Solar Neutrinos: Is There a Future?

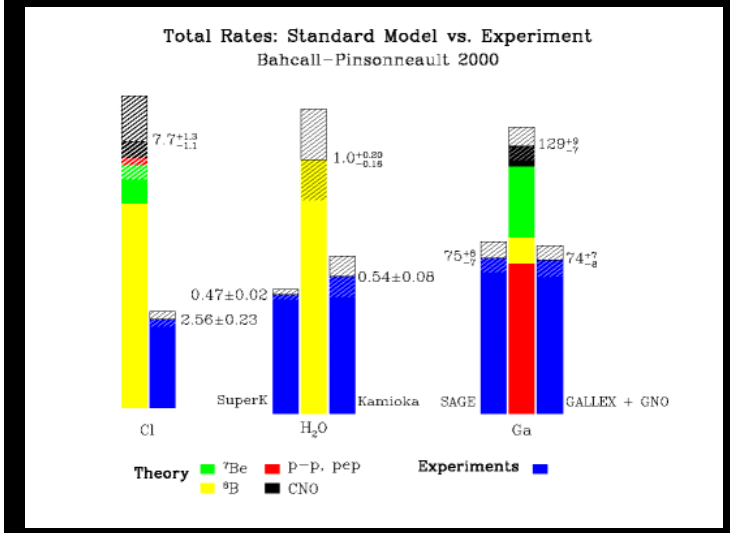
John Beacom, The Ohio State University

The Ohio State University's Center for Cosmology and AstroParticle Physics

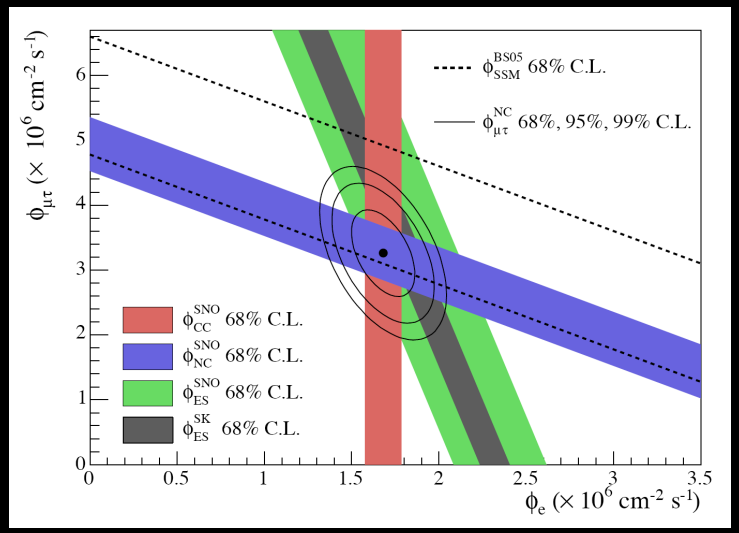
Thesis

Particle-Physics View

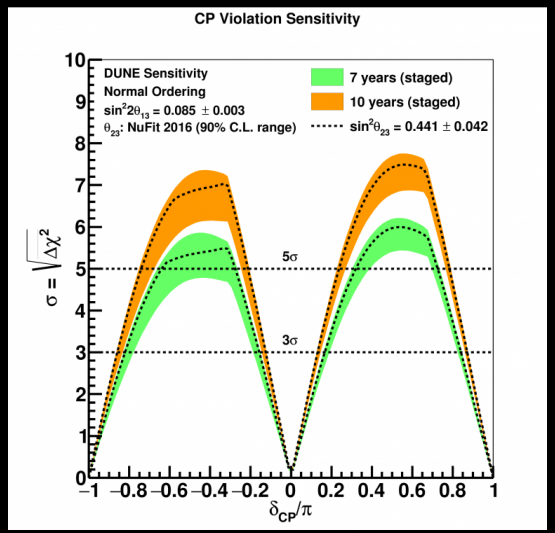
Original-Gangster Epoch

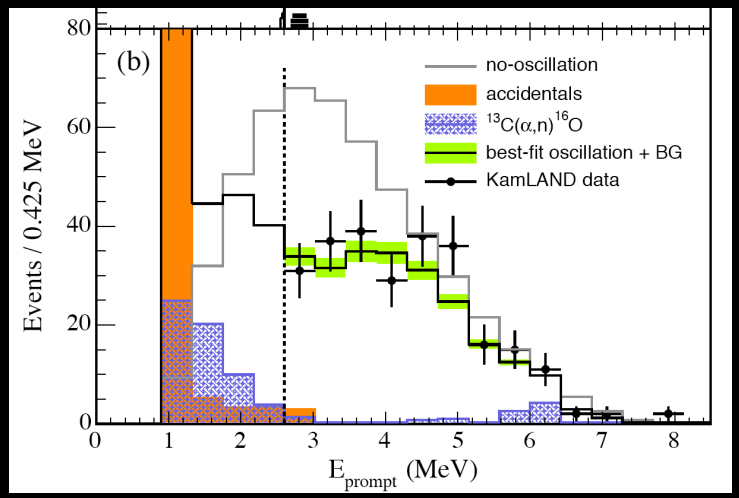


First Golden Epoch



Coming Golden Epoch





Conclusions

Solar Neutrinos: Is There a Future?

No

Antithesis

Astrophysics View

the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

John Bahcall (1964)

Synthesis

Correct View

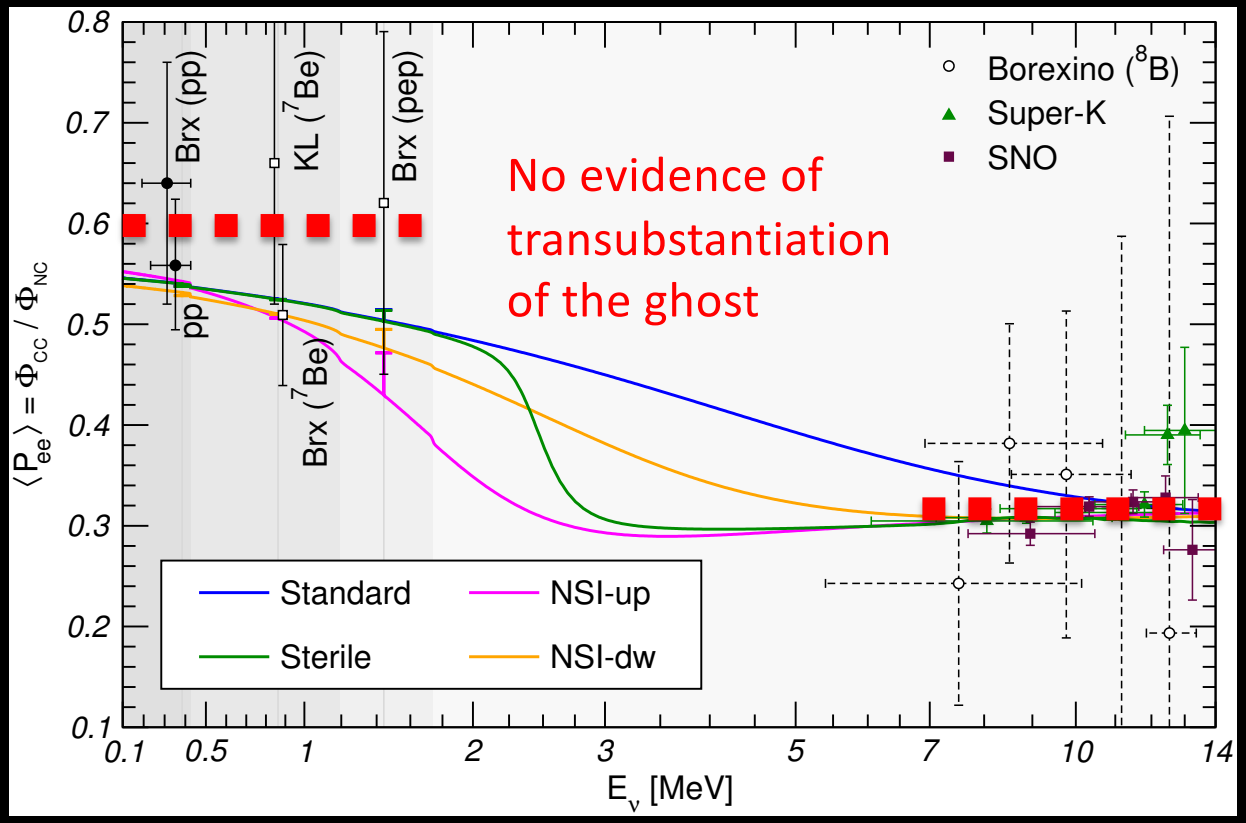
Probe particle physics beyond reach of the lab using the extremes of astrophysics

