

Neutrino oscillations through matter

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[T.G, M. Lucente, [arXiv:2303.15527](#) [hep-ph]]

Outline

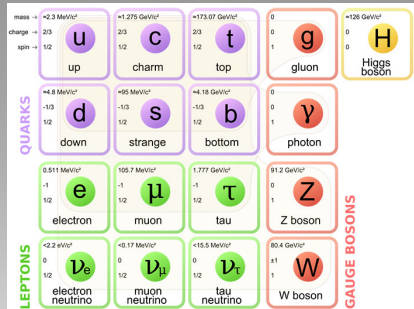
- ❶ Neutrinos in the Standard Model
- ❷ Neutrino Oscillations
 - In vacuum
 - In the Sun
 - Through Earth
- ❸ Experimental detection of solar neutrinos
- ❹ PEANUTS
- ❺ Conclusions and outlook

Neutrinos in the SM

Neutrinos in the SM

- Neutral massless fermions
- The SM has 3 neutrino flavours
- ν_e (1956) - ν_μ (1962) - ν_τ (2000)
- Only couple weakly to W/Z bosons, e.g. $n \rightarrow p e^- \nu_e$
- They must be very light

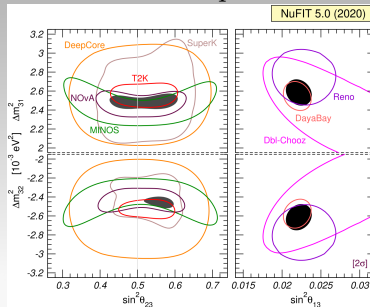
$$\sum m_\nu < 0.16 \text{ eV}$$



- In 1968 the Homestake experiment measured a lack of solar neutrinos as predicted by solar models
- Bruno Pontecorvo proposed oscillation solution in 1969
- Anomalies confirmed by (Super-)Kamiokande, GALLEX and SAGE
- In 2001 the SNO experiment confirmed oscillations as the source of the discrepancy

Neutrinos in the SM

- Many independent confirmations
 - Solar neutrino experiments: SNO, Super-Kamiokande
 - Atmospheric neutrino experiments: IceCube, DeepCore
 - Reactor Neutrino experiments: KamLAND, DayaBay, Double-Chooz
 - Accelerator neutrino experiments: MINOS, Reno, T2K, NoVa
- Good agreement on the oscillations parameters



[NuFit, JHEP 09 (2020) 178]

Neutrino oscillations in vacuum

Oscillations in vacuum

- Neutrino flavour e.s. are not mass e.s. $|\nu_\alpha, t\rangle = U_{\alpha i}^* |\nu_i, t\rangle$
- In vacuum neutrinos propagate as mass eigenstates following Schrödinger equation

$$\frac{d}{dt} |\nu_i, t\rangle = -i H_{ij} |\nu_j, t\rangle \quad \text{where} \quad H_{ij} |\nu_j, t\rangle = E_j \delta_{ij} |\nu_j, t\rangle$$

which has a planar wave solution

$$|\nu_i, t\rangle = e^{-i E_i t} |\nu_i, 0\rangle \rightarrow |\nu_\alpha, t\rangle = U_{\alpha i}^* e^{-i E_i t} U_{\beta i} |\nu_\beta, 0\rangle \approx U_{\alpha i}^* e^{-i \frac{m_i^2}{2E} x} U_{\beta i} |\nu_\beta, 0\rangle$$

- So the probability of flavour e.s. α manifesting as flavour e.s. β after propagating in vacuum is

$$\begin{aligned} P_{\nu_\alpha \rightarrow \nu_\beta} &= |\langle \nu_\beta | \nu_\alpha \rangle|^2 = |U_{\alpha i}^* e^{-i E_i t} U_{\beta i}|^2 = |U_{\alpha i}|^2 |U_{\beta i}|^2 + \sum_{i \neq j} e^{-i(E_i - E_j)t} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \frac{\Delta m_{ij}^2 L}{2E} \end{aligned}$$

Oscillations in vacuum

- PMNS matrix
(Pontecorvo-Maki-Nakagawa-Sakata)

$$U = R_{23}\Delta R_{13}\Delta^* R_{12}$$

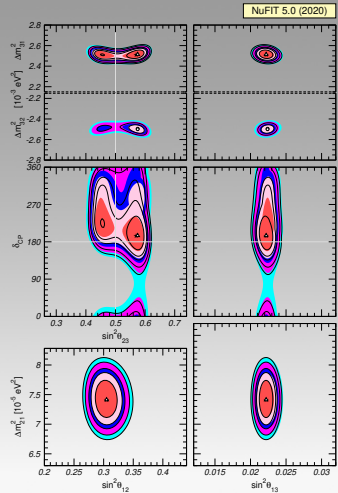
$$R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix},$$

$$R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix},$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$\Delta = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}.$$

