Non-standard Neutrinos

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@

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Non-standard Neutrinos

Non-Standard Interactions

Decoherence

Magnetic Moment

Neutrino decay, Mass-varying neutrinos, Lorentz-violation / Violation of Equivalence Principle, Stochastic neutrinos...

Non-standardness in Cosmology

Non-Standard Interactions (NSI)

Generic Parameterization – dimensional six operator with new heavy mediator (in comparison with typical momentum transfer)

Charged Current (CC): $$(\bar{\nu}_\alpha \gamma_\mu P_L l_\beta)(\bar{f}\,'\gamma^\mu P f)$$

- stringently constrained by scattering cross-sections

Neutral Current (NC): $$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f}\gamma^\mu P f)$$

- weakly constrained by scattering cross-sections
- effcts on forward-coherent scattering

Non-Standard Interactions (NSI)

Lagrangian:

$$L = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

Interaction strenght in comparison with Weak Interaction

Non-Standard Interactions (NSI)

- *Only vector (L+R) interactions contribute to flavour oscillation*

$$\sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta}(\ldots) = \sum_{f,\alpha,\beta} \epsilon^{f}_{\alpha\beta}(\ldots) \quad ; \quad \epsilon^{f}_{\alpha\beta} = \epsilon^{f,L}_{\alpha\beta} + \epsilon^{f,R}_{\alpha\beta}$$

- *Assumption that neutrino flavour structure is independent from fermion involved in interaction*

$$\sum_{f,\alpha,\beta} \epsilon^{f}_{\alpha\beta}(\ldots) = \sum_{f,\alpha,\beta} \eta^f \epsilon_{\alpha\beta}(\ldots)$$

- *Ordinary matter composed by u and d quarks (ok, and elétrons).*

$$\sum_{f,\alpha,\beta} \eta^f \epsilon_{\alpha\beta}(\ldots) = \sum_{\alpha,\beta}(\xi^d + \xi^u)\epsilon_{\alpha\beta} N_e(\ldots)$$

Non-Standard Interactions (NSI)

Possible parameterization (Esteban et al., 1805.044530):

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta)$$

$$\xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)$$

$$(\xi^d + \xi^u)\epsilon_{\alpha\beta}(\ldots) = \epsilon^{\eta}_{\alpha\beta}$$

$$0.5 < \tan\eta < 2$$

Both ϵ^u and ϵ^d positive

Non-Standard Interactions (NSI)

Hamiltonian:

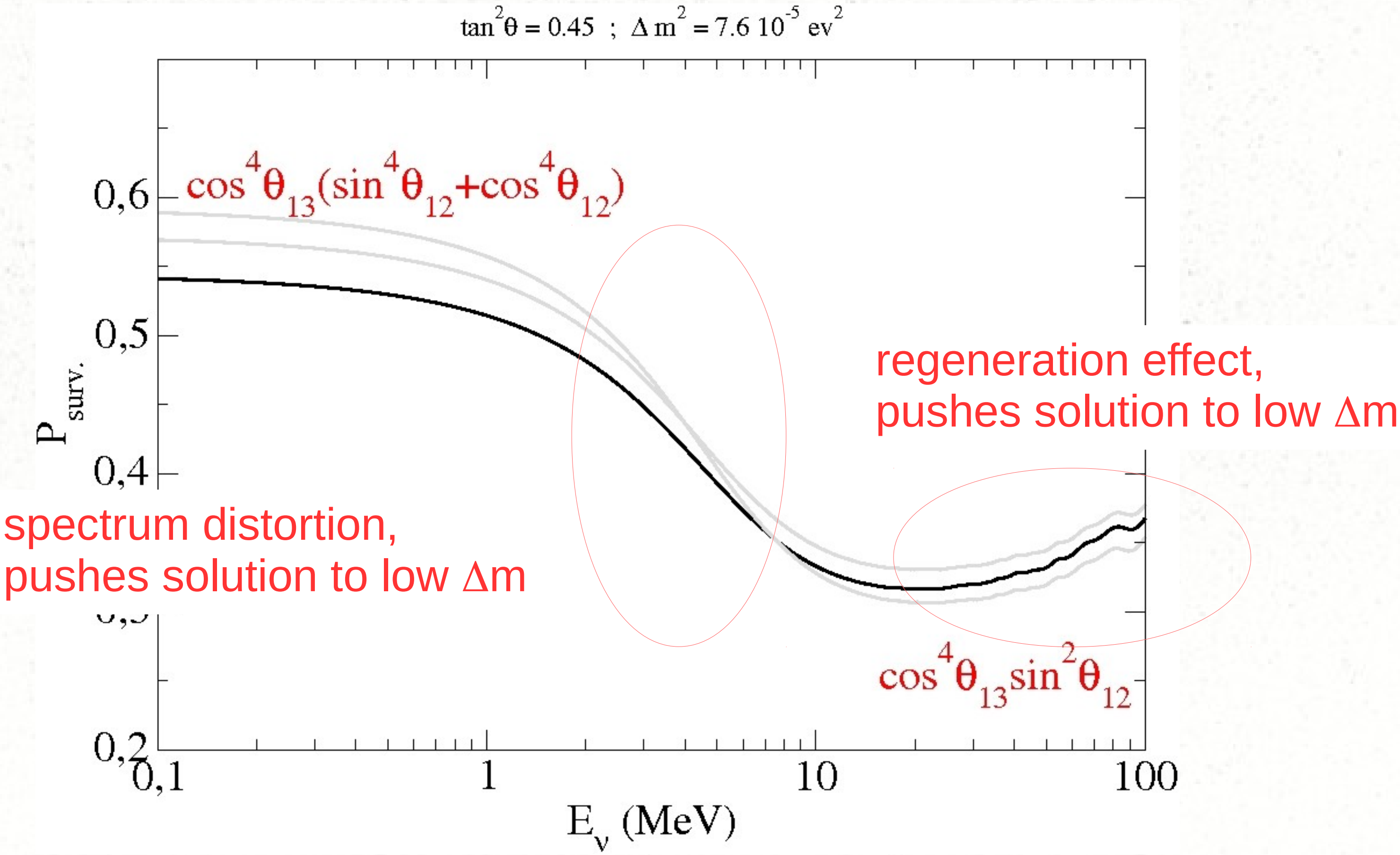
standard interaction

$$H = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

NSI, also has a *x* depence through matter density and composition
(η dependence suppressed)

Non-Standard Interactions (NSI)

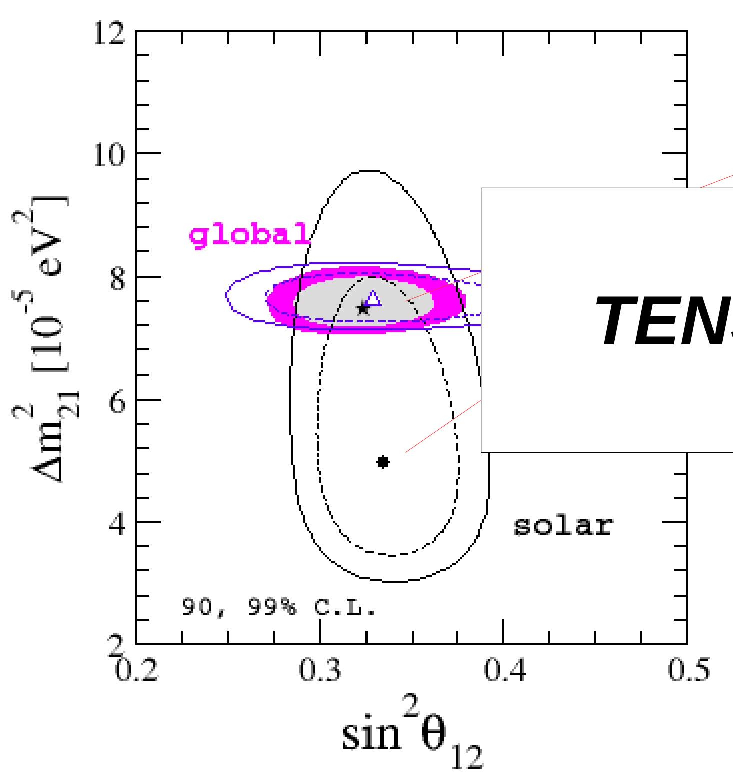
Solar Neutrinos:



Non-Standard Interactions (NSI)

Solar Neutrinos:

http://globalfit.astroparticles.es



TENSION

"***tension***" between solar and KamLAND bfp.

tatistical Flutuation?

lew physics that lower
mLAND region?

• New physics that raise solar bfp?

Non-Standard Interactions (NSI)

You're are not suppose to name it.
Once you name it, you start
getting attached to it!

