DAPNIA-SPhT Joint Seminar, 21 May 2007

Exotic Neutrino Physics

in the light of LSND, MiniBooNE and other data

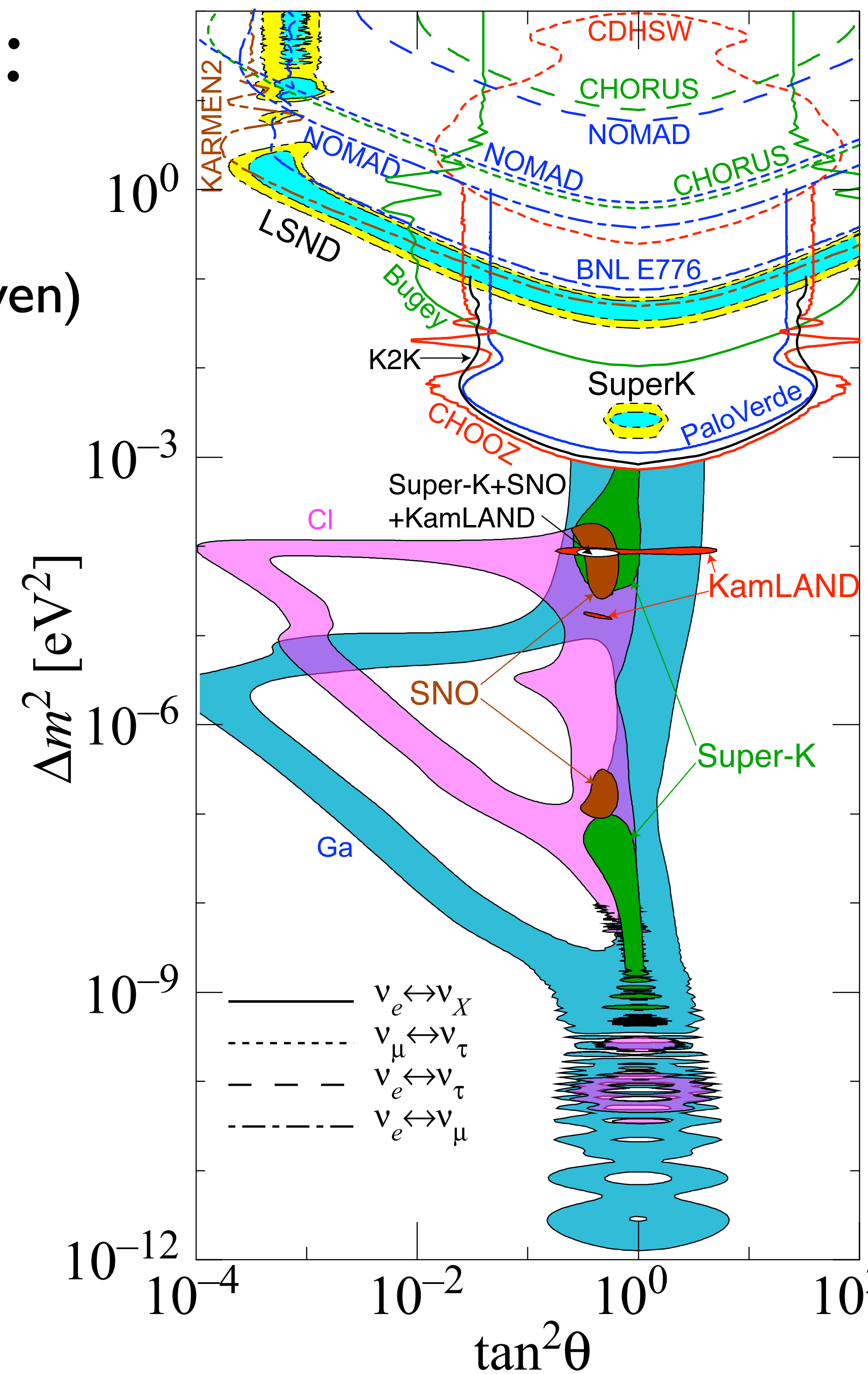
Marco Cirelli + Stéphane Lavignac
SPhT - CEA/Saclay

Introduction

Neutrino Physics (pre-MiniBooNE):

Everything fits in terms of:

3 neutrino oscillations (mass-driven)



http://hitoshi.berkeley.edu/neutrino

Particle Data Group 2006

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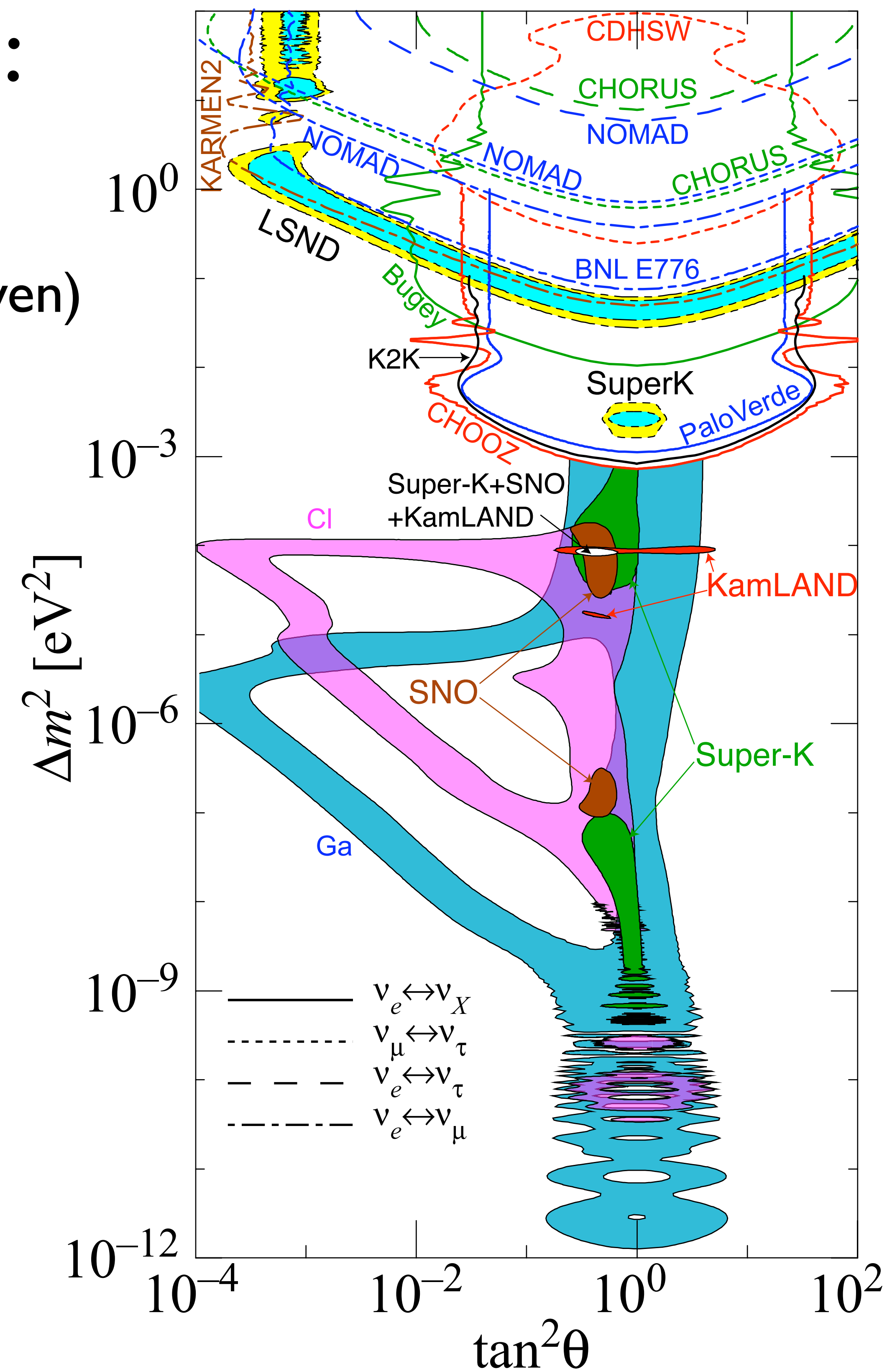
ν_e, ν_μ, ν_τ $\quad m_1, m_2, m_3$

$\theta_{12}, \theta_{23}, \theta_{13}$ $\quad \delta_{CP}$



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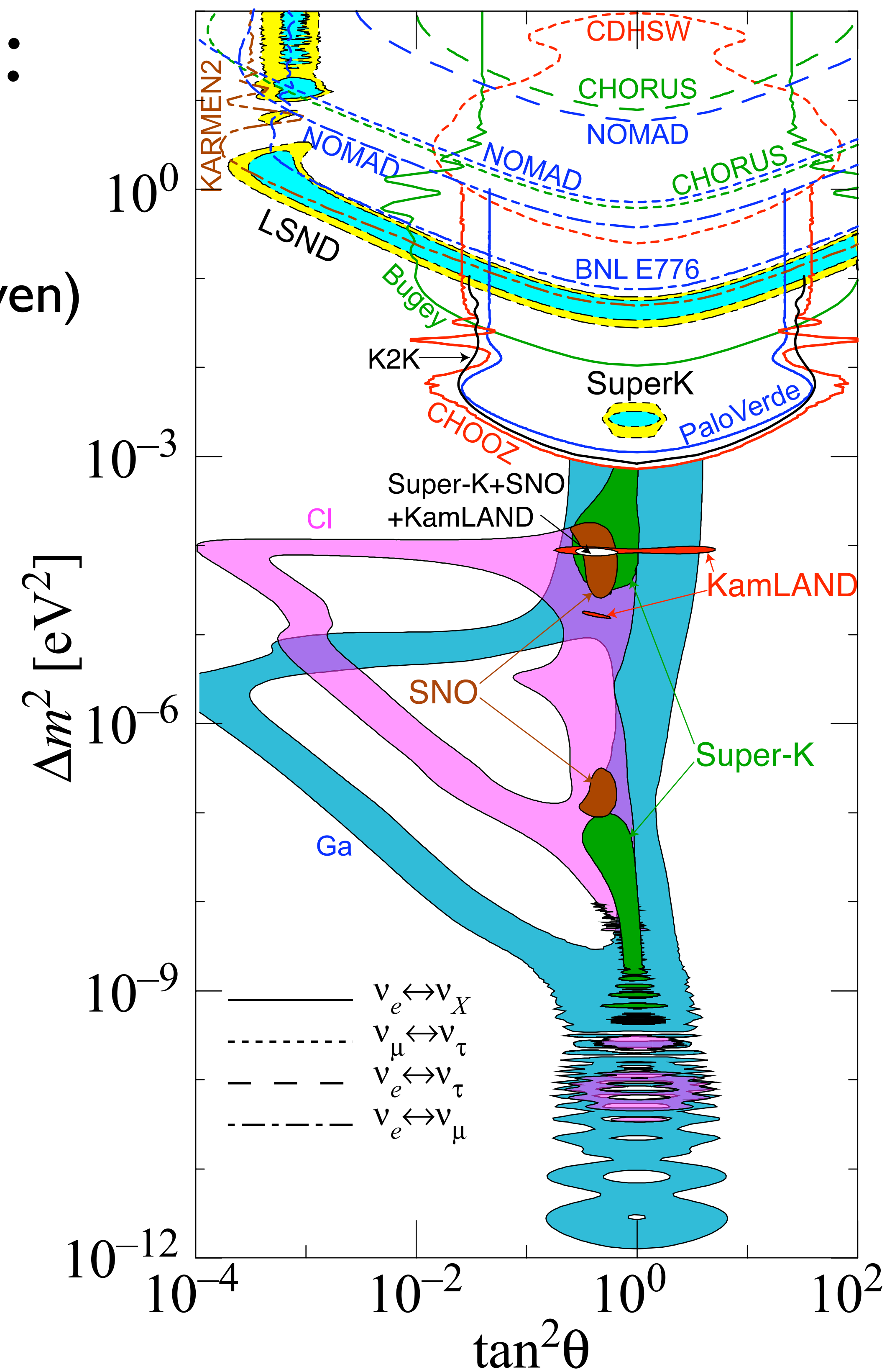
$$|\nu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu(t)\rangle = e^{-E_1 t}\cos\theta|\nu_1\rangle + e^{-E_2 t}\sin\theta|\nu_2\rangle$$

$E_i = p + m_i^2/2p$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta}\sin^2\frac{\Delta m^2 L}{E}$$



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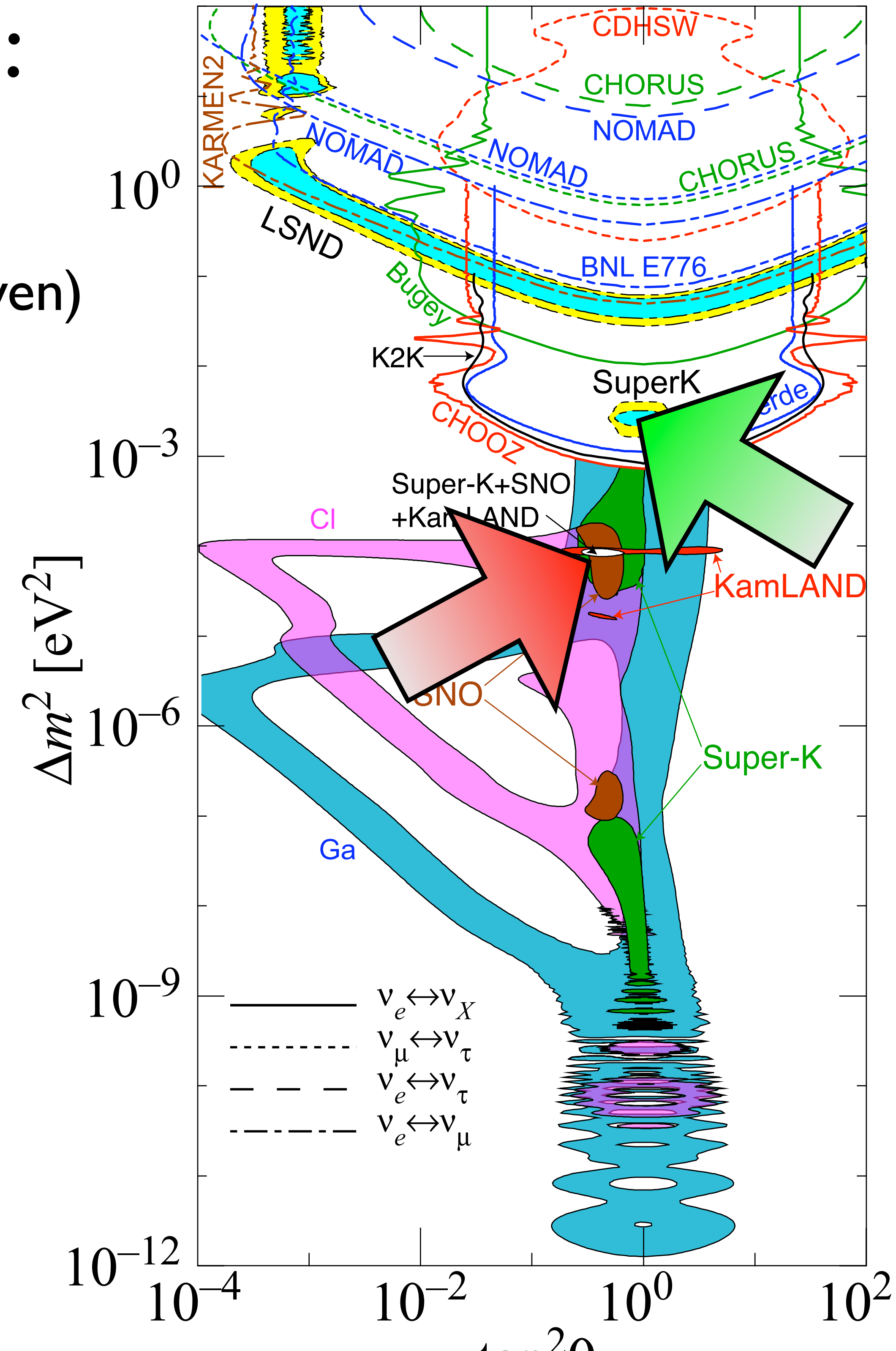
Simple phenomenology:

solar $\nu_e \to \nu_{\mu,\tau}$: $\Delta m^2_{21}, \theta_{12}$

atmo $\nu_\mu \to \nu_\tau$: $\Delta m^2_{32}, \theta_{23}$

SBL $\nu_{e,\mu} \to \nu_x$: $\Delta m^2_{32}, \theta_{13}$



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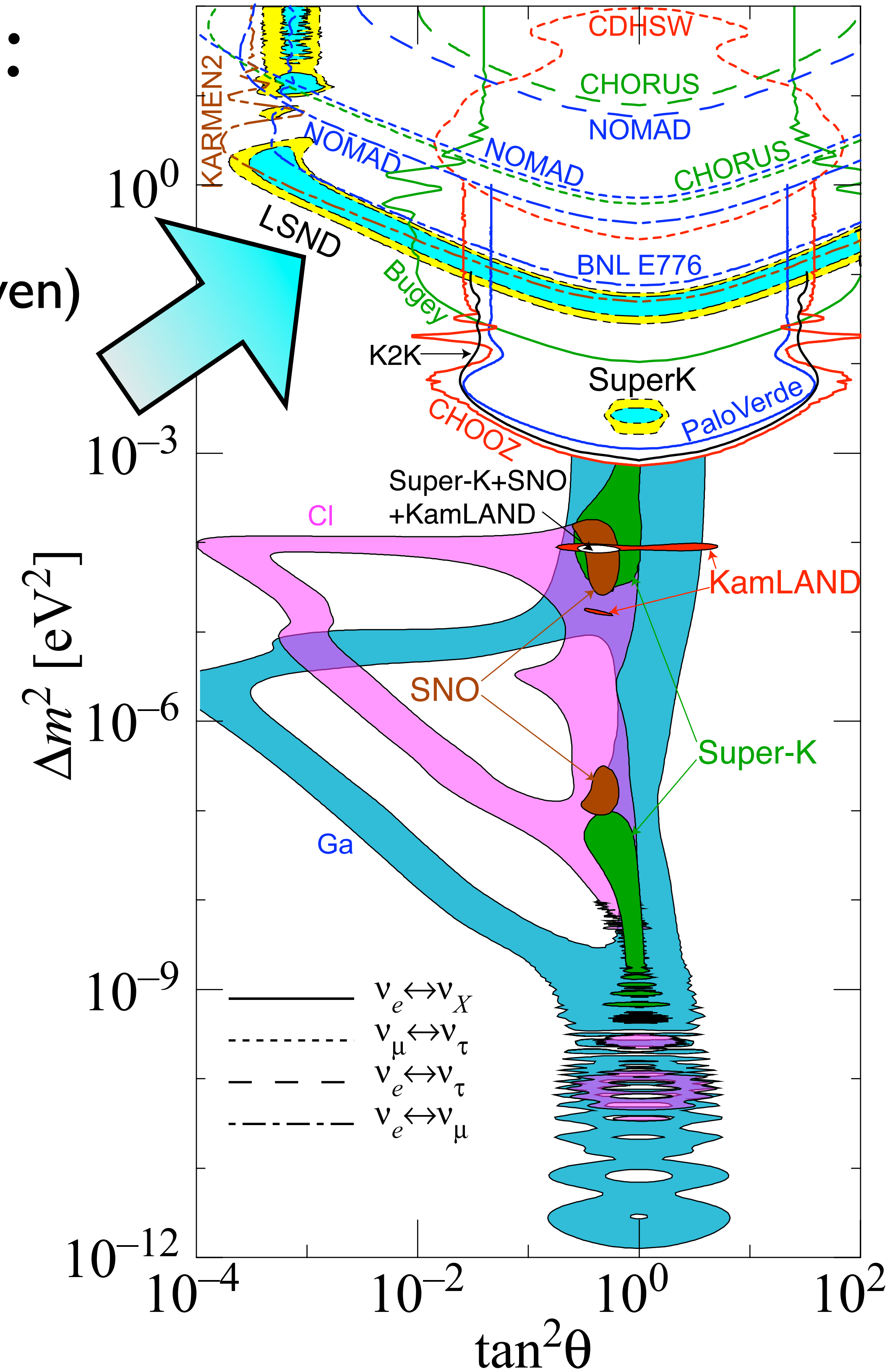
But: LSND does not fit:

$$\Delta m^2_{\mathrm{LSND}} \simeq 1\ \mathrm{eV}^2$$

$$\theta_{\mathrm{LSND}} \simeq 10^{-3}$$



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Introduction

The LSND signal does not fit.

Complicate the simple picture:
- add new flavours
- modify oscillation physics (more or less radically)

Sterile neutrinos, ~~CPT~~, ~~Lorentz~~, MaVaNs, xDims, anomalous muon decay, neutrino decay...

Beyond resolving the LSND puzzle, this exotic neutrino physics might be justified by *new physics* beyond the SM, and might give rise to *subleading* effects in other neutrino experiments.

Introduction

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We will review aspects of:

Sterile neutrinos, ~~CPT~~, ~~Lorentz~~, MaVaNs, xDims,
anomalous muon decay, neutrino decay...

