Measurements of
Coherent Elastic Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

Kate Scholberg, Duke University

Gran Sasso Science Institute Online Seminar

May 6, 2020

OUTLINE

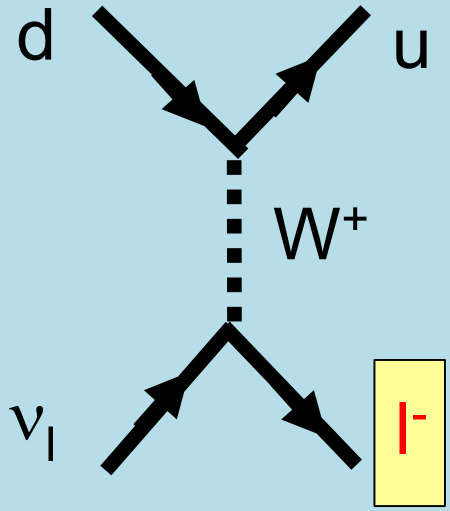
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations
- How to measure CEvNS
- The COHERENT experiment at the SNS
- First light with CsI[Na]
- Second measurement with LAr: 

- Future prospects

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

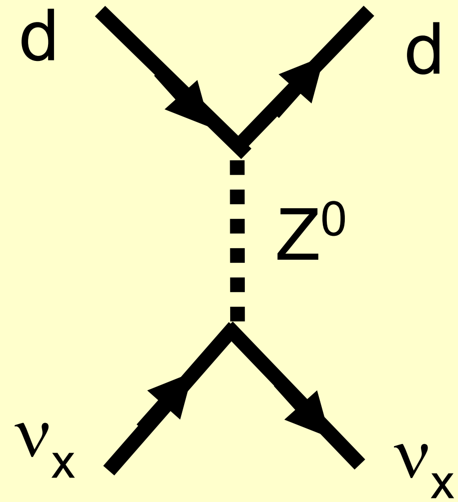


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)

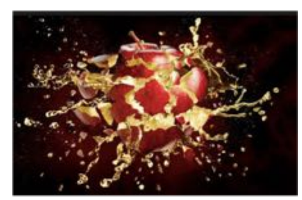


Flavor-blind

Neutrino interactions with Nuclei

Deep Inelastic Scattering

keV MeV GeV TeV PeV



Neutrino interactions with Nuclei

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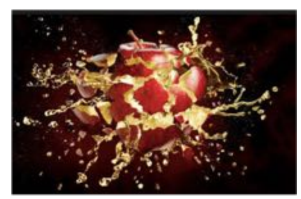


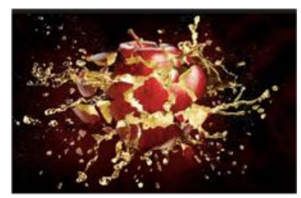
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino interactions with Nuclei

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

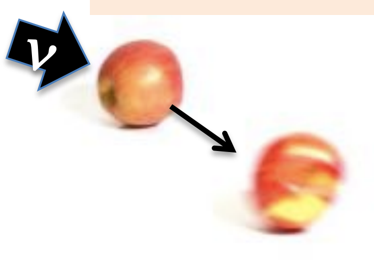
We are considering the low-energy regime and the ***gentlest*** interaction with nuclei

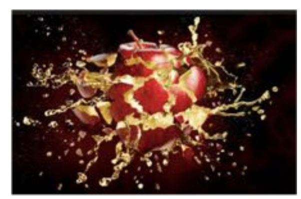
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV

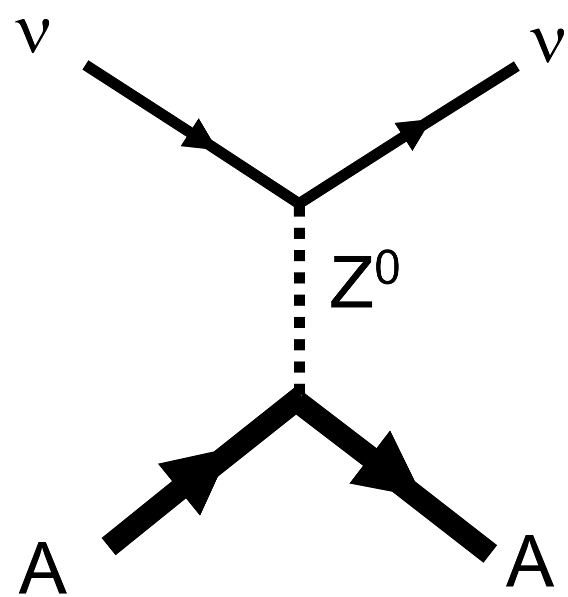




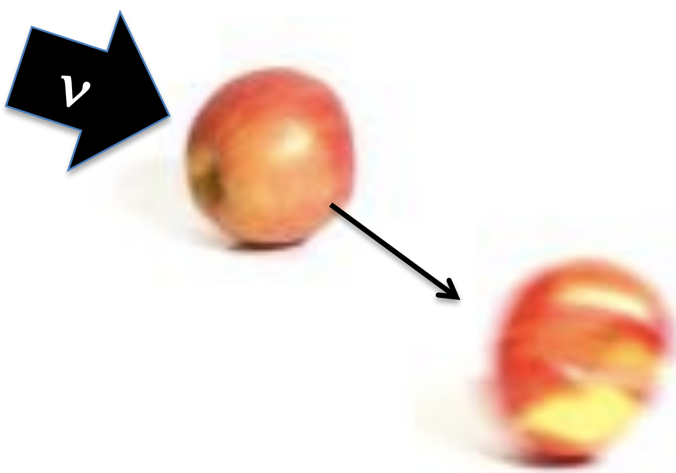
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

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_ν~ 50 MeV



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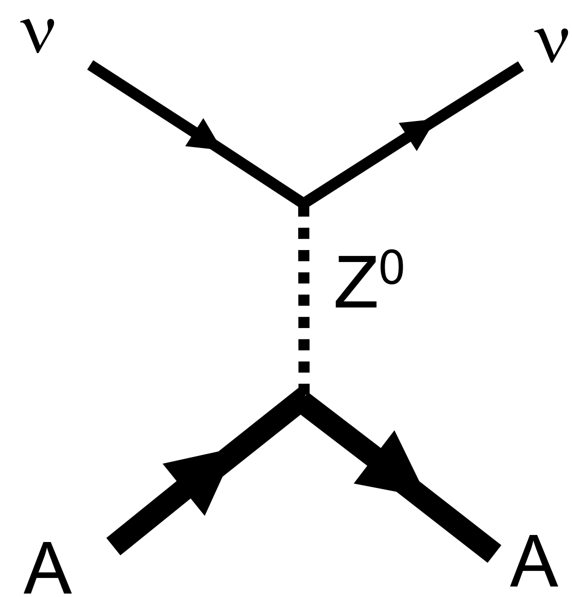

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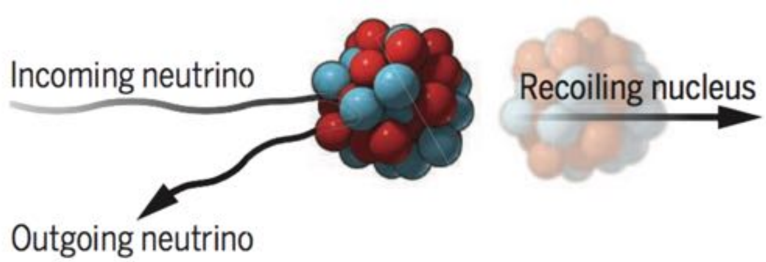


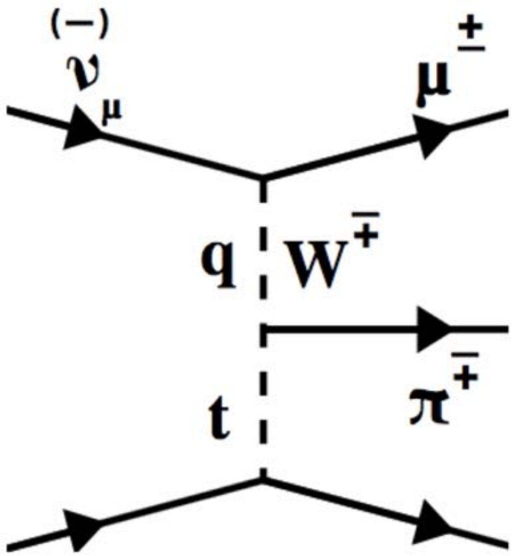
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

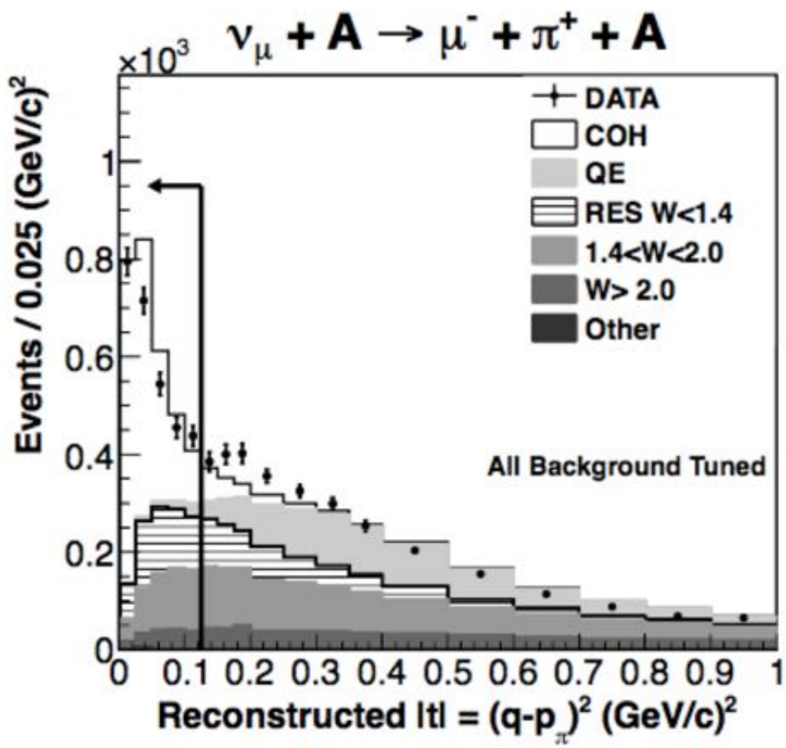
A: no. of constituents

Image: J. Link *Science* Perspectives

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



not
THAT!



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

`\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}`

First proposed >40 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

Standard Model prediction for CEvNS differential cross section

(probability of kicking a nucleus with recoil energy T)

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

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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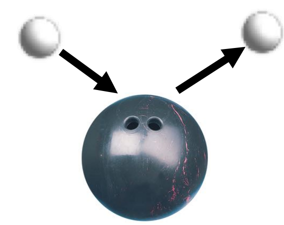
kinematics:

ping-pong ball hits bowling ball



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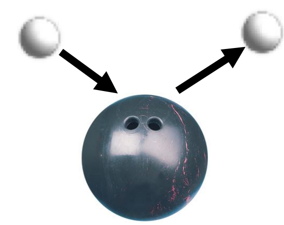

Form factor: F=1 ➔ full coherence

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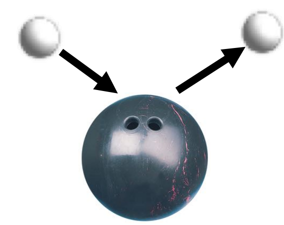

weak nuclear charge

Form factor: F=1 ➔ full coherence

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

Standard Model prediction for differential cross section

(probability of kicking a nucleus with recoil energy T)

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

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 $\Longrightarrow Q_W \propto N$

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

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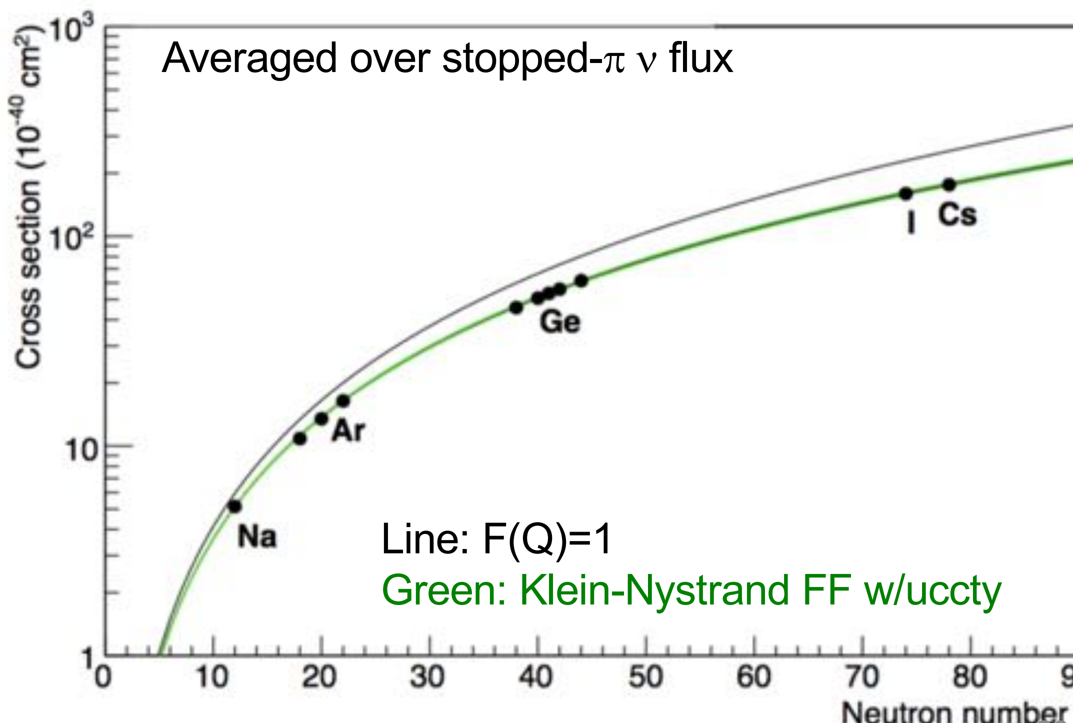
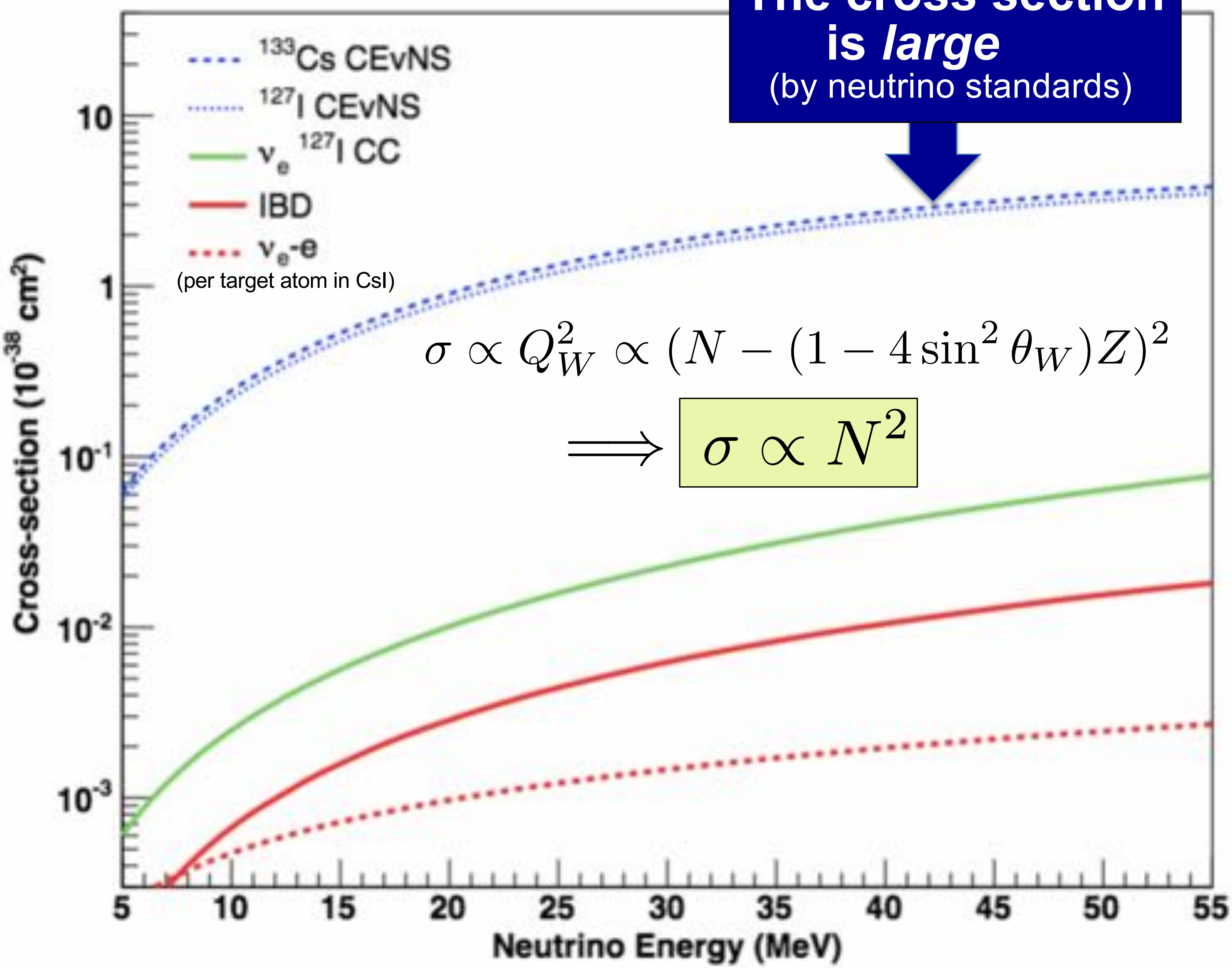
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

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



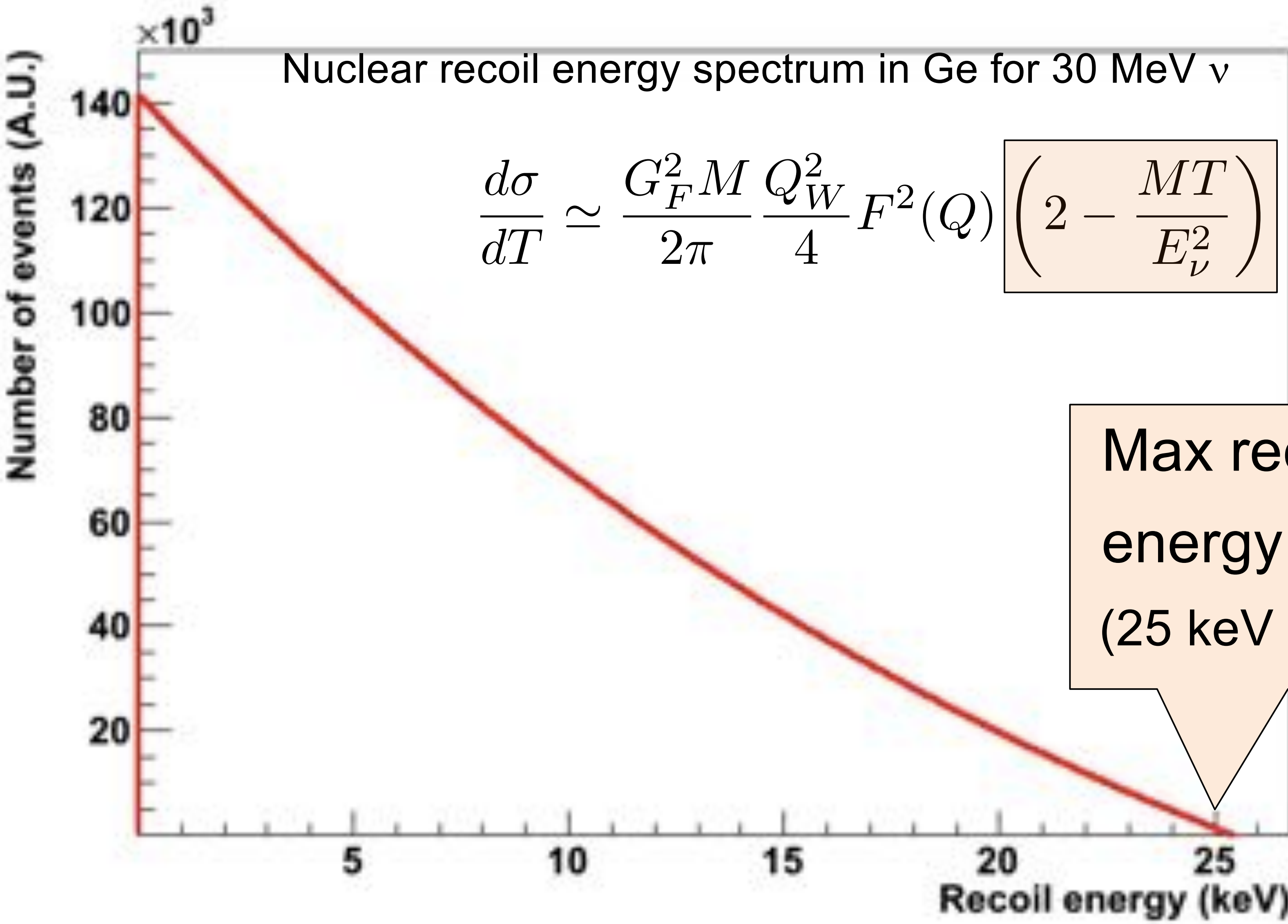


The cross section is *large*
(by neutrino standards)

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

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

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

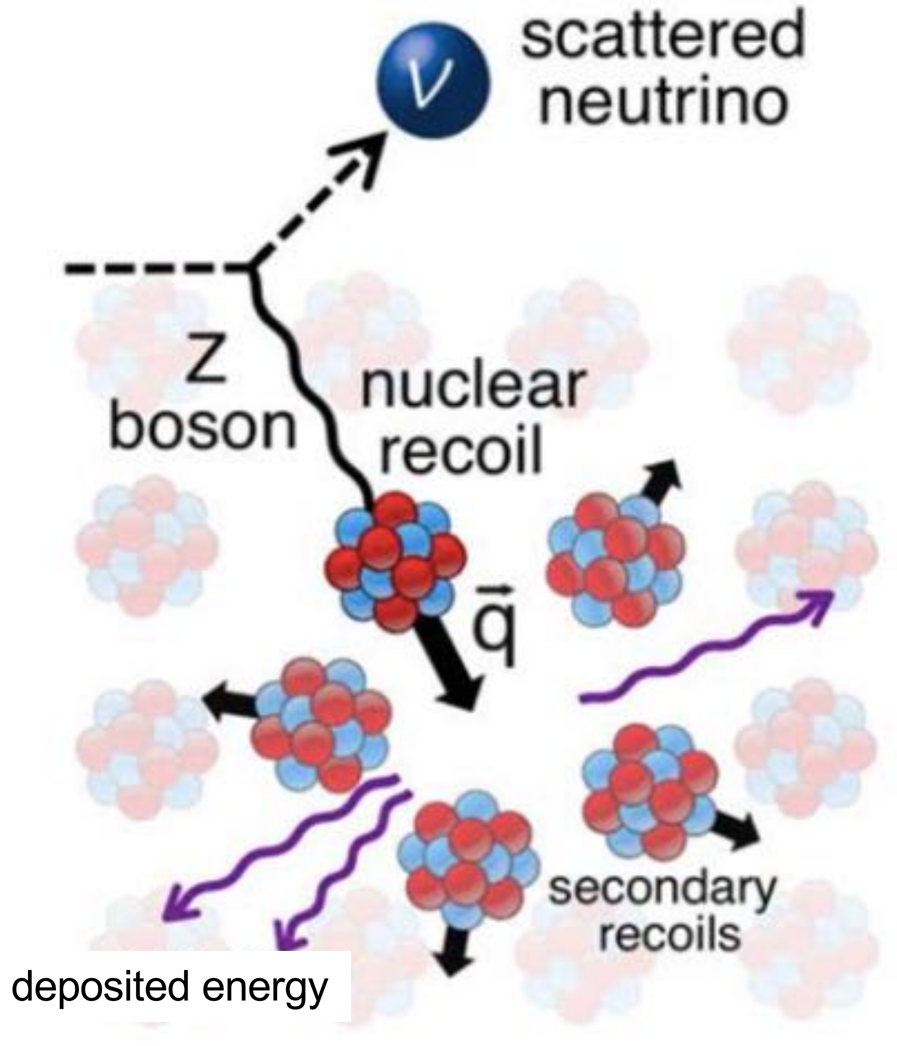


$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Max recoil energy is ~$2E_\nu^2/M$ (25 keV for Ge)

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

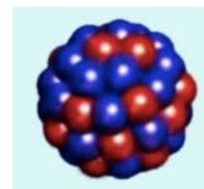
CEvNS: what's it good for?

