CEvNS HEAVEN

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AstroDark
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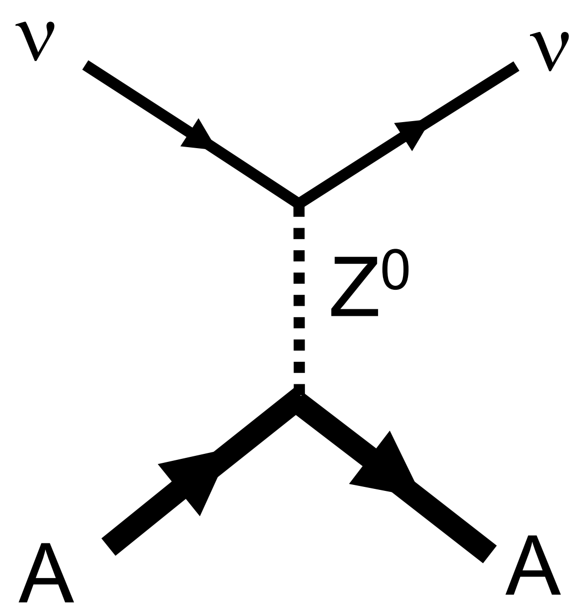
OUTLINE

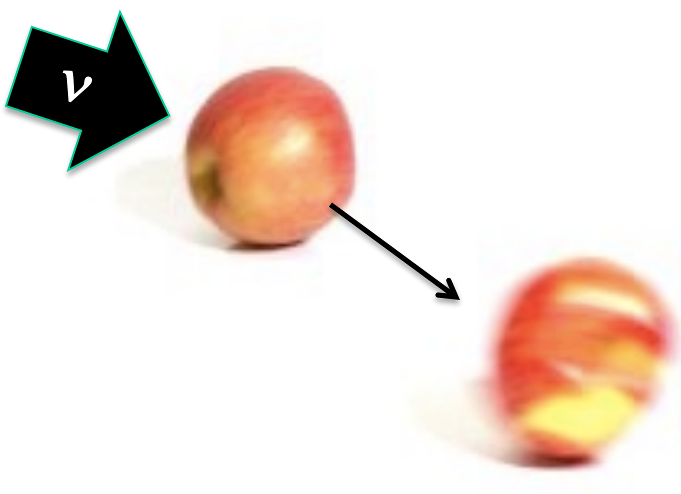
- **CEvNS**
  - Coherent elastic neutrino interactions with nuclei
  - How to measure it
  - COHERENT results
  - Status and prospects of measurements
- **Heaven**
  - Neutrinos from supernovae and what we can measure
- **CEvNS Heaven**
  - CEvNS as a supernova process
  - CEvNS as a supernova detection channel

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



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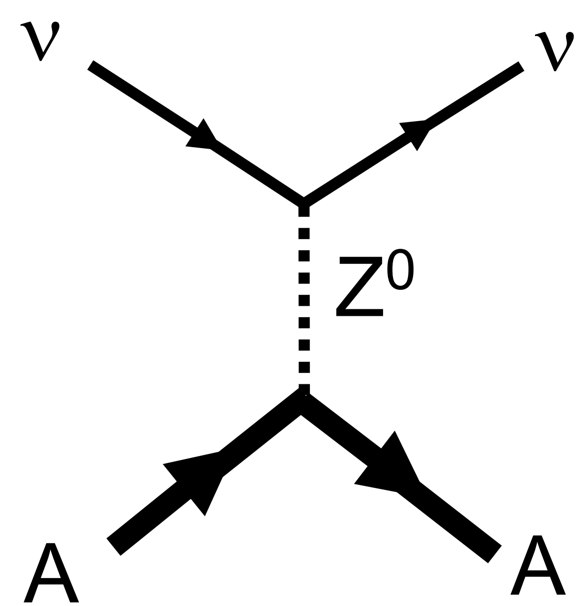
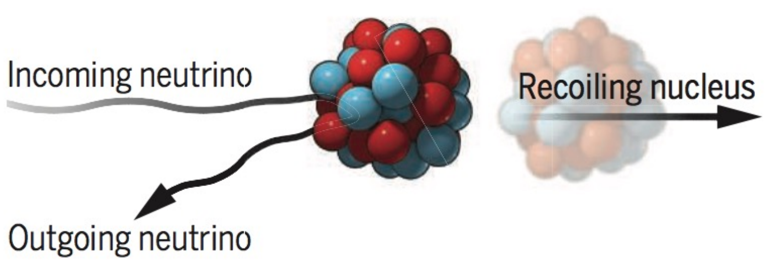


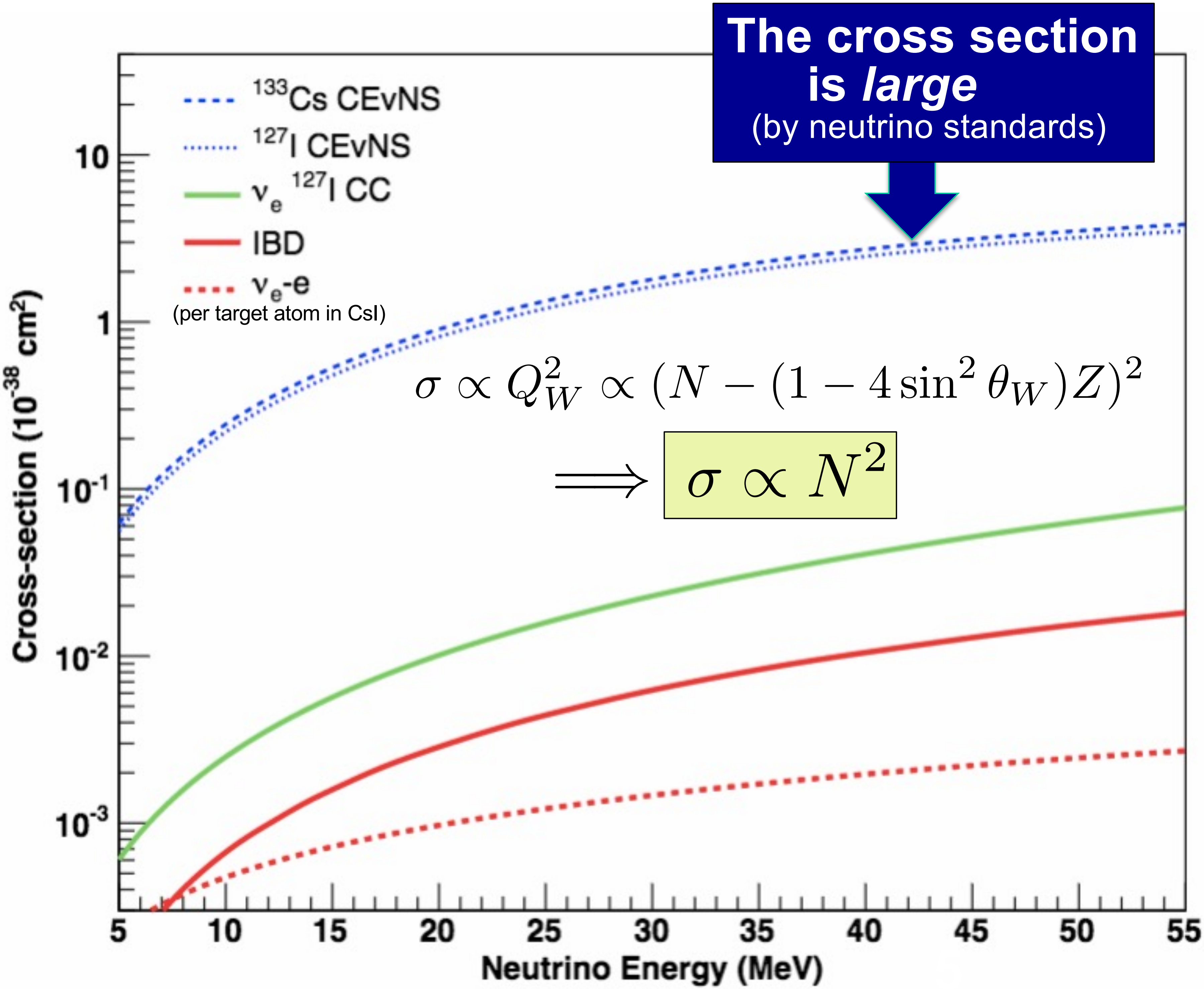
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer



For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

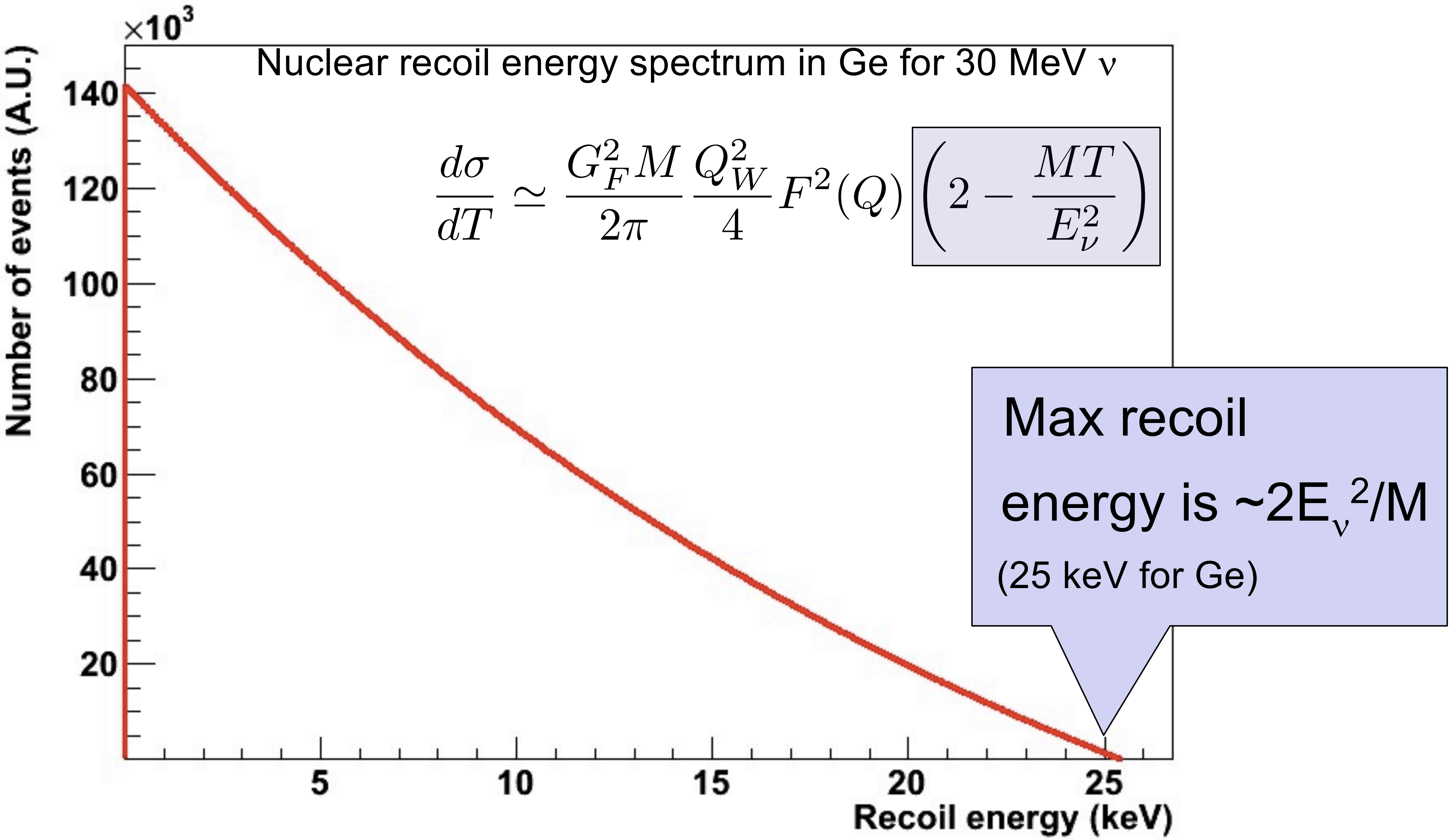
A: no. of constituents

Image: J. Link *Science* Perspectives



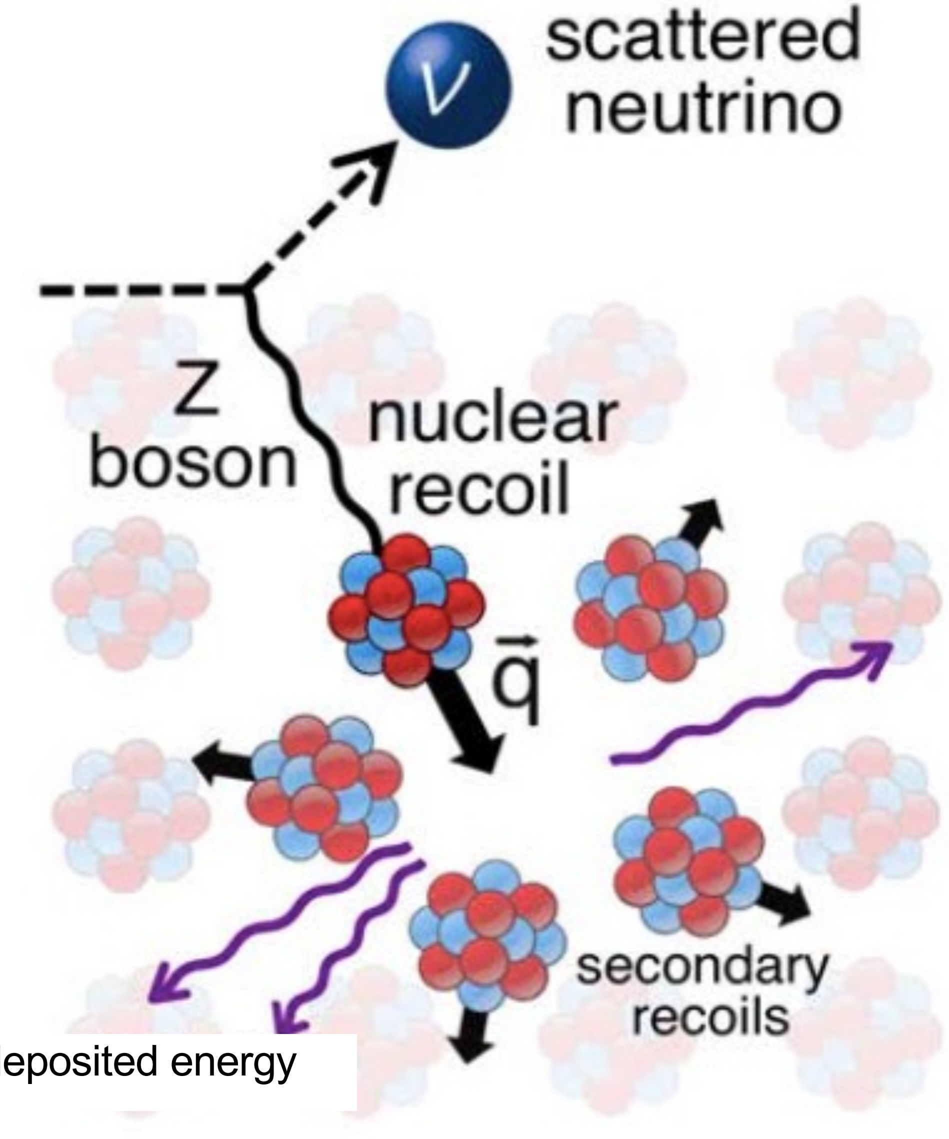
The cross section is *large*
(by neutrino standards)
^{133}Cs CEvNS
^{127}I CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
(per target atom in CsI)
$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$
$$\Longrightarrow \sigma \propto N^2$$
Cross-section (10^{-38} cm^2)
Neutrino Energy (MeV)

Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**

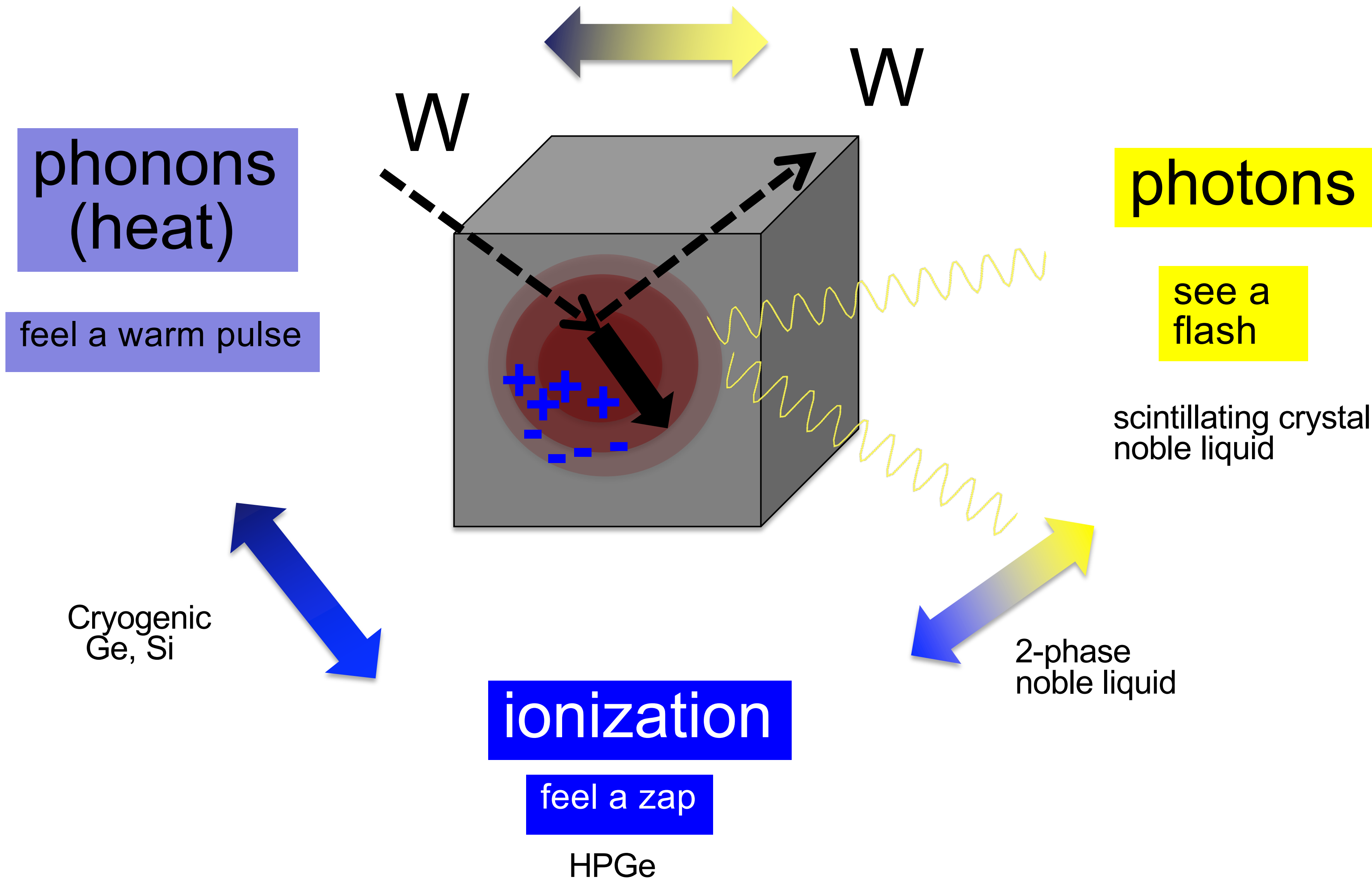


The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

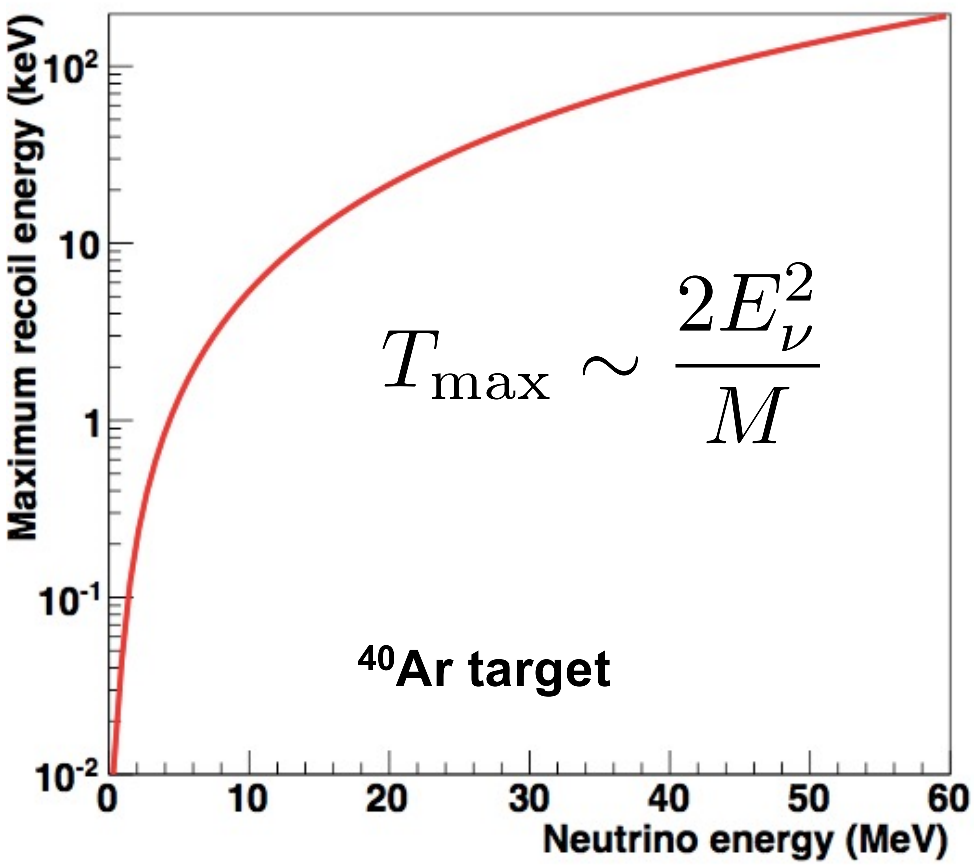


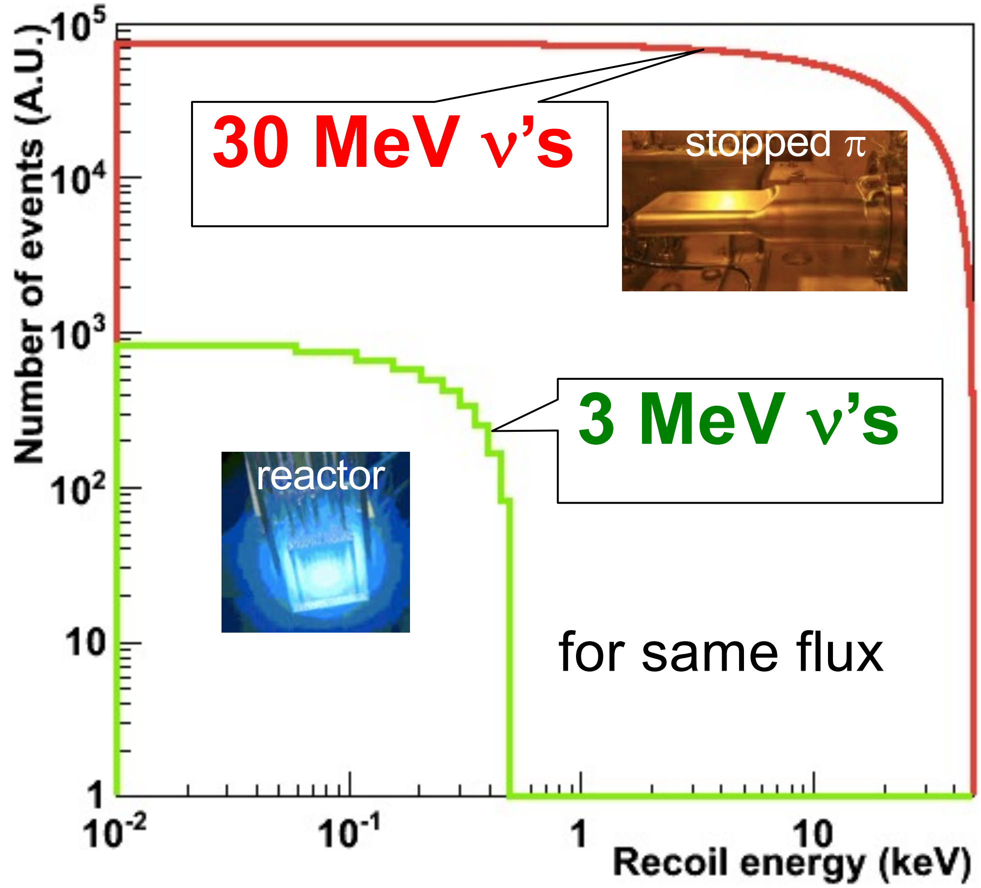
Low-energy nuclear recoil detection strategies



http://dmrc.snu.ac.kr/english/intro/intro1.html

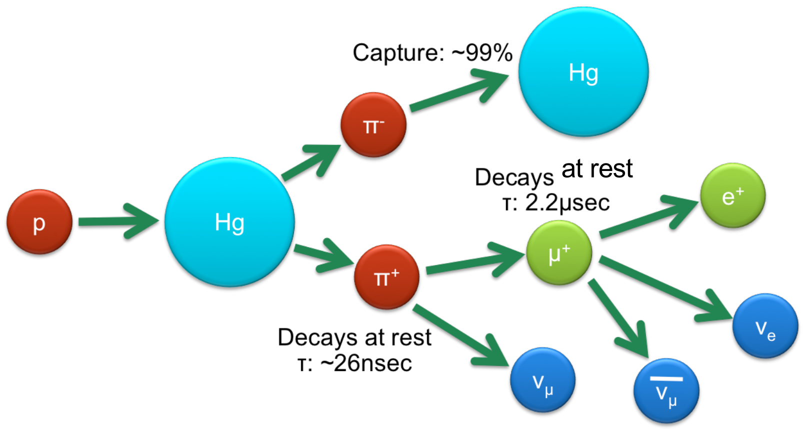
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

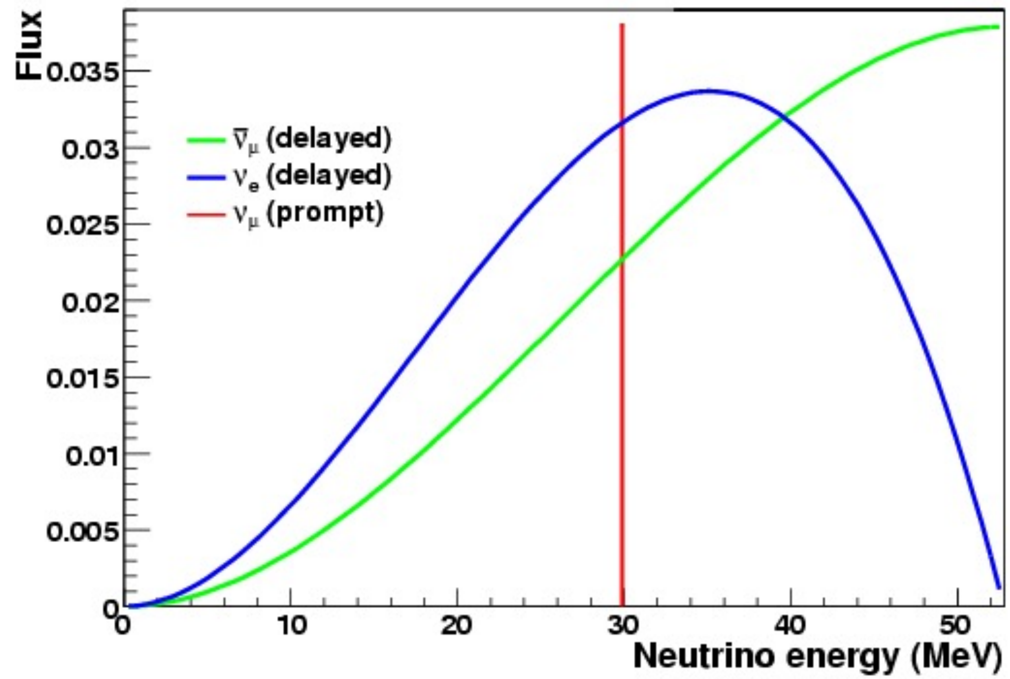




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

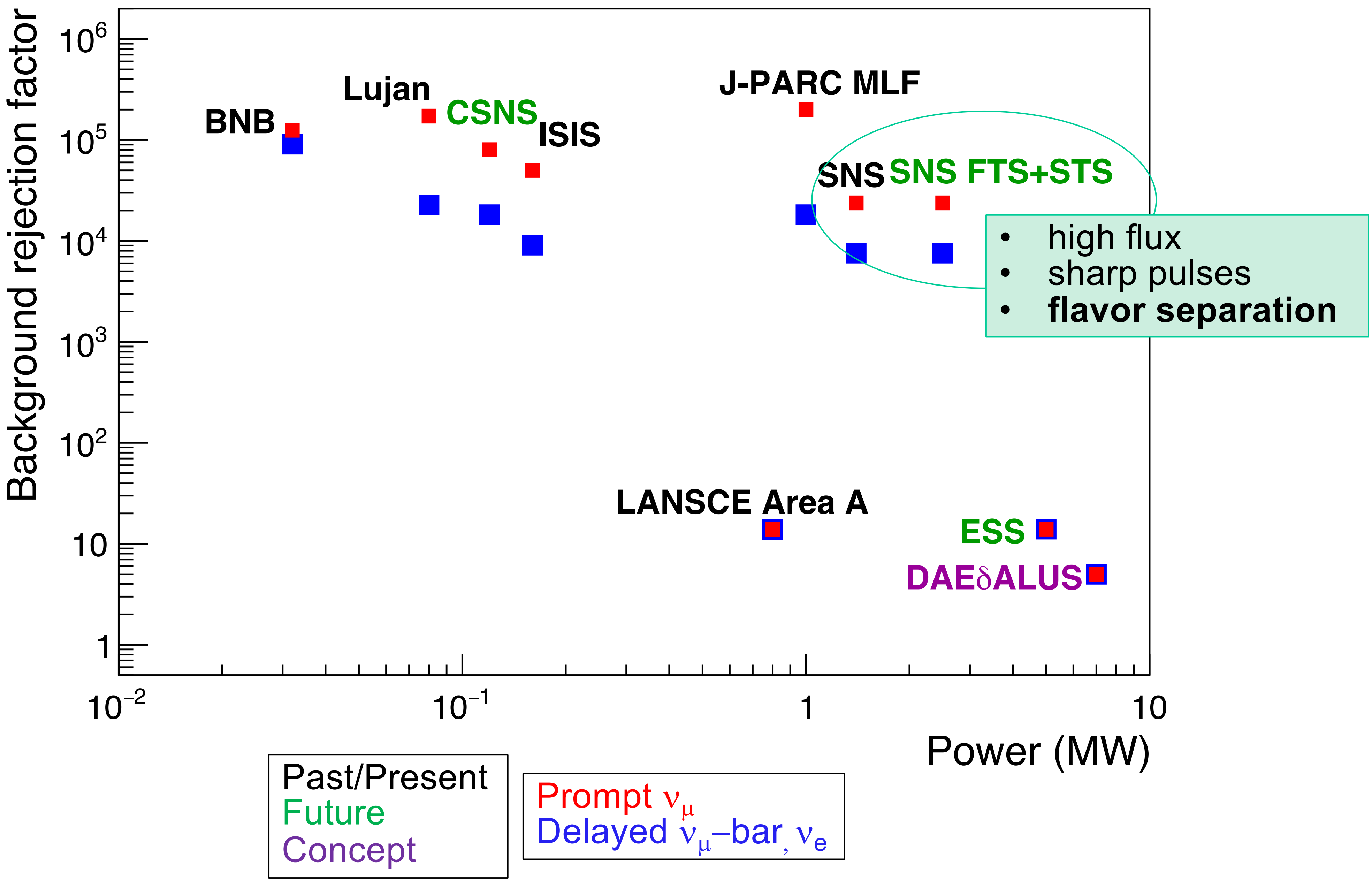
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

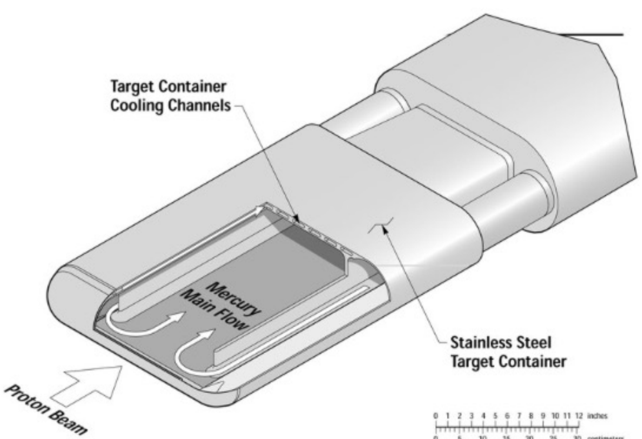
$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Comparison of stopped-pion neutrino sources





Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

The COHERENT collaboration

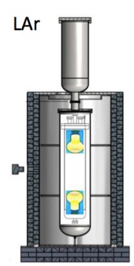
http://sites.duke.edu/coherent

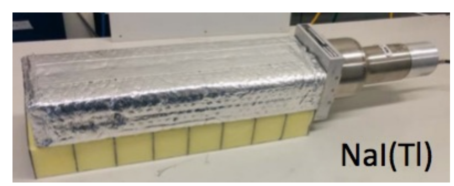
~90 members,
19 institutions
4 countries

COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal flash	14.6	19.3	6.5
Ge	HPGe PPC zap	18	22	<few
LAr	Single-phase flash	24	27.5	20
NaI[Tl]	Scintillating crystal flash	185*/3338	25	13

Multiple detectors for N^2 dependence of the cross section

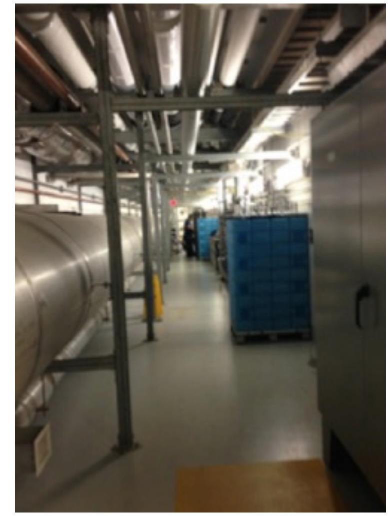


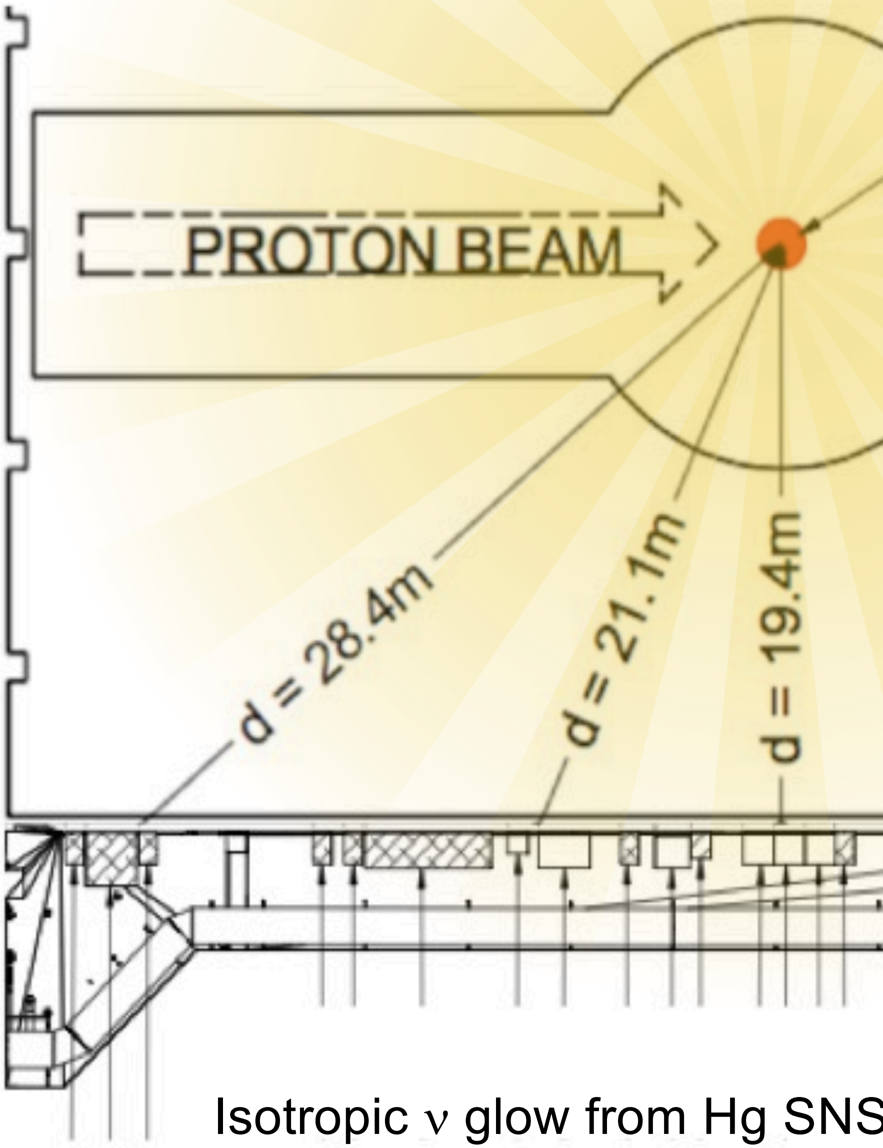


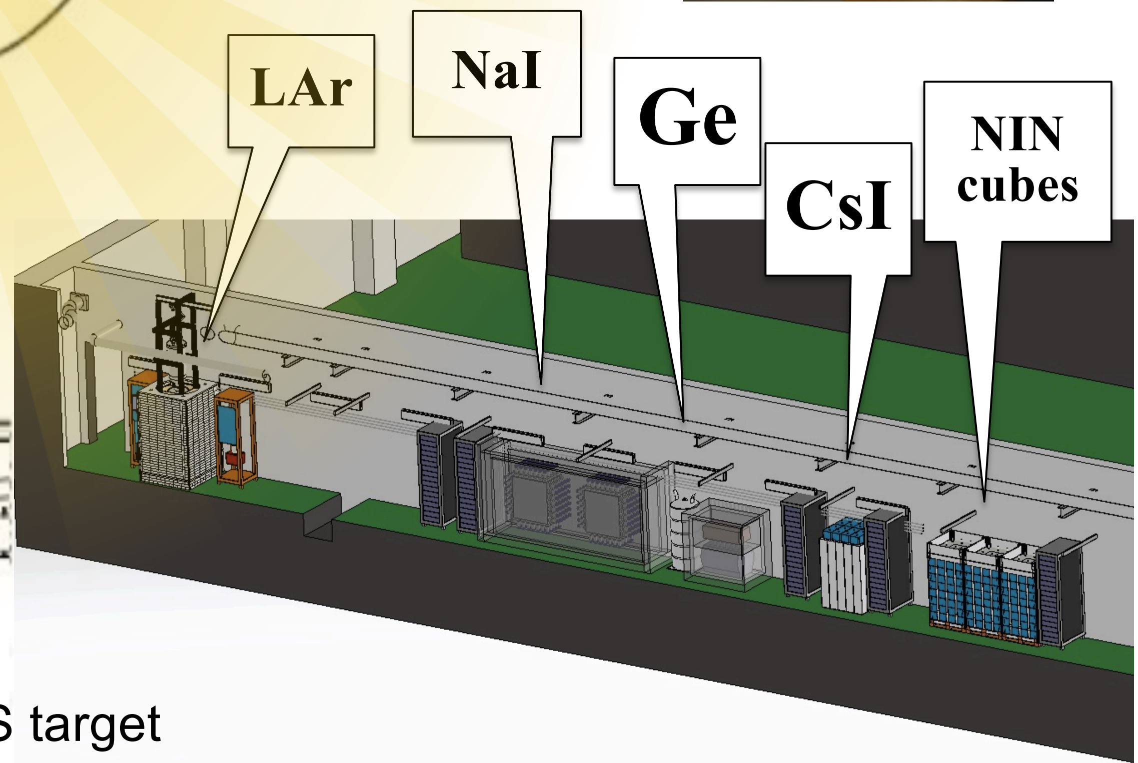
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking down “Neutrino Alley”

