Solar and Supernova Neutrinos at SURF

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CoSSURF – South Dakota School of Mines & Technology

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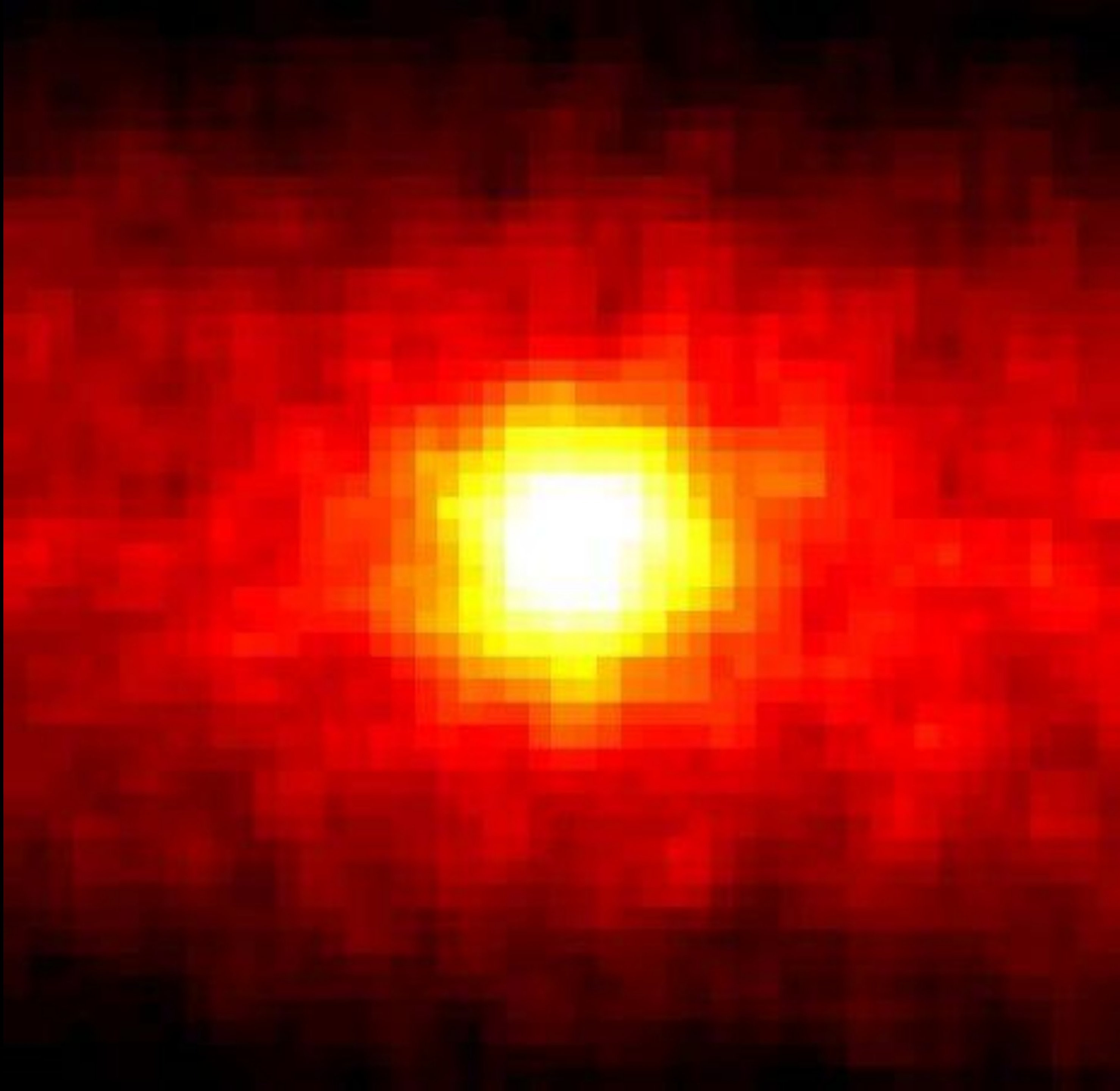
Solar neutrinos

