Recent results from the Sudbury Neutrino Observatory

XIX International Workshop on Neutrino Telescopes
February 19, 2021

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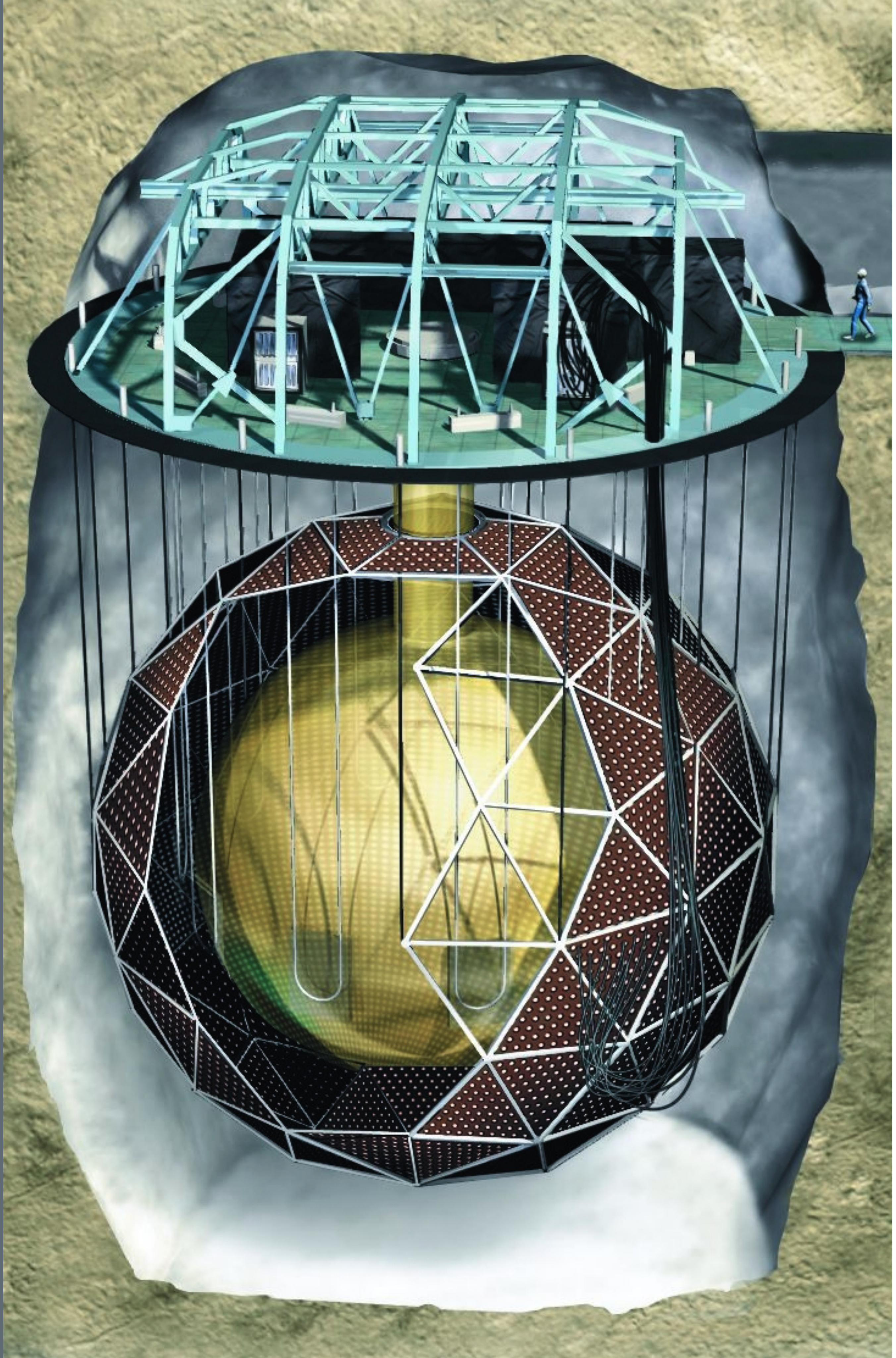
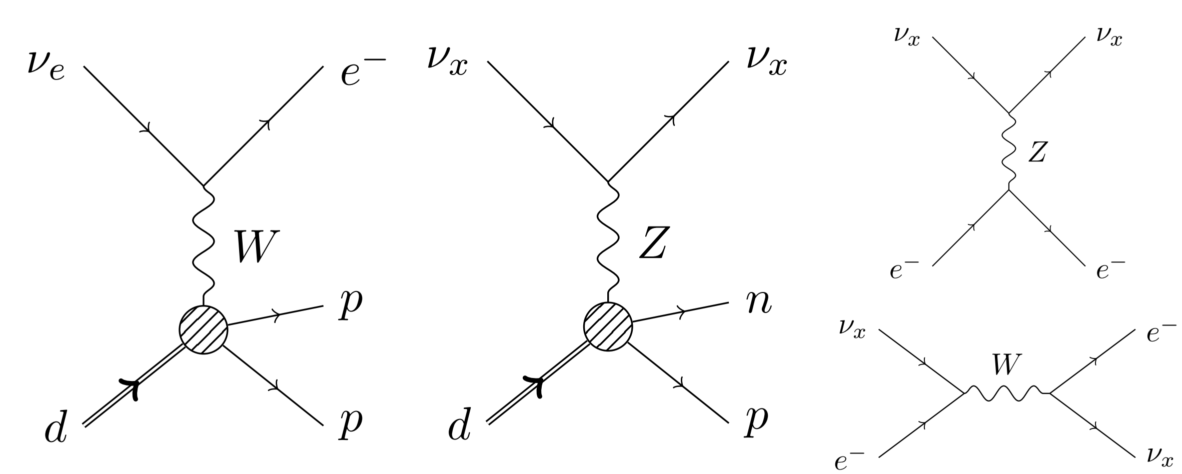
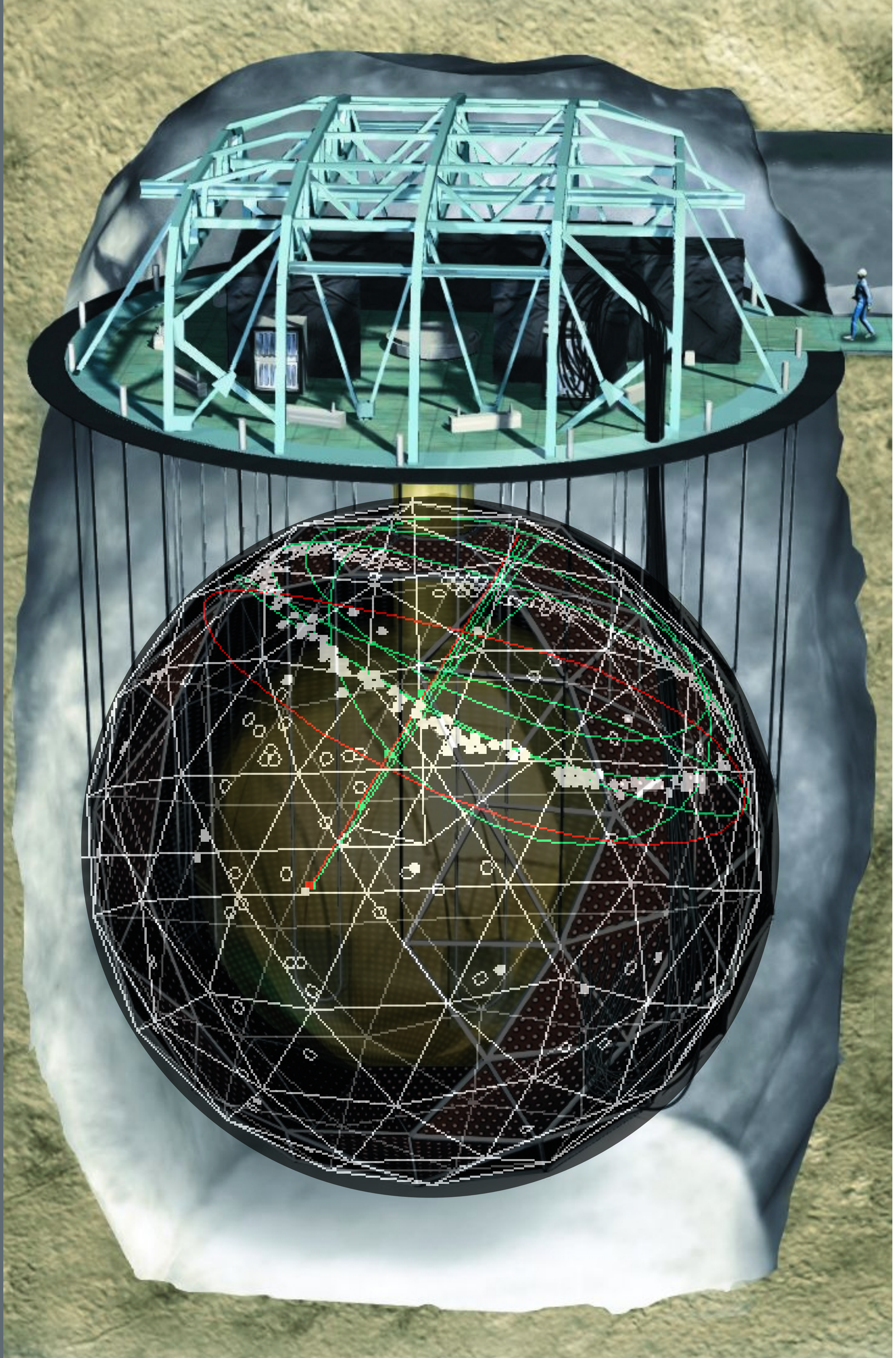


The Sudbury Neutrino Observatory Experiment

- Operated 1999 – 2006
- 5890 ± 94 mwe flat overburden
- 1 ktonne target volume
  - Phase I: D_2O
  - Phase II: D_2O + NaCl
  - Phase III: D_2O + ^{3}He counters
- Ring-imaging Cherenkov detector, ~9500 photomultiplier tubes



Charged Current (CC),
Neutral Current (NC), and
Elastic Scattering (ES) channels



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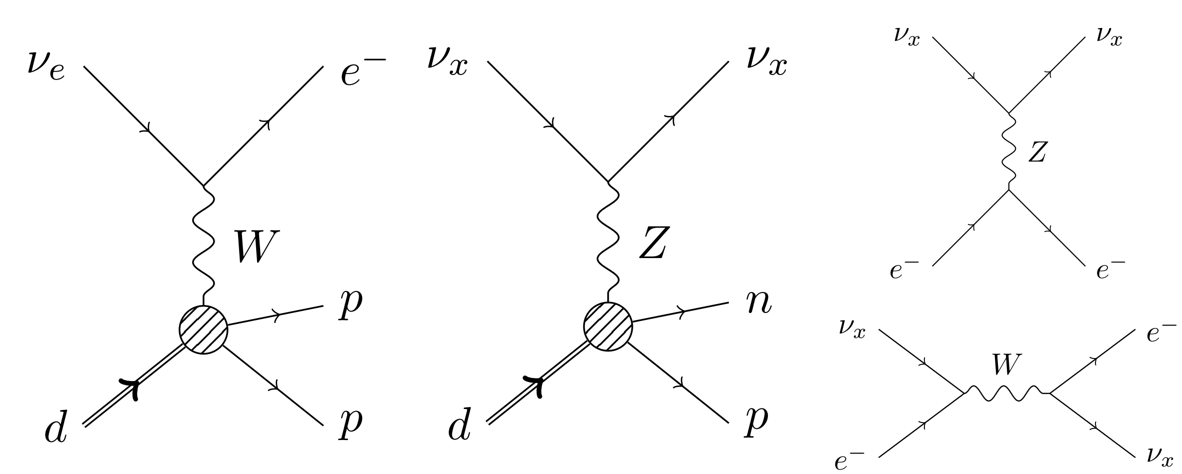

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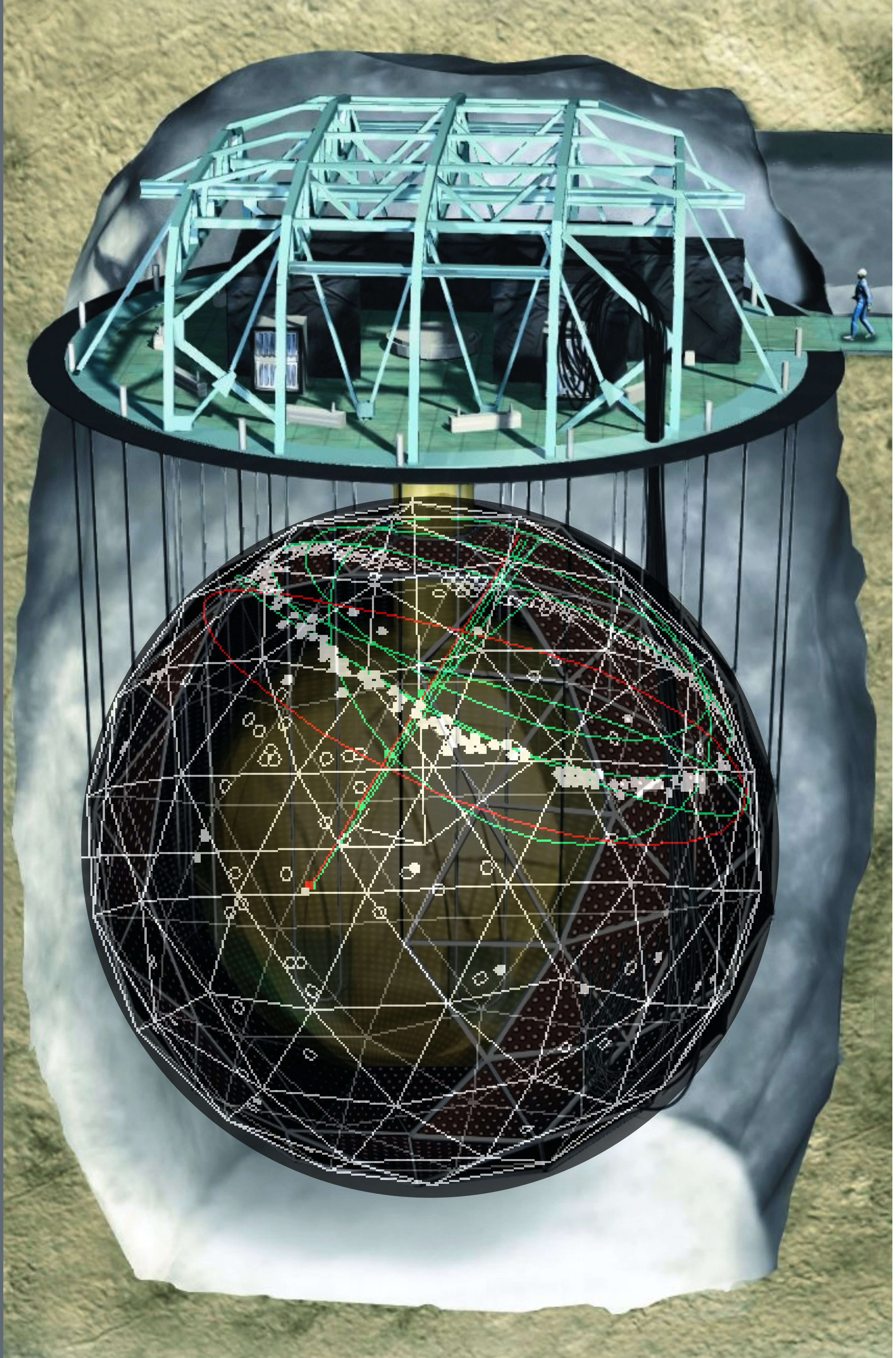

