Coherent Elastic Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

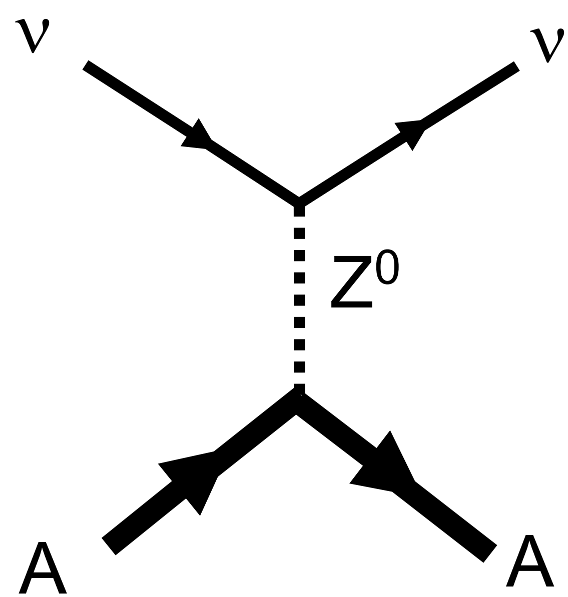
Kate Scholberg, Duke University,

TAUP 2019, Toyama

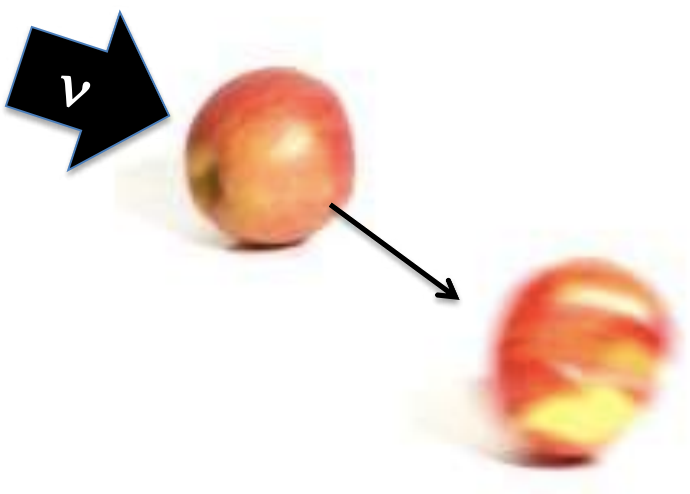
September 13, 2019

Coherent elastic neutrino-nucleus scattering (CEvNS)

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



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



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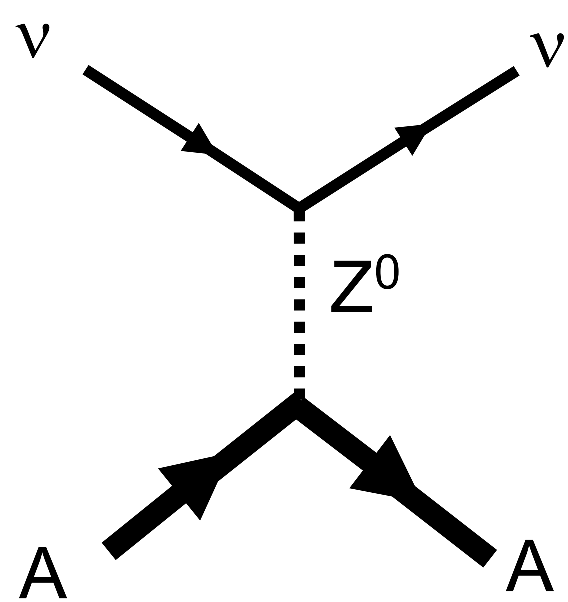
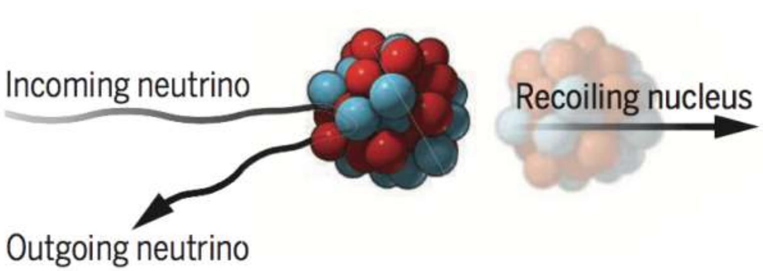


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



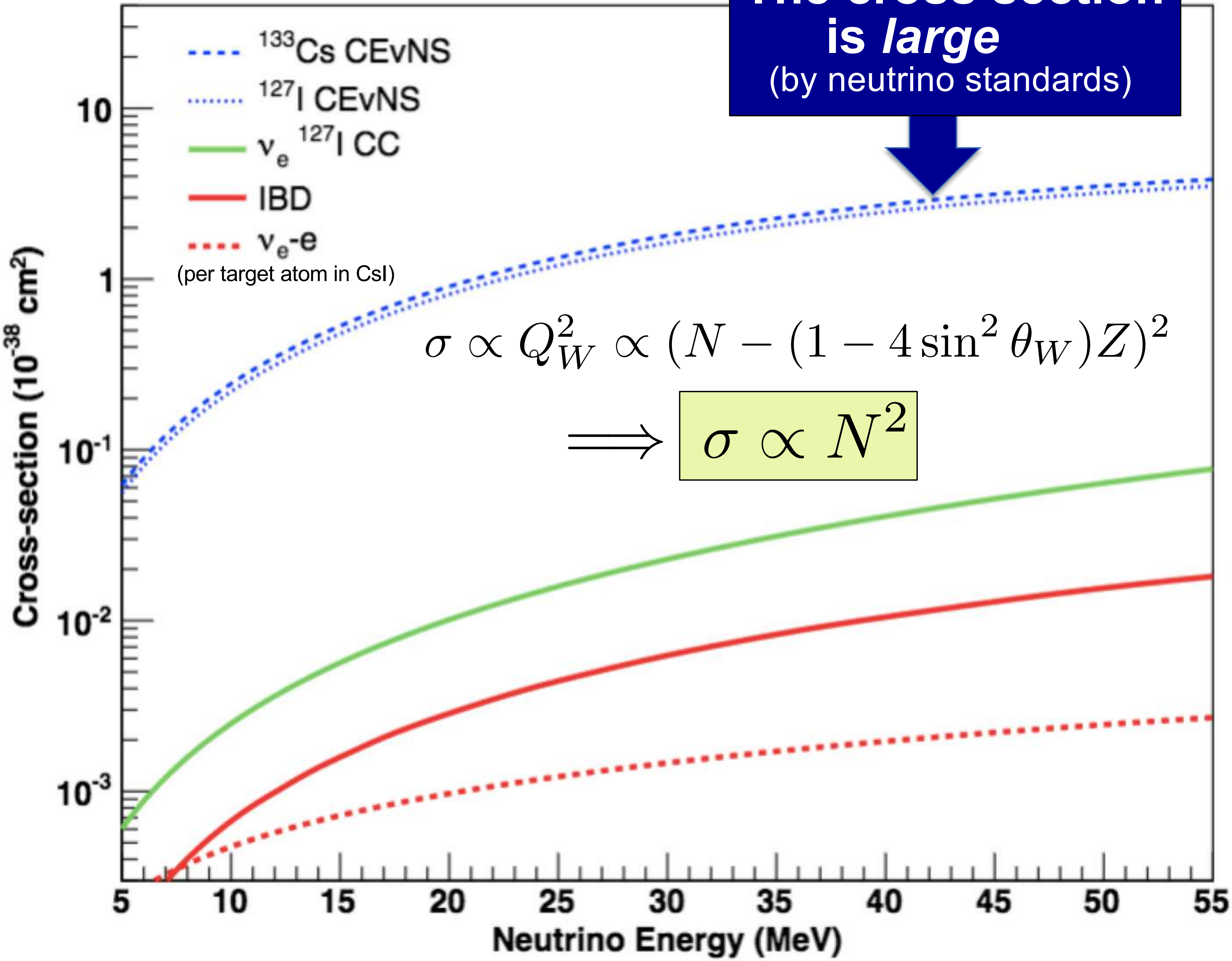
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

A: no. of constituents

Image: J. Link *Science* Perspectives

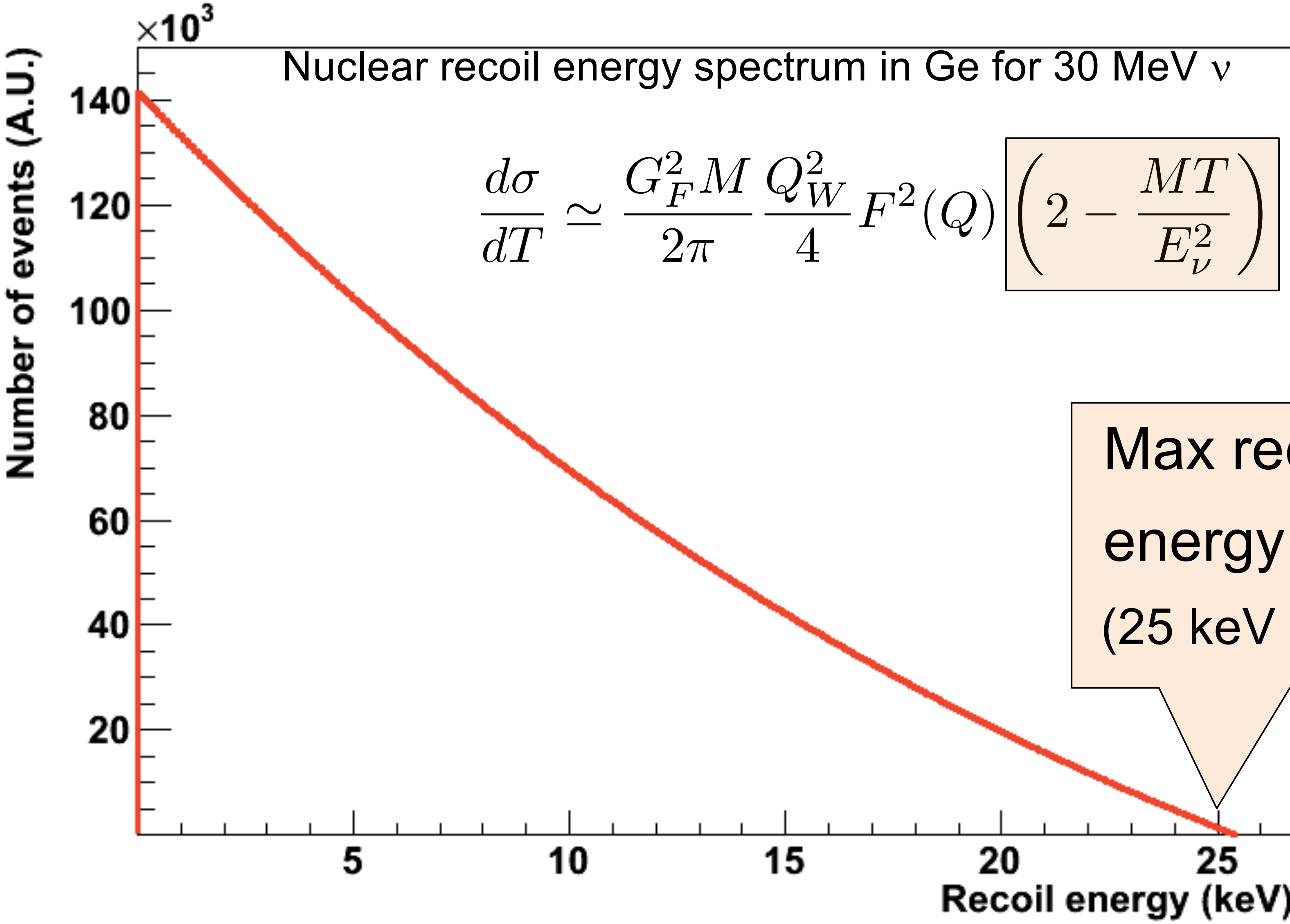
The cross section is *large*
(by neutrino standards)



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

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

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



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

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

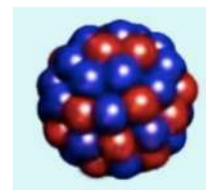
CEvNS: what's it good for?

!

(not a complete list!)

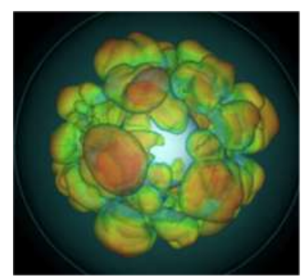
CEvNS as a **signal**
for signatures of *new physics*

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

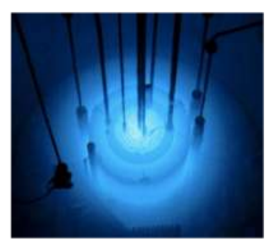


CEvNS as a **background**
for signatures of new physics

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



CEvNS as a **practical tool**



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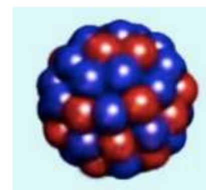

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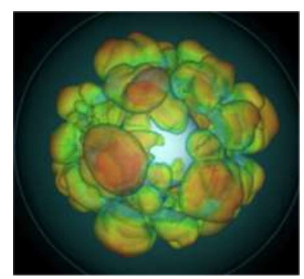

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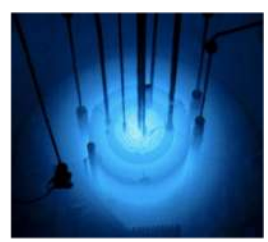

The cross section is cleanly predicted in the Standard Model

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

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

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

The cross section is cleanly predicted in the Standard Model

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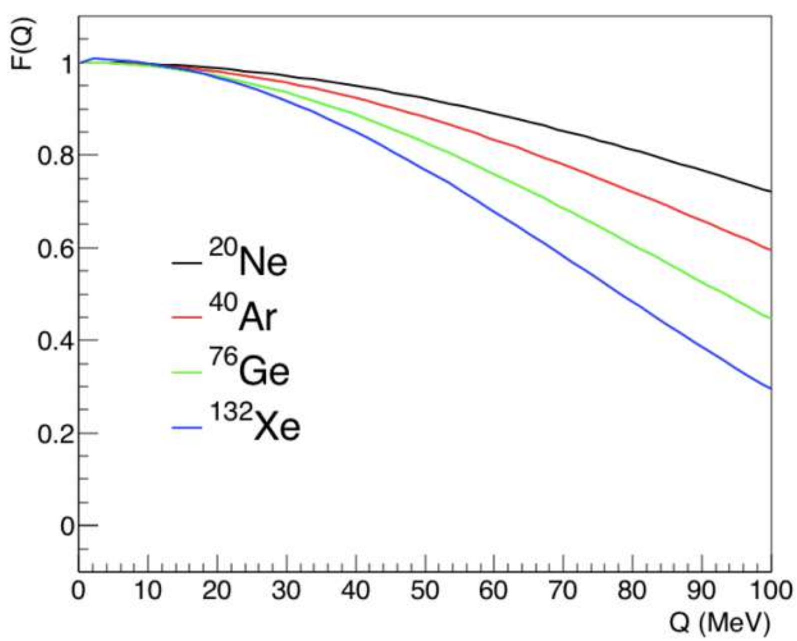
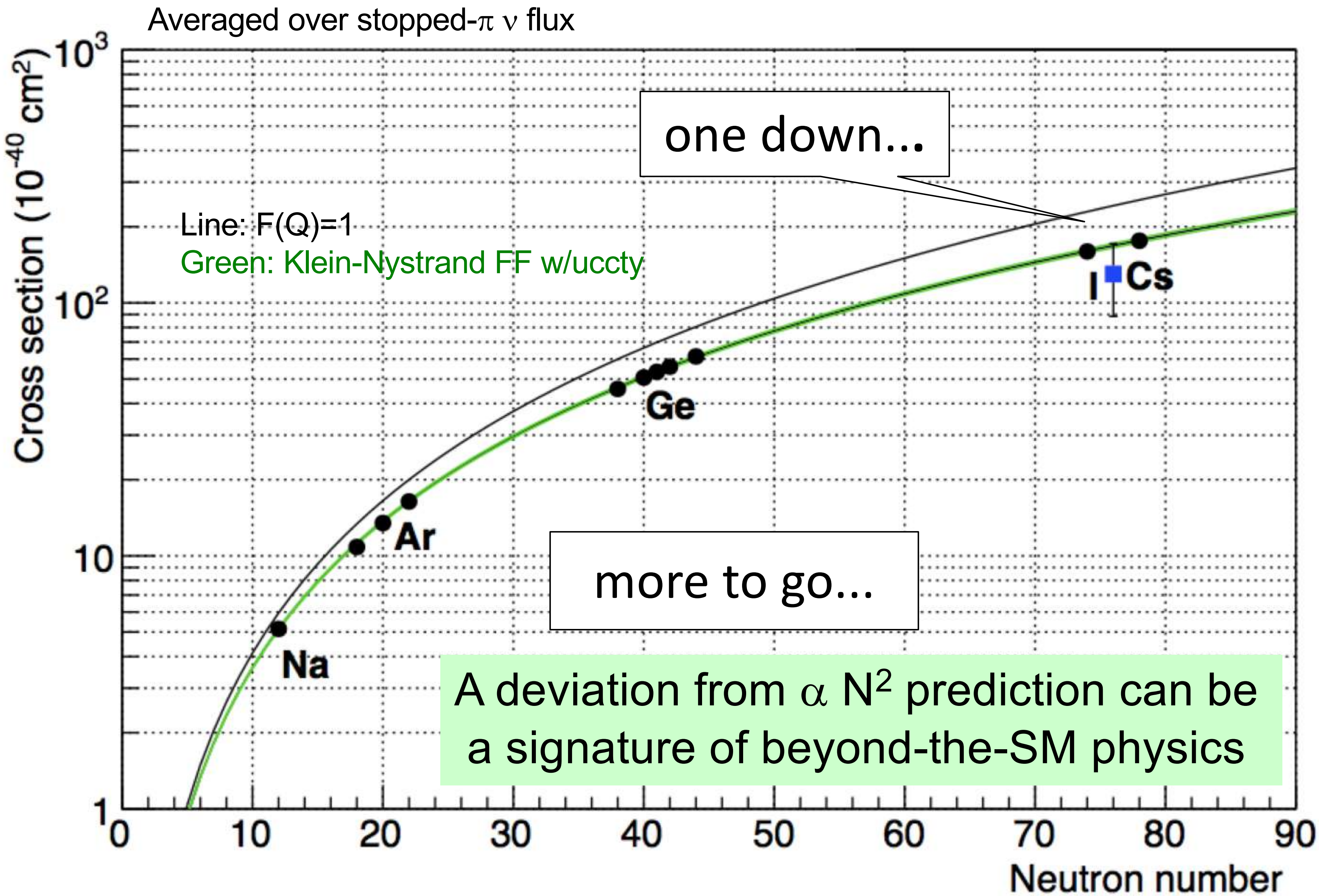
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2 M T)}$: momentum transfer

