A few closing thoughts

Alex Friedland
Theory group

SLAC NATIONAL ACCELERATOR LABORATORY

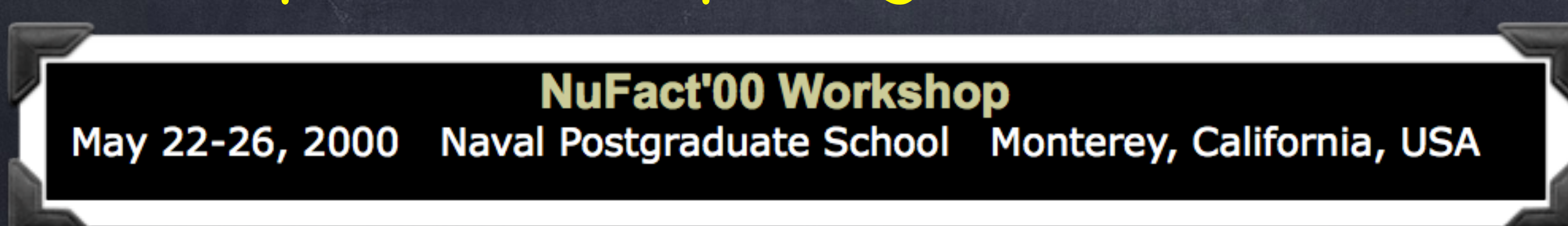
August 18, 2018

The twentieth workshop in this series

1999 - Lyon, France
2000 - Monterey, California, USA
2001 - Tsukuba, Japan
2002 - London, UK
2003 - New York, New York, USA
2004 - Osaka, Japan
2005 - Frascati, Italy
2006 - Irvine, California, USA
2007 - 2007 - Okayama, Japan
2008 - Valencia, Spain
2009 - Chicago, Illinois, USA
2010 - Mumbai, India
2011 - Geneve, Switzerland
2012 - Williamsburg, Virginia, USA
2013 - Beijing, China
2014 - Glasgow, UK
2015 - Rio de Janeiro, Brazil
2016 - Quy Nhon, Vietnam
2017 - Uppsala, Sweden

A bit of personal perspective

- NuFact '00 was my first conference
  - In Berkeley, most of my travel budget had been spent to attend the TASI school
  - With whatever was left over, I drove to Monterey
  - You can still find that wonderful meeting on the web, including all the talks!
    - https://www.cap.bnl.gov/mumu/conf/nufact00/



It may be worth pondering just how far we’ve come as a field since then

The standard lore two decades ago

- The TASI summer school I attended was called
  - "Supersymmetry, Supergravity, and Supercolliders"
- Going in, I knew about "superconductivity" or "superfluidity"
- After four weeks of the school, I concluded that in particle physics, "Super-" had a very specific, distinct technical meaning
  - "A really cool theoretical idea that doesn't exist in nature"
- Wisely though, the school 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

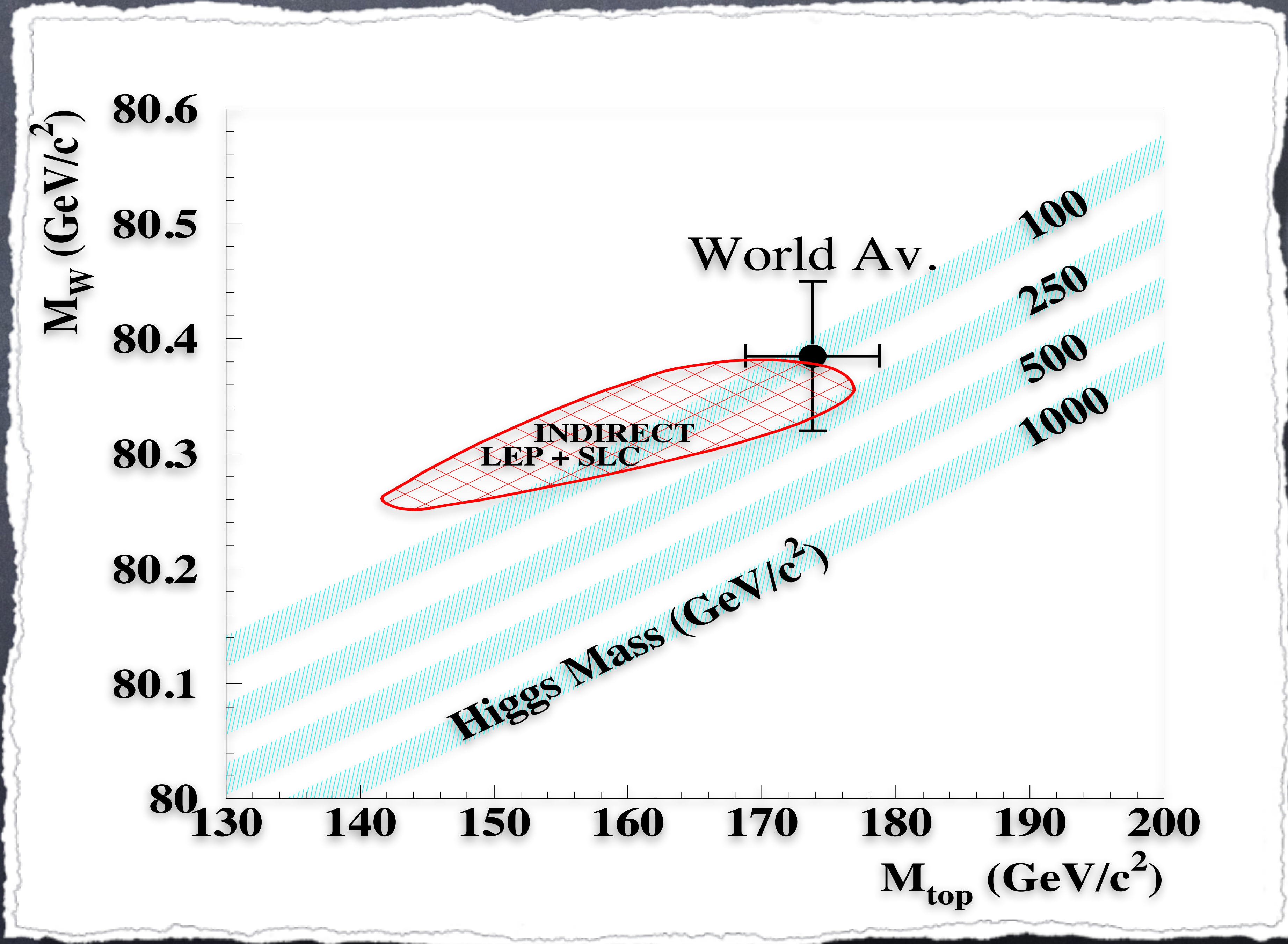
The principle components of the Standard Model and the status of their experimental verification are reviewed.

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

$\Delta(m^2) < 0.0075$ 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)

$\Delta(m^2) < 0.09$ 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

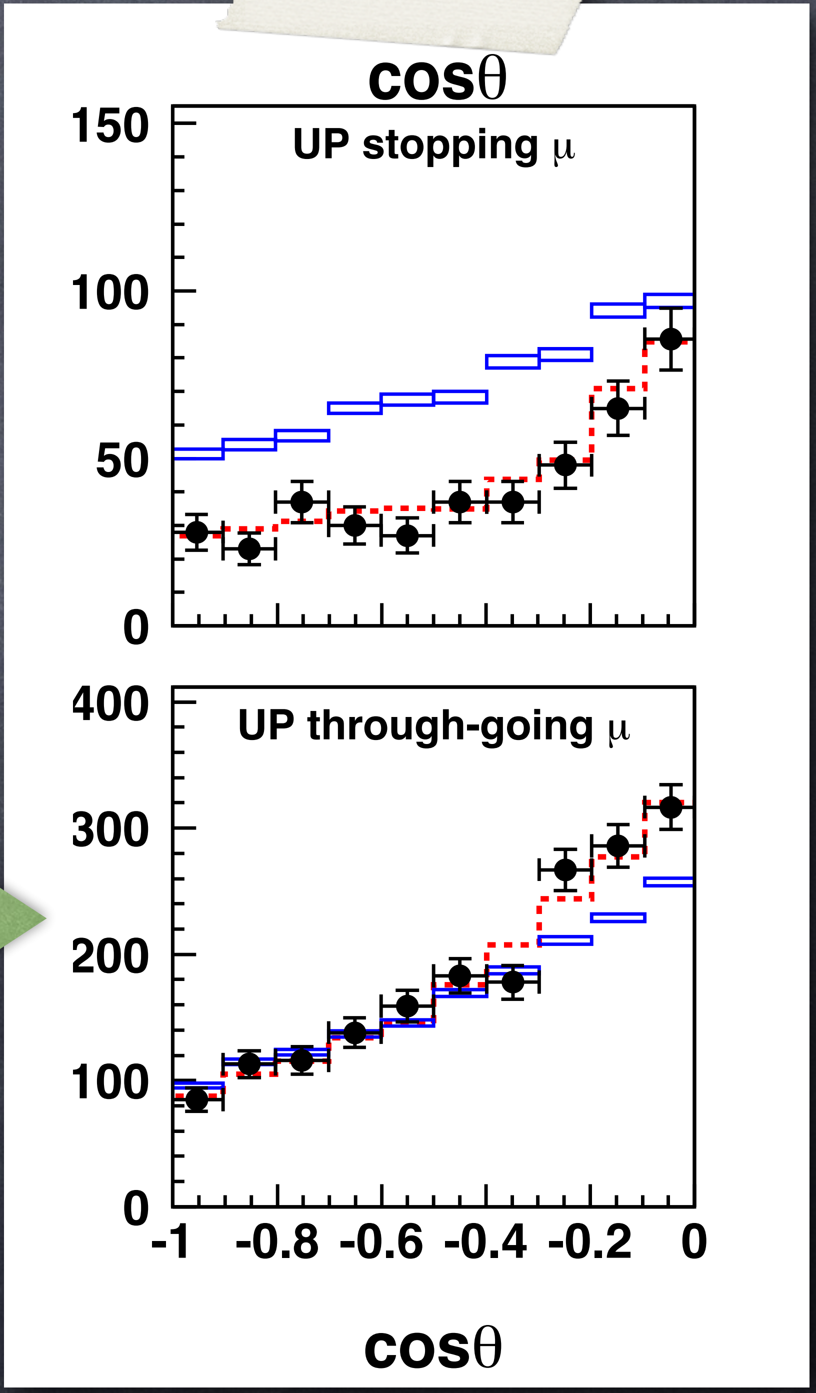
There is now rather convincing evidence that neutrinos have nonzero mass from the apparent observation of neutrino oscillations, where the neutrinos come from π (or K) $\rightarrow\ \mu \rightarrow\ e$ decays in the atmosphere; the mesons are produced in cosmic-ray cascades.

