Novel neutrino interactions + supernova neutrinos

Alexander Friedland, T-2

NSI work with

Michael Graesser, Ian Shoemaker, Luca Vecchi

SN work with

J. Cherry, J. Carlson, H. Duan, G. Fuller

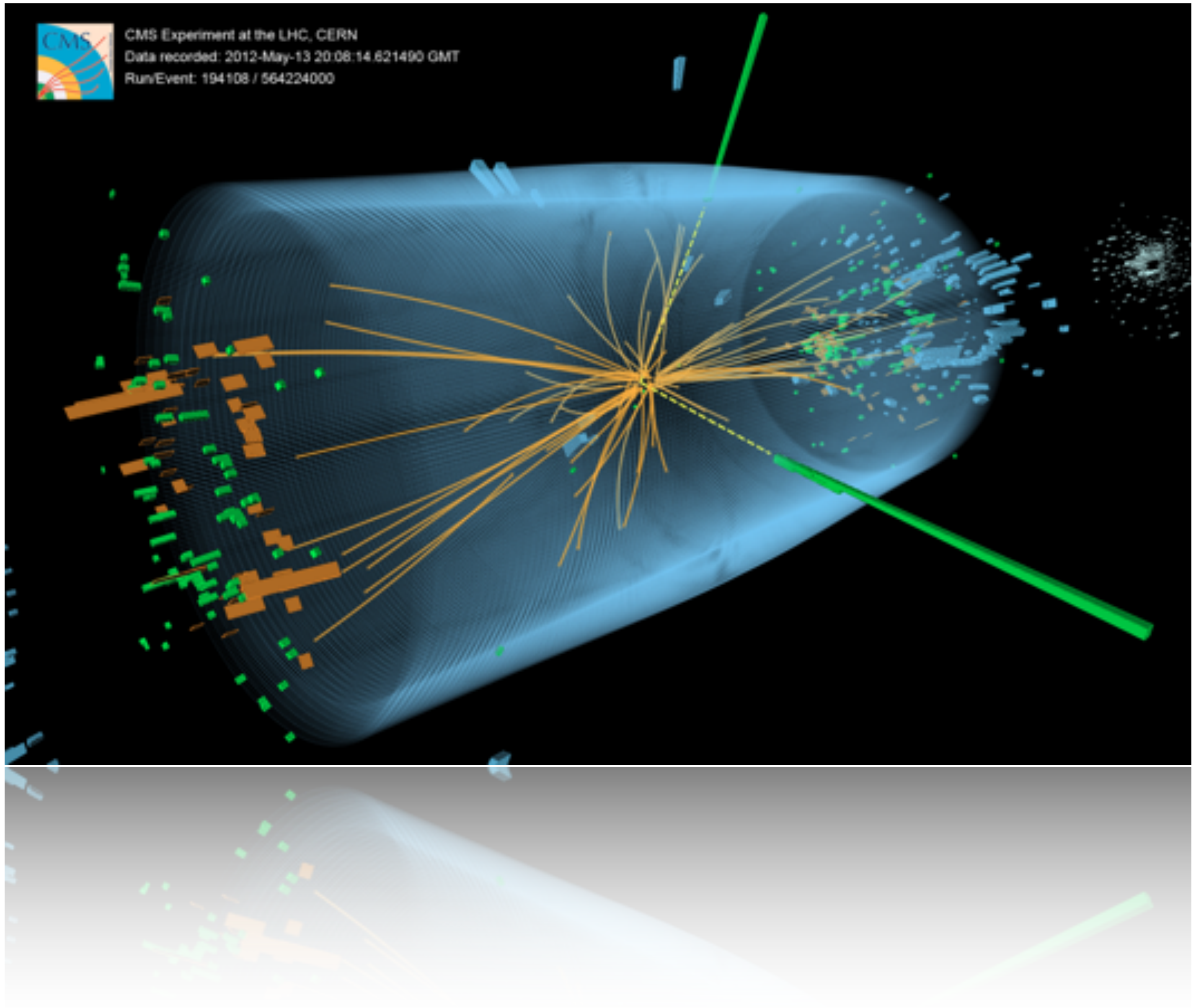
LBNE science

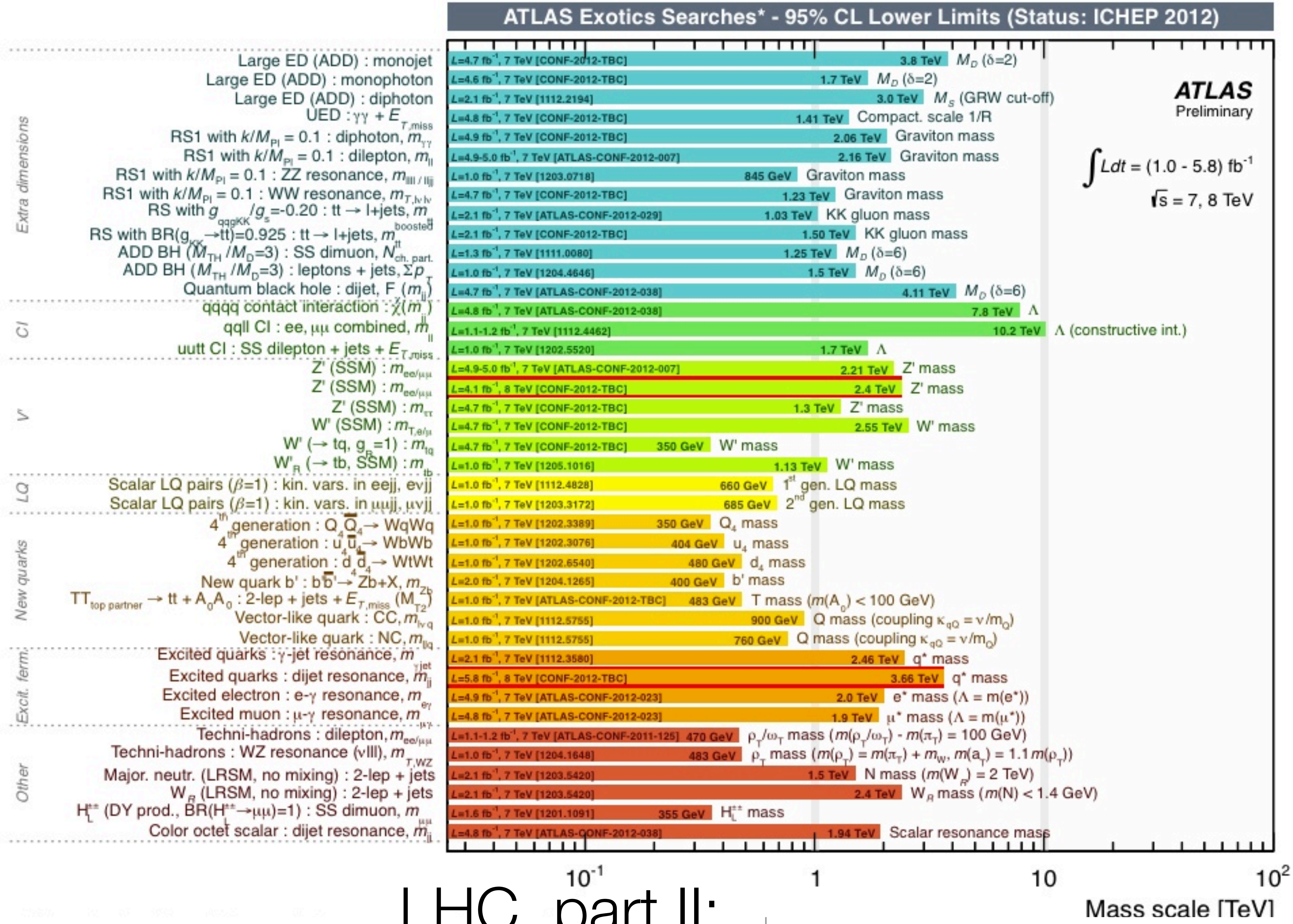
- Bread-and-butter neutrino physics:
  - CPV
  - Mass hierarchy
  - Known angles and splittings
- Nucleon decay
- New physics in beam neutrino oscillations
- Supernova

This talk

Comparison: LHC

- Was designed to find the Higgs
    - Specifically, detectors were optimized for H → γγ
- The discovery made front page of almost every newspaper in the world!

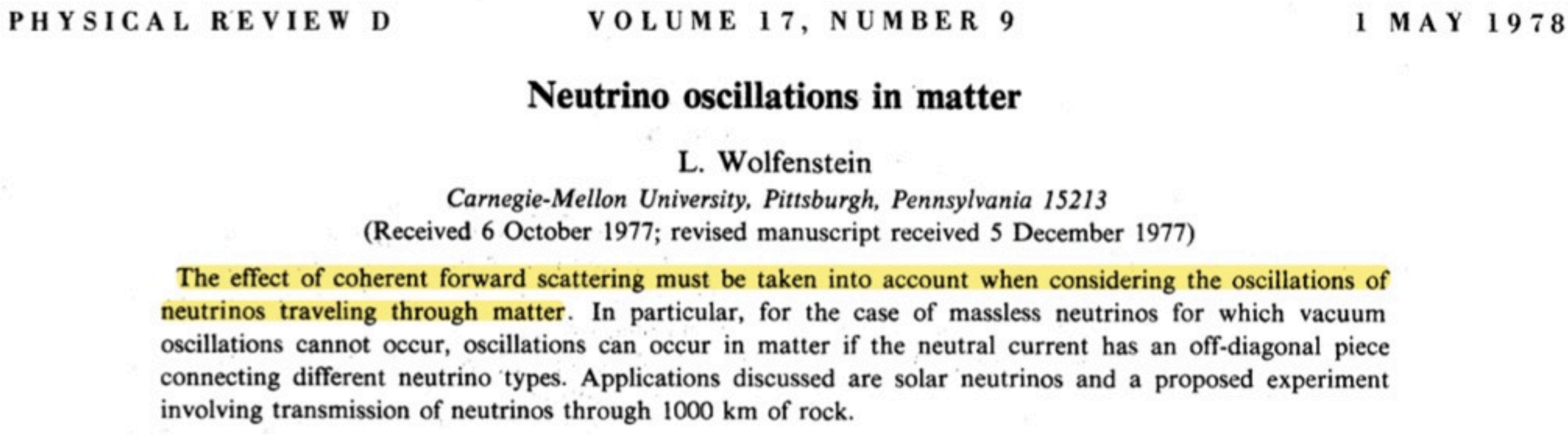




LHC, part II: fishing expedition

SUSY, Extra dim, techni-stuff, ...

Generalizing Fermi



PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 6 October 1977; revised manuscript received 5 December 1977)

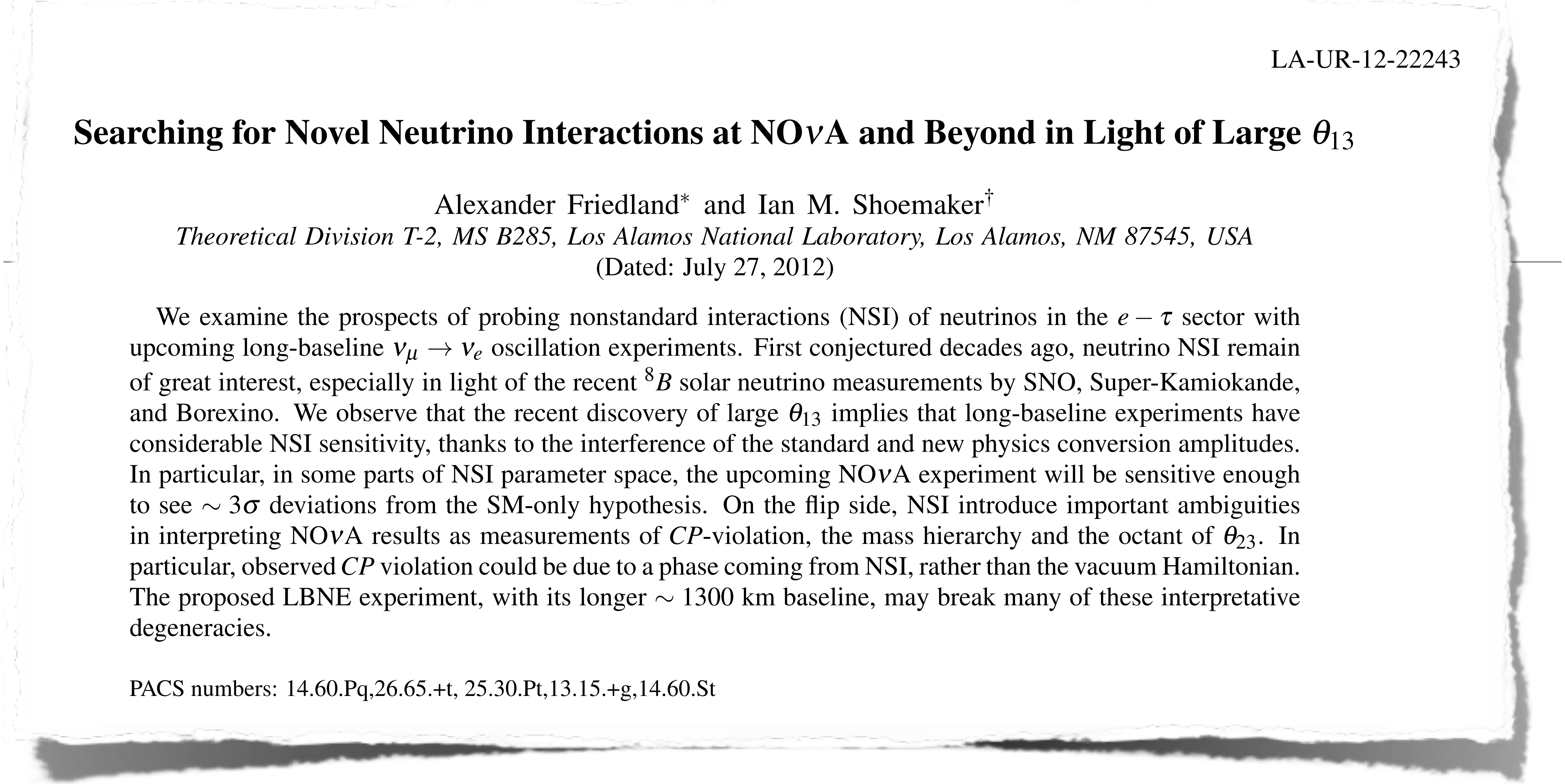
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\,\epsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho\nu_\beta)(\overline{f}\gamma_\rho P f)$$

Neutrino Flavor

f =SM fermion
P=L,R

Laid the foundation for the MSW effect and pointed out that NSI can modify neutrino propagation.



LA-UR-12-22243

Searching for Novel Neutrino Interactions at NOνA and Beyond in Light of Large θ_{13}

Alexander Friedland* and Ian M. Shoemaker†
Theoretical Division T-2, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

(Dated: July 27, 2012)

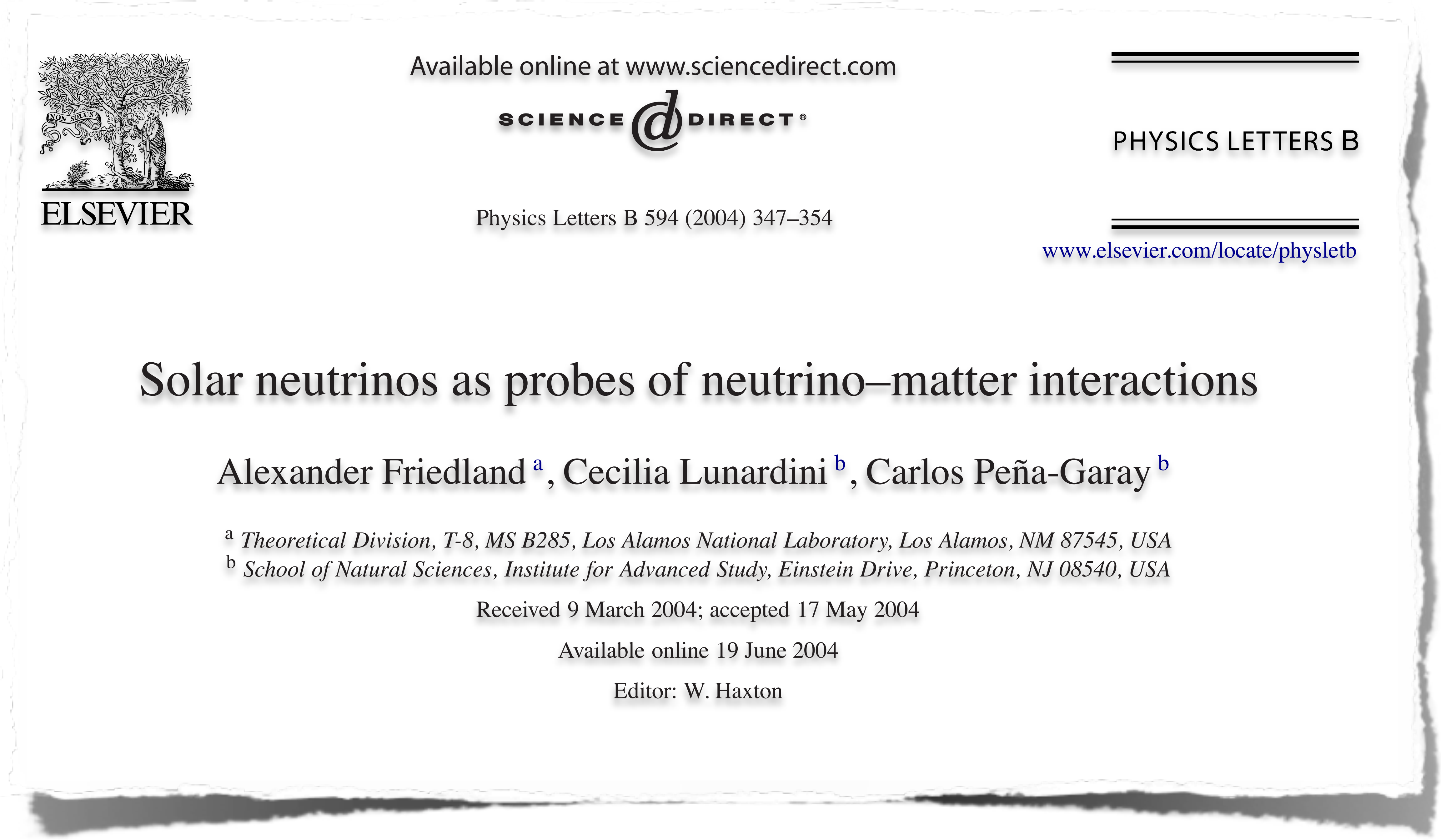
We examine the prospects of probing nonstandard interactions (NSI) of neutrinos in the $e-\tau$ sector with upcoming long-baseline $\nu_\mu \to \nu_e$ oscillation experiments. First conjectured decades ago, neutrino NSI remain of great interest, especially in light of the recent ^8B solar neutrino measurements by SNO, Super-Kamiokande, and Borexino. We observe that the recent discovery of large θ_{13} implies that long-baseline experiments have considerable NSI sensitivity, thanks to the interference of the standard and new physics conversion amplitudes. In particular, in some parts of NSI parameter space, the upcoming NOνA experiment will be sensitive enough to see $\sim 3\sigma$ deviations from the SM-only hypothesis. On the flip side, NSI introduce important ambiguities in interpreting NOνA results as measurements of CP-violation, the mass hierarchy and the octant of θ_{23}. In particular, observed CP violation could be due to a phase coming from NSI, rather than the vacuum Hamiltonian. The proposed LBNE experiment, with its longer $\sim$ 1300 km baseline, may break many of these interpretative degeneracies.