- Mixing angles $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$

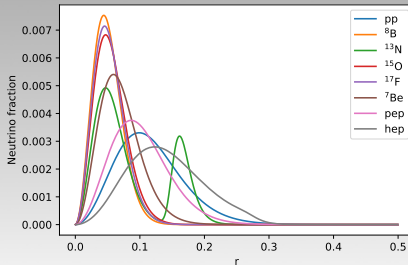


[NuFit, JHEP 09 (2020) 178]

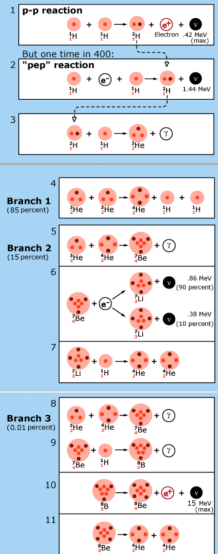
Neutrino oscillations in the Sun

Oscillations in the Sun

- Solar neutrinos are produced in the Sun via fusion processes
- The main sources of ν s are the pp , pep and ${}^7\text{Be}$ and ${}^8\text{B}$ chains



- ν s are produced over a wide radius $\rightarrow$ incoherent flux



Oscillations in the Sun

- The propagation of a neutrino in a medium with matter potential $V(x)$ can be parametrised as (Mikheyev-Smirnov-Wolfenstein effect)

$$H(x) = U^* \text{diag}(k) U^T + V(x) \text{diag}(1, 0, 0)$$

where

$$k_i = \frac{m_i^2}{2E}, \quad V(x) = \sqrt{2} G_F n_e(x)$$

- Hamiltonian simplification #1: $H \rightarrow \Delta R_{23}^T H \Delta^* R_{23}$

$$H(x) = R_{13} R_{12} \text{diag}(k) R_{12}^T R_{13}^T + V(x) \text{diag}(1, 0, 0)$$

- Hamiltonian simplification #2: $H \rightarrow H - U^* \mathbb{1} U^T$

$$\text{diag}(k) \rightarrow \frac{1}{2E} \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \quad \text{or} \quad \frac{1}{2E} \text{diag}(-\Delta m_{21}^2, 0, \Delta m_{32}^2)$$

Oscillations in the Sun

- In a medium of slow varying density (like the Sun), oscillations proceed adiabatically and n_e constant
- The Hamiltonian for constant density

$$H = \frac{1}{2E} U^* \text{diag}(0, \Delta m_{21}^2, \delta m_{31}^2) U^T + V \text{diag}(1, 0, 0)$$

- One can then perform a rotation of the Hamiltonian so that

$$H = \frac{1}{2E} T^* \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) T^T \quad \text{where} \quad T = U(\tilde{\theta}_{12}, \tilde{\theta}_{13}, \theta_{23}, \delta)$$

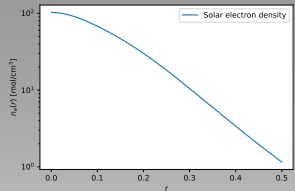
where the matter rotated angles $\tilde{\theta}_{12}$ and $\tilde{\theta}_{13}$ are

$$\cos 2\tilde{\theta}_{13} = \frac{\cos 2\theta_{13} - 2EV/\Delta m_{ee}^2}{\sqrt{(\cos 2\theta_{13} - 2EV/\Delta m_{ee}^2)^2 + \sin^2 2\theta_{13}}}$$

$$\cos 2\tilde{\theta}_{12} = \frac{\cos 2\theta_{12} - A'/\Delta m_{21}^2}{\sqrt{(\cos 2\theta_{12} - A'/\Delta m_{21}^2)^2 - \sin^2 2\theta_{12} \cos^2(\tilde{\theta}_{13} - \theta_{13})}}$$

