# Coherent Elastic Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

Kate Scholberg, Duke University,

Erice International School of Nuclear Physics, 41st Course

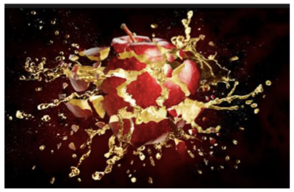
September 23, 2019

# 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

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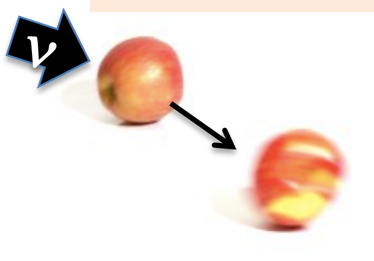
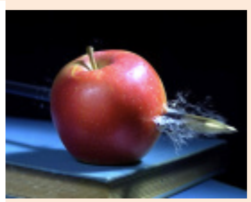
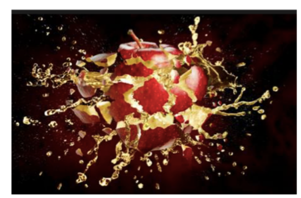


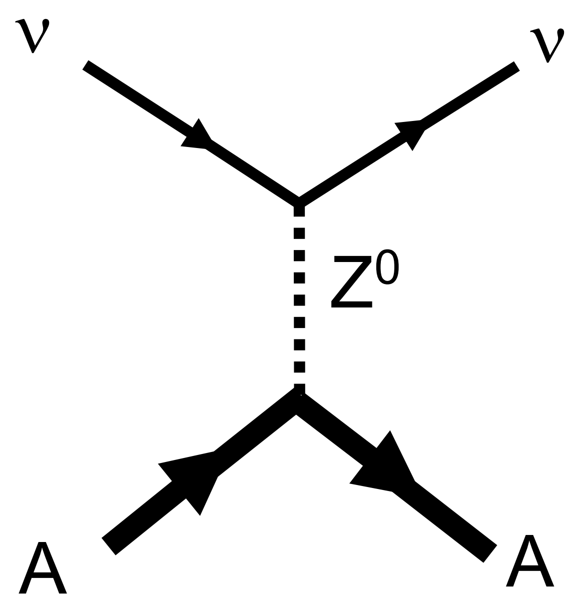





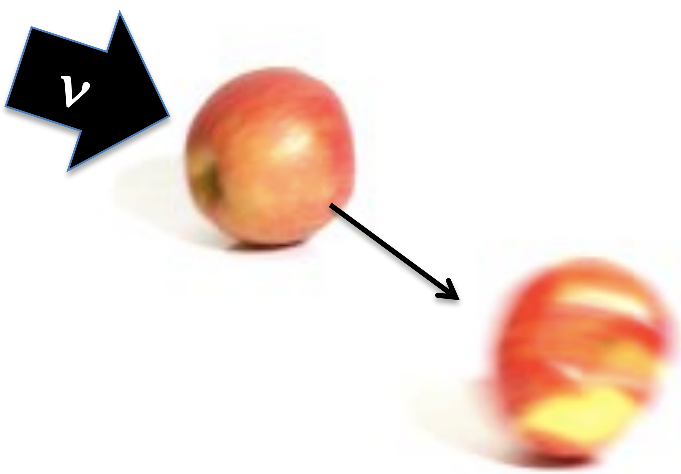
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

# Coherent elastic neutrino-nucleus scattering (CEvNS)

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




A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



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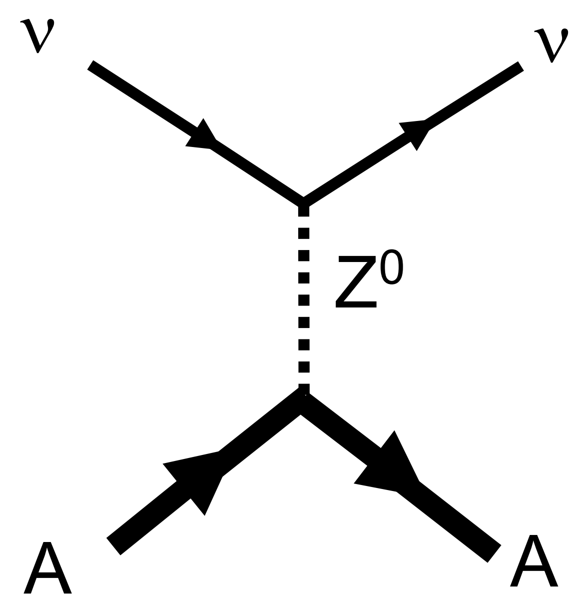


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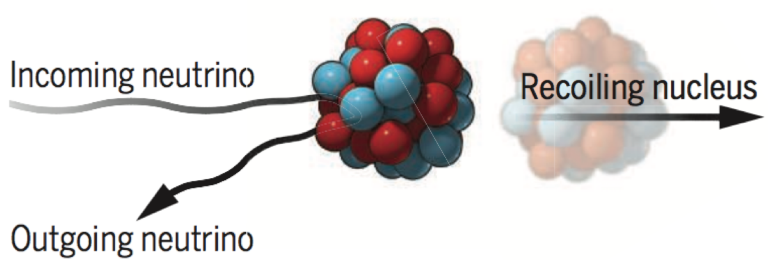


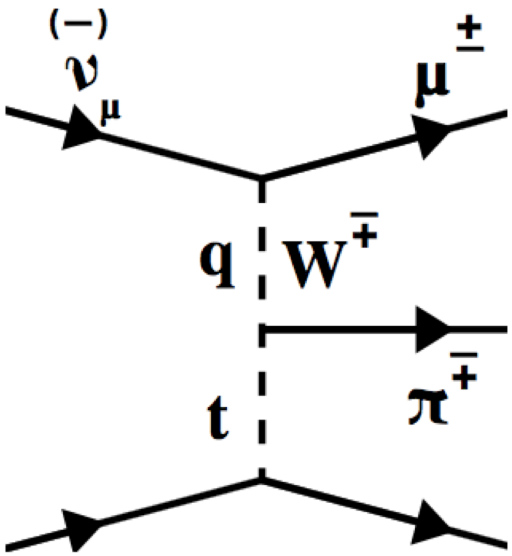

Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

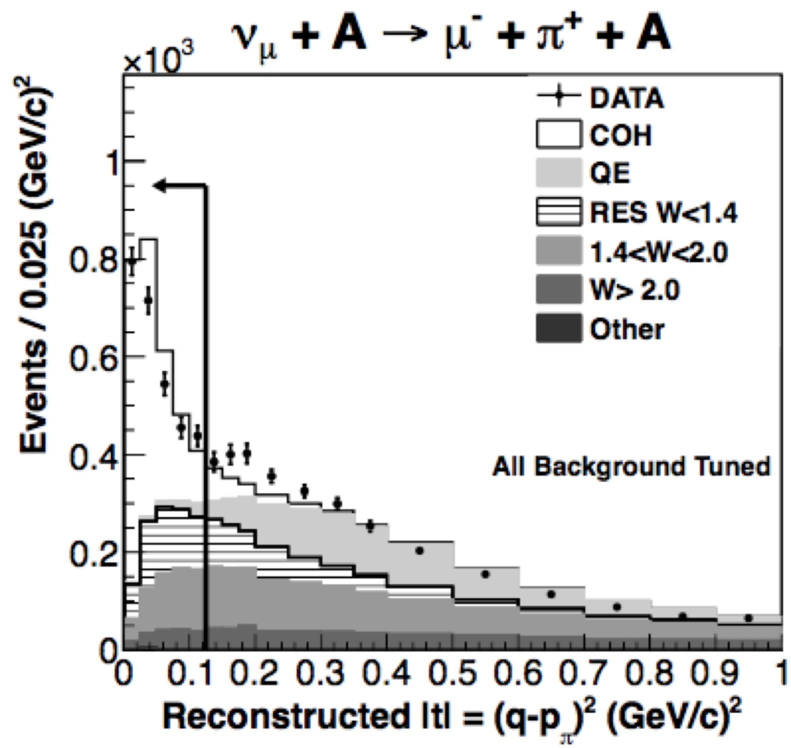
A: no. of constituents

Image: J. Link *Science* Perspectives

# This is ***not*** coherent pion production ***(inelastic)***








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

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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
- CE$\nu$NS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced "sevens"...

spread the meme!

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# First proposed >4 decades 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)

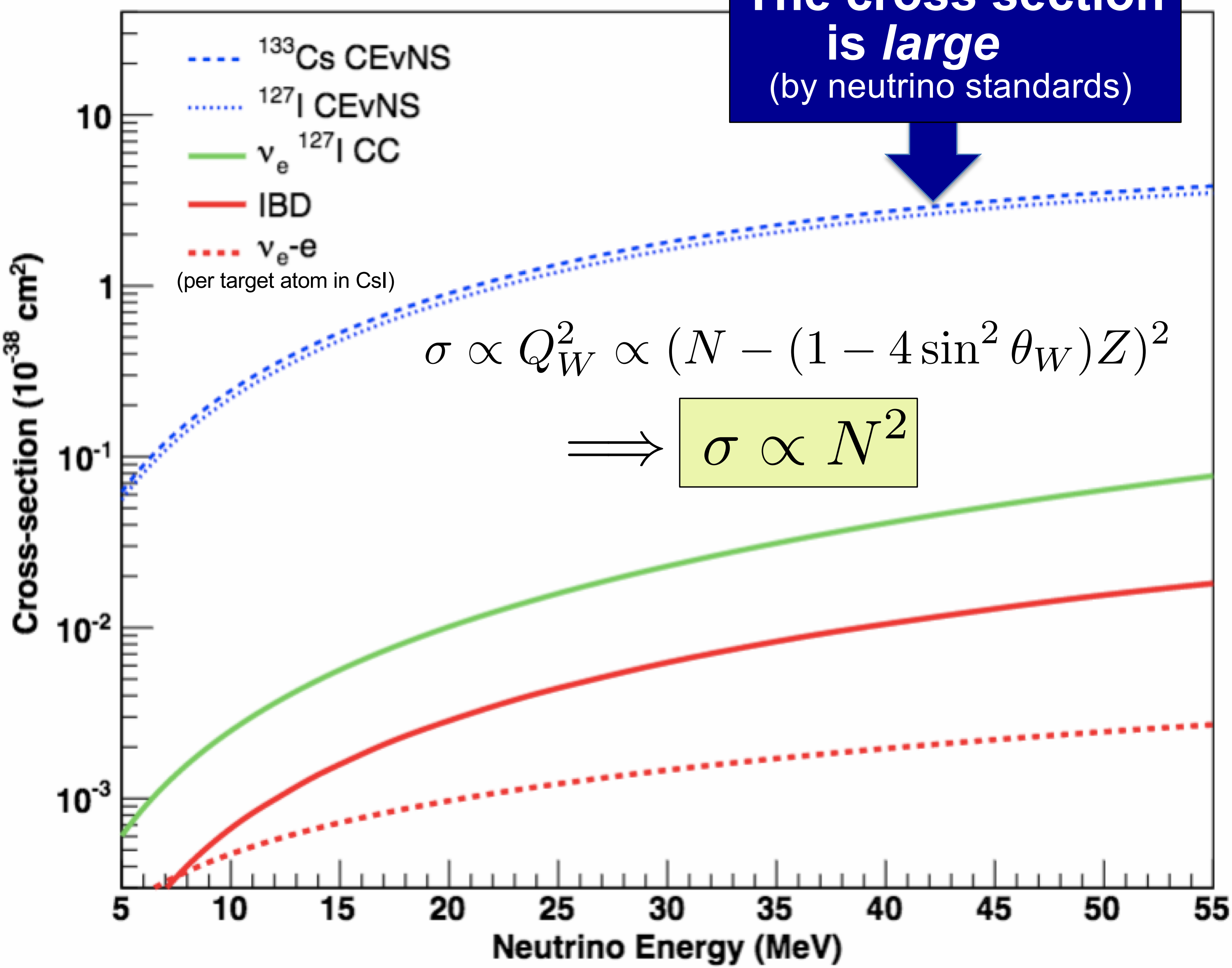
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical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

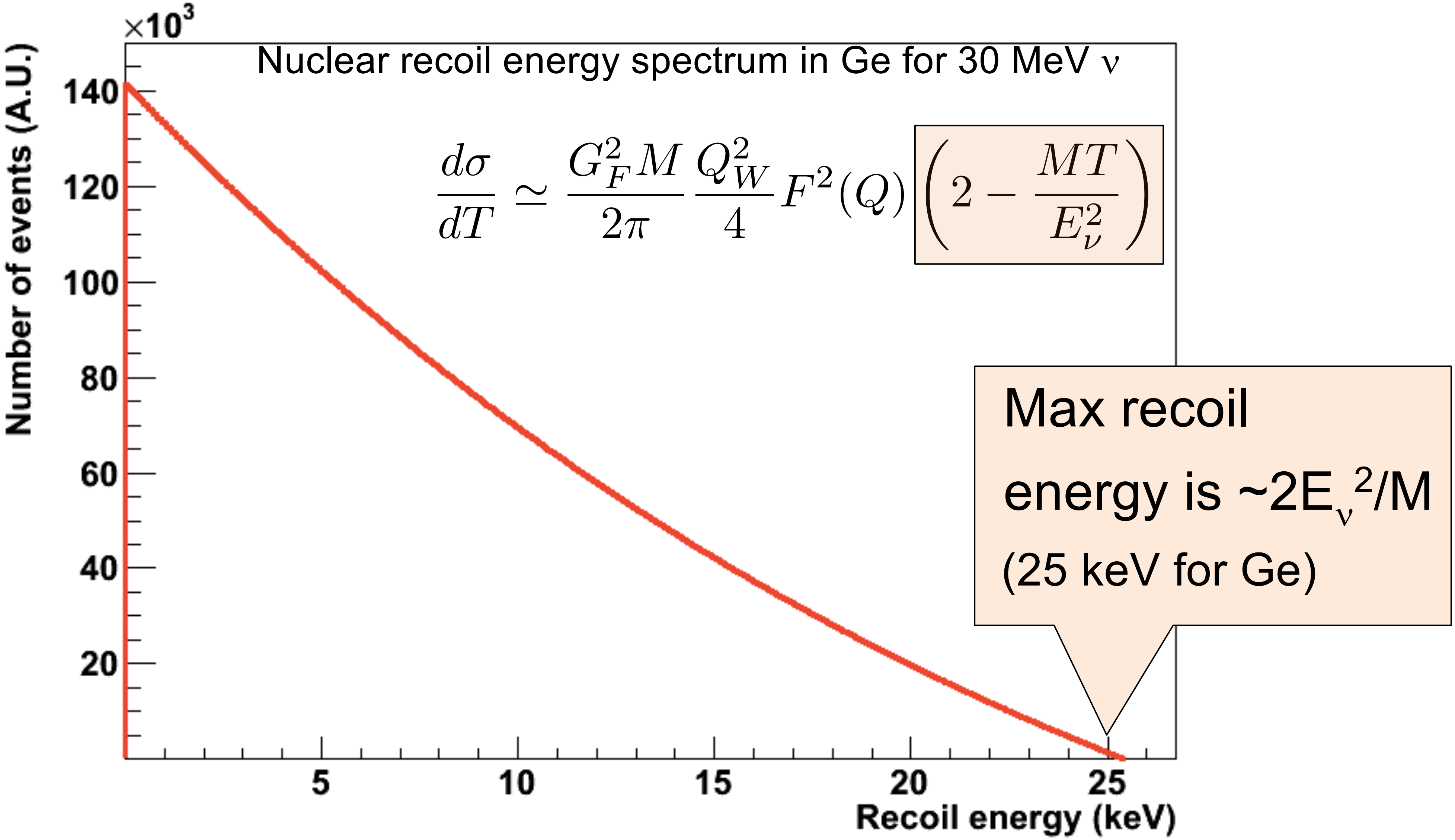
**The cross section is *large***
(by neutrino standards)

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

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



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

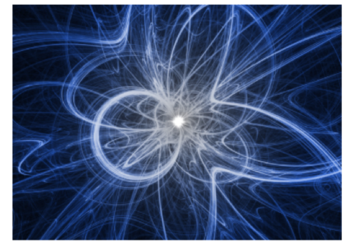


## CEvNS: what's it good for?

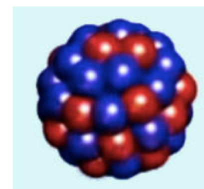
① So ② Many ③ Things !

(not a complete list!)

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

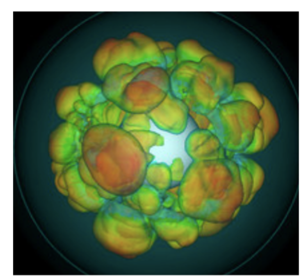


CEvNS as a **signal**
for understanding of "old" physics

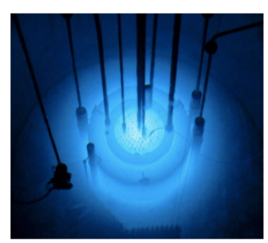


CEvNS as a **background**
for signatures of new physics


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



CEvNS as a **practical tool**



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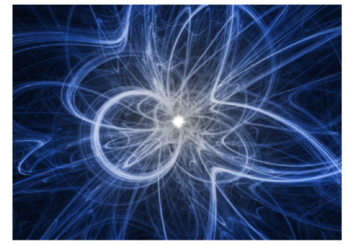

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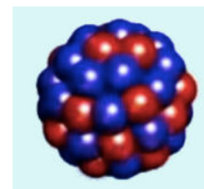

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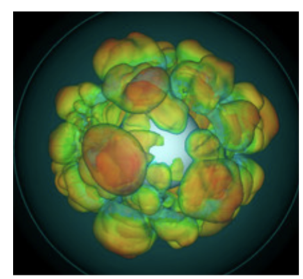

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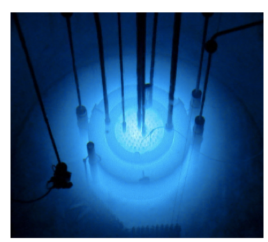

# The cross section is cleanly predicted in the Standard Model

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

$E_\nu$: 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

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

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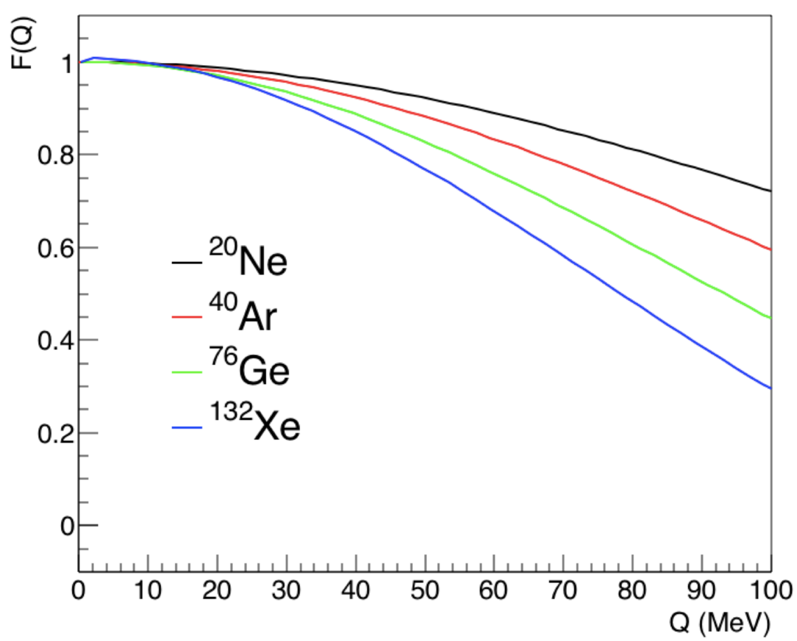
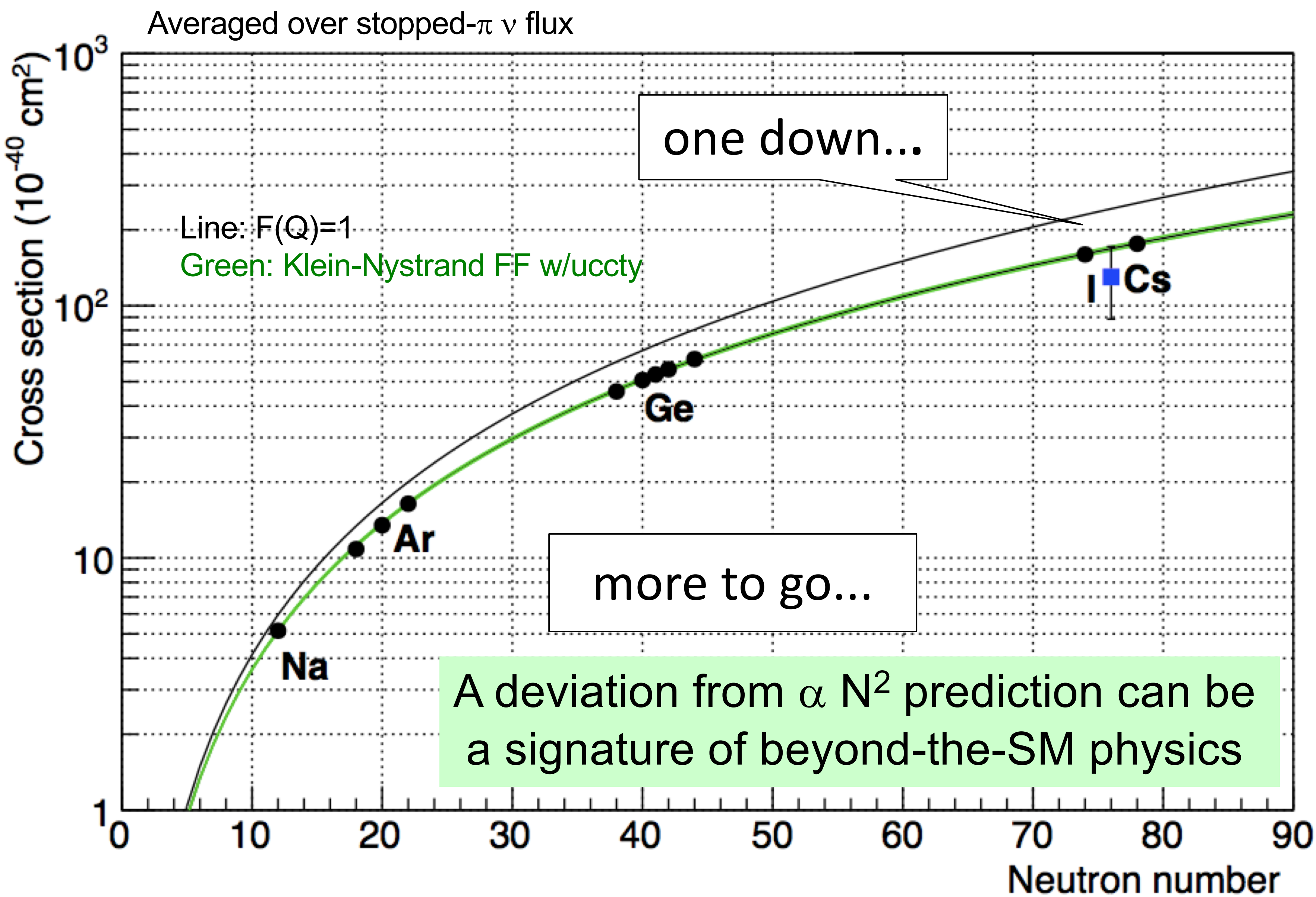
$E_\nu$: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

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




form factor suppresses cross section at large Q

# Need to measure $N^2$ dependence of the CEvNS xscn

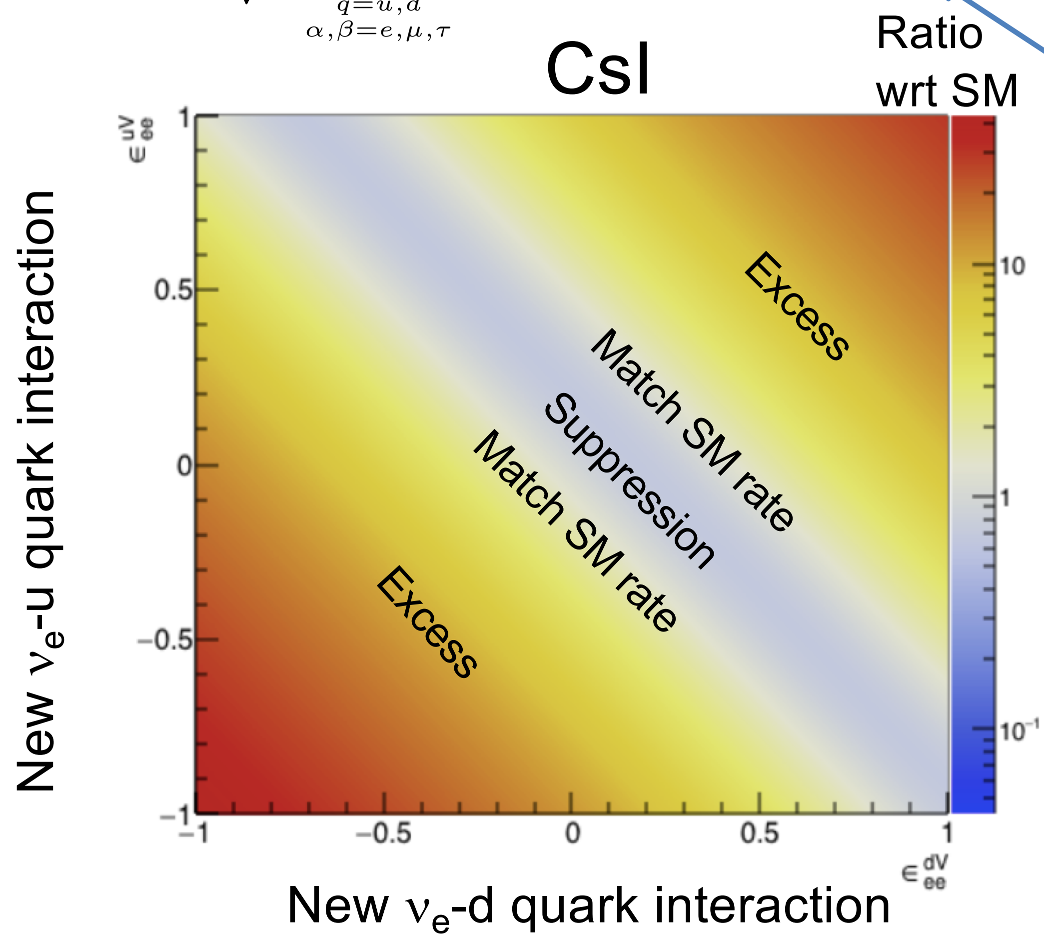


# Non-Standard Interactions of Neutrinos:

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'

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

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

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

"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

Talk by Dimitrios Papoulias

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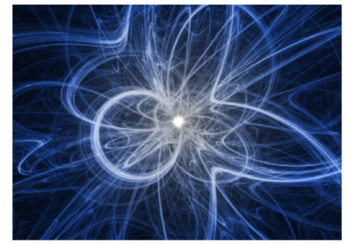

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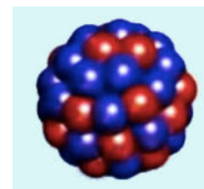

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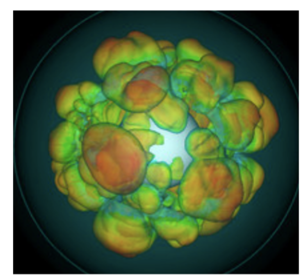

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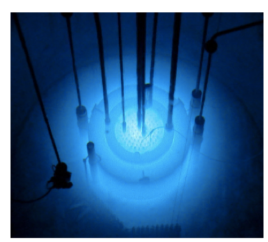
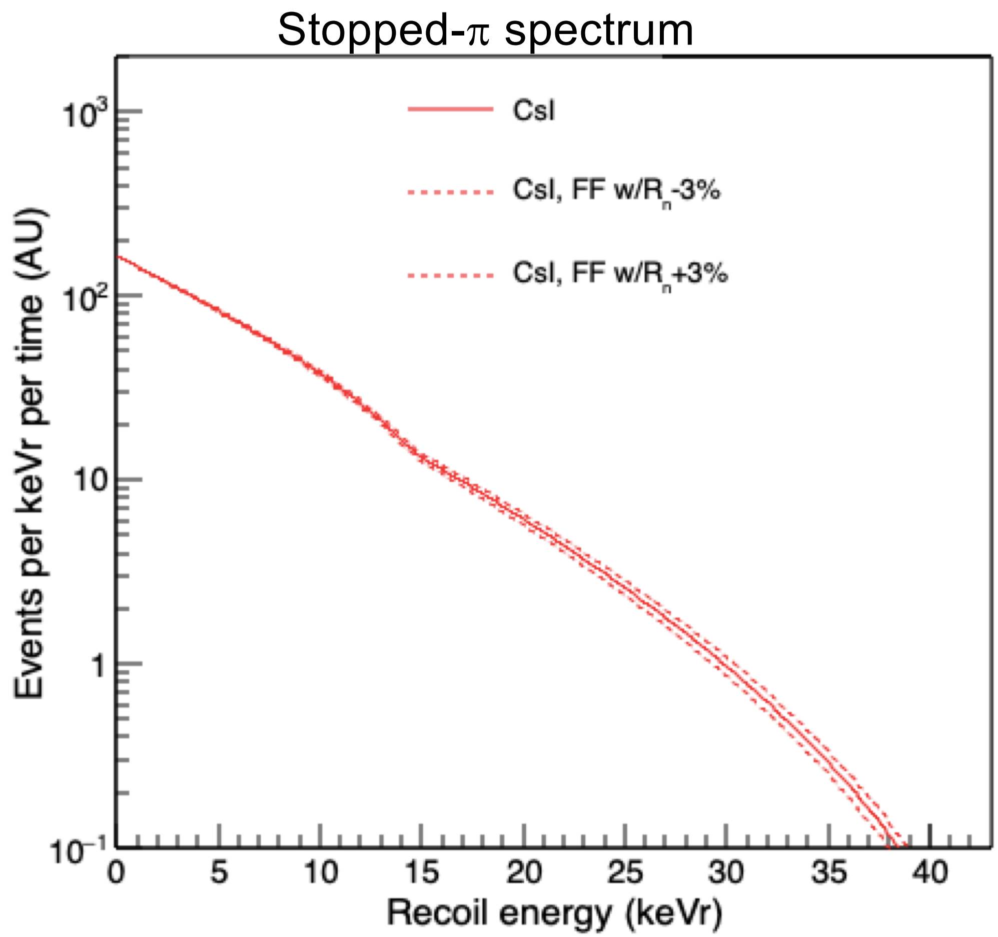


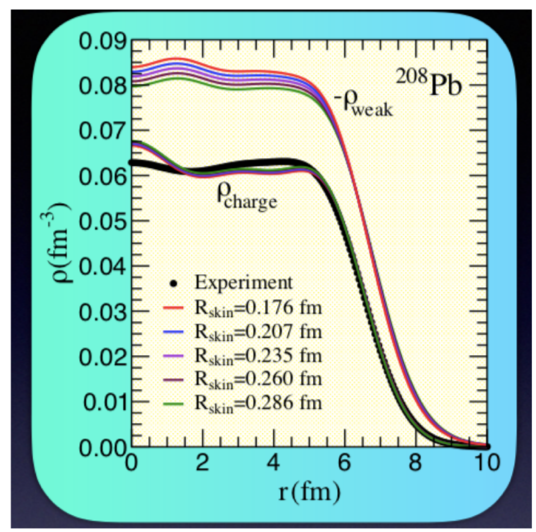
# What can we learn about **nuclear physics** with CEvNS?




