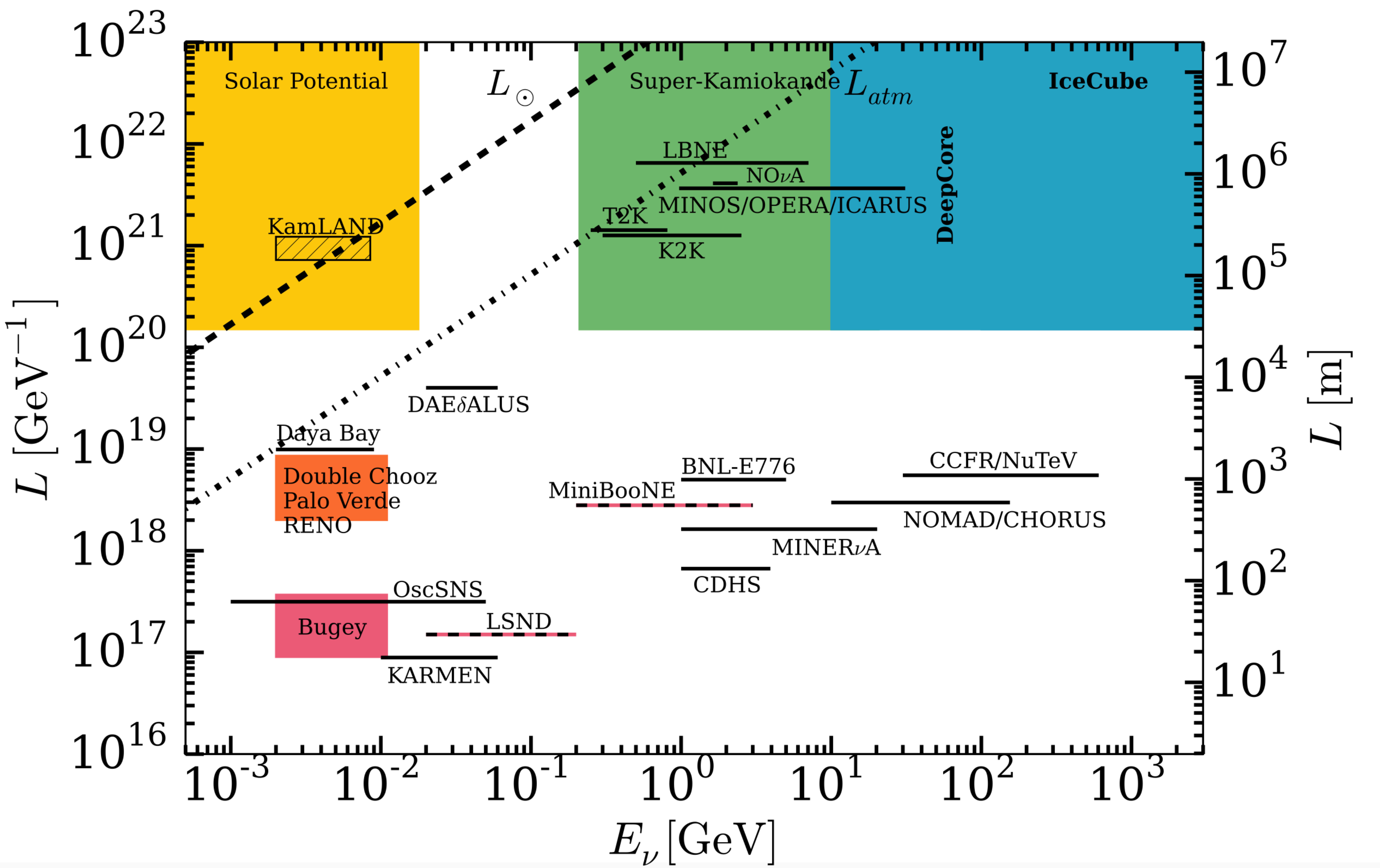
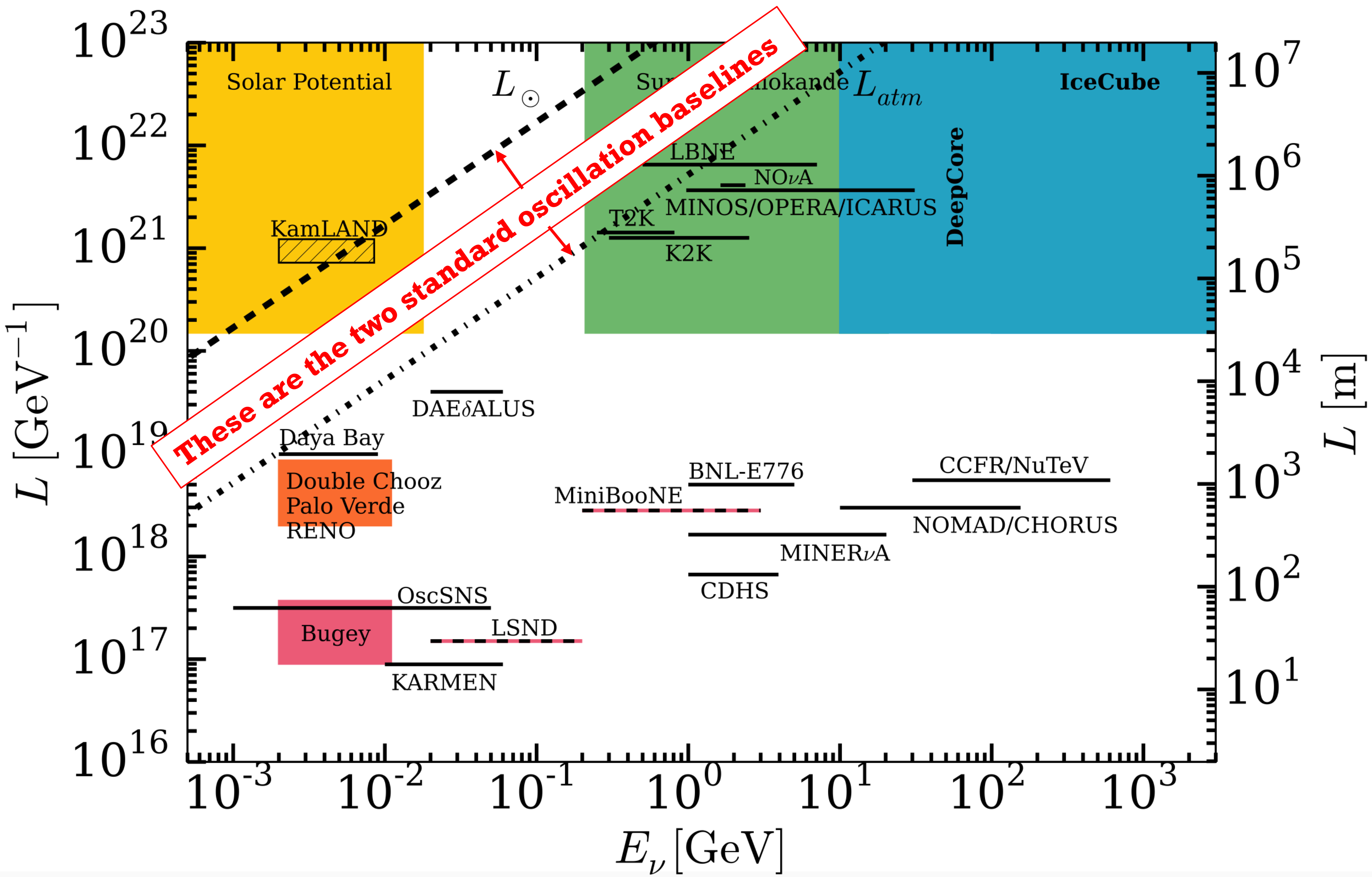
NEUTRINOS IN NUCLEAR PHYSICS

Ben Jones, University of Texas at Arlington

4



$$P_{osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L/E\right)$$



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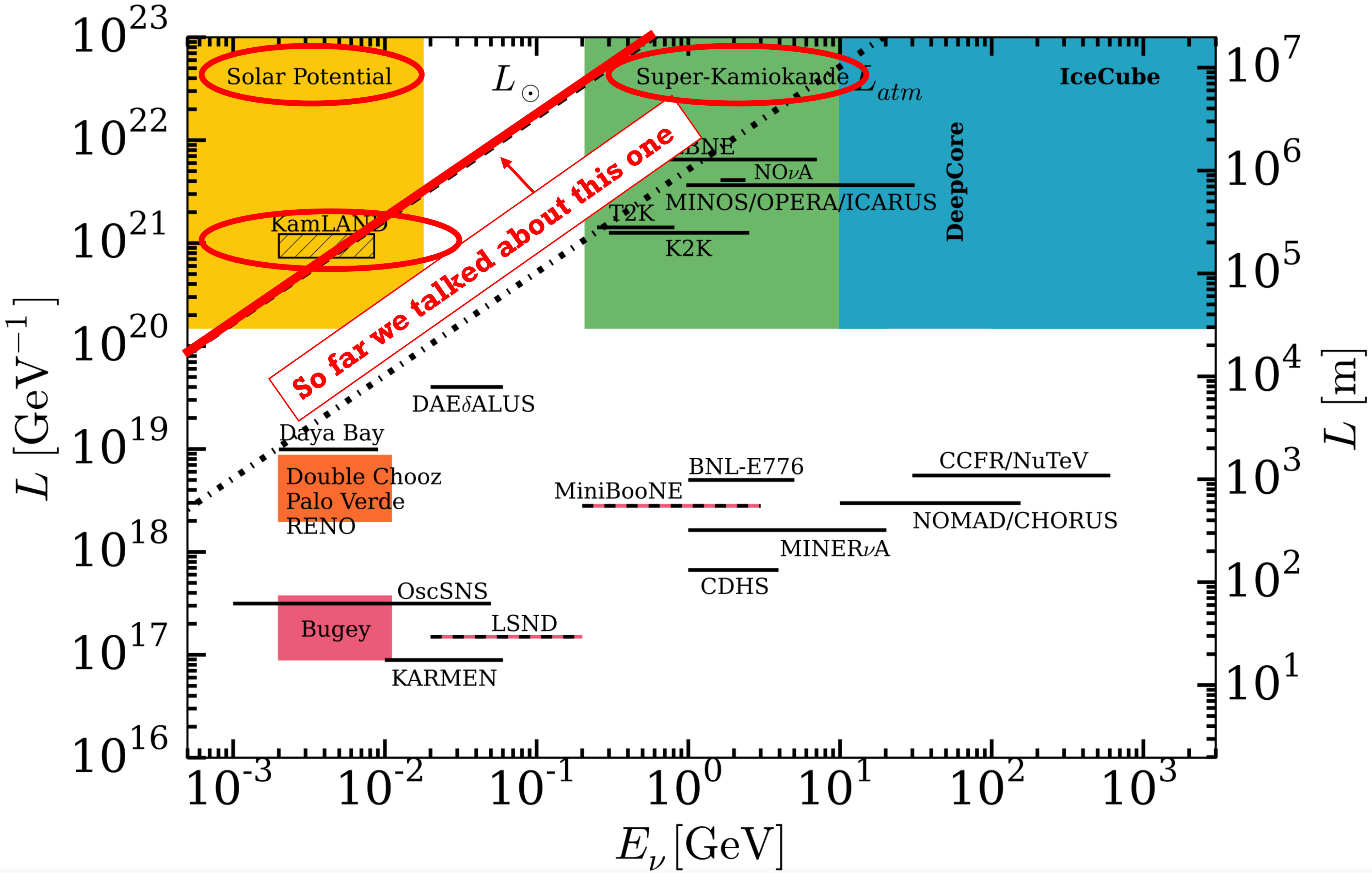

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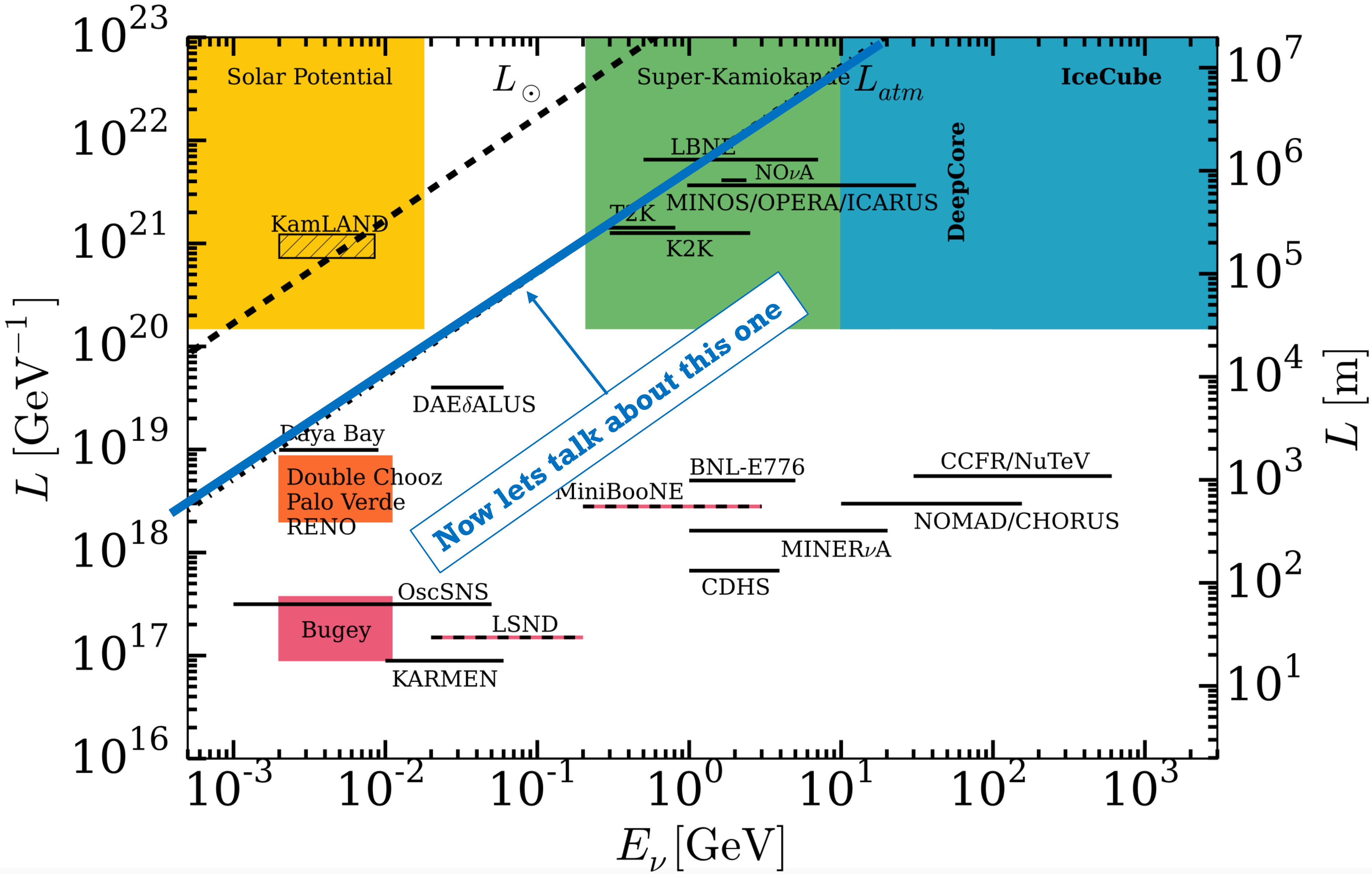

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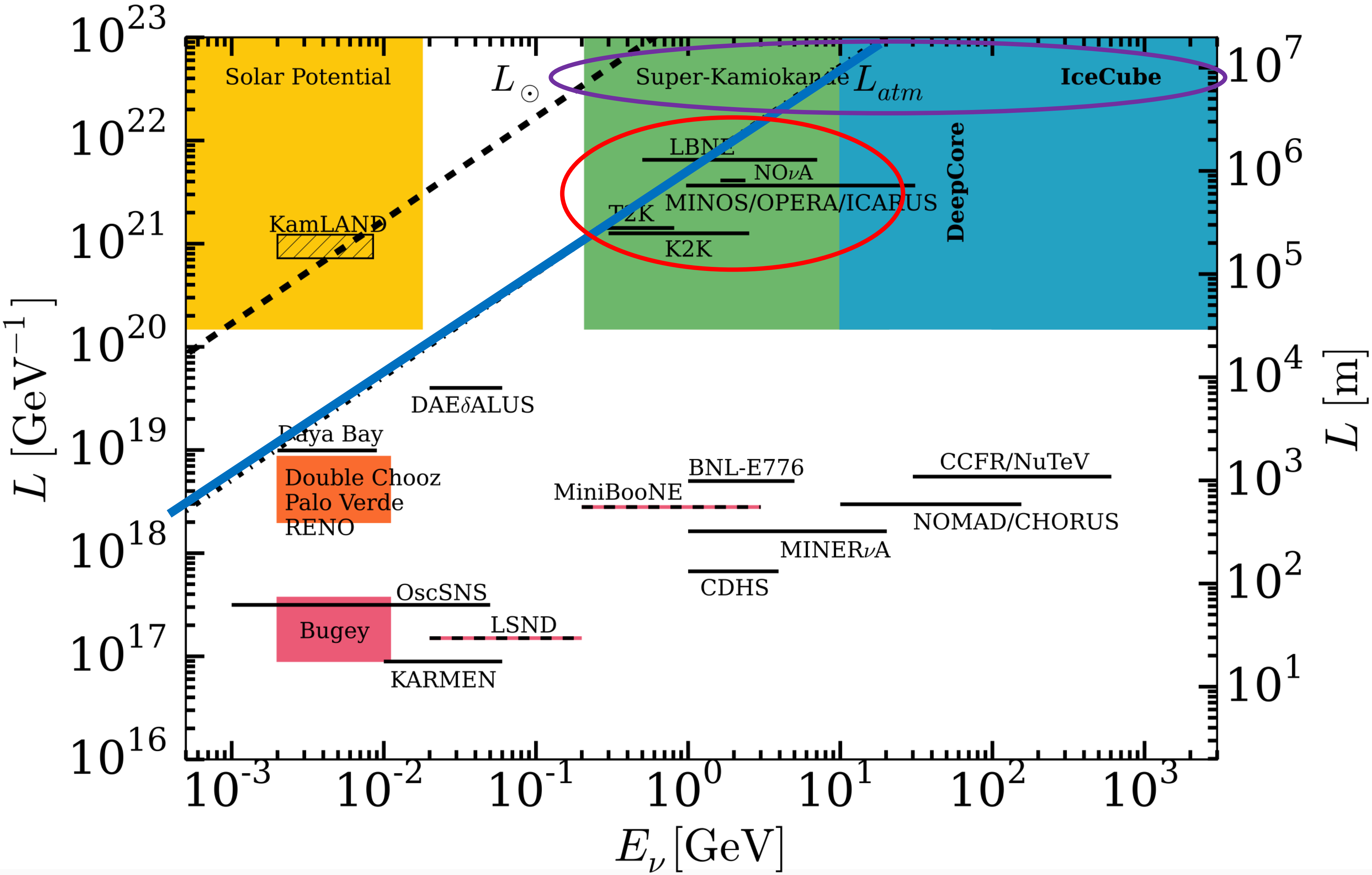

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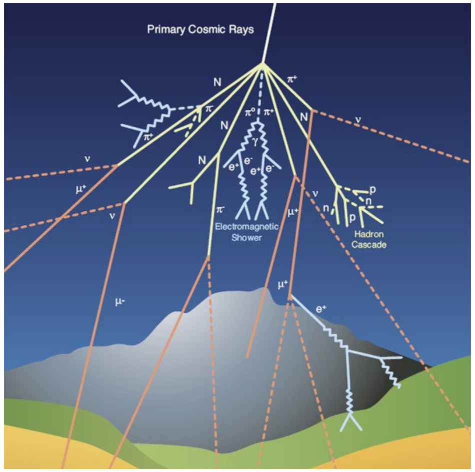
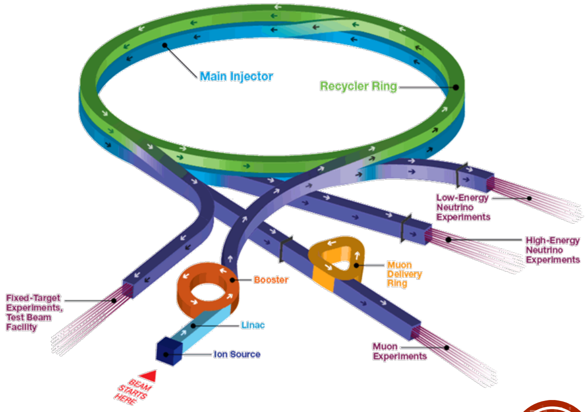
>GEV NEUTRINOS

- To get GeV neutrinos, we have two options:



- **Atmospheric, from cosmic ray air showers**
  - 4pi coverage
  - From all baselines around the Earth
  - Wide energy coverage (but steeply falling with E).
  - Flux is what nature gives us.

- **Man-made, from particle accelerators**
  - Directional beam.
  - Precisely fixed baseline.
  - Flux that can be controlled and manipulated.

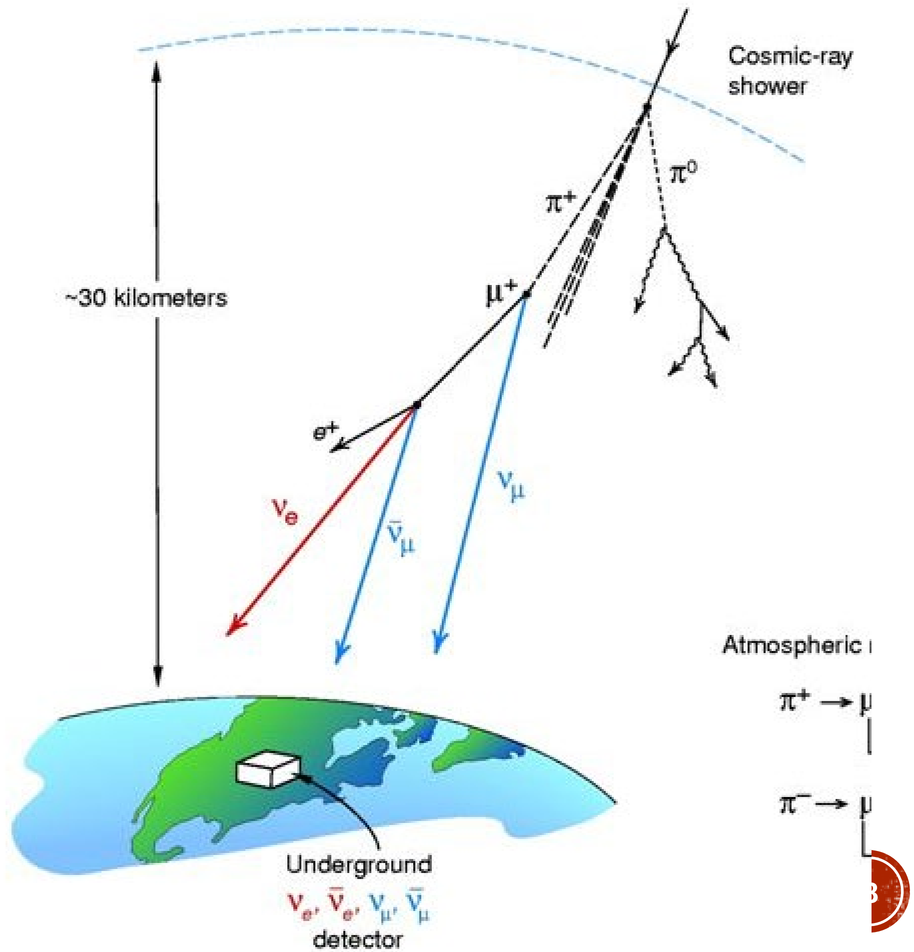


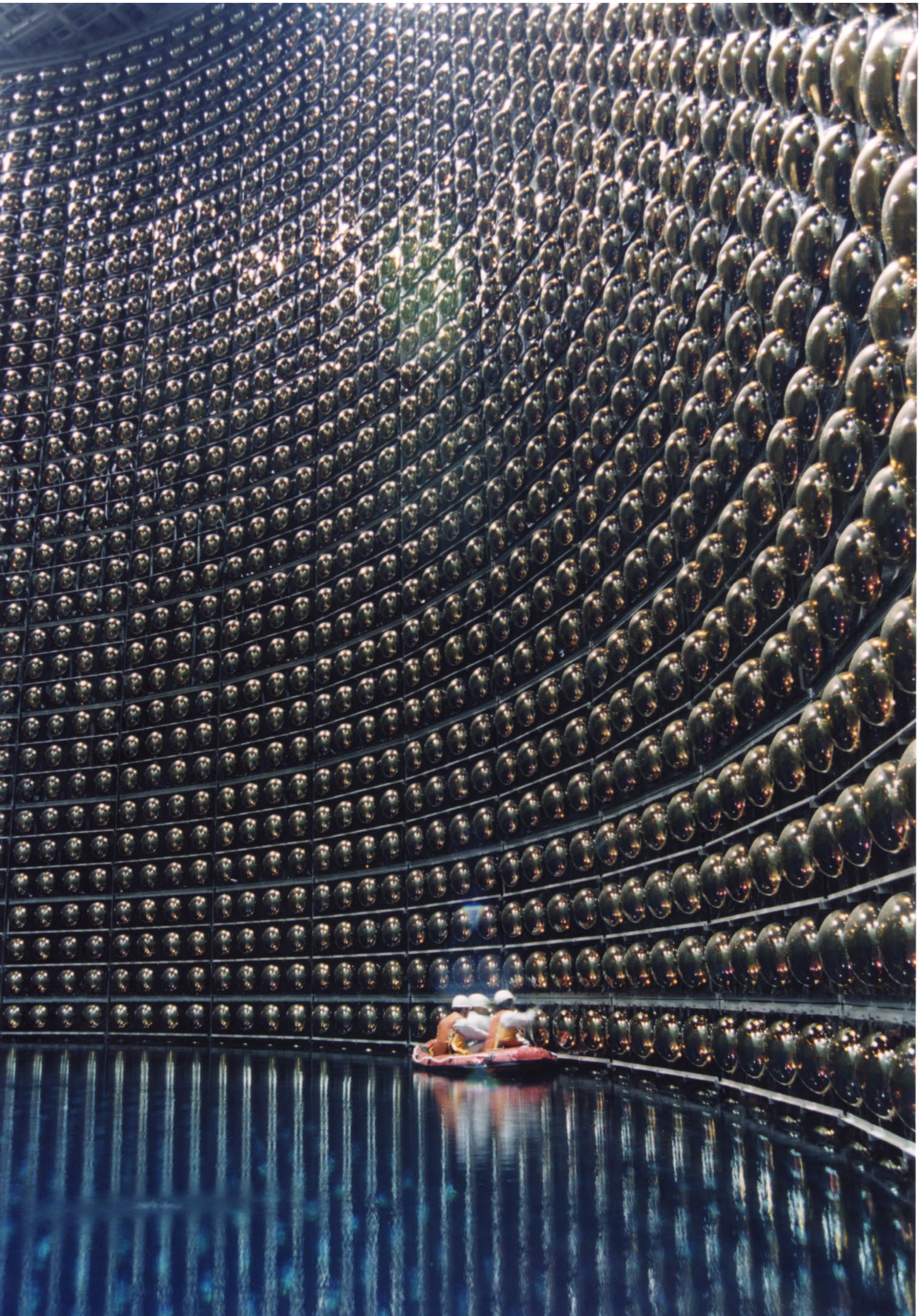
ATMOSPHERIC NEUTRINOS

- Atmospheric neutrinos are produced in air showers initiated by cosmic rays in the upper atmosphere.

- These create copious hadrons and muons that decay to neutrinos.

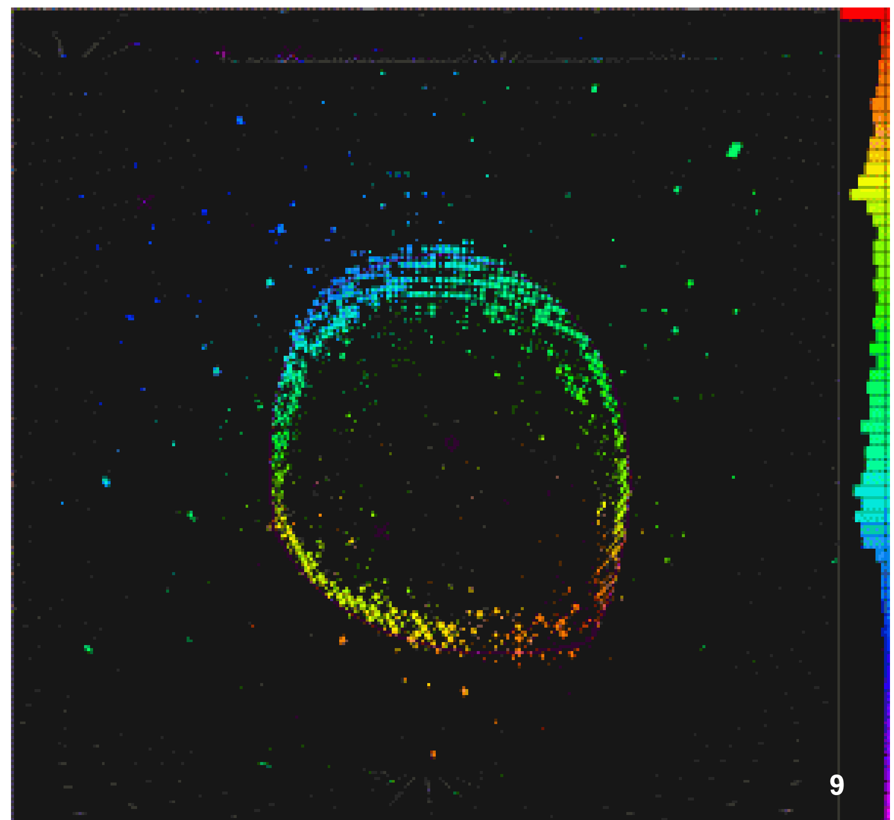
- For E<1TeV the Earth is transparent to neutrinos, so looking for "upward-going" tracks or showers is a good handle to search for atmospheric neutrinos.

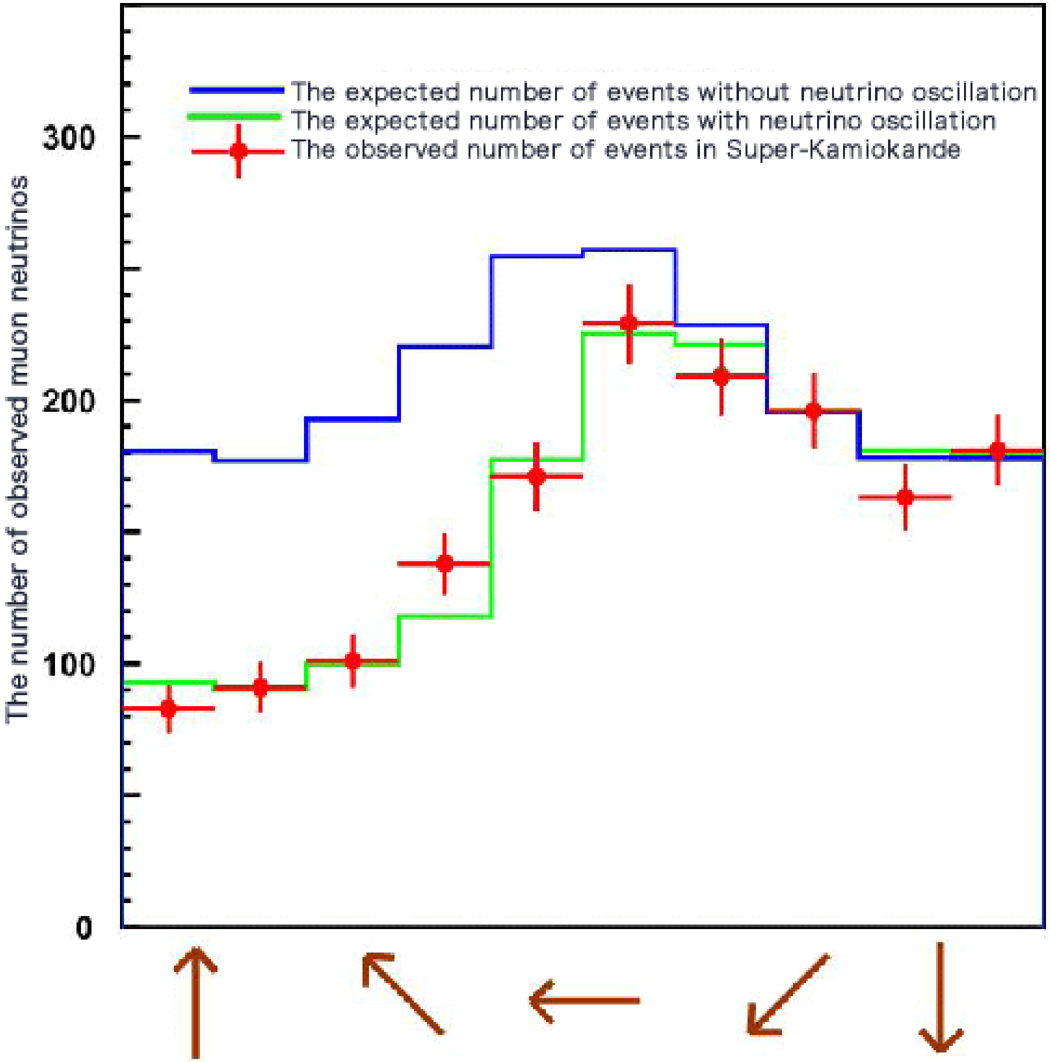




SUPERKAMIOKANDE

20,000 ton water Cerenkov detector –sees multi-GeV atmospheric neutrinos which do point back to source

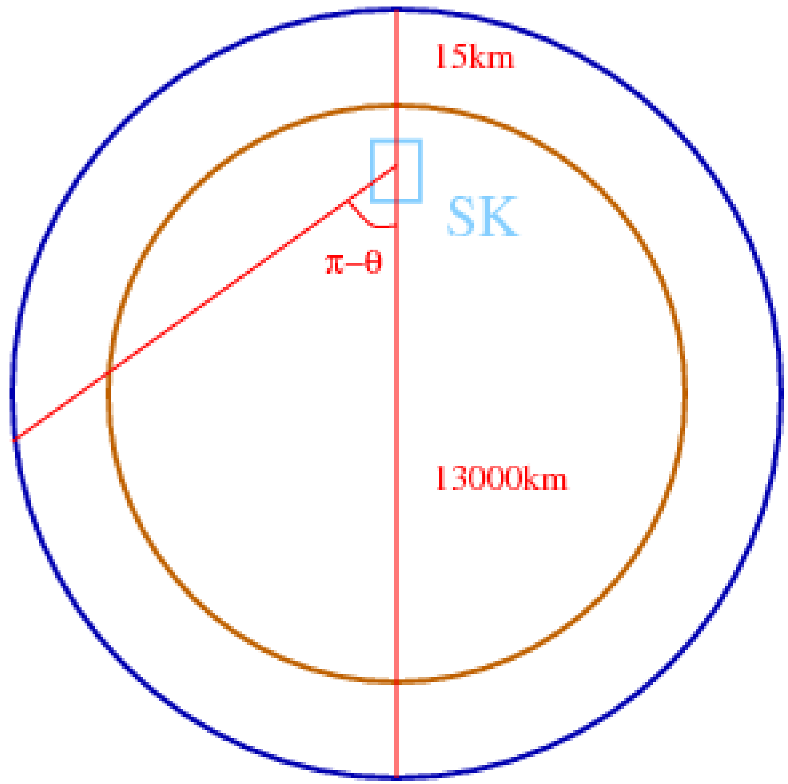




Upward going Neutrinos
Flight length:12800km
Only a half of the expected number (blue line) was observed.