PACS numbers: 14.60.Pq,26.65.+t, 25.30.Pt,13.15.+g,14.60.St

- Simplifying framework:
  - a single term: a flavor changing qq$\nu_e\nu_\tau$ interaction
  - subdominant to the SM weak interactions

$$H_{mat}^{flav} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 & |\varepsilon_{e\tau}|\, e^{-i\delta_\nu} \\ 0 & 0 & 0 \\ |\varepsilon_{e\tau}|\, e^{i\delta_\nu} & 0 & 0 \end{pmatrix}$$

Solar neutrinos, 2004



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Solar neutrinos as probes of neutrino–matter interactions

Alexander Friedland [a], Cecilia Lunardini [b], Carlos Peña-Garay [b]

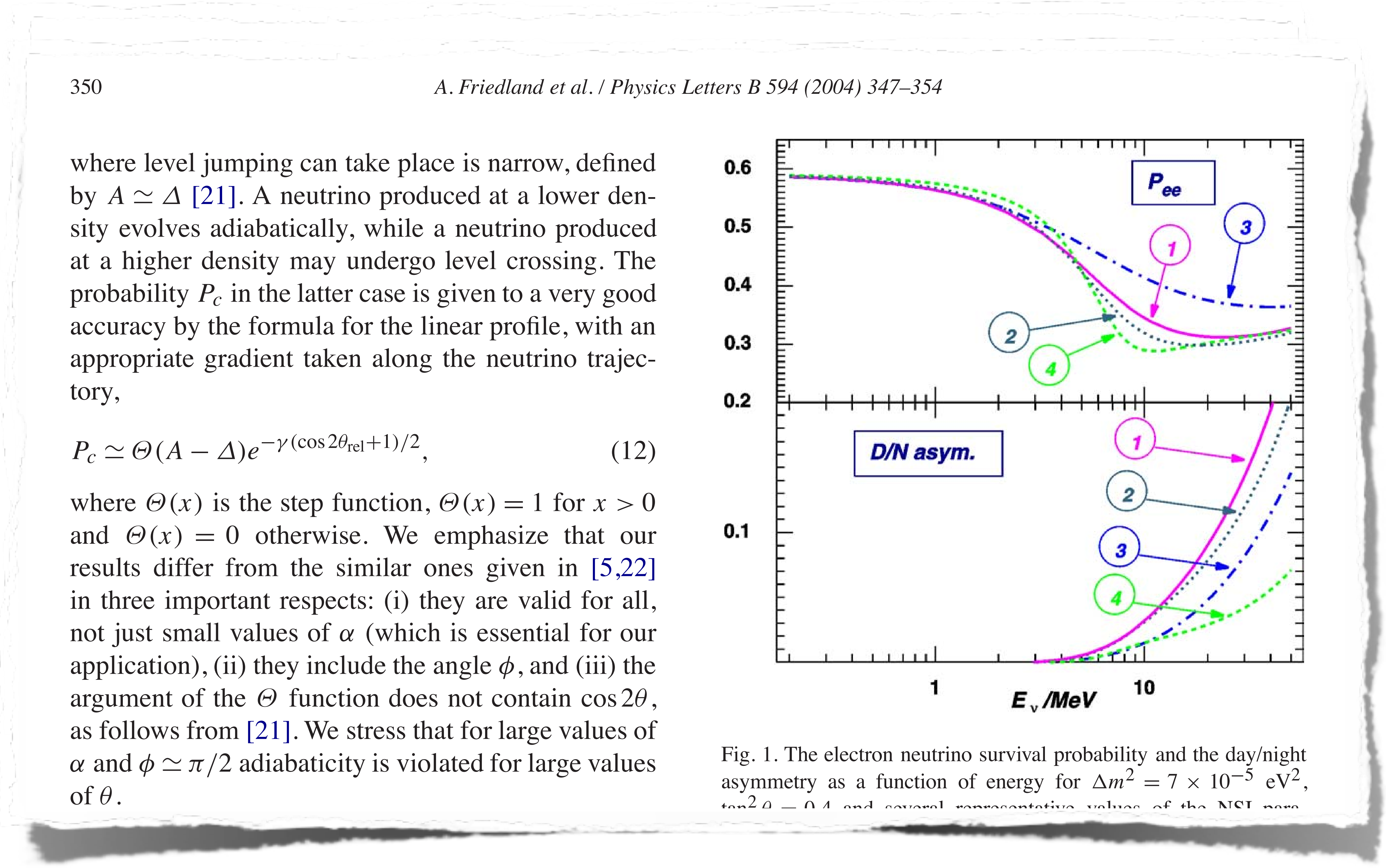
[a] Theoretical Division, T-8, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b] School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA

Received 9 March 2004; accepted 17 May 2004

Available online 19 June 2004

Editor: W. Haxton

Solar neutrinos, 2004



350 *A. Friedland et al. / Physics Letters B 594 (2004) 347–354*

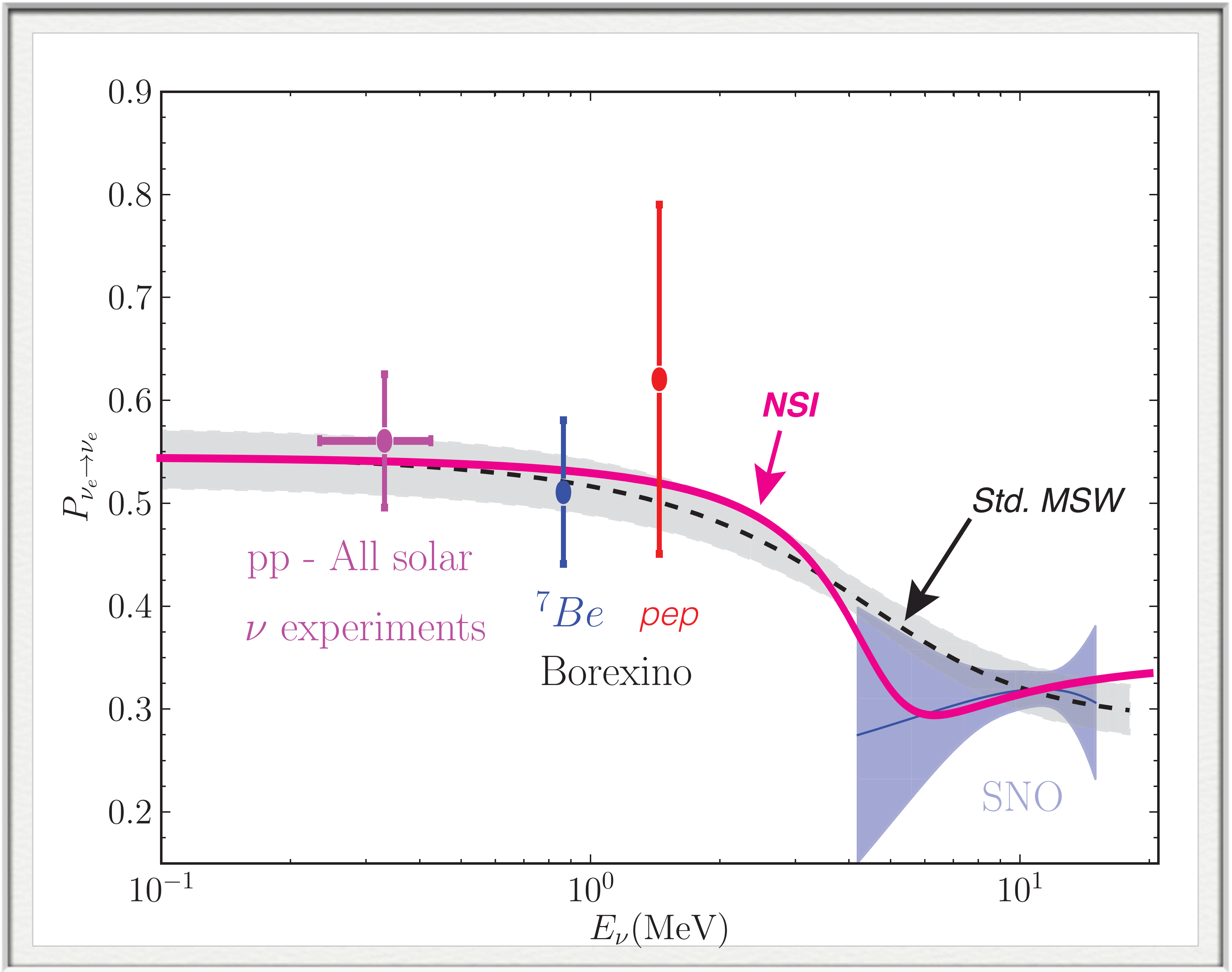
where level jumping can take place is narrow, defined by $A \simeq \Delta$ [21]. A neutrino produced at a lower density evolves adiabatically, while a neutrino produced at a higher density may undergo level crossing. The probability P_c in the latter case is given to a very good accuracy by the formula for the linear profile, with an appropriate gradient taken along the neutrino trajectory,

$$P_c \simeq \Theta(A - \Delta) e^{-\gamma(\cos 2\theta_{\text{rel}}+1)/2}, \tag{12}$$

where $\Theta(x)$ is the step function, $\Theta(x) = 1$ for $x > 0$ and $\Theta(x) = 0$ otherwise. We emphasize that our results differ from the similar ones given in [5,22] in three important respects: (i) they are valid for all, not just small values of α (which is essential for our application), (ii) they include the angle ϕ, and (iii) the argument of the Θ function does not contain $\cos 2\theta$, as follows from [21]. We stress that for large values of α and $\phi \simeq \pi/2$ adiabaticity is violated for large values of θ.

Fig. 1. The electron neutrino survival probability and the day/night asymmetry as a function of energy for $\Delta m^2 = 7 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.4$ and several representative values of the NSI para-

Solar neutrinos, 2012



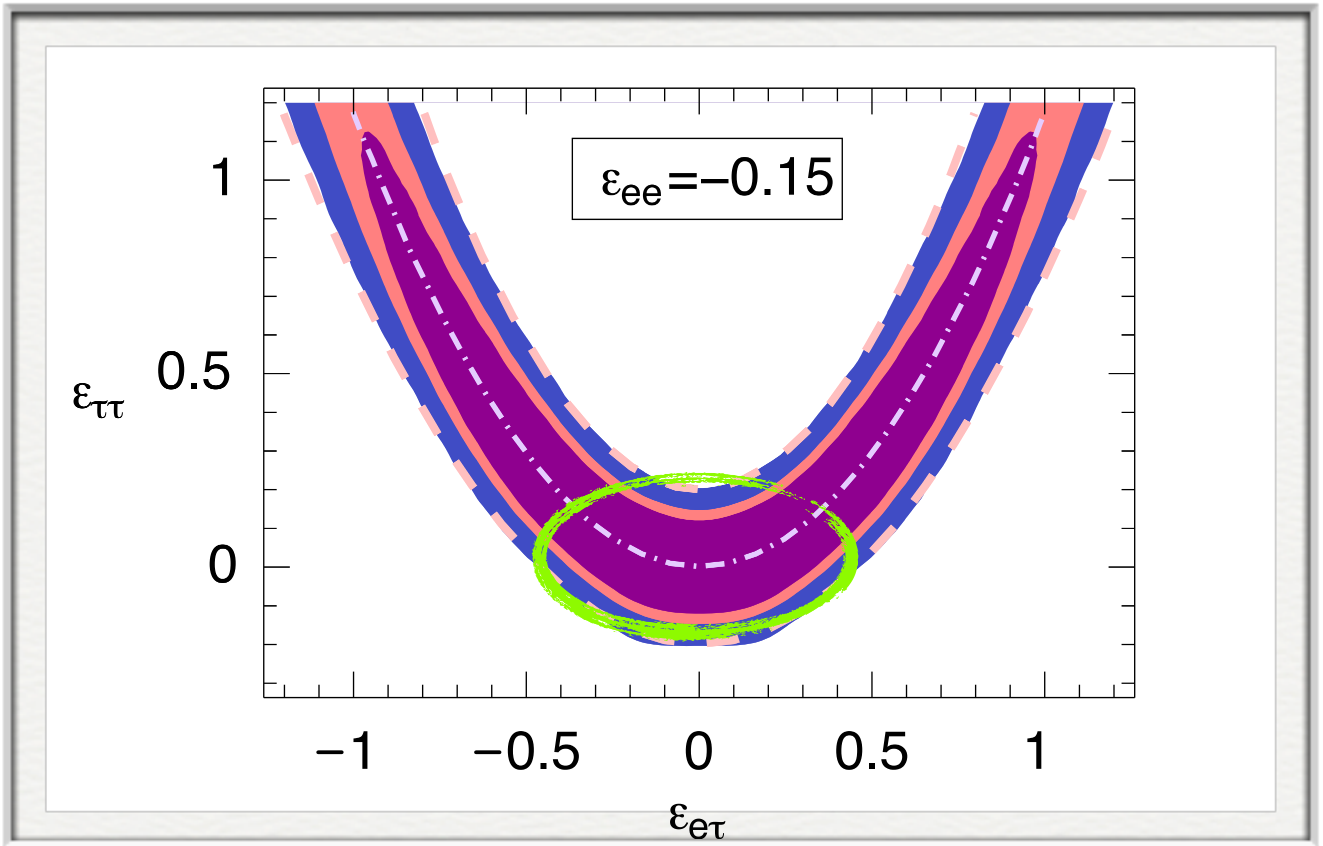
SNO 3-phase analysis 2011; our fit

Similar story with Borexino, SuperK; see Palazzo, PRD 2011

Atmospheric neutrinos

- Friedland, Lunardini, Maltoni, PRD 2004;
  Friedland, Lunardini, PRD 2005

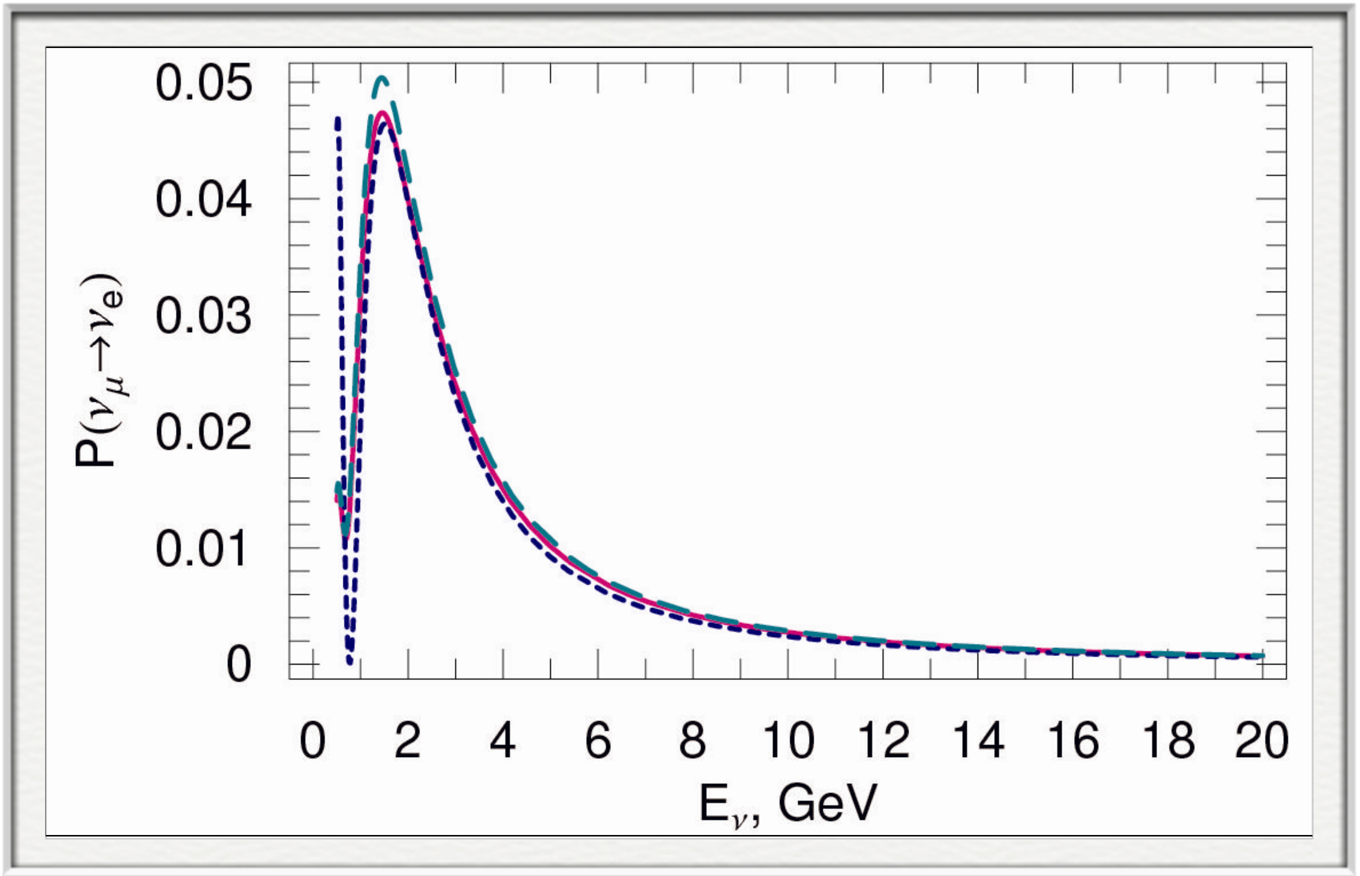
- SuperK probes the same e-τ NSI with atmospheric neutrinos
- Data over 5 decades in energy! But energies not well-resolved
- As a consequence $\varepsilon_{e\tau}$ up to ~0.5 allowed, even without special cancellations
  - Weaker than solar



See Gonzalez-Garcia, Maltoni, Salvado, arXiv:1103.4365v2 for a recent update

1000 km of rock: MINOS, NOνA, LBNE

- The flavor-changing NSI cause small nu-e appearance
- This could fake the effect of theta13 pretty closely
- One might think that only large NSI (same size at the SM weak interactions) can be probed...