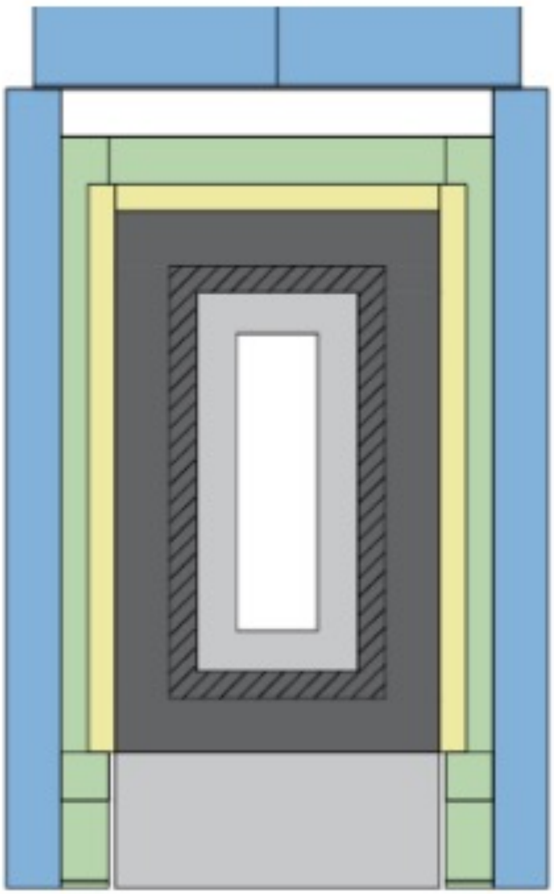


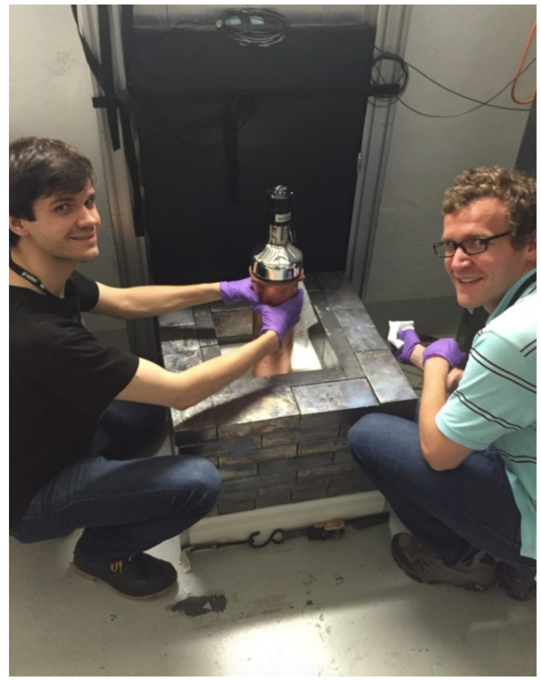




Isotropic ν glow from Hg SNS target

The CsI Detector in Shielding in Neutrino Alley at the SNS



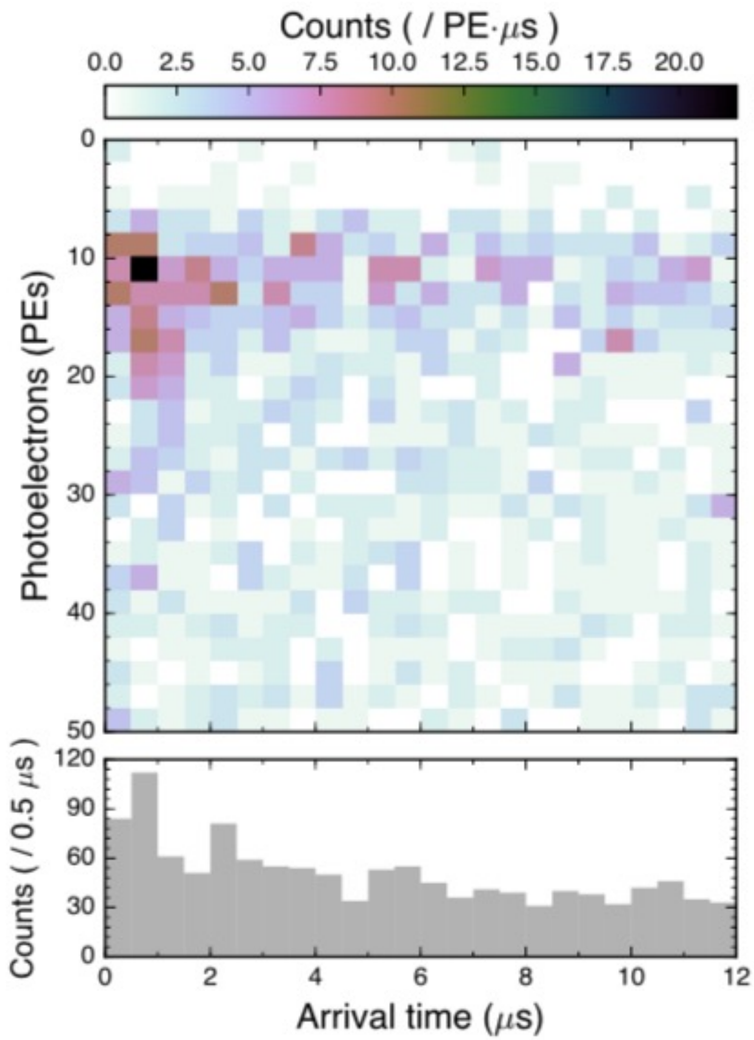


A hand-held detector!

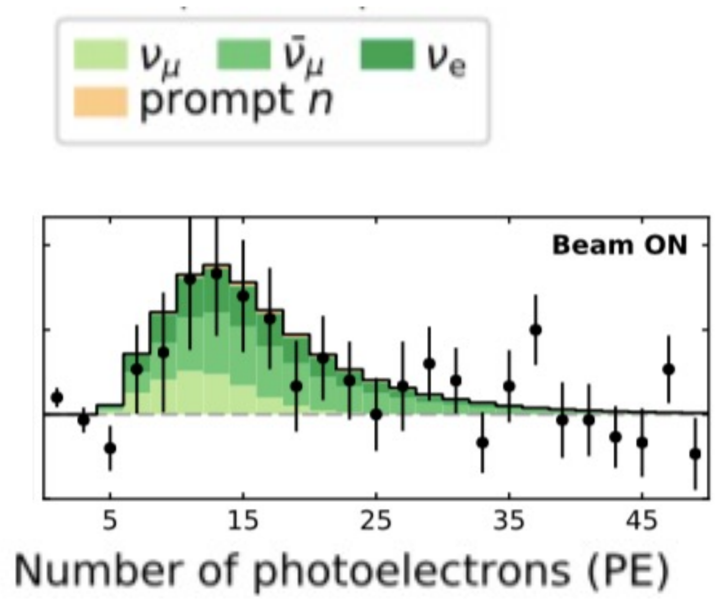
Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3''	2''	4''	2''	4''
Colour					

First light at the SNS (stopped-pion neutrinos) with 14.6-kg CsI[Na] detector



DOI: 10.5281/zenodo.1228631



Background-subtracted and integrated over time

$$\mathrm{PE} \propto T \propto Q^2$$

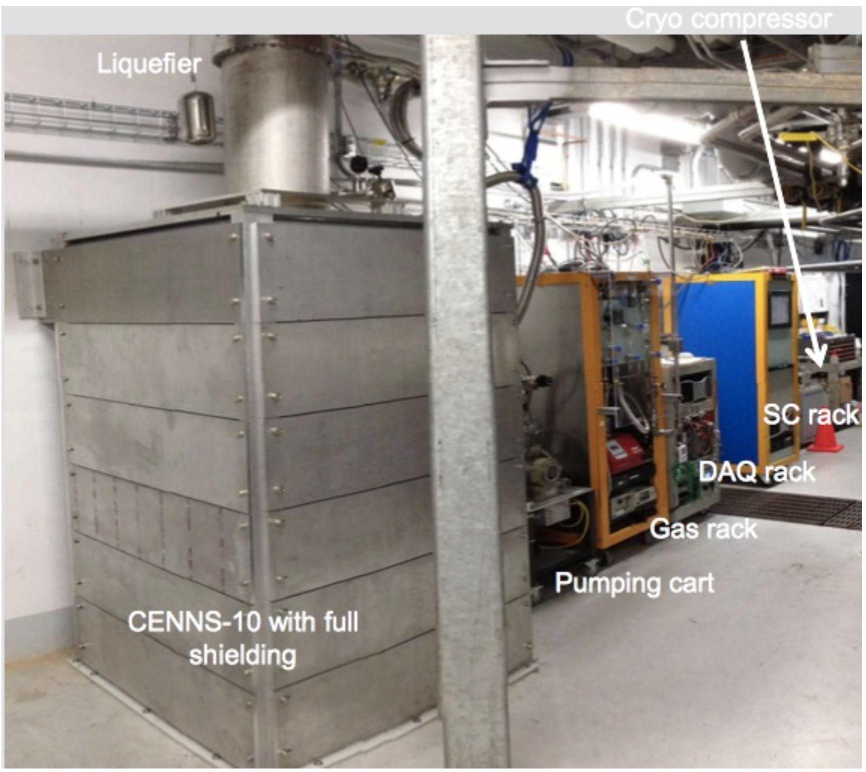
→ measure of the Q spectrum

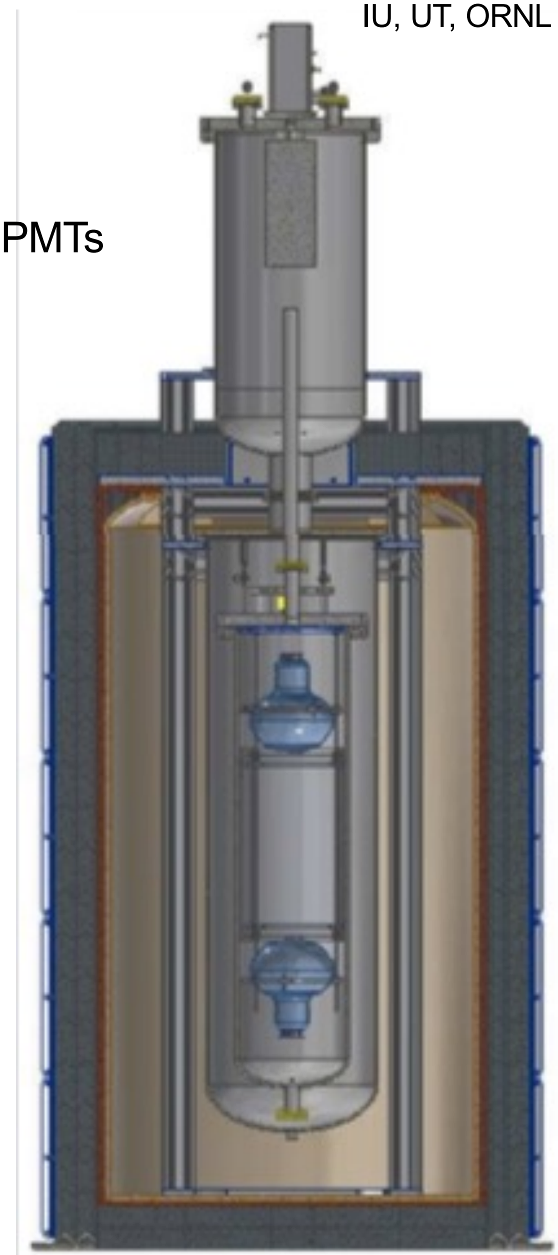
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

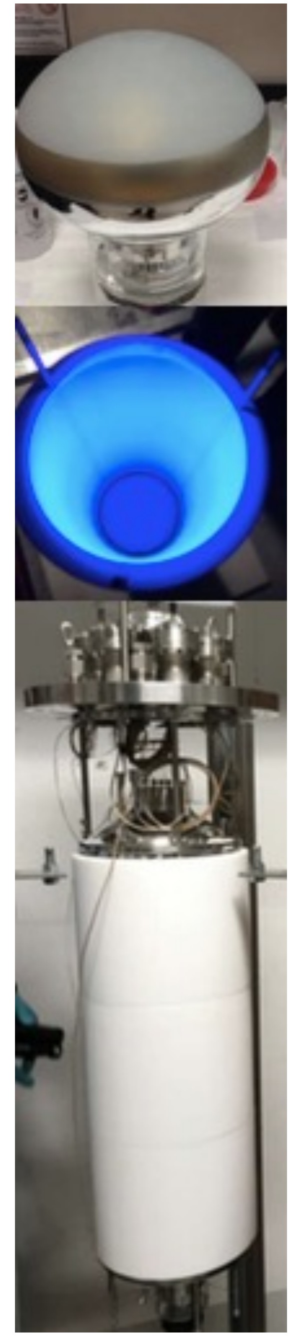
Single-Phase Liquid Argon

- ~24 kg active mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
    - 8” borosilicate glass window
    - 14 dynodes
    - QE: 18%@ 400 nm
- Wavelength shifter: TPB-coated Teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
    - PT90 single-state pulse-tube cold head

IU, UT, ORNL

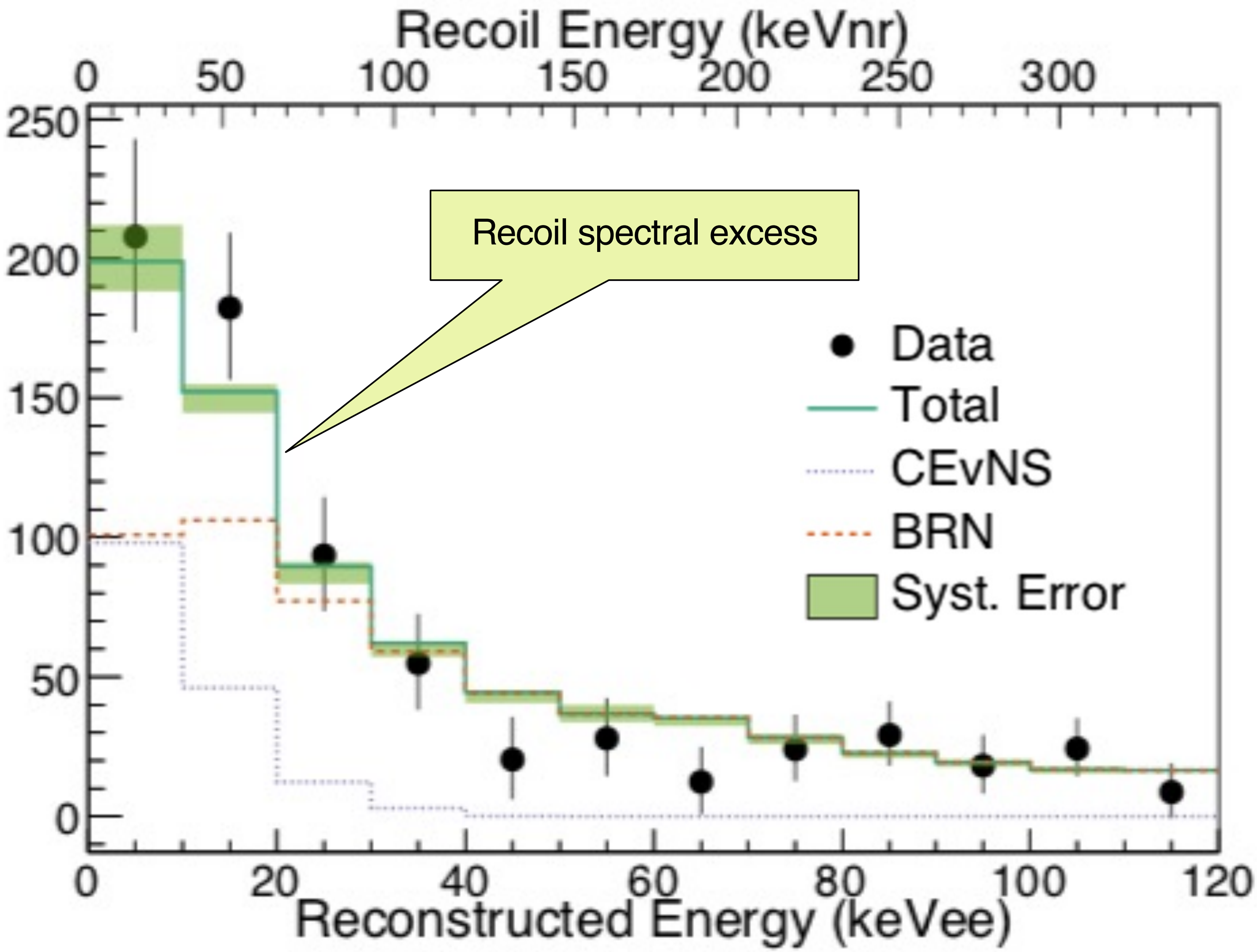




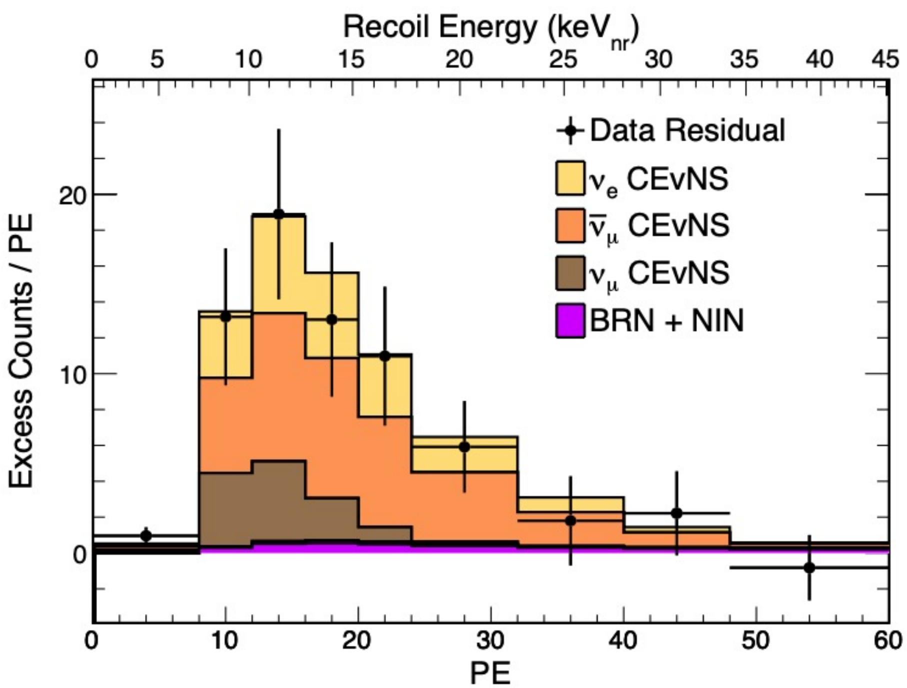


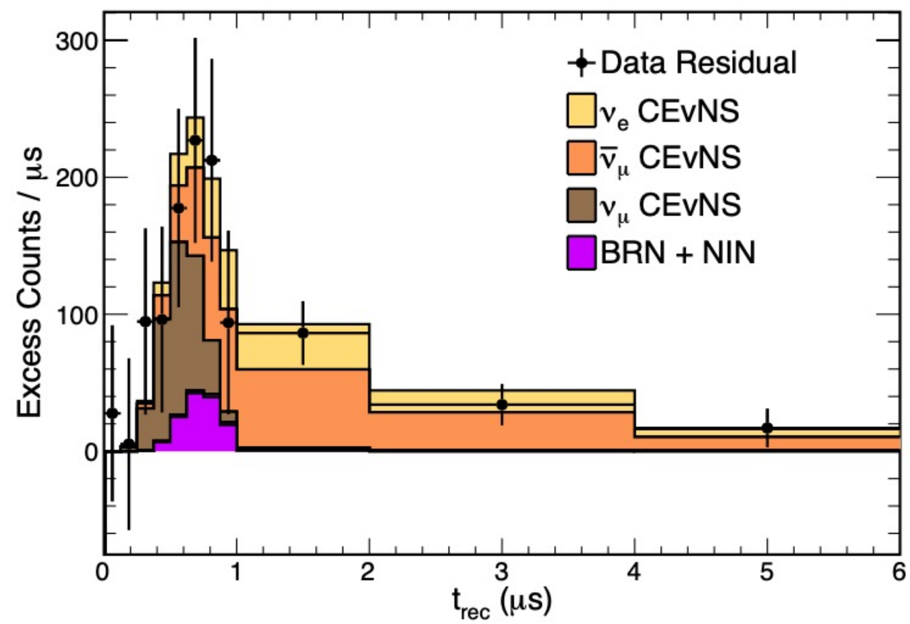
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

