Abstract

Neutrinos are the second most abundant known particle in the Universe and are produced abundantly in many extreme astrophysical environments. This gives us the opportunity to study neutrinos in ways not accessible in human made environments. I will discuss low energy ($<$GeV) neutrinos from our own Sun and from exploding stars, supernova, in our galaxy and beyond. I will also discuss intermediate energy neutrinos ($\sim$GeV to ~ 50 GeV) produced in the Earth's atmosphere that travel through the Earth. Predicting the fluxes from these sources involve challenging calculations, the neutrinos experience non-trivial flavor changing during propagation, and all stages of the propagation provide excellent sensitivity to new physics. High energy neutrinos (> 10 TeV) have been detected, but our understanding of their origin remains incomplete. I will discuss possible sources, standard physics to probe, and new physics to probe with these sources. Finally, despite the difficulty in detection, neutrinos are powerful tools to peer inside otherwise opaque environments.

Neutrinos: Atmospheric, Solar, Astrophysical, and More

Peter B. Denton

FNAL NPC Neutrino University

June 10, 2026

Brookhaven National Laboratory

About Me

1. Grew up in Michigan
2. Bachelors in physics and math from Rice, '10

   Visited Fermilab to do accelerator physics

3. PhD from Vanderbilt, '16
4. Year at Fermilab working with Stephen Parke, '15-'16
5. Postdoc at the Niels Bohr International Academy, '16-'18
6. Faculty at Brookhaven, '18-present

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Research interests

- Neutrino oscillations
- New physics in neutrinos
- Astroparticle physics
- Black holes
- Dark matter

Other interests

- Ultimate frisbee
- Hiking
- Piano
- Photography

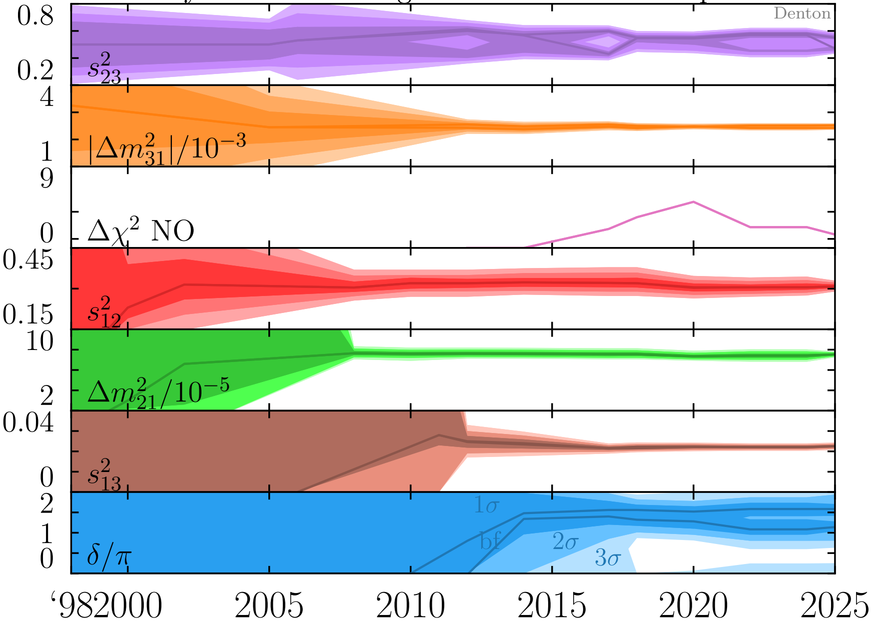
Stop by third floor (374) anytime next 1.5 weeks

Resources

"Neutrino Oscillations in the Three Flavor Paradigm" - PBD 2501.08374

Particle Data Group (PDG) "14. Neutrino Masses, Mixing, and Oscillations" - M.C. Gonzalez-Garcia, R. Wendel
https://pdg.lbl.gov/2026/reviews/rpp2026-rev-neutrino-mixing.pdf

History of our knowledge of the six oscillation parameters



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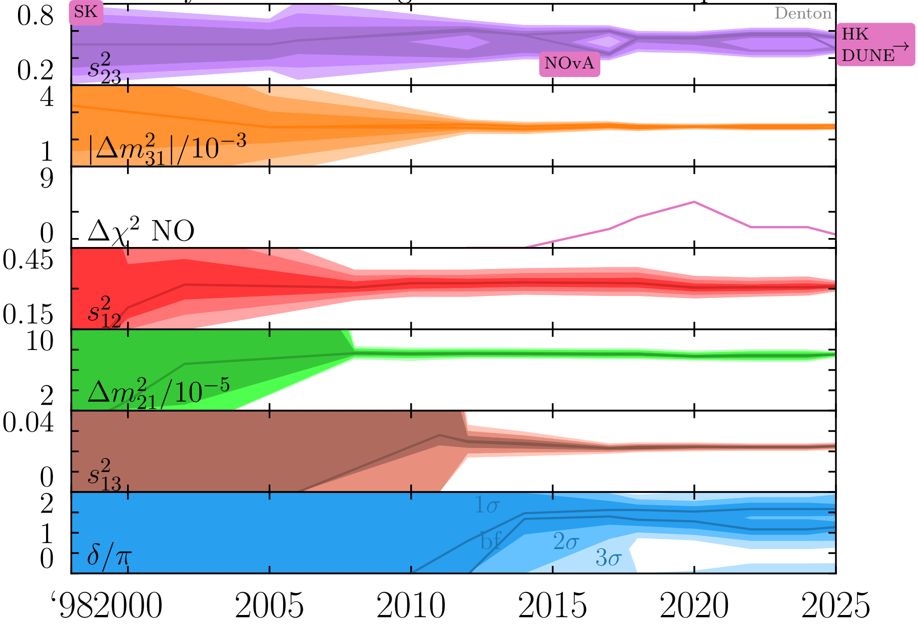

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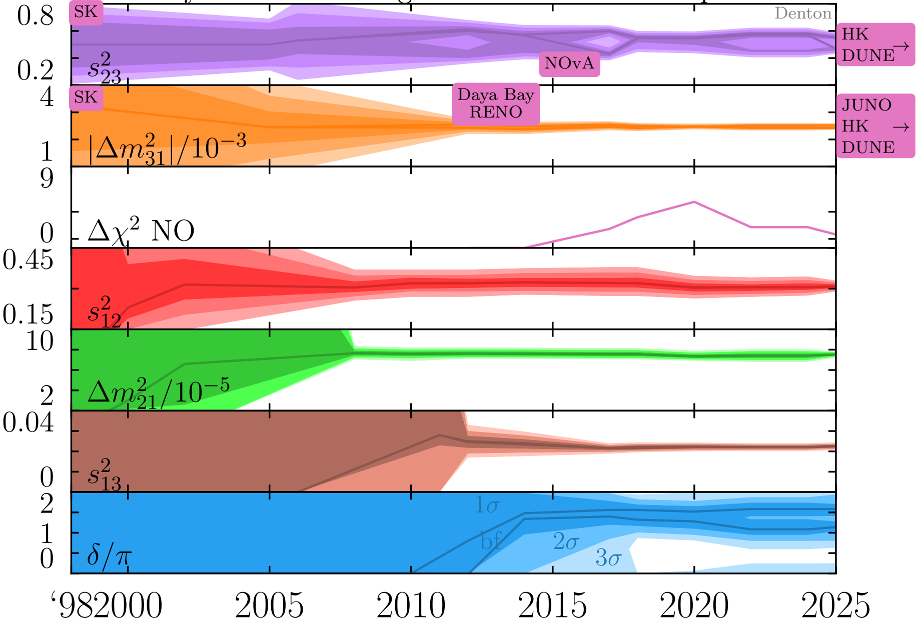

