p = Hx\partial_x$, with H the Hubble parameter
- restrict to an "average momentum" approx. $\langle y \rangle$, based on $\varrho(x,y) \rightarrow f_{FD}(y)\,\rho(x)$

➢ The EoM become

$$i\frac{d\rho}{dx} = \frac{1}{2Hx}\left\langle\frac{1}{y}\right\rangle\left[M^2,\rho\right] - \frac{\sqrt{2}G_F}{Hx}\left[\frac{8\langle y\rangle}{3m_w^2}E_l,\rho\right] + \frac{\sqrt{2}G_F}{Hx}\left[\left(-\frac{8\langle y\rangle}{3m_z^2}E_\nu + N_\nu\right),\rho\right] + \frac{C[\rho]}{Hx}$$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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$$i\frac{d\rho}{dx} = \frac{1}{2Hx}\left\langle\frac{1}{y}\right\rangle\underbrace{[M^2,\rho]}_{\text{Vacuum term}} - \frac{\sqrt{2}G_F}{Hx}\left[\frac{8\langle y\rangle}{3m_w^2}E_l,\rho\right] + \frac{\sqrt{2}G_F}{Hx}\left[\left(-\frac{8\langle y\rangle}{3m_z^2}E_\nu + N_\nu\right),\rho\right] + \frac{C[\rho]}{Hx}$$

Vacuum term
with M neutrino mass matrix
$\mathcal{U}^+ \mathcal{M}^2 \mathcal{U}$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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"symmetric" matter effect
(2th order term)

$$E_l = diag(\varepsilon_e,0,0,0)$$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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ν−ν term
→ non-linear term
given by to the symmetric and asymmetric terms

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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symmetric term

$\propto(\rho+\bar{\rho})$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
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asymmetric term

$\propto (\rho - \bar{\rho}) \to L$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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Collisional term

$\propto G_F^2$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002

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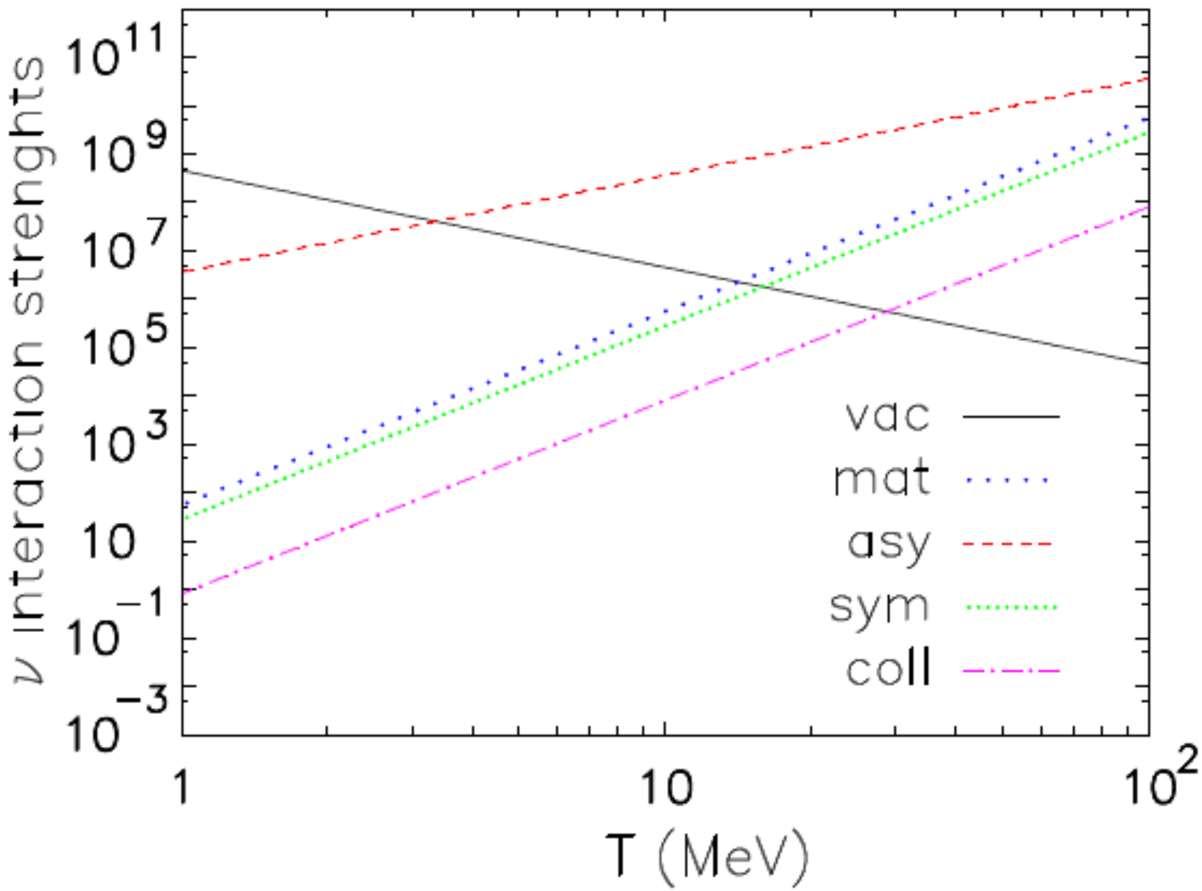
$$i\frac{d\overline{\rho}}{dx} = -\frac{1}{2Hx}\left\langle \frac{1}{y} \right\rangle [M^2,\overline{\rho}] + \frac{\sqrt{2}G_F}{Hx}\left[\frac{8\langle y\rangle}{3m_w^2}E_l,\overline{\rho}\right] + \frac{\sqrt{2}G_F}{Hx}\left[\left(+\frac{8\langle y\rangle}{3m_z^2}E_\nu + N_\nu\right),\overline{\rho}\right] + \frac{C[\overline{\rho}]}{Hx}$$