COHERENT Liquid Argon CEvNS Results



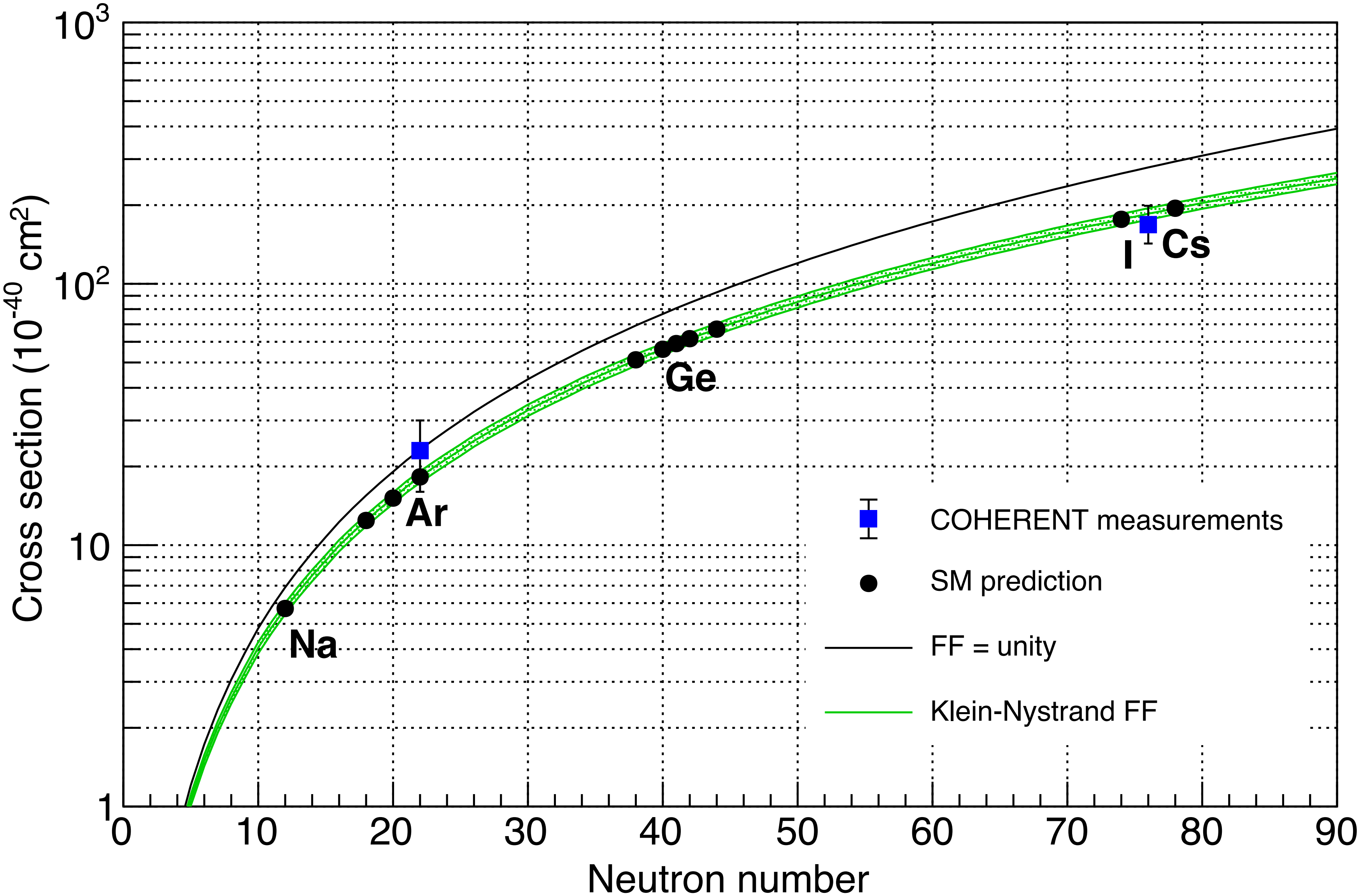
Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis





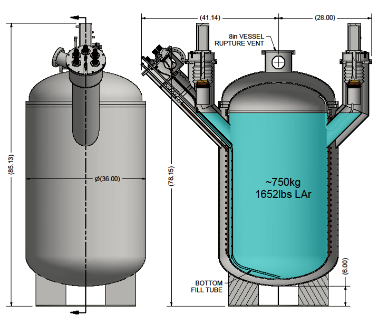
Full dataset results: arXiv:2110.07730
Quenching factor measurement: arXiv:2111.02477

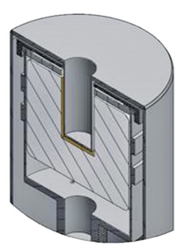
Measurements in CsI and Ar from COHERENT

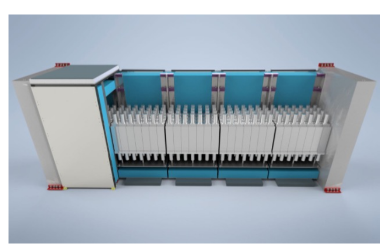


COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	19.3	6.5	9/2015	Decommissioned
Ge	HPGe PPC	18	22	<few	2022	Funded by NSF MRI, in progress
LAr	Single-phase	24	27.5	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	25	13	2022, high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes

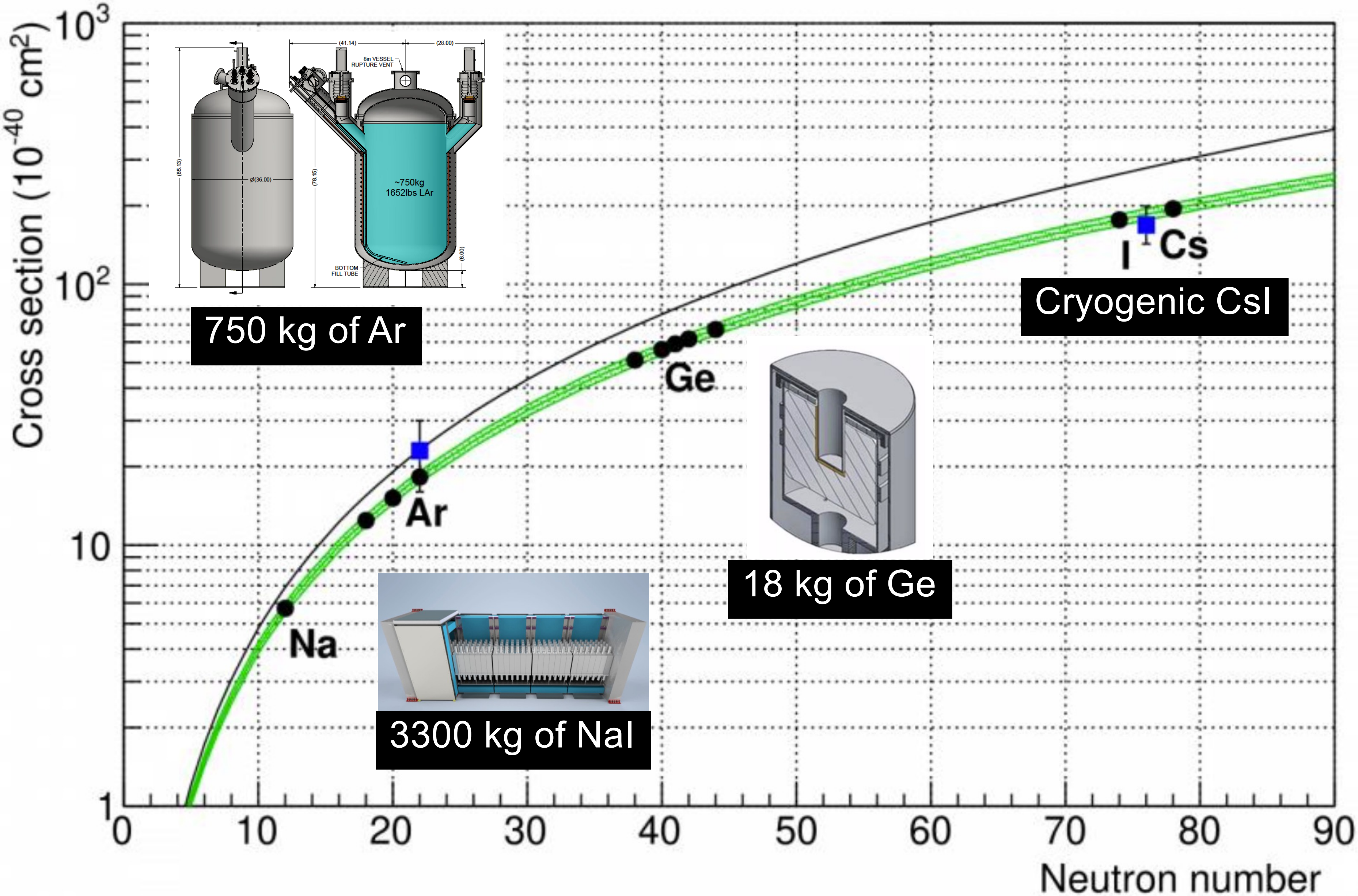






+D_2O for flux normalization
+ CryoCsI
+ concepts for other targets...

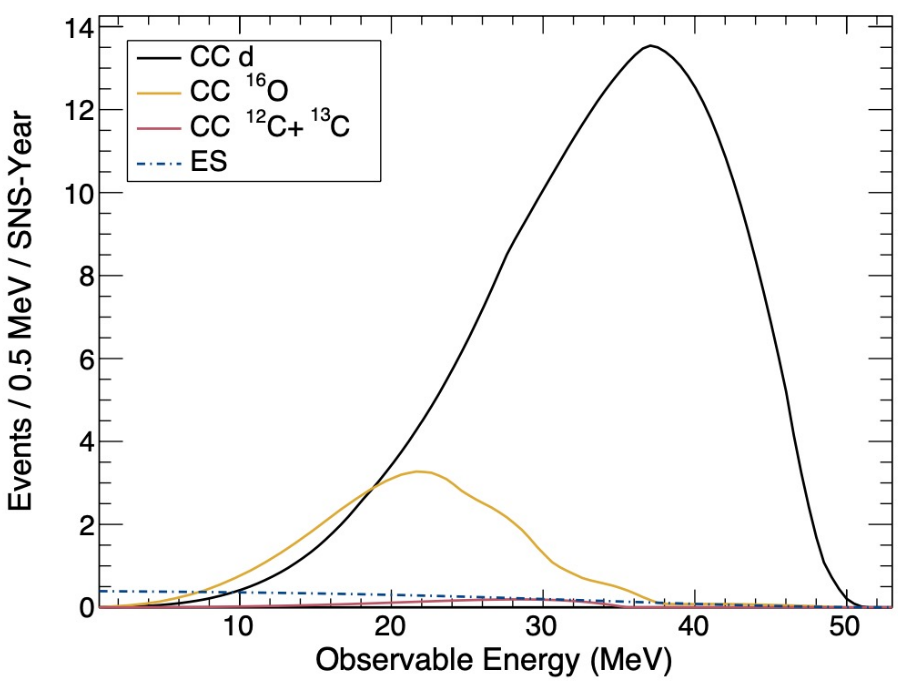
COHERENT future deployments

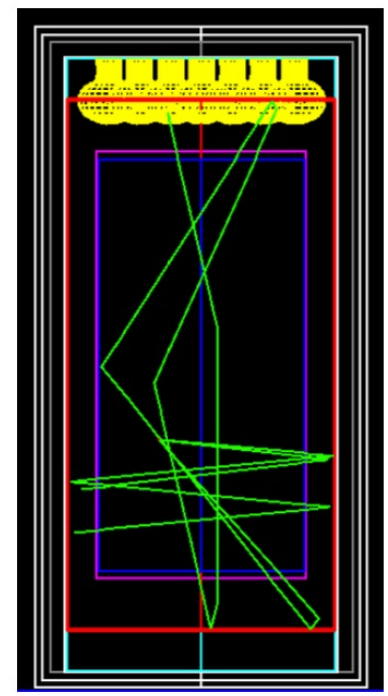


Heavy water detector in Neutrino Alley

Dominant current uncertainty is ~10%, on neutrino flux from SNS

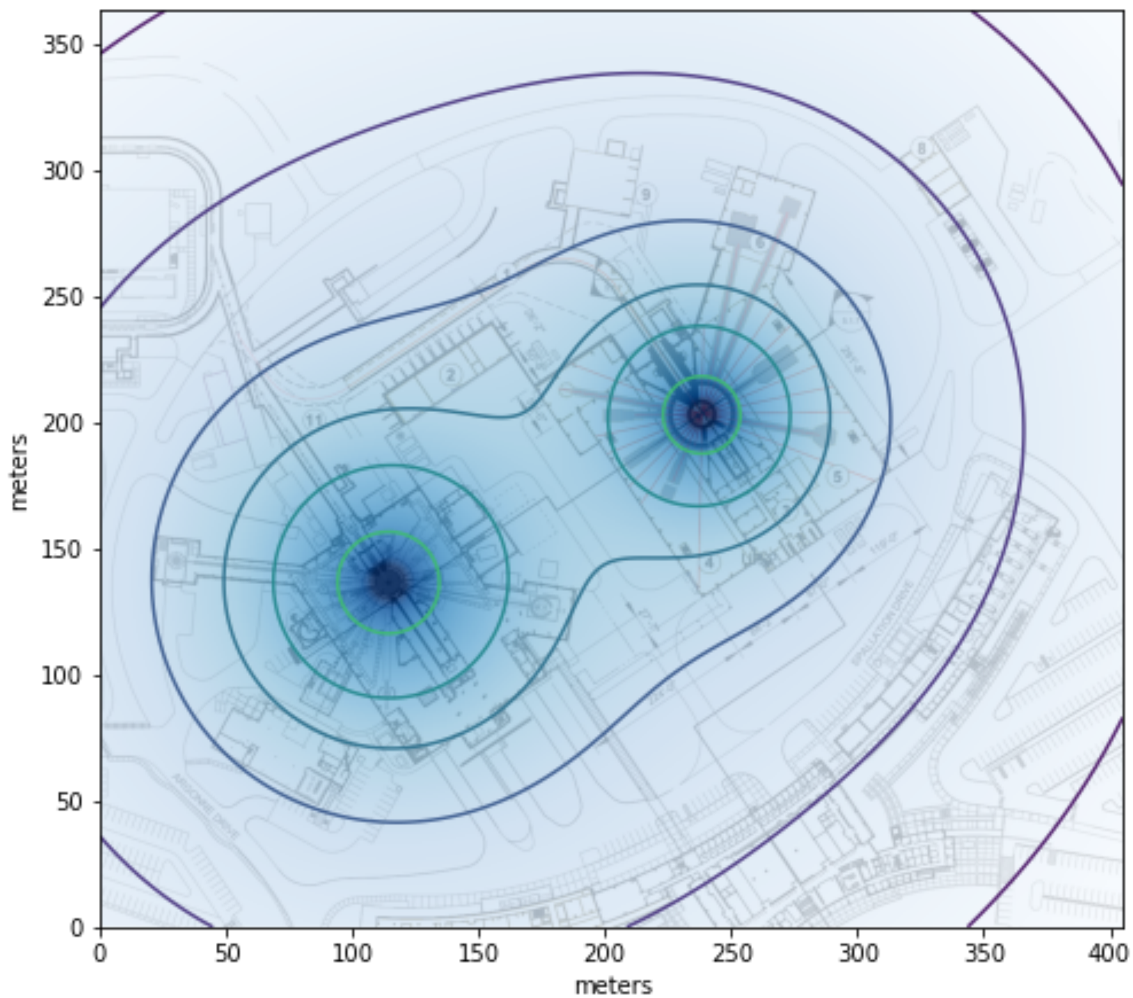
$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ cross section known to ~1-2%





Measure electrons to determine flux normalization

SNS Proton Power Upgrade to 2 MW, Second Target Station upgrade to 2.8 MW

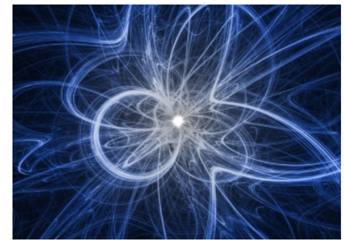


Many exciting possibilities for ν's + DM!

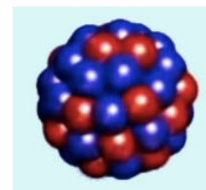
CEvNS: what's it good for?

! (not a complete list!)

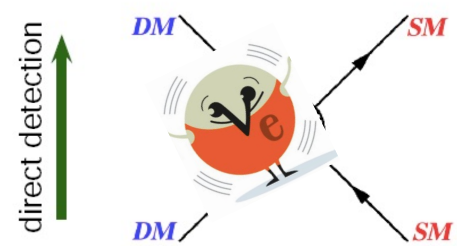
CEvNS as a **signal**
for signatures of *new physics*



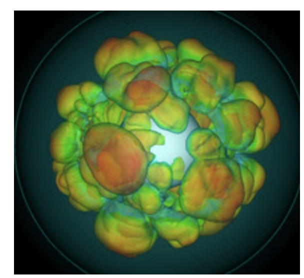
CEvNS as a **signal**
for understanding of "old" physics



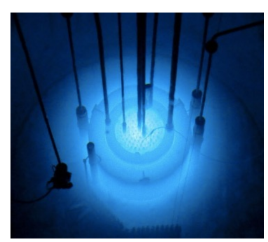
CEvNS as a **background**
for signatures of new physics



CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



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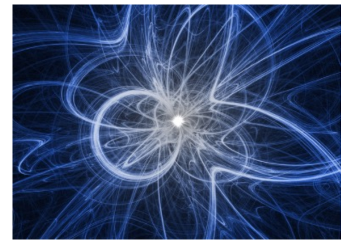

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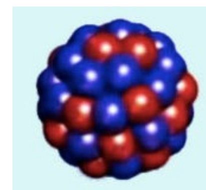
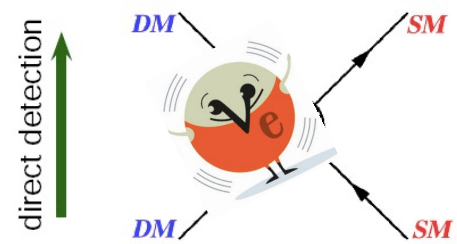


CEvNS as a **background**
for signatures of new physics (DM)



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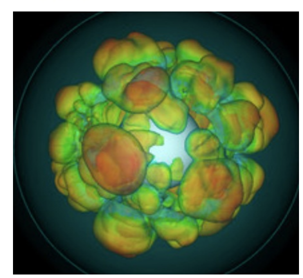

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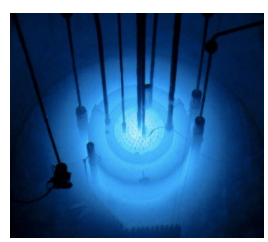
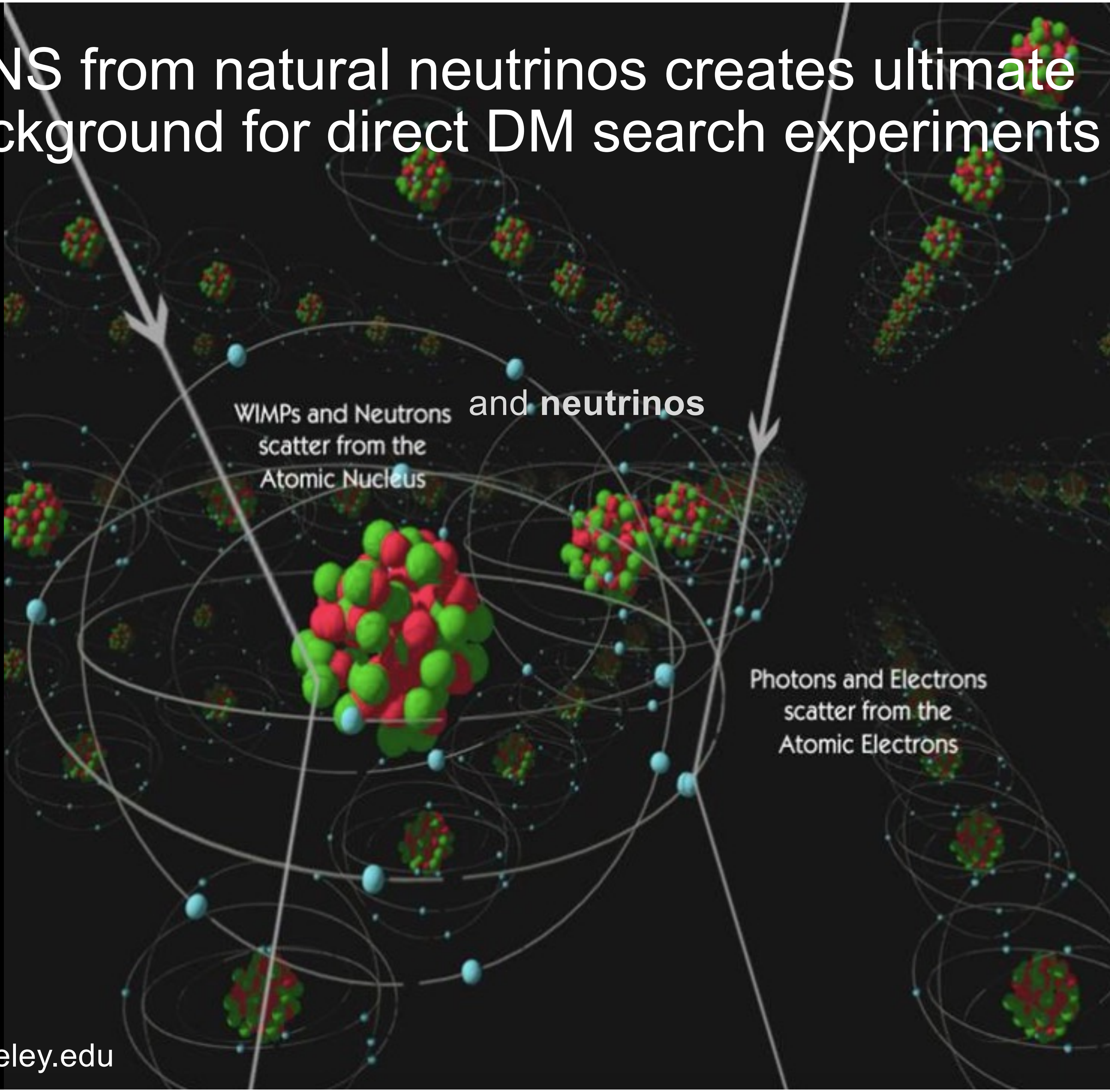