$\sin^2 2\theta_{13} = 0.07$ or

$\sin^2 2\theta_{13} = 0 +$ NSI $\varepsilon_{e\tau} \sim 1$

Friedland, Lunardini, PRD 2006

Interference of amplitudes

A.F. ,C. Lunardini, PRD (2006); A.F., I. Shoemaker, arXiv:1207.6642

$$P(\nu_\mu \to \nu_e) \simeq \left| G_1 \sin\theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos\theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2 ,$$

$$\begin{aligned} G_1 &\simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \cos\theta_{23} + \Delta \sin 2\theta_{13} e^{i\delta} , \\ G_2 &\simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \sin\theta_{23} - \Delta_\odot \sin 2\theta_{12} . \end{aligned}$$

- Two channels, solar and atmospheric; NSI amplitude appears in both

Interference of the large theta13 term with the NSI term dramatically enhances the sensitivity!

- ***NSI has its own CV-violating phase; interference depends on the relative phases!***

Relevant scales

- Assuming $E_\nu = 2$ GeV, $\theta_{23} = \pi/4$, and $\theta_{13} = 8.7^\circ$

$$\begin{aligned} \Delta \sin 2\theta_{13} &= 0.87 \times 10^{-13} \text{ eV}, \\ \sqrt{2} G_F n_e \cos\theta_{23} &= 0.76 \times 10^{-13} \text{ eV}, \\ \Delta_\odot \sin 2\theta_{12} &= 0.09 \times 10^{-13} \text{ eV}. \end{aligned}$$

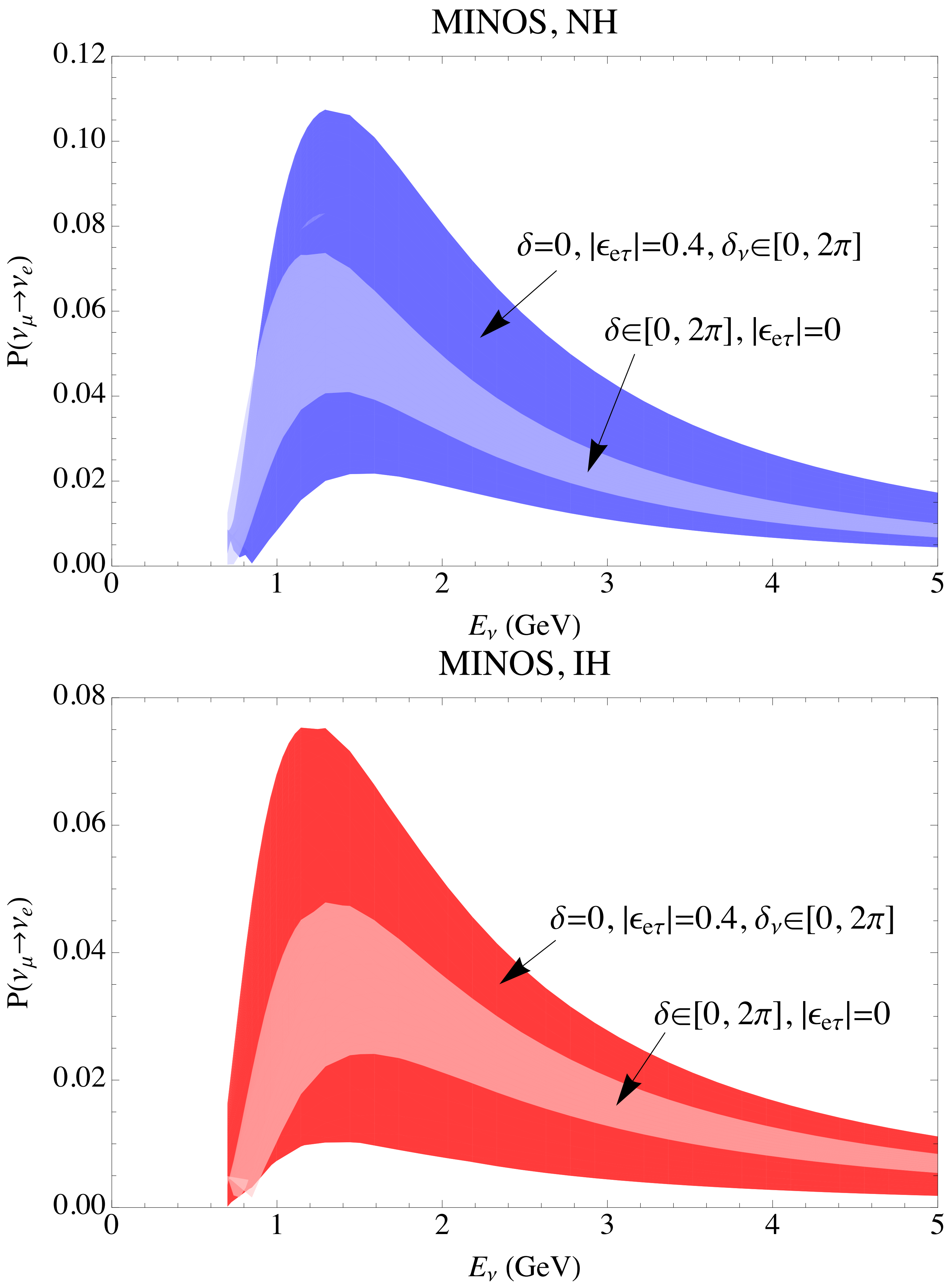
- For standard physics, the solar term is 0.1 of atm. Upon interference, ~20% modulation (hence, search for CP requires precision)

- Assuming NSI $\varepsilon_{e\tau}$ ~0.2, roughly motivated by the solar spectral data, we have

  - Atm > NSI > solar

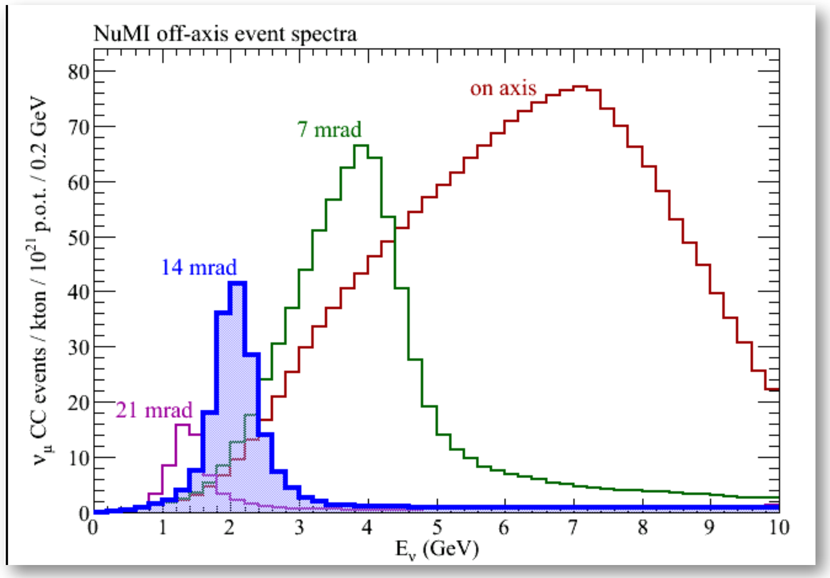
MINOS and “solar-inspired” NSI

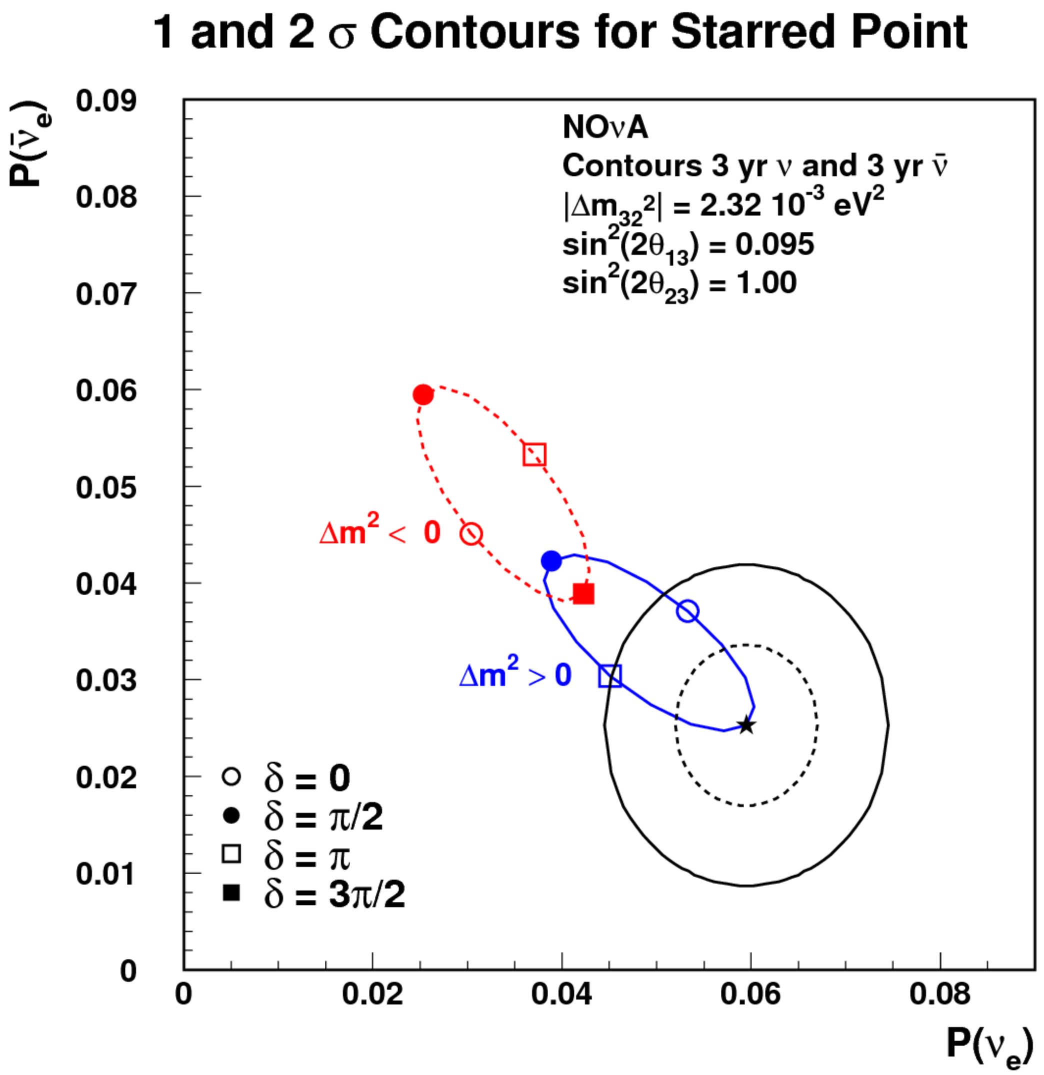
- Interference makes for a pretty large effect
    - Useful constraint already possible
    - On the other hand, NSI can confuse the hierarchies
- Need more sensitivity. NOvA?



NOvA bi-probability: standard case

- Interference between solar and atm. terms depends on the phase
- Instead of plotting the energy spectrum people often show the “bi-probability” plot (Minakata, Nunokawa, JHEP 2001).
- Esp. useful for NOvA, since it’s a narrow band off-axis beam with E ~ 2 GeV

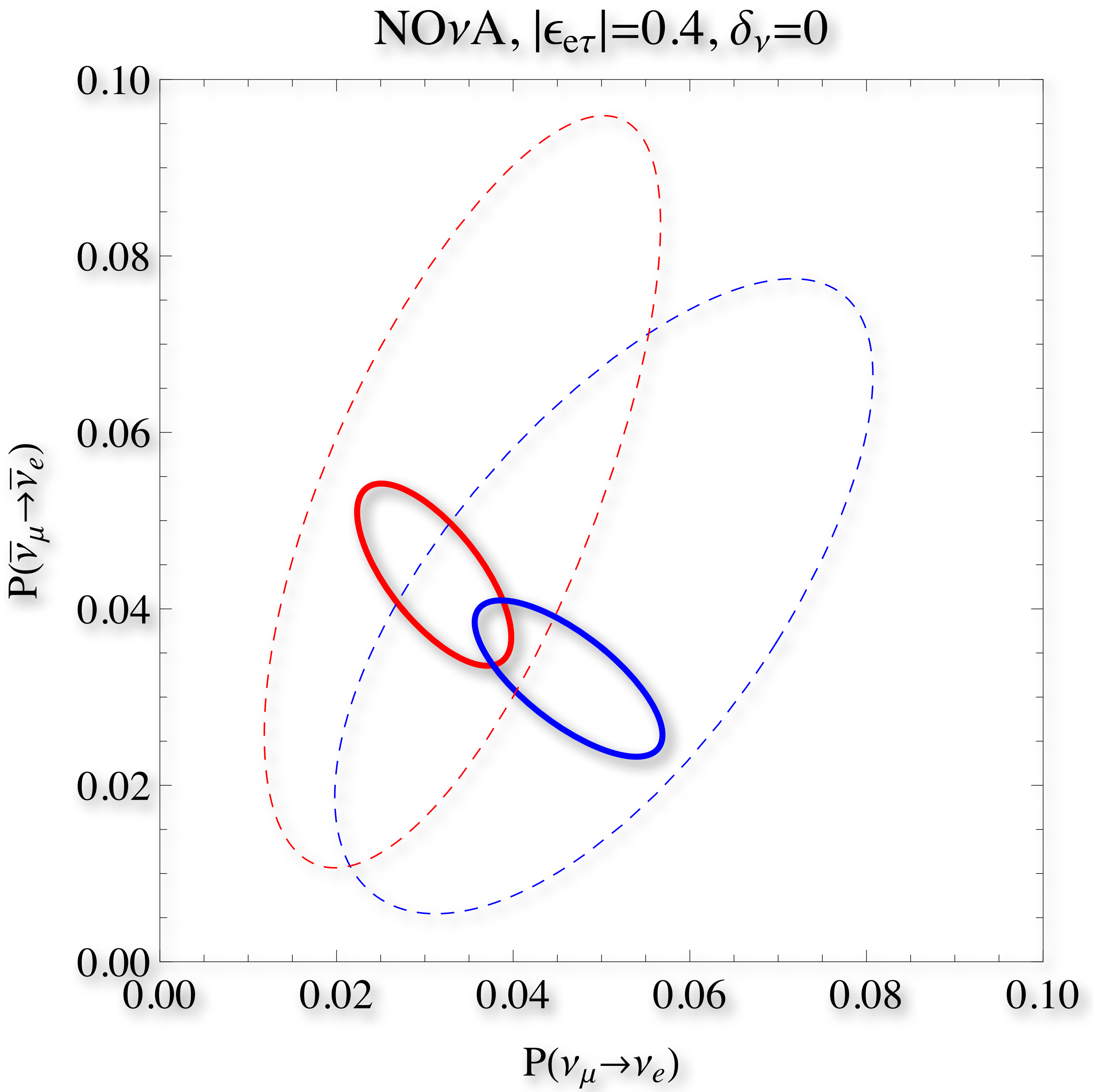




Ryan Patterson, NU 2012

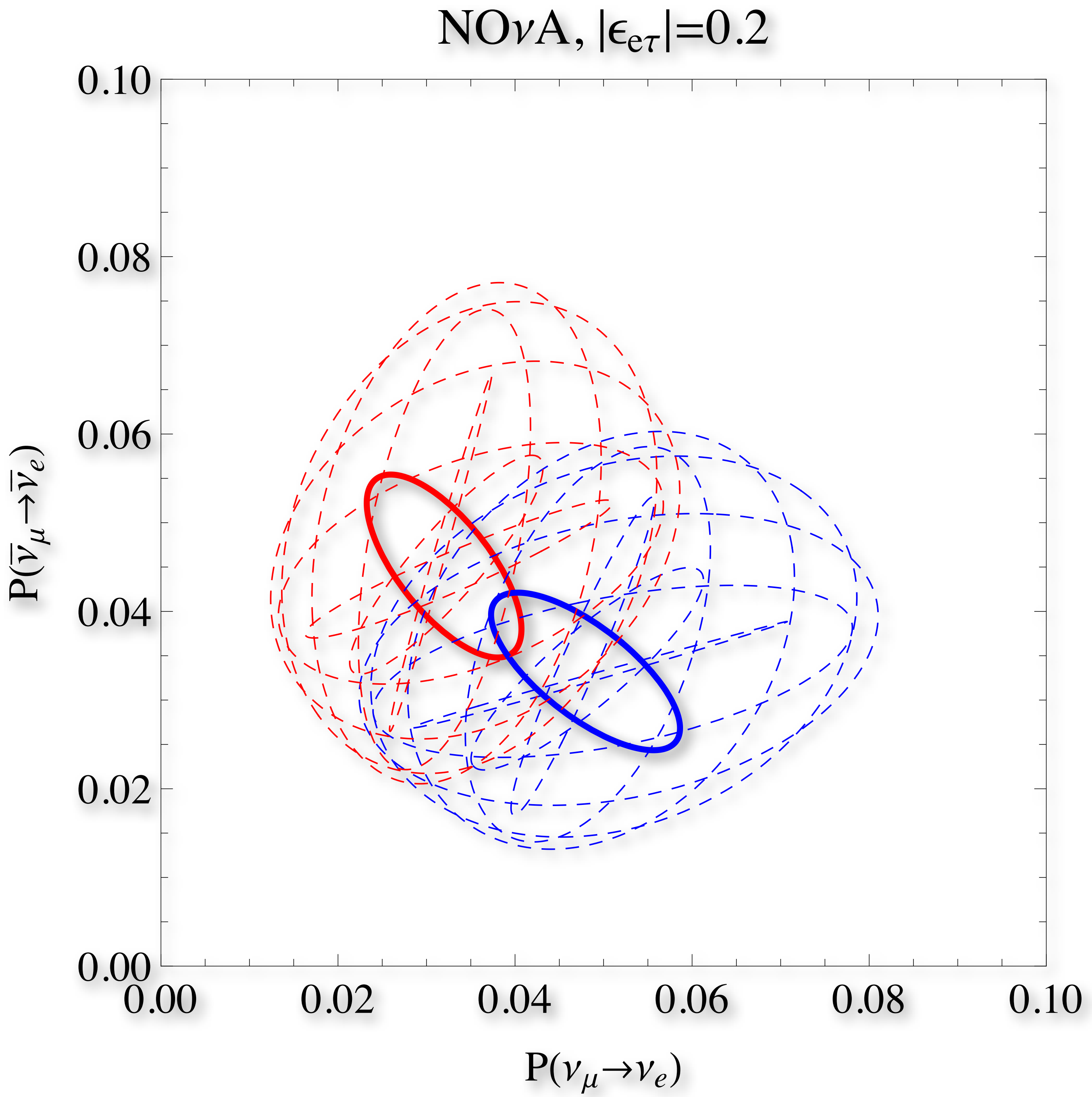
But what if there are also NSI?