$$\Delta m_{ee}^2 = \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

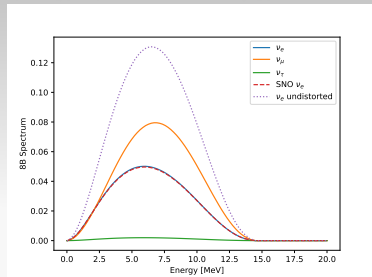
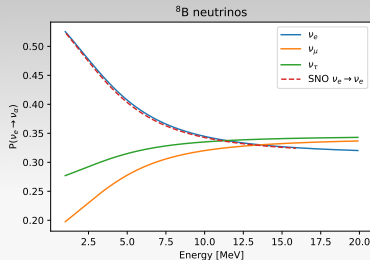
$$A' = 2EV \cos^2 \tilde{\theta}_{13} + \Delta m_{ee}^2 \sin^2(\tilde{\theta}_{13} - \theta_{13})$$



Oscillations in the Sun

- Adiabatic propagation $\rightarrow \nu$ s evolve as pure mass e.s.
- At a given location in the Sun $r = R/R_\odot \rightarrow$
 $P_{\nu_e \rightarrow \nu_i}^\odot(E, r) = |T_{ei}(E, n_e(r))|^2$
- Averaging over all production points, at the surface

$$P_{\nu_e \rightarrow \nu_i}^\odot(E) = \int_0^1 dr |T_{ei}(E, n_e(r))|^2 f(r), \quad \int_0^1 f(r) = 1$$



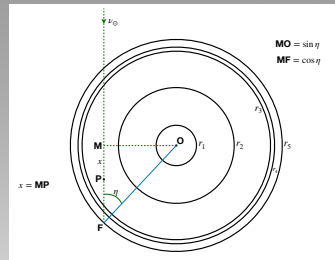
Neutrino oscillations through Earth

Oscillations through Earth

- Neutrinos with energies below $\sim$ TeV scatter elastically with the electrons in the Earth
- The electron density is parametrised as

$$N_j(r) = \alpha_j + \beta_j r^2 + \gamma_j r^4$$

for each shell j and depending on the radial coordinate r

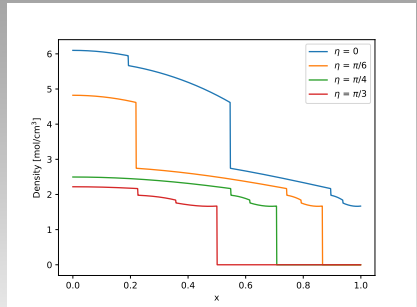
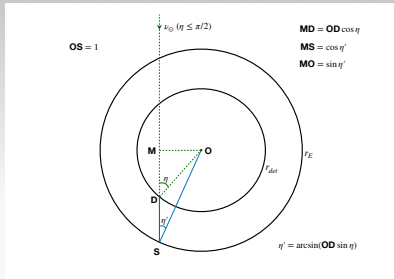


j	Shell	$[r_{j-1}, r_j]$	α_j	β_j	γ_j
1	Inner core	$[0, 0.192]$	6.099	-4.119	0.000
2	Outer core	$[0.192, 0.546]$	5.803	-3.653	-1.086
3	Lower mantle	$[0.546, 0.895]$	3.156	-1.459	0.280
4	Transition Zone	$[0.895, 0.937]$	-5.376	19.210	-12.520
5	Upper mantle	$[0.937, 1]$	11.540	-20.280	10.410

Oscillations through Earth

- Neutrinos don't usually travel radially, but with incident angle η
- We need density that neutrinos see along their path $x \rightsquigarrow N_j(x, \eta)$

$$\begin{aligned}
 N_j(x, \eta) &= \alpha'_j + \beta'_j x^2 + \gamma'_j x^4, \\
 \alpha'_j &= \alpha_j + \beta_j \sin^2 \eta + \gamma_j \sin^4 \eta, \\
 \beta'_j &= \beta_j + 2\gamma_j \sin^2 \eta, \\
 \gamma'_j &= \gamma_j,
 \end{aligned}$$



- For detectors underground we need to convert

$$\eta' = \arcsin(r_{det} \sin \eta)$$

Oscillations through Earth

- MSW Hamiltonian $H(x) = \frac{1}{2E} U^* \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^T + V(x) \text{diag}(1, 0, 0)$
- The generic evolver operator for a neutrino flavour e.s.

