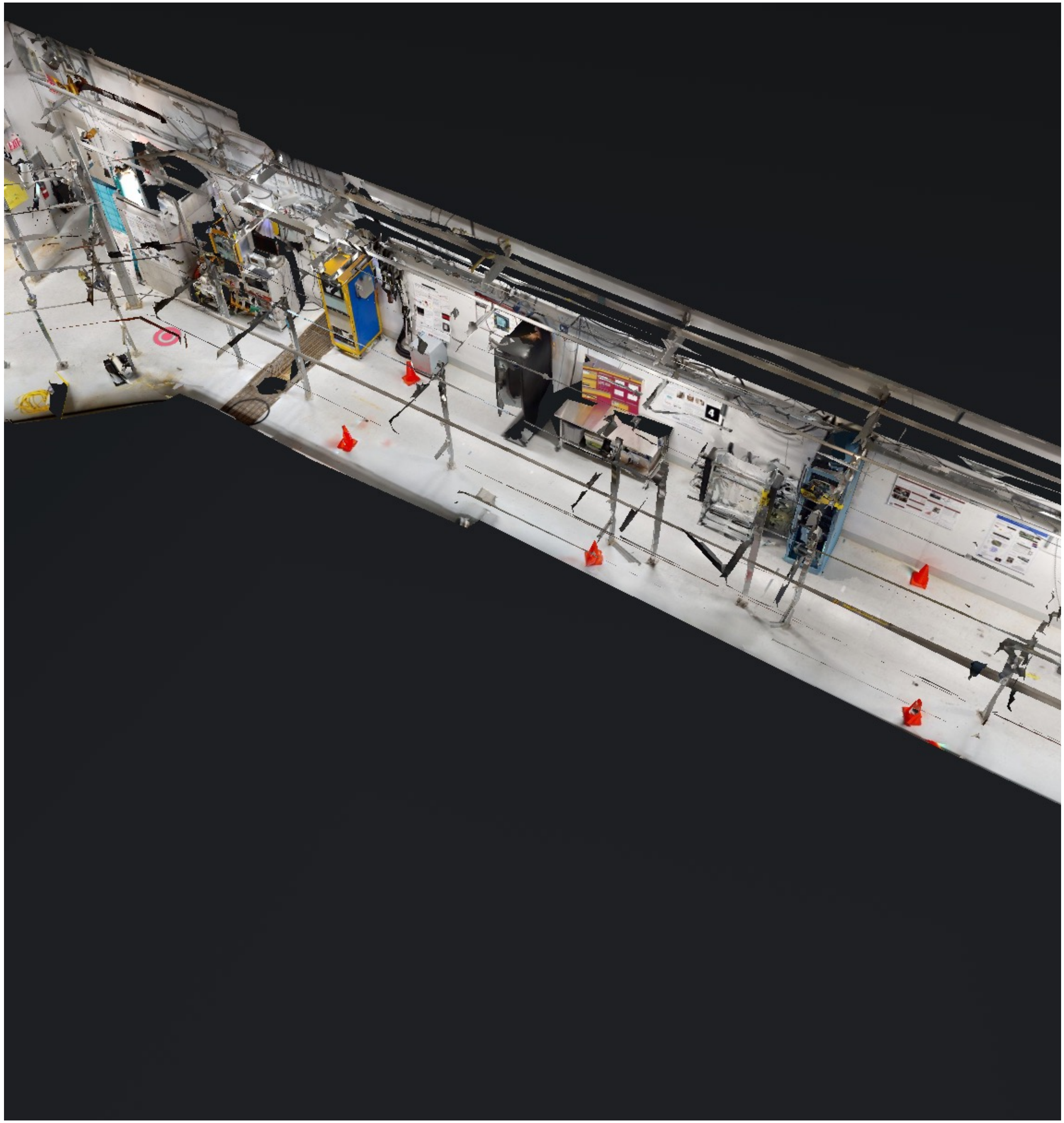
Neutrino Interactions



Kate Scholberg,
Duke University

MPA Summer School 2021:

Fundamental Interactions in Particle, Hadron and Nuclear Physics

September 2021

Outline of Lecture Topics

General overview

- Neutrino sources
- Neutrino interactions with matter
- Particle detection techniques

Mon

- Physics with neutrinos in the ~1-100 MeV range
- Physics with stopped-pion neutrino sources

Tue

- Physics in Neutrino Alley at the Spallation Neutron Source
- The COHERENT Experiment
- Future prospects

Thu

Specific example

Neutrino interactions over a range of energies

Deep Inelastic Scattering

keV MeV GeV TeV PeV

Neutrino interactions over a range of energies

Deep Inelastic Scattering

keV MeV GeV TeV PeV

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino interactions over a range of energies

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

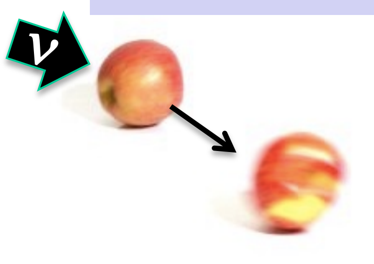
Neutrino interactions over a range of energies

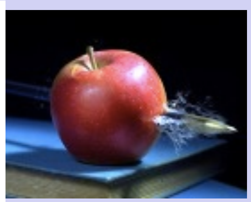
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV





Interactions with nucleons inside nuclei, often disruptive, hadroproduction

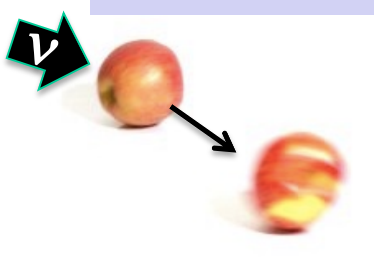
This is the ***gentlest*** interaction of a neutrino with a nucleus

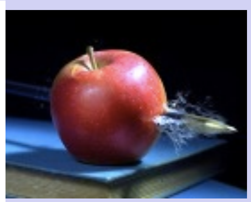
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



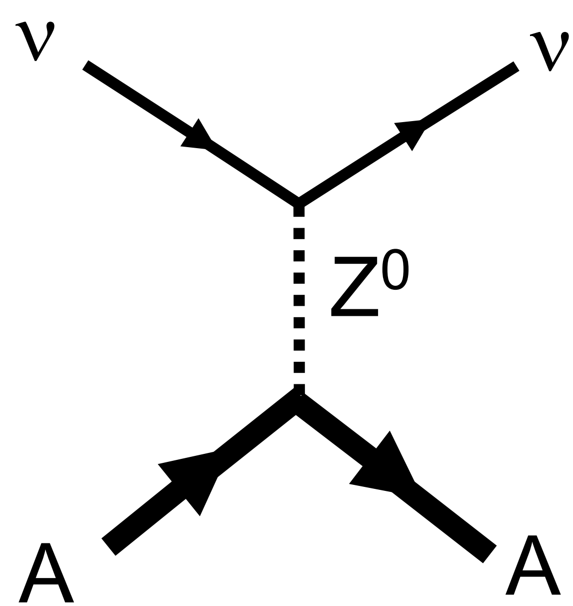


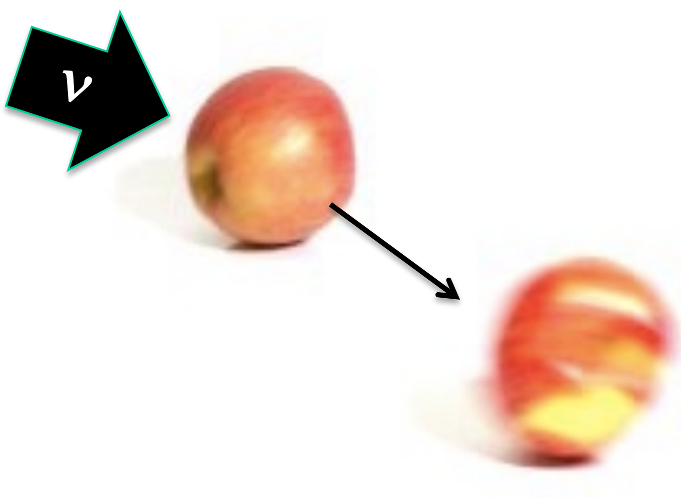
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

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 $E_\nu \sim$ 50 MeV





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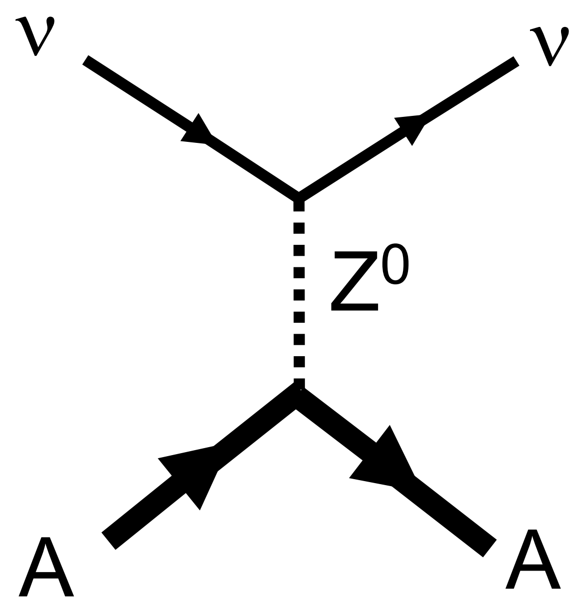
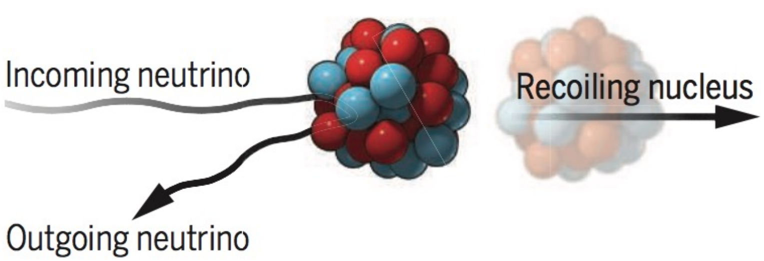


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



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

First proposed >47 years ago!

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

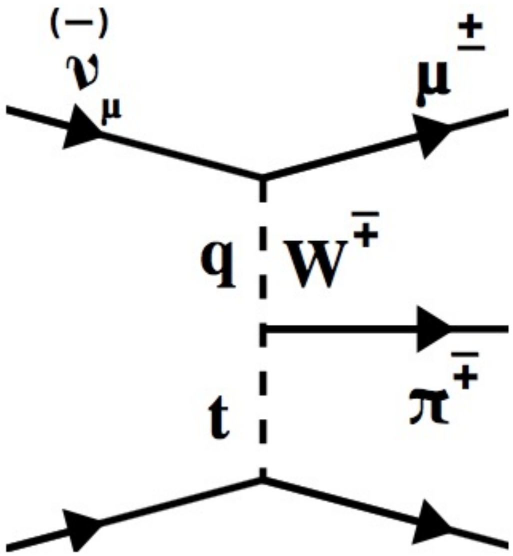
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

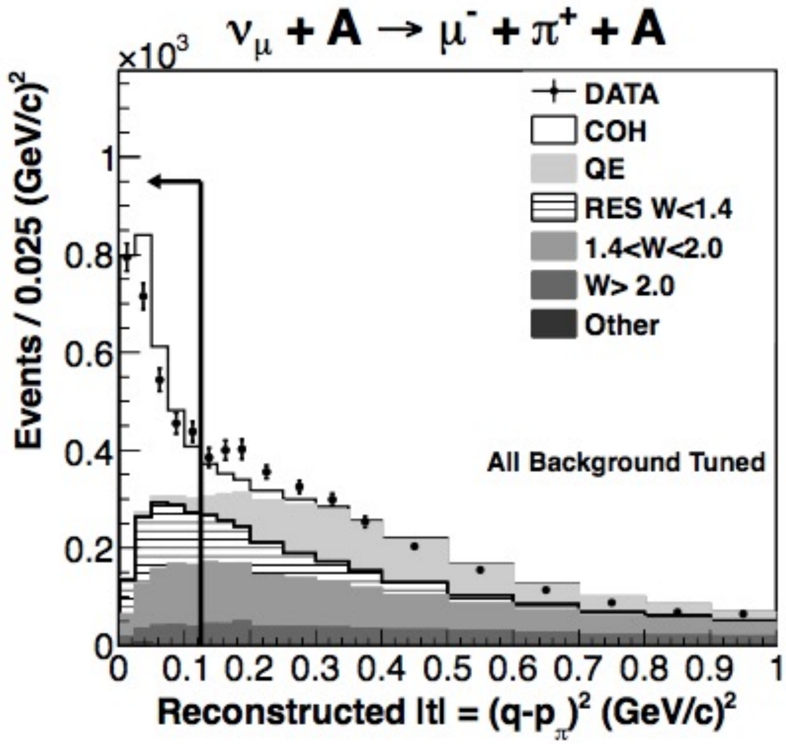
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Also: D. Z. Freedman et al., “The Weak Neutral Current and Its Effect in Stellar Collapse”, Ann. Rev. Nucl. Sci. 1977. 27:167-207

This is ***not*** coherent pion production, a strong interaction process ***(inelastic)***



not **THAT!**



A. Higuera et. al, MINERvA collaboration, PRL 2014 113 (26) 2477

How do you pronounce "CEvNS"?

A. "KEVENS"

B. "KENZ"

C. "KENSE"

D. "SEVENS"

E. "SENSE"

F. "SENZ"

\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}

Standard Model prediction for CEvNS differential cross section

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T):
momentum transfer

(probability of kicking a nucleus with recoil energy T)

Fermi constant (SM parameter)

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

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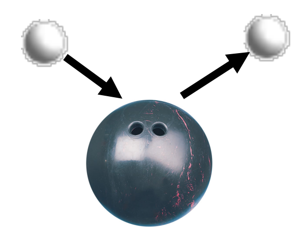
kinematics:
ping-pong ball hits bowling ball



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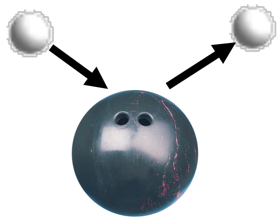
Form factor: F=1 ➔ full coherence



Standard Model prediction for CEvNS differential cross section

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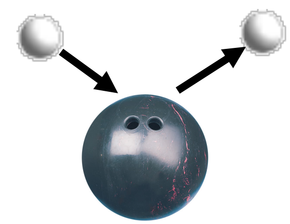

Form factor: F=1 ➔ full coherence

weak nuclear charge

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

Standard Model prediction for differential cross section

(probability of kicking a nucleus with recoil energy T)

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2 M T)}$: momentum transfer

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

weak nuclear charge

No. of neutrons

No. of protons

$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$

$\sin^2\theta_W = 0.231$,
so protons unimportant

$$\Longrightarrow \quad Q_W \propto N$$

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{\boxed{Q_W^2}}{4} \boxed{F^2(Q)} \left(2 - \frac{MT}{E_\nu^2}\right)$$

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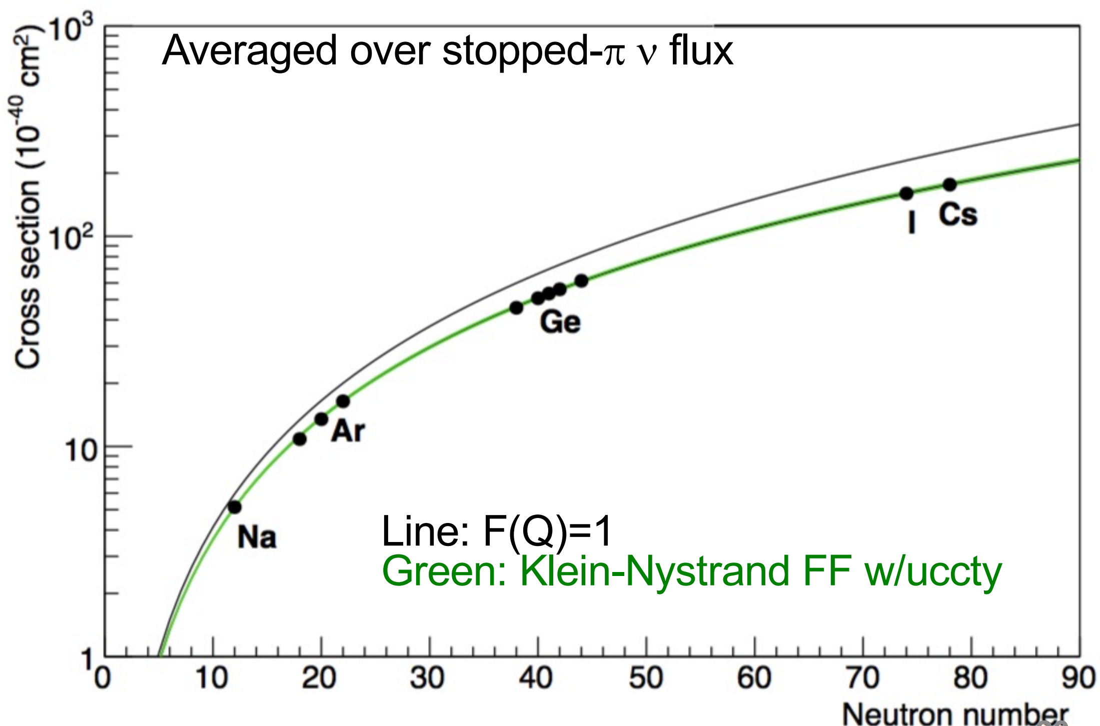
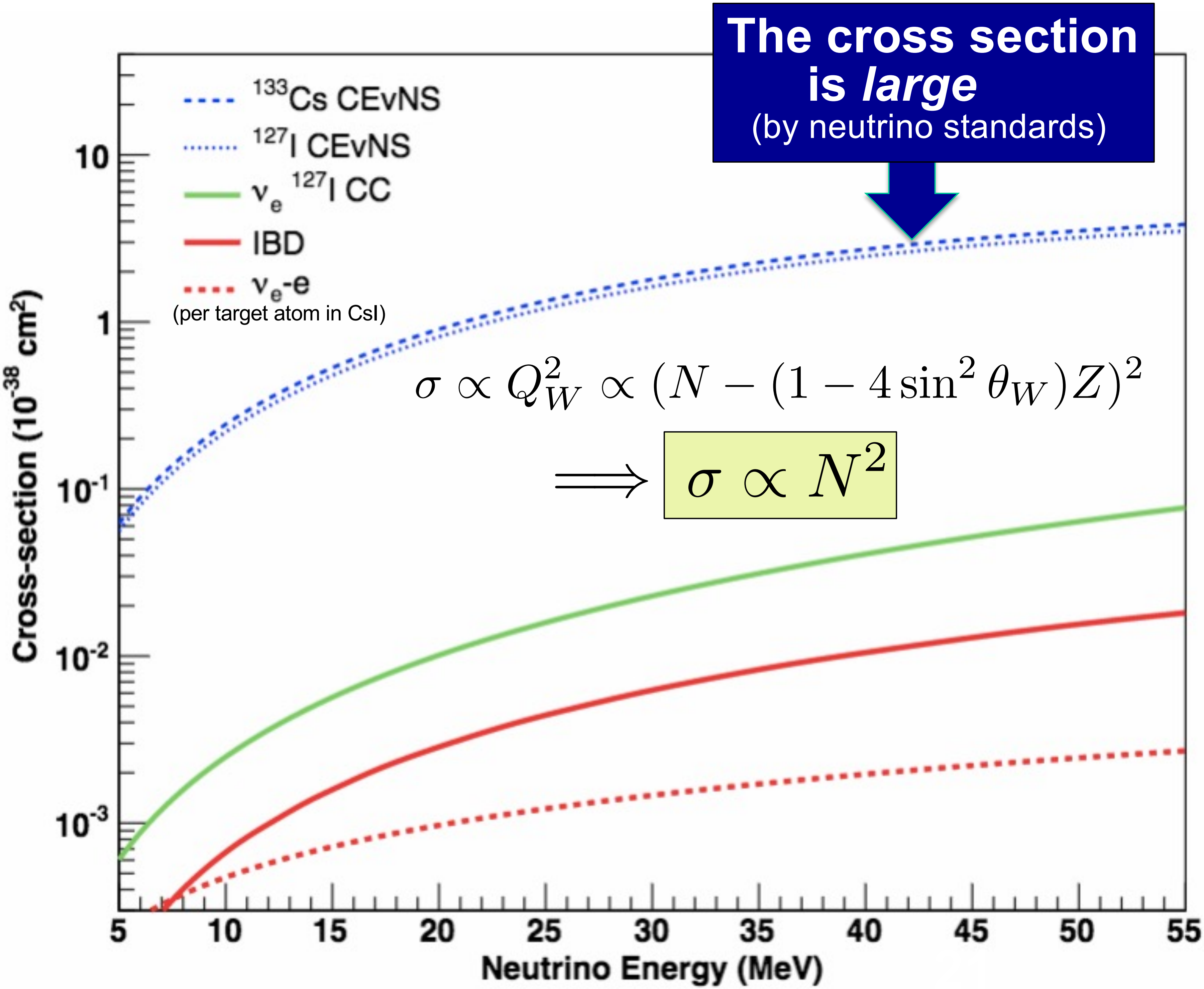
weak nuclear charge

Form factor: F=1 ➔ full coherence

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$

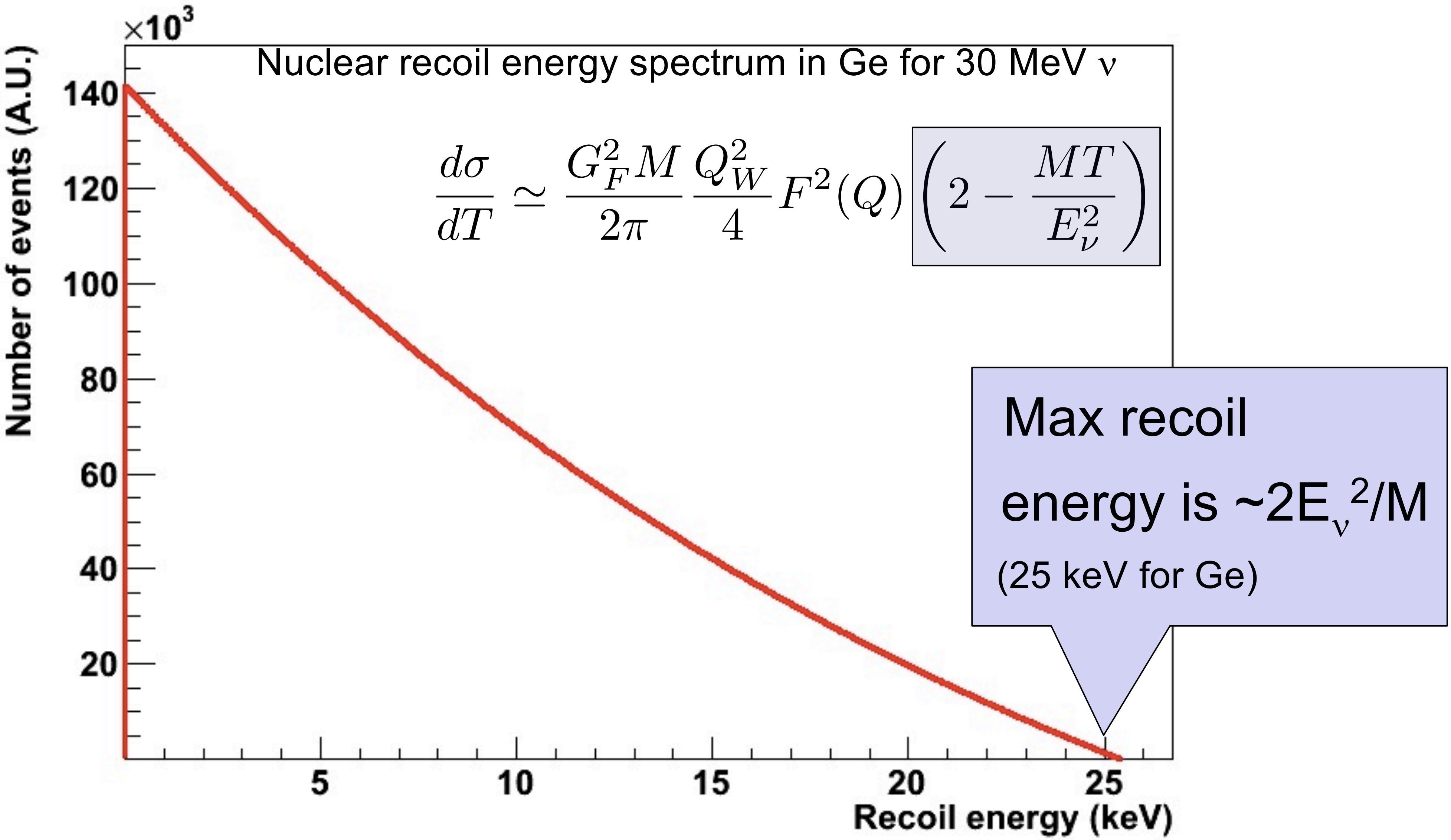




$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

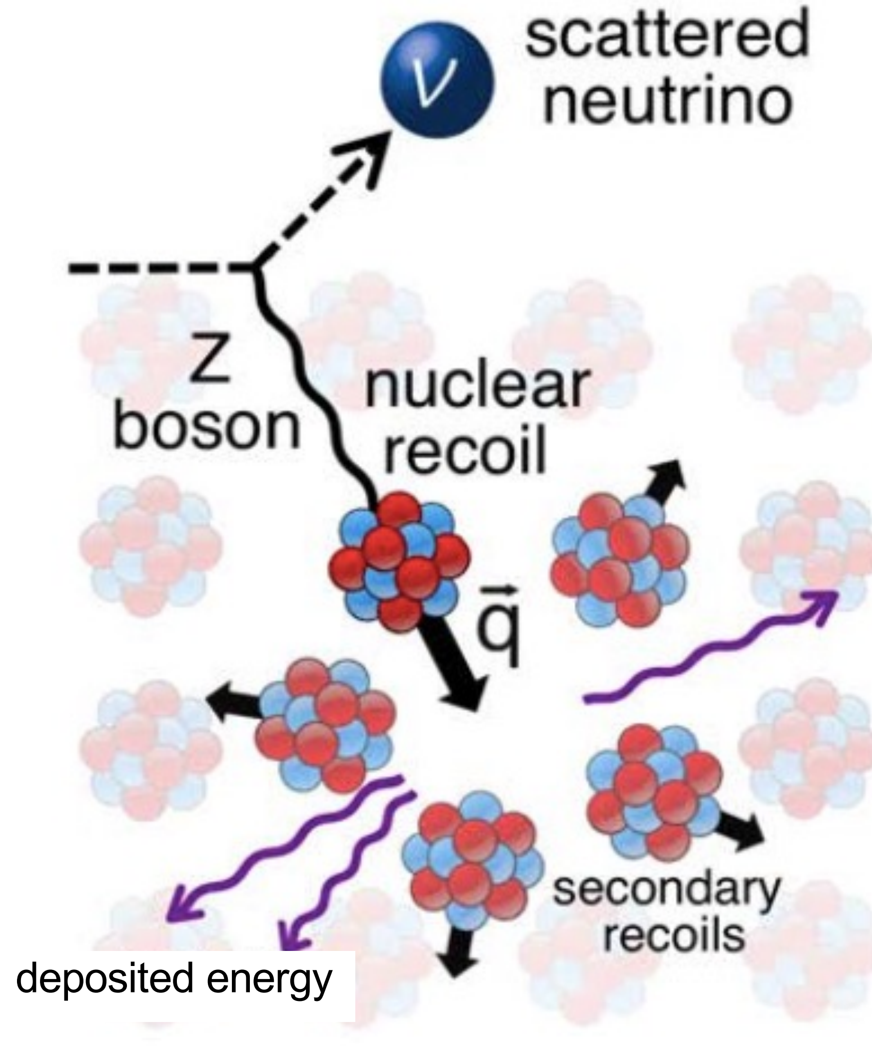
$$\implies \boxed{\sigma \propto N^2}$$

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

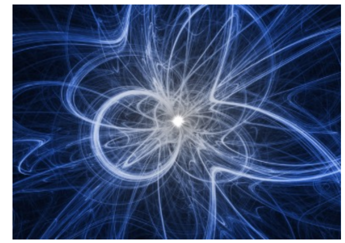


➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

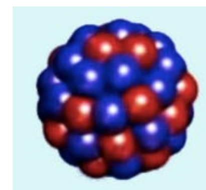
CEvNS: what's it good for?

! (not a complete list!)

