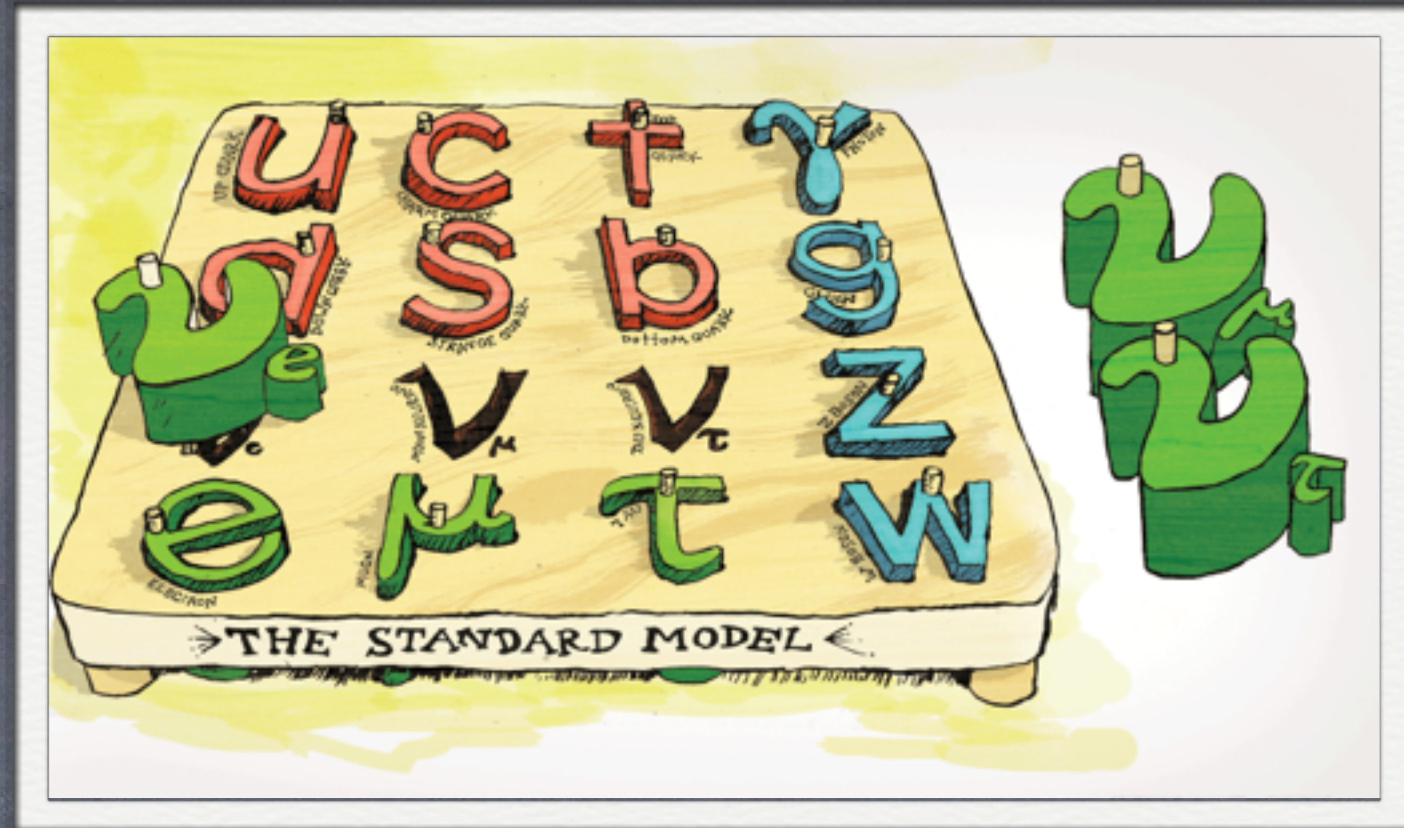


Neutrino physics

Alex Friedland
LANL

SLAC Summer Institute
July 2013

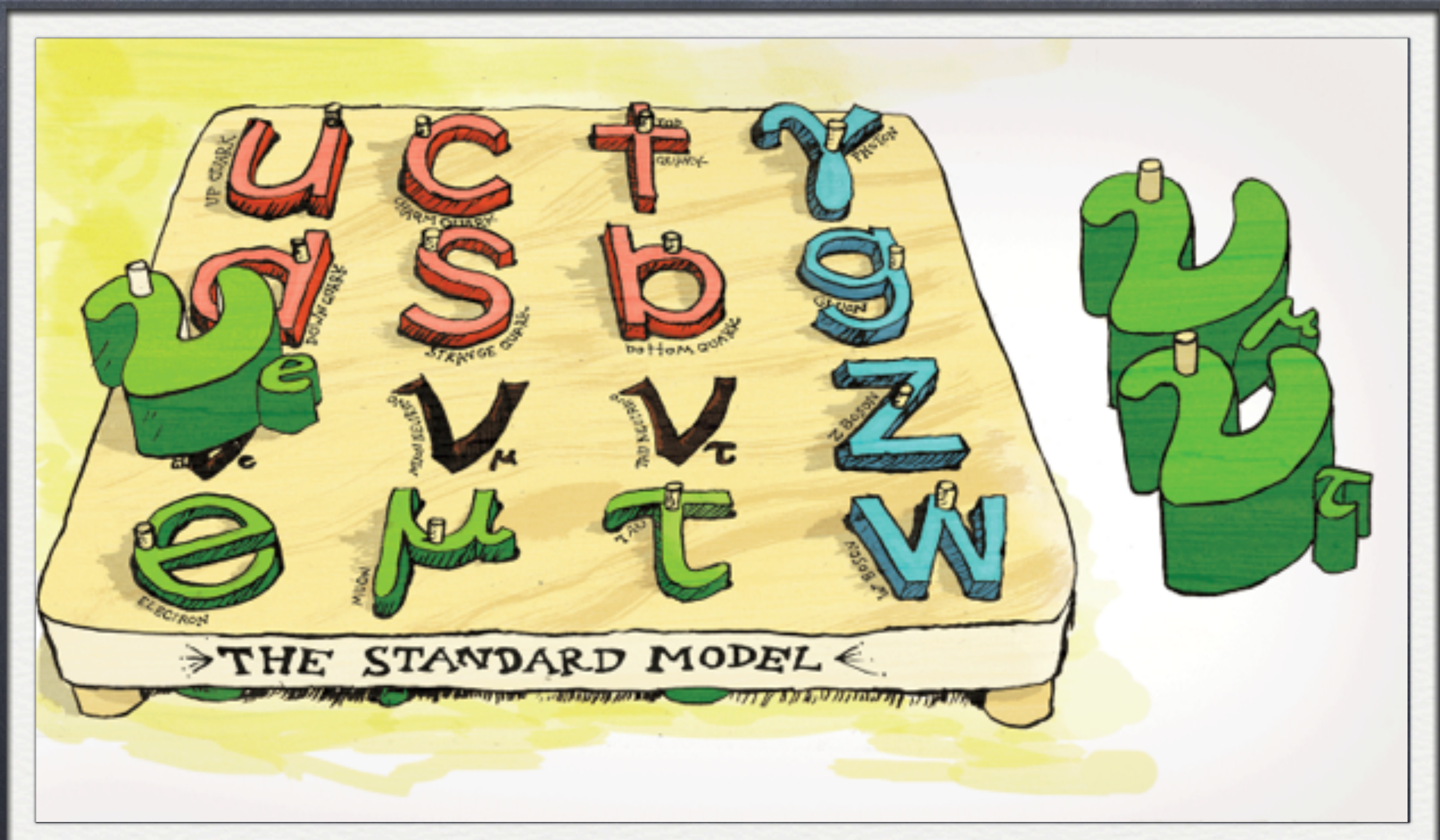
Q1: Where is Los Alamos?

"But can I also see some American ID?"

Q2: find an inaccuracy in this illustration

Source: Symmetry magazine feature

http://www.symmetrymagazine.org/article/february-2013/neutrinos-the-standard-model-misfits



Target audience: students

- Reminded me of TASI 1997
- That summer school was called
  - "Supersymmetry, Supergravity, and Supercolliders"
- wisely, it started out with lectures on
- "The Standard model and why we believe it"
  - delivered by a SLAC theorist JoAnne Hewett

So let's look back

hep-ph/
9810316

SLAC-PUB-7930

THE STANDARD MODEL AND WHY WE BELIEVE IT * †

J.L. HEWETT
Stanford Linear Accelerator Center, Stanford, CA 94309

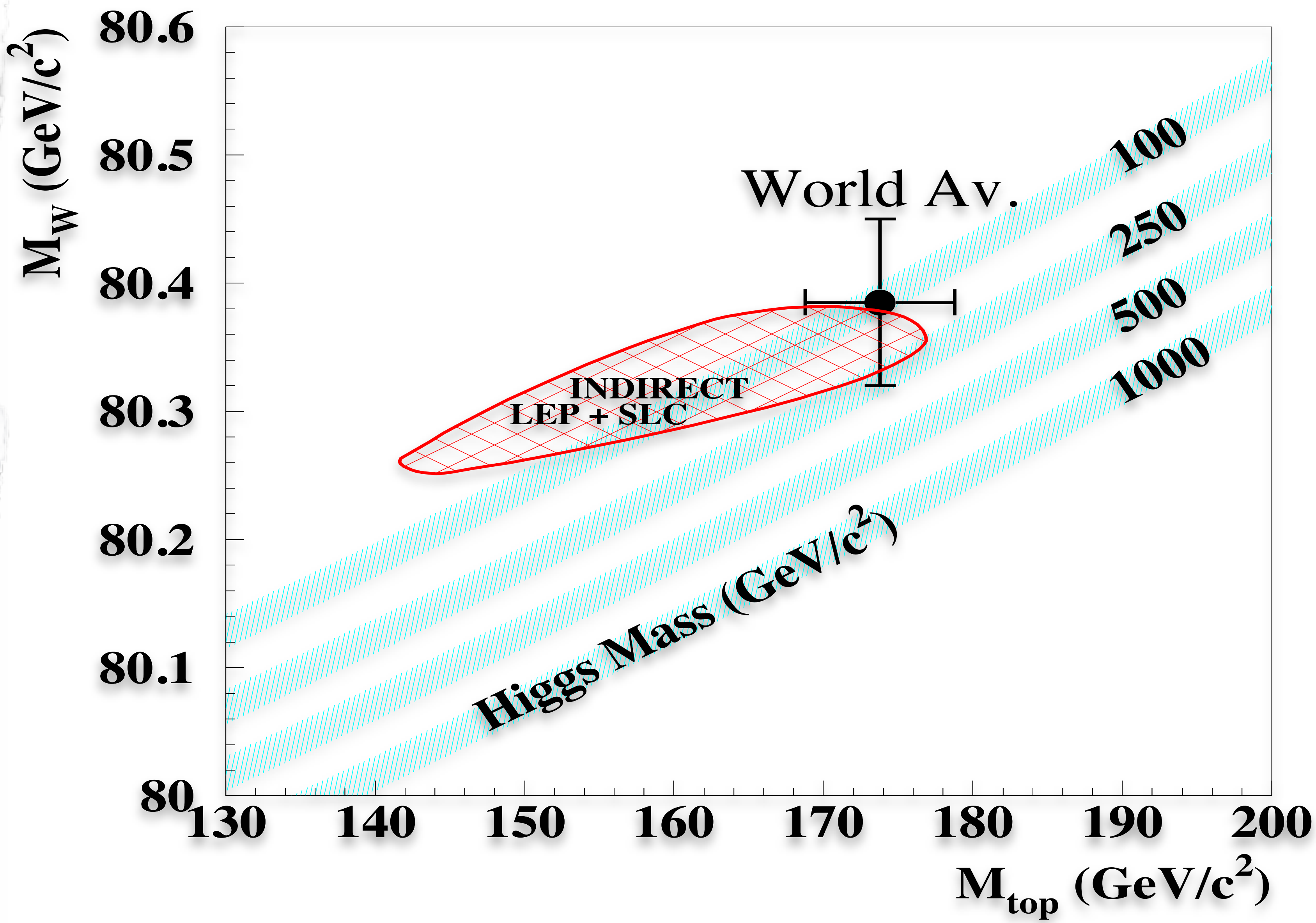
The principle components of the Standard Model and the status of their experimental verification are reviewed.

1 The Standard Model

The Standard Model (SM), which combines the $SU(2)_L \times U(1)_Y$ Glashow - Weinberg - Salam theory of electroweak interactions [1] together with Quantum Chromodynamics,[2] constitutes a remarkable achievement. The formulation of the theory as a renormalizable quantum theory preserves its predictive power beyond tree-level computations and allows for the probing of quantum effects. An array of experimental results confirm every feature of the theory to a high degree of precision, at the level of testing higher order perturbation theory. In fact, at present there are no compelling pieces of evidence that are in conflict with the SM. In these lectures I will review the components of the SM and the extent to which they have been tested.

So let's look back

Fig. 18



So let's look back

p. 5

- All aspects have impressive agreement with all experimental data

Despite these successes there remain a number of important questions which the SM does not address. These include:

- The fermion masses and mixings and the nature of CP-violation
- Neutrino masses and oscillations
- The number of generations

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2) < 0.0075\ \text{eV}^2$, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

$\Delta(m^2) < 0.09\ \text{eV}^2$, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

PDG 1996

http://pdg.lbl.gov/1996/www_2ltab.ps

While no direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained, suggestive evidence has come from solar neutrino observations, from anomalies in the relative fractions of ν_e and ν_μ observed in energetic cosmic-ray air showers, and possibly from a $\overline{\nu}_e$ appearance experiment at Los Alamos. Sample limits are:

Solar Neutrinos

Detectors using gallium ($E_\nu \gtrsim 0.2$ MeV), chlorine ($E_\nu \gtrsim 0.8$ MeV), and Ĉerenkov effect in water ($E_\nu \gtrsim 7$ MeV) measure significantly lower neutrino rates than are predicted from solar models. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with $\Delta m^2 \leq 10^{-5}$ eV^2 causing the disappearance of ν_e.

Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This could be explained by oscillations leading to the disappearance of ν_μ with $\Delta m^2 \approx 10^{-3}$ to 10^{-2} eV^2.

PDG 1998

http://pdg.lbl.gov/1998/sumtab/02lw.pdf

There is now rather convincing evidence that neutrinos have nonzero mass from the apparent observation of neutrino oscillations, where the neutrinos come from π (or K) $\rightarrow \mu \rightarrow e$ decays in the atmosphere; the mesons are produced in cosmic-ray cascades.

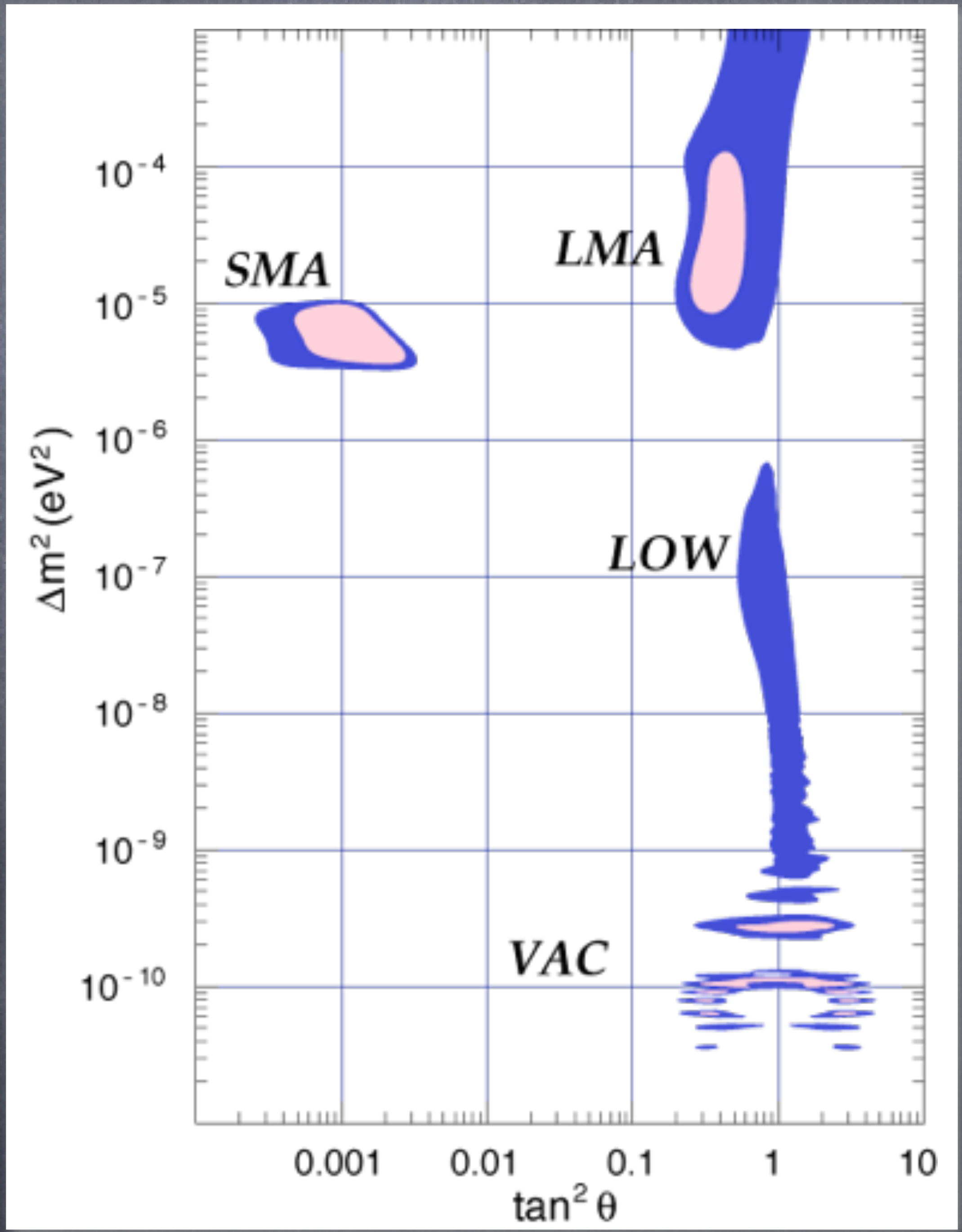
PDG 2000

http://pdg.lbl.gov/2000/lxxx_index.pdf

By that point, I was hooked!