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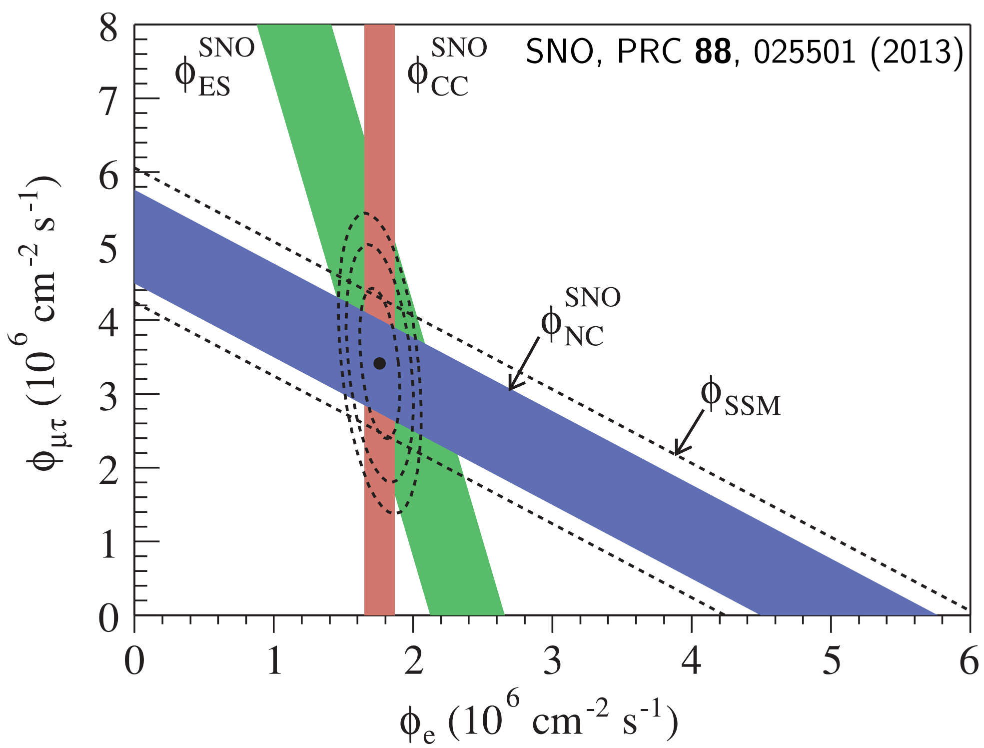

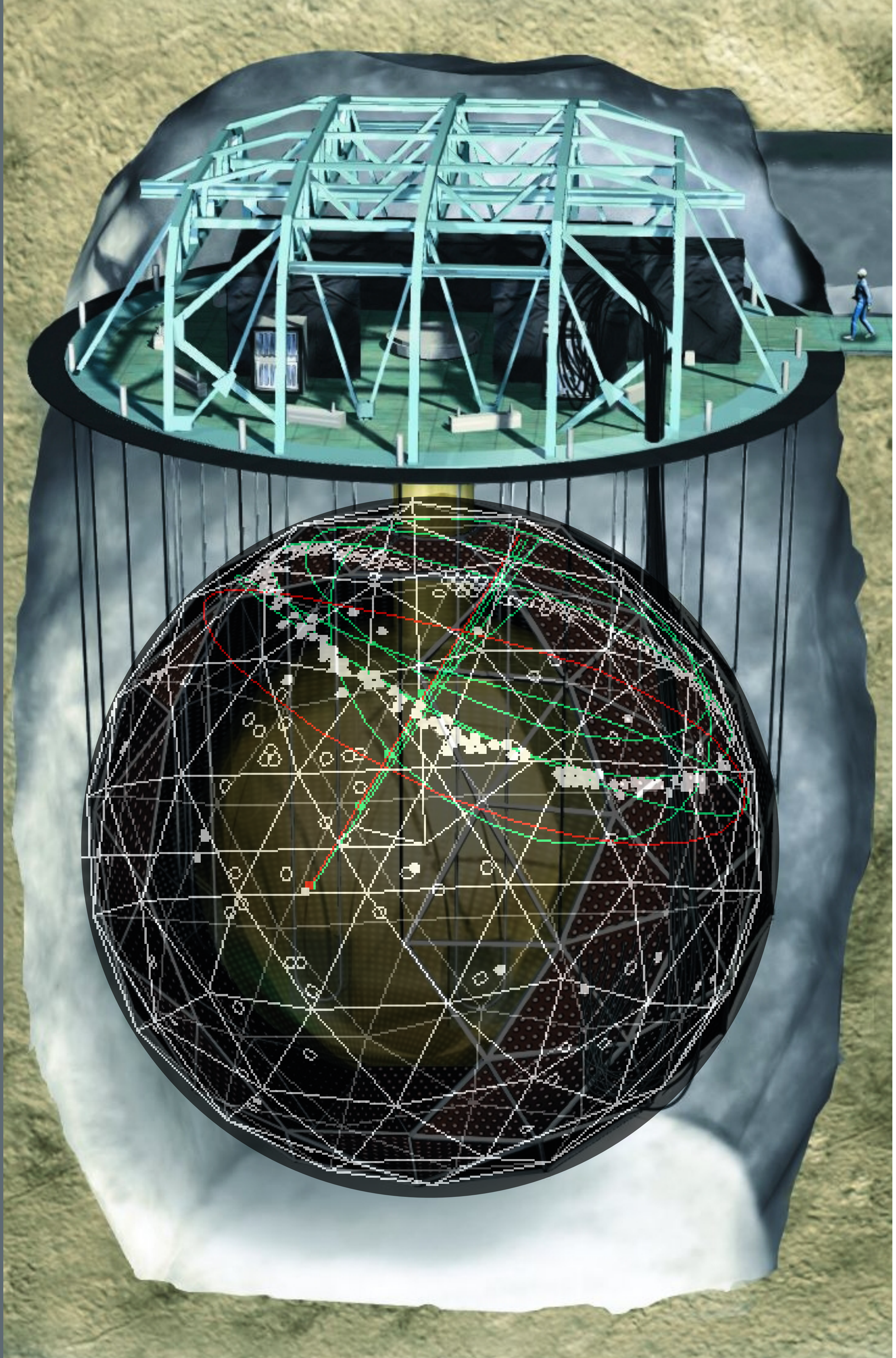

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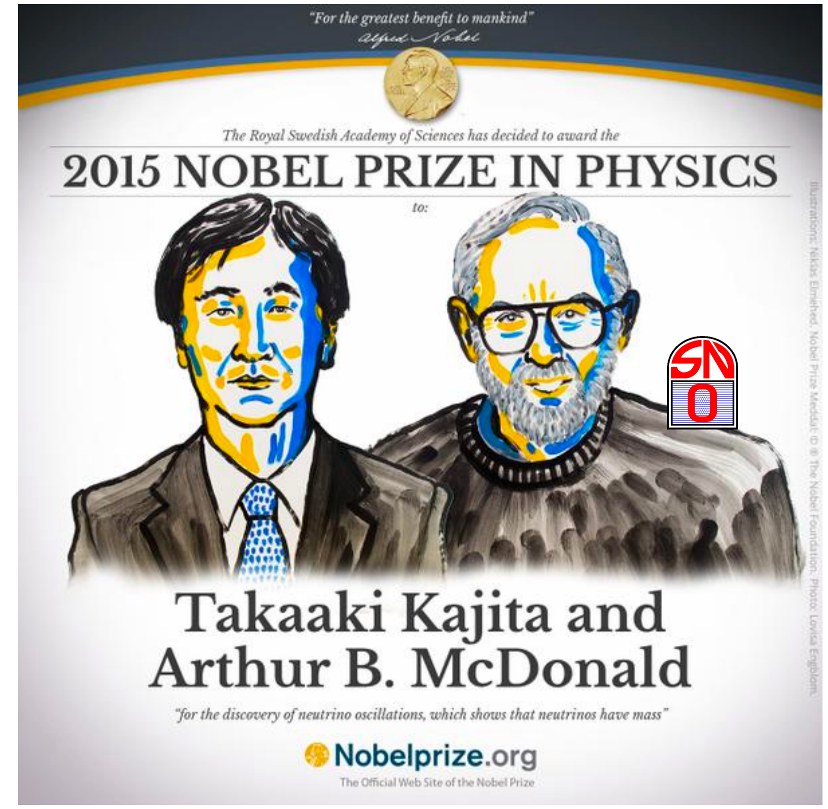
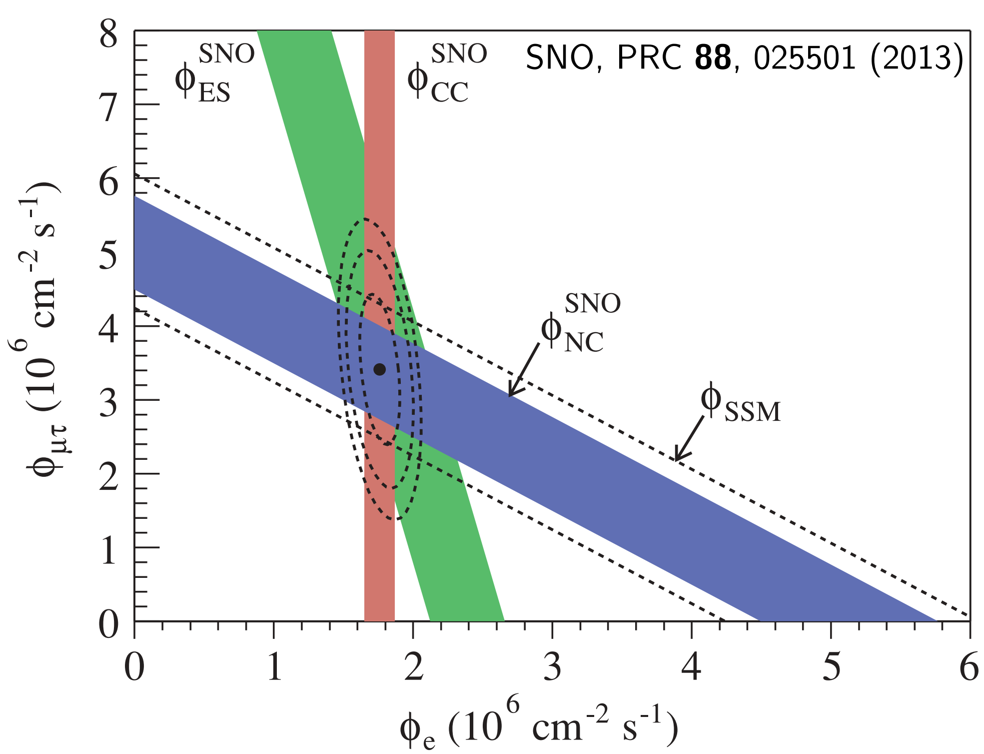
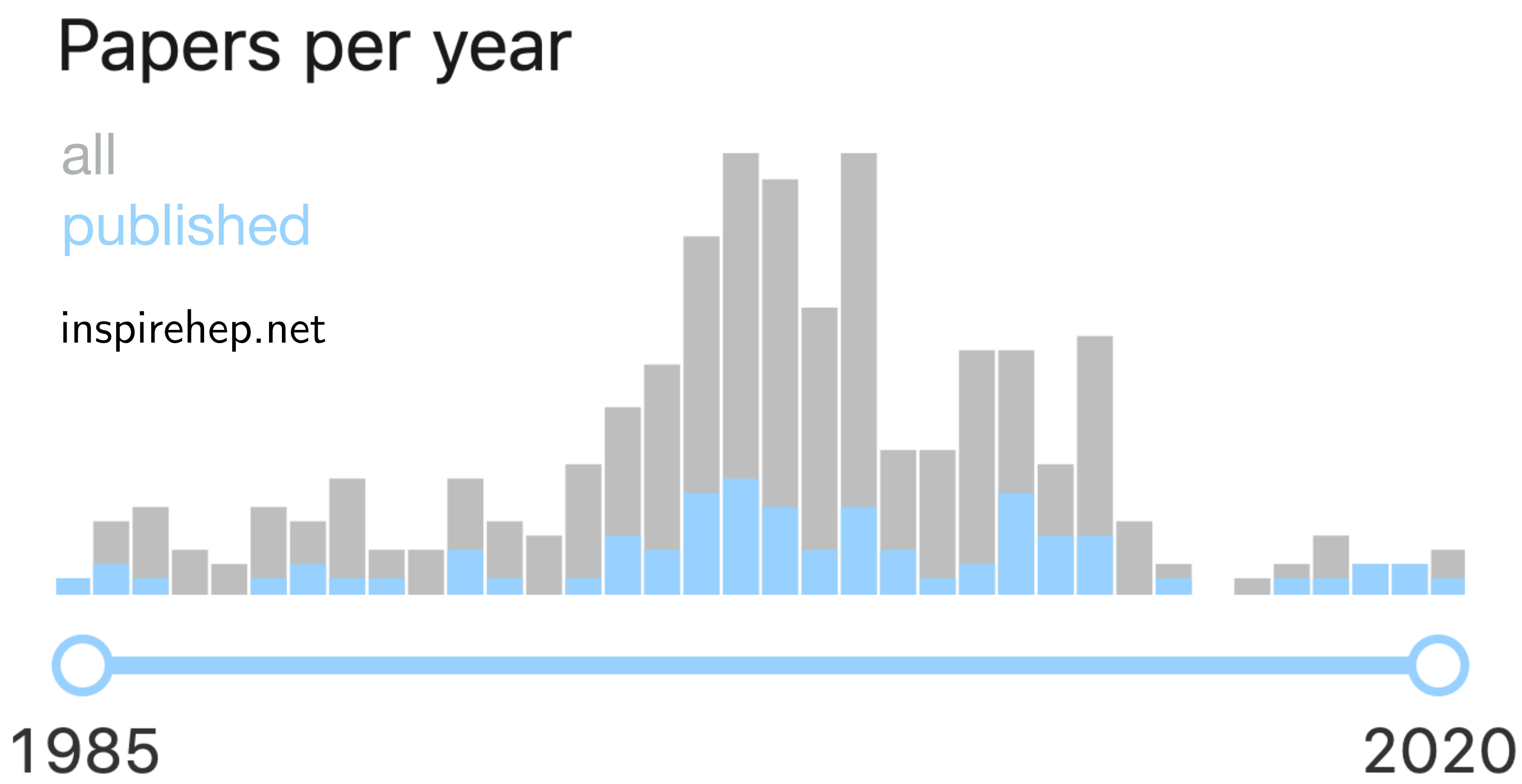