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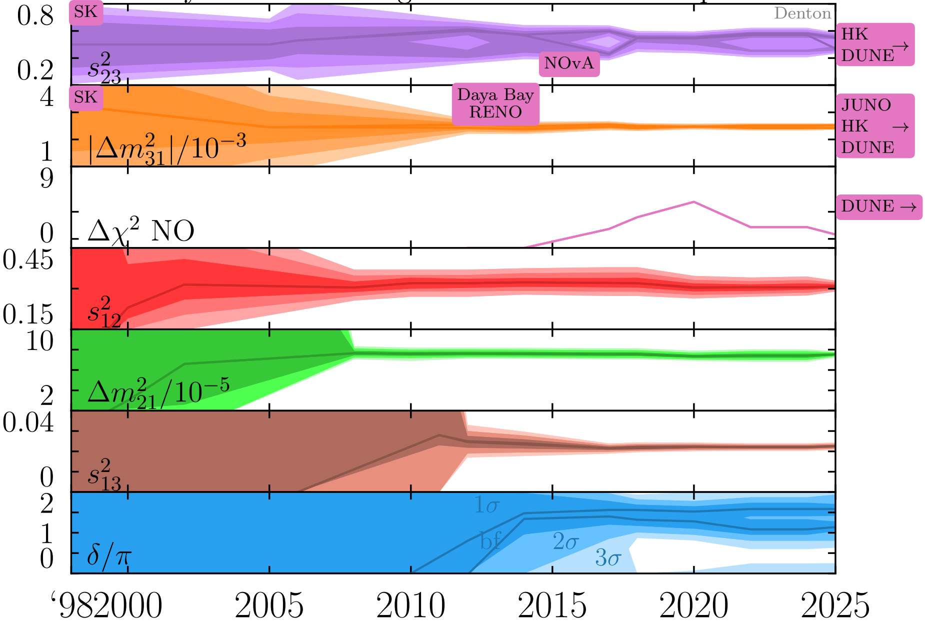

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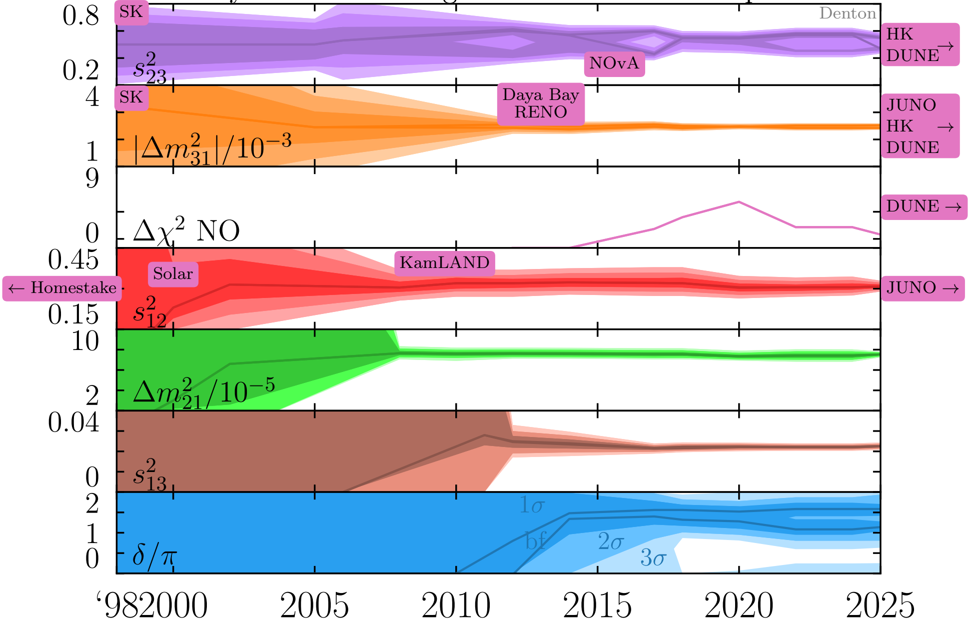

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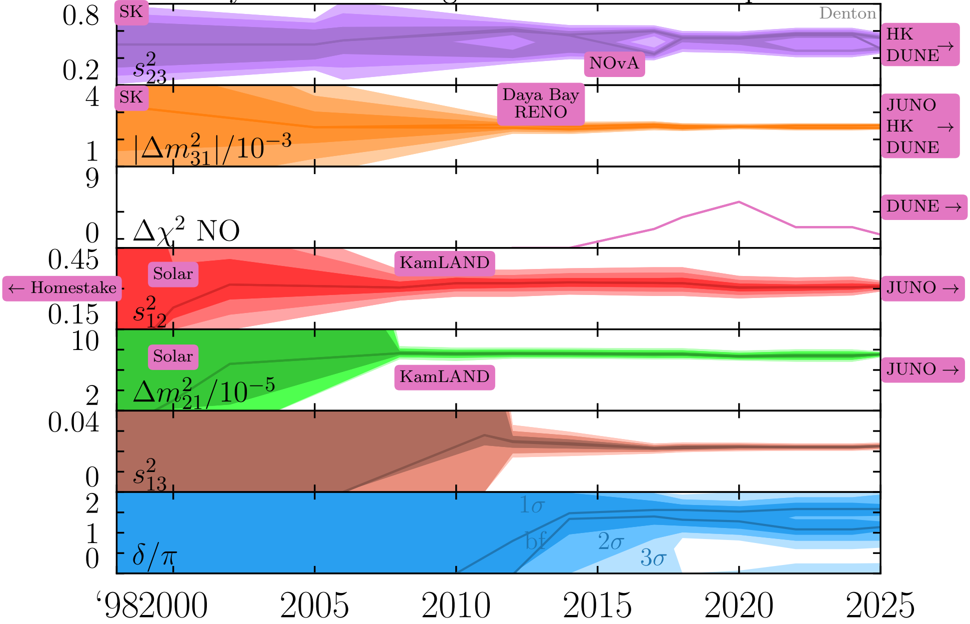

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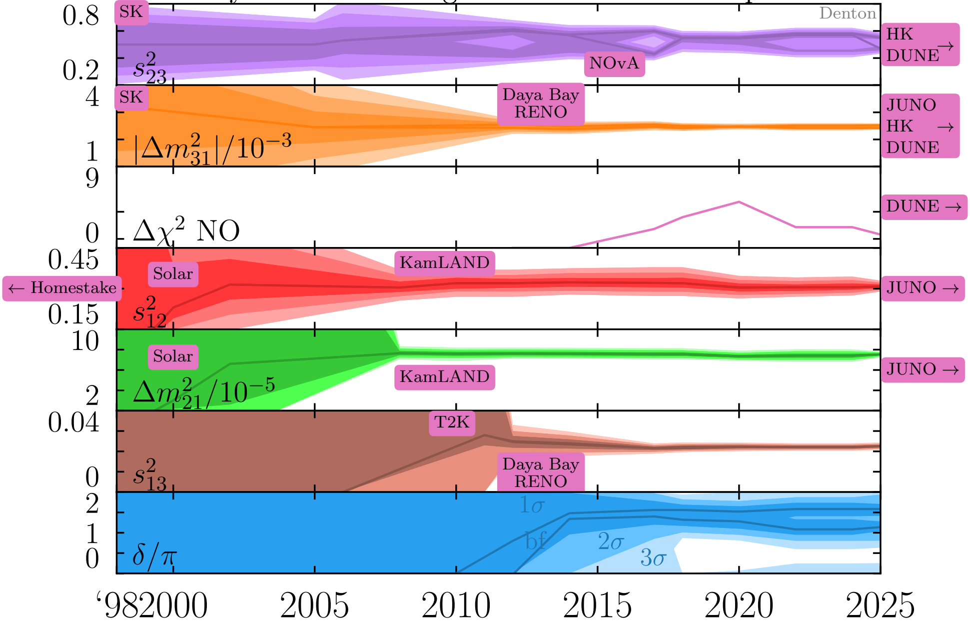

