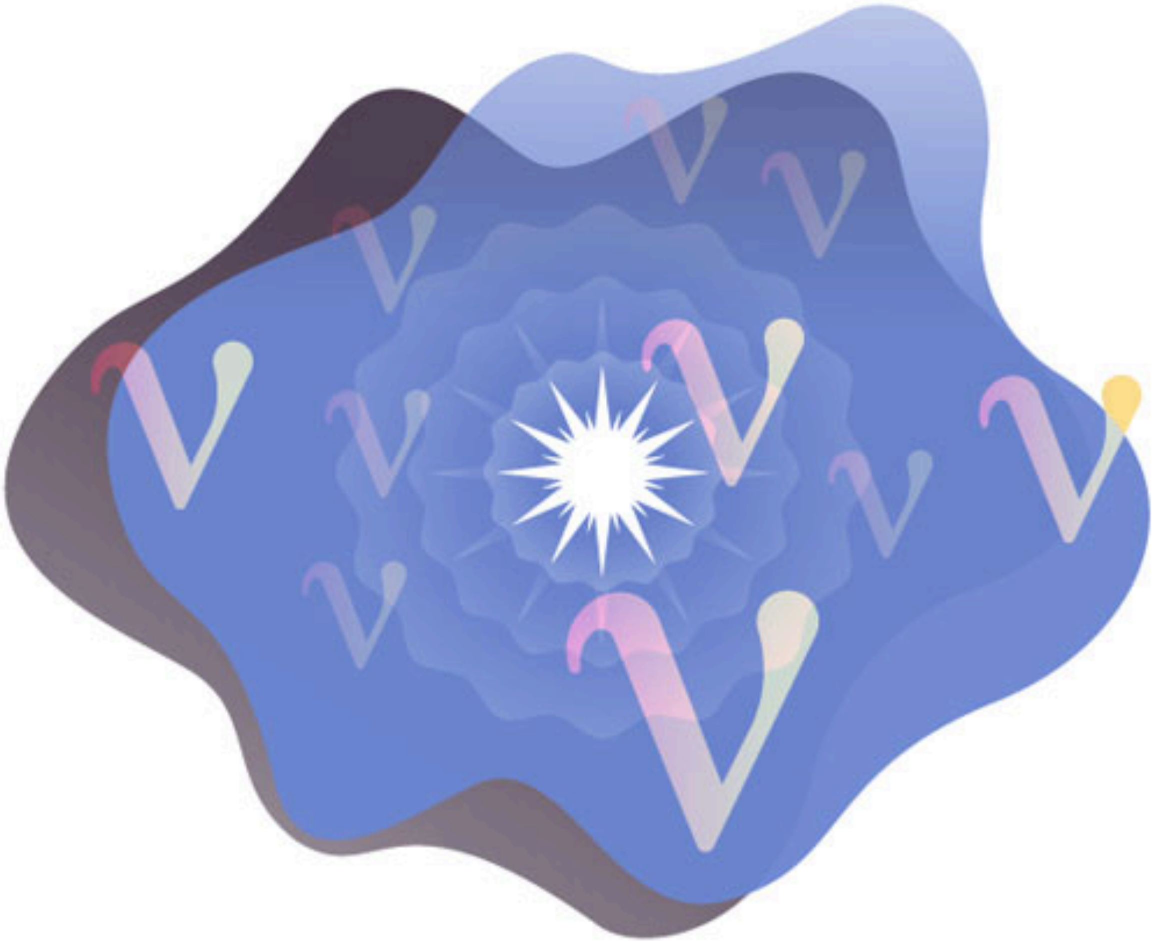
Coherent Scattering and the Flavor Physics and Detection of Supernova Neutrinos



Kate Scholberg, Duke University
CIPANP 2018, Palm Springs
May 31, 2018

https://scitechdaily.com/ten-facts-about-supernovae/supernovae-are-neutrino-factories/

OUTLINE

- **Neutrinos from Core-Collapse Supernovae**
  - The nature of the signal and what it can tell us
  - Detection of supernova neutrinos
- **Coherent elastic neutrino-nucleus scattering** (CEvNS)
  - The nature of the process
  - Measurement status and prospects
- **CEvNS and Supernovae**
  - CEvNS as a supernova process
  - CEvNS as a supernova detection channel

This talk is the union of some of my favorite things...

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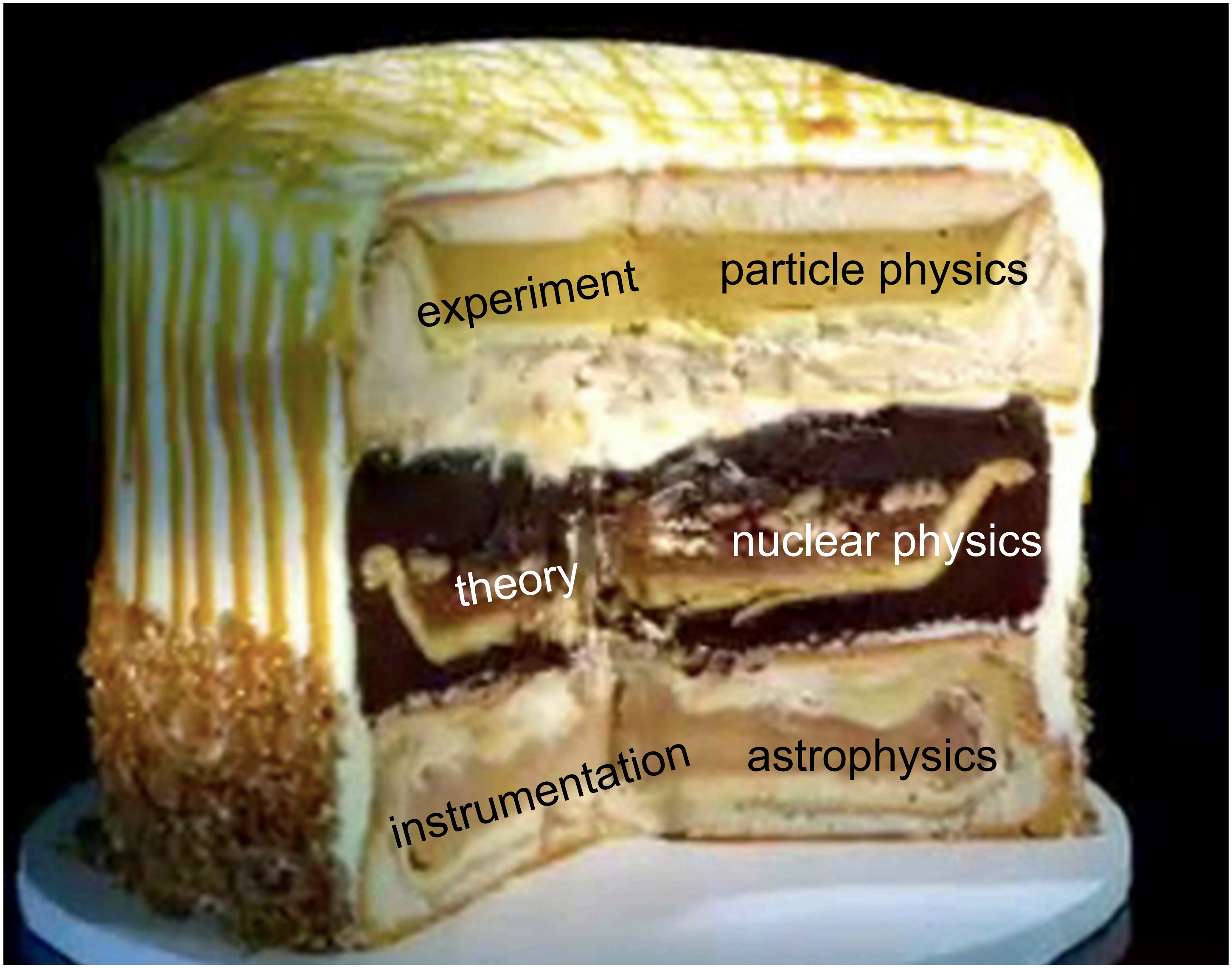
Cake
and
pie

(It's also about the CIPANPiest topic ever...)



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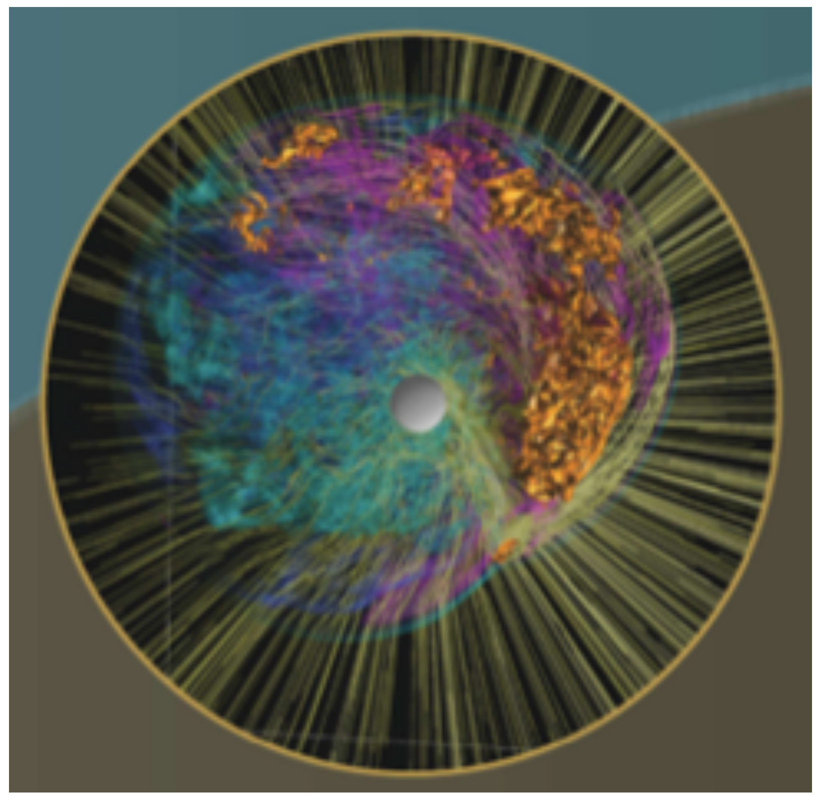
The core-collapse neutrino signal

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)

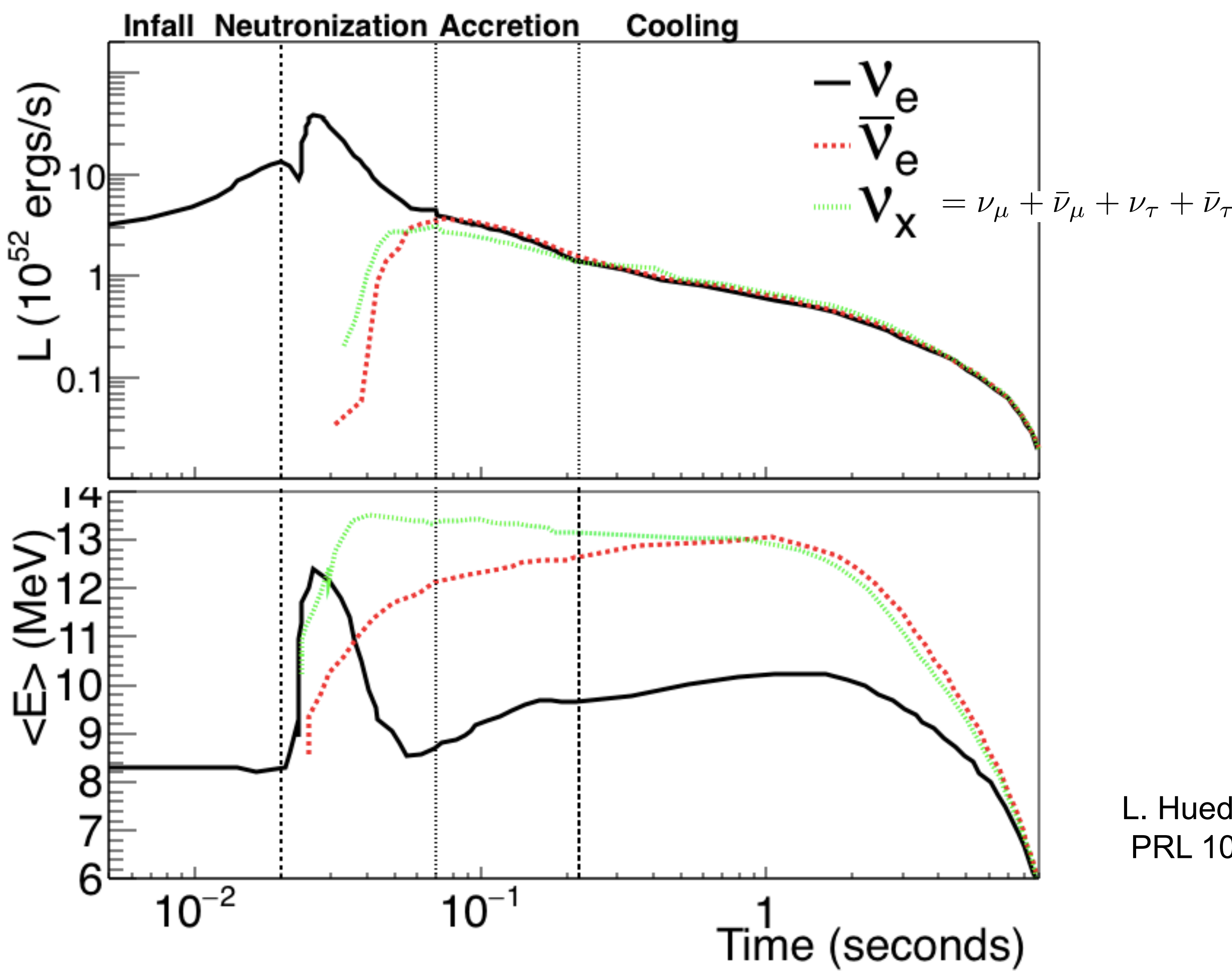
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

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



Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*



L. Huedepohl et al., PRL 104 251101

Generic feature: $$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

(may or may not be robust)

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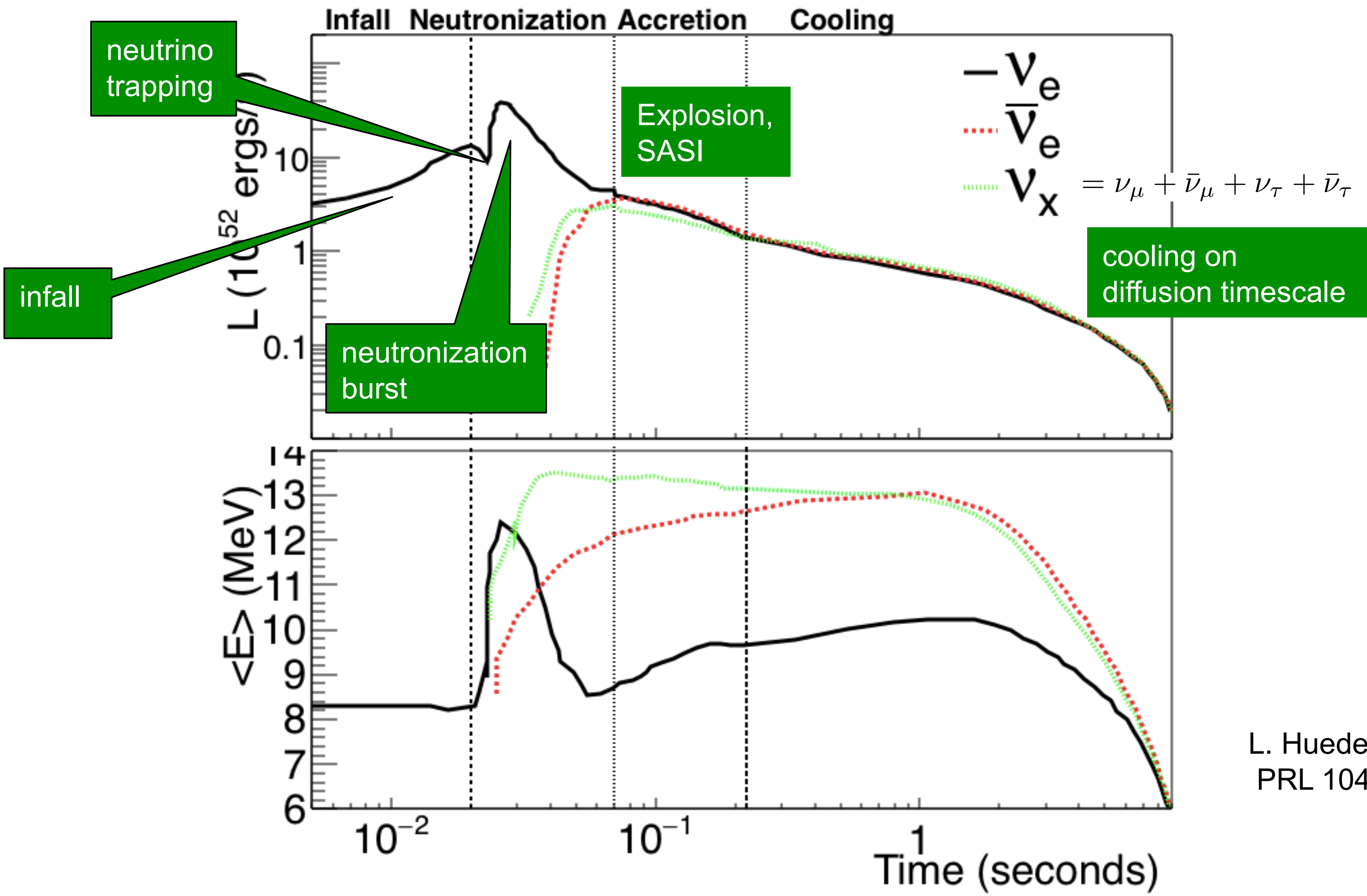

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Generic feature:

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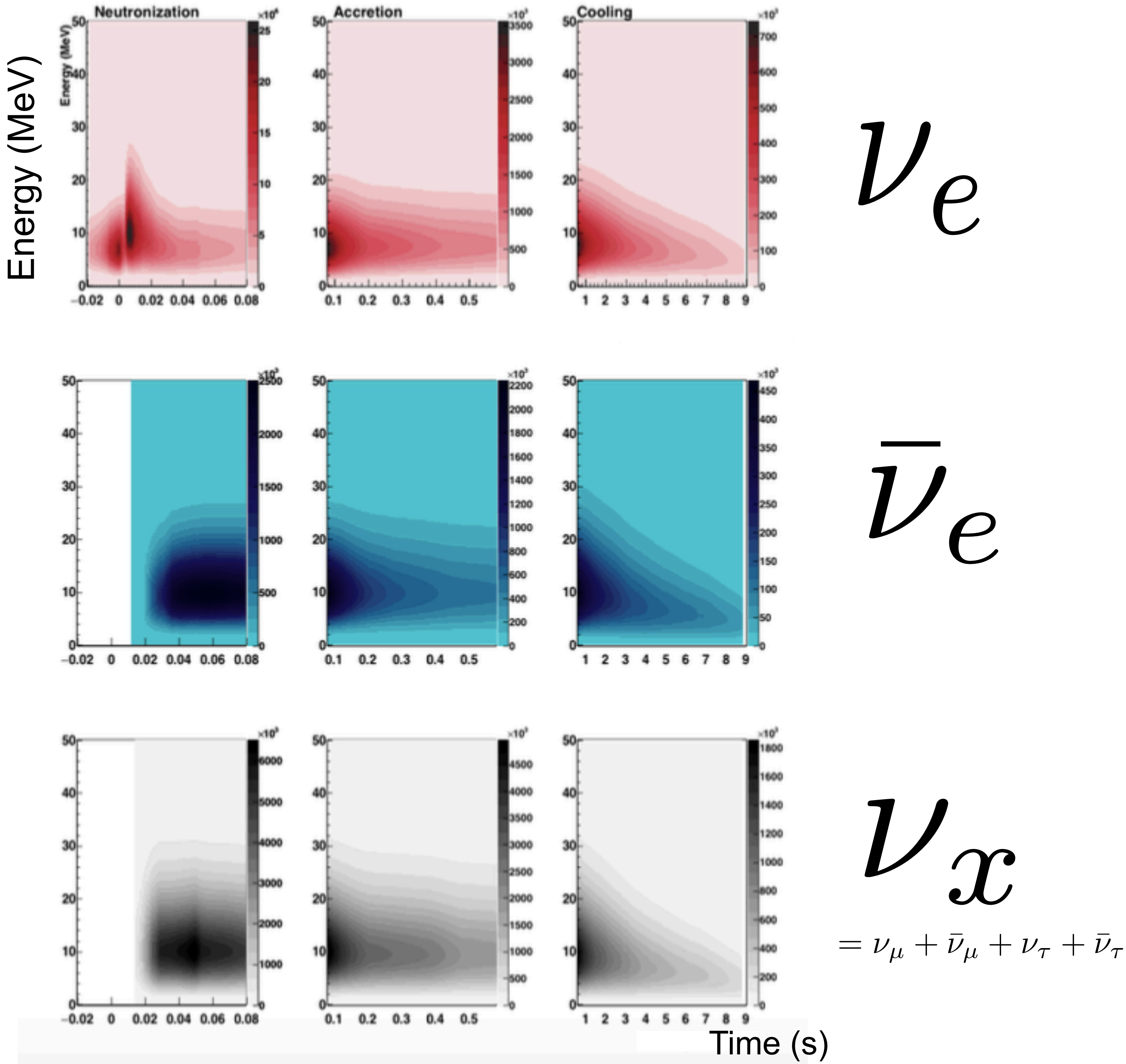
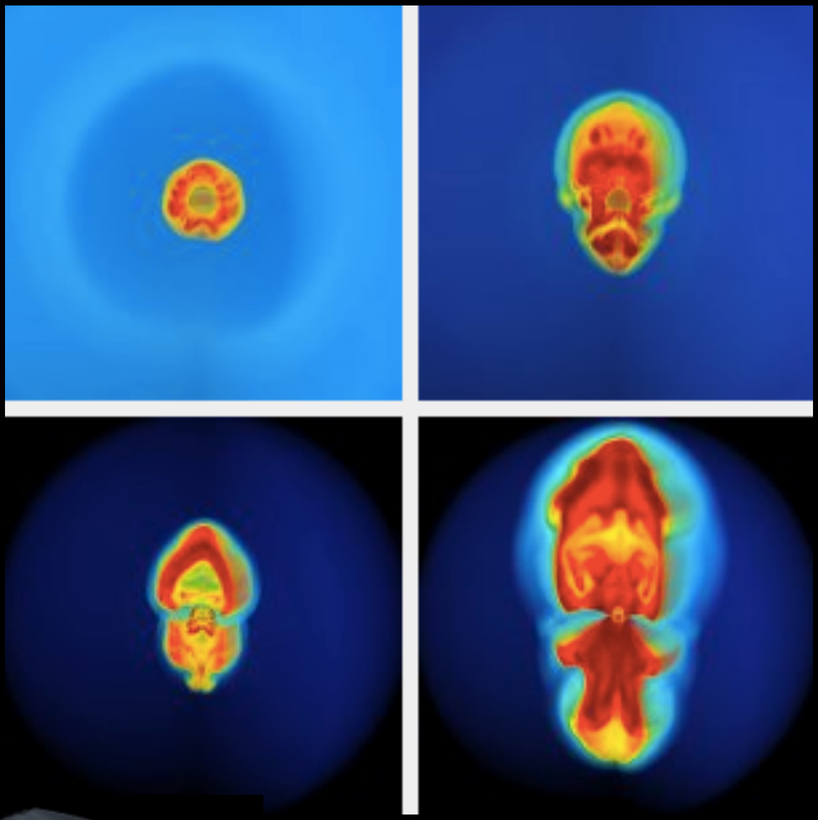
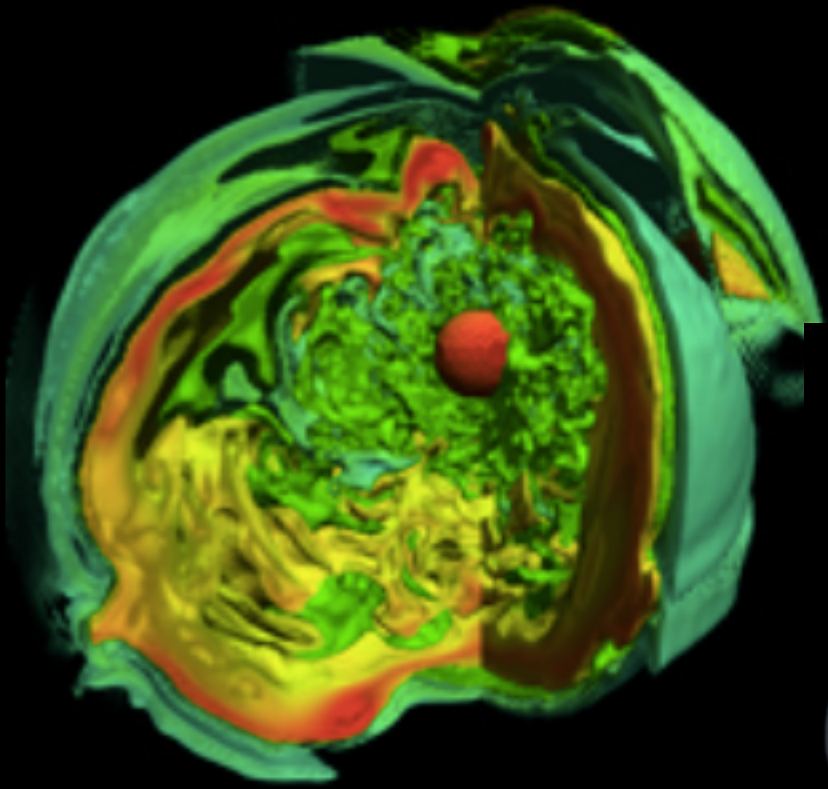
Fluxes as a function of time and energy



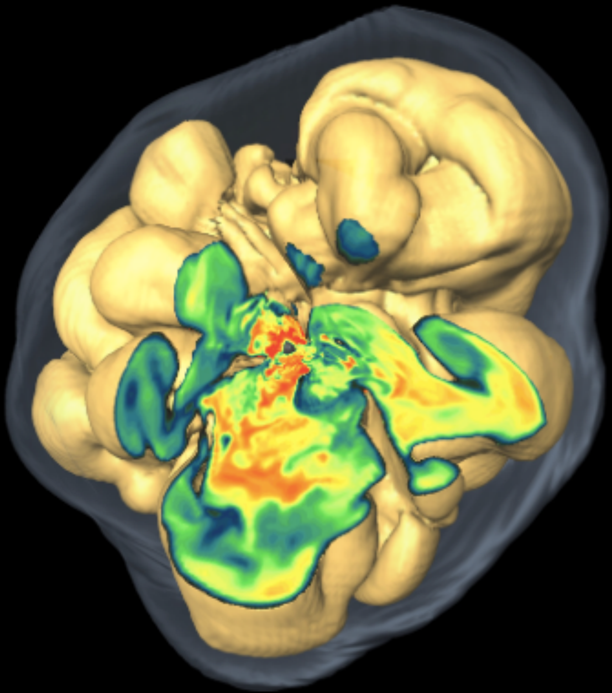
The core-collapse supernova explosion is still not fully understood... numerical study ongoing



Marek & Janka



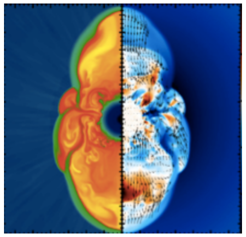
Blondin, Mezzacappa, DeMarino



Neutrinos are intimately involved

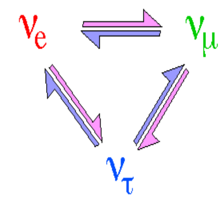
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments



from flavor, energy, time structure of burst

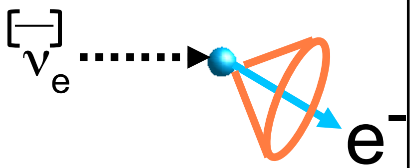
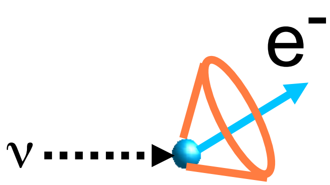
NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

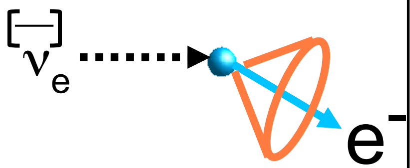
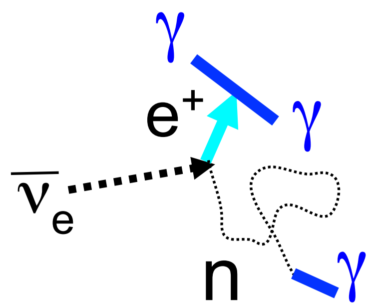
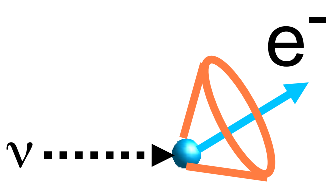
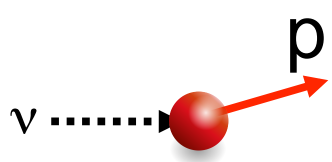
input from photon (GW) observations

+ EARLY ALERT

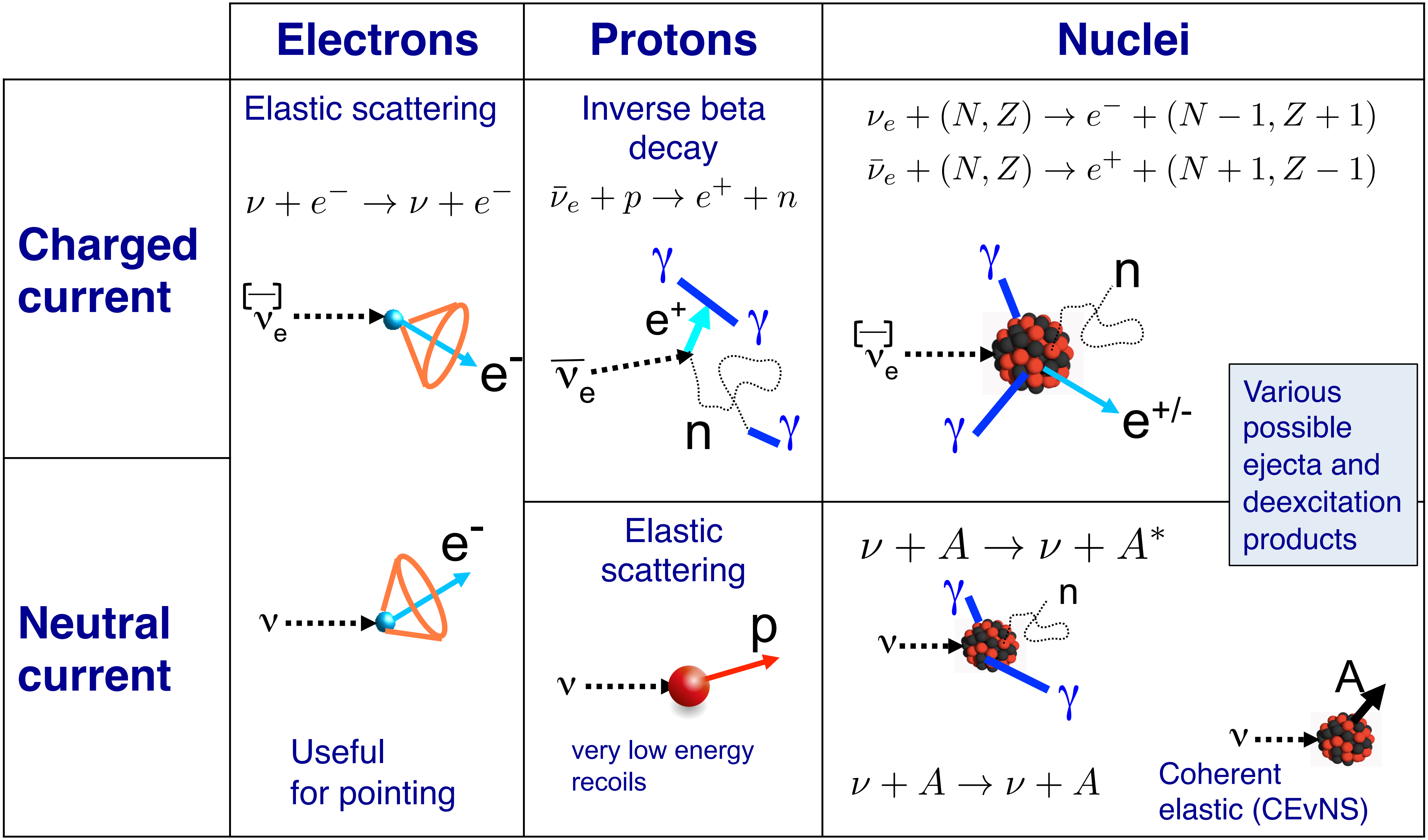
Supernova-relevant neutrino interactions

	Electrons		
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 		
Neutral current	 Useful for pointing		

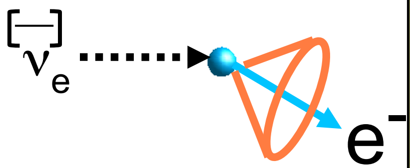
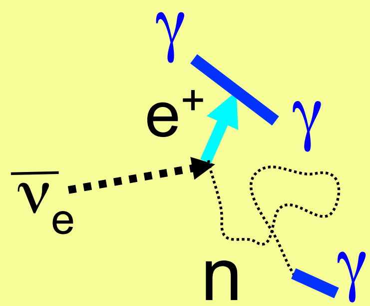
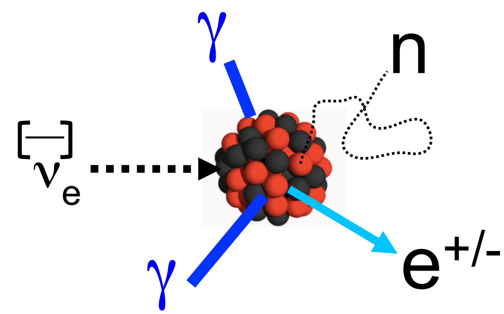
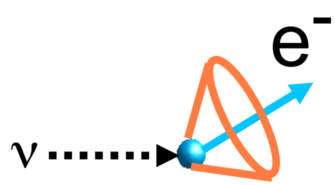
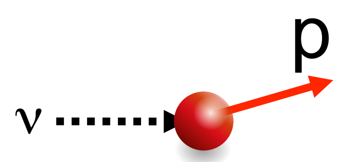
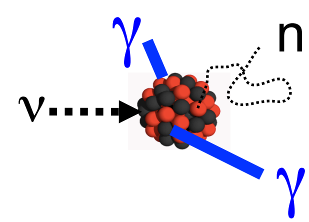
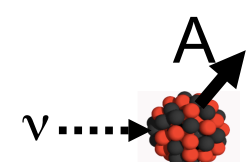
Supernova-relevant neutrino interactions

	Electrons	Protons	
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

Supernova-relevant neutrino interactions

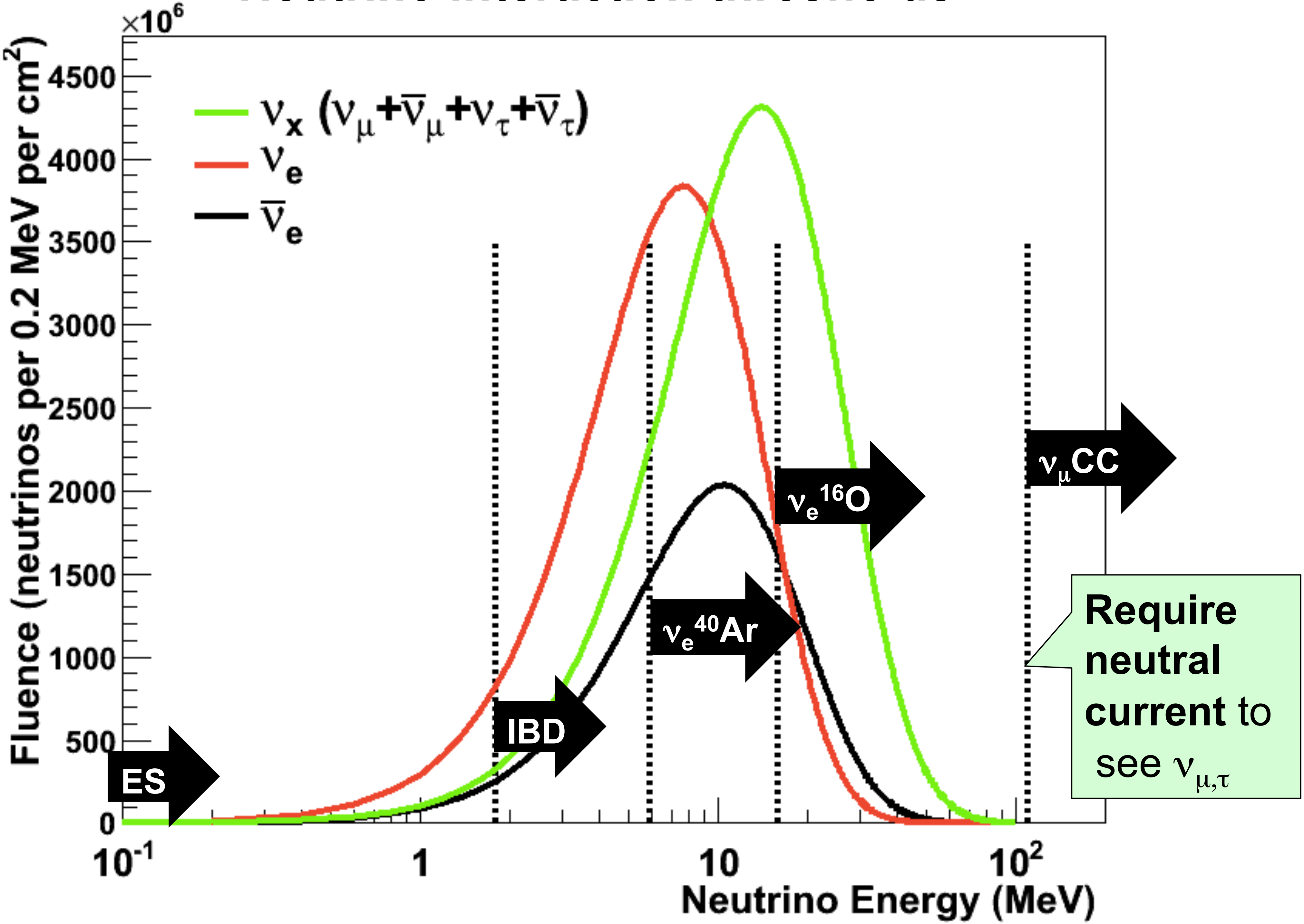


Supernova-relevant neutrino interactions

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

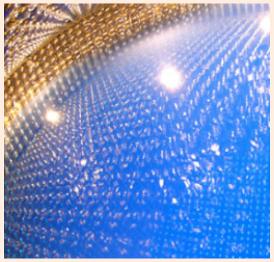
IBD (electron *anti*neutrinos) dominates for current detectors