"for the discovery of neutrino oscillations, which shows that neutrinos have mass."





A few highlights:

H. Chen, PRL **55**, 1534 (1985)
"A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions."

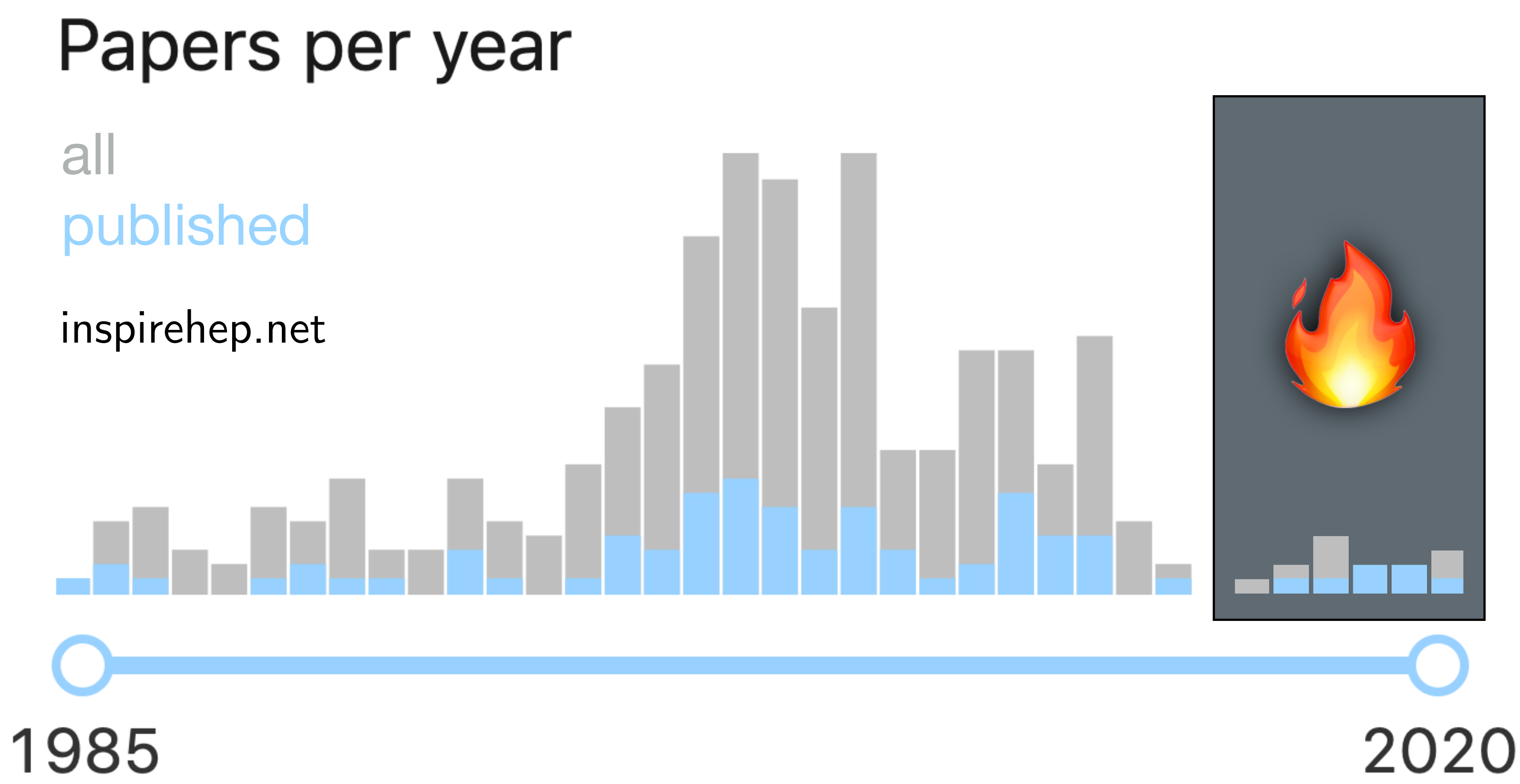
PRL **87**, 071301 (2001)
"The total flux of active ^{8}B neutrinos is ... in close agreement with the predictions of solar models."

PRL **89**, 011301 (2002)
Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory

PRL **92**, 181301 (2004)
"dissolved NaCl in the heavy water to enhance the sensitivity"

PRC **81**, 055504 (2010)
Low Energy Threshold Analysis of the Phase I and Phase II Data Sets of the Sudbury Neutrino Observatory

PRC **88**, 025501 (2013)
Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory



Recent results:

PRD **98**, 112013 (2018)
Tests of Lorentz invariance at the Sudbury Neutrino Observatory

PRD **99**, 032013 (2019)
Constraints on Neutrino Lifetime from the Sudbury Neutrino Observatory

PRD **99**, 112007 (2019)
Measurement of Neutron Production in Atmospheric Neutrino Interactions at the Sudbury Neutrino Observatory

PRD **100**, 112005 (2019)
Cosmogenic Neutron Production at the Sudbury Neutrino Observatory

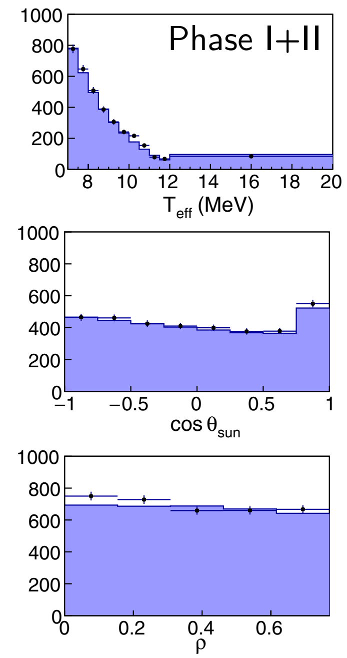
PRD **102**, 062006 (2020)
Search for hep solar neutrinos and the diffuse supernova neutrino background using all three phases of the Sudbury Neutrino Observatory

PRD **98**, 112013 (2018)

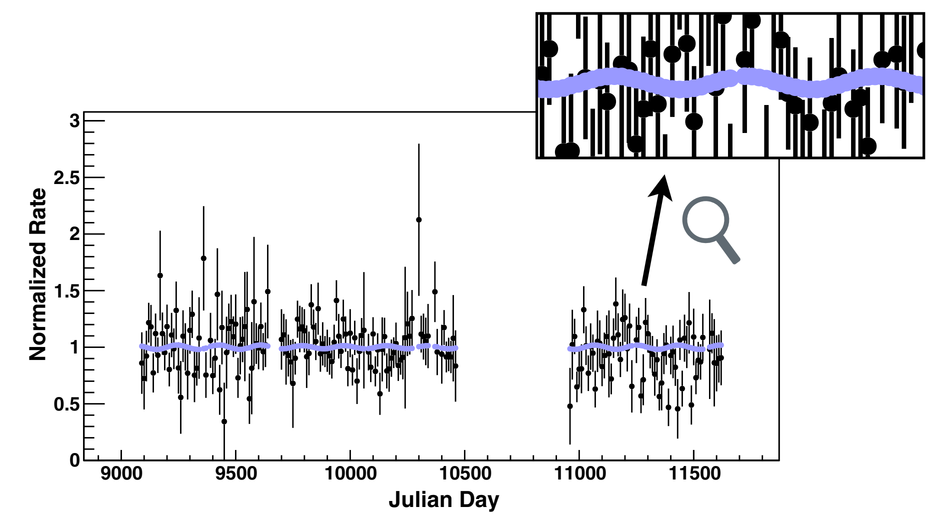
Lorentz Invariance

via Solar Neutrino Oscillations

- Search for energy/time dependent distortions in the solar neutrino oscillation probabilities
- Generic constraints on Fourier modes as well as Dirac-type Lorentz violating (LV) operators via the Standard Model Extension[1,2,3] framework
- *New* constraints on 38 LV parameters and *improved* constraints on 16 more



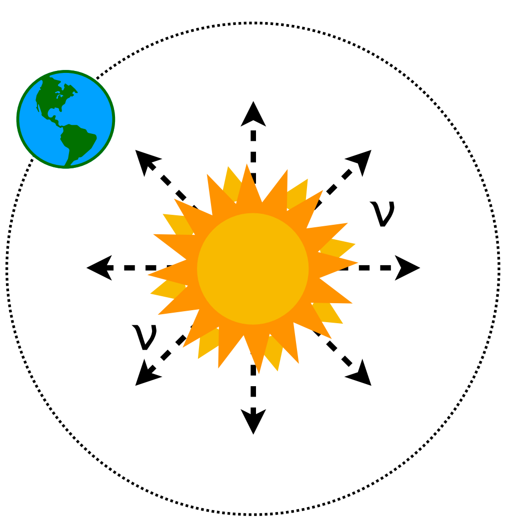
Fit for $E^2 \sin 2\omega t$ term

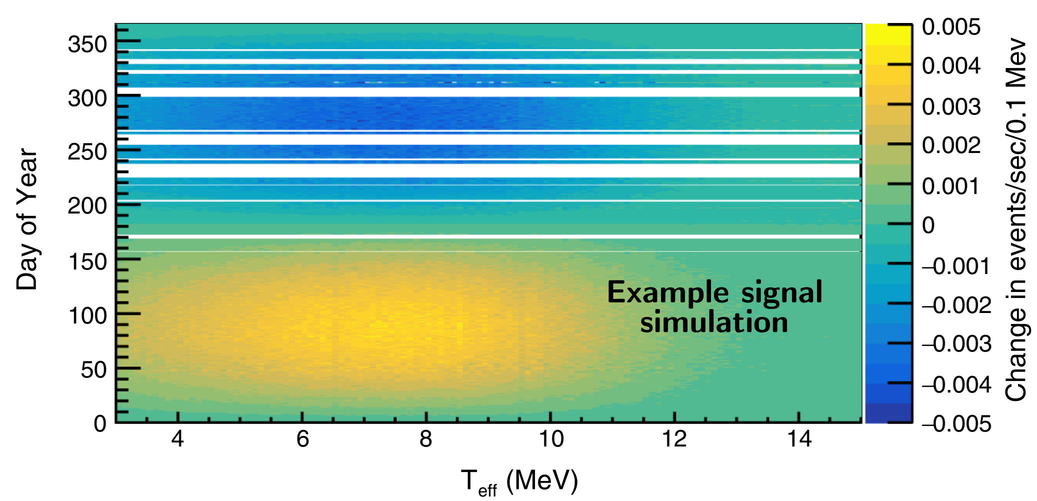


$$\delta P^{(1)}_{ee} = \mathfrak{Re} \sum_{jm} Y_{jm}(\hat{p})\left(E(a^{(3)}_{\text{SNO}})_{jm} - E^2 (c^{(4)}_{\text{SNO}})_{jm}\right)$$

E.g. $\frac{1}{2}\sqrt{\frac{3}{\pi}} \sin\Omega (c^{(4)}_{\text{SNO}})_{10} - \frac{1}{2}\sqrt{\frac{3}{2\pi}} \cos\Omega\, \mathfrak{Im}(c^{(4)}_{\text{SNO}})_{11} \quad \leftrightarrow \quad E^2 \sin\omega t$

Mode	LV signal
E	$7.0^{+7.2+5.9}_{-7.5-6.7}$ GeV^{-1}
$E \sin\omega t$	$0.0^{+7.2+2.1}_{-7.3-2.2} \times 10^{-1}$ GeV^{-1}
$E \cos\omega t$	$0.2^{+7.3+2.2}_{-7.4-2.3} \times 10^{-1}$ GeV^{-1}
E^2	$3.0^{+3.3+2.7}_{-3.4-3.1} \times 10^{2}$ GeV^{-2}
$E^2 \sin\omega t$	$0.7^{+6.4+1.7}_{-6.5-1.8} \times 10^{1}$ GeV^{-2}
$E^2 \cos\omega t$	$-0.2^{+6.5+1.9}_{-6.6-1.9} \times 10^{1}$ GeV^{-2}
$E^2 \sin 2\omega t$	$5.8^{+6.5+1.6}_{-6.4-1.8} \times 10^{1}$ GeV^{-2}
$E^2 \cos 2\omega t$	$-4.4^{+6.5+1.7}_{-6.6-1.8} \times 10^{1}$ GeV^{-2}





