Astrophysical Neutrinos at SURF

Dan Pershey – Duke University

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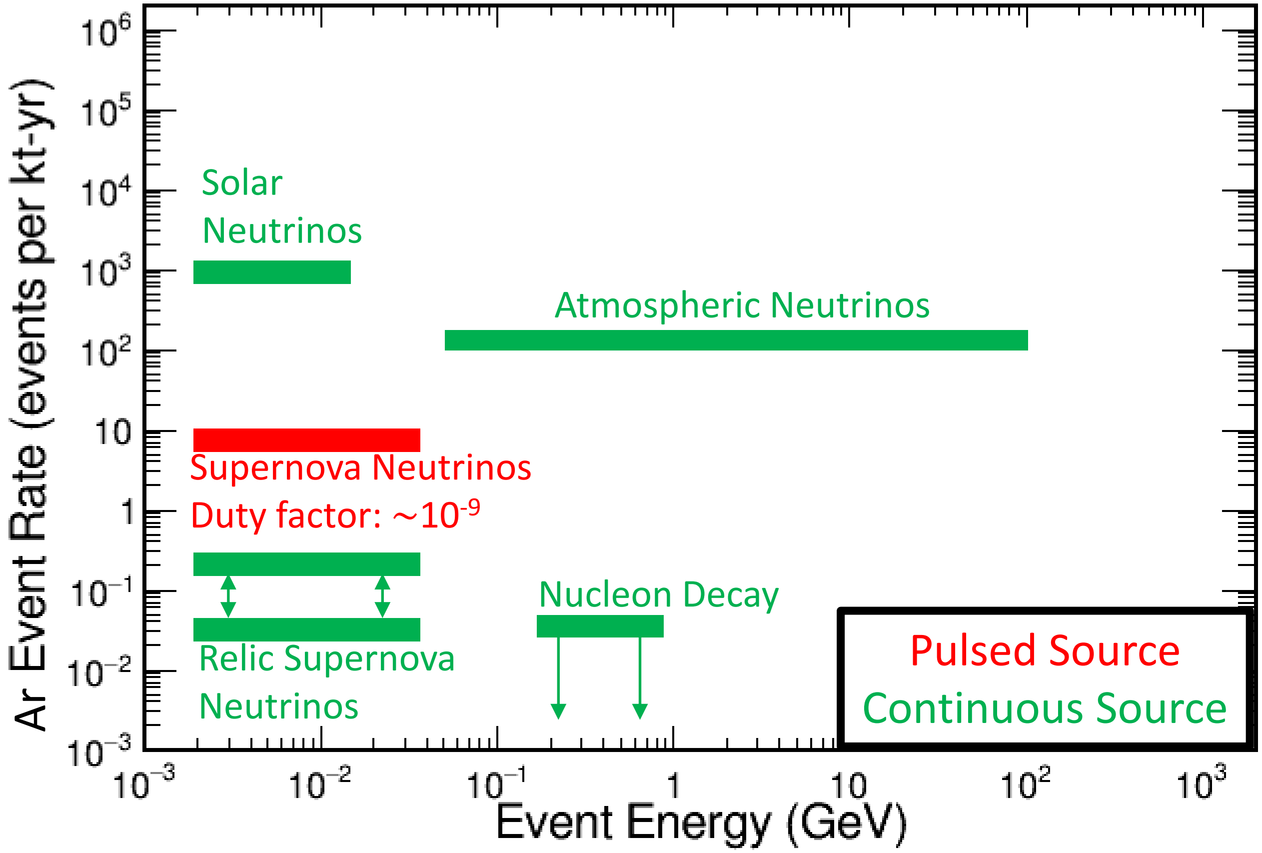
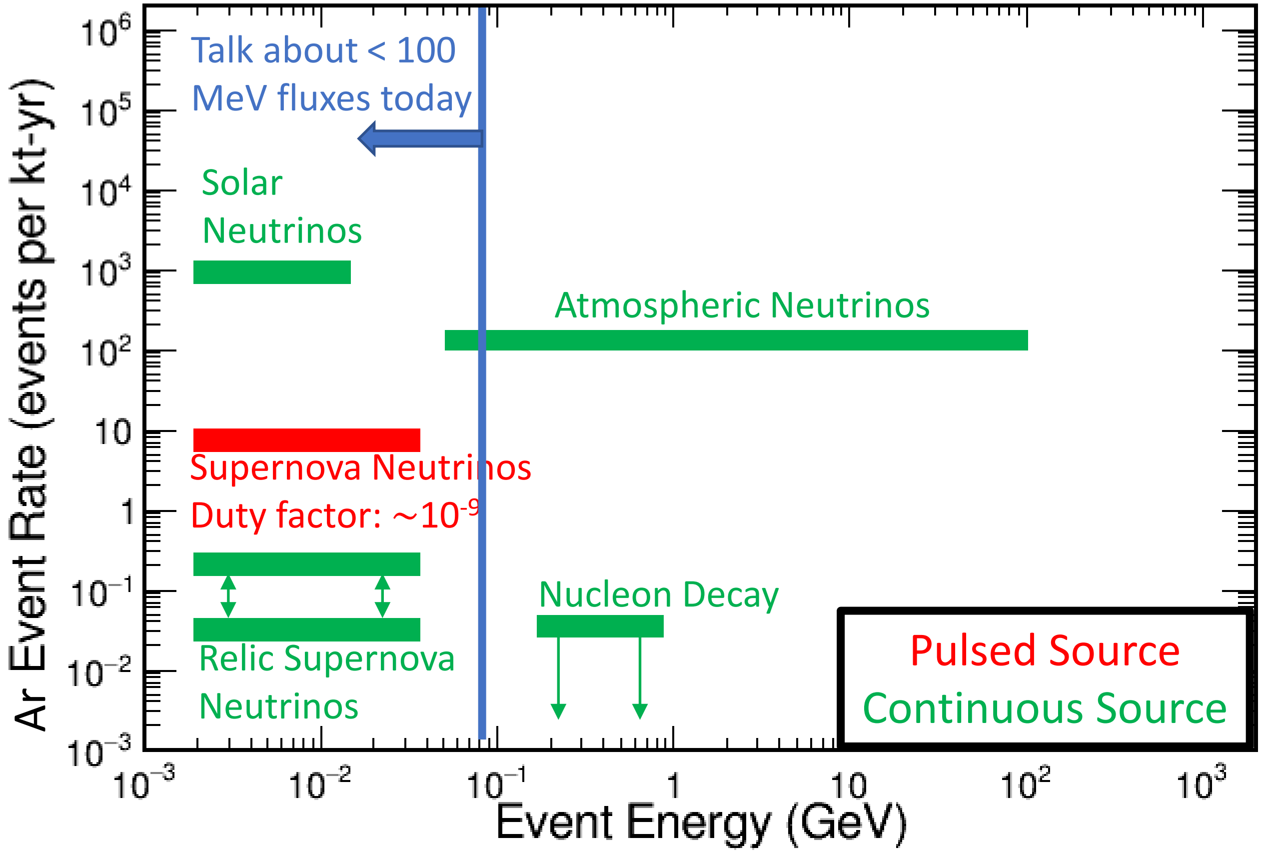
CoSSURF 2022 – Rapid City, SD

Astroparticle events in underground detectors



- Physics program accessible to underground detectors spans several orders of magnitude of energy and event rate
- Many additional physics searches not shown: dark matter, neutrino NSI, sterile neutrino, neutrino tridents, etc.

Astroparticle events in underground detectors



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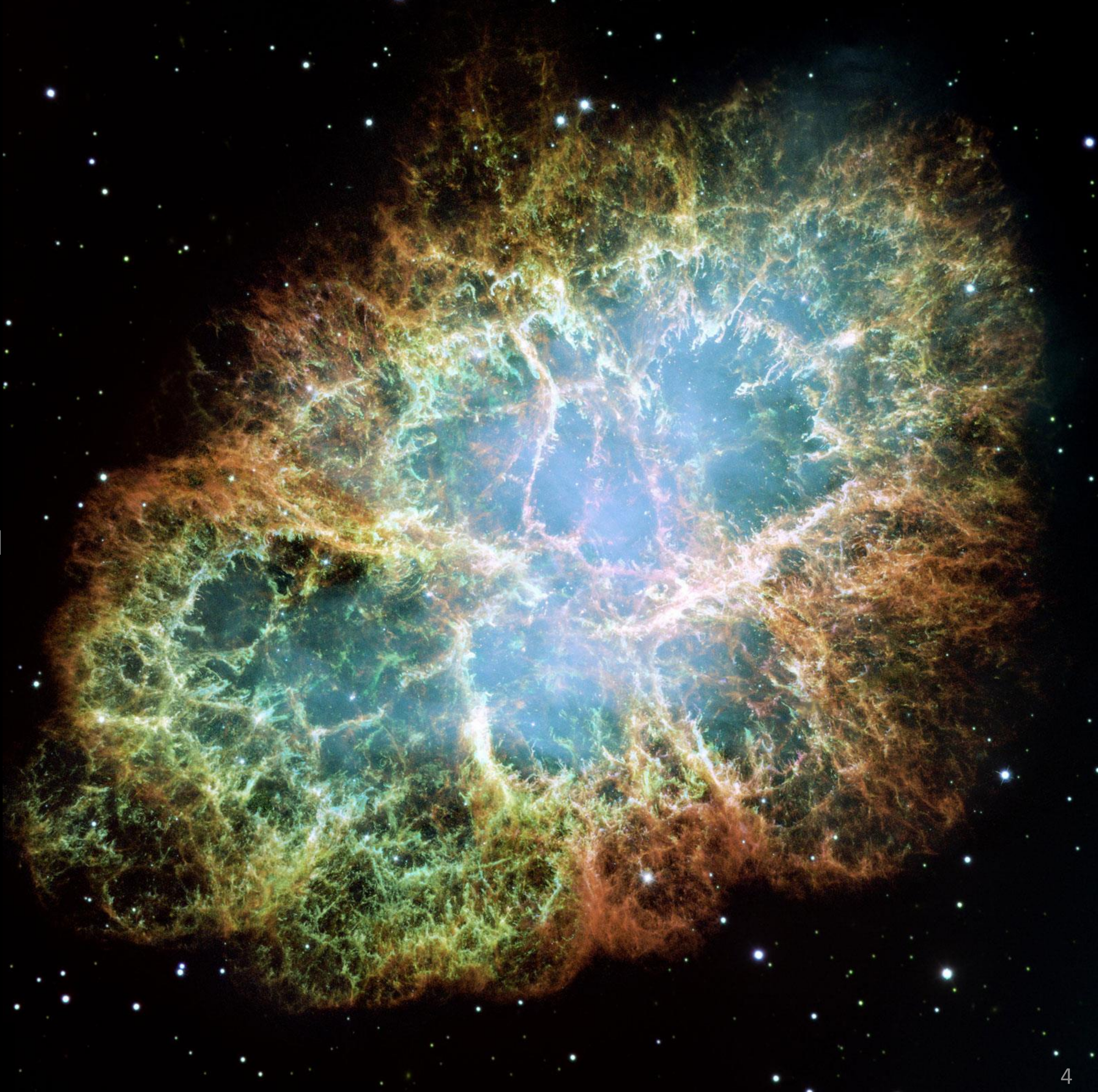
Supernova neutrinos