P S Amanik and G C McLaughlin 2009 *J. Phys. G: Nucl. Part. Phys.* 36 015105

K. Patton et al., Phys.Rev. C86 (2012) 024612

Observable is **recoil spectrum shape**




Neutron radius and "skin" ($R_n$-$R_p$) relevant for understanding of neutron star EOS!

J. Piekarewicz

But: 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

At current level of precision,
form factor shape is **not a dominant effect**
... but we will need to think carefully about
how to disentangle these effects for the longer term

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

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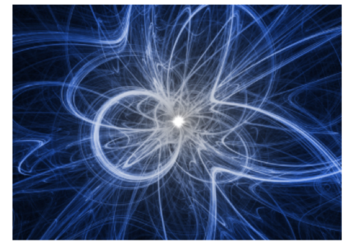

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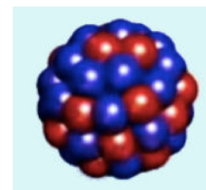
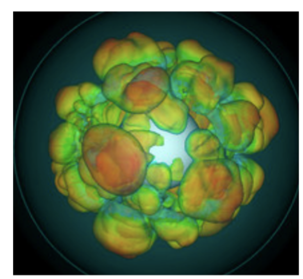
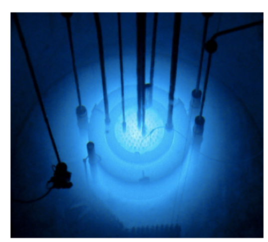


CEvNS as a **background**
for signatures of new physics (DM)

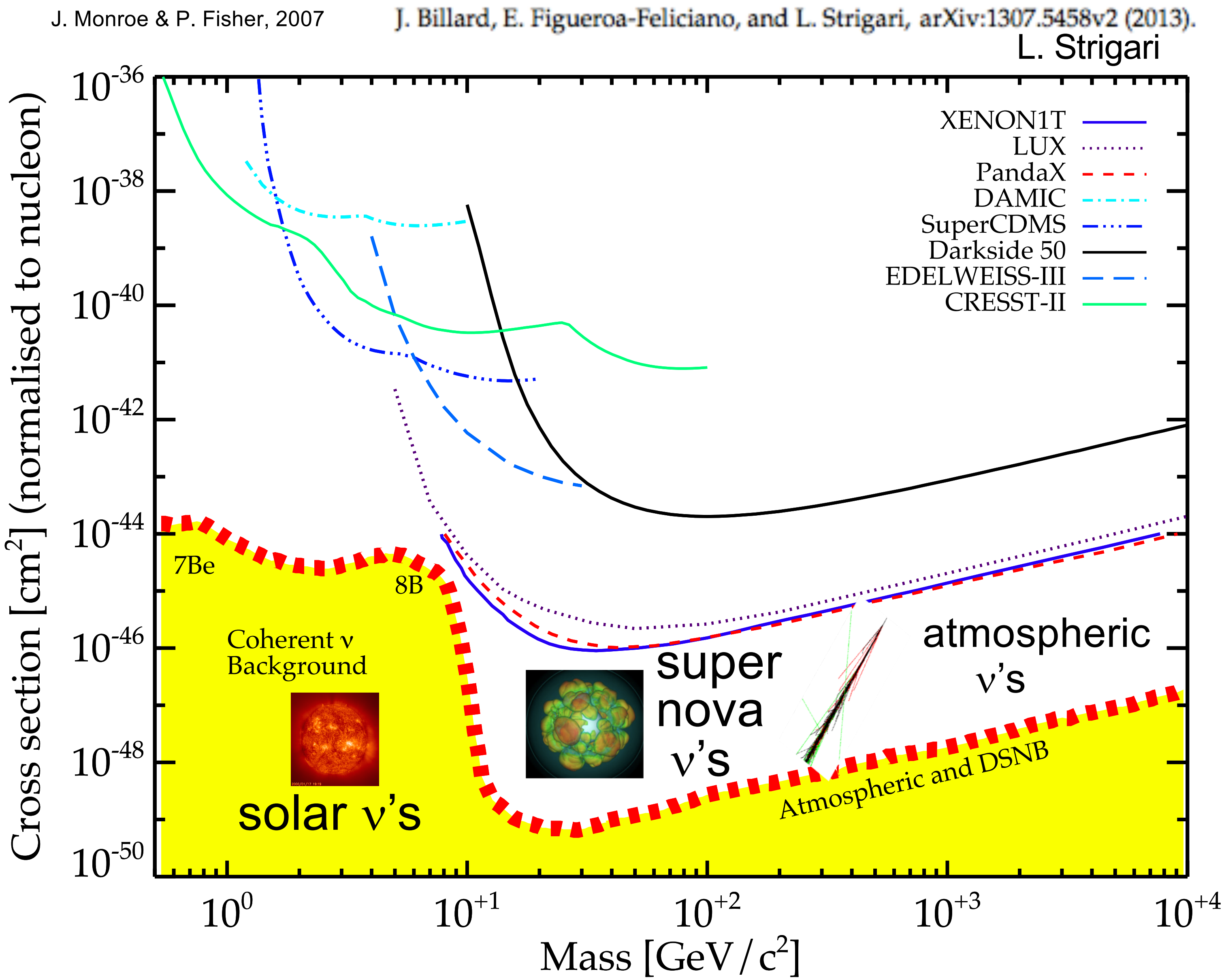

CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



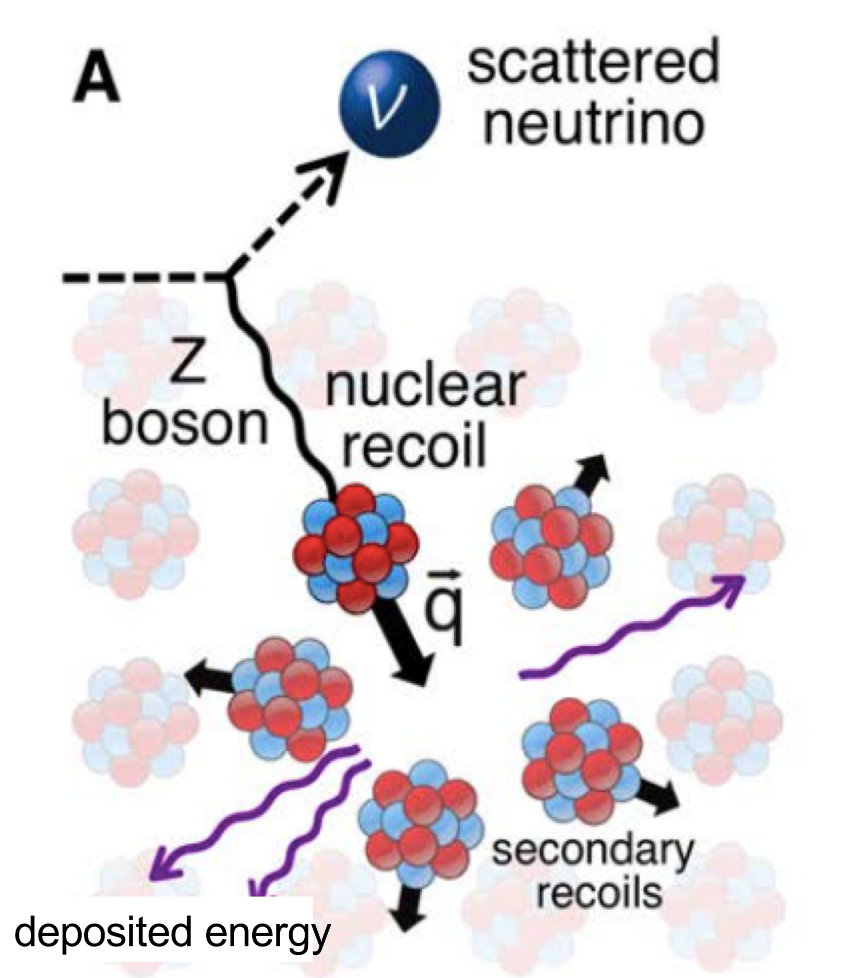
# The so-called "neutrino floor" (**signal!**) for direct DM experiments



# How to measure CEvNS

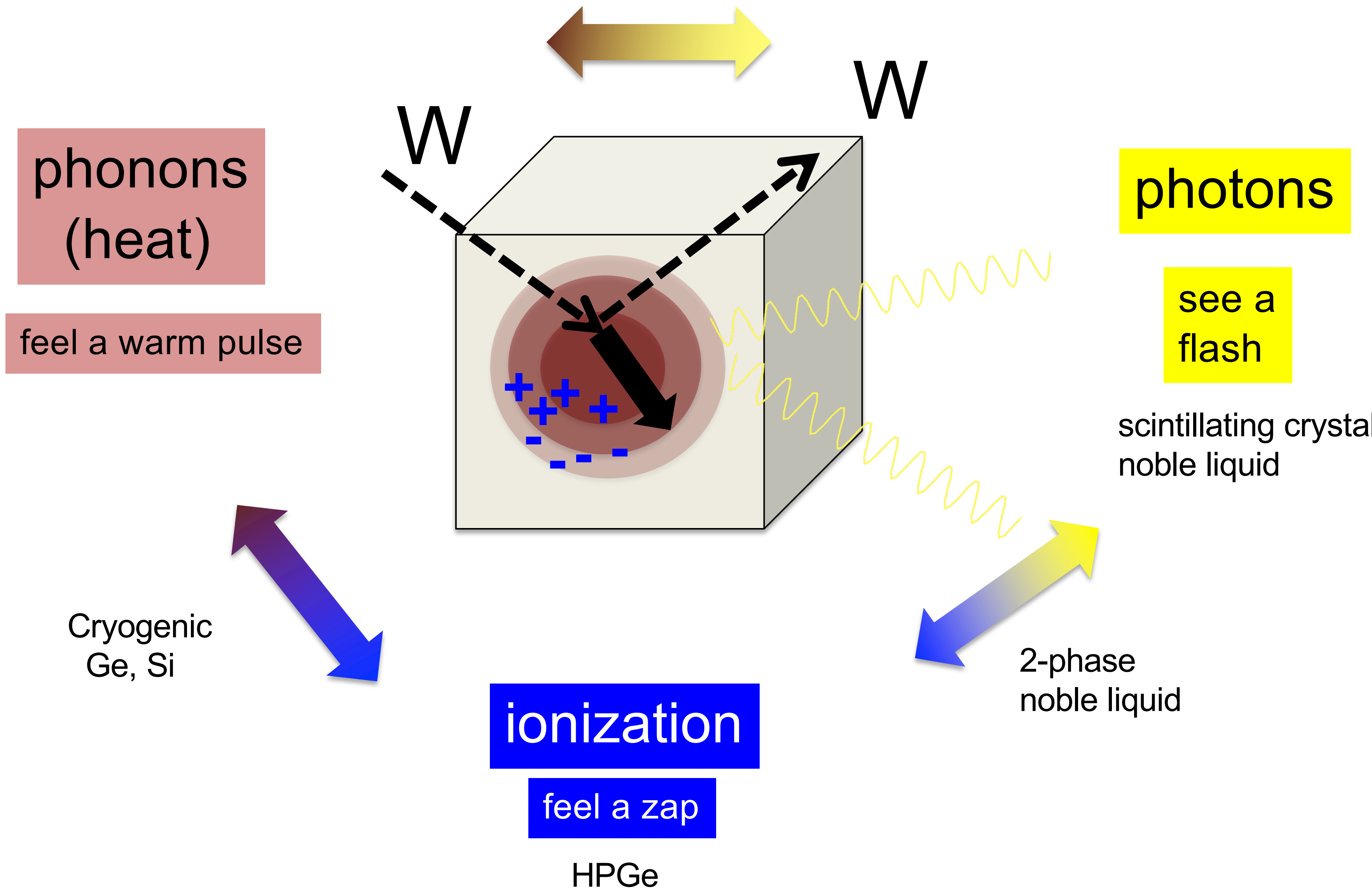
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



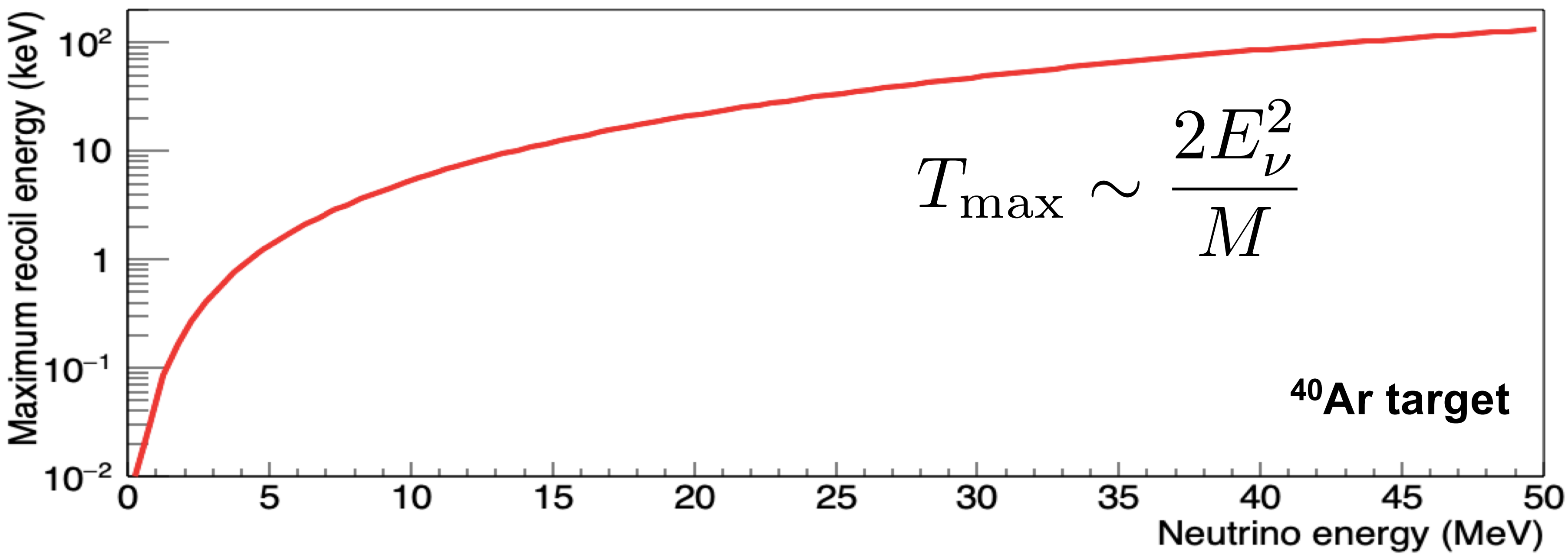

➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10’s of keV recoils

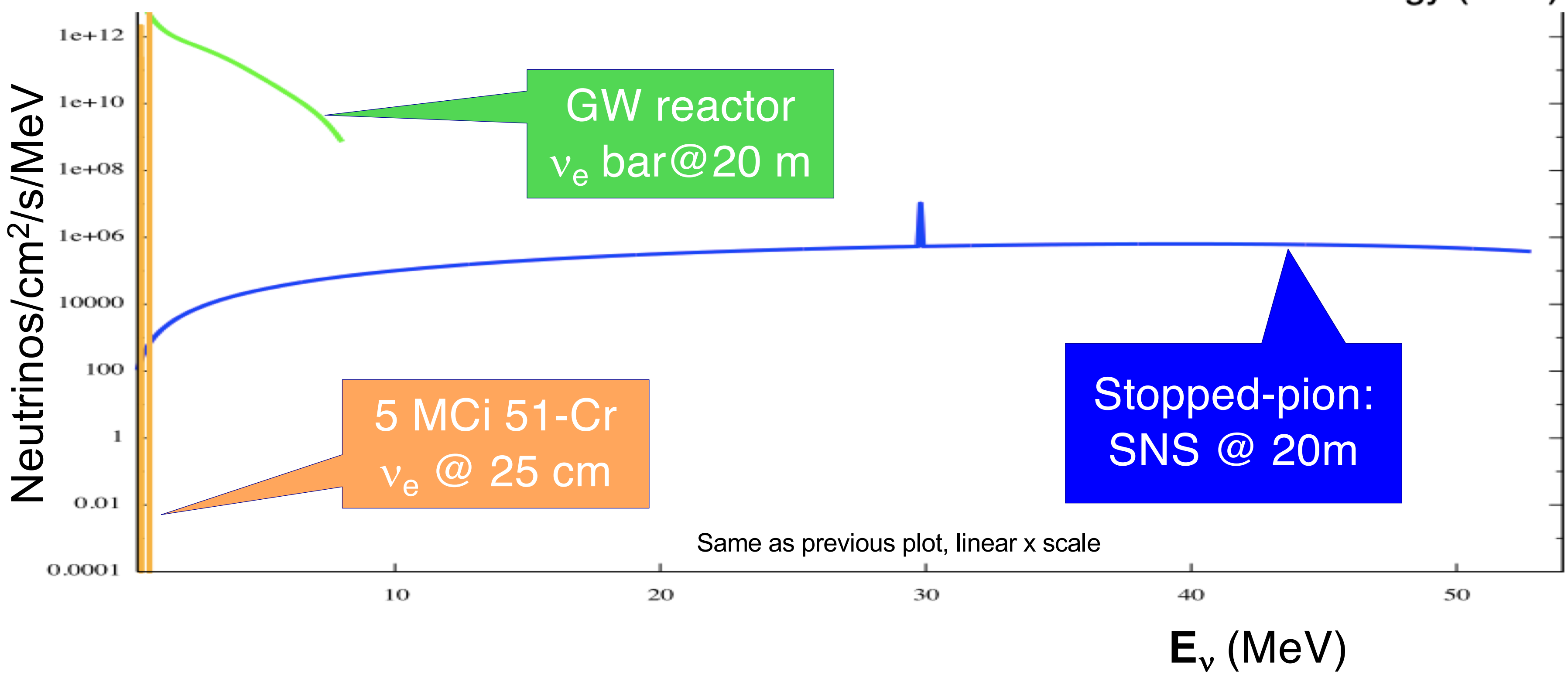
# Low-energy nuclear recoil detection strategies




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

Maximum recoil energy as a function of $E_\nu$



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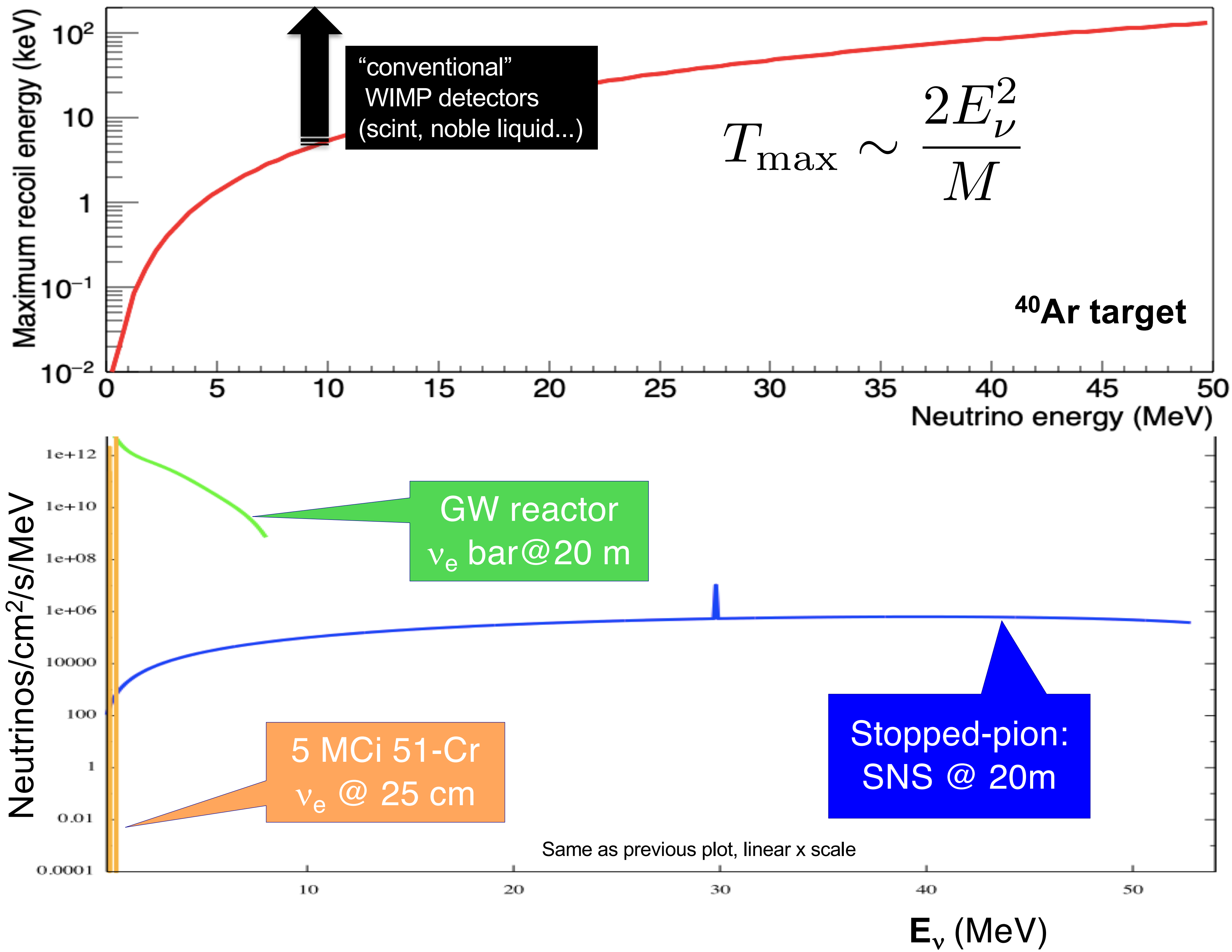

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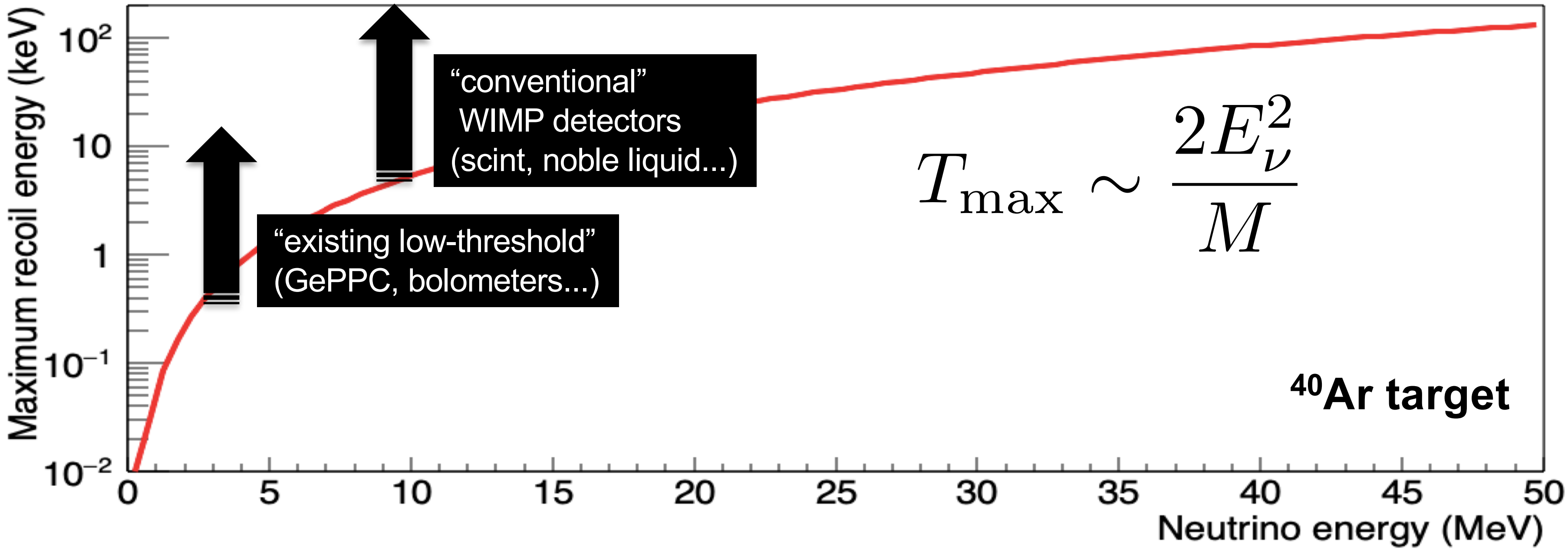