PDG 2000

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

By that point, I was hooked

This is what New Physics looks like

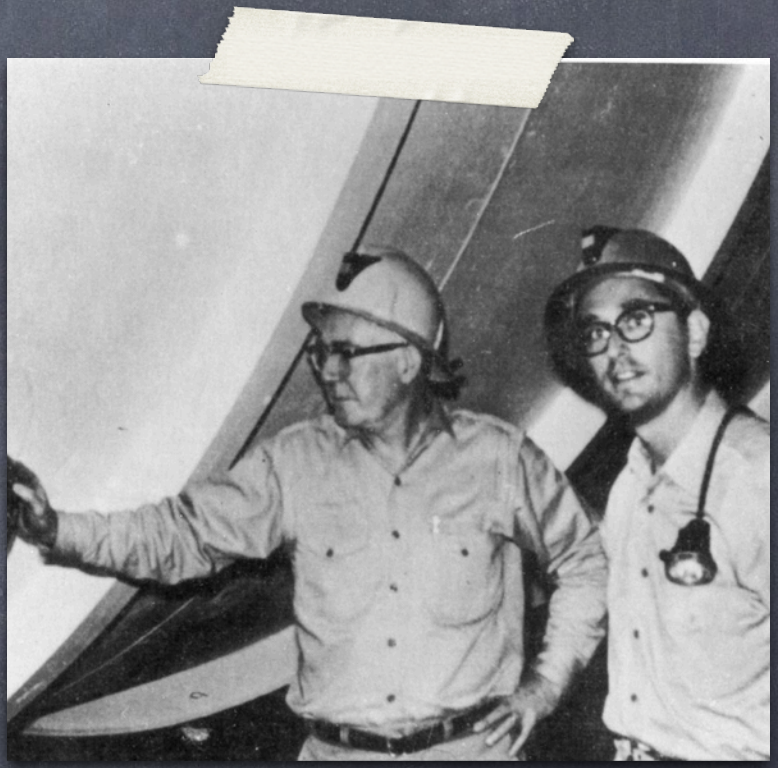


The story of solar neutrinos

- A very instructive tale of Pride and Prejudice
- The first neutrino oscillation effect was observed in 1968, at Homestake
  - 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

- http://www.bnl.gov/bnlweb/raydavis/BB_sept1967.pdf
- No mention of oscillations
- Nobody rushes to repeat this measurement for the next two decades

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.

Matter matters

- Wolfenstein 1978: matter effect, by analogy with the Kaon regeneration in matter
  - Index of refraction (due to coherent forward scattering) 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 NSI (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!

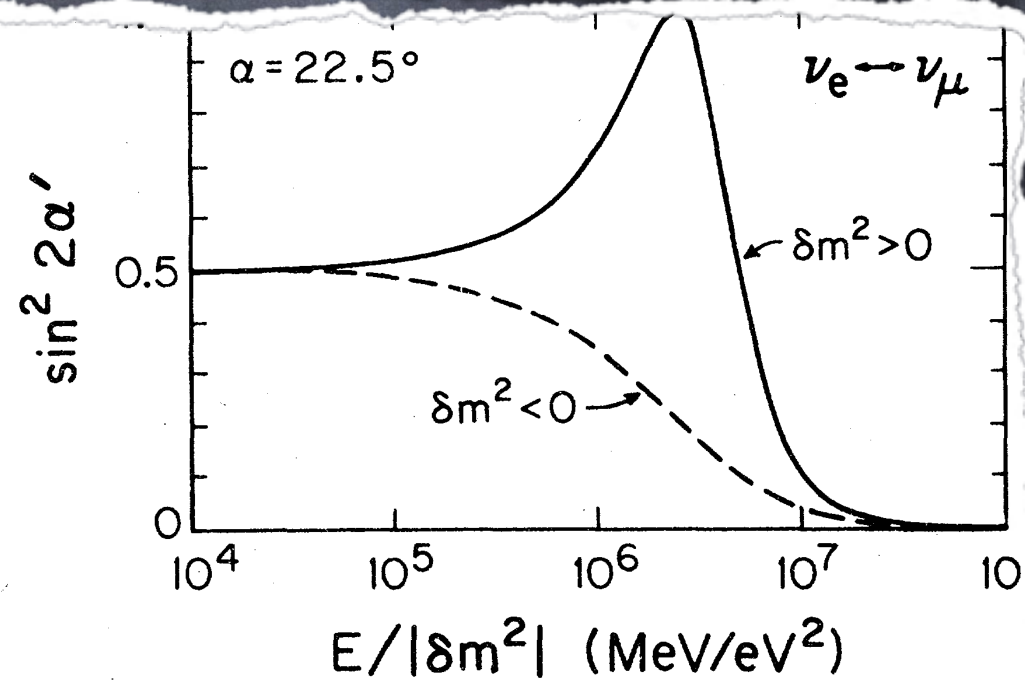


FIG. 1. Matter-to-vacuum eigenmass-squared differ ence ratio and matter amplitude $\sin^2 2\alpha'$ for oscillation of two neutrinos with vacuum amplitude $\sin^2 2\alpha = 0.5$ (α

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

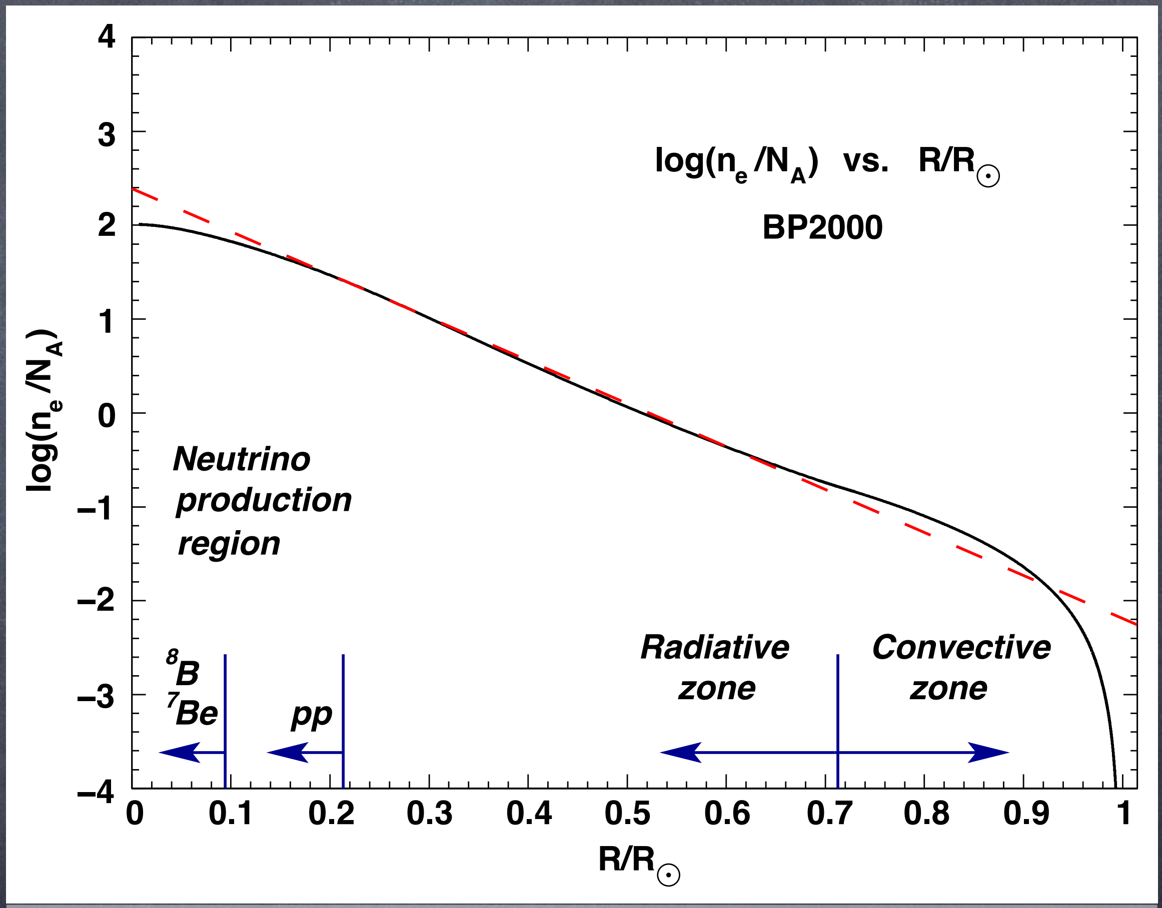
Comments (June 2007)

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 HEP 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

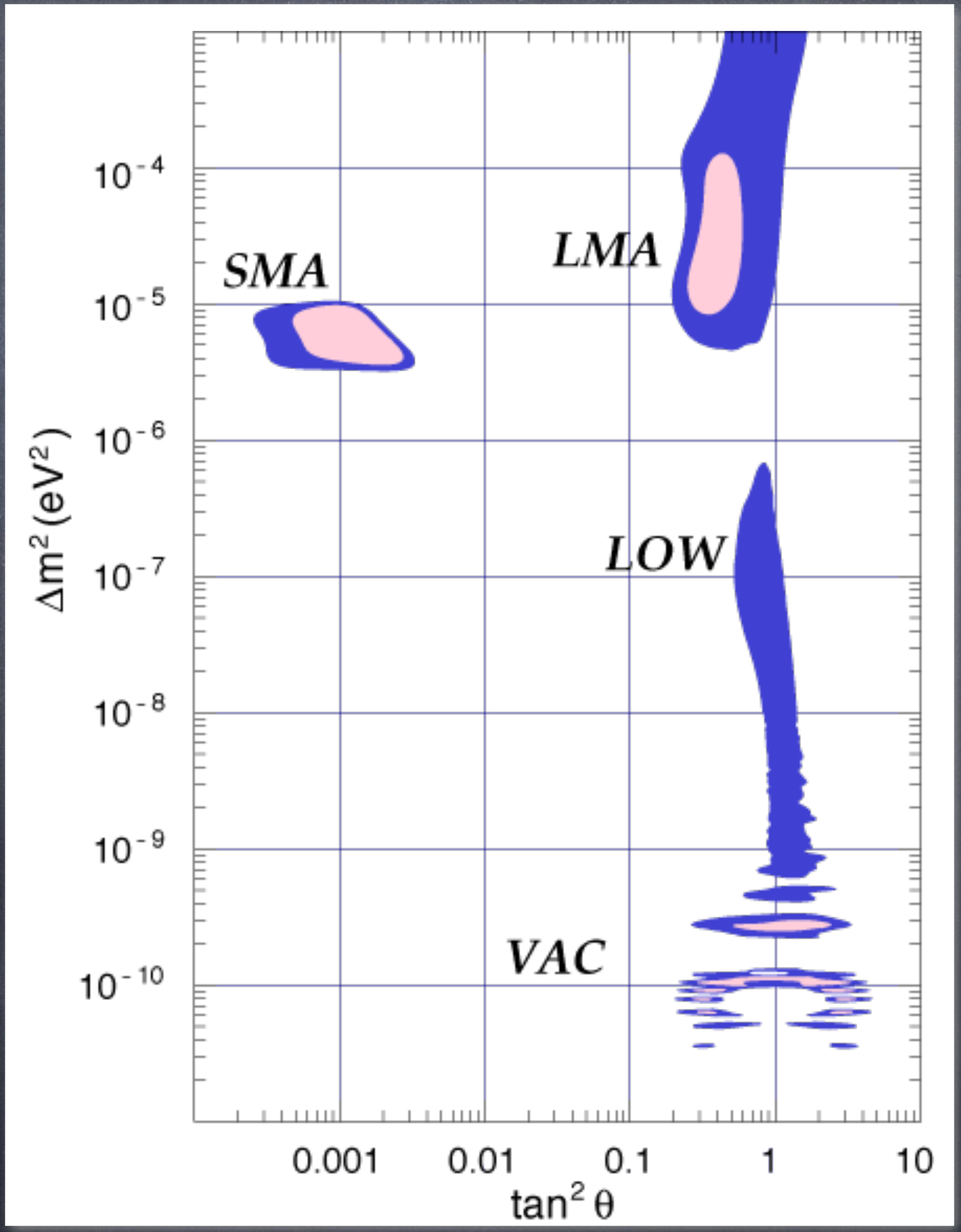
- Other quotes in Bahcall, physics/0406040