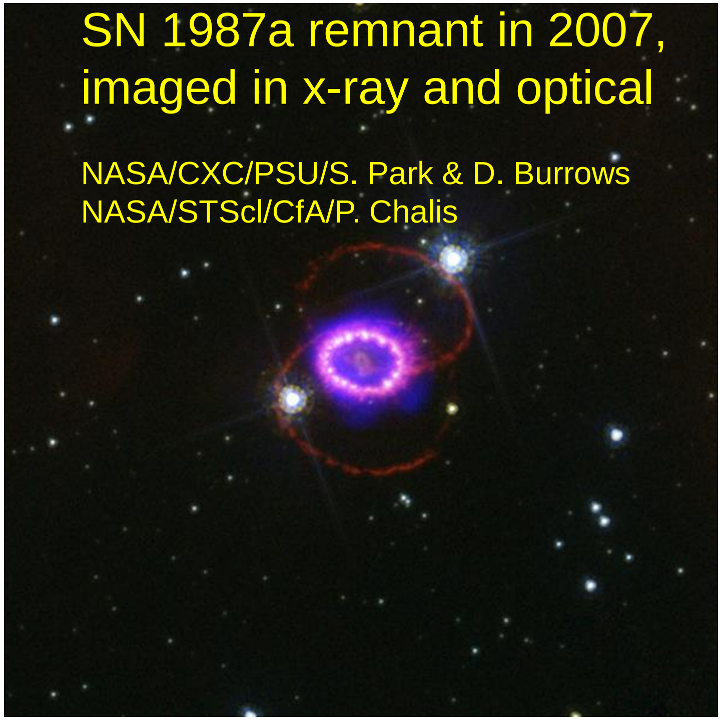
Crab nebula, remnant of supernova recorded in 1054



A core-collapse supernova

- When a star collapses, it releases its gravitational binding energy ($\sim 10^{53}$ ergs) as
  - Neutrinos (99%)
  - Light (0.01%)
  - KE of ejected matter (1%)
- Burst of neutrinos lasts ≈ 10 seconds
- 1-3 such events in our galaxy per century

- A single event would teach us:
- Astrophysics
  - Core-collapse mechanism, neutronization rate, neutrino diffusion, black hole formation, nuclear density in neutron star
- Particle physics
  - Neutrino magnetic moment, absolute mass, oscillations, sterile neutrinos



A burst of neutrinos was observed in supernova 1987a, associated with the death of a star in the Large Magellanic Cloud

$\approx 20\ \bar{\nu}_e$ interactions between Kamiokande, IMB, and Baksan

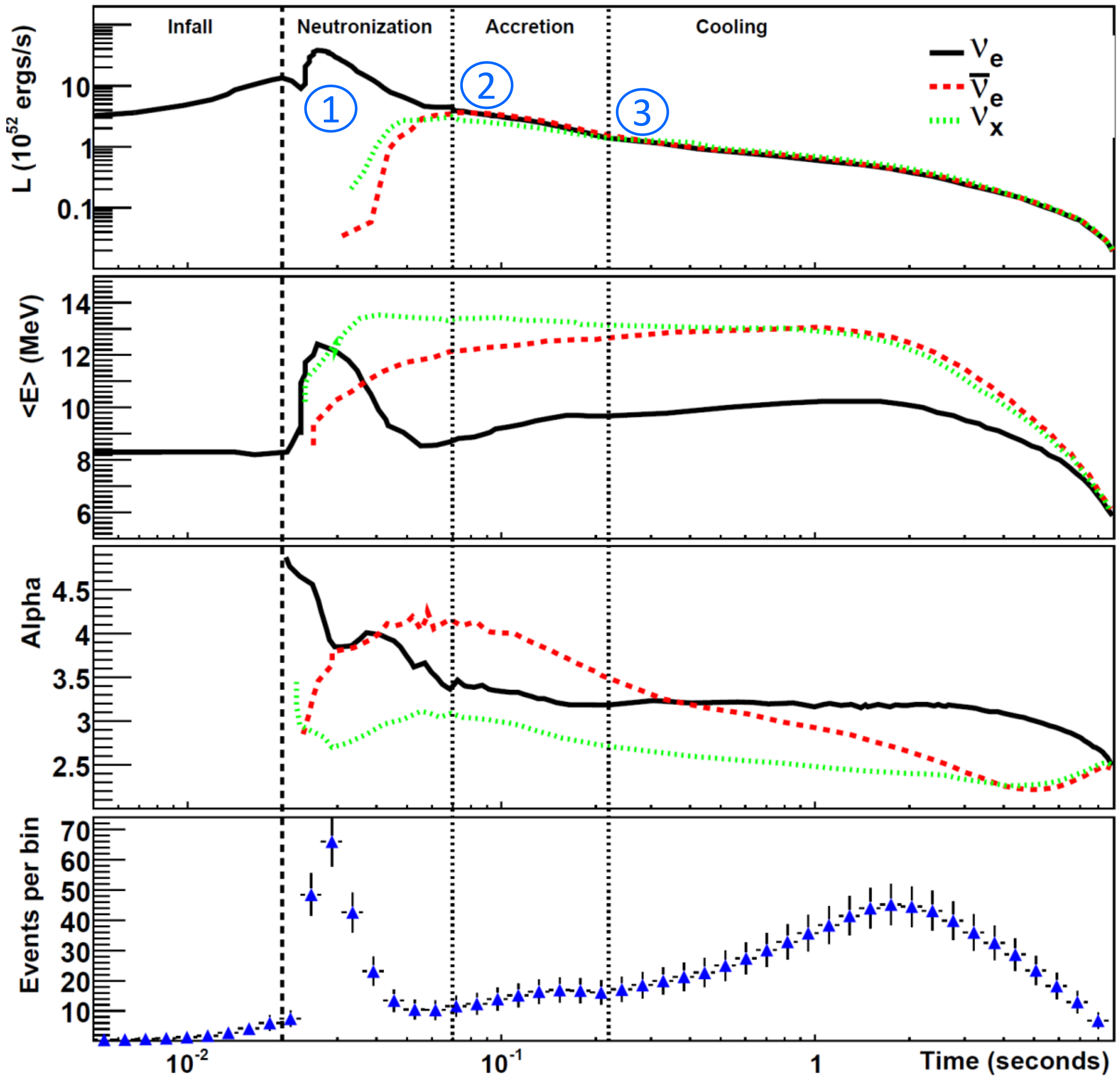
Neutrino production in a supernova

1. Neutronization through electron capture in the core gives a short-lived, intense flash of ν_e

2. Neutrino production then dominated by matter falling into the core

3. Emission then slowly cools as neutrinos diffuse

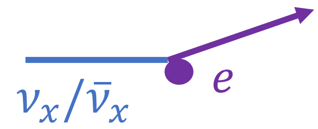
Detectors on Earth see handful to several thousand events from a galactic supernova to collapse model



Interactions of supernova neutrinos

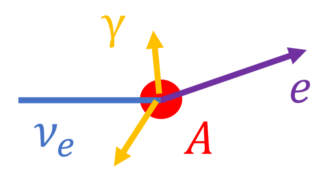
Electron scattering (ES)

- $\nu_x + e \rightarrow \nu_x + e$
- Pro: pointing – e/ν directions correlate
- Different cross section for ν_e/ν_x



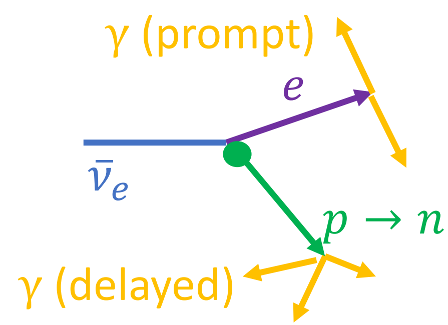
Charged current on nuclei (CC)

- $\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$
- Pro: calorimetry – e/ν energies correlate
- Nucleon / gamma emission possible



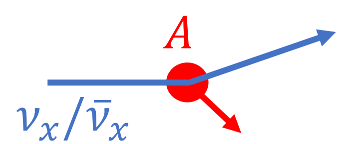
Inverse beta decay (IBD)

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- Correlated n capture for bkg rejection
- Low energy threshold, ≈ 2 MeV



Coherent elastic neutrino-nucleus scattering (CEvNS)

- $\nu_x + A \rightarrow \nu_x + A$
- Low-energy nuclear recoil hard to detect
- NC process treats all flavors equally