$$|\nu_\alpha, t\rangle = \mathcal{U}_{\alpha\beta}(t) |\nu_\beta, 0\rangle$$

- Plugging it into the Schrödinger equation for $|\nu_\alpha, t\rangle$

$$\frac{d}{dt} |\nu_\alpha, t\rangle = -i H_{\alpha\beta}(t) |\nu_\beta, t\rangle \Rightarrow \frac{d}{dt} \mathcal{U}_{\alpha\gamma}(t) = -i H_{\alpha\beta}(t) \mathcal{U}_{\beta\gamma}(t)$$

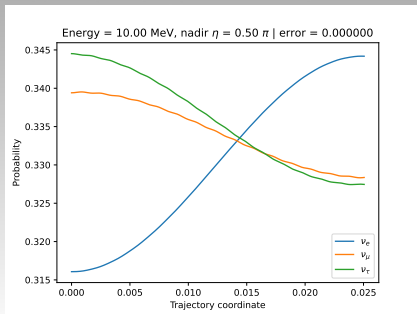
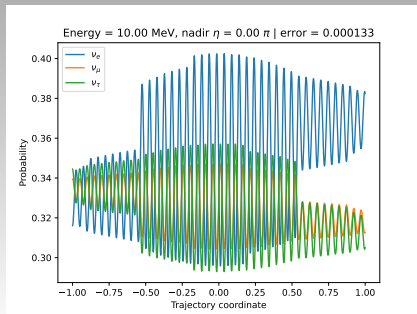
- One can find a formal solution of the equation

$$\mathcal{U}(t_f, t_i) = \mathcal{T} e^{-i \int_{t_i}^{t_f} dt H(t)} = \mathcal{T} e^{-i \int_{x_i}^{x_f} dx H(x)}$$

- A numerical solution of $\mathcal{U}$ for each neutrino path $[x_i, x_f]$ can be found, which gives the full oscillation path

Oscillations through Earth

- Example solution for oscillations for a $E = 10$ MeV for an arbitrary ν state with approximate equal flavour weights
- Barely any oscillations during the day ($\pi/2 \leq \eta < \pi$)
- Because of n_e there is a “regeneration” of ν_e



- Numerical solution very CPU intensive $\rightsquigarrow$ analytical approximation

Oscillations through Earth

- We can approximate the density per shell around the average

$$n_e(x) = \bar{n}_e + \delta n_e(x), \quad \bar{n}_e = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} dx \, n_e(x)$$

- Then the hamiltonian can be expanded as

$$H(x) = H_0 + \sqrt{2}G_F \bar{n}_e \text{diag}(1, 0, 0) + \sqrt{2}G_F \delta n_e(x) \text{diag}(1, 0, 0) = \bar{H} + \delta H(x)$$

- We can then write the evoluter as a Dyson series

$$\begin{aligned} \mathcal{U}(x_f, x_i) &= \mathbb{1} + \sum_{n=1}^{\infty} \frac{(-1)^n}{n!} \int_{x_i}^{x_f} dx_1 \int_{x_i}^{x_f} dx_2 \cdots \int_{x_i}^{x_f} dx_n \mathcal{T}[H(x_1)H(x_2) \dots H(x_n)] \\ &= \bar{\mathcal{U}}(x_f, x_i) - i \int dx \, \bar{\mathcal{U}}(x_f, x) \delta H(x) \bar{\mathcal{U}}(x, x_i) + \mathcal{O}(\delta H^2) \end{aligned}$$

- For x_i and x_f within a shell $\mathcal{U}(x_f, x_i) = \mathcal{U}^{(0)}(x_f, x_i) + \mathcal{U}^{(1)}(x_f, x_i)$

Oscillations through Earth

- The zeroth order (constant) part can be solved exactly as

$$\mathcal{U}^{(0)}(x_f, x_i) = e^{-i\bar{H}(x_f - x_i)} = e^{-i\frac{\text{tr}\bar{H}}{3}L} e^{-iT L} = e^{-i\frac{\text{tr}\bar{H}}{3}L} \sum_{a=1}^3 e^{-i\lambda_a L} M_a$$

- where the matrix $T = \bar{H} - \text{tr}\bar{H}\mathbb{1}/3$
- λ_a are the roots of the characteristic equation

$$\lambda^3 + c_1\lambda + c_0 = 0$$

$$c_0 = -\det T$$

$$c_1 = T_{11}T_{22} - T_{12}T_{21} + T_{11}T_{33} - T_{13}T_{31} + T_{22}T_{33} - T_{23}T_{32}$$

- And the M_a matrix

$$M_a = \frac{1}{3\lambda_a^2 + c_1} \left((\lambda_a^2 + c_1)\mathbb{1} + \lambda_a T + T^2 \right)$$

