New solar neutrino analyses with argon detectors

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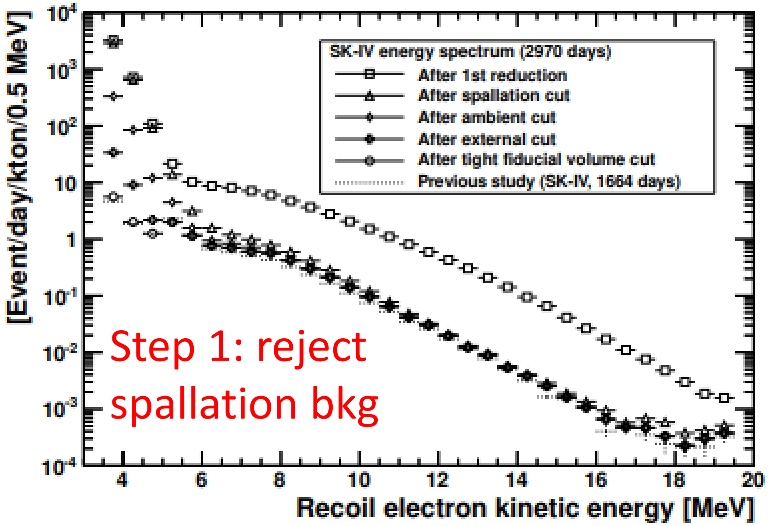
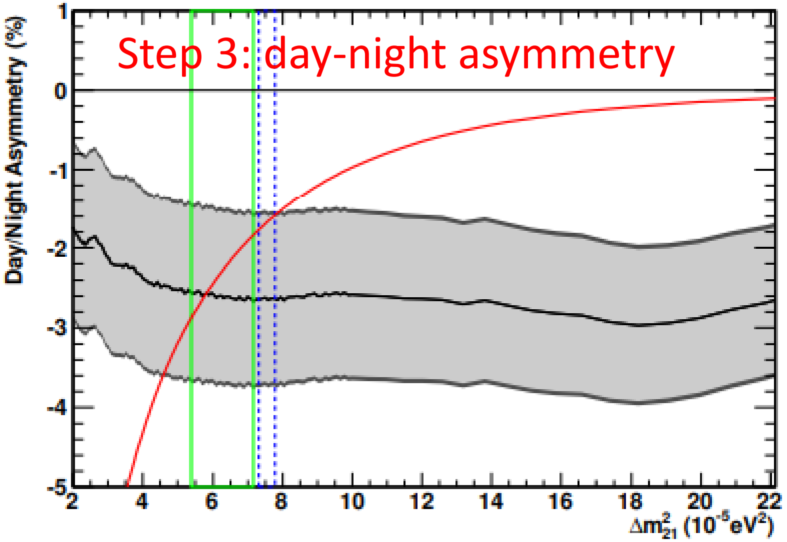
Oct 17, 2024

How current solar neutrino analysis works



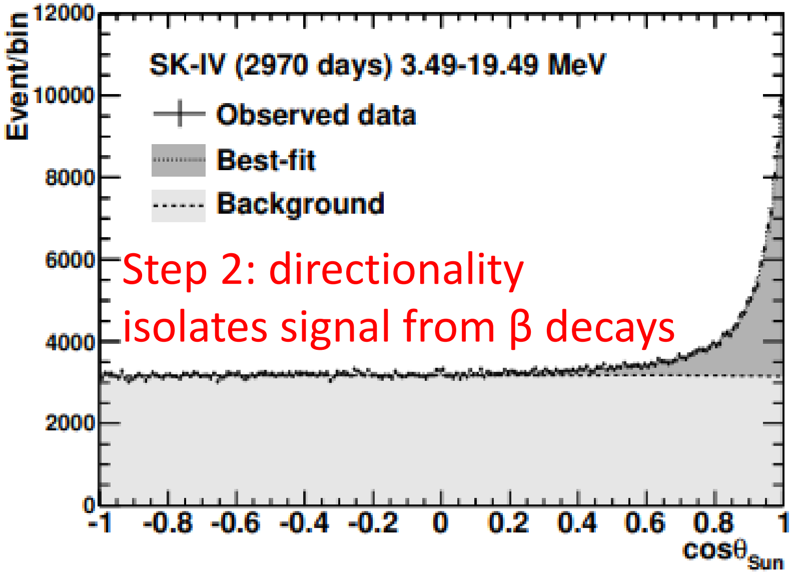
Step 1: reject spallation bkg



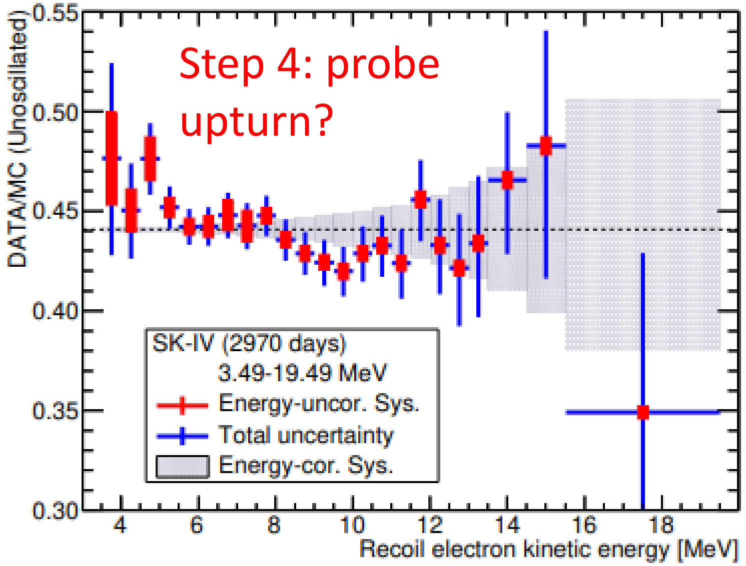
Step 3: day-night asymmetry

Electron scatter signal isolated by spallation cuts and direction

Difficult to understand oscillations that depend on E_ν with E_e spectra



Step 2: directionality isolates signal from β decays



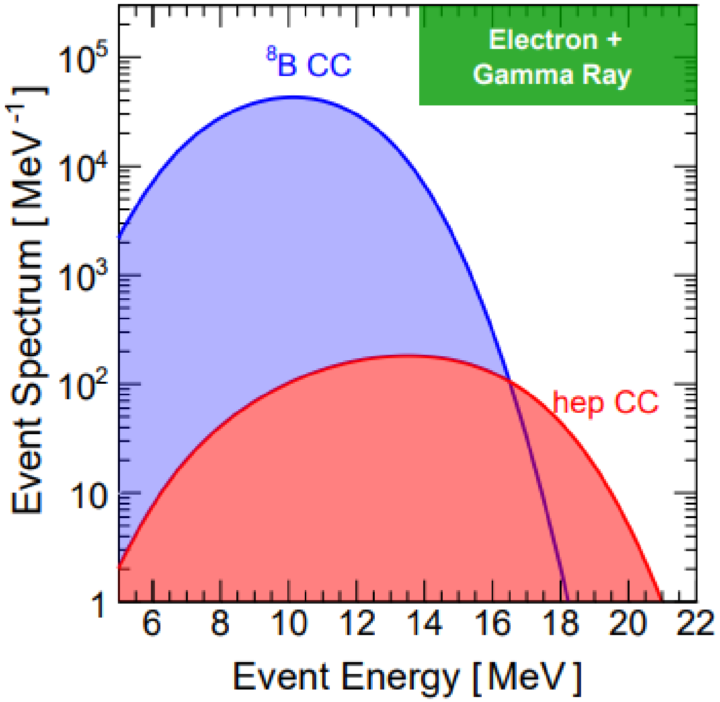
Step 4: probe upturn?

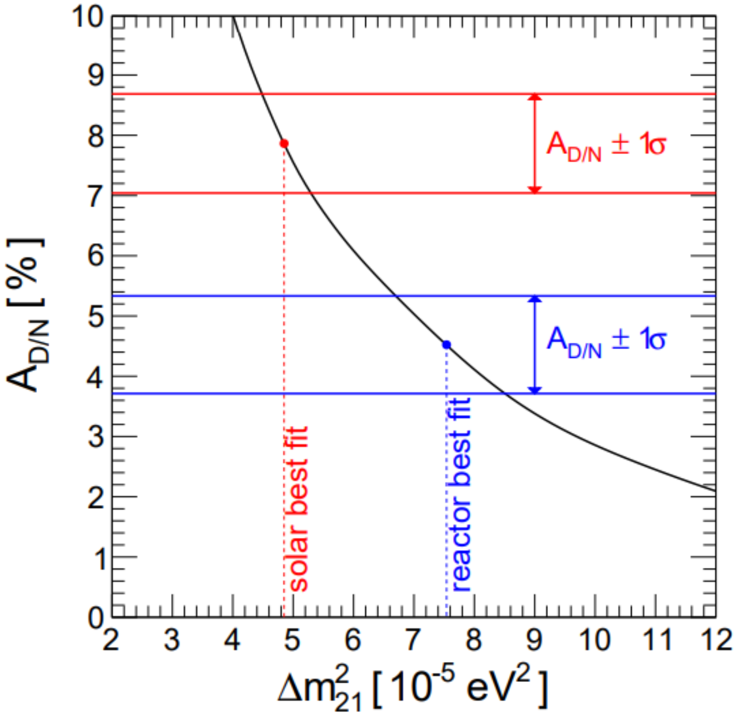
ES channel also sensitive to all neutrino flavors, but with different weights, also smears out characteristics of ν_e flux

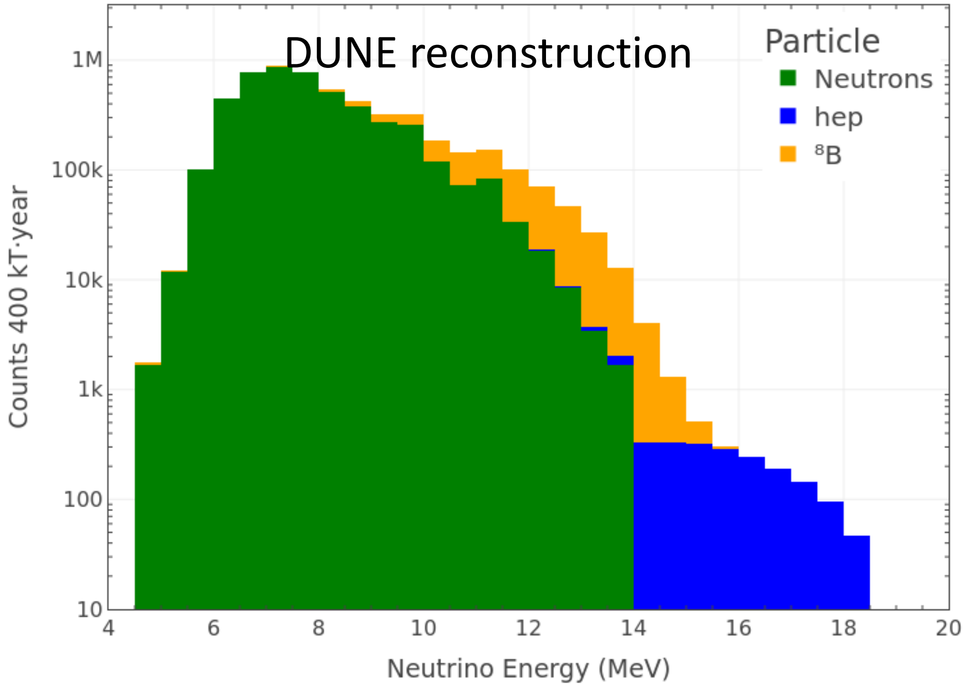
Desire for next generation experiments to precisely understand day-night diffs and probe the solar upturn