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Why ~~Lorentz~~ and/or ~~CPT~~

Lorentz, CPT: - fundamental ingredients of ordinary Quantum Field Theories (including the SM)

- have been tested with high precision (K^0-$\bar{K}^0$ system, charged lepton sector...)

Why should they be violated in the neutrino sector?

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Why should they be violated in the neutrino sector?

- neutrinos are "special": no conserved charge, can be Majorana $\Rightarrow$ requires new physics beyond SM
- $m_\nu \sim \mathrm{eV}$ suggests $\Lambda_{\mathrm{new}} \sim \frac{M^2_{\mathrm{weak}}}{m_\nu} \sim 10^{-4} M_{\mathrm{Pl}}$: Quantum Gravity might violate Lorentz and/or CPT

Still **very speculative** possibilities!

Lorentz

Basics

Possible origin: - spontaneous breaking
- non trivial background in x-dim
- non-commutative field theory
- quantum gravity...

In absence of an explicit model, parameterize as:

Colladay, Kostelecky 1997

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\not{\rm Lorentz}}$$

for neutrinos (renormalizable case): Kostelecky, Mewes 2003

$$\mathcal{L}_{\not{\rm Lorentz}} = (a_\mu)_{ij} \bar{L}_i \gamma^\mu L_j + \frac{i}{2} (c_{\mu\nu})_{ij} \bar{L}_i \gamma^\mu \overset{\leftrightarrow}{D^\nu} L_j$$

charged leptons interactions $\Rightarrow \frac{a_\mu}{\rm GeV}, c_{\mu\nu}$ must be tiny

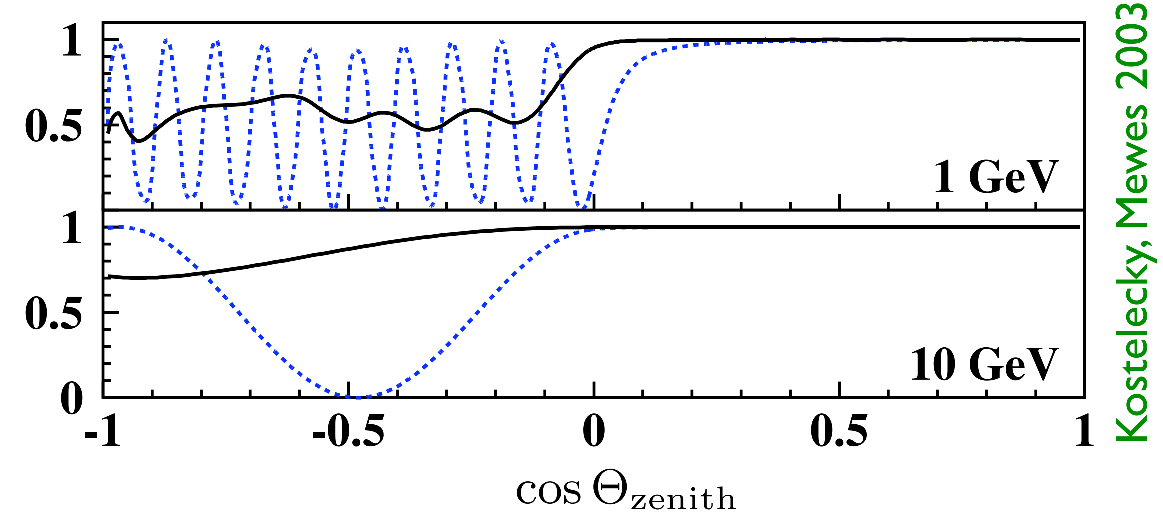
but $\sim 10^{-17}$ is enough to affect neutrino propagation!

~~Lorentz~~ phenomenology

-Unusual **energy dependence** of flavor conversions:

instead of usual $\frac{L}{E}$: L or $L\,E$

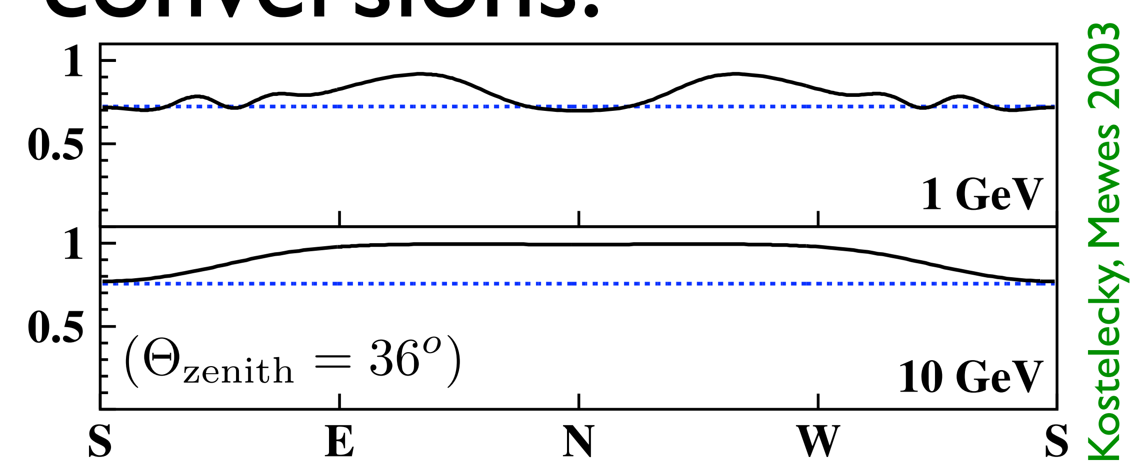
however *conspiracies* can reproduce the usual dependance at given energies:



-**Direction dependence** of flavor conversions:

atmospheric neutrinos at SK:

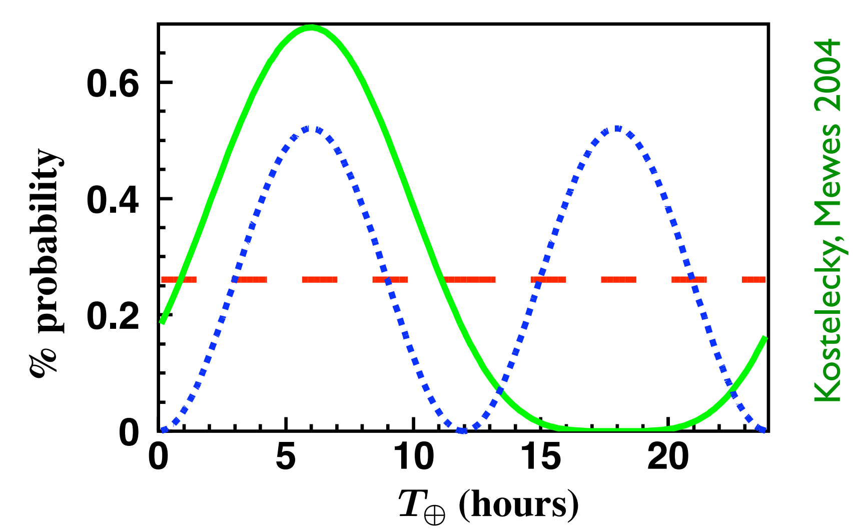
$P_{\nu_\mu \to \nu_\mu}$ depends on *azimuthal* angle



terrestrial experiments:

$P_{\bar\nu_\mu \to \bar\nu_e}$ changes due to Earth rotation

(plot: LSND, with day average $\langle P_{\bar\nu_\mu \to \bar\nu_e}\rangle = 0.26\%$)



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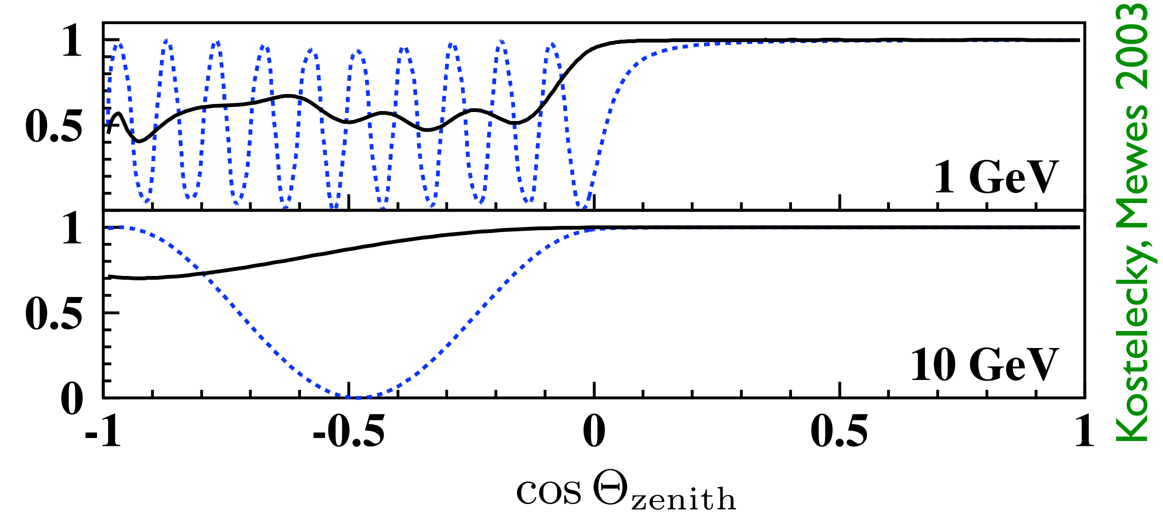

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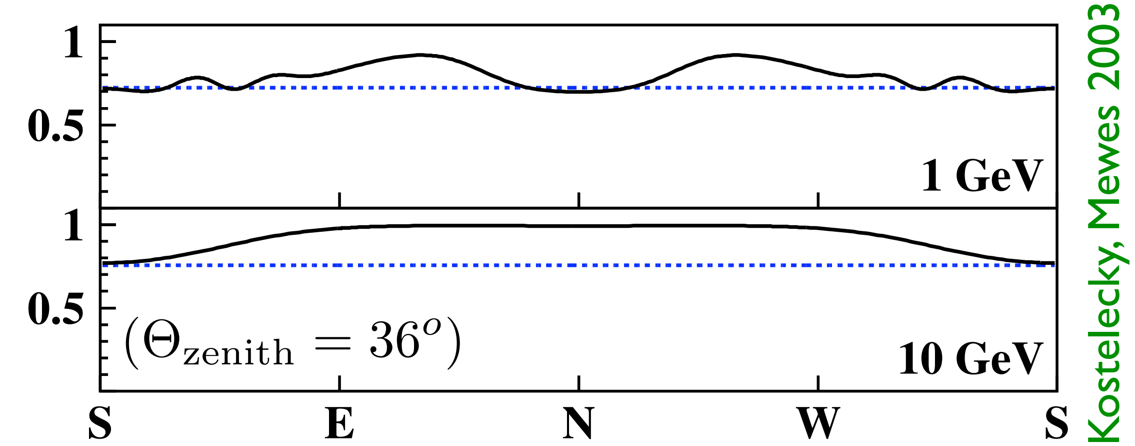

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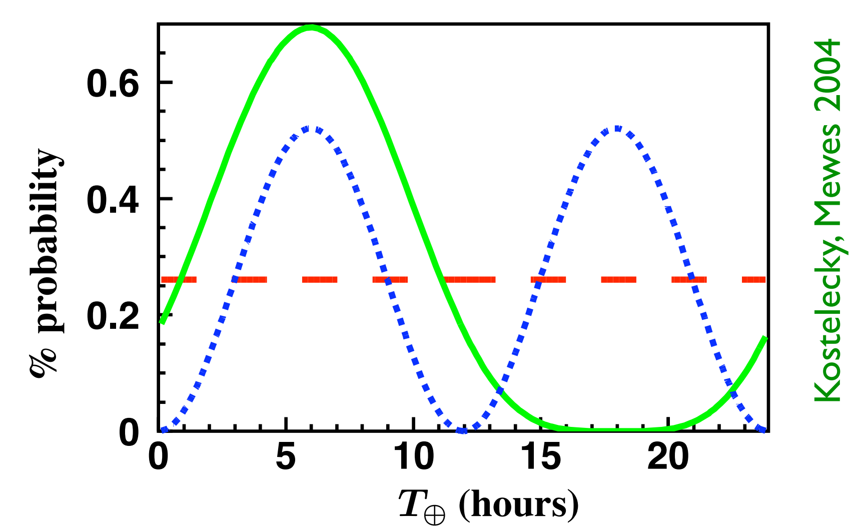

A very non-conventional phenomenology, very unlikely to fit all neutrino data.

A ~~Lorentz~~ model for LSND

de Gouvêa, Grossman 2006

- allow: *massive* neutrinos + ~~Lorentz~~
- drop: directional dependence
- encode all ~~Lorentz~~ effects in the dispersion relation $E = E(\vec{p})$:

$$E \simeq \underbrace{|\vec{p}| + \frac{m^2}{2|\vec{p}|}}_{\textit{standard}} + \underbrace{\frac{f(|\vec{p}|^2)}{2|\vec{p}|}}_{\textit{\sout{Lorentz}}}$$

and take $f(|\vec{p}|) = 2E_0\, a_N \left(\frac{|\vec{p}|}{E_0}\right)^{2N}$

$\left(|\vec{p}| \gg m, \sqrt{f}\right)$

- assume ~~Lorentz~~ for one state only: $|\nu_{\rm L}\rangle = \cos\zeta\cos\theta_{\rm L}\,|\nu_e\rangle + \cos\zeta\sin\theta_{\rm L}\,|\nu_\mu\rangle + \sin\zeta\,|\nu_\tau\rangle$

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standard *~~Lorentz~~*

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Neutrino oscillations are described by: $i\frac{d\nu_\alpha}{dt} = H_{\alpha\beta}\,\nu_\beta$

$$H = U_{\rm PMNS}\begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E}\end{pmatrix}U^\dagger_{\rm PMNS} + a_N\left(\frac{E}{E_0}\right)^{2N-1}\begin{pmatrix} c^2_\zeta c^2_{\theta_L} & c^2_\zeta c_{\theta_L} s_{\theta_L} & c_\zeta s_\zeta c_{\theta_L} \\ c^2_\zeta c_{\theta_L} s_{\theta_L} & c^2_\zeta s^2_{\theta_L} & c_\zeta s_\zeta s_{\theta_L} \\ c_\zeta s_\zeta c_{\theta_L} & c_\zeta s_\zeta s_{\theta_L} & s^2_\zeta \end{pmatrix}$$

mass-induced oscillations *~~Lorentz~~-induced oscillations*

A ~~Lorentz~~ model for LSND

(A) LSND, SBL $\frac{\Delta m^2_{ij}\, L}{E} \ll 1$: oscillations dominated by ~~Lorentz~~

$$P_{\mu e} \simeq \cos^4\zeta\ \sin^2 2\theta_{\rm L}\ \sin^2\left[a_N \left(\frac{E}{E_0}\right)^{2N-1} \frac{L}{2}\right]$$

LSND $\Rightarrow \cos^4\zeta\ \sin^2 2\theta_{\rm L} \gtrsim 10^{-3}$

$$P_{\mu\tau} \simeq \sin^2 2\zeta\ \sin^2\theta_{\rm L}\ \sin^2\left[a_N \left(\frac{E}{E_0}\right)^{2N-1} \frac{L}{2}\right]$$

SBL $\Rightarrow$ $\cos^4\zeta\ \sin^2 2\theta_{\rm L} < 1.1\ 10^{-3}$, $\sin^2 2\zeta\ \sin^2\theta_{\rm L} < 3.3\ 10^{-4}$

choose: $\sin\zeta = 0$ and $\sin^2 2\theta_{\rm L} = 1.1\ 10^{-3}$.

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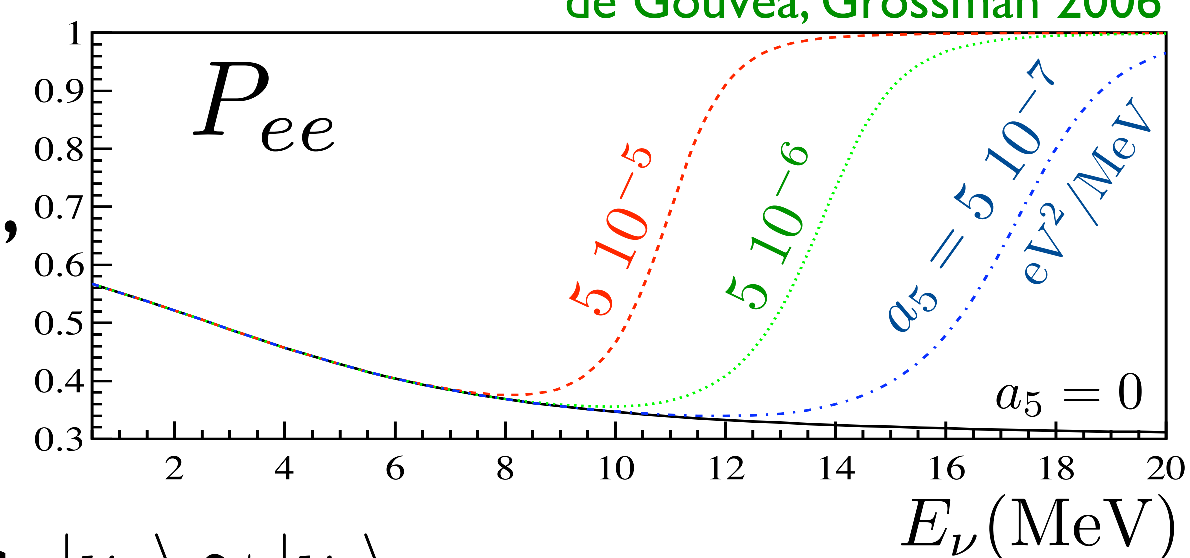

(B) solar neutrinos + Kamland:

~~Lorentz~~ effects must be suppressed,

large N: $\left(\frac{E}{E_0}\right)^{2N-1} \ll 1$ for $E < E_0$

(C) atmospheric: with these choices, $|\nu_{\rm L}\rangle \simeq |\nu_e\rangle$

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations unaffected.

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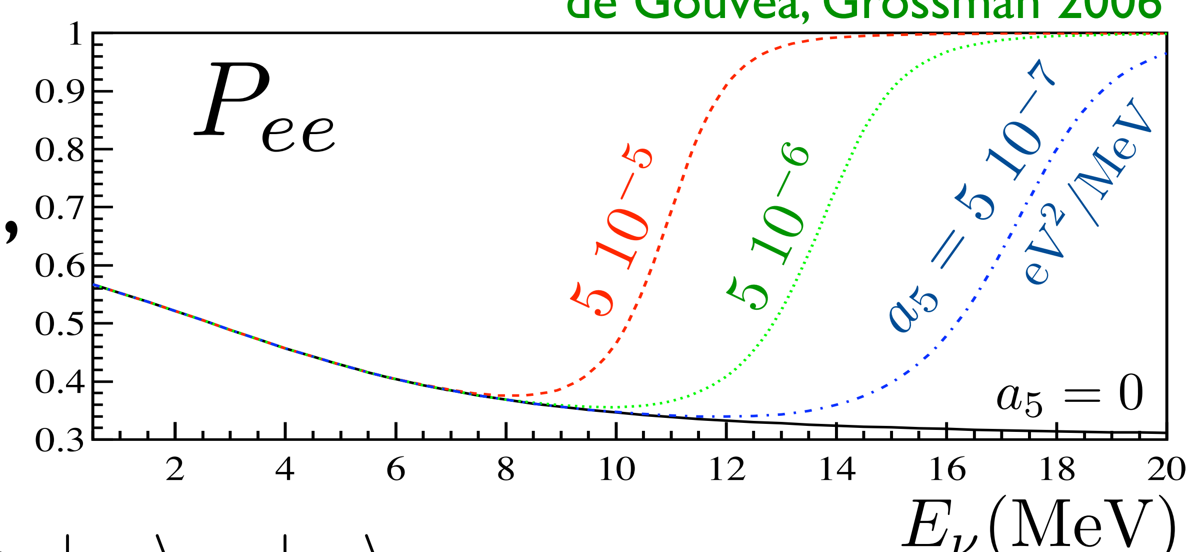


(C) atmospheric: with these choices, $|\nu_{\rm L}\rangle \simeq |\nu_e\rangle$

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations unaffected.