Probe astrophysics beyond reach of EM data using the penetrating power of neutrinos

Must do together

Recent decreased activity is a lack of experiments, not good questions

Discovery Potential: Particle Physics



Maltoni and Smirnov (2016)

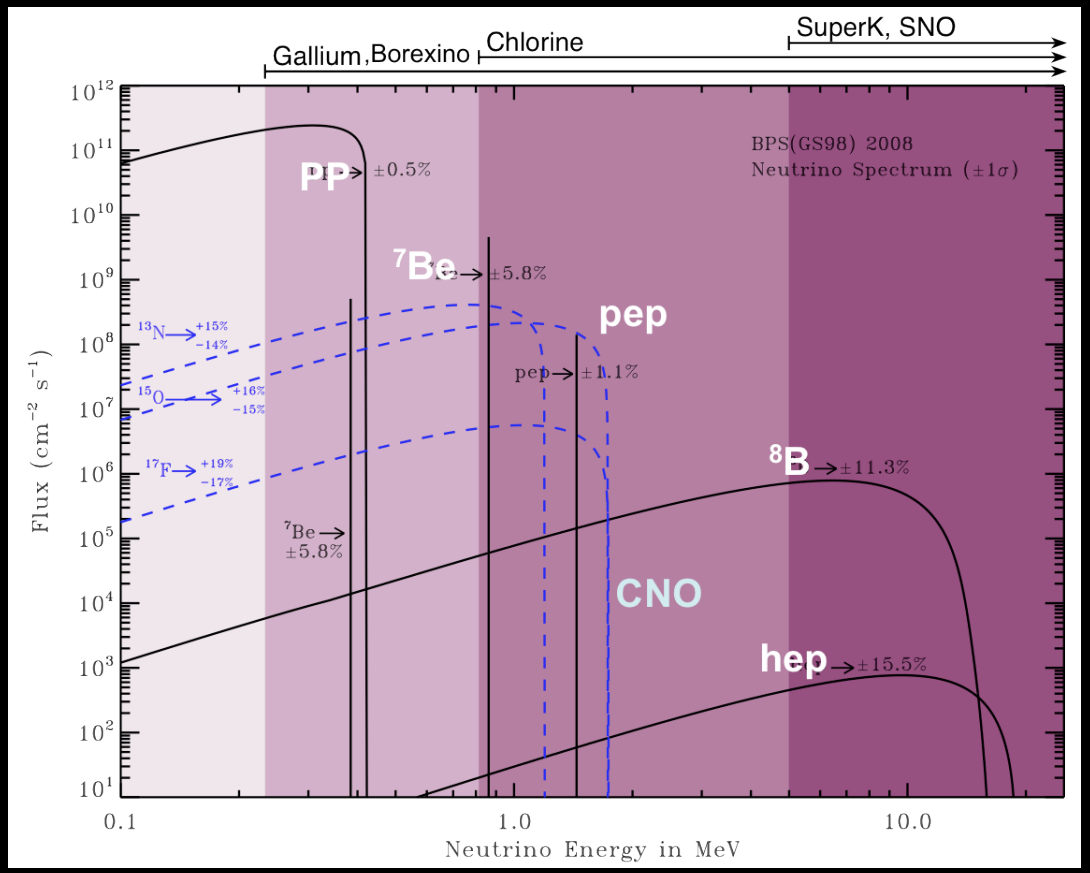
Directly measure energy dependence of MSW effect

Test solar-reactor dm^2 discrepancy

Many ways to search for new physics

Needs precise astrophysics to maximize potential

Discovery Potential: Astrophysics



Precisely measure 8B flux and hence core temperature

Discover *hep* flux and hence probe density profile

Measure CNO flux and hence probe metallicity puzzle

Needs precise particle physics to maximize potential

Move Forward

Two-Pronged Attack

Enu < few MeV	Enu > few MeV
Fluxes *high*	Fluxes *low*
Need new detectors at ton–kton scale	Need new detectors at 10-kton scale
Hard to improve on Borexino!	Hard to improve on SK, SNO!

Solar Neutrinos in LAr: Highlights of Prior Work

- 1986: Bahcall, Baldo-Ceolin, Cline, and C. Rubbia
  Prospects for ICARUS (~ 0.01 DUNE mass) are promising

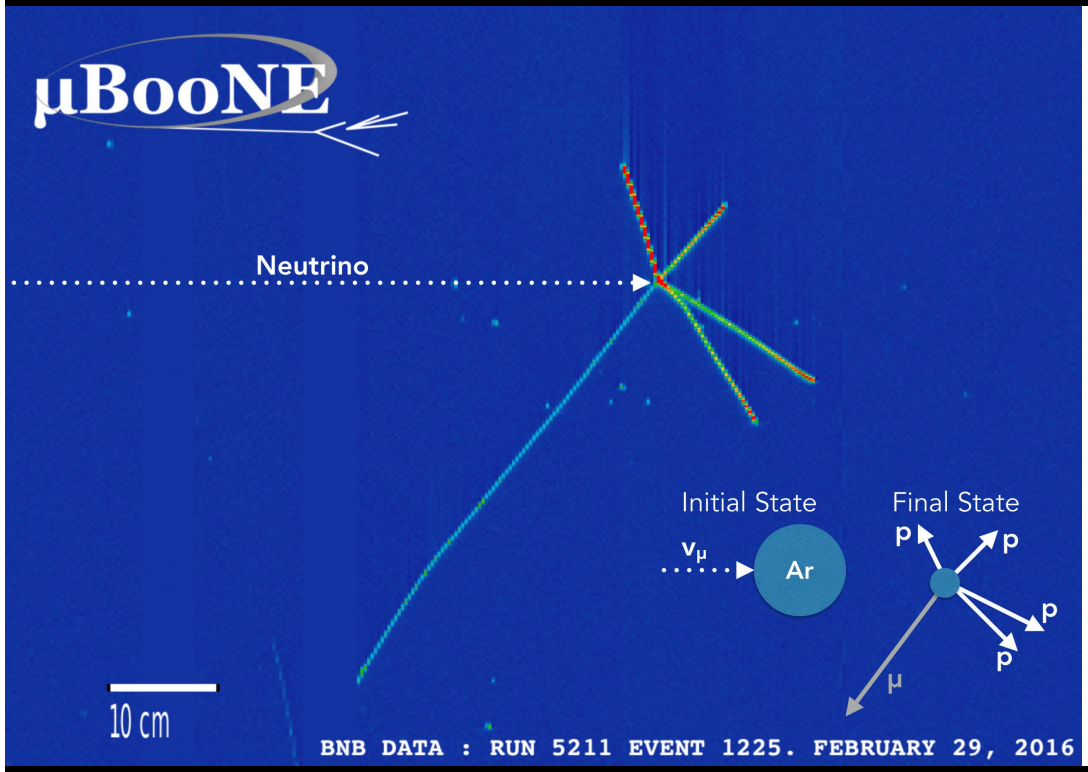
- 2000: Arneodo et al. (ICARUS Collaboration)
  Practical experience strengthens that case