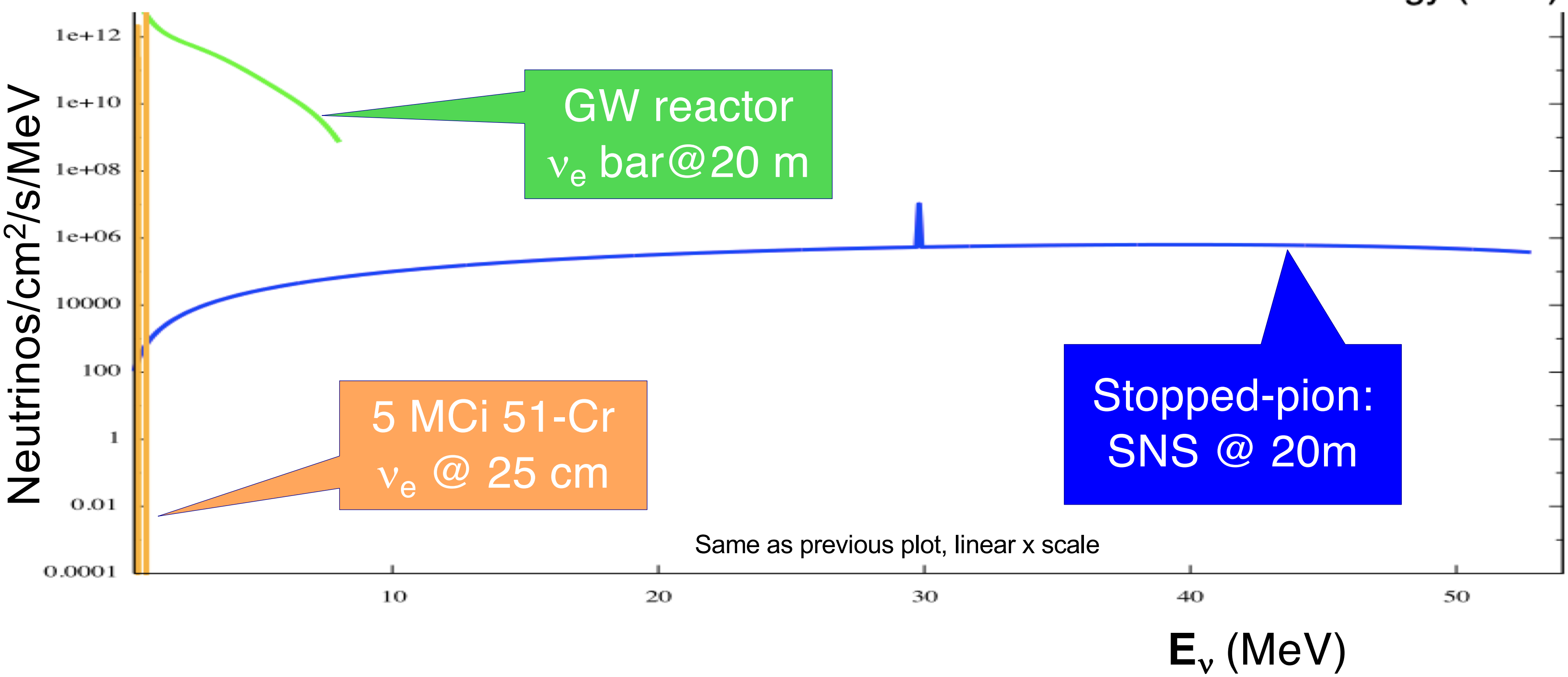

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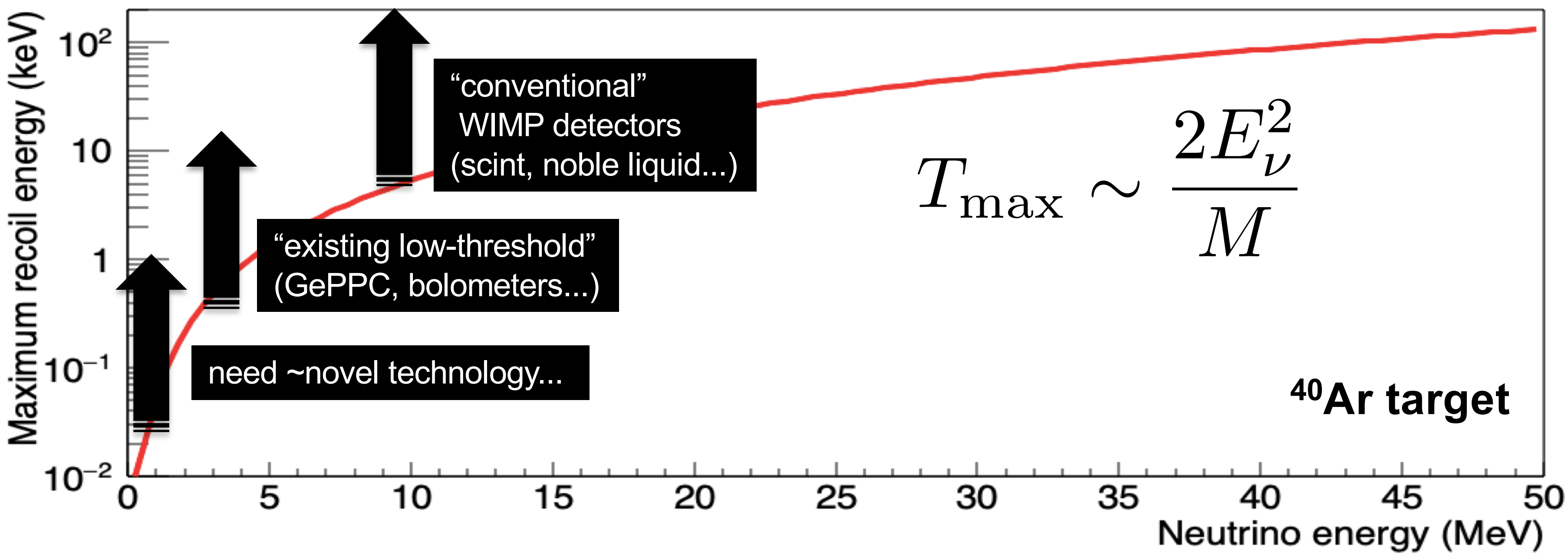
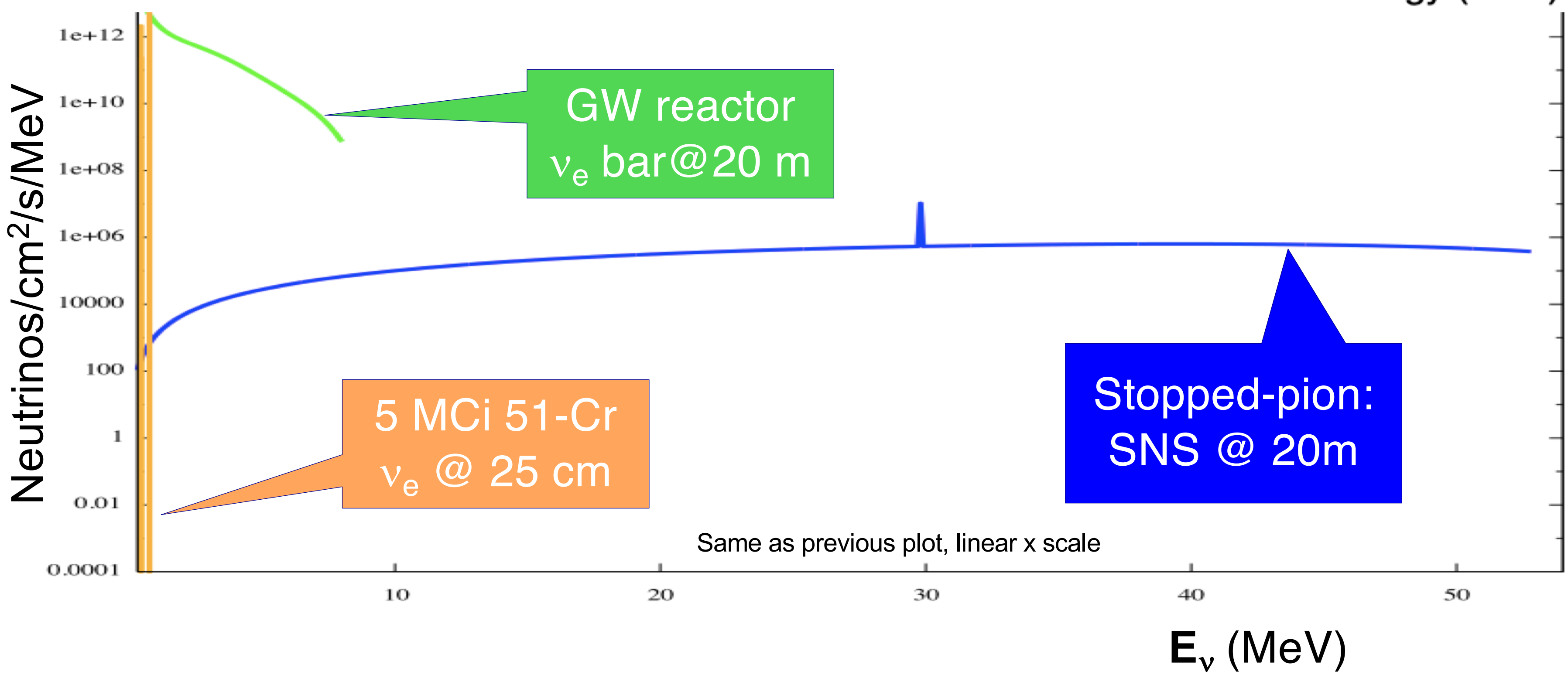
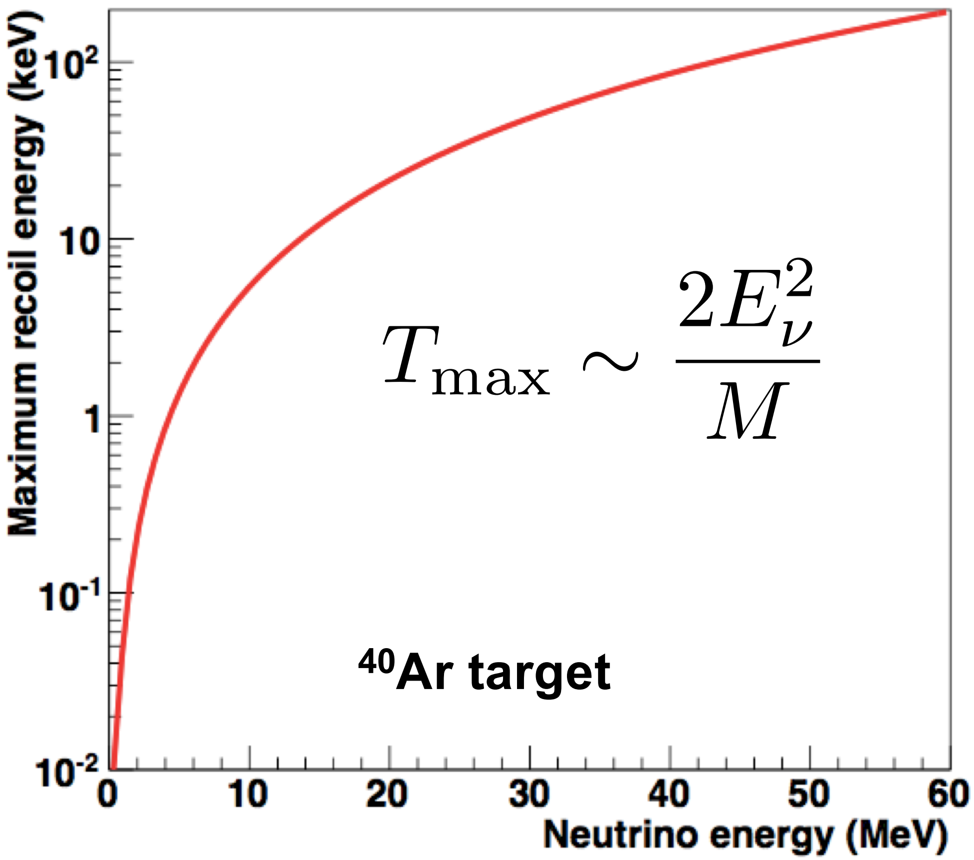
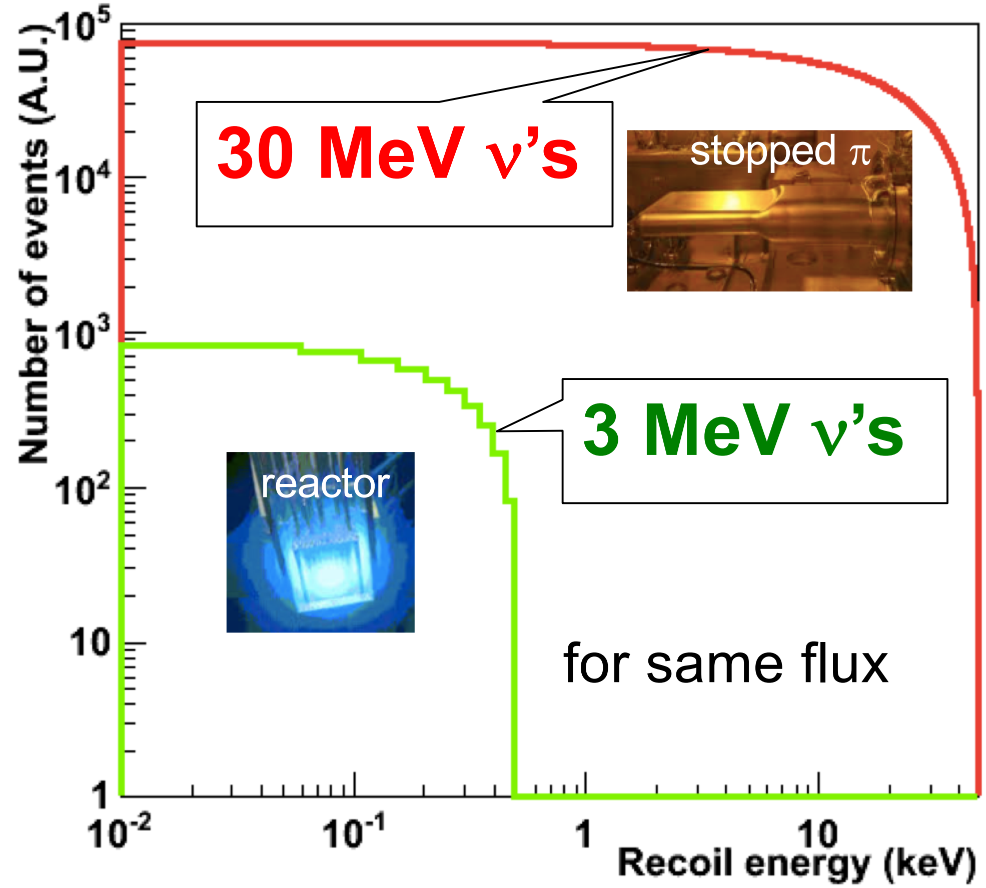


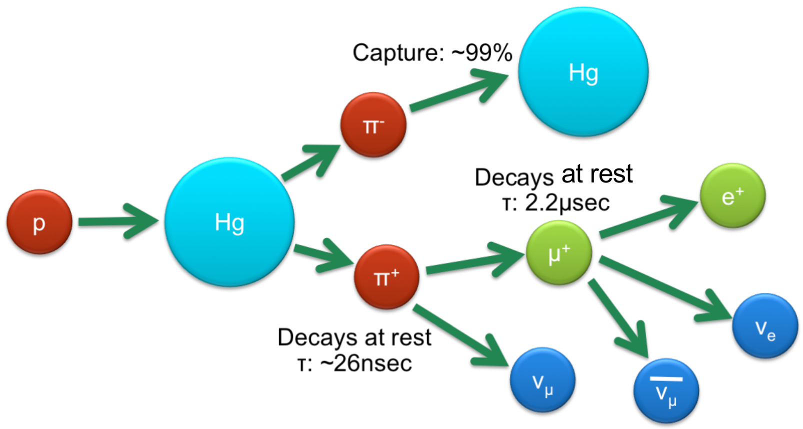
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

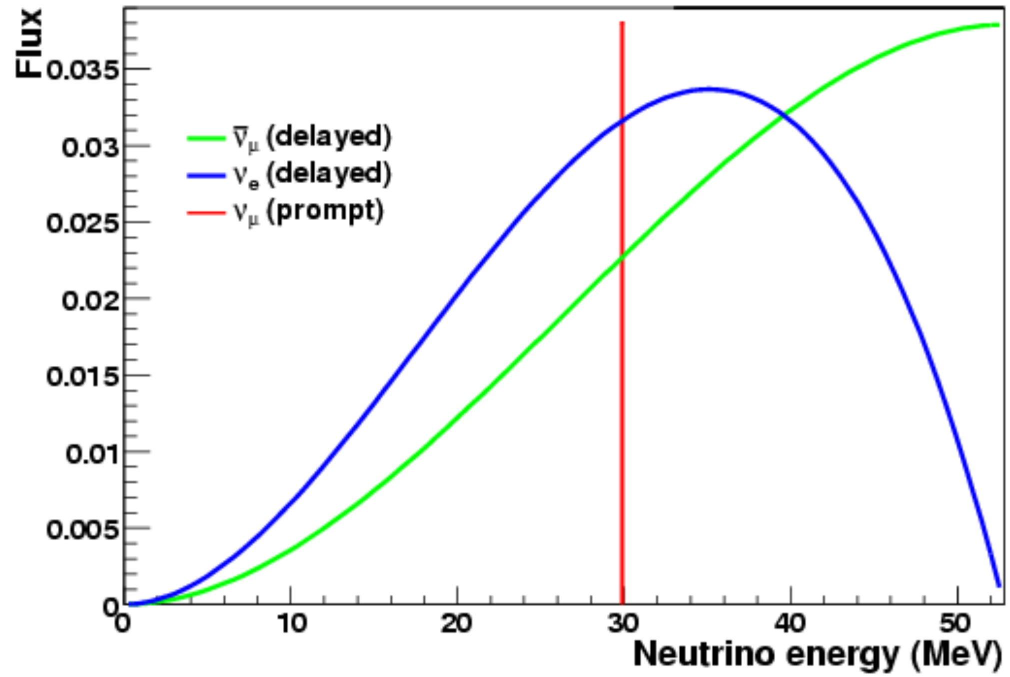



Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

# Stopped-Pion (πDAR) Neutrinos




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

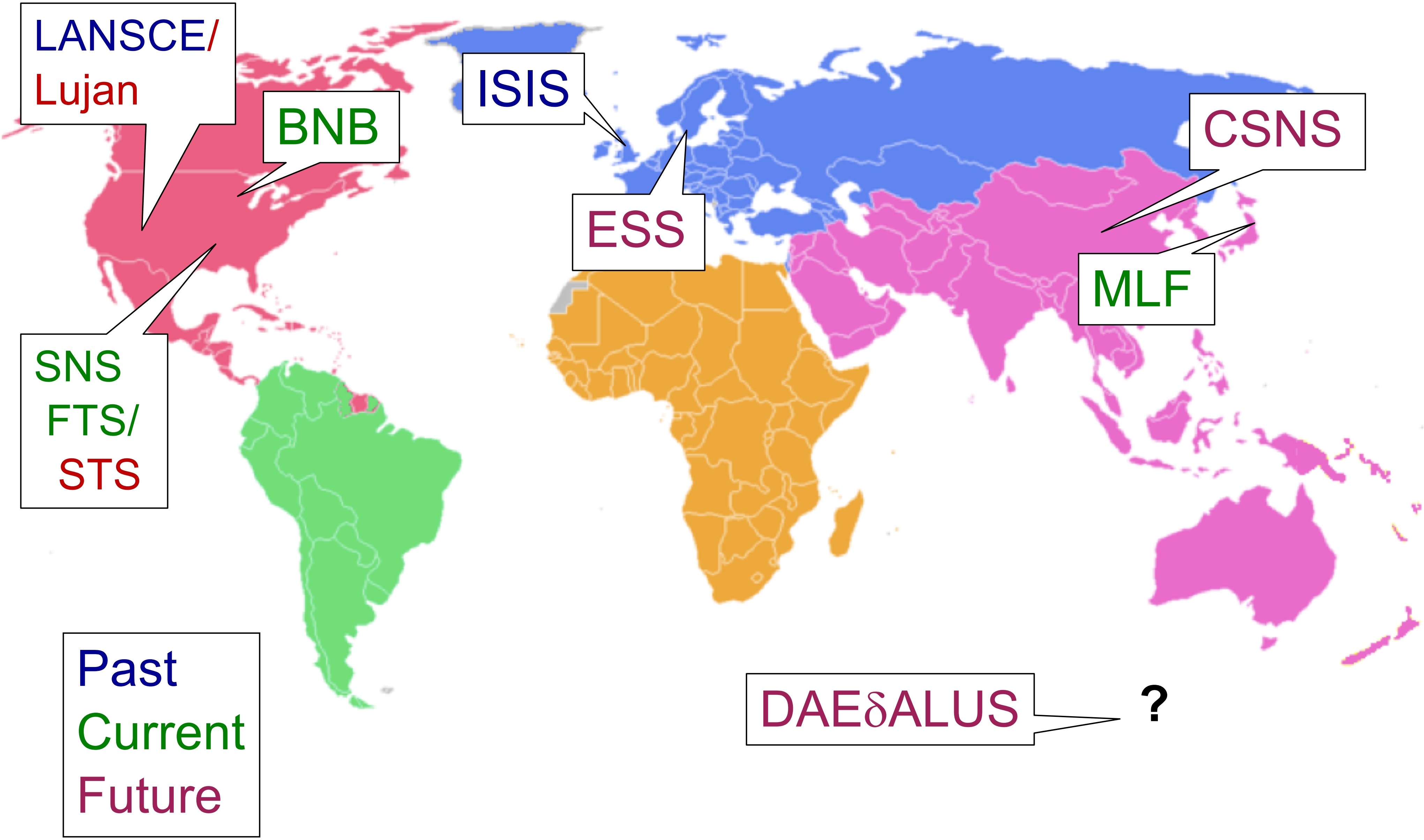
2-body decay: monochromatic 29.9 MeV $\nu_\mu$
PROMPT

$$\downarrow$$

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

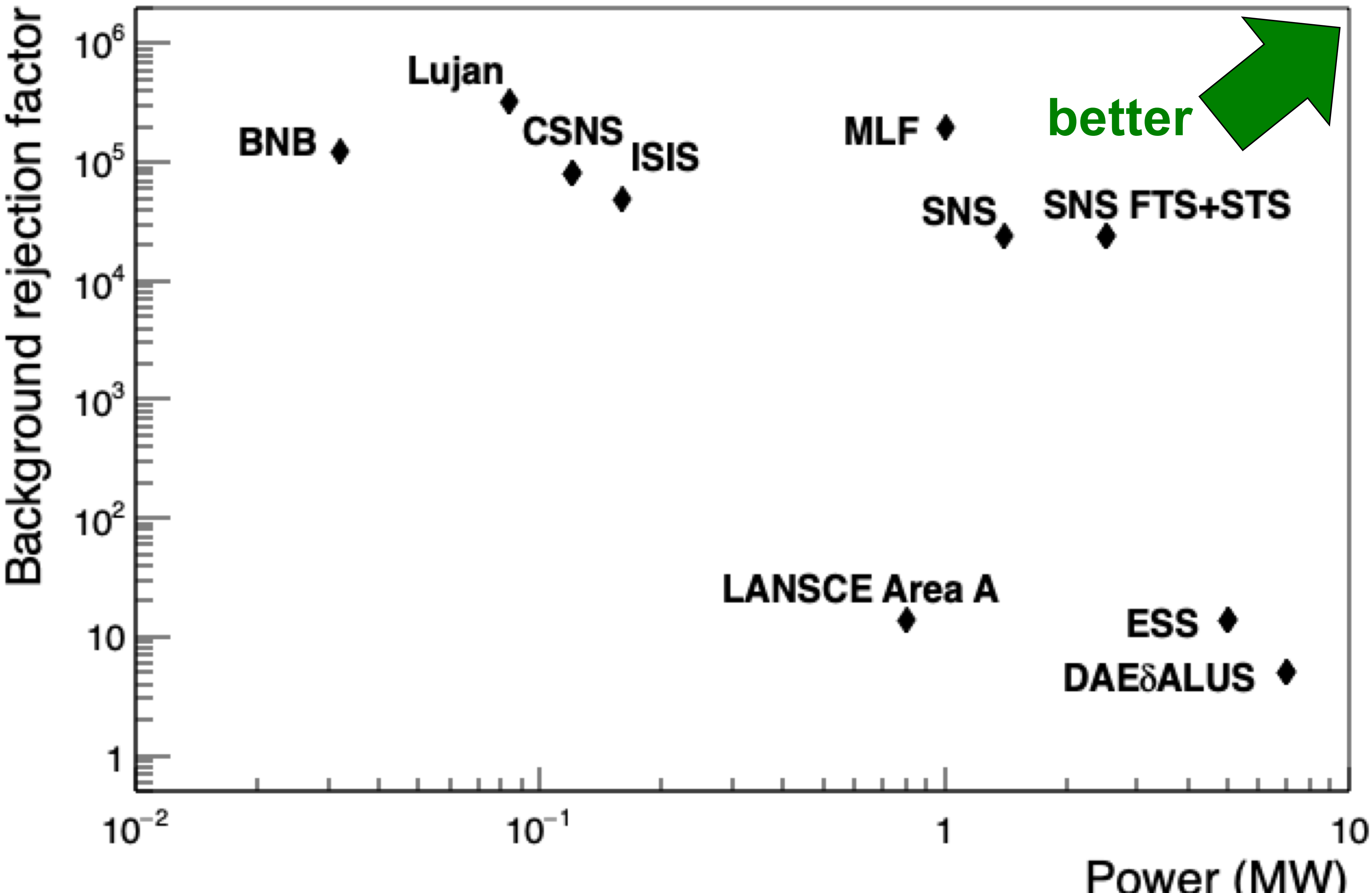
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