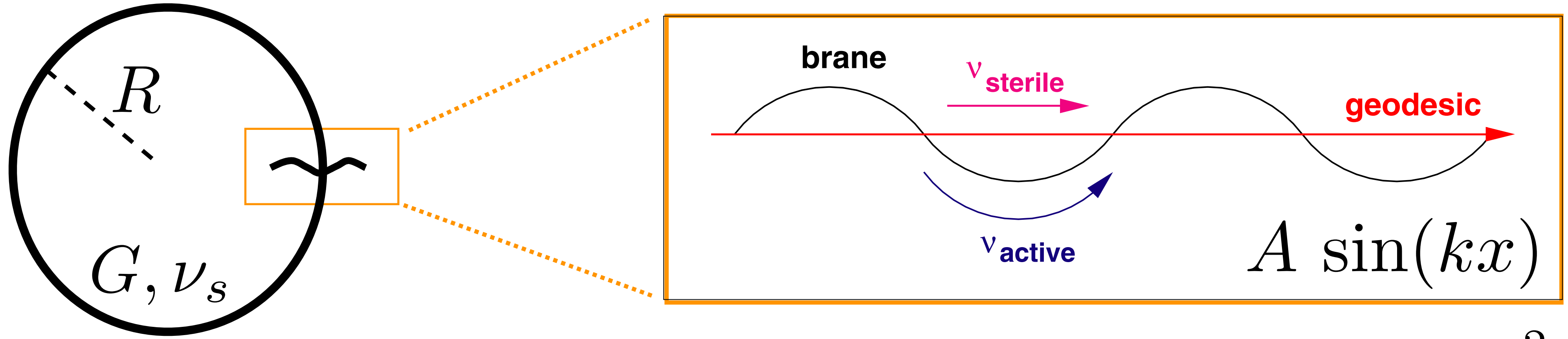
Bottom line: a highly non-trivial energy dependence is needed to fit all data. Even more so after **MiniBooNE**.

Sterile shortcuts in Extra Dimensions

Sterile shortcuts in x-dims

Päs, Pakvasa, Weiler 2005

Framework: a large extra dimension, with a wavy brane



$$\epsilon = \frac{L_{5\mathrm{d}} - L_{4\mathrm{d}}}{L_{5\mathrm{d}}} \simeq \left(\frac{Ak}{2}\right)^2$$

neutrino states evolution:

$$|\nu_\alpha\rangle = e^{-E(t+\Delta t)}|\nu_\alpha\rangle$$

$$|\nu_{\mathrm{s}}\rangle = e^{-Et}|\nu_{\mathrm{s}}\rangle$$

$$H = U \begin{pmatrix} \frac{\Delta m^2}{2E} & \\ & 0 \end{pmatrix} U^\dagger + \frac{1}{2} E\epsilon \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$$

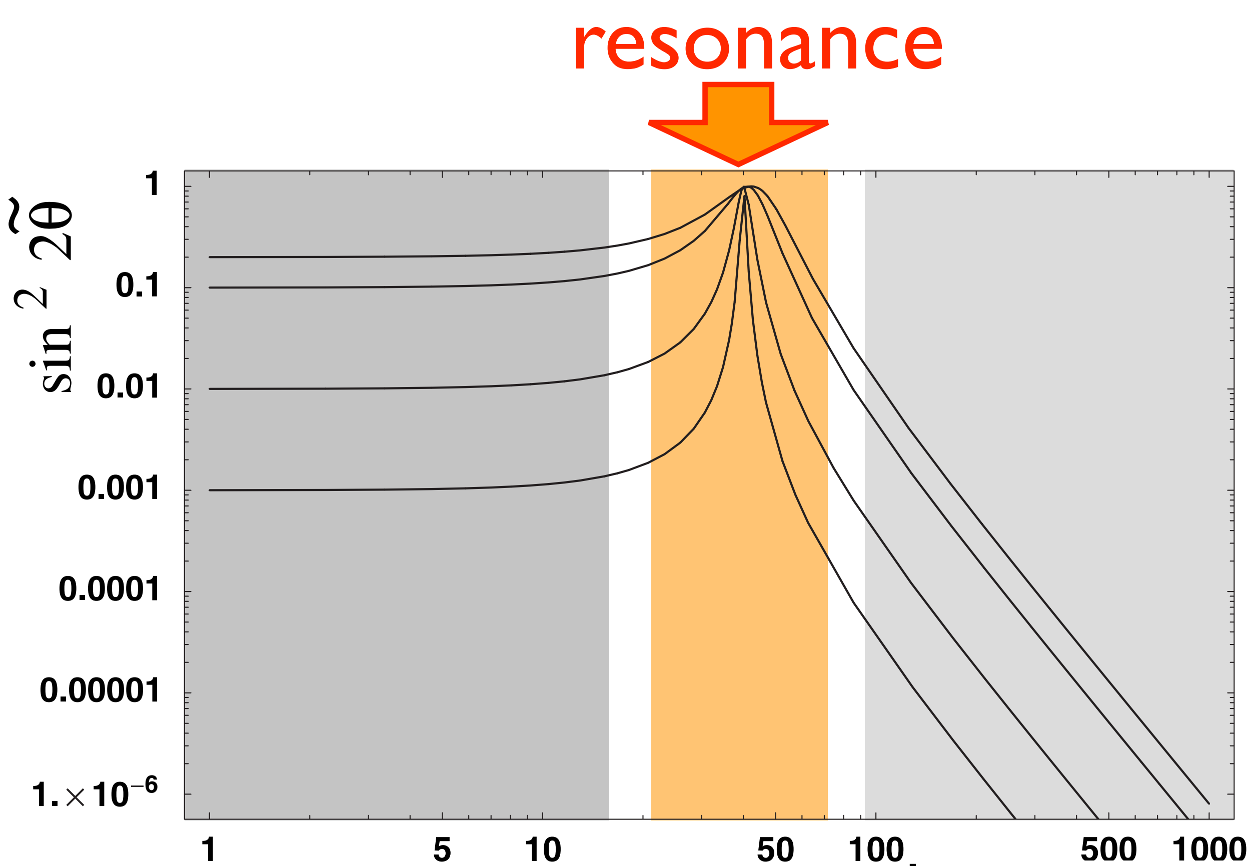
a resonance in the oscillation probability:

$$E_{\mathrm{res}} = \sqrt{\frac{\Delta m^2 \cos 2\theta}{2\epsilon}}$$

Sterile shortcuts in x-dims

Päs, Pakvasa, Weiler 2005

Oscillation probability determined by neutrino energy.



below resonance

Bugey

standard oscillations

choose small θ_{es}

LSND

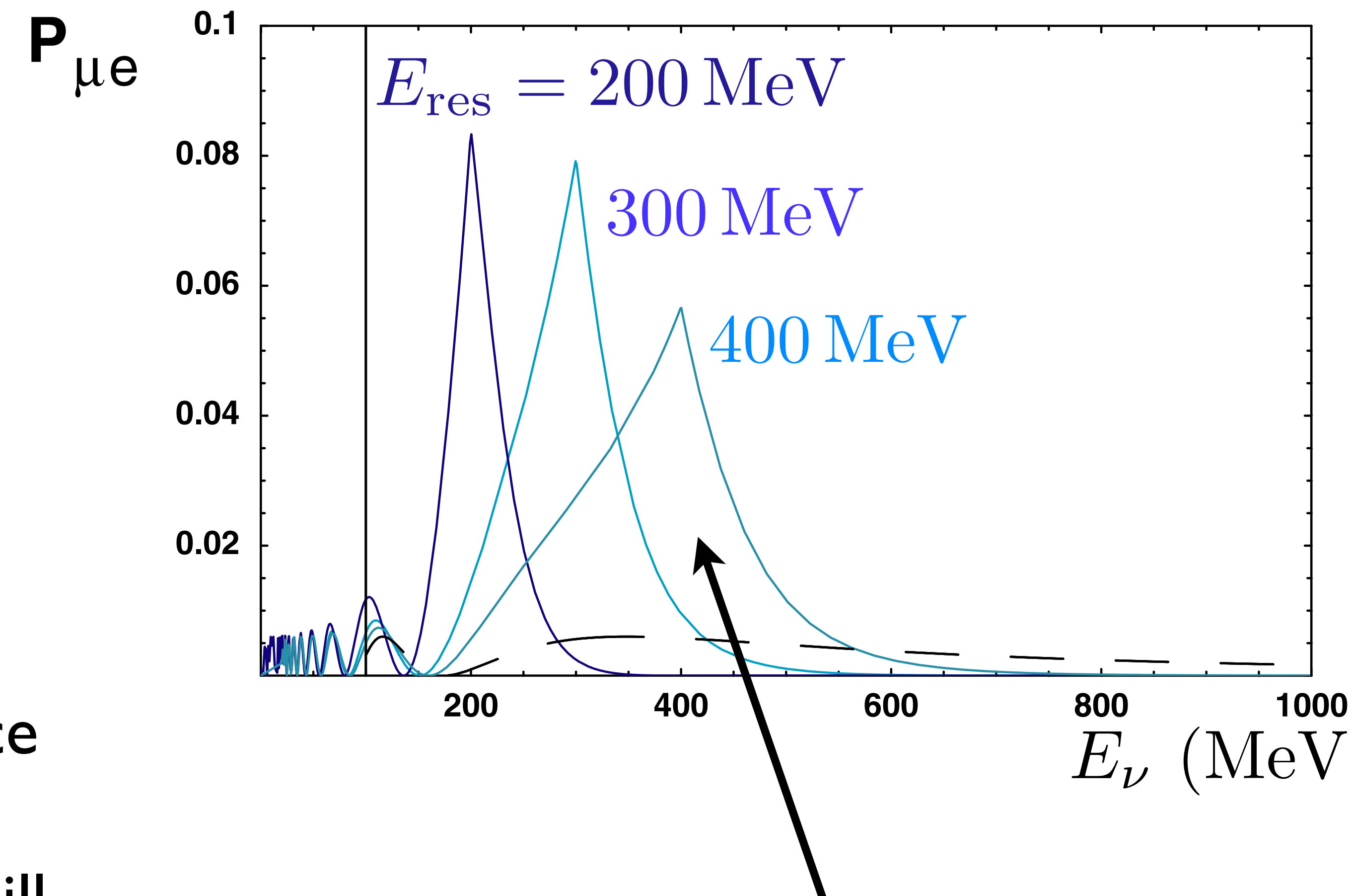
above resonance

CDHS

suppressed oscill

for any $\theta_{\mu s}$

***Pre*dictions for MiniBooNE:**



oscillation peak at $E \simeq E_{res}$

and no signal at $E > E_{res}$

CPT

Basics

CPT is conserved in any local, Lorentz invariant QFT.

(1) ~~CPT~~ can be induced by ~~Lorentz~~
(see above discussion)

(2) ~~CPT~~ can manifest itself in $m \neq \bar{m}$ (requires non-locality):
Origin: non-perturbative effects in strings, quantum gravity...
In the neutrino sector, the main motivation is LSND.
From other sectors, there are strong bounds:

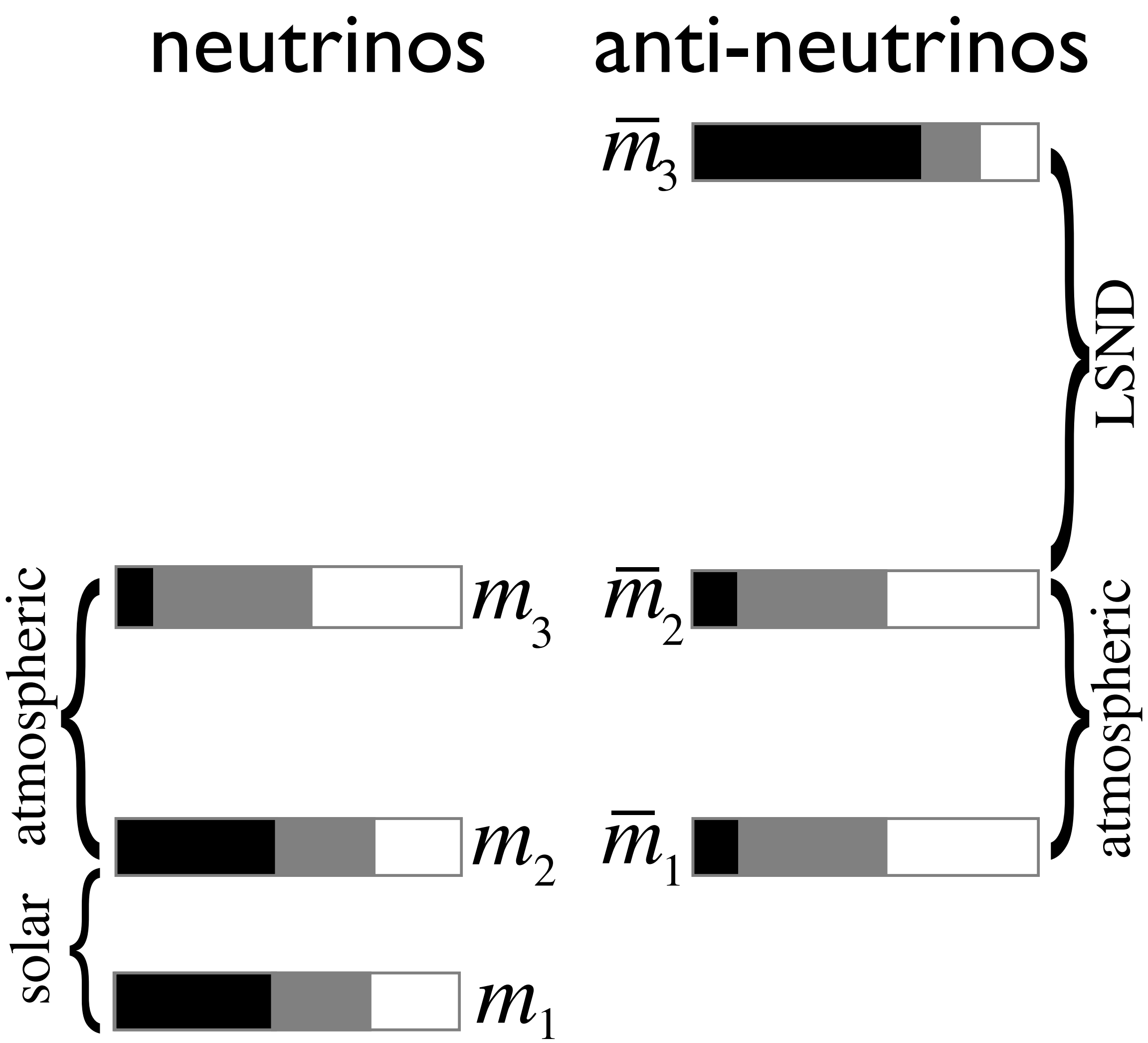
$$(m_{K^0} - m_{\bar{K}^0}) < 10^{-18} m_K$$

$$(m_{e^+} - m_{e^-}) < 10^{-9} m_e$$

Phenomenological approach:
assume that ~~CPT~~ couples dominantly to neutrinos
and use new parameters $\bar{m}_i \neq m_i$ and $\bar{\theta}_{ij} \neq \theta_{ij}$

~~CPT~~ version 1

Murayama, Yanagida 2001
Baremboim et al. 2001



- solar ν_e oscillate with $\Delta m^2_{21} \equiv \Delta m^2_{\rm Sun}$
- atmospheric ν_μ and $\bar{\nu}_\mu$ with
$$\Delta m^2_{31} = \Delta \bar{m}^2_{31} \equiv \Delta m^2_{\rm atm}$$
- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta \bar{m}^2_{31} \equiv \Delta m^2_{\rm LSND}$

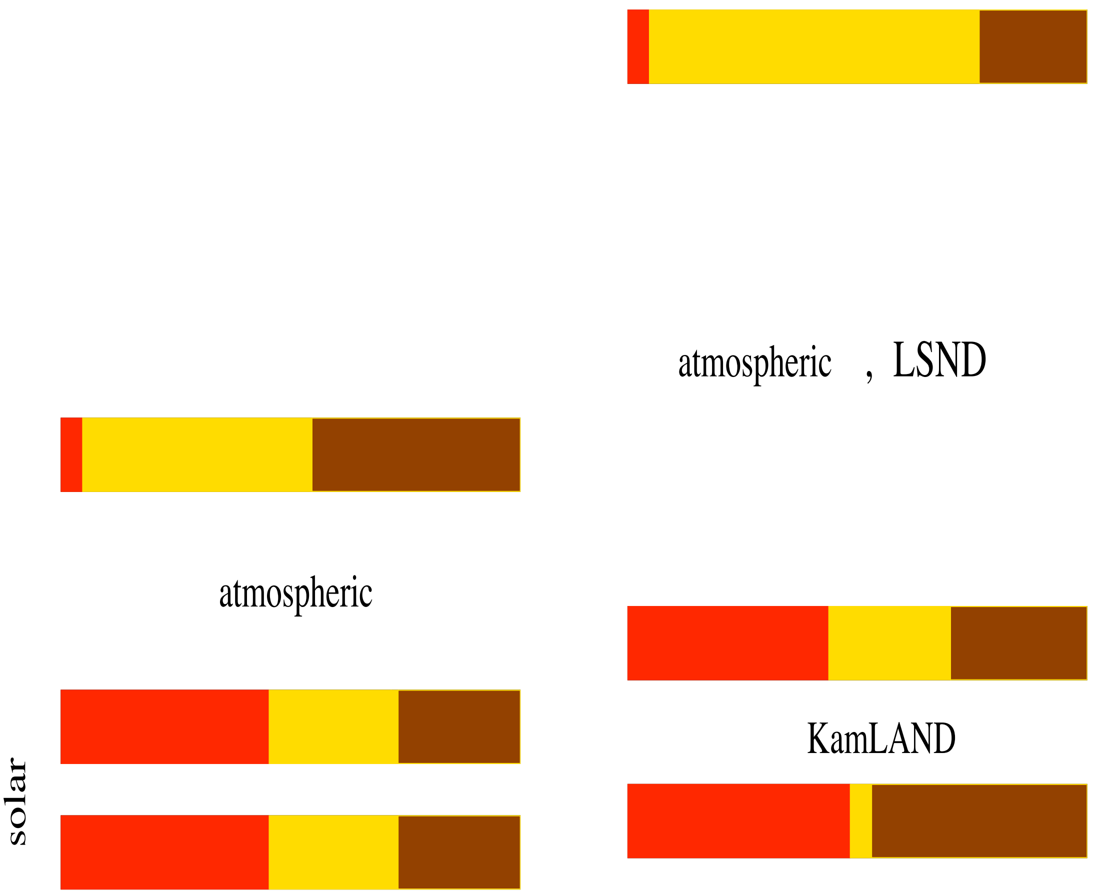
But: Kamland: (2002)

$\bar{\nu}_e$ disappear with $\Delta \bar{m}^2$ consistent with solar Δm^2;
this ~~CPT~~ scenario: disfavoured.

~~CPT~~ version 2

Barenboim et al. 2002
Strumia 2002

neutrinos   anti-neutrinos



- atmospheric ν_μ oscillate with $\Delta m^2_{31} \equiv \Delta m^2_{\rm atm}$
- atmospheric $\bar{\nu}_\mu$ with $\Delta \bar{m}^2_{31} \equiv \Delta m^2_{\rm LSND}$
- Kamland $\bar{\nu}_e$ disappear with $\Delta \bar{m}^2$ consistent with solar Δm^2

➡ A dedicated global fit is needed.