Strength of the different interactions



Mirizzi, N.S., Miele, Serpico 2012

$L = -10^{-4}$

kept constant

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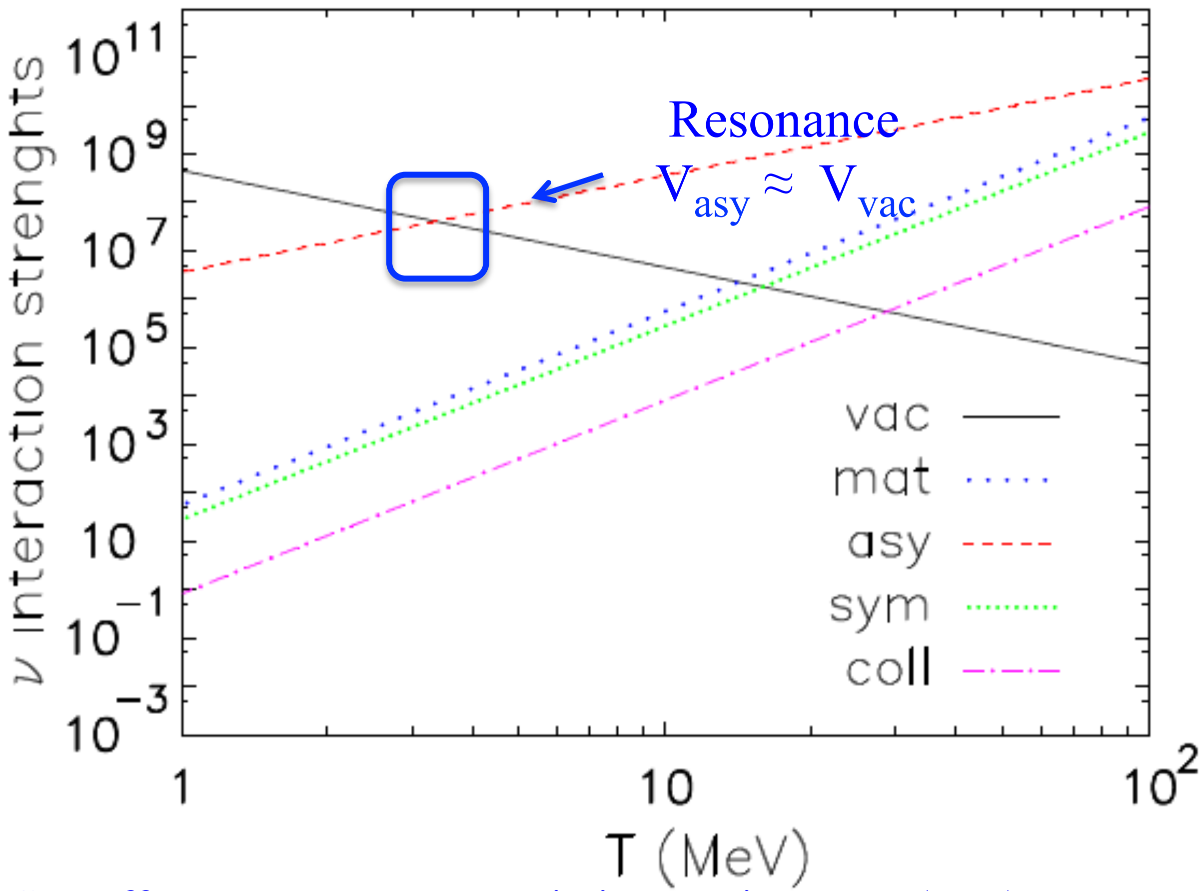

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kept constant

MSW effect on ν-ν asymmetric interaction term (V_{asy})

- For L < 0 → resonance occurs in the anti– ν channel
- For L > 0 → resonance occurs in the ν channel

Best-fit parameters in the active and sterile sectors

Global 3 ν oscillation analysis, in terms of best-fit values

Parameter	Best fit
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92
δ/π (NH)	1.08
δ/π (IH)	1.09

Fogli et al., 2012

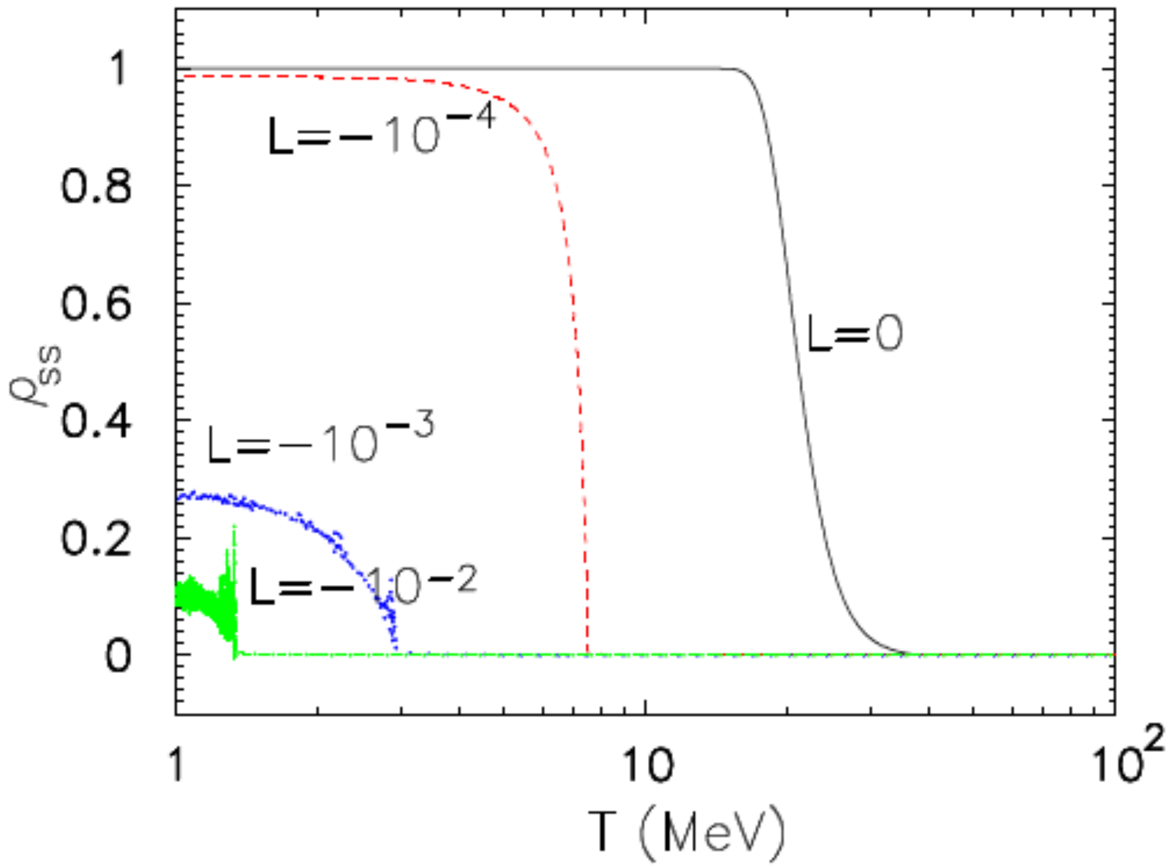
Best-fit values of the mixing parameters in 3+1 fits of short-baseline oscillation data.