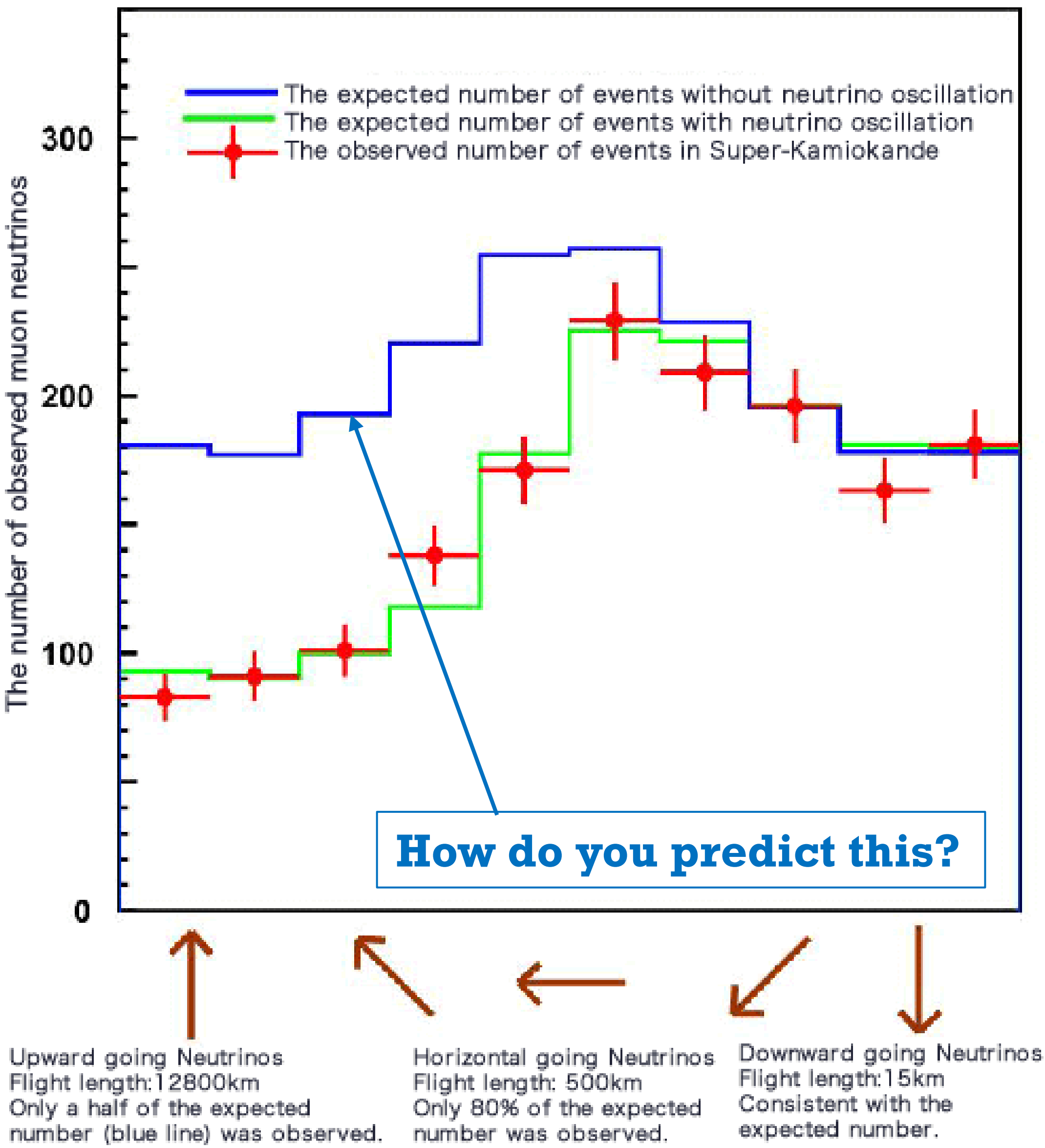
Horizontal going Neutrinos
Flight length: 500km
Only 80% of the expected number was observed.

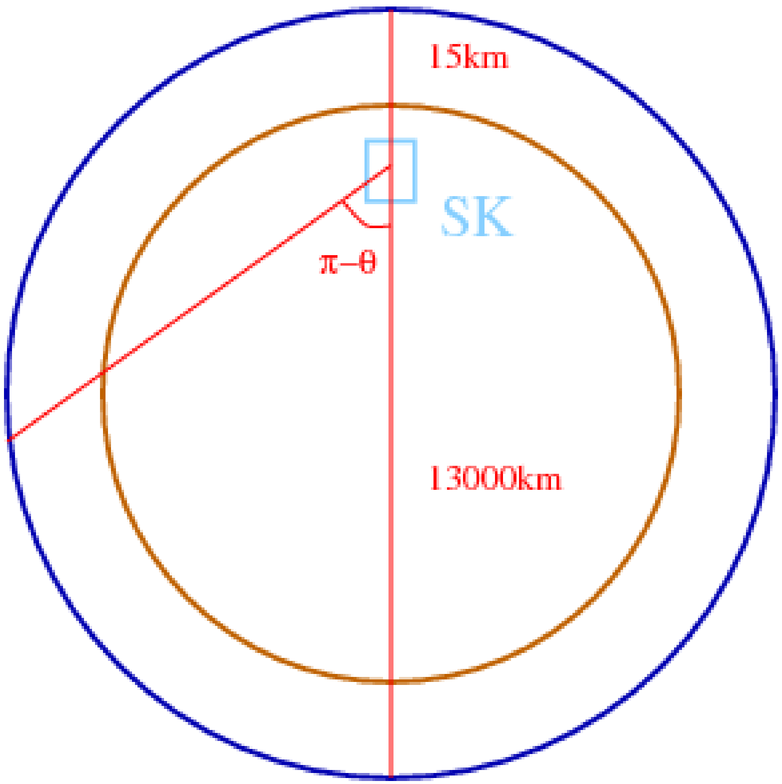
Downward going Neutrinos
Flight length:15km
Consistent with the expected number.



Muon neutrinos disappearing as a function of distance...?

Demonstration that muon neutrinos disappear with distance. Nobel prize 2015.





Muon neutrinos disappearing as a function of distance…?

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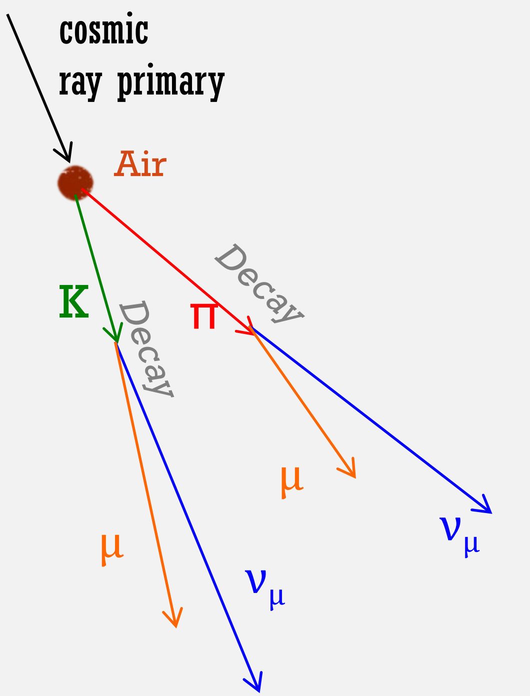
PRODUCTION OF ATMOSPHERIC NEUTRINOS

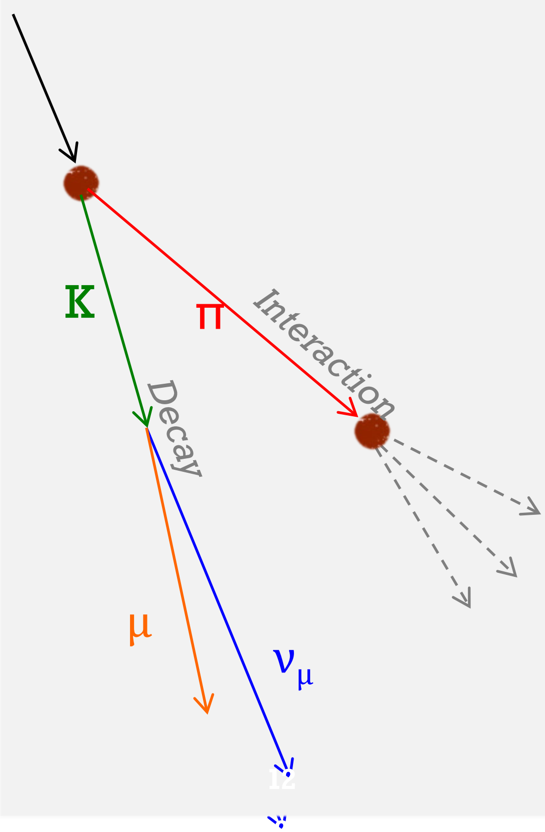
Lowest energy

Mostly atmospheric π



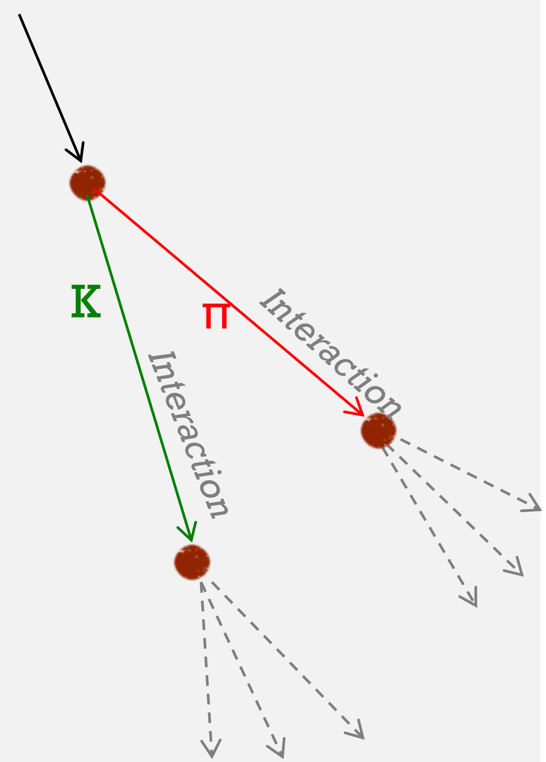
Higher energy

Mostly atmospheric K

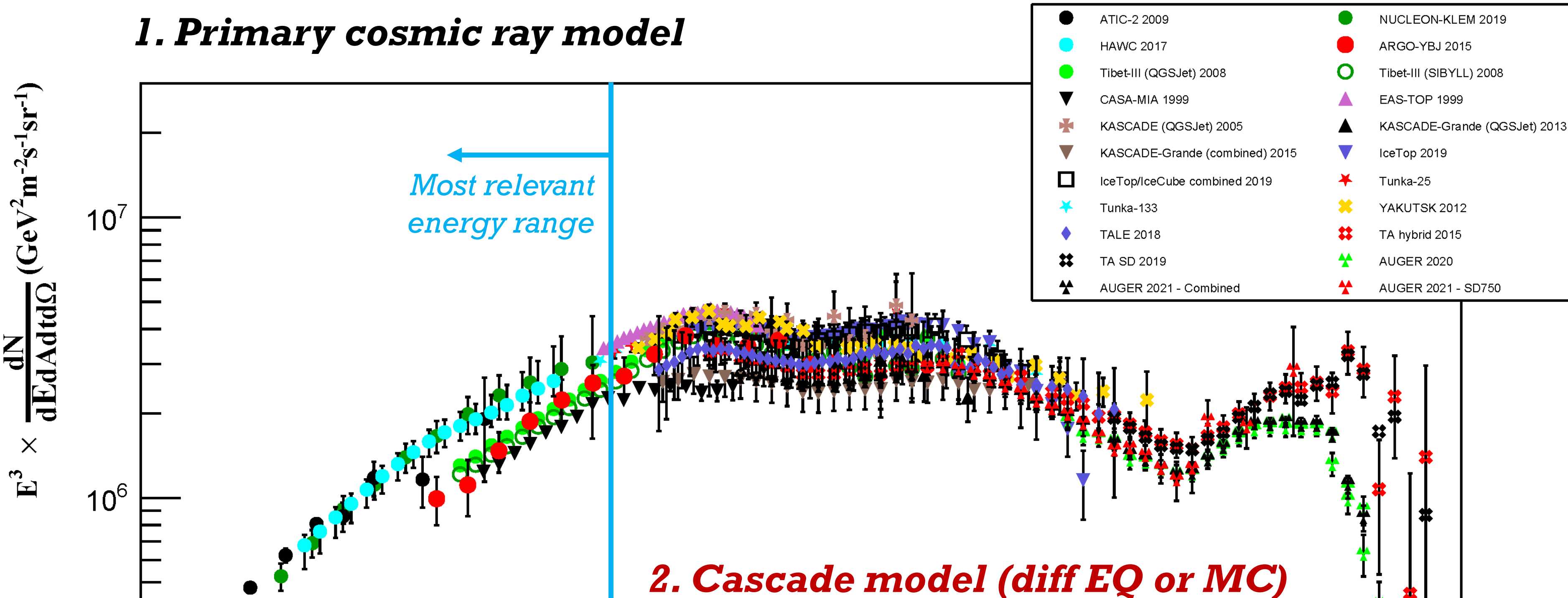


Highest energy

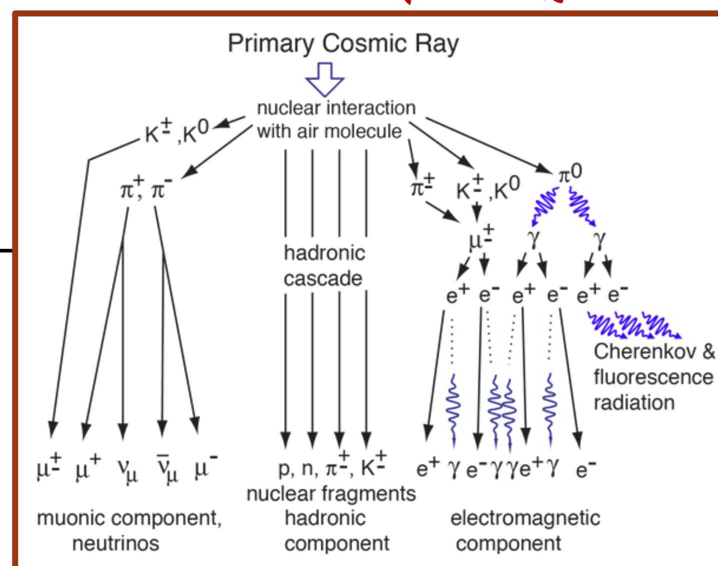
Mostly astro / prompt



1. Primary cosmic ray model

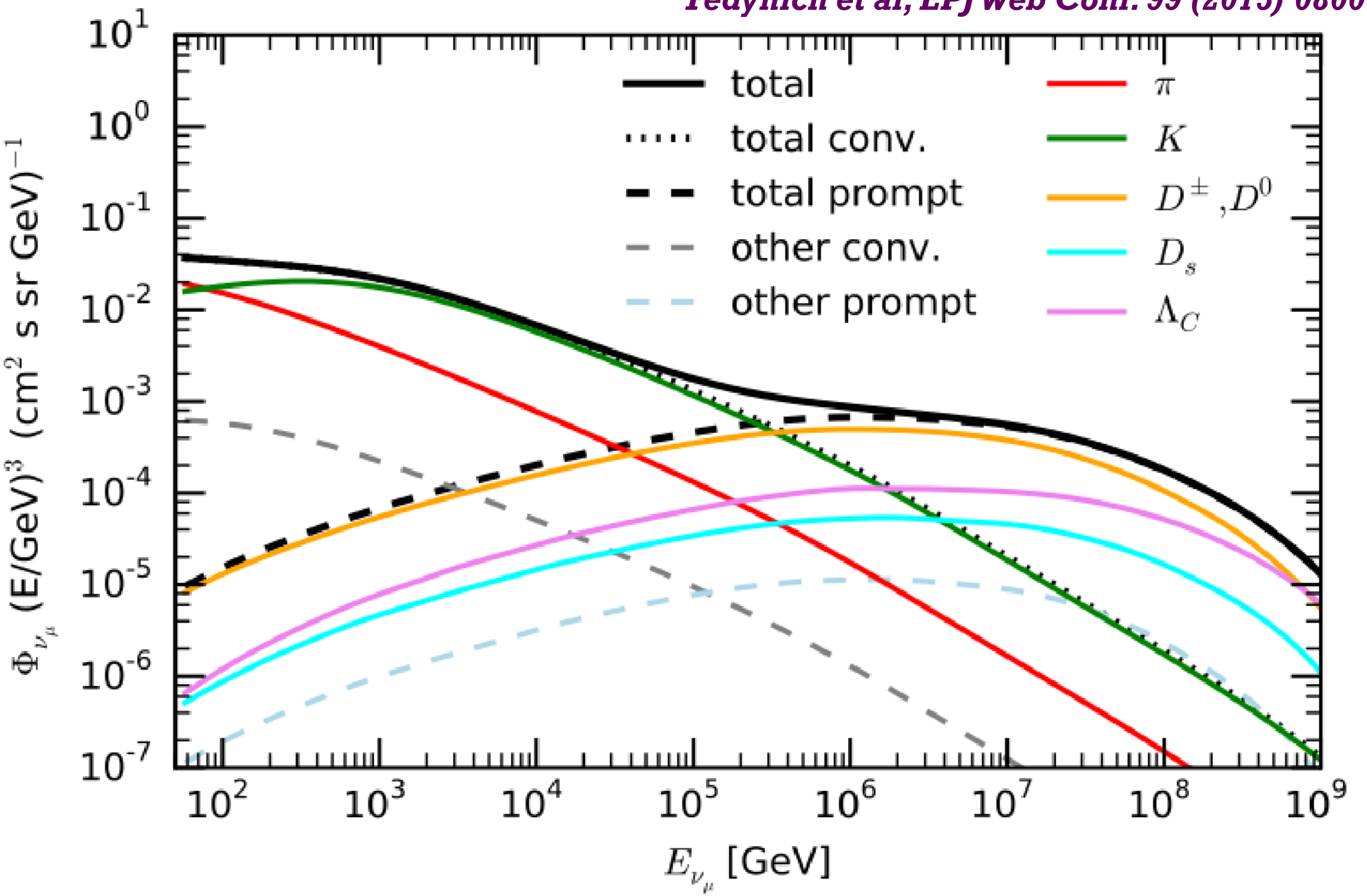


2. Cascade model (diff EQ or MC)

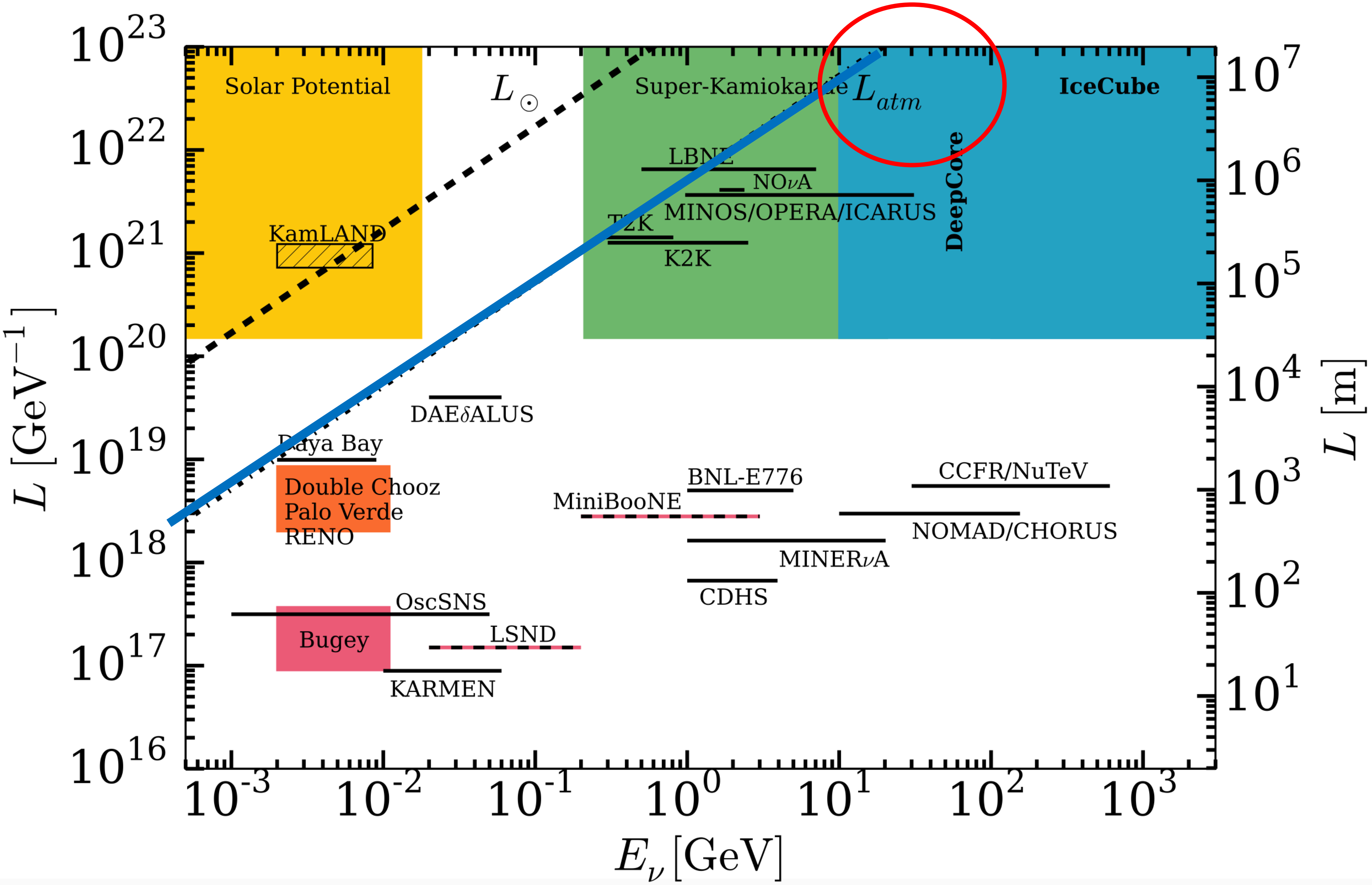


ATMOSPHERIC FLUX PREDICTIONS

Fedynich et al, EPJ Web Conf. 99 (2015) 08001

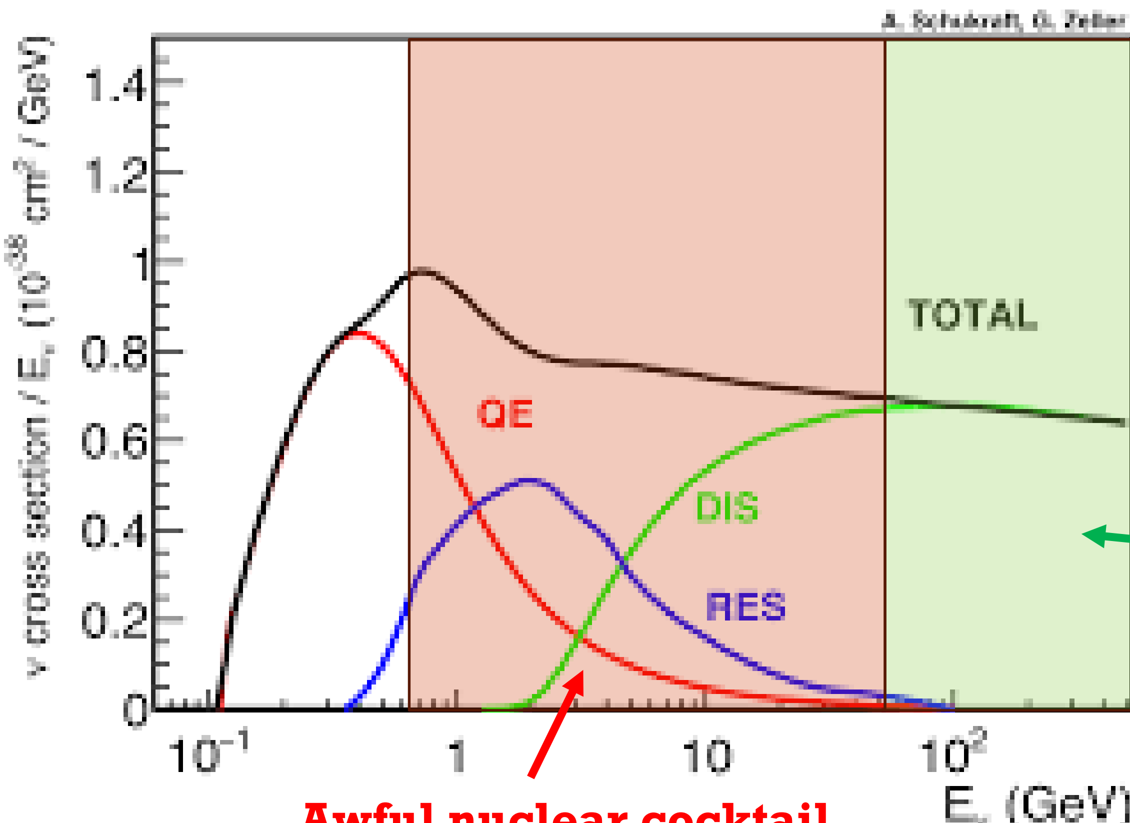


pi/K production ratio, spectral slope, nu/nubar ratio are all challenging to predict a-priori.


Solar Potential
$L_\odot$
Super-Kamiokande
L_{atm}
IceCube
DeepCore
LBNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
KamLAND
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
BNL-E776
MiniBooNE
CCFR/NuTeV
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
Bugey
LSND
KARMEN
L [GeV^{-1}]
L [m]
E_ν [GeV]

CROSS SECTIONS ACROSS ENERGIES

- At high energy, neutrino detection process switches from CCQE and resonant scattering to deep inelastic scattering.
- Cross section uncertainties are thus ***far smaller*** in the high energy regime. Appealing to study oscillations there, if we can!



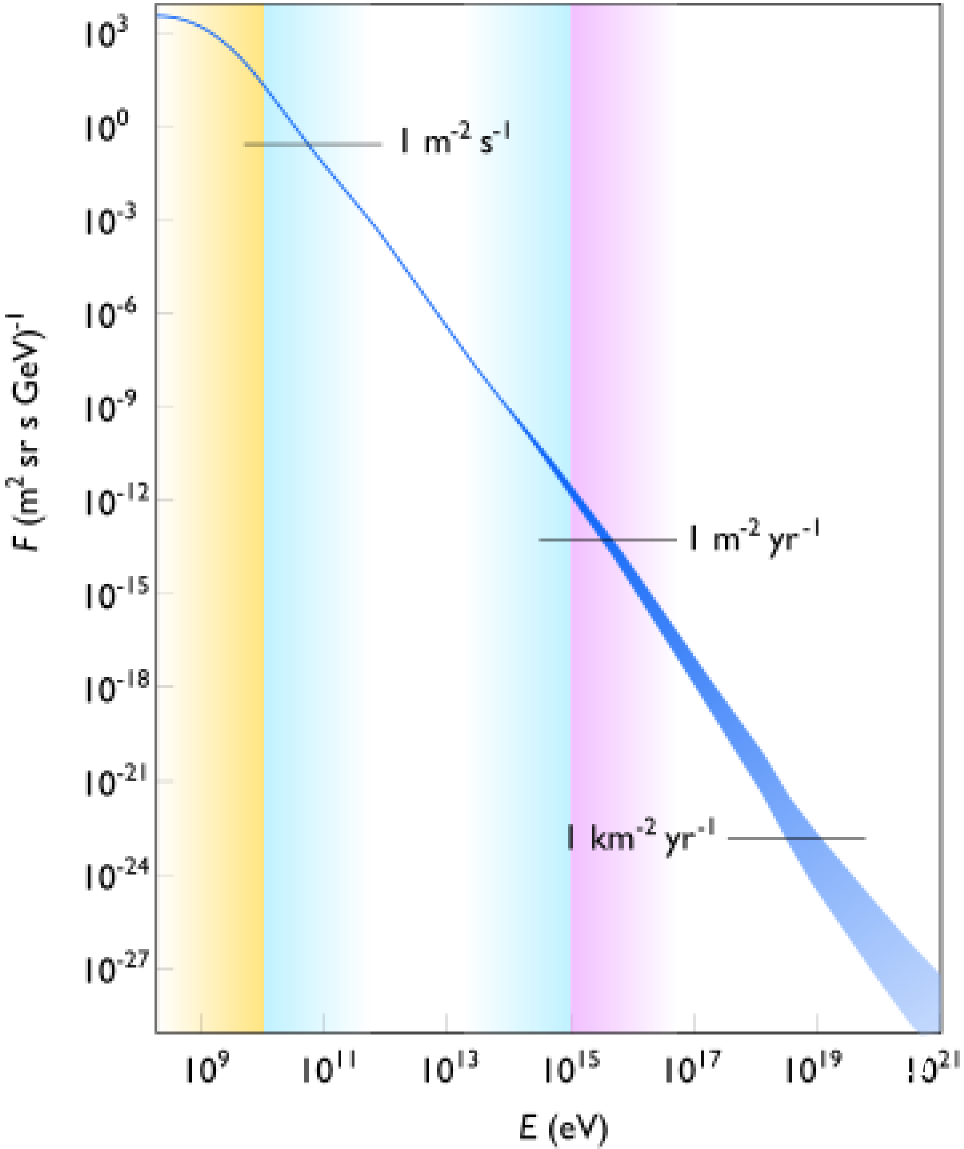
DIS = Small uncertainties.

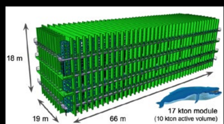
Awful nuclear cocktail from hell – challenging…

HOW TO STUDY HIGH E OSCILLATIONS

- We don’t currently have accelerator neutrino beams at these energies.
- Atmospheric neutrinos are an option.
- But those neutrinos are made by cosmic ray interactions, and the rate falls fast with energy.
- To measure ~100-1 TeV neutrinos, need a very large detector.

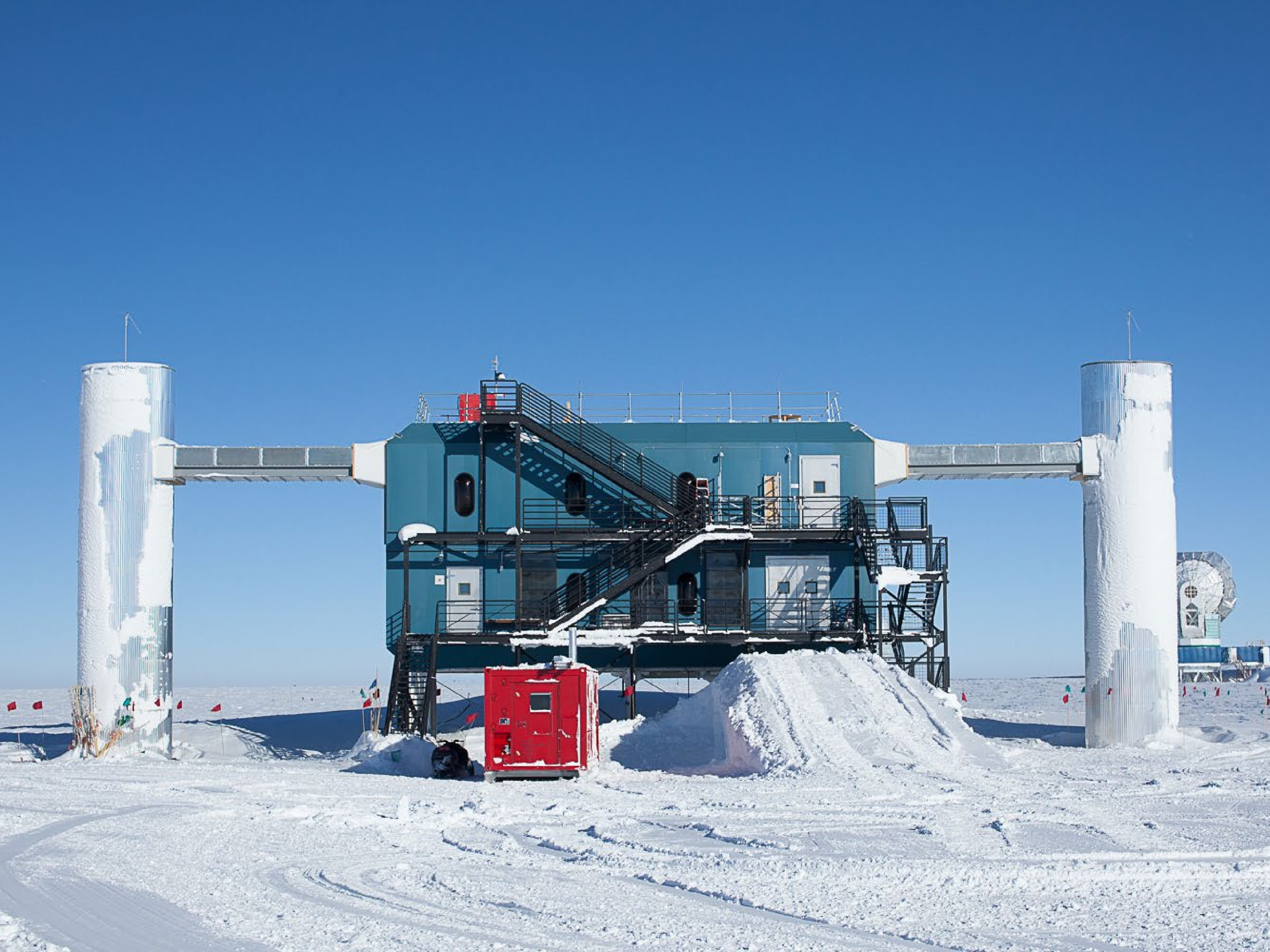
Primary cosmic ray energy spectrum

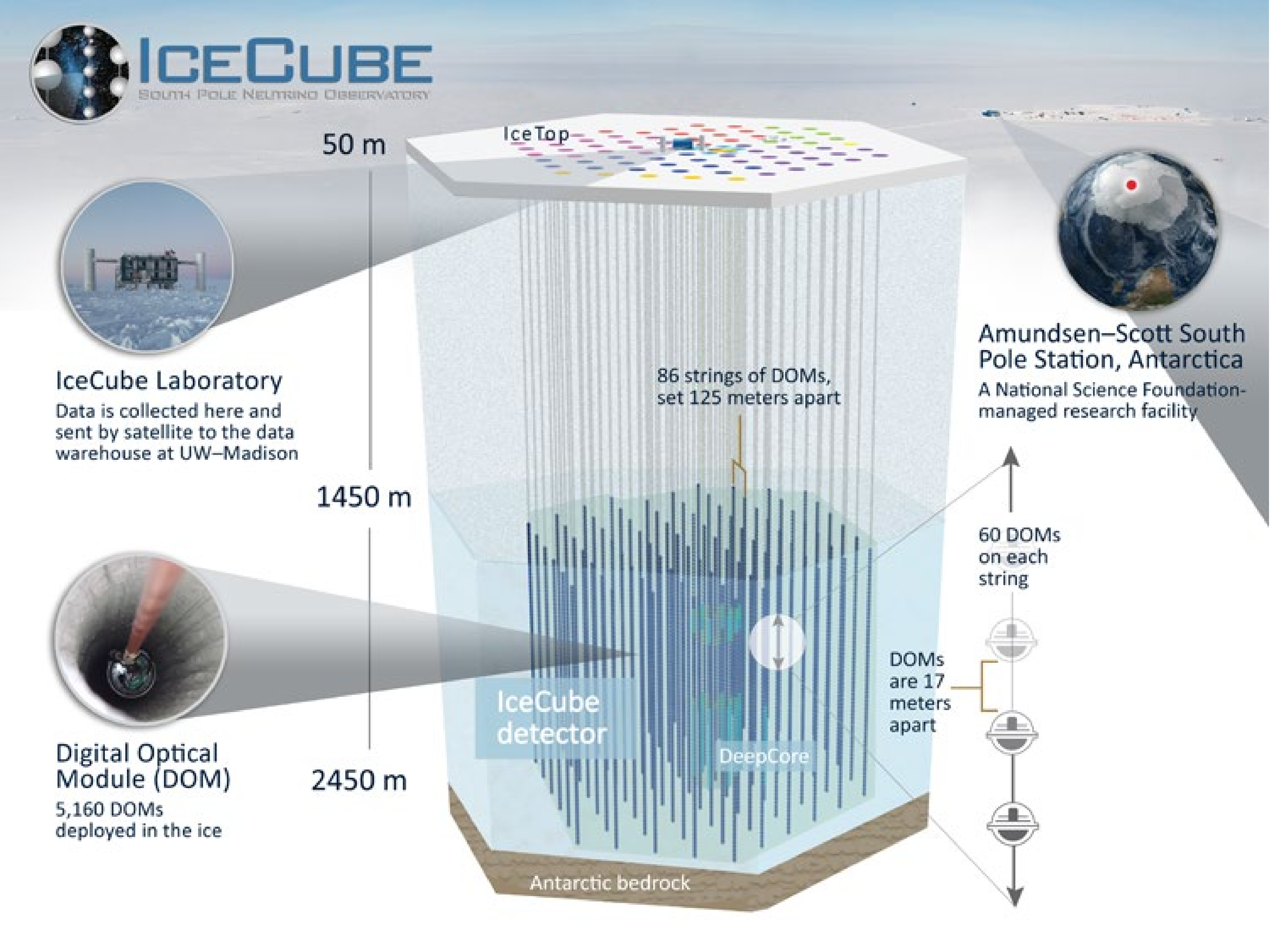




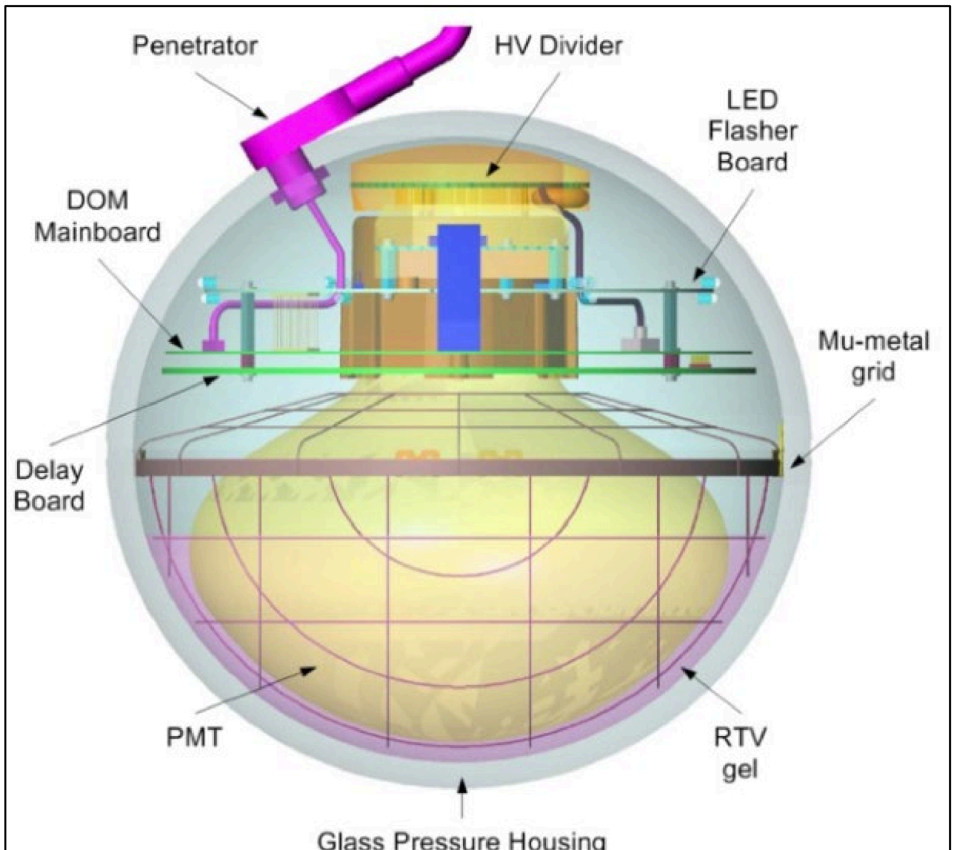
10kT DUNE far detector module, for scale

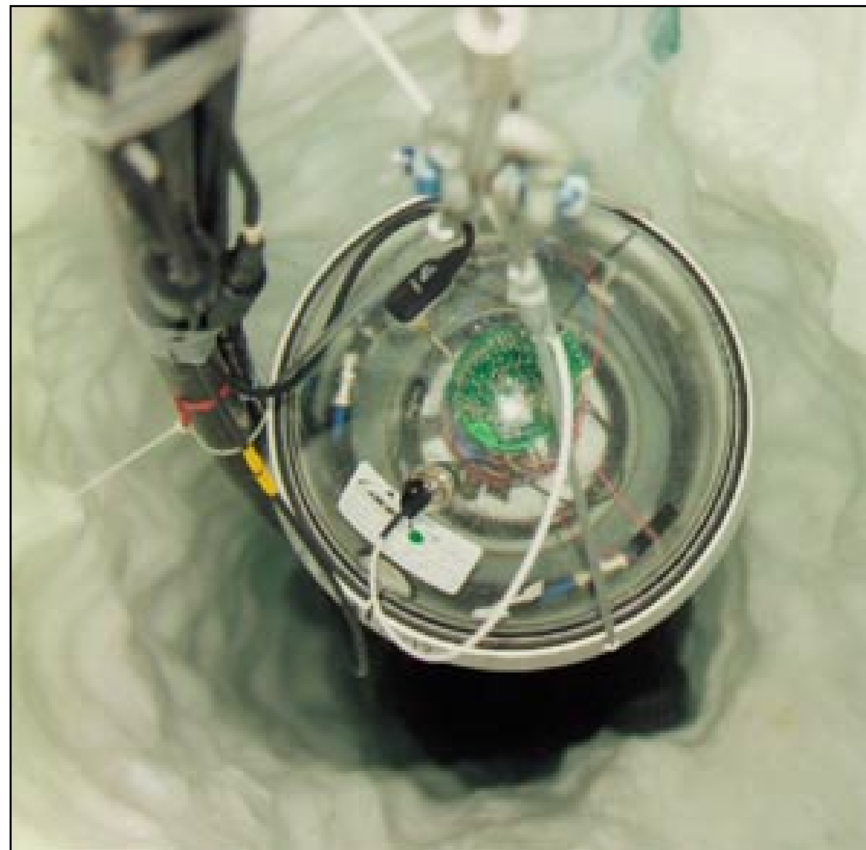
One detector this large, please.