1 So
2 Many
3 Things
!

(not a complete list!)

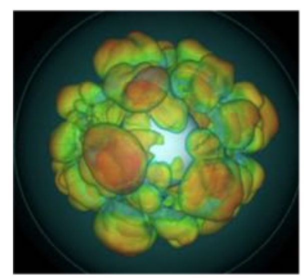
CEvNS as a **signal**
for signatures of *new physics*

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

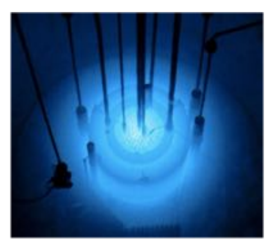


CEvNS as a **background**
for signatures of new physics

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



CEvNS as a **practical tool**



CEvNS: what's it good for?

① So ② Many ③ Things **!** (not a complete list!)

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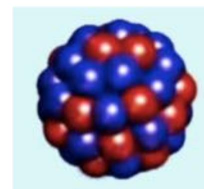

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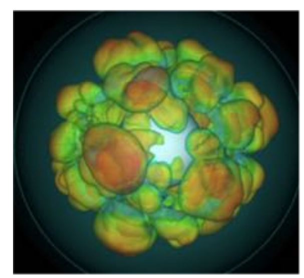
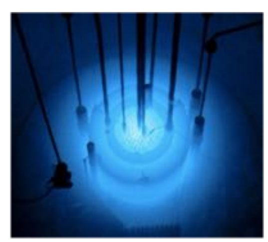


CEvNS as a **signal** for *astrophysics*

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
$Q = \sqrt{(2MT)}$: 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

$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = 0.4955$$
$$g_A^n = -0.5121.$$

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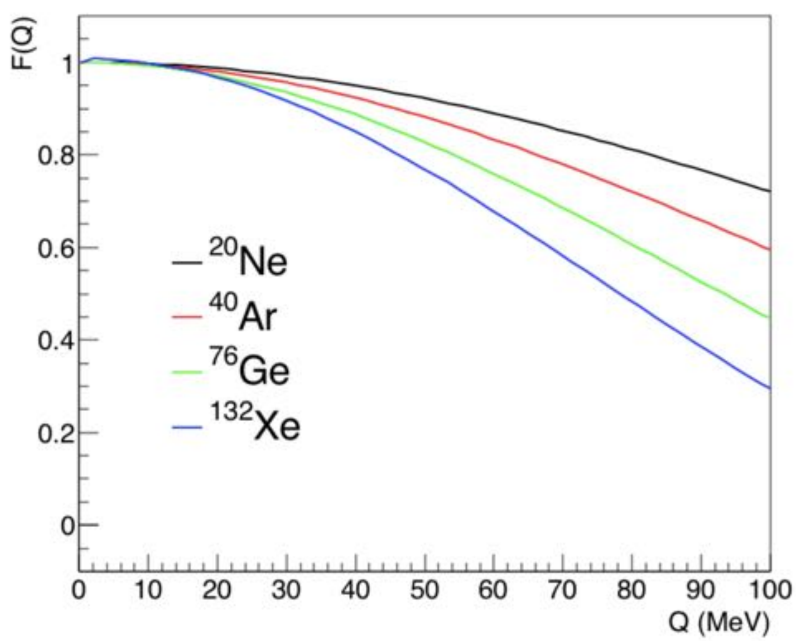
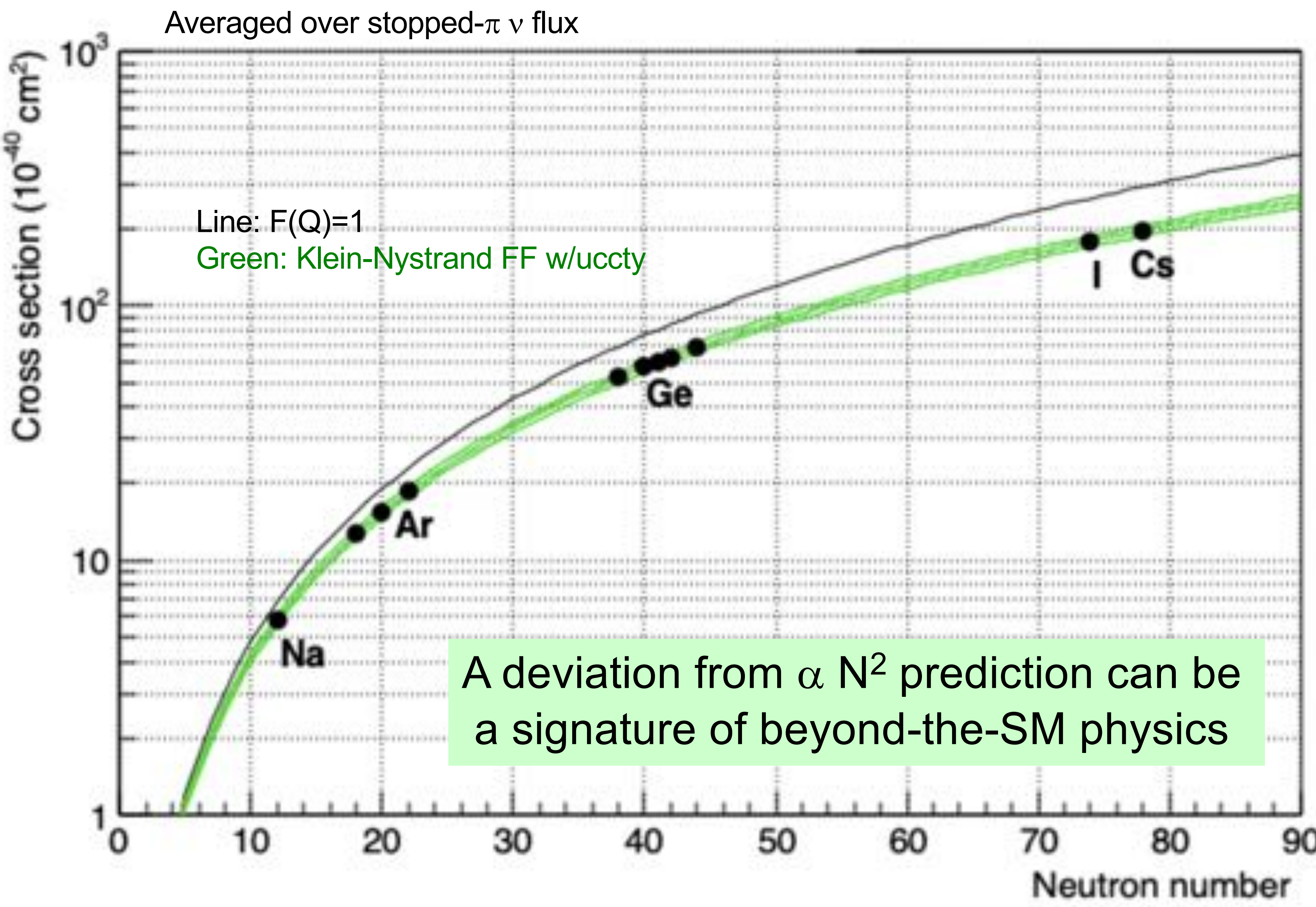
F(Q): nuclear **form factor**, <~5% uncertainty on event rate



form factor suppresses cross section at large Q

Need to measure **N² dependence** of the CEvNS xscn

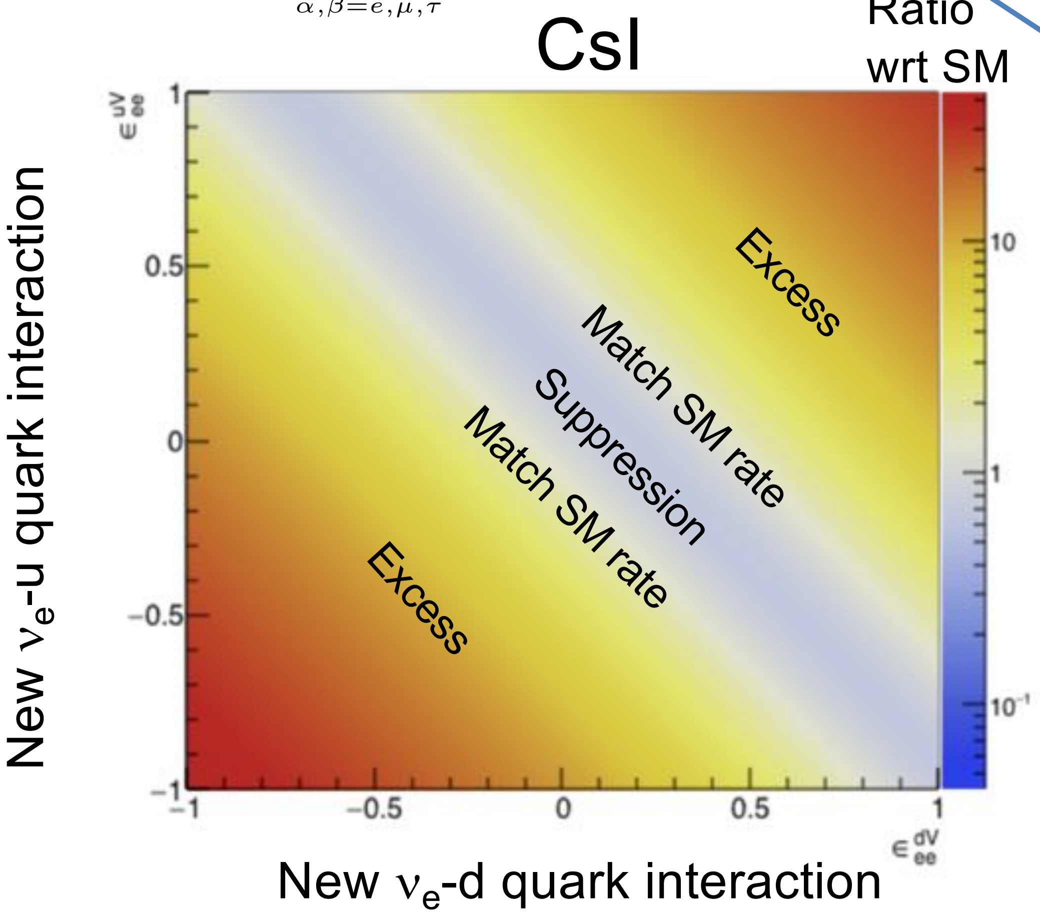


Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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

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



If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

For heavy mediators, expect ***overall scaling*** of CEvNS event rate, depending on N, Z

Example models: Barranco et al. JHEP 0512 & references therein: extra neutral gauge bosons, leptoquarks, R-parity-breaking interactions

More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf

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

BSM Light Mediators

SM weak charge

$$Q^2_{\alpha,\mathrm{SM}} = \left(Z g_p^V + N g_n^V\right)^2$$

Effective weak charge in presence of light vector mediator Z'

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

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?

!

(not a complete list!)

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for signatures of *new physics*

CEvNS as a **signal**
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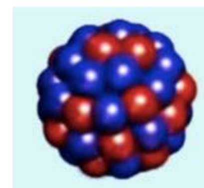
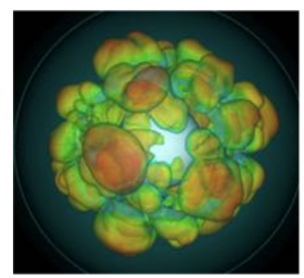
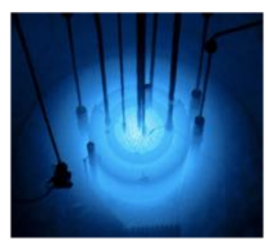


CEvNS as a **background**
for signatures of new physics (DM)



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

CEvNS as a **practical tool**

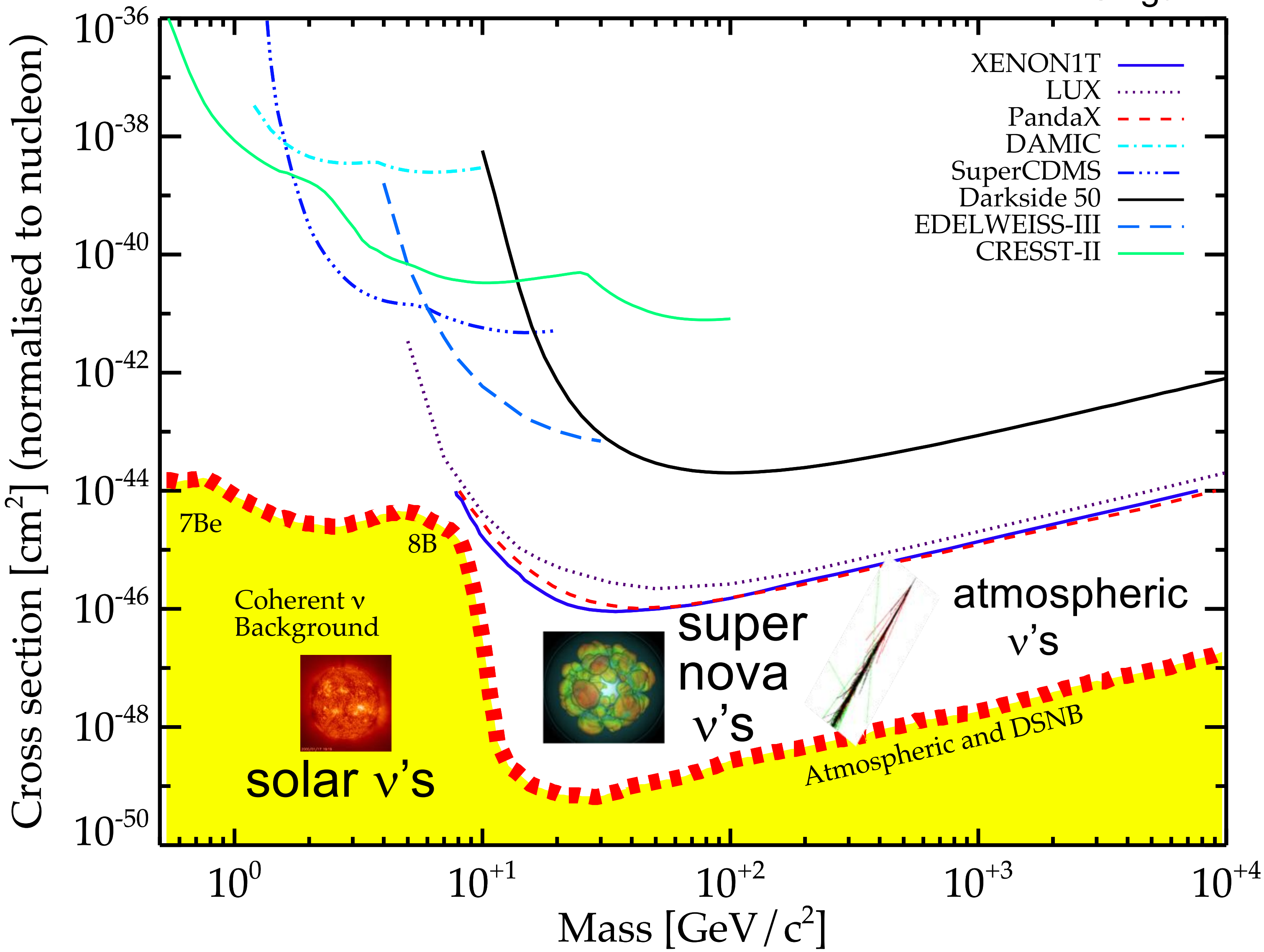


The so-called "neutrino floor" (**signal!**) for direct DM experiments

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

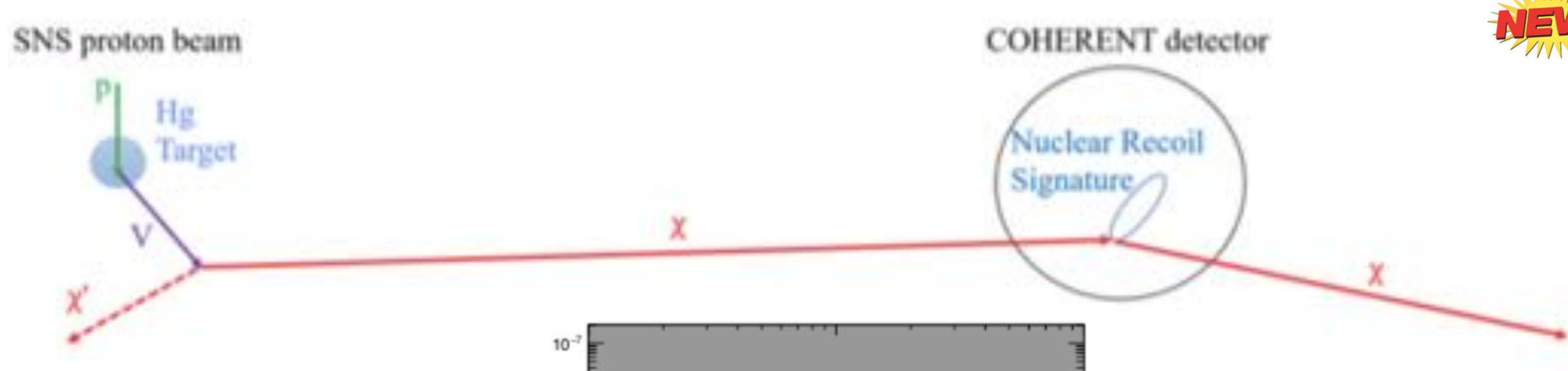
} decay product χ then makes nuclear recoil

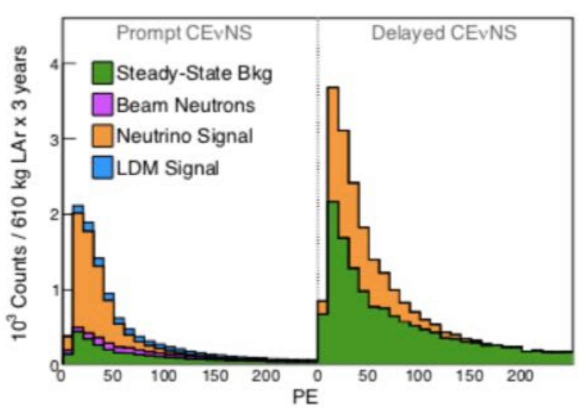
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

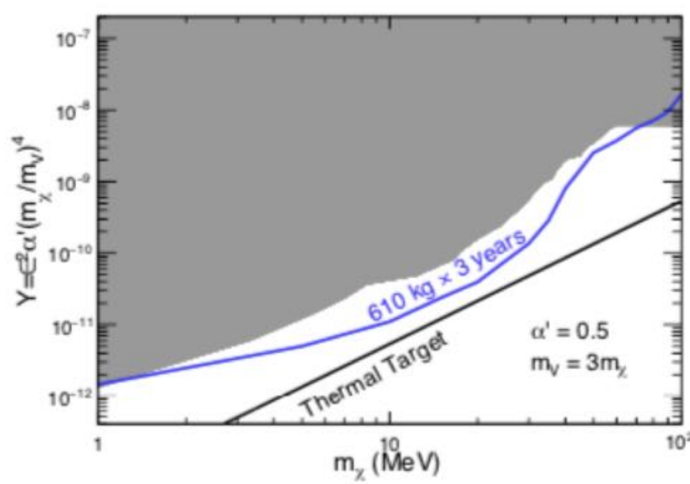
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

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!