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

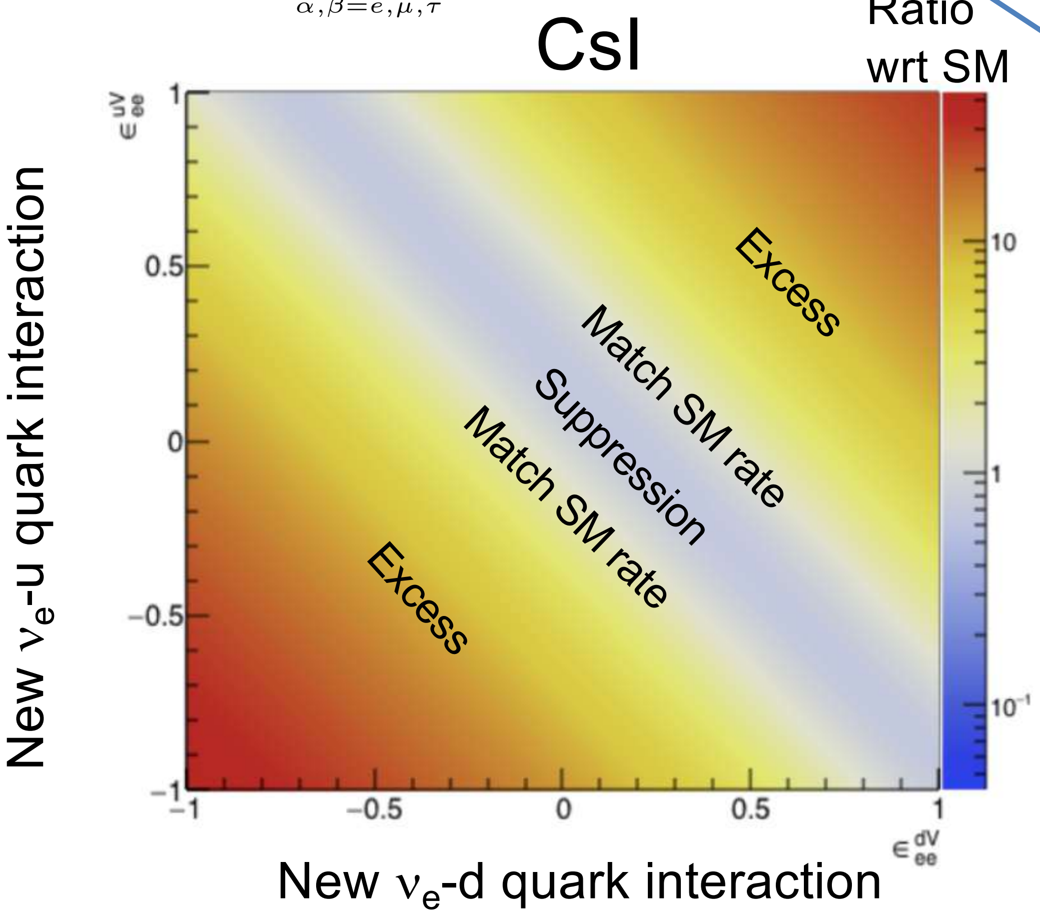


Non-Standard Interactions of Neutrinos:

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

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

"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

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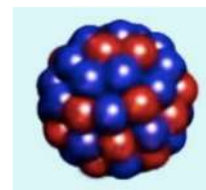
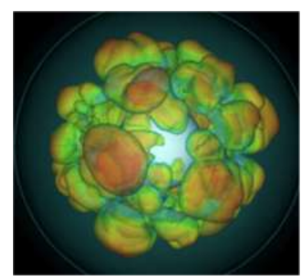
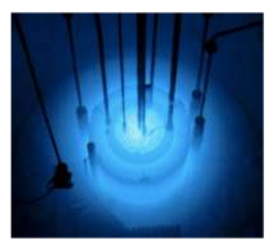


CEvNS as a **background**
for signatures of new physics (DM)

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



CEvNS as a **practical tool**

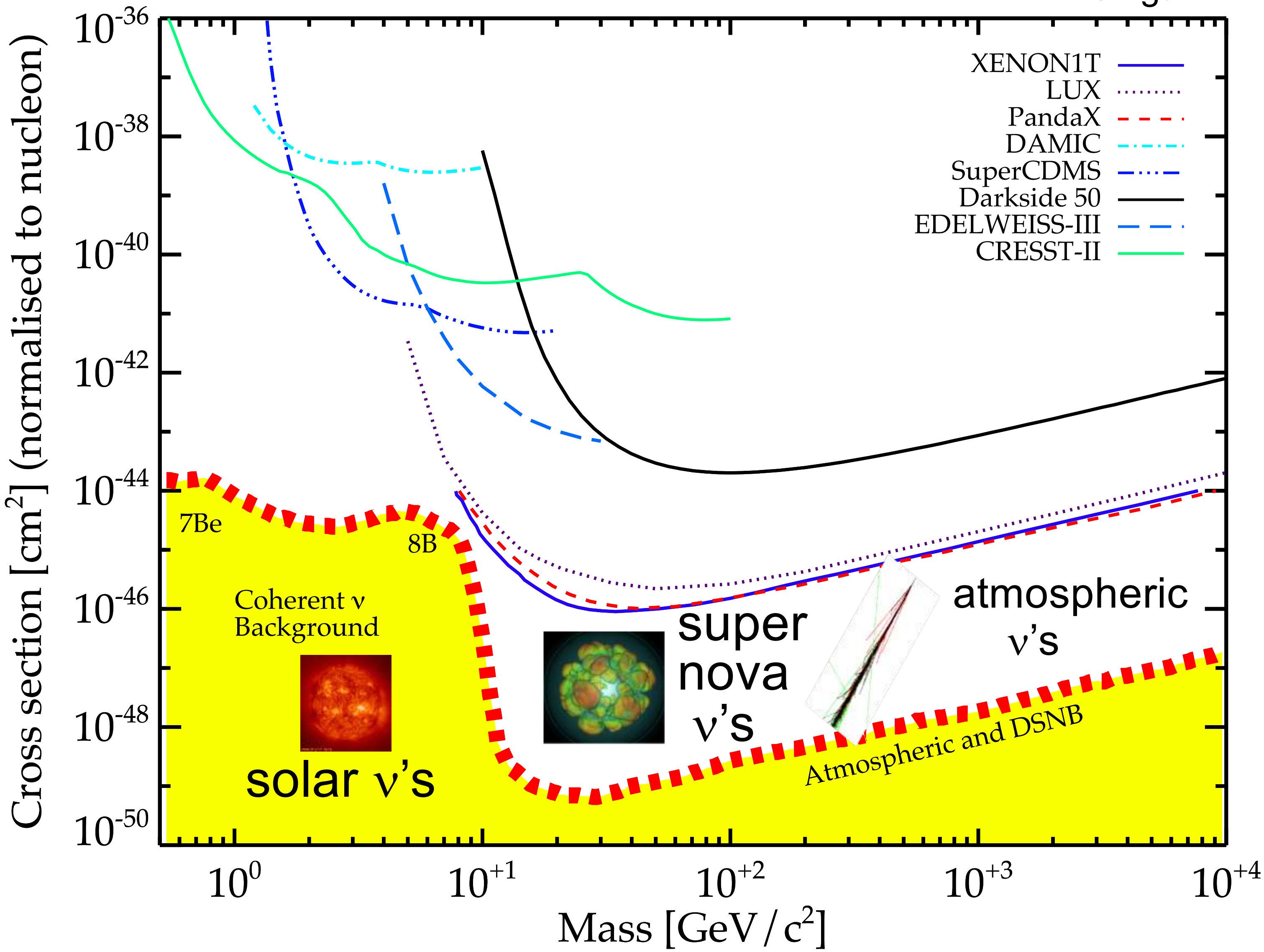


The so-called “neutrino floor” (**signal!**) for direct DM experiments

J. Monroe & P. Fisher, 2007

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

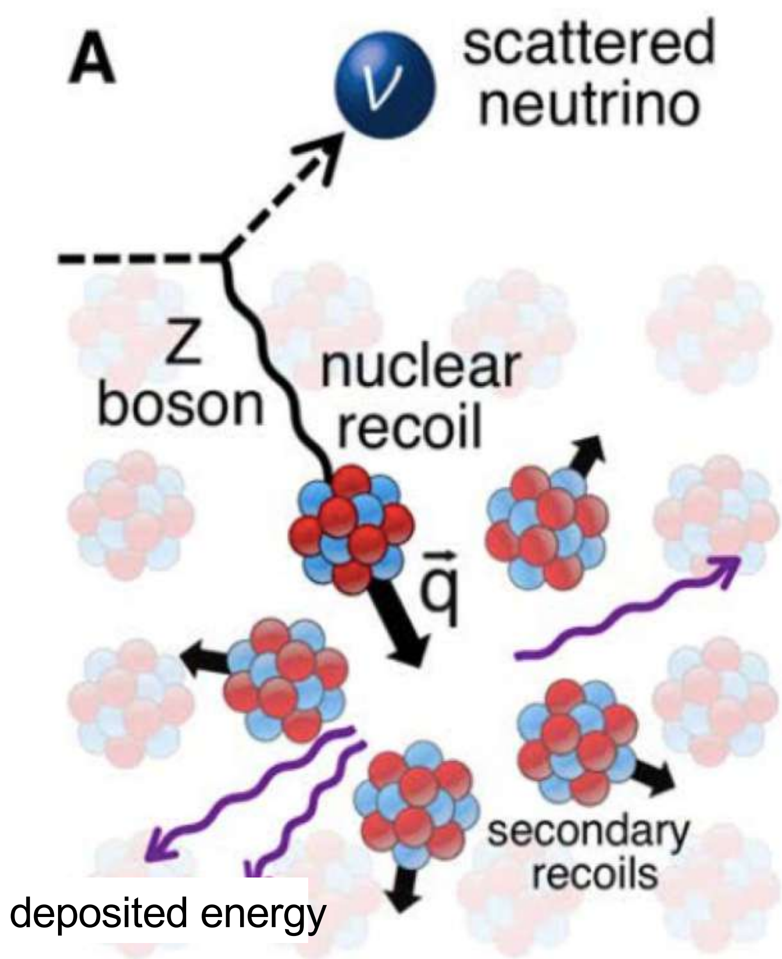
L. Strigari



How to measure CEvNS

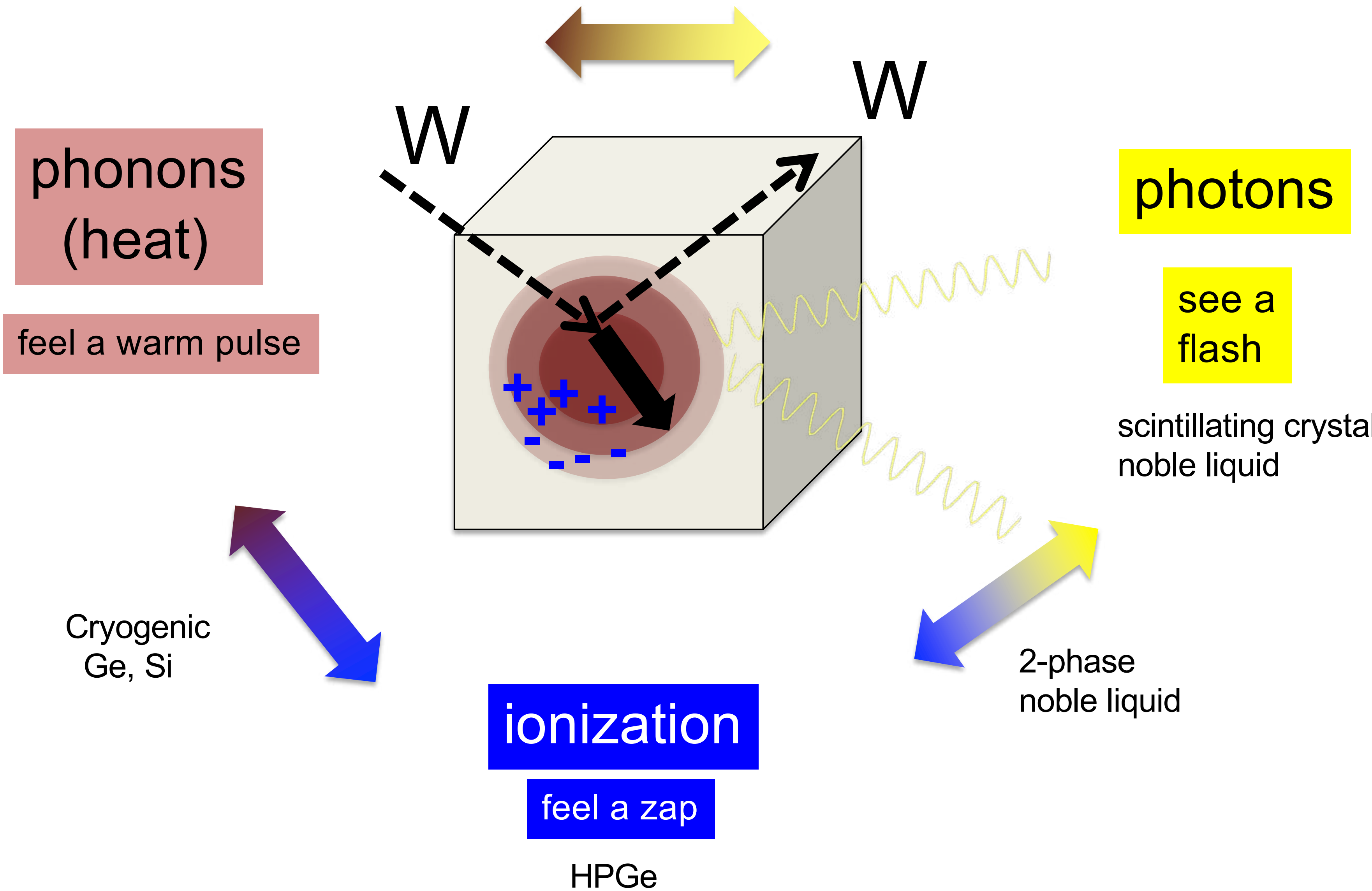
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



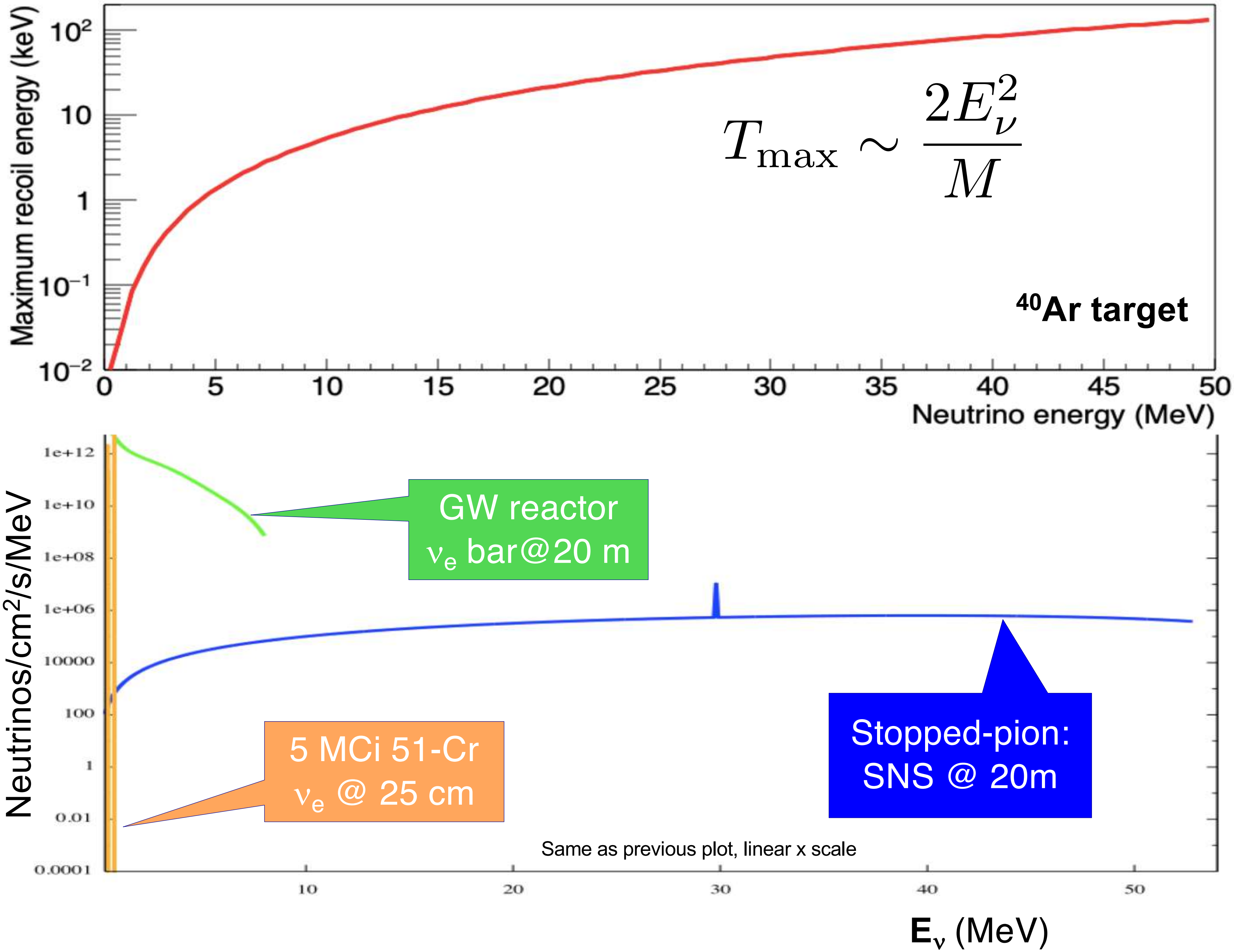
➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10’s of keV recoils

