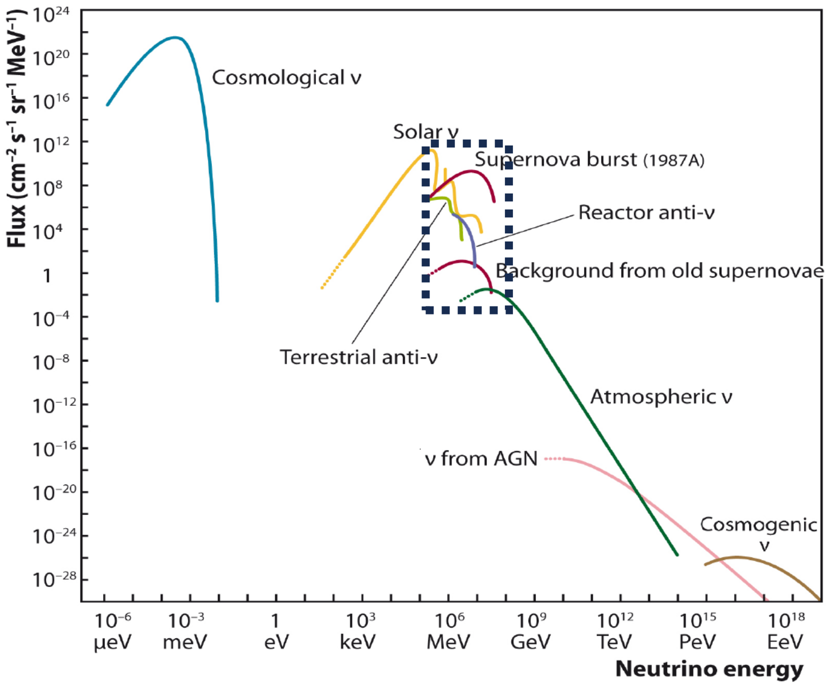
Low-energy physics and APEX

Dan Pershey (FSU) // Feb 8, 2024

Outline

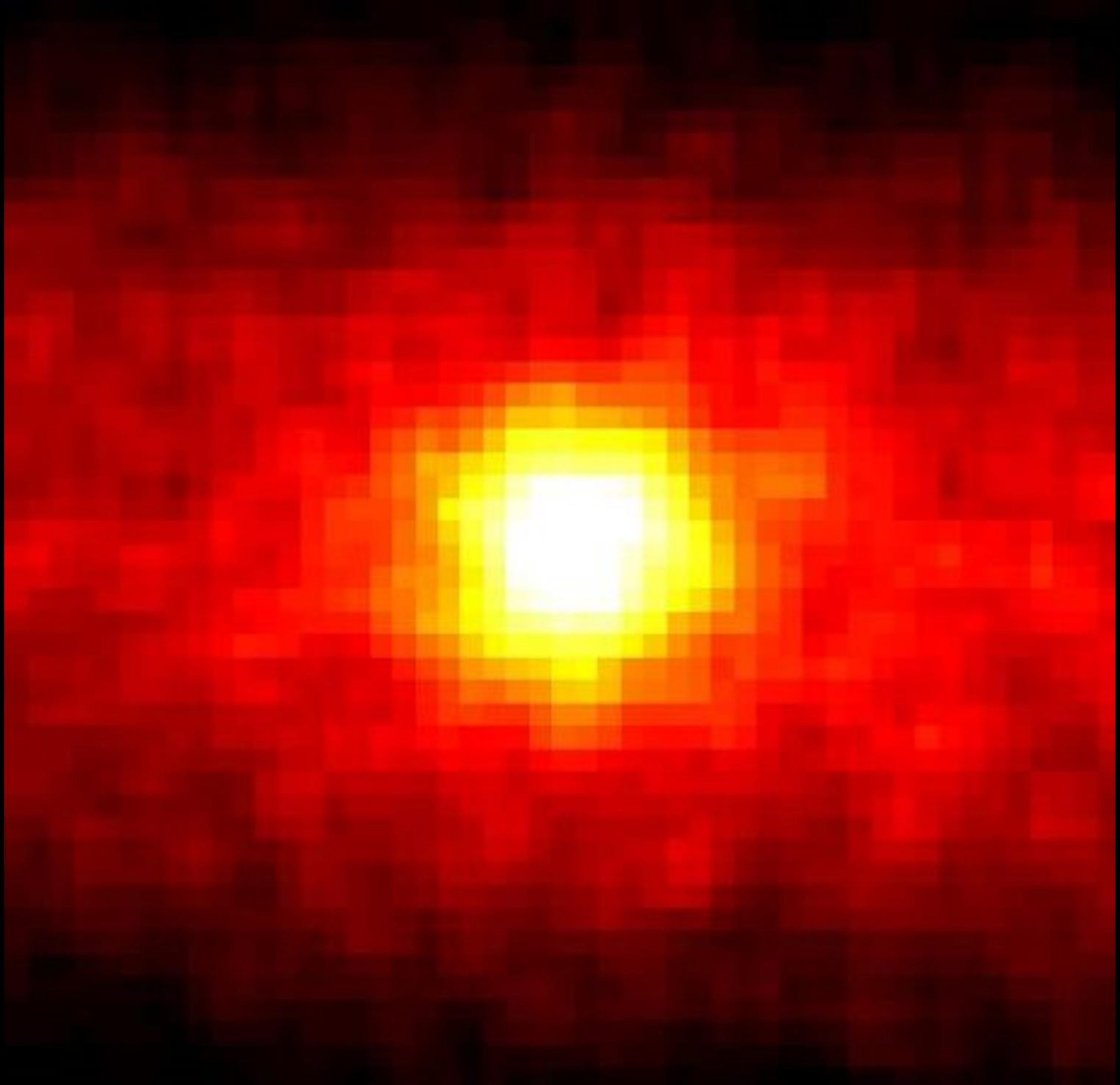
- ❑ Brief intro to general DUNE LE physics followed by five specific cases where APEX FD-3 bolsters our reach
- ❑ Part 1: Solar neutrinos
- ❑ Part 2: Supernova neutrinos



- ❑ APEX improves light yield by an order of magnitude over HD design
  - Ideas that exploit 1) improved energy resolution, 2) threshold, 3) radiological background rejection, 4) neutron tagging in neutrino interactions
- ❑ Physics gains through improved oscillation measurements, BSM searches, and enhanced supernova sensitivity

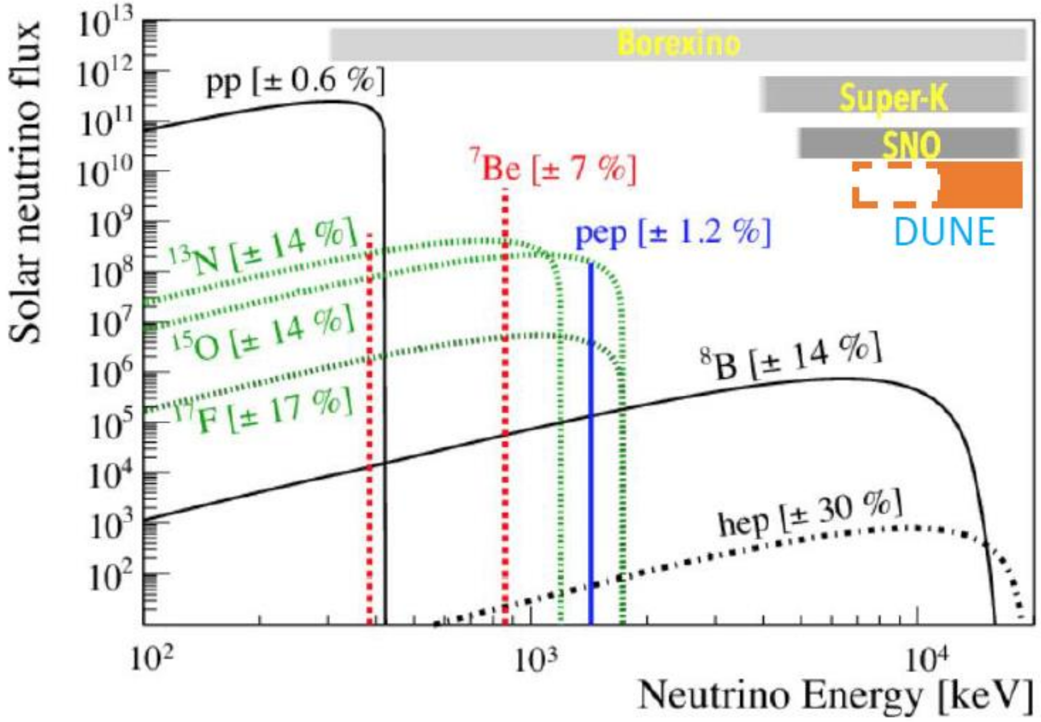
Solar neutrinos

First photo of the sun taken from below a mountain
–SK collaboration

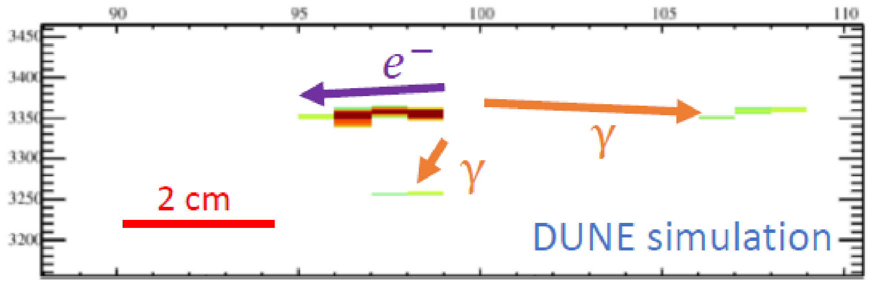


Low-energy physics: solar neutrinos

- Enormous size and sensitivity to astro ν_e flux makes DUNE an excellent next-gen solar experiment
- Relatively high threshold – only sensitive to ^{8}B neutrinos
- Event rates on order of 1 / 10 kt-hr