Supernova detection strategies

Water Cherenkov

IBD + ES
Cheap, reliable technology
Scalable – Mt-scale detectors giving enormous datasets
Current experiments: Super-Kamiokande (SK), IceCube
Future experiments: Hyper-Kamiokande (HK)

Liquid scintillator

ES + CC + NC + IBD
Good energy resolution for calorimetry
Current experiments: SNO, NOvA
Future experiments: JUNO

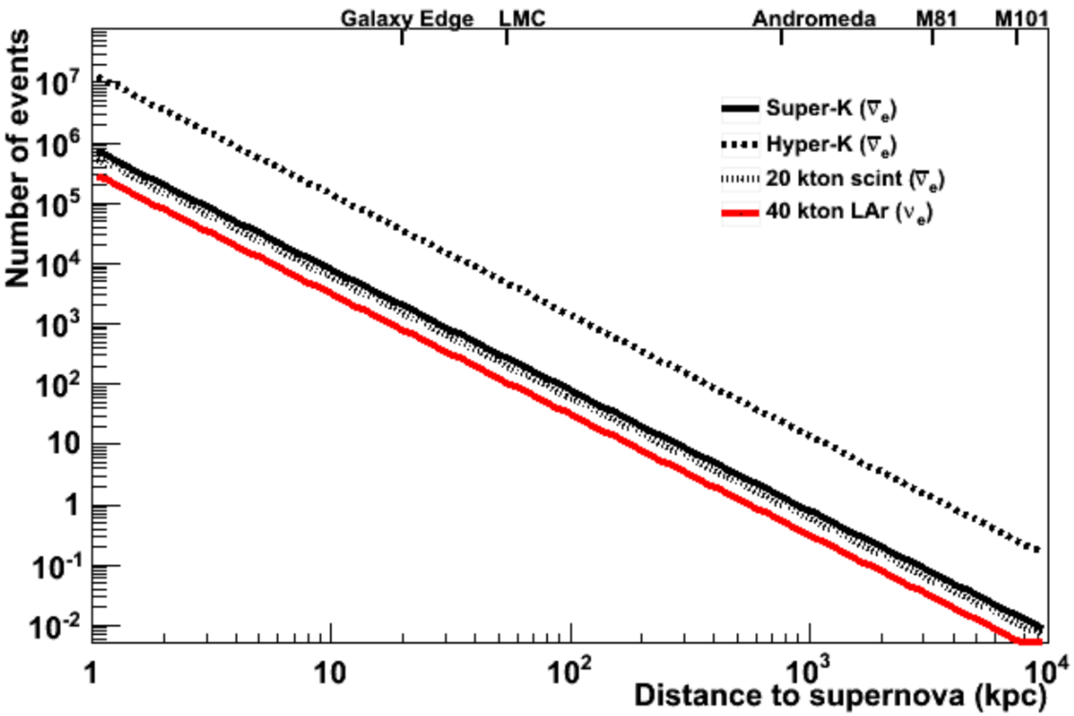
Nobel elements

CC + CEvNS
Ar TPC experiments give fantastic tracking resolution
Xenon TPC experiments give very low event threshold
Significant activity at SURF with DUNE (future) and LZ (current)

Supernova event rates

Would see 4-100 thousand events from galactic star in future large-scale supernova detectors

Bursts from Andromeda observable with HK



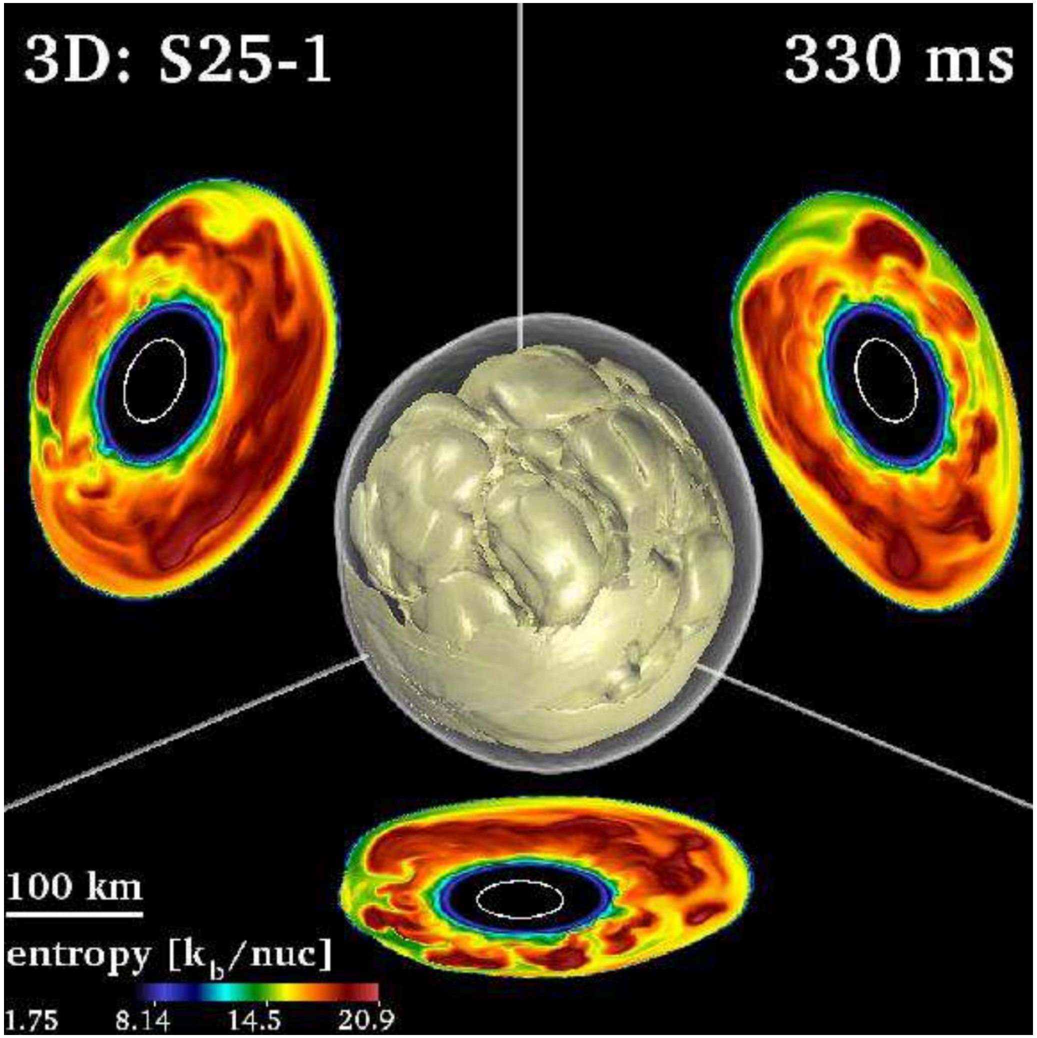
Channel	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

Example: DUNE
Will see a few thousand events from galactic supernova mostly from CC and ES channels

Supernova flux model: PRL104 (2010) 251101

Understanding the collapse mechanism

- ❑ Very complex system with 3D modeling of shock wave only possible in last 10 years
- ❑ Offers precise prediction for neutrino rates that can be tested with a new, large-dataset observation

