Secluded Neutrinos: From Planck to Icecube

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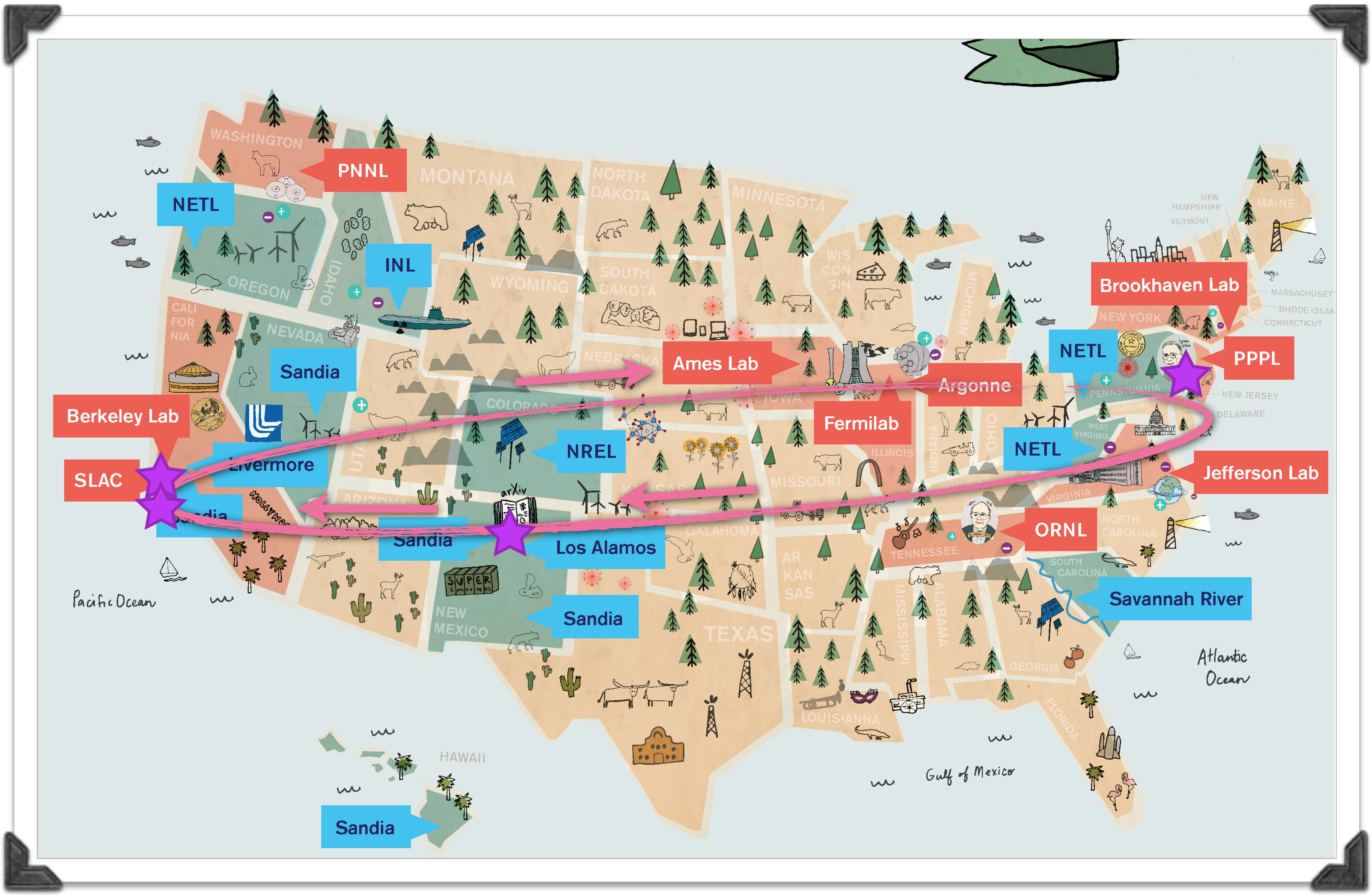
SLAC

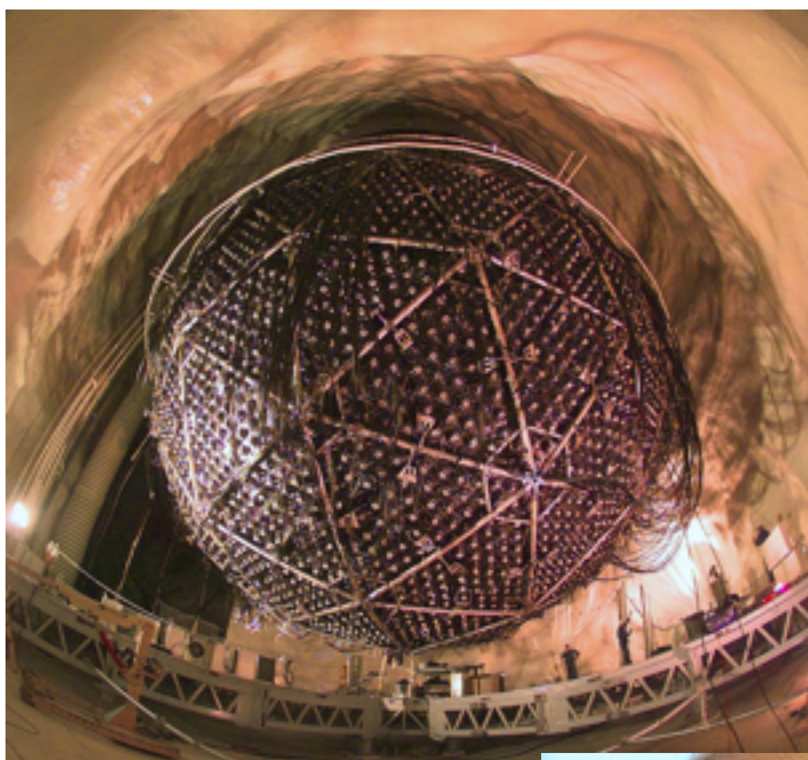
Bay Area Particle Theory Seminar

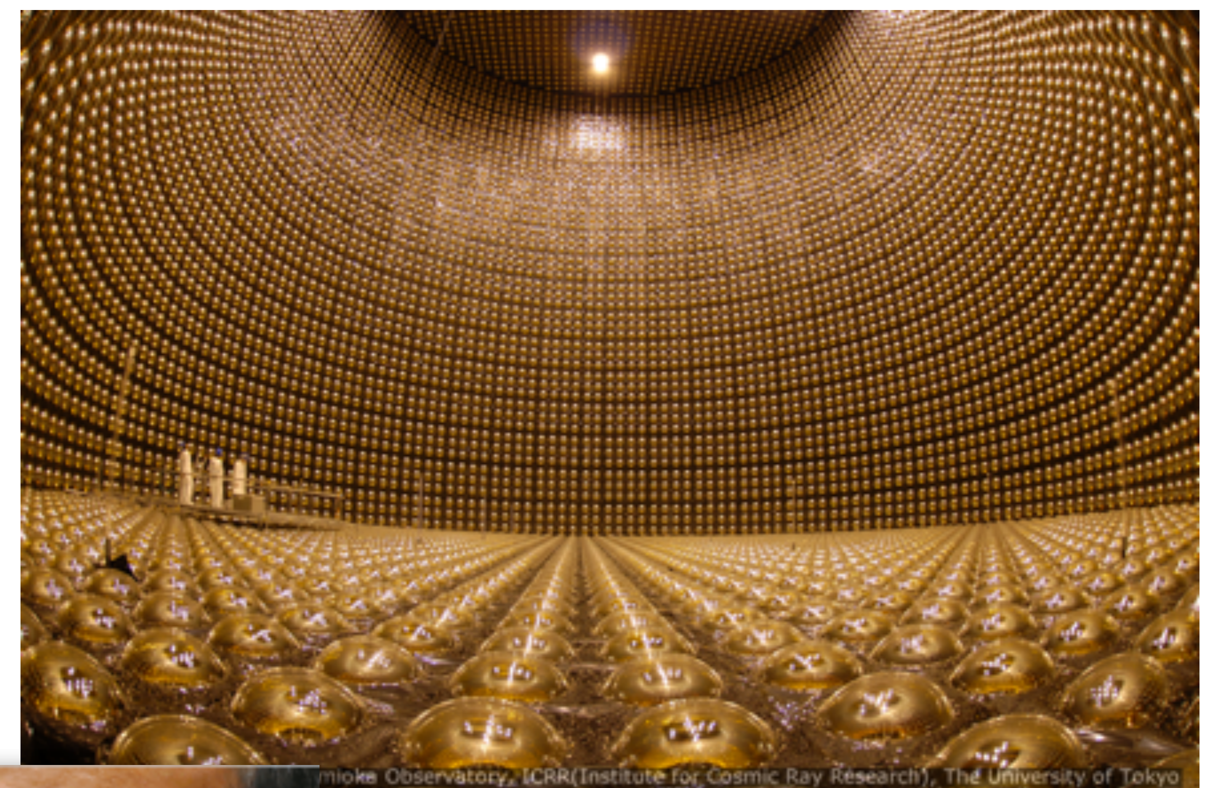
Oct 9, 2015

An interesting way to cross the Bay



This is a good week for neutrino physics





How is this year’s prize different from 2002?

- In 2002, the prize was given to Ray Davis (Homestake) and Masatoshi Koshiba (Kamiokande) for "for pioneering contributions to **astrophysics**, in particular for the detection of cosmic neutrinos".

- This time, the prize is explicitly for proving that neutrinos oscillate and hence have masses. This year’s prize is for neutrino **particle physics**.

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

A number of “problems” (solar) or “anomalies” (atmospheric, LSND)

The Standard Model reigned

hep-ph/
9810316

SLAC-PUB-7930

THE STANDARD MODEL AND WHY WE BELIEVE IT * †

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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

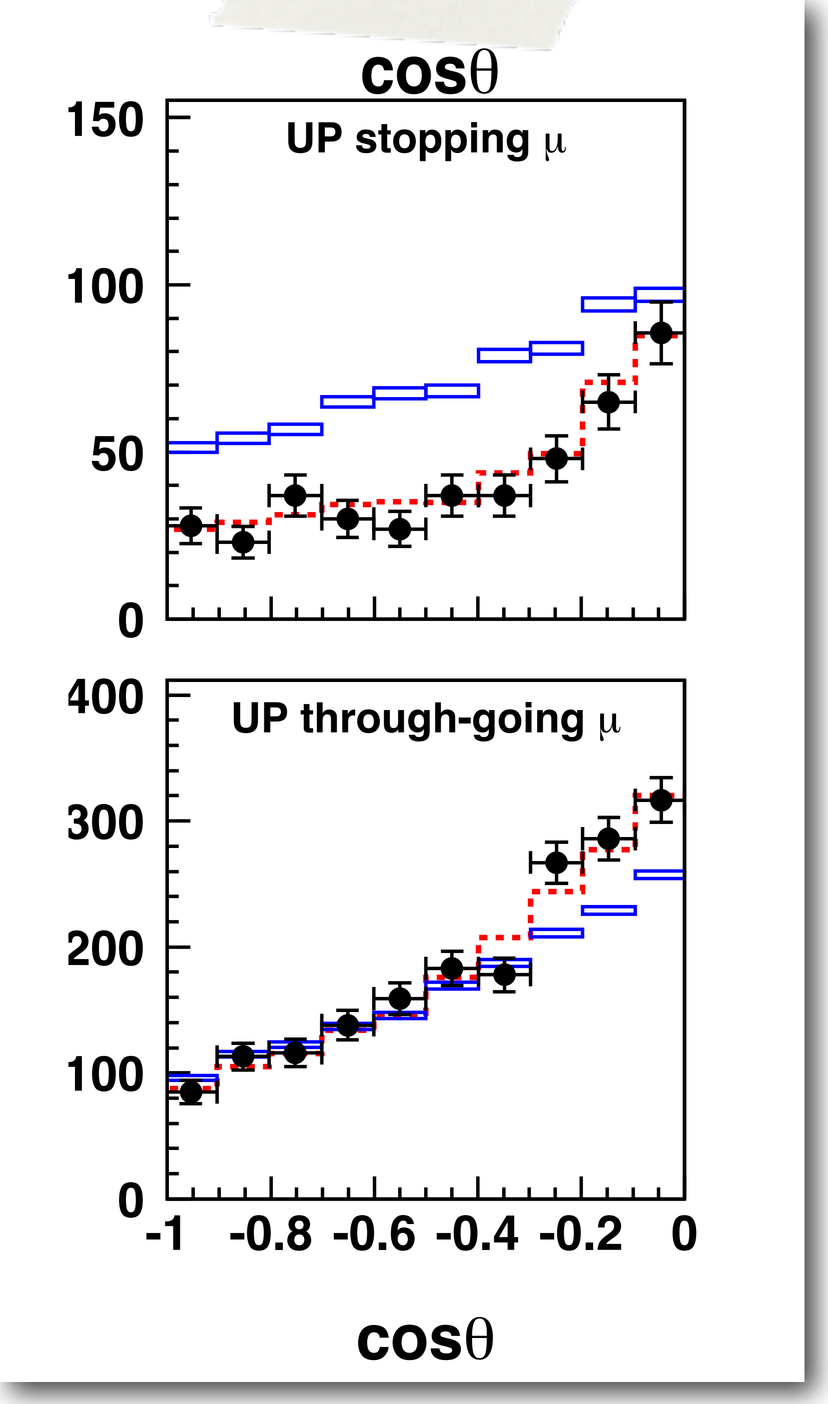
The Standard Model (SM), which combines the $SU(2)_L \times U(1)_Y$ Glashow - Weinberg - Salam theory of electroweak interactions [1] together with Quantum Chromodynamics,[2] constitutes a remarkable achievement. The formulation of the theory as a renormalizable quantum theory preserves its predictive 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.

