New Forces for Sterile ν' s

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Outline

- review of standard results
- review of MaVaNs
- can self interactions change constraints?

ν's-what's left?

✓ Δm^2 and mixing angles-done!

1. absolute mass scale-cosmology, Katrin
2. mass hierarchy-long baseline, Daya Bay II
3. CPV-long baseline
4. short baseline (SBL) ?

New "sterile" ν's?

- experimental motivation-short baseline expts, cosmology
  - marginally better fits to data
- theoretical motivation--GUTs, dark energy, hidden sectors, portals…

Who are sterile ν's?

- additional members of GUT multiplets?
  - Why aren't they heavy? Why are ν masses tiny?
- members of a new "sector", not related to leptons?
  - connected with dark energy scale?
  - hidden nearly susy sector with tiny $m_{3/2}$?
  - new forces?

Usual Phenomenological fits

- consider Δm^2 in 0.1-1000 eV^2 range

  (avoiding some constraints from astrophysics)

- globally fit all or some data

  (assuming no exotic effects other than sterile neutrinos)

- include 1, 2 or 3 sterile neutrinos in eV mass range

  (tension with cosmology)

Global fit to SBL

Conrad,Ignarra,Karagiorgi,Shaevitz,Spitz (CIKSS)
arXiv1207.4765

- Positive “indications” from LSND, MiniBoone, reactors of mixing with heavy sterile states
- Constraints from many expts