	3+1
$\chi^2_{\rm min}$	100.2
NDF	104
GoF	59%
Δm^2_{41} [eV^2]	0.89
$\lvert U_{e4}\rvert^2$	0.025
$\lvert U_{\mu 4}\rvert^2$	0.023
Δm^2_{51} [eV^2]	
$\lvert U_{e5}\rvert^2$	
$\lvert U_{\mu 5}\rvert^2$	
η	
$\Delta\chi^2_{\rm PG}$	24.1
NDF$_{\rm PG}$	2
PGoF	6×10^{-6}

Giunti and Laveder, 2011

3 + 1 Scenario

Mirizzi, N.S., Miele, Serpico 2012



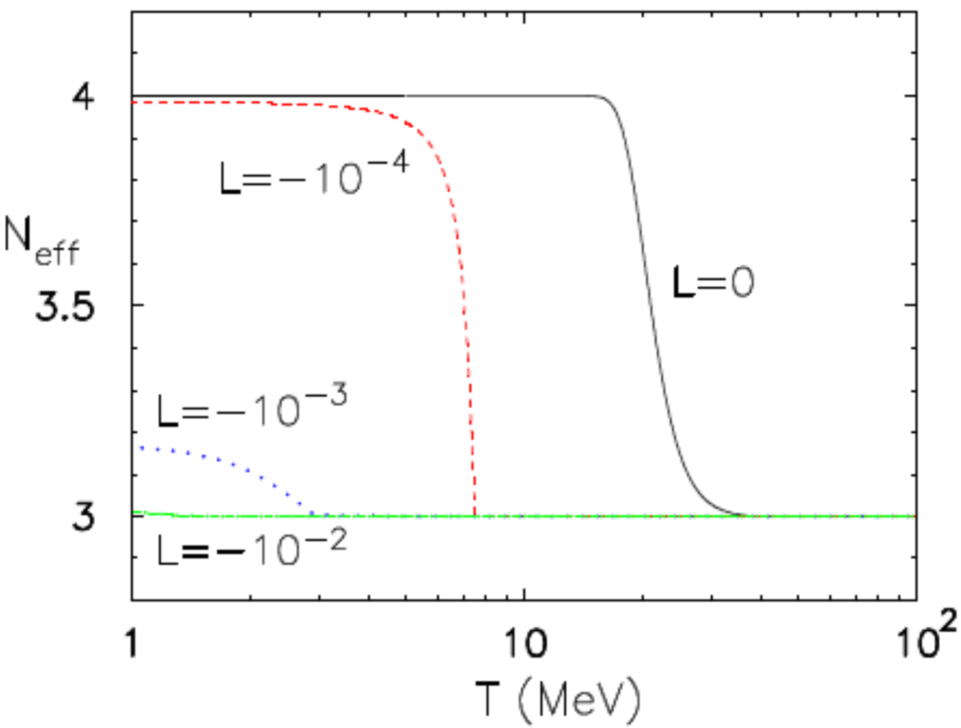
- L = 0 → ν_s copiously produced at T ≤ 30MeV (not resonantly)
- L≠ 0 → ν_s are produced "resonantly" when $V_{asy} \approx V_{vac}$

Increasing L, the position of the resonance shifts towards lower T → less adiabatic resonance → ν_s production less efficient (Adiabaticity parameter scales as T)

Di Bari and Foot 2002

Consequences on N_{eff}

Mirizzi, N.S., Miele, Serpico 2012



- $|L| \leq 10^{-4}$, ν_s fully populated and the ν_a repopulated by collisions → $N_{eff} \sim 4$
  → tension with cosmological mass bounds (and with BBN data)
- $|L| = 10^{-3}$, ν_s produced close to ν-decoupling ($T_d \sim$2-3 MeV) where ν_a less repopulated → effect on N_{eff} less prominent.
  If $\Delta N_{eff} > 0.2$ it will be detected by Planck (public data release expected early 2013).
- $L > 10^{-2}$, no repopulation of ν_a
  →negligible effect on N_{eff} even if ν_s slightly produced.
  Possible future extra-radiation should be explained by some other physics (hidden photons, sub-eV thermal axions etc.?)