Oscillations through Earth

- The first order term of the evolutor

$$\bar{\lambda}_a = \lambda_a + \text{tr} \bar{H} / 3$$

$$\begin{aligned} \mathcal{U}^{(1)}(x_f, x_i) &= -i \int_{x_i}^{x_f} dx \mathcal{U}^{(0)}(x_f, x) \delta H(x) \mathcal{U}^{(0)}(x, x_i) \\ &= -i \sum_{a,b} \int_{x_i}^{x_f} dx e^{-i\bar{\lambda}_a(x_f-x)} M_a \text{diag}(\sqrt{2}G_F \delta n(x), 0, 0) M_b e^{-i\bar{\lambda}_b(x-x_i)} \\ &= -i \sum_{a,b} M_a \text{diag}(\sqrt{2}G_F I_{ab}(x_f, x_i), 0, 0) M_b \end{aligned}$$

- where the integral I_{ab}

$$I_{ab}(x_f, x_i) = \int_{x_i}^{x_f} dx e^{-i\bar{\lambda}_a(x_f-x)} \delta n(x) e^{-i\bar{\lambda}_b(x-x_i)}$$

can be solved analytically because $\delta n(x)$ is just a polynomial in x

$$\delta n(x) = \alpha' - \bar{n}_e + \beta' x^2 + \gamma' x^4$$

Oscillations through matter

- Analytical solution for the evolver within a shell $\mathcal{U}(x_i, x_f)$
- For a path crossing n shells at boundaries $(x_1, \dots, x_n)$

$$\mathcal{U}(x_f, x_i) = \mathcal{U}(x_f, x_{n-1})\mathcal{U}(x_{n-1}, x_{n-2}) \dots \mathcal{U}(x_2, x_1)\mathcal{U}(x_1, x_i)$$

- Evolver has the property

$$\mathcal{U}(0, -x) = \mathcal{U}(x, 0)^T$$

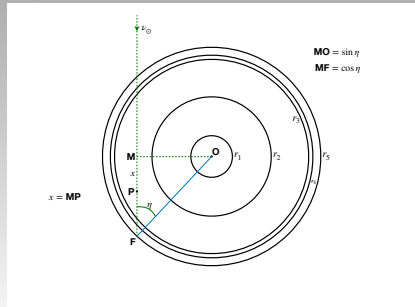
- Only need half path ($0 \leq \eta < \pi/2$)

$$\mathcal{U}(x_F, x_I) = \mathcal{U}(x_F, 0)\mathcal{U}(x_F, 0)^T$$

- Underground detector $x_{det} < x_F$

$$\mathcal{U}(x_{det}, x_I) = \mathcal{U}(x_{det}, 0)\mathcal{U}(x_F, 0)^T$$

- For $\pi/2 \leq \eta < \pi$ crust density constant $\mathcal{U}^{(1)}(\eta) = e^{-ix_{det}(\eta)}(\text{diag}(\sqrt{2}G_F n_1, 0, 0))$



Oscillations through matter

- Recap on probability of oscillation at detector

$$P_{\nu_\alpha \rightarrow \nu_\beta}(x_{det}) = |\langle \nu_\beta, x_{det} | \nu_\alpha, x_I \rangle|^2 = |\mathcal{U}_{\alpha\beta}(x_{det}, x_I)|^2$$

- If the incoming neutrino is a mass eigenstate

$$|\nu_i, x_I\rangle = U_{\alpha i} |\nu_\alpha, x_I\rangle \quad \rightarrow \quad P_{\nu_i \rightarrow \nu_\beta} = |\mathcal{U}_{\alpha\beta}(x_{det}, x_I) U_{\alpha i}|^2$$

- Or for an arbitrary neutrino state

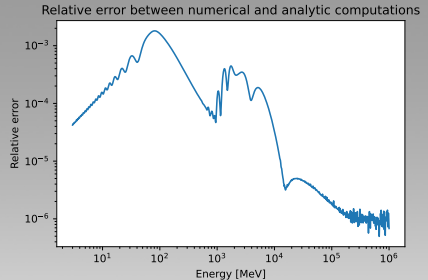
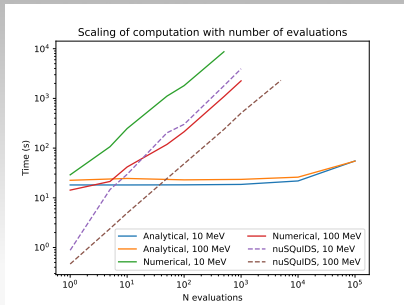
$$|\nu, x_I\rangle = c_\alpha(x_I) |\nu_\alpha, x_I\rangle \quad \rightarrow \quad P_{\nu \rightarrow \nu_\beta} = |\mathcal{U}_{\alpha\beta}(x_{det}, x_I) c_\alpha|^2$$