Non-Standard Interactions (NSI)

Solar Neutrinos:

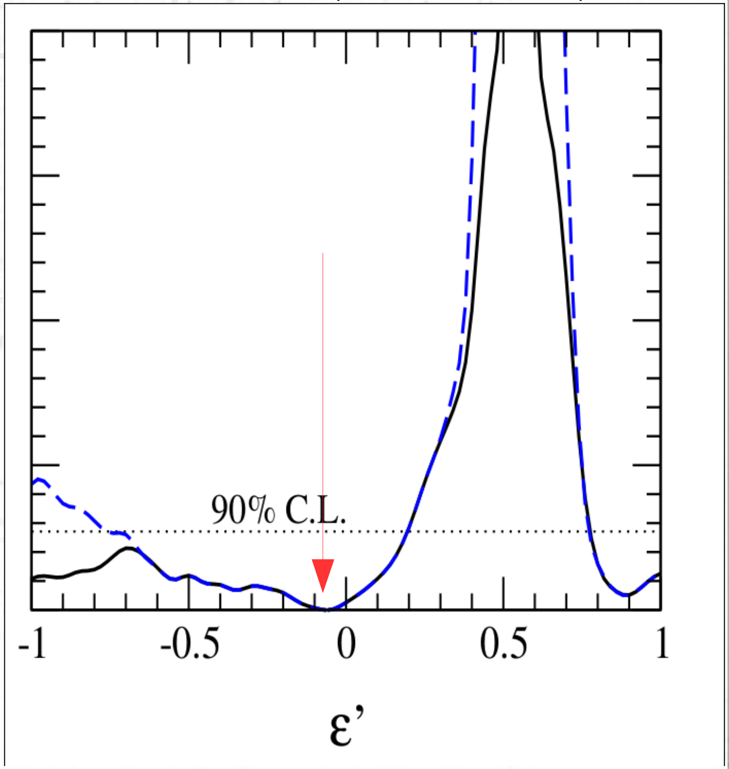
- ***New physics that raises solar bfp?***
  - ***increase interactions through NSI***

In 2 families, only d-quarks:

$$H_{NSI} = \sqrt{2} G_F N_d \begin{pmatrix} 0 & \epsilon \\ \epsilon & \epsilon' \end{pmatrix}$$

negative values would enhance matter effects

O. G. Miranda et al., JHEP 0610:008,2006

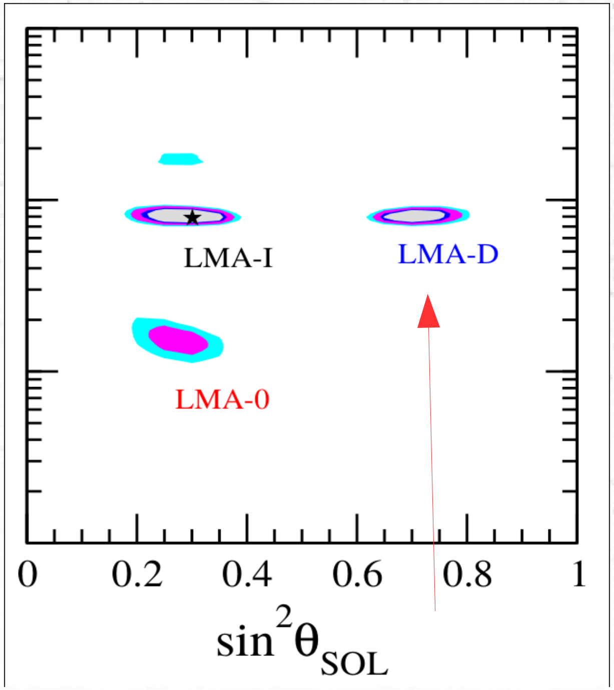


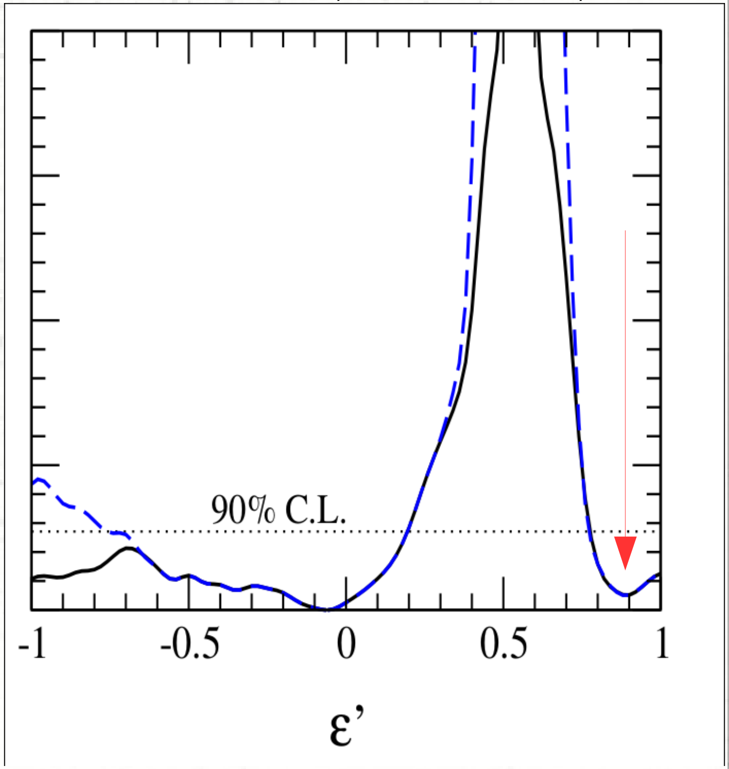
Non-Standard Interactions (NSI)

Other interesting features:

- ***New allowed regions for large positive NSI and "inverted hierarchy" (not that one!)***

O. G. Miranda et al., JHEP 0610:008,2006





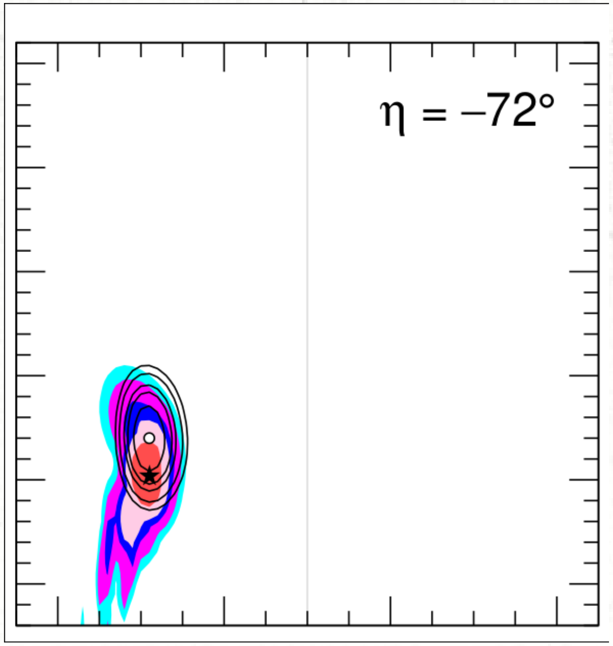
Non-Standard Interactions (NSI)

Other interesting features:

- ***Possible cancelation of NSI inside the Sun with negative ε^d and positive ε^u, and no constraints with solar data***

- ***Large NSI effects in KamLAND, lower Δm region***

Esteban et al, 1805.4530



however...

Non-Standard Interactions (NSI)

Atmospheric and long-baseline Neutrinos:

$$\epsilon_{\alpha\beta}^{\oplus} = (2 + Y_n^{\oplus})\epsilon_{\alpha\beta}^{\mu} + (1 + 2Y_n^{\oplus})\epsilon_{\alpha\beta}^{d} = \epsilon_{\alpha\beta}^{\eta}(\xi^p + Y_n^{\oplus}\xi^n)$$

