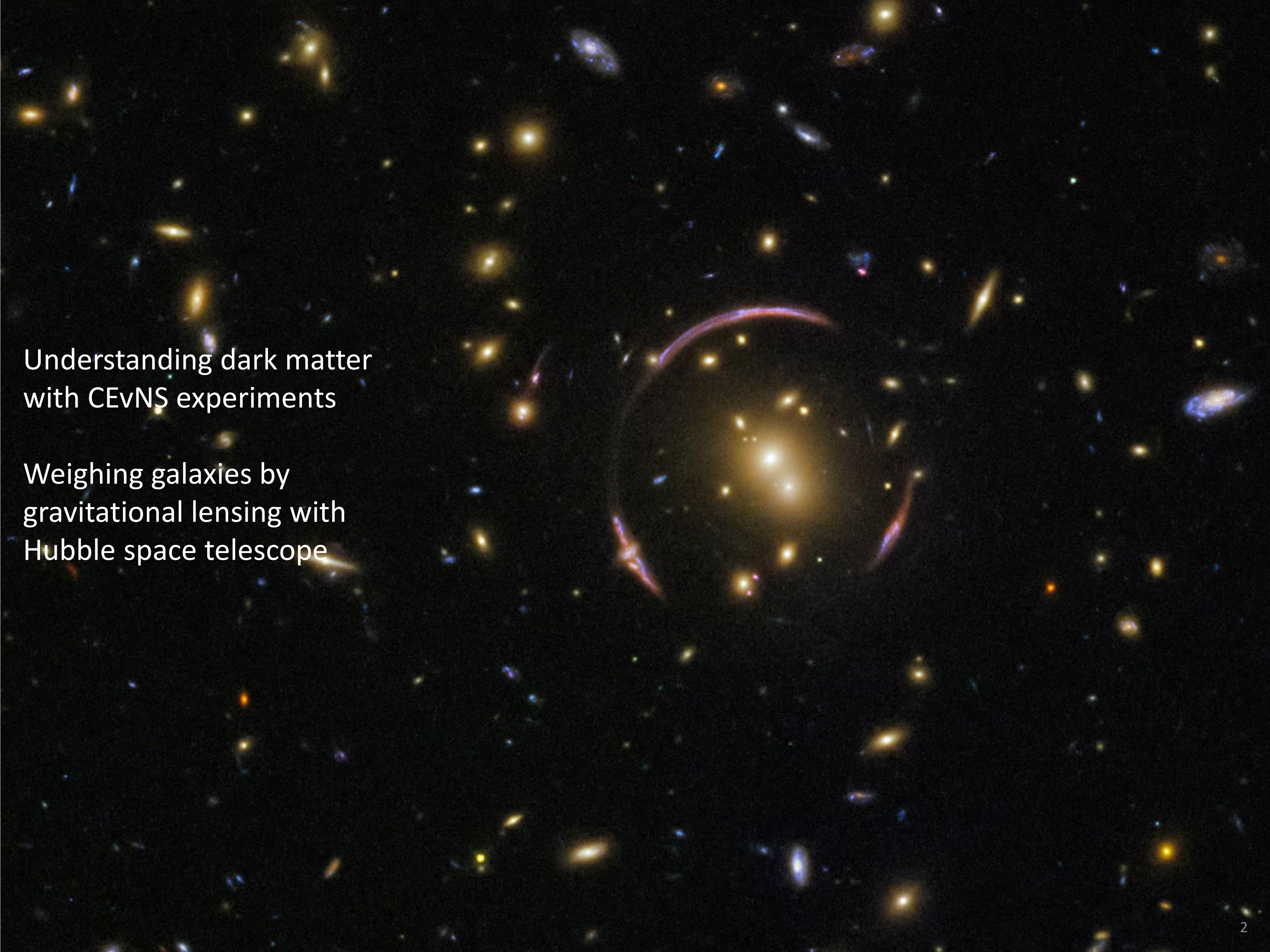
Understanding the cosmos and the stars through neutrinos

Dan Pershey (Duke University)

FPCP 2022, University of Mississippi, May 25, 2022

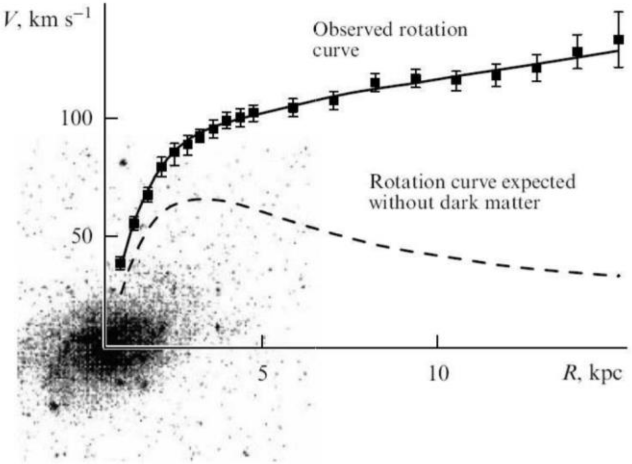


Understanding dark matter
with CEvNS experiments

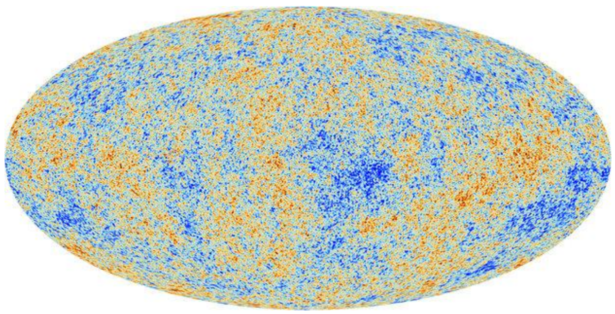
Weighing galaxies by
gravitational lensing with
Hubble space telescope

Dark matter in our universe

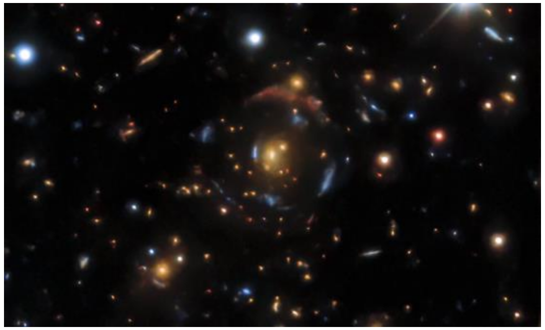
A. Zasov et al., arXiv 1710:10630 (2017)



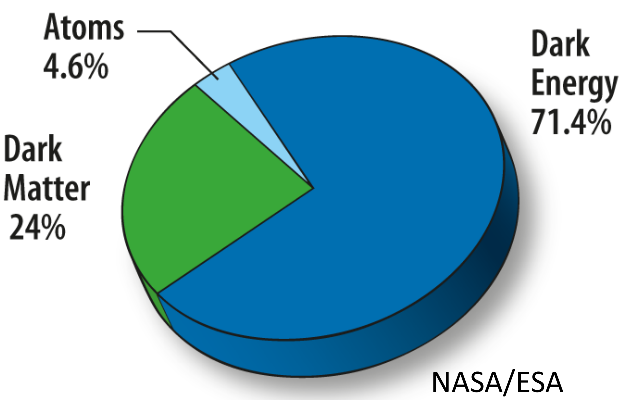
Plank, Astron Astrophys **641** A1 (2020)



X. Huang et. Al, ApJ 909 27 (2021)



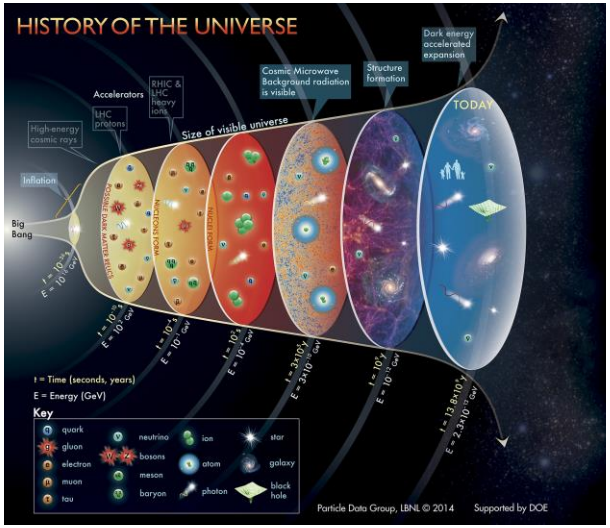
- First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)
- In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter
- Continuing understanding distribution of dark matter from weak gravitational lensing data
- 100 years since postulation, and we still haven't found the particle nature of DM despite many attempts – new physics we know exists, we just need to find a new place to look

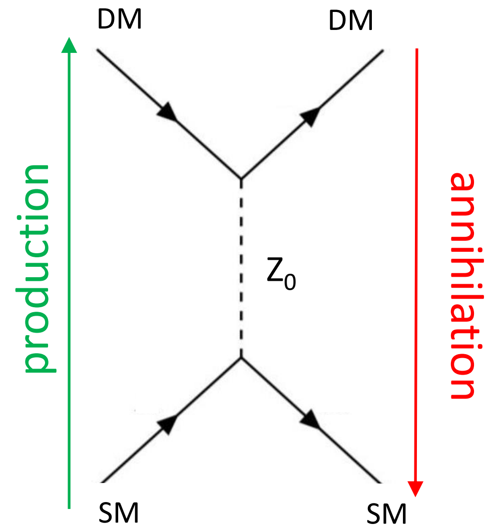


NASA/ESA

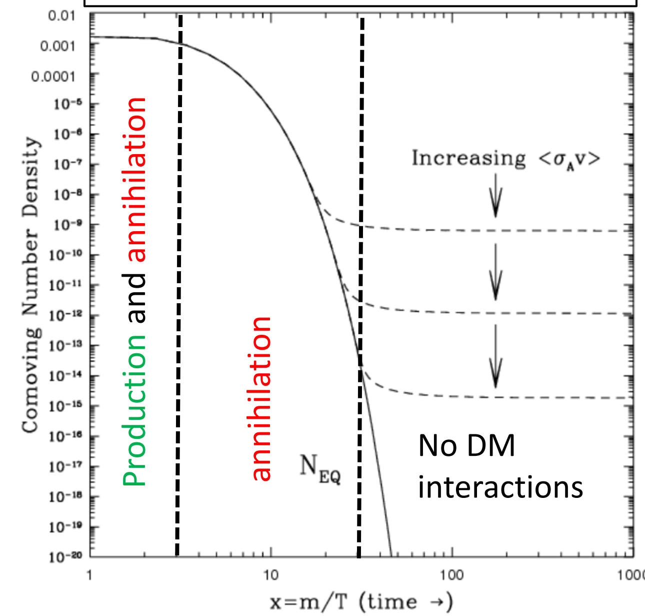
TODAY

Origin of weakly-interacting dark matter





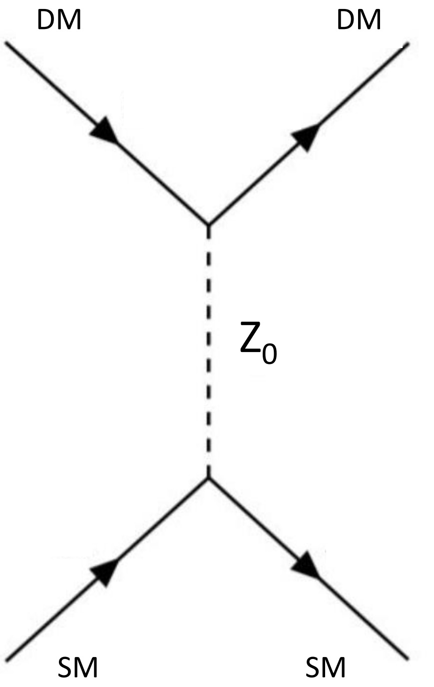
C. Chatterjee, arXiv: 1901.05658 (2019)



- ❑ Assuming that DM is a particle that interacts weakly with standard-model (SM) matter, in the very early universe, DM was in thermal equilibrium with SM fermions
  - As the universe cools, DM production is no longer kinematically allowed, and the DM concentration falls exponentially
  - Later, as the universe continued expanding, the DM concentration became so low that DM annihilation stopped since DM particles could no longer find partners to annihilate with
- ❑ At this point, the universe "freeze-out" of DM occurred, with the DM concentration fixed to the modern observed value
- ❑ Freeze-out concentration depends on DM cross section – higher cross section implies DM can annihilate even when less dense so that concentration is lower
  - Modern relic abundance tells us what the cross section is (as a function of DM mass)

Low-mass DM phenomenology

- For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force
- The DM scattering cross section is $\sigma \sim m_\chi^2 / m_z^4$
  - Lower DM mass → lower cross section → higher DM abundance
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing modern the universe



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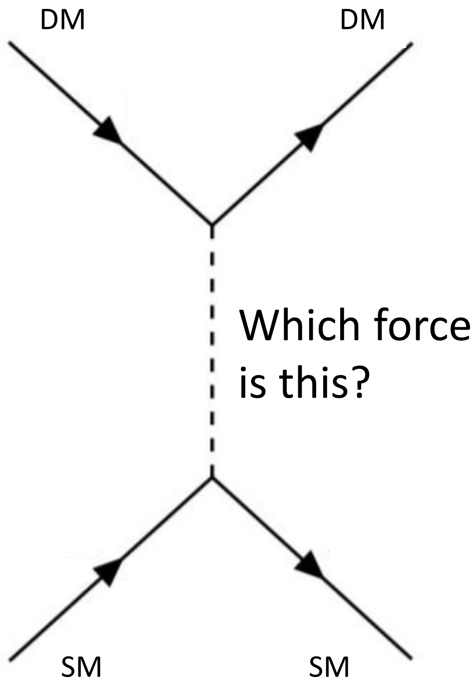
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing modern the universe
- No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, V
- In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales

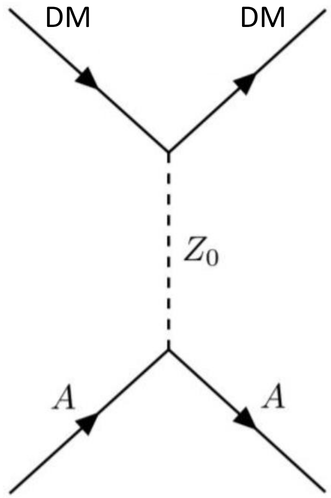


- Simple, general model assumes a vector mediator that kinematically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2}\varepsilon^2 F_{\mu\upsilon} V^{\mu\upsilon}$
- Model parameters
  - DM and mediator masses: m_χ and m_V
  - SM-mediator and DM-mediator couplings: ε and α_D
- Relic abundance given in terms of $Y = \varepsilon^2 \alpha_D (m_\chi/m_V)^4$

Classical WIMP mass regime:
Lee and Weinberg, Phys. Rev. Lett. **39** 165 (1977)
Early sub-GeV DM phenomenology:
Fayet, Phys. Rev. **D70**, 023514 (2004)
Boehm and Fayet, Nuc. Phys. **B683**, 219 (2004)
Pospelov et al., Phys. Lett. **B662**, 53 (2008)
Coherent DM scattering / DM at the SNS:
deNiverville et al., Phys. Rev. **D84**, 075020 (2015)
Dutta et al., Phys. Rev. Lett. **123**, 061801 (2019)

Direct detection of dark matter

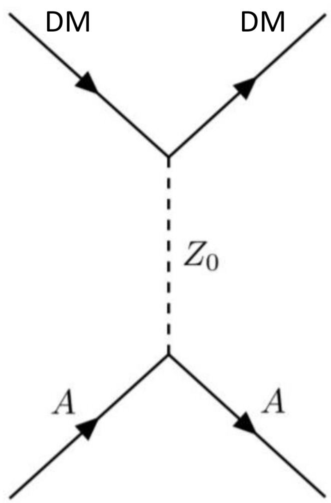
DM scattering



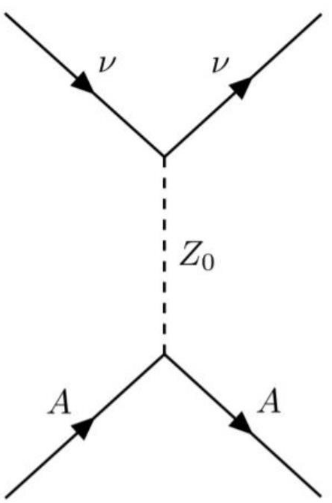
- ❑ DM scattering: experiments search for coherent scattering off nuclei giving the nucleus a small, observable energy – as small as sub-keV
- ❑ Nucleons recoil in phase → quantum coherence makes cross section $\propto A^2$
  - Low recoils but large cross section → need low-threshold detector with sizes up to multi-ton scale

