Measurements of
Coherent Elastic Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

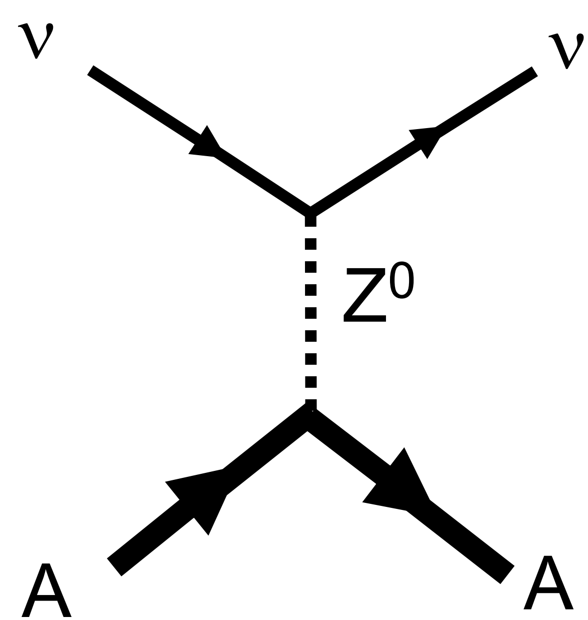
Kate Scholberg, Duke University

MITP Virtual Workshop

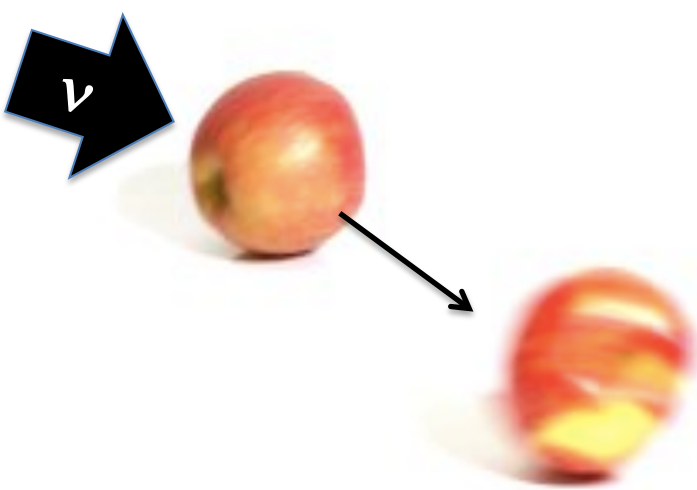
July 27, 2020

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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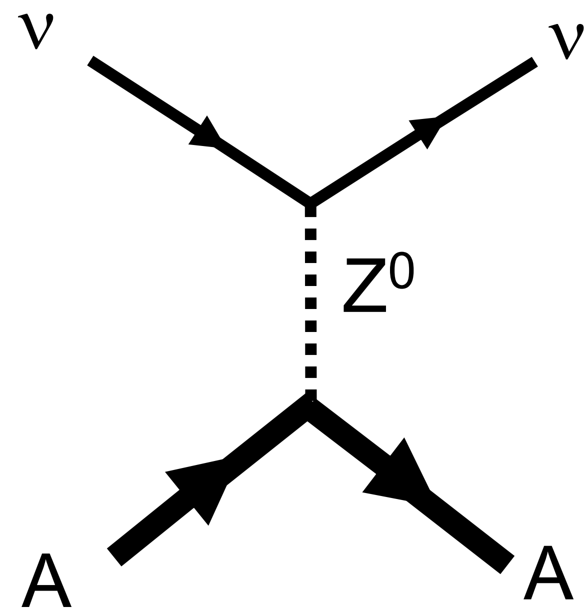

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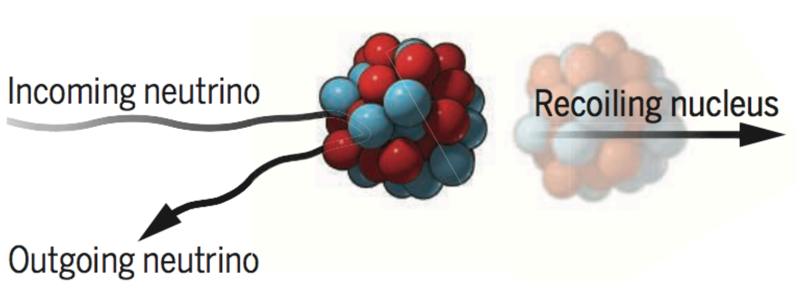
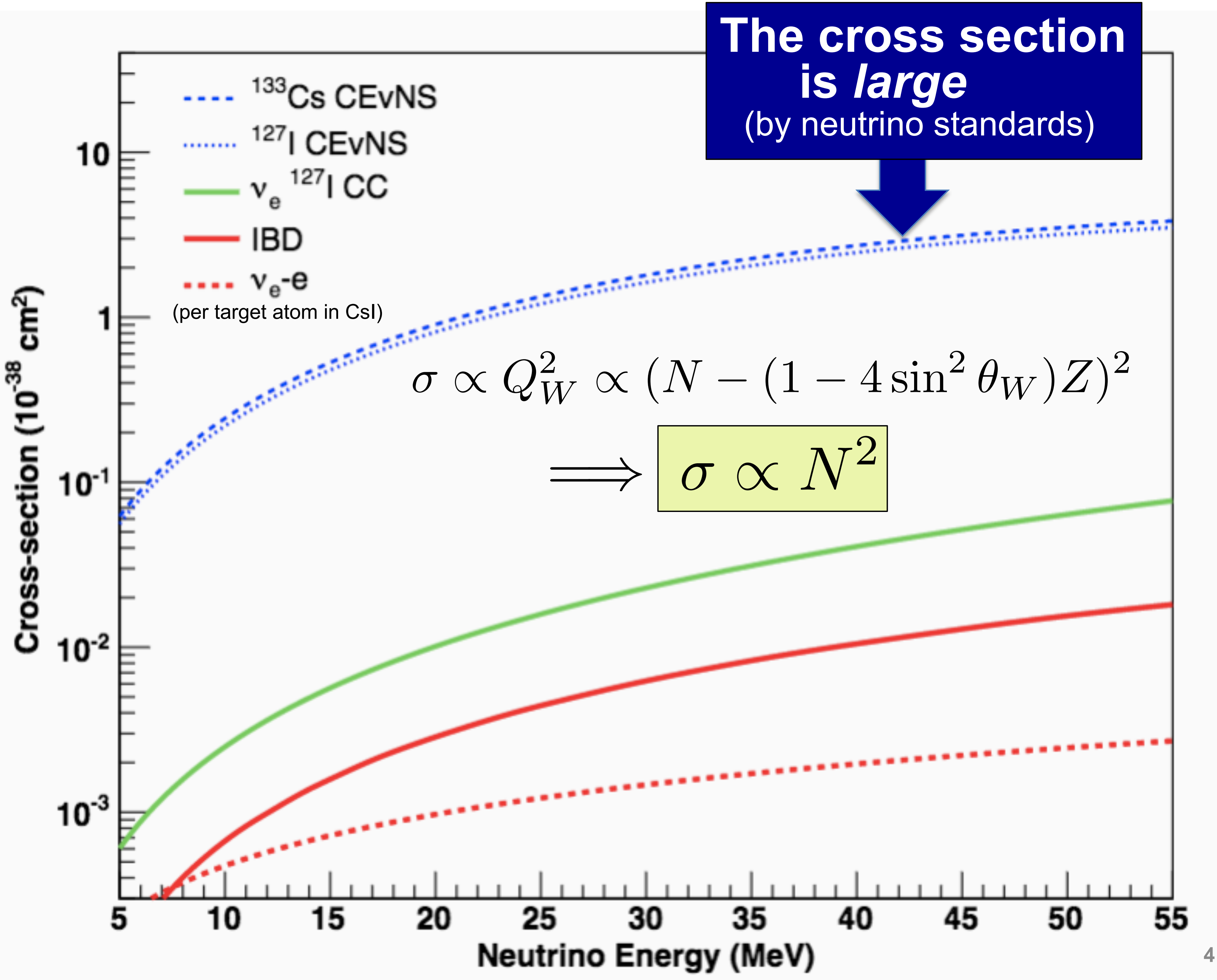


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

A: no. of constituents

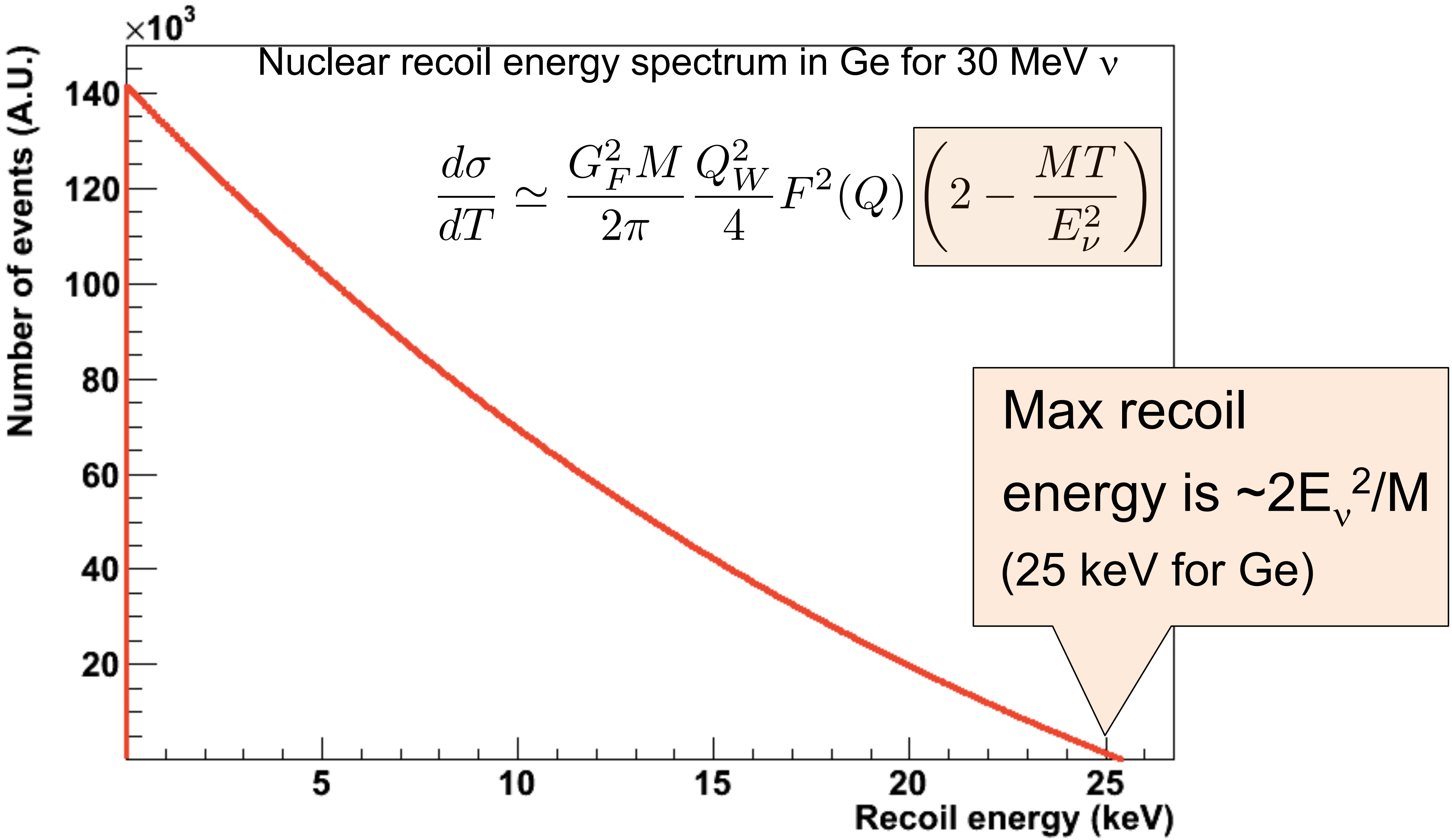
Image: J. Link *Science* Perspectives



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

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

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



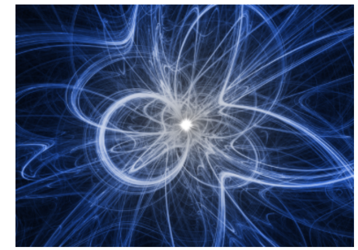
CEvNS: what's it good for?

1 So
2 Many
3 Things

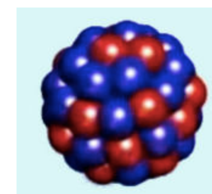
!

(not a complete list!)

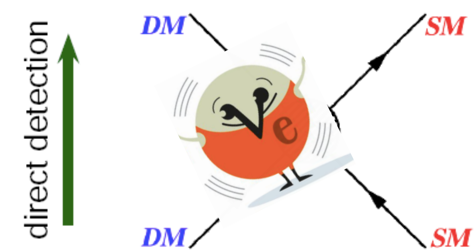
CEvNS as a **signal**
for signatures of *new physics*



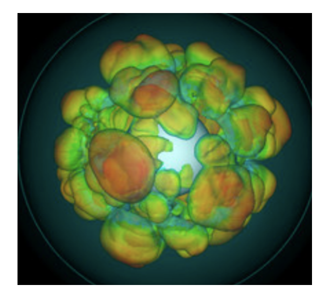
CEvNS as a **signal**
for understanding of "old" physics



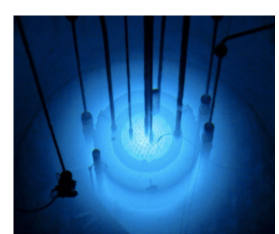
CEvNS as a **background**
for signatures of new physics



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!)

CEvNS as a **signal**
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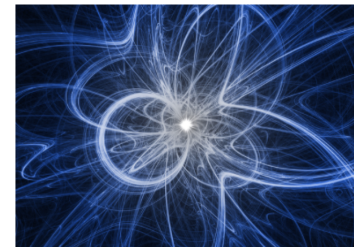

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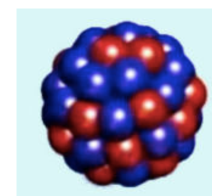

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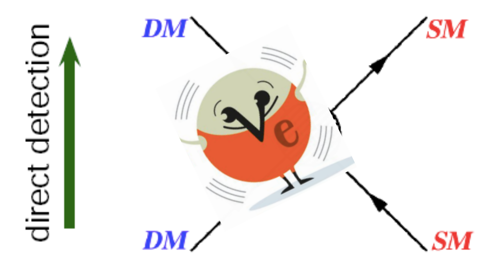

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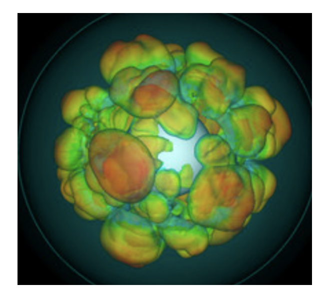

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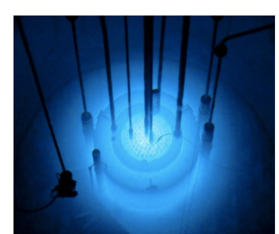

The cross section is cleanly predicted in the Standard Model

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

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2 M T)}$: 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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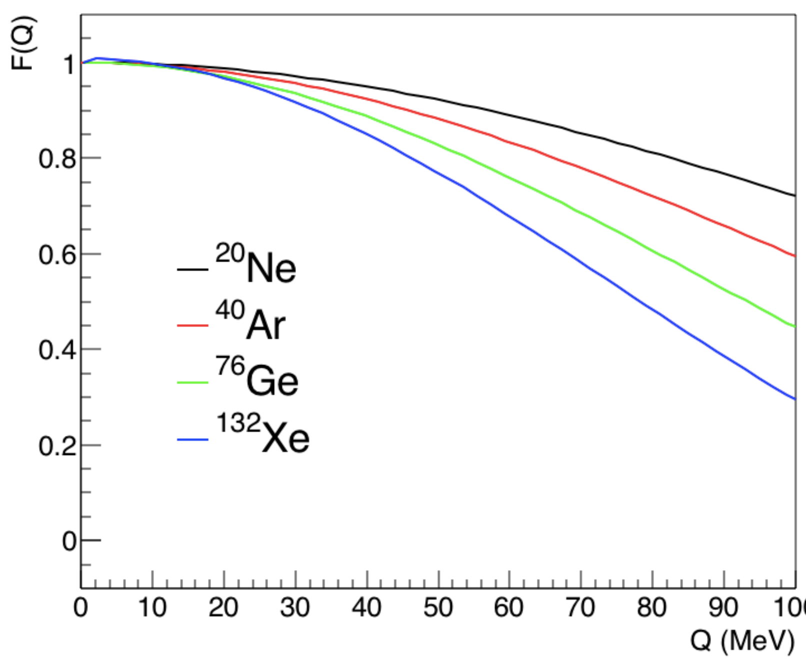
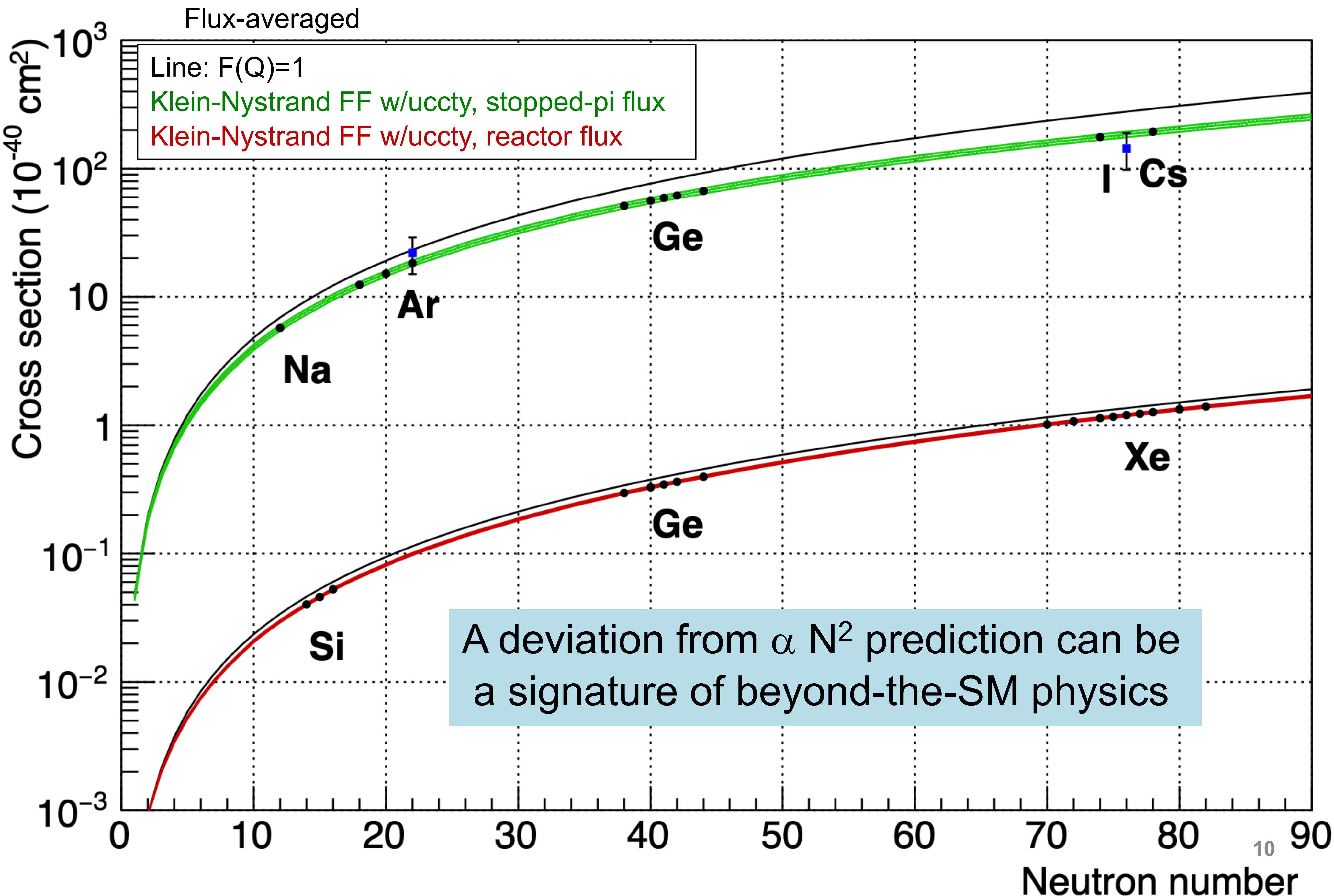
F(Q): nuclear **form factor**, <~5% uncertainty on event rate



form factor suppresses cross section at large Q

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

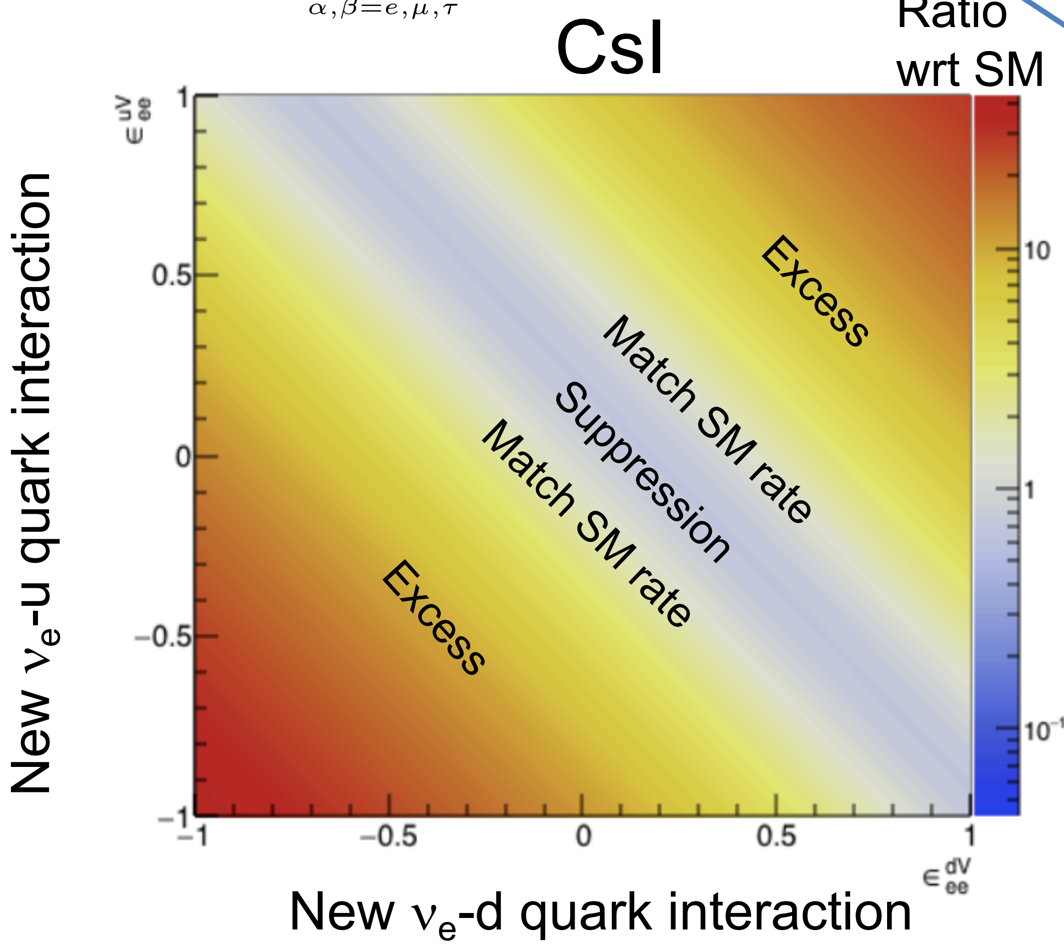


Non-Standard Interactions of Neutrinos:

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

Effective weak charge in presence of light vector mediator Z'

$$Q^2_{\alpha,\mathrm{SM}} = (Zg_p^V + Ng_n^V)^2$$

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

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

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

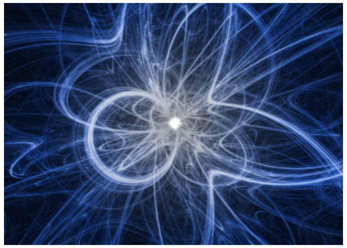
"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

CEvNS: what's it good for?

! (not a complete list!)

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



CEvNS as a **signal**
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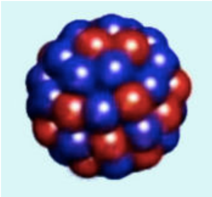
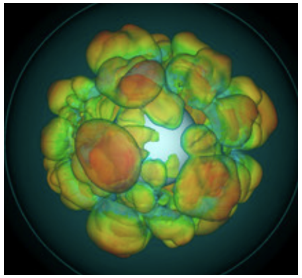
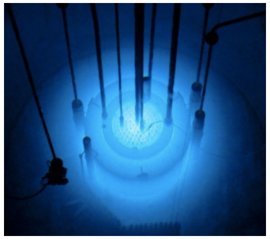


CEvNS as a **background**
for signatures of new physics

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

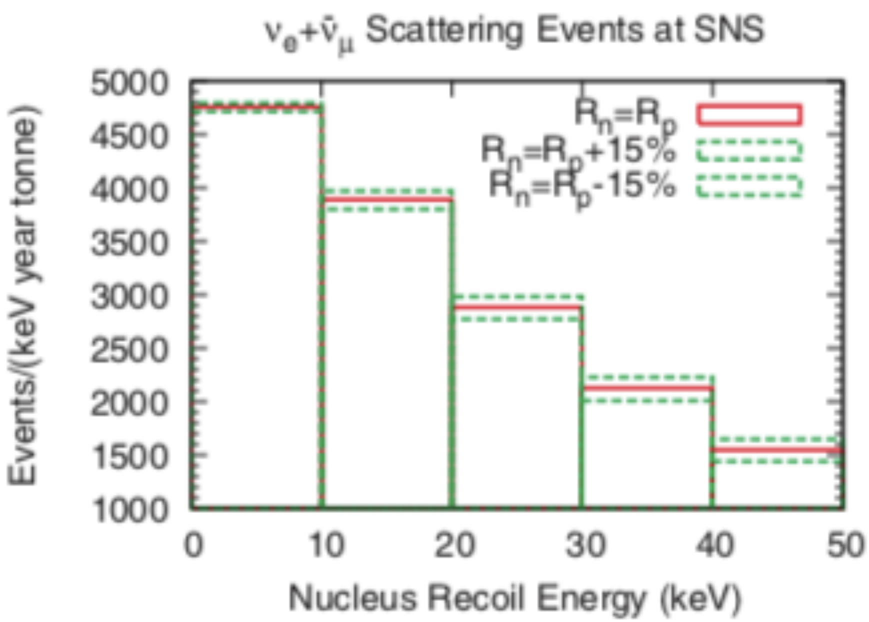
Received 19 June 2008
Published 30 October 2008
Online at stacks.iop.org/JPhysG/36/015105

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

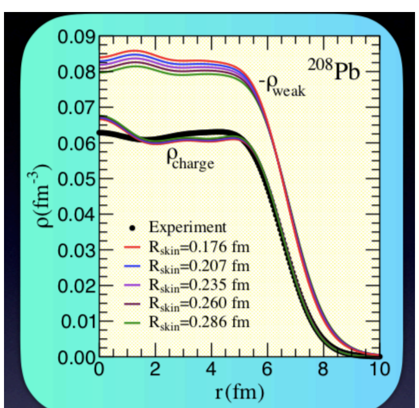
Kelly Patton[1,*] Jonathan Engel[2,†] Gail C. McLaughlin[1,‡] and Nicolas Schunck[3§]
[1] Physics Department, North Carolina State University, Raleigh, North Carolina 27695, USA
[2] Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599, USA
[3] Physics Division, 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

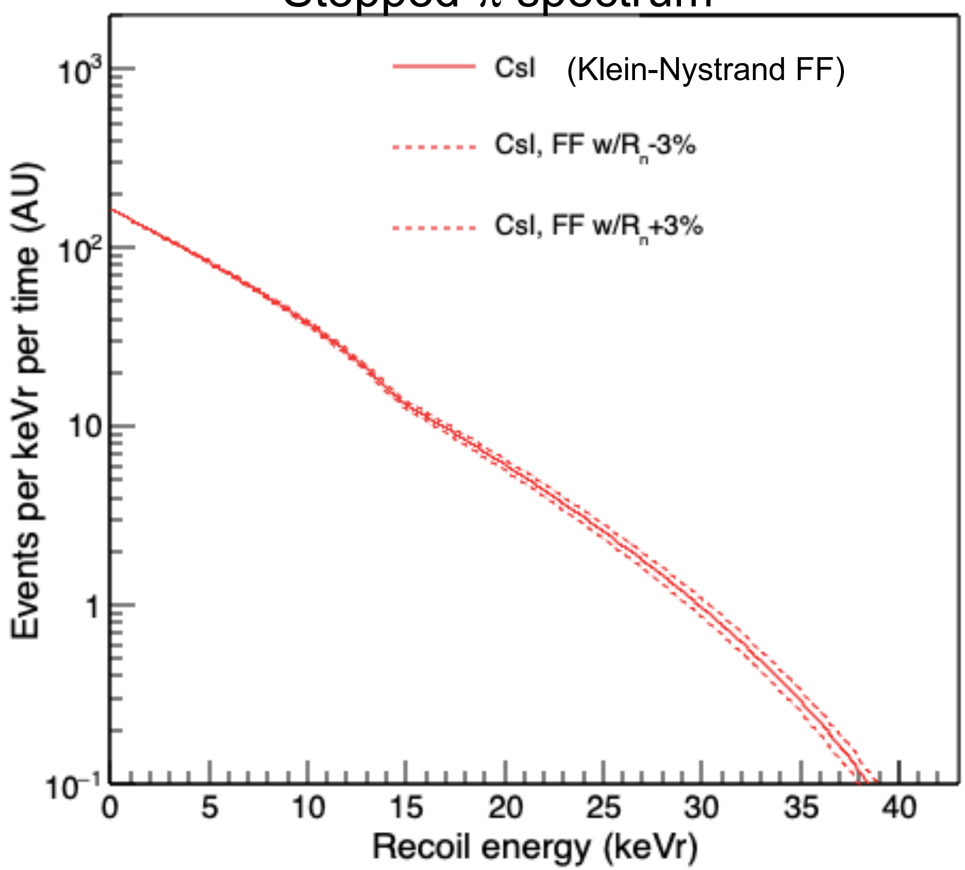


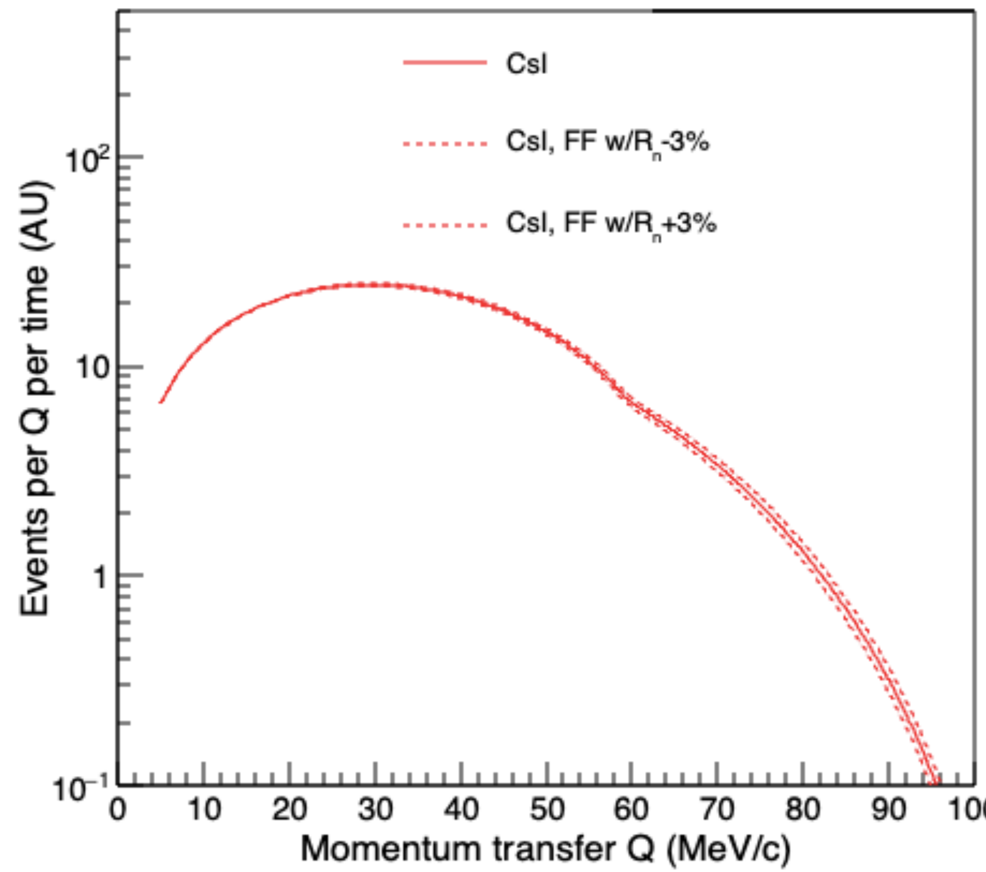
J. Piekarewicz

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**... but this will change!**

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"]

CEvNS: what's it good for?