Finding the solar upturn

The power of argon



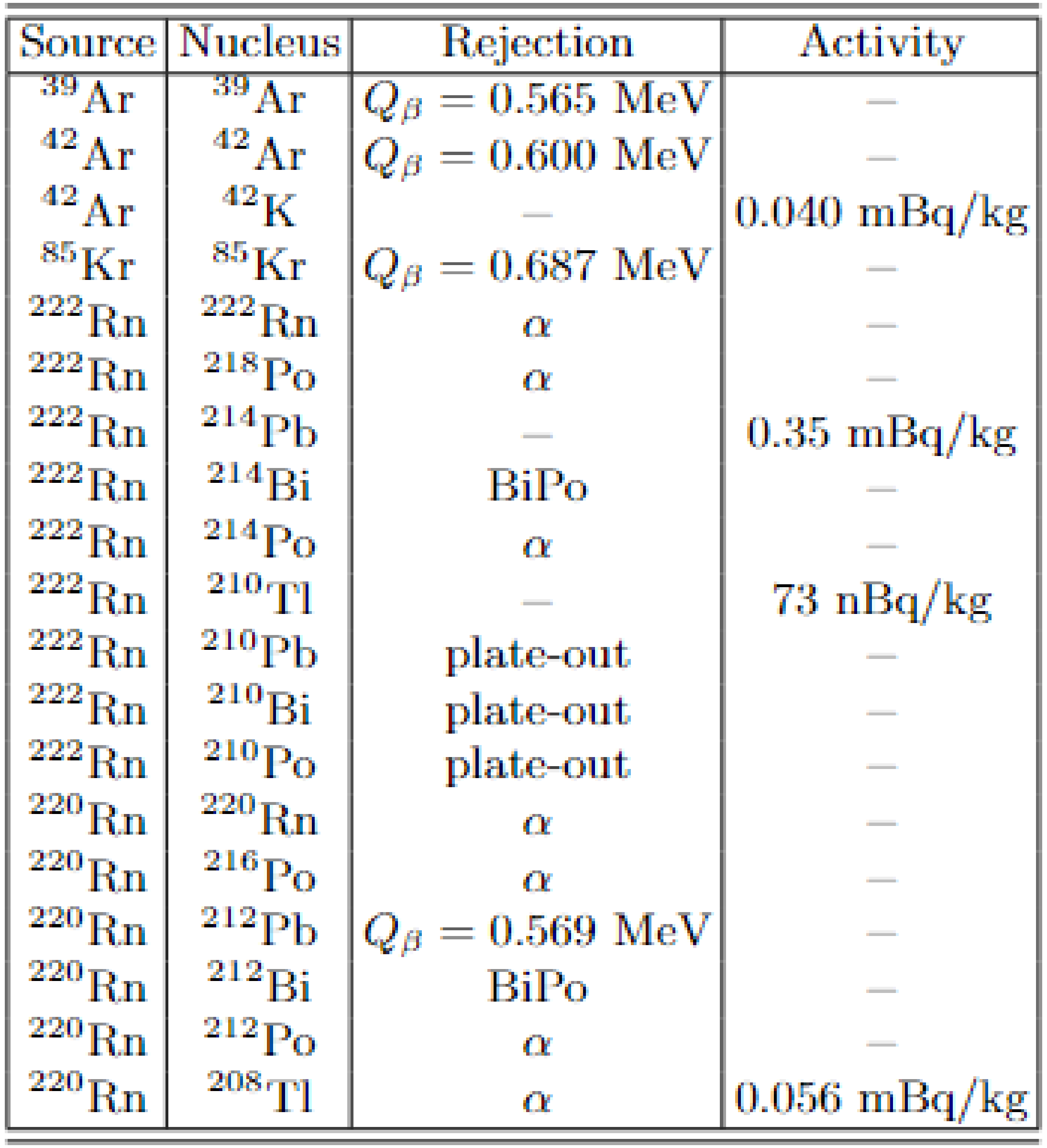




- ☐ Large CC xsec – good energy resolution + day-night asymmetry
- ☐ TPC technology – good tracking and calorimetry
- ☐ High light yield – scintillation gives additional analysis stream
  - Q+L -> improved energy reconstruction + quenching ID (α rejection)

Problem: intrinsic argon backgrounds

- Environmental radioactive noble nuclei contaminate liquid argon
- Most decays are not signal-like and can be rejected
  - Charge quenching rejects α's
  - Low-*Q* value β's below energy ROI BiPo's
  - Fiducialization removes plate-out
- Perform light-only (almost) analysis
  - Poisson energy smearing: LY = 180 PE/MeV
  - Assume 1 m vertex resolution
  - α rejection uses charge quenching



Source	Nucleus	Rejection	Activity
^{39}Ar	^{39}Ar	$Q_\beta = 0.565$ MeV	–
^{42}Ar	^{42}Ar	$Q_\beta = 0.600$ MeV	–
^{42}Ar	^{42}K	–	0.040 mBq/kg
^{85}Kr	^{85}Kr	$Q_\beta = 0.687$ MeV	–
^{222}Rn	^{222}Rn	α	–
^{222}Rn	^{218}Po	α	–
^{222}Rn	^{214}Pb	–	0.35 mBq/kg
^{222}Rn	^{214}Bi	BiPo	–
^{222}Rn	^{214}Po	α	–
^{222}Rn	^{210}Tl	–	73 nBq/kg
^{222}Rn	^{210}Pb	plate-out	–
^{222}Rn	^{210}Bi	plate-out	–
^{222}Rn	^{210}Po	plate-out	–
^{220}Rn	^{220}Rn	α	–
^{220}Rn	^{216}Po	α	–
^{220}Rn	^{212}Pb	$Q_\beta = 0.569$ MeV	–
^{220}Rn	^{212}Bi	BiPo	–
^{220}Rn	^{212}Po	α	–
^{220}Rn	^{208}Tl	α	0.056 mBq/kg

Solution: the golden channel

- Story as old as the first detection of the neutrino – find a signal channel with time-correlated energy deposits
  - Explore forest of deexcitation gammas – there is one with long, 480 ns lifetime
  - Decay happens in 65% of Fermi transitions and 25% of total solar interactions
- Golden channel – prompt+delayed scintillation time profile
  - $E_1 = E_\nu - 2.73$ MeV
  - $E_2 = 1.65$ MeV
- High performance PDS gives good E / vtx resolution for correlation

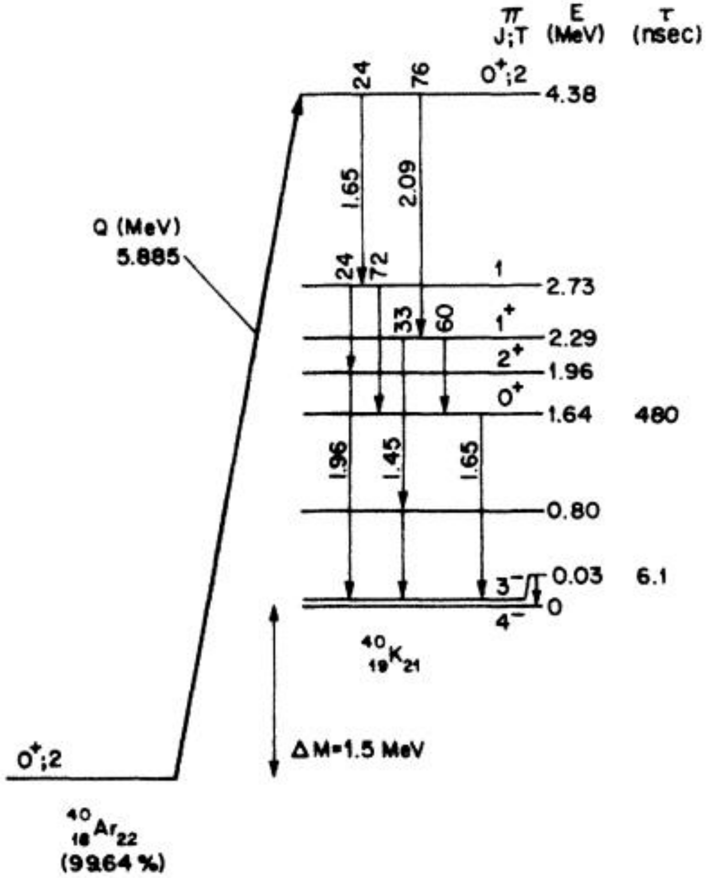
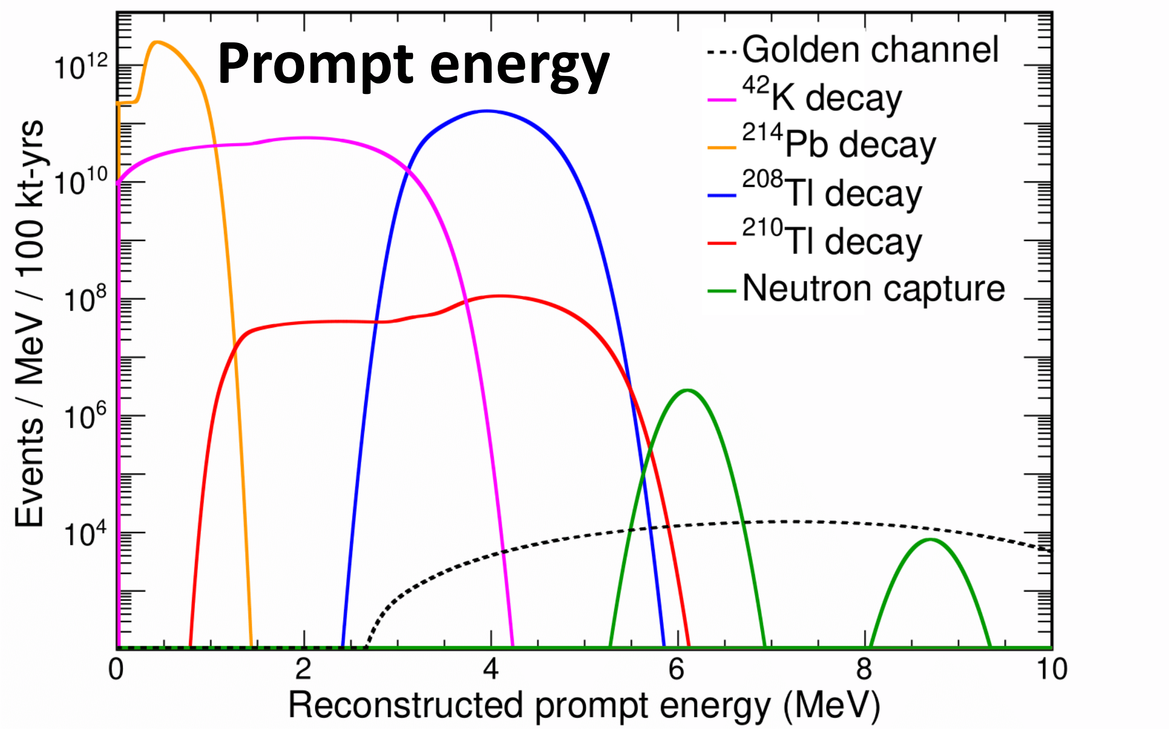
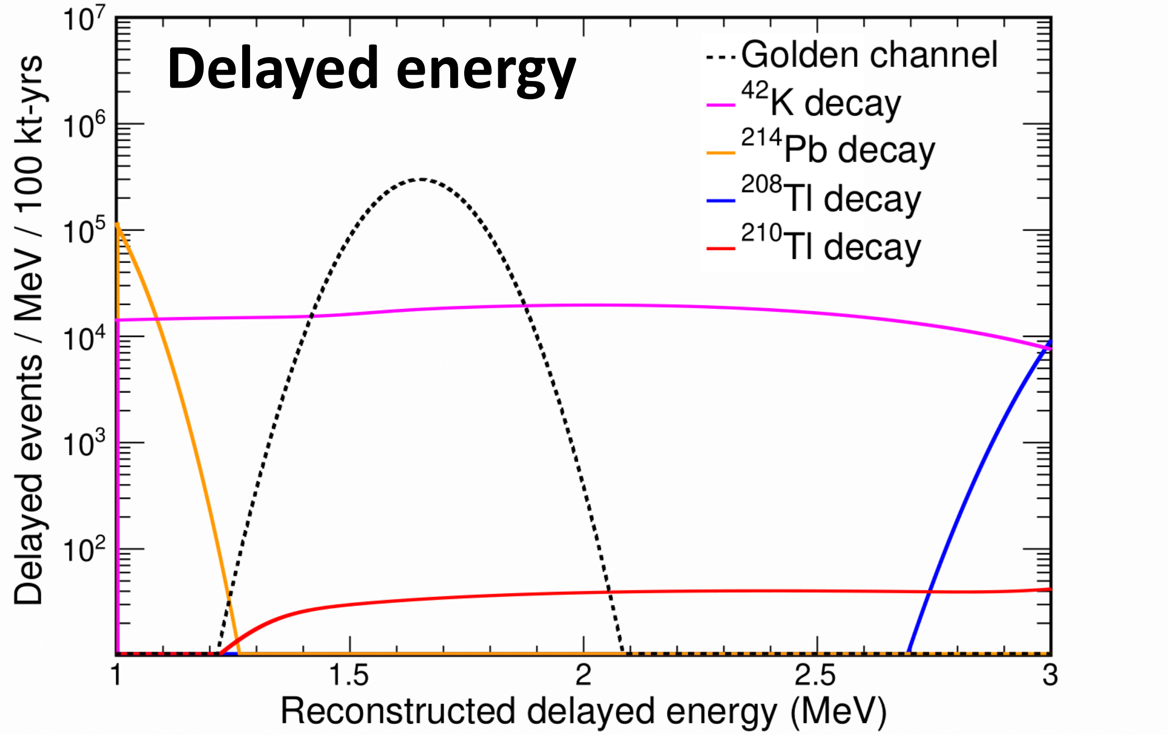


FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.