Direct detection of dark matter and CEvNS

DM scattering



CEvNS



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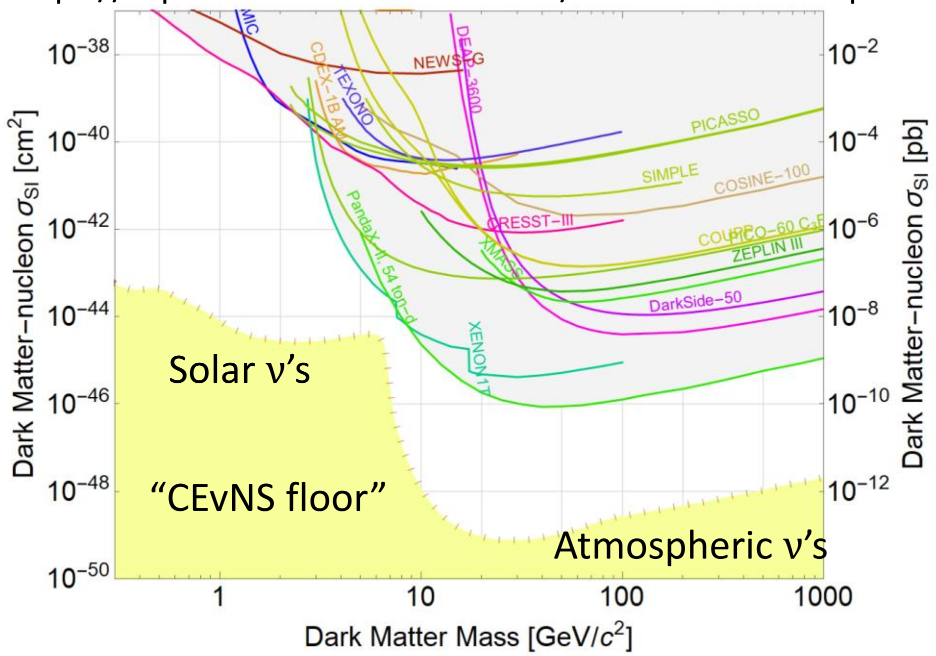
- CEvNS: analogous interaction but with neutrino, rather than DM, scattering off nuclei
- Very similar processes – any CEvNS detector is also a DM detector and vice versa

Seeing CEvNS events in dark matter detectors

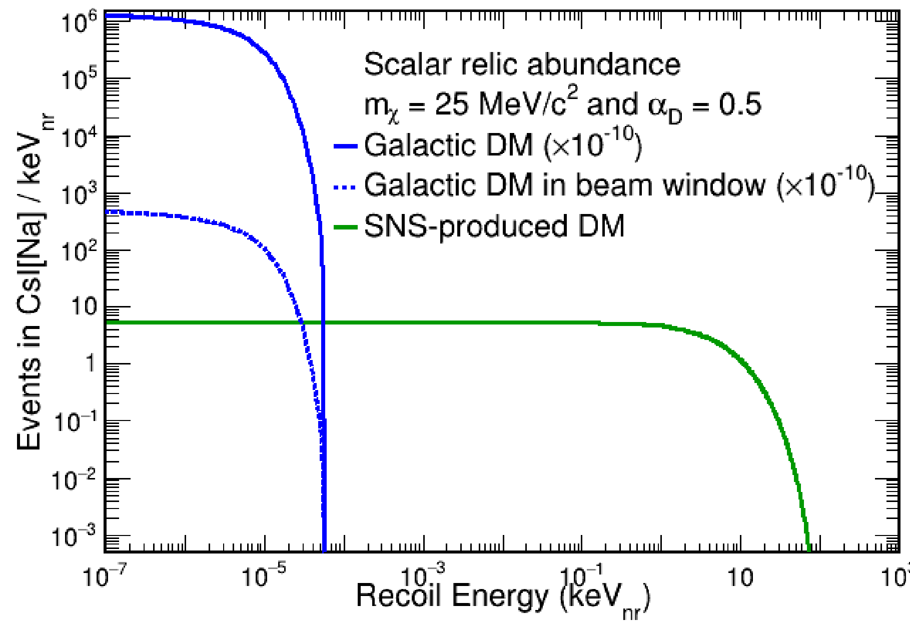
https://supercdms.slac.stanford.edu/dark-matter-limit-plotter



- ❑ CEvNS is an ultimate background for dark matter detection experiments
- ❑ Cosmogenic sources of neutrinos can produce CEvNS in dark matter detectors – the CEvNS floor – and expected rates are not far from current sensitivities
  - Several experiments will soon see CEvNS from ^{8}B solar neutrinos
  - First search with expected sensitivity from xenon1t: PRL **126** 091301 (2021)

Want to find sub-GeV DM? Go to an accelerator

- Galactic DM is slow, thermal with β around 0.001 → struck nuclei get very soft kick
  - Maximum recoil energy $2p_\chi^2/m_{\text{Nuc}} \approx 0.01$ eV for 25 MeV/c² DM
  - Much less than scintillation / ionization thresholds
  - About 1 kT for liquid Xe or liquid Ar detectors
  - Coherent DM-nucleus scattering unobservable



- DM produced at accelerators would be relativistic
  - Maximum recoil energy $2p_\chi^2/m_{\text{Nuc}} \approx 100$ keV → $10^7\times$ higher recoil energies compared to galactic DM

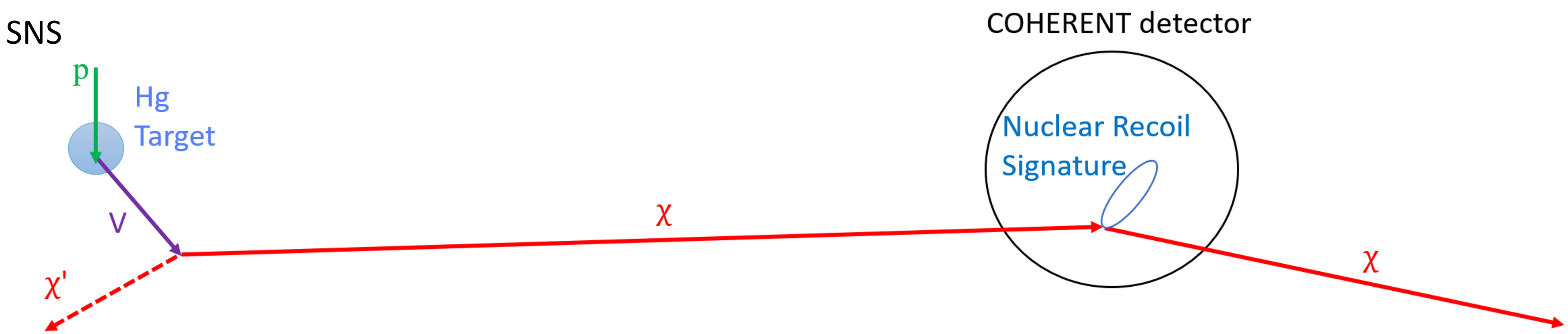
Detecting coherent DM-nucleus scattering easily within reach of CEvNS detectors, such as those deployed by COHERENT that have thresholds between 1 and 20 keV$_{nr}$

COHERENT at the Spallation Neutron Source at ORNL
+ Dark Matter + Neutrinos

- 1.4 MW proton beam on mercury target at T_p = 1.01 GeV
- Pulse width is 340 ns FWHM at 60 Hz, reducing backgrounds by a factor of $\sim 3\times10^4$ from beam pulsing

- Opportunistic neutrino program expands fundamental physics reach of the SNS
- Possible production of dark matter / hidden sector particles

Making DM at the SNS



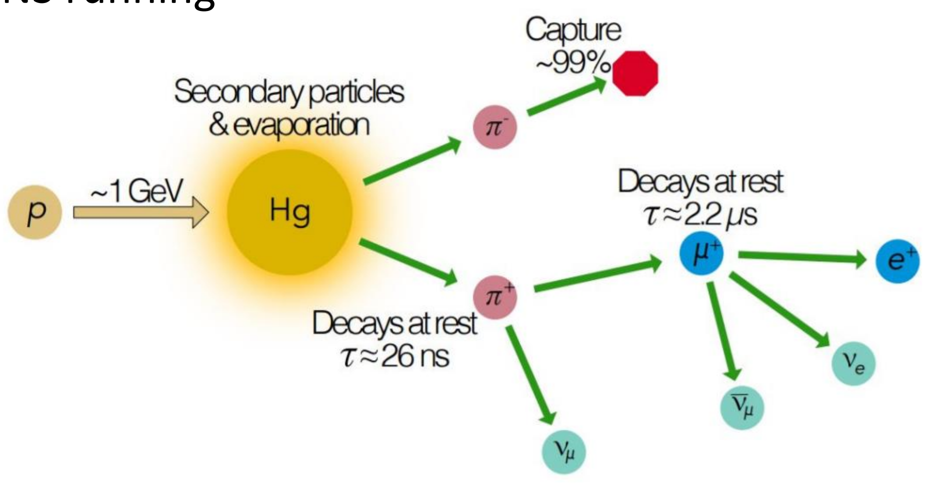
- Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- This may include mediator particles between SM and DM particles
  - Dominant production from $\pi^0/\eta^0 \to V\gamma$
- Mediator decays to a pair of DM particles, sending a flux out of the SNS
  - Suitable detector placed in this flux can directly detect DM particles scattering within the detector

Neutrino flux at the SNS

- Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

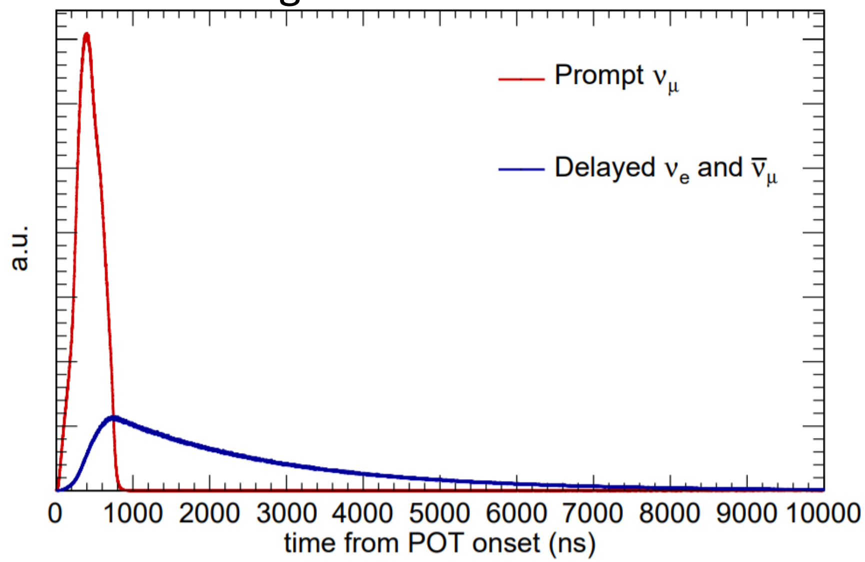
    $\pi^+ \rightarrow \mu^+ + \nu_\mu \quad : \tau = 26\text{ ns}$

    $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad : \tau = 2200\text{ ns}$
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature

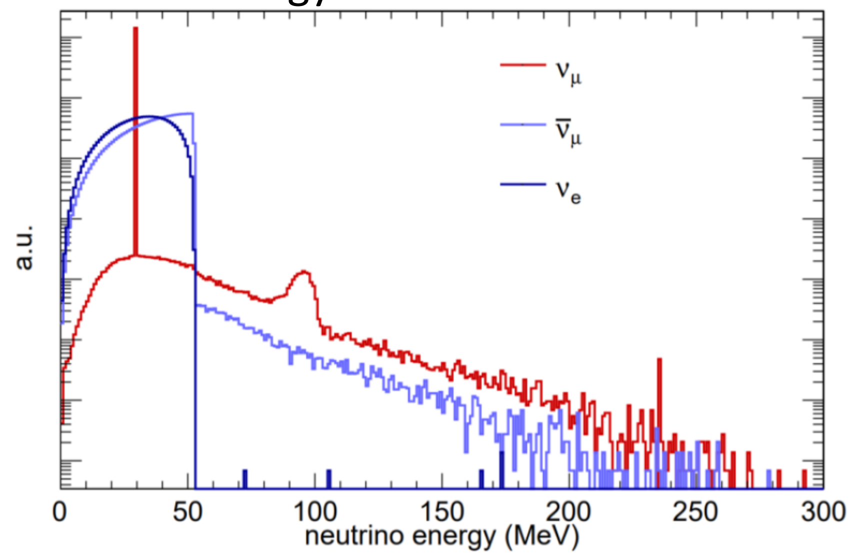


- Flux shape is very well known and very small contribution from decay in flight at the SNS

