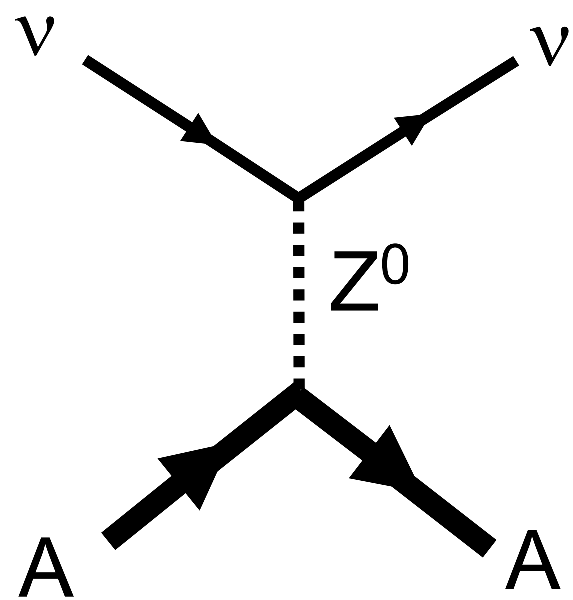
COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING EXPERIMENTAL PROGRAMS

Kate Scholberg,
Duke University

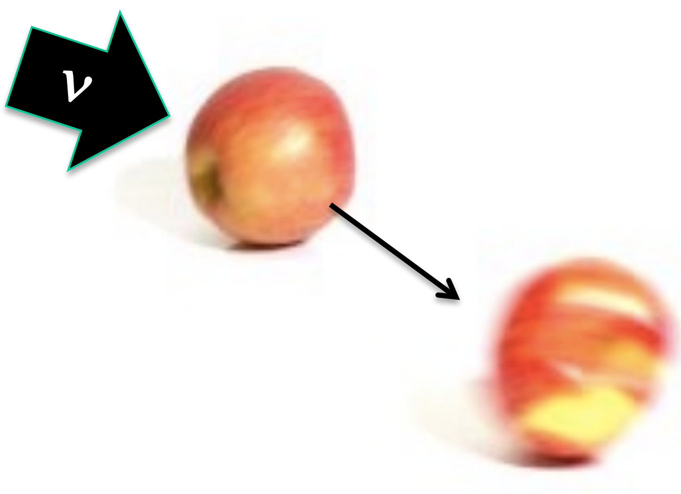
PANIC 2021
September 2021

Coherent elastic neutrino-nucleus scattering (CEvNS)

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

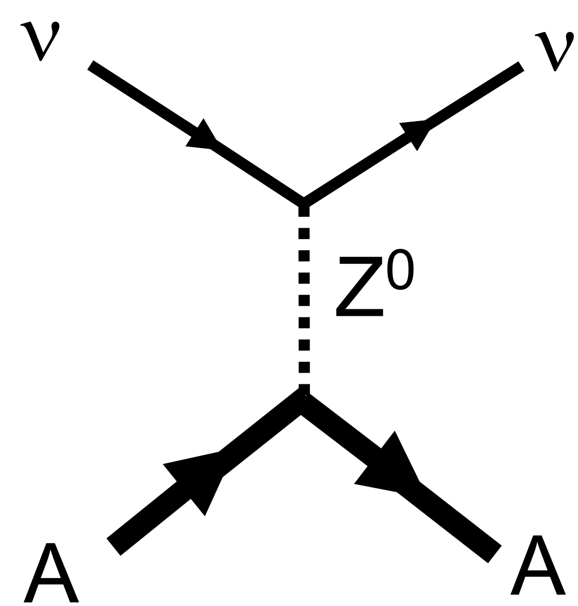


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



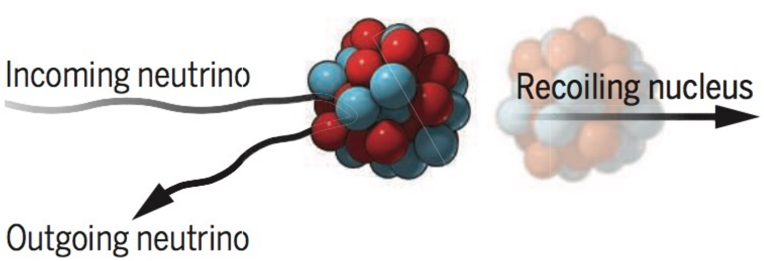
Coherent elastic neutrino-nucleus scattering (CEvNS)

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



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

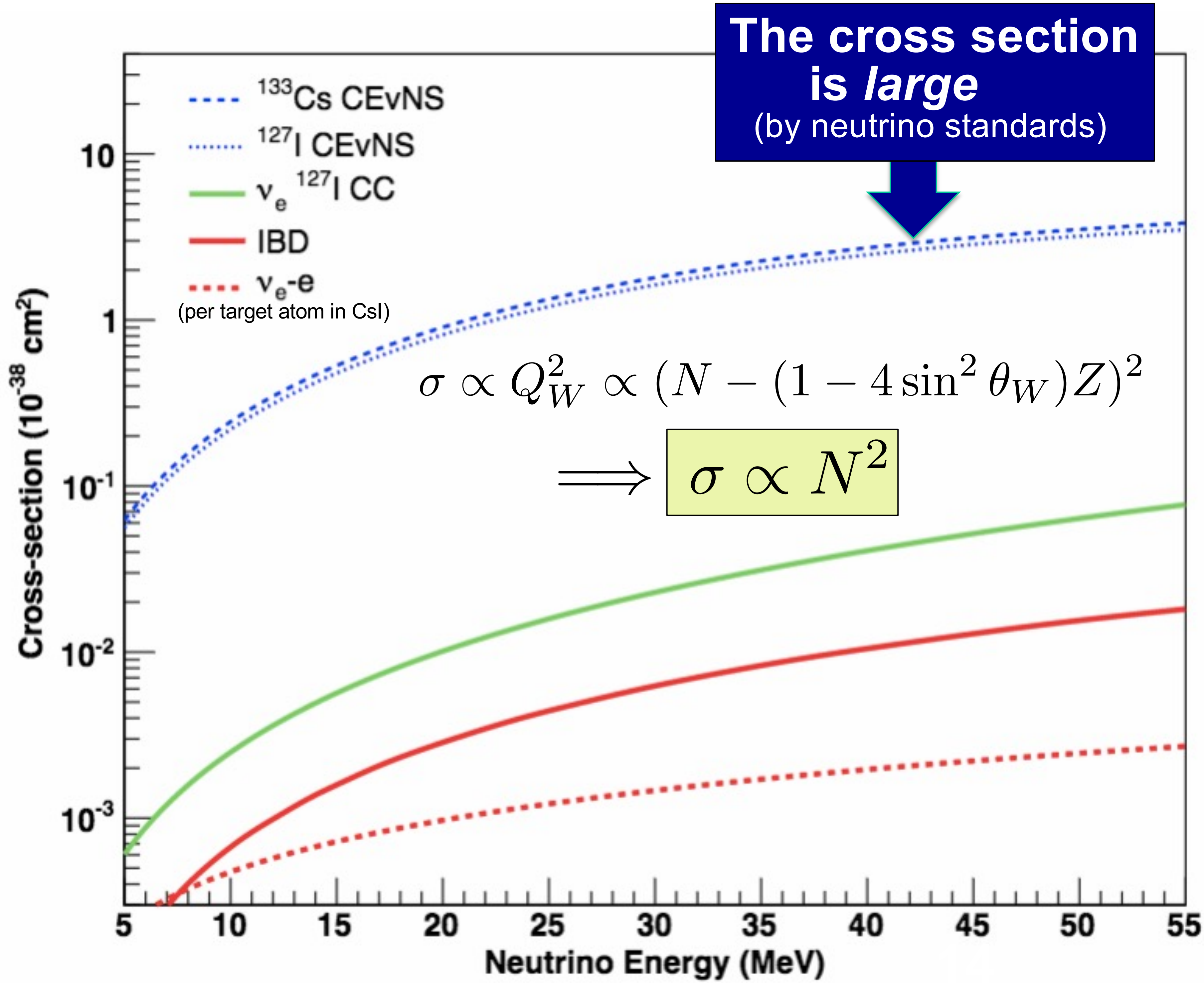
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer



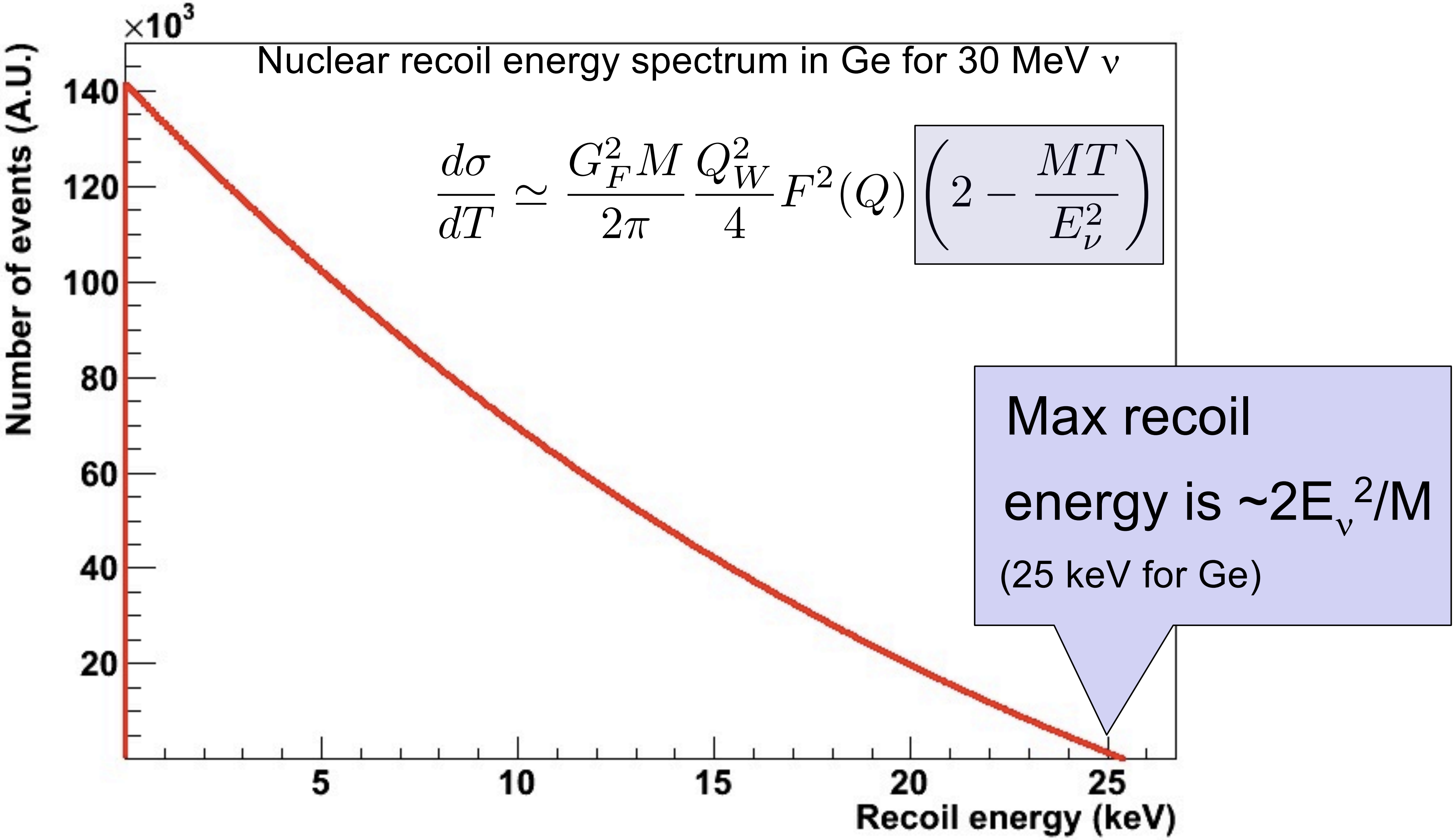
For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives


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

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



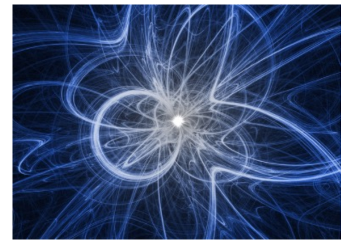
CEvNS: what's it good for?

1. So
2. Many
3. Things

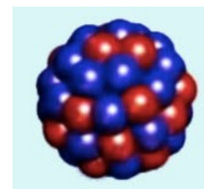
!

(not a complete list!)

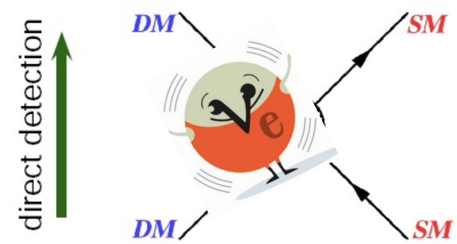
CEvNS as a **signal**
for signatures of *new physics*

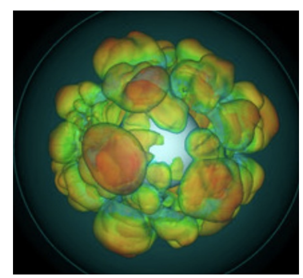


CEvNS as a **signal**
for understanding of "old" physics



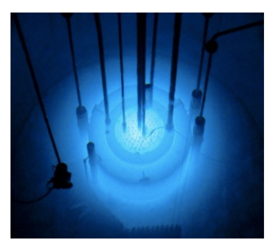
CEvNS as a **background**
for signatures of new physics





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

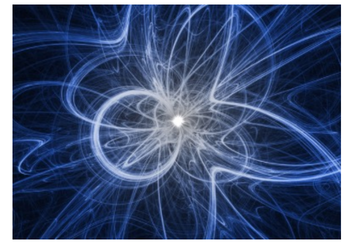
CEvNS as a **practical tool**



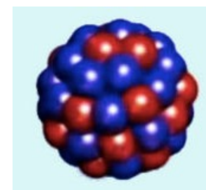
CEvNS: what's it good for?

! (not a complete list!)

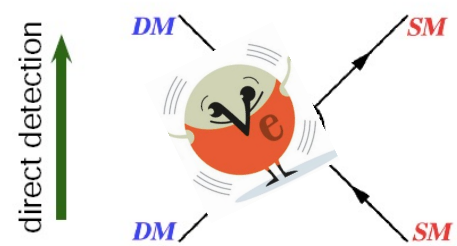
CEvNS as a **signal**
for signatures of *new physics*



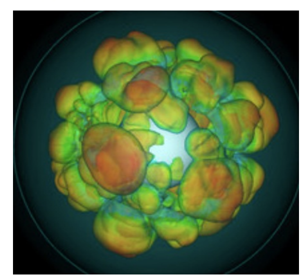
CEvNS as a **signal**
for understanding of "old" physics



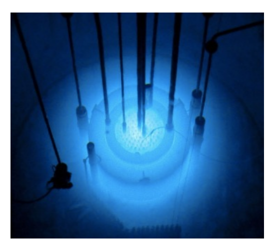
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



The cross section is cleanly predicted in the Standard Model

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

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

G_V, G_A: SM weak parameters

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

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

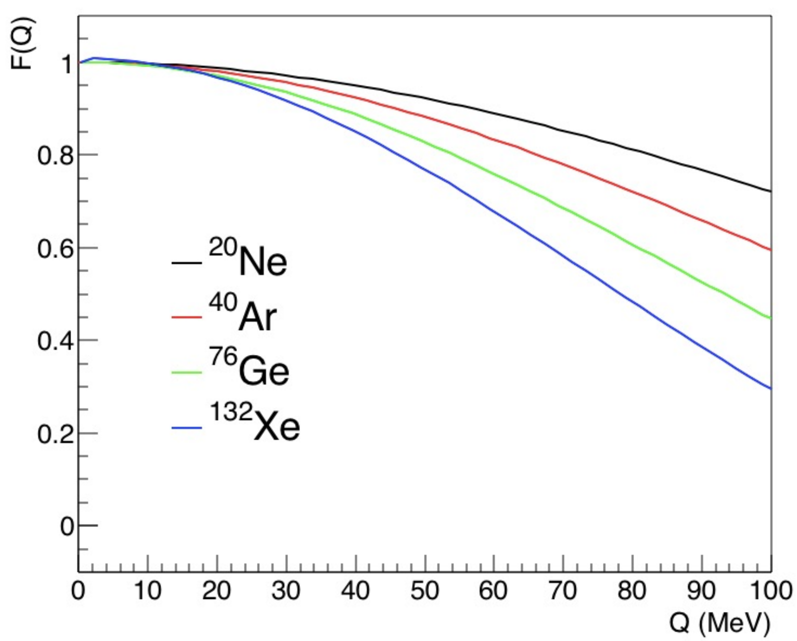
$$\boxed{\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}}$$

The cross section is cleanly predicted in the Standard Model

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

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

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

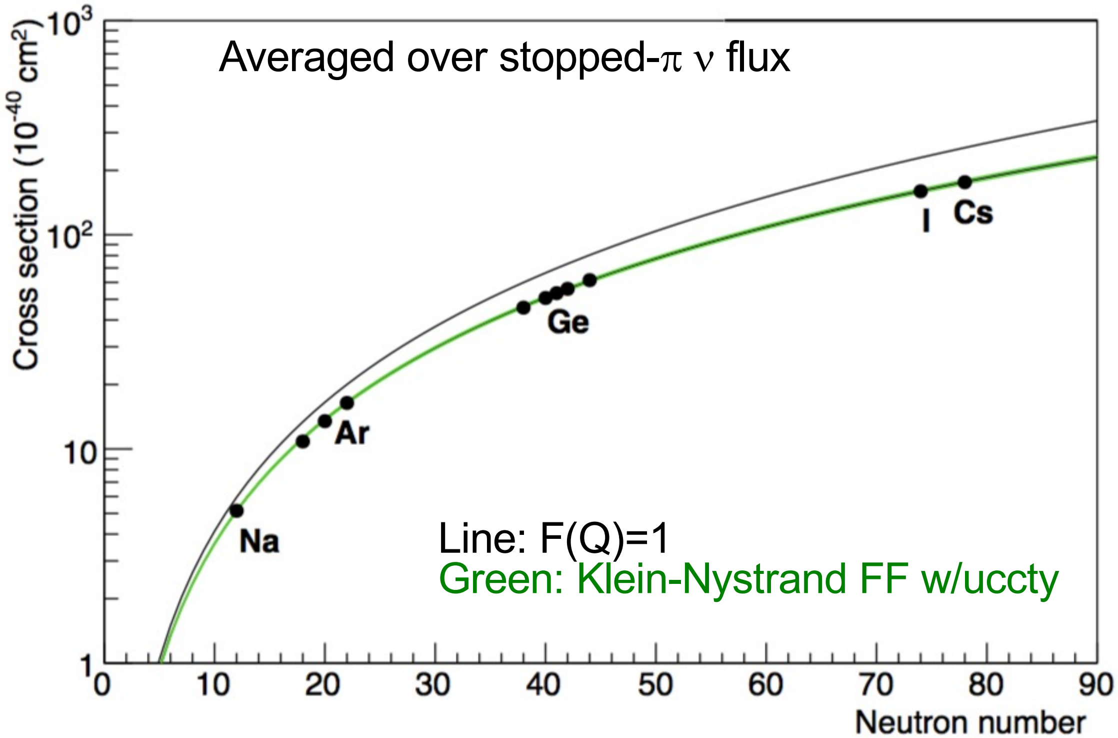


form factor suppresses cross section at large Q

The CEvNS rate is a clean SM prediction

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

small nuclear uncertainties



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

Non-Standard Interactions of Neutrinos:

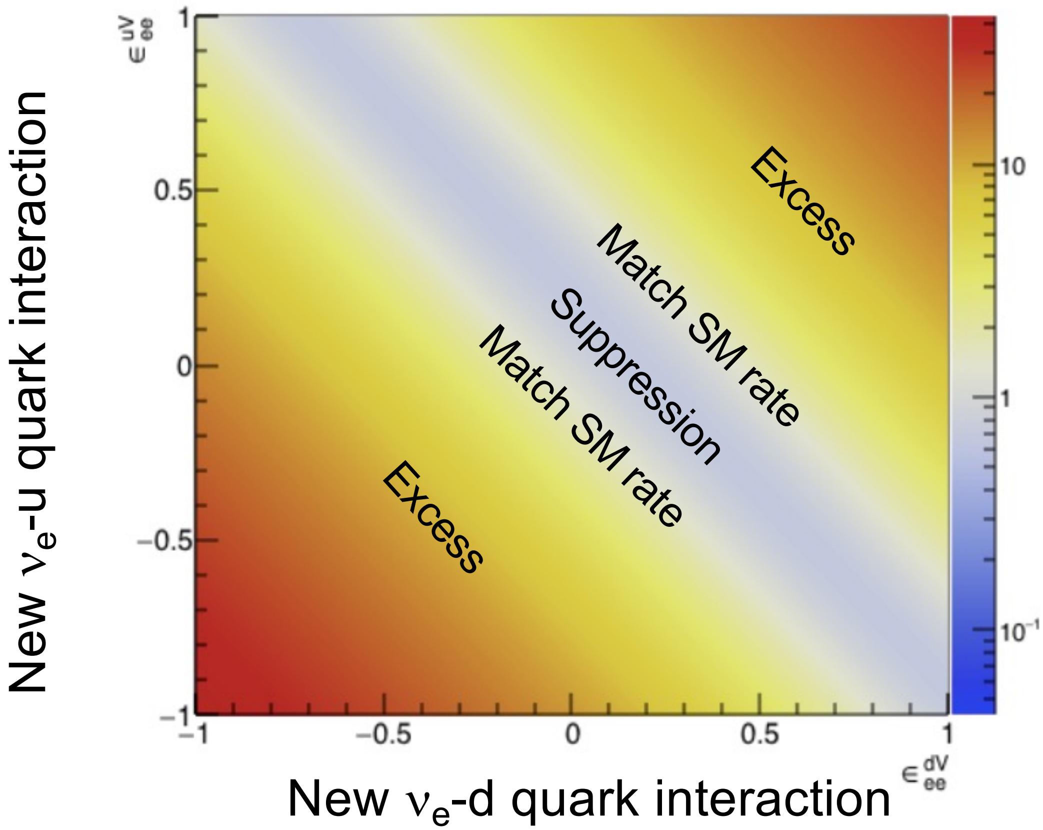
new interaction **specific to ν's**

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

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

CsI

Ratio
wrt SM



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'

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

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

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

"True" disappearance with baseline-dependent Q distortion

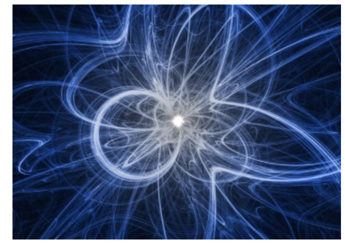
e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

More from O. Miranda and D. Papoulias

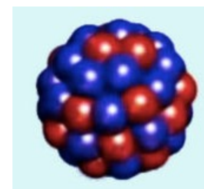
CEvNS: what's it good for?