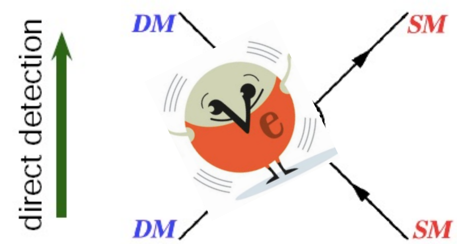
CEvNS as a **signal**
for signatures of *new physics*



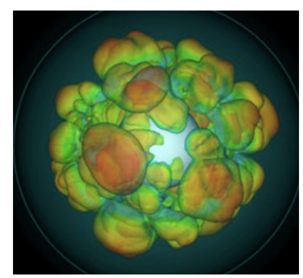
CEvNS as a **signal**
for understanding of "old" physics



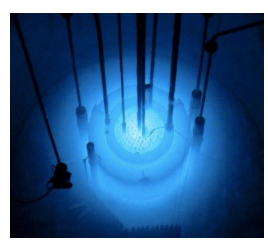
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



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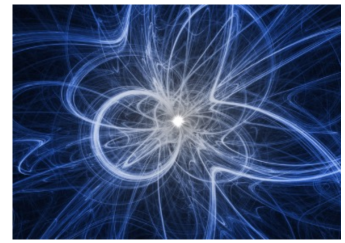

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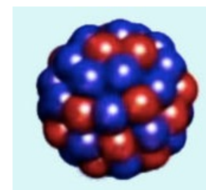

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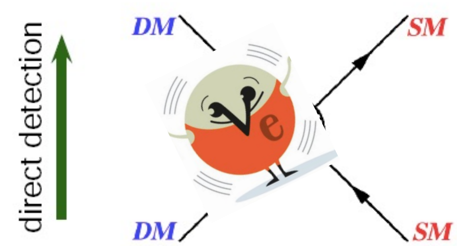

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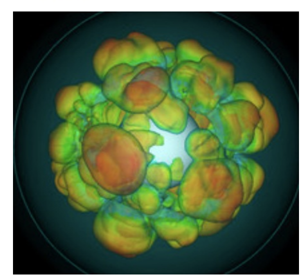
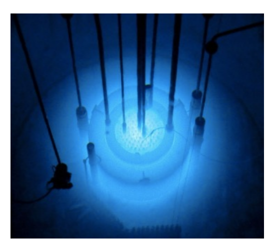


CEvNS as a **practical tool**



The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

G_V, G_A: SM weak parameters

vector $G_V = g_V^p Z + g_V^n N,$ ← dominates

axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)$ ← small for most nuclei, zero for spin-zero

$$\boxed{\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}}$$

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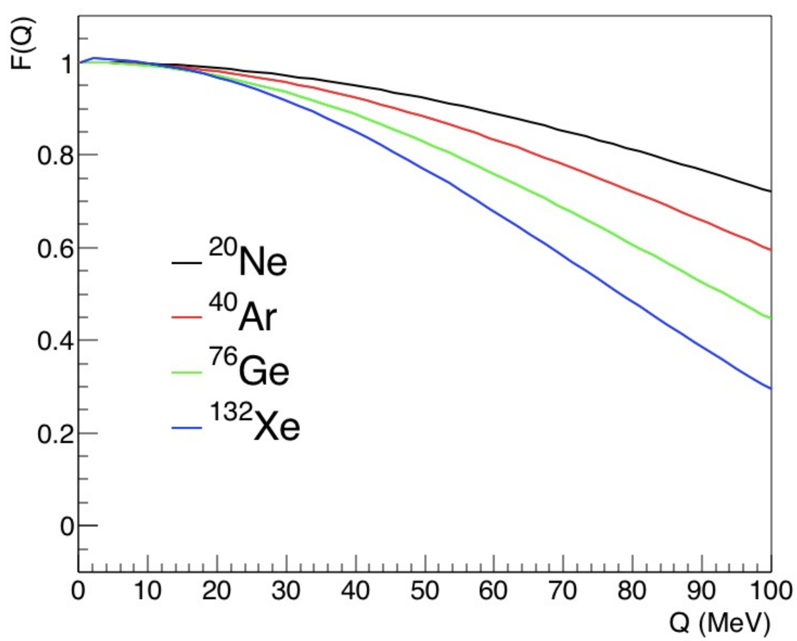
F(Q): nuclear **form factor**, <~5% uncertainty on event rate

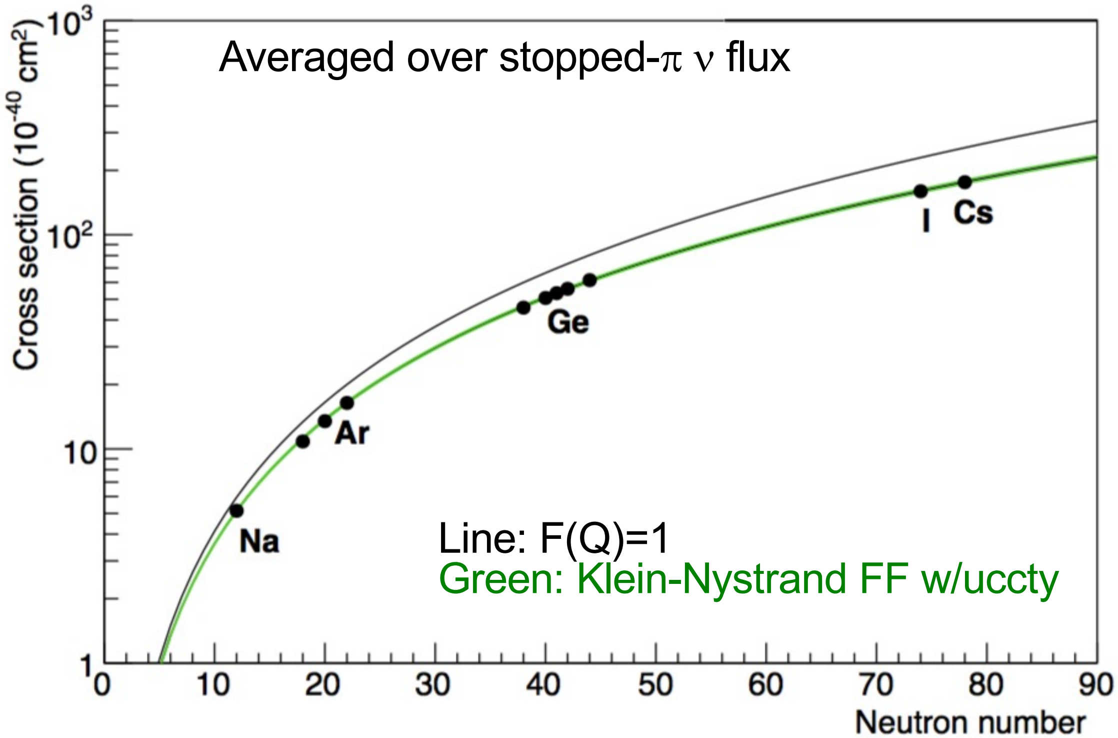


form factor suppresses cross section at large Q

The CEvNS rate is a clean SM prediction

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} \boxed{F^2(Q)} \left(2 - \frac{MT}{E_\nu^2}\right)$$

small nuclear uncertainties



A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

Searching for BSM Physics with CEvNS

A first example: simple counting to constrain **non-standard interactions (NSI)** of neutrinos with quarks

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

"Model-independent" parameterization

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL} [\bar{q}\gamma_\mu (1-\gamma^5) q] + \varepsilon_{\alpha\beta}^{qR} [\bar{q}\gamma_\mu (1+\gamma^5) q])$$

ε's parameterize new interactions

"Non-Universal": ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

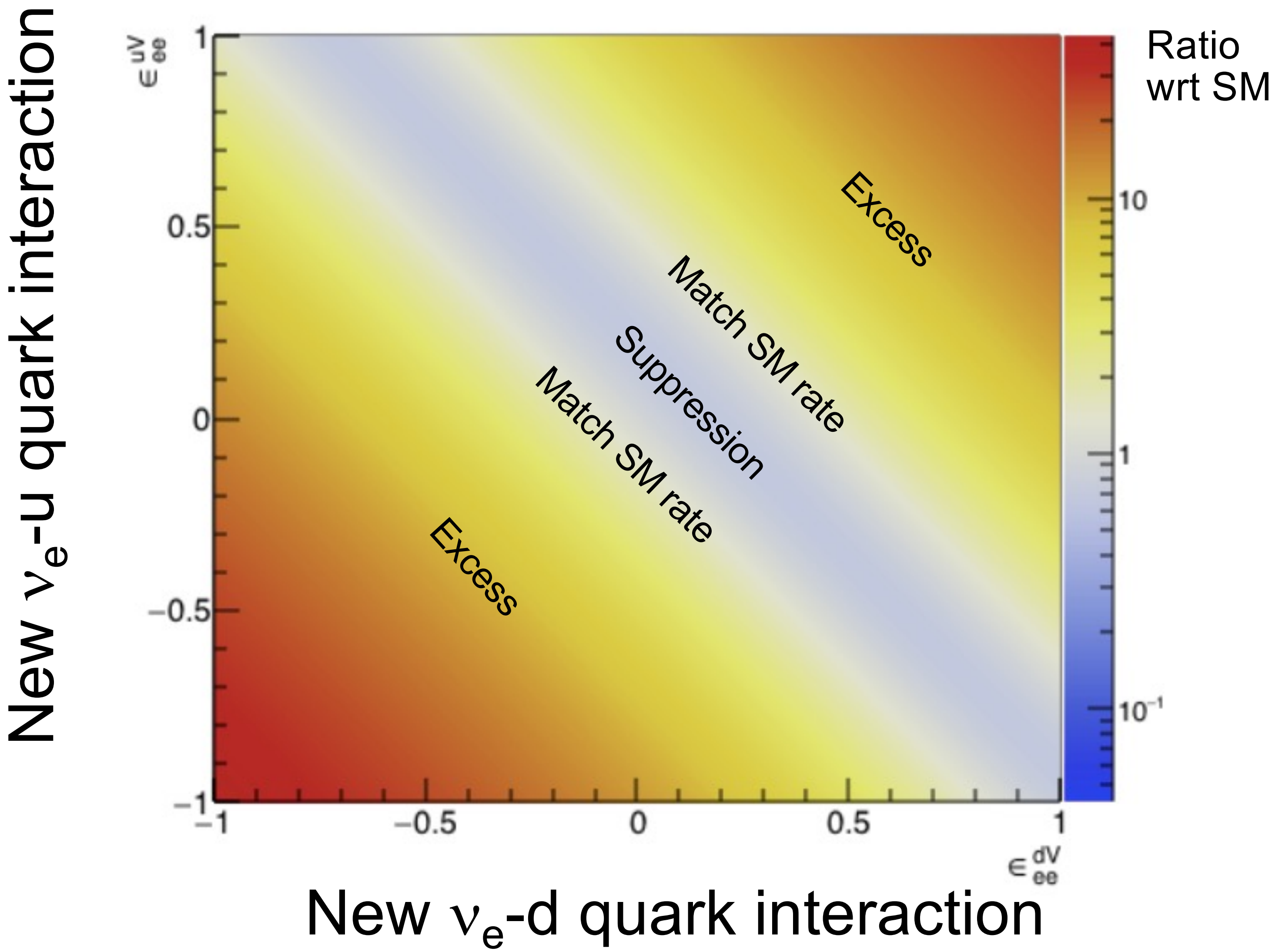
Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha \neq \beta$

$\Rightarrow$ some are quite poorly constrained (~unity allowed)

Signatures of **Beyond-the-Standard-Model Physics**

Look for a CEvNS **excess** or **deficit** wrt SM expectation

CsI



Other new physics results in a
distortion of the recoil spectrum (Q dependence)

BSM Light Mediators

SM weak charge

Effective weak charge in presence of light vector mediator Z'

$$Q^2_{\alpha,\mathrm{SM}} = (Z g_p^V + N g_n^V)^2 \quad \Rightarrow \quad Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M^2_{Z'})} \right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M^2_{Z'})} \right) \right]^2$$

specific to neutrinos and quarks

e.g. arXiv:1708.04255

Neutrino (Anomalous) Magnetic Moment

e.g. arXiv:1505.03202, 1711.09773

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right)$$

Specific ~1/T upturn at low recoil energy

Sterile Neutrino Oscillations

$$P^{\mathrm{SBL}}_{\nu_\alpha \to \nu_\alpha}(E_\nu) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

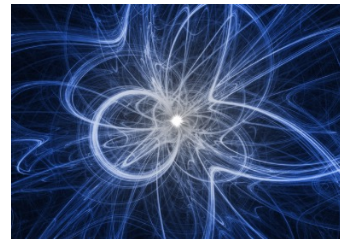
"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

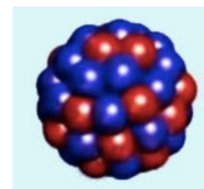
CEvNS: what's it good for?

① So
② Many
③ Things
!
(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**
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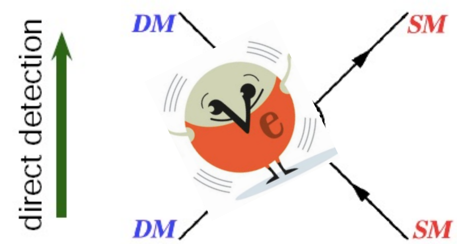
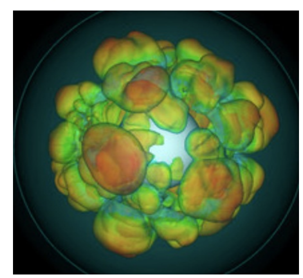
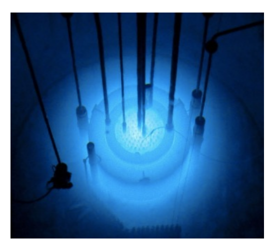


CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



What can we learn about **nuclear physics** with CEvNS?

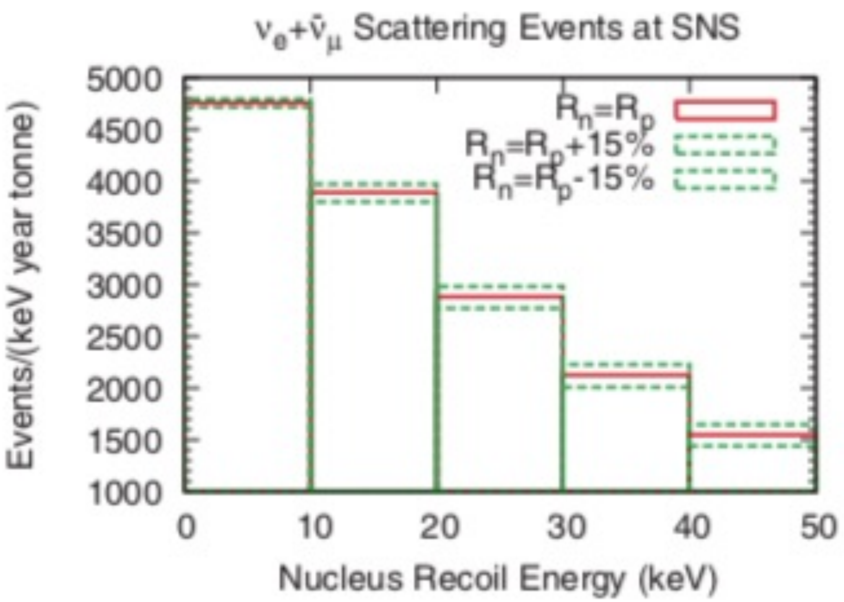
Nuclear neutron form factor from neutrino–nucleus coherent elastic scattering

P S Amanik and G C McLaughlin

Department of Physics, North Carolina State University, Raleigh, NC 27695-8202, USA

Received 19 June 2008
Published 30 October 2008
Online at stacks.iop.org/JPhysG/36/015105

Abstract
We point out that there is potential to study the nuclear neutron form factor through neutrino nucleus coherent elastic scattering. We determine numbers of events for various scenarios in a liquid noble nuclear recoil detector at a stopped pion neutrino source.



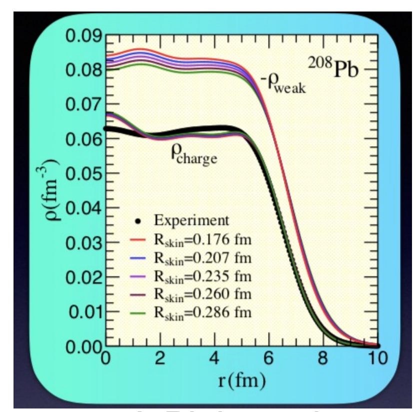
Neutrino-nucleus coherent scattering as a probe of neutron density distributions

Kelly Patton[1,*] Jonathan Engel[2,†] Gail C. McLaughlin[1,‡] and Nicolas Schunck[3,§]
[1] *Physics Department, North Carolina State University, Raleigh, North Carolina 27695, USA*
[2] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599, USA*
[3] *Physics Division, Lawrence Livermore Laboratory, Livermore, California 94551 USA*
(Dated: July 4, 2012)

Neutrino-nucleus coherent elastic scattering provides a theoretically appealing way to measure the neutron part of nuclear form factors. Using an expansion of form factors into moments, we show that neutrinos from stopped pions can probe not only the second moment of the form factor (the neutron radius) but also the fourth moment. Using simple Monte Carlo techniques for argon, germanium, and xenon detectors of 3.5 tonnes, 1.5 tonnes, and 300 kg, respectively, we show that the neutron radii can be found with an uncertainty of a few percent when near a neutrino flux of 3×10^7 neutrinos/cm^2/s. If the normalization of the neutrino flux is known independently, one can determine the moments accurately enough to discriminate among the predictions of various nuclear energy functionals.

Observable is **recoil spectrum shape**

Neutron radius and "skin" (R_n-R_p) relevant for understanding of neutron stars

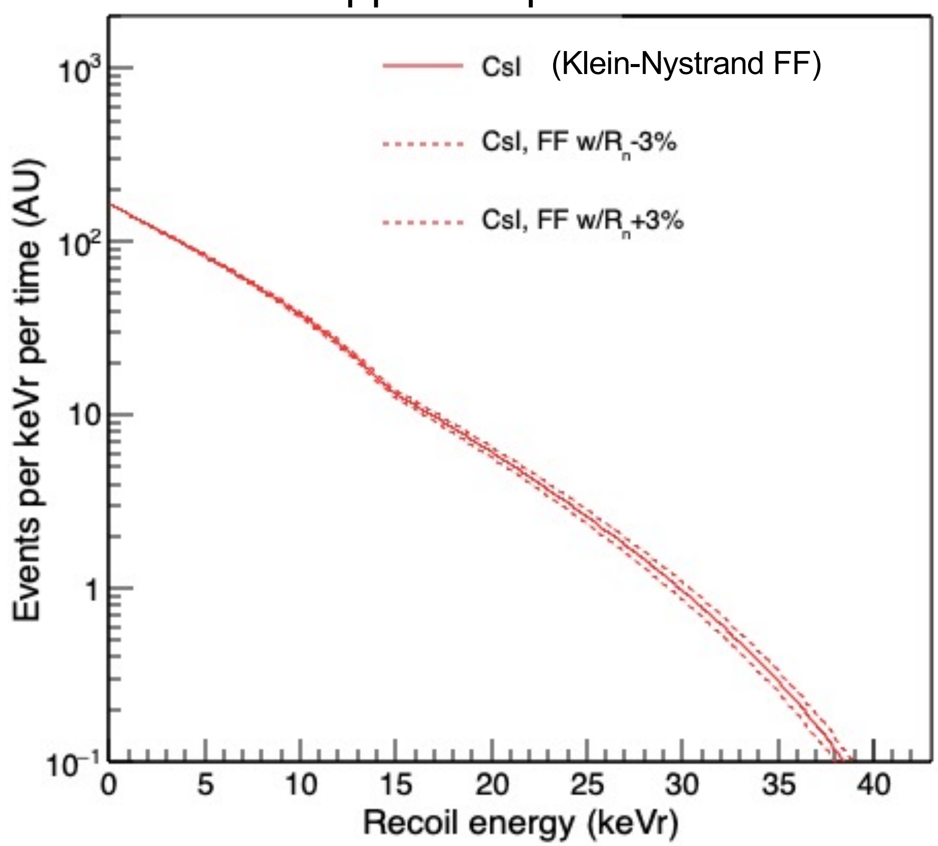


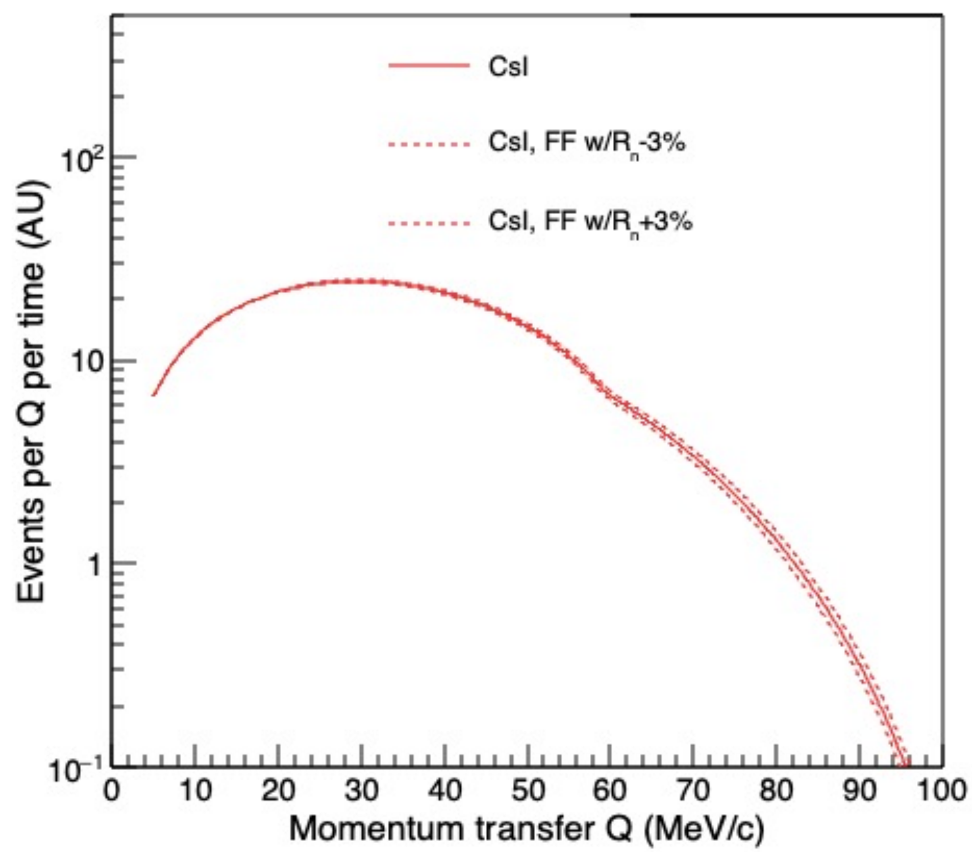
J. Piekarewicz

Effect of form-factor *uncertainty* on the recoil spectrum: estimate as R_n +/- 3%

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

Stopped-π spectrum





At current level of experimental precision, form factor uncertainty is small effect

So: if you are hunting for BSM physics as a distortion of the recoil spectrum

… uncertainties in the form factor are a nuisance!

There are degeneracies in the observables between "old" (but still mysterious) physics

and "new" physics

We will need to think carefully about how to disentangle these effects and understand uncertainties, for the longer term

[See also: D. Aristizabal Sierra et al. arXiv:1902.07398, recent INT workshop "Weak Elastic Scattering with Nuclei"]

Summary of what we can get at experimentally

Observables:

Event rate
Recoil spectrum ($T=Q^2/2M$)
[In principle: scattering angle... hard]

Spectral shape systematics are hard!

Knowable/controllable parameters:

Neutrino flavor, via source, and timing
(reactor: ν_e-bar, stopped-π: ν_e, ν_μ-bar, ν_μ)
N, Z via nuclear target type
Baseline
Direction with respect to source

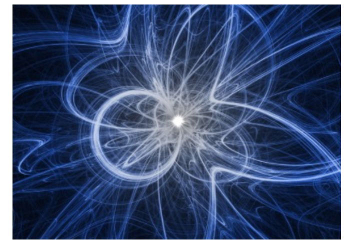
CEvNS: what's it good for?

1 So
2 Many
3 Things

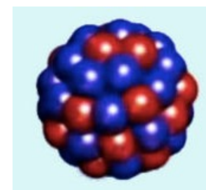
!

(not a complete list!)

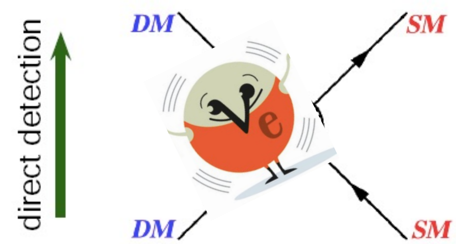
CEvNS as a **signal**
for signatures of *new physics*



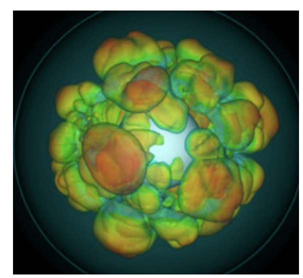
CEvNS as a **signal**
for understanding of "old" physics



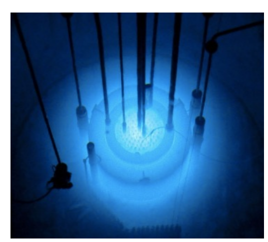
CEvNS as a **background**
for signatures of new physics (DM)



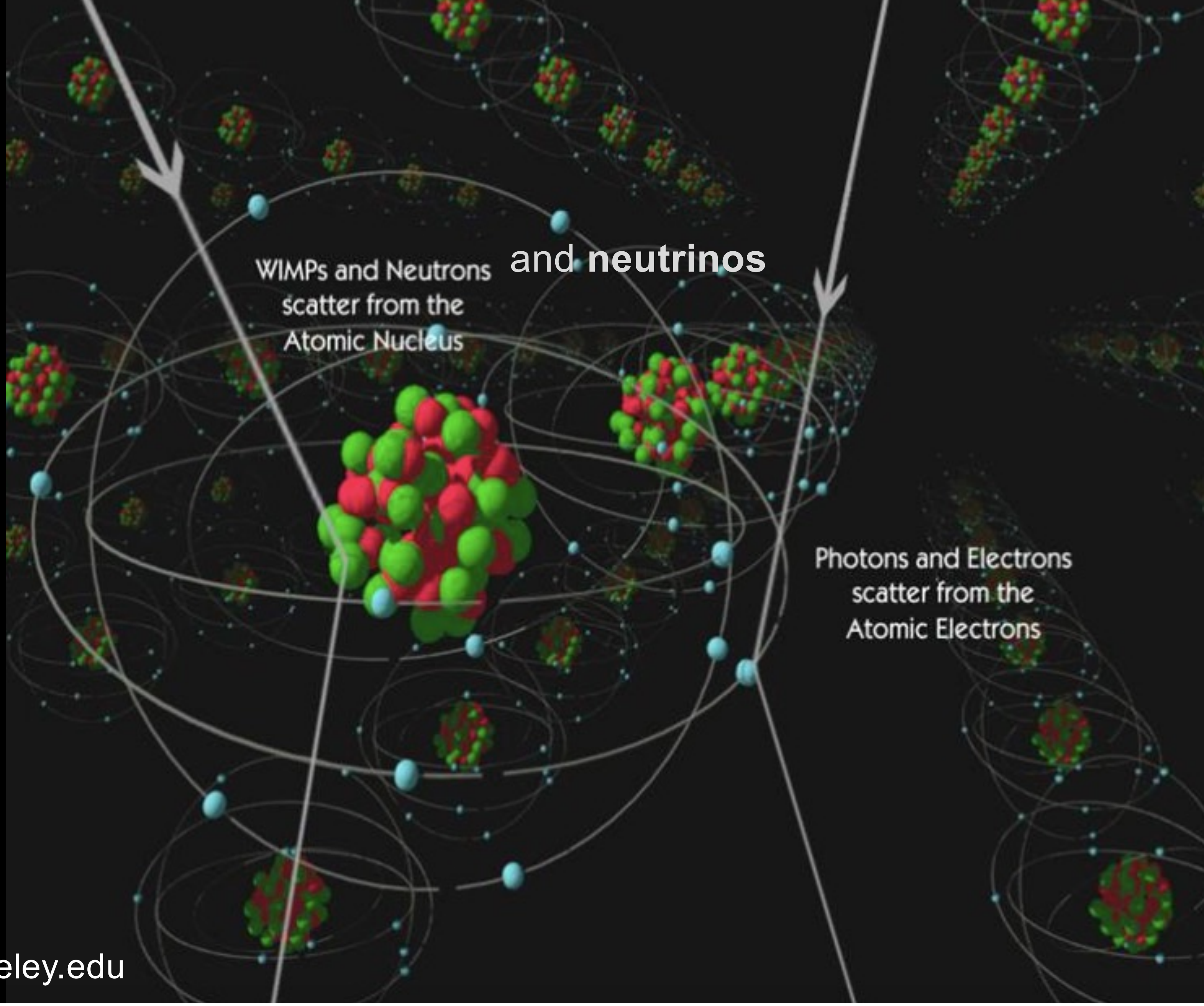
CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



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



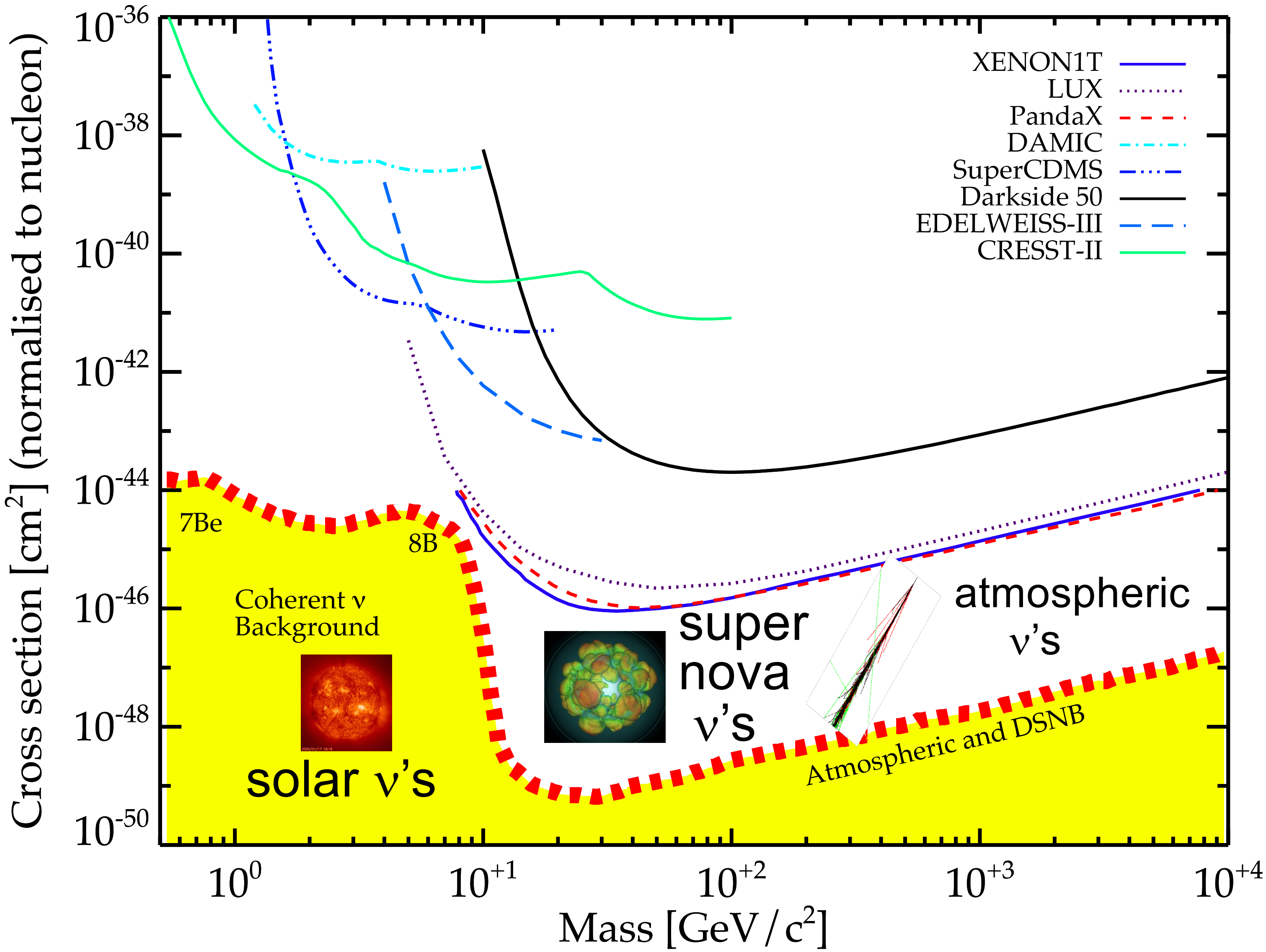
cdms.berkeley.edu

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

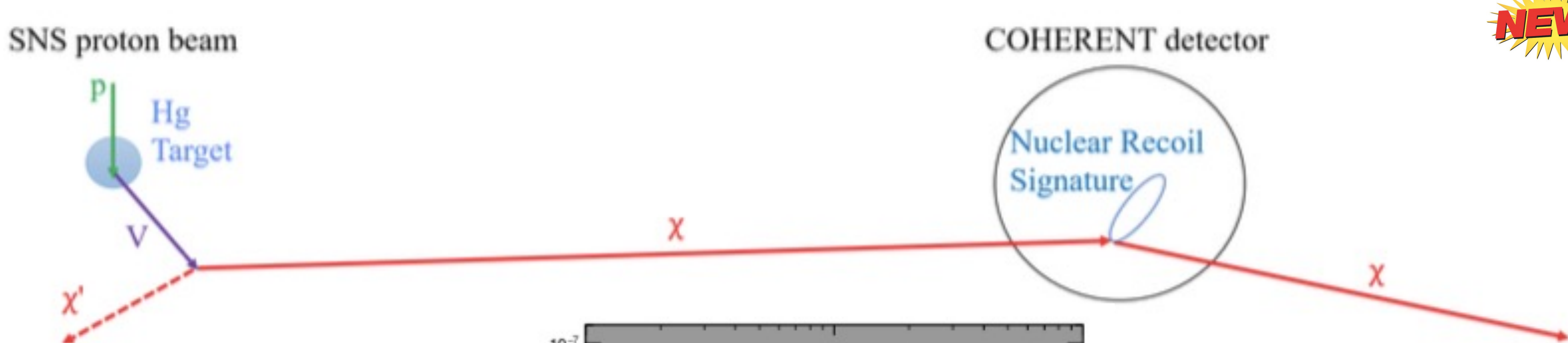
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

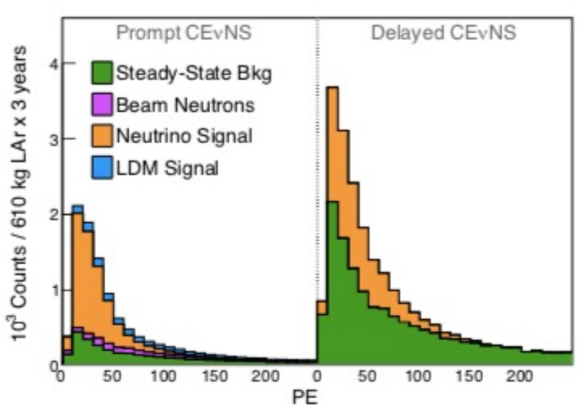
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

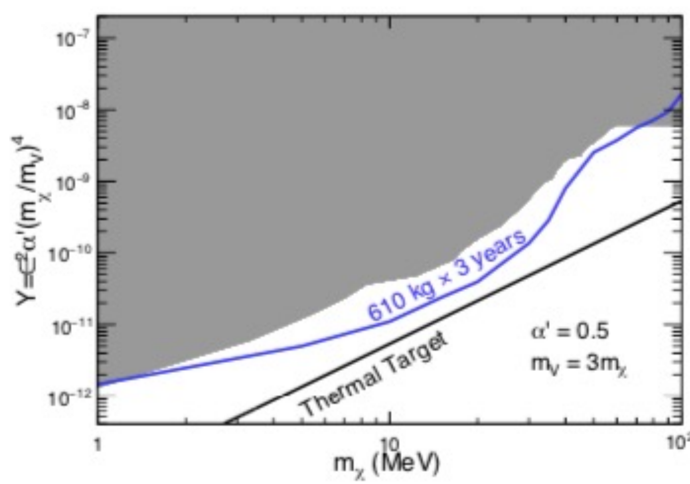
B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)

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

NEW!





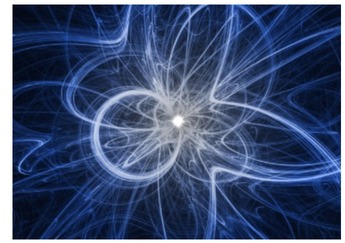


Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

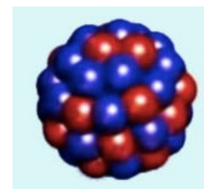
CEvNS: what's it good for?

(not a complete list!)