protons neutrons effective coupling

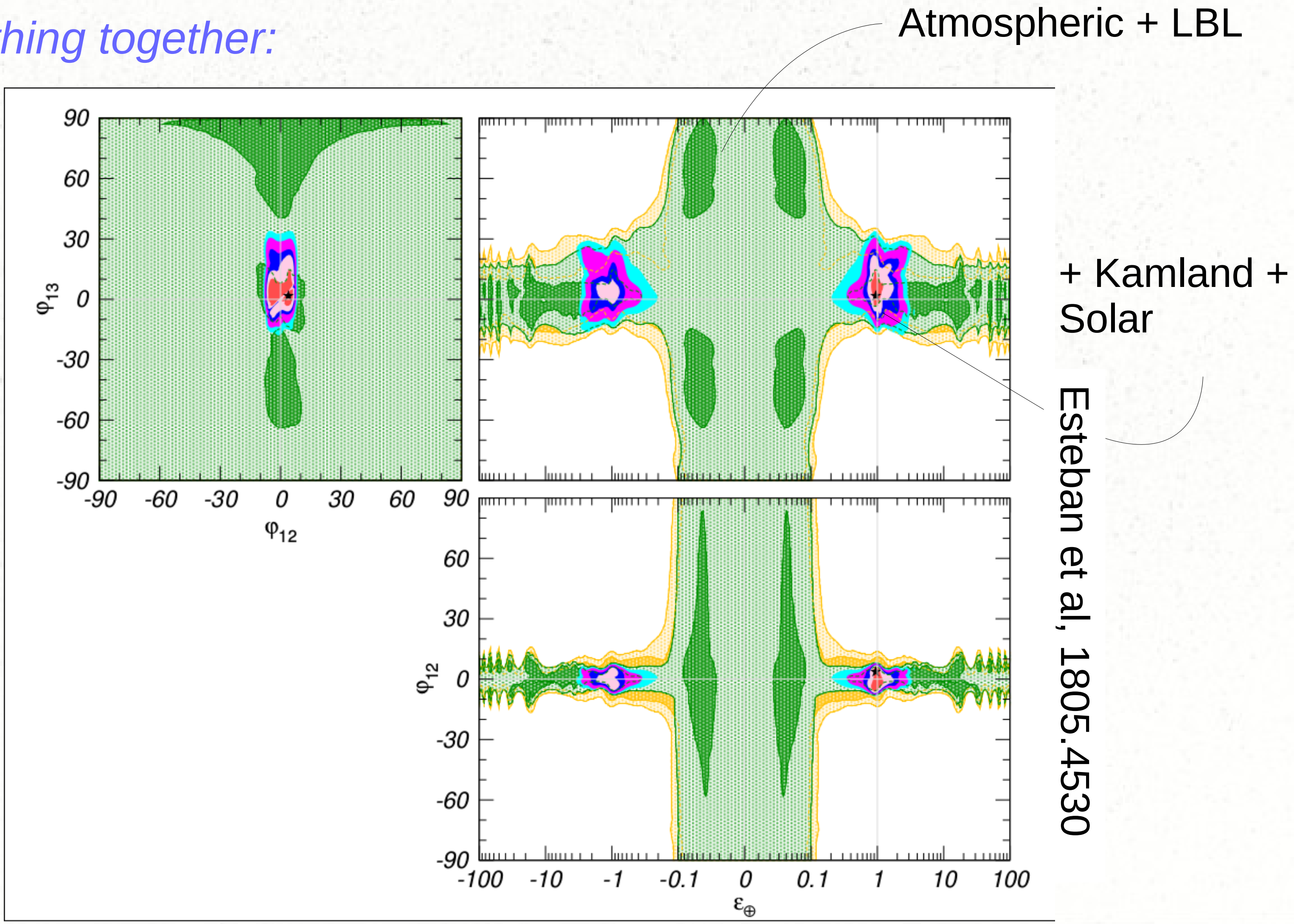
- virtually constant in Earth's Mantle, some mild variation for atmospheric neutrinos.
- possible cancelations depending on d-quarks and u-quarks interactions
- several different parameterizations. For instance:

$$H_{\text{mat}} = Q_{\text{rel}} U_{\text{mat}} D_{\text{mat}} U_{\text{mat}}^{\dagger} Q_{\text{rel}}^{\dagger} \quad \text{with} \quad \begin{cases} Q_{\text{rel}} = \operatorname{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i\alpha_1 - i\alpha_2}\right), \\ U_{\text{mat}} = R_{12}(\varphi_{12}) R_{13}(\varphi_{13}) \tilde{R}_{23}(\varphi_{23}, \delta_{\text{NS}}), \\ D_{\text{mat}} = \sqrt{2} G_F N_e(x) \operatorname{diag}(\varepsilon_{\oplus}, \varepsilon'_{\oplus}, 0) \end{cases}$$

Esteban et al, 1805.4530

Non-Standard Interactions (NSI)

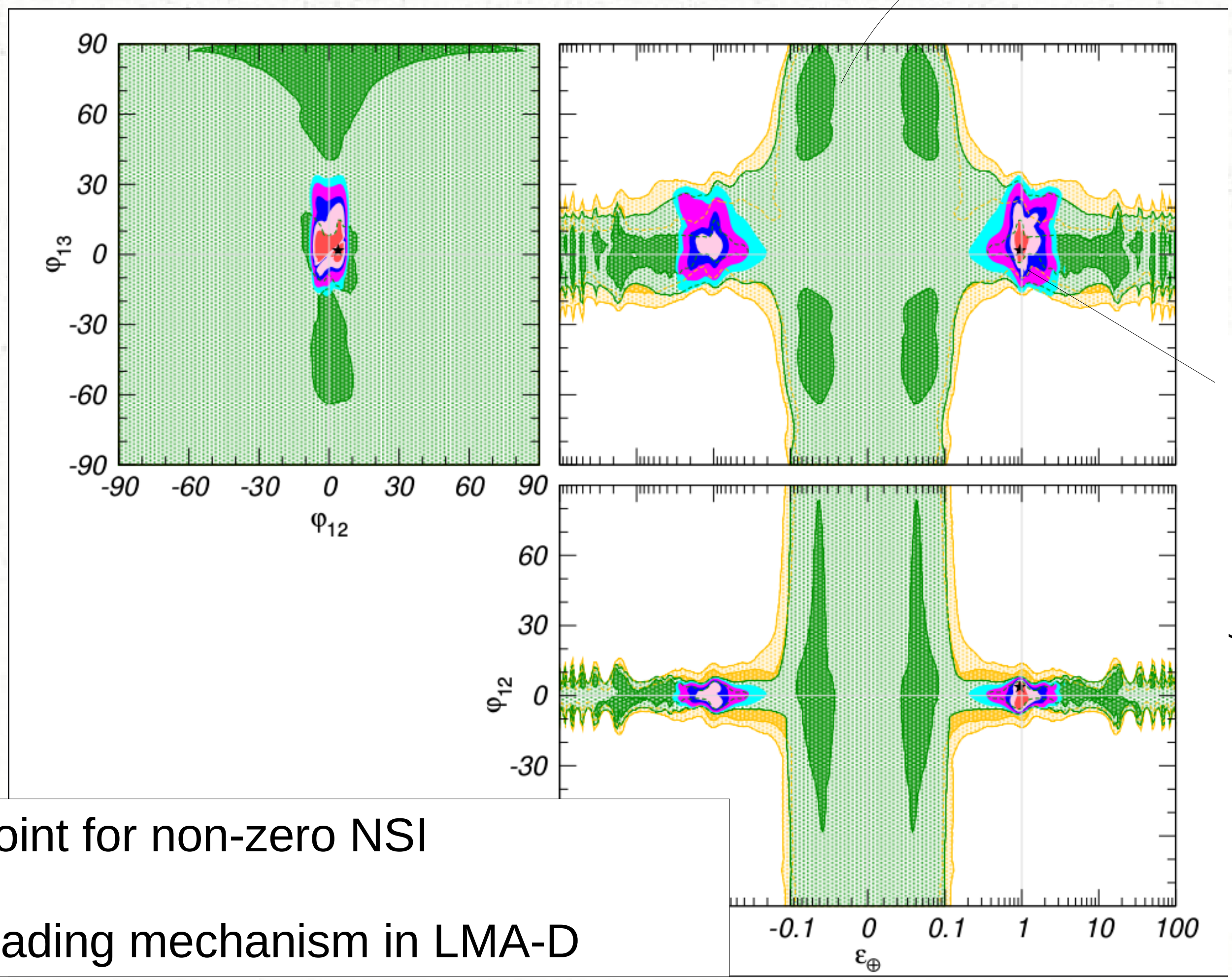
Everything together:



Non-Standard Interactions (NSI)

Everything together:

Atmospheric + LBL



+ Kamland + Solar

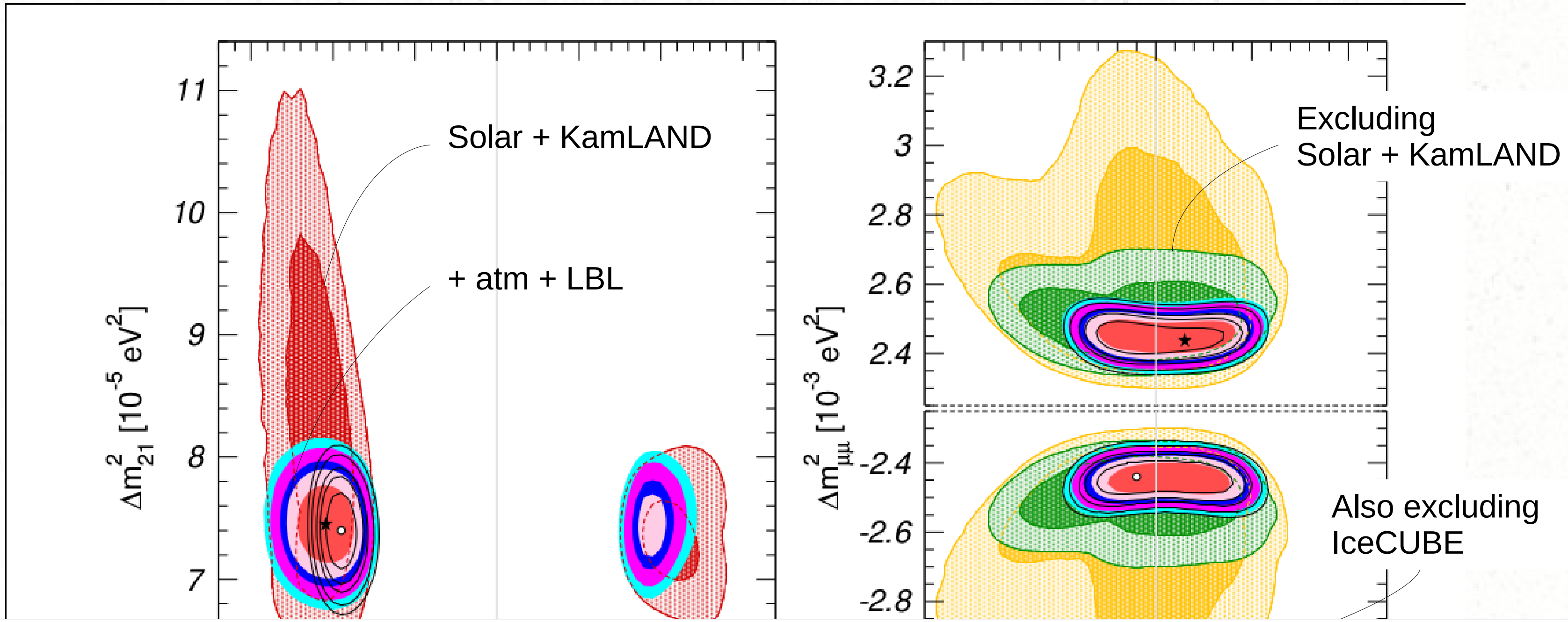
Esteban et al, 1805.4530

- Best fit point for non-zero NSI

- NSI as leading mechanism in LMA-D

Non-Standard Interactions (NSI)

Everything together, in usual oscillation parameters:



- good determination of usual parameters, but only with different data sets combined
- one exception: LMA-D still there!
- at the end, NSI does not help to solve KamLAND x solar neutrinos tension

Non-Standard Interactions (NSI)

What now?

DUNE Exercise: Considering the disappearance channel at Dune (well described by a 2-families probability), estimate its sensitivity to non-standard interactons by the effects on mixing angle and squared mass differences.

- *Look for the DUNE's precision in stablishing the values of Δm^2 and θ_{23}*

- *Analyse the effects of ε's on effective Δm^2 and θ_{23}*

- *Estimate the limits obtainable on ε's.*

Other non-standard scenarios

Dissipation: *non-standard interaction with non-standard environment, using Open System framework.*

$$\frac{d}{dt}\rho(t) = -i[H,\rho] + D(\rho)$$

Liouville equation

Non-standard decoherence effects

If no energy exchange between environment and neutrinos **DECOHERENCE**

With energy exchange between environment and neutrinos **RELAXATION**

Other non-standard scenarios

Decoherence:

Energy conservation

$$D(\rho) = \frac{1}{2}\sum_{k}^{N^2-1}\left([V_k, \rho V_k^\dagger] + [V_k\rho, V_k^\dagger]\right) \quad ; \quad [H, V_k] = 0$$

In 2 families, simplest case: $V_k = \sqrt{\gamma}\sigma_3$

Pauli matrix

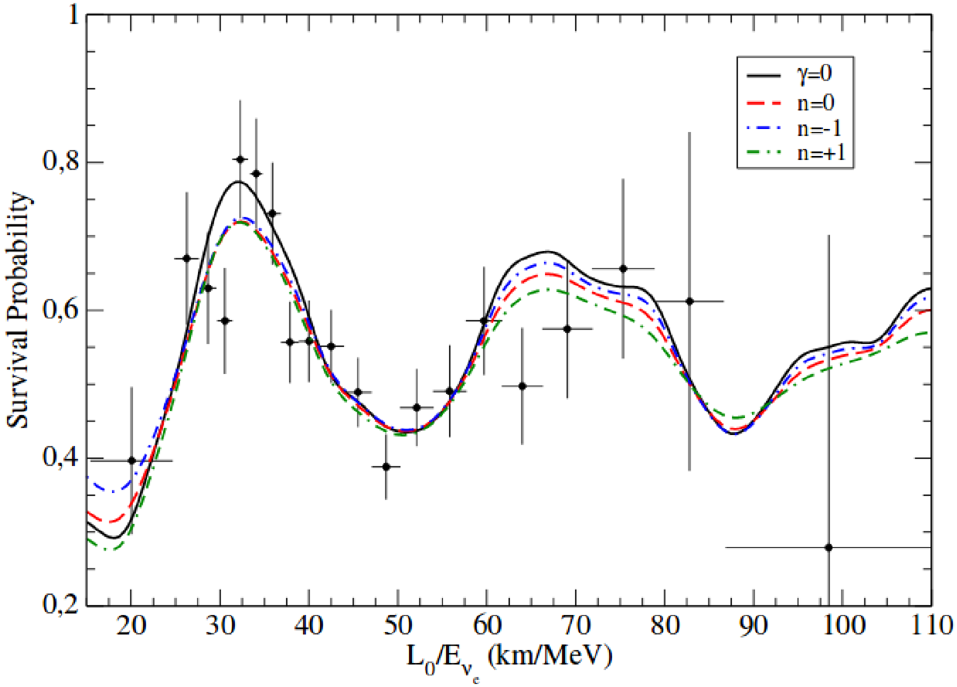
$$P_{\nu_a\nu_a} = 1 - \frac{1}{2}\sin^2(2\theta)\left[1 - e^{-\gamma x}\cos\left(\frac{\Delta m^2}{2E}x\right)\right]$$

- suppresses interference terms in neutrino conversion
- does not induce mass eigenstates conversion.

Other non-standard scenarios

Decoherence:

- Kamland



Balieiro et al, PRD 95 (2017) 113005

- small improvement on fit to data
- stringent limits to large decoherence effects

Other non-standard scenarios

Decoherence + Relaxation:

$$P_{\nu_a \nu_a} = \frac{1}{2}\left[1 + e^{-\Gamma_2 x}\cos^2 2\theta + e^{-\Gamma_1 x}\sin^2 2\theta \cos\left(\frac{\Delta m^2}{2E}x\right)\right]$$

- induces equipartition between neutrino flavours

- stringent limits should come from largest distances

Other non-standard scenarios

Magnetic moment:

- changes both neutrino cross-sections.

$$\frac{d\sigma_{\rm EM}}{dT_e}(T_e, E_\nu) = \pi r_0^2 \mu_{\rm eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

- and neutrino flavour conversions.