# Stopped-Pion Neutrino Sources Worldwide



from duty cycle

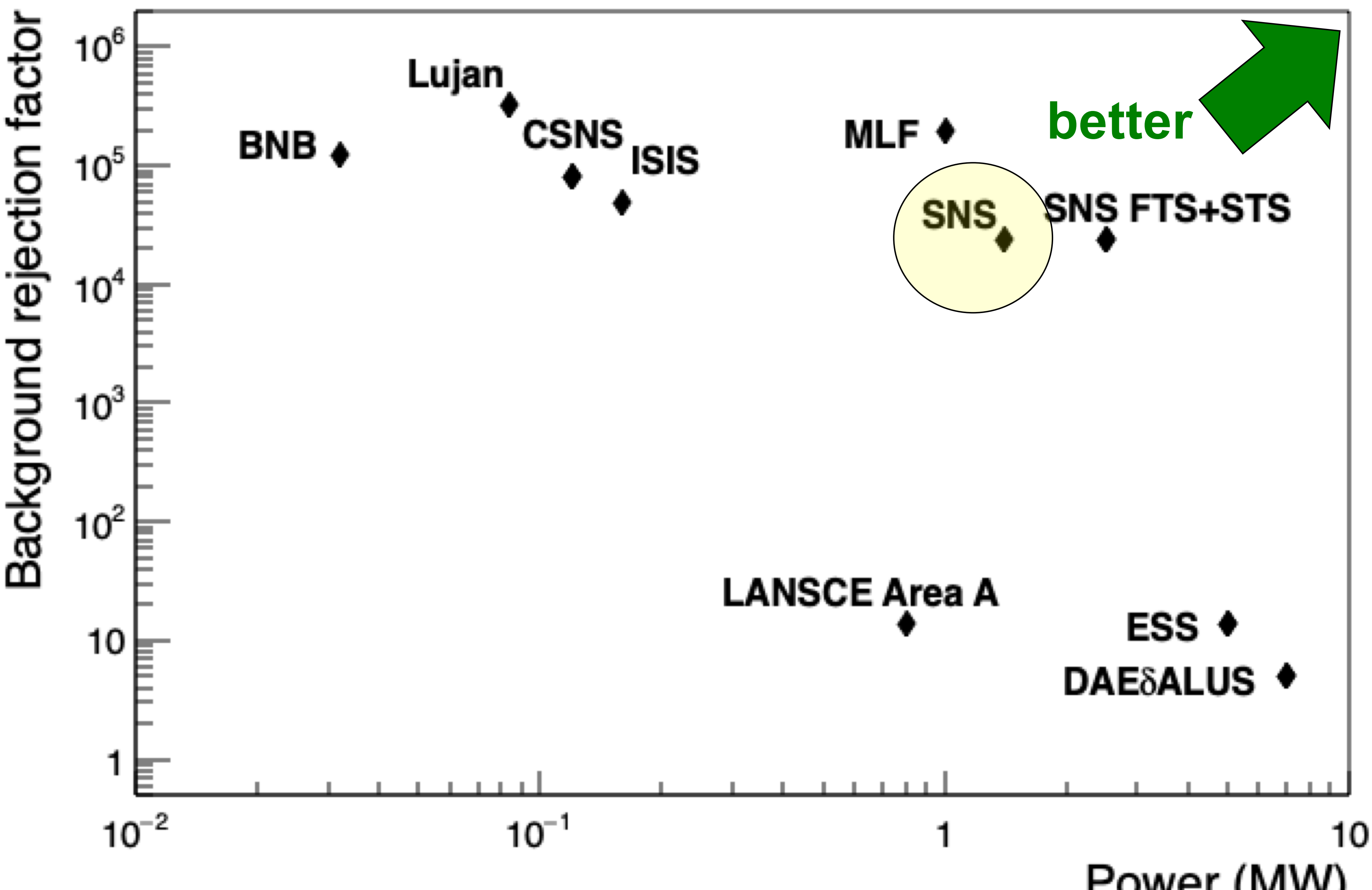
# Comparison of pion decay-at-rest ν sources



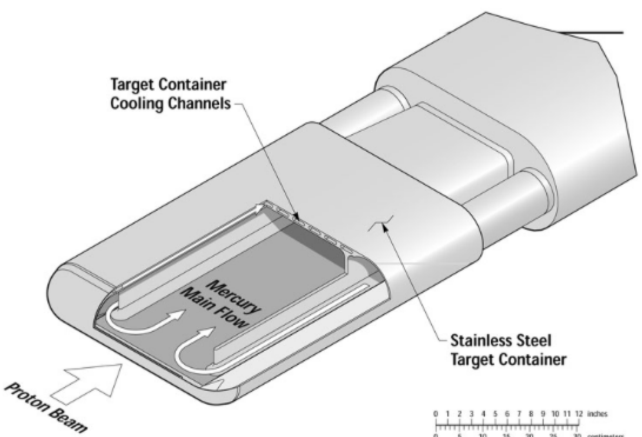

$\propto \nu$ flux

# Comparison of pion decay-at-rest ν sources

from duty cycle




$\propto \nu$ flux


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

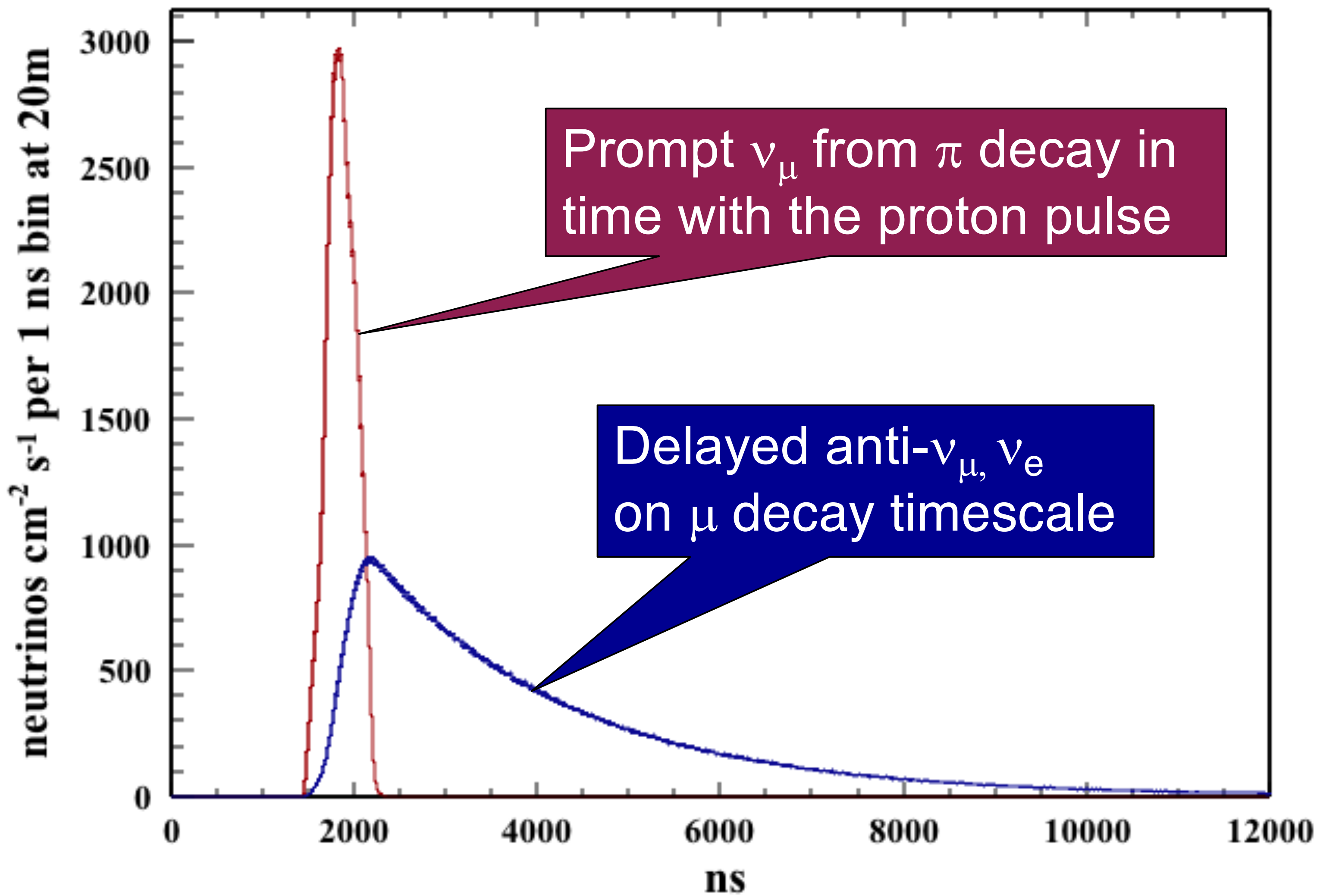
http://sites.duke.edu/coherent

~90 members,
20 institutions
4 countries

arXiv:1509.08702

# Time structure of the SNS source

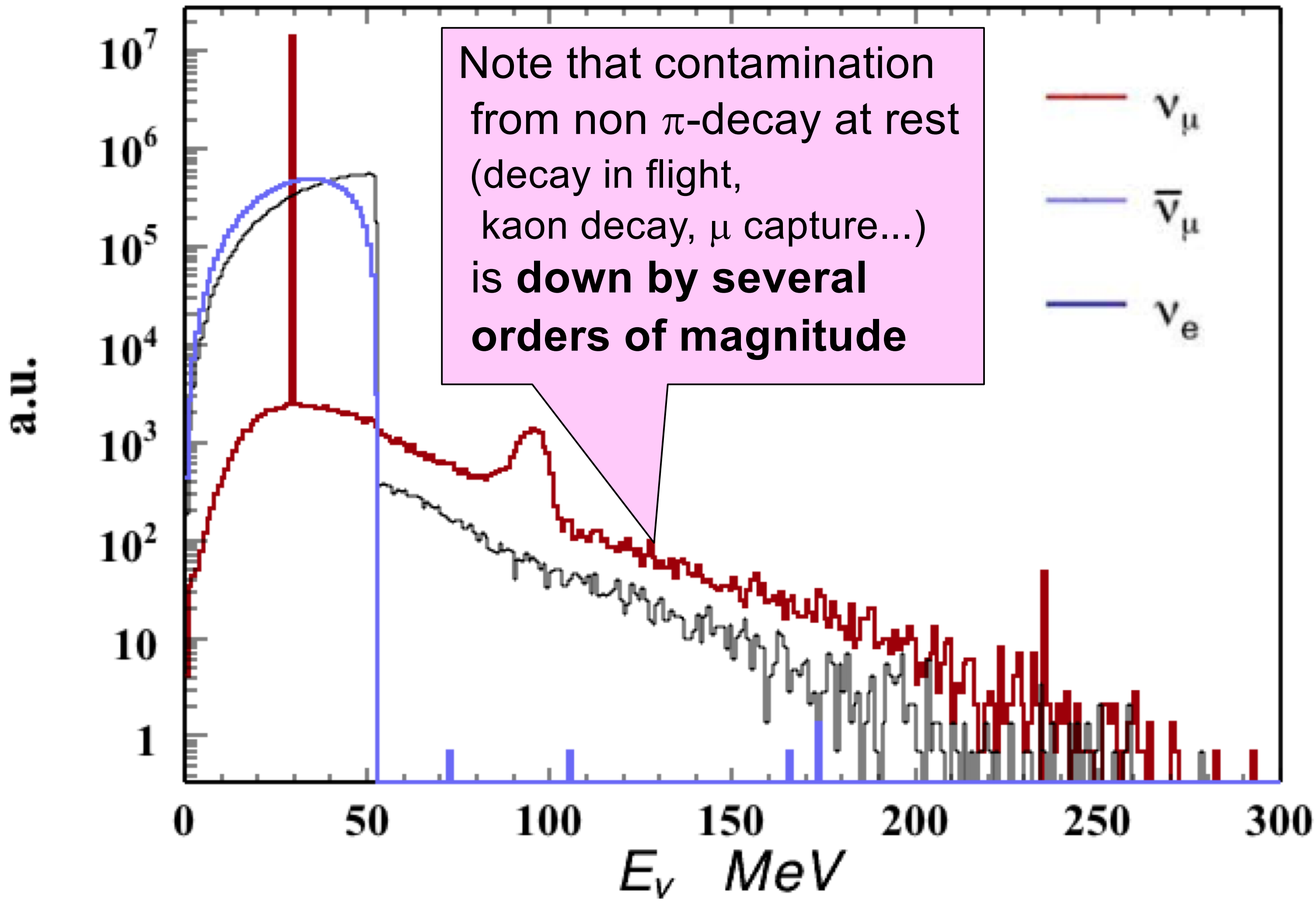
60 Hz *pulsed* source




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



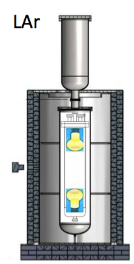

SNS flux (1.4 MW):
**430 x $10^5$ ν/cm$^2$/s**
@ 20 m

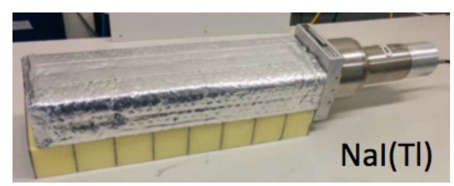
# COHERENT CEvNS Detectors

| 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

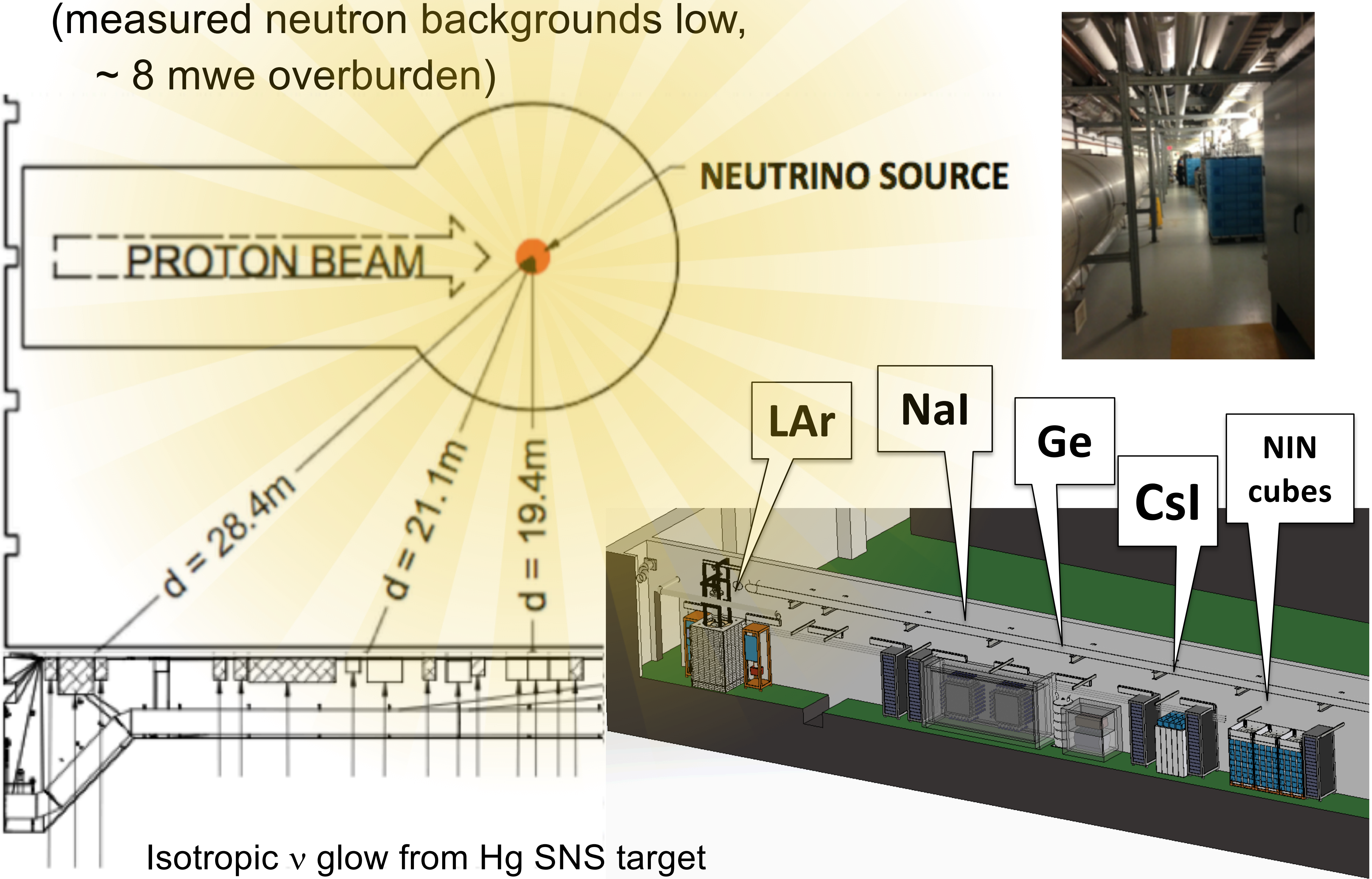




# Siting for deployment in SNS basement

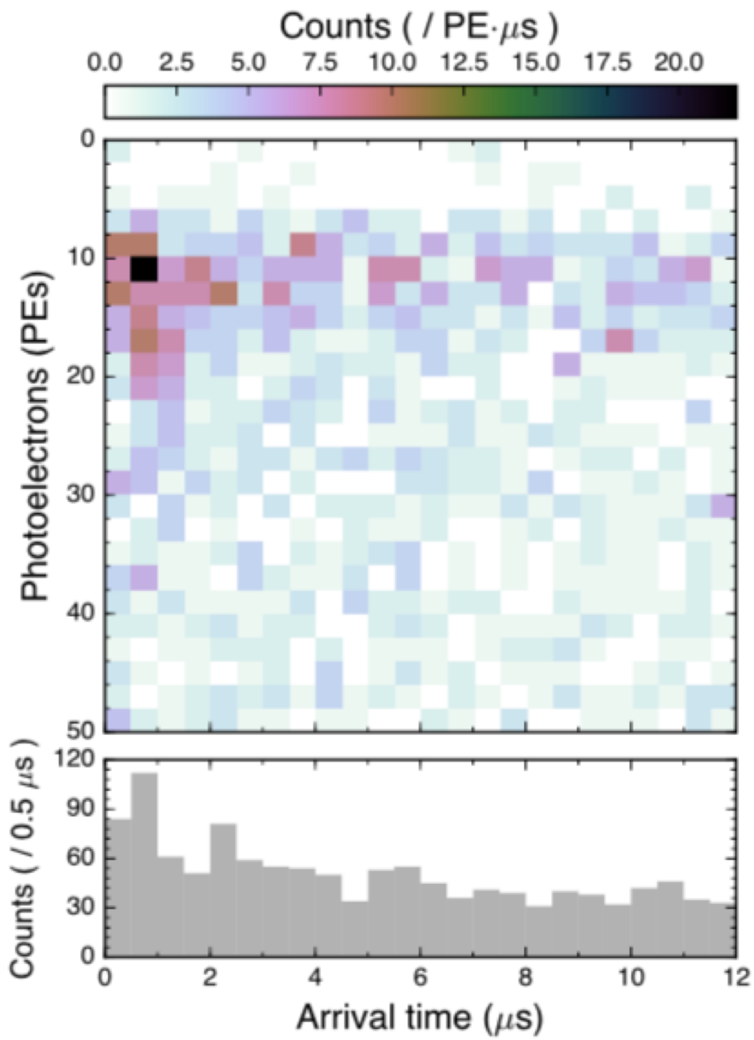
(measured neutron backgrounds low,
~ 8 mwe overburden)

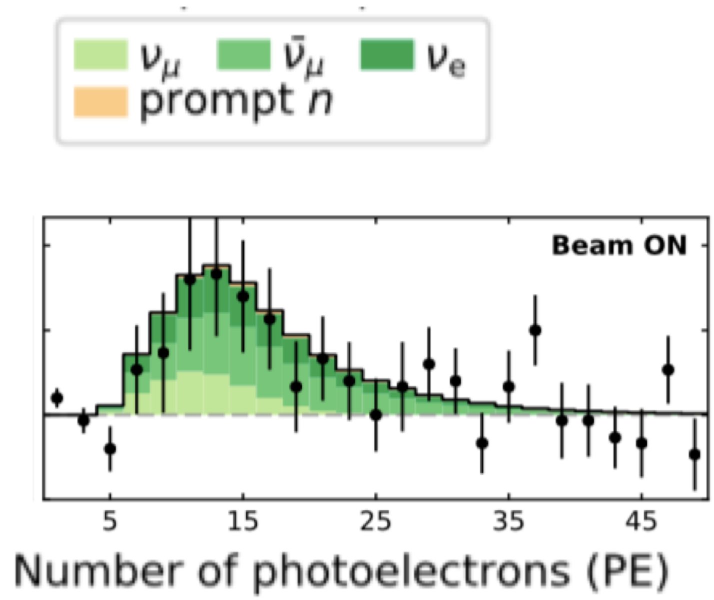



Isotropic ν glow from Hg SNS target

View looking down "Neutrino Alley"

# **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

# 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

# Reducing systematic uncertainties

2017 CsI measurement

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

Dominant uncertainty (detector-dependent)

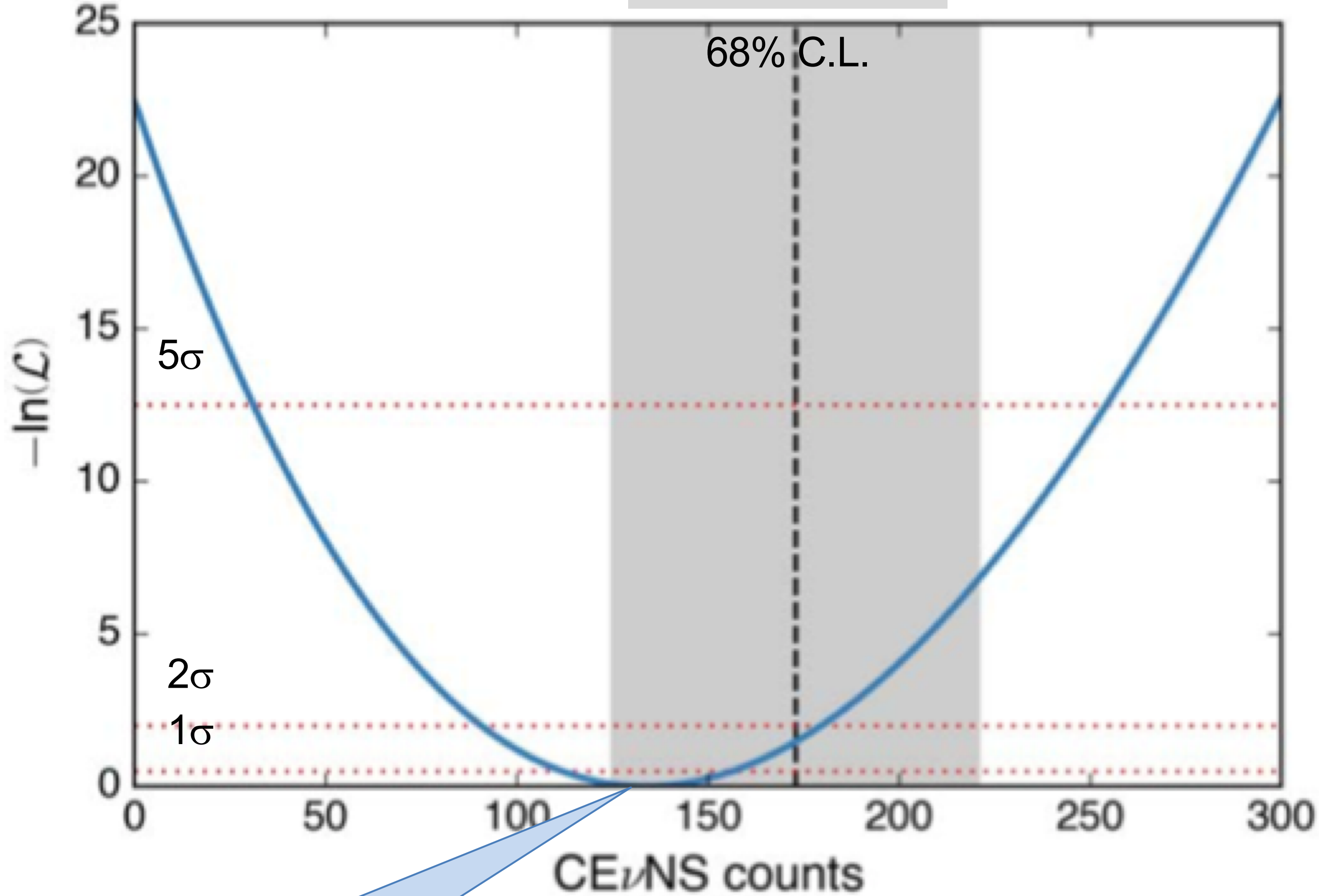
Next largest uncertainty (affects all detectors)

- ancillary quenching factor measurements are important for the physics program
- $D_2O$ for flux normalization also planned

  ($\nu_e$-d interaction has few % theoretical uncertainty)

# Results of 2D energy, time fit

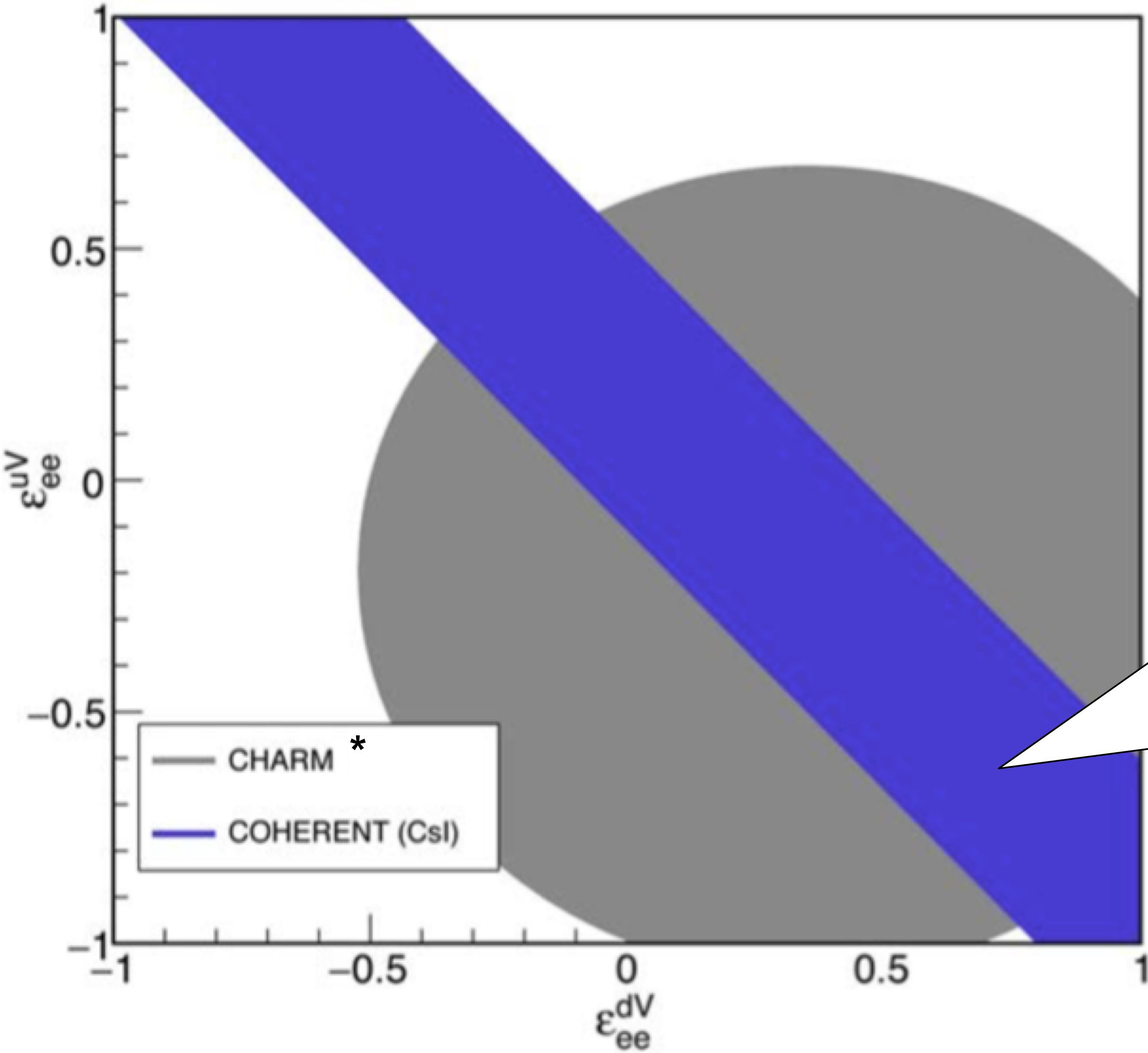
SM prediction, 173 events




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

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

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




- Assume all other ε's zero

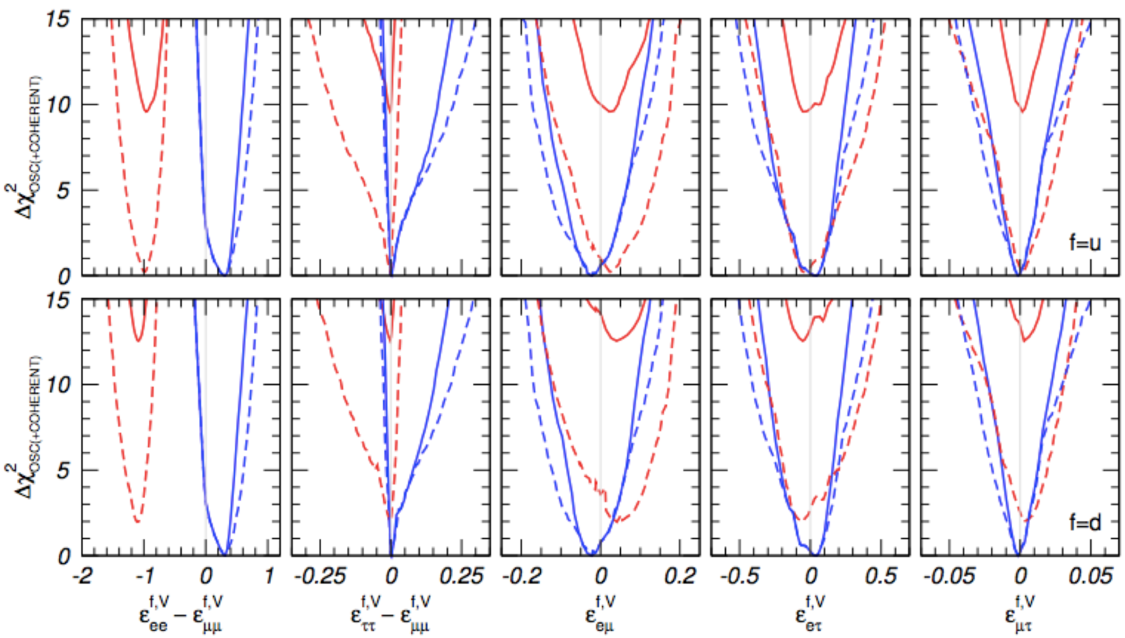
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