① So
② Many
③ Things

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CEvNS as a **signal**
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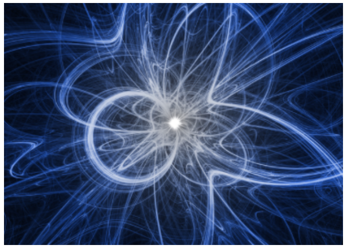

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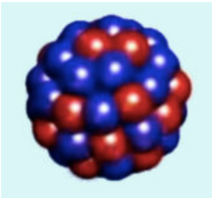
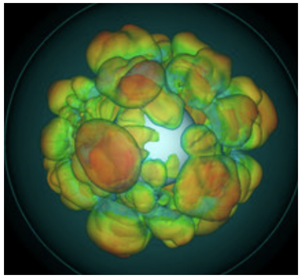
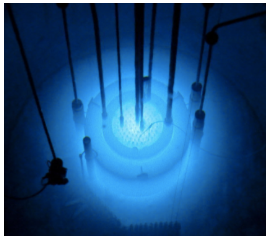


CEvNS as a **background**
for signatures of new physics (DM)

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



CEvNS as a **practical tool**

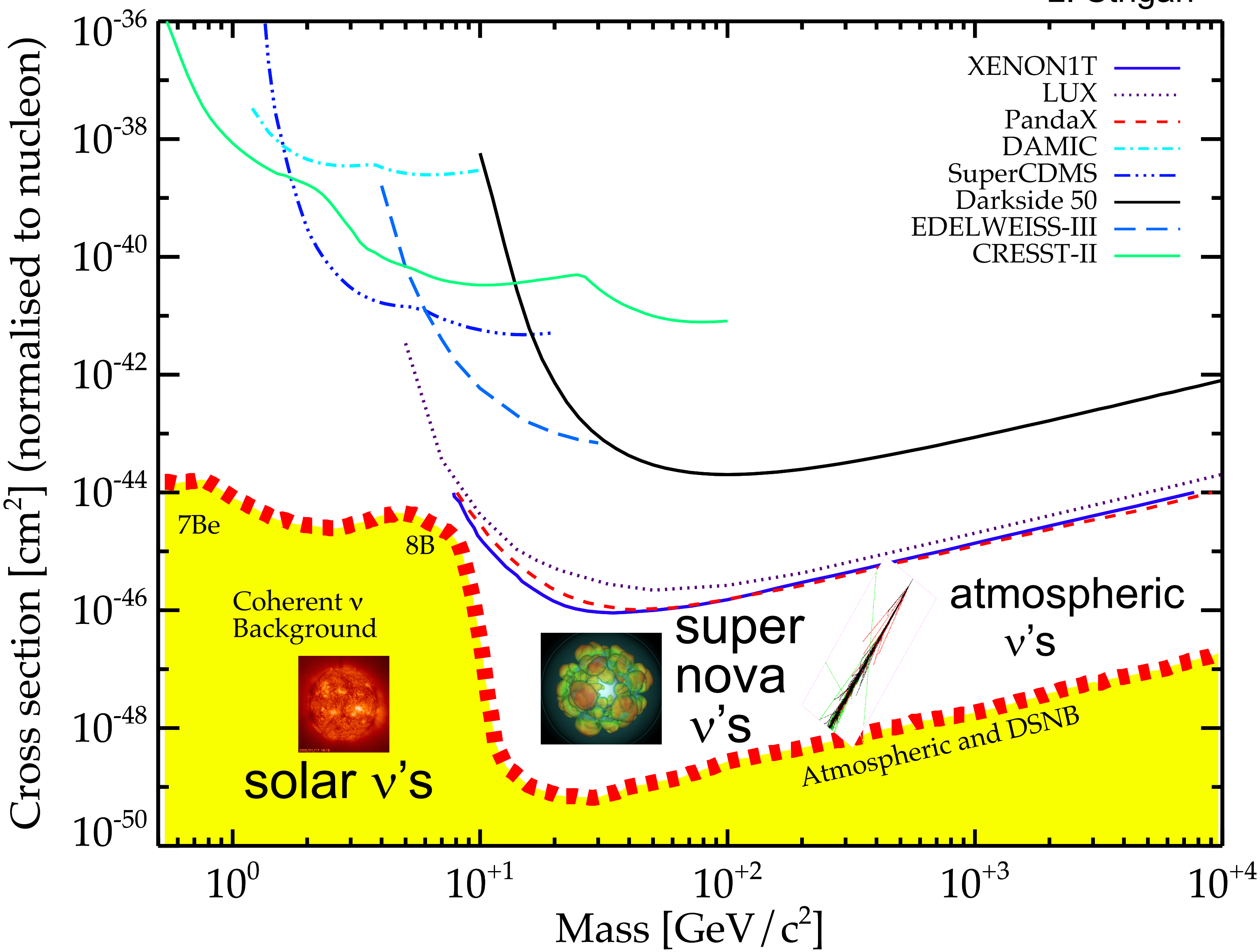


The so-called “neutrino floor” (**signal!**) for direct DM experiments

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

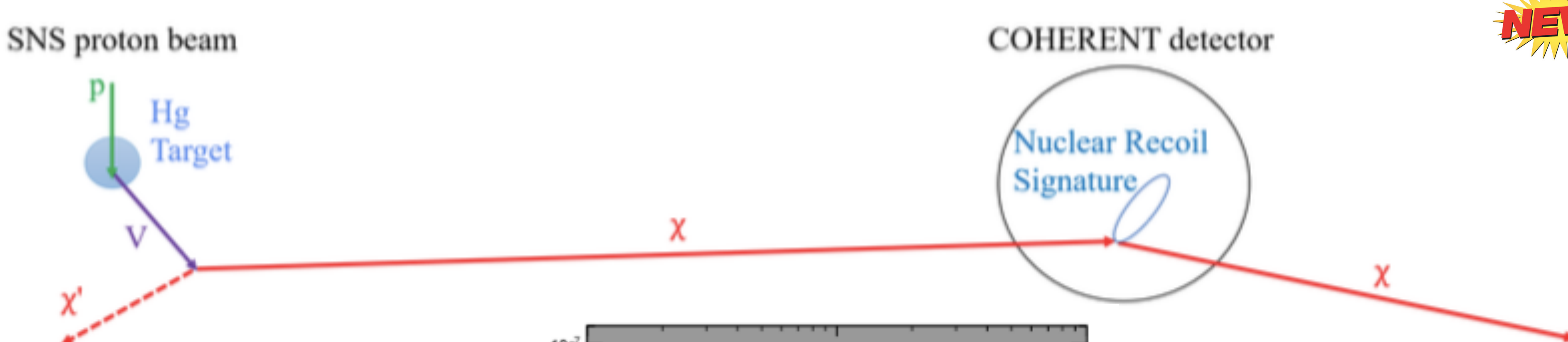
$\Big\}$ decay product χ then makes nuclear recoil

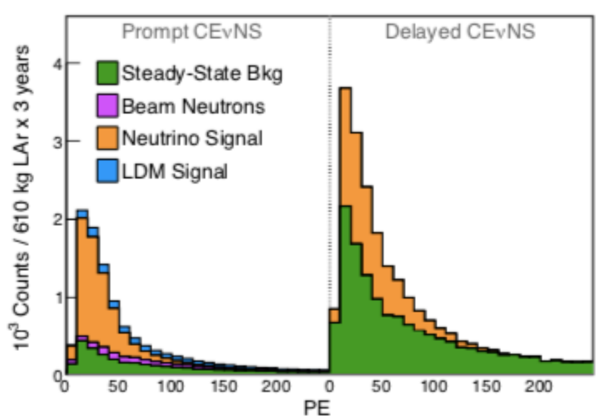
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

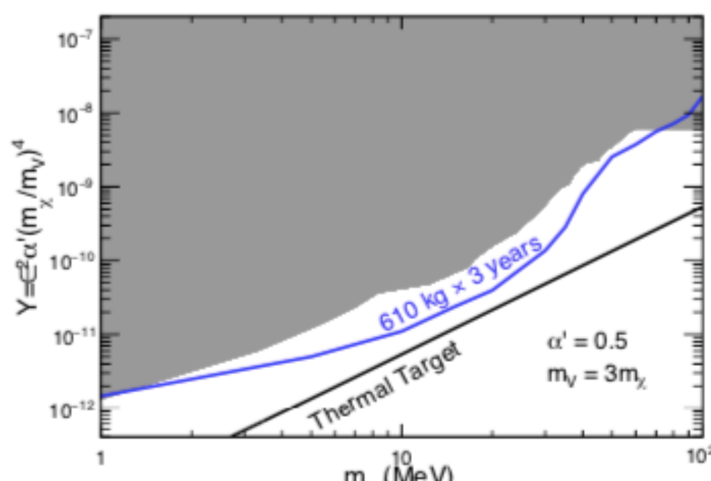
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

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!





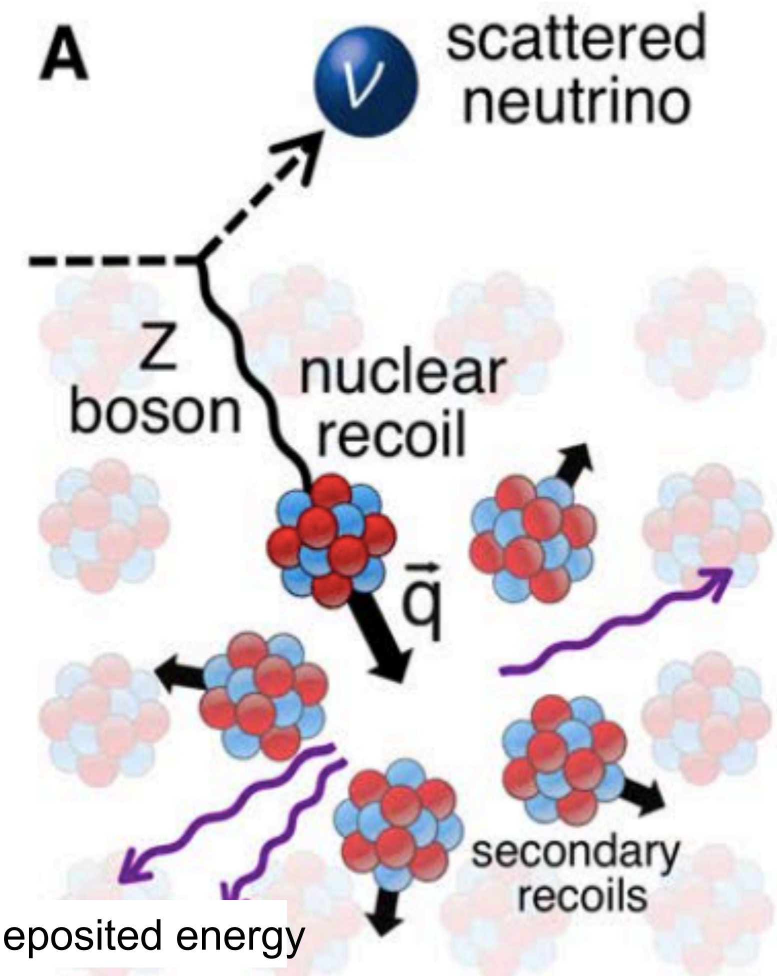


Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

How to measure CEvNS

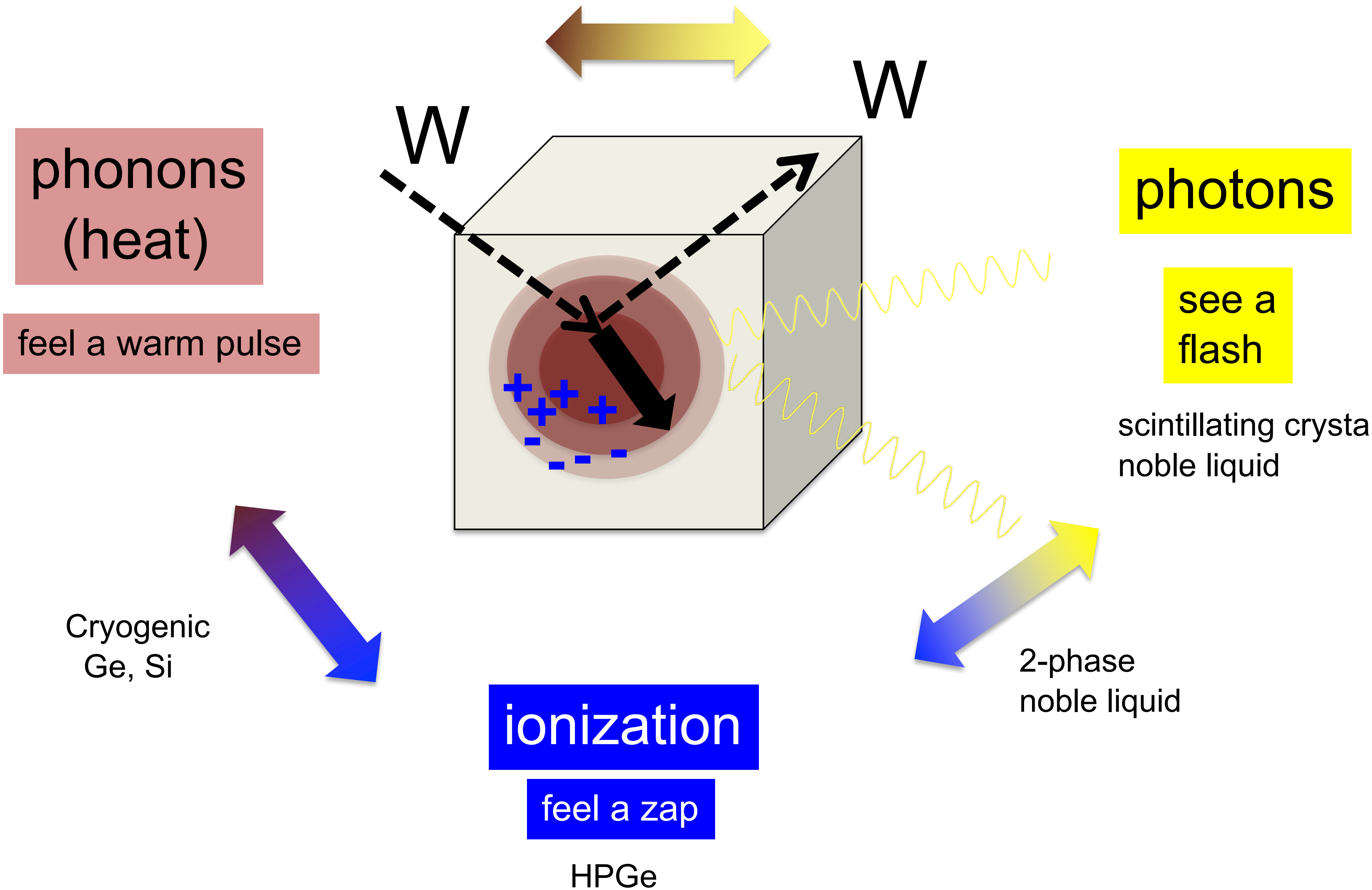
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

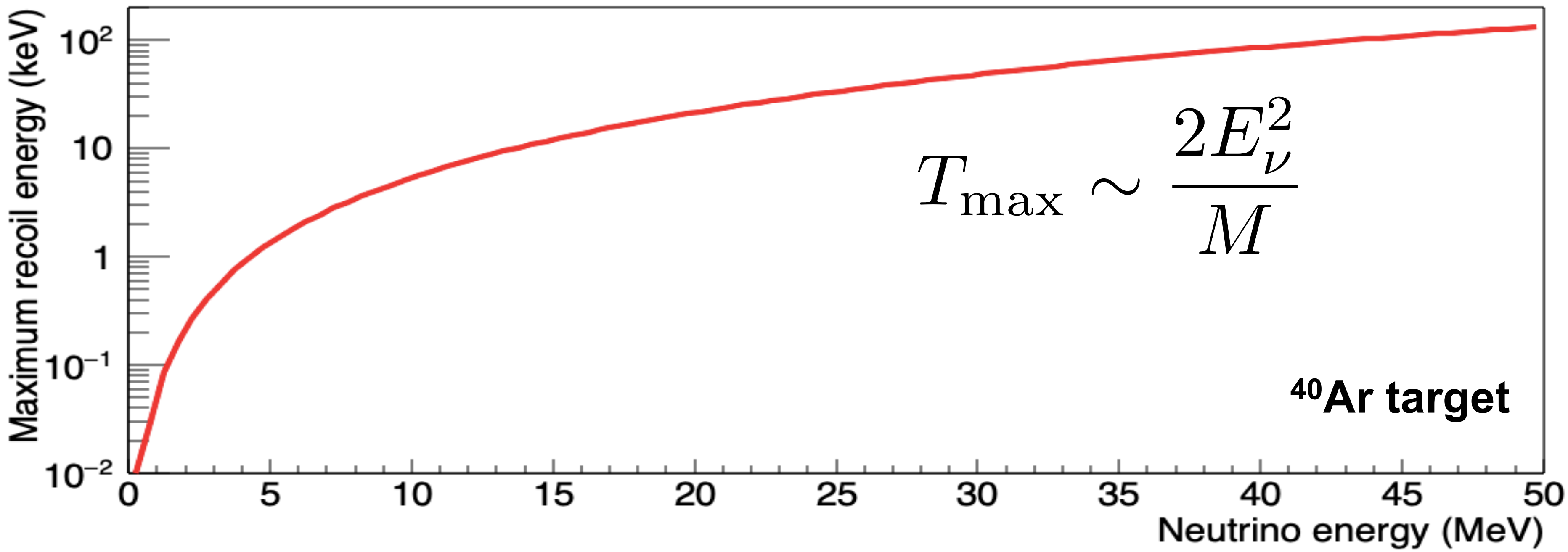


➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10's of keV recoils

Low-energy nuclear recoil detection strategies



Maximum recoil energy as a function of E_ν



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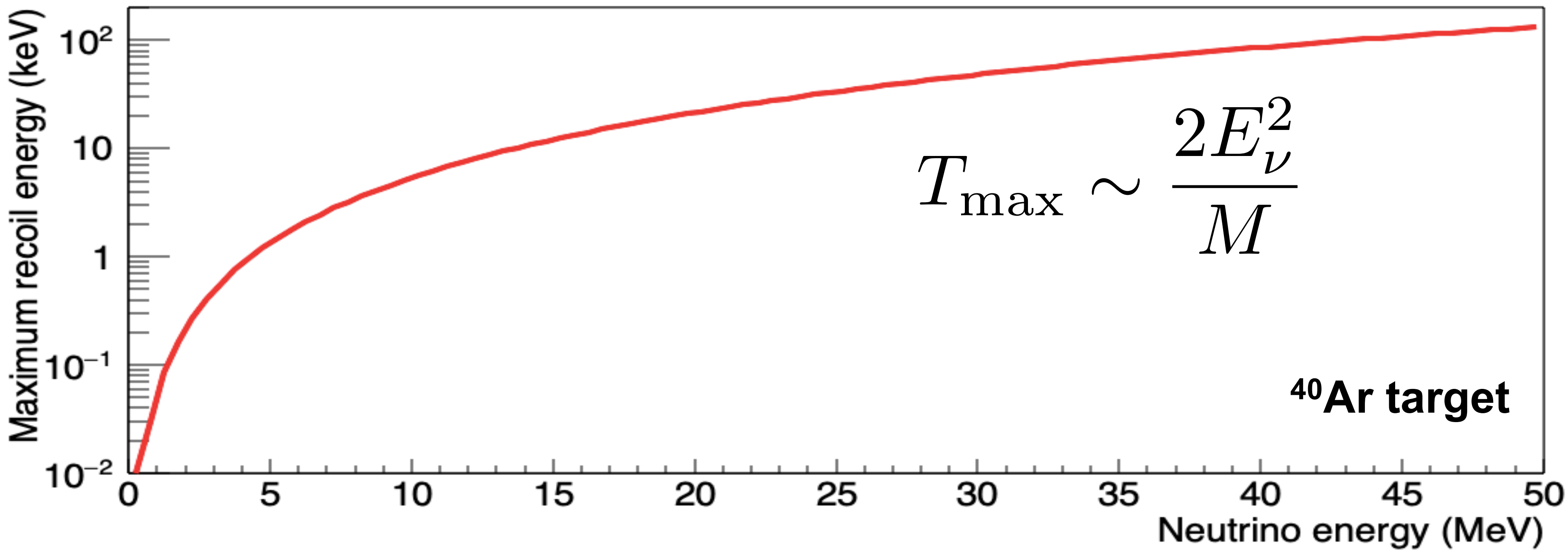

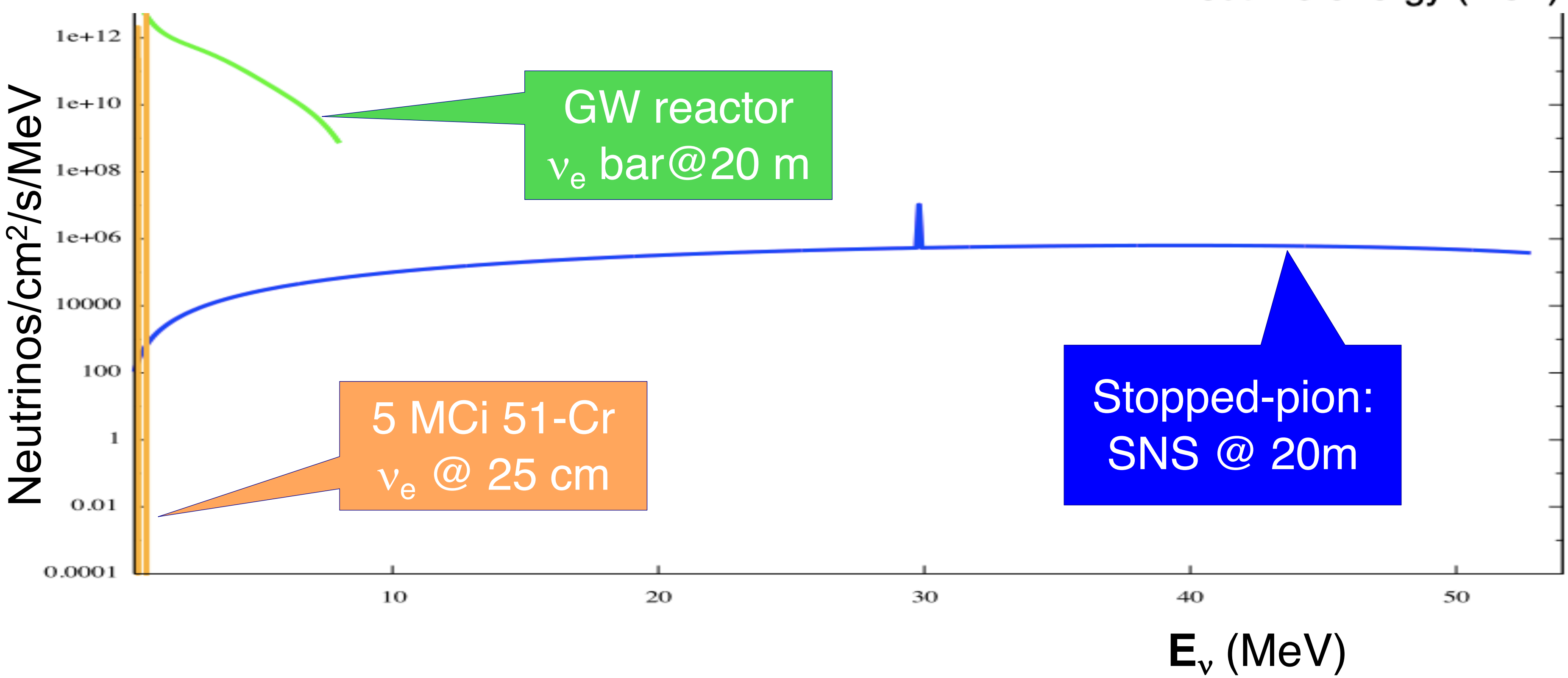

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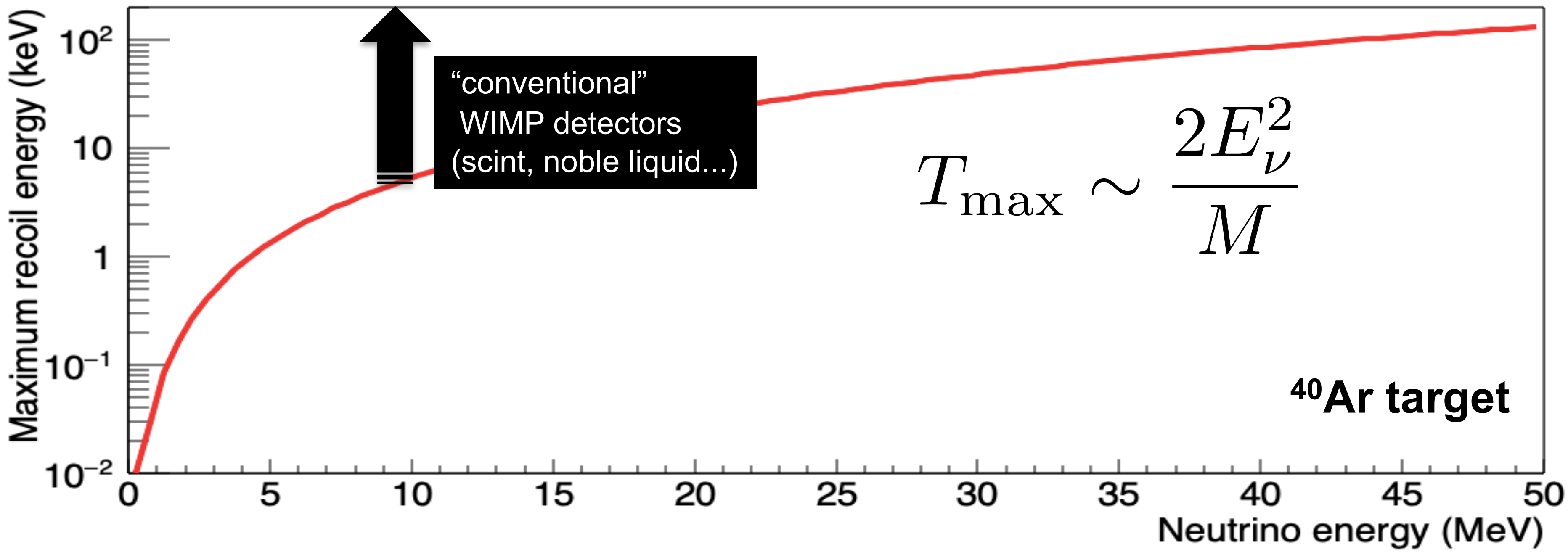

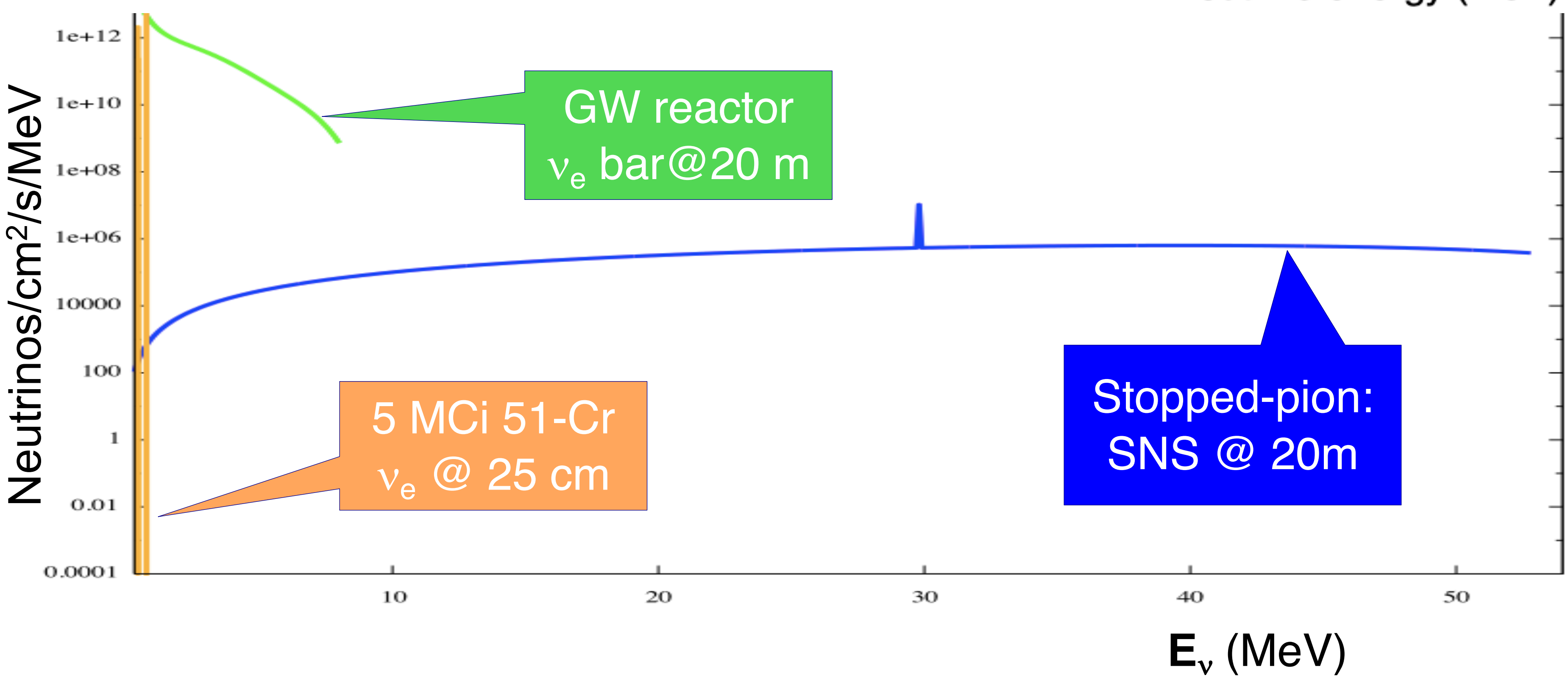

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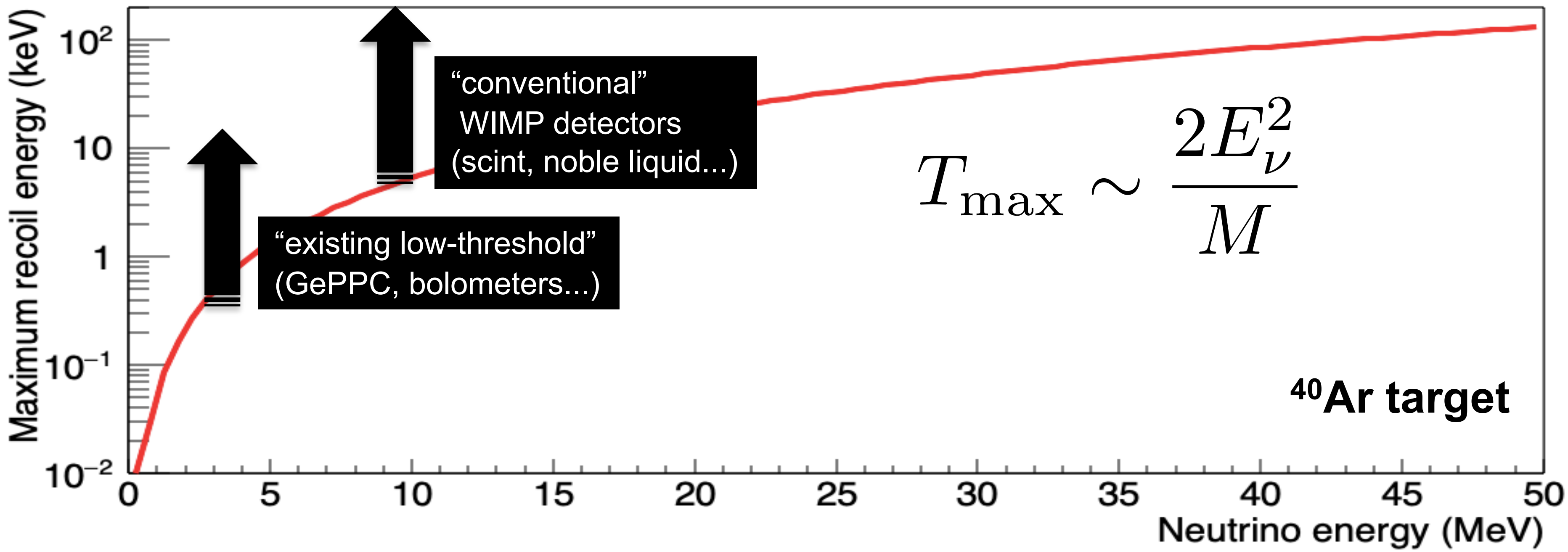