Low-energy nuclear recoil detection strategies



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

Maximum recoil energy as a function of E_ν



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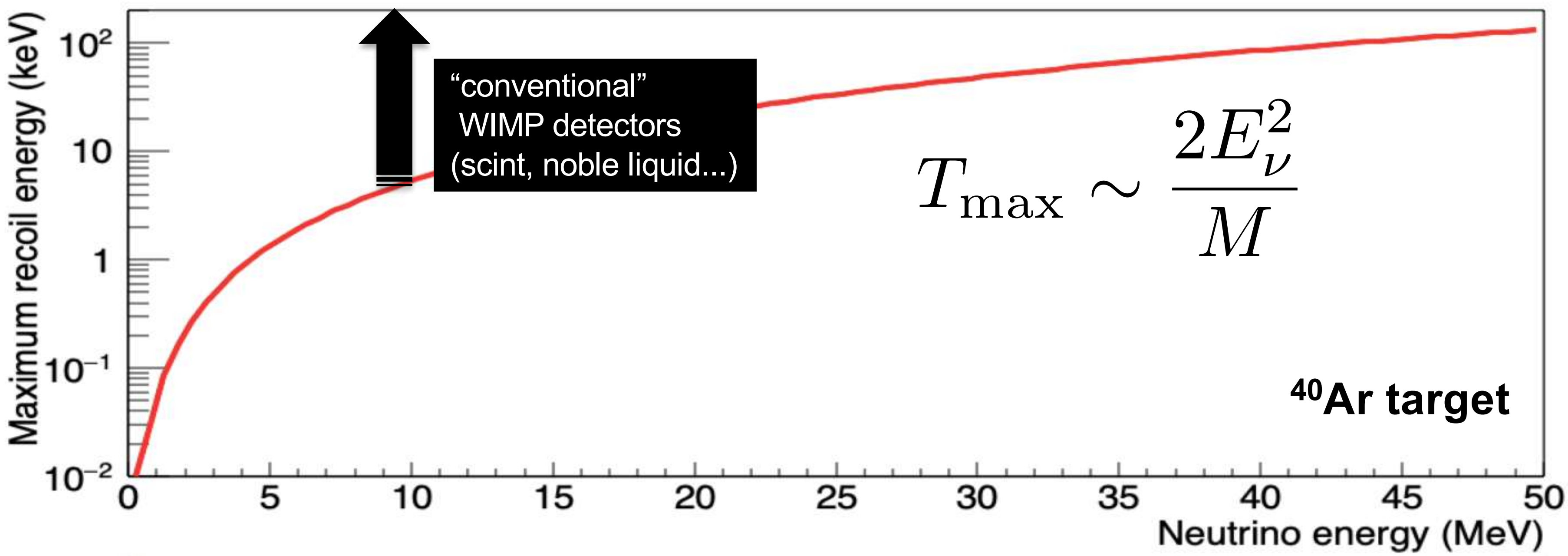
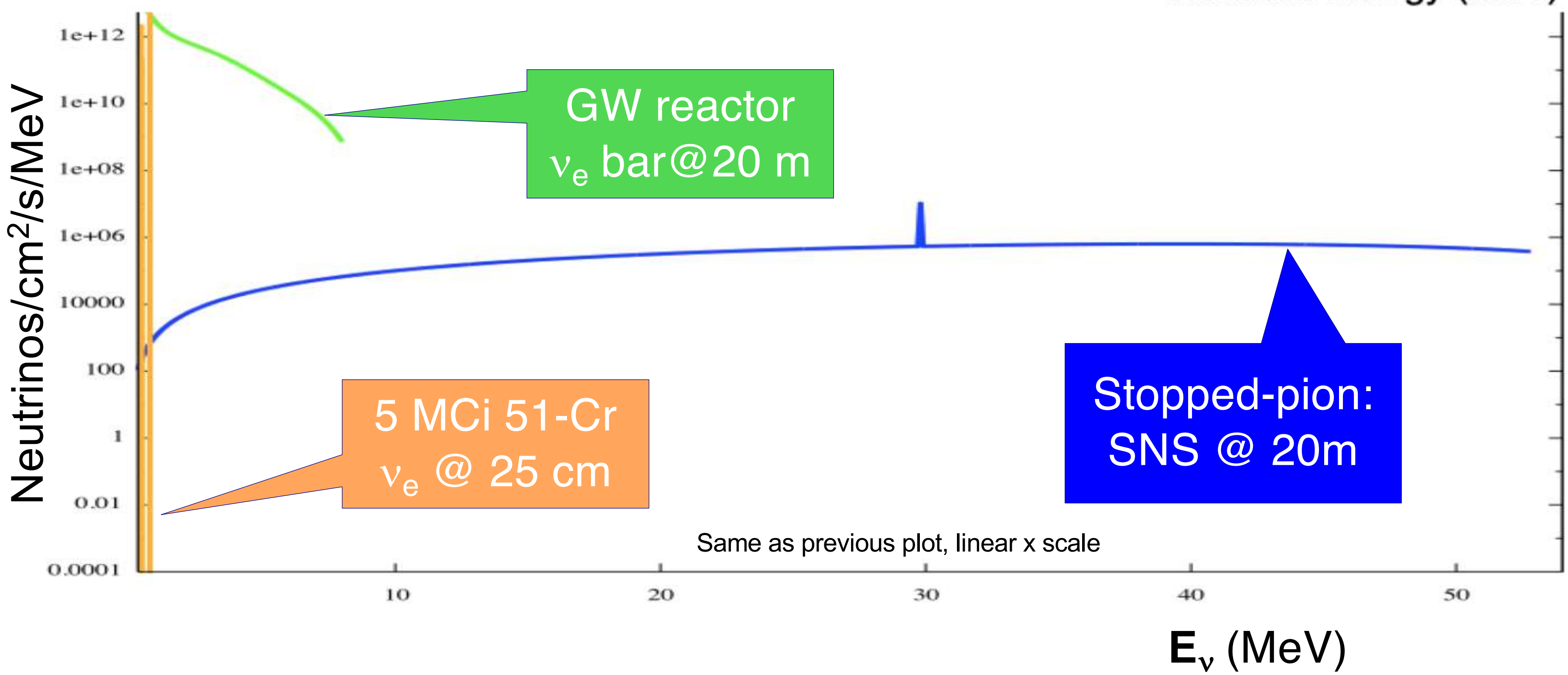
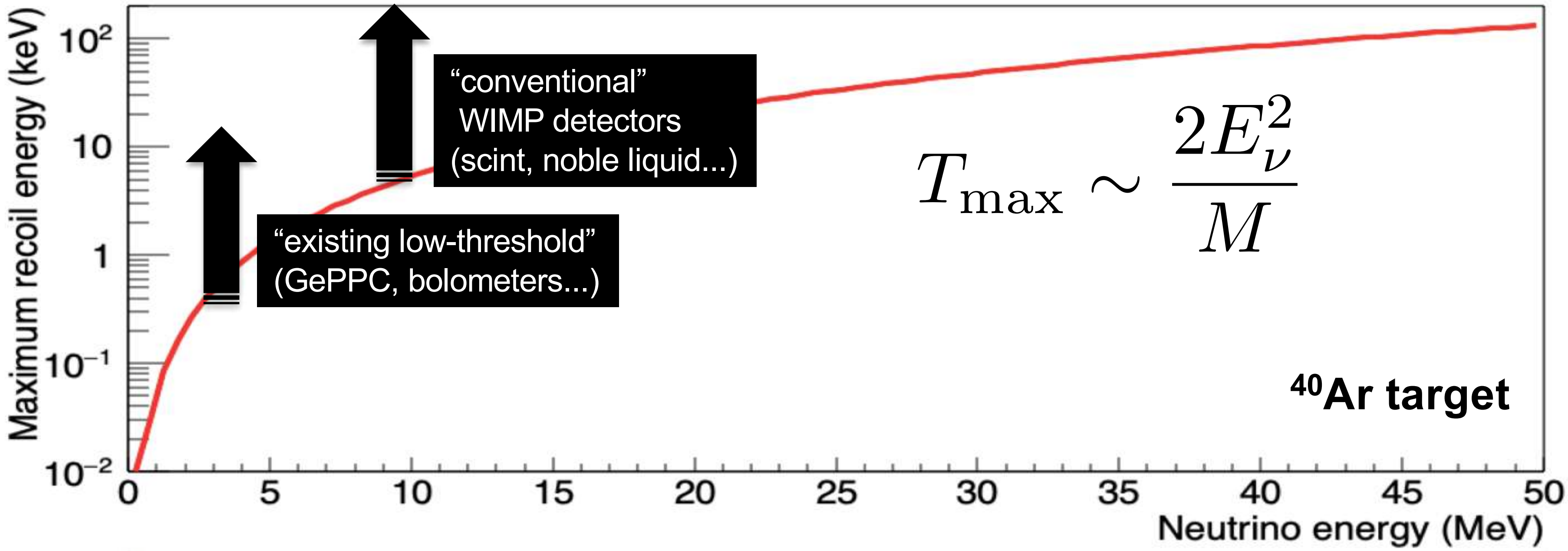
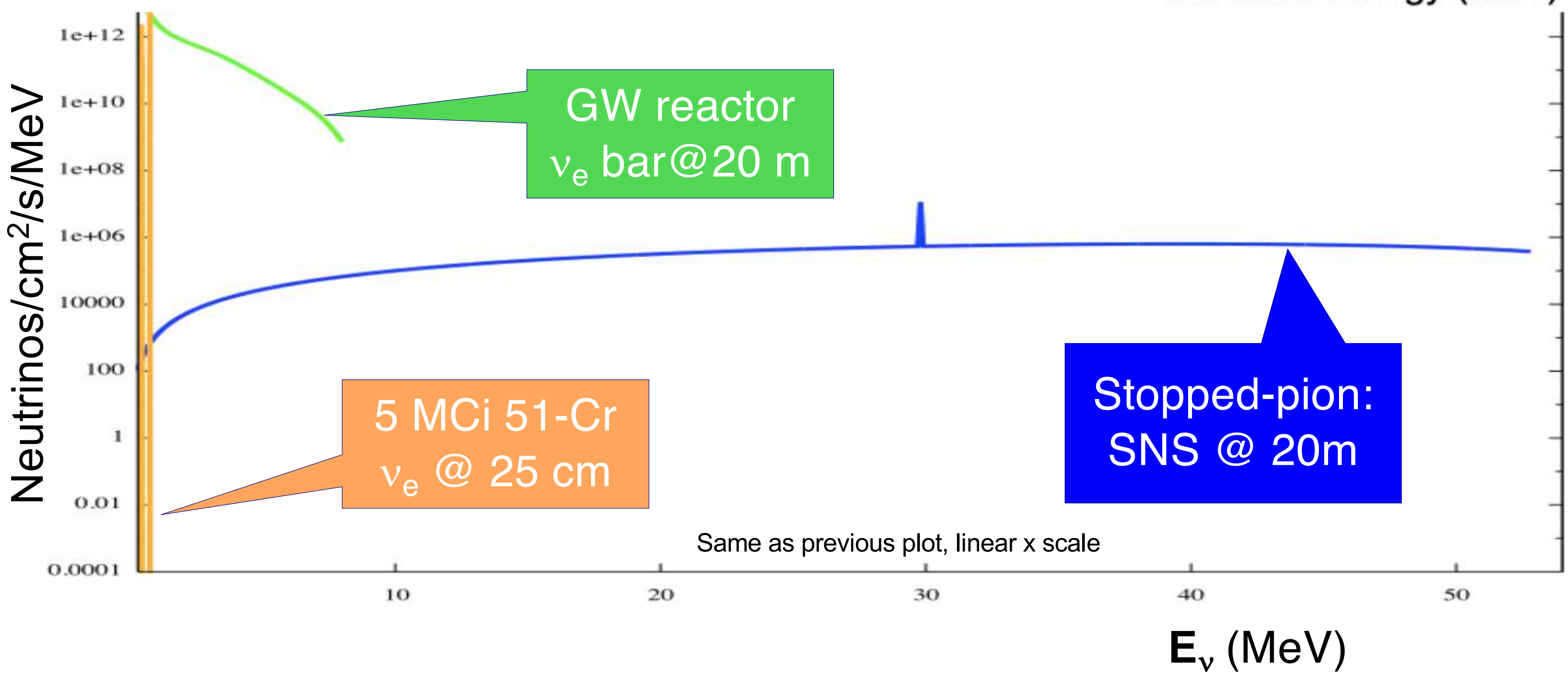