SBL ν_e appearance

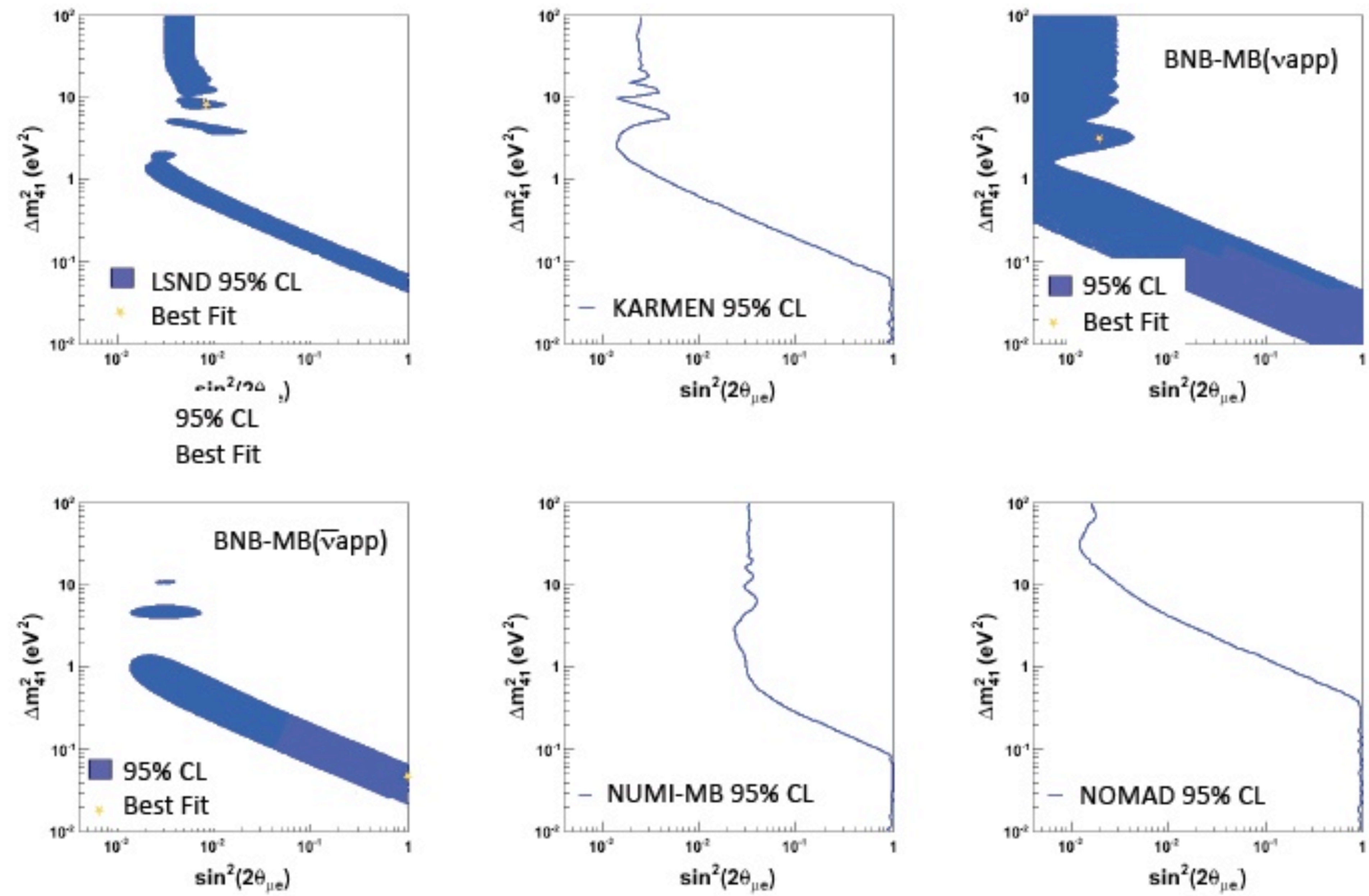


Figure 1: Summary of $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ results, shown at 95% CL. Top row: LSND, KARMEN, BNB-MB(νapp); Bottom row: BNB-MB($\bar{\nu}$app), NuMI-MB(νapp), NOMAD. See Sec. 3.2 for details and references.