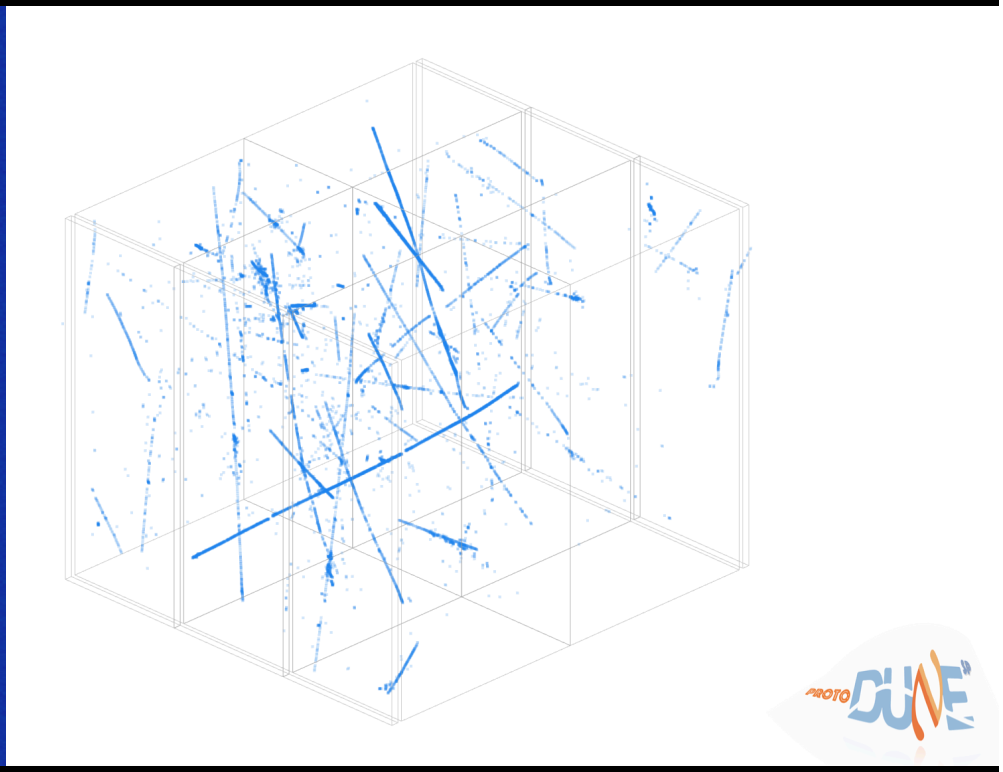
- Later: Various LBNE/DUNE documents
  Brief discussions about prospects

- 2015: Franco et al. (~ DarkSide Collaboration)
  Prospects for low-energy detection are promising

- 2016: Ioannisian, Smirnov, and Wyler
  DUNE Day-Night (and dm^2) sensitivity could be excellent

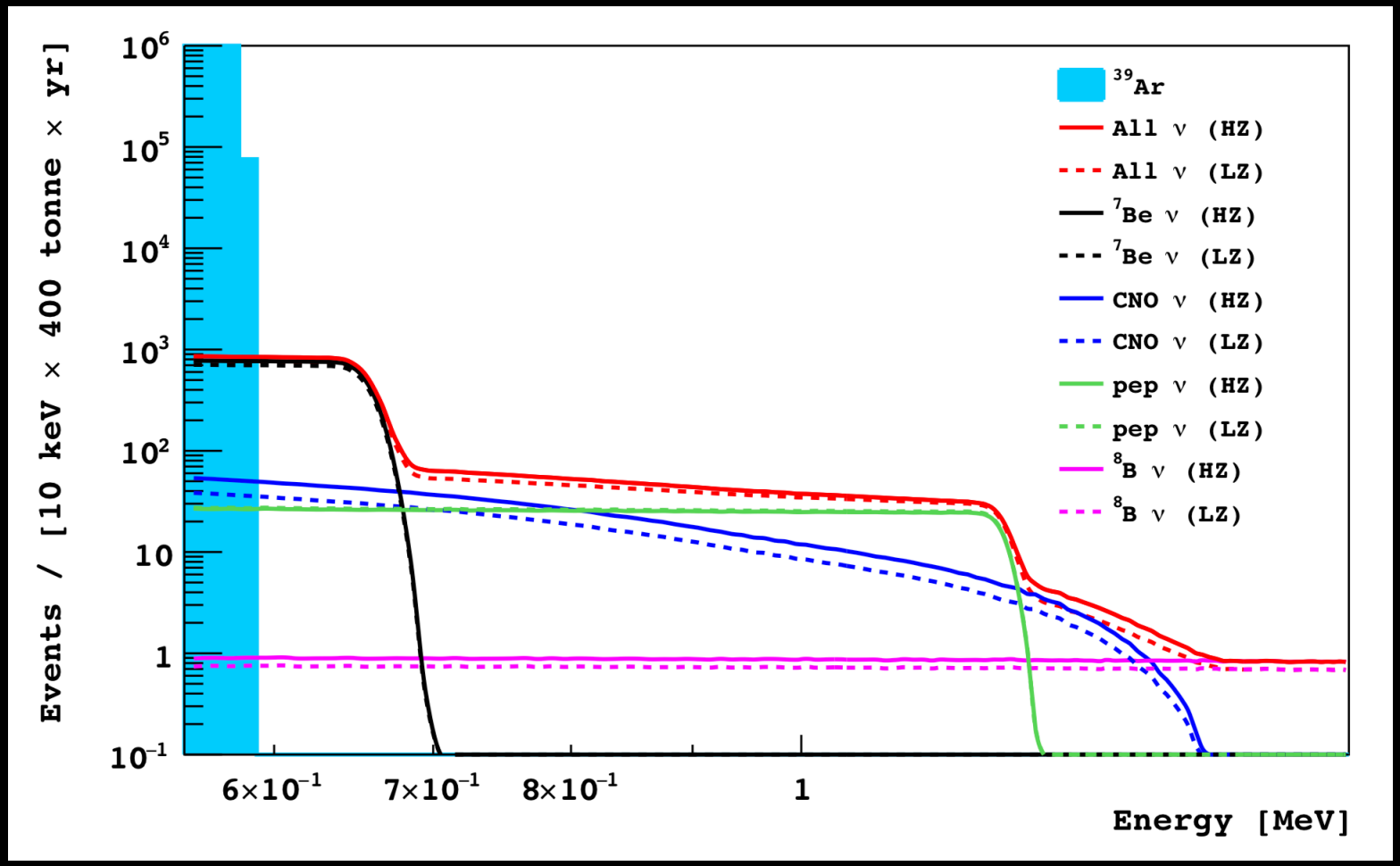
What's Special About Liquid Argon?





3d reconstruction, particle ID, granularity, visualization, …

Low-Energy Prospects



D. Franco et al., arXiv:1510.04196

DarkSide upgrades could measure low-E solar neutrinos well

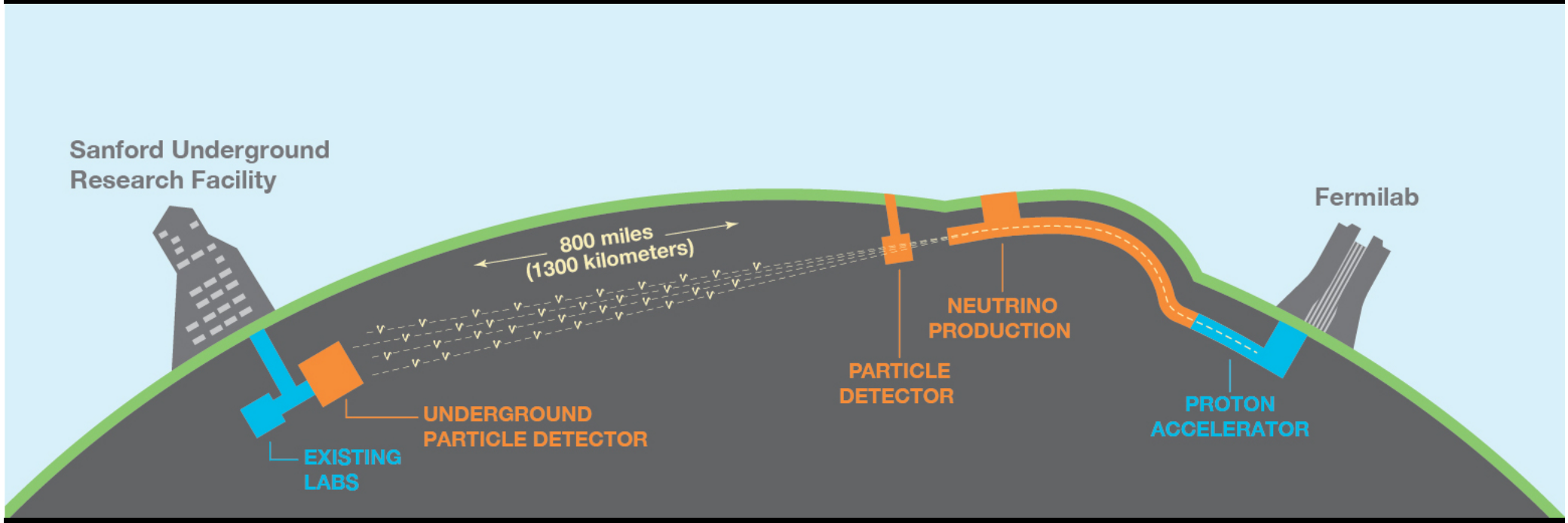
First Comprehensive Study of Solar Neutrinos in DUNE

1. Capozzi, Li, Zhu, Beacom, *"DUNE as the Next-Generation Solar Neutrino Experiment,"* Phys. Rev. Lett. 123, 131803, (2019) [arXiv:1808.08232]