Same as previous plot, linear x scale

Maximum recoil energy as a function of E_ν





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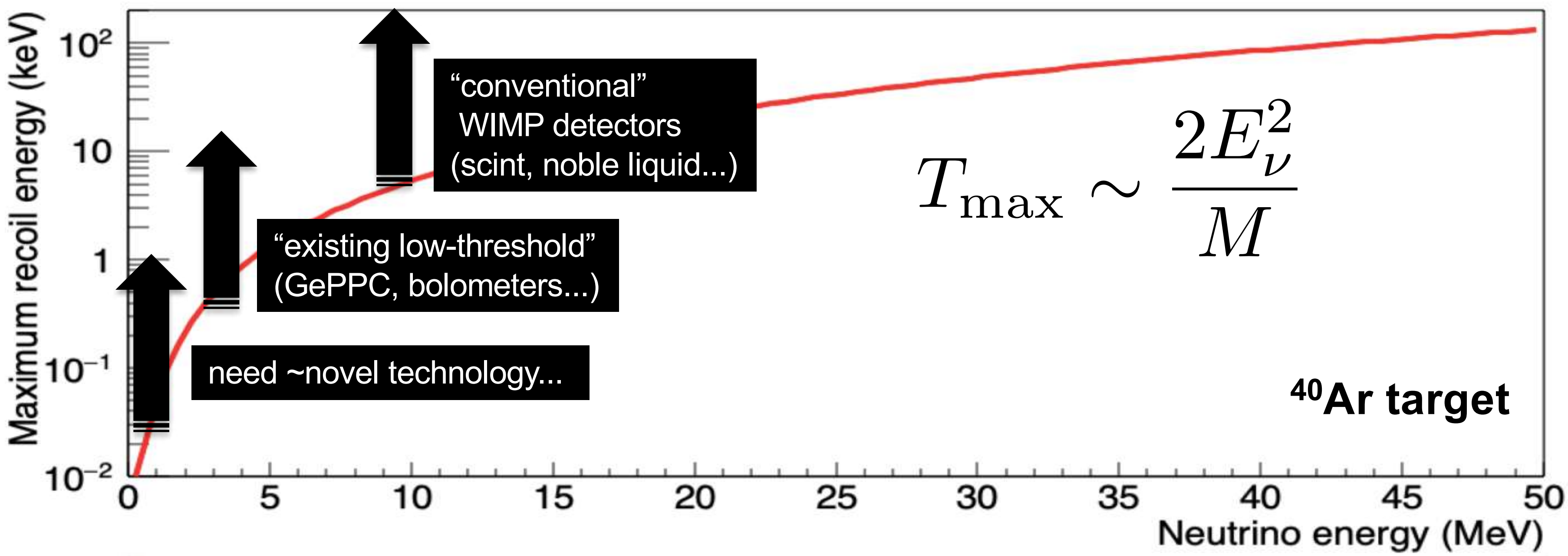
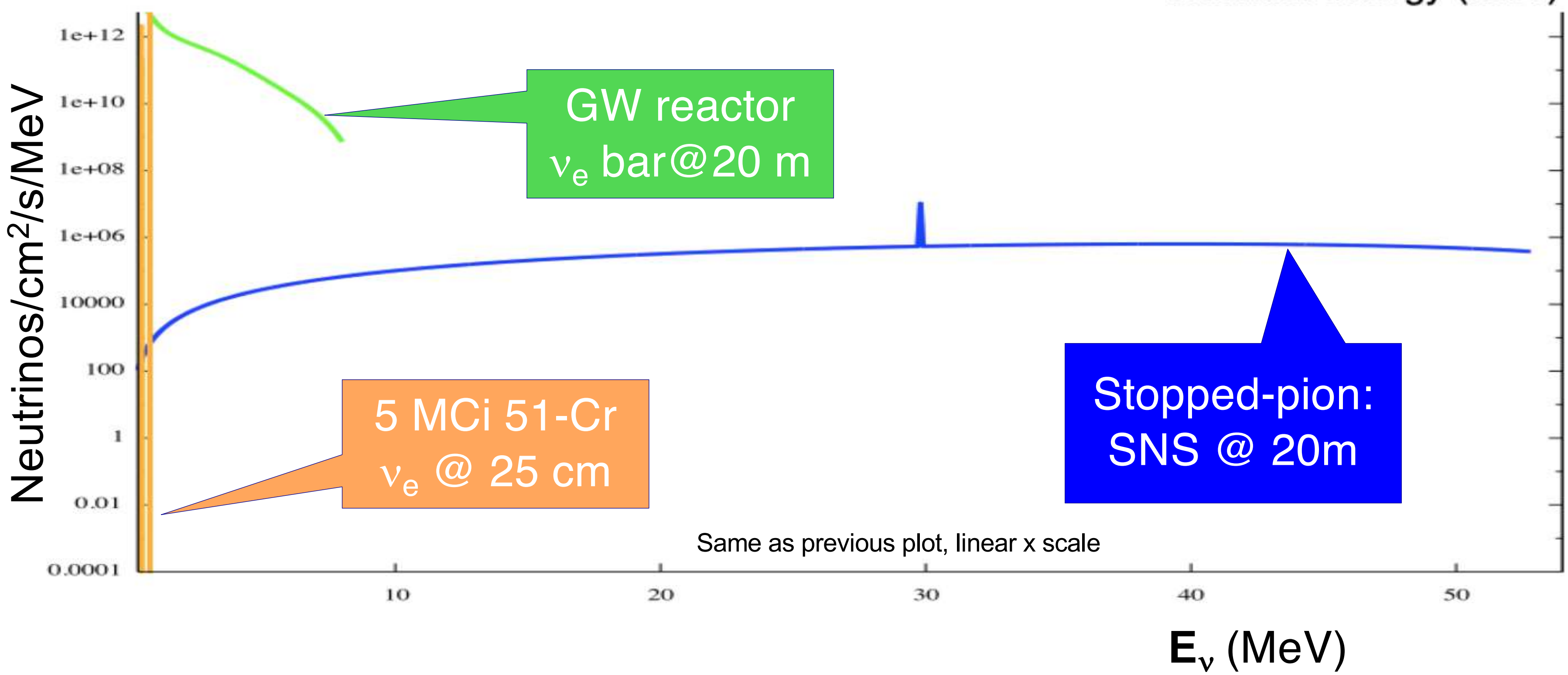
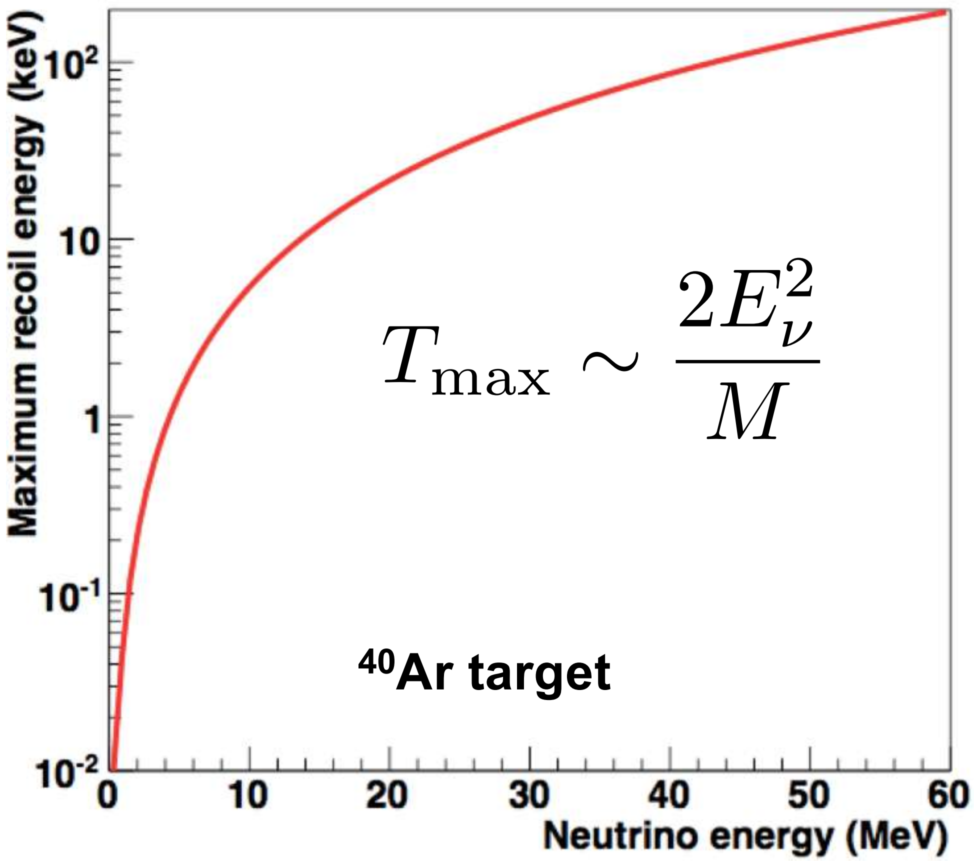
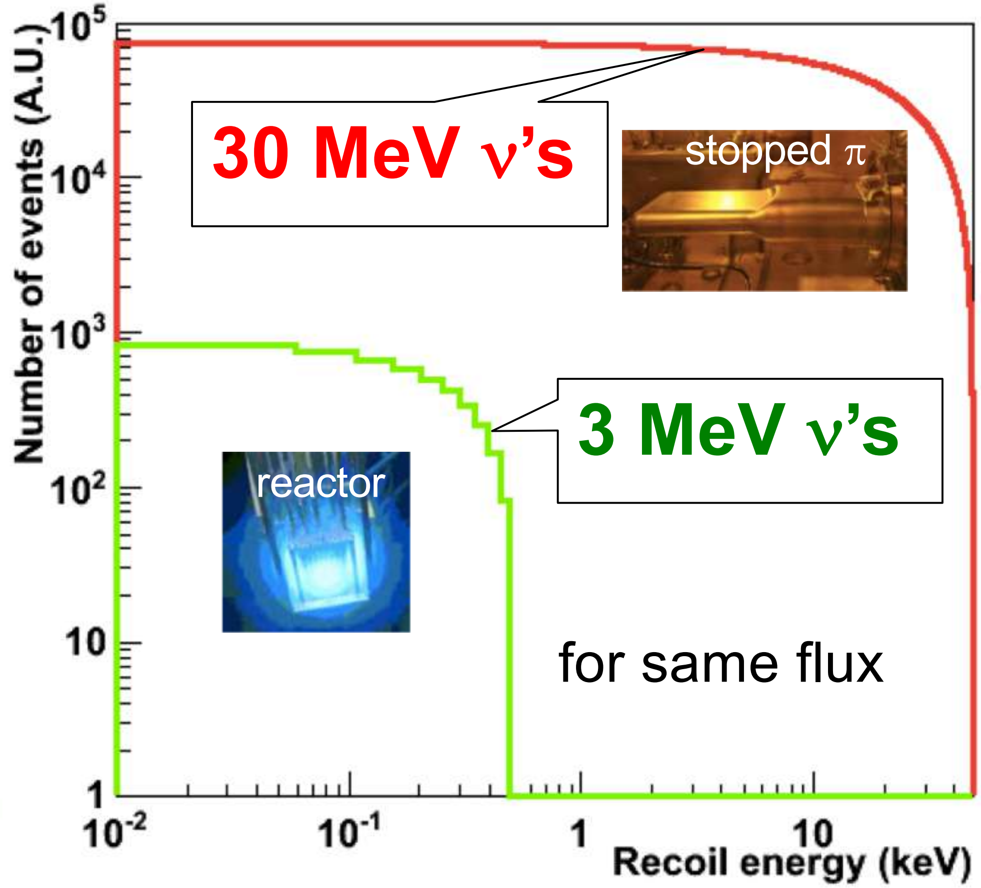




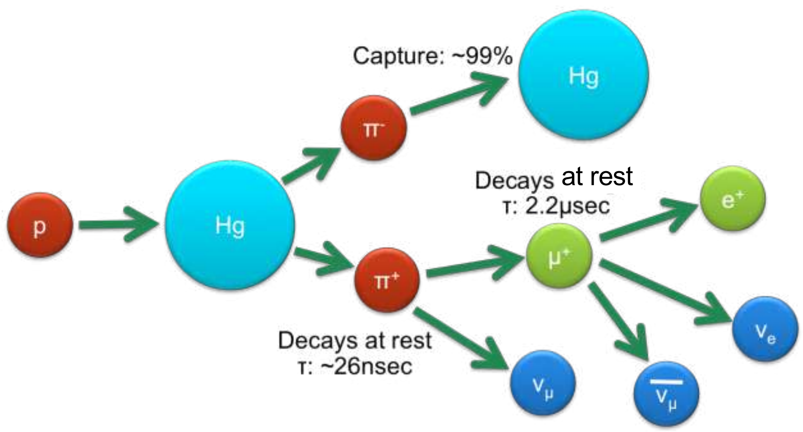
Both **cross-section** and **maximum recoil energy** **increase with neutrino energy**:

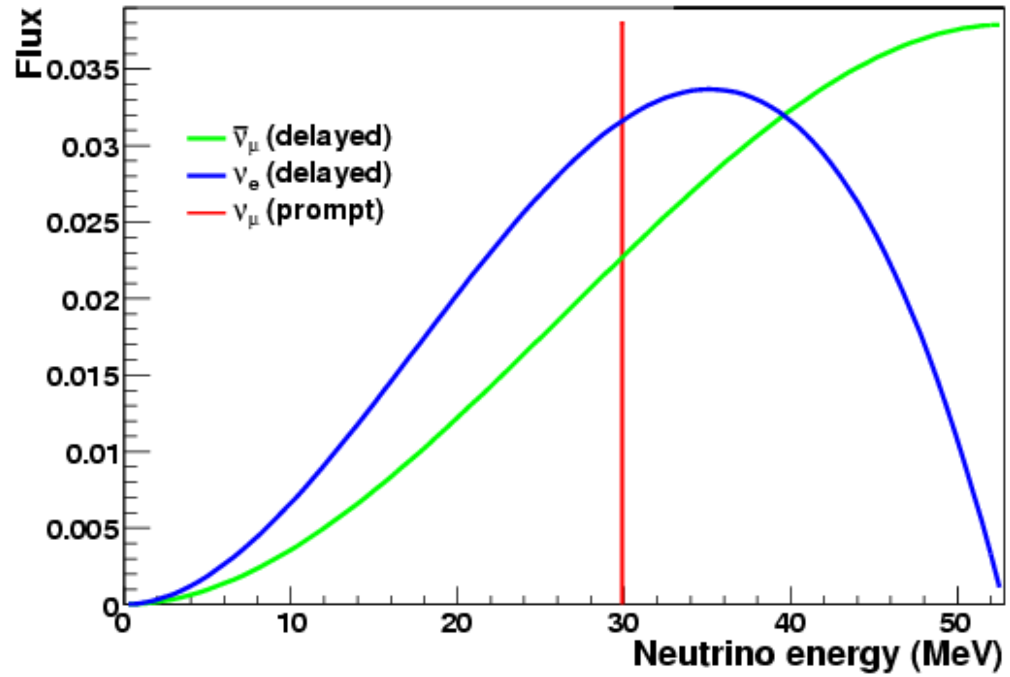




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \to \mu^+ + \nu_\mu$$

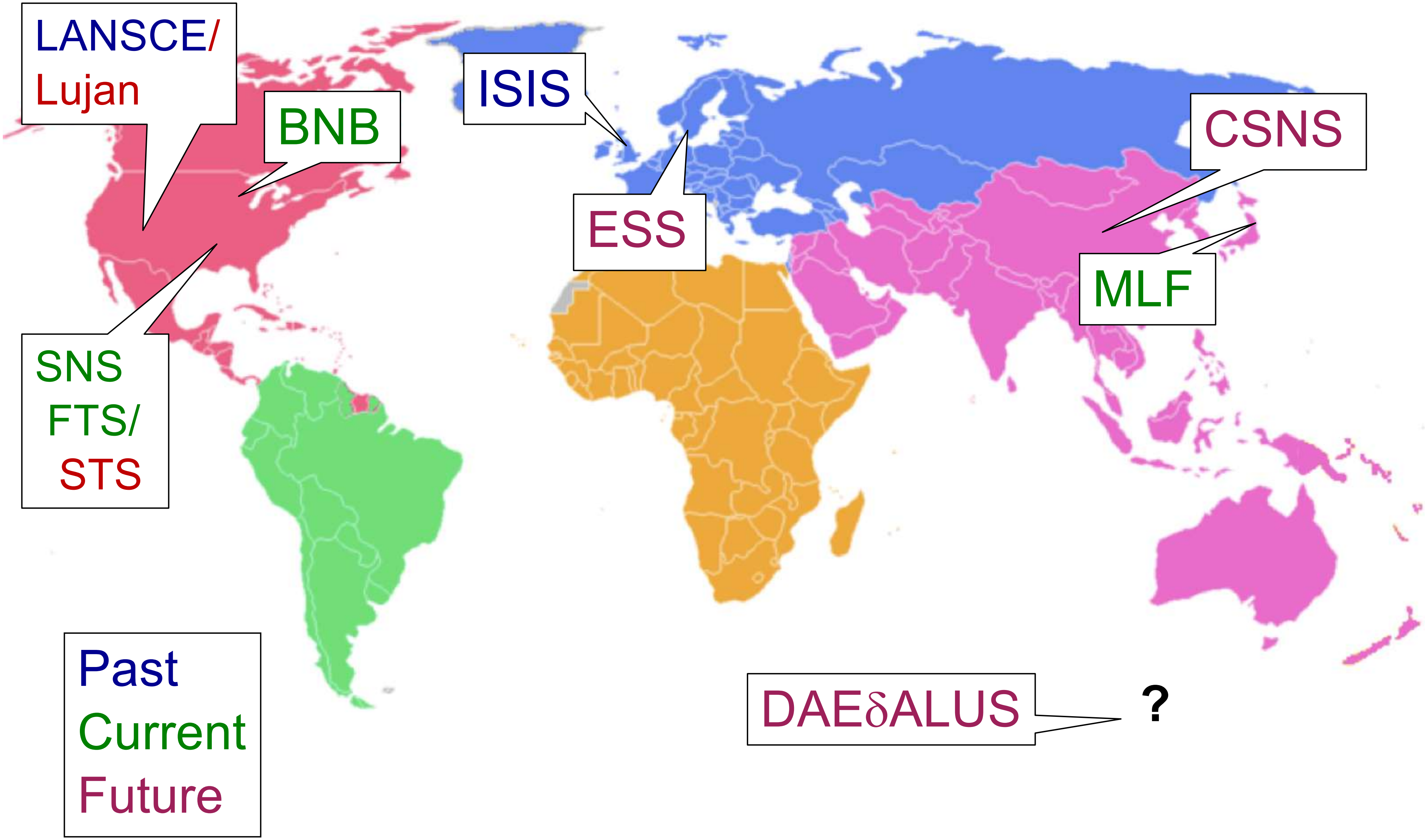
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

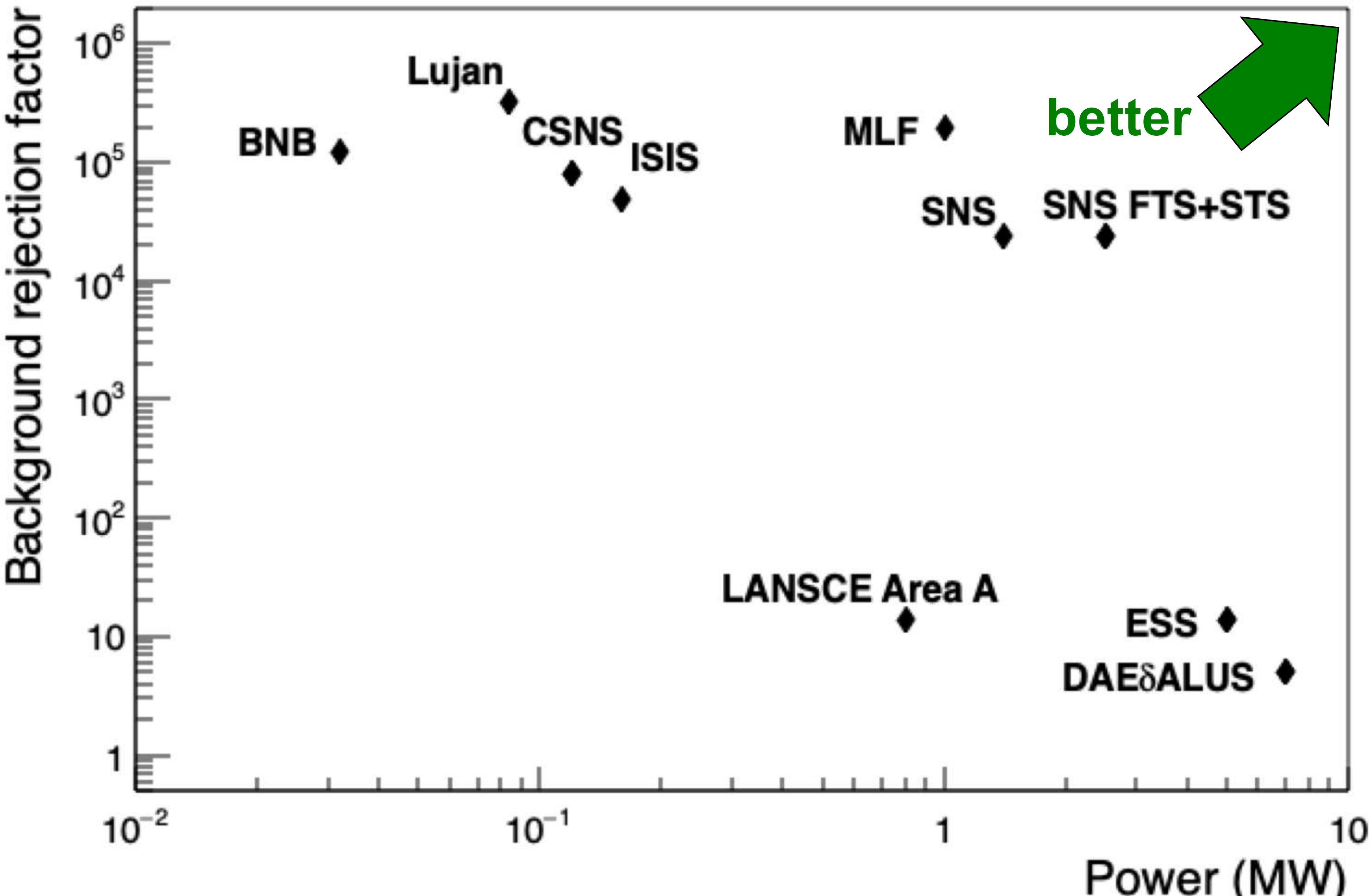
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Neutrino Sources Worldwide