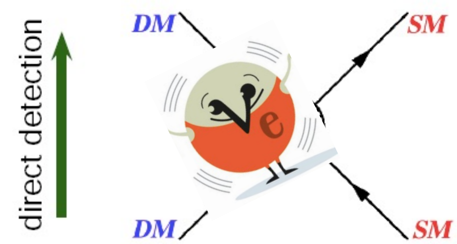
CEvNS as a **signal**
for signatures of *new physics*



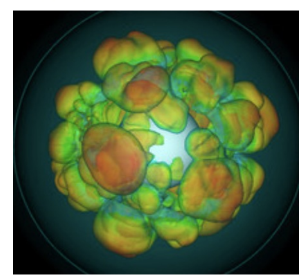
CEvNS as a **signal**
for understanding of "old" physics



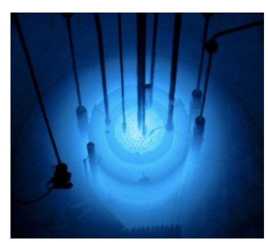
CEvNS as a **background**
for signatures of new physics (DM)



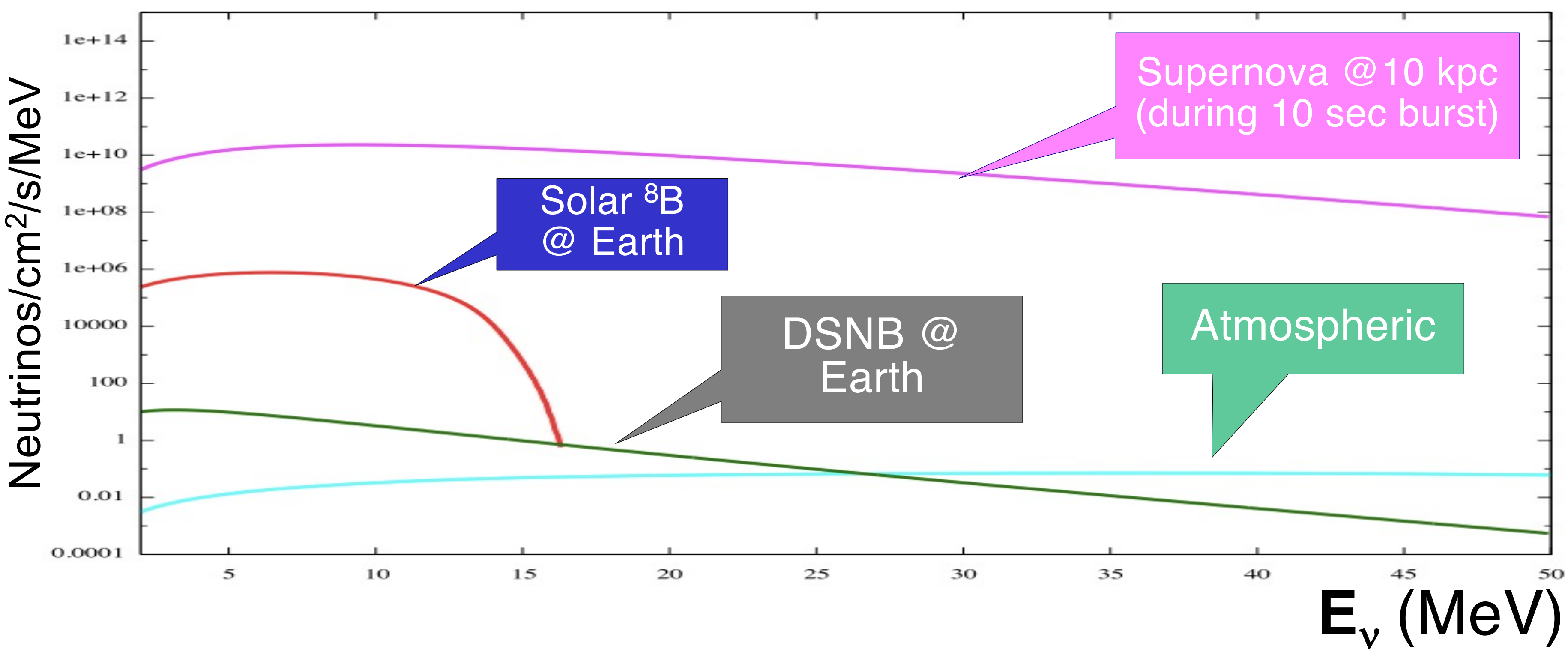
CEvNS as a **signal** for *astrophysics*



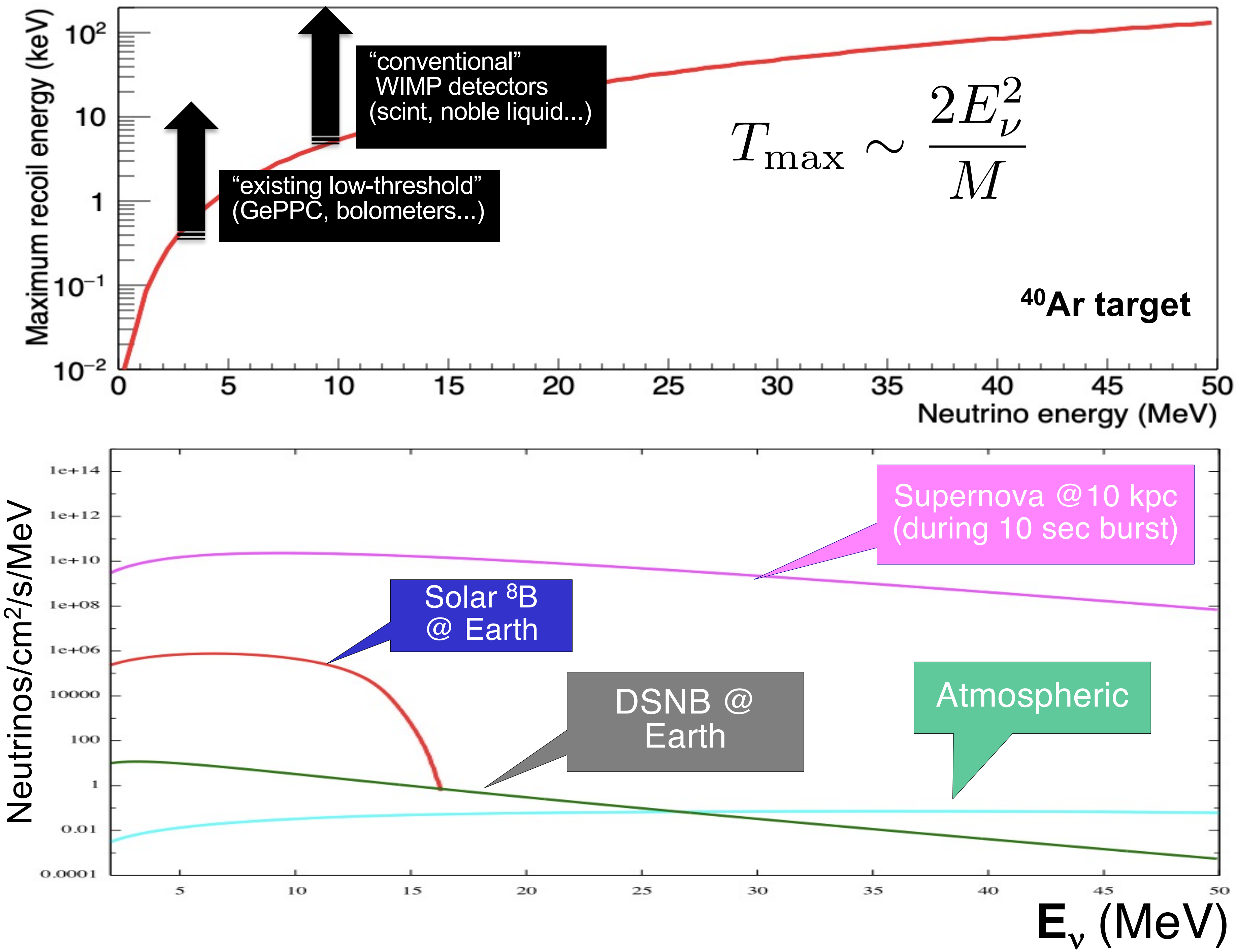
CEvNS as a **practical tool**



Natural neutrino fluxes

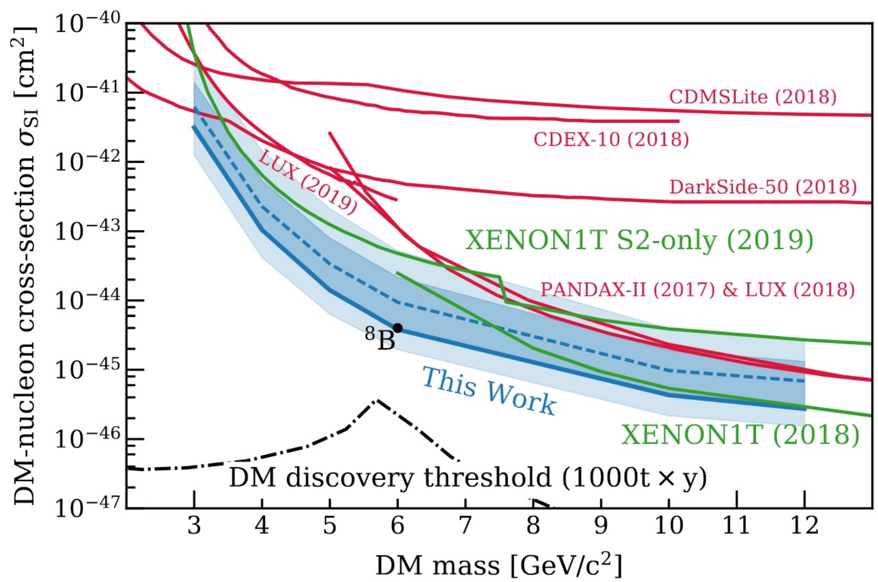


Natural neutrino fluxes

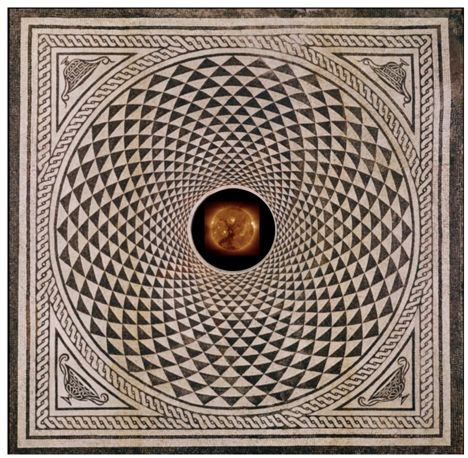


Search for CEvNS from solar neutrinos with the XENON-1T experiment

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...

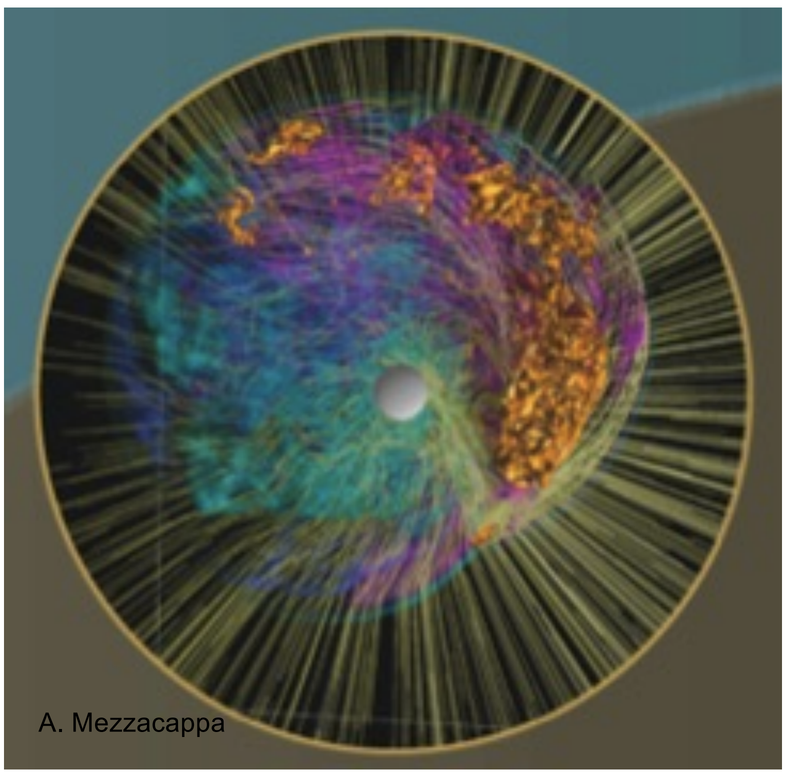


Neutrinos from core-collapse supernovae

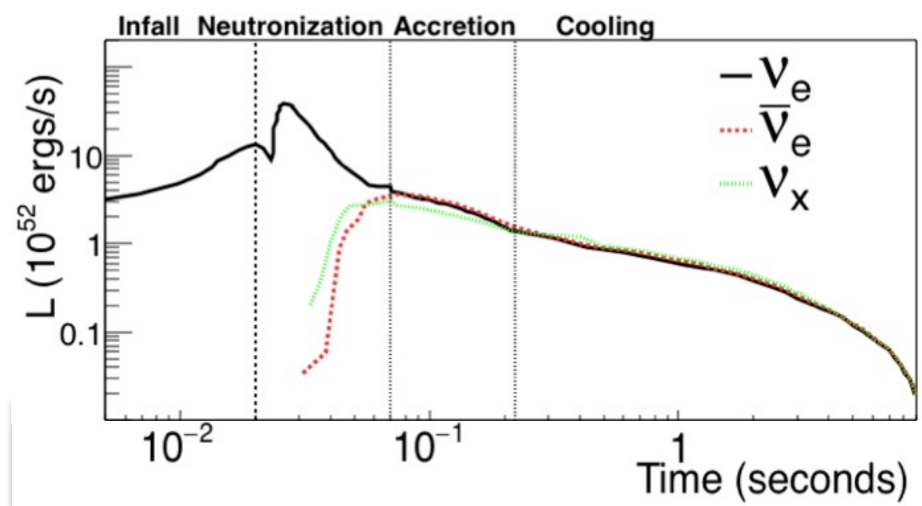
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

Energy *can* escape via ν's

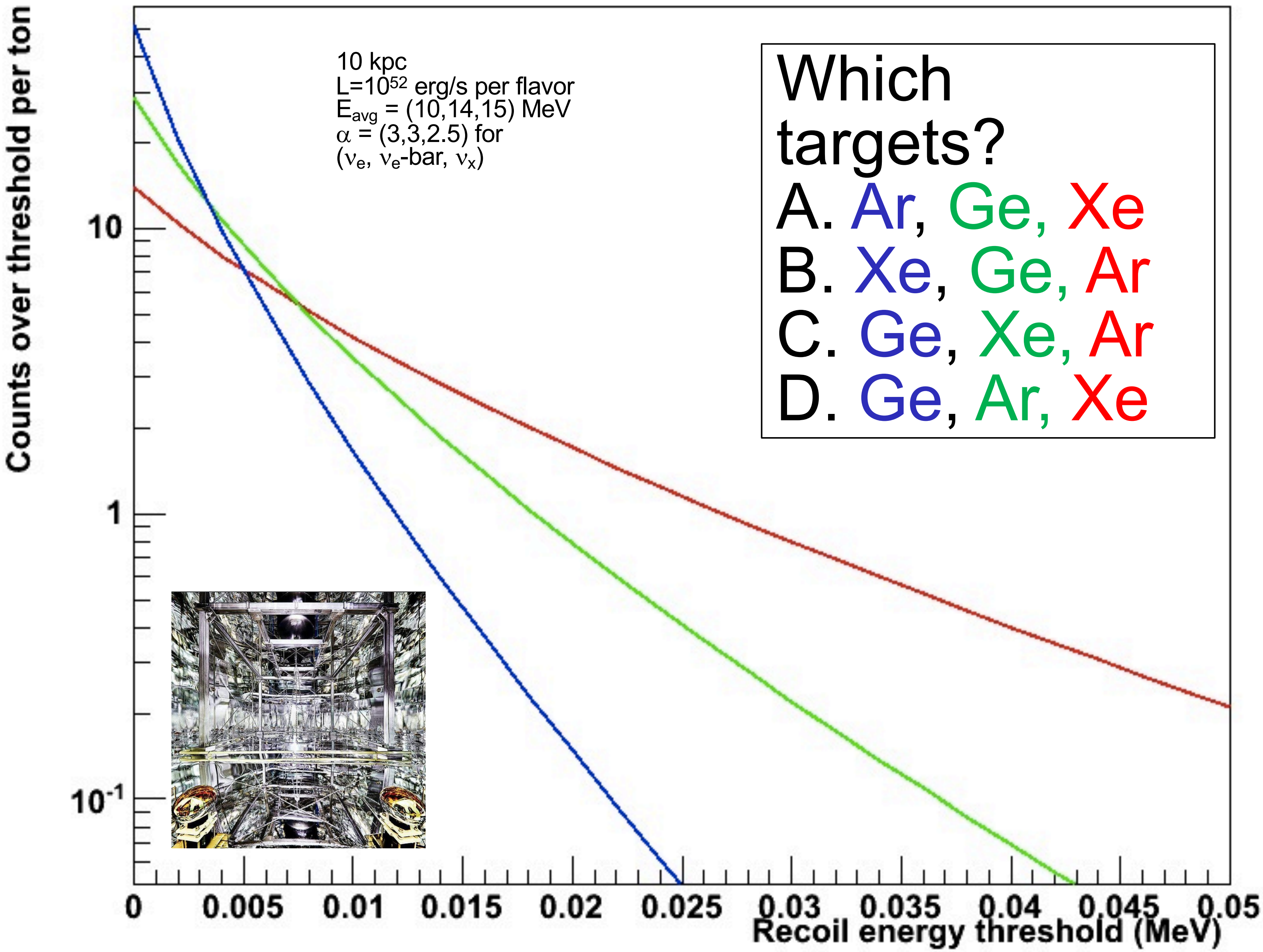
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



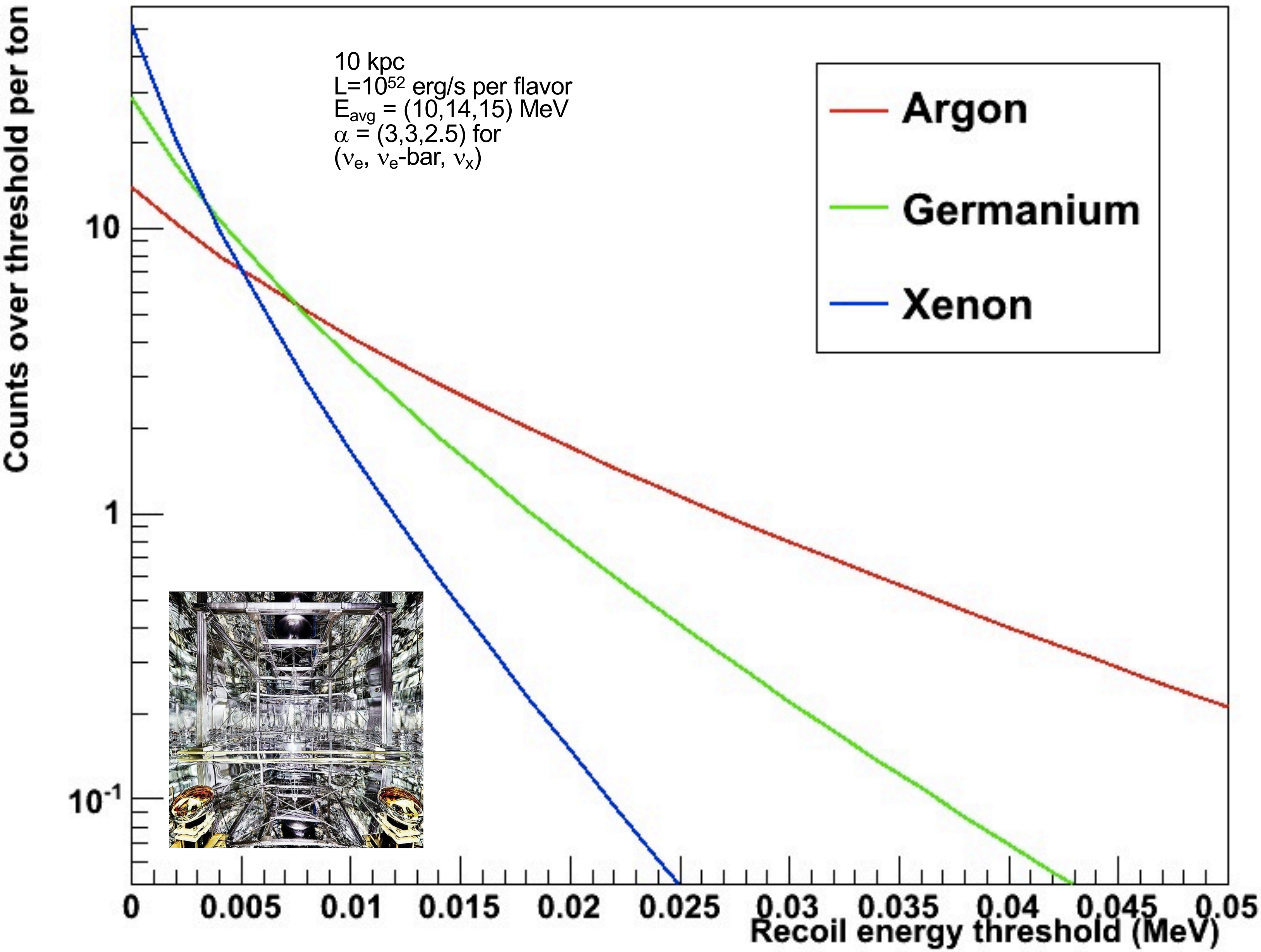
Timescale: *prompt* after core collapse, overall Δt~10's of seconds



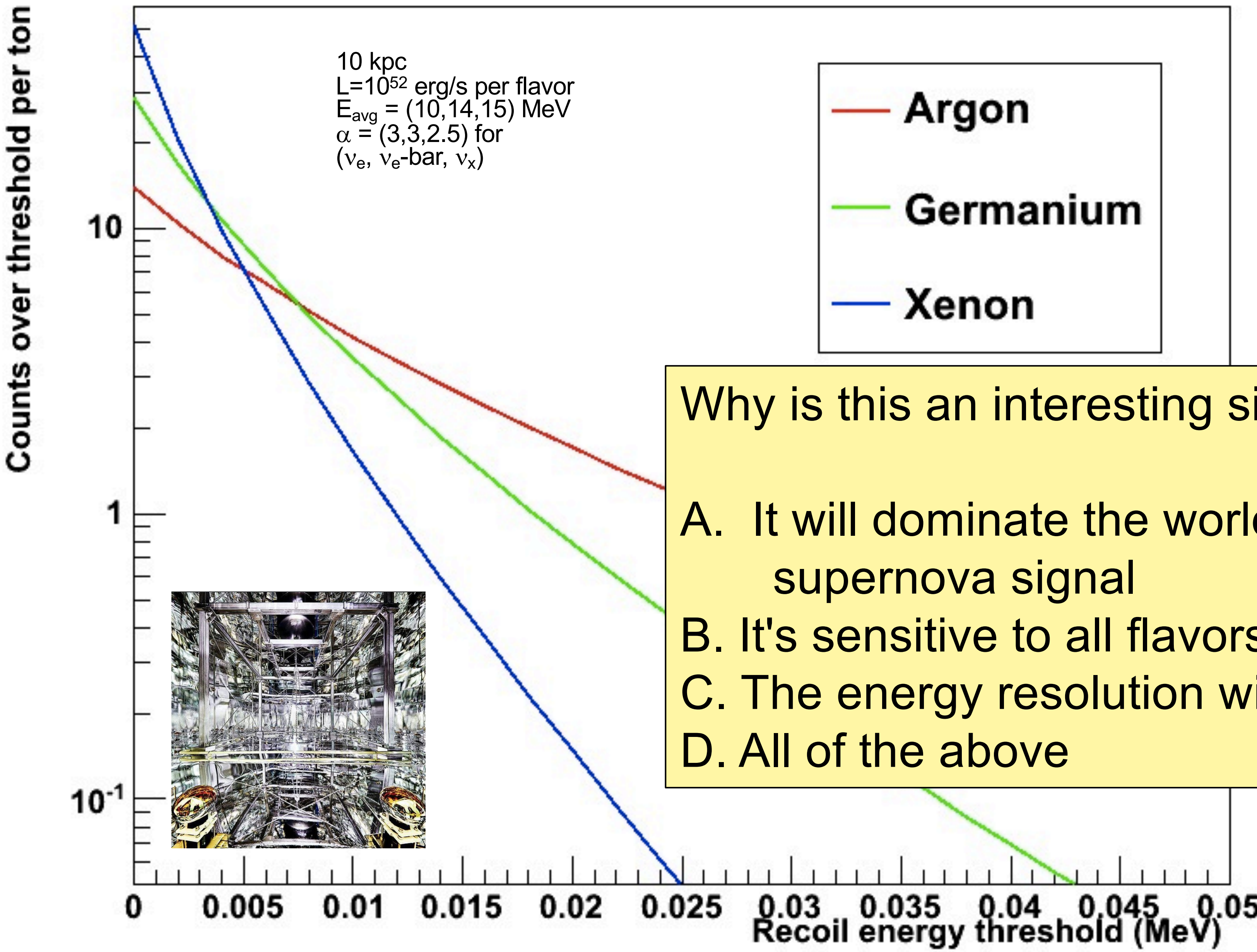
Supernova neutrinos in tonne-scale DM detectors



Supernova neutrinos in tonne-scale DM detectors



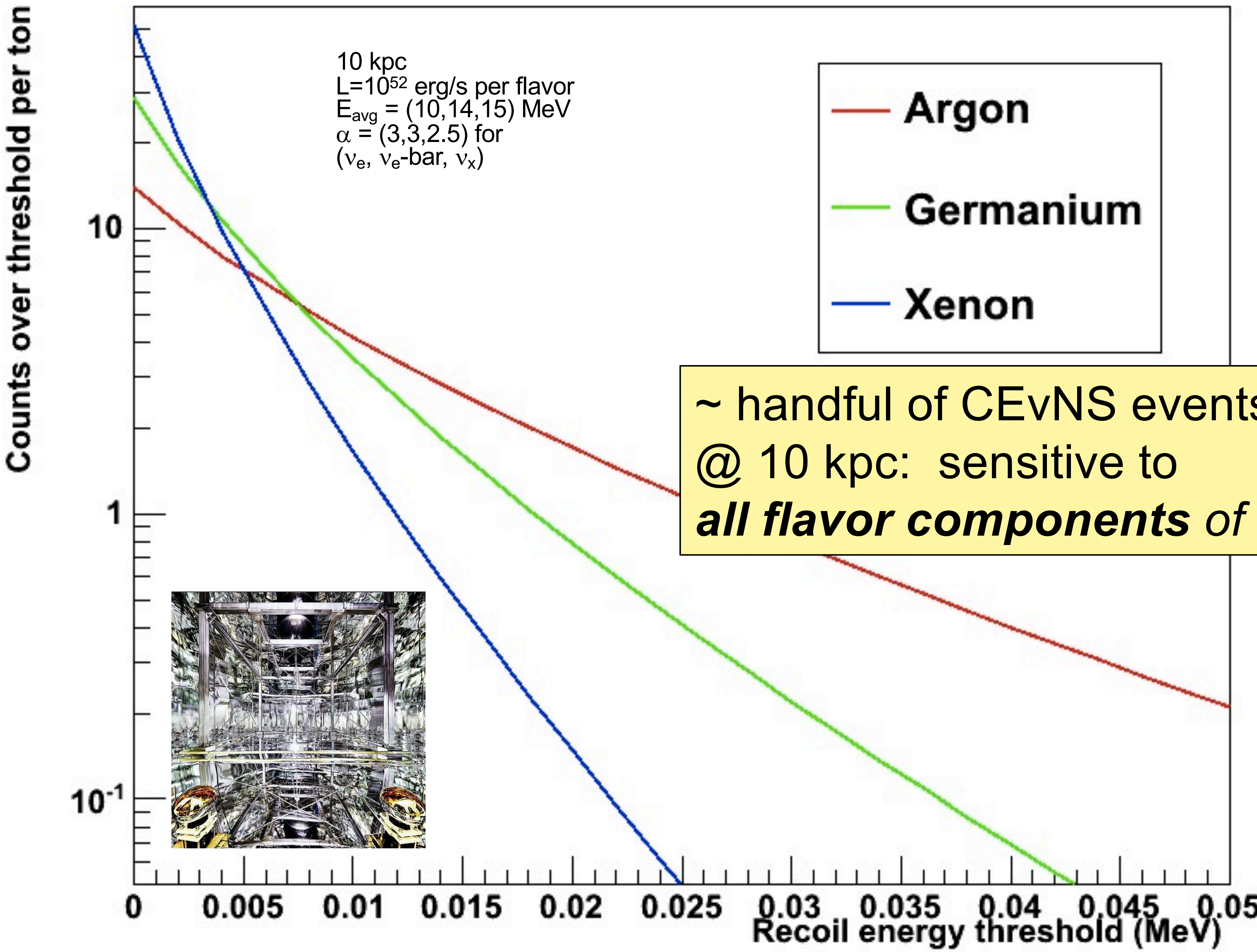
Supernova neutrinos in tonne-scale DM detectors



Why is this an interesting signal?

A. It will dominate the worldwide supernova signal
B. It's sensitive to all flavors of the burst
C. The energy resolution will be good
D. All of the above

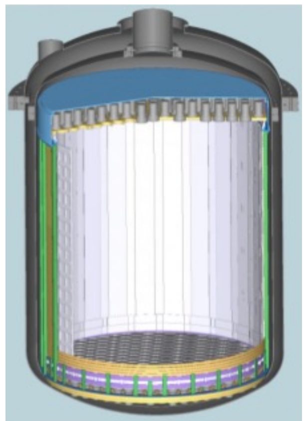
Supernova neutrinos in tonne-scale DM detectors

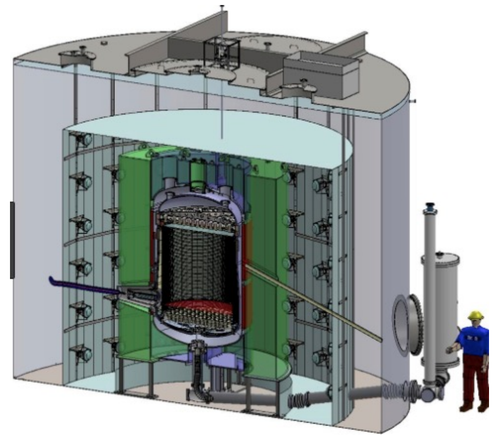


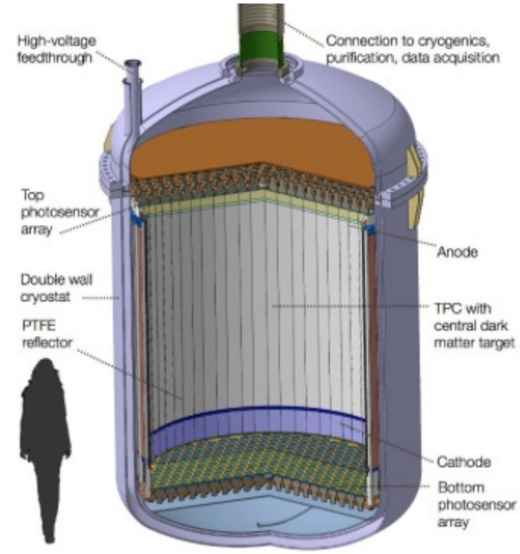
~ handful of CEvNS events per tonne @ 10 kpc: sensitive to ***all flavor components*** *of the flux*

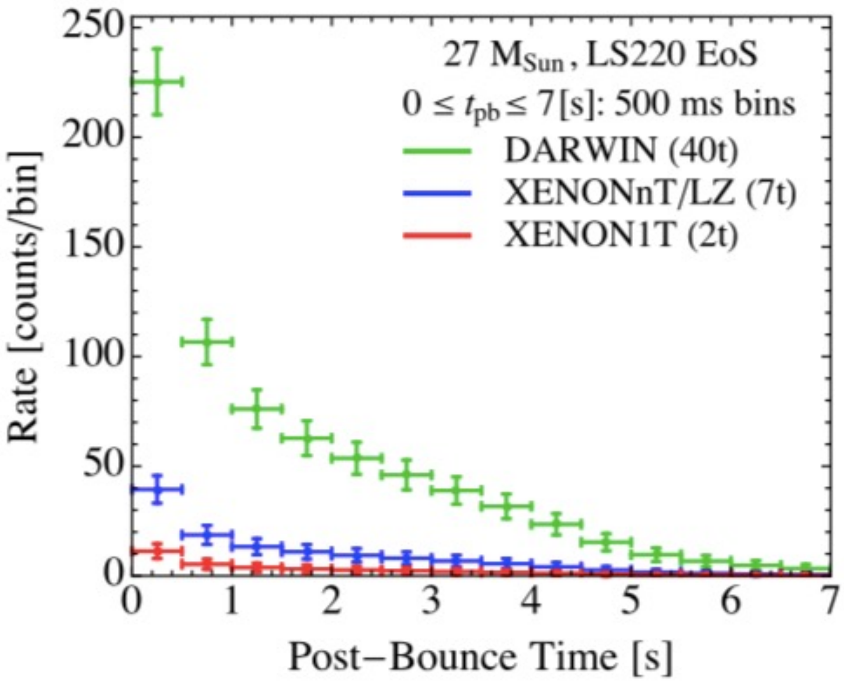
Detector example: **XENON/LZ/DARWIN**

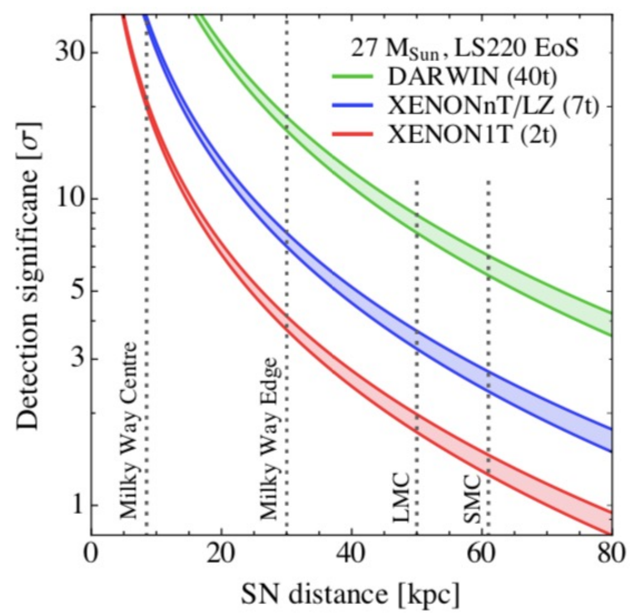
- dual-phase xenon time projection chambers