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

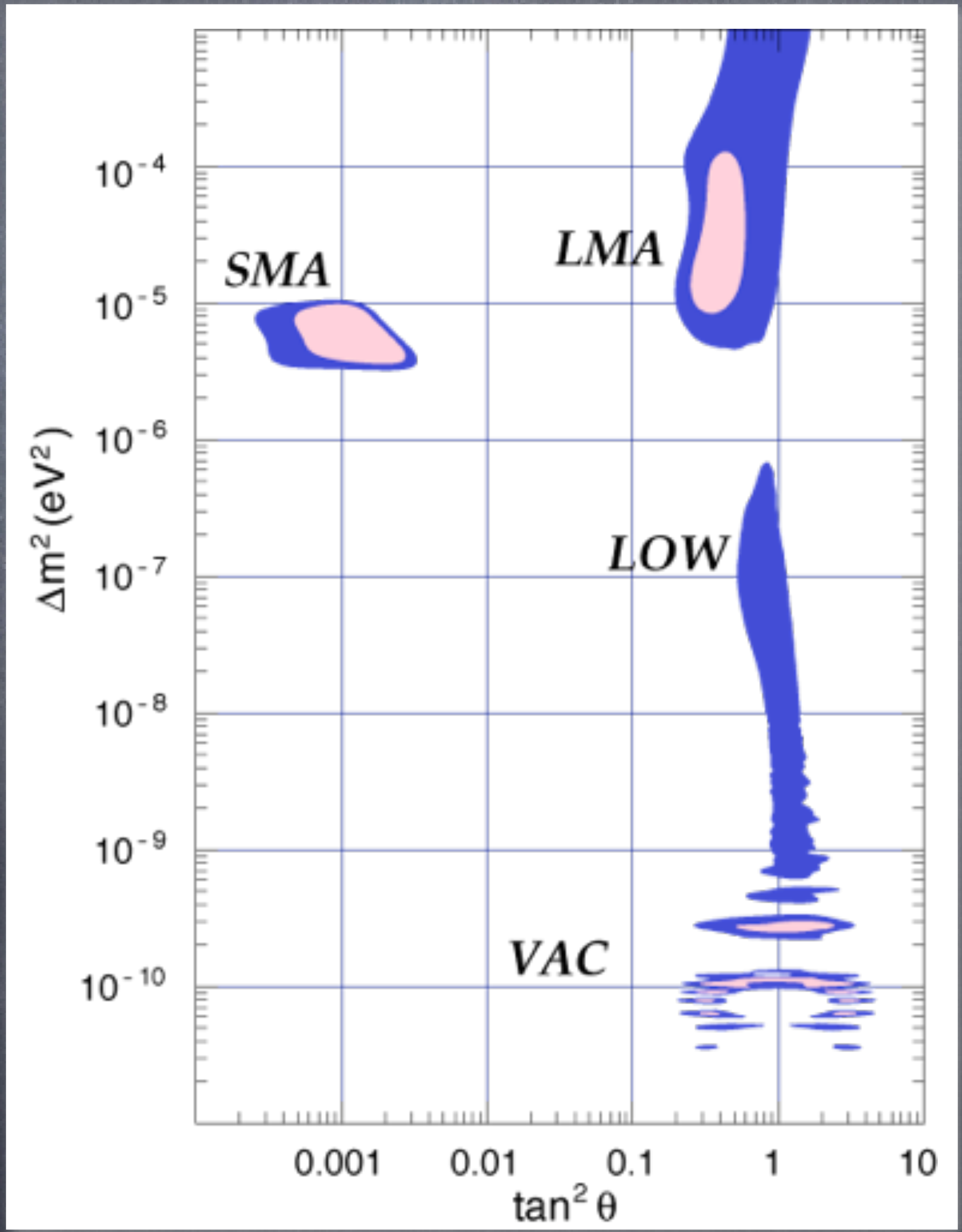
- The first neutrino oscillation effect was observed in 1968, by the Homestake experiment in the US
  - 100,000 gallons of dry-cleaning fluid (tetrachloroethylene) 4,850 feet underground. Every few weeks, extracted Ar, formed by

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

  - Expected ~ 51 atoms of Ar (solar model calculation by John Bahcall), but Davis saw only ~ 17
  - In 2002, Ray Davis received his Nobel prize (and Bahcall should have!)
  - The Homestake mine is now a science lab, hosting LUX and Majorana demonstrator and getting prepared to host DUNE

Solar neutrinos, early 2000

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

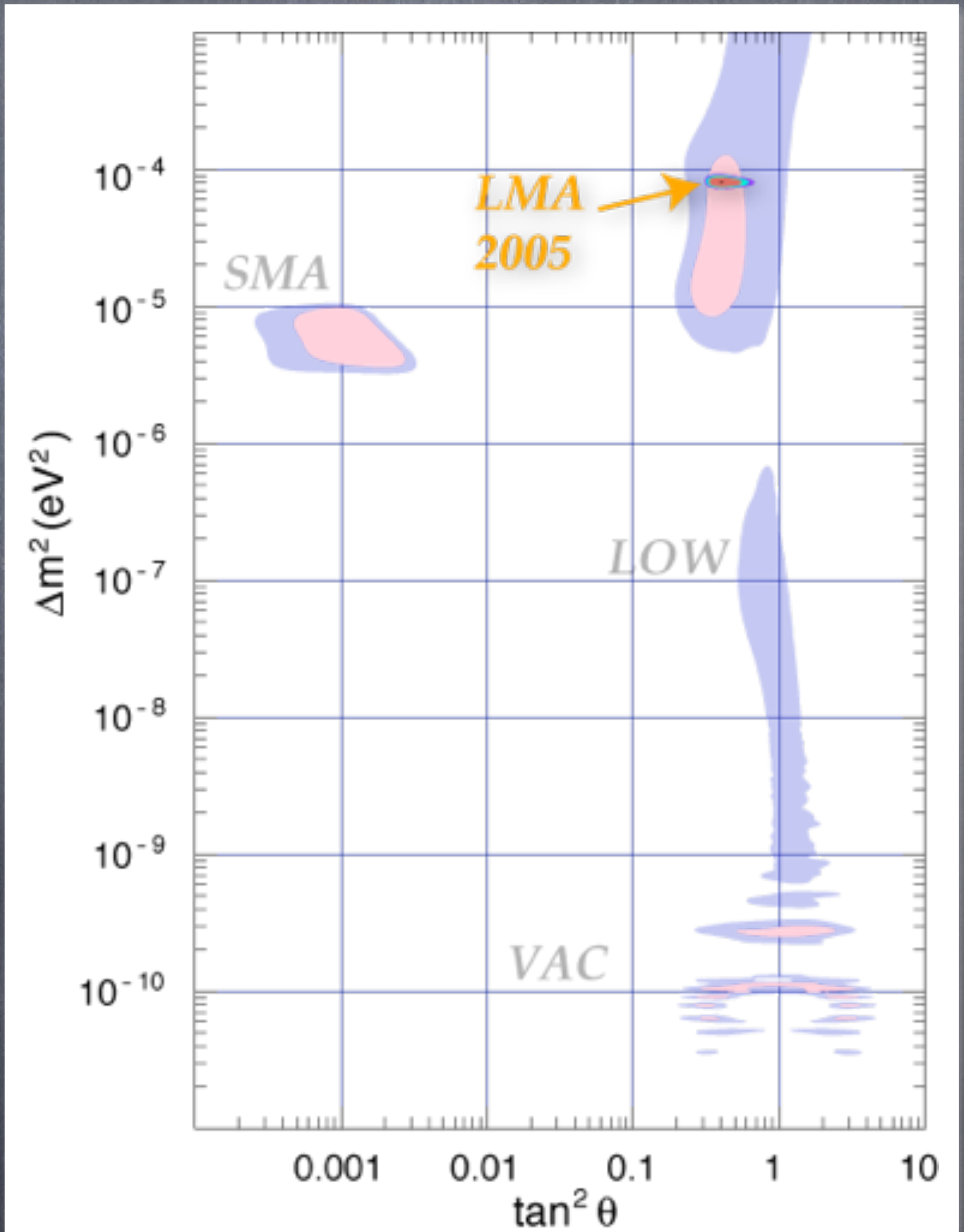


A. de Gouvea, A.F., H. Murayama, PLB 490, 125 (2000)
A.F., PRL 85, 936 (2000)

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
- Ironically, the mixing angle is large

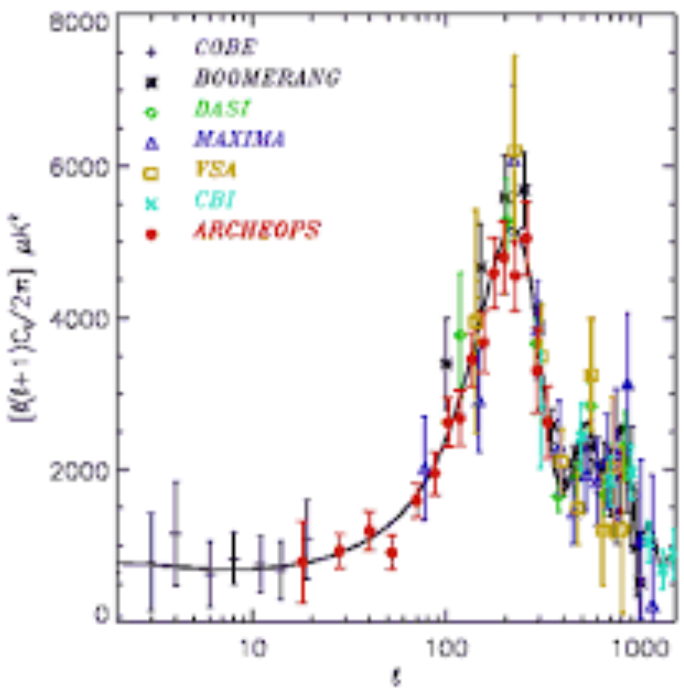
KamLAND Collab., PRL 94, 081801 (2005)
SNO Collab., PRL 92, 181301 (2004)