from duty cycle

Comparison of pion decay-at-rest ν sources



$\propto \nu$ flux

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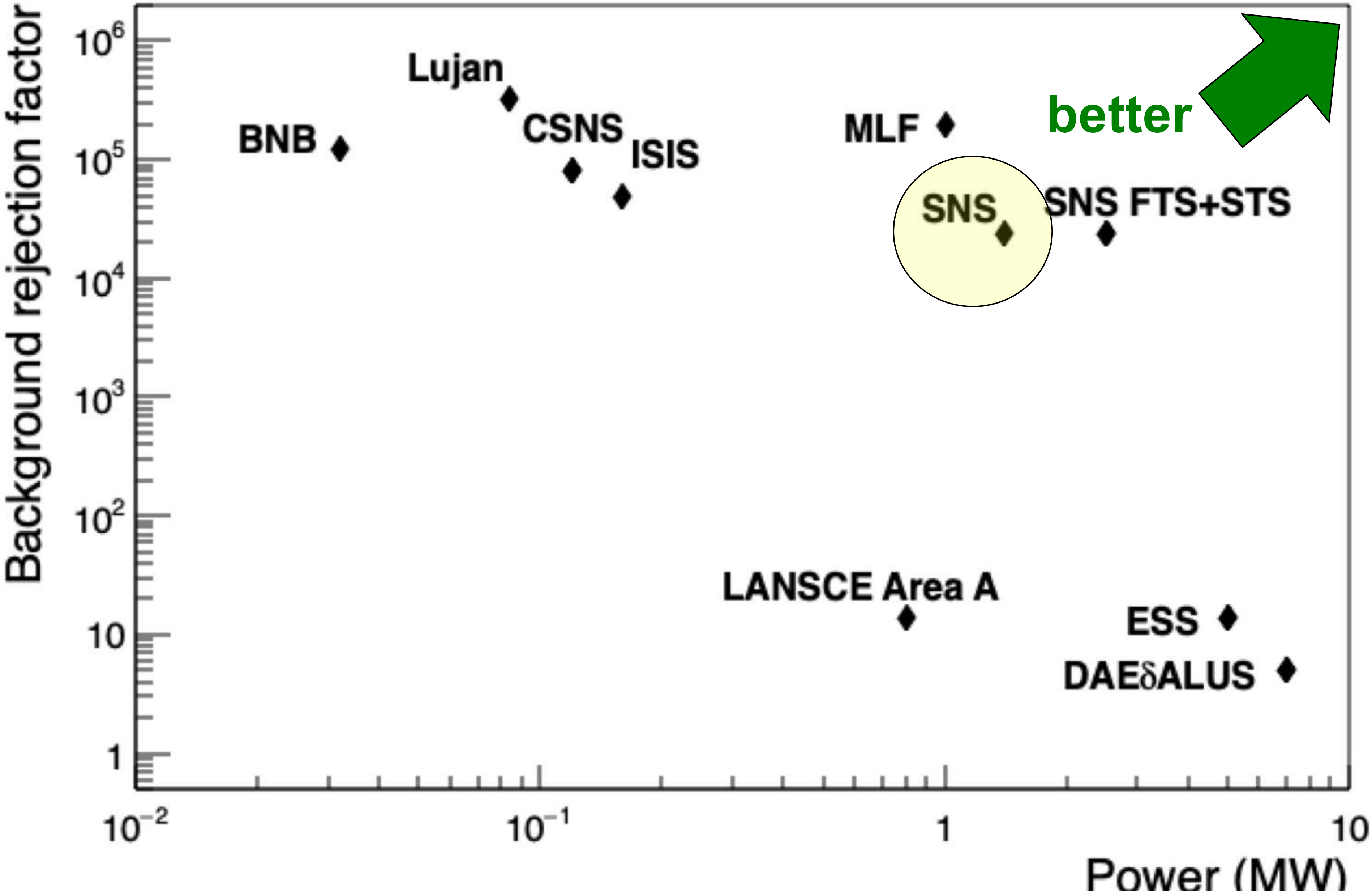

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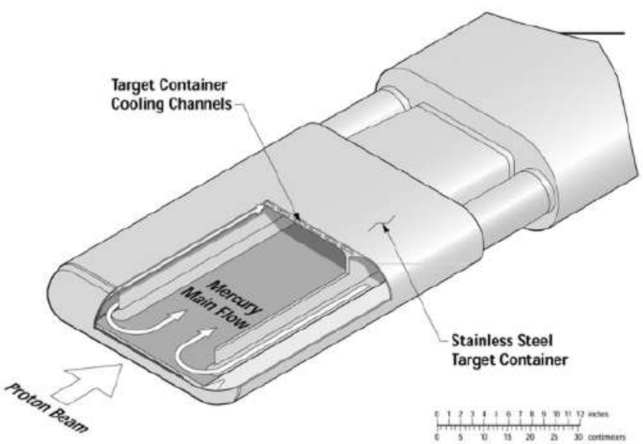


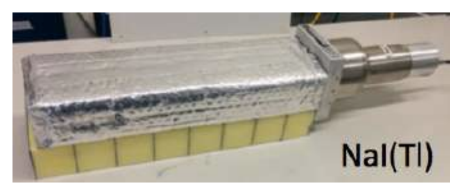
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

COHERENT CEvNS Detectors

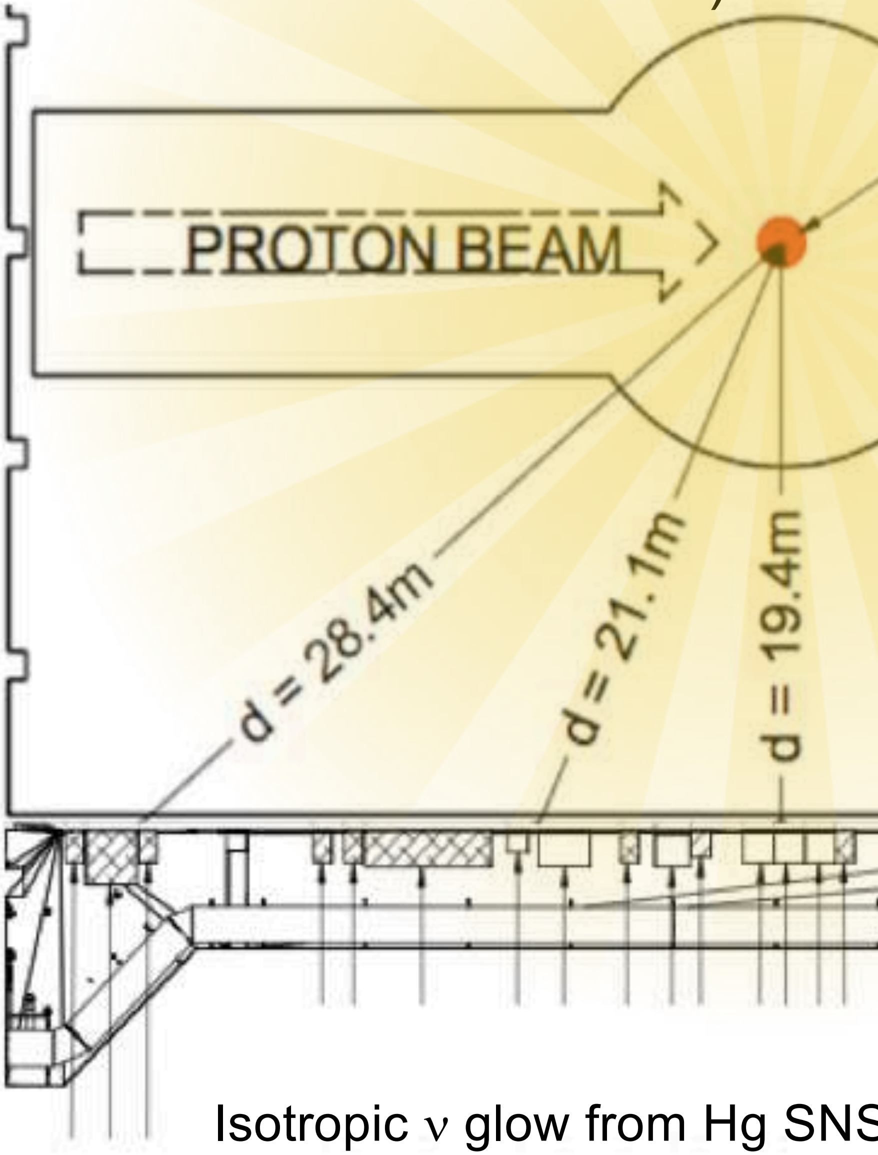
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal — flash	14.6	19.3	6.5
Ge	HPGe PPC — zap	16	20	<few
LAr	Single-phase — flash	22	29	20
NaI[Tl]	Scintillating crystal — flash	185*/3338	28	13

Multiple detectors for N^2 dependence of the cross section

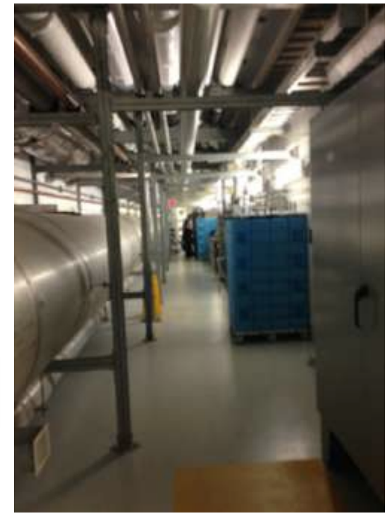


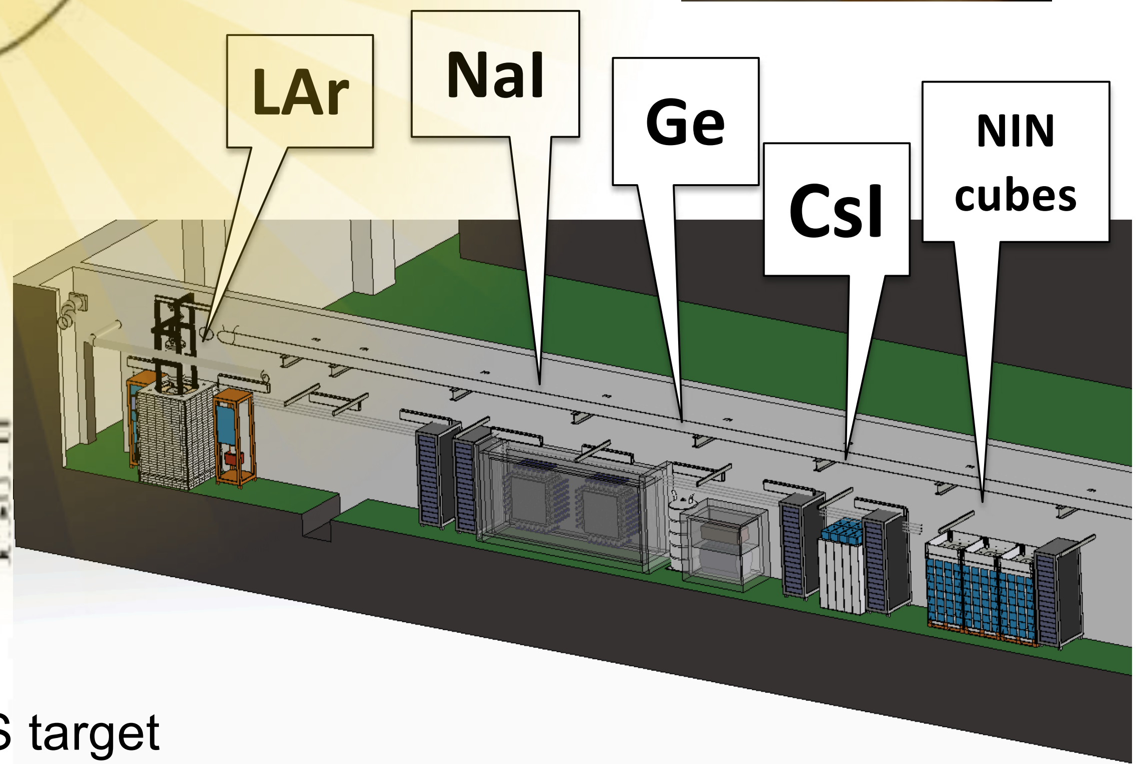
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)



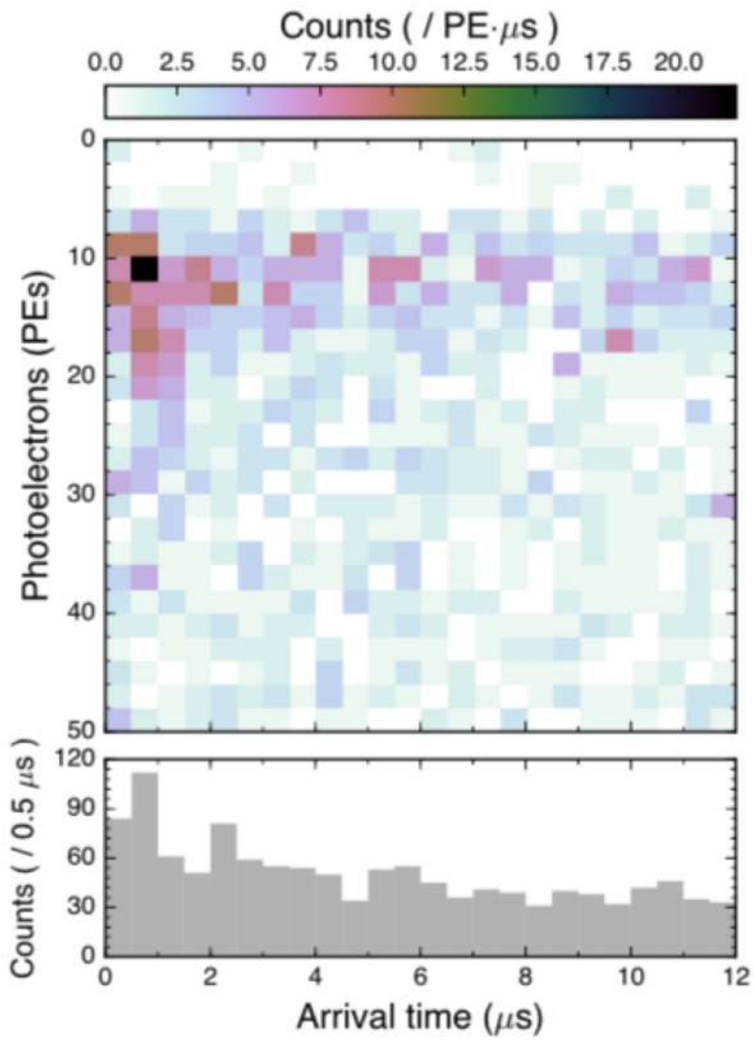
View looking
down "Neutrino Alley"