$$< \bar{\nu}|\nu > \propto \mu B$$

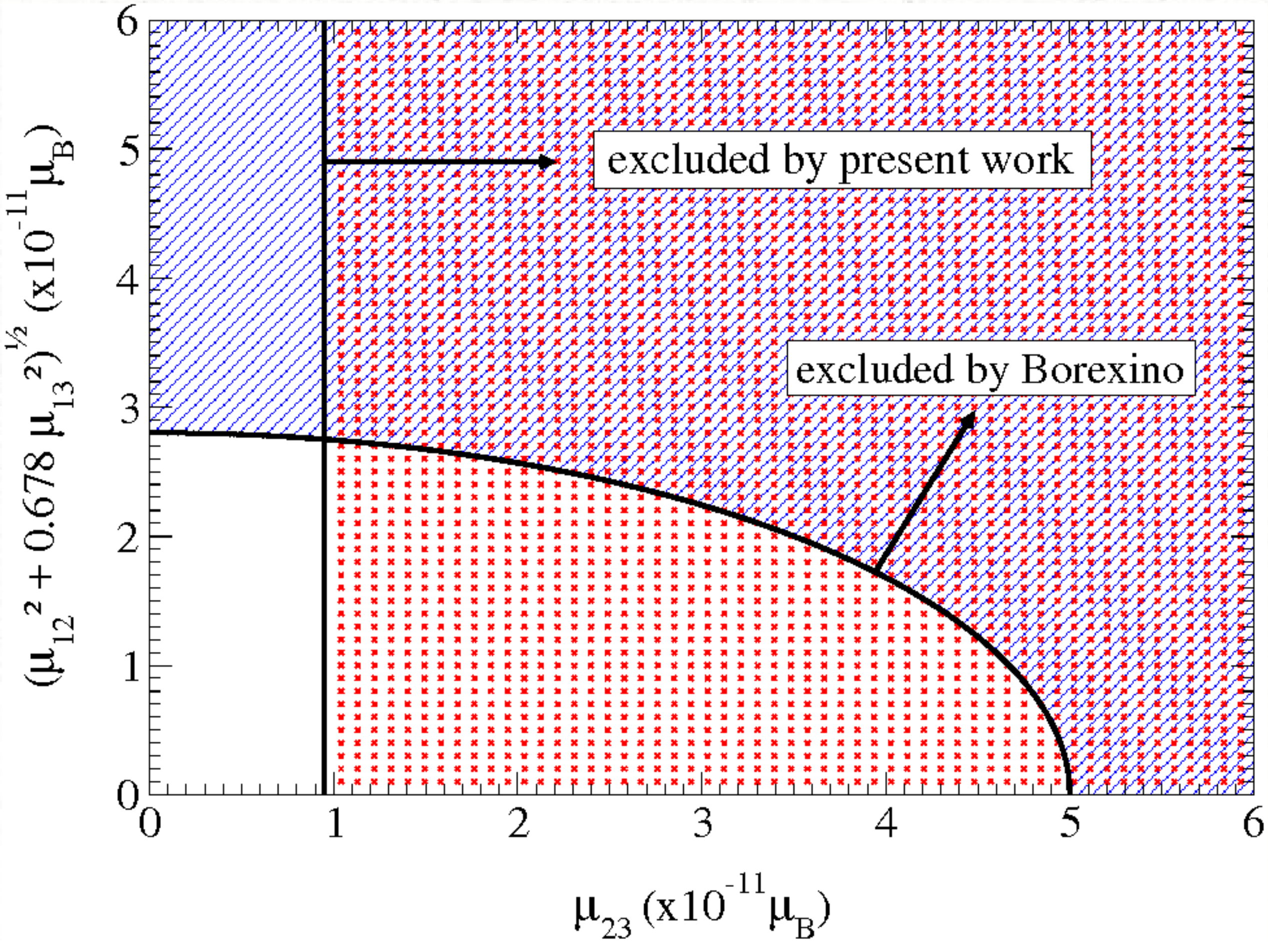
- could probe magnetic fields in astrophysical objects.

- strongly constrained by absence of electron anti-neutrinos in solar neutrino flux

Other non-standard scenarios

Magnetic moment:

Guzzo et al, PRD



Other non-standard scenarios

Neutrino decay

Mass-varying neutrinos

Lorentz-violation / Violation of Equivalence Principle

Stochastic neutrinos

Each mechanism has distintincts signatures in neutrino data.

So far standard oscillation mechanism is robust, and only
limits are obtained on non-standard physics.

No clear signature or necessity for non-standard mechanism so far (*).

(*) Reactor Anomaly?
Sterile Neutrinos?
KamLAND x Solar neutrinos tension?

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KamLAND x Solar neutrinos tension?

Sterile Neutrinos

➔ Recently, some short-baseline neutrino experiments presented some tension between the data and the standard neutrino oscillation paradigm.

- Reactor Neutrino Anomaly: supression of reactor neutrino signal at very close detectors.
- LSND/MiniBoone: appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ flux

➔ Such tension can be alleviated by the inclusion of a fourth neutrino generation, sterile, which mixes with the three active neutrinos.

$$\Delta m_s^2 \sim 1eV^2$$
$$sin^2 2\theta_s \lesssim 10^{-1}$$

Does cosmology has something to say about that?

Sterile Neutrinos

- A new neutrino family would behave as radiation during part of Universe history. Bounds on N_{eff} would apply to such scenario if fourth family are in equilibrium.

Neutrinos in very dense medium

Flavour Oscillation

$$i\frac{d}{dt}[\nu_\alpha] = \left(\frac{M^2}{2p} + V^{int}\right)[\nu_\alpha]$$

Flavour Oscillation with density matrix formalism:

$$i\frac{d\rho_{\vec{p}}}{dt} = [\Omega^0_{\vec{p}}, \rho_{\vec{p}}] + [\Omega^{int}_{\vec{p}}, \rho_{\vec{p}}]$$

$$\Omega^0_{\vec{p}} = \frac{M^2}{2p}$$

$$\Omega^{int}_{\vec{p}} = \sqrt{2}G_F N_{e^-}$$

Neutrinos in very dense medium

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$$\Omega^0_{\vec{p}} = \frac{M^2}{2p}$$

pósitrons as well

$$\Omega^{int}_{\vec{p}} = \sqrt{2}G_F(N_{e^-} - N_{e^+})$$

Neutrinos in very dense medium

$$i\frac{d\rho_{\vec{p}}}{dt} = [\Omega^0_{\vec{p}}, \rho_{\vec{p}}] + [\Omega^{int}_{\vec{p}}, \rho_{\vec{p}}]$$

$$\Omega^0_{\vec{p}} = \frac{M^2}{2p}$$

$$\Omega^{int}_{\vec{p}} = \sqrt{2}G_F(N_{e^-} - N_{e^+} - 8pE/3m_W^2)$$

2nd order expansion

Neutrinos in very dense medium

$$i\frac{d\rho_{\vec{p}}}{dt} = [\Omega^0_{\vec{p}}, \rho_{\vec{p}}] + [\Omega^{int}_{\vec{p}}, \rho_{\vec{p}}] + C[\rho_{\vec{p}}, \bar{\rho}_{\vec{p}}]$$

νν interaction

$$\Omega^0_{\vec{p}} = \frac{M^2}{2p}$$

$$\Omega^{int}_{\vec{p}} = \sqrt{2}G_F(N_{e^-} - N_{e^+} - 8pE/3m^2_W)$$

$$C = \sqrt{2}G_F\left[\rho - \bar{\rho} - \frac{8p}{3m^2_Z}(\bar{U} + U)\right]$$

$$\rho = \int\frac{d^3p}{(2\pi)^3}\rho_{\vec{p}} \qquad U = \int\frac{d^3p}{(2\pi)^3}p\rho_{\vec{p}}$$

Neutrinos in very dense medium

$$i\frac{d\rho_{\vec{p}}}{dt} = [\Omega^0_{\vec{p}}, \rho_{\vec{p}}] + [\Omega^{int}_{\vec{p}}, \rho_{\vec{p}}] + C[\rho_{\vec{p}}, \bar{\rho}_{\vec{p}}]$$

raction

THINGS BECOME NON-LINEAR!

$$\Omega^{int}_{\vec{p}} = \sqrt{2}G_F(N_{e^-} - N_{e^+} - 8pE/3m_W^2)$$

$$C = \sqrt{2}G_F\left[\rho - \bar{\rho} - \frac{8p}{3m_Z^2}(\bar{U} + U)\right]$$

