Abstract

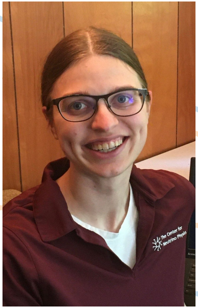
The most phenomenologically important properties of neutrinos are the facts that they don't interact with regular matter very much and that during propagation they change which charged lepton they like to interact with. The presence of matter does modify the propagation of neutrinos, somewhat, and I use this fact along with known oscillation parameters to probe environments that cannot be otherwise directly probed. In particular, I will show how low energy atmospheric neutrinos provide information about the Earth's core and that this can be determined by DUNE. I will also use current data from solar neutrino experiments, constrained by reactor neutrino data, to determine the density in the core of the Sun via neutrinos for the first time, as well as future sensitivities. Finally, I will also discuss ways of using the Earth to measure the neutrino cross section at the highest energies possible.

Shining the Neutrino Flashlight into the Darkest Places

Peter B. Denton

June 3, 2025

2007.10334 with Yves Kini
2110.01148 with Rebekah Pestes
2502.17546 with Charles Gourley



Outline

1. Knowledge of oscillations
2. Probe the density profile of the Earth
   - Absorption
   - Oscillations
3. Use the density of the Earth to determine the neutrino cross section
4. Probe the density of the center of the Sun

Ask not what your country can do for you. . .
Ask what you can do for your country

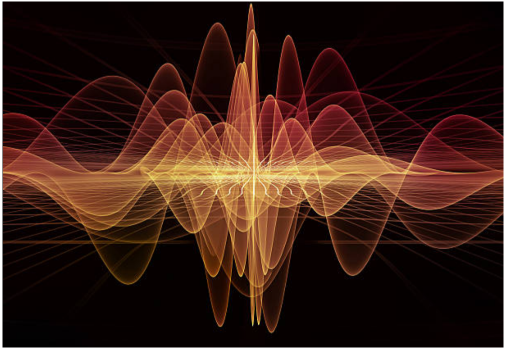
JFK 1961

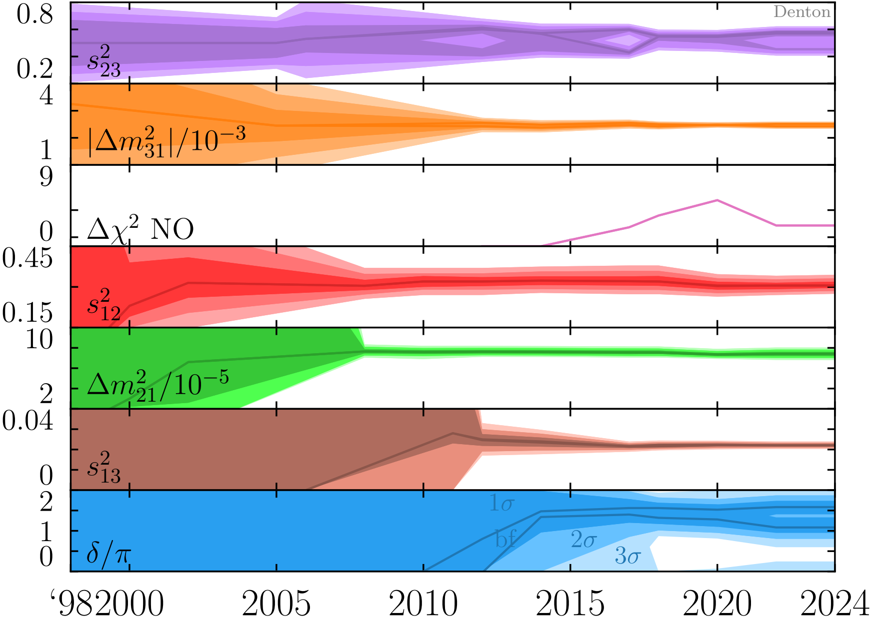
Ask not what your country can do for you…
Ask what you can do for your country

JFK 1961

Ask **both** what neutrinos can do for you…
And what you can do for neutrinos

What can we learn about neutrinos?