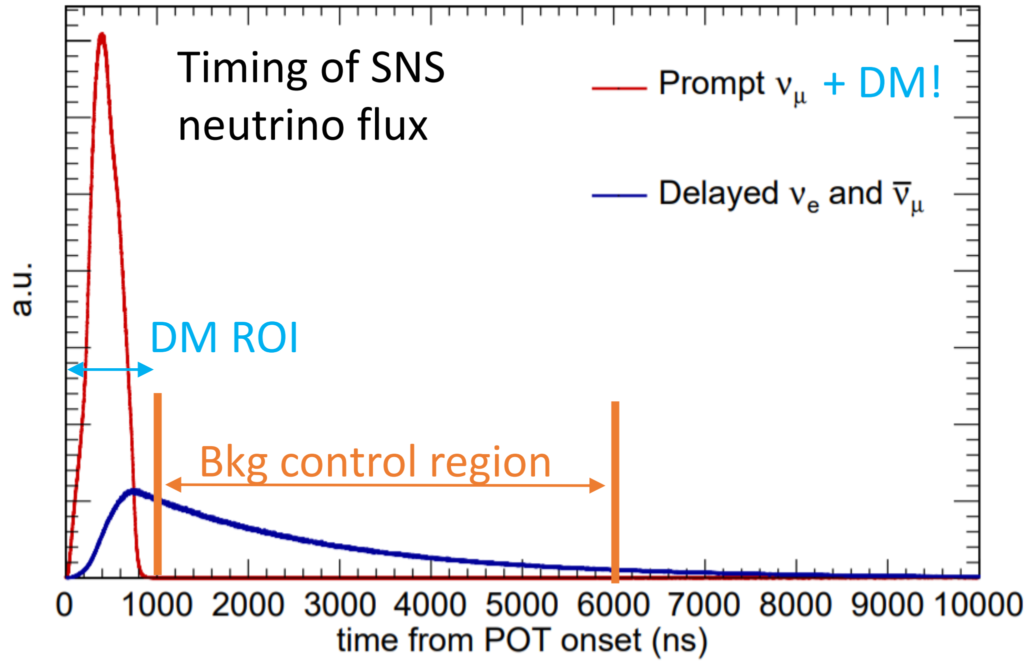
Timing distribution at SNS



Energy distribution at SNS

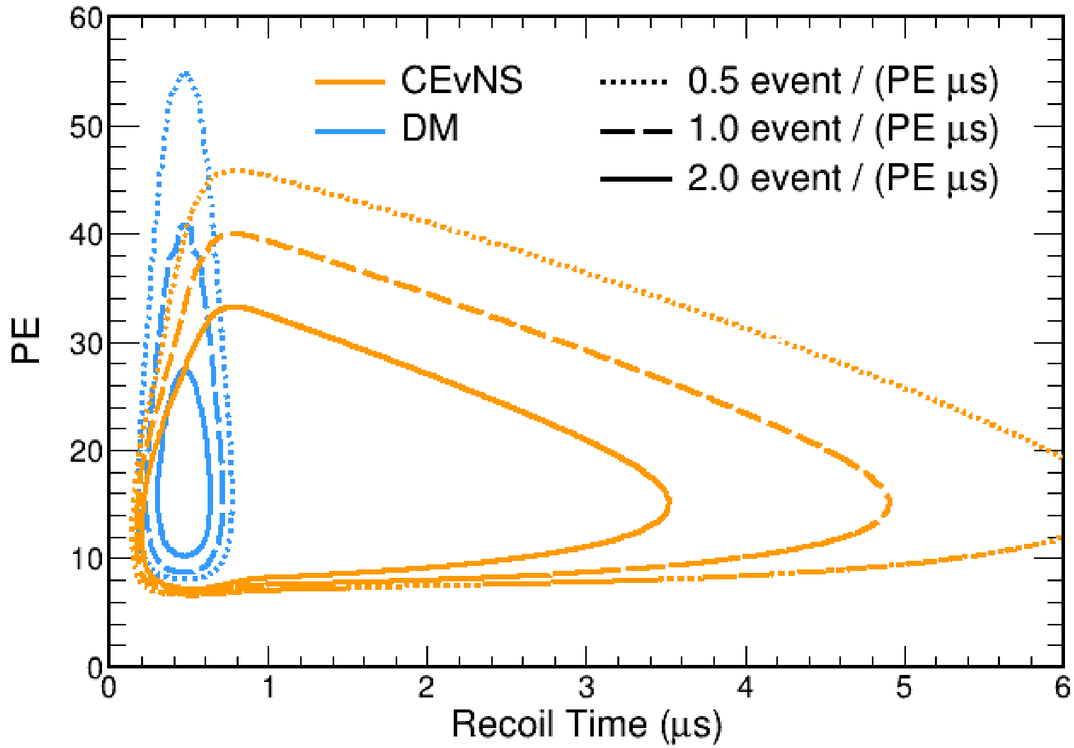


Advantages of spallation sources: constraining uncertainties



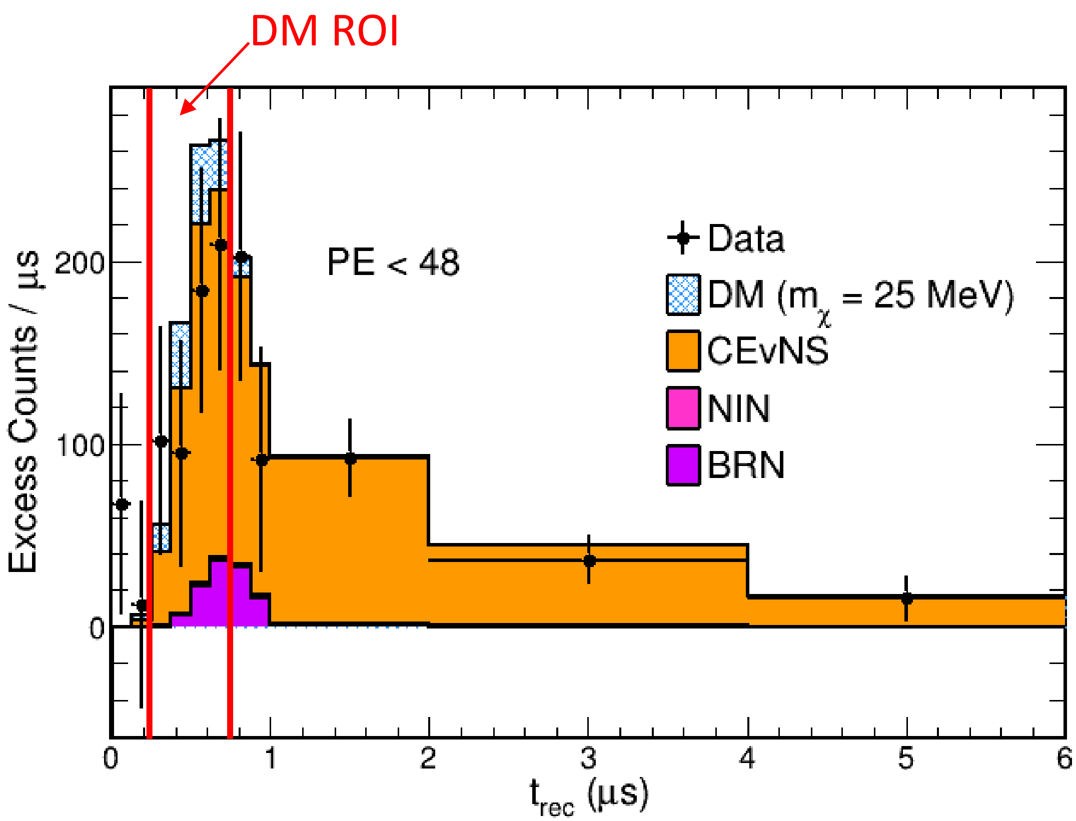
- CEvNS is the principal beam-related background for DM search
  - SM cross section precisely calculated, but uncertainties in detector response unique to each detector
- Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\upsilon_e/\bar{\upsilon}_\mu$ flux
- The delayed time window gives us a control sample – can constrain systematic uncertainties in situ and use to refine background estimates in the DM timing ROI
- Ensures DM search never systematics limited – syst uncertainty shrinks as fast as stat

Predicted excess in COHERENT CsI[Na] detector



- Can search for DM using CEvNS data from the COHERENT CsI[Na] detector – a 14.6-kg low-threshold scintillation detector
- Very different timing distributions expected for CEvNS and DM scattering events
- 2D fit to data for these two signals will give an estimate of DM produced at the SNS

Current dark matter data at SNS: CsI[Na]

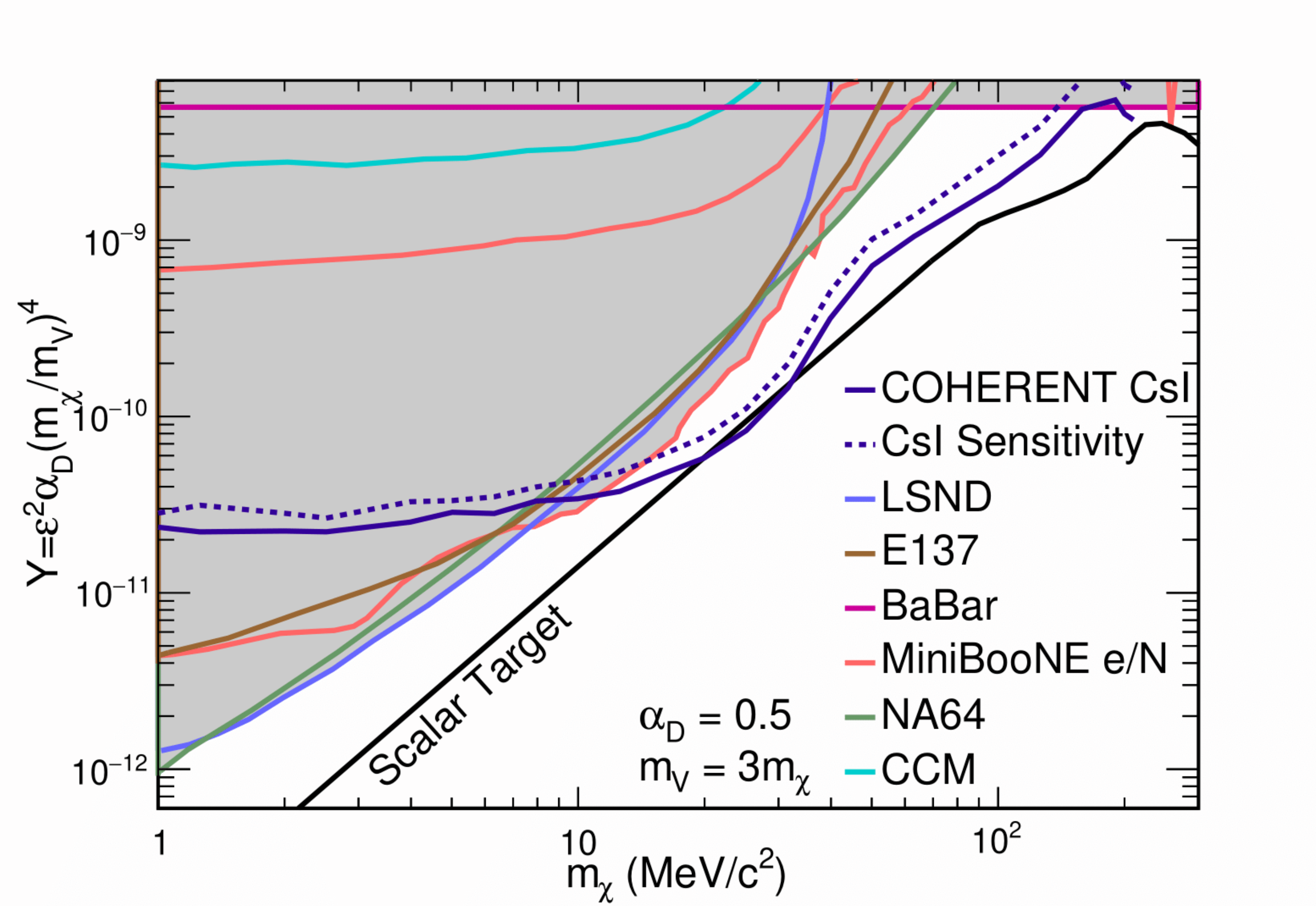


	Prediction	Data
CEvNS	341 ± 41	320 ± 33
BRN	27.6 ± 6.9	25.8 ± 6.6
NIN	7.6 ± 2.7	7.4 ± 2.7

- COHERENT data is consistent with predictions for the standard-model backgrounds within expected errors with slight deficit in DM ROI

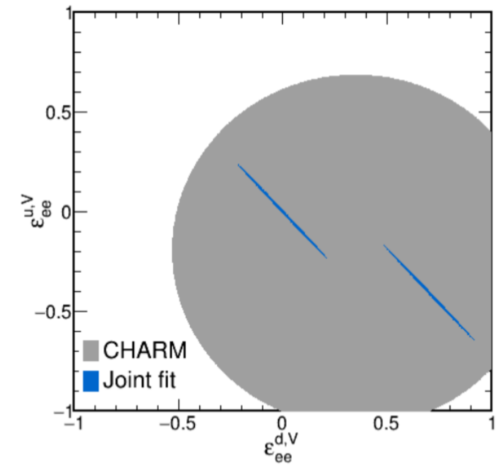
COHERENT constraint on sub-GeV dark matter

- At 90% confidence, CsI data significantly improves on constraints for masses 11 - 165 MeV/c^2
  - Constraint slightly stronger than our sensitivity due to deficit of events in DM timing ROI
- First to probe beyond the scalar target that matches the DM relic abundance
- Achieved with small 14.6 kg detector – but we can build bigger promising a bright future

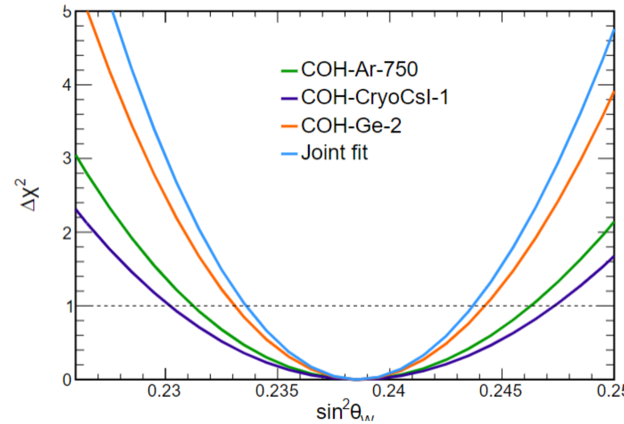


Additional physics with CEvNS

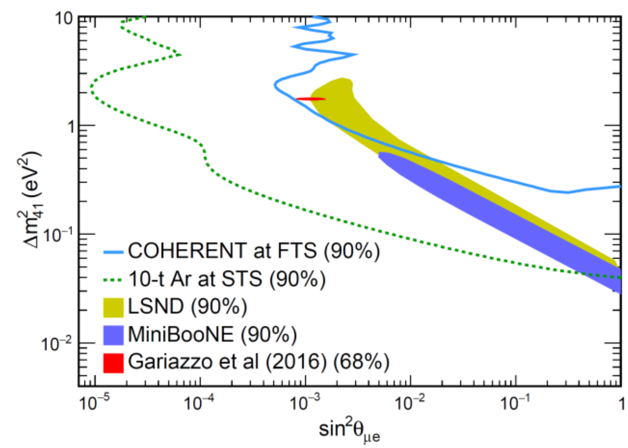
- CEvNS has exciting potential to discover BSM physics on its own right – a few brief examples:
- Search for quark-neutrino BSM interactions
  - Interaction strength known poorly for NC scattering, with O(100%) uncertainty on couplings to various quarks
  - Important for properly calculating matter effects in neutrino oscillation experiments



- Measuring weak mixing angle at $Q^2 \approx (50\ \text{MeV})^2$
  - Deviations from SM prediction expected for BSM scenarios such as dark photons which may explain g-2
  - 1% sensitivity possible with future COHERENT data

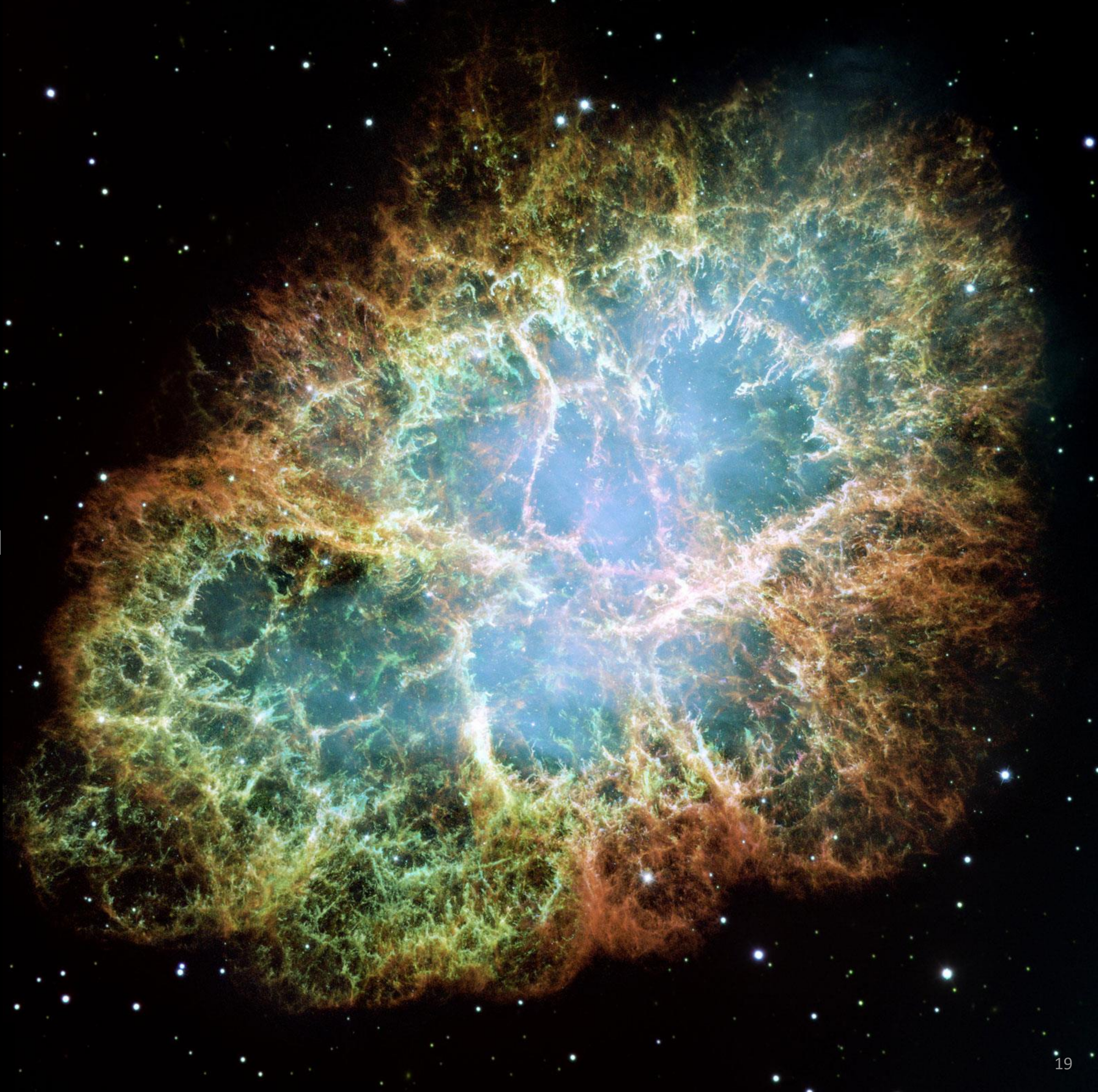


- Search for exotic neutrino oscillations
  - Significant evidence for oscillations beyond three-flavor framework – LSND and MiniBooNE anomaly
  - May be evidence for a fourth neutrino, a sterile eigenstate
  - Data is not consistent, however, with future COHERENT data covering parameter space consistent with anomalies