In hindsight

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

Solar neutrinos, circa NuFact'00

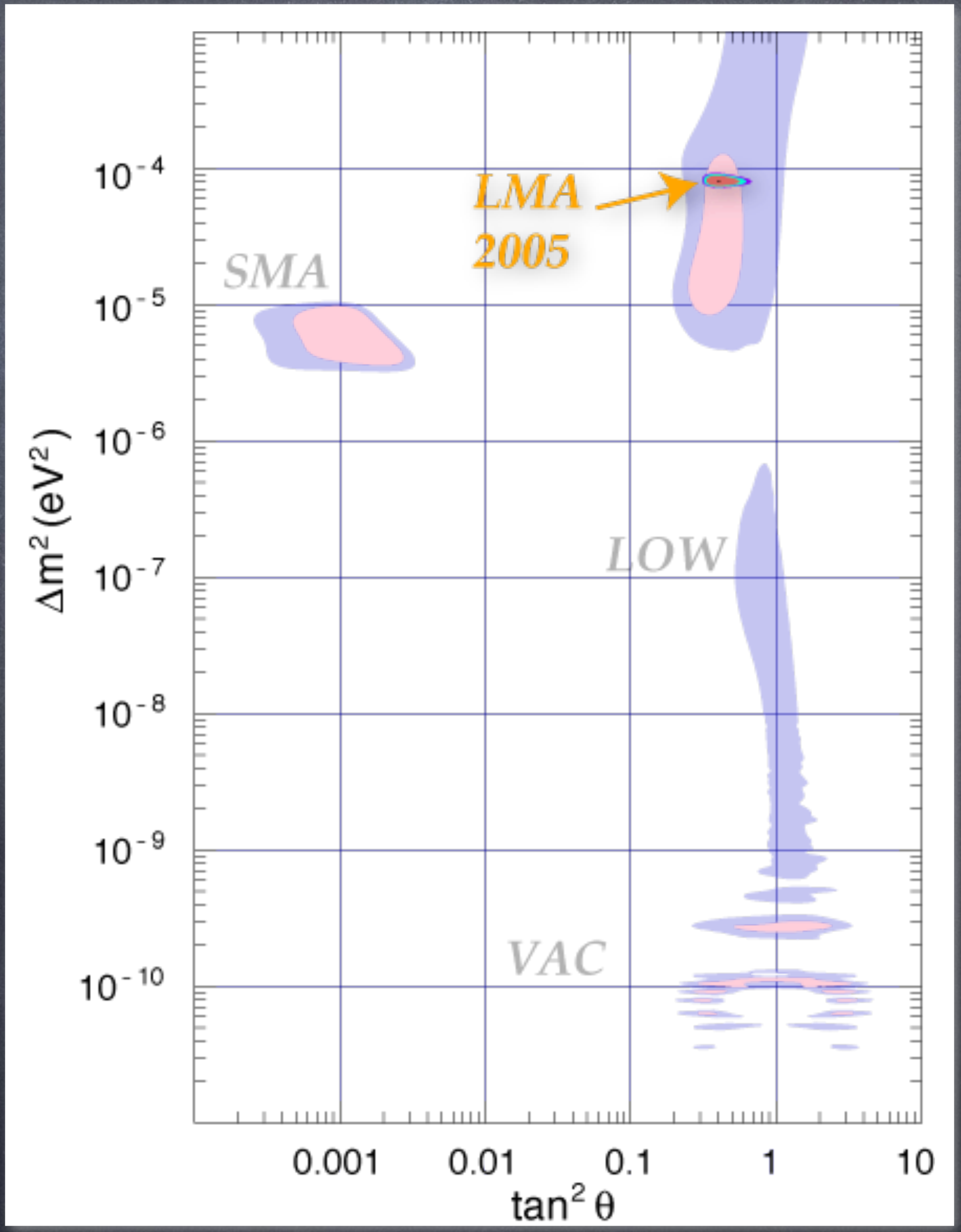
- A number of solutions possible, with masses and mixing angles spanning orders of magnitude



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

And by 2005

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

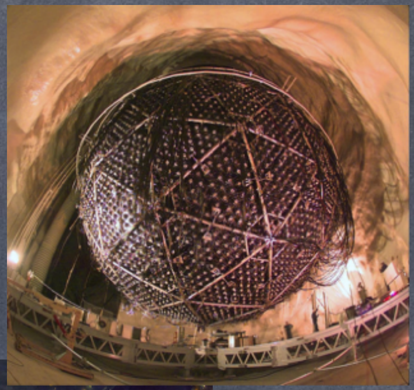


KamLAND Collab., PRL 94, 081801 (2005)
SNO Collab., PRL 92, 181301 (2004)

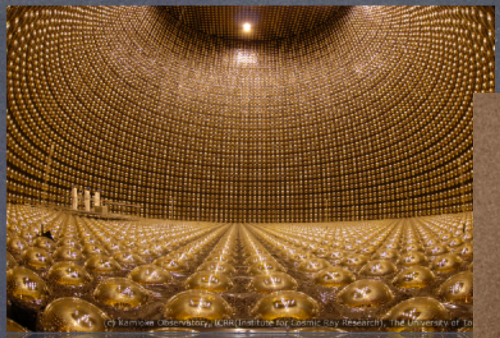
Tremendous progress since

FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

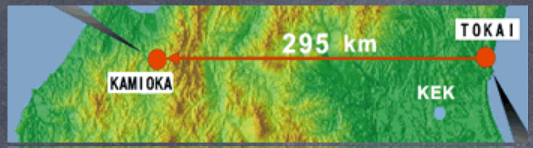
SNO



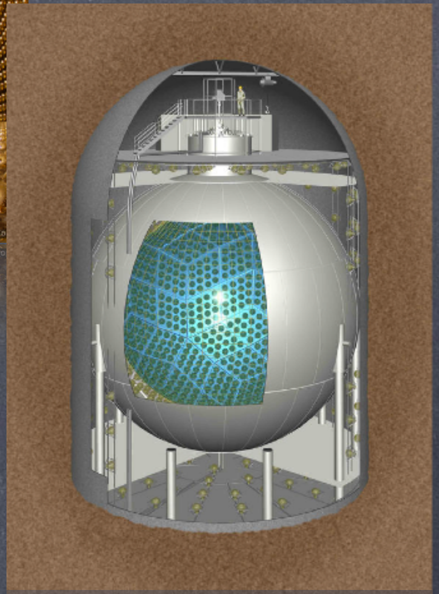
Super-K



Daya Bay



T2K

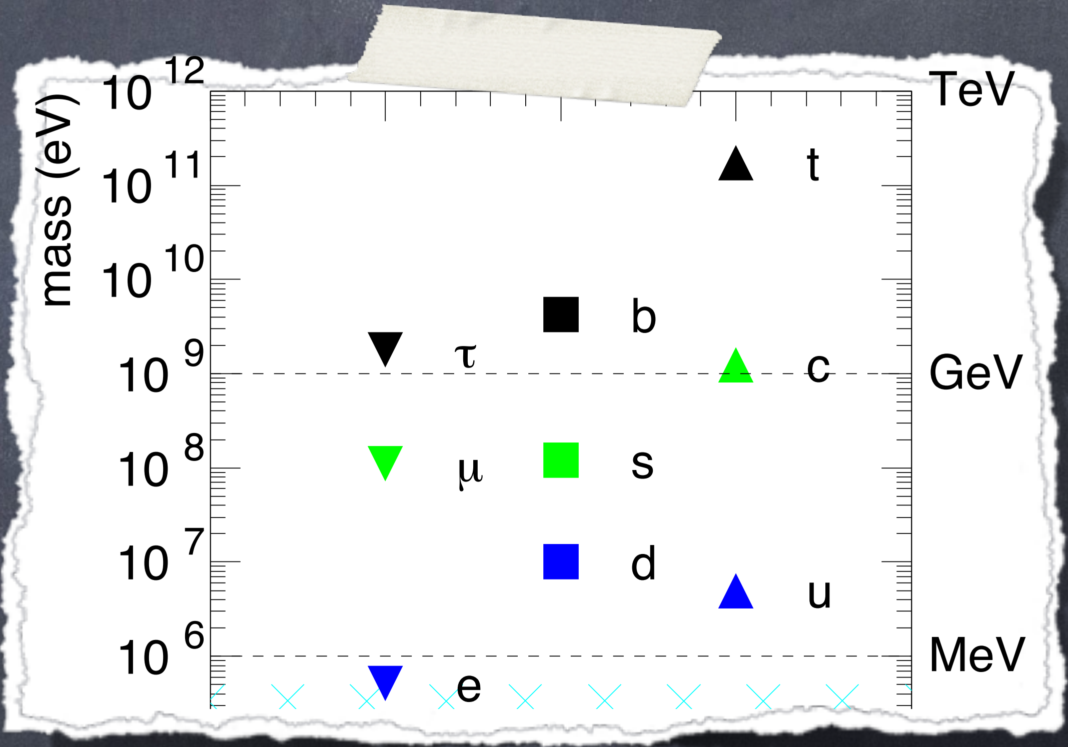


KamLAND

- Every year, there have been important experimental developments in the field
- E.g., θ_{13}: from unknown to best-measured in a blink of an eye, with major implications from the long-baseline program to supernova neutrinos
- IceCUBE UHE neutrinos, CMB/LSS data, SBL surprises, cross sections, coherent NC ...

What's so special about neutrino masses?