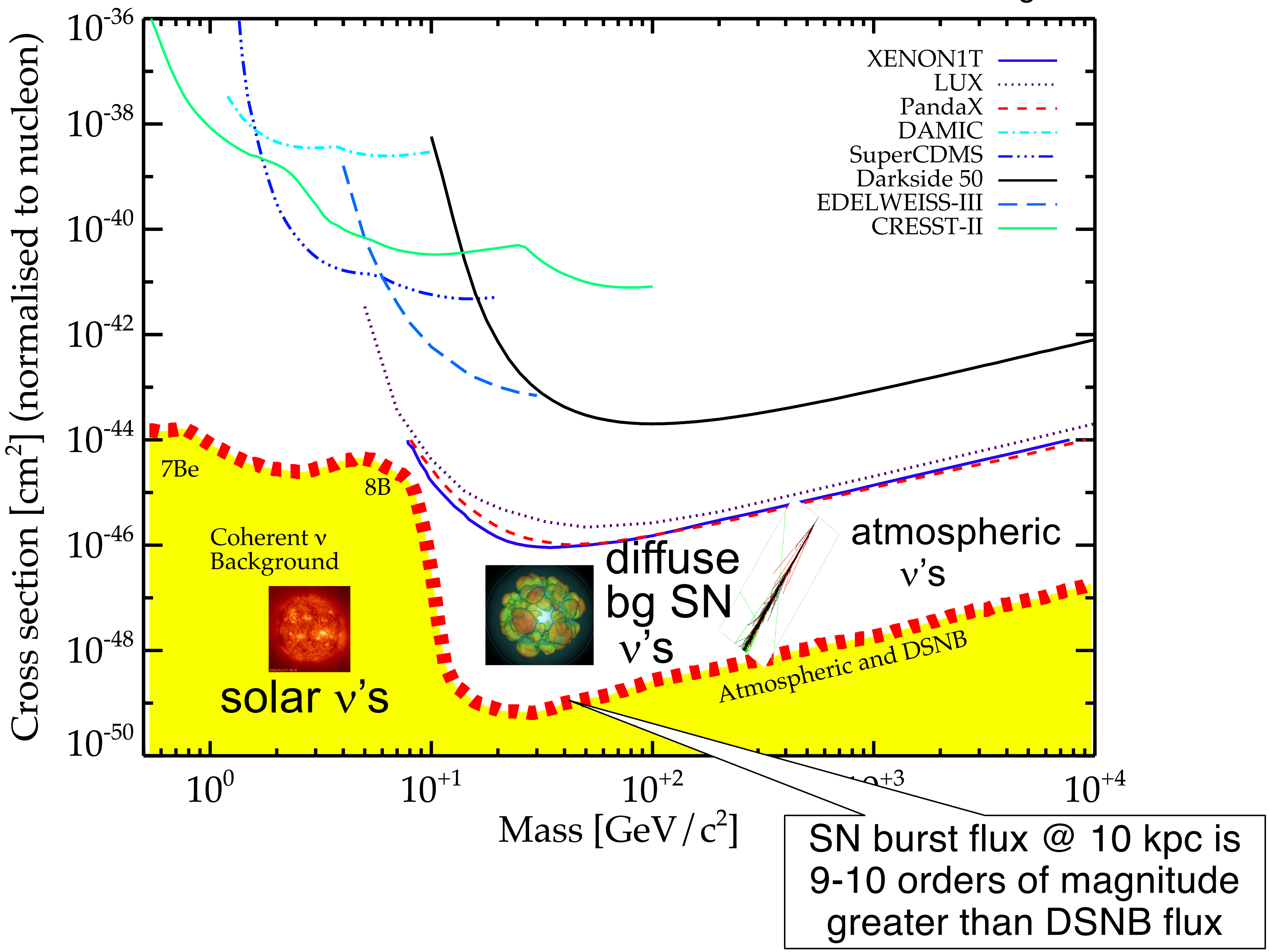


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

The so-called “**neutrino floor**” for DM experiments

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

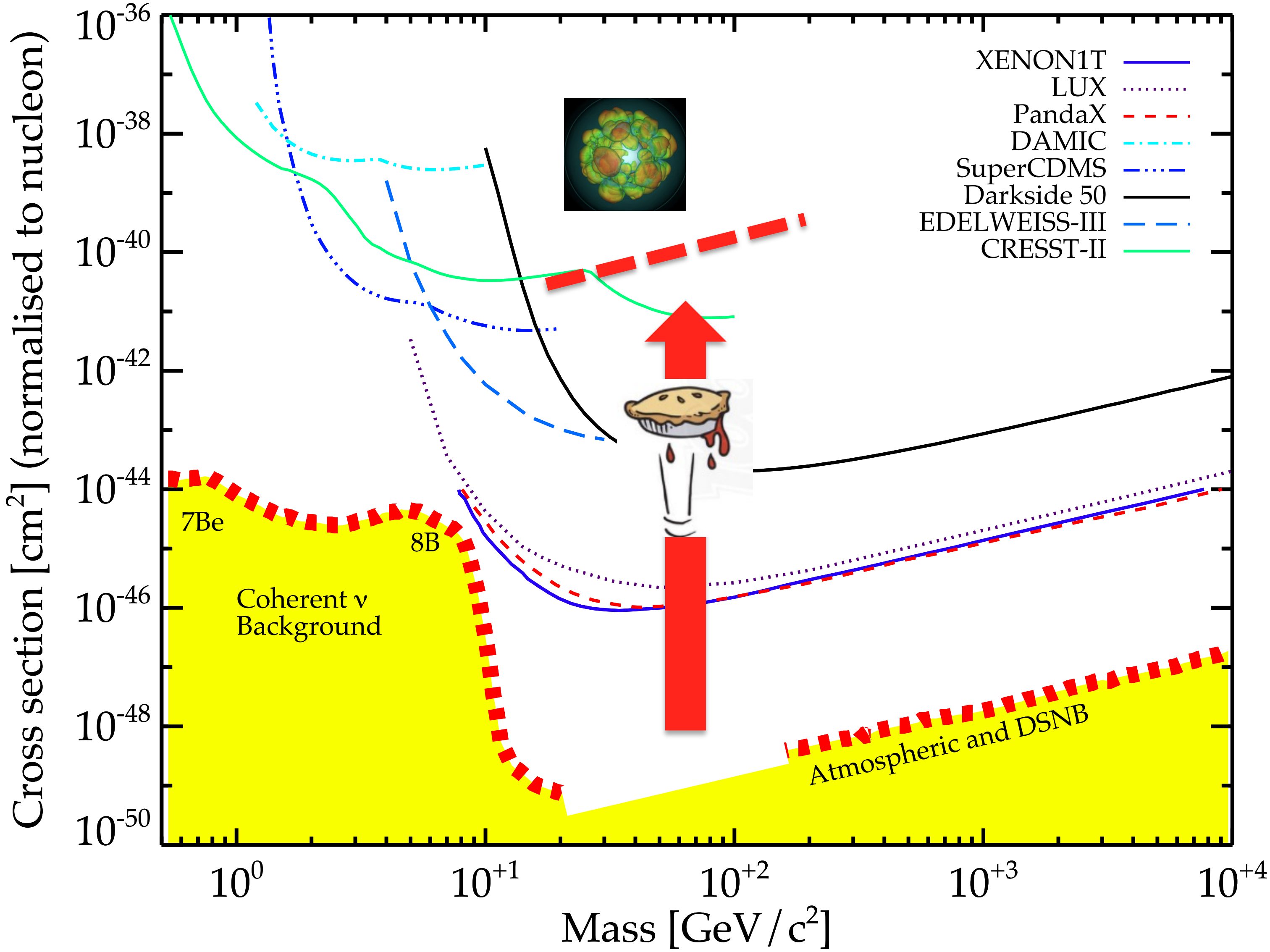
L. Strigari



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

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

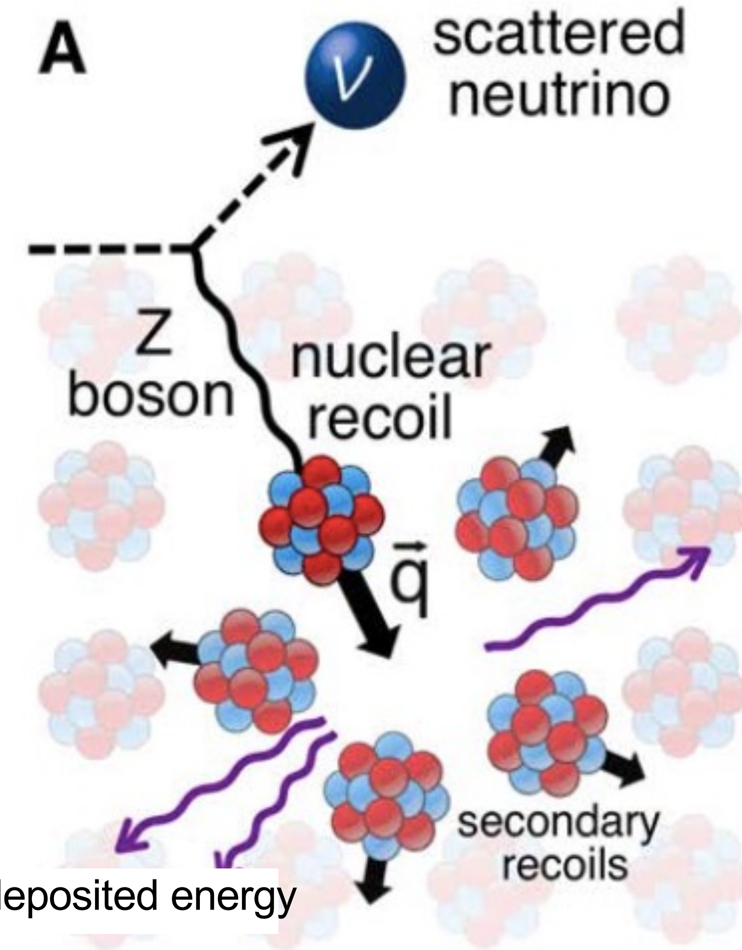
L. Strigari



How to measure CEvNS

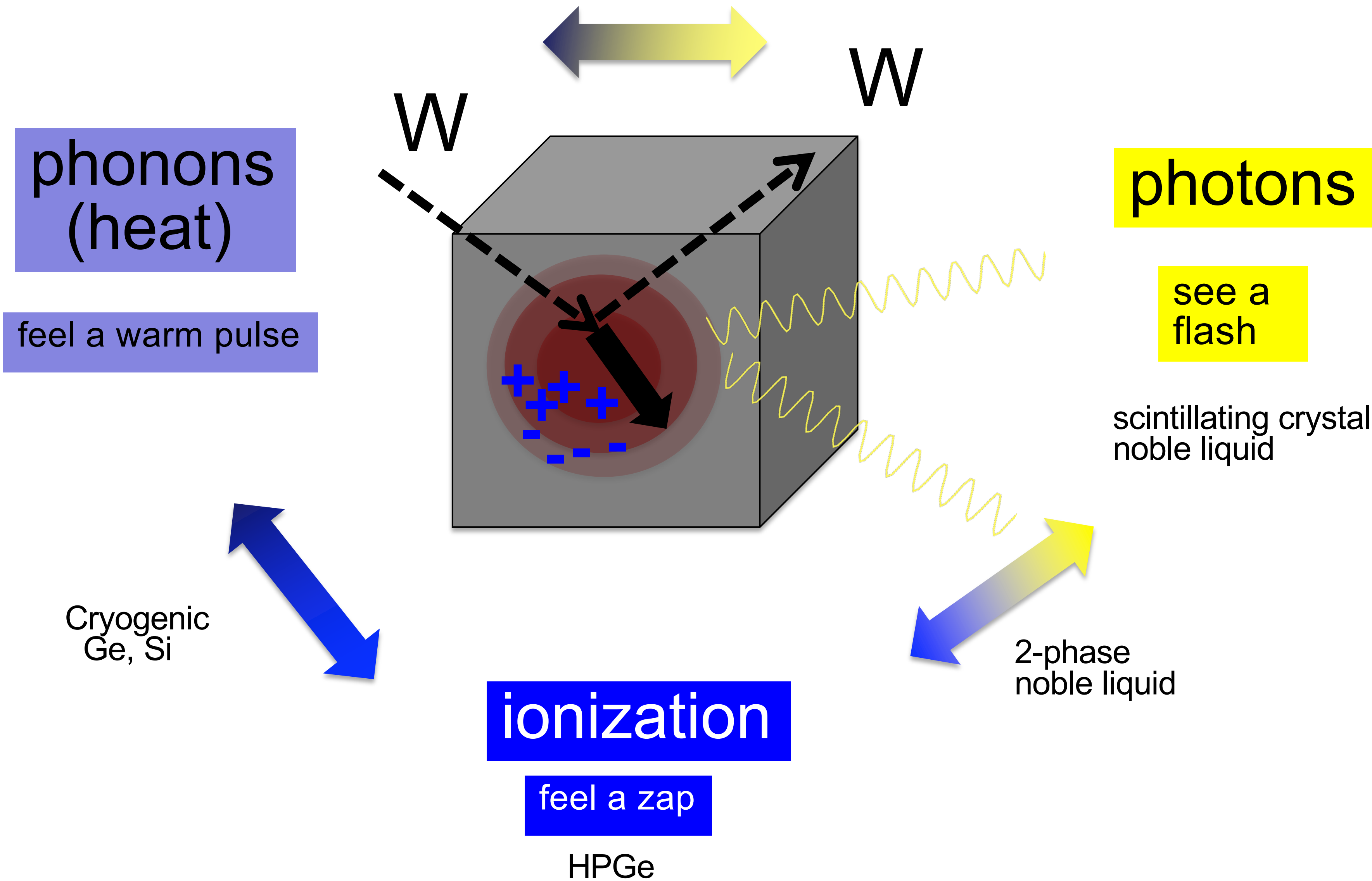
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



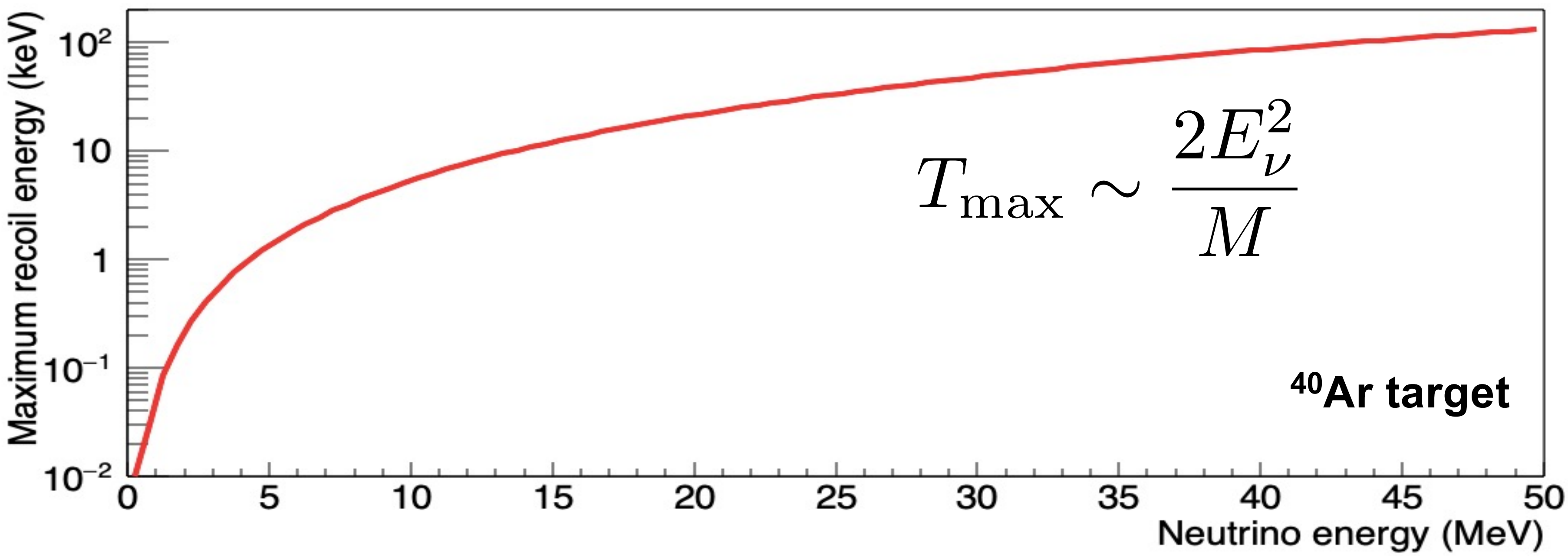
➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10's of keV recoils

Low-energy nuclear recoil detection strategies



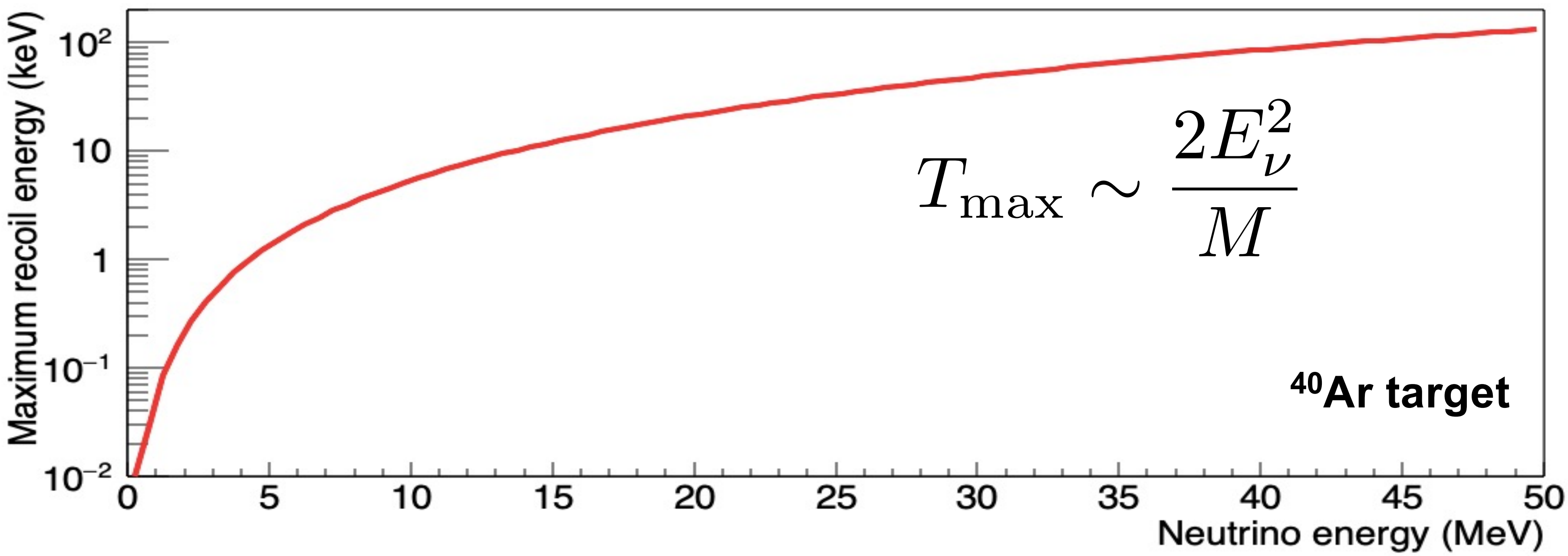
http://dmrc.snu.ac.kr/english/intro/intro1.html

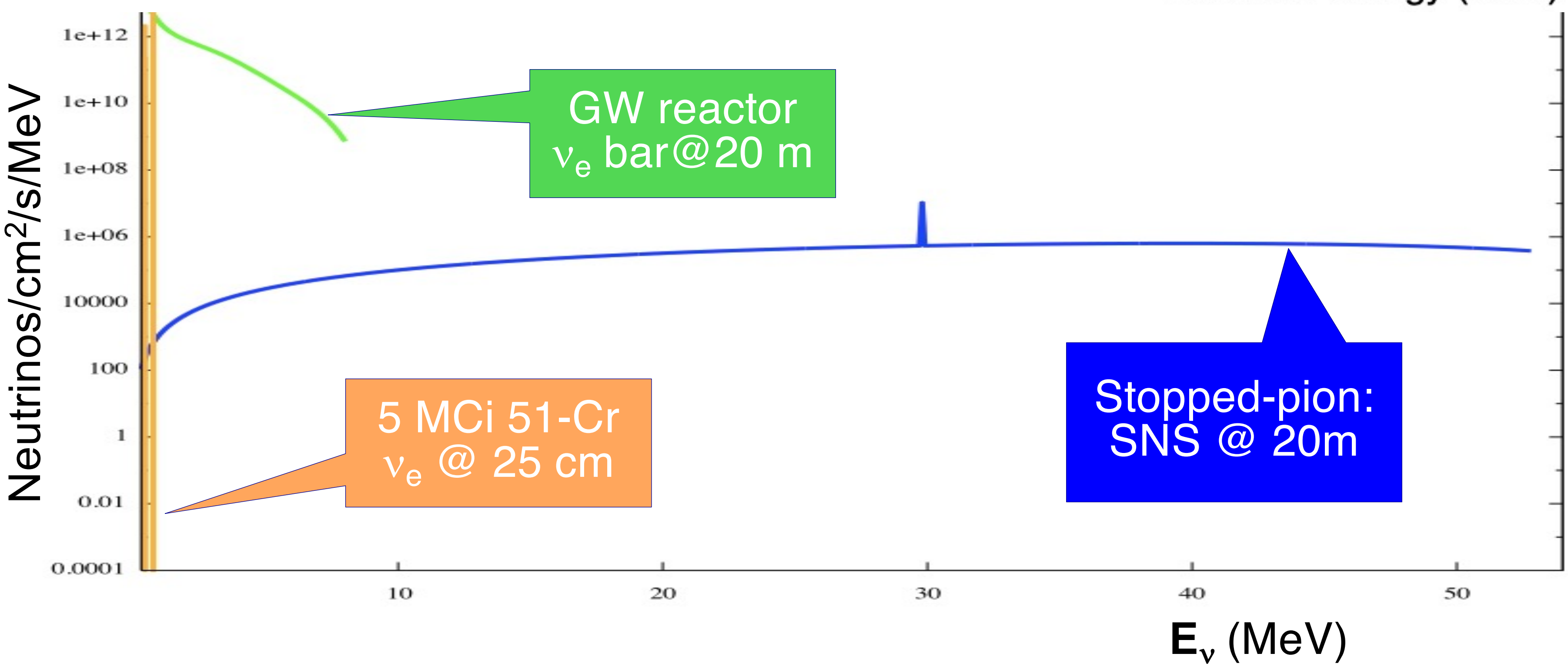
Maximum recoil energy as a function of E_ν



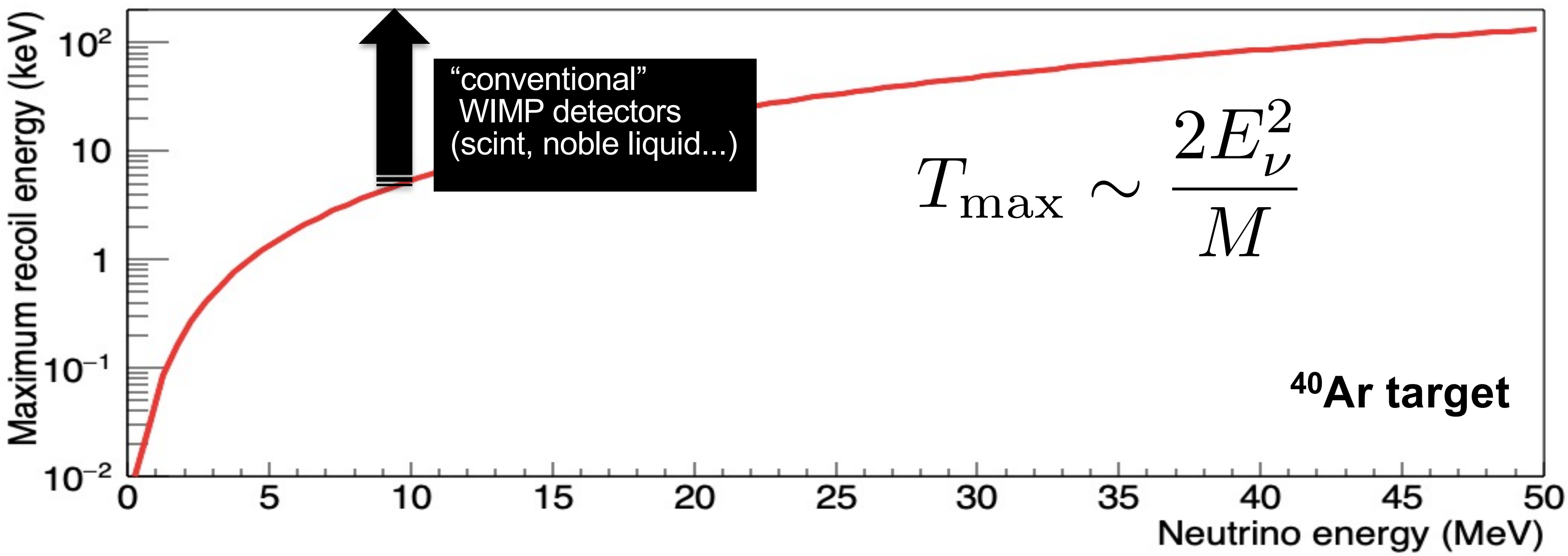
$$T_{\max} \sim \frac{2E_\nu^2}{M}$$

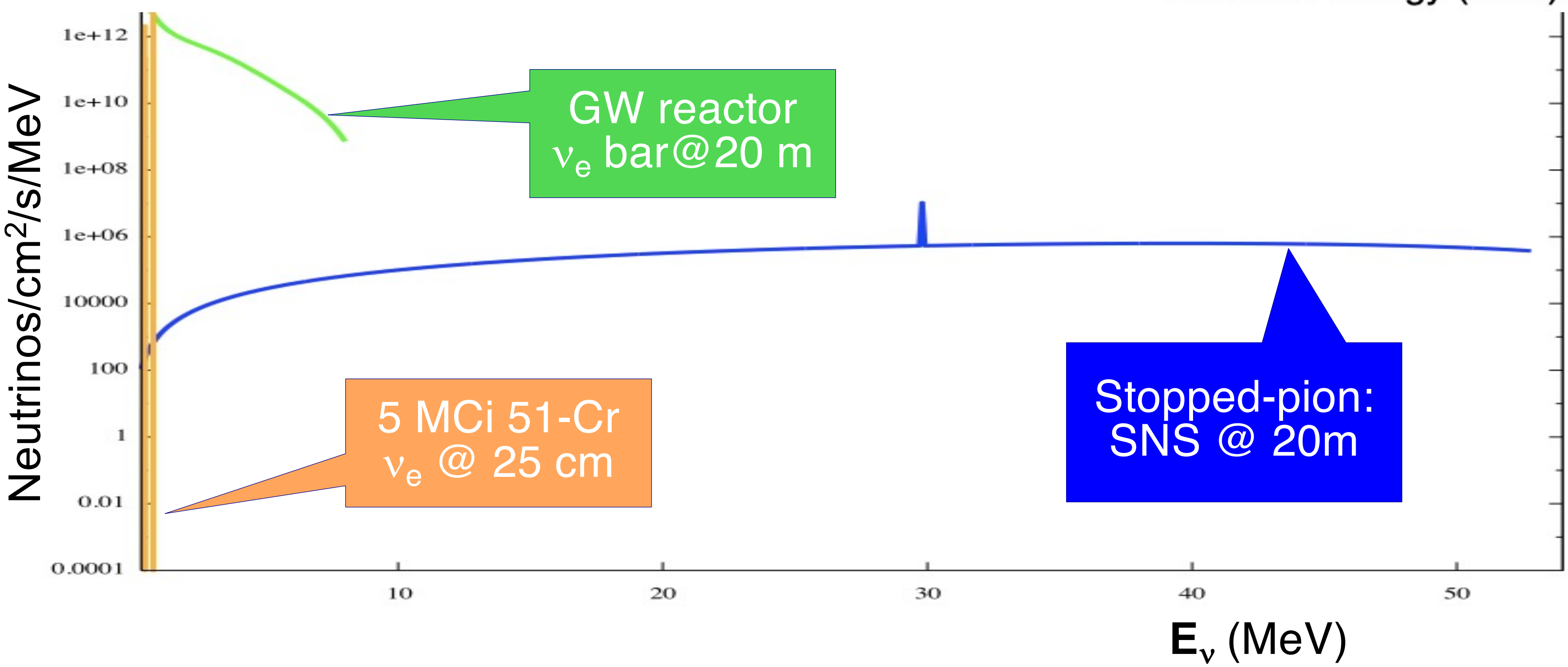
Maximum recoil energy as a function of E_ν



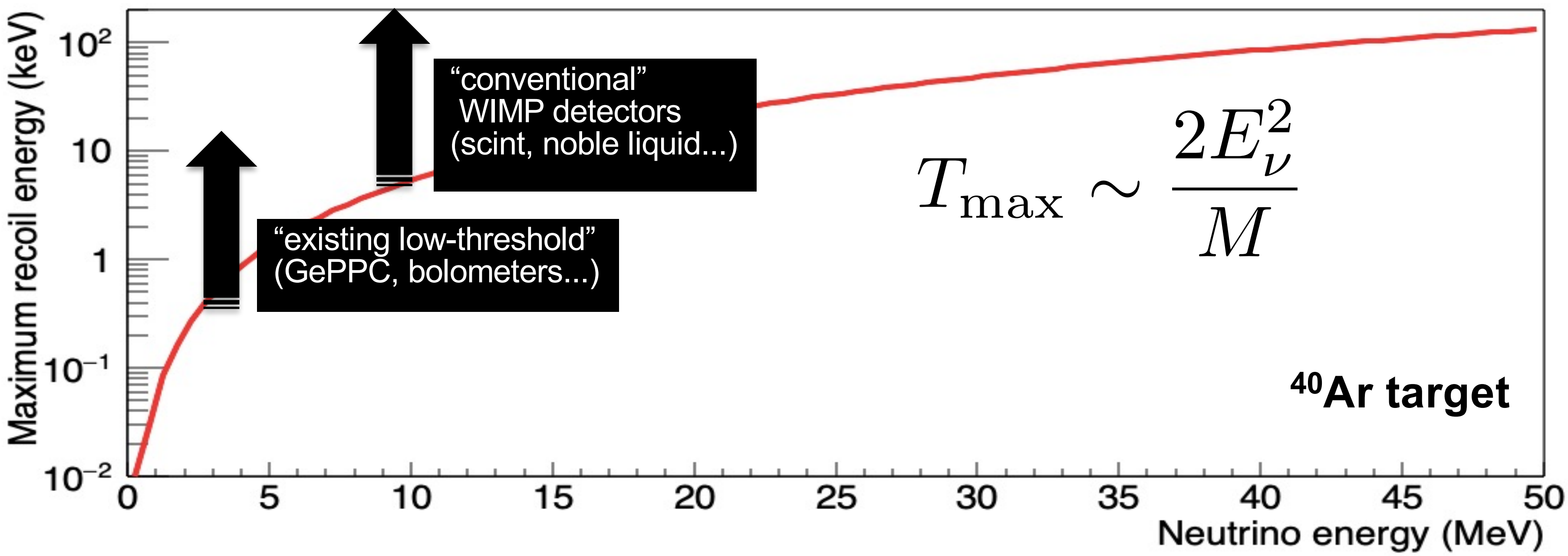


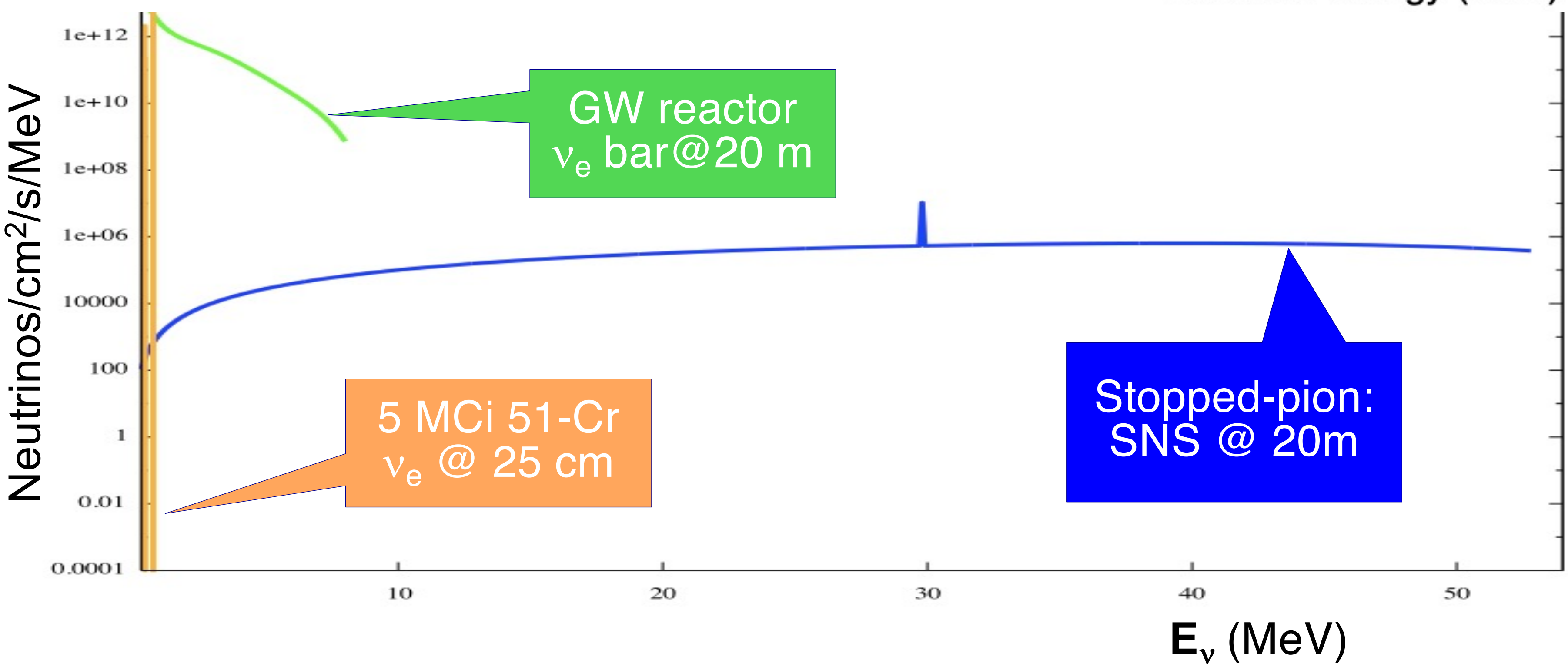
Maximum recoil energy as a function of E_ν