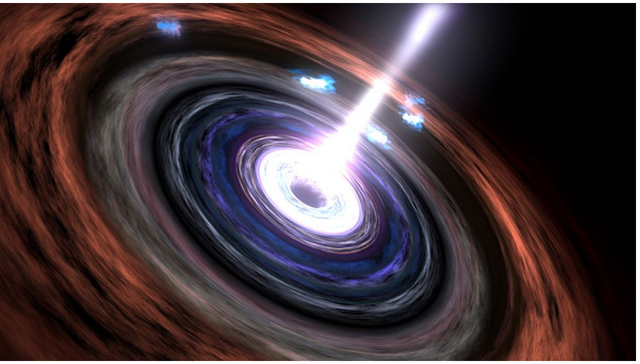

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and
sent by satellite to the data
warehouse at UW–Madison
Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice
86 strings of DOMs,
set 125 meters apart
IceCube
detector
DeepCore
Antarctic bedrock
Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility
60 DOMs
on each
string
DOMs
are 17
meters
apart

DIGITAL OPTICAL MODULES

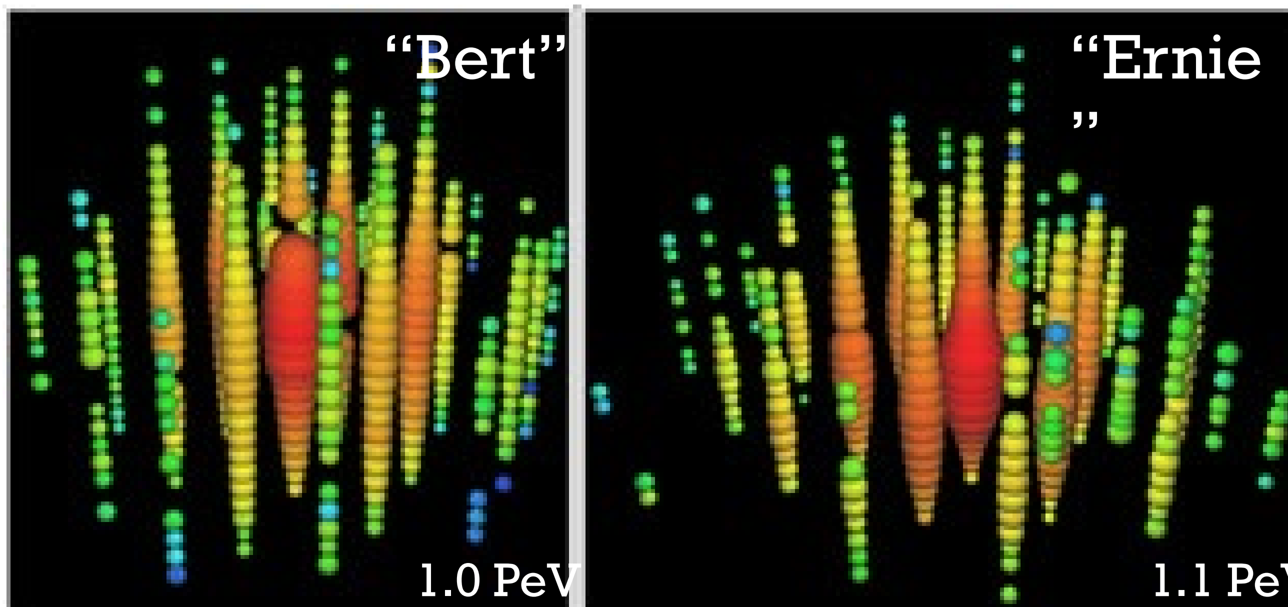




ASTROPHYSICAL NEUTRINOS



IceCube observed the flux of ultra-high-energy astrophysical neutrinos in 2013 and continues to accumulate statistics and identify sources.

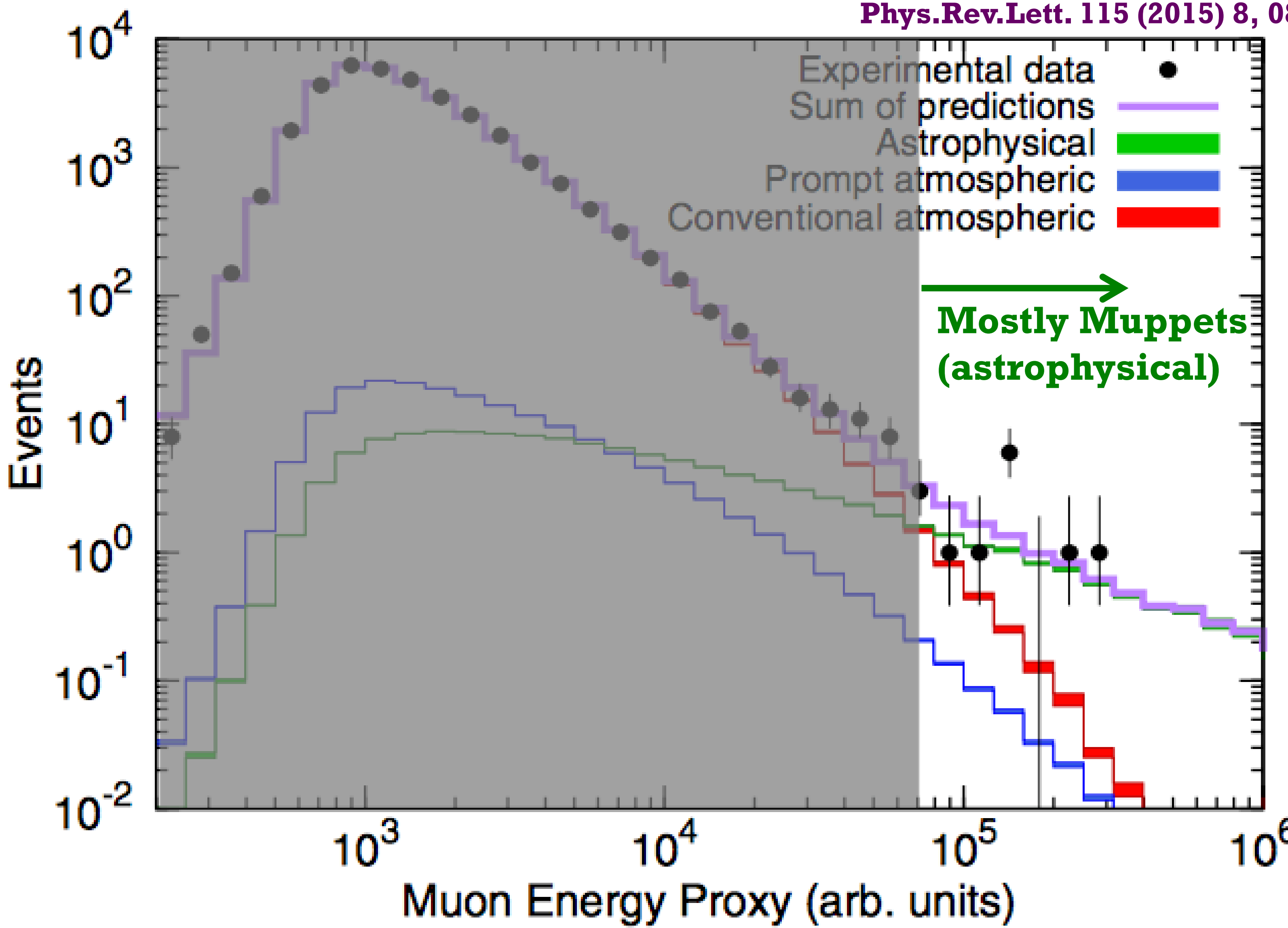


Phys.Rev.Lett. 113 (2014) 101101

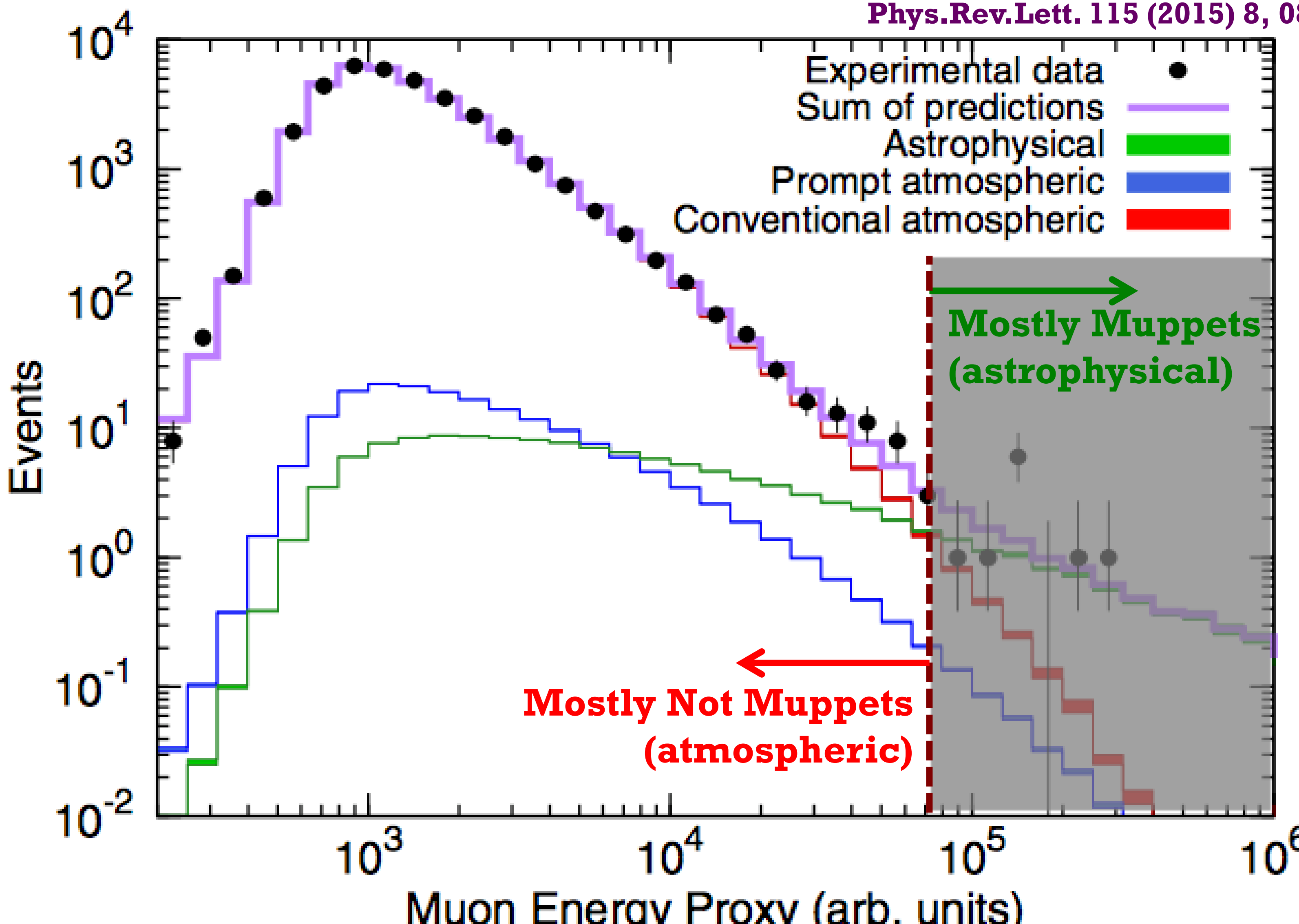
These are HESE (High Energy Starting Event) cascades

- Photons are detected at DOMs with 125 m spacing
- On-board DAQ digitizes the pulse and sends digital data to ICL at surface
- Space and time information provide event geometry and direction

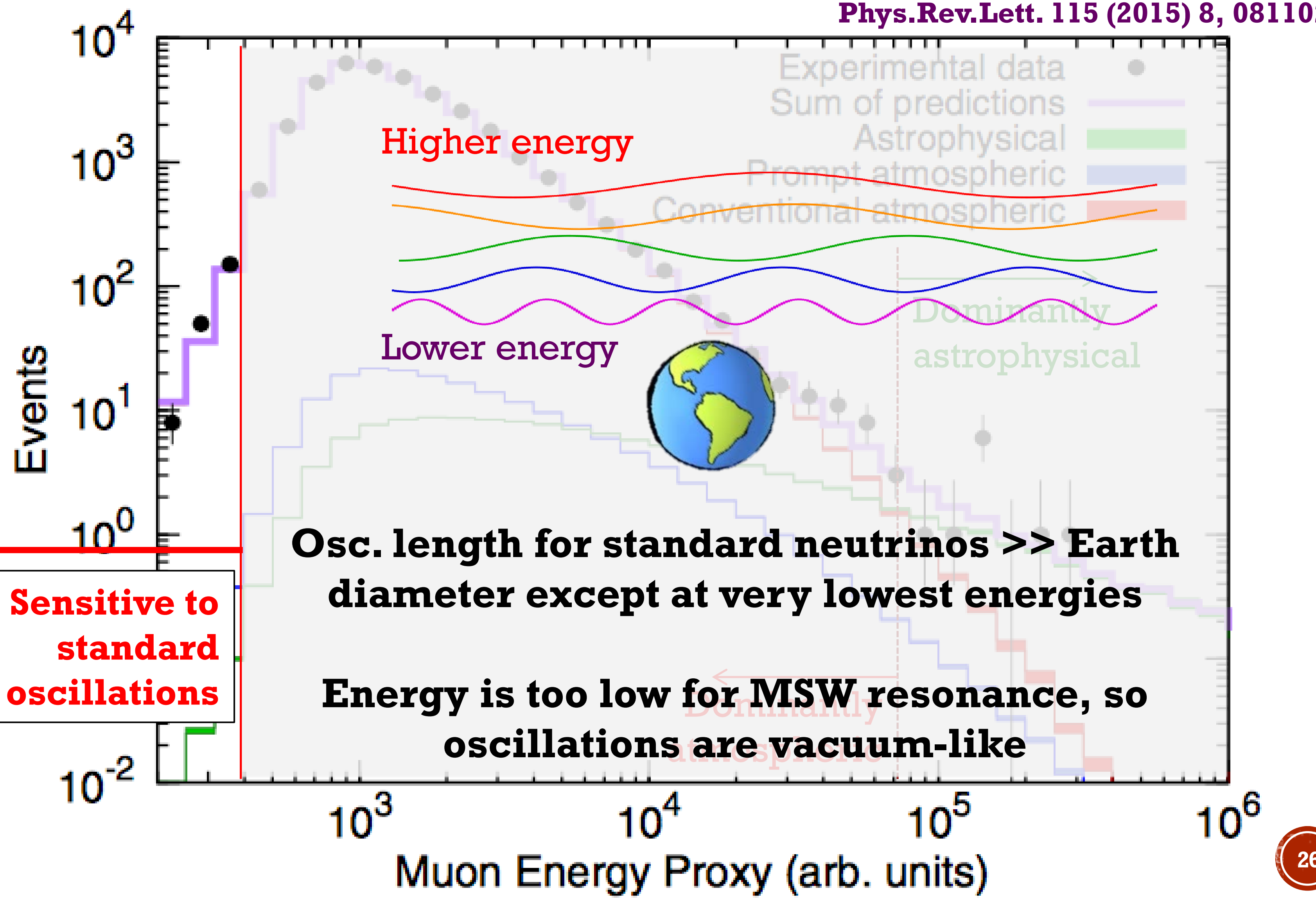
Phys.Rev.Lett. 115 (2015) 8, 081102



Phys.Rev.Lett. 115 (2015) 8, 081102



Phys.Rev.Lett. 115 (2015) 8, 081102

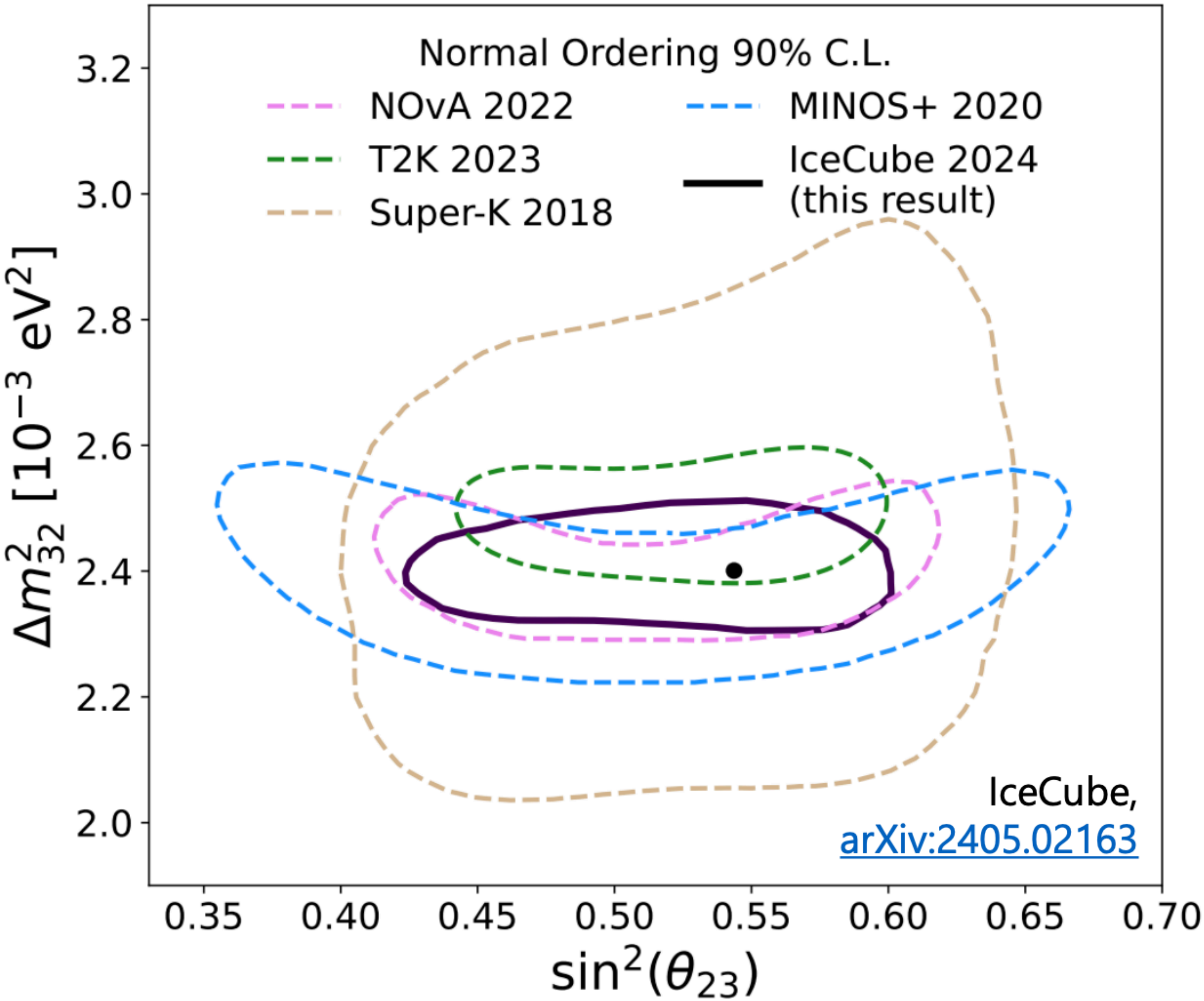


Sensitive to standard oscillations

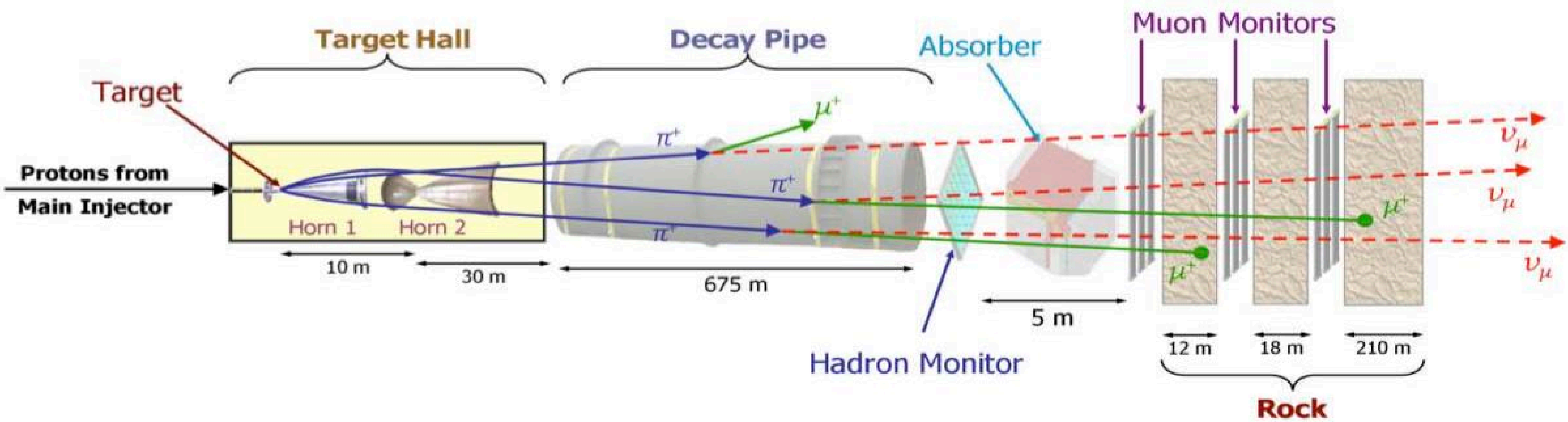
Osc. length for standard neutrinos >> Earth diameter except at very lowest energies

Energy is too low for MSW resonance, so oscillations are vacuum-like

IceCube latest result from Neutrino2024

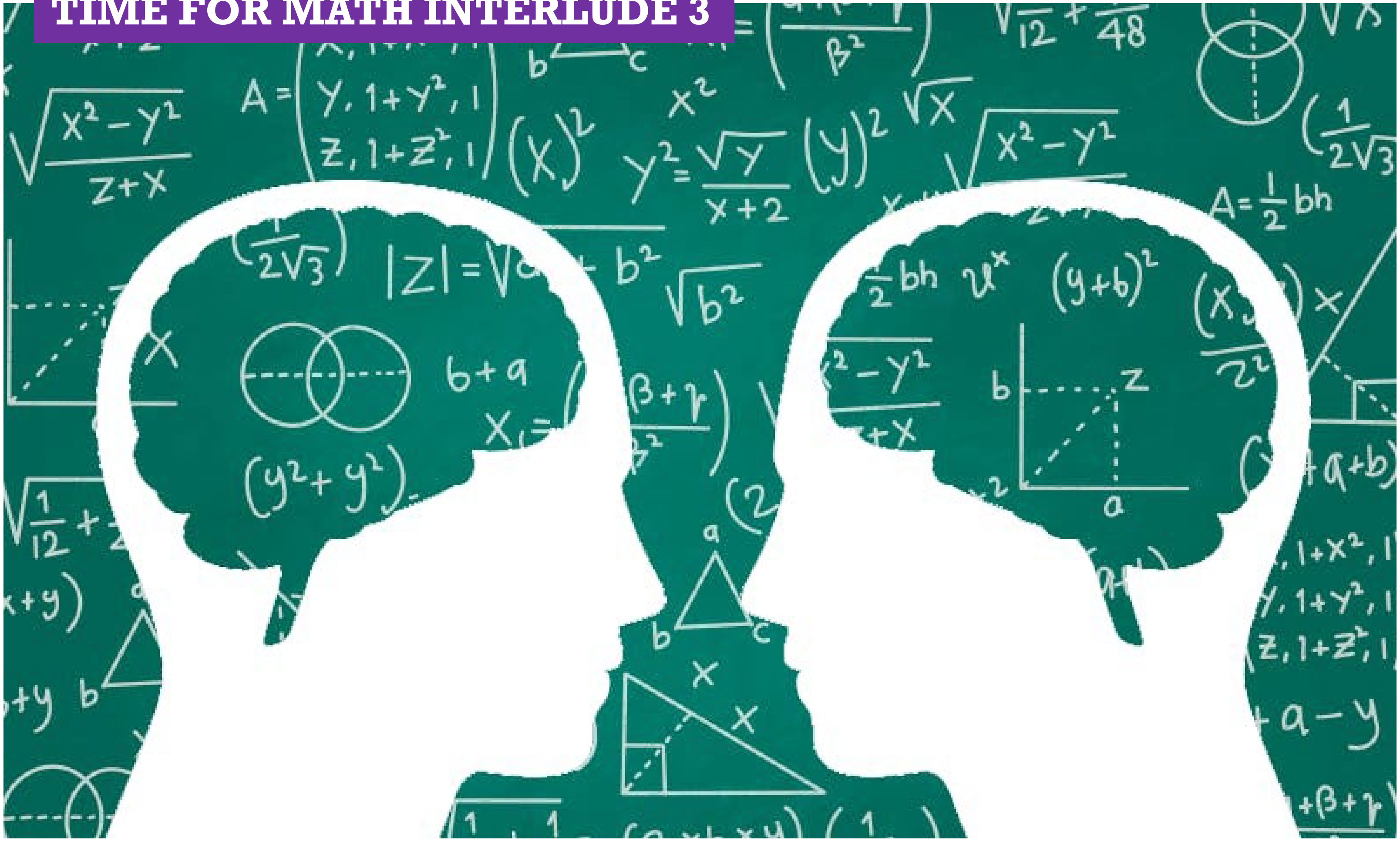


ACCELERATOR NEUTRINO EXPERIMENTS



- **Neutrinos are a "tertiary beam":**
  - Protons hit a target to make hadrons
  - Hadrons decay to make neutrinos
  - Neutrinos travel though rock at end of decay pipe while everything else is absorbed.

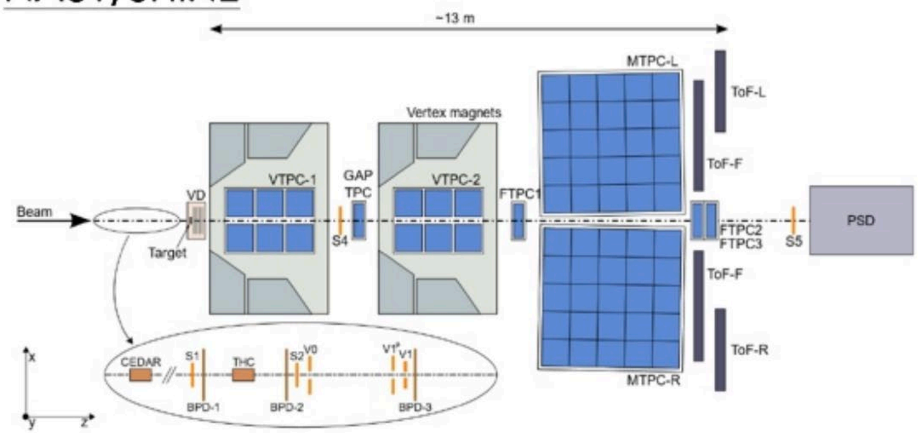
TIME FOR MATH INTERLUDE 3



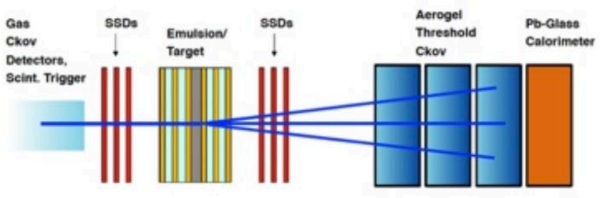
HADRONIC UNCERTAINTIES

- Flux uncertainties derive primarily from hadron production physics.

NA61/SHINE

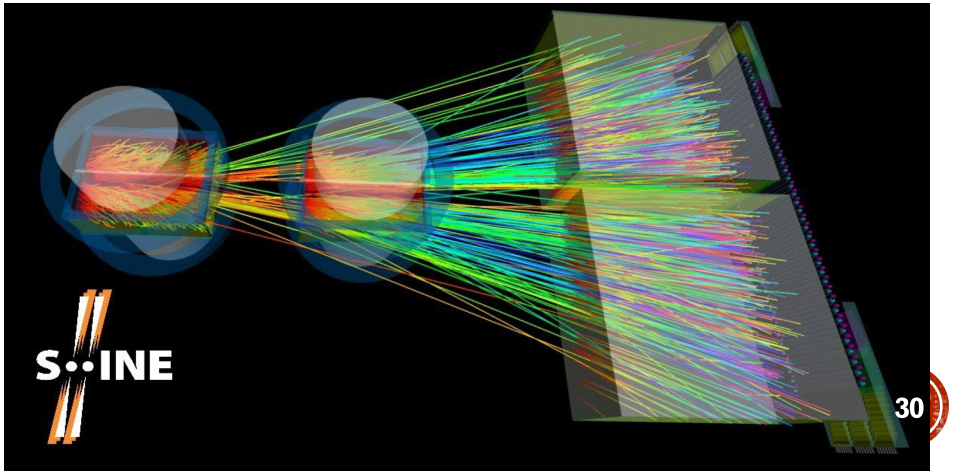


EMPHATIC



- Dedicated test beam experiments work to tune the neutrino production codes in this regime.

- The problem is far from solved.



THREE-FLAVOR OSCILLATIONS

- Technically all three neutrino masses participate in these oscillations.

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

- This actually offers a significant benefit – the possibility to probe lepton-sector CP violation (CPV is impossible with only two flavors participating)

THREE-FLAVOR OSCILLATIONS

- Technically all three neutrino masses participate in these oscillations.

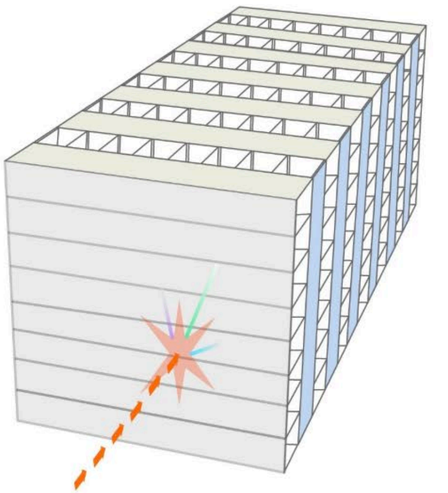
Matter Effect

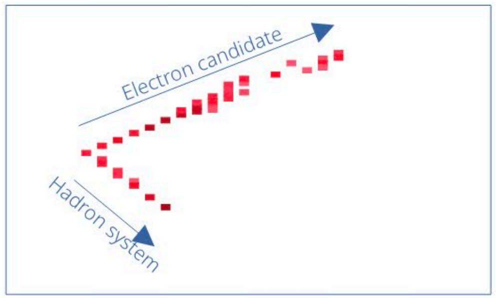
CP-violation

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta_{\rm CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

- This actually offers a significant benefit – the possibility to probe lepton-sector CP violation (CPV is impossible with only two flavors participating)

NOvA
active scintillator calorimeters

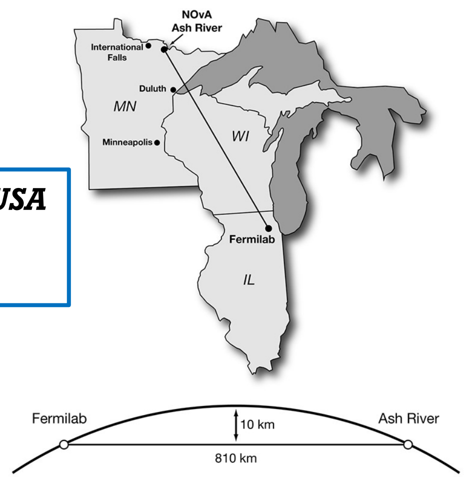




see significant energy from both lepton and hadron systems: "calorimetric" E_ν reconstruction

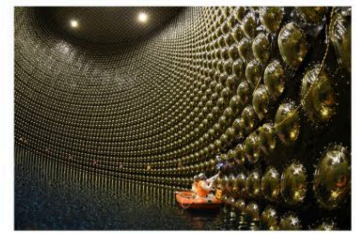
& functionally equivalent detectors

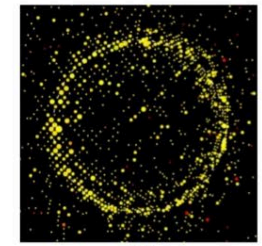
shared uncertainties mostly cancel



Fermilab to Ash River, USA
810 km
E ~ 5 GeV

T2K
water Cherenkov FD





ν_e-like

see only lepton energy: "kinematic" E_ν reconstruction

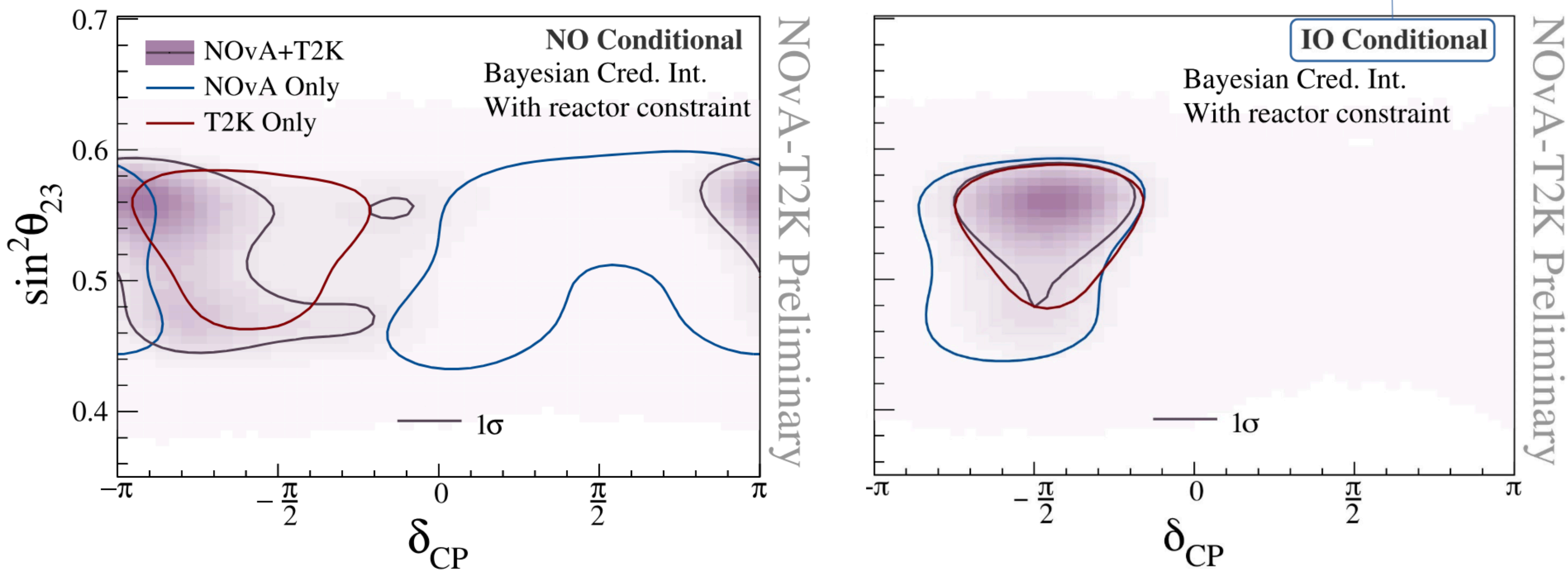
Hybrid gas TPC & scintillator tracker ND

ND+FD shared uncertainties explicitly fitted & constrained via model

JPARC to SuperK, Japan
295 km
E ~ 200 MeV

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

"assuming IO is true"
(does not include relative probability of IO vs. NO)



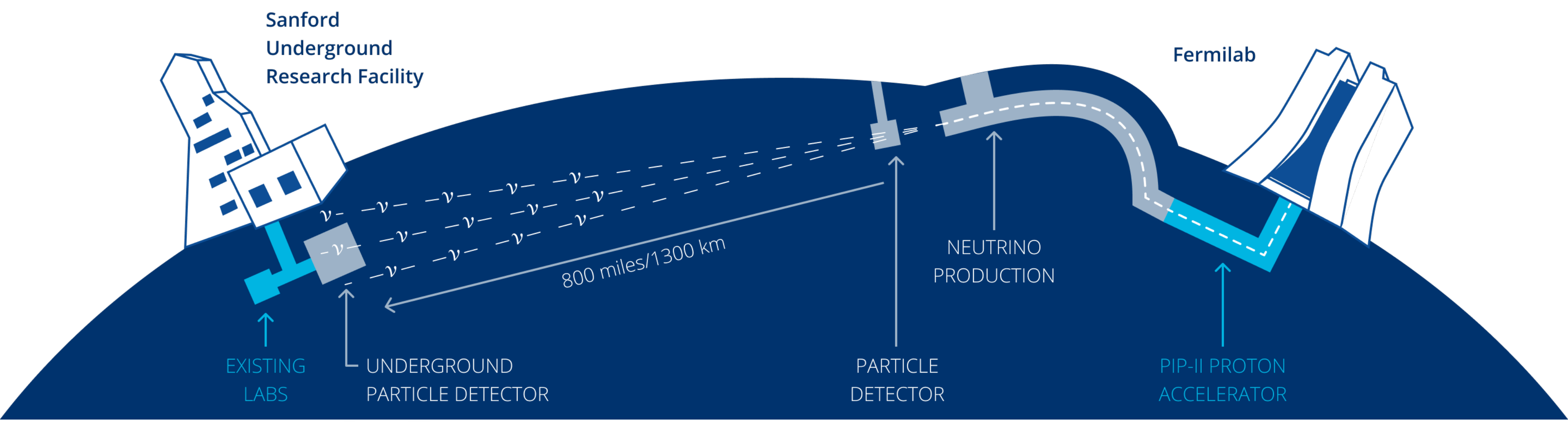
Under the normal ordering, they are in tension.