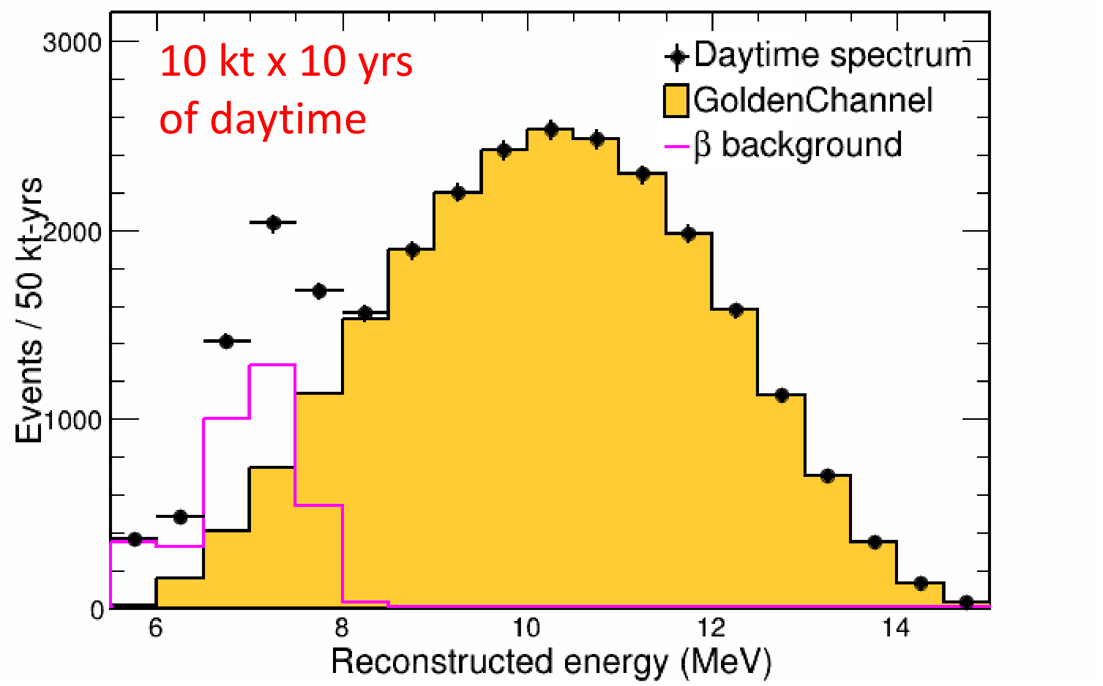
Selected background rate for DUNE

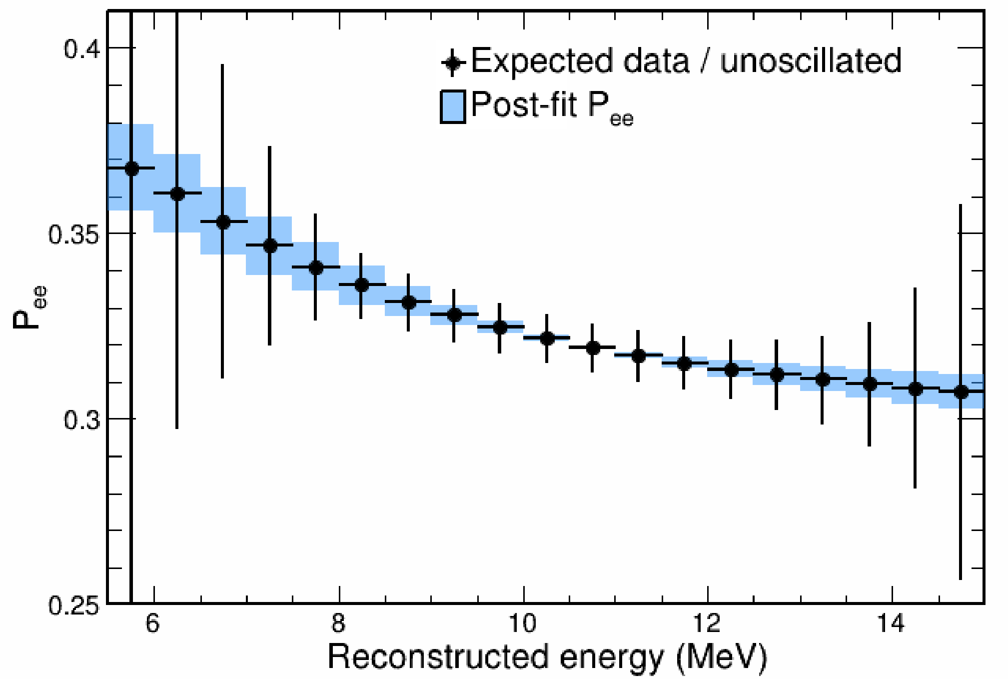




- ❑ O(1e12 bkg) / 100 kt-yrs in prompt ROI (dominated by ^{208}Tl decay)
- ❑ O(3e-8) bkg rejection factor after requiring delayed coincidence

Golden channel analysis

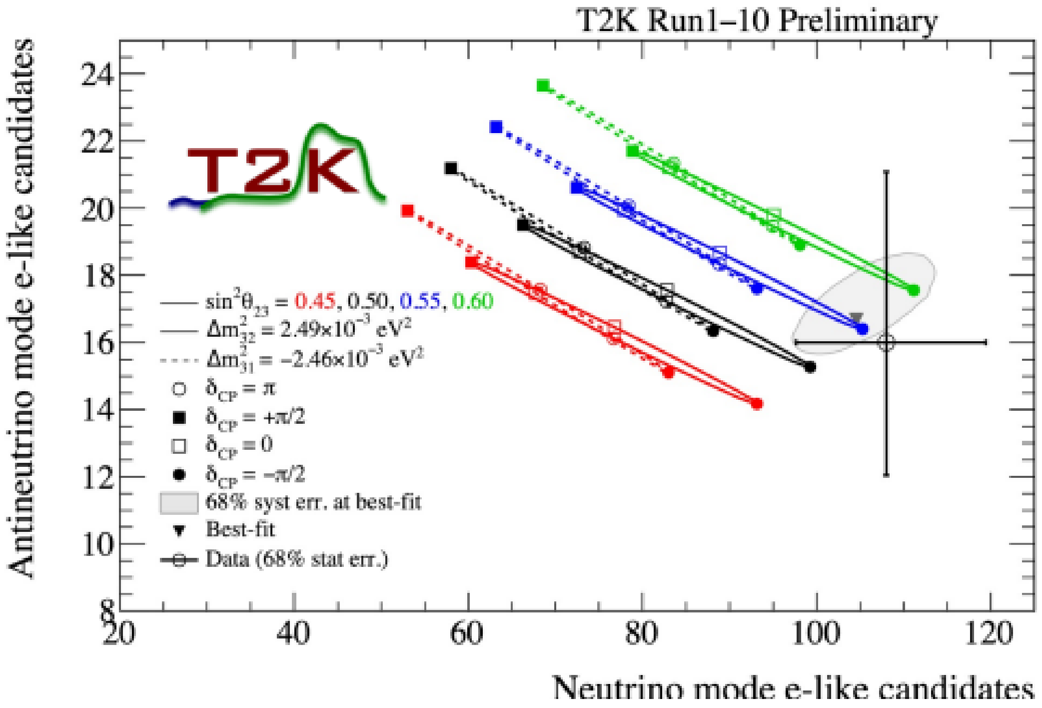


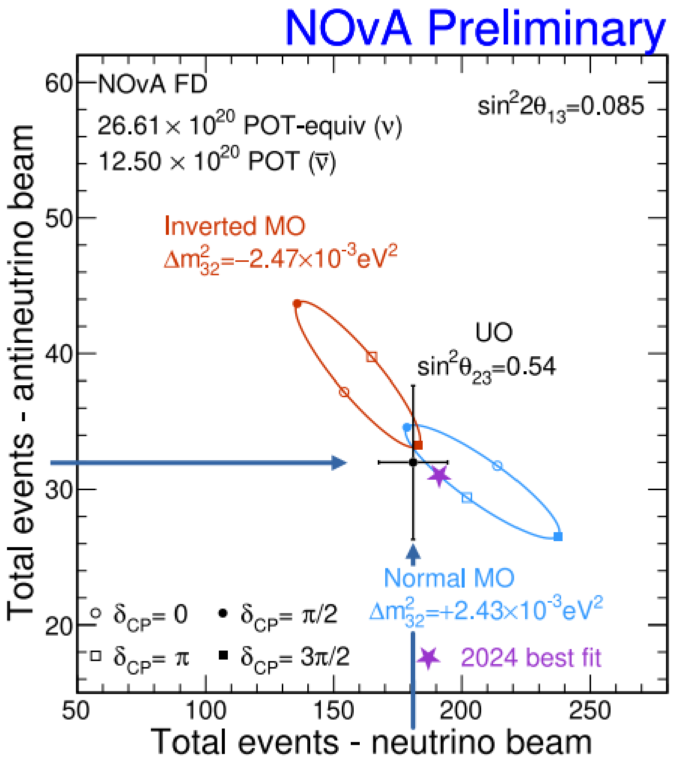


- Select only night-time events to mitigate complication of wiggles
  - 2370/yr signal + 355/yr bkg
  - Upturn visible down to 6 MeV + bkg free above 8 MeV
- Shape-only fit: upturn visible at 4σ and Δm^2_{21} measured at 15%
- Allows night-time studies to complement -> extra physics with solar ν

Twilight neutrinos

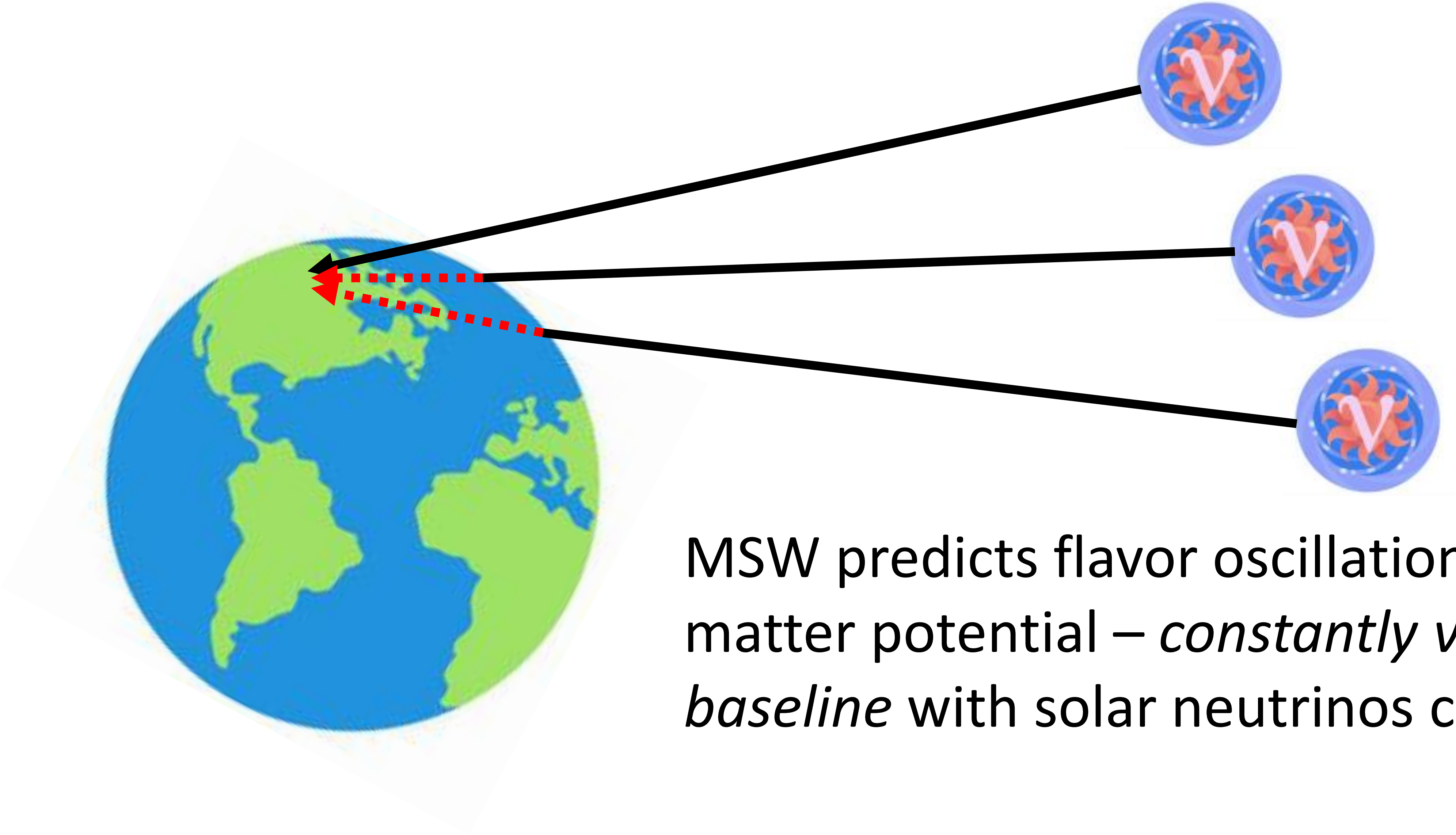
Testing the MSW effect





- Long baseline results rely on matter potential to break degeneracy
- Matter effects calculated with MSW model – is it valid?
- NOvA and T2K may now point to non-standard behavior (stats low!)