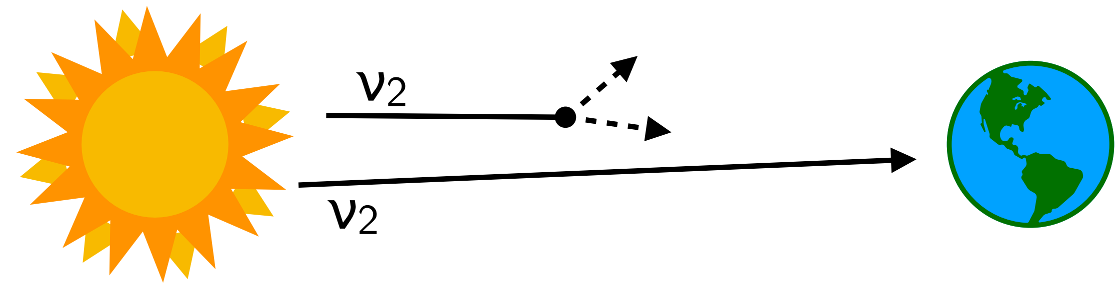
With no LV signal observed, new and improved constraints

[1]PRD **55**, 6760 (1997), [2]PRD **58**, 116002 (1998), [3]PRD **85**, 096005 (2012)

Neutrino Lifetime

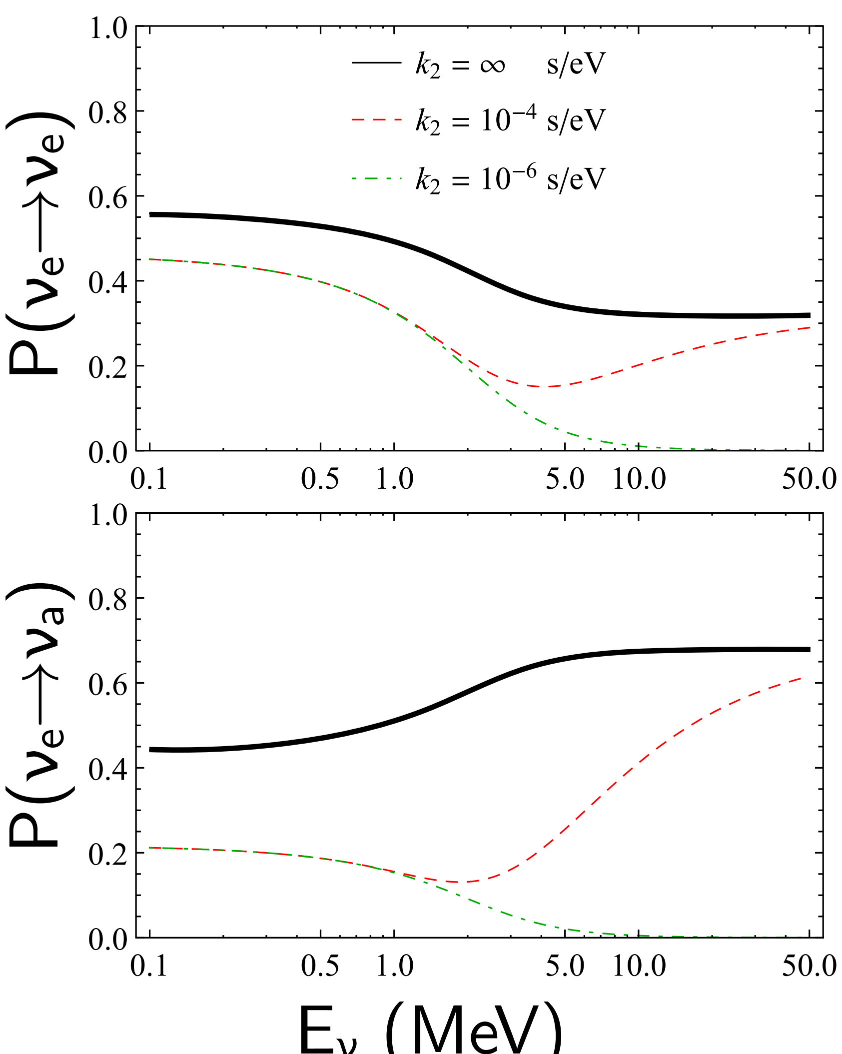
Solar Neutrino Decay

- Energy-dependent neutrino disappearance
- Induced by non-radiative neutrino decays to fully invisible final states
- New likelihood fit for ^{8}B survival probability, with floating $k_i = \tau_i / m_i$

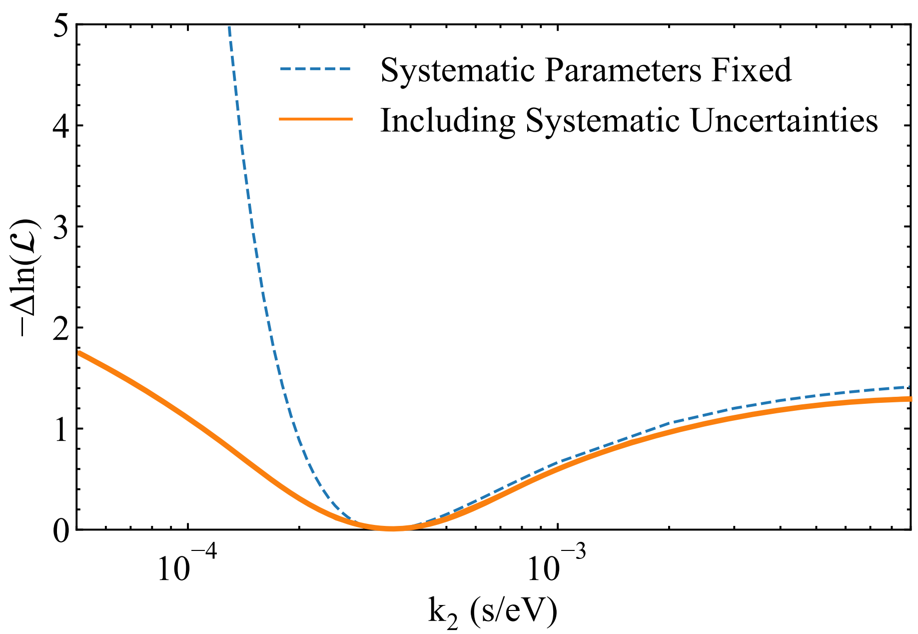


$$P_{ee} = \sum_i \psi_i |U_{ie}|^2 \qquad P_{ea} = \sum_i \psi_i |U_{i\mu}|^2 + \psi_i |U_{i\tau}|^2$$

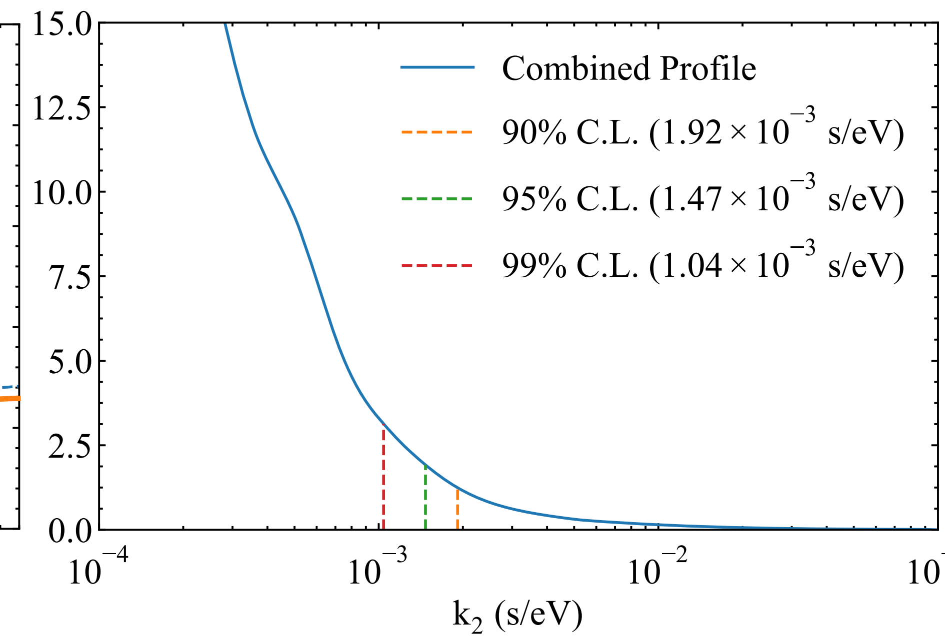
$$\psi_i \approx e^{-L/(Ek_i)} \phi_i = e^{-L/(Ek_i)} |\langle \nu_{mi}(V_e) | \nu_e \rangle|^2$$



SNO only



SNO + SuperK + Borexino + KamLAND + GNO/GALLEX/SAGE + Homestake



$k_2 > 8.08 \times 10^{-5}$ s/eV (90% CL) **$k_2 > 1.92 \times 10^{-3}$ s/eV (90% CL)** ★

Consistent with MSW oscillations and no decay

PRD **99**, 112007 (2019)

Neutron Production

via Atmospheric Neutrino Interactions

- Atmospheric neutrino–induced neutrons
- Measured multiplicity as a function of energy and interaction channel
- Leverage high neutron detection efficiency: 15% (Phase I), 40% (Phase II)
- Probe GeV-scale interaction physics
  - Proton decay search backgrounds
  - ν vs. $\bar{\nu}$ neutron production
  - Modeling of neutrino-nucleus cross sections, final state interactions (FSI)

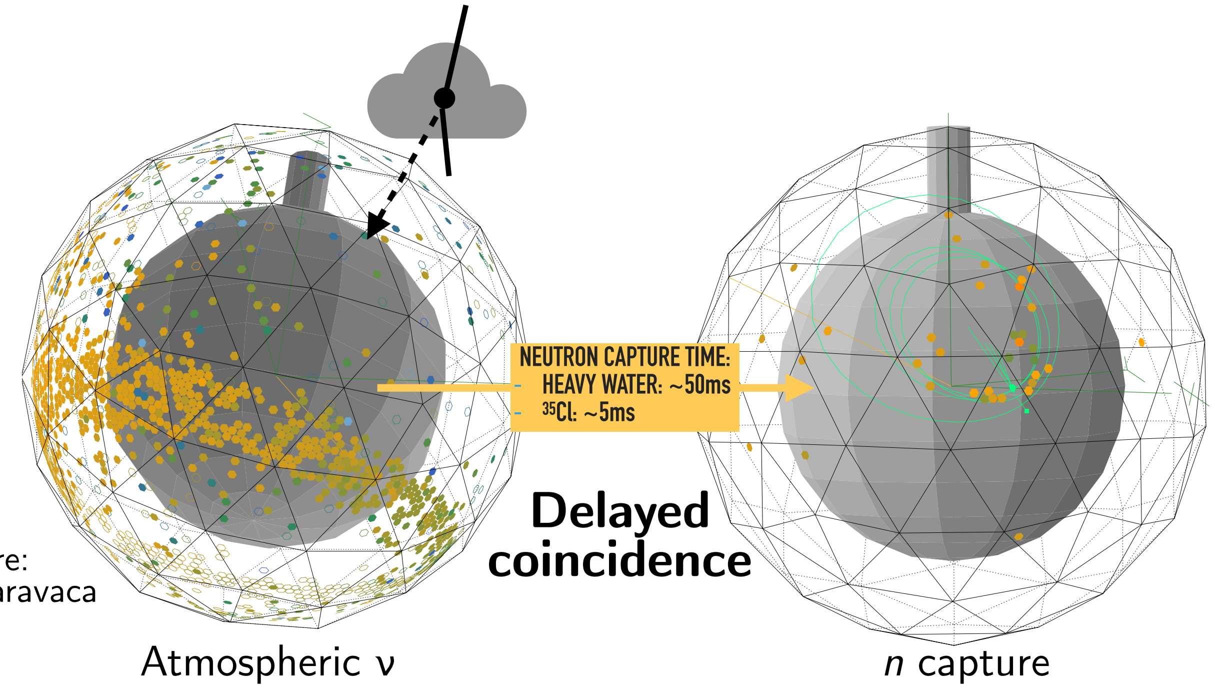
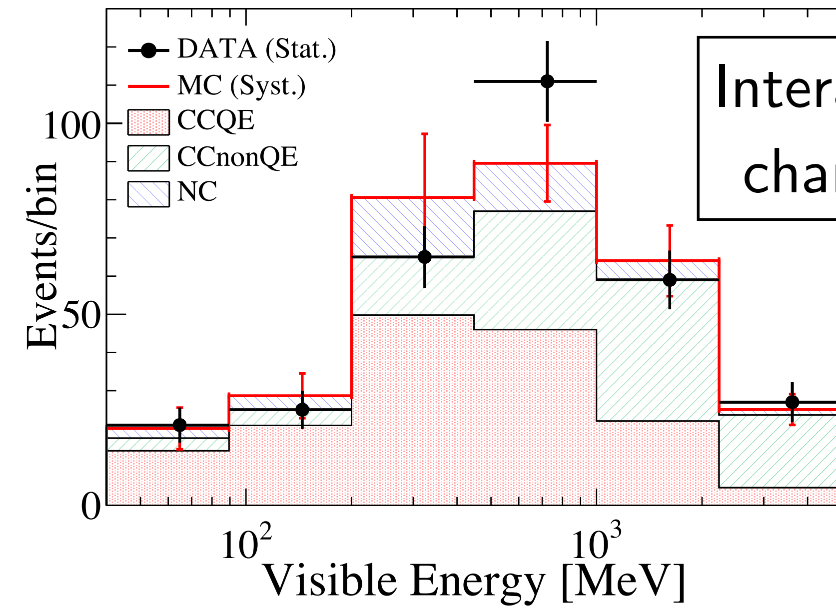
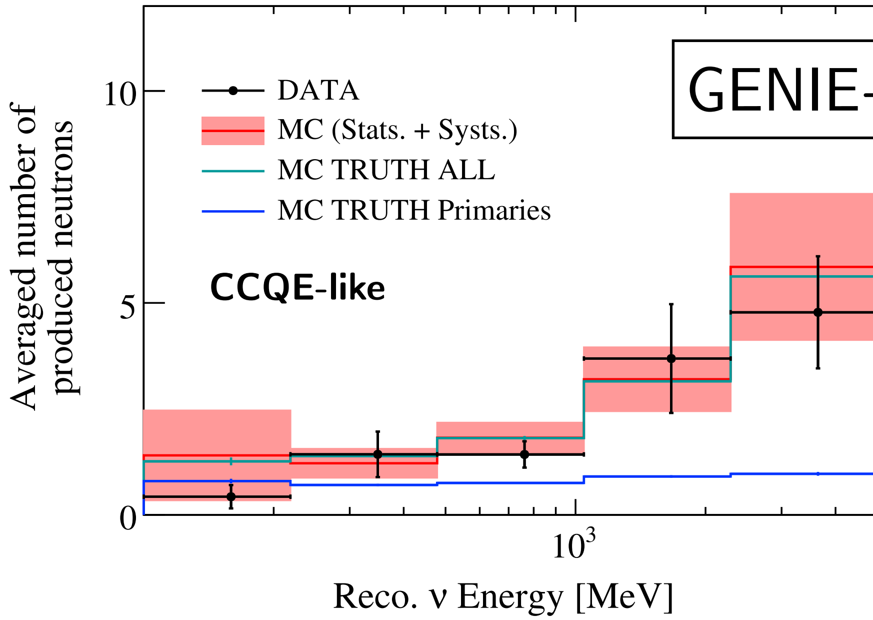
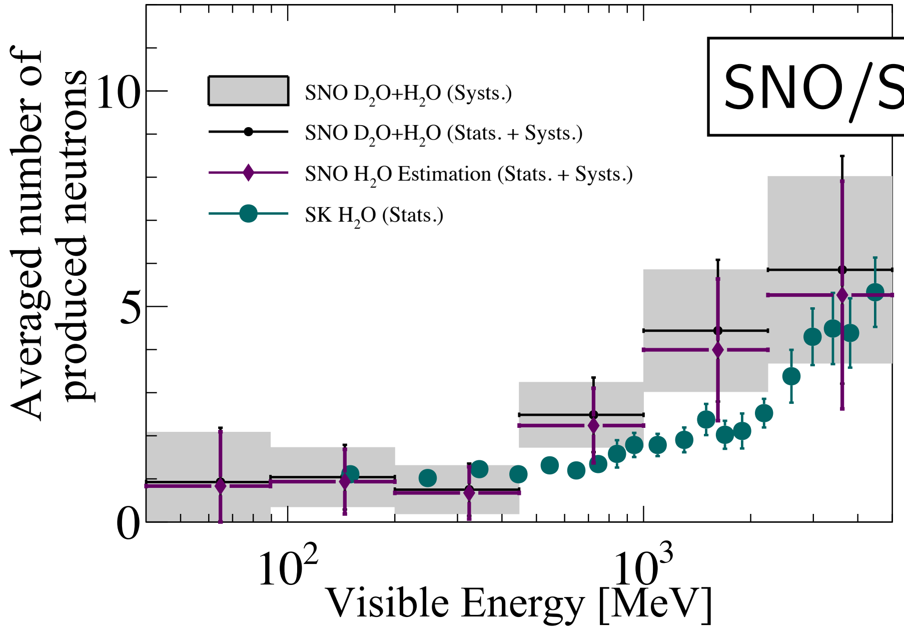