SBL ν_μ disappearance

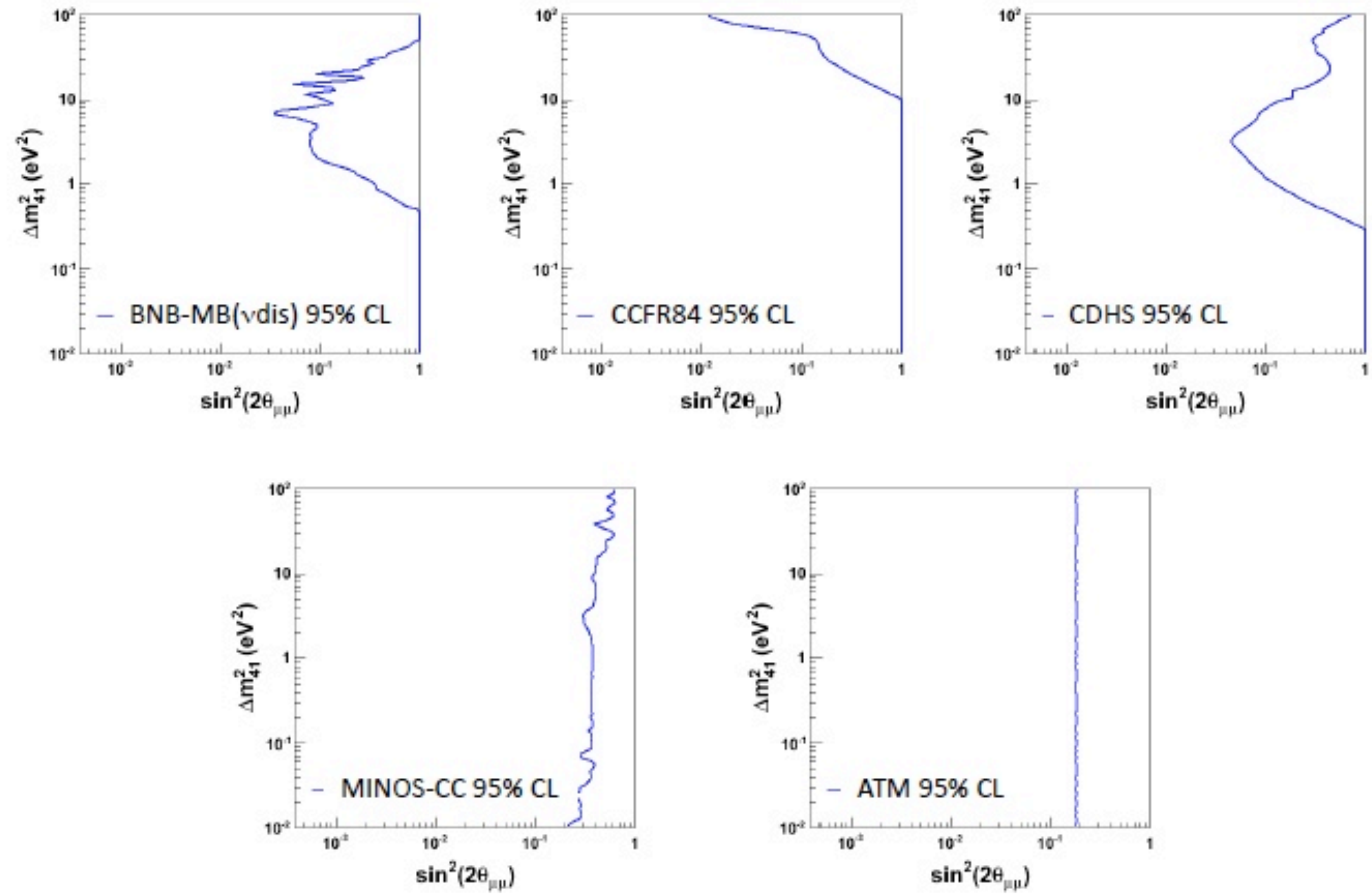


Figure 2: Summary of $\bar{\nu}_\mu \to \bar{\nu}_\mu$ and $\nu_\mu \to \nu_\mu$ results, shown at 95% CL. Top row: BNB-MB(νdis), CCFR84, CDHS; Bottom row: MINOS-CC, ATM. See Sec. 3.2 for details and references.

SBL ν_e disappearance

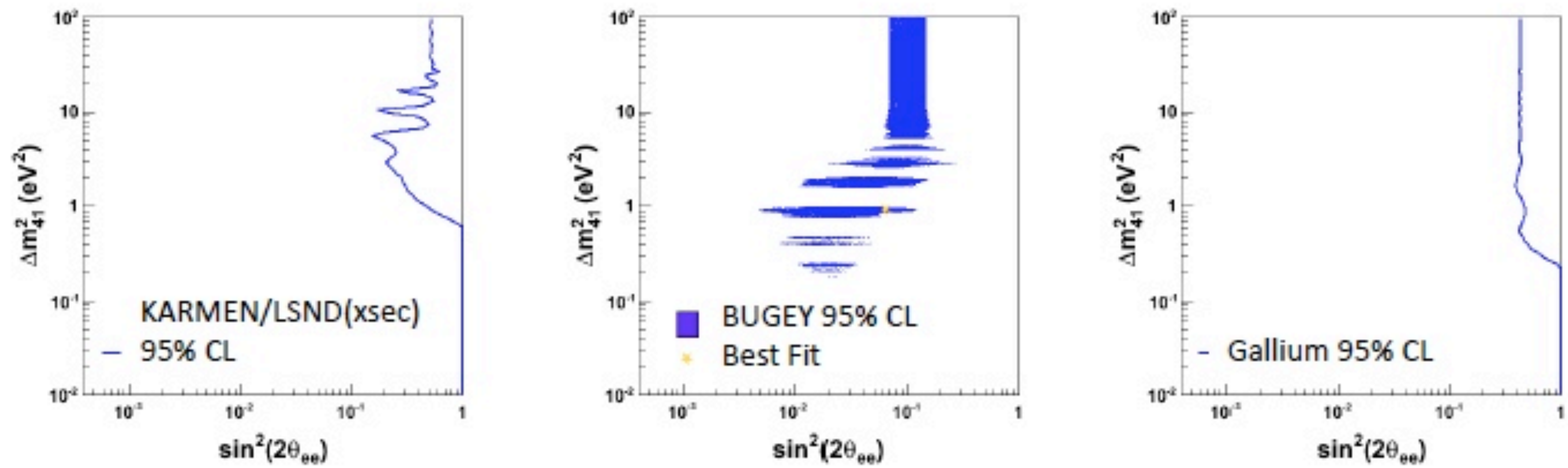


Figure 3: Summary of $\bar{\nu}_e \to \bar{\nu}_e$ and $\nu_e \to \nu_e$ results, shown at 95% CL. From left: KARMEN/LSND(xsec), Bugey, and Gallium. See Sec. 3.2 for details and references.