Solar neutrinos, early 2000

- A number of solutions possible, with masses and mixing angles spanning orders of magnitude (more on this later)

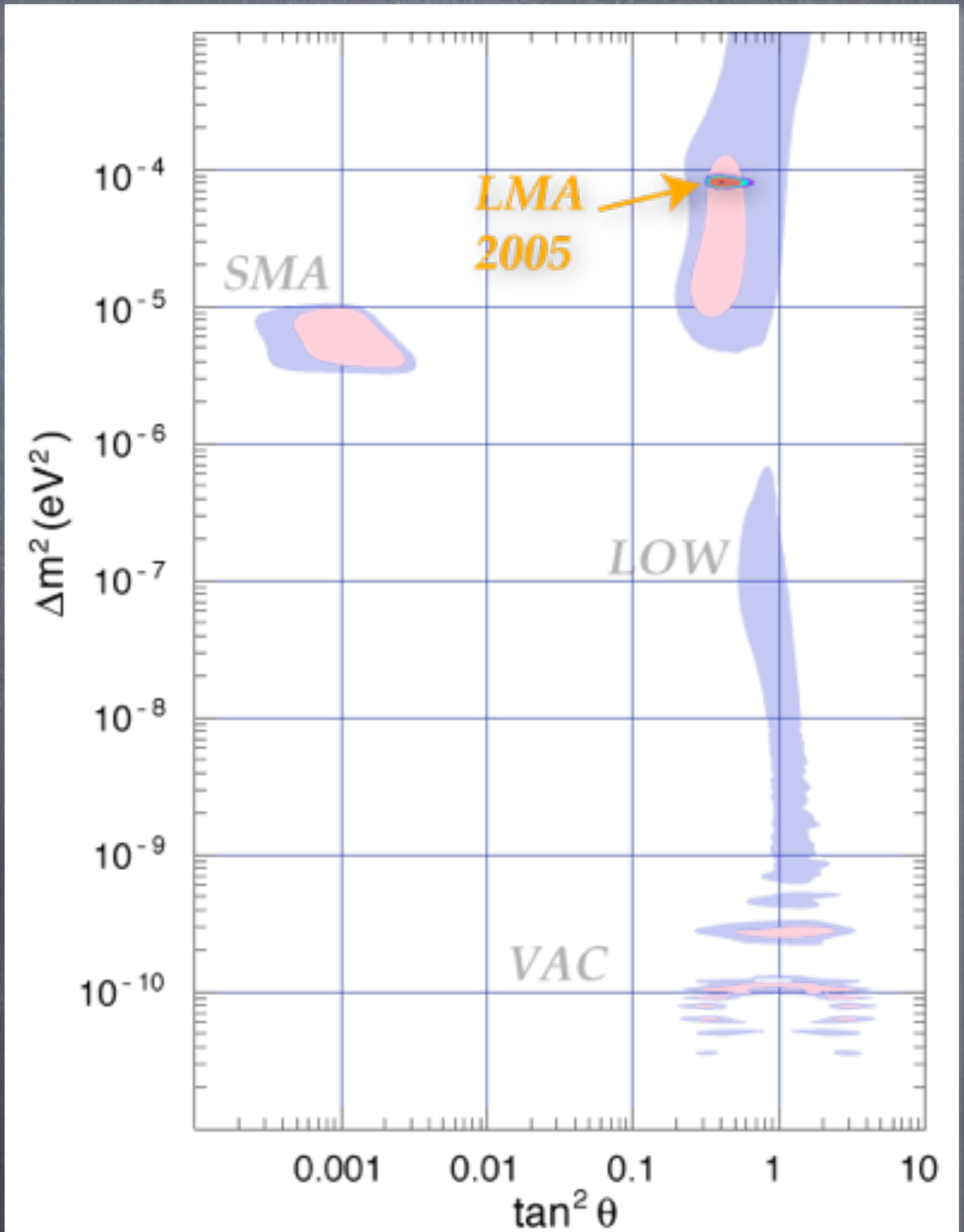


A. de Gouvea, A.F., H. Murayama, PLB 490, 125 (2000)
A.F., PRL 85, 936 (2000)

And by 2005

- KamLAND+SNO +SuperK+Homestake +GALLEX/SAGE
- KamLAND constrains Δm^2, while the angle θ_{12} is better constrained by the solar data

KamLAND Collab., PRL 94, 081801 (2005)
SNO Collab., PRL 92, 181301 (2004)



Remarks by John Bahcall on receiving the Dan David Prize: 5/18/03.

I would like to tell you a story that amazes me.

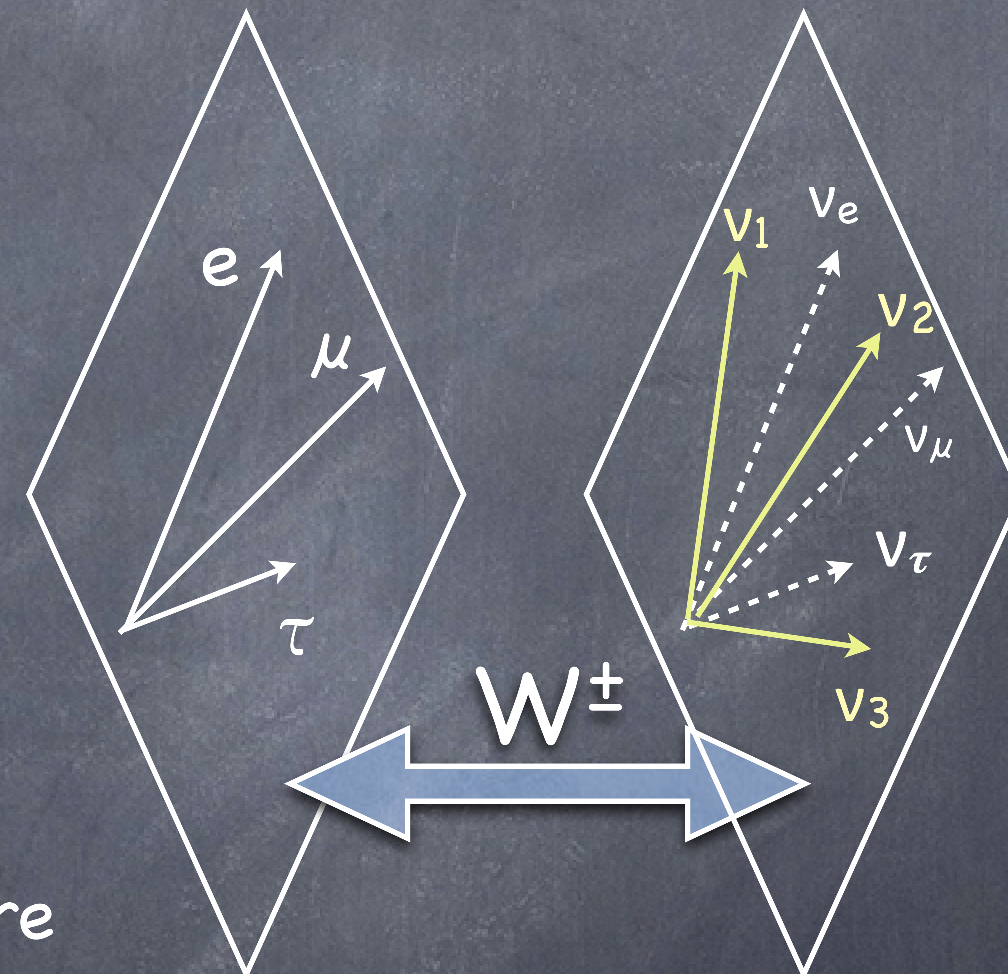
In May 2001, scientists announced two important discoveries based on beautiful measurements made in a Canadian mine and in an underground laboratory in Japan.

The scientists used flashes of light in the bottom of a mine to determine the temperature in the center of the Sun and to establish the properties of exotic subatomic particles called neutrinos.

http://www.sns.ias.edu/~jnb/Papers/Popular/DanDavid/amazing.pdf

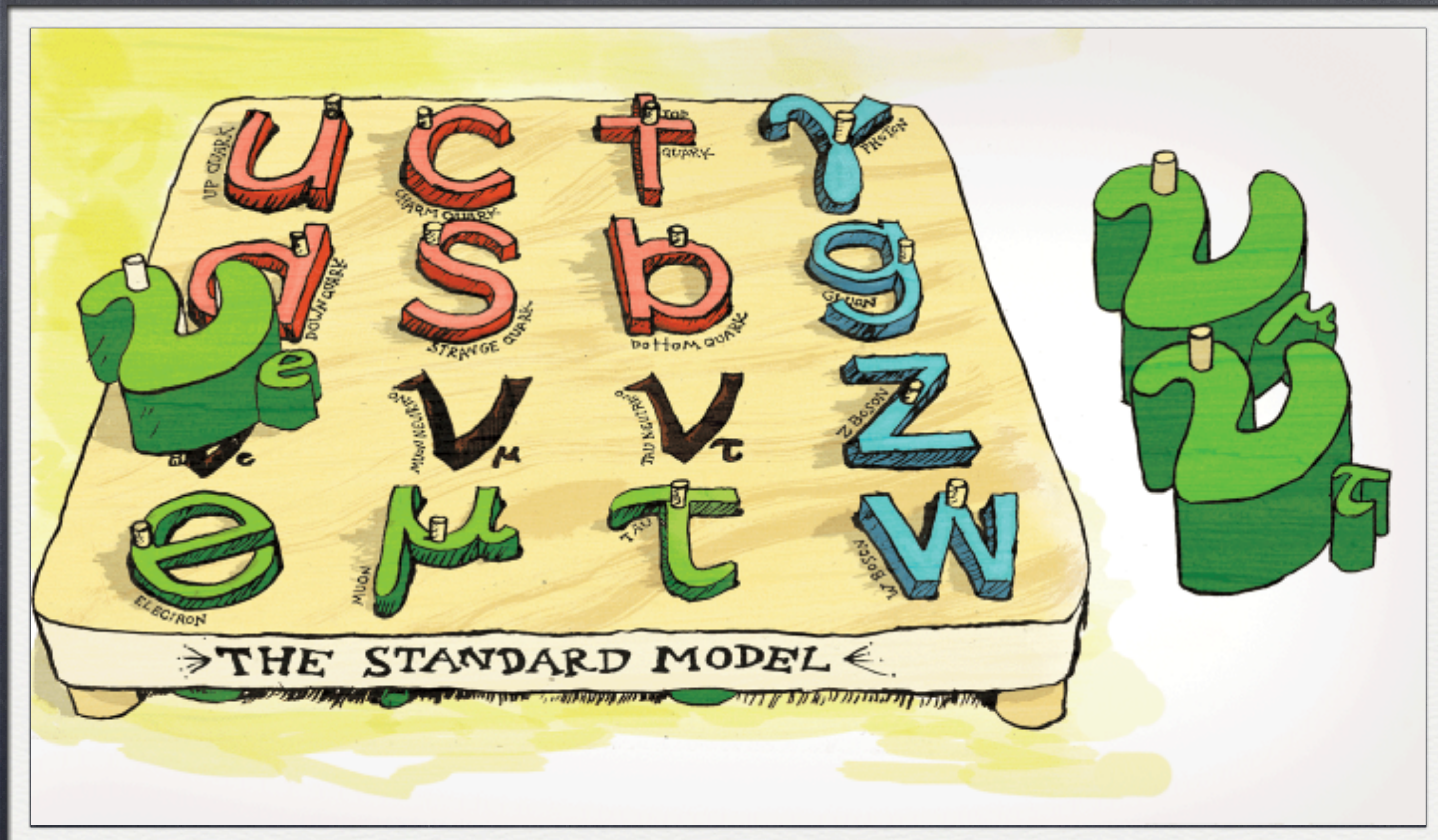
What do we call a particle?

- A mass eigenstate
  - think, e.g., e vs μ vs τ
- Before the discovery of oscillations, neutrinos were the only particles defined as flavor eigenstates (by their interactions with the W,)
- We now know what neutrino particles are
  - They have been given imaginative names
    - ν_1, ν_2, ν_3



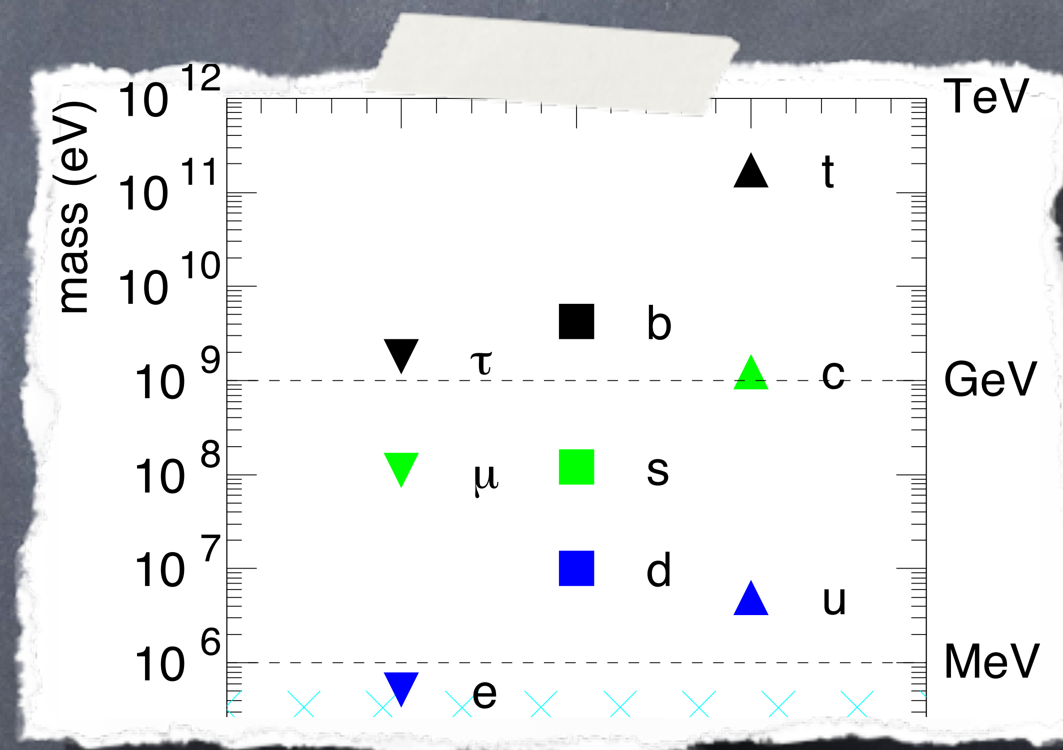
Note large misalignment between the two neutrino bases

Let's see what Symmetry magazine calls a particle



How do we measure neutrino masses?

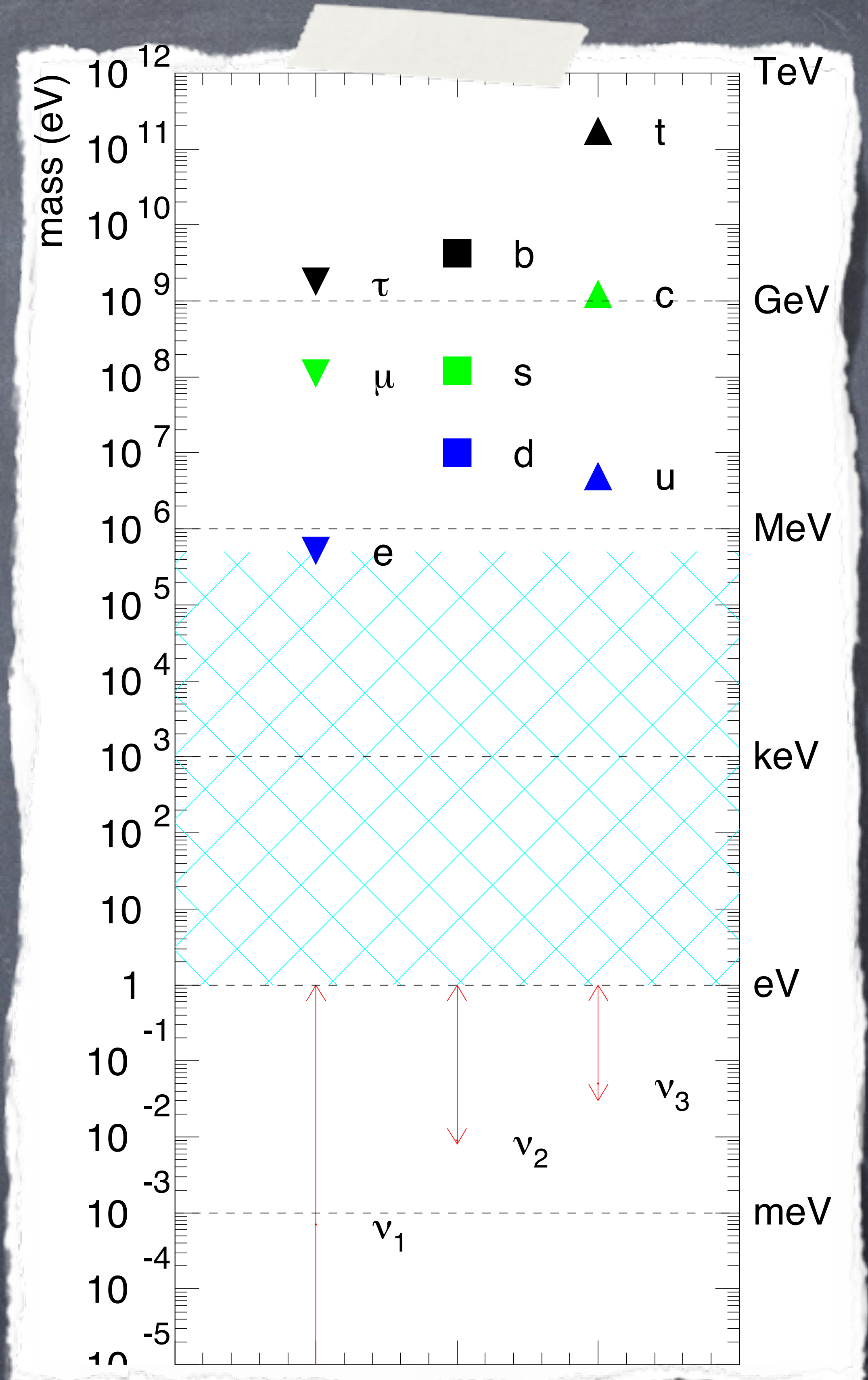
- Neutrino have a mass
- Other particles have masses ...