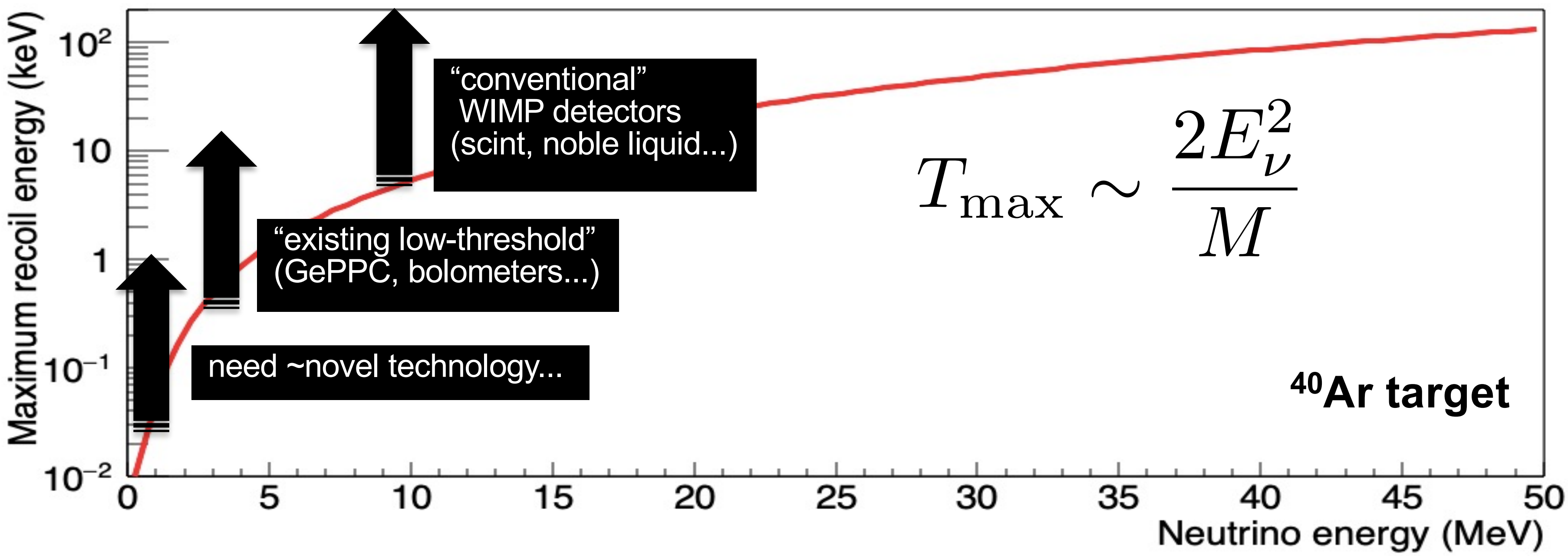


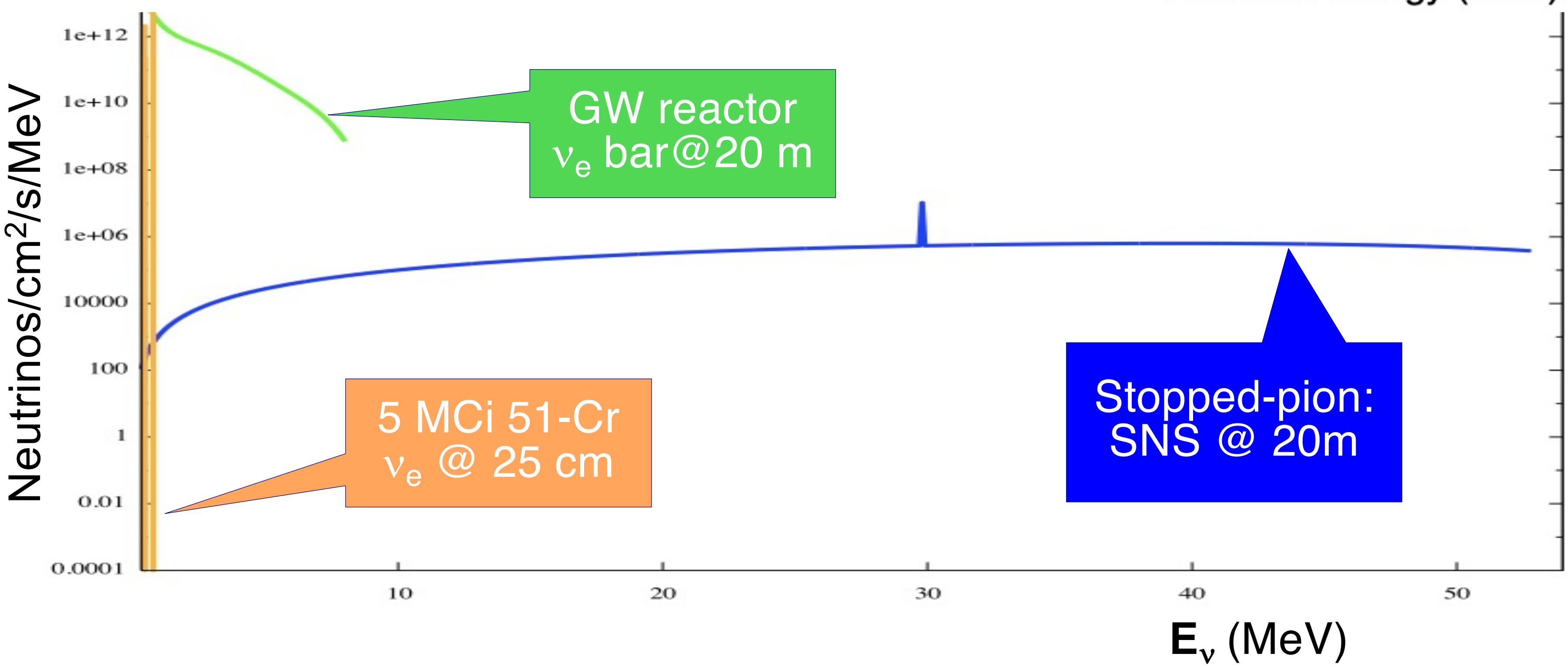
Maximum recoil energy as a function of E_ν



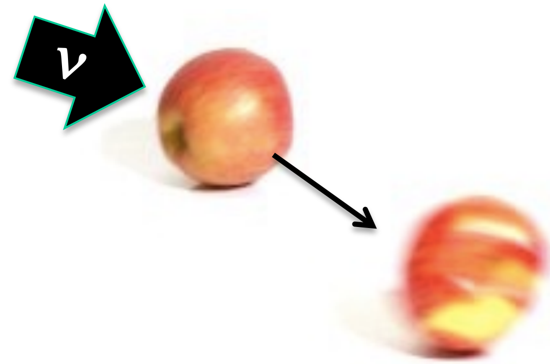


Maximum recoil energy as a function of E_ν





How to detect CEvNS?

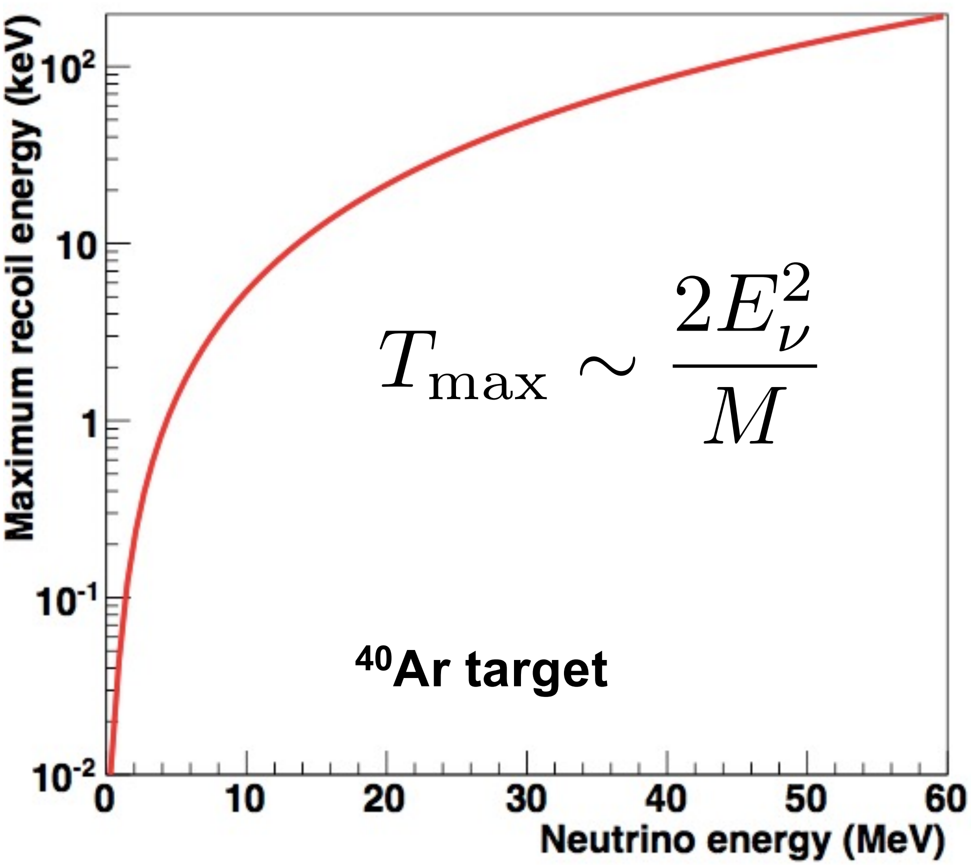


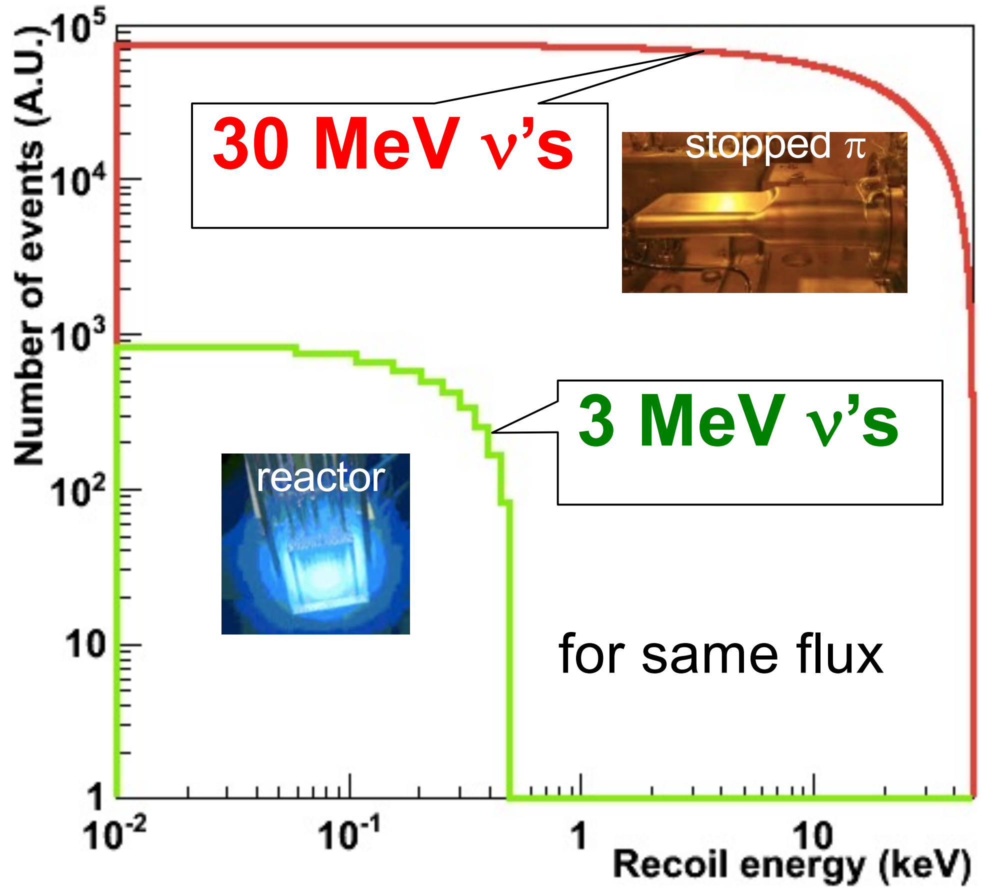
You need a neutrino source
and a detector

What do you want for your ν source?

- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

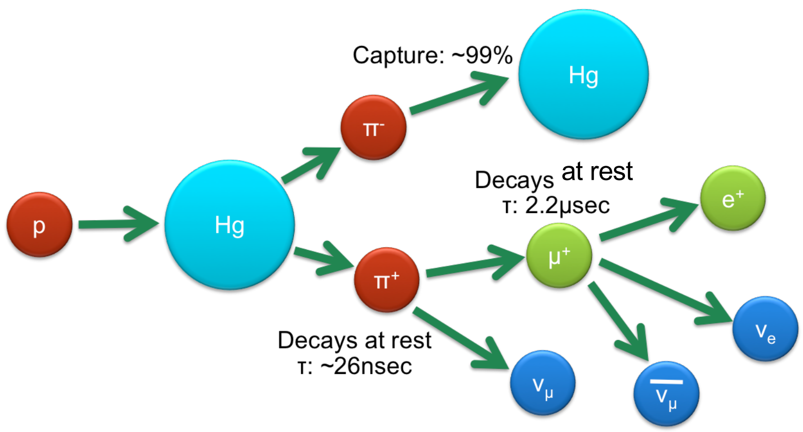
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

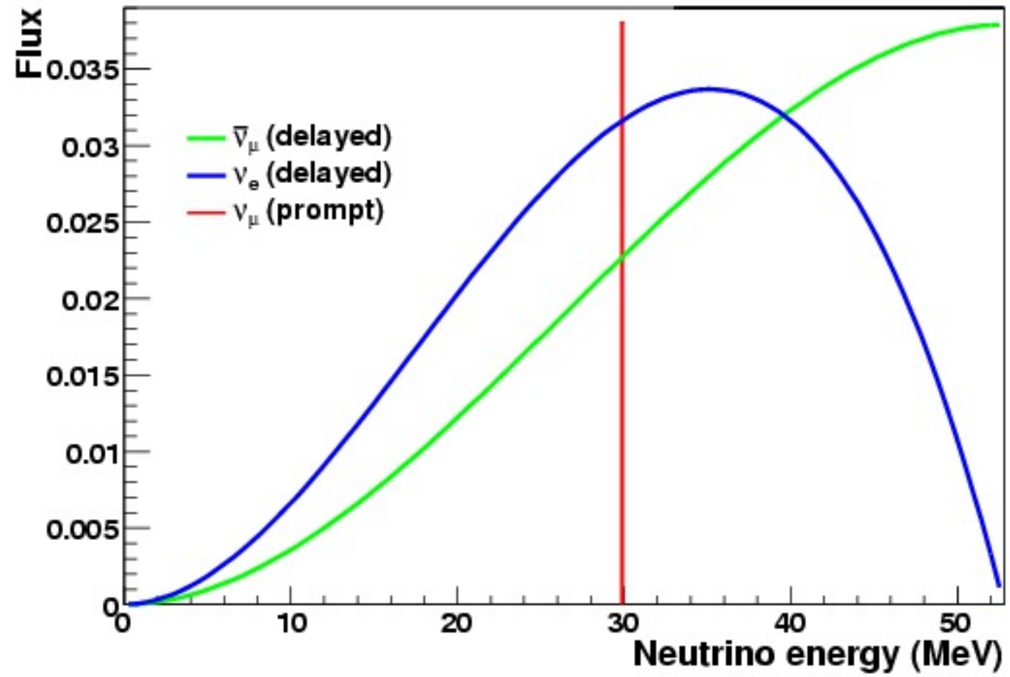




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





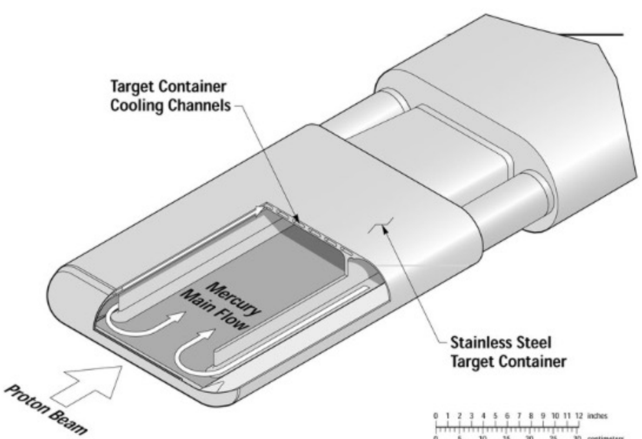
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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)

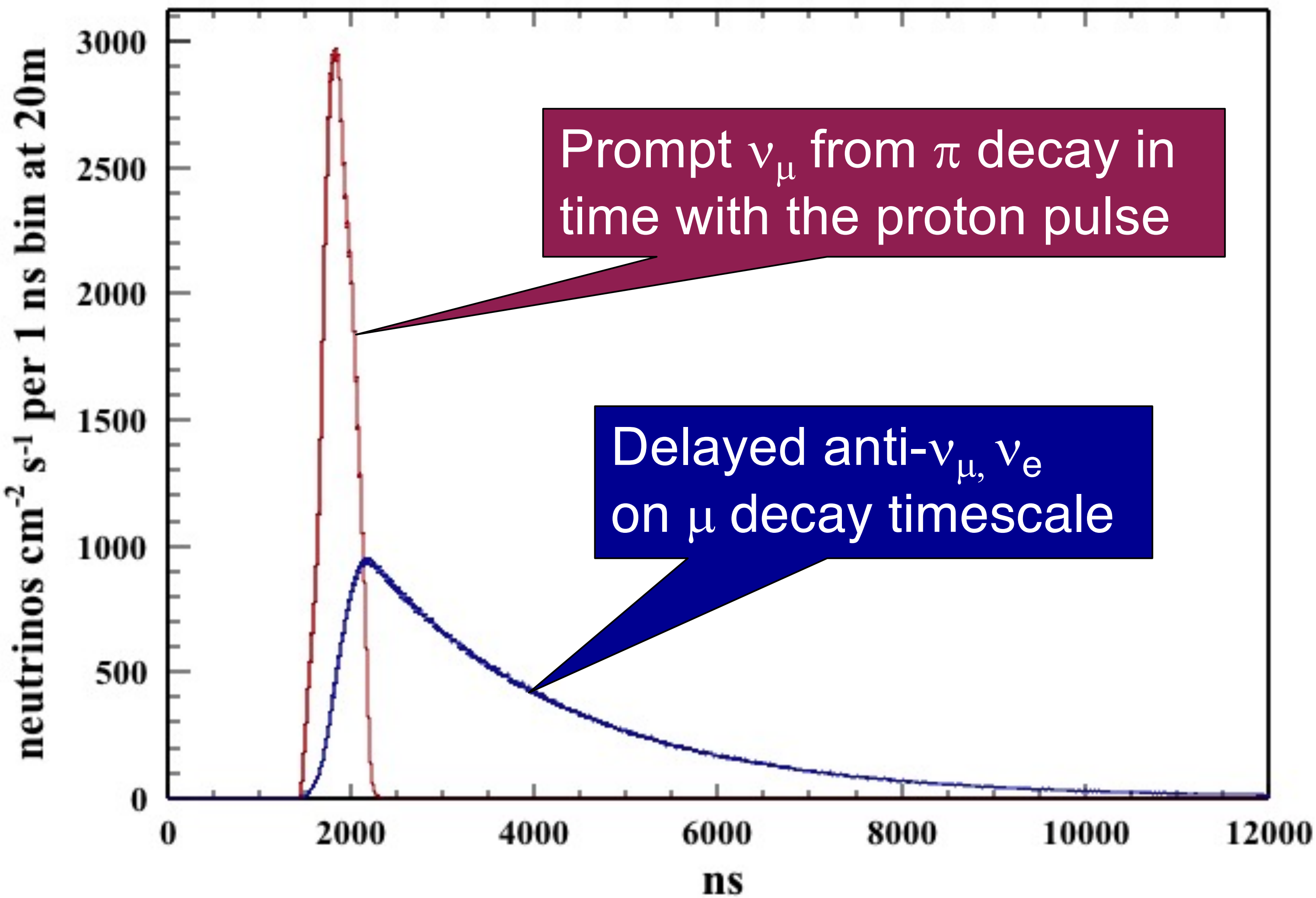


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

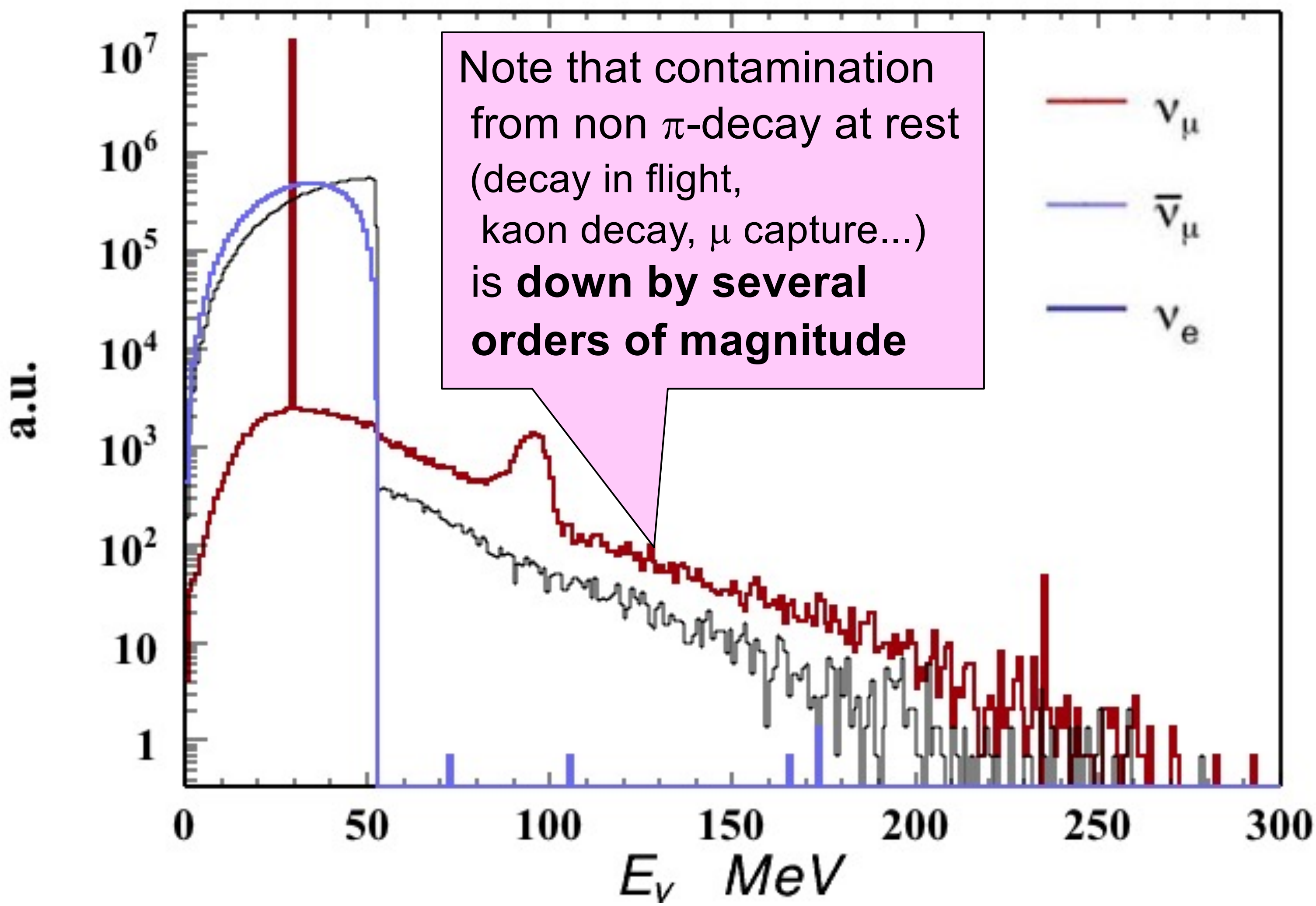
60 Hz *pulsed* source



Background rejection factor ~few x 10^{-4}

The SNS has **large, extremely clean** stopped-pion ν flux

0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

The COHERENT collaboration

http://sites.duke.edu/coherent

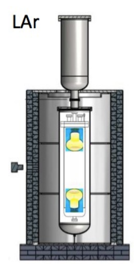
~90 members,
19 institutions
4 countries

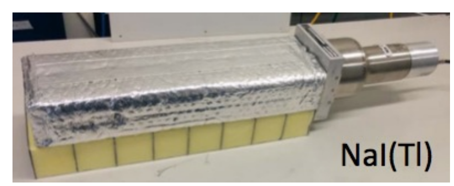
arXiv:1509.08702

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

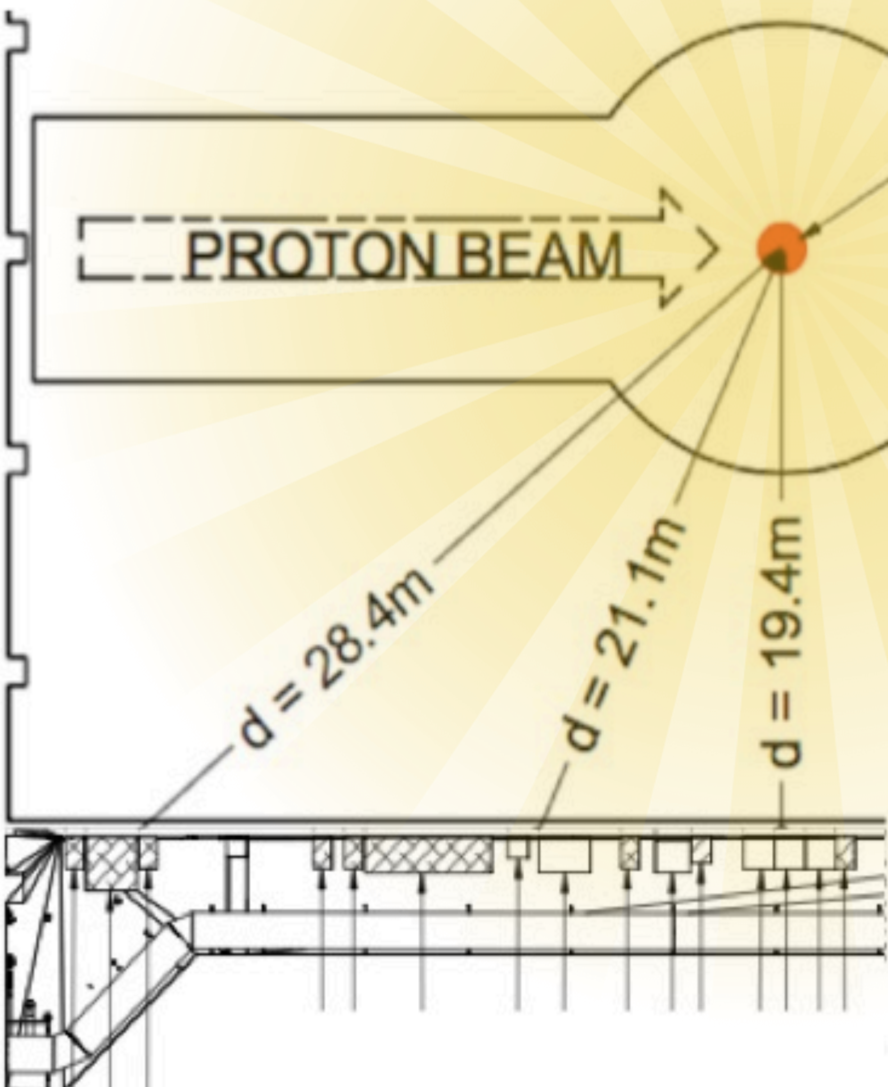


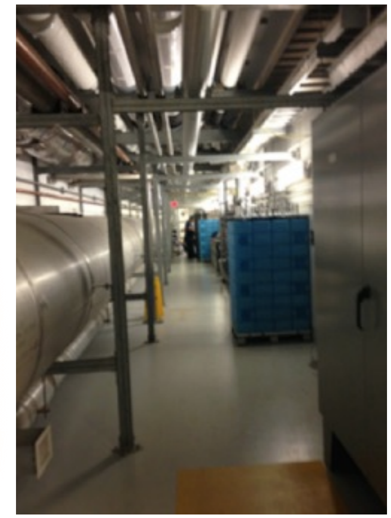


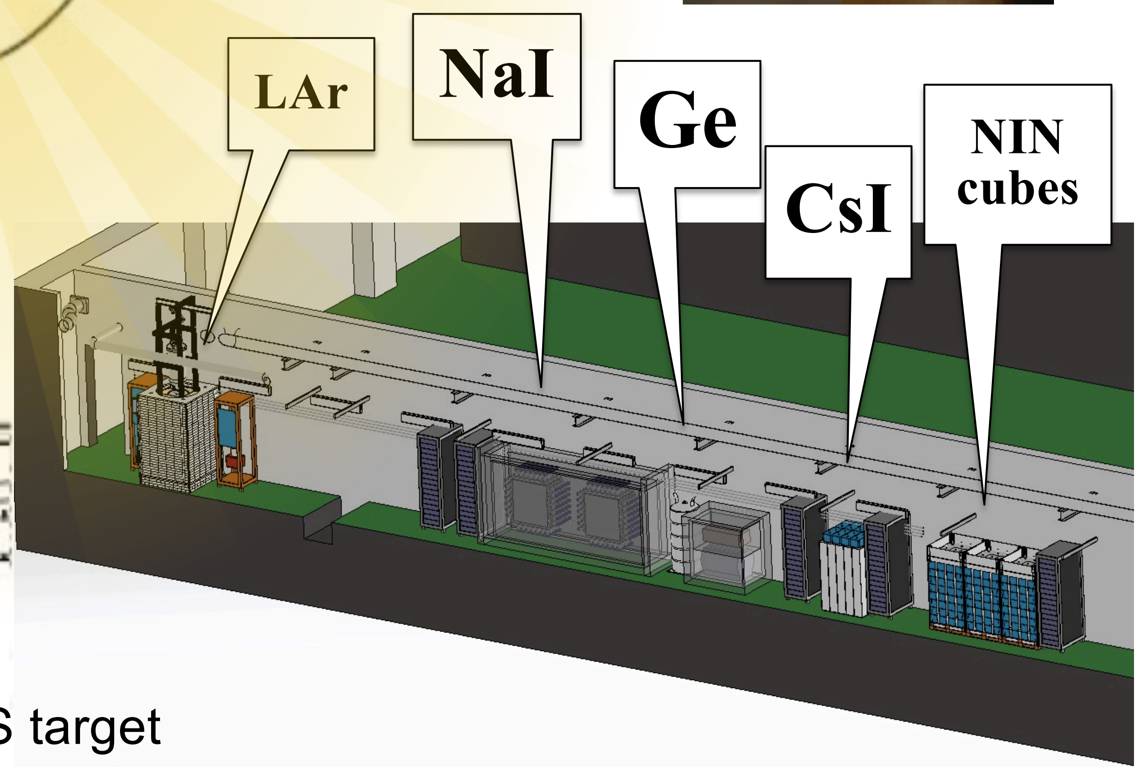
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking down “Neutrino Alley”

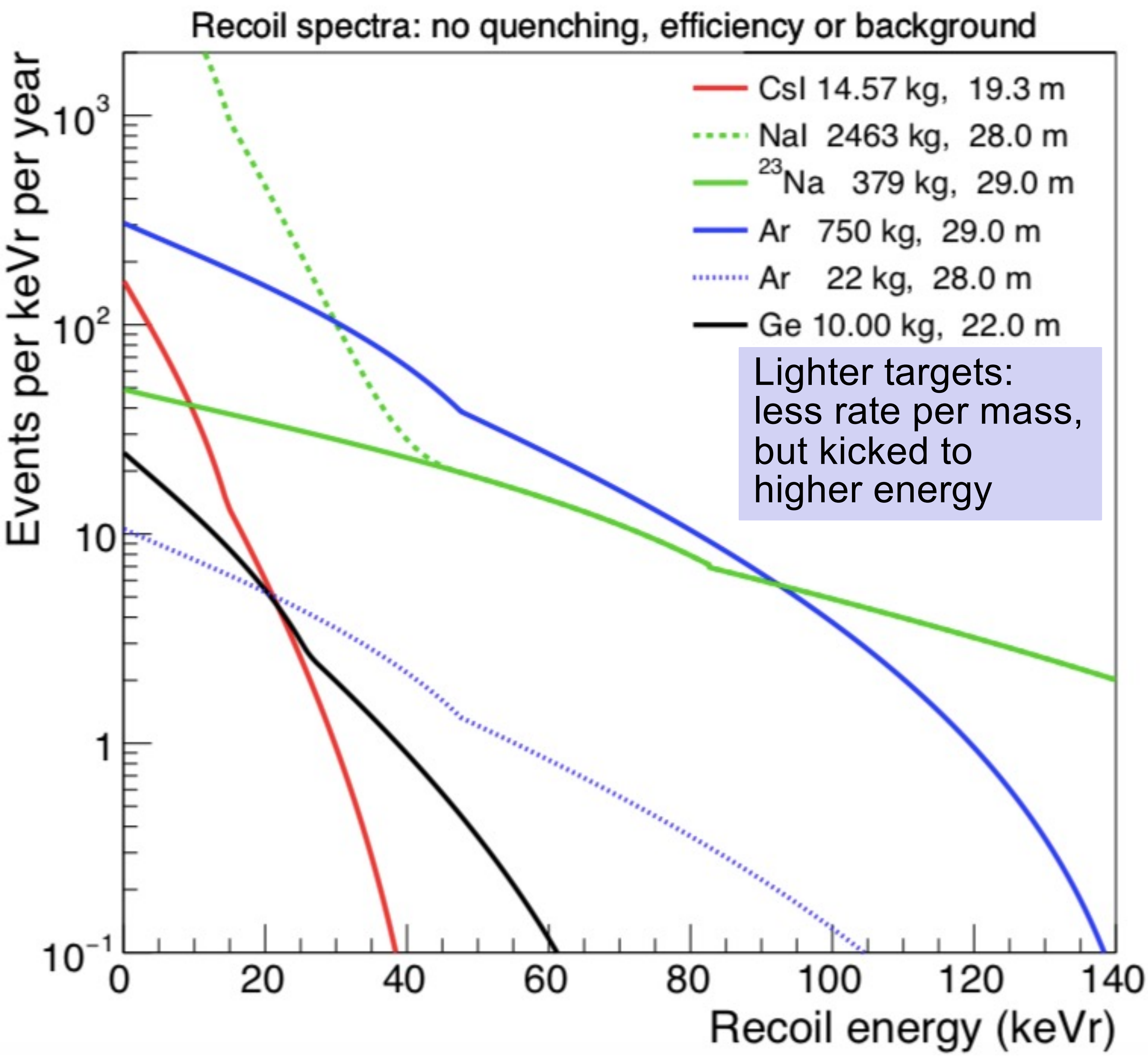






Isotropic ν glow from Hg SNS target

Expected recoil energy distribution



If 100 counts are expected in 10 kg of argon at 20 m, how many are expected in 100 kg at 40 m?