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

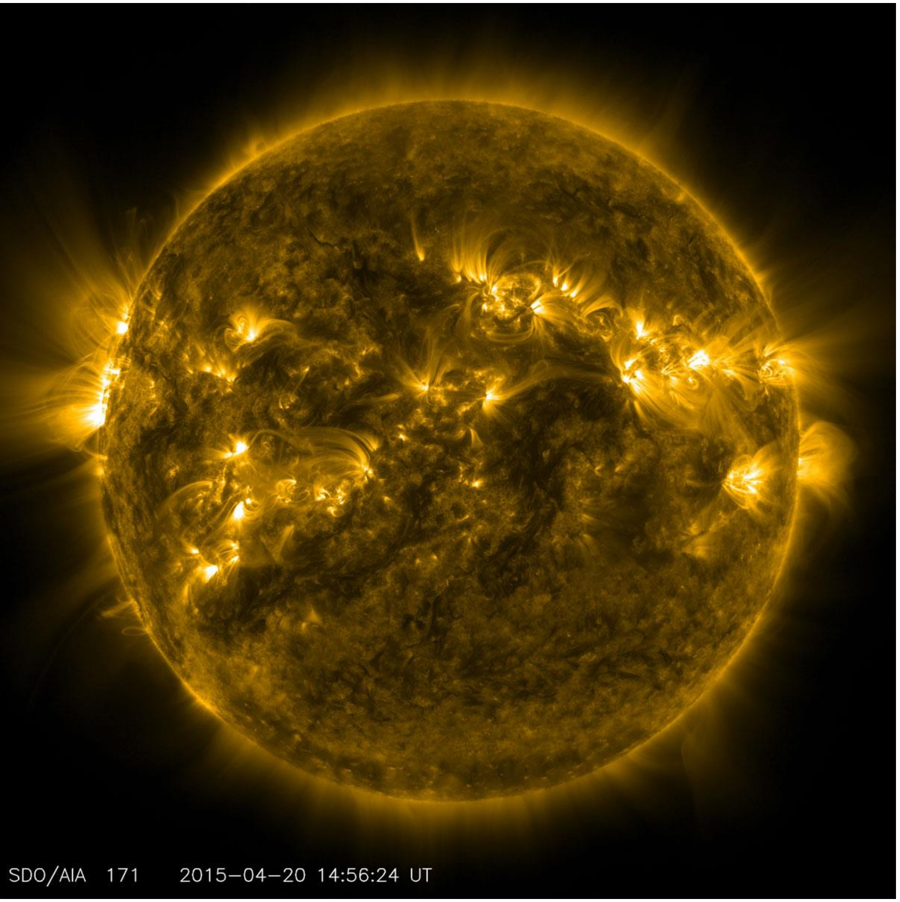


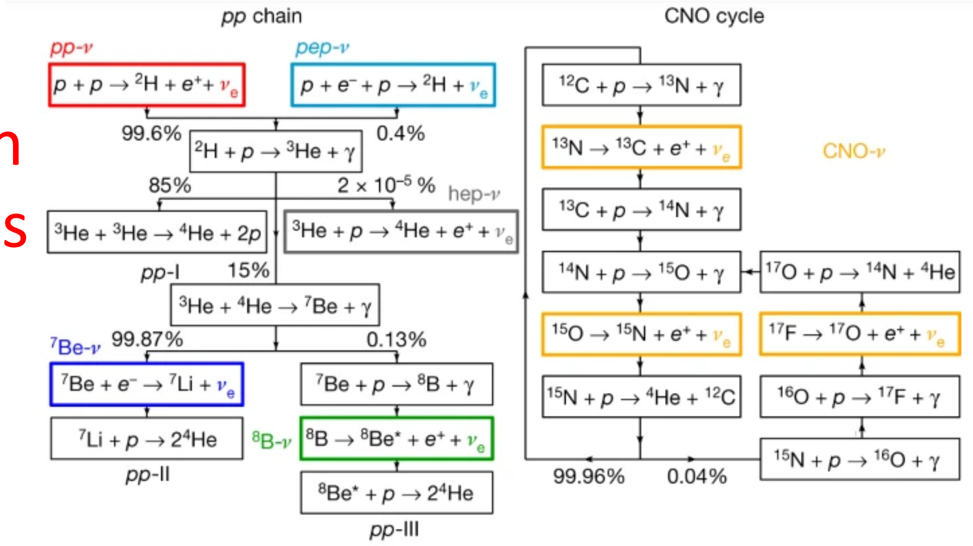
Hunting neutrinos from the sun

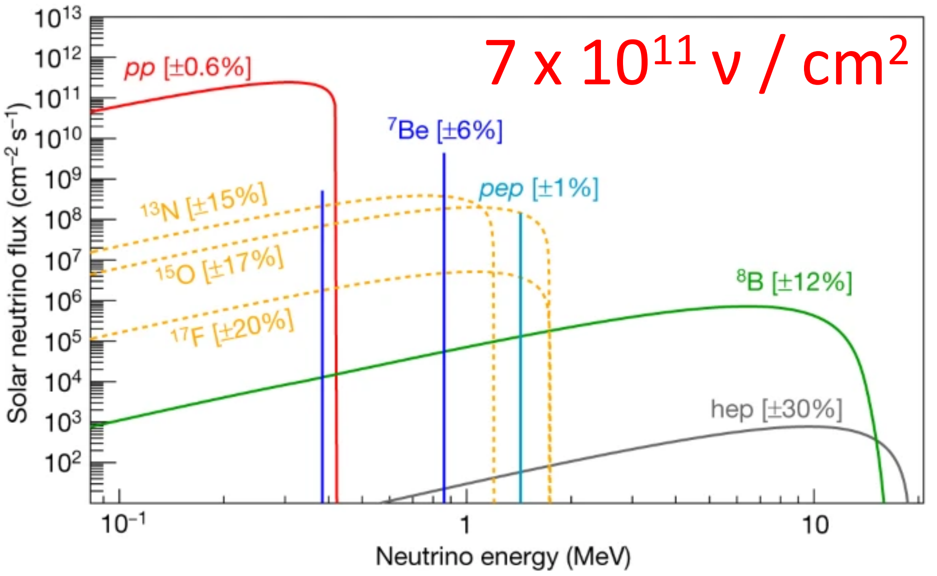
Sun produces energy by fusing

H to He in stellar core

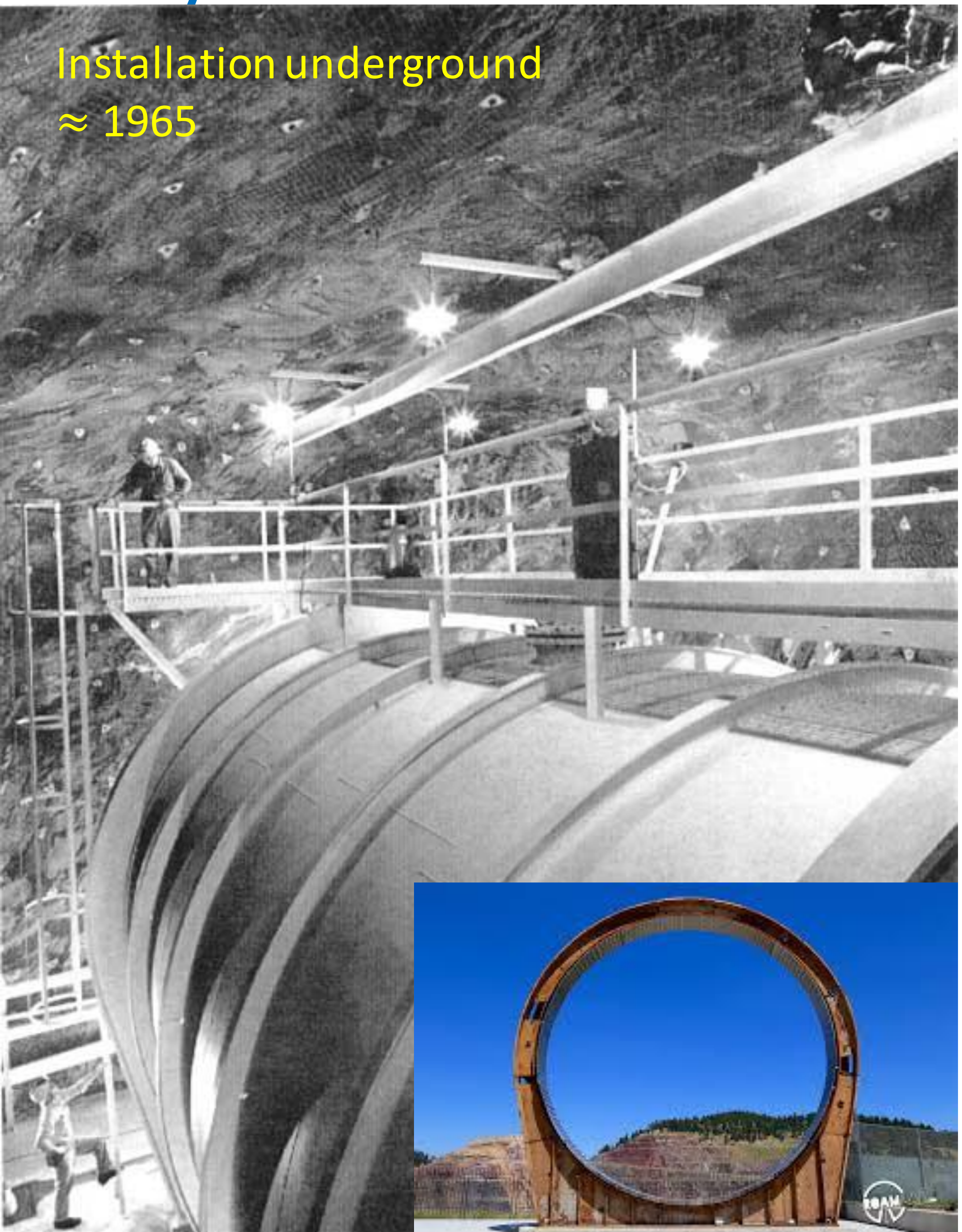
Huge flux at Earth – physicists can probe core directly with neutrinos







Ray Davis – Discovery at SURF



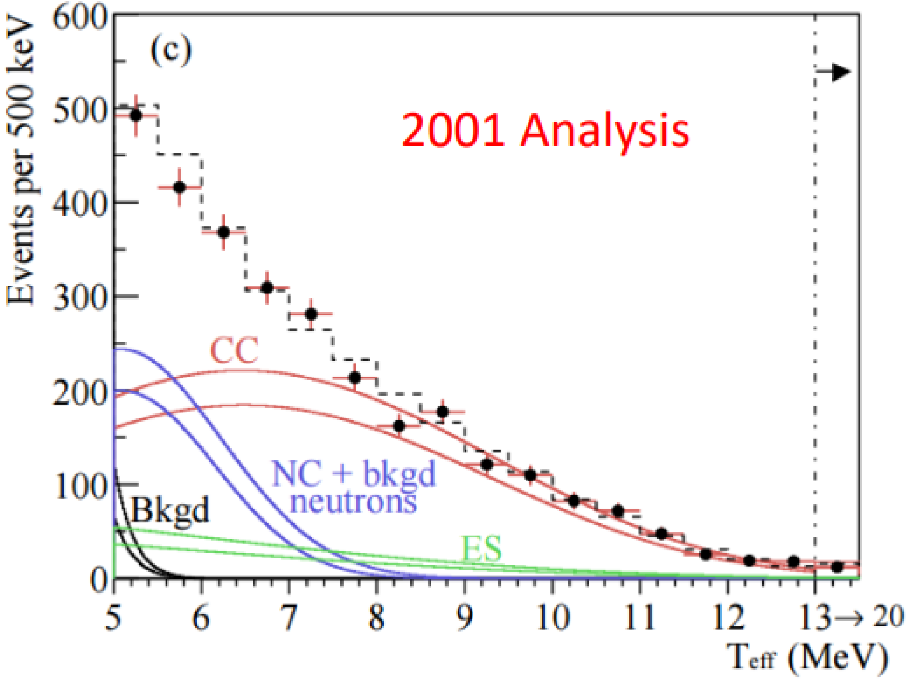
- Davis searched for solar neutrinos via interaction:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

- Built 620 ton tank of dry cleaning fluid (C_2Cl_4)
- Ar atoms produced separated from C_2Cl_4 by bubbling He through tank
- Ar/He separated using a charcoal trap at 77 K
- Sees ≈ 15 ^{37}Ar / month
- Only 1/3 expectations!

Discovering neutrino oscillations

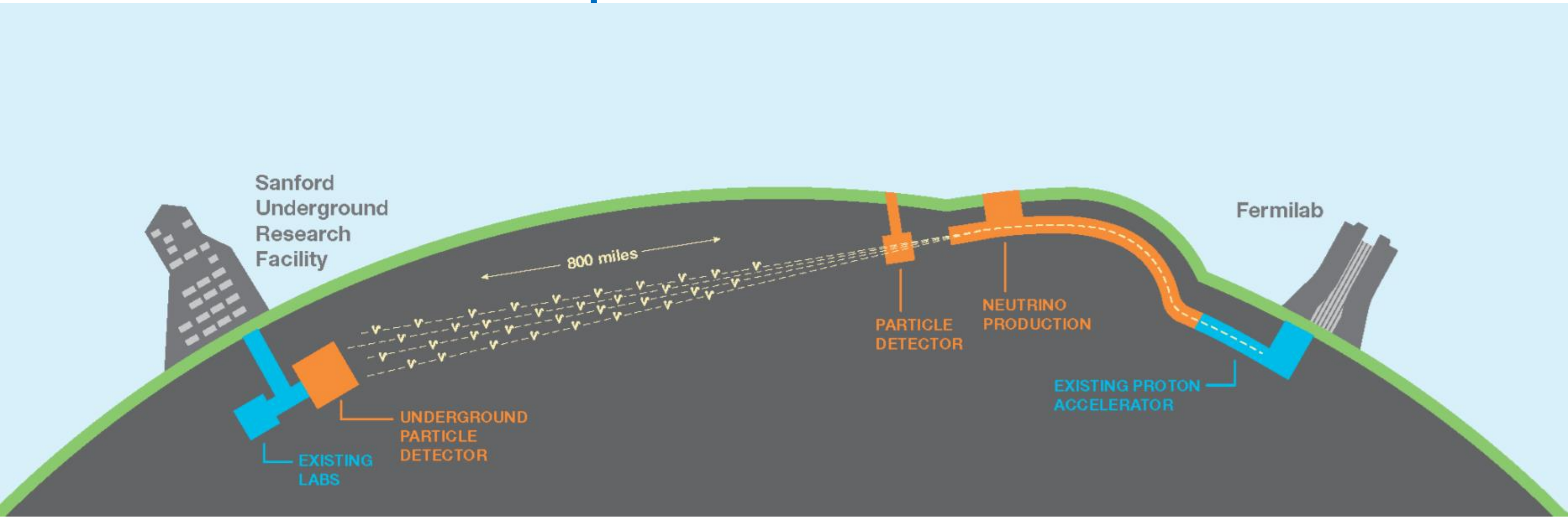
The SNO experiment confirmed low rate observed by Davis due to neutrino oscillations



Heavy water detectors are sensitive to multiple flavors by measuring three interactions

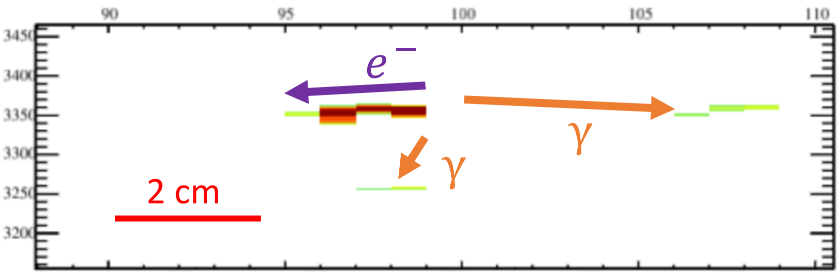
Total neutrino flux agrees with solar model, but ν_e flux is low