Figure: J. Caravaca







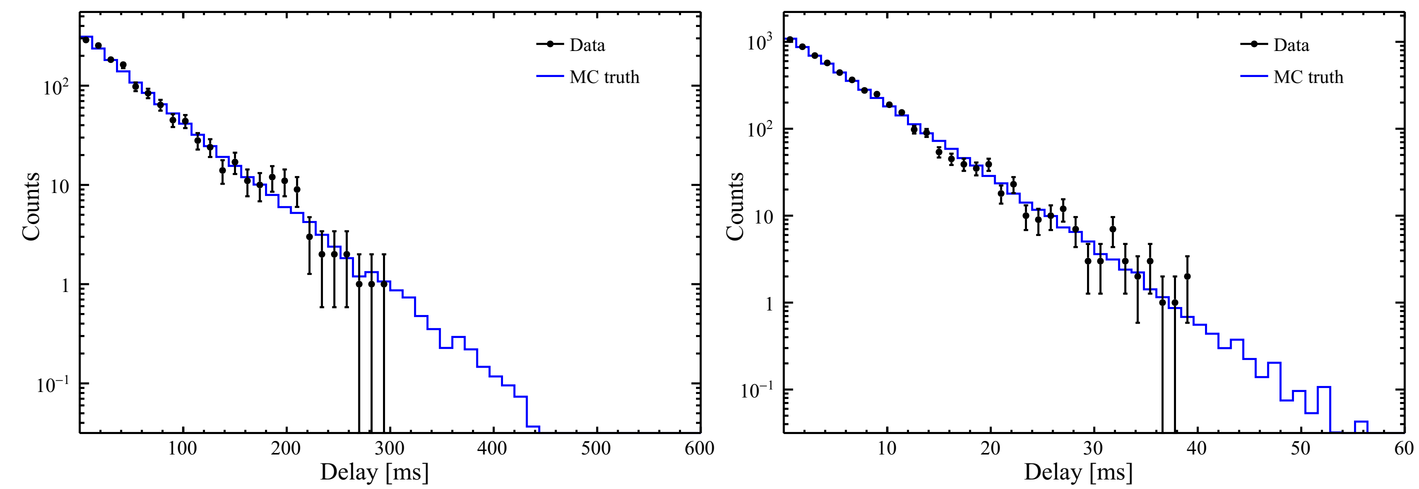
PRD **100**, 112005 (2019)

Neutron Production

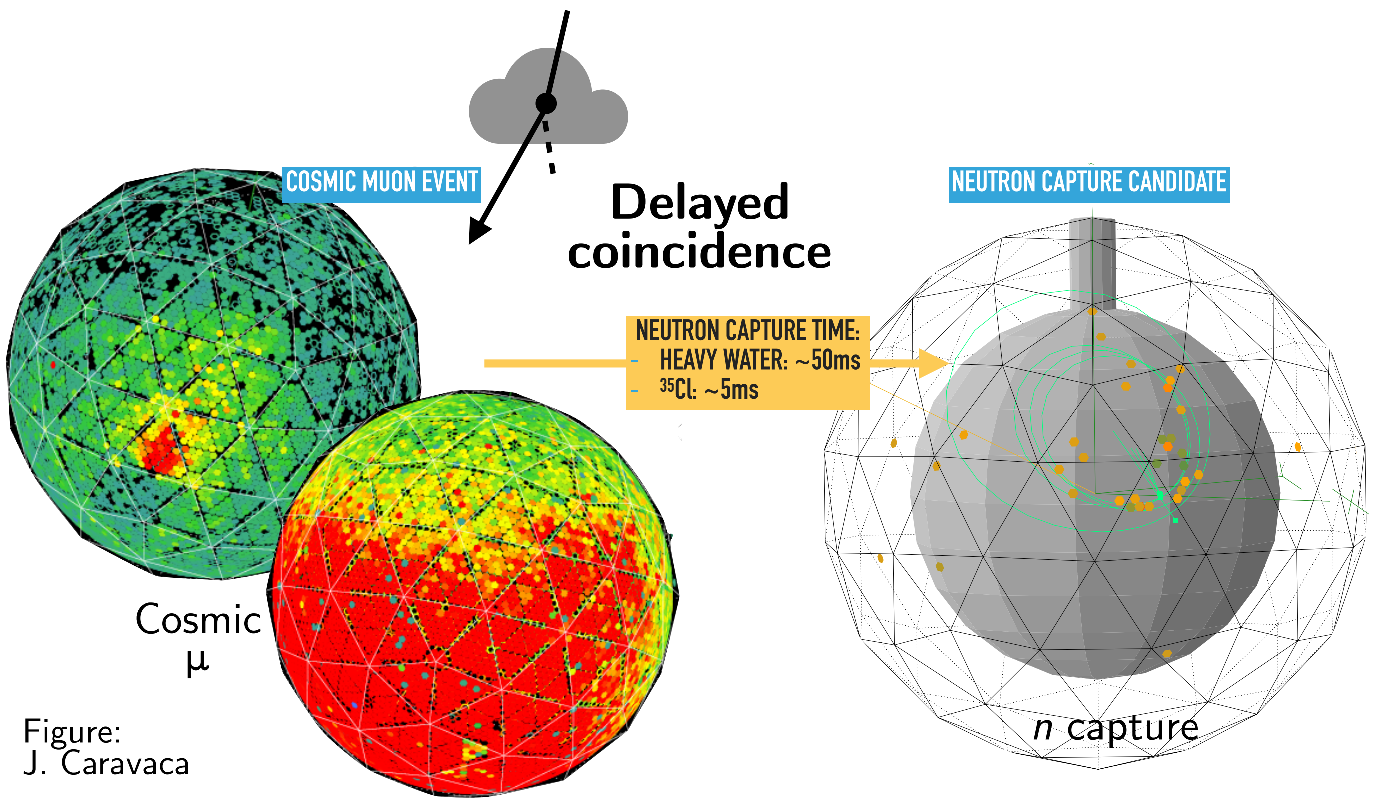
via Cosmic Muon Interactions

- Cosmic ray muon–induced neutrons
- (~70 μ/day down at 6800')
- First measurement in D_2O
- Deep-underground location at SNOLAB
- Constrains nuclear models and backgrounds for rare-event searches
- Input for interaction modeling in simulations, e.g. Geant4

Neutron capture time



Phase I (D2O): 48.5±1.3 ms   Phase II (with NaCl): 5.29±0.07 ms



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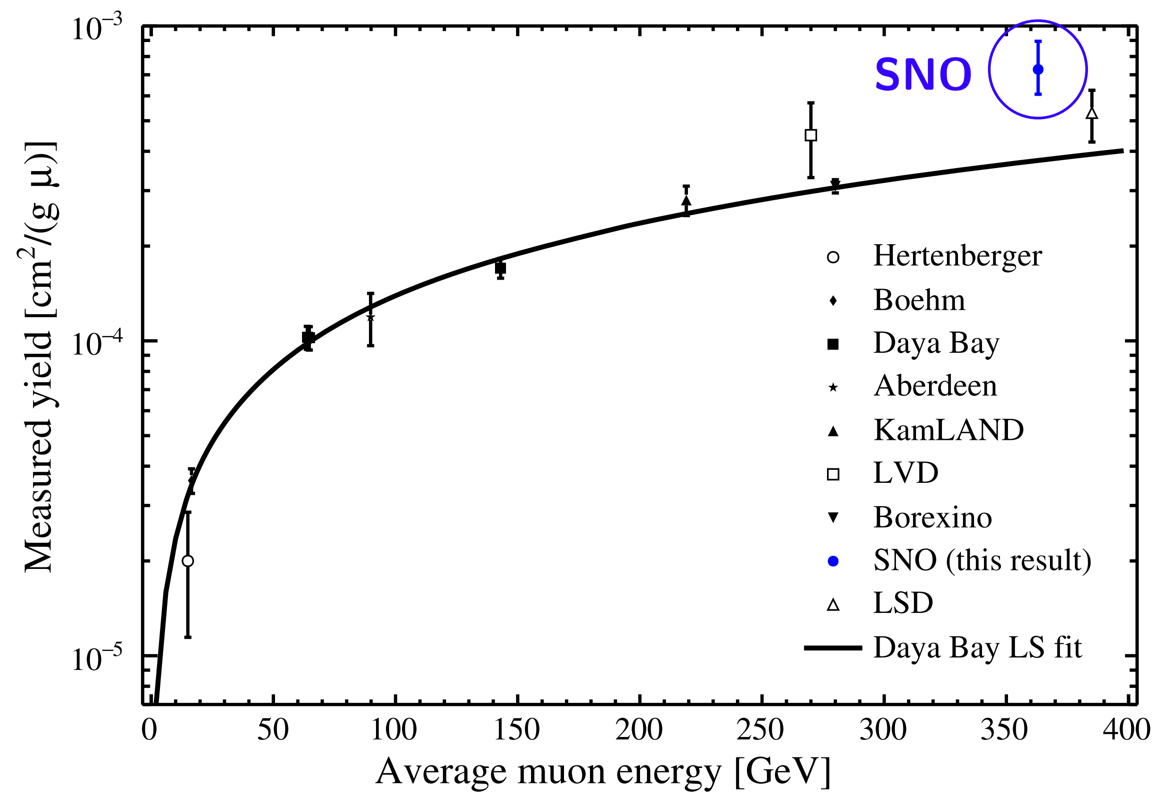