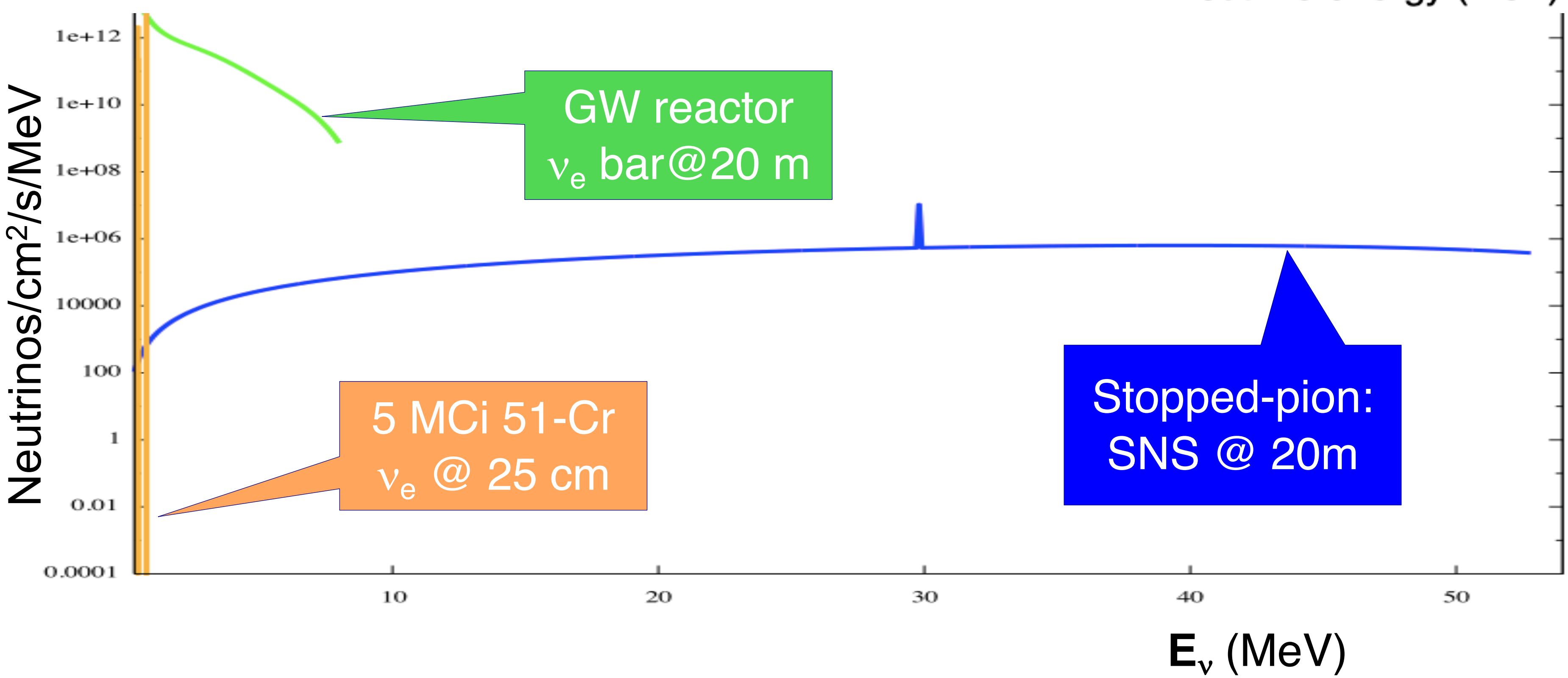

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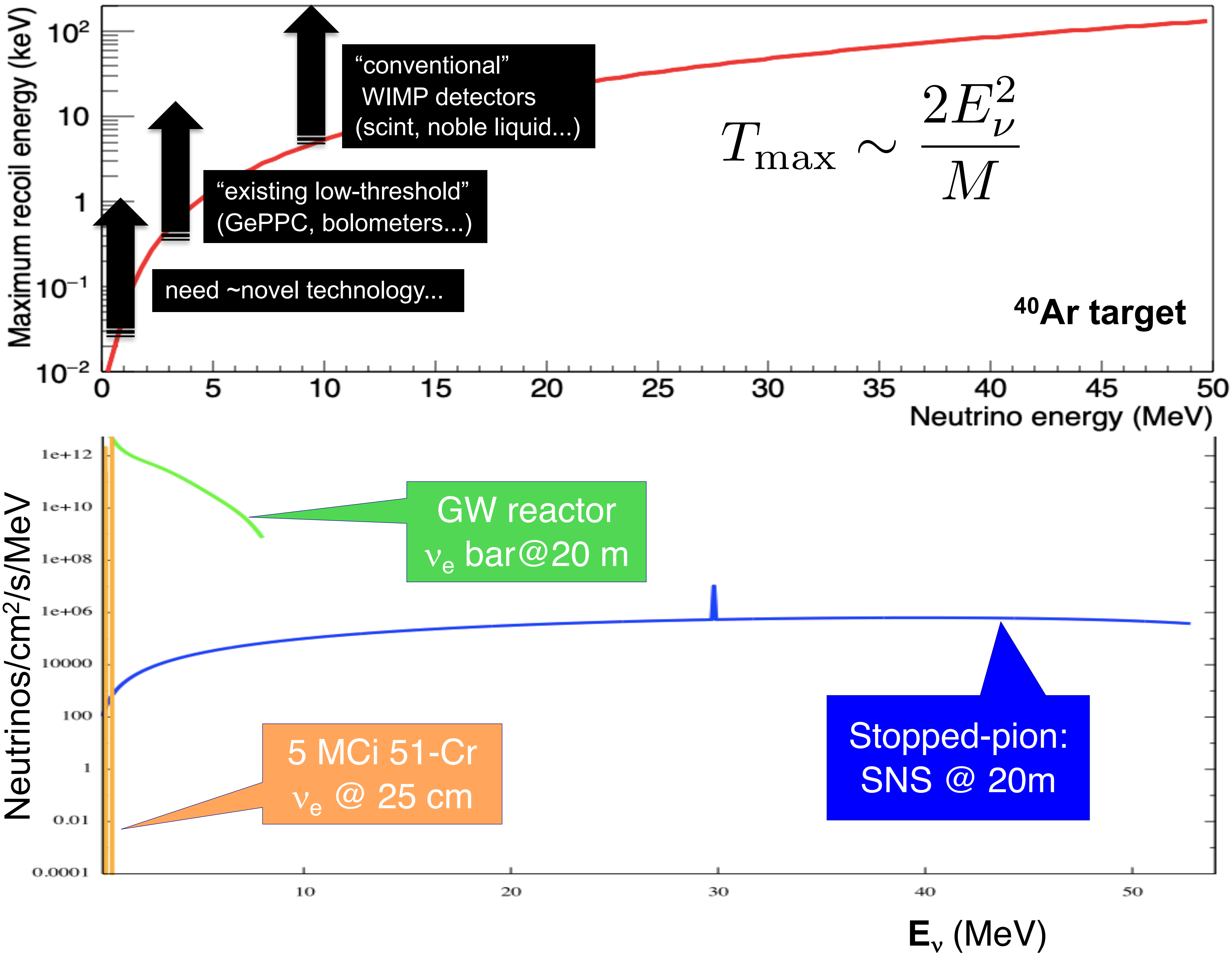
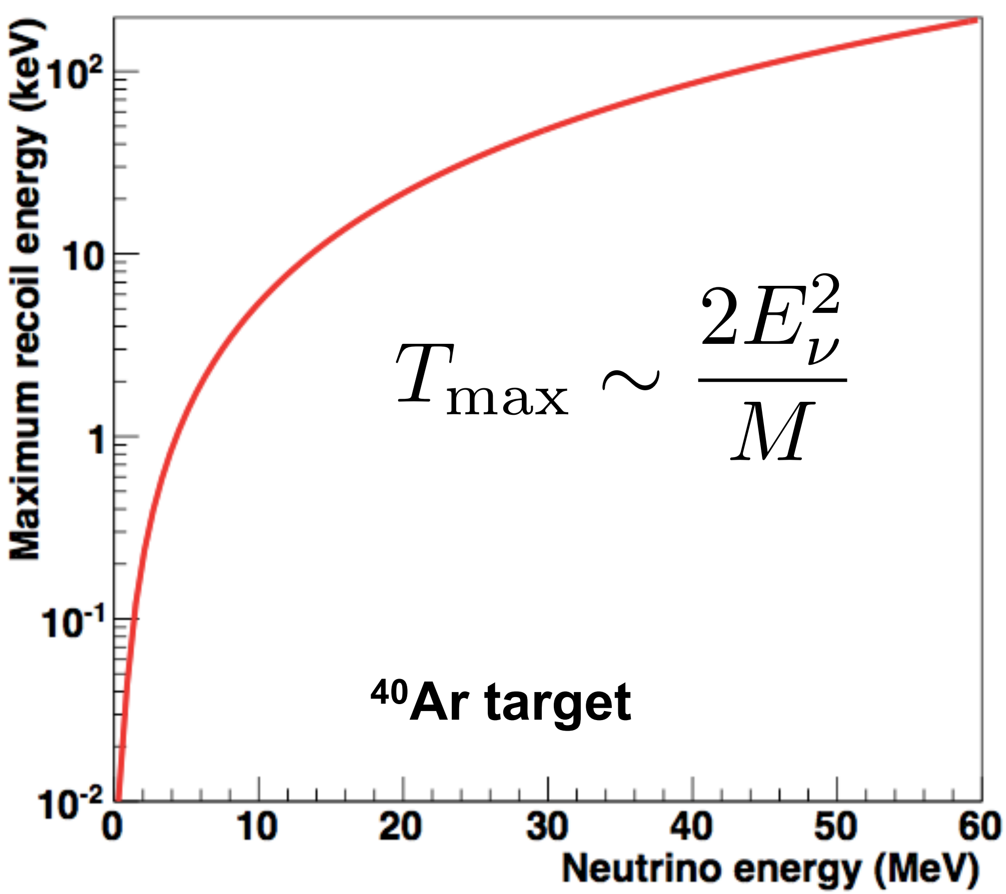
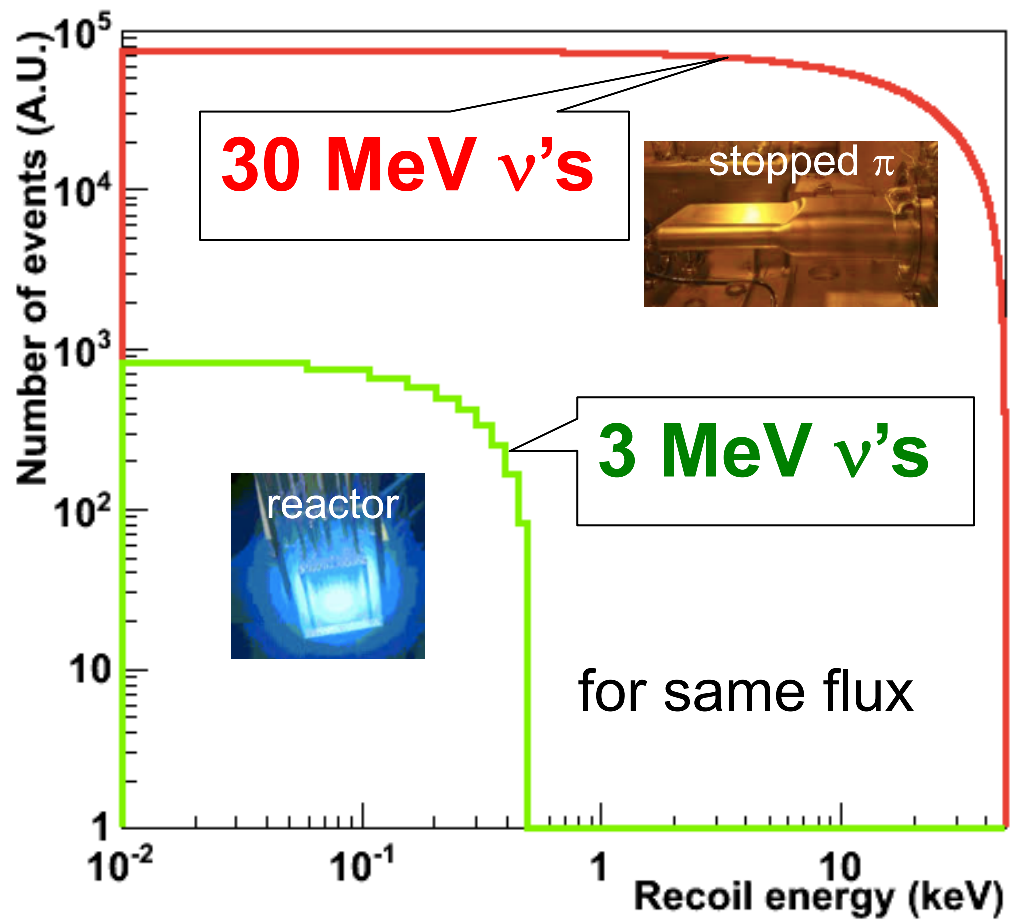


Both **cross-section** and **maximum recoil energy** **increase with neutrino energy**:





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

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)

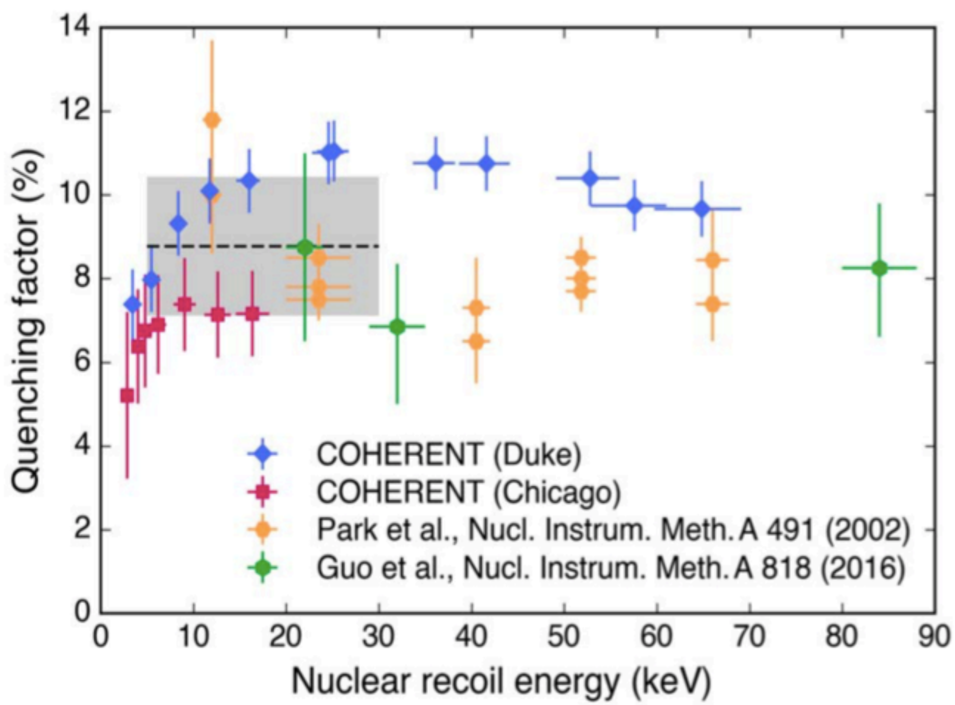
N, Z via nuclear target type

Baseline

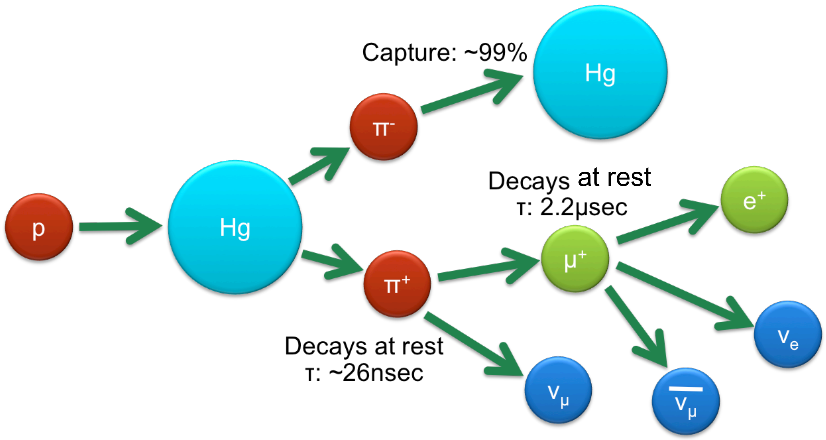
Direction with respect to source

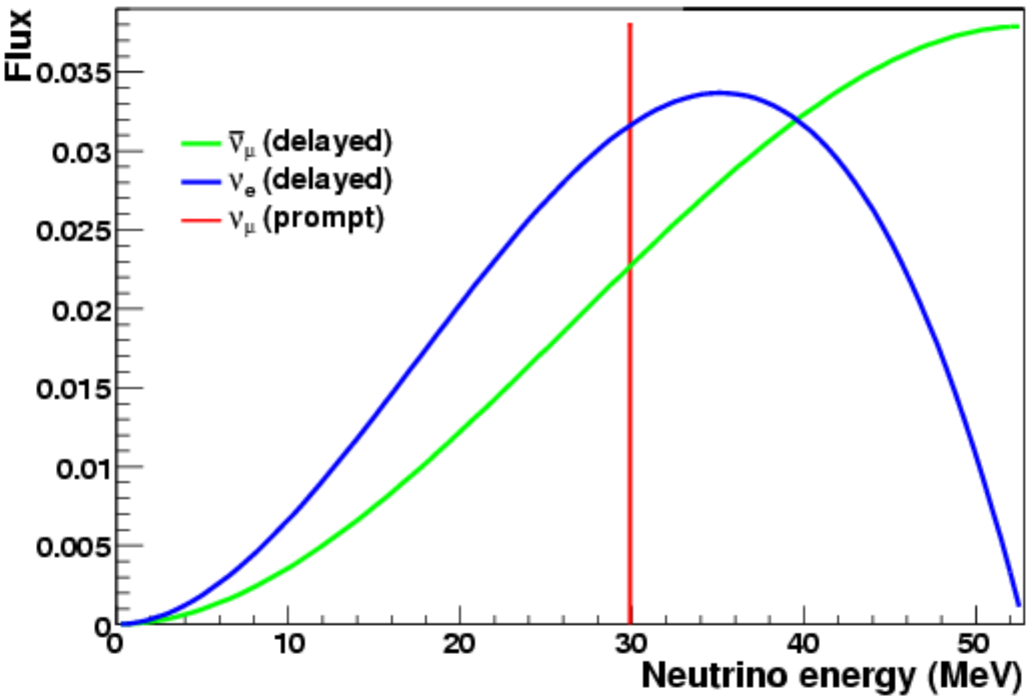
Some experimental issues to keep in mind

- Efficiency is a function of T, and has shape uncertainties
- Low energy thresholds are hard to achieve
- "Quenching factor" (observable recoil energy compared to electron energy deposition) and other detector response has T shape uncertainties
- T shape uncertainties **have correlations**
- Energy resolution matters
- Backgrounds matter (a lot)
- There are flux normalization and shape uncertainties
- All of these are **very target- and detector-dependent**
- It's very hard work to get a handle on these parameters and their (correlated) uncertainties



Stopped-Pion (πDAR) Neutrinos





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

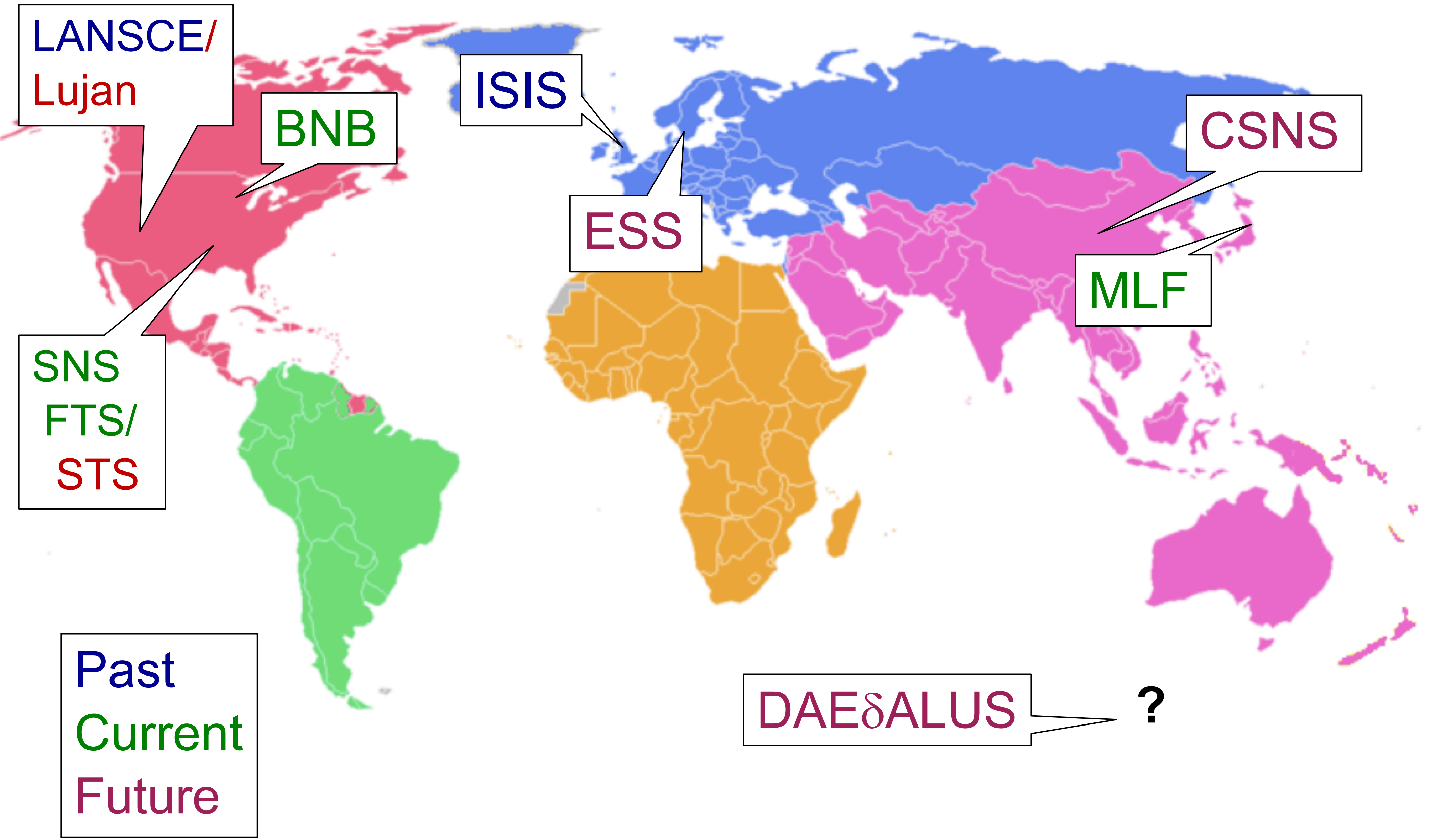
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

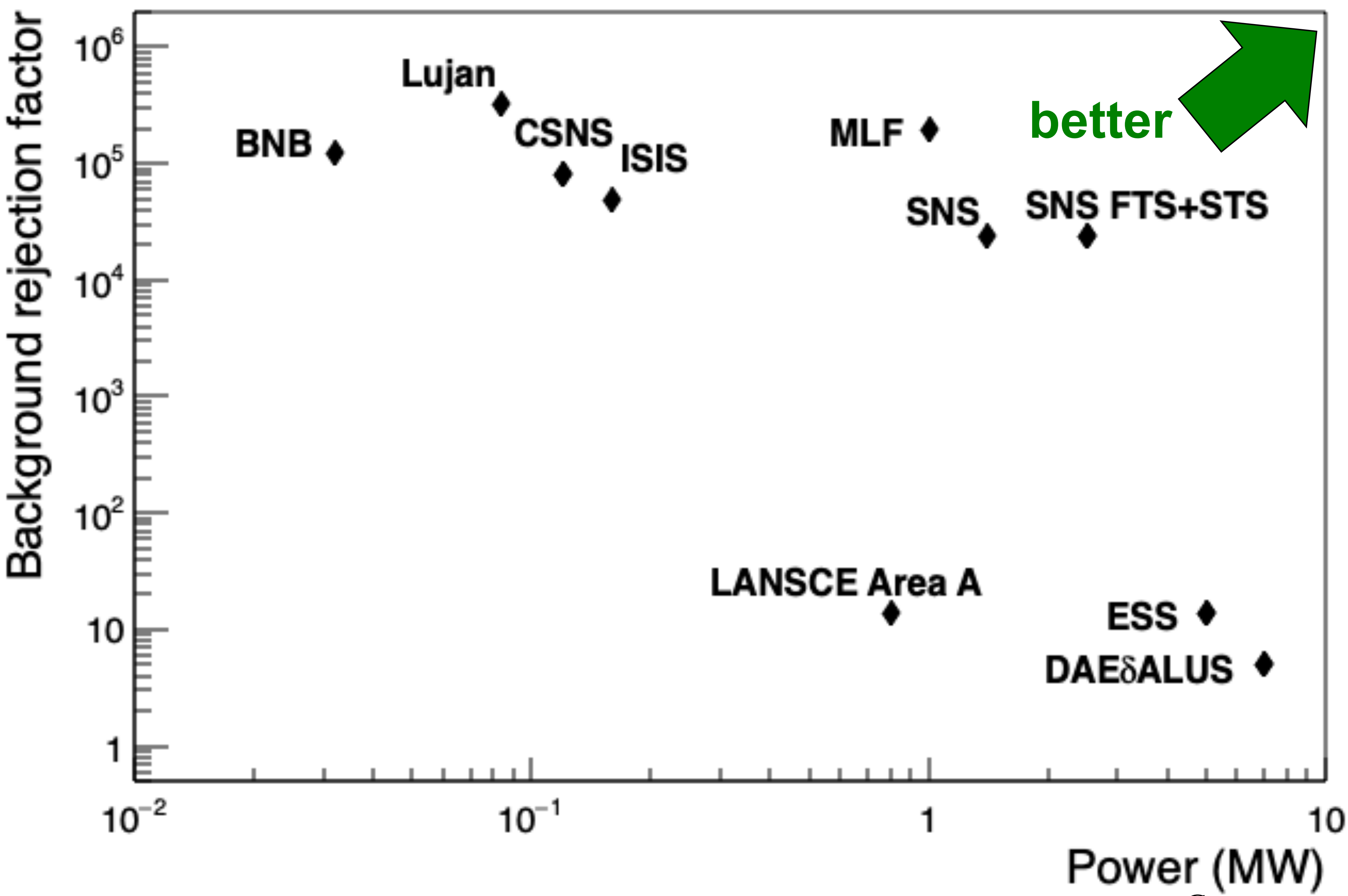
3-body decay: range of energies
between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Neutrino Sources Worldwide



from duty cycle

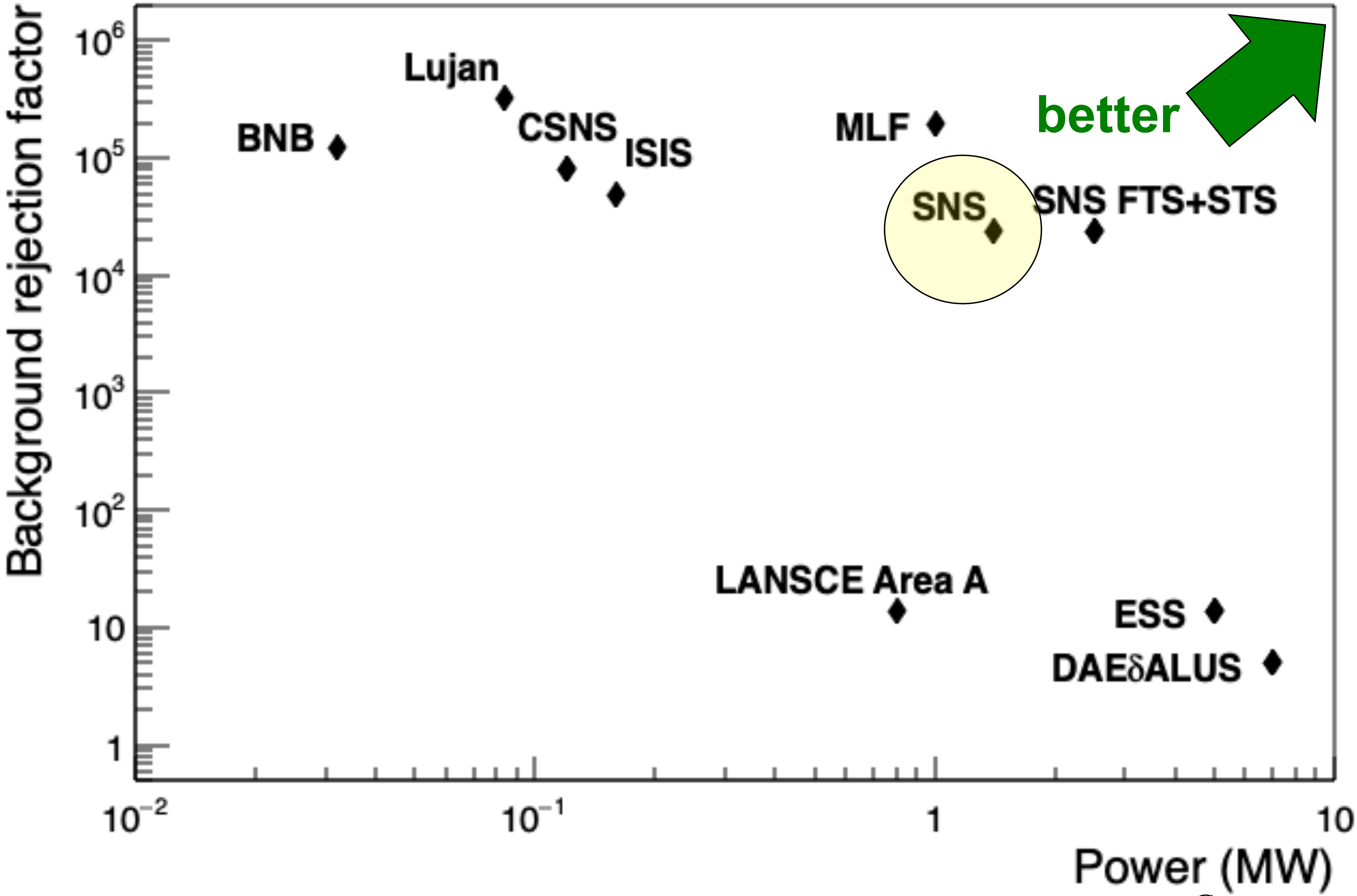
Comparison of pion decay-at-rest ν sources



$\propto \nu$ flux

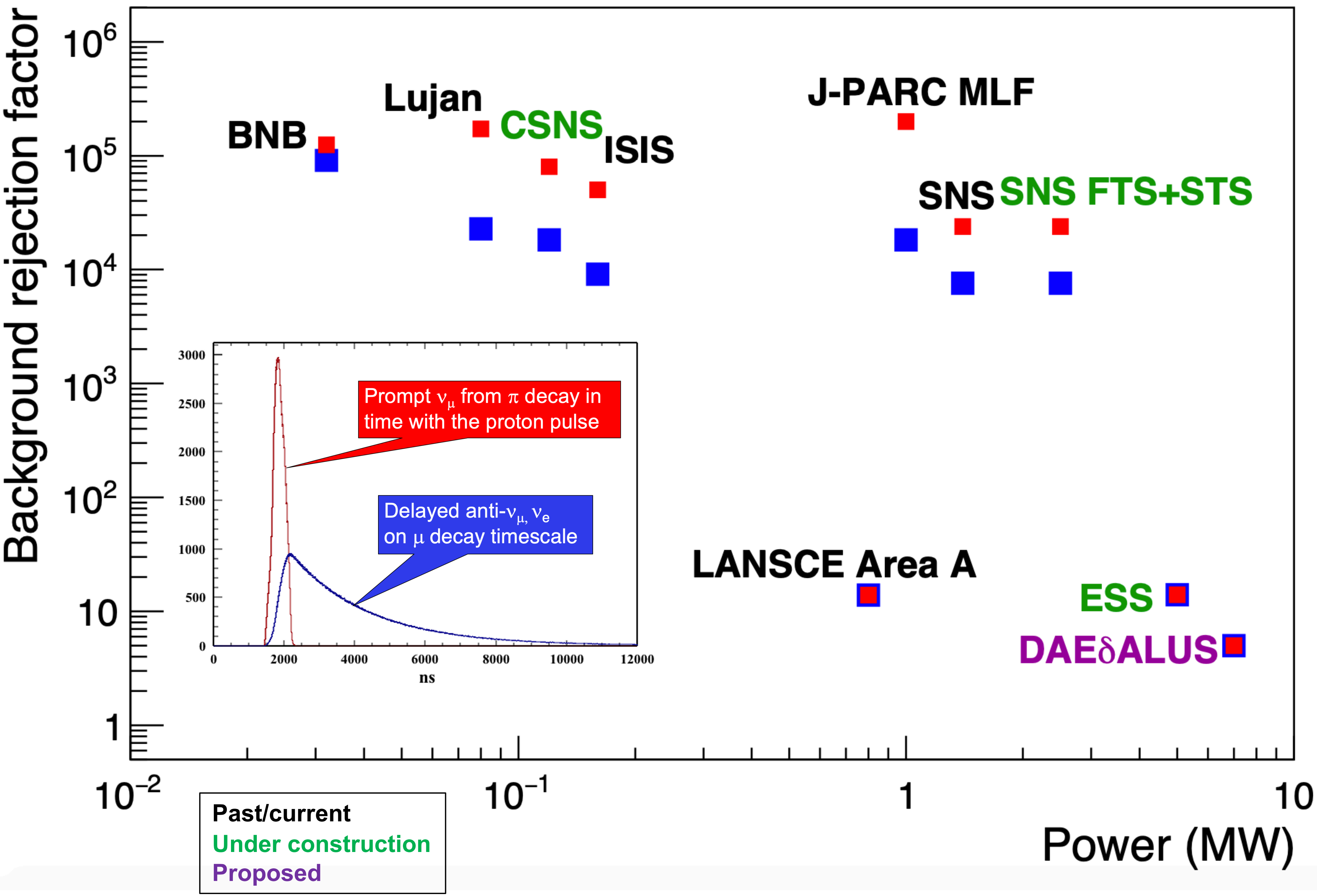
Comparison of pion decay-at-rest ν sources

from duty cycle



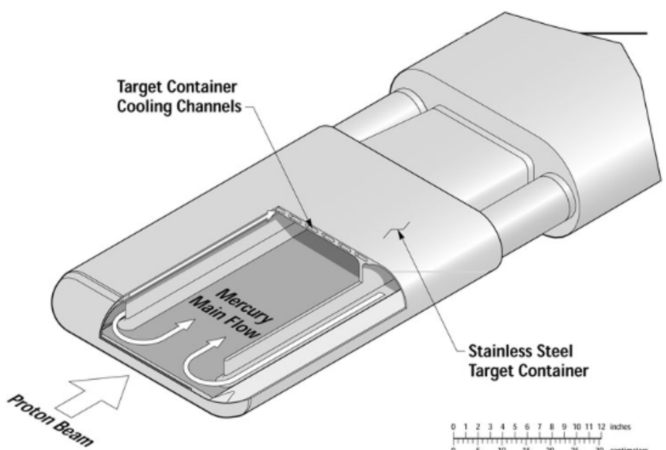
$\propto \nu$ flux

Flavor separation with beam timing can be helpful!