Results of CIKSS

$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}U_{e4}|^2 \quad x_{41} = |m_4^2 - m_1^2|L/(4E)$$

- 1 sterile: $P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 x_{41} = P_{\bar{\mu}\bar{e}}$
  - appearance and disappearance incompatible
  - ν $\overline{\nu}$ incompatible
- 2,3 steriles $P_{\mu e} \neq P_{\bar{\mu}\bar{e}}$
  - allows CPV in SBL to make ν $\overline{\nu}$ compatible
  - still some tension between appearance, disappearance
  - some tension with nucleosynthesis $\Delta N_\nu = 0.66^{+0.47}_{-0.45}\ (1\sigma)$

Anchordoqui, Goldberg, Steigman
arXiv1211.0186

CIKSS results

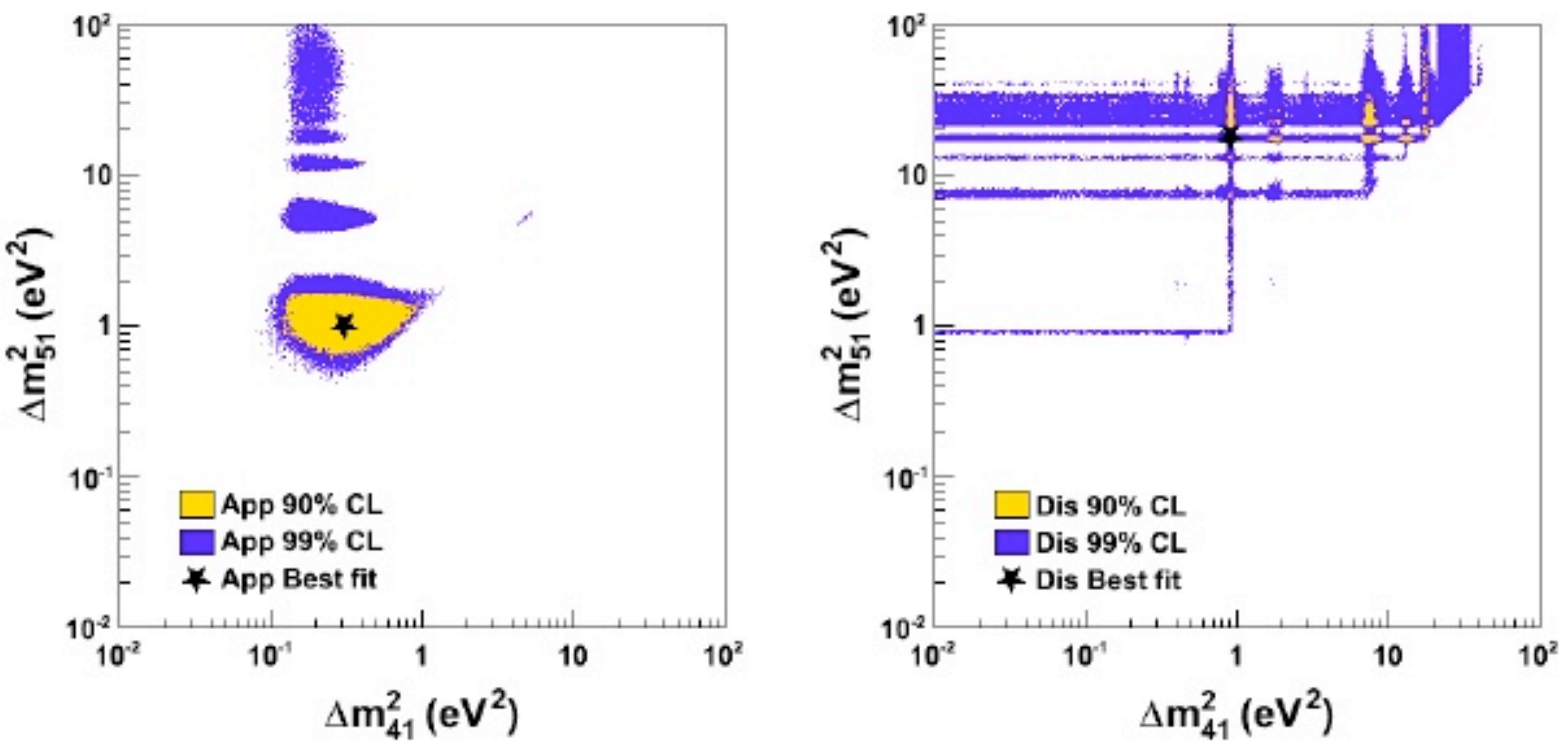


Figure 9: The Δm^2_{51} vs. Δm^2_{41} correlations from fits to appearance (left) and disappearance (right) data in a (3+2) model.