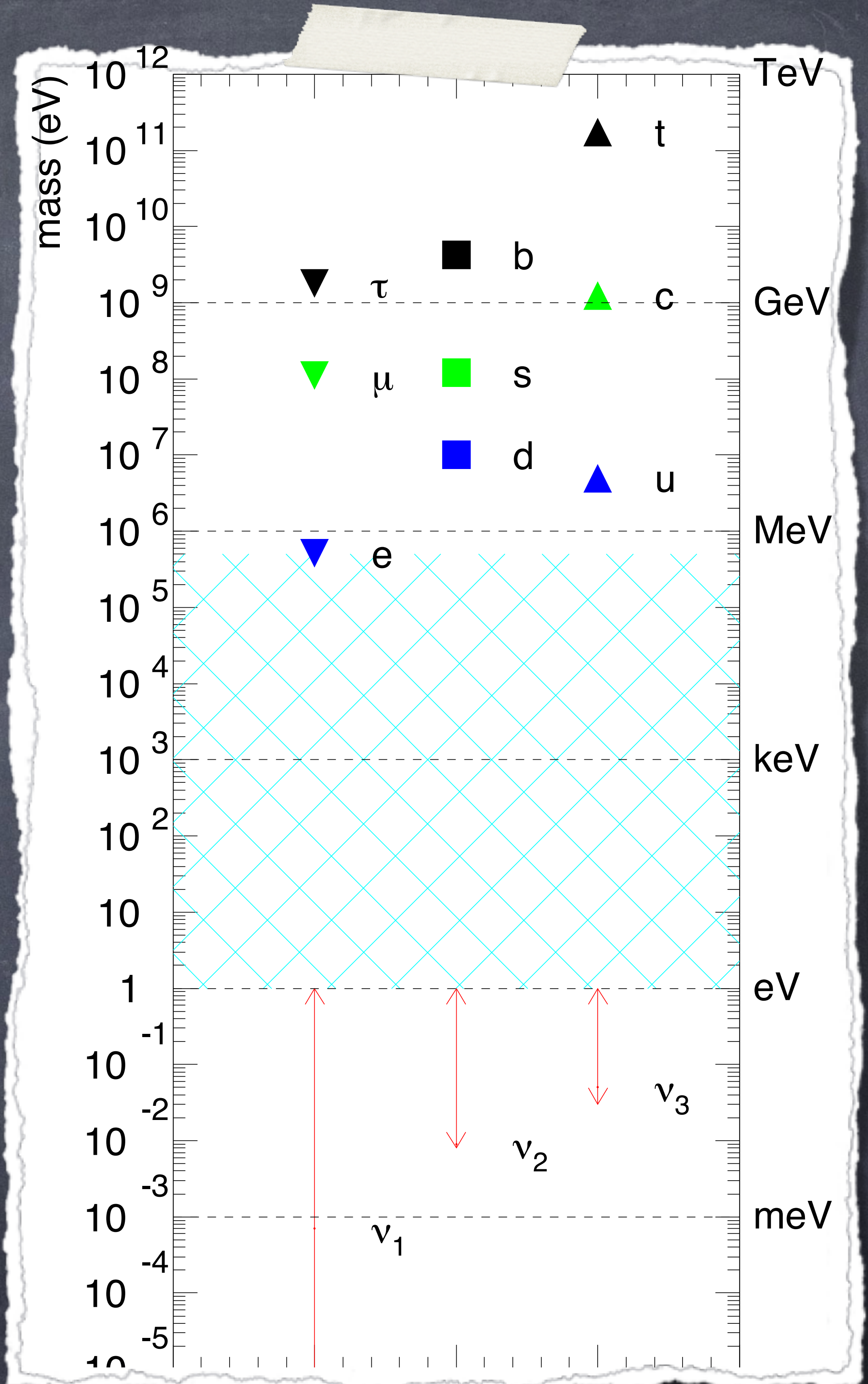
- Neutrinos have masses
- Other particles have masses ...



But neutrino masses are unusual

From the experimental point of view, neutrinos are absurdly light and, moreover, interact only through the weak force

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; (n)EXO, Majorana, GERDA, KamLAND-Zen, SNO+
- Slow neutrinos down by redshift; use gravity for detection
  - cosmology; CMB, LSS, lensing
- Use interferometry
  - oscillation experiments; reactor, accelerator beams, solar, atmospheric, supernova

From the theoretical point of view

- Most people would bet neutrinos are probably Majorana (seesaw). One cannot just write down a Majorana mass term by hand, gauge invariance requires that it come from a dim-5 operator
  - (LH)(LH)/Λ -> $\nu\nu\langle v\rangle^2$ / Λ
  - Weinberg in the 1970s noted that this is the only possible dim-5 operator; beyond dim 5, lots more stuff
    $$\bar{L}\sigma^{\mu\nu}W^{\mu\nu}He_R,\ \ \bar{L}H\sigma^{\mu\nu}W^{\mu\nu}LH,\ \ (LL)q_R q_R,\ \ ...$$
- That's already not bad: neutrino physics is in position where the GUT physics would have been had we discovered proton decay
  - finally, a higher-dim operator; it is a message from new physics at a very high scale, violating accidental symmetry of the SM; this new scale could explain our origin (leptogenesis)

Yet, it can be even more interesting

- 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?

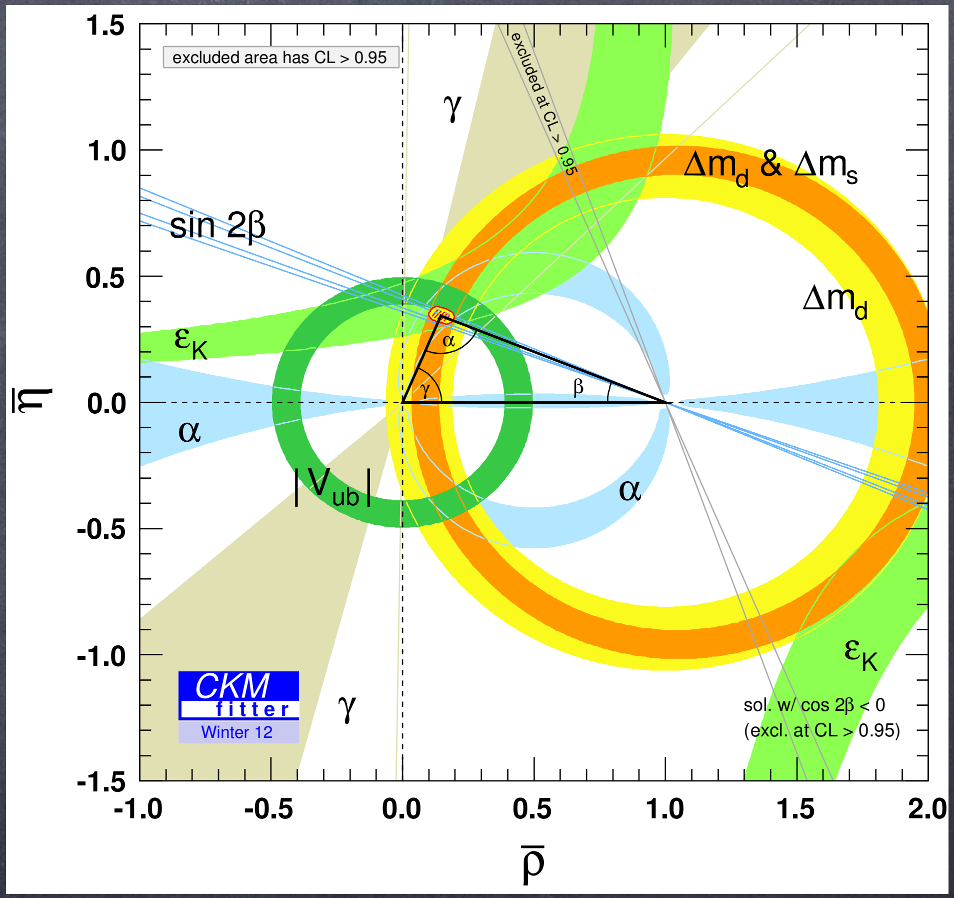
- In the extreme case, new physics could be light, right under our nose, just extremely weakly coupled
- We already search for it everywhere we can, we should definitely look in the place where we found physics beyond the Standard Model
  - Light right-handed neutrino partners
  - Light DM/Dark sectors
  - Hidden neutrino interactions
  - …
- It's an experimental question

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 check if there's additional new physics
  - That's what you are doing!



Need something like this for the neutrino sector

Example: Simplest NSI

- Following Wolfenstein, let's suppose new flavor-changing interactions
  - For illustration, 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 term, can be due to many different kinds of underlying physics

Effect on solar neutrino spectra, D/N signal

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,

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

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.