But neutrino masses are unusual

and neutrinos interact through a weak, non-renormalizable, operator

We can't slow them down to weigh at our leisure



Need extraordinary measures

- Endpoint spectra of a beta decay EXTREMELY accurately
  - beta-decay of tritium; Katrin
- Majorana mass term is an operator that violates something
  - Neutrinoless double-beta decay; EXO, Majorana, GERDA
- Slow neutrinos down by redshift; use gravity for detection
  - cosmology; CMB, LSS, lensing
- Use interferometry
  - oscillation experiments

Some of these are covered in other lectures

- Double-beta decay -- an hour-long talk by Michelle Dolinski tomorrow
- Numerous cosmology talks later this week, which I hope will touch on neutrinos
- Wonderful afternoon talks on T2K, Daya Bay, and IceCUBE last Thursday
- Overview of nu sources and detectors -- 2 hours by Sam Zeller later today

Interferometry 101

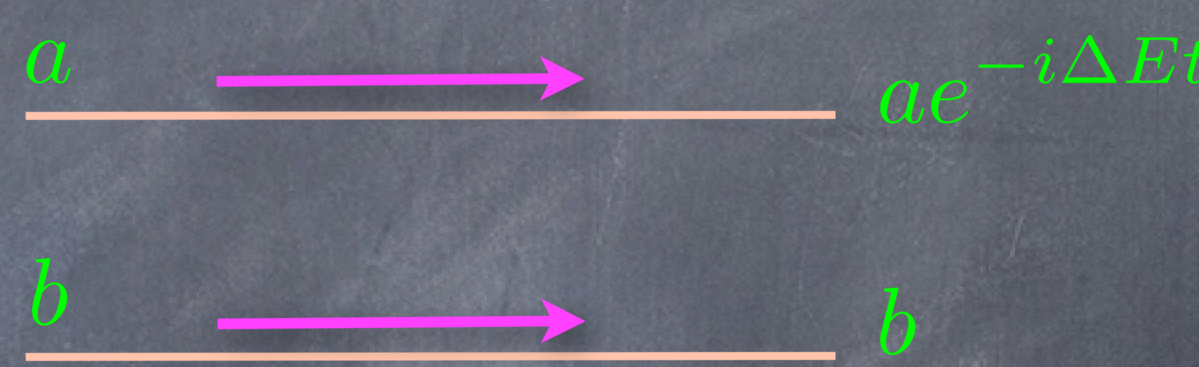
- Usual argument: start with the ultra-relativistic expansion

$$E = \sqrt{m^2 + p^2} \simeq p^2 + m^2/2p$$

- assume the two states have the same momentum, then

$$\Delta E \simeq \Delta m^2/2p$$

- Or, assume they have the same energy
- Or, assume the have the same velocity
- In fact, it's neither



Interferometry 101

- In fact, it's neither
- For example, for the ^8B decay reaction in the Sun there are amplitudes to go into three final states with different particles
- Q3: show that the standard expression for ΔE is valid
- Q4: It may seem that we can just measure the energy of the neutrino accurately enough to decide which final state it went into.
  - How's this consistent with oscillations?

$$^8B \to {}^8Be + e^+ + \nu_1$$
$$\to {}^8Be + e^+ + \nu_2$$
$$\to {}^8Be + e^+ + \nu_3$$

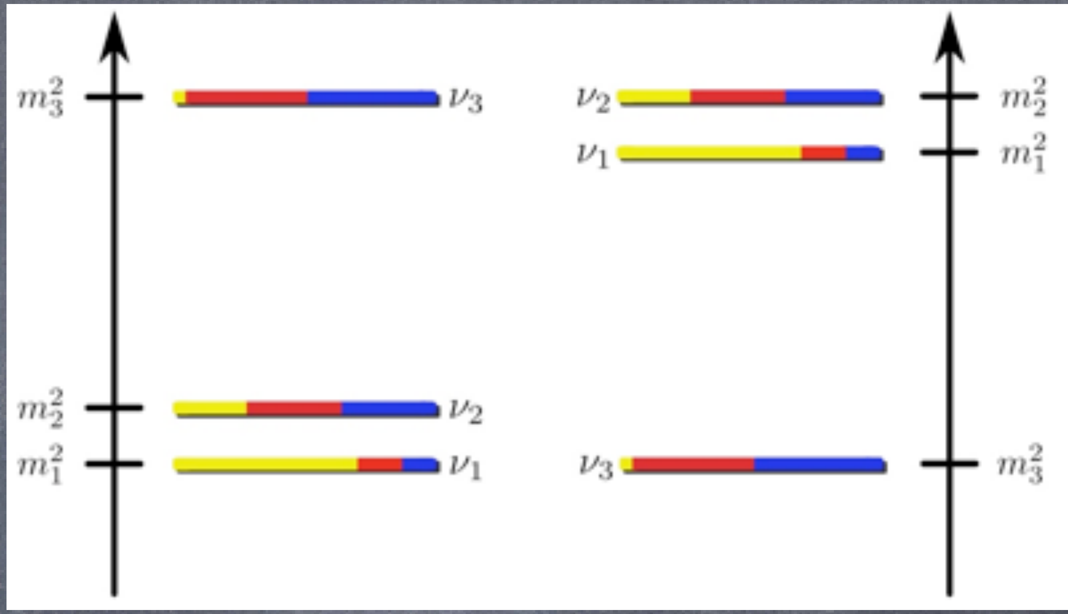
$$\Delta E \simeq \Delta m^2/2p$$

Hint: think uncertainty principle

Accurate energy measurement entails loss of position measurement

What we presently know about neutrinos

- Two mass splittings,
  - Δm^2_{atm} ~2.3 x10^{-3} eV,
  - Δm^2_{sol} ~7.1 x10^{-5} eV
- Three mixing angles,
  - θ_{23}~ 45°±8°,
  - θ_{12}~ 34°±1°,
  - θ_{13}~ 8.7°±0.3°
    - θ_{13}: from unknown to best measured in a blink of an eye



Known unknowns:

mass hierarchy

CP phase δ,

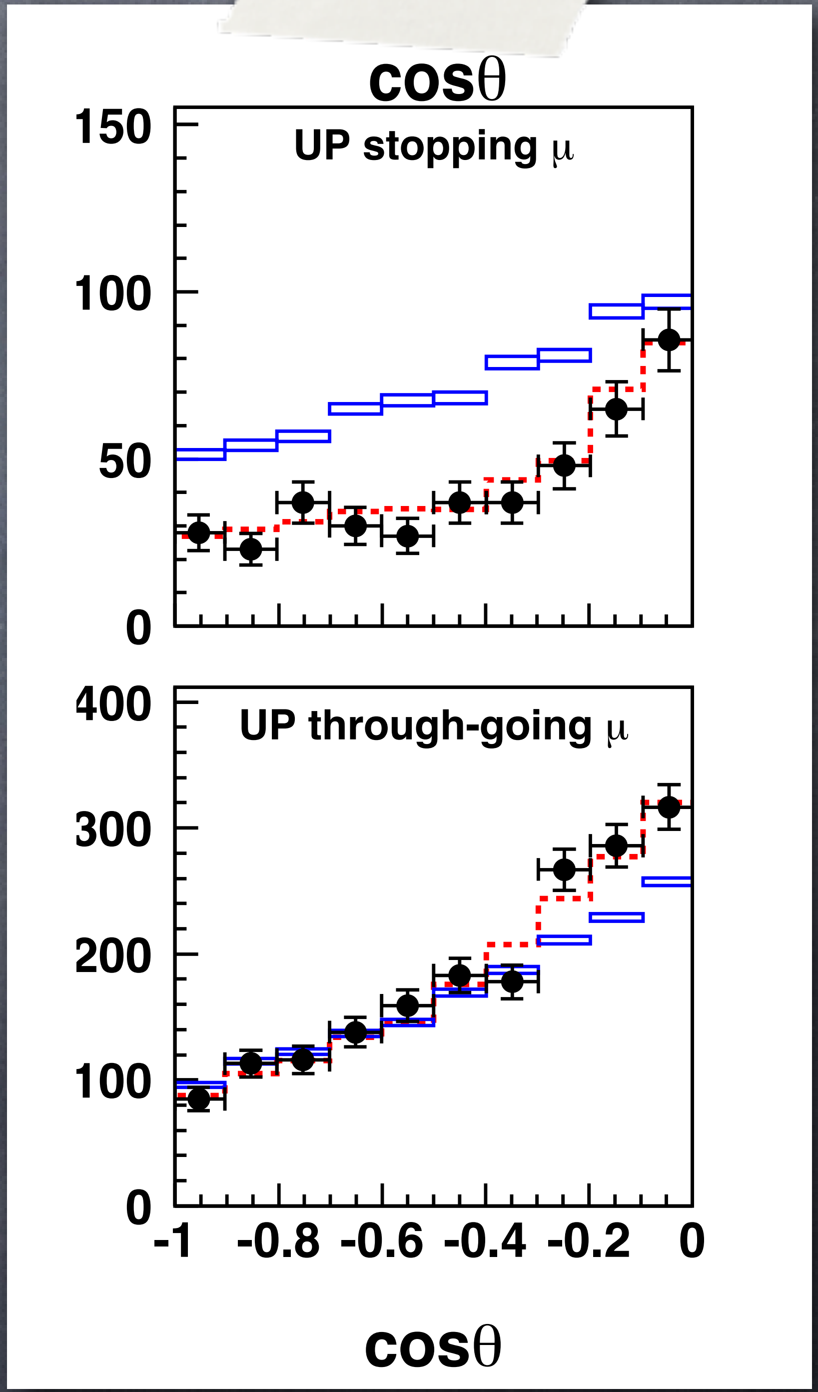
Dirac or Majorana

Atmospheric neutrinos

- For atmospheric neutrinos with a few GeV energies
- $l_{osc} \sim E/\Delta m^2_{atm} \sim 10^3$km,

  good distance scale to probe on the scales of the earth
- Super-Kamiokande!
- $\nu_\mu \to \nu_\tau$ oscillation

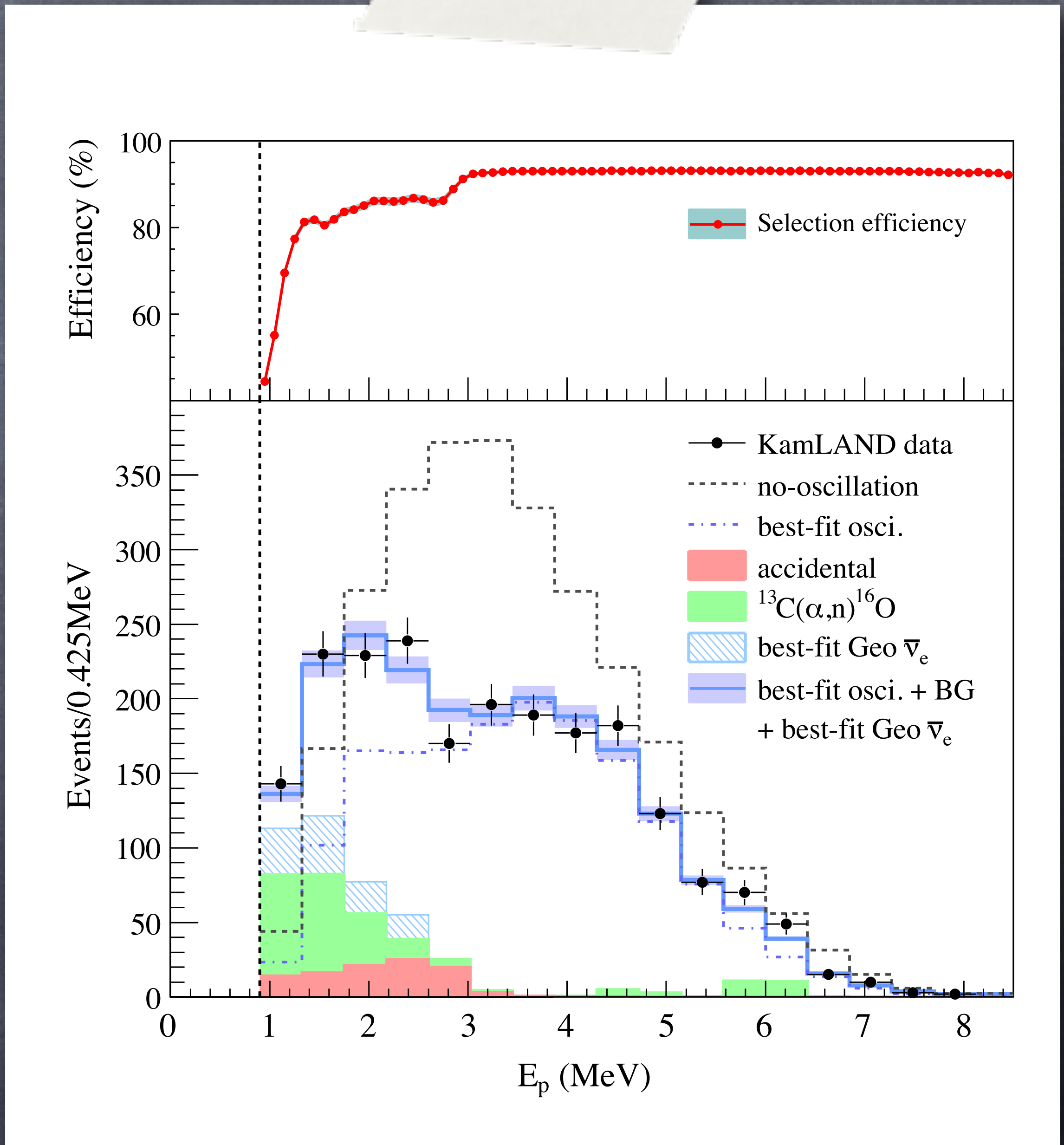
  favored



Reactor neutrinos, KamLAND

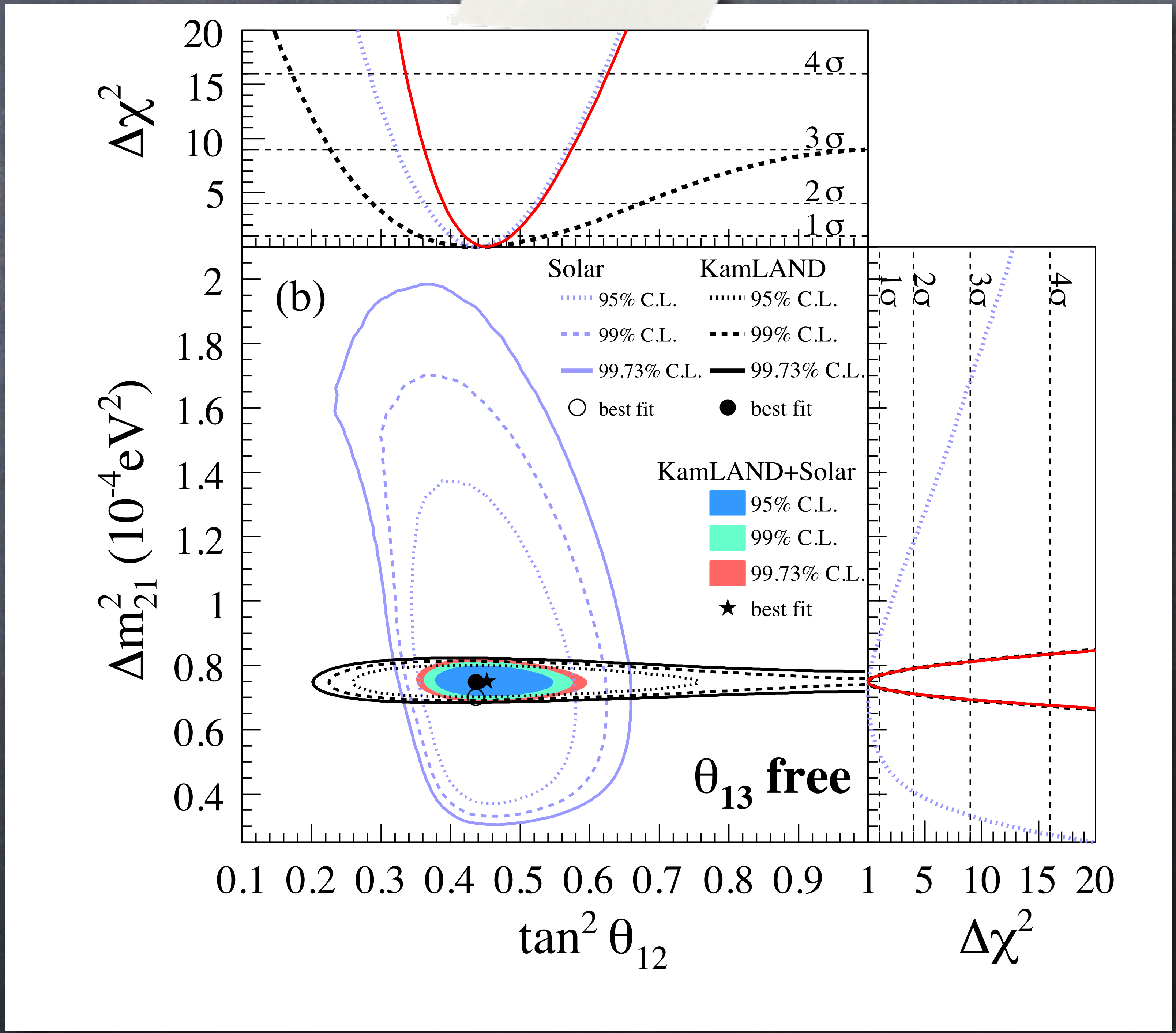
- For reactor antineutrinos with a few MeV energies
- $l_{osc} \sim E/\Delta m^2_{sol} \sim 10^2$km,

  good distance scale to probe on the scales of Japan
- The most precise measurement of Δm^2_{sol}