- Let’s take $\varepsilon_{e\tau} = +0.4$, as in the earlier solar plot



Next step: vary the NSI phase

- Let's take a different approach: we don't care about solar data, just trying to constrain NSI.
- Take small $|\varepsilon_{e\tau}| \sim 0.2$, vary its phase freely
- The result is big regions in the bi-probability space



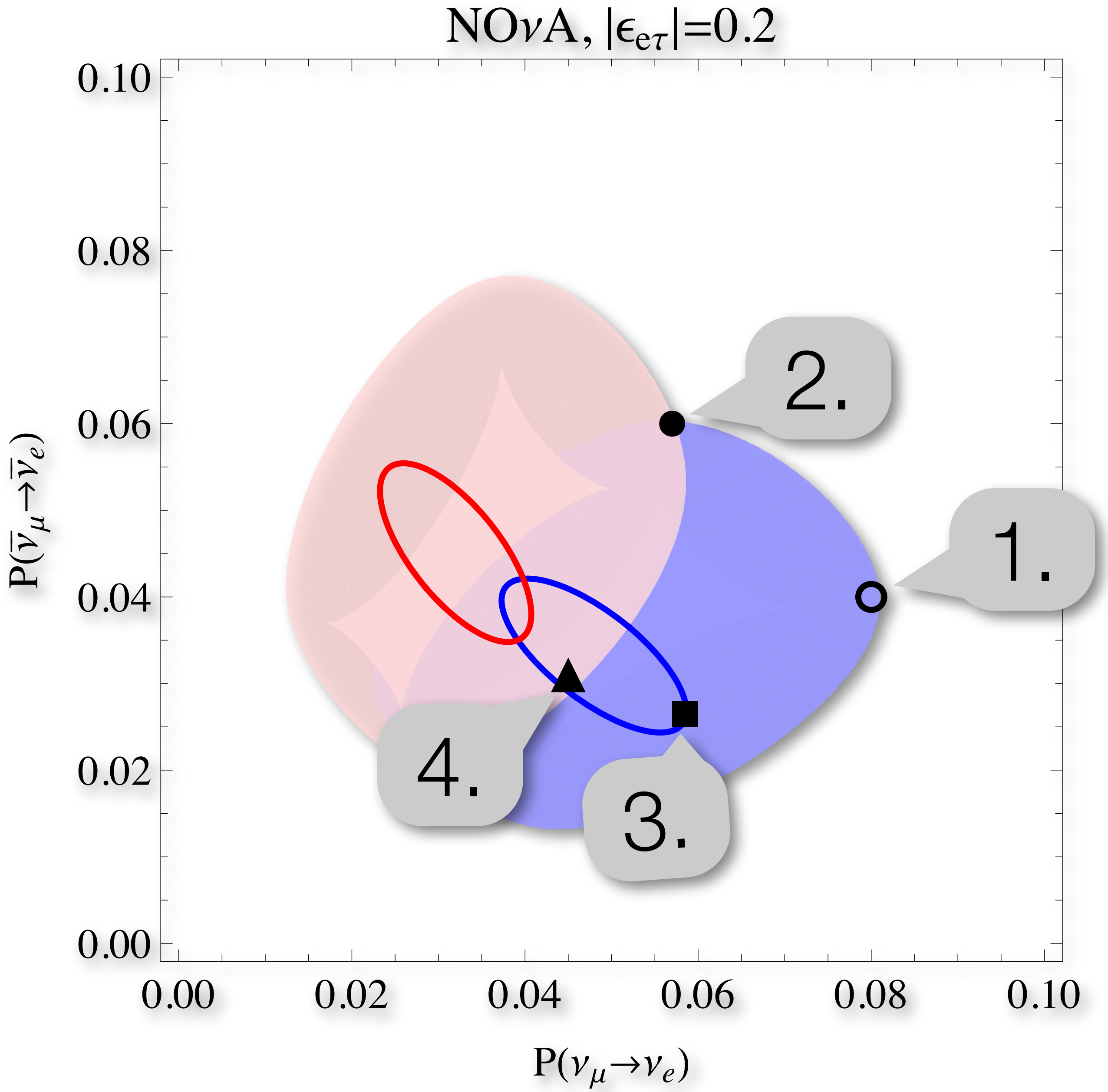
Qualitatively different possibilities

1. Large deviation from the standard ellipses: detection of new physics + mass hierarchy!

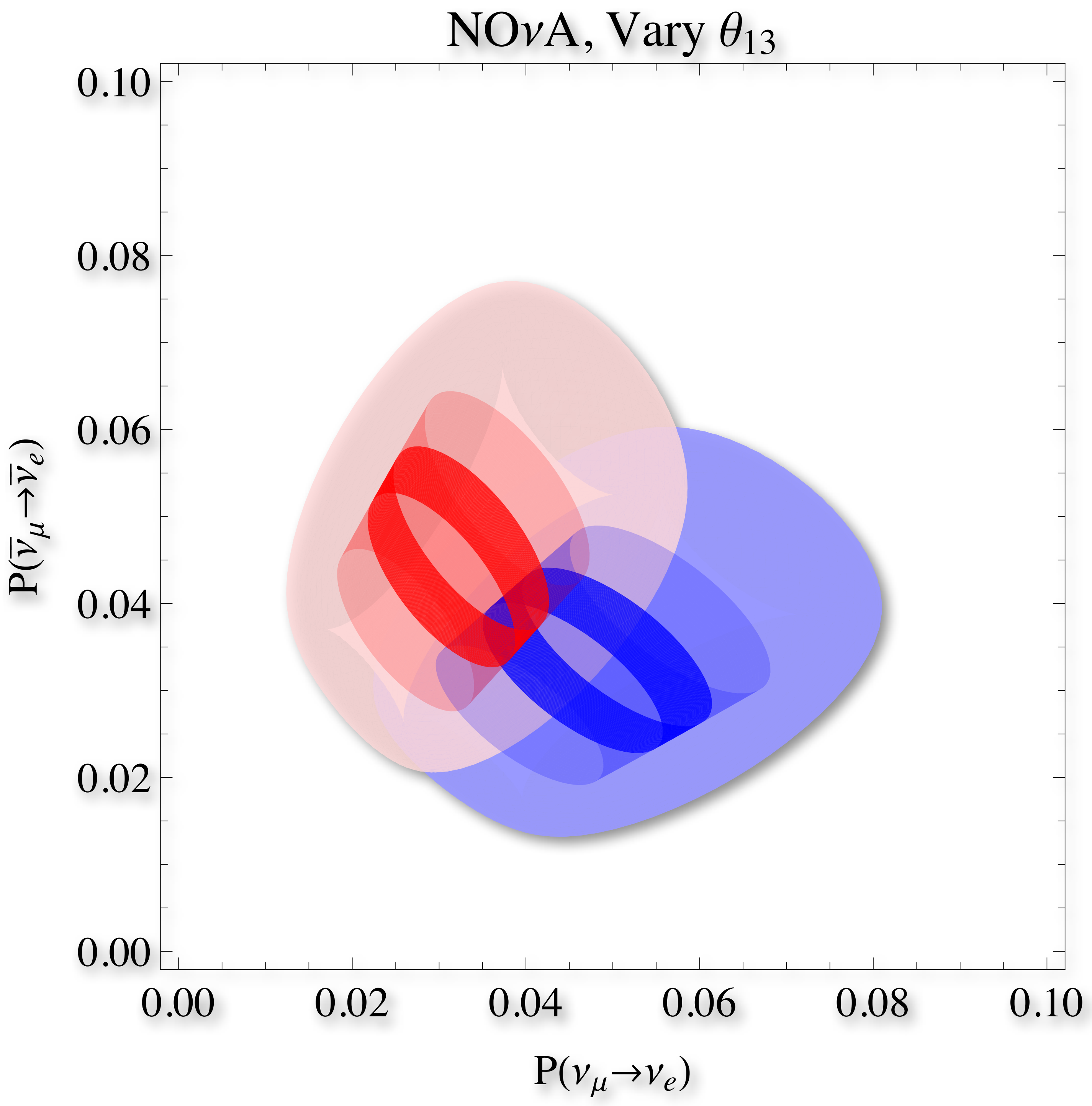
2. Large deviation from the standard ellipses: detection of new physics, but mass hierarchy is confused

3. Mass hierarchy measured, but no don't know if NSI or not

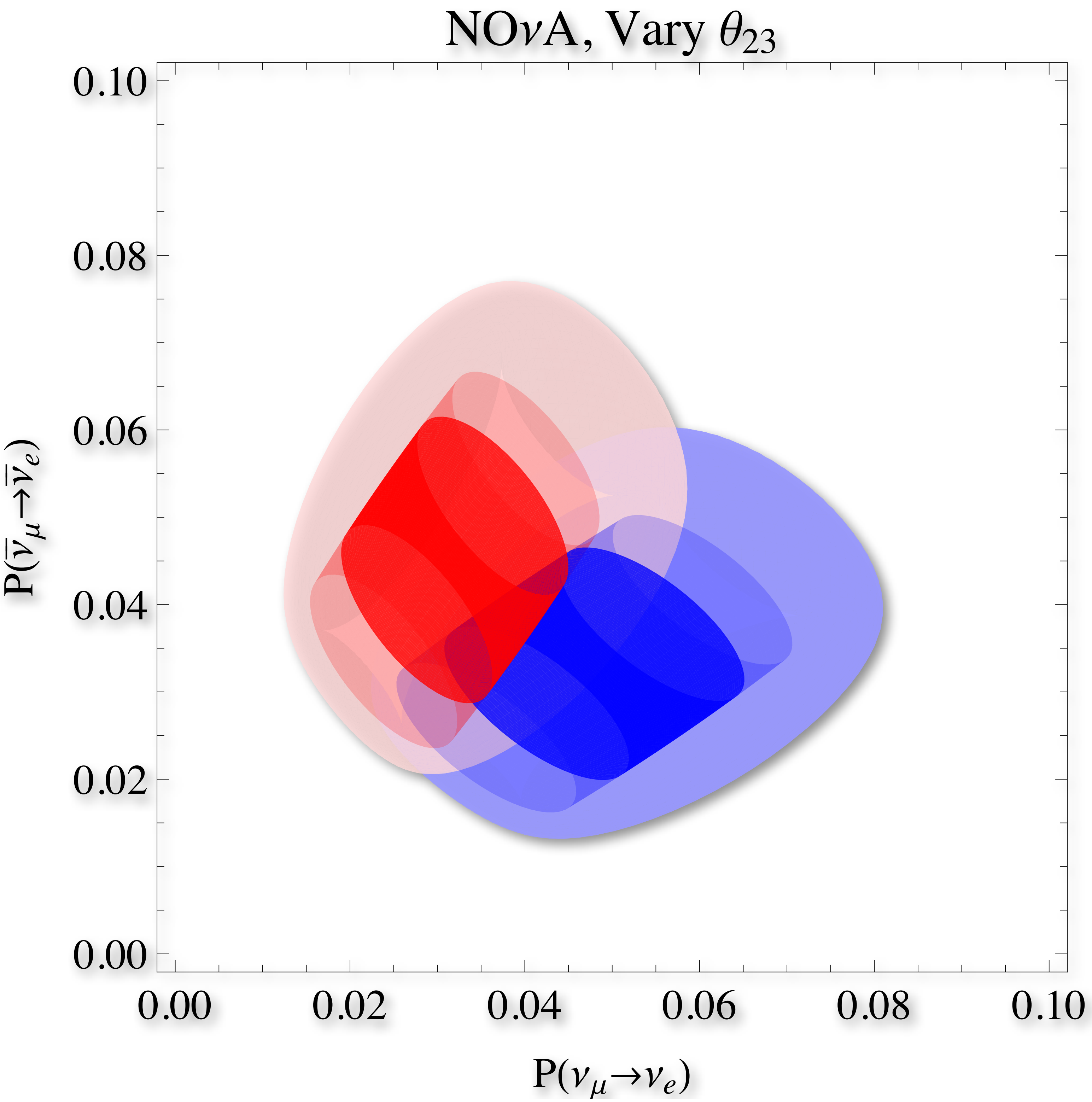
4. Complete confusion



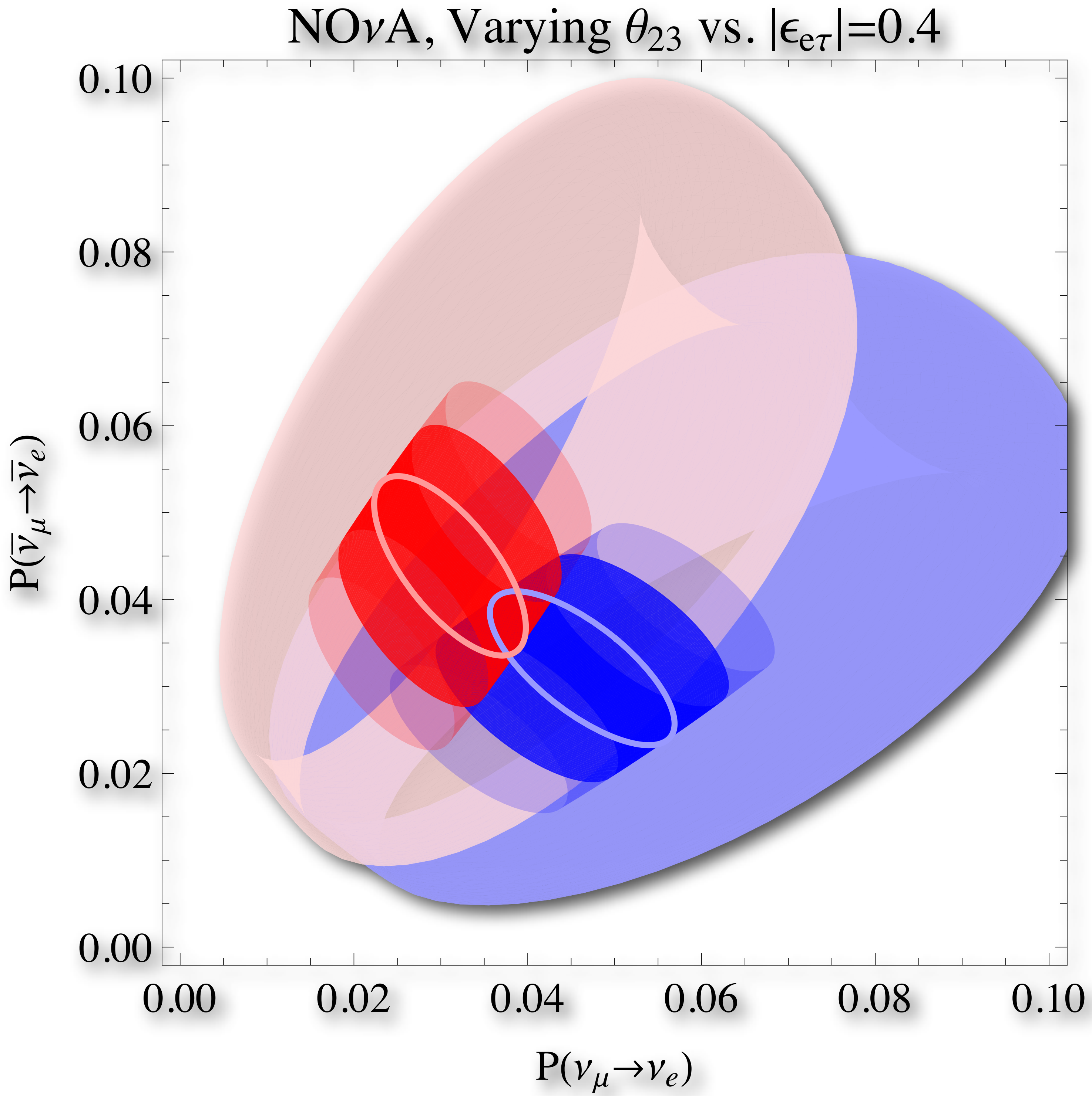
Degeneracies: theta13



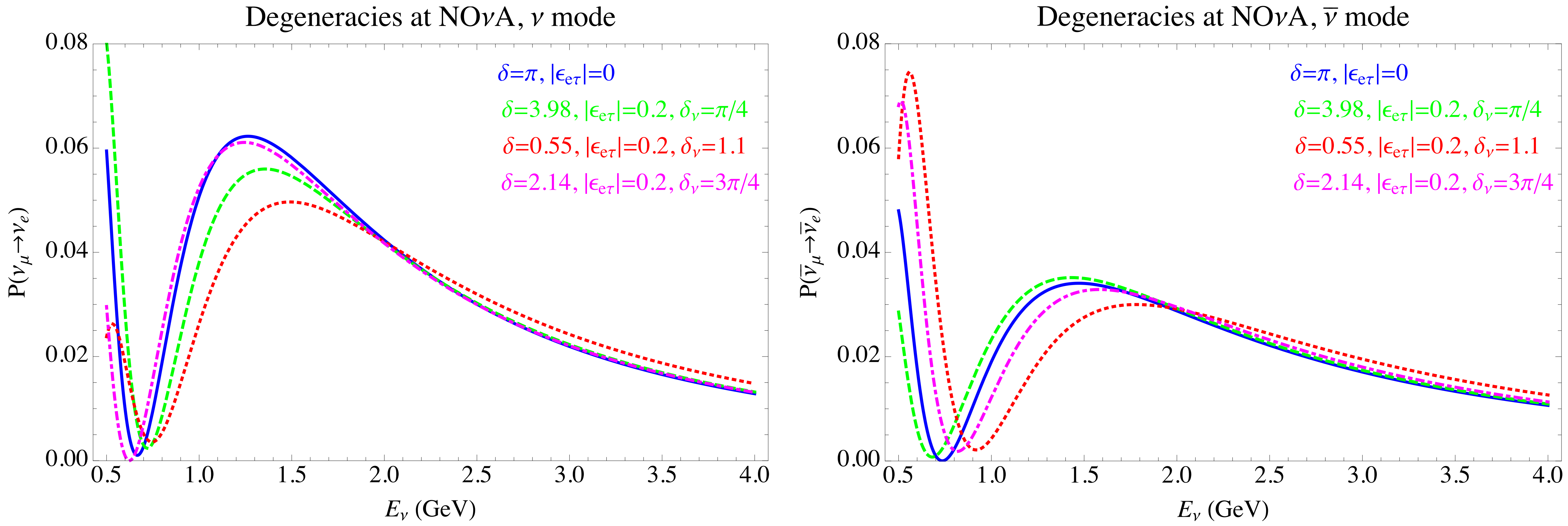
theta23 confusion: octant measurement?