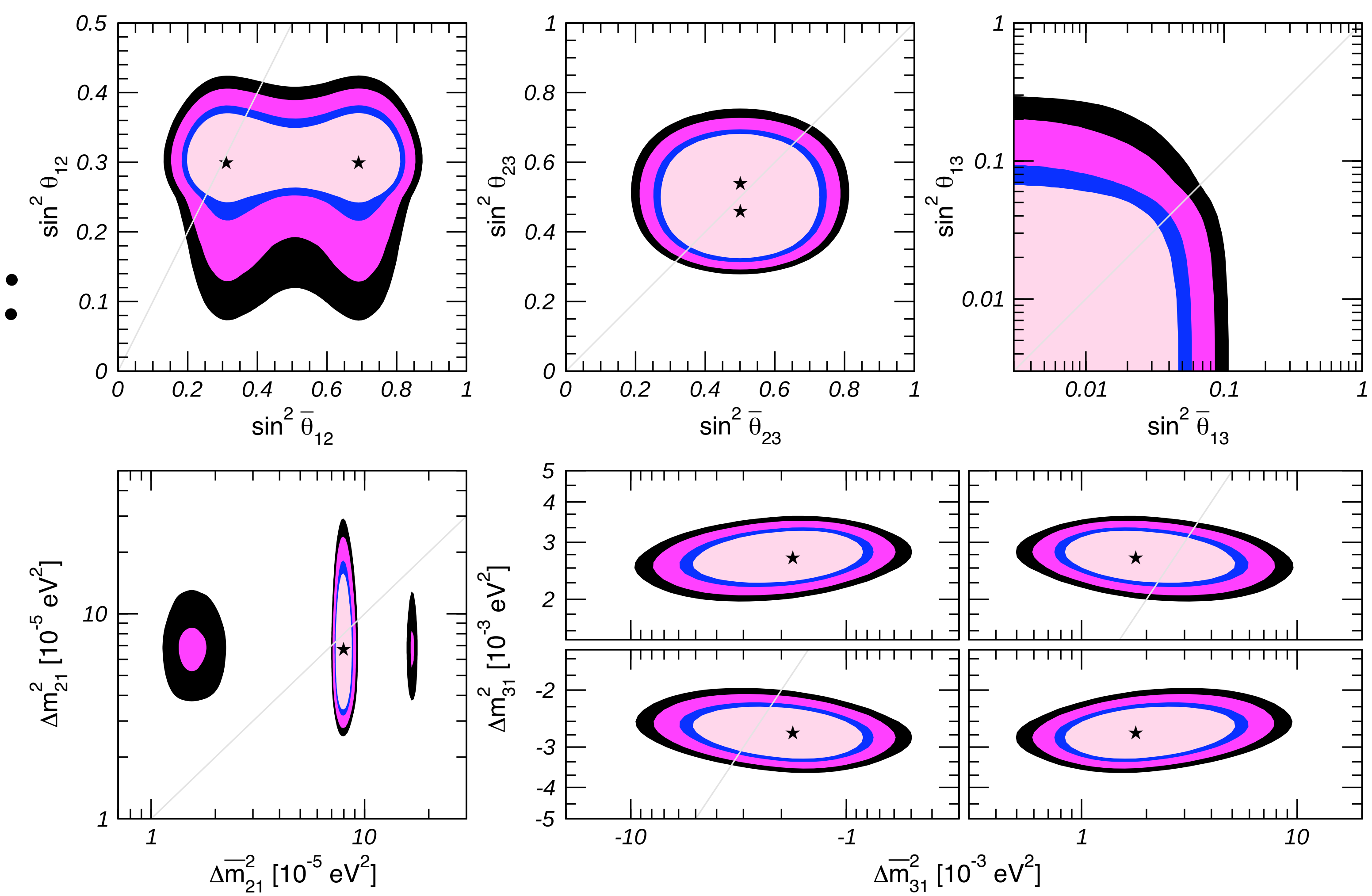
~~CPT~~ global fit

Gonzalez-Garcia, Maltoni, Schwetz 2003
updated in Gonzalez-Garcia, Maltoni 2007

First: all data but LSND: best fit is very close to CPT conserving

$$\begin{aligned} \Delta m^2_{21} &= 6.8 \times 10^{-5}\ \text{eV}^2\,, & \Delta \bar{m}^2_{21} &= 7.9 \times 10^{-5}\ \text{eV}^2\,, \\ |\Delta m^2_{31}| &= 2.7 \times 10^{-3}\ \text{eV}^2\,, & |\Delta \bar{m}^2_{31}| &= 1.8 \times 10^{-3}\ \text{eV}^2\,, \\ \sin^2\theta_{12} &= 0.30\,, & \sin^2\bar{\theta}_{12} &= 0.31 \text{ or } 0.69\,, \\ \sin^2\theta_{13} &= 0\,, & \sin^2\bar{\theta}_{13} &= 0\,, \\ \sin^2\theta_{23} &= 0.46 \text{ or } 0.54\,, & \sin^2\bar{\theta}_{23} &= 0.5\,. \end{aligned}$$

Then: how much ~~CPT~~ is allowed by all-but-LSND data:



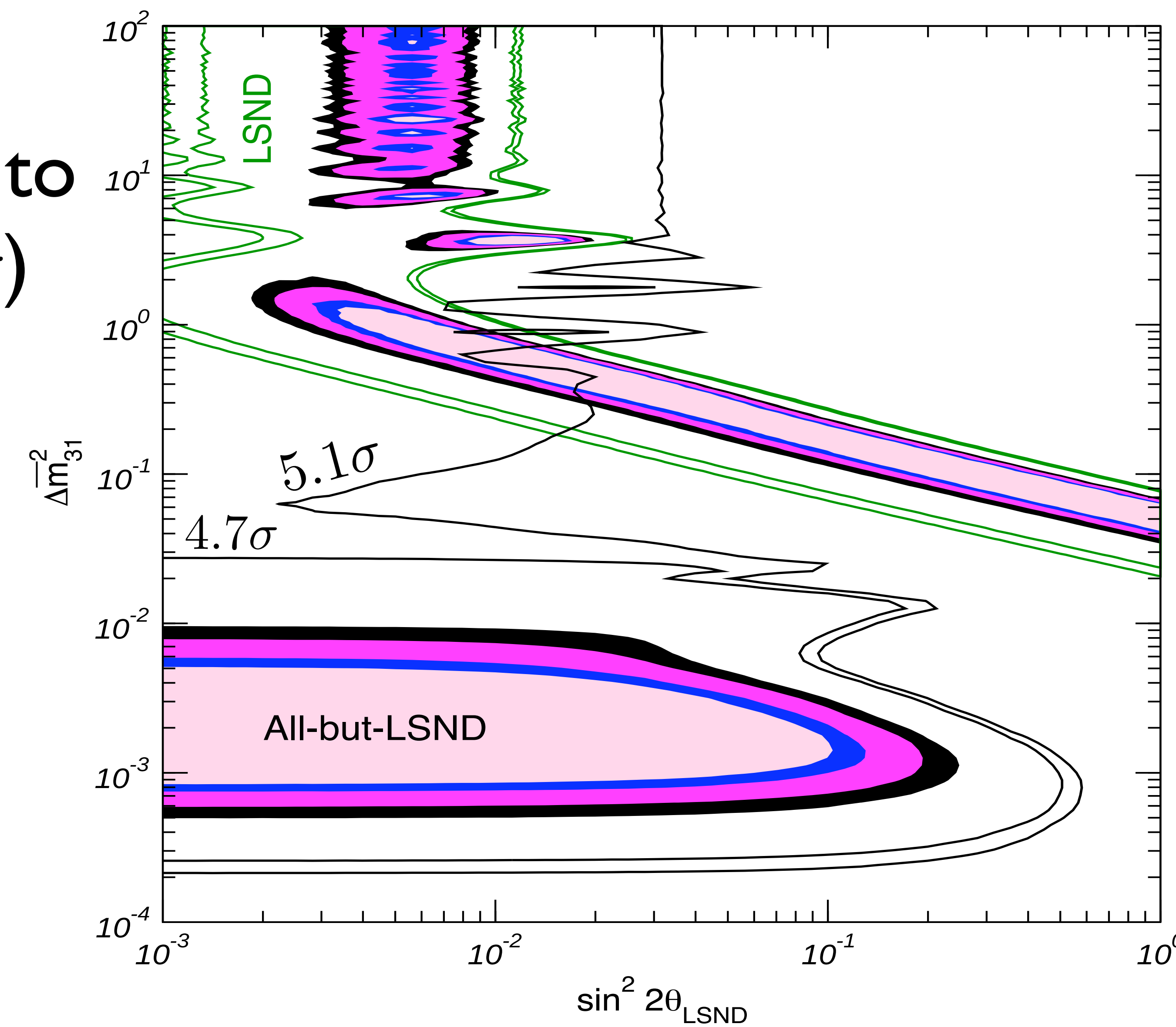
~~CPT~~ global fit

Gonzalez-Garcia, Maltoni, Schwetz 2003
updated in Gonzalez-Garcia, Maltoni 2007

Finally: compare with LSND:

disagreement mainly due to $\Delta\bar{m}^2_{31} < 10^{-2}\text{eV}^2$ (at 3σ)

agreement is possible at $> 4.7\sigma$ only



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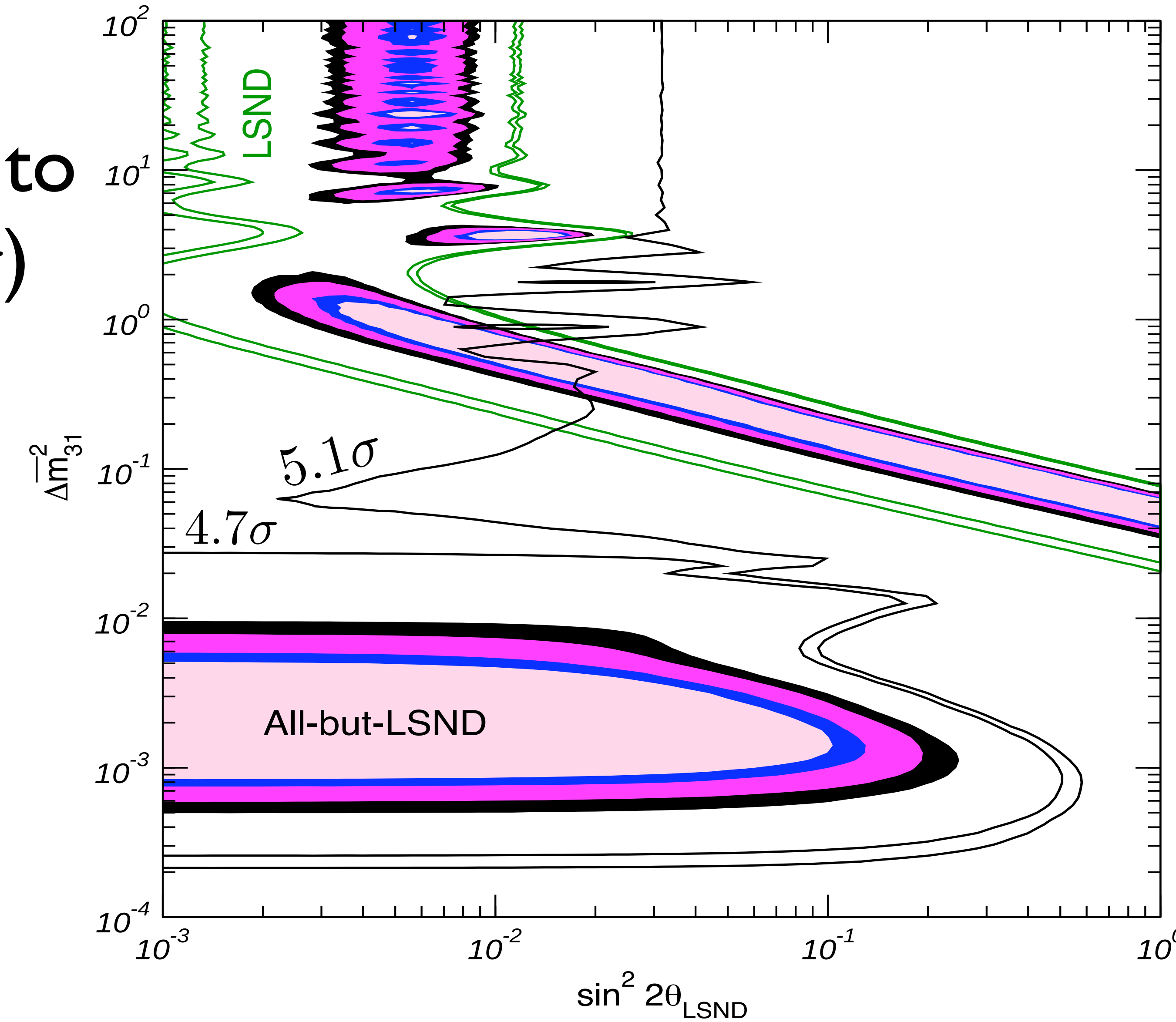


~~CPT~~ cannot account for LSND + all-but-LSND.

~~CPT~~ + one sterile neutrino?? Barger, Marfatia, Whisnant 2003

viable mass schemes exist; not affected by MiniBooNE ν data.

MiniBooNE $\bar{\nu}$ channel could discriminate between them.

Sterile Neutrinos

Basics

The SM provides 3 neutrinos $\Longrightarrow$ 2 independent Δm^2

(m_1, m_2, m_3)

$$\Delta m^2_{\rm Sun} = 8^{+0.3}_{-0.3} \cdot 10^{-5}\,{\rm eV}^2\,, \quad \Delta m^2_{\rm Atm} = 2.5^{+0.2}_{-0.2} \cdot 10^{-3}\,{\rm eV}^2$$

If anything requires $\Delta m^2 \neq \Delta m^2_{\rm Sun,Atm} \Longrightarrow$ 1 extra neutrino with no SM interactions (Z-width): "sterile"

LSND is such a case. Okada, Yasuda 1996, Bilenky et al 1998, Barger 2000...

But also:
- r-process nucleosynthesis G.Fuller >2000, G.McLaughlin 2006
- pulsar kicks A.Kusenko >1997
- solar flux modulation Caldwell, Sturrock 2005
- ...

Basics

From the theory point of view: any fermion with no SM gauge interactions is a sterile neutrino

SM +	→	right handed ν
"mirror world"	→	mirror fermion
string theory	→	modulino
global sym in SuSY	→	goldstino
...		...

Nothing forbids its mixing with active neutrinos

$$\mathcal{L} \supset \frac{M}{2}\nu_s^2 + \frac{m_D}{v}\nu_s L H$$

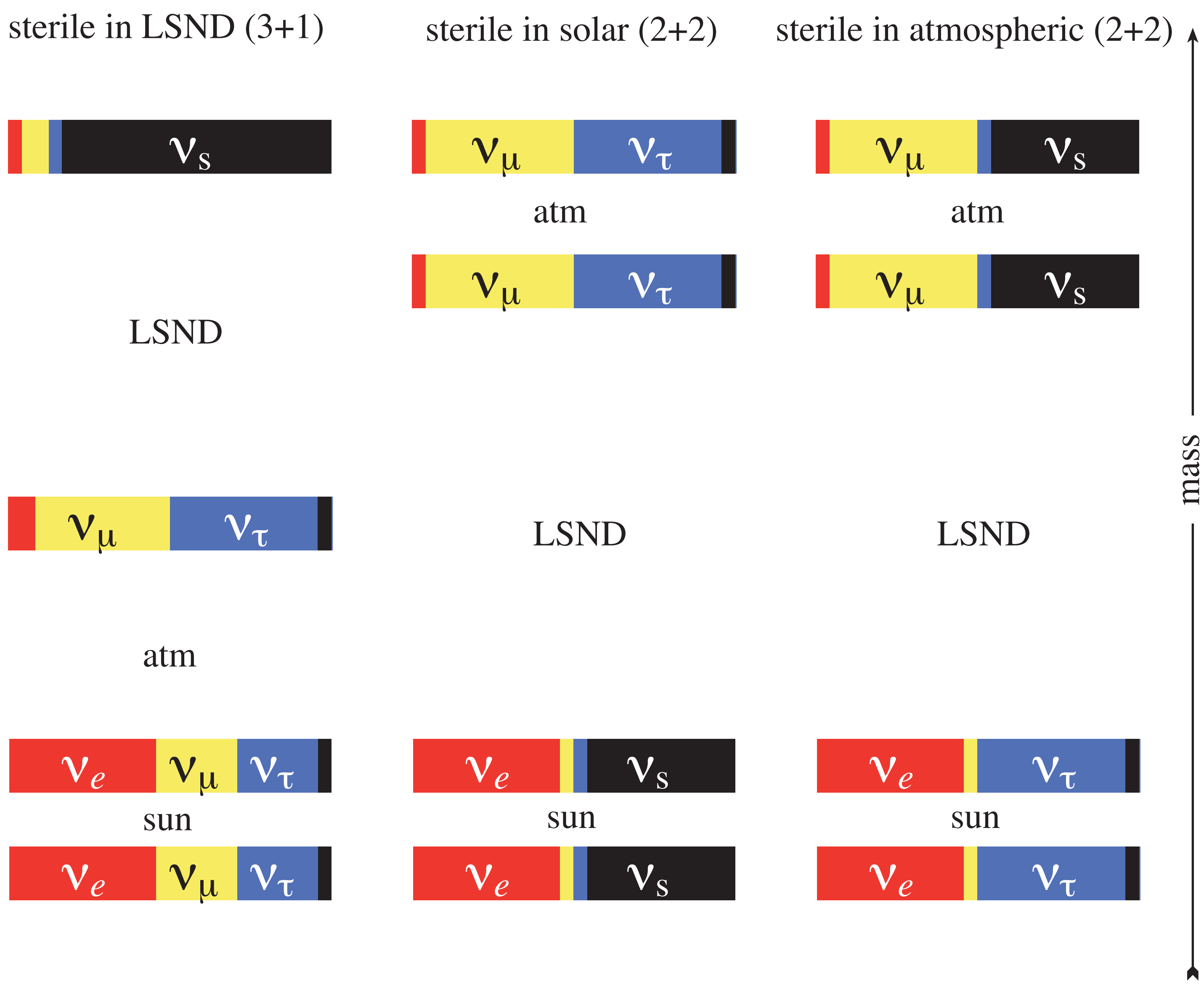
effectively parameterized by its mass and mixing angle(s)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = V \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Steriles and LSND

Mass schemes:

"3+1" "2+2"



Strumia, Vissani review

Steriles and LSND

Mass schemes:

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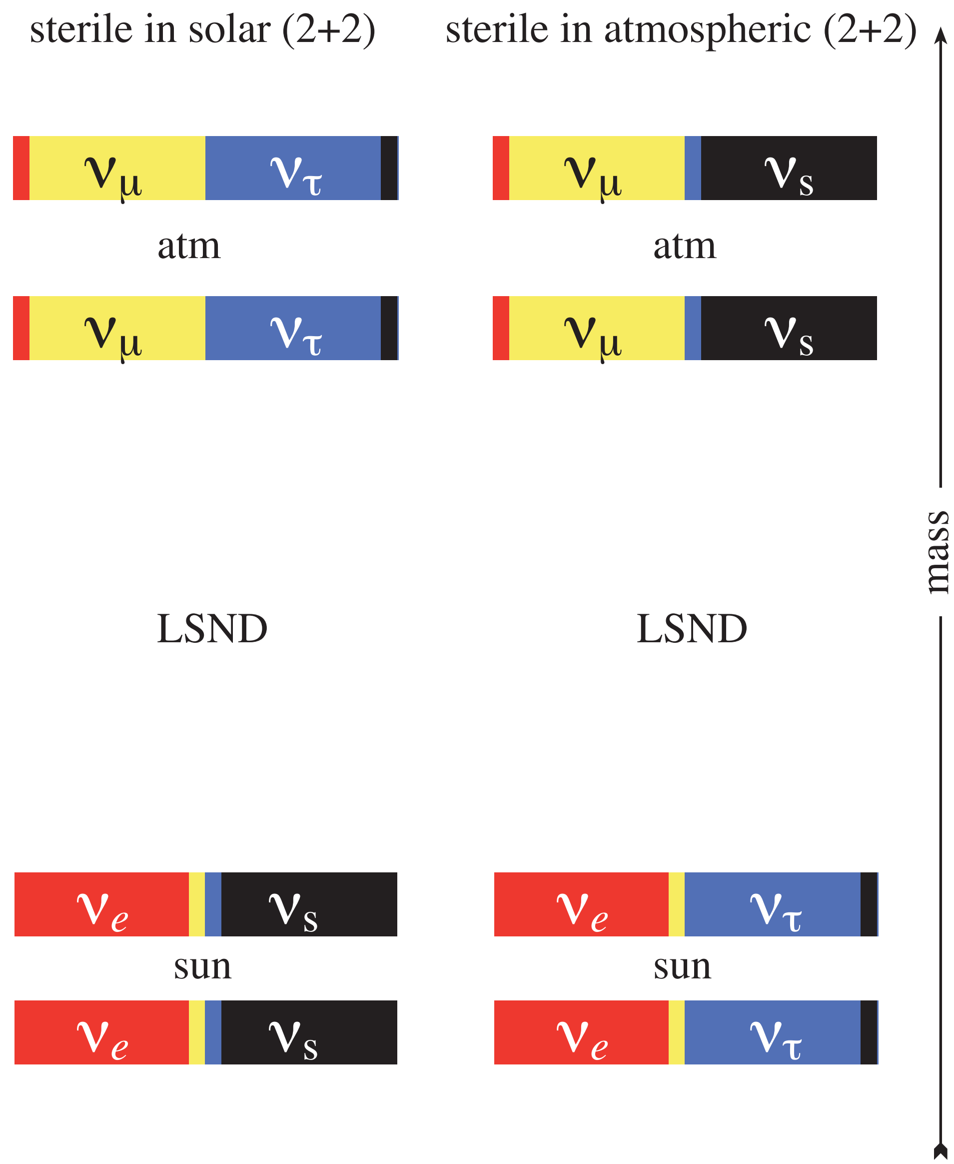
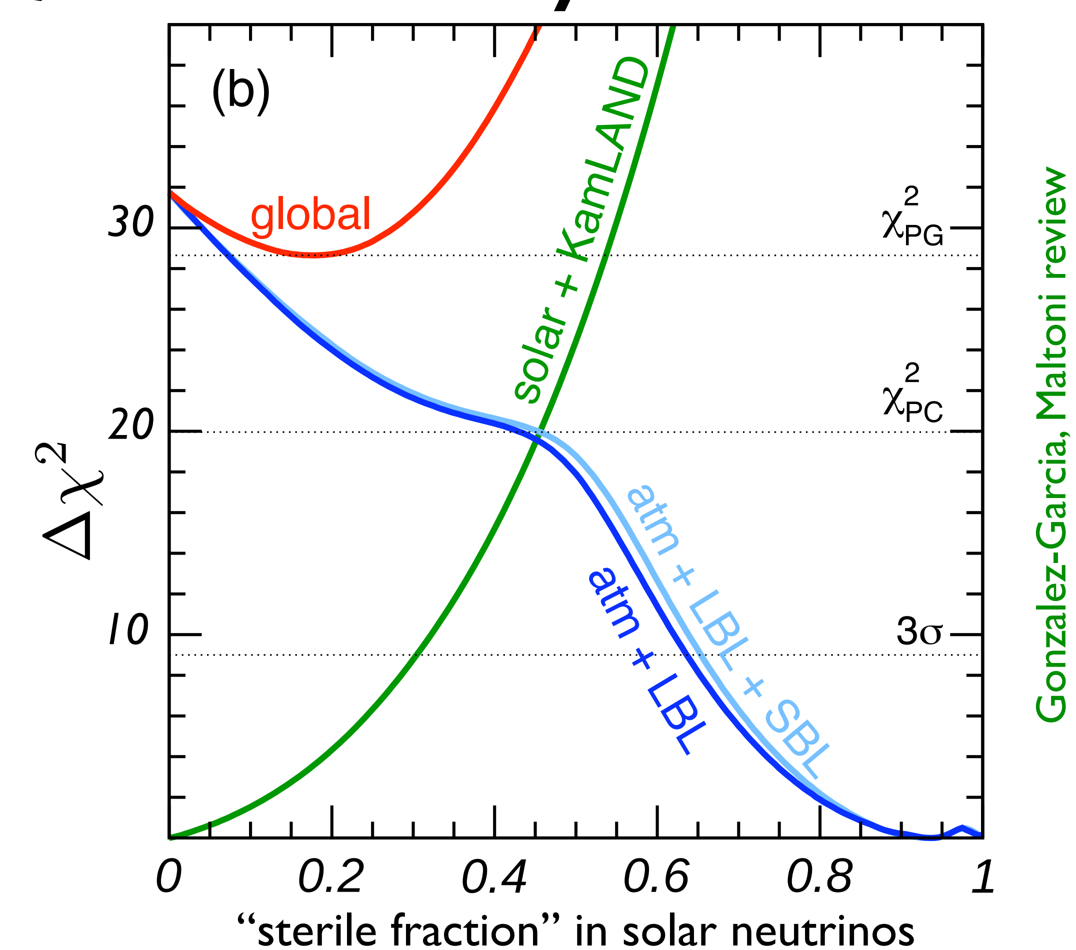