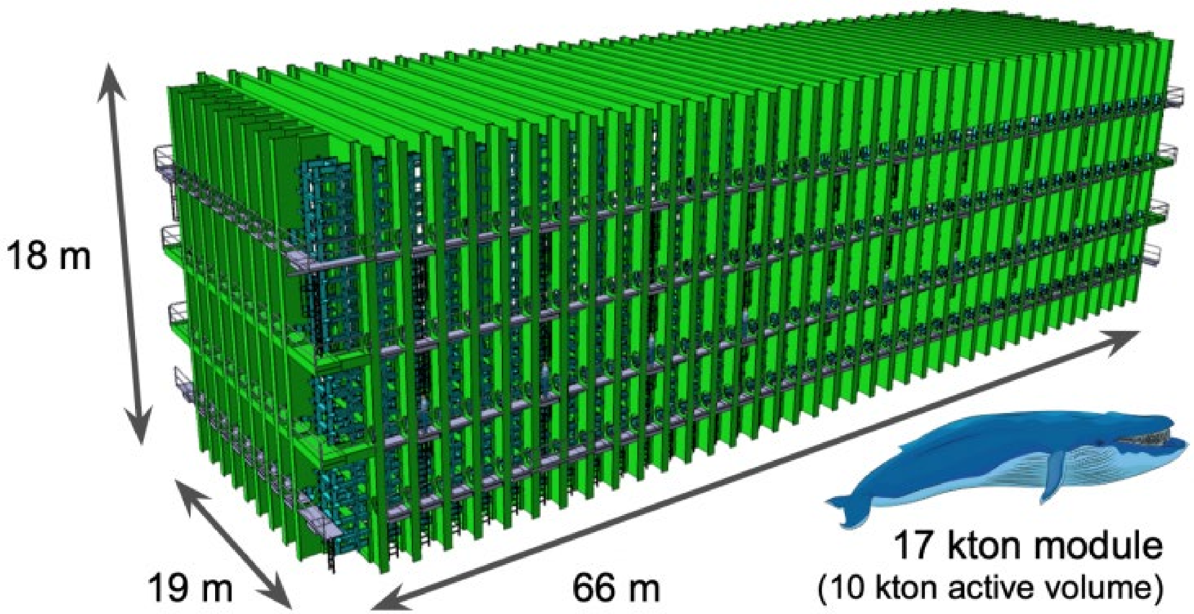
Under the inverted ordering, they more or less agree.

But other experiments marginally disfavor the inverted ordering.

Future experiments like DUNE and HyperK will need to sort this out.

DUNE


Sanford
Underground
Research Facility
Fermilab
800 miles/1300 km
NEUTRINO
PRODUCTION
EXISTING
LABS
UNDERGROUND
PARTICLE DETECTOR
PARTICLE
DETECTOR
PIP-II PROTON
ACCELERATOR


18 m
19 m
66 m
17 kton module
(10 kton active volume)

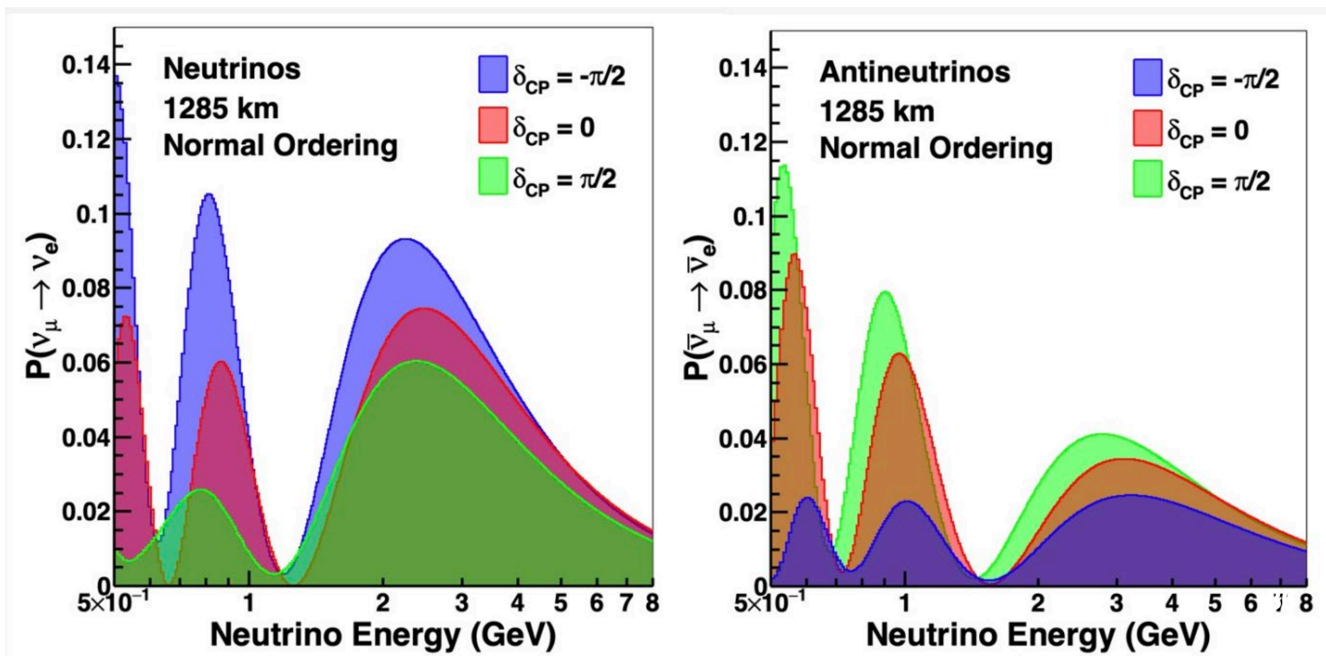
NEUTRINOS AND ANTINEUTRINOS

- On changing from neutrinos to antineutrinos, both the sign of a and the sign of delta in this equation changes.

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\rm CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

The DUNE program will operate in both neutrino and antineutrino modes to try to untangle these effects.

Potential to establish leptonic CP violation →

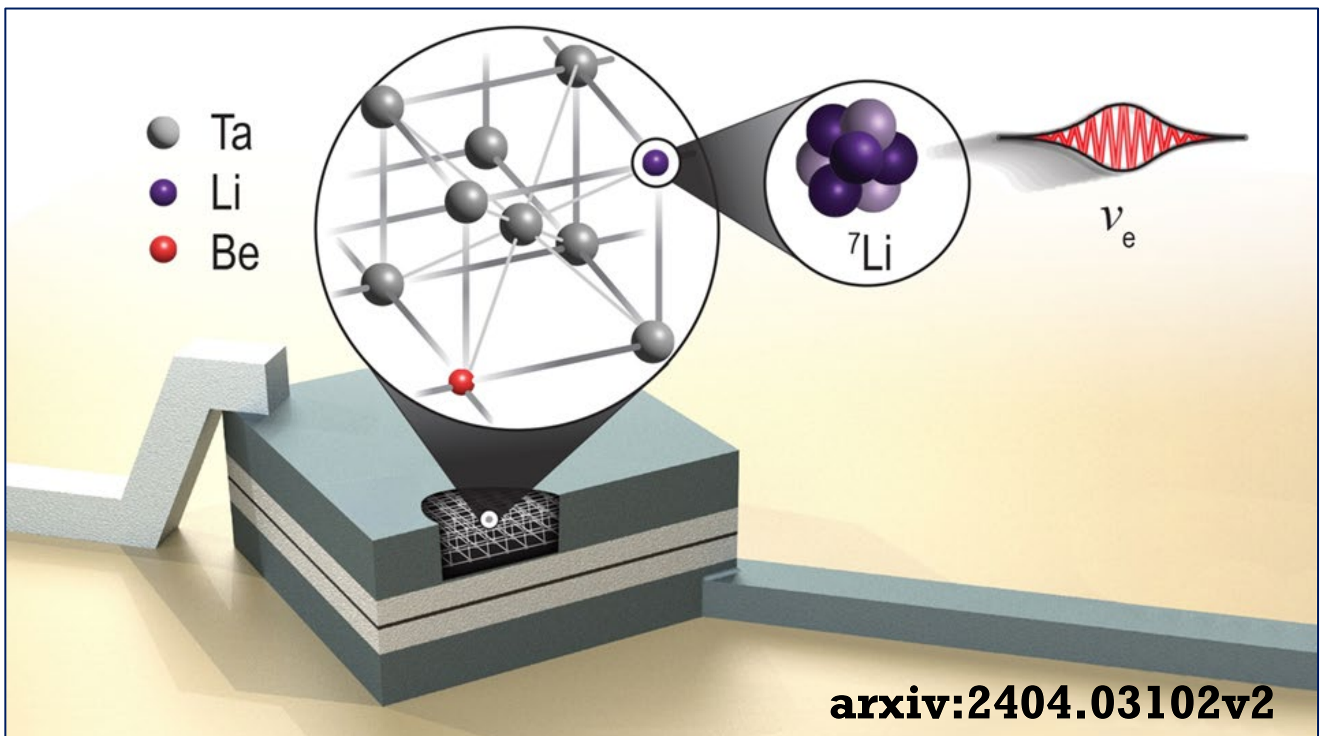


OK, TIME FOR A CHANGE OF GEAR…

(by special request of one of the NNPSS participants…)

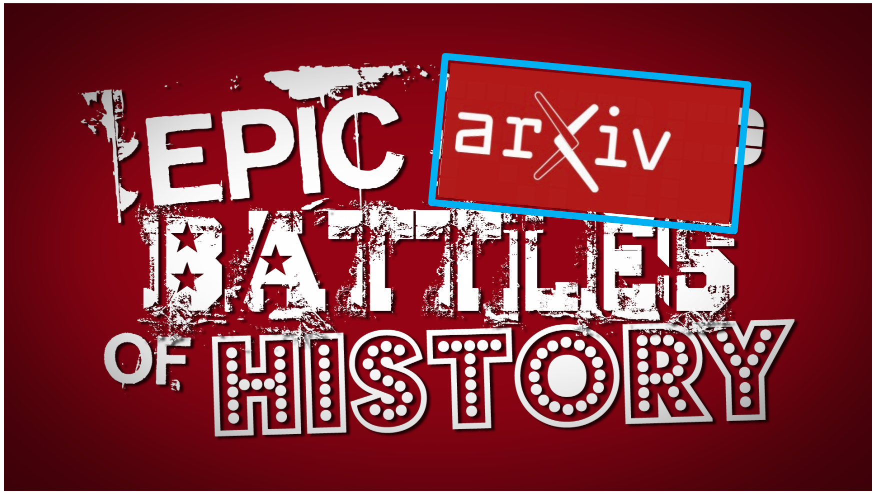
BEEST EXPERIMENT

- BeEST has recently put out a result that has generating much interest.
- Radioactive ^{7}Be atoms implanted in superconducting tunnel junctions.
- Measure the width of the electron capture spectrum and attempt to infer the neutrino wave width based on its entanglement.
- This is the **first direct attempt** to measure the neutrino wavepacket width.



LAST MINUTE PROGRAM CHANGE

(stuff I was going to show on sterile neutrinos → backups)



Since it's the final lecture…

Direct Experimental Constraints on the Spatial Extent of a Neutrino Wavepacket

Joseph Smolsky[1*], Kyle G Leach[1,2*], Ryan Abells[3], Pedro Amaro[4], Adrien Andoche[5], Keith Borbridge[1], Connor Bray[1,6],

arXiv > hep-ph > arXiv:2404.19746

High Energy Physics – Phenomenology

[Submitted on 30 Apr 2024]

The Width of an Electron-Capture Neutrino Wave Packet

B.J.P. Jones, E Marzec, J. Spitz

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Dynamical pion collapse and the coherence of conventional neutrino beams

B. J. P. Jones

Phys. Rev. D **91**, 053002 – Published 4 March 2015

Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets

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Evgeny Akhmedov and Alexei Y. Smirnov

arXiv > hep-ph > arXiv:2209.00561

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High Energy Physics – Phenomenology

[Submitted on 1 Sep 2022]

Comment on "Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets"

B.J.P. Jones

PHYSICAL REVIEW D

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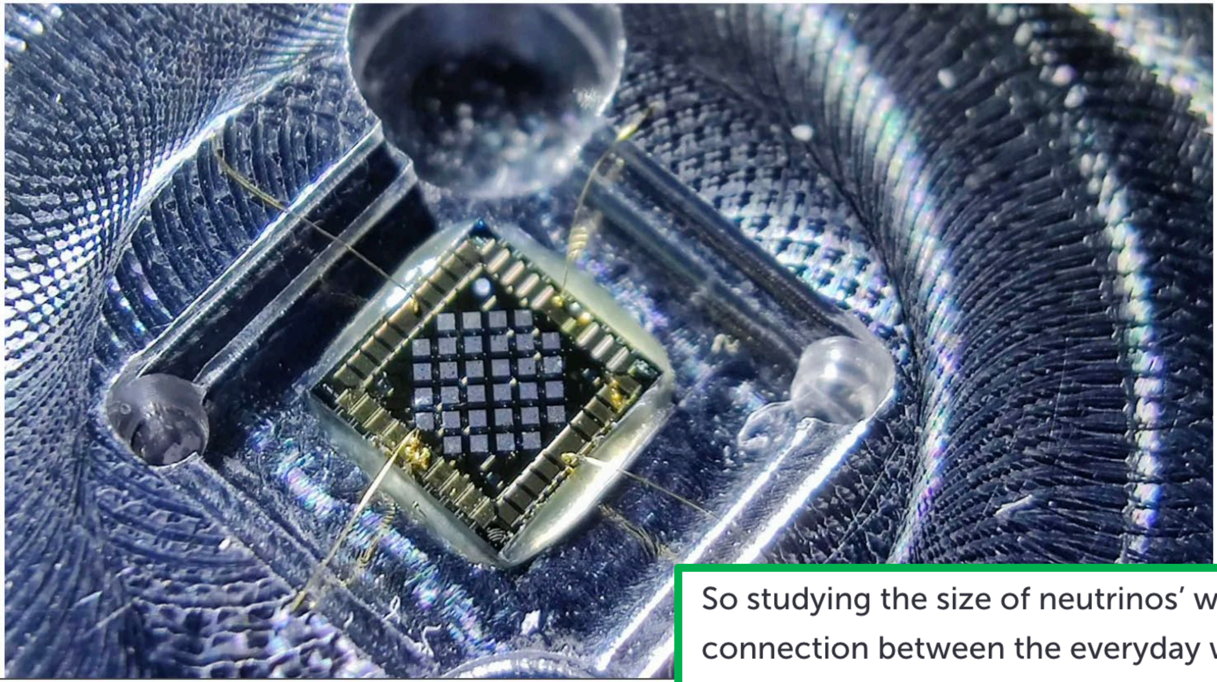
Width of a beta-decay-induced antineutrino wave packet

B. J. P. Jones, E. Marzec, and J. Spitz

Phys. Rev. D **107**, 013008 – Published 27 January 2023

The neutrino's quantum fuzziness is beginning to come into focus

Physicists set a limit on the uncertainty of the subatomic particle's position



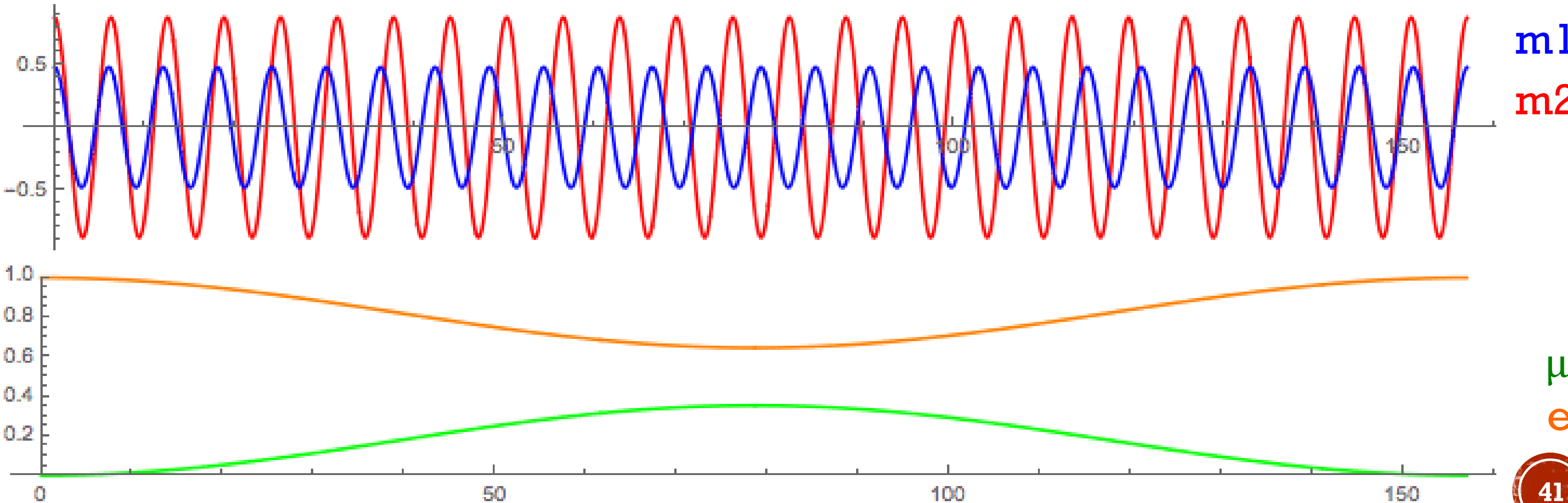
ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

So studying the size of neutrinos' wave packets could help unveil the connection between the everyday world of classical physics and the strangeness of quantum physics, says Benjamin Jones, a neutrino physicist at the University of Texas at Arlington who was not involved with the experiment. "If you can predict something like this and then measure it, then you really validate some of the ideas that people have about how the classical world emerges from an underlying quantum reality," he says. "And that's what really got me excited about this in the first place."

PLANE WAVES AND OSCILLATIONS

Many have identified problems with this picture. It implies:

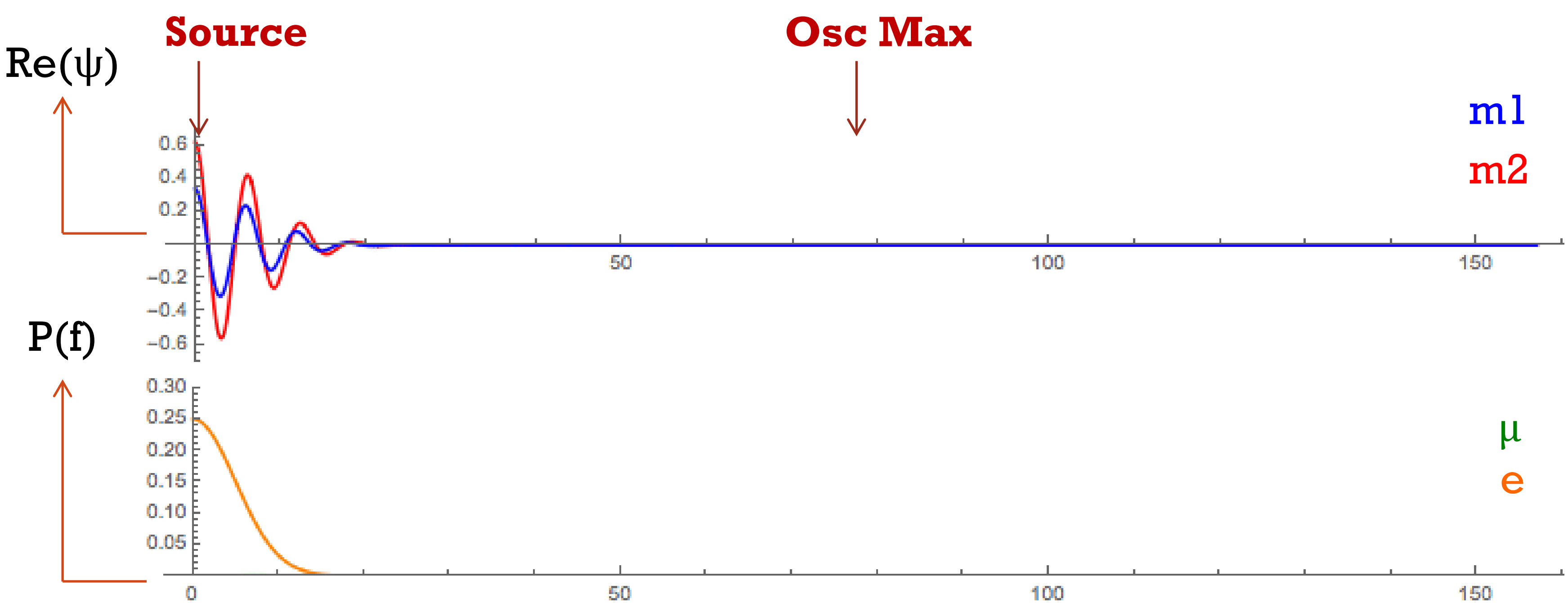
1) Neutrino can be anywhere, at any time (and zero probability to be there!)
2) Superluminal transmission is possible
3) Perfect energy definition forbids oscillations.
4) Same energy or same momentum? *Etc etc*



PROPAGATION WITH WAVEPACKETS

No process can make a neutrino of perfectly defined momentum.

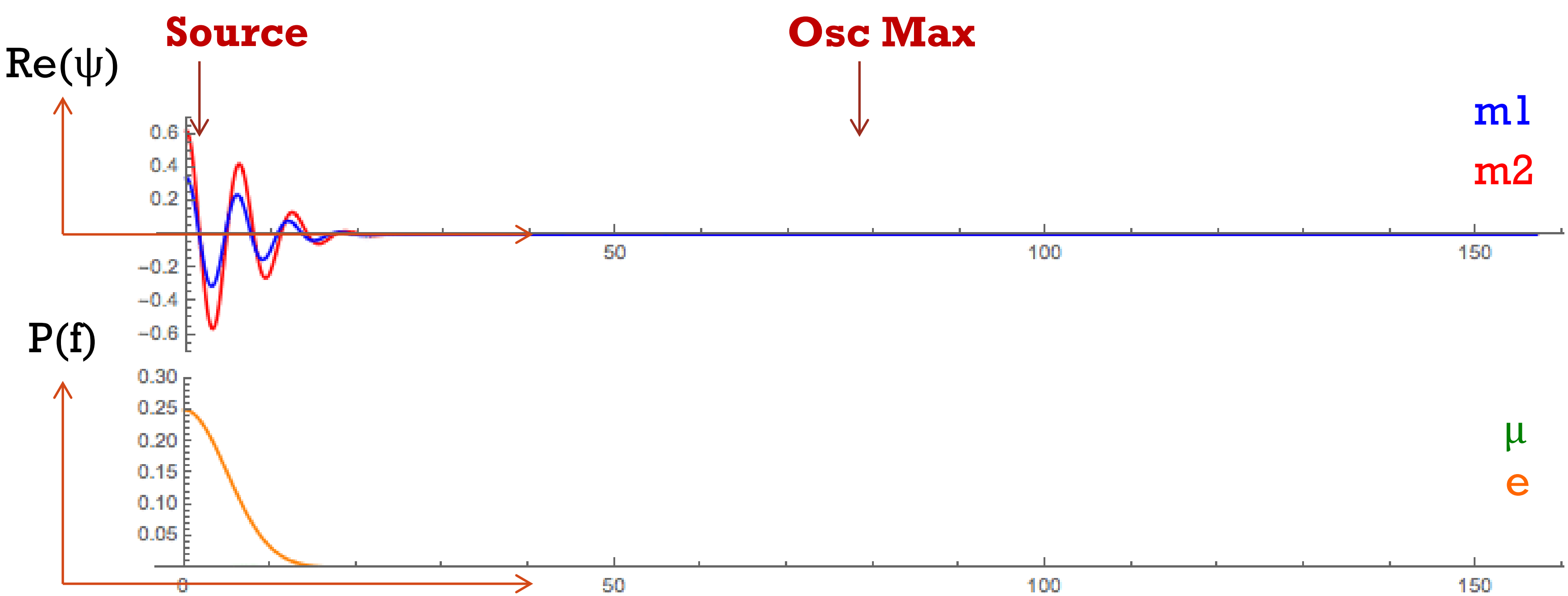
Source makes a wave-packet with some momentum and some position width



- Phase velocity is not changed – so neither is oscillation length
- Wave-packet moves with group velocity of approx. c for very light neutrinos

PROPAGATION WITH WAVEPACKETS

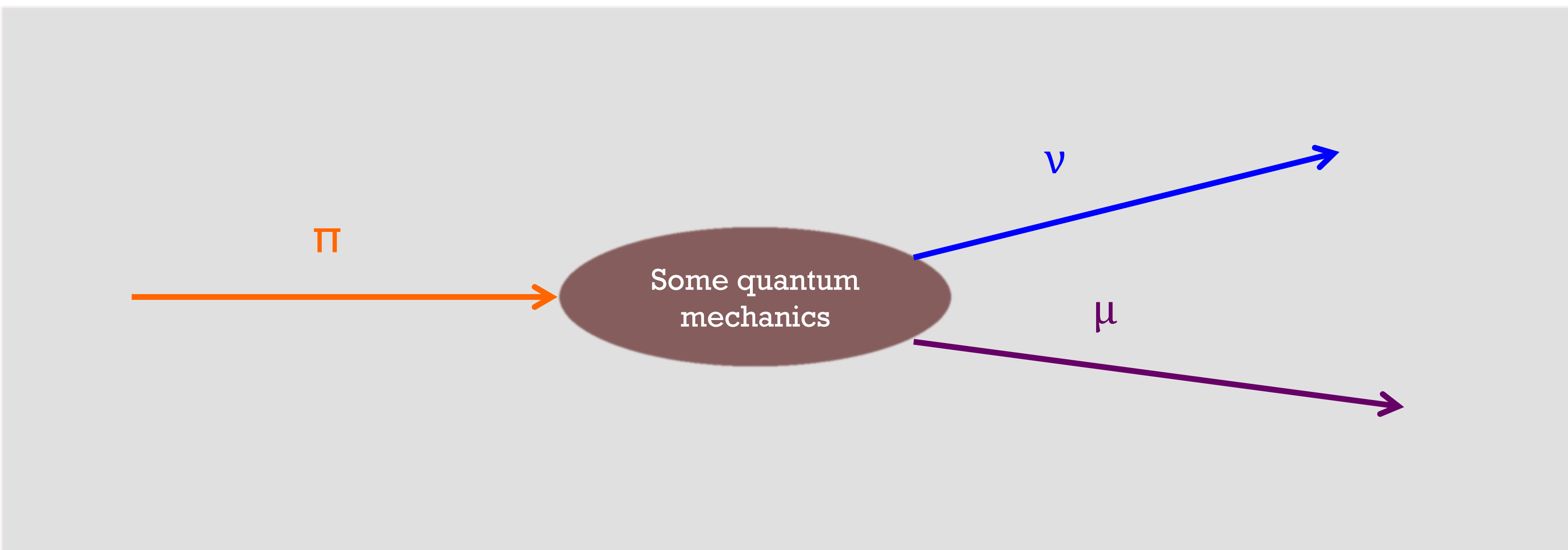
Because the different mass states have different group velocities, they go at different speeds. Eventually they will separate and not oscillate any more.



- This is sometimes called "decoherence" but I'll call it "coherence loss" to distinguish from beyond-standard-model decoherence.

SO, HOW FAR TIL THAT HAPPENS??

To predict the coherence distance we need to know the wave packet width.

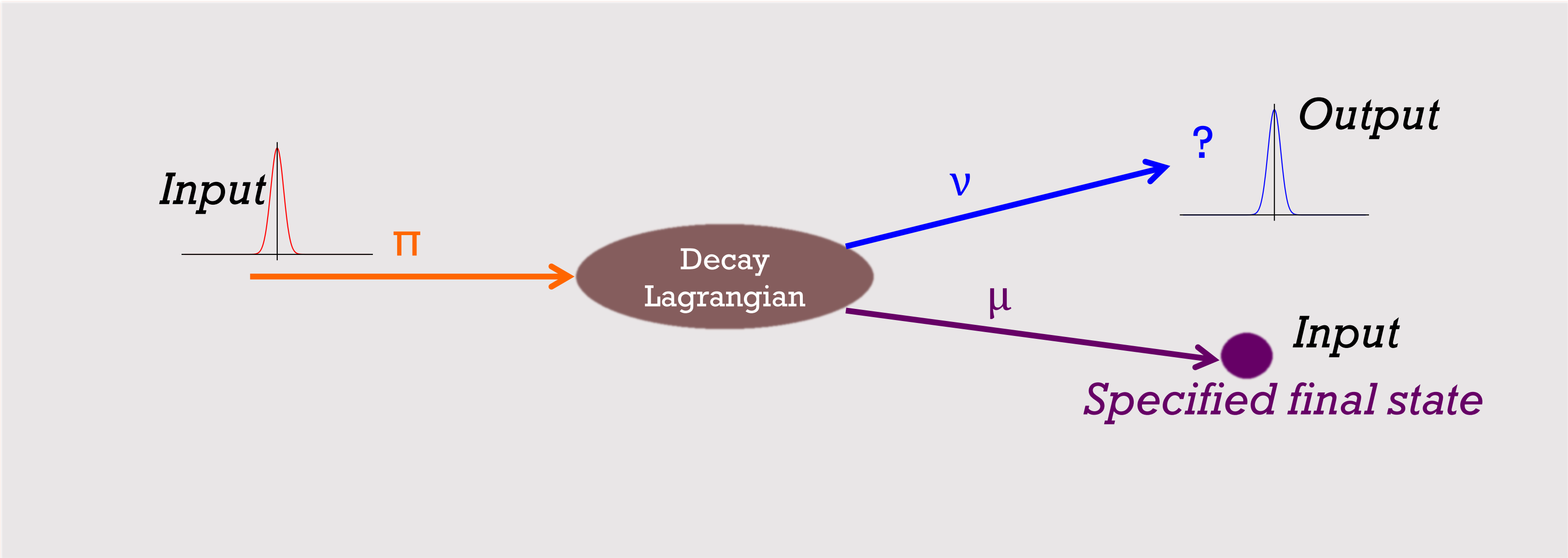


Is our understanding of neutrino production processes sufficiently descriptive to let us predict the wave packet width?

EXTERNAL WAVE-PACKET PICTURE

- Some progress was made by Beuthe, Akmedov +Smirnov :

- They calculated neutrino state emerging from a pion of a specified width, alongside a specified detected muon



Phys. Rept 375, 2-3, 105, 2003
Phys.Atom.Nucl.72:1363-1381, 2009

But …
now there are two unknown states, rather than one!

EXTERNAL WAVE-PACKET PICTURE

- Having done the calculation to go parent → neutrino,
- The favored approach to calculate the parent width is to…

- **Wave our hands enthusiastically and make something up!**

- *The width of the incoming pion wave-packet must be:*

1. **The inverse of its mass width?**
2. **The mean-free path between collisions?**
3. **Something to do with its form factor / physical size?**
4. **The length of the decay region?**
5. **The amount of time the experimentalist wasn't paying attention?**
6. **Very small / big / … something?**

?

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For every complex problem, there is an answer that is clear, simple, elegant, and wrong (H.L.Mencken)

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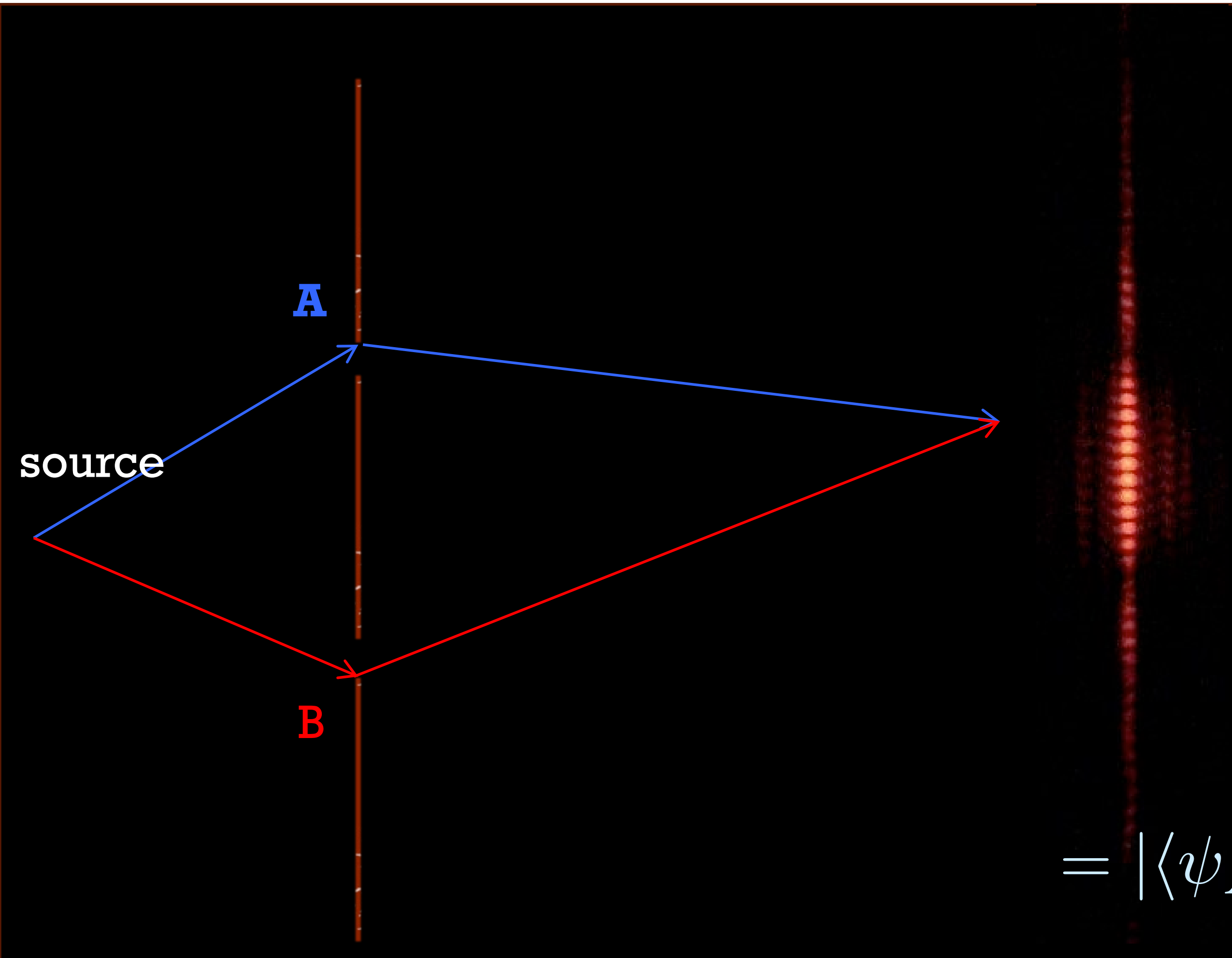
For every complex problem, there is an answer that is clear, simple, elegant, and wrong (H.L.Mencken)

Many people have strong feelings about their favorite. But we need a rigorous recipe to separate the viable from non-viable options.