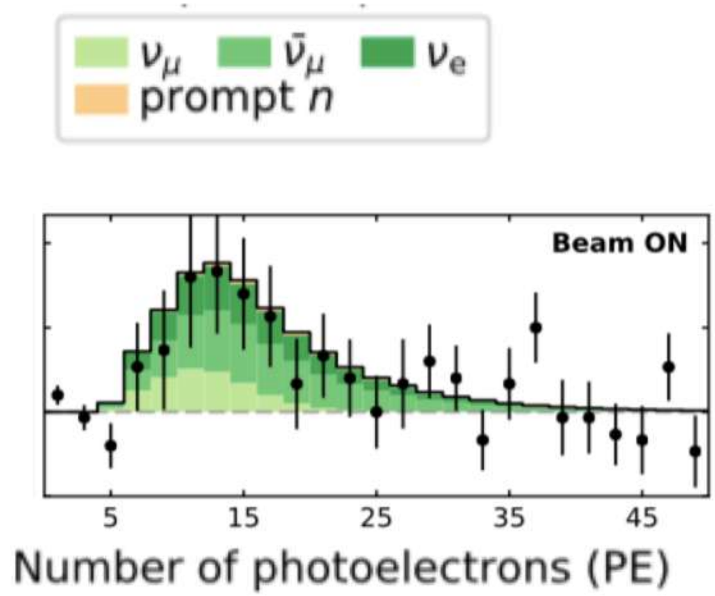




Isotropic ν glow from Hg SNS target

First light at the SNS (stopped-pion neutrinos) with 14.6-kg CsI[Na] detector





Background-subtracted and integrated over time

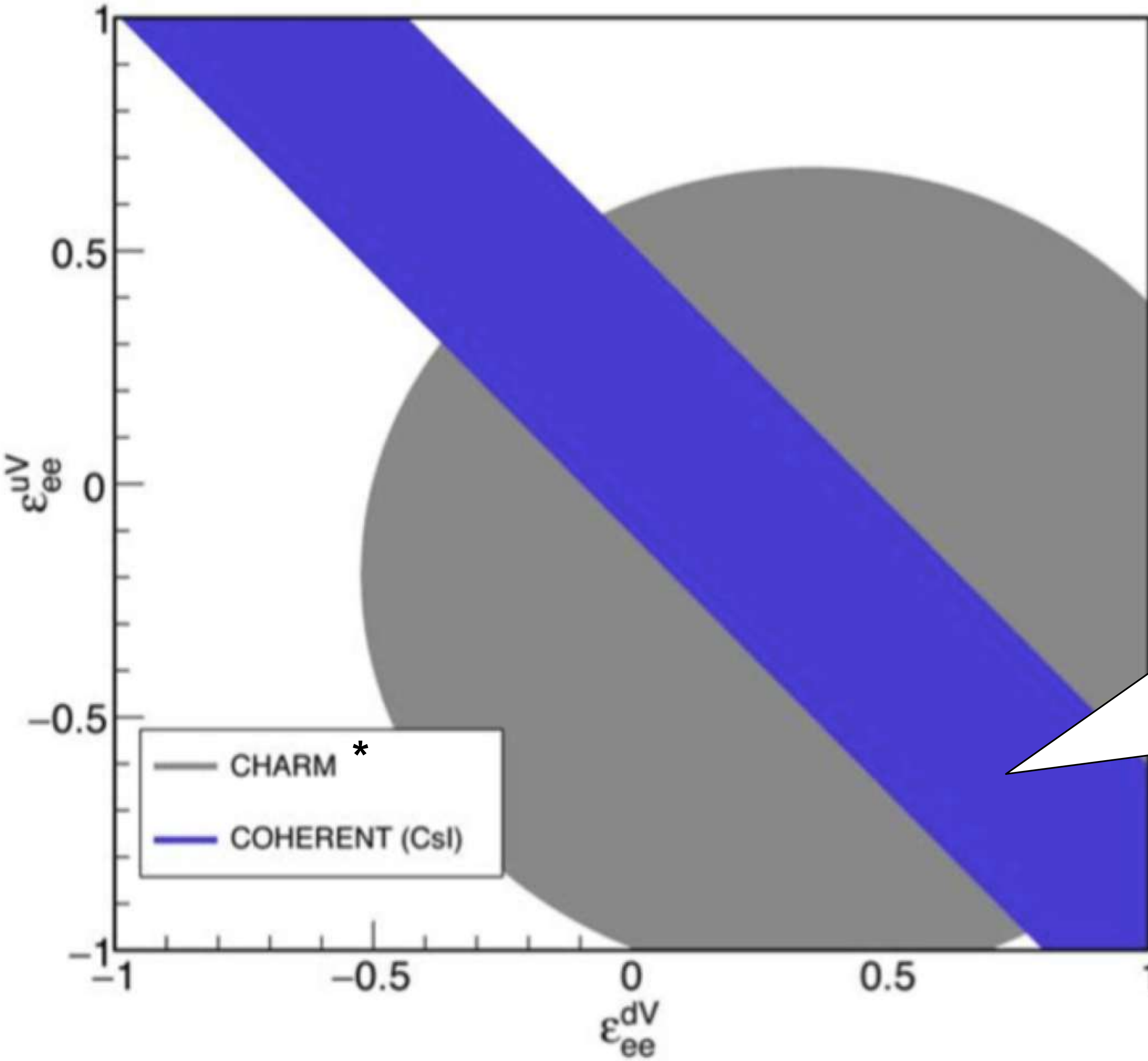
$$\mathrm{PE} \propto T \propto Q^2$$

→ 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

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



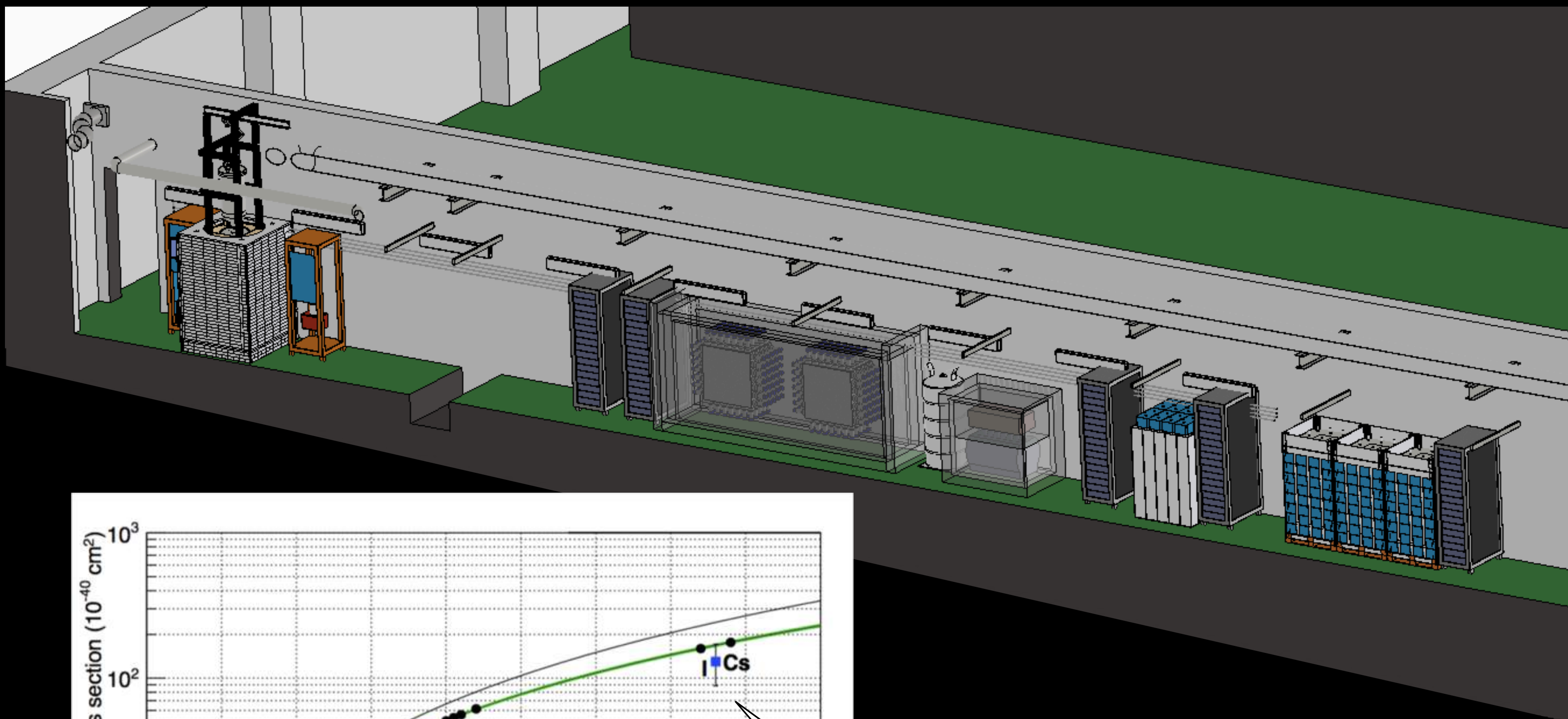
- Assume all other ε's zero

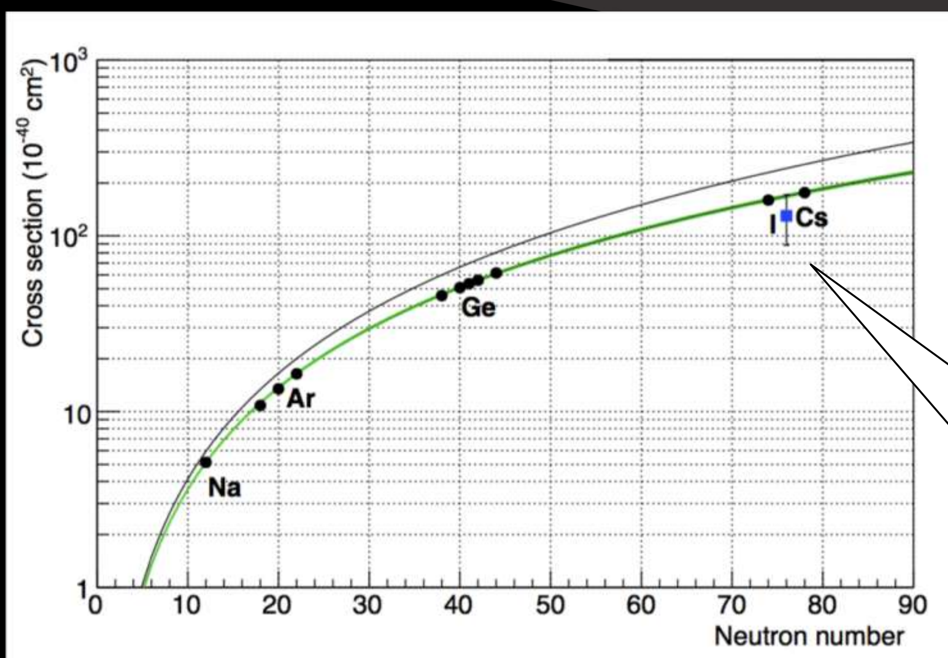
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

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

*CHARM constraints apply only to heavy mediators

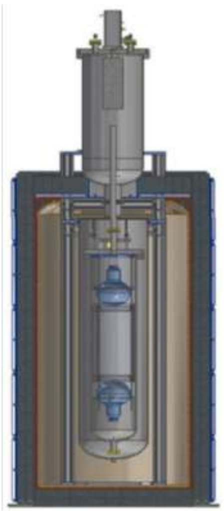
What's Next for COHERENT?

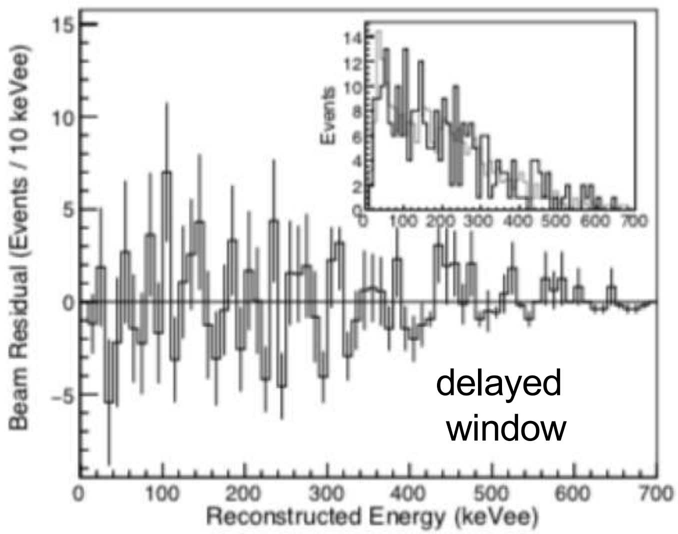




One measurement so far! Want to map out N^2 dependence

COHERENT LAr Engineering Run Result

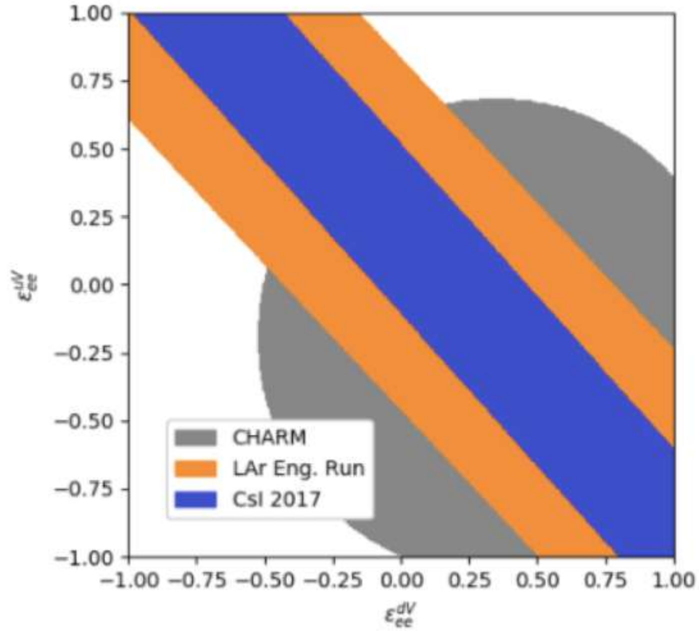




measure 1 ± 4 (stat), expect <1

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

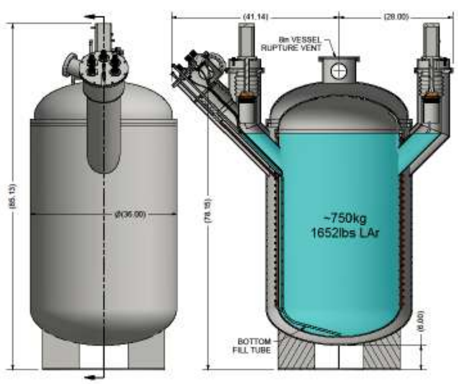
Matt Heath, Indiana U., thesis
APS April meeting
Just posted on arXiv

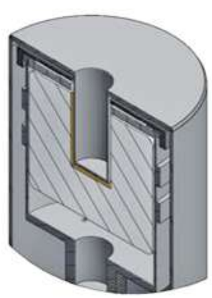


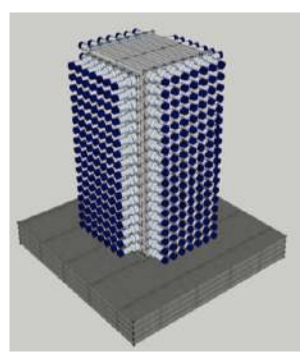
- **Results from more CsI running,** improved QF & analysis
- **Results from 22-kg LAr detector**
- Treatment of shape systematics
- Accelerator-produced DM sensitivity

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



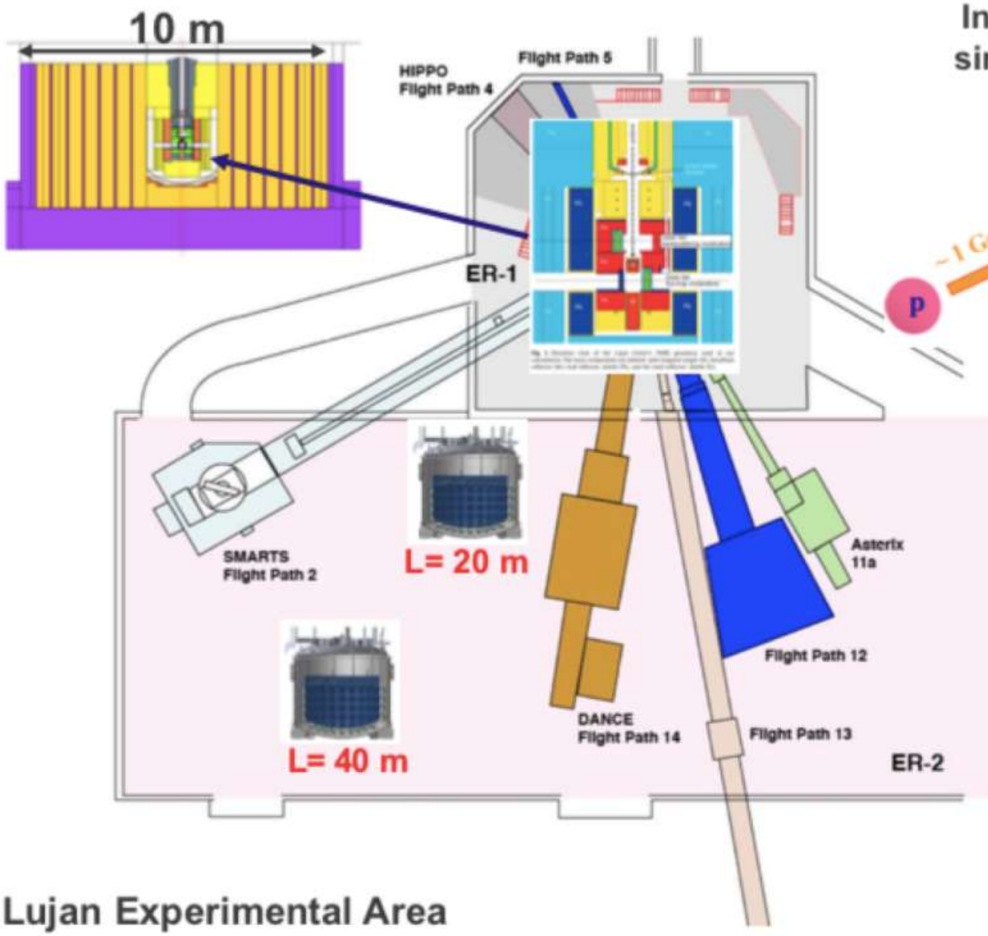




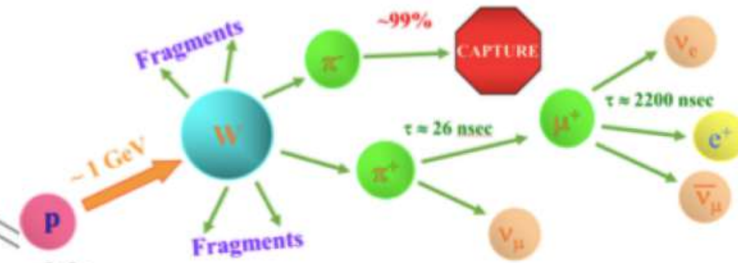
+D_2O for flux normalization

+ concepts for other targets...