The DUNE experiment



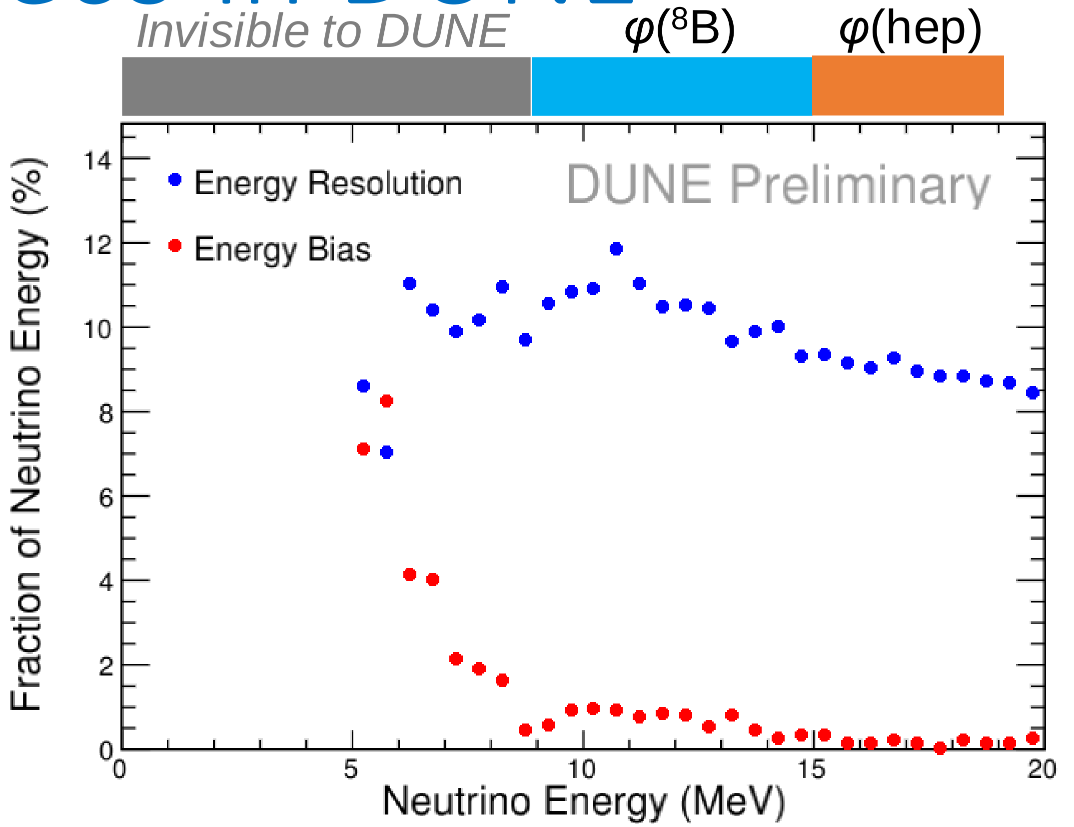
- Large, 40 kton (fiducial) mass with 4300 mwe overburden makes DUNE ideal for searching for rare astroparticle phenomena
  - Assume in this talk a DUNE with four liquid argon TPC modules
- DUNE will further constrain neutrino oscillation parameters including the CP-violating phase angle
  - Measured using a high-purity $\nu_\mu/\bar{\nu}_\mu$ beam produced at Fermilab

Solar neutrino reco in DUNE



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

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

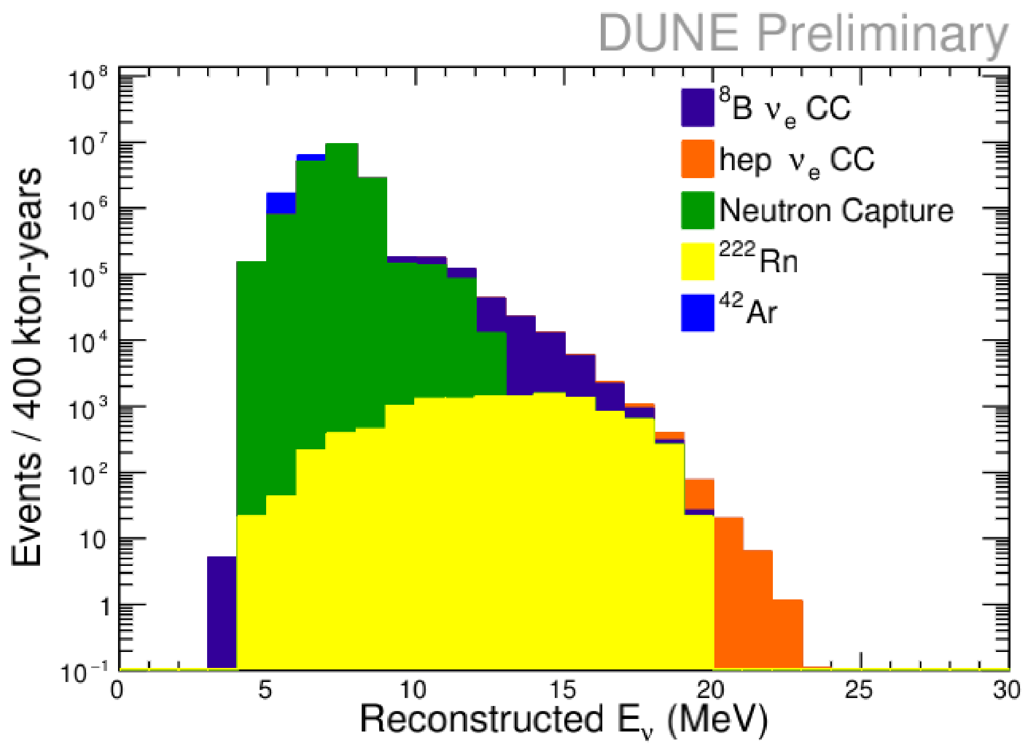


- Reconstruct events calorimetrically – sum all energy deposited in electron track and gamma cascade blips
  - PDS gives t_0 for electron lifetime correction and fiducialization
- We achieve 9-12% resolution on neutrino energy throughout the solar energy range

Solar neutrinos in DUNE

- Solar ^{8}B + hep flux is enormous – several tagged events / day / kt
- But also huge background rate, we need to understand what energy range to study
  - Neutron capture drowns events below 9 MeV

Bkg	Rate
$^{40}Ar(n,\gamma)$	44 / t-yr
$^{36}Ar(n,\gamma)$	0.62 / t-yr
$^{40}Ar(\alpha,\gamma)$	0.051 / t-yr



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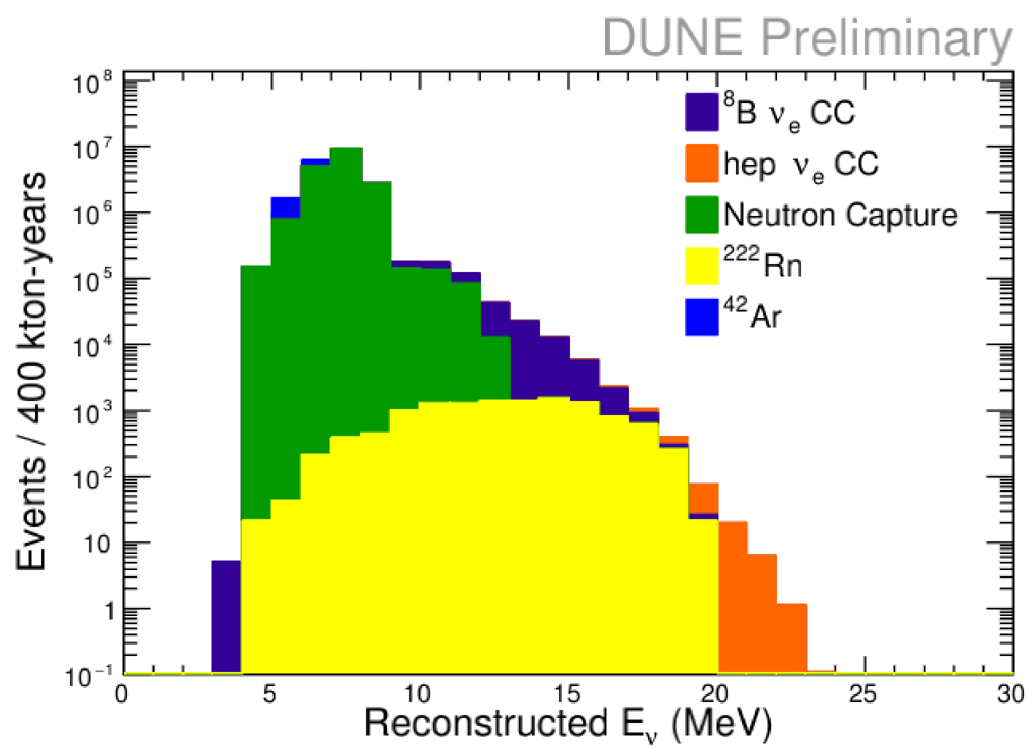
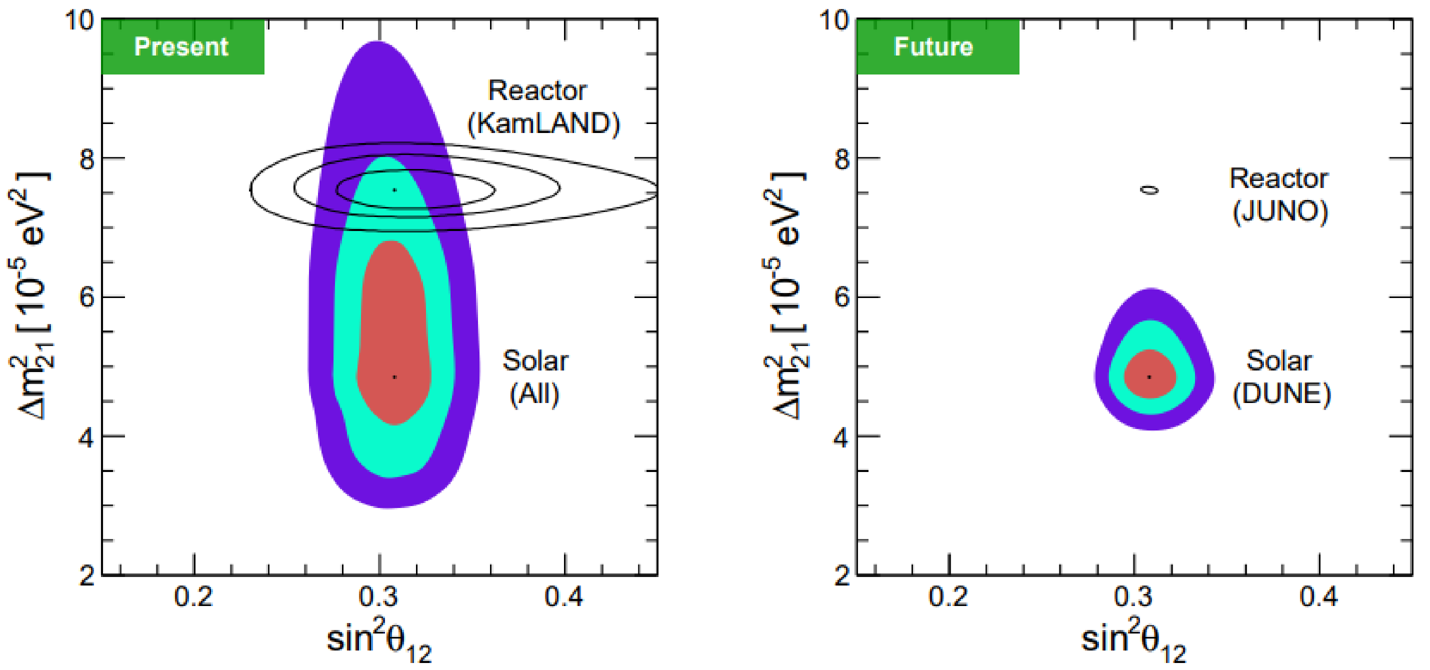
- DUNE will measure the yet-unobserved hep flux
  - ^{3}He + p fusion
  - Low flux, high energy
- 5σ discovery within first 20 kt-yrs of exposure