- Precision tracking: many interesting reco and channel tagging opportunities



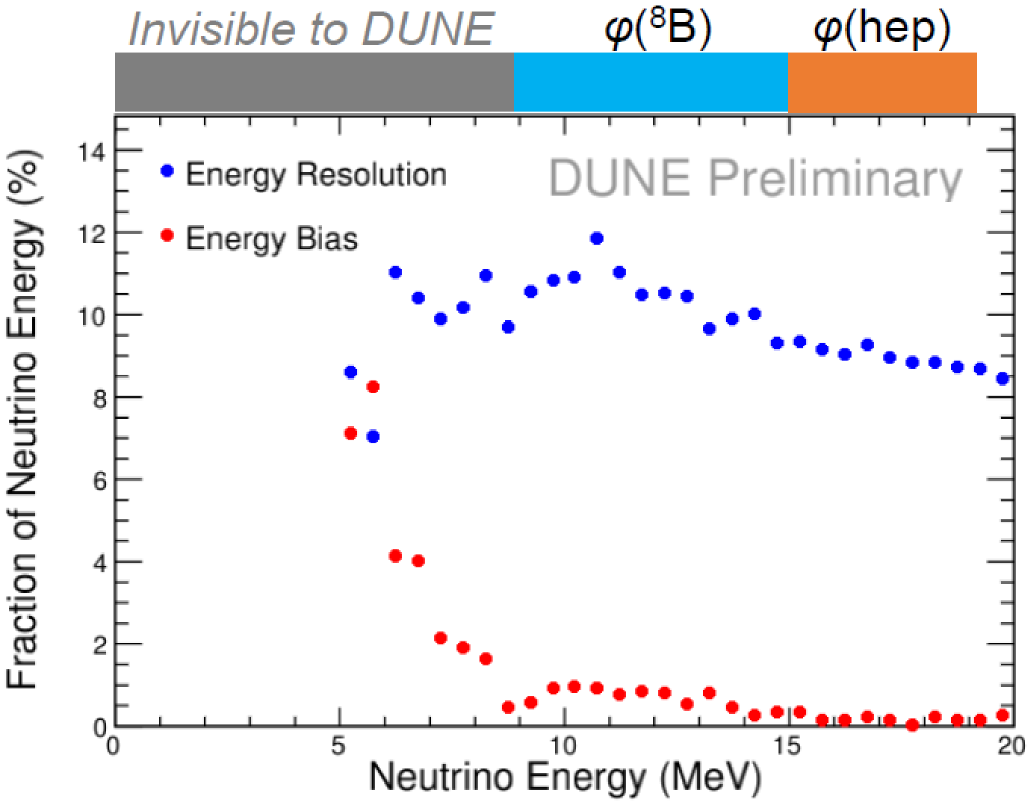
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

In DUNE, CC channel dominates signal: leaving a ≈10 MeV electron and gamma cascade in detector

Precision energy reconstruction!

Solar neutrino energy resolution

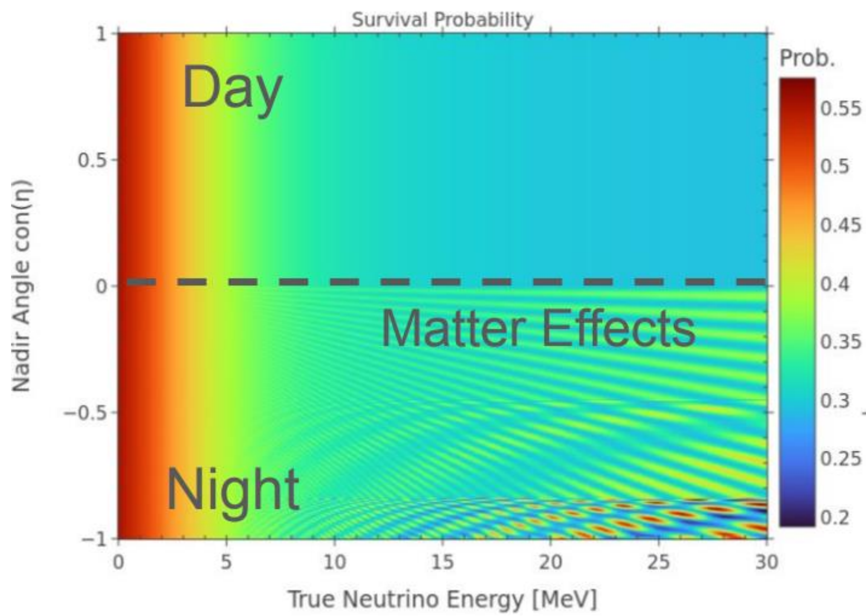
- For HD, optimal energy resolution from the TPC
  - Calorimetric sum of electron + gamma energies
  - Drift correction from associated OpFlash
  - 8-10% energy resolution



- APEX would significantly improve light collection – up to 109(180) for min(average) LY from Flavio's talk at the collaboration meeting
  - Can push down to ≈ 2-4% depending on neutrino position and energy

Resolving the solar mass splitting parameter

- There is a partial regeneration of the ν_e component of the solar flux as neutrinos travel through Earth – enhanced rate at night
  - Day/night asymmetry produces oscillations in survival probability as a function of true neutrino energy and nadir angle
  - Amplitude and frequency relates directly to Δm^2_{21}



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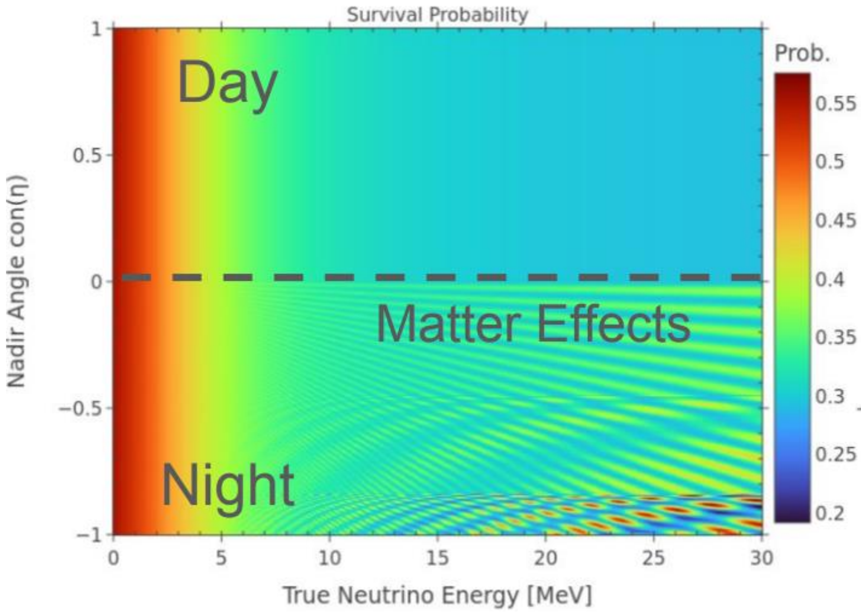
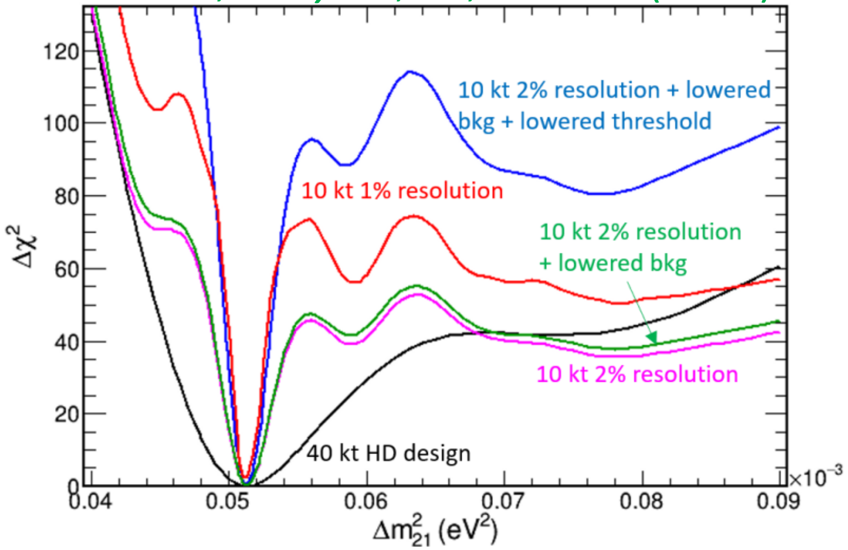