YOUNGS TWO-SLIT EXPERIMENT



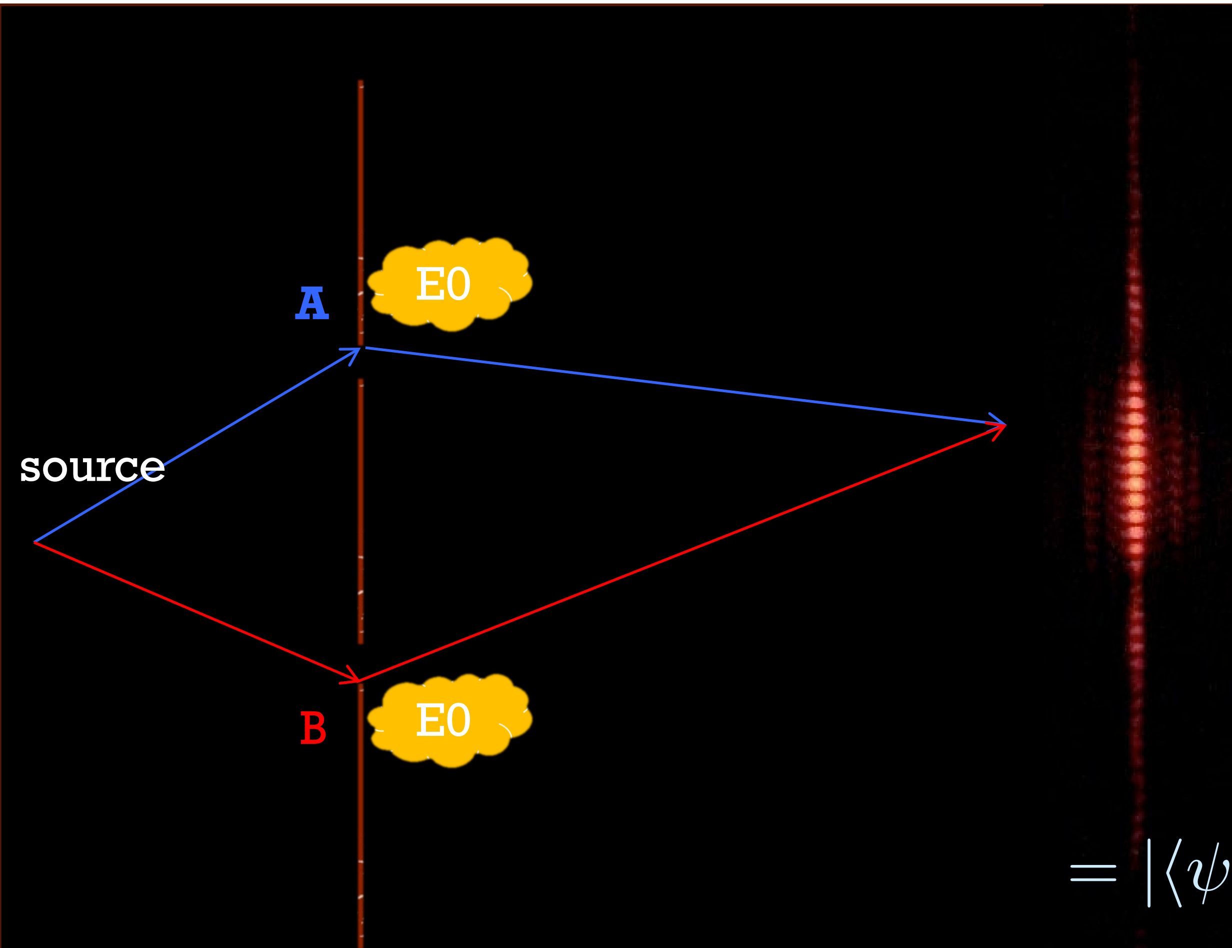
$$I = |\langle\psi|\psi\rangle|^2$$

$$= |\langle\psi_A + \psi_B|\psi_A + \psi_B\rangle|^2$$

$$= |\langle\psi_A|\psi_A\rangle + \langle\psi_B|\psi_B\rangle + 2Re\langle\psi_A|\psi_B\rangle|^2$$

YOUNGS TWO-SLIT EXPERIMENT

What if we add an environment?



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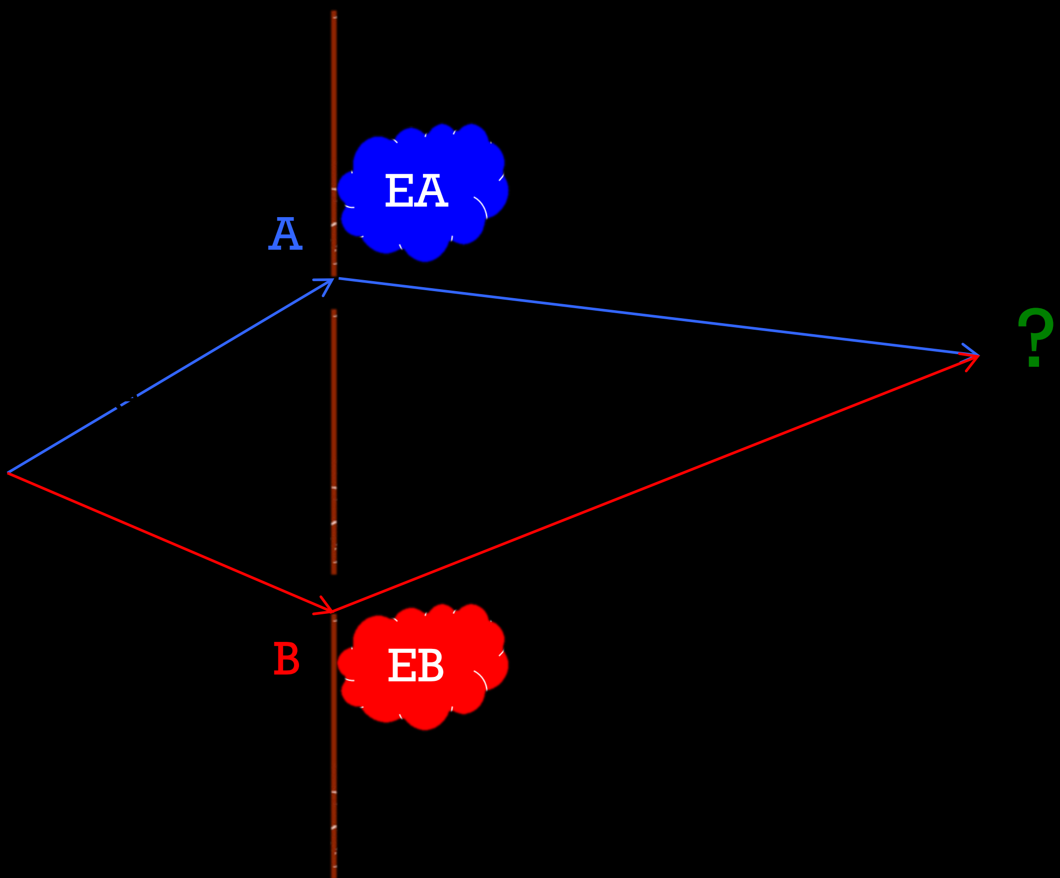


The particle becomes entangled with the environment via its interactions

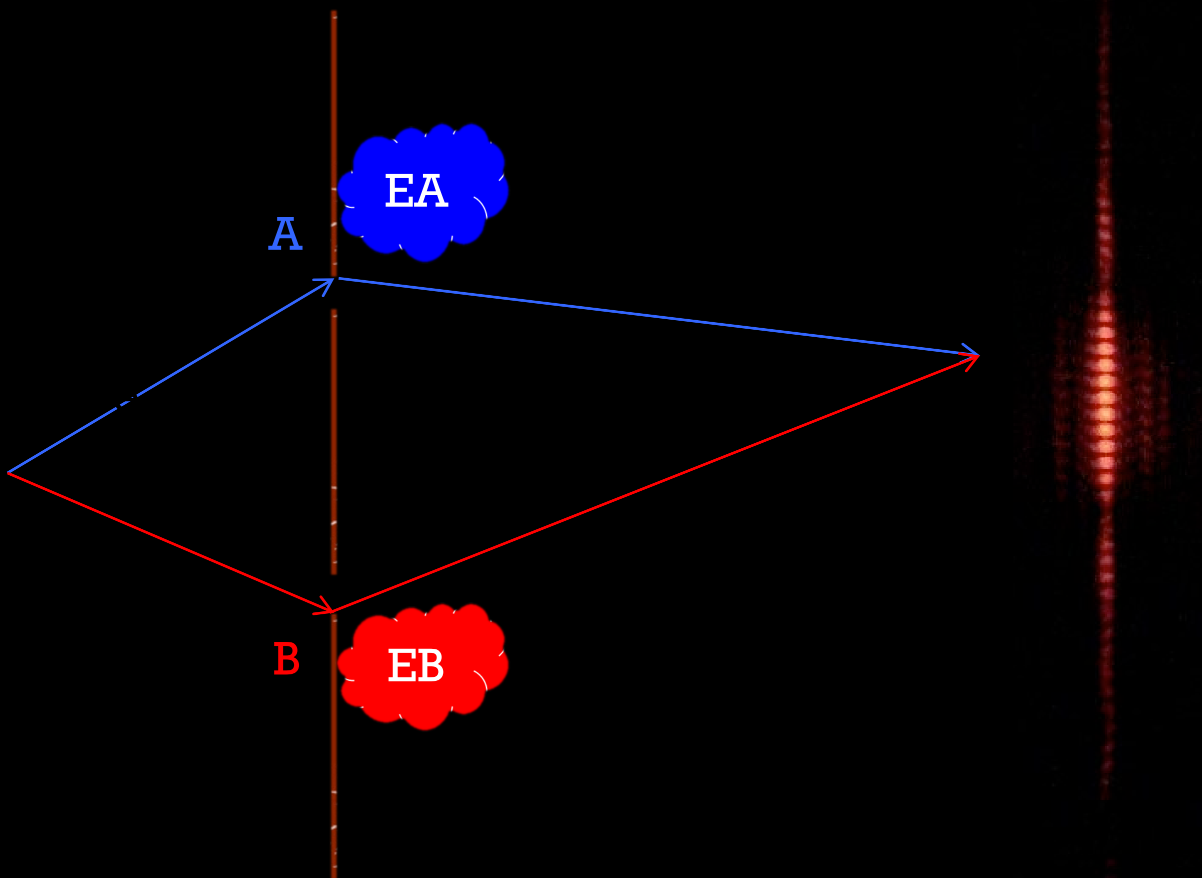
$$|\psi_A>|E_0>\rightarrow|\psi_A>|E_A>$$
$$|\psi_B>|E_0>\rightarrow|\psi_B>|E_B>$$

The interference pattern now depends on how much overlap there is between E_A, E_B

$$I=|\langle\psi|\psi\rangle|^2$$

$$=|\langle\psi_A|\psi_A\rangle+\langle\psi_B|\psi_B\rangle+2Re\langle\psi_A|\psi_B\rangle\langle E_A|E_B\rangle|^2$$

YOUNGS TWO-SLIT EXPERIMENT



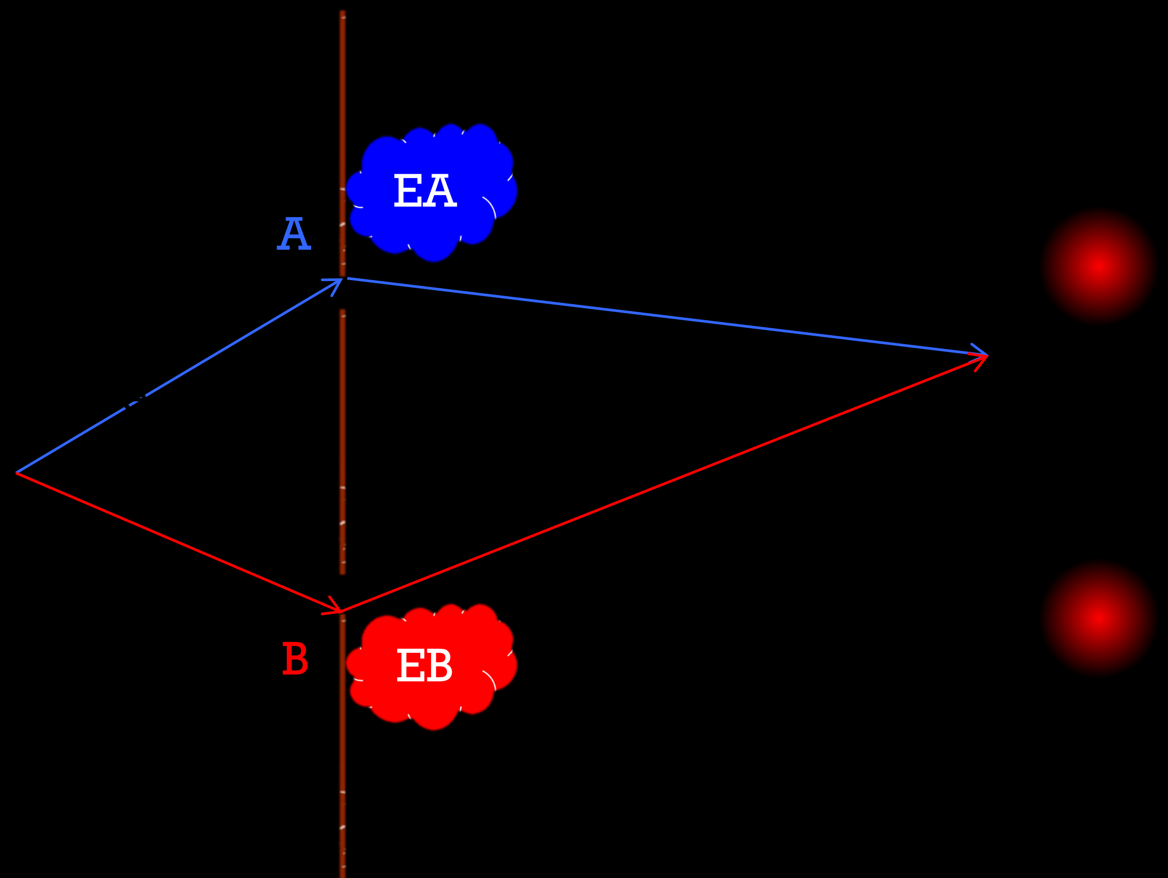
Extreme cases :

$$< E_A | E_B >= 1$$

Fully quantum-mechanical-looking particles

$$= |\langle\psi_A|\psi_A\rangle + \langle\psi_B|\psi_B\rangle + 2Re\langle\psi_A|\psi_B\rangle\langle E_A|E_B\rangle|^2$$

YOUNGS TWO-SLIT EXPERIMENT



Extreme cases :

$$< E_A | E_B >= 0$$

Fully classical-looking particles

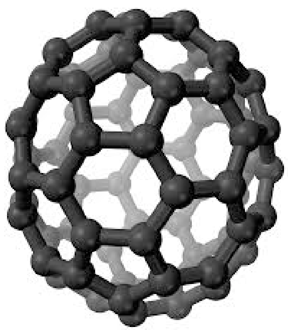
$$= |\langle \psi_A | \psi_A \rangle + \langle \psi_B | \psi_B \rangle + 2Re \langle \psi_A | \psi_B \rangle \langle E_A | E_B \rangle|^2$$

SEEING DECOHERENCE IN PRACTICE

VOLUME 88, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 2002

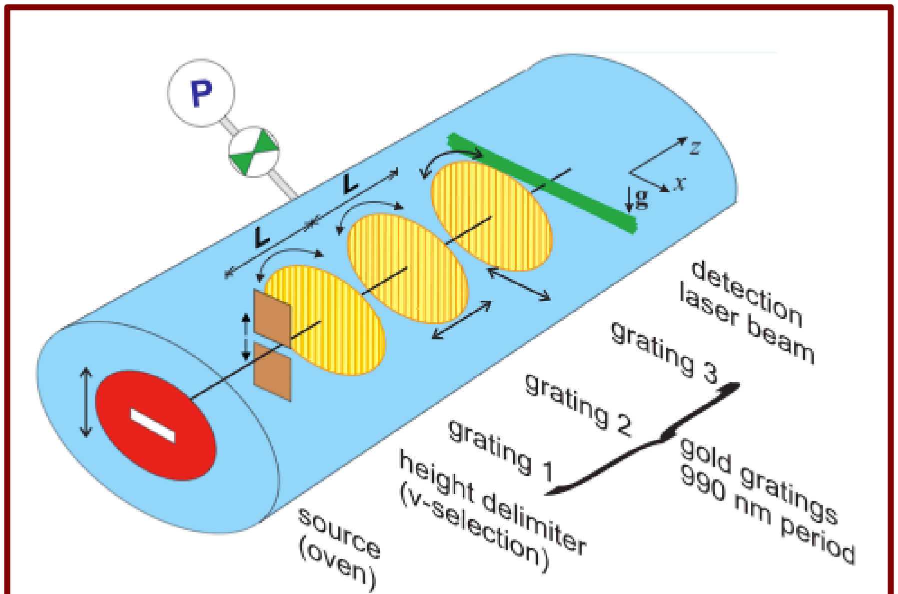
Matter-Wave Interferometer for Large Molecules

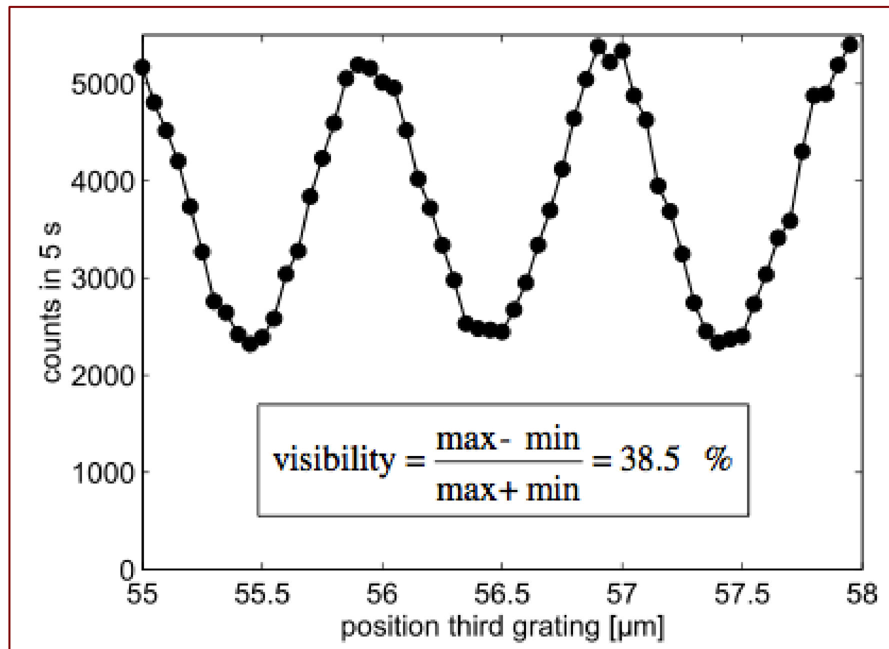
Björn Brezger, Lucia Hackermüller, Stefan Uttenthaler, Julia Petschinka, Markus Arndt, and Anton Zeilinger*
Universität Wien, Institut für Experimentalphysik, Boltzmanngasse 5, A-1090 Wien, Austria
(Received 20 November 2001; published 26 February 2002)



e.g. Talbot Lau interferometry with C_{70} fullerenes

This experiment has in fact been done!





Appl. Phys. B 77, 781–787 (2003)
DOI: 10.1007/s00340-003-1312-6
Applied Physics B
Lasers and Optics

Decoherence in a Talbot–Lau interferometer: the influence of molecular scattering

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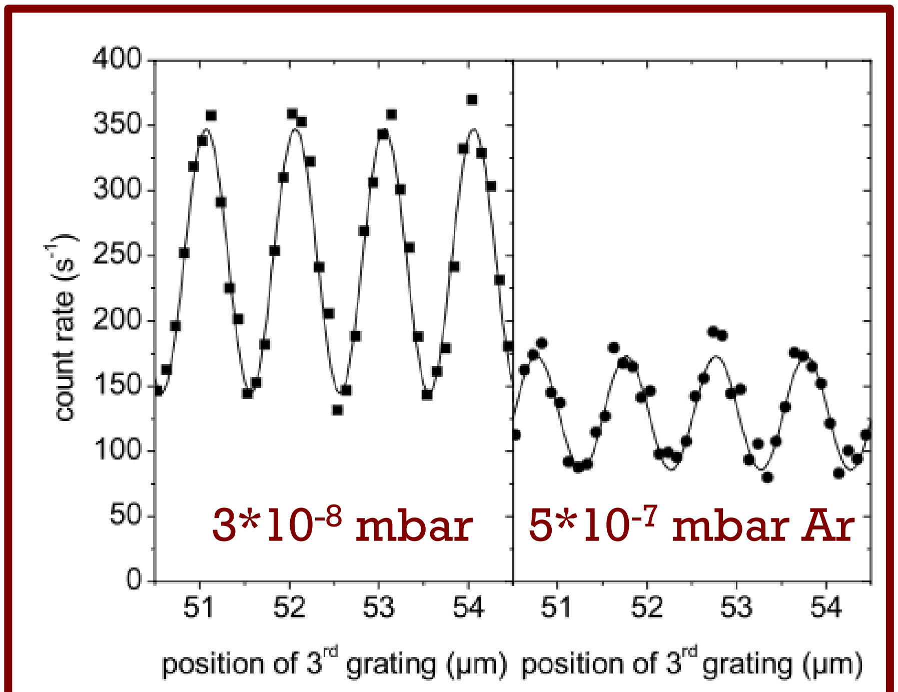
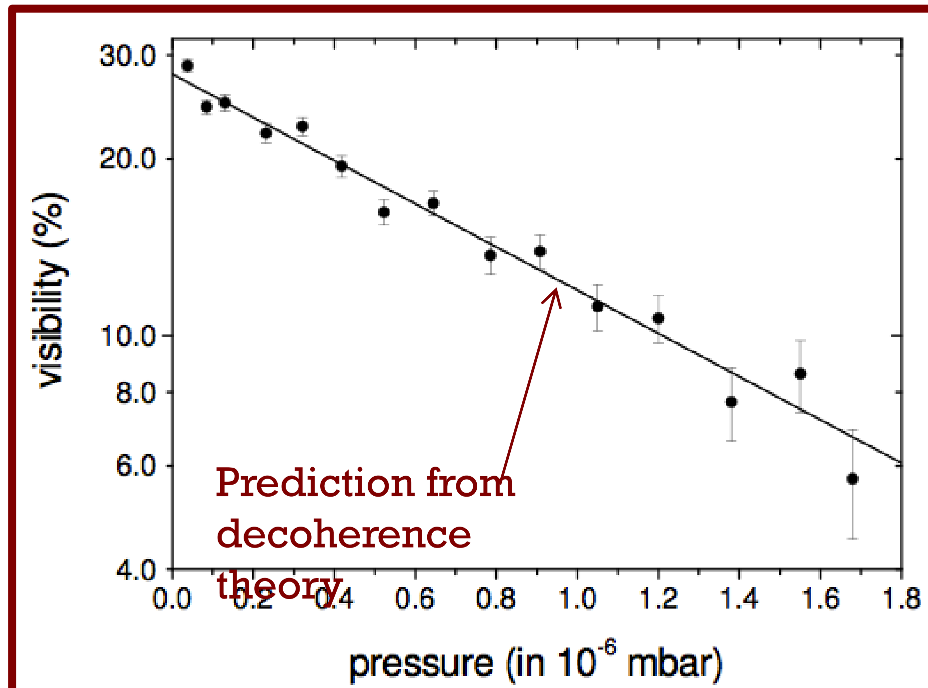
K. HORNBERGER
B. BREZGER*
A. ZEILINGER
M. ARNDT✉
Institut für Experimentalphysik der Universität Wien, Boltzmanngasse 5, 1090 Wien, Austria

Environmental gasses are bled into the vacuum chamber. These cause scattering interactions.

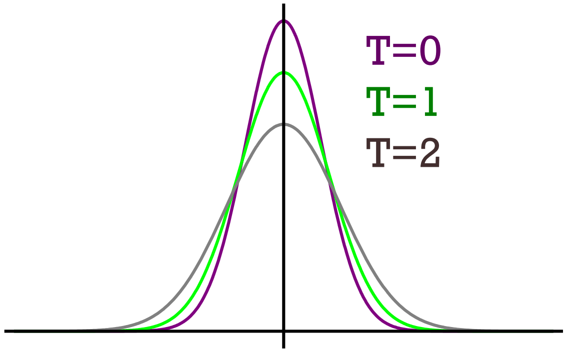
Entanglements generated with the environment encode "which way" information and suppress coherent superpositions.





LOCALIZATION BY SCATTERING IN ENVIRONMENTS

1. Quantum particles will naturally delocalize over time:



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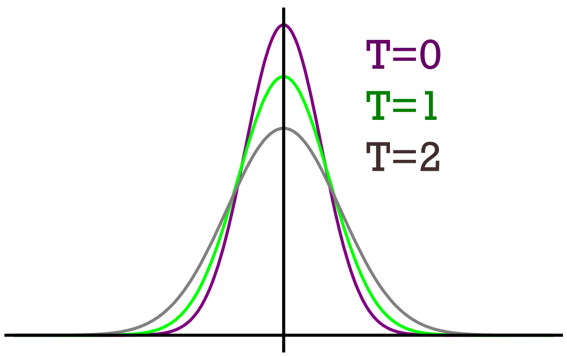
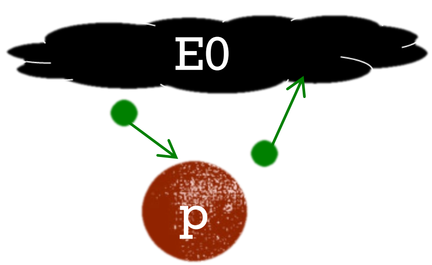


2. But scattering with the environment re-localizes them:



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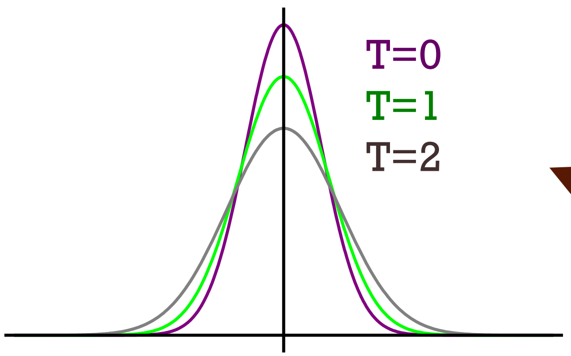

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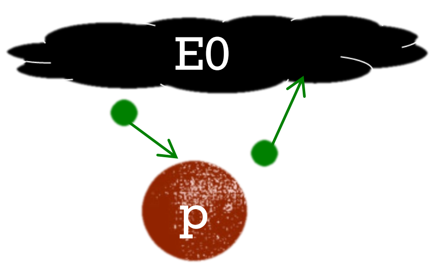

These compete, and it drives the localization scale of quantum objects in their environments.

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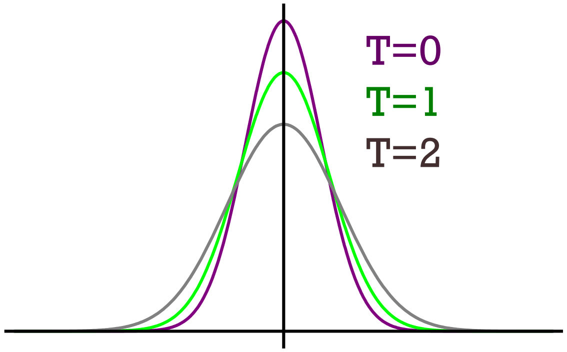


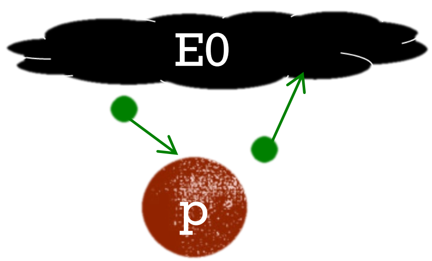
Foundations of Physics Letters, Vol. 6, No. 6, p. 571-590 (1993)

APPARENT WAVE FUNCTION COLLAPSE CAUSED BY SCATTERING

Max Tegmark

**one of my favorite papers by anyone ever*

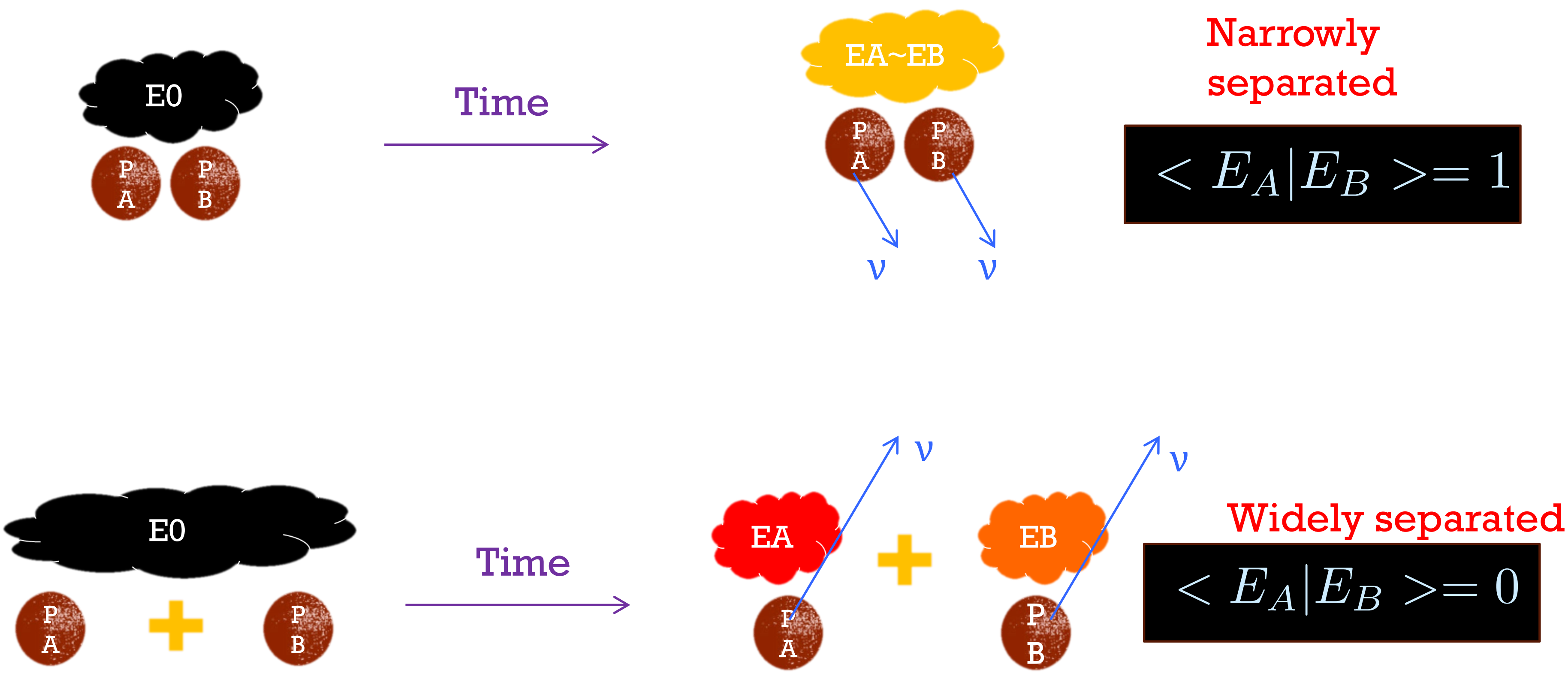
2. But scattering with the environment re-localizes them:



Cause of apparent wave function collapse	Free electron	$10\mu m$ dust	Bowling ball
300K air at 1 atm pressure	10^{-6} m	10^{-17} m	10^{-21} m
300K air in lab vacuum	10^{7} m	10^{-13} m	10^{-18} m
Sunlight on earth	10^{9} m	10^{-12} m	10^{-17} m
300K photons	10^{4} m	10^{-12} m	10^{-16} m
Background radioactivity	n/a	10^{-11} m	10^{-15} m
Quantum gravity	10^{4} m	10^{-9} m	10^{-15} m
GRW effect	10^{19} m	10^{-9} m	10^{-15} m
Cosmic microwave background	10^{10} m	10^{-8} m	10^{-14} m
Solar neutrinos	n/a	n/a	10^{-13} m

POSITION STATES OF A DECAYING PARTICLE

- The particle (in superposition of positions) emits a neutrino. Will the neutrino state from each emitter add coherently (oscillate) or not?



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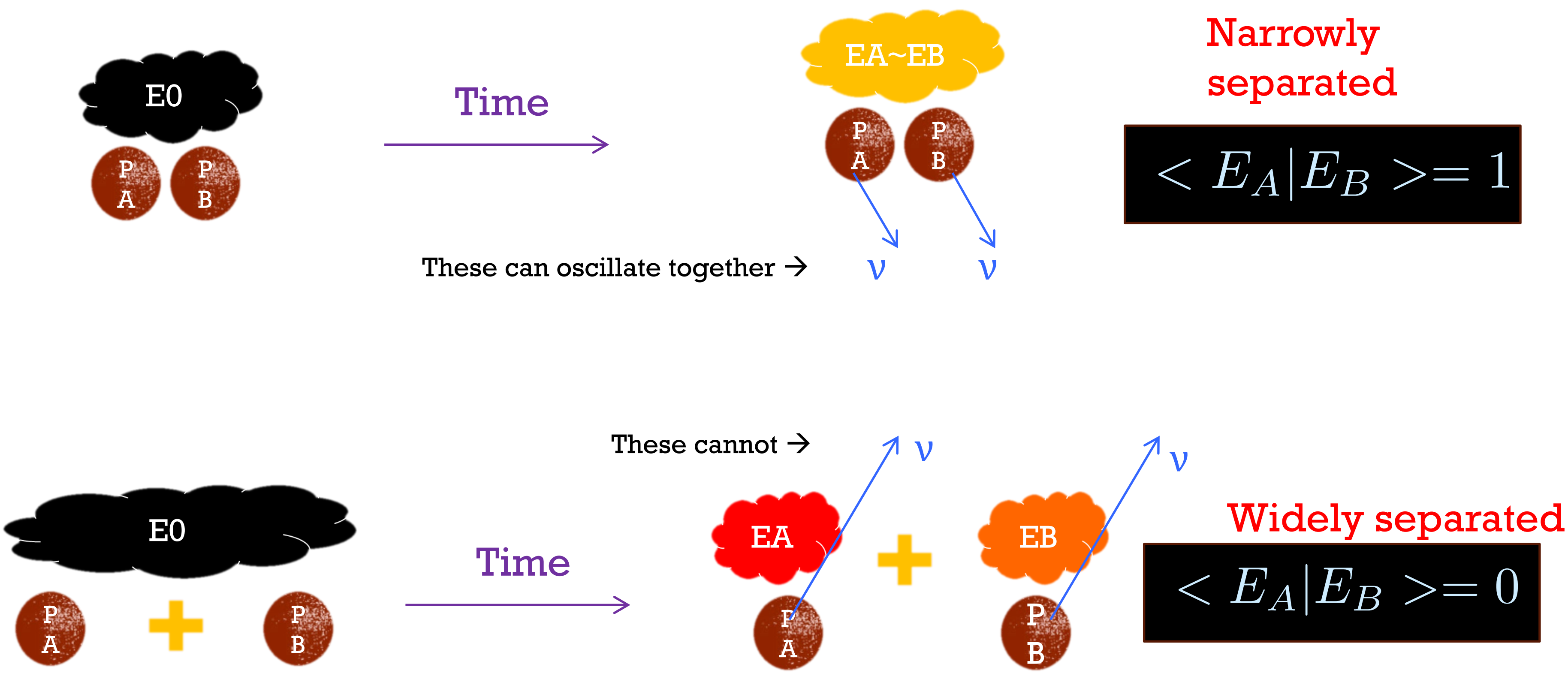


QUANTUM WIDTHS

- **A quantum system thus has more than one notion of ”width”:**
  - **A.** How uncertain are you about its position?
  - **B.** How uncertain would you be about its position if you knew all you could about all the other particles in the Universe?