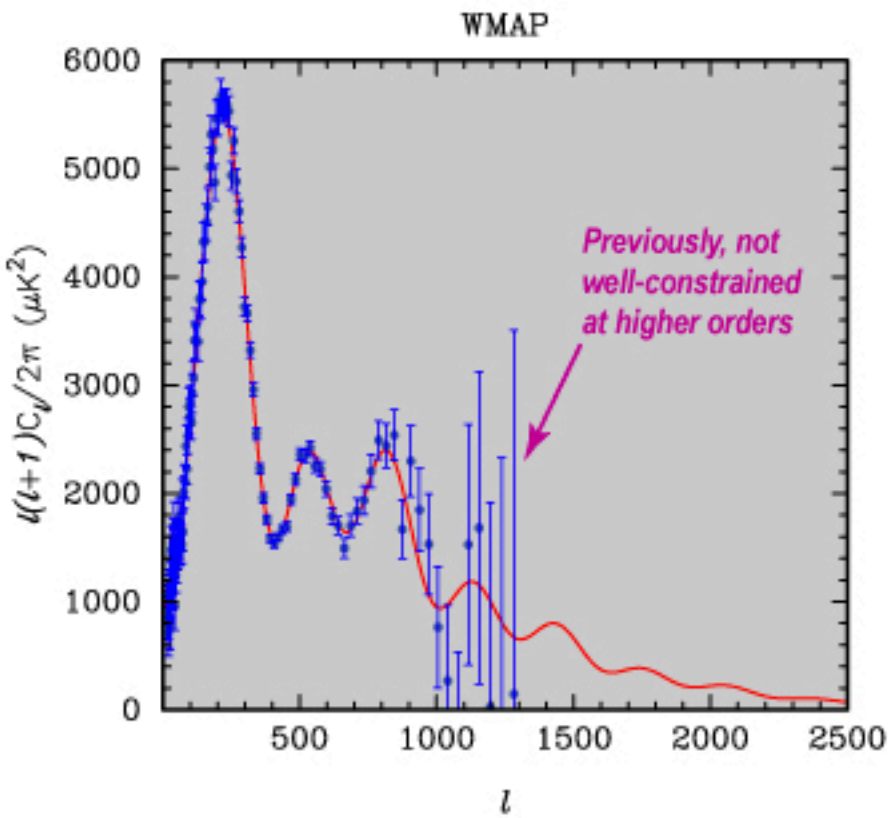


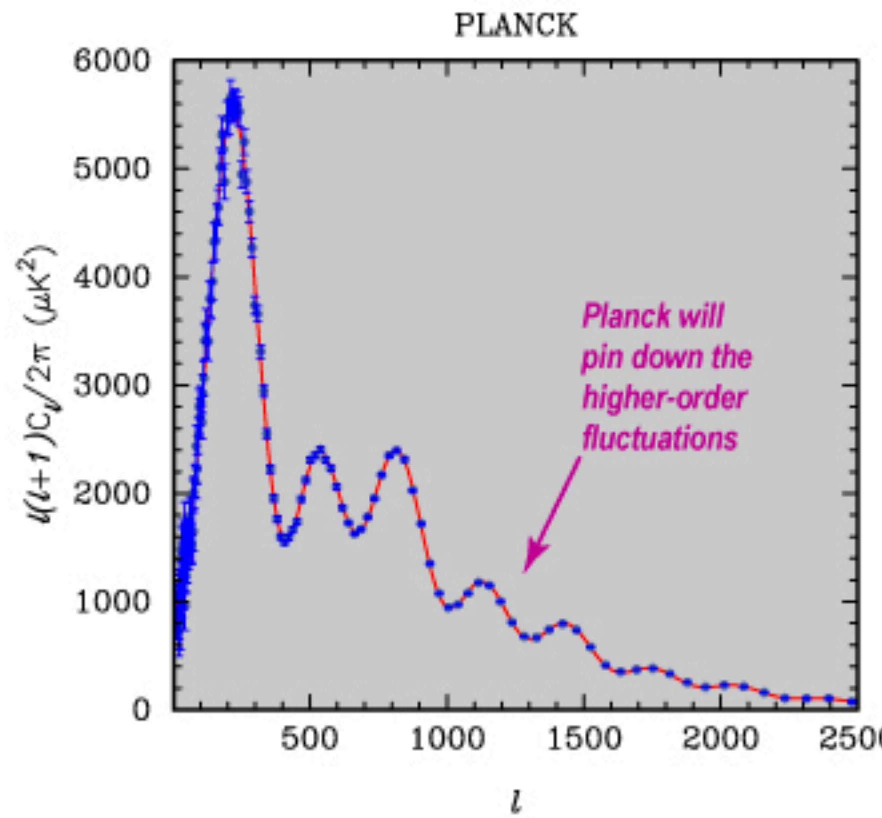
Fast-forward to now

- Oscillations have been conclusively measured in solar, atmospheric, beam and reactor neutrinos.
- This includes energy and distance-dependent smoking gun features.
- All three angles are now measured.
    - There was a suspicion that theta13 could be vanishingly small, but thanks to recent results from Daya Bay we know it is quite large.
    - The flavor structure of the lepton sector looks very different from the quark sector.
    - What was a discovery a dozen years ago is now entering phase 2, precision stage measurements. Just like cosmology over the same time period.

Compare to progress in CMB measurements

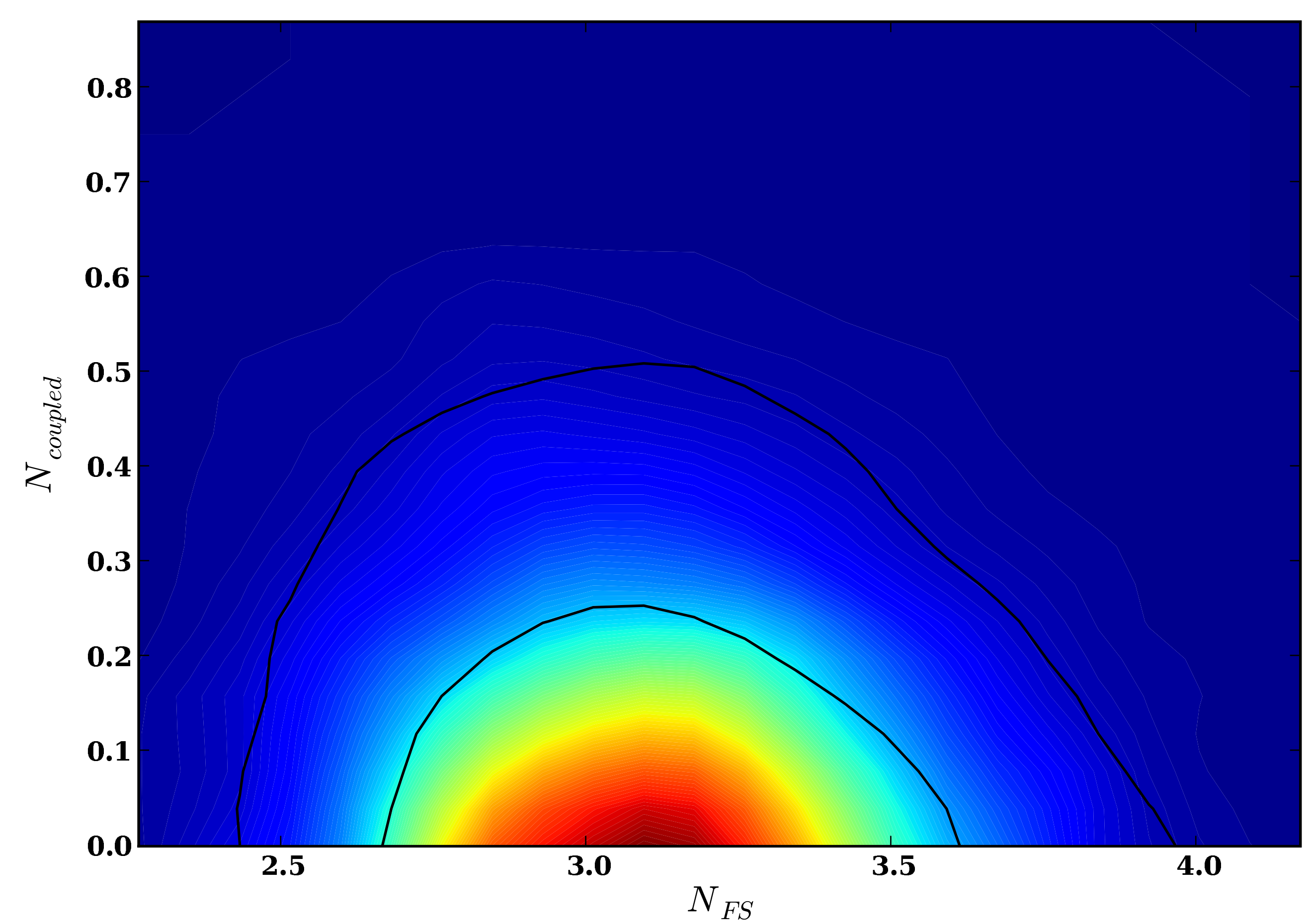






Relic neutrinos: cosmological data

- While we have not detected relic neutrinos directly, we clearly see their presence in the CMB data. Can't fit the data without them.
- Planck 2015 [arXiv:1502.01589] reports $N_{eff}=3.15\pm0.23$ and for the mass $m_\nu < 0.23$ eV
- *Not only we measure that there are relic neutrinos, we can even see their inhomogeneities and detect their free-streaming behavior*



Friedland, Zurek, Bashinsky, 0704.3271
PLANK forecast for free-streaming/coupled neutrino sensitivity

More neutrino astronomy!