! (not a complete list!)

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

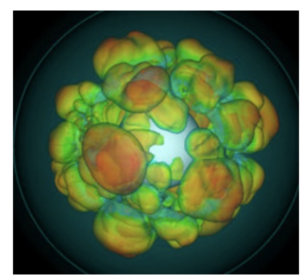


CEvNS as a **signal**
for understanding of "old" physics

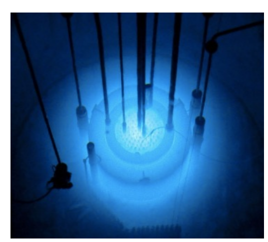


CEvNS as a **background**
for signatures of new physics (DM)

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



CEvNS as a **practical tool**

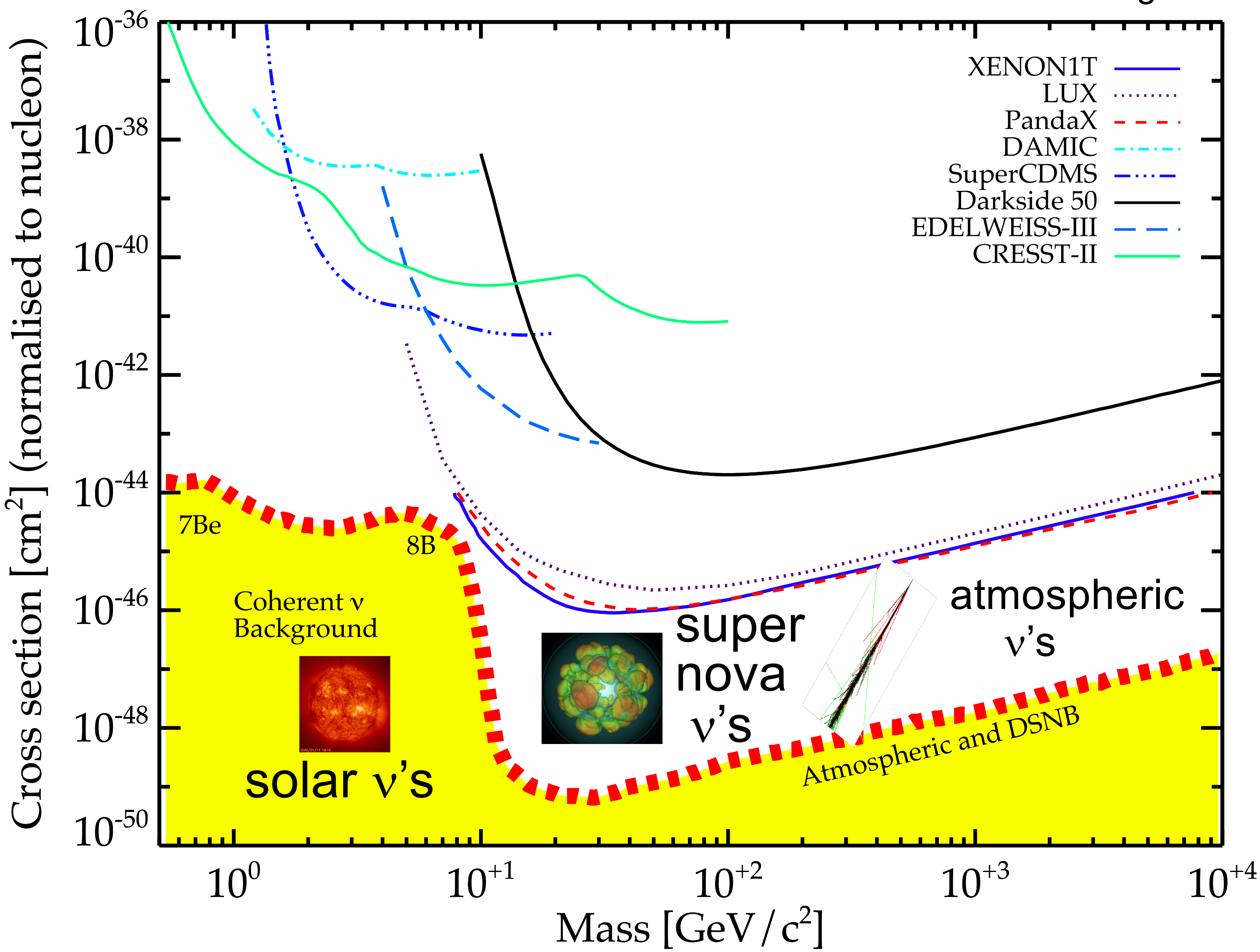


The so-called "neutrino floor" (**signal!**) for direct DM experiments

J. Monroe & P. Fisher, 2007

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

L. Strigari



Light **accelerator-produced DM** direct detection possibilities

(CEvNS is *background*)

- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

} decay product χ then makes nuclear recoil

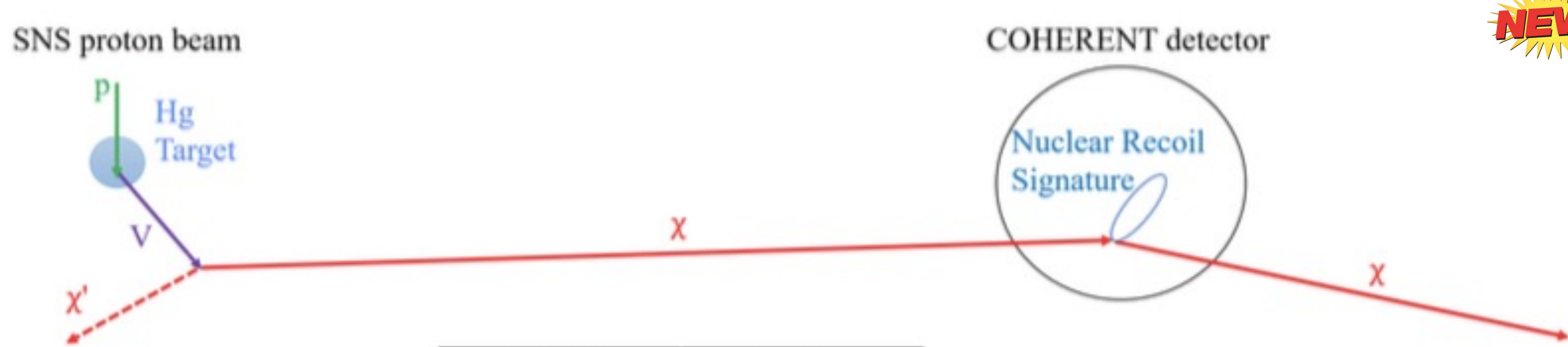
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

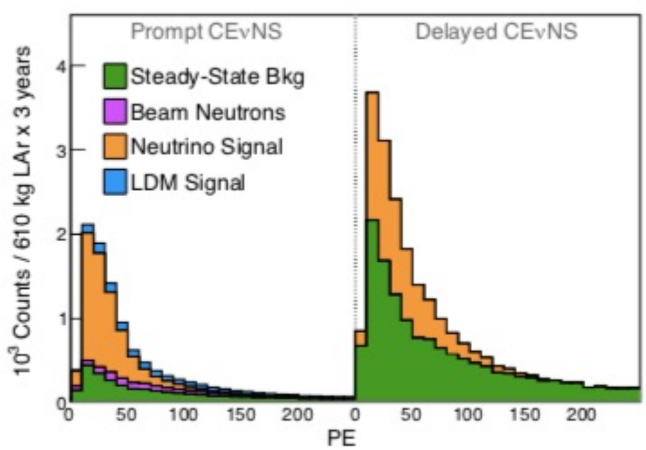
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

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

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

NEW!





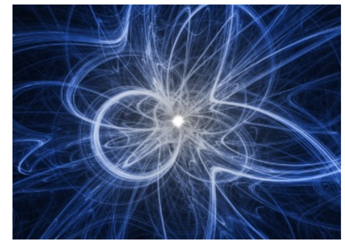
Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

CEvNS: what's it good for?

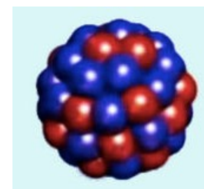
1 So
2 Many
3 Things
!

(not a complete list!)

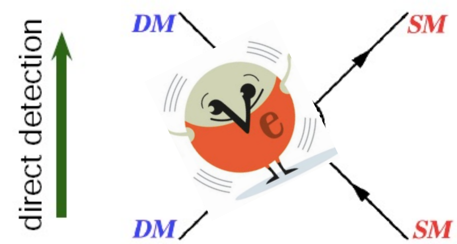
CEvNS as a **signal**
for signatures of *new physics*



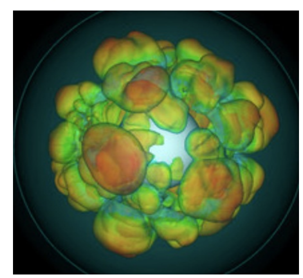
CEvNS as a **signal**
for understanding of "old" physics



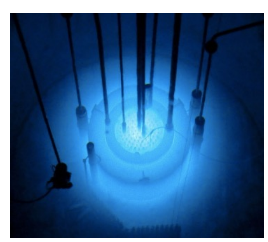
CEvNS as a **background**
for signatures of new physics (DM)



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

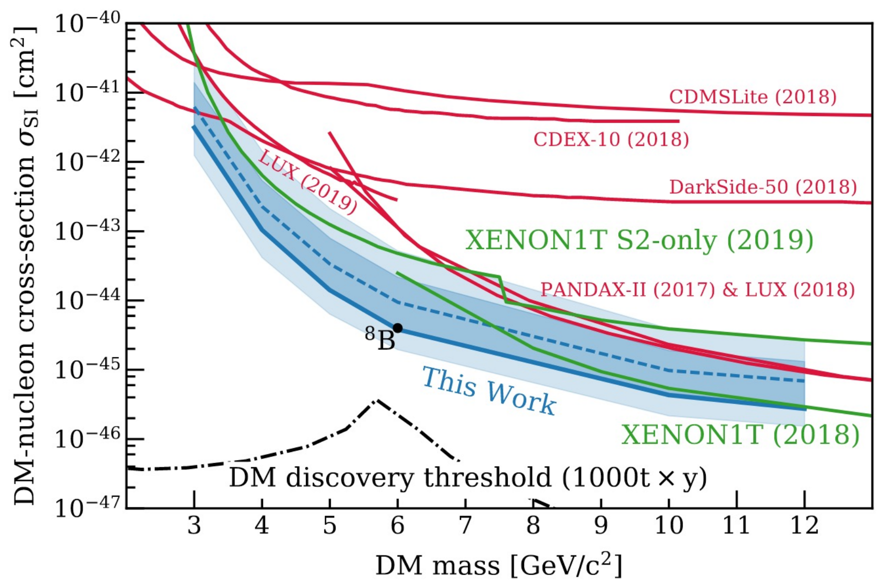


CEvNS as a **practical tool**

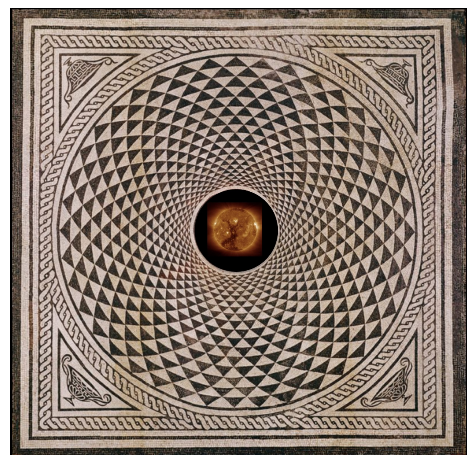


Search for CEvNS from solar neutrinos with the XENON-1T experiment

Phys.Rev.Lett. 126 (2021) 091301, arXiv: 2012.02846



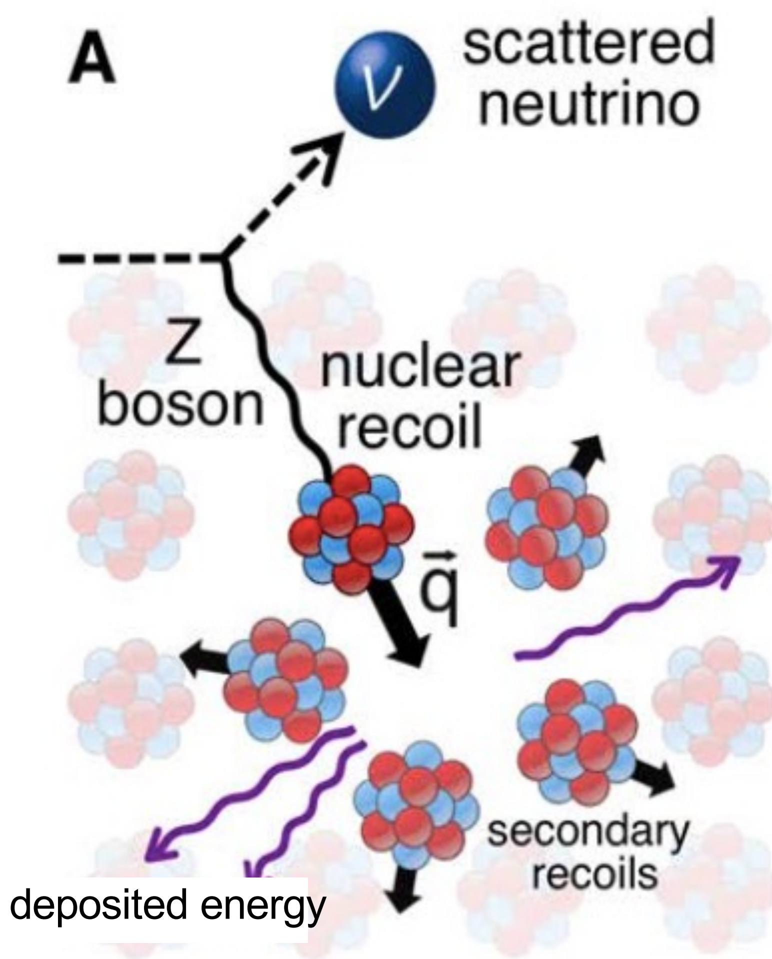
Limit only so far
... but will eventually hit the floor...
sometimes there are
interesting things to see
if you look down...



How to measure CEvNS

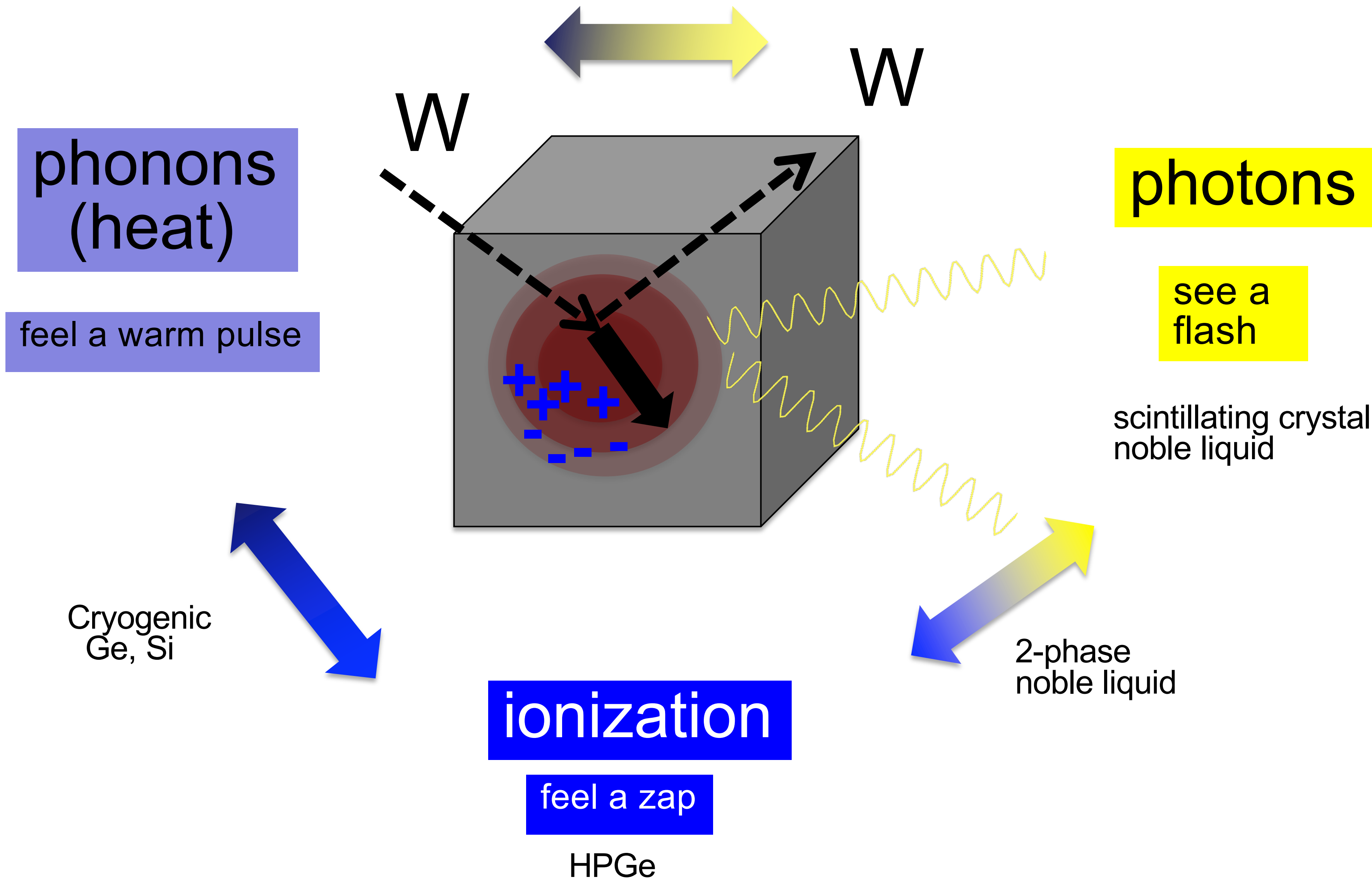
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



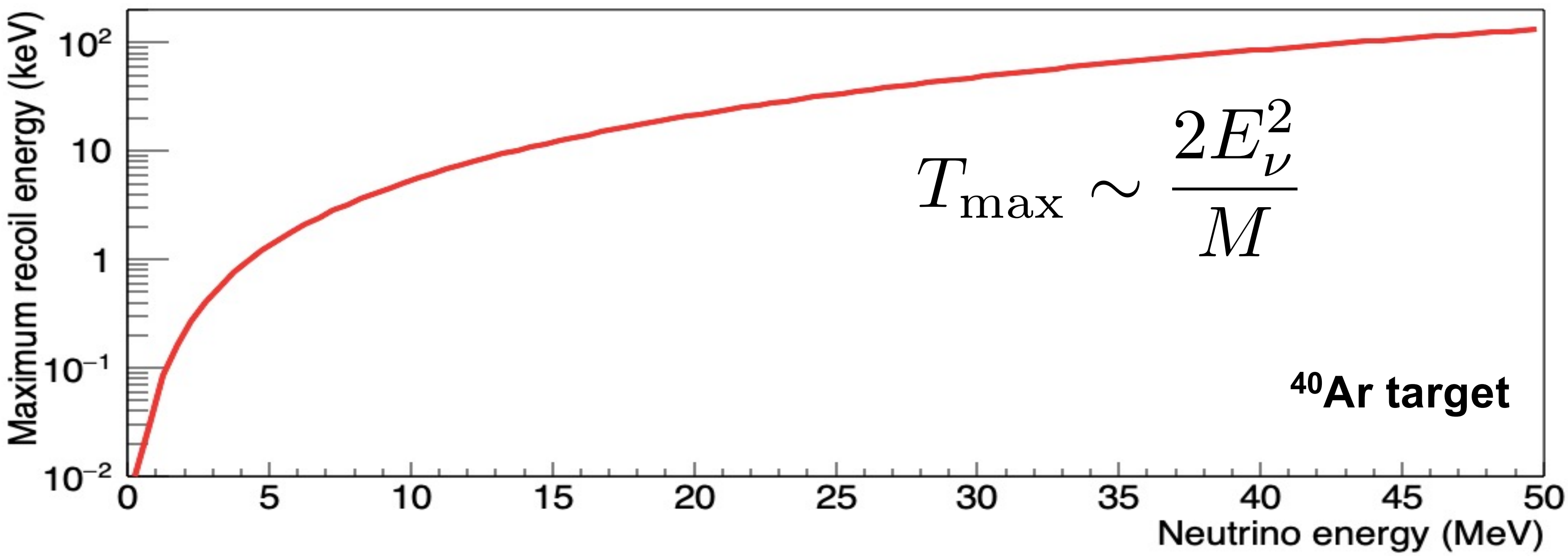
➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10's of keV recoils