Testing MSW with twilight neutrinos

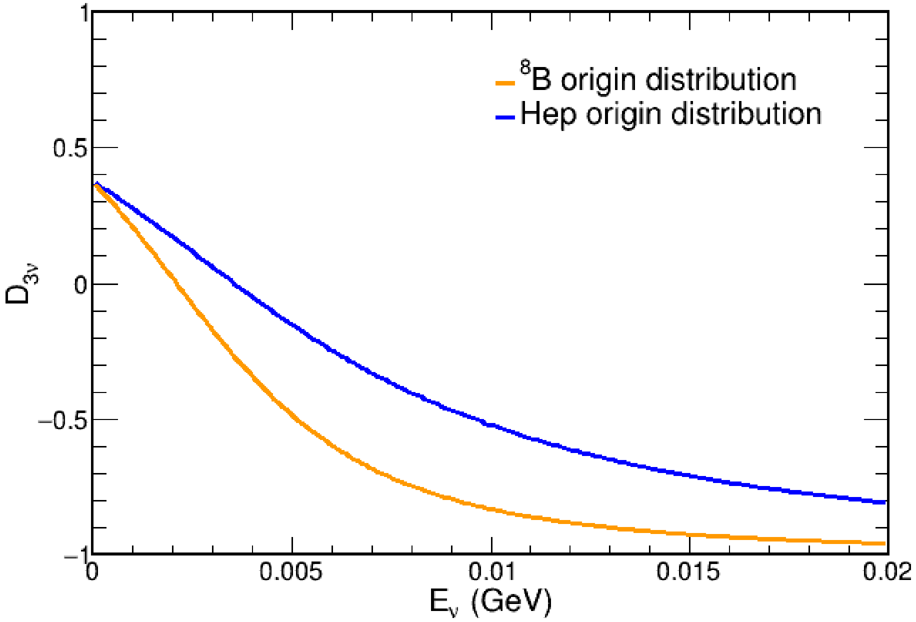


MSW predicts flavor oscillations in matter potential – *constantly varying baseline* with solar neutrinos can test

Review of mixing nomenclature in the sun

- Neutrinos arrive at Earth as a mix of mass eigenstates
  - $\approx \cos\theta_{13}\left(\sqrt{\frac{1+\cos 2\theta_{\text{mat}}}{2}}\,|\nu_1\rangle + \sqrt{\frac{1-\cos 2\theta_{\text{mat}}}{2}}\,|\nu_2\rangle\right) + \sin\theta_{13}\,|\nu_3\rangle$
  - $\cos 2\theta_{\text{mat}} = \frac{K\cos 2\theta_{12} - V_{CC}}{\sqrt{(K\cos 2\theta_{12} - V_{CC})^2 + (K\sin 2\theta_{12})^2}}$ $\boxed{K \equiv \frac{\Delta m_{21}^2}{2E_\nu}}$
  - $D_{3\nu} = \int \cos(2\theta_{\text{mat}}(r_{\text{prod}}))\,P(r_{\text{prod}})\,dr_{\text{prod}}$

[Blennow, Ohlsson, Snellman, PRD 69 073006 (2004)](#)



$D_{3\nu}$ = -1 for $|\nu_e\rangle_{\text{mat}} = |\nu_2\rangle$ never fully realized

Observed signals in experiments depend on the local electron density at production

Study overview

- In high-energy limit, MSW resonance completely activated, solar neutrinos arrive as $\approx |\nu_2\rangle$
- As they enter Earth, matter effects change flavor content of $|\nu_2\rangle$ which induces oscillations – the wiggles
  - Night-time excess of event rate observed
- $P_{ee}^{n} - P_{ee}^{d} \cong \frac{V_{CC}E_{\nu}}{\Delta m_{21}^{2}} \cos^{6}\theta_{13}\, D_{3\nu} \sin^{2} 2\theta_{12} \sin^{2}\frac{\Delta m_{21}^{2} L}{4E_{\nu}}$

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$$\boxed{V_{CC} = \sqrt{2}G_F N_e}$$

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Technically, mass splitting
depends on matter densi
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- Goal – determine if DUNE solar neutrinos give a precision test of MSW model of oscillation frequency and amplitude
- Limited by E res, short-baseline “twilight” neutrinos carry sensitivity

Comparison to long-baseline

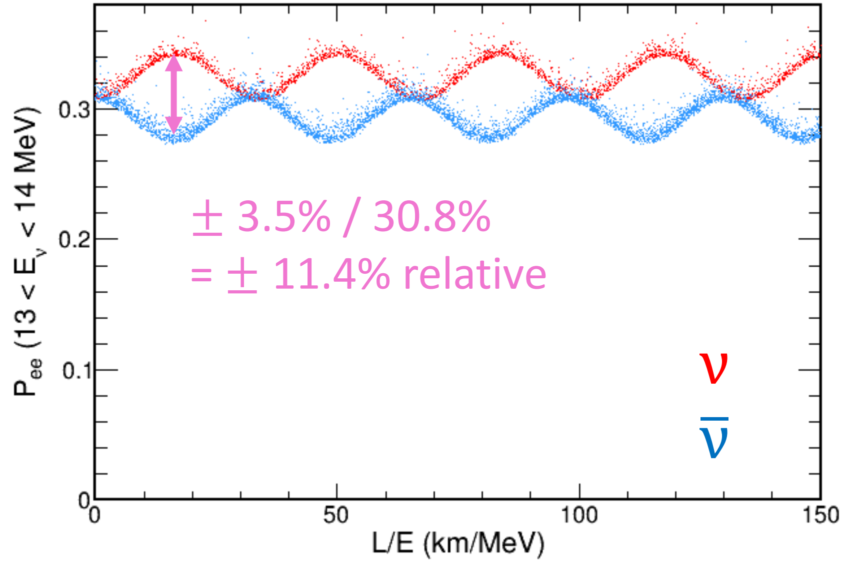
Night excess scale

$$A = \frac{V_{CC} E_\nu}{\Delta m_{ij}^2}$$

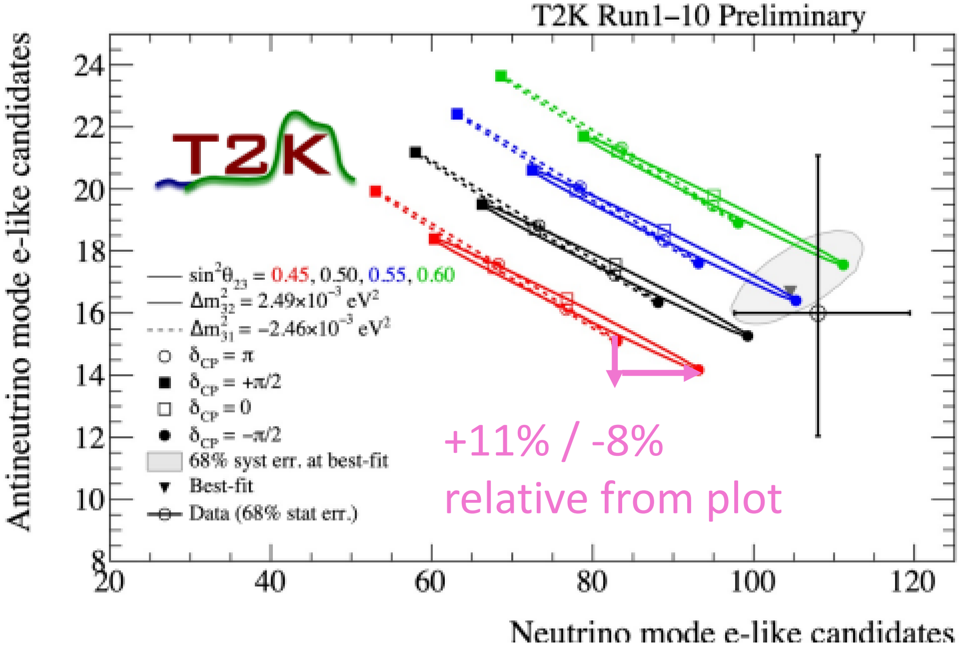
V_{CC} ≈ 1.2e-13 eV @ 3 gm/cm^3

	V_{CC}	E_ν	Δm_{ij}^2	A
^{8}B Solar	1.3e-13 eV	14 MeV	7.5e-5 eV^2	0.027
DUNE LBL	1.2e-13 eV	2.8 GeV	2.4e-3 eV^2	0.14
T2(H)K LBL	1.2e-13 eV	0.6 GeV	2.4e-3 eV^2	0.030

Solar neutrinos have approximately same degree of matter asymmetry as T2(H)K for long-baseline