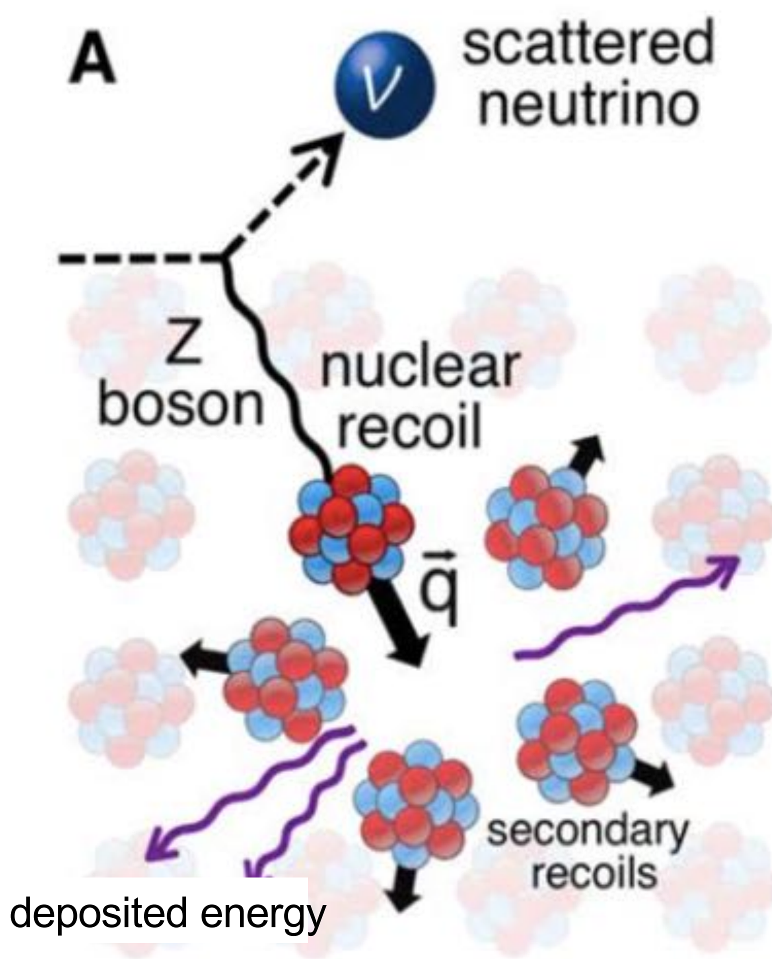


Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

How to measure CEvNS

The only experimental signature:

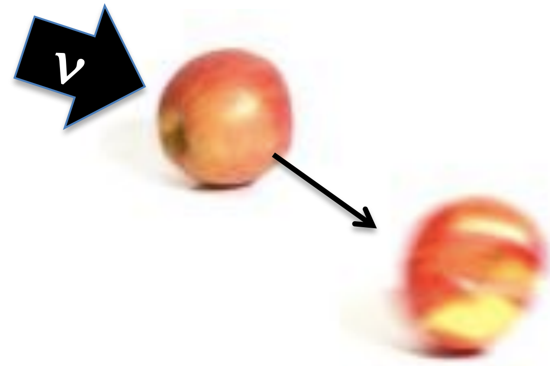
tiny energy deposited by nuclear recoils in the target material



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

How to detect CEvNS?

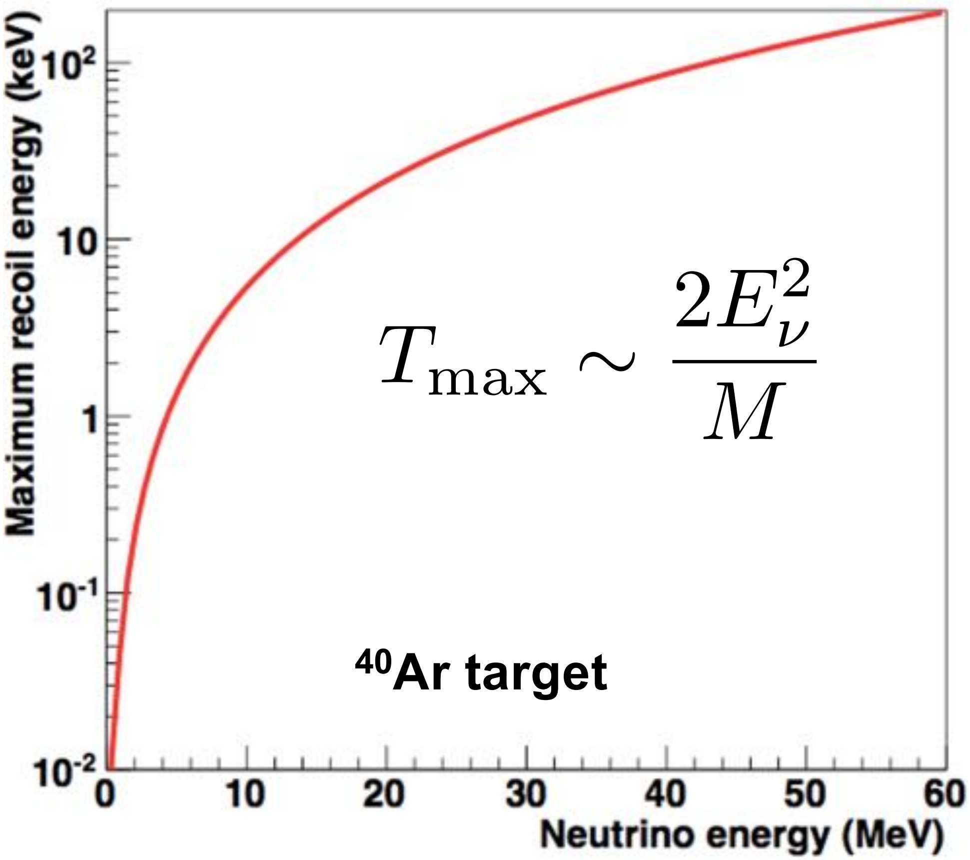
You need a neutrino source
and a detector

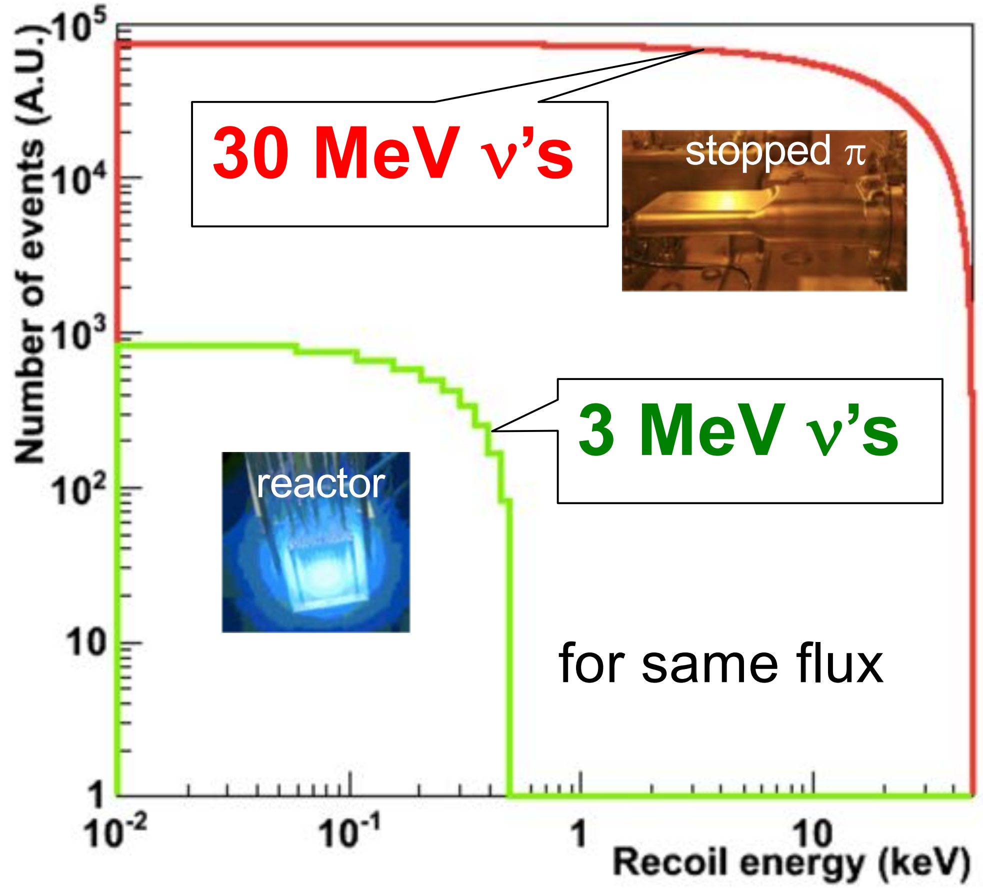


What do you want for your ν source?

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

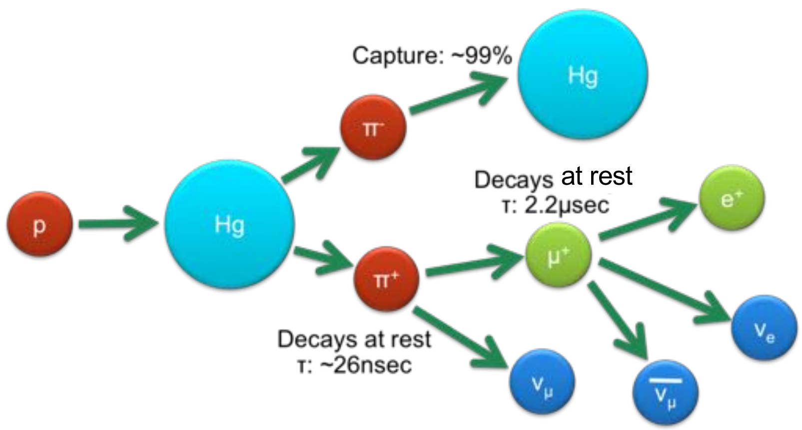
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

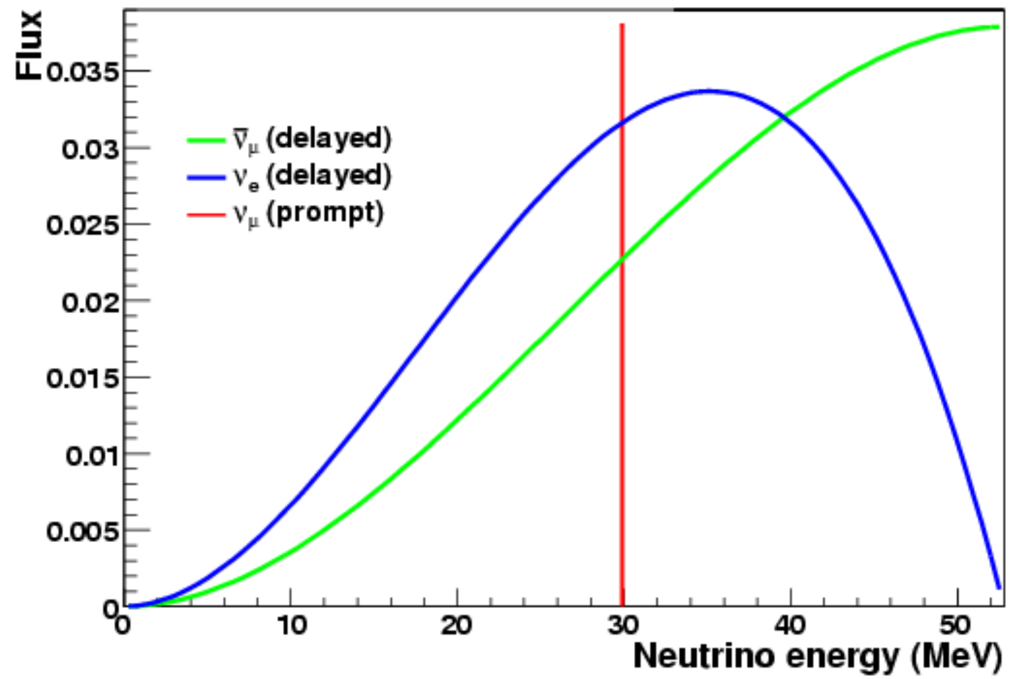




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

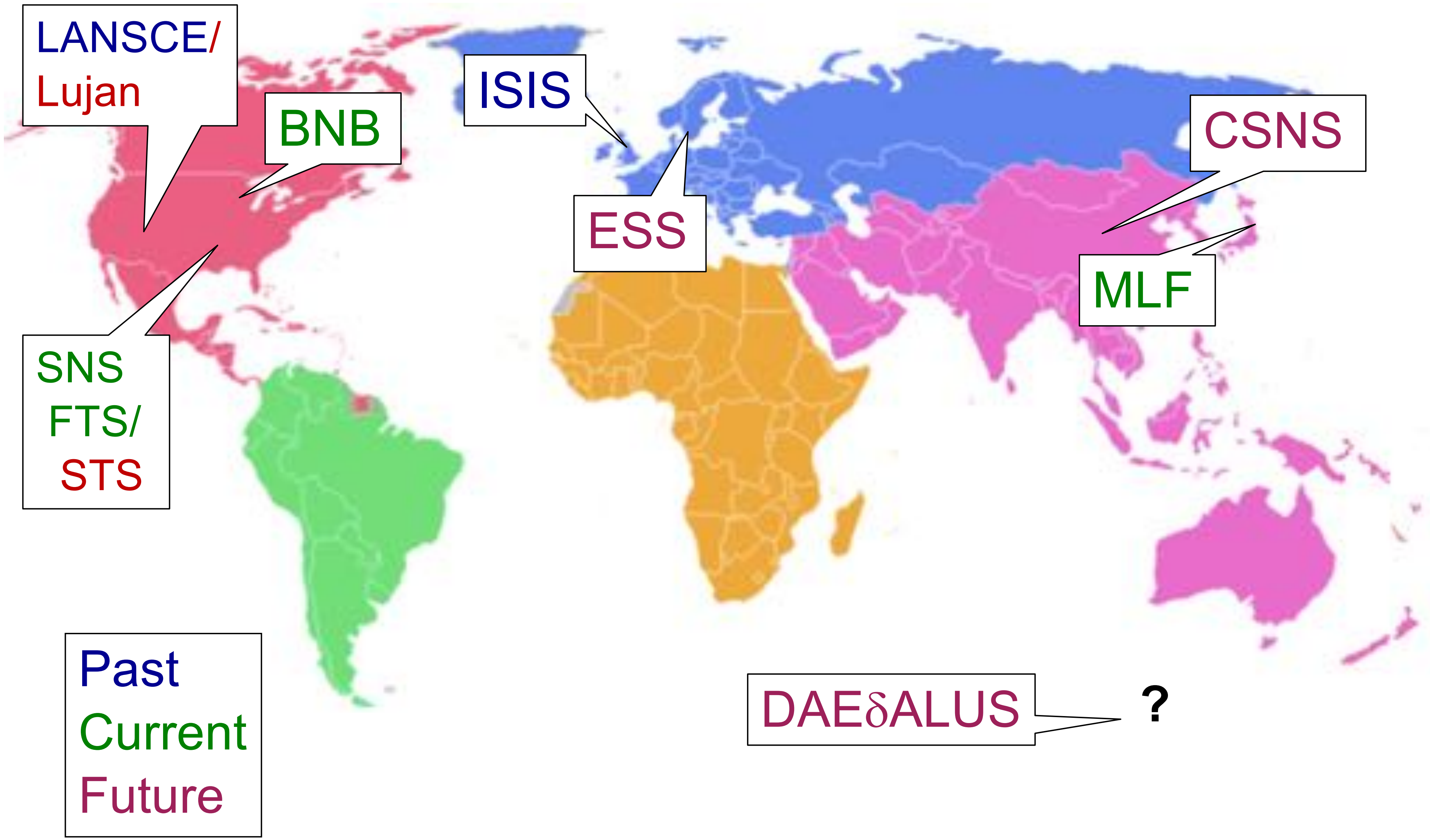
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

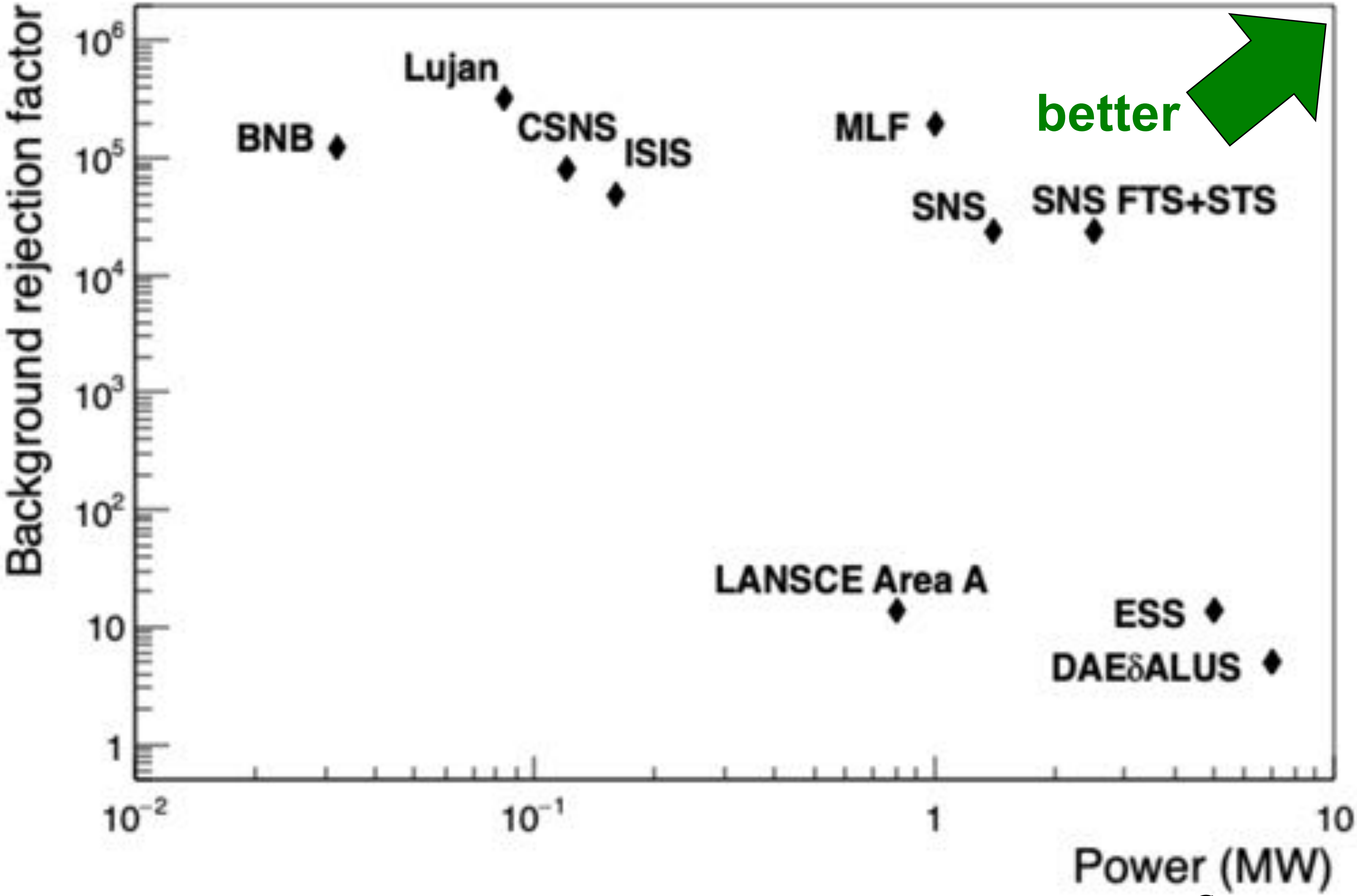
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Neutrino Sources Worldwide



from duty cycle

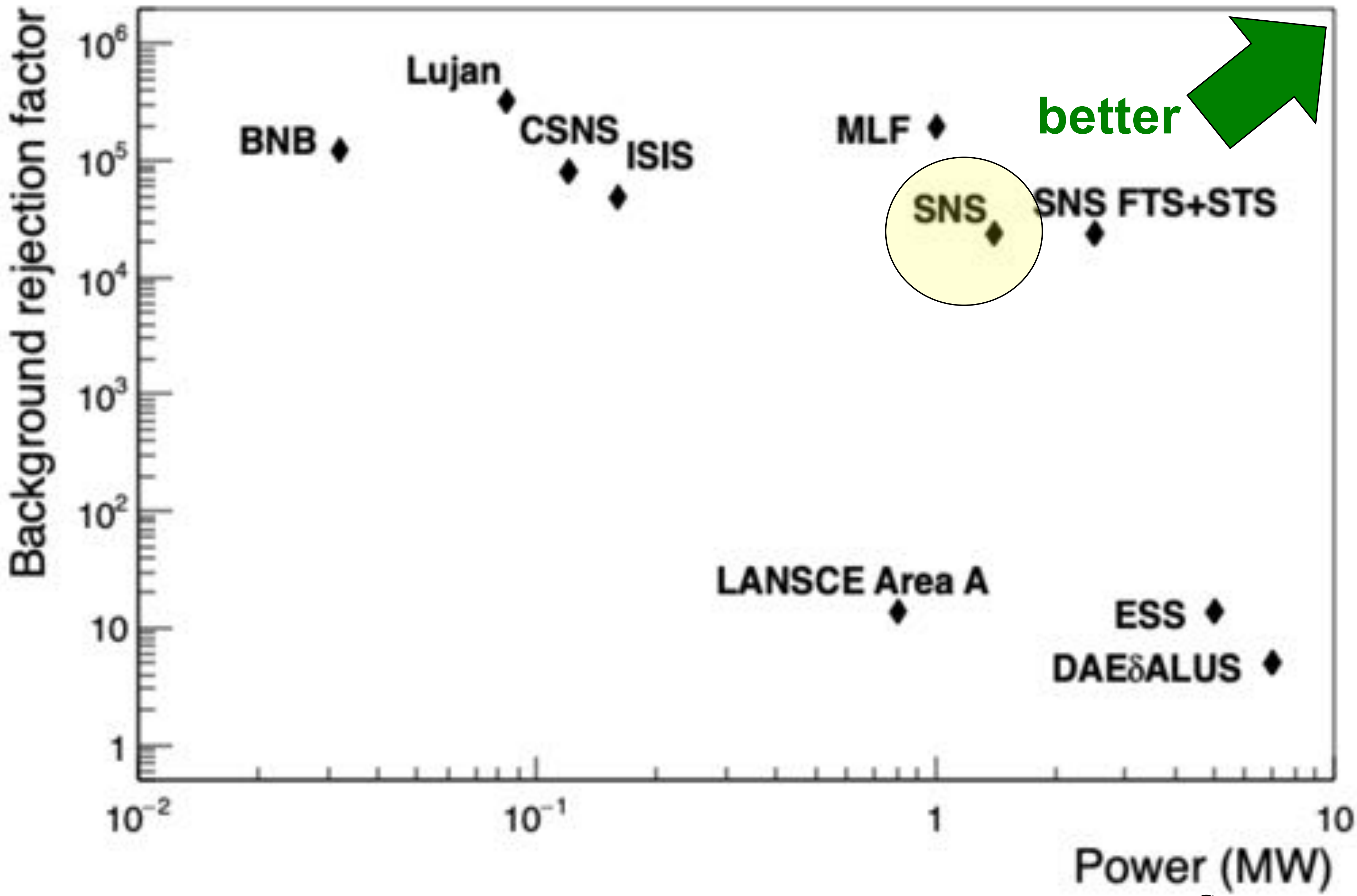
Comparison of pion decay-at-rest ν sources



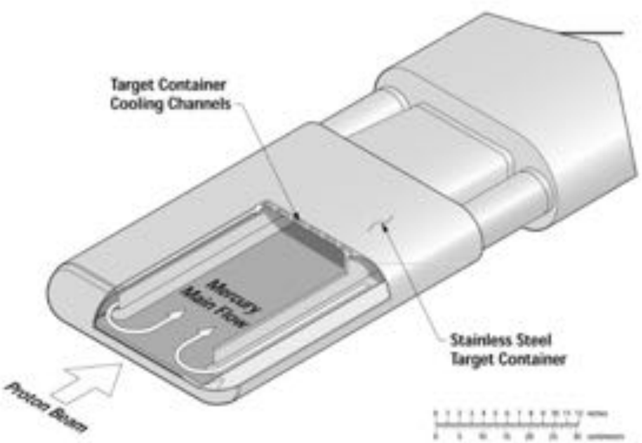
$\propto \nu$ flux

Comparison of pion decay-at-rest ν sources

from duty cycle



$\propto \nu$ flux



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!