- Meanwhile, there have been other major discoveries in neutrino astrophysics. In the last two years, IceCube has been reporting UHE neutrinos of ~ PeV energies, likely coming to us from cosmological distances.
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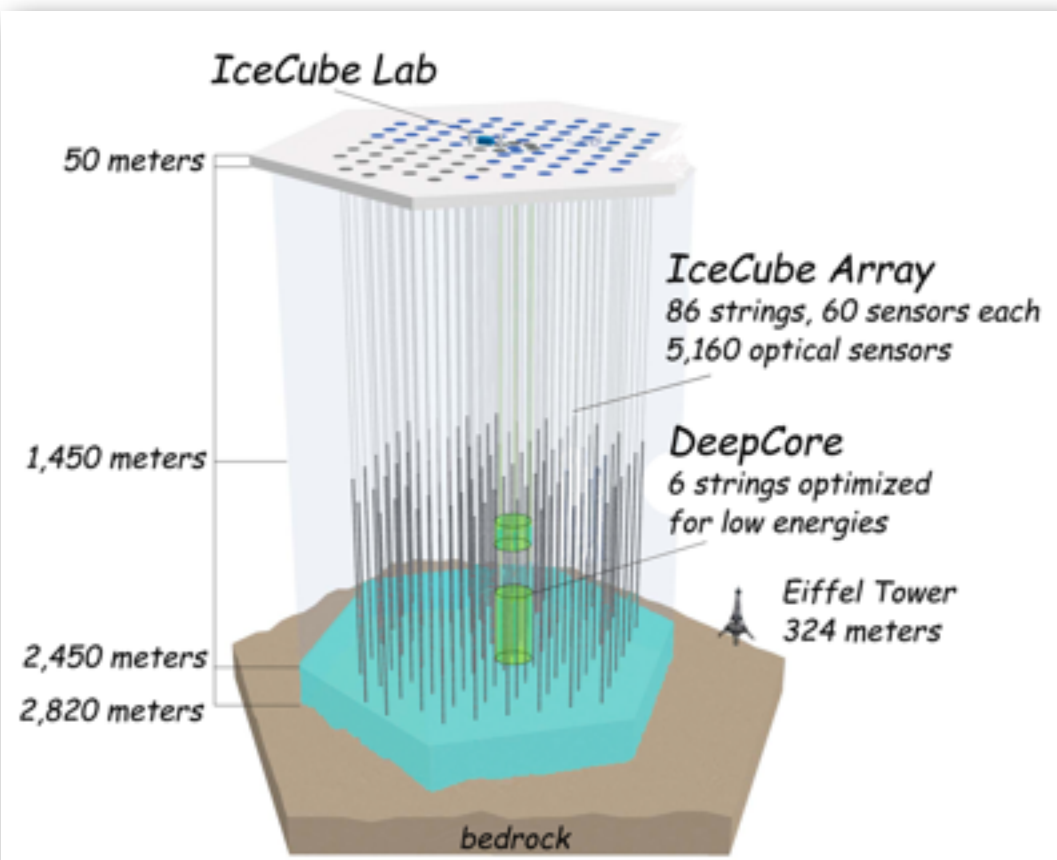
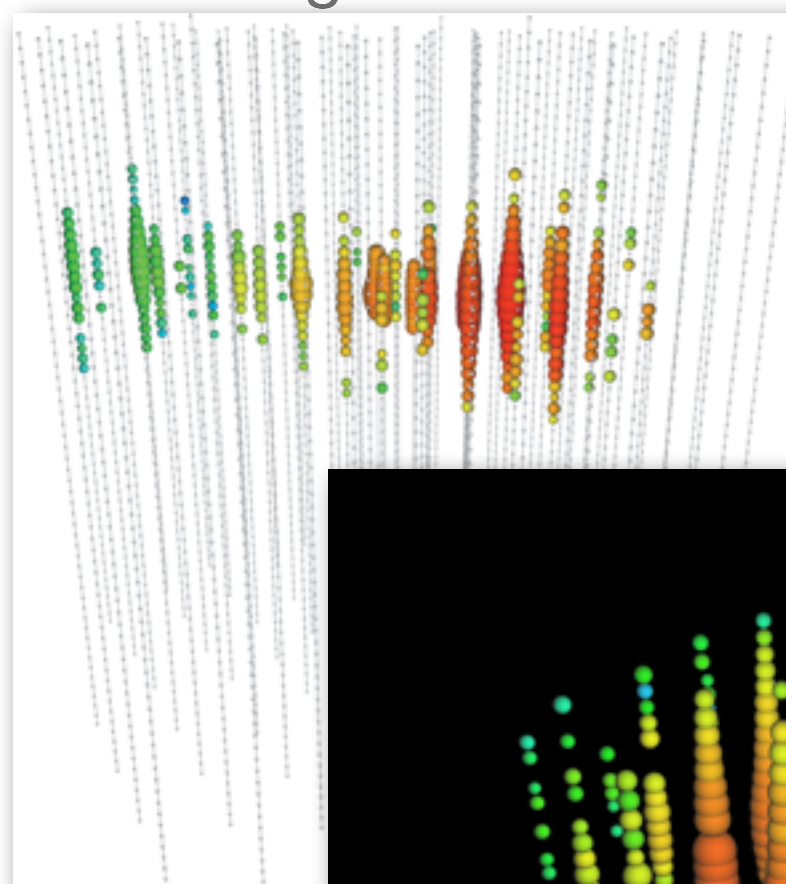
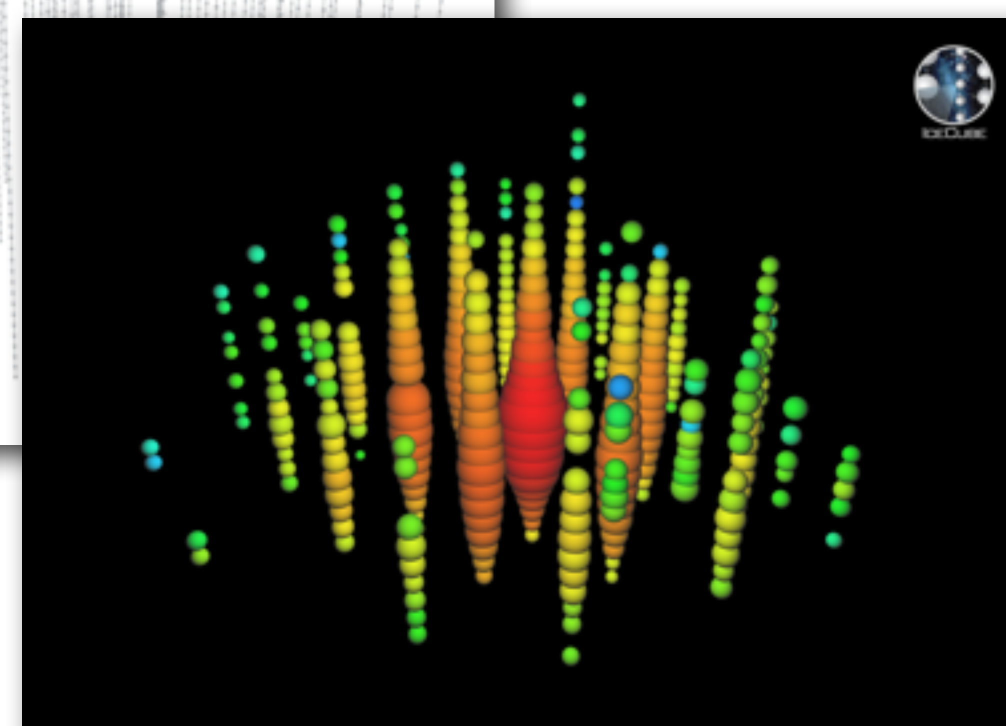






Digression: WHY does the SM work so well?

- Not a simple question. The answer is: Nobody knows for sure. It's a mystery. Maybe a curse.

- Perfectly sensible to suppose that the SM is not an ultimate theory, but embedded in a more complete framework.

- Taking the SM as an effective theory, great many effective higher-dim operators. Yet, somehow, everyone we could probe one, it wasn't there. From K-Kbar mixing, to $\mu \to e\gamma$, to proton decay.

Digression: WHY does the SM work so well?

- Alternatively, one could have additional light fields.
  - For example, the smallness of the theta parameter is attractively explained by a new light field, axion.
- Once you have these new fields, you could have new couplings to the SM fields. E.g, axion-photon coupling. Or even dim-4 operators, such as the Higgs portal (mixing) or dark photon KM portal.
- Again, the results of all such searches have so far been negative. If there is a light sector, it must really be well secluded.

Neutrino mass

- Now, the neutrino mass measurement breaks this mold. Either there is the first measured dim-5 operator (Weinberg) or new light states (right handed neutrinos). Or both.

- If neutrino mass is purely Dirac, RH neutrino states exist and they are paired up with the LH ones. In the simple see-saw mechanism, they are up near the GUT scale. Anything in between is possible. Experimental question.

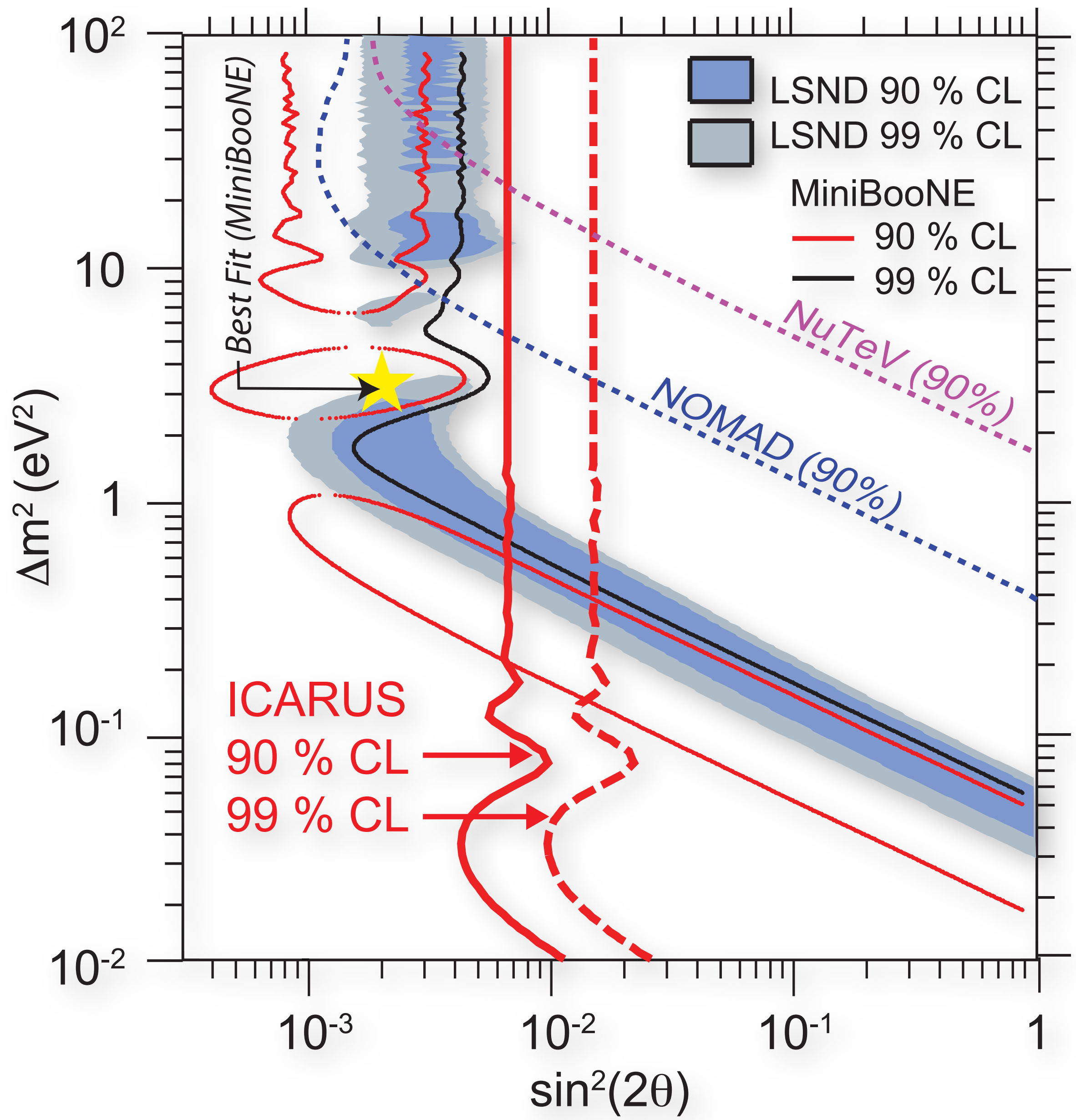
- What about that old LSND anomaly? 3.8 sigma

- MiniBooNE was supposed to test it. After a decade of running, with one detector, it didn't resolve it. Rather, it has its own anomalies (also about 4 sigma).

What do neutrinos tell us about particle physics?

- Not obvious. We don't presently understand. But it would be great to find out.
  - Neutrino masses are in the category of "who ordered that?" physics.
  - Many years ago, lots of new "elementary" particles seemed like a distraction from the main line of theoretical thought, to unify gravity and electromagnetism.
  - Very smart people ignored this distraction. Others paid attention and pursued it. Turned out, E&M was unified with the weak interaction.
    - There is no guarantee that neutrino masses will turn out the same way. We will know once we explore them!

Present-day status of the anomaly?