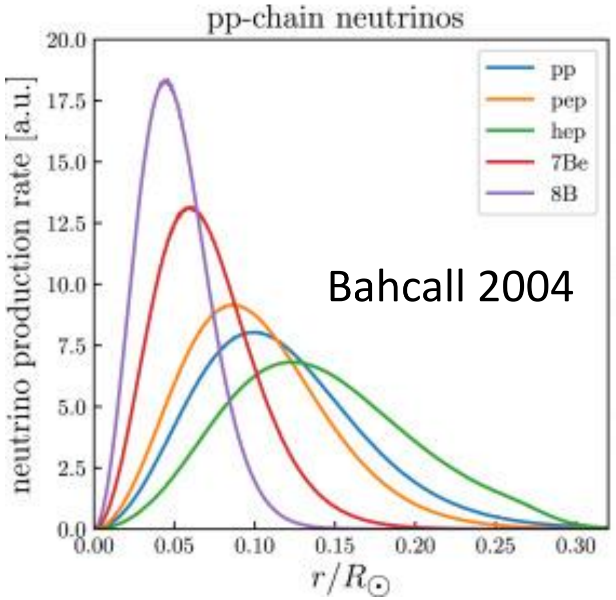


± 3.5% / 30.8%
= ± 11.4% relative

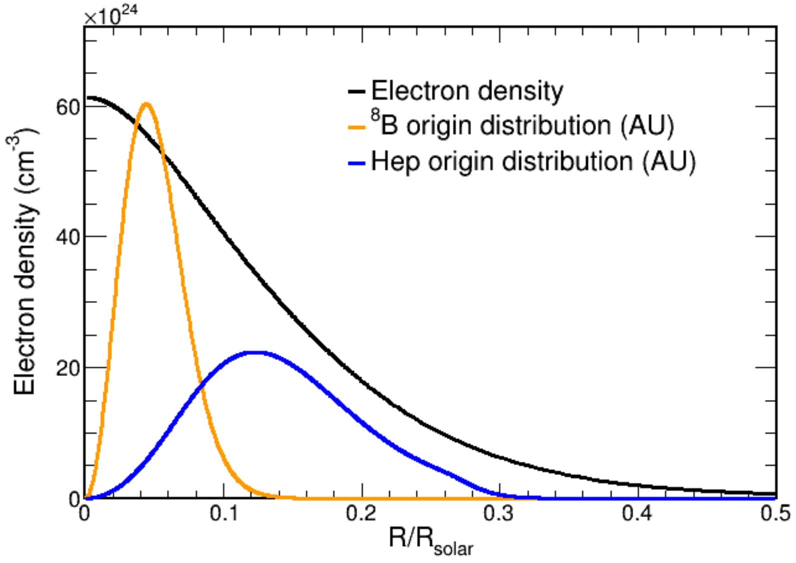


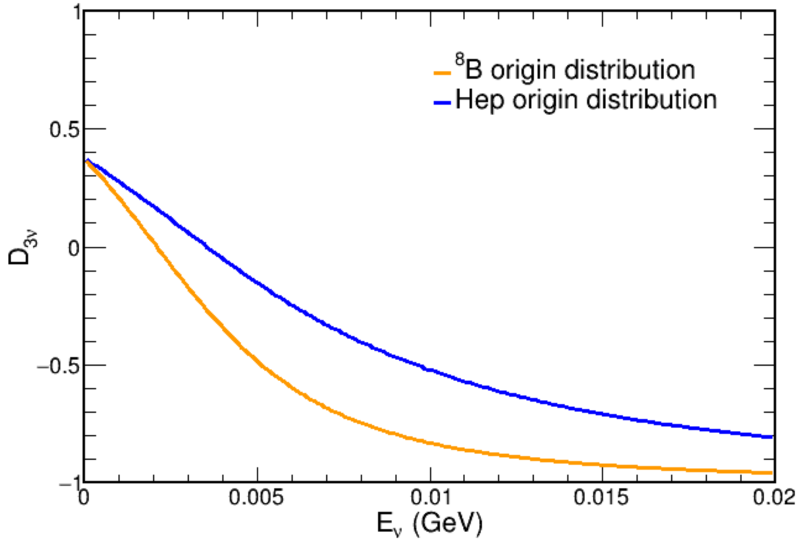
+11% / -8%
relative from plot

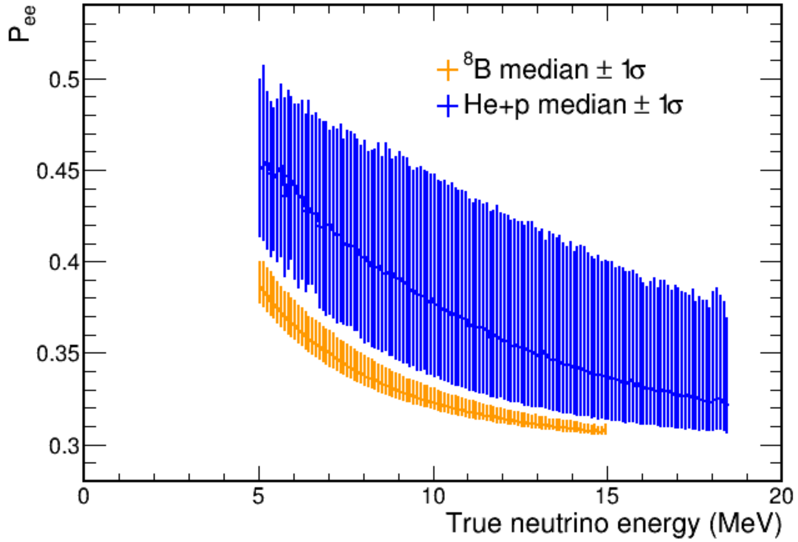
Regions that support fusion complicates picture



Bahcall 2004







- Distribution of production densities → distribution $|\nu_2\rangle$ of content → distribution of critical E_ν for upturn
- This is a precision oscillation study, incorporate this effect

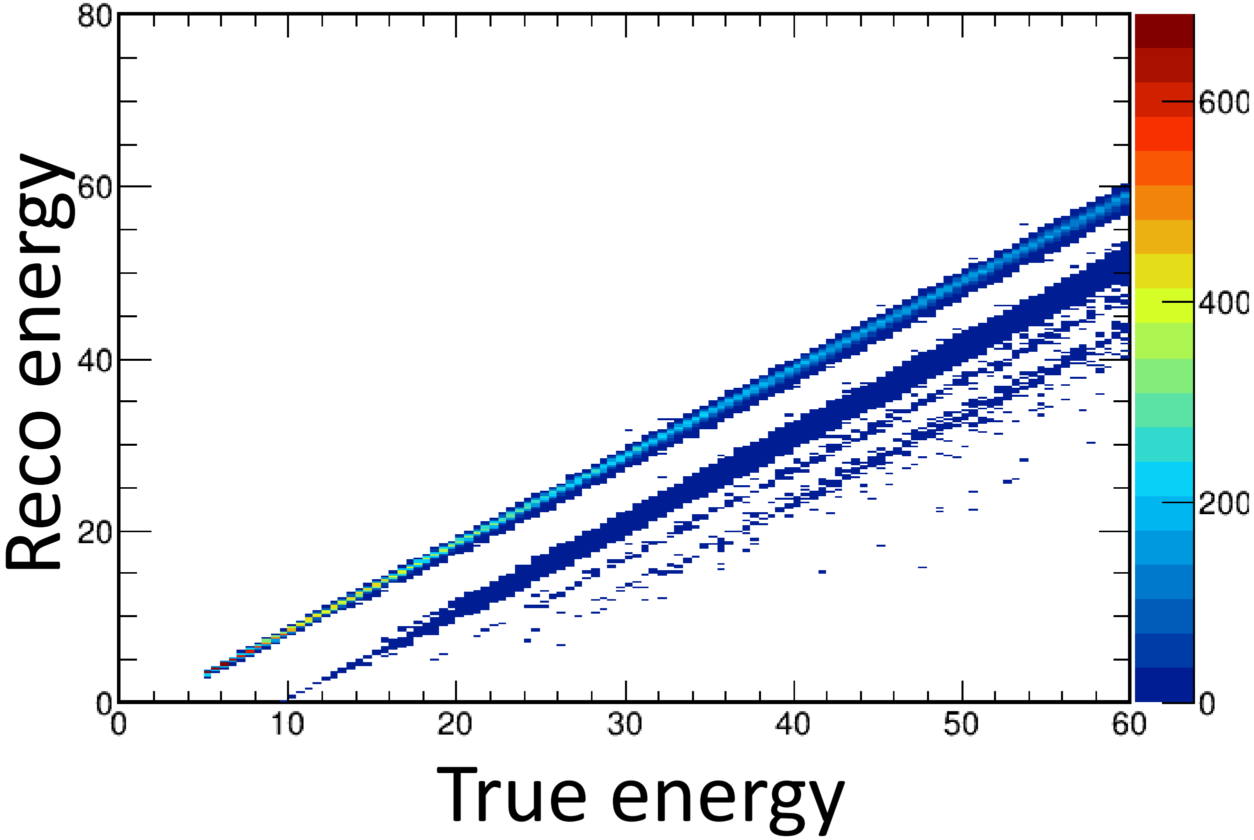
Simulating a solar neutrino sample

- ☐Focus on ^{8}B neutrinos

1. Pull electron density form spectrum radial distribution
2. Pull random nadir angle from expected yearly distribution
3. Pull random neutrino energy uniformly over flux energy range
4. Calculate $P_{ee}(r_{prod}, \cos\eta\,, E_\nu)$
5. Apply event weight $= P_{ee}(r_{\mathrm{prod}}, \cos\eta\,, E_\nu)$
6. Continue until spectrum integral is:
   - – 20.6k events / 17 kt-yrs x (10 x 17 kt-yrs) – Sergio’s selected event rate

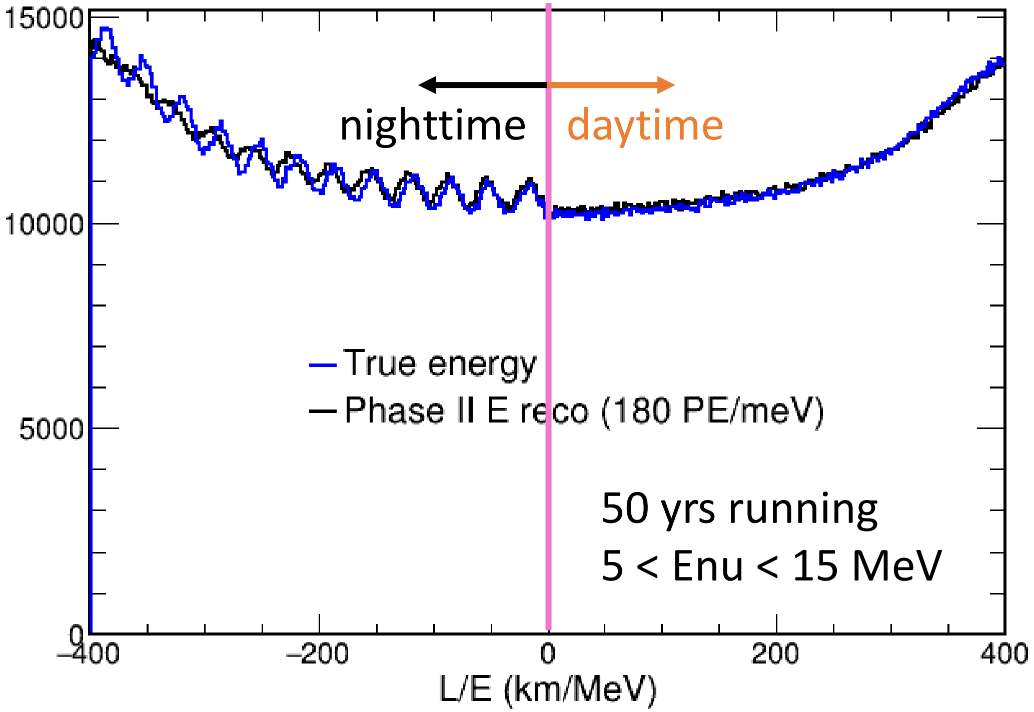
Detector resolution assumptions

- ❑Energy resolution matters! Use phase II detector response from Wei Shi's study
  - 75 keV for Q threshold
  - 180 PE/MeV LY
- ❑Looking at phase I detector res from Sergio is on the docket



Predicting twilight neutrinos

- Expected observed solar neutrino rate (5 – 15 MeV) as a function of baseline through Earth
  - $P_{ee}^{n} - P_{ee}^{d} \cong C \sin^2 \frac{\Delta m_{21}^2 L}{4E_\nu}$