A. 2.5

B. 25

C. 100

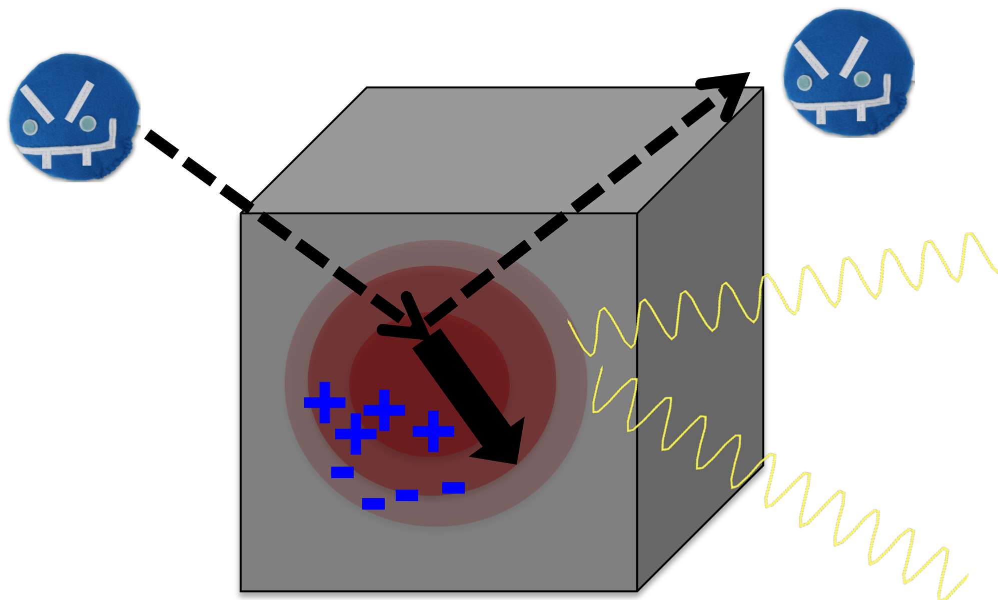
D. 250

E. 2500

Backgrounds

Usual suspects:
- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not your friends*



Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

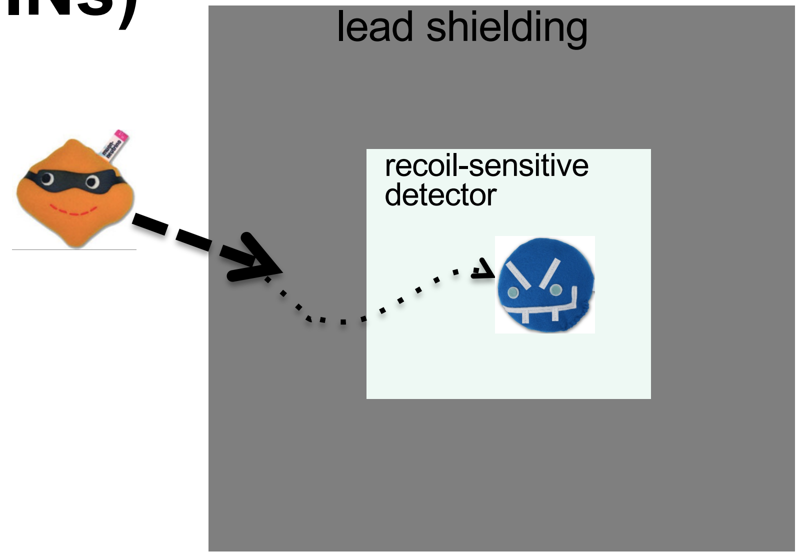
A “friendly fire” in-time background:
Neutrino Induced Neutrons (NINs)

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

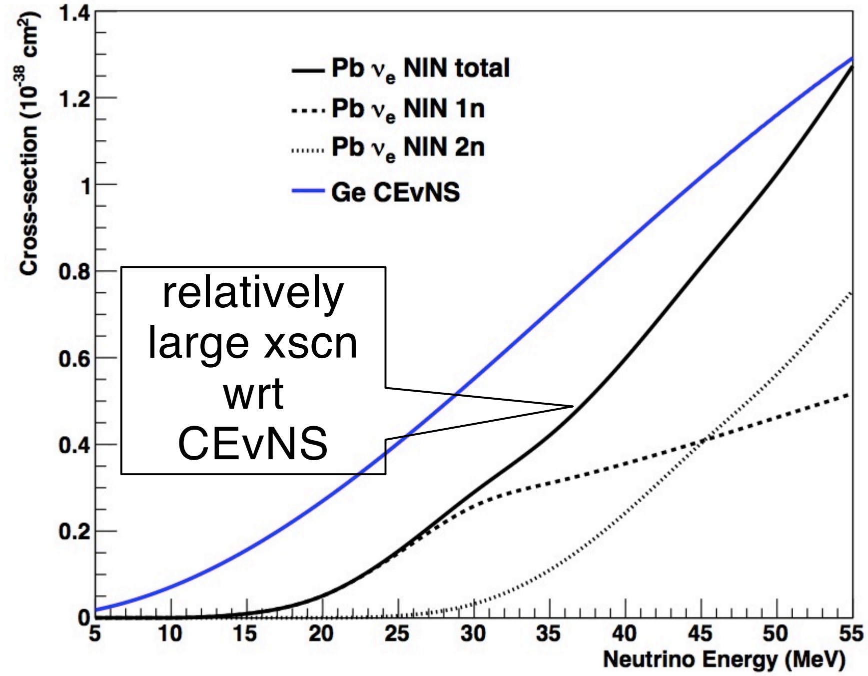
$\searrow$ 1n, 2n emission

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x \quad \mathrm{NC}$$

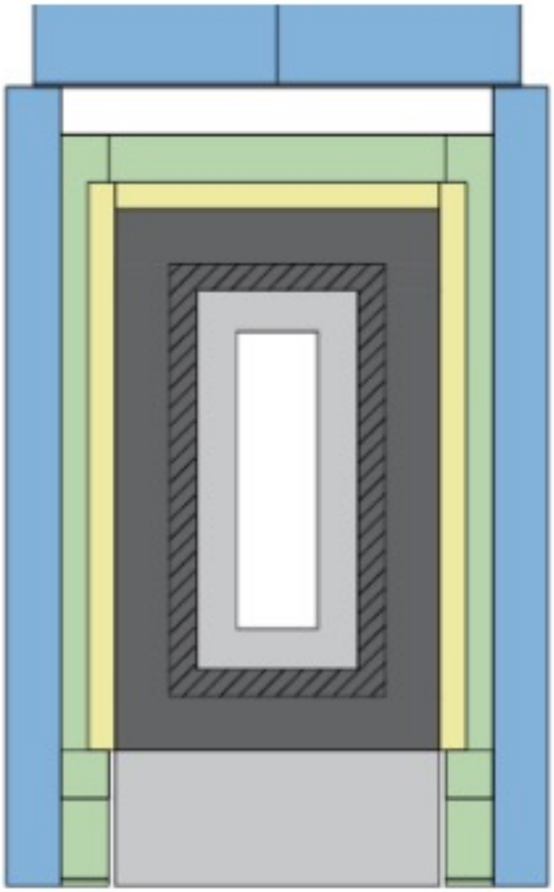
$\searrow$ 1n, 2n, γ emission

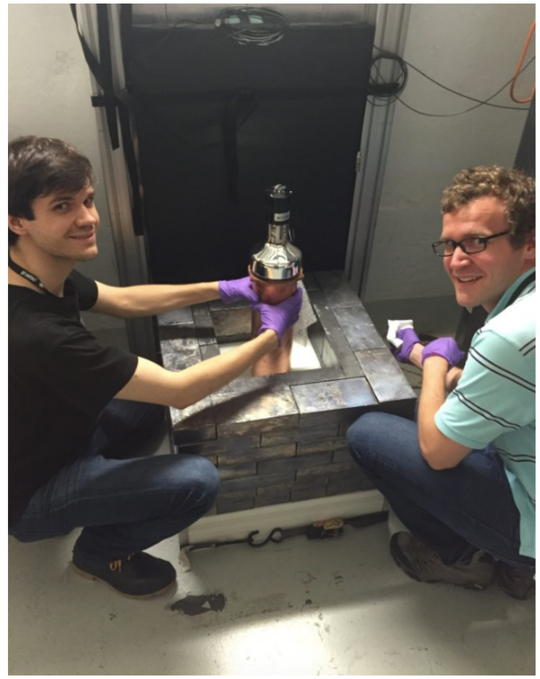


- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in xscn calculation
- [Also: a signal in itself, e.g, HALO SN detector]

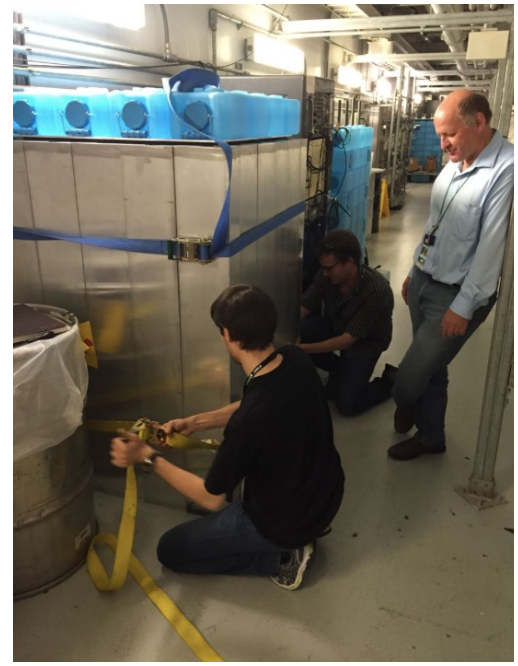


The CsI Detector in Shielding in Neutrino Alley at the SNS





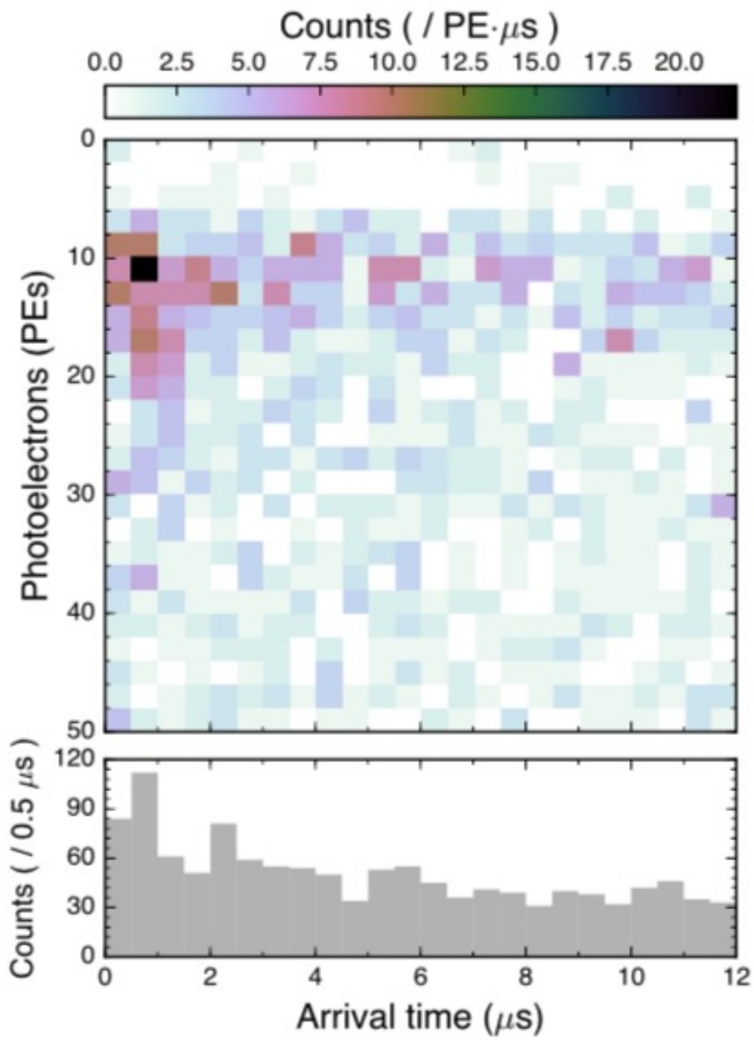
A hand-held detector!



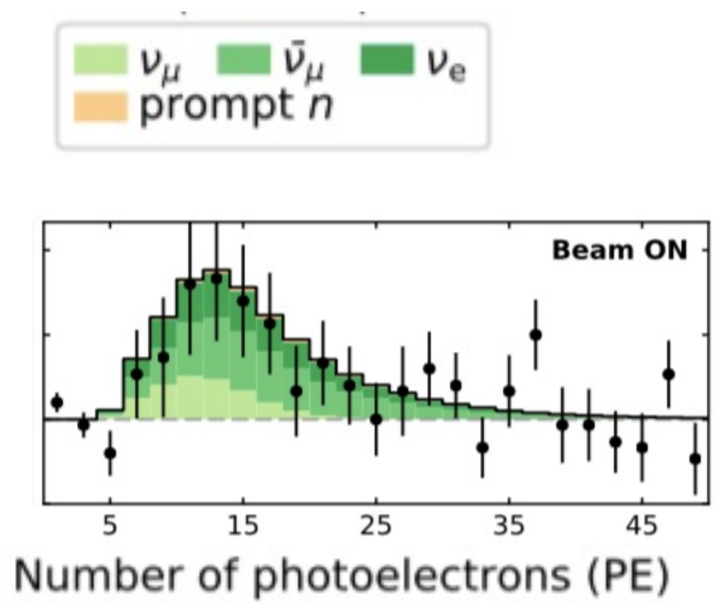
Almost wrapped up...

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



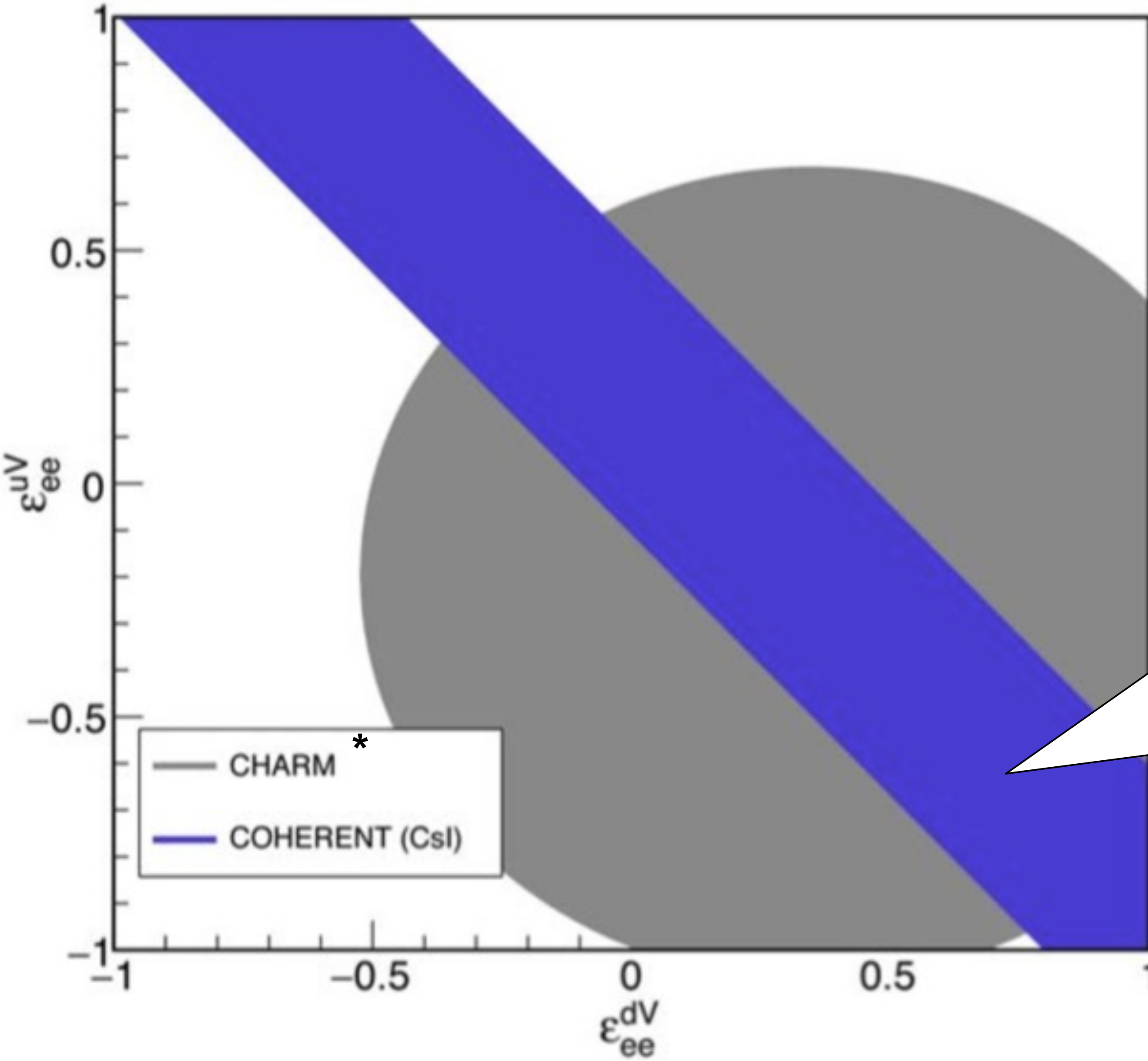
Background-subtracted and integrated over time

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

→ measure of the Q spectrum

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

Neutrino non-standard interaction constraints for current CsI data set:

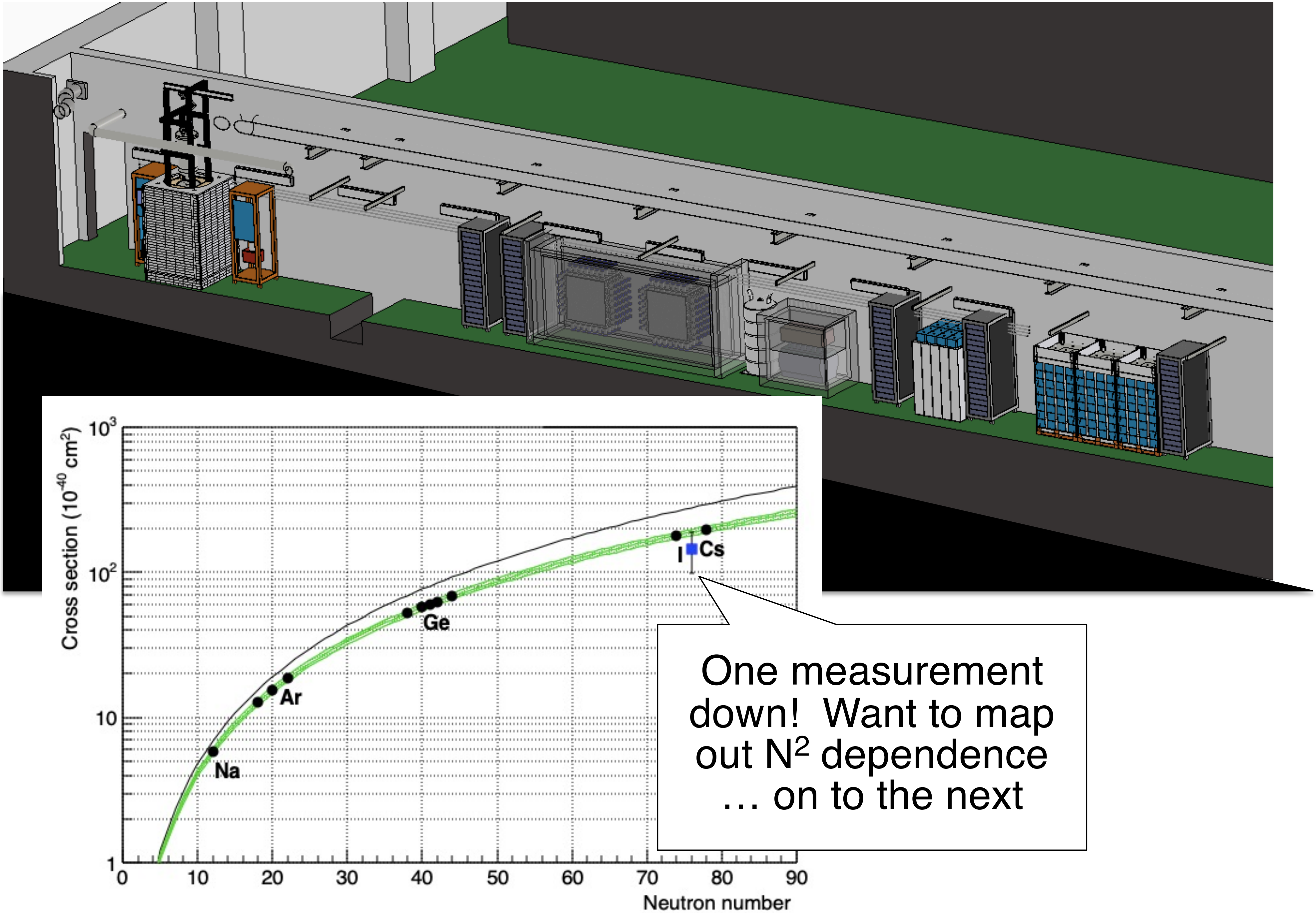


- Assume all other ε's zero

Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899, many more!

*CHARM constraints apply only to heavy mediators

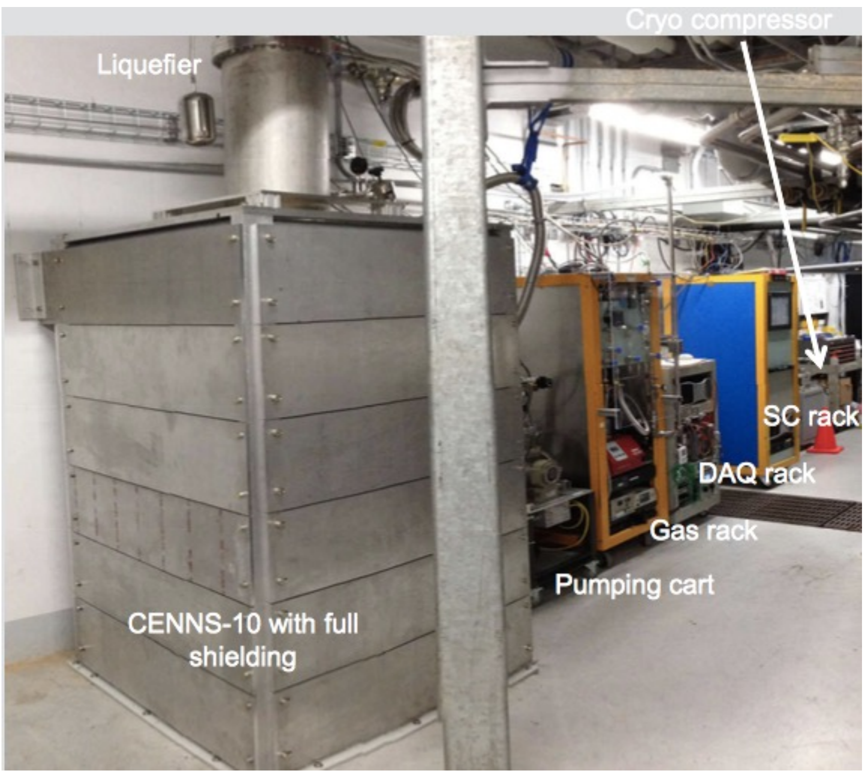


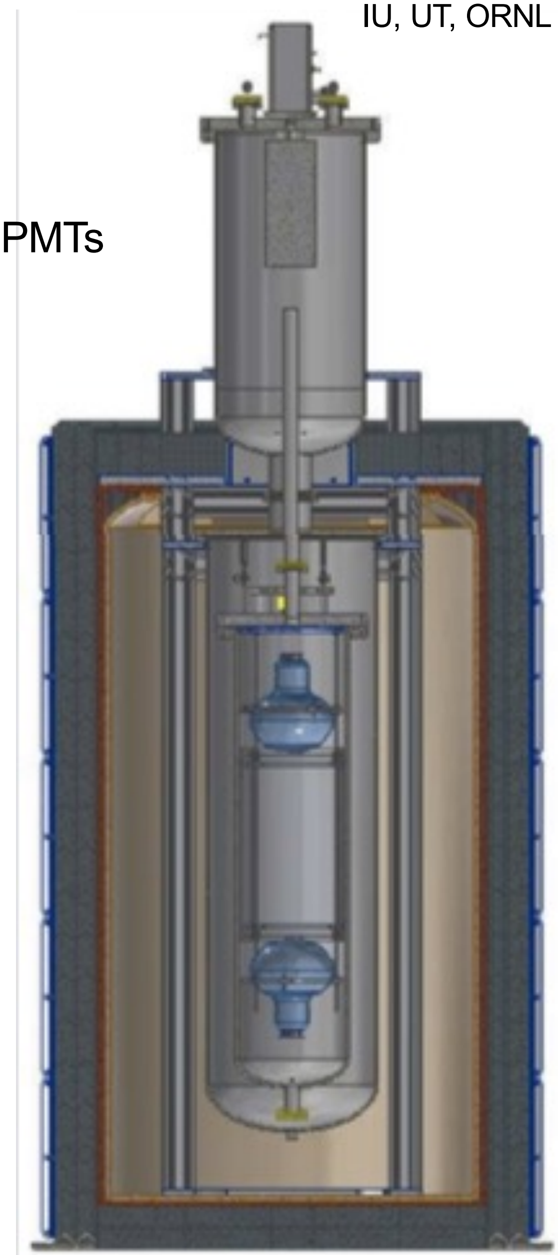
One measurement down! Want to map out N^2 dependence … on to the next

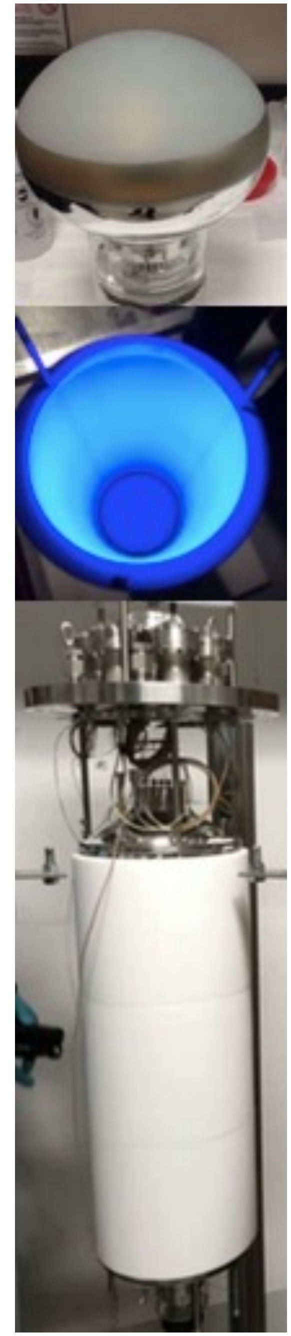
Single-Phase Liquid Argon

- ~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



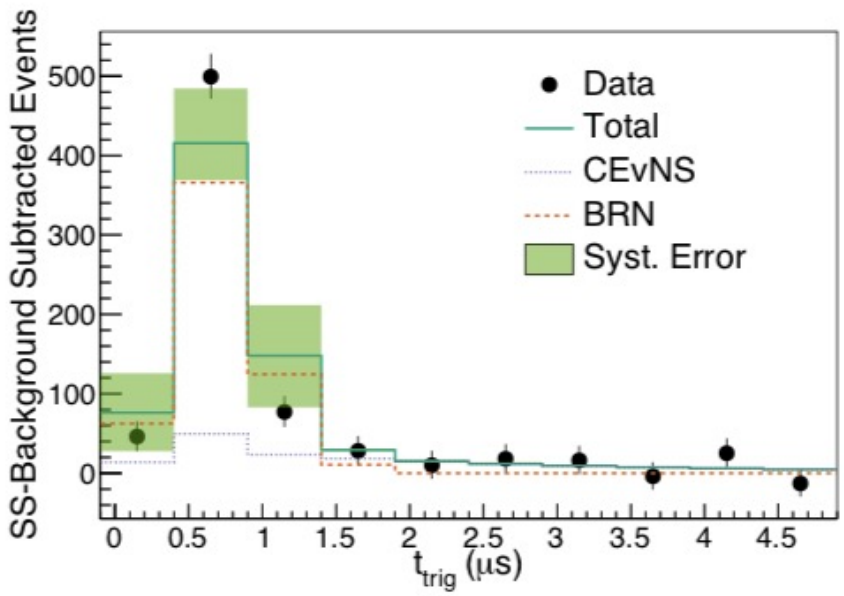


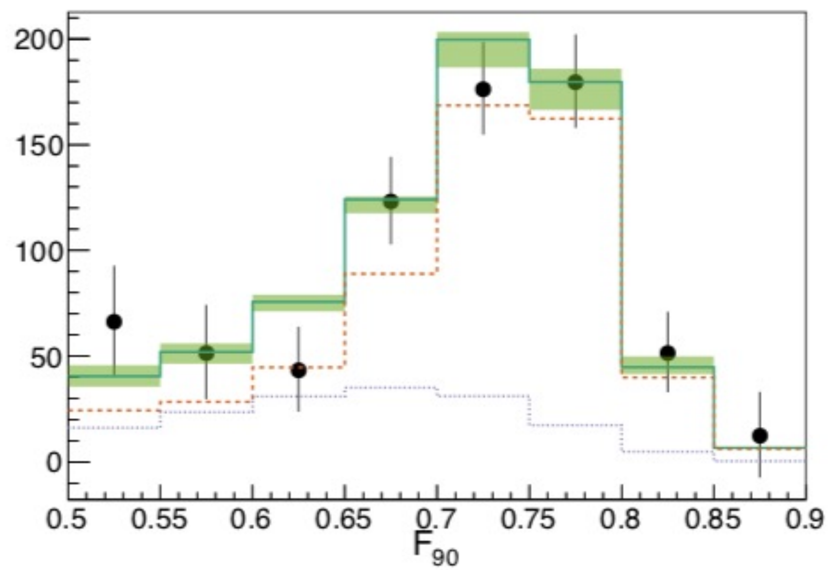


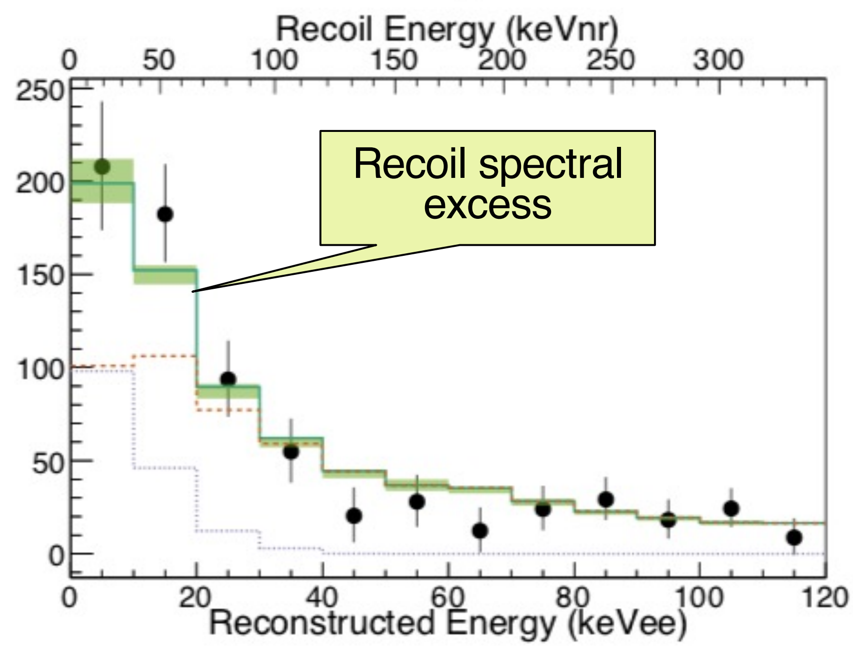
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