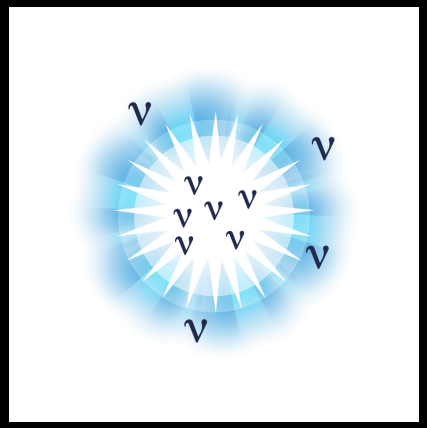
2. Same, see extensive *Supplemental Material*

3. Zhu, Li, Beacom, *"Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds,"* Phys. Rev. C 99, 055810 (2019) [arXiv:1811.07912]

Behold DUNE

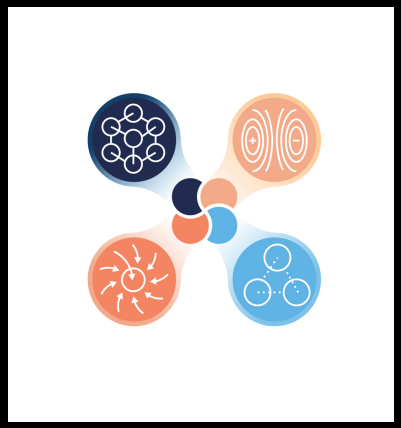


Origin of Matter



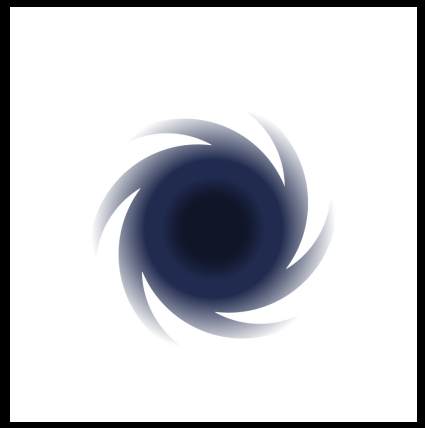
(Nu vs. Nu-bar)

Unification of Forces



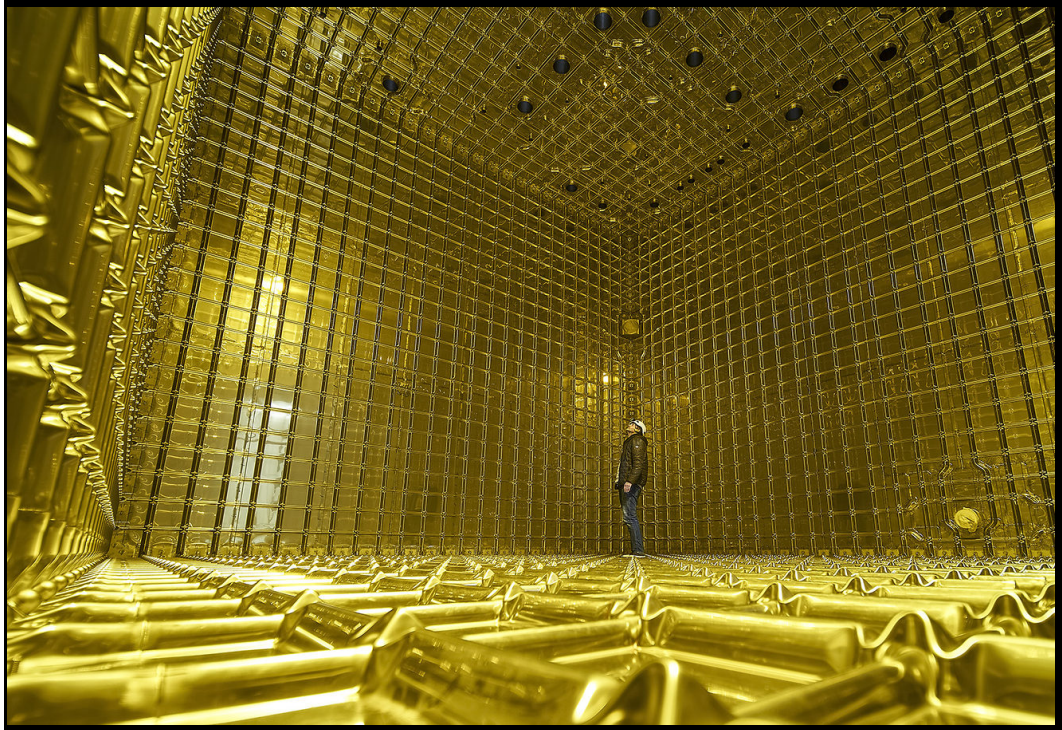
(Proton Decay)

Black Hole Formation



(Supernova Neutrinos)

DUNE Detector and Properties



Giant buckets of LAr:
Four modules, each 10 kton

Key assumptions:
Triggering, processing, etc.
Read out as TPCs (charge)
Energy threshold 5 MeV
Energy resolution 7%
Angular resolution ~ 25 deg

More details about technical requirements given below

Our Goals for DUNE-Solar

Particle Physics:

Best precision on sin^2
Best precision on dm^2
Powerful tests of new physics in comparison to JUNO reactor data

Astrophysics:

Best precision on 8B flux
Best precision on hep flux
Powerful tests of new astrophysics in comparison to other solar data

Must break essential degeneracies between the two

Our Strategy, Part 1

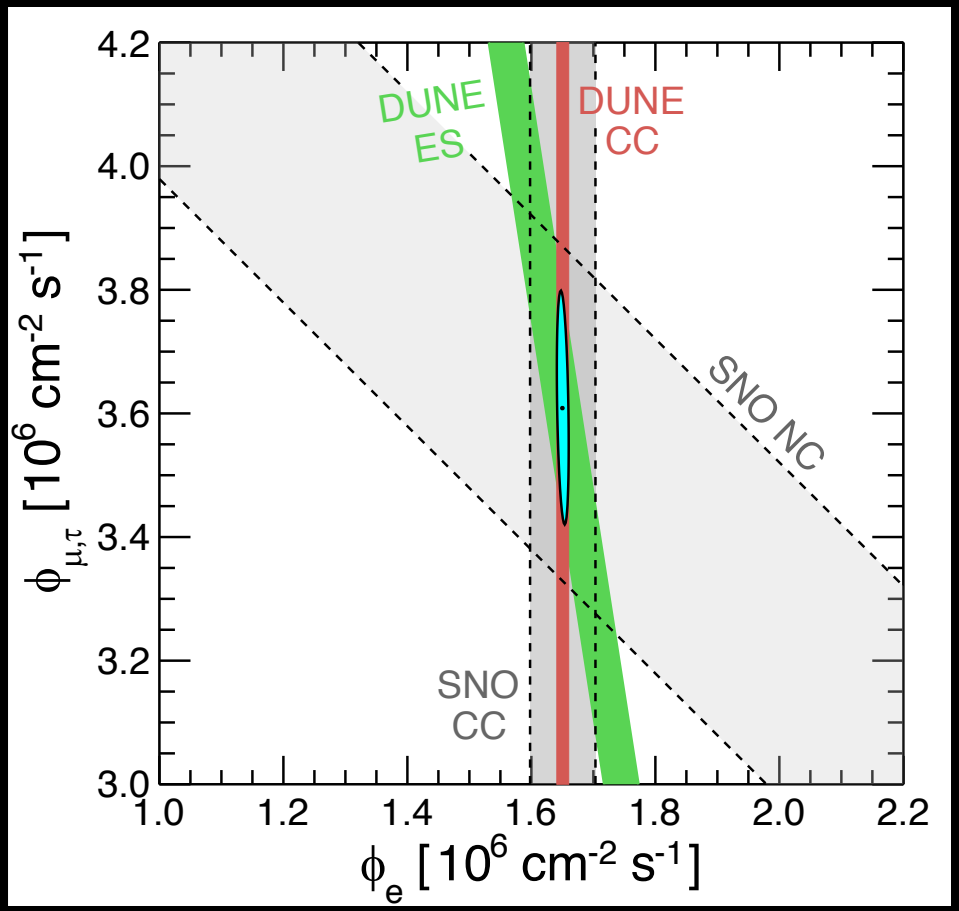
- The degeneracy between $\sin^2\theta_{12}$ and $\phi(^8\mathrm{B})$ can be broken by separately measuring two detection channels:

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^* , \qquad (1)$$

for which the rate scales as $R_{\mathrm{Ar}} \propto \phi(^8\mathrm{B}) \times \sin^2\theta_{12}$, and

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- , \qquad (2)$$

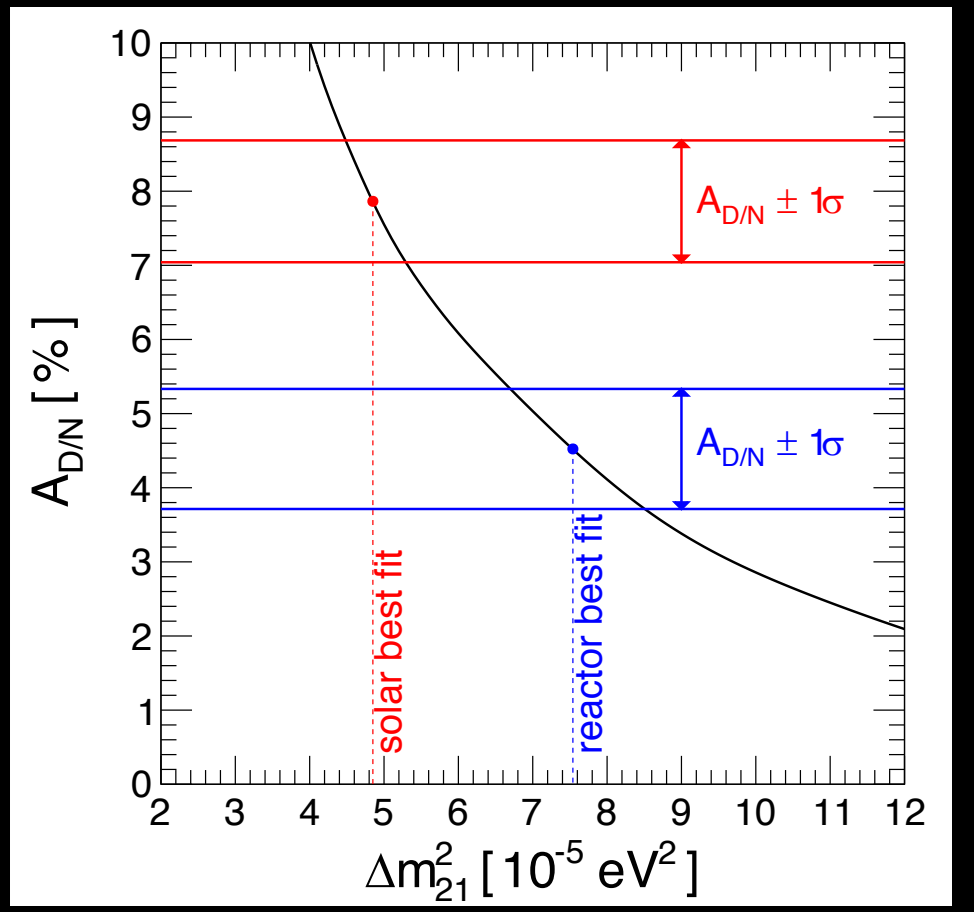
which scales as $R_e \propto \phi(^8\mathrm{B}) \times \left(\sin^2\theta_{12} + \frac{1}{6}\cos^2\theta_{12}\right)$.



Isolate sin^2, 8B flux with crossing (and huge statistics)

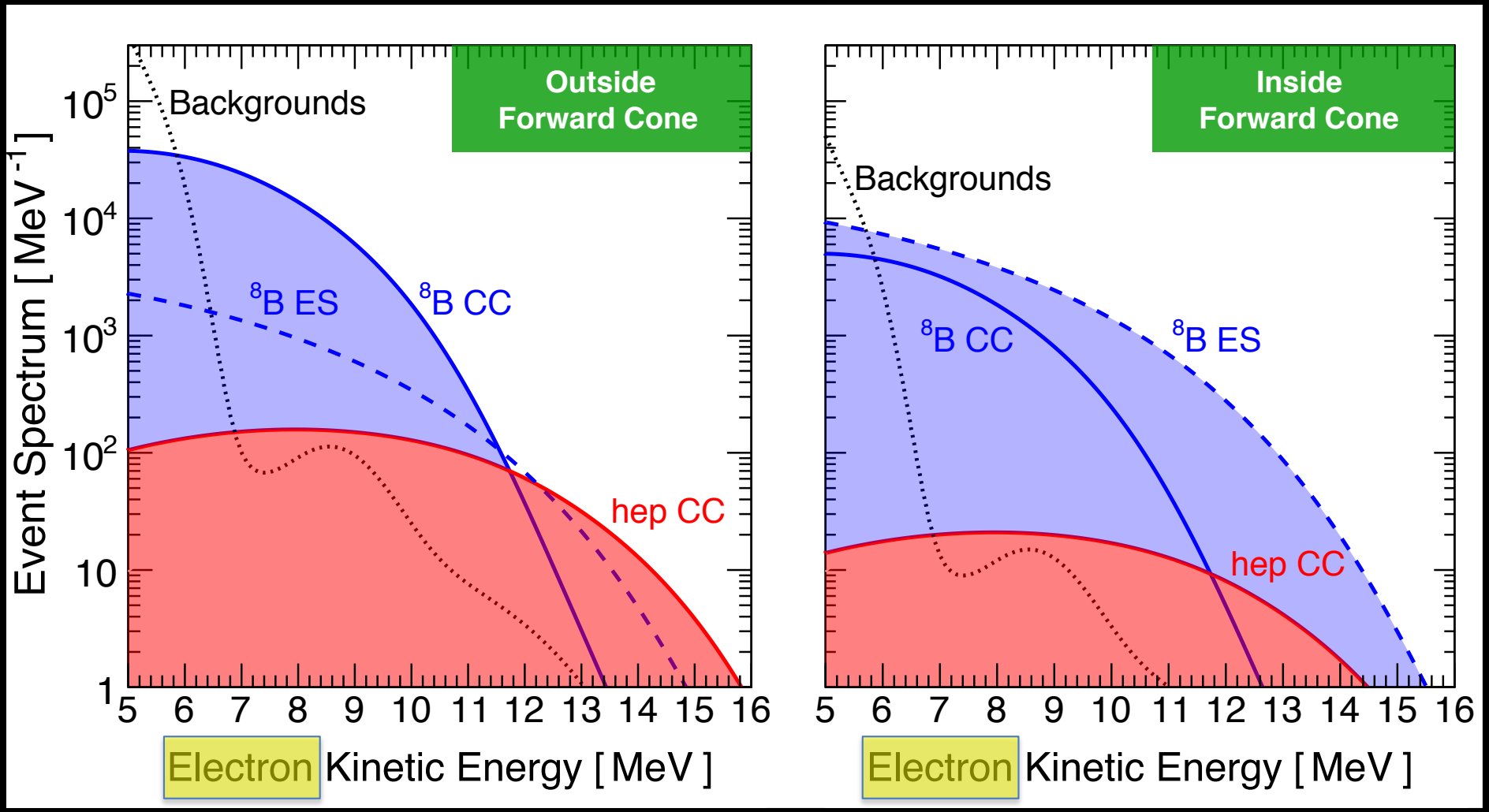
Our Strategy, Part 2

- Δm^2_{21} can be isolated through the day-night flux asymmetry, $A_{D/N} = (D - N)/\frac{1}{2}(D + N)$, which scales as $\propto 1/\Delta m^2_{21}$. For the solar Δm^2_{21}, an exposure of 100 kton-year, and using only events above 6 MeV and outside the forward cone, we expect $D = 3.04 \times 10^4$ and $N = 3.29 \times 10^4$ signal events, along with 0.83×10^4 background events in total. Considering only statistical uncertainties, $A_{D/N} \simeq -(7.9 \pm 0.8)\%$ ($\sim 10\sigma$). Though