50 yrs running
5 < Enu < 15 MeV

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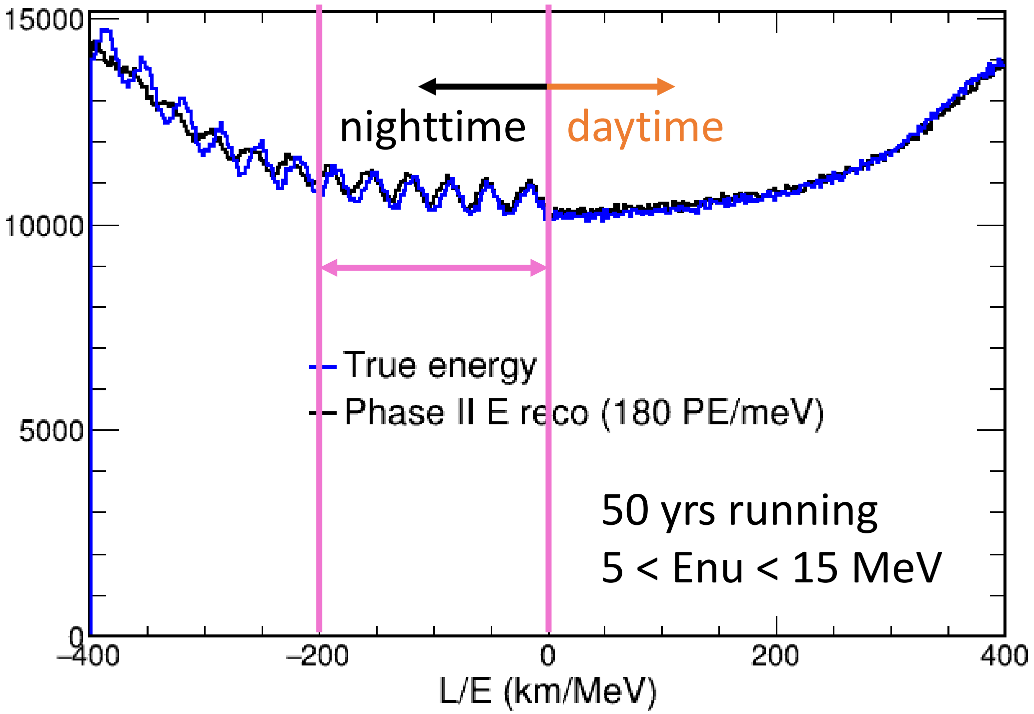
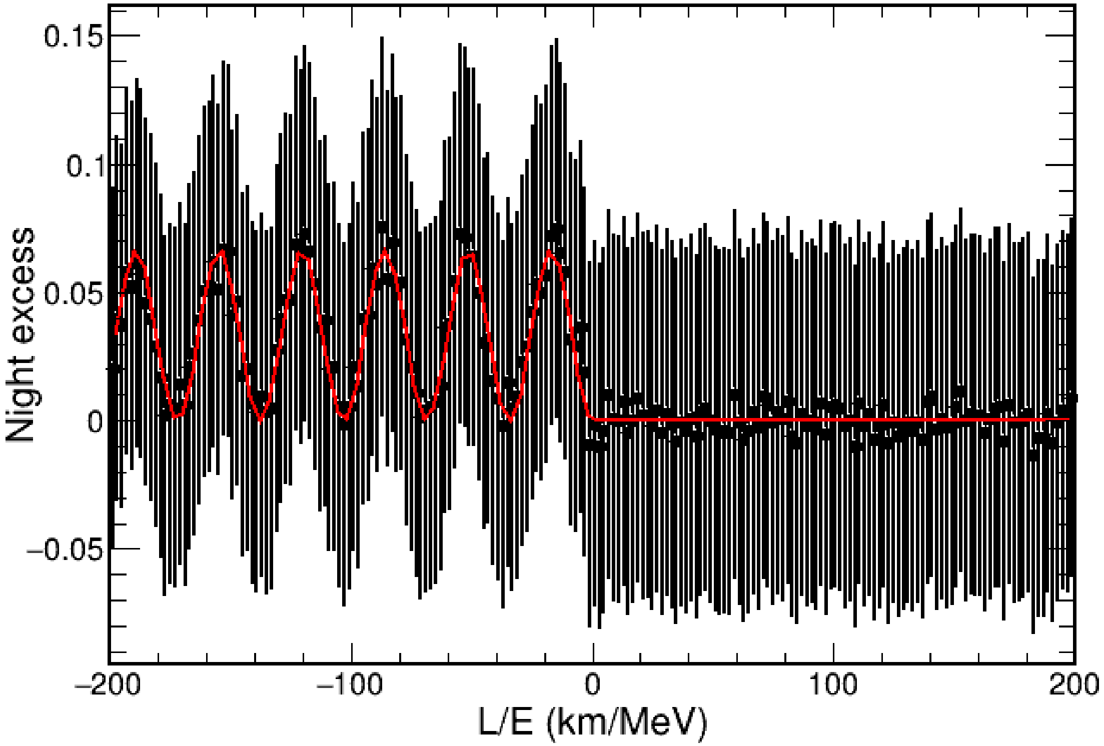


- For L/E < ~ -200 km/MeV, energy resolution smear out oscillation behavior even for phase II resolution
  - How well can we determine amplitude / frequency of oscillation for L/E<200

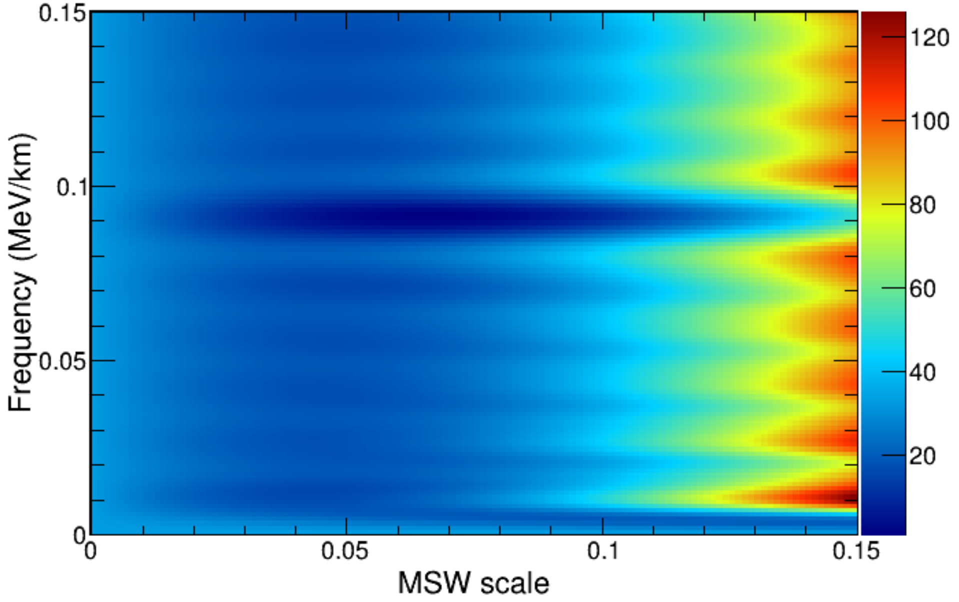
Mock data – 10 yrs of phase II

$5 < E_{reco} < 15$ MeV

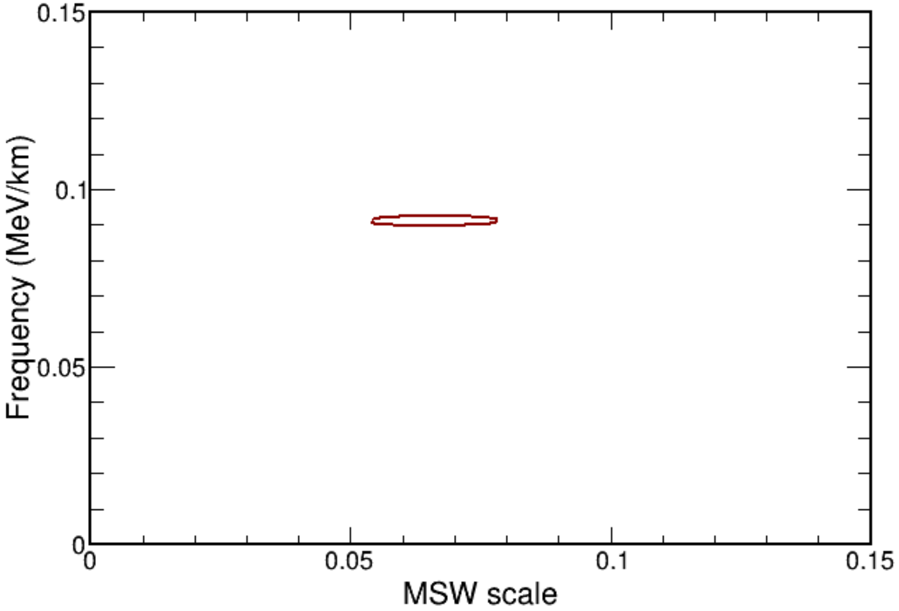


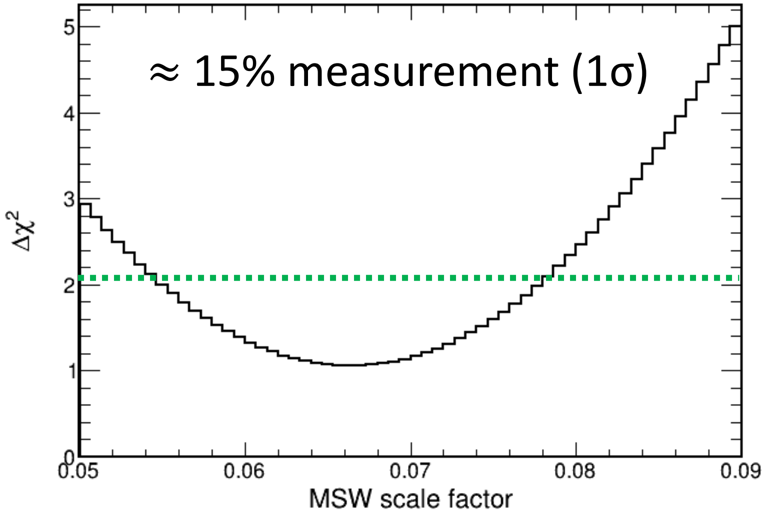
- ❑ Correct for nadir distribution shape, fit to polynomial: $p_0 + p_2x^2 + p_4x^4$ and apply to baseline prediction for night
- ❑ Normalize by day-time prediction to determine the night excess
- ❑ Select L/E < 200 km/MeV
  - With E ≈ 10 MeV → L < 2000 km → < 40 min after sunset / before dawn
- ❑ Six oscillation maxima are observed

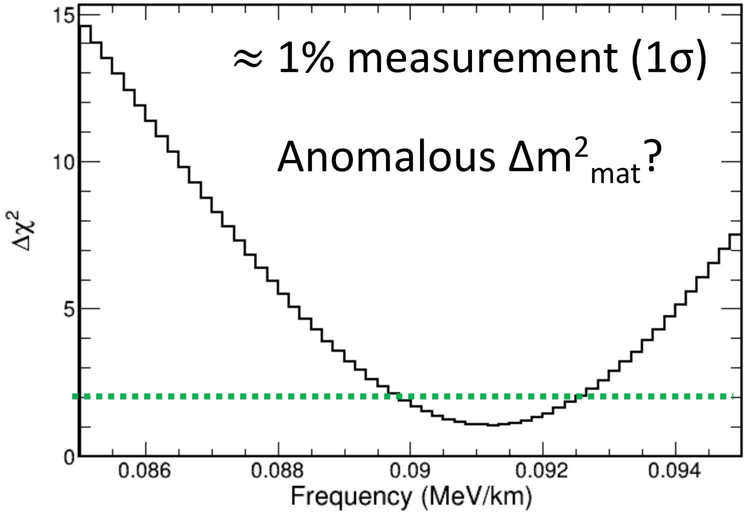
First attempt at oscillation contours



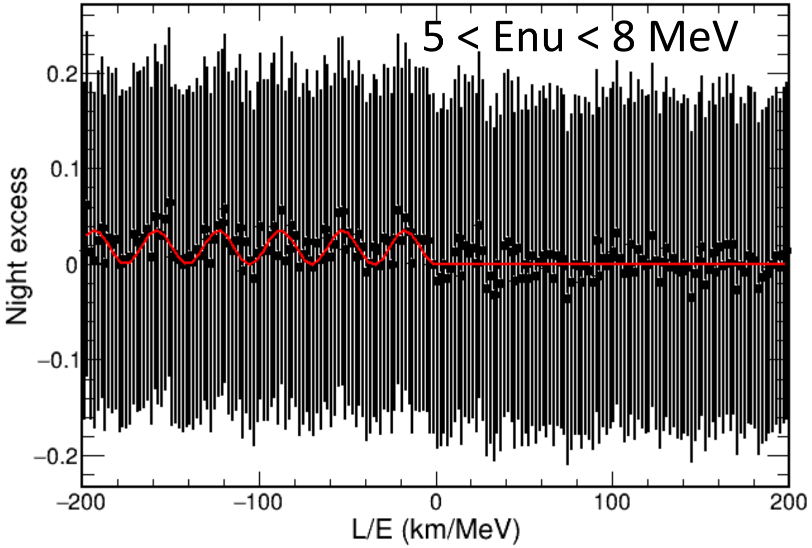
- ❑ 10 yrs of phase II solar neutrino data
- ❑ Great 1σ measurement of Δm^2
  - Can test adjustment due to matter effects
- ❑ Scale factor less-well determined, can be improved with late night neutrinos