Neutrino interaction thresholds



Supernova neutrino detector types

Water



$\bar{\nu}_e$

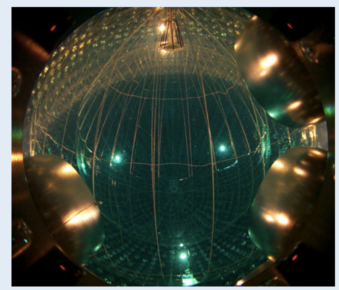
Water, long-string

$\bar{\nu}_e$

Argon

ν_e

Scintillator

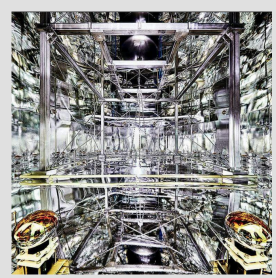


$\bar{\nu}_e$

Lead

ν_e

DM (Noble liquid)

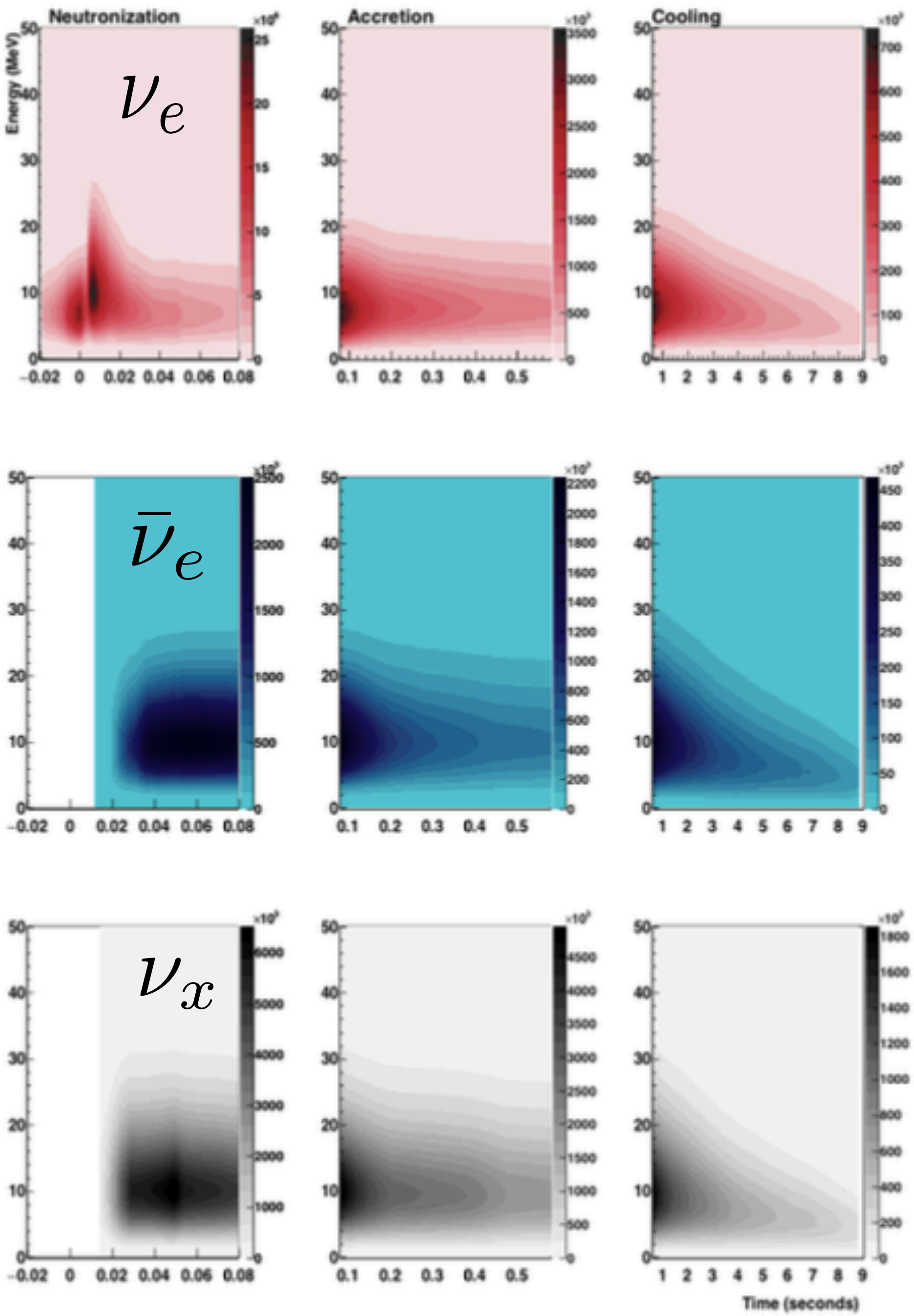


ν_x

For supernova neutrinos, the more the merrier!

What we *want* to measure

Neutrino fluxes vs E, t



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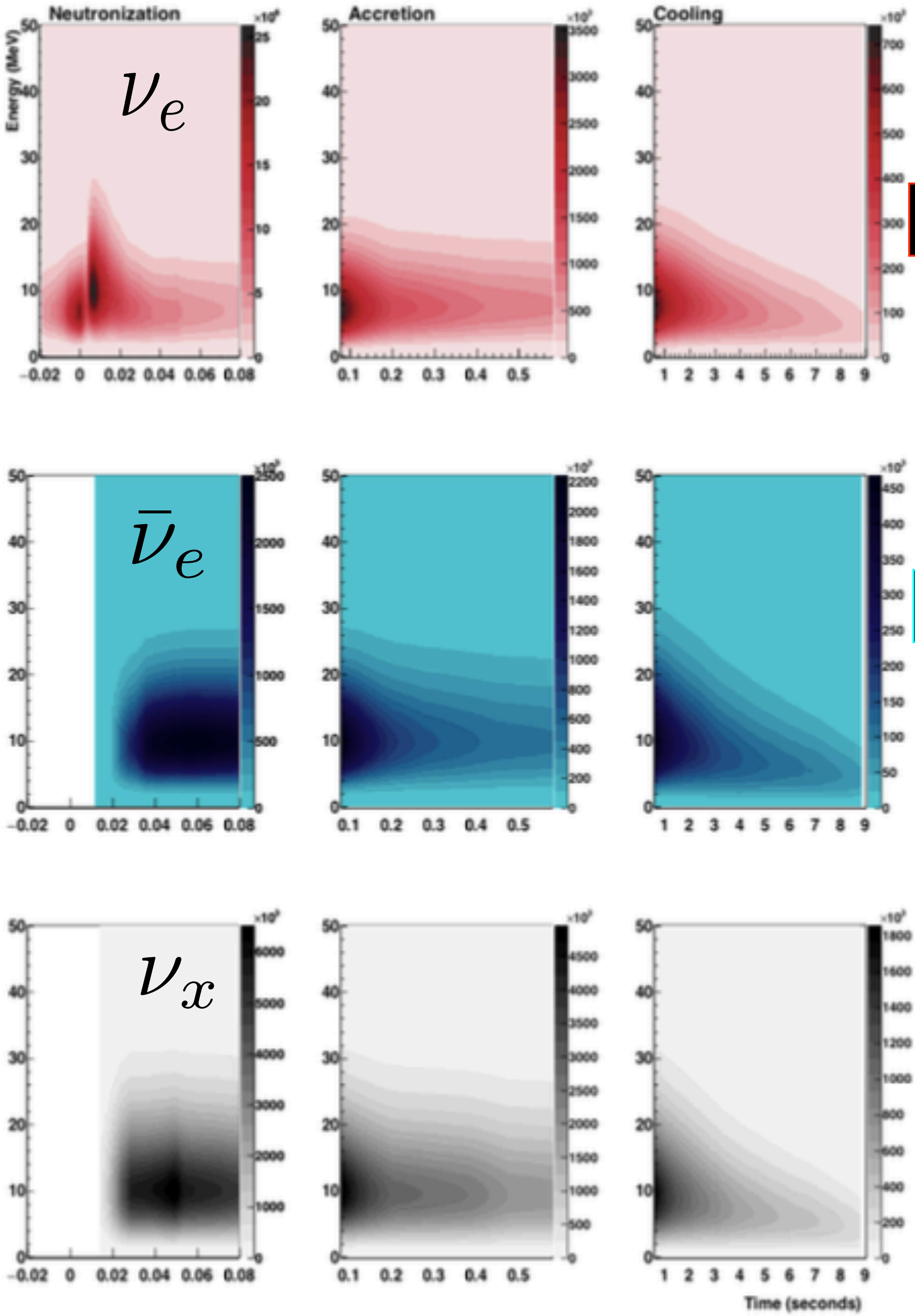
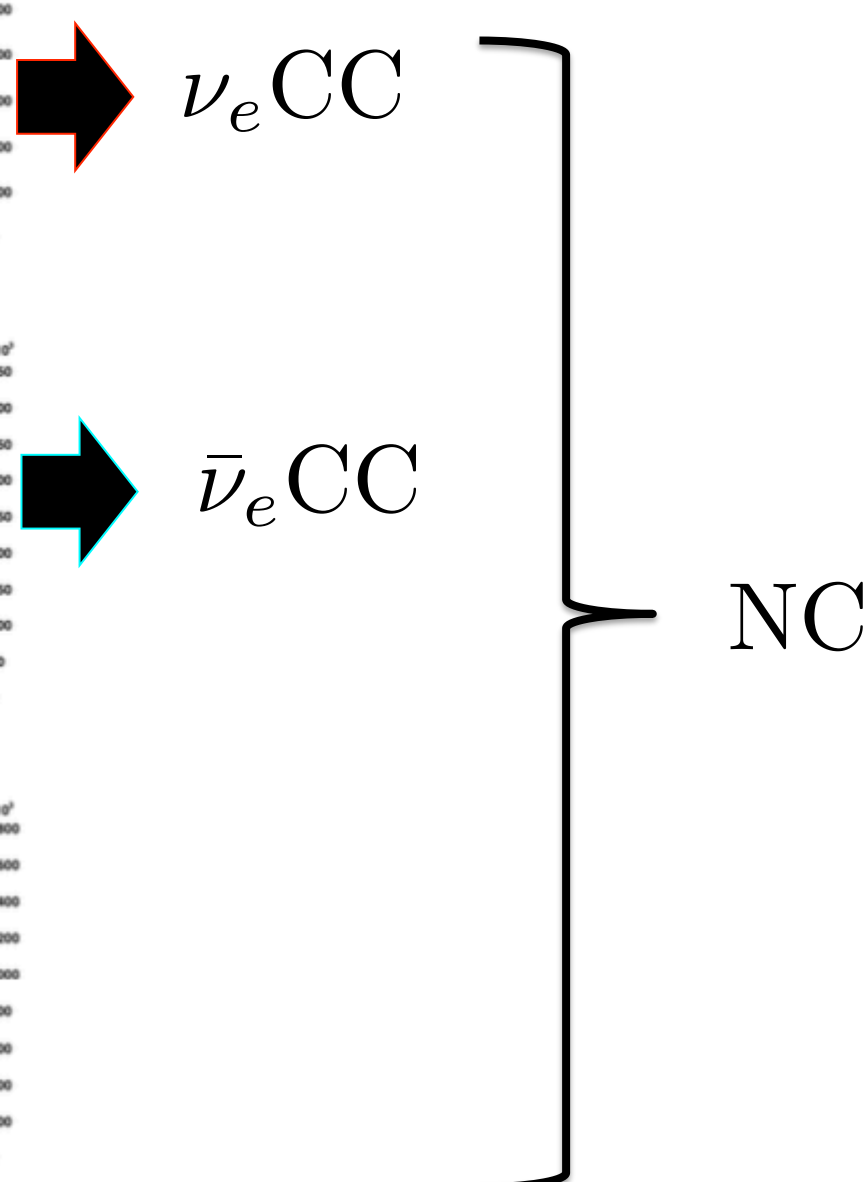
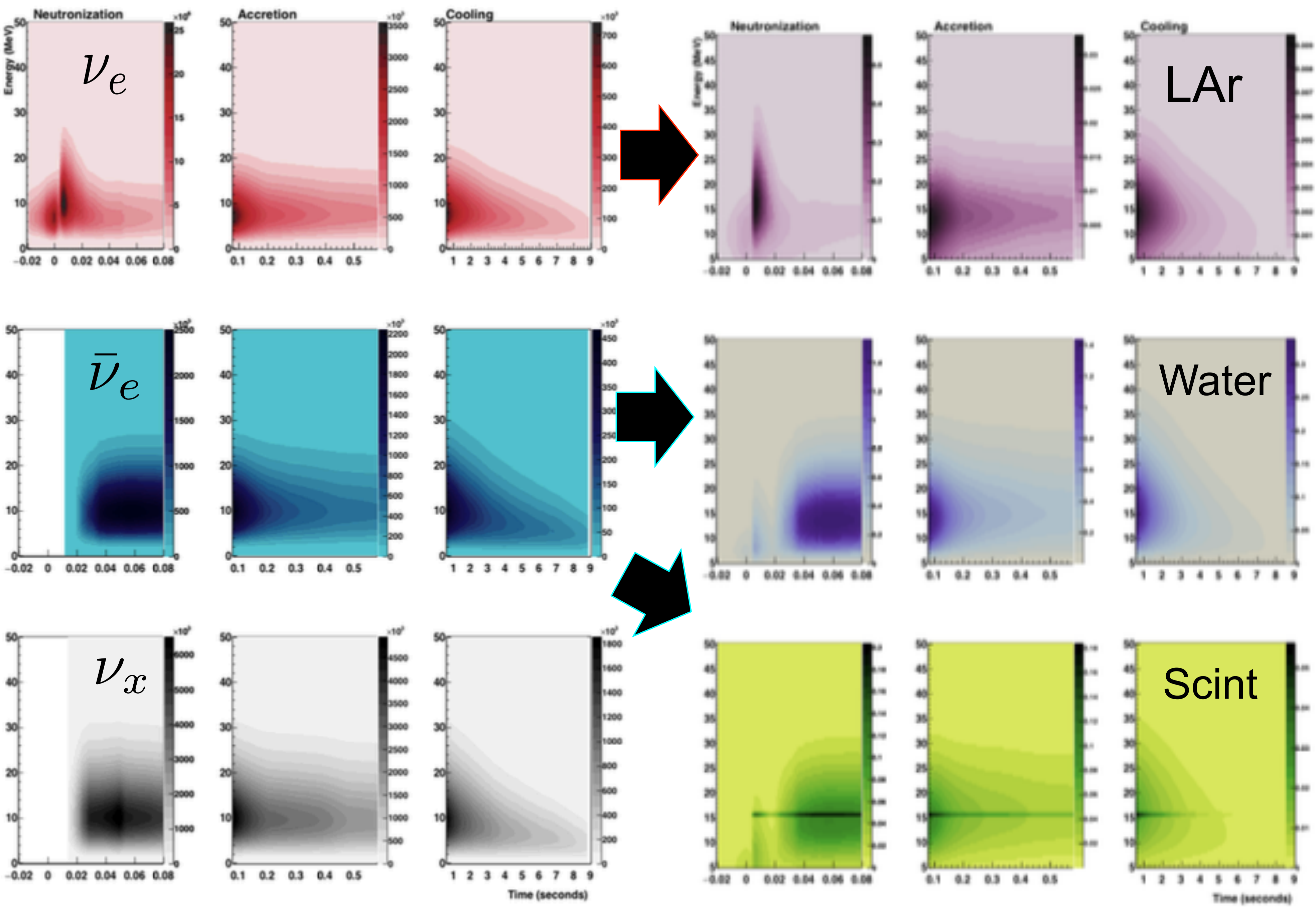


What we *can* measure

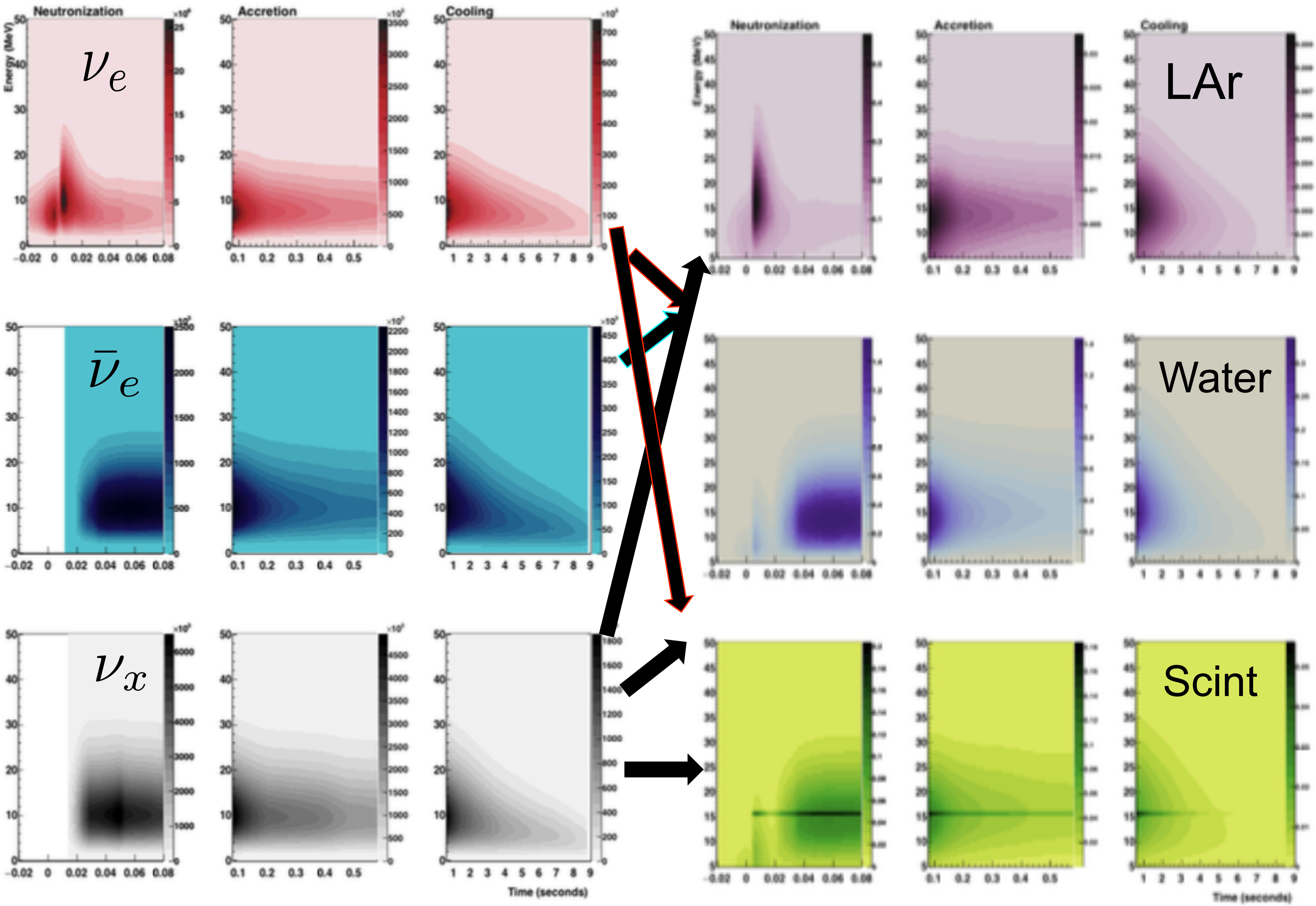
Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)