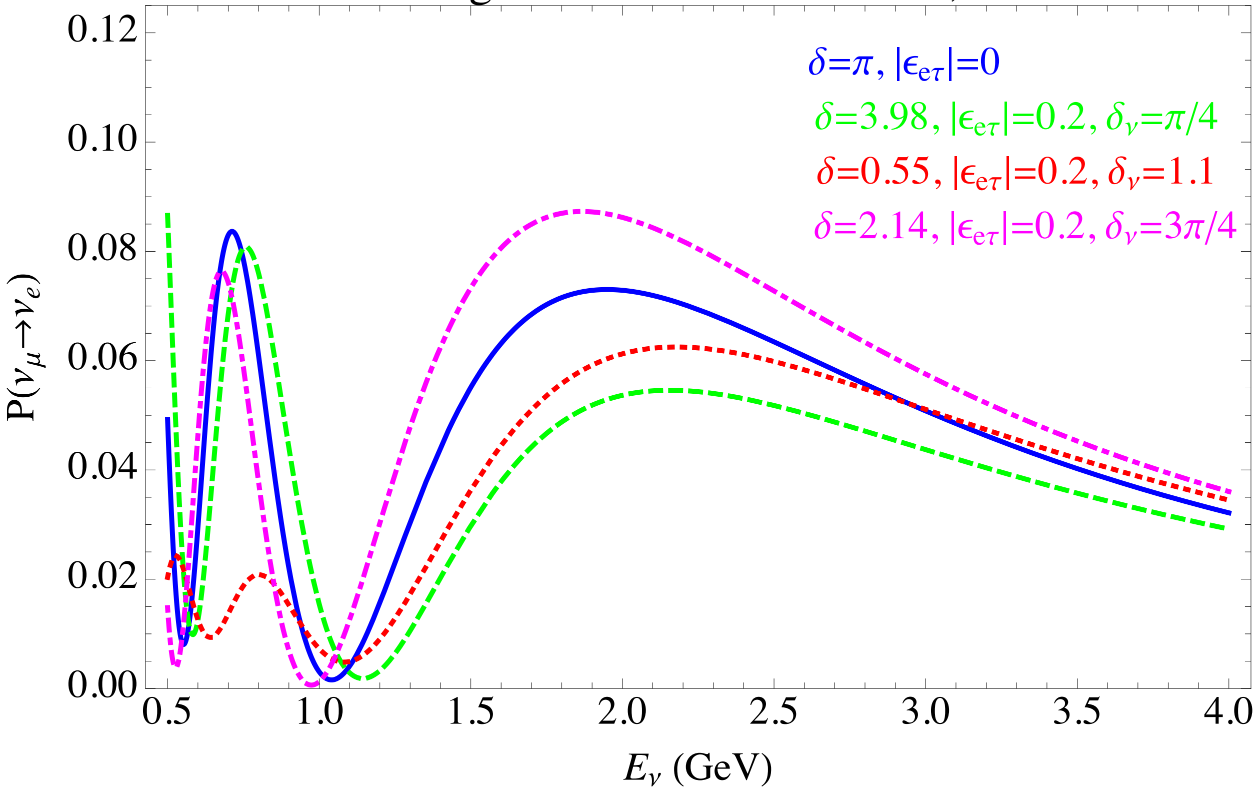
What about $|\varepsilon_{e\tau}| \sim 0.4$?



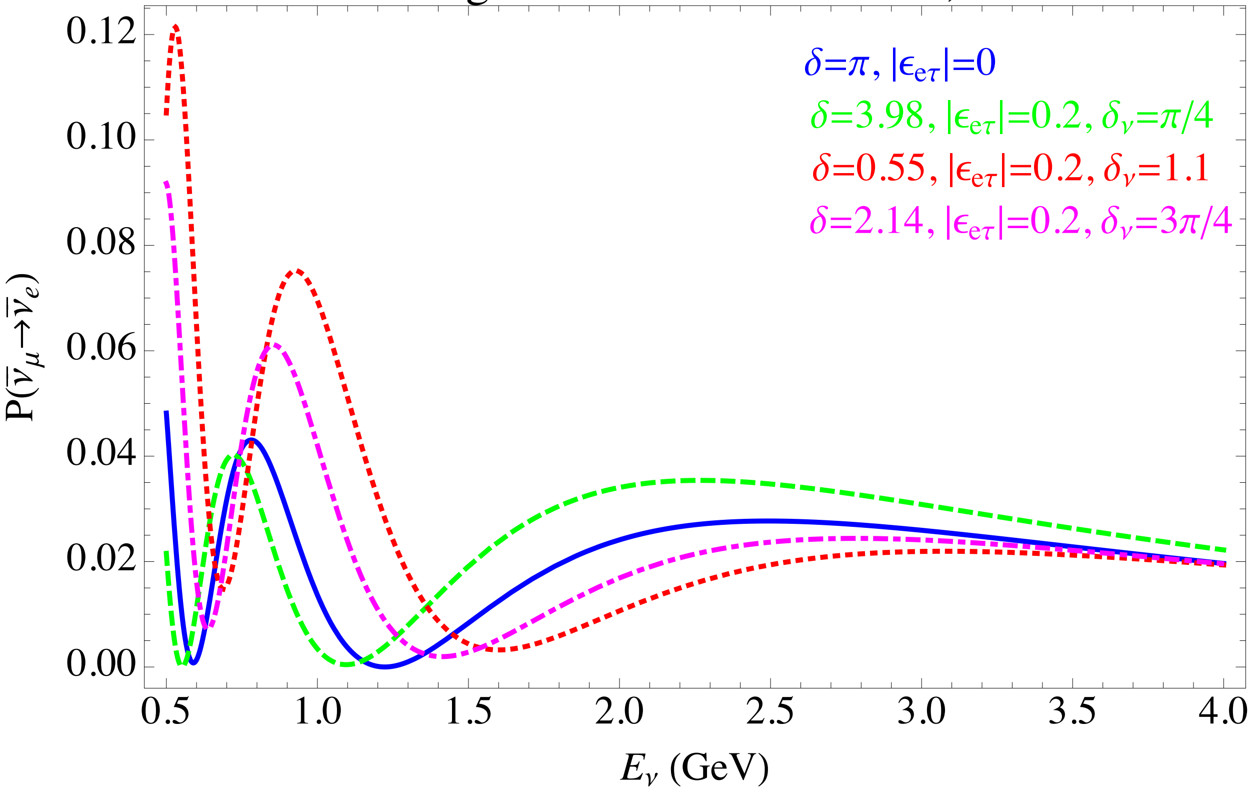
Degeneracies for point 4



Solution: go to longer baseline!



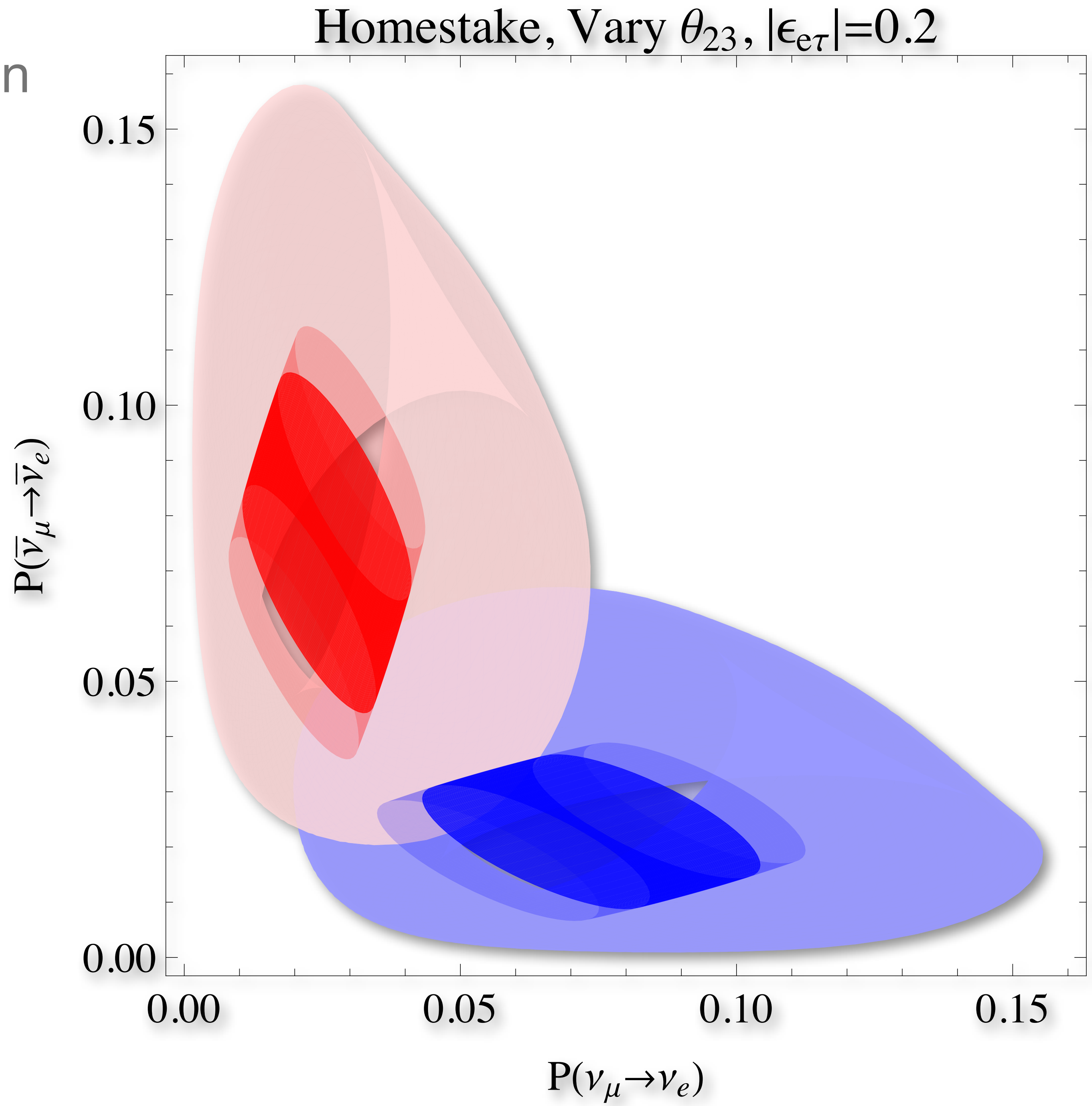
NOνA degeneracies at Homestake, ν mode



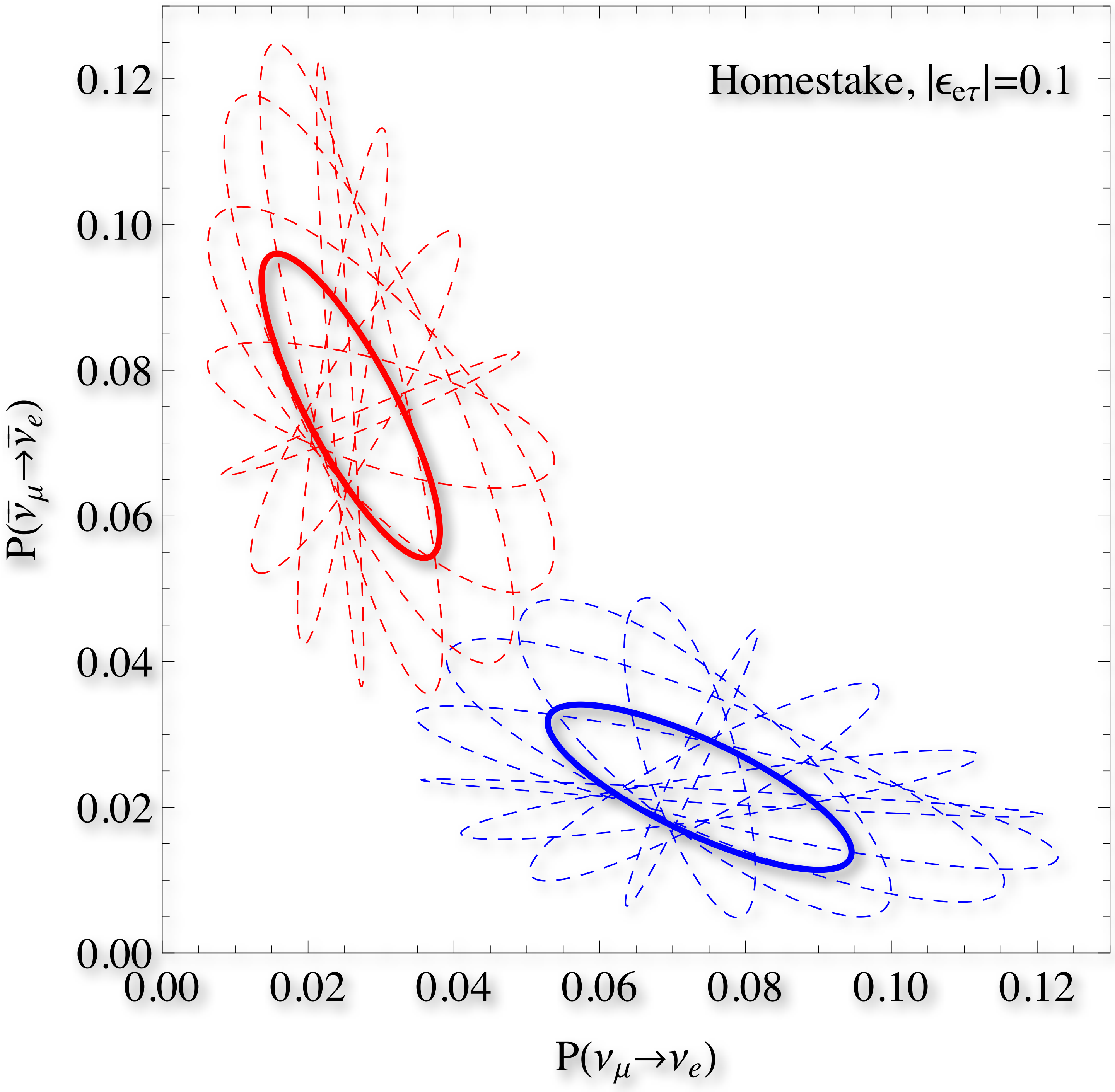
NOνA degeneracies at Homestake, $\overline{\nu}$ mode