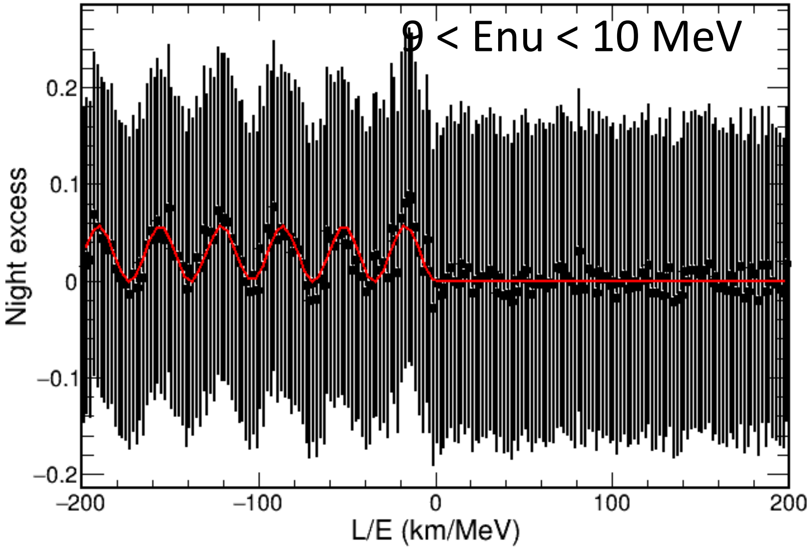


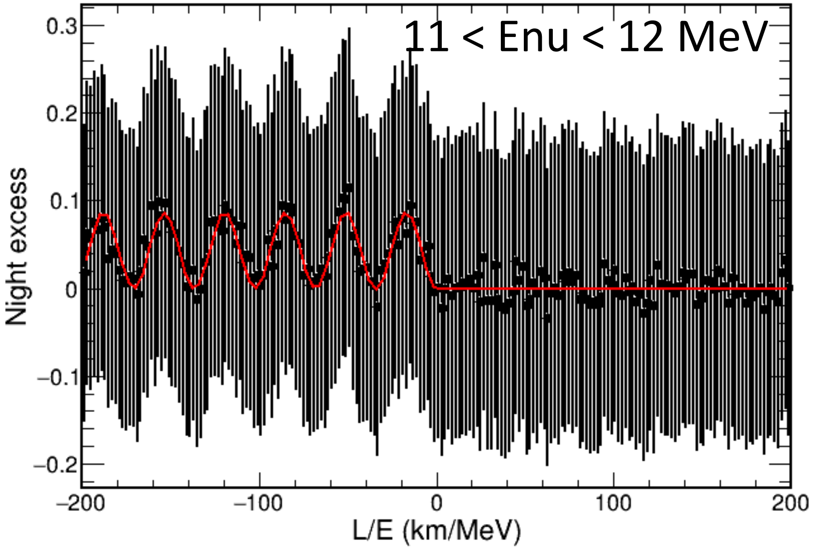


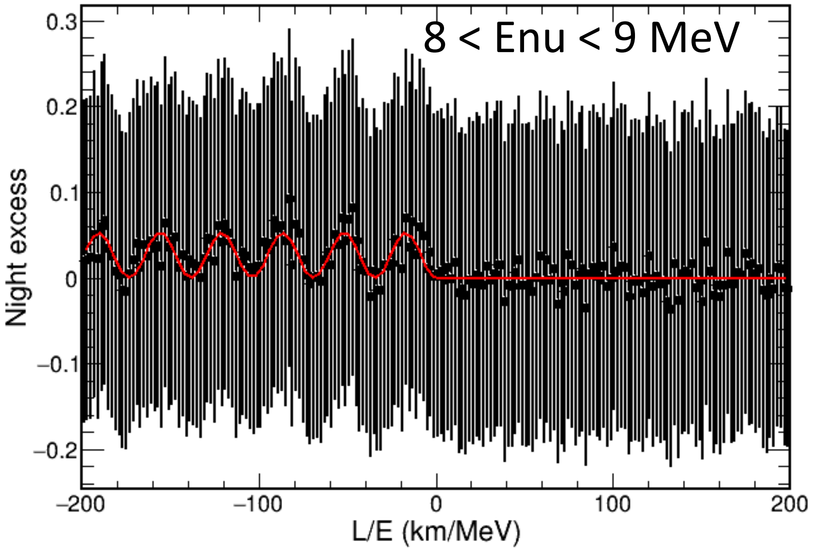


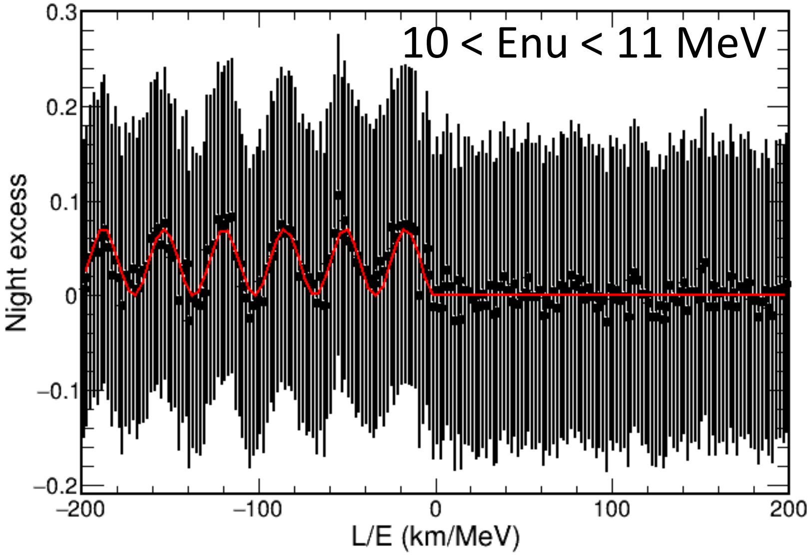
Spectra in energy bins

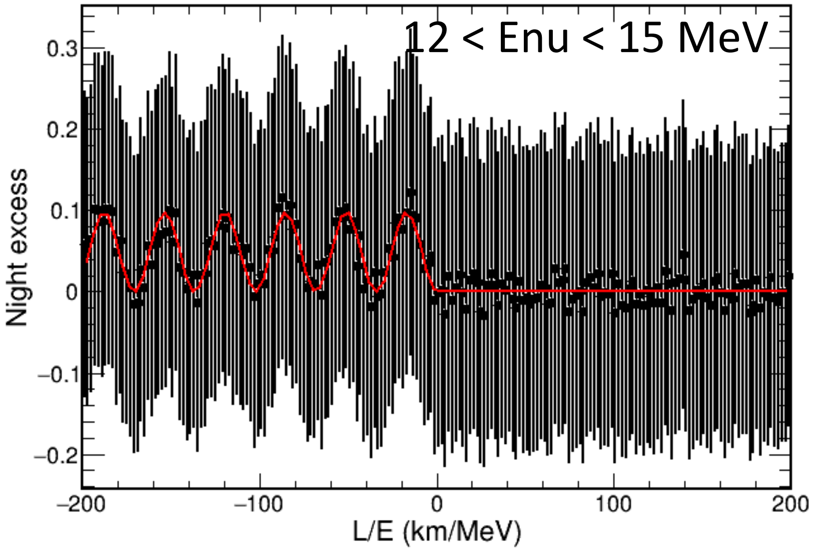




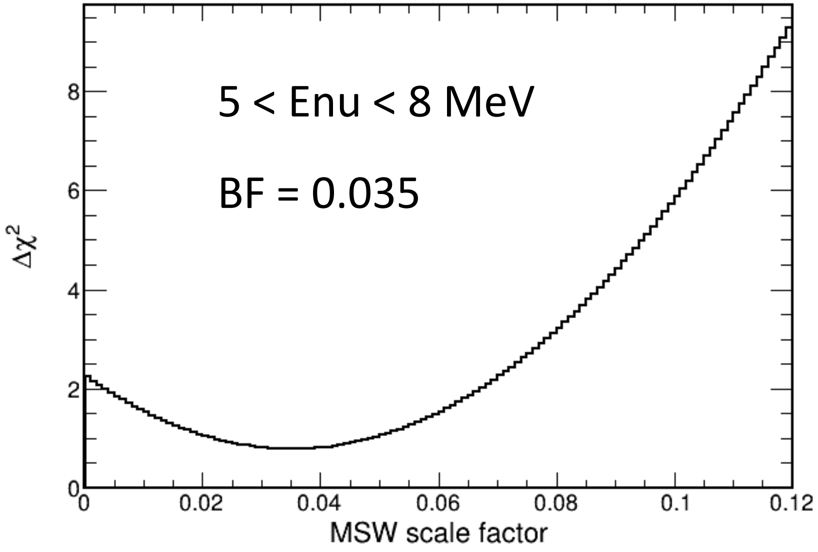




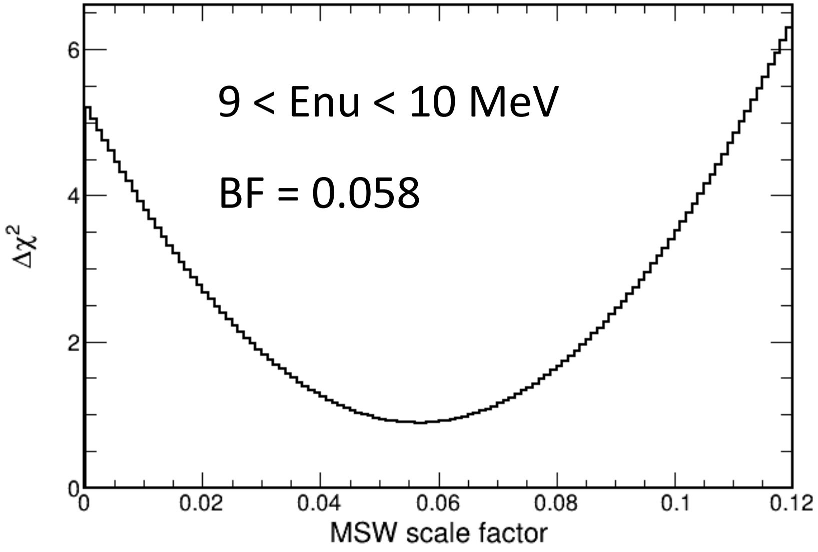




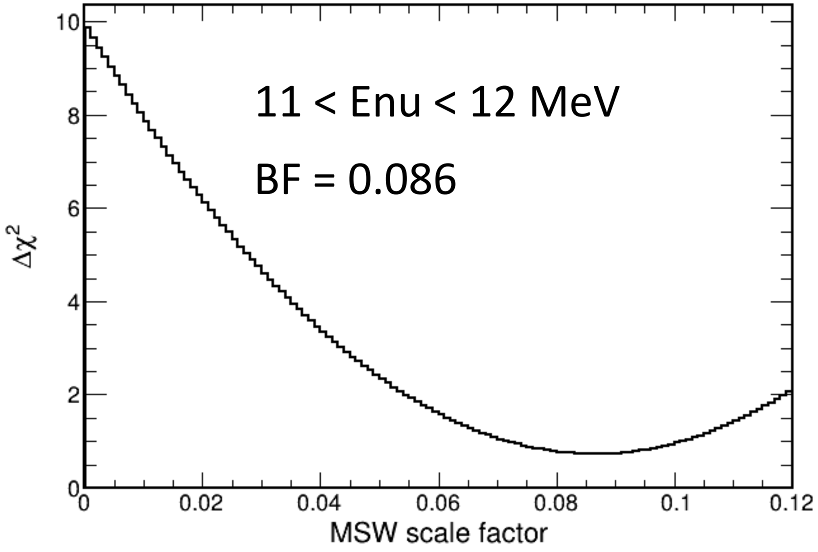
Sensitivity in energy bins – MSW scale


5 < Enu < 8 MeV

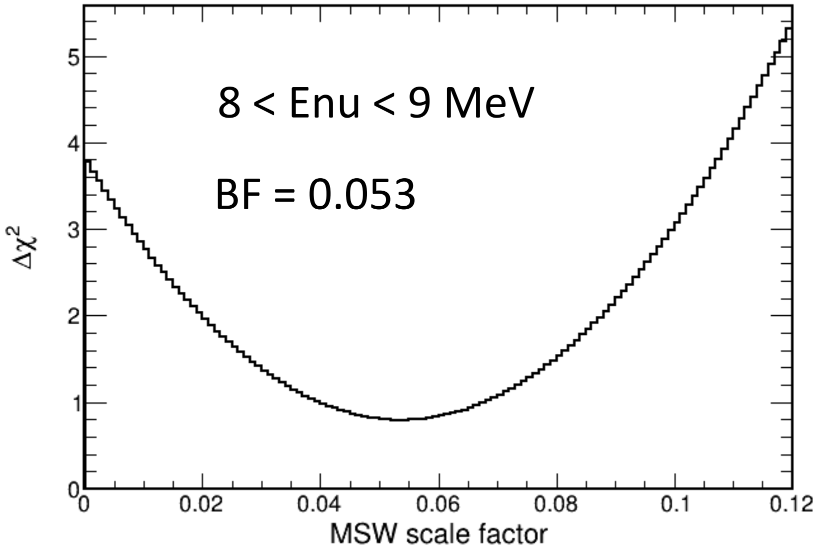
BF = 0.035


9 < Enu < 10 MeV

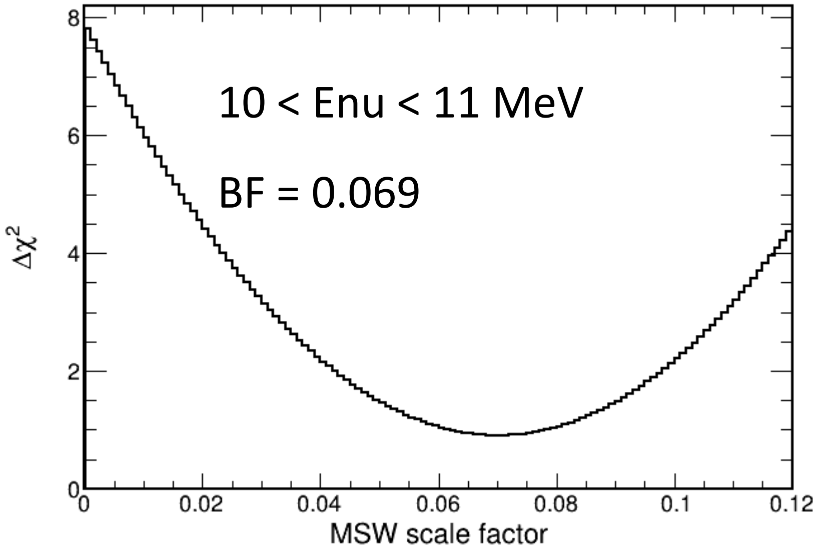
BF = 0.058


11 < Enu < 12 MeV

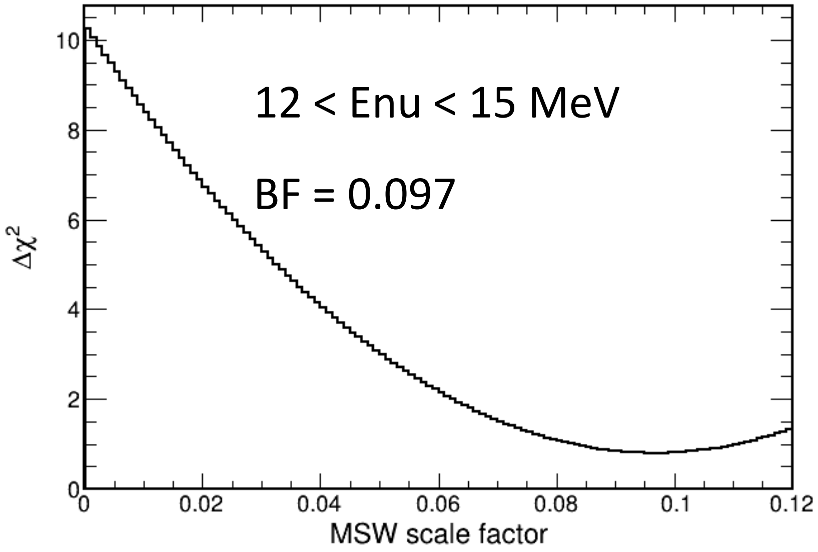
BF = 0.086


8 < Enu < 9 MeV

BF = 0.053

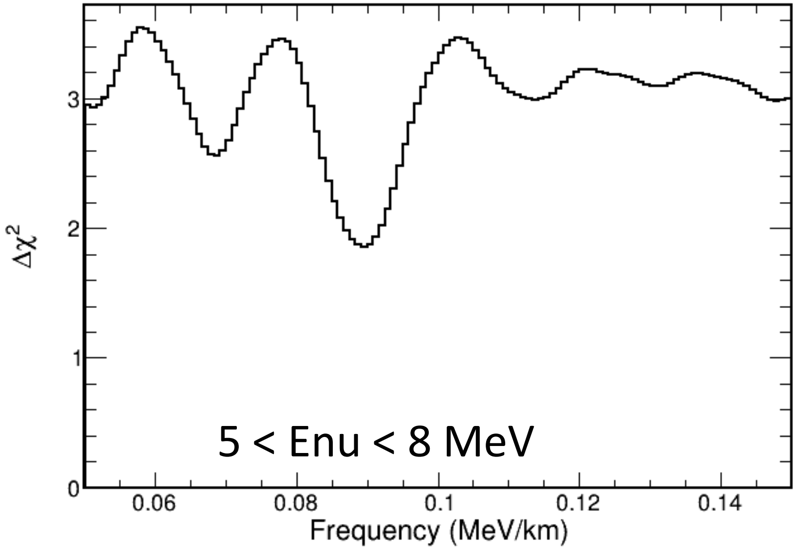

10 < Enu < 11 MeV

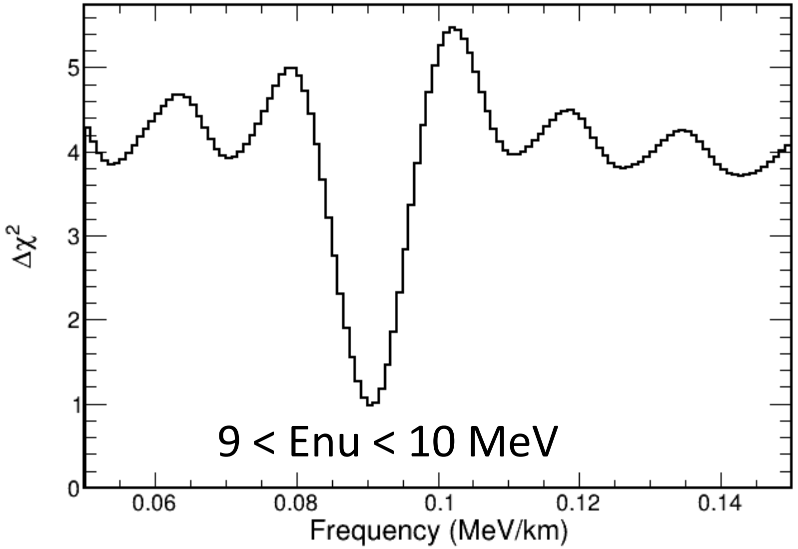
BF = 0.069

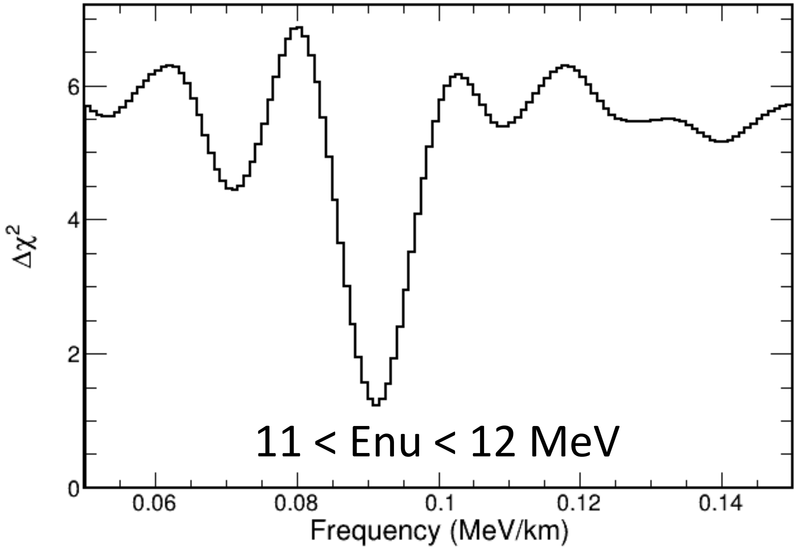

12 < Enu < 15 MeV

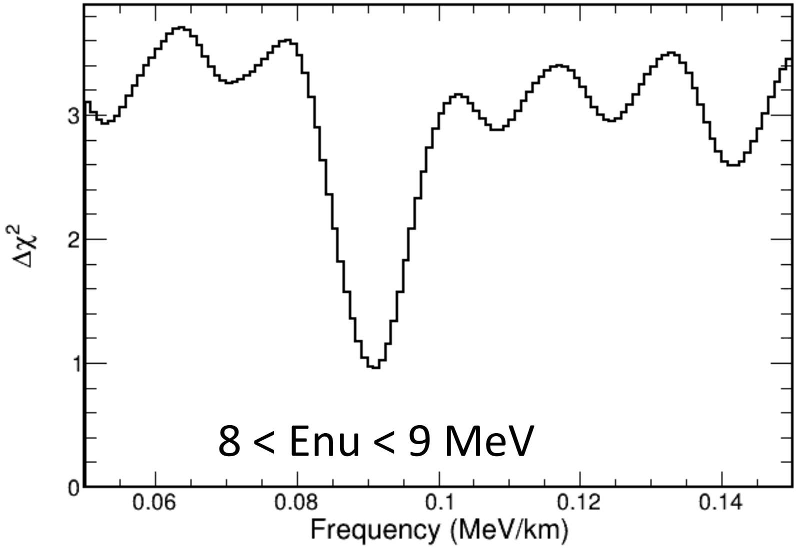