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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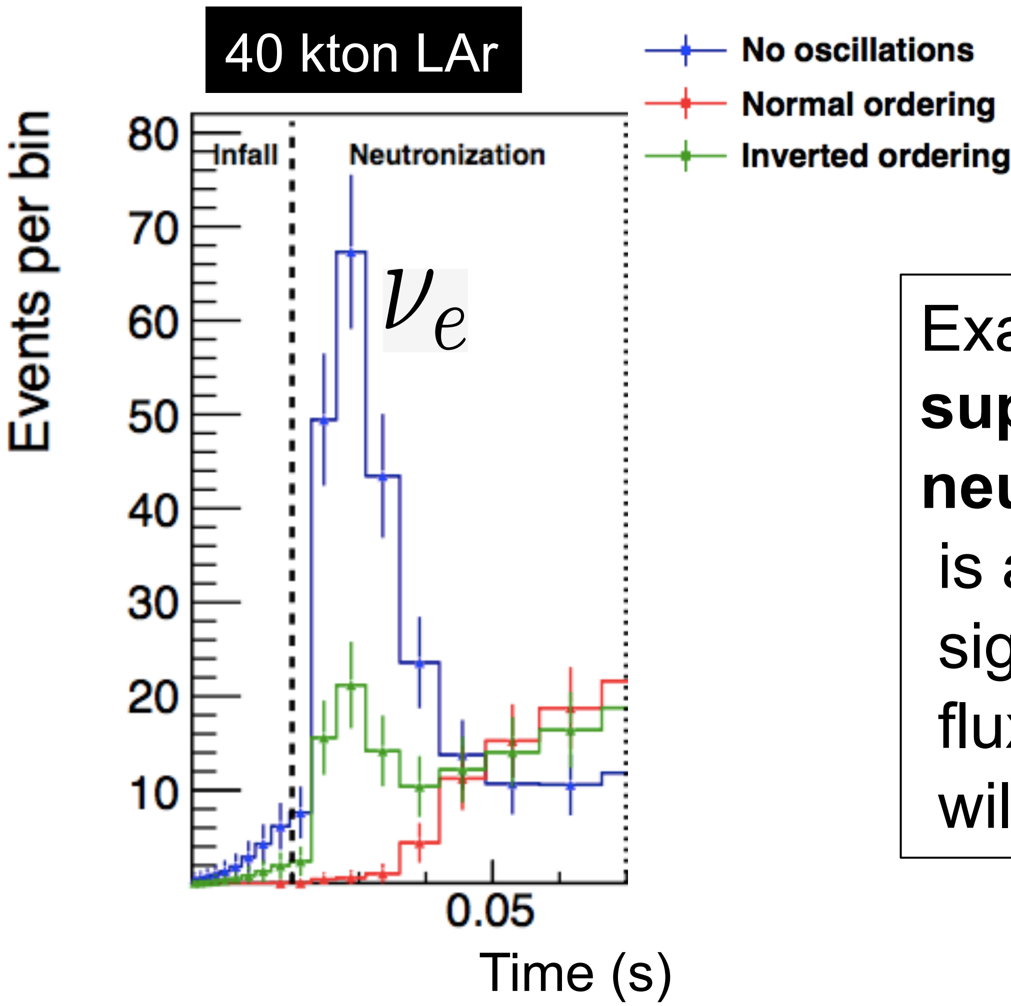

Example:
suppression of the neutronization burst ν_e is a robust mass ordering signature; knowing total flux via tagged NC will help to interpret

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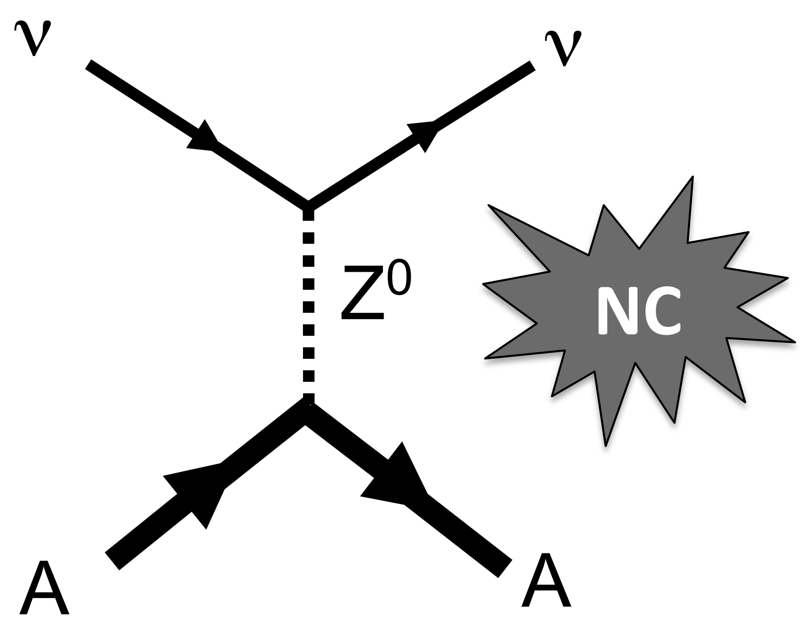
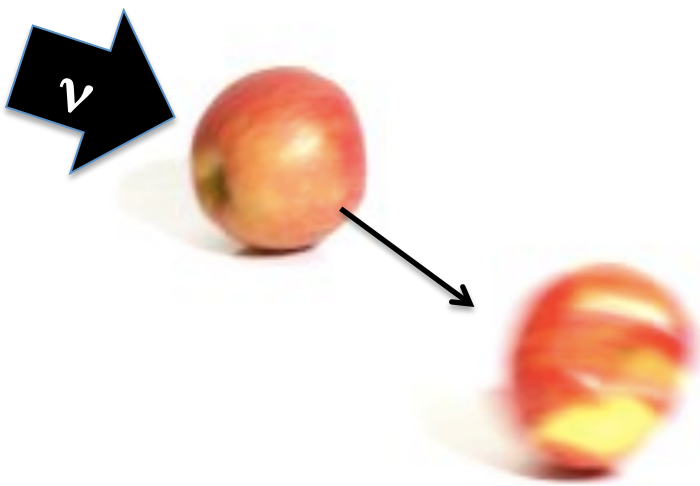
Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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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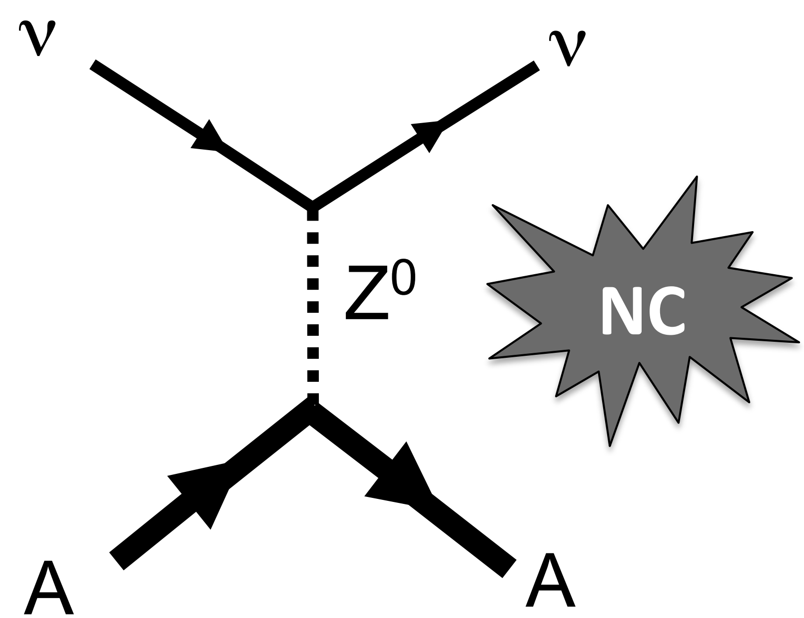

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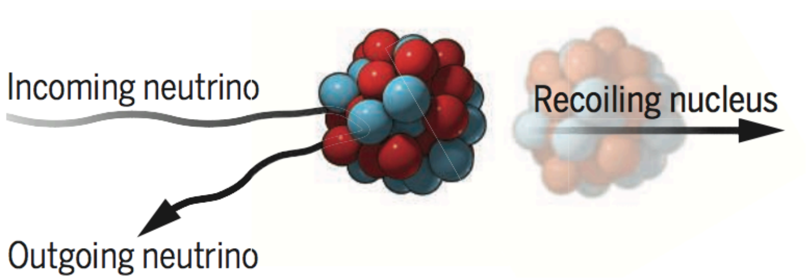


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn]   A: no. of constituents

Image: J. Link *Science* Perspectives

See also J. Newstead slides, NMNM 3

`\begin{aside}`

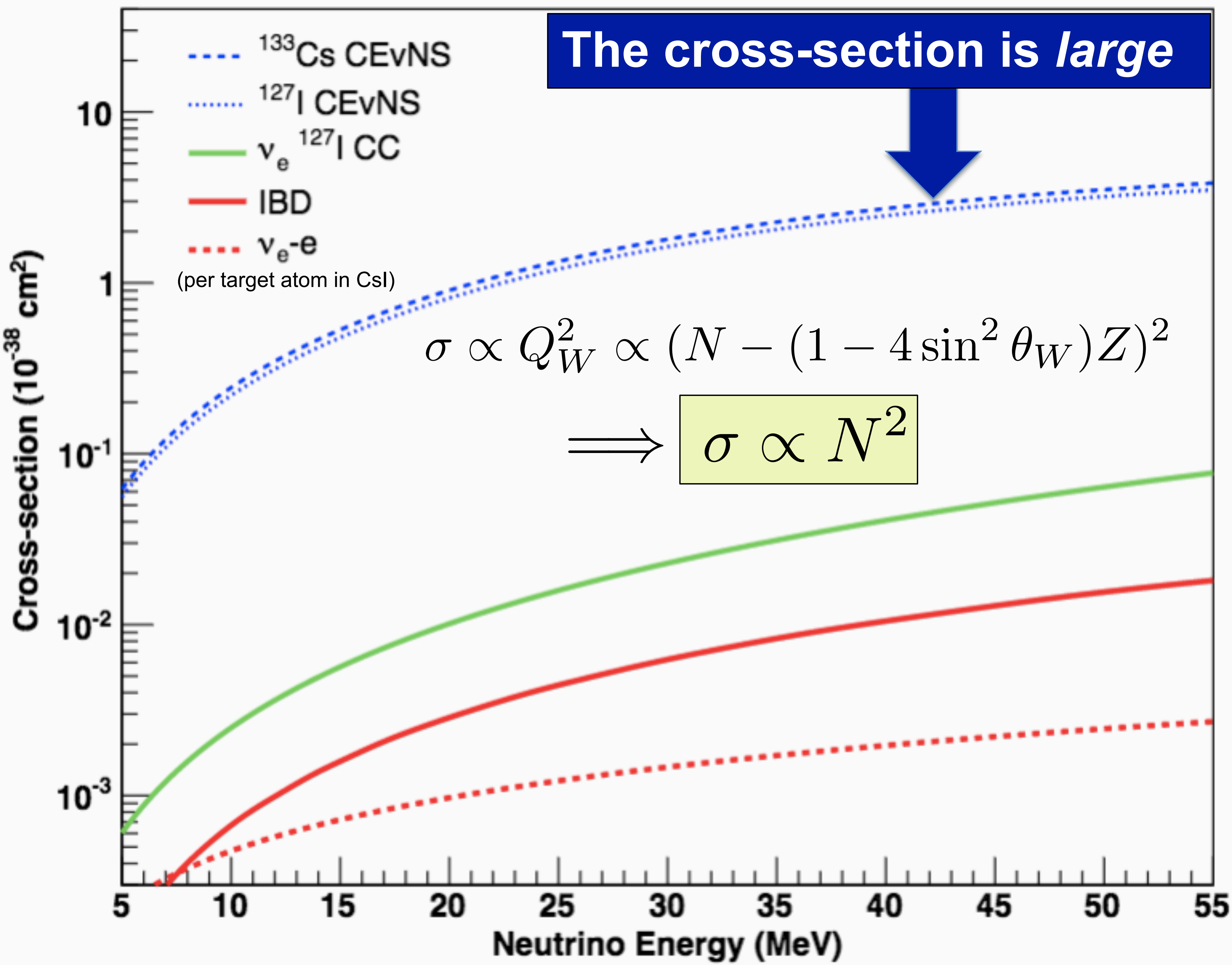
Literature has CNS, CNNS, CENNS, ...

- I prefer including “E” for “elastic”... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I’m told “NN” means “nucleon-nucleon” to nuclear types
- CEνNS is a possibility but those internal Greek letters are annoying

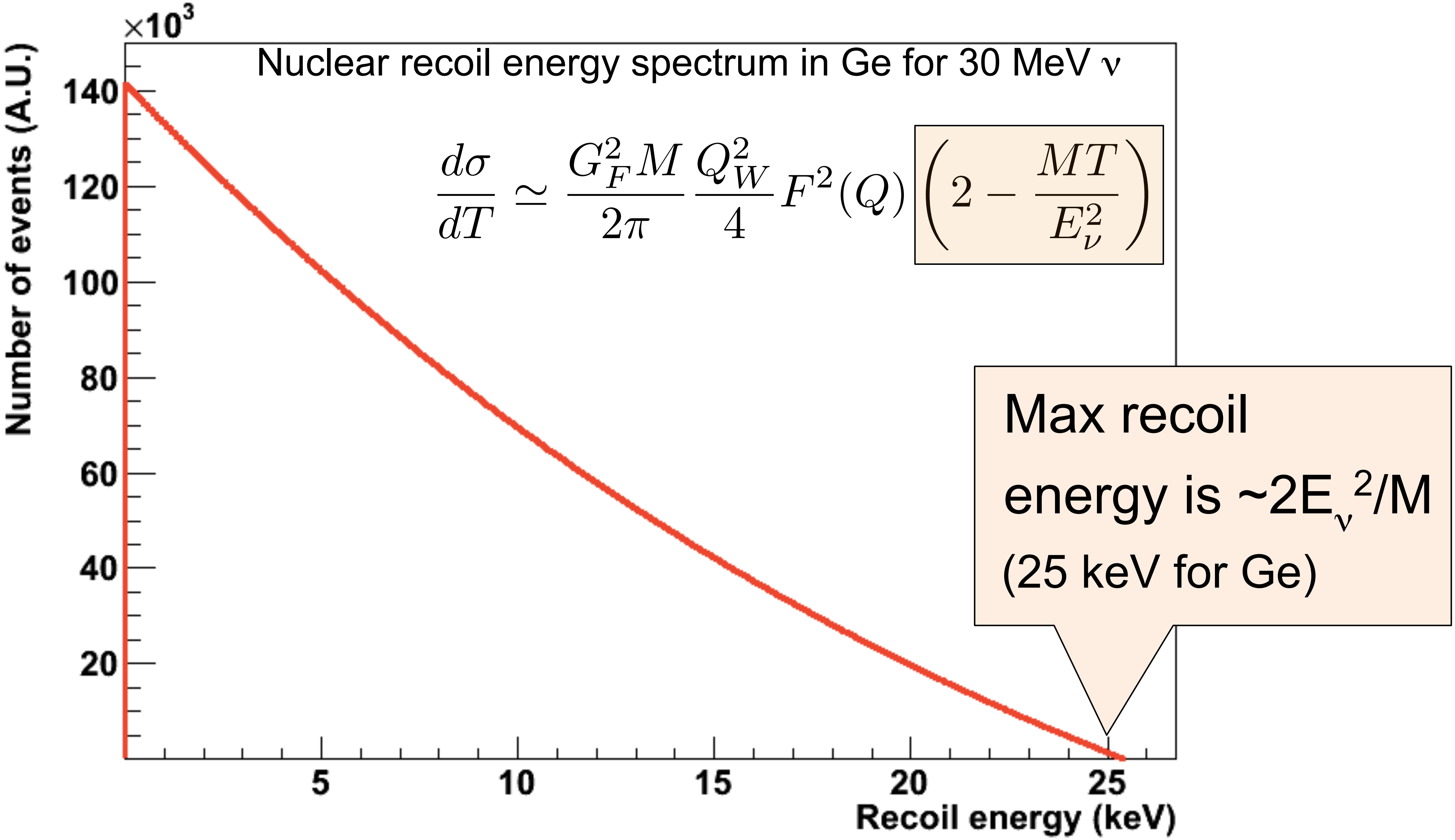
➔ **CEvNS**, pronounced “sevens”...

spread the meme!

`\end{aside}`

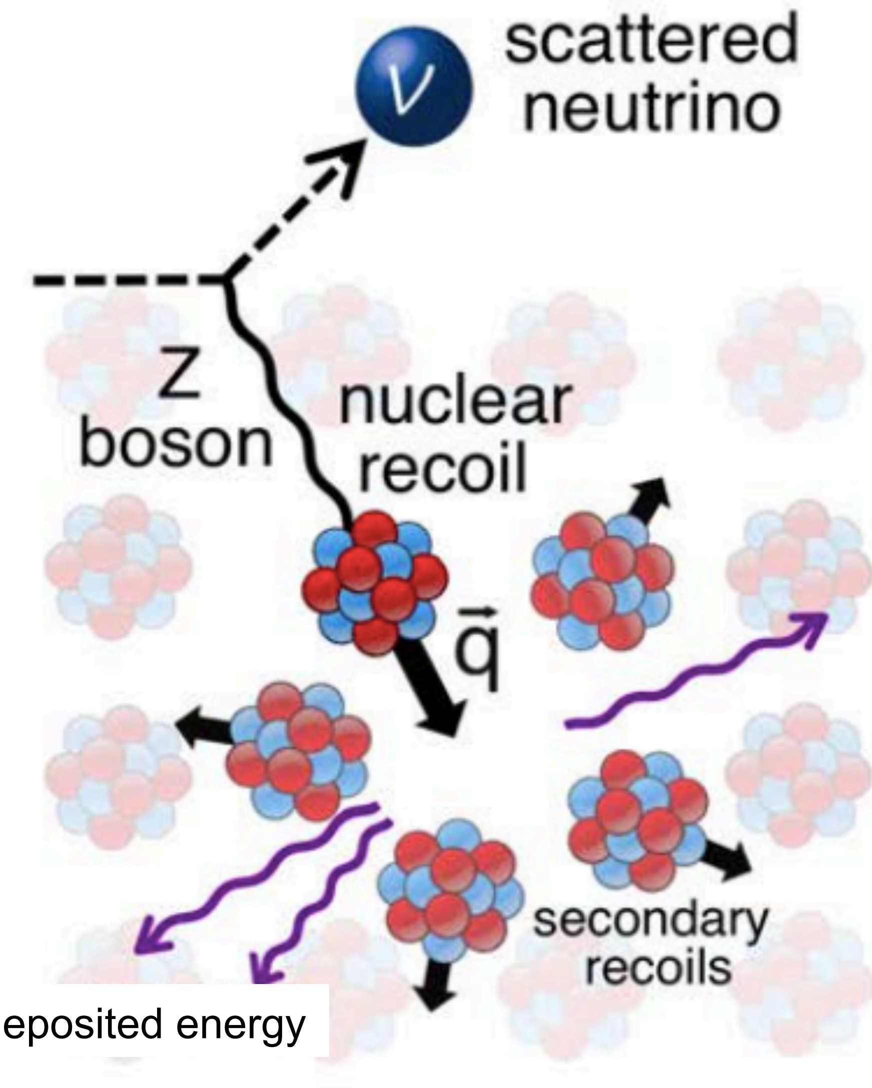

The cross-section is *large*
^{133}Cs CEvNS
^{127}I CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
(per target atom in CsI)
$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$
$$\Longrightarrow \sigma \propto N^2$$
Cross-section (10^{-38} cm^2)
Neutrino Energy (MeV)
10
1
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
25
30
35
40
45
50
55

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



The only experimental signature:

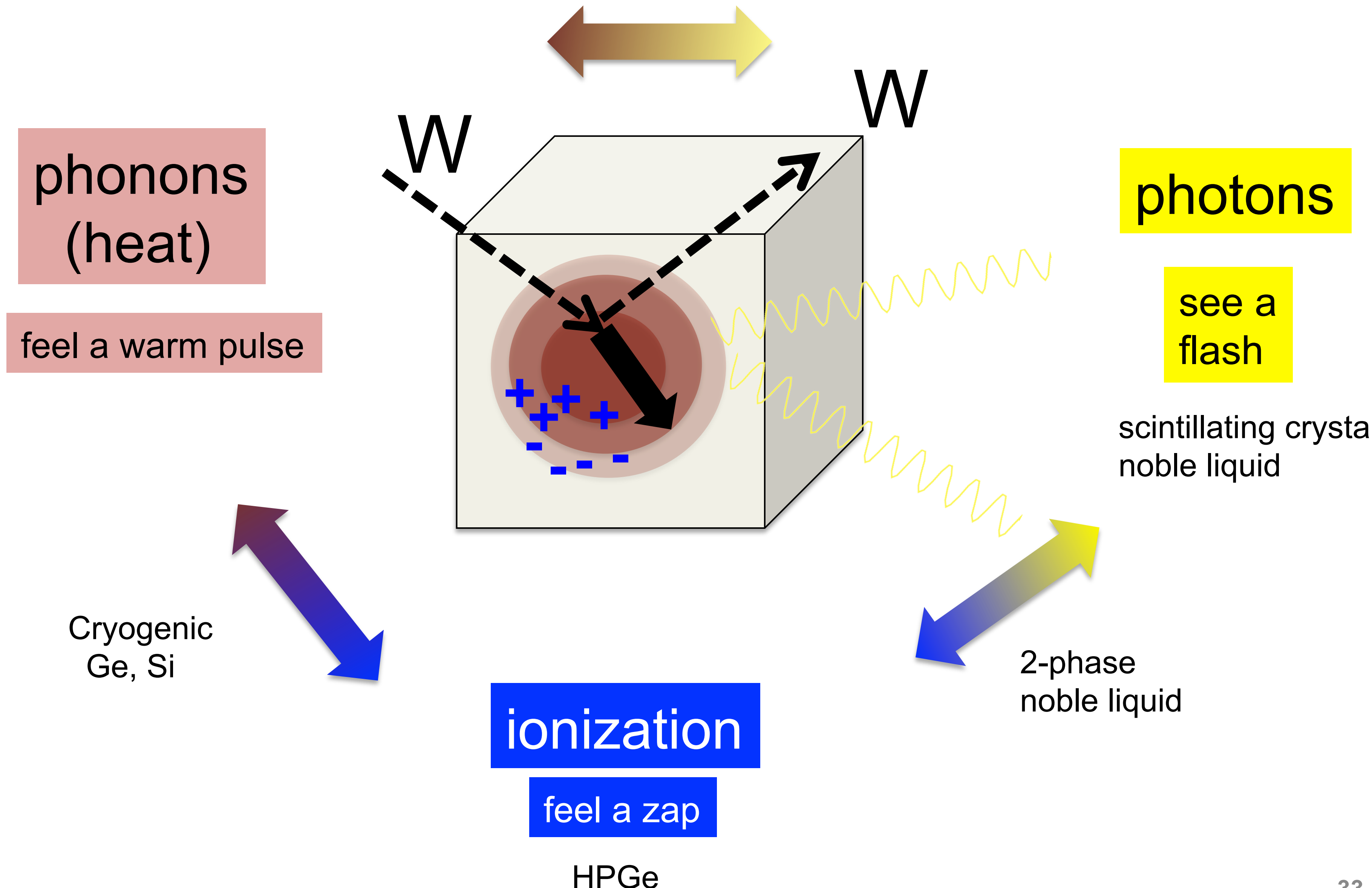
tiny energy deposited by nuclear recoils in the target material



➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

Now, ***detecting*** the tiny kick of the neutrino...

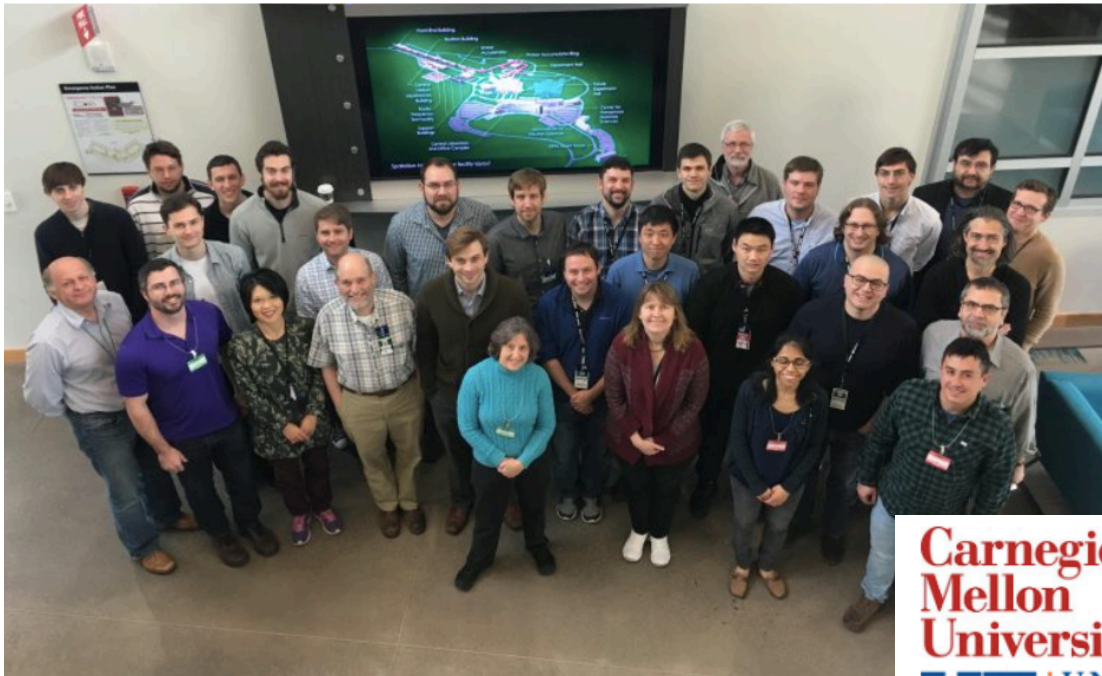
This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors



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

The COHERENT collaboration

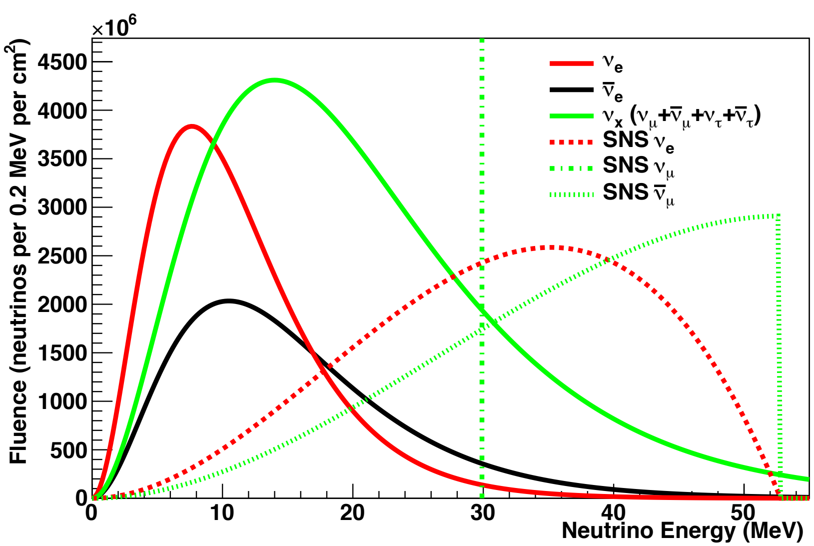
http://sites.duke.edu/coherent

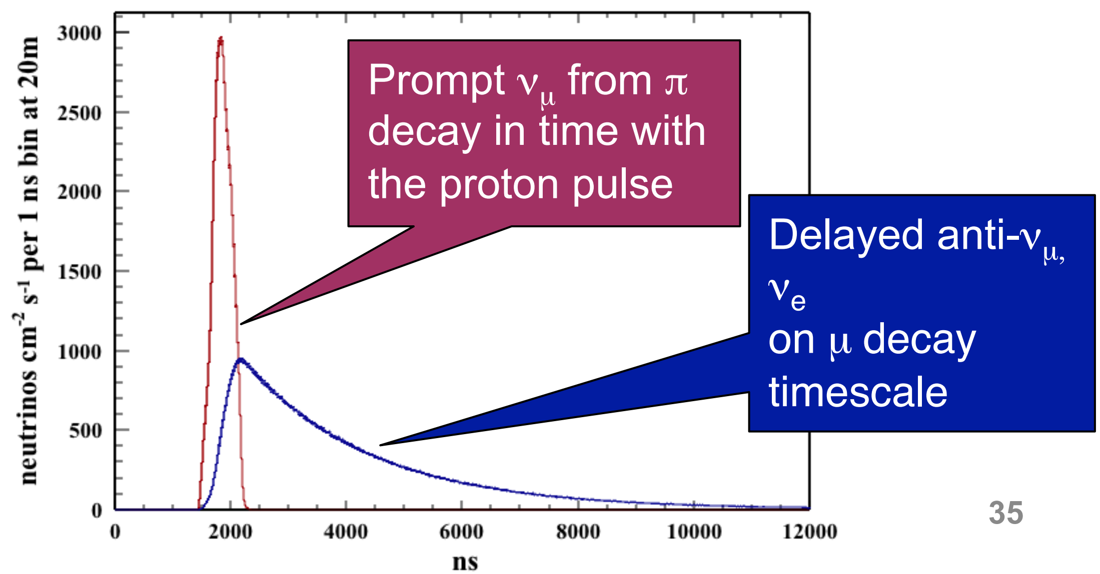


~80 members,
19 institutions
4 countries

arXiv:1509.08702

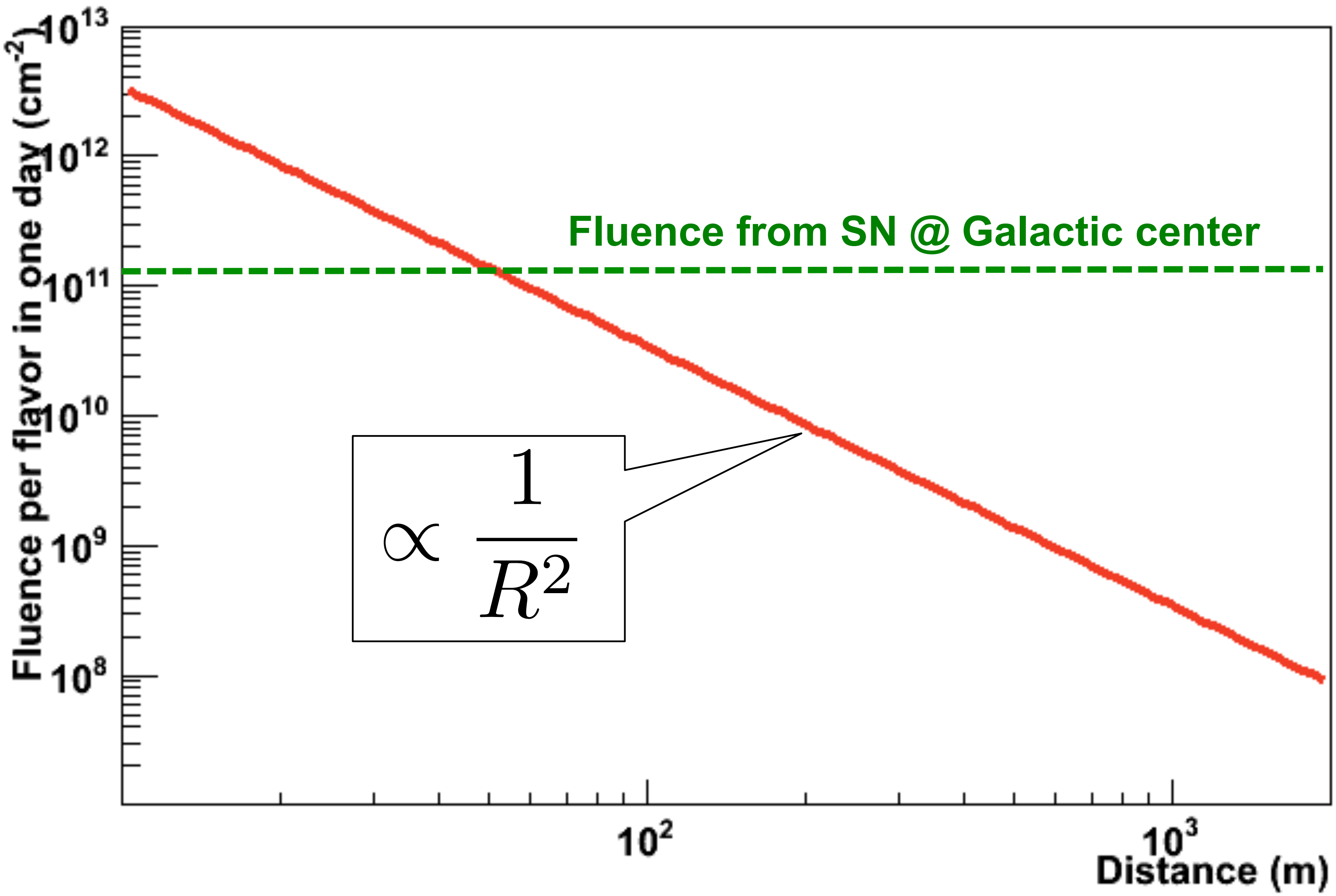
Free supernova-like, pulsed neutrinos!





Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

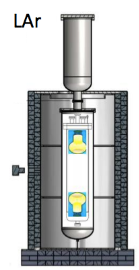
(or 0.2 microsupernovae per pulse, 60 Hz of pulses)

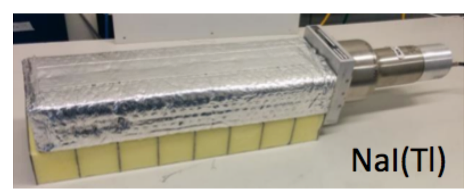


COHERENT CEvNS Detectors

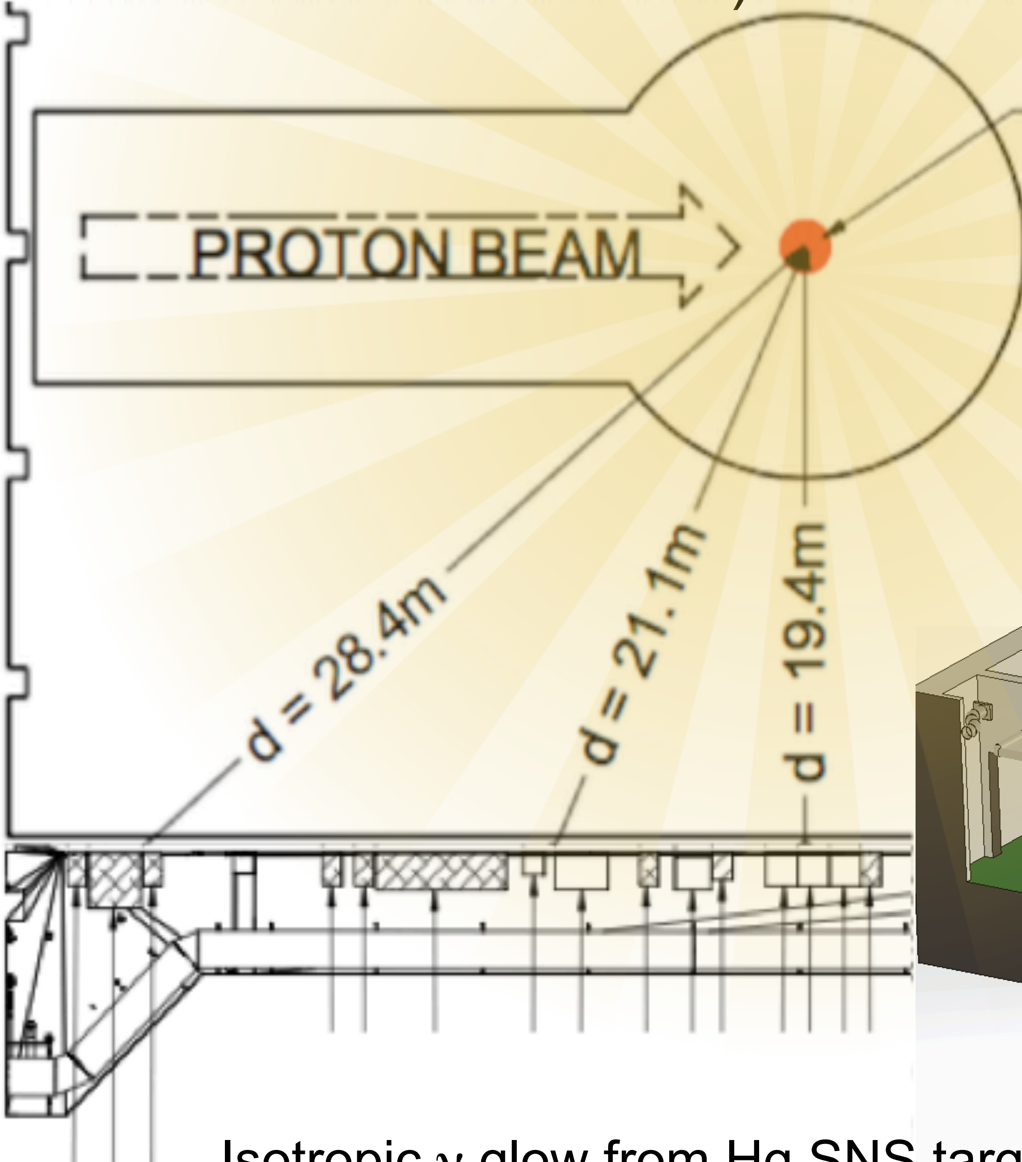
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal (flash)	14.6	19.3	6.5
Ge	HPGe PPC (zap)	10	22	5
LAr	Single-phase (flash)	22	29	20
NaI[Tl]	Scintillating crystal (flash)	185*/ 2000	28	13

Multiple detectors for N^2 dependence of the cross section

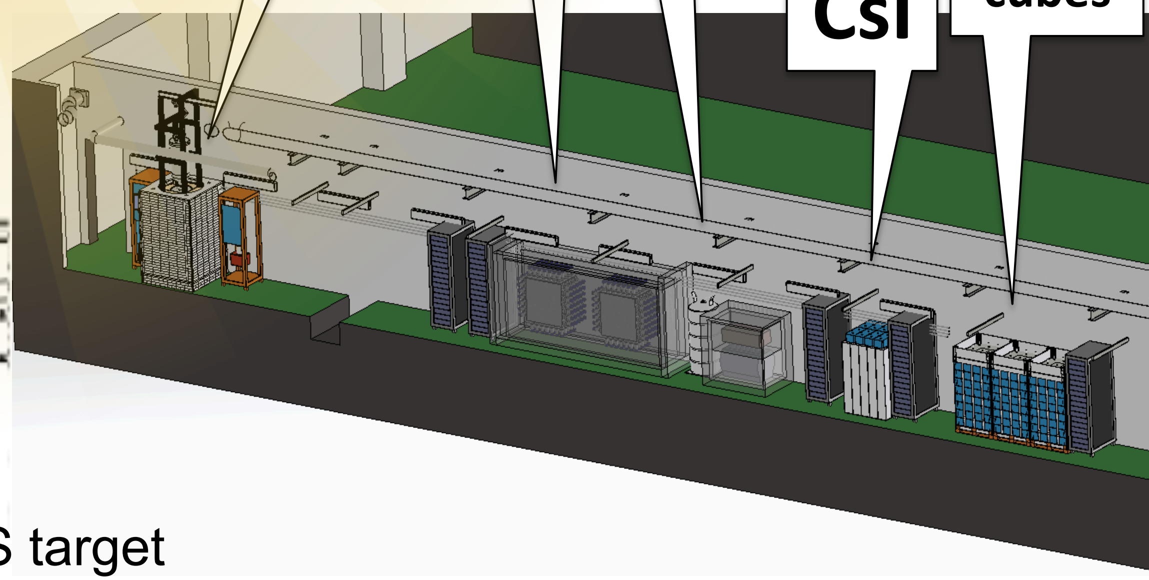




Siting for deployment in SNS basement
(measured neutron backgrounds low,
~ 8 mwe overburden)