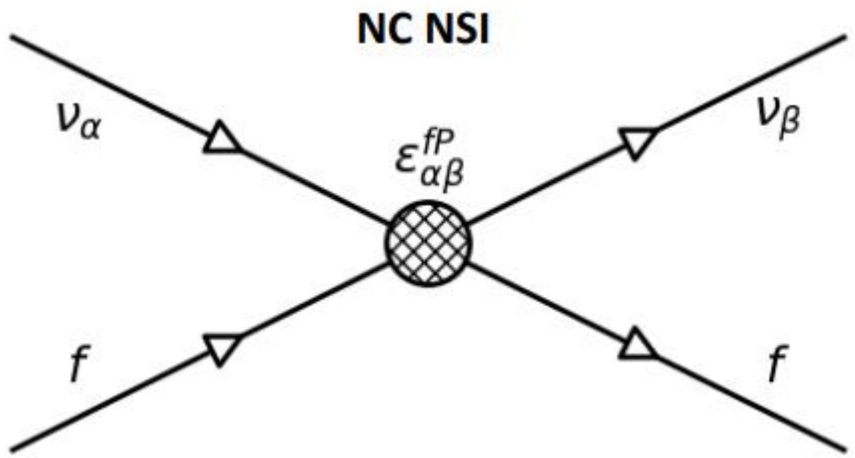
SloMo, *J Phys G*, **50**, 060502 (2023)



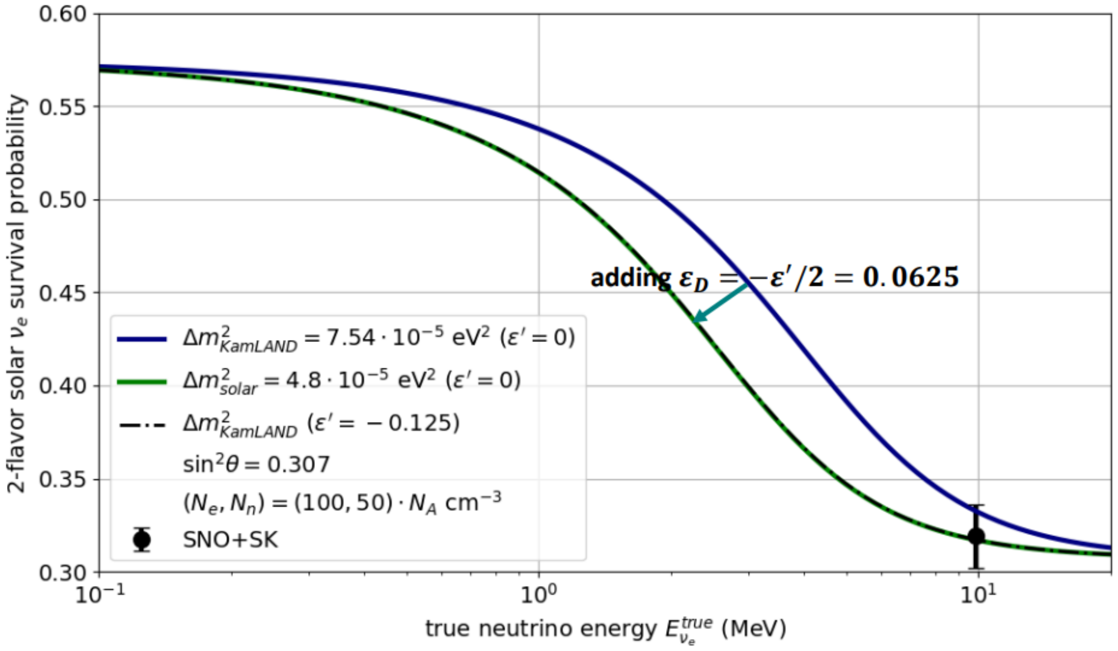
- Energy resolution everything for resolving wiggles in survival probability map
- No APEX-specific study, but SloMo paper showed single 10 kt module with 2% energy resolution outperforms 40 kt of HD

Beyond SM oscillations: searching for neutrino NSI

- Mapping the survival probability (P_{ee}) as a function of energy constrains neutrino NSI interactions (Gleb Sinev on indico)

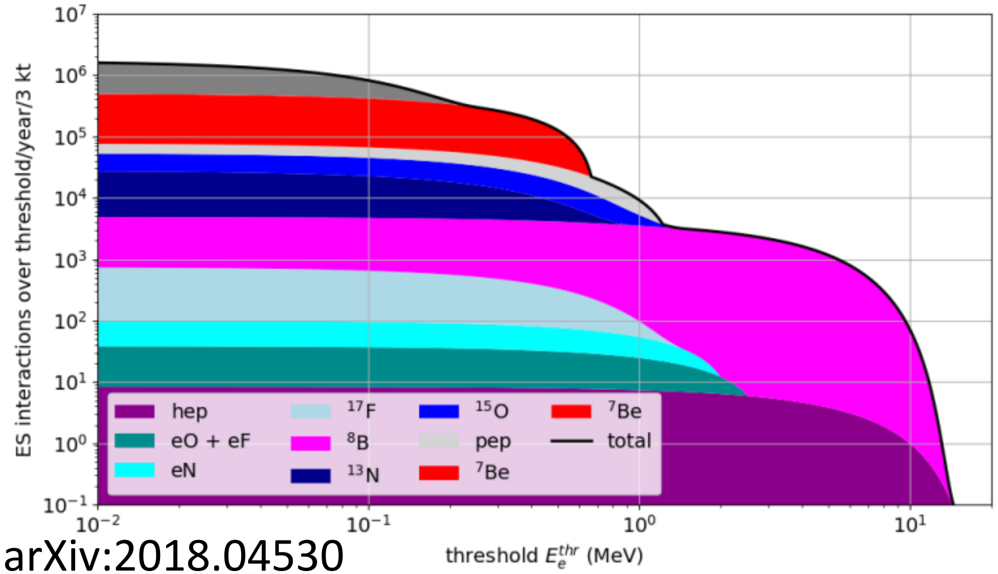


- Solar survival probability depends on the interaction potential in the solar interior -> adding extra interactions will change energy dependence of P_{ee}



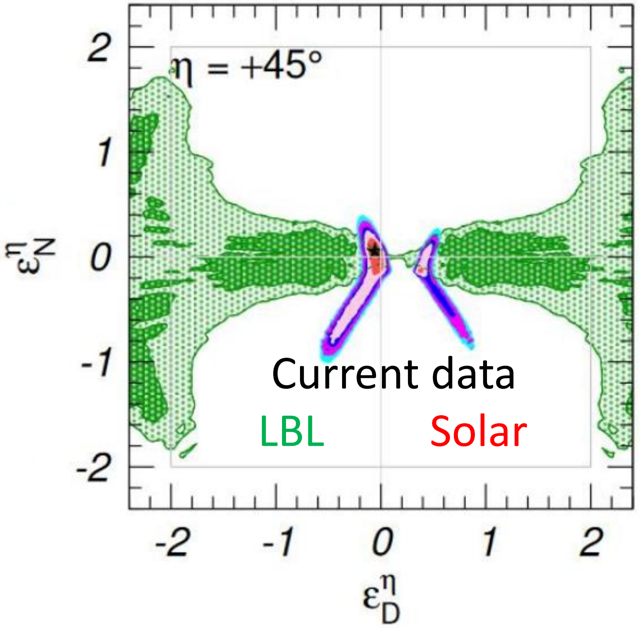
Beyond SM oscillations: searching for neutrino NSI

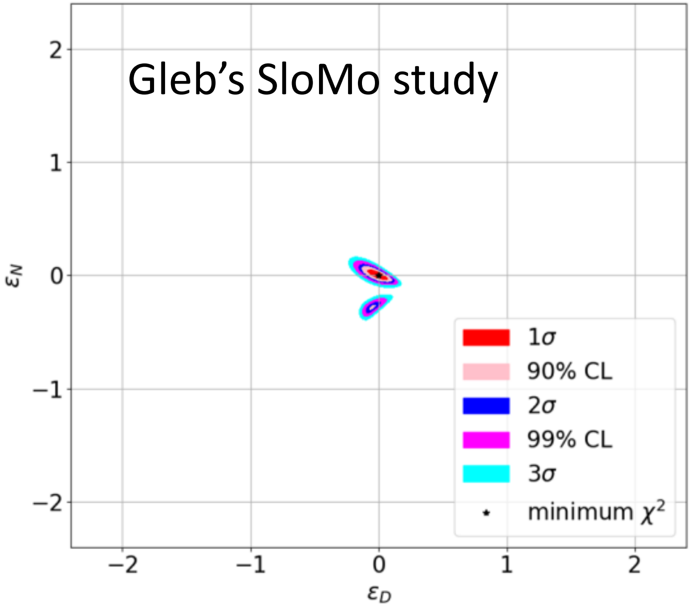
- With good energy resolution, APEX can veto backgrounds such as neutron captures -> extend ROI to lower energy
  - 1 MeV threshold would give 3e4 ES/10 ktyr
  - At low energy, allowing us to map out energy dependence of P_{ee}!