Supernova neutrinos

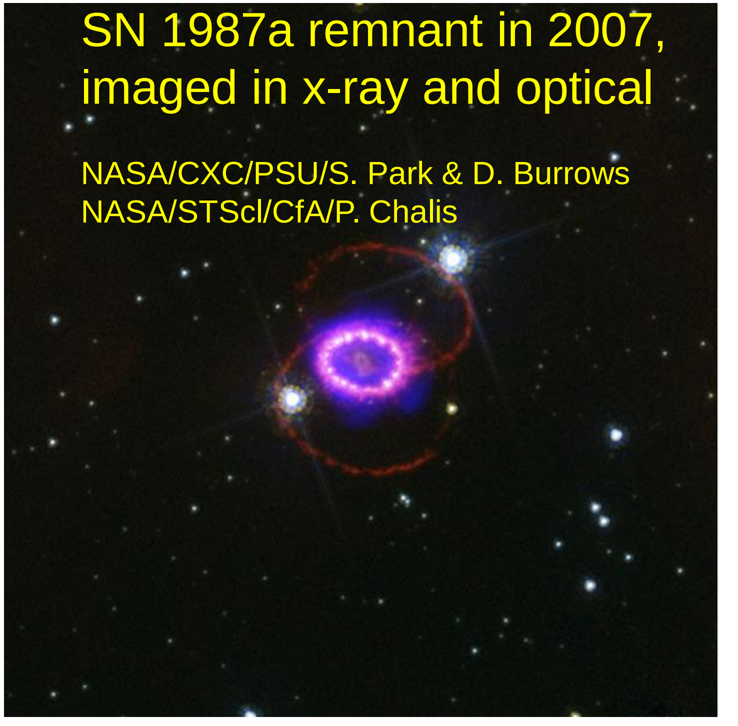
Crab nebula, remnant of supernova recorded in 1054



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 $\approx$ 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

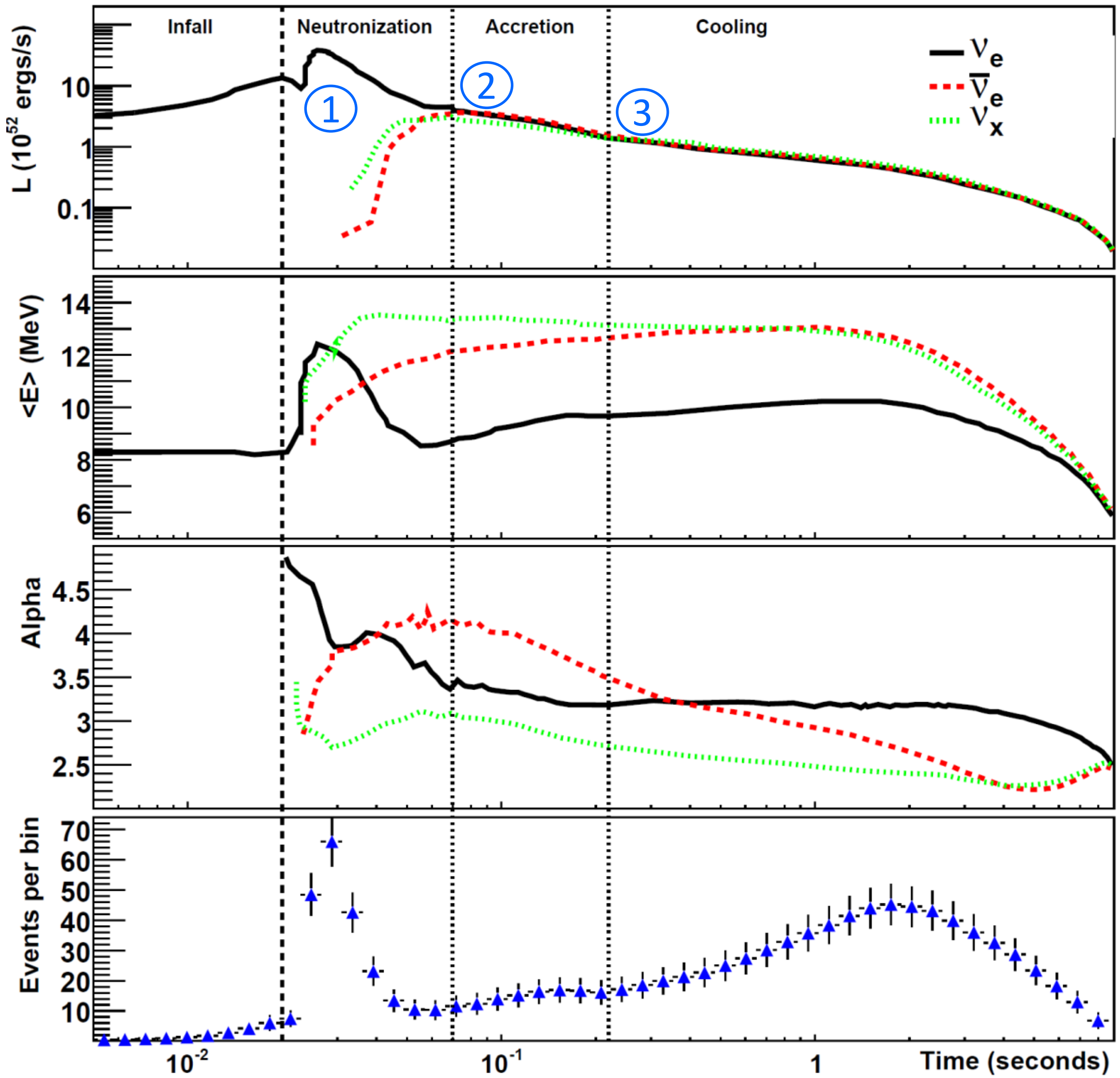
Neutrino production in a supernova

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



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

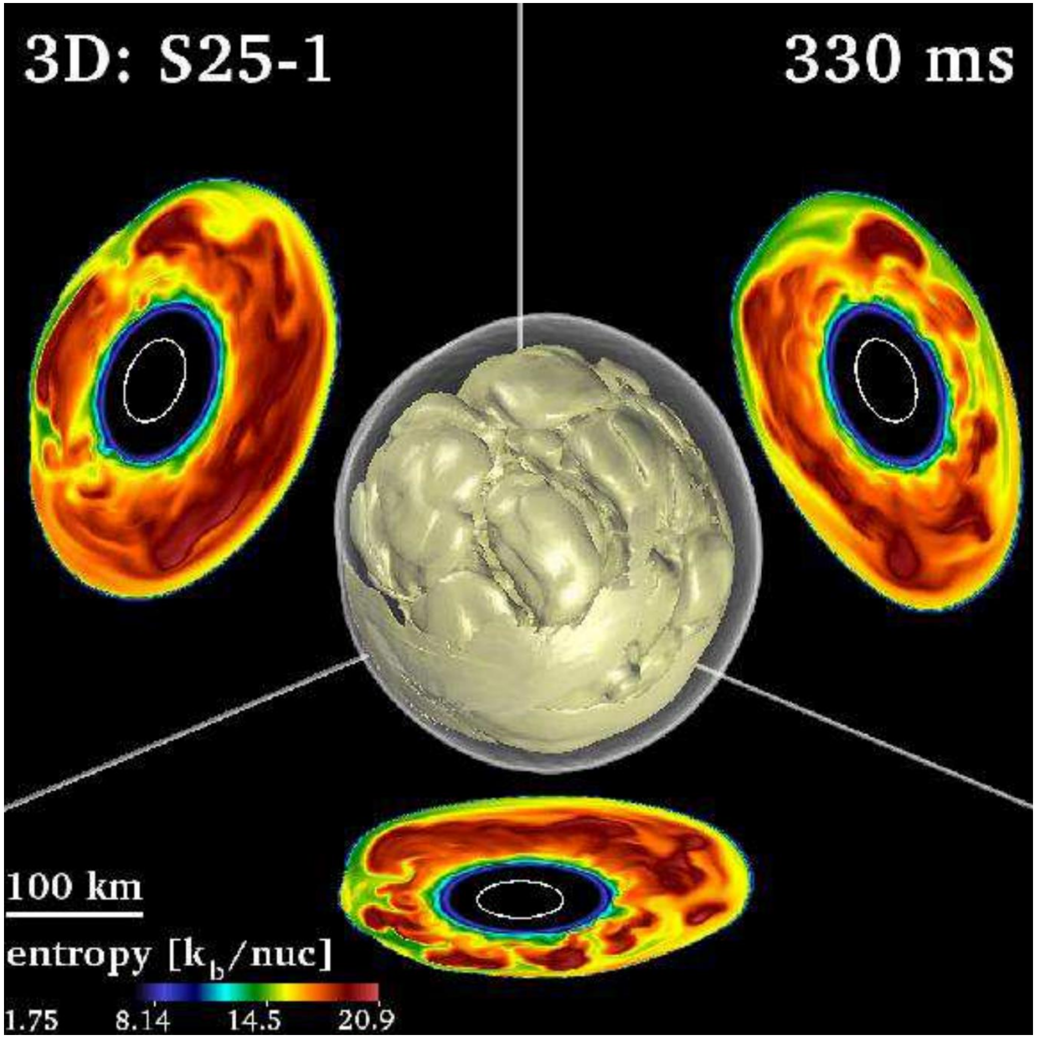
ES + CC + NC + IBD
Good energy resolution for calorimetry
Current experiments: SNO, NOvA
Future experiments: JUNO

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)

Understanding the collapse mechanism

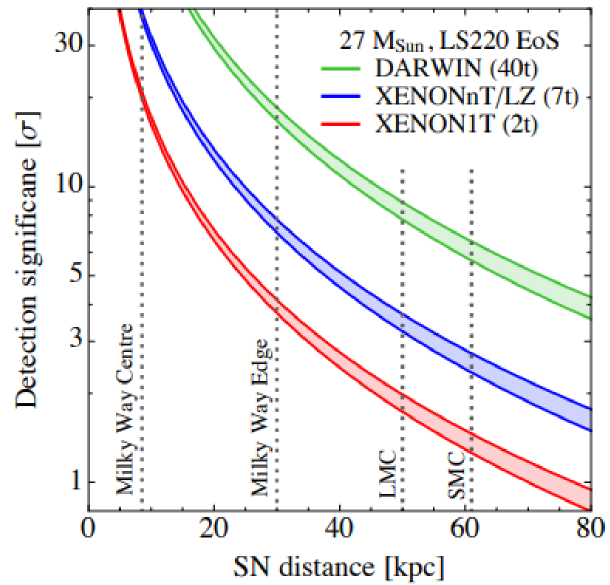
- Very complex system with 3D modeling of shock wave only possible in last 10 years
- Offers precise prediction for neutrino rates that can be tested with a new, large-dataset observation

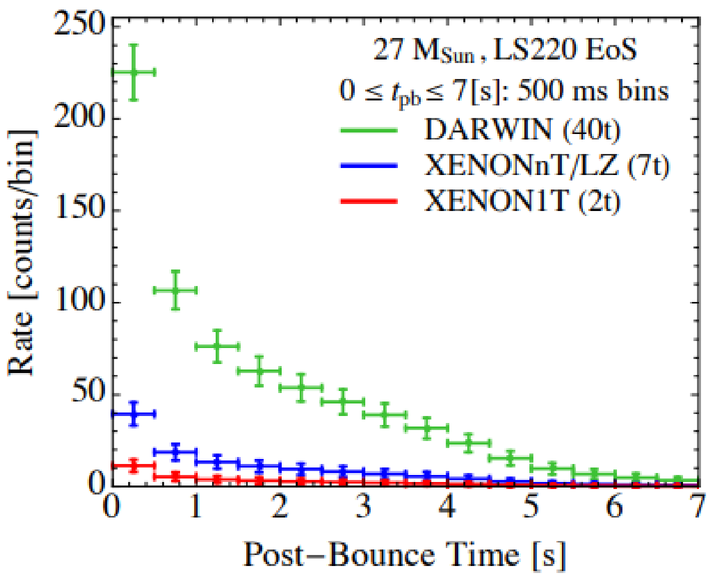


ApJ **770** 66

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



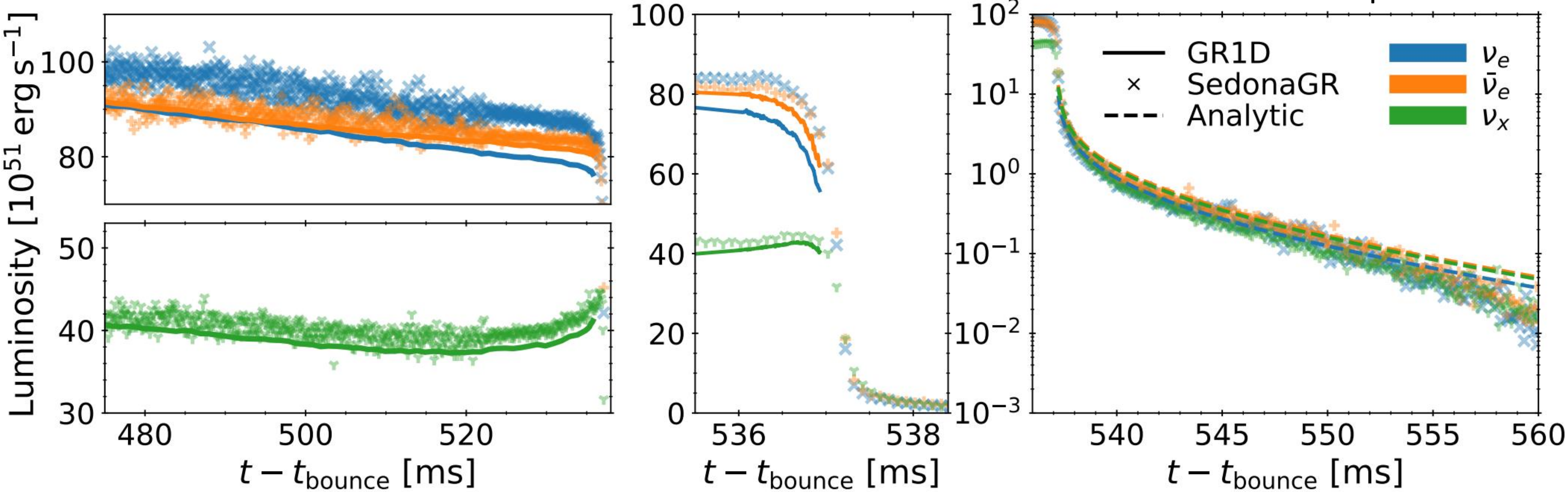


- Expect > 100 detected CEvNS events from the next galactic supernova
- Since CEvNS is NC, the time trace gives the total neutrino flux at a given time without uncertainties on evolution of flavor composition

Phys Rev **D94** 103009 (2016)

Detecting black hole daughters

ApJ **926** 212



- 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

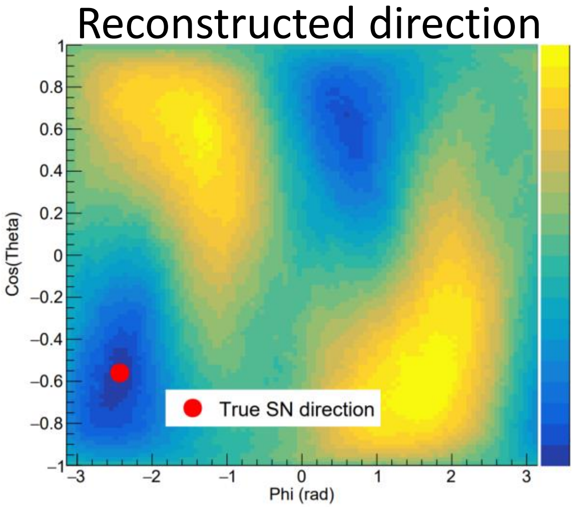
1987 supernova, Anglo-Australian Observatory

- 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 ≈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

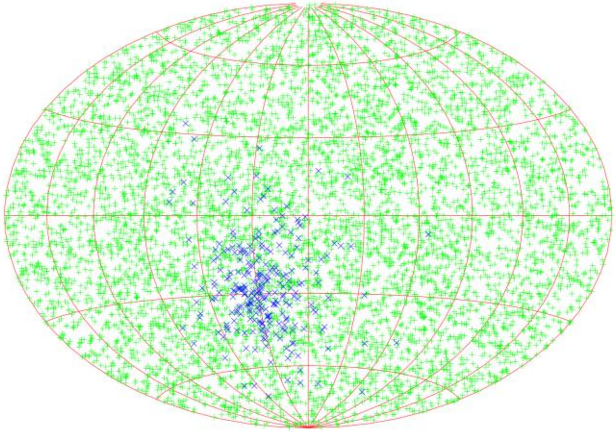
Strategies to estimate supernova direction