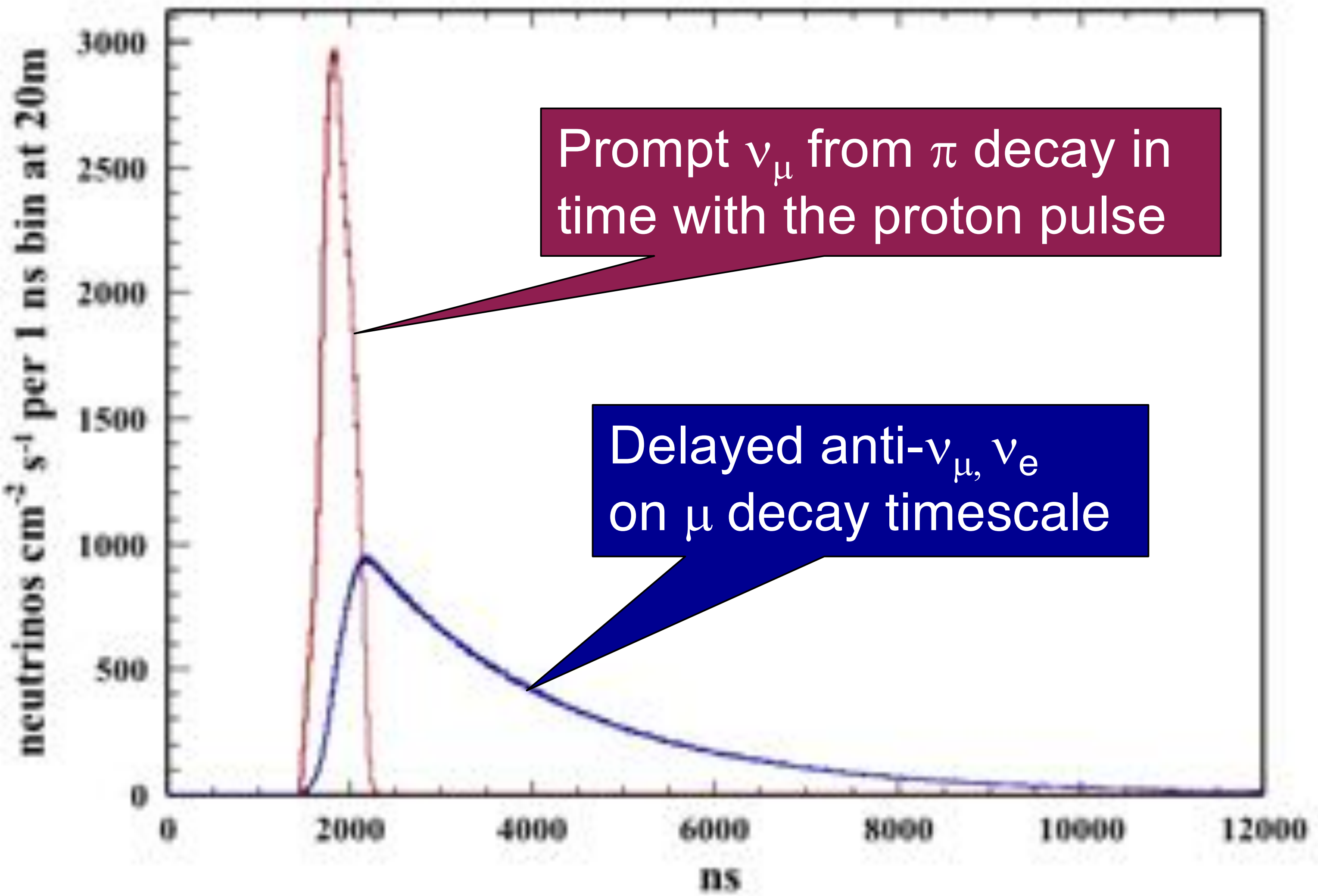
These are *not* crummy
old cast-off neutrinos...

These are *not* crummy old cast-off neutrinos...

They are of the highest quality!

Time structure of the SNS source

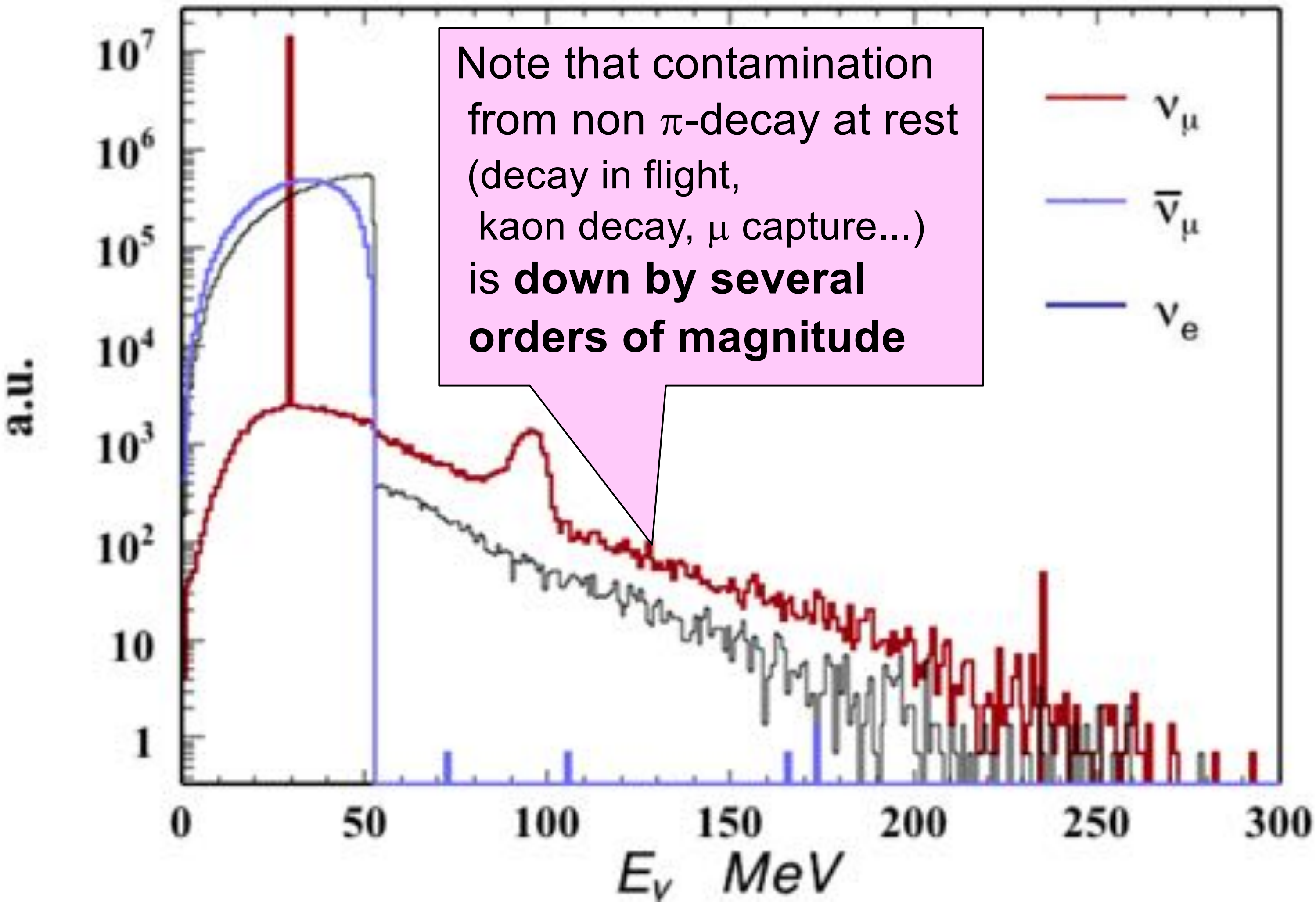
60 Hz *pulsed* source



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

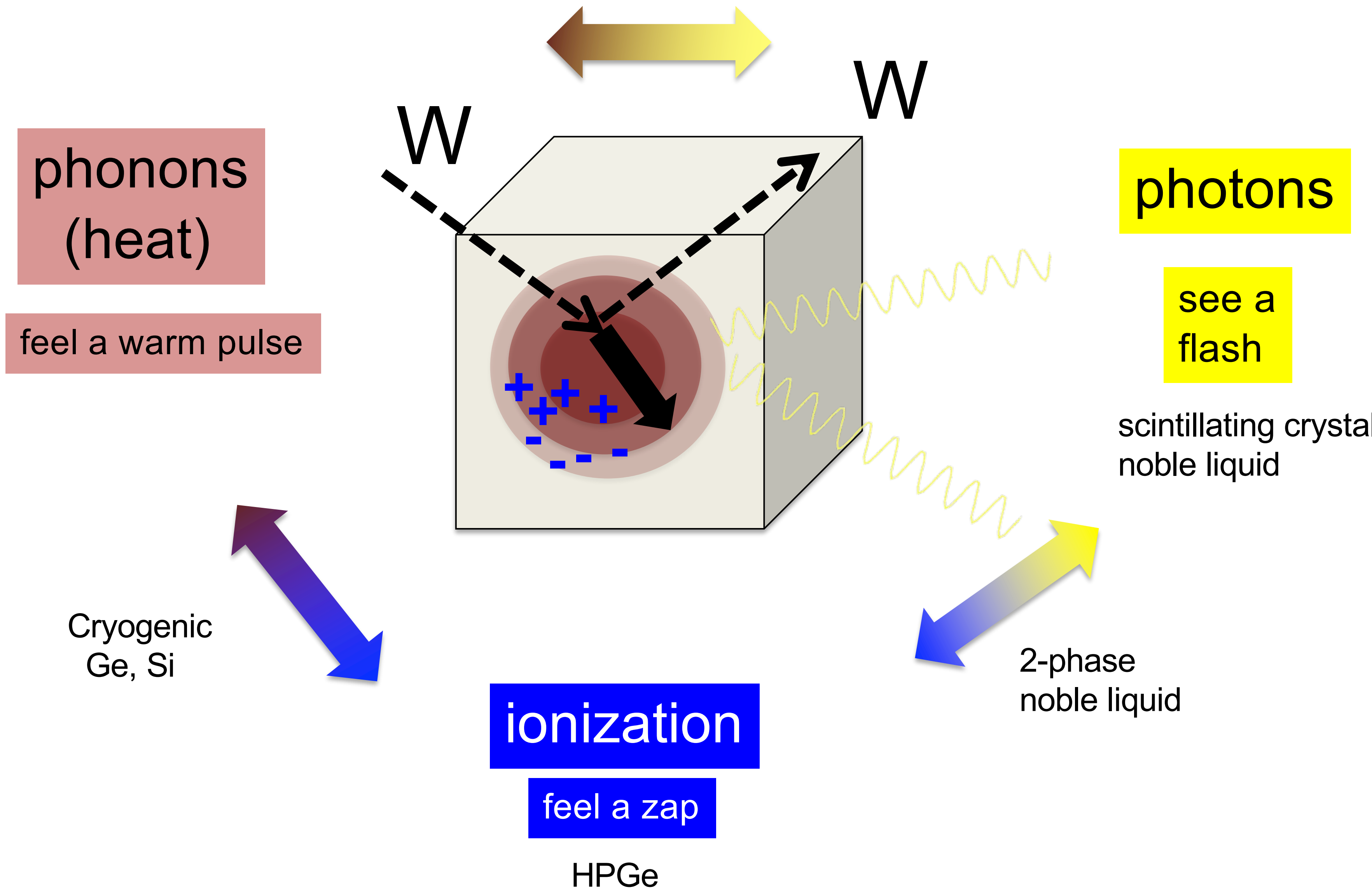
The SNS has **large, extremely clean** stopped-pion ν flux

0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

Low-energy nuclear recoil detection strategies



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

The COHERENT collaboration

http://sites.duke.edu/coherent

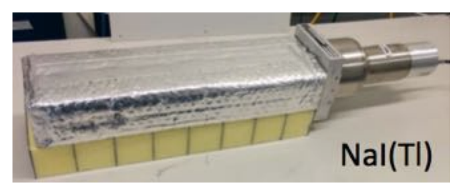
~90 members,
20 institutions
4 countries

arXiv:1509.08702

COHERENT CEvNS Detectors

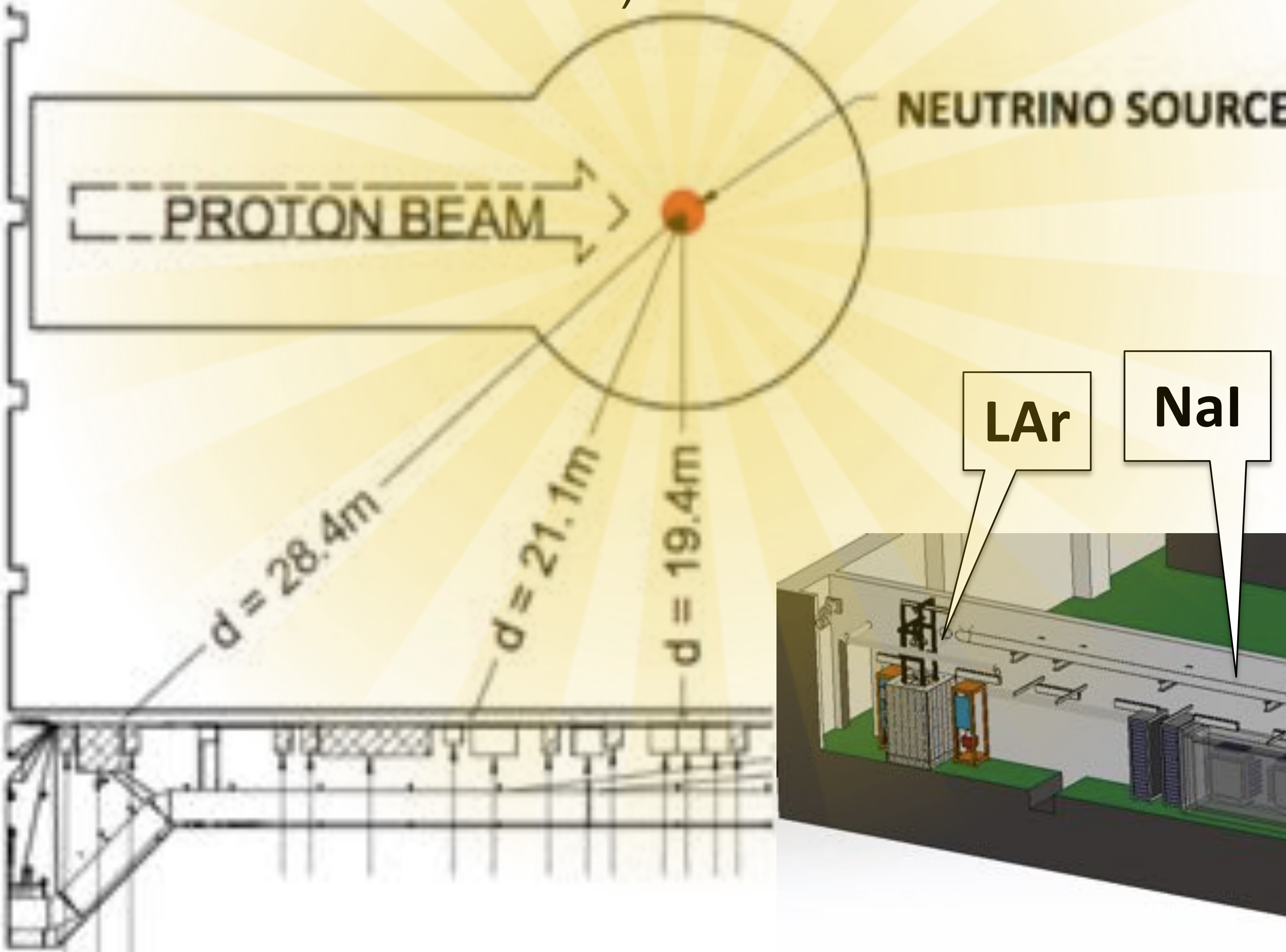
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal flash	14.6	19.3	6.5
Ge	HPGe PPC zap	16	20	<few
LAr	Single-phase flash	22	29	20
NaI[Tl]	Scintillating crystal flash	185*/3338	28	13