BF = 0.097

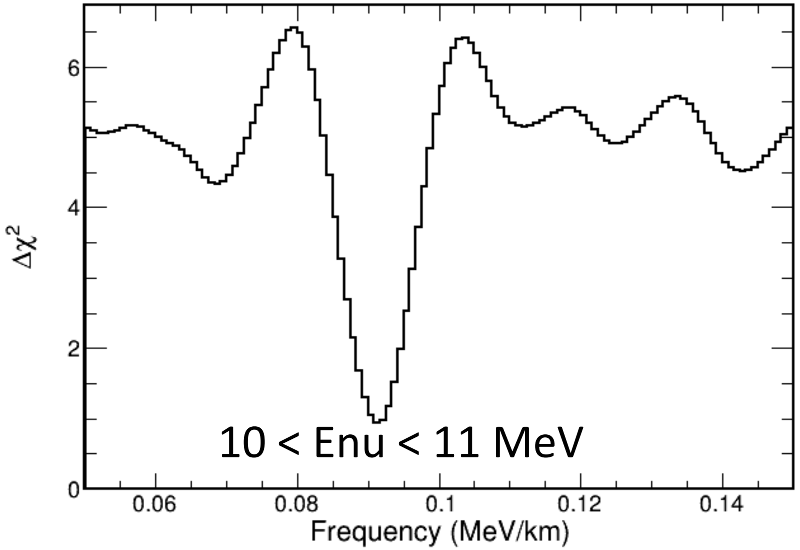
Sensitivity in energy bins – frequency

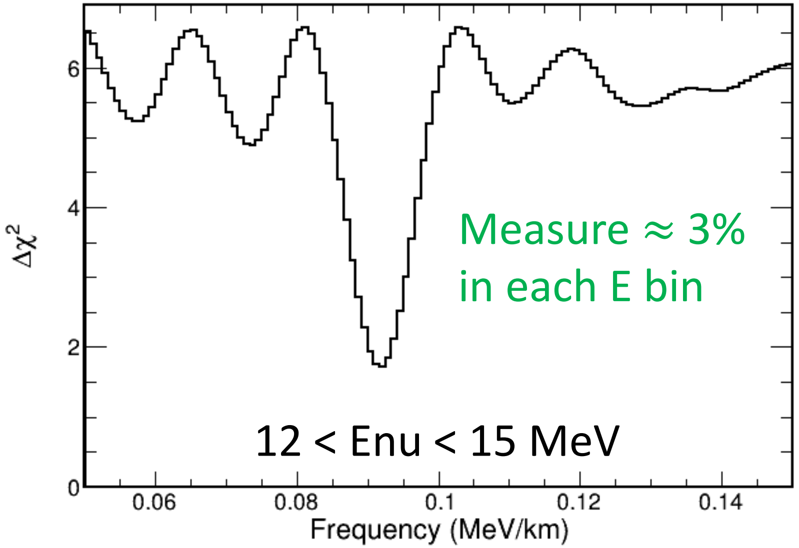












Measure ≈ 3%
in each E bin

Impressions and next steps

- ☐ New physics available if we have 1 module with excellent resolution
  - Phase II owns this physics!
- ☐ Golden analysis channel allows analysis of the solar upturn giving independent measurement of Δm^2
  - Good resolution tests energy dependence of upturn
- ☐ Twilight neutrinos also Δm^2 (1% at 1σ) – maybe test departure of Δm^2 from vacuum value?
  - With JUNO, multiple probes overconstrain the solar neutrino picture allowing new physics tests
- ☐ Sensitivity to MSW scale less good (15% at 1σ) – resolution-averaged neutrinos from late at night can also measure this parameter
- ☐ Very basic studies – need more study with realistic detector models