Future oscillation sensitivity

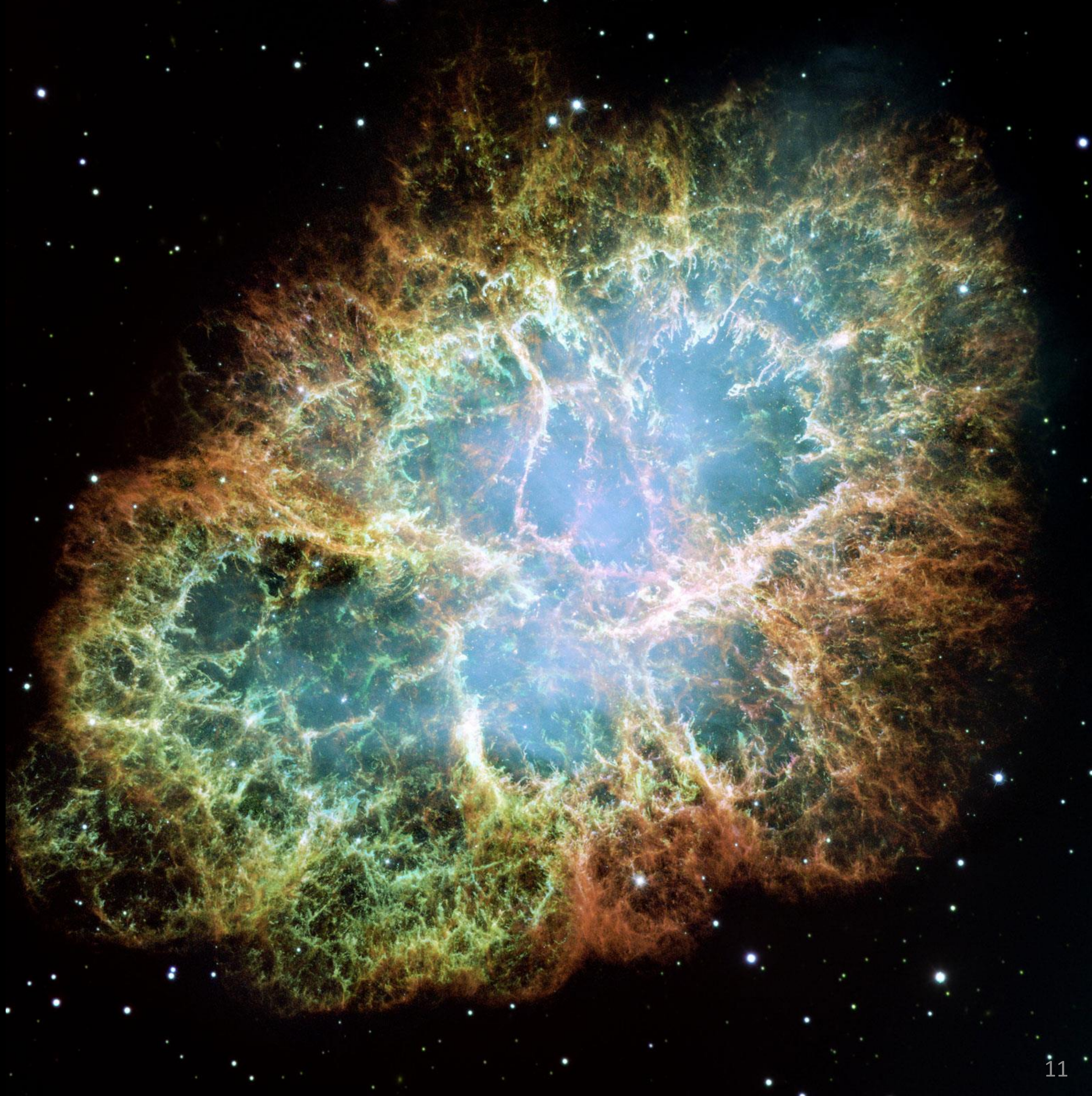
PRL **123** 131803



- ❑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!

Supernova neutrinos

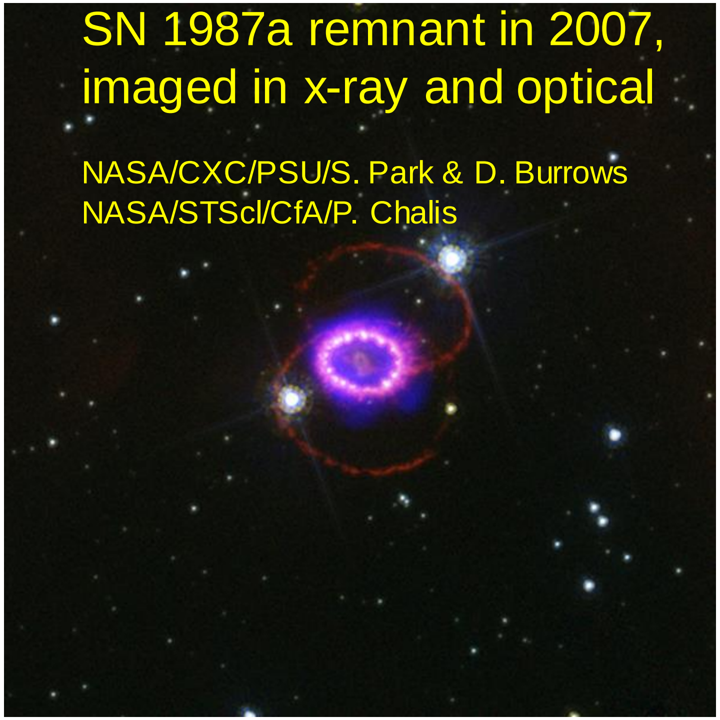
Crab nebula, remnant of supernova recorded in 1054



A core-collapse supernova

- When a star collapses, it releases its gravitational binding energy (~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

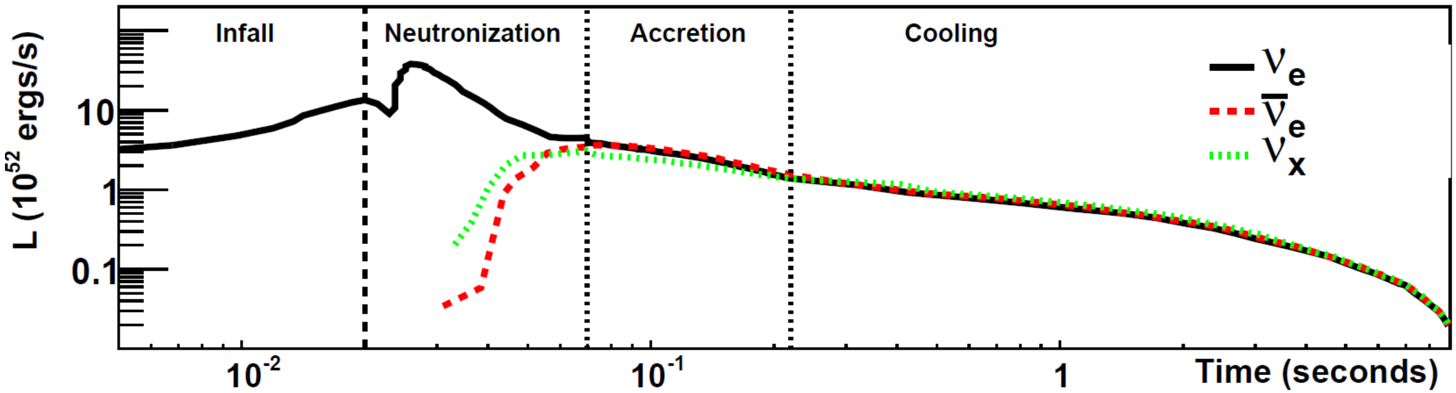
- A single event would teach us:
- Astrophysics
  - Core-collapse mechanism, neutronization rate, neutrino diffusion, black hole formation, nuclear density in neutron star
- Particle physics
  - Neutrino magnetic moment, absolute mass, oscillations, sterile neutrinos



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

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

Neutrinos emission in a supernova



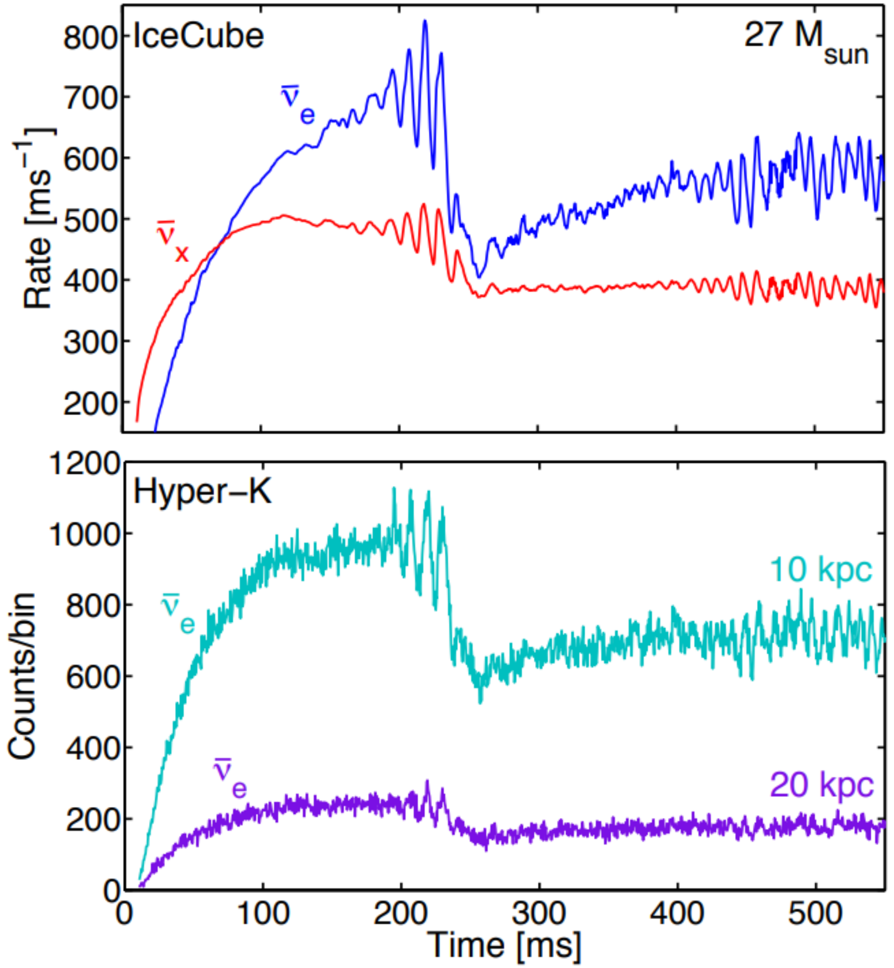
- After a heavy star exhausts its supply of fusible nuclei within its core, it releases neutrinos in three discernable epochs during a supernova
  - 1. Neutronization through electron capture in the core gives a short-lived, intense flash of ν_e
  - 2. Neutrino production then dominated by matter falling into the core
  - 3. Emission then slowly cools as neutrinos diffuse