Multiple detectors for N^2 dependence of the cross section

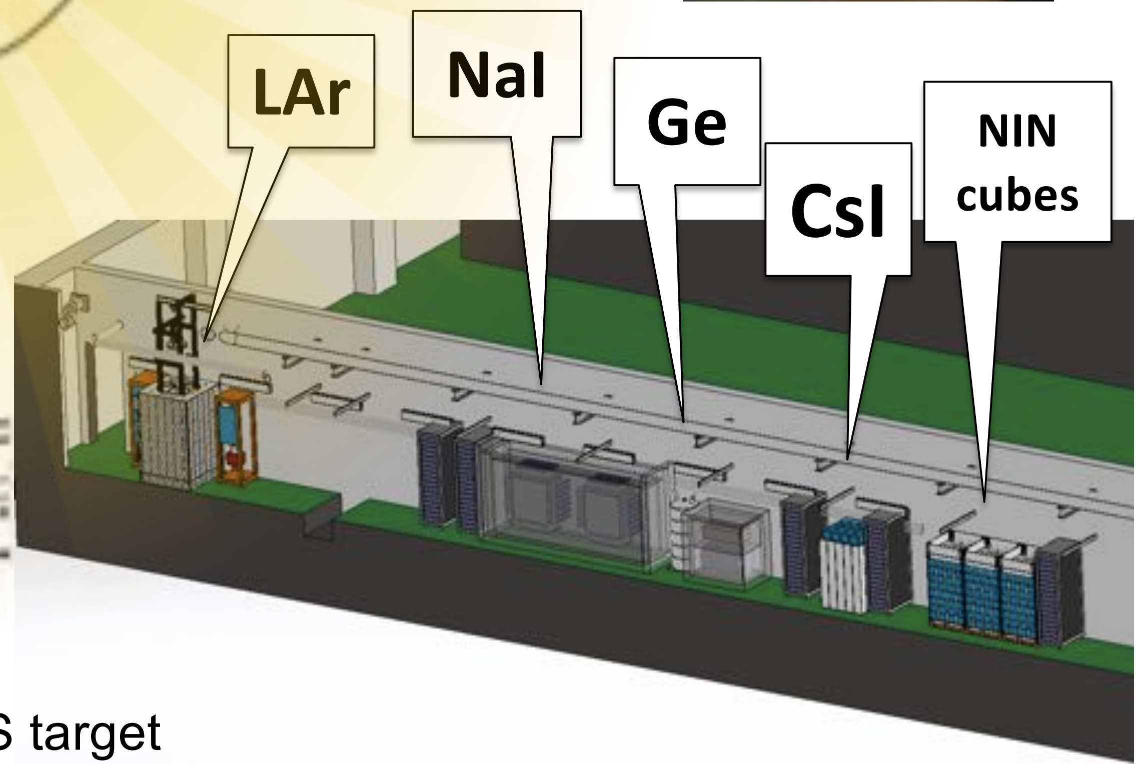


Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

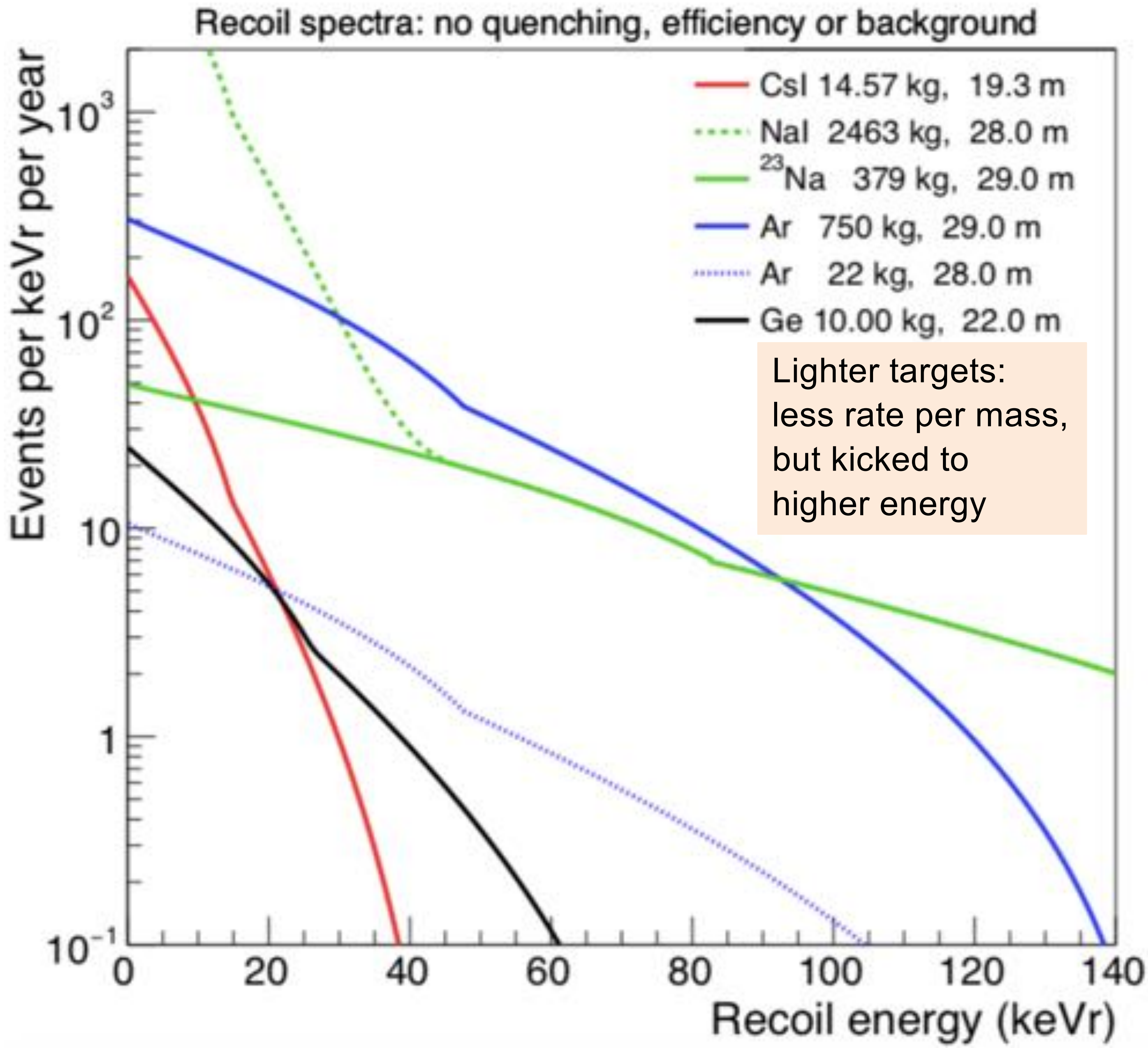


View looking down "Neutrino Alley"



Isotropic ν glow from Hg SNS target

Expected recoil energy distribution

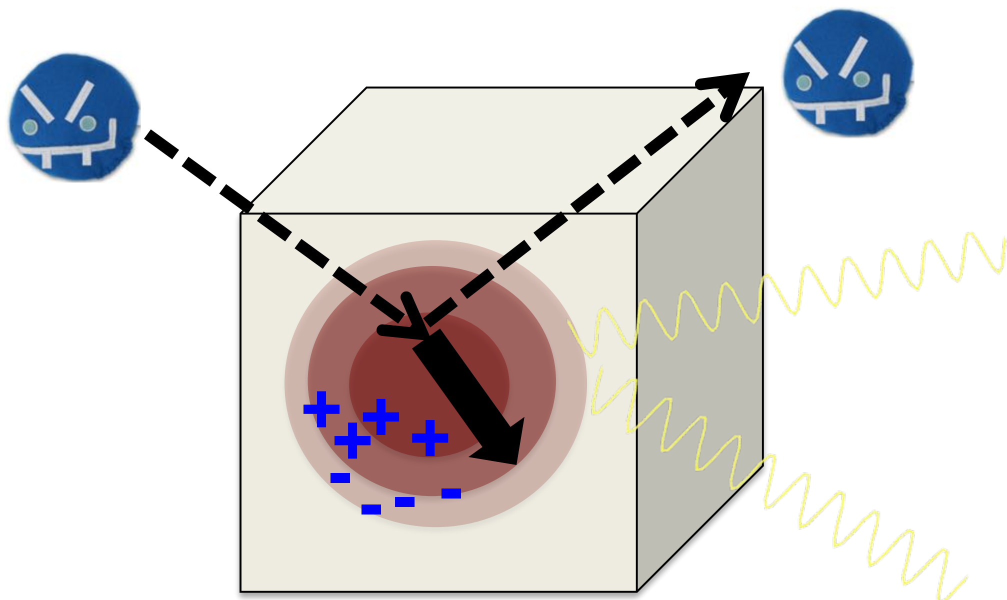


Backgrounds

Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

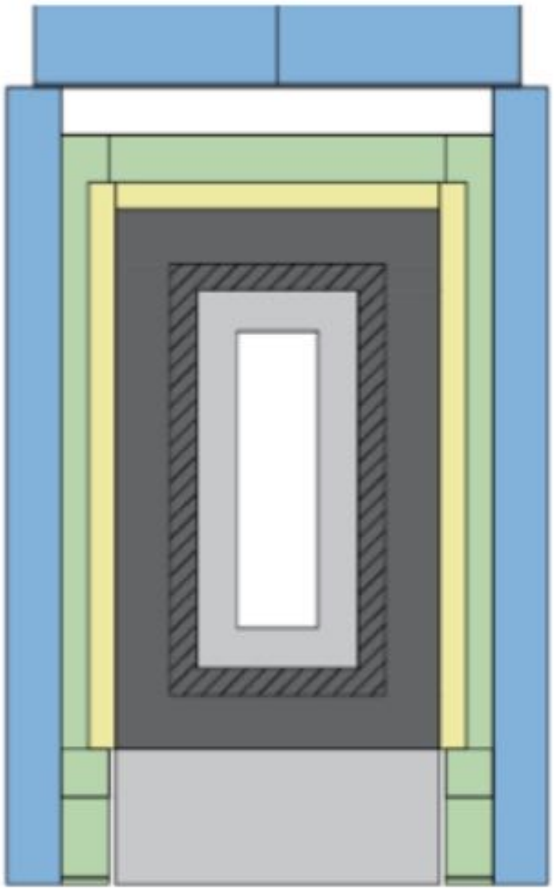
Neutrons are especially not your friends*

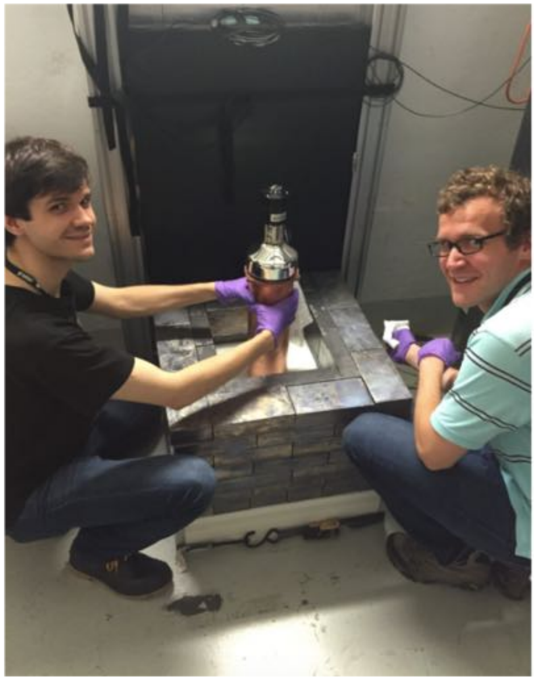


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

The CsI Detector in Shielding in Neutrino Alley at the SNS



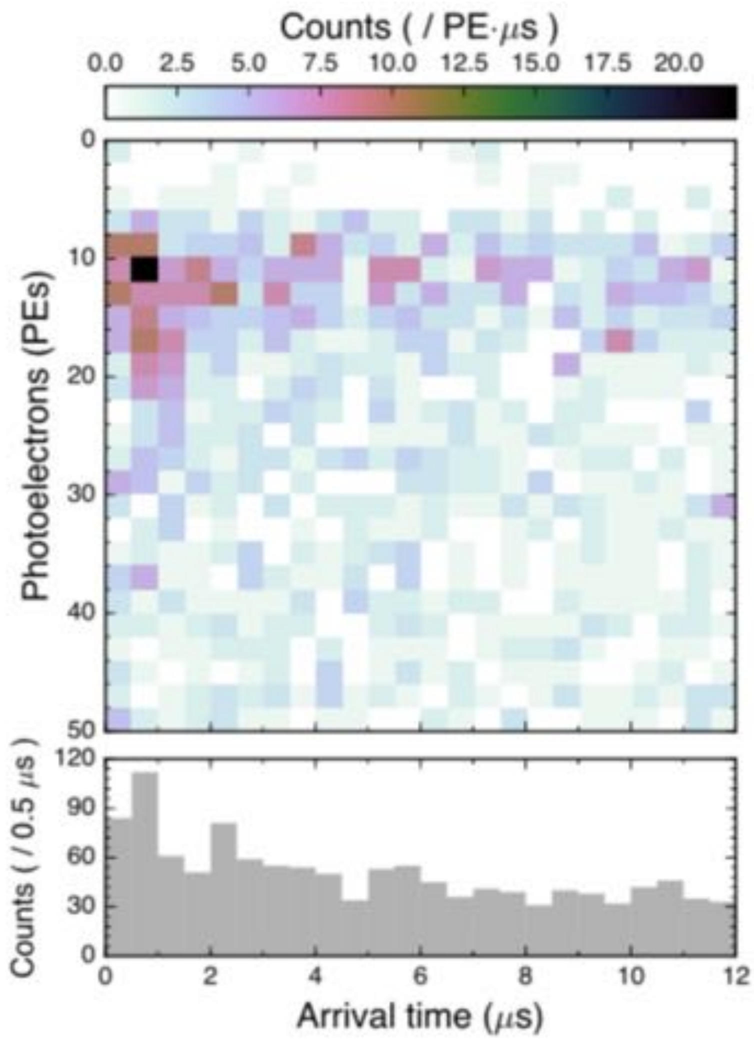


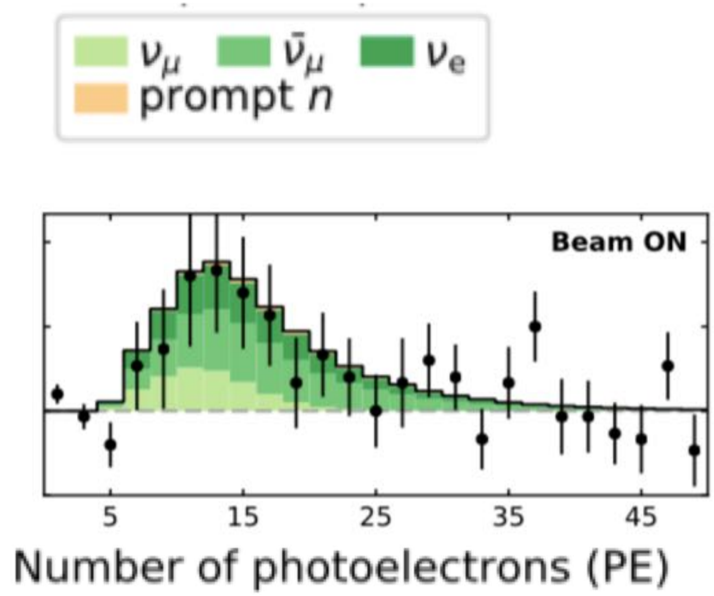
A hand-held detector!

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





Background-subtracted and integrated over time

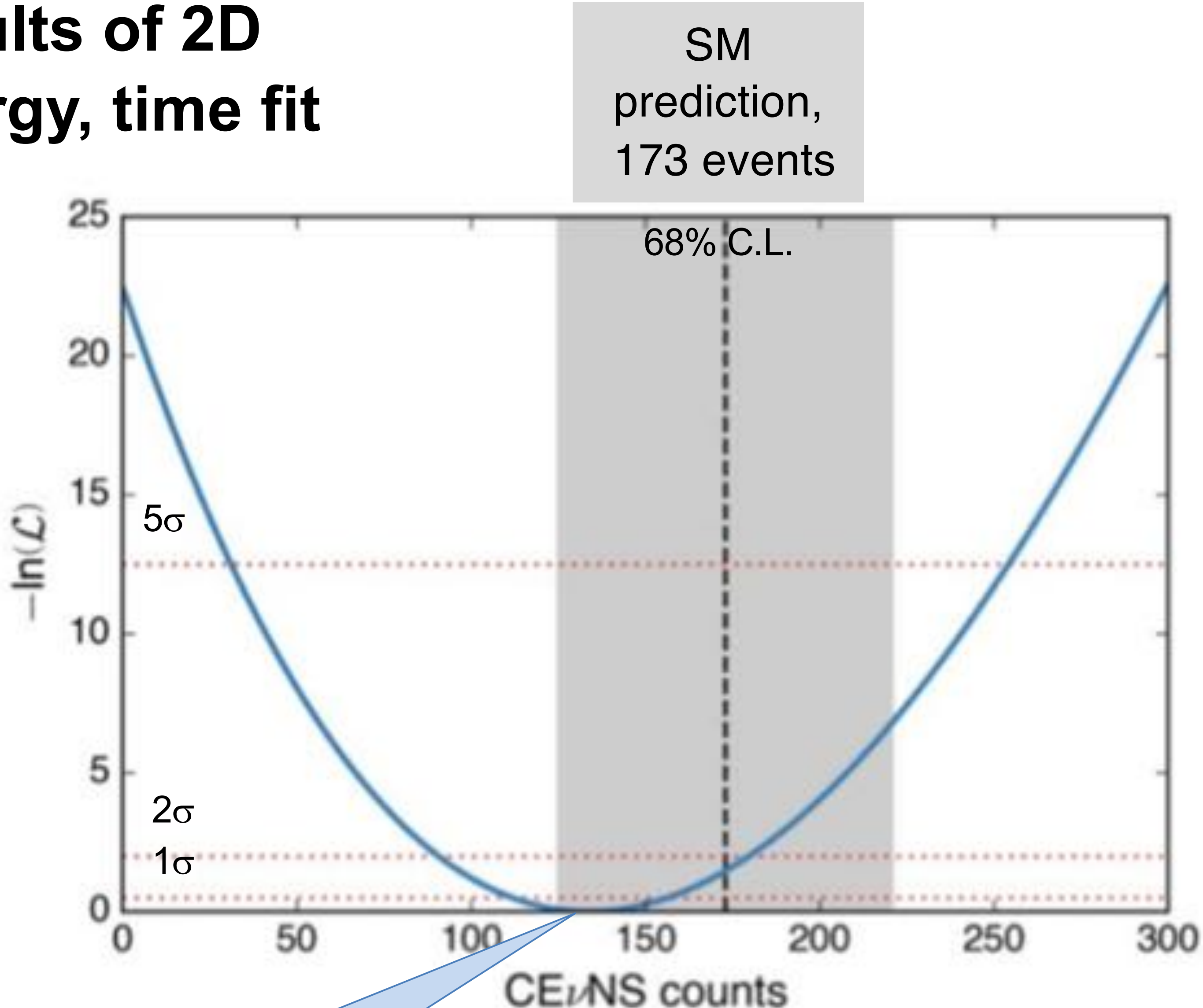
$$\mathrm{PE} \propto T \propto Q^2$$

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

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

Results of 2D energy, time fit



Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

Signal, background, and uncertainty summary numbers

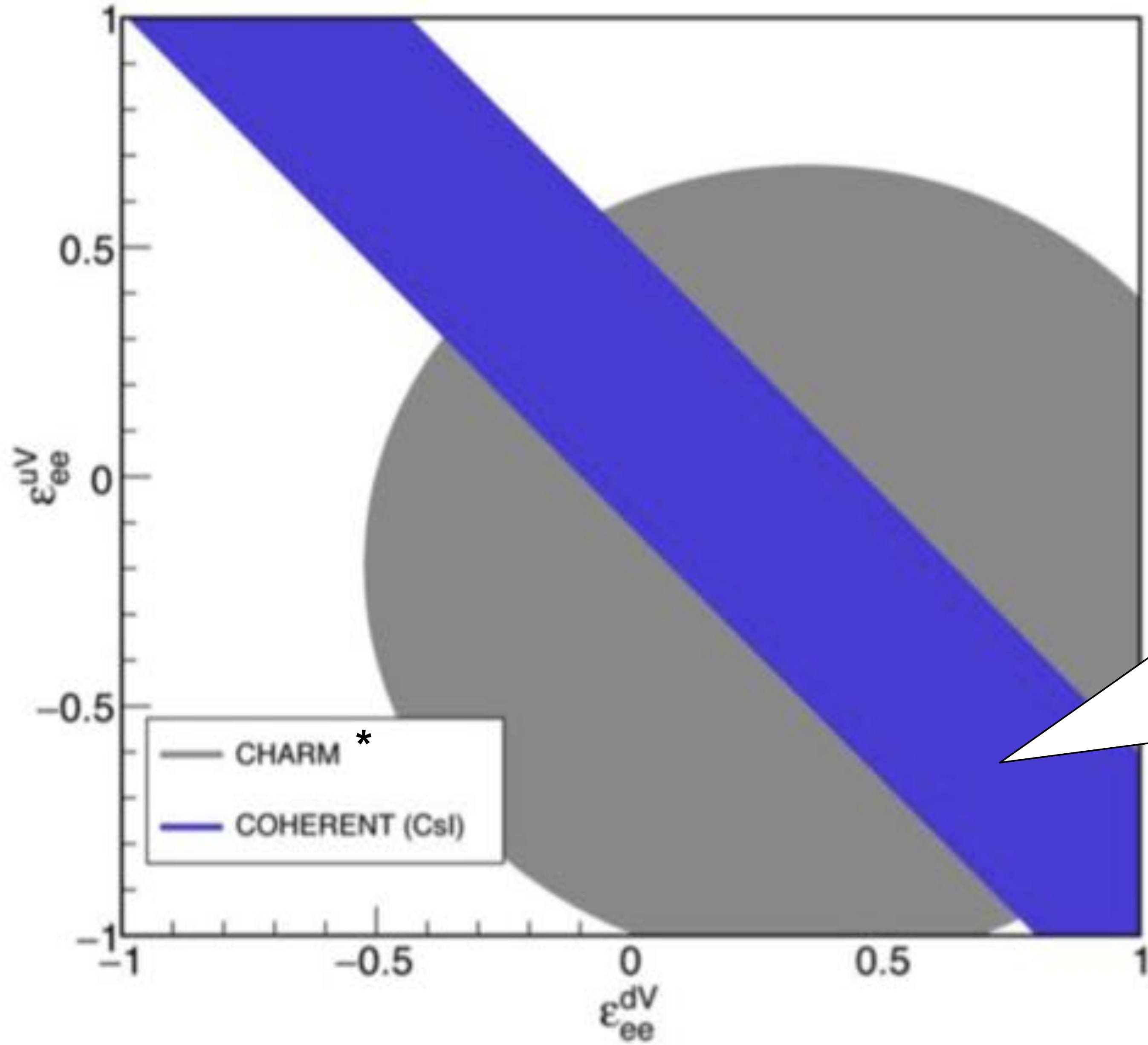
$6 \leq PE \leq 30$, $0 \leq t \leq 6000$ ns

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Dominant uncertainty (← Quenching factor)