Spallation Neutron Source

Oak Ridge National Laboratory, TN



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

The neutrinos are free!

The COHERENT collaboration

http://sites.duke.edu/coherent

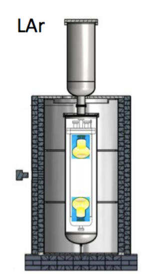
~90 members,
20 institutions
4 countries

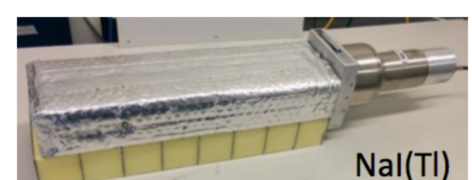
arXiv:1509.08702

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

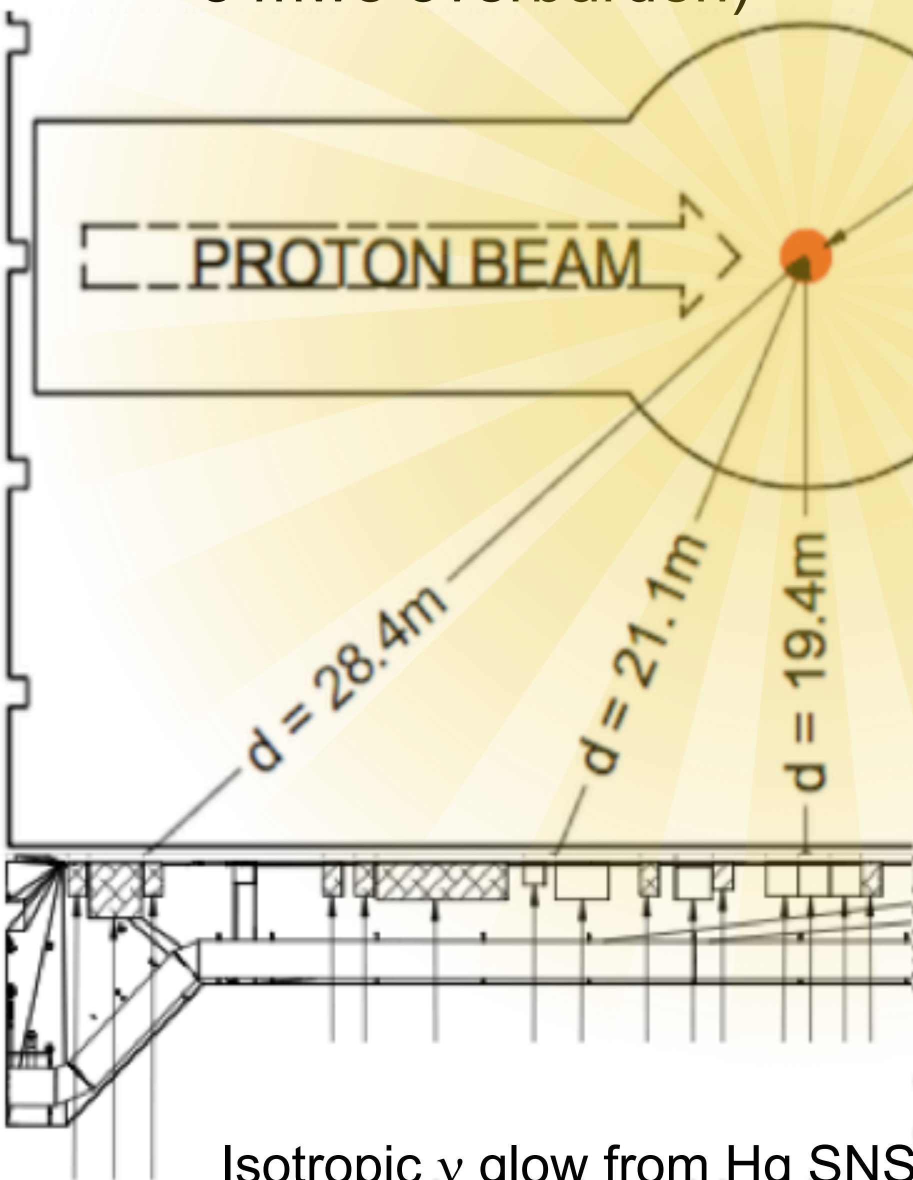
Multiple detectors for N^2 dependence of the cross section





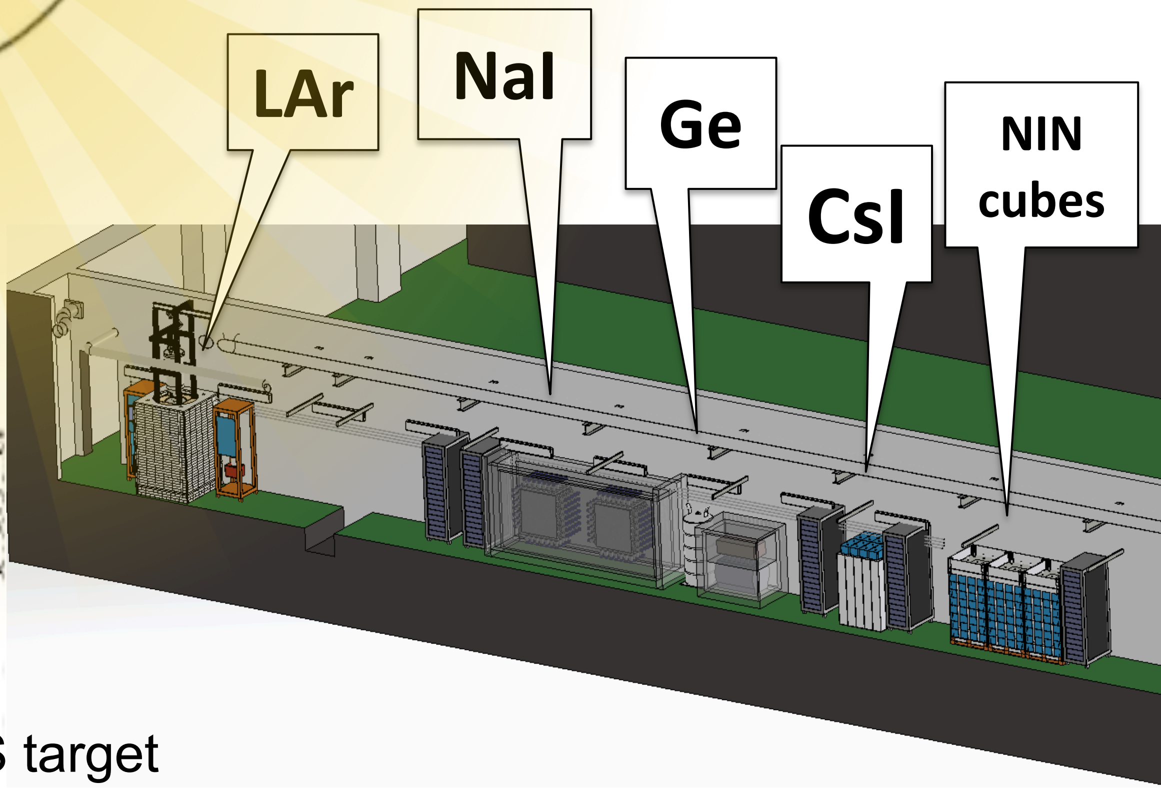
Siting for deployment in SNS basement

(measured neutron backgrounds low, ~ 8 mwe overburden)

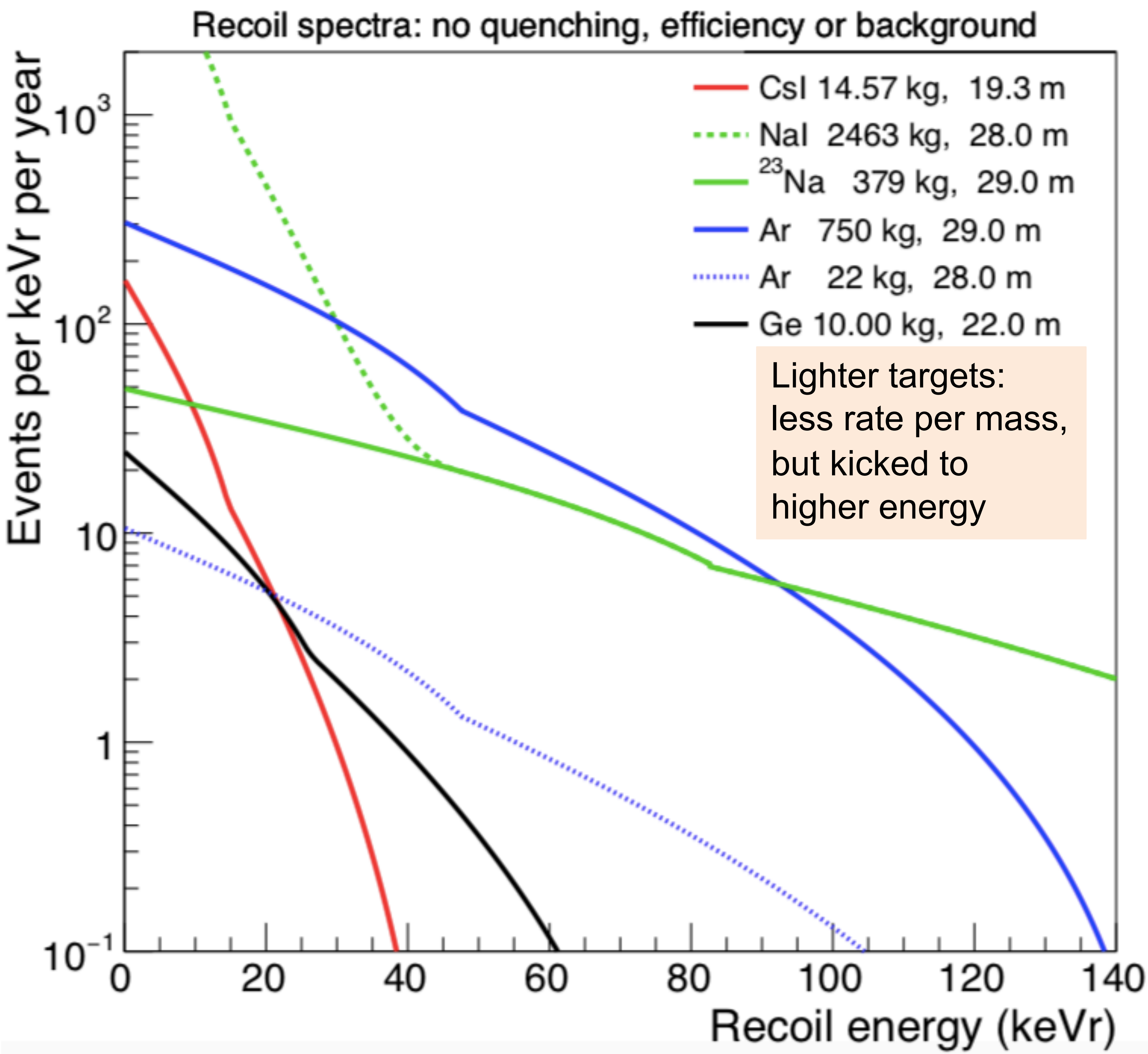


Isotropic ν glow from Hg SNS target

View looking down "Neutrino Alley"



Expected recoil energy distribution

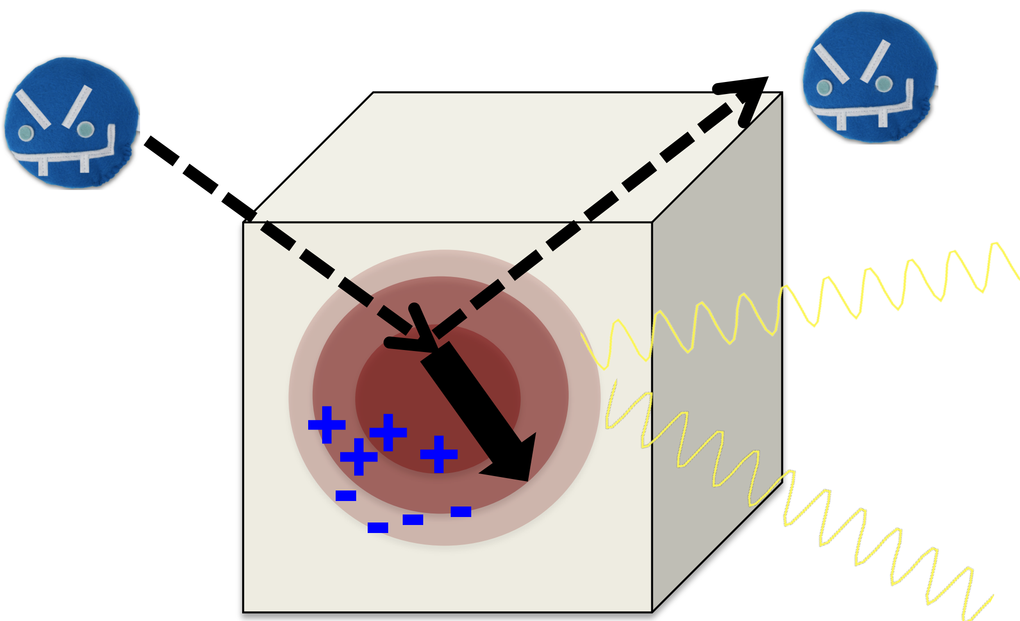


Backgrounds

Usual suspects:

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

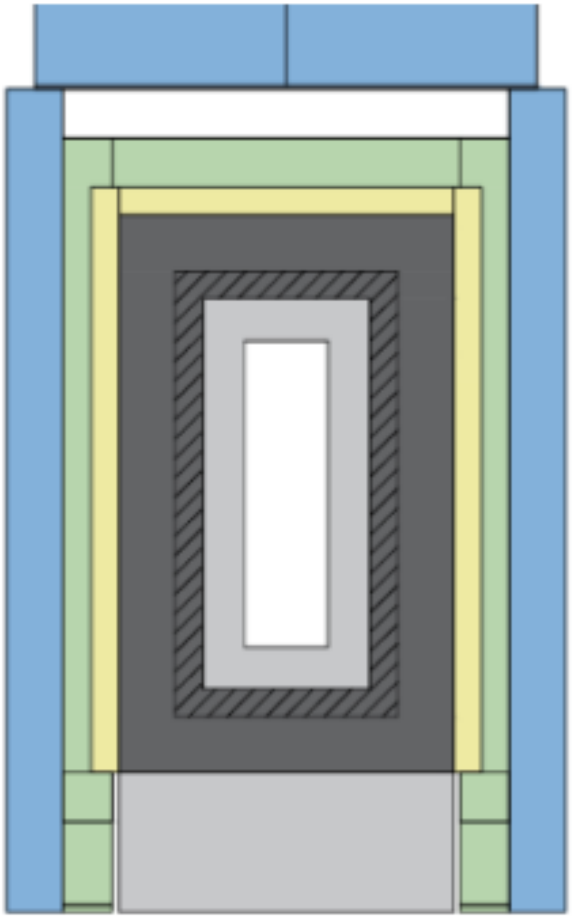
Neutrons are especially not your friends*

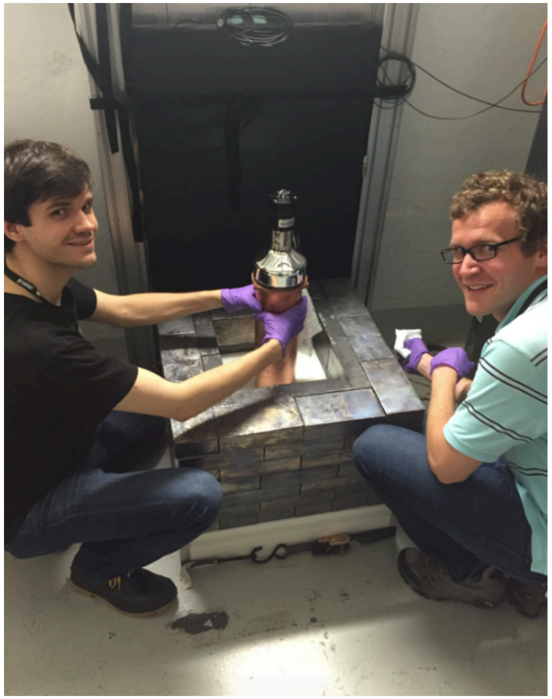


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

The CsI Detector in Shielding in Neutrino Alley at the SNS



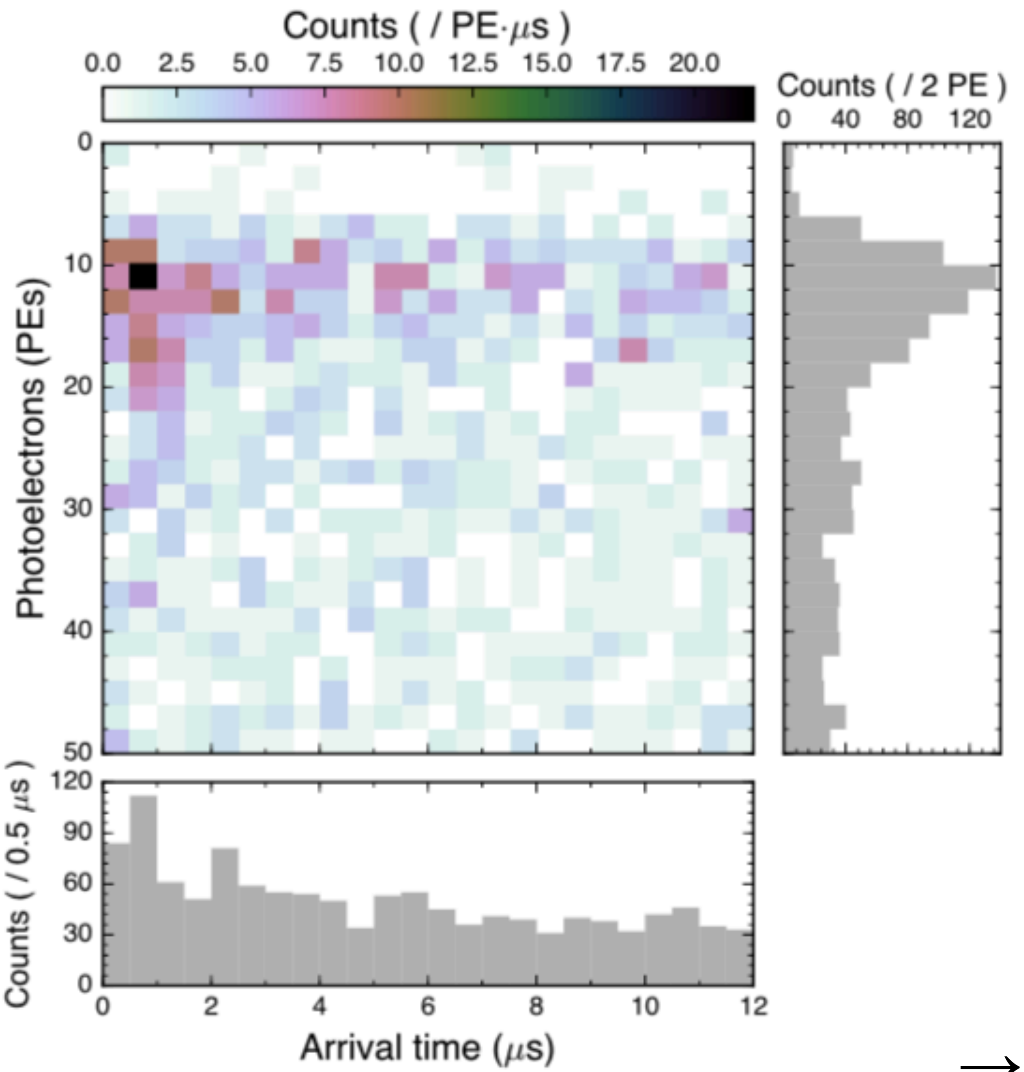


A hand-held detector!

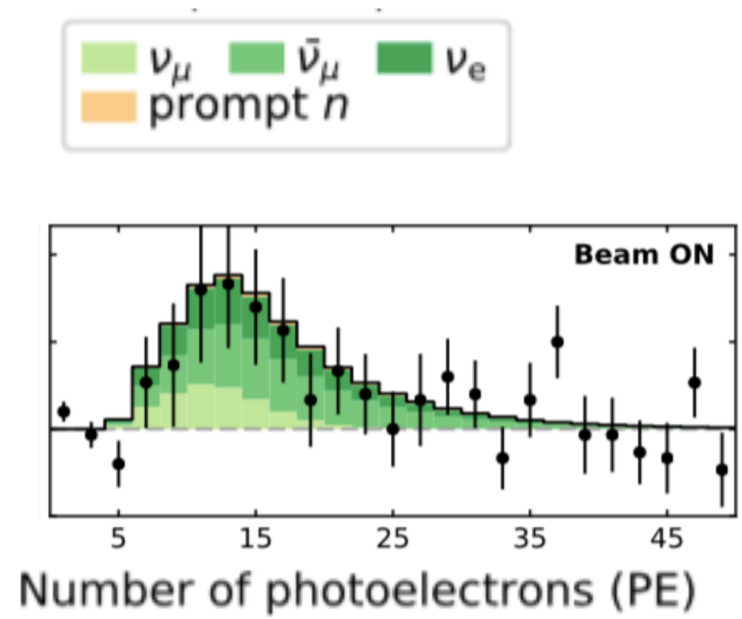
Almost wrapped up...

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



DOI: 10.5281/zenodo.1228631



Background-subtracted and integrated over time

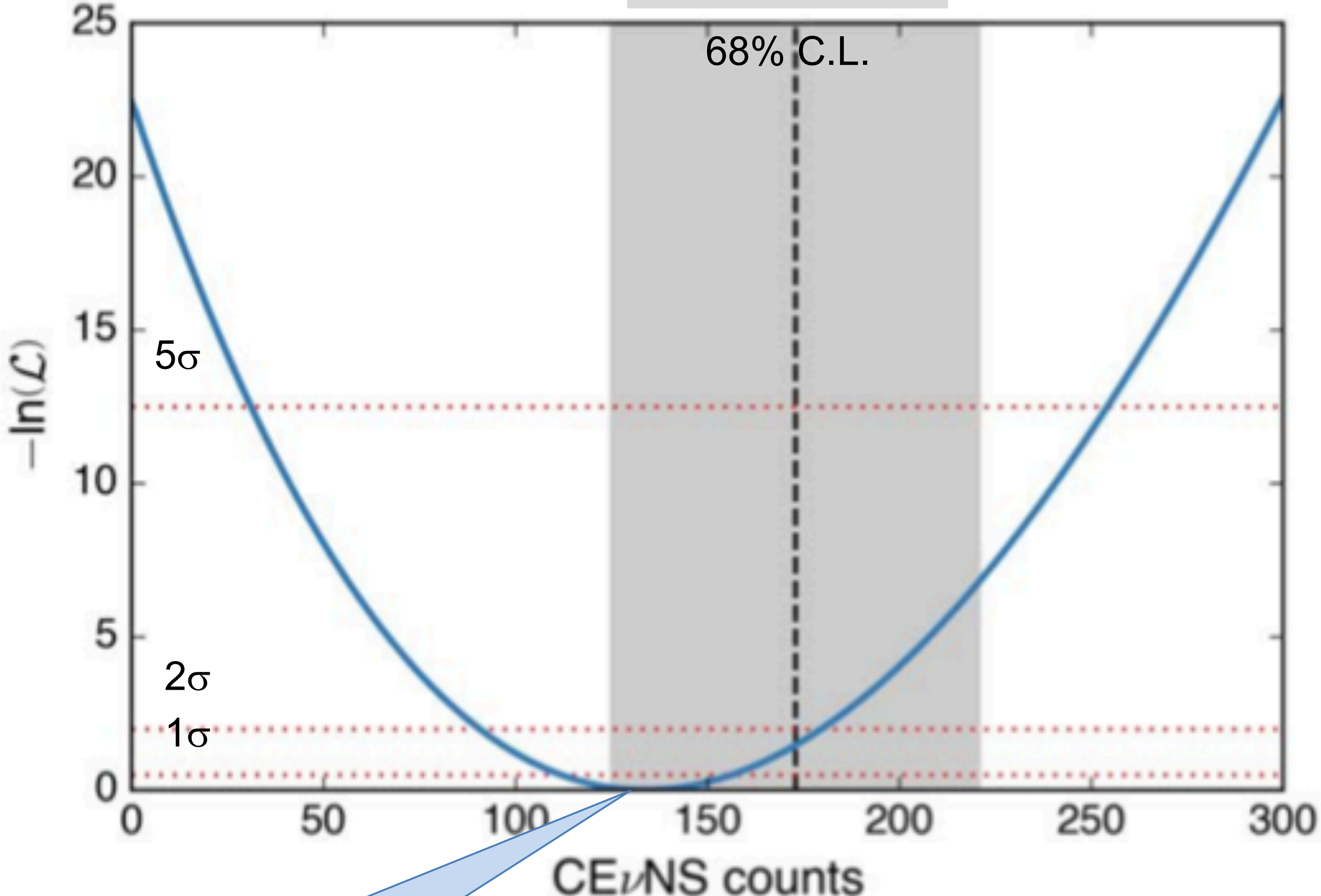
$$\mathrm{PE} \propto T \propto Q^2$$

→ measure of the Q spectrum

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

Results of 2D energy, time fit

SM prediction, 173 events



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

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

Signal, background, and uncertainty summary numbers

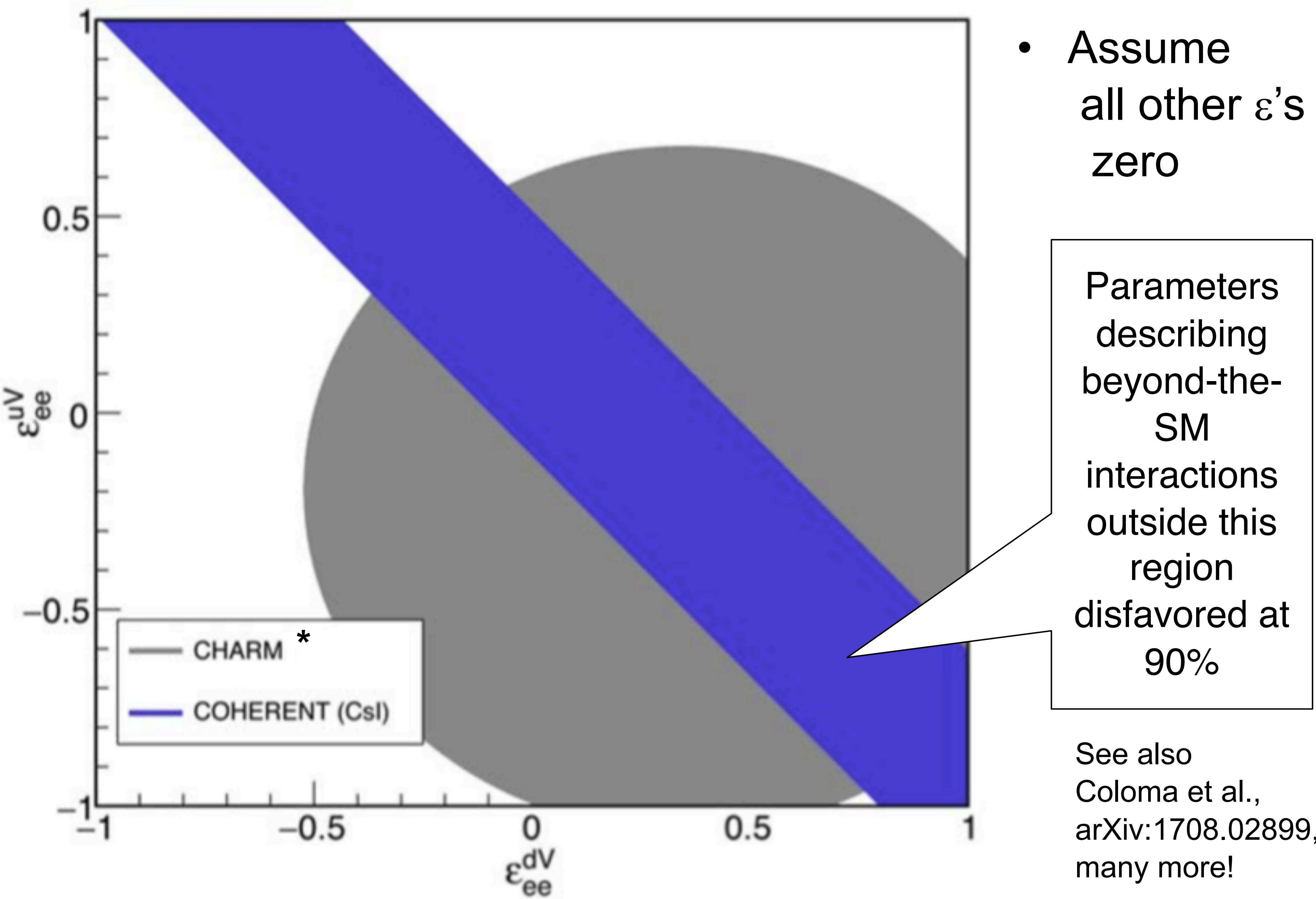
6 ≤ PE ≤ 30, 0 ≤ t ≤ 6000 ns

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

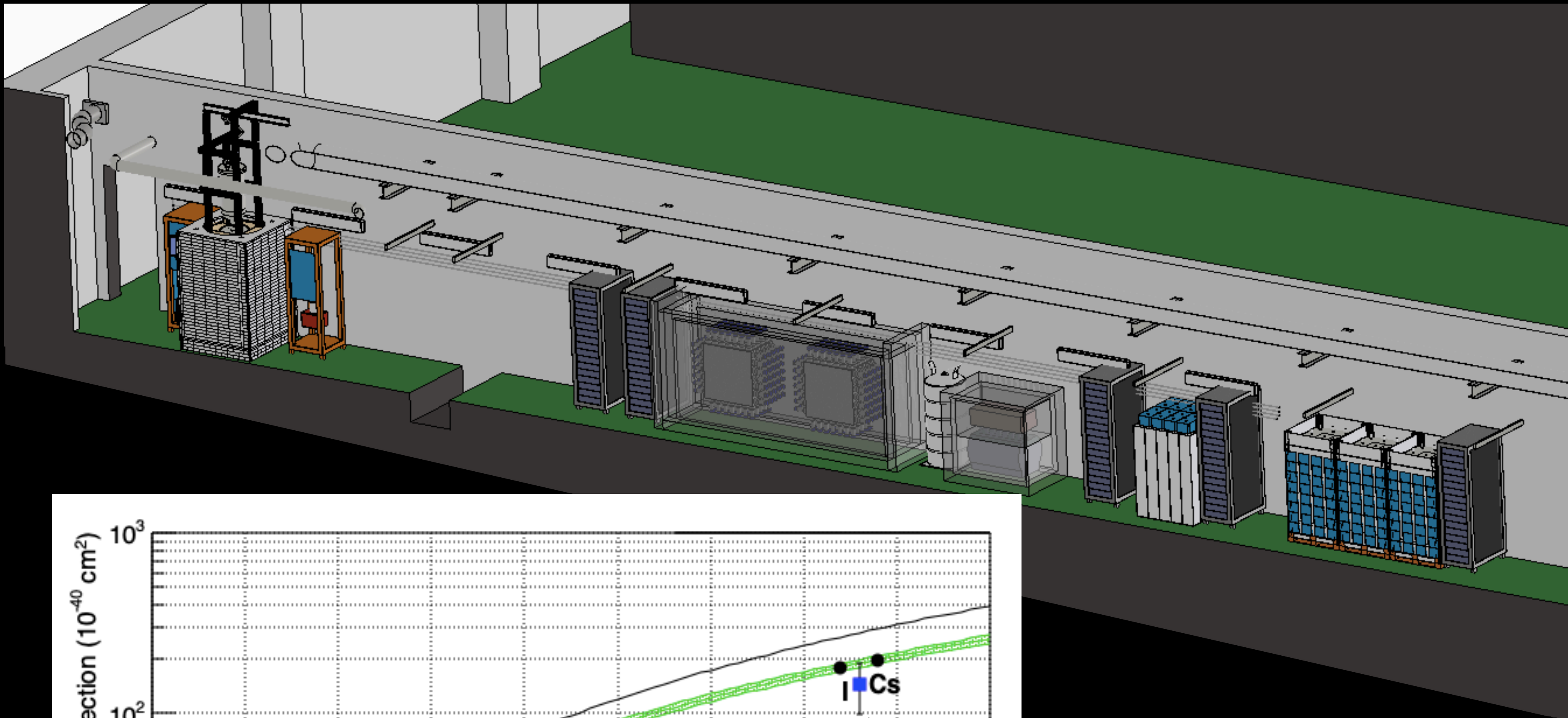
Neutrino non-standard interaction constraints for current CsI data set:

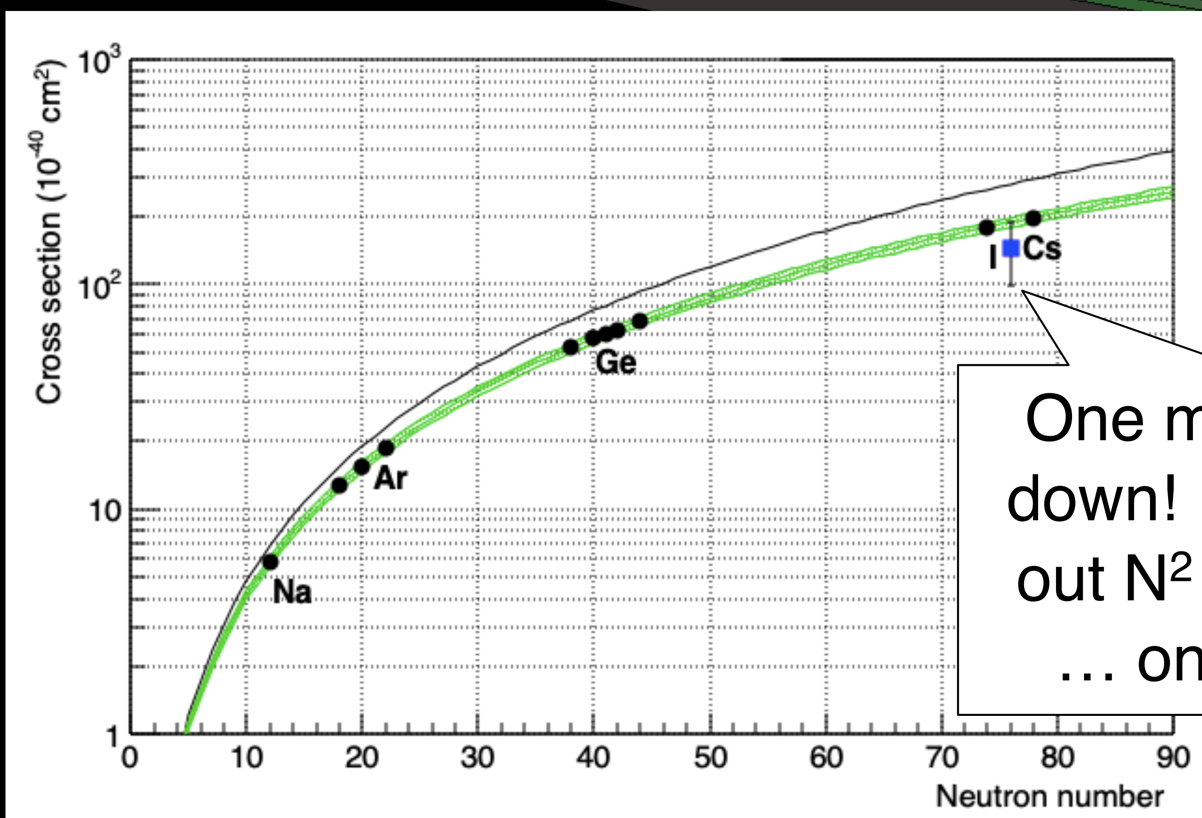


- Assume all other ε's zero

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

*CHARM constraints apply only to heavy mediators



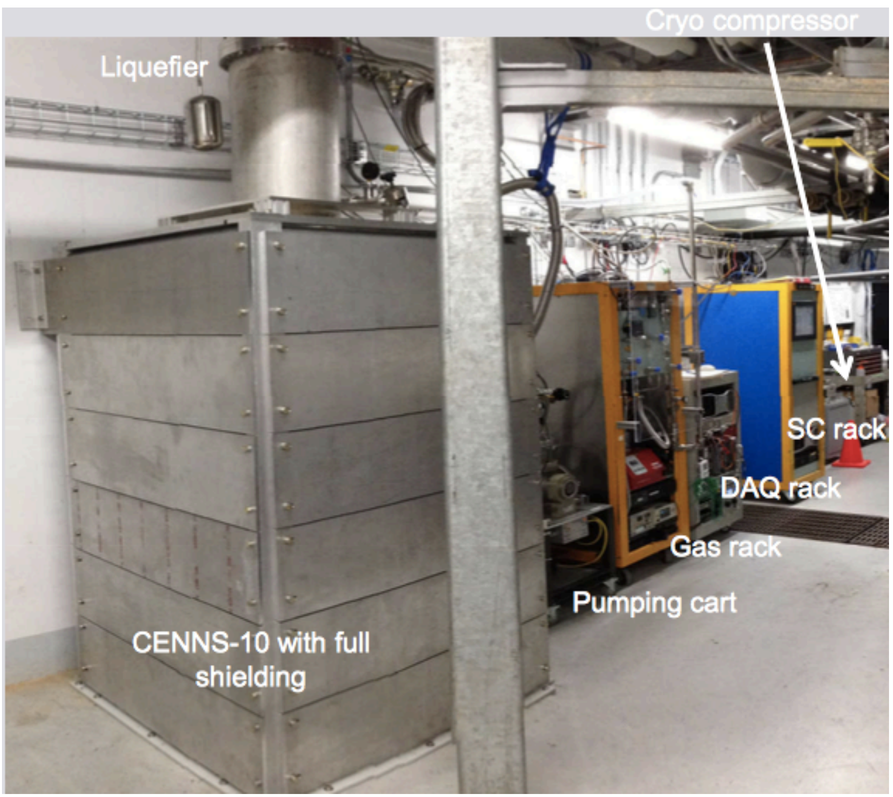


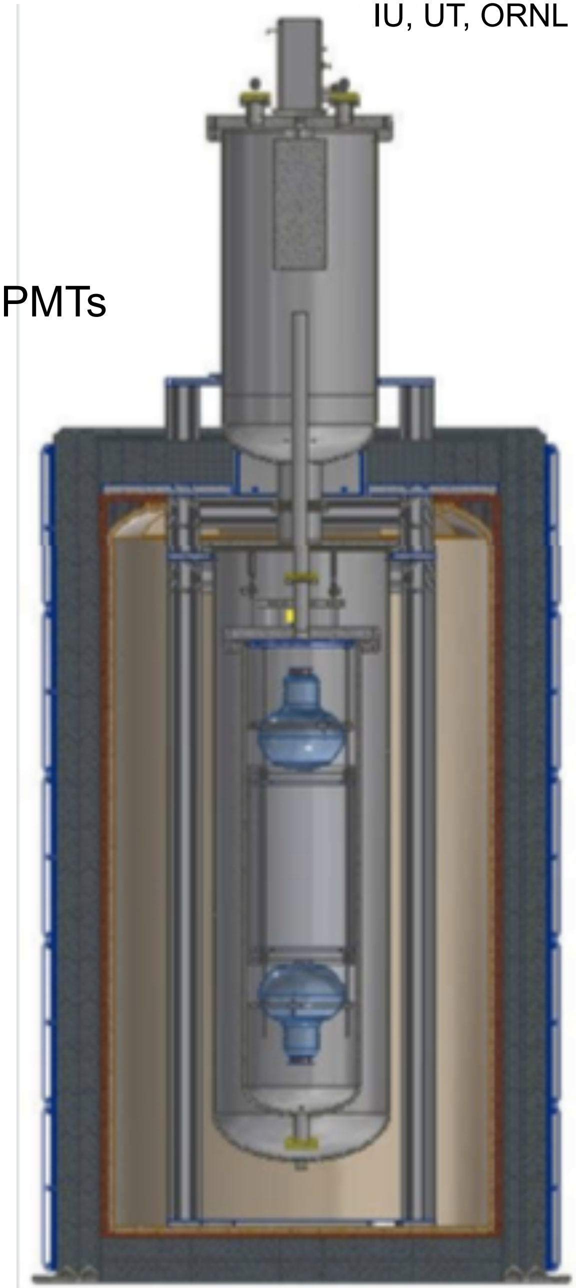
One measurement down! Want to map out N^2 dependence … on to the next

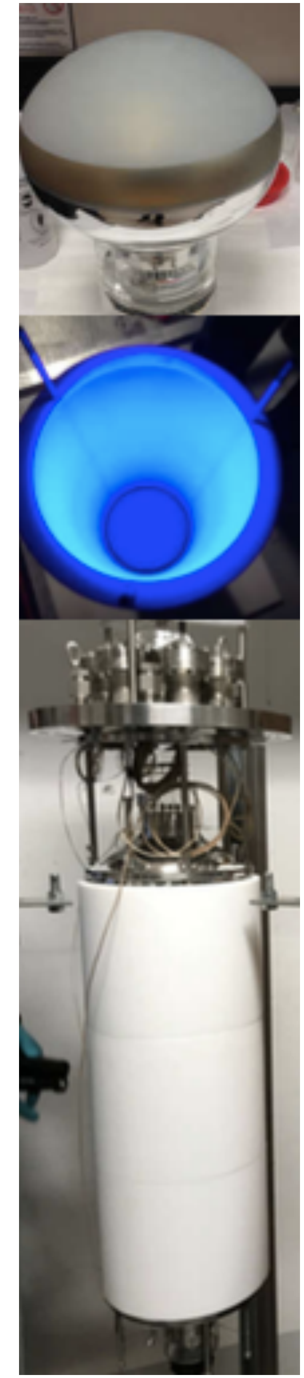
Single-Phase Liquid Argon

- ~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



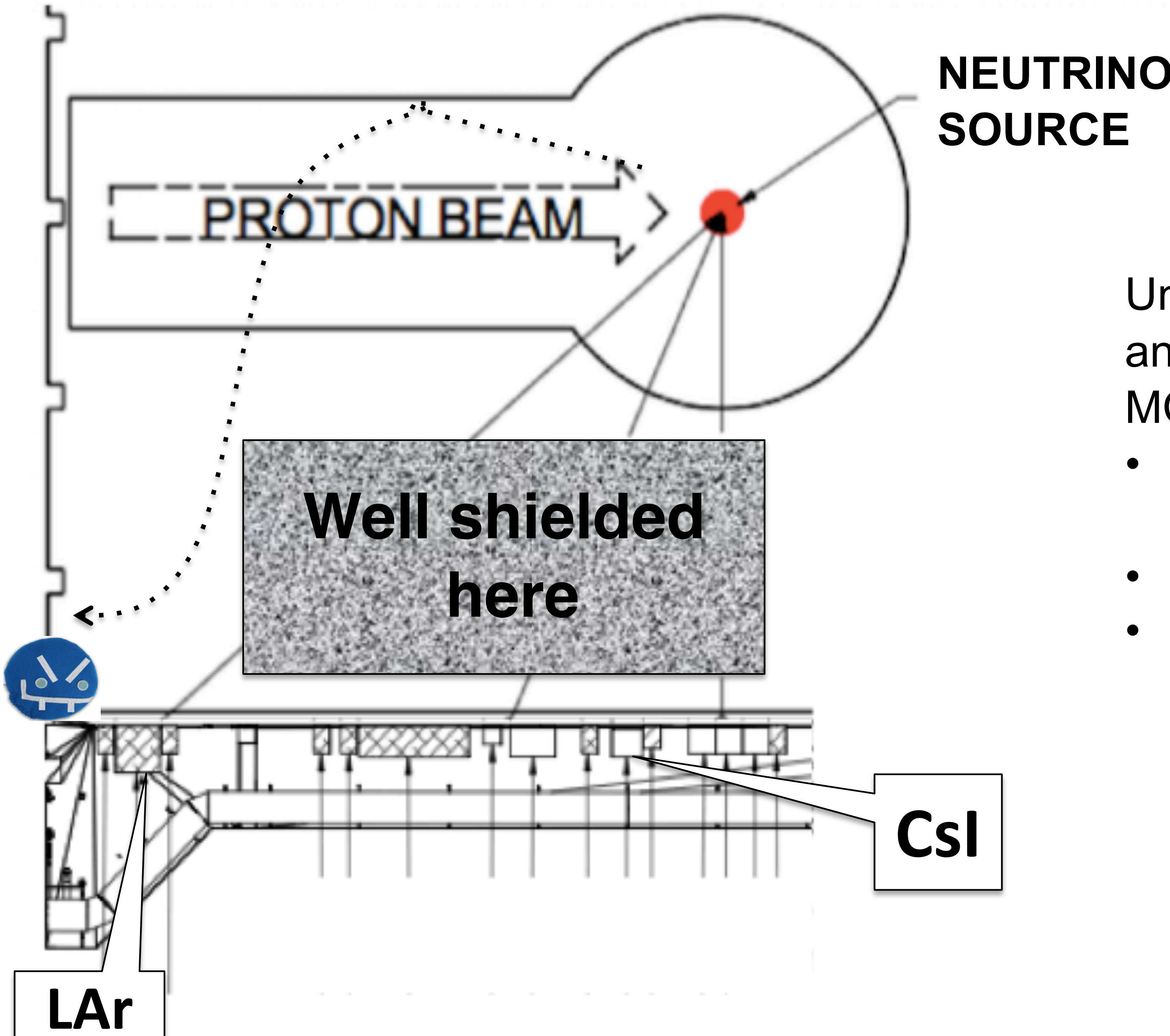




Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB

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

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

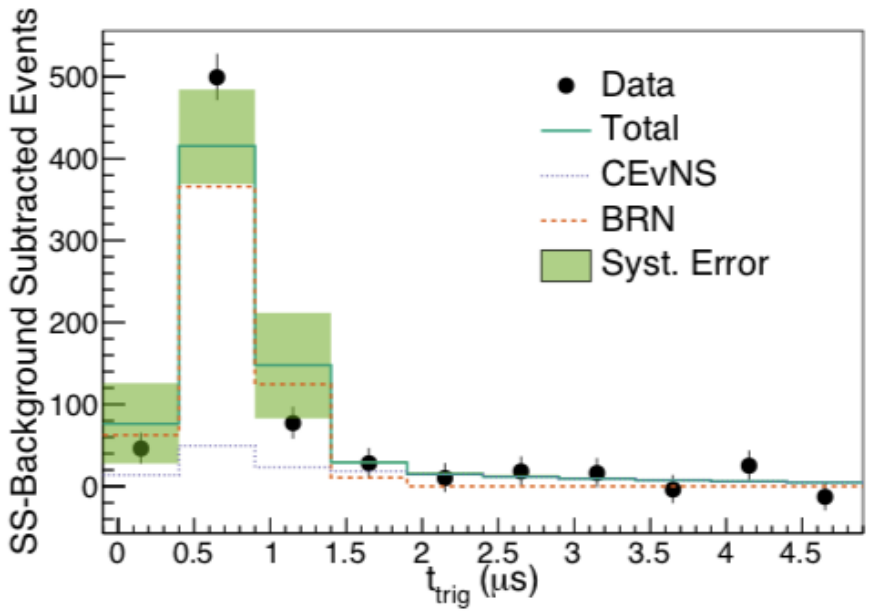


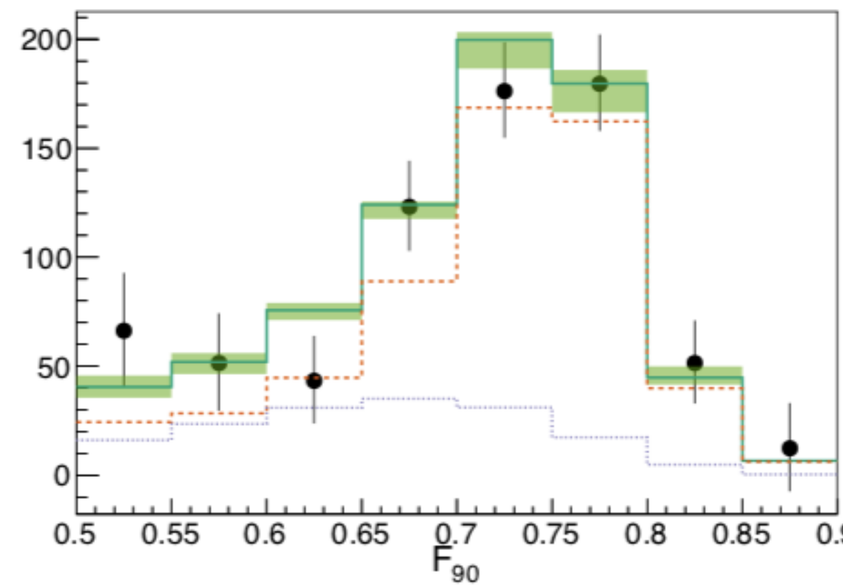
Understand spectrum and time structure by MC tuned using

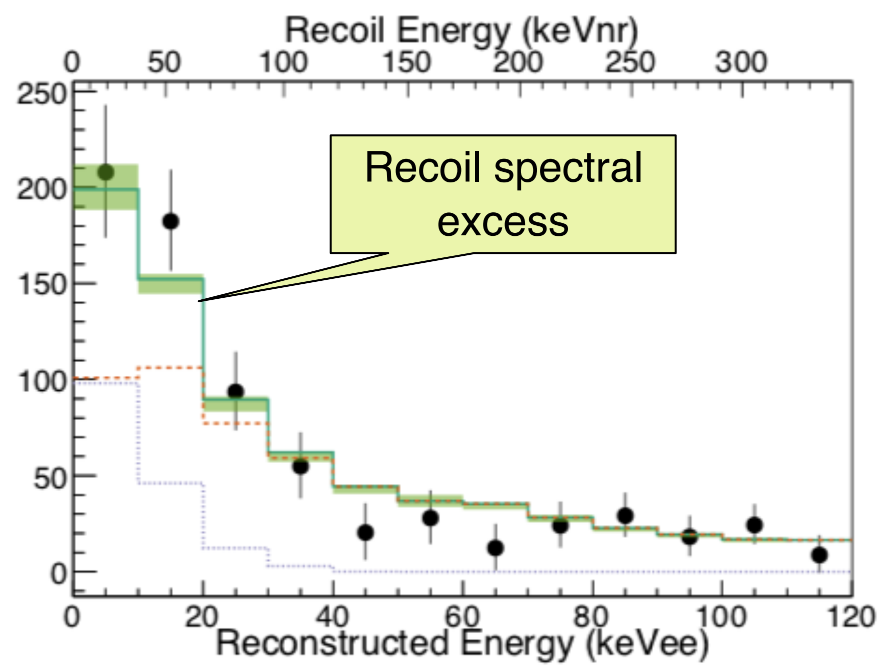
- Engineering run data
  Phys.Rev. D100 (2019) no.11, 115020
- No-water shield run
- High-energy sideband

Likelihood fit in time, recoil energy, PSD parameter

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





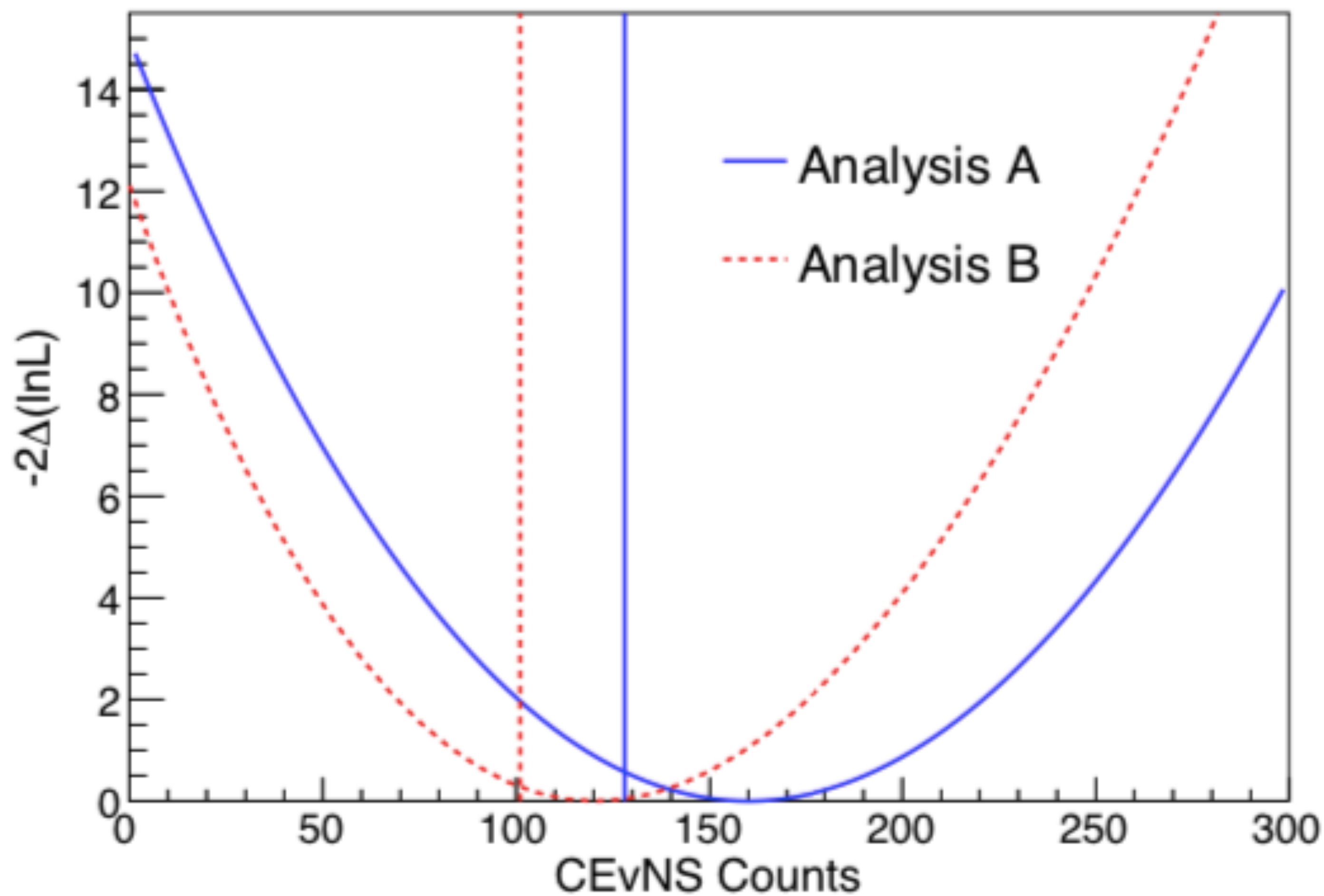


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

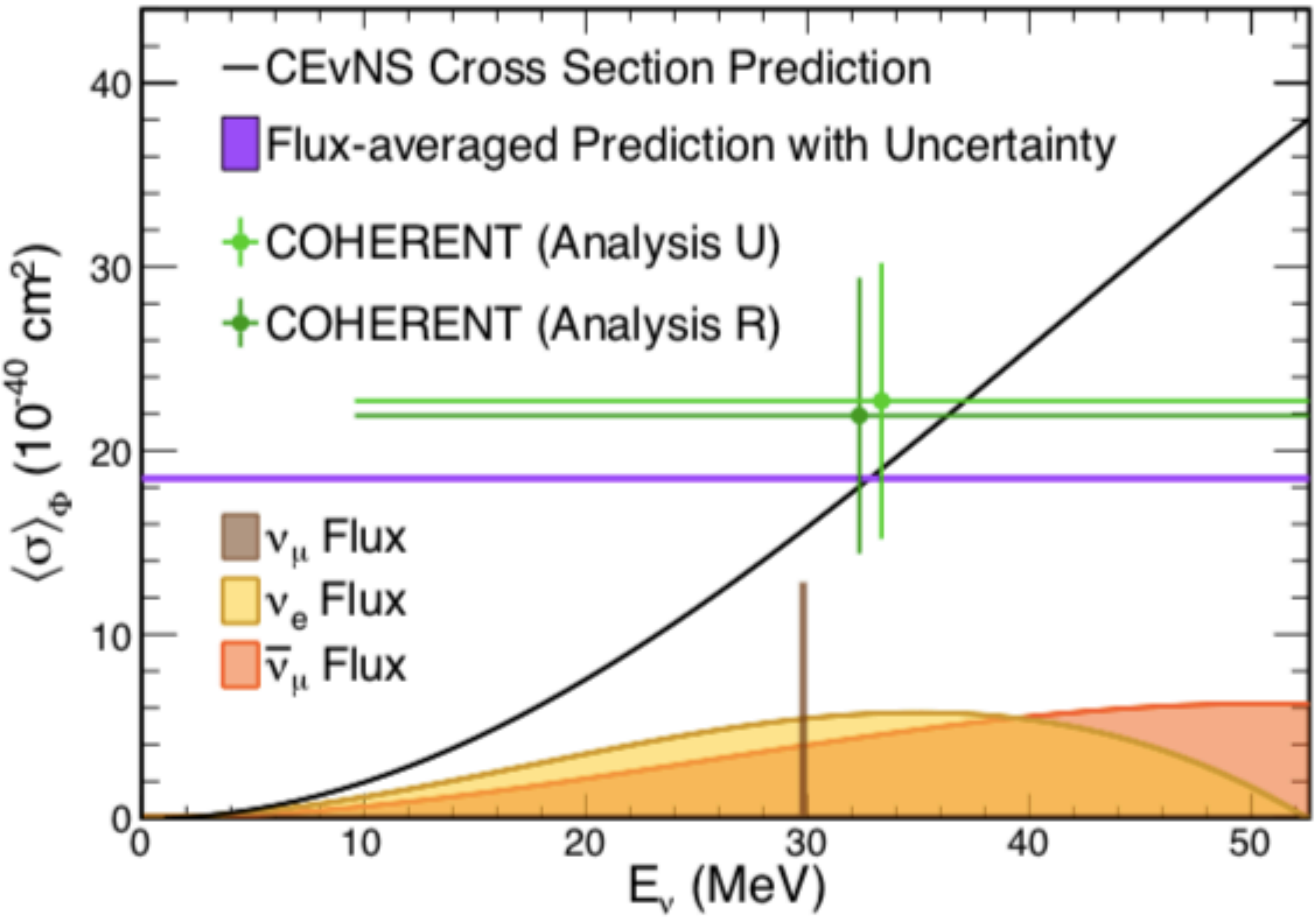
CEvNS Count Results from Likelihood

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

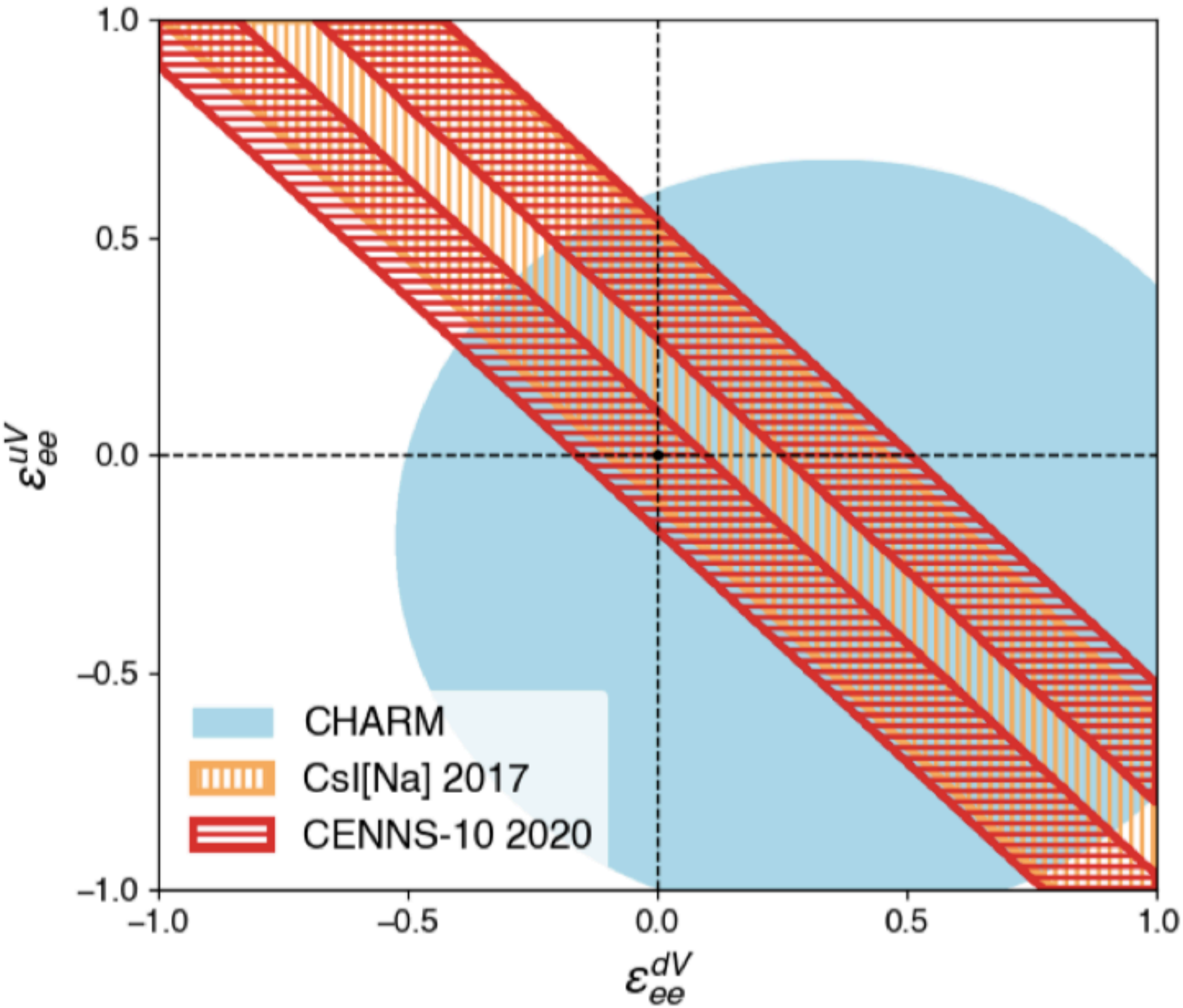
Moscow: $121 \pm 36(\mathrm{stat.}) \pm 15(\mathrm{sys.})$ Reject null@ 3.1σ



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%

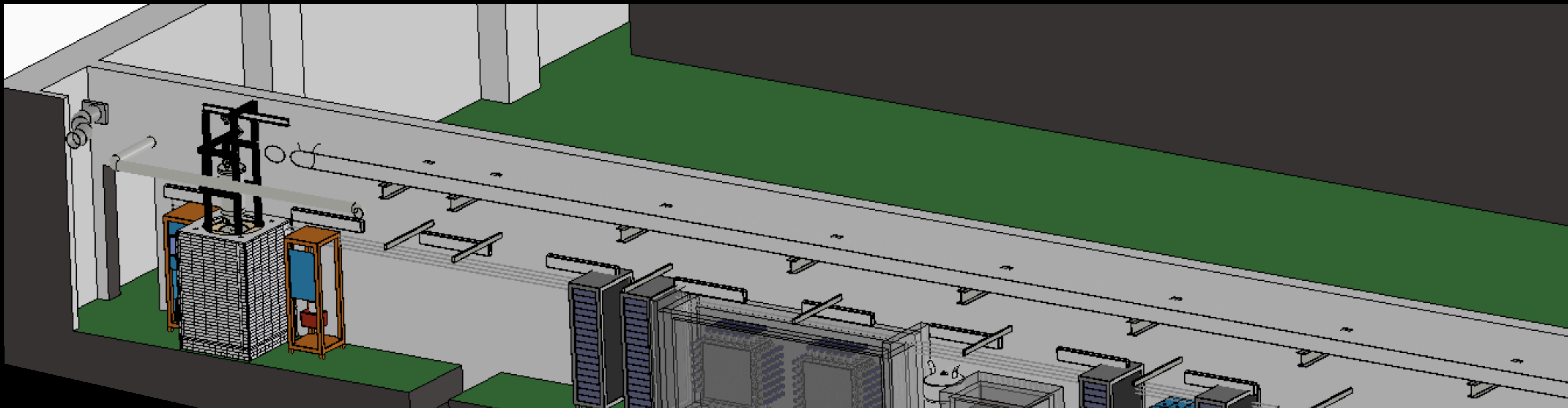
(Analysis A)

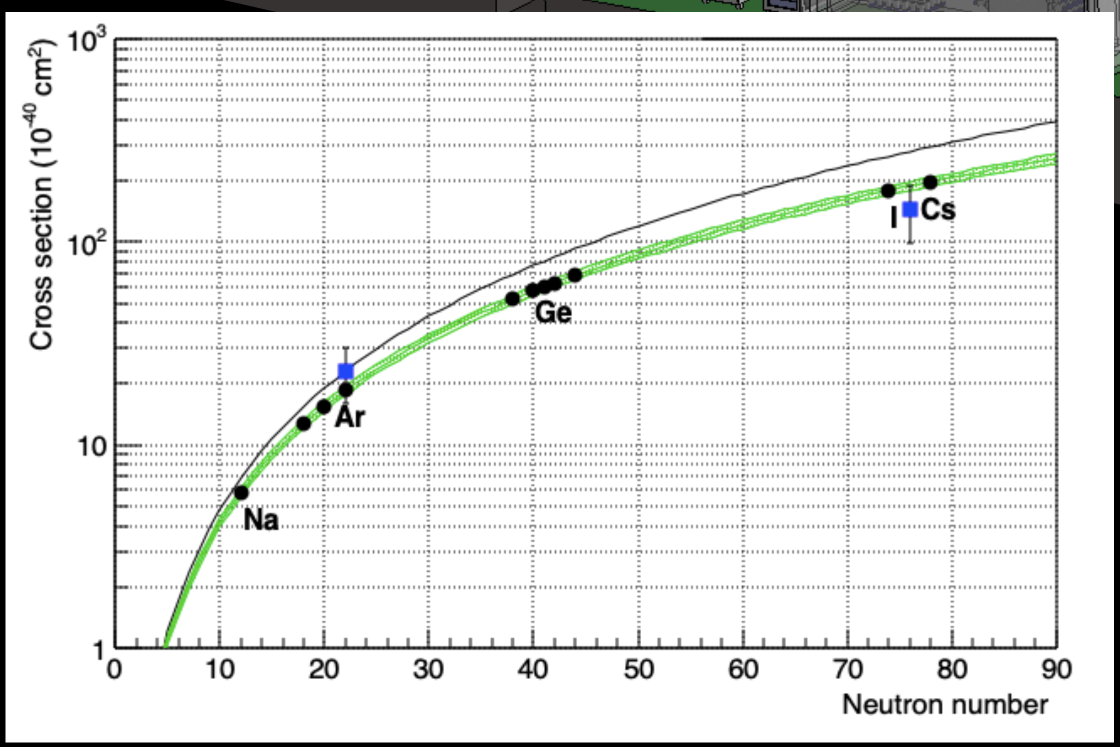
Dominant single uncertainty

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?