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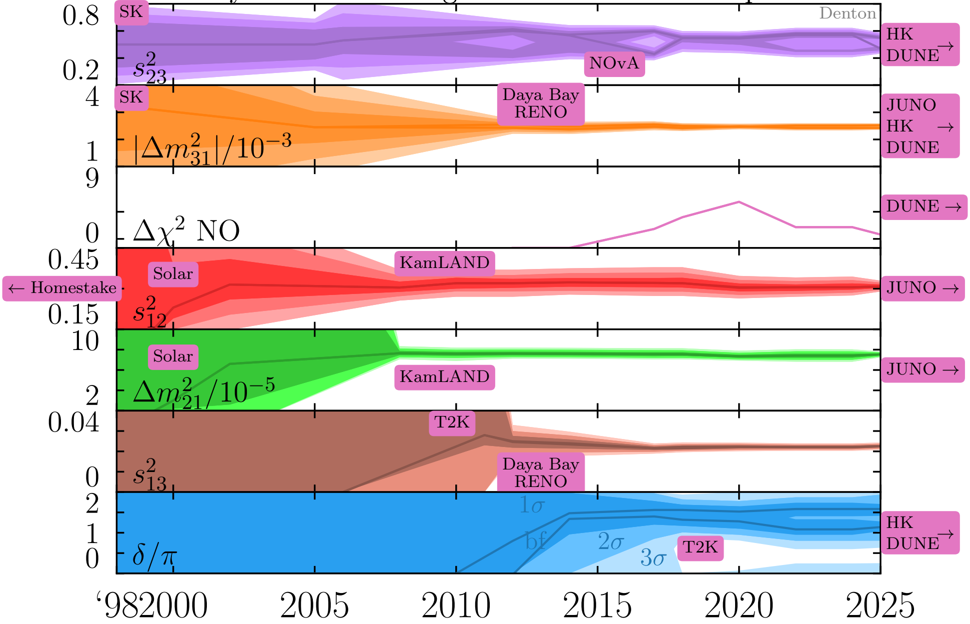

Outline

1. Neutrinos feel the vibes of the matter around them
2. Cosmic rays hit the atmosphere $\Rightarrow$ neutrinos: the Earth is the experiment
3. The Sun produces a lot of neutrinos; exactly how many?
4. Supernova are neutrino factories; neutrinos get to talk to each other
5. There are high energy astrophysical neutrinos, where are they from?
6. Neutrinos probe opaque environments

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Neutrinos Lead to Unexpected Discovery in Basic Math (Quanta)

Hamiltonian Dynamics

Schrödinger equation:

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$$H_{\rm flav}(t) = \frac{1}{2E}\left[U\begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix} a(x) & & \\ & 0 & \\ & & 0\end{pmatrix}\right]$$

Assume ν's are ultrarelativistic: $E_i \to p + m_i^2/2E$, $t \to L$

See also e.g. E. Akhmedov, A. Smirnov 0905.1903

Why do we discuss $\Delta m^2_{ij} = m_i^2 - m_j^2$ and not just m_i^2?

Matter effect: $a = 2\sqrt{2}G_F N_e E$

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Why do we discuss $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and not just m_i^2?

Matter effect: $a = 2\sqrt{2}G_F N_e E$

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}$$

For more on parameterizations see: PBD, R. Pestes 2006.09384

Why can we ignore Majorana phases in oscillations?

Matter Effect: Constant

In vacuum:

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) = \sum_{i=1}^{3} U_{\alpha i}^* \, e^{-i m_i^2 L/2E} \, U_{\beta i} \qquad\qquad P_{\alpha\beta} = |\mathcal{A}_{\alpha\beta}|^2$$

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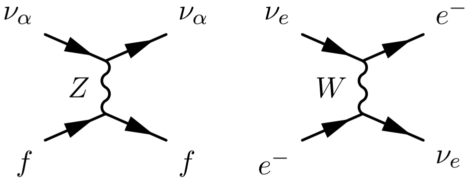
In matter ν's propagate in a new basis that depends on $a \propto N_e E_\nu$.



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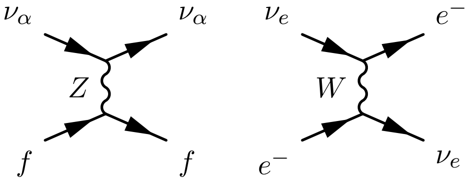

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Why isn't there a term in the Hamiltonian for the Z boson diagram?

Assume $H_{\rm flav}(x) \simeq H_{\rm flav}$ is approximately constant:

$$\mathcal{A} = e^{-iH_{\rm flav}L}$$

Matter Effect: Varying

Solar neutrinos in an adiabatically changing matter potential

Solution = MSW effect

S. Mikheev, A. Smirnov Nuovo Cim. C9 (1986) 17-26

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Neutrinos in supernovae experience MSW effect too,
but they also experience neutrino-neutrino interactions

Propagation in SNe is much more involved

Matter Effect Open Questions

- Matter has only been measured in the Sun, by combining solar with reactor. Confirm it in the Earth.
- New physics that looks like the matter effect takes the form of vector non-standard neutrino interactions: vNSI. Is there evidence for this? Can we constrain it?
- There is a degeneracy within new physics (vNSI) related to measuring the matter effect and the mass ordering ($\operatorname{sgn}\Delta m^2_{31}$) called LMA-Dark. Can we rule it out?
- How well do we know the density of the Earth/Sun?

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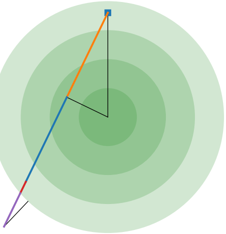

PBD, S. Parke 2511.04735

Atmospheric Neutrinos

1. Production
2. Propagation
3. Detection

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Atmospheric Neutrino Production

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3. $\pi^{\pm}$ decay to $\mu + \nu_\mu$
   3.1 Low energy muons: decay to $e + \nu_\mu + \nu_e \Rightarrow (\nu_e : \nu_\mu : \nu_\tau) \simeq (1 : 2 : 0)$
   3.2 High energy muons: hit Earth and lose energy $\Rightarrow (0 : 1 : 0)$

We often refer to this energy loss as dE/dx
$\pi^{\pm} \to e + \nu_e$ happens 0.01%
Kaons also produced, $K^{\pm} \to \nu_e + \cdots = 0.08 K^{\pm} \to \nu_\mu + \ldots$

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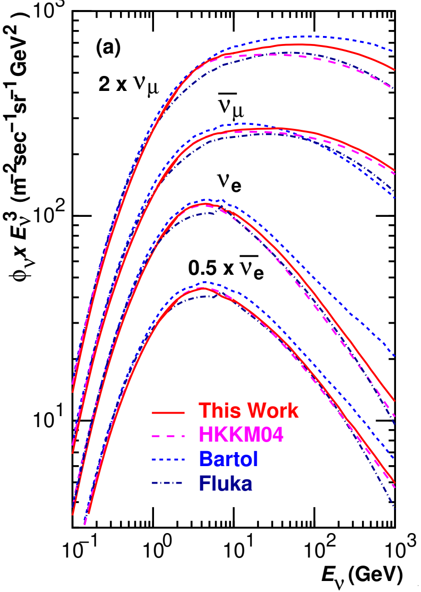
Q: What non-pion production mechanisms
for high energy neutrinos are interesting?