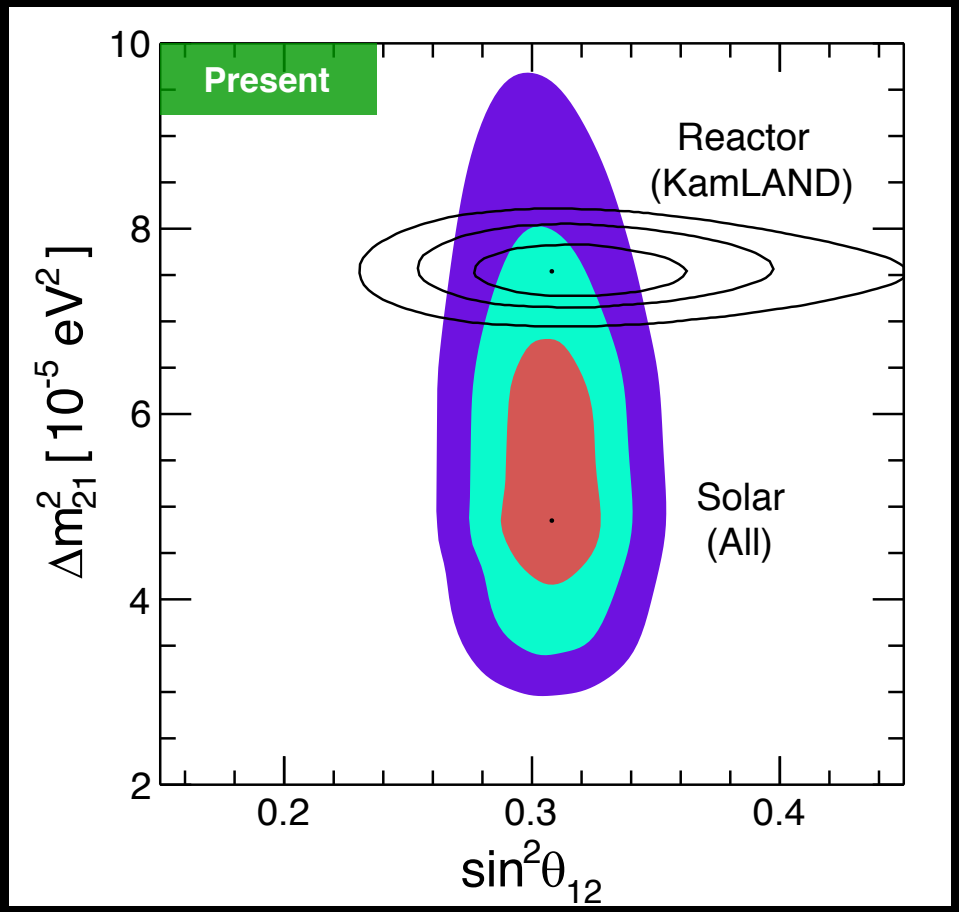
Isolate dm^2 with day-night effect (and huge statistics)

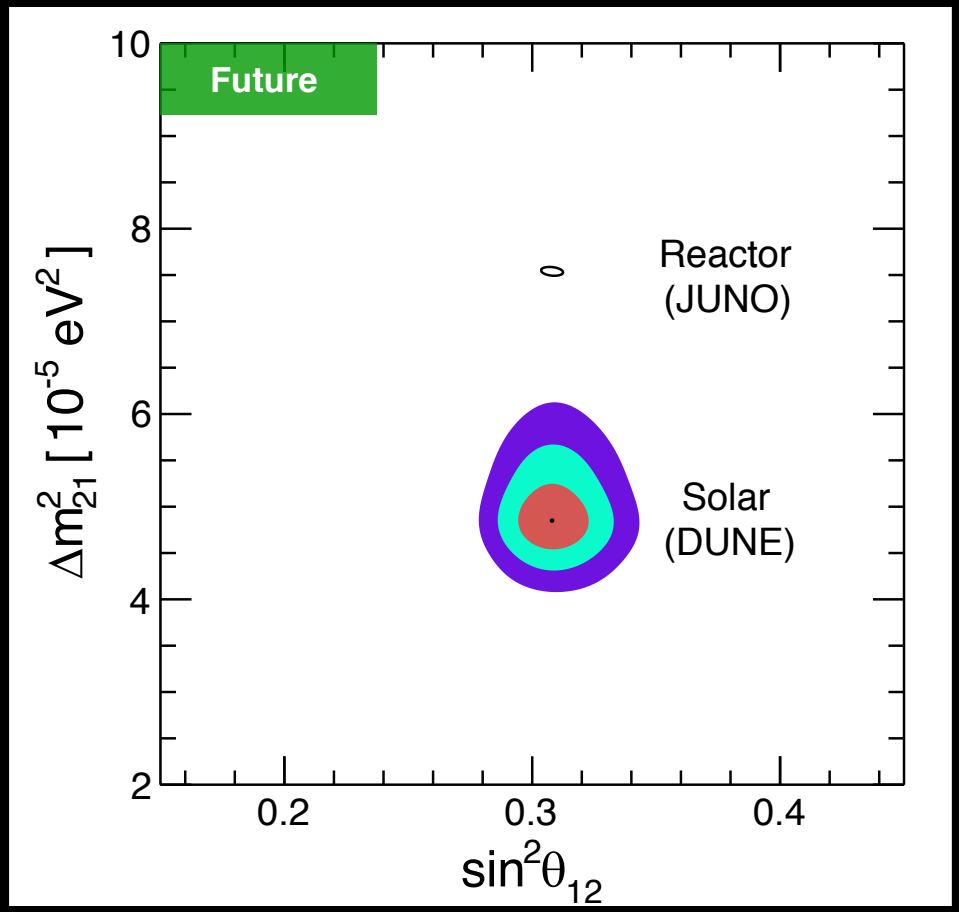
Calculated Spectra



In each panel, we assume only statistical separation

Calculated Sensitivity





In addition, 8B flux measured to ~ 2.5%, hep flux to ~ 11%

Arguments for DUNE-Solar

Importance:

Significant discovery opportunities in particle physics, astrophysics

Feasibility:

Our results suggest this is possible for relatively modest investments

Efficiency:

No other proposed detector is shown capable of meeting all goals

Urgency:

Otherwise, these goals may be forever unmet

Obstacle 1: Cross-Section Uncertainties

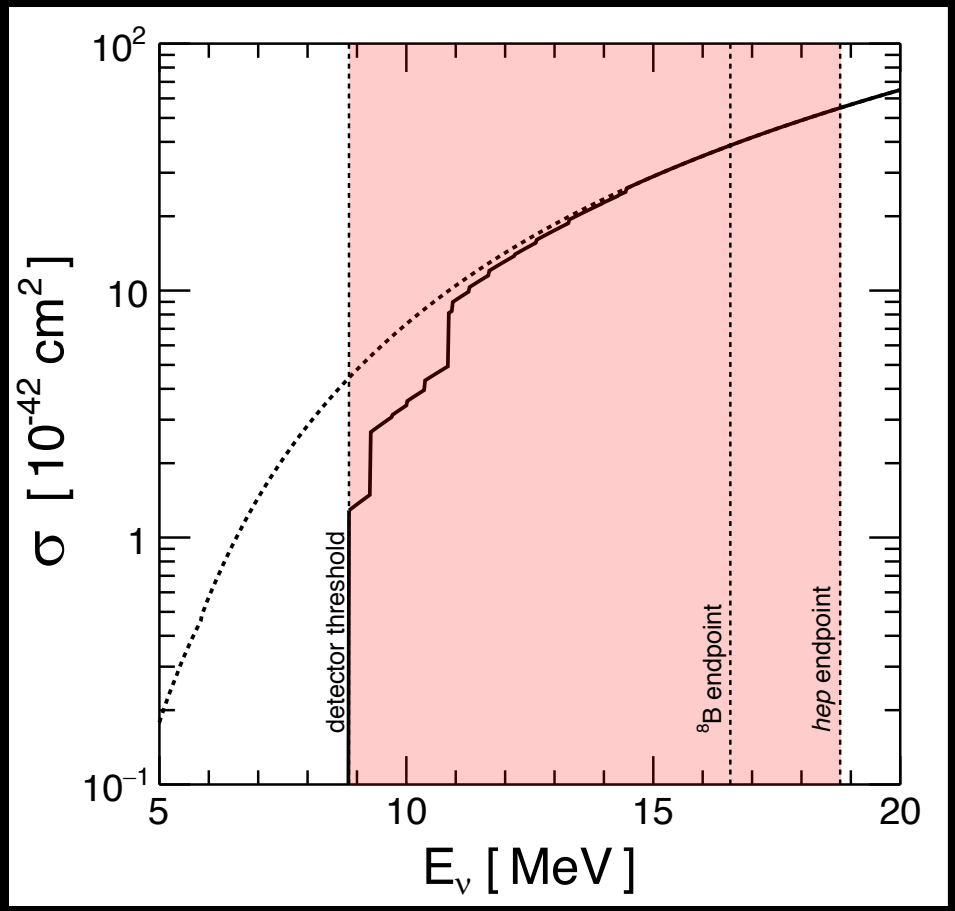
At leading order, the total cross section is

$$\sigma(E_\nu) = \sum_i \frac{G_{F,\beta}^2 \left|V_{ud}\right|^2}{\pi} \left|\mathcal{M}_{o\to i}\right|^2 E_e^i \, p_e^i \, F(Z, E_e^i), \quad \text{(A2)}$$