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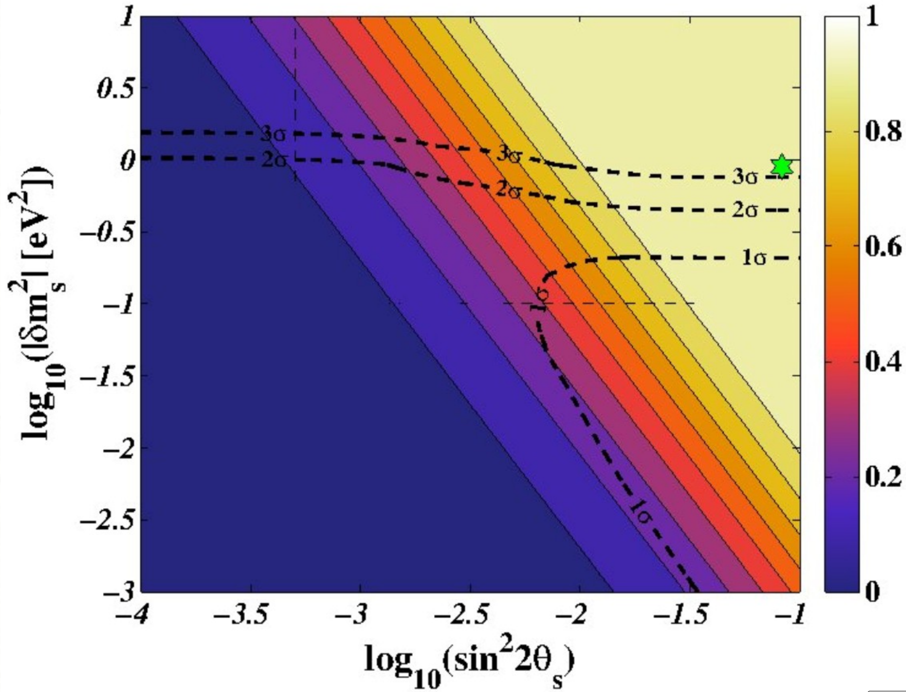
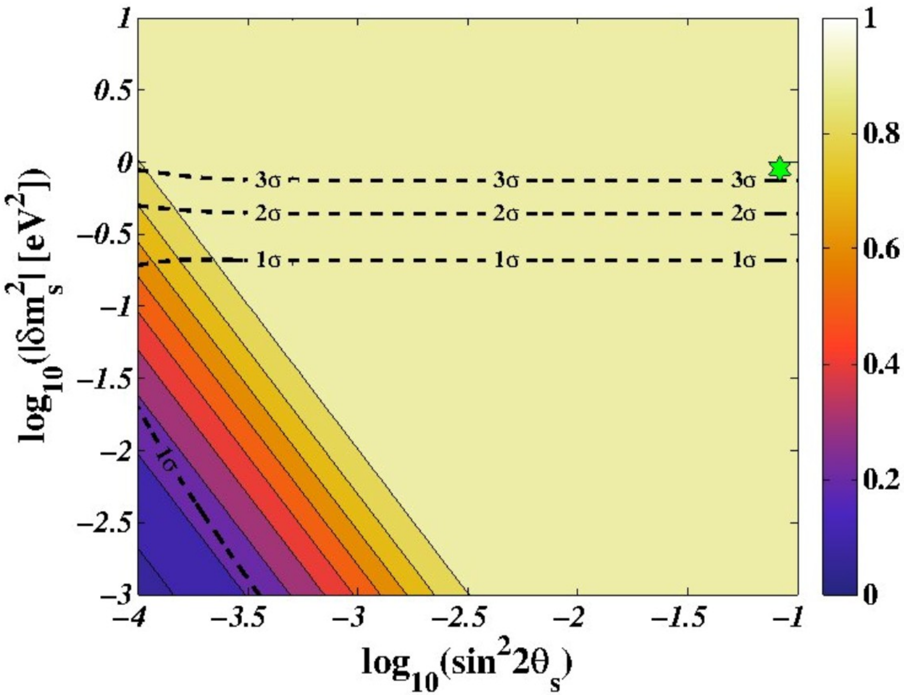
MiniBoone Sterile Neutrinos in Cosmology



Normal Hierarchy,
non-Resonant Production



Inverted Hierarchy,
Resonant Production

Hannestad et al., JCAP 1207, 025

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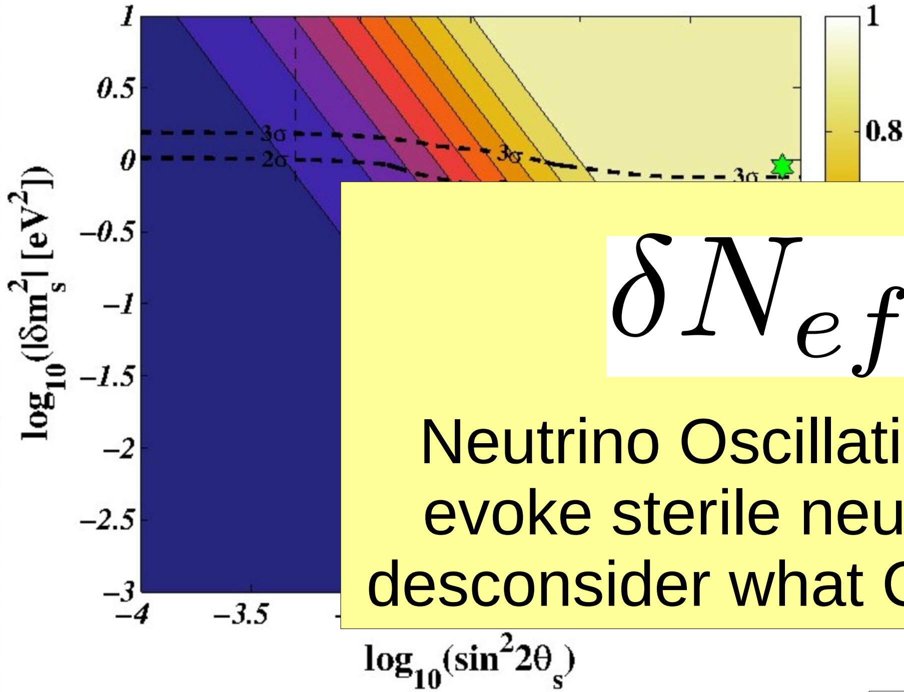
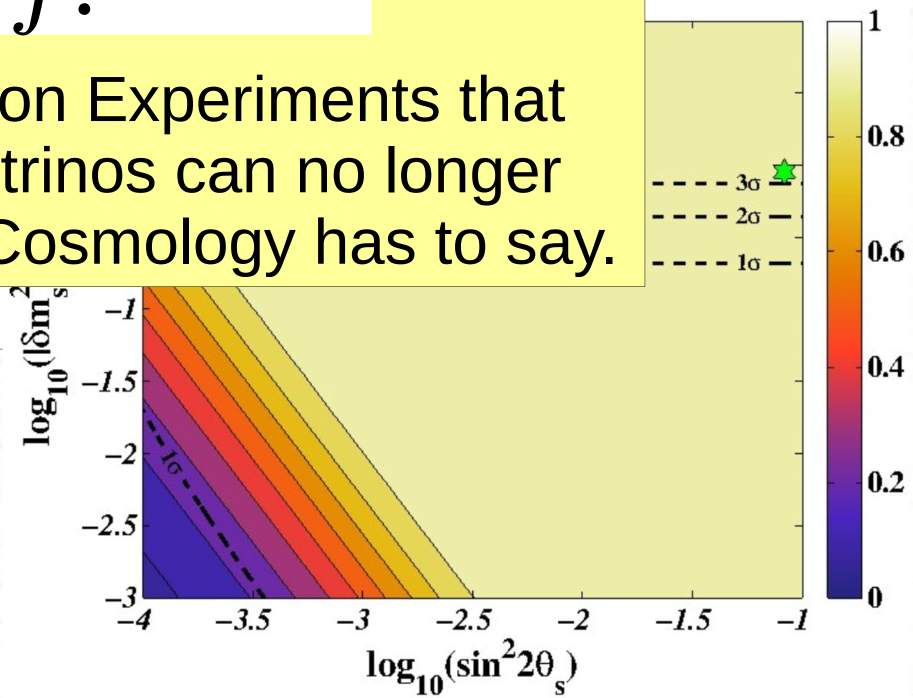


Normal Hierarchy,

non-Resonant Production

$$\delta N_{eff.} \approx 1$$

Neutrino Oscillation Experiments that evoke sterile neutrinos can no longer desconsider what Cosmology has to say.