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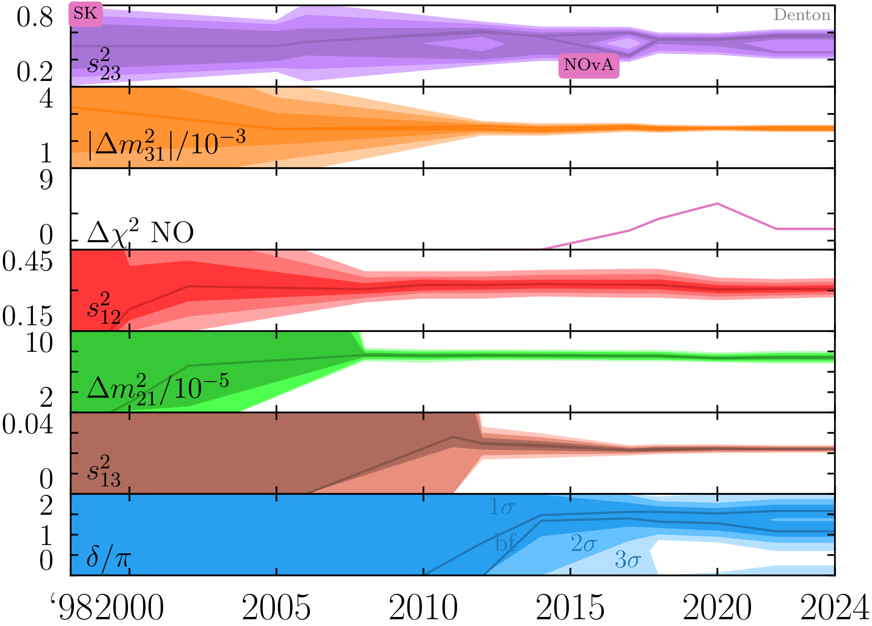
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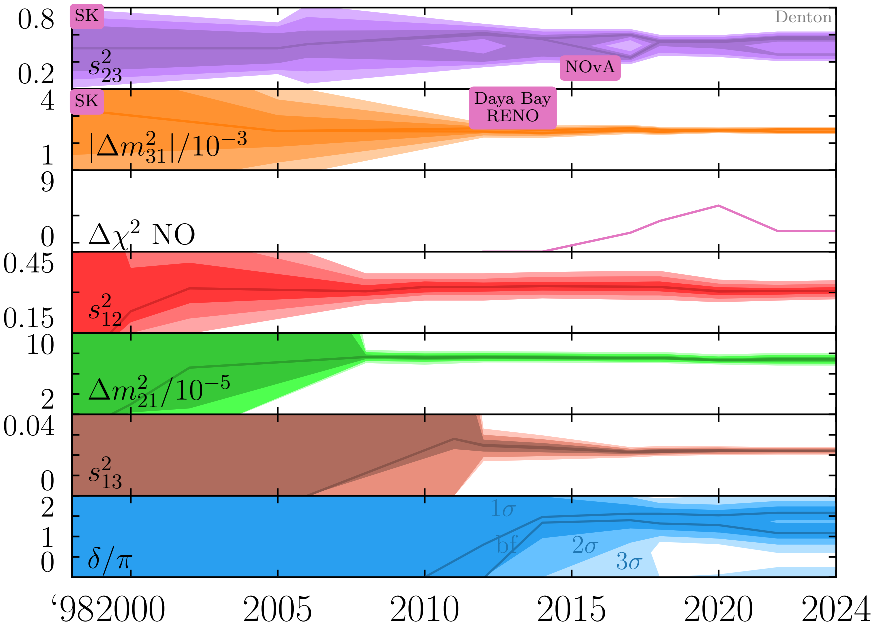
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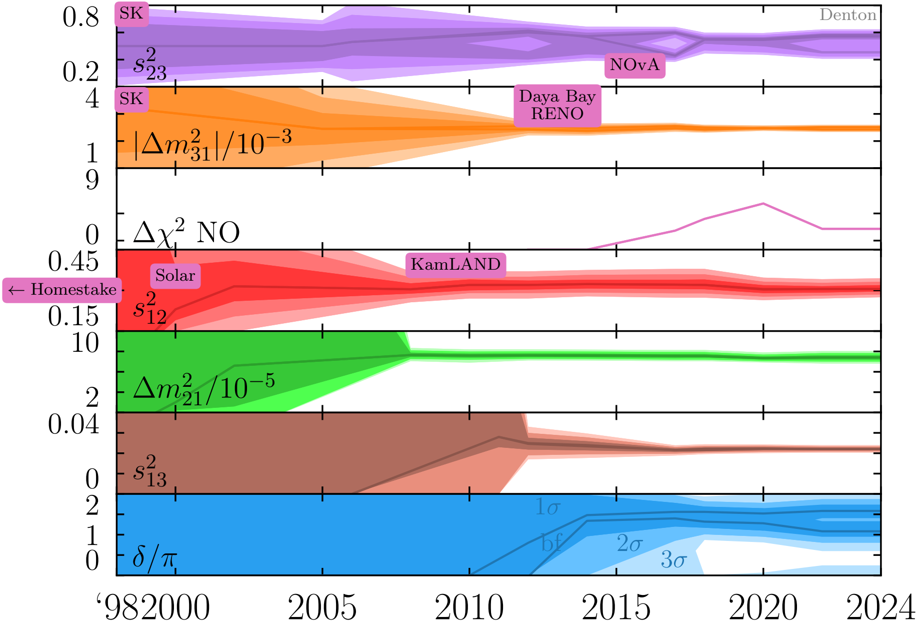
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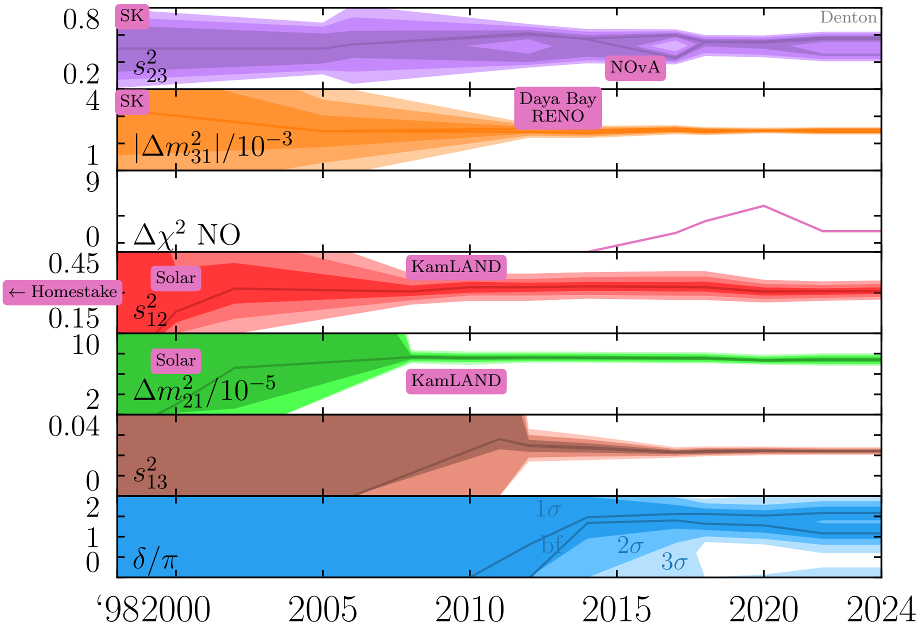