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

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



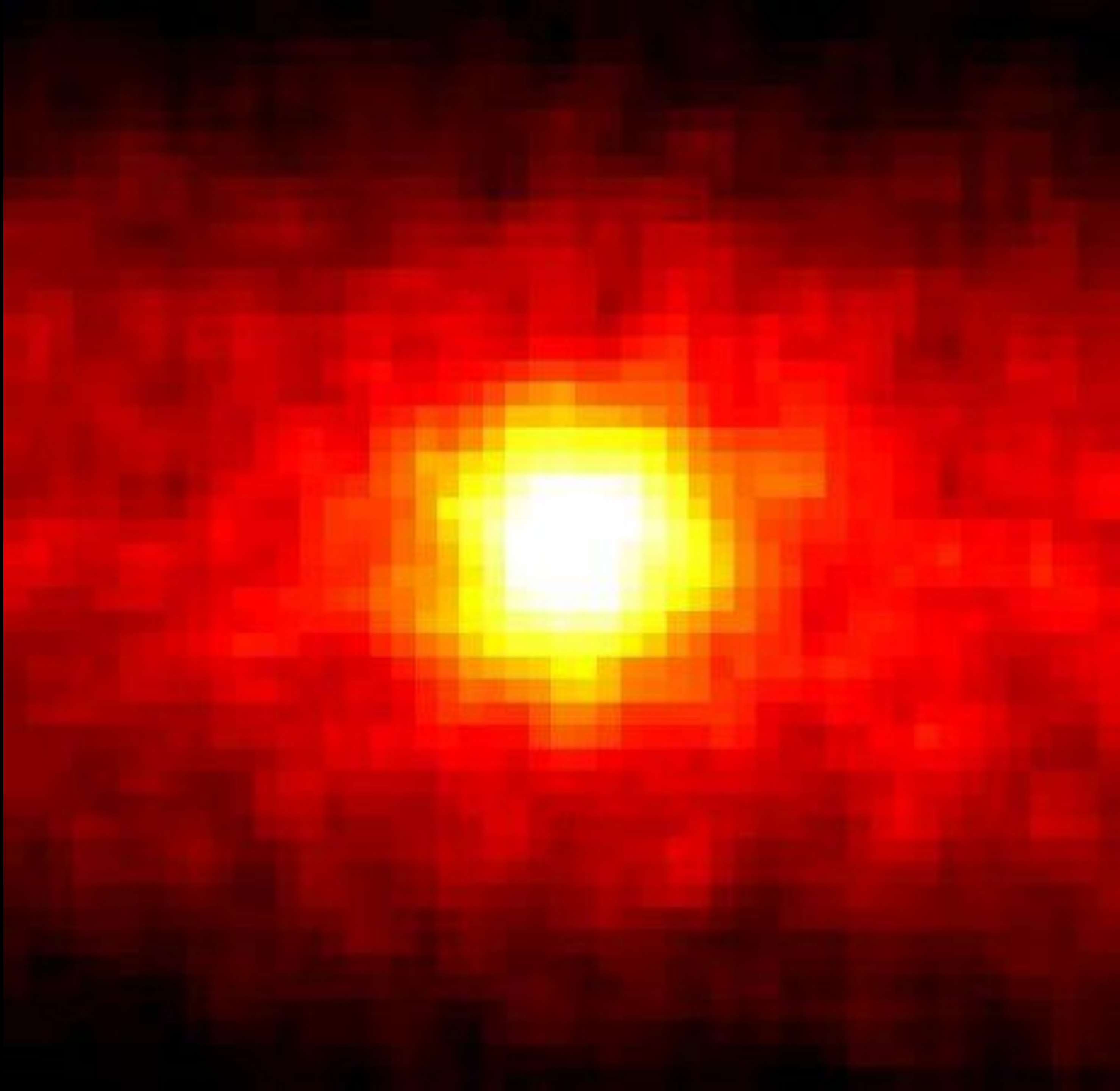
Gd-loaded water Cherenkov detectors:
≈300 ES interactions
IBD rejection through coincidence with neutron capture
Estimate ≈2-3 deg resolution



PRD **68**, 093013

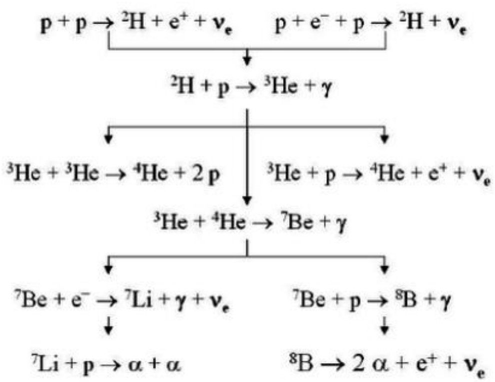
Solar neutrinos

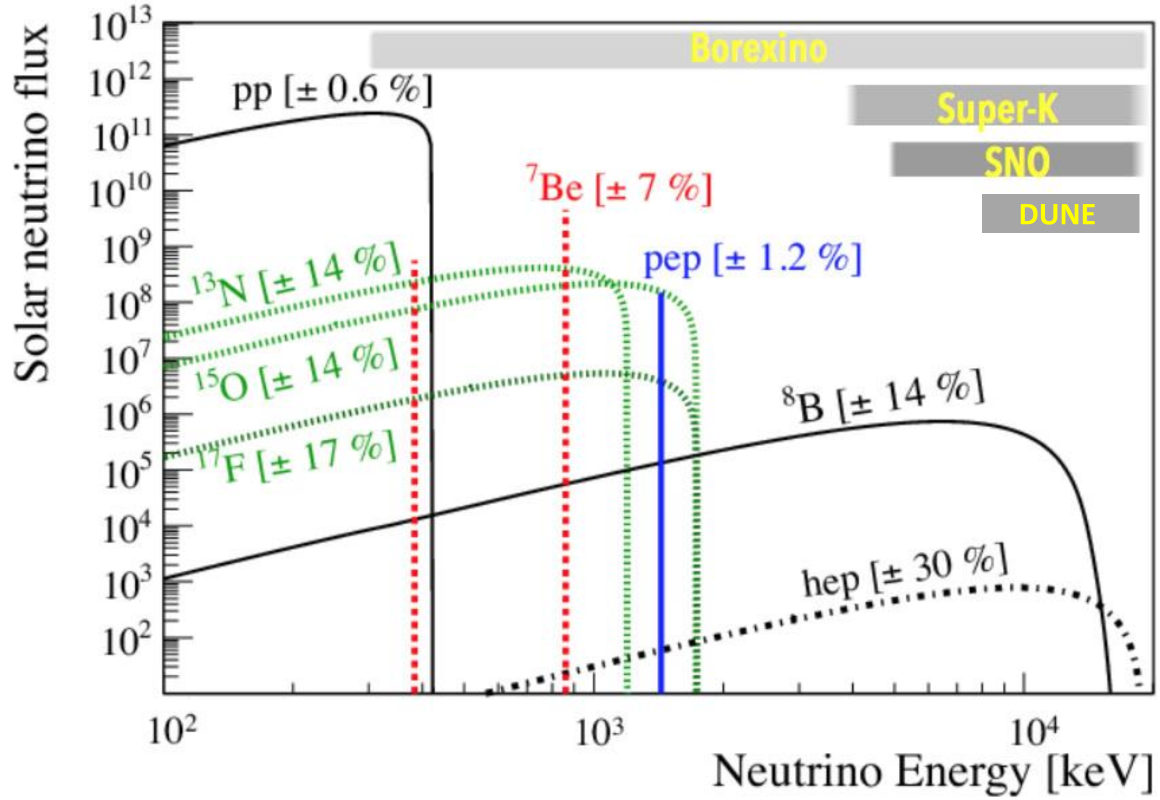
First photo of the sun taken from below a mountain –SK collaboration



Solar neutrino flux

^{4}He production in sun

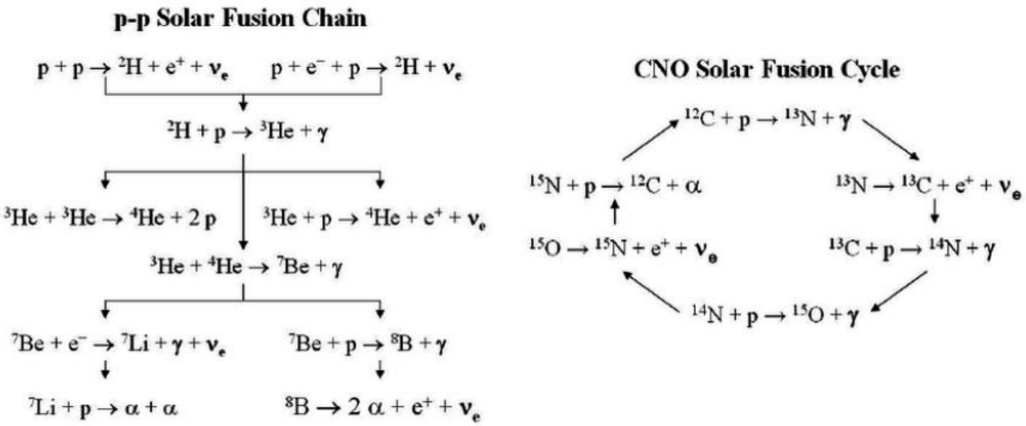




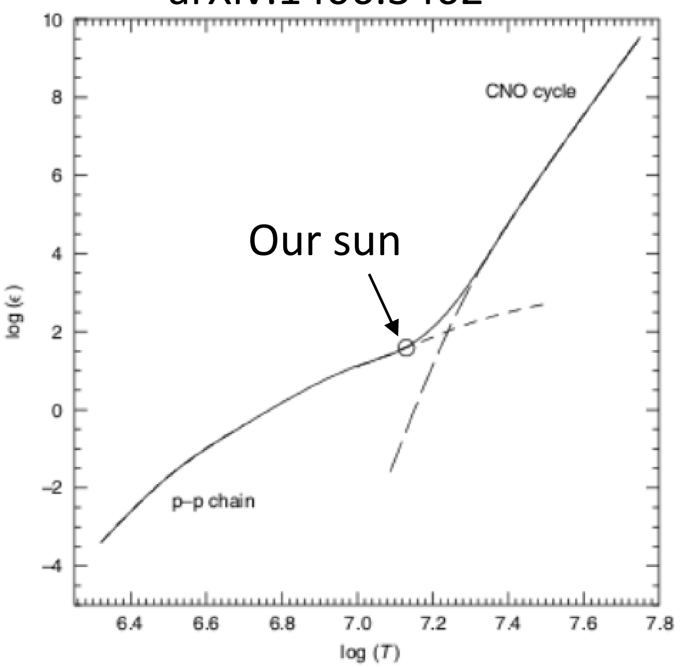
- ❑The sun produces an enormous flux of neutrinos with energies < 19 MeV
  - Only way to probe solar core and understand the interior fusion processes
  - Homestake experiment (Ray Davis) – solar neutrino experiment gave first confirmation that sun's energy is produced by fusion
  - Solar neutrinos also gave first evidence of neutrino oscillations / neutrino mass

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

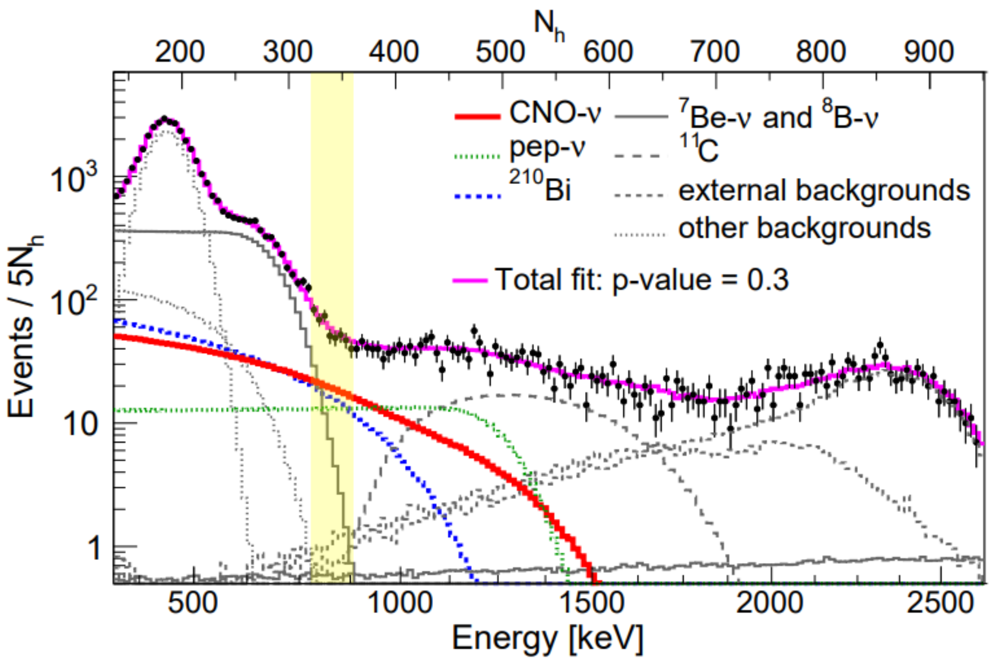


arXiv:1406.3462

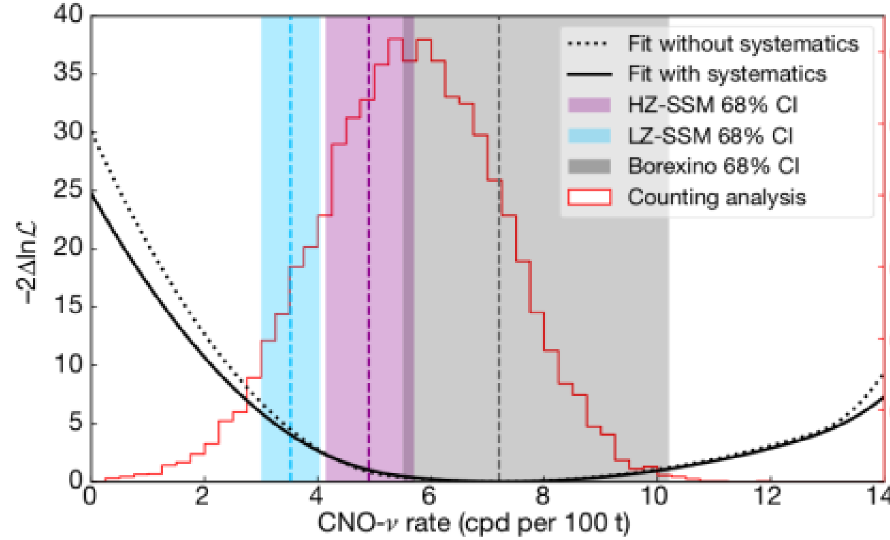


- The sun lies within the narrow mass range where both processes contribute
  - 99% pp-chain + 1% CNO-cycle neutrinos
- First measurement by Borexino in 2020
- Precision measurements of the CNO flux and normalization will validate solar model and improve understanding of other stars

Borexino: CNO discovery



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

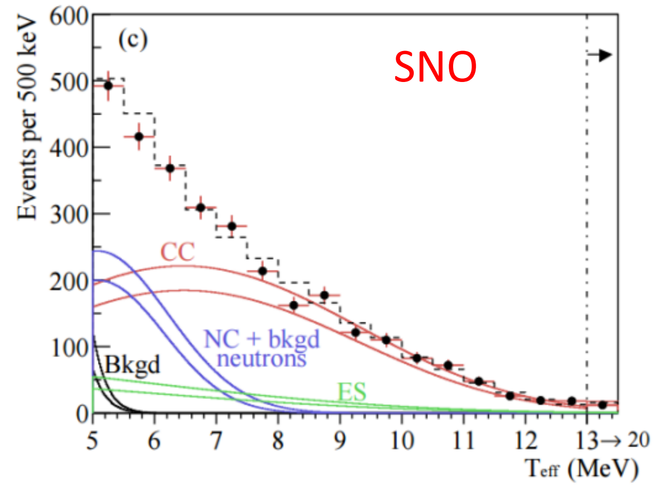


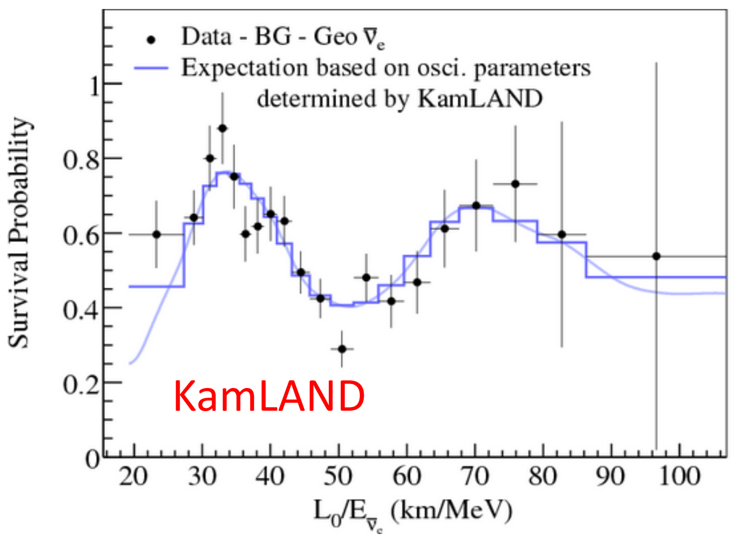
- Borexino is a 100t scintillator detector at LNGS designed to study the
- Good energy resolution of electron recoils allows a small region of recoil energy where CNO dominates according to the standard solar model
- A likelihood fit gives 5σ evidence for existence of the CNO flux with a normalization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