Atmospheric Neutrino Production



M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, T. Sanuki astro-ph/0611418

Open Atmospheric Neutrino Flux Problems

1. Heavier mesons produce neutrinos with a different spectrum: predict this theoretically and measure it

   See work by Mary Hall Reno+, e.g. 2212.07865

2. There are fewer muons at very high energies than predicted by the models

   See e.g. K. Cheminant, et al. 2302.07932

In addition to astroparticle experiments (IceCube, KM3NeT, Auger, Telescope Array, ...), the LHC plays an important role too

Atmospheric Neutrinos

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2. **Propagation**
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Propagation in Sharply Varying Matter

Solve the Schrödinger equation

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Exponential requires computing eigenvalues and eigenvectors of H_j,
for good precision through the Earth, repeat this many times

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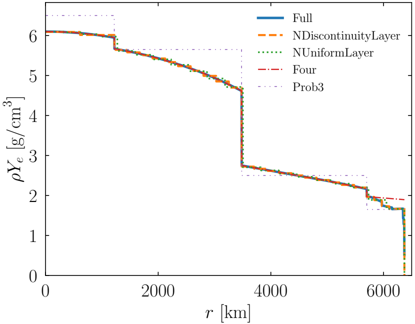
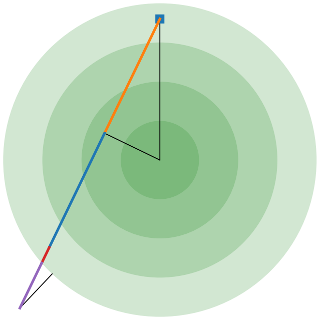
Standard libraries for matrix exponentiation work
Can be much more clever

PBD, S. Parke 2511.04735
github.com/PeterDenton/NuFast-Earth

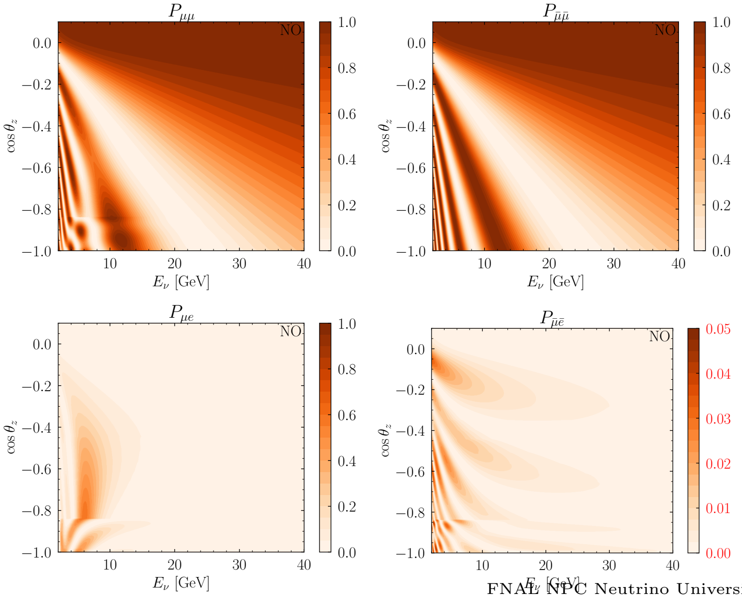
Earth Trajectories



Preliminary Reference Earth Model (PREM)



Atmospheric Neutrino Oscillations: NO



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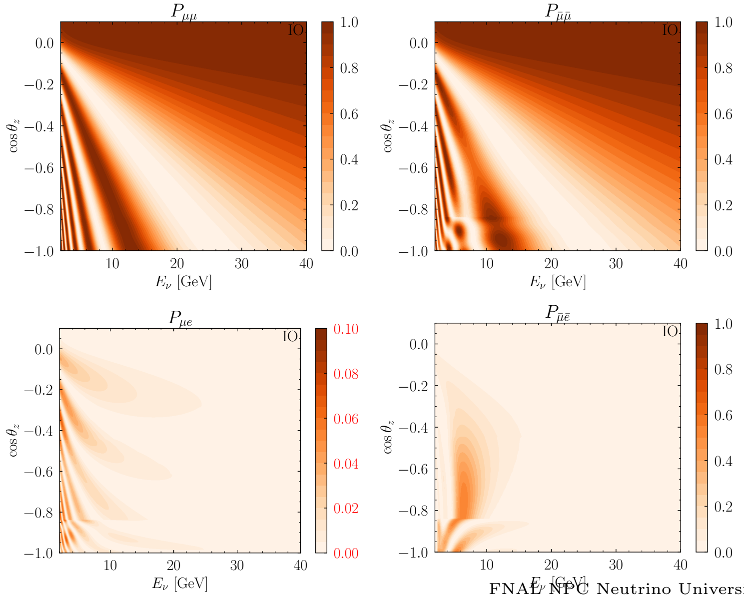

Atmospheric Neutrinos

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2. Propagation
3. **Detection**

Atmospheric Neutrino Detection

1. Need large volume

   Event rate falls off rapidly with energy

2. Need large overburden

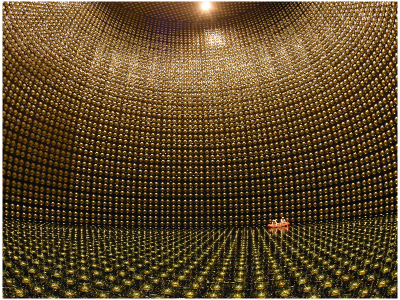
   Reduce down-going atmospheric muon background

3. Need direction information: $L \simeq -2R\cos\theta_z$

   $\cos\theta_z = -1 \Rightarrow$ core-crossing
   $\cos\theta_z = 0 \Rightarrow$ horizontal
   $\cos\theta_z = 1 \Rightarrow$ down-going

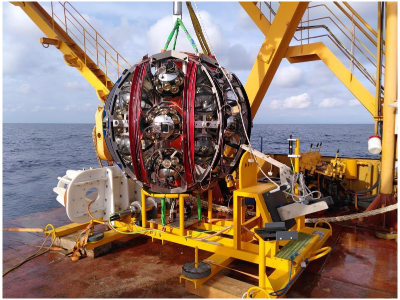
Atmospheric Neutrino Detectors Today and Tomorrow

SuperKamiokande → HyperKamiokande



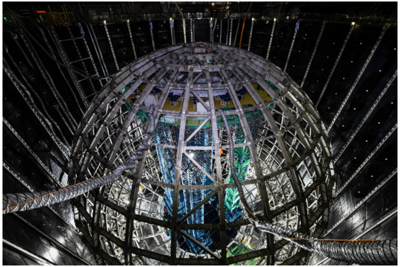
Huge water Cherenkov
Good overburden
Good PMT coverage