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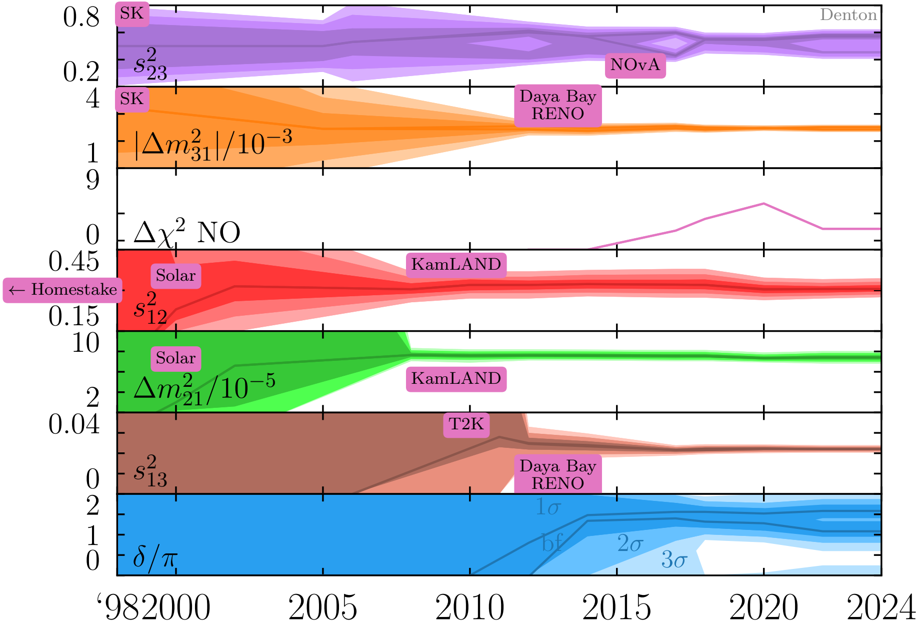
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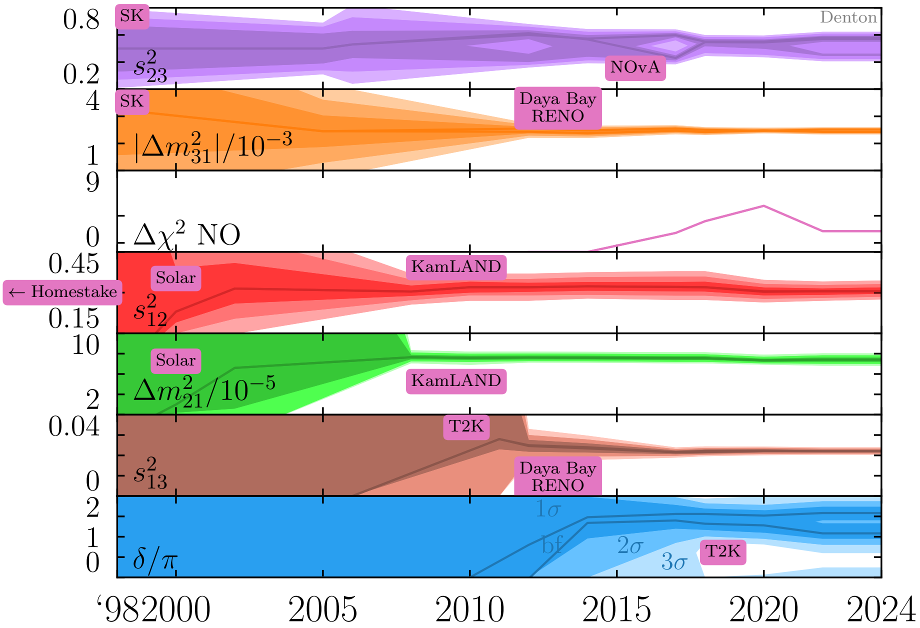

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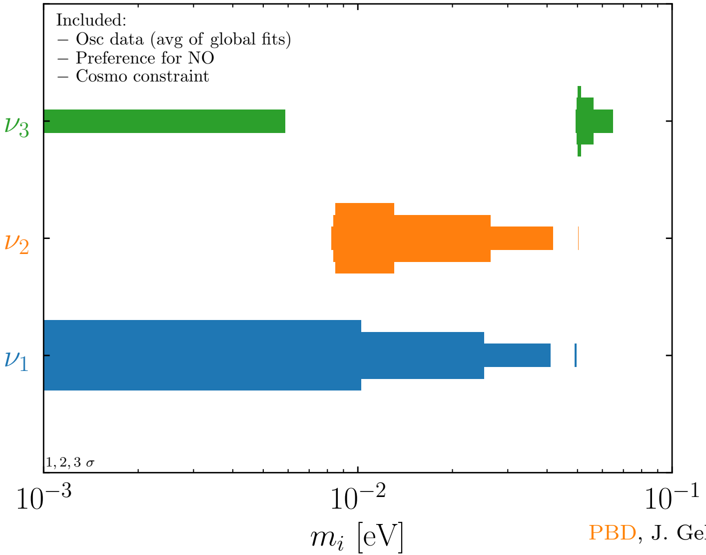
Absolute masses



PBD, J. Gehrlein 2308.09737

What can neutrinos do for us?

Density profile of the Earth

Preliminary reference Earth model *

Adam M. Dziewonski [1] and Don L. Anderson [2]

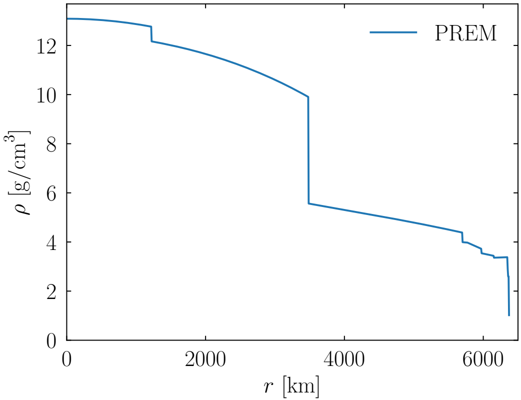
[1] *Department of Geological Sciences, Harvard University, Cambridge, MA 02138 (U.S.A.)*
[2] *Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125 (U.S.A.)*

(Received December 3, 1980; accepted for publication December 5, 1980)

Dziewonski, A.M. and Anderson, D.L., 1981. Preliminary reference Earth model. Phys. Earth Planet. Inter., 25: 297–356.

A large data set consisting of about 1000 normal mode periods, 500 summary travel time observations, 100 normal mode Q values, mass and moment of inertia have been inverted to obtain the radial distribution of elastic properties, Q values and density in the Earth's interior. The data set was supplemented with a special study of 12 years of ISC phase data which yielded an additional 1.75×10^6 travel time observations for P and S waves. In order to obtain satisfactory agreement with the entire data set we were required to take into account anelastic dispersion. The introduction of transverse isotropy into the outer 220 km of the mantle was required in order to satisfy the shorter period fundamental toroidal and spheroidal modes. This anisotropy also improved the fit of the larger data set. The horizontal and vertical velocities in the upper mantle differ by 2–4%, both for P and S waves. The mantle below 220 km is not required to be anisotropic. Mantle Rayleigh waves are surprisingly sensitive to compressional velocity in the upper mantle. High S_n velocities, low P_n velocities and a pronounced low-velocity zone are features of most global inversion models that are suppressed when anisotropy is allowed for in the inversion.

The Preliminary Reference Earth Model, PREM, and auxiliary tables showing fits to the data are presented.