CEvNS from natural neutrinos creates ultimate background for direct DM search experiments



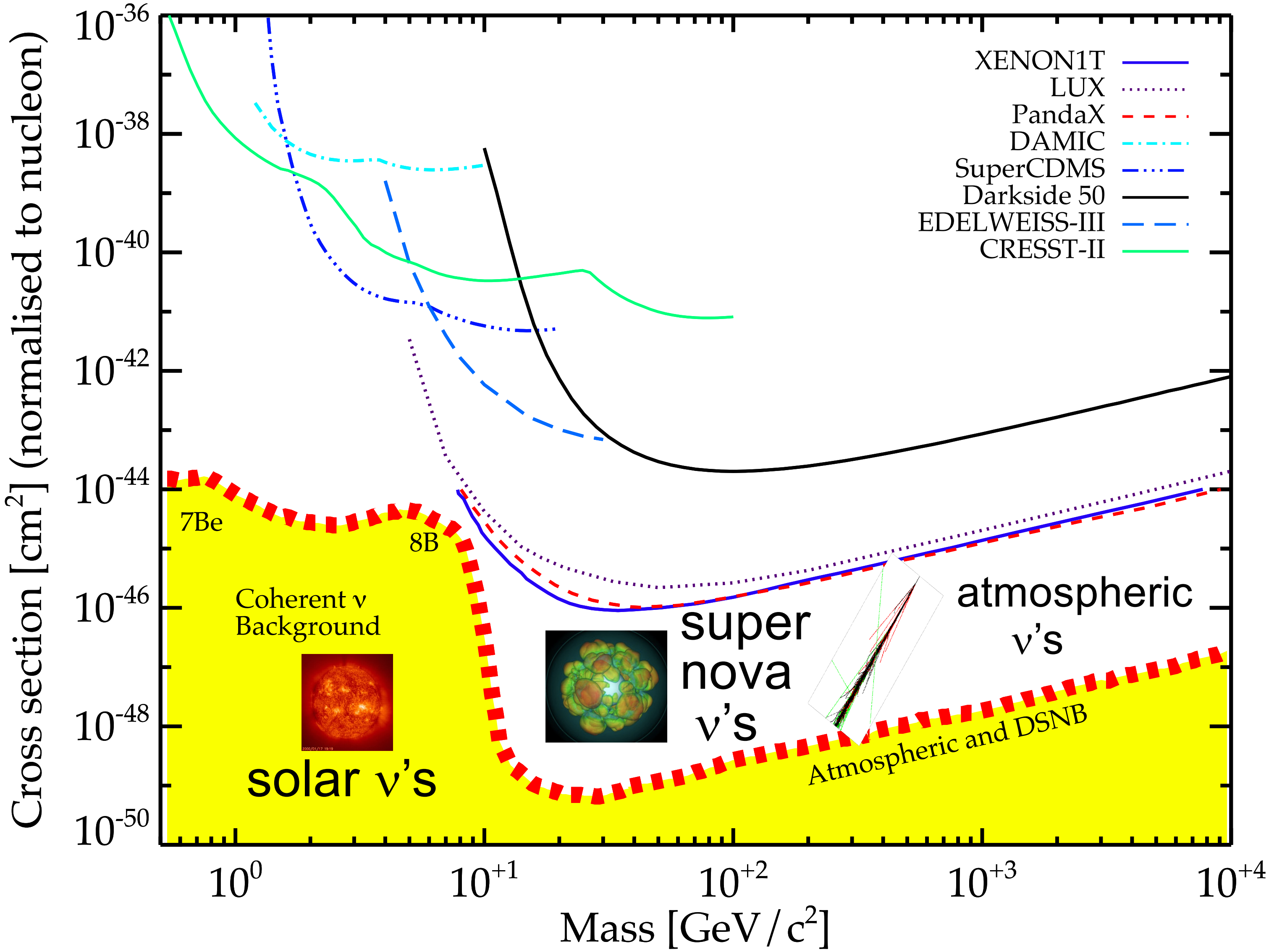
cdms.berkeley.edu

The so-called "neutrino floor" (**signal!**) for direct DM experiments

J. Monroe & P. Fisher, 2007

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



Light **accelerator-produced DM** direct detection possibilities

(CEvNS is *background*)

- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

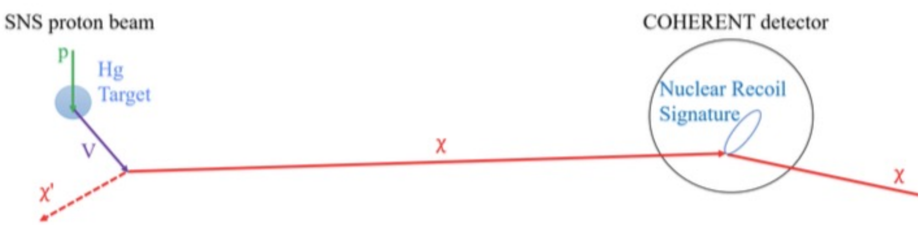
} decay product χ then makes nuclear recoil

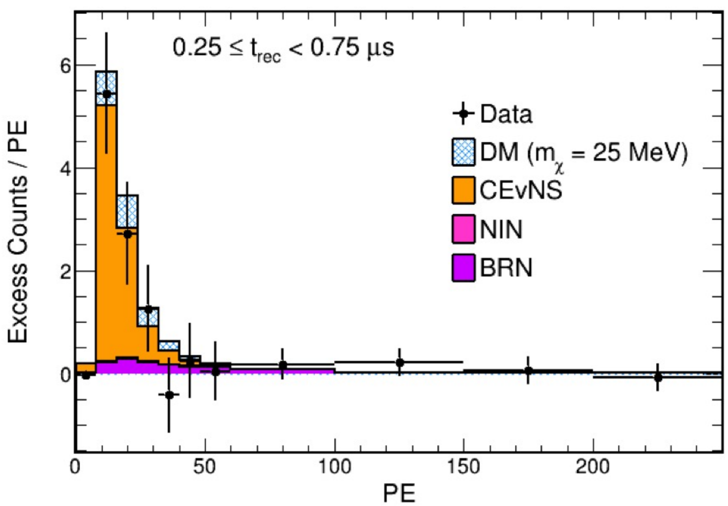
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

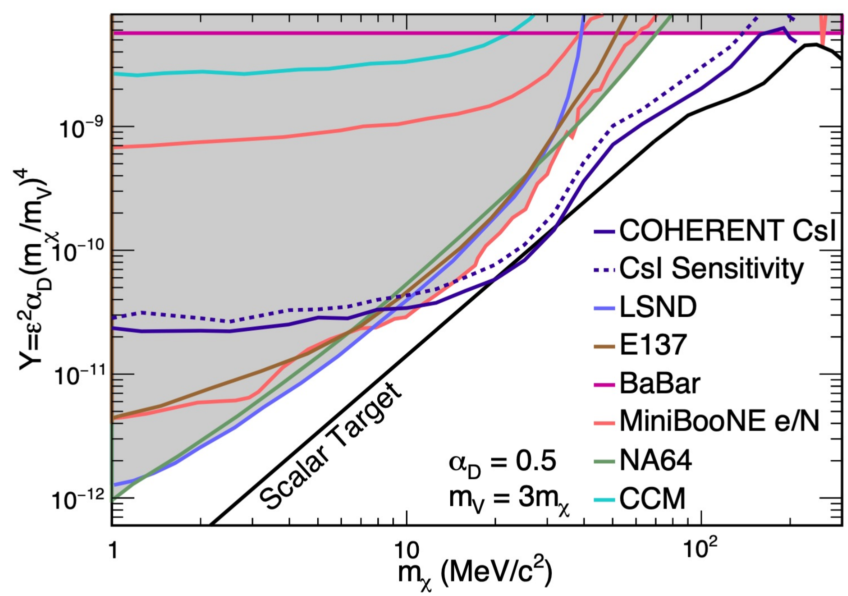
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)

B. Dutta et al., arXiv:1906.10745
COHERENT, arXiv:1911.6422







NEW!

Expect characteristic *time, recoil energy, angle* distribution for DM vs CEvNS

Limits down to cosmological expectation for scalar DM particle

arXiv:2110.11453

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! (not a complete list!)

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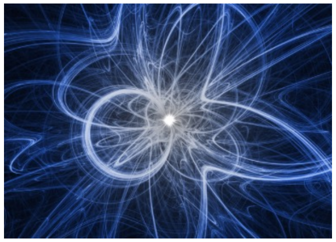
for signatures of *new physics*



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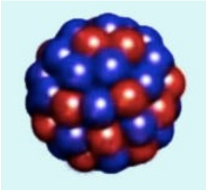
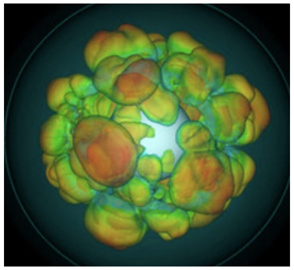
for understanding of "old" physics

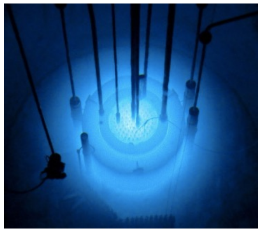


CEvNS as a **background**
for signatures of new physics (DM)

CEvNS as a **signal** for *astrophysics*

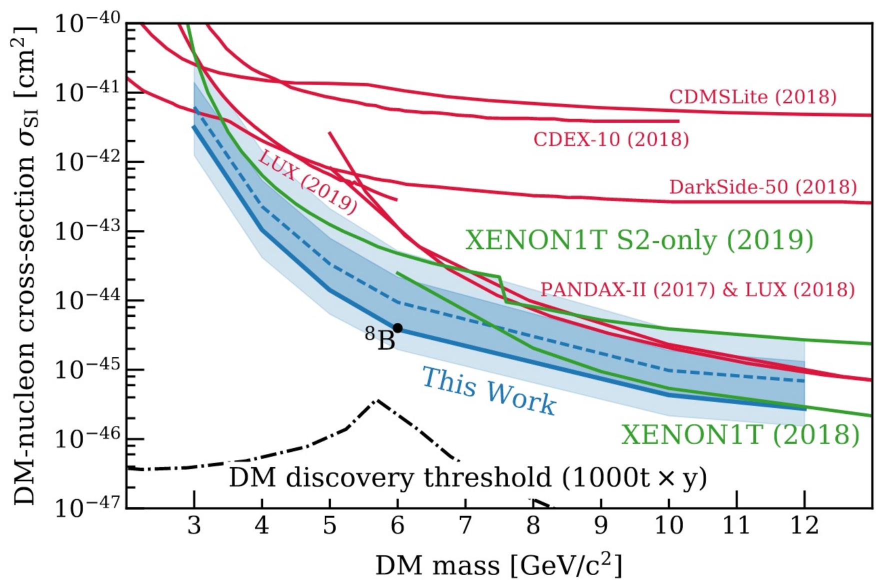


CEvNS as a **practical tool**

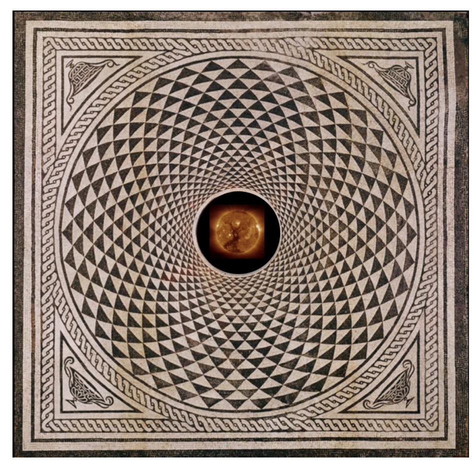


Search for CEvNS from **solar neutrinos** with the XENON-1T experiment

Phys.Rev.Lett. 126 (2021) 091301, arXiv: 2012.02846



Limit only so far
... but will eventually hit the floor...
sometimes there are
interesting things to see
if you look down...

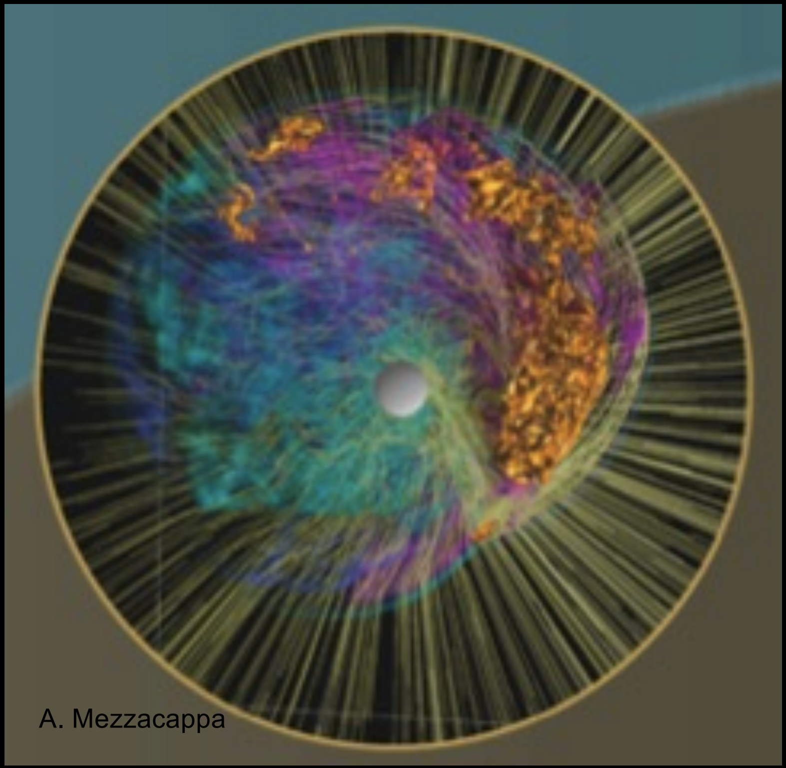


Neutrinos from core-collapse supernovae

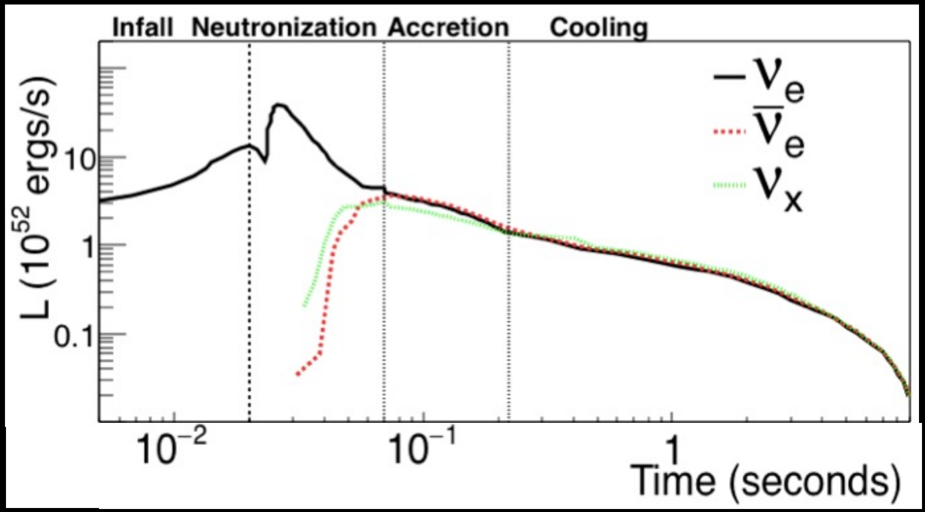
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

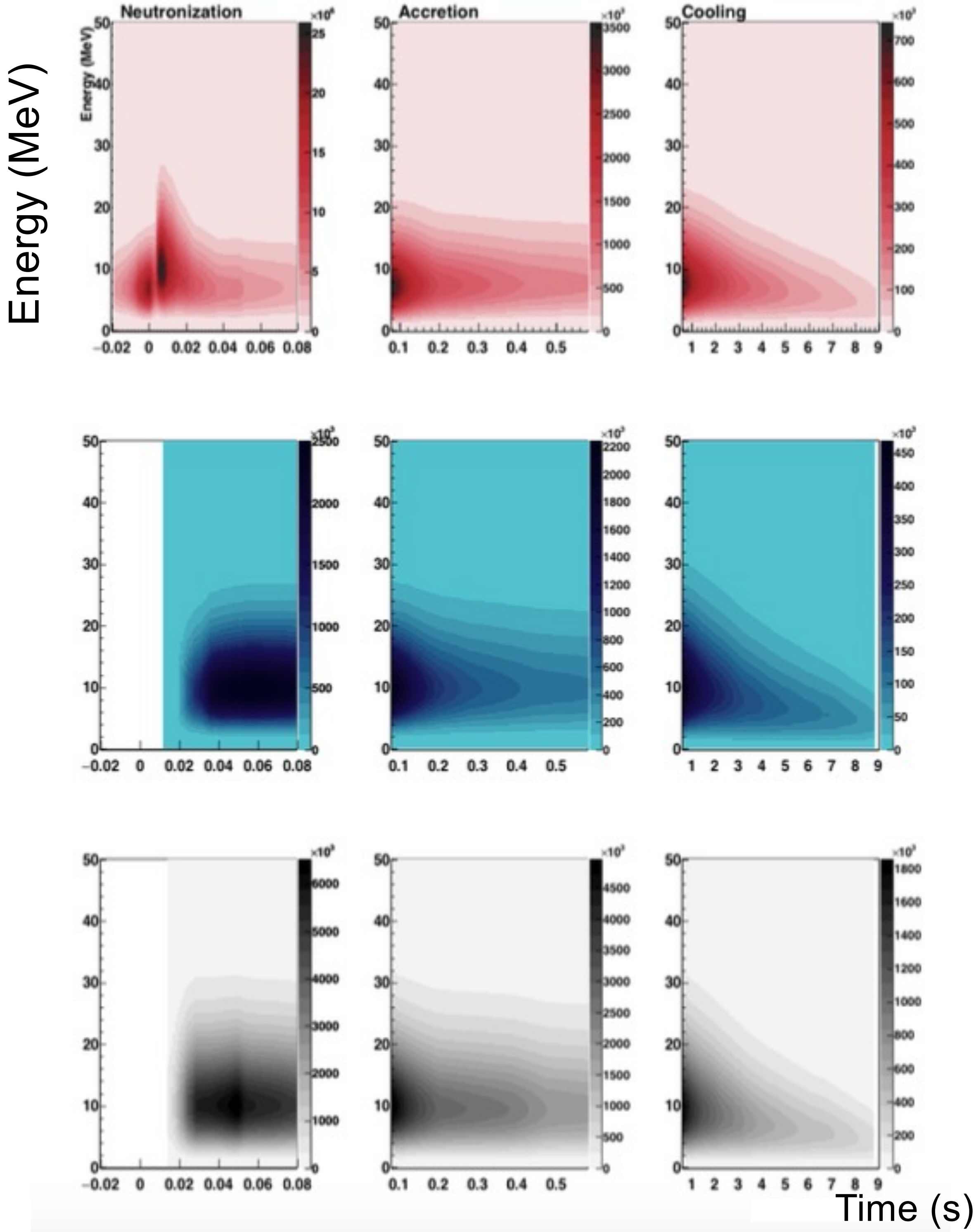
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Fluxes as a function of time and energy