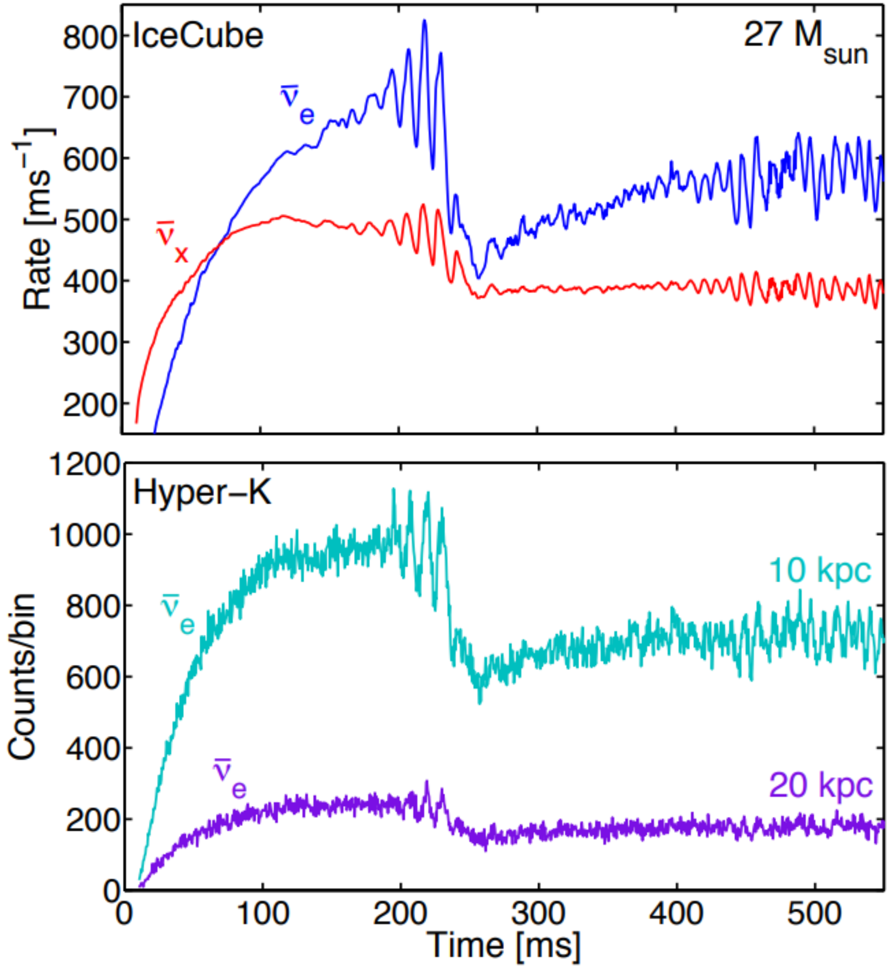


ApJ **770** 66

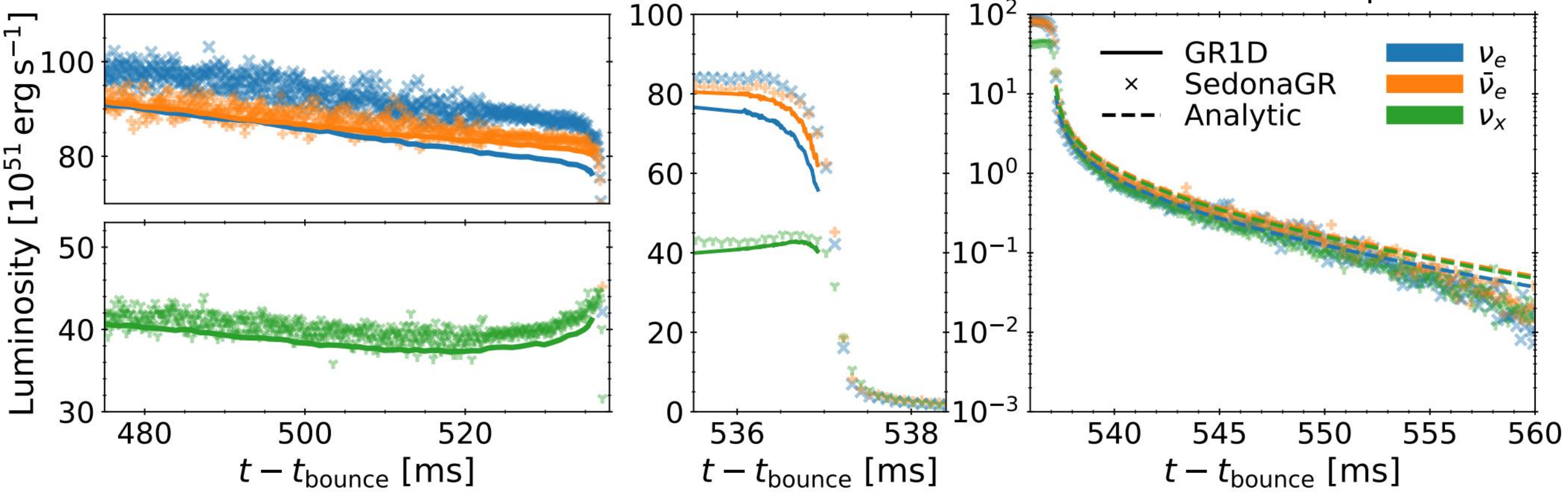
SASI oscillations

- Supernova collapse model and simulations suggest an oscillating rate of neutrino production in the first second of the explosion
- Related to turbulence in the neutrino heating in the star leading to standing accretion shock instability (SASI) oscillations
- Observing these oscillations would validate the basic collapse model and probe the oscillation frequency, a measure of the progenitor mass

PRL **111**, 121104



Detecting black hole daughters



- The neutrino signal can discriminate between neutron star and black hole forming supernova
- During black hole formation, an event horizon is created about 0.5s after the start of the collapse quickly quenching the neutrino flux
- Subsequent tail of neutrino flux arising from neutrino scattering between source and Earth

Supernova pointing

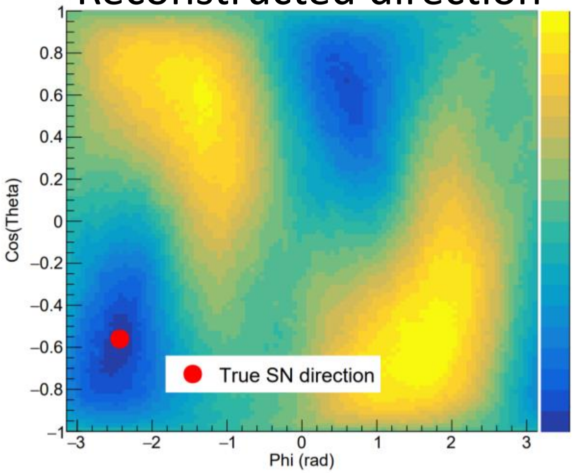
1987 supernova, Anglo-Australian Observatory

- ❑ Studying the light signal from the supernova also interesting from the beginning of the collapse through several months after explosion
- ❑ The neutrino burst arrives at Earth $\approx$hour before light from the explosion and can warn optical astronomers of an event and tell them where to look
  - Neutrino signal facilitates multi-messenger study of supernovae

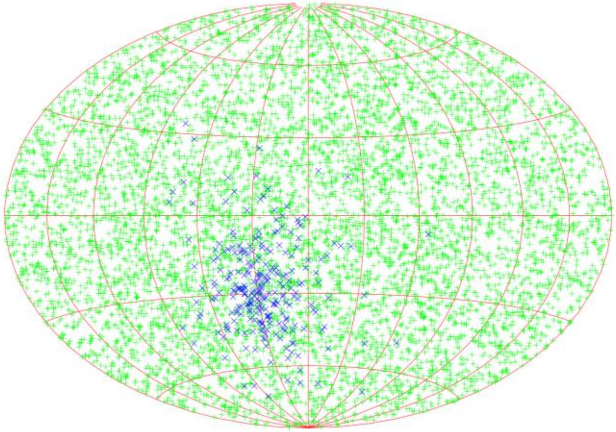
Strategies to estimate supernova direction

- The electron and neutrino directions are highly correlated in an ES event

Reconstructed direction



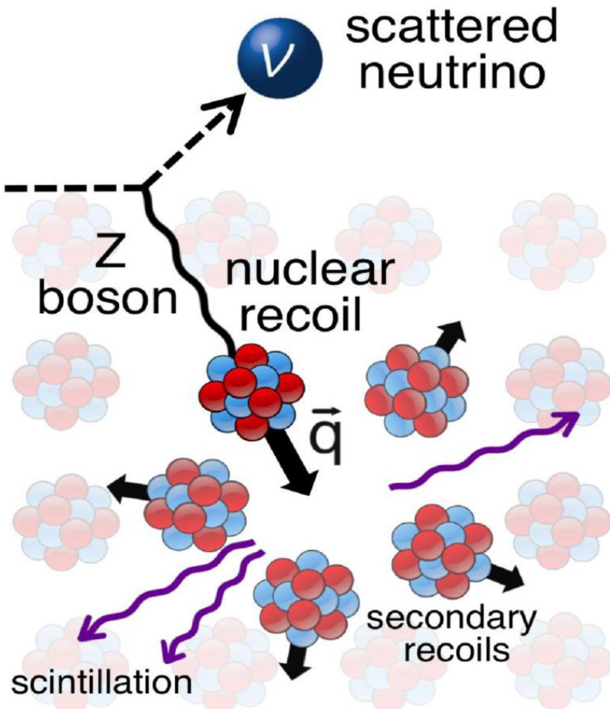
Liquid argon TPC detectors:
≈260 ES interactions
Interaction identification possible with excellent tracking resolution
Estimate ≈5 deg angular resolution



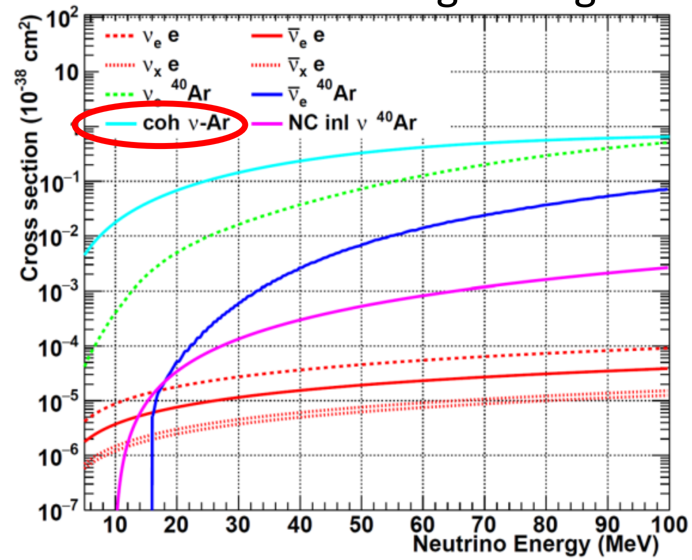
PRD **68**, 093013

Gd-loaded water Cherenkov detectors:
≈300 ES interactions
IBD rejection through coincidence with neutron capture
Estimate ≈2-3 deg resolution

CEvNS as a supernova detection channel

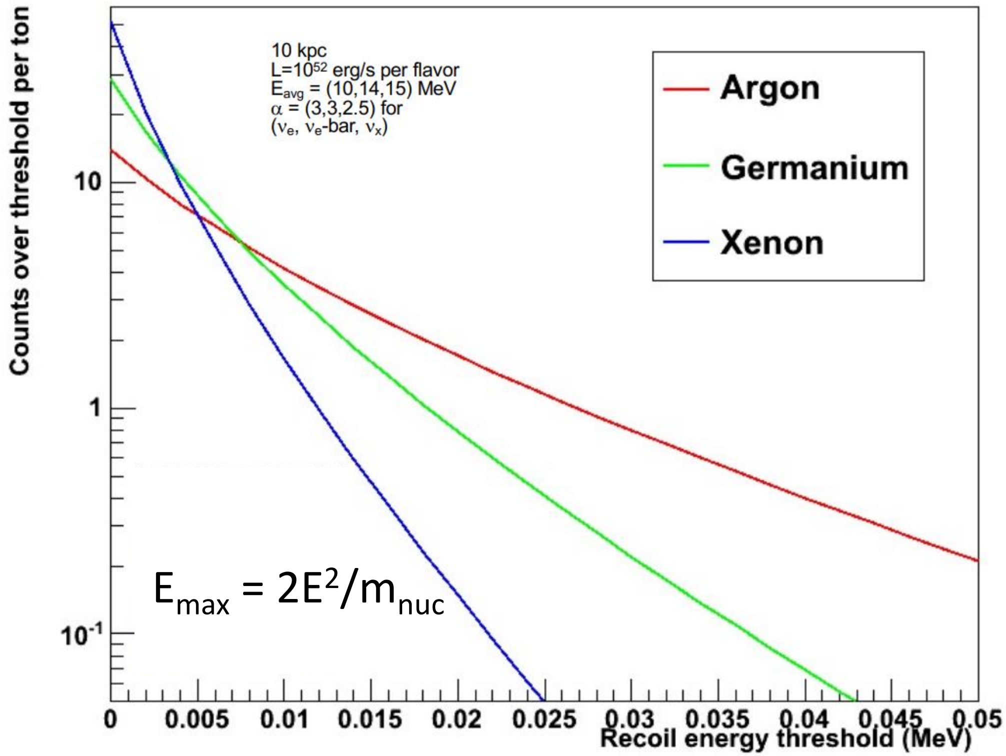


Neutrino scattering off argon



- ❑ Coherent elastic neutrino nucleus scattering (CEvNS) is a NC process where a neutrino kicks a nucleus giving it a small but observable recoil energy
- ❑ Very large cross section compared to low-energy neutrino processes
- ❑ NC → same cross section for all flavors advantageous for supernova