Low-energy nuclear recoil detection strategies

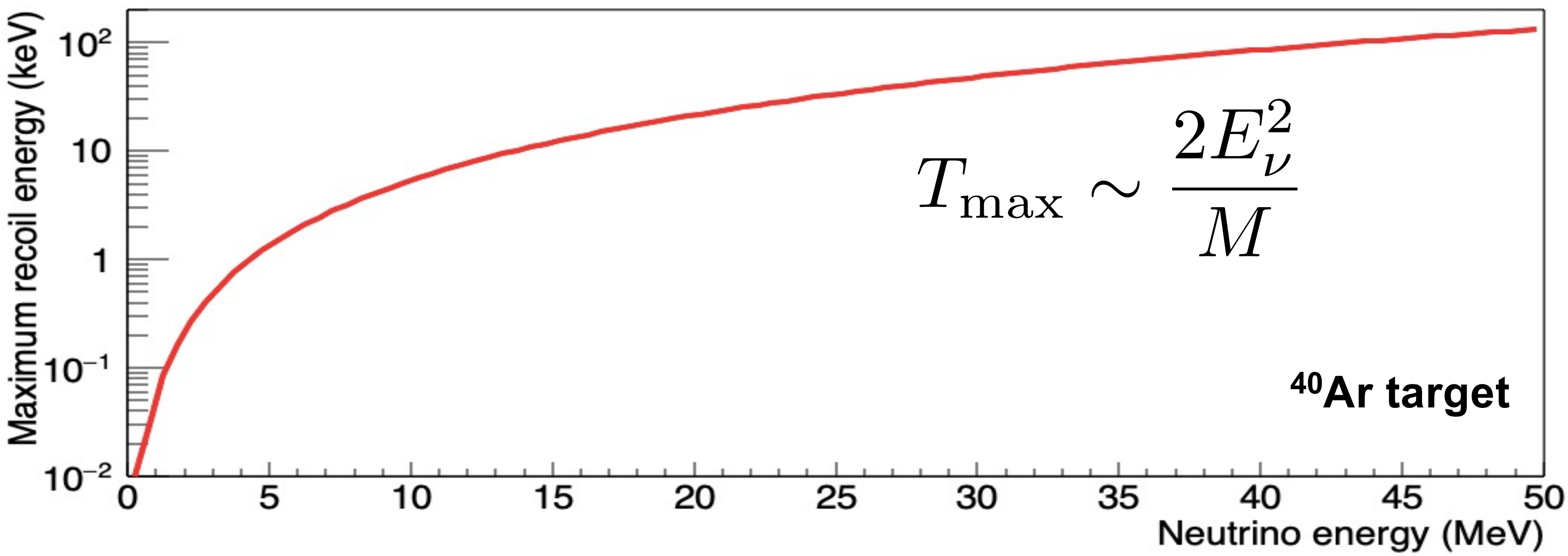


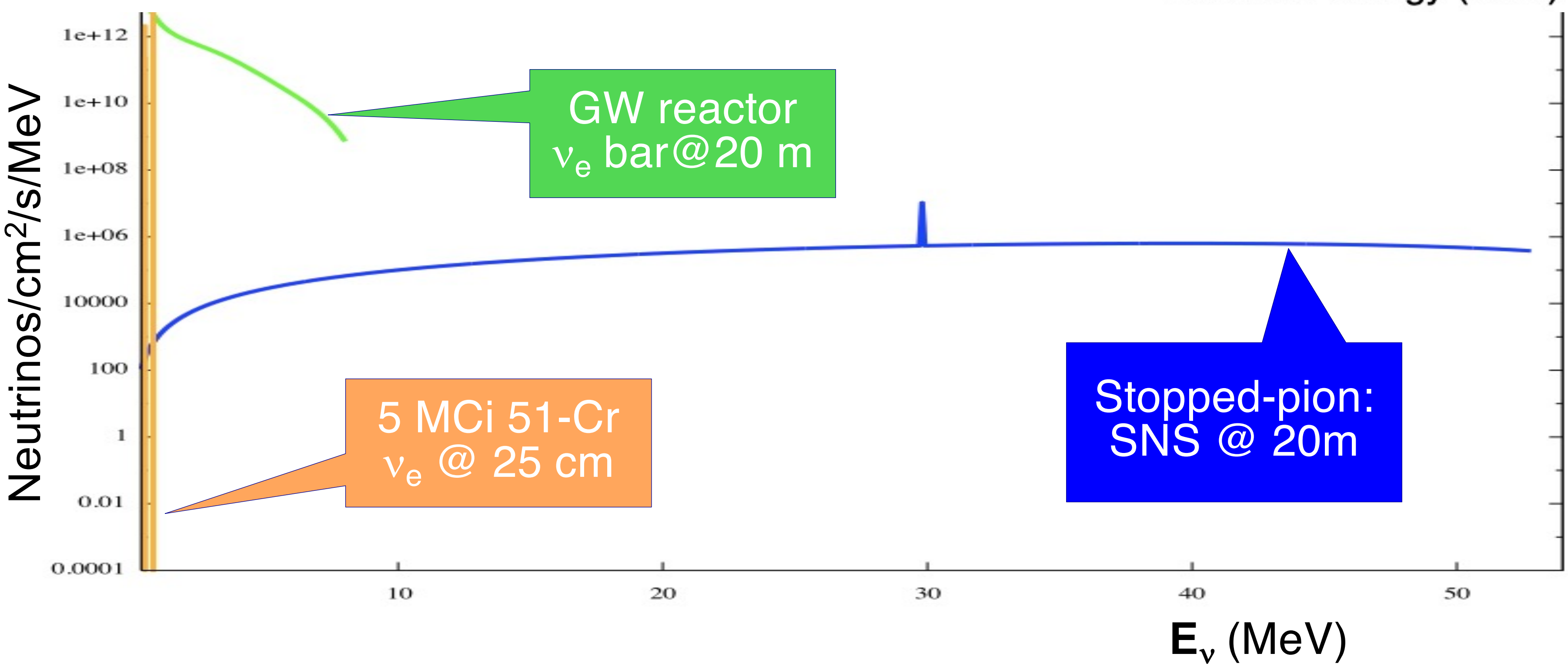
http://dmrc.snu.ac.kr/english/intro/intro1.html

Maximum recoil energy as a function of E_ν

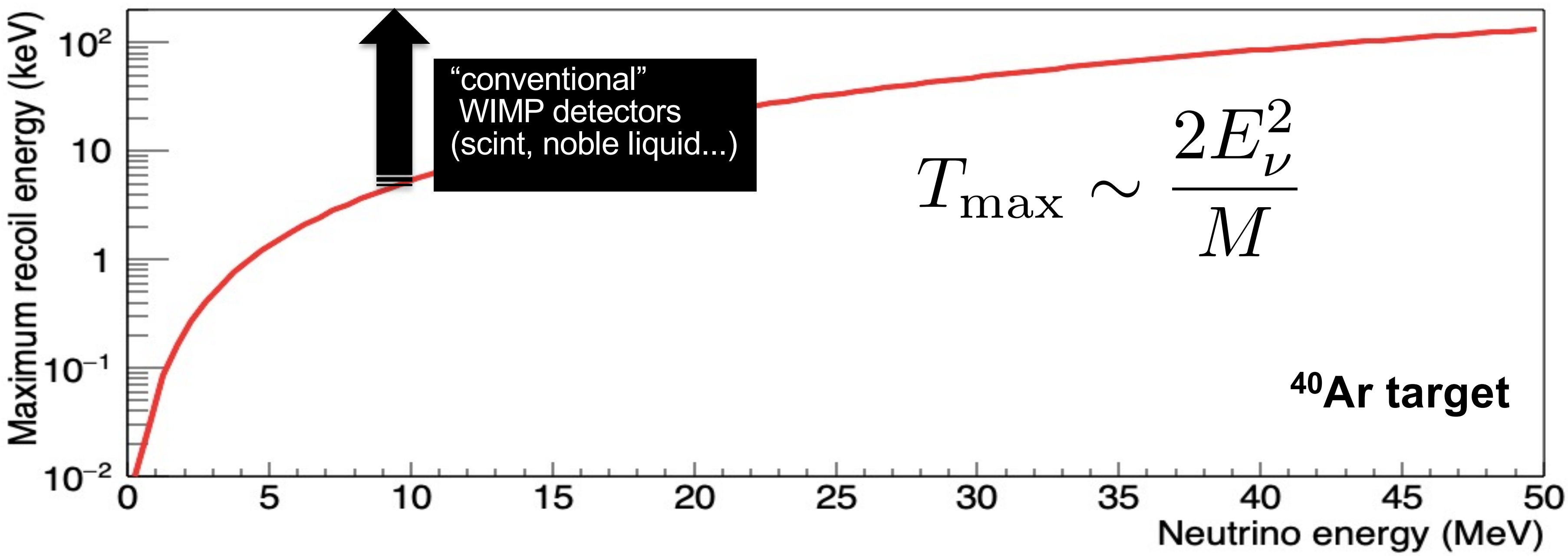


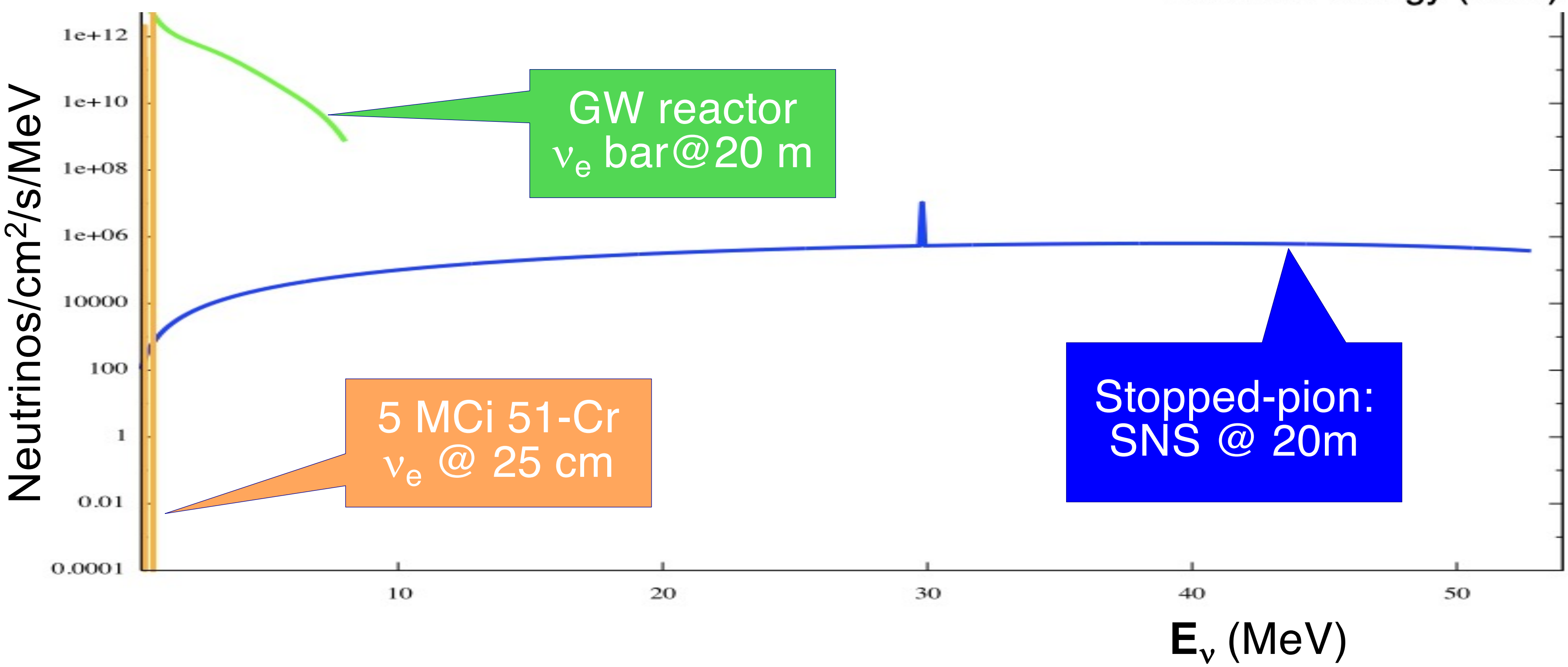
Maximum recoil energy as a function of E_ν



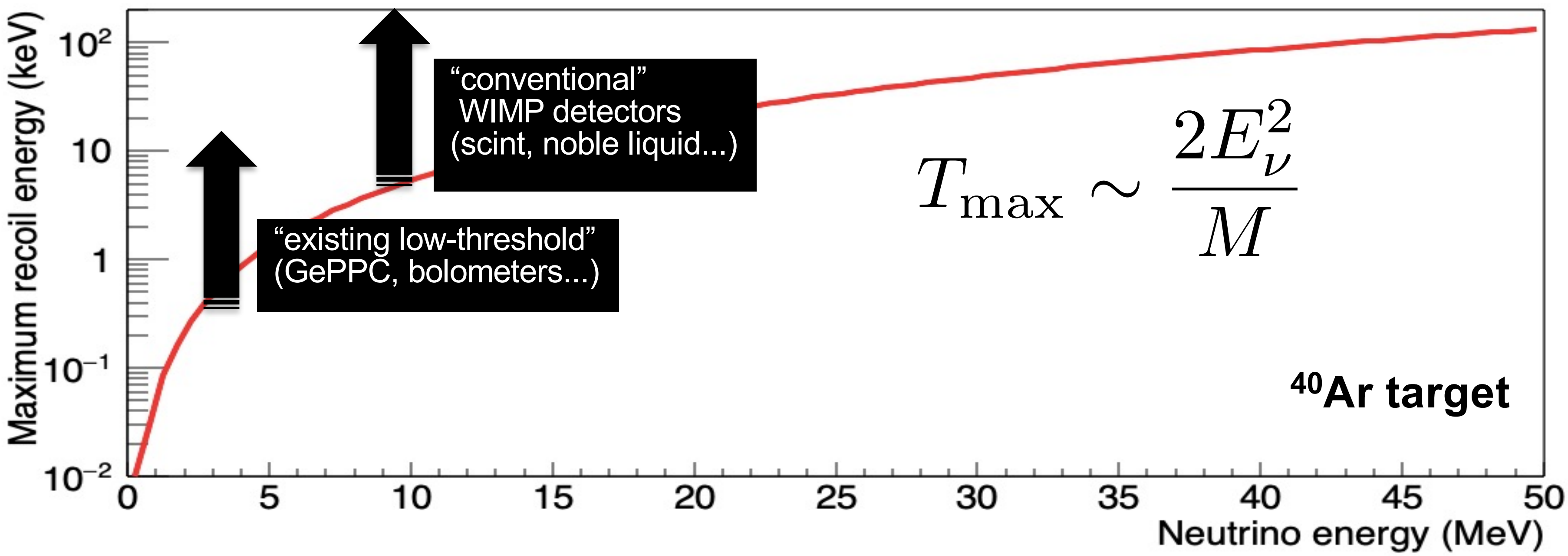


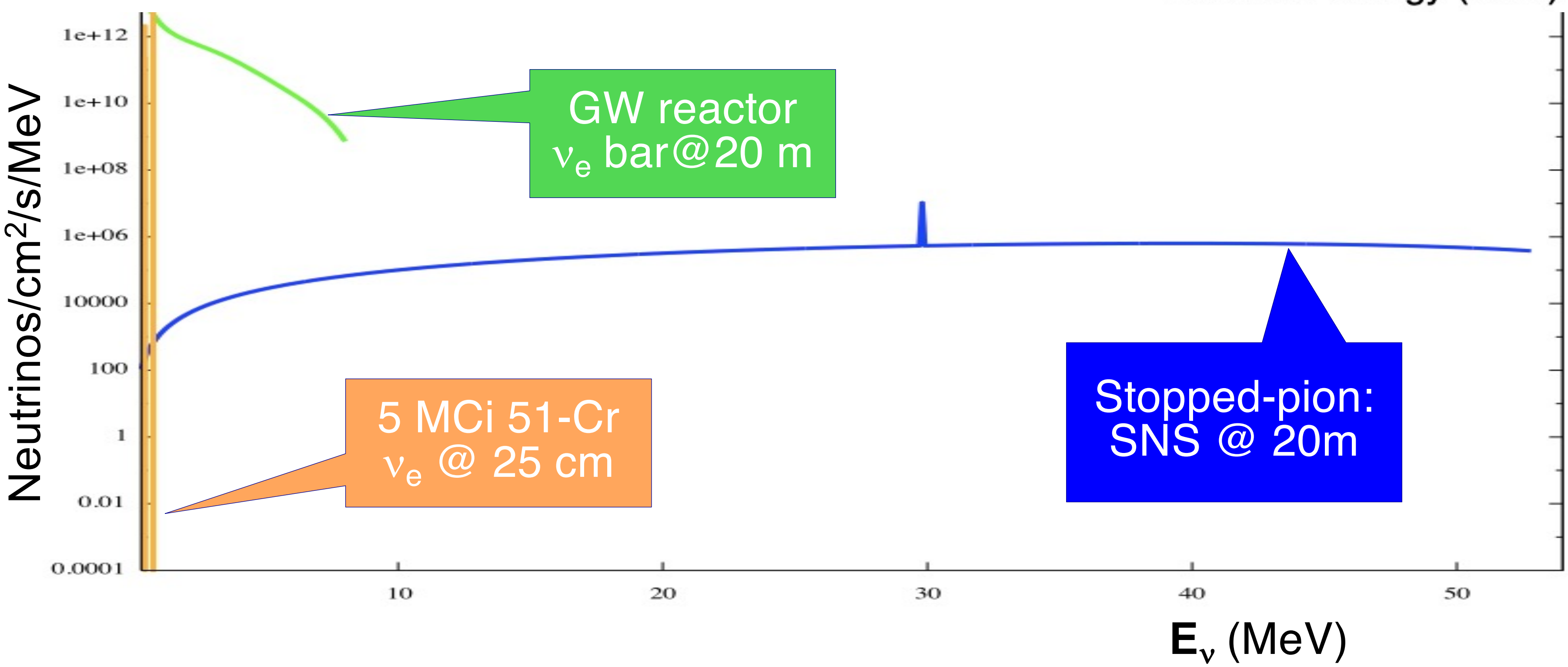
Maximum recoil energy as a function of E_ν



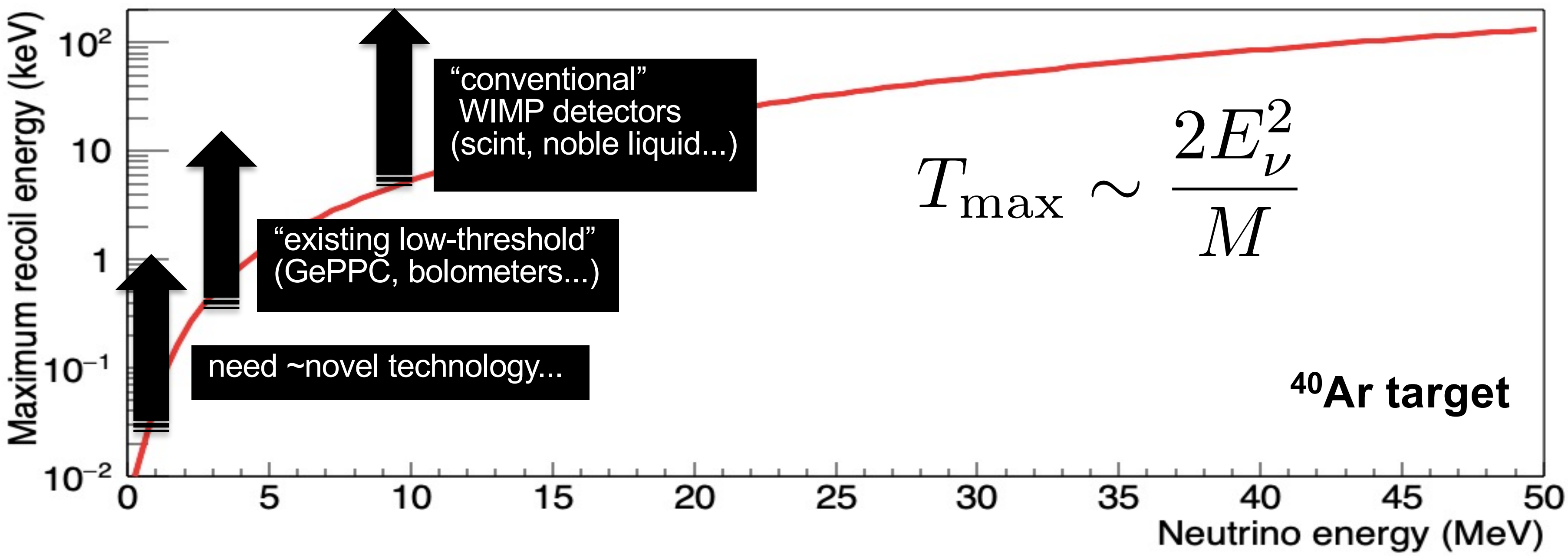


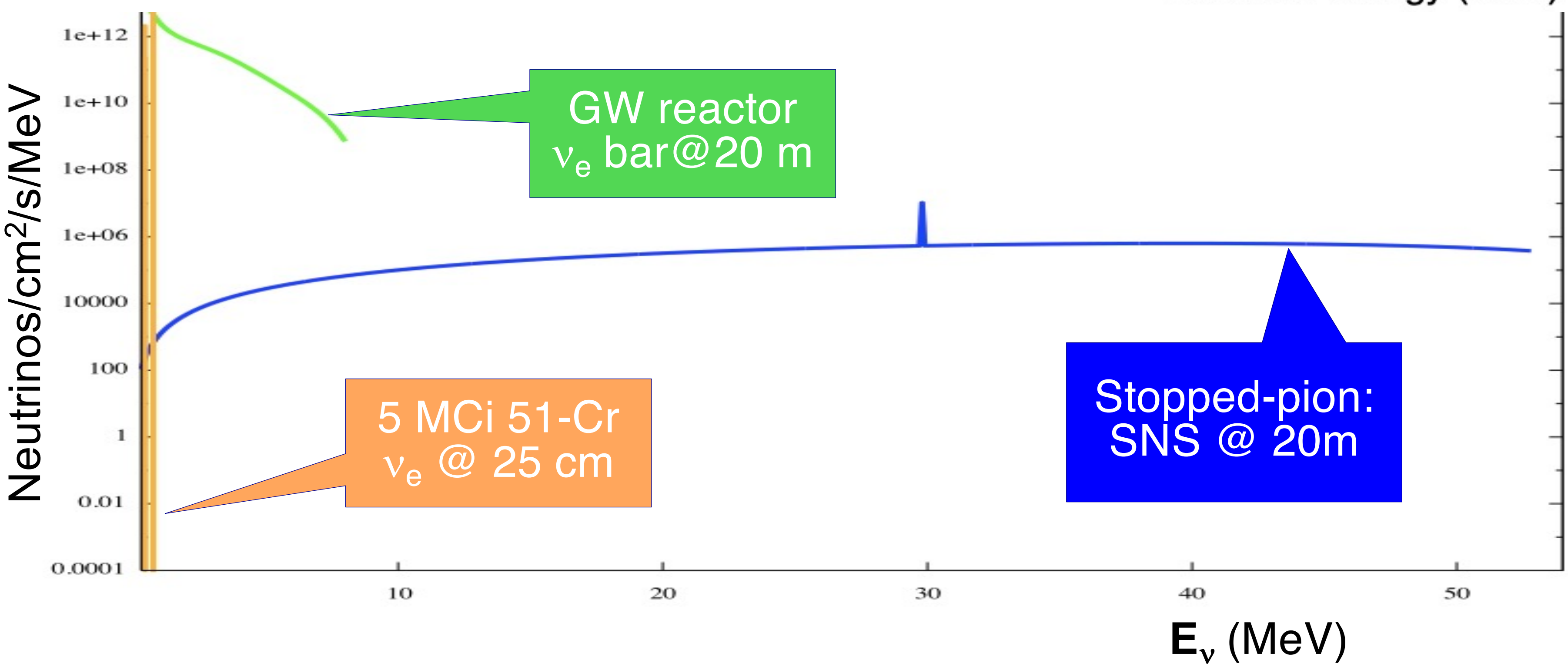
Maximum recoil energy as a function of E_ν