For the final states we consider, the transition amplitudes squared can be expressed as

$$\left|\mathcal{M}_{o\to i}\right|^2 = B_i(\mathrm{F}) + B_i(\mathrm{GT}), \quad \text{(A3)}$$

- Day-Night independent of uncertainties
- Detailed review of cross section, plus a sketch of how to measure it at a stopped-pion source, in S.M. of our PRL



Uncertainty ~ 10%; best outcomes if we push to < 1%

Obstacle 2: Detector Response

Reaction identification

If we could tag nuclear gammas, we can identify

nu-e + 40Ar → e- + 40K*, 40K* → 40K + gamma

to reduce backgrounds

Energy measurement

If we could tag nuclear gammas, we can reconstruct the neutrino energy (good for signal) and reduce backgrounds

Energy resolution

If energy resolution was good, we can reduce backgrounds

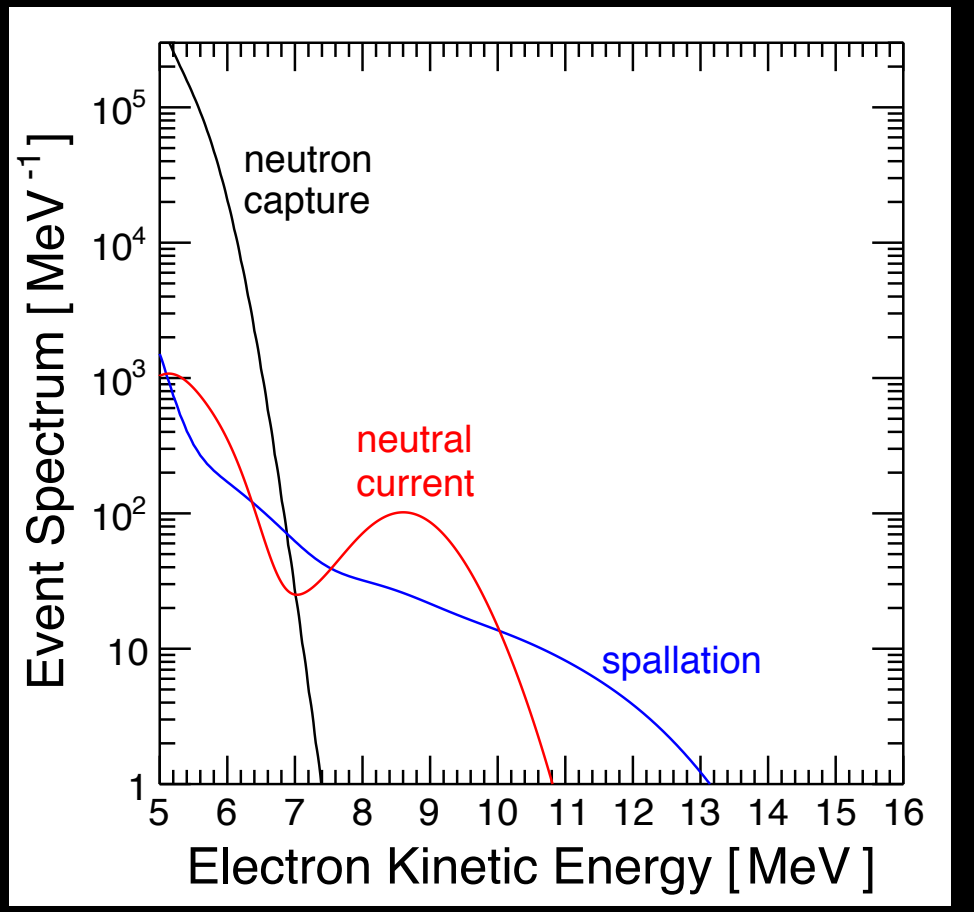
We made very conservative assumptions

Obstacle 3: Detector Backgrounds

~ 40 cm H_2O shielding would reduce neutrons by ~ 4×10^3

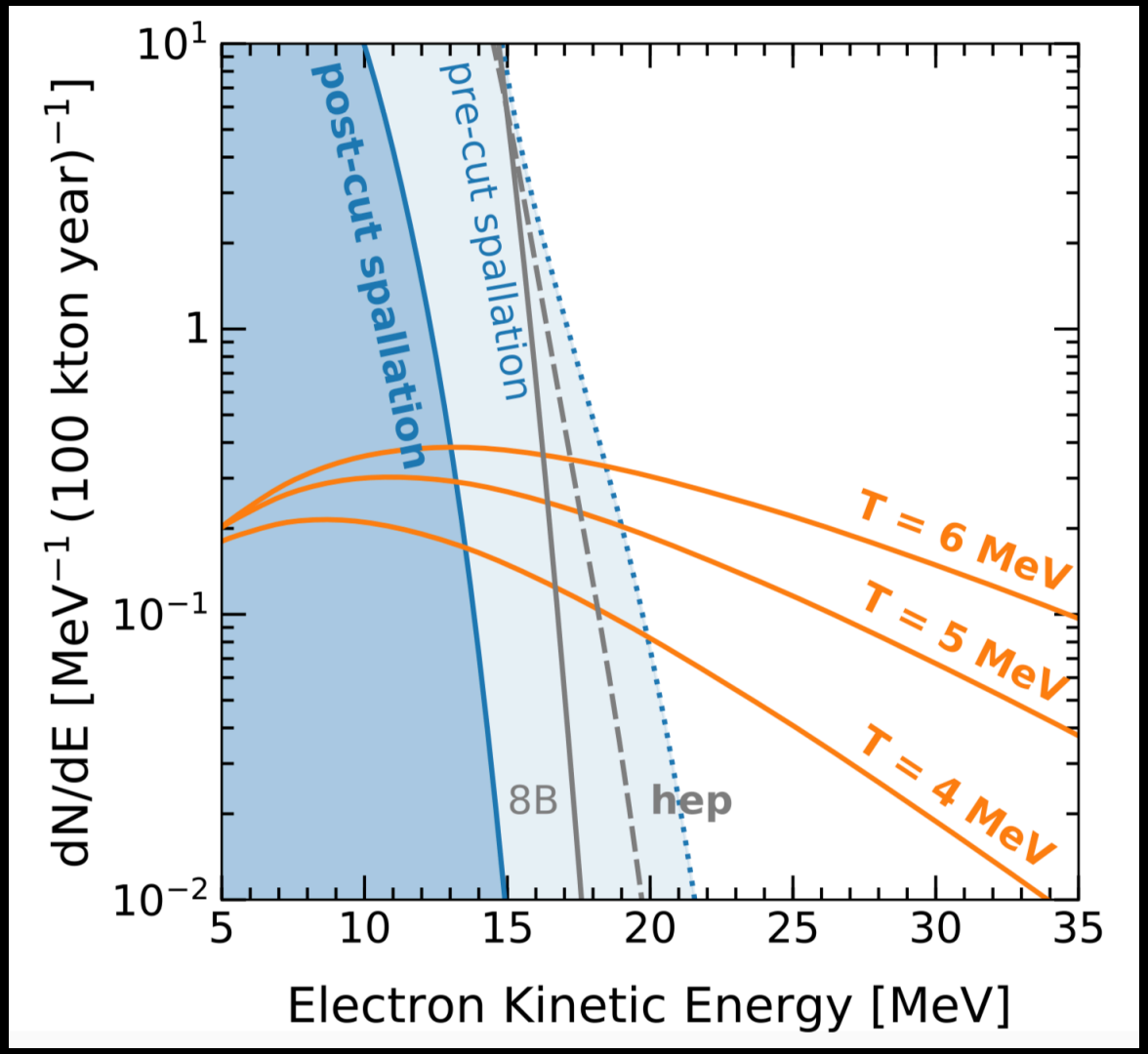
Spallation is very controllable

Extensive studies of low-energy backgrounds in our PRC article



Backgrounds fall very steeply with energy

Side Note: DSNB in DUNE



Zhu, Li, Beacom (2019)

Solar neutrinos become the primary background

Ongoing Work on Solar Neutrinos in DUNE

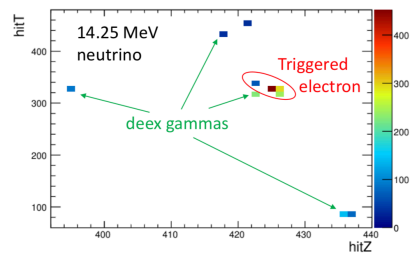
Many parts, general and solar, led by many DUNE experimental groups, including:

1. Reconstruction and solar sensitivity (Duke group, Kate Scholberg et al.)
2. Radon-induced backgrounds (SDSMT group, Juergen Reichenbacher et al.)
3. Neutron-capture backgrounds (Sussex group, Simon Peeters et al.)