- Gleb has mature sensitivity study for SloMo showing new parameter space to explore
  - SloMo LY ≈ 200 PE/MeV, similar to APEX

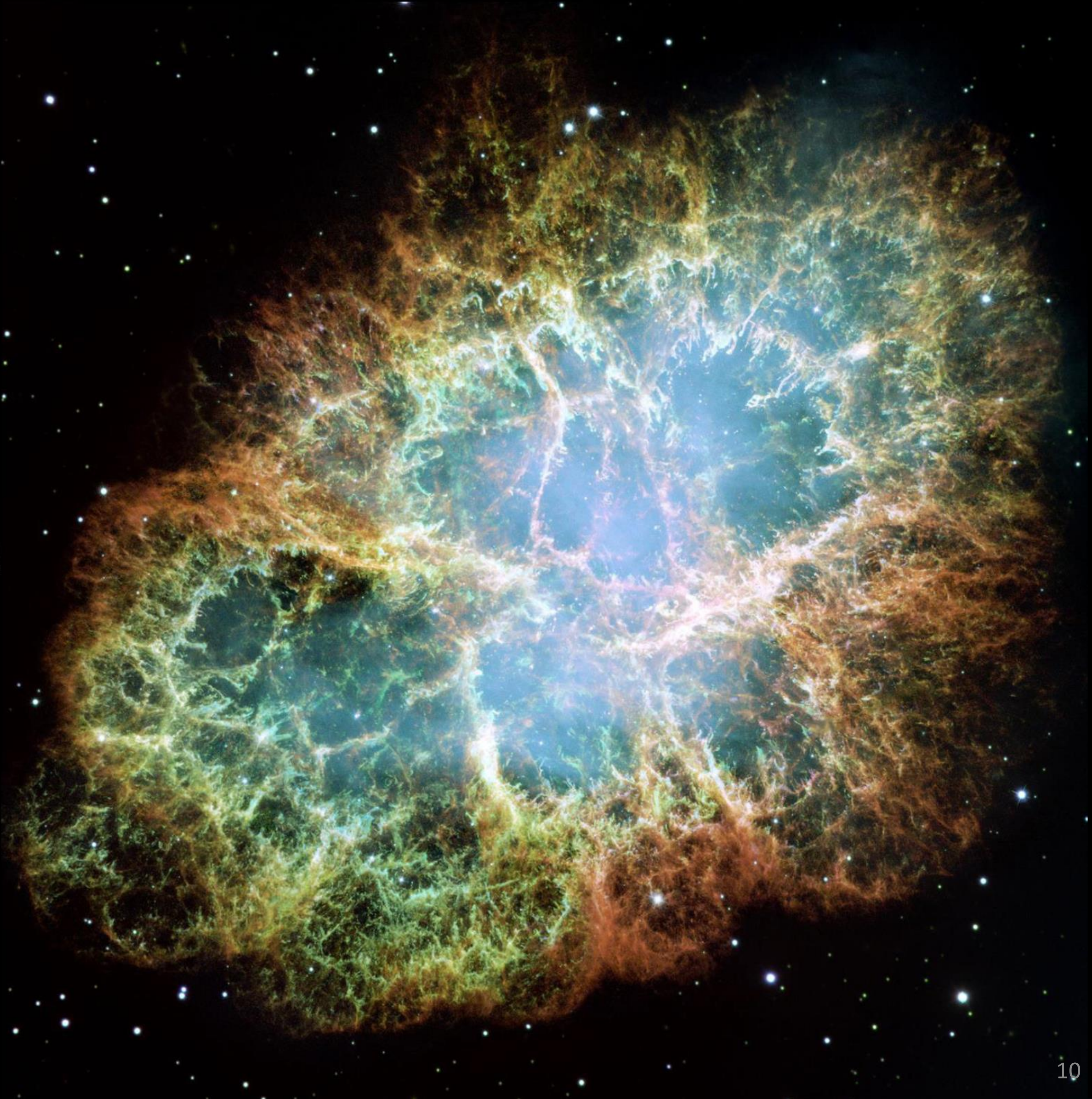
Esteban et al. arXiv:2018.04530



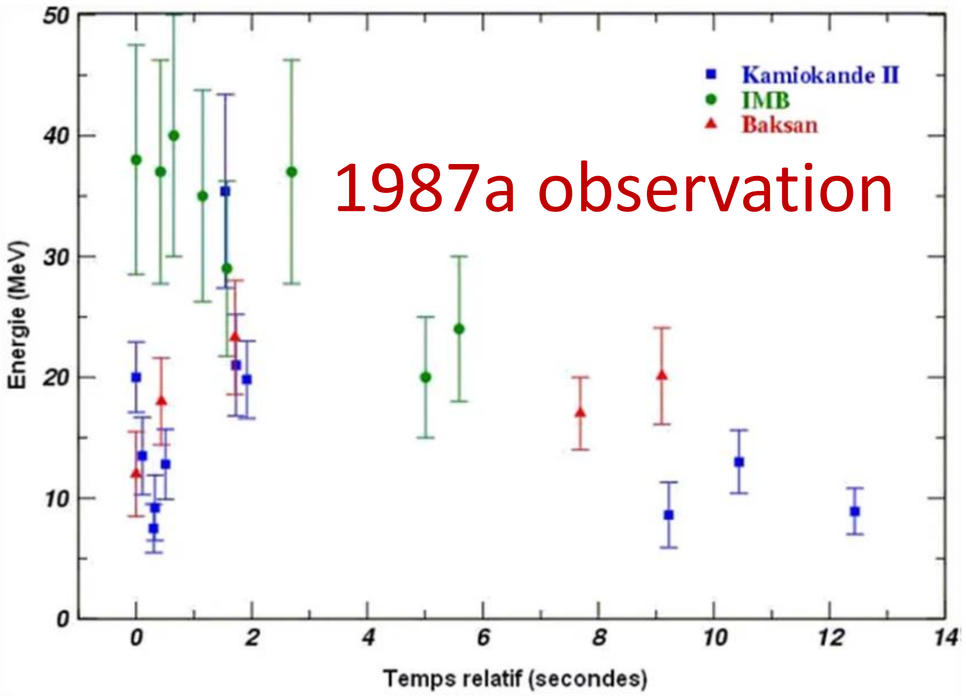


Supernova neutrinos

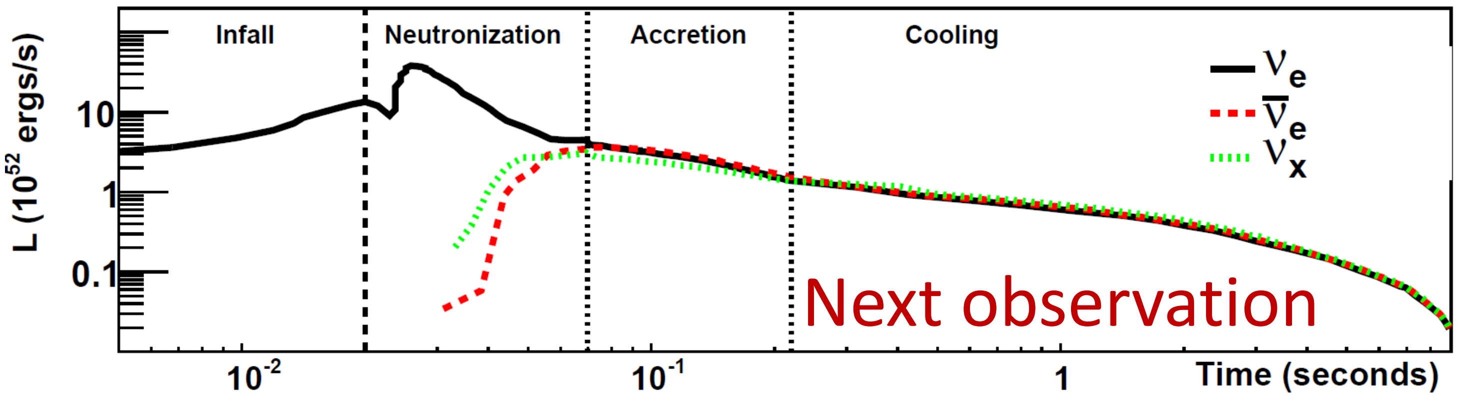
Crab nebula, remnant of supernova recorded in 1054



Low-energy physics: supernova neutrino bursts



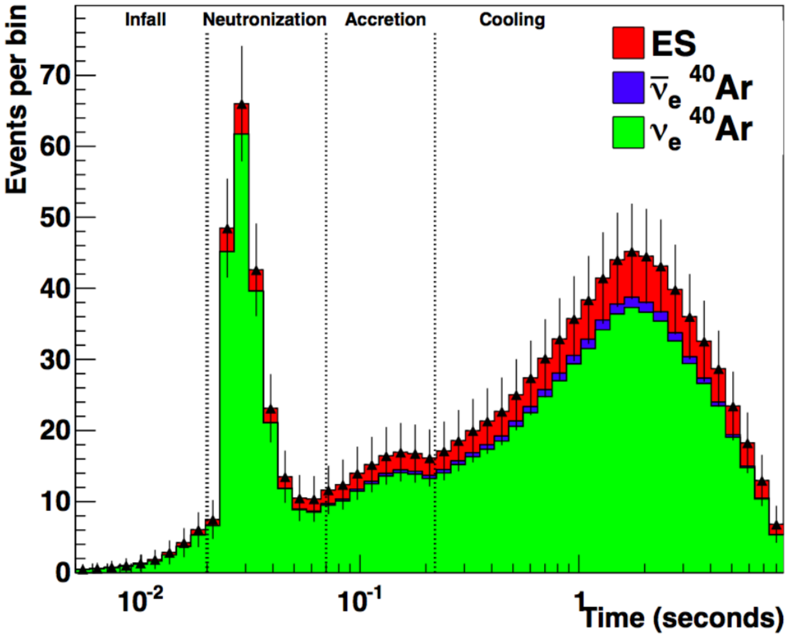
- A core-collapse supernova (CCSN) releases 10^{58} neutrinos in 10 s
- Rich astrophysics and particle physics opportunities, but collapses are rare
- DUNE has unique sensitivity to ν_e flux!