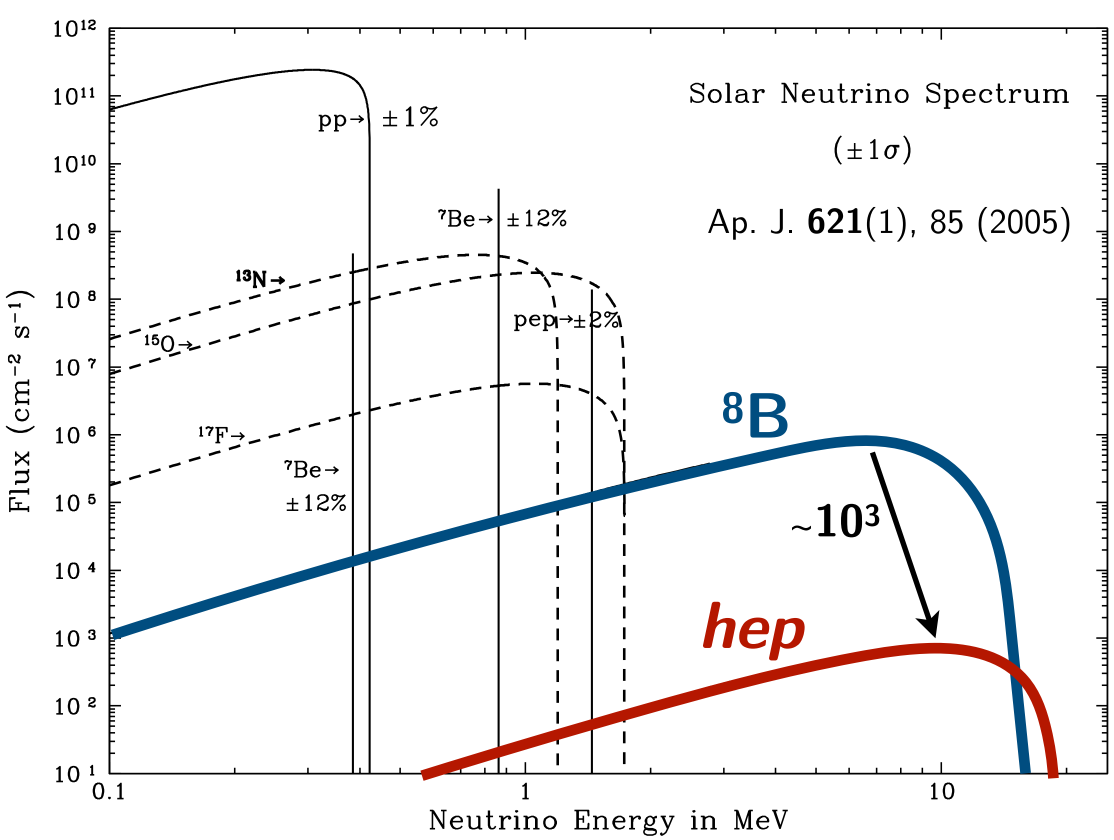
PRD **102**, 062006 (2020)

hep & DSNB Neutrinos

A Search with the Full SNO Dataset

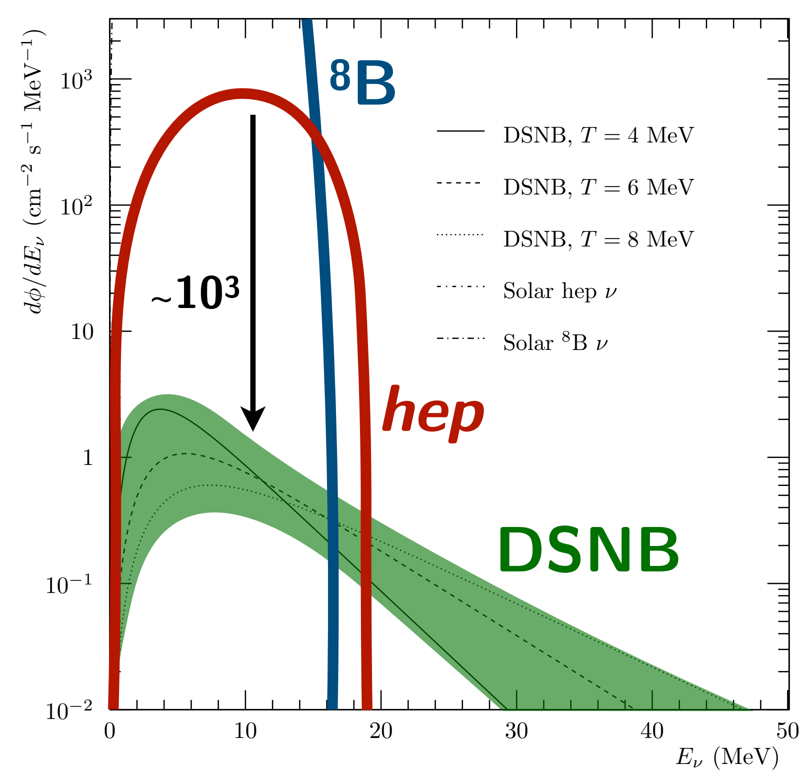
hep Solar Neutrinos

- ^{3}He+p fusion: ^{3}He(p,e$^+\nu_e$)^{4}He
- Highest-energy solar neutrino flux
- The last unobserved in the *pp* chain
- Sensitivity through SNO's ν_e–d CC
- Complete the *pp* picture, test SSM, extends 2006 SNO Phase I analysis[1]



Diffuse Supernova Neutrino Background

- Diffuse glow of past core-collapse SNe
- Redshifted spectrum with a tail beyond the 18 MeV *hep* endpoint
- SNO sensitive to DSNB ν_e via CC
- Information on average SNe neutrino luminosity and temperature

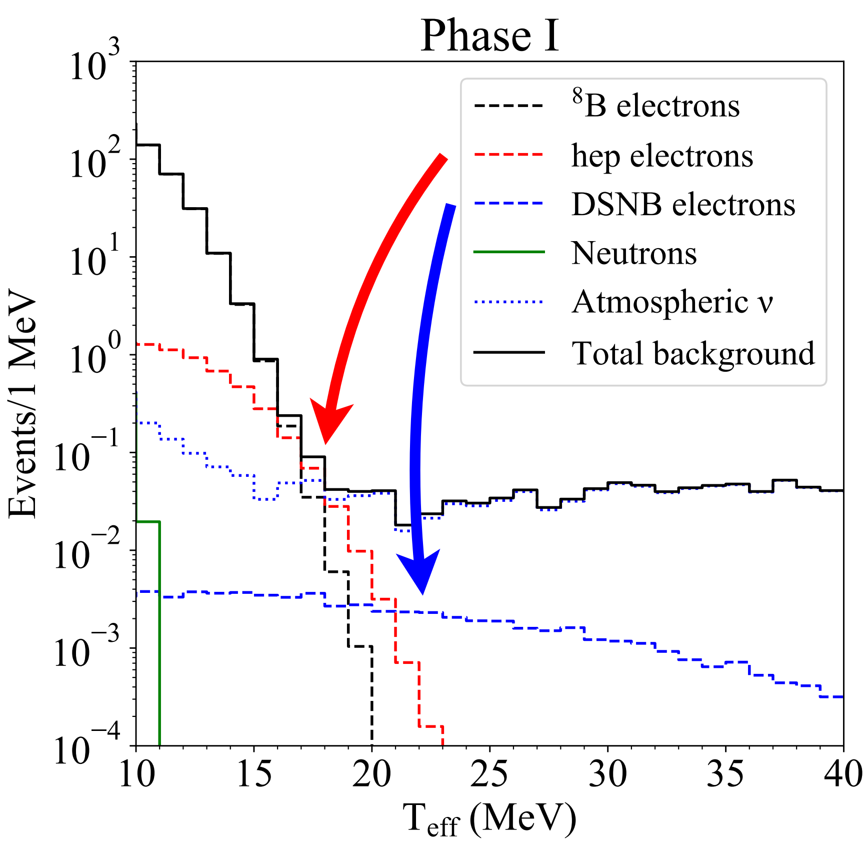


[1]Astrophys. J. **653**, 1545 (2006)

Model: Beacom & Strigari, Annu. Rev. Nucl. Part. Sci **60**, 439 (2010).

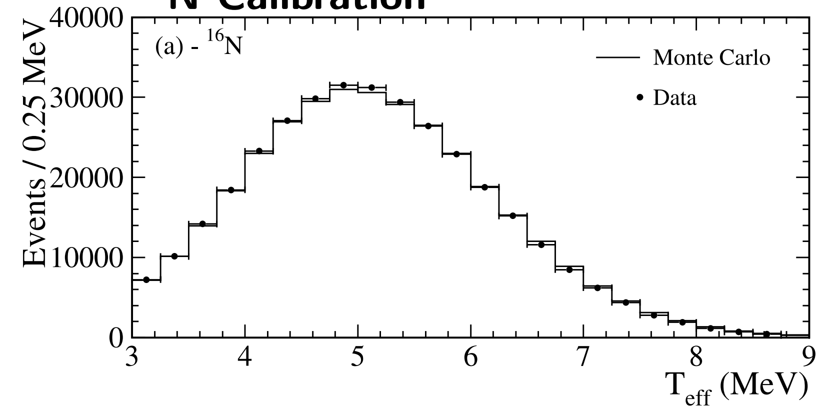
hep & DSNB Neutrinos

Signals & Backgrounds

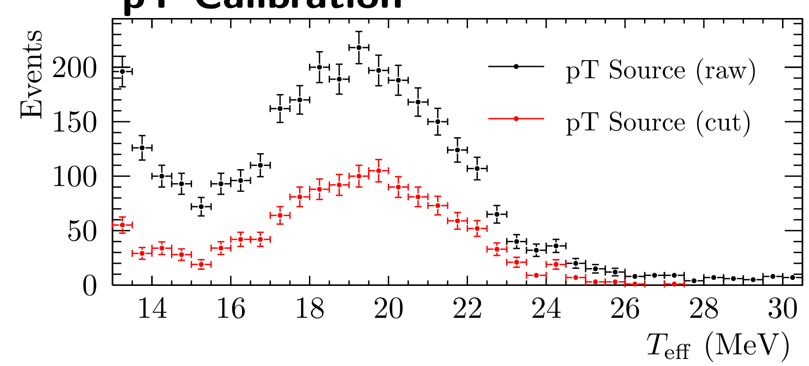


1. Energy Response Modeling

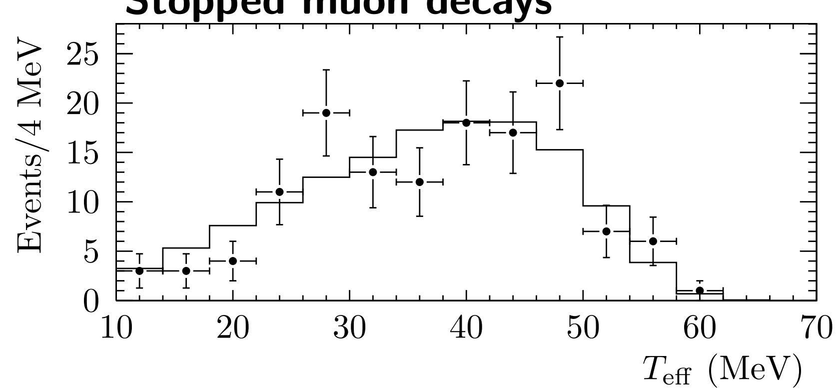
^{16}N Calibration[1]



pT Calibration



Stopped muon decays

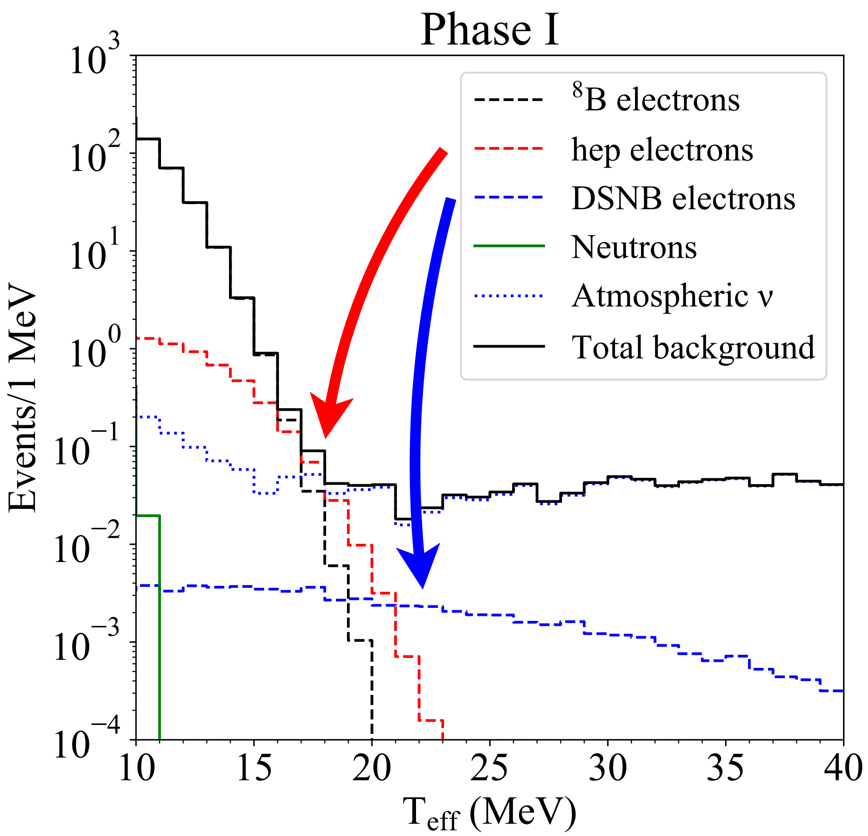


[1]Phys. Rev. C **88**, 025501 (2013)

PRD **102**, 062006 (2020)

hep & DSNB Neutrinos

Signals & Backgrounds



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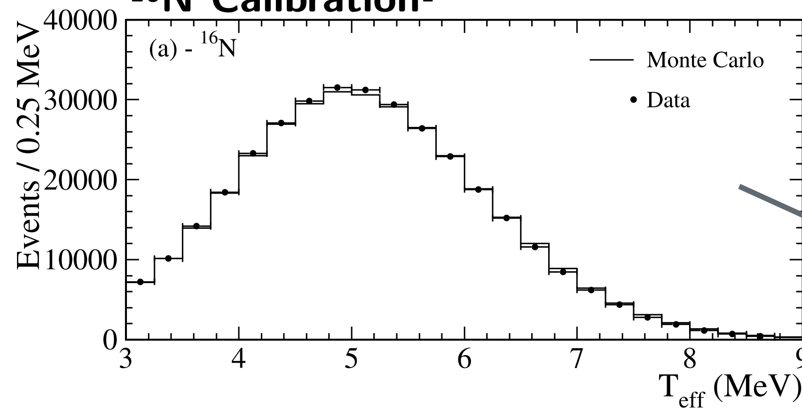