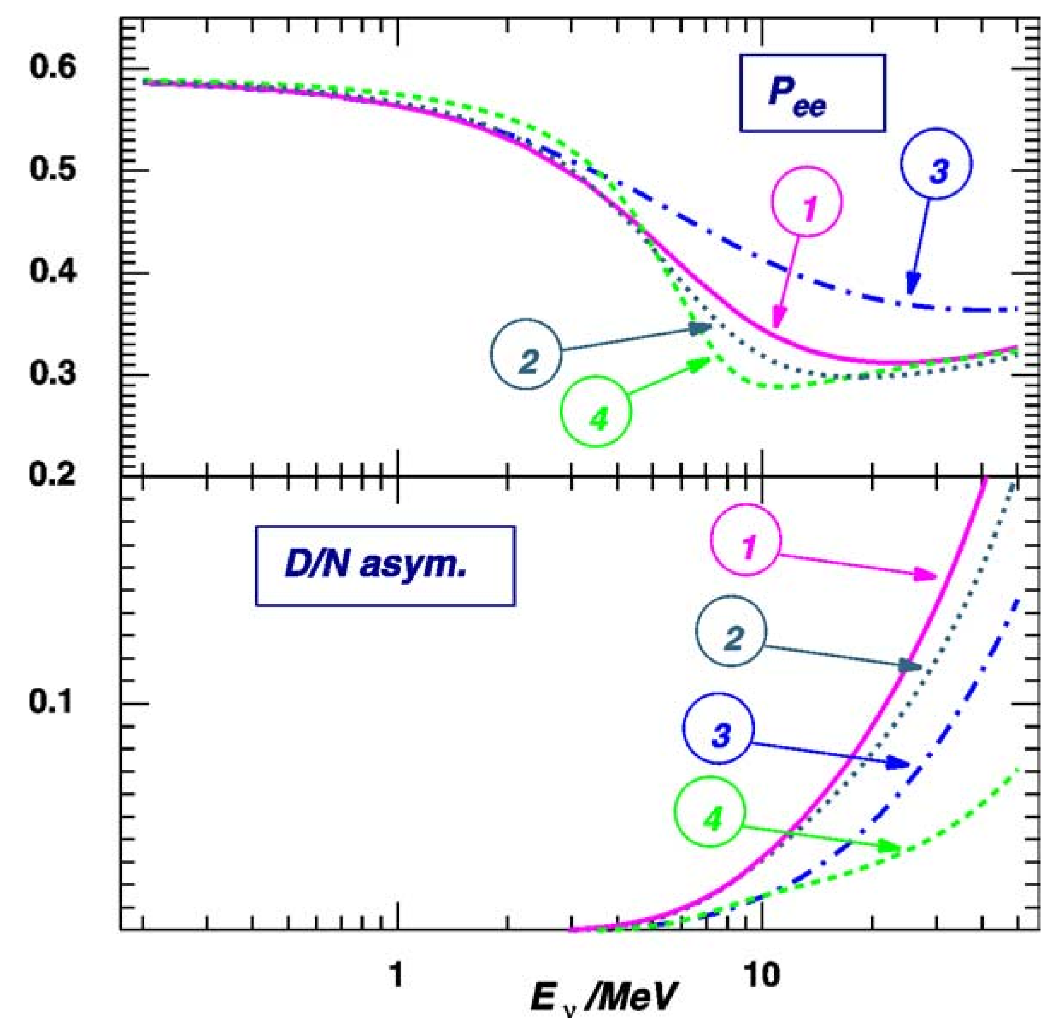
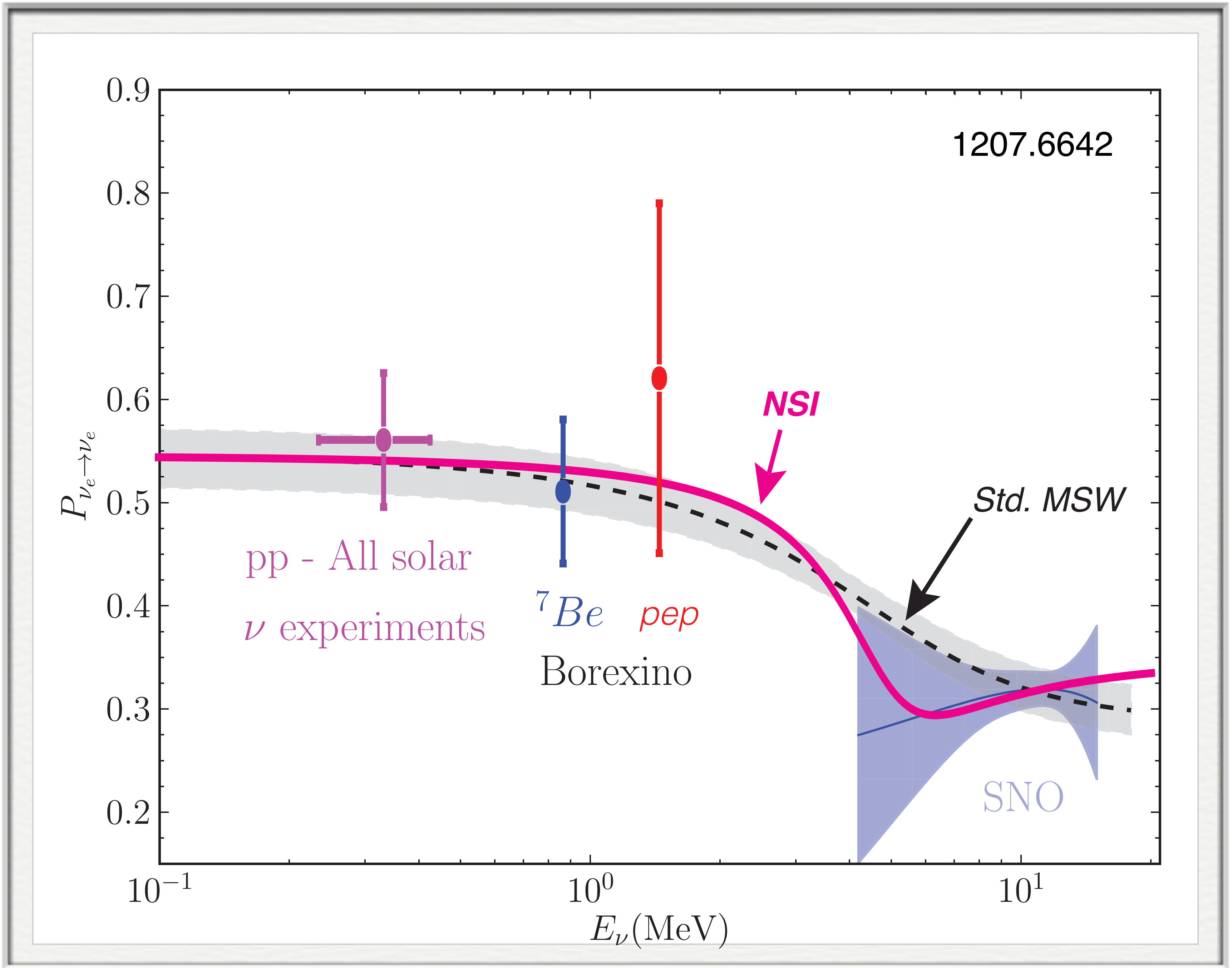


Fig. 1. The electron neutrino survival probability and the day/night asymmetry as a function of energy for $\Delta m^2 = 7 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.4$, and several representative values of the NSI para-

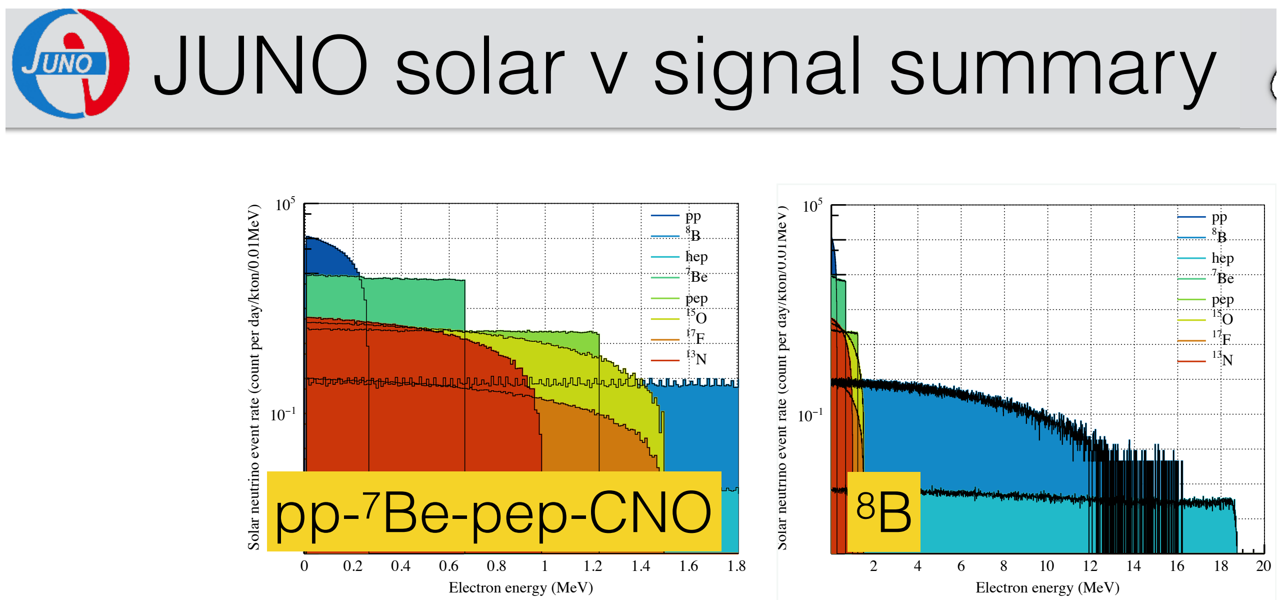
Solar neutrinos, 2012



SNO 3-phase analysis 2011; our fit from hep-ph/1207.6642

Similar story with Borexino, SuperK; see e.g. Palazzo, 2011

JUNO and COHERENT give us brand new tools to address this problem!



what is rate? **is there upturn?**

See talks by Xuefeng Ding on JUNO

See talk by Phil Barbeau on COHERENT

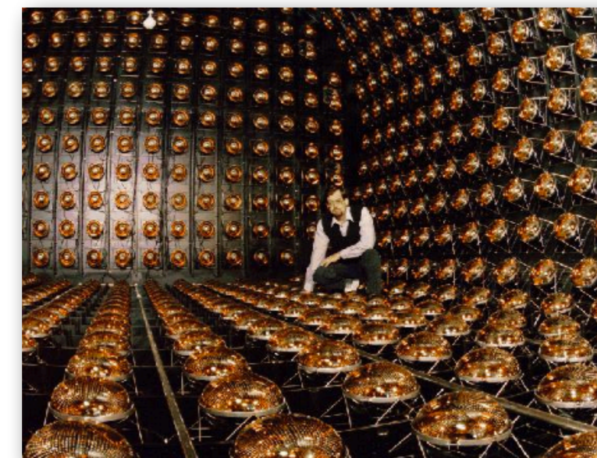
Sterile neutrinos at oscillation experiments

- A 20-year-old mystery

VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

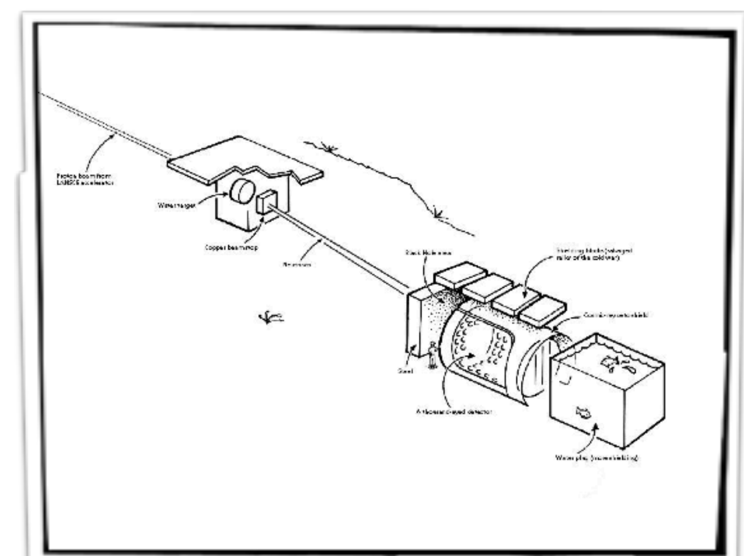
Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility

C. Athanassopoulos,[12] L.B. Auerbach,[12] R.L. Burman,[7] I. Cohen,[6] D.O. Caldwell,[3] B.D. Dieterle,[10] J.B. Donahue,[7] A.M. Eisner,[4] A. Fazely,[11] F.J. Federspiel,[7] G.T. Garvey,[7] M. Gray,[3] R.M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9] H.J. Kim,[8] W.C. Louis,[7] R. Majkic,[12] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] G.B. Mills,[7] R.A. Reeder,[10] V. Sandberg,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] R. Tayloe,[7] G.J. VanDalen,[1] W. Vernon,[2,4] N. Wadia,[8] J. Waltz,[5] Y-X. Wang,[4] D.H. White,[7] D. Works,[12] Y. Xiao,[12] S. Yellin[3]
LSND Collaboration