Bi-probability at Homestake

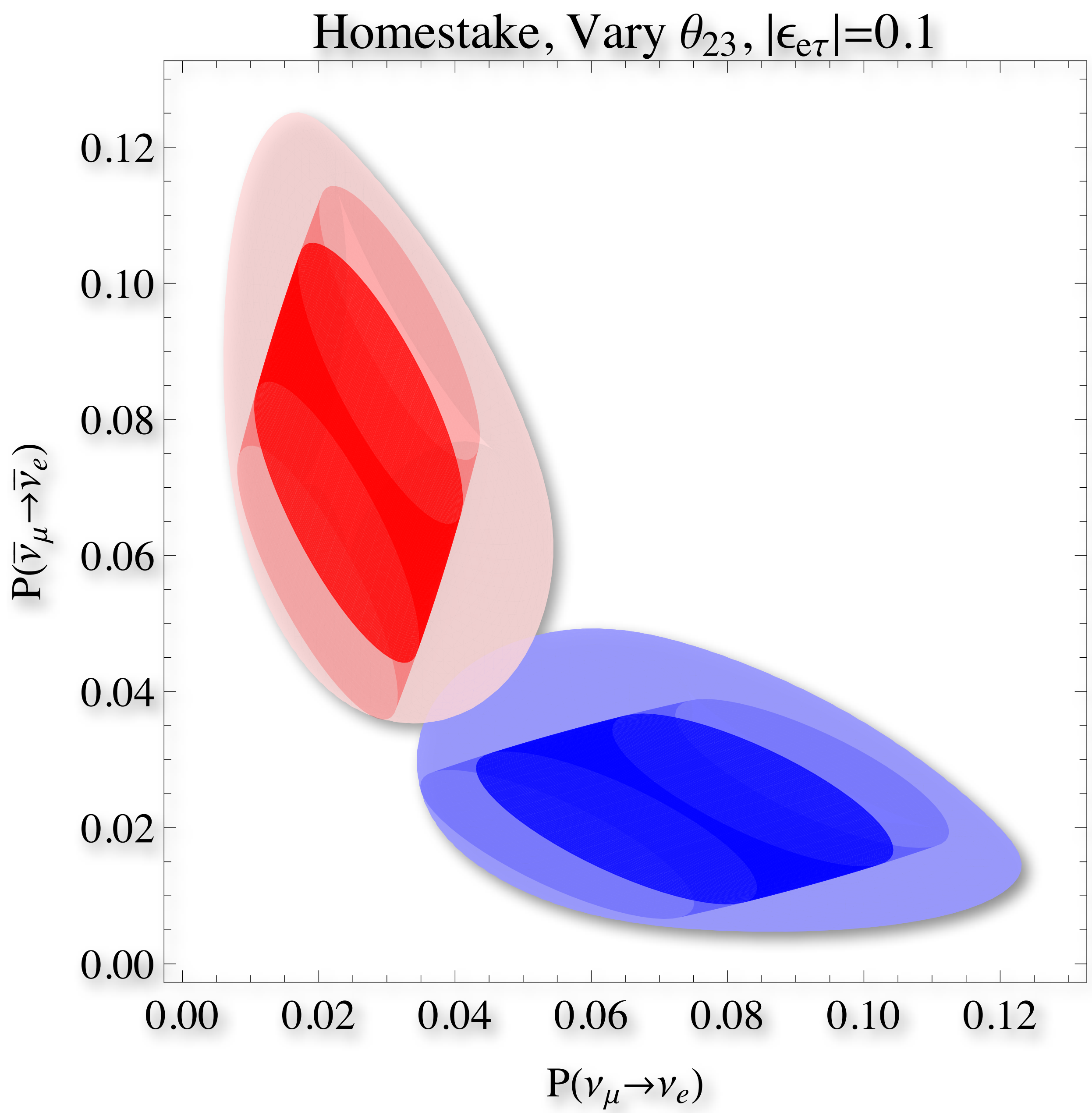
- Chose 2 GeV for comparison



Homestake: probe smaller NSI



Homestake: probe smaller NSI



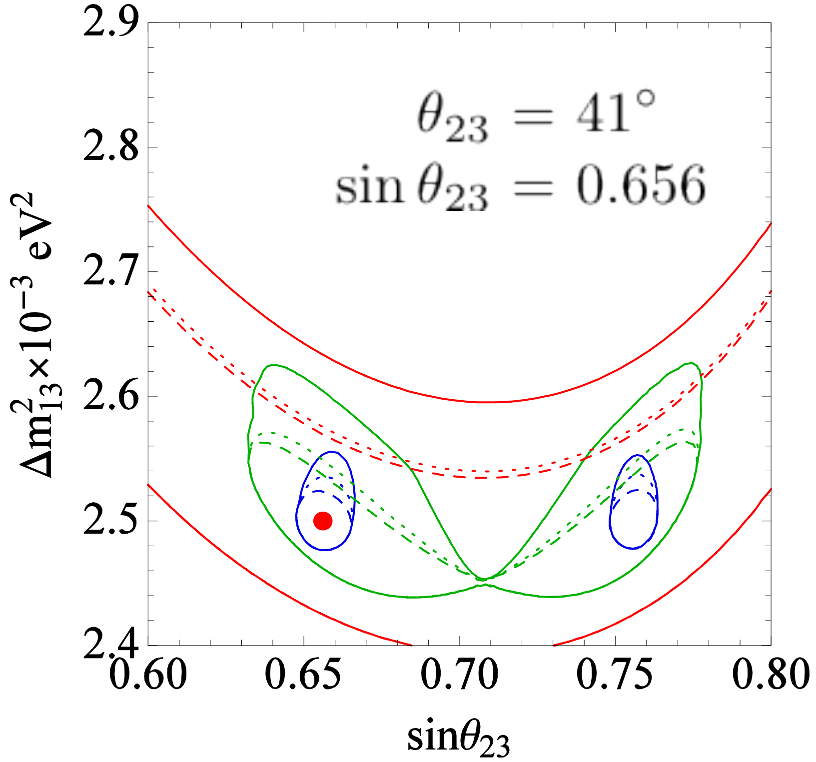
Longest baseline: atm. neutrinos -> IceCUBE!

Presently allowed values:

$\Delta m^2_{32} \in (2.18 - 2.64)10^{-3}\mathrm{eV}^2(2\sigma)$ (MINOS)

$\sin\theta_{23} \in (0.63 - 0.79)(2\sigma)$ (Super-Kamiokande)

IceCube Deep Core:



Observable energies of 5 to 50 GeV
10 energy bins, 4 angular bins

vs.

1st energy bin, 1 angular bin +
9 energy bins, 4 angular bins

vs.

Exclude first 2 energy bins:
8 energy bins, 4 angular bins

$\theta_{13} = 0.01$ - - - - - - - - - - -

vs

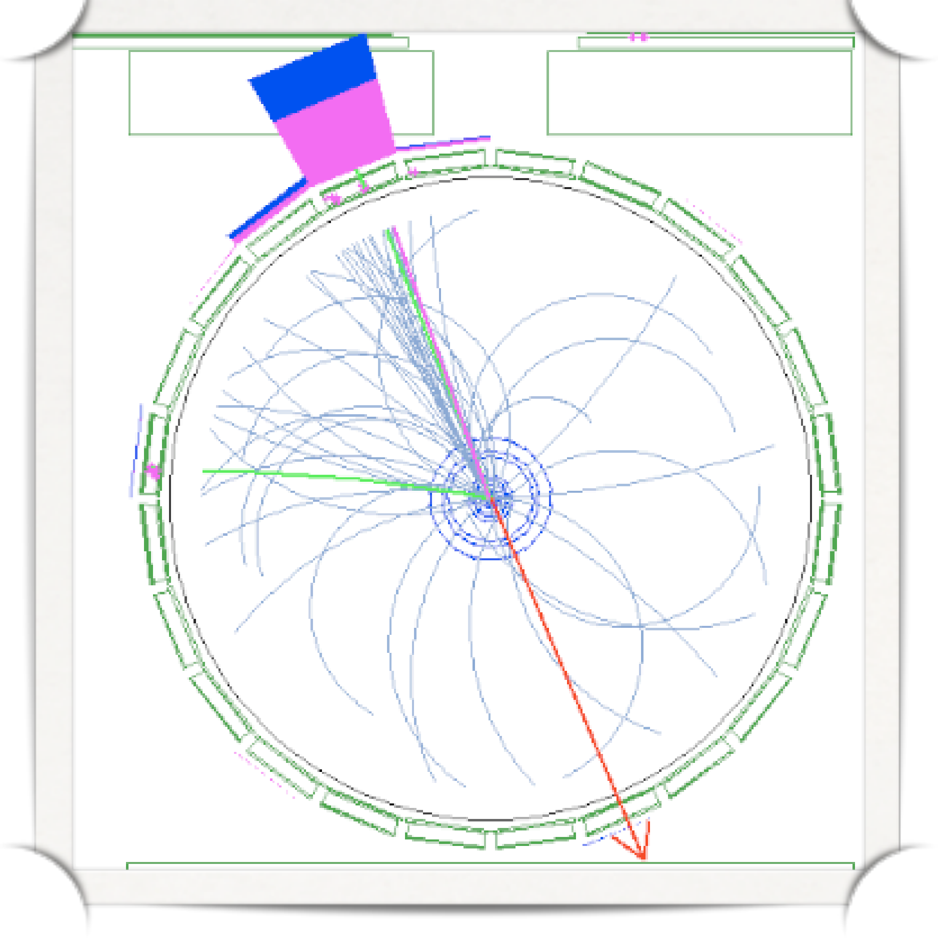
$\theta_{13} = 0.01 \pm 0.02$ ....

vs

θ_{13} completely free ————————

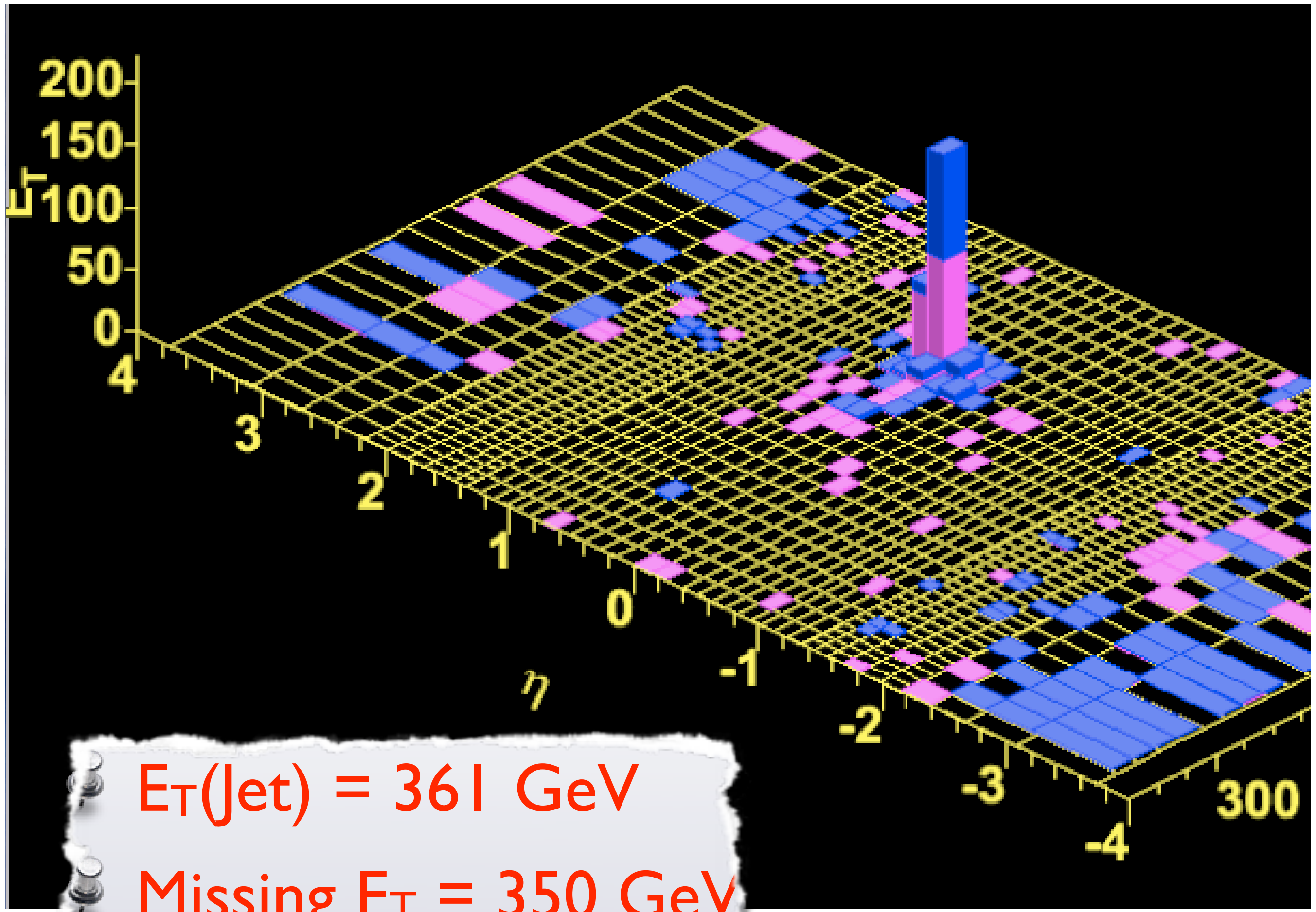
I. Mocioiu, talk at INFO 11, Santa Fe

Collider bounds:
LHC Monojet searches



- “monophoton” or “monojet” events recoiling against “nothing”

- “nothing” could be, e.g., dark matter particles, extra-dim KK gravitons, etc



E_T(Jet) = 361 GeV

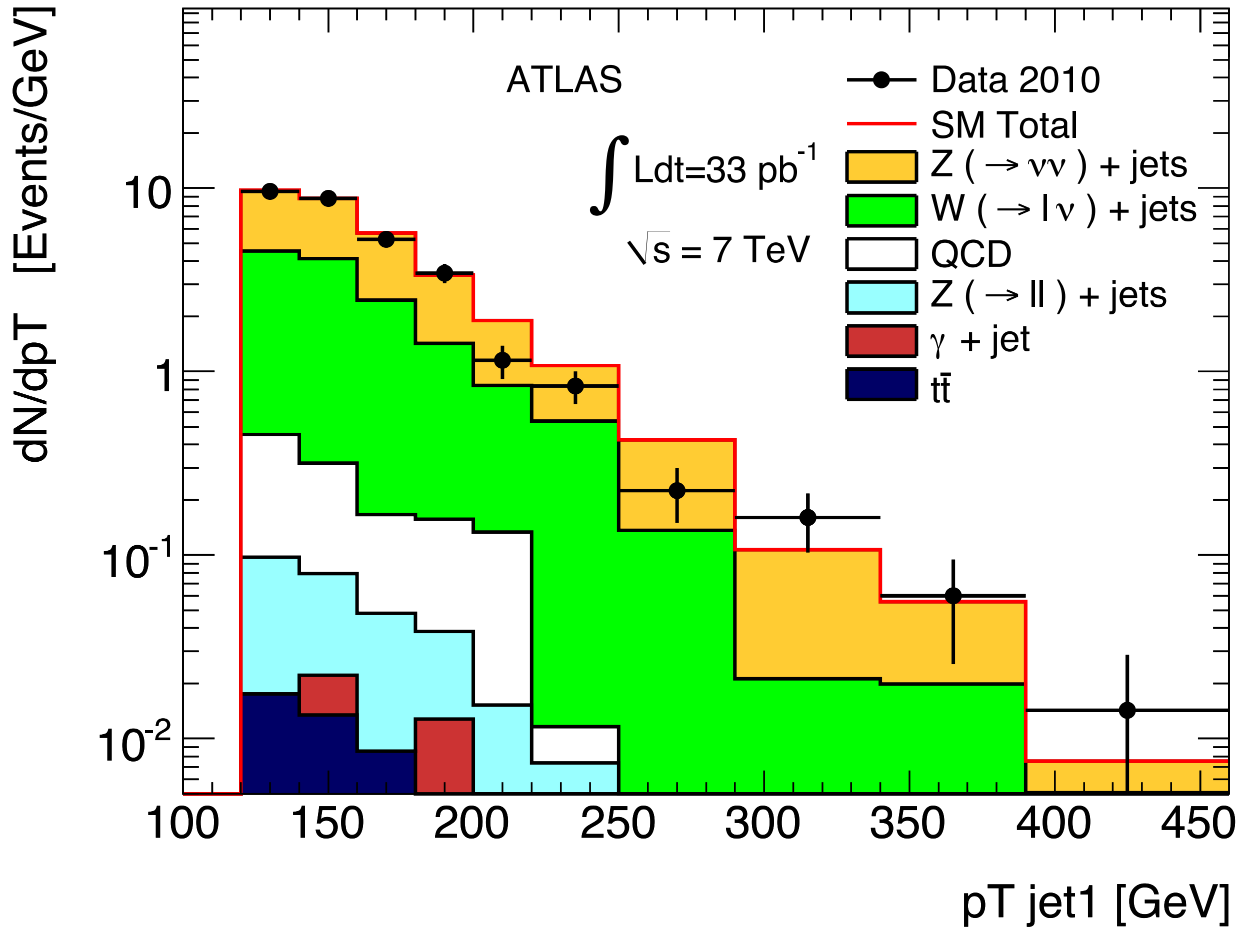
Missing E_T = 350 GeV

Some of the (many) papers on these searches

- Large extra dimensions (ADD):
    - Mirabelli, Perelstein, Peskin, PRL 1999
    - Vacavant & Hinchliffe, J. Phys. G 2001
    - CDF Collaboration, PRL 2006, PRL 2008
- DM:
    - Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, PLB 2011; PRD 2011
    - Bai, Fox, Harnik, JHEP 2010
    - Rajaraman, Shepherd, Tait, Wijangco, arXiv:1108.1196
    - Fox, Harnik, Kopp, Tsai, arXiv:1109.4398

Neutrinos are Backgrounds

- Standard Model physics that leads to monojet events
- jet + Z ➞ jet + νν-bar
- jet + W ➞ jet + eν
    - ➞ jet + μν
    - ➞ jet + τν
- NSI modify BG rate
- May fake DM/KK states



ATLAS, arXiv:1106.5327, Phys. Lett. B 2011

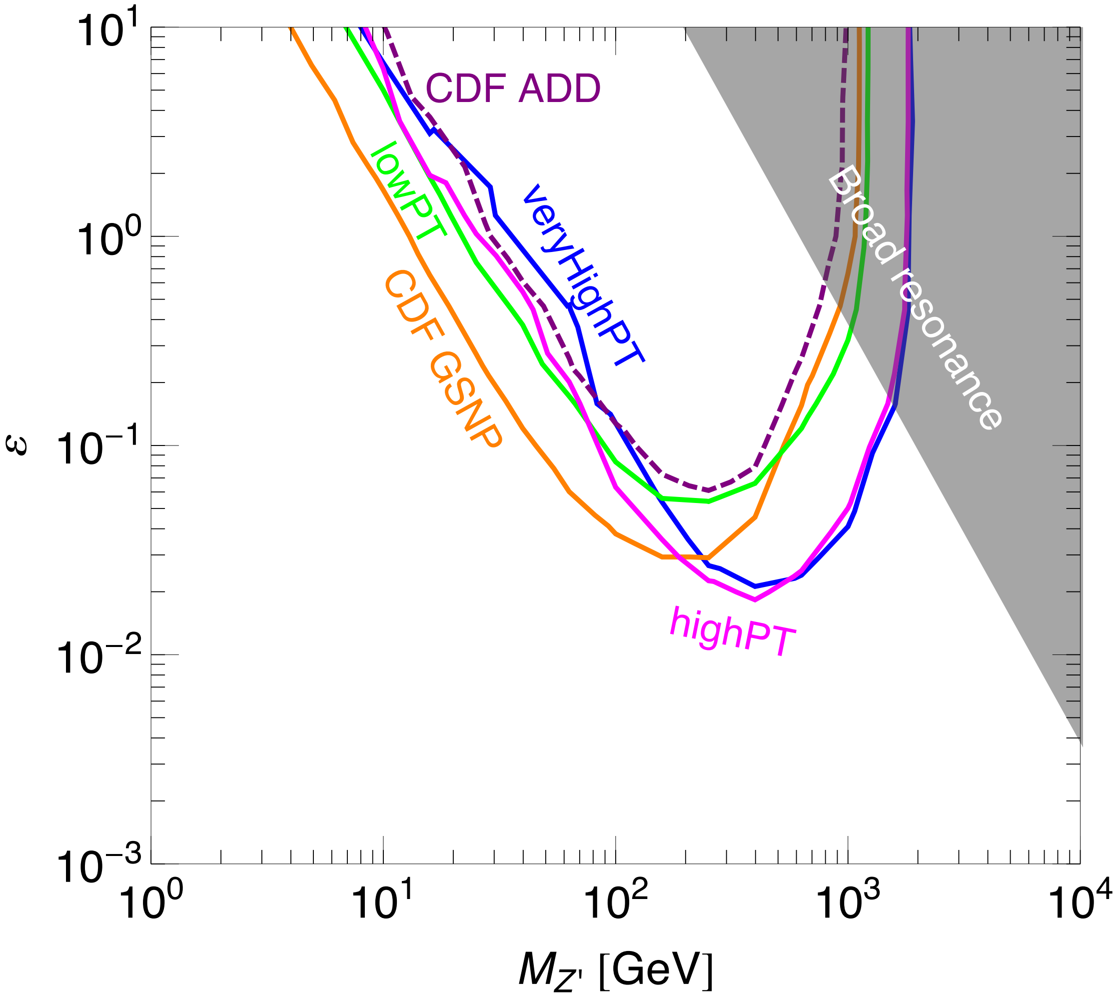
Constraints on neutrino NSI

- Neutrino NSI modify the rate of monojet events

- Monojet data from the Tevatron and LHC provide a useful constraint, especially if the new physics scale is in the hundred GeV range (s-channel), but weaker if it's above or below