It is B that dictates the coherence of oscillations

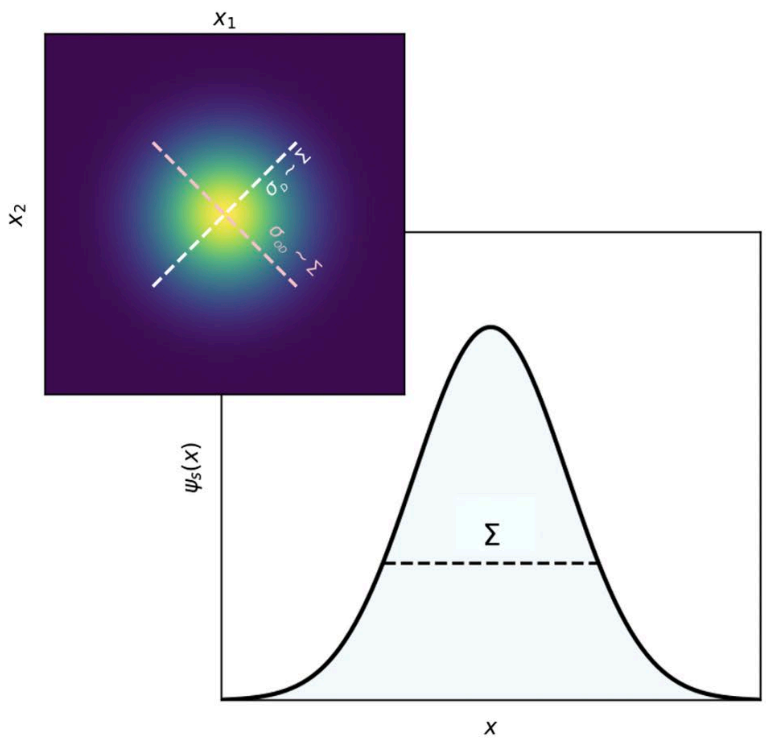
DENSITY MATRICES:

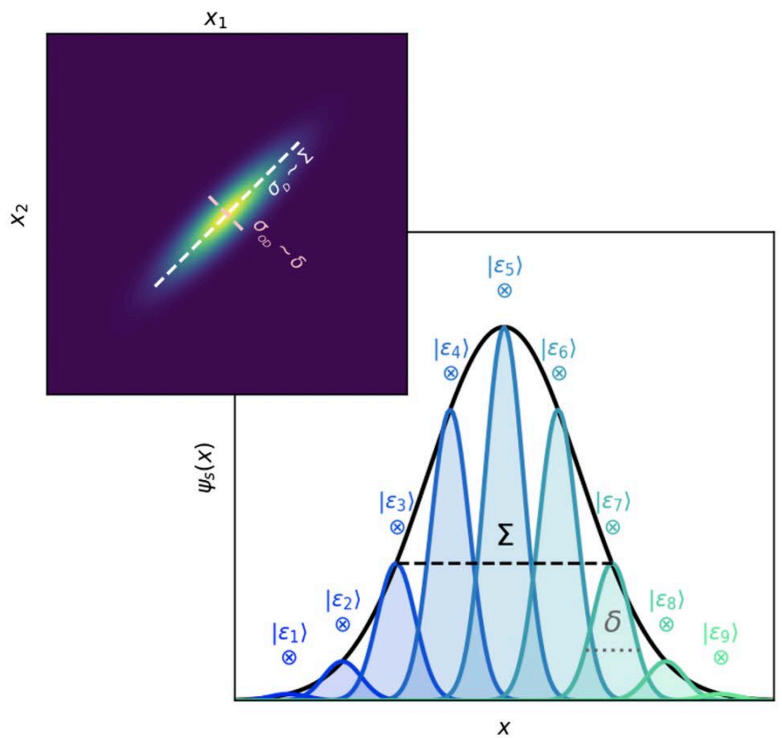
$$\rho_s = \sum_k P_k |\psi_k\rangle\langle\psi_k| = \sum_k \langle\lambda_k|\rho|\lambda_k\rangle \equiv \mathrm{Tr}_\epsilon[\rho],$$

- **A quantum system thus has more than one notion of ”width”:**
  - **Diagonal.** How uncertain are you about its position?
  - **Off-diagonal.** How uncertain would you be about its position if you knew all you could about all the other particles in the Universe?

*It is **Off-diagonal width** that dictates the coherence of oscillations*

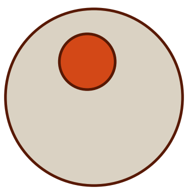
This information is elegantly encoded within a “reduced density matrix”:



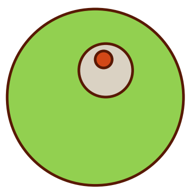


LOCALIZATION SCALES

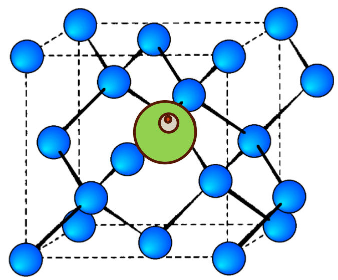
- What if there are cascading scales of delocalization?



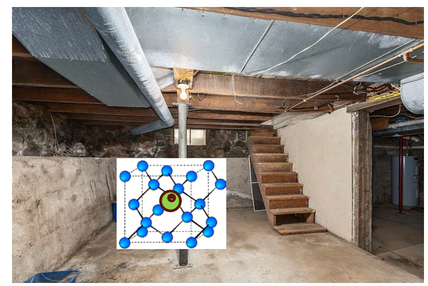
Nucleon is localized in a nucleus



Nucleus is localized in potential of atom



Atom is localized in a material

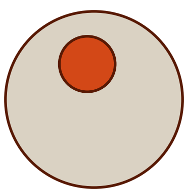


Material is localized in the basement

Etc…

How do you know which one to choose?

- There *is* an unambiguous recipe.
- Construct the **total system density matrix** including **all of these** entanglement scales.
- Then trace out **all non-observed** degrees of freedom.
- The result will be a **reduced density matrix** which encodes the relevant scale in its off-diagonal width.



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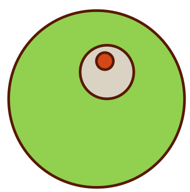

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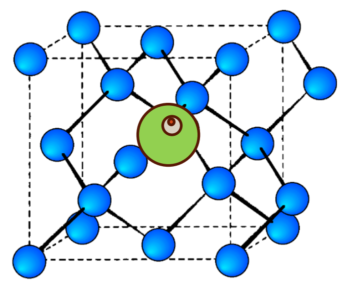

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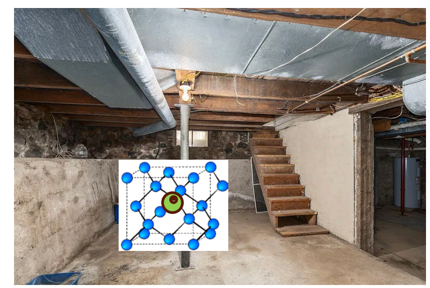


Material is localized in the basement

Etc…

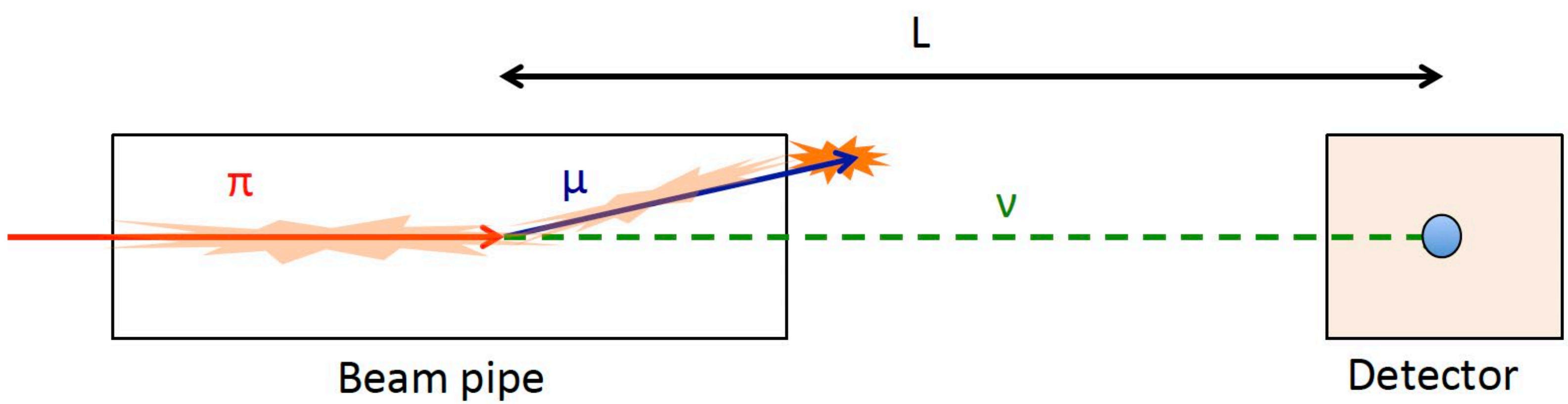
Often, but not always, it will be the more localized scale in the problem*

→ ***Don't trust that intuition. Build the density matrix and find out.***

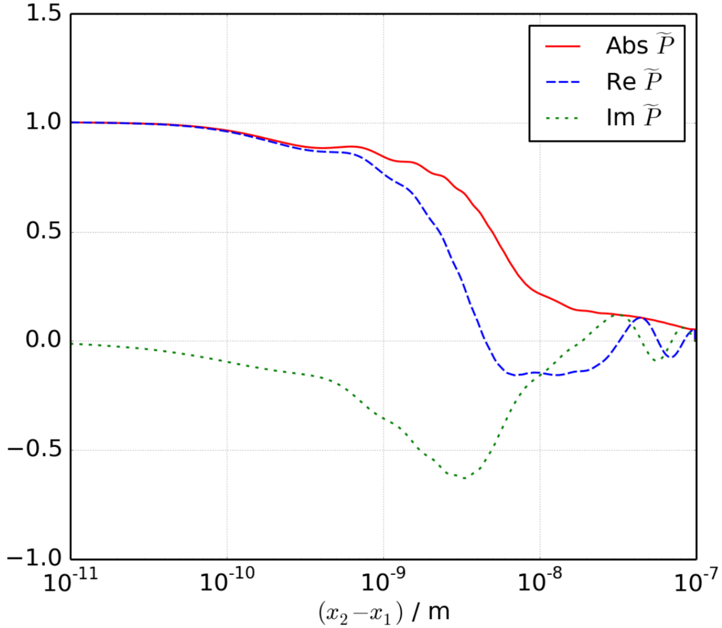
*(*just as an example, electron capture does not follow this rule-of-thumb)*

PION DECAY CALCULATION

- In an experiment with a pion beam, interactions with decay-pipe gas cause localization inversely proportional to momentum-transfer of those interactions.
- The parent pion then kinematically transfers its width to the neutrino
- After the decay, the pion is gone. What matters is what the environment "knew" about where the pion was when it decayed.

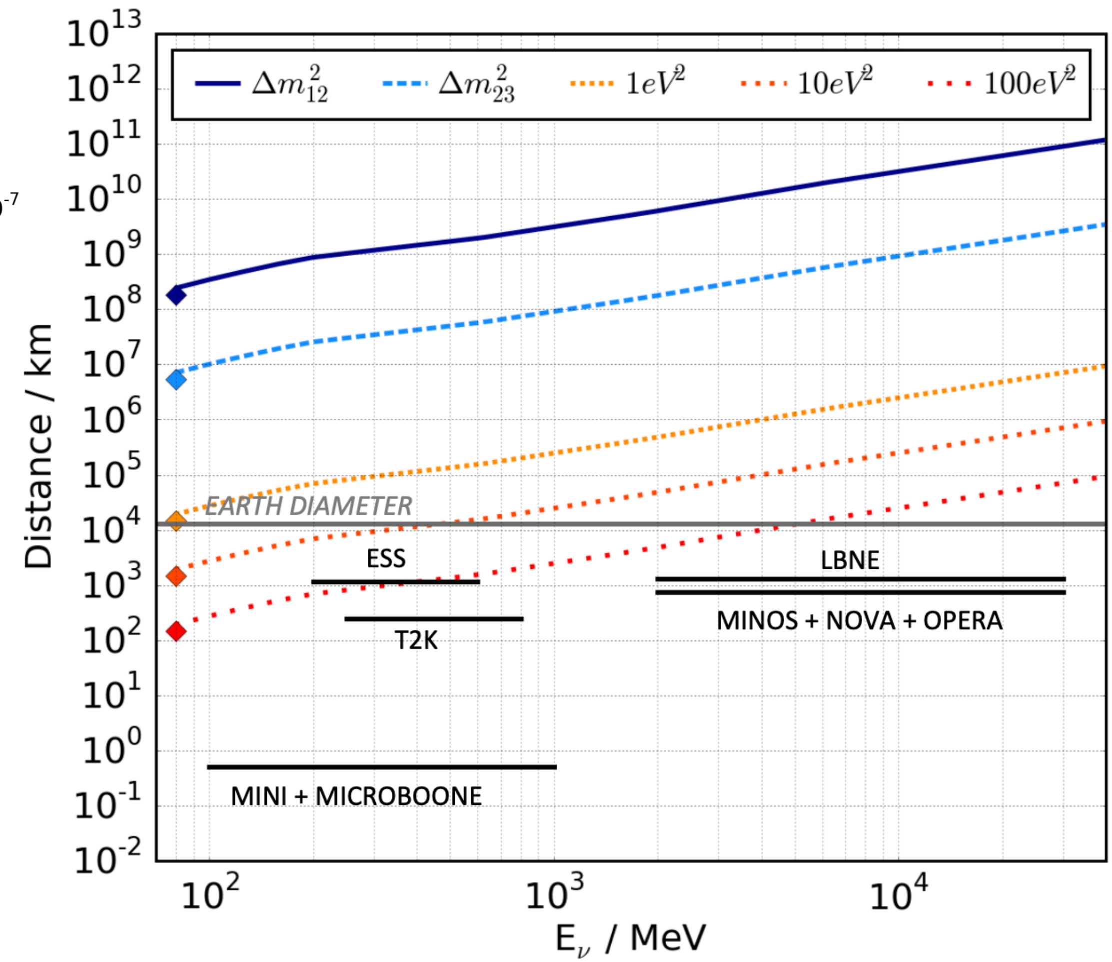


It is the momentum transfer in interactions and the time between scatters, <u>not</u> simply the mean free path, that dictates the localization scale in this system.



← Localizing effect is momentum transfer from pion-air scattering in decay pipe, calculable with the PAI model.

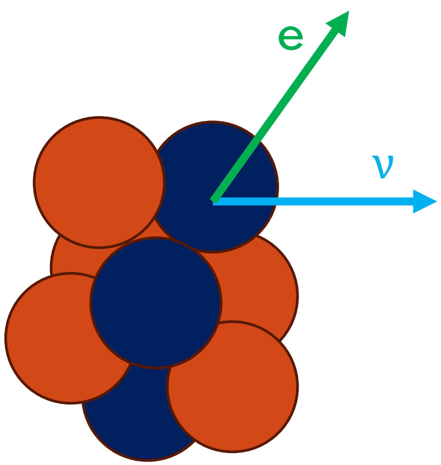
^ Density matrix gets multiplied by this on each scattering interaction, disperses in between

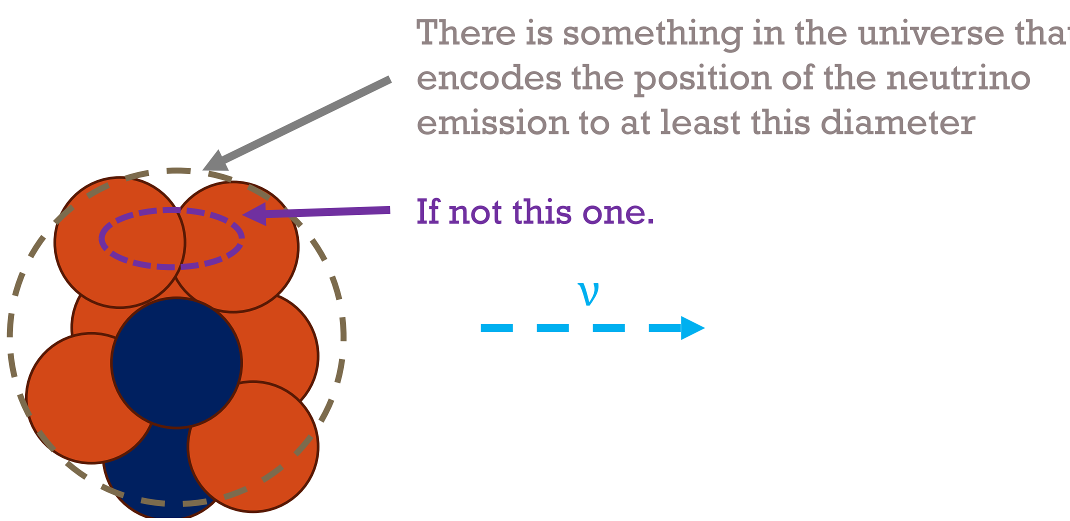


We will likely never observe this effect with the known neutrinos in terrestrial experiments →

BETA DECAY EFFECT

- Unlike pion decay, in an experiment with a beta source, the nucleus is still there after the decay.
- The residual nucleus thus encodes the origin of the neutrino to within about the nuclear size.
- It may also encode it to within the scale of inter-nucleon correlations.

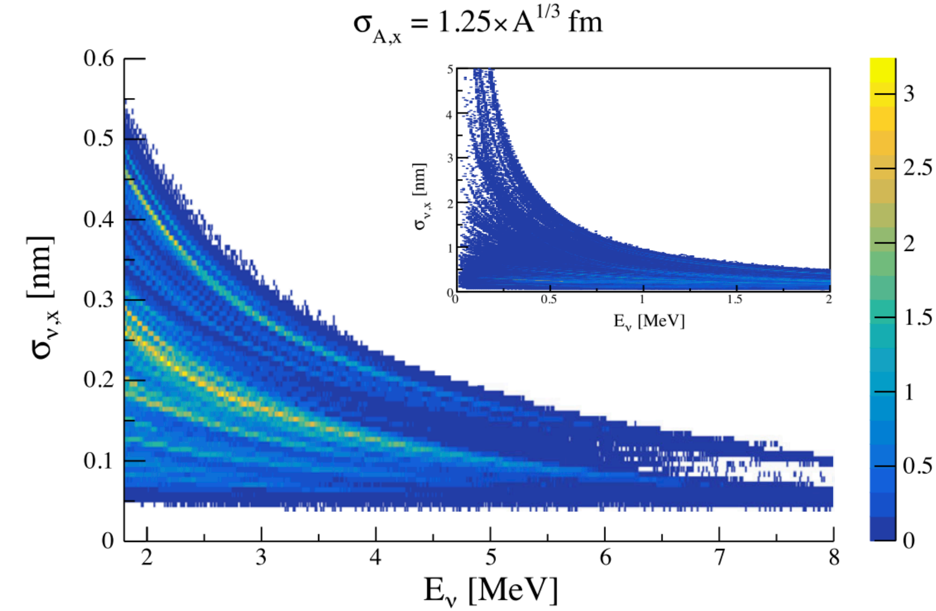


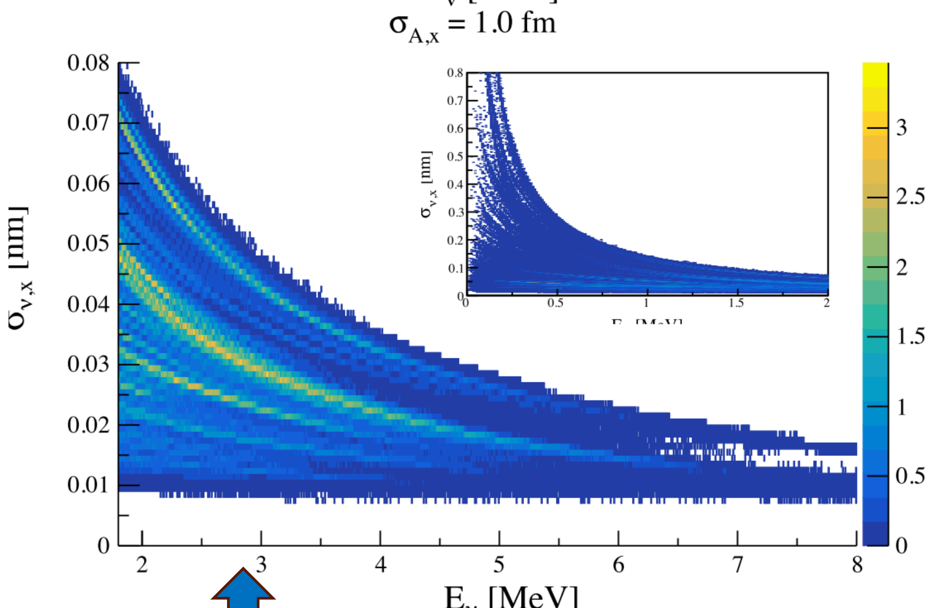


From a "toy model" derivation →

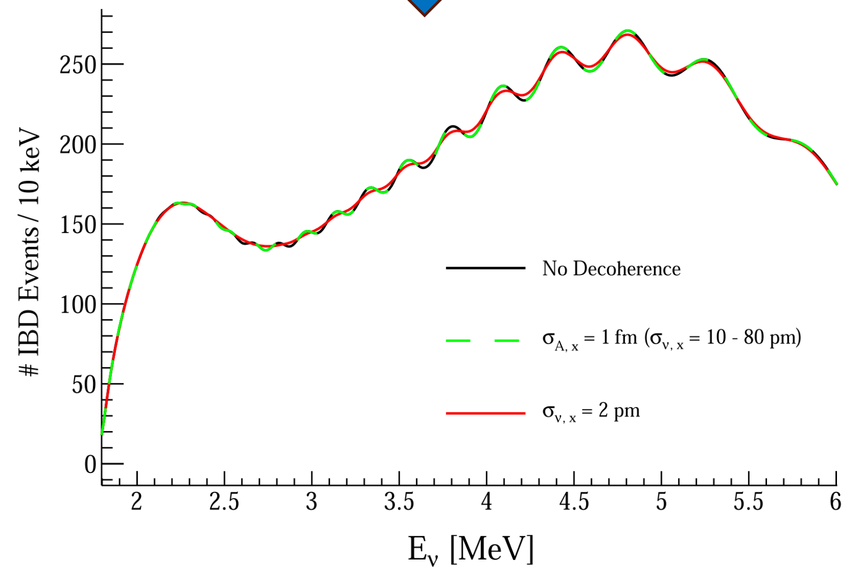
$$\bar{\Delta}^2_{OD}(x) = \frac{1}{4A} = \frac{1}{4}\left[\frac{1}{4N^2\sigma_M^2} + \left(\frac{N-1}{N}\right)\frac{1}{4\sigma_N^2} + \frac{N-1}{4\sigma_c^2}\right]^{-1}.$$

Atom in material — Nuclear size — Nuclon correlations





JUNO has the best hope of seeing this, but it looks very difficult.



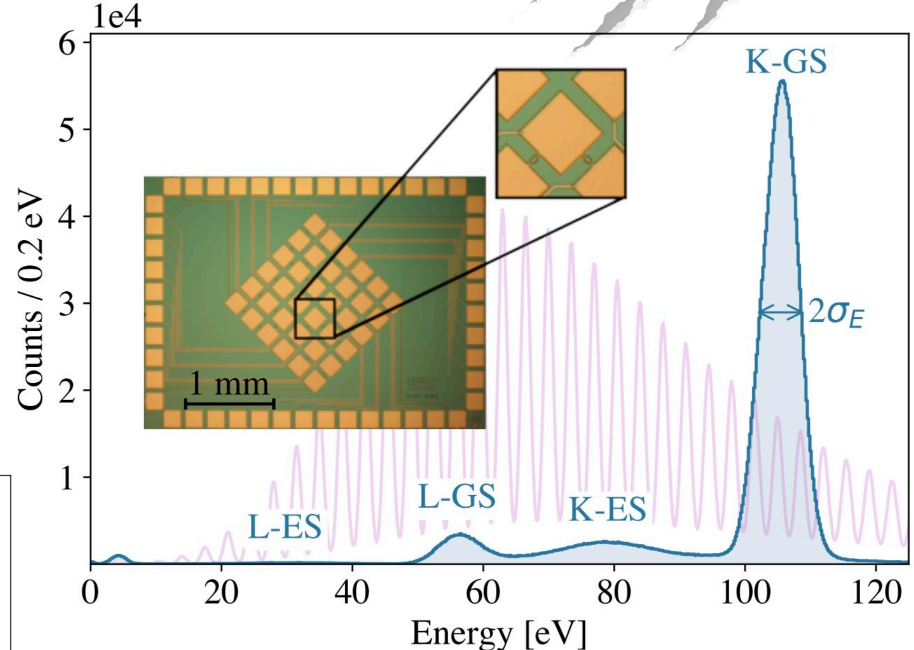
We are exploring using quantum Monte Carlo of the nuclear wave function to go beyond the toy model picture.

Then need to integrate those dynamics over all the damn fission branches!!

THE BEEST ELECTRON CAPTURE MEASUREMENT

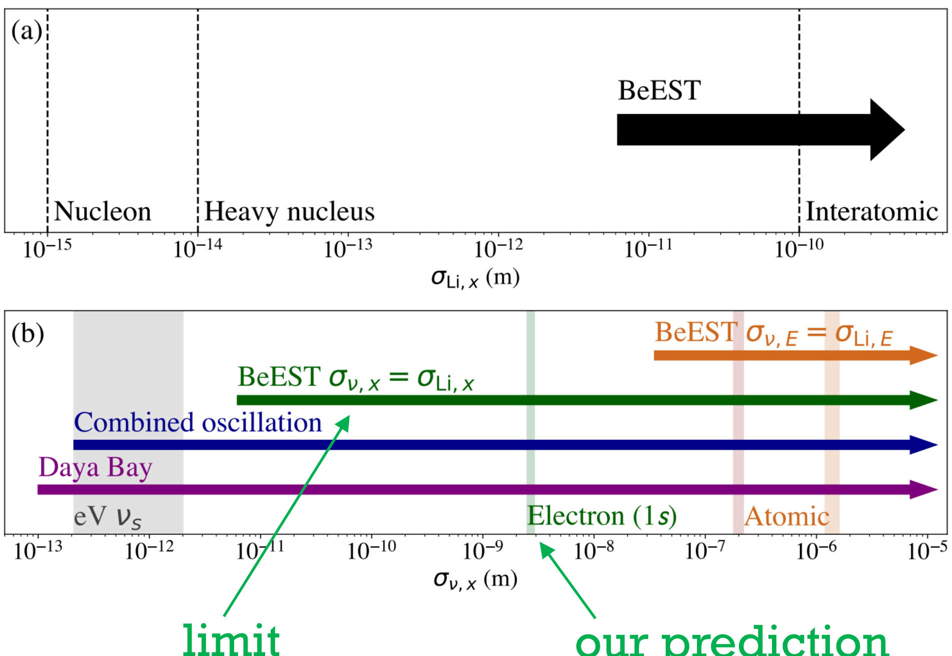
^{7}Be in STJs reconstruct electron capture spectrum very precisely.

Momentum width of peak implies minimal possible wave packet size, through Heisenberg principle.

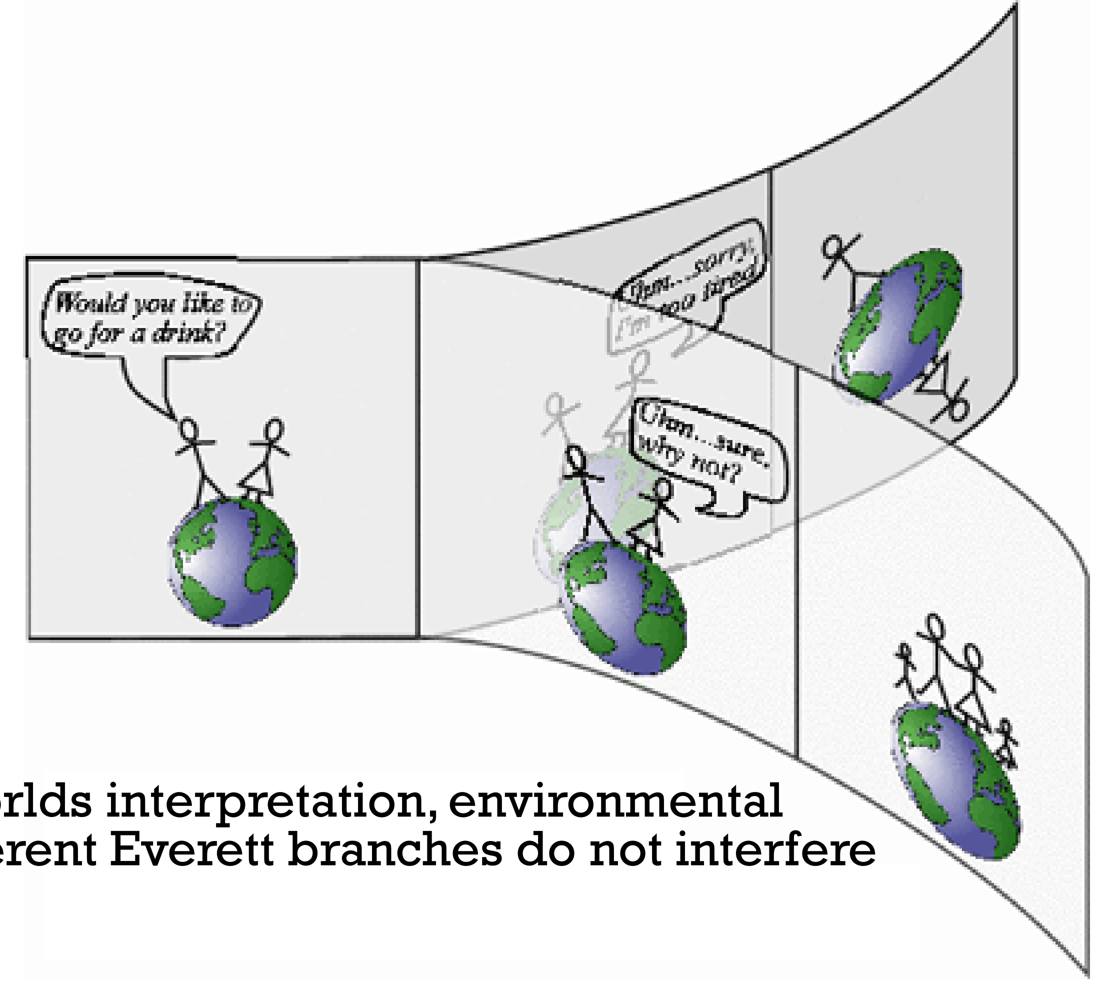


Peak width mainly determined here by condensed matter effects.

← Alas, it is not yet sensitive to relevant distance scales… (but exciting to try!)



ENVIRONMENTAL DECOHERENCE AND THE OBSERVER PROBLEM



- If you subscribe to the many-worlds interpretation, environmental decoherence explains why different Everett branches do not interfere with each other.

- For some, this seems sufficient resolution to the QM observer problem.

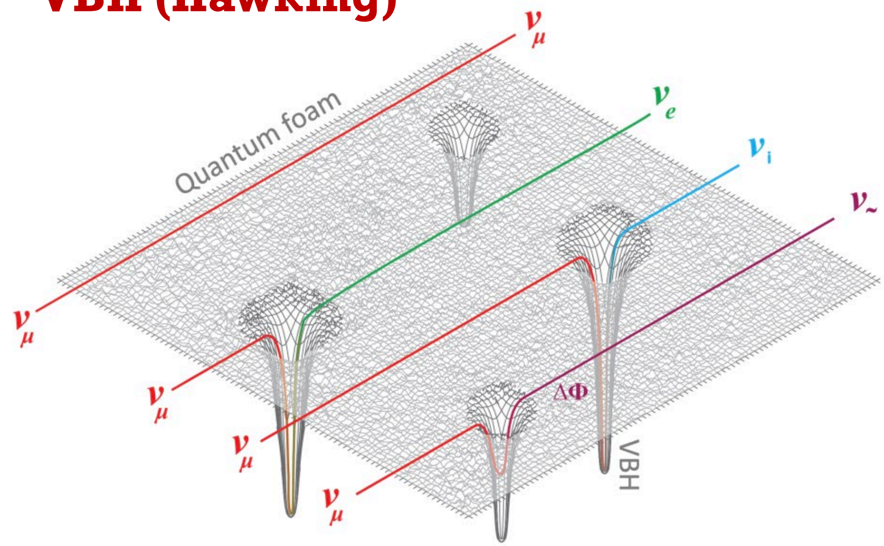
- For others (including Steven Weinberg, Roger Penrose, and many others), there remains an observer problem associated with why observers experience only one branch, and how the Born rule emerges, that could require new physics beyond QM to resolve.

NONUNITARY EVOLUTION

Penrose: General Relativity and Gravitation. ***28*** *(5): 581–600*

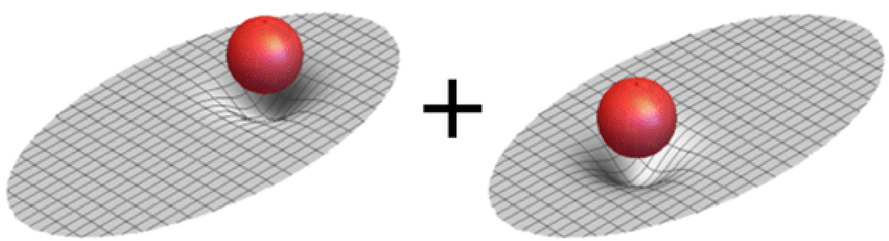
- Penrose and others suggest that QM must at some level become non-unitary, for reasons associated with gravity.
- They postulate that this adds the missing ingredient "special sauce" to resolve the observer problem.
- **This non-unitarity is testable with neutrino oscillations.**
- There are two mechanisms which slightly give different phenomenology:
  - Hawking / Wheeler *(space-time foam creates microscopic black holes that sap information from neutrino wave function)*
  - Penrose / Diosi *(metric curvature affects direction of time and hence quantum phase)*

VBH (Hawking)

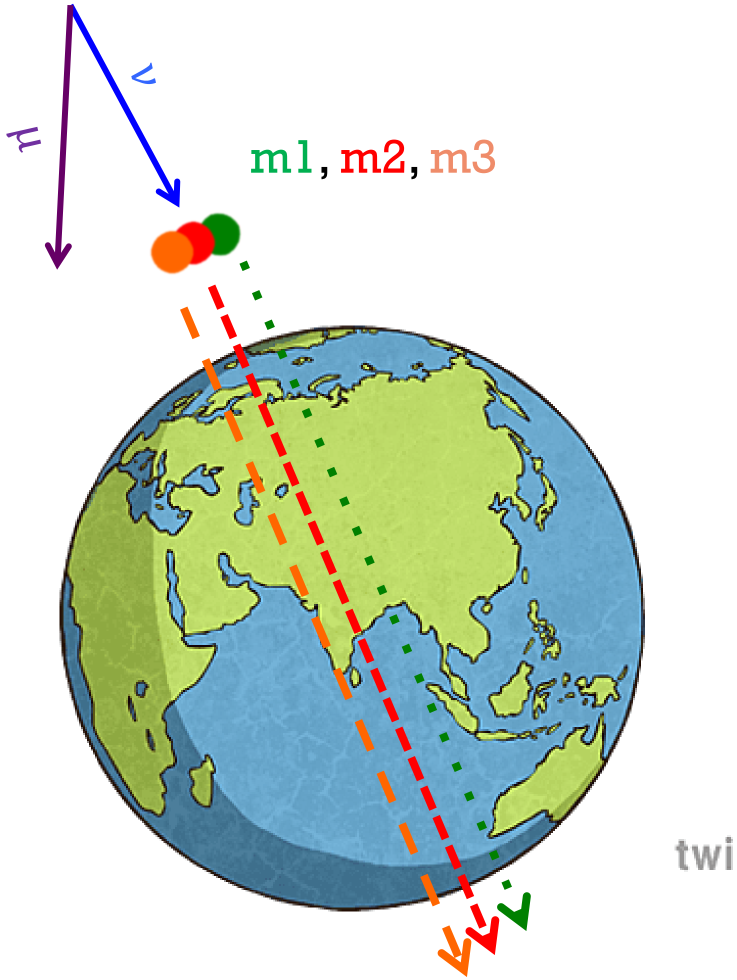


Information is lost in scatters

Metric curvature (Penrose/Diosi)



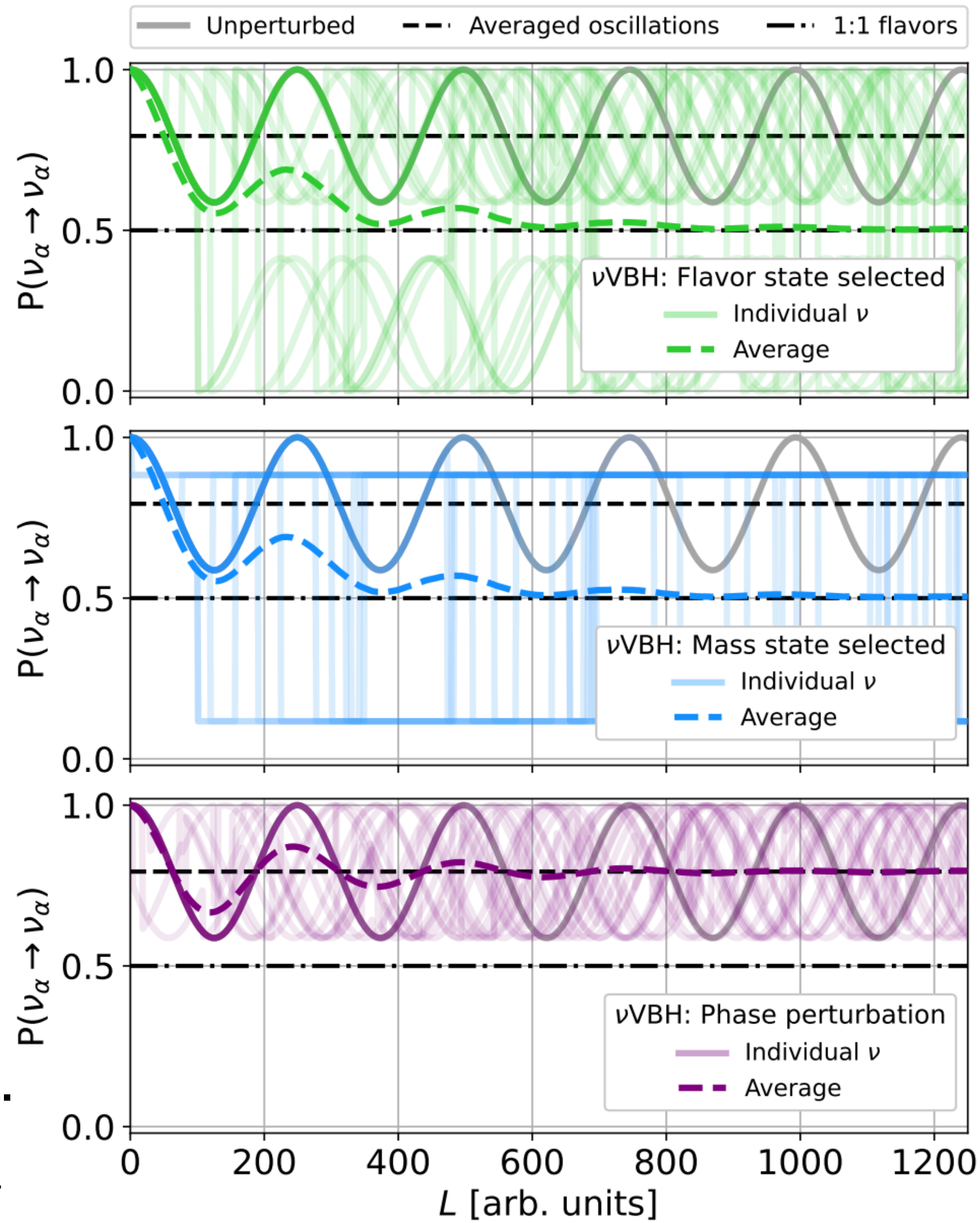
e^{-iHt} is different because t is different



Neutrino oscillations are a very long baseline, very high energy, three-arm interferometer.