ν_e

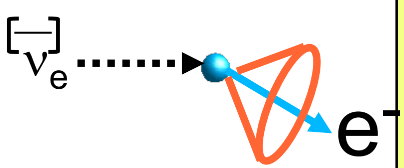
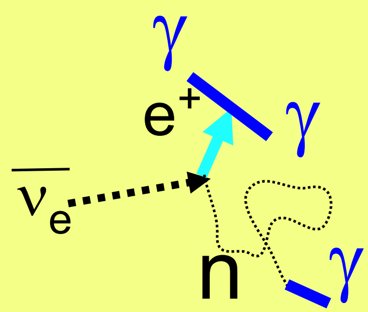
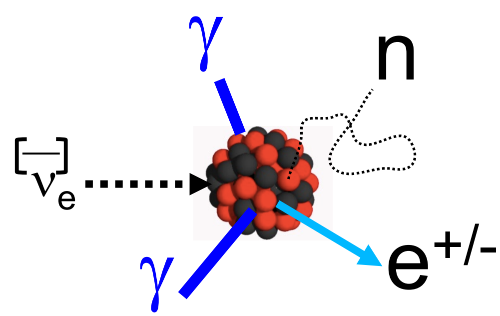
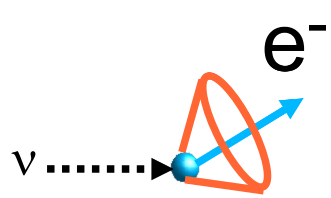
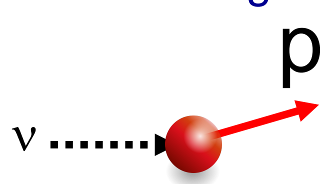
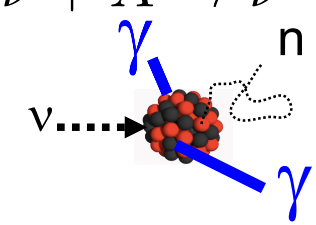
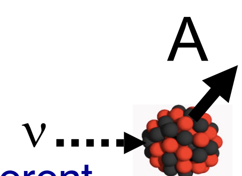
$\bar{\nu}_e$

ν_x

$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

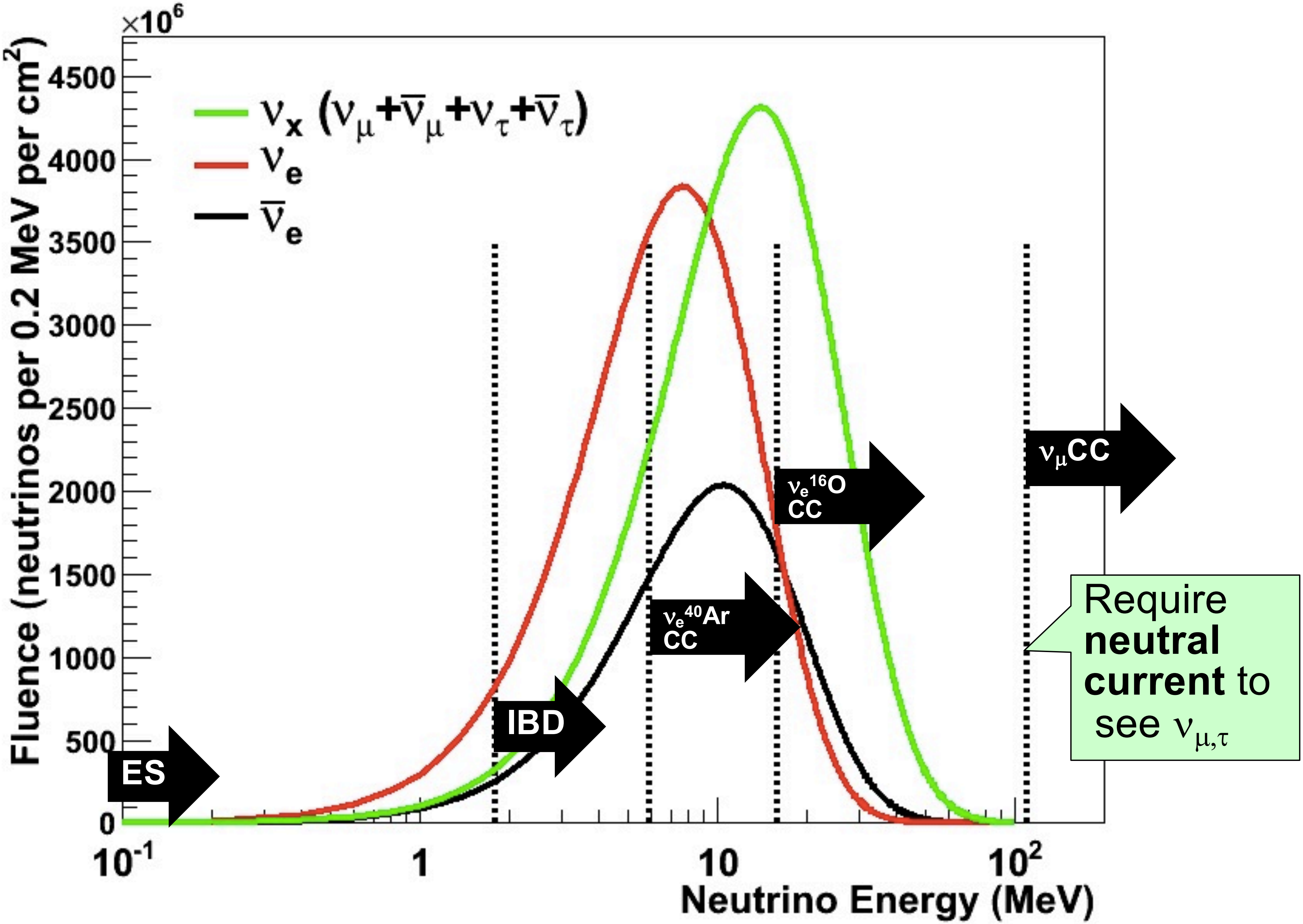
"Garching model",
L. Huedepohl et al.

Supernova-relevant neutrino interactions

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

IBD (electron *anti*neutrinos) dominates for current detectors

Neutrino interaction thresholds



Supernova neutrino detector types

Water

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

Water, long-string

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

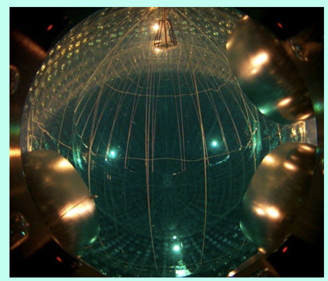
$\bar{\nu}_e$

Argon

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

ν_e

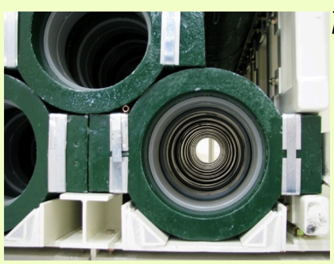
Scintillator



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

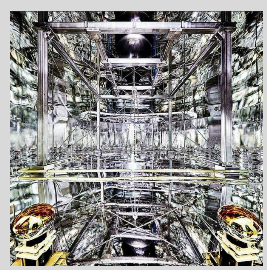
Lead



$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

ν_e

DM (Noble liquid)

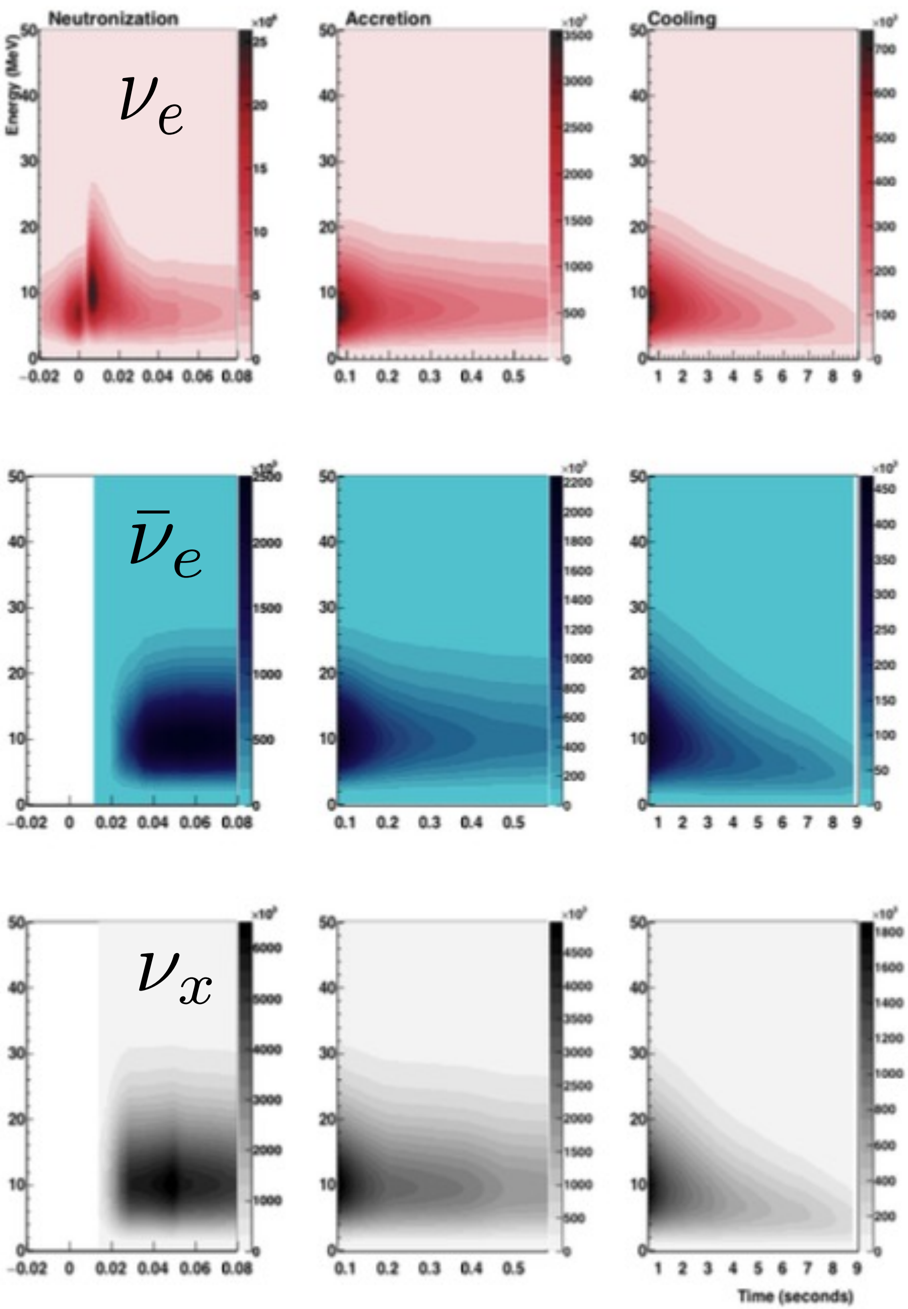


$$\nu_x + \mathrm{A} \rightarrow \nu_x + \mathrm{A}$$

ν_x

What we *want* to measure

Neutrino fluxes vs E, t

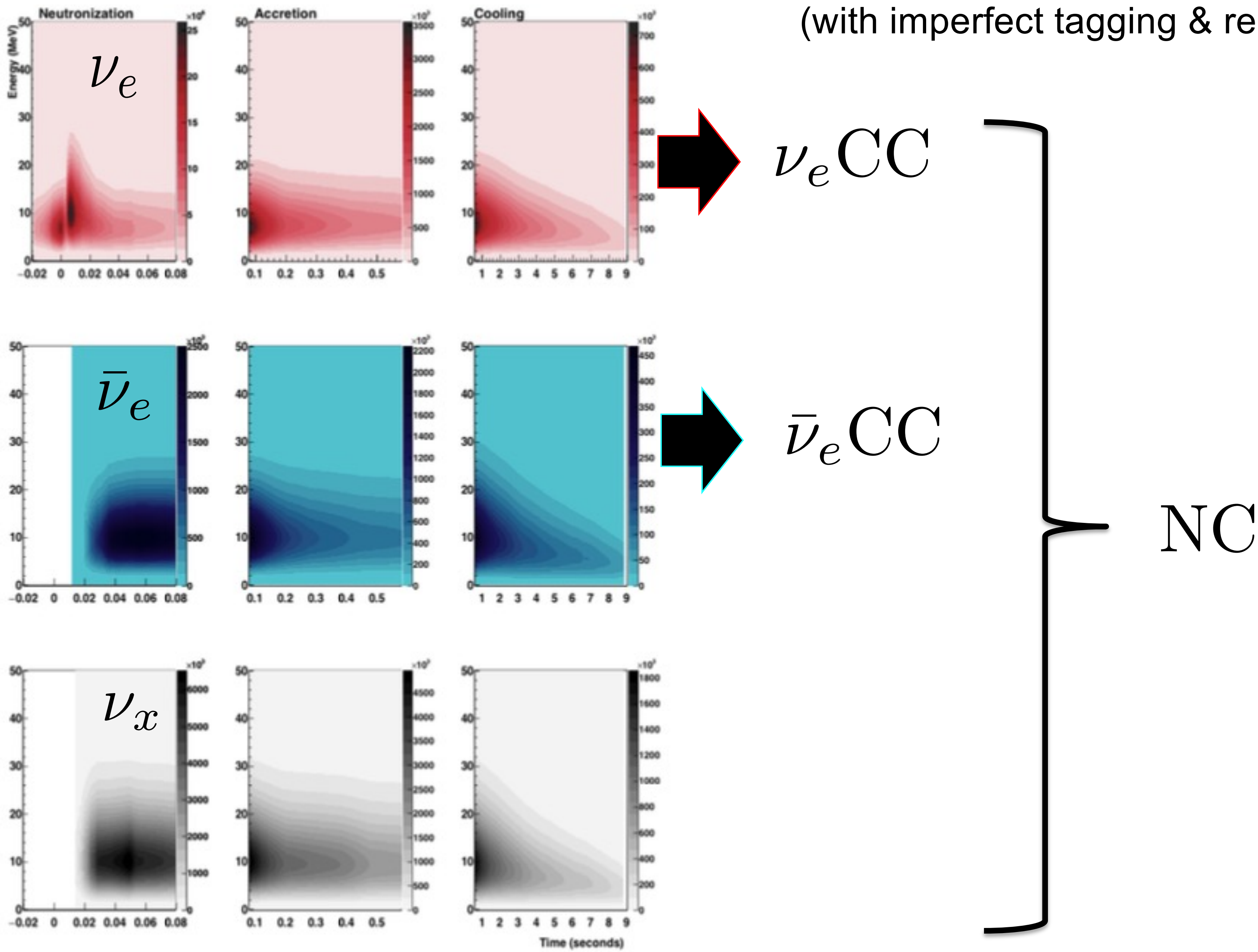


What we *want* to measure

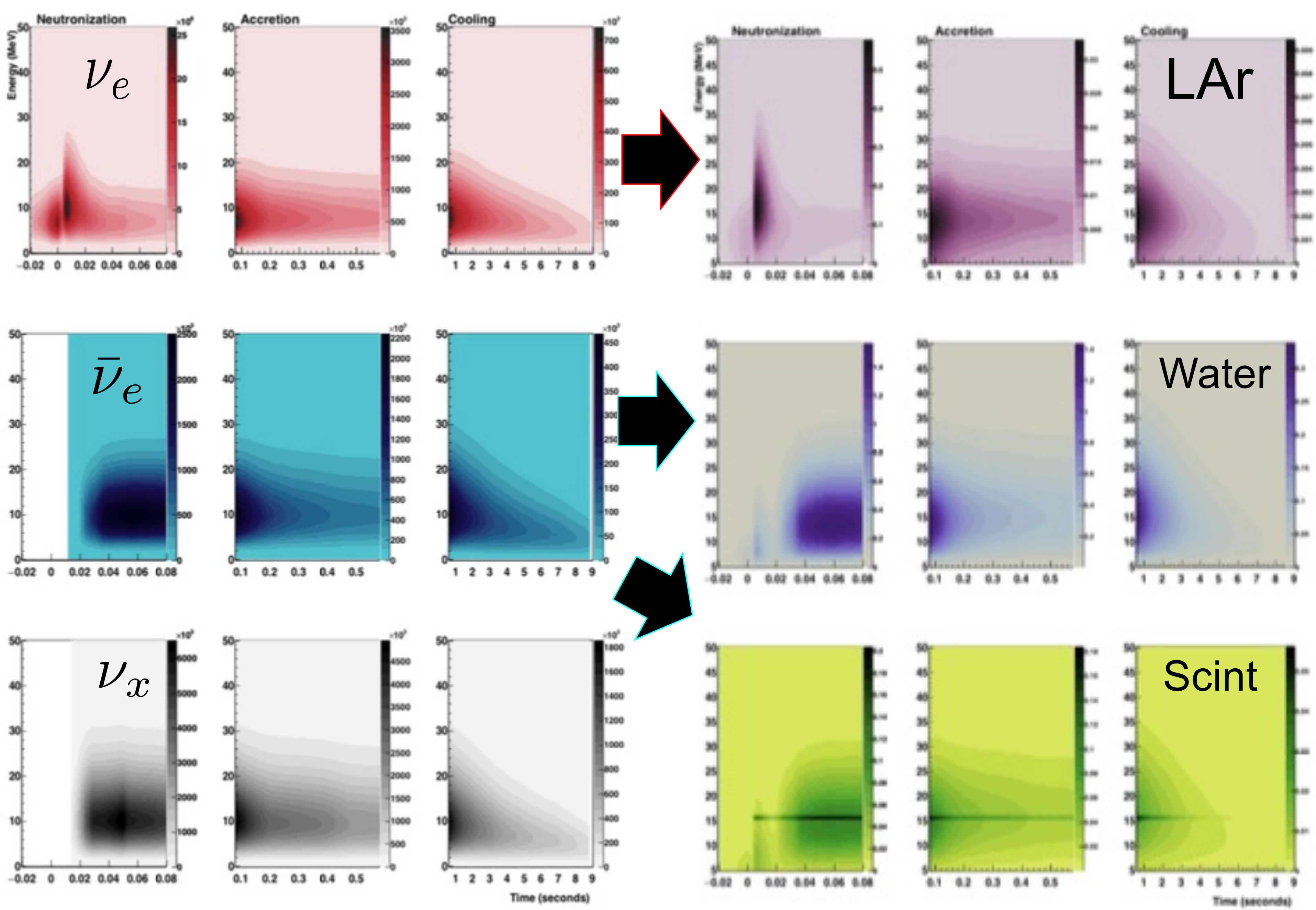
Neutrino fluxes vs E, t

What we *can* measure

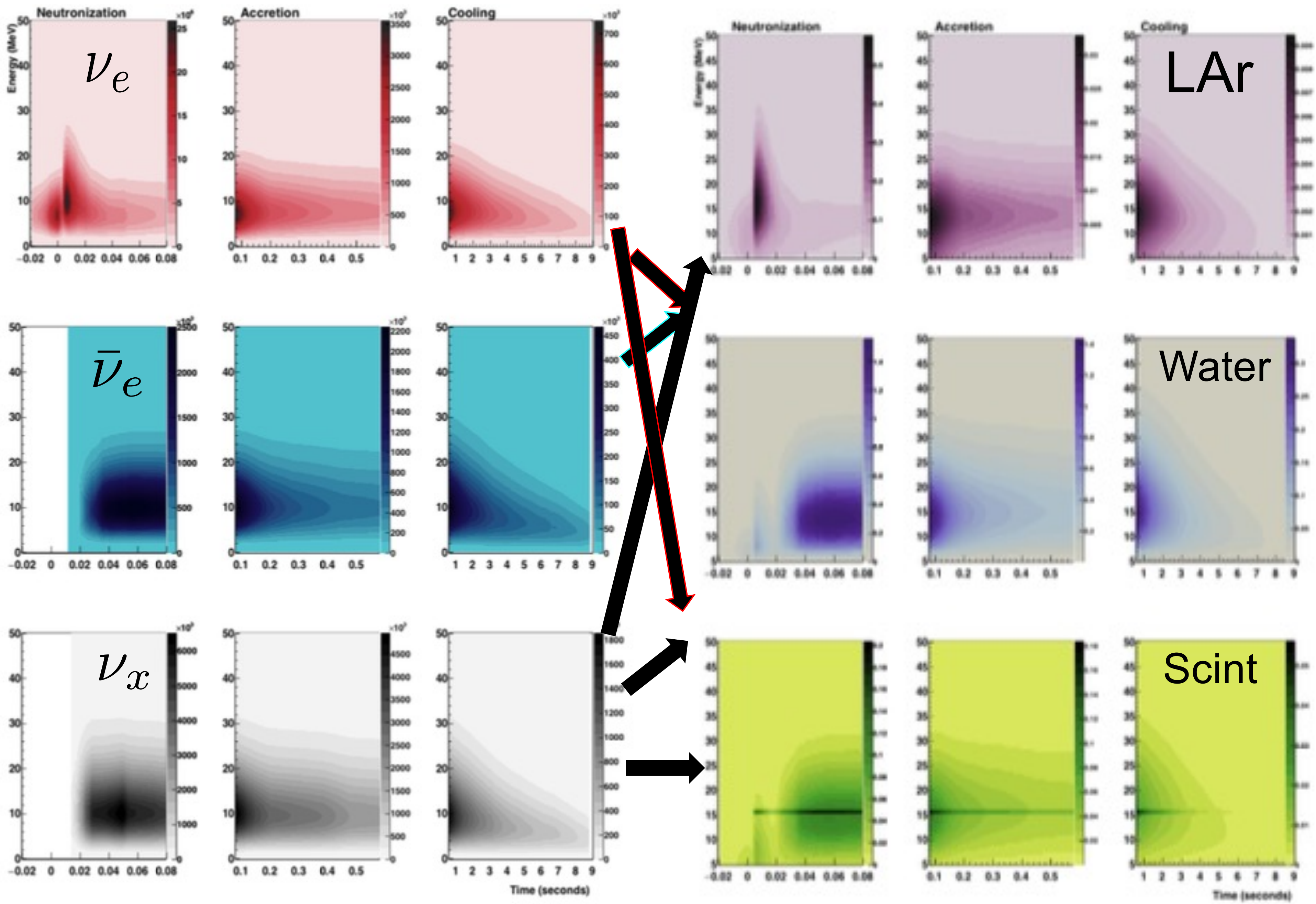
Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)



Neutrino fluxes vs E, t | Dominant channels | Event rates vs E, t



Subdominant channels are in the mix too,
and not always easily taggable... may be hard to disentangle!