IceCube & KM3NeT



Massive water Cherenkov
Good overburden
Poor PMT coverage

DUNE & JUNO

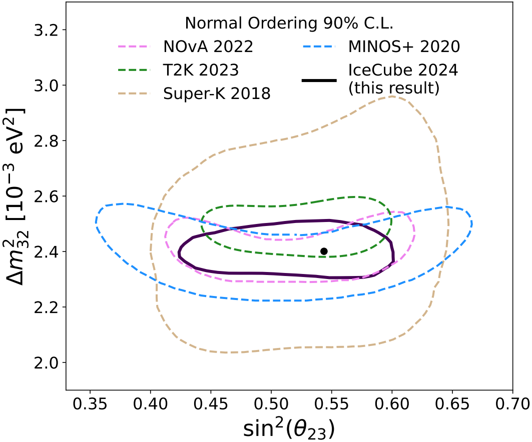


"Small" LArTPC/liquid scintillator
Excellent overburden
Excellent PID/PMT

Atmospheric Neutrino Results

Atmospherics predominantly measure:

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



IceCube 2405.02163

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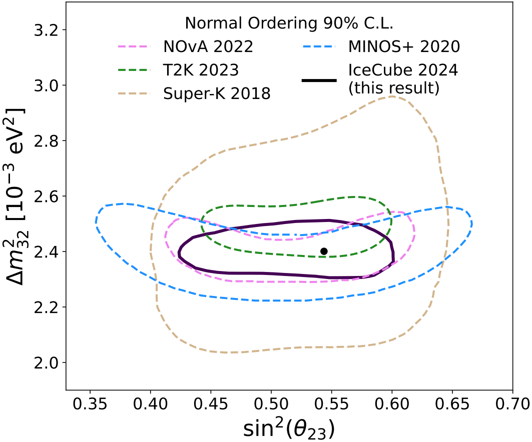
Hint: See e.g. H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283



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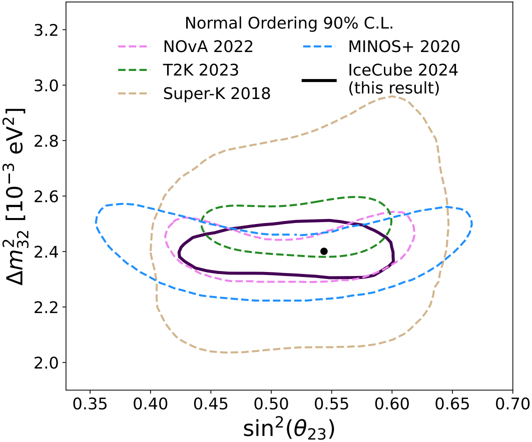
There is also information about the mass ordering and potentially CP violation



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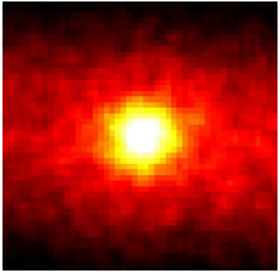

SuperKamiokande image of the Sun in neutrinos

Solar Neutrinos

Problem: Too few neutrinos from the Sun

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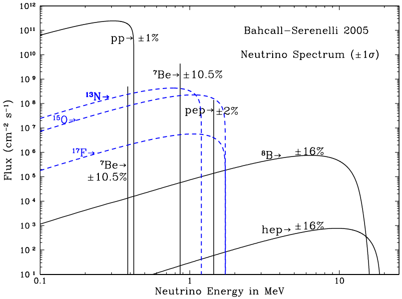
1. John Bahcall predicted the solar neutrino flux



^{8}B flux $\propto T^{24-25}$

J. Bahcall et al. nucl-th/9601044

Solar Neutrinos

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$E_{\nu,\mathrm{tr}} = 0.8$ MeV

Homestake ApJ. 496 (1998) 505-526

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Predicted: 9.3, 6.4, 7.6

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Perhaps ^{8}B is way lower than expected?

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Measured ν_e flux: 2.56 ± 0.23
Predicted: 9.3, 6.4, 7.6

Perhaps ^{8}B is way lower than expected?

Perhaps Homestake is wrong?

Solar Neutrinos

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Leased the water from a reactor for 1CAD (+ lots of insurance)

SNO nucl-ex/0204008

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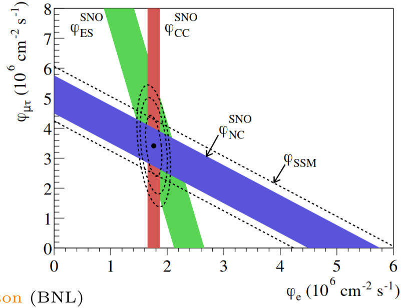

SNO nucl-ex/0204008

Solar Neutrino Probability

1. Compute Hamiltonian at production point

$$H_{\rm flav}=\frac{1}{2E}\left[UM^2U^\dagger+A\right]$$

$A=\text{diag}(a,0,0)$ is the matter effect, $a\propto N_eE$

2. Compute eigenvectors of H: $V^\odot_{\alpha i}$

$V^\odot$ is unitary, composed of normalized eigenvectors
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4. Ensure mass eigenstates remain mass eigenstates. Adiabaticity parameter:

$$\gamma = \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \frac{\Delta m^2_{21}/2E}{|\dot{N}_e/N_e|}$$

Probability of jump at resonance: $P_j \simeq \exp(-\frac{\pi}{2}\gamma)$

Ensure that $\gamma \gg 1$ at resonance: $a = \Delta m^2_{21} \cos 2\theta_{12}$

S. Parke 2212.06978 (1986)
See also: A. Dighe, A. Smirnov hep-ph/9907423

$\vdots$

Solar Neutrino Probability

5. Propagate to Earth: $P_{ij} = \delta_{ij}$

Solar neutrinos decohere:
it is mass states that are relevant

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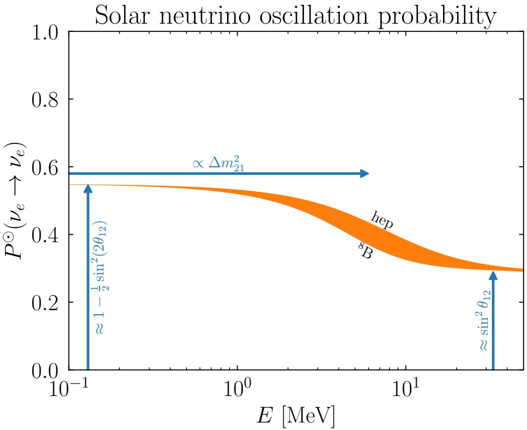

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PBD 2501.08374

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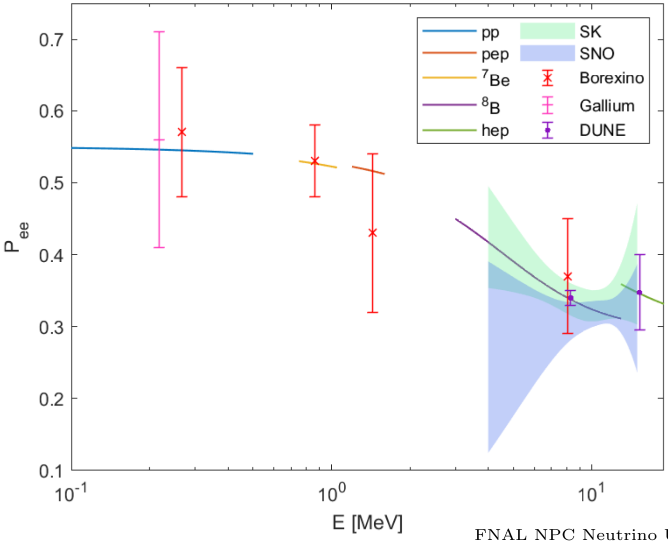
Solar Neutrino Measurements