Likelihood fit in time, recoil energy, PSD parameter

Beam-unrelated-background-subtracted projections of 3D likelihood fit

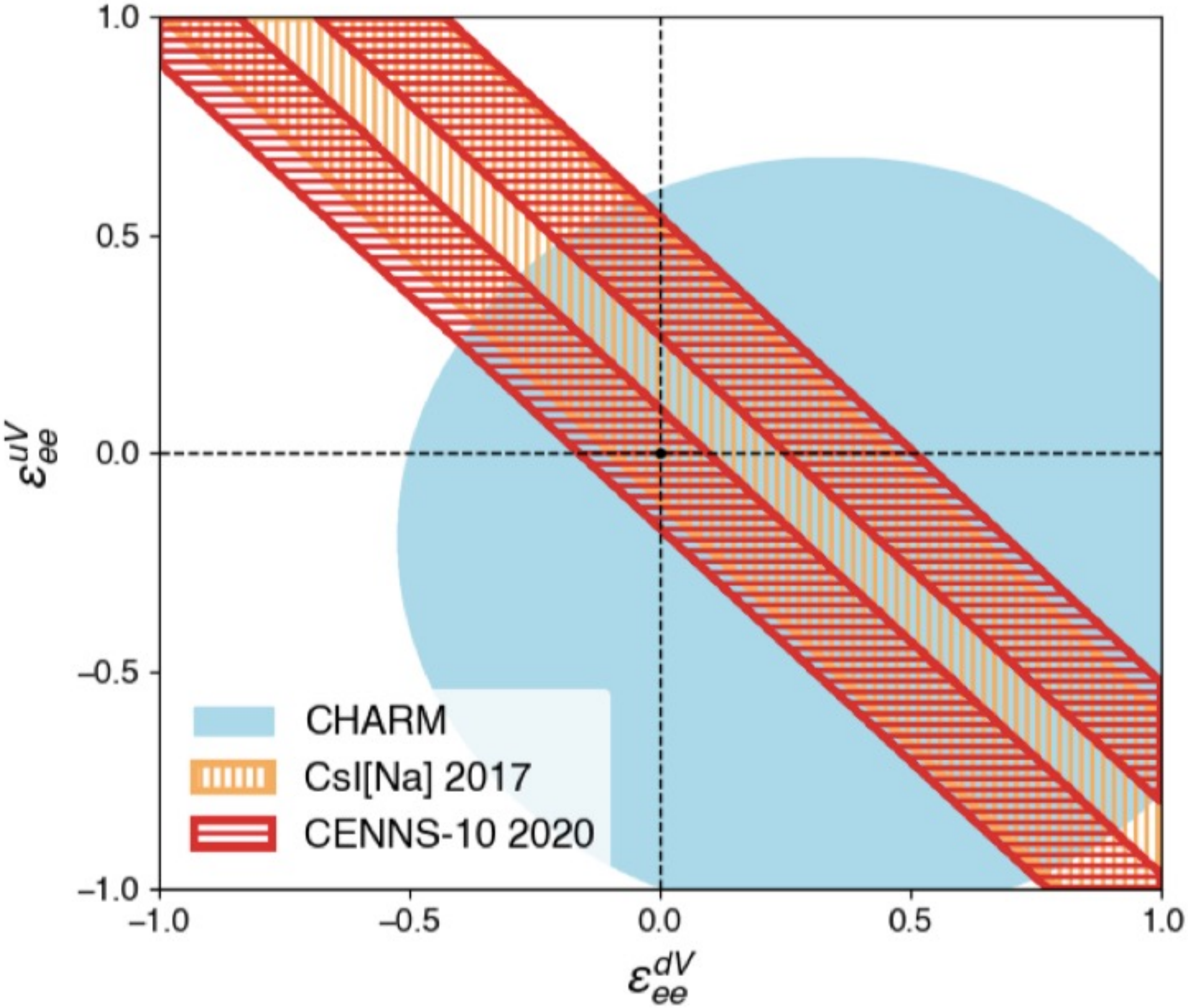




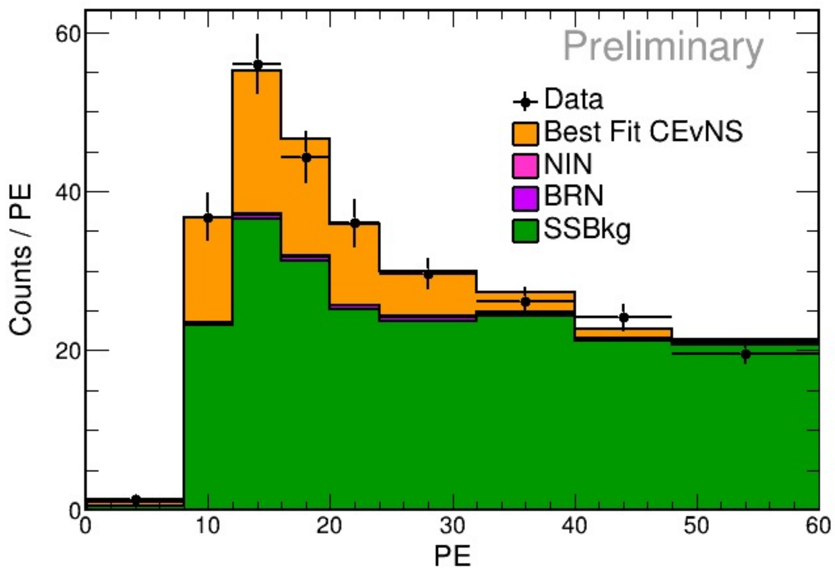


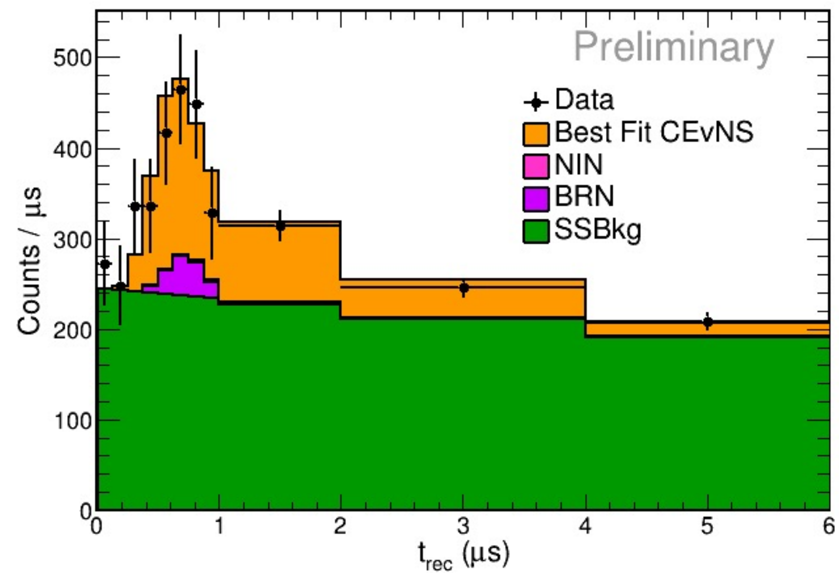
- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

New Constraints on NSI parameters



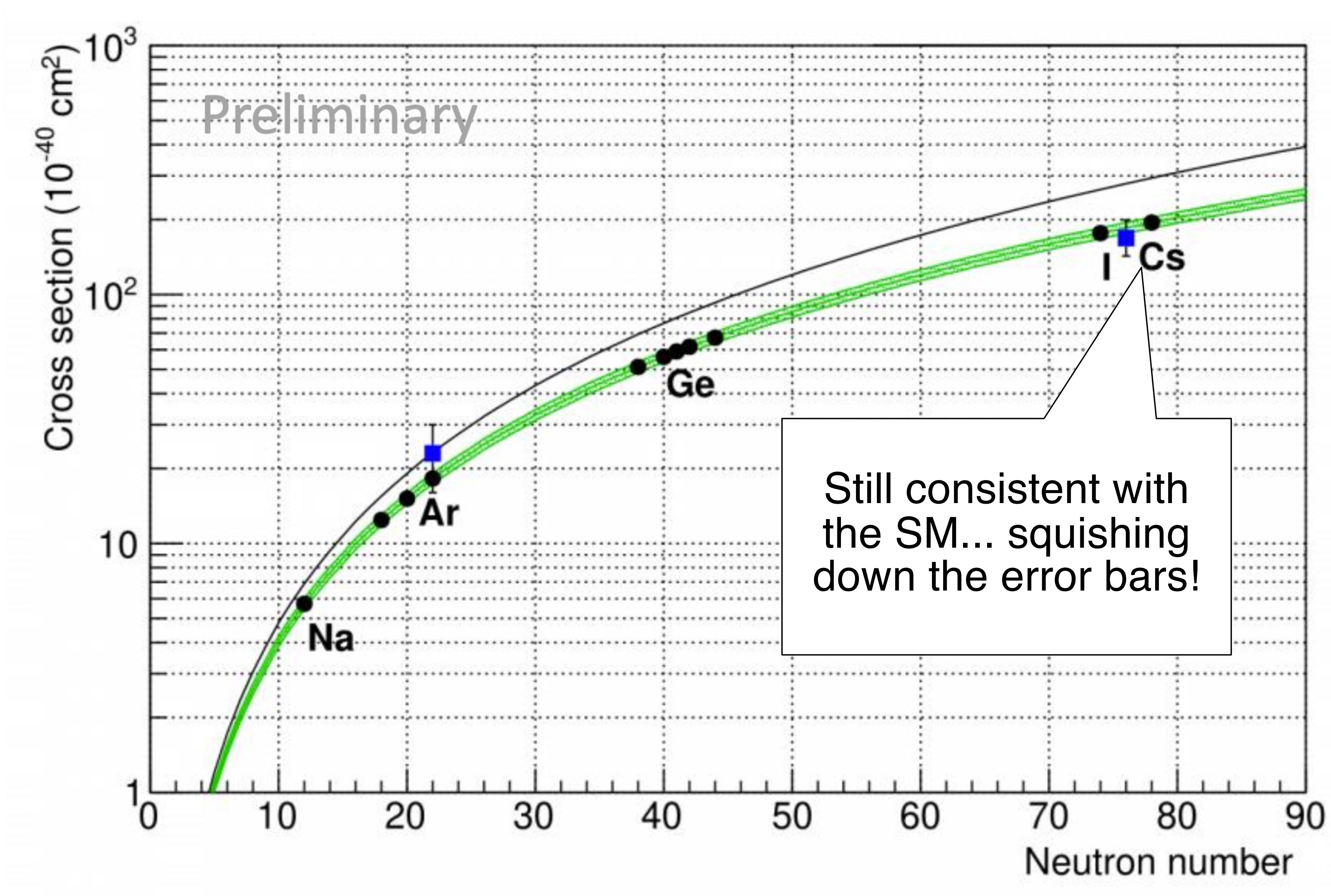
Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis





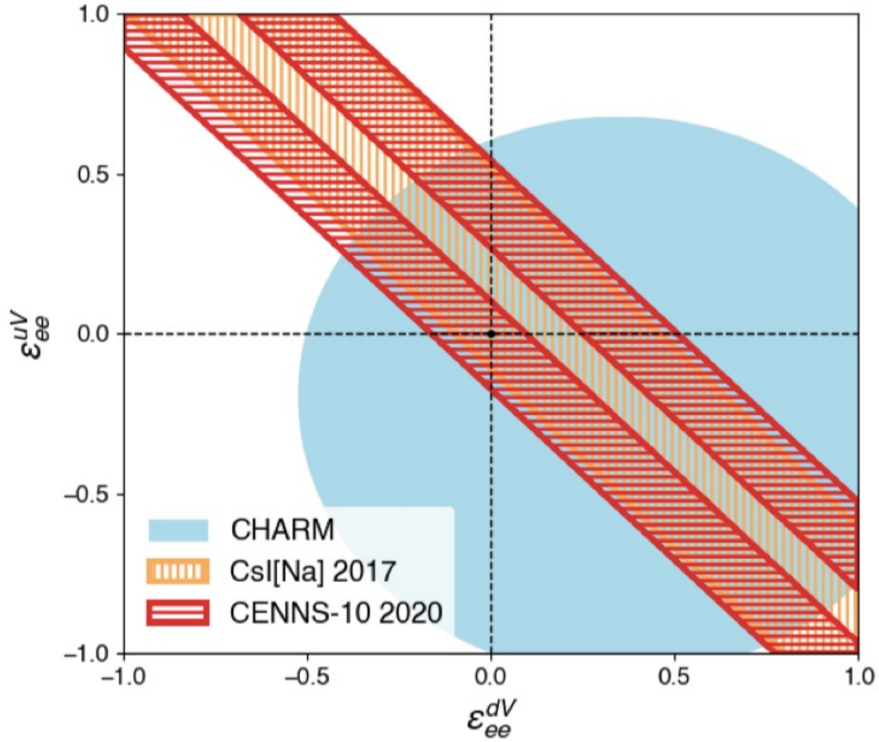
Best fit results

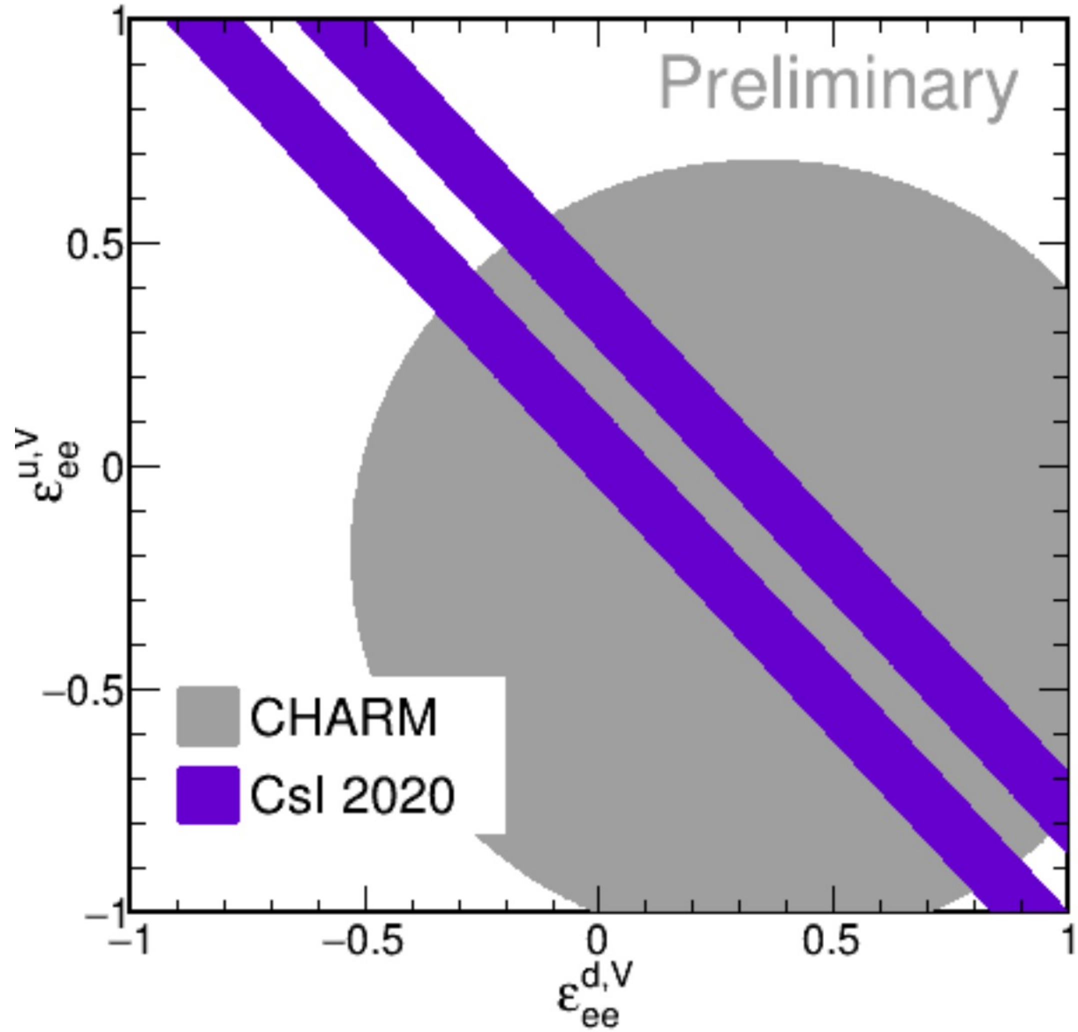
Steady-state background	1273
Beam-related neutrons	17
Neutrino-induced neutrons	5
CEvNS	306

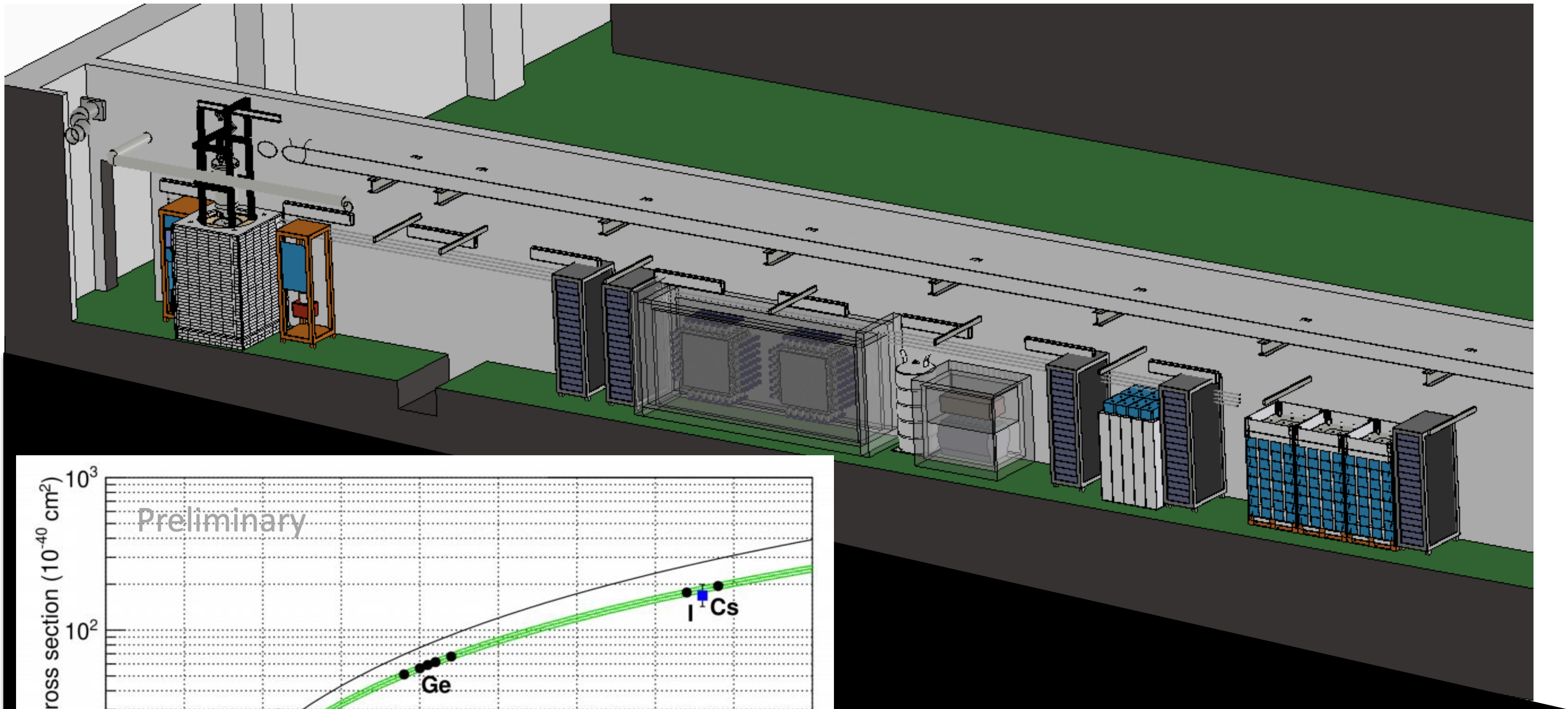


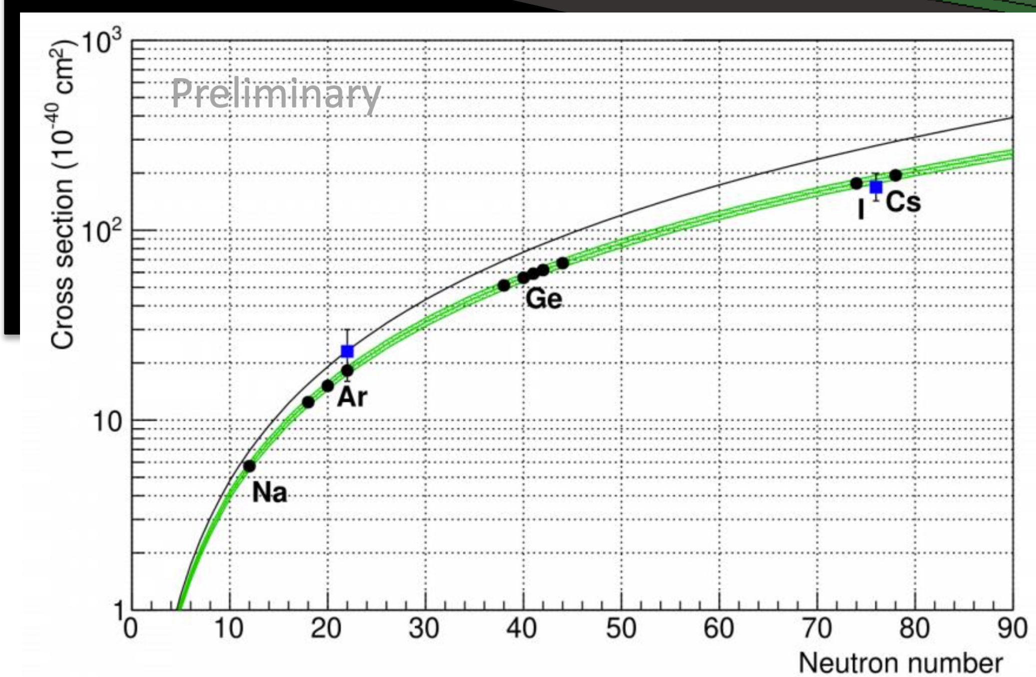
Preliminary
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
Still consistent with the SM... squishing down the error bars!

And squeezing down the possibilities for new physics...





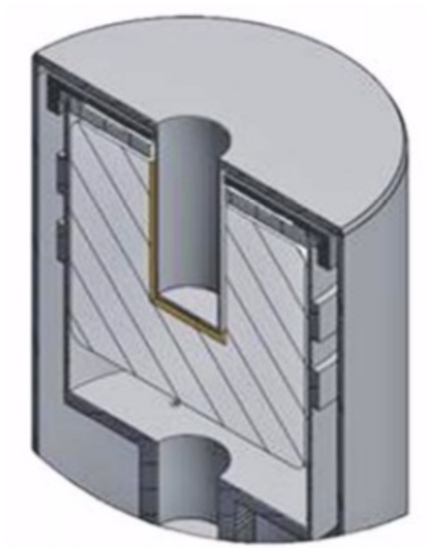




Preliminary
Cross section (10^{-40} cm^2)
Neutron number
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Na
Ar
Ge
I
Cs

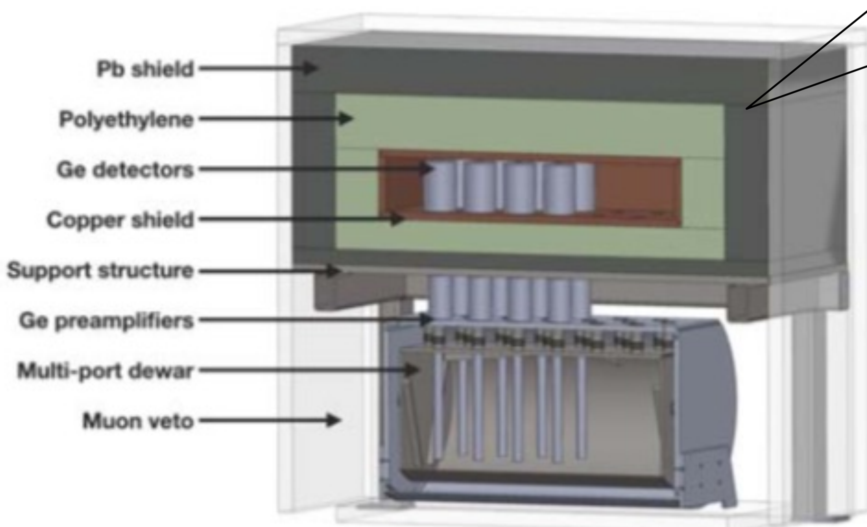
High-Purity Germanium Detectors

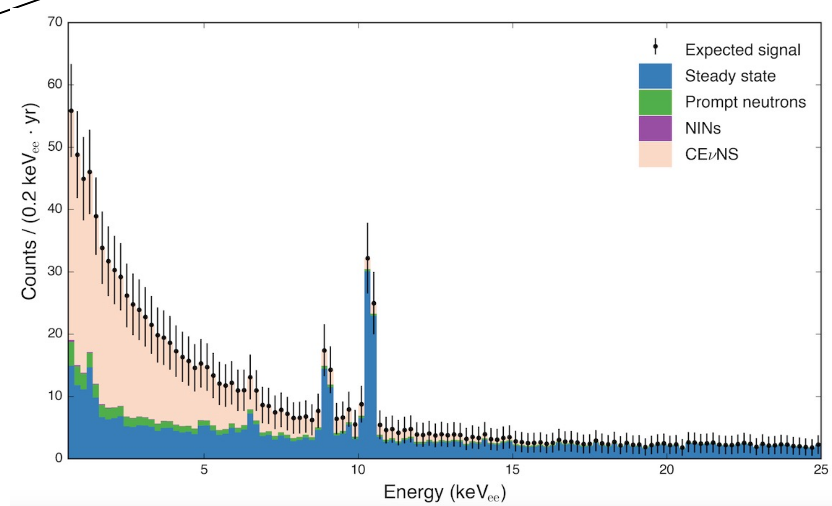
P-type Point Contact



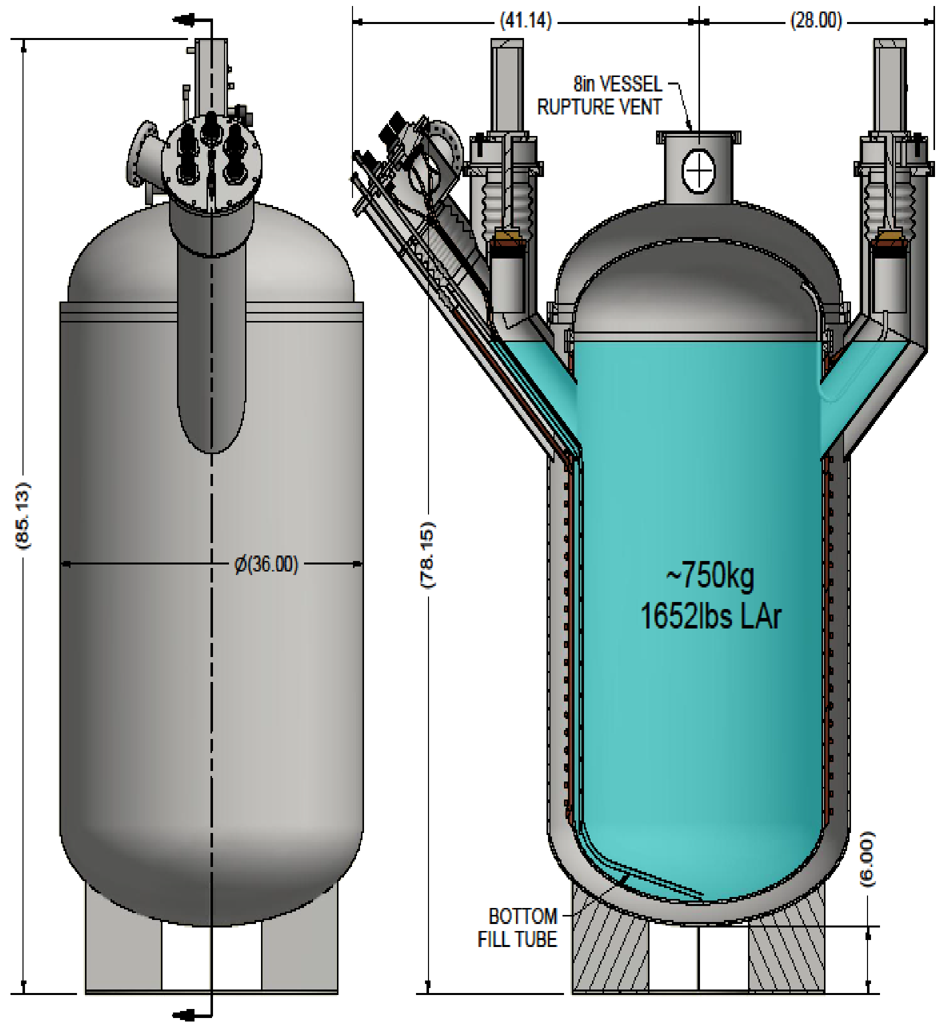
- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

- 8 Canberra/Mirion 2 kg detectors in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors

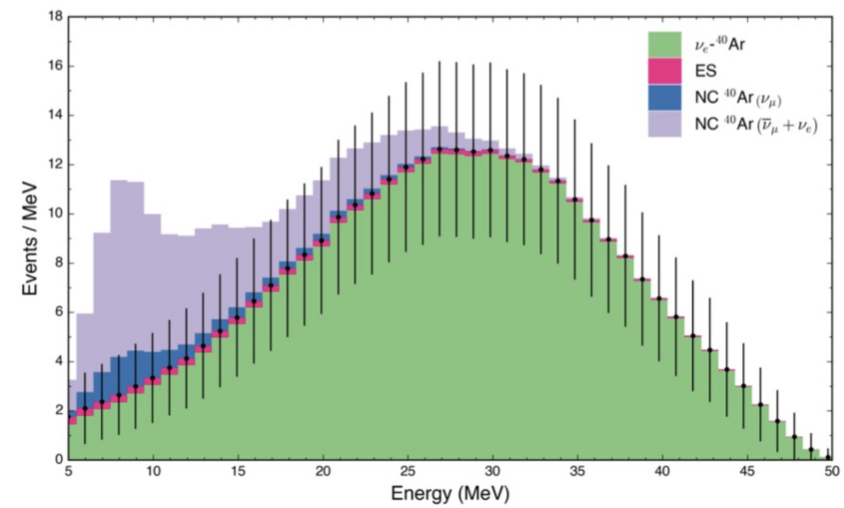




Tonne-scale LAr Detector



- 750-kg LAr will fit in the same place, will reuse part of existing infrastructure
- Could potentially use underground argon



CC/NC **inelastic** in argon of interest for supernova neutrinos

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

NC $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$

If ~7000 CEvNS interactions per year are detected in 1 ton of argon at the SNS, about how many ν_eCC events would be expected?