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

*CHARM constraints apply only to heavy mediators

## A COHERENT enlightenment of the neutrino Dark Side

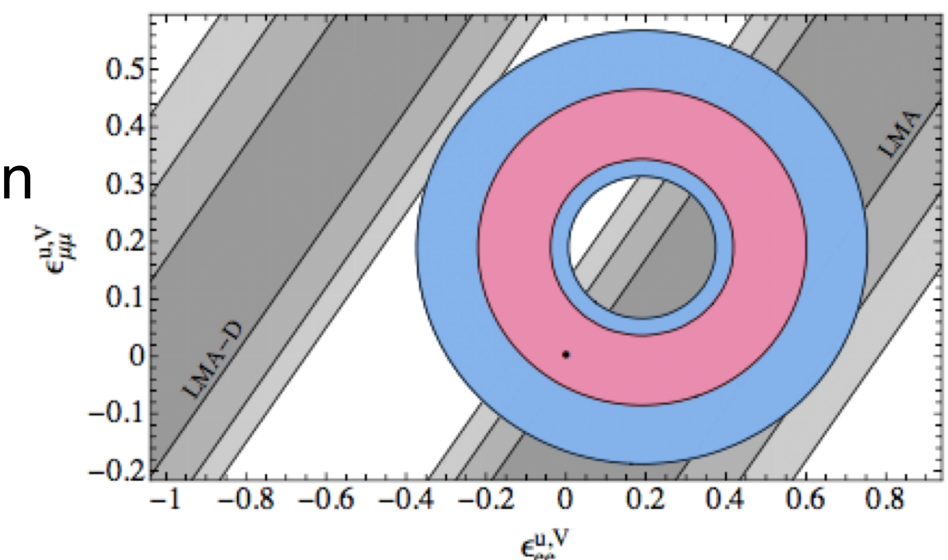
Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]




Global fits to COHERENT + oscillation experiments

Solid: COHERENT
Dashed: COHERENT + osc
Blue: LMA ($\theta_{12} < \pi/4$)
Red: LMA-D ($\theta_{12} > \pi/4$)
("dark side", still allowed with NSI)

1σ, 2σ allowed regions projected in ($\varepsilon_{ee}^{uV}$, $\varepsilon_{\mu\mu}^{uV}$) plane

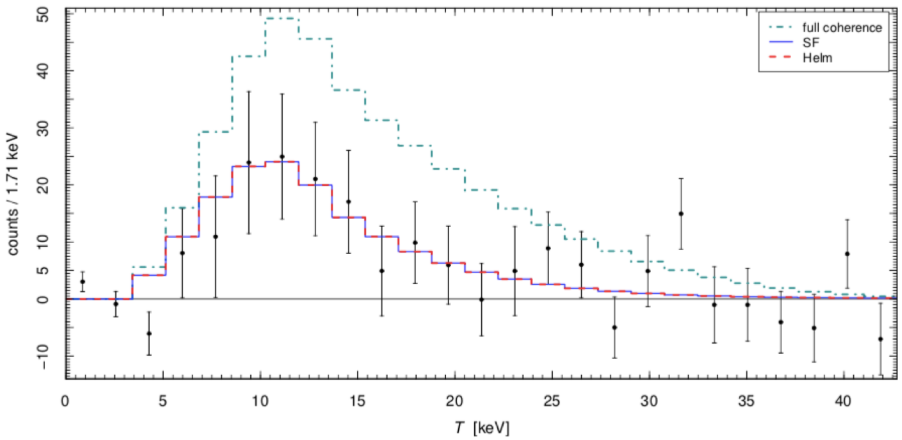


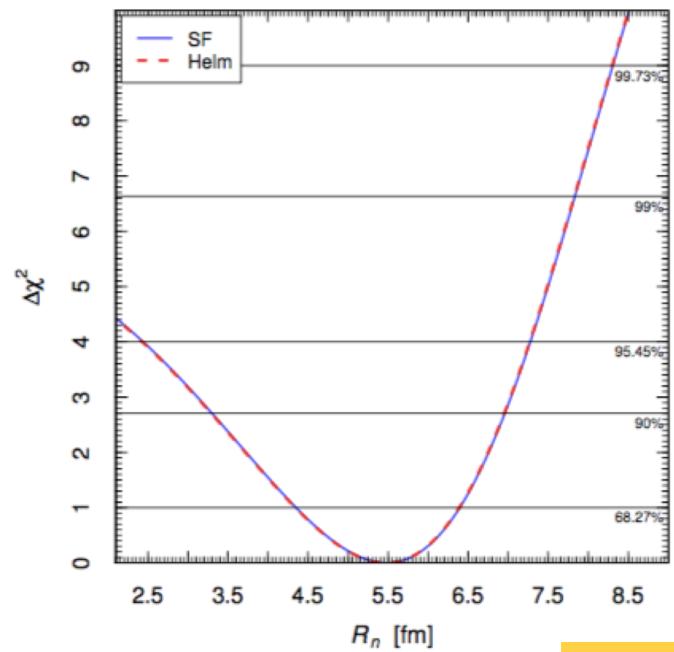

Already meaningful constraints!

See talk by Dimitrios Papoulias

# 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

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

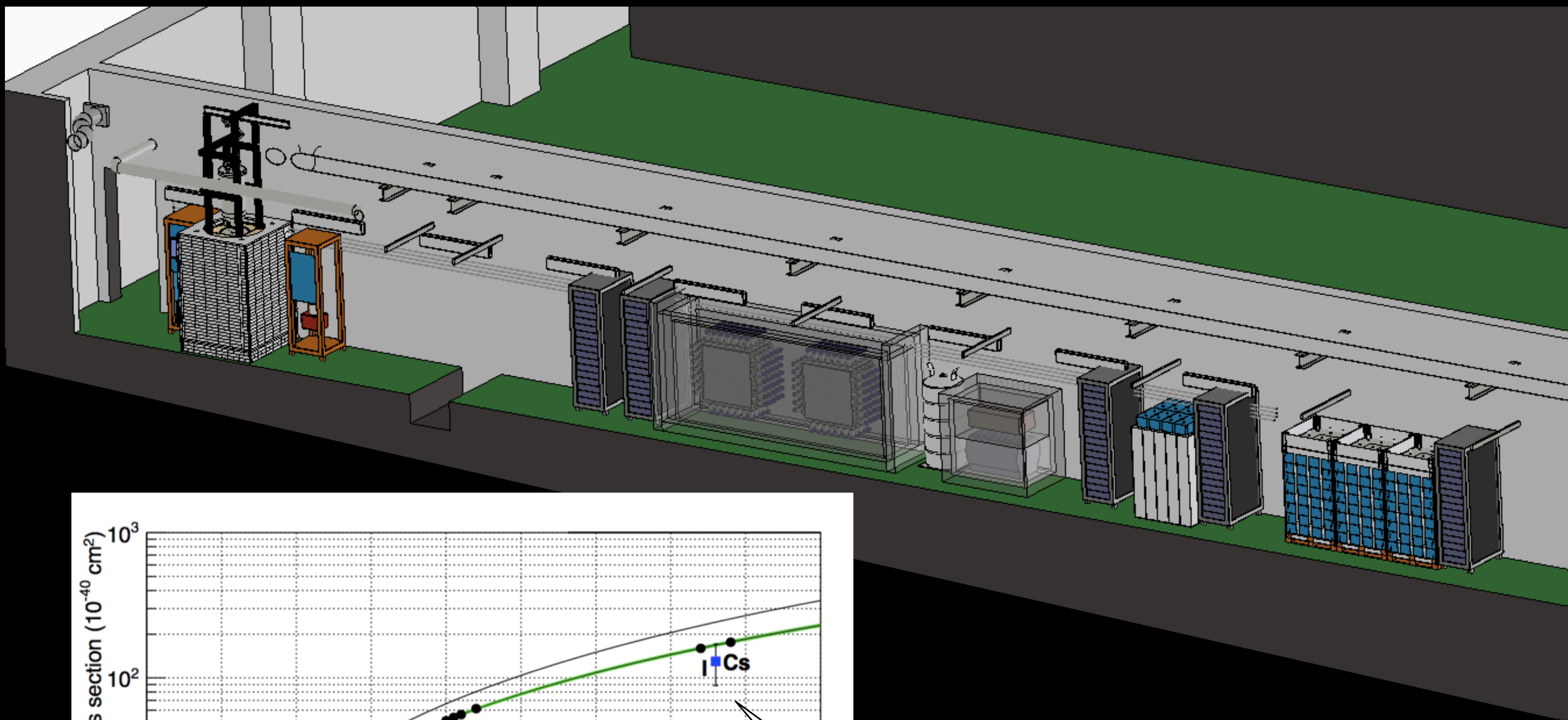
$$R_n = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}. \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \mathrm{fm}.$$

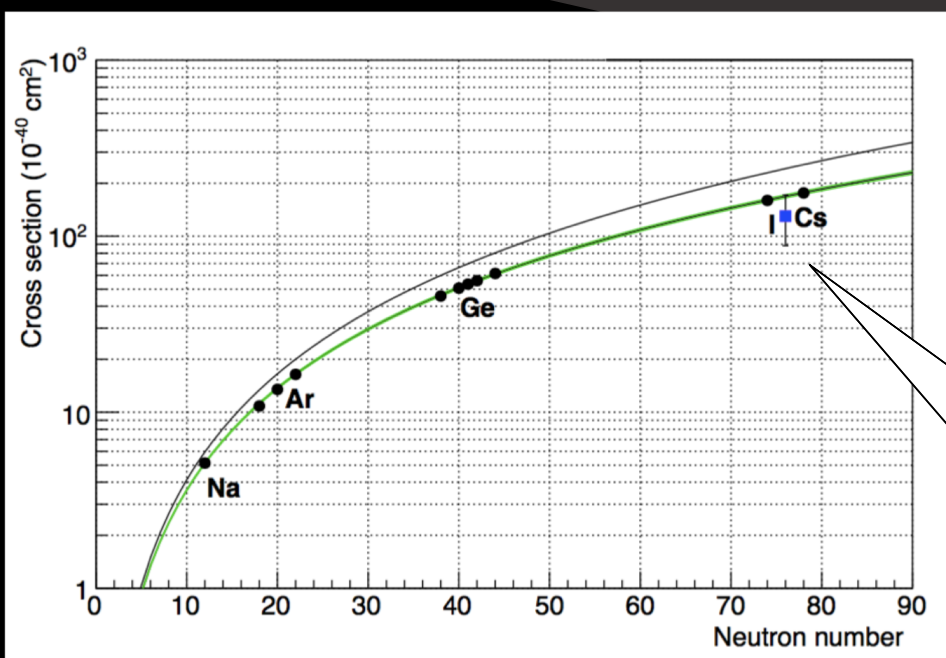

Spectral shape systematics are hard!

- 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**

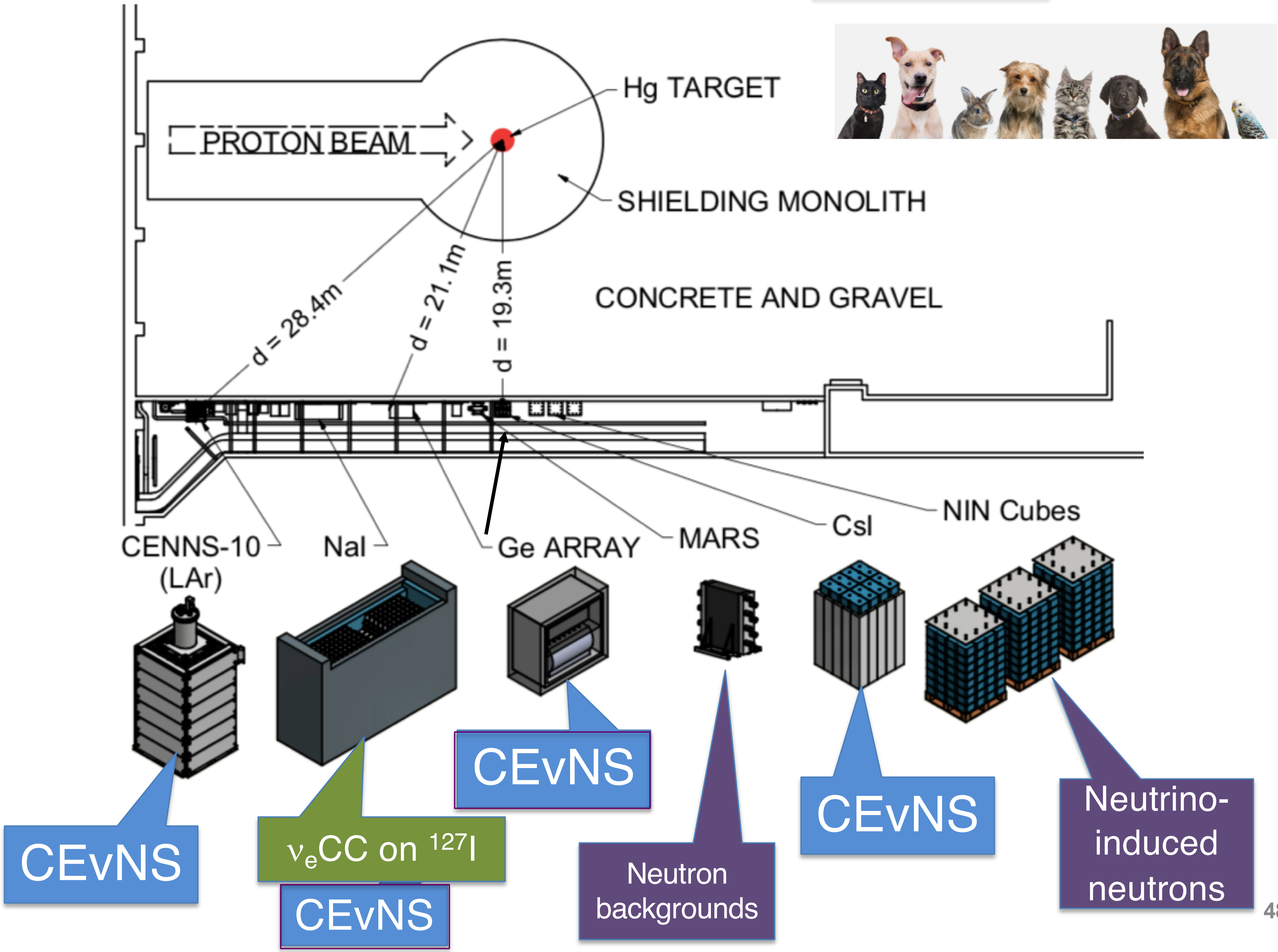
# What's Next for COHERENT?





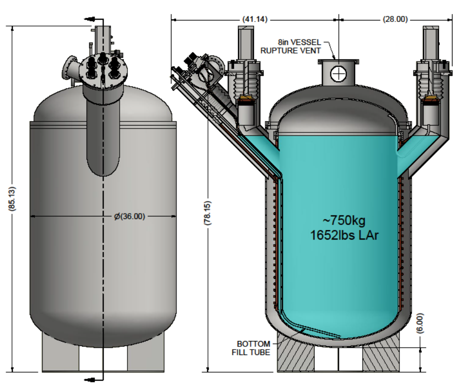

One measurement so far! Want to map out $N^2$ dependence

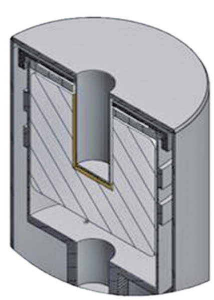
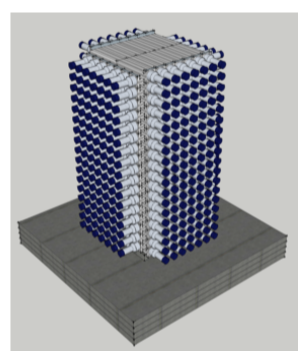
# Neutrino Alley Deployments: current & near future



# 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 |



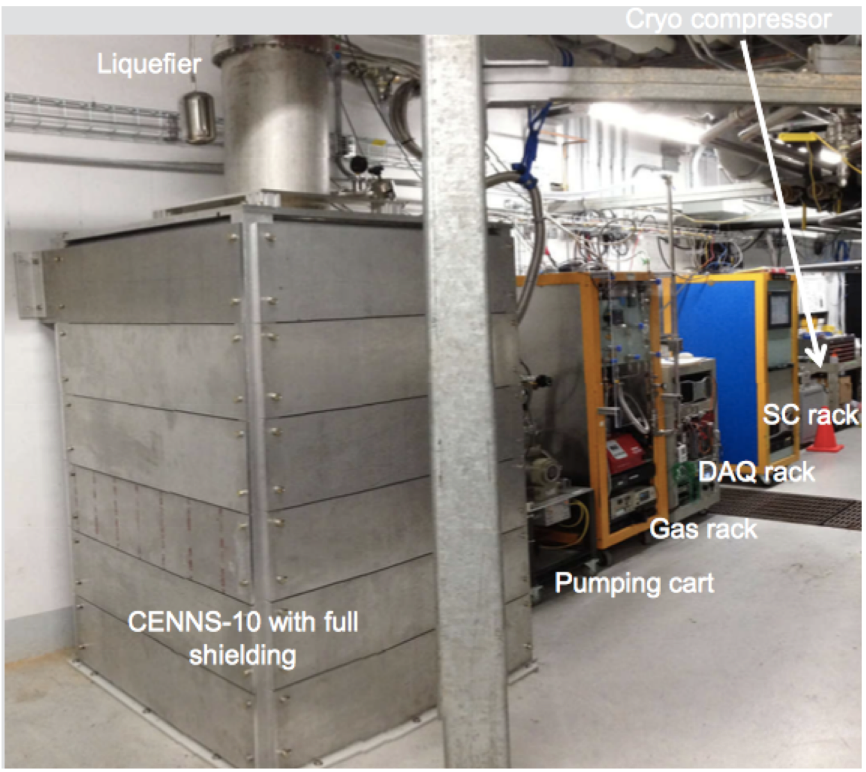




+$D_2O$ for flux normalization

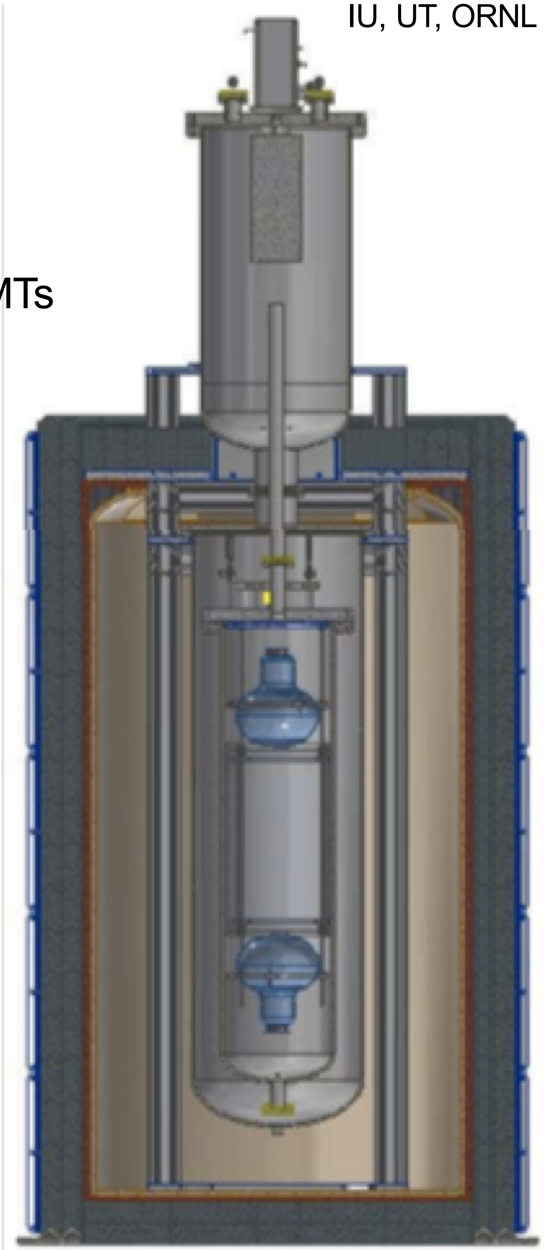
+ concepts for other targets...

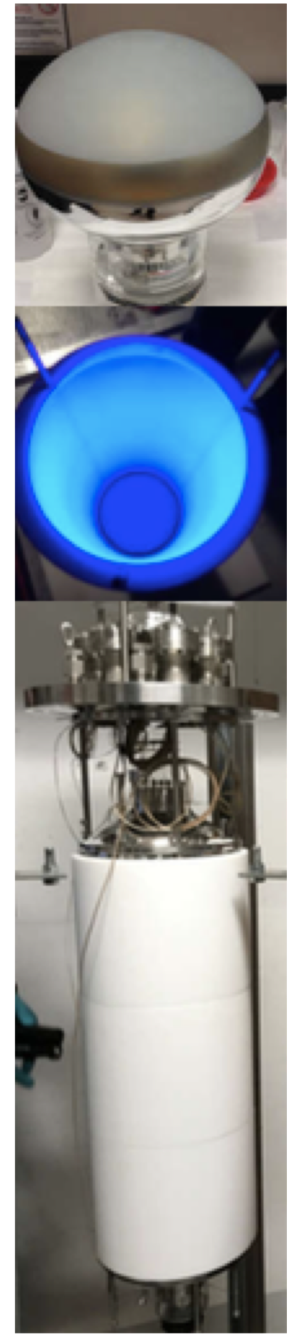
# Single-Phase Liquid Argon

- ~22 kg fiducial mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
    - 8” borosilicate glass windown
    - 14 dynodes
    - QE: 18%@ 400 nm
- Wavelength shifter: TB-coated teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
    - PT90 single-state pulse-tube cold head