  - Systematics limited, already with 1 fb^{-1} of data (last July)

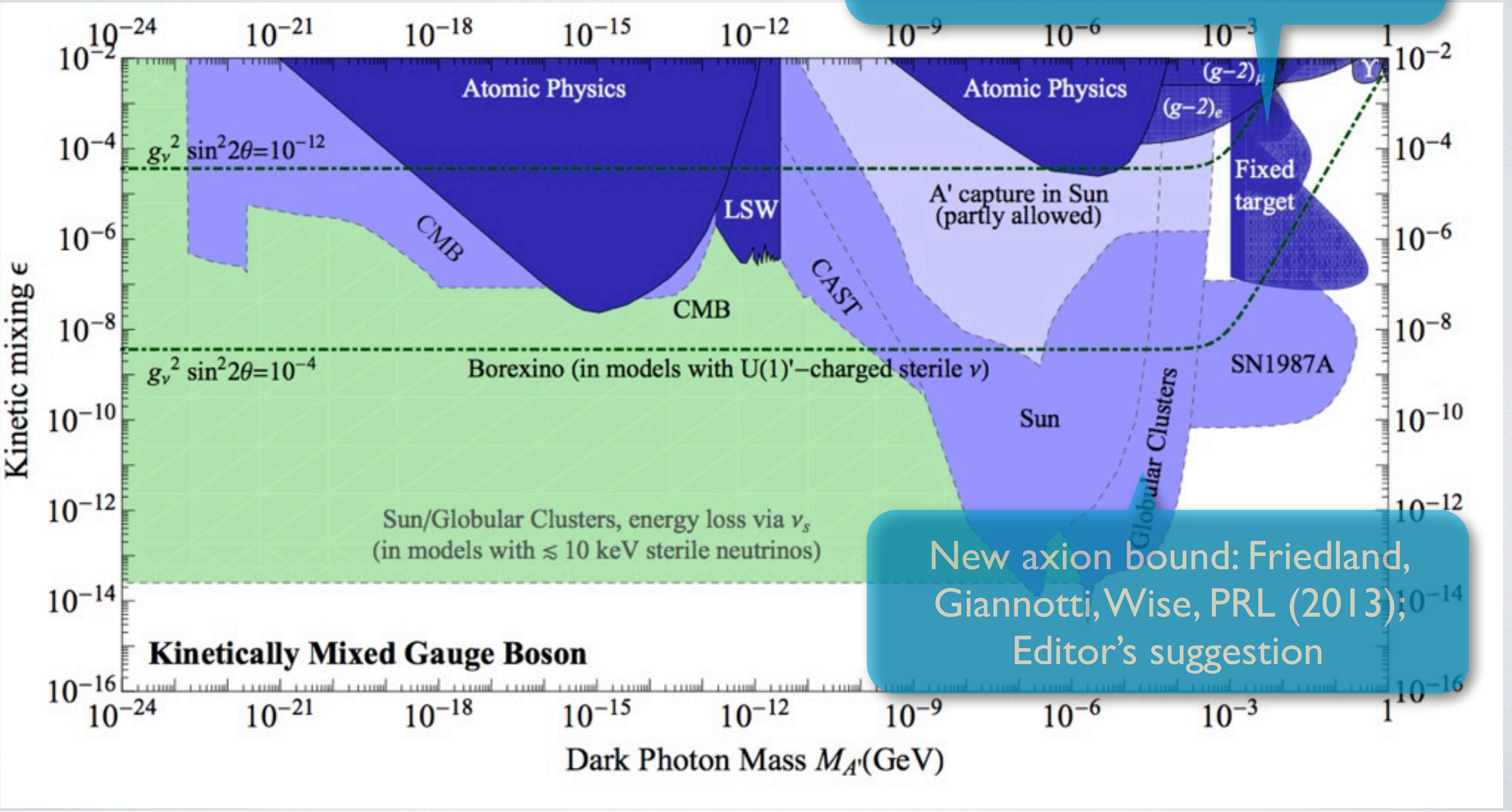
- LHC and neutrino oscillation experiment can probe the same physics!



A. F., Graesser, Shoemaker, Vecchi;
Phys. Lett. B 714, 267 (2012)

LOW SCALE:VERY RICH PHYSICS

[Harnik, Kopp, Machado (2012)]



MiniBOONE beam dump experiment

New axion bound: Friedland, Giannotti, Wise, PRL (2013); Editor’s suggestion

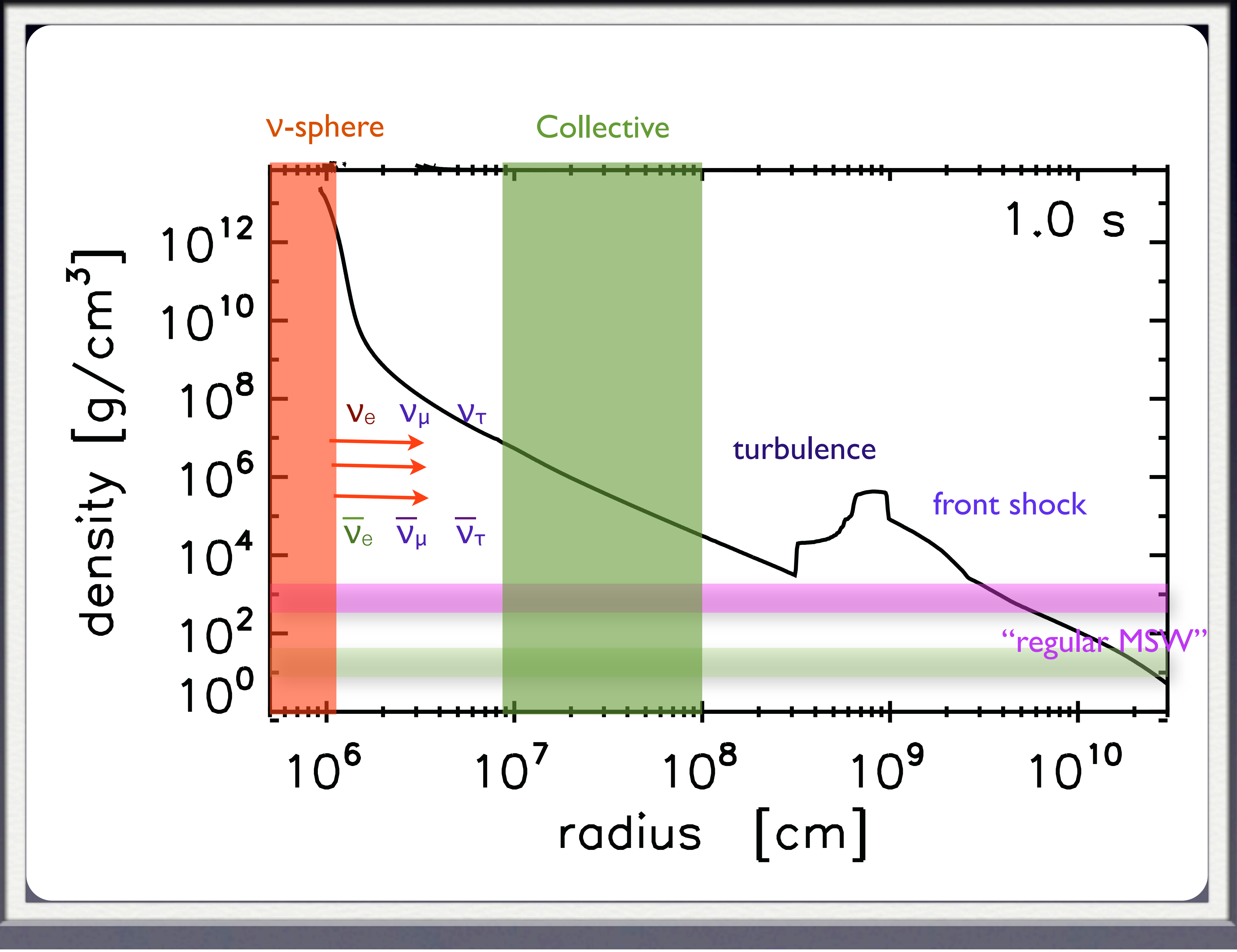
Conclusions NSI

- NSI framework could be used to gauge the reach of different experiments
- Solar neutrinos may be providing a hint. Not excluded by other experiments.
- Sensitivity of long-baseline experiments benefits from large θ13 (interference!)
- Additional source of CP-violation! What have you measured?
- *Multiple baselines*, *spectral information* desired to correctly interpret data and understand degeneracies.
- Connections to collider experiments, dark matter searches, stellar cooling, etc
    - Very interesting physics!

part 2

Supernova neutrinos give us the most beautiful and complicated oscillation problem we know

SN ν oscillations: physics cartoon

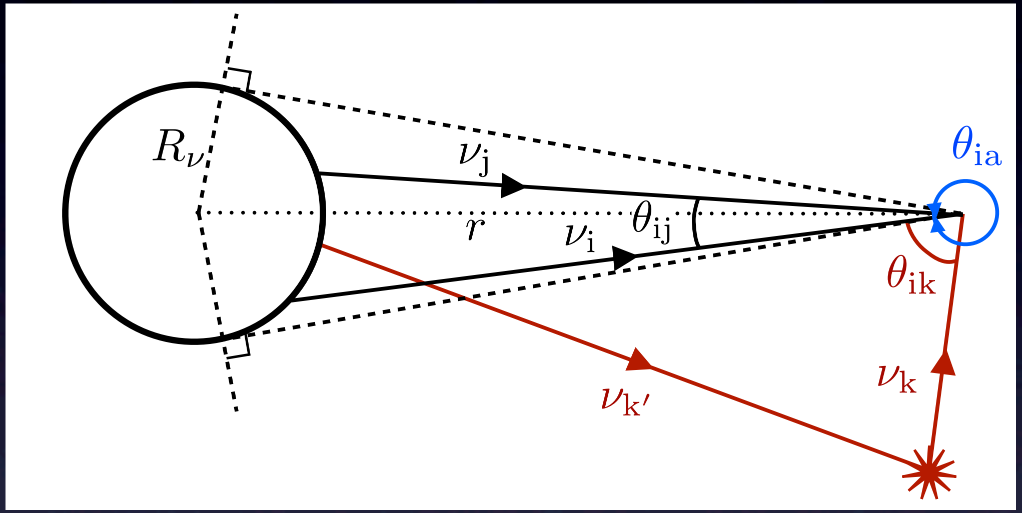


Neutrinos oscillating in unison

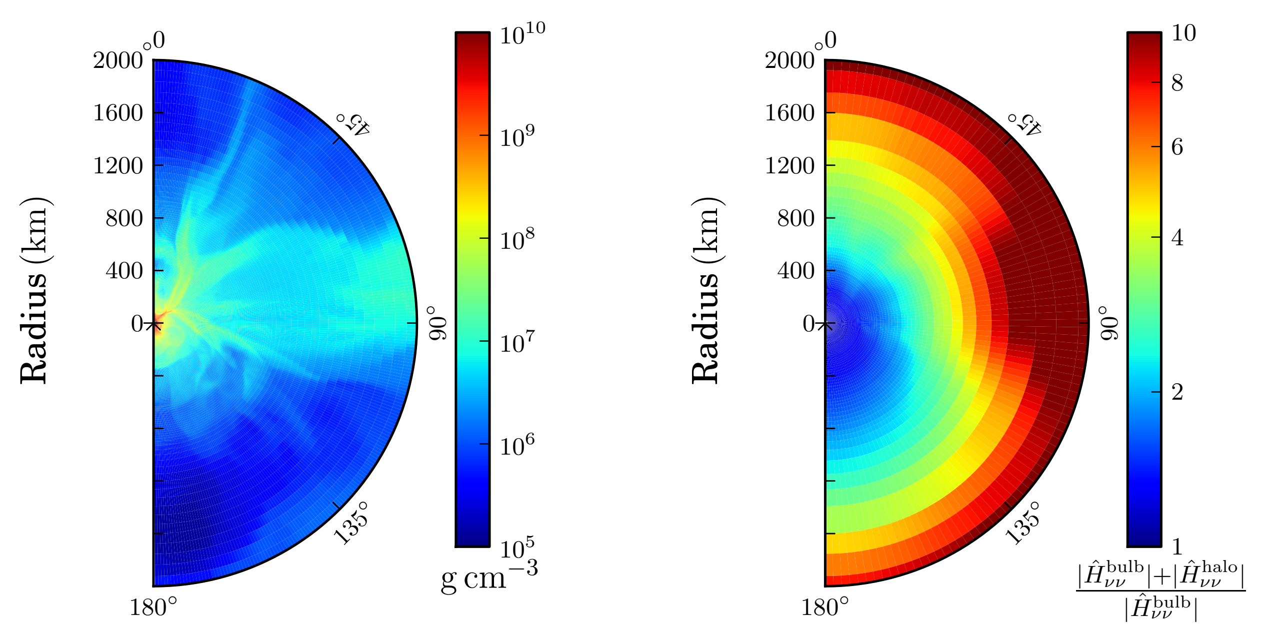
- A lot of activity in recent years
- It has been shown that the physics is qualitatively different in different stages of the explosion
  - First second -- accretion phase
  - Later time -- cooling phase

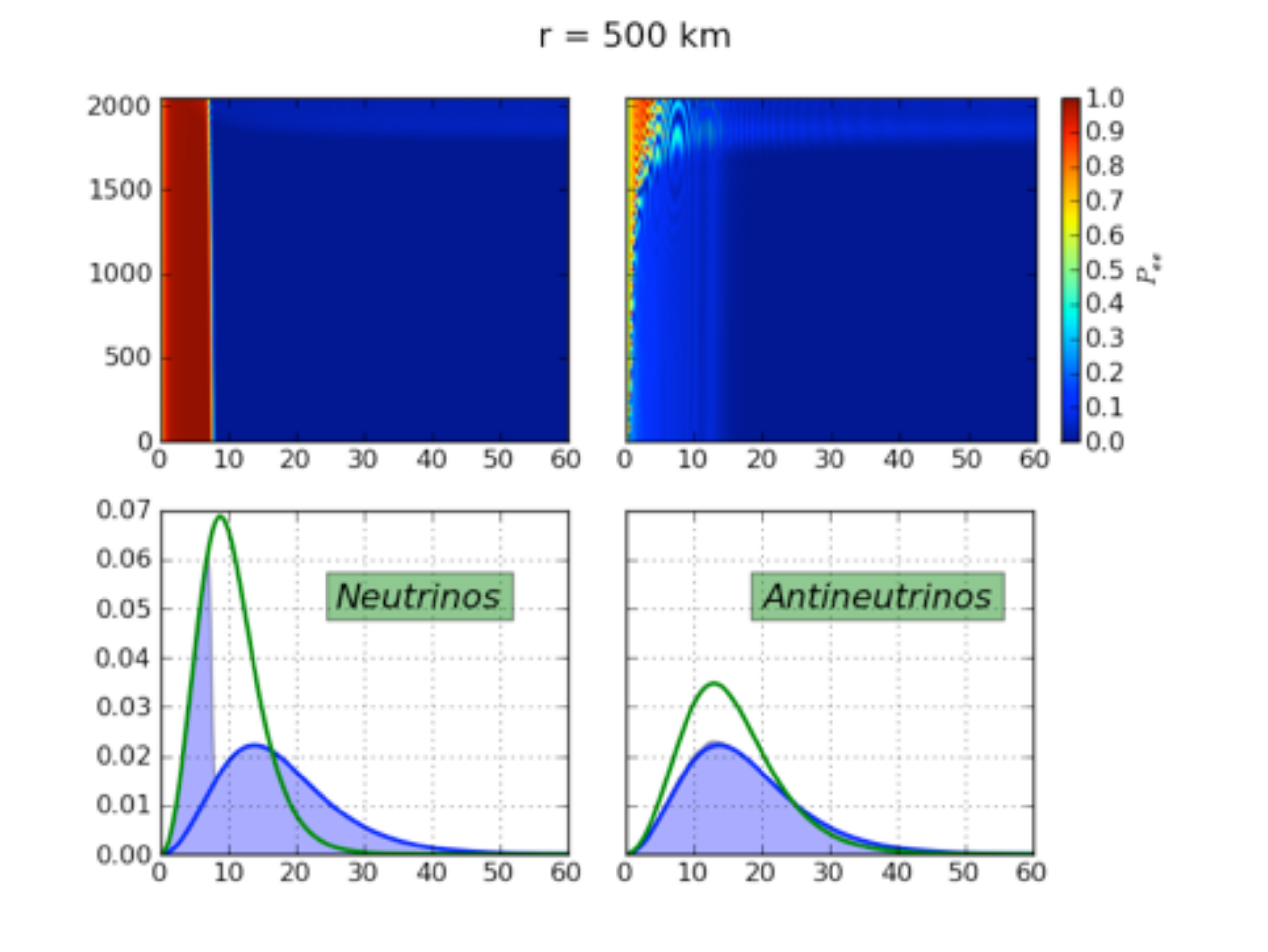
What happens during the first second?