arXiv1006.5276

Hamaan, Hannestad, Raffelt, Tamborra, Wong

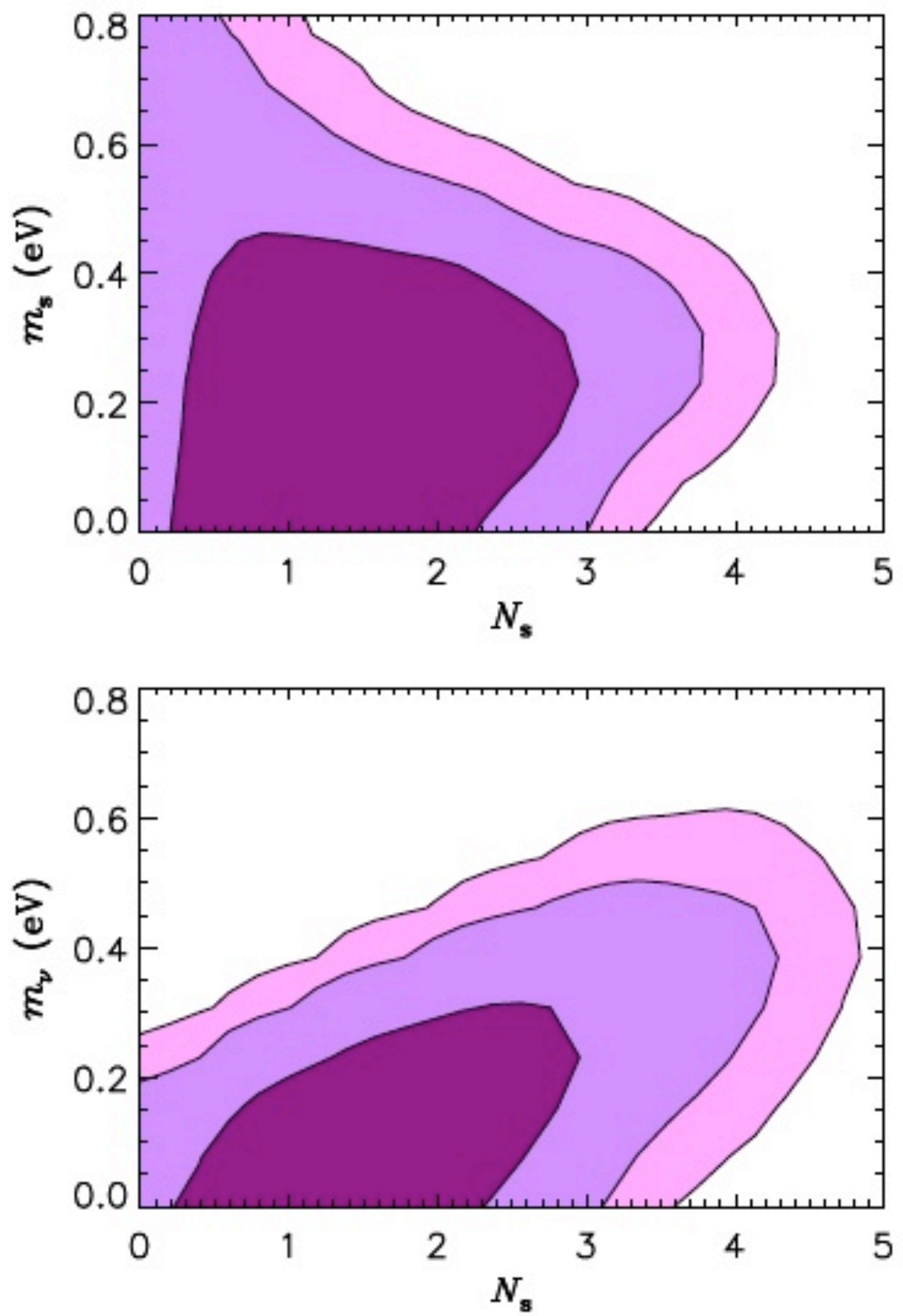


FIG. 1: 2D marginalized 68%, 95% and 99% credible regions for the neutrino mass and thermally excited number of degrees of freedom N_s. *Top:* The $3 + N_s$ scheme, in which ordinary neutrinos have $m_\nu = 0$, while sterile states have a common mass scale m_s. *Bottom:* The $N_s + 3$ scheme, where the sterile states are taken to be massless $m_s = 0$, and 3.046 species of ordinary neutrinos have a common mass m_ν.