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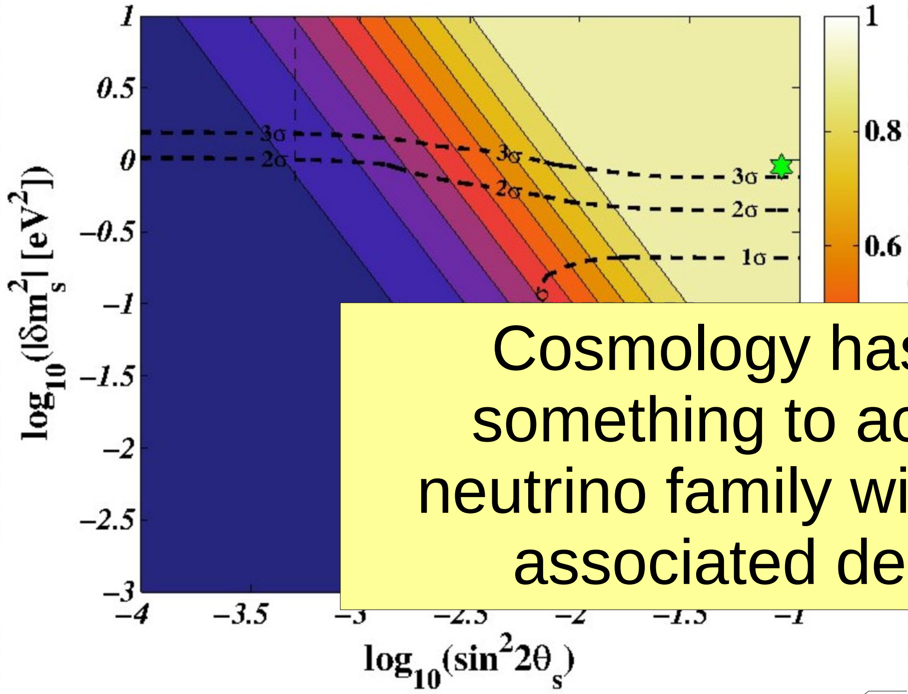
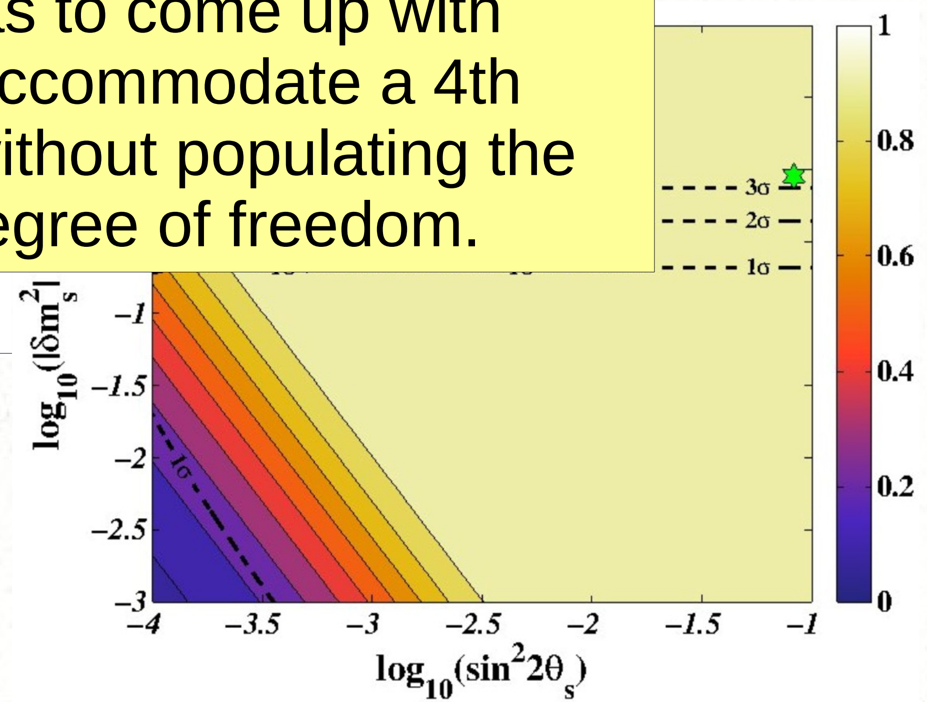


Normal Hierarchy,
non-Resonant Production

Cosmology has to come up with something to accommodate a 4th neutrino family without populating the associated degree of freedom.



Inverted Hierarchy,
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What about ”non-standard” Sterile Neutrinos?

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Large lepton asymmetry: Lepton asymmetry in neutrino sector is not so strongly bounded. $L\sim10^{-2}$ can supress population of sterile state in early universe, through blocking of sterile neutrino thermalization.

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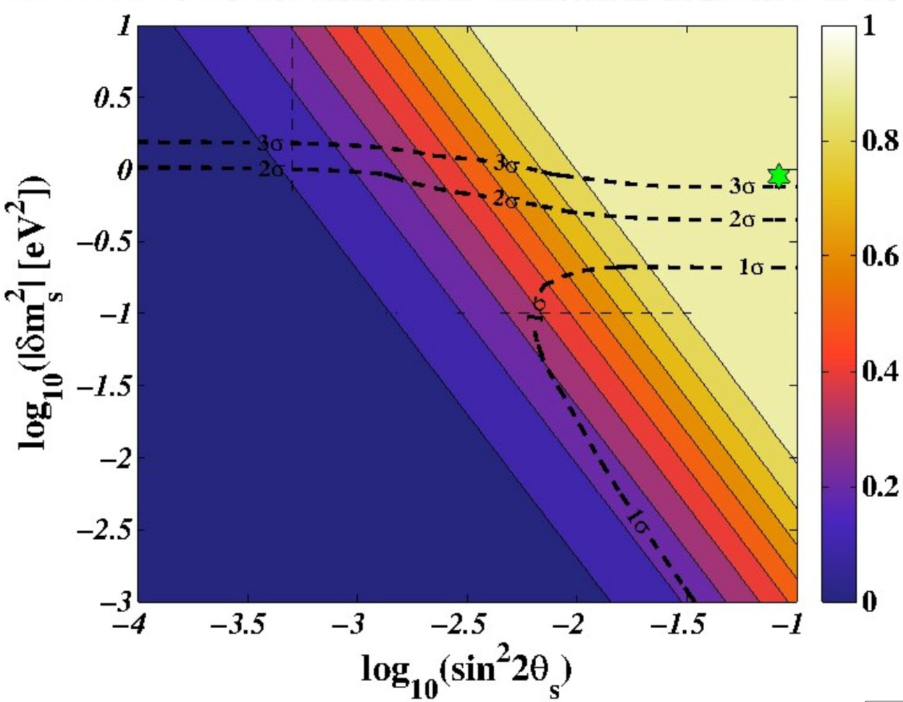

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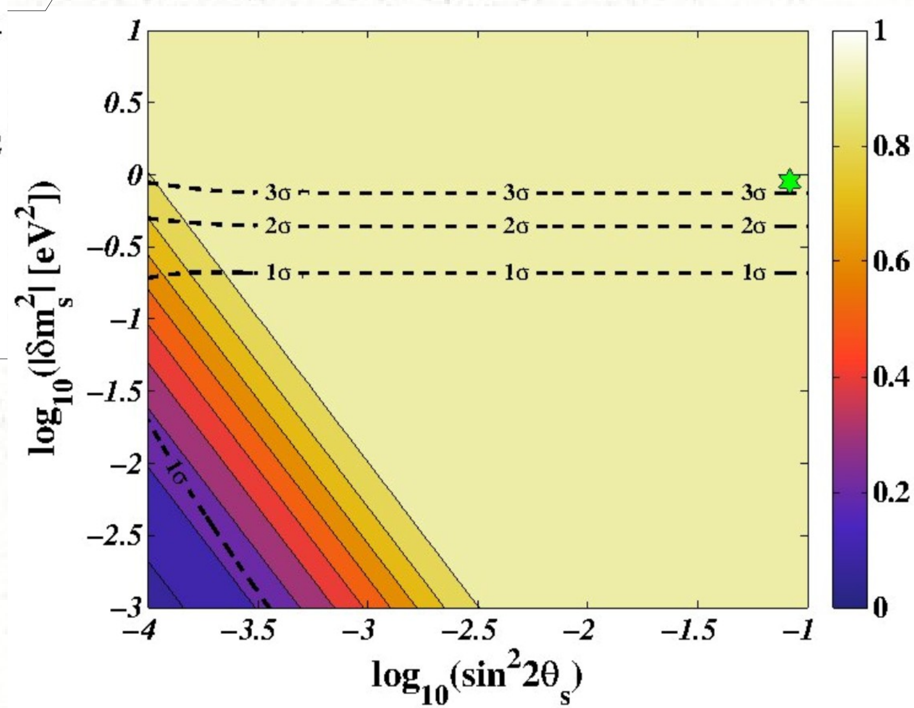
non-Resonant Production



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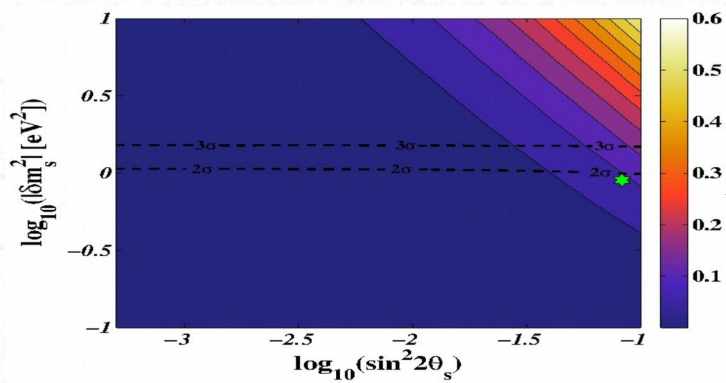

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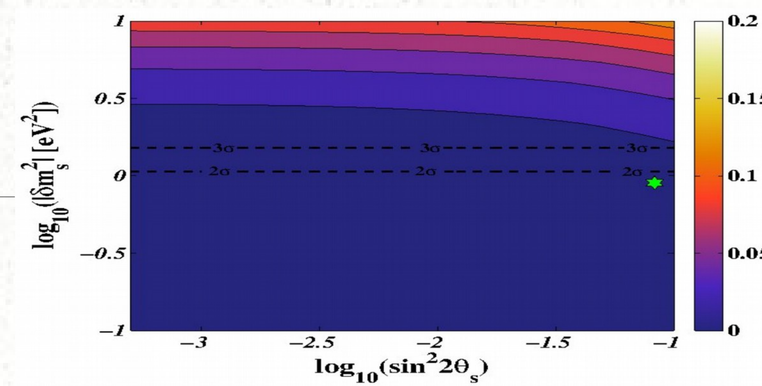