- DUNE expects to see several thousand events from a galactic supernova to test time/energy profiles

SASI oscillations

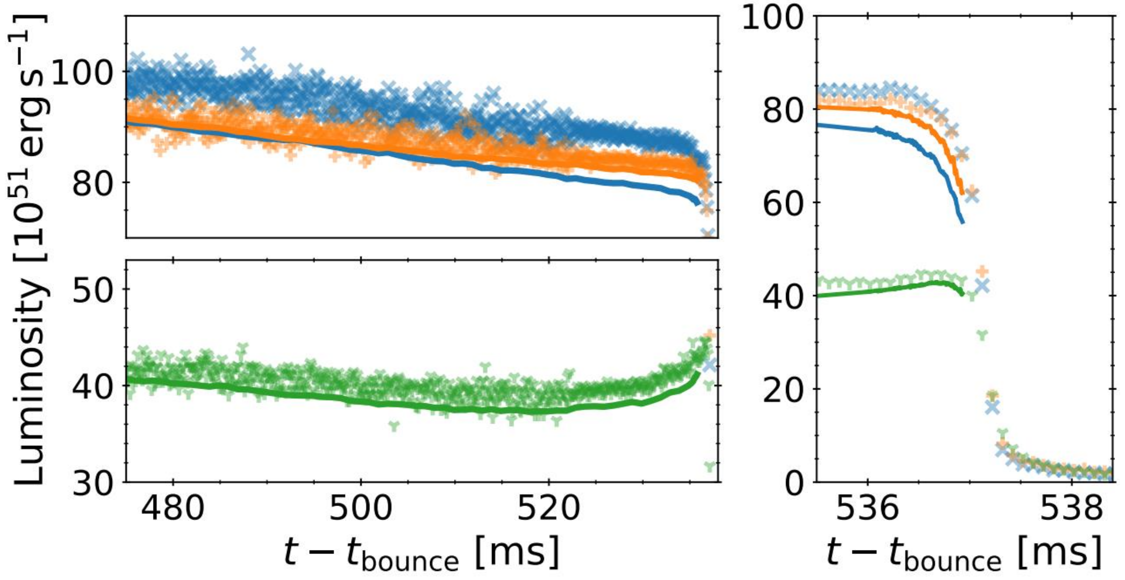
Tamborra, Hanke, Muller, Janka, and Raffelt, PRL **111**, 121104

- As matter accretes onto proto-neutron star, the shock wave periodically compress the nuclear core and adjusting the neutrino emission rate and energy
  - Standing accretion shock instability (SASI) oscillations
- Measuring these oscillations validate the basic collapse model and probe the oscillation frequency, a measure of the properties of the proto-neutron star



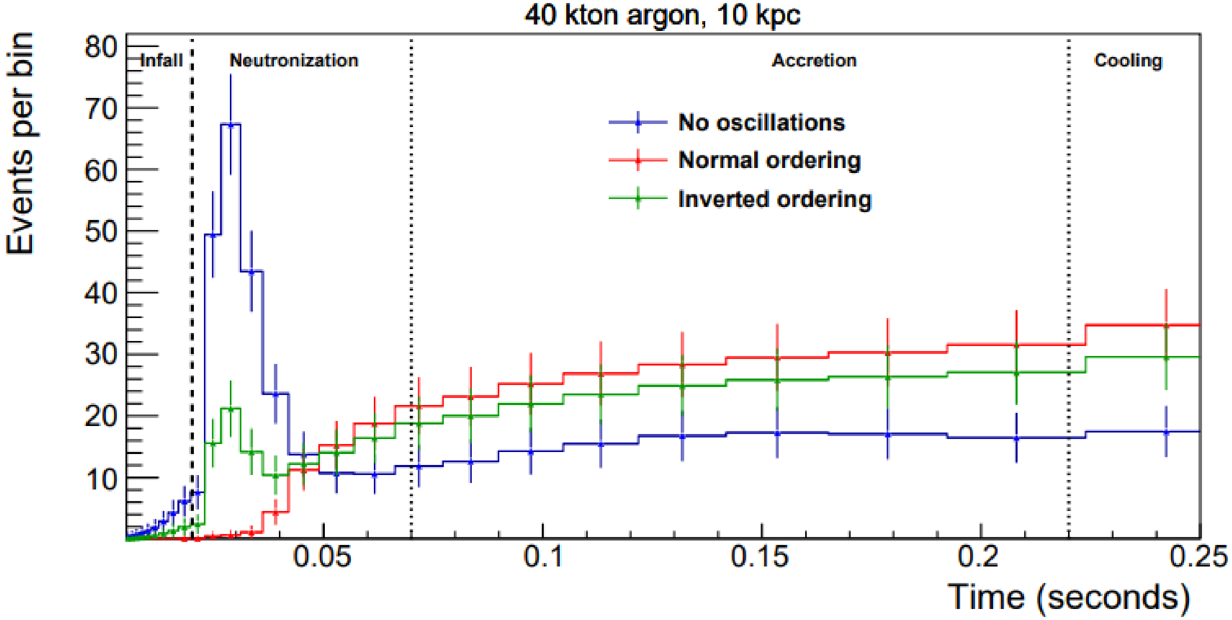
Detecting black hole formation

Gullin, O'Connor, Wang, Tseng, *Astrophys. J.* **926** 212 (2022)



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

Observing the neutronization burst

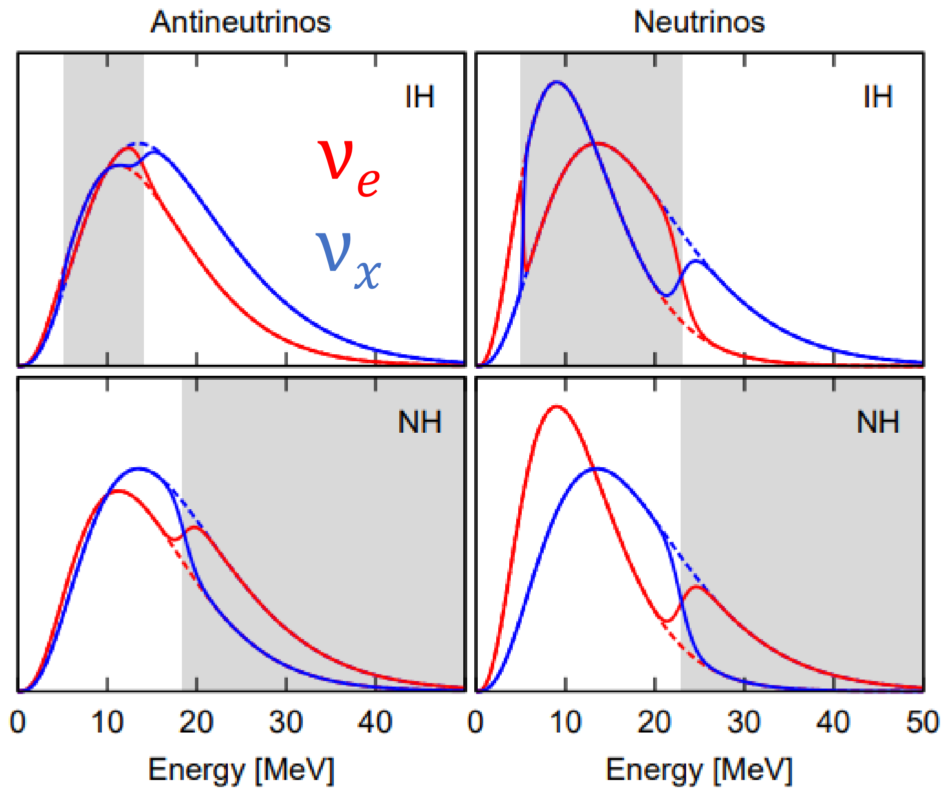


- An intense flux ν_e of is produced from neutronization early in the collapse – DUNE can uniquely search for this peak due to dominant ν_e CC sensitivity
- But, the ν_e content from neutronization depends on several unknowns
  - Neutrino mass ordering
  - Collective oscillations from ν-ν scattering
  - Underlying model – physics uncertainties in core collapse
- Observing neutrino flux with multiple flavors is only way to probe physics

SN and neutrino self interactions

Dasgupta, Dighe, Raffelt, Yu, Smirnov, Phys Rev Lett 103 051105 (2009)

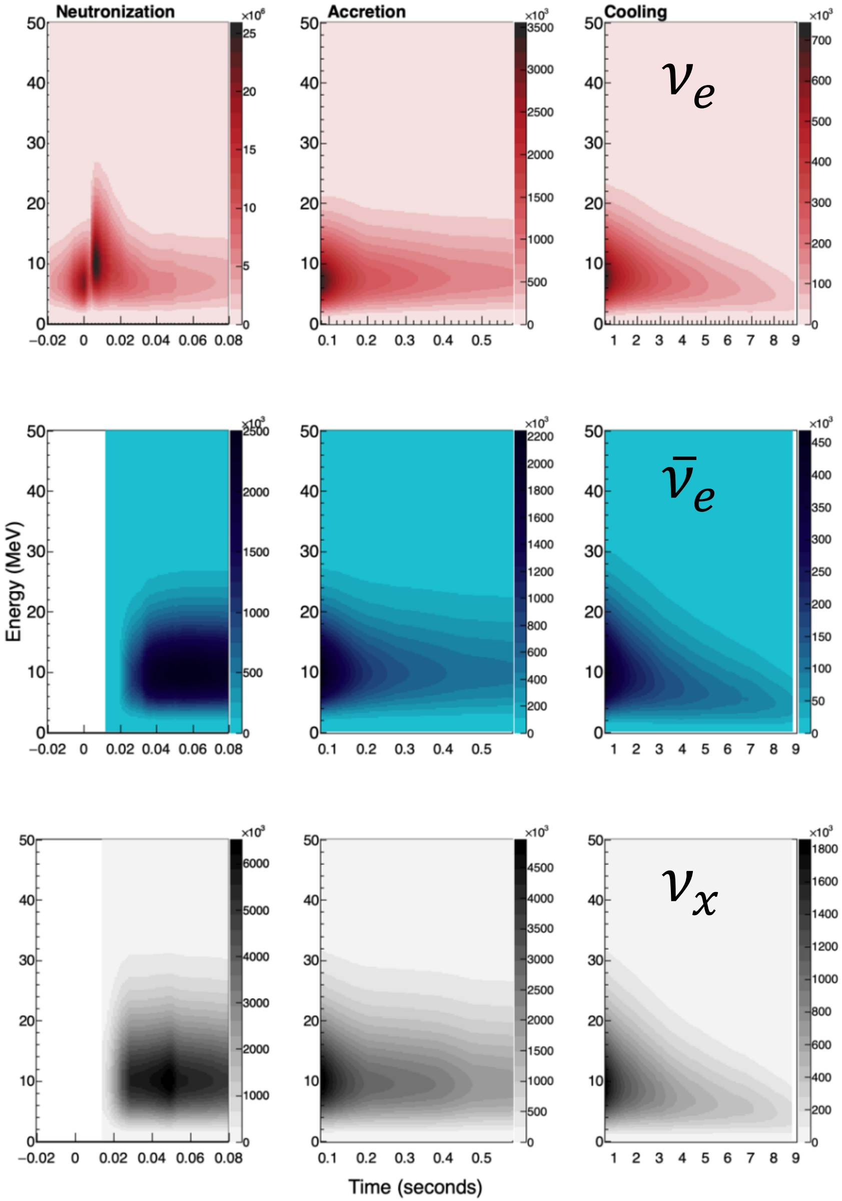
- Neutrino self interactions are poorly understood
- High density in a SN ideal for testing this physics!