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

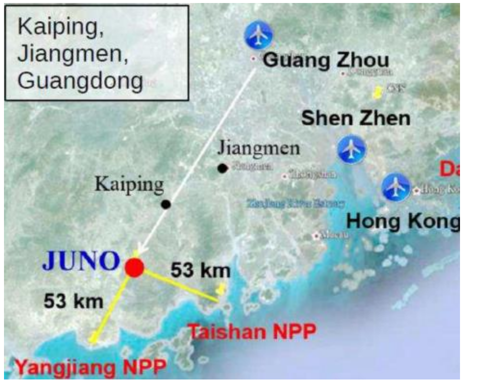
- Both solar and terrestrial reactor experiments observe neutrino oscillations, but disagree on the value of the mass splitting by 1.4σ
- This discrepancy may point to new physics such as BSM matter effects within the sun and should be tested with next-generation experiments

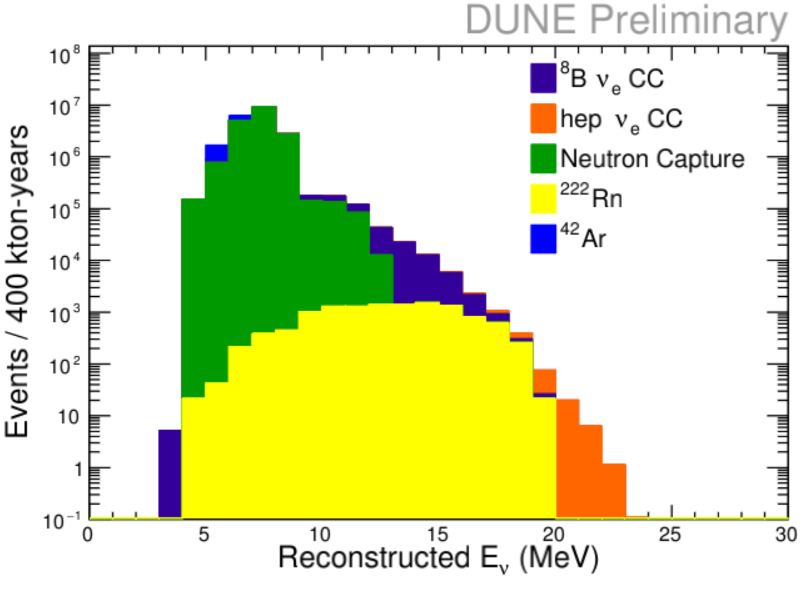
The next generation of experiments

Large sample, precision measurements!

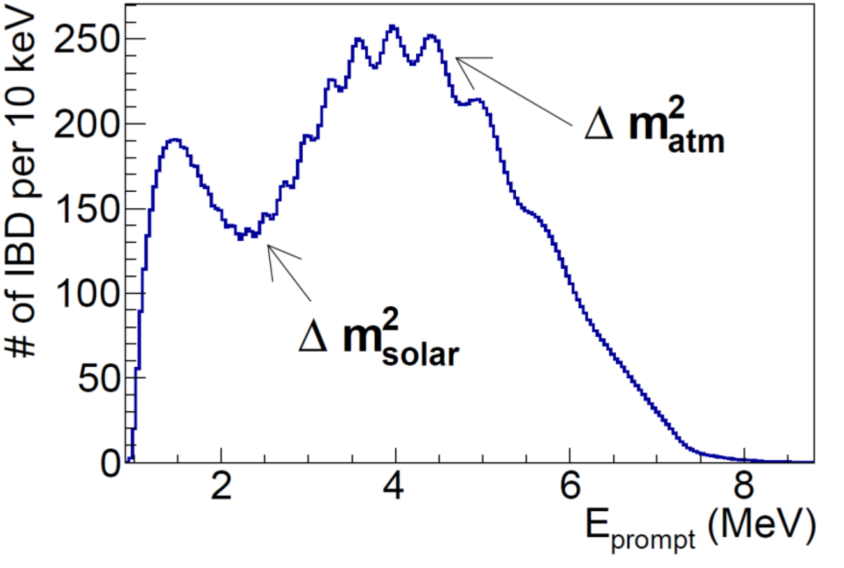
DUNE, in addition to supernova neutrinos, will also collect a large, > 10^6 CC event, sample of solar neutrinos

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



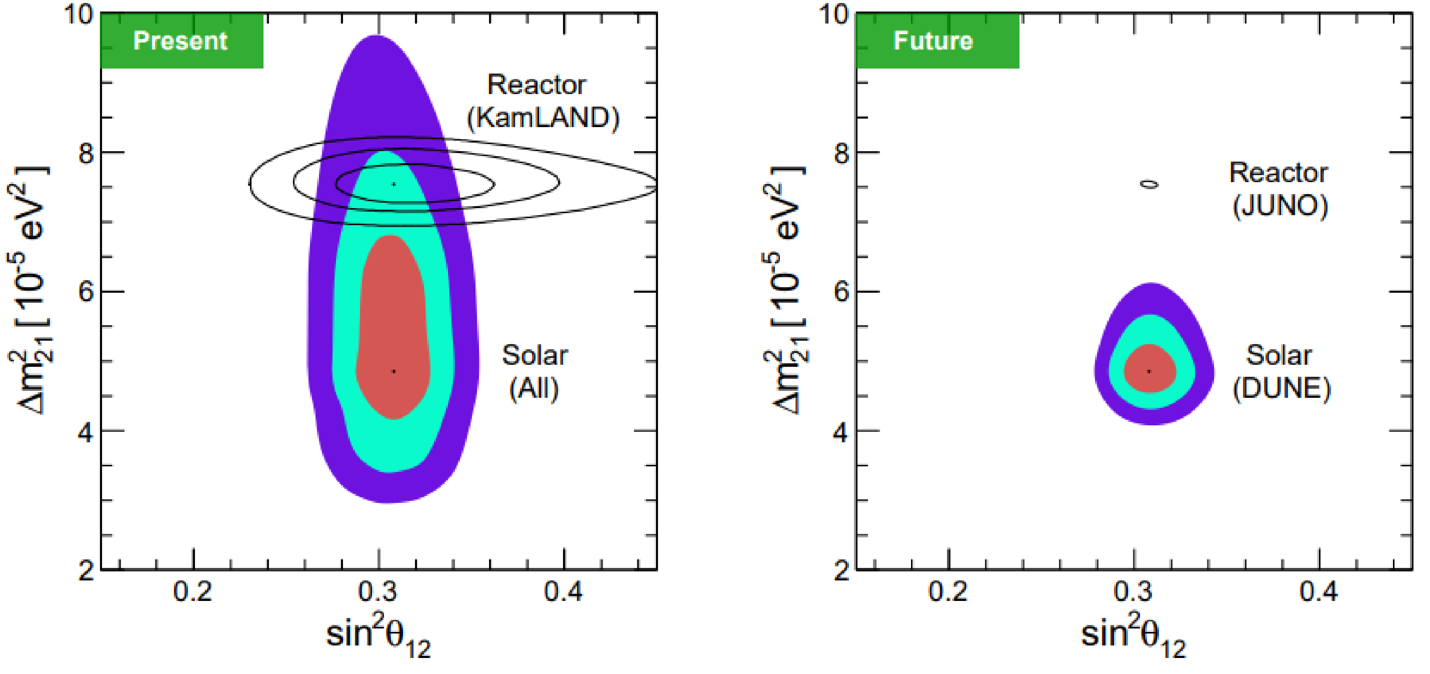


J. Phys **G43** 030401 (2016)



Future sensitivity to solar oscillations

PRL **123** 131803



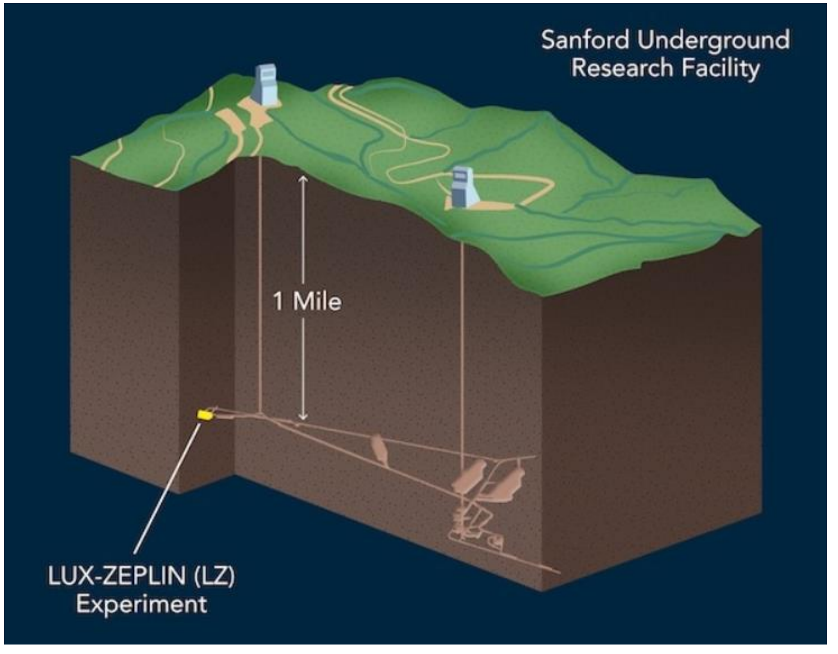
- ❑ Future data may resolve SNO/SK and KamLAND discrepancy at 5σ
- ❑ DUNE sensitivity largely comes from day/night effect – a partial regeneration of the ν_e flux due to matter effects in Earth
  - Also, the ratio is less sensitive to systematic errors
- ❑ Book isn't closed on solar oscillations – interesting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

Summary

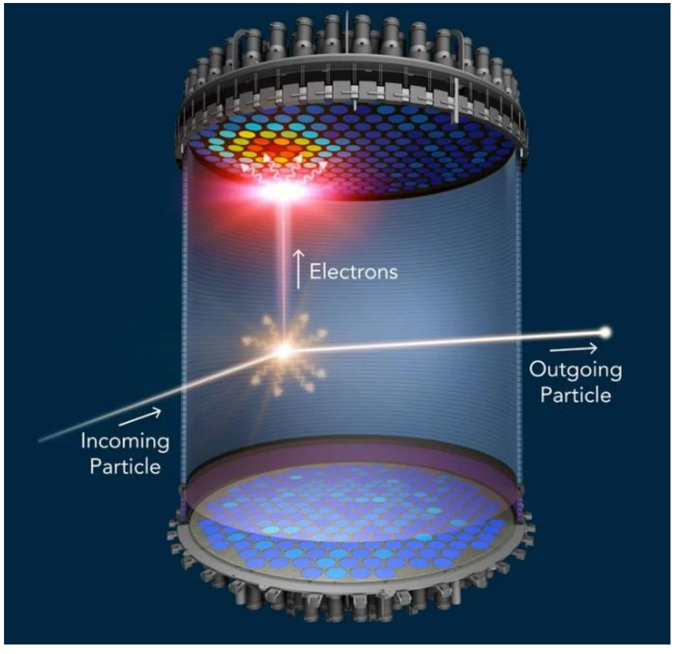
- Large overlap between neutrino experiments and cosmology / astrophysics
  - The neutrino process, CEvNS, is very similar to WIMP scattering – any CEvNS detector is also an efficient dark matter detector
  - Core-collapse supernova of massive stars release an intense burst of neutrinos that can be detected from across the galaxy – terrestrial neutrino experiments witness the final seconds of a star’s life and are the only way to directly observe the core-collapse mechanism
  - Measuring neutrinos produced in the sun give the only way to probe fusion processes in the solar interior and historically important, giving first indication of neutrino oscillations

Detecting DM – e.g. Lux Zeplin (LZ)

LZ site at SANFORD – https://lz.lbl.gov/

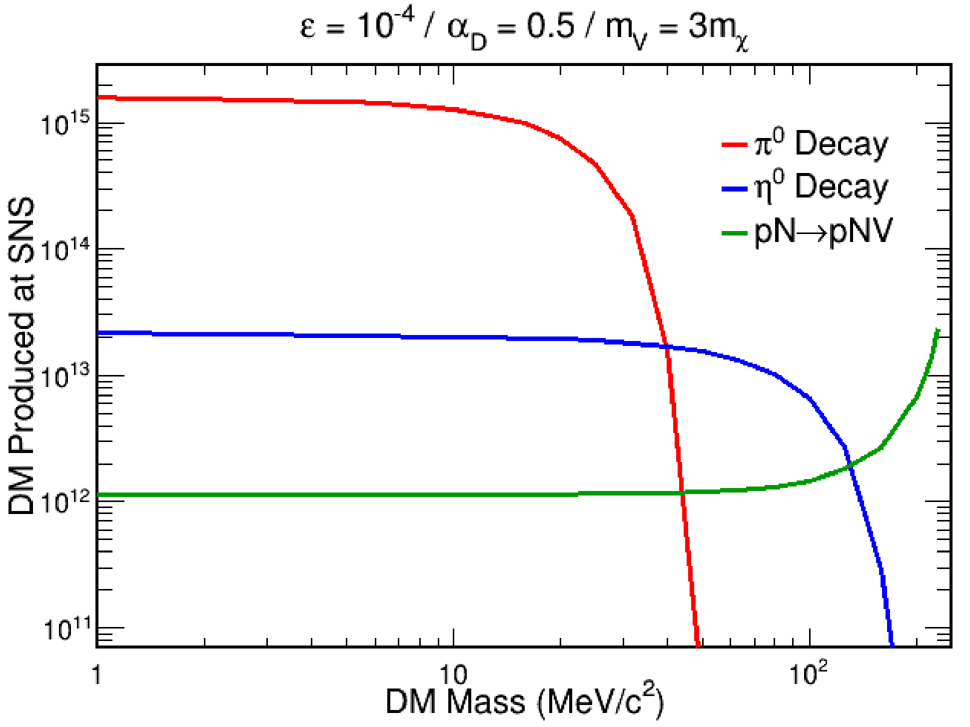


WIMP scattering in xenon TPC



- From freeze-out model, scattering rates for DM are low, but within reach of very low background underground detectors
- DM may interact coherently with nuclei, giving small but observable nuclear recoil energy

DM production channels

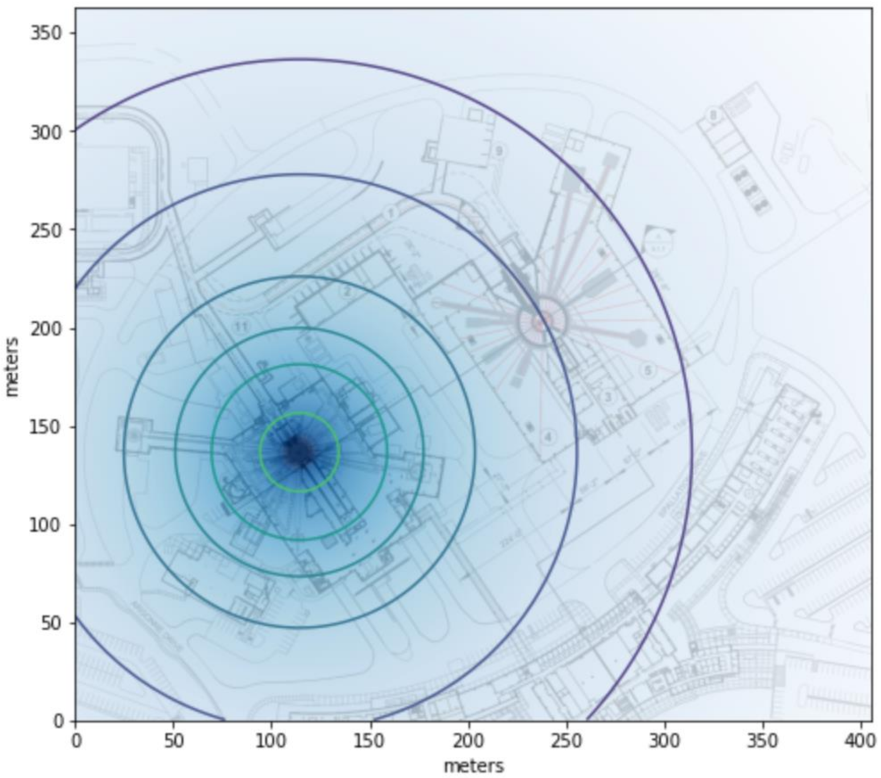


- Our expected dark matter flux is produced through three channels
  - $\pi^0 \to V\gamma$ decay: dominant channel where kinematically allowed, $2m_\chi < m_\pi$,
  - $\eta^0 \to V\gamma$ decay: similarly only contributes for $2m_\chi < m_\eta$
  - $pN \to pNV$ bremsstrahlung: only dominant at high energies and rate increases significantly at the ρ resonance, $m_V \approx m_\rho$