Inverted Hierarchy,
Resonant Production

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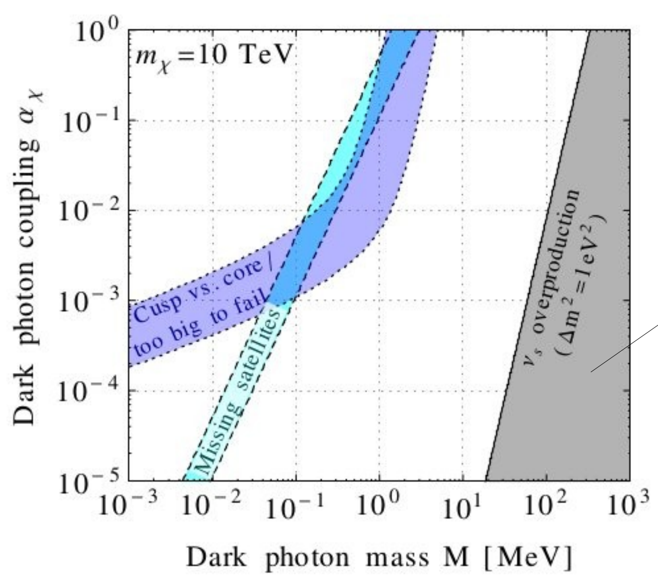
Secret Interactions: Sterile Neutrinos can be strongly self-coupled through secret Fermi 4-point interactions:

$$G_X = \frac{g_X^2}{M_X^2}$$

Leading to a new potential term in neutrino Quantum Kinetic Equations. Sterile Neutrino thermalization is supressed.



N_{eff}~1

B. Dasgupta and J. Kopp, PhysRevLett.112.031803,
see also Pospelov, PRD84 (2011) 085008

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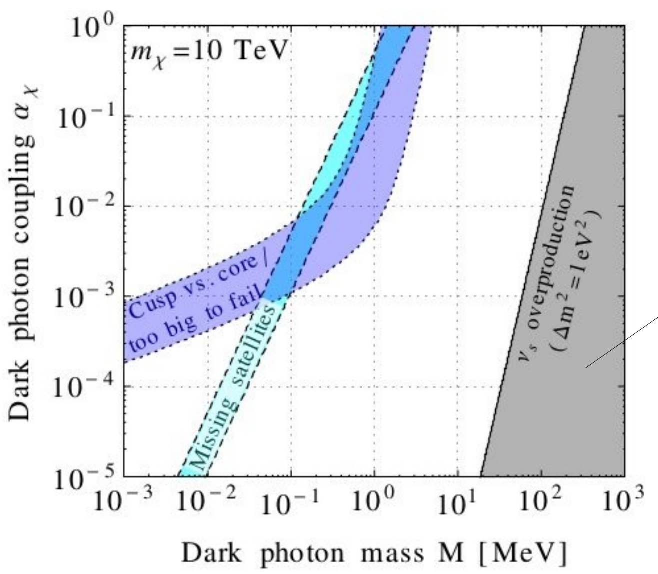
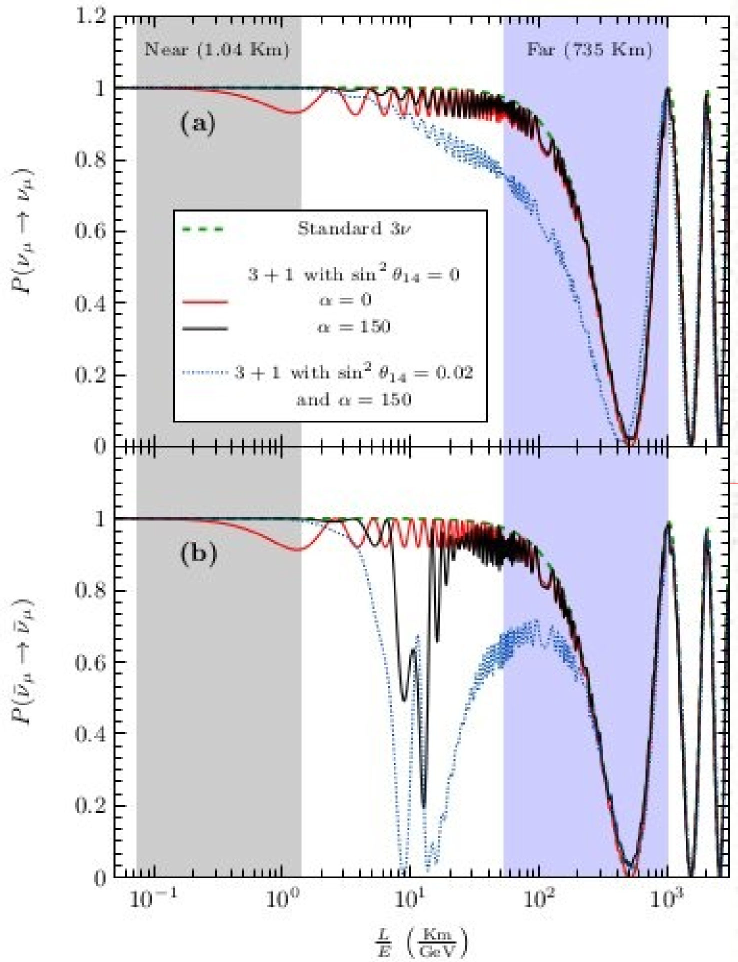


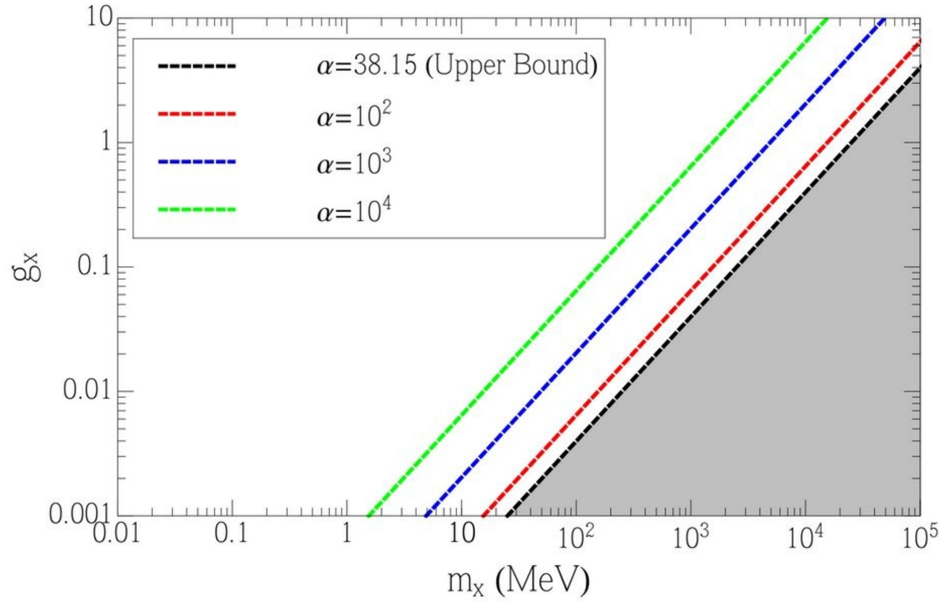
$N_{eff} \sim 1$

However...

B. Dasgupta and J. Kopp, PhysRevLett.112.031803,
see also Pospelov, PRD84 (2011) 085008

Secret Interactions: Such large interaction could affect also neutrino oscillation probabilities in long-base line experiments, as MINOS.





Orlando Peres and Zahra Tabrizi, preliminary

Pseudo-scalar self-Interactions: (arxiv:1508.02504)

- sterile neutrino secret interactions through a light pseudo-scalar supress sterile neutrino production until after neutrino decoupling.

$$\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4 .$$

- latter production of sterile neutrinos through contact with active neutrinos

- strongly coupled $\phi\nu$ fluid at late times. Rich phenomenology and better fit to cosmological observables.

"(...) it could be another indication that we are seeing the first signs of new, hidden interactions in the dark sector."

Conclusions

- There is no such thing as ”non-standard” neutrino phenomenology. Each non-standard model has its own consequences on neutrino observables.

- As in standard scenarios, we must take into account several different experiments in different contexts (cosmology included) to achieve a global picture of limits and possibilities.

- For now, we only have limits and hints, and no clear indication for the presence of non-standard physics on neutrino sector.

- But that’s the way it goes. Hopefully dark-matter people will agree!