A. Dziewonski, D. Anderson
Physics of the Earth and Planetary Interiors, 25 (1981) 297

Density profile of the Earth: Modern

Many nonsymmetric features identified in recent years

- Earth's liquid core contains tidally driven flows connected to the magnetic field

  B. Buffett Nature 468 (2010) 952
- Torsional wave with six year period

  N. Gillet, et al. Nature 465 (2010) 74
- Earth's core seems to be anisotropic

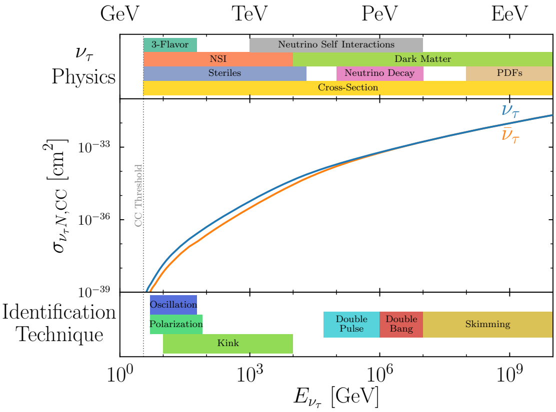
  A. Morelli, A. Dziewonski, J. Woodhouse Geo. Res. Lett. 13 (1986) 13
  L. Vinnik, B. Romanowicz, L. Breger Geo. Res. Lett. 21 (1994) 16
  H. TkalČić, B. Kennett AJES 55 (2008) 4
  D. Frost, et al. Nat. Geo 14 (2021) 531

All information on Earth's interior from seismic data

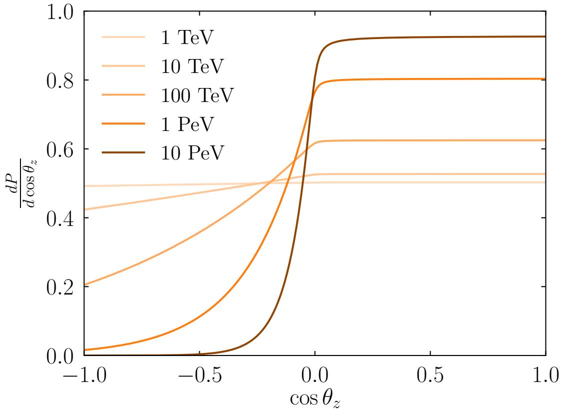
Neutrino probes

1. Absorption
2. Oscillations via Wofenstein matter effect

Absorption

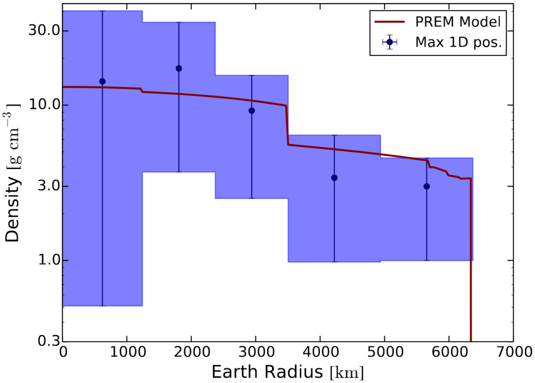


PBD, et al. 2203.05591



Astrophysical neutrinos at IceCube

- IceCube has detected an extragalactic flux of neutrinos 50 TeV $\sim$ 10 PeV
- Neutrino experiments typically prefer upgoing to downgoing
- Upgoing event rate is suppressed by the high cross section



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

Caveats

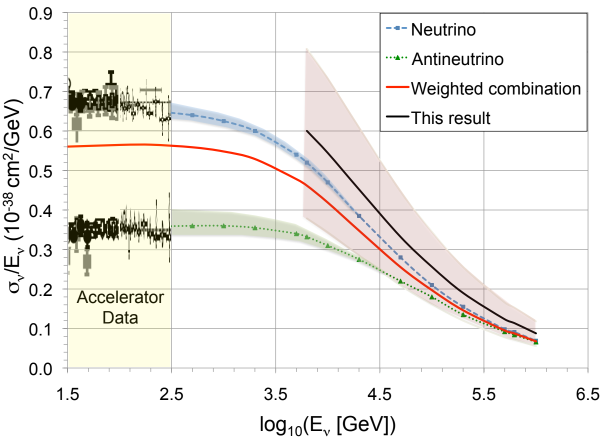
- Assumes an isotropic flux
  - There is a subleading galactic component that will slightly shift this

PBD, D. Marfatia, T. Weiler 1703.09721
IceCube 2307.07576
Baikal 2411.05608

      - Need to check that result is robust under various galactic or other local source scenarios
- Dark matter captured in Earth + new neutrino interactions
- Can invert absorption to determine the cross section

Dense environments provide levers on neutrino properties

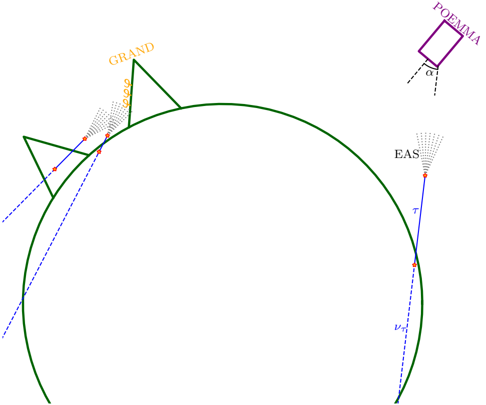
IceCube + absorption ⇒ cross section

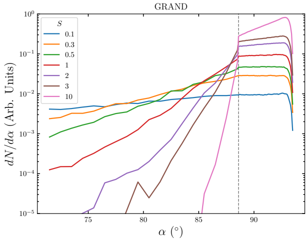


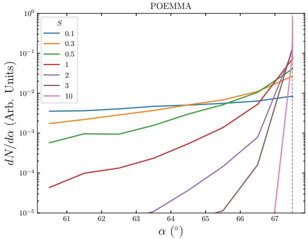
IceCube 1711.08119

Highest energy neutrino cross sections: PeV-EeV

Earth-/mountain-skimming provides information about ν_τ *only*



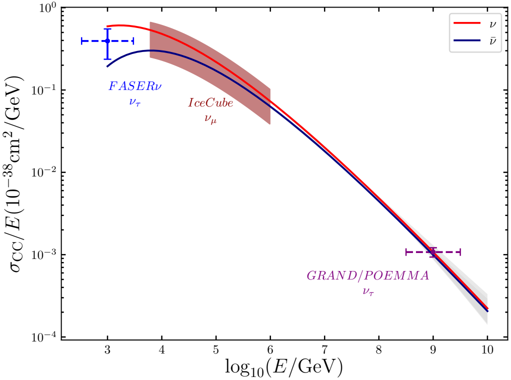




PBD, Y. Kini 2007.10334

ν_τ cross section

Flux unknown $\Rightarrow$ assume 100 events



PBD, Y. Kini 2007.10334

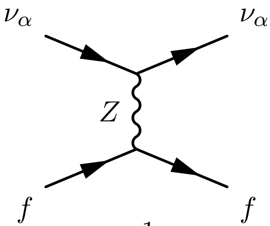
See also I. Esteban, S. Prohira, J. Beacom 2205.09763

- PDF uncertainties become relevant
- UHE neutrinos can constrain PDFs

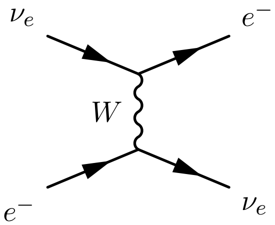
  V. Bertone, R. Gauld, J. Rojo 1808.02034
- Only possible with tau neutrinos!