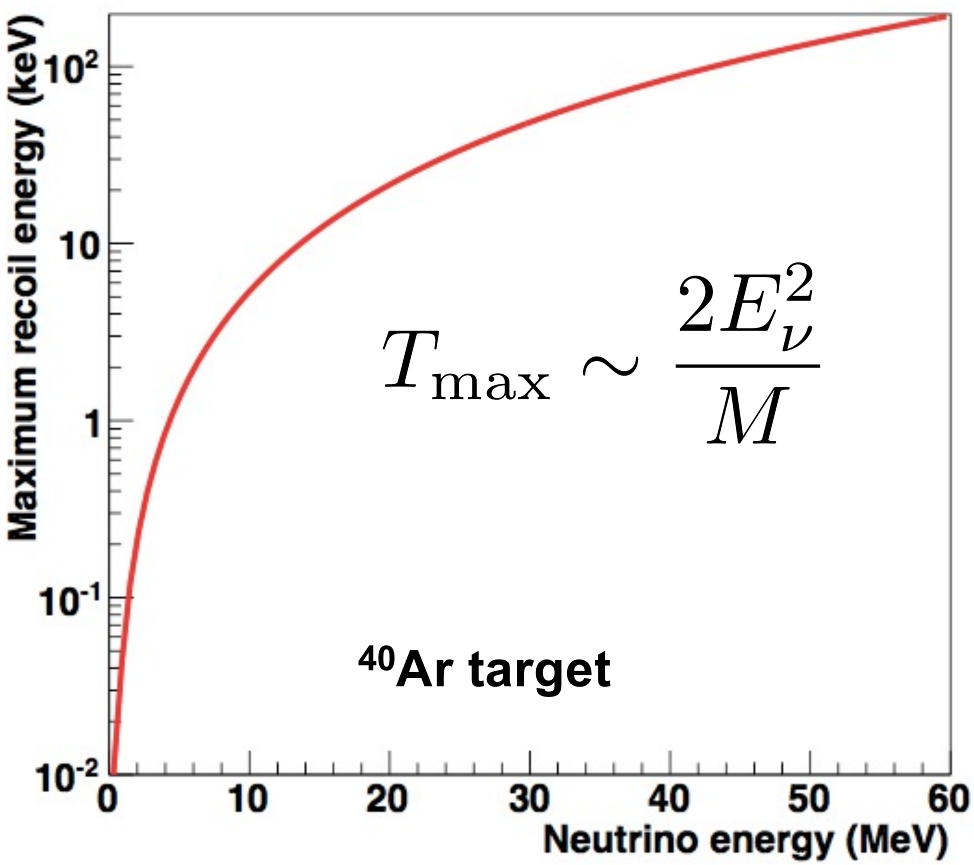


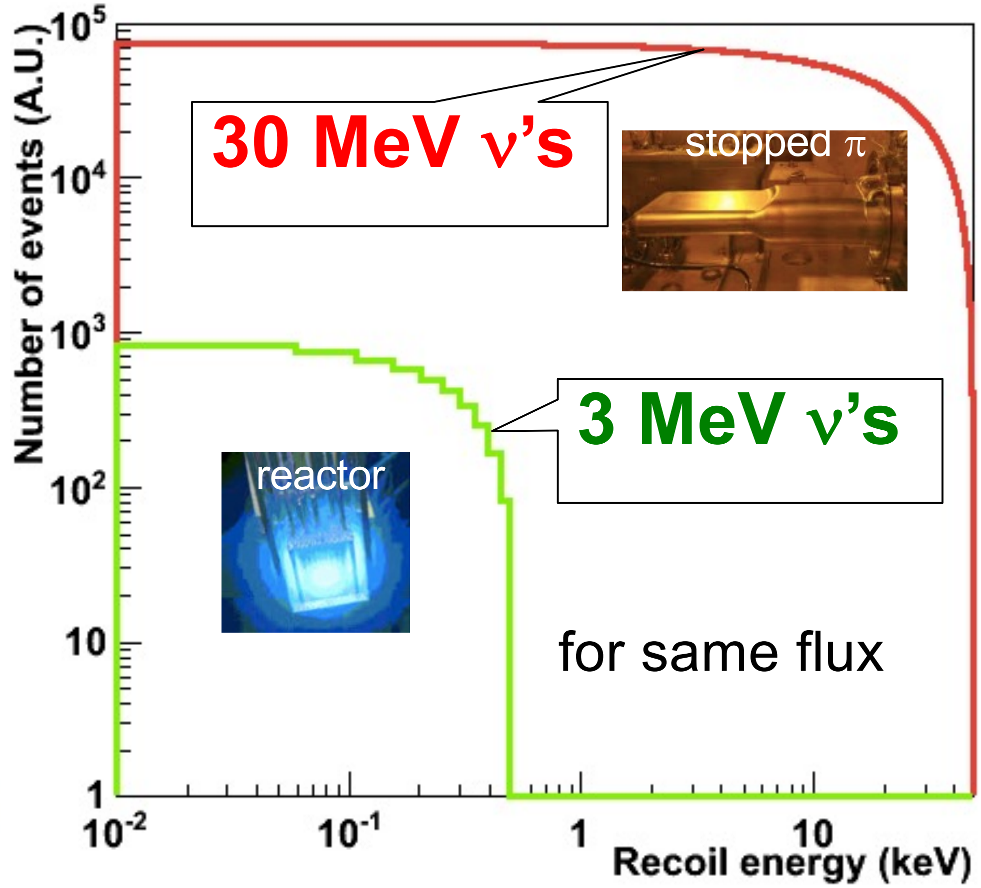
Maximum recoil energy as a function of E_ν





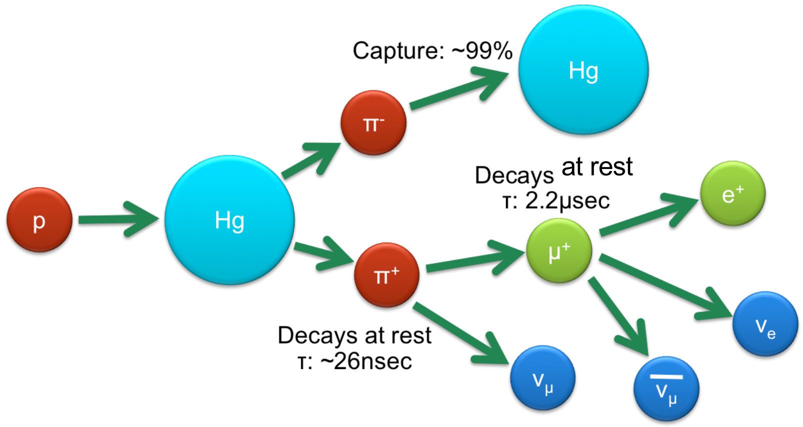
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