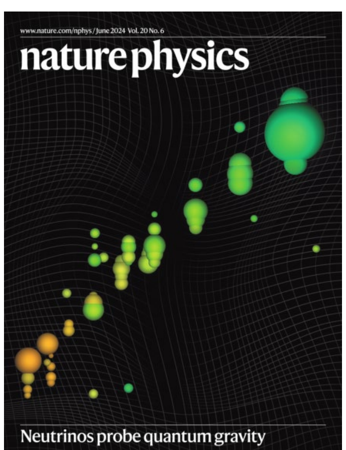
One DeBroglie wavelength at 10 TeV is 10^{-20}m.

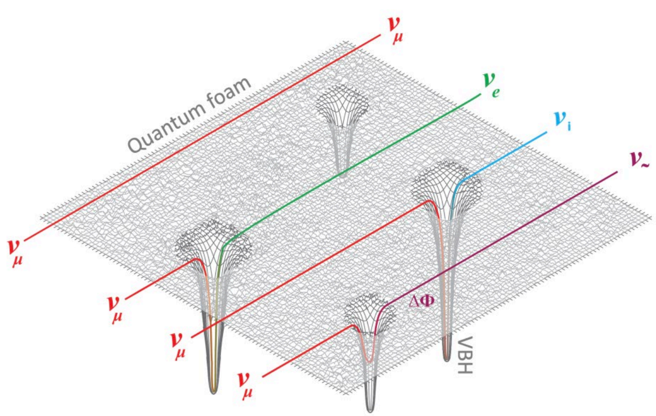
So difference in evolution phase of 10^{-28} between mass states gives observable signatures →

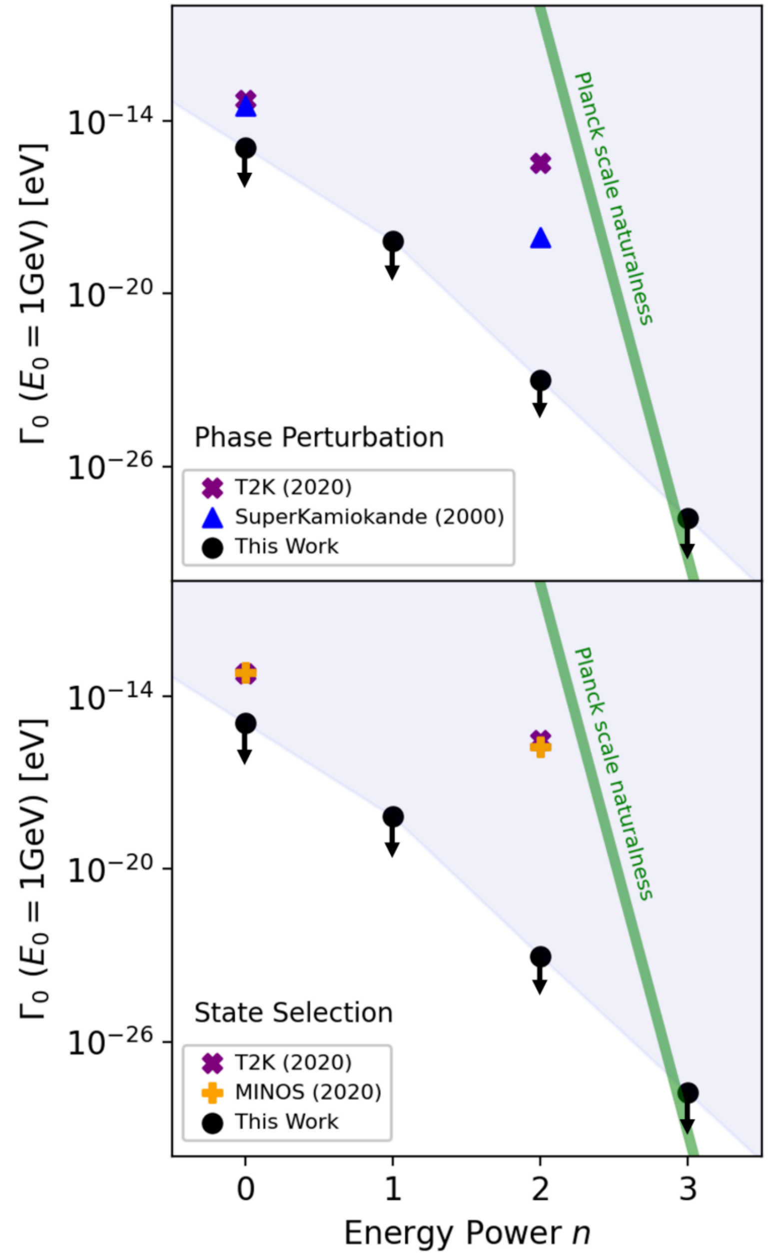


VBH DECOHERENCE

- Tested at IceCube using high energy atmospheric neutrinos.
- There is an unknown energy scaling: well motivated options are N=0 and N=2.
- Limits span natural Planck scale expectations over much of the viable parameter space.
- Given no complete theory of quantum gravity, hard to rule it out absolutely. Still, O(10^6) advance isn't nothing →







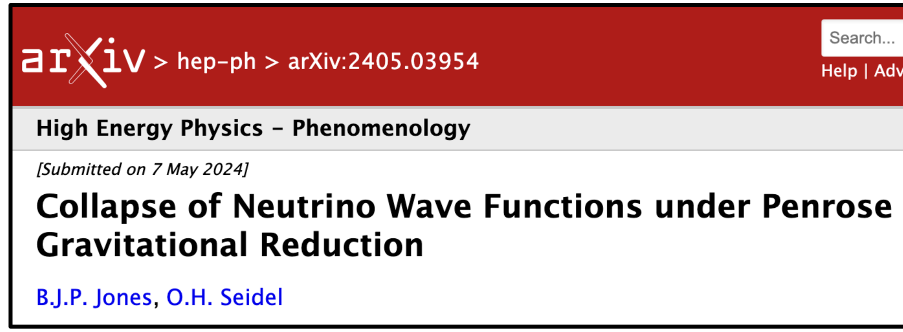
PENROSE DECOHERENCE

- The Penrose model is a bit more complicated, since the actual size of the wave function entangled with a metric configuration, and this affects the rate of collapse.

- Since we have technology to predict the wave packet widths, we can now also predict the rate of this effect.

- Tentatively, seems like the IceCube data confronts this model, though a proper calculation of wave packet widths in atmospheric neutrinos would be needed to be conclusive →

- ***(If you want to collaborate on this with me, let me know!)***


arXiv > hep-ph > arXiv:2405.03954

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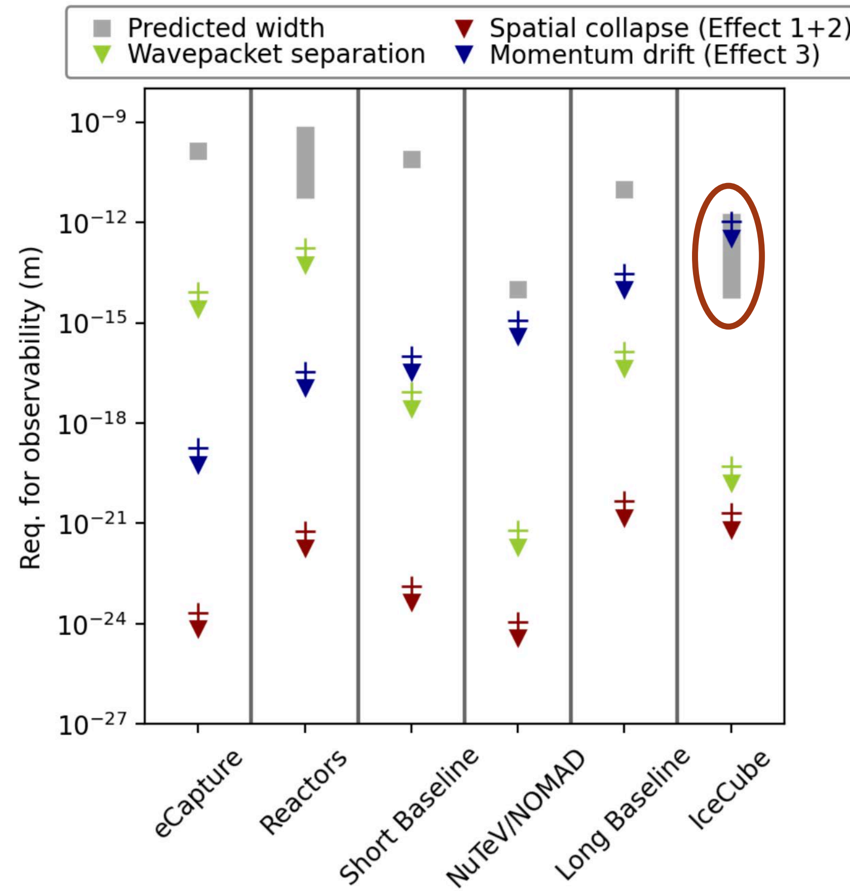
High Energy Physics – Phenomenology

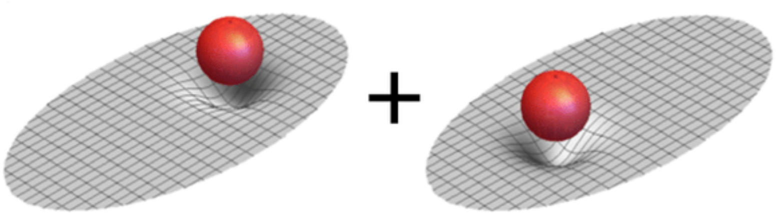
[Submitted on 7 May 2024]

Collapse of Neutrino Wave Functions under Penrose Gravitational Reduction

B.J.P. Jones, O.H. Seidel

Accepted, PRD



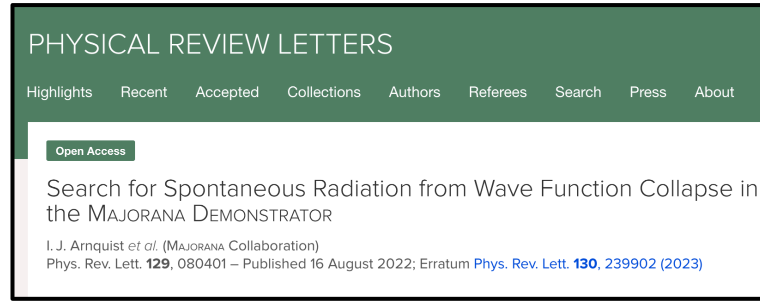


COLLAPSE RADIATION

- Finally, if wave functions collapse stochastically, some models suggest that would be equivalent to an "acceleration", and hence electrons in matter would radiate.

- This radiation has been sought by Majorana Demonstrator and others.

- The effect was not seen at the level estimated for given Penrose-scale collapses.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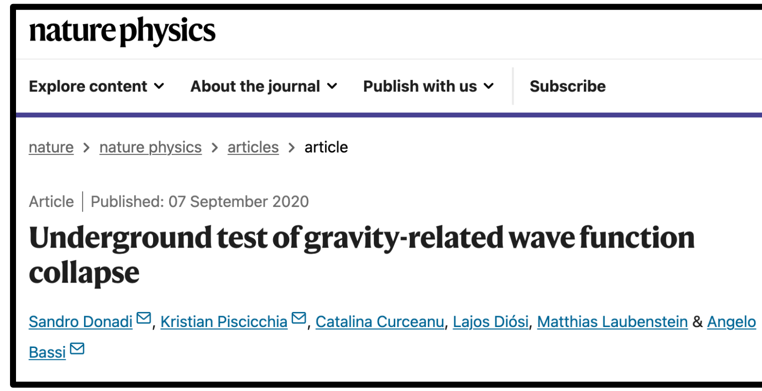
Search for Spontaneous Radiation from Wave Function Collapse in the MAJORANA DEMONSTRATOR

I. J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. Lett. **129**, 080401 – Published 16 August 2022; Erratum Phys. Rev. Lett. **130**, 239902 (2023)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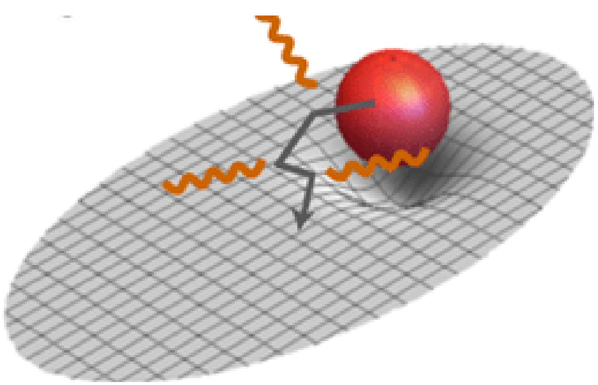
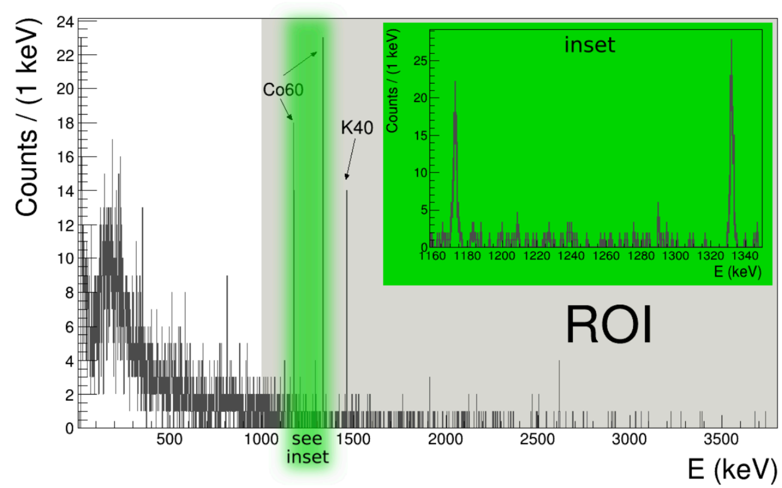
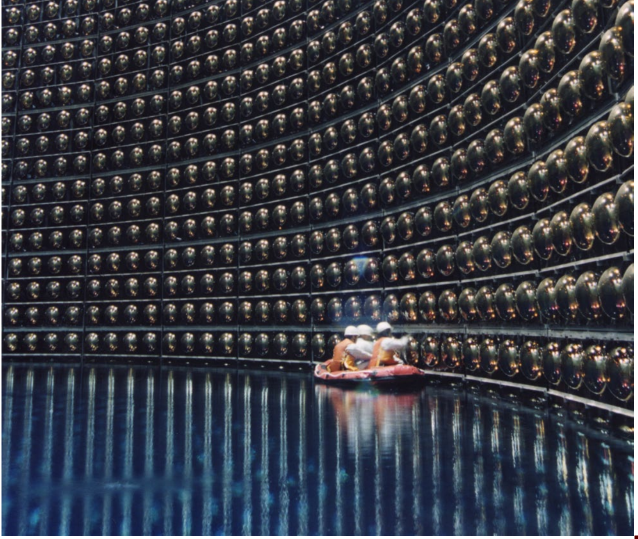
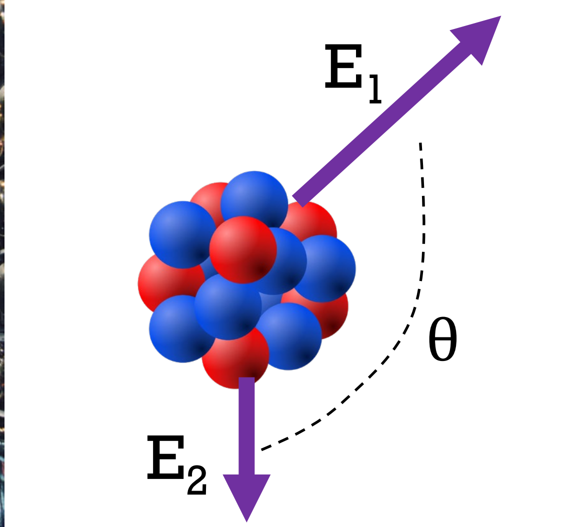
Article | Published: 07 September 2020

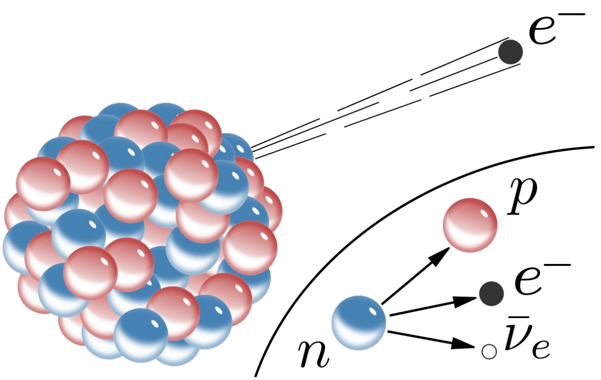
Underground test of gravity-related wave function collapse

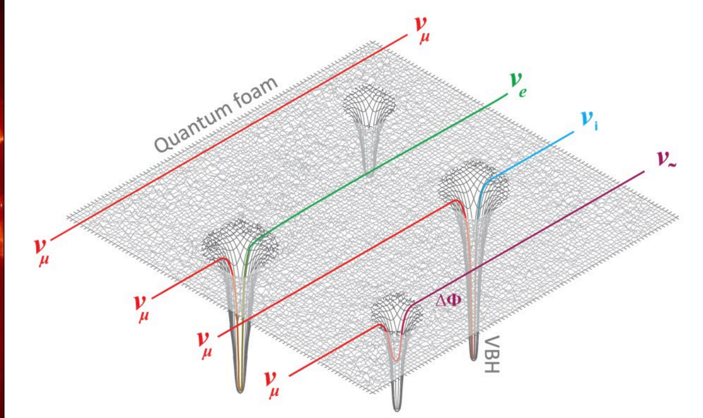
Sandro Donadi, Kristian Piscicchia, Catalina Curceanu, Lajos Diósi, Matthias Laubenstein & Angelo Bassi

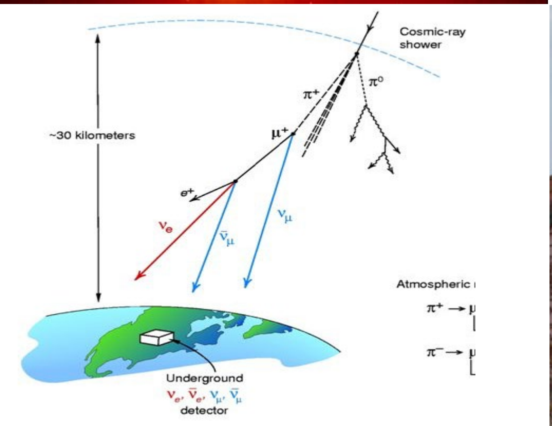






E_1
θ
E_2

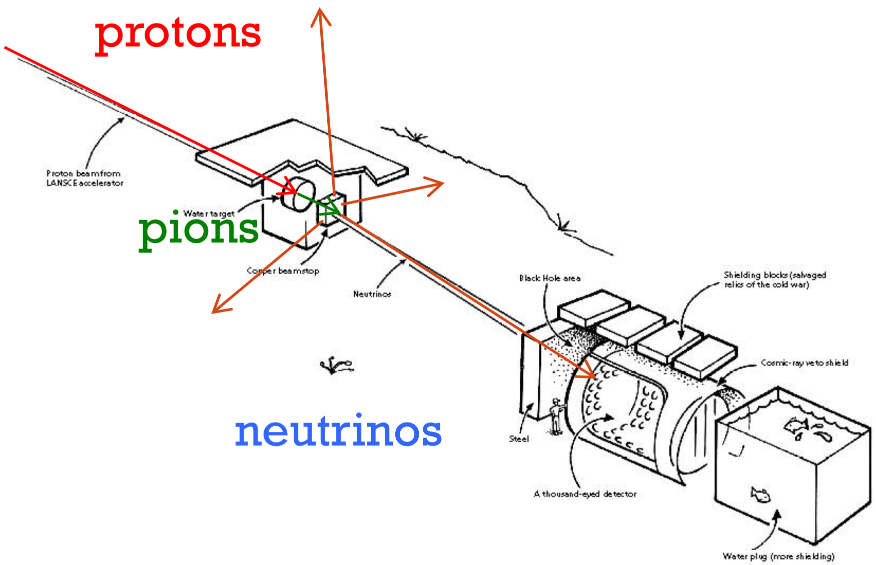


e^-
p
e^-
n
$\bar{\nu}_e$

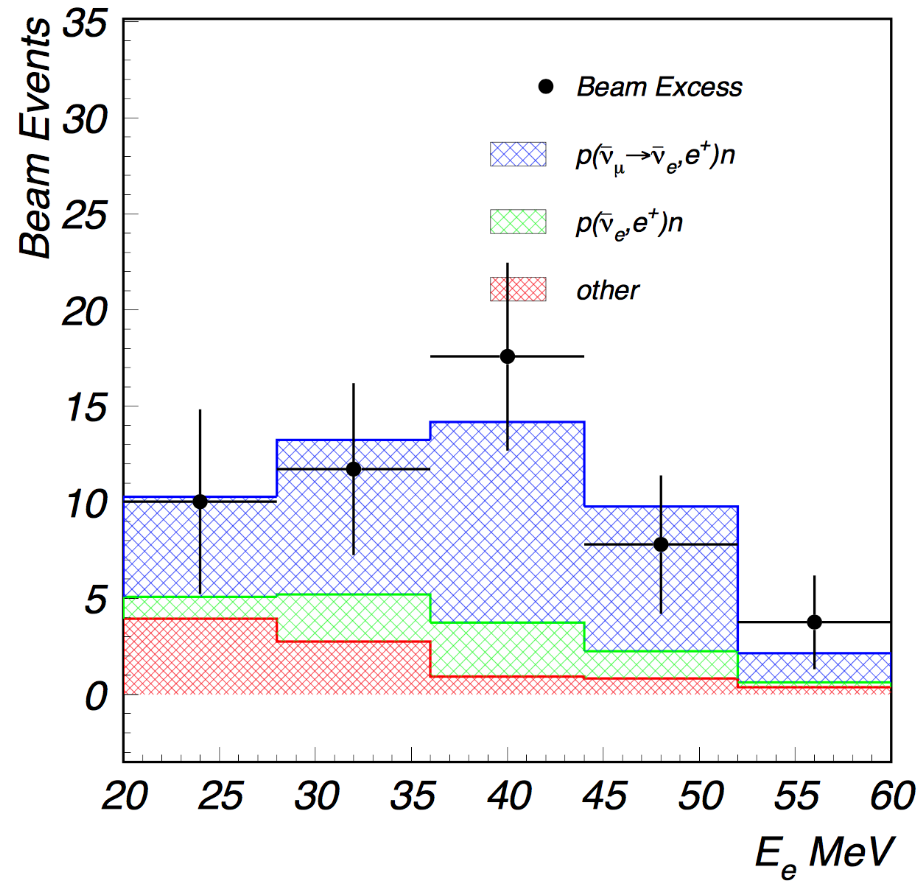
THANK YOU
FOR
YOUR
ATTENTION!

Quantum foam
ν_μ
ν_e
ν_i
$\nu_\sim$
$\Delta\Phi$
VBH


Cosmic-ray shower
π^+
π^0
μ^+
~30 kilometers
e^+
ν_e
$\bar{\nu}_\mu$
ν_μ
Atmospheric
Underground
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$
detector


OSCILLATION ANOMALIES : LSND

$$\Delta m^2_{14} >> \Delta m^2_{13}, \Delta m^2_{23}$$





π+ stop in material, then decay:

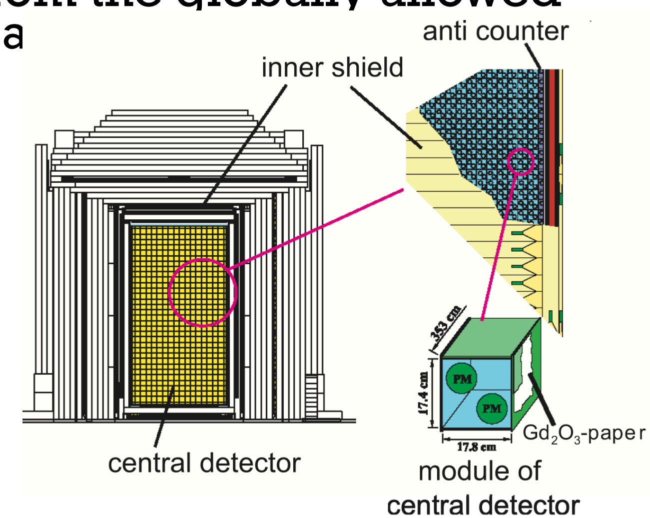
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

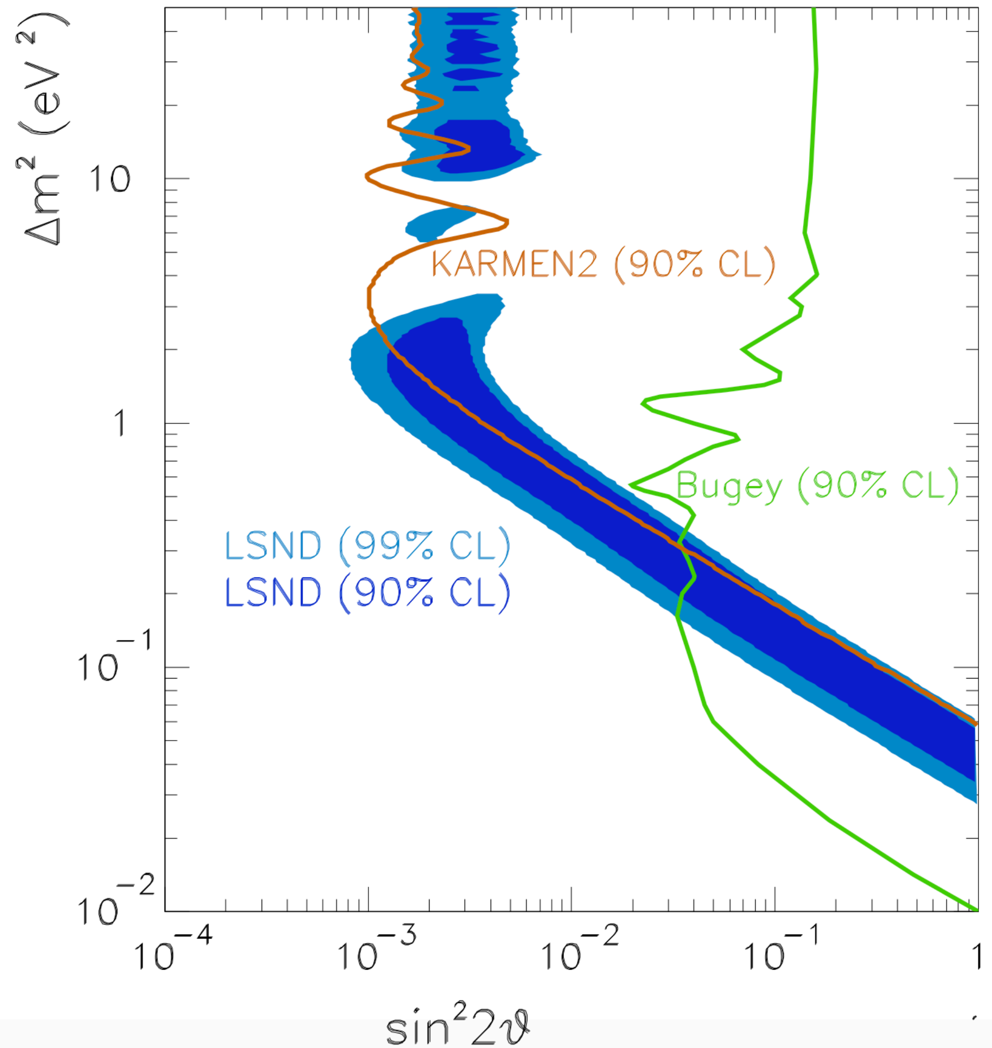
Very small intrinsic $\bar{\nu}_e$ *background*

NON-OBSERVATION AT KARMEN

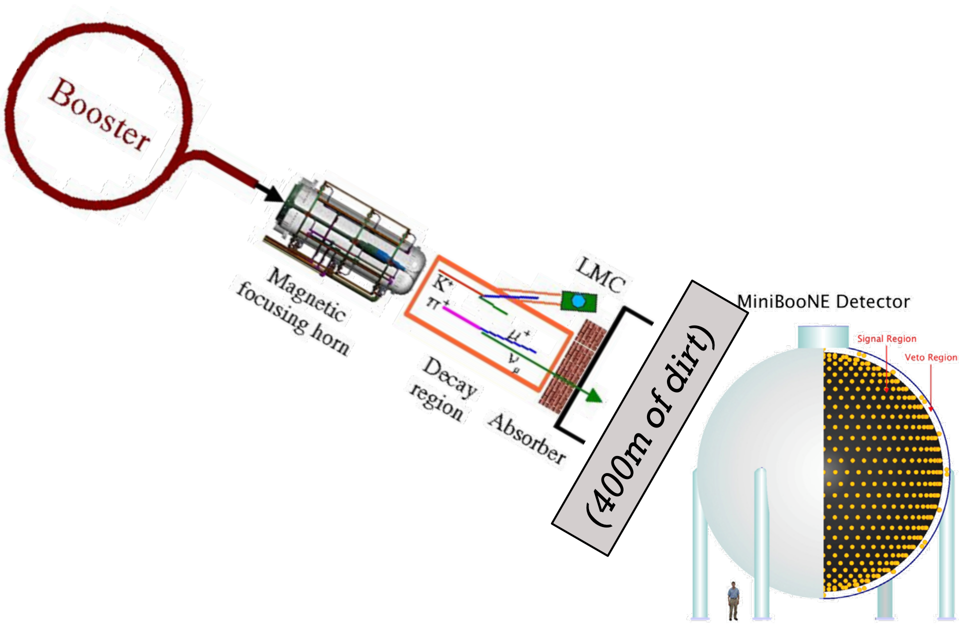
- Shorter baseline, lower beam power non-observation of $\bar{\nu}_e$ appearance using very similar approach to LSND.

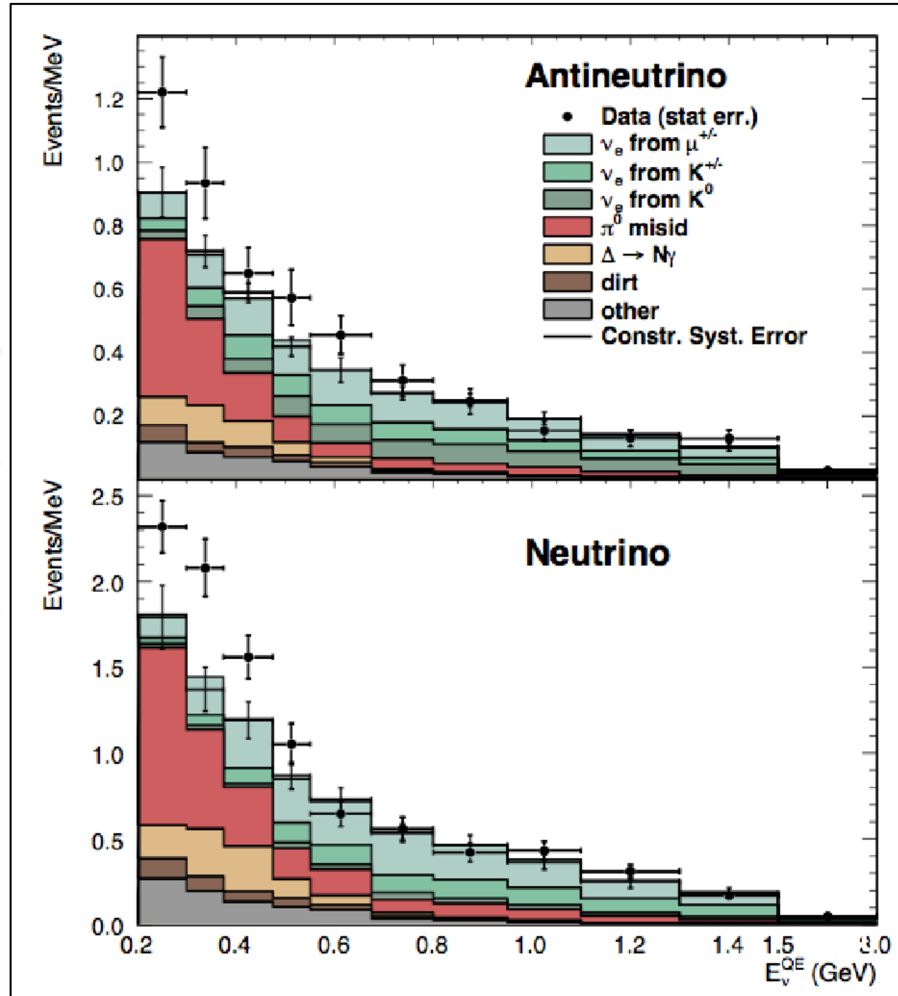
- Karmen Squeezes available parameter space and is responsible for hammering out the high mass regions from the globally allowed pa





OSCILLATION ANOMALIES : MINIBOONE



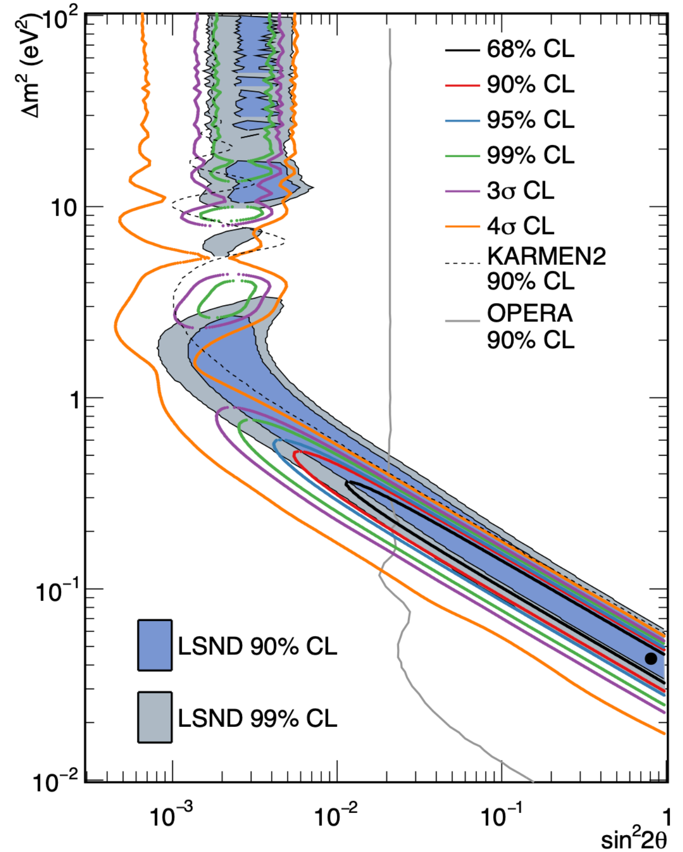


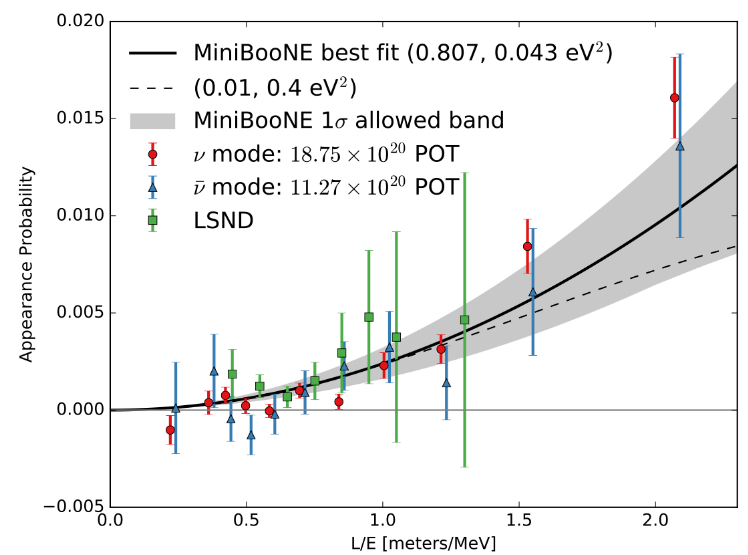
Focussed π+ or π- decay in flight to make ν_μ mostly $\bar{\nu}_\mu$ or

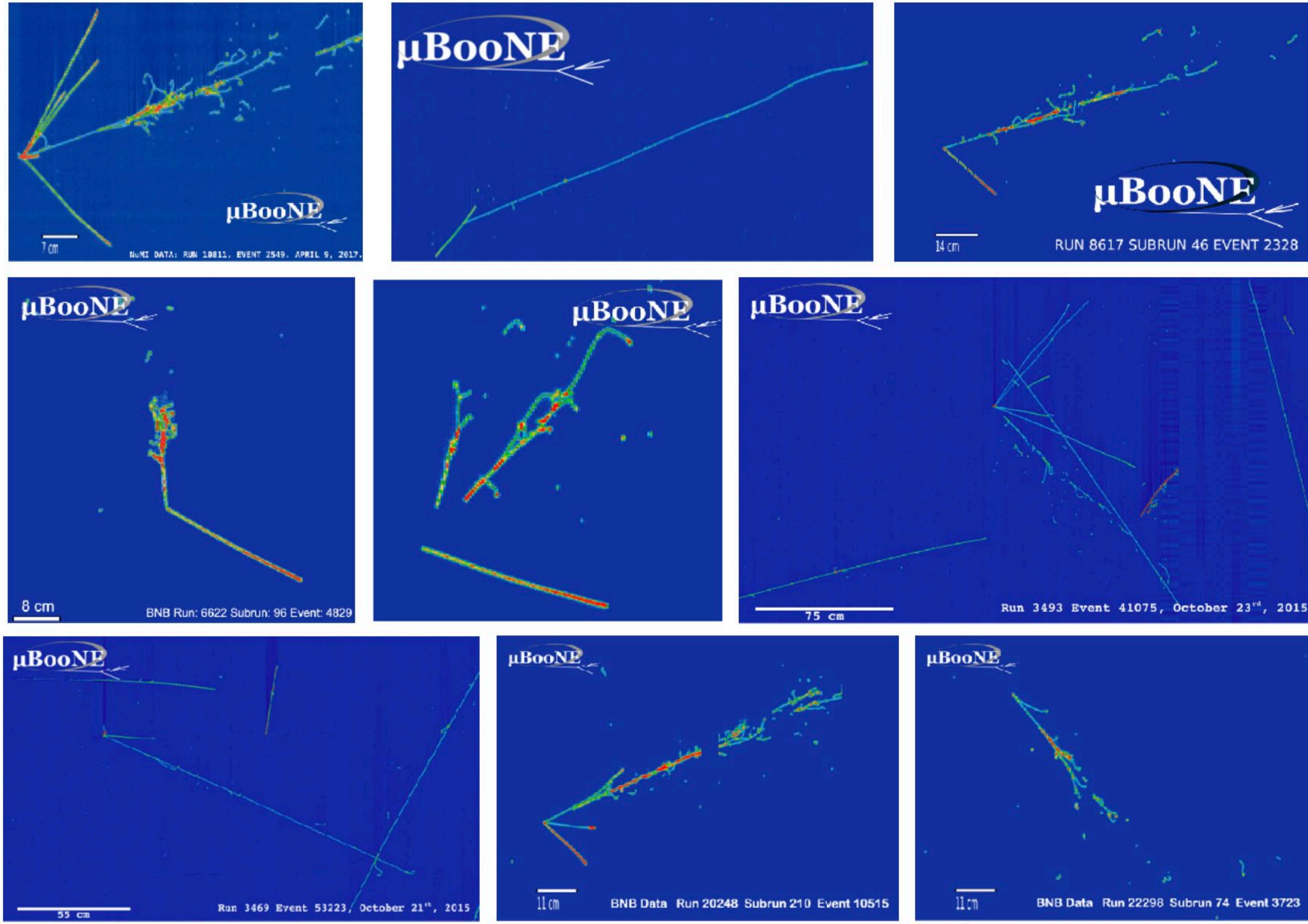
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

MINIBOONE'S FINAL DATASET

- **MiniBooNE continued to accumulate statistics – SM now rejected at >5sigma.**
  - With anomalous flavor change apparent in both neutrino and antineutrino modes.
- **There are well known challenges of modelling GeV neutrino interactions**
  - But - no reasonable model has been able to explain MiniBooNE effect in term of nuclear effects to date.
- **The MiniBooNE effect is more consistent with sterile neutrinos than with the standard model.**
  - And the sterile neutrino models MiniBooNE likes are also liked by LSND.
  - On the other, it is arguably not really consistent with either SM or SM+steriles.