IU, UT, ORNL

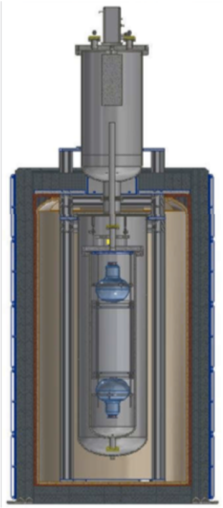


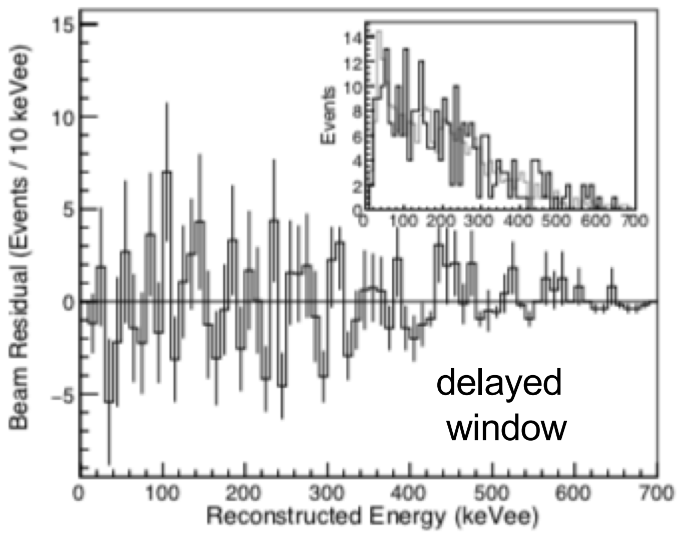


Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

# COHERENT LAr Engineering Run Result

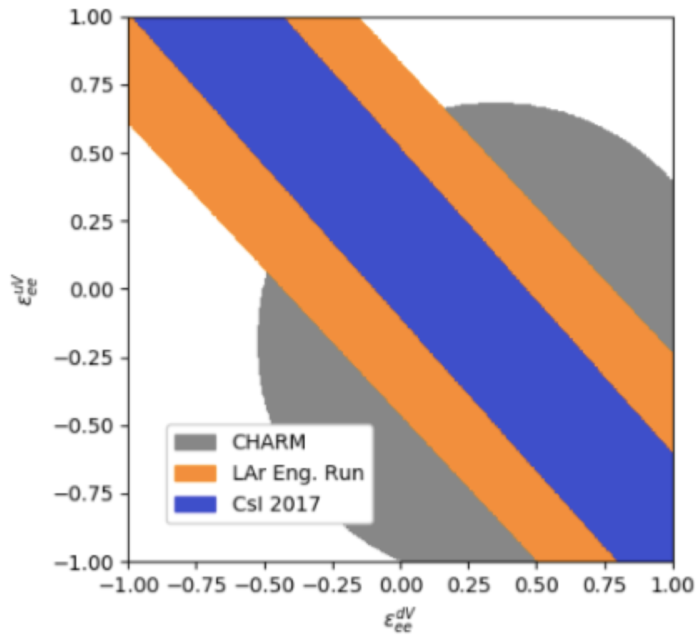
Matt Heath, Indiana U., thesis
APS April meeting
Just posted on arXiv






measure 1 ± 4 (stat), expect <1

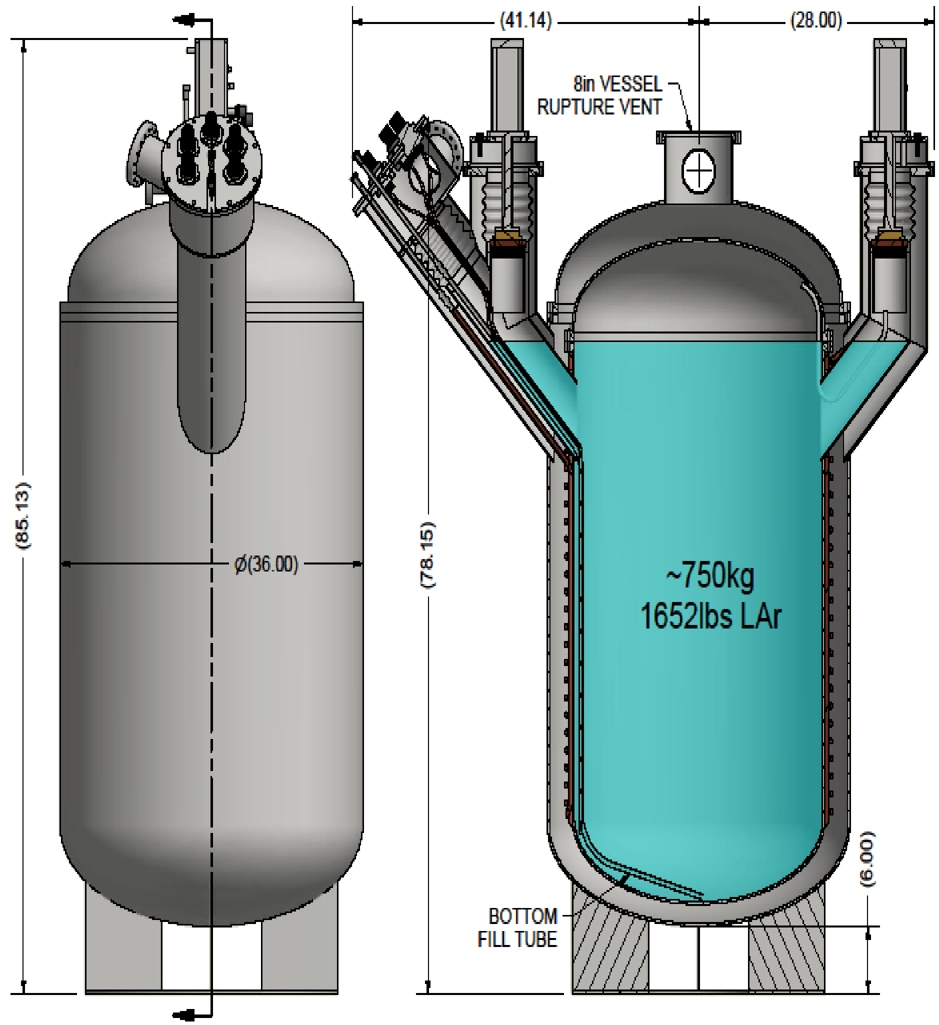
$\sigma_{\text{flux-avg}} < 3.4 \times 10^{-39}\,\text{cm}^2$



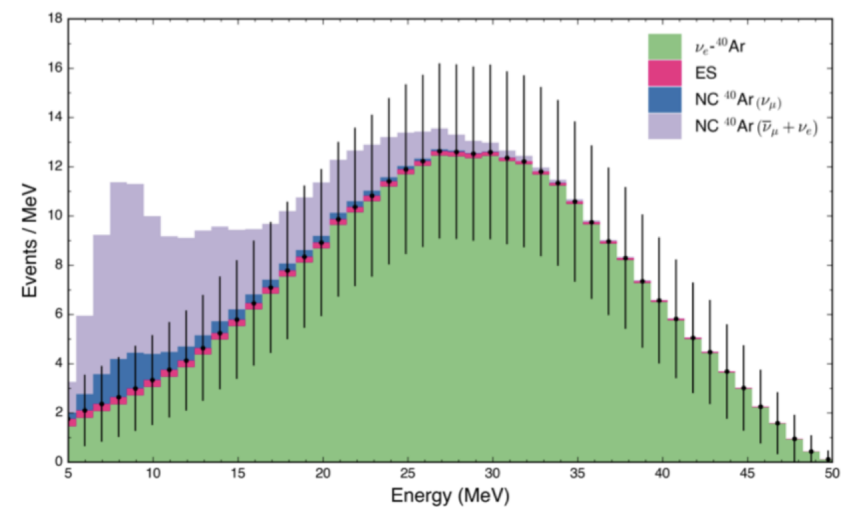


- **Results from more CsI running,** improved QF & analysis
- **Results from 22-kg LAr detector**
- Treatment of shape systematics
- Accelerator-produced DM sensitivity

# Tonne-scale LAr Detector




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



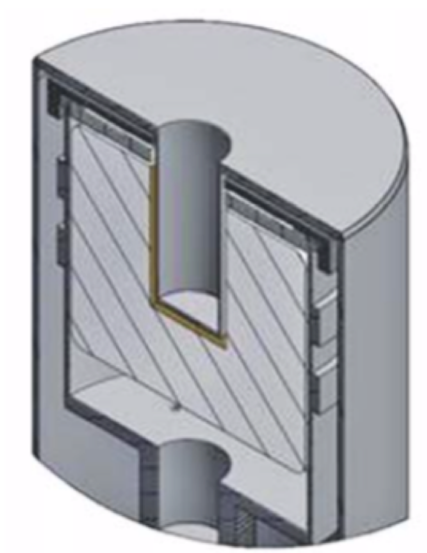

CC/NC **inelastic** in argon of interest for supernova neutrinos

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

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

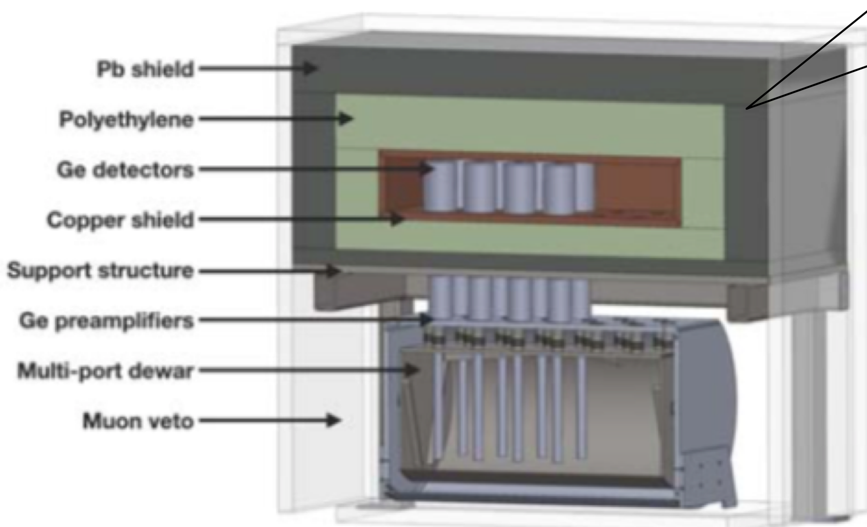
# High-Purity Germanium Detectors

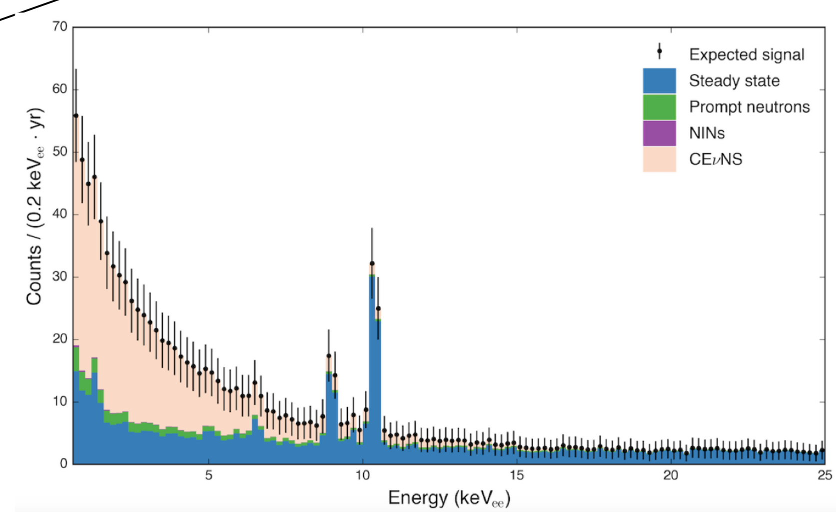
P-type Point Contact



- 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

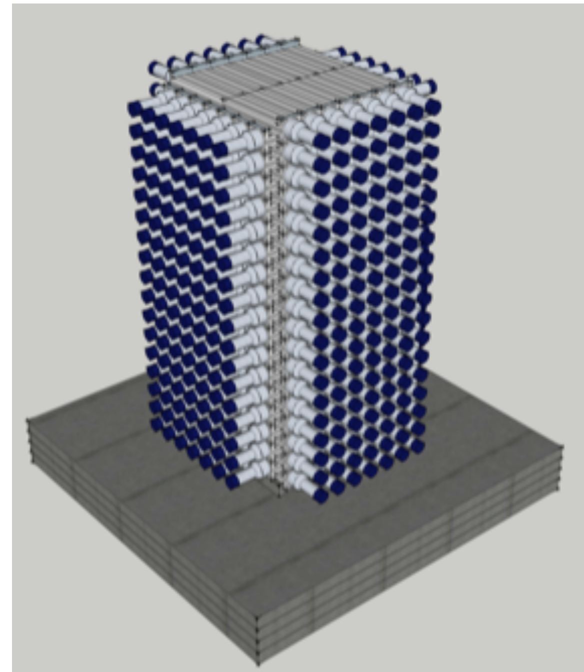


# Sodium Iodide (NaI[Tl]) Detectors (NaIvE)

- 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



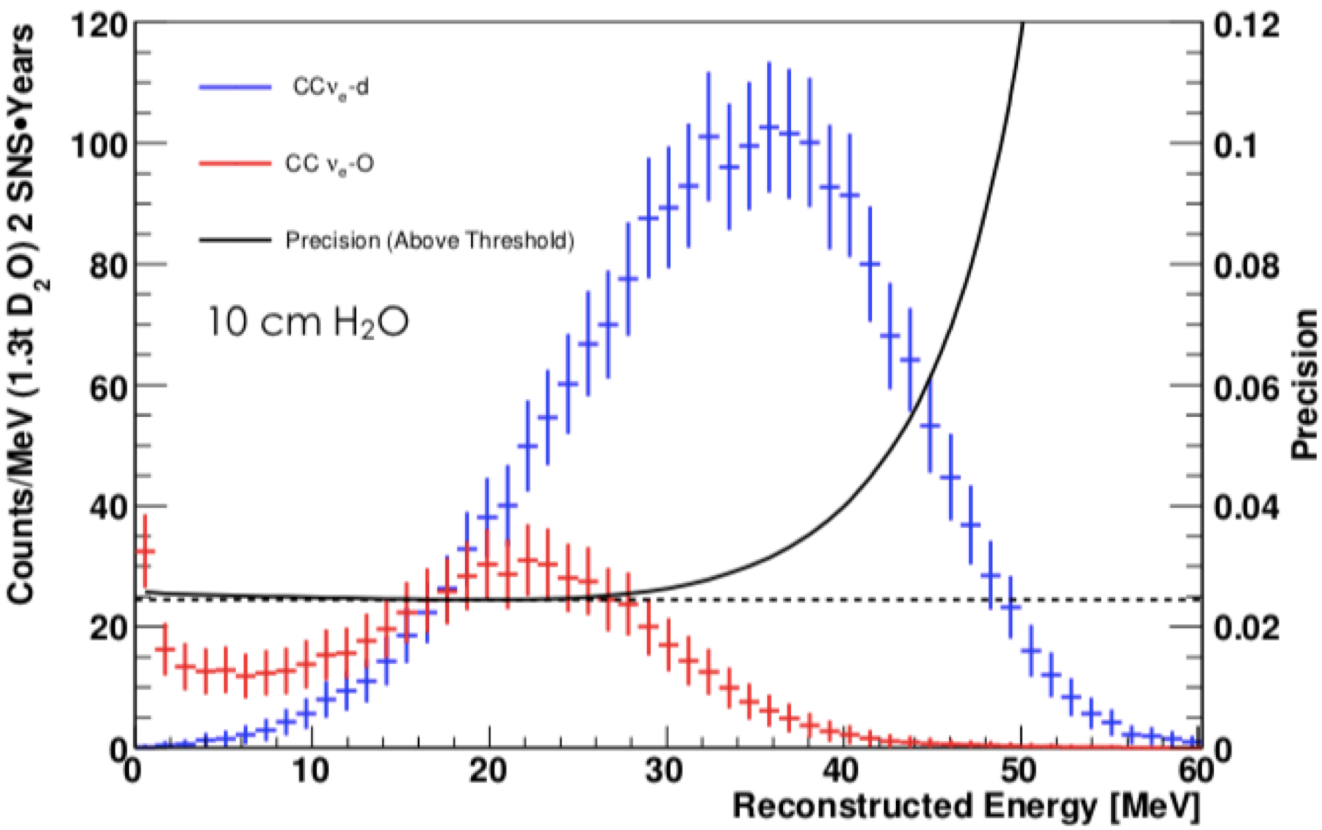
In the meantime: **185 kg deployed at SNS** to go after $\nu_e$**CC on $^{127}$I**

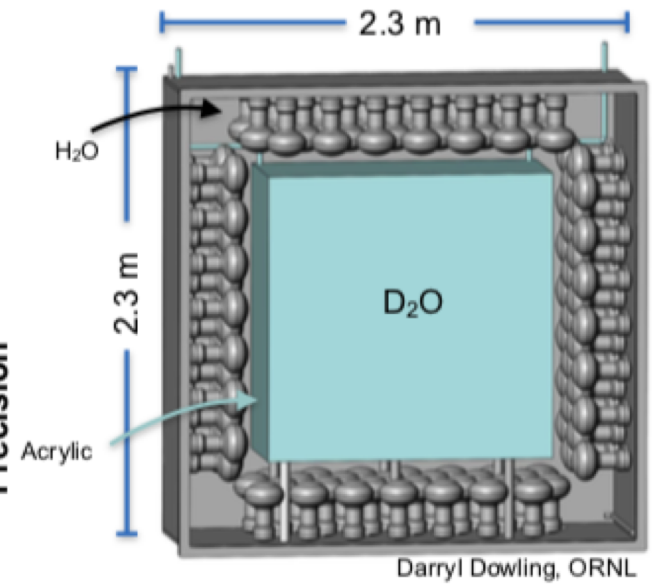
| Isotope | Reaction Channel | Source | Experiment | Measurement ($10^{-42}$ cm$^2$) | Theory ($10^{-42}$ cm$^2$) |
|---|---|---|---|---|---|
| $^{127}$I | $^{127}$I$(\nu_e, e^-)^{127}$Xe | Stopped $\pi/\mu$ | LSND | $284 \pm 91$(stat) $\pm 25$(sys) | 210-310 [Quasi-particle] (Engel *et al.*, 1994) |

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

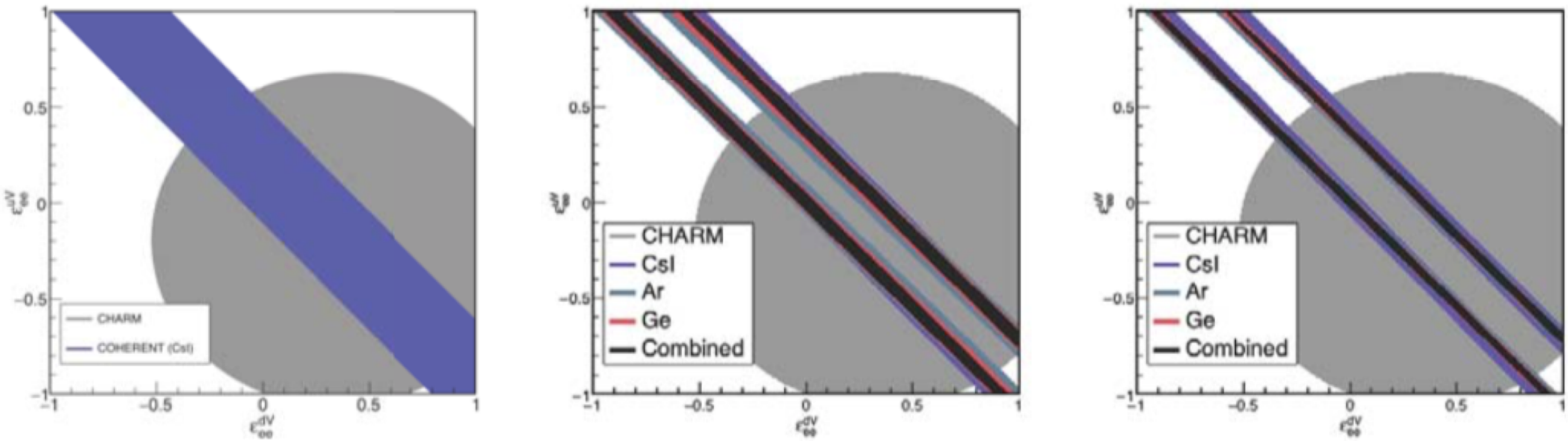



- 1.3 tons $D_2O$ within acrylic inner vessel
- 10 cm $H_2O$ "tail catcher" for high energy $e^-$
- 112 8" bialkali photomultipliers

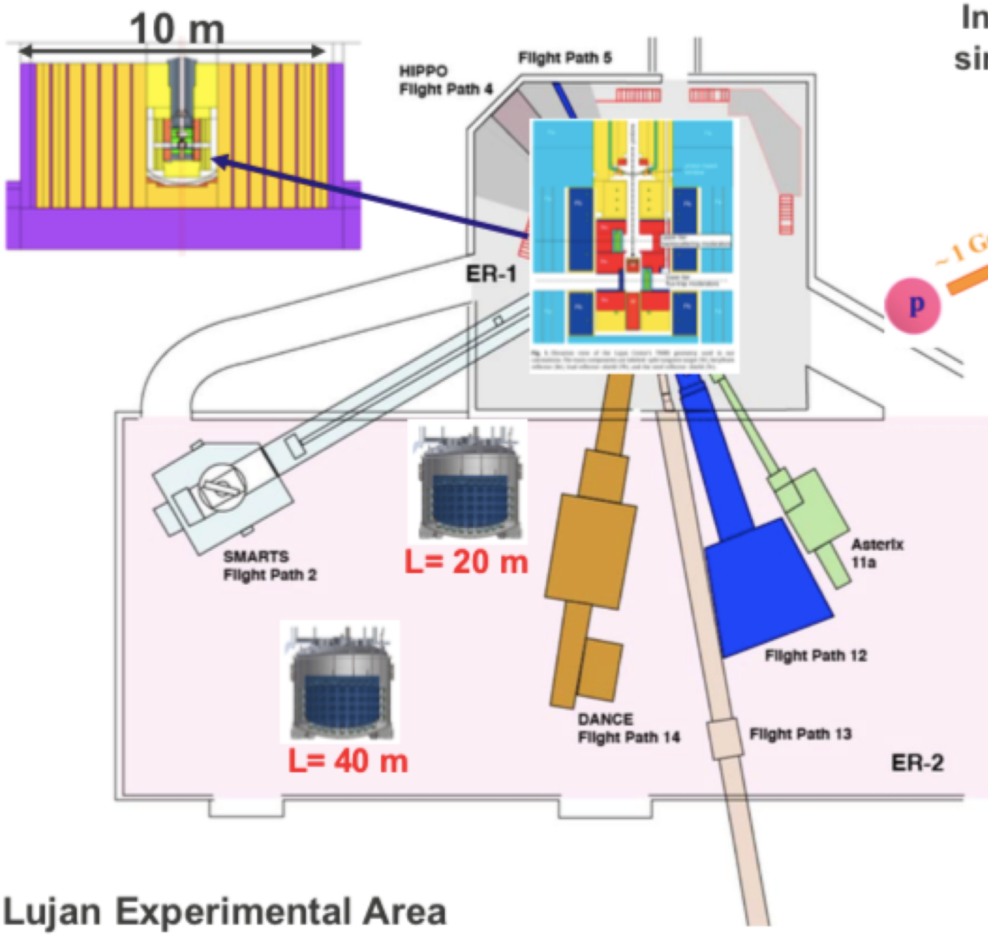
➔ ~few percent precision on flux normalization

# Estimated future sensitivities for NSI

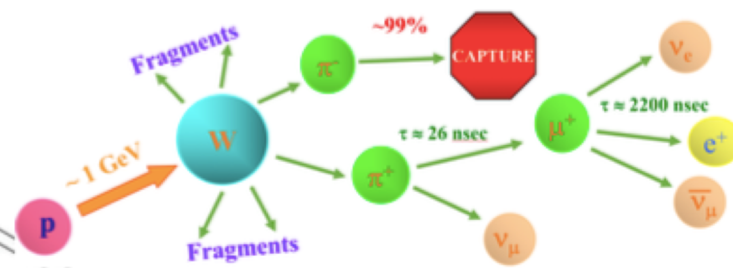



***Combination*** of targets improves sensitivity

# **Coherent Captain Mills @ Lujan:** single-phase LAr




Intense source muon neutrinos: target MCNP simulation flux $4.74\times10^{5}$ $\nu$/cm$^2$/s at 20 m



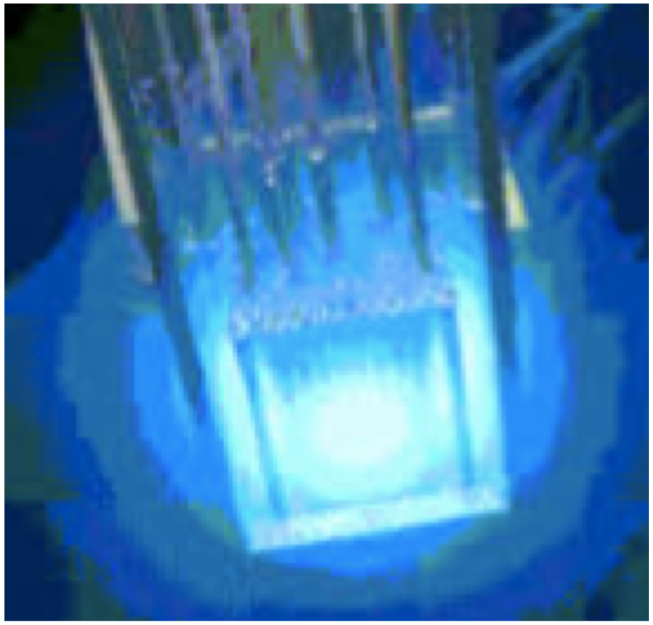


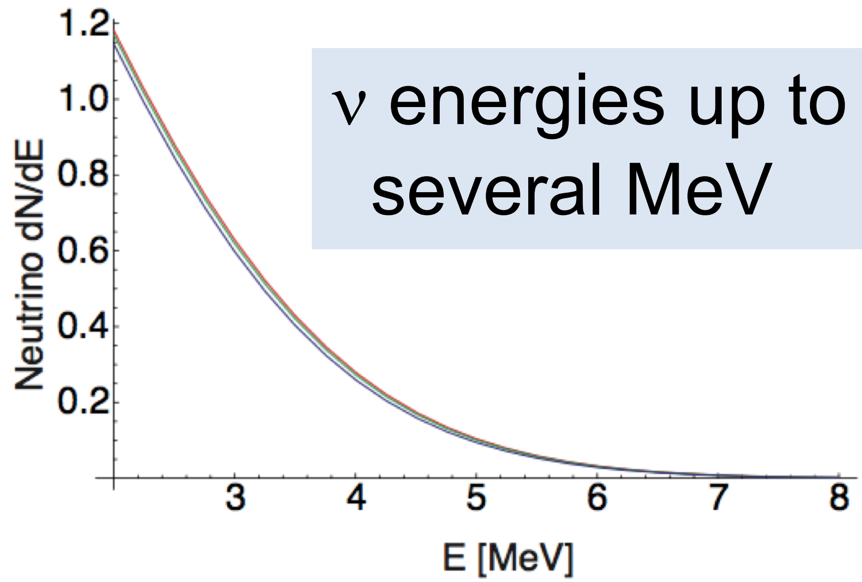
**Lujan Experimental Area**

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

Primary focus on sterile neutrinos (see D. Caratelli plenary talk, TAUP 2019)

# Neutrinos from nuclear reactors



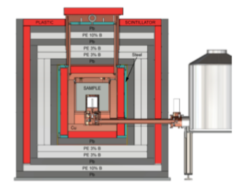
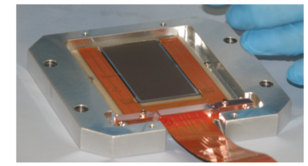


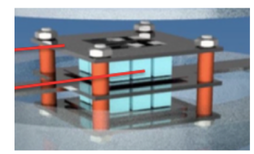

$\nu$ energies up to several MeV

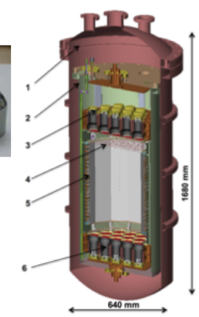
- $\nu_e$-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~$2 \times 10^{20}$ $s^{-1}$ per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

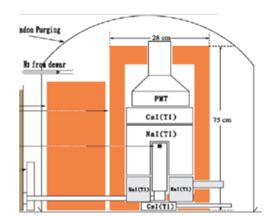
# Reactor CEvNS Efforts Worldwide

| Experiment | Technology | Location |
|---|---|---|
| **CONNIE** | Si CCDs | Brazil |
| **CONUS**<br>Talk by M. Lindner, | HPGe | Germany |
| **MINER** | Ge/Si cryogenic | USA |
| **NuCleus** | Cryogenic $CaWO_4$ , $Al_2O_3$ calorimeter array | Europe |
| **$\nu$GEN** | Ge PPC | Russia |
| **RED-100** | LXe dual phase | Russia |
| **Ricochet** | Ge, Zn bolometers | France |
| **TEXONO** | p-PCGe | Taiwan |





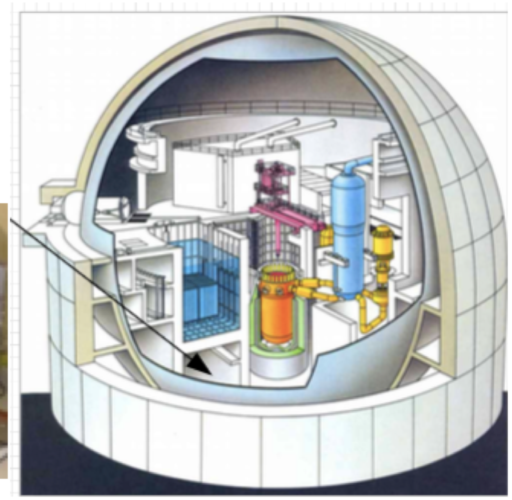


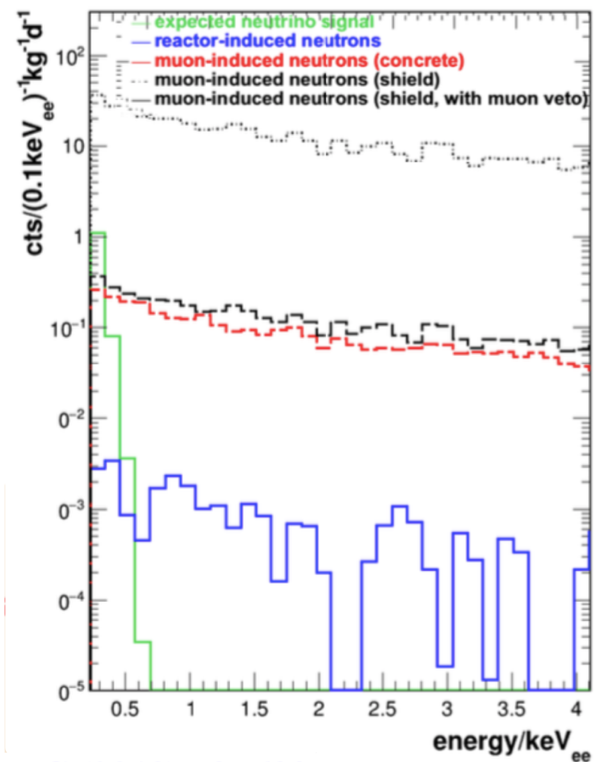
Many novel low-background, low-threshold technologies