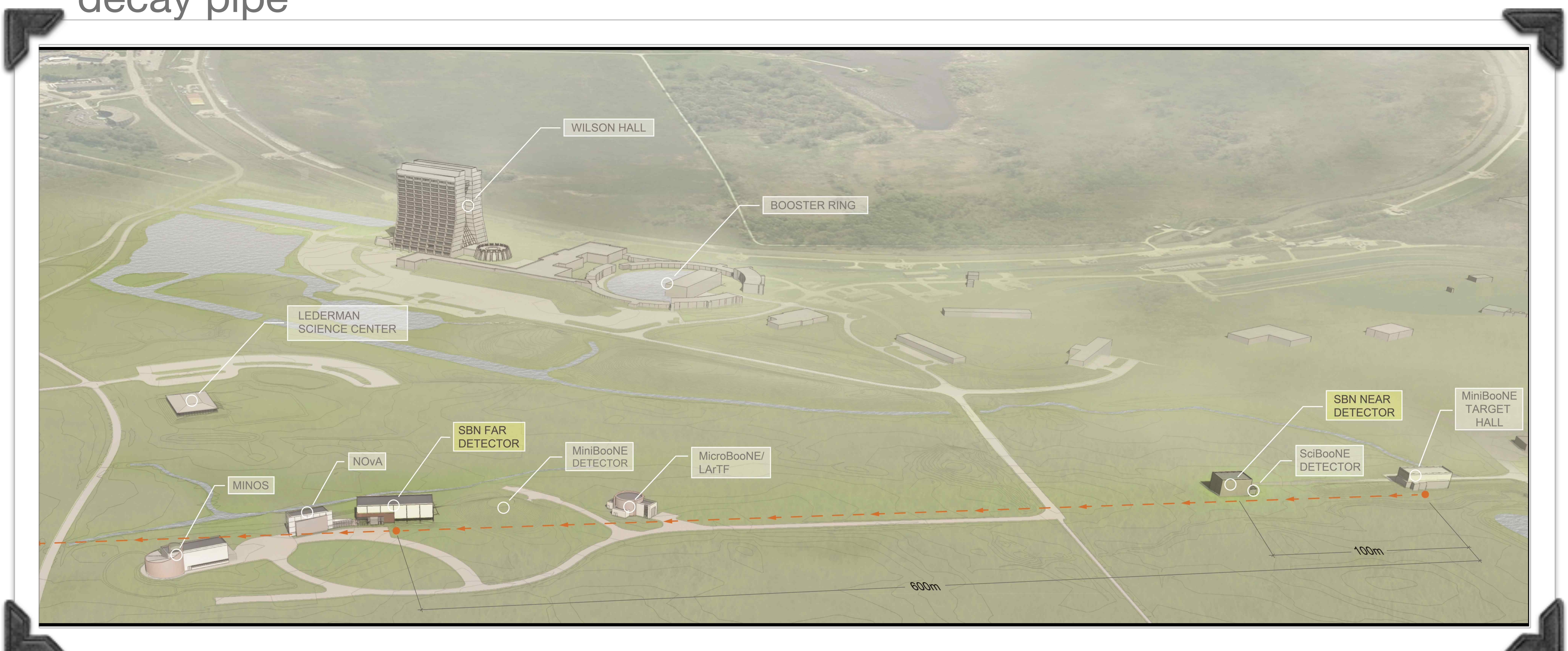


ICARUS, 1307.4699

Short-baseline oscillations

- Fermilab is planning is in the process of developing and launching its Short-Baseline Neutrino Oscillation Program (2018)

- 3 detectors in the Booster Neutrino Beam, at different distances from the decay pipe



What about PLANCK??

- Planck 2015 [arXiv:1502.01589] reports N_{eff}=3.15±0.23 and for the mass m_ν < 0.23 eV

- *What happens if the sterile neutrino interpretation of the short-baseline anomalies is confirmed?*

- *That would imply new physics!*

Sterile neutrino production in the early universe

- Oscillations + collisions!

- SM neutrino decoupling from electron-positron plasma: σ n ~ expansion rate

$$G_F^2 T^2 T^3 \sim T^2/M_{pl} \to T_{dec}^{SM} \sim (G_F^2 M_{pl})^{-1/3} \sim 2 \text{ MeV}$$

- If sterile neutrinos are brought into equilibrium with active earlier, dangerous!

- Oscillations alone:

$$P(\nu_a \to \nu_s) = \sin^2 2\theta_{as} \sin^2(\Delta m^2/4Et) \to (1/2)\sin^2 2\theta_{as}$$ for t> 4E/Δm^2

- Collisions are flavor-sensitive; project the state on the |e>, |s> flavor basis state, allows oscillations to restart. Rate of flavor change: $G_F^2 T^2 T^3 (1/2) \sin^2 2\theta_{as}$

Dolgov & Barbieri (1990) + hundreds more since

- Equilibration: $G_F^2 T^2 T^3 \sin^2 2\theta_{as} \sim T^2/M_{pl} \to T_{eq}^{SM} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim 10 \text{ MeV}$

Active-sterile conversion: earlier times

- We saw that

$$T_{eq}^{SM} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim 10 \text{ MeV}$$

- The situation changes when

$$G_F^2 T^2 T^3 \gtrsim \Delta m^2/T \to T \gtrsim (\Delta m^2/G_F^2)^{1/6} \sim 50 \text{ MeV}$$

- The active-sterile system was again not in equilibrium earlier!

  - When collisions are more frequent than the oscillation length, the oscillations are rest too soon (the Quantum Zero effect)
  - The (CP-symmetric) medium creates an MSW potential, ~ $G_F^2 T^5$, that suppresses oscillations [Notzold and Raffelt (1988)]

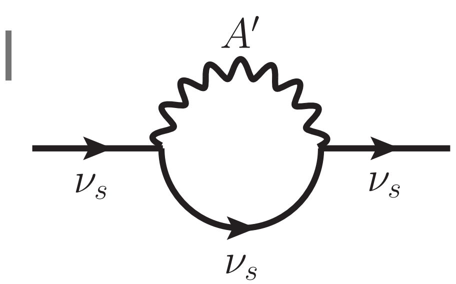
- For sufficiently small mixing angles, the ν_s production is never equilibrated; in the scenario of ν_s DM, this allows making just enough ν_s, without overclosing the universe [Dodelson and Widrow (1994)]

New interactions in the hidden sector

- Can sterile neutrinos with the mixing angle required by the short-baseline anomaly be reconciled with cosmology?

- Suppress mixing angle with a new term in the MSW potential

B. Dasgupta, J. Kopp, PRL (2014);
S. Hannestad, R. S. Hansen, and T. Tram, PRL (2014);
originally Babu & Rothstein, Phys.Lett. B275 (1992) 112-118



- Imagine that the sterile neutrinos are not sterile, they carry a hidden gauge quantum number. That would generate a new potential.

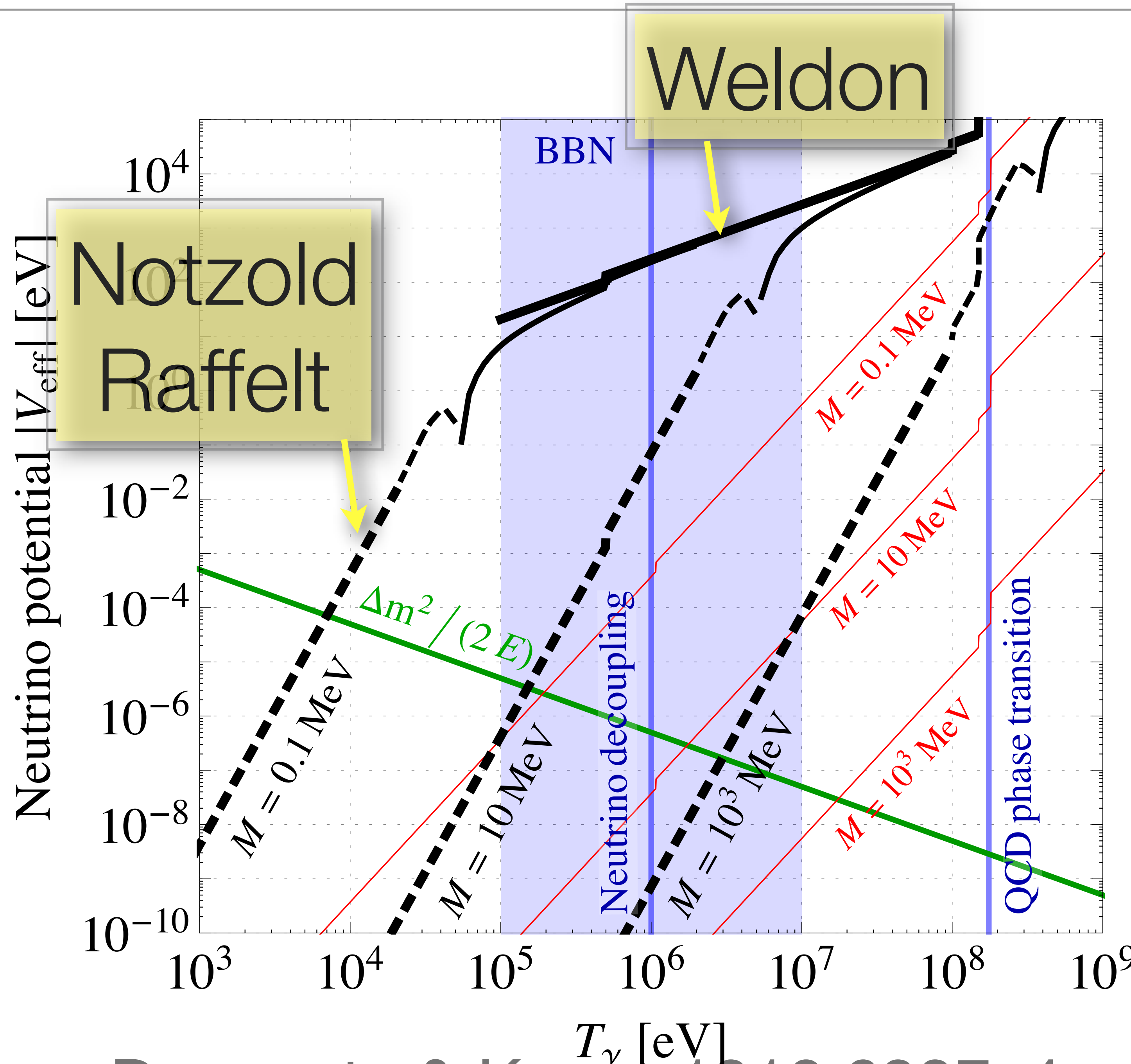
  - Repeating the standard arguments, one finds two regimes for the potential

- $$V \sim -\frac{g^4 E T^4}{M^4}, \; T, E \ll M$$ Notzold & Raffelt (1988)

  $$V \sim +\frac{g^2 T^2}{E}, \; T, E \gg M$$ Weldon (1982)

K. Enqvist, K. Kainulainen, and J. Maalampi, Nucl.Phys. B349, 754 (1991).
C. Quimbay and S. Vargas-Castrillon, Nucl.Phys. B451, 265 (1995), hep-ph/9504410.