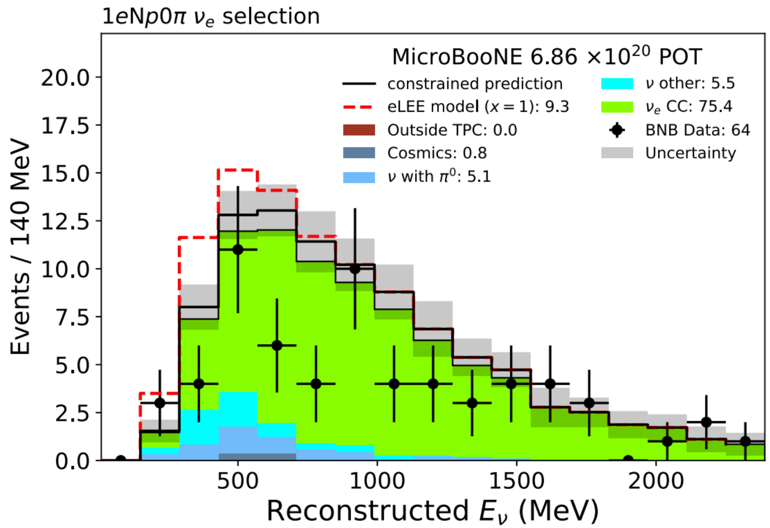


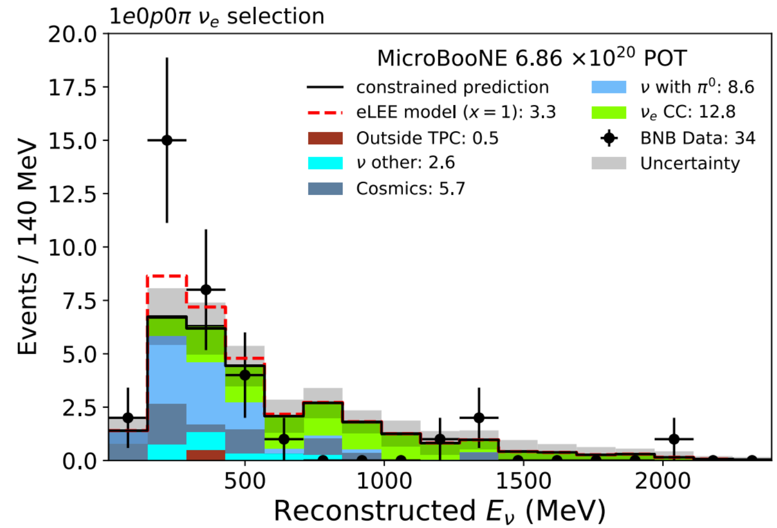


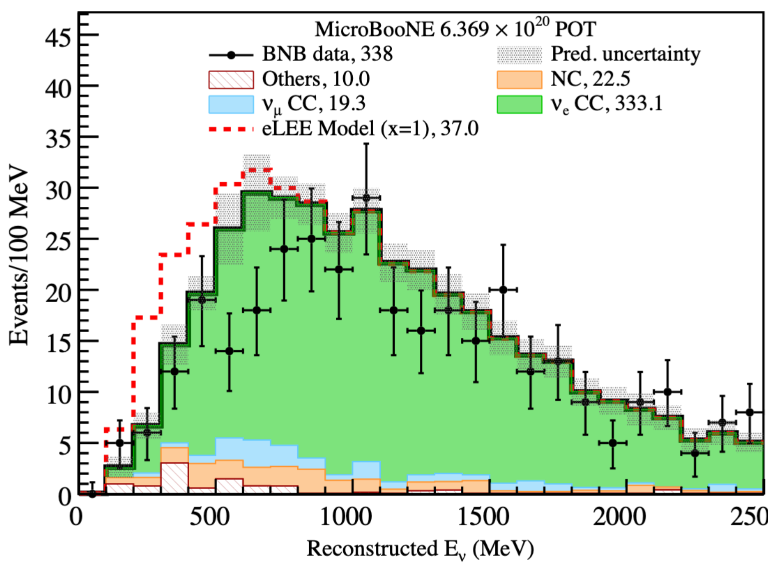
7 cm
NuMI DATA: RUN 10811. EVENT 2549. APRIL 9, 2017.
14 cm
RUN 8617 SUBRUN 46 EVENT 2328
8 cm
BNB Run: 6622 Subrun: 96 Event: 4829
75 cm
Run 3493 Event 41075, October 23rd, 2015
55 cm
Run 3469 Event 53223, October 21st, 2015
11 cm
BNB Data Run 20248 Subrun 210 Event 10515
11 cm
BNB Data Run 22298 Subrun 74 Event 3723

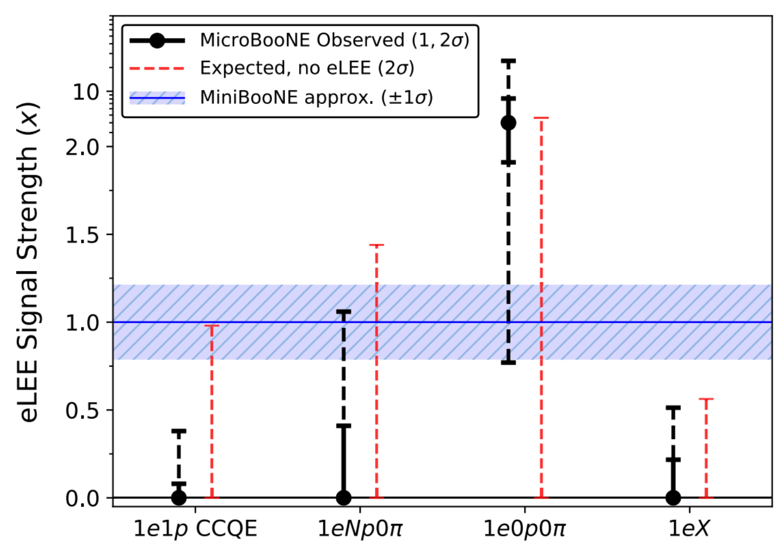
MICROBOONE LEE RESULTS

- MicroBooNE did not validate the MiniBooNE low E excess:









CONNECTION BETWEEN CHANNELS

If sterile neutrinos were to explain the electron neutrino appearance anomalies…

$$\sin^2 2\theta_{\mu e} = 4\,\overbrace{\underbrace{|U_{e4}|^2}_{\nu_e \text{ disappearance}}\underbrace{|U_{\mu 4}|^2}_{\nu_\mu \text{ disappearance}}}^{\nu_\mu \text{ to } \nu_e \text{ appearance}}$$

Then it would be mandatory to see signatures at some level in both electron and muon neutrino disappearance channels.

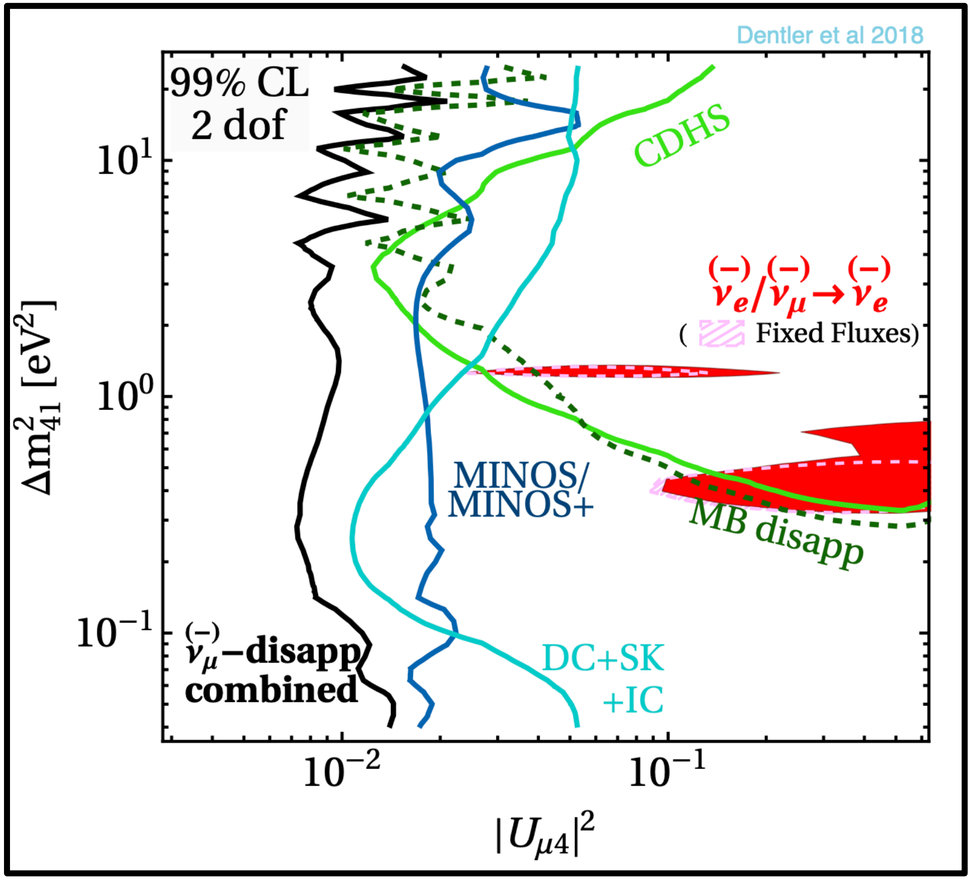
$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2),$$

$$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2),$$

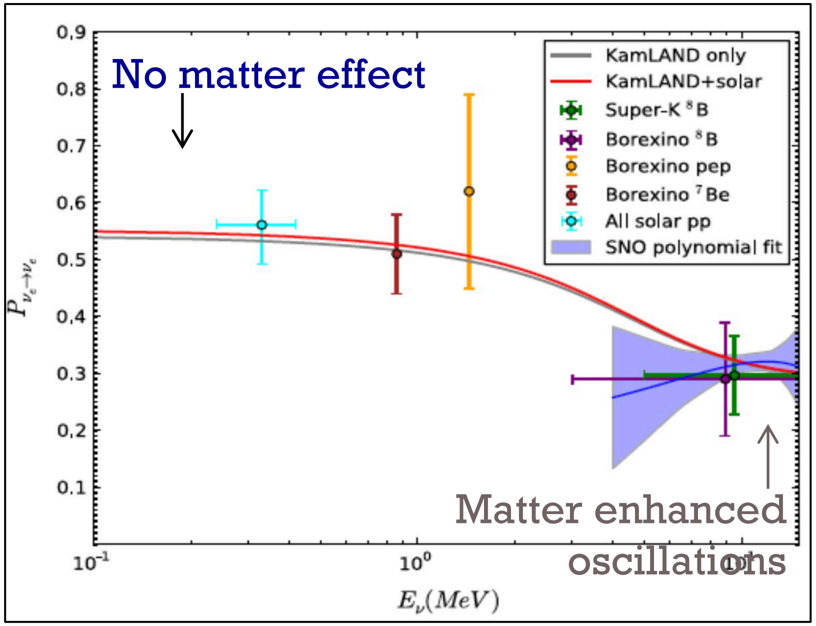
MUON NEUTRINO DISAPPEARANCE

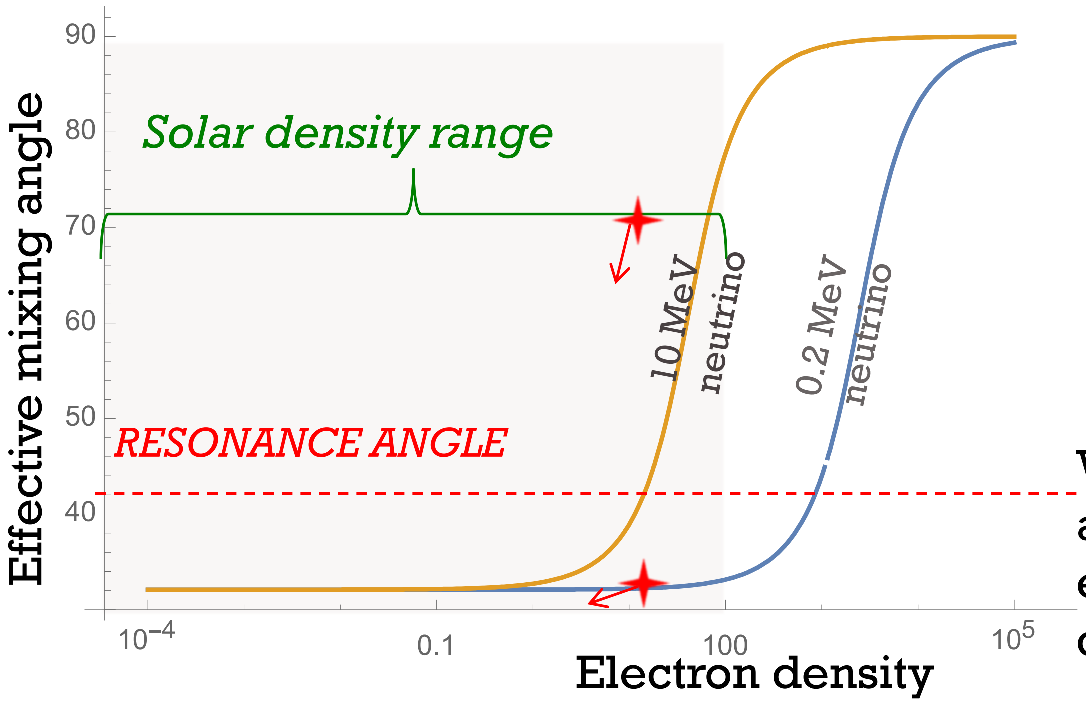
- So far, no observation of muon neutrino disappearance connected with sterile neutrino oscillations from any experiment.

- Strong negative results from IceCube, SuperKamiokande, MINOS and MINOS+.



Recall solar MSW effect we derived two lectures ago:

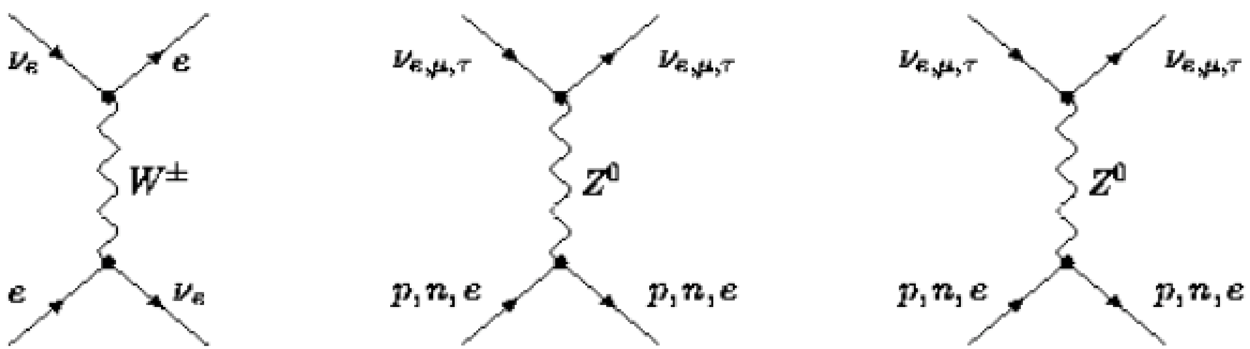




When crossing the resonance angle (sufficiently slowly) we expect maximal flavor conversion

STERILE NEUTRINOS IN MATTER

- Sterile neutrinos do not interact with matter AT ALL!
- Thus new MSW-type effects are to be expected.

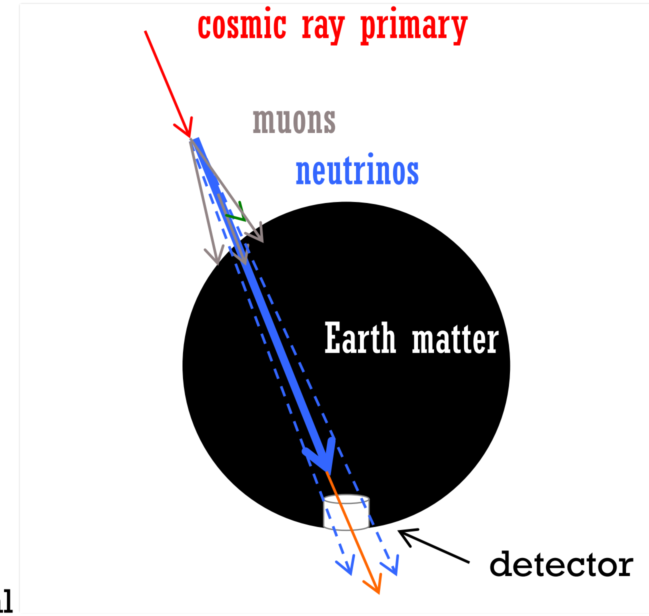


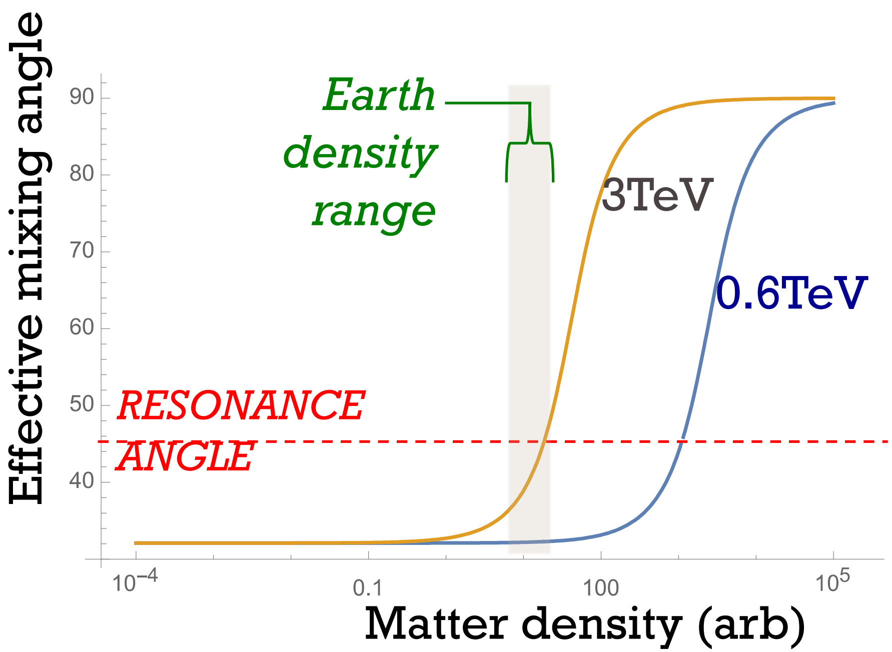
Electron flavor **mu / tau flavor** **Sterile flavor**

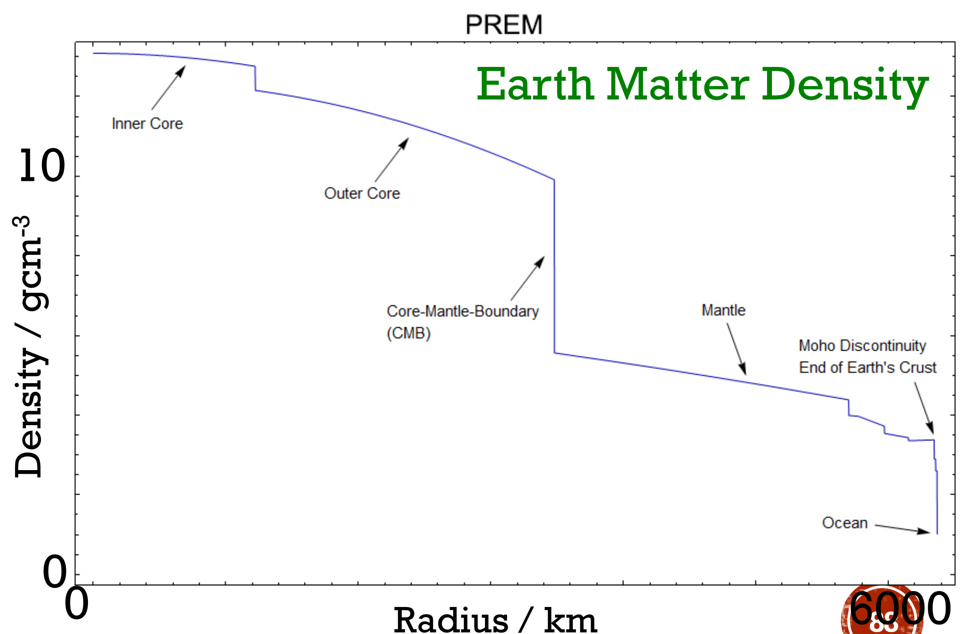
For full phenomenology : ***Esmali and Smirnov, JHEP 1312 (2013) 014***

MSW RESONANT STERILE NEUTRINOS

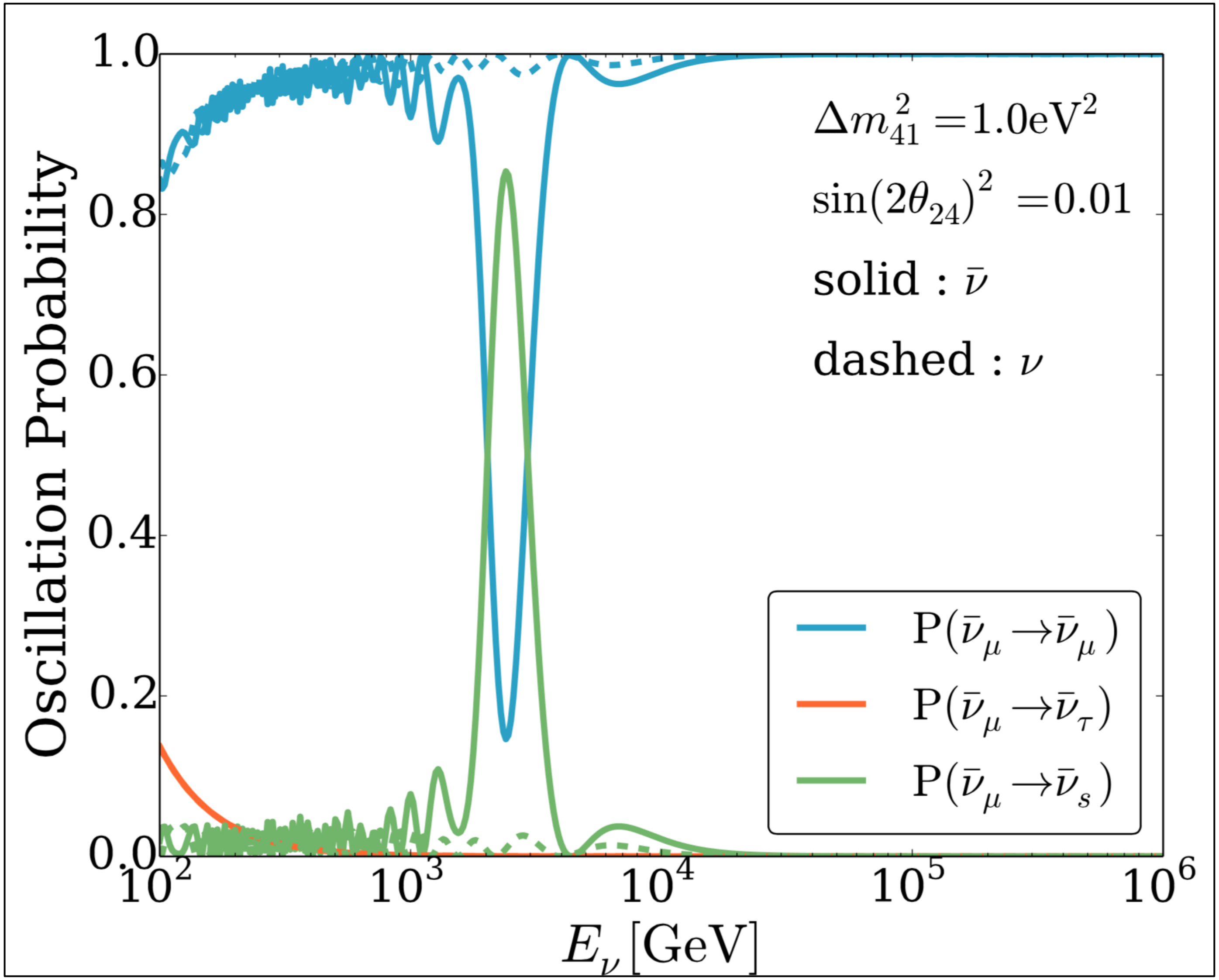
- Δm^2 too large for resonance in the Sun
- Much higher energy neutrinos and antineutrinos are produced in cosmic ray air showers
- They cross the Earth, with active species feeling the matter potential







MSW RESONANT STERILE NEUTRINOS



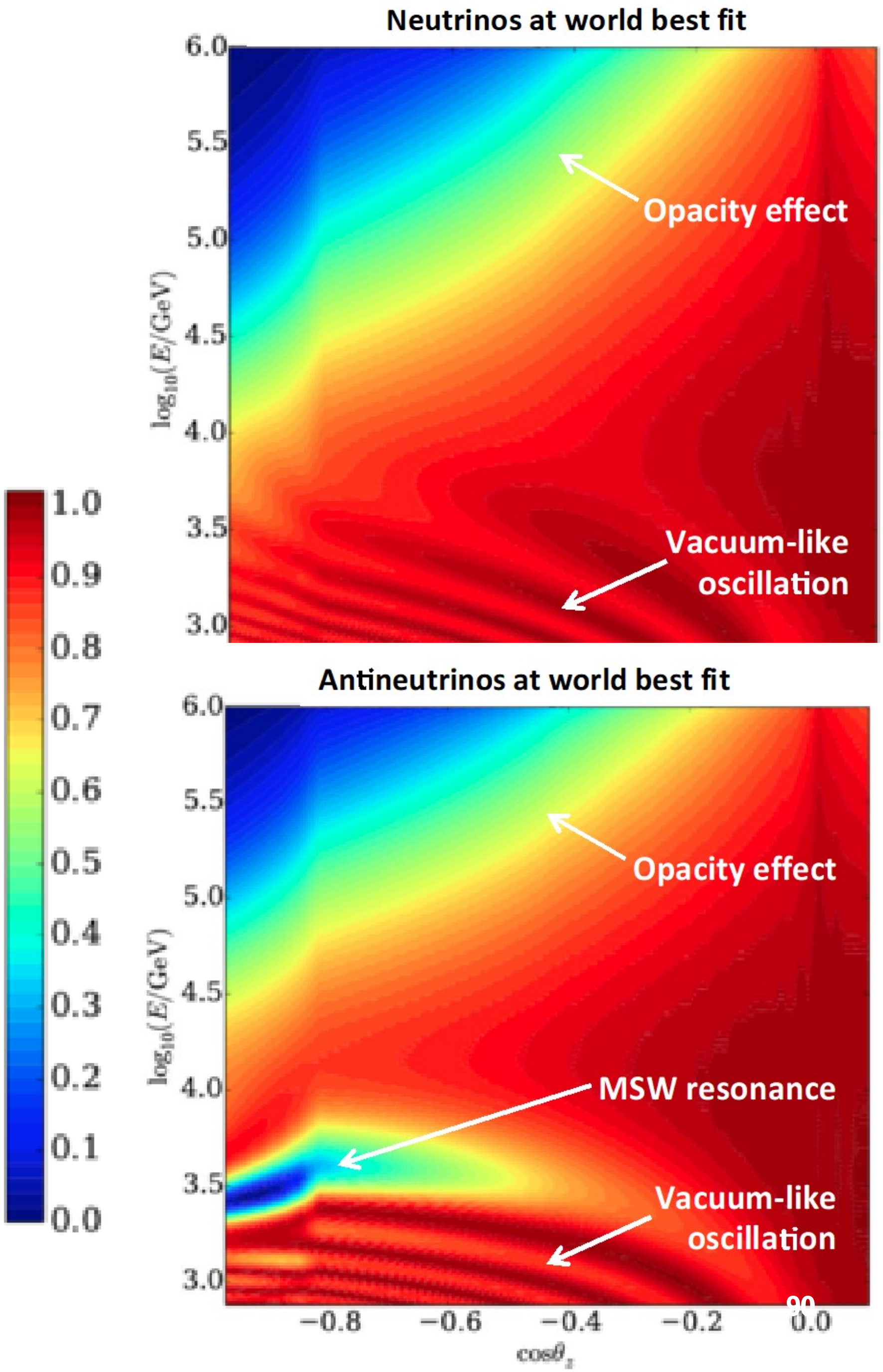
PREDICTING THE MSW OSCILLATION

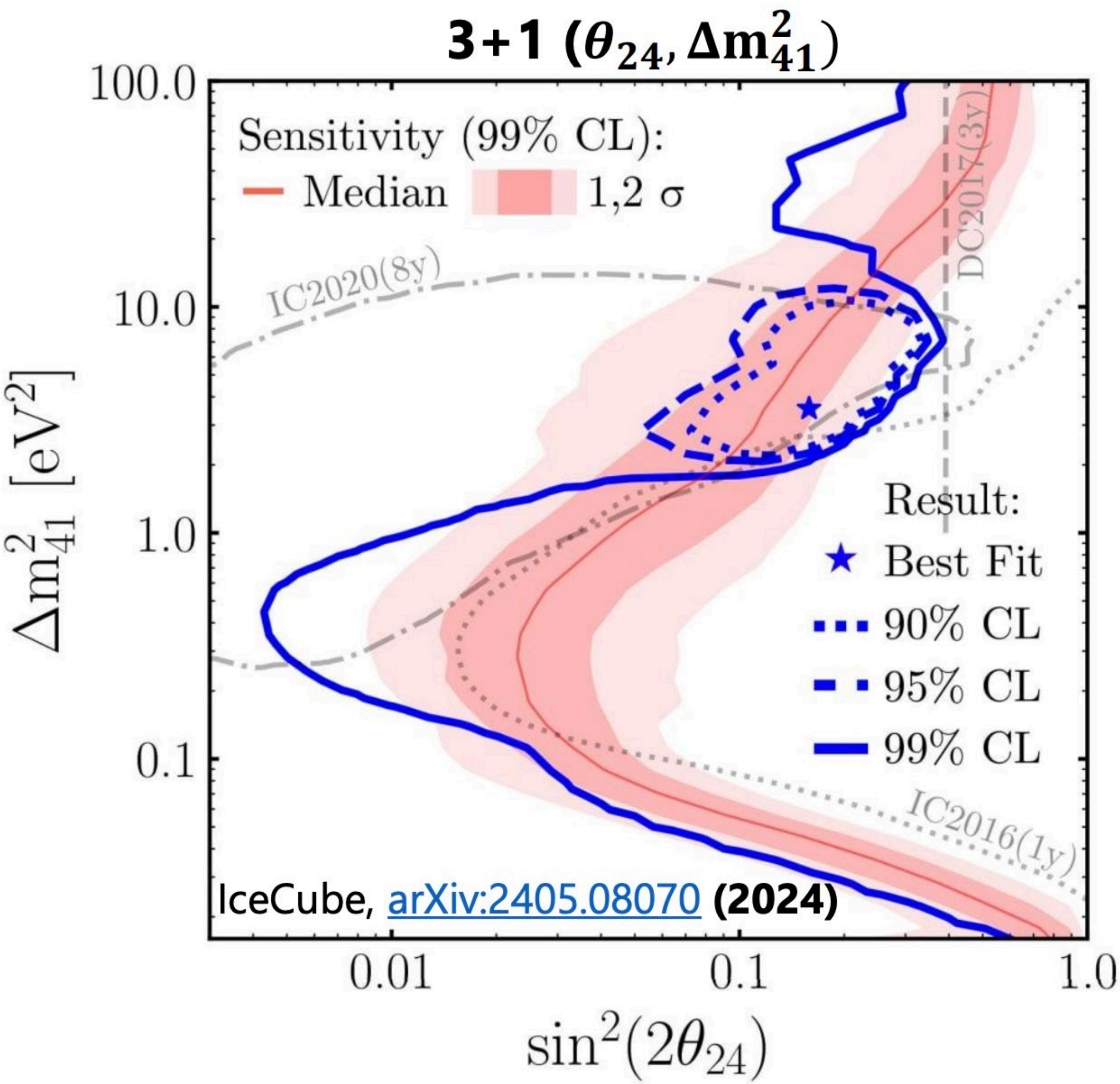
At these energies, have refractive (MSW) phenomena, and also significant incoherent scatter cross section.

Have to include both effects to predict survival probability - and they are non-trivially coupled

→ **numerically solve flavor evolution master equation through Earth density profile for truth-level oscillation solution.**

nuSQuIDs: https://github.com/arguelles/nuSQuIDS





ICECUBE SEES…

- Closed contour at 95CL.
- A rather high-mass solution, but not inconsistent with LEE measurements.
- Gets stronger with each unblinding…