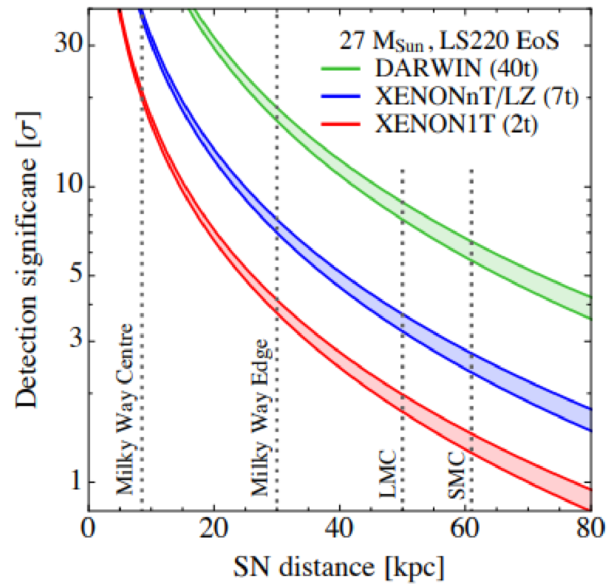
CEvNS recoils – low threshold detectors

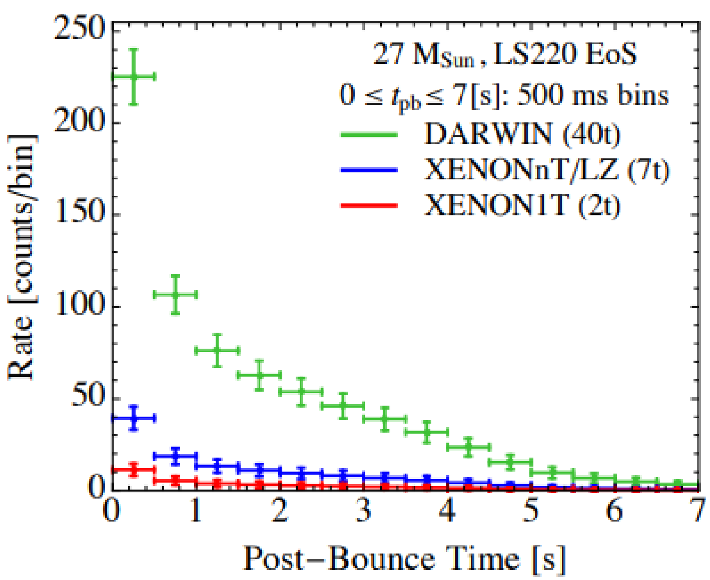


- The observable nuclear recoil is very low in energy < 100 keV for supernova neutrinos
- Trade-off: lower mass detectors can give valuable data if they have a sufficiently low threshold

CEvNS with Xe dark matter experiments

- DM experiments designed to observe coherent DM nucleus scattering and can detect individual CEvNS events from a supernova
- Though small mass, large cross section allows > 5σ discovery for any galactic supernova with current generation (LZ – 5.6t fiducial)
- Multi-ton detectors important for global data of the next supernova





- Expect > 100 detected CEvNS events from the next galactic supernova
- Since CEvNS is NC, the time trace gives the total neutrino flux at a given time without uncertainties on evolution of flavor composition

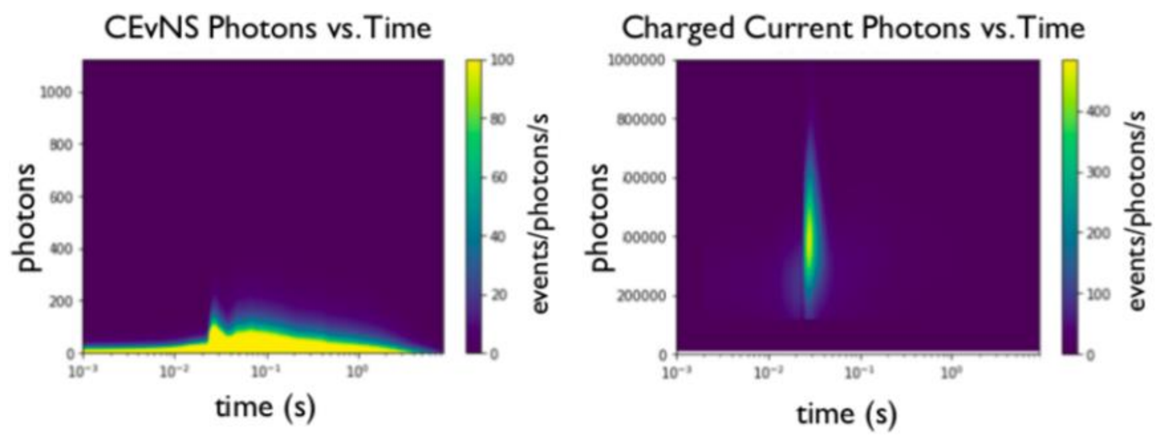
Phys Rev **D94** 103009 (2016)

CEvNS in DUNE – the CEvNS glow

- CEvNS events are below threshold in DUNE, but they will interact in the argon and make a significant amount of light
  - ≈100x as many CEvNS compared to CC from cross section
  - ≈6x as many CEvNS compared to CC from using all flavors in flux
  - ≈0.001x as much visible energy per event (10 keV vs 10 MeV)
  - ≈0.2x quenching for nuclear recoils
- In all, expect about 10% as much light coming from CEvNS as the CC channel for DUNE
- Even if each CEvNS recoil is below threshold, the combined effect of CEvNS will give a measurable increase in scintillation in DUNE

Separating CEvNS and CC light in DUNE

A. Major and K. Scholberg, Preliminary



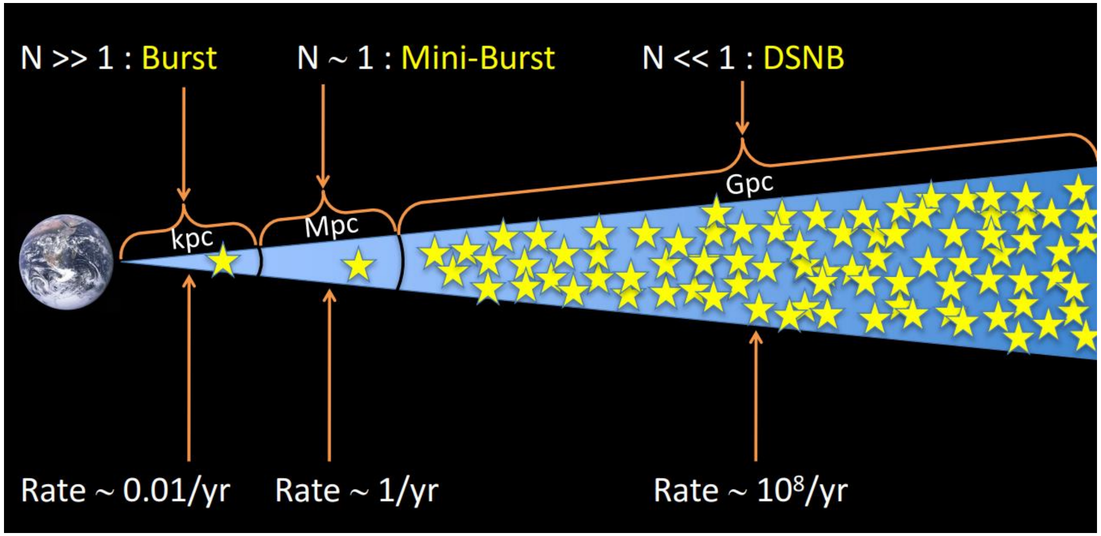
- ❑ Charged current and radiological backgrounds produce more scintillation
  - But their scintillation comes in infrequent spurts
- ❑ CEvNS events will be frequent, distributed over the duration of the supernova burst, and can be detected over background by looking at time slices with now more than a few detected photons

- ❑ Outlook promising, though still in development – new paper soon

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 $\propto r^2$
Two effects cancel out and the total flux of supernova events sums up to a finite contribution even at Gpc scales

Guaranteed signal! No waiting for burst



- A DSNB measurement gives information on typical supernova spectrum and can measure the fraction of supernovae that yield black hole daughters

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

Density of supernova events (/Mpc³/s)