KamLAND vs solar

arXiv: 1009.4771



Reactor neutrinos, Daya Bay

- For reactor antineutrinos with a few MeV energies
- $l_{osc} \sim E/\Delta m^2_{atm} \sim 1$ km,

  good distance scale to probe next to a power station

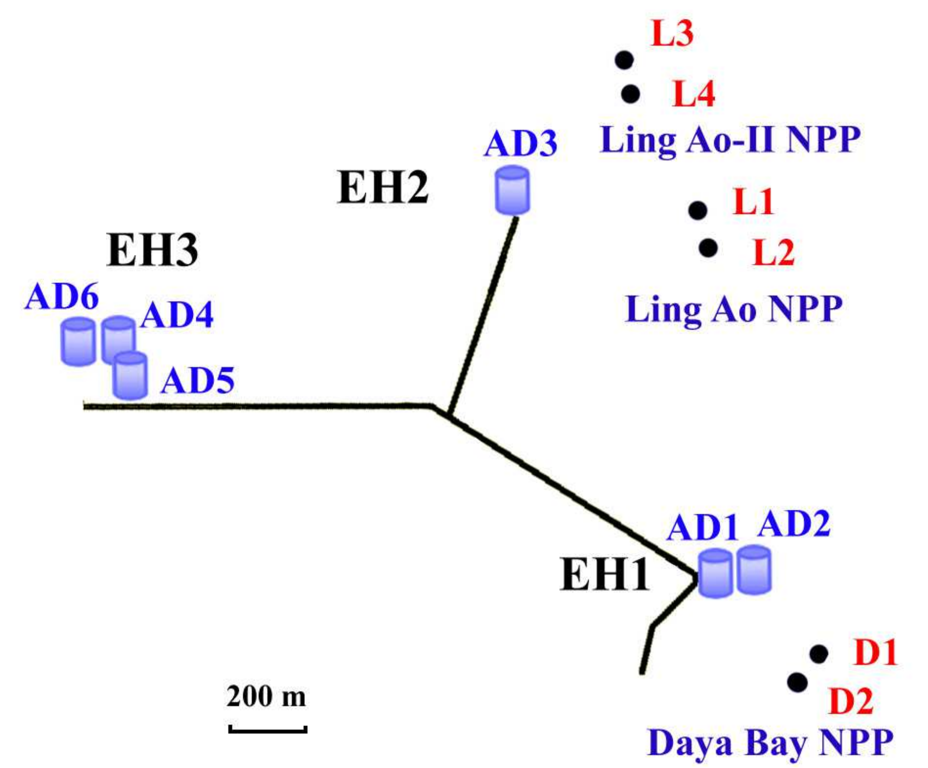
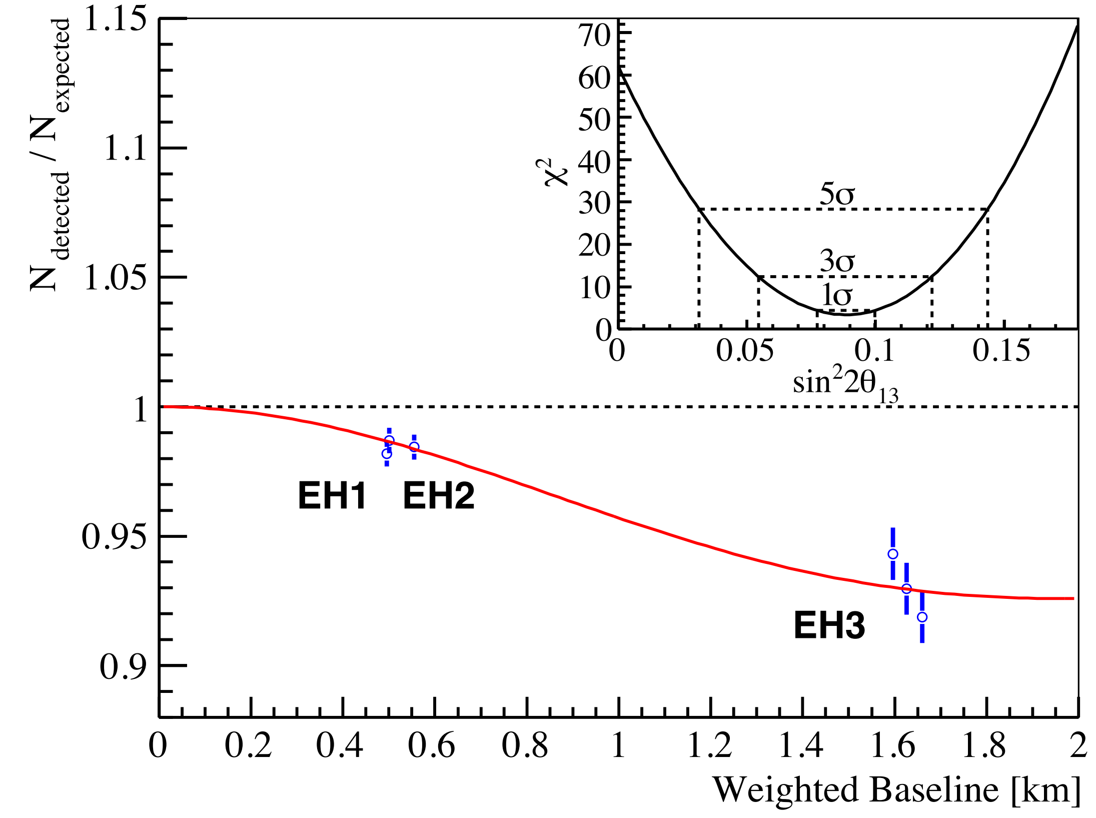


Fig. 1. Layout of the Daya Bay experiment. The dots represent reactor cores, labeled as D1, D2, L1, L2, L3 and L4. Six antineutrino detectors (ADs) were installed in three experimental halls (EHs).

Reactor neutrinos, Daya Bay

arXiv:1210.6327

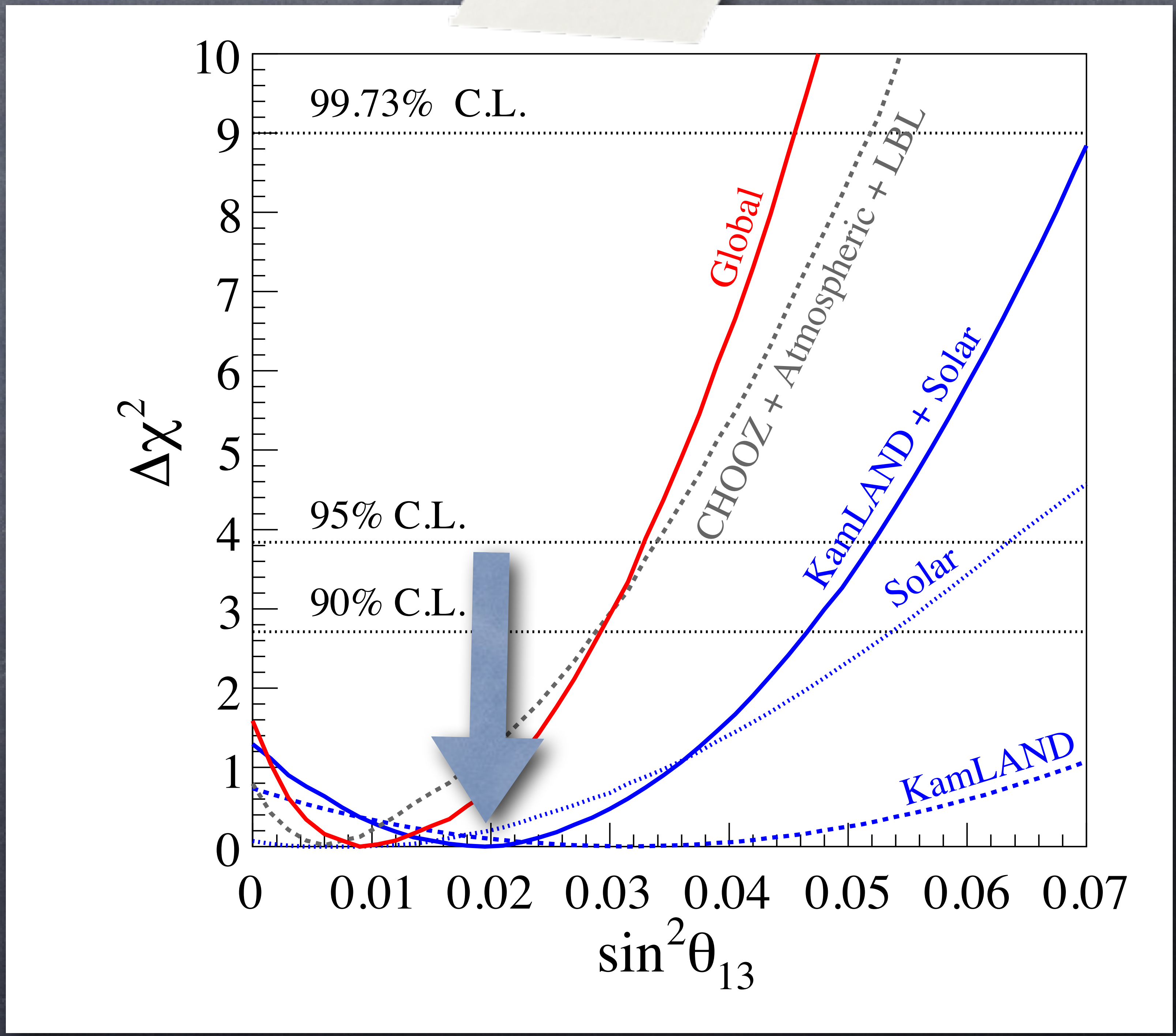
- At the far detector, R=0.944±0.007(stat) ±0.003(syst)
- See last week's talk by Kazuhiro Terao
- Also by Silvestro Di Luise on the T2K theta13 results
  - appearance!



KamLAND, solar, Daya Bay

arXiv:
1009.4771

Global fits
may be in our
future
as in T2K+NOvA
+LBNE+SK
+IceCuBE+...



The story of solar neutrinos

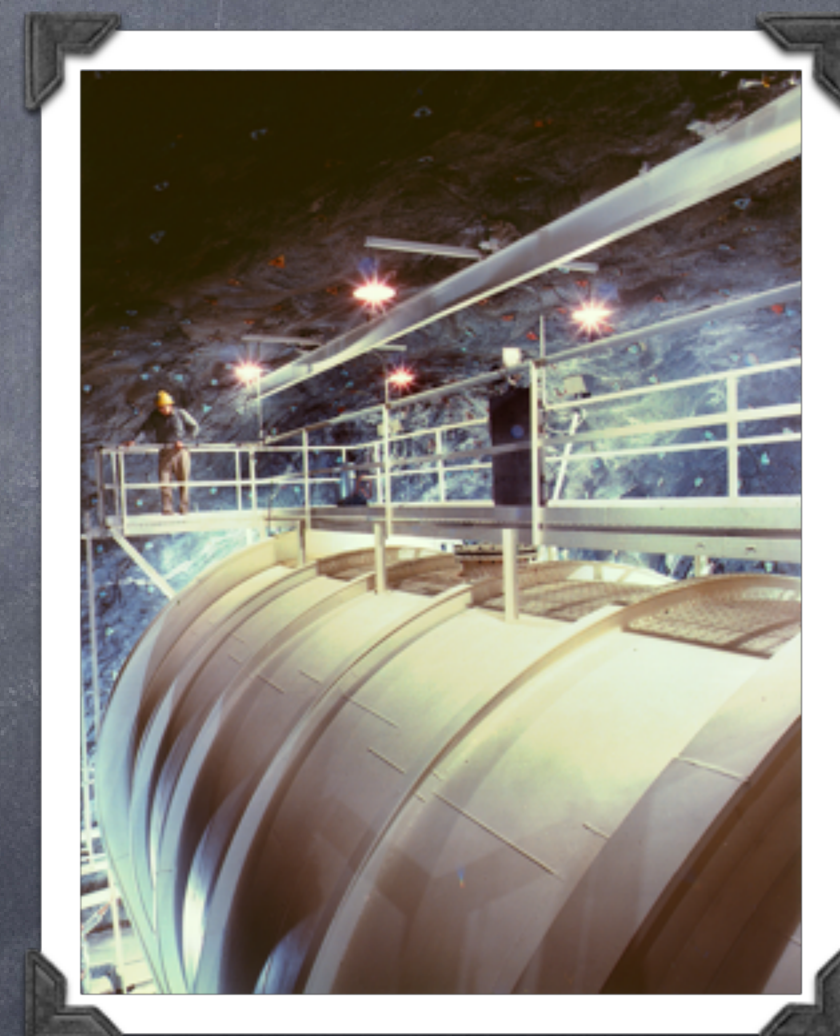
- Very instructive tale of Pride and Prejudice
  - Naturalness and Fine-Tuning
- Mr. Lund of last week would've been impressed!
- Maybe there's a lesson there for the rest of us also...

Neutrino oscillations

- The first neutrino oscillation effect was observed in 1968, by the Homestake experiment in the US
  - 100,000 gallons of dry-cleaning fluid (tetrachloroethylene) 4,850 feet underground. Every few weeks, extracted Ar, formed by

$$\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar$$

  - Expected ~ 51 atoms of Ar, but saw only ~ 17



BULLETIN BOARD

Volume 21, Number 36 Published by the BNL Public Relations Office September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

The theoretical forecast had led scientists to believe that the neutrino emission from the sun would allow from 1.5 to 5 neutrino captures per day. In the single experiment performed to date, Dr. Davis reports that the capture rate in the underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture allowed Dr. Davis and his group to calculate the flux from the Boron-8 decay to be approximately 60 million solar neutrinos per square inch per second at the earth's surface. Previous calculations had predicted the flux could be anywhere from 40 million to 150 million solar neutrinos per square inch per second at the earth's surface.

- http://www.bnl.gov/bnlweb/raydavis/BB_sept1967.pdf
- No mention of oscillations

Matter matters

- Wolfenstein 1978: matter effect, by analogy with the Kaon regeneration in matter
  - Coherent forward scattering (index of refraction) is different for ν_e and ν_μ, ν_τ (birefringence)
  - Correct equations (up to the sign and $\sqrt{2}$)
  - But, a large part of the paper is on new physics FCNC (flavor conversion without masses)
  - And, the evolution equations in the falling solar density profile are not actually solved
    - Similar scenario later plays out for collective oscillations in supernovae

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Matter effects on three-neutrino oscillations

V. Barger and K. Whisnant
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

S. Pakvasa
Physics Department, University of Hawaii at Manoa, Honolulu, Hawaii 96822

R. J. N. Phillips
Rutherford Laboratory, Chilton, Didcot, Oxon, England
(Received 4 August 1980)

We evaluate the influence of coherent forward scattering in matter upon neutrino oscillations in the three-neutrino picture. We write down the exact solution and also approximate first-order solutions that exhibit general features more transparently. Oscillation characteristics in matter that could be observed in deep-mine experiments are discussed and illustrated using an oscillation solution suggested by solar and reactor data.

- Comes tantalizingly close!

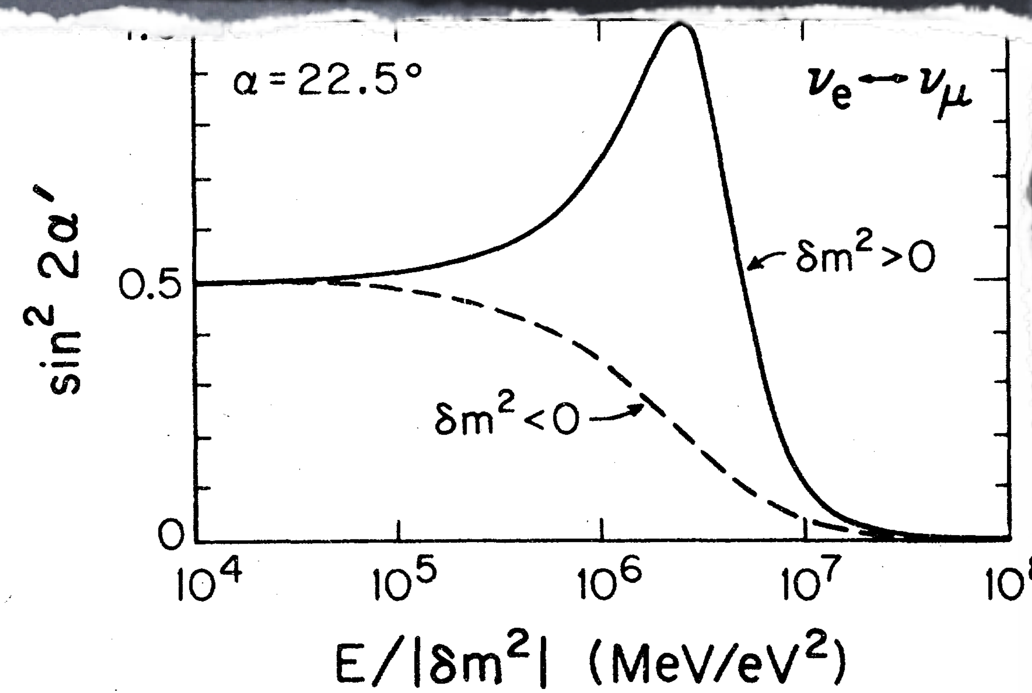


FIG. 1. Matter-to-vacuum eigenmass-squared difference ratio and matter amplitude $\sin^2 2\alpha'$ for oscillations of two neutrinos with vacuum amplitude $\sin^2 2\alpha = 0.5$ (α

MSW, 1985-86

- Mikheev and Smirnov solved the evolution equation in the solar density profile
- Find large conversion possible for small vacuum mixing
- The paper is originally rejected
- They attempt repackaging in the supernova neutrino context, bury the word “resonance”
  - see arxiv:0706.0454