Neutrinos in matter

1. Neutrinos propagate through Earth/Sun/... largely unobstructed
2. But the presence of matter modifies how they propagate!
3. Weak interaction tells neutrinos what basis to be in by modifying energy levels



$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$

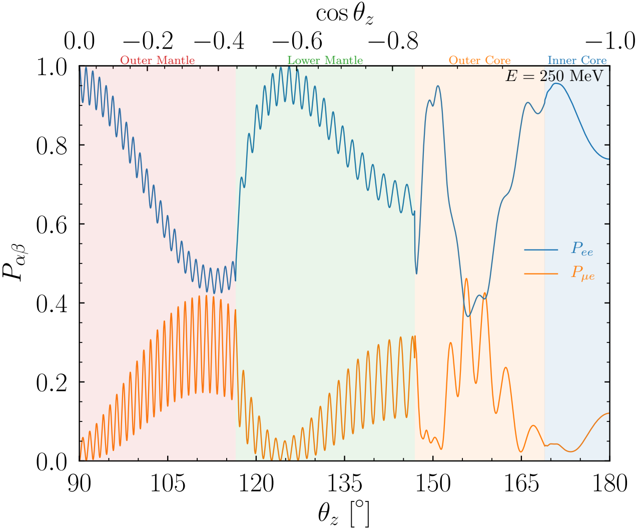


$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$

L. Wolfenstein, PRD 17 (1978)

$$H_f = \frac{1}{2E}\left[UM^2U^\dagger + \begin{pmatrix} 2EV_{\rm CC} & & \\ & 0 & \\ & & 0 \end{pmatrix}\right]$$

Low energy atmospheric neutrinos probe Earth density profile



Resonance in the Earth

What does MSW mean?

L. Wolfenstein PRD 17 (1978)
S. Mikheyev, A. Smirnov SJNP 42 913 (1985)

1. The matter effect
   - Helps DUNE determine the mass ordering
   - Is a misnomer; from the Wolfenstein paper only
2. Adiabatically locking in a large mixing angle
   - Explains solar neutrino problem; relevant in supernova
   - Can enhance a very small mixing angle to a sizable one (only happens in BSM)
   - Deviations characterized by "jump" probabilities

S. Parke PRL 57 1275 (1986)
PBD, Y. Kini 2411.13634

3. **Parametric enhancement** in "castle wall" potential
   - Happens when one wall size is equal to one oscillation length at that density
   - Can be relevant in Earth's core; plays role in mass ordering from atmospherics

Parametric enhancement

Need a half integer oscillations in mantle, core, and then mantle again:

$$\left|\frac{\widetilde{\Delta m^2_{21m}} L_m}{4E}\right| = \frac{\pi}{2}(2k_m + 1)$$

$$\left|\frac{\widetilde{\Delta m^2_{21c}} L_c}{4E}\right| = \frac{\pi}{2}(2k_c + 1)$$

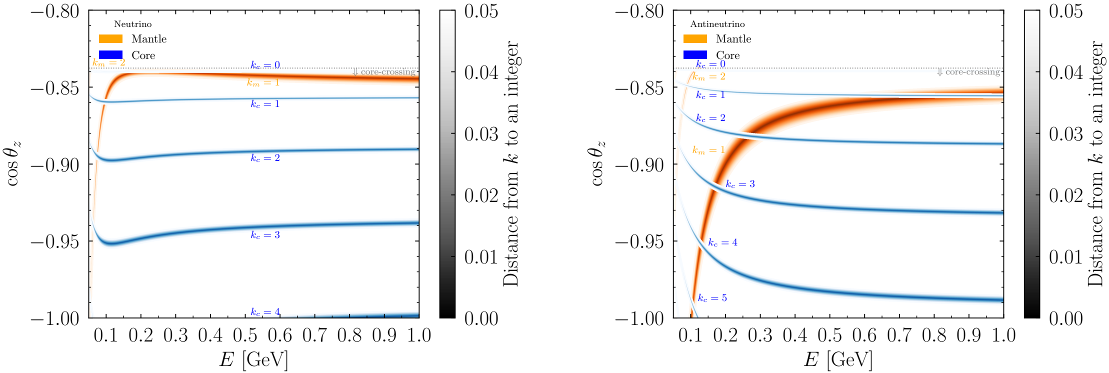
$$\widetilde{\Delta m^2_{21}} = \Delta m^2_{21}\sqrt{(\cos 2\theta_{12} - c^2_{13} a/\Delta m^2_{21})^2 + \sin^2 2\theta_{12}}$$

PBD, S. Parke 1902.07185

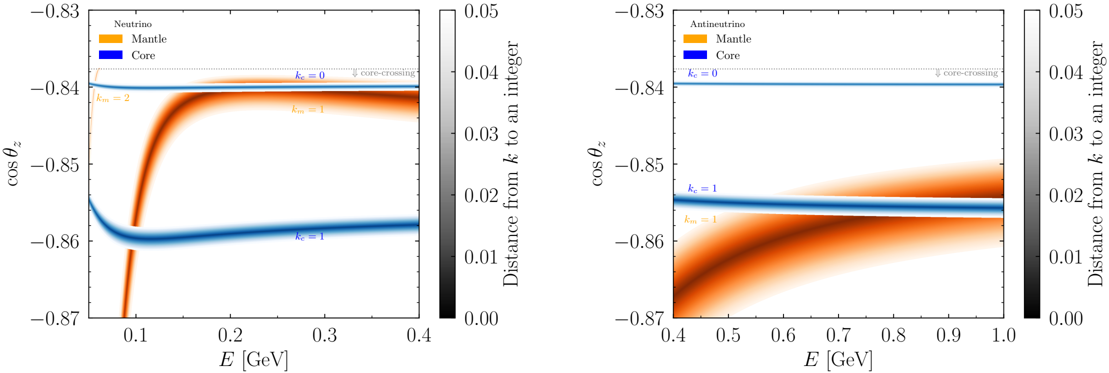
$$L_m = -r_E \cos\theta_z - \sqrt{r_c^2 - r_E^2 \sin^2\theta_z}$$

$$L_c = 2\sqrt{r_c^2 - r_E^2 \sin^2\theta_z}$$

Where are the parametric resonances in the Earth?