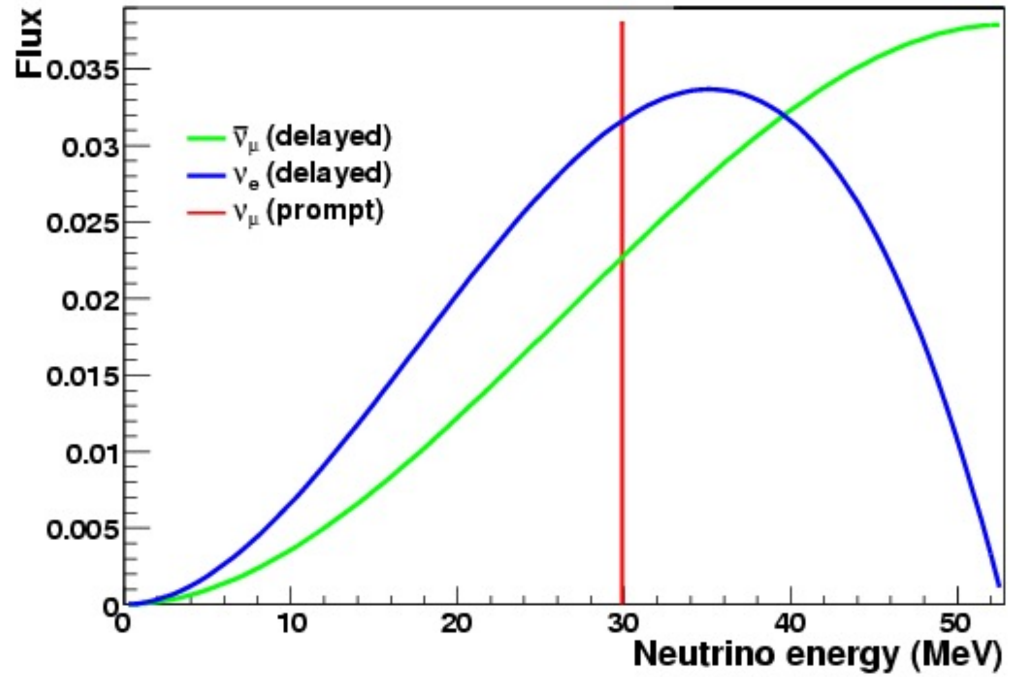




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

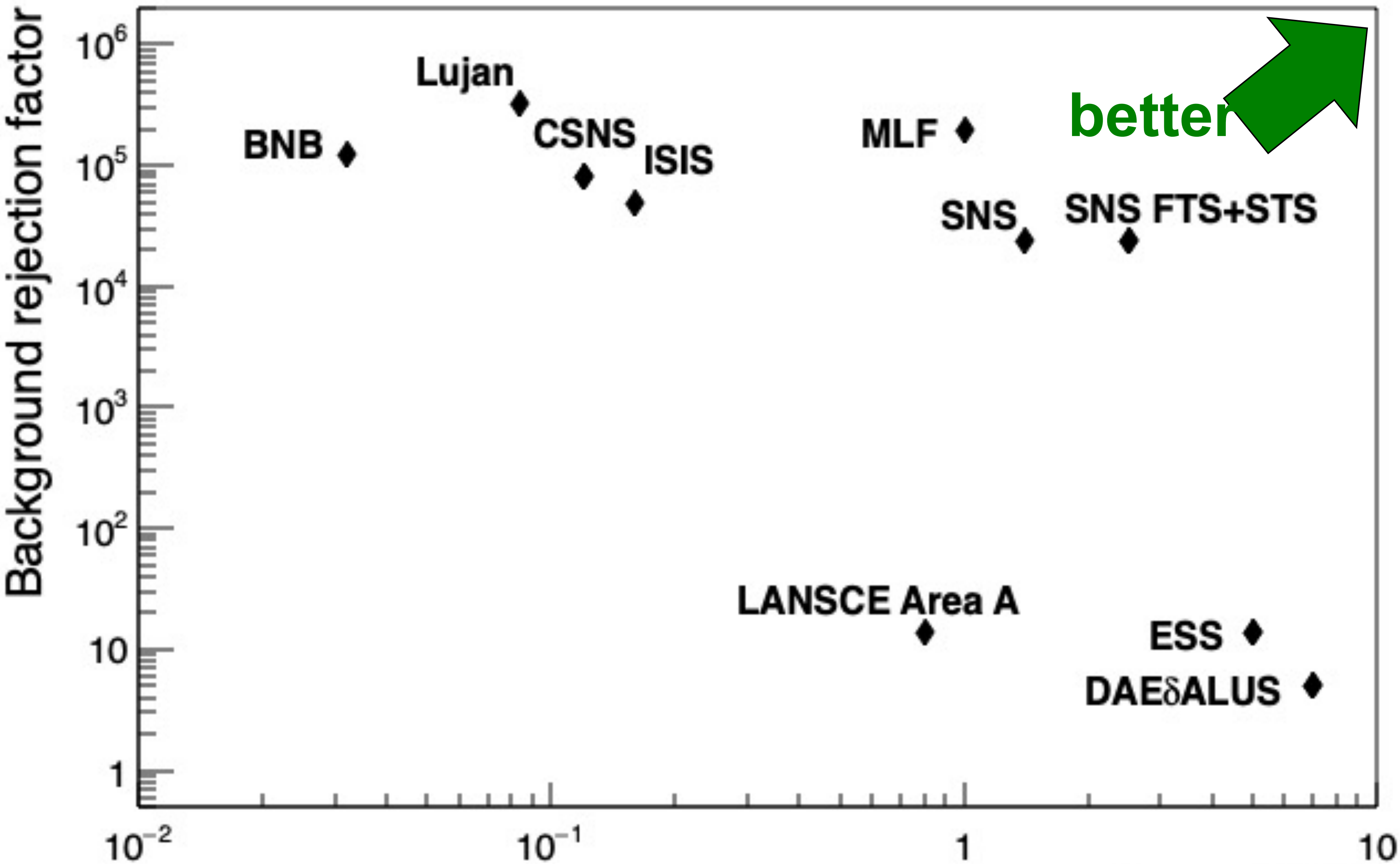
$$\downarrow$$

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

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

Comparison of pion decay-at-rest ν sources

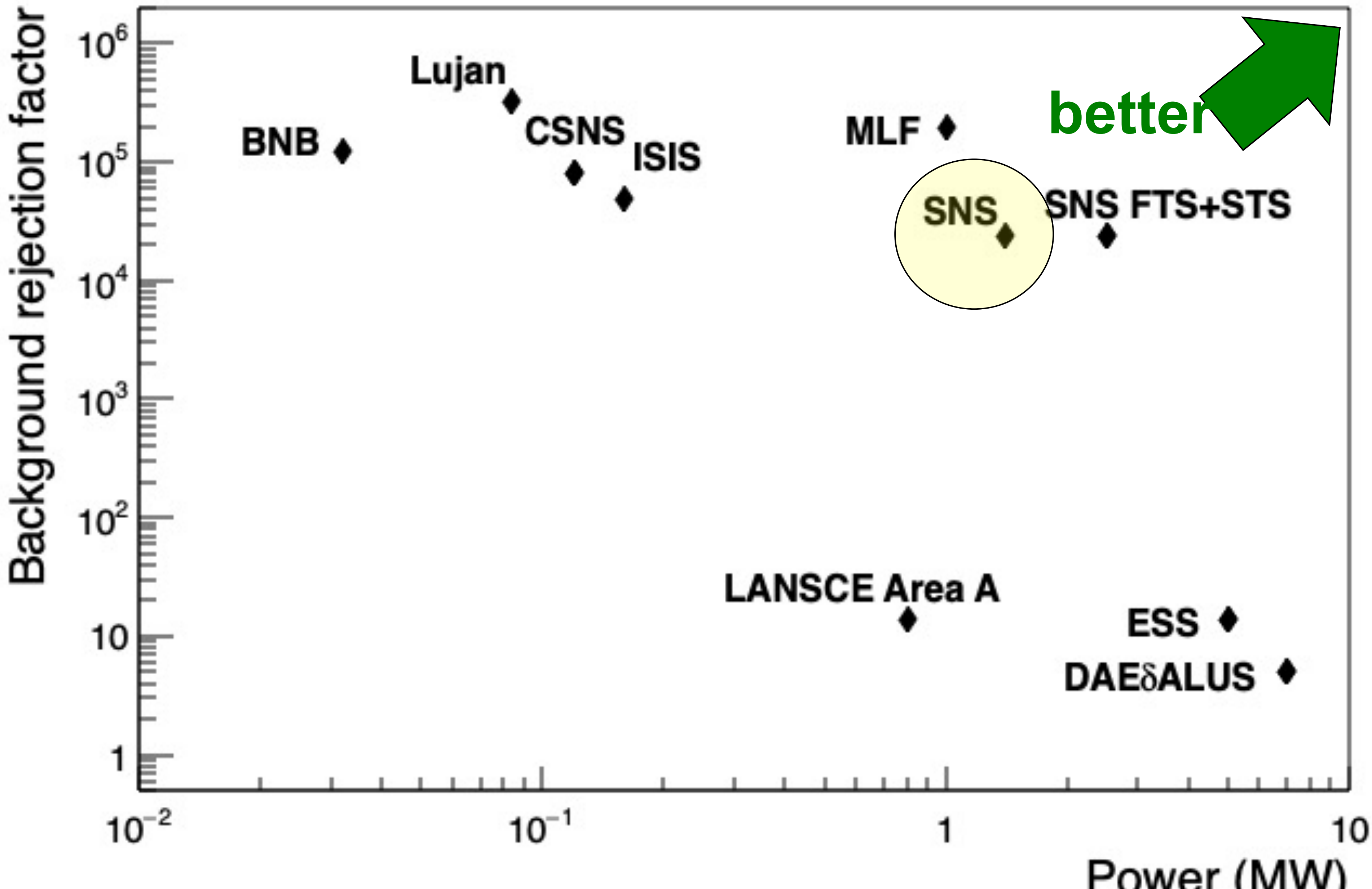
from duty cycle



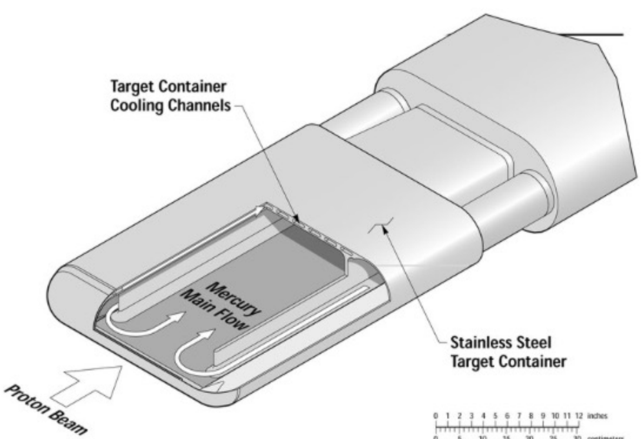
$\propto \nu$ flux

from duty cycle

Comparison of pion decay-at-rest ν sources



$\propto \nu$ flux

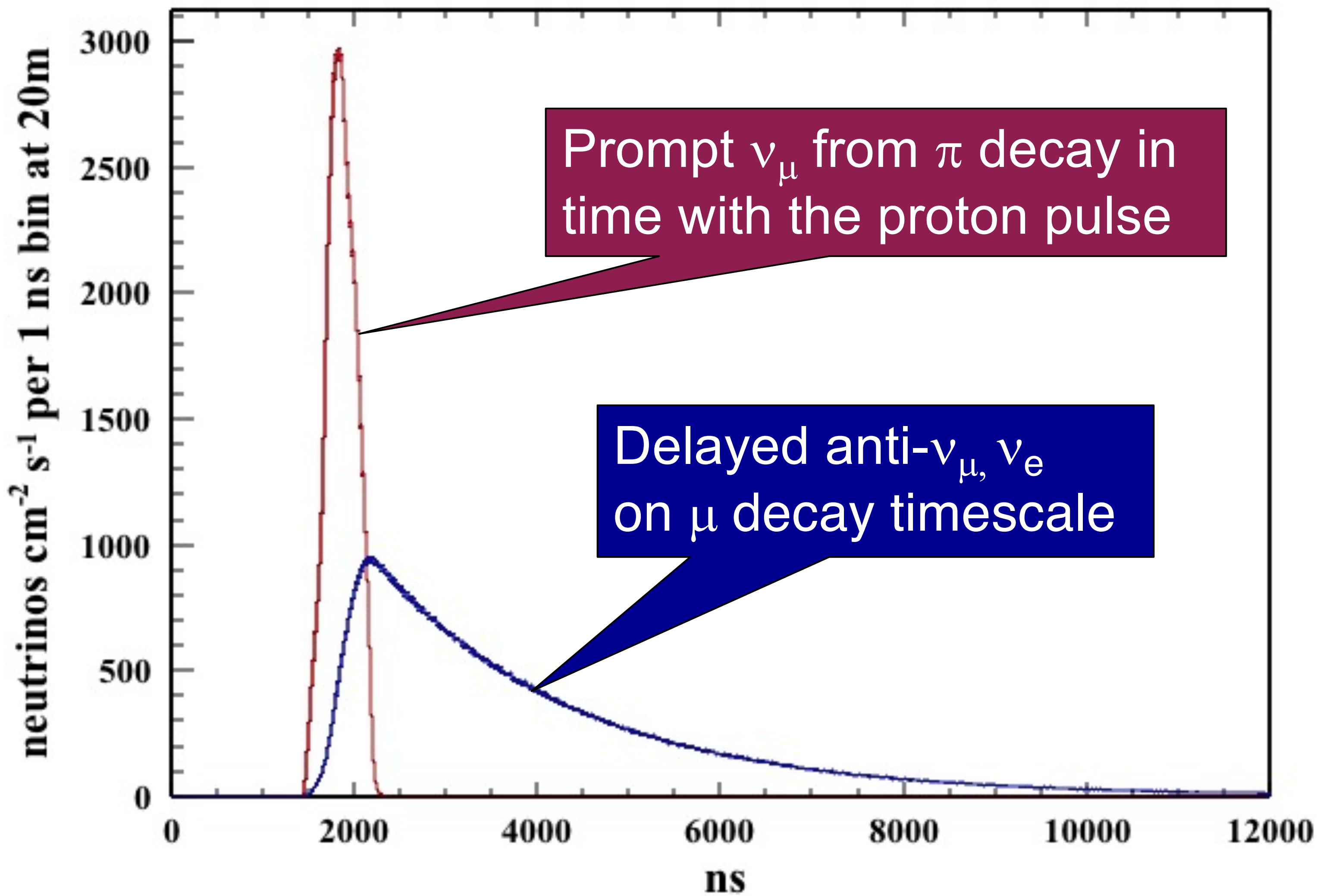


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

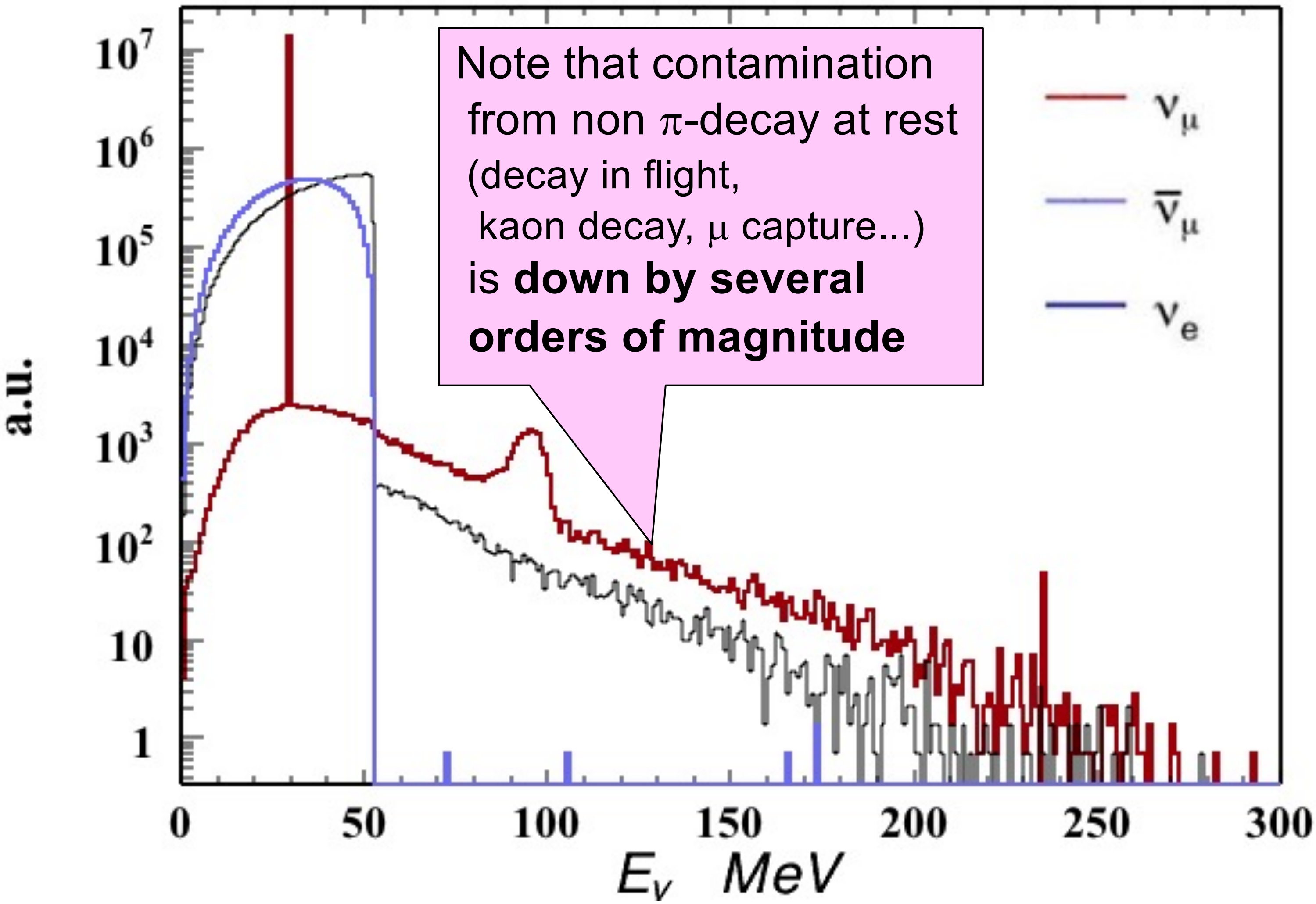
60 Hz *pulsed* source



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

The COHERENT collaboration

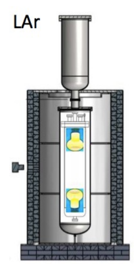
http://sites.duke.edu/coherent

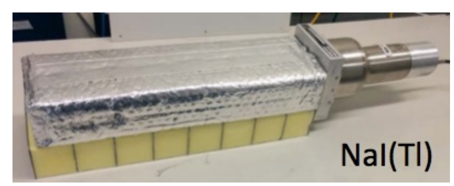
~90 members,
19 institutions
4 countries

COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal flash	14.6	19.3	6.5
Ge	HPGe PPC zap	18	22	<few
LAr	Single-phase flash	24	27.5	20
NaI[Tl]	Scintillating crystal flash	185*/3338	25	13

Multiple detectors for N^2 dependence of the cross section

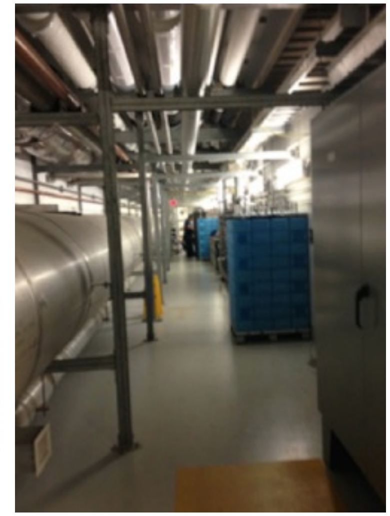


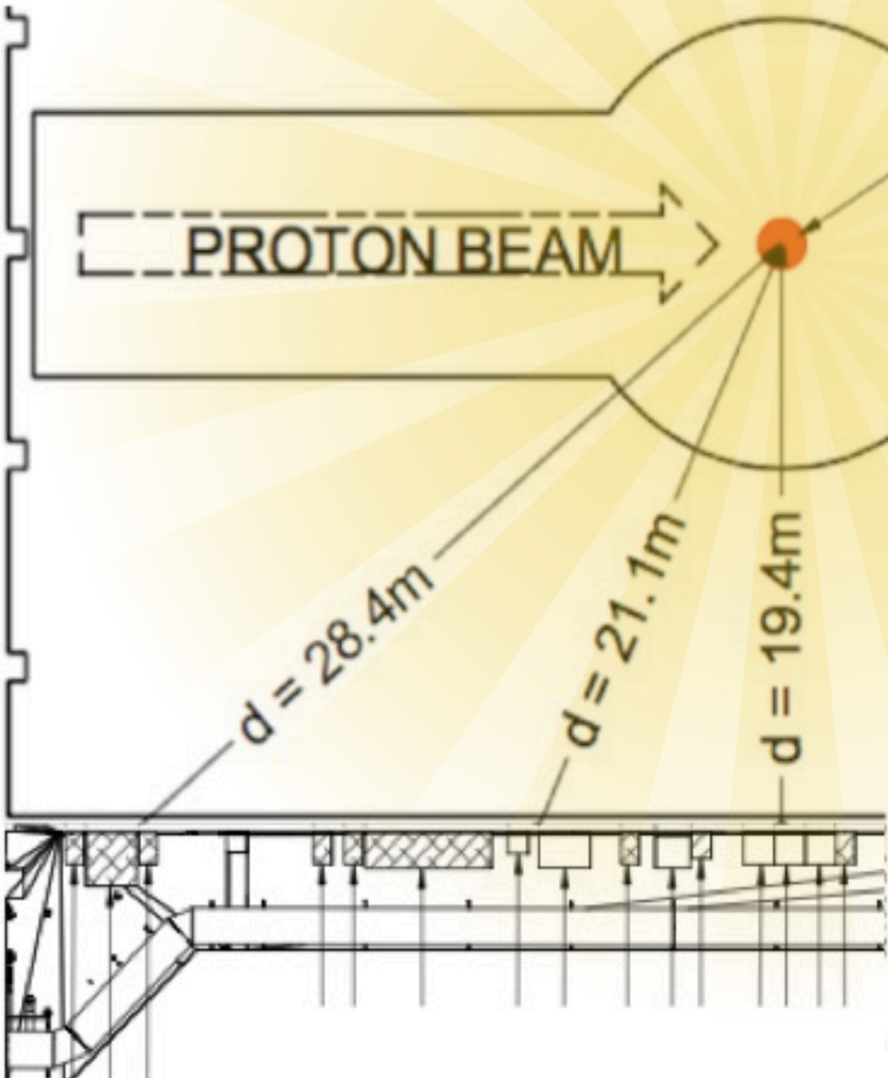


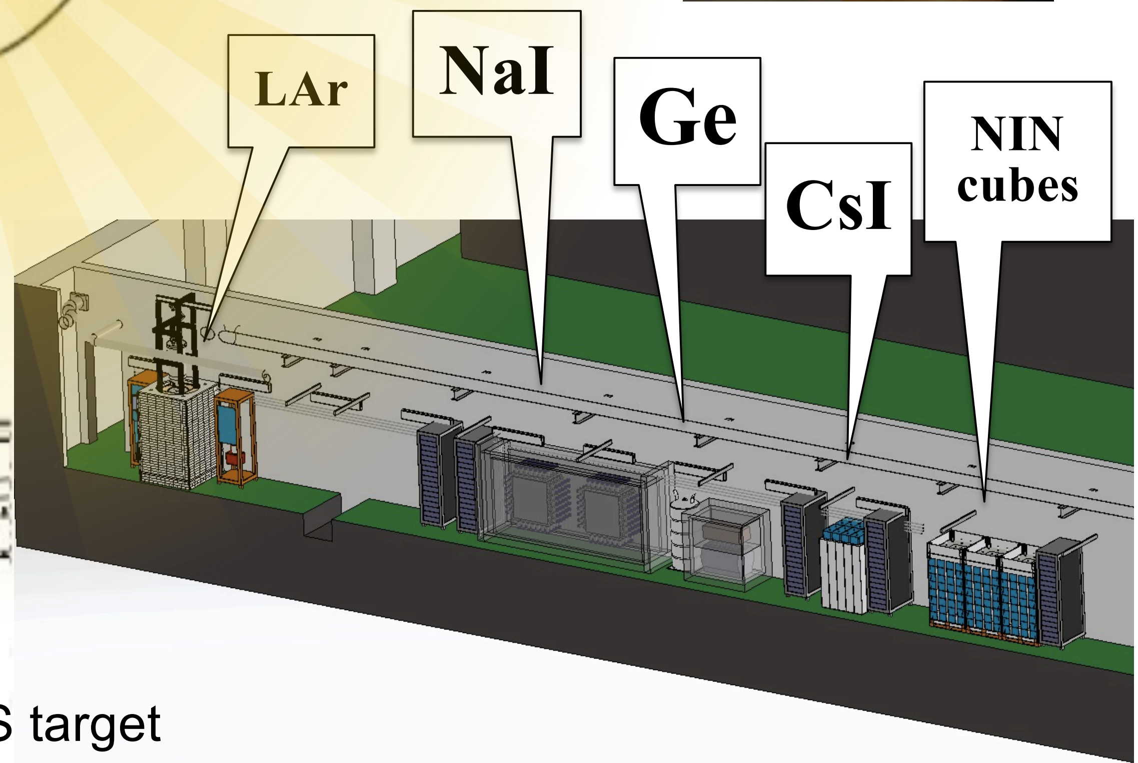
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking down “Neutrino Alley”

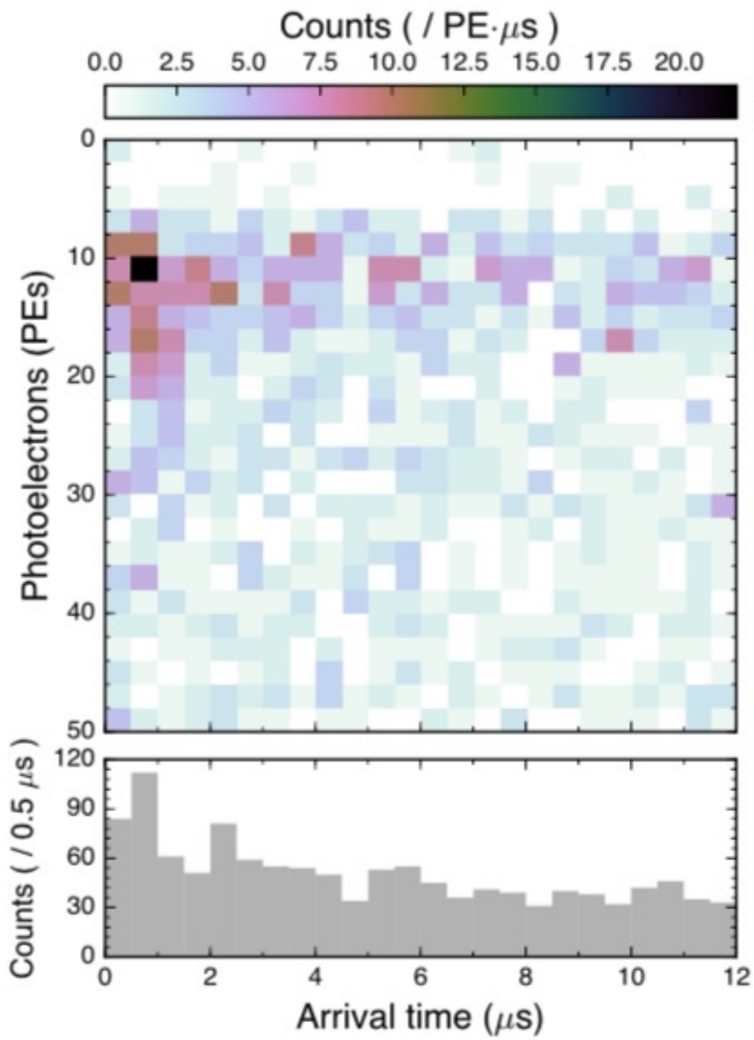


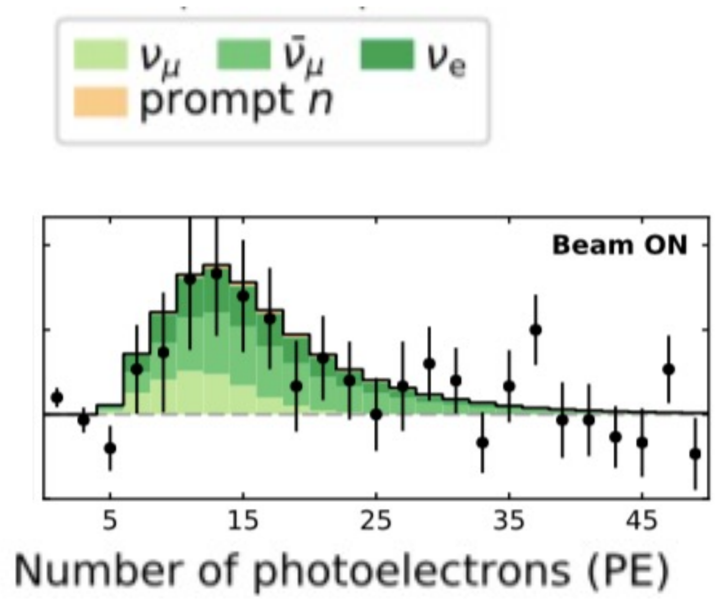




Isotropic ν glow from Hg SNS target

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

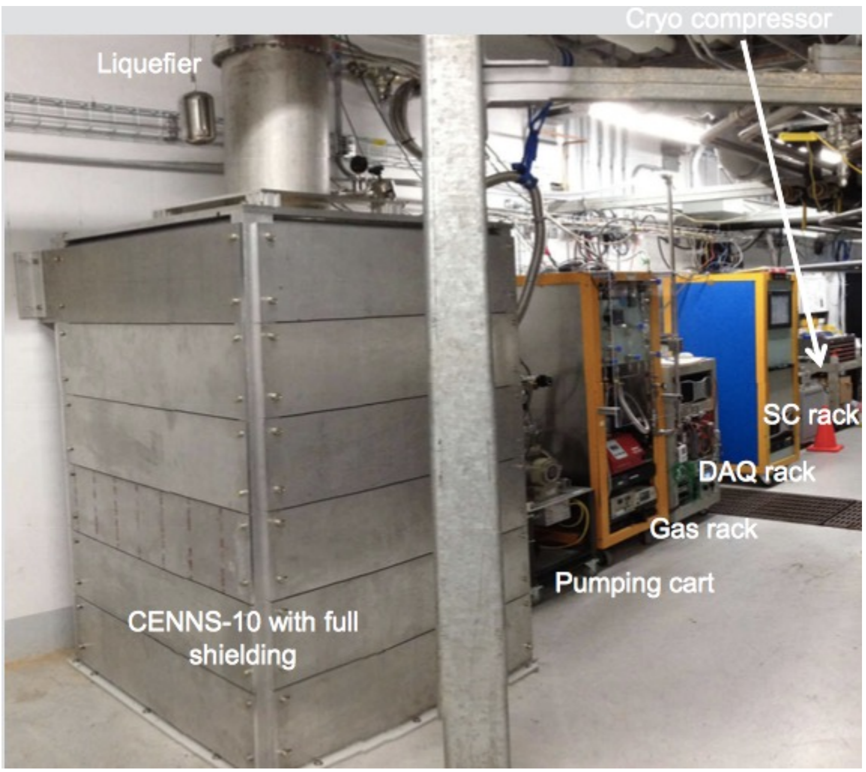
DOI: 10.5281/zenodo.1228631

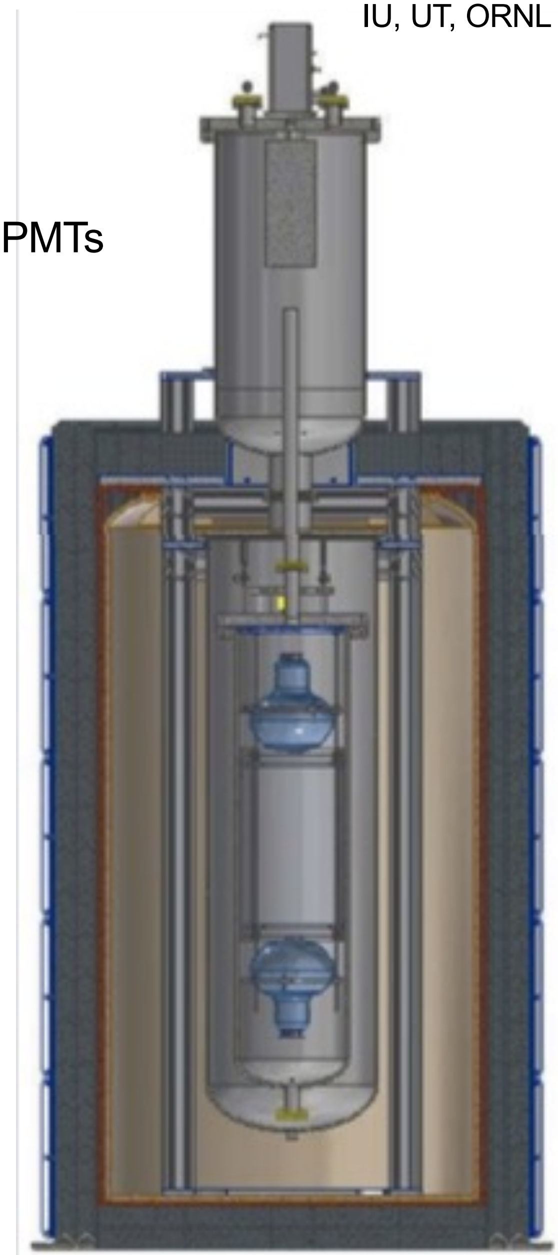
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

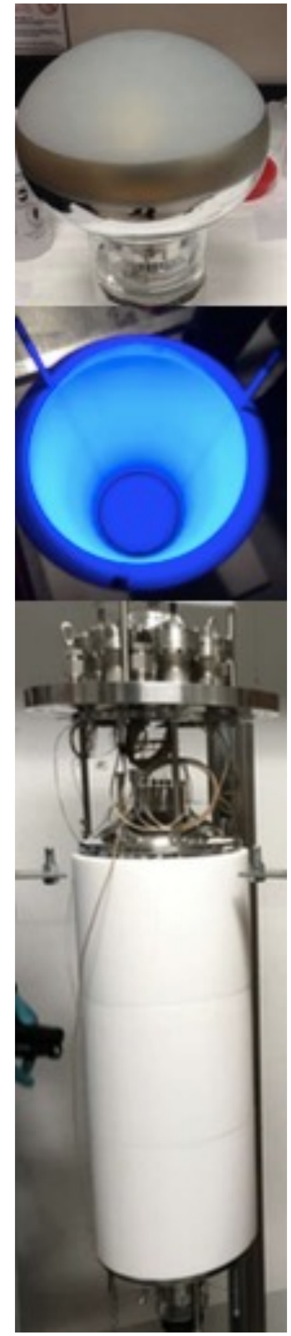
Single-Phase Liquid Argon

- ~24 kg active mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
  - 8” borosilicate glass window
  - 14 dynodes
  - QE: 18%@ 400 nm
- Wavelength shifter: TPB-coated Teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
  - PT90 single-state pulse-tube cold head