Effects of a heavy ν₅ on oscillations involving ν₄

average over rapid oscillations

$$x_{41} = |m_4^2 - m_1^2| L/(4E)$$

$$P_{\nu_\mu(\bar\nu_\mu)\to\nu_e(\bar\nu_e)} = \sin^2 2\theta_{\mu e} \sin^2(x_{41} \pm \beta) + \kappa, \quad (4)$$

CPV

with the definitions

changes amplitude for appearance vis a vis disappearance

$$\begin{aligned} \sin^2 2\theta_{\mu e} &= 4|U_{\mu 4}|^2 |U_{e4}|^2 r \\ \kappa &= |U_{\mu 4}|^2 |U_{e4}|^2 \{(1-r)^2 + a[(1-r)^2 + 4r\sin^2\beta]\} \end{aligned} \quad (5)$$

where $+(-)$ is for ν ($\bar\nu$) oscillations,

includes effects of phase space for ν_5 mass

$$\begin{aligned} r &\equiv |U_{\mu 4}^* U_{e4} + U_{\mu 5}^* U_{e5}| \,/\, |U_{\mu 4}^* U_{e4}| \\ \beta &\equiv \tfrac{1}{2}\tan^{-1}\left(\frac{\sin\phi |U_{e5}||U_{\mu 5}|}{|U_{e4}||U_{\mu 4}| + \cos\phi |U_{e5}||U_{\mu 5}|}\right) \end{aligned} \quad (6)$$

and $\phi \equiv \arg\left(\frac{U_{e5}U_{\mu 5}^*}{U_{e4}U_{\mu 4}^*}\right)$. β is the CP-odd parameter that can account for differences in ν and $\bar\nu$ oscillations.

- Effective non-unitary mixing matrix among light ν allows SBL CPV with only 1 light sterile
- reduction (but no elimination) of tension with SBL

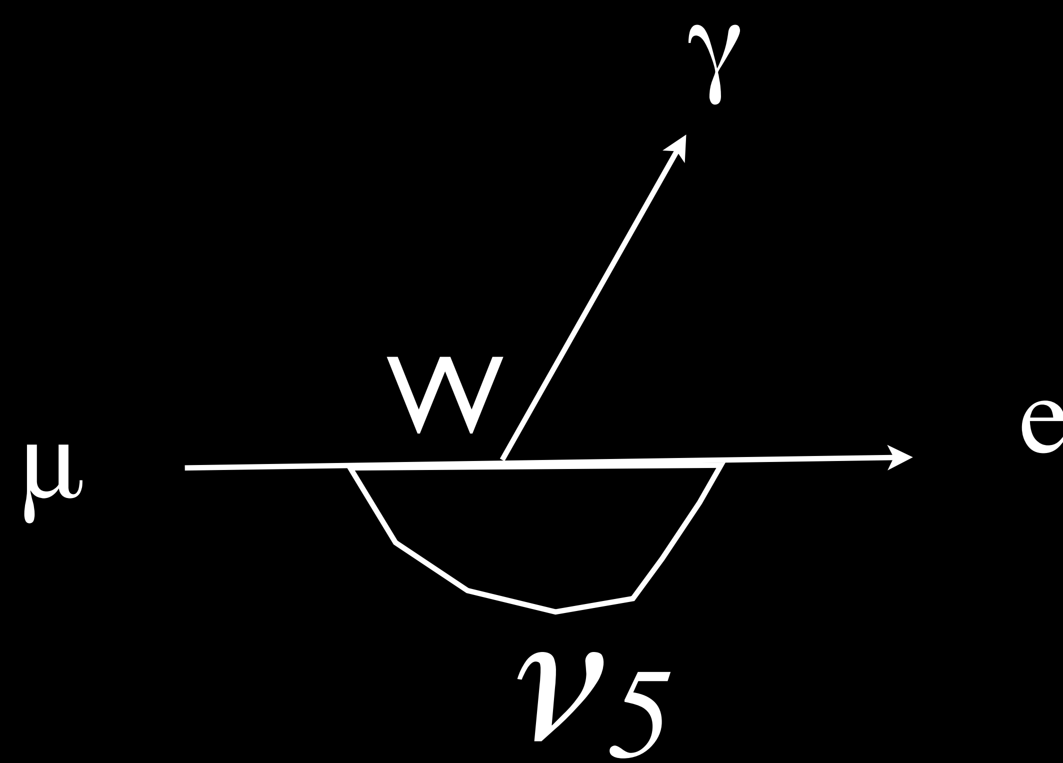
3+1+1 heavyish? (> 33 eV)