PBD, C. Gourley 2502.17546



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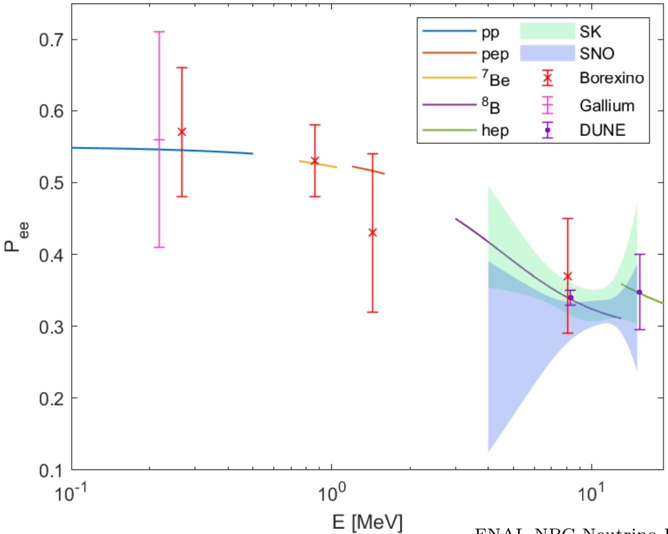
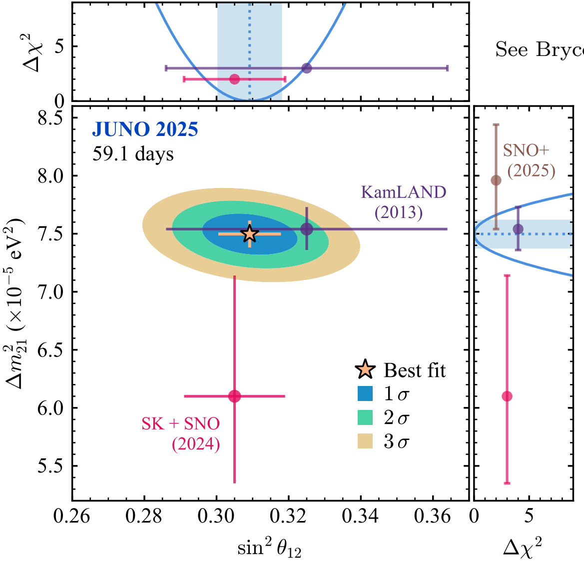


Why discontinuities?

Solar Parameters: SuperK, SNO, KamLAND, JUNO



JUNO 2511.14593
See Bryce Littlejohn's lecture next week

Challenge Questions: Solar Neutrinos

Q: How big is the jump probability at 5 MeV?

Q: Do we see more solar neutrinos during the day or the night?

Q: SNO measured a CC to NC ratio of $\sim 1/3$ of solar neutrinos. KamLAND and JUNO's measurements of reactor neutrinos confirmed the measurement of solar neutrinos by SNO and others. Given the reactor measurements, what other values, if any, could SNO have measured?

Nighttime Solar Neutrinos

At night solar neutrinos experience partial regeneration:
There are more ν_e's from the Sun at night than during the day!

SuperK has $\sim 2\sigma$ evidence for this effect; DUNE and HK aim to measure it well

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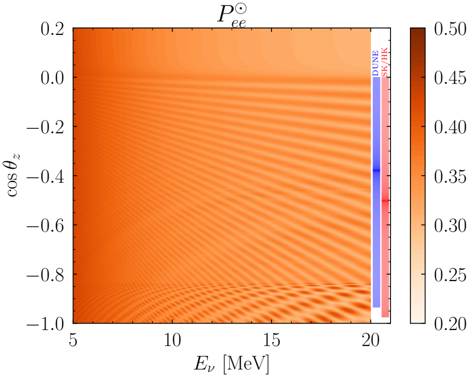
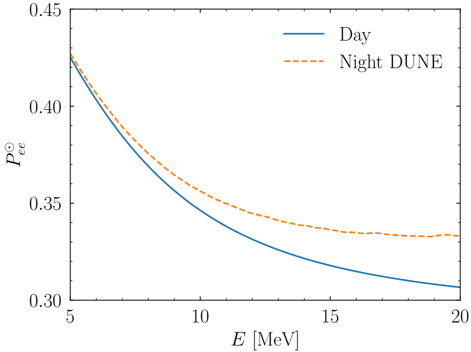




Figs. made with **NuFast-Earth** (github.com/PeterDenton/NuFast-Earth) from PBD, S. Parke 2511.04735

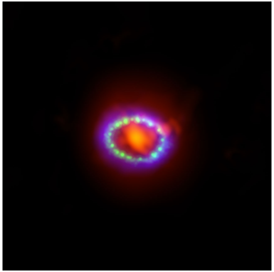
Solar Neutrino Open Questions

- Measure the day-night effect, confirm matter effect in the Earth.
- Detect the hep flux.
- New physics: sterile neutrinos, vector/scalar non-standard interactions, unitarity violation, ...
- Build on Borexino's CNO measurements; understand metalicity discrepancy.

⋮

Outline

1. Neutrinos feel the vibes of the matter around them
2. Cosmic rays hit the atmosphere ⇒ neutrinos: the Earth is the experiment
3. The Sun produces a lot of neutrinos; exactly how many?
4. **Supernova are neutrino factories; neutrinos get to talk to each other**
5. There are high energy astrophysical neutrinos, where are they from?
6. Neutrinos probe opaque environments



Composite image of Supernova 1987A (ESO)

Core-Collapse Supernova

1. Large stars $\gtrsim 8\ M_\odot$, towards end of fuel, onion structure forms
2. Fusion ends, pressure support falls, star collapses, neutrons begin to form

Changing $p \to n$ releases neutrinos, which type?

3. Infalling matter bounces off creating a shockwave
4. Shockwave stalls, matter continues accreting onto protoneutron star, neutrinos restart shock
5. Neutrinos drive the explosion
6. Neutrino neutrino interactions are very important; neutrinos become trapped "neutrinosphere"
7. Thermal-ish neutrinos emitted from neutrinosphere
8. Essentially all the gravitational energy of the star is converted to neutrinos

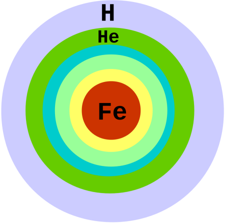


Fig. courtesy of A. Suliga

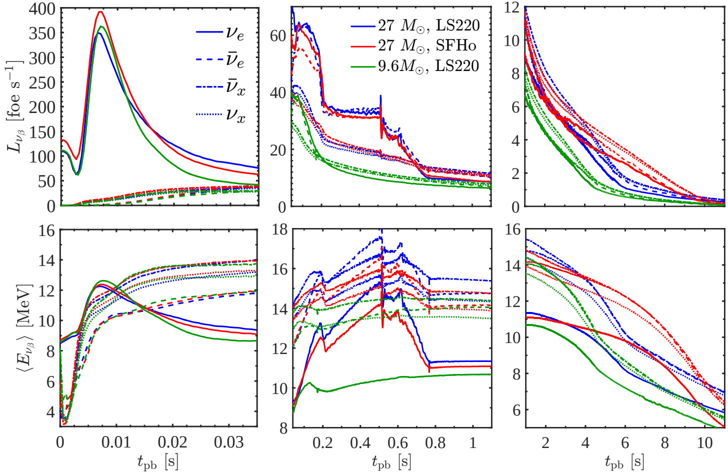
In 1987, we saw ~ 25 neutrinos across three detectors from SN

Core-Collapse Supernova Neutrinos

Neutronization burst

Accretion

Cooling



A. Suliga, PBD, et al. 1804.03157

Core-Collapse Supernova Neutrino Open Questions

- Is there new particle physics in neutrinos in the SN? During propagation from the SN to the Earth? When detected?
- Exactly how do neutrinos change flavor in a SN when $\nu - \nu$ interactions are important?
- Can we see the Diffuse Supernova Neutrino Background? Some early hints from SuperK

  See e.g. A. Suliga 2207.09632 for a recent DNSB review
- What heavy elements are produced in SN via r-process and what is the role of ν flavor during the SN?
- When will the next one go off?? And what is the actual rate in the Milky Way?