IU, UT, ORNL



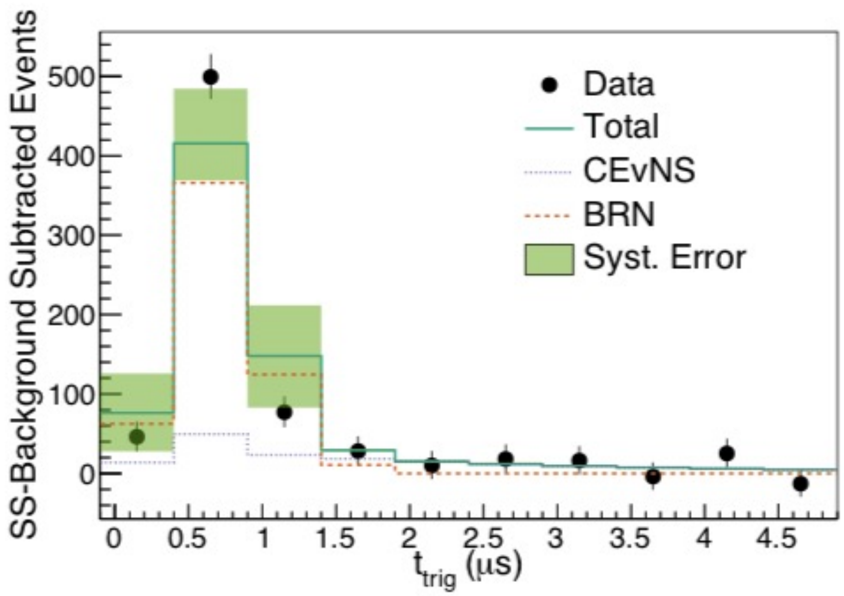


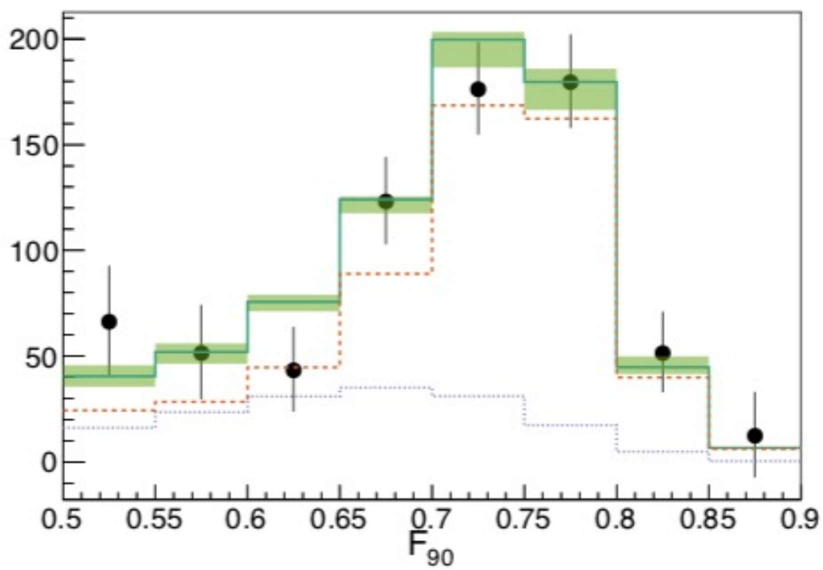


Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

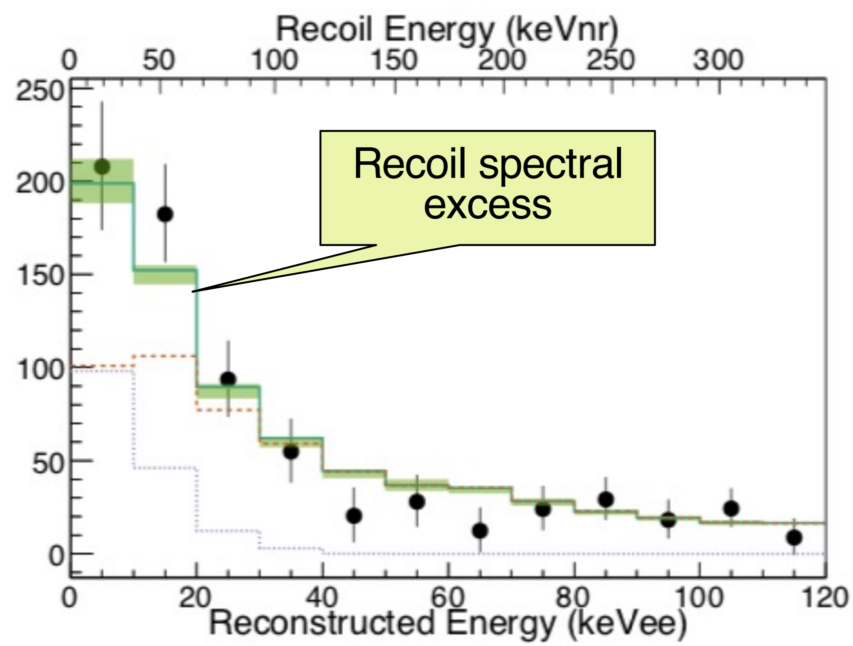
Likelihood fit in time, recoil energy, PSD parameter

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

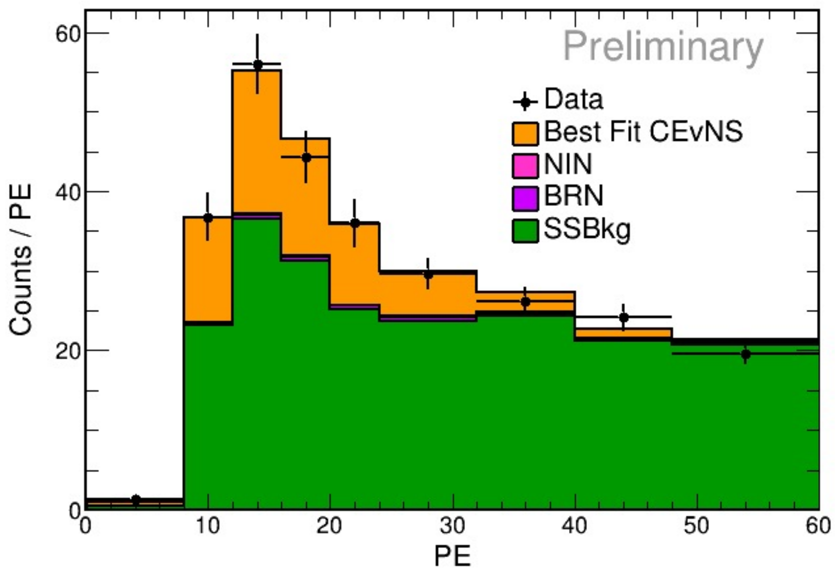


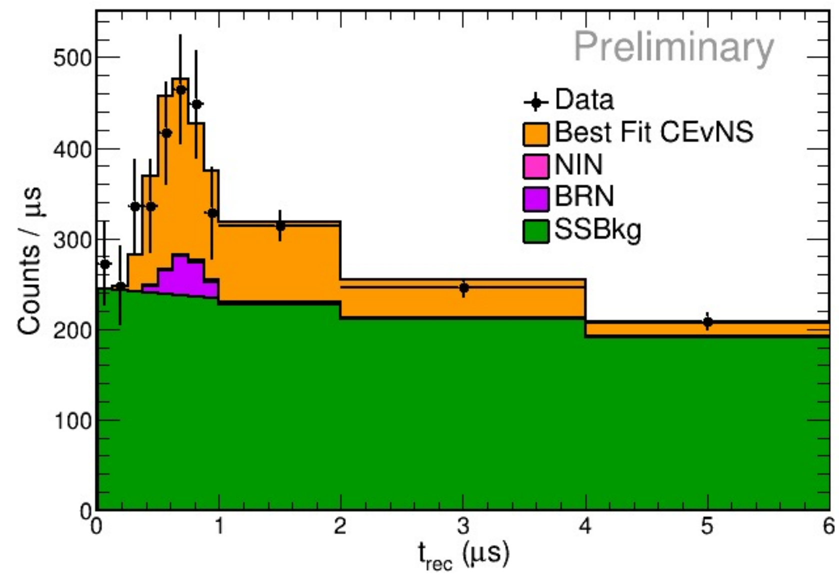


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the “A” analysis)



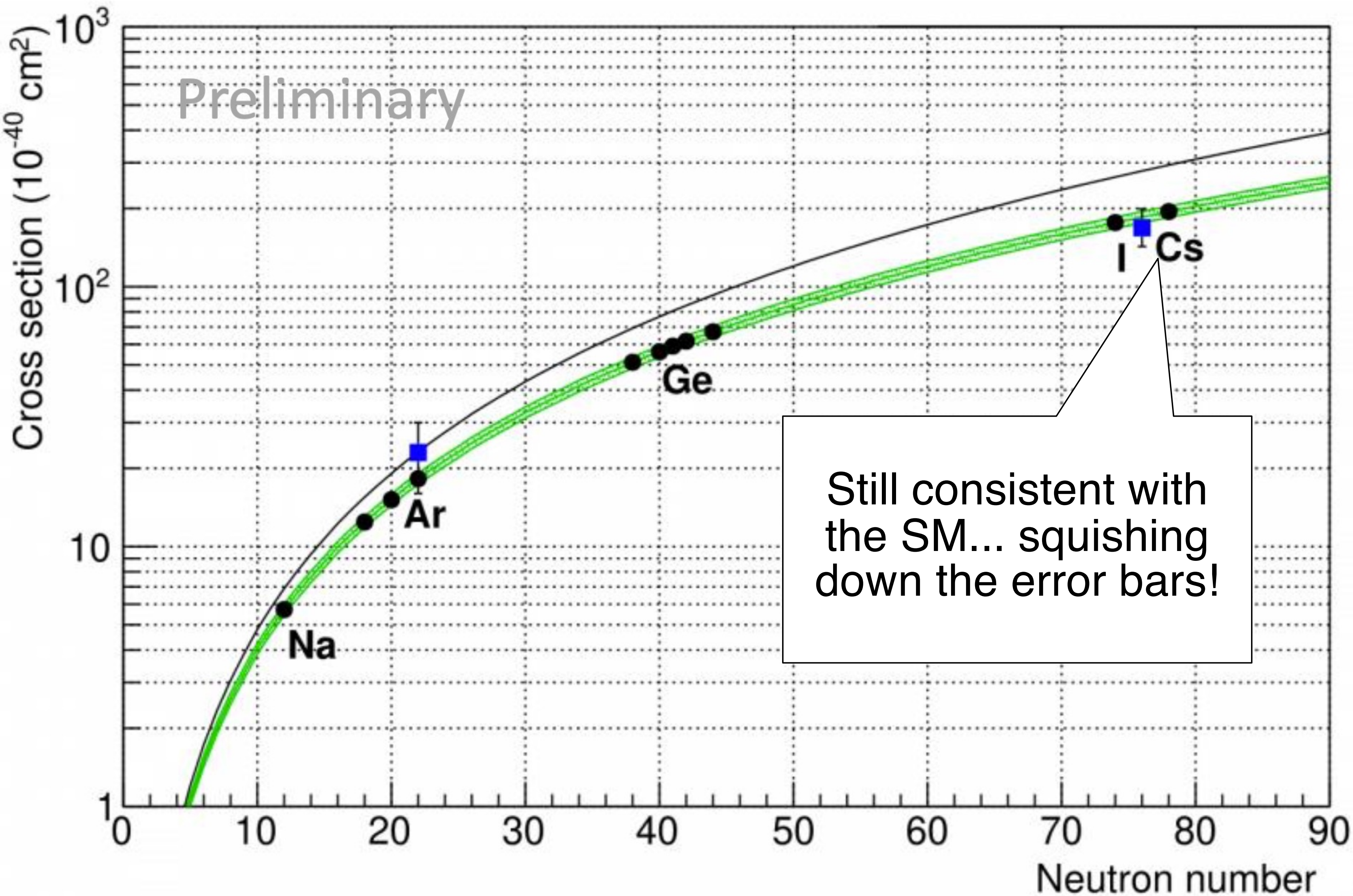
Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis



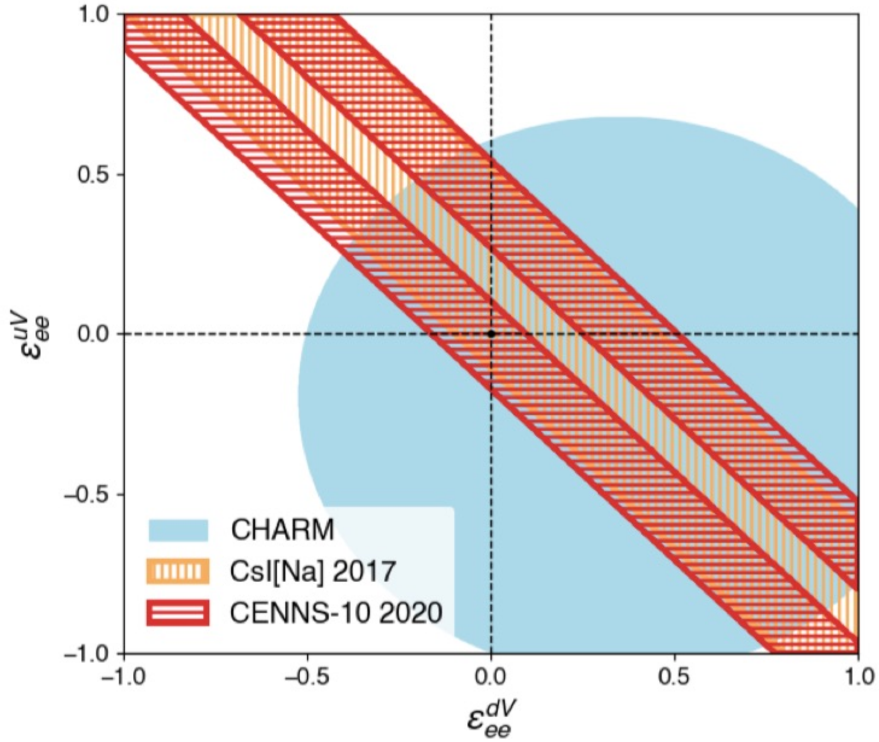


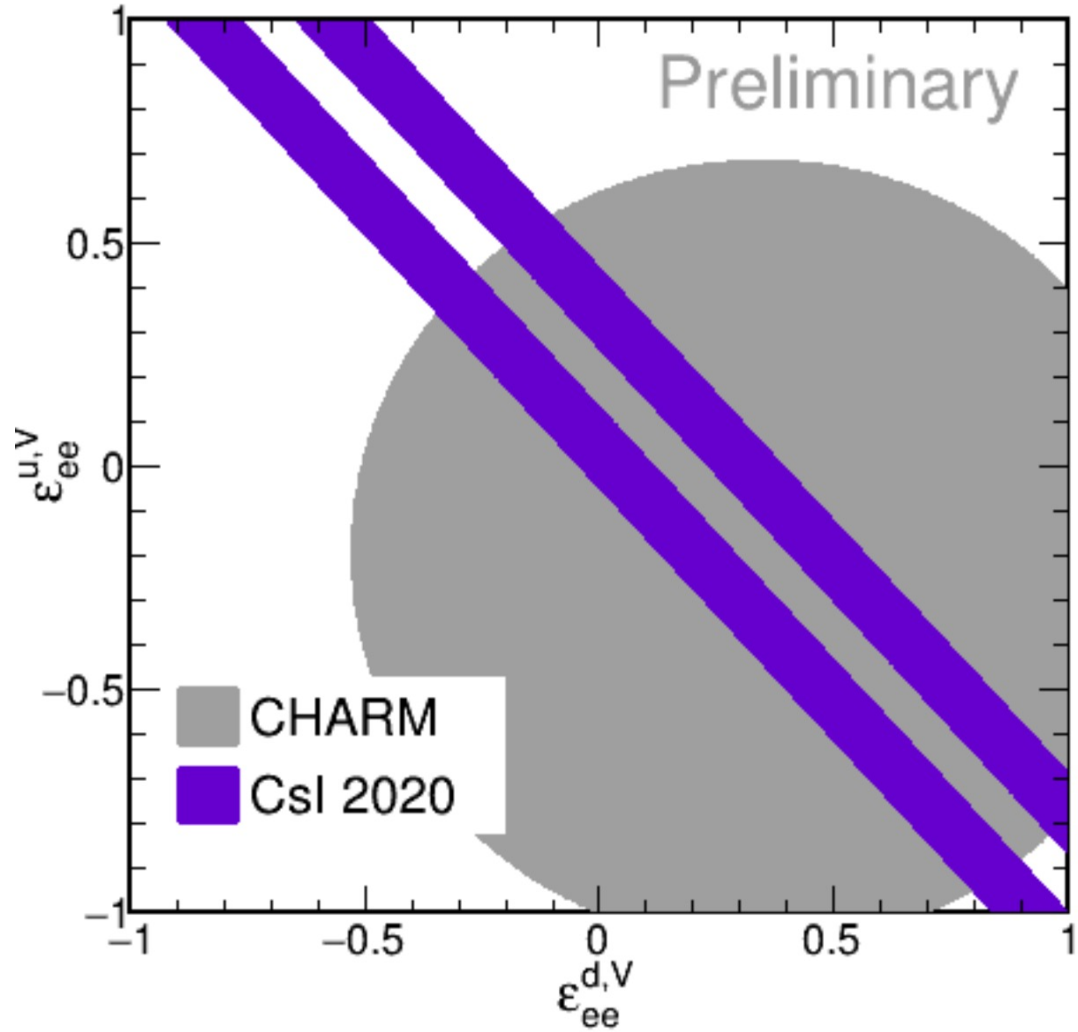
Best fit results

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


Cross section (10^{-40} cm^2)
Neutron number
Preliminary
Na
Ar
Ge
I
Cs
Still consistent with the SM... squishing down the error bars!

And squeezing down the possibilities for new physics...



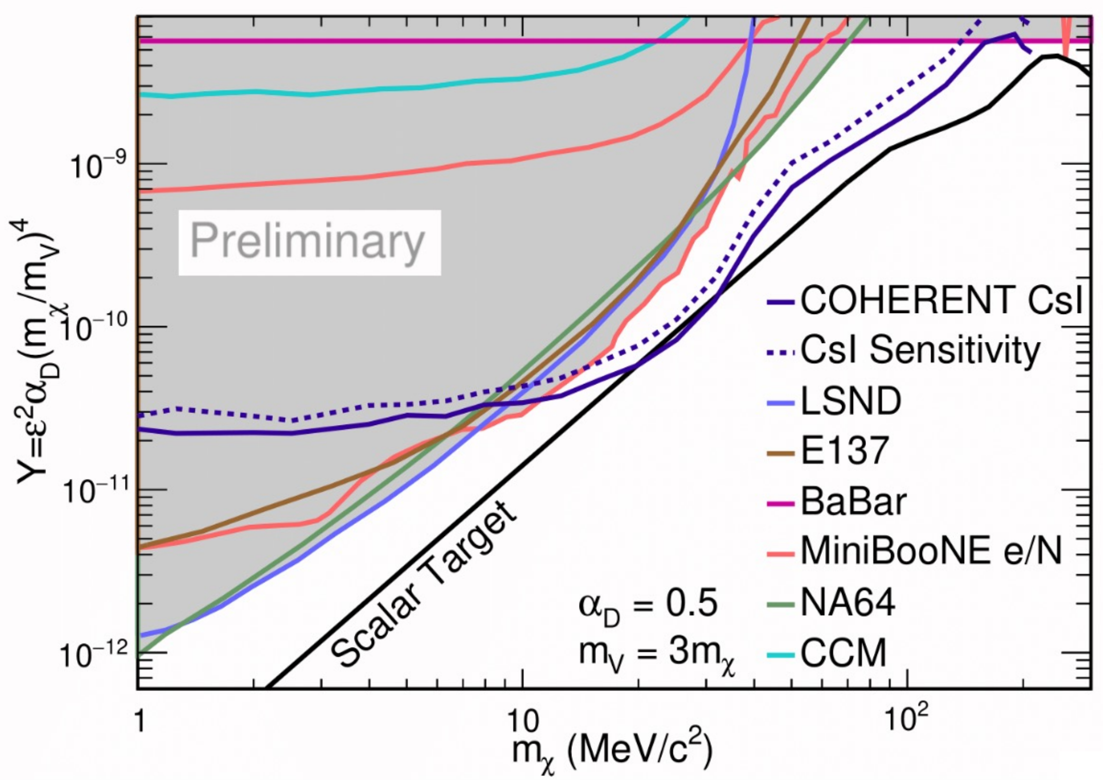


CEvNS as background for accelerator-produced DM

https://indico.phy.ornl.gov/event/126/

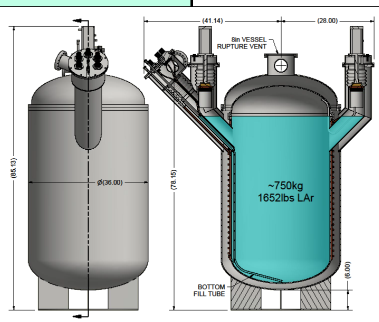
COHERENT constraint on sub-GeV dark matter

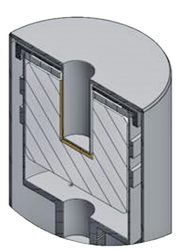
- At 90% confidence, CsI data significantly improves on constraints for masses 11 - 165 MeV/c^2
  - Constraint slightly stronger than our sensitivity due to deficit of events in DM timing ROI
- First to probe beyond the scalar target that matches the DM relic abundance
- Achieved with small 14.6 kg detector – but we can build bigger promising a bright future

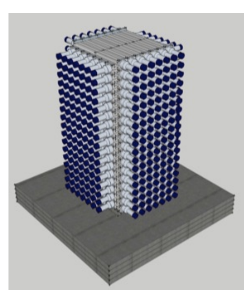


COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	19.3	6.5	9/2015	Decommissioned
Ge	HPGe PPC	18	22	<few	2021	Funded by NSF MRI, in progress
LAr	Single-phase	24	27.5	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	25	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes



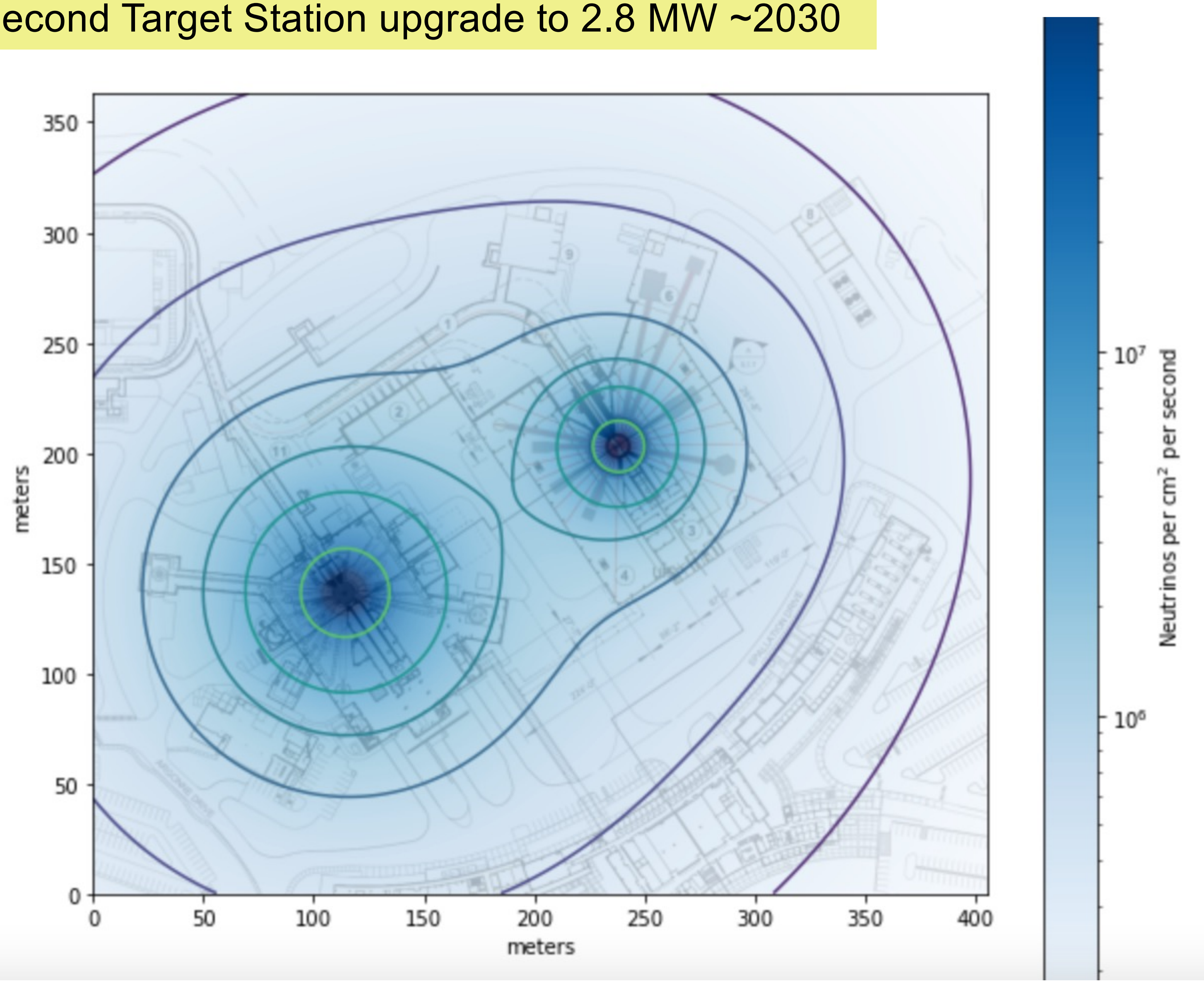




+D_2O for flux normalization
+ concepts for other targets...