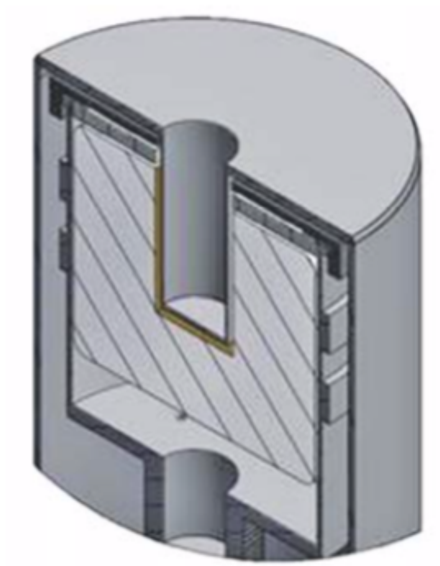




Two down!
But still more to go!

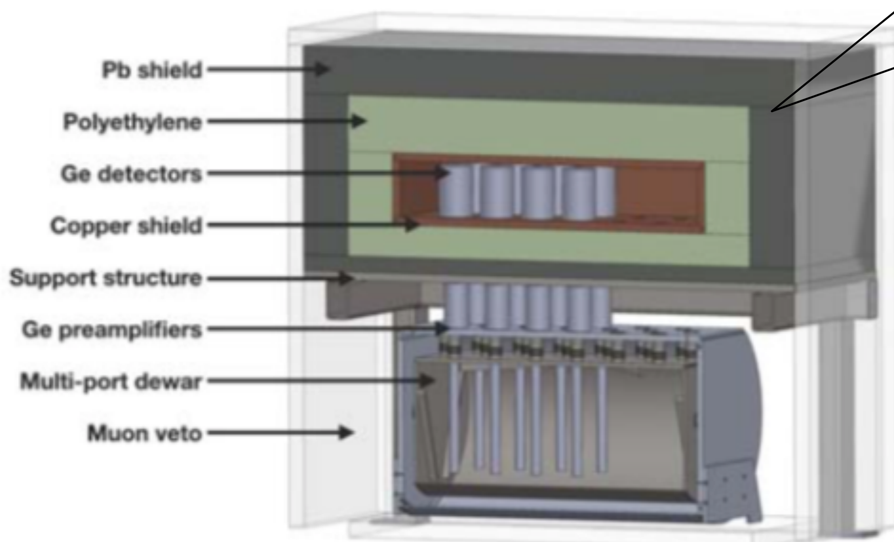
High-Purity Germanium Detectors

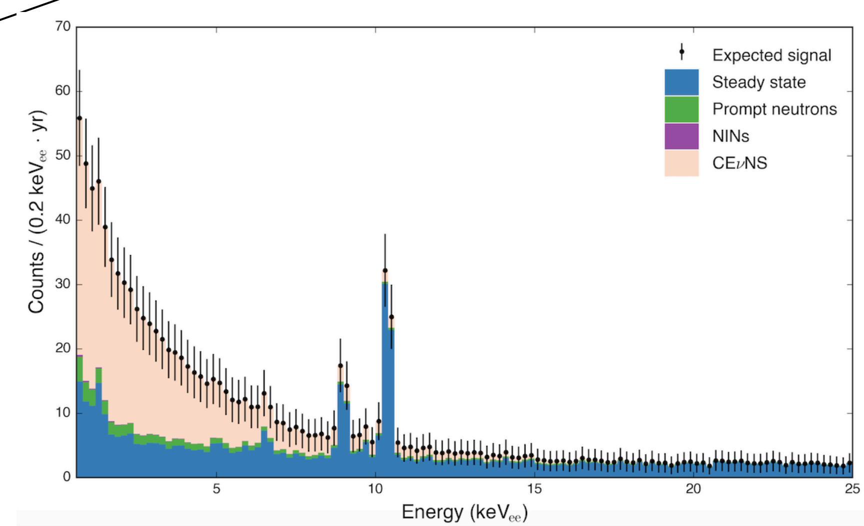
P-type Point Contact



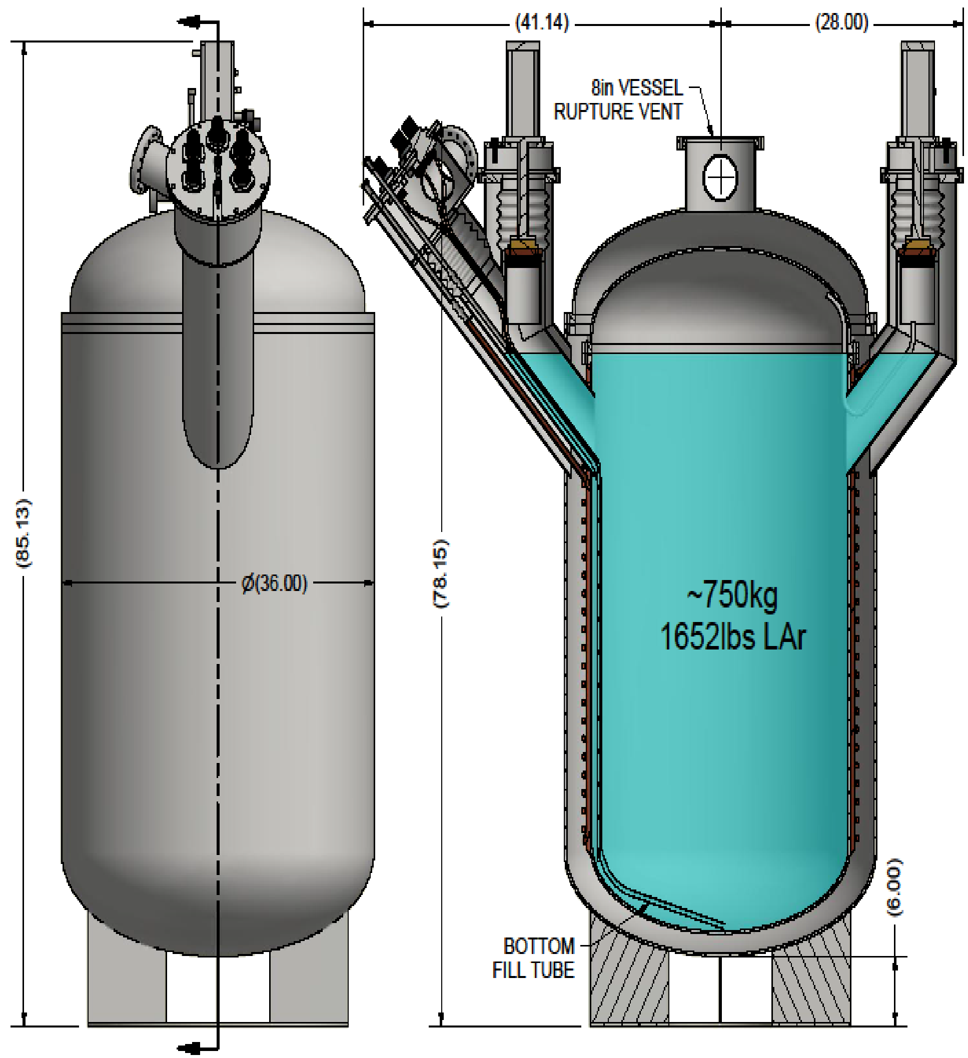
- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

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

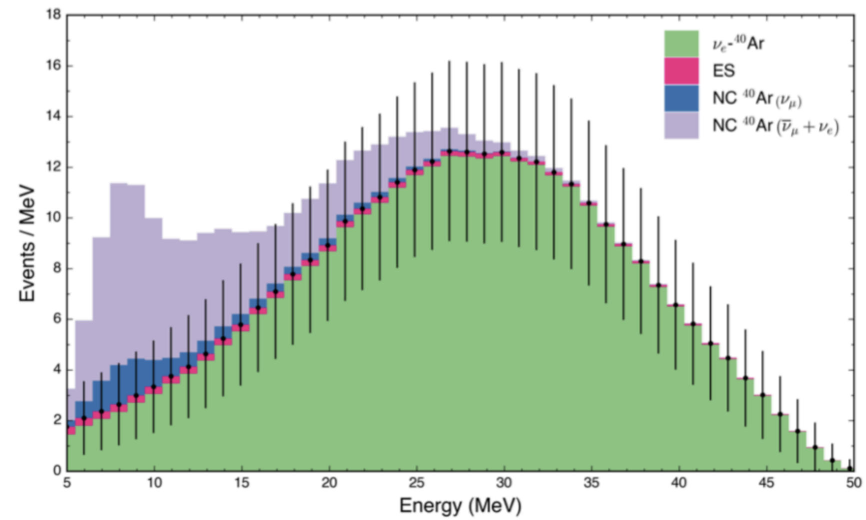




Tonne-scale LAr Detector



- 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

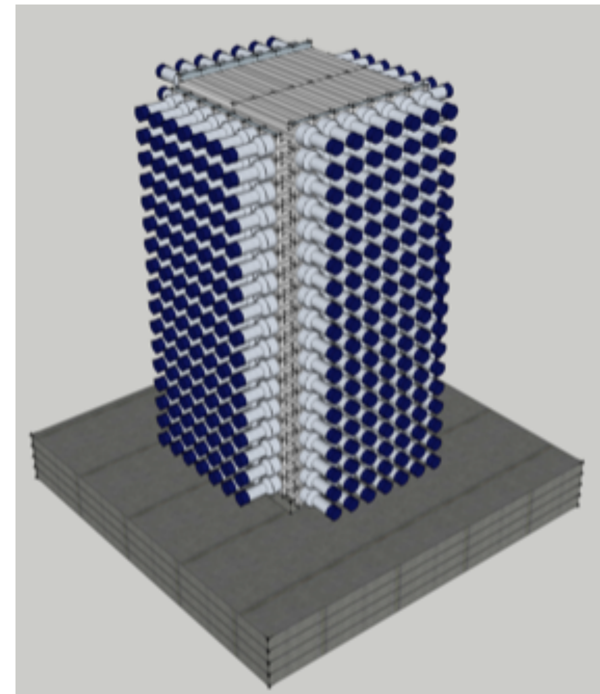
CC $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

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

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

- up to 9 tons available, 3.3 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



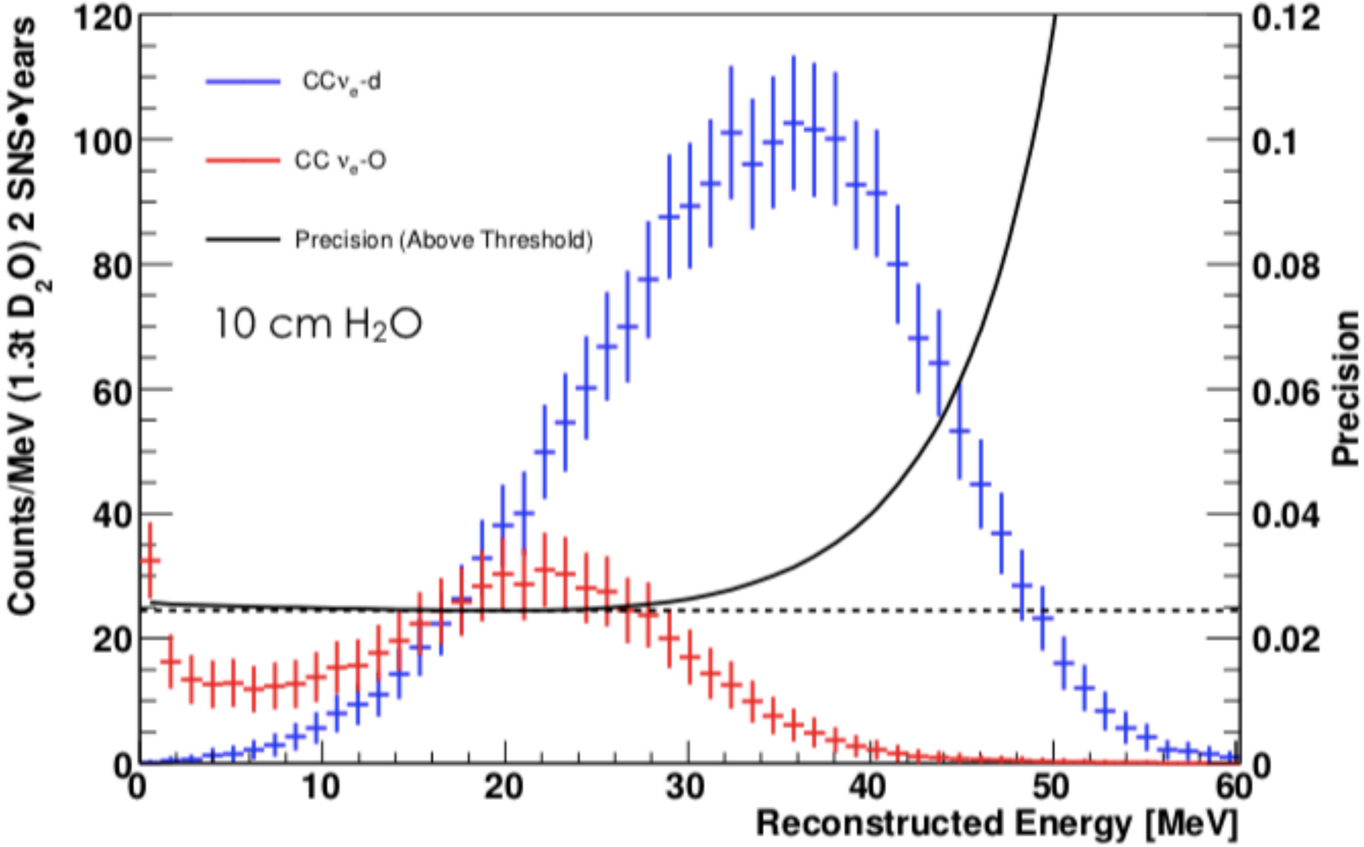
In the meantime: **185 kg deployed at SNS** to go after ν_e**CC on ^{127}I**

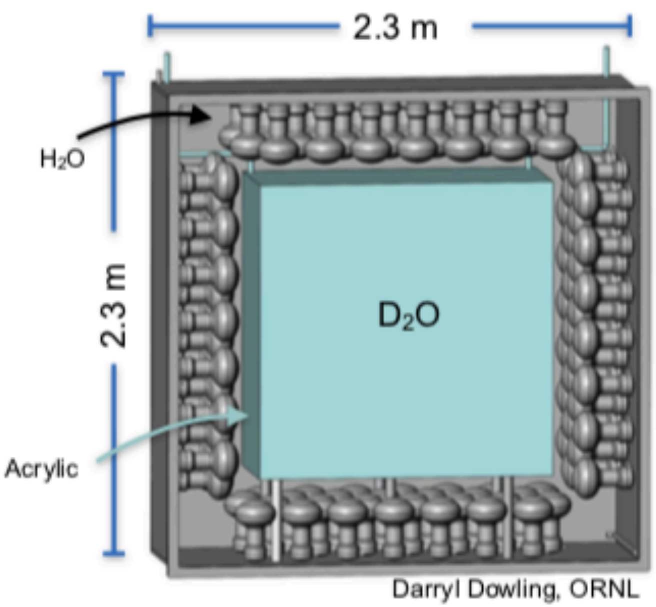
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	$284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

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



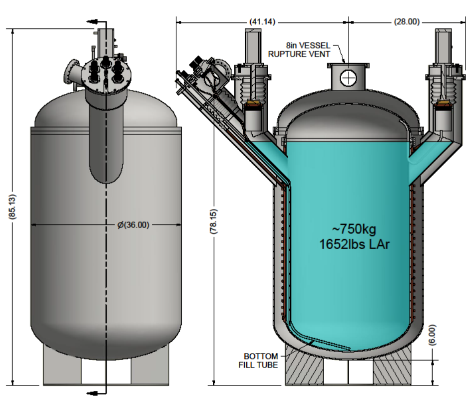


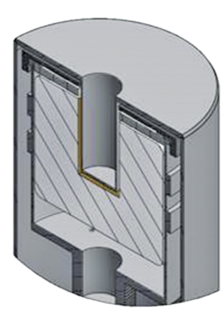
- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O "tail catcher" for high energy e^-
- 112 8" bialkali photomultipliers

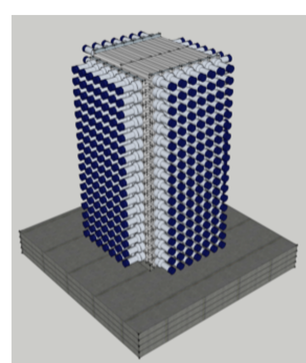
➔ ~few percent precision on flux normalization

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



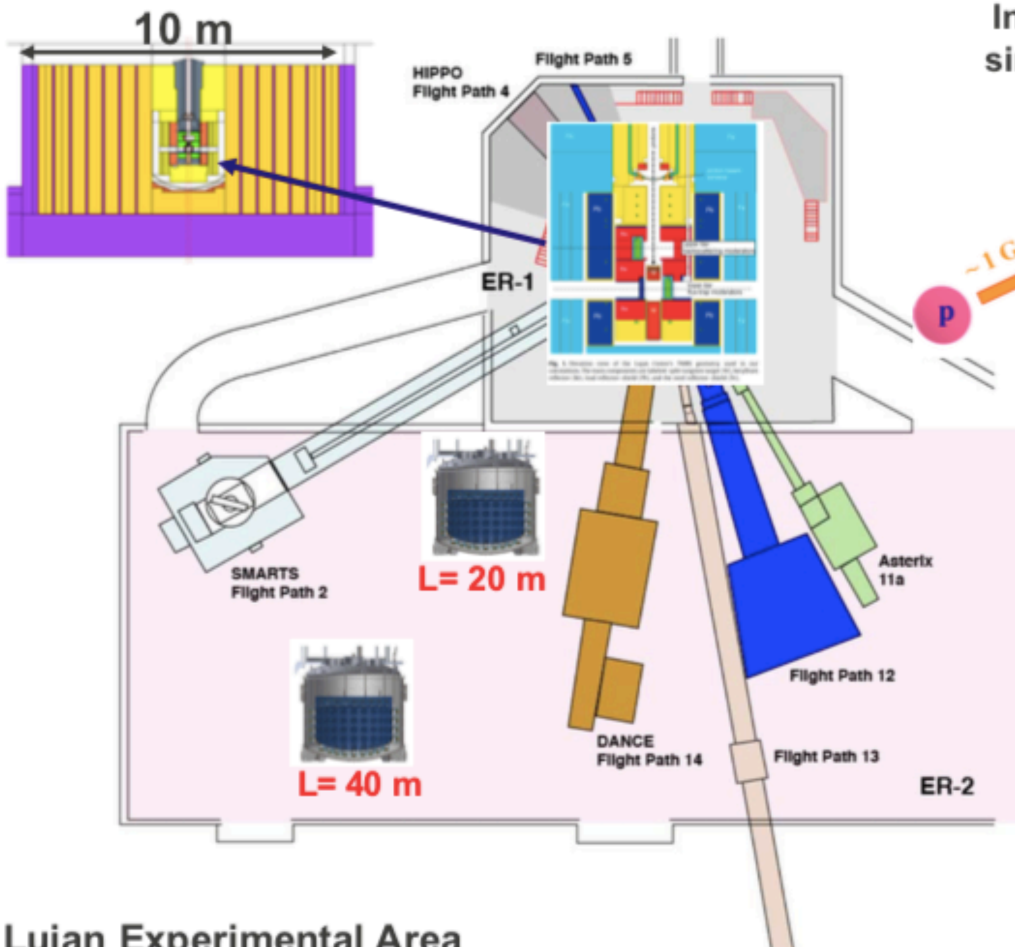




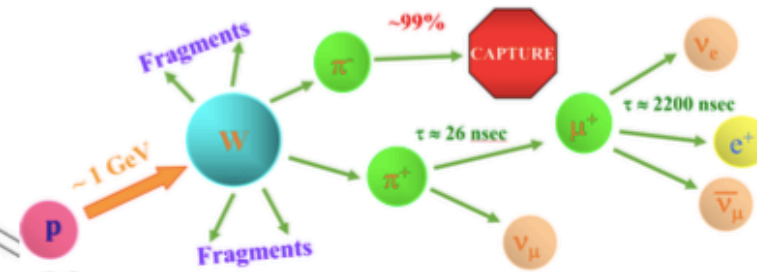
+D_2O for flux normalization

+ concepts for other targets...

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

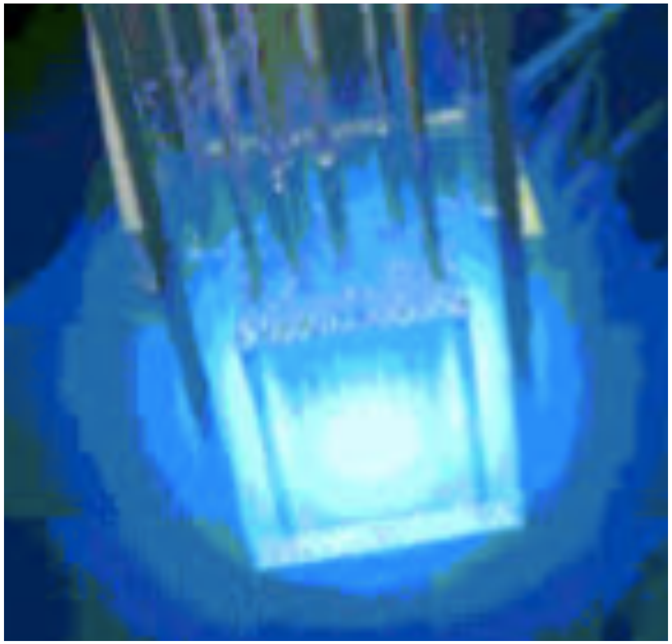


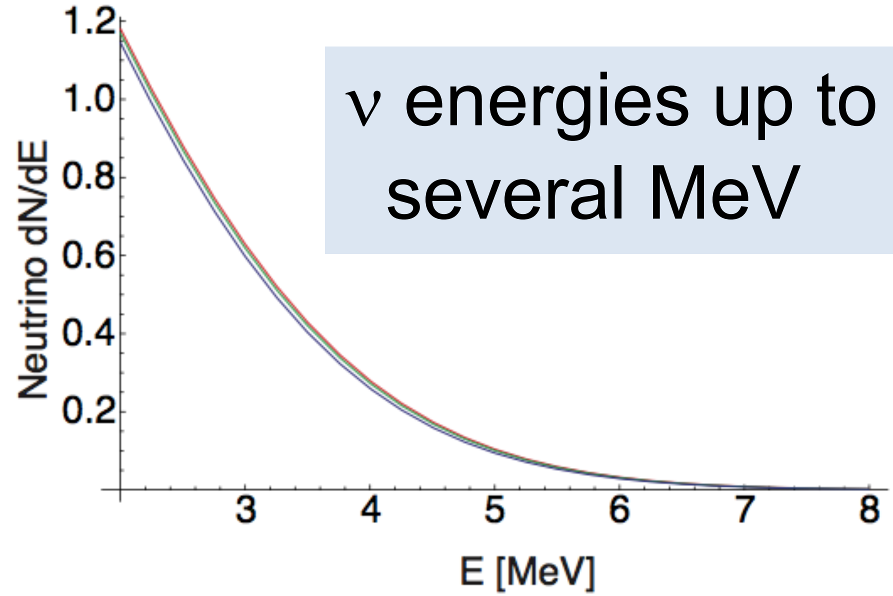
Lujan Experimental Area

- 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 & accelerator-produced DM

Neutrinos from nuclear reactors



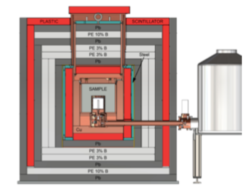
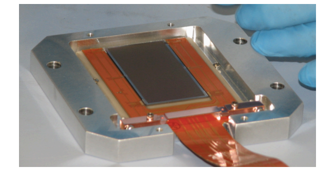


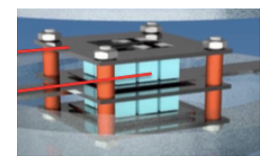
ν energies up to several MeV

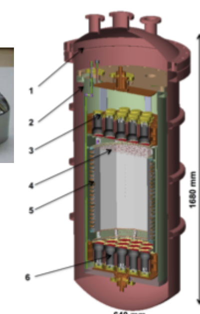
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

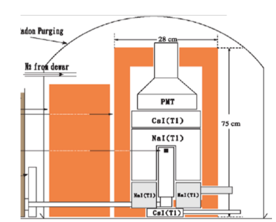
Reactor CEvNS Efforts Worldwide

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





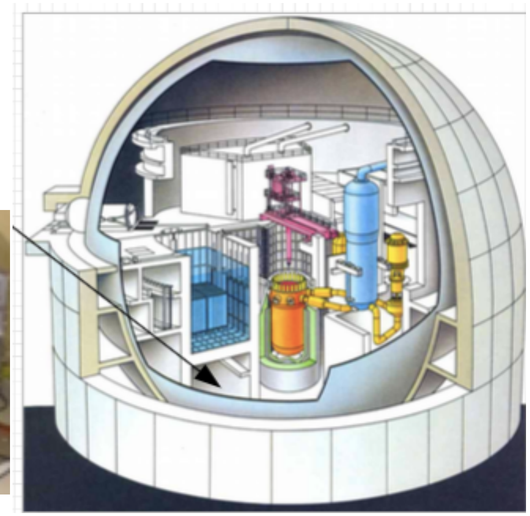


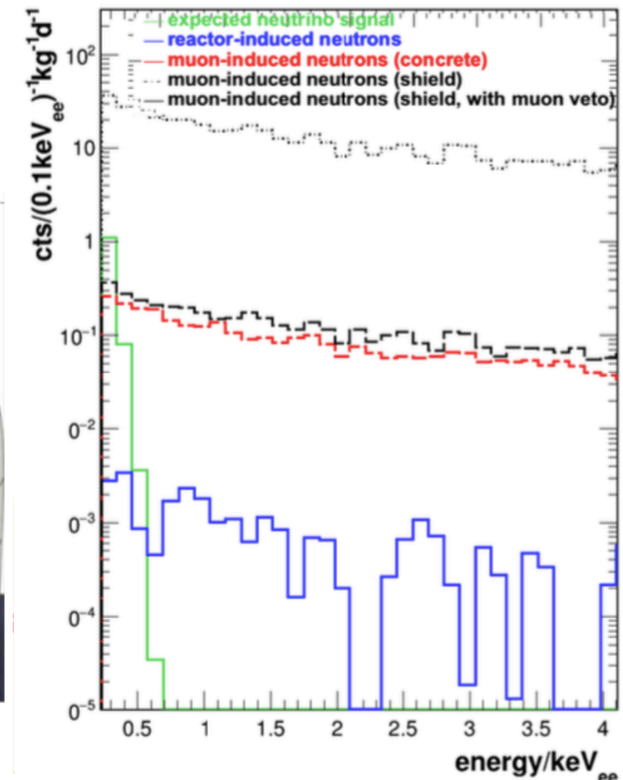
+ more...

many novel low-background, low-threshold technologies

CONUS

- Brokdorf 3.9 GW reactor
- 17 m from core
- 4 kg Ge PPC
- ~300 eV threshold





Eur. Phys. J. C (2019) 79: 699

Rate comparison (all detectors):

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	2.4 σ	2.3 σ

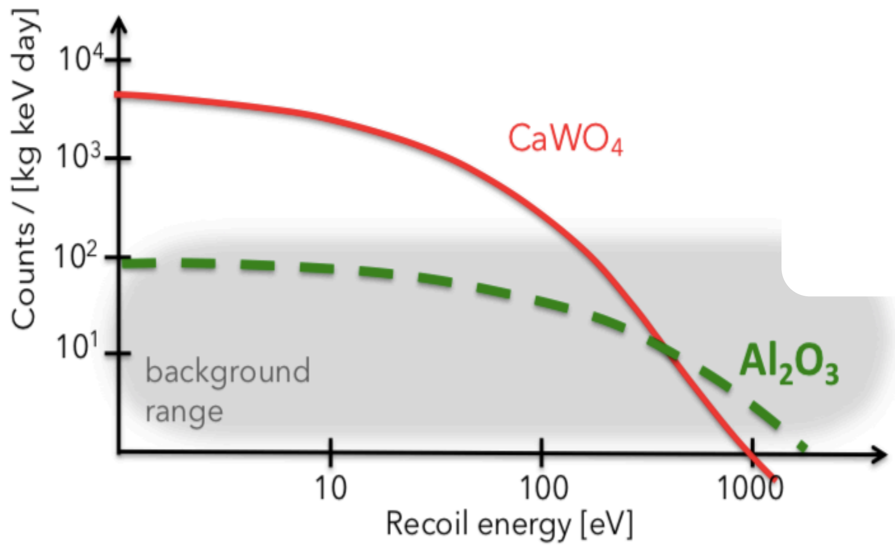
Some systematics still under study

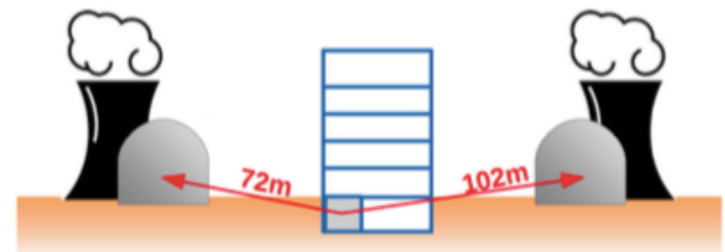
(*) Including stat. uncertainty and above efficiencies

W. Maneschg, Nu2018

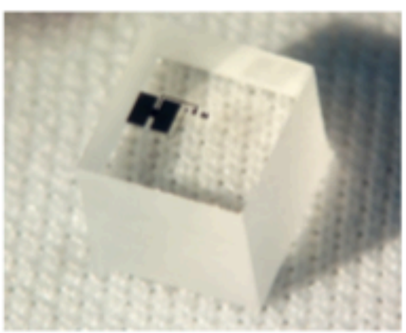
NUCLEUS

"gram-scale cryogenic calorimeters"





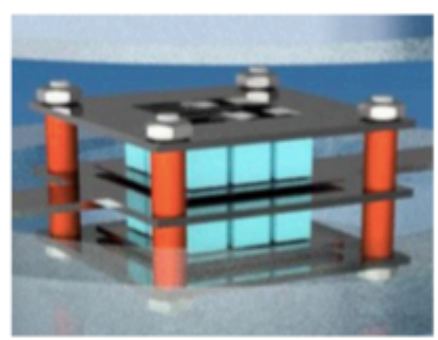
NUCLEUS 1g



2017-2019

straight forward

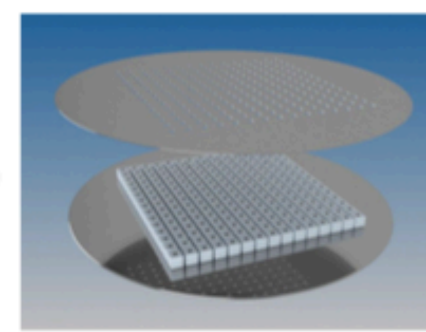
NUCLEUS 10g



2020-2022

major R&D

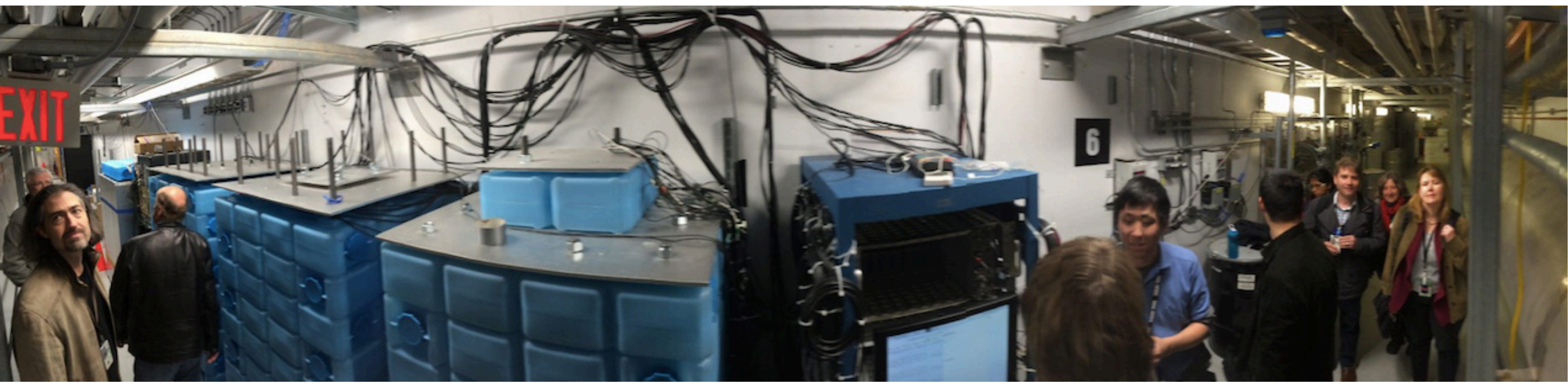
NUCLEUS 1kg



>2024

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...)