ν_s has a role in

solar: excluded by SNO $\nu_e \to \nu_{\mu,\tau}$

atmo: excluded by SK $\nu_\mu \to \nu_\tau$

Quantitatively:



Steriles and LSND

Mass schemes:

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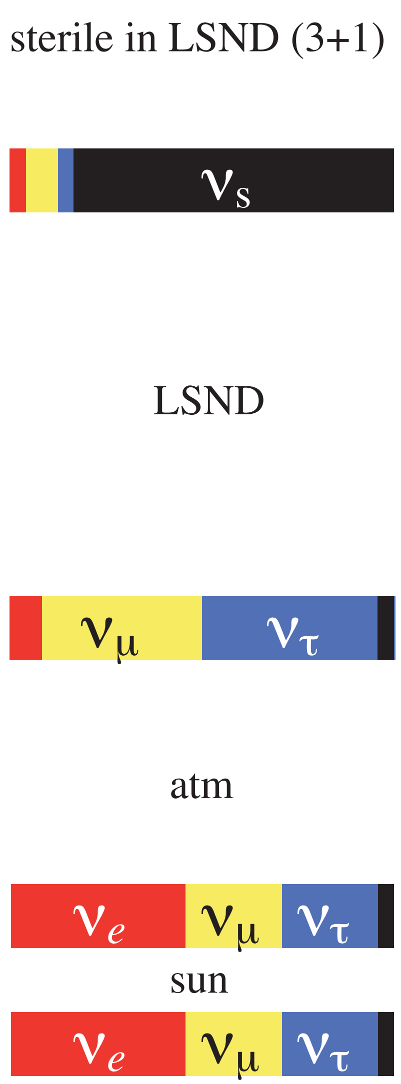

$$\bar{\nu}_\mu \longrightarrow \bar{\nu}_{\rm s} \longrightarrow \bar{\nu}_e$$

$$P_{\mu e} = \sin^2 2\theta_{\mu s} \sin^2 2\theta_{es} \sin^2\left(\frac{\Delta m^2_{\rm LSND} L}{4E_\nu}\right)$$

constraints on individual angles
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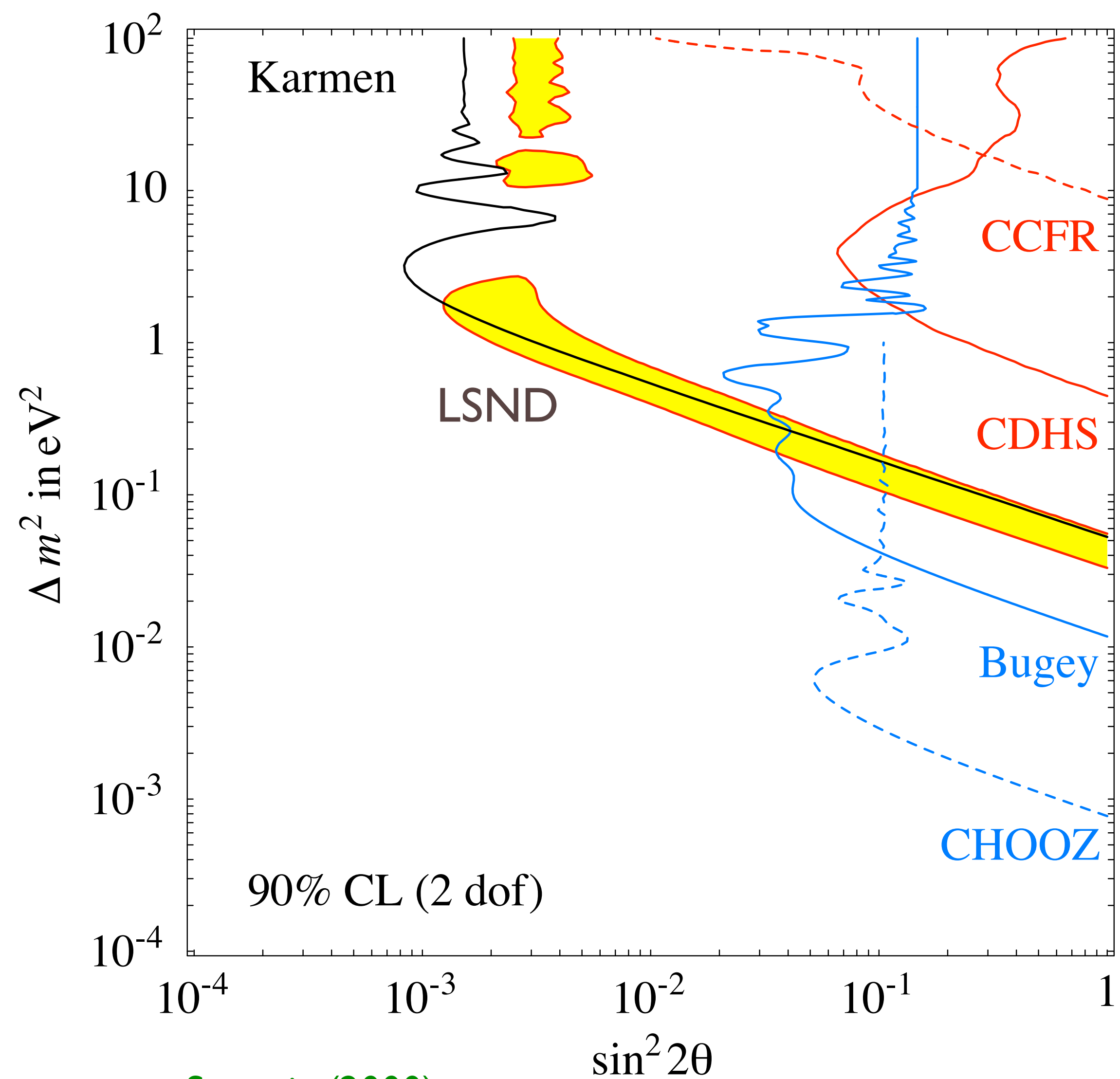

Strumia (2000)

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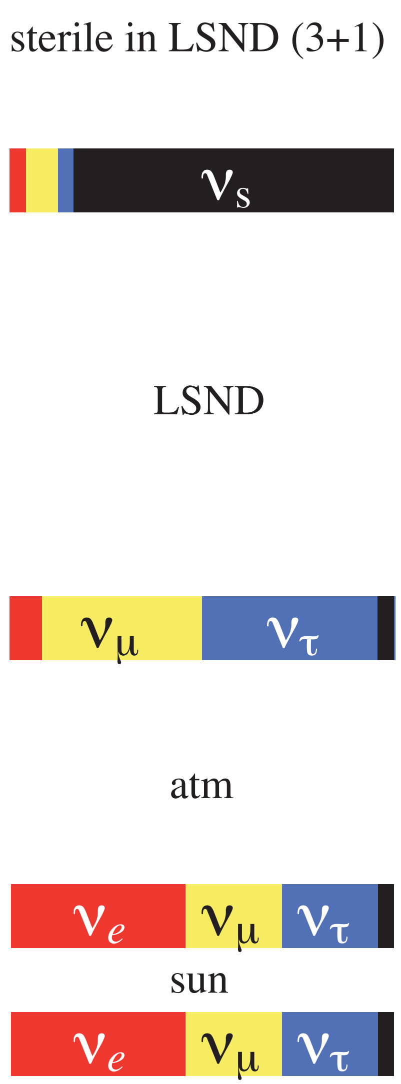

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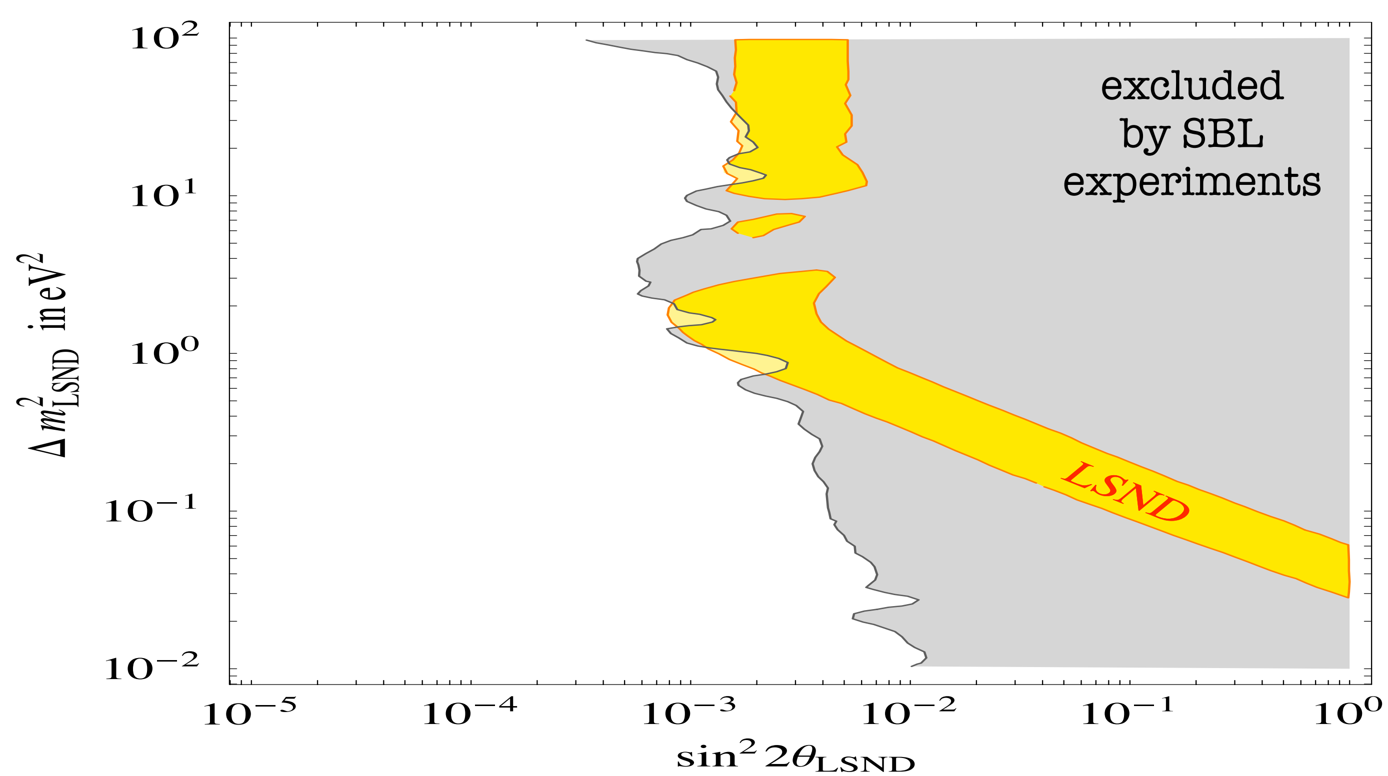

LSND islands barely survive
(bad goodness of fit (more later))

Steriles and cosmology

Cosmology constrains number and masses of neutrinos.

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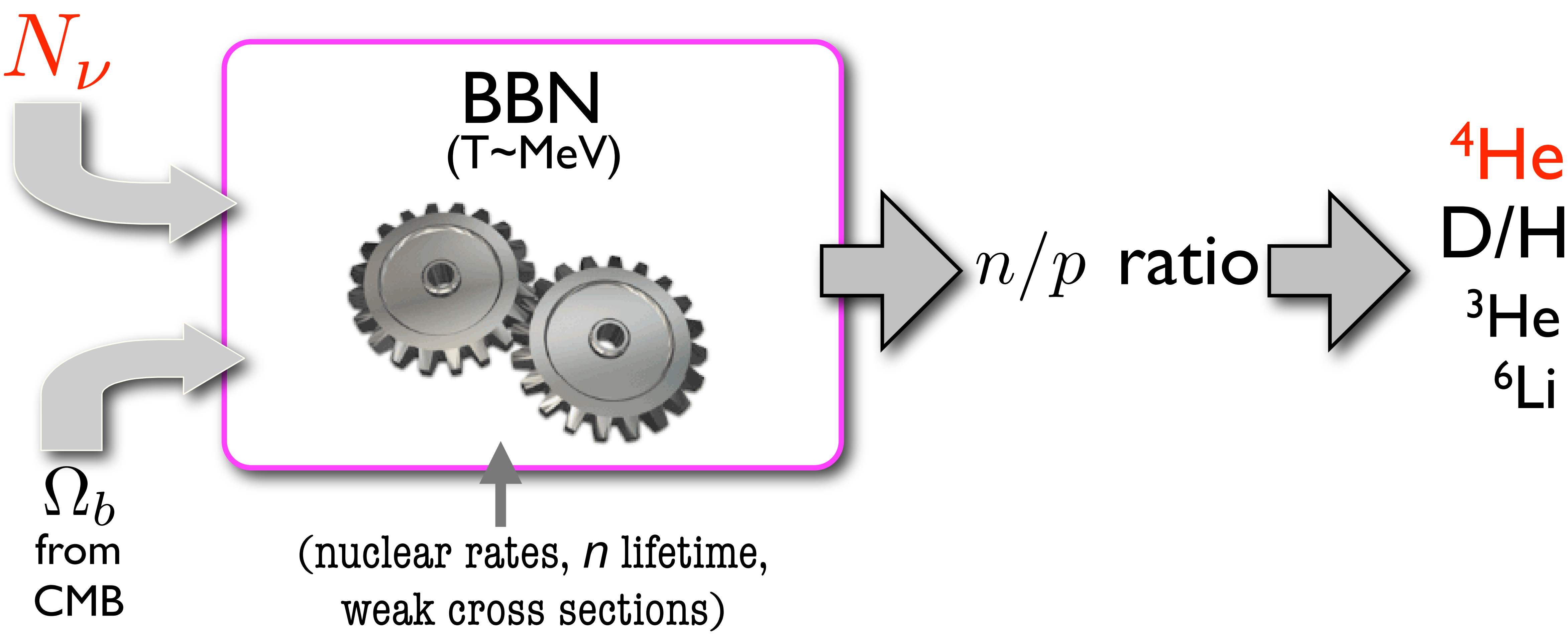
BigBang Nucleosynthesis:



(i) more neutrinos $\Longrightarrow$ faster expansion $\Longrightarrow$ more He

(ii) $\nu_e \longrightarrow \nu_s$ deplete $\nu_e \Longrightarrow$ modified weak rates $\Longrightarrow$ more He

(e.g. $\Gamma(n\,\nu_e \longleftrightarrow p\,e^-)$)

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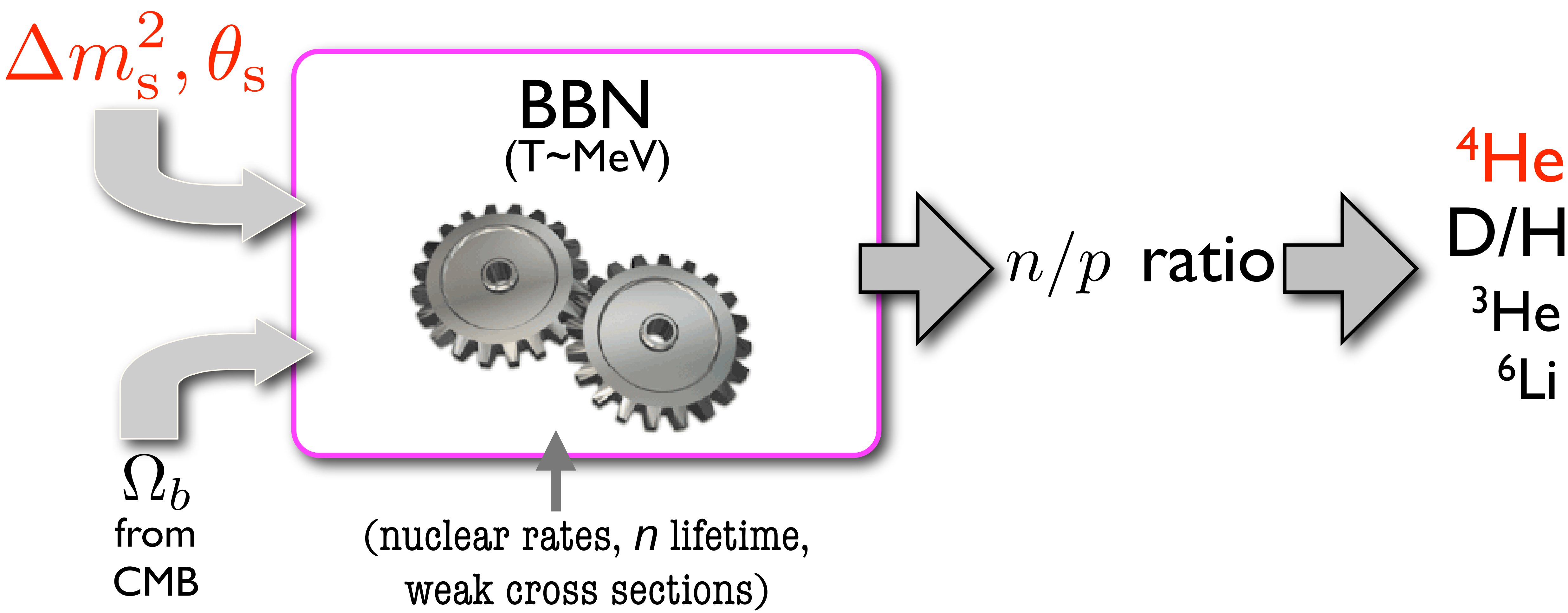

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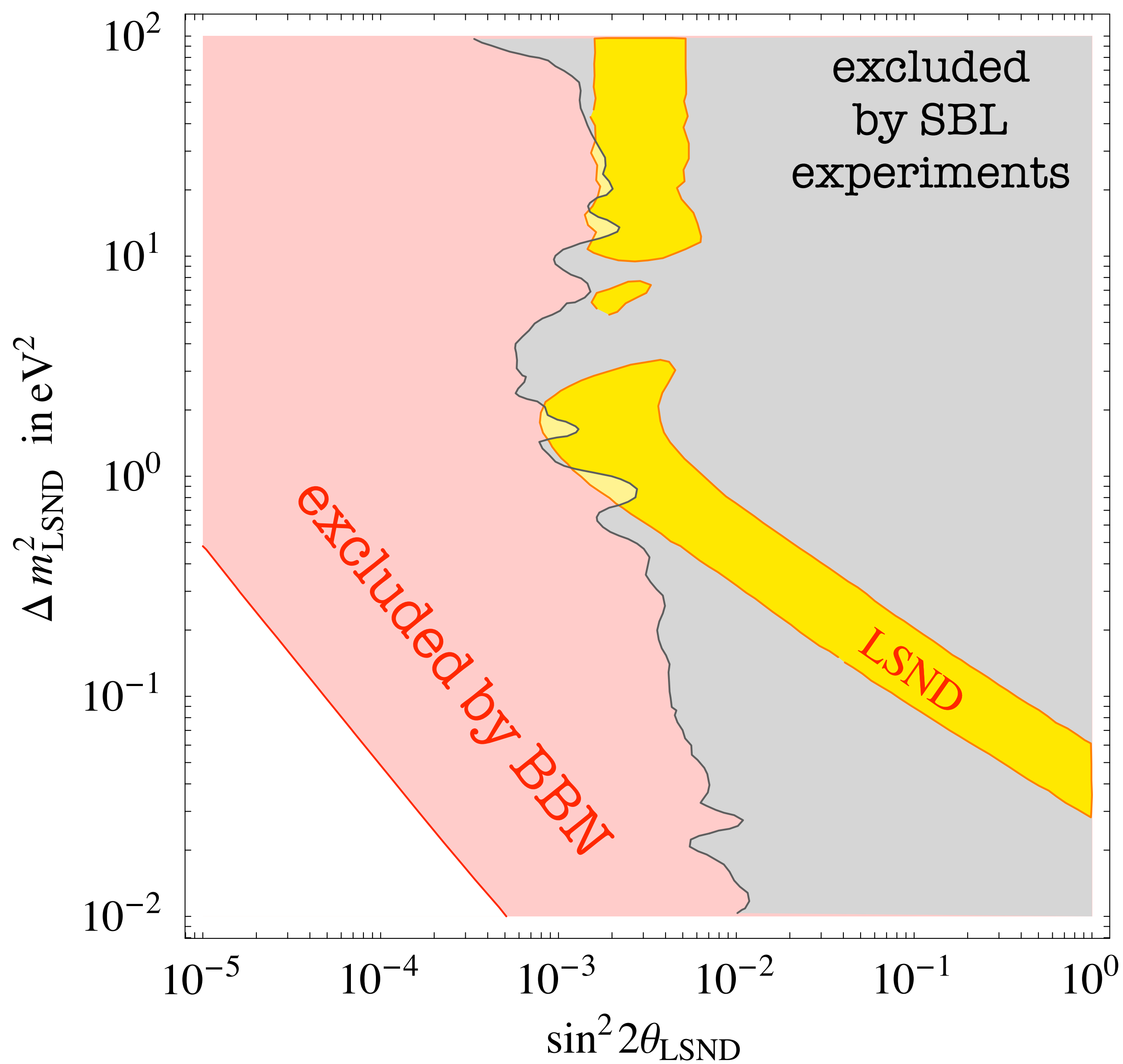