- Neutrino oscillations become non-linear, introducing "flux-swap" effects

- Highly sensitive probe of EW theory and any dark sector phsyics that may interact with neutrinos

Goal: determine the neutrino flux



- Include neutrinos in multi-messenger observation of collapse and measure the differential flux
- Beyond precise reconstruction of kinematics, we must probe all flavors to fully understand the core collapse
  - ν_e – observe neutronization
  - $\nu_e + \bar{\nu}_e$ CC – good for calorimetry
  - ν_x NC – no oscillation ambiguity

	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
LZ	0%	0%	100%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

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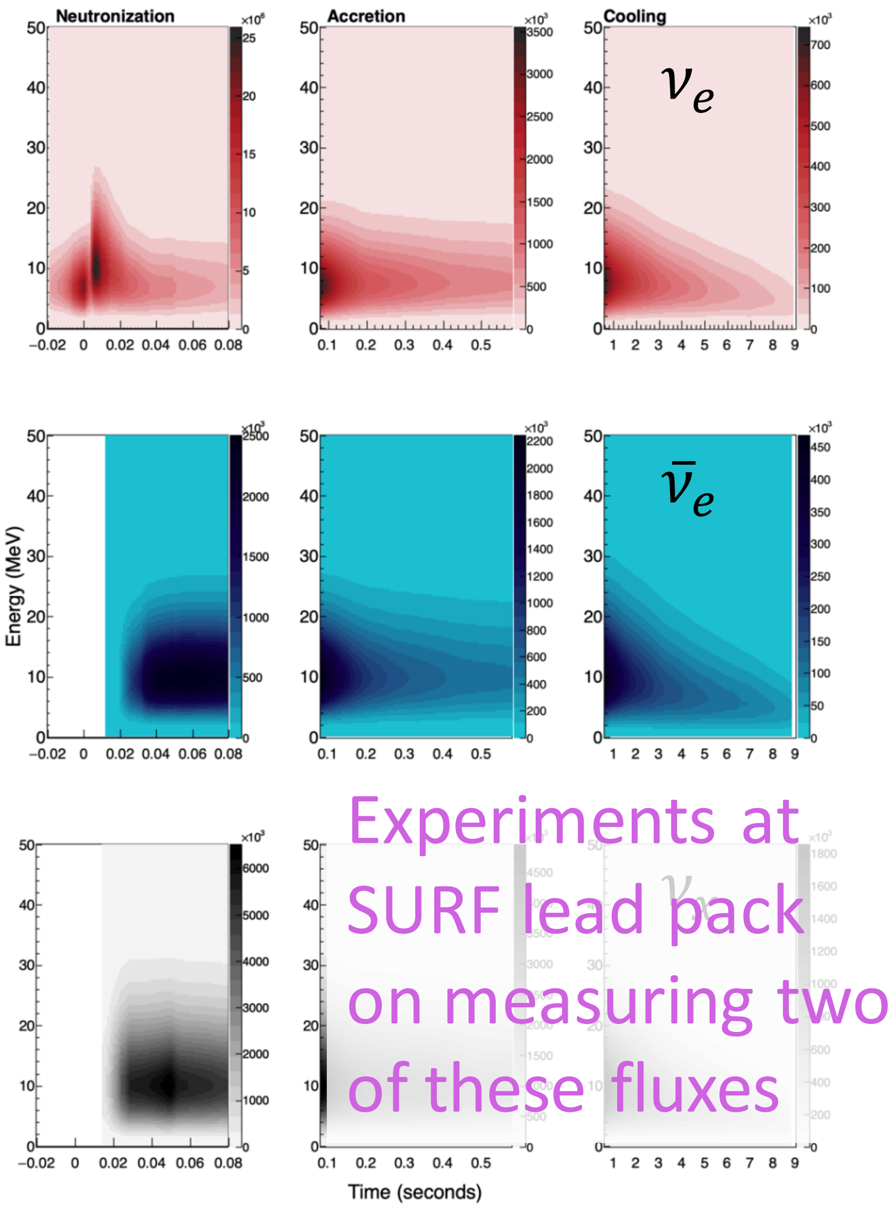

Experiments at SURF lead pack on measuring two of these fluxes

- Include neutrinos in multi-messenger observation of collapse and measure the differential flux
- Beyond precise reconstruction of kinematics, we must probe all flavors to fully understand the core collapse
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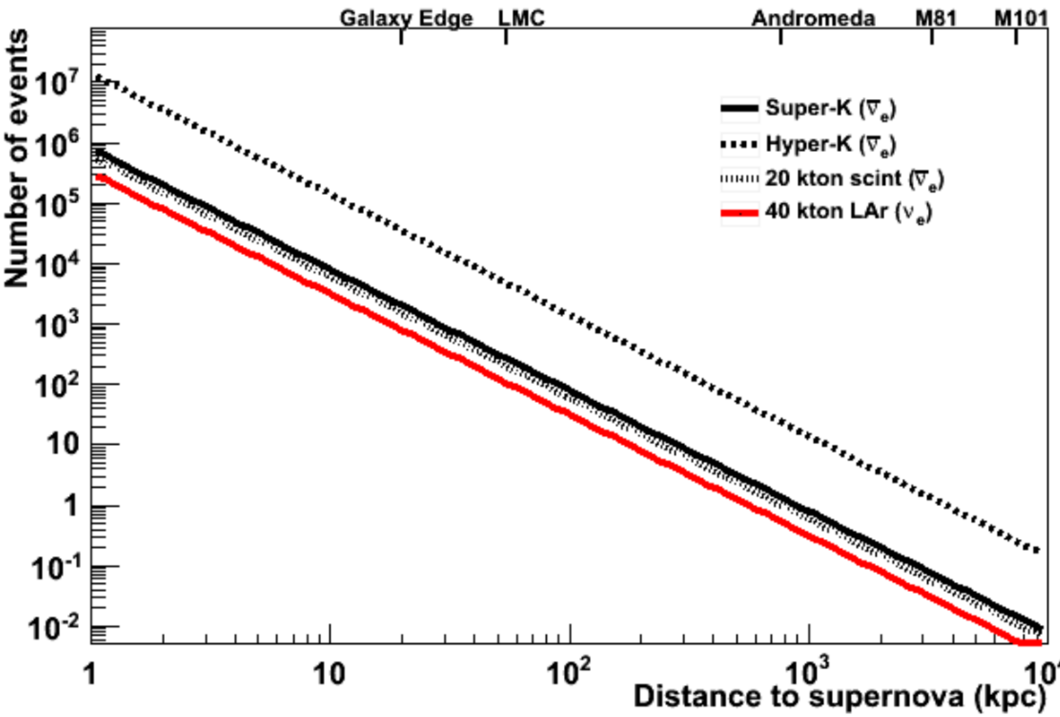
Supernova event rates at DUNE

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

Bursts from Andromeda observable with HK

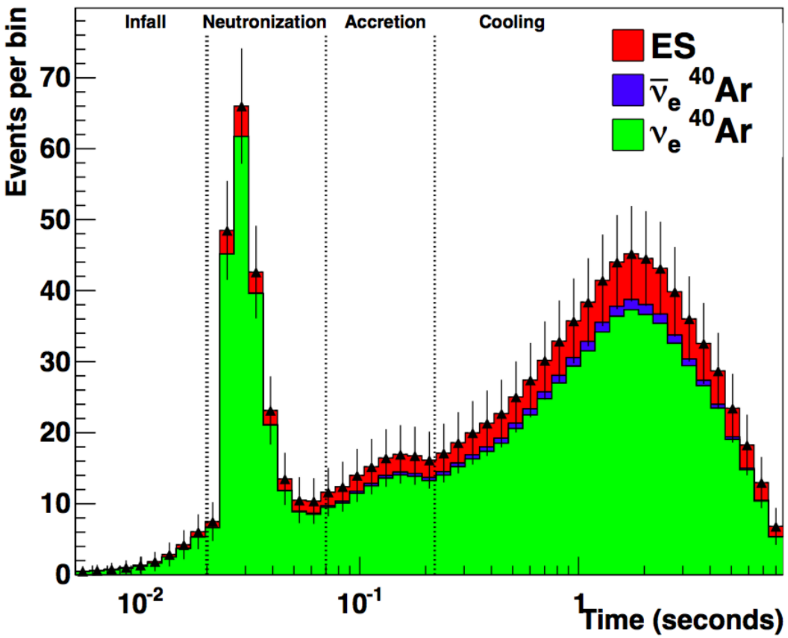


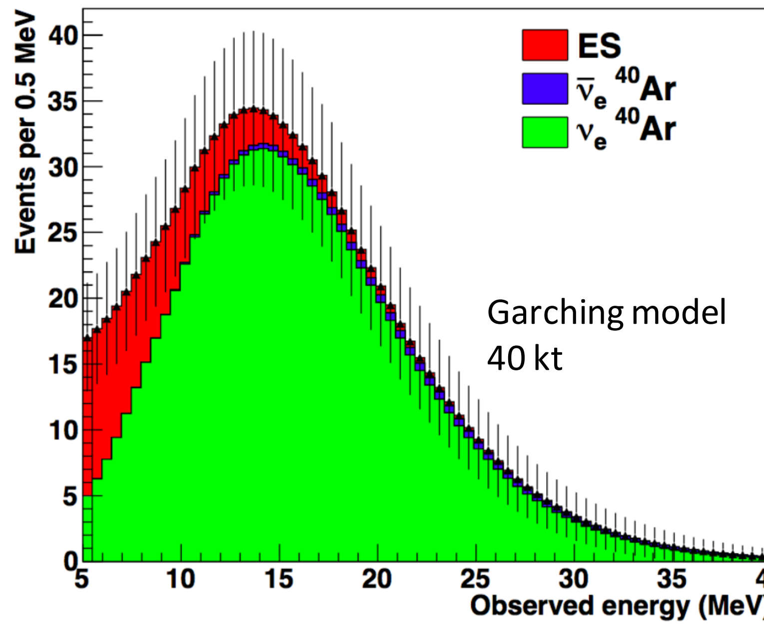
Channel	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