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

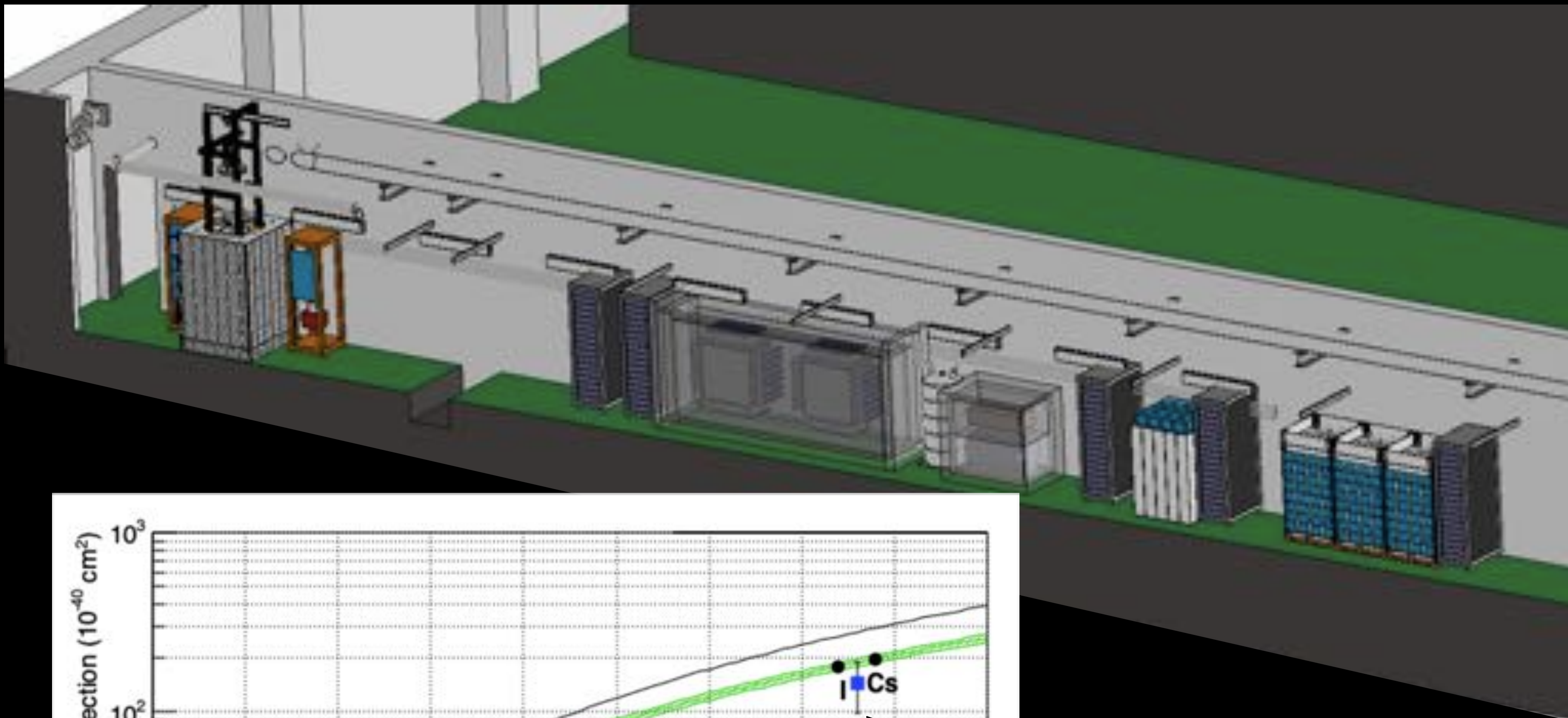


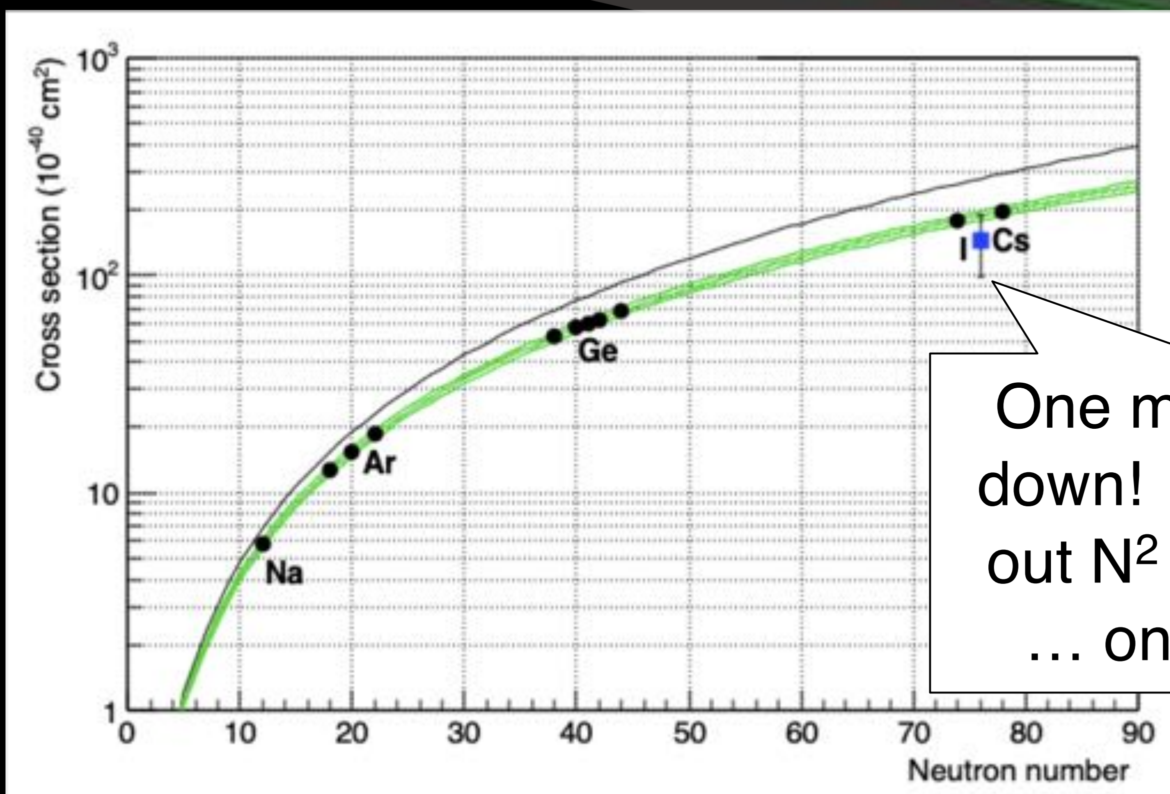
- Assume all other ε's zero

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

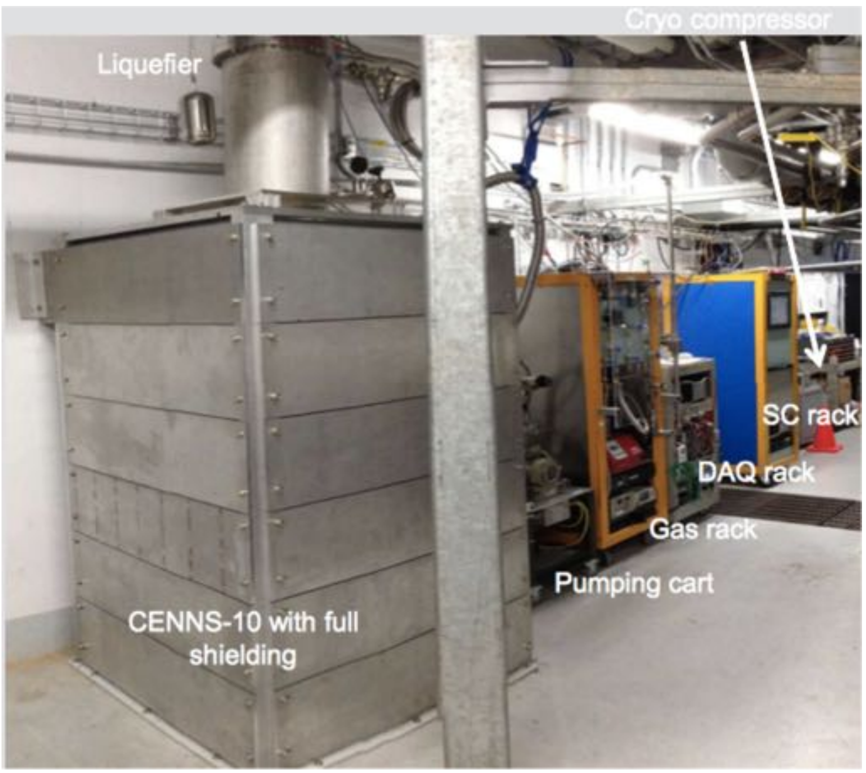




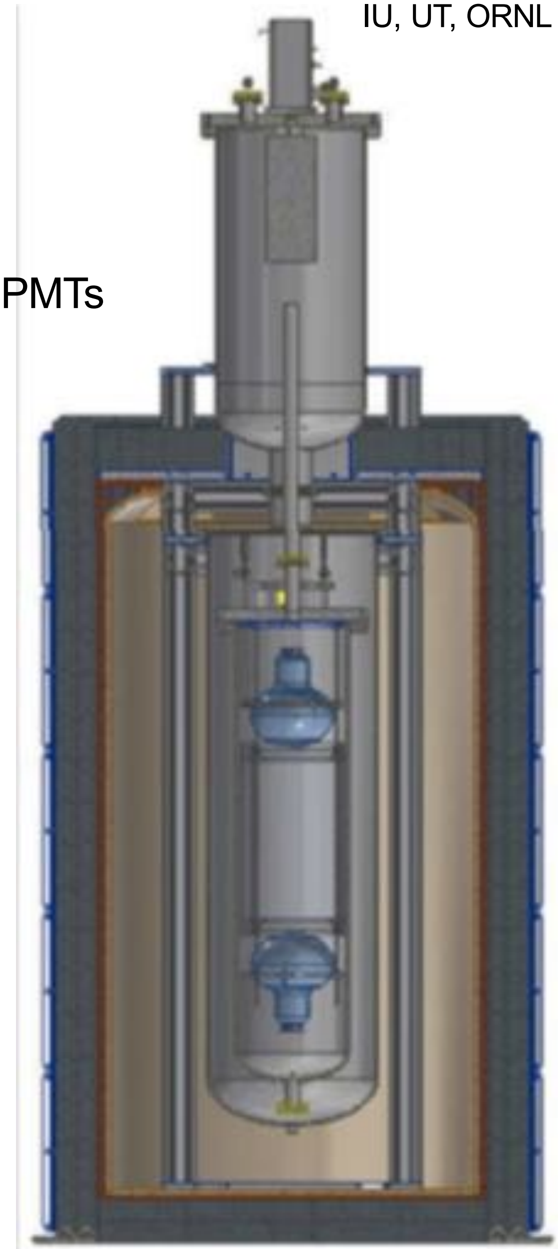
One measurement down! Want to map out N^2 dependence … on to the next

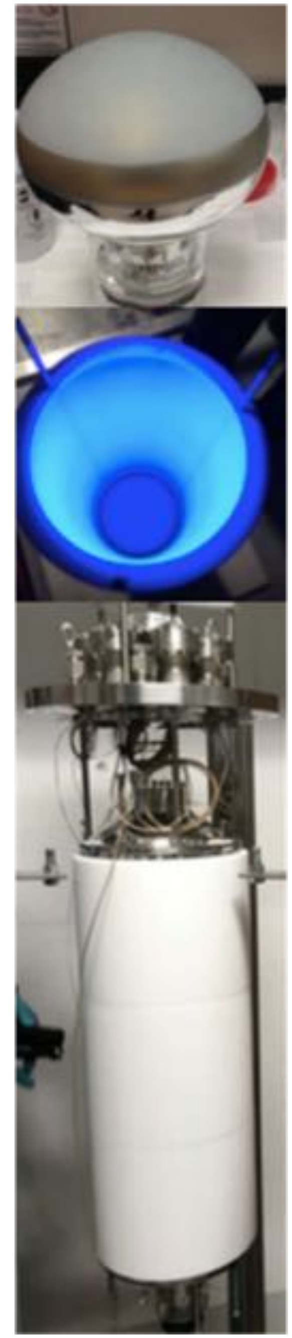
Single-Phase Liquid Argon

- ~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



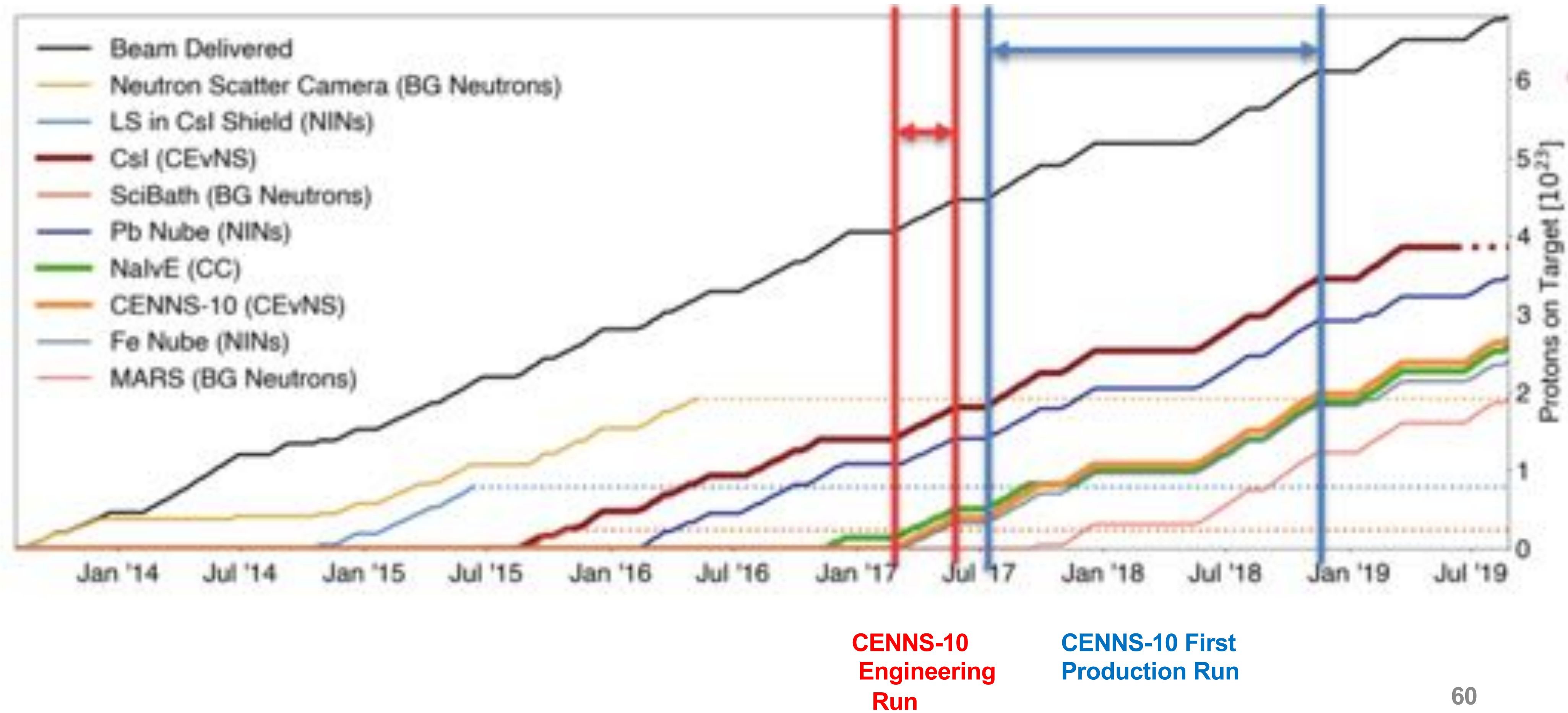


Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB

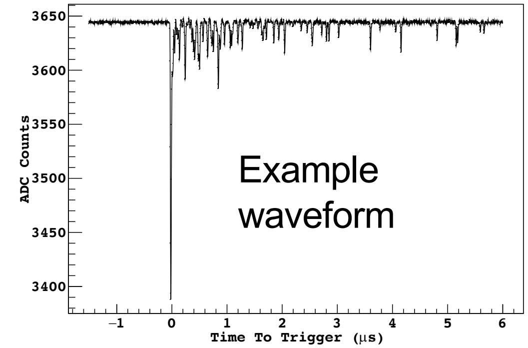
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

LAr CENNS-10 Data Taking

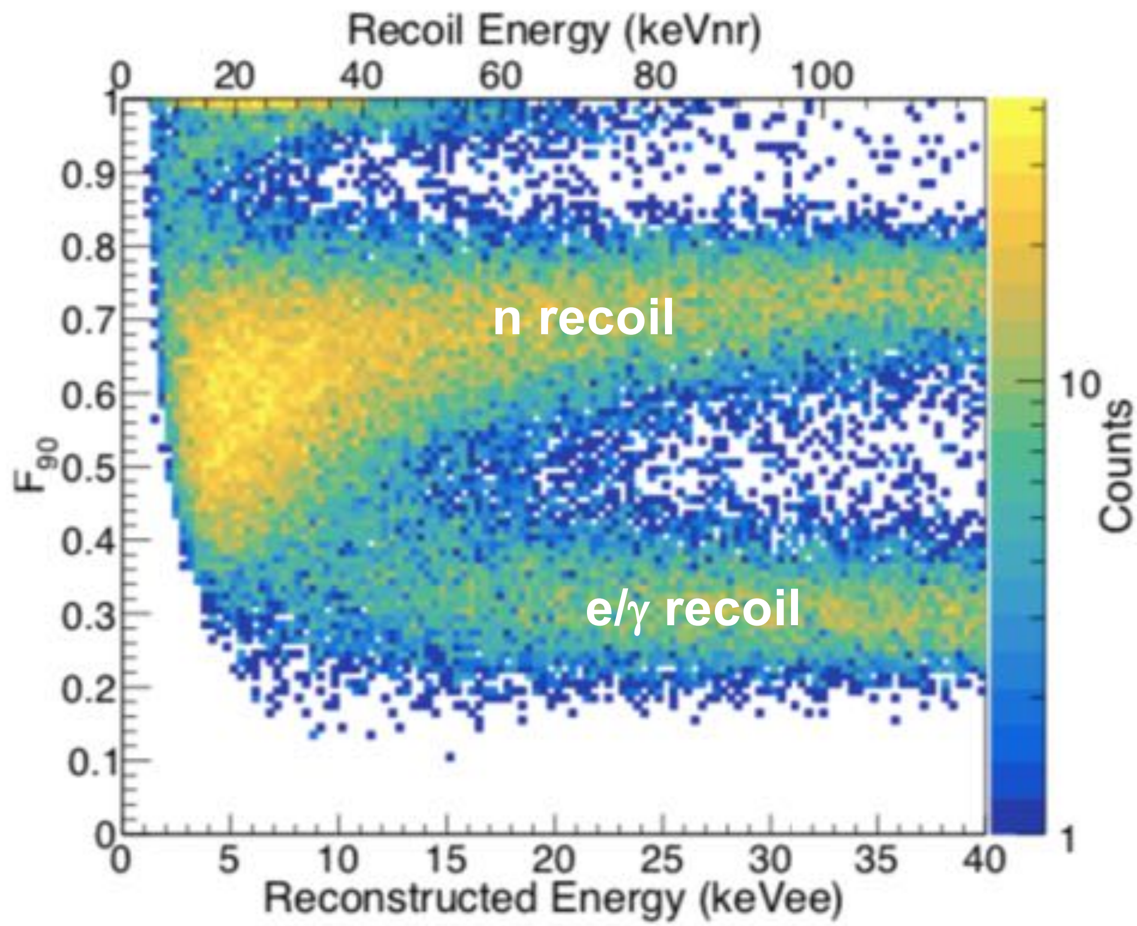
- Engineering Run of total 1.8 GWhr (~0.4 x 10^{23} POT) of integrated beam power from February-May 2017
- Data set considered for first physics result (First Production Run) reported here is total 6.1 GWhr (~1.4 x 10^{23} POT) of integrated beam power from July 2017-November 2018



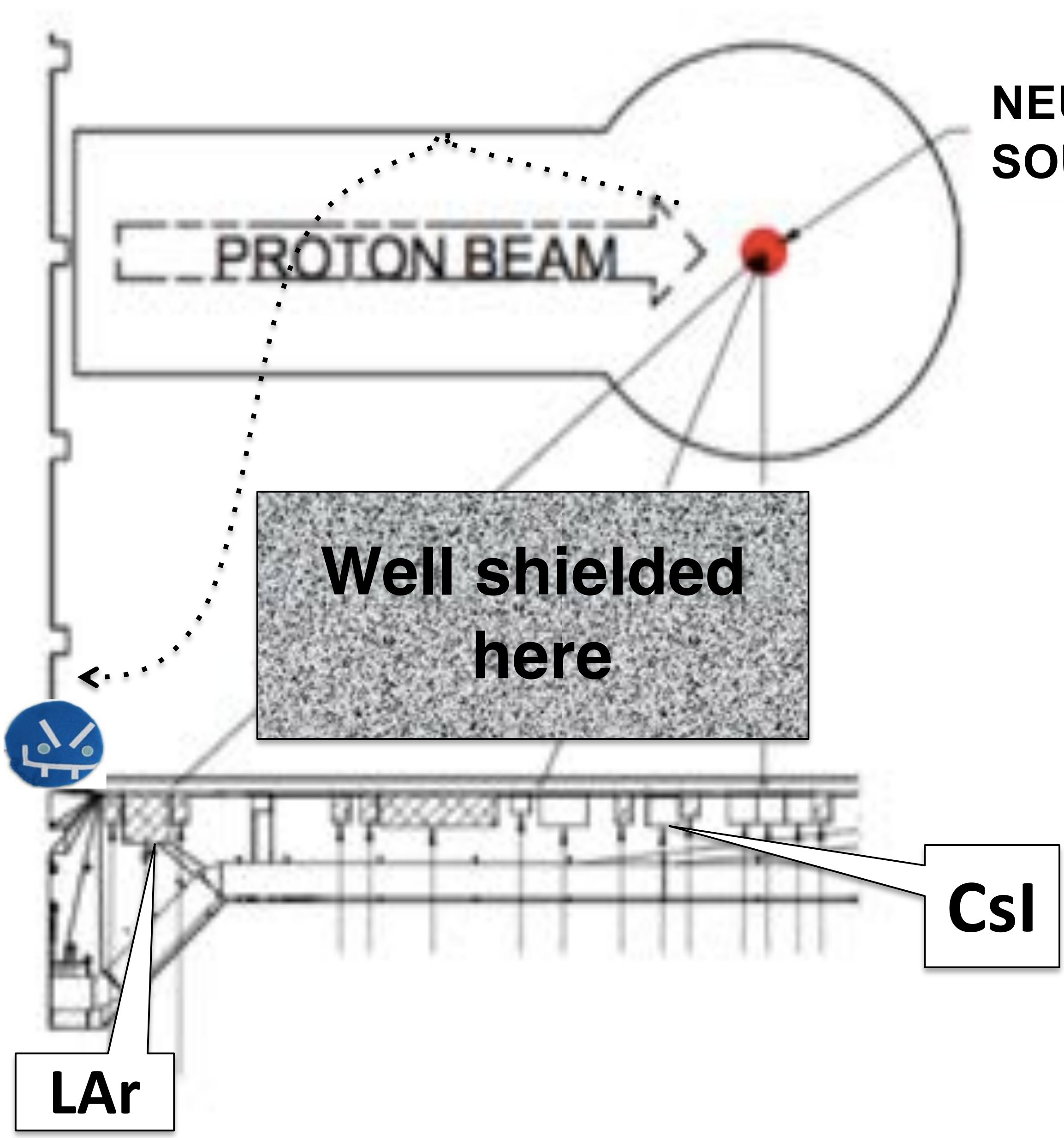
Use **pulse-shape discrimination** to select recoils