Neutral-current SN events are especially valuable...

- Measure **total flux, all flavors**
  - total energy in neutrinos
  - improves flavor transition knowledge
- **All-flavor spectral information** also valuable

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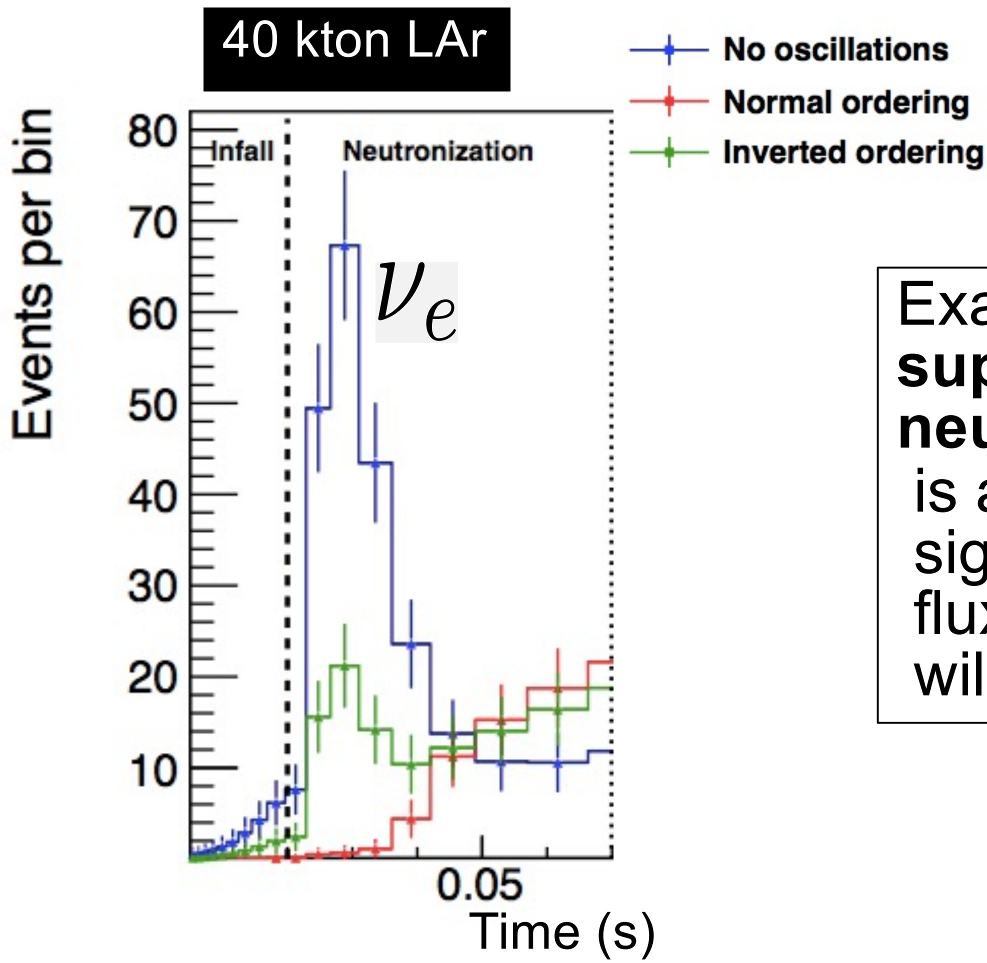


$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

Example:
suppression of the neutronization burst ν_e is a robust mass ordering signature; knowing total flux via tagged NC will help to interpret

CEvNS **in the supernova itself**

Progress of Theoretical Physics, Vol. 54, No. 5, November 1975

Supernova Explosion and Neutral Currents of Weak Interaction

Katsuhiko SATO

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received May 12, 1975)

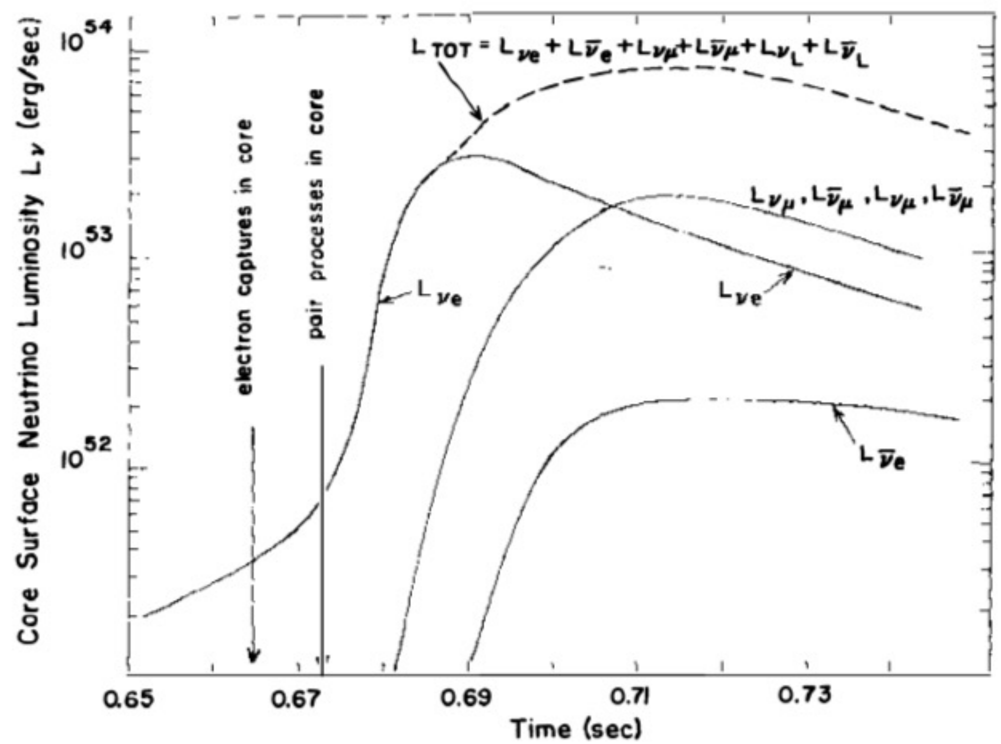
Recognized early as a key process in the core collapse and explosion

Ann. Rev. Nucl. Sci. 1977. 27: 167–207

THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

Daniel Z. Freedman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

David N. Schramm[1] *and David L. Tubbs*[2]
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637



First suggestion for **supernova detection via CEvNS**:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

First exploration in modern context:

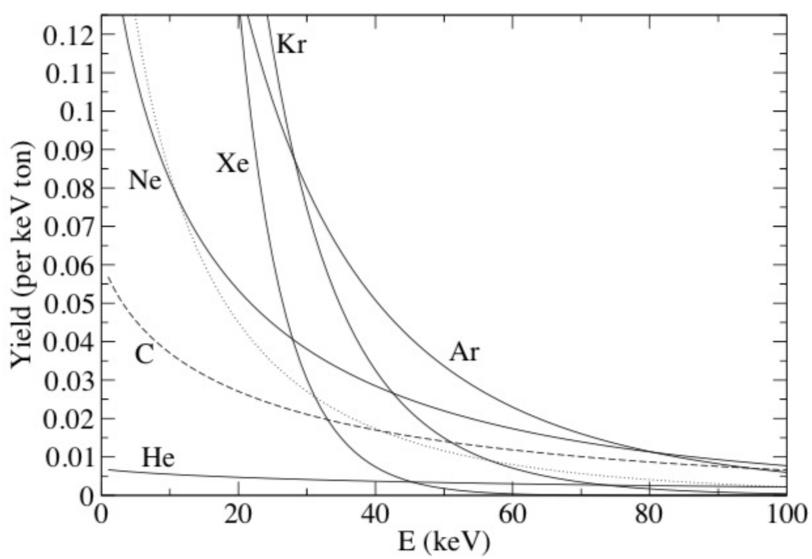
PHYSICAL REVIEW D **68**, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

C. J. Horowitz*
Nuclear Theory Center and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

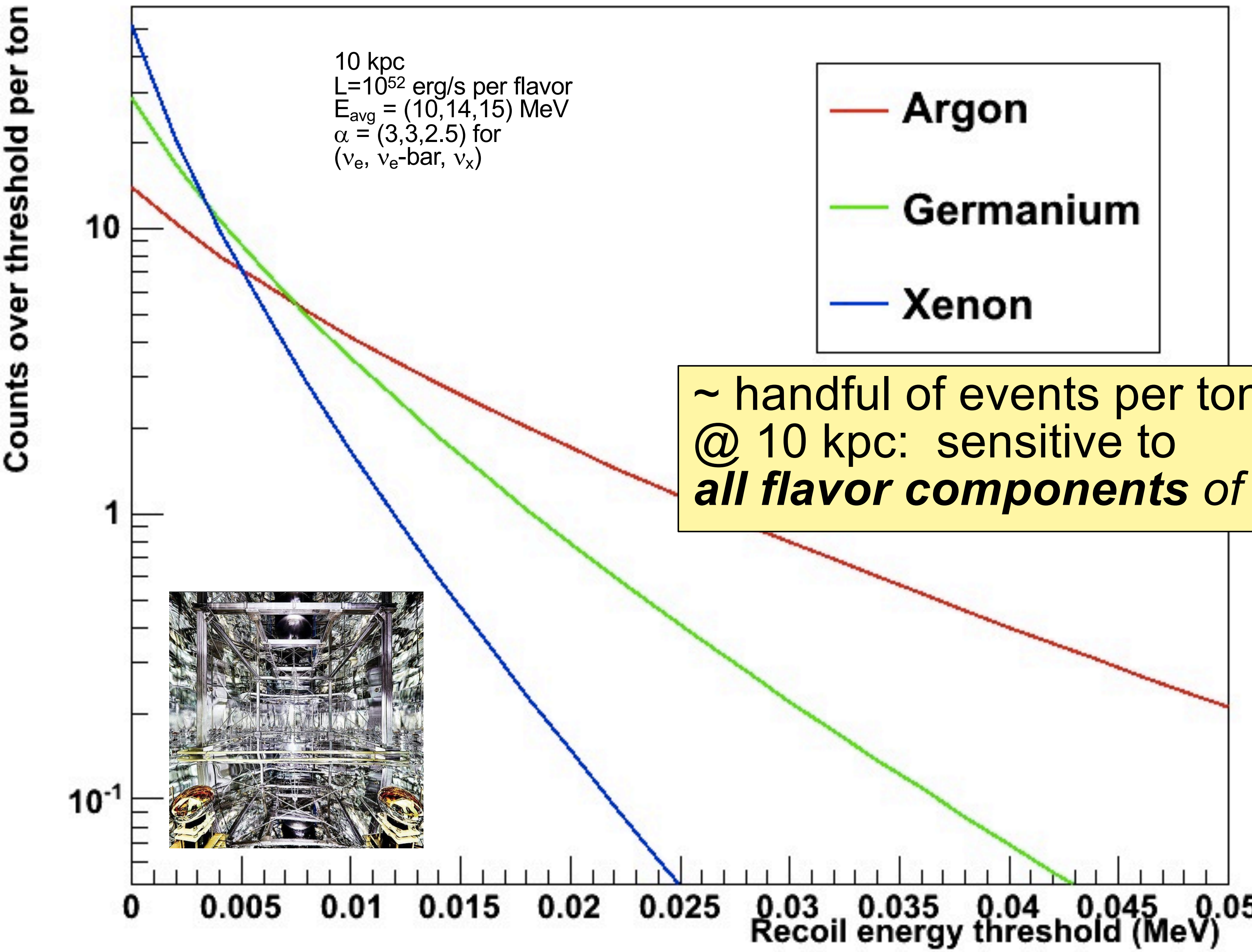
K. J. Coakley
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

D. N. McKinsey
Physics Department, Princeton University, Princeton, New Jersey 08544, USA
(Received 5 February 2003; published 28 July 2003)



- WIMP DM detectors tend to be low background, low threshold (10's of keV or less)
- Scalability to large mass is desirable

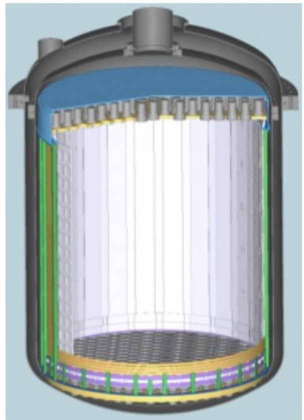
Supernova neutrinos in tonne-scale DM detectors

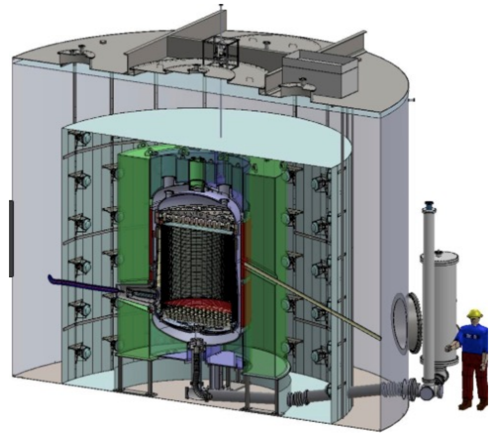


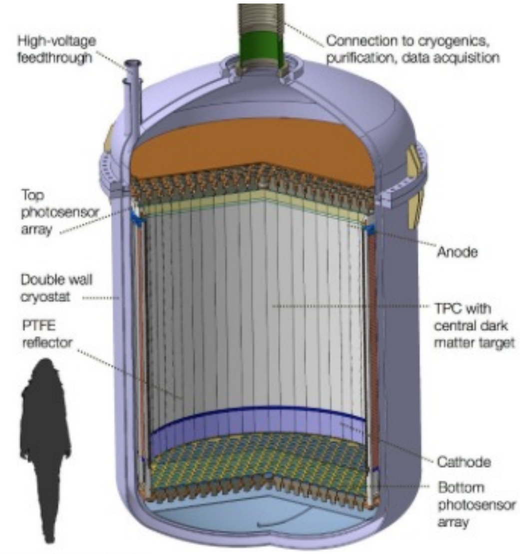
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

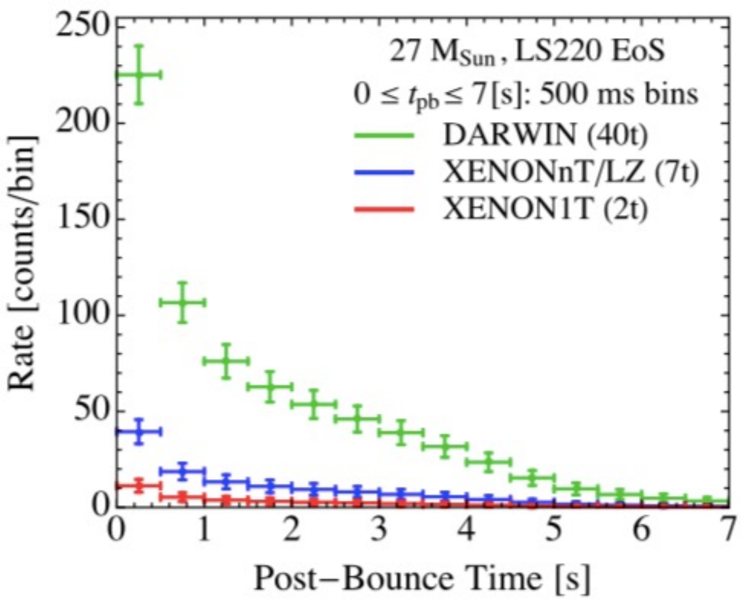
Detector example: **XENON/LZ/DARWIN**

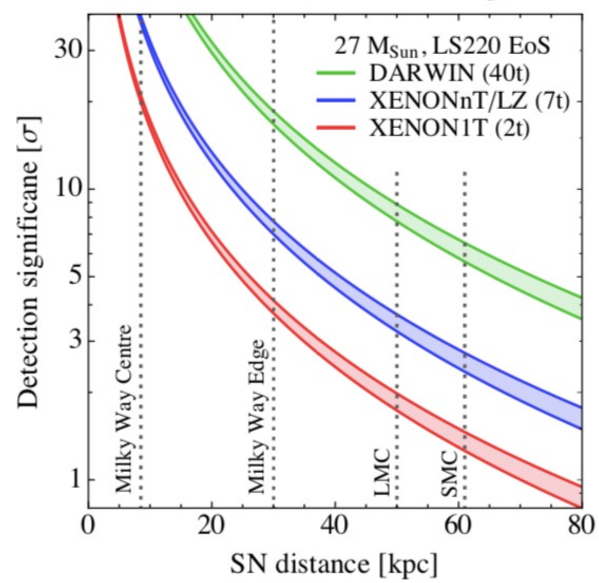
- dual-phase xenon time projection chambers











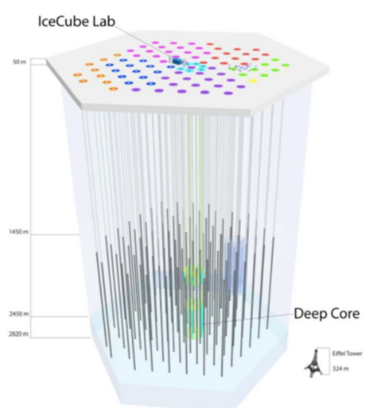
Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

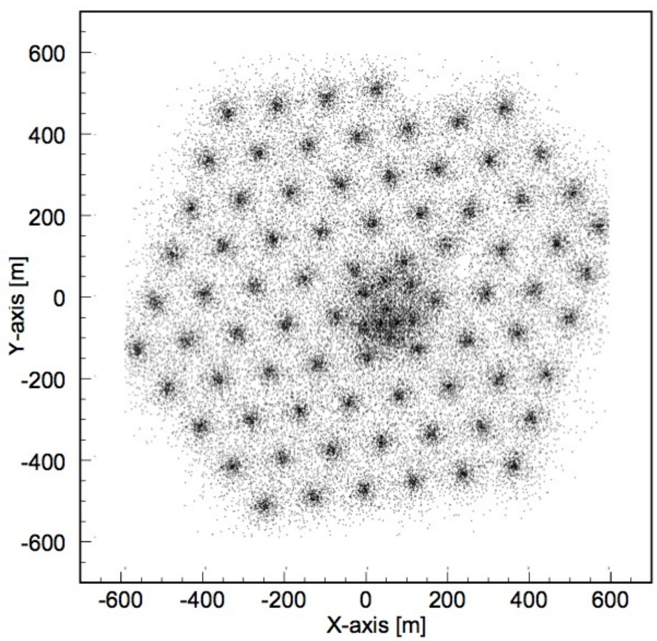
Also: DarkSide-20K, ARGO, RES-NOvA,...