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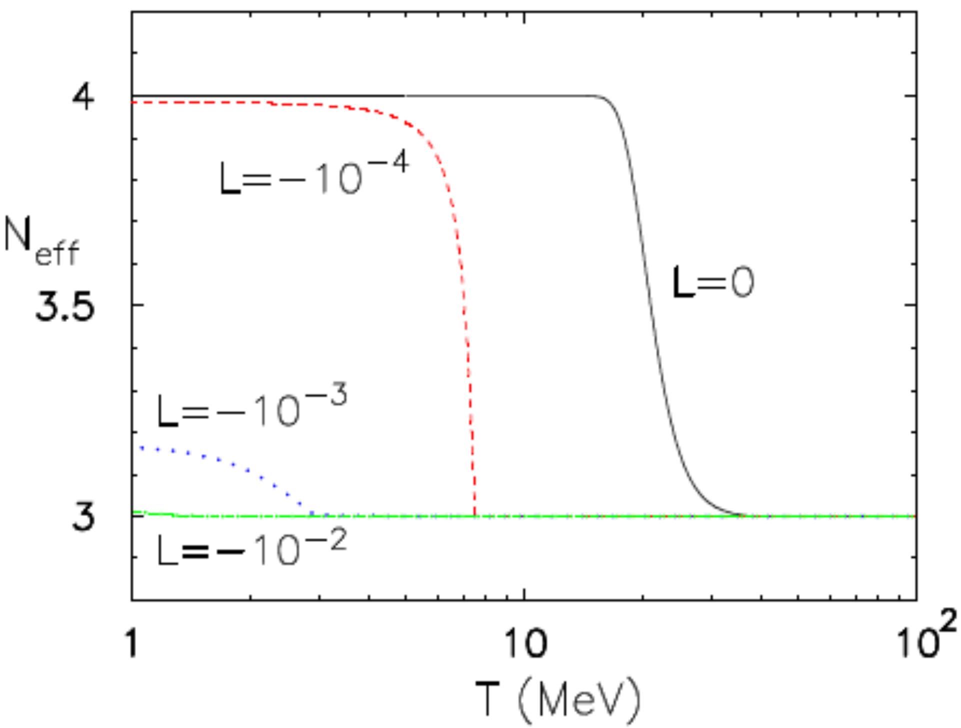
Mirizzi, N.S., Miele, Serpico 2012



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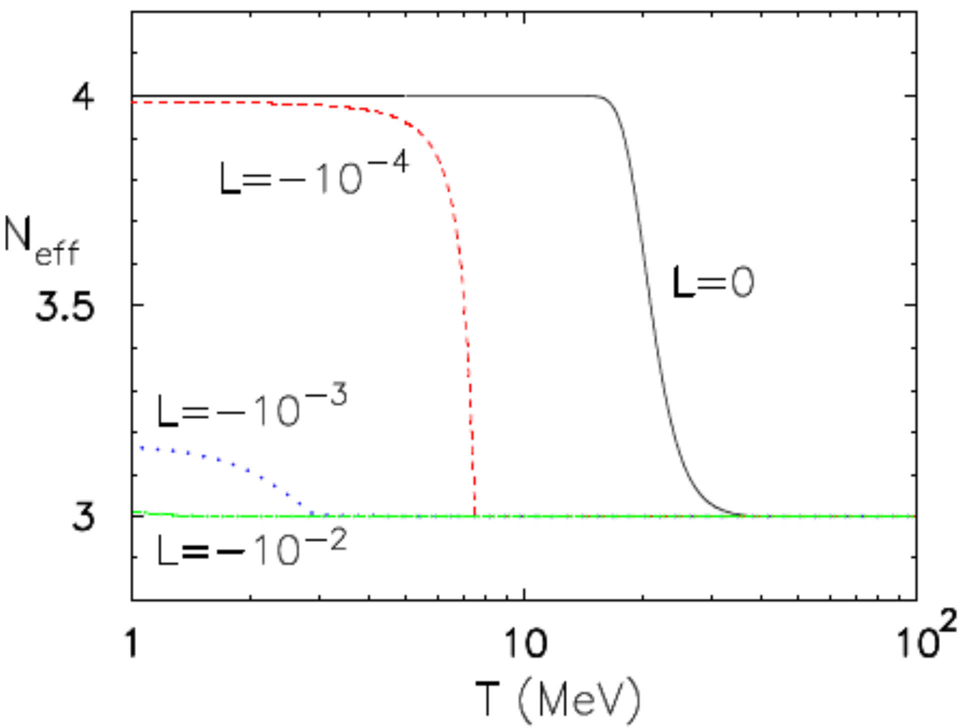
Attention:

The lack of repopulation of ν_e would produce distorted distributions, which can anticipate the n/p freeze-out and hence increase the ^4He yield → Possible impact on the BBN (Multi-momentum treatment necessary!)

Qualitative estimate of the effects on BBN

Mirizzi, N.S., Miele, Serpico 2012



$$T_F \propto \left(\frac{\sqrt{22/7 + N_{\rm eff}}}{1+\rho_{ee}} \right)^{1/3}$$

↓

$$\frac{\delta Y_p}{Y_p} = 0.044\, \delta N_{\rm eff} - 0.27\, \delta \rho_{ee}$$