F90: fraction of light in first 90 ns

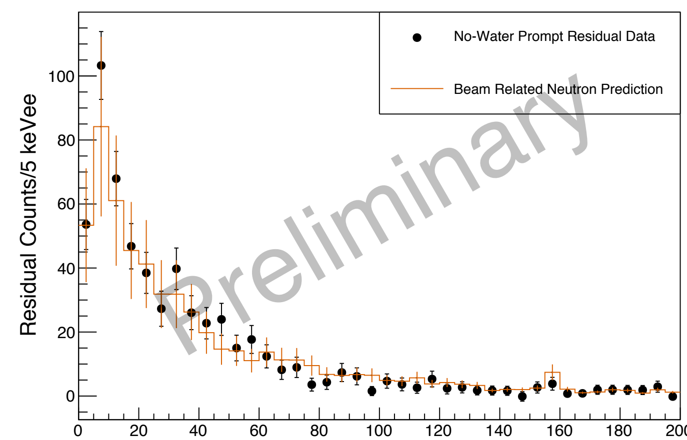


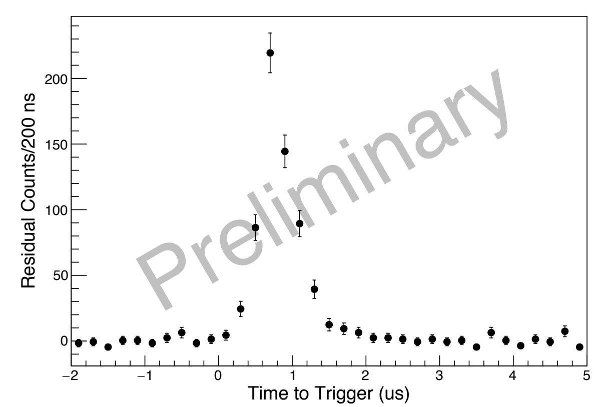
Beam-related neutrons: in the alcove, need more attention (still tractable)



Understand spectrum and time structure by MC tuned using

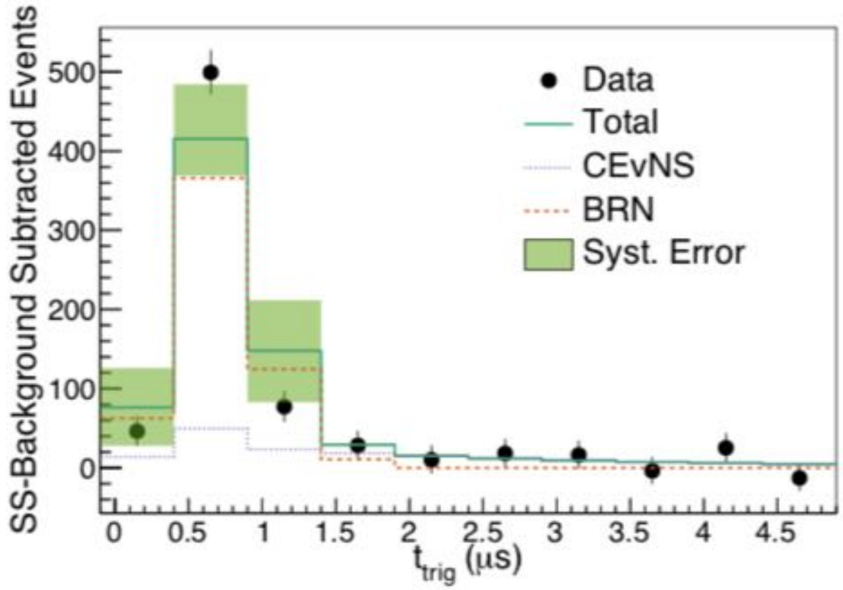
- Engineering run data
  Phys.Rev. D100 (2019) no.11, 115020
- No-water shield run
- High-energy sideband

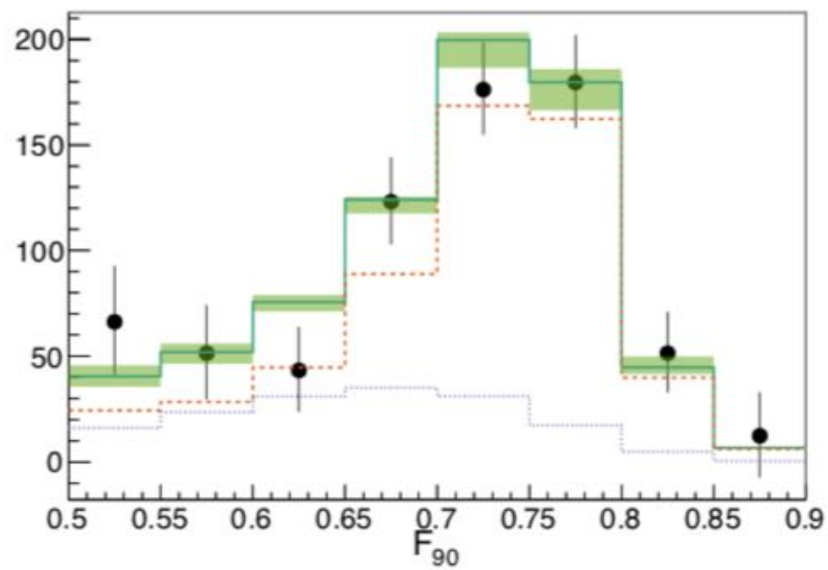


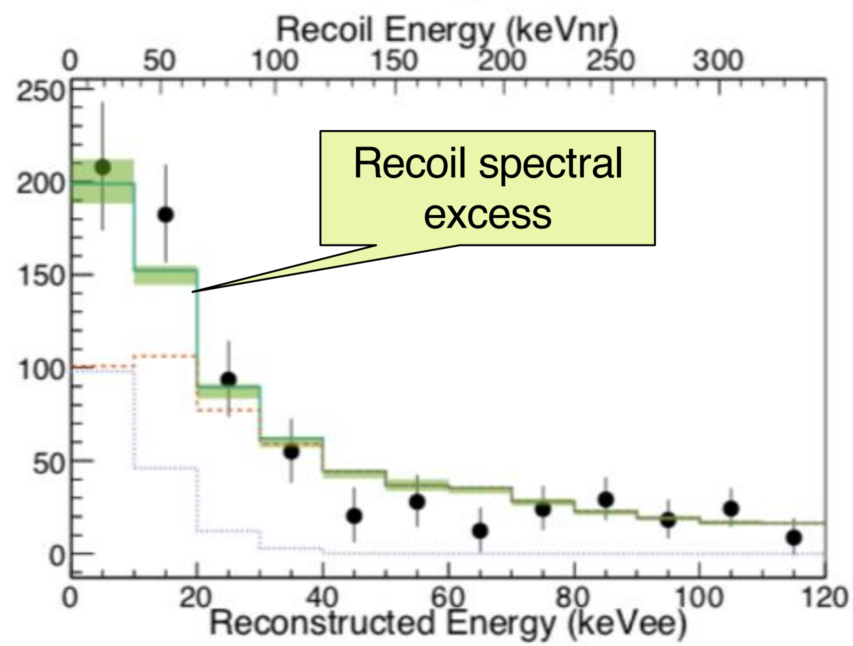


Likelihood fit in time, recoil energy, PSD parameter

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





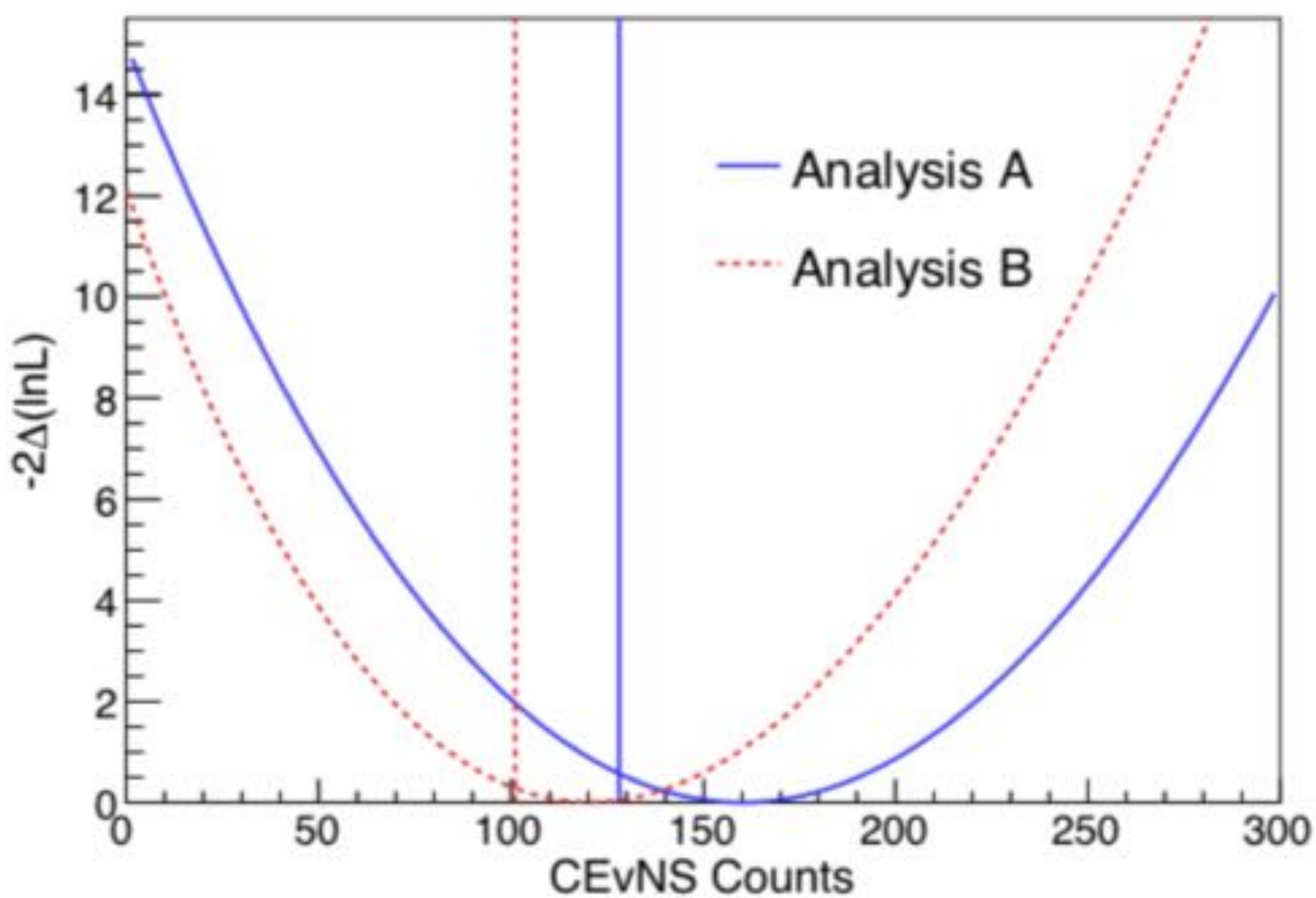


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

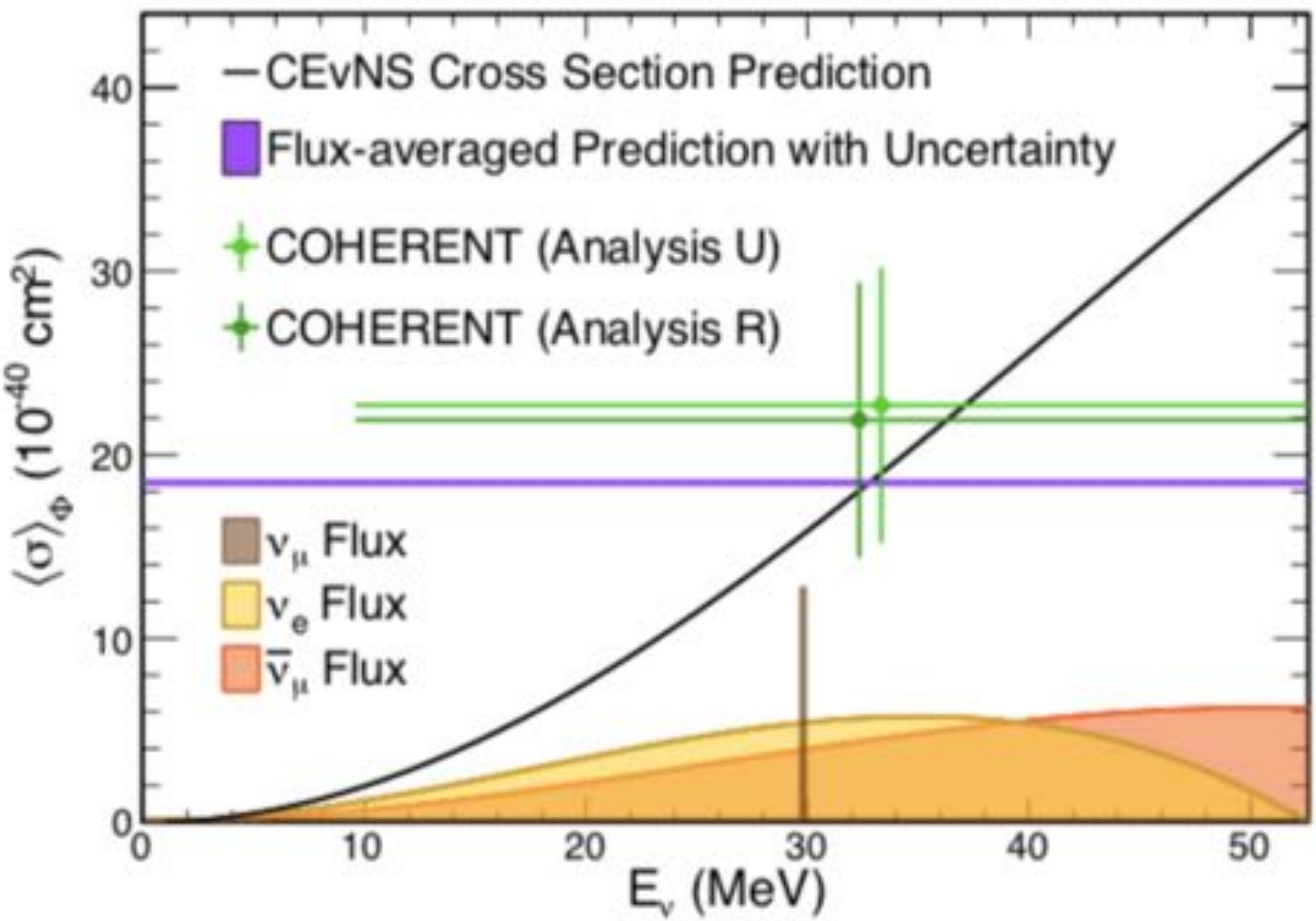
CEvNS Count Results from Likelihood

US: $159 \pm 43(\text{stat.}) \pm 14(\text{sys.})$ Reject null@ 3.5σ

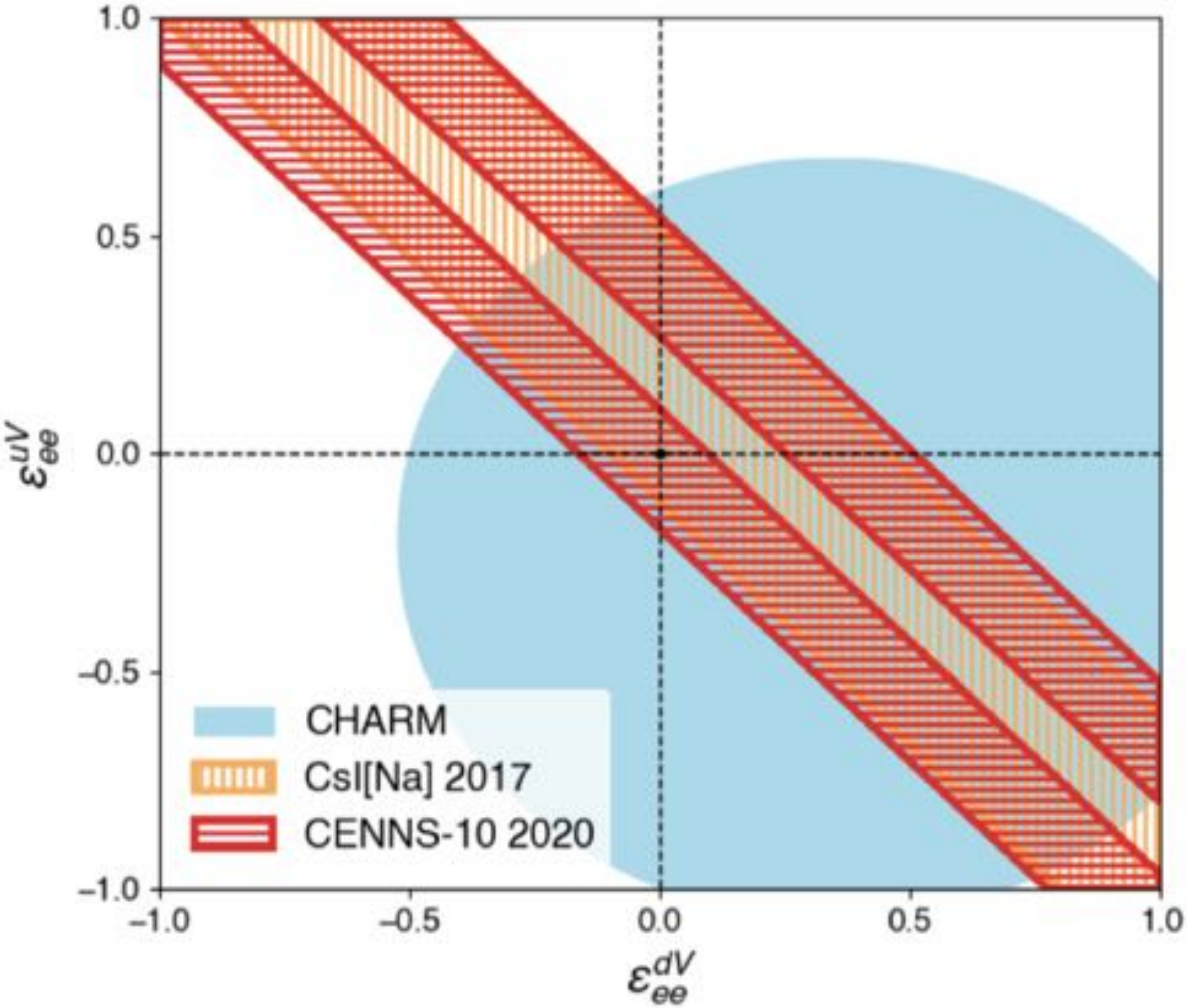
Moscow: $121 \pm 36(\text{stat.}) \pm 15(\text{sys.})$ Reject null@ 3.1σ



Flux-averaged cross section results



New Constraints on NSI parameters



Systematic Uncertainties

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

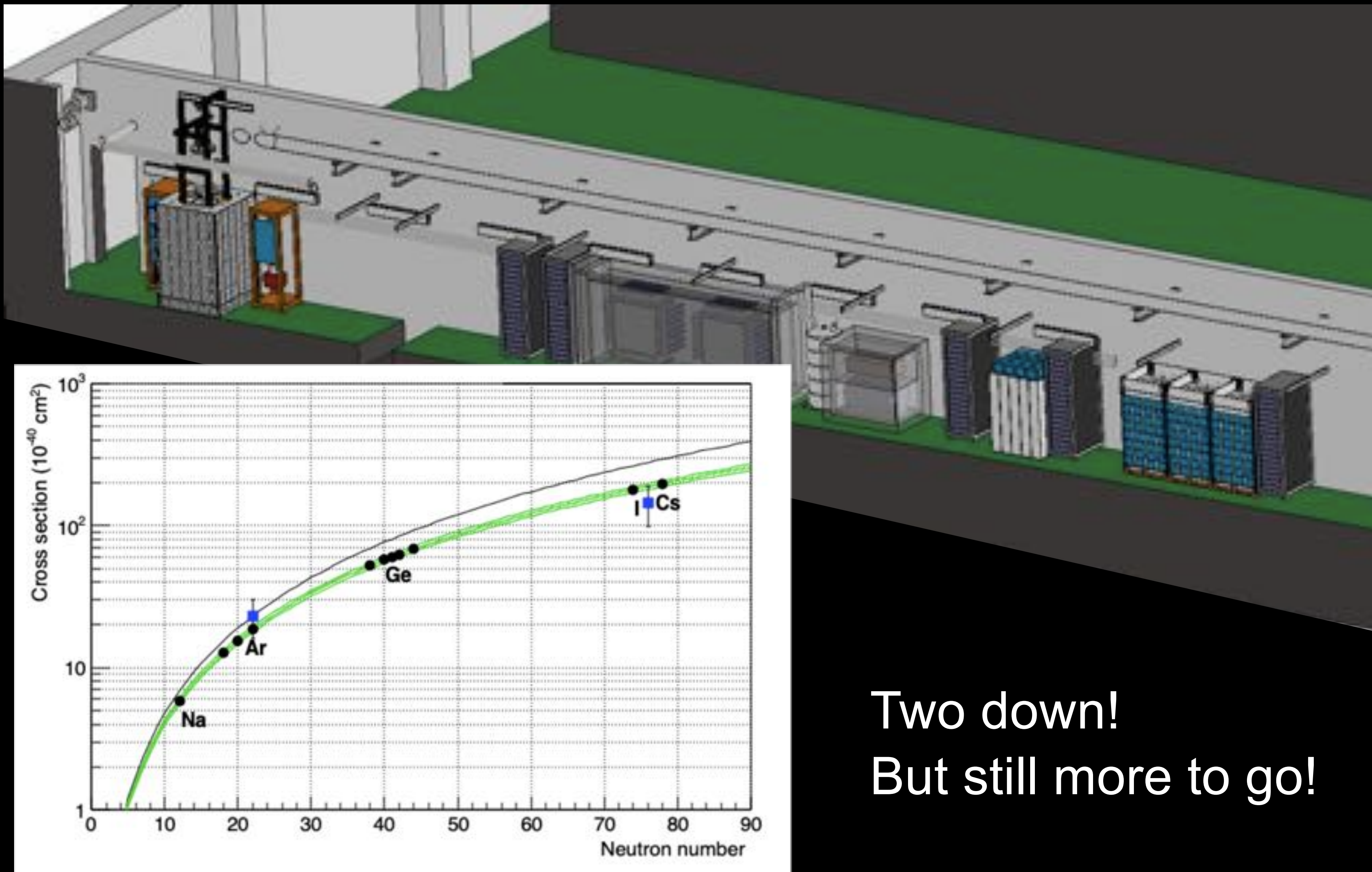
(Analysis A)

Dominant single uncertainty

Additional Likelihood Fit Shape-Related Errors	
Error Source	Fit Event Uncertainty
CEvNS Prompt Light Fraction	4.5%
CEvNS Arrival Mean Time	2.7%
Beam Related Neutron Energy Shape	5.8%
Beam Related Neutron Arrival Time Mean	1.3%
Beam Related Neutron Arrival Time Width	3.1%
Total Error	8.5%

But now many similar-size contributions

What's Next for COHERENT?