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

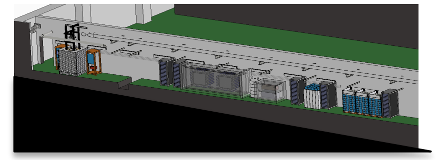
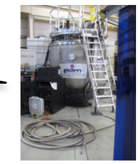
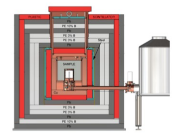
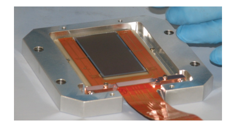
SNS power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030

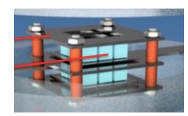


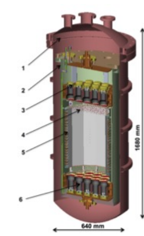
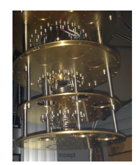
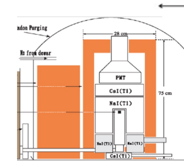
Many exciting possibilities for ν's + DM!

Many CEvNS Efforts Worldwide [incomplete]

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

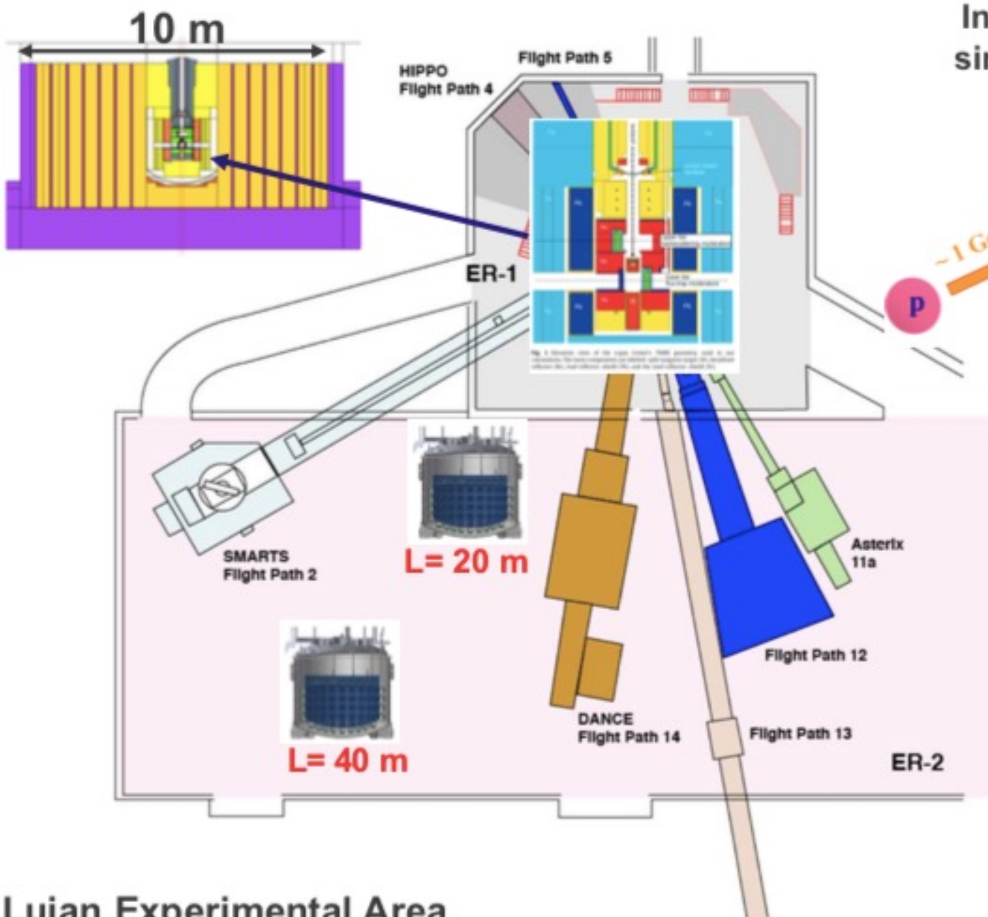


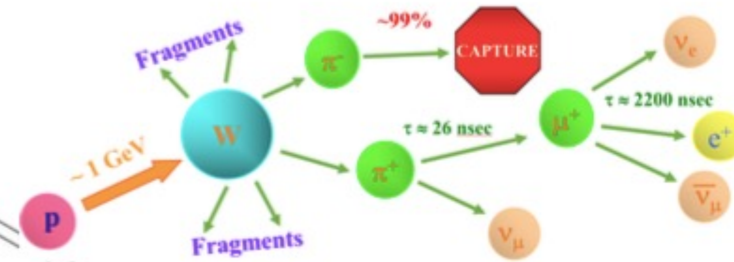
+ DM detectors, +directional detectors +more...

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

Coherent Captain Mills @ Lujan: single-phase LAr



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

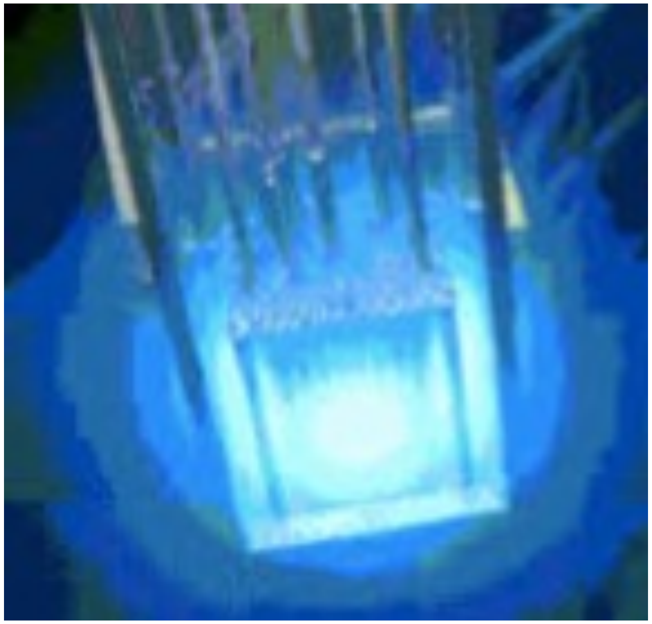


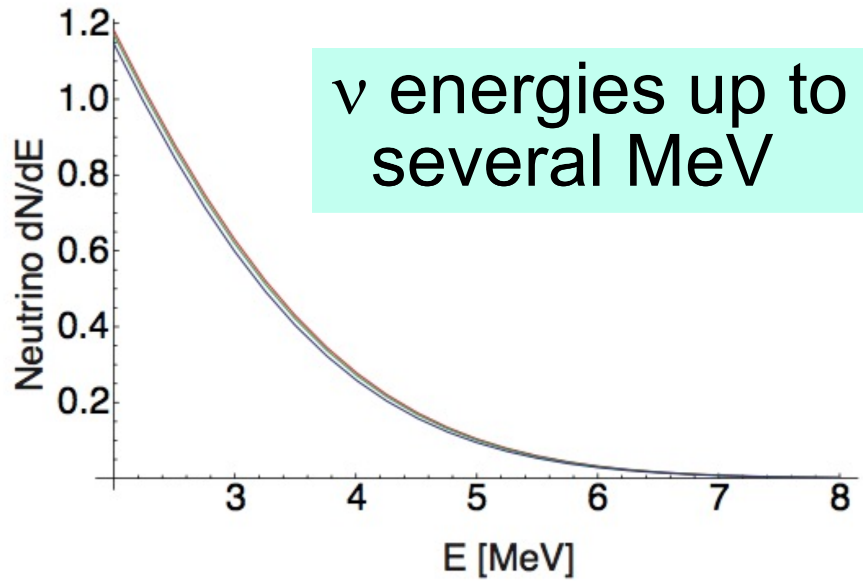
Lujan Experimental Area

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

Primary focus on sterile neutrinos & DM search

Neutrinos from nuclear reactors





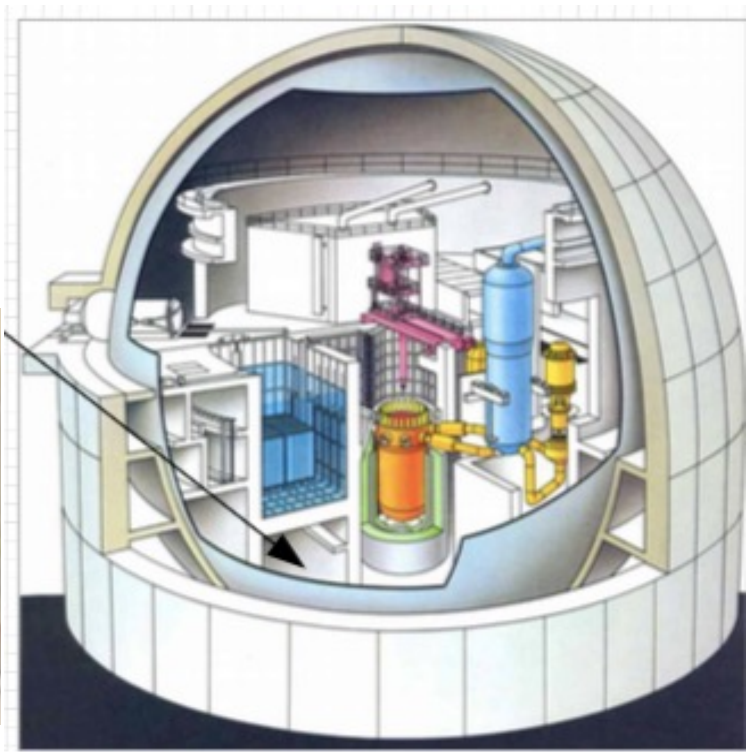
ν energies up to several MeV

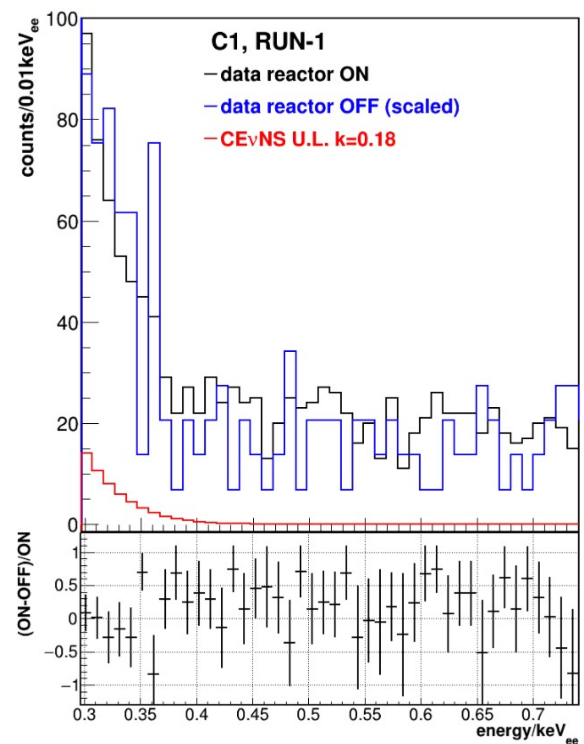
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

CONUS

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

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



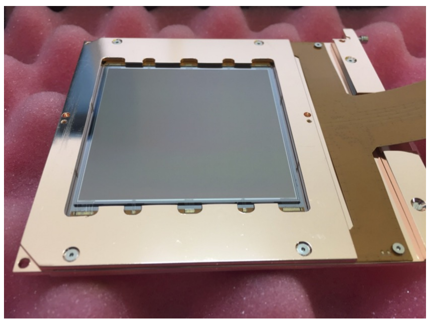


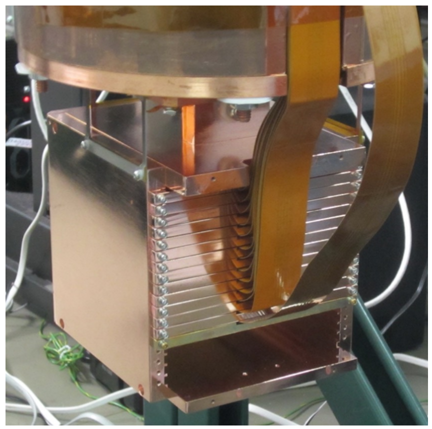
<85 events in ROI @90 CL

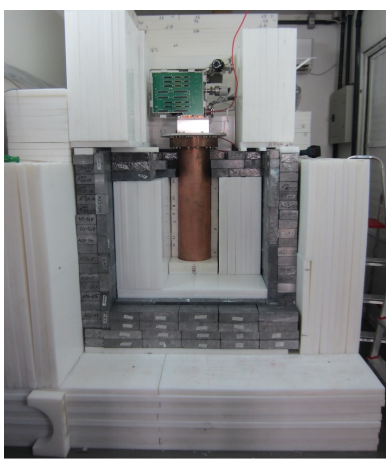
See J. Hakenmuller's talk next!

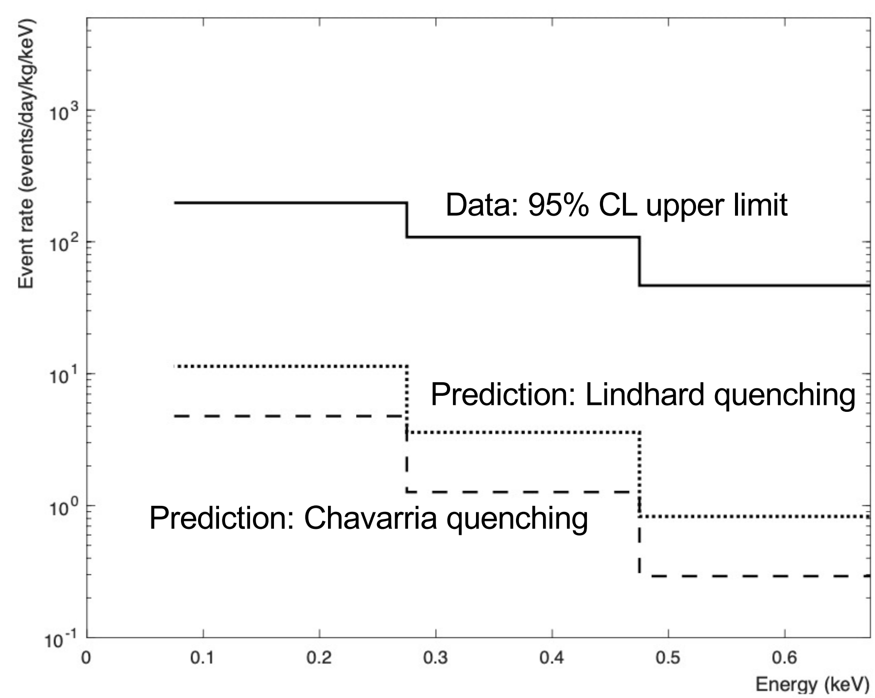
CONNIE

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





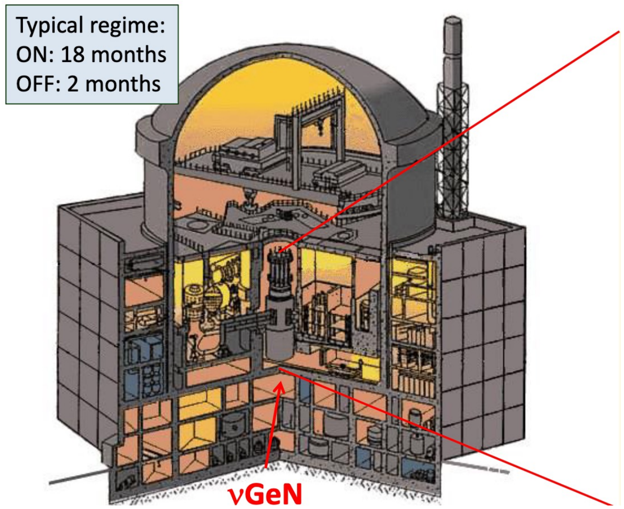


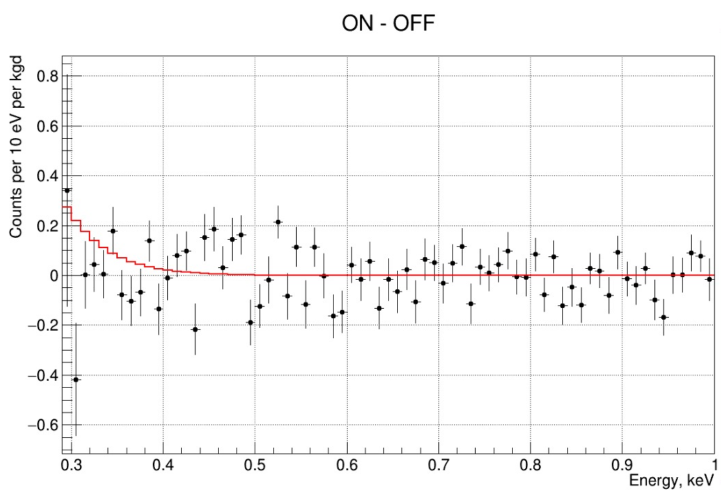


Phys.Rev.D 100 (2019) 9, 092005
arXiv: 1906.02200 [physics.ins-det]

νGEN

- Kalinin Nuclear Power Plant, 3 GWth, Russia
- 10 m from core
- 1.5 kg Ge deployed (+3 more)



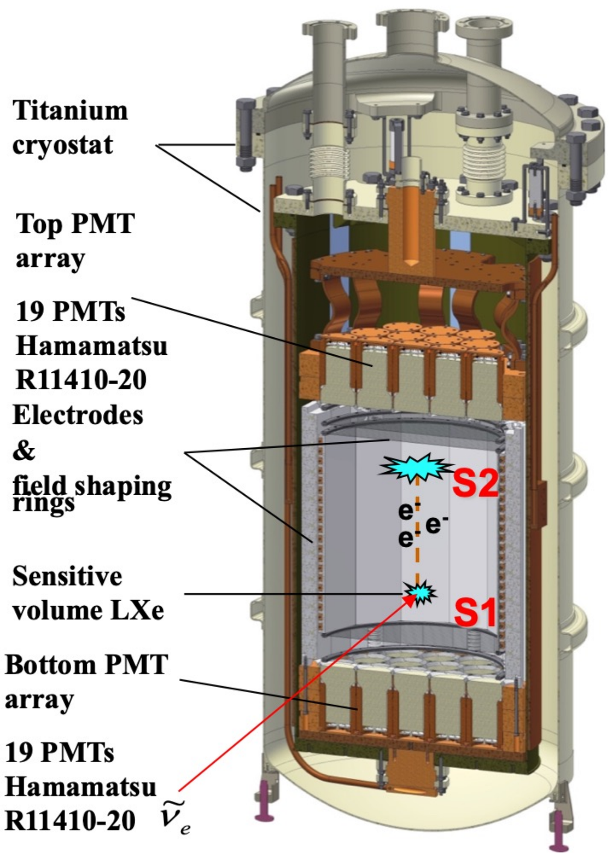


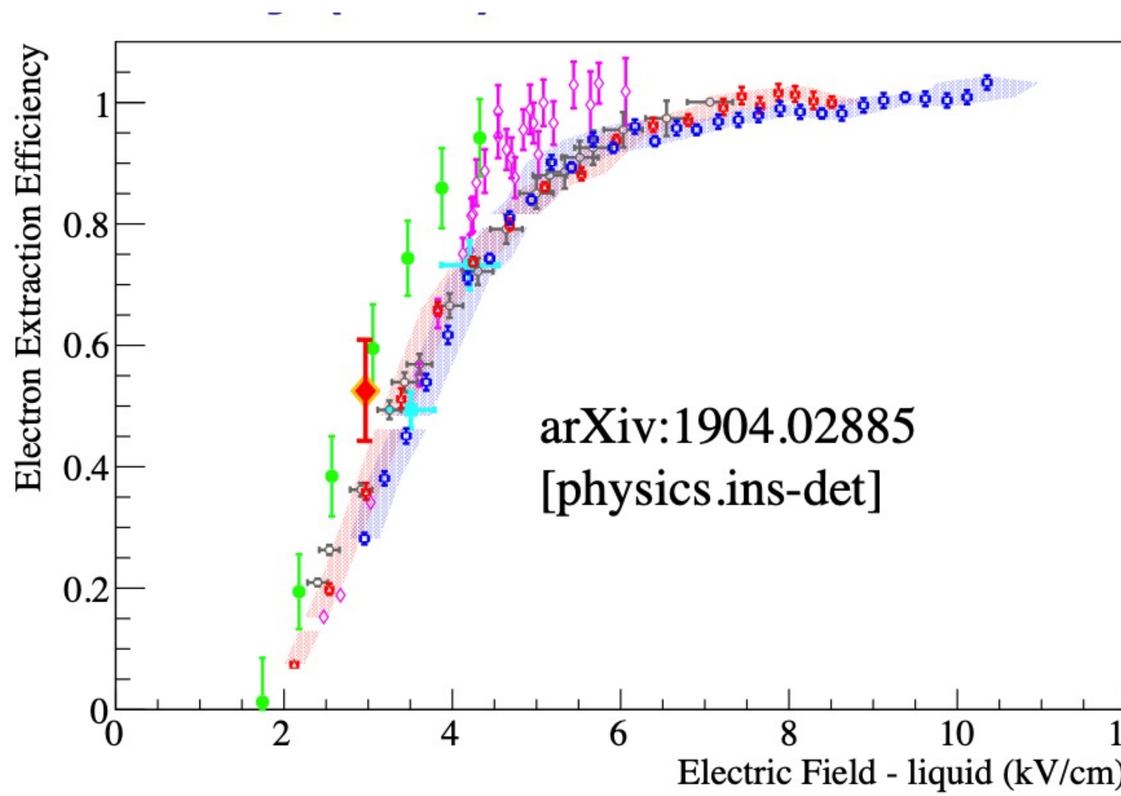
- Analysis of the data gives **[0..0.47] cts/kgd** for CEνNS 90% C.L. in energy region of [0.32..0.36] keV.
- The expected rate of the events from CEνNS is **0.46 cts/kgd.** This value has not fully known due to uncertainties of quenching and high energy neutrino spectra from the reactor. So no tension is visible so far?