- If neutrinos come from the Sun as an incoherent flux of mass e.s.

$$P_{\nu_e \rightarrow \nu_\beta}(x_{det}) = |\mathcal{U}_{\alpha\beta}(x_{det}, x_I) U_{\alpha i}|^2 P_{\nu_e \rightarrow \nu_i}^\odot$$

Oscillations through Earth

- Analytical solution still an approximation
- Relative error between numerical and analytical is small (at worst 10^{-3})



- Speed gain is enormous for large number of evaluations
- For 10^3 evaluations
 $T(\text{analytical}) \sim 20 \text{ s}$
 $T(\text{numerical}) \sim 1 \text{ h}$
- $\Rightarrow$ PEANUTS

Experimental detection of solar neutrinos

Exposure

- Experiments collect data over some time, the averaged probability

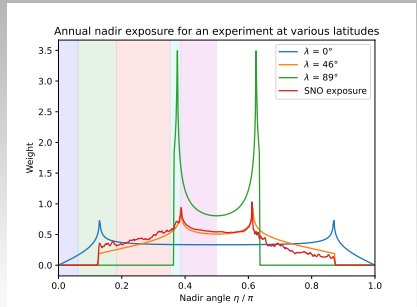
$$\langle P \rangle = \frac{\int_{\tau_{d1}}^{\tau_{d2}} d\tau_d \int_{\tau_{h1}}^{\tau_{h2}} d\tau_h P(\eta)}{\int_{\tau_{d1}}^{\tau_{d2}} d\tau_d \int_{\tau_{h1}}^{\tau_{h2}} d\tau_h} = \int_0^\pi d\eta P(\eta) \int_{\tau_{d1}}^{\tau_{d2}} d\tau_d \frac{d\tau_h(\tau_d, \eta)}{d\eta} = \int_0^\pi d\eta W(\eta) P(\eta)$$

- Ideal exposure $W(\eta)$ can be computed with

$$\tau_h = \arccos \left(\frac{\sin \lambda \sin \delta_S + \cos \eta}{\cos \lambda \cos \delta_S} \right)$$

$$\delta_S = \arcsin(-\sin \delta_E \cos \tau_d)$$

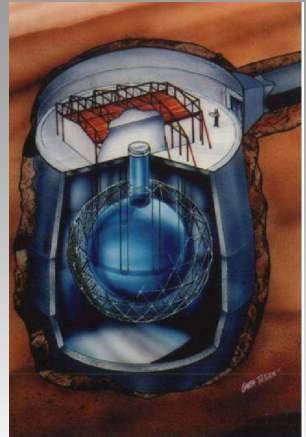
- Actual exposure function provided by experiment
 - E.g. SNO provides $W(\cos \theta)$
 - Zenith angle $\theta = \pi - \eta$



SNO

- SNO - Sudbury Neutrino Observatory
- SNO was a Cherenkov detector located somewhere in Canada (Sudbury, duh)
- 1k tonnes of heavy water (D_2O)
- Surrounded by $\sim 10k$ PMTs
- Operated 3 phases according to n detection (n efficiency)
 - Phase I: γ rays from D_2O capture
 - Phase II: γ rays from NaCl caputre
 - Phase III: NCD array
- Ran from 1999 to 2006
- First confirmation of solar ν oscillations

[SNO Collaboration, Phys.Rev.C 88 (2013) 025501]



SNO

- The SNO experiment detects solar neutrinos from the ${}^8B$ fraction
- Neutrinos interact via three processes

$\nu_x + e^- \rightarrow \nu_x + e^-$	(ES)
$N = N_{CC} + N_{NC} + N_{ES}$	$\nu_e + d \rightarrow p + p + e^-$
	(CC)
- Number of expected events per process