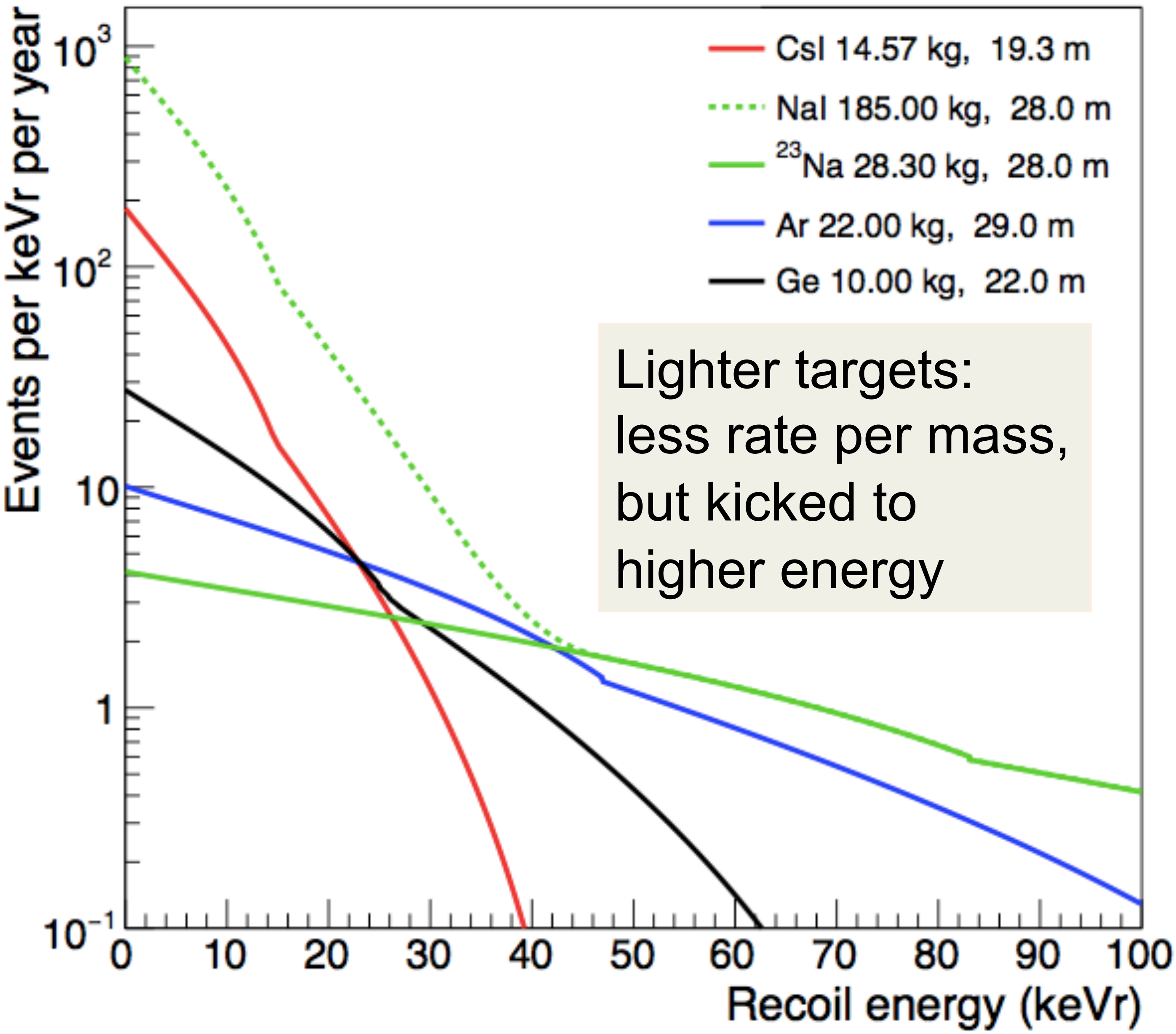


View looking
down "Neutrino Alley"



Isotropic ν glow from Hg SNS target

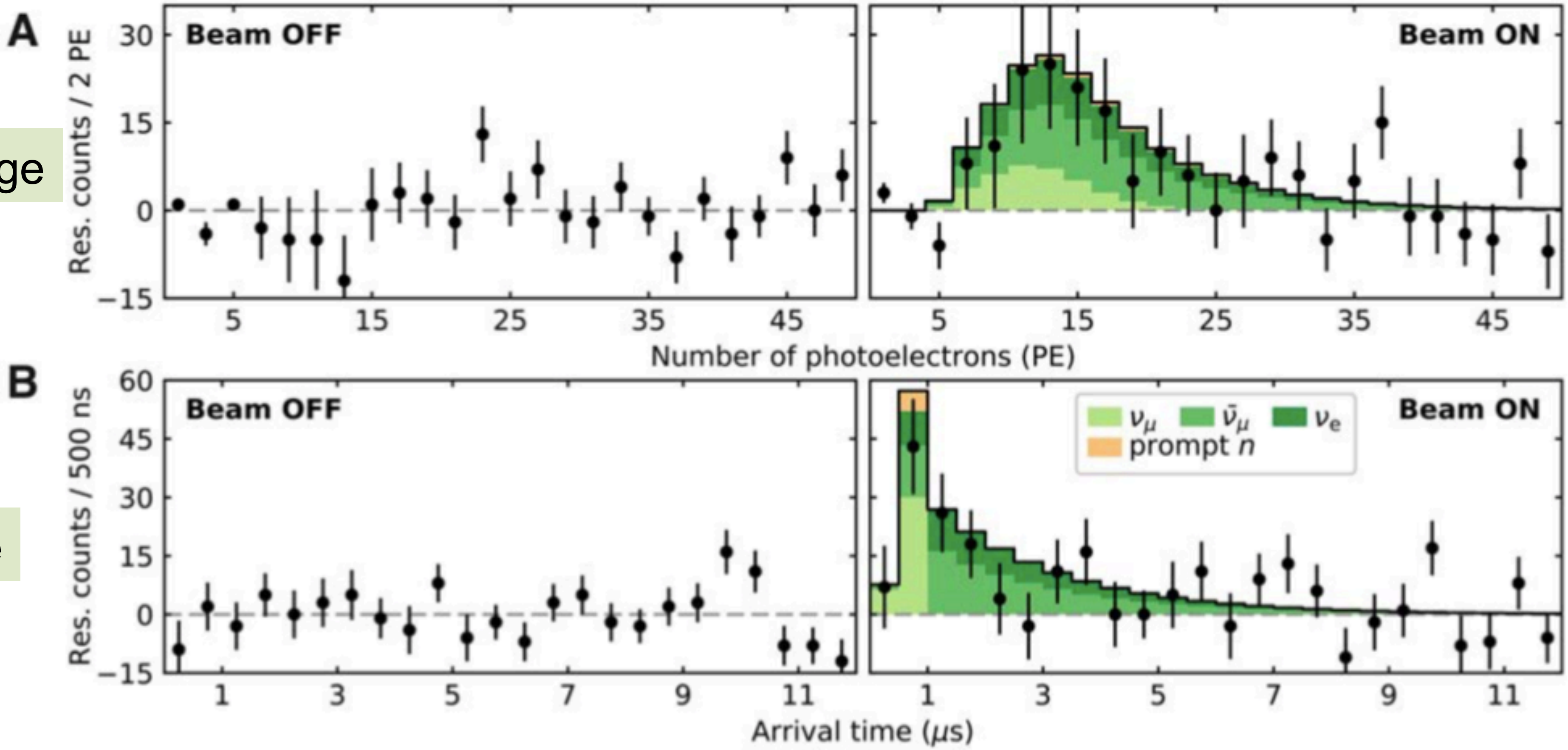
Expected recoil energy distribution



First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time



Observation of coherent elastic neutrino-nucleus scattering

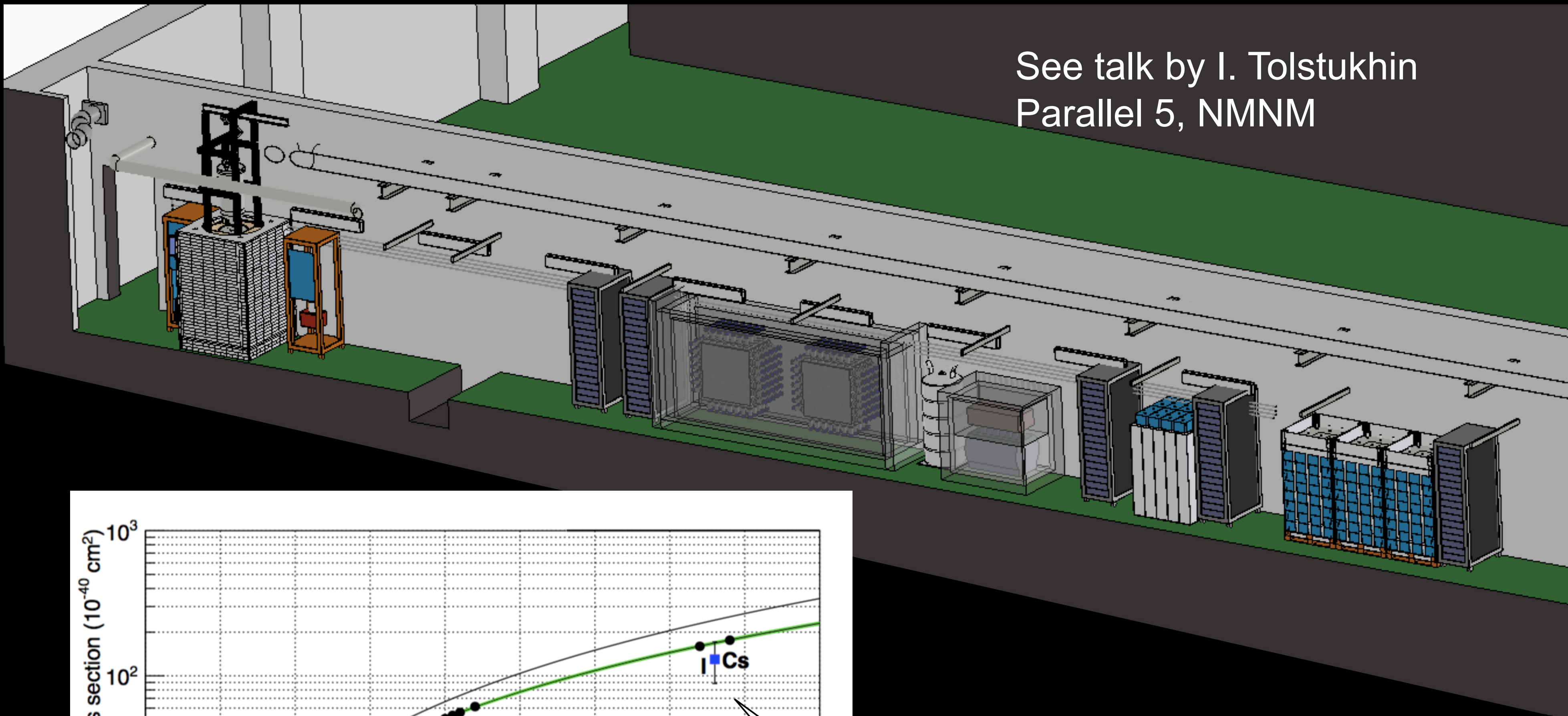
D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...
+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

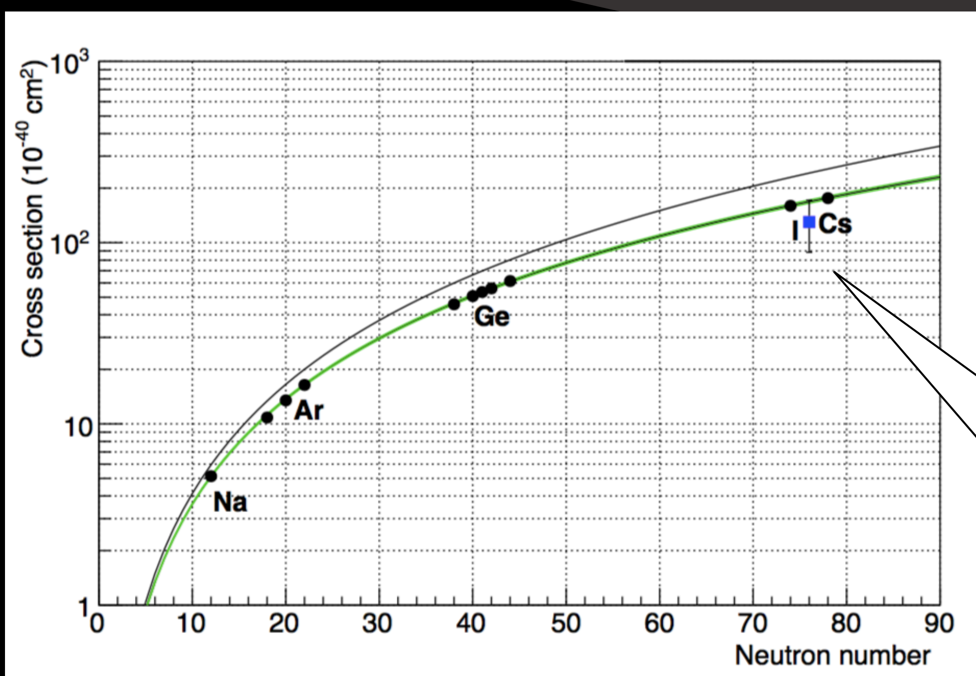
Peer Reviewed
← see details

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

What's Next for COHERENT?



See talk by I. Tolstukhin
Parallel 5, NMNM



One measurement so far! Want to map out N^2 dependence

OUTLINE

- **Neutrinos from Core-Collapse Supernovae**
  - The nature of the signal and what it can tell us
  - Detection of supernova neutrinos
- **Coherent elastic neutrino-nucleus scattering** (CEvNS)
  - The nature of the process
  - Measurement status and prospects
- **CEvNS and Supernovae**
  - CEvNS as a supernova process
  - CEvNS as a supernova detection channel

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)

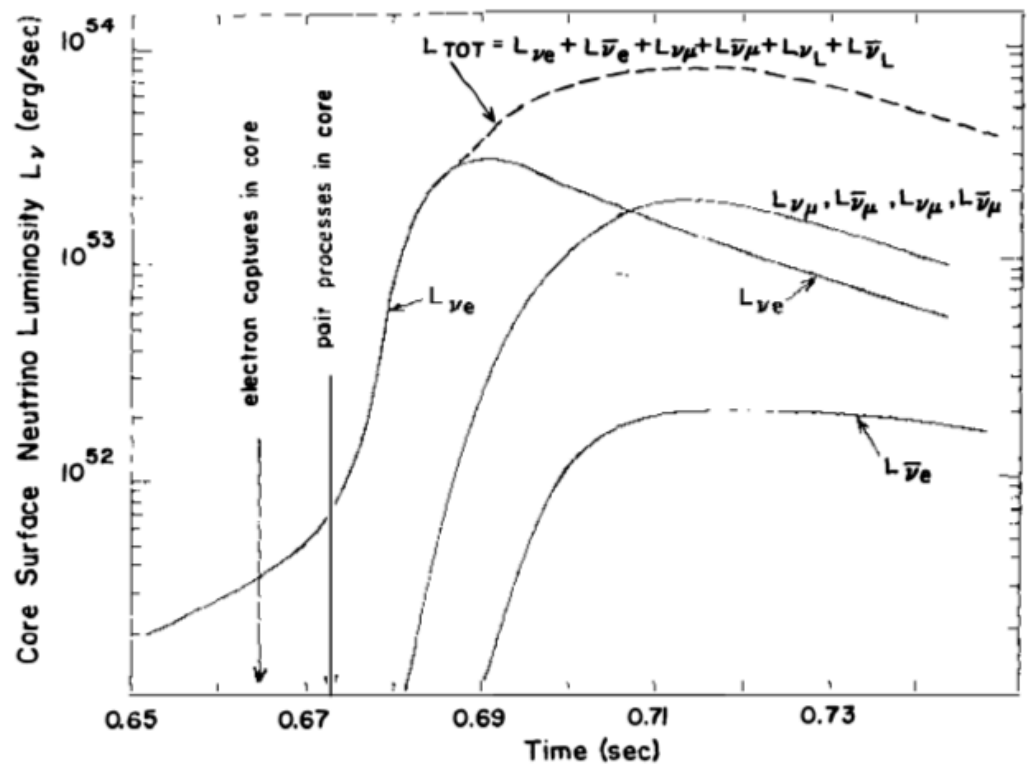
Recognized early as a key process in the core collapse and explosion

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

THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

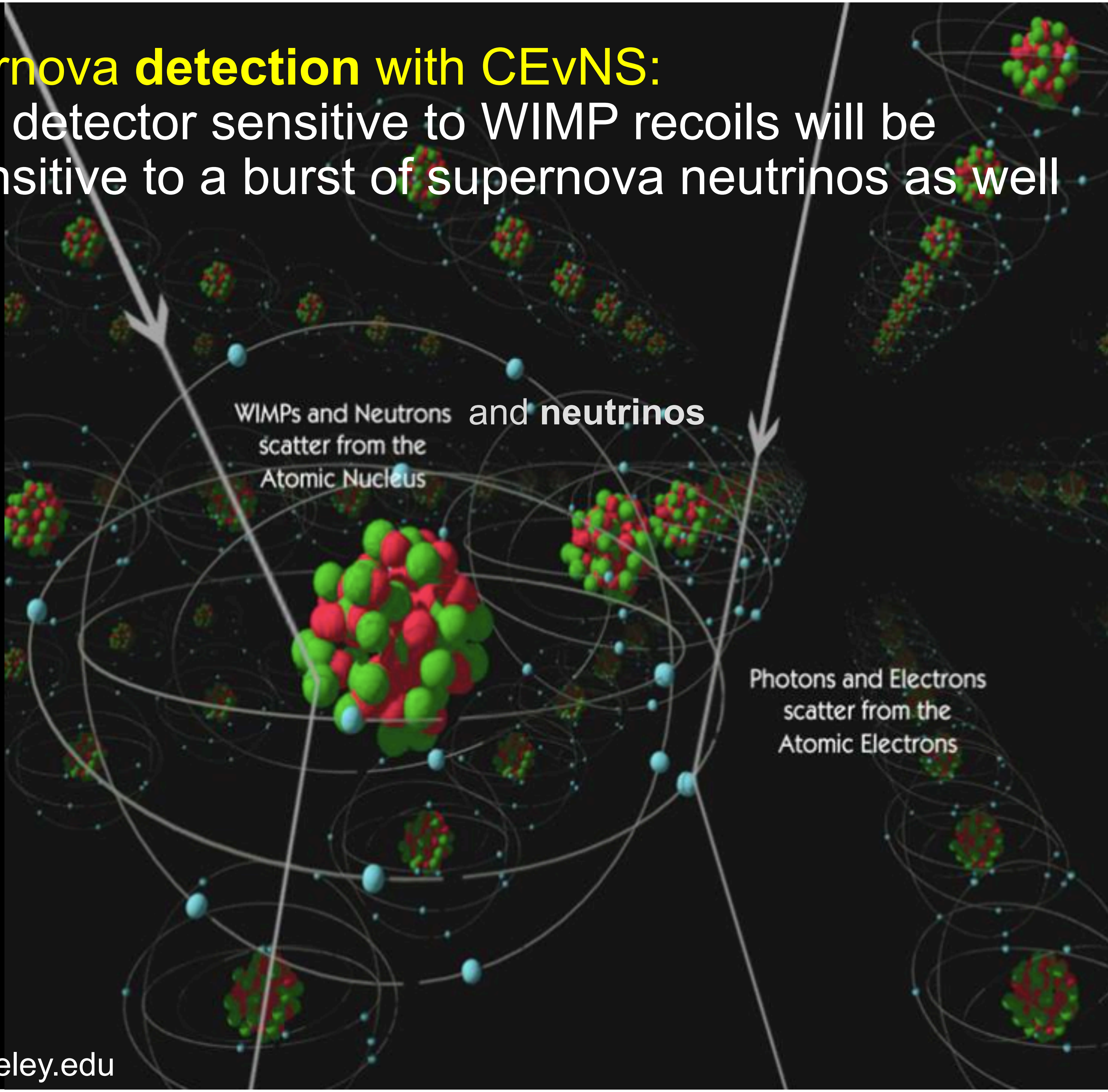
Daniel Z. Freedman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