(Received 9 May 1996)

A search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility b using $\overline{\nu}_\mu$ from μ^+ decay at rest. The $\overline{\nu}_e$ are detected via the reaction $\overline{\nu}_e\, p \rightarrow e^+\, n$, correlated with a γ from $np \rightarrow d\gamma$ (2.2 MeV). The use of tight cuts to identify e^+ events with correlated γ rays yields 22 events with e^+ energy between 36 and 60 MeV and only 4.6 ± 0.6 background events. A fit to the e^+ events between 20 and 60 MeV yields a total excess of $51.0^{+20.2}_{-19.5} \pm 8.0$ events. If attributed to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$



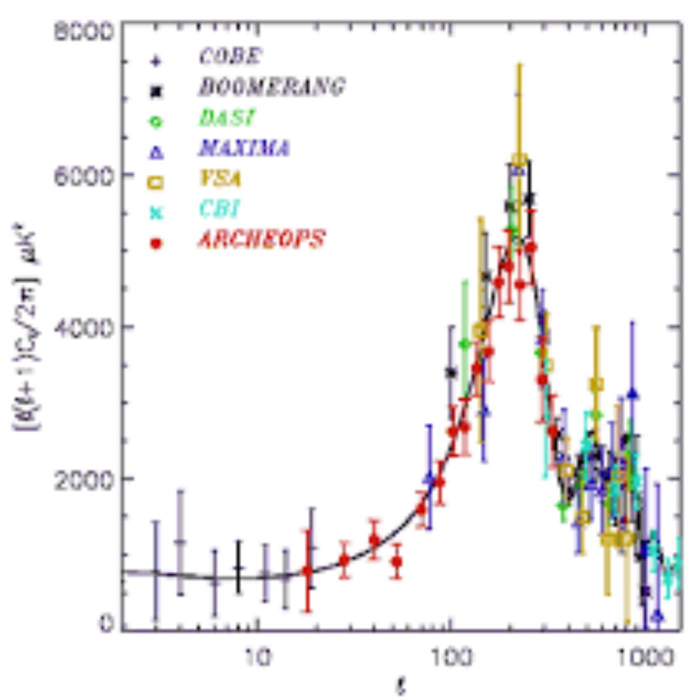
Since then, MiniBOONE, Reactor flux anomaly, gallium source anomaly. See arXiv:1805.12028, talks by Žarko Pavlović, Georgia Karagiorgi for the latest

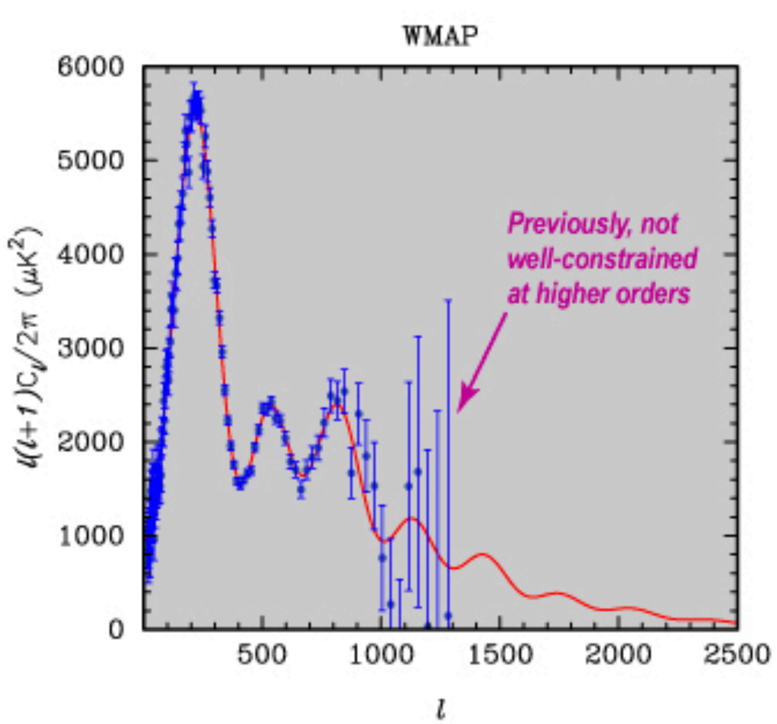
Sterile neutrinos: cosmological problems?

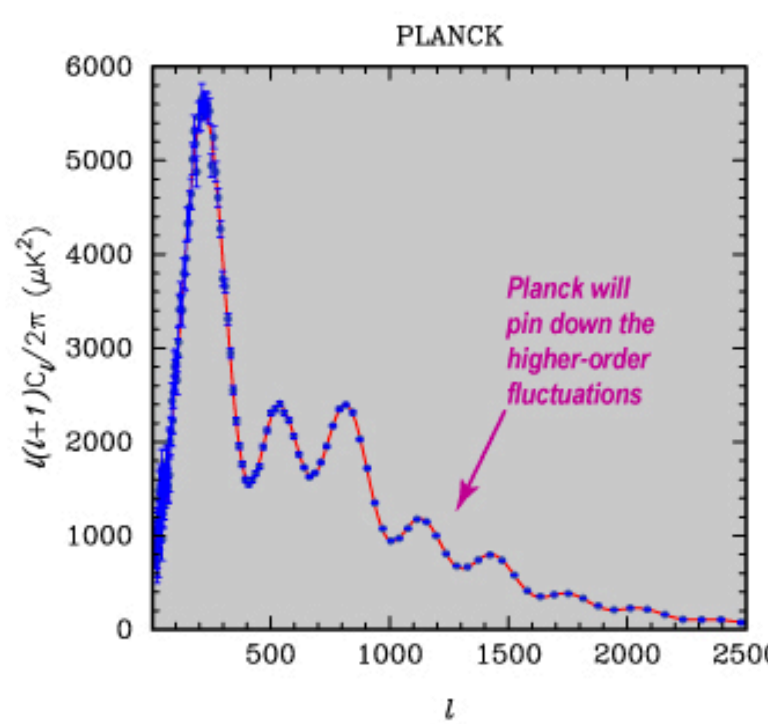
- Recent results from Planck measure relativistic energy density in the universe at matter/rad equality -> CMB decoupling

- Planck 2015 [arXiv:1502.01589] reports $N_{eff}=3.15\pm0.23$ and for the mass $m_\nu < 0.23$ eV

- ***Are sterile neutrinos that the SBN program plans to search for already ruled out by cosmology?***







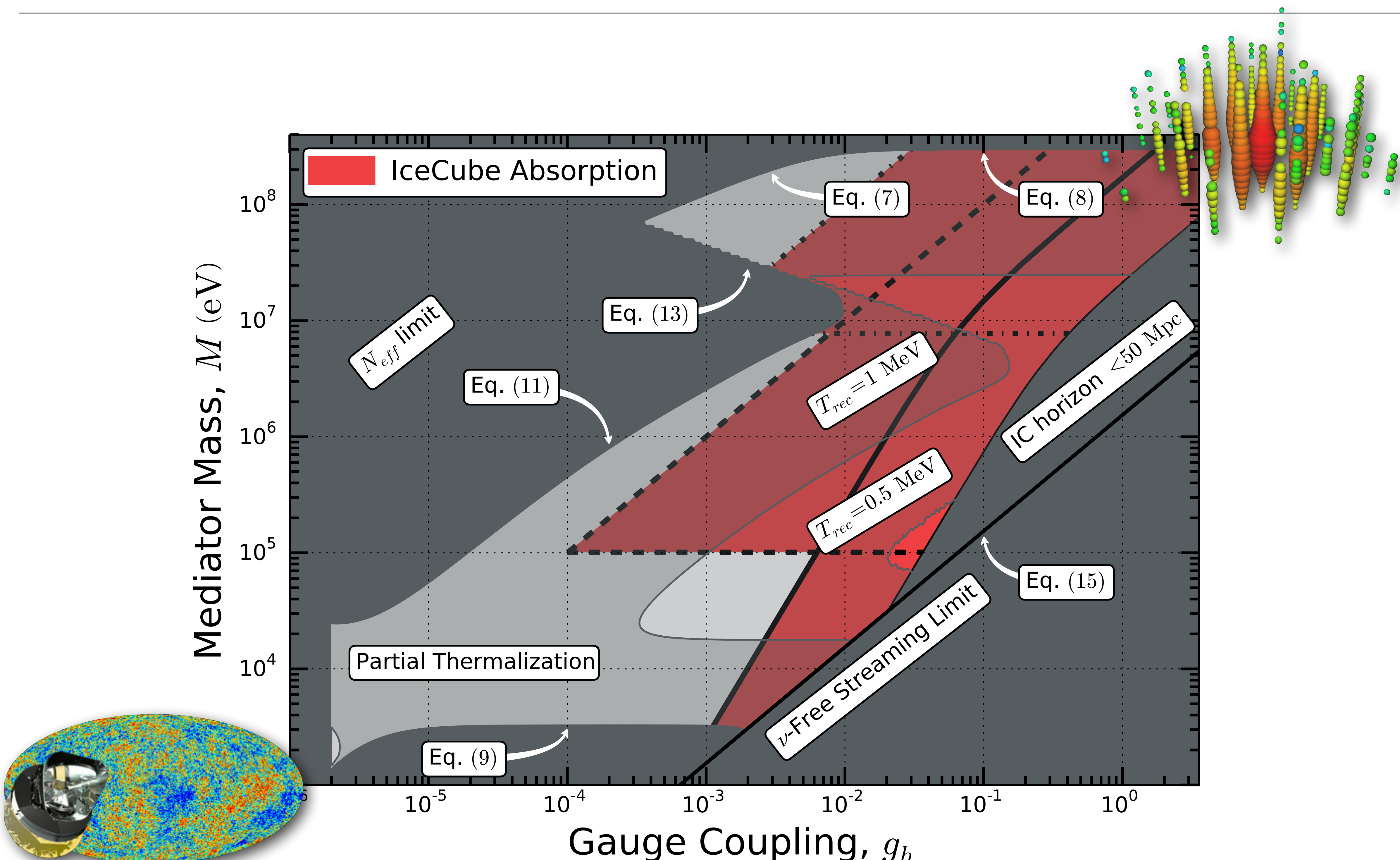
New physics: hidden interactions

- What if sterile neutrinos interacted through their own force?