	$\nu_x + d \rightarrow p + n + \nu_x$
	(NC)

$$\frac{dN_{CC}}{dT_{\text{eff}}} = N_D \int \int dT_e dE_\nu \frac{d\Phi}{dE_\nu} \frac{d\sigma_{CC}(E_\nu)}{dT_e} \langle P_e(E_\nu) \rangle R(T_e, T_{\text{eff}})$$

$$\frac{dN_{ES}}{dT_{\text{eff}}} = n_e \int \int dT_e dE_\nu \left(\frac{d\sigma_{ES}^e(E_\nu)}{dT_e} \langle P_e(E_\nu) \rangle + \frac{d\sigma_{ES}^{\mu,\tau}(E_\nu)}{dT_e} \langle P_{\mu,\tau}(E_\nu) \rangle \right) \frac{d\Phi}{dE_\nu} R(T_e, T_{\text{eff}})$$

$$N_{NC} = \epsilon_n N_D \int dE_\nu \frac{d\Phi}{dE_\nu} \sigma_{NC} \langle P_{\text{tot}}(E_\nu) \rangle$$

- With reconstruction function

$$R(T_e, T_{\text{eff}}) = \frac{1}{\sqrt{2\pi}\sigma_T} \exp \left[-\frac{(T_{\text{eff}} - T_e - \Delta_T)^2}{2\sigma_T^2} \right]$$

- Attempt to reproduce the results of the SNO experiment (Phase I)

$$\mathcal{L} = \sum_i \sum_{\text{phase}} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(N_i - \mathcal{O}_i)^2}{2\sigma_i^2}\right)$$

- Parameters

$$\theta_{12} \in [0.1, 0.9] \text{ rad}$$

$$\Delta m_{21}^2 \in [1, 15] \cdot 10^{-5} \text{ eV}^2$$

- 9 syst uncertainties

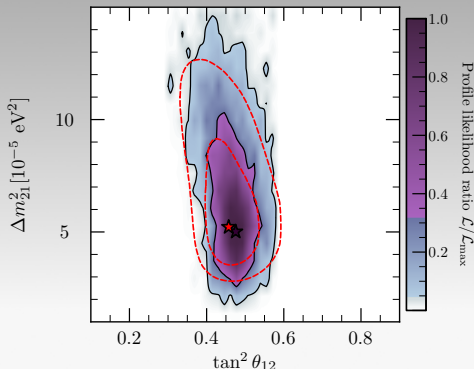
$$\{\sigma_{T_{\text{eff}}}, \sigma_{\sigma}, \sigma_n, \sigma_{bkg}, \dots\}$$

- GAMBIT v2.4, diver v1.0.4

$$\rightarrow N_P = 15200, \theta = 10^{-6}$$

$$\rightarrow 760 \text{ MPI proc}$$

$$\rightarrow \sim 300k \text{ samples}$$



PEANUTS: Propagation and Evolution of Active Neutrinos

[T.G, M. Lucente, [arXiv:2303.15527](#) [hep-ph]]

PEANUTS

- PEANUTS is an open source Python package
<https://github.com/michelelucente/PEANUTS>
- Computes oscillation probabilities at Sun surface and detector locations below the Earth
- Dependencies: numpy, numba, os, copy, time, math, cmath, mpmath, scipy, pyinterval, decimal, pandas, pyyaml, pylha
- Optimised for speed (see plot above) using numba jit
- Two (three) running modes:
 - *Simple* mode: command line, limited functionality
 - *Expert* mode: yaml files, full functionality
 - (*God* mode: via GAMBIT)
- Command line commands in *simple* mode

```
run_prob_sun.py [options] <energy> <fraction> [ <th12> <th13> <th23> <delta> <dm21> <dm31>]
```

```
run_prob_earth.py [options] -f/-m <state> <energy> <eta> <depth> [<th12> <th13> <th23> <delta>  
<dm21> <dm31>]
```

PEANUTS

- *Expert* mode:

```
run_peanuts.py -f <my_yaml_file>
```

- Solar probabilities

```
Energy: 15

Neutrinos:

  dm21: 7.42e-05
  dm3l: 2.51e-03
  theta12: 5.83638e-01
  theta23: 8.5521e-01
  theta13: 1.49575e-01
  delta: 3.40339

Solar:

  fraction: "hep"
  flux: true
  spectrum: "distorted"
  spectra: {"8B": "Data/8B_shape_Winter_et_al.csv"}
```

- Exposure

```
depth: 3000
latitude: 45
#exposure_time: [0,365]
exposure_samples: 100
exposure_normalized: true
#exposure_file: "Data/SnoCosZenith.dat"
#exposure_samples: 480
#exposure_angle: "CosZenith"
```