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

Supernova flux model: PRL104 (2010) 251101

DUNE event rate from a SN



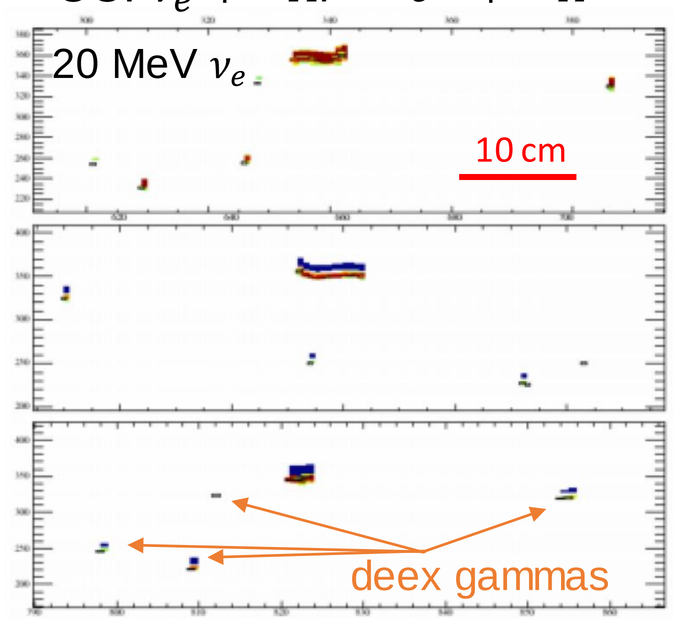


- We are most sensitive to the ν_e CC interaction – but we will observe others
  - Unique to DUNE, other detectors largely sensitive to anti-ν_e from IBD
- We can further exploit the reconstruction capabilities of the DUNE TPC to separate the flavors

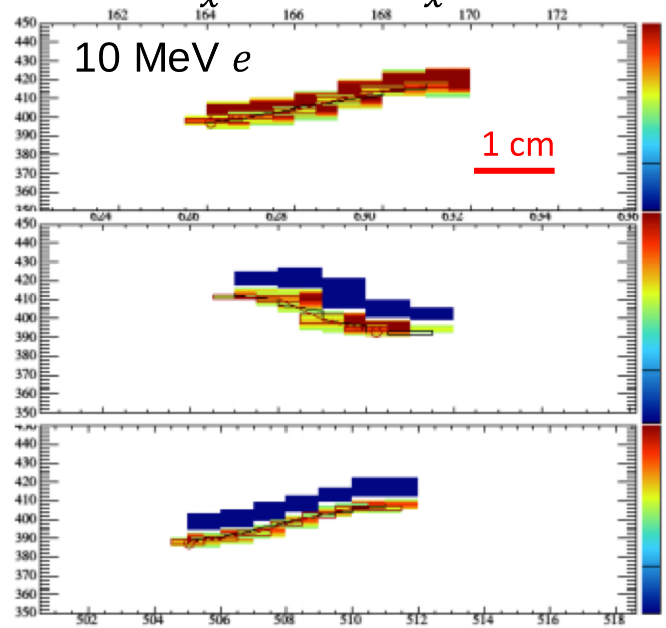
See talks by Gleb Sinev and Shawn Westerdale on Thursday for more!

Isolating interaction channels

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

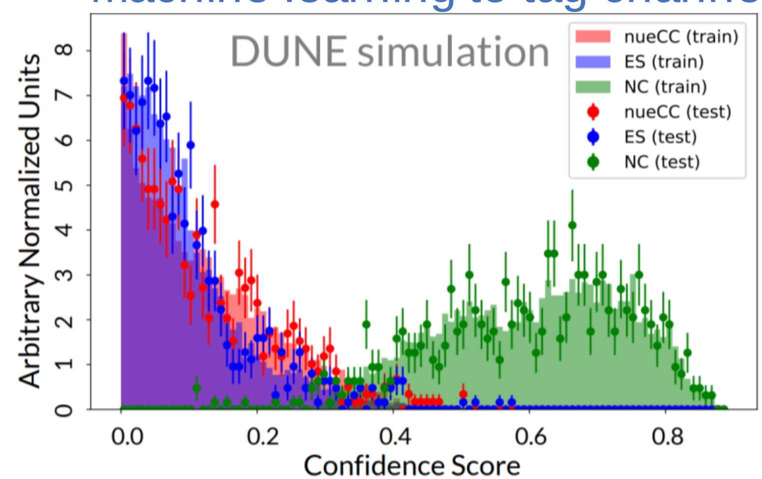


ES: $\nu_x + e^- \rightarrow \nu_x + e^-$



- Precision tracking of particles in TPC
  - Electron track visible in CC and ES
  - Comptons from deexcitation gammas show up as small blips surrounding electron track
- Can discriminate between channels based on deexcitation gammas

Machine learning to tag channels



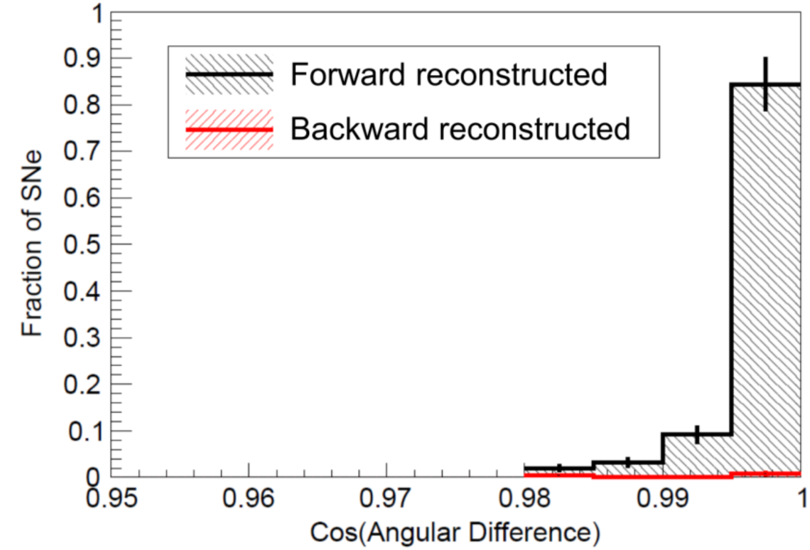
Pinpointing a supernova with DUNE

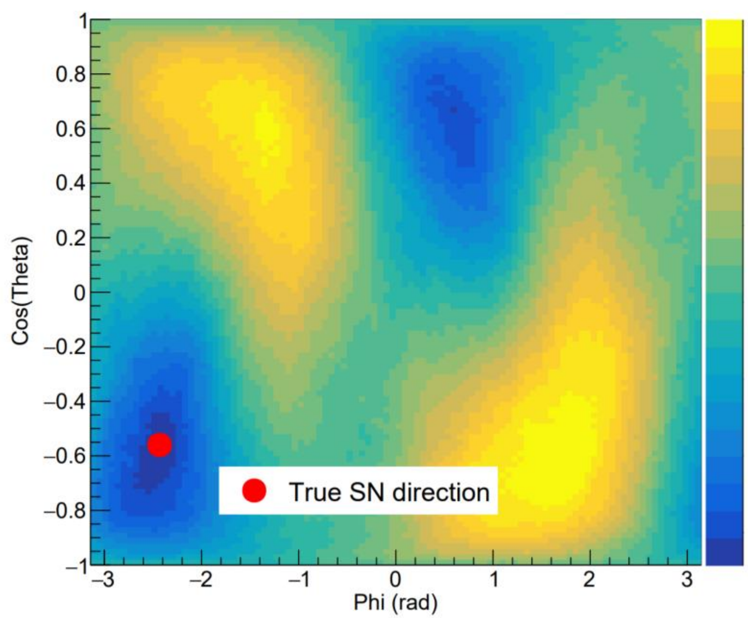
1987 supernova, Anglo-Australian Observatory

- 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 ≈hour before light so we can warn optical astronomers of an event and indicate source location
  - Neutrino signal facilitates multi-messenger study of supernovae

Pinpointing a supernova with DUNE

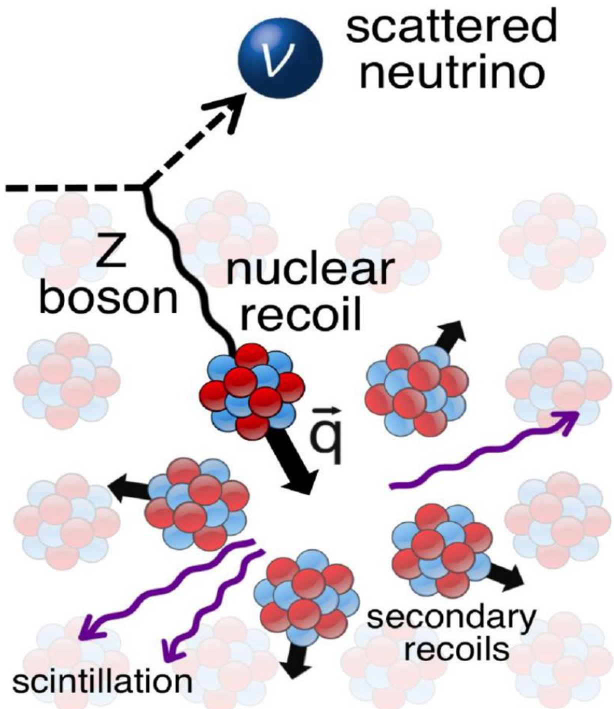
- Simulated supernova at 10 kpc with the GKVM model
  - 260 ES scattering events
    - Low-Q^2 $\rightarrow$ great pointing
  - 3350 CC events
    - $\approx$ isotropic