A.N., arXiv1010.3970; Fan and Langacker, arXiv1201.6662; Kuflik, McDermott and Zurek, arXiv1205.1791 (KMZ);

- only 1 eV scale light sterile neutrino
- 1 (or more) much heavier sterile neutrinos
- very little parameter space when all constraints including astrophysics included
- when 2011 MB data included, still tension between appearance and disappearance

Constraints on heavy ν's

- $\mu \to e\gamma$
- μ lifetime
- $\pi, K \to \ell\, \nu_5$
- visible ν_5 decays
- *BBN*
- *SN1987A*



little room for heavy ν's? (KMZ)

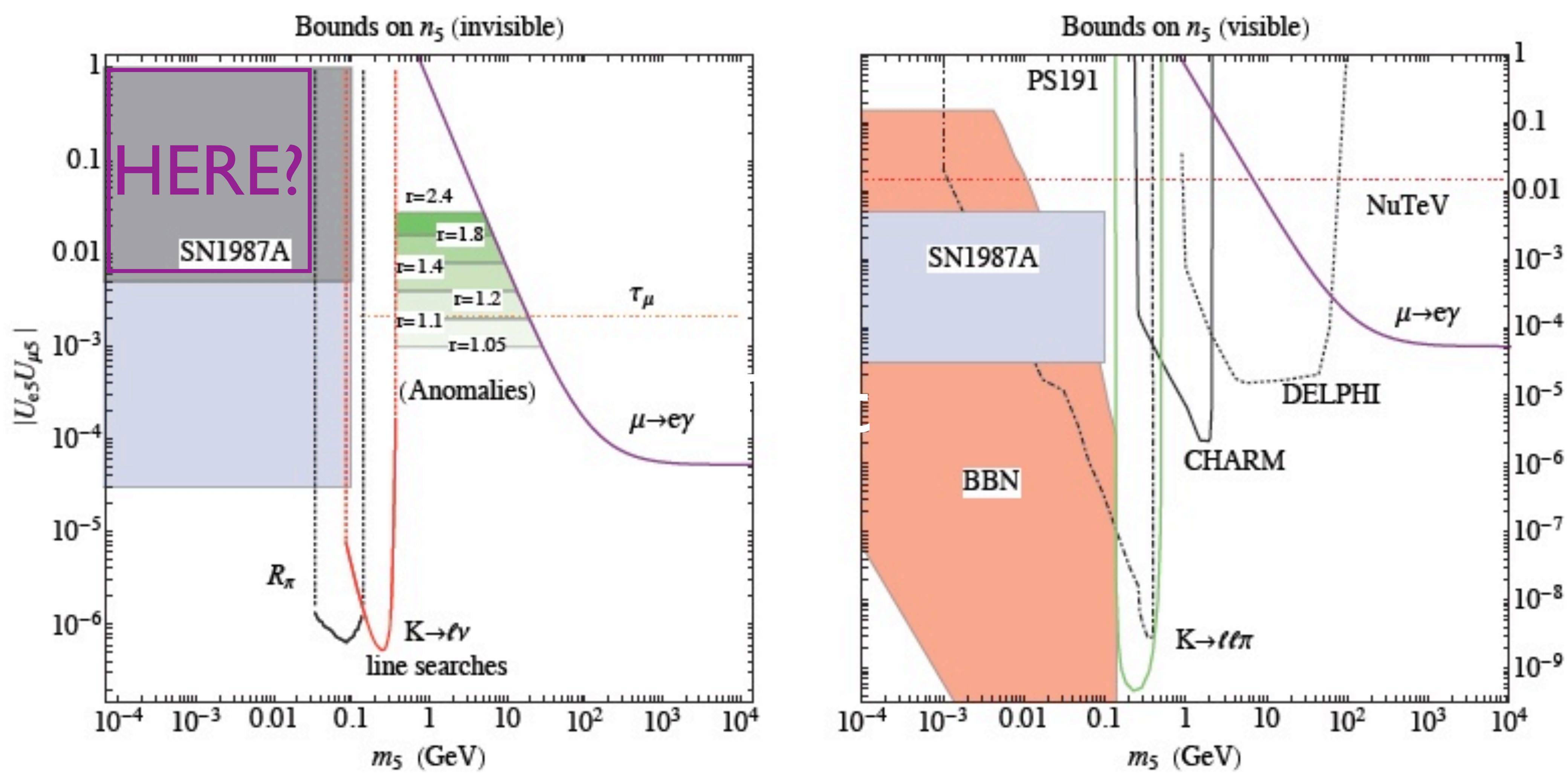


FIG. 5: Exclusion regions from BBN [34] (right frame) and SN1987A [35] (both frames), as well as bounds from the NuTeV oscillation search [16] (red dotted, right frame), R_π [37, 38] (left frame), measurements of τ_μ [38–42] (left frame), collider and line searches [38, 43–49] (both frames), and searches for $\mu \to e\gamma$ [50] (both frames). The left panel shows lines of constant values of r from 1.05 to 2.4 (for the calculation of r, we assume no CP violation and take $|U_{e4}U_{\mu 4}| = 0.023$, as explained in the text). To avoid clutter, we avoid repeating the τ_μ and NuTeV lines in both plots, although each is valid in both cases.

Inconsistent sterile ν's are Great ν's!

- for MaVaNs

  (Mass Varying Neutrinos)

  Fardon, A.N., Weiner, arXiv/astro-ph/0309800 (FAW)

  D.B. Kaplan, A.N., Weiner, arXiv/hep-ph/0401099

  Zurek, arXiv/hep-ph/0405141

MaVaN review

- light scalar field ("acceleron") a, $m_a \sim 10^{-3}$eV
- couples to light sterile ν
- "Mini seesaw" contribution to active neutrino mass m_ν
- $m_\nu \rightarrow m_\nu(a)$, environmental mass dependence
- Both active and sterile ν masses depend on <a>
  - ➡ sterile mass↑, active mass ↓
- <a> depends on ν density, possibly also on matter density
- non vanishing cosmological ν density contributes to effective potential for <a> with dark energy eos

Smoking Guns for MaVaNs

- Effects of environment in neutrino oscillations?
- Tritium endpoint searches for absolute ν mass depends on density of source?
- Cosmologically "impossible" sterile neutrinos?
- Astrophysically "inconsistent" neutrino masses?