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



Supernova **detection** with CEvNS:

any detector sensitive to WIMP recoils will be sensitive to a burst of supernova neutrinos as well



cdms.berkeley.edu

First suggestion:

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:

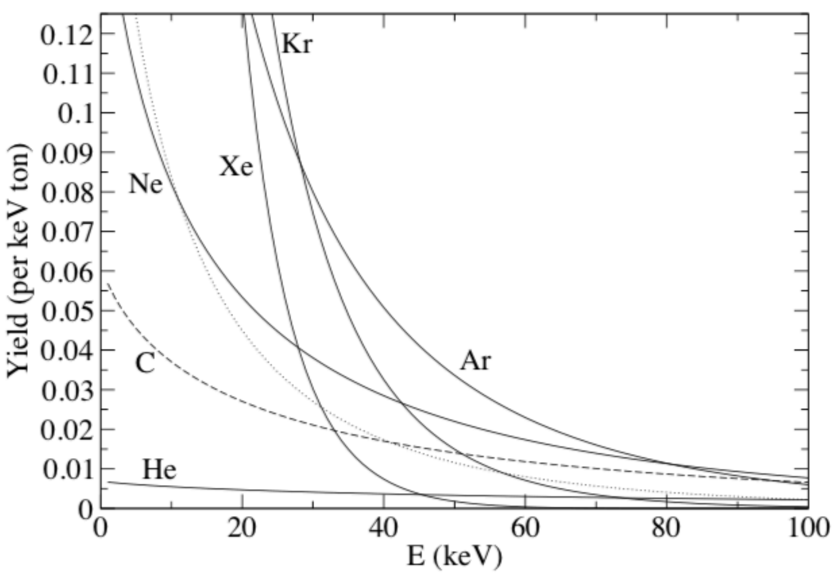
PHYSICAL REVIEW D **68**, 023005 (2003)

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

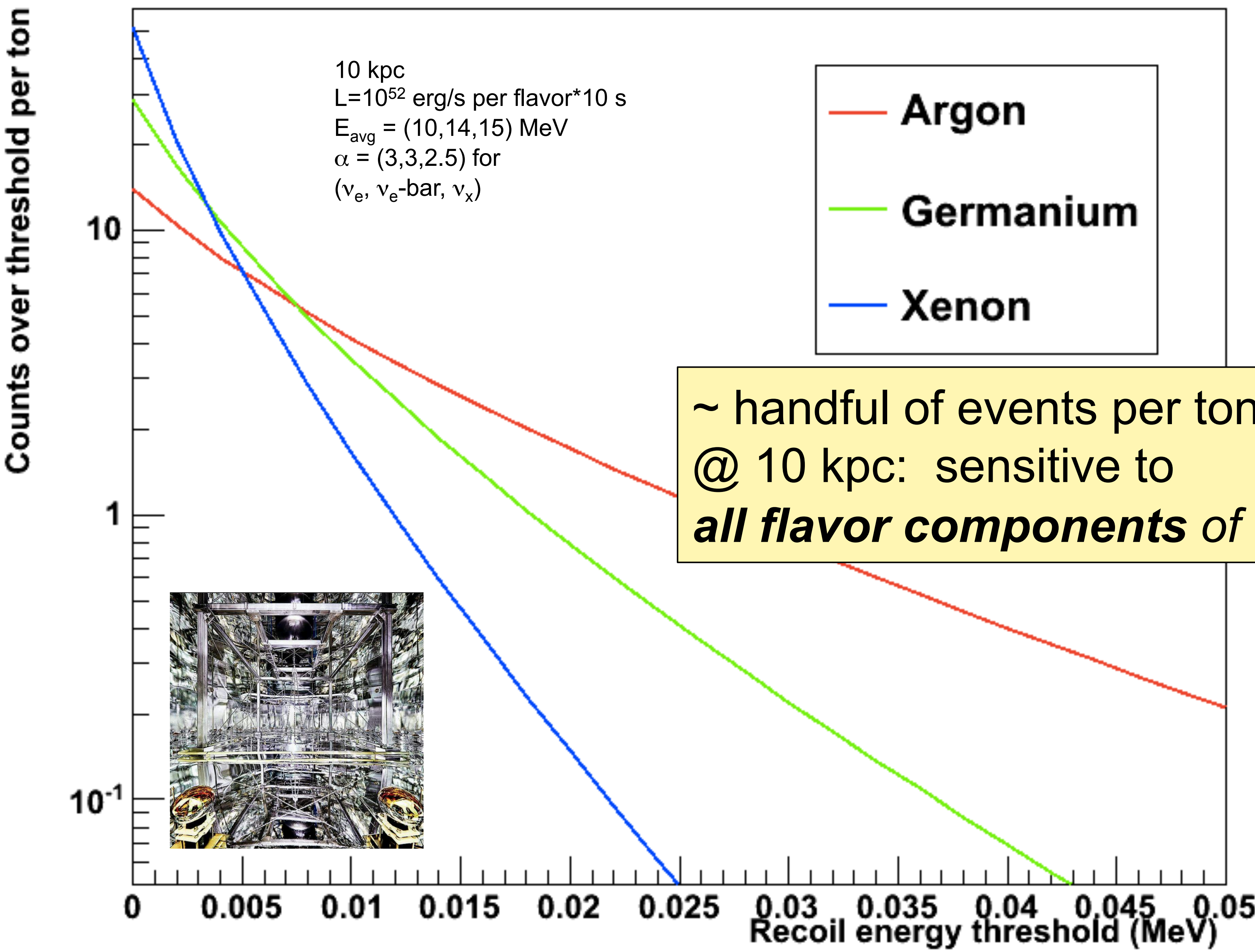
K. J. Coakley
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

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



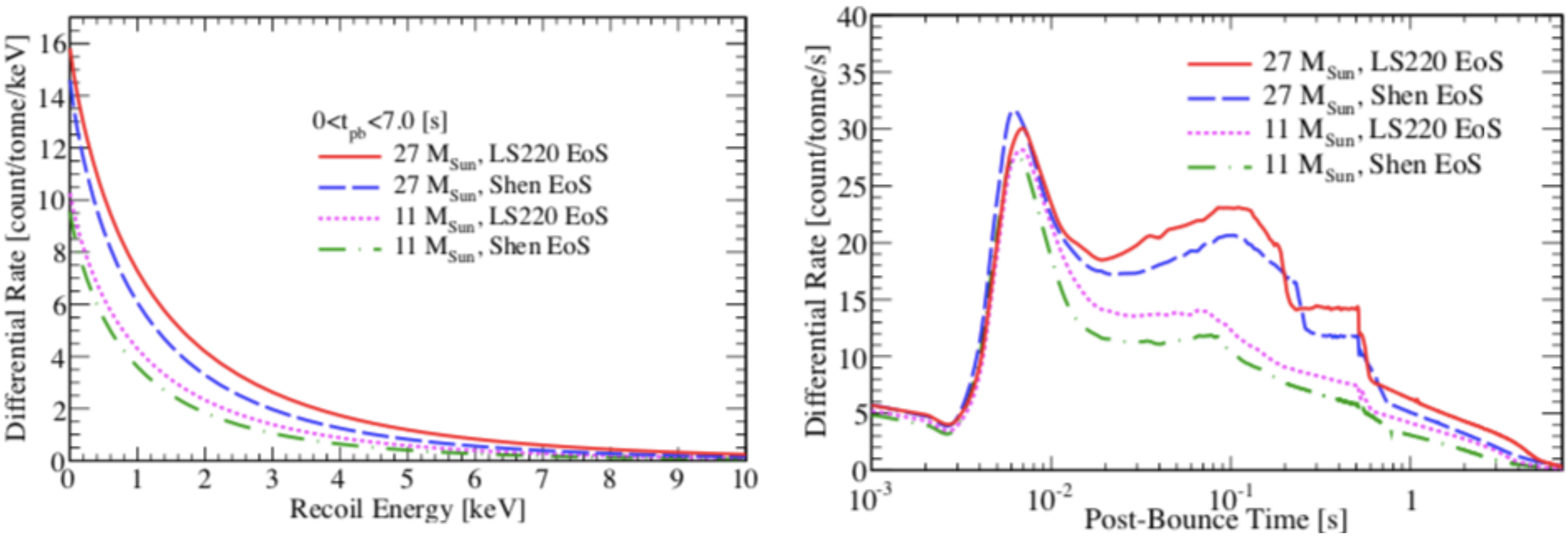
- WIMP DM detectors tend to be low background, low threshold (10's of keV or less)
- Scalability to large mass is desirable

Supernova neutrinos in tonne-scale DM detectors



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

Information on the **all-flavor neutrino flux**, and on the **all-flavor neutrino spectrum**, in both integrated counts and recoil spectrum

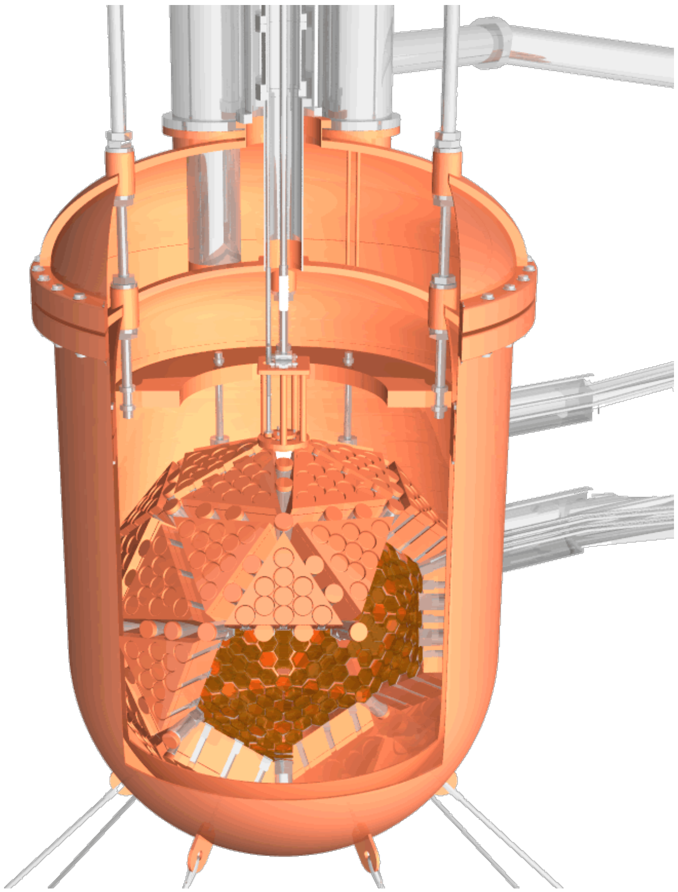


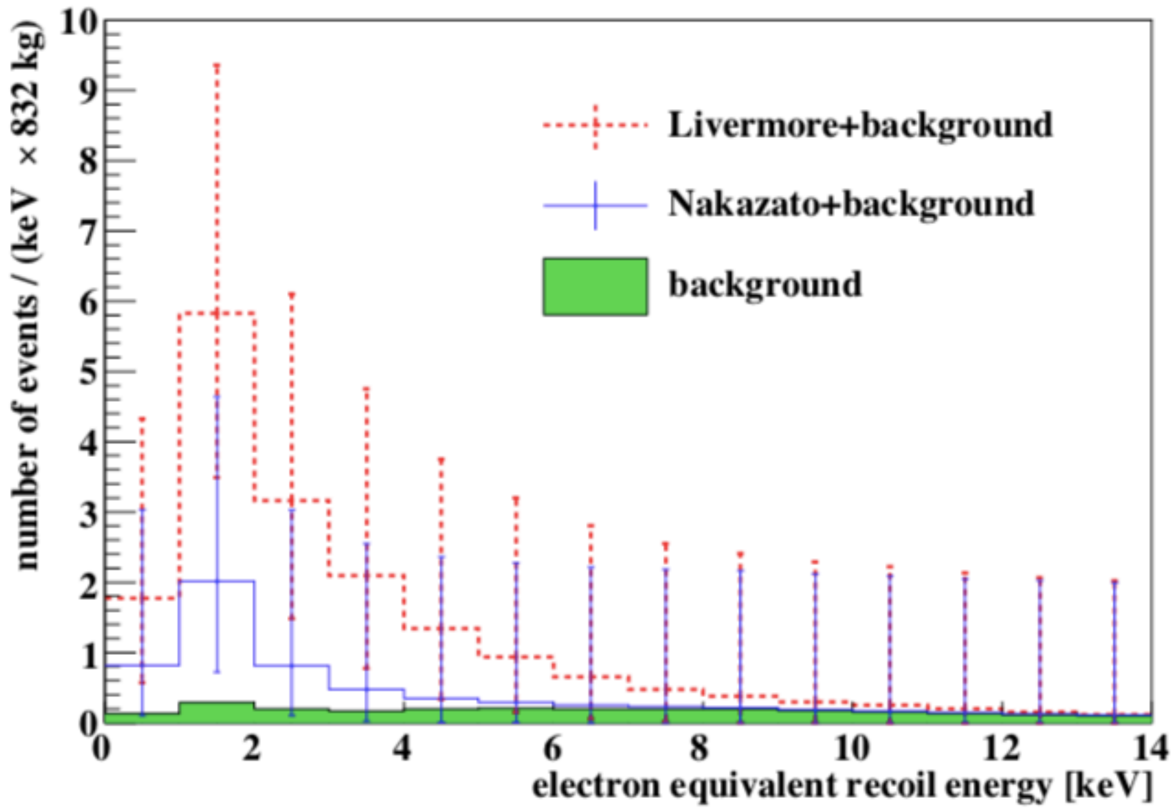
Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Recoil energy distribution and counts vs time for some specific models

Detector example: **XMASS**

- tonne-scale single-phase xenon

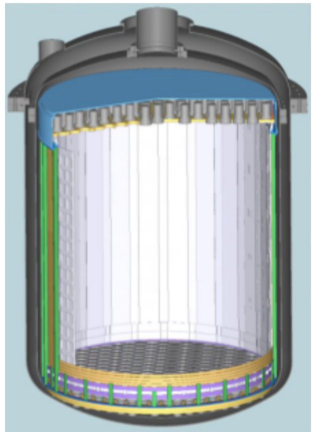


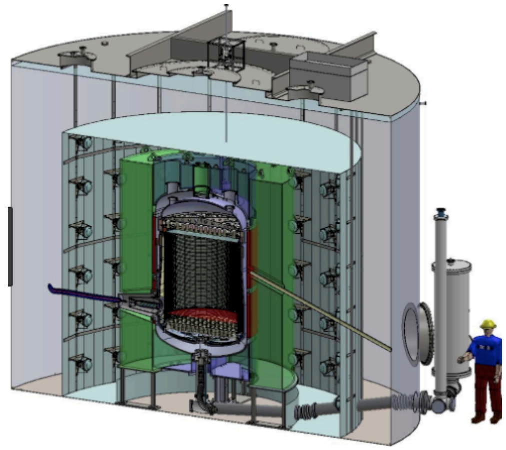


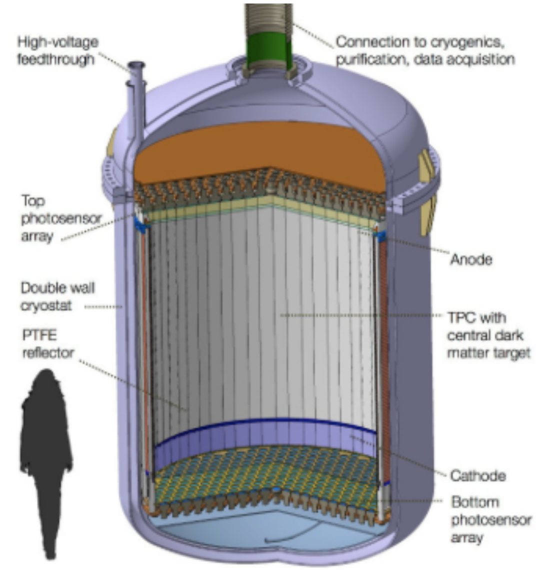
Abe et al. (2017). *Astroparticle Physics*. http://doi.org/10.1016/j.astropartphys.2017.01.006

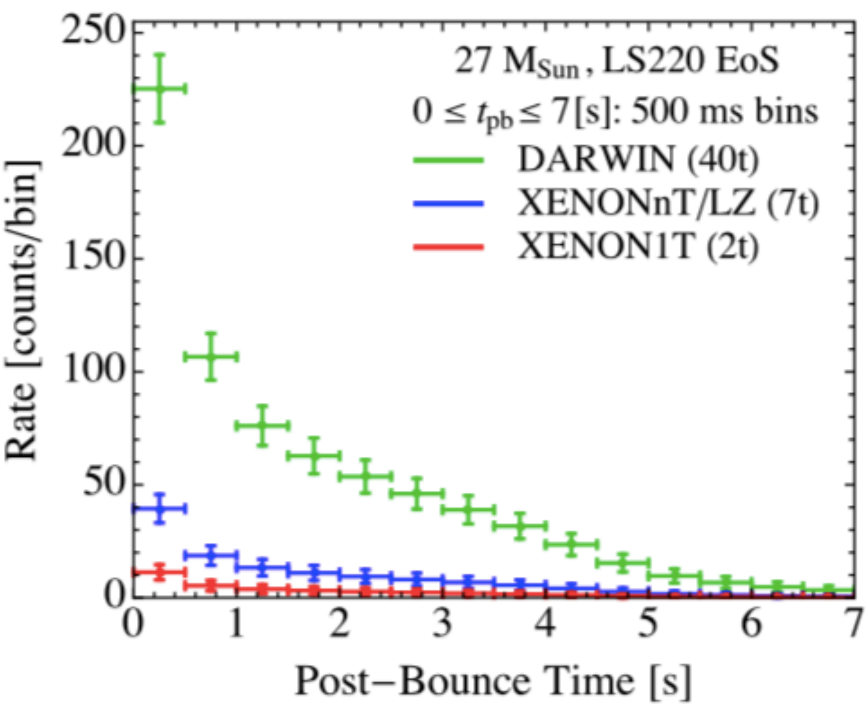
Detector example: **XENON/LZ/DARWIN**

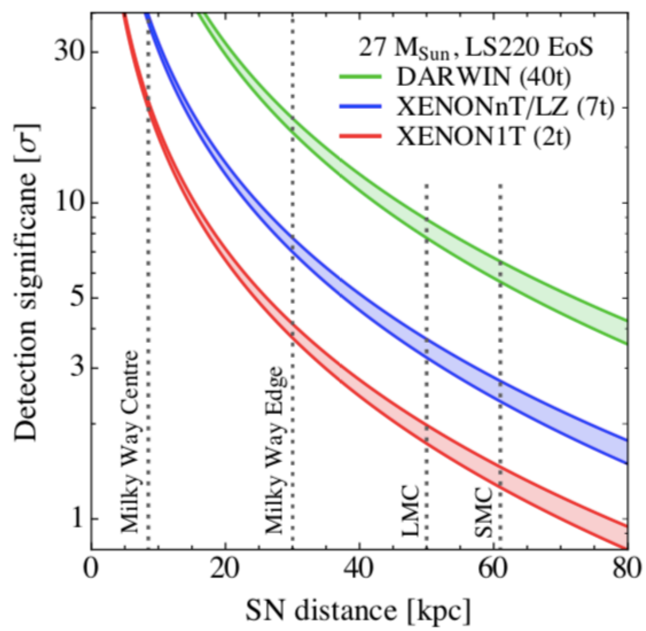
- dual-phase xenon time projection chambers