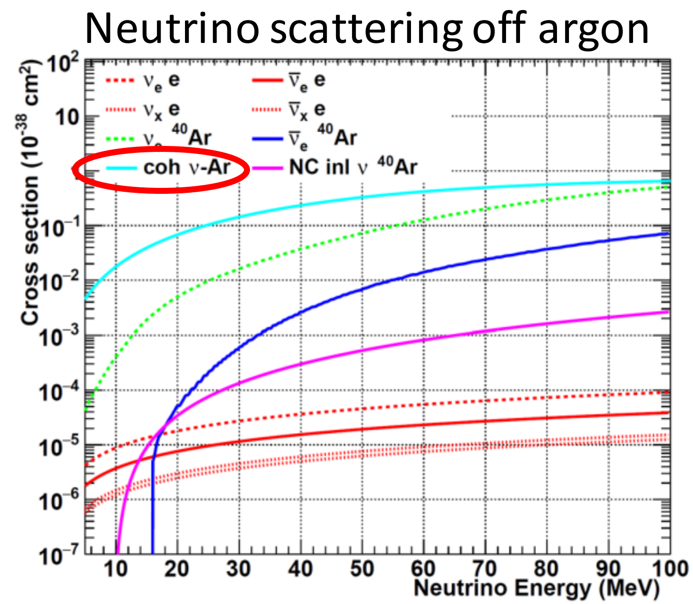




- TPC allows flavor discrimination so the ν_e CC component can be mitigated
- Exploiting the directionality of $\nu - e$ scattering events, we can determine the direction of the supernova to $\approx$ 4.5 deg

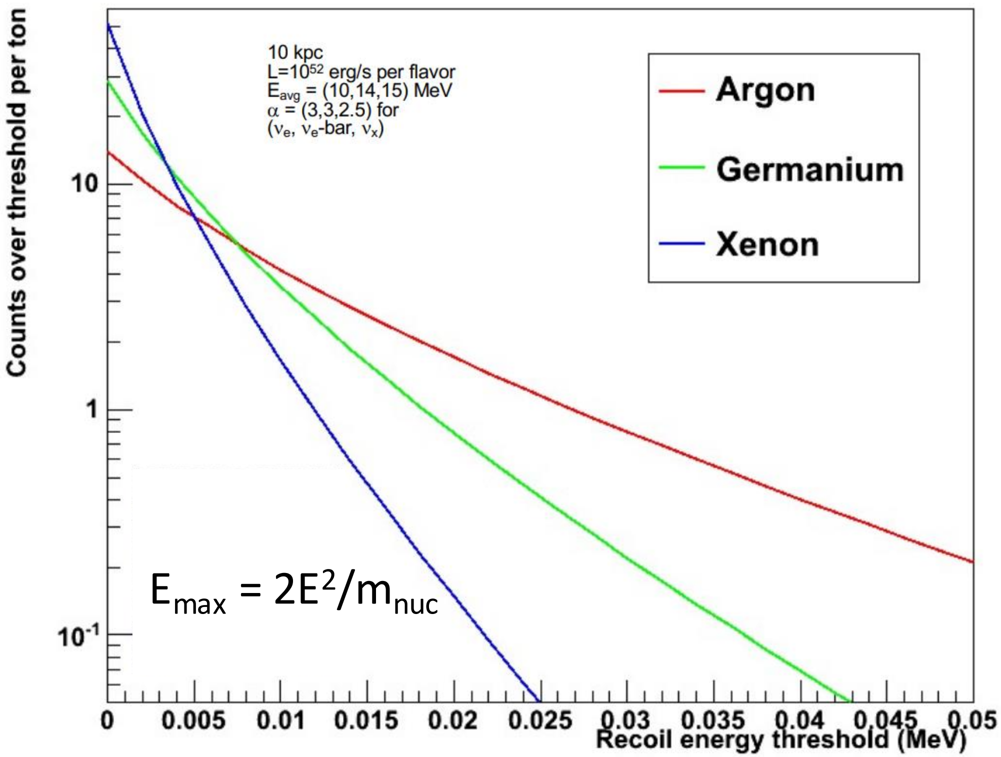
CEvNS as a SN neutrino channel





- 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

Detecting CEvNS: low thresholds



The observable nuclear recoil is very low in energy < 100 keV for supernova neutrinos

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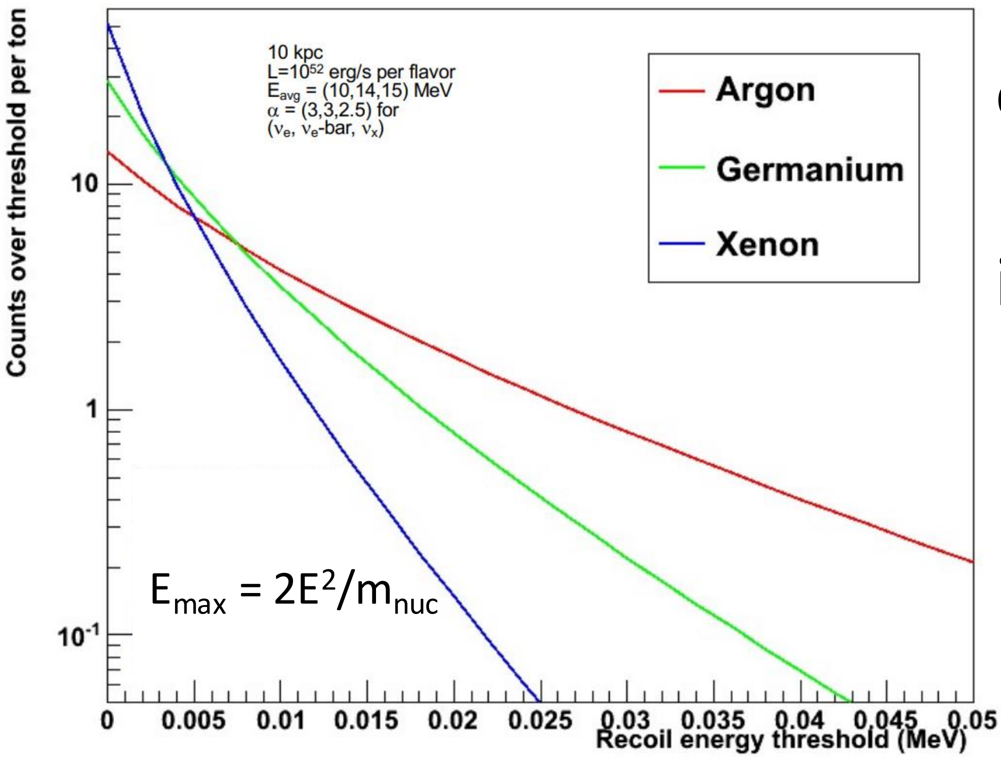
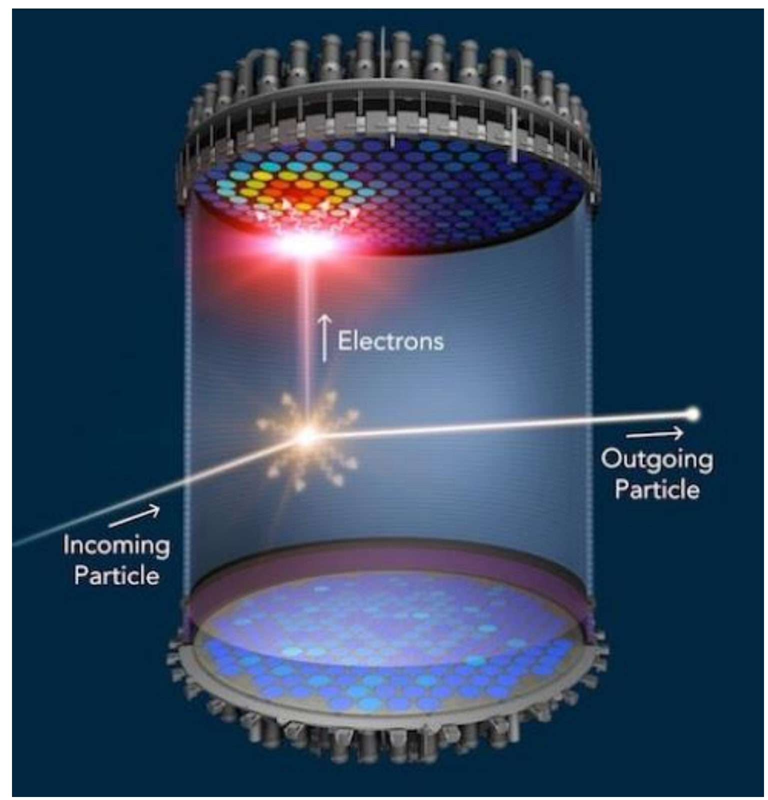


Dark matter detectors have exquisitely low threshold

LZ at SURF and others will see interactions from next SN



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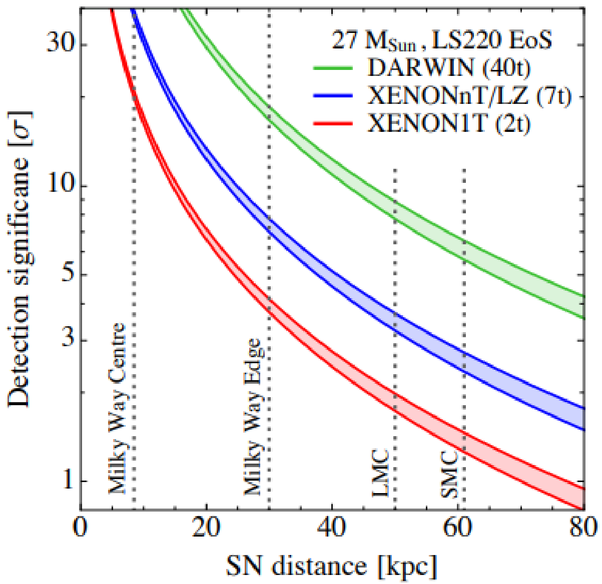
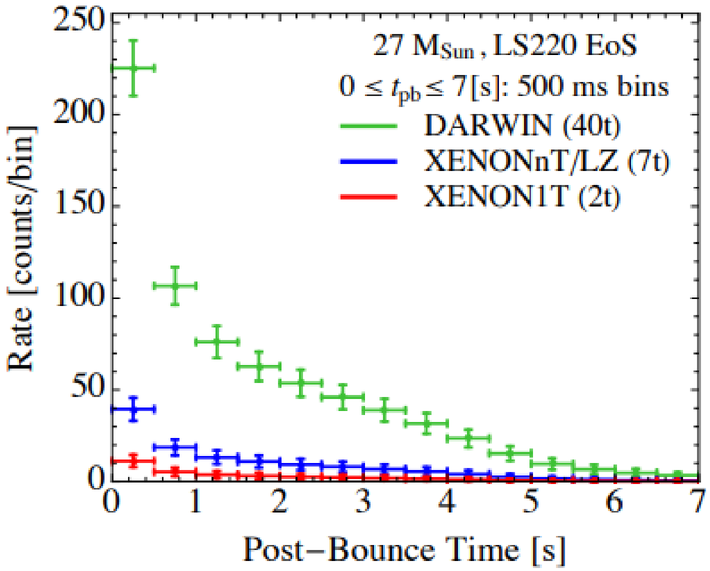
SN neutrinos in DM experiments

- 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)

Thank you