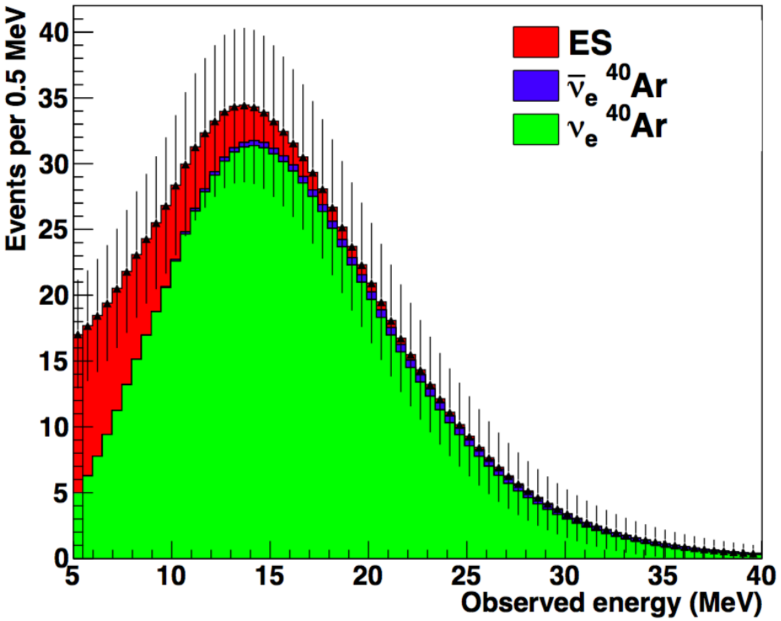


Detector complementarity!

	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

Event expectations at DUNE



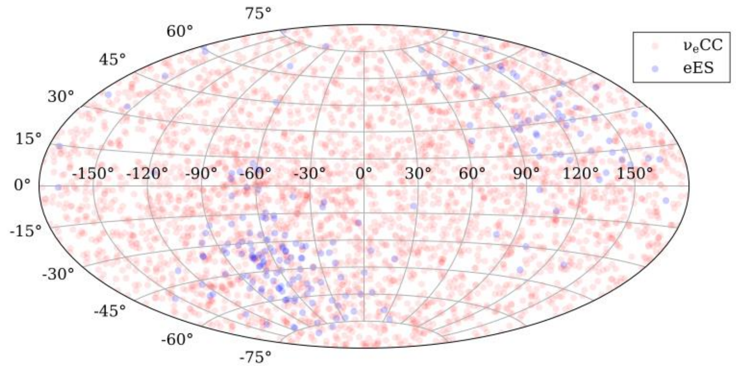


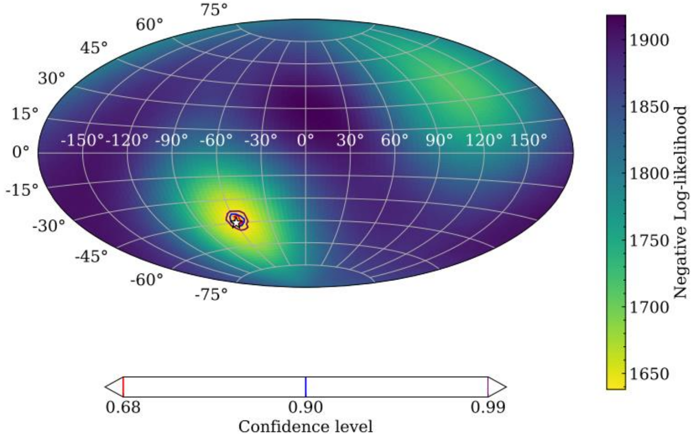
Event rates at 10 kpc

Channel	Events "GKVM" model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

- Expect a few thousand interactions from a typical galactic CCSN
  - Three epochs of supernova collapse visible in timing spectrum
  - Good calorimetry and precision reconstruction from TPC
- DUNE most sensitive to ν_e flux through CC channel but can identify subdominant channels such as ES

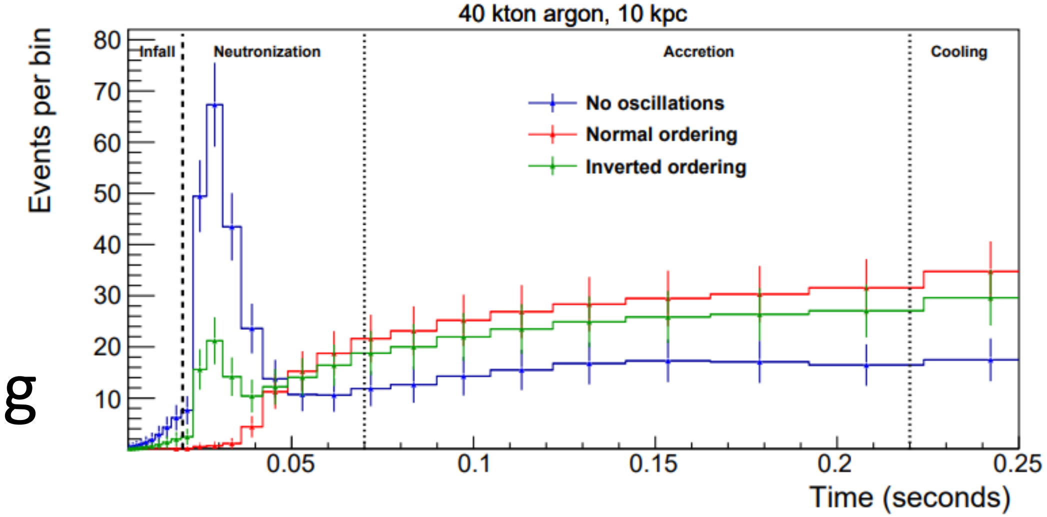
DUNE physics goals

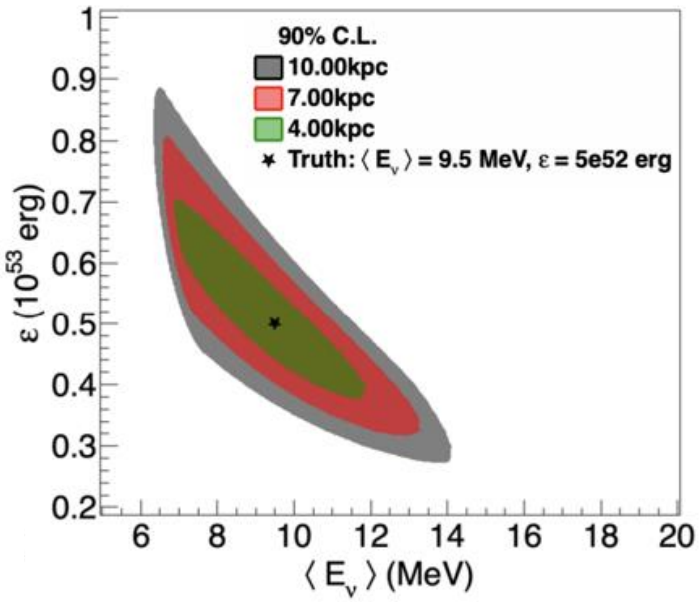




Supernova pointing
DocDB 27538
ES events constrain source to 4.3 deg

Timing features disentangle particle physics questions such as mass ordering



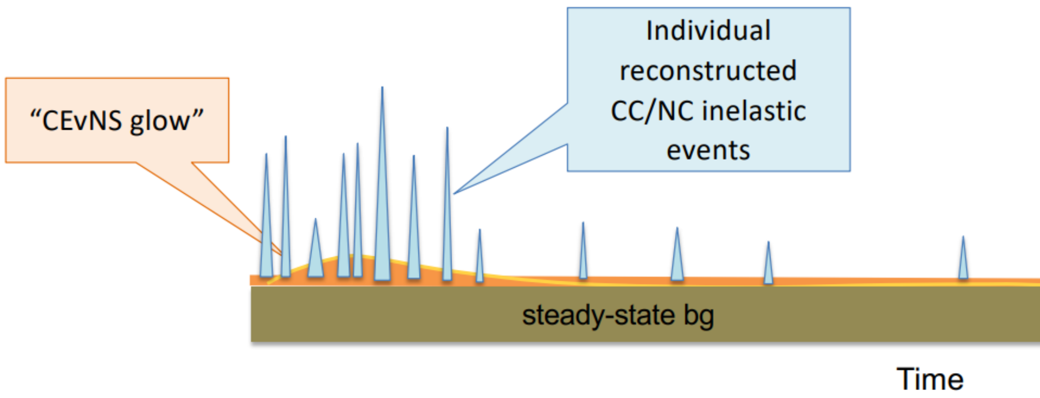


We can extract astrophysical parameters from the neutrino energy spectrum such as the temperature distribution and total luminosity