Where are the parametric resonances in the Earth?



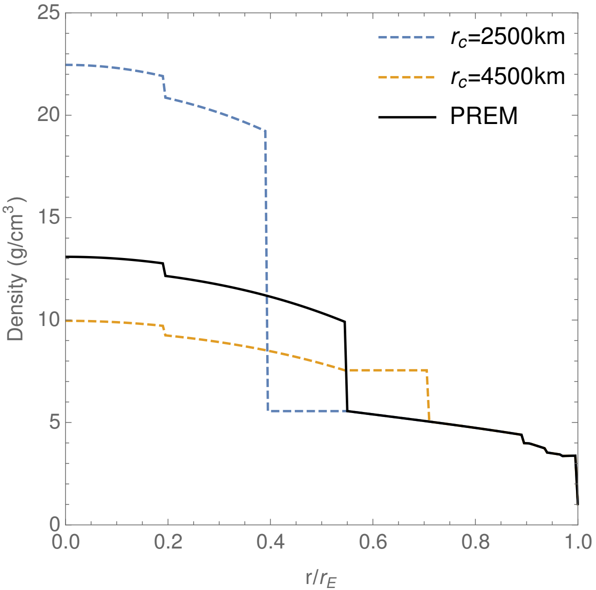
Vary Earth's core, fix the total mass

$$\rho(r)=\begin{cases}C\rho^0_{\rm PREM}(r) & r<r_c<r_c^0\\ \rho^0_{\rm PREM}(r_c^0)_+ & r_c<r<r_c^0\\ \rho^0_{\rm PREM}(r) & r_c<r_c^0<r\end{cases}$$

$$\rho(r)=\begin{cases}D\rho^0_{\rm PREM}(r) & r<r_c^0<r_c\\ D\rho^0_{\rm PREM}(r_c^0)_- & r_c^0<r<r_c\\ \rho^0_{\rm PREM}(r) & r_c^0<r_c<r\end{cases}$$

$$C=\frac{\int_0^{r_c^0}drr^2\rho^0_{\rm PREM}(r)-\frac{\rho(r_c^0)_+}{3}\left[(r_c^0)^3-r_c^3\right]}{\int_0^{r_c}drr^2\rho^0_{\rm PREM}(r)}$$

$$D=\frac{\int_0^{r_c}drr^2\rho^0_{\rm PREM}(r)}{\int_0^{r_c^0}drr^2\rho^0_{\rm PREM}(r)+\frac{\rho(r_c^0)_-}{3}\left[r_c^3-(r_c^0)^3\right]}$$



Atmospherics at DUNE

- DUNE has modest sensitivity to atmospherics in 100 MeV – 1 GeV
  - IceCube falls off below 6 GeV
  - SuperK falls off below 1 GeV
  - JUNO may have sub-GeV and sub-100 MeV sensitivity, but limited angular sensitivity

A. Suliga, J. Beacom 2306.11090

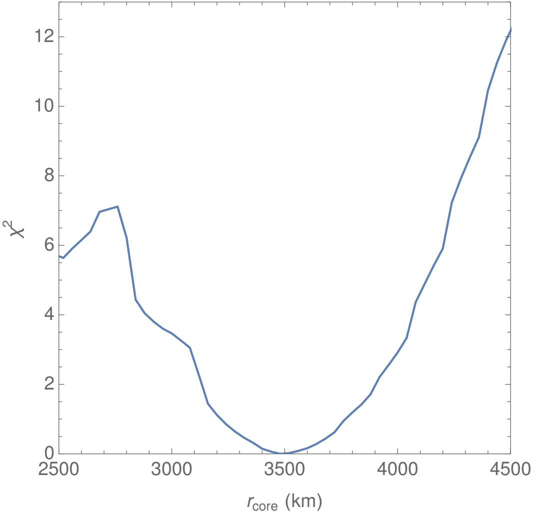
- Consider CC 0π and either 1p (ν) or 0p ($\bar{\nu}$)
- We assume flavor discrimination, but no $\nu/\bar{\nu}$ discrimination
- Do not include partially contained ($\sim 25\%$) events
- Use `nuSquids`

C. Arguelles, J. Salvado, C. Weaver 2112.13804

- 400 kt yr (10 years of full detector)

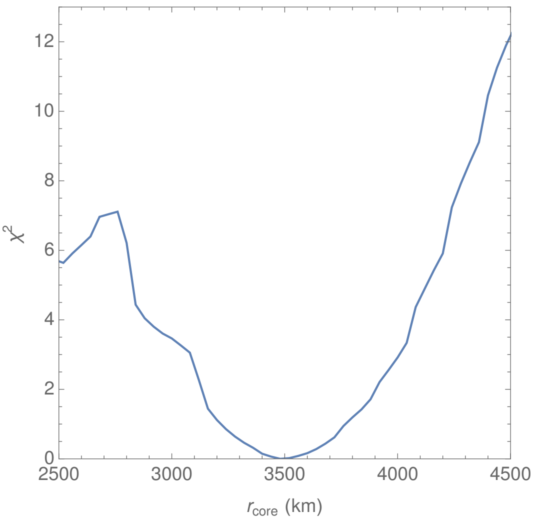
Follows K. Kelly, et al. 1904.02751
with corrections from DUNE 2002.03005

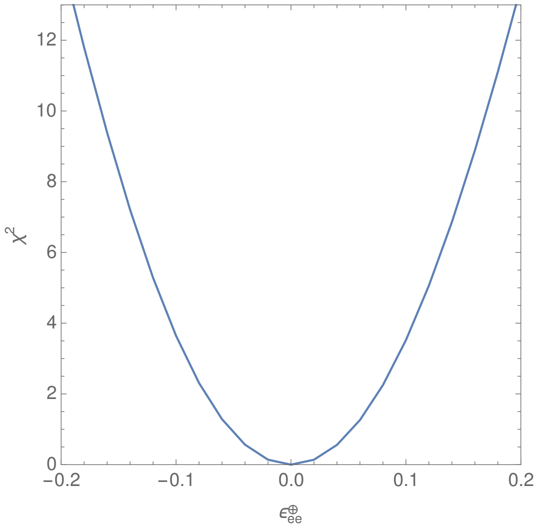
Core radius constraint



PBD, R. Pestes 2110.01148
See also K. Kelly, et al. 2110.00003

Core radius constraint





PBD, R. Pestes 2110.01148
See also K. Kelly, et al. 2110.00003

Solar density profile

- Standard solar models evolve isotropic models to equilibrium
  - Modest uncertainties throughout the star
  - Numerous models
- Helioseismology takes data from the Sun to infer inner properties
  - Convergence at the $\sim 1-10\%$ level
  - Complete loss of sensitivity in the core