See H. Wong, Nu2018 talk for a more detailed survey

# 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 $\sigma$ | 2.3 $\sigma$ |

(*) Including stat. uncertainty and above efficiencies

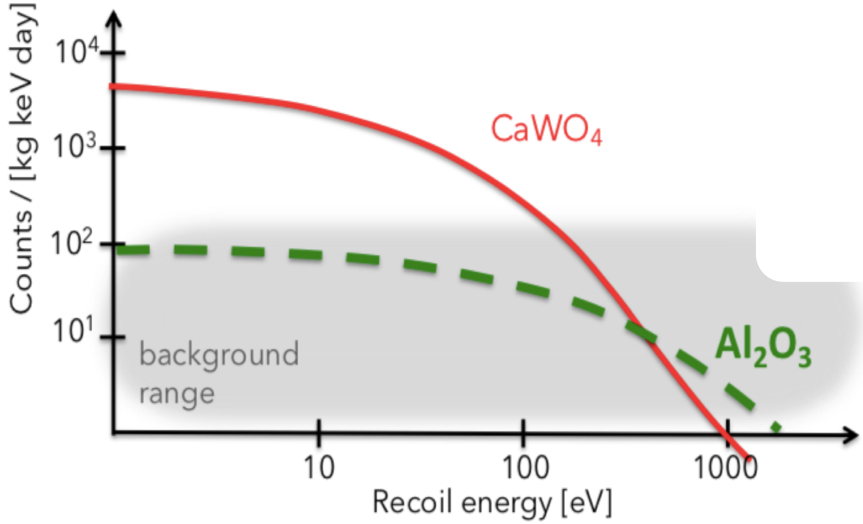
Some systematics still under study

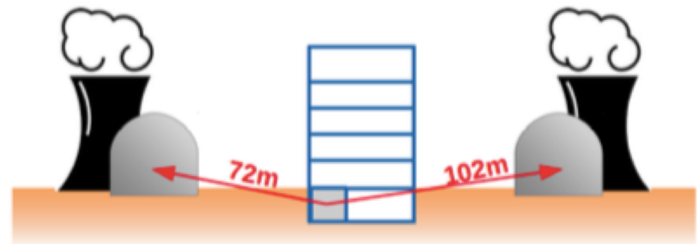
W. Maneschg, Nu2018

Talk by M.anfred Lindner

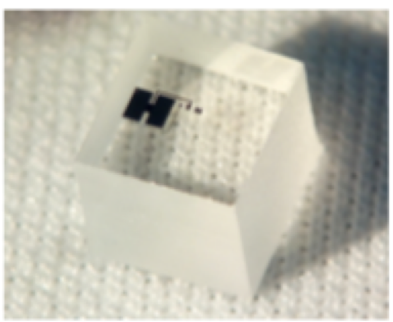
# NUCLEUS

"gram-scale cryogenic calorimeters"



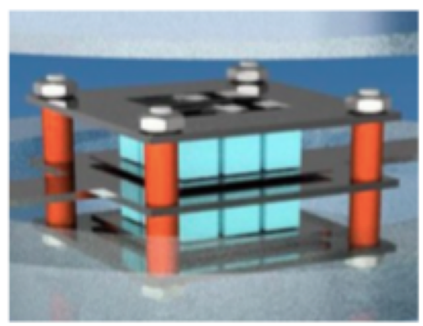

NUCLEUS 1g



2017-2019

straight
forward

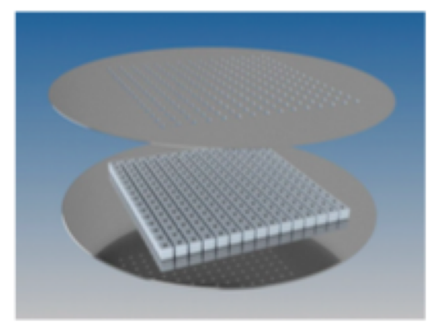
NUCLEUS 10g



2020-2022

major
R&D

NUCLEUS 1kg



>2024

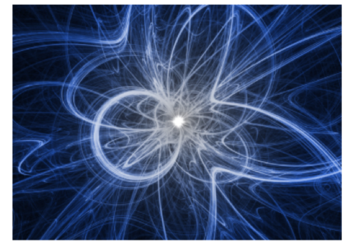
# CEvNS: what's it good for?

1 So
2 Many
3 Things

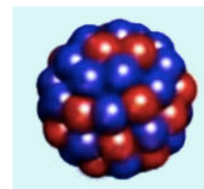
!

(not a complete list!)

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

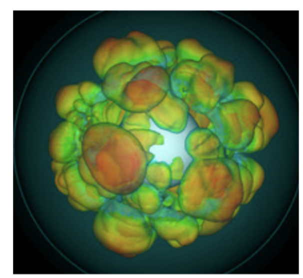


CEvNS as a **signal**
for understanding of "old" physics

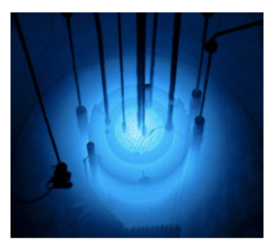


CEvNS as a **background**
for signatures of new physics (DM)

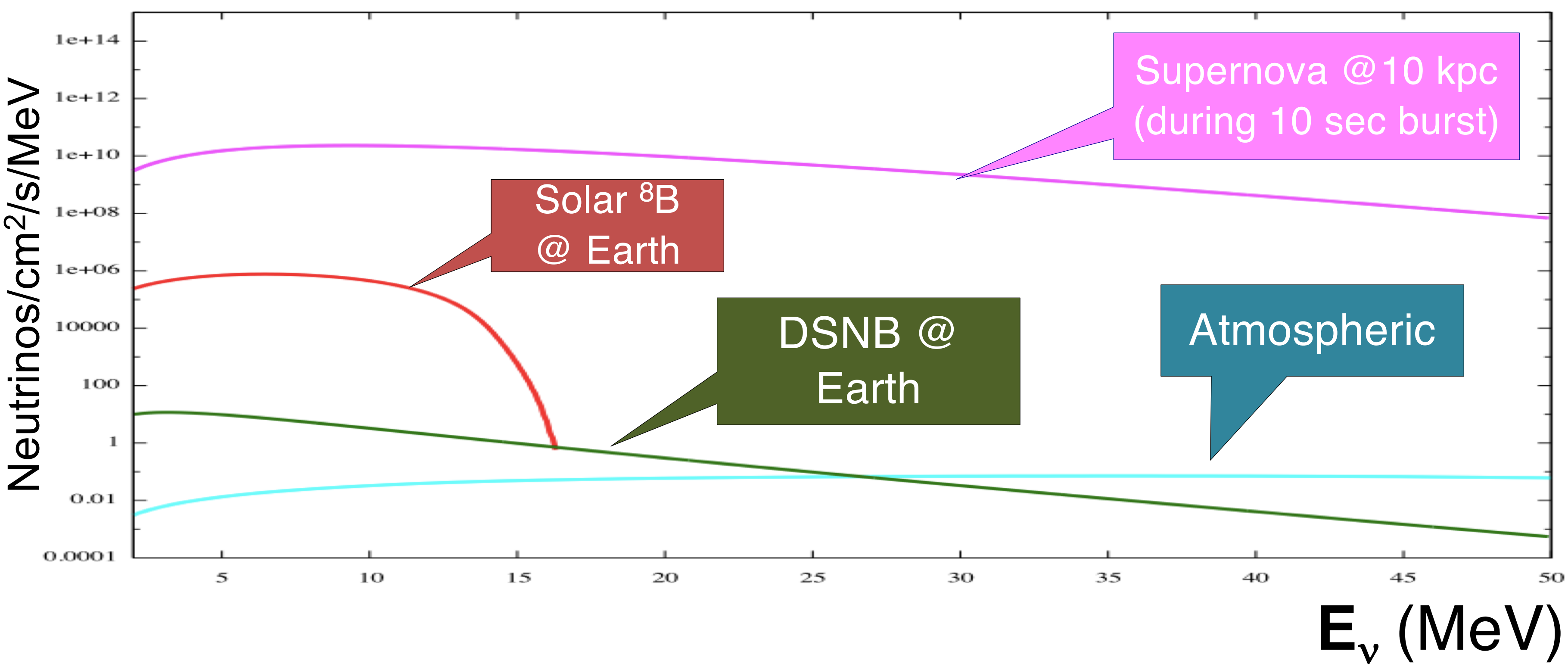

CEvNS as a **signal** for *astrophysics*



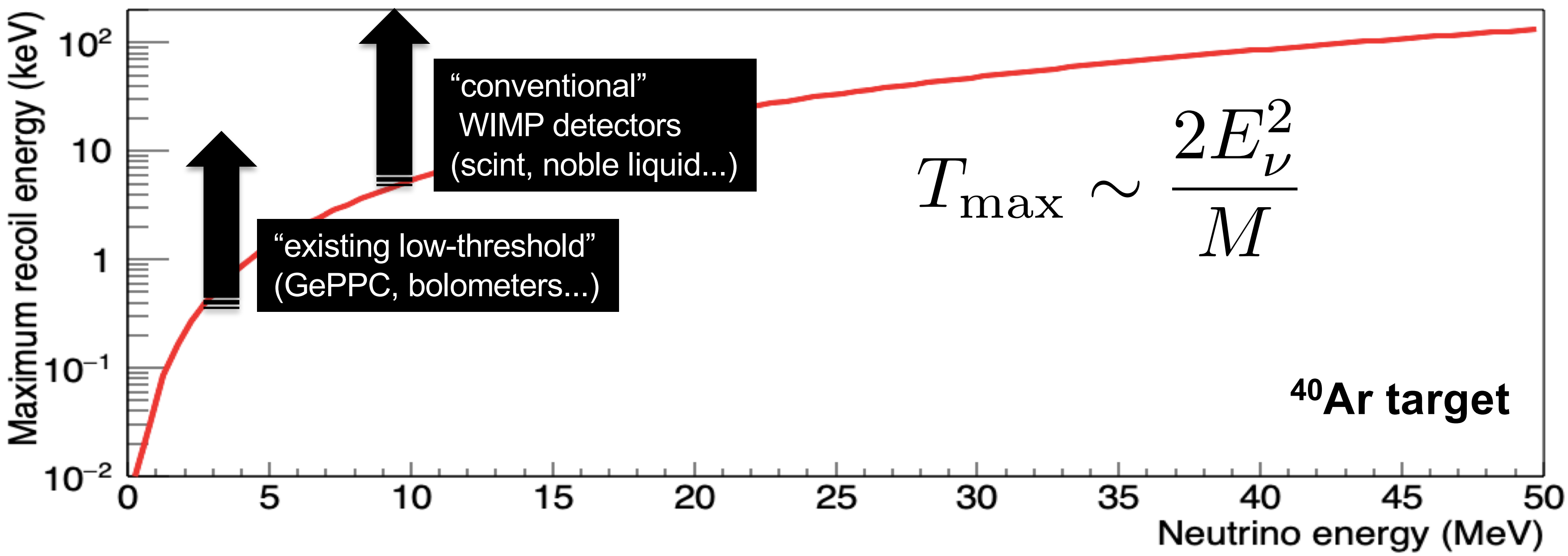
CEvNS as a **practical tool**

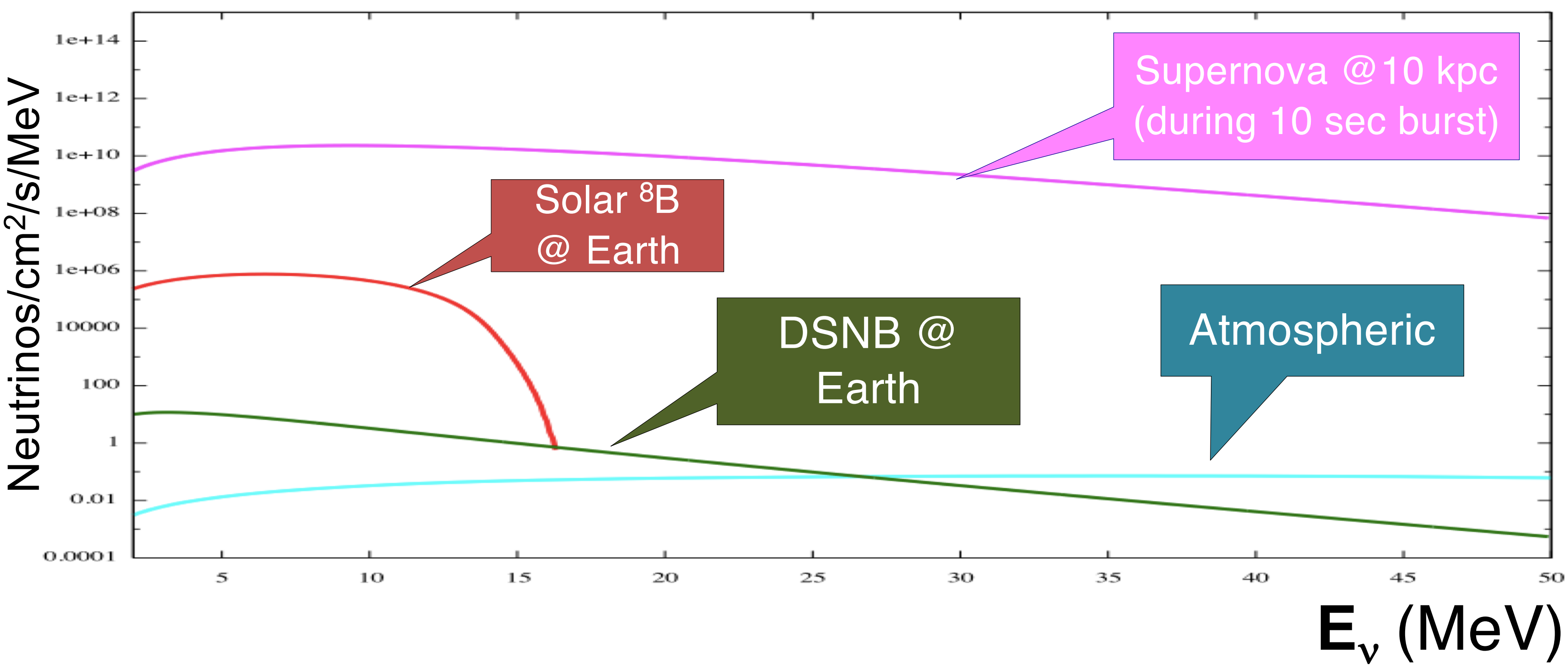


# Natural neutrino fluxes



# Natural neutrino fluxes

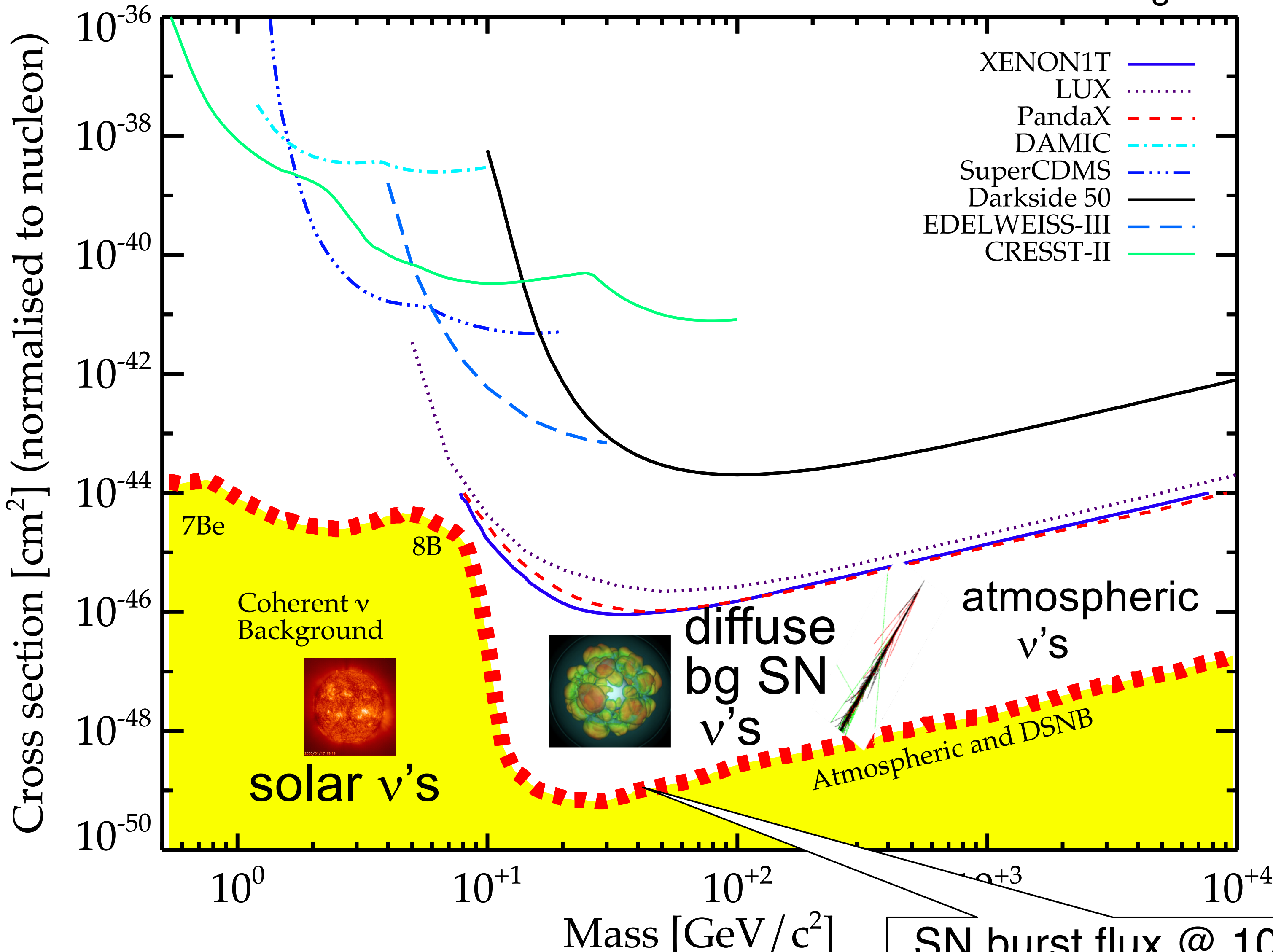


# The so-called “**neutrino floor**” for DM experiments

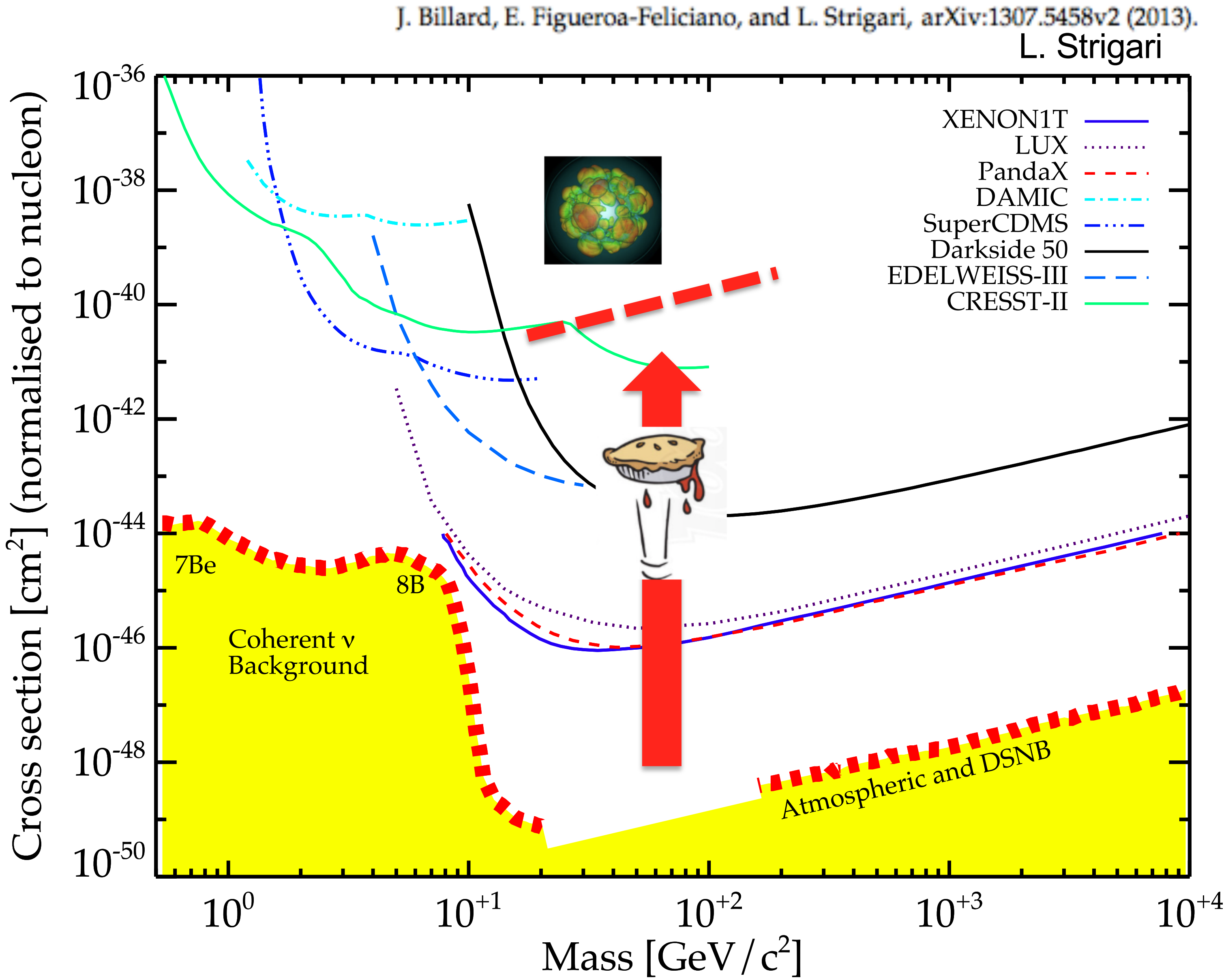
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

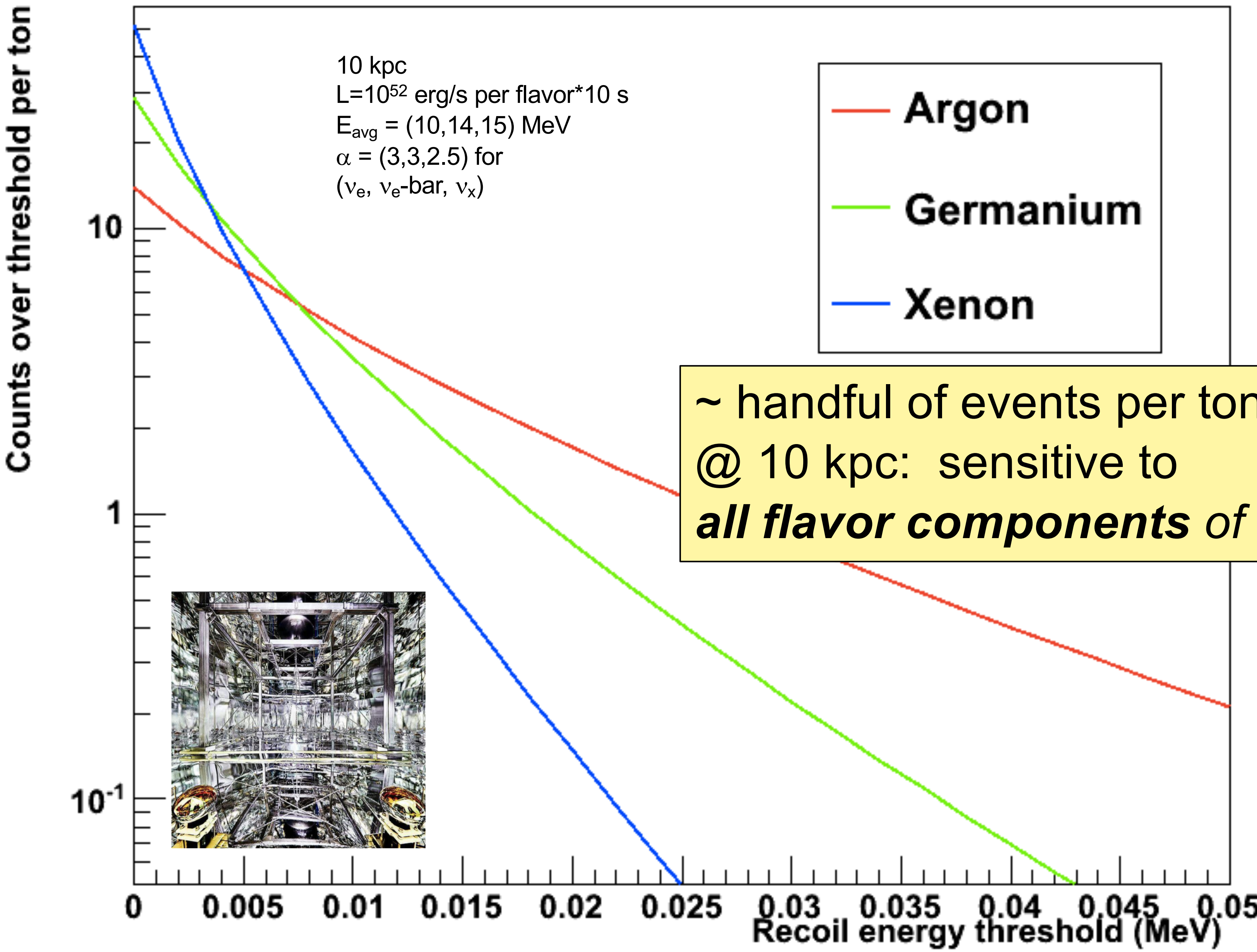



SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

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



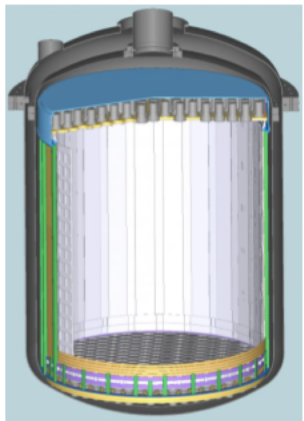
# Supernova neutrinos in tonne-scale DM detectors