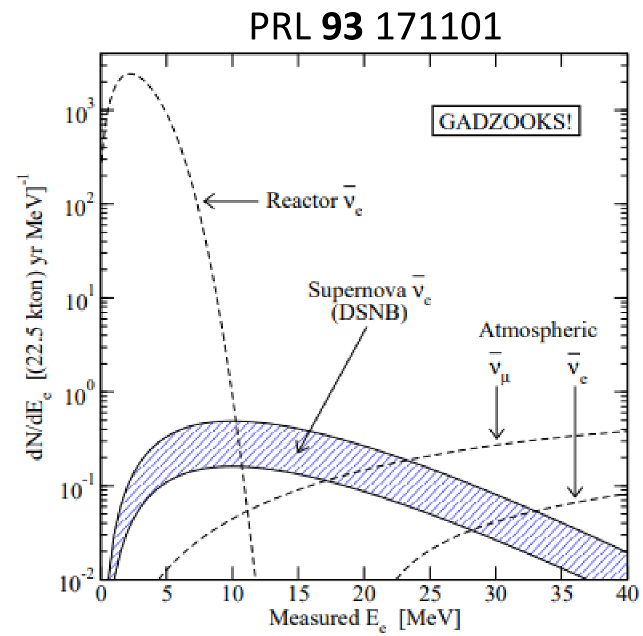
Neutrino spectrum released by supernova (redshifted)

Inflation effects

Searching for DSNB

- Most sensitive detectors search for $\bar{\nu}_e$ flux looking for IBD events
  - Water Cherenkov (SK/HK)
  - Liquid scintillator (JUNO)
- Major backgrounds are reactor and atmospheric backgrounds with a small window of DSNB visible with electron energies in the 10 – 25 MeV range

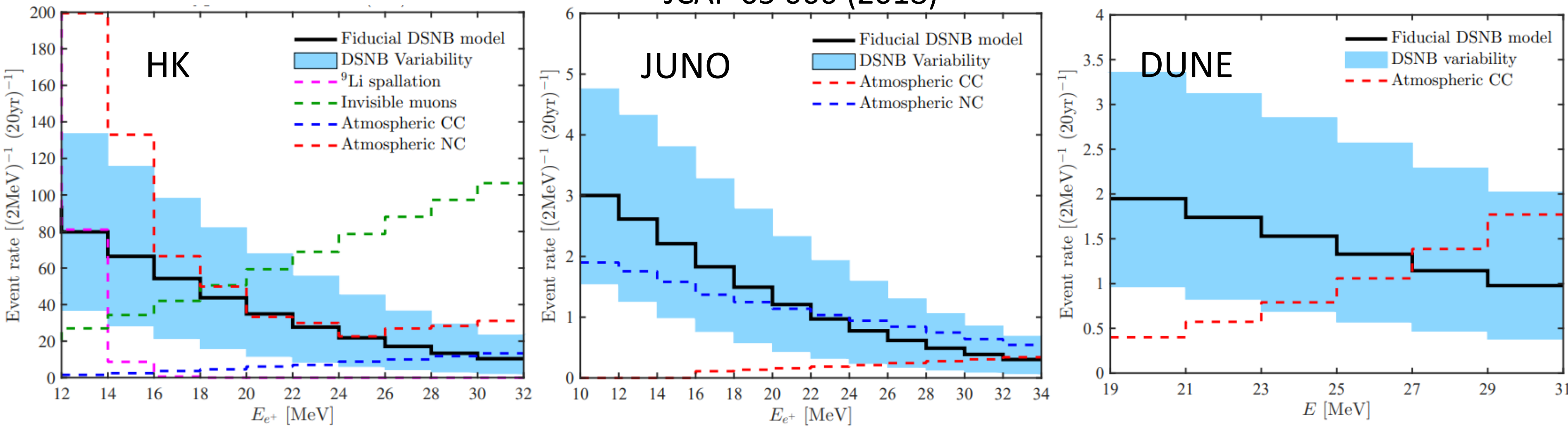
PRL **93** 171101



- Current best limit from SK is roughly 6x the center of theoretically predicted – not so far from a discovery
- Dominant background for SK comes from Michel electrons following a sub-threshold muon produced in an atmospheric interactions
  - SK loaded with Gd specifically for this measurement
  - Observable neutron from IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) will veto Michel electrons

Expected DSNB spectra

JCAP 05 066 (2018)



- In the next decade, we expect a meager collection of DSNB $\bar{\nu}_e$
  - SK-Gd – 4.1σ (S = 26 and B = 12)
  - JUNO – 2.7σ (S = 12 and B = 6)

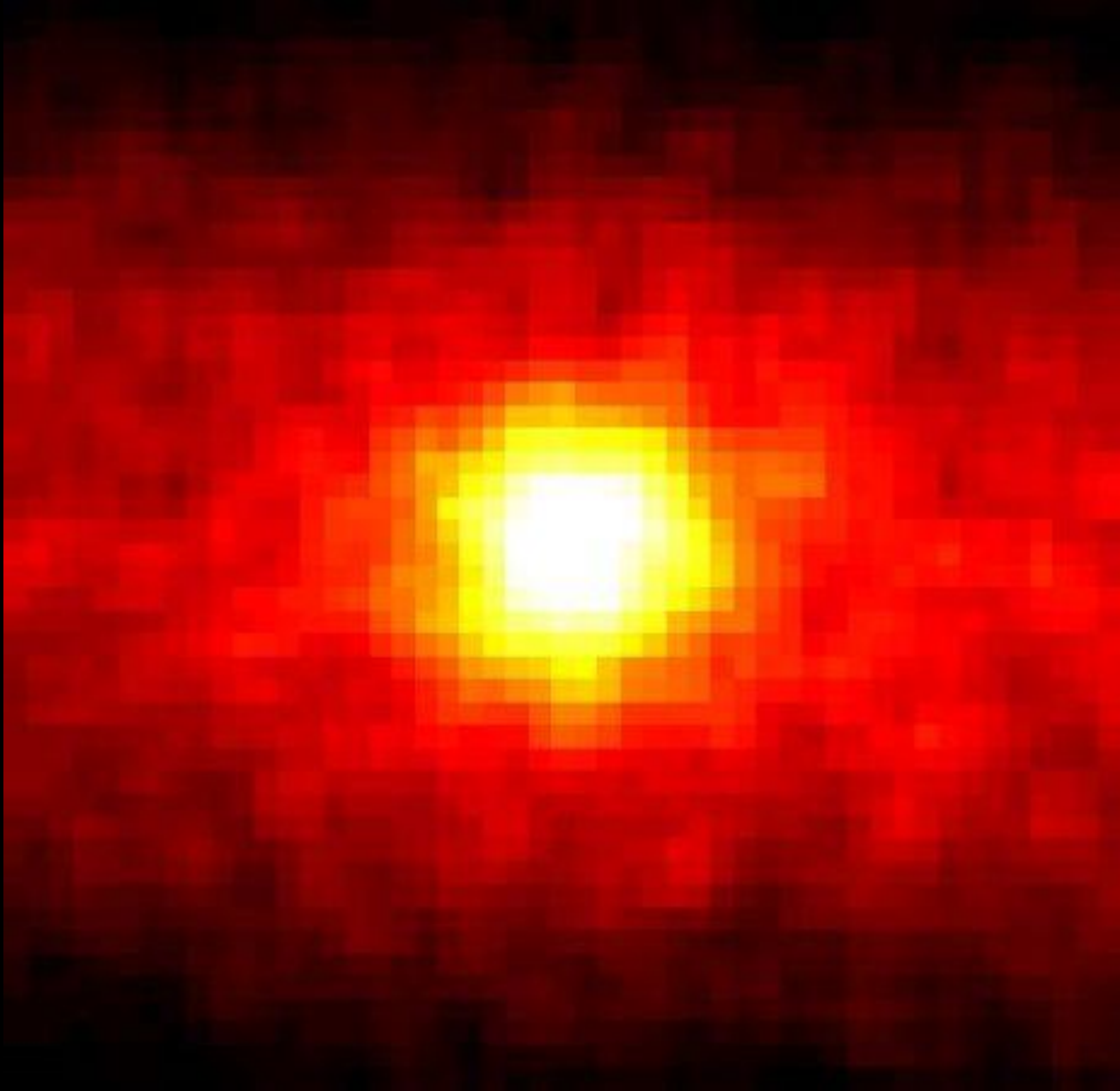
(arXiv: 2202.12920)

- Initial dataset will begin to answer astrophysics questions like typical energy of supernova neutrino

- DUNE sensitivity yet too be determined – more challenging solar neutrino background to reject – but would be only experiment sensitive to ν_e