- Earth probabilities

```
Energy: 20

Neutrinos:

  dm21: 7.42e-05
  dm3l: 2.51e-03
  theta12: 5.83638e-01
  theta23: 8.5521e-01
  theta13: 1.49575e-01
  delta: 3.40339

Earth:

  state: [0.4, 0.2, 0.6]
  antinu: True
  basis: "flavour"
  eta: 0.8
  depth: 3000
  evolved_state: true
```

```
Energy: [20,100]

Neutrinos:

  dm21: 7.42e-05
  dm3l: 2.51e-03
  theta12: 5.83638e-01
  theta23: 8.5521e-01
  theta13: 1.49575e-01
  delta: 3.40339

Solar:

  fraction: "8B"

Earth:

  eta: 0.8
  depth: 3000

Output: "stdout"
#Output: "out.dat"
```

PEANUTS

Propagation and Evolution of Active NeUTrinoS (PEANUTS)

=====

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PEANUTS 1.0 is open source and under the terms of the GPL-3 license.

Documentation and details for PEANUTS can be found at
T. Gonzalo and M. Lucente, arXiv:2303.15527

=====

Computing the probabilities on the surface of the Sun with values

```
theta_{12}      : 0.583638
theta_{13}      : 0.149575
theta_{23}      : 0.85521
delta_CP        : 3.40339
Delta m_{21}^2   : 7.42e-05 eV^2
Delta m_{31}^2   : 0.00251 eV^2
Energy          : [20, 100] MeV
Neutrino fraction : 88
```

Computing the probability on Earth with values

```
Delta m_{31}^2   : 0.00251 eV^2
Energy          : [20, 100] MeV
Nadir angle     : 0.8 rad
Depth           : 3000 m
Evolution method : analytical
```

Running PEANUTS...

# Probabilities	Psolar (e)	Psolar (mu)	Psolar (tau)	Pearth (e)	Pearth (mu)	Pearth (tau)
# E [MeV]						
2.00000E+1	2.97104E-1	3.68314E-1	3.34583E-1	3.05813E-1	3.64606E-1	3.29672E-1
2.88889E+1	2.92024E-1	3.72145E-1	3.35831E-1	3.21298E-1	3.59786E-1	3.18966E-1
3.77778E+1	2.89461E-1	3.74029E-1	3.36510E-1	3.62465E-1	3.44930E-1	2.92663E-1
4.66667E+1	2.87527E-1	3.75413E-1	3.37060E-1	3.71685E-1	3.45589E-1	2.83187E-1
5.55556E+1	2.85686E-1	3.76706E-1	3.37608E-1	4.12507E-1	3.29153E-1	2.58728E-1
6.44444E+1	2.83703E-1	3.78082E-1	3.38214E-1	3.48497E-1	3.48350E-1	3.03244E-1
7.33333E+1	2.81422E-1	3.79656E-1	3.38922E-1	4.09865E-1	3.32820E-1	2.57715E-1
8.22222E+1	2.78695E-1	3.81530E-1	3.39776E-1	2.85720E-1	3.76403E-1	3.39010E-1
9.11111E+1	2.75351E-1	3.83823E-1	3.40826E-1	4.94128E-1	2.87560E-1	2.20227E-1
1.00000E+2	2.71176E-1	3.86683E-1	3.42142E-1	5.48606E-1	2.75072E-1	1.78856E-1

Conclusions and Outlooks

Conclusions

- Neutrino oscillations only (?) clear evidence of BSM physics
 - Solar neutrinos were the first to provide sufficient proof
 - Critical to understand precisely matter effects on oscillation
- Numerical solution to oscillation probability very slow
 - Not suitable for large scale parameter scans
 - Scales badly with the shape and size of oscillation matrix
 - Analytical approximation is needed $\rightsquigarrow$ PEANUTS
- PEANUTS fast and flexible Python tool for neutrino oscillations
 - Probability of oscillation at Sun surface and Earth detector location
 - Super user friendly with multiple operational modes
 - Easy to interface to other tools (e.g. GAMBIT)
- However, there are limitations to the approach
 - Only adiabatical evolution of neutrinos in the Sun
 - Inelastic scattering ($E > \text{TeV}$) in the Earth not included
 - Atmospheric effects (atmospheric neutrinos) $\rightsquigarrow$ PEANUTS v2.0
 - Beyond 3 ν s oscillations $\rightarrow$ sterile ν s, NSI, axion- ν effects,...