Cirelli, Marandella, Strumia, Vissani 2004
Di Bari et al. 2000

having taken conservatively

^{4}He $= 0.25 \pm 0.01$

Particle Data Group 2006

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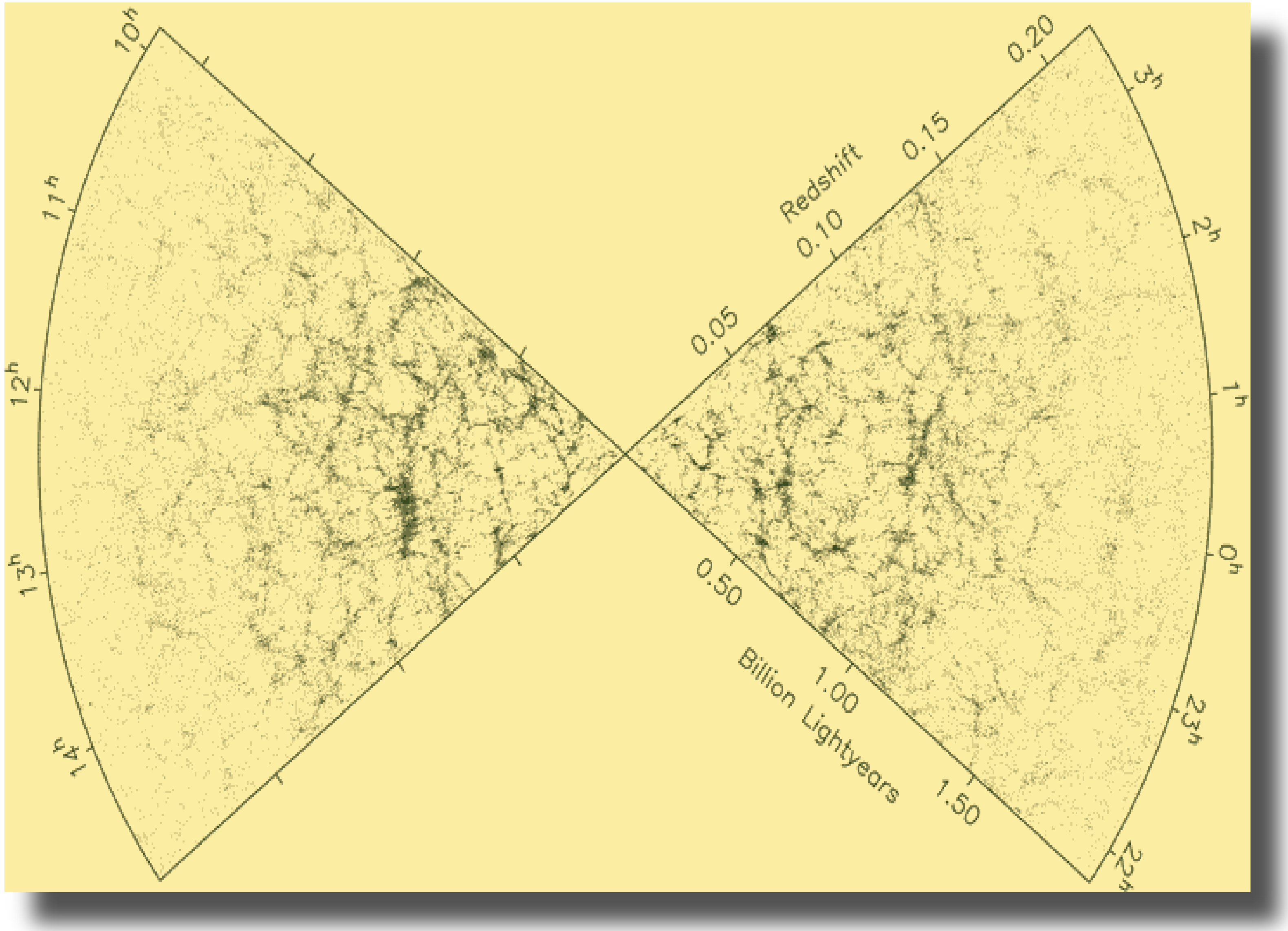
Galaxy Surveys:



2dF Galaxy Redshift Survey

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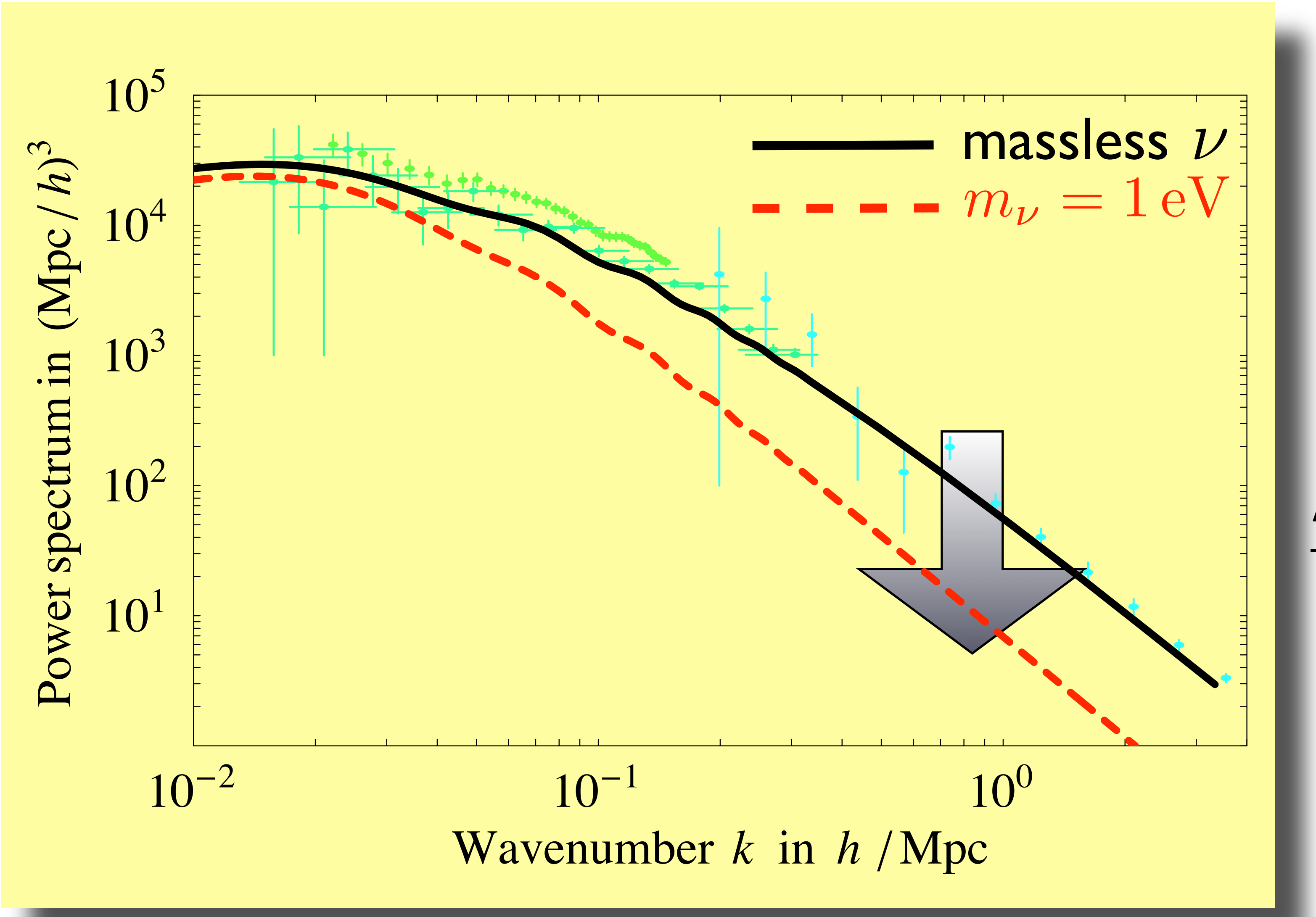

$$\frac{\Delta P}{P} \simeq -8 \frac{\sum m_\nu}{93\,\mathrm{eV}^2 \Omega_m h^2}$$

massive neutrinos free stream out of the forming structures,

i.e. smoothen small inhomogeneities,

i.e. suppress power on small scales

Steriles and cosmology

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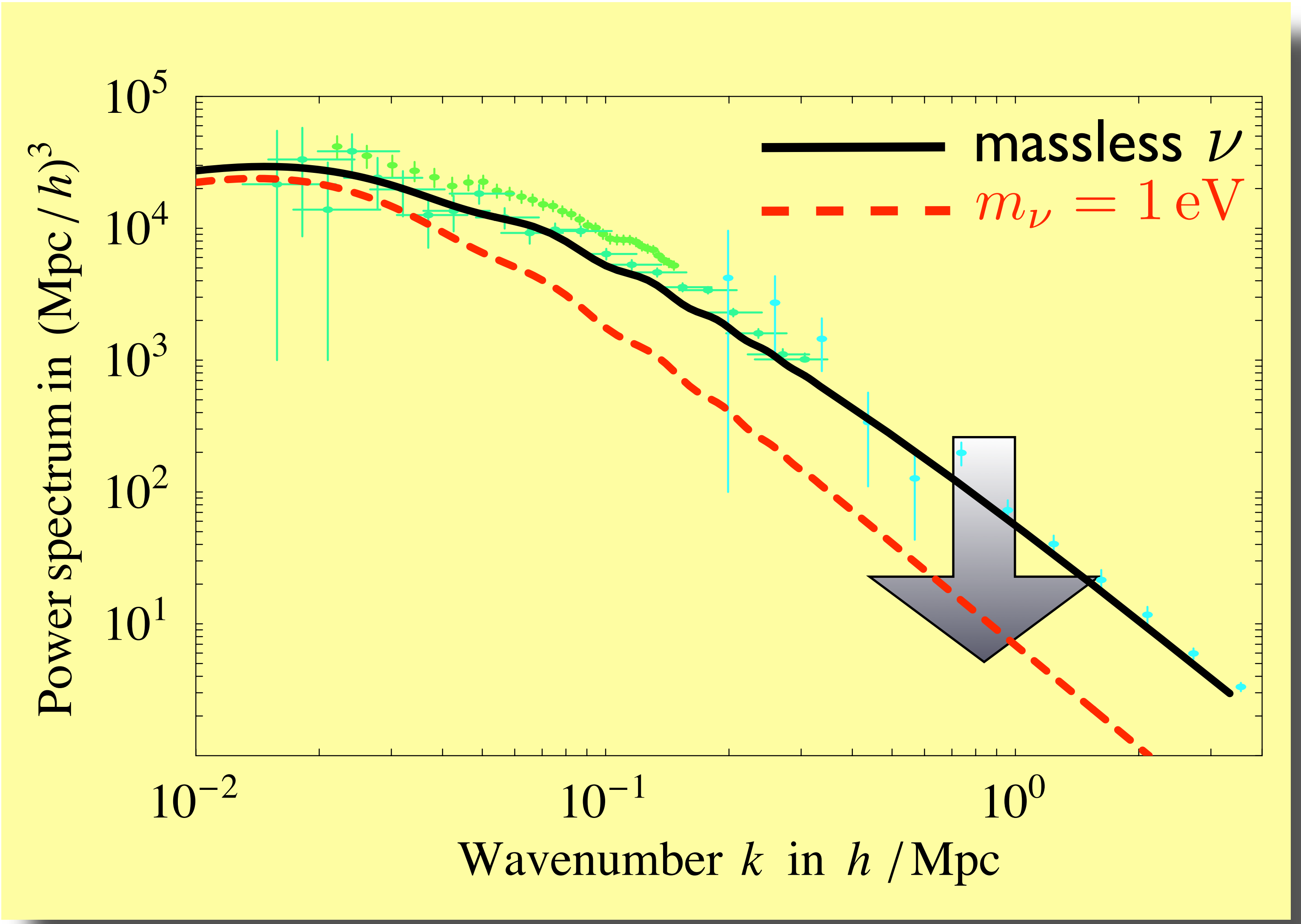

a bound on $\sum m_\nu$, including sterile neutrinos!

conservatively $\sum m_\nu < 0.73\,\mathrm{eV}$ (99.9% C.L.)

Cirelli, Strumia 2006
+ many others

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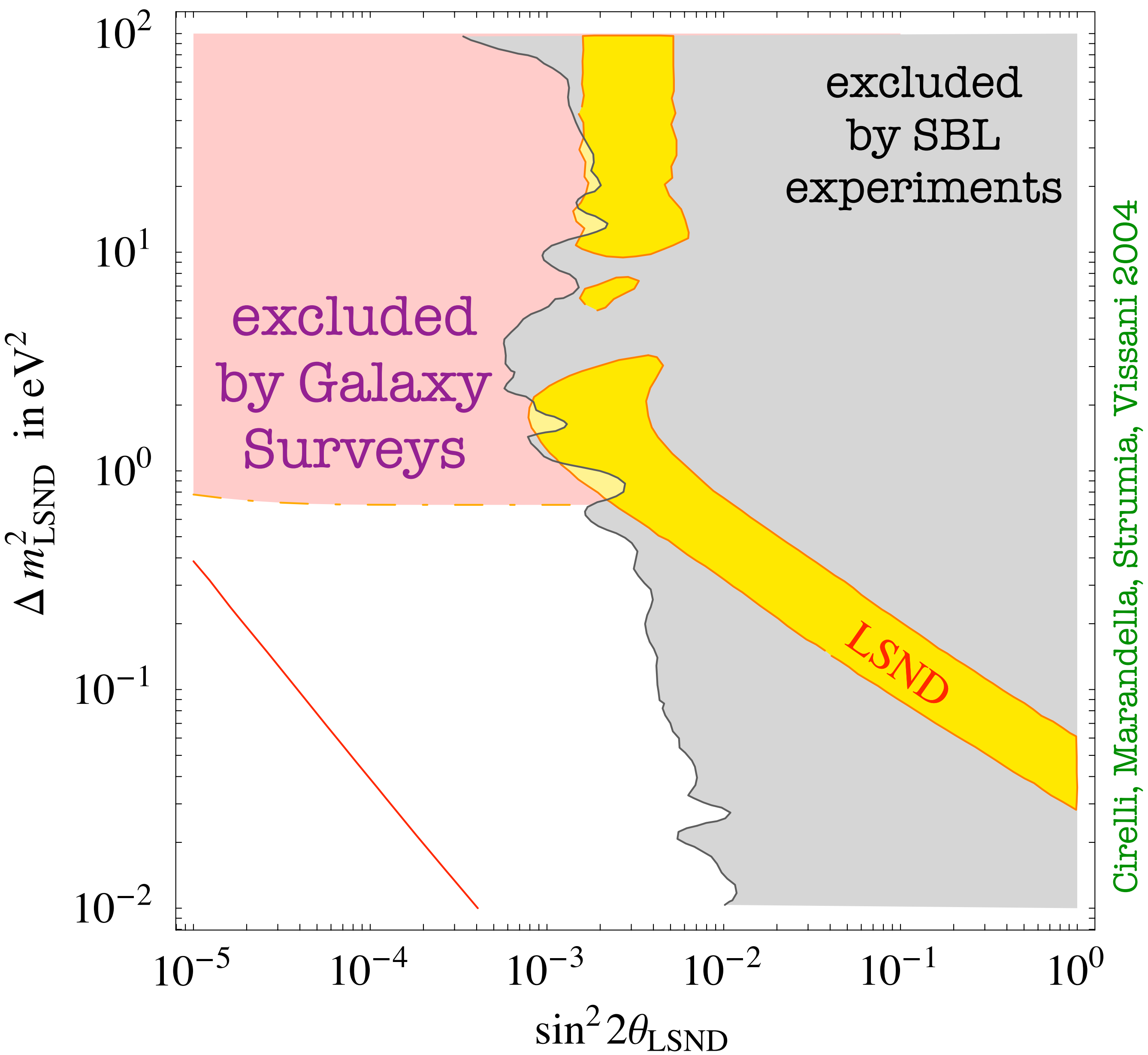

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- low T_{RH} scenarios (the Universe exited from inflation very late)

  Gelmini et al. 2004

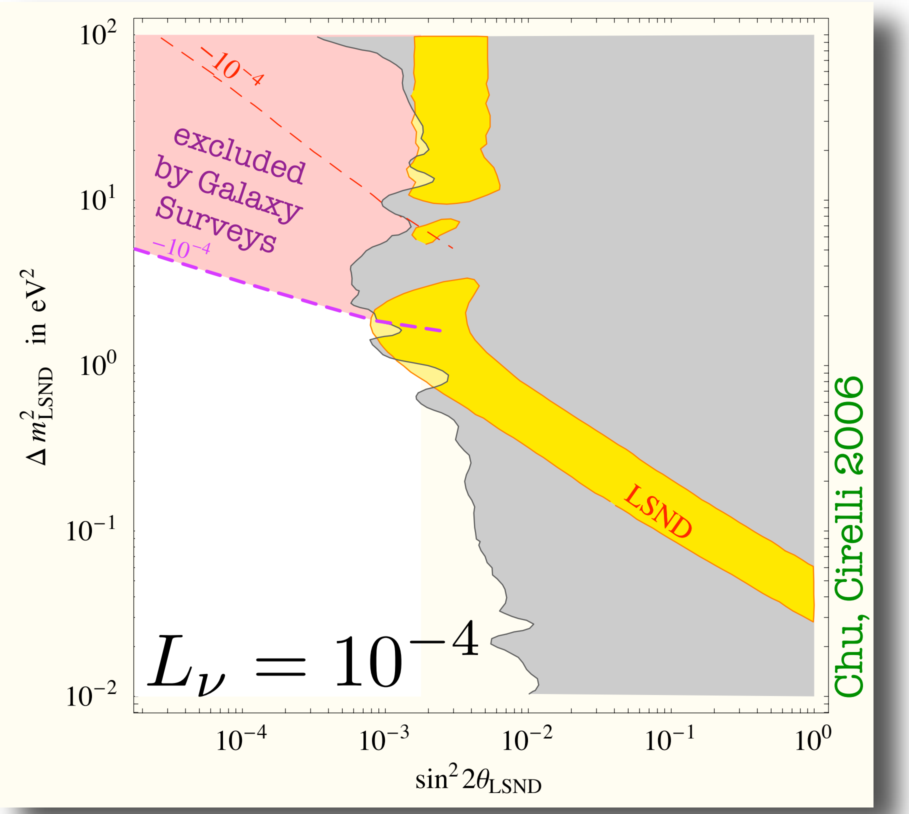
- exotic neutrino interactions (all neutrinos in the Universe decayed into scalars)

  Beacom et al. 2003

- large leptonic asymmetry

$$L_\nu = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$$

Foot, Volkas 1995



Chu, Cirelli 2006

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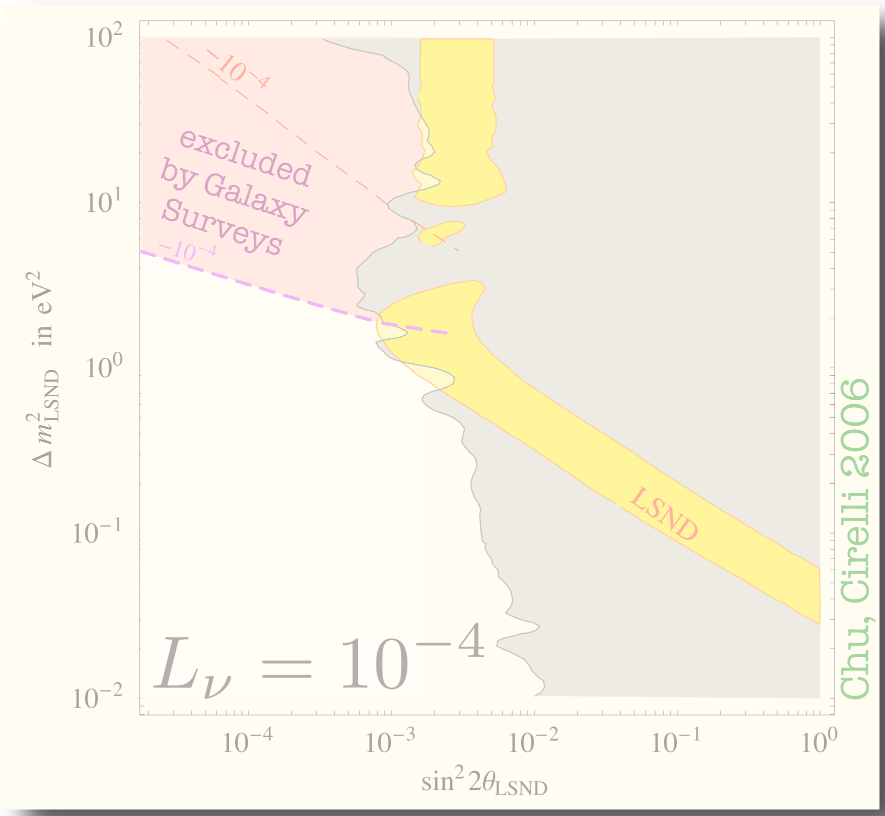


Q. Do they carry an uncertainty? Yes (statistical & methodological).

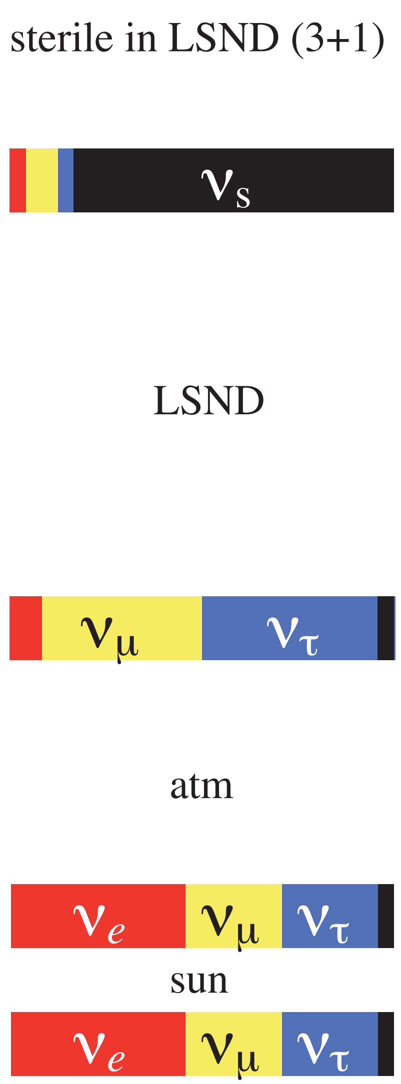
The discussed limits are conservative.