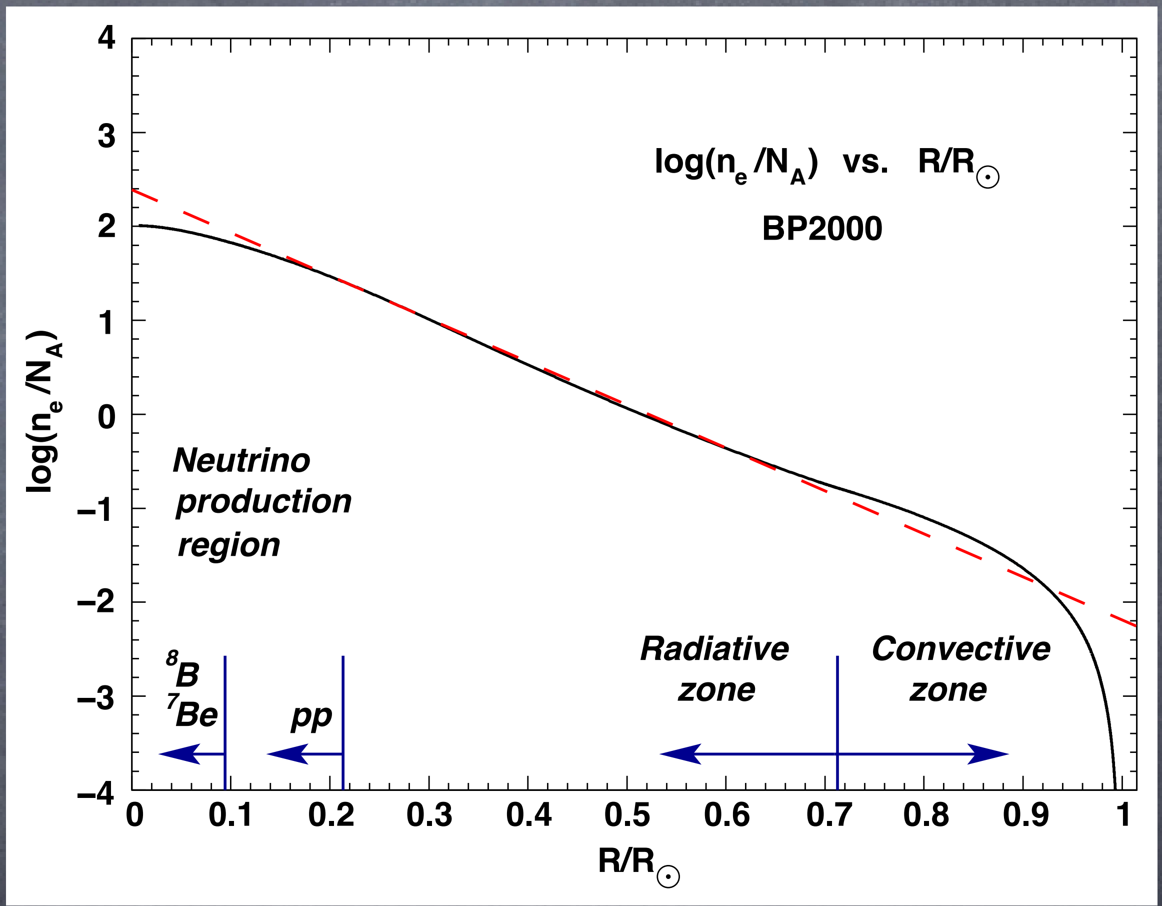
Comments (June 2007)

1. This paper presents, in particular, our first analytic results on the adiabatic conversion of neutrinos in matter. It has been written in summer-fall 1985. In attempt to avoid problems with publication (we had before), we tried to hide the term “resonance”, and did not discussed applications to the solar neutrinos; also we have not included references to our previous papers on the resonance enhancement of neutrino oscillations.

This short paper has been submitted to JETP Letters in the fall 1985 and successfully ... rejected. It was resubmitted to JETP in December of 1985. The results of the paper have been reported at the 6th Moriond workshop in January 1986 and included in several later reviews. The paper was reprinted in “Solar Neutrinos: The first Thirty Years”, Ed. J. N. Bahcall, et al., Addison-Wesley 1995.

MSW then is accepted by the neutrino practitioners

- Large conversion for small mixing angles
  - And people know that mixing angles are naturally small
- Generic result, since the solar density profile spans orders of magnitude



Meanwhile, the community at large remains skeptical

- Georgi & Luke, Nucl Phys B347, 1-11 (1990)

> Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly

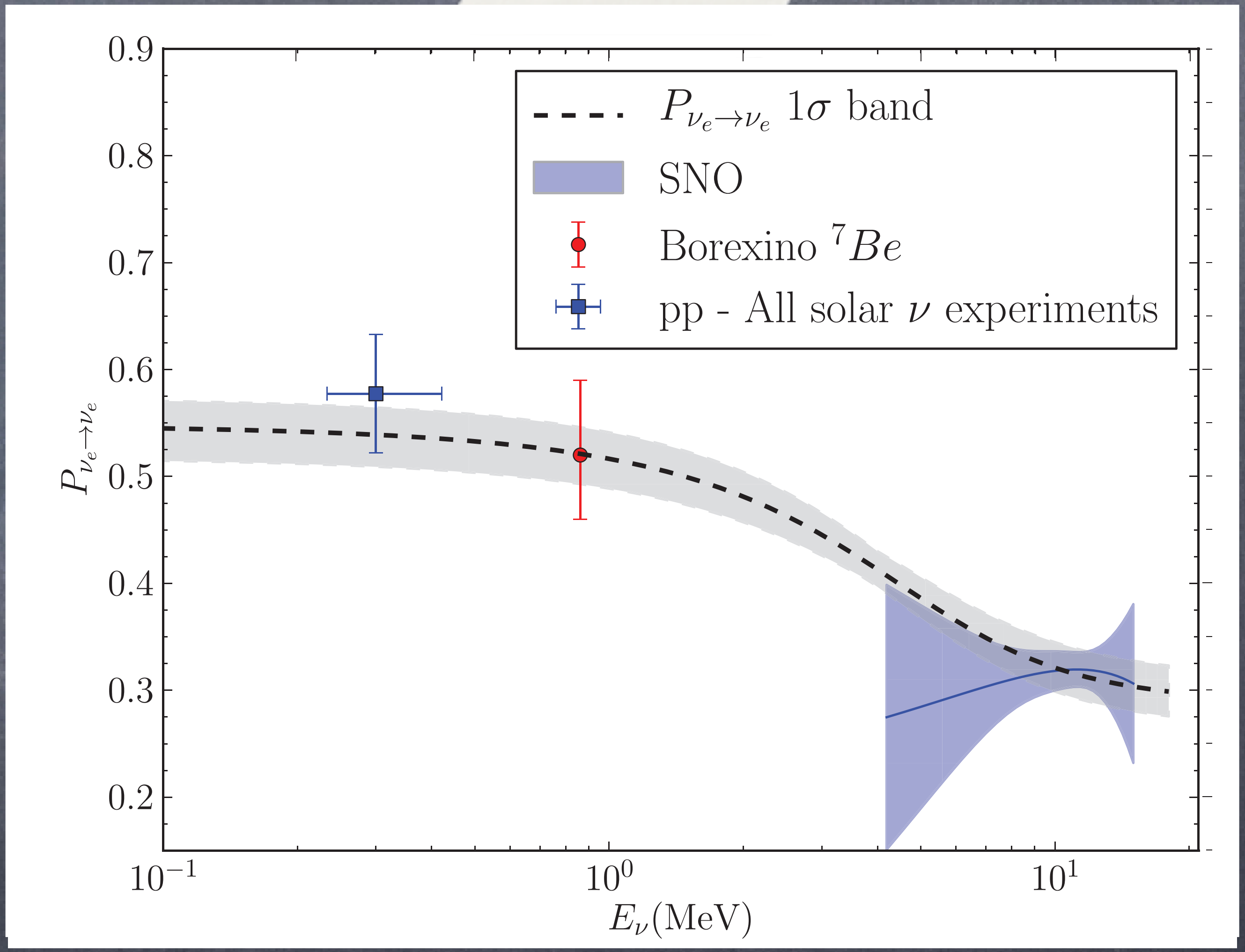
- Other quotes in Bahcall, physics/0406040

In hindsight

- The θ_{12} mixing angle eventually turns out to be large
  - The hierarchy of small mixings is not present in the lepton sector
- The mass-squared splitting turns out to be fine-tuned to the matter density in the center of the Sun

Solar neutrinos: MSW

- Electron neutrino survival probability is energy-dependent
- Nontrivial, requires a coincidence of something
- The matter density in the Sun, the solar mass splitting and the neutrino energy ~ 1 MeV conspire



$$\sqrt{2} G_F n_\odot \sim \Delta m^2_{sol} / 2E_\nu$$

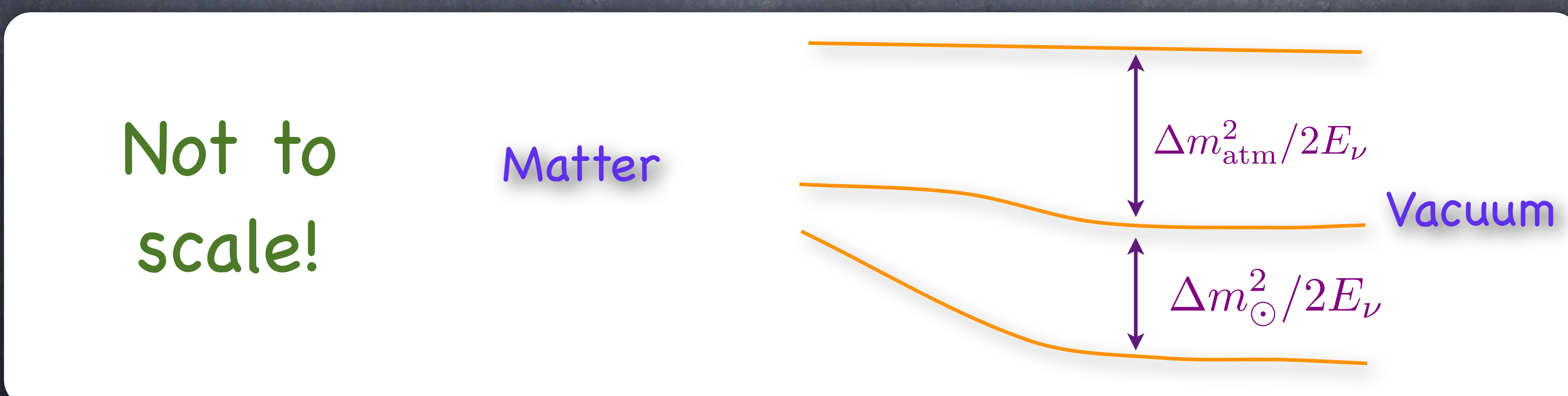
Neutrino flavor oscillations in stars 101

- Solar neutrinos: simple quantum mechanics problem

$$i\partial_t|\psi_i\rangle = H_{\rm osc}|\psi_i\rangle$$

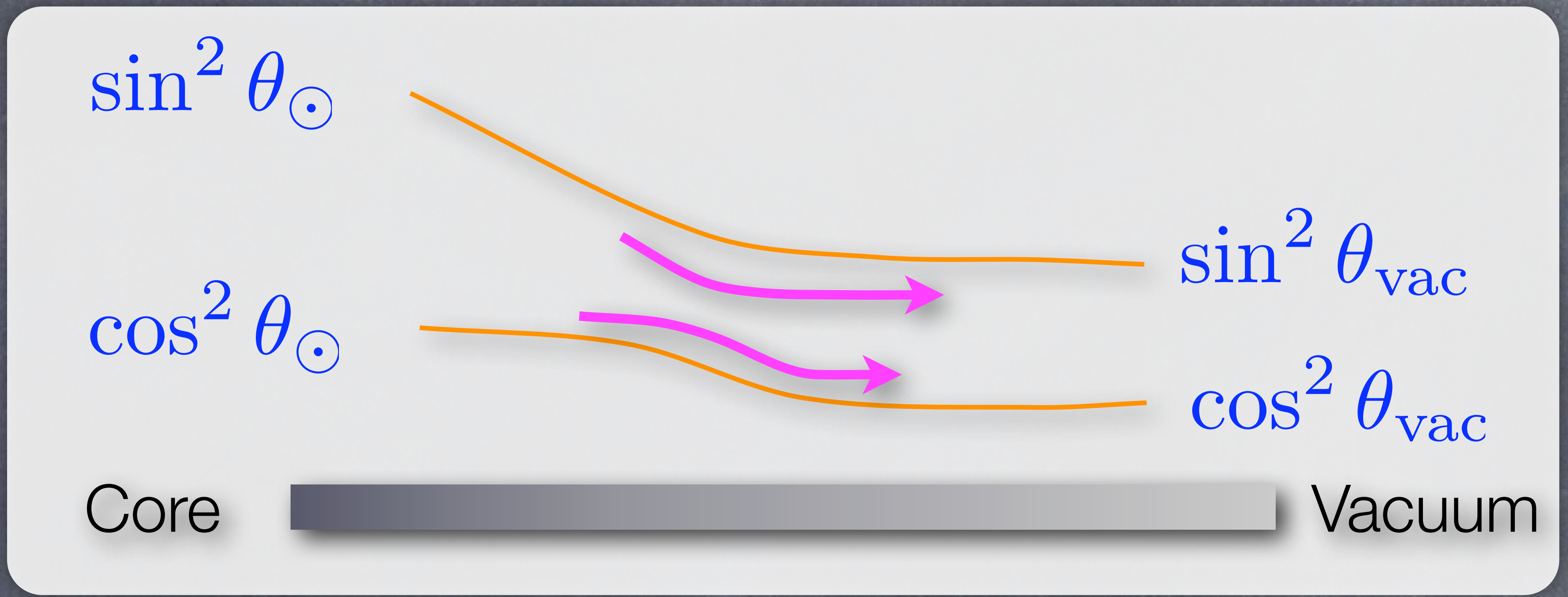
$$H_{\rm osc} = H_{\rm vac} + H_{\rm matter} \rightarrow H_{\rm ee} = \sqrt{2}G_F N_e$$

Hamiltonian eigenvalues (for normal hierarchy)



2-state oscillations

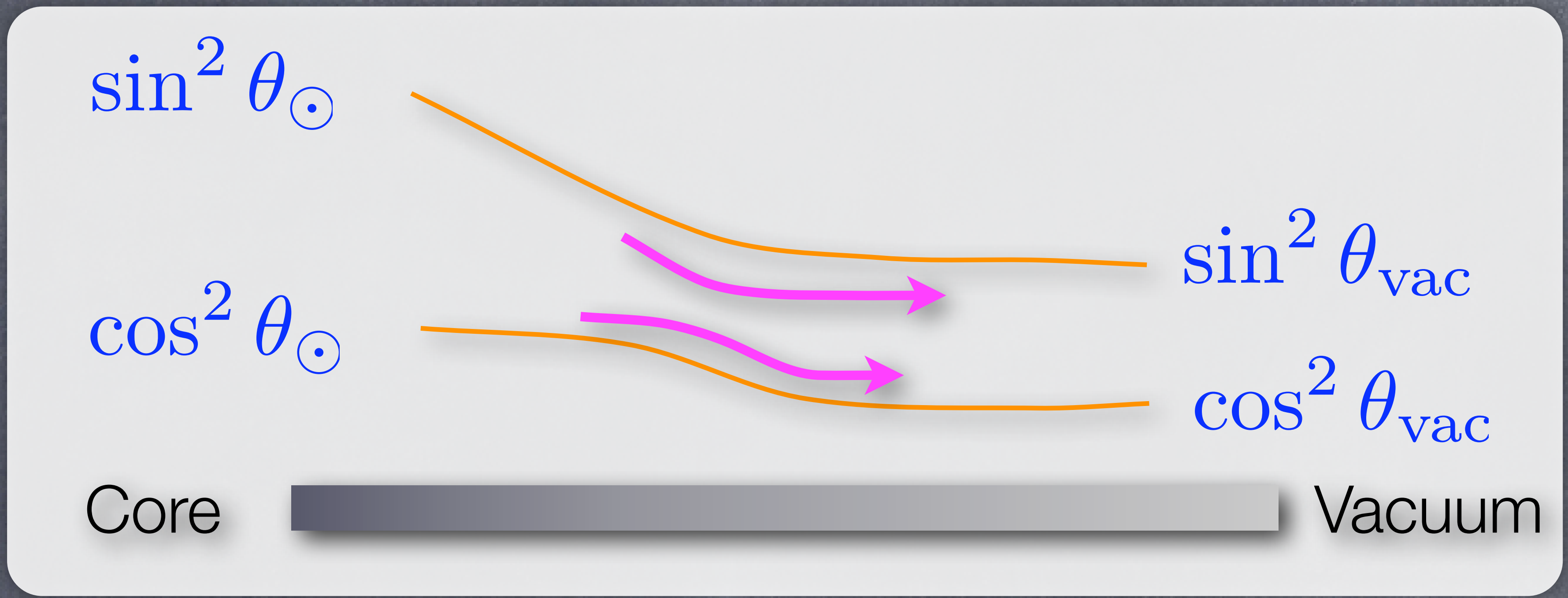
$$P_2(\nu_e \rightarrow \nu_e) \quad = \quad \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$



- The evolution is adiabatic (no level jumping), since l_{osc} << density scale height ($|d \ln\rho /dr|^{-1}$)
- Q5: convince yourself of that
  - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (why? KamLAND)

2-state oscillations

$$P_2(\nu_e \to \nu_e) \quad = \quad \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$



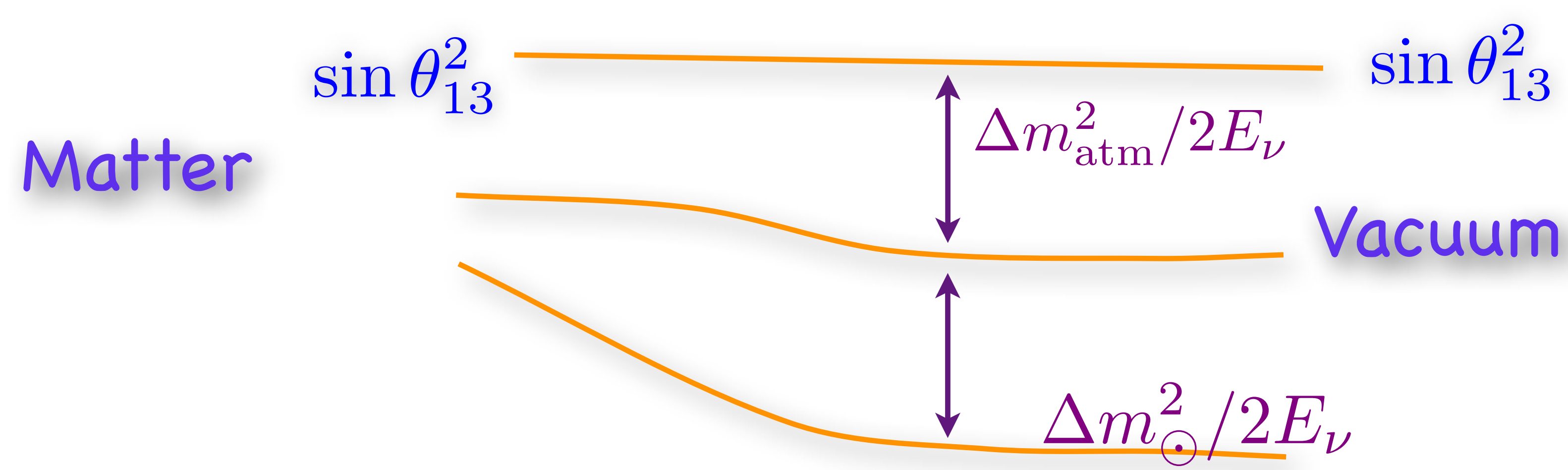
- Also, the coherence between the states is lost
- Q6: convince yourself of that
  - Hint: How does the oscillation length compare to the size of the production region?