Coherent Captain Mills @ Lujan: single-phase LAr



Intense source muon neutrinos: target MCNP simulation flux $4.74 \times 10^5\ \nu/cm^2/s$ at 20 m

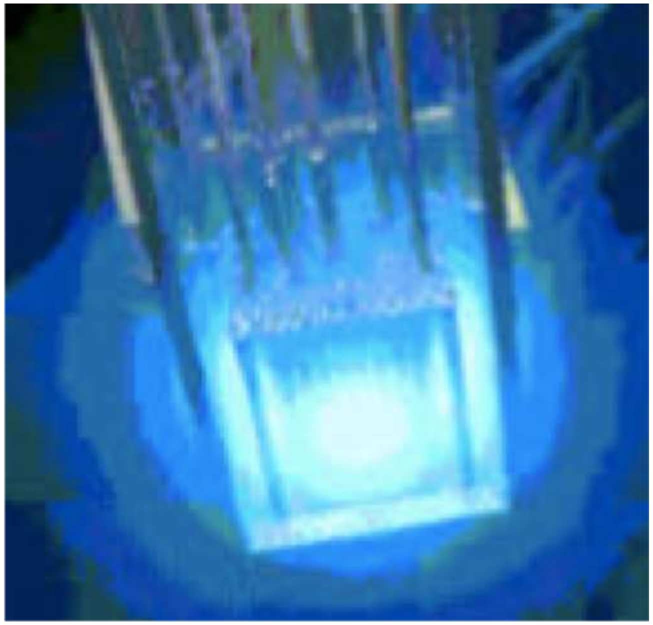


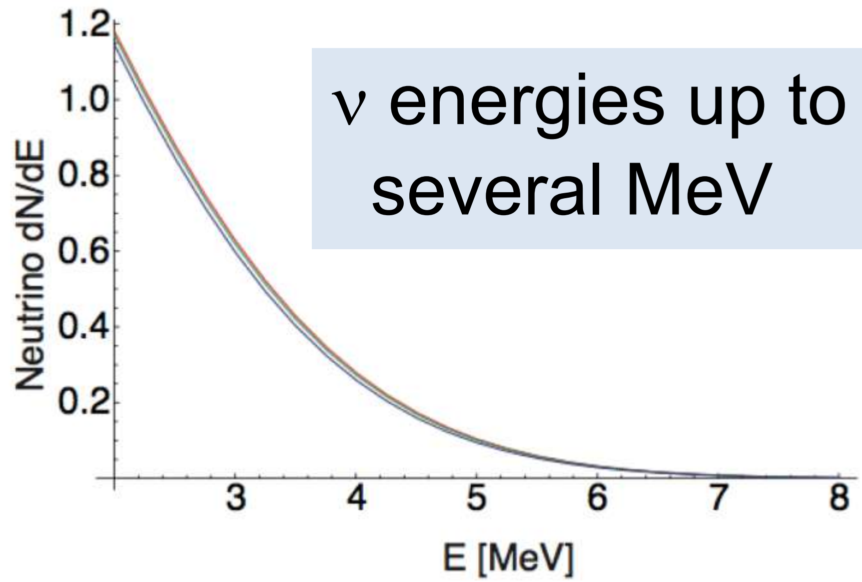
Lujan Experimental Area

- 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 (see D. Caratelli plenary talk)

Neutrinos from nuclear reactors



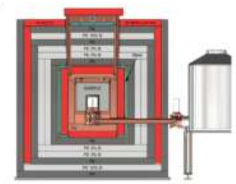


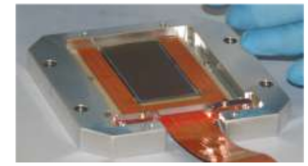
ν energies up to several MeV

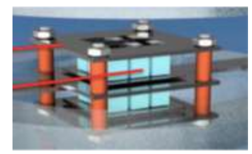
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~$2\text{x}10^{20}$ s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

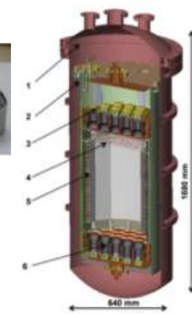
Reactor CEvNS Efforts Worldwide

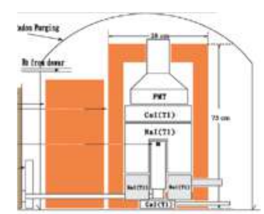
Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS Talk by M. Lindner, Neutrino #21	HPGe	Germany
MINER	Ge/Si cryogenic	USA
NuCleus Talk by R. Strauss, Neutrino #21	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn bolometers	France
TEXONO Talk by V. Sharma , Neutrino #21	p-PCGe	Taiwan









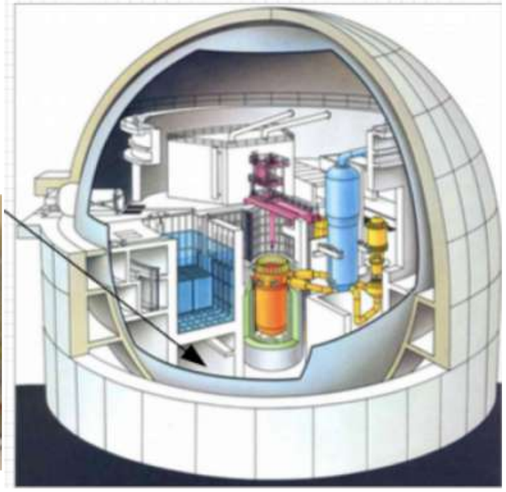


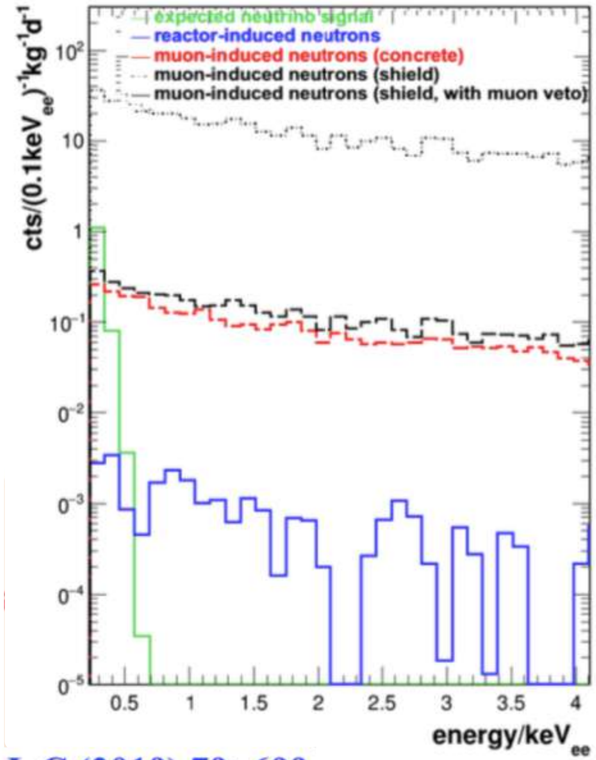
Many novel low-background, low-threshold technologies

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 σ	2.3 σ

Some systematics still under study

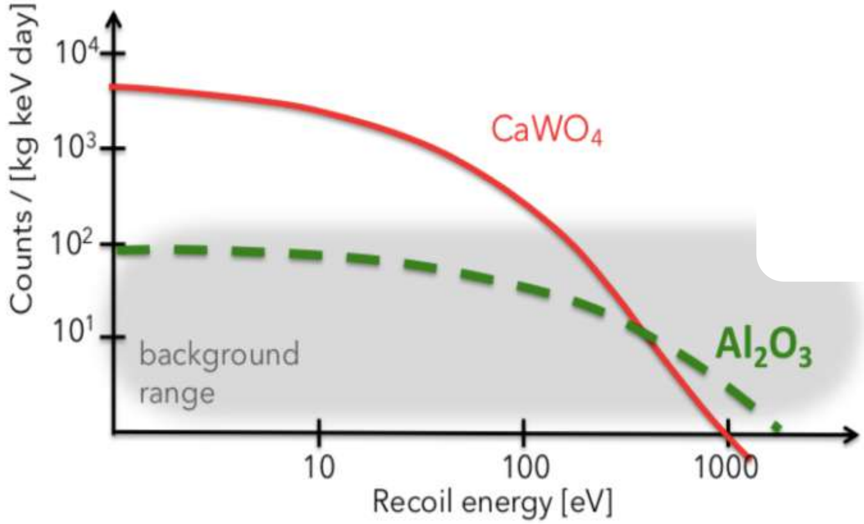
(*) Including stat. uncertainty and above efficiencies

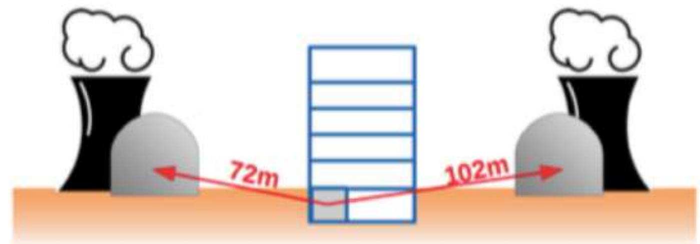
W. Maneschg, Nu2018

Talk by M. Lindner, Neutrino #21

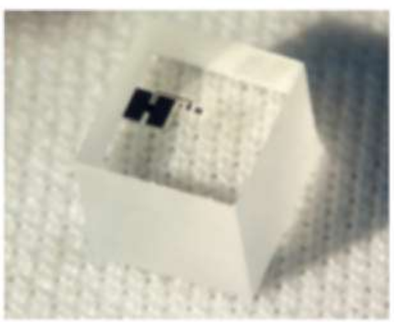
NUCLEUS

"gram-scale cryogenic calorimeters"





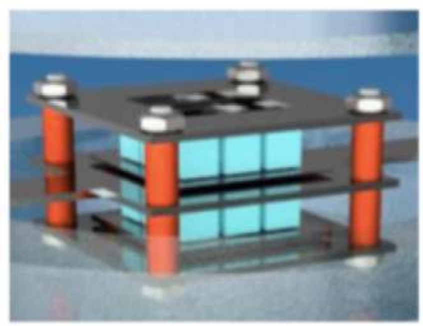
NUCLEUS 1g



2017-2019

straight forward →

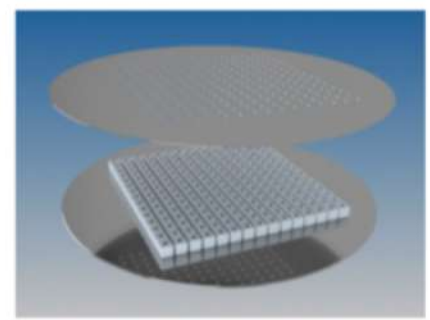
NUCLEUS 10g



2020-2022

major R&D →

NUCLEUS 1kg



>2024

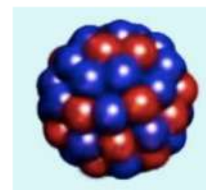
Talk by R. Strauss, Neutrino #21

CEvNS: what's it good for?

! (not a complete list!)

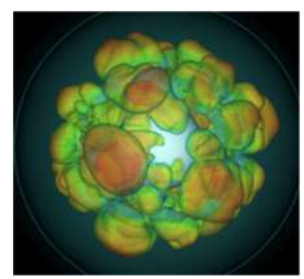
CEvNS as a **signal**
for signatures of *new physics*

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

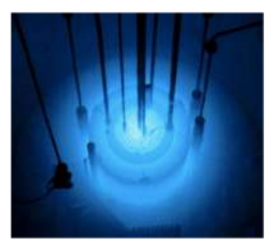


CEvNS as a **background**
for signatures of new physics (DM)

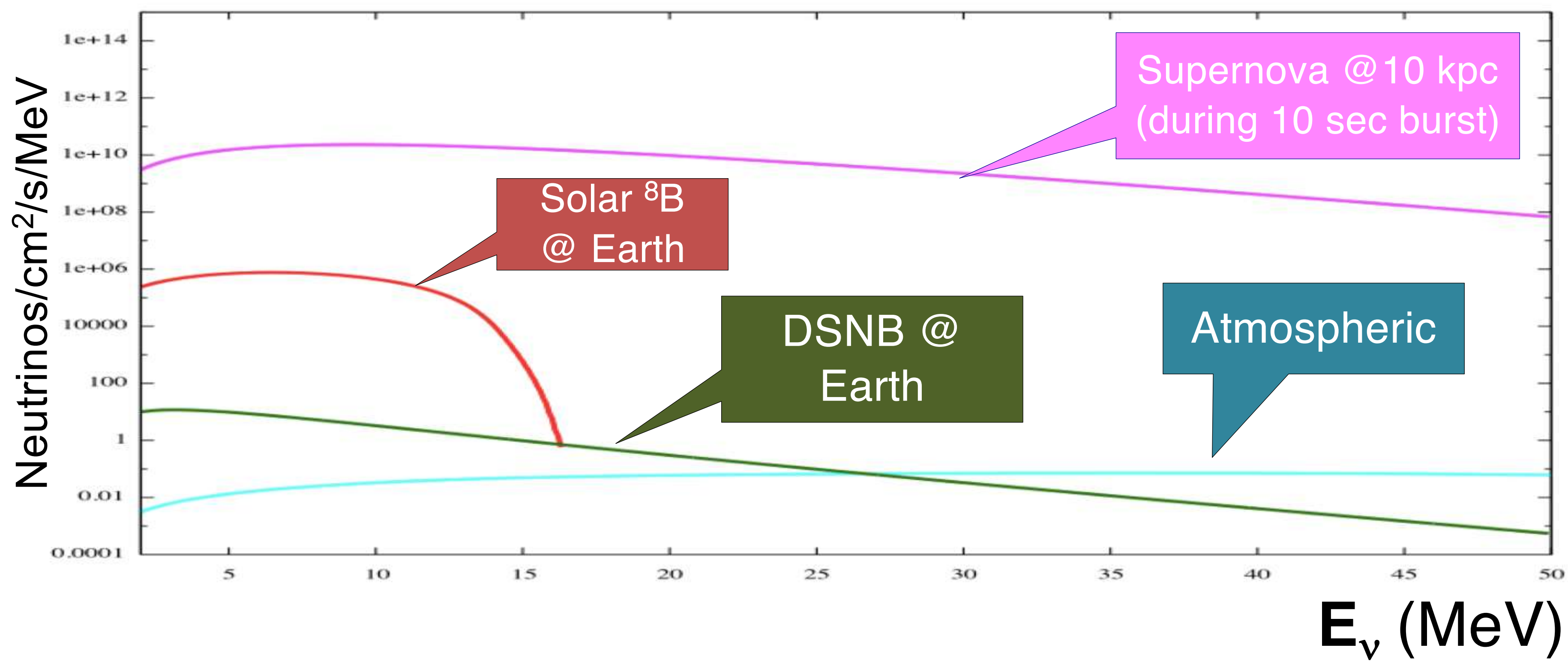
CEvNS as a **signal** for *astrophysics*