Directionality of flux at the SNS

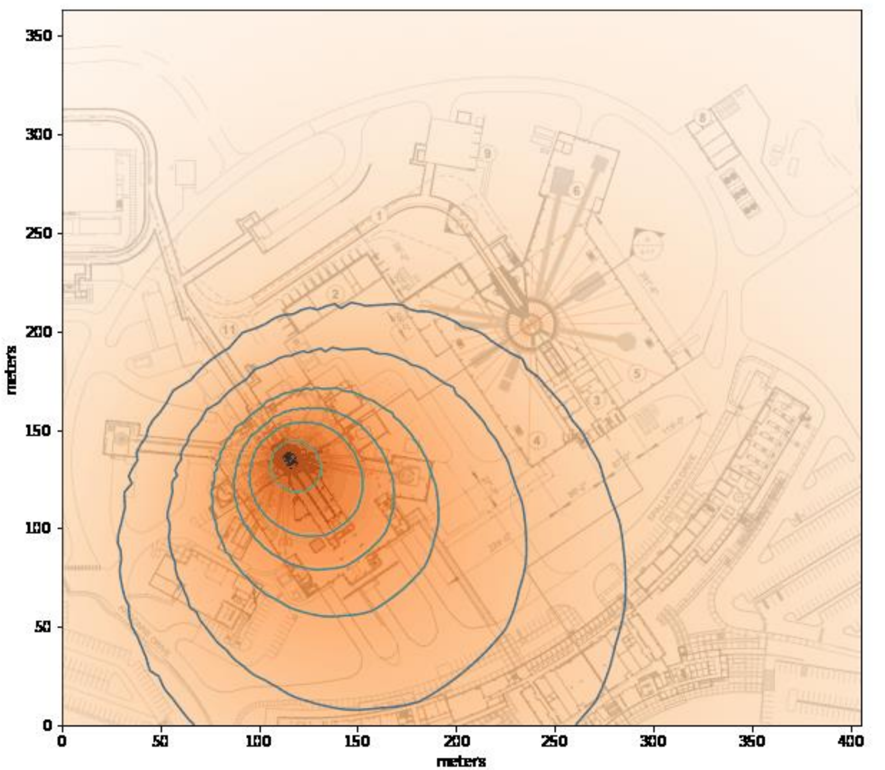
Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS



DM produced in-flight – is boosted

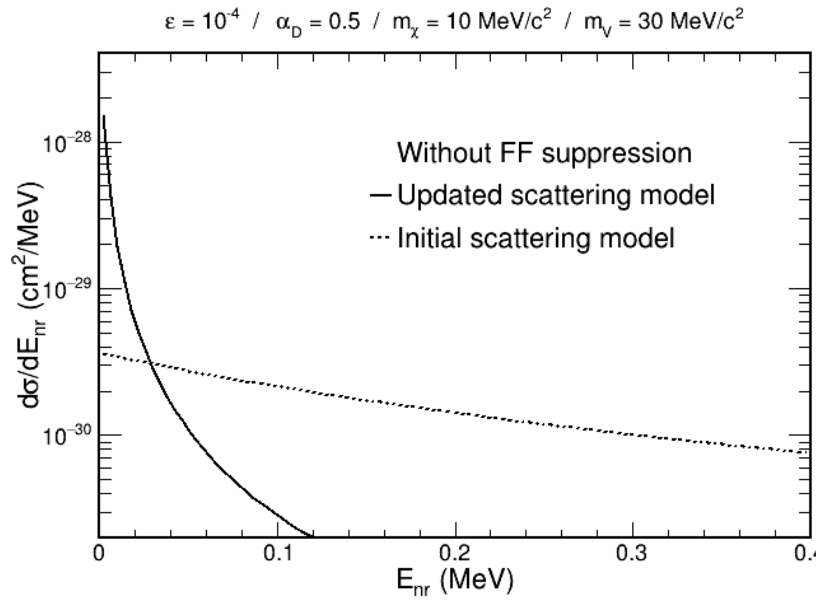
A forward-directed detector would optimize DM / background



- After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

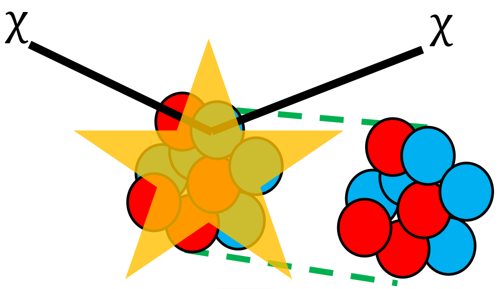
Recent updates to cross section generator (BdNMC)

- DM particles scatter with coherent cross section
  - $\frac{d\sigma}{dE_r} = 4\pi Z^2 \varepsilon^2 \alpha_{EM} \alpha_D \frac{2 m_N E_\chi^2}{p_\chi^2 (m_V^2 + 2 m_N E_r)^2} |F(Q^2)|^2$



- This model has changed significantly since our previous sensitivity estimates
- 1: A substitution of $m_p \rightarrow m_N$ for a proper treatment of coherent scattering
  - Overall increases cross section, but spectrum is much softer – detector thresholds much more impactful for DM analyses
  - Degrades (Improves) sensitivity for DM masses below (above) 10 MeV/c^2
- 2: A more accurate form factor treatment
  - BdNMC now uses the nuclear form factor accounting for spread of protons within nucleus rather than the proton form factor accounting for spatial spread of charge within each proton
  - Significantly reduces sensitivity at higher masses
- 3: Improved configured resolution of DM scattering cross section from 100 MeV to 1 MeV
  - Gives slight reduction in event rate, but is more accurate

Advantages of low-recoil detectors: cross section



$$\lambda = h/\sqrt{Q^2} \gg R_p$$

- We're dealing with low enough Q^2 that the deBroglie wavelength is large compared to nuclear radius
- All nucleons within nucleus recoil coherently from neutrino or DM scattering
- Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

- This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- Game-changing – investing in a small 14-kg detector can compete with multi-ton detectors

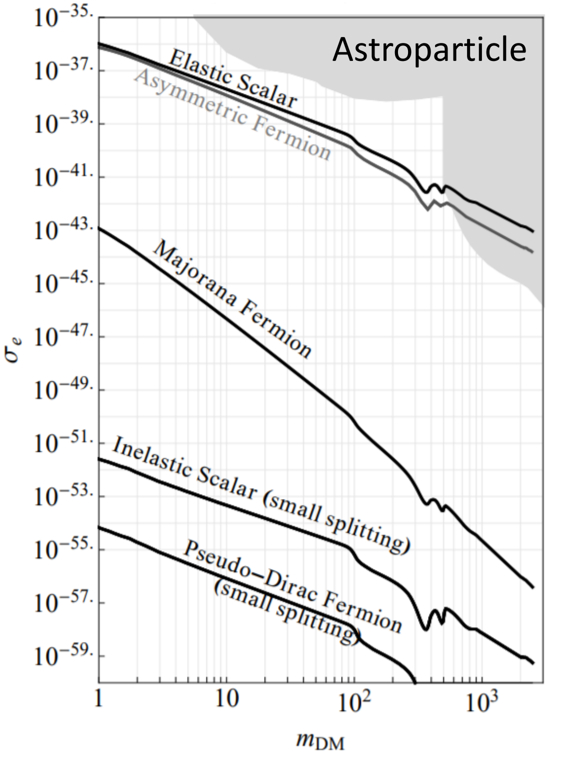
Direct-detection experiments searching for light dark matter

	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146

Advantages of accelerator searches: less model dependent

- Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM
- But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed $v/c < 0.001$
- Predictions span 20 orders of magnitude

arXiv 1707.04591



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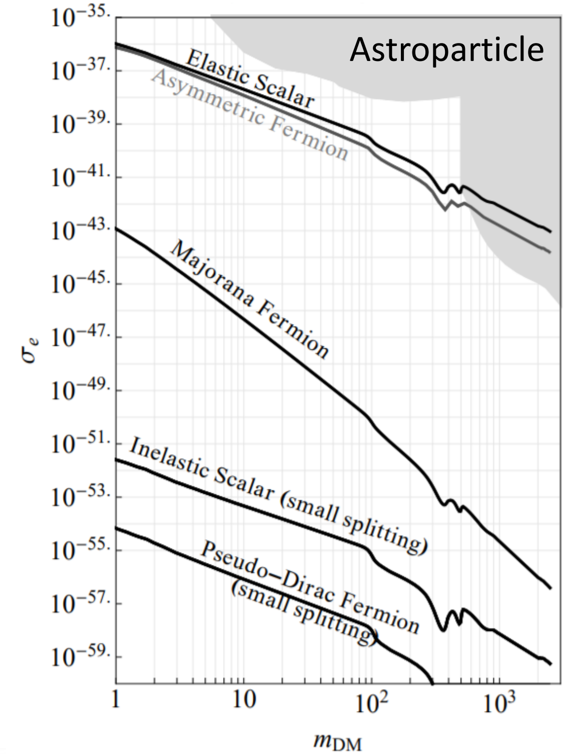

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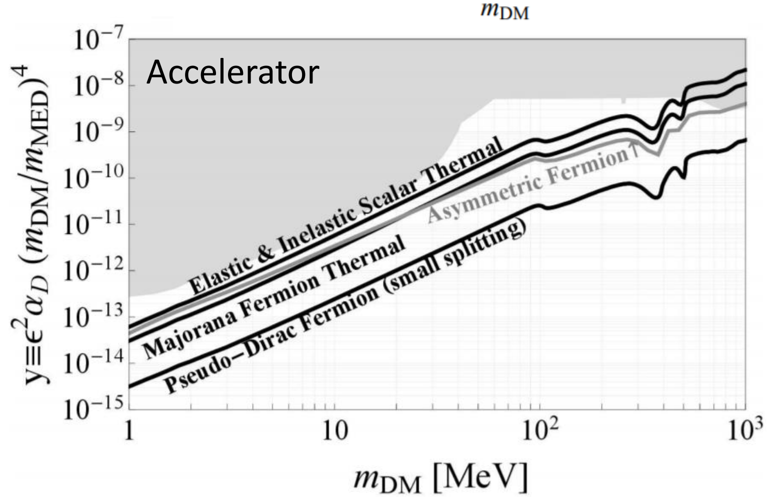
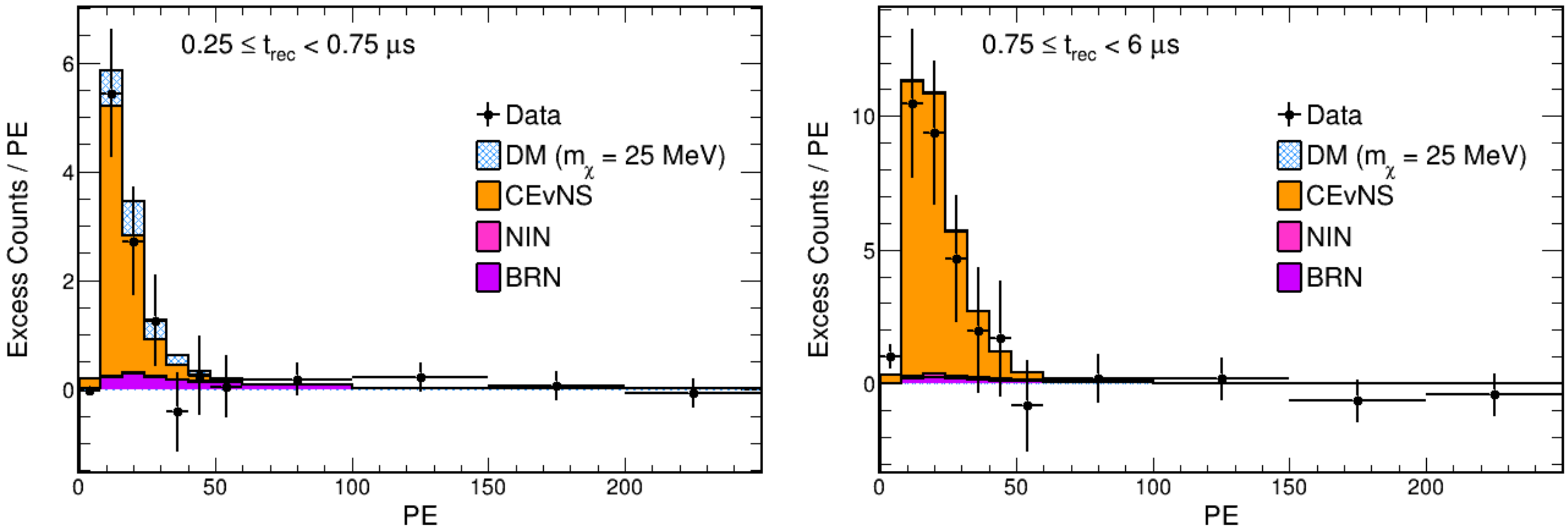


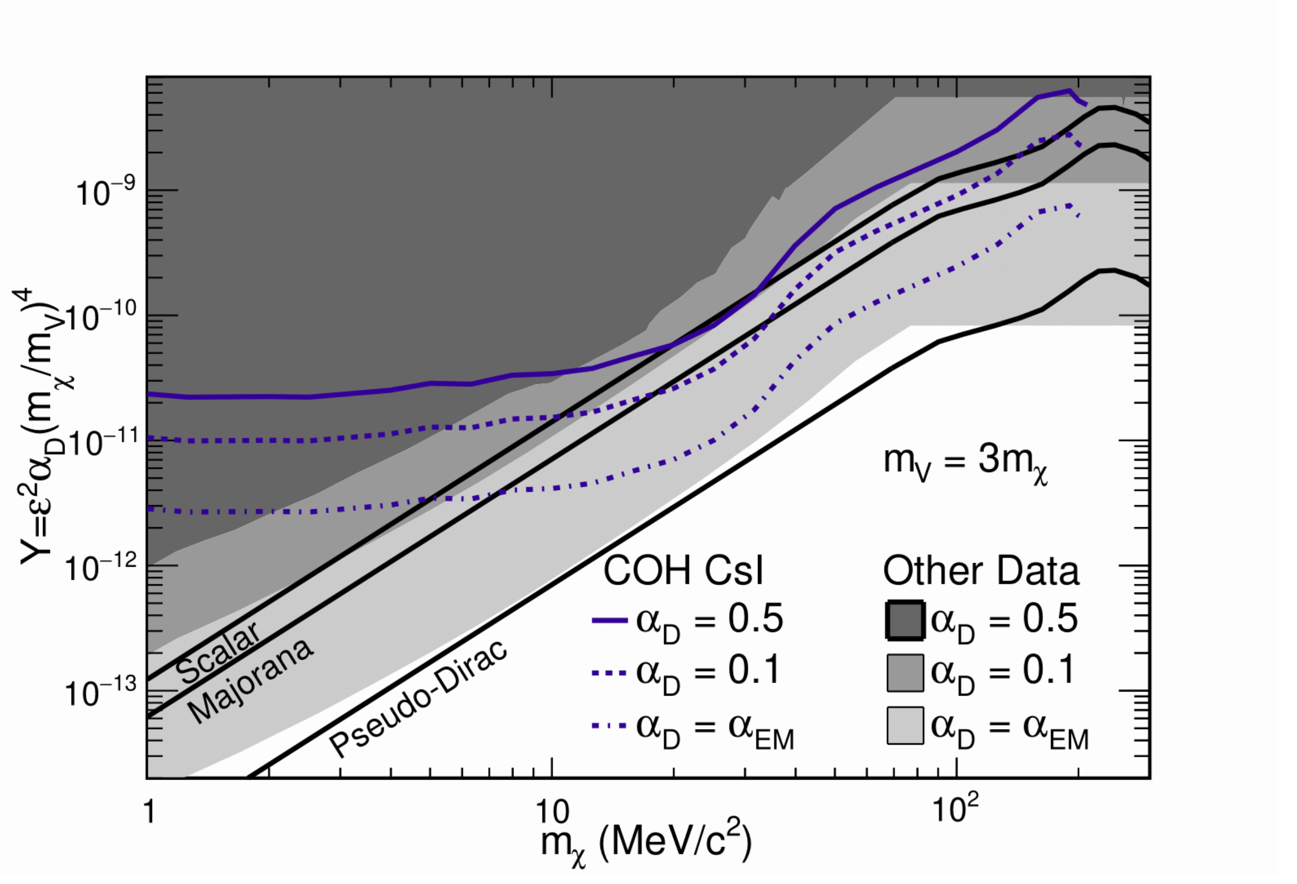
- At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- COHERENT gets the best of both worlds
  - Independent of DM particle nature like accelerator methods
  - Large coherent cross section like astroparticle methods