3-state oscillations

- The third state provides a ~ 4.5% correction

$$P_3(\nu_i \to \nu_i) = \sin\theta_{13}^4 + \cos\theta_{13}^4 P_2(\nu_i \to \nu_i)$$
$$\simeq 0.955 P_2(\nu_i \to \nu_i)$$

Not to scale!



- Notice that the projection of the electron neutrino on the third state is $\sin\theta_{13}^2$, unaffected by matter

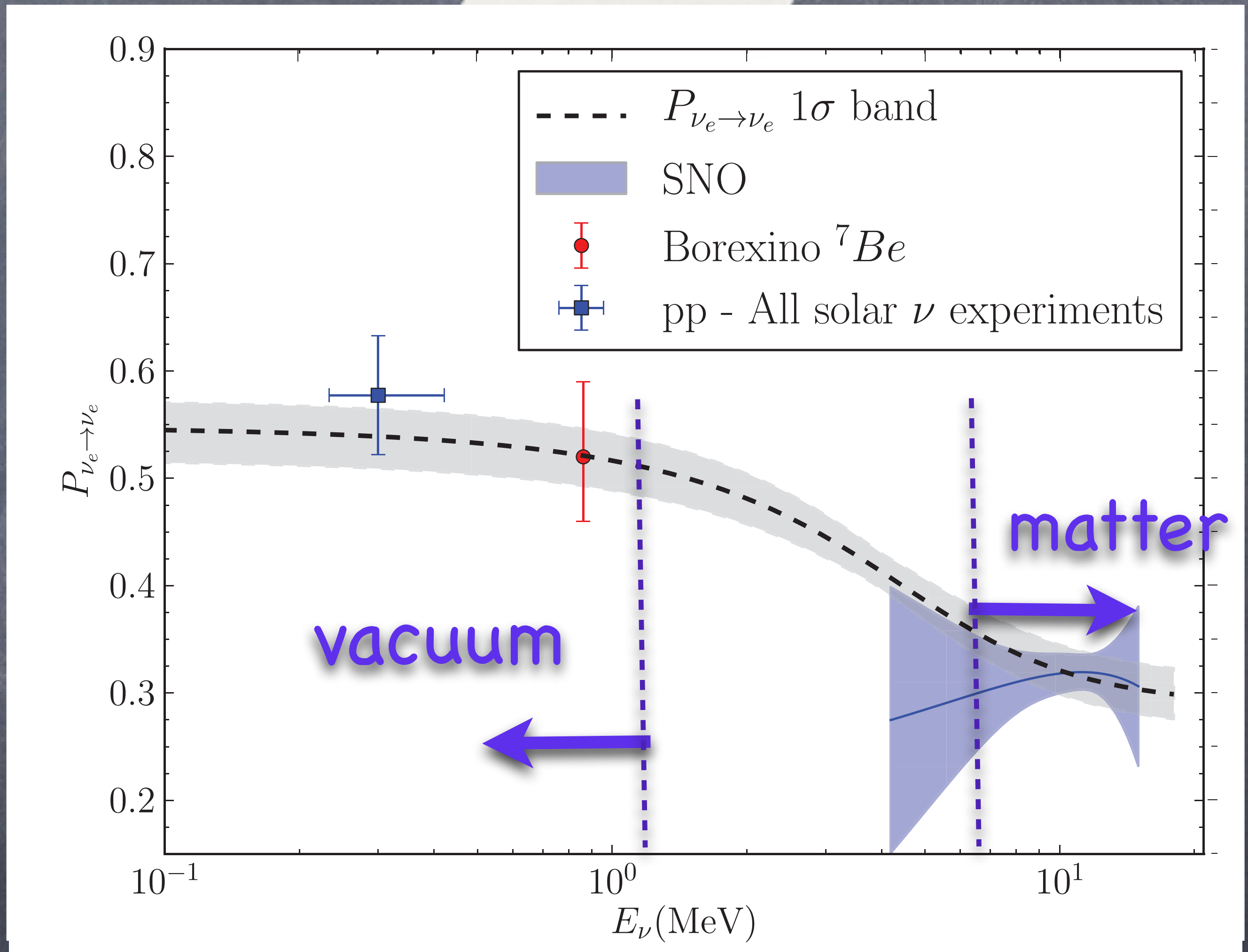
Now, back to the data

- The low-energy neutrinos (< 1 MeV) are in the vacuum oscillation regime (matter doesn't matter)

$$P_3(\nu_e \to \nu_e) \quad \to \quad \cos^4\theta_{13}(\sin^4\theta_{12} + \cos^4\theta_{12})$$

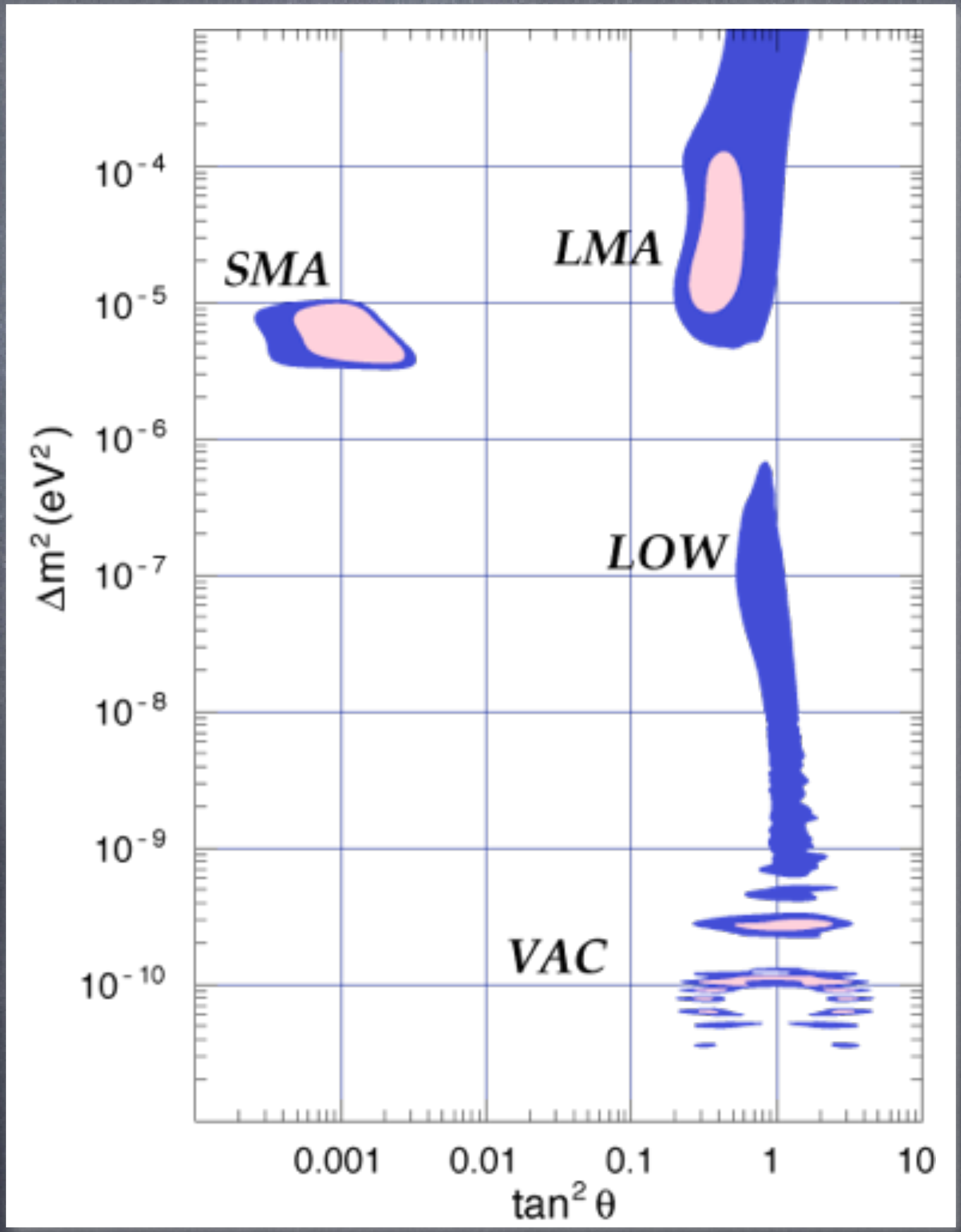
- while the high energy ^8B neutrinos are in the matter dominated regime (produced as ν_2)

$$P_3(\nu_e \to \nu_e) \quad \to \quad \cos^4\theta_{13}\sin^2\theta_{12}$$



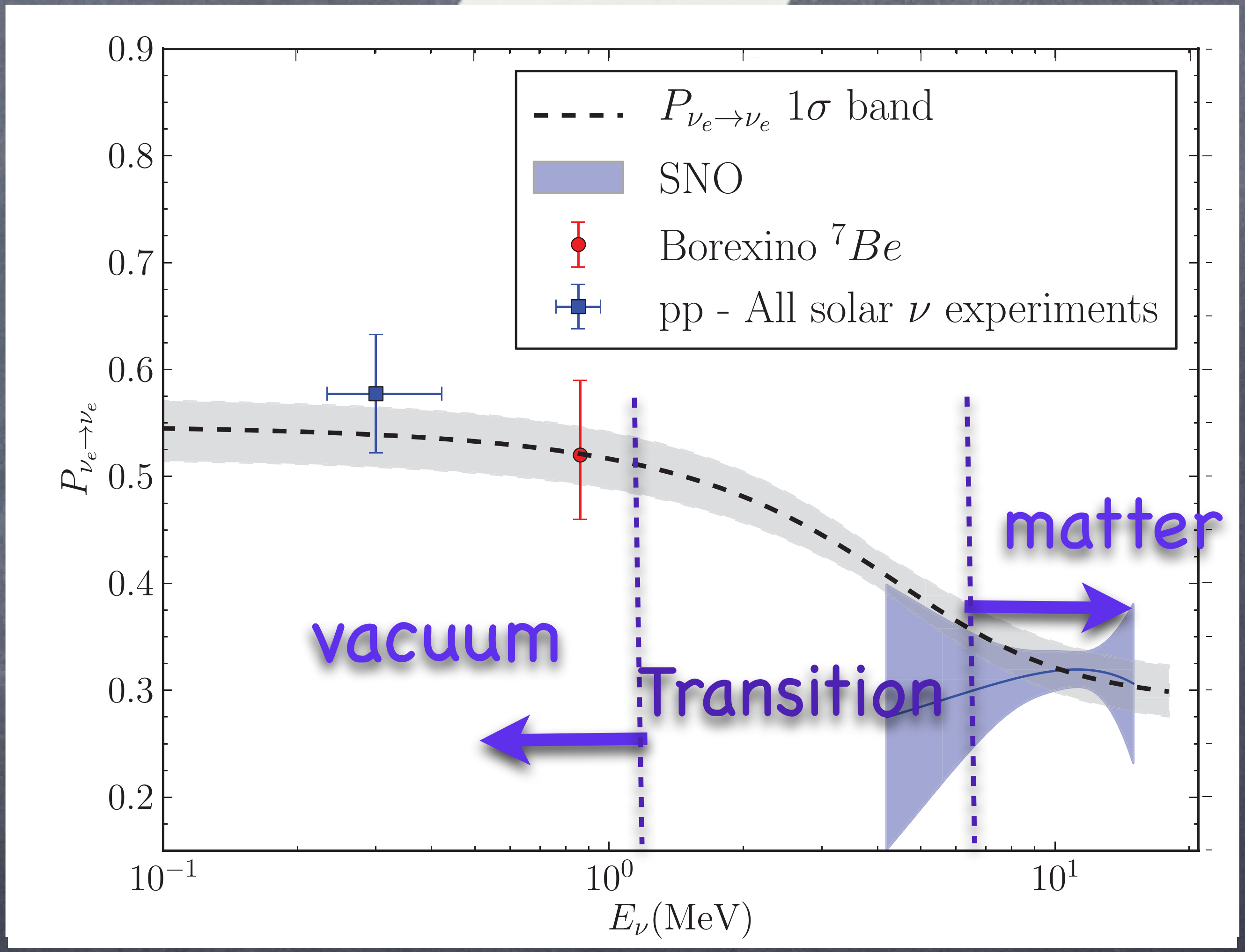
Comment

- All solutions possible in 2000 had to be tuned in some way
- VAC: osc length to 1 A.U.
- LOW: resonance in the Earth
- SMA: on the boundary of adiabatic and non-adiabatic + tuned to the central solar density



How about the intermediate solar energies?

- Here, matter and vacuum terms at the production point are comparable
- We can check that the matter potential is indeed what SM says it should be
- Constrain the original Wolfenstein's idea about nonstandard interactions



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.

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

- Lots of NSI papers since then
    - Hundreds in the last ten years alone

Is this a sane thing to study?

- Ok, we have discovered neutrino masses, but we understand them, right?
- We think they are probably Majorana and come from the See-saw Mechanism, which looks very pretty

for large M_R, $\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$ has eigenvalues M_R and m_D^2/M_R

- Neutrino physics is in a position where the GUT physics would be if we discovered proton decay:
  - something fundamental, a message from a very high scale, but what can we do about it?

Dimension-5 operator argument

- The SM is not the ultimate theory, but an effective low-energy theory, embedded into something more complete at high scale Λ
  - $L = L_{SM}+L_5/\Lambda+L_6/\Lambda^2+\dots$
- It can be shown that the lowest dimension non-renorm. operator gives the (Majorana) neutrino mass (Weinberg, 1970s)
  - $(LH)(LH)/\Lambda \to \nu\nu\langle v\rangle^2/\Lambda$
  - beyond dim 5, lots more stuff $\bar{L}\sigma^{\mu\nu}W^{\mu\nu}He_R,\ \bar{L}H\sigma^{\mu\nu}W^{\mu\nu}LH,\ (LL)q_Rq_R,\ \dots$
- We were supposed to discover neutrino mass first and we did!
  - success?

Let's dwell on this a bit

- Implicit in this logic is the belief that the nearest scale of new physics Λ is extremely high
- Upon accepting such belief, one may want to stop doing most of the experimental particle physics
  - with the possible exception of nucleon decay searches and
  - searches for other dim 5 operators, e.g., axion $aF\tilde{F}$
- If, on the other hand, new physics is at, or below, ~10 TeV, other higher dimension operators come into play

Light new physics?

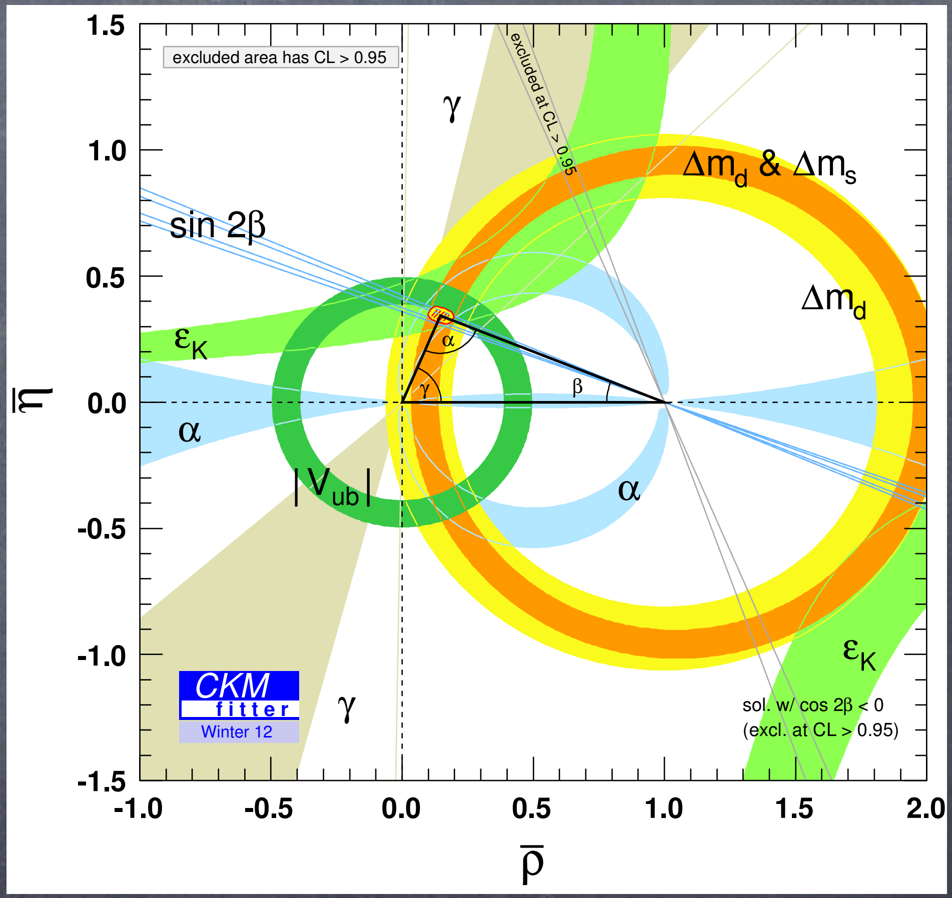
- In the extreme case, new physics could be light, right under our nose, just very weakly coupled
  - Right-handed neutrino partner
  - 8 GeV light WIMP
  - < 1 eV axion
  - ...