A reasonable fit to a SSM:

$$\log_{10}\left(\frac{N_e\cdot\ \mathrm{cm}^3}{N_A}\right)=-4.58\frac{r}{R_\odot}+2.39$$

J. Bahcall, M. Pinsonneault, S. Basu astro-ph/0010346

Neutrinos in the Sun

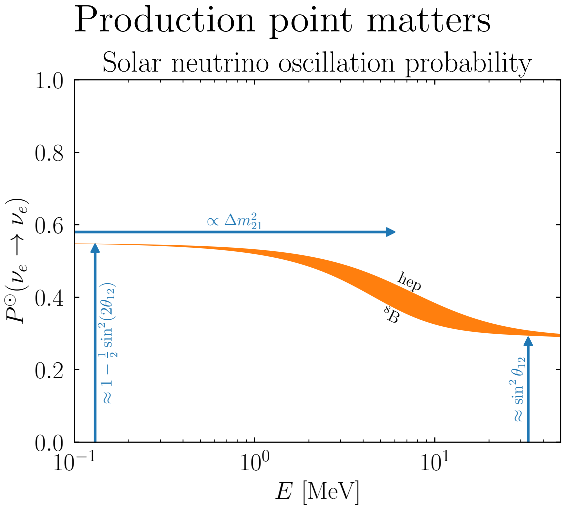
$$P_{ee}^{\odot} \approx \begin{cases} 1 - \frac{1}{2}\sin^2 2\theta_{12} & E \ll 1 \text{ MeV} \\ \sin^2\theta_{12} & E \gg 10\text{MeV} \end{cases}$$

$$P_{ee}^{\odot} \approx \frac{c_{13}^4}{2}\left[1 + \cos 2\theta_{12}\frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}}\right] + s_{13}^4$$

$$P_{ee}^{\odot} = \sum_{i=1}^{3} |\hat{U}_{ei}|^2 |U_{ei}|^2$$

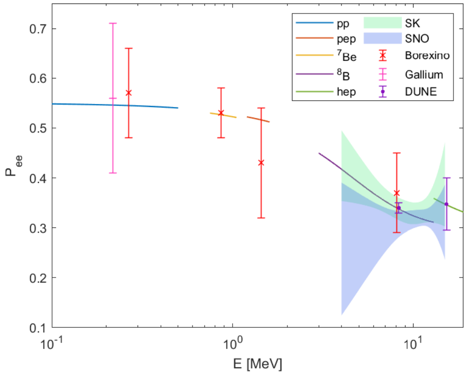
$a = 2\sqrt{2}G_F N_e E \propto Y_e \rho$
$\hat{U}$ diagonalizes H at production point
Focus on daytime neutrinos

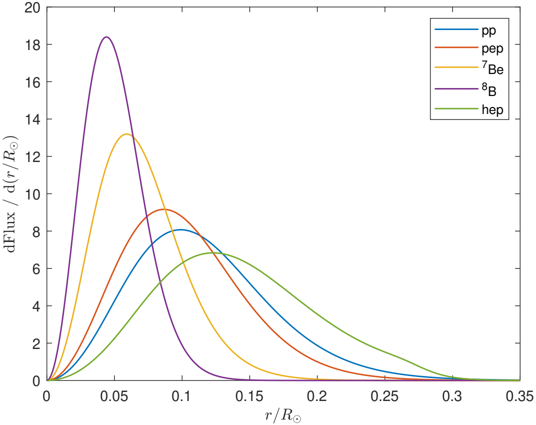
Day time solar neutrino disappearance probability



PBD 2501.08374

Day time solar neutrino disappearance probability





PBD, C. Gourley 2502.17546

Information flow

1. Day time solar data alone constraints the slope somewhat
   - Need medium/high energy neutrinos for some matter effect dependence
   - Need different sources to probe different parts of the Sun
2. Need independent determination of oscillation parameters:

$$P_{ee}^{\rm reactor} \approx 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Ignore $\Delta m^2_{21} < 0$ solutions

   - KamLAND is okay

     KamLAND 1303.4667
   - JUNO will be great

     JUNO 2204.13249
3. Ignore regeneration
   - Depends on Earth density
   - Provides some Δm^2_{21} information; not competitive

Data sets

- Current solar data:
  - SuperK: ^{8}B

    SuperK 2312.12907
  - SNO: ^{8}B

    SNO 1109.0763
  - Borexino: *pp*, ^{7}Be, *pep*, ^{8}B

    Borexino Nature (2018)
  - Gallium experiments: *pp*

    GALLEX PLB (1999)
    SAGE astro-ph/9907113
    GNO hep-ex/0006034
    SAGE NPB (2001)
    SAGE 0901.2200
- Current reactor data

  KamLAND 1303.4667

Data sets

- Current solar data:
  - SuperK: ^{8}B

    SuperK 2312.12907
  - SNO: ^{8}B

    SNO 1109.0763
  - Borexino: *pp*, ^{7}Be, *pep*, ^{8}B

    Borexino Nature (2018)
  - Gallium experiments: *pp*

    GALLEX PLB (1999)
    SAGE astro-ph/9907113
    GNO hep-ex/0006034
    SAGE NPB (2001)
    SAGE 0901.2200
- Current reactor data

  KamLAND 1303.4667
- Future solar data:
  - DUNE: ^{8}B, *hep*

    F. Capozzi, et al. 1808.08232
    DUNE 2002.03005
- Future reactor data

  JUNO 2204.13249

Data scenarios

Current

SuperK, SNO, Gallium, Borexino, KamLAND

Current+JUNO

Above plus JUNO

Current+JUNO+DUNE

Above plus DUNE solar

Two ways to parameterize Sun's density

Three bins:

$$\frac{r}{R_\odot} \in \begin{cases} [0, 0.05) & \text{Bin 1} \\ [0.05, 0.1) & \text{Bin 2} \\ [0.1, 0.5) & \text{Bin 3} \end{cases}$$