Extras/backups

Writing separate

$F_n^V(Q)$, $F_n^A(Q)$, $F_p^V(Q)$, $F_p^A(Q)$ form factors

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

$$G_V = g_V^p F_V^p(Q) Z + g_V^n F_V^n(Q) N$$

$$G_A = g_A^p F_A^p(Q)(Z_+ - Z_-) + g_A^n F_A^n(Q)(N_+ - N_-)$$

Currently, assuming these are **all the same**,
except for extra neutron skin for $F_n^V(Q)$

- axial contributions are smaller than experimental uctty now
- proton contributions also quite unimportant

Three form-factor functional forms studied in detail for COHERENT:

"Helm"

$$F(Q) = \frac{3}{QR_0}\left(\frac{\sin(QR_0)}{(QR_0)^2} - \frac{\cos(QR_0)}{QR_0}\right) e^{-Q^2 s^2/2}$$

$$R = 1.2A^{1/3} \quad s = 0.9$$

"Klein-Nystrand"

$$F(Q) = \frac{3(\sin(QR) - QR\cos(QR_n))}{(QR)^3(1 + a_k^2 Q^2)}$$

$$R = 1.2A^{1/3} \qquad a_k = 0.7$$

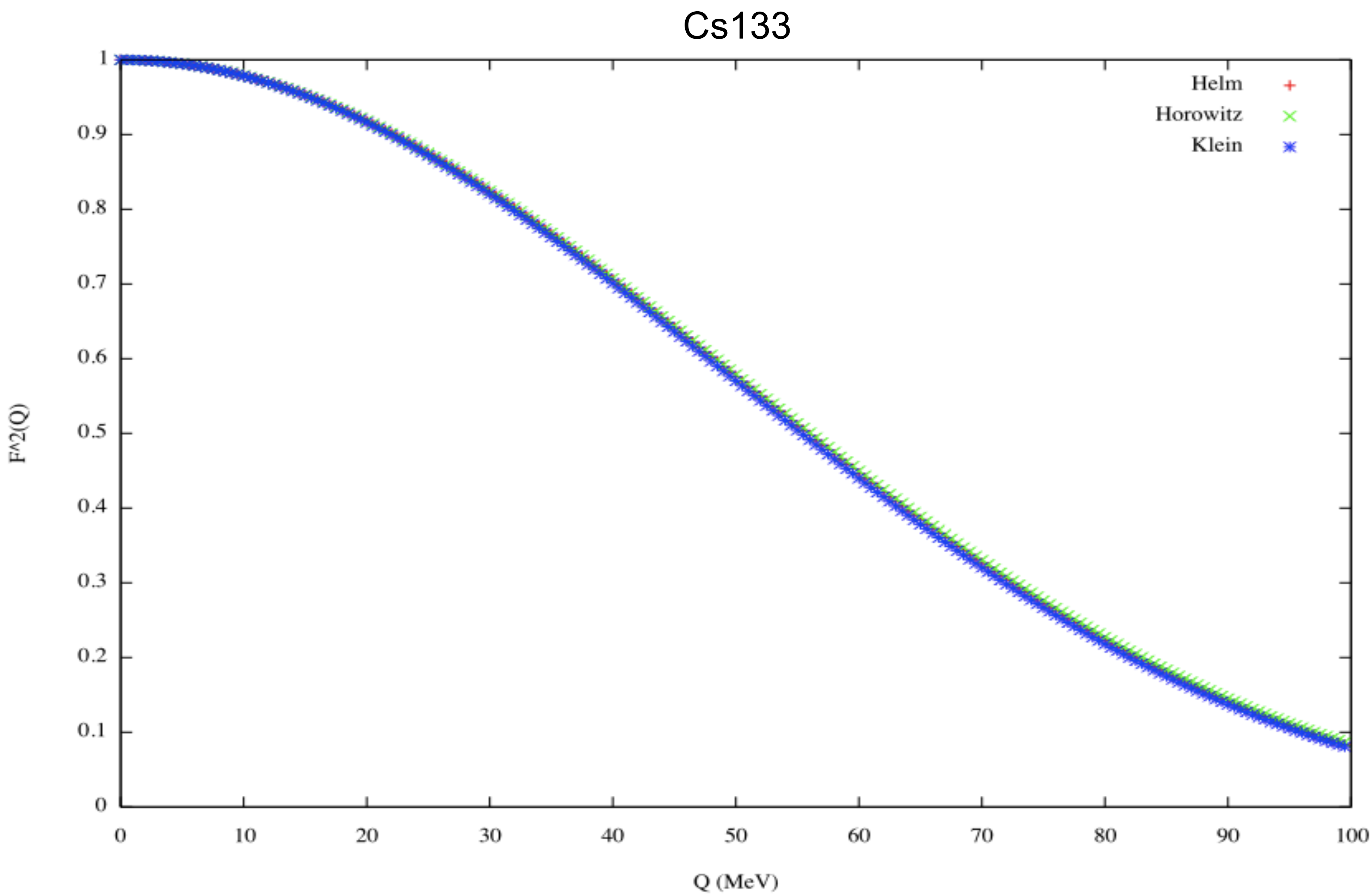
"Horowitz"

Numerical files from Chuck Horowitz, "based on relativistic mean field interaction FSUgold that does a good job reproducing the binding energy and charge radii of many nuclei"

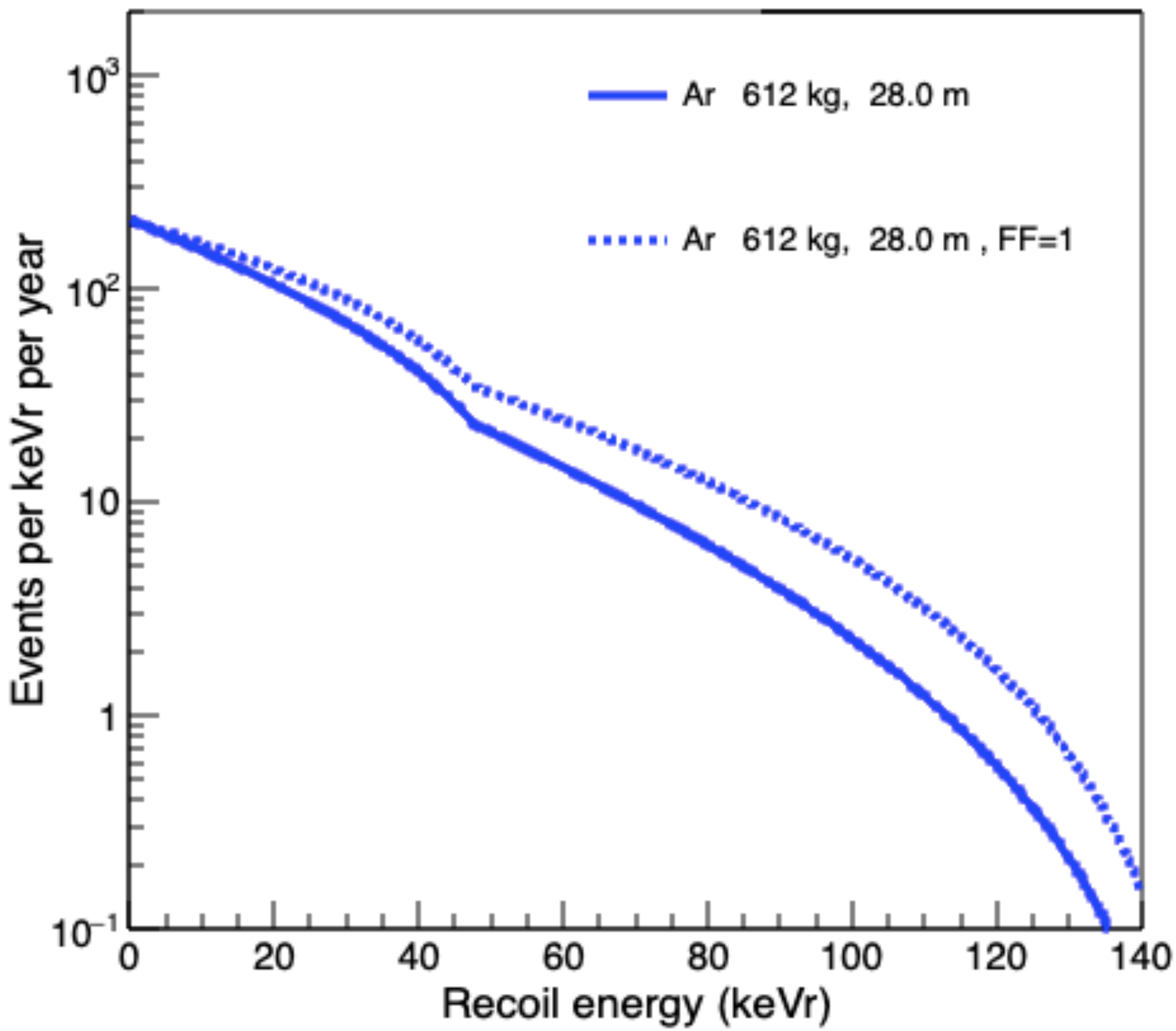
Neutron skin adjustment $R = 1.2A^{1/3} + 1.01\frac{A - 2Z}{A}$

also looked at: "solid sphere", Lewin-Smith;
did not look at "symmetrized Fermi function"

Different parameterizations give very similar shapes



Effect of the form factor on the recoil spectra



Approaching the form factor as

something to *measure* using CEvNS…

assume the SM is true, **learn about the nucleus**

(and astrophysics!)

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

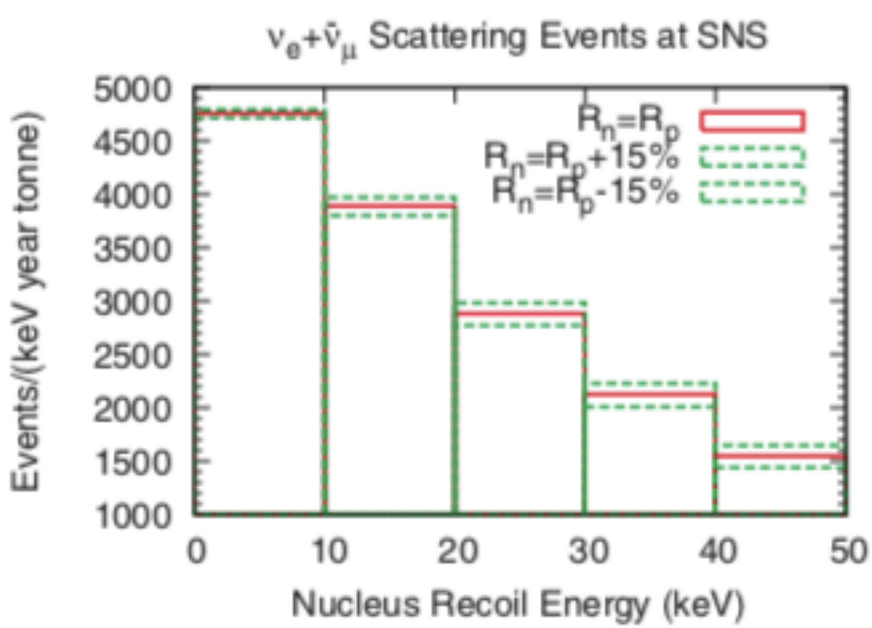
We point out that there is potential to study the nuclear neutron form factor through neutrino nucleus coherent elastic scattering. We determine numbers of events for various scenarios in a liquid noble nuclear recoil detector at a stopped pion neutrino source

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.



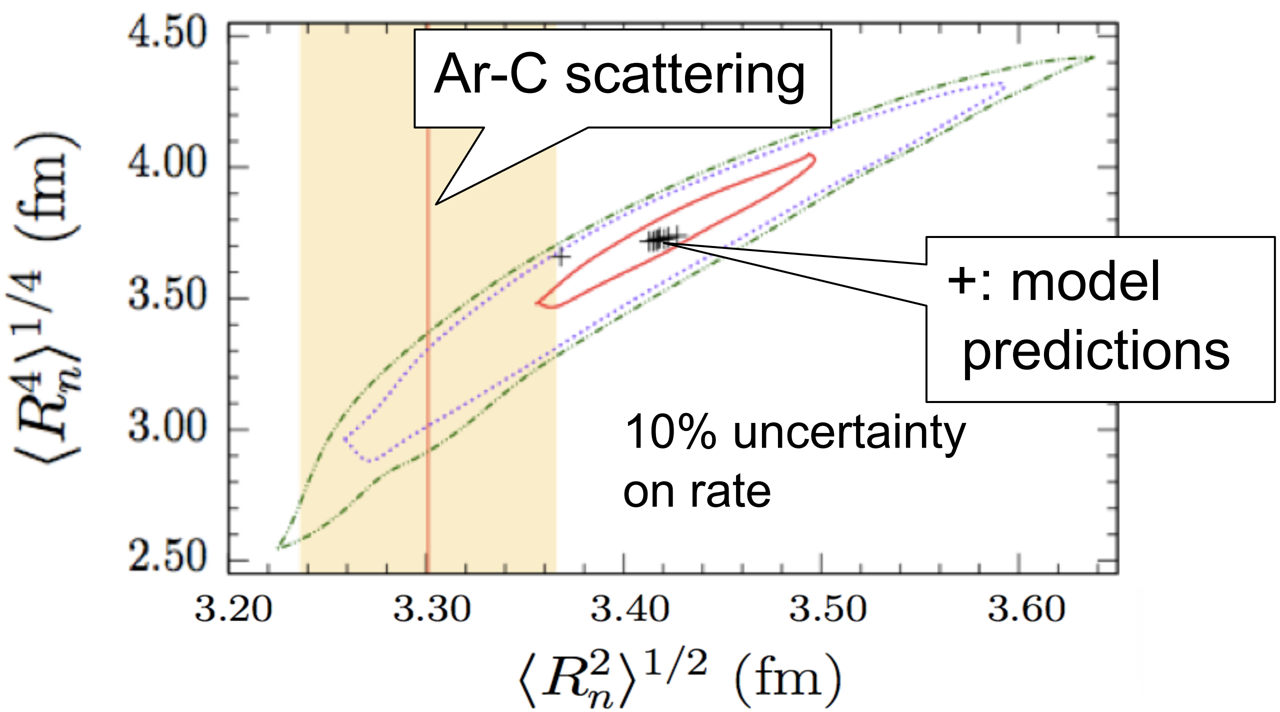
Observable is **recoil spectrum shape**

Approach: expand in moments of the neutron radius

$$F_n(Q^2) \approx \int \rho_n(r)\left(1 - \frac{Q^2}{3!}r^2 + \frac{Q^4}{5!}r^4 - \frac{Q^6}{7!}r^6 + \cdots\right) r^2 dr$$
$$\approx N\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - \frac{Q^6}{7!}\langle R_n^6\rangle + \cdots\right) (6)$$

$$\langle R_n^k \rangle = \frac{\int \rho_n r^k d^3 r}{\int \rho_n d^3 r}$$

Example: tonne-scale experiment at πDAR source

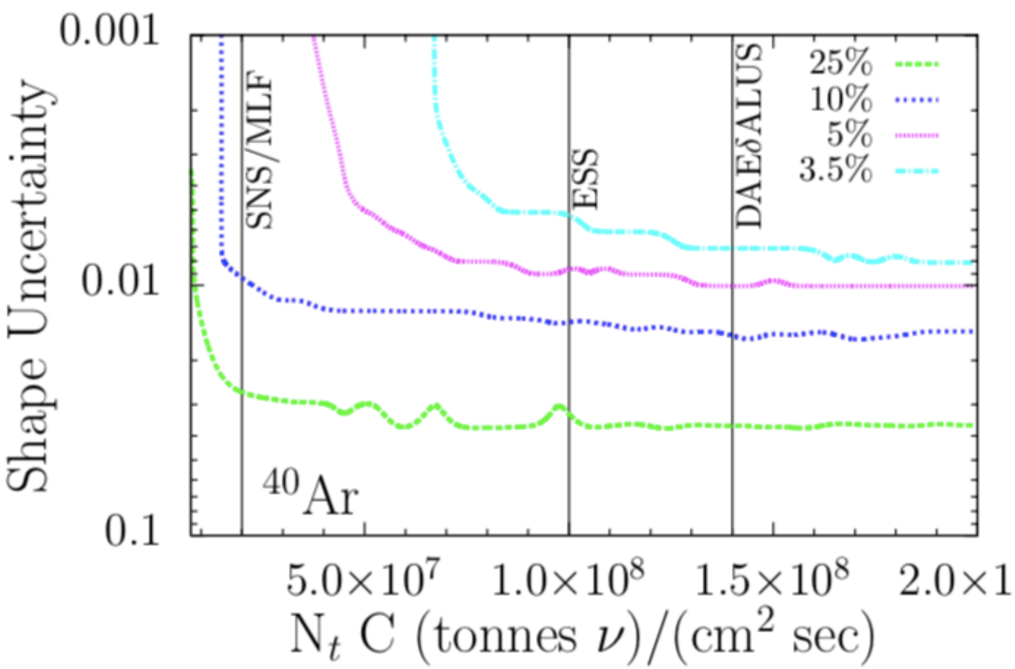


K. Patton et al., PRC86 (2012) 024612

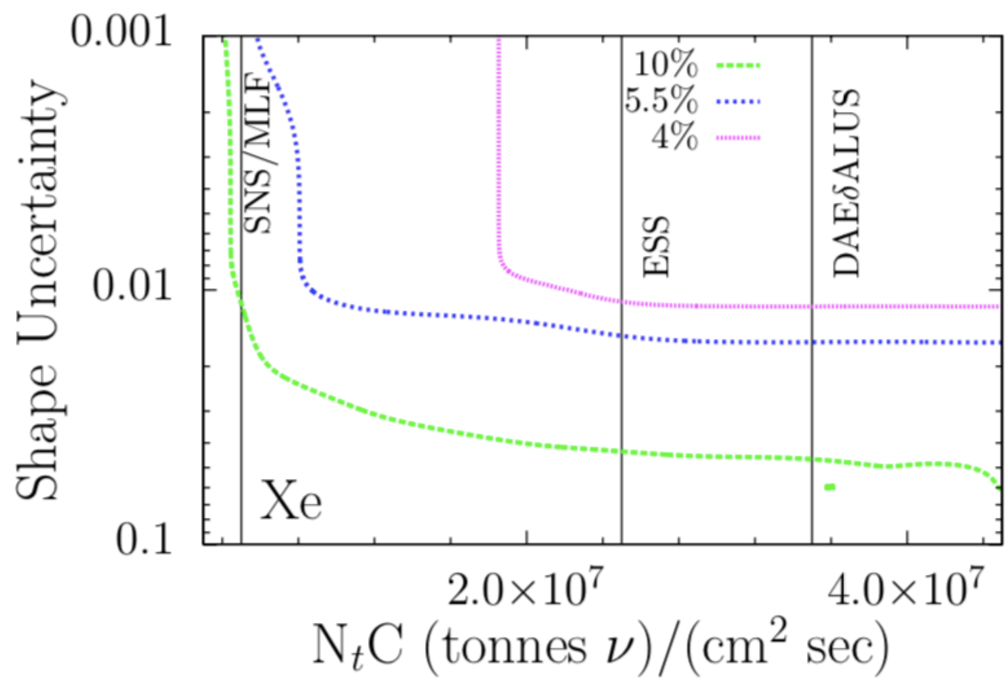
More studies with this approach

KELLY M PATTON et al.

Int J Mod Phys E, 2013 vol. 22 (06)
p. 1330013



uncertainty in $\langle R_n^2 \rangle^{1/2}$ at the 90% confidence level



uncertainty in $\langle R_n^4 \rangle_{\mathrm{eff}}^{1/4}$ at the 90% confidence level

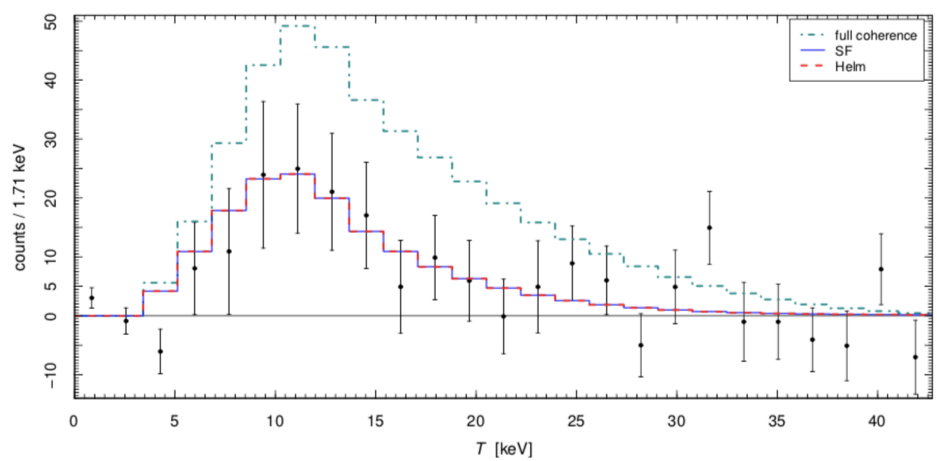
Lines: 2 tonnes @ 20 m

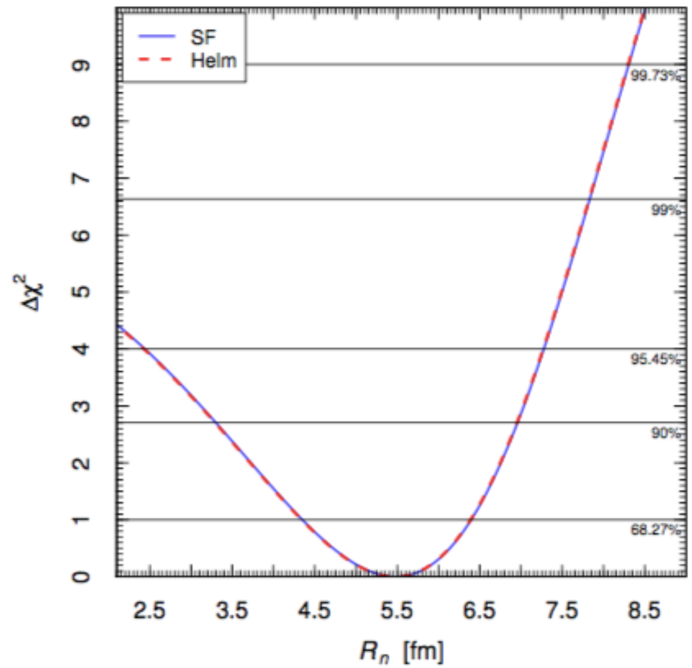
4th moment

Uses uncertainties uncorrelated bin by bin,
which is probably too conservative

First fit to the COHERENT CsI data

M. Cadeddu, C. Giunti, Y. F. Li, and Y. Y. Zhang. "Average CsI neutron density distribution from COHERENT data." (2017). 1710.02730.





Helm functional form

$$F_N^{\mathrm{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2},$$

$$\boxed{R_n = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}. \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \mathrm{fm}.}$$

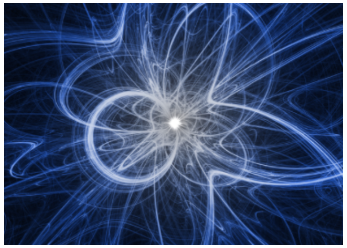
- Fit to neutron radius resulting in ~18% uncertainty, as well as neutron skin measurement
- Does not handle bin-by-bin correlation of systematics (e.g., from QF)

COHERENT will have better measurement soon, + handling of shape systematics w/ correlations

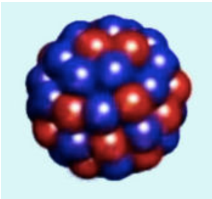
CEvNS: what's it good for?

! (not a complete list!)

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

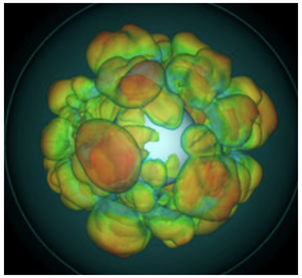


CEvNS as a **signal**
for understanding of "old" physics

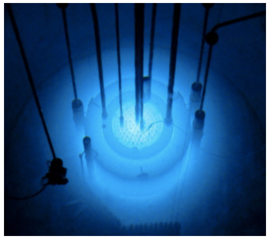


CEvNS as a **background**
for signatures of new physics (DM)

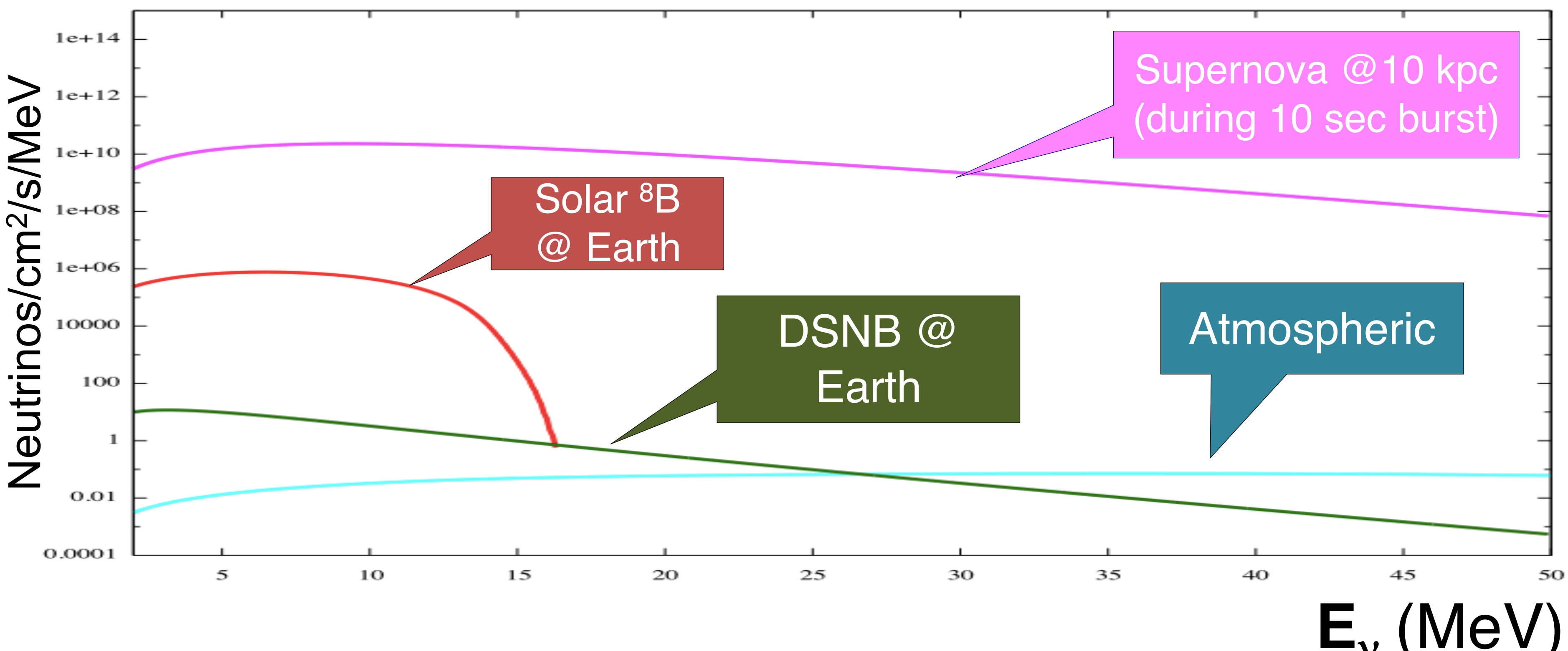
CEvNS as a **signal** for *astrophysics*