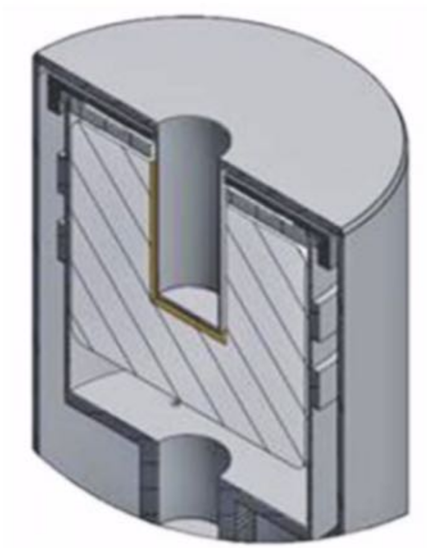


Two down!

But still more to go!

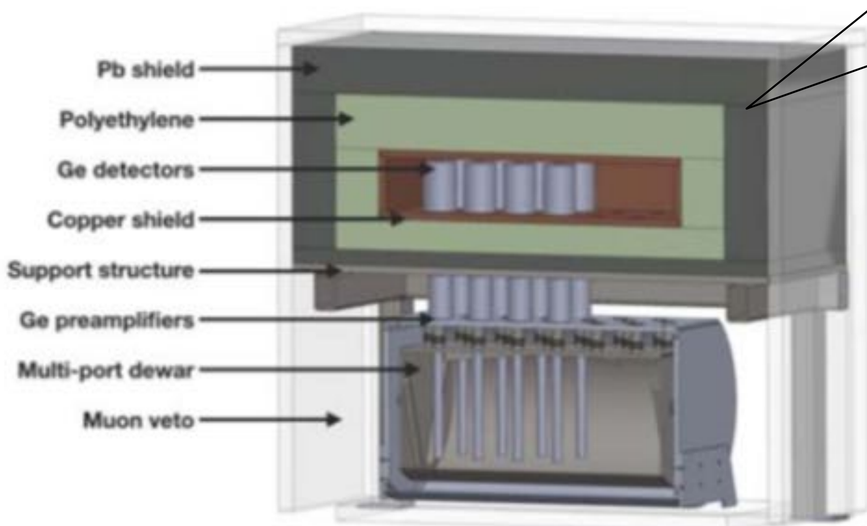
High-Purity Germanium Detectors

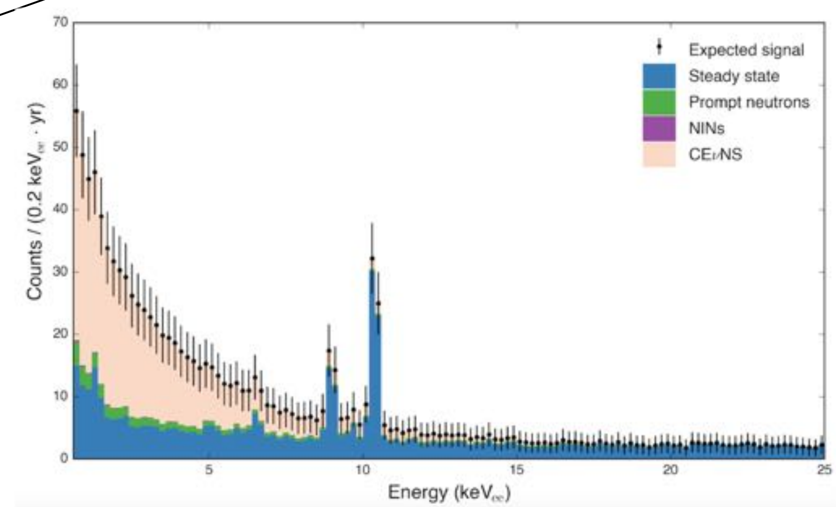
P-type Point Contact



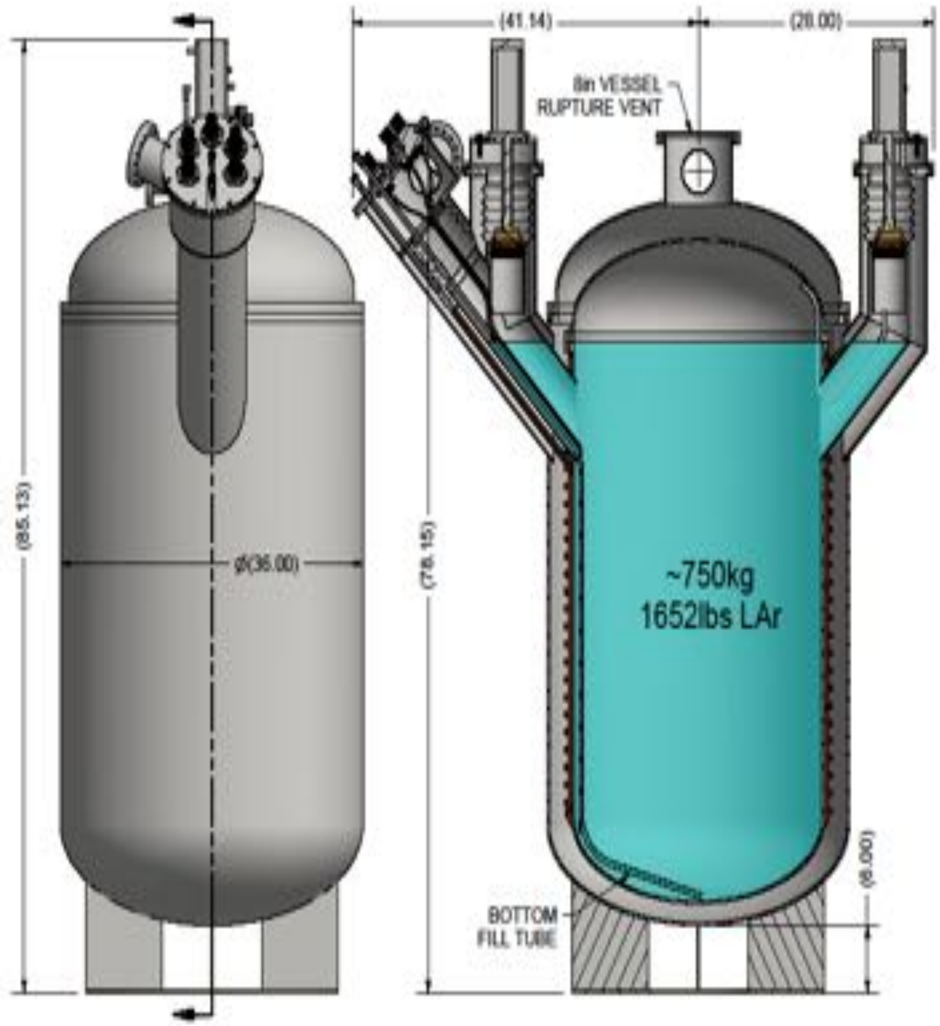
- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

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

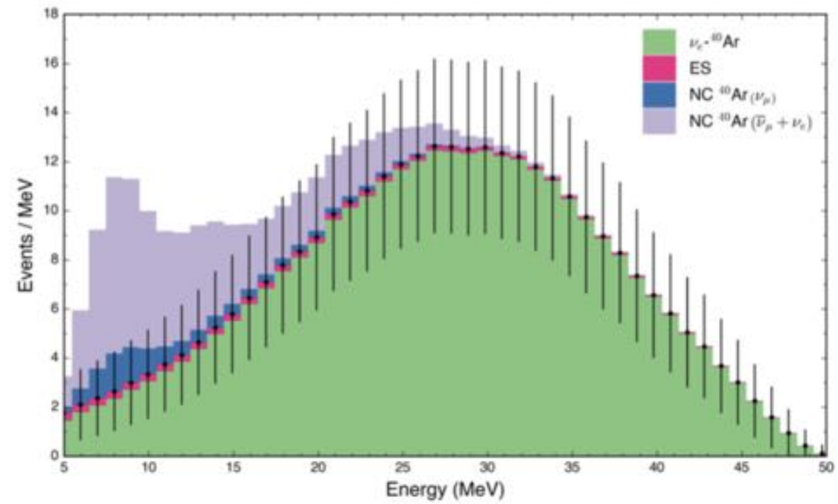




Tonne-scale LAr Detector



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



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

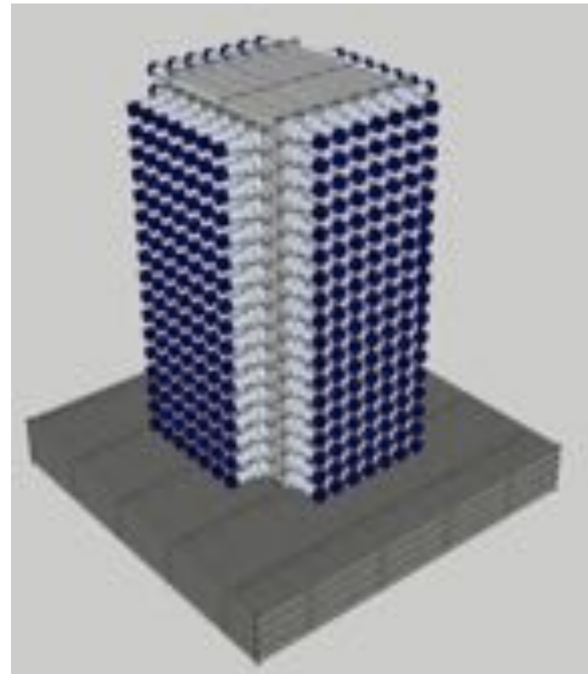
$$\text{CC} \quad \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

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

Sodium Iodide (NaI[Tl]) Detectors (NaIvE)

- up to 9 tons available, 2 tons in hand
- QF measured
- require PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement
- development and instrumentation tests underway at UW, Duke

Multi-ton concept



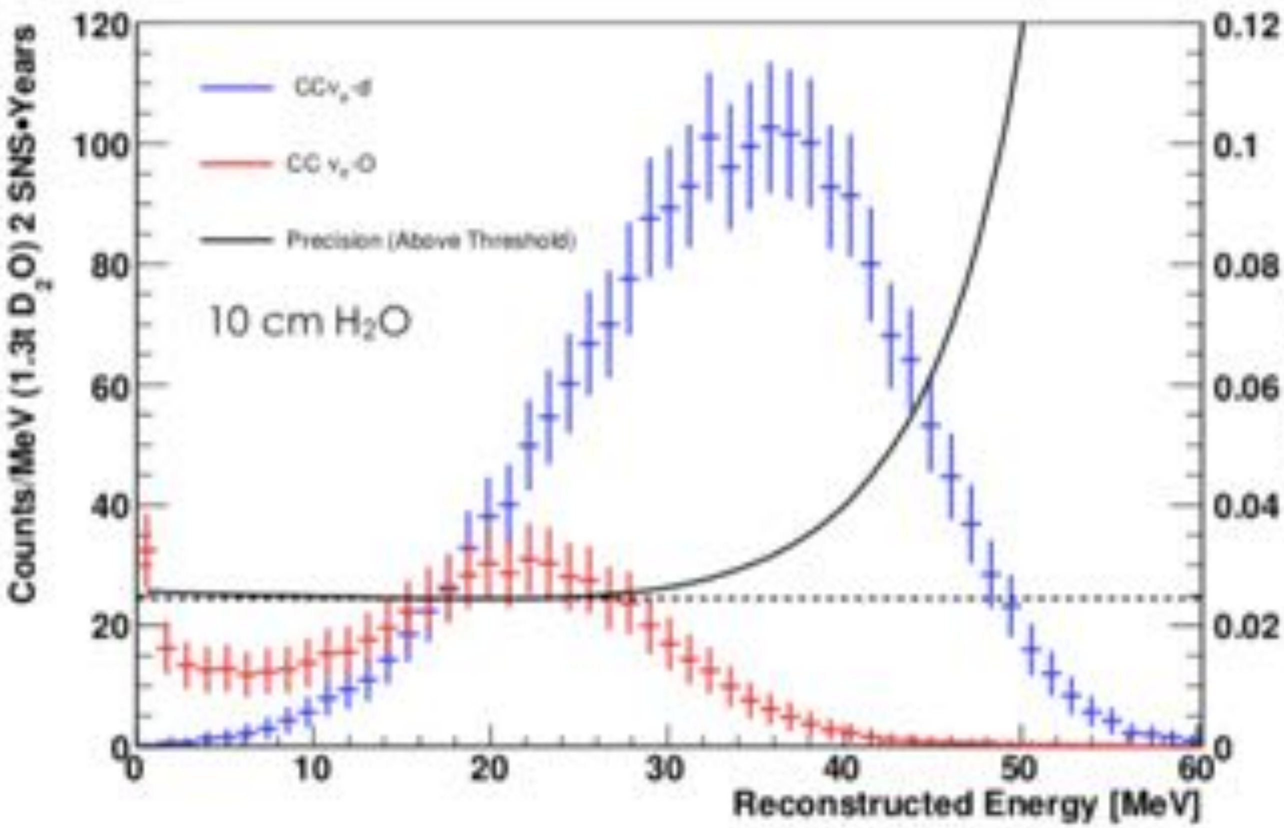
In the meantime: **185 kg deployed at SNS** to go after ν_e**CC on** ^{127}**I**

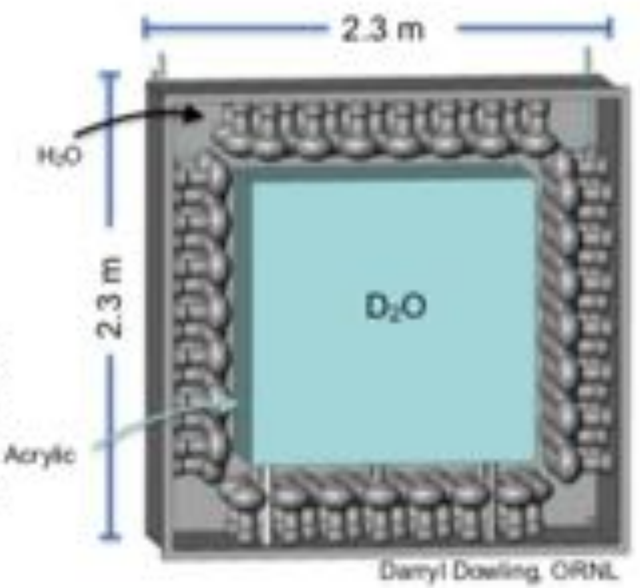
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	$284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

Heavy water detector in Neutrino Alley

Measurement Precision with 2 SNS years at 1.4 MW



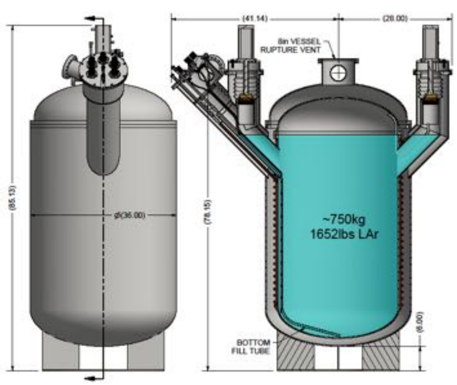


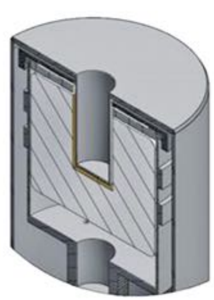
- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O "tail catcher" for high energy e
- 112 8" bialkali photomultipliers

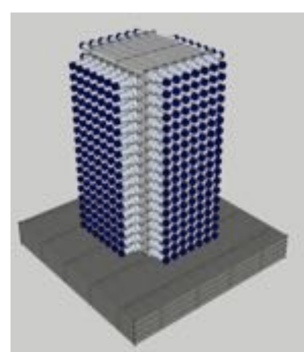
➔ ~few percent precision on flux normalization

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	20	6.5	9/2015	Decommissioned
Ge	HPGe PPC	16	20	<few	2020	Funded by NSF MRI, in progress
LAr	Single-phase	22	20	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes







+D_2O for flux normalization

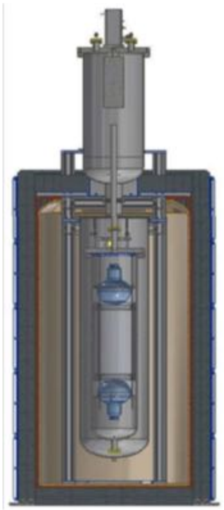
+ concepts for other targets...

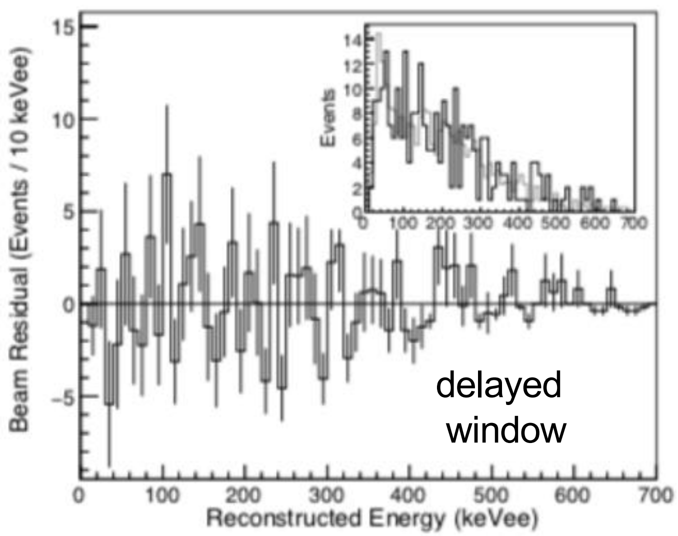
Summary

- **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 LAr!
- **Meaningful bounds on beyond-the-SM physics**

- **It's just the beginning....** more CsI+NaI+Ge soon
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments are joining the fun!
  (CCM, TEXONO, CONUS, CONNIE, MINER, RED, Ricochet, NUCLEUS...)

COHERENT LAr Engineering Run Result

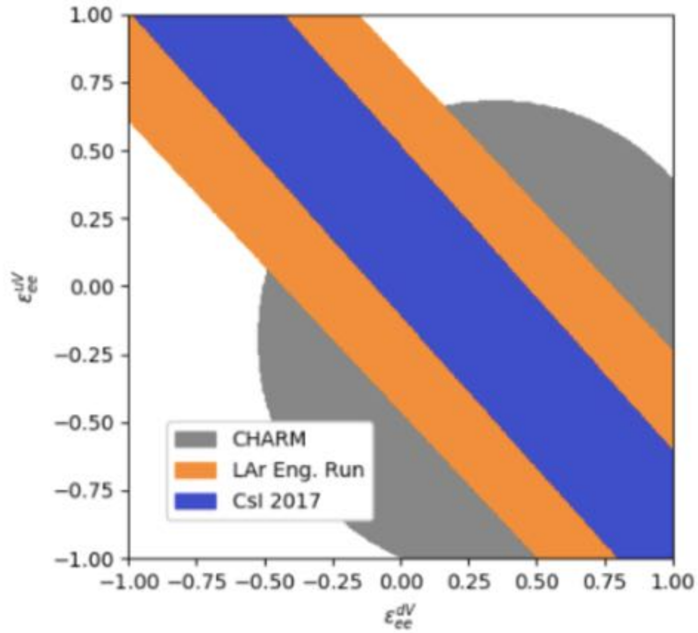




measure 1 ± 4 (stat), expect <1

$\sigma_{\text{flux-avg}} < 3.4 \times 10^{-39}\ \text{cm}^2$

Matt Heath, Indiana U., thesis
APS April meeting
Just published



- **Results from more CsI running,** improved QF & analysis
- **Results from 22-kg LAr detector**
- Treatment of shape systematics
- Accelerator-produced DM sensitivity