SM model works much better that it should

- On the one hand, Nature should have no unprotected masses
  - All unprotected masses stay at the scale of new physics by loop corrections
  - It's gratifying that besides the Higgs all other elementary particles have protected masses
- On the other hand, every possible higher-dimensional operator we are sensitive to is just not there!
  - besides neutrino masses
- We don't know what this means; we've been humbled by Nature

Why is the SM so successful?

- The strategy should be to cast your net wide and look for possible new effects everywhere
- In the case of neutrinos, this means overmeasure and overconstrain the sector to make sure there's no additional new physics
  - neutrinos, being very weakly interacting, can be good for probing certain kinds of new physics



Need something like this for the neutrino sector

NSI: Simplifying framework

- Following Wolfenstein, let's suppose new flavor-changing interactions
  - For clarity, just a single term: a flavor changing $qq\nu_e\nu_\tau$ interaction

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

  - subdominant to the SM weak interactions
  - Effective low-energy interaction, can be due to many different kinds of underlying physics

Solar neutrinos, 2004

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,

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

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.

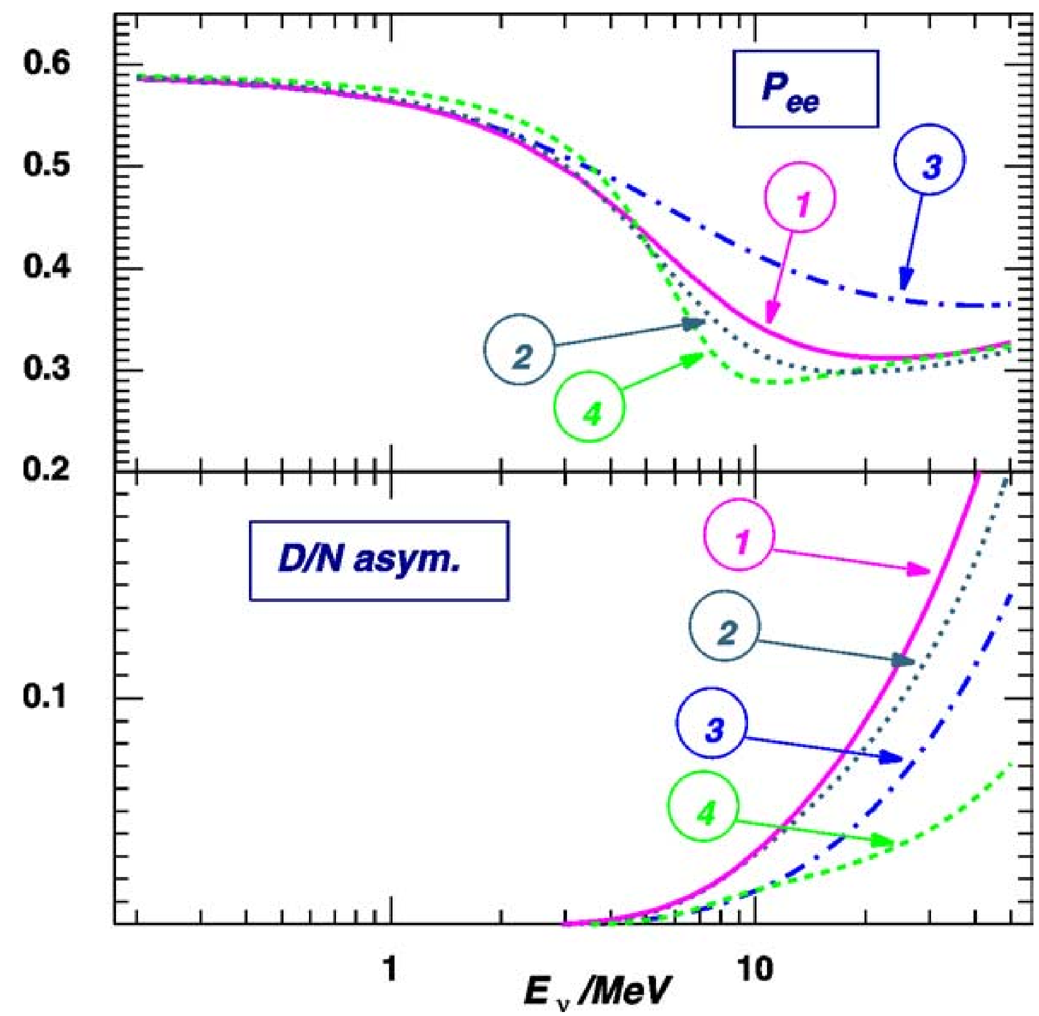
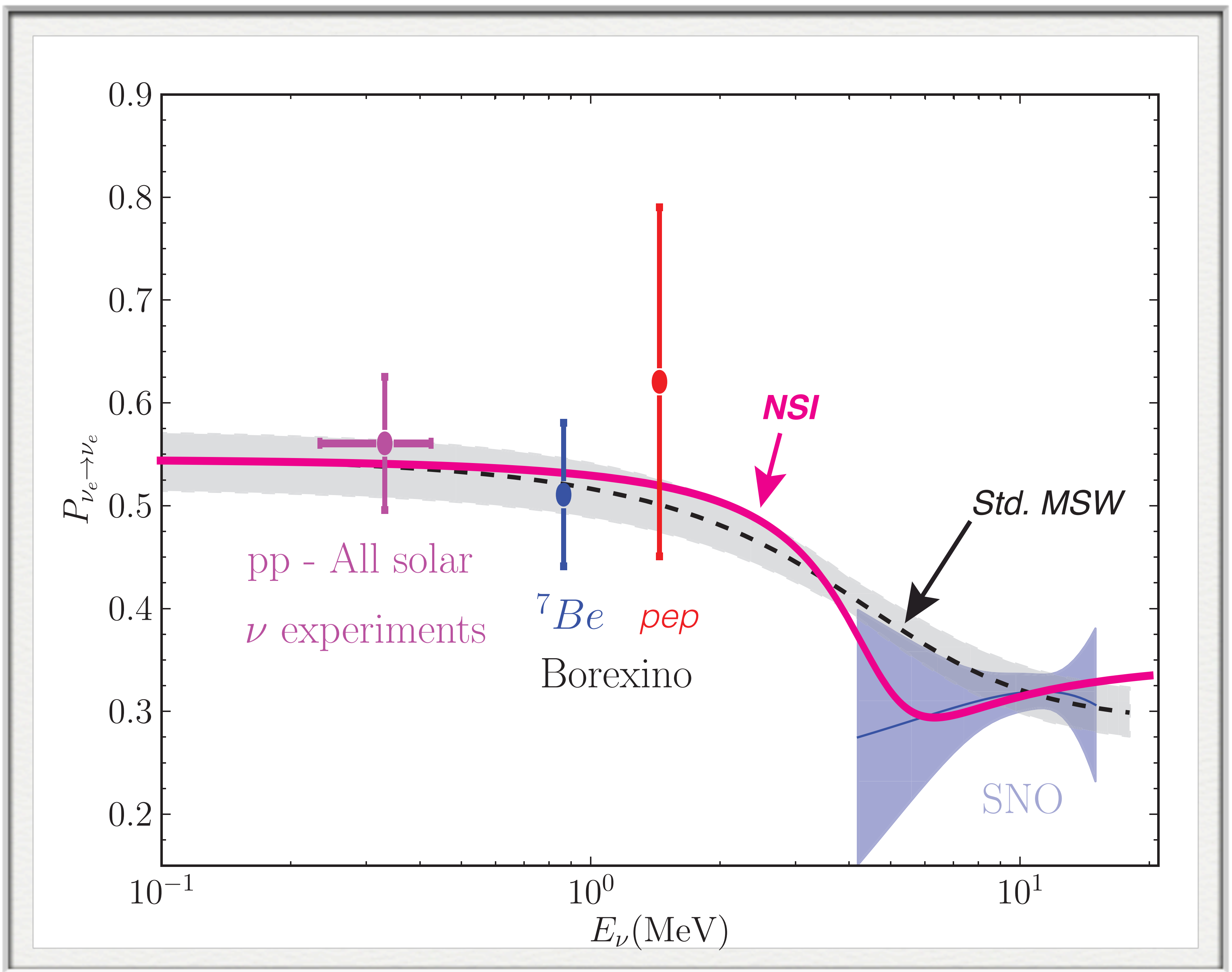


Fig. 1. The electron neutrino survival probability and the day/night asymmetry as a function of energy for $\Delta m^2 = 7 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.4$ and several representative values of the NSI para-

Solar neutrinos, 2012

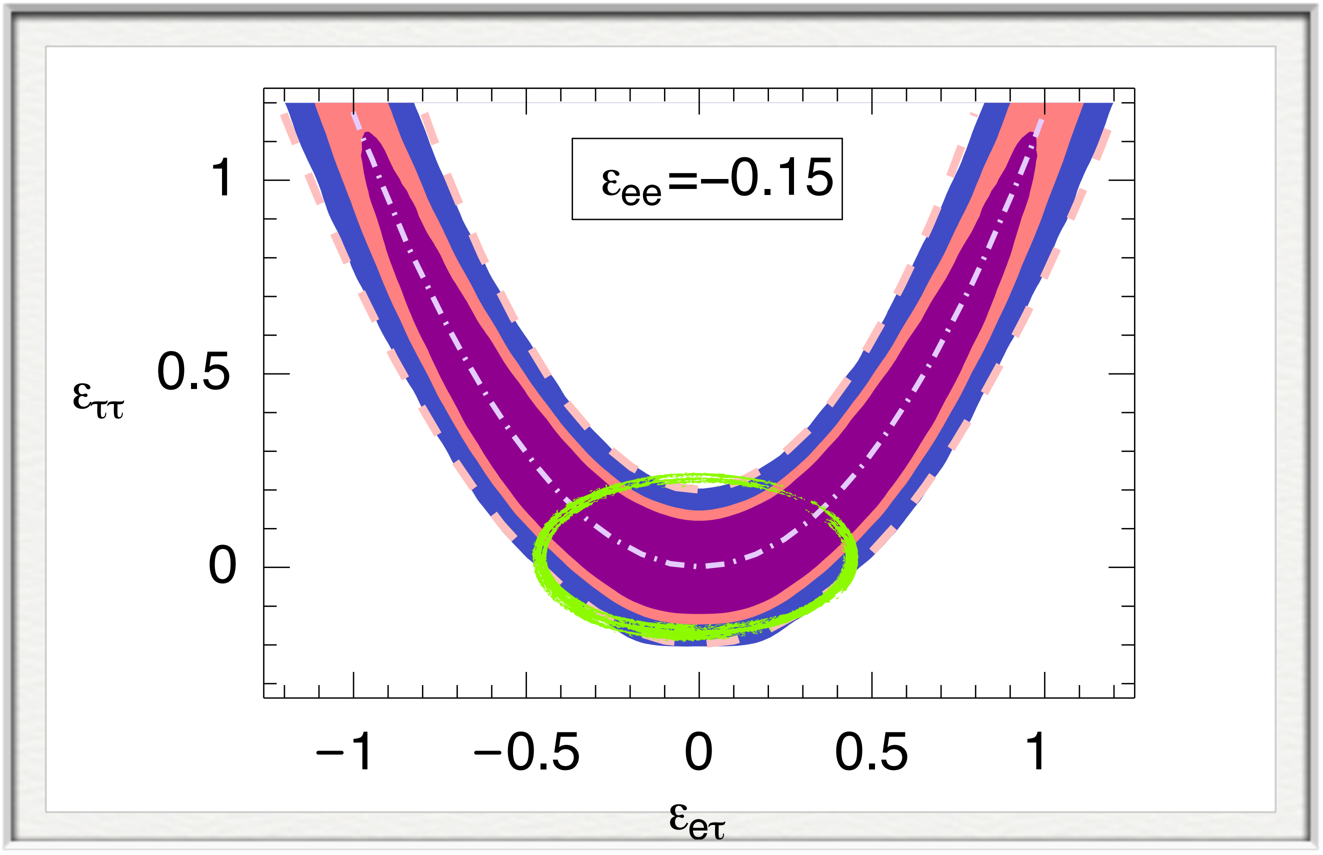


SNO 3-phase analysis 2011; our fit

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

Atmospheric neutrinos

- The same e-τ NSI shows up in atm. neutrinos at SuperK
- Data over 5 decades in energy! But energies not well-resolved
- $\varepsilon_{e\tau}$ up to ~0.5 allowed, even without special cancellations
  - Weaker than solar

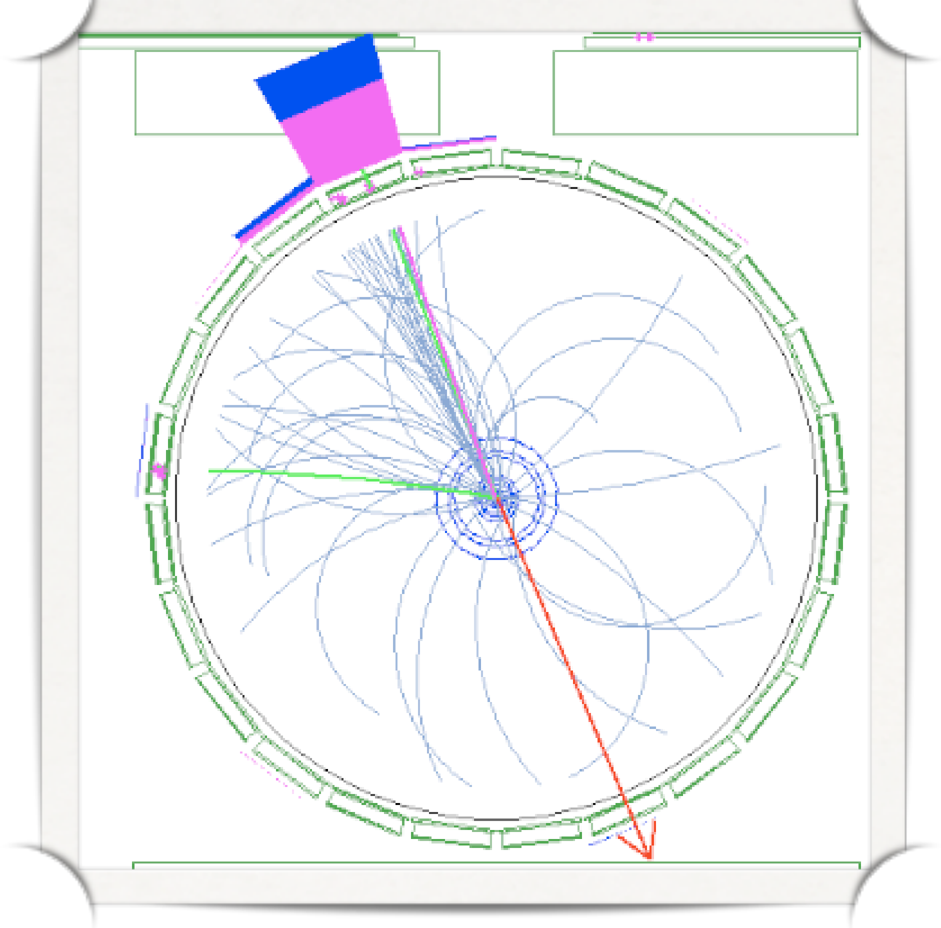


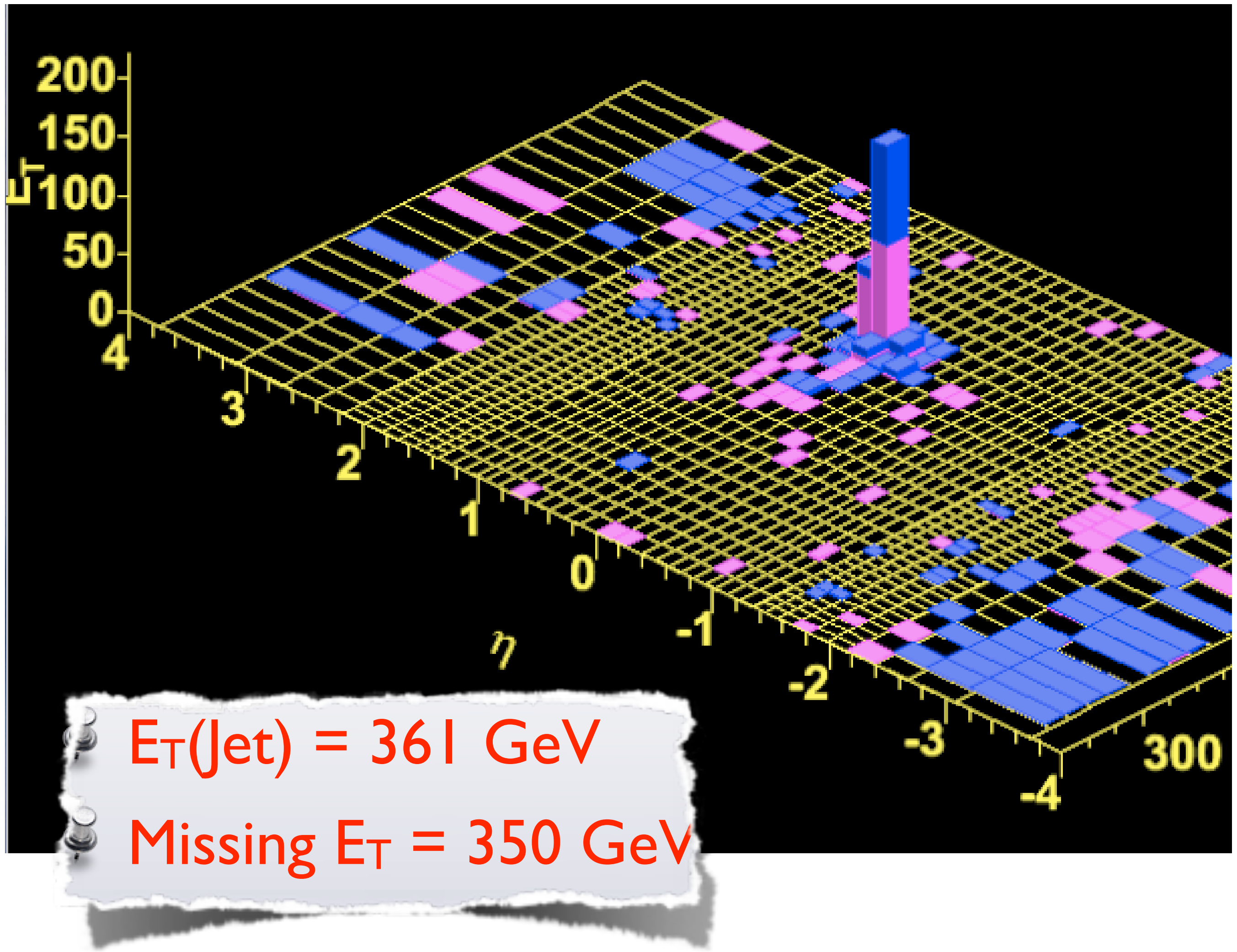
A.F., Lunardini, Maltoni, PRD 2004

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

Collider NSI bounds: LHC Monojet searches

- “monojet” events contain a single prominent jet recoiling against “nothing”
- “nothing” could be, e.g., dark matter particles, extra-dim KK gravitons, etc