CEvNS glow of a supernova

Kate Scholberg, DPF 2019

- Supernova neutrinos will also produce CEvNS in our detectors
- NC neutrino-induced nuclear recoils
- Low energy / event, but high event rate will result in “glow”, an increased rate of 1-few PE optical flashes
- Compared to CC interactions:
  - ≈ 100x the cross section
  - ≈ 6x the flux (all nu flavors)
  - ≈ 0.001x the visible energy / event
  - ≈ 0.2x light from nuclear quenching
  - = 0.12x total light from CC

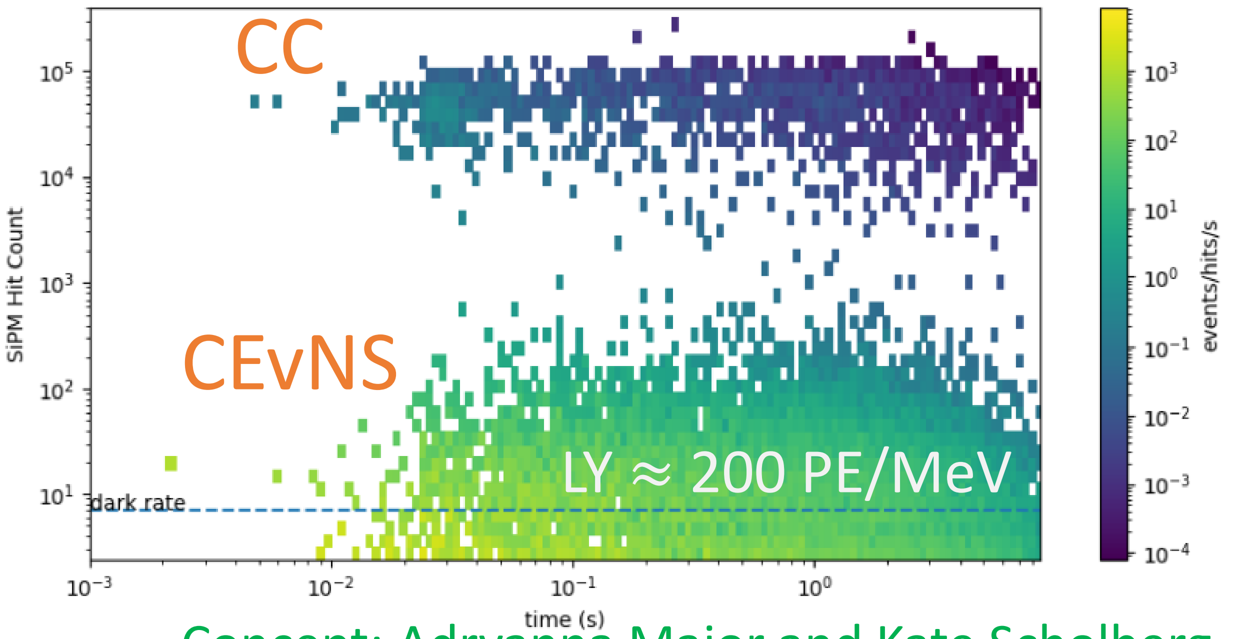


In 10 kt – expect ≈ 800 CC events
= 800 x 20 MeV x 180 PE/MeV ≈ 3e6 PE from CC
-> 3e5 PE from CEvNS over ≈ 10 seconds

Isolating light from CEvNS

- Increase in low-PE flashes vs time
- All in light yield: SloMo study with similar light yield shows CEvNS distinguishable from dark rate
  - Study of statistical power with backgrounds underway
- LY higher by order of magnitude in APEX design vastly improves APEX power

SloMo, *J Phys G*, **50**, 060502 (2023)



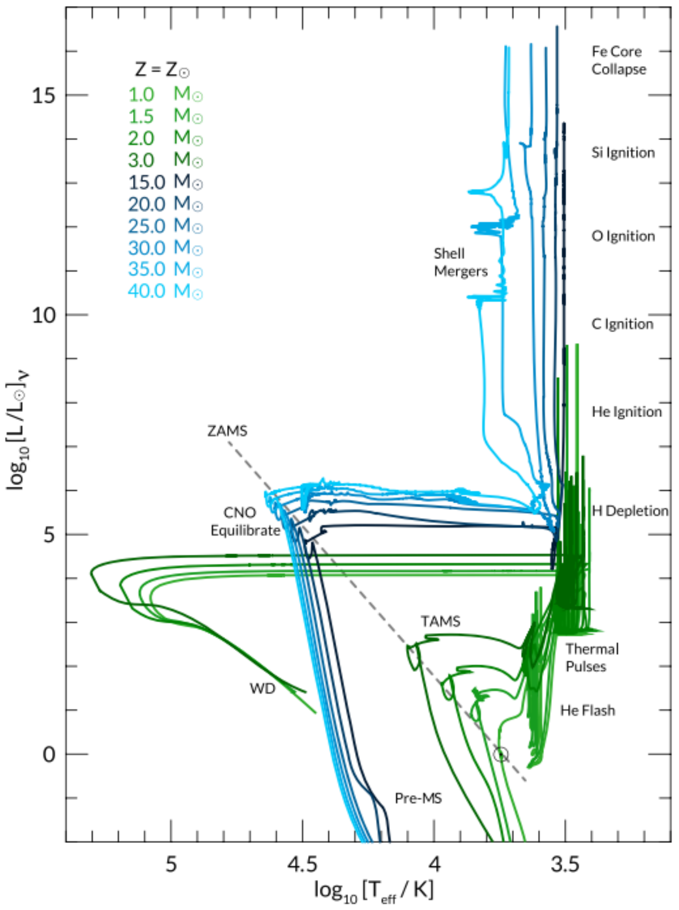
Concept: Adryanna Major and Kate Scholberg

- DUNE would independently measure ν_e and ν_x components of flux

Pre-SN neutrinos

- Si burning starts ~ 2 hrs before CCSN, we can detect pre-SN neutrinos from a couple kpc
  - In final seconds, the pre-SN flux is %-level of peak SN luminosity
  - Valuable for SNEWS – an early warning for neutrinos
  - Stellar structure during this period is uncertain, answers interesting physics questions in its own right
  - Each individual detector has modest sensitivity, SNEWS will aggregate signals from multiple detectors

Farag et al., *APHYS J*, **893**, 133 (2020)



Pre-SN neutrinos and DUNE

- Thermal and nuclear processes both contribute to total pre-SN flux

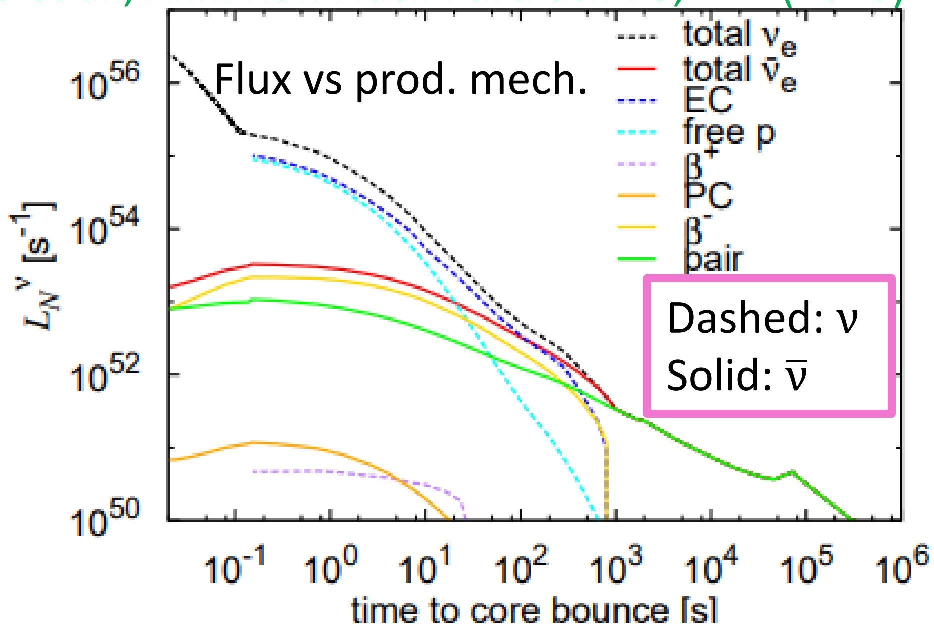
ν

$$(Z,A) + e^- \longrightarrow (Z-1,A) + \nu_e$$
$$p + e^- \longrightarrow n + \nu_e,$$

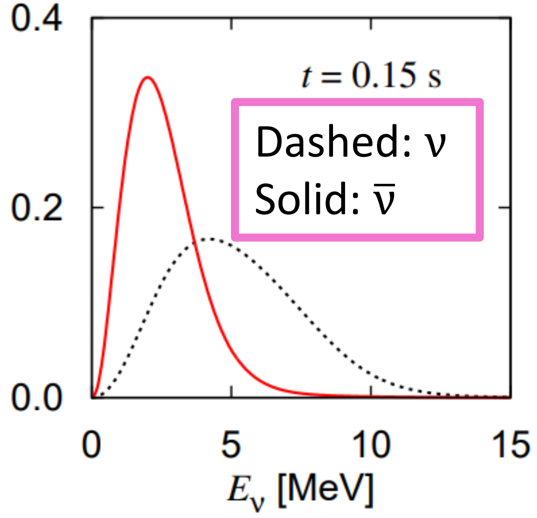
$\bar{\nu}$

$$e^+ + e^- \longrightarrow \nu + \bar{\nu}$$
$$(Z,A) \longrightarrow (Z+1,A) + e^- + \bar{\nu}_e.$$