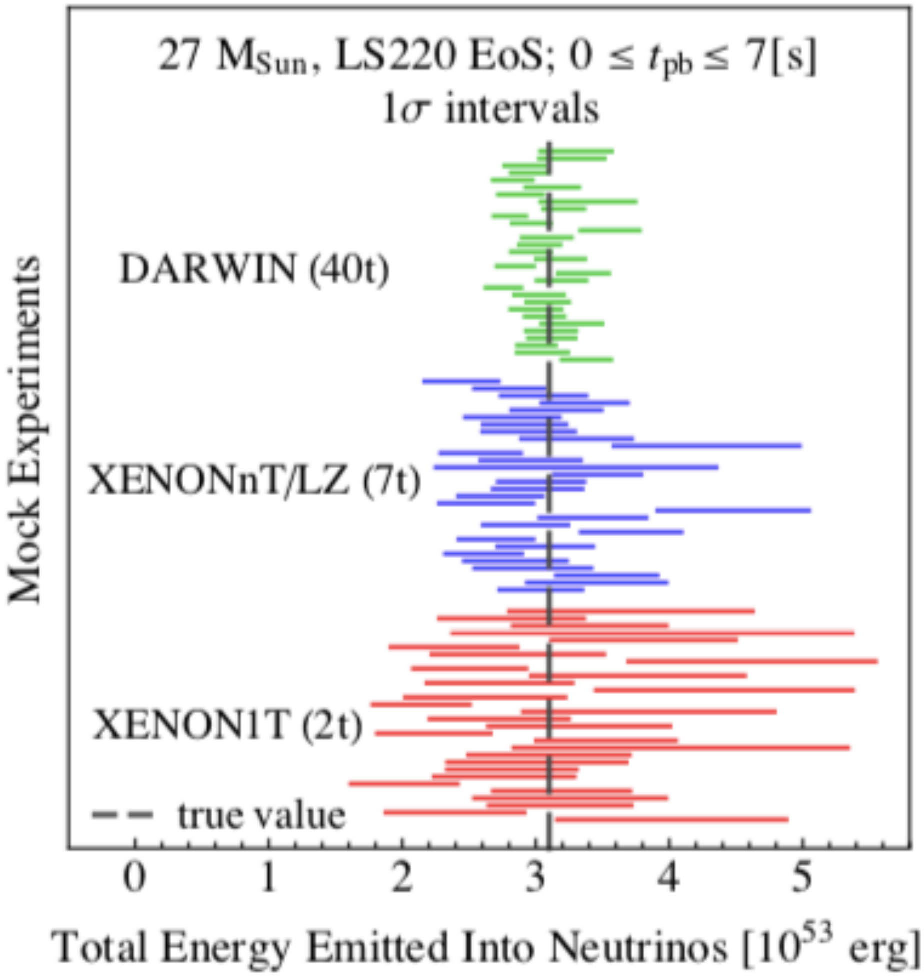


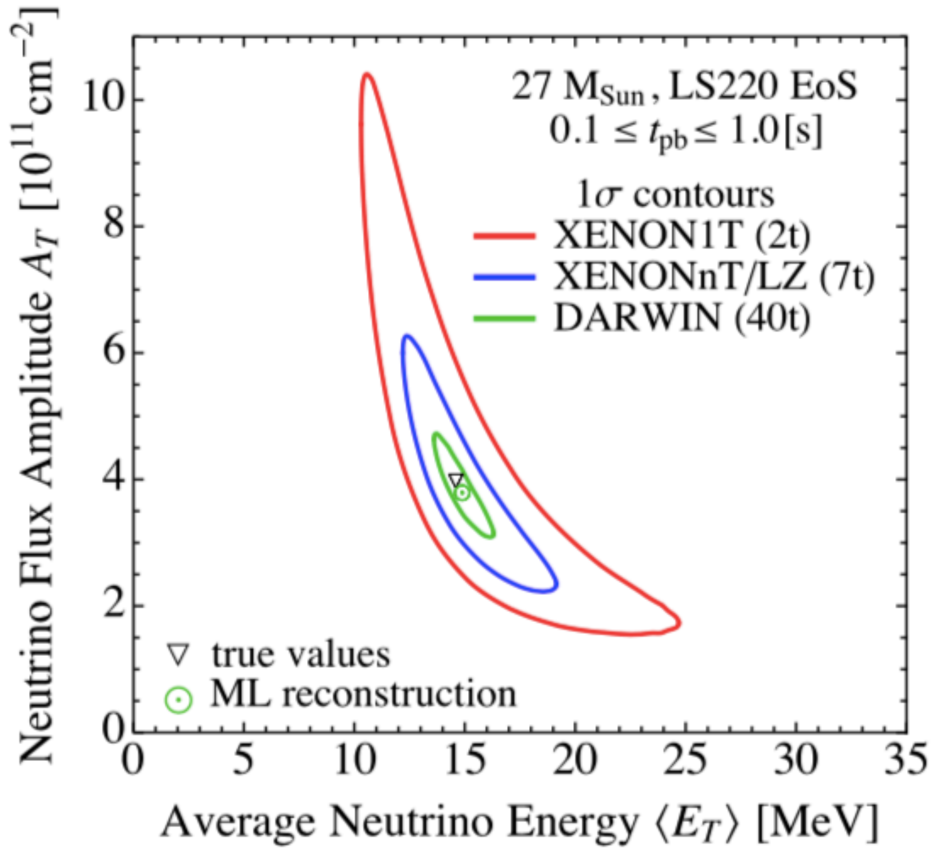




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

What will be learned?

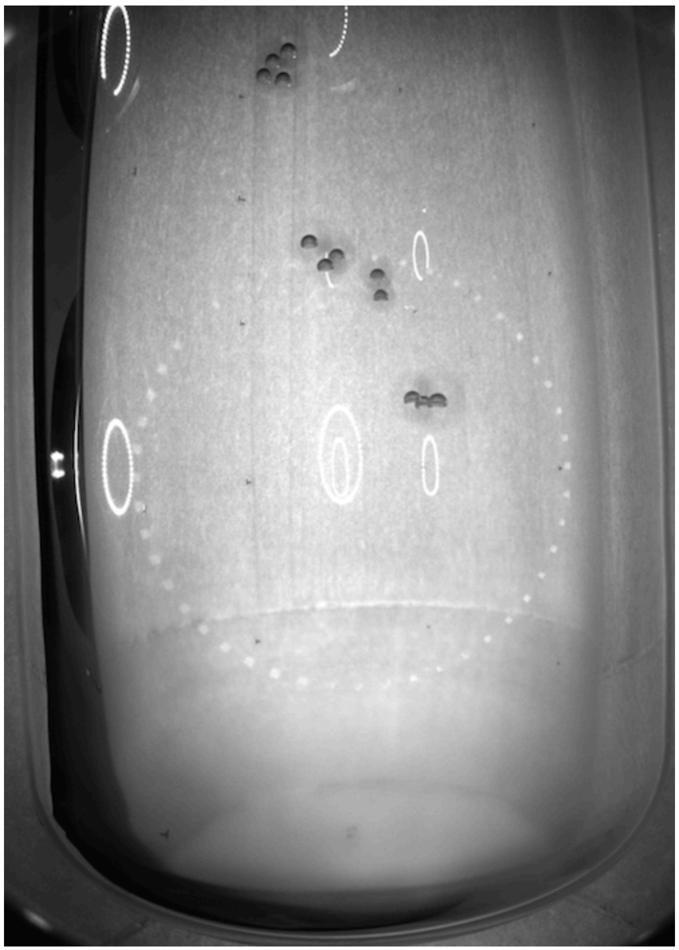




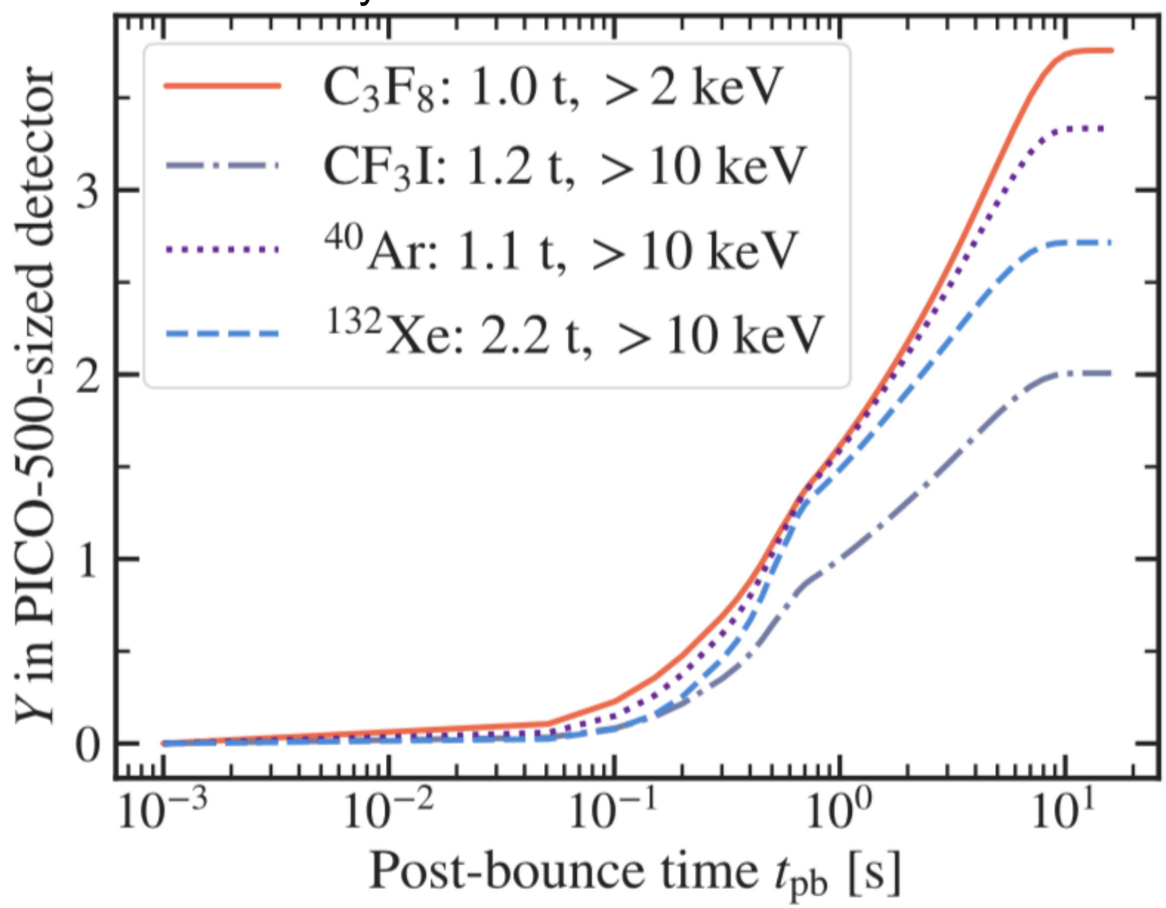
Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Example: **PICO-500**

- tonne-scale superheated-fluid bubble chamber
- <~10 keV threshold, high recoil event sample purity
- could see multiple bubbles if detector kept superheated over seconds



Preliminary

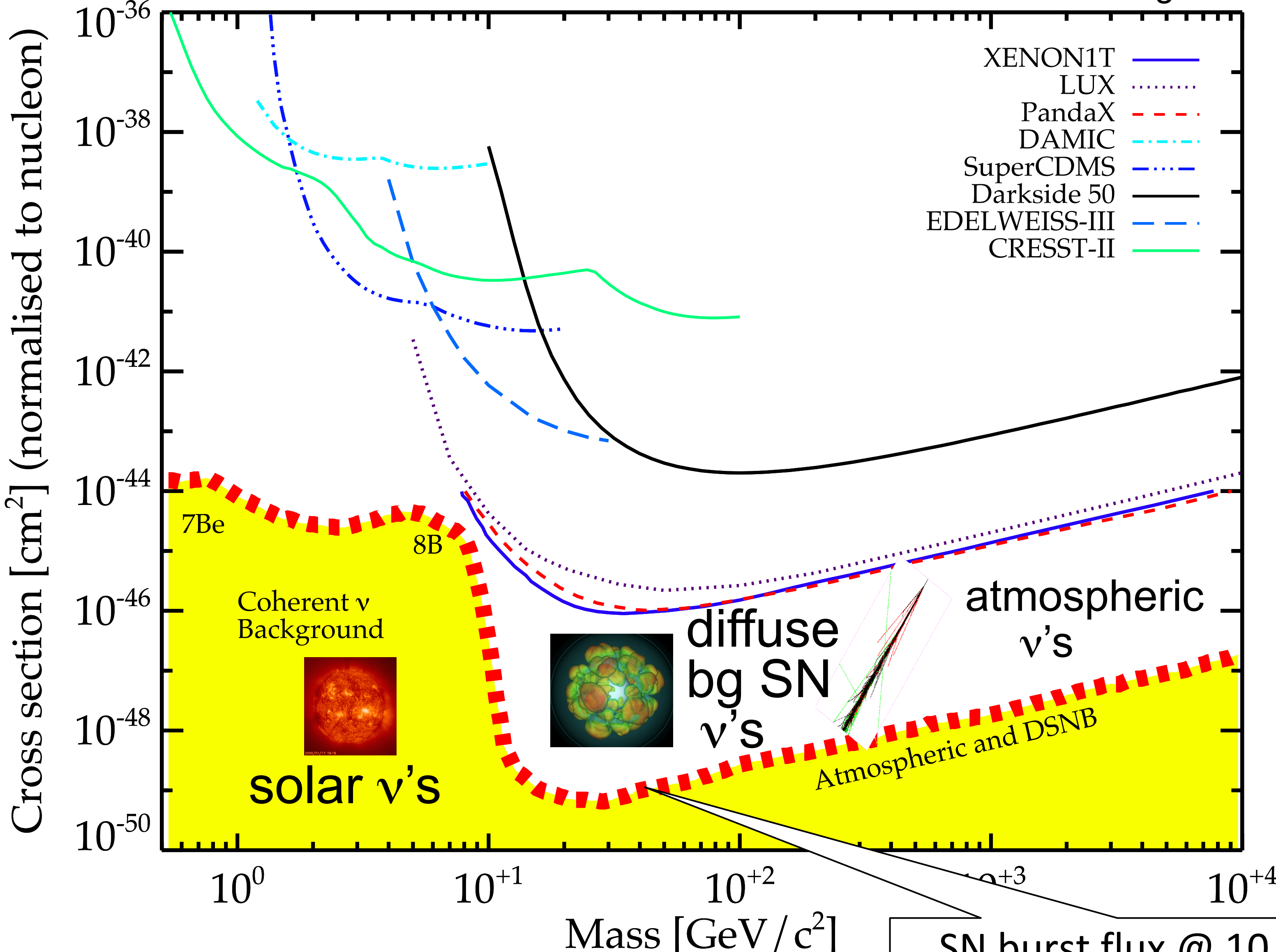


S. Fallows, T. Kozynets, C. Krauss, in preparation

The so-called "**neutrino floor**" for DM experiments

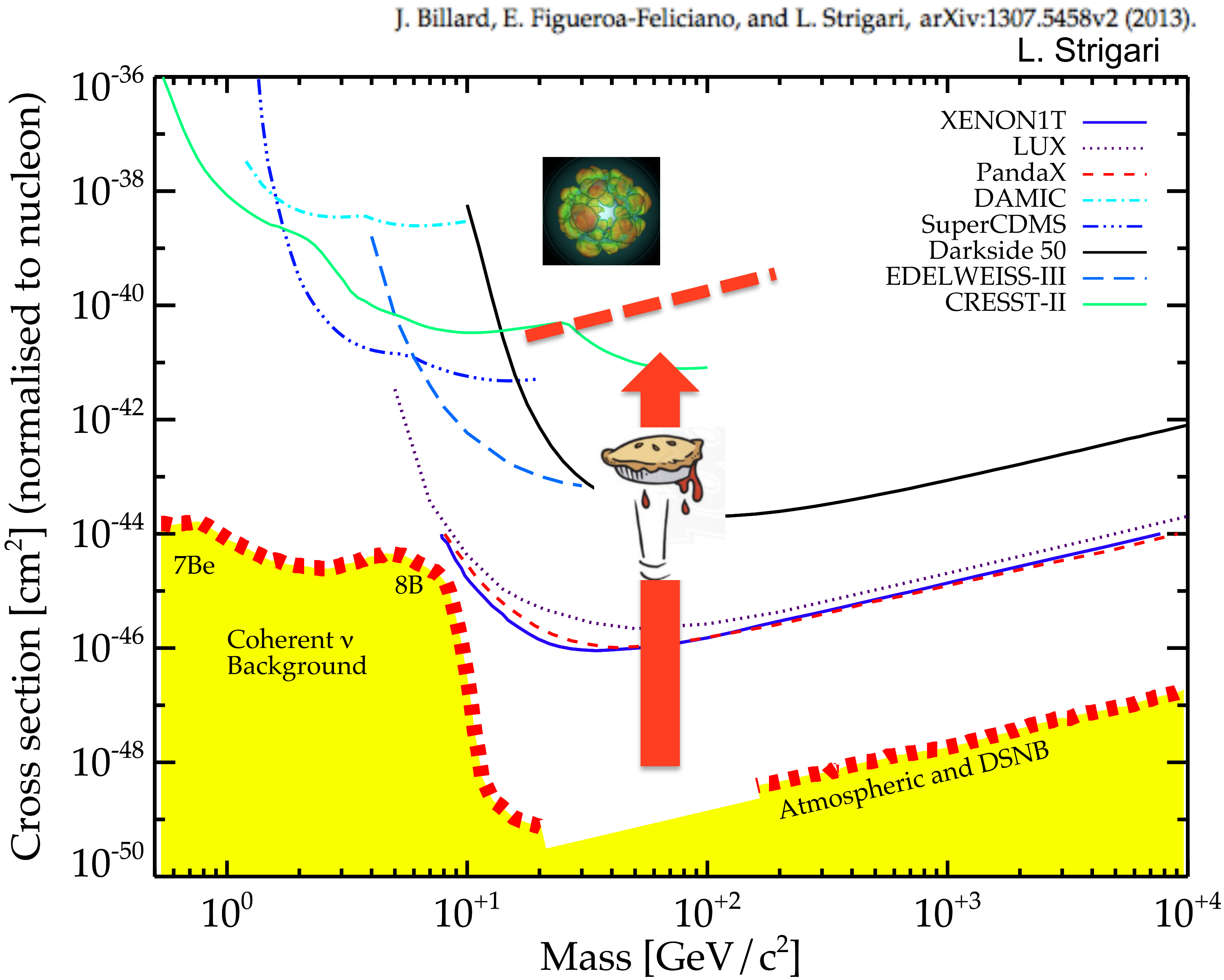
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

Think of a SN burst as “**the ν floor coming up to meet you**”



Summary

- **Core-collapse supernova neutrinos:**
  - vast information in flavor-energy-time profile
  - **NC info is especially valuable!** total energy, all-flavor profile

- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
  - **First light** from COHERENT at the SNS

- **Supernova neutrinos and 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