More Optimism: Reconstruction

Low-E Neutrino Topology (ν_e CC)

- $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$ channel is sensitive to $\varphi(\nu_e)$
  - Scattering to the ground state is forbidden
  - So deex gammas accompany signal

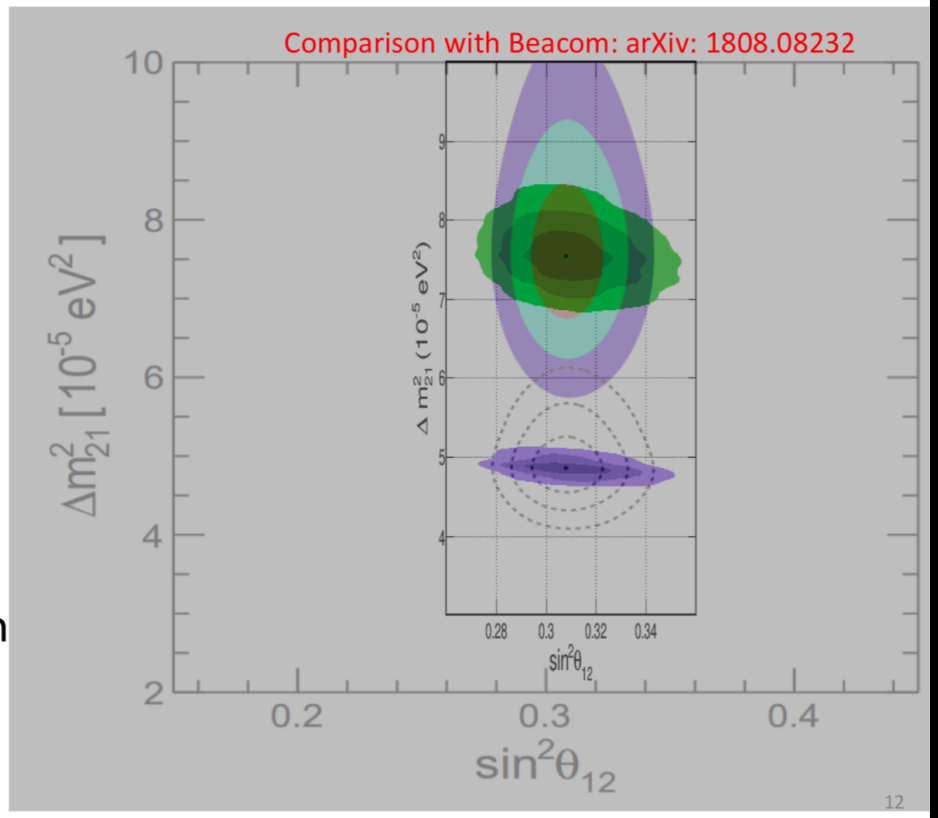


- Event topology is simple en
  are rare
  - Electron and gamma reconst

Dan Pershey (Duke) talk at
Background Mitigation Strategies Workshop,
https://indico.fnal.gov/event/43870/
July 2020

Comparison with Theoretical Sensitivity Predictions

- Our sensitivity to Δm^2_{21} is quite strong compared to theorists' predictions
- Adding η as a fitting variable ends up giving us a great sensitivity boost
  - All the little ripples in osc prob collectively pull the fits
- Can push current tension between SNO/SK and KamLAND up to 10σ

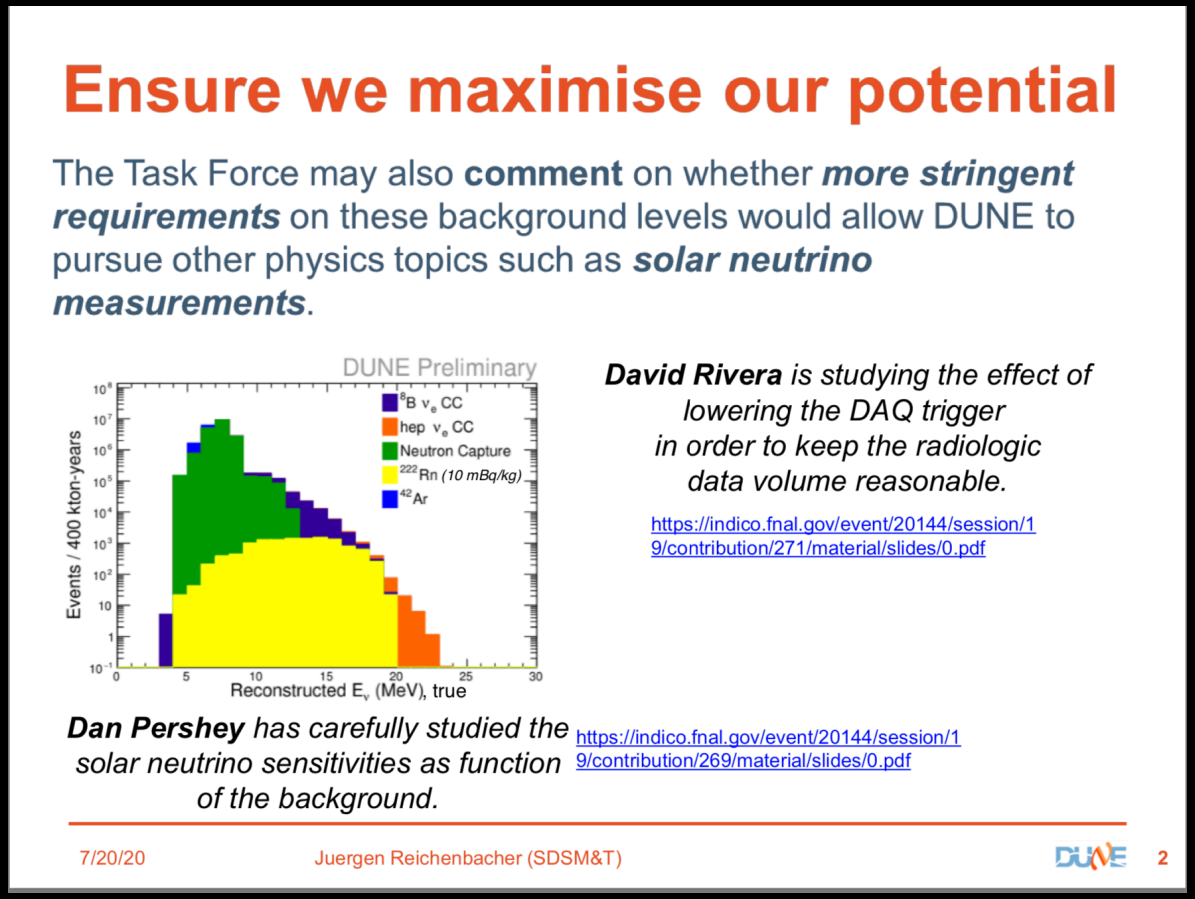


This is great!

More Pessimism: Radon

There is a nasty cross section for 40Ar(alpha,gamma) that is activated by alphas from 222Rn

However, this is only important if the 222Rn levels are *far* above those for SK, SNO



Juergen Reichenbacher (SDSMT) talk at Background Mitigation Strategies Workshop, https://indico.fnal.gov/event/43870/ July 2020

More Uncertainty: Shielding

Most dangerous background is neutrons from the walls undergoing capture in the detector volume

Shielding could kill this, but people too easily say, “Impossible!”

Our calculations show that just filling in the waffle holes would give a big benefit; could used boxed water, fireproof plastic pellets, etc.

This needs further investigation

Concluding Remarks

- With new liquid-argon detectors, we can lead exciting new solar-neutrino studies, opening substantial discovery space in particle physics and astrophysics
- It is critical to DUNE's overall science program to succeed at measuring low energies well
- Lack of recent activity is a lack of experiments, not good questions

Solar Neutrinos: Is There a Future?

Yes