1. Innermost bin is dominantly ^{8}B
2. Middle bin is a mixture
3. Last bin has almost no ^{8}B; *hep* matters

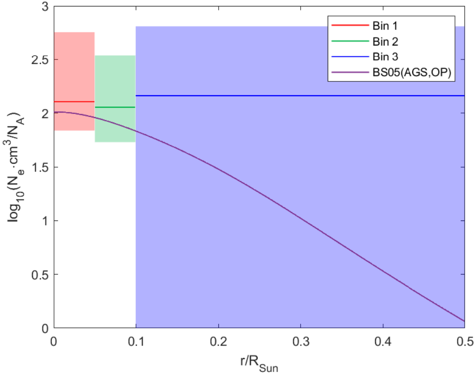
Power law:

$$\log_{10}\left(\frac{N_e \cdot \text{ cm}^3}{N_A}\right) = A\frac{r}{R_\odot} + B$$

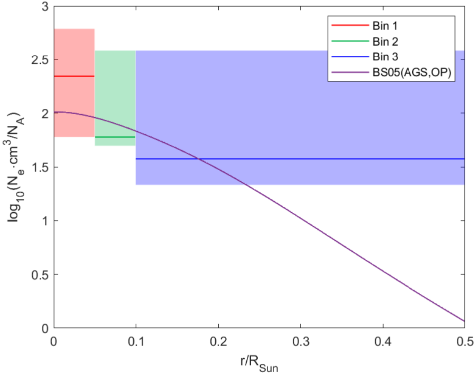
Expect $A \simeq -4.58$, $B \simeq 2.39$

Results: bins

Current



Current+JUNO+DUNE



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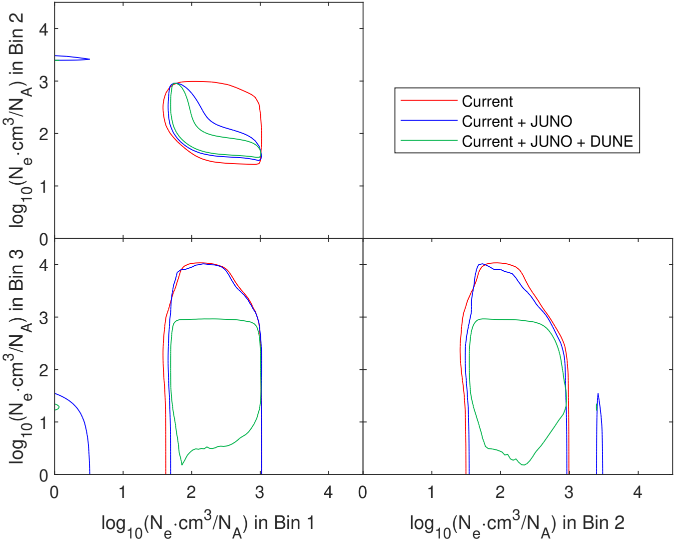
Results: bins corner plot



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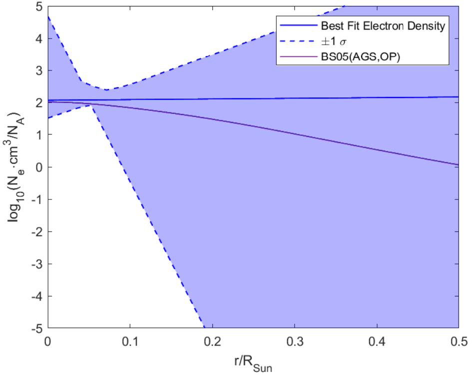
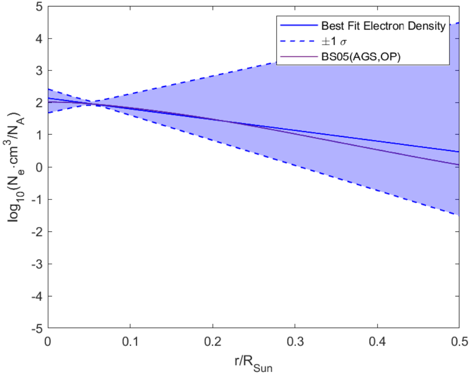
Results: power law

Current



Current+JUNO+DUNE



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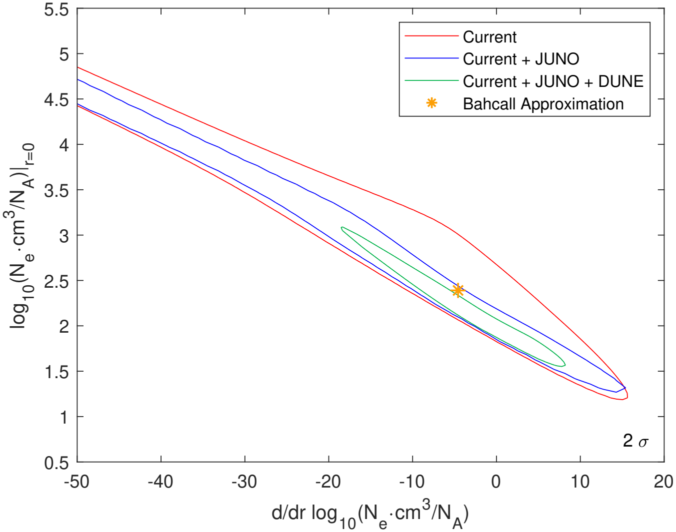
Results: power law projection



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Discussion

- Lower limit in large radius improves due to *hep* measurement

HyperK may also get this $\sim 3\sigma$
HyperK 1805.04163

- Upper limits don't improve much; constraint dominated by appearance of next resonance
- Steps lead to modification of MSW solution
  - Instead take sigmoid functions
- Modification of solar model will lead to changes to temperature, pressure, etc.

See also M. Zaidel, J. Beacom 2504.10583

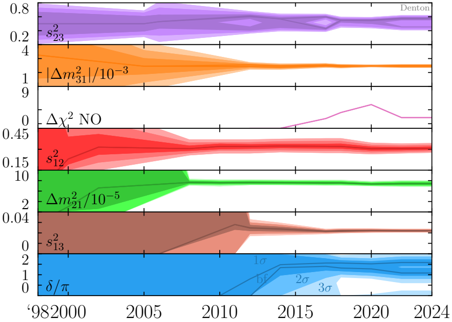
- Absorption and oscillations probe weak charge, not total density
  - Can be recast into neutron fraction or metalicity constraint
  - Can be recast into dark matter constraint
  - Seismology probes inertial EM coupled mass

Neutrino flashlight summary

- Neutrinos can shine a flashlight into opaque environments
- Neutrinos can tell us about the Earth
- IceCube reaches high enough energies for absorption
- DUNE will reach low enough energies for oscillations
- Solar data provides the first neutrino probe for the density of the Sun
- The Earth tells us the neutrino cross section up to $\sim$PeV today and $\sim$EeV tomorrow

Backups

References



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