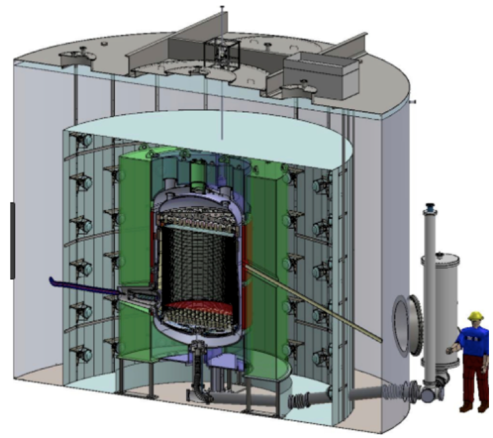


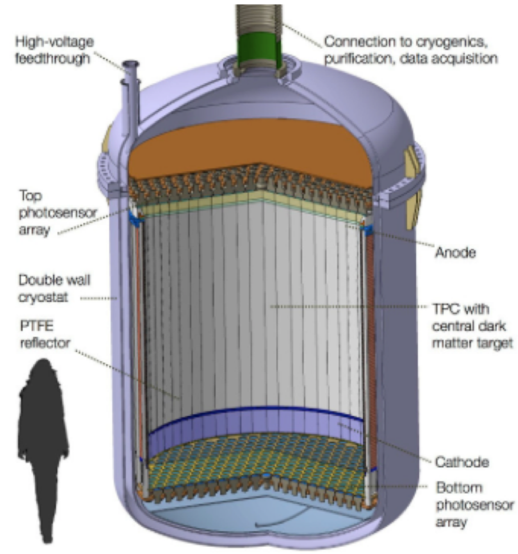

~ handful of events per tonne
@ 10 kpc: sensitive to
***all flavor components*** *of the flux*

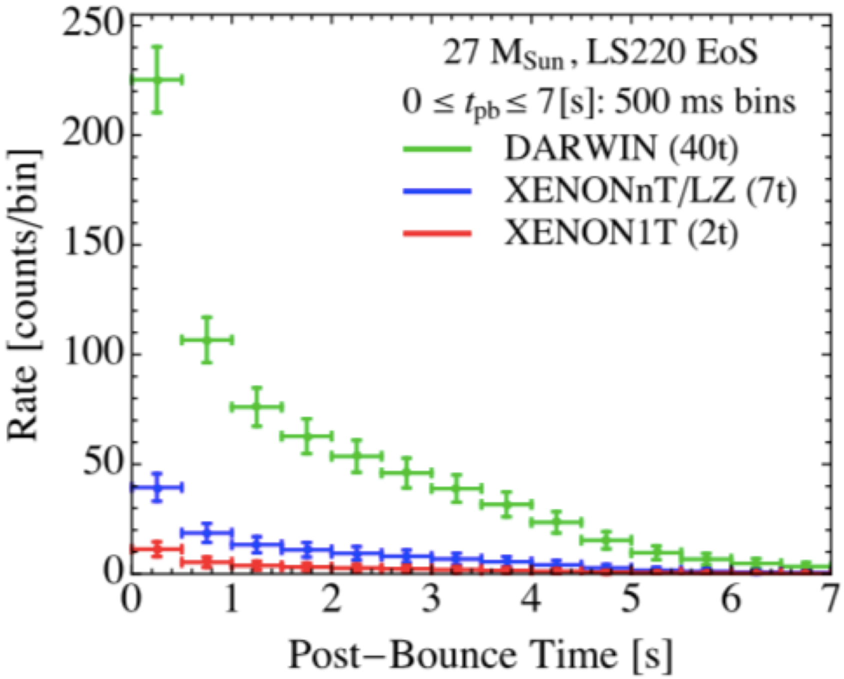
# Detector example: **XENON/LZ/DARWIN**

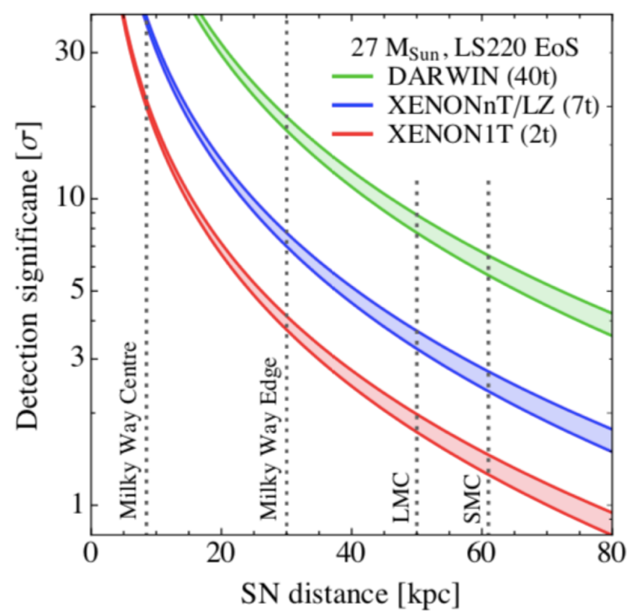
- dual-phase xenon time projection chambers







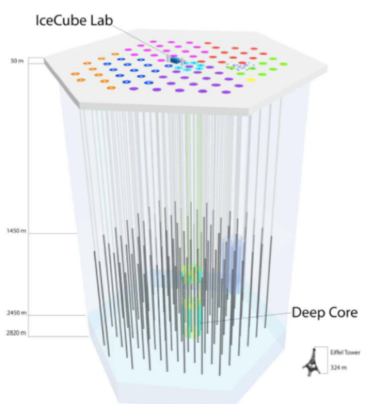

Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

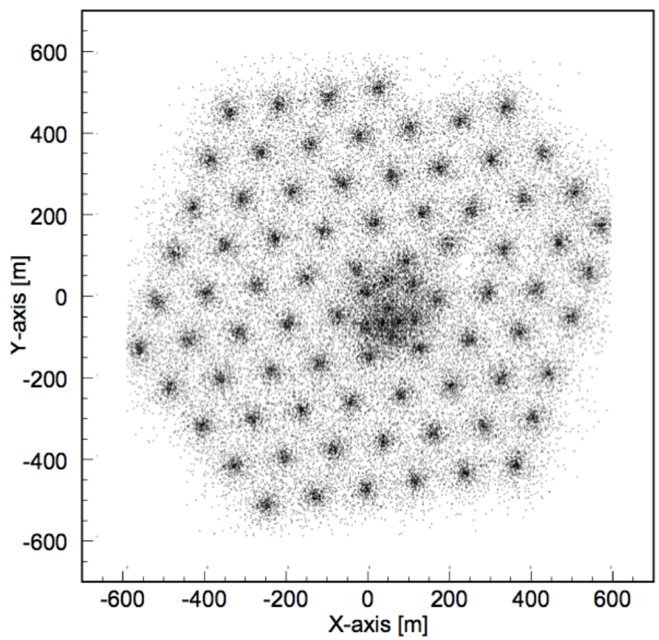
# New idea in early stages of exploration:

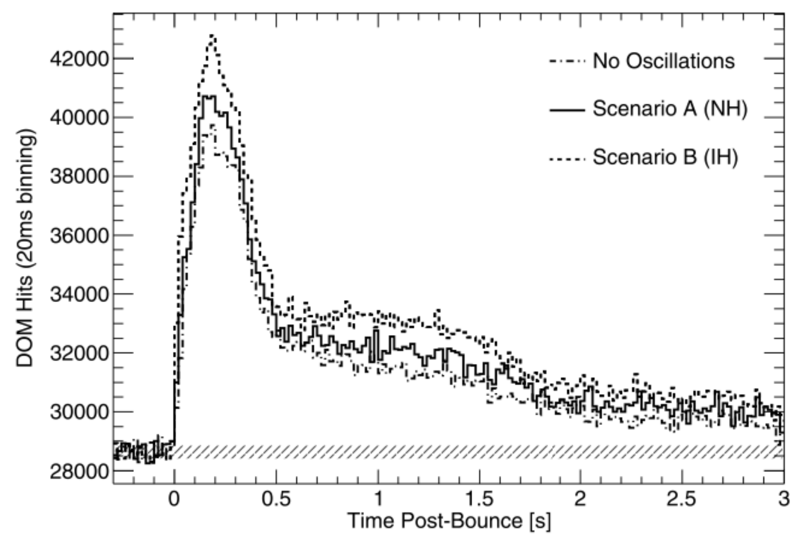
Adryanna Smith and Gleb Sinev @ Duke

## "CEvNS Glow" in large, high-threshold neutrino detectors

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




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

# Back-of-the-envelope:

## CEvNS signal vs Inelastic (CC/NC) signal:

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

~$10^2$ more CEvNS events per target wrt CC

~$10^{-3}$ less energy deposited per event for CEvNS wrt CC

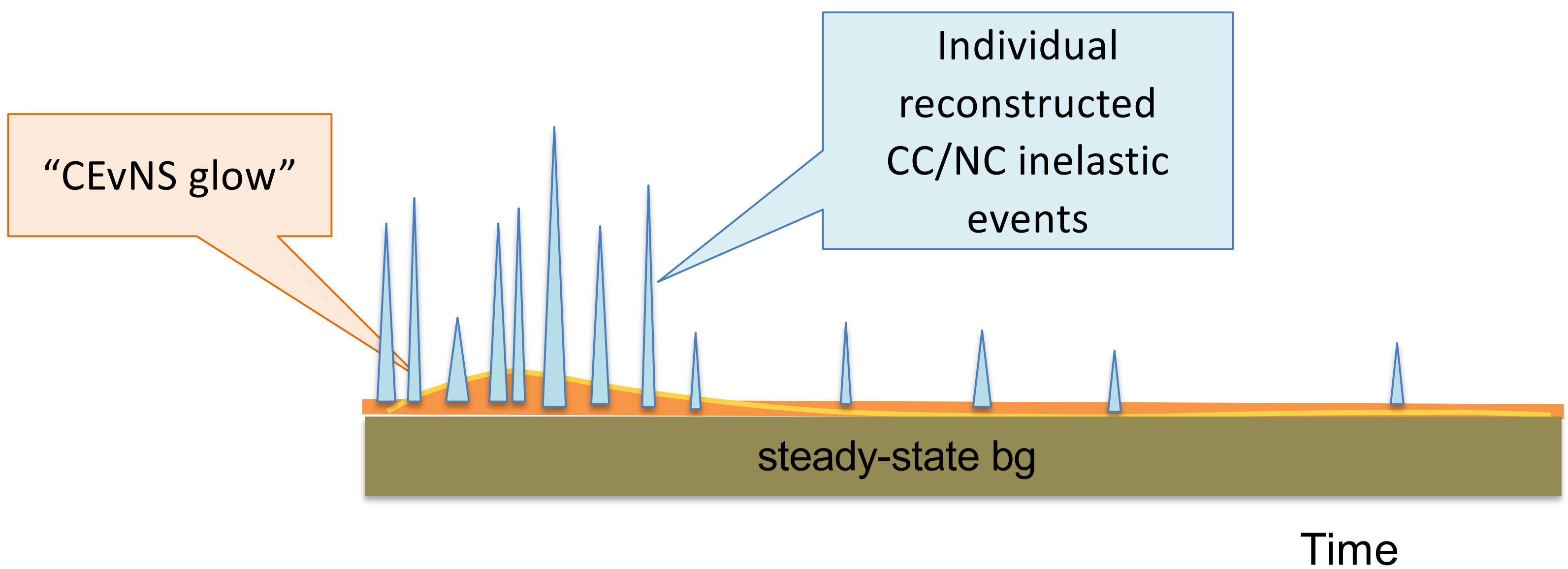
~ 6 due to sensitivity to all flavors

~0.001-0.2 quenching factor (photons wrt e/$\gamma$ energy deposit) for nuclear recoil wrt CC

➔Total CEvNS photons are **~few-10% of CC-generated photons**, but, **diffused over the burst** rather than in individual event spikes

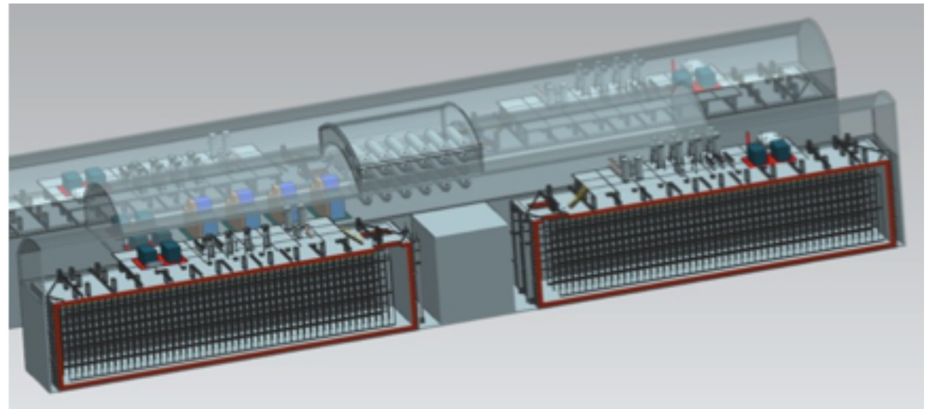
Issue is whether they exceed Sqrt[background]

(and triggering may be challenging!)



# Preliminary studies by A. Smith (+ G. Sinev)

For **DUNE**:  40 kt LAr,
~24,000 photons/MeV
TPC + photon detectors

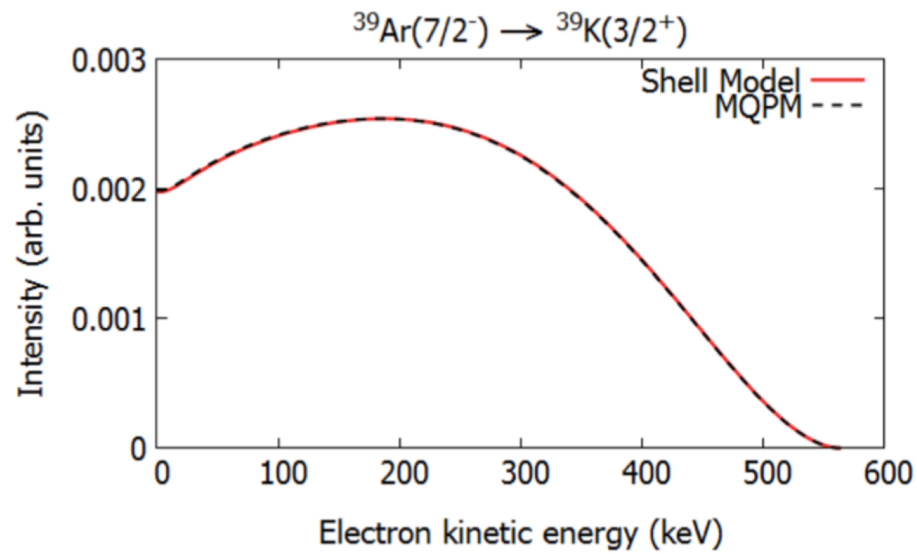


Most pernicious
 issue for CEvNS glow:

## $^{39}$Ar $\beta$ decays

(dominant radiological)

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



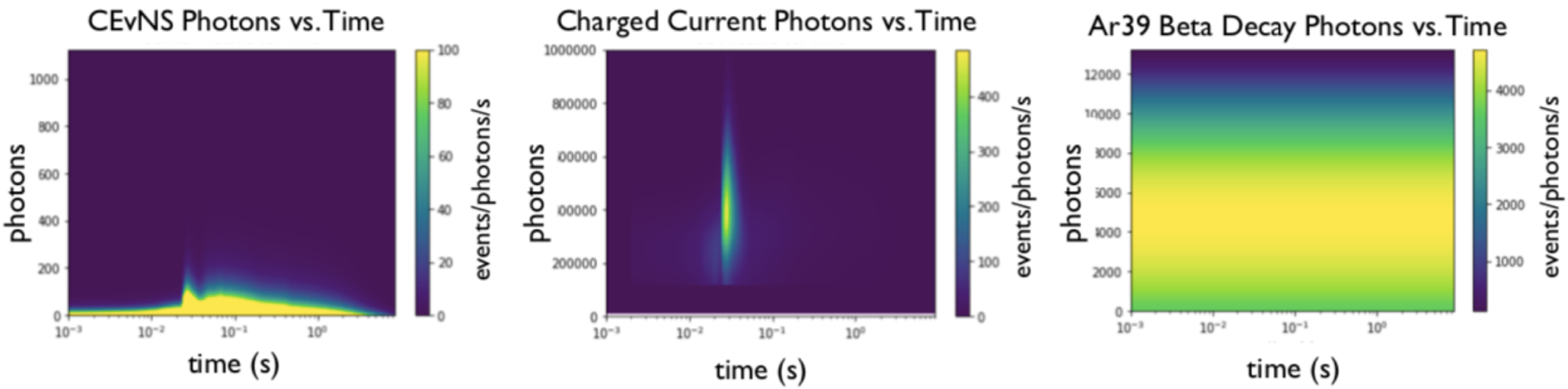

J. Kostensalo et al. (2017) arXiv:1705.05726

# Preliminary calculations of photon production:

"Garching" supernova model, 10 kt, 10 kpc

A. Smith

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

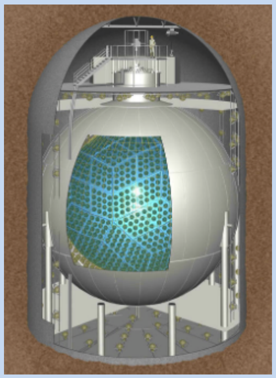



## Underway and TBD:

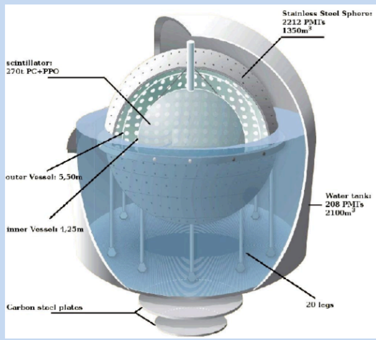
- photon transport (analytic & MC) and detection efficiencies
- additional backgrounds
- triggering not yet considered...
  serious challenge; may be able to trigger on CC
- **distribution** of observed $N_{pe}$ may help select signal
- ...study still in early stages!
- "CEvNS buzz" too?

# Also looking at **organic liquid scintillator**

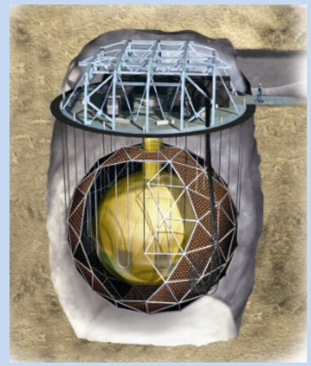
**KamLAND**
(Japan)
1 kton

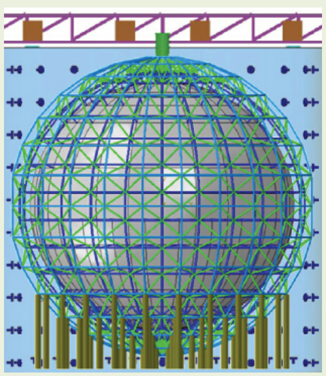


**Borexino**
(Italy)
0.33 kton



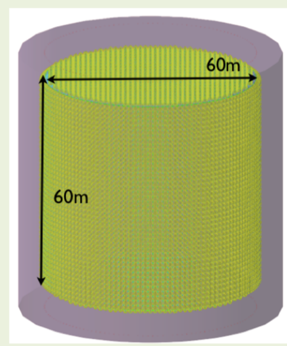

**SNO+**
(Canada)
1 kton



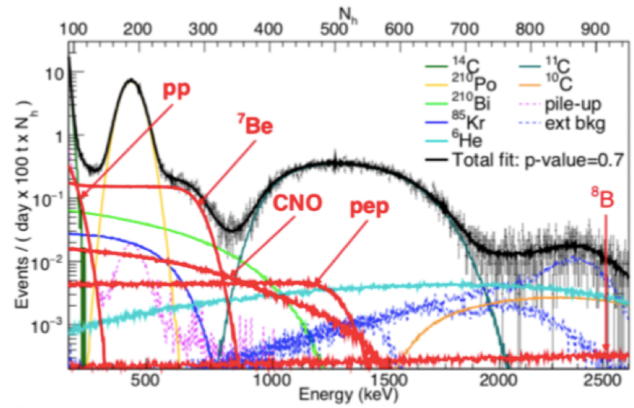


**JUNO**
(China)
20 kton

**Jinping**
(China)
2 kton




**THEIA**
(TBD)
50-100 kton
WbLS




From Borexino Collaboration
M. Agostini et al (2017) arXiv:1707.09279v2

- backgrounds tend to be quite low
- ~0.1% quenching for carbon recoils, ~1% for proton recoils

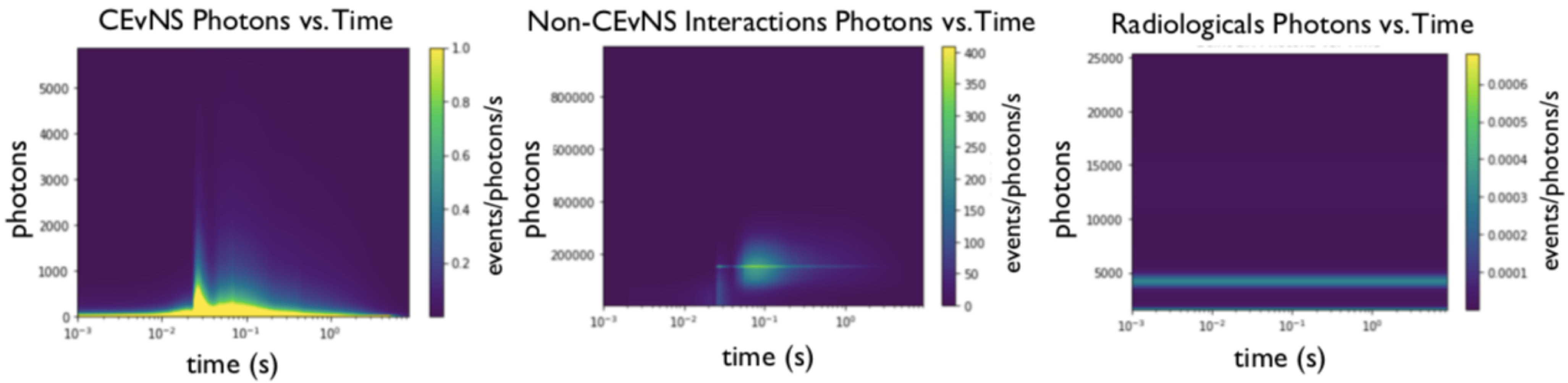
# Preliminary calculations of photon production in scintillator:

“Garching” supernova model, 10 kt, 10 kpc

A. Smith

$^{12}C$ CEvNS+NC$\nu$p

IBD+CC$\nu_e$+NC

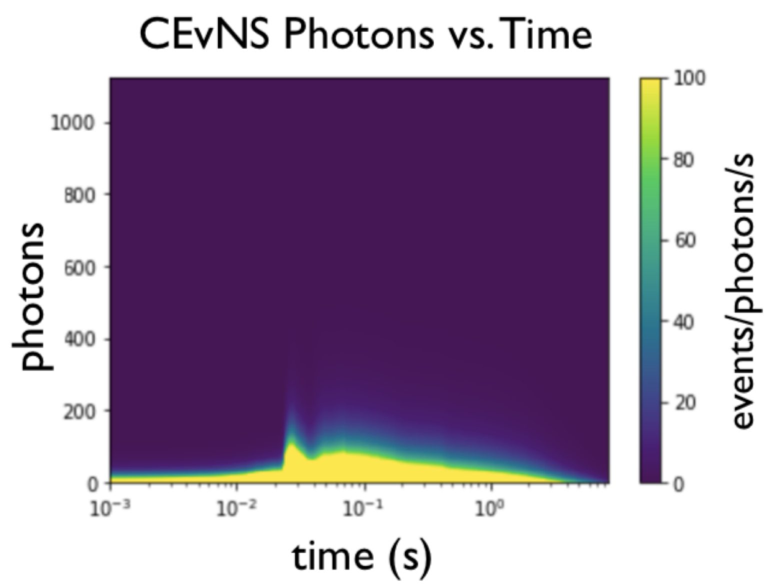



- similar studies underway... still in early stages!
- backgrounds are much less severe in clean scintillator detectors
- dark counts need to be considered

# Recap of CEvNS & supernovae

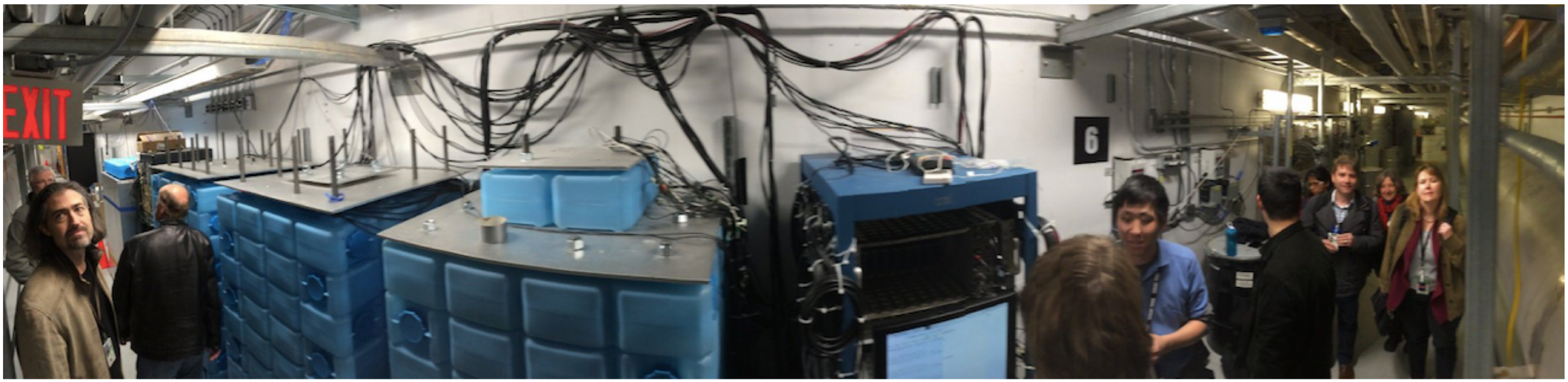
- **Core-collapse supernova neutrinos:**
  - vast information in flavor-energy-time profile
  - **NC info is especially valuable!** total energy, all-flavor profile

- **Supernova neutrinos and CEvNS:**
  - CEvNS is an important process inside the SN
  - CEvNS is a **supernova neutrino burst detection channel** w/ NC spectral info, tonne-scale DM detectors can exploit
  - New idea: **CEvNS glow** in large, higher-threshold neutrino detectors ... challenging, but still exploring



# Summary

- **CEvNS:**
  - large cross section, but tiny recoils, $\alpha$ 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
- **Meaningful bounds on beyond-the-SM physics**




- **It's just the beginning....** LAr + more CsI 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...)

# Magnificent CEvNS 2019

9-11 November 2019
The PIT
America/New_York timezone


Search...

- Overview
- Travel and accomodations
- Call for Abstracts
- Timetable
- Book of Abstracts
- Registration
- Participant List
- Remote participation

The second iteration of the Magnificent CEvNS workshop, focused on the process of coherent elastic neutrino-nucleus scattering (CEvNS).

Proposed in 1974, but unobserved until 2017, the physics accessible with CEvNS is broad. The goal of Magnificent CEvNS is to bring together a broad community of researchers working either directly or peripherally on CEvNS to foster enriching discussions to help direct the field as it continues to grow, forming and strengthening connections between experimentalists and theorists/phenomenologists.

*Magnificent CEvNS 2019 is supported by generous contributions from The CoSMS Institute and Triangle Universities Nuclear Laboratory.*

**Starts** 9 Nov 2019, 08:30
**Ends** 11 Nov 2019, 17:00
America/New_York

The PIT
462 W Franklin St
Chapel Hill, NC 27516
USA

Grayson Rich
Kate Scholberg
Louis Strigari
Matthew Green
phil barbeau