Kato et al., *Ann. Rev. Nucl. Part. Sci.* **70**, 121 (2020)



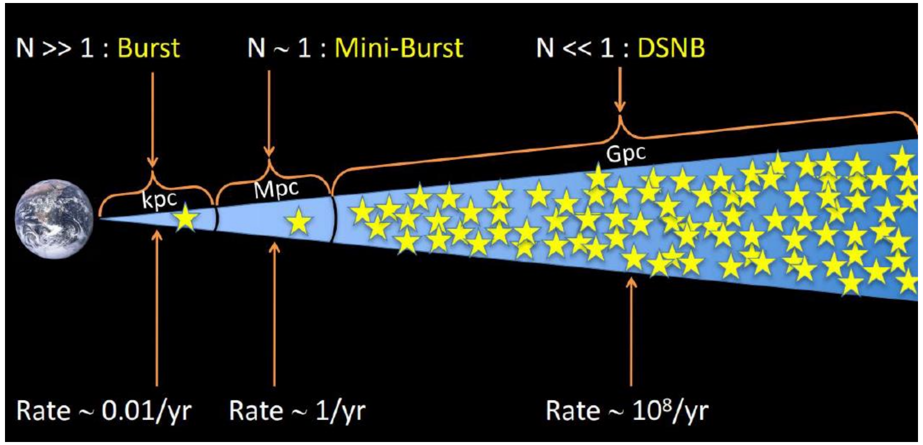
- DUNE with neutrino sensitivity, has interesting role
  - In final 100 s, neutrino flux rises sharply
  - Also becomes more energetic
- DUNE evt rate 7-880 evts at 1 kpc (40 kt, > 5 MeV)
- APEX connection: energy resolution and backgrounds



The diffuse supernova neutrino background (DSNB)

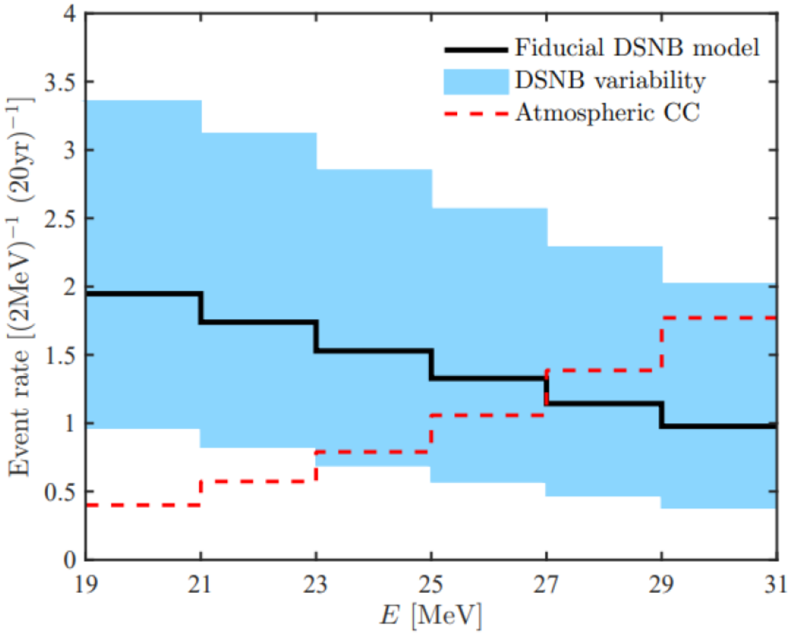
The neutrino flux from a supernova depends on distance, $\propto 1/r^2$. But, further from Earth, the density of stars increases $\propto r^2$. Effects cancel and the total flux of supernova sums up to a finite contribution up to Gpc scales (neglecting inflation)

John Beacom



Guaranteed signal! No waiting for burst

Moller et al., *J. Cosmo. And Astro. Phys.* **05**, 066 (2018)



- Measurement gives information on typical supernova spectrum and measures the fraction of supernovae that make black holes

Density of supernova events (/Mpc³/s)

Inflation effects

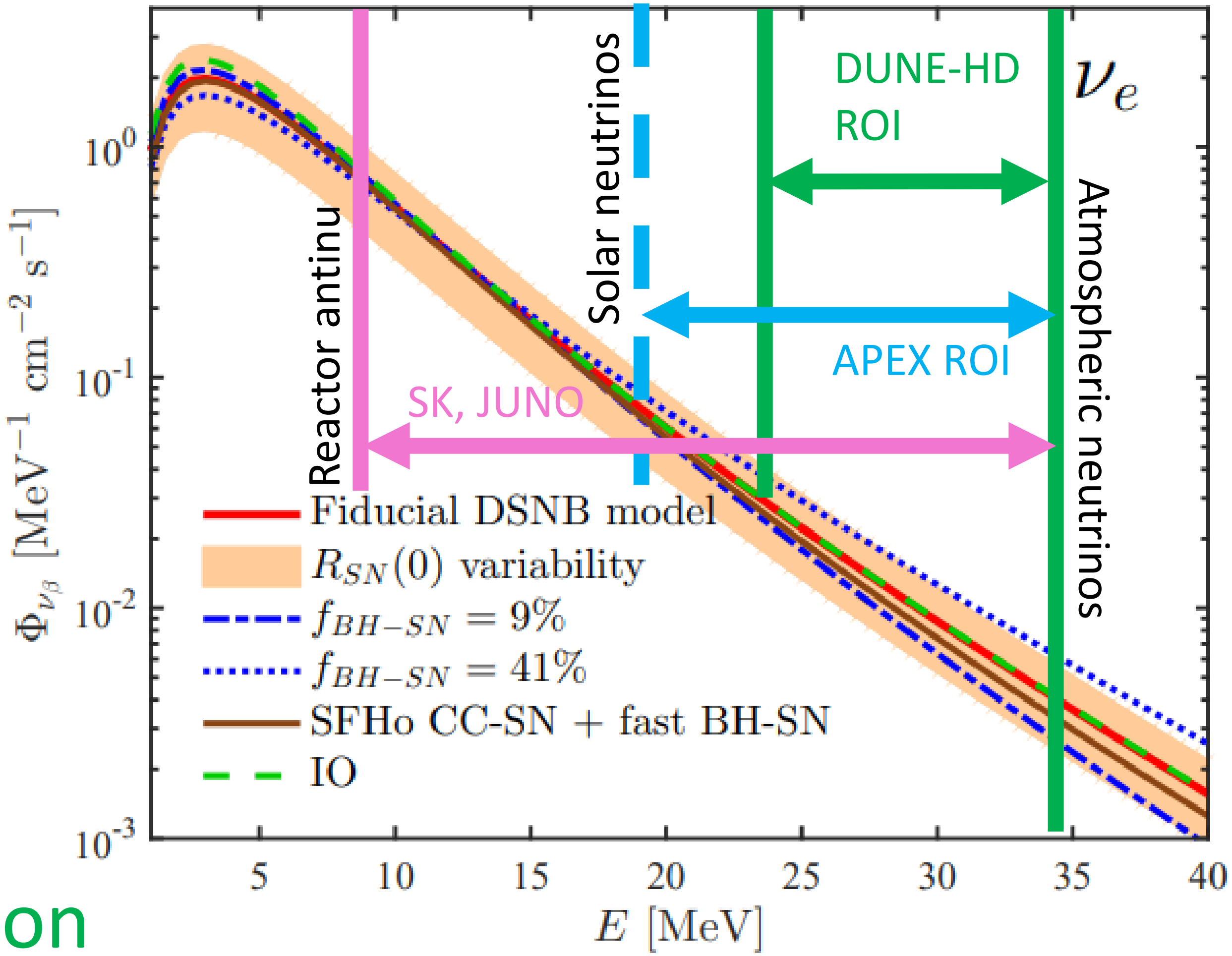
$$\frac{d\Phi}{dE} = \int_0^{z_{max}} R_{SN}(z) \times \frac{dN(E'_\nu)}{dE'_\nu}(1+z) \times \left| c\frac{dt}{dz} \right| dz$$

Neutrino spectrum released by supernova (redshifted)