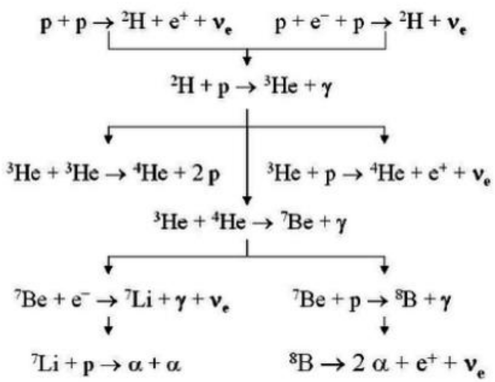
Solar neutrinos

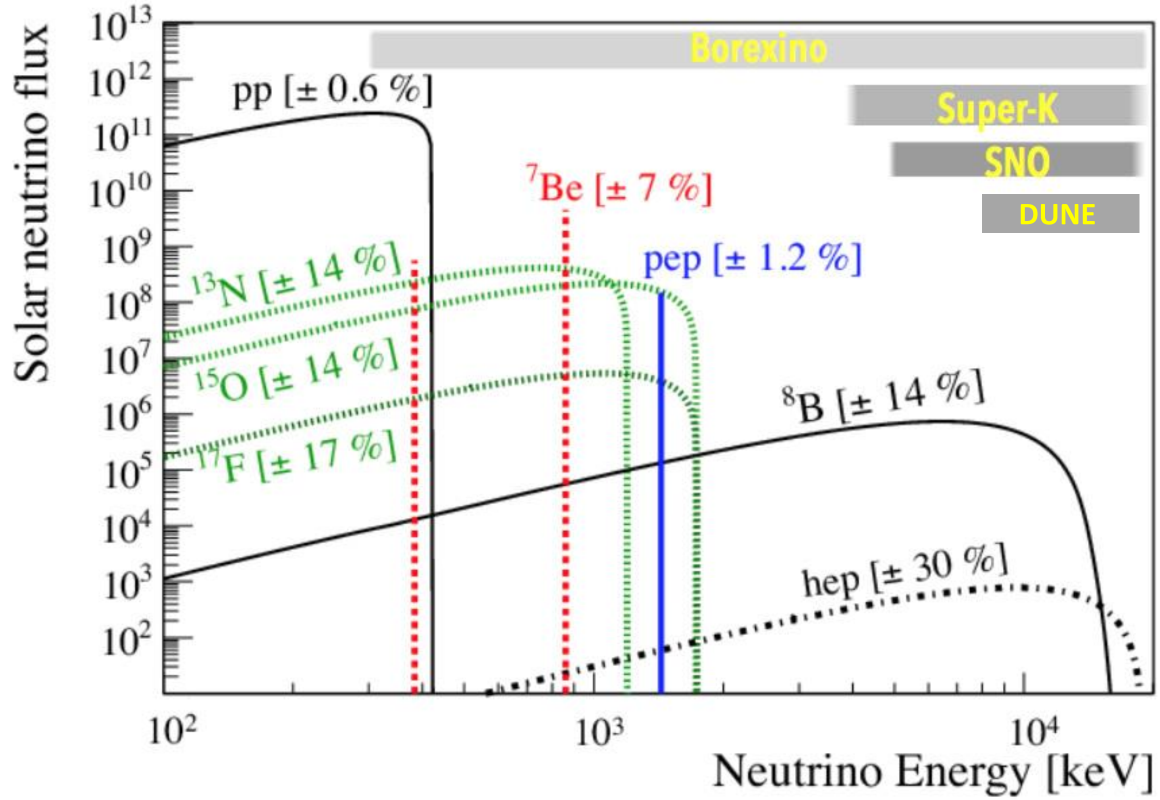
First photo of the sun taken from below a mountain –SK collaboration



Solar neutrino flux

^{4}He production in sun



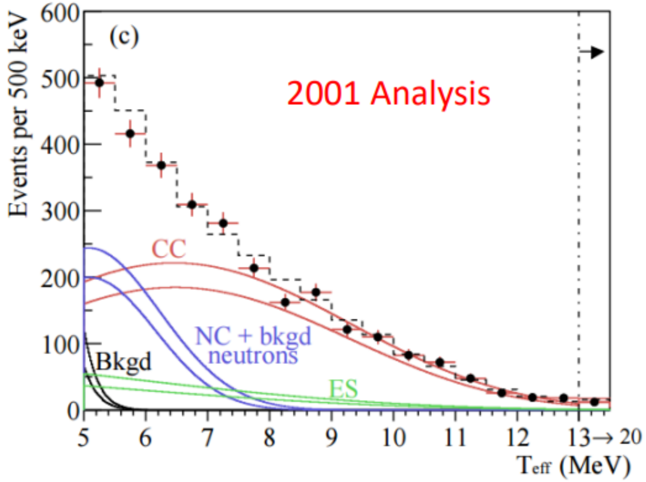


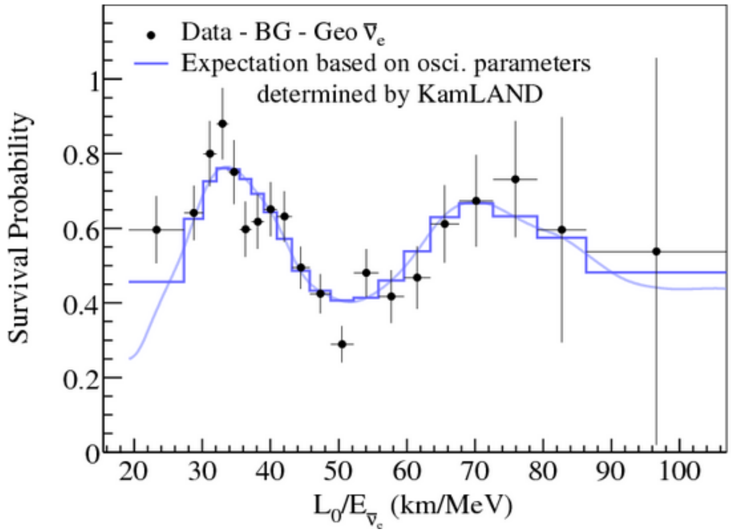
- The sun produces an enormous flux of neutrinos with energies < 19 MeV
- Only way to probe solar core and understand the interior fusion processes
- Solar neutrinos gave first evidence of neutrino oscillations / neutrino mass
- Though well-studied, several astrophysics and particle physics questions still remain

Neutrino oscillations with solar neutrinos

SNO and SuperKamiokande measured oscillations using neutrinos produced by our sun

SNO solidified oscillation hypothesis by simultaneously measuring CC/NC/ES components





KamLAND: measured oscillations using neutrinos from multiple reactors with similar baselines

Test of neutrino oscillations in a laboratory setting that confirmed L/E dependence

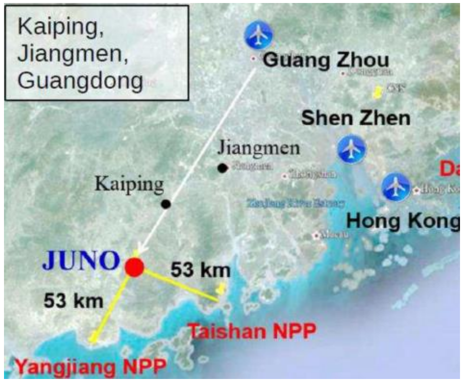
- Both solar and terrestrial reactor experiments observe neutrino oscillations, but disagree on the value of the mass splitting by 1.4σ
- This discrepancy may point to new physics such as BSM matter effects within the sun and should be tested with next-generation experiments

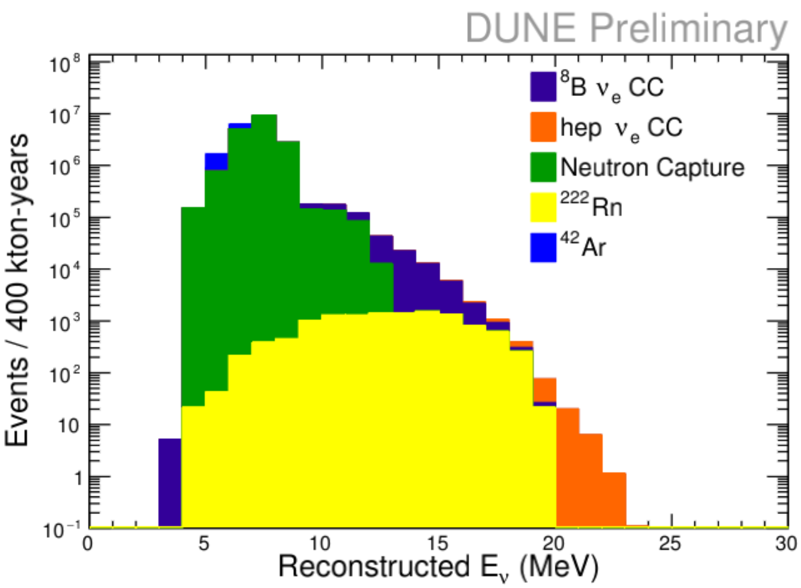
The next generation of experiments

Large sample, precision measurements!

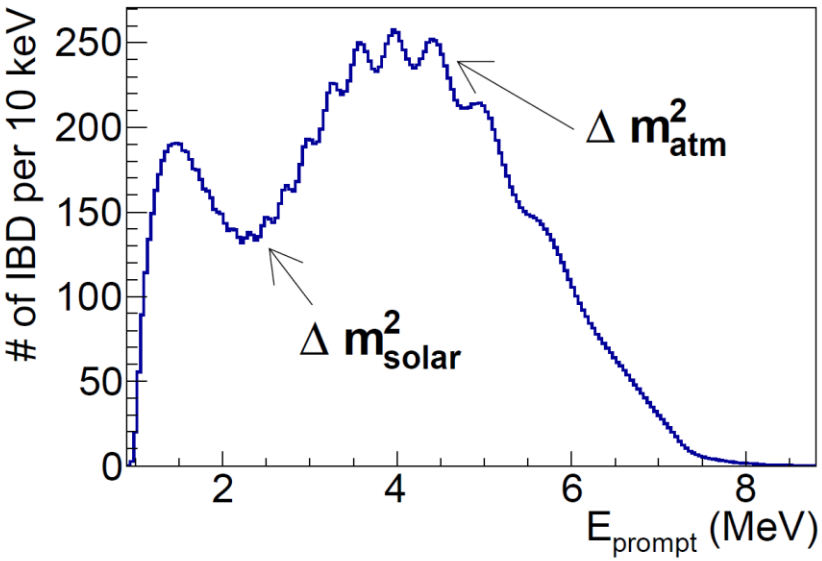
DUNE, in addition to supernova neutrinos, will also collect a large, > 10^6 CC event, sample of solar neutrinos

JUNO will detect neutrinos from nearby nuclear reactors studying oscillations with > 10^6 IBD events