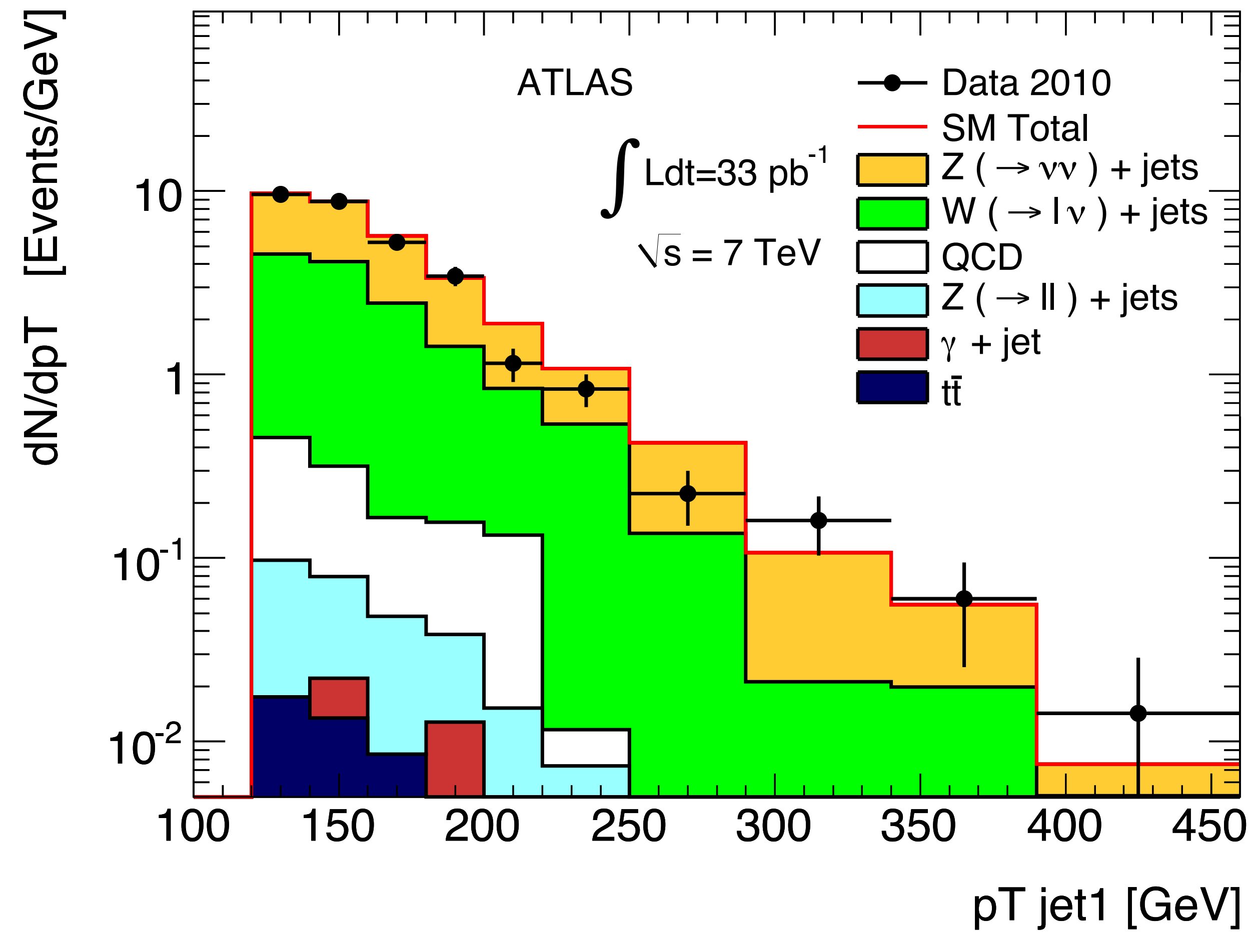


Some of the (many) papers on these searches

- 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

Do NSI remain contact at the LHC energies?

- If yes, bounds in the Table

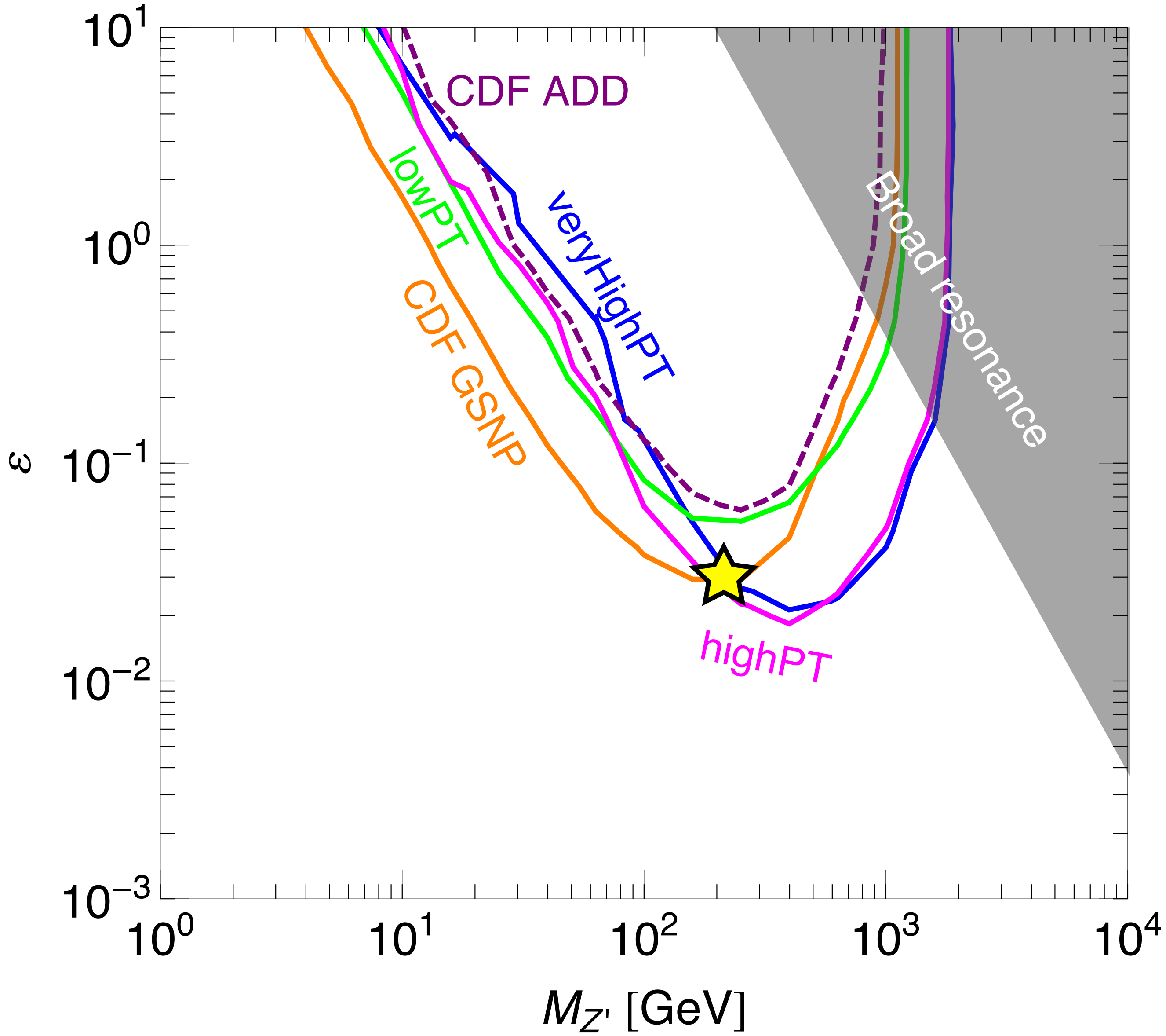
	CDF		ATLAS [31]		
	GSNP [32]	ADD [4, 5]	LowPt	HighPt	veryHighPt
$\varepsilon^{uP}_{\alpha\beta=\alpha}$	0.45	0.51	0.40	0.19	0.17
$\varepsilon^{dP}_{\alpha\beta=\alpha}$	1.12	1.43	0.54	0.28	0.26
$\varepsilon^{uP}_{\alpha\beta\neq\alpha}$	0.32	0.36	0.28	0.13	0.12
$\varepsilon^{dP}_{\alpha\beta\neq\alpha}$	0.79	1.00	0.38	0.20	0.18

- Notice that these NSI are *per quark*! Keep in mind when comparing to NSIs in oscillation experiments

- But what if the NSI are not contact?

- No longer "model-independent"

LHC and Tevatron monojet constraints



Also directly translates into a DM bound

-Tevatron data is more constraining for

$$m_{Z'} \lesssim 200 \text{ GeV}$$

Contact:

$$\sigma_{monojet} \sim \alpha_s g_q^2 g_X^2 \frac{p_T^2}{M^4}$$

Light mediator:

$$\sigma_{monojet} \sim \alpha_s g_q^2 g_X^2 \frac{1}{p_T^2}$$

-Would a yet softer cut yield better bounds?

Neutrinos vs. DM

- If we see an anomaly in monojet events, is it a signature of extra dimensions, dark matter, or neutrino NSI?

- Neutrino NSI could be potentially distinguished by their companion multilepton events (SU(2) symmetry)

  - example: people suggested contact dimension-8 interactions $q_R(LH)(LH)q_R$

  - These should lead to qq -> WW ll

- Turns out that 3-lepton events at the LHC (latest published 5 fb^{-1} sample) come close to the sensitivity of monojets

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

Heavy Majorana masses at the LHC

Unlike 0ν2β process, searching for like-sign dimuons

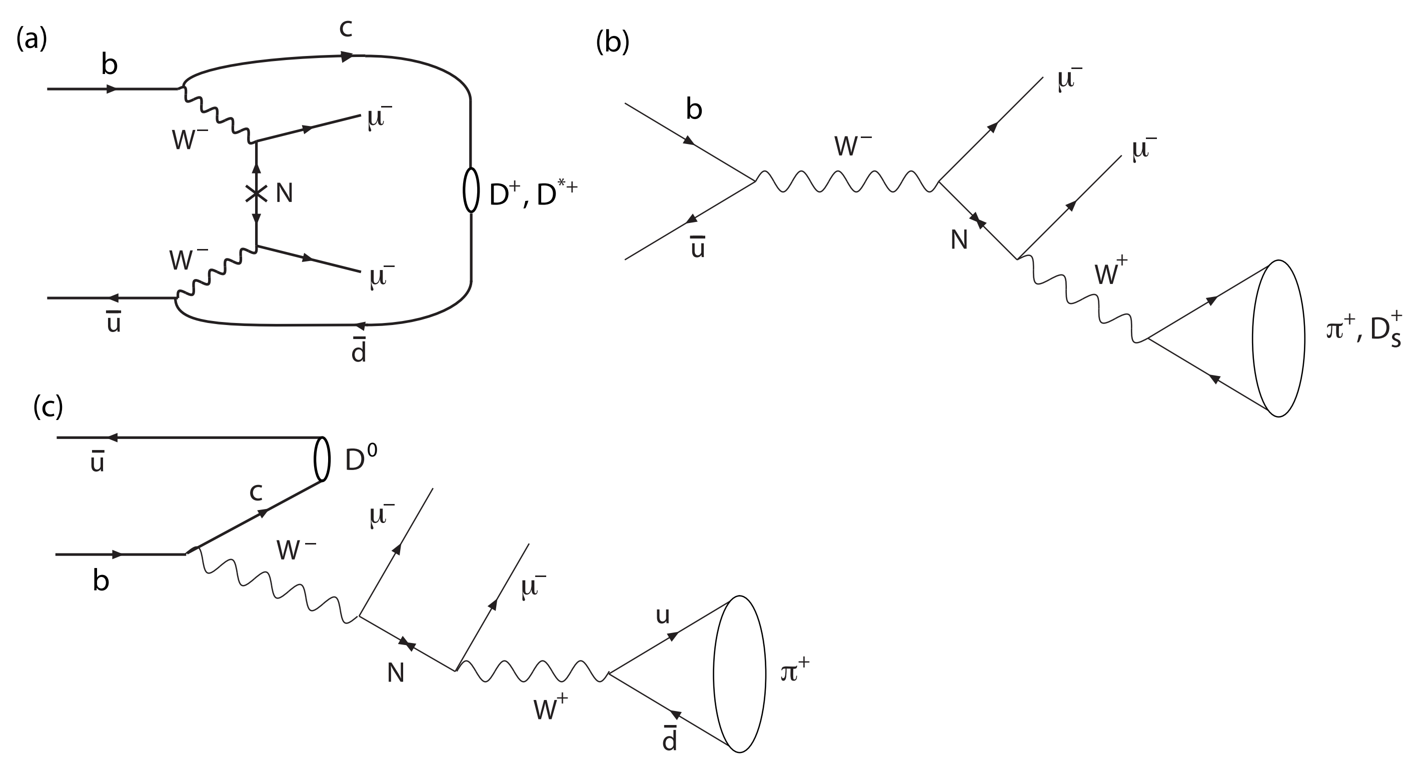


Figure 2: Feynman diagrams for B decays involving an intermediate heavy neutrino (N). (a) $B^- \to D^{(*)+}\mu^-\mu^-$, (b) $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, and (c) $B^- \to D^0\pi^+\mu^-\mu^-$.

Bounds

See last week's talk by Marina Artuso

Table 4: Summary of upper limits on branching fractions. Both the limits on the overall branching fraction assuming a phase space decay, and the range of limits on the branching fraction as a function of Majorana neutrino mass (M_N) are given. All limits are at 95% CL.

Mode	$\mathcal{B}$ upper limit	Approx. limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
$\pi^+\mu^-\mu^-$	1.3×10^{-8}	$(0.4 - 1.0) \times 10^{-8}$
$D_s^+\mu^-\mu^-$	5.8×10^{-7}	$(1.5 - 8.0) \times 10^{-7}$

LHCb, PRD85, 112004 (2012)

See also BELLE, PRD84 (2011) 071106

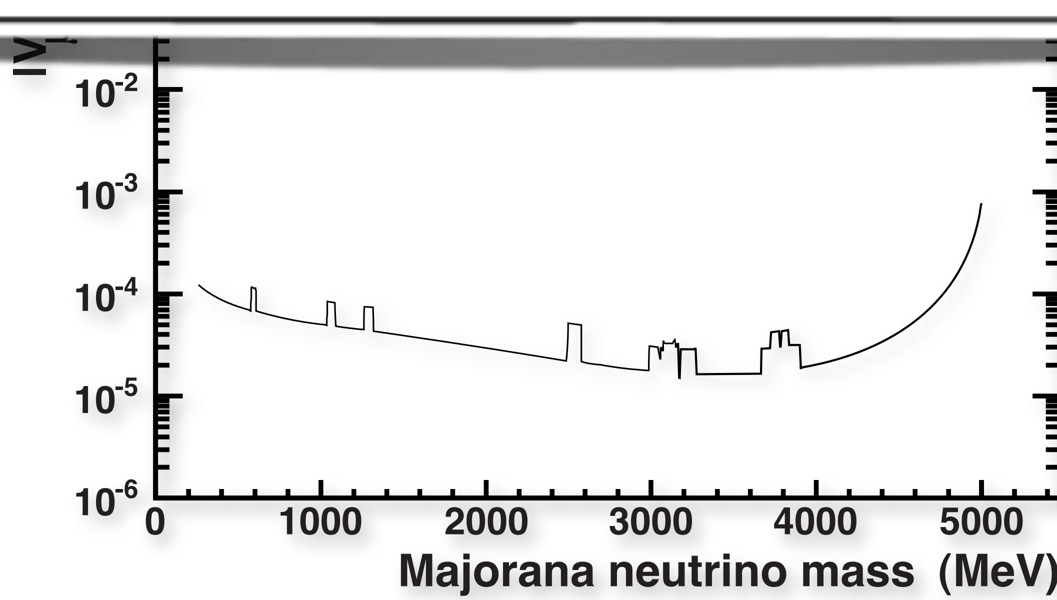


Figure 15: Upper limits on $|V_{\mu 4}|^2$ at 95% CL as a function of the Majorana neutrino mass from the $B^- \to \pi^+\mu^-\mu^-$ channel.

To be continued tomorrow:

- Long-baseline oscillations
- Neutrino astrophysics
  - Stellar cooling bounds on neutrinos
  - Supernova neutrino oscillations
- Neutrinos in cosmology (briefly)

Tentative conclusions

- Neutrino do not have much regard for DOE frontiers
  - Neither does this speaker
- It's a good thing this year's program is called
  - Journeys Through the Frontier
- Kudos to the organizers for this choice!