Mixing suppression



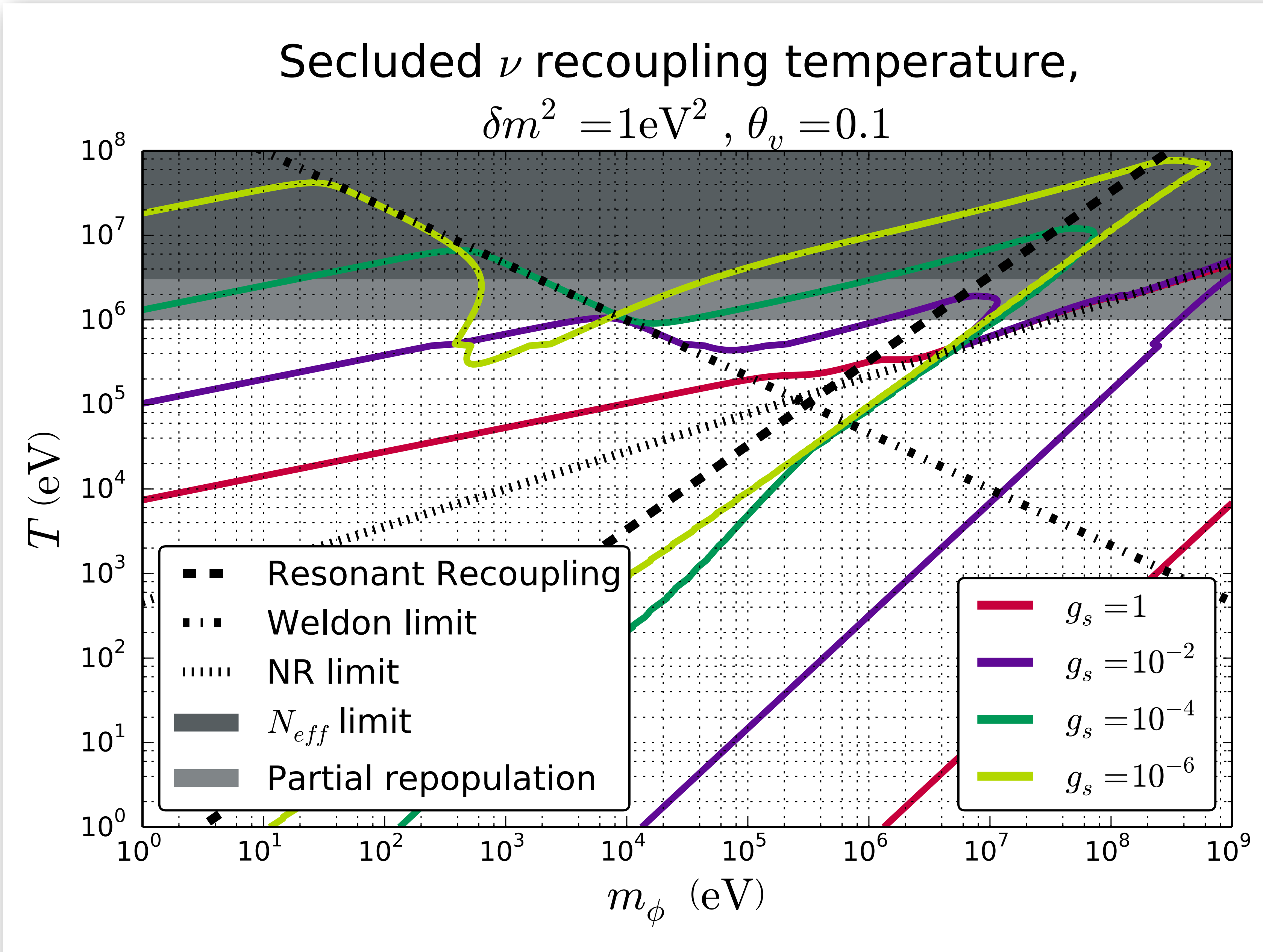
- Fig. from Dasgupta & Kopp, 1310.6337v4

Controversy!

- Dasgupta and Kopp, PRL **112** , 031803 (2014) -> Secret interactions suppress the active-sterile mixing angle in the early Universe
- Hannestad, Hansen, and Tram, PRL **112,** , 031802 (2014) -> Mixing + collisions don't violate N_eff bounds for heavy mediators.
- Mirizzi, Mangano, Pianti, and Saviano, Phys. Rev. D **91** (2015) These models agree with Planck, but only marginally.
- Archidiacono, Hannestad, Hansen, and Tram, Phys. Rev. D **91 (**2015) -> Everything works great for VERY low mass mediators.
- Chu, Dasgupta, Kopp, arXiv:1505.02795 -> There is more allowable parameter space than Mirizzi et al. found.

We do not agree with any of them!

Cherry, Friedland, Shoemaker, to appear



Large coupling: excluded by free-streaming

- Notice that for for large coupling, neutrinos, even the ones predominantly active, become non-free-streaming at the CMB epoch

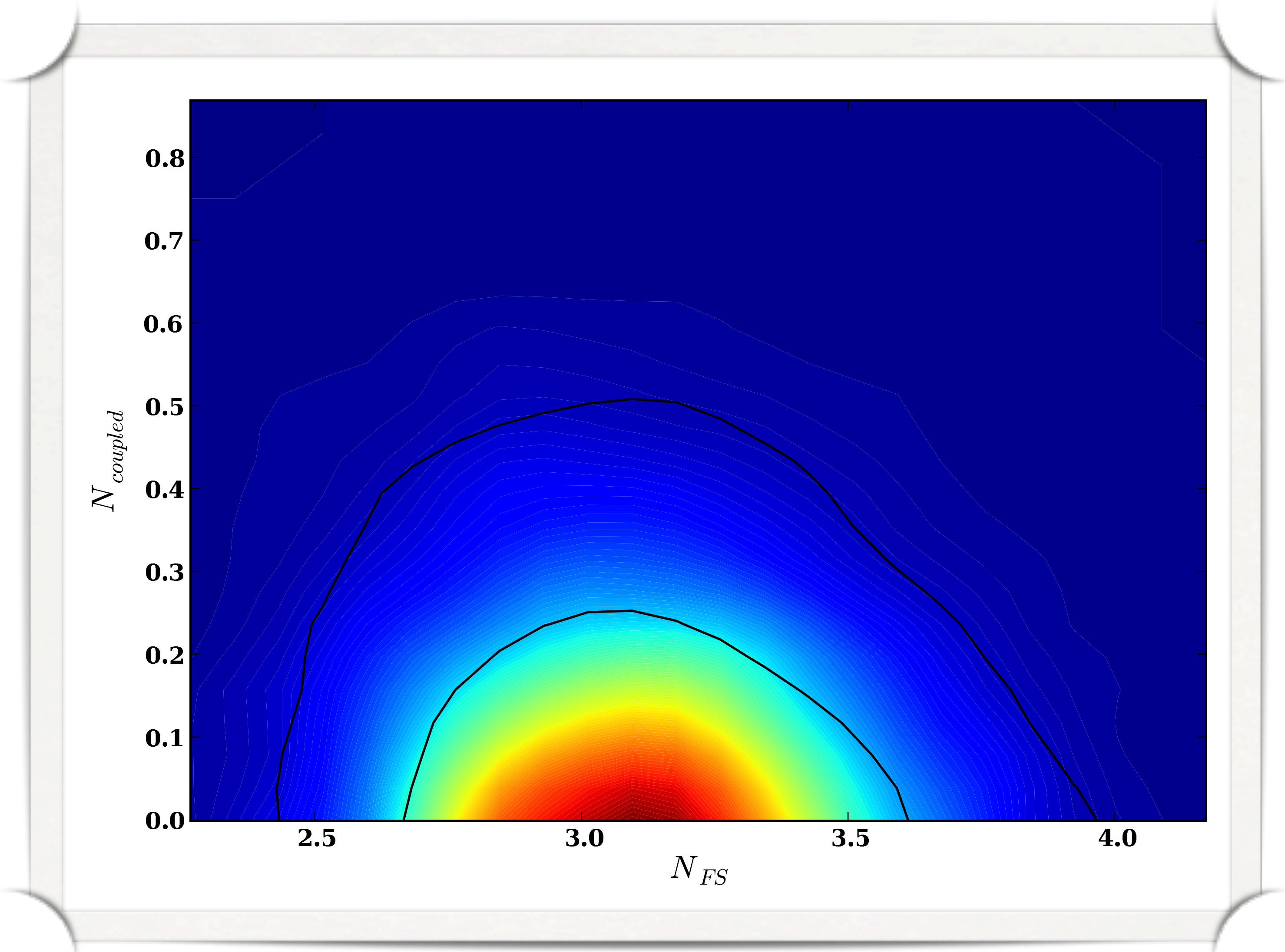
- This would be in conflict with PLANCK

$$g_{eff} < (T_{rec}/M_{pl})^{1/4}(M/T_{rec})$$

Friedland, Zurek, Bashinsky, 0704.3271

$$g_{eff} < 10^{-7}(M/1\ \mathrm{eV})$$

Here, g_{eff} is effective coupling, g sin$\boldsymbol{\theta}$□ □



- Planck 2015 [arXiv: 1502.01589] reports N_{eff}=3.15±0.23 and for the mass m_ν < 0.23 eV

In fact, such light, secluded sectors are not uncommon

Self-interacting dark matter

- To get rid of cold cores, bring them in contact with hotter components of the halo. (Spergel & Steinhardt, PRL 2000 + hundreds more)
  - DM-DM scattering. Required cross section is

$$\sigma \sim 1\ \mathrm{cm}^2 (m_X/g) \sim 10^{-24}\ \mathrm{cm}^2 (m_X/\mathrm{GeV})$$

  - Huge cross section! 10^2 fm^2 $\Rightarrow (10^7$ eV$)^{-2}$
  - The mediator particle in the **<10 MeV** range could do it

Secluded sector

- Obviously, such a light mediator must be well isolated from the Standard Model fields
- Search strategies depend on the form of the "portal" between the secluded and SM sectors
    - Known portals: kinetic mixing (dark photon searches), Higgs mixing
- Another important possibility: through neutrino mixing
    - Suppose the secluded sector contains a light fermion, which couples to the mediator ϕ. This fermion can mix with SM neutrinos.
        - *"Neutrino Portal"*

Neutrino Portal Framework

- The dark sector has a Higgs mechanism with a field η that gives ϕ its **light** mass

$$\mathcal{L} \sim LH\nu_R + \nu_D \eta \nu_R + M\nu_R\nu_R$$

- Simple renormalizable see-saw Lagrangian. Upon integrating out the heavy right-handed ν_R , one gets a light “sterile” ν_D mixing with the usual active neutrinos in L

- $$\mathcal{L}_{eff} \sim \frac{(LH)(\nu_D \eta)}{M}$$

- Akin to “baryonic neutrino” in Pospelov, arXiv:1103.3261, only the hidden gauge group does not directly couple to the SM baryon number (which could induce large NSI)

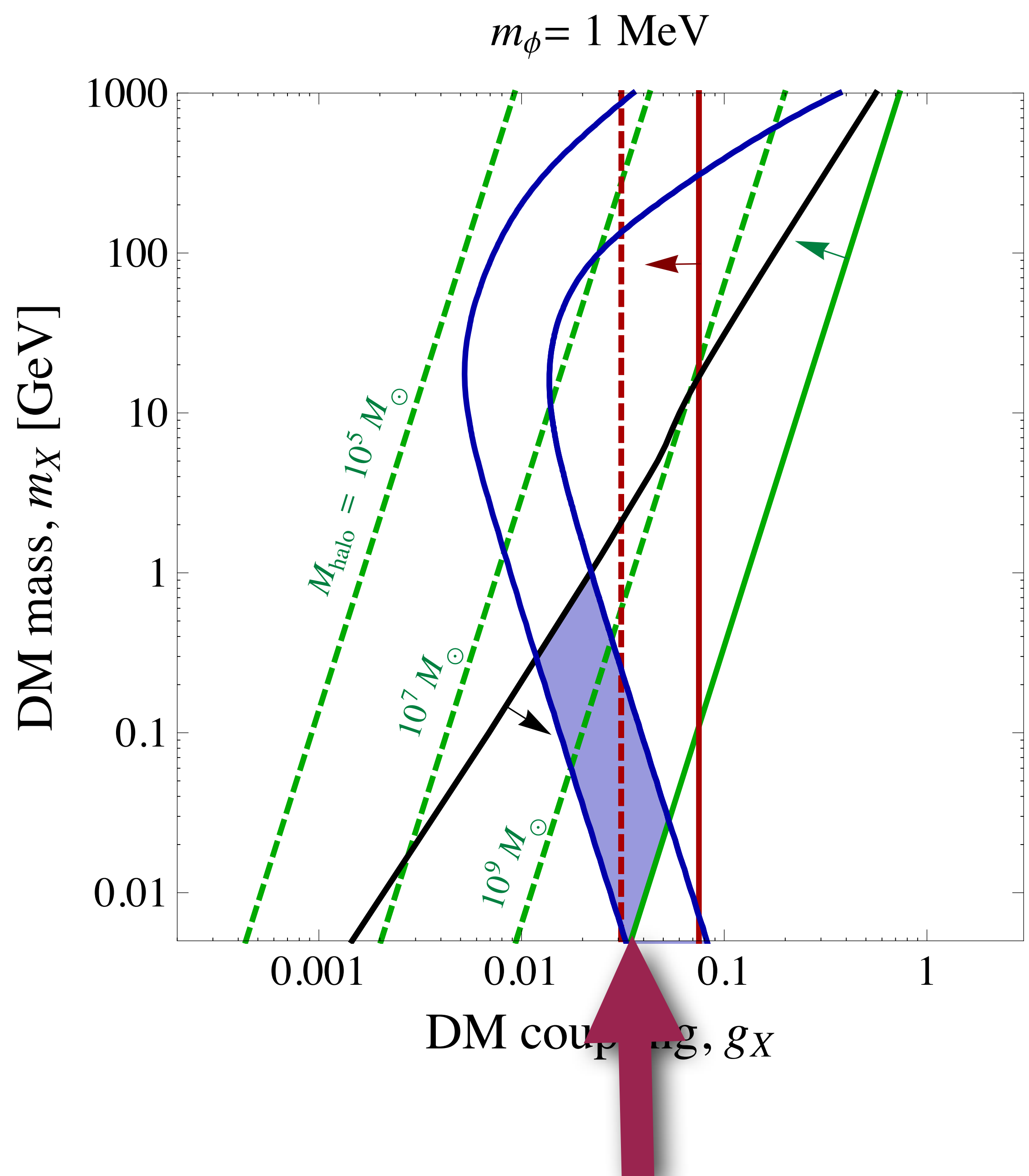
Dark-matter interactions with neutrinos?