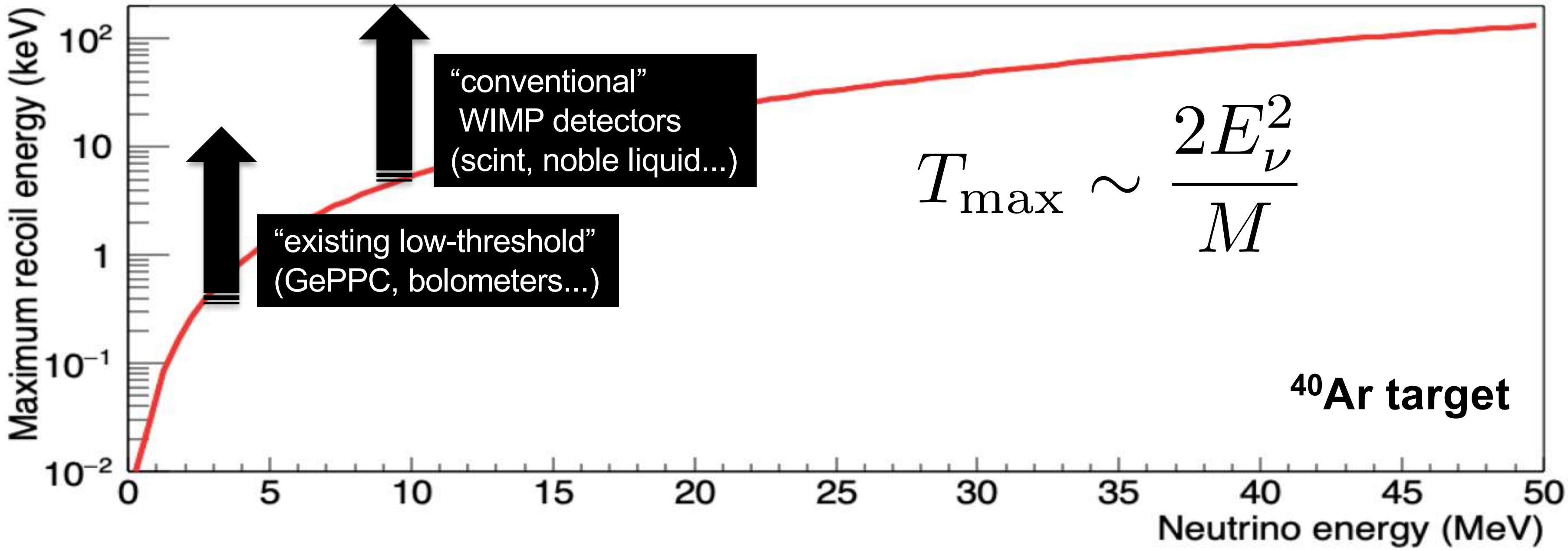
CEvNS as a **practical tool**

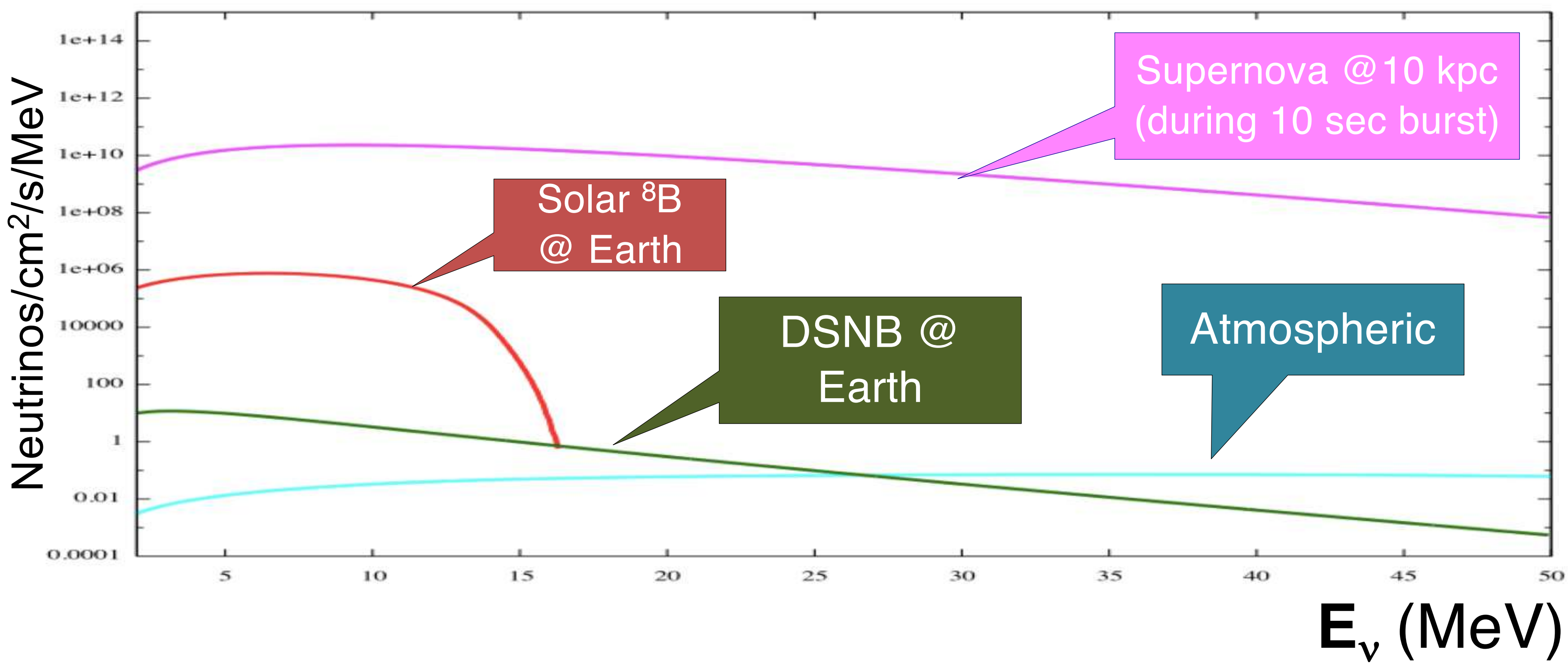


Natural neutrino fluxes



Natural neutrino fluxes

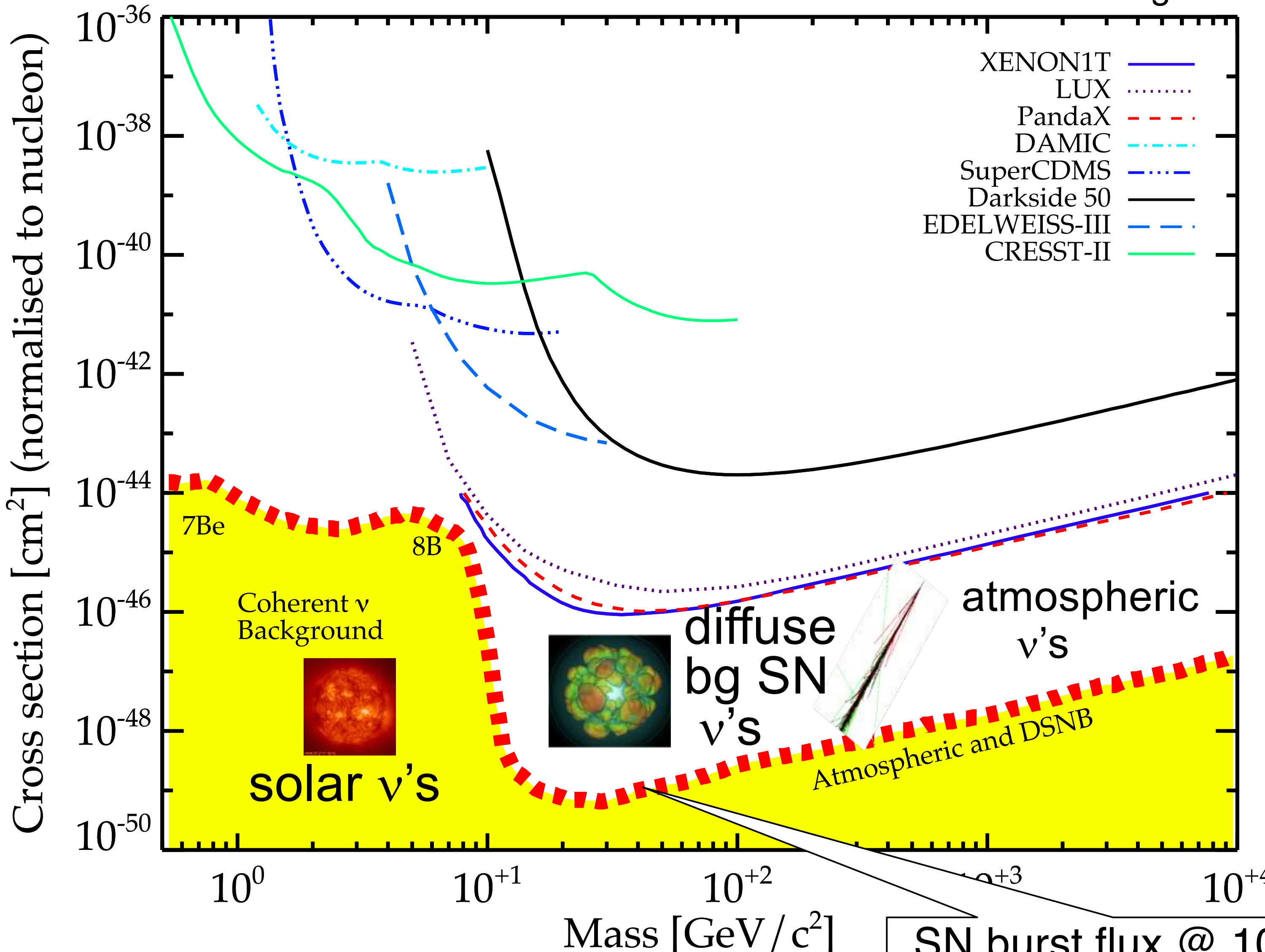




The so-called "**neutrino floor**" for DM experiments

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

L. Strigari

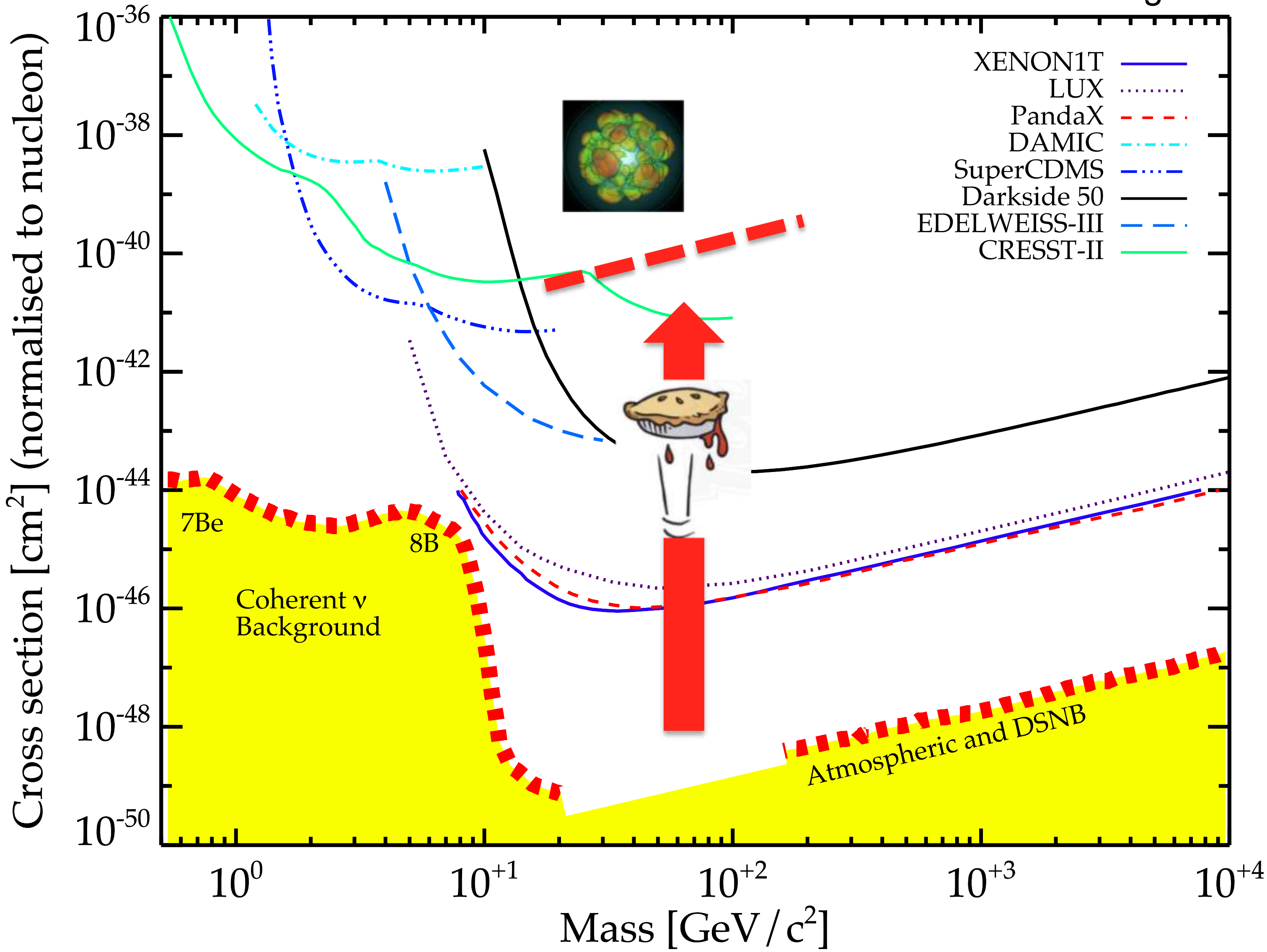


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

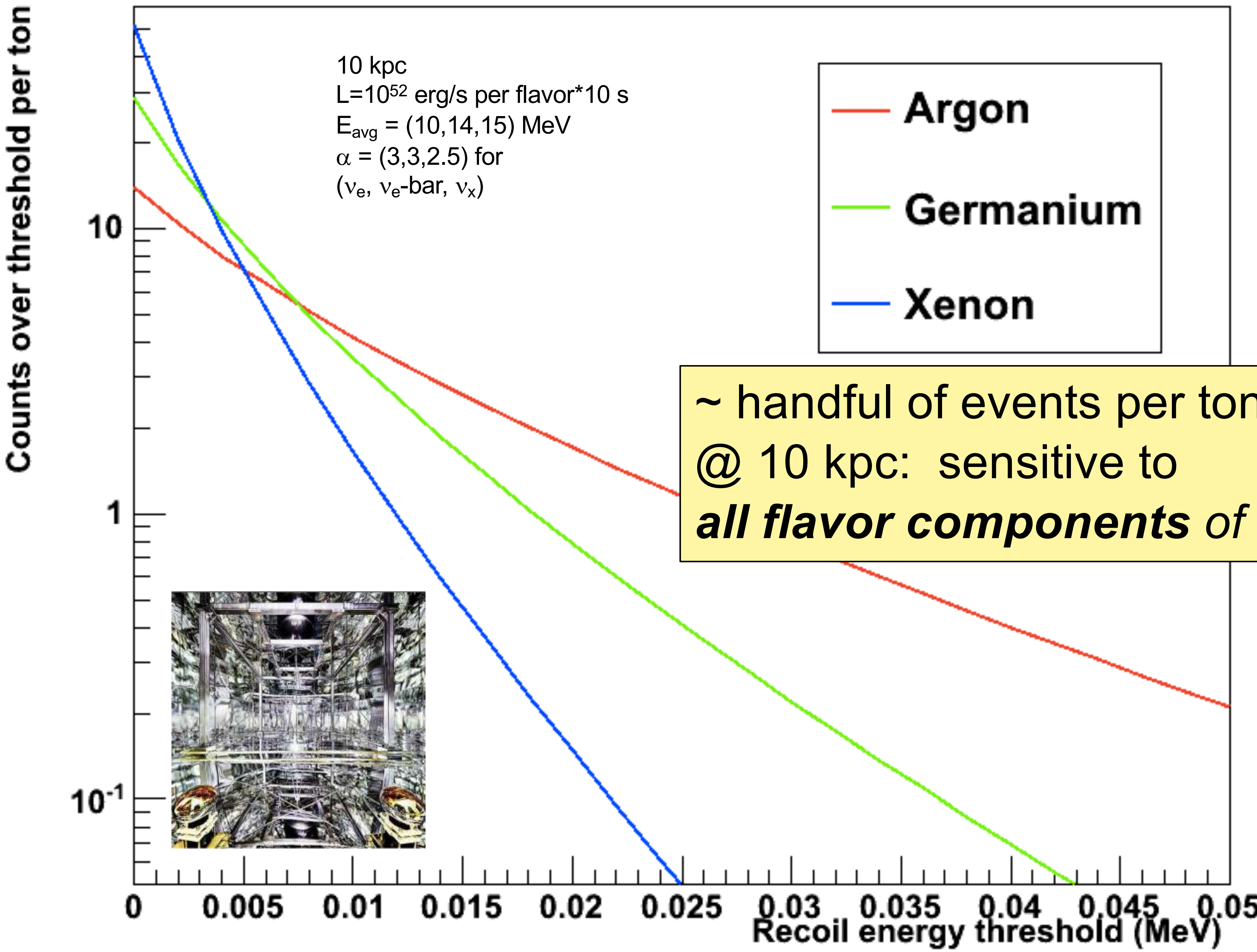
Think of a SN burst as “**the ν floor coming up to meet you**”

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

L. Strigari



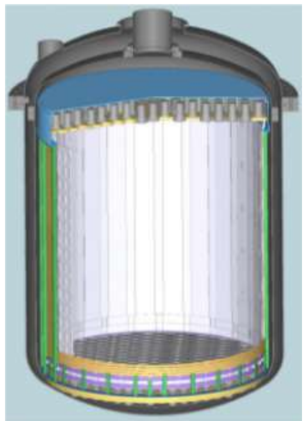
Supernova neutrinos in tonne-scale DM detectors

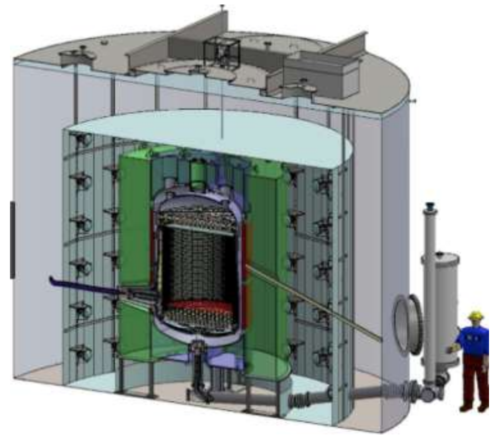


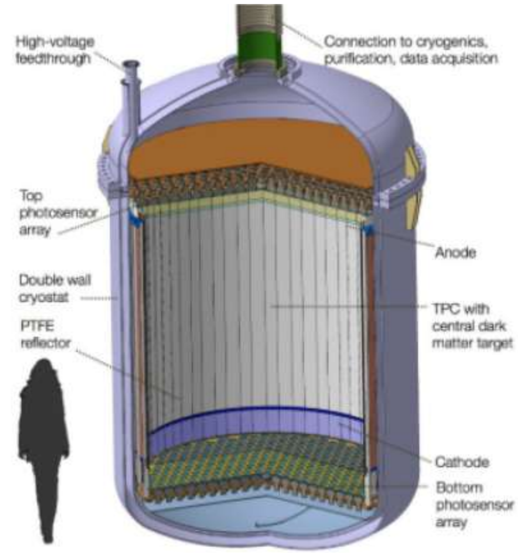
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

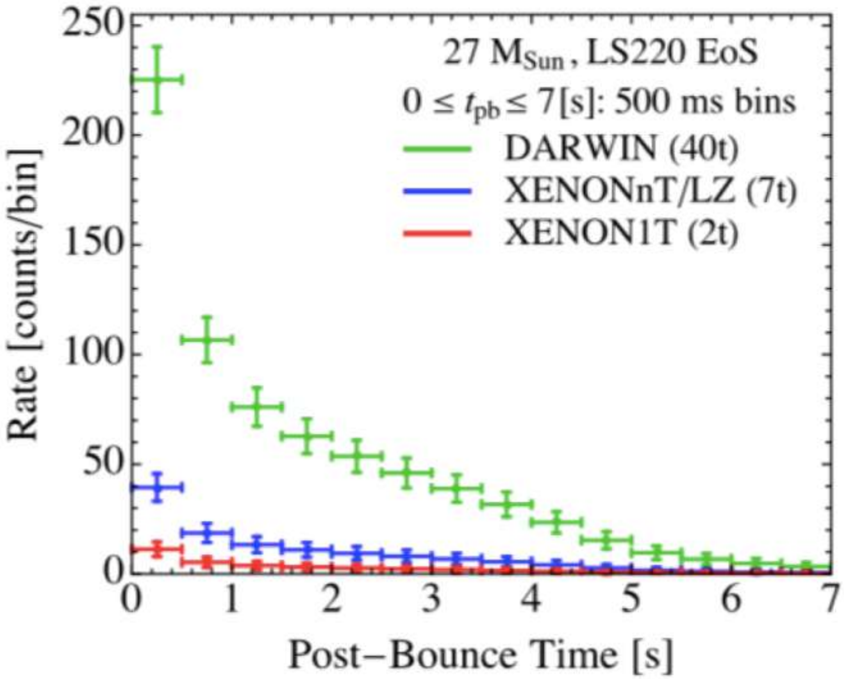
Detector example: **XENON/LZ/DARWIN**