$\vdots$

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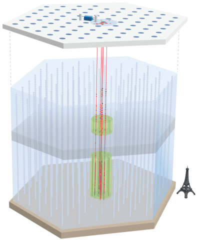

IceCube Neutrino Observatory

Bigger is Better

1970s: high energy astrophysical νs with huge water detectors?

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   - The Deep Underwater Muon and Neutrino Detection Project
   - Began in 1976 off Hawaii
   - Down to 4.8 km depth!
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phys.hawaii.edu/~dumand/

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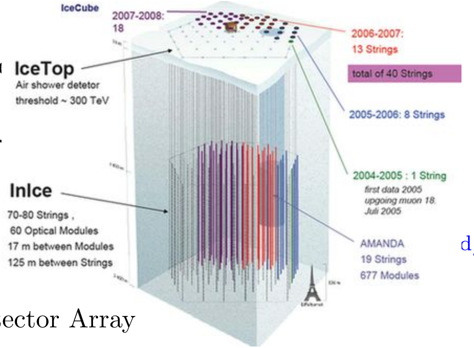

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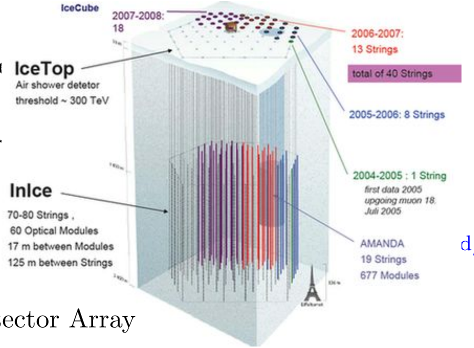

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4. KM3NeT: similar, but in Mediterranean, under construction now, early data

How to Detect High Energy Astrophysical Neutrinos

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  1. Track: ν_μ CC, or $\nu_\tau \to \tau \to \mu$ CC
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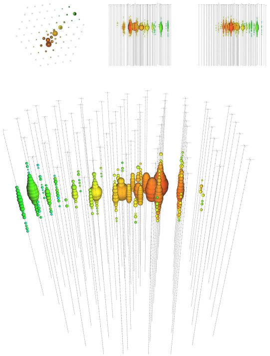
     - Lower limit on E (muon often escapes)



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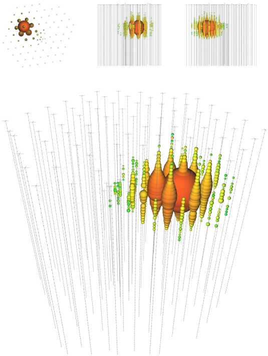

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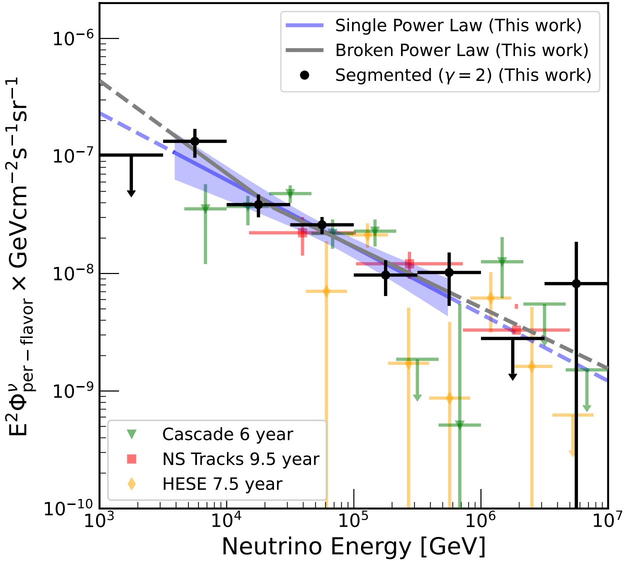
  2. Muons from atmospheric air showers
     - Makes downgoing searches hard $\Rightarrow$ focus on upgoing
     - At high energies $\gtrsim$ 100 TeV, flux falls off
     - At high energies $\gtrsim$ 100 TeV, Earth begins to become opaque to neutrinos

The Measured High Energy Astrophysical Neutrino Spectrum



IceCube 2402.18026

Even Bigger is Even Better

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  2. Baloon experiment over the South Pole; huge effective area
  3. Detected cosmic ray air showers reflected off the ice
  4. 4 upgoing air showers at $\sim 30^\circ$ below horizon with energy $\sim 10^9$ GeV?

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- Many next generation ideas out there
  1. Lots of loops of wire measure radio over Nebraska size area (GRAND, RNOG)
  2. Satellite looking at airshowers in the atmosphere (POEMMA, EUSO)
  3. Telescope on a mountain looking at a mountain (BEACON, TAMBO, TRINITY)

High Energy Astrophysical Neutrino Open Questions

- What are their origins? How are they accelerated? What connections to cosmic rays and γ rays should there be? Are there more than one class of sources?
- What is the origin of the ANITA events and the KM3NeT event? Why are they not seen by IceCube and Auger?
- What kinds of new particle physics can be probed? Do these or other anomalies indicate new physics?

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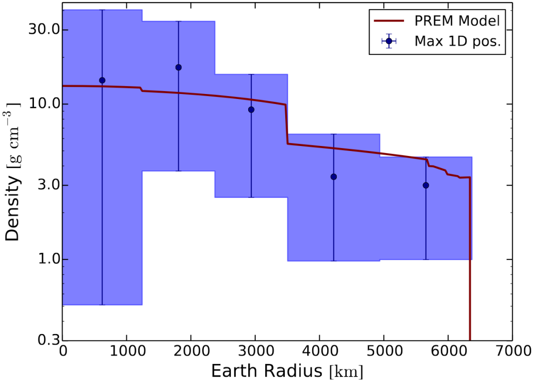
Terrestrial Tomography