- An existing small population of hidden neutrinos would induce an MSW potential suppressing mixing between ν_a and ν_h. Could shut off $\nu_a \rightarrow \nu_h$ thermalization.
    - Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

- The physics of this problem is much more subtle than previously believed
    - Numerous physical regimes to consider
        - *Dodelson-Widrow, Quantum Zeno, Resonant, etc*
    - Can flavor recoupling be delayed until T ~ 1 MeV?
        - Yes, in a very specific parameter range
        - Interestingly, a dark force in this range can have a profound impact on Dark Matter structure formation
            - Details in Cherry, A.F., Shoemaker, arXiv:1411.1071
    - ***Completely testable***

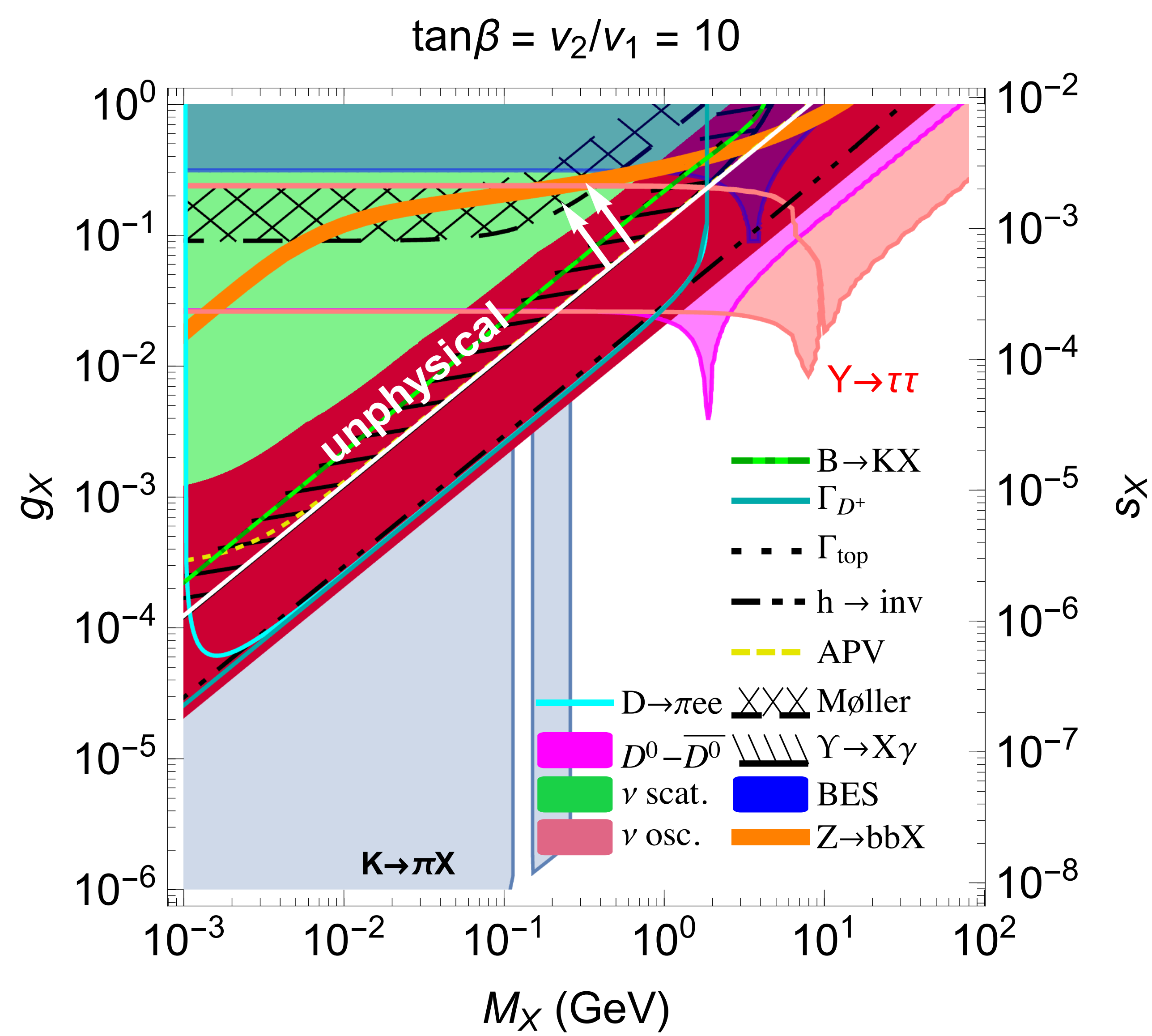
This is an example of a question that requires collaboration of theory and experiment



Cherry, A.F., Shoemaker, arXiv:1605.06506 for details

Here's another example: flavor physics below the Fermi scale

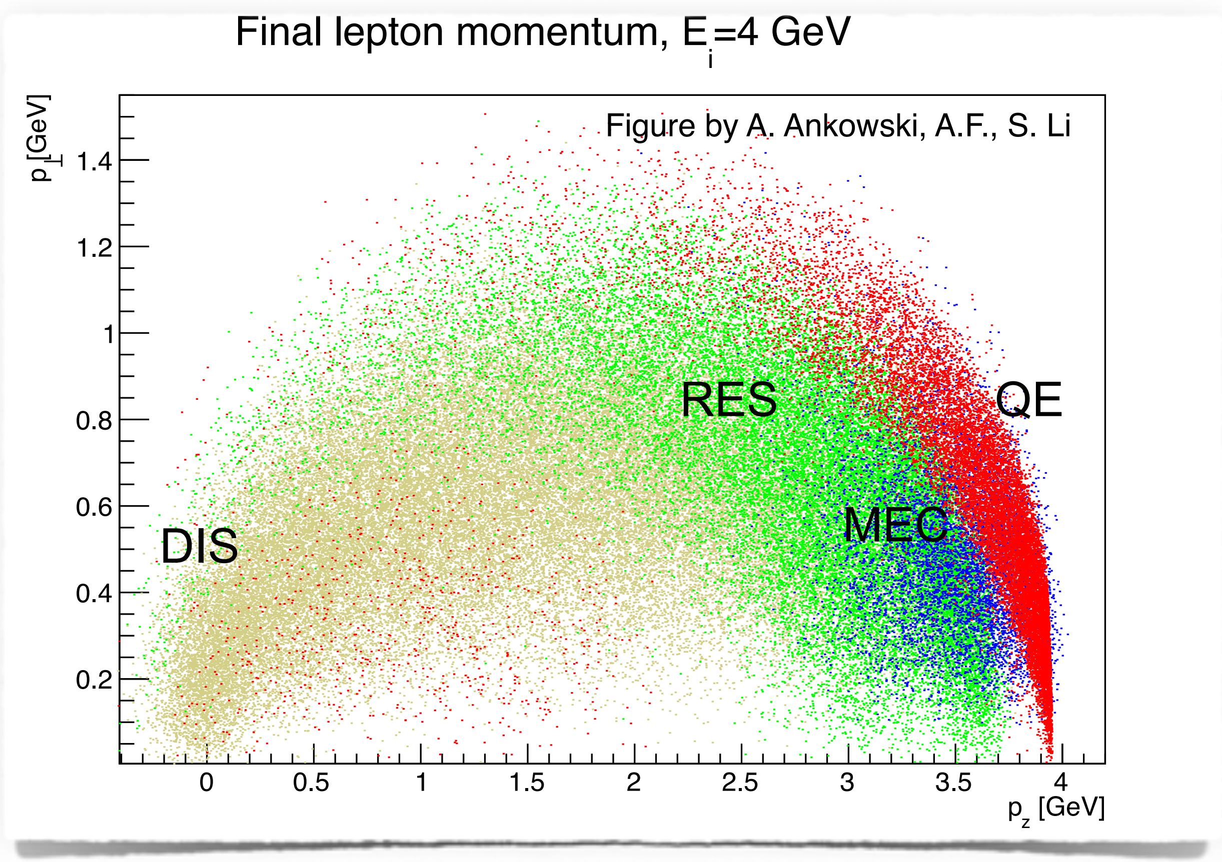
- New physics scenario: weakly gauge the 3rd generation
- Dozens of constraints!
  - From rare meson decays to atomic parity violations, to NSI oscillation effects
- Neutrino physics intertwined with the rest of the field
- See K.Babu, A. F., P. Machado, I. Mocioiu, arXiv:1705.01822 for details



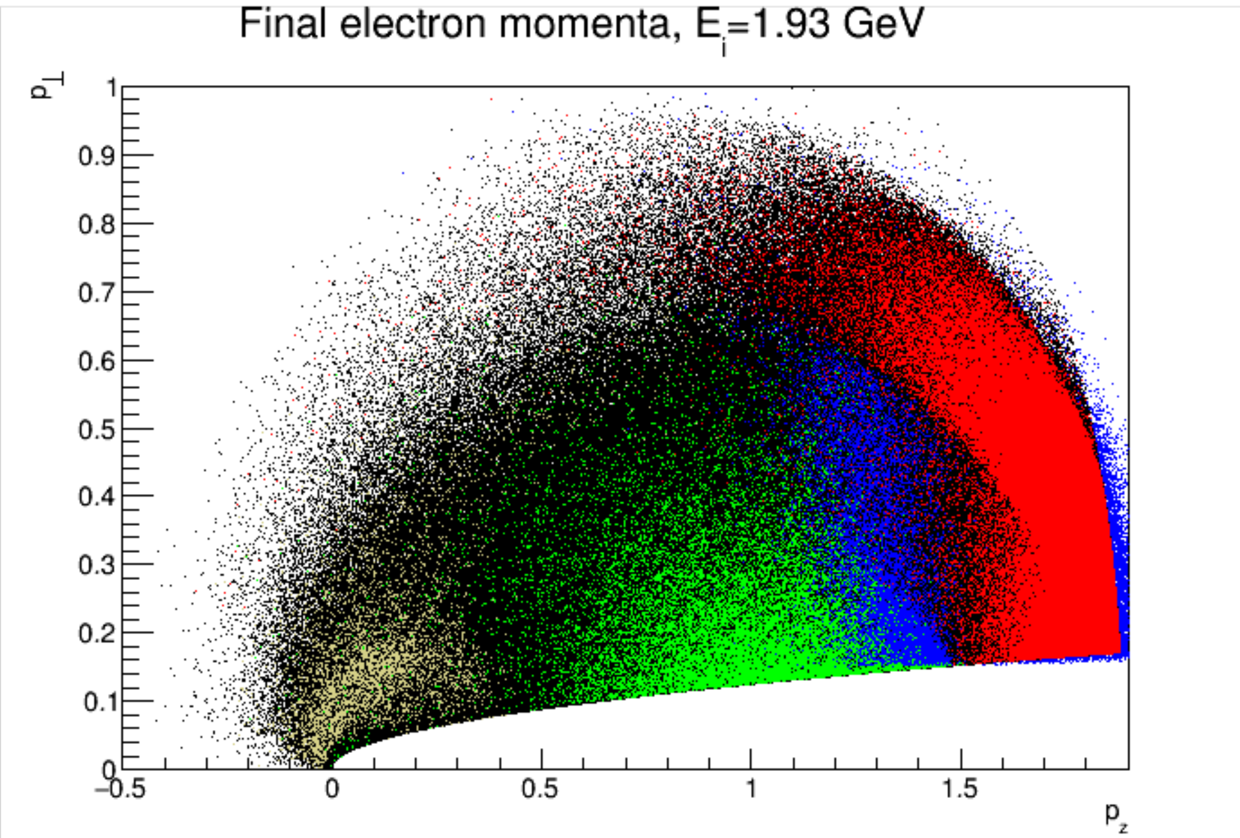
Last but not least, there is the elephant in the room