https://indico.ific.uv.es/event/6178/contributions/15547/attachments/9260/12116/lubashevskiy_vGeN.pdf

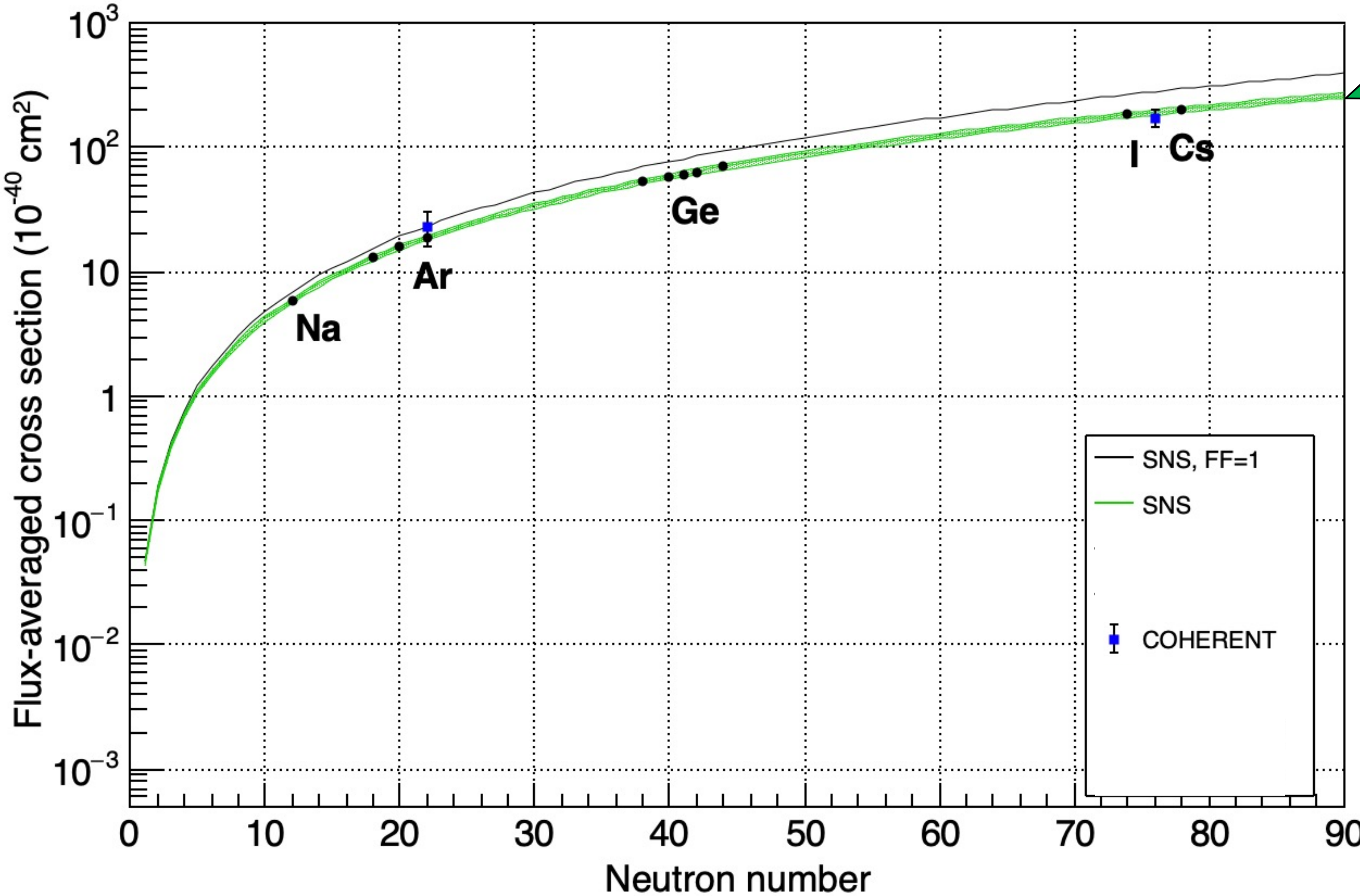
RED-100

- Kalinin Nuclear Power Plant, 3 GWth, Russia
- 19 m from core
- 100-kg Xe, dual-phase
- ~4 SE (single electron) threshold



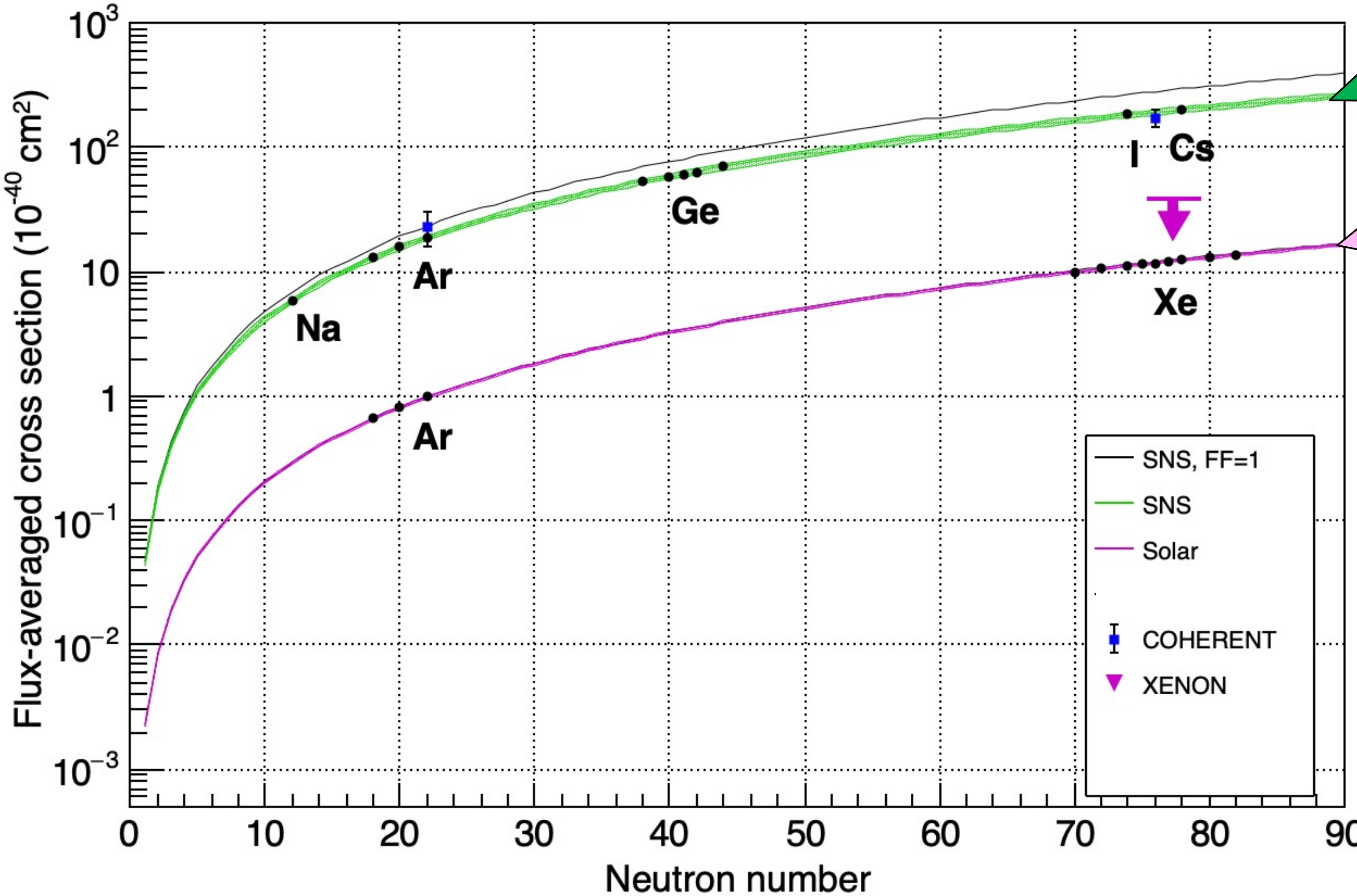


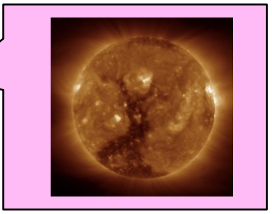
Summary of CEvNS Results



So far: measurements in CsI, Ar from COHERENT

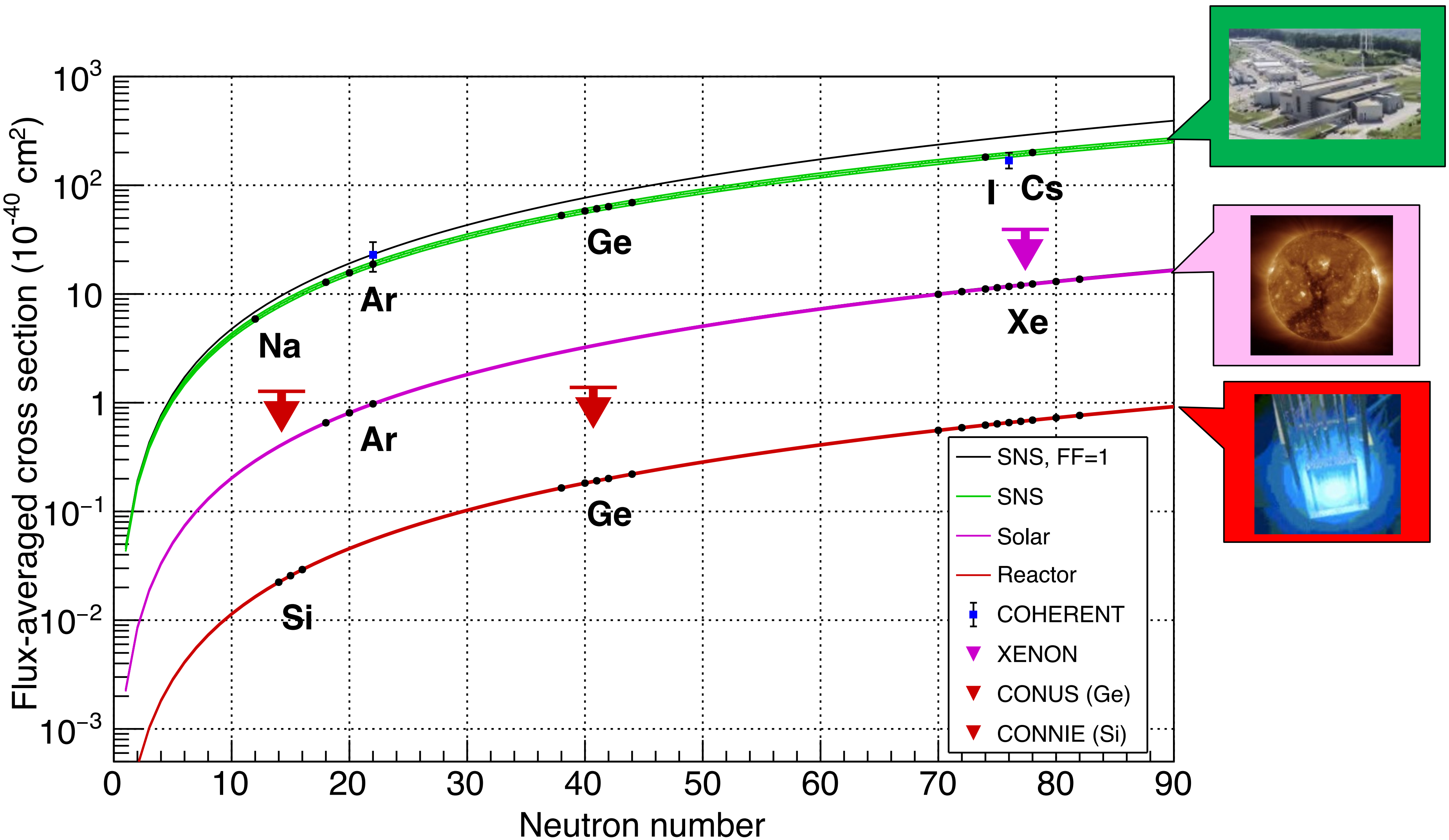
Summary of CEvNS Results





Limits from XENON on solar CEvNS

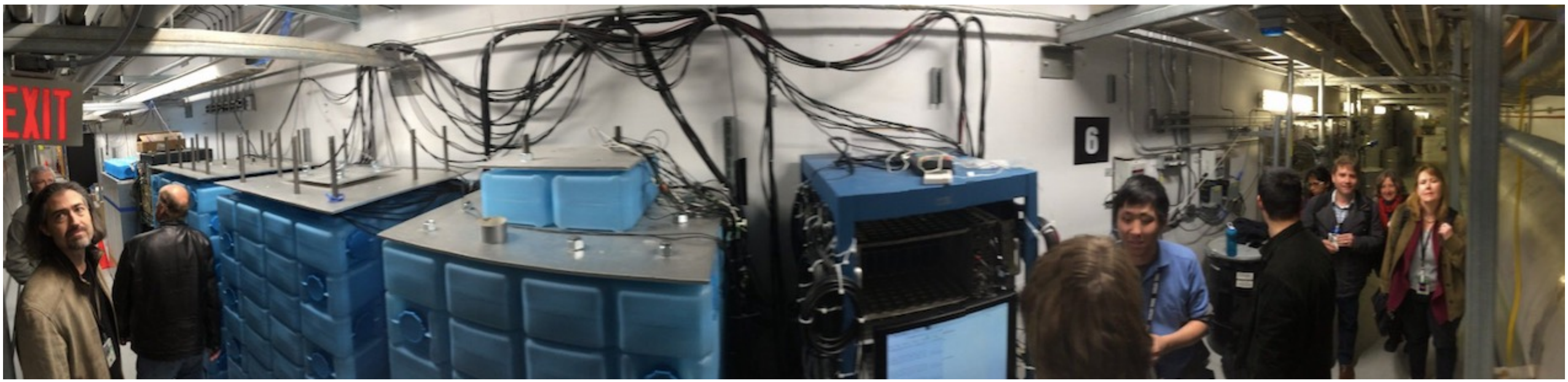
Summary of CEvNS Results



Limits on reactor CEvNS in Ge, Si... looking forward to more soon!

Summary

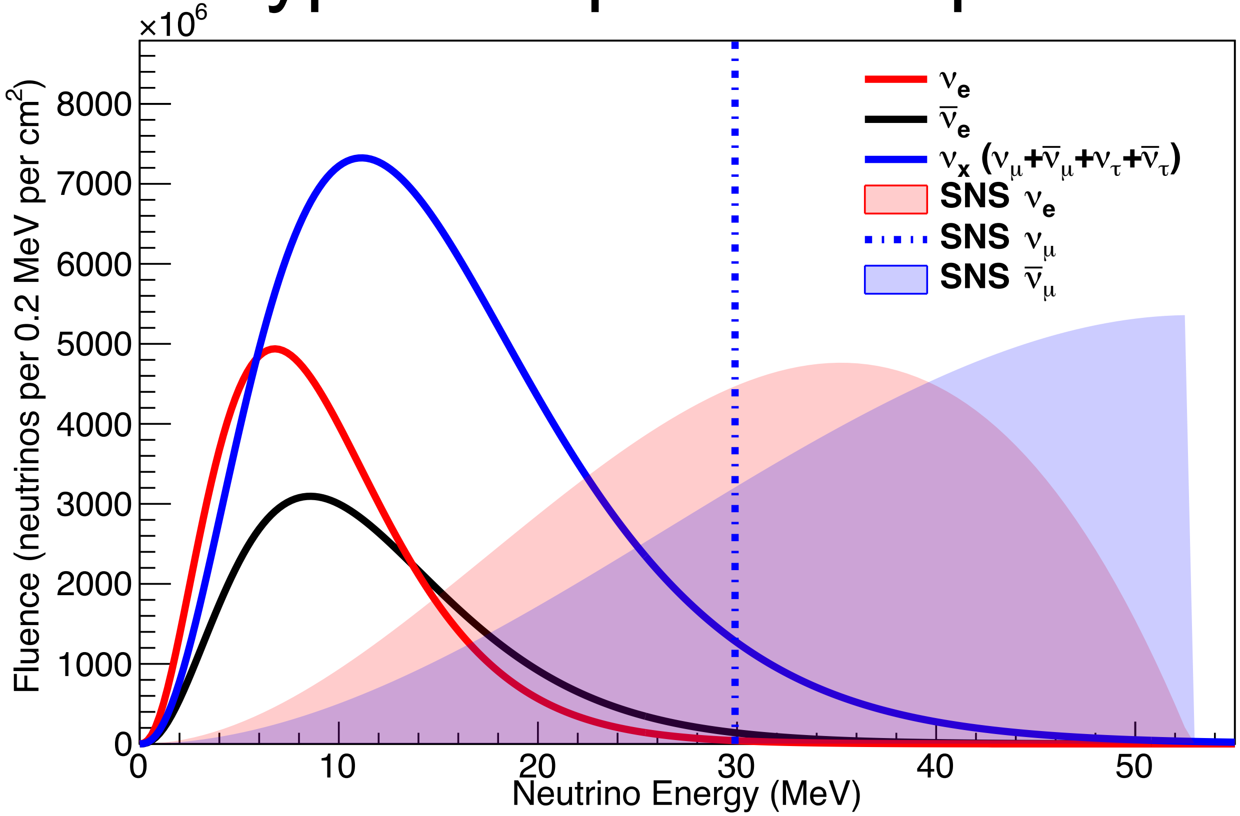
- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
- **First measurement** by COHERENT CsI[Na] at the SNS... now Ar, + more CsI data!
- **Meaningful bounds on beyond-the-SM physics**



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

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

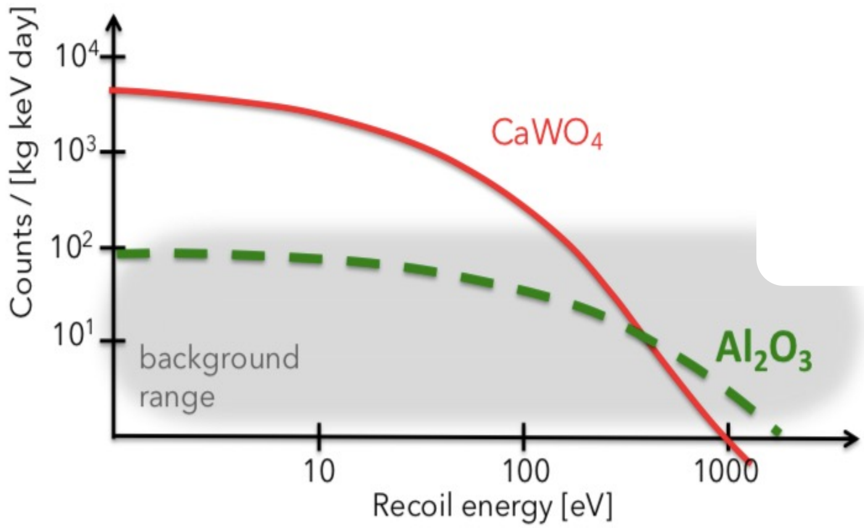
Neutrinos from stopped pions overlap with the typical supernova spectrum

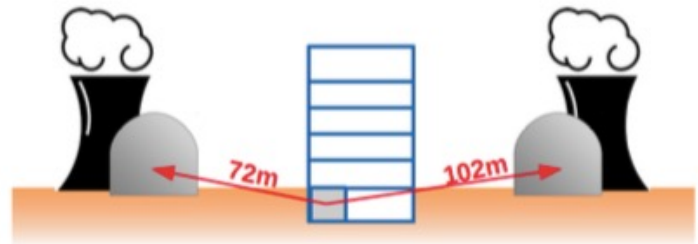


Available at the Spallation Neutron Source

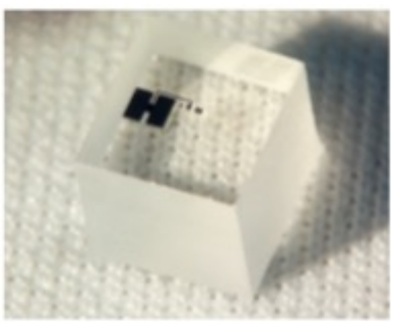
NUCLEUS

"gram-scale cryogenic calorimeters"





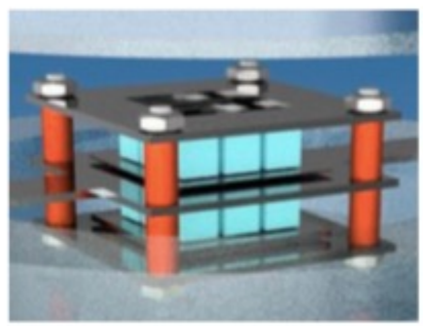
NUCLEUS 1g



2017-2019

straight forward

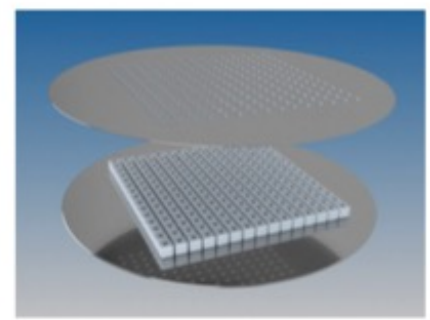
NUCLEUS 10g



2020-2022

major R&D

NUCLEUS 1kg



>2024