Recoil distribution of data



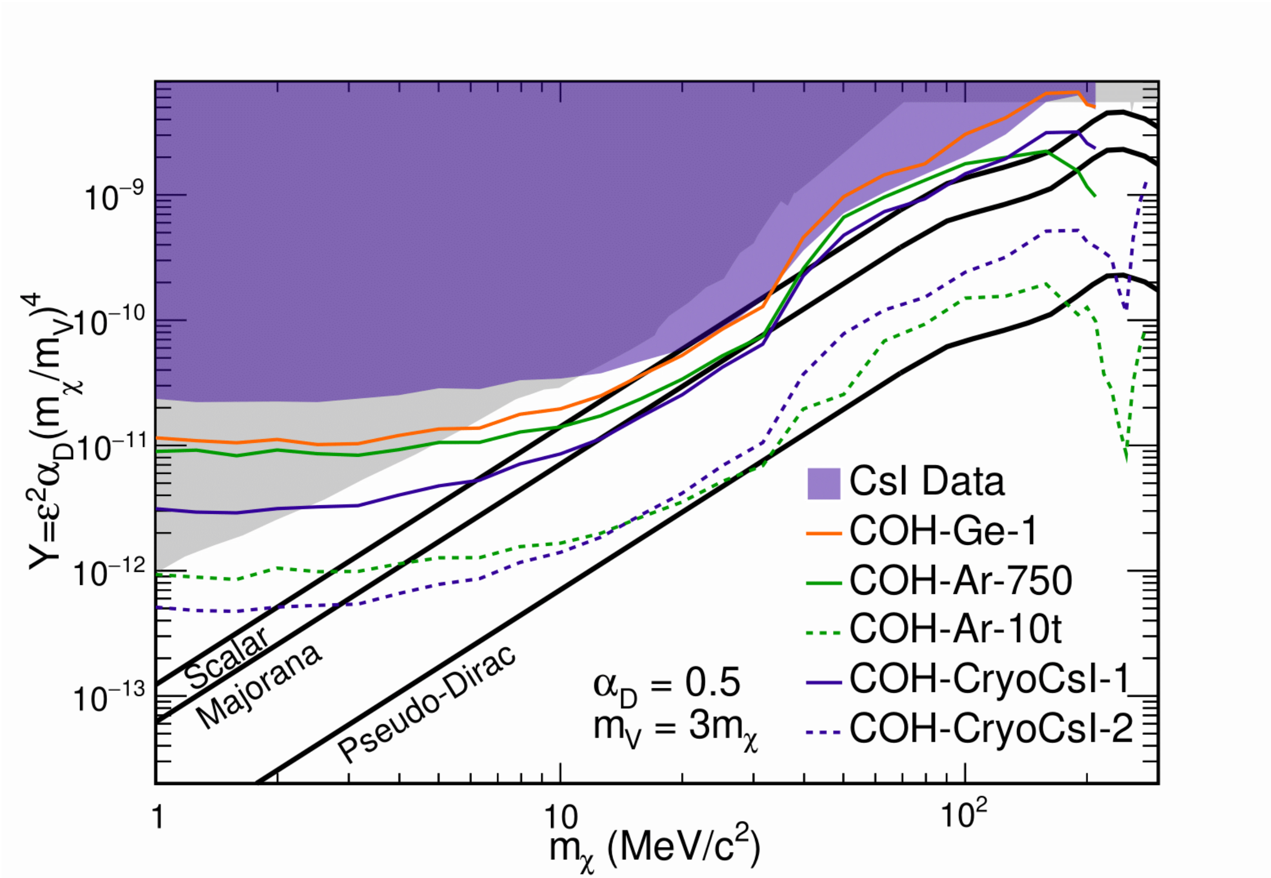
- Data also agrees well with the background-only prediction for the recoil energy distribution
  - $\chi^2 = 103/120$ for background-only 2D fit
- Look for an excess in the DM ROI while controlling backgrounds with delayed events

Less conservative scenarios: lowering α_D



- Our dark matter model has two couplings: ε and α_D
  - Complicates parameter space since our relic abundance depends on $Y \propto \varepsilon^2\alpha_D$
- Our contour depends on our assumption of α_D – smaller values give tighter constraints
- $\alpha_D = 0.5$ is the largest, most conservative assumption before perturbative effects important

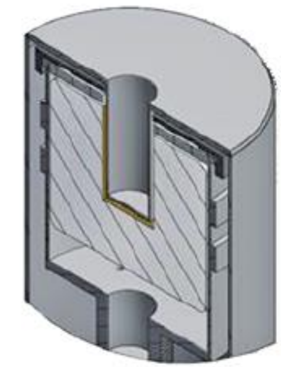
Future sensitivity to dark matter from COHERENT

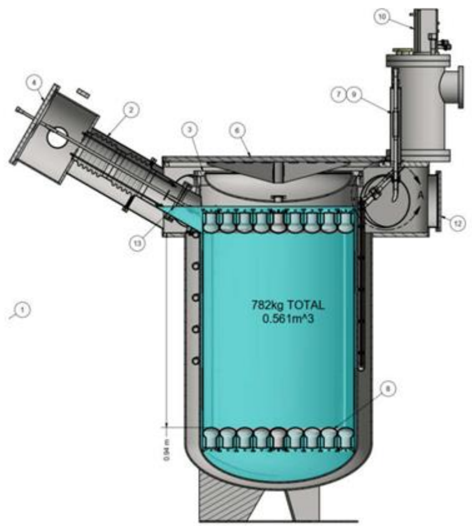


- Immediate future: germanium detector currently being commissioned – will fully explore scalar target at lower masses
- In coming years: future argon and cryogenic CsI detector – will be sensitive to a lower DM flux and probe the Majorana fermion target
- In next decade: large detectors placed forward at the STS will begin to ambitiously test even the most pessimistic spin scenarios

Future COHERENT dark matter detectors

- COH-Ge-1: 18 kg of Ge PPC detectors
- Low threshold, $\sim 0.2\ \mathrm{keV_{ee}}$, improves sensitivity at low masses
- Funded with NSF MRI, detector commissioning summer 2022

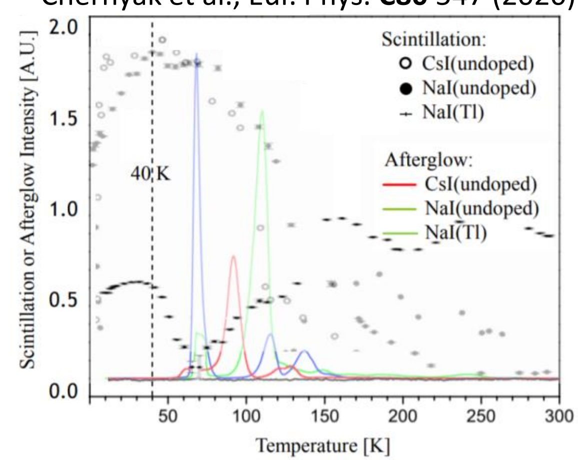




- COH-Ar-750: next-generation argon scintillator
- Large 610-kg fiducial volume
- Preliminary plans for 10-t argon detector at the STS placed forward from beam exploiting DM flux directionality

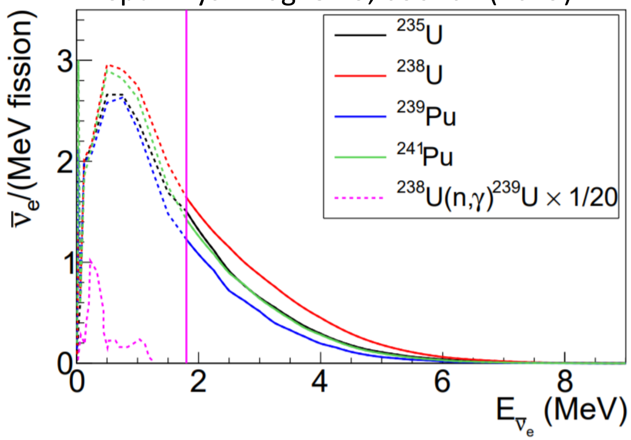
- COH-CryoCsI-1: future 10-kg, undoped CsI scintillator
- Crystals cooled to 40 K, significantly reducing afterglow scintillation while improving overall light yield
- With low threshold and high Z, small detector has very favorable sensitivity

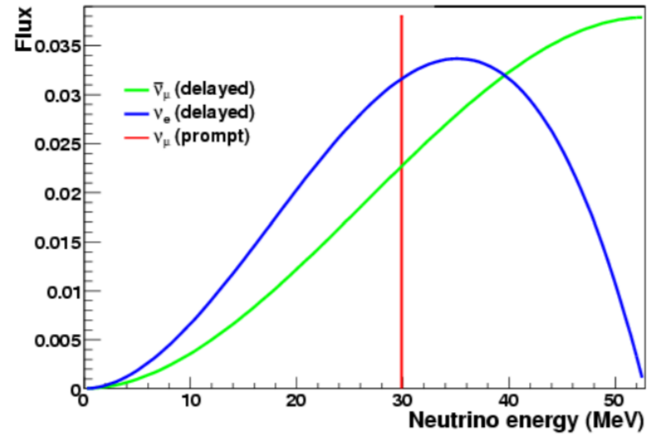
Chernyak et al., Eur. Phys. **C80** 547 (2020)



High-flux Sources for Low-energy Neutrinos

Rept. Phys. Prog. 82 3, 036201 (2019)





- Nuclear reactors
  - Very high flux: $\sim 2\times10^{20}\ \bar{\nu}_e$ / s
  - Maximum recoil energy for CsI: 1 keV
  - Reactor-off data → in-situ background constraint

reactors win

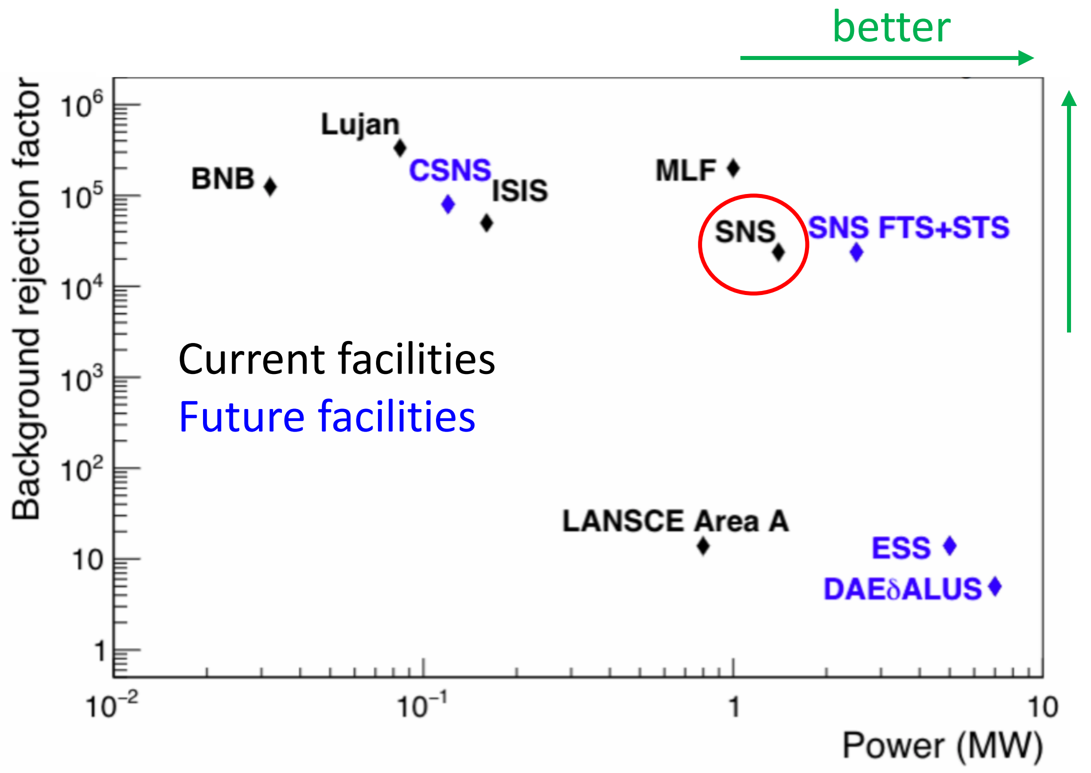
- Pion decay-at-rest (πDAR) at accelerators
  - High flux: $\sim 3\times10^{14}\ \nu_\mu/\nu_e/\bar{\nu}_\mu$ / s
  - Maximum recoil energy for CsI: 15 keV
  - Pulsed beam → in-situ background constraint

πDAR wins

Fermilab collaboration

Coherent Captain Mills @

Selecting a πDAR Source



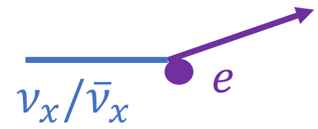
- For selecting a source, we want
  - High beam power → faster accumulation of signal
  - Low duty factor → improved background rejection through beam pulsing

- Move to the Spallation Neutron Source at ORNL
  - Upgrade will double beam power and construct second target station by 2028

Interactions of supernova neutrinos

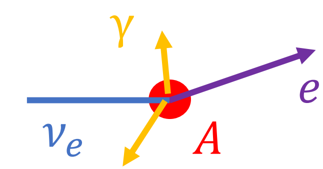
❑ Electron scattering (ES)

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



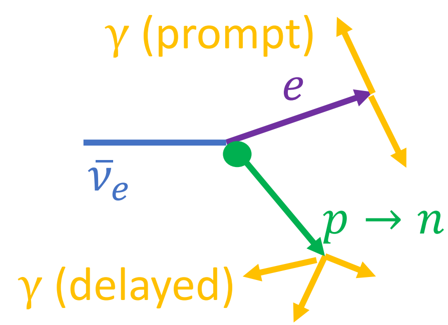
❑ Charged current on nuclei (CC)

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



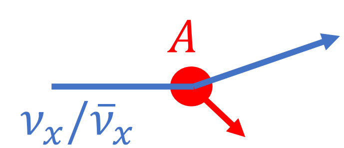
❑ Inverse beta decay (IBD)

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



❑ Coherent elastic neutrino-nucleus scattering (CEvNS)

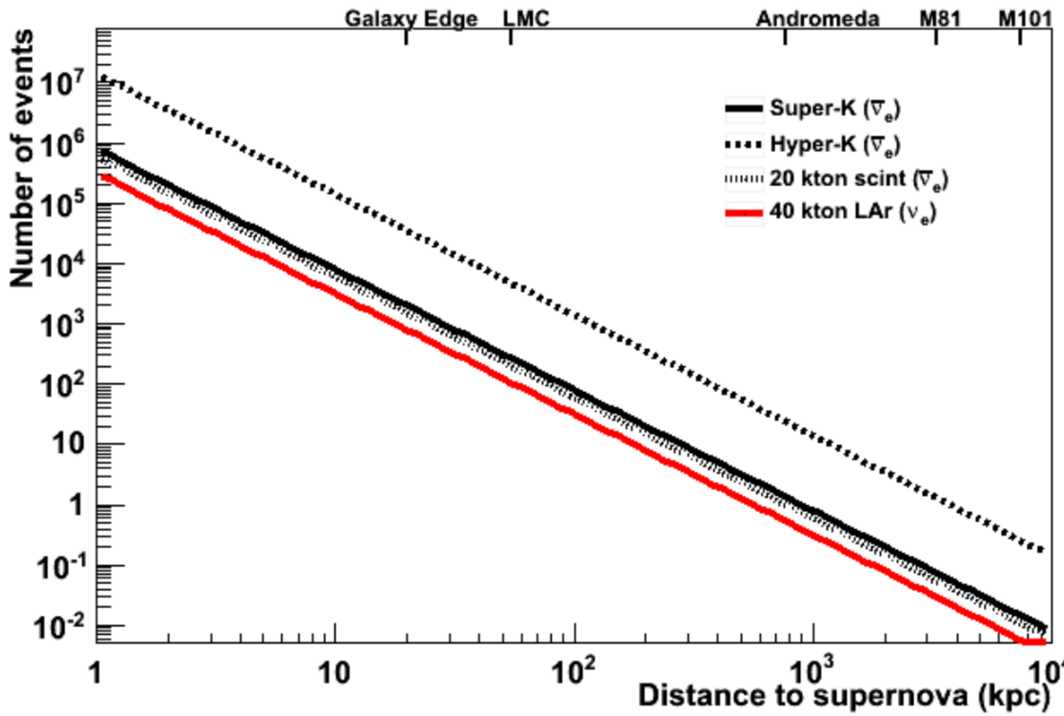
- $\nu_x + A \rightarrow \nu_x + A$
- Low-energy nuclear recoil hard to detect
- NC process treats all flavors equally



Supernova 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