HE neutrinos are absorbed in the Earth
Assumes isotropic flux



A. Donini, S. Palomares-Ruiz, J. Salvado 1803.05901

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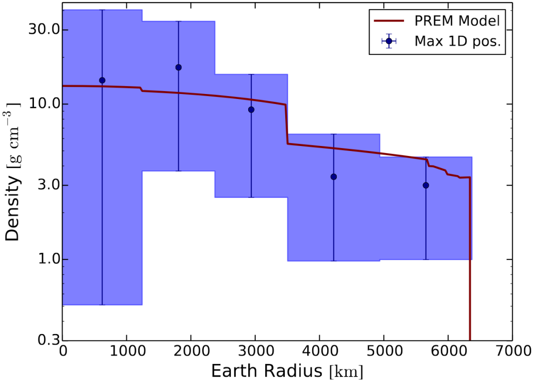
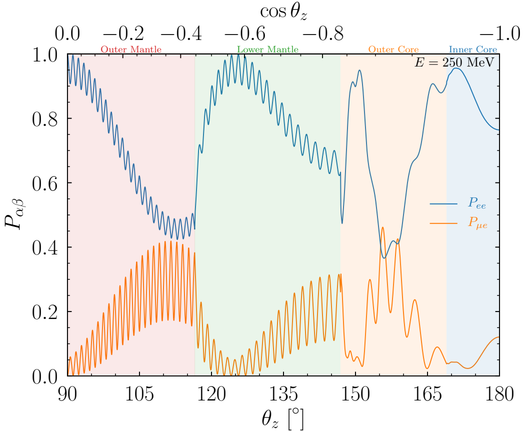
Assumes isotropic flux



A. Donini, S. Palomares-Ruiz, J. Salvado 1803.05901

Can also do this with oscillations

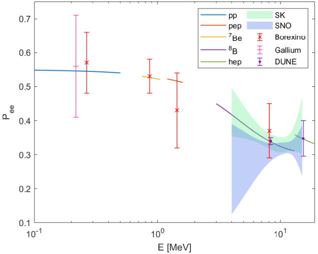


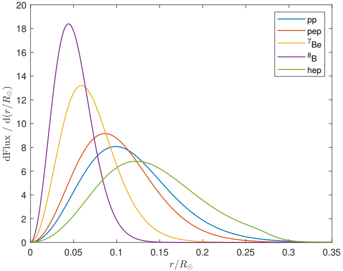
PBD, R. Pestes 2110.01148 (PRD)

DUNE-atm can measure $r_{\rm core}^{\oplus}$ to 9%

See also K. Kelly, et al. 2110.00003

Solar Tomography





Solar neutrinos constrain Sun's density at different radii

PBD, C. Gourley 2502.17546

Solar Tomography

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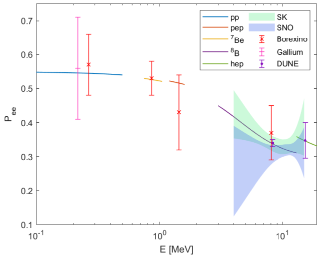
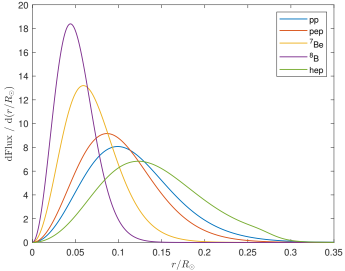
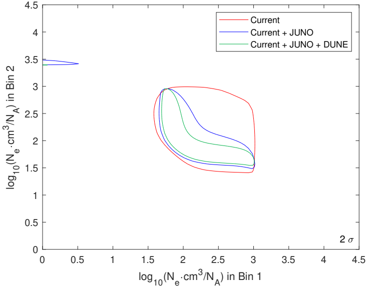


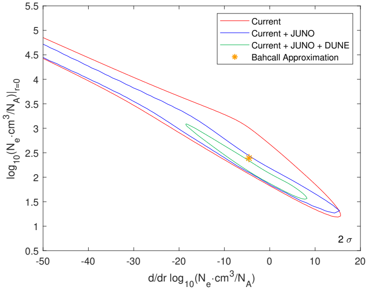


Bin 1: $\frac{r}{R_\odot} \in [0, 0.05]$

Bin 2: $\frac{r}{R_\odot} \in [0.05, 0.1]$

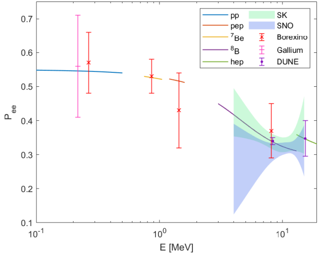


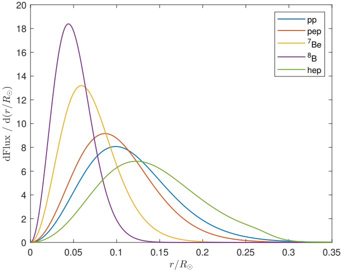
$$\log_{10} N_e = Ar + B$$



PBD, C. Gourley 2502.17546

Solar Tomography





Solar neutrinos constrain Sun's density at different radii

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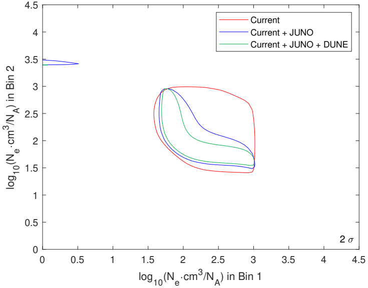

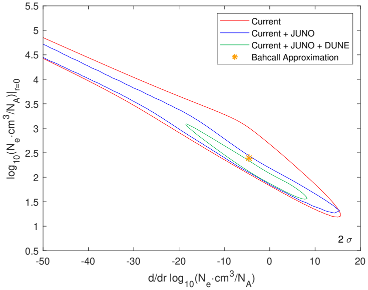

First determination of Sun's density with neutrinos

Only way to probe innermost 5% of the Sun

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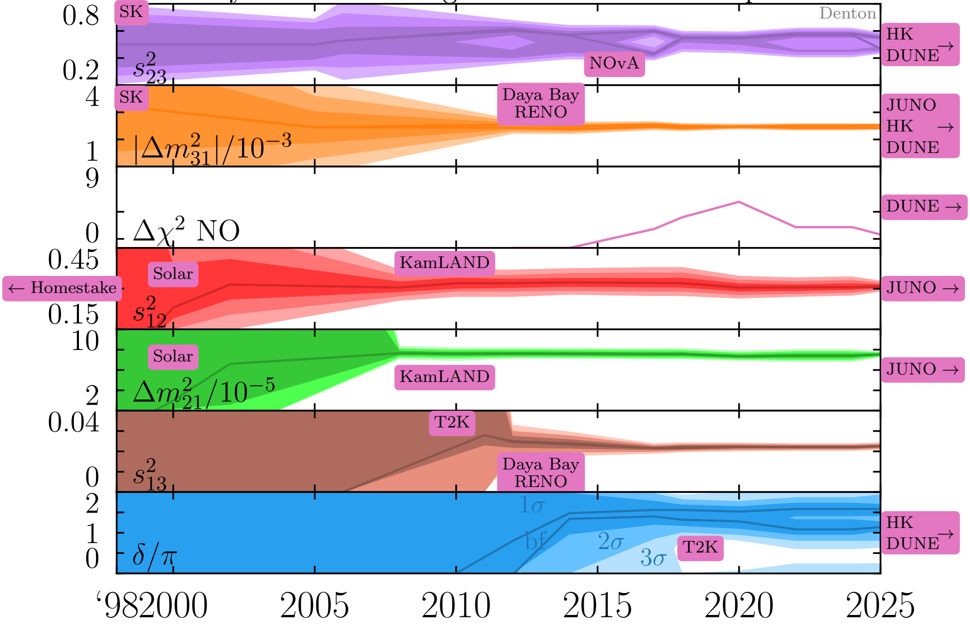
History of our knowledge of the six oscillation parameters



Discussion time!