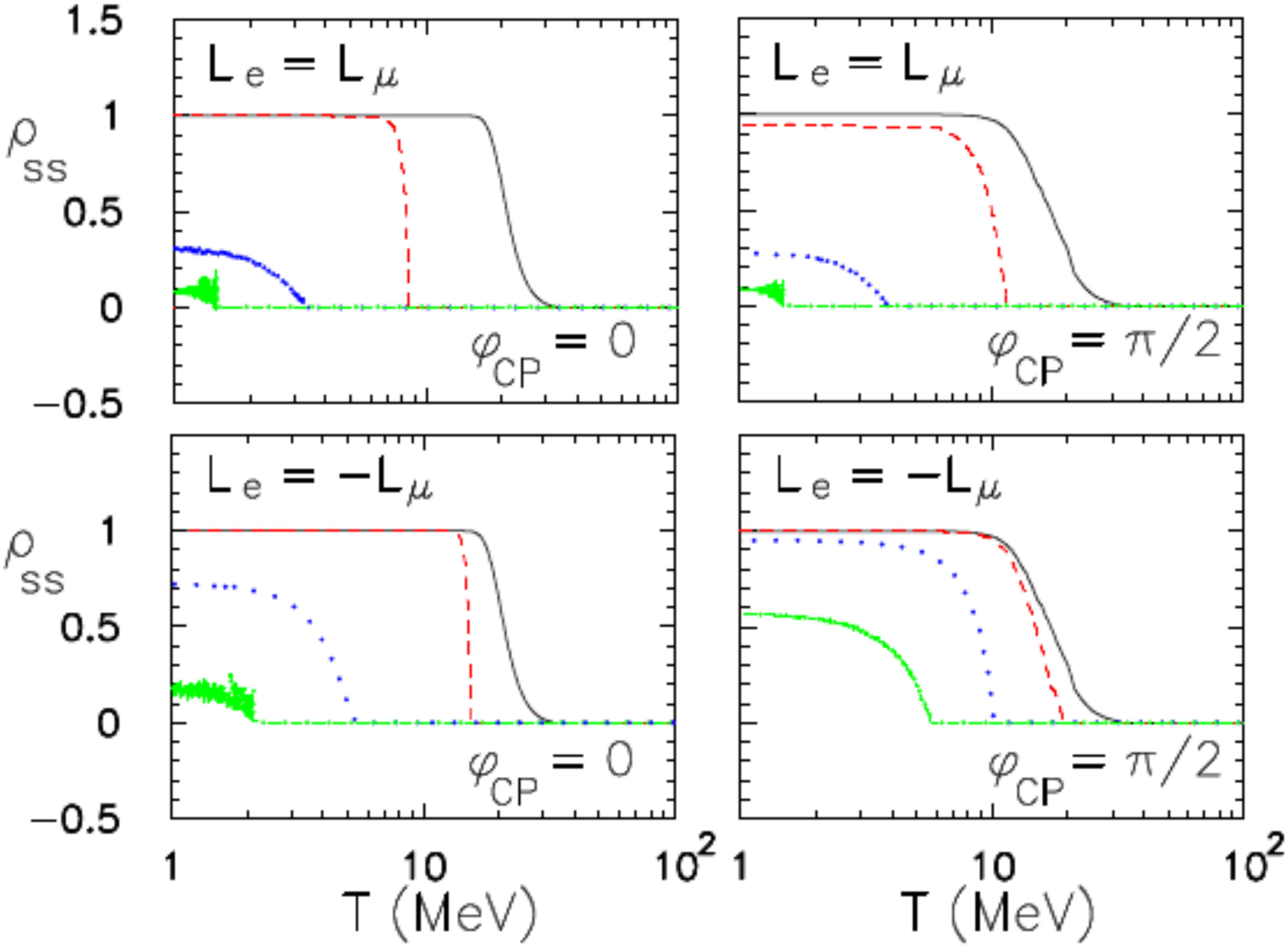
Dolgov and Villante, 2002

- L=0 : δN_{eff} =1 and $\delta\rho_{ee}$= 0 → variation in ^{4}He of ~ 4% *barely allowed*
- L=|10|$^{-2}$: δN_{eff} ~ 0 and $\delta\rho_{ee}$= -5% → variation in ^{4}He of ~ 1%
- L=|10|$^{-3}$: δN_{eff} ~ 1% and $\delta\rho_{ee}$ ~ 1% → variation in ^{4}He of ~ 2%

} Large effects on BBN

2 + 1 Scenario

Mirizzi, N.S., Miele, Serpico 2012



L = 0

L = -10^{-4}

L = -10^{-3}

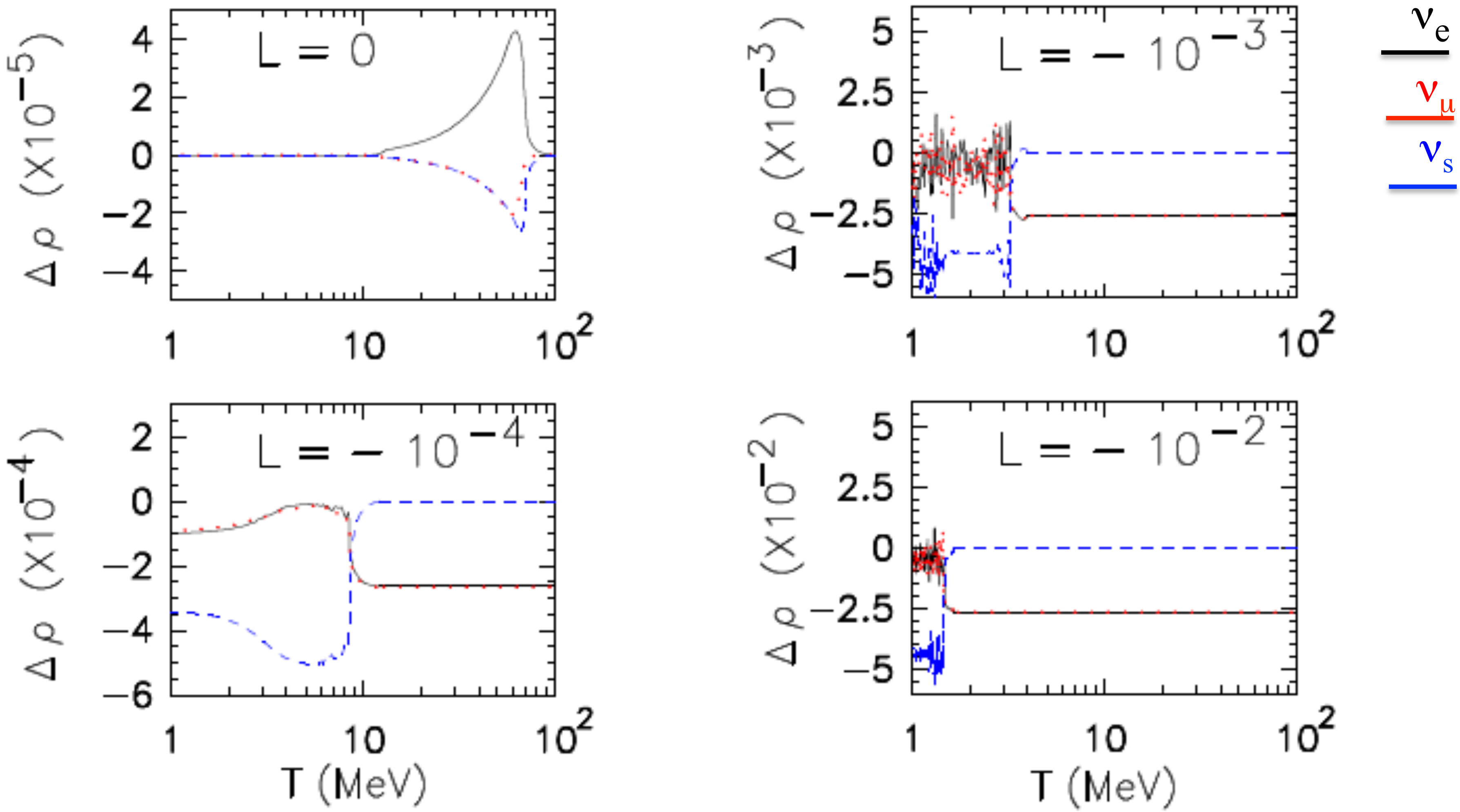
L = -10^{-2}

L~10^{-3} conservative limit → Suppression crucially depends on the scenario considered