- energy spectrum of solar ν_e inconsistent with standard large mixing angle MSW?

Disecting the SN1987A constraints

- heavier, mostly sterile ν's produced via oscillations +decoherence
- matter effects suppress oscillations into lighter sterile ν's
- mean free path of mostly sterile heavy ν's is longer

➡mostly sterile heavy ν's cool supernovae and observed ν signal wouldn't have happened

Avoiding SN constraints: I, the MaVaN way

- sterile mass ~ <a>, active mass ~ 1/<a>
- V_{eff} for acceleron gets large environmental correction
  - high neutrino density
  - coupling to charged lepton
- <a> much larger in early universe, supernovae
- sterile MaVaN ν's always heavier than the temperature, abundance thermally suppressed always
- mixing with active ν's suppressed during BBN, supernovae

Avoiding SN constraints: II, the sticky sterile force way

- "sterile" refers to no standard model interactions
- assumes all interactions of sterile ν's come from mixing with ordinary ν's
- sterile ν's could be (quasi-)Dirac, heavier than MeV, charged under new short range U(1), short lifetime for heavier ν into lighter ν + boson
- decay products overcool supernovae? (KMZ)
- Not if interactions between lighter ν + boson reduce mean free path (A.N. and Jinrui Huang, in progress)

Avoiding ν constraints: III, the exotic MSW way

- A.N. and J.Walsh,arXiv:0711.1363, with Englehardt arXiv: 0802.0762
  - new light gauge boson with small coupling to ordinary ν (e.g. from kinetic mixing with weak boson),
  - possible large coupling to sterile ν
- MSW analog effect ~ $E \rho g_s g_a / M_V^2$: g_s = sterile ν charge
  - Can be much larger than usual MSW for oscillations into sterile ν, suppress oscillations at supernova densities.

Summary

- "I have done a terrible thing; I have invented a particle that cannot be detected"-Pauli, apologizing for the neutrino, a desperate invention to accomodate experimental results
- ν physics has been exciting, even weirder than Pauli imagined and full of surprises, possible window into new forces, unification and GUT energy scales
- Hope sterile ν is at least this terrible
- The study of "non-linear" (=interacting) physics is like the study of "non-elephant" biology (Reynolds)