Future data will reduce all errors.

Steriles and LSND

Mass schemes:

"3+1"



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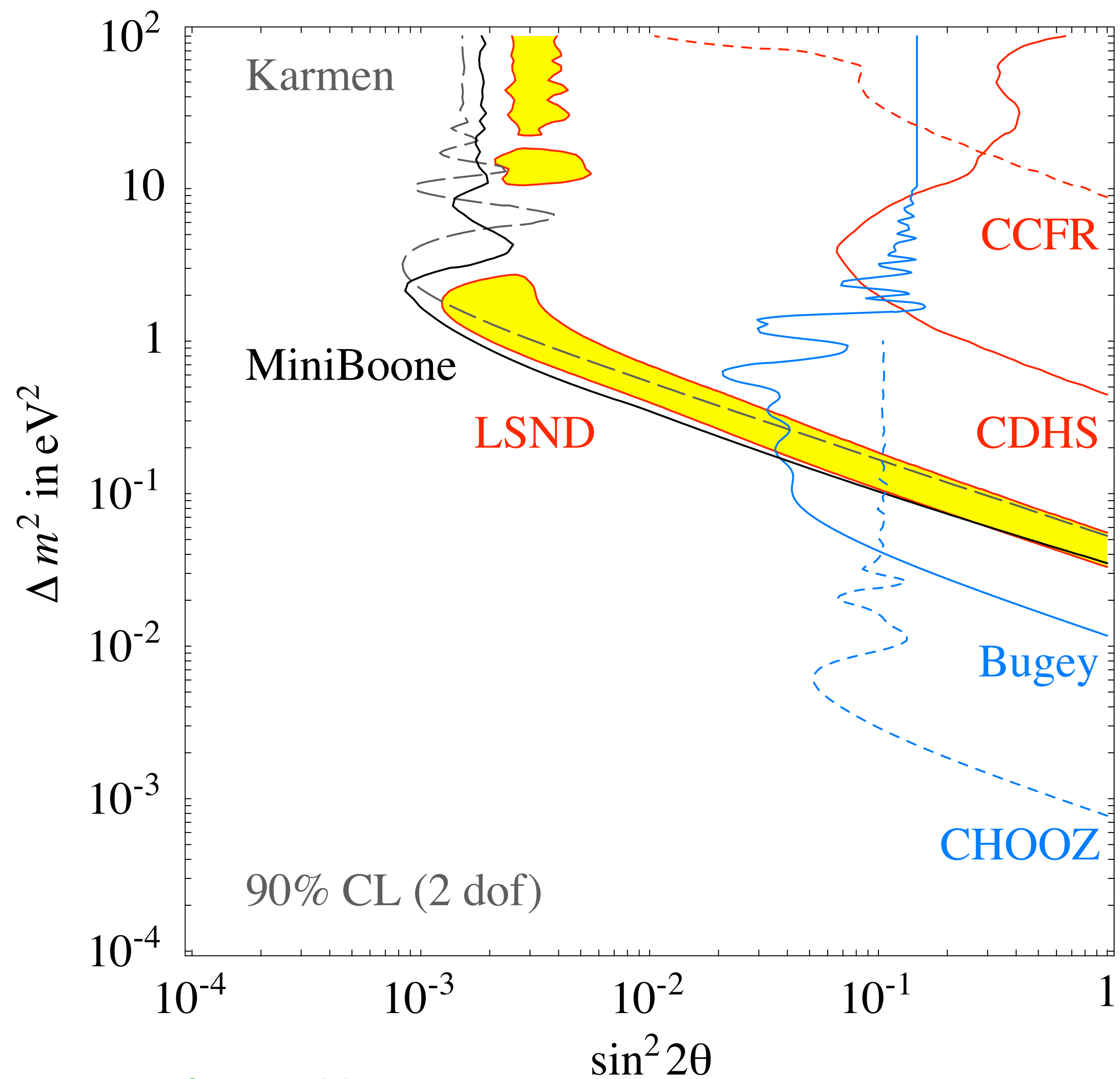

Strumia, Vissani review

Global fit:

$$\chi^2 = 24.7 \ (2 \text{ dof})$$

incompatible at $\gtrsim 4\,\sigma$

Maltoni, Schwetz 2007 (0705.0107)

Steriles and LSND

Mass schemes:

“3+2”

Sorel, Conrad, Shaevitz (2004)

$$\Delta m^2_{15} \simeq 22 \text{ eV}^2$$
$$\Delta m^2_{14} \simeq 0.9 \text{ eV}^2$$

Not a big improvement: the 2nd sterile adds disappearance channel for $\nu_{e,\mu}$, tension with Bugey, Chooz etc is exacerbated.

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Even more so after **MiniBooNE**.

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the extra CP phase δ allows $\bar{\nu}$ (LSND) $\neq \nu$ (MiniBooNE)

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \propto \cos\left(\frac{\Delta m^2_{54} L}{E} \mp \delta_{\rm CP}\right)$$

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Maltoni, Schwetz 2007

The bounds from standard cosmology *apply* + *apply*.

Mass Varying Neutrinos

Basics

Scale of neutrino masses: $\sqrt{\Delta m^2_{\rm Sun}} \simeq 8\ 10^{-3}\,\rm eV$

Dark Energy current density: $\sqrt[4]{\rho_{\rm de}} \simeq 2\ 10^{-3}\,\rm eV$

Maybe they are coupled, maybe they "track" each other:

$$m_\nu \rightsquigarrow m_\nu(\mathcal{A})$$

Fardon, Nelson, Weiner 2003
Hung 2000 - Gu, Wang, Zhang 2003

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Potential energy of the system:

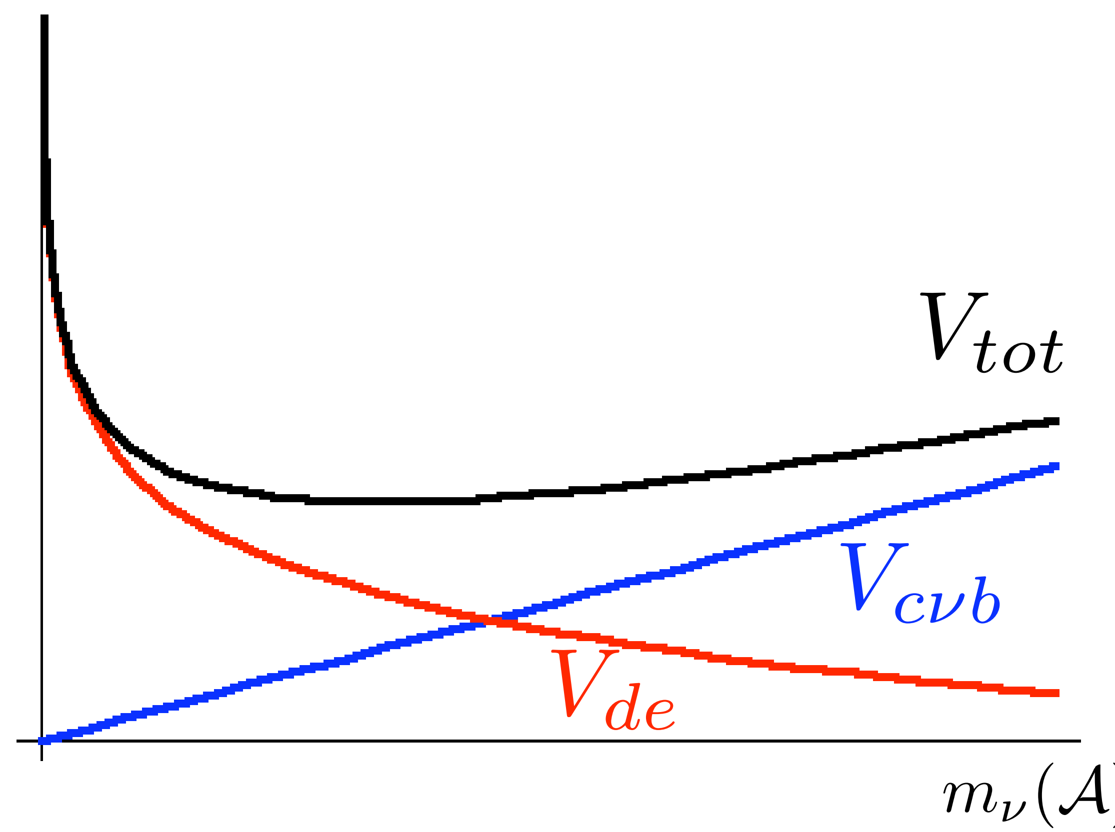
$$V_{\rm tot} = V_{\rm de} + V_{c\nu b}$$

$$V_{c\nu b} = m_\nu(\mathcal{A})\, n_{c\nu b}$$

$$V_{\rm de} = \Lambda^4 \log(\mu/m_\nu)$$

minimization:

$$\frac{dV_{\rm tot}(m_\nu)}{dm_\nu} \equiv 0 \Longrightarrow\ m_\nu = \frac{\Lambda^4}{n_{c\nu b}}$$



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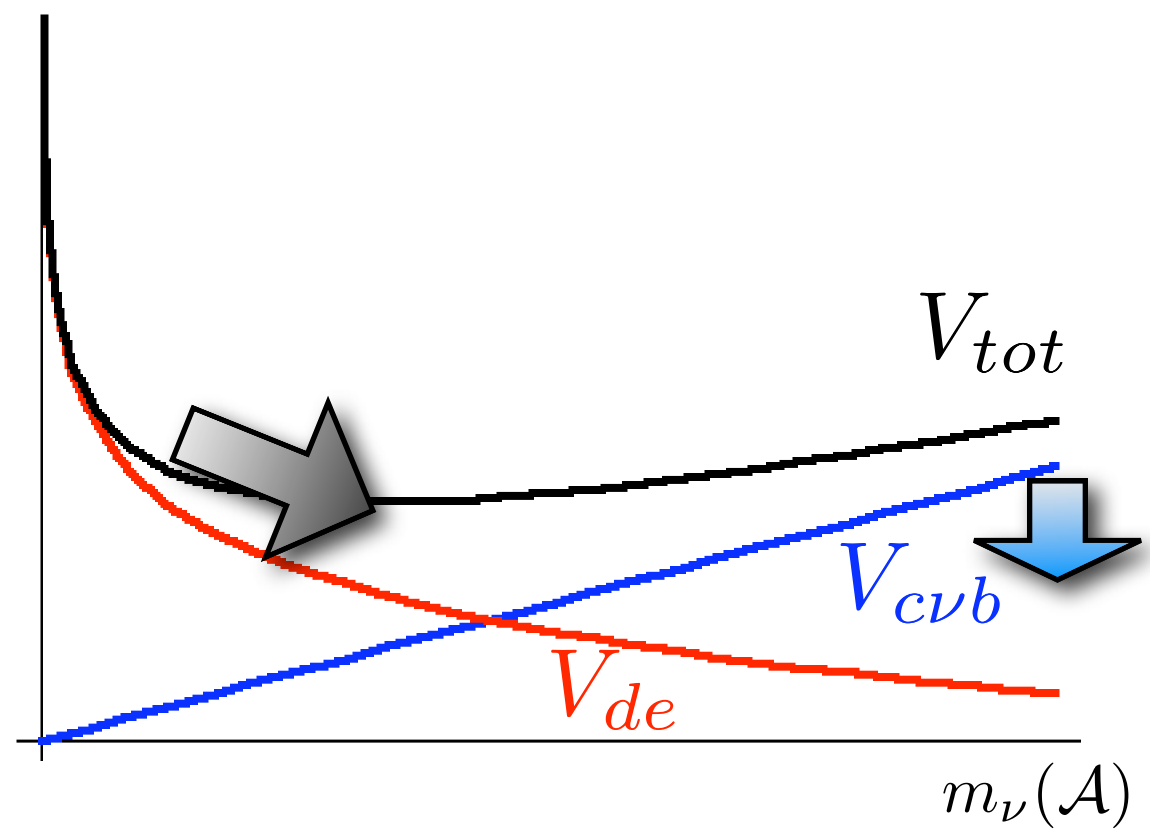

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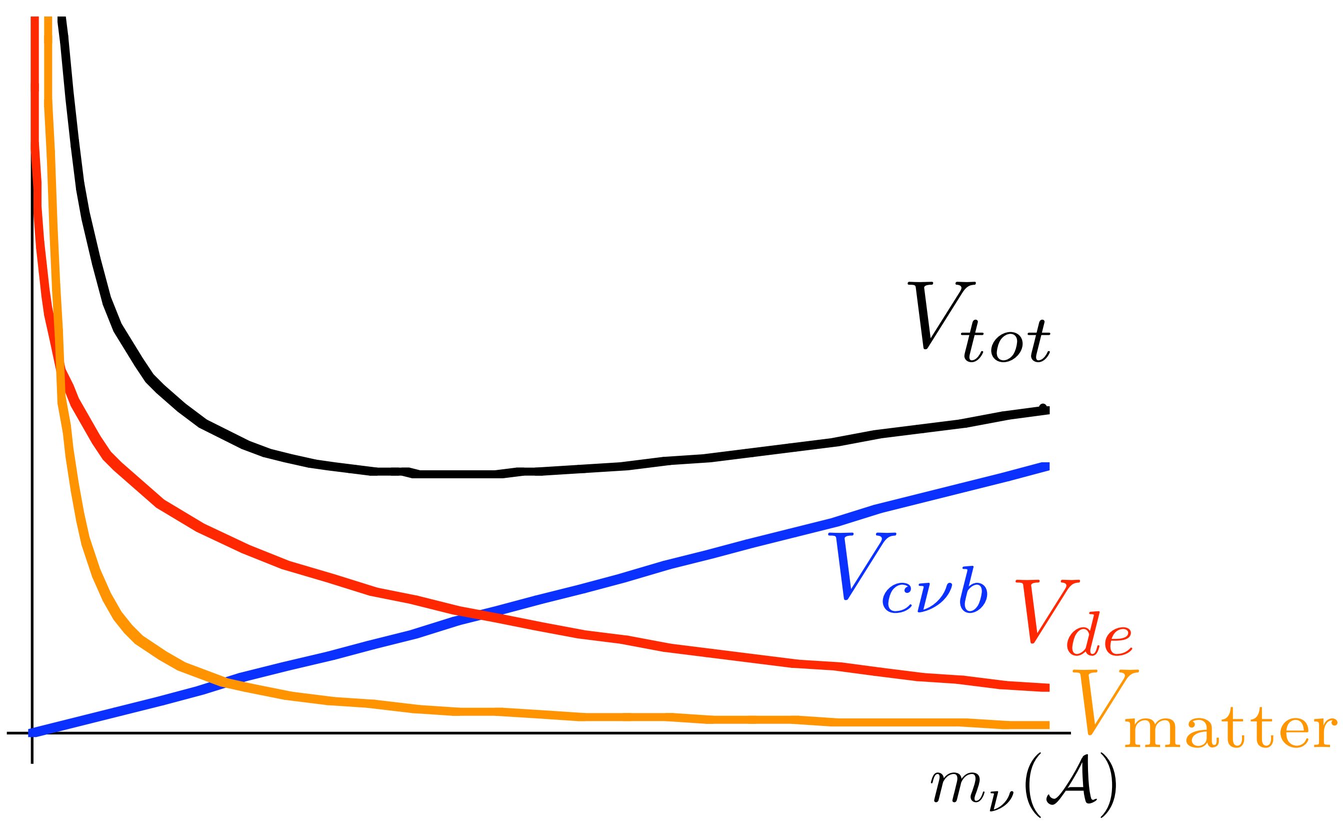

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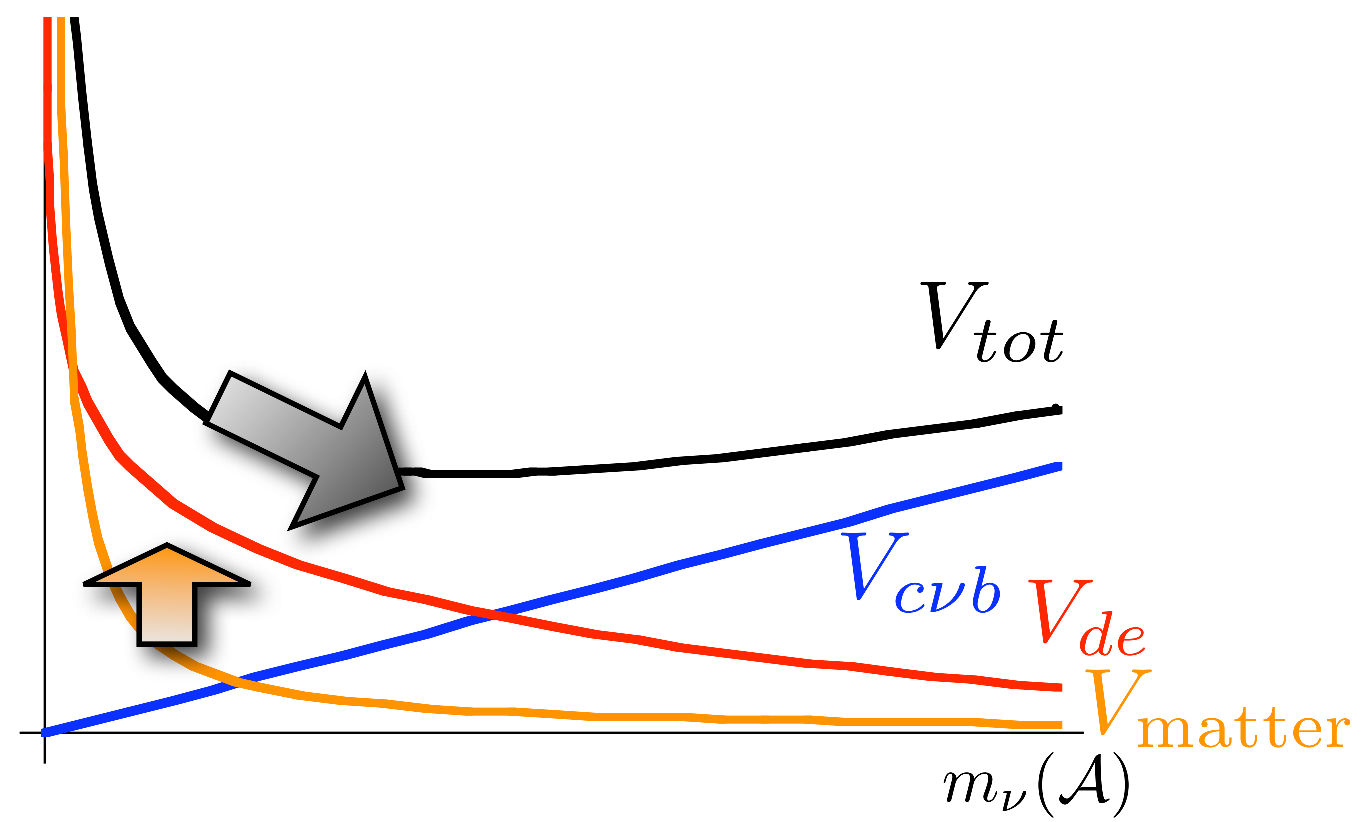