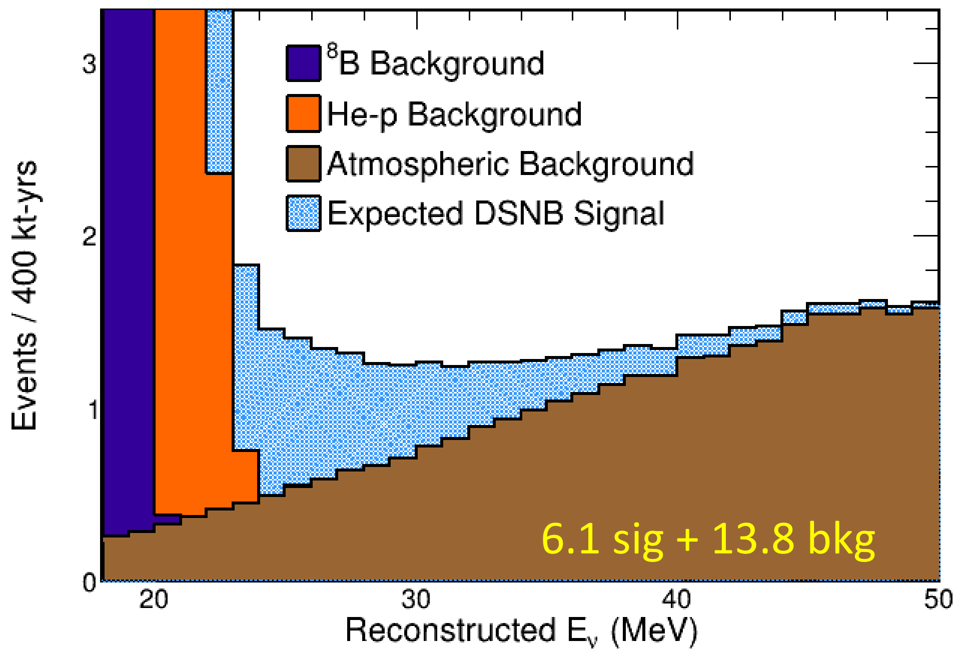
- DUNE has unique sensitivity to the neutrino component, but sensitivity is not great

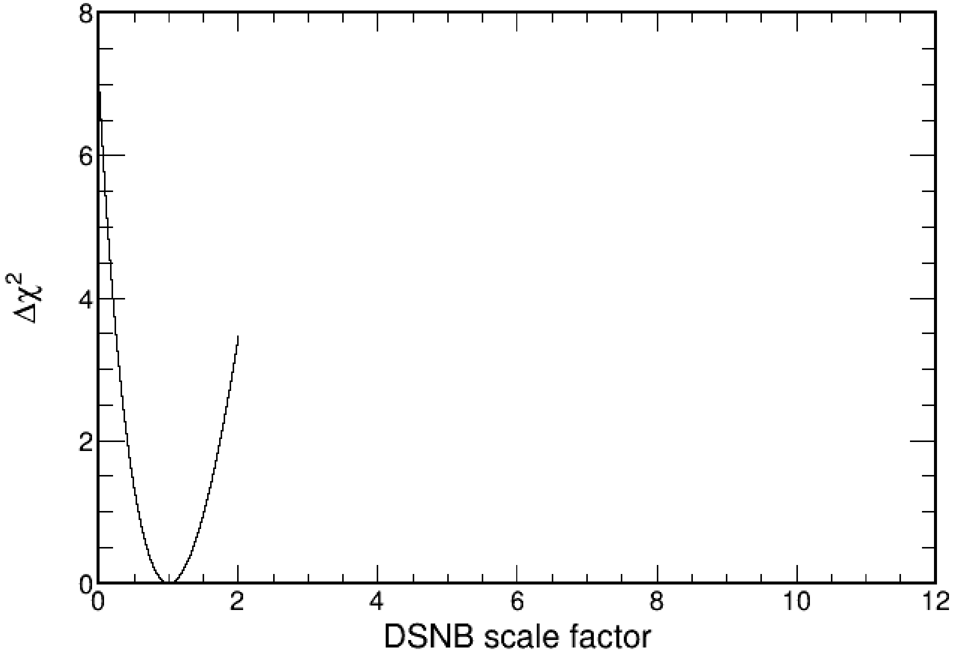
Diffuse supernova neutrinos

- Fundamentally easier for water, scintillator detectors sensitive to antineutrinos (ultimate bkg is reactor anti-nus vs solar nus)
- DUNE sensitivity is not great – right at detection level
  - However, DUNE can make interesting statement on f_{BH}
- APEX could improve outlook in two ways: improve energy resolution to tame backgrounds and push ROI to lower energy regimes



Sensitivity for DUNE-HD



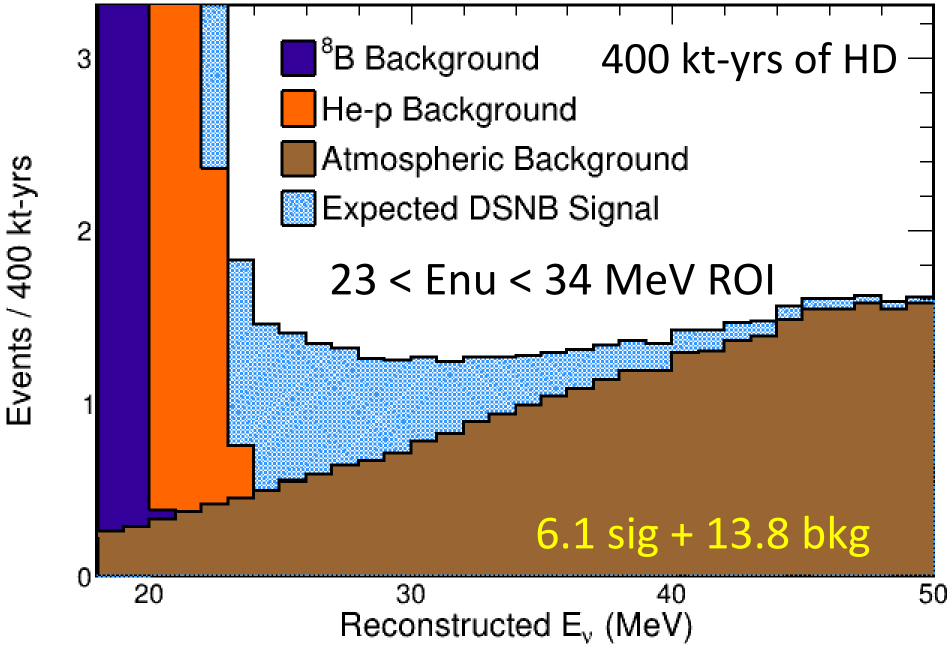


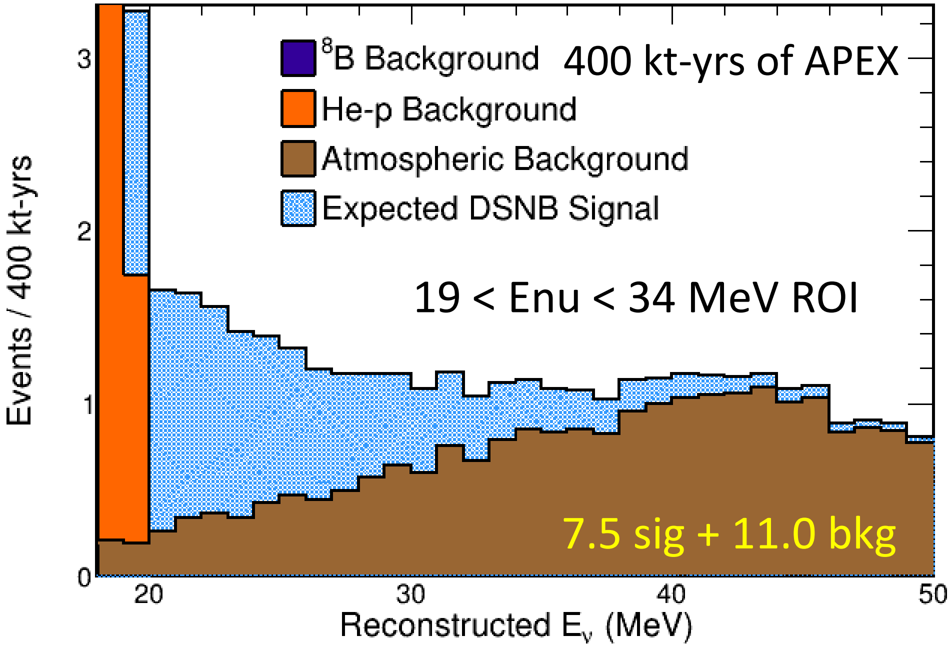
Using simulation as-is
Just at detection threshold: 2.6 σ @ 10 yrs

Models also predict exotics for solar/SN in this ROI such as dark matter

- DSNB is a faint signal and is sandwiched between irreducible solar and atmospheric neutrino background
  - Only see 0.5-1 signal / yr
  - No radiological bkg expected at these energies -> DSNB possible in DUNE

Blue-sky optimistic sensitivity for an APEX module





1: Energy resolution:
Min LY = 109 PE/MeV
-> Flavio at Collab. Meet.
Solar endpoint is 18.8 MeV
1/sqrt(19 * 109) = 2.2%
2: Tag 100% of atmos. bkg that emits a neutron
3: realistic efficiency for signal

- Much improved energy resolution and bkg rejection possible
- Lowers analysis region of interest, and increases FOM from 2.6 σ for 400 kt-yrs of HD to 4.1 σ for 400 kt-yrs of APEX
- APEX plot needs more realistic before being quotable

Interesting potential!
More study needed

Summary

- Many questions remaining that low-energy astrophysical neutrinos can address, and DUNE is unique sensitivity with ν_e sensitivity
- Quick studies suggest APEX-like improvements to PDS improves:
  - oscillations and solar mixing parameters
  - NSI searches with solar neutrinos
  - opportunity to measure SN ν_x flux with CEvNS
  - pre-SN neutrino
  - DSNB search
- Thank you for the opportunity to talk, low-energy physics is interested in your work! Collaboration helps understand the positive physics consequences from your hardware innovation