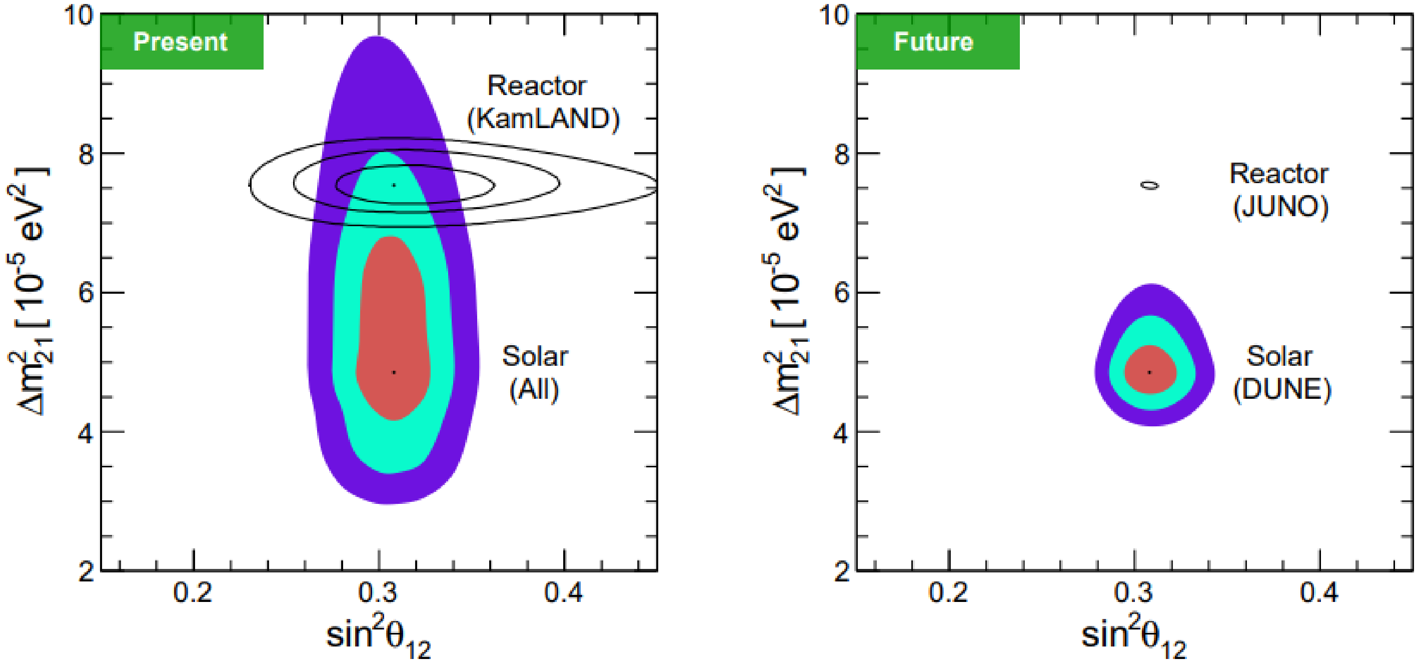


J. Phys **G43** 030401 (2016)



Future sensitivity to solar oscillations

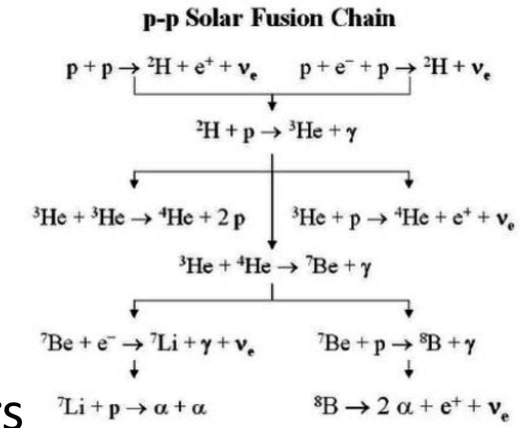
PRL **123** 131803

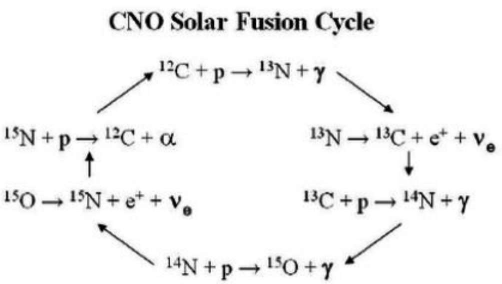


- Future data may resolve SNO/SK and KamLAND discrepancy at 5σ
- DUNE sensitivity largely comes from day/night effect – a partial regeneration of the ν_e flux due to matter effects in Earth
  - Also, the ratio is less sensitive to systematic errors
- Book isn't closed on solar oscillations – interesting data ahead!

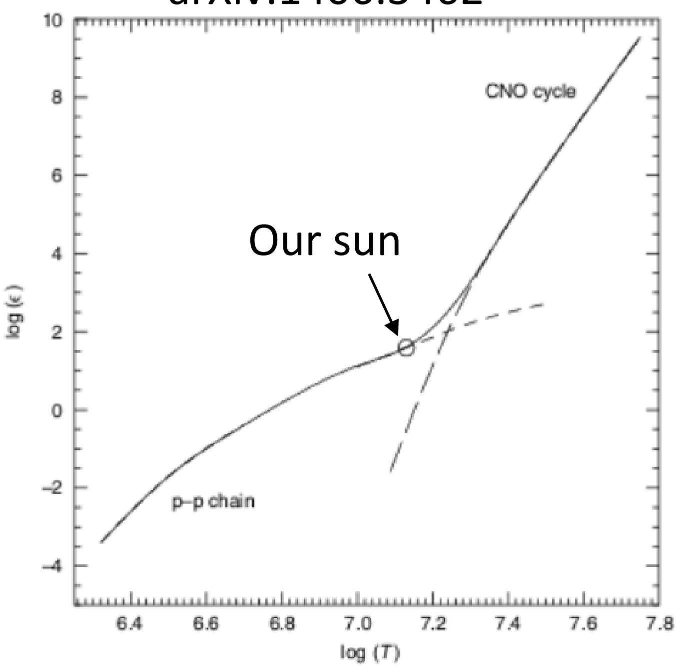
The CNO cycle

- There are two dominant fusion chains to produce ^{4}He in stars each with a characteristic neutrino flux
- Lighter stars use the pp-chain
- CNO-cycle dominates heavy stars



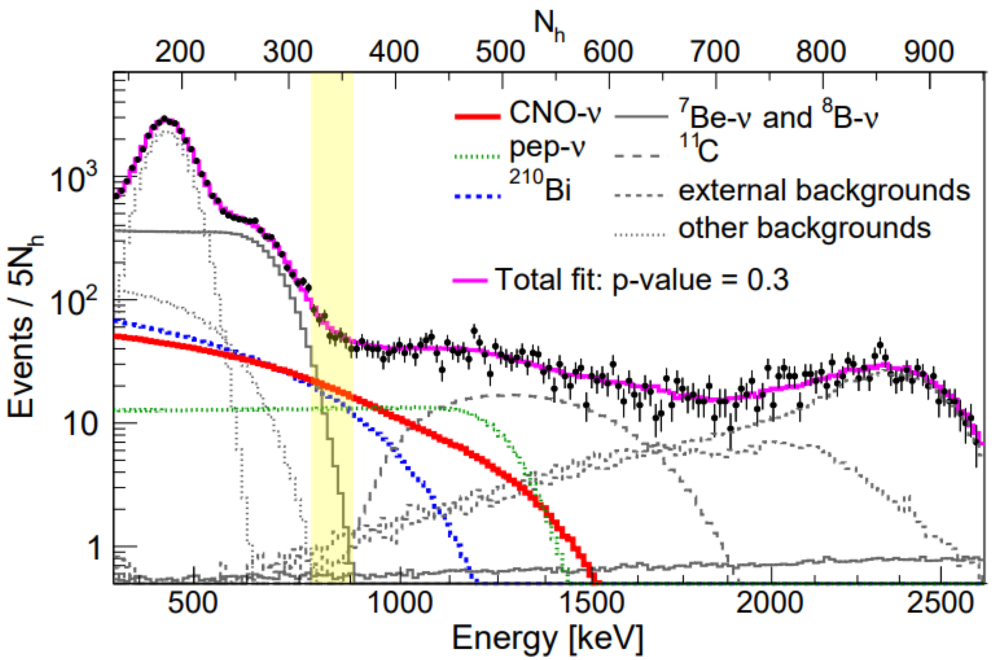


arXiv:1406.3462

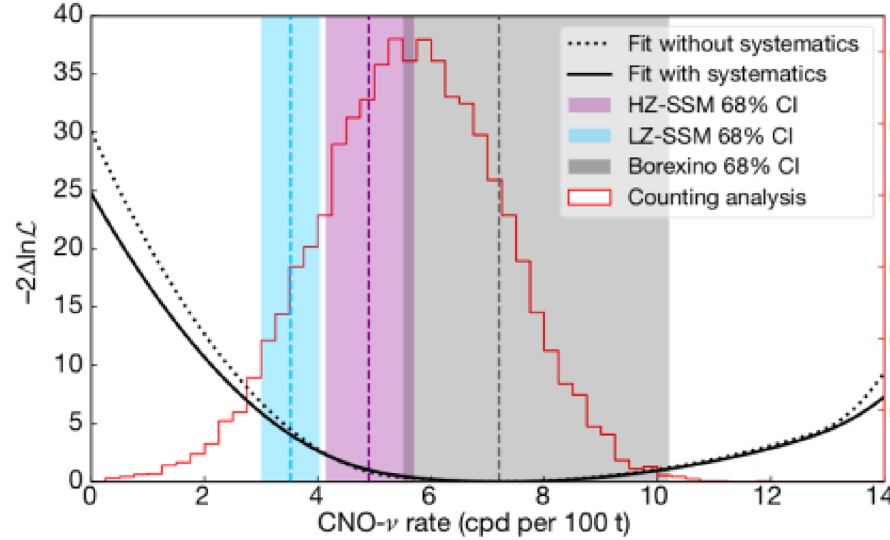


- The sun lies within the narrow mass range where both processes contribute
  - 99% pp-chain + 1% CNO-cycle neutrinos
- First measurement by Borexino in 2020
- Precision measurements of the CNO flux and normalization will validate solar model and improve understanding of other stars

Borexino: CNO discovery



Nature **587**, 577-582 and arXiv:2105.09211



- Borexino is a 100t scintillator detector at LNGS designed to study the
- Good energy resolution of electron recoils allows a small region of recoil energy where CNO dominates according to the standard solar model
- A likelihood fit gives 5σ evidence for existence of the CNO flux with a normalization consistent with expectations – though errors remain large

Thank you