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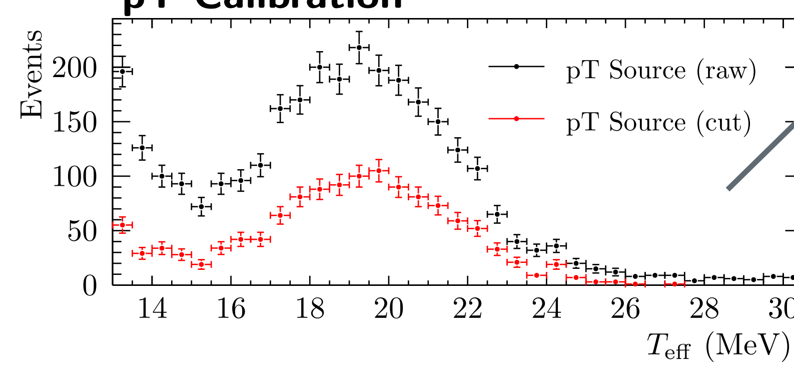

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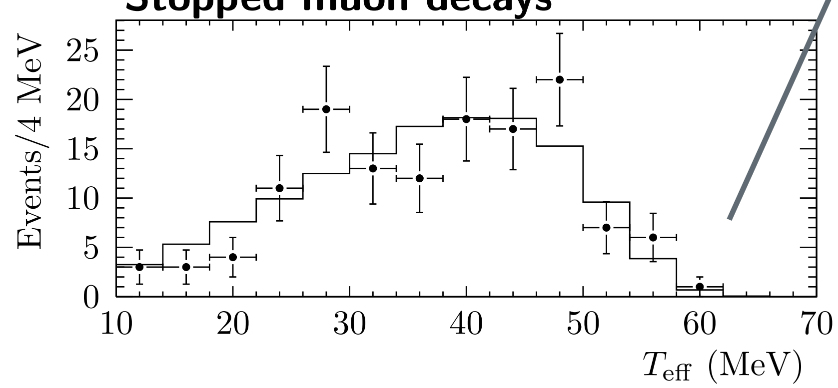
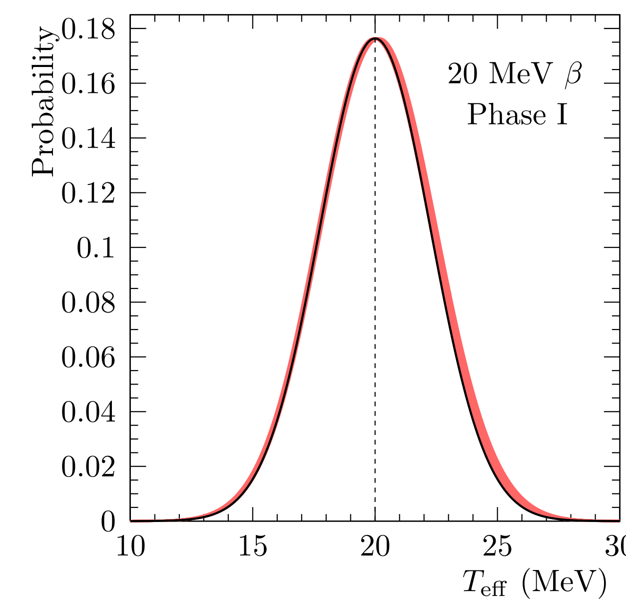
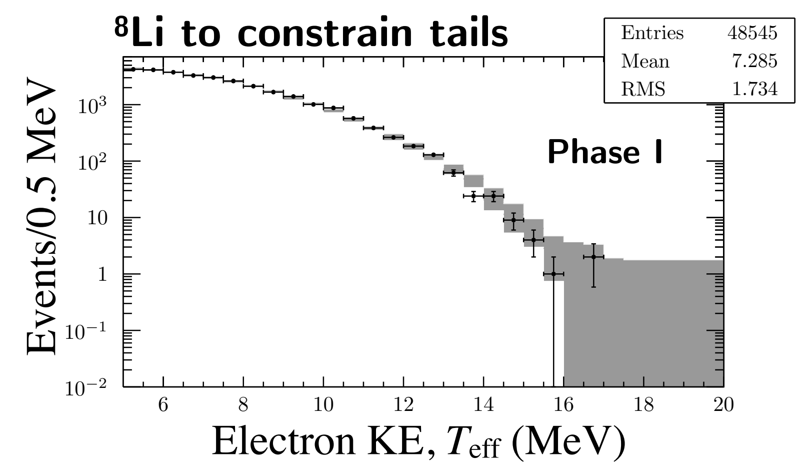


$$T' = T + (\Delta_S^{(0)} + \Delta_S^{(1)} \cdot T) \cdot T + \Delta_R \cdot (T - T_{\text{true}})$$



+

^{8}Li to constrain tails



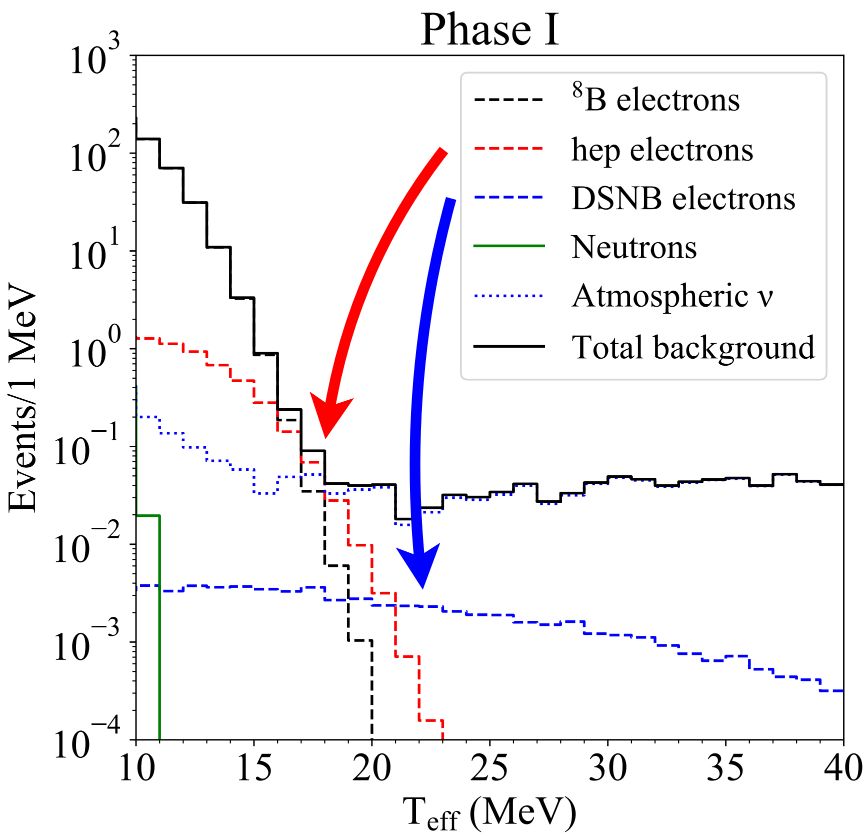
Calibration source data is augmented with Michel electrons to extend the model across the **full energy range** of interest

[1]Phys. Rev. C **88**, 025501 (2013)

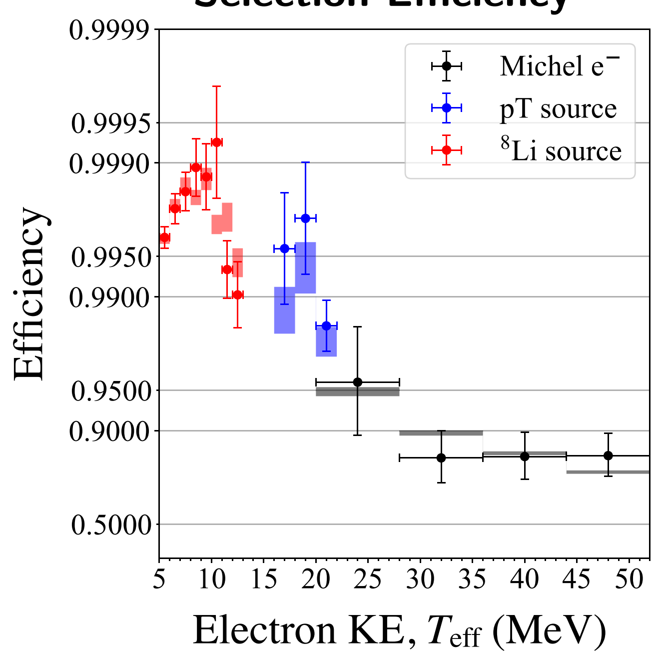
PRD **102**, 062006 (2020)

hep & DSNB Neutrinos

Signals & Backgrounds



Selection Efficiency



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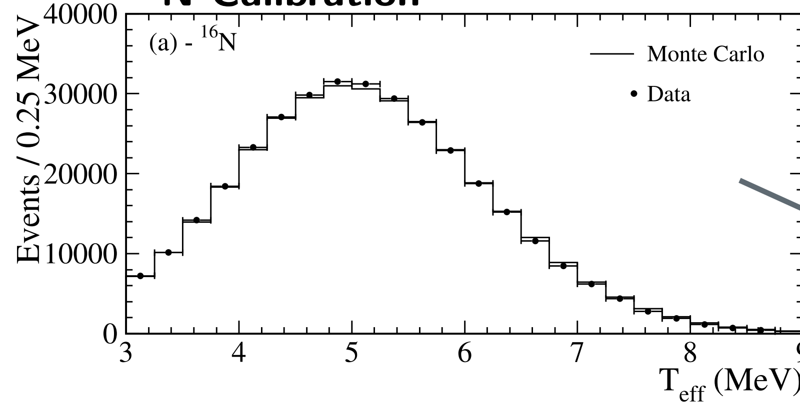

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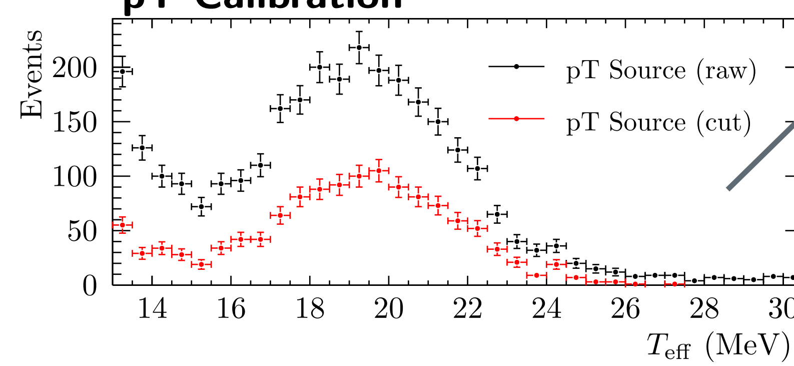

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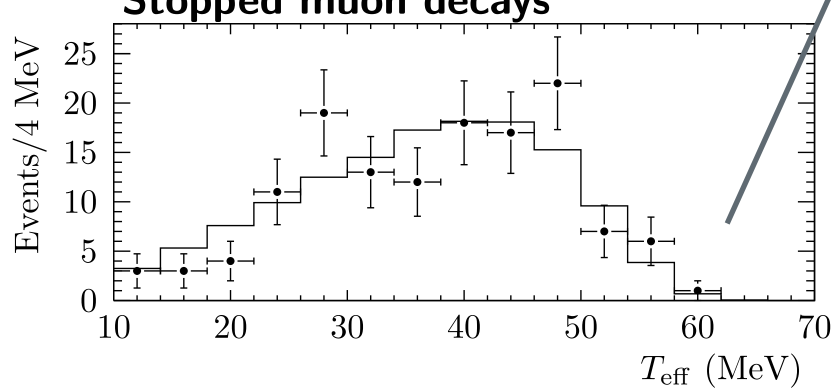

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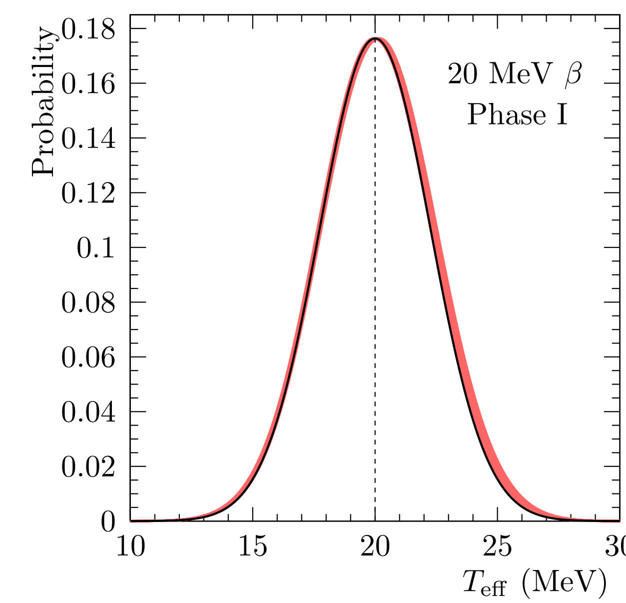

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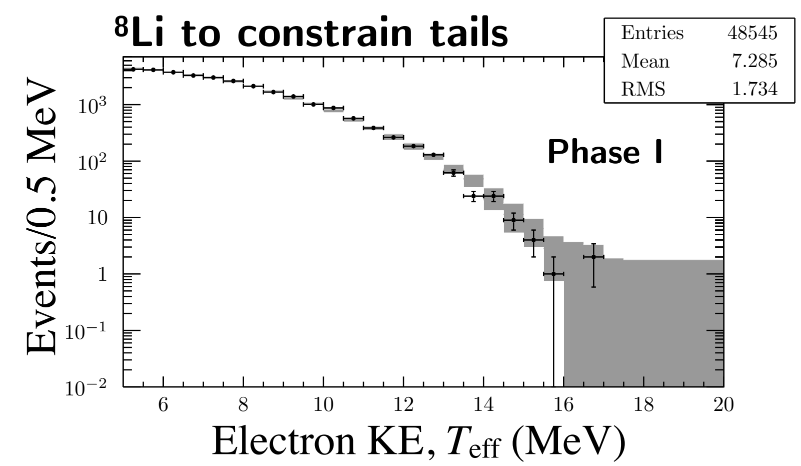