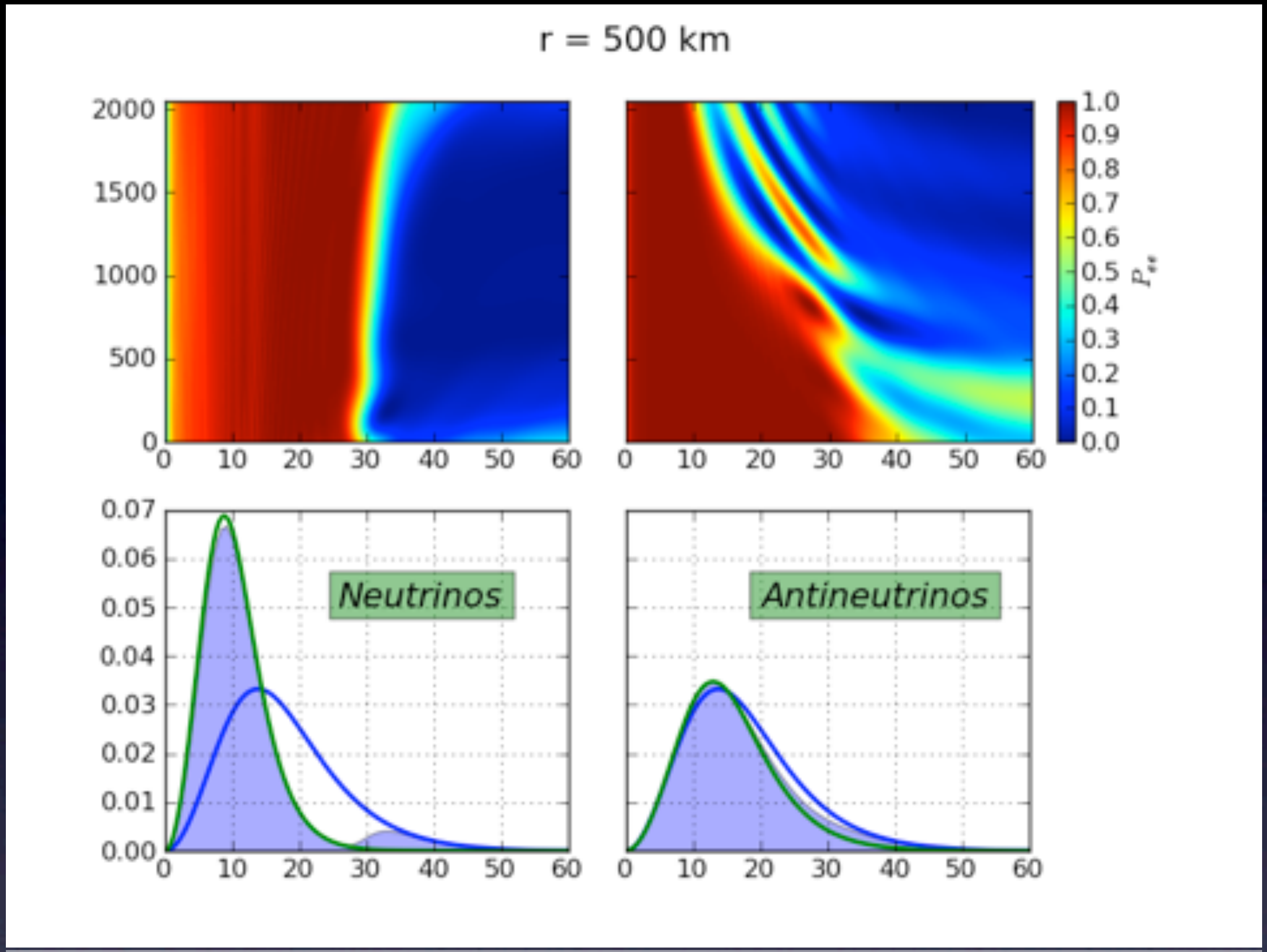
Cherry, Carlson, A.F., Fuller, Vlasenko, PRL (2012)



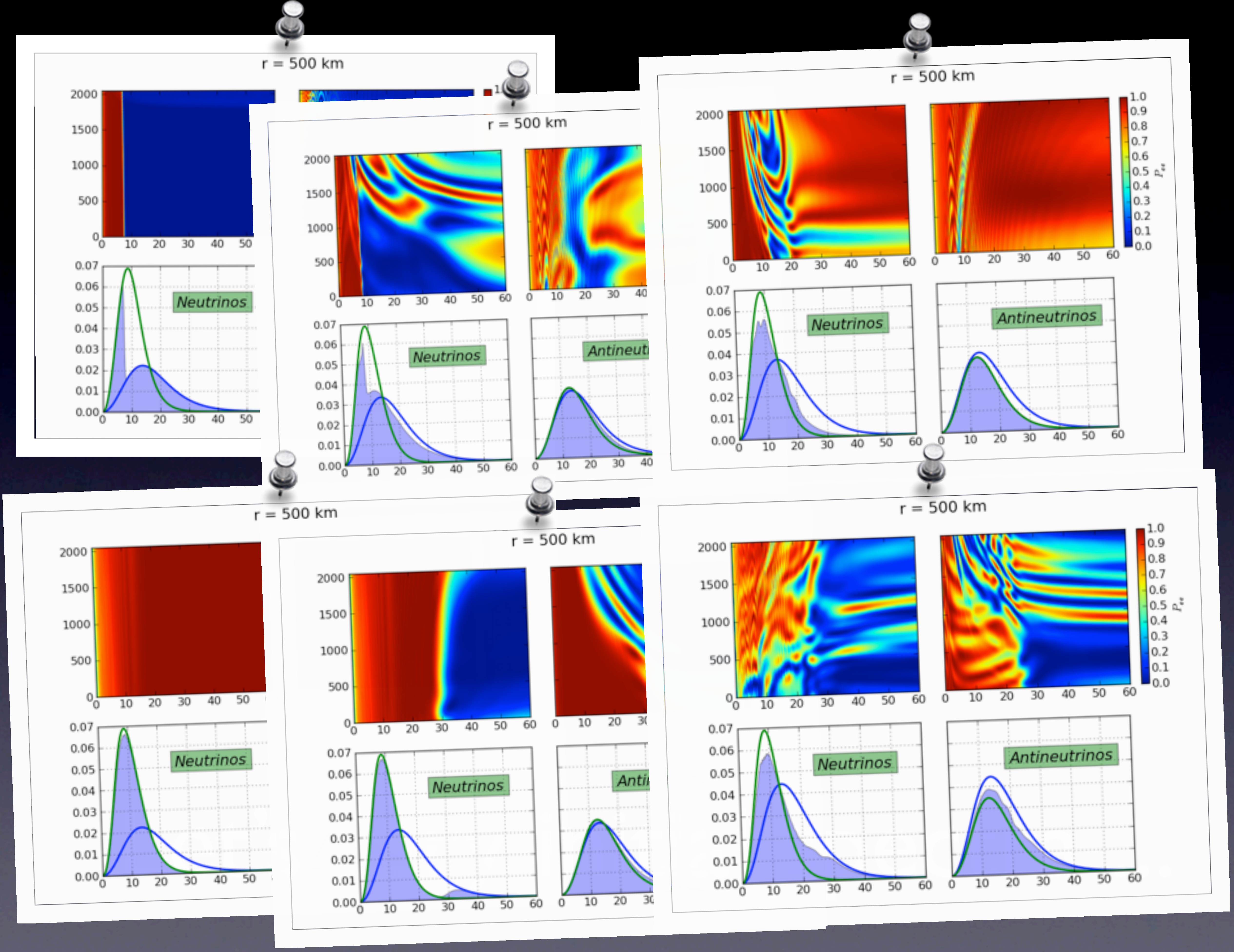
- Scattered neutrinos dominate oscillation Hamiltonian
- Matter inhomogeneous, plus some scattering is backward
- Nobody knows how to do this problem at the moment: need "super-supercomputing"?







Qualitatively different patterns depending on the emitted spectra, sign of the hierarchy...


r = 500 km
2000
1500
1000
500
0
10
20
30
40
50
60
0.07
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0.01
0.00
Neutrinos
Antineutrinos
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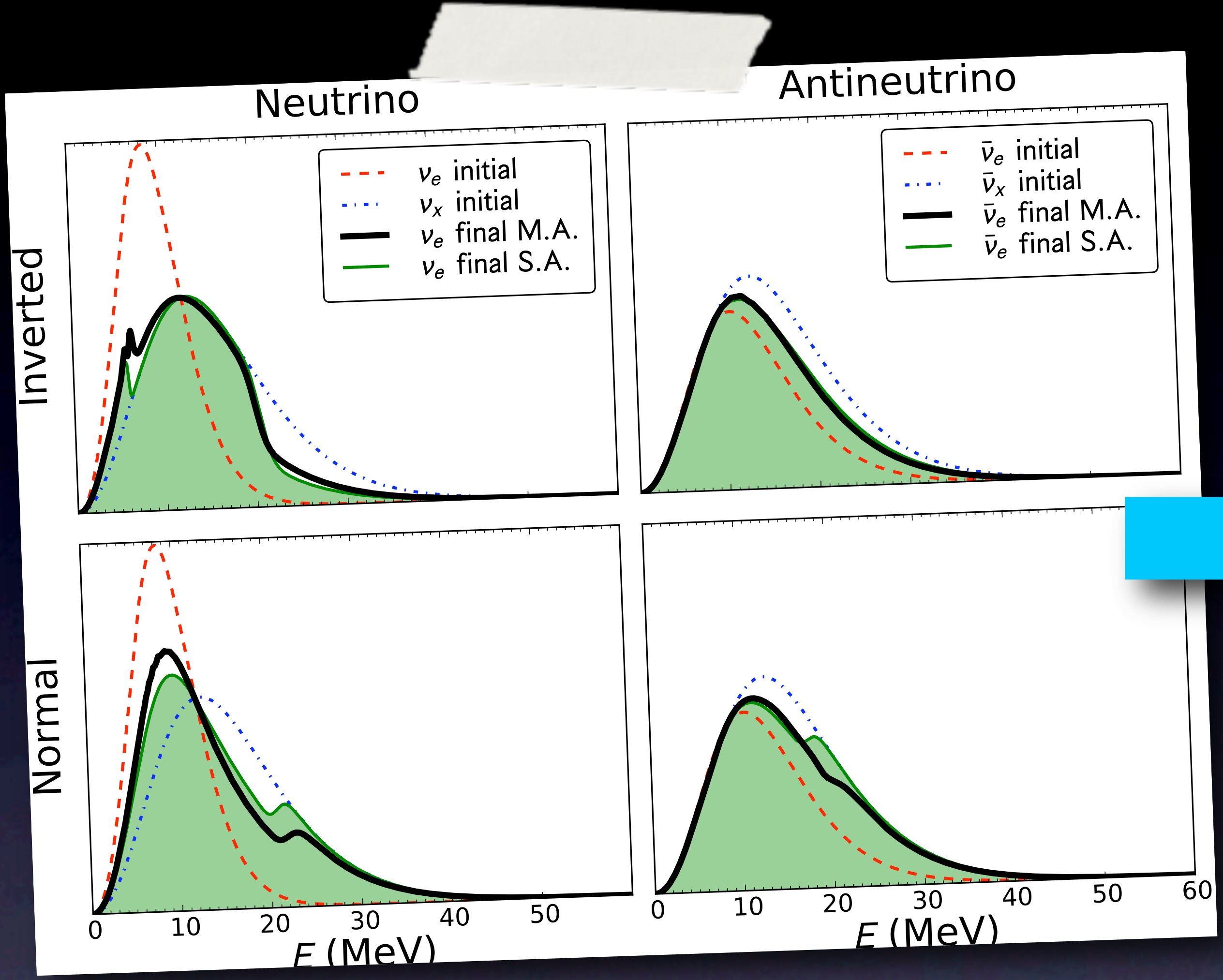
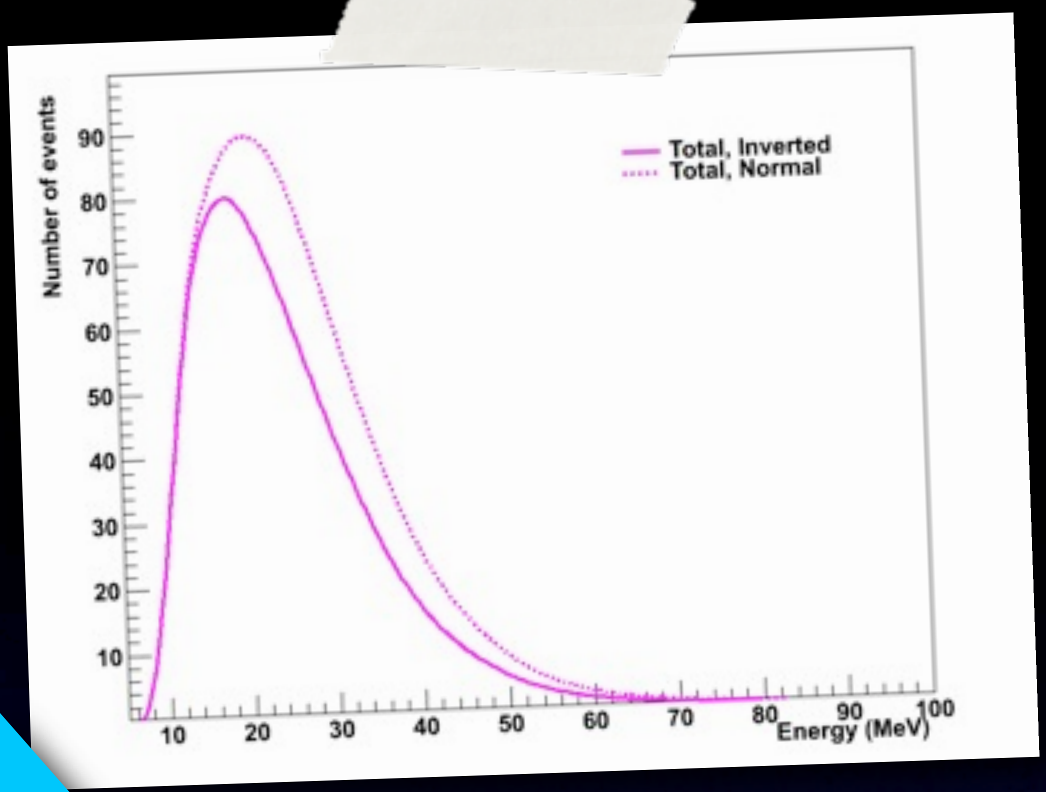
P_{ee}





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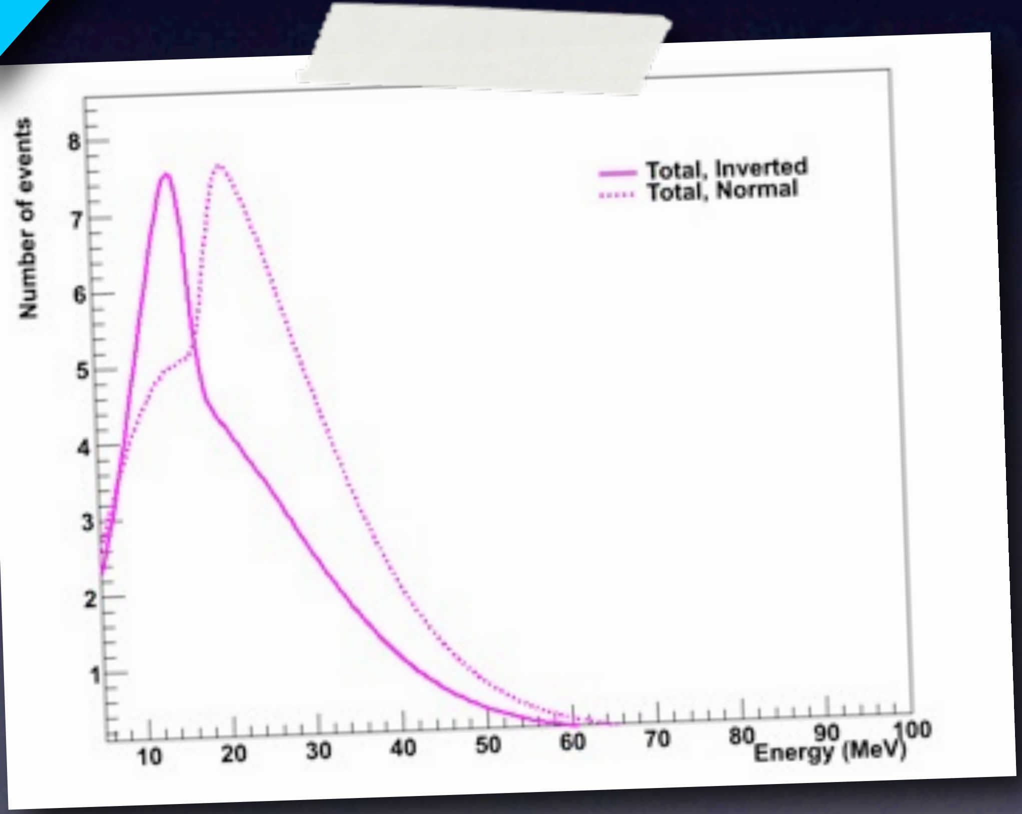

LAr

LBNE physics report: SN working group (arXiv:1110.6249)

* spectra by Duan & Friedland

* detector modeling by Kate Scholberg & co

Summary on SN

- The physics of SN neutrino oscillations is extremely rich, much more interesting than thought 10 years ago!
  - Remarkable progress even without data!
- Collective oscillations: qualitatively new regime, inaccessible in the lab
- In some regimes, as yet unsolved (e.g., the first second)
- Known physics → not optional
- *Needed*: feed different late-stage oscillation scenarios through software modeling detector response
  - Vary oscillation regimes, vary detector parameters