Neutrino asymmetry evolution

(2+1) with $L=L_e=L_\mu$ and $\phi_{cp} = 0$ $\Delta\rho \propto L$

Mirizzi, N.S., Miele, Serpico 2012



Conclusions

- ✓ Current precision cosmological data show a preference for extra relativistic degrees of freedom (beyond 3 active neutrinos).

- ✓ ν_s interpretation of lab neutrino anomalies does not quite fit into the simplest picture. Necessary to suppress the sterile neutrino production in the Early Universe.

- ✓ A possibility to reconcile cosmological and laboratory data would be the introduction of a neutrino asymmetry.

- ✓ Solving the non-linear EOM for ν_a-ν_s oscillations in a 3+1 scenario, we find that $L > 10^{-3}$ necessary to suppress the sterile neutrino production. (Suppression crucially depends on the scenario considered).

- ✓ However, $L > 10^{-3}$ could leave a significant imprint on BBN trough the depletion of ν_e and $\overline{\nu}_e$ (multi-momentum treatment of the EOM necessary)

Conclusions

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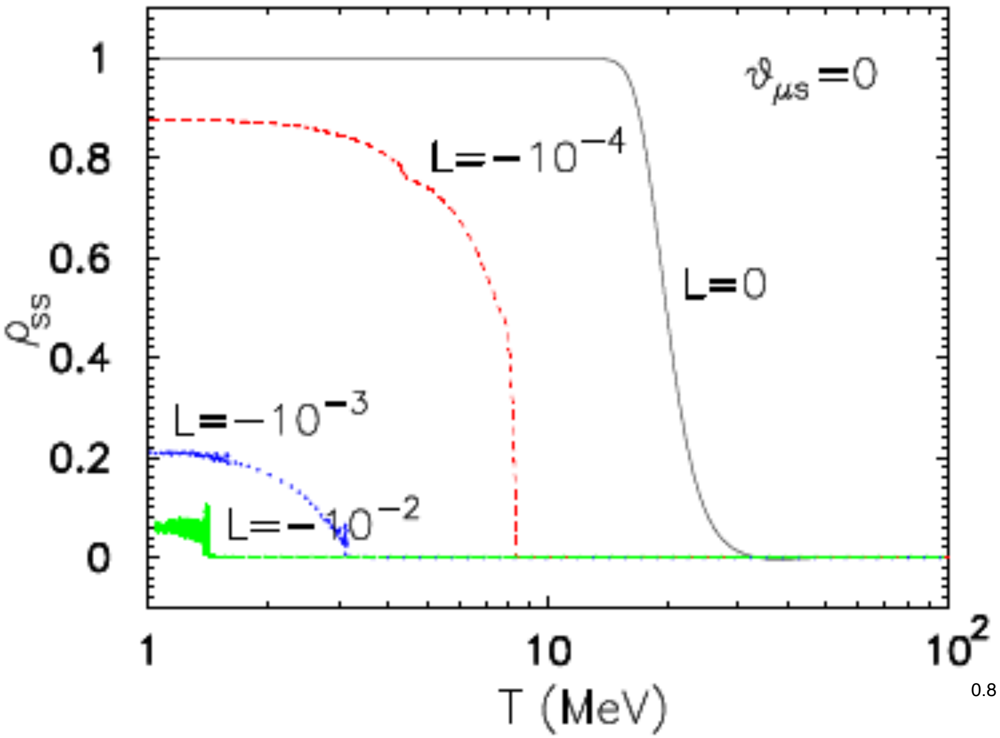
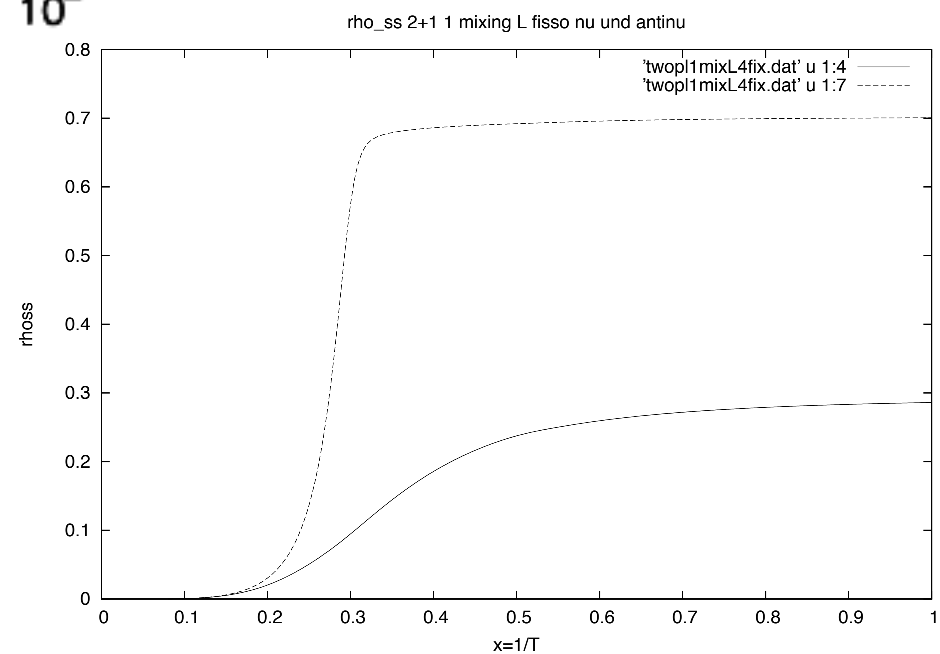
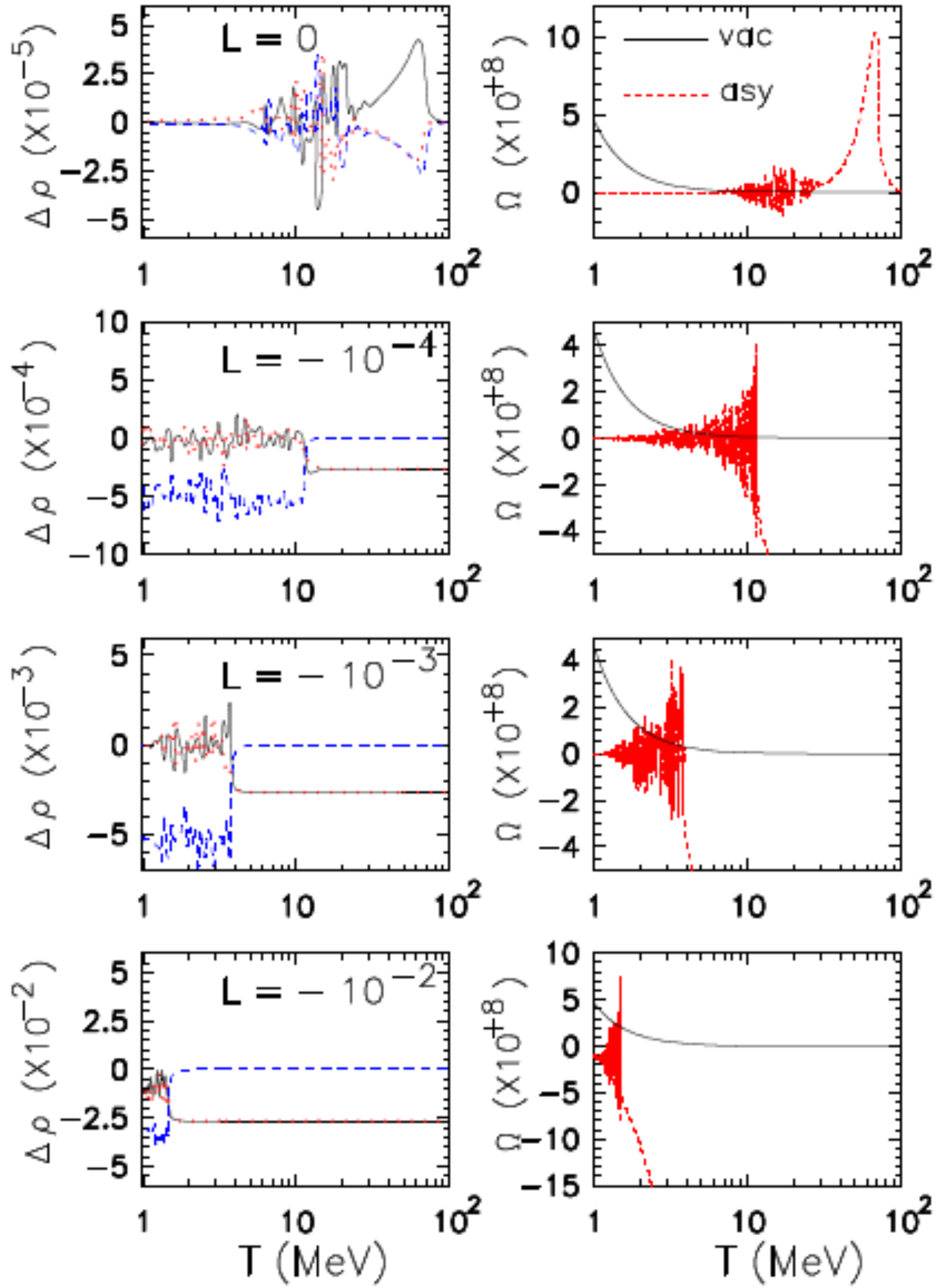
Not too easy to mask sterile neutrinos in cosmology!