- Interestingly, coupling between dark matter and neutrinos gives the second mechanism to alleviate the small-scale structure problems
    - Boehm et al, 2001, 2002, 2004; van den Aarssen, Bringmann, and Pfrommer, 2012
    - Coupling of SM to neutrinos early would keep DM density fluctuations from collapsing, until kinetic decoupling

$$M_{halo} \sim 10^8 M_\odot \left(\frac{\mathrm{keV}}{T_{KD}} \right)^3$$

    - Mediator masses of <10 MeV work! (see later)

Results: self-interactions + kinetic decoupling + relic DM abundance



Cherry, Friedland, Shoemaker, arXiv:1411.1071

Testing neutrino-neutrino interactions?

- We have discussed DM-DM and DM-neutrino interactions.
- How about neutrino-neutrino interactions?
- This may be the hardest interaction among the SM particles to constrain!
- A classic problem!
  - Bounds of the order of 10^3-10^5 G_F have been quoted

Volume 32B, number 2 PHYSICS LETTERS 8 June 1970

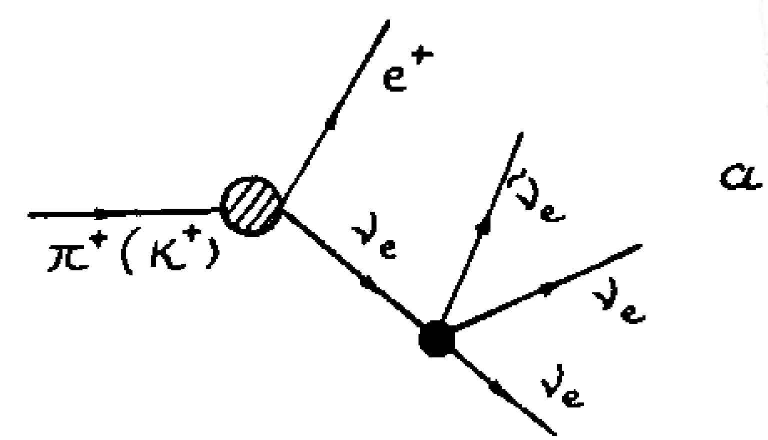
ON THE ν - ν INTERACTION

D. Yu. BARDIN, S. M. BILENKY, B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 28 April 1970

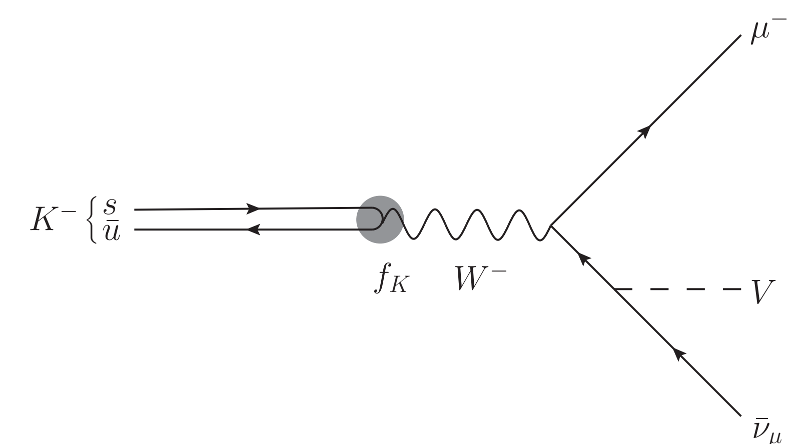
A new hypothetical interaction between neutrinos is considered. It is shown that even relatively strong $\nu_e - \nu_e$, $\nu_\mu - \nu_\mu$ and $\nu_e - \nu_\mu$ interactions are not in contradiction with existing data and upper limits for the corresponding interaction constant are obtained. New experiments are suggested which might give information on $\nu - \nu$ interactions.

- Bardin, Bilenky, Pontecorvo (1970)
- Barger, Keung, Pakvasa (1982)
- Manohar (1987)
- Kolb & Turner (1987)
- Fuller, Mayle, Wilson (1988)
- Bilenky, Bilenky, Santamaria (1993)
- ...



Most of these constraints are complete avoided

- The neutrino portal framework is distinct from hard 4-fermi interactions:
  - Neutrinos in laboratory are produced as flavor states, don't have the ν_S component until they oscillate.
- In dense environments such as supernova, large matter potential reduces the admixture of the "sterile" state --> Manohar 1987 does not apply. Detailed analysis warranted!



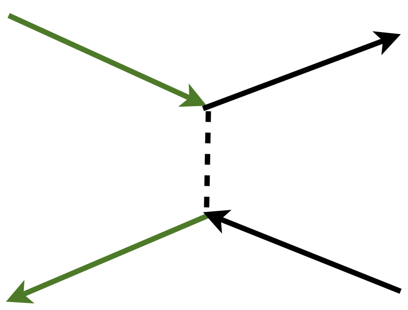
Neutrino-neutrino collider?

- We need to collide neutrino mass eigenstates, which have admixture of the “sterile” component that endows them with new interactions
- Not feasible in a terrestrial lab, but we can use the universe as the lab
- **Icecube** has observed neutrinos in the PeV energy range, that likely originate from cosmological distances
- These neutrinos on their way to us travel through the relic neutrino background. Both the beam and the background had enough time to oscillate and separate into mass eigenstates.

Light mediator

- It is well known that in the SM the universe is transparent to neutrinos with energies below ~10^{22} eV

- We now have a light mediator particle



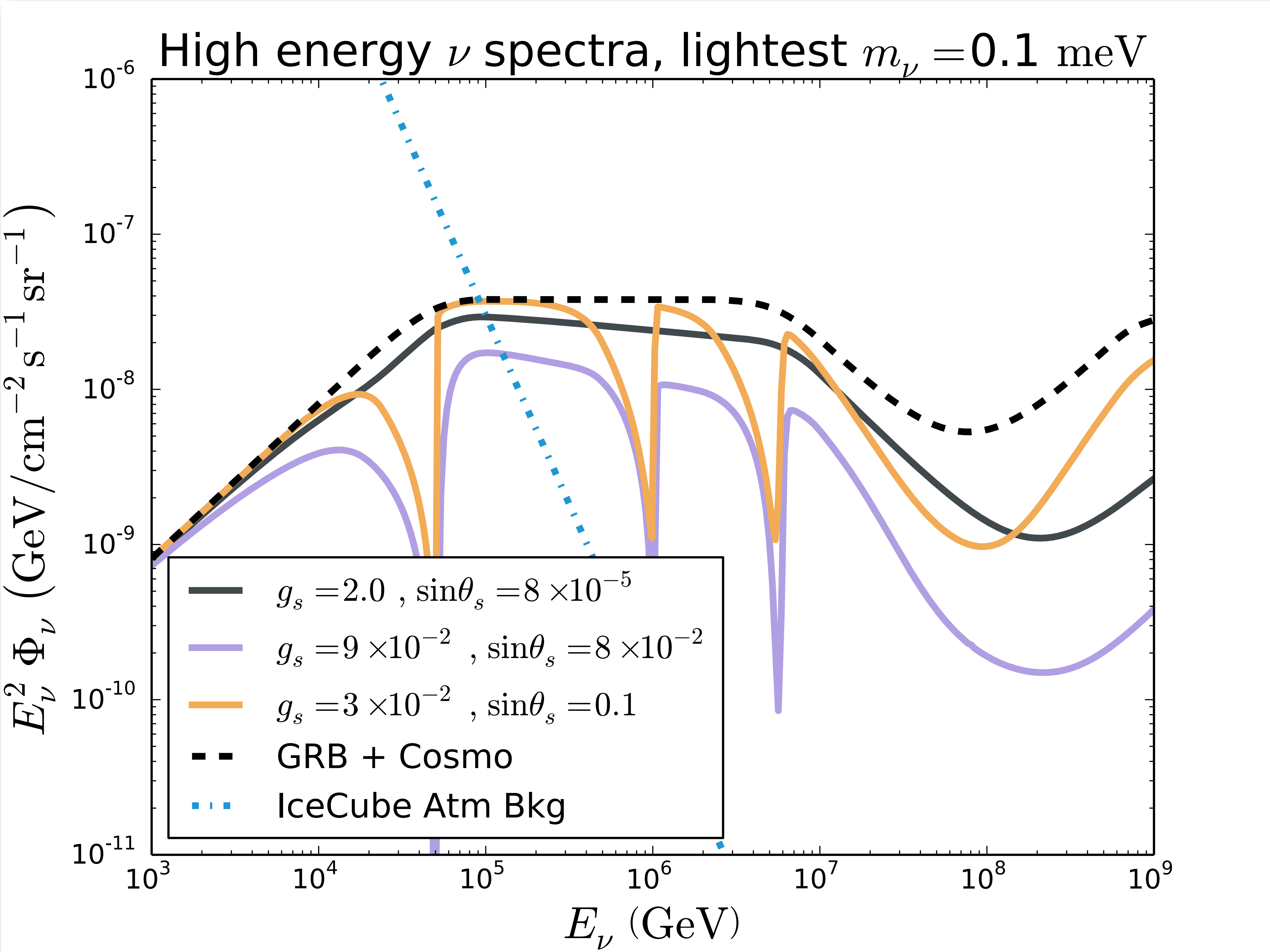
  - resonant condition

$$m_\phi^2 = s \approx 2 m_\nu E_\nu$$

$$\Longrightarrow m_\phi \sim \sqrt{(10^{-1}\ \mathrm{eV})(10^{15}\ \mathrm{eV})} \sim 10^7\ \mathrm{eV}$$

  - ***The same mass scale as for the dark matter self-interactions!***

  - After scattering, neutrinos are mostly converted into the “sterile” state, disappear from the observed flux