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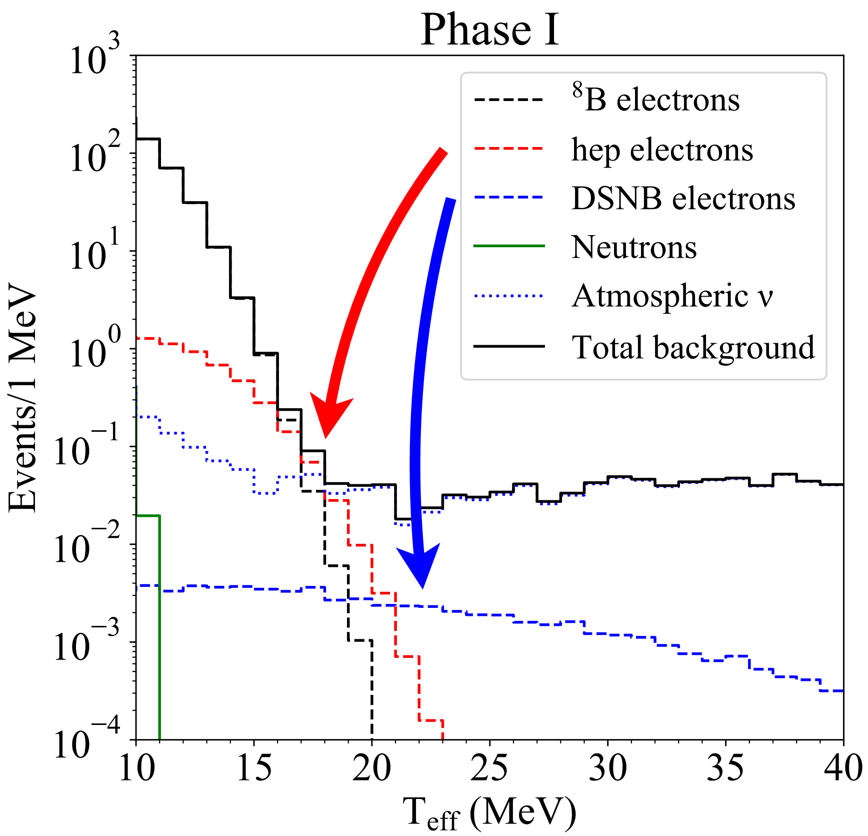
hep & DSNB Neutrinos

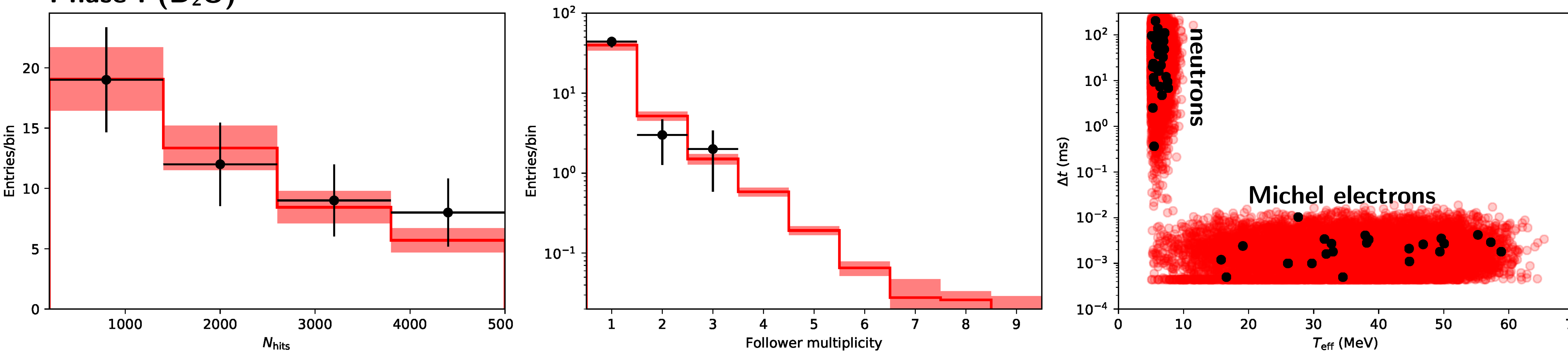
Signals & Backgrounds



2. Atmospheric Neutrinos

- GENIE[1] (v2) used to model neutrino interactions and model systematic
- Validated with a dedicated fully-contained atmospheric neutrino sample
- Agreement within systematics for rate, spectrum, multiplicity of neutron and muon followers
- Published characteristics of 13 atmospheric neutrino candidates in the 35–100 MeV range

Phase I (D_2O)

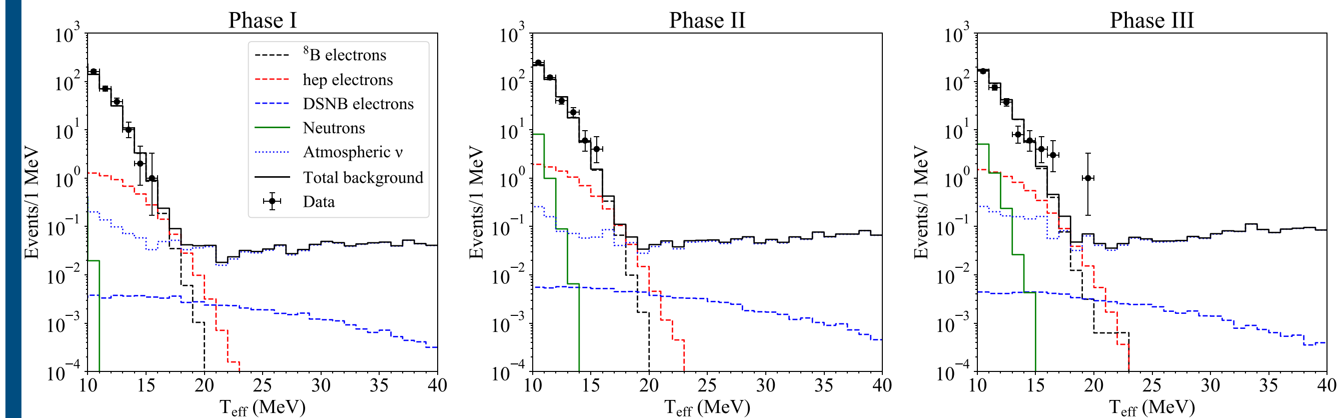


[1]NIM A **614**, 87 (2010)

hep & DSNB Neutrinos

Analysis & Results

Box analysis for hep and DSNB, and additional **likelihood fit for hep** only



	Expected signal	Expected background	Events observed
Phase I *hep*	0.84 ± 0.08	3.14 ± 0.63	3
Phase II *hep*	1.28 ± 0.06	5.37 ± 0.65	6
Phase III *hep*	0.98 ± 0.05	5.38 ± 0.52	13
Total *hep*	3.09 ± 0.12	13.89 ± 1.09	22
Phase I DSNB	0.02 ± 0.00	0.62 ± 0.10	0
Phase II DSNB	0.03 ± 0.00	0.91 ± 0.15	0
Phase III DSNB	0.02 ± 0.00	1.06 ± 0.17	0
Total DSNB	0.08 ± 0.00	2.58 ± 0.26	0

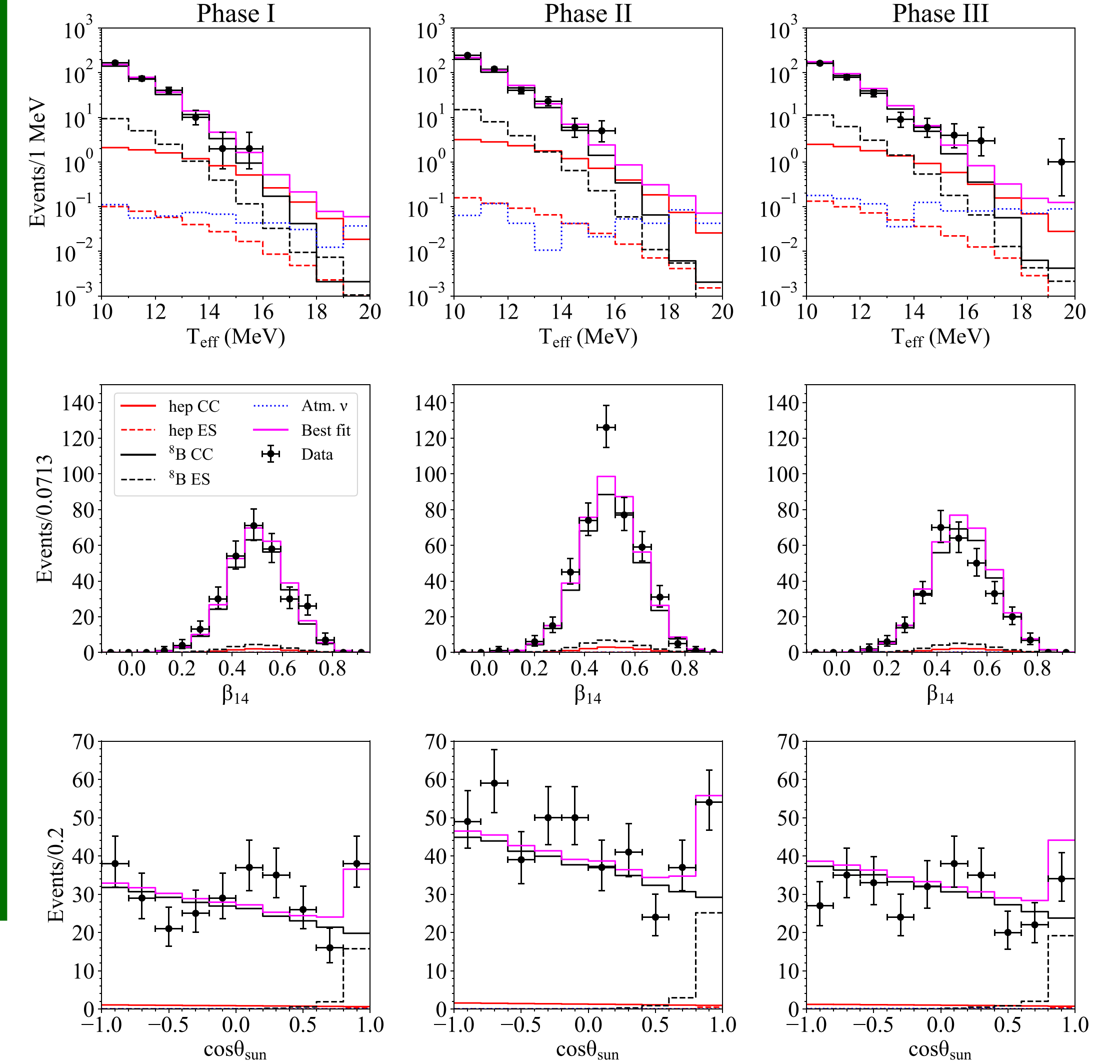
***p* ~ 8%**

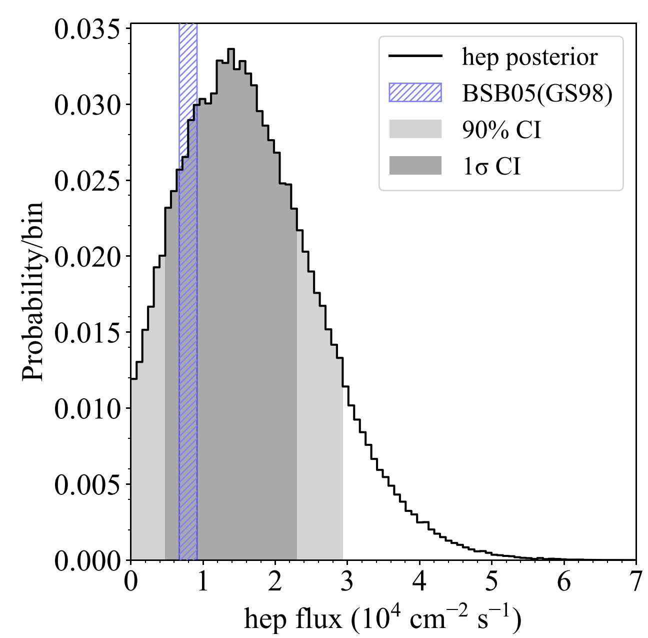
Bayesian one-sided 90% CI:

$\Phi_{hep} < 40 \times 10^3$ cm^{-2} s^{-1}

$\Phi_{DSNB}{}^* < 19$ cm^{-2} s^{-1} ($22.9 < E_\nu < 36.9$ MeV)

(*sensitivity ~ 30 cm^{-2} s^{-1})





Bayesian 90% CI:

$\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1}

BSB05(GS98) SSM[1,2]:

$\Phi_{hep} = 7.93(1\pm0.155) \times 10^3$ cm^{-2} s^{-1}

Consistent with SSM and zero *hep* flux

[1]Ap.J.Suppl.Ser. **165**, 400 (2006), [2]Nucl.Phys.B **168**, 115 (2007)

Conclusions

Summary and Outlook

PRD **98**, 112013 (2018)
Tests of Lorentz invariance at the Sudbury Neutrino Observatory

PRD **99**, 032013 (2019)
Constraints on Neutrino Lifetime from the Sudbury Neutrino Observatory

PRD **99**, 112007 (2019)
Measurement of Neutron Production in Atmospheric Neutrino Interactions at the Sudbury Neutrino Observatory

PRD **100**, 112005 (2019)
Cosmogenic Neutron Production at the Sudbury Neutrino Observatory

PRD **102**, 062006 (2020)
Search for hep solar neutrinos and the diffuse supernova neutrino background using all three phases of the Sudbury Neutrino Observatory

- Several recent results from SNO, spanning from fundamental symmetries to solar neutrinos
- Improved limits on Lorentz violation, neutrino lifetime, and DSNB ν_e flux
- New measurements of neutron production and *hep* solar neutrinos using SNO's unique large D_2O dataset
- Stay tuned for more to come!