MaVaNs and LSND

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null oscillation searches in vacuum/air: Bugey, Chooz, Karmen...

positive oscillation signals occur in matter: solar, Kamland, atmo, LSND

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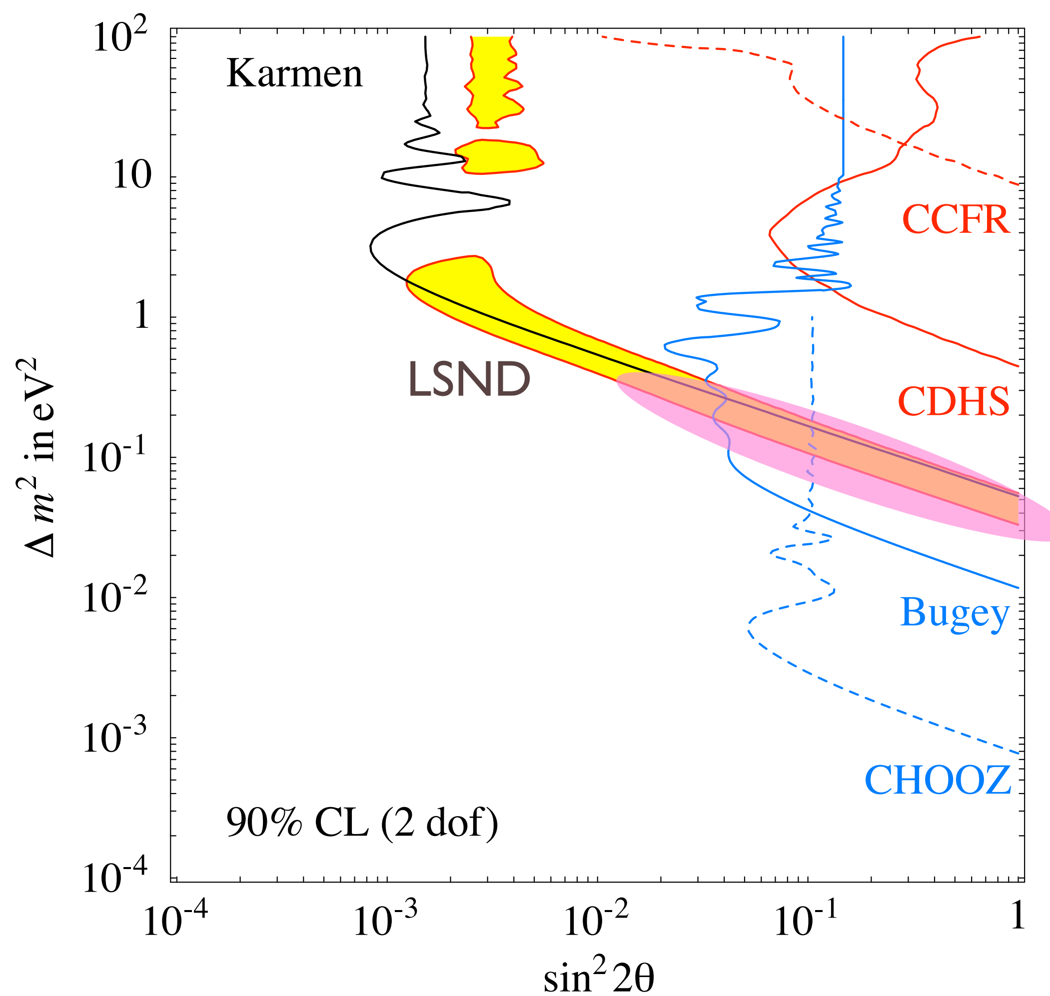

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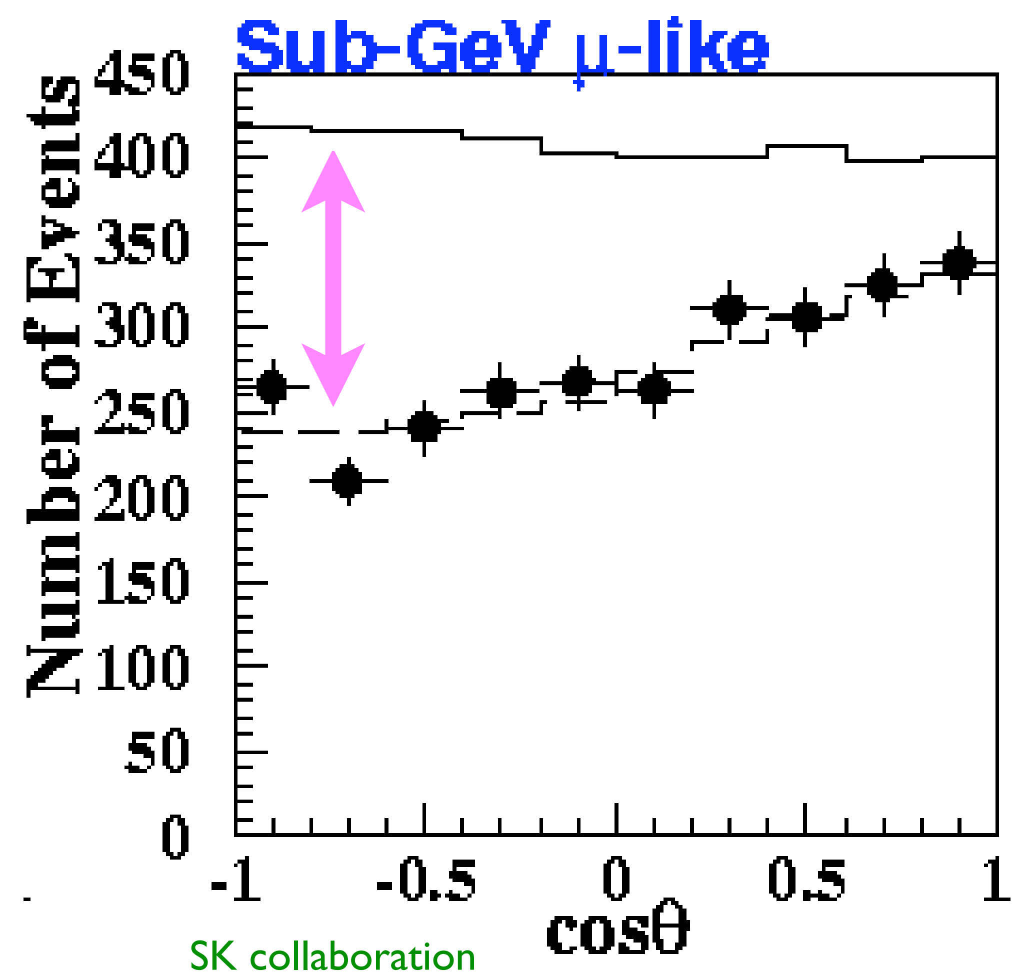

SK collaboration

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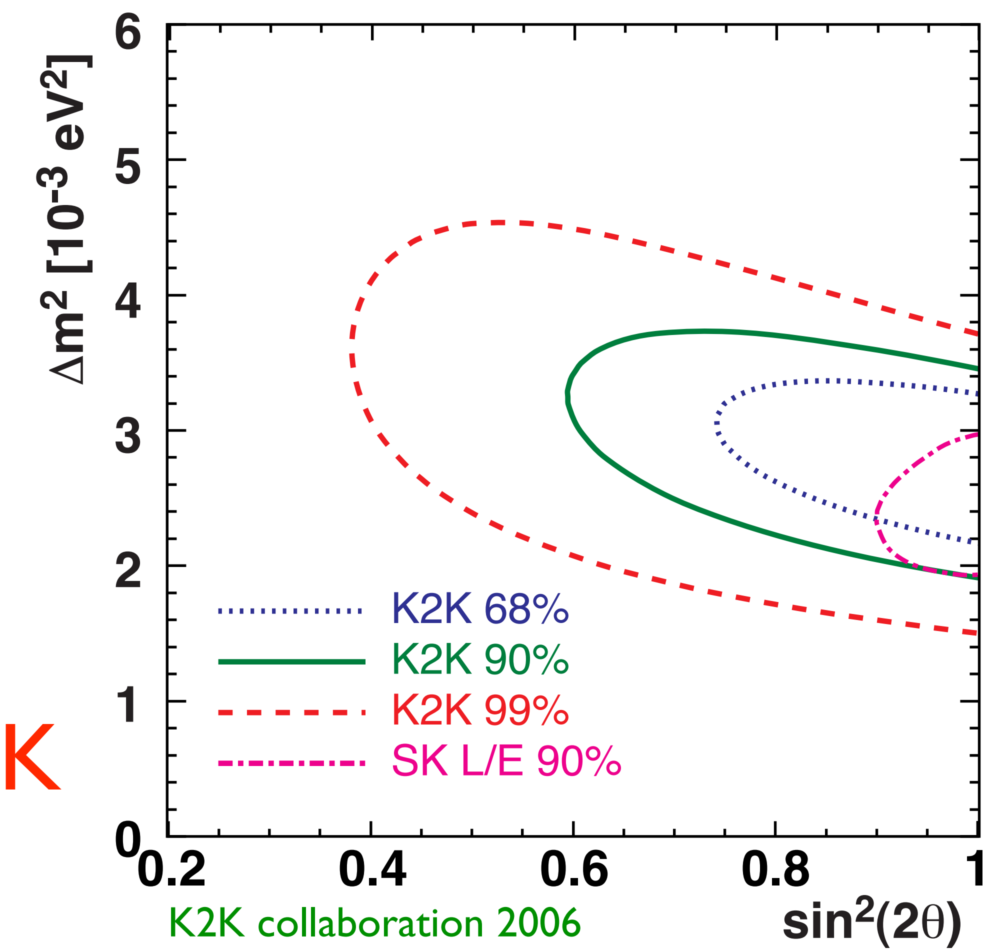

K2K collaboration 2006

However:

incompatible with SK high-E and K2K

$\Rightarrow$ Does ***not*** work.

MaVaNs and LSND

3+1 MaVaNs model??

Barger, Marfatia, Whisnant 2006

MaVaNs and LSND

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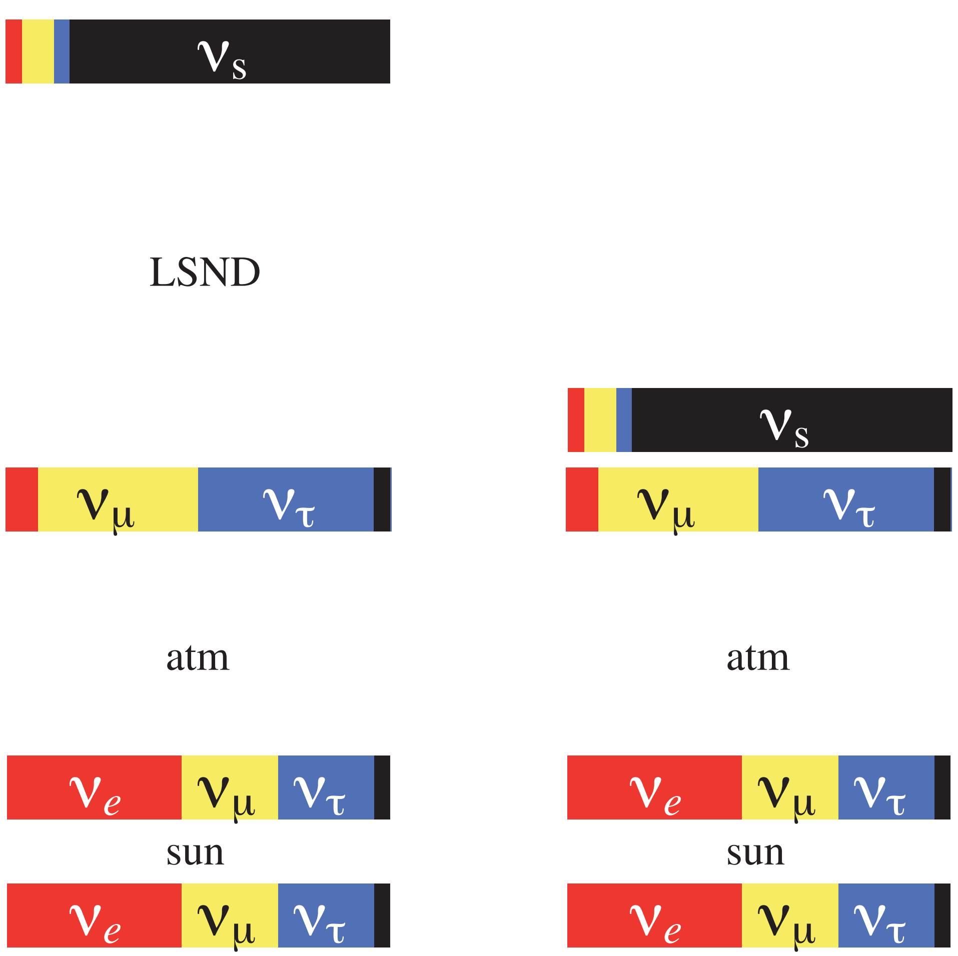
Simplified sketch:

in matter (explains LSND) | in vacuum/air (avoids Chooz, Bugey)



The model is more complicated:

for technical reasons, requires

- null MiniBooNE,
- large $\theta_{13}(\sim 15^o)$, only in matter (null DChooz, signal in Daya Bay, LBL)

A summary for LSND

model $(\mathcal{E} = \mathcal{E}xotic)$		
standard	3 active	
$\mathcal{E}$	sterile (2+2, 3+1, 3+2...) MaVaNs ~~CPT~~ ~~Lorentz~~ muon decay ...	
$\mathcal{E}^2$	sterile MaVaNs sterile ~~CPT~~ sterile N-std cosmo sterile decay sterile x-dim shortcuts	

A summary for LSND

model		mainly killed by
standard	3 active	(never born)
ε	sterile (2+2, 3+1, 3+2...)	solar, atmo, (SBL), std cosmo,
	MaVaNs	SK, K2K
	~~CPT~~	solar + Kamland + atmo
	~~Lorentz~~	tension with SBL, other data
	muon decay	Karmen
	...	
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A summary for LSND

model		mainly killed by	future?
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	...		
ε^2	sterile MaVaNs		DChooz, DayaBay, LBL
	sterile ~~CPT~~		MiniBooNE $\bar{\nu}$
	sterile N-std cosmo	**MiniBooNE**	cosmology itself
	sterile decay	**MiniBooNE**	
	sterile x-dim shortcuts		**MiniBooNE low E_ν**

Conclusions

The LSND puzzle prompted theorists to investigate many scenorios of exotic neutrino physics, most of which now disfavoured.

In a more general perspective:

The exotic physics stimulated by LSND

- opens to interesting sectors of new physics
- may appear as *subleading* effect in other ν exp's

Neutrino Physics

- is the physics of the *least tested* particles in SM
- has *discovered new physics* in the latest 15y

Back-up slides

MaVaNs and LSND

Signal	Channel	Environment
SNO	$\nu_e \to \nu_e, \nu_\mu, \nu_\tau$	solar-interior
Super-K(solar)	$\nu_e \to \nu_e, \nu_\mu$	solar-interior
Super-K(atm)	$\nu_\mu \to \nu_x$	air/HDM
KamLAND	$\nu_e \to \nu_x$	HDM
K2K	$\nu_\mu \to \nu_x$	HDM
LSND	$\nu_\mu \to \nu_e$	HDM
Null Search	**Channel**	**Environment**
KARMEN	$\nu_\mu \to \nu_e$	$\sim$ 50% air
Bugey	$\nu_e \to \nu_x$	air
CHOOZ	$\nu_e \to \nu_x$	$\sim 80-90\%$ air
Palo Verde	$\nu_e \to \nu_x$	$\sim$ 95% HDM
CDHS	$\nu_\mu \to \nu_x$	Unknown
NOMAD	$\nu_\mu \to \nu_\tau$ $\nu_e \to \nu_\tau$	$\sim$ 60% HDM
CHORUS	$\nu_\mu \to \nu_\tau$ $\nu_e \to \nu_\tau$	$\sim$ 60% HDM
Future Expmt.	**Channel**	**Environment**
MiniBooNE	$\nu_\mu \to \nu_e$	HDM
OPERA	$\nu_\mu \to \nu_\tau$	HDM
MINOS	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$	HDM

(HDM = High Density Medium)

~90% HDM according to J. Steinberger (Barger et al 2006)

K.Zurek 2004

K2K results in 2003

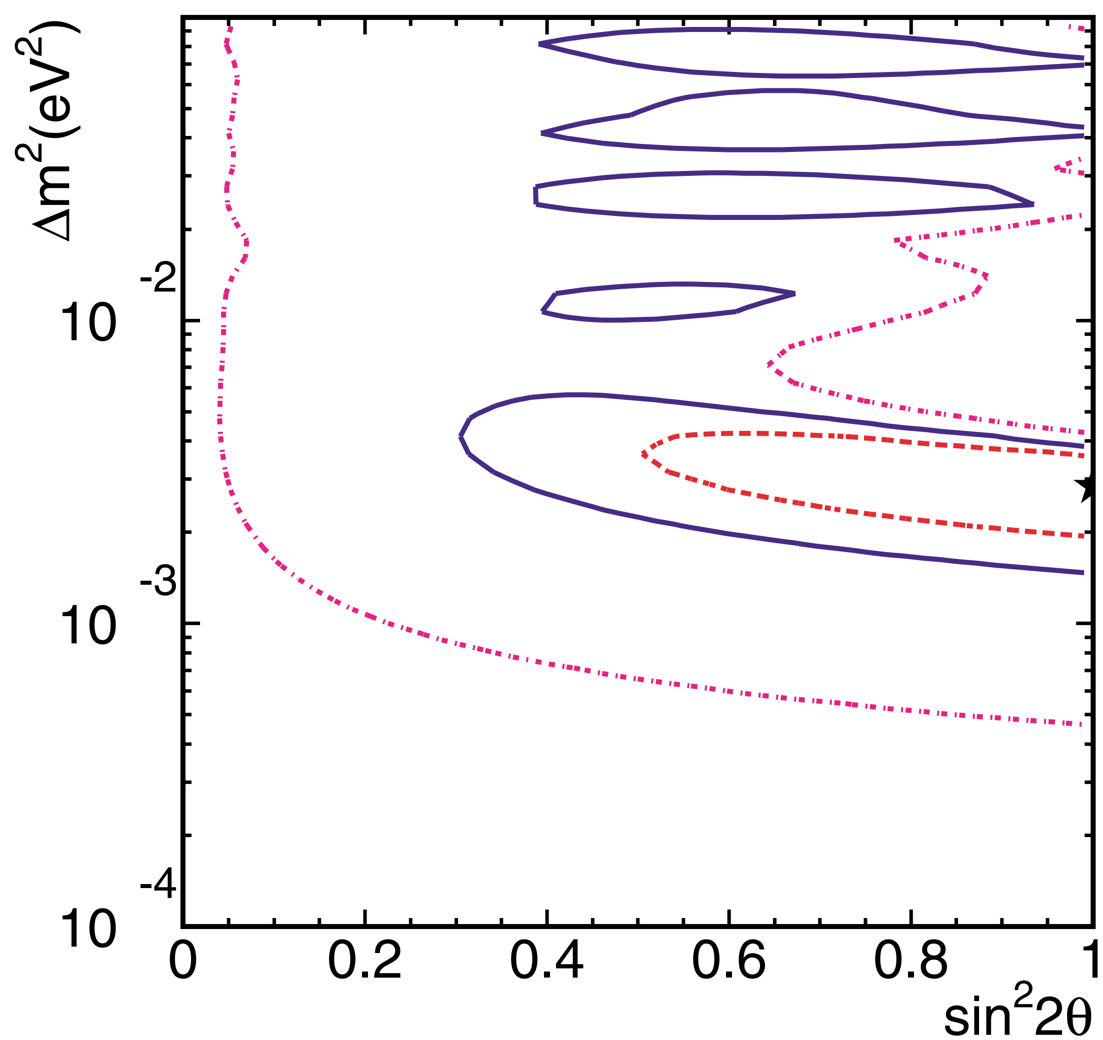

FIG. 3 (color online). Allowed regions of oscillation parameters. Dashed, solid, and dot-dashed lines are 68.4%, 90%, and 99% C.L. contours, respectively. The best-fit point is indicated by the star.