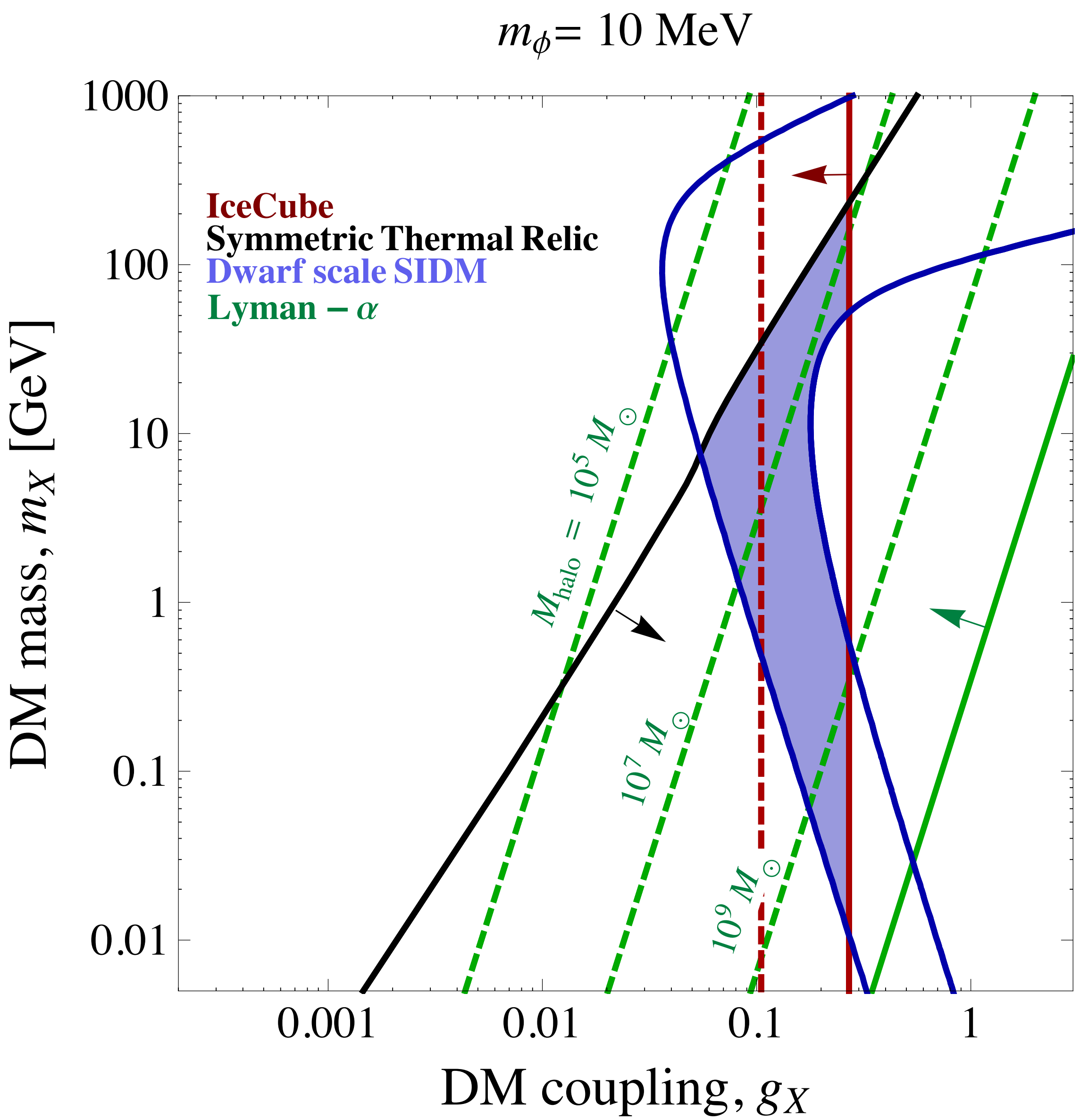


Example calculation

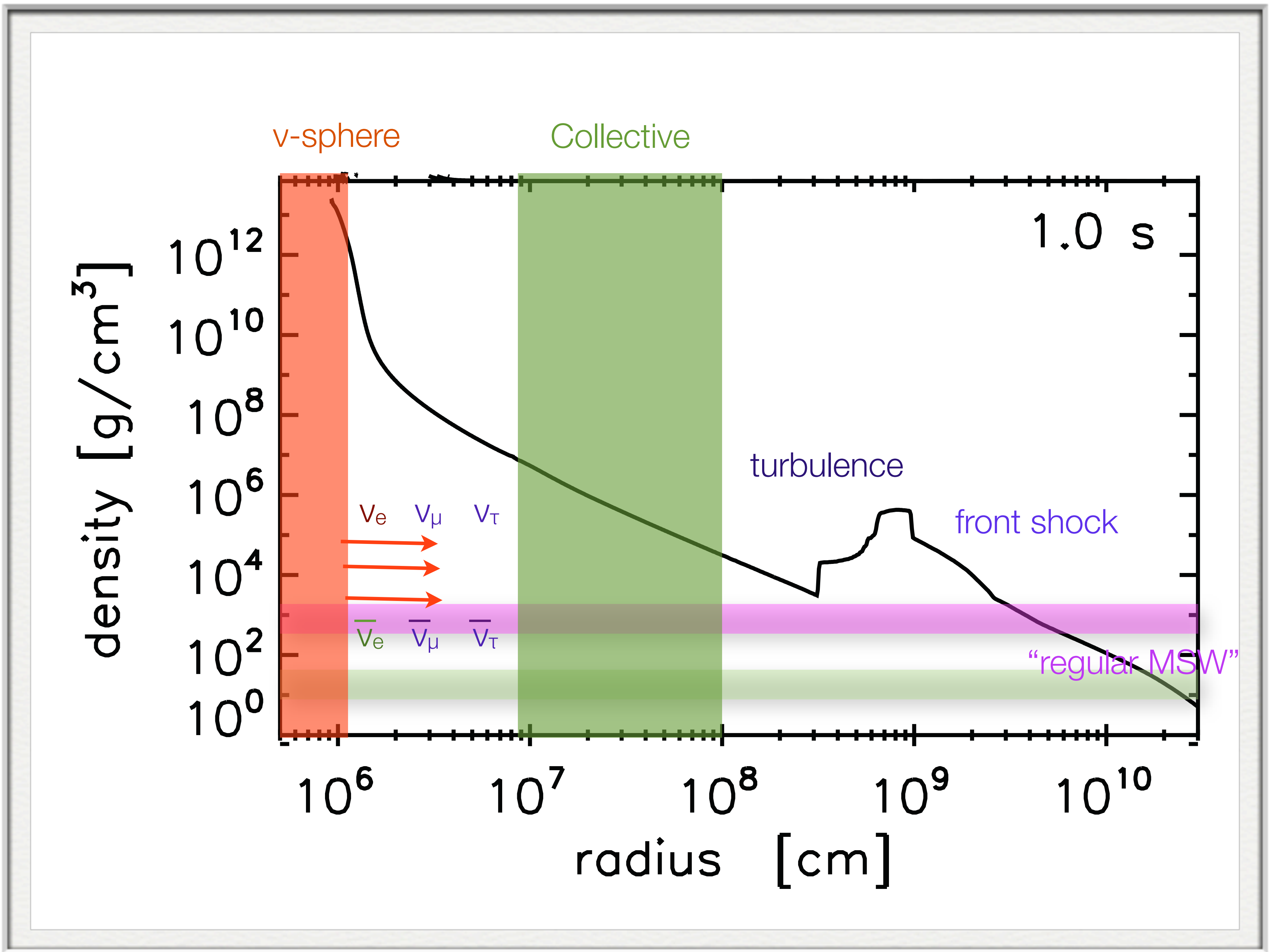
Sources are GBRs (Waxman-Bahcall) + AGNs at high E

More interesting implications: source correlations

- Too much absorption would be mean no isotropy of sources
- Intermediate range could mean absorption from far sources
  - GZK-type horizon for neutrinos
  - Look for source correlations!



More to understand: effect on SN ν's



Neutrino "self-refraction"

- Neutrinos undergo flavor conversion in the background of other neutrinos

- The neutrino induced contribution depends on the flavor states of the background neutrinos

$$\sqrt{2}G_F \sum_{\vec{p}} n_i (1 - \cos\Theta_{\vec{p}\vec{q}}) |\psi_{\vec{p}}\rangle\langle\psi_{\vec{p}}|$$

- Rich many-body physics, with many regimes

- Modified neutrino-neutrino interactions could change this drastically? How? What's the signature DUNE can look for?

Fuller et al, Notzold & Raffelt 1988;
Pantaleone 1992; ...
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

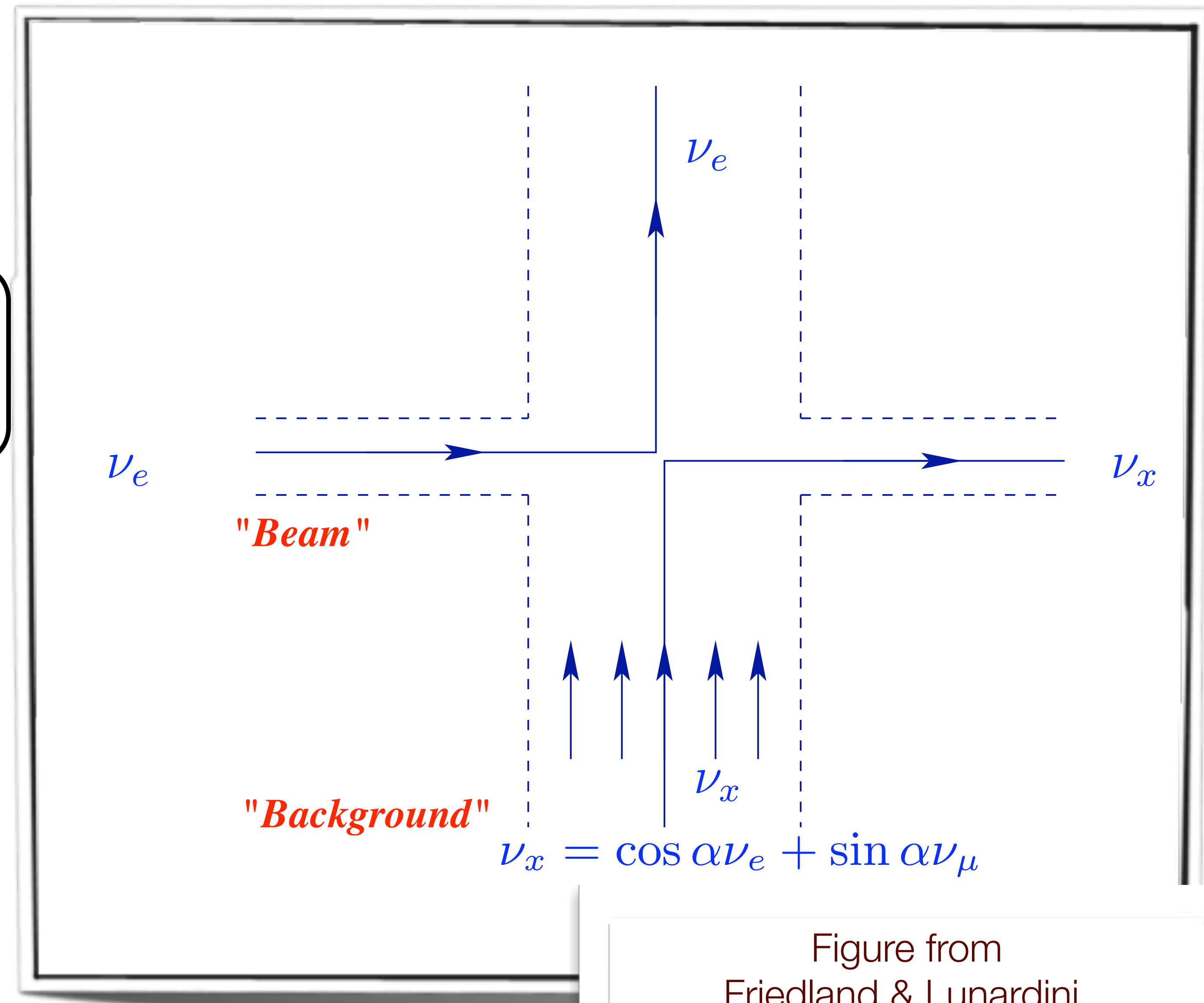


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

In summary

- Neutrino field has progressed tremendously in the last two decades, both with terrestrial and astrophysical/cosmological sources
- With zeroth-order things measured, the next-generation experiments will probe the standard 3-neutrino paradigm.
- Precision data at several baselines should resolve the nagging “anomalies”
- Larger version of IceCube will have enough statistics to look for anomalous absorption effects caused by hidden light mediators
- Next-generation cosmological probes will also test these scenarios
- Observation of the next Galactic supernova with DUNE, SK, IceCube/PINGU could provide a wealth of astrophysical and particle physics information. Need to be prepared to read this signal.