Thank you



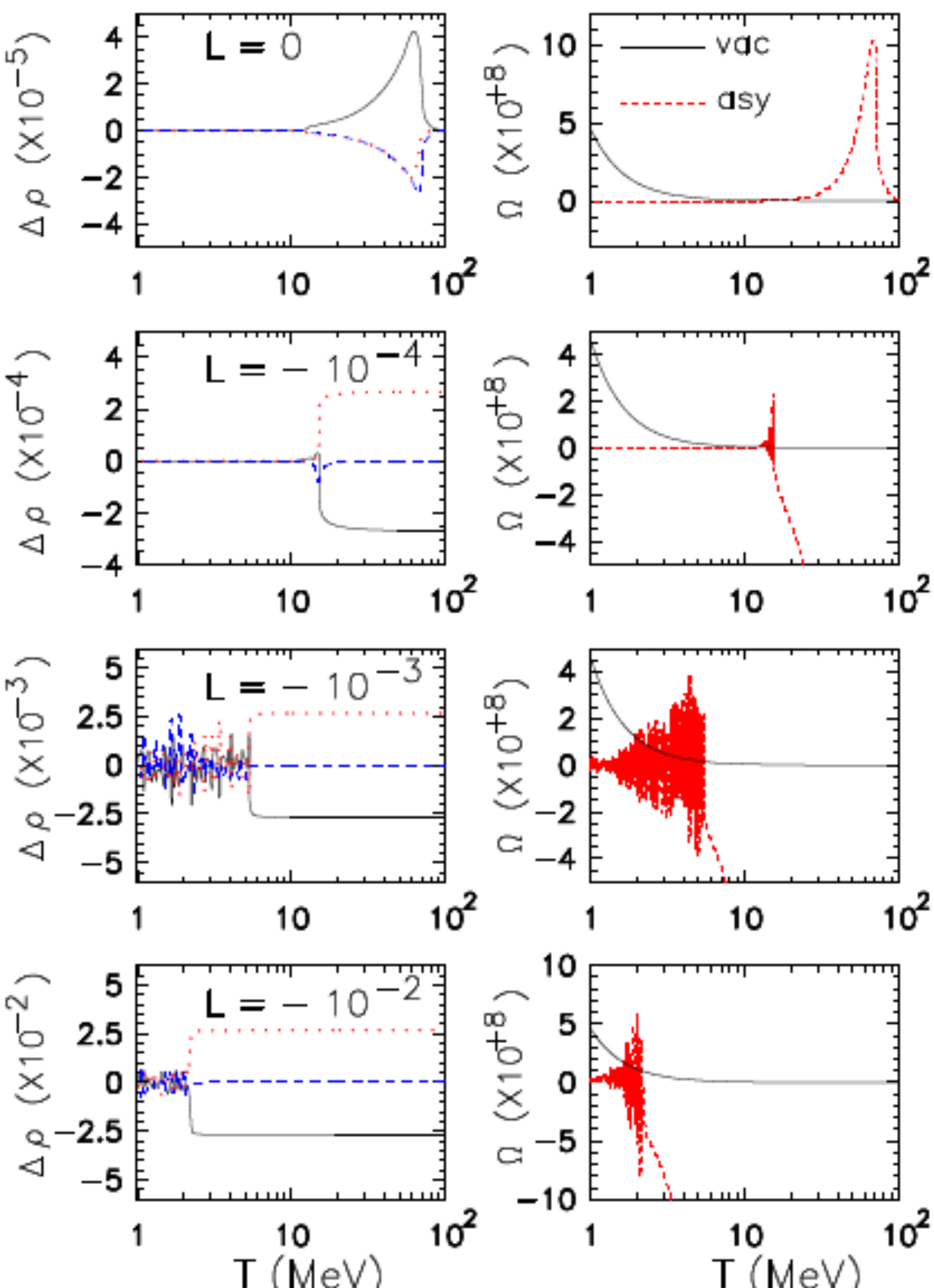
$\vartheta_{\mu s}=0$





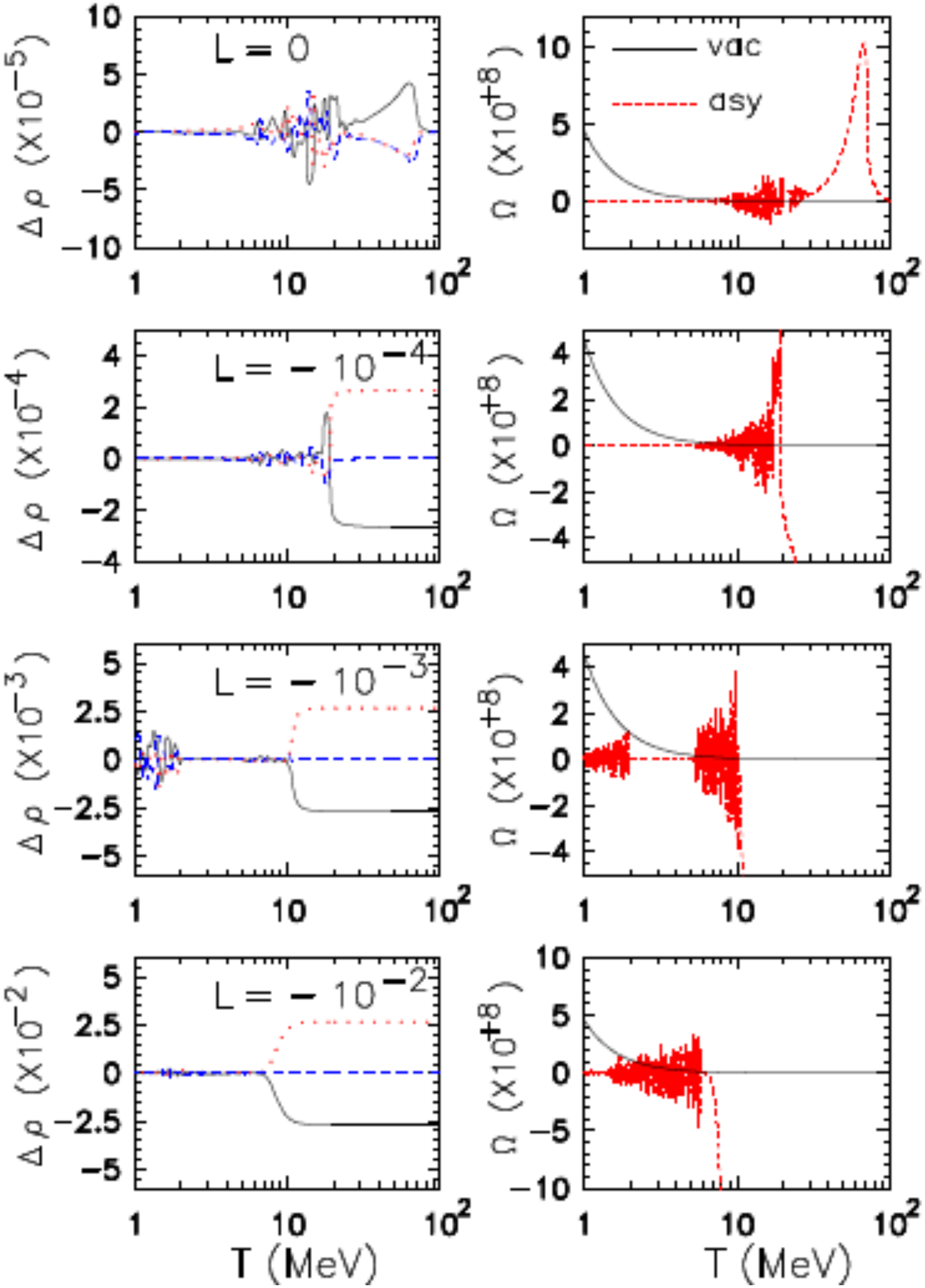
(2+1) case with $L = L_e = L_\mu$

$$\varphi_{\rm CP} = \pi/2$$



(2+1) case with $L = L_e = -L_\mu$

and $\varphi_{\rm CP} = 0$



$(2{+}1)$ case with $L = L_e = -L_\mu$

$\varphi_{\rm CP} = \pi/2$