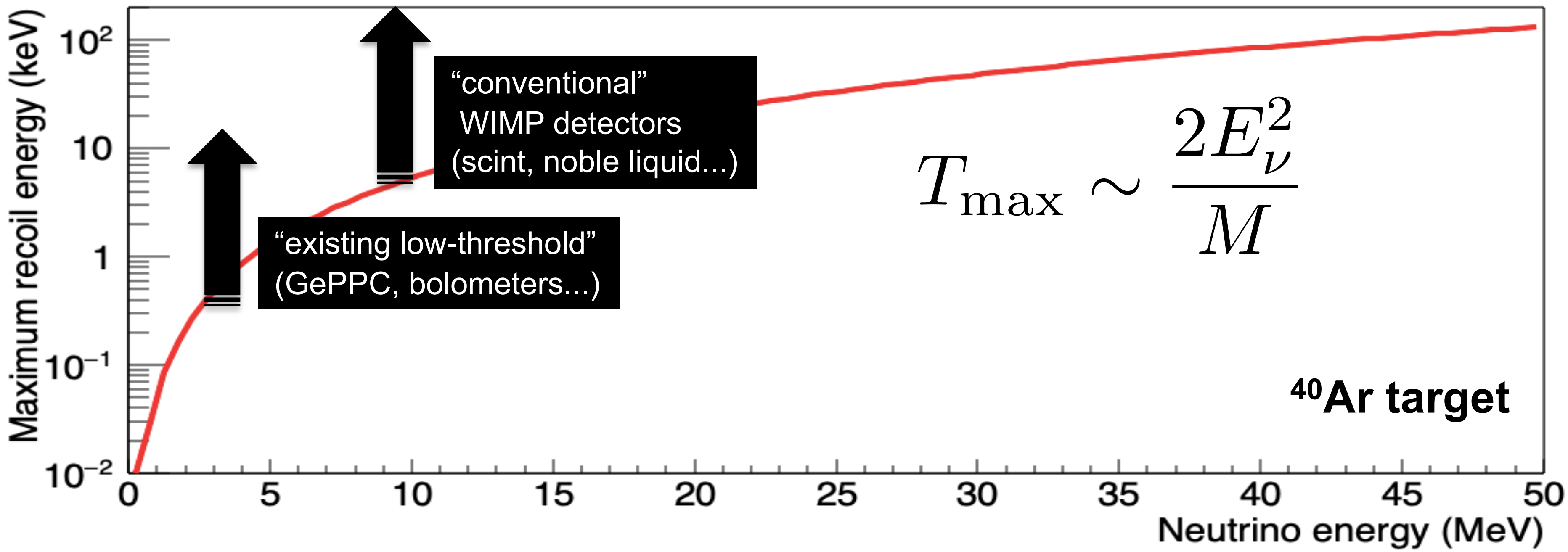
CEvNS as a **practical tool**

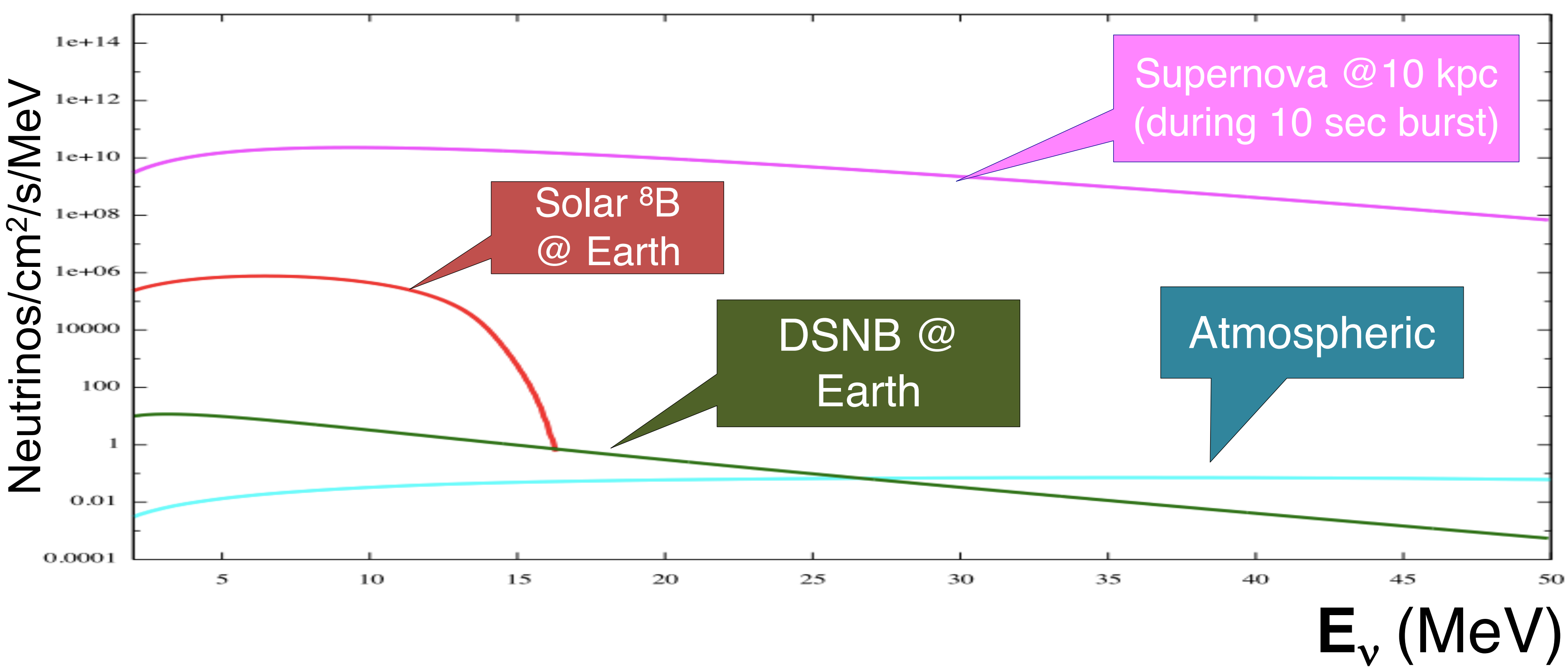


Natural neutrino fluxes



Natural neutrino fluxes

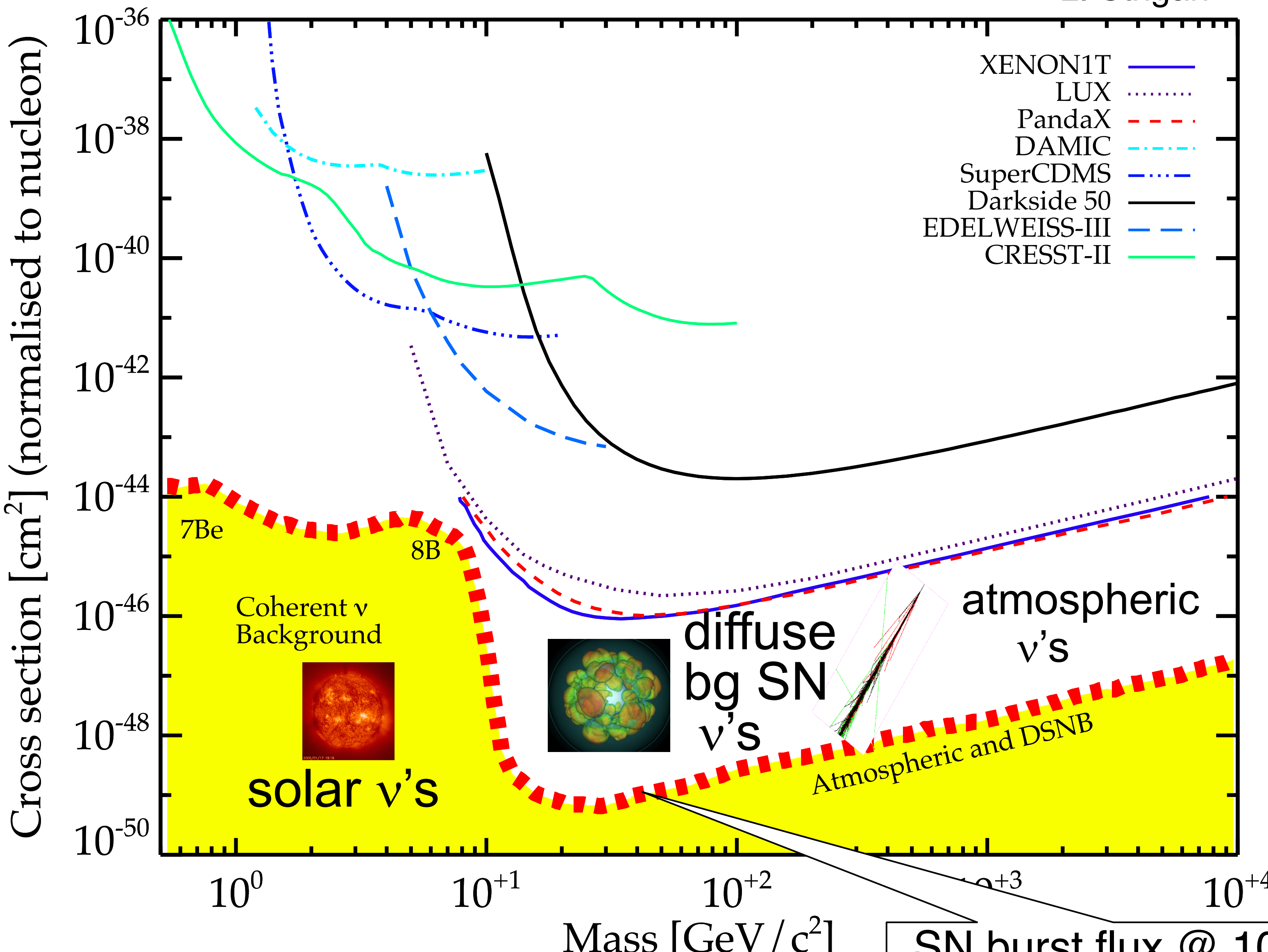




The so-called “**neutrino floor**” for DM experiments

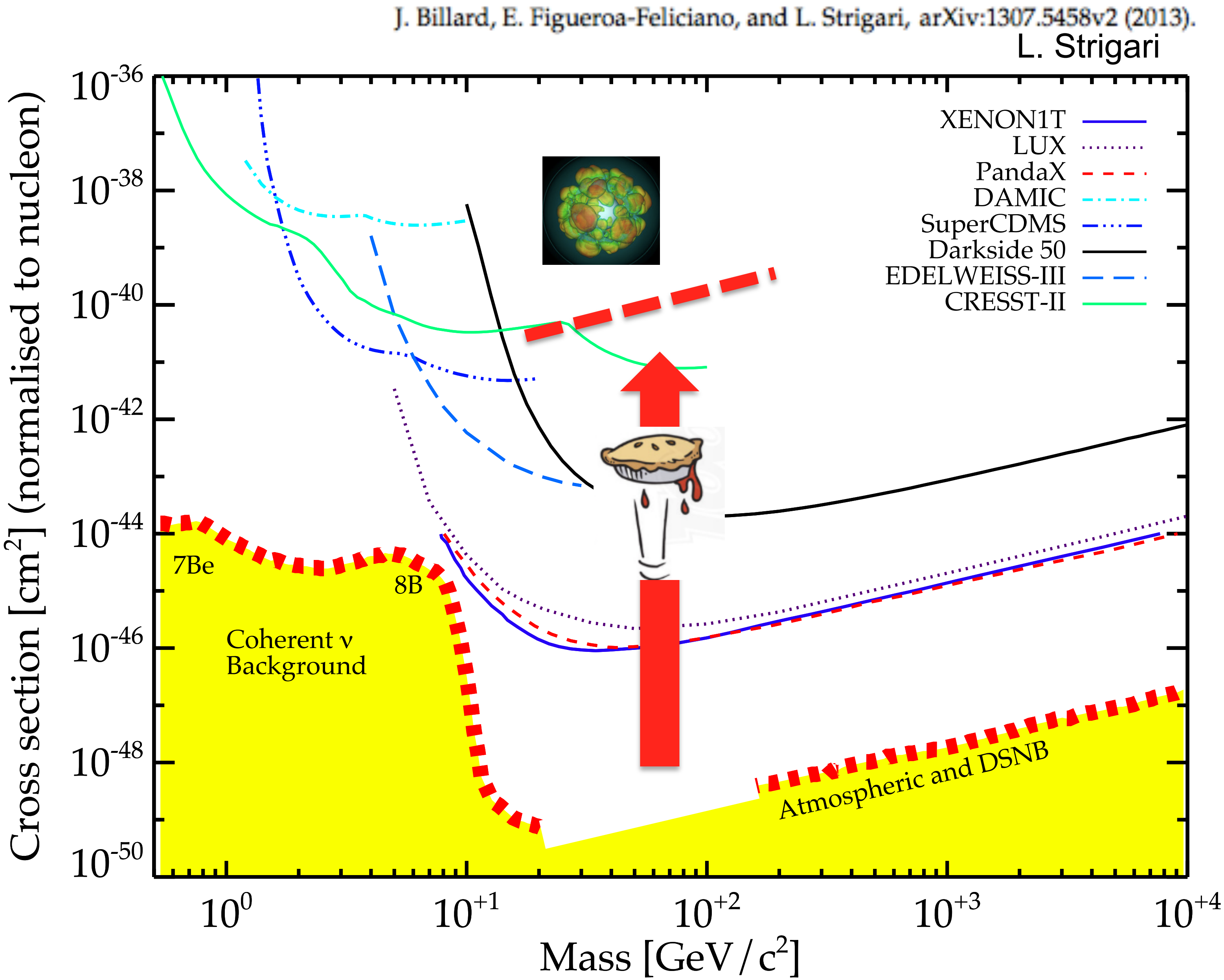
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

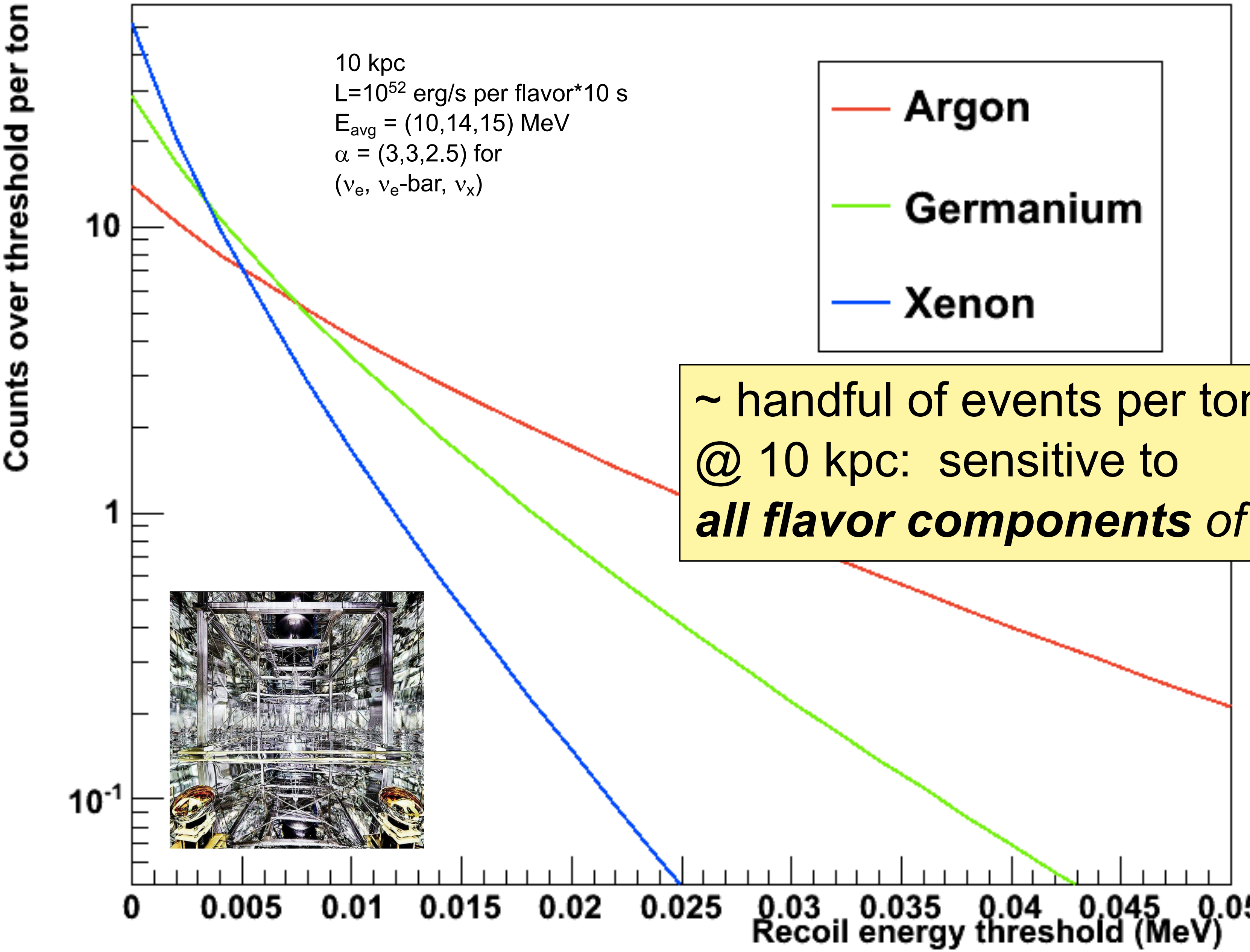


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

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



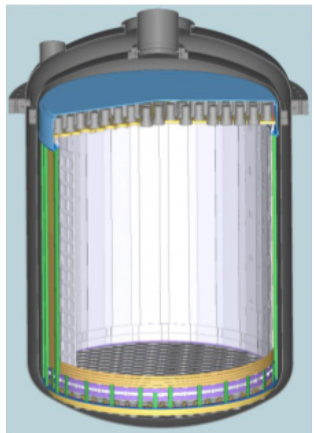
Supernova neutrinos in tonne-scale DM detectors

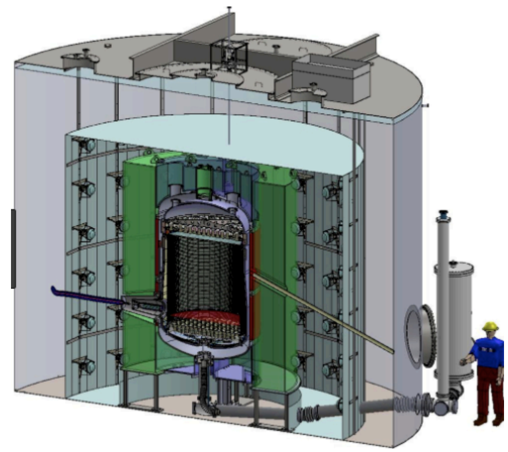


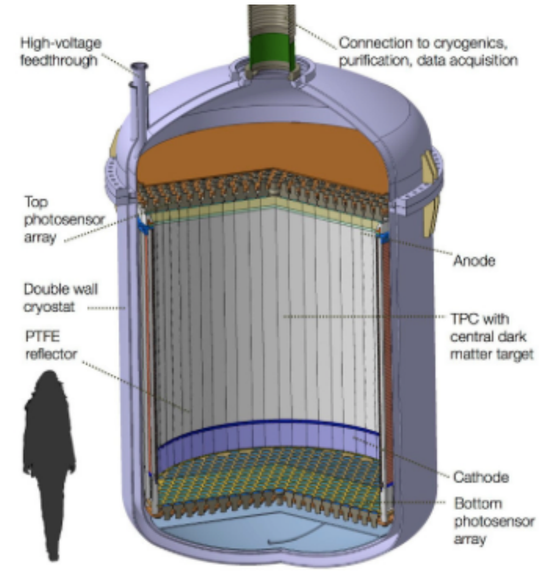
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

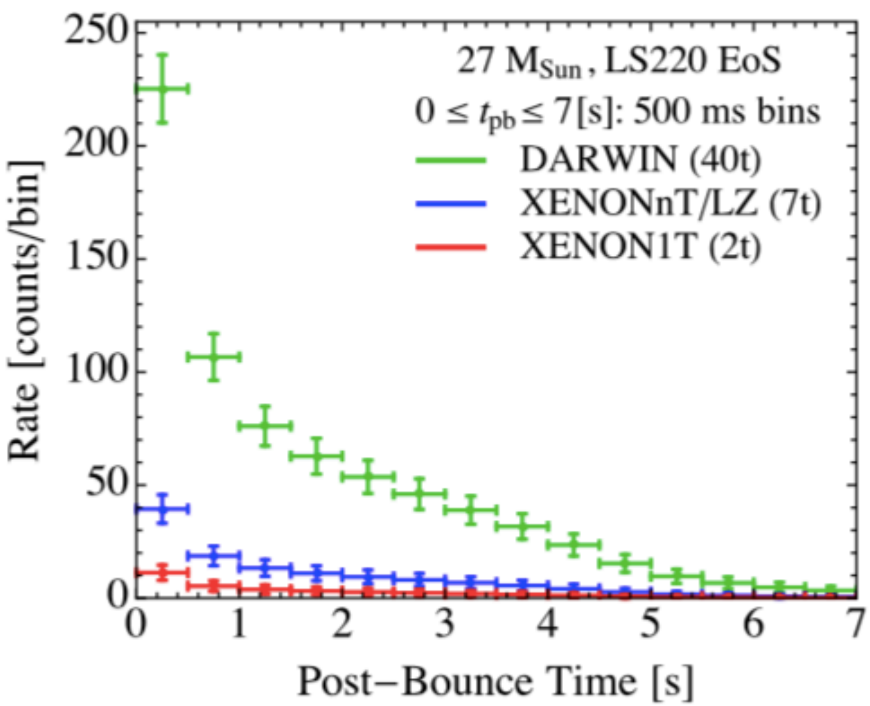
Detector example: **XENON/LZ/DARWIN**

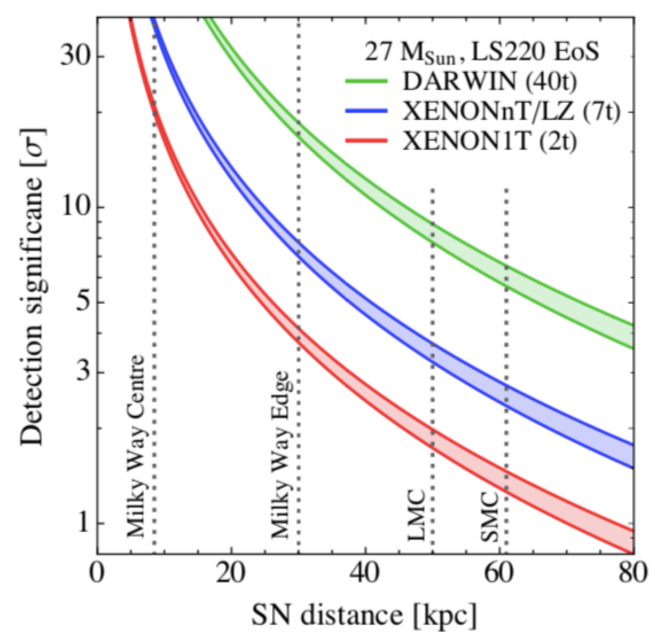
- dual-phase xenon time projection chambers







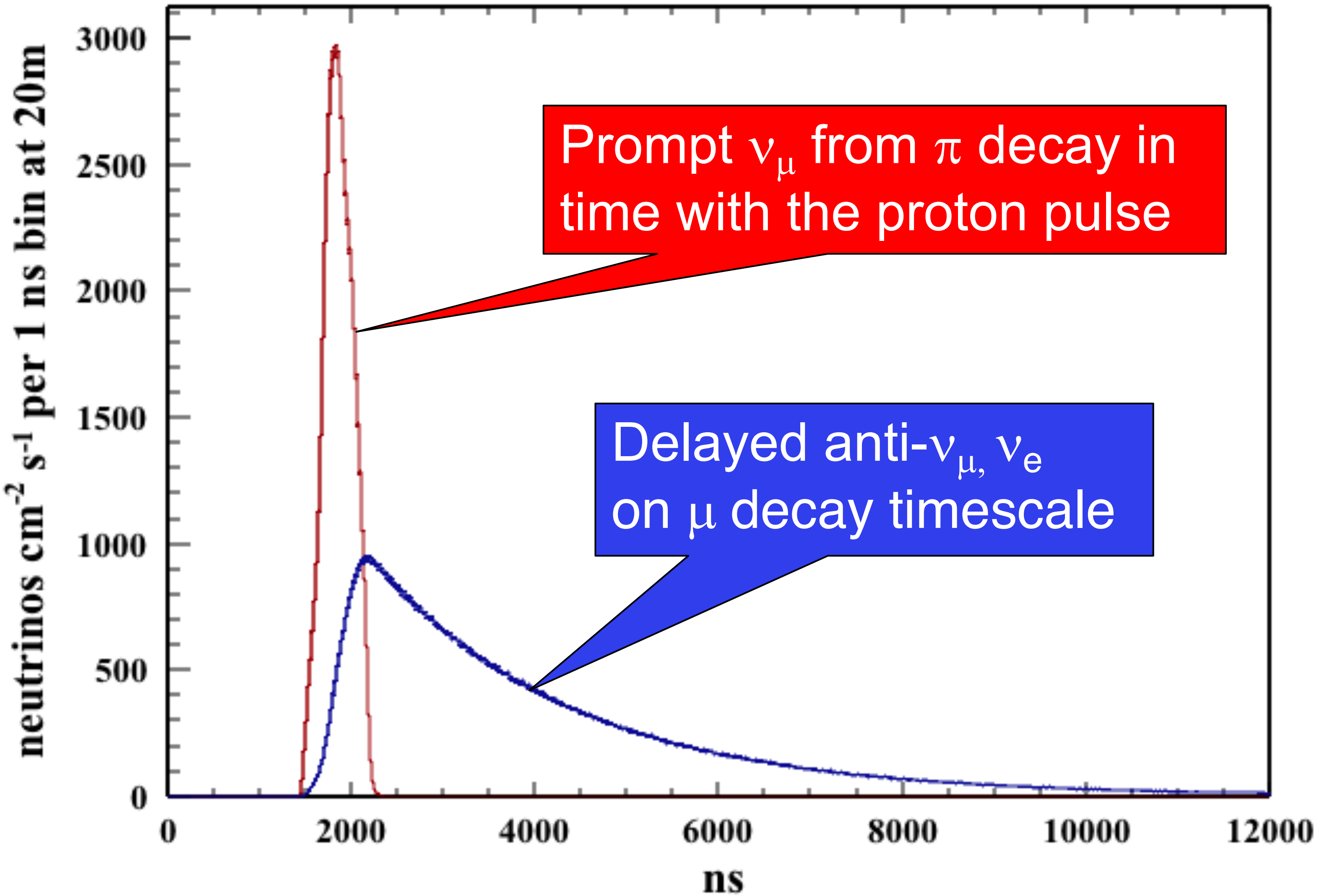




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Time structure of the SNS source

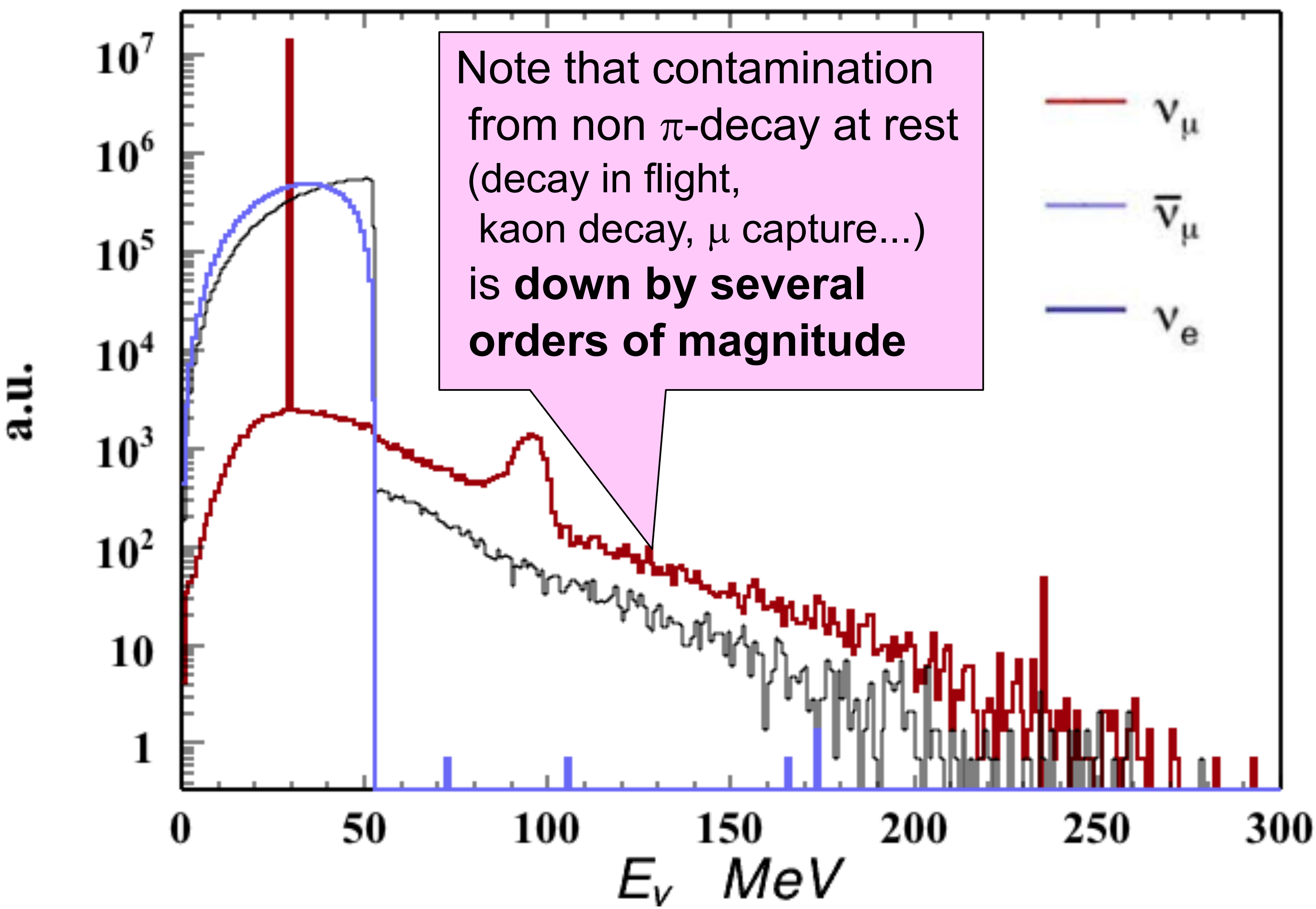
60 Hz *pulsed* source



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

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

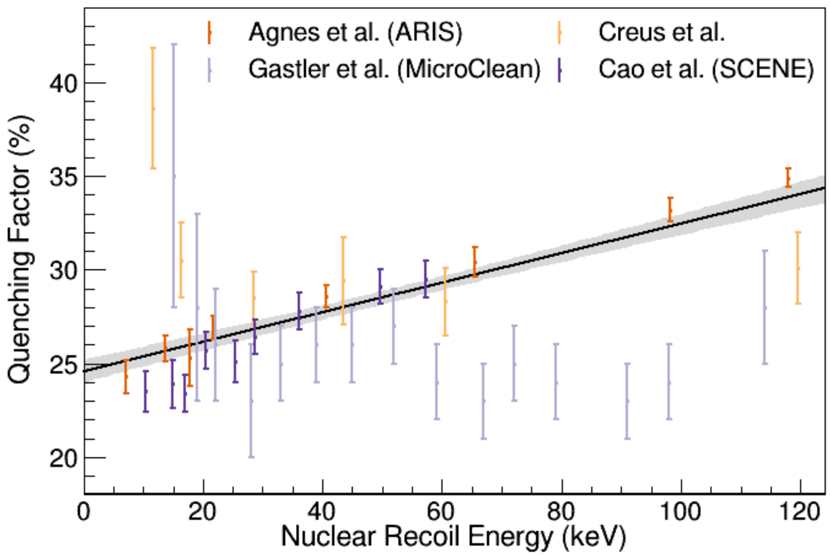
0.08 neutrinos per flavor per proton on target

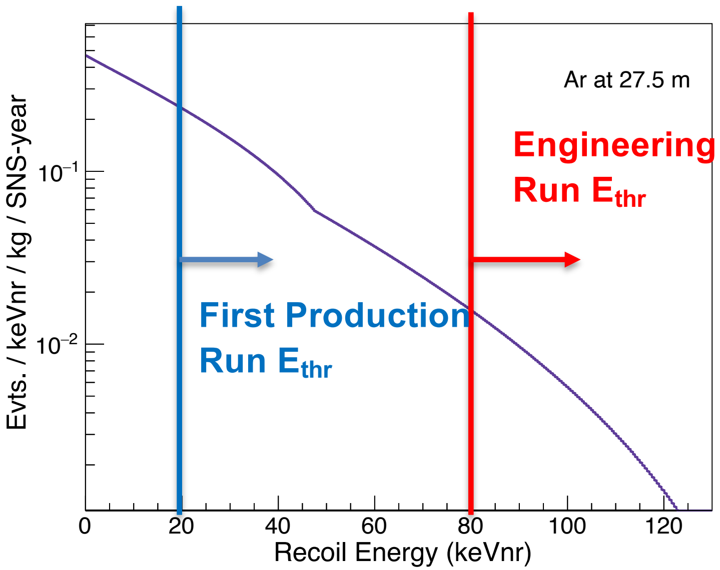


SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

LAr Quenching Factor

- Measurement of ratio of measured energy deposited from a nuclear recoil to measured energy deposited by an electron recoil at known energy
- Multiple measurements of LAr quenching factor in CEvNS region of interest
- Linear model fit to literature data over recoil energy range of 0-125 keVnr
  - 2% average relative uncertainty on quenching factor value in region of interest (ROI) from 0-125 keVnr
- Provides conversion from keVnr (nr = ‘nuclear recoil’) to keVee (ee = ‘electron equivalent’)





CENNS-10 Calibration

- Calibrate detector with variety of gamma sources
  - Measured light yield: 4.6 ± 0.4 photoelectrons/keVee
  - At ^{83m}Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source