A. 70000

B. 3000

C. 300

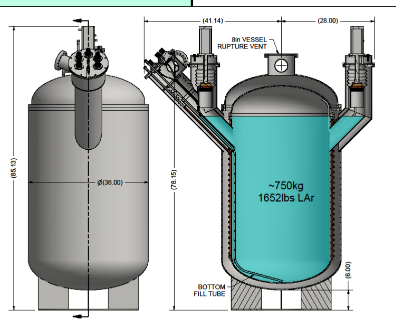
D. 70

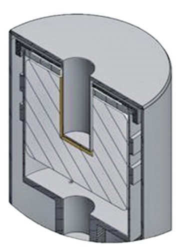
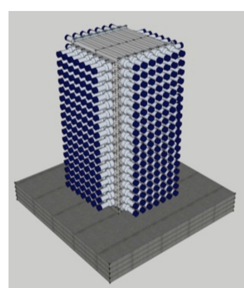
E. 3

F. 0.1

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	2021	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	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes

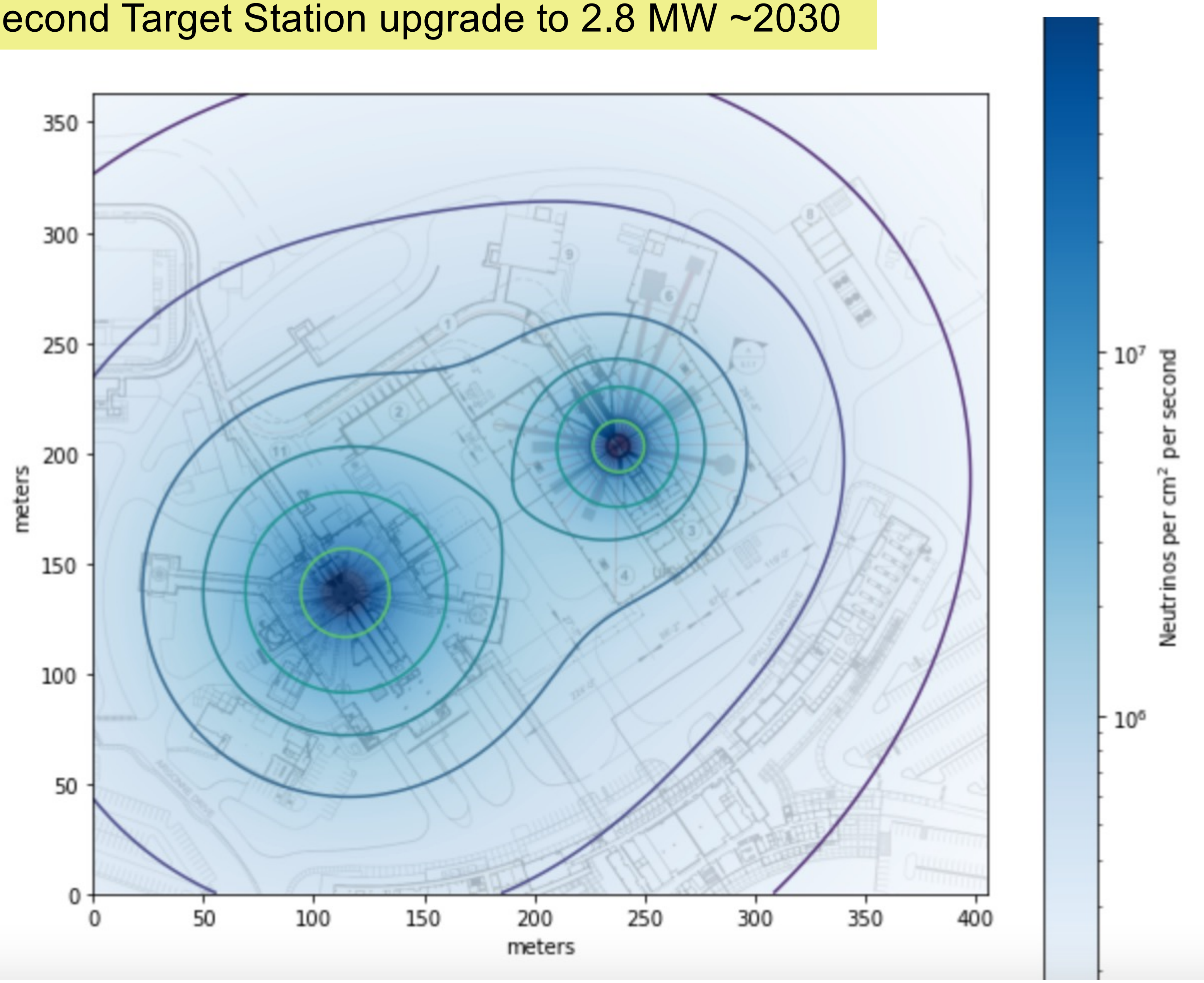



+D_2O for flux normalization
+ concepts for other targets...

+ power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030

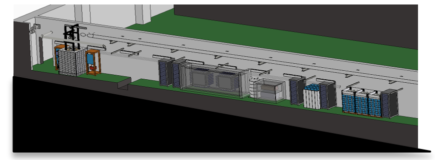
SNS power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030

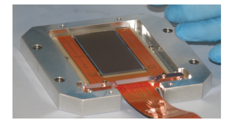


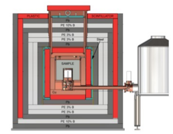
Many exciting possibilities for ν's + DM!

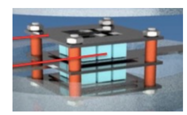
Many CEvNS Efforts Worldwide

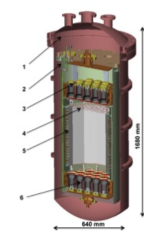
Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NuCleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn bolometers	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactors

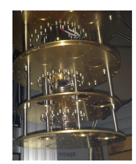


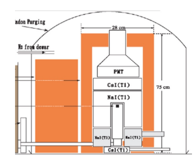








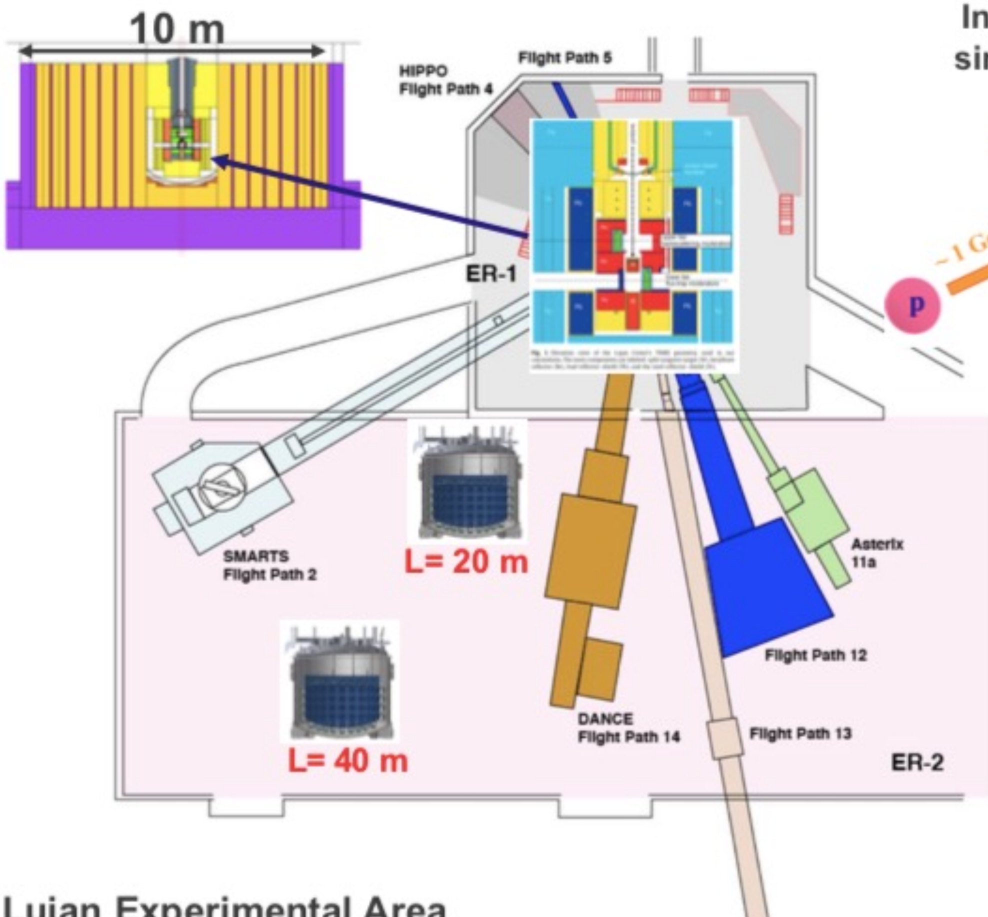




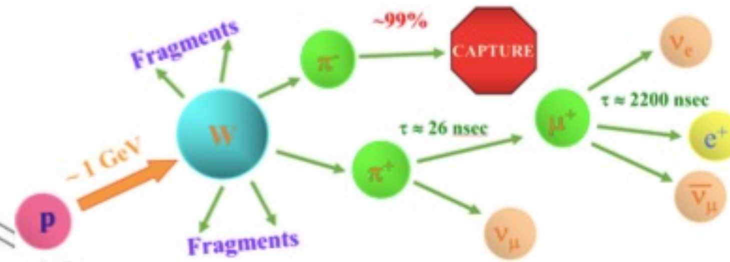
+ DM detectors, +directional detectors +more...

many novel low-background, low-threshold technologies!!

Coherent Captain Mills @ Lujan: single-phase LAr



Intense source muon neutrinos: target MCNP simulation flux 4.74x10^5 ν/cm^2/s at 20 m

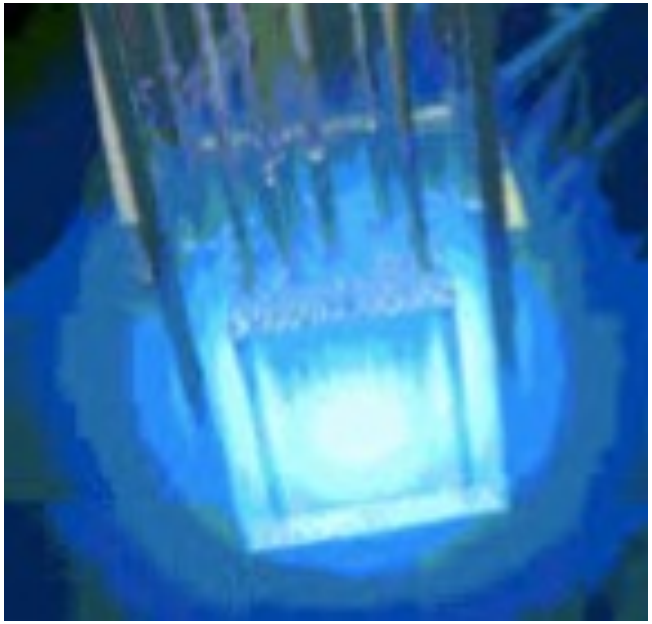


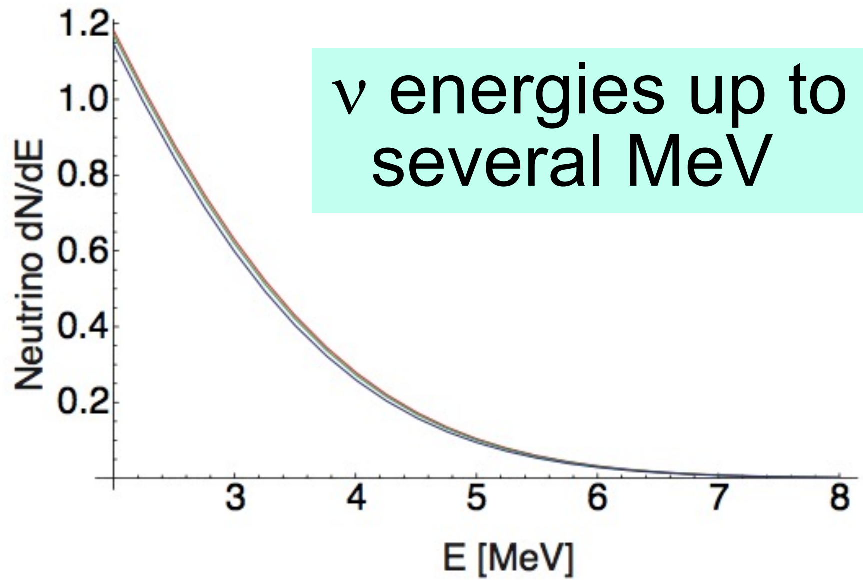
Lujan Experimental Area

- Space for large 10-ton liquid Argon ν detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

Primary focus on sterile neutrinos & DM search

Neutrinos from nuclear reactors





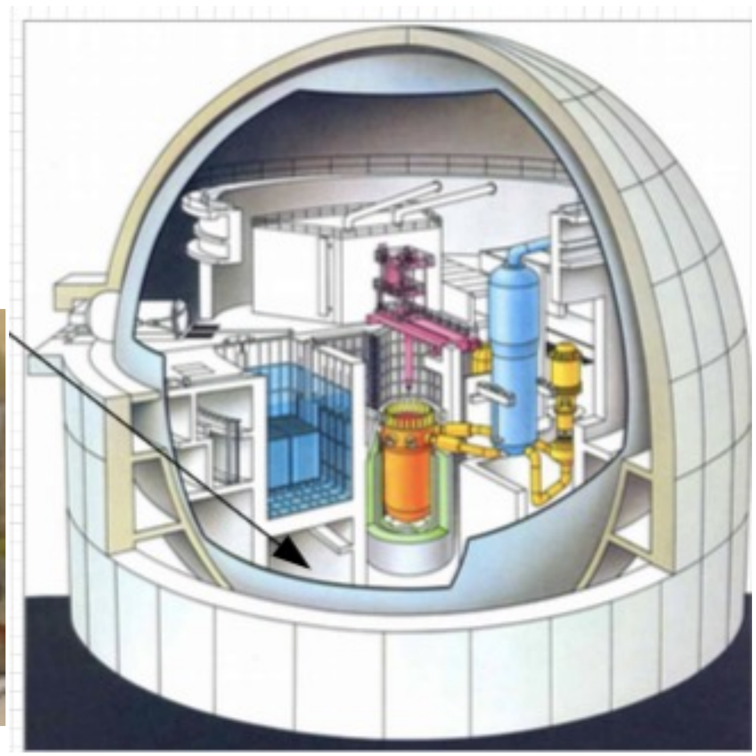
ν energies up to several MeV

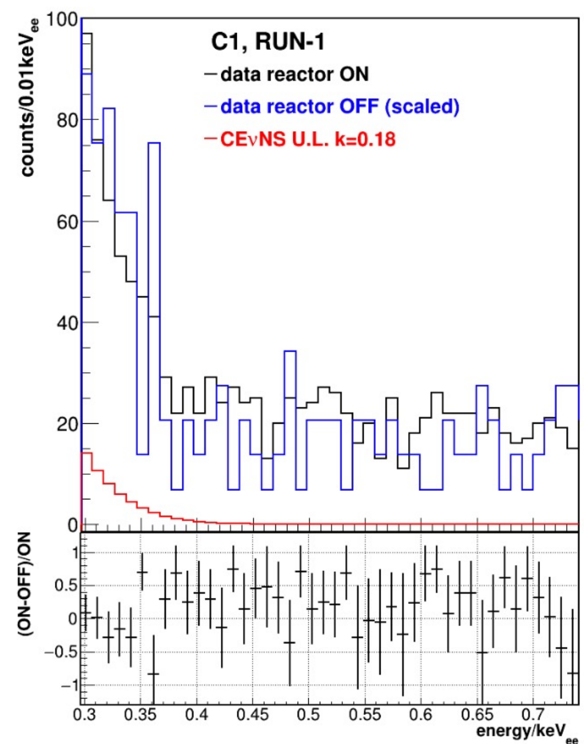
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

CONUS

- Brokdorf 3.9 GWth reactor, Germany
- 17 m from core
- 4 kg Ge PPC
- ~300 eVee threshold

Phys.Rev.Lett. 126 (2021) 4, 041804 arXiv: 2011.00210 [hep-ex]

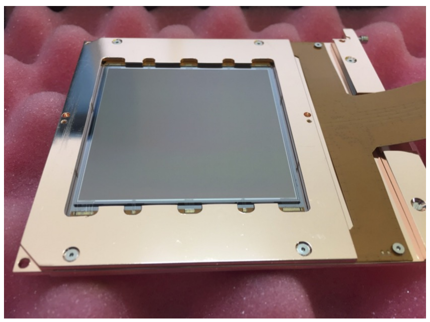


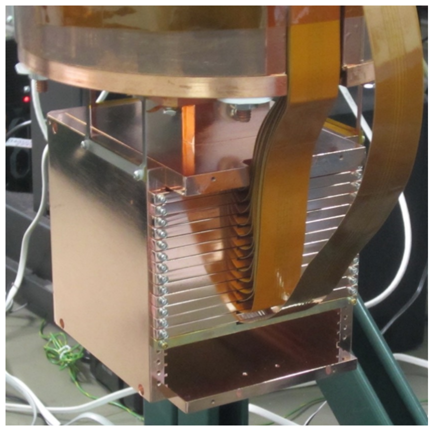


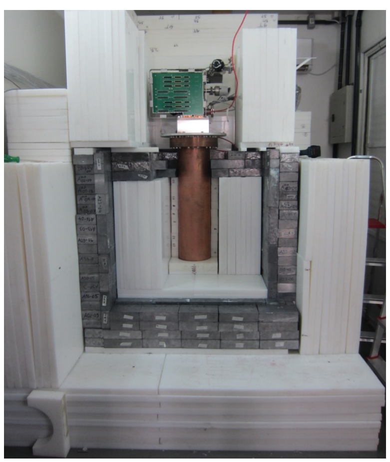
<85 events in ROI @90 CL

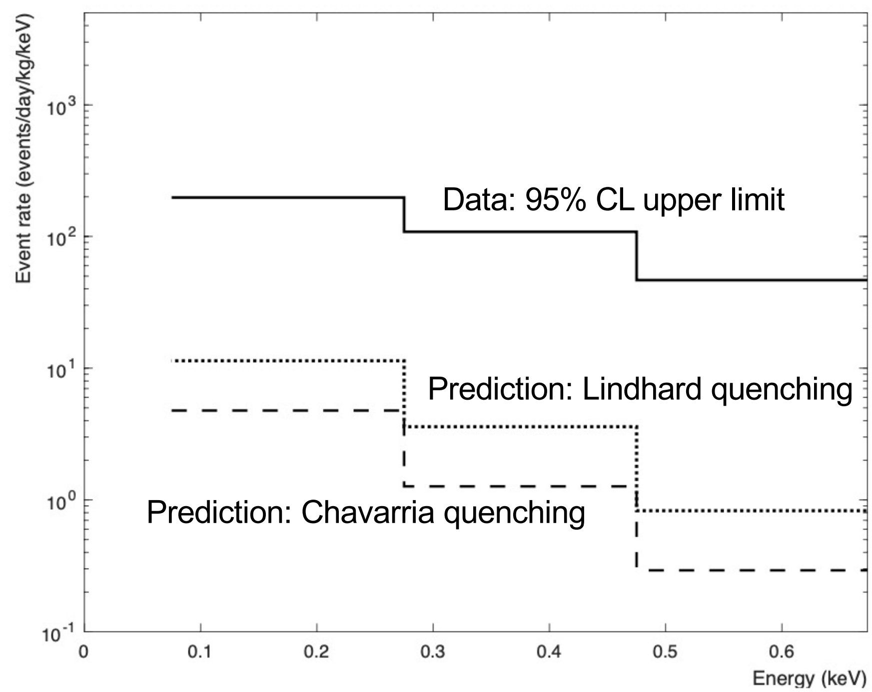
CONNIE

- Angra-2 3.8 GWth nuclear reactor, Brazil
- 32 m from core
- 47.6 g Si CCDs
- ~0.1 keVee threshold



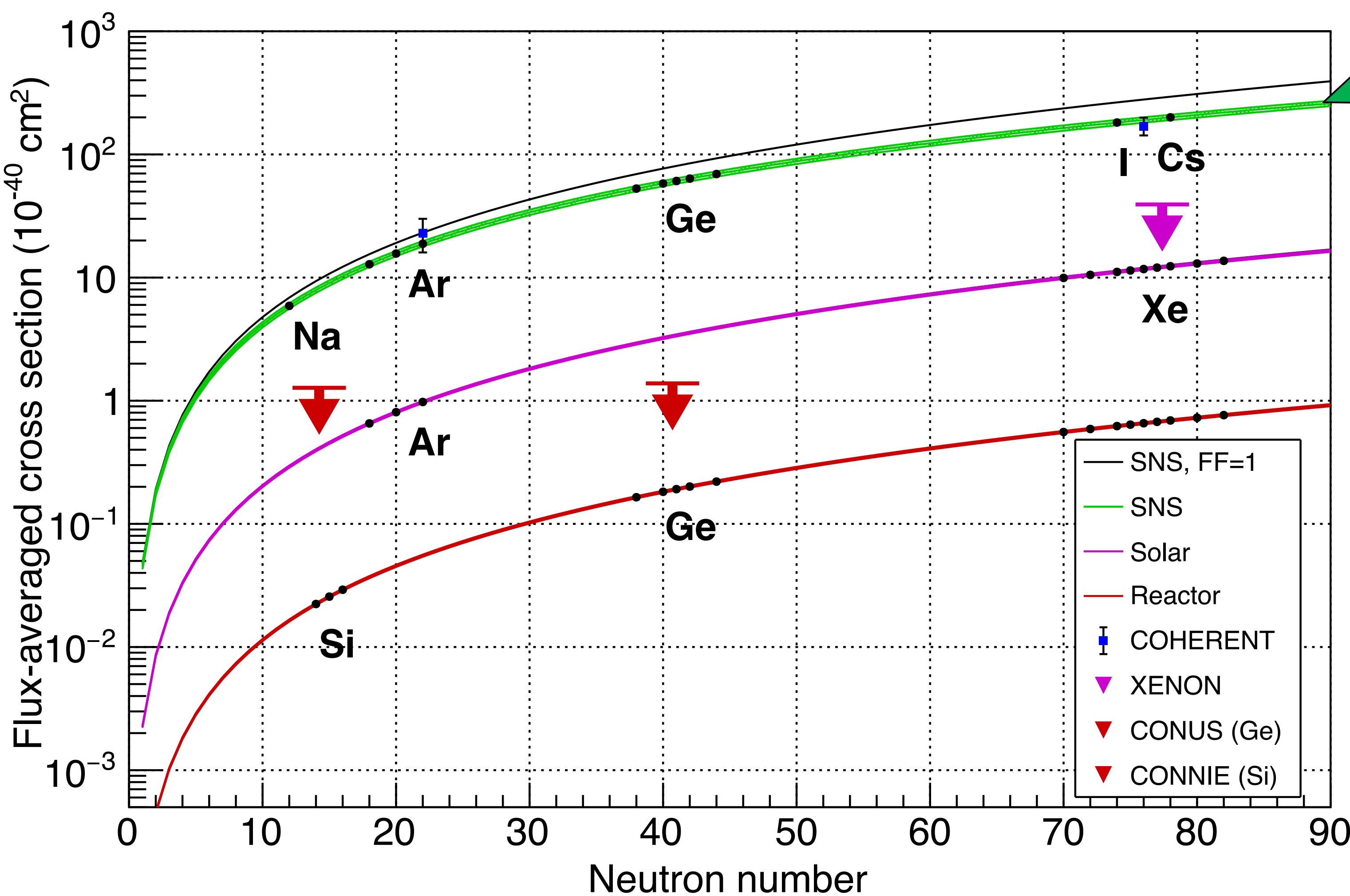






Phys.Rev.D 100 (2019) 9, 092005
arXiv: 1906.02200 [physics.ins-det]

Summary of CEvNS Results



So far: measurements in CsI, Ar from COHERENT
... looking forward to more soon!

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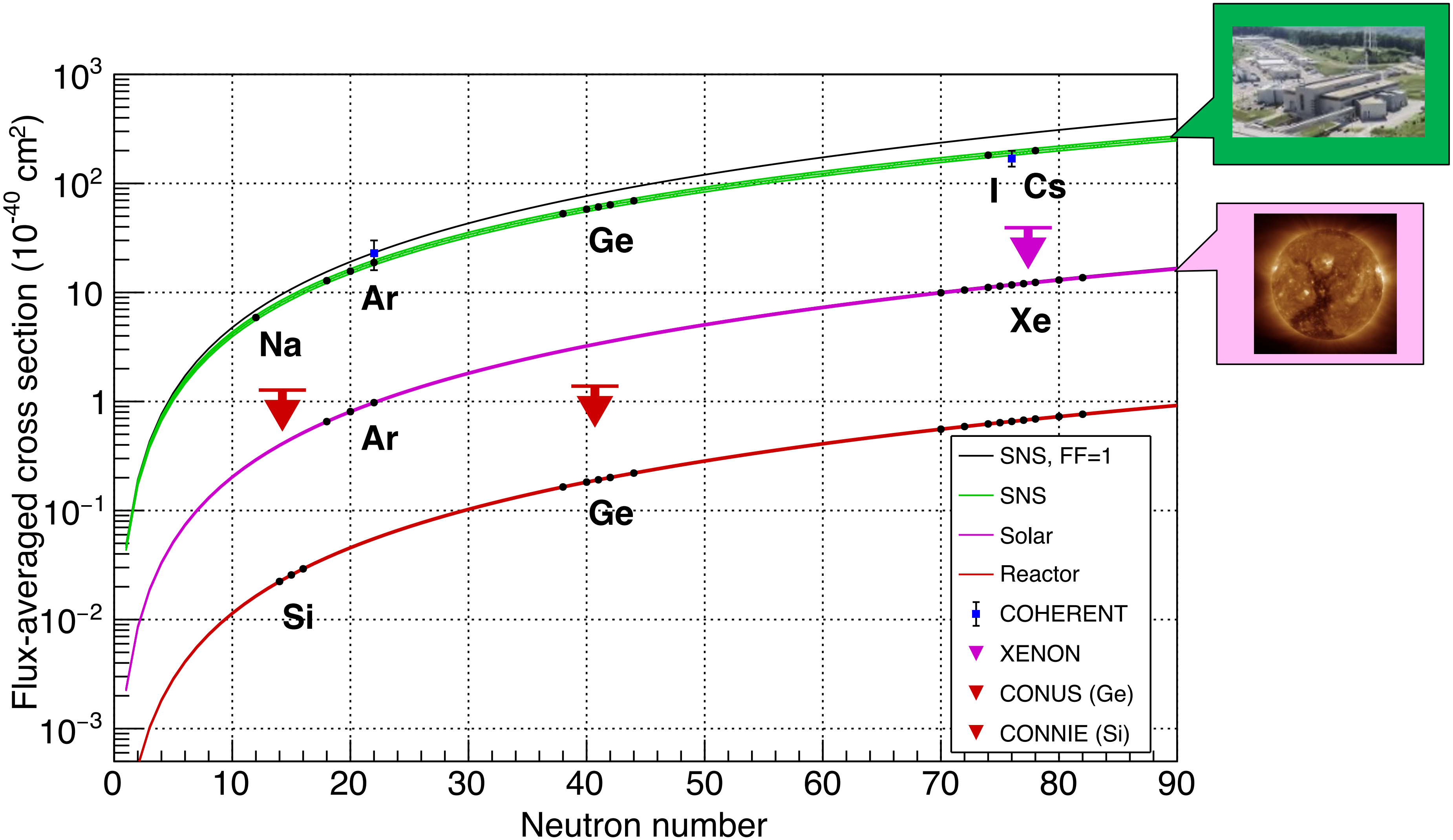

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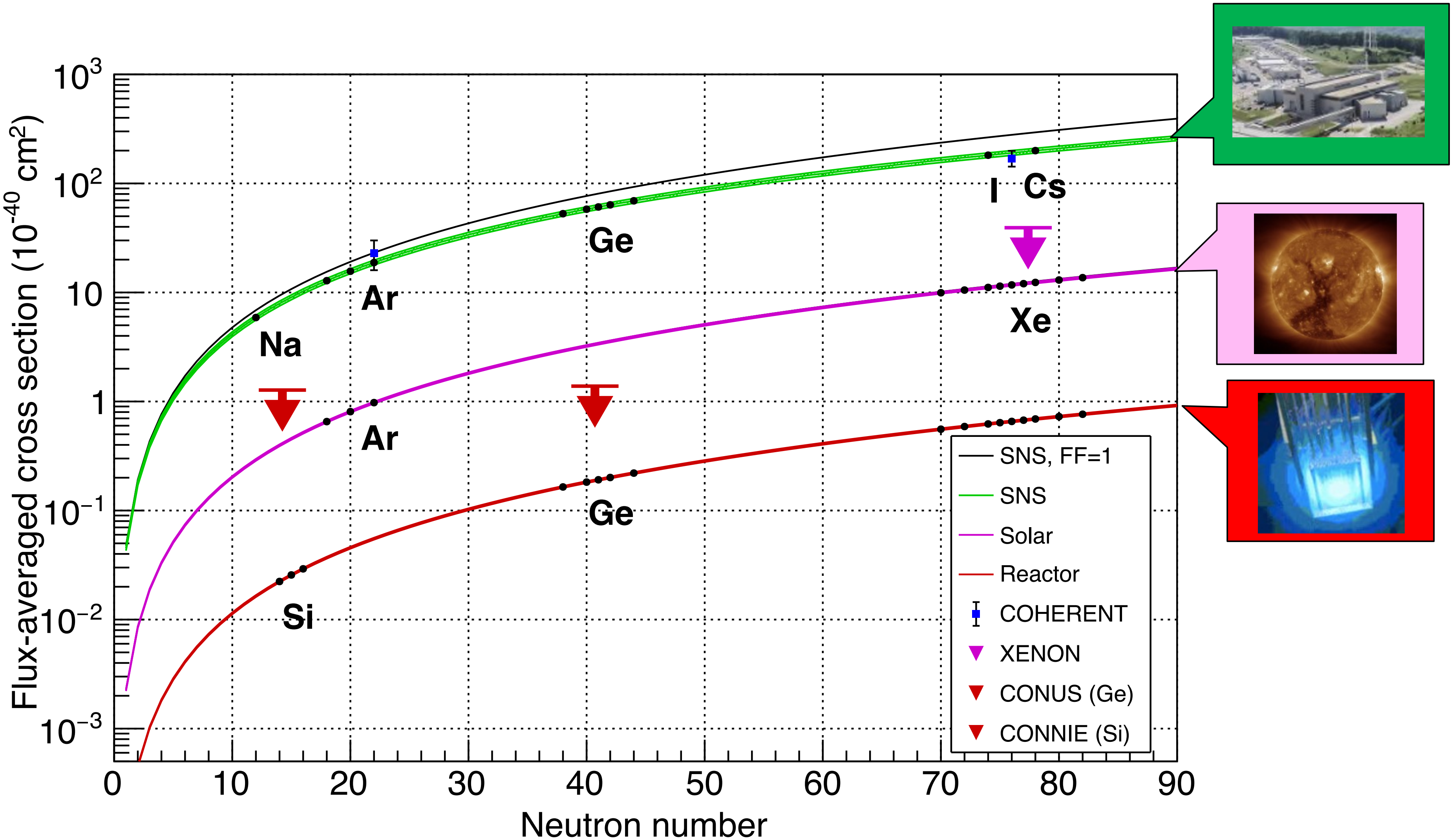

So far: measurements in CsI, Ar from COHERENT
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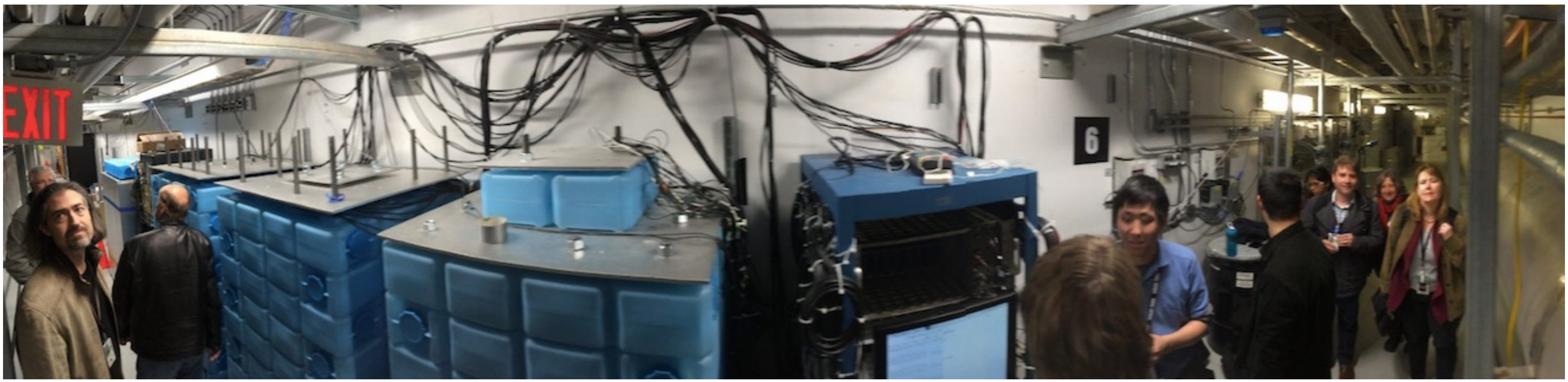
Take-away points from the lecture

- **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 measurement** by COHERENT CsI[Na] at the SNS... now Ar, + more CsI data!
- **Meaningful bounds on beyond-the-SM physics**



- Nore NaI+Ge CEvNS soon, (+ inelastics)!
- Multiple targets, upgrades and new ideas in the works!
- "Neutrino Avenue" at the Second Target Station?

- Other CEvNS experiments will join the fun!
  (CCM, TEXONO, CONUS, CONNIE, MINER, RED, Ricochet, NUCLEUS...)