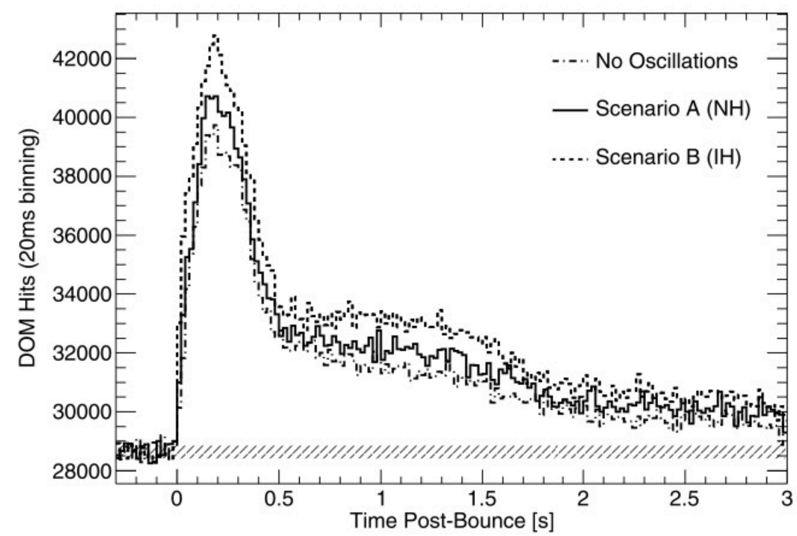
“CEvNS Glow” in large, high-threshold neutrino detectors

Adryanna Major and Gleb Sinev @ Duke

“IceCube-style” supernova detection:
Cherenkov photons in ice observed as
time-dependent single- (and double-)hit glow over ~10 sec

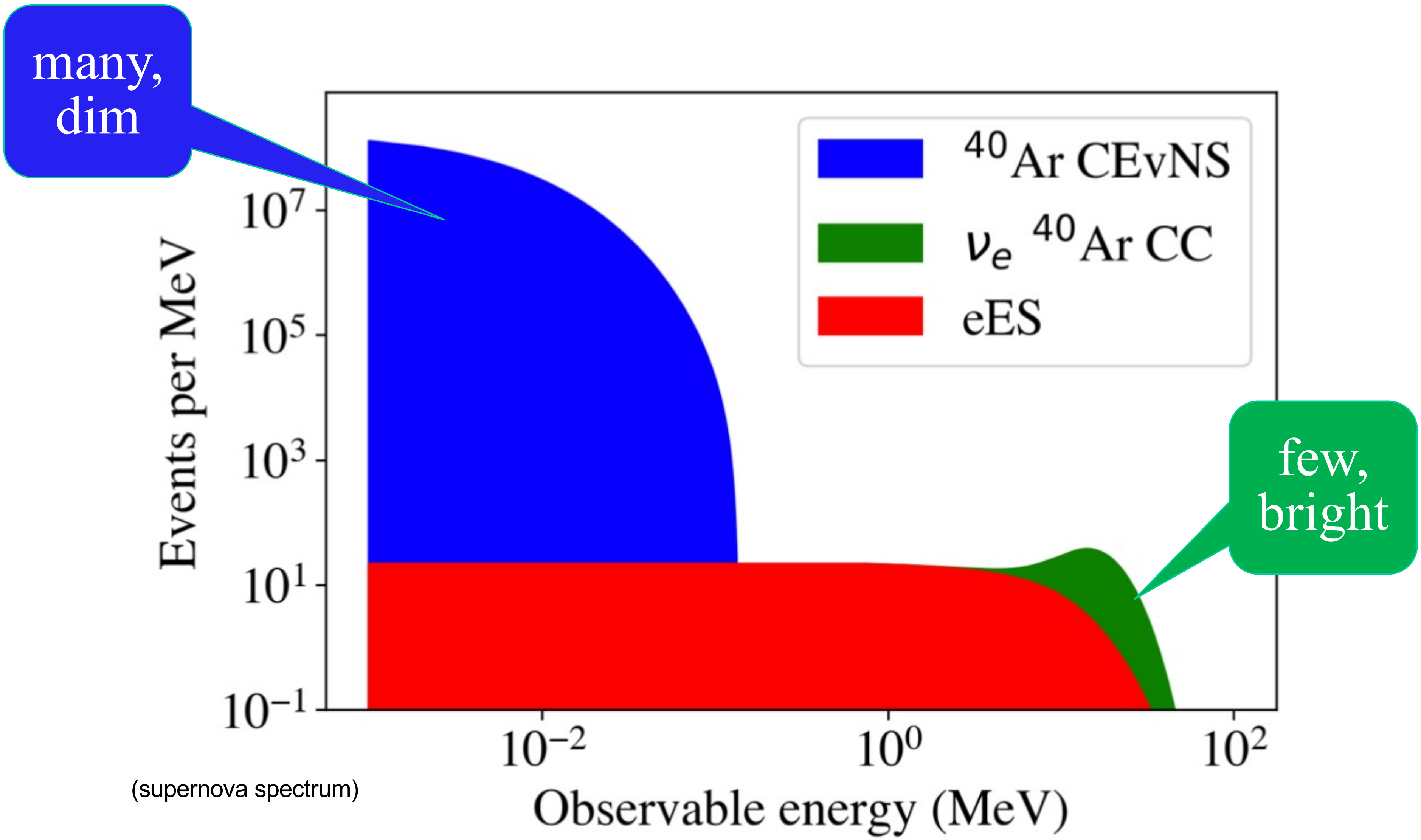






IceCube collaboration, A&A 535, A109 (2011)

Observable energy in argon



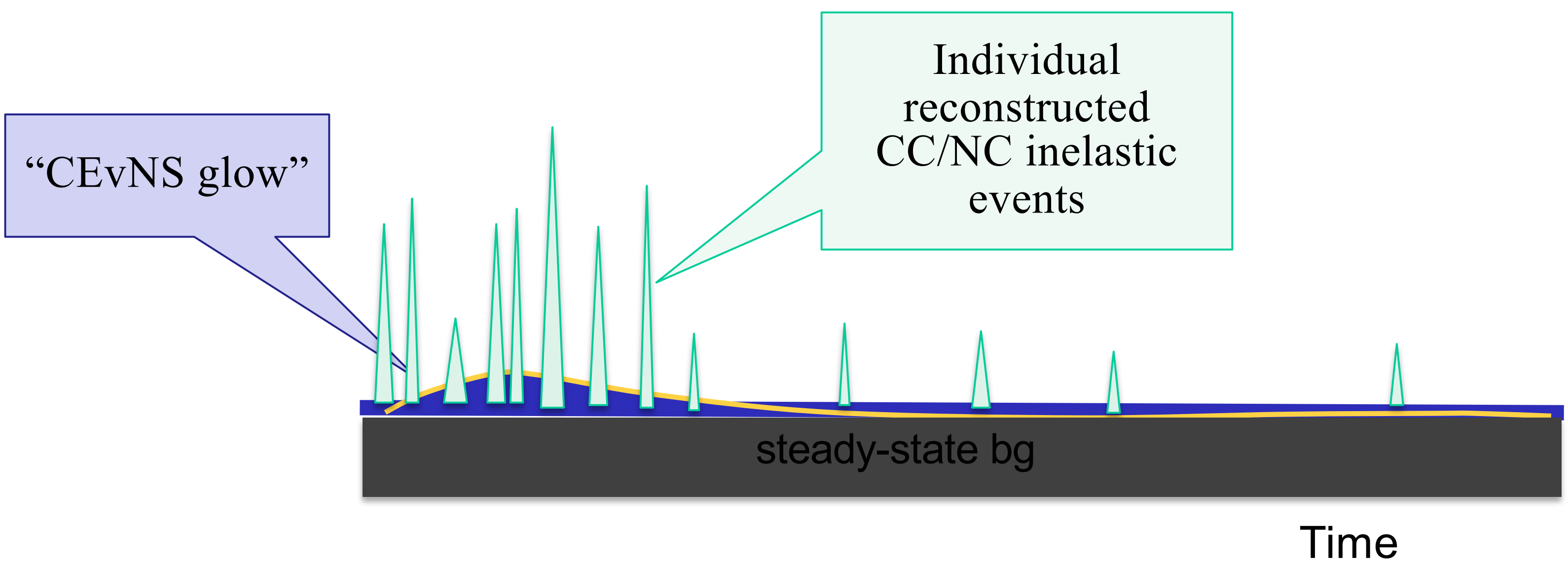
(supernova spectrum)

Back-of-the-envelope:
CEvNS signal vs Inelastic (CC/NC) signal:

e.g., $\nu_x + A \rightarrow \nu_x + A$ vs $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ in argon, or IBD in scint

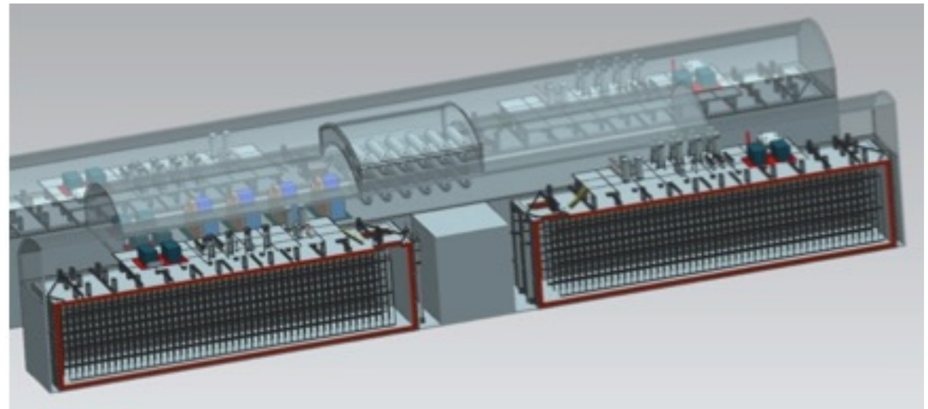
~10^2 more CEvNS events per target wrt CC
~10^{-3} less energy deposited per event for CEvNS wrt CC
~ 6 due to sensitivity to all flavors
~0.001-0.2 quenching factor (photons wrt e/γ energy deposit) for nuclear recoil wrt CC

➔Total CEvNS photons are **~few-10% of CC-generated photons**, but, **diffused over the burst** rather than in individual event spikes
Issue is whether they exceed Sqrt[background]
(and triggering may be challengin!)



For **DUNE**: 40 kt LAr,

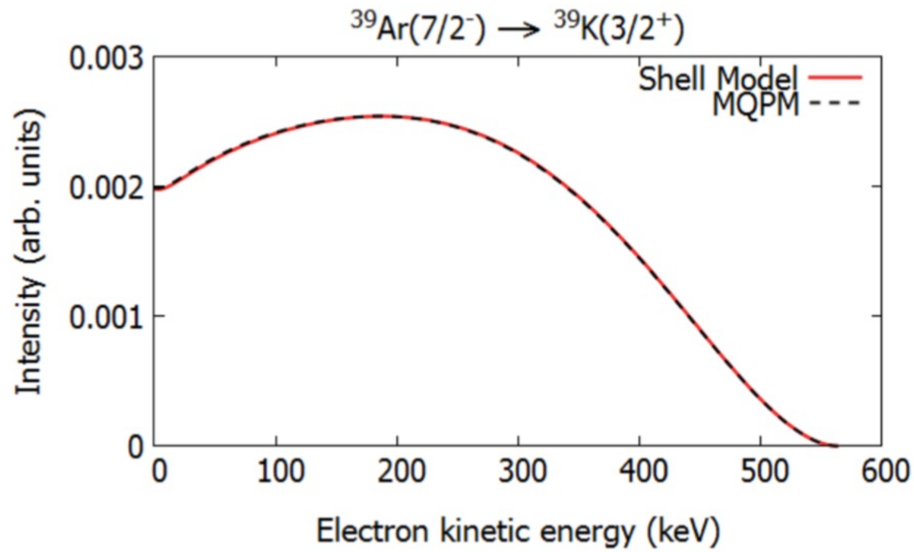
~24,000 photons/MeV
TPC + photon detectors



Most pernicious issue for CEvNS glow: ^{39}**Ar β decays**

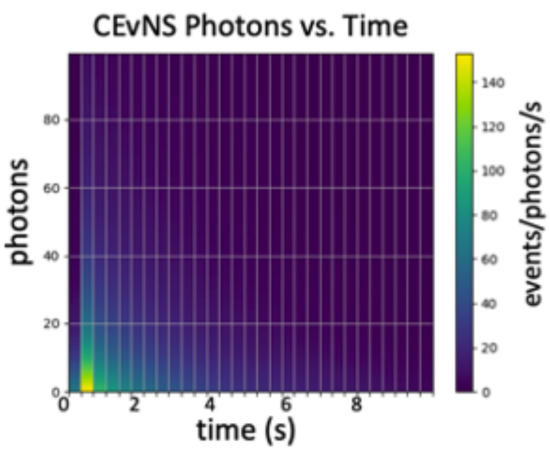
(dominant radiological)

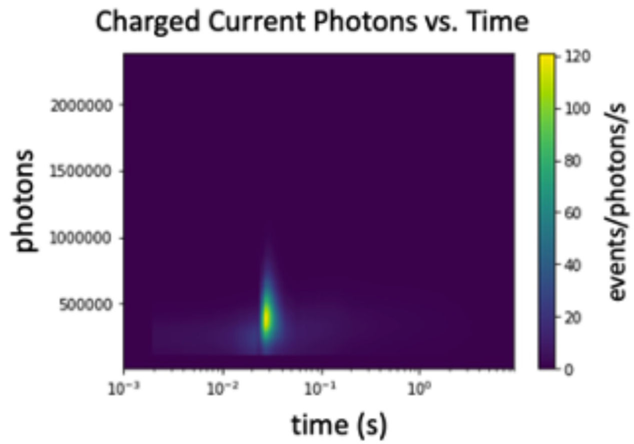
- 1 Bq/kg
- 260-yr half-life
- in principle can be mitigated w/underground argon
  (but 40 kton of it a challenge...)

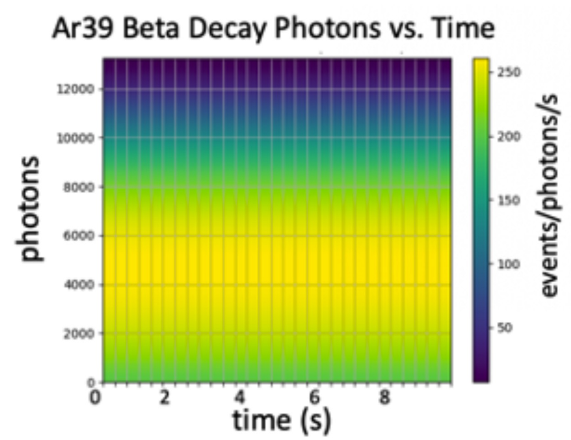


J. Kostensalo et al. (2017) arXiv:1705.05726

CEvNS Glow Photons in LAr: calculation by A. Major, Duke

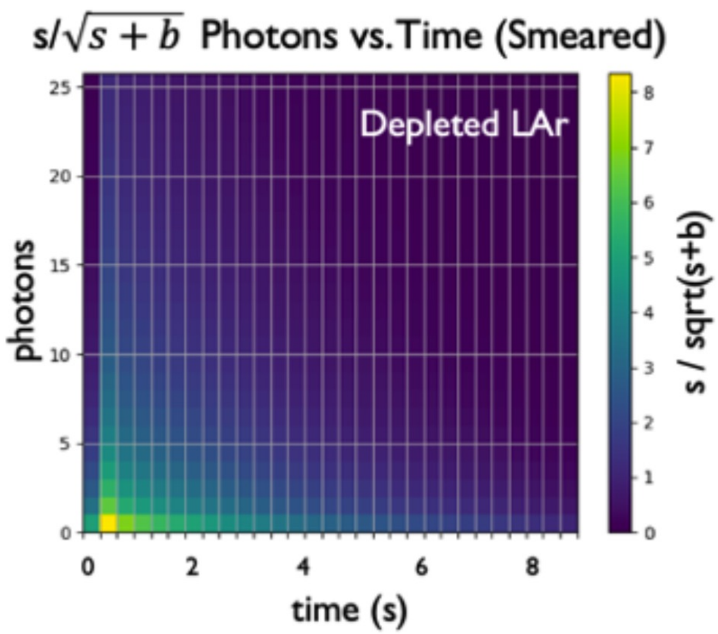






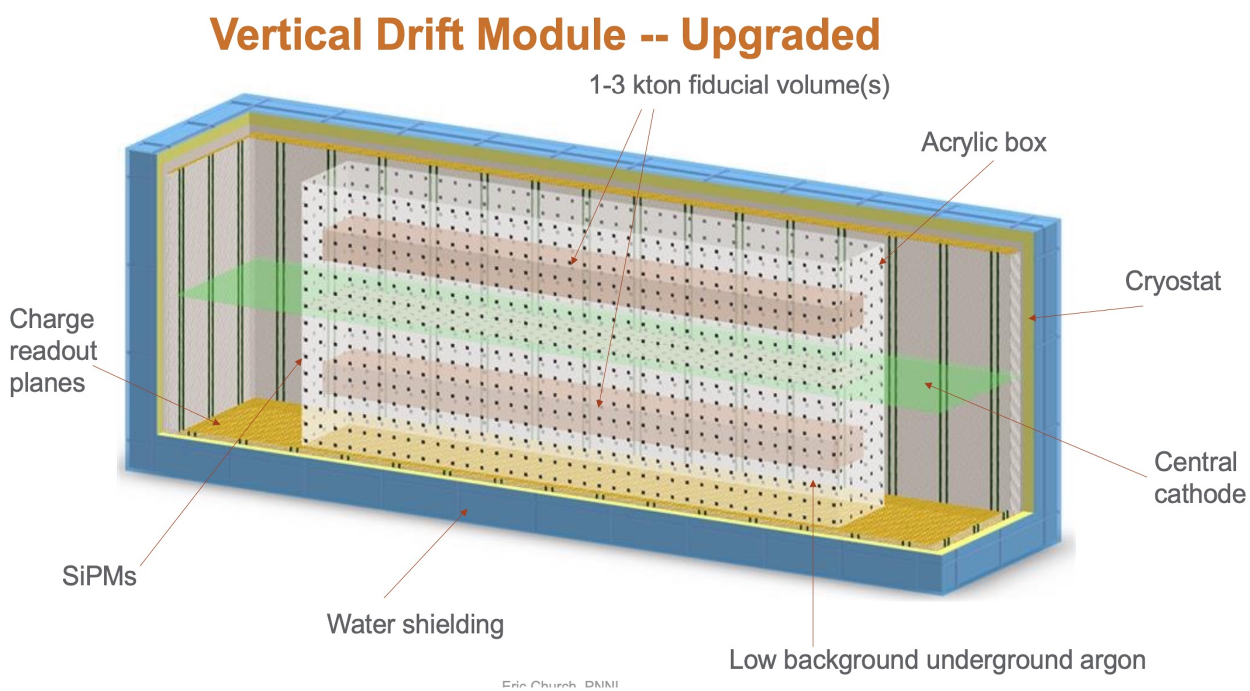
"Garching" supernova model, 10 kt, 10 kpc

Detected photons in simplified detector with ^{39}Ar x 0.001

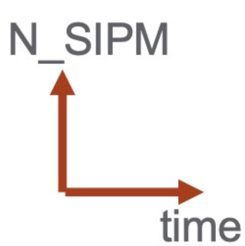


information
in time,
detected photon
multiplicity
spectrum

Approximate features matched by G4 sim of DUNE low-bg module



E. Church
LIDINE 2021



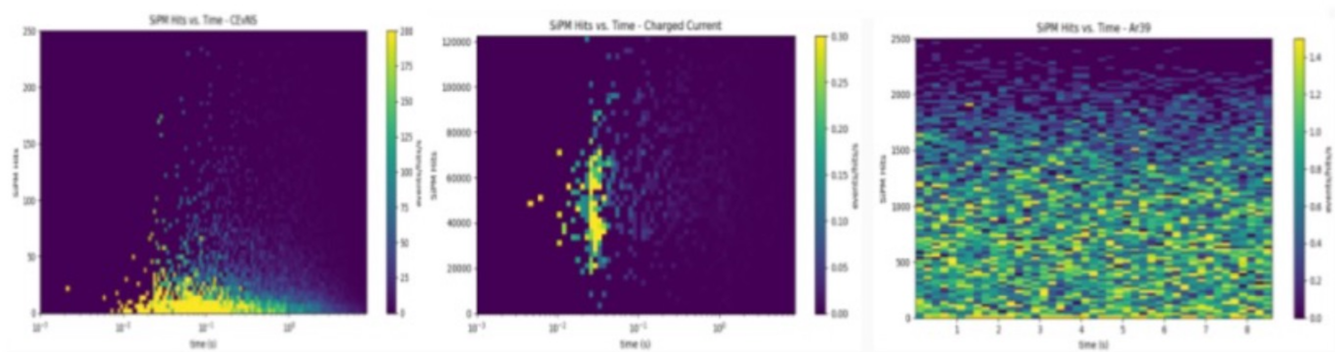


Figure 6: Figures from Carmelo Ortiz, DUNE low energy physics working group meeting,https://indico.fnal.gov/event/50302/

Carmelo Ortiz, Duke

- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-π ν's
  - CsI & Ar measurements by COHERENT, more soon!
- **HEAVEN: supernova neutrinos**
  - vast information in flavor-energy-time profile
  - **NC info is especially valuable!** total energy, all-flavor profile
- **CEvNS Heaven: SN ν's & CEvNS**
  - CEvNS is an important process inside the SN
  - CEvNS is a **supernova neutrino burst detection channel** w/ NC spectral info, tonne-scale DM detectors can exploit
  - Maybe even in large detectors!