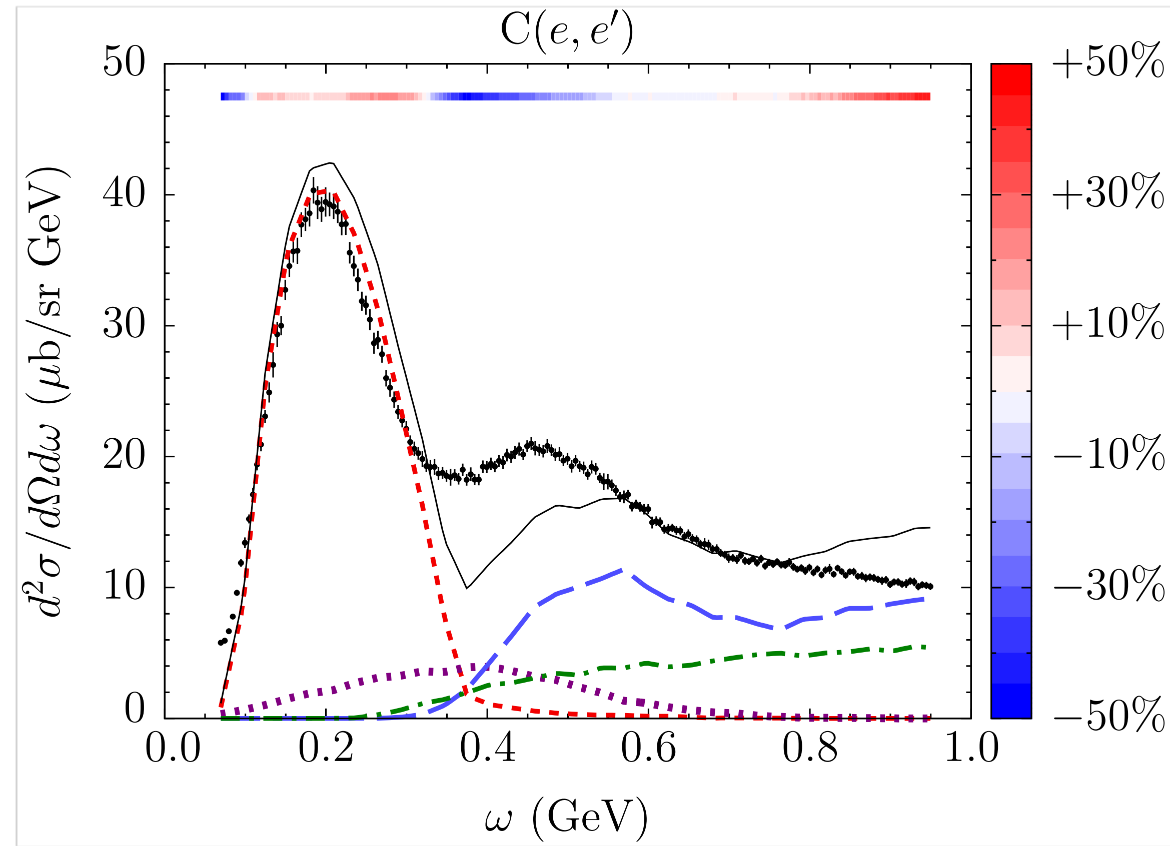
- Modeling of neutrino cross sections at Ev ~1-5 GeV
- See, e.g, the talk by Jorge Morfin

◆ Since ***over 50% of the DUNE events*** have W greater than the Delta mass (W ≈≥ 1.4 GeV), we need to consider what we do(little)/do-not(big) know about this region!



Electron scattering comparison





- Generator predictions show considerable discrepancies with the electron scattering data collected at JLab last year

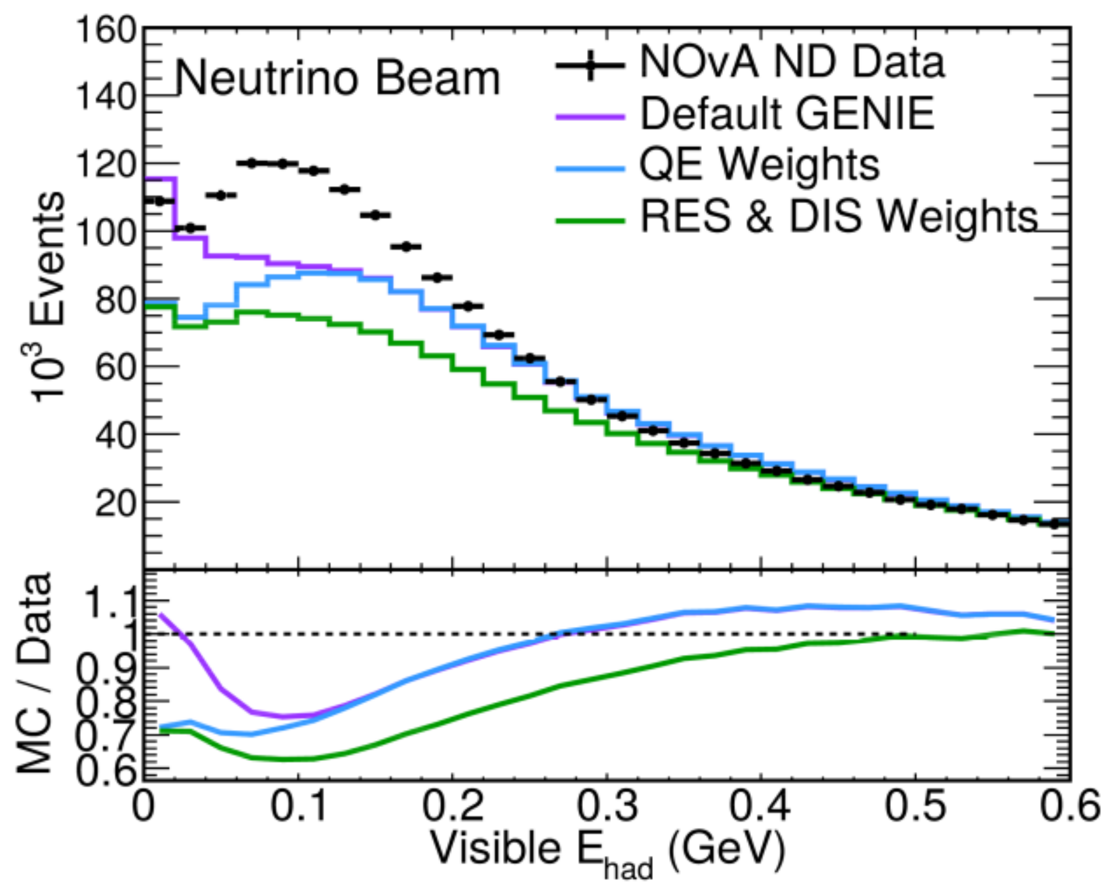
  - Ankowski, A.F., Li, in prep

Also now wealth of neutrino scattering data

- NOvA and MINERvA have collected state-of-the-art datasets

- Required extensive generator "tuning" to obtain agreement

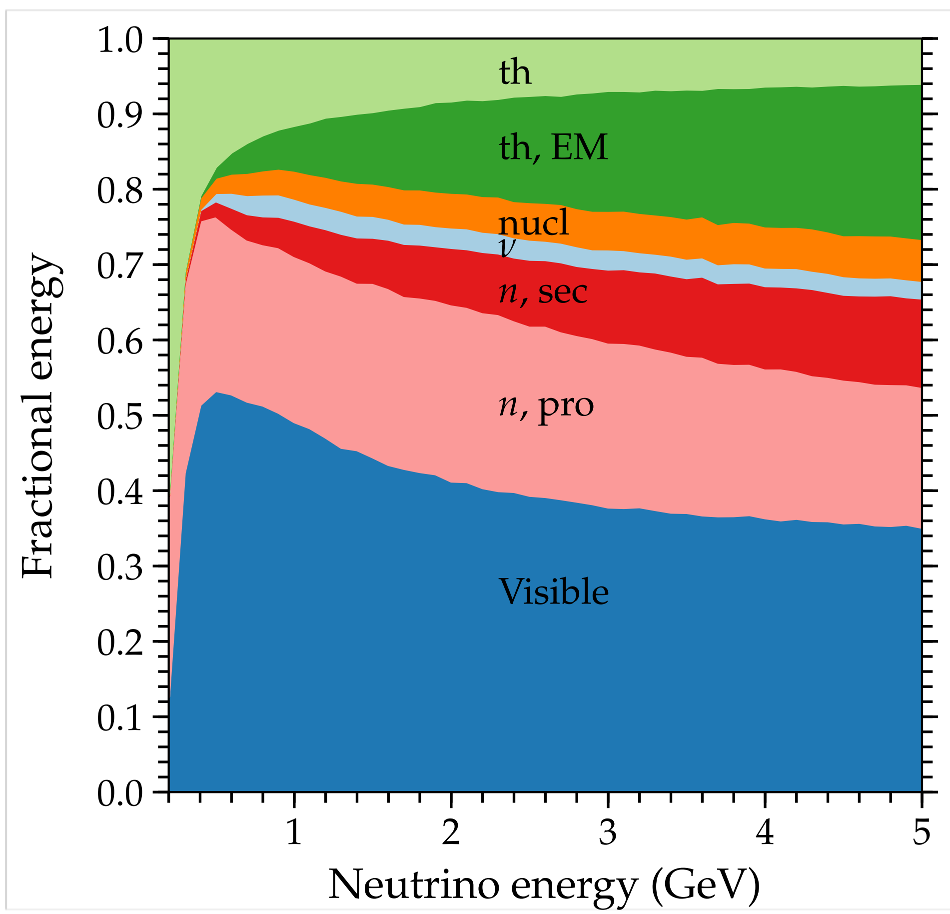
- It is very important to make these results public ASAP, so that a collaborative theory-experimental effort can understand the physics behind these tunes.



[NOvA has cross section measurements in progress which will help address some of these questions:
see M. Judah, talk #71, Mon. 8/13, WG2]

see talk by Jeremy Wolcott

Example question: what fraction of the hadronic energy is visible in DUNE?



- A.F., S. Li, to appear

- This is modeled under default GENIE, v 2.12.8

- We would very much like to repeat this with the NOvA tune!

Conclusions

- Neutrino physics is at the forefront of particle physics: this is where new physics is!
- In 20 years of NuFact meetings, our field moved from the initial discovery phase into today's precision era
  - Early robust observables of factor of 2 or 3 became precision goals of 5-10% or less
- Lots of talks heard here. Rapid progress, vast amounts of new data, ambitious goals
- To succeed in the new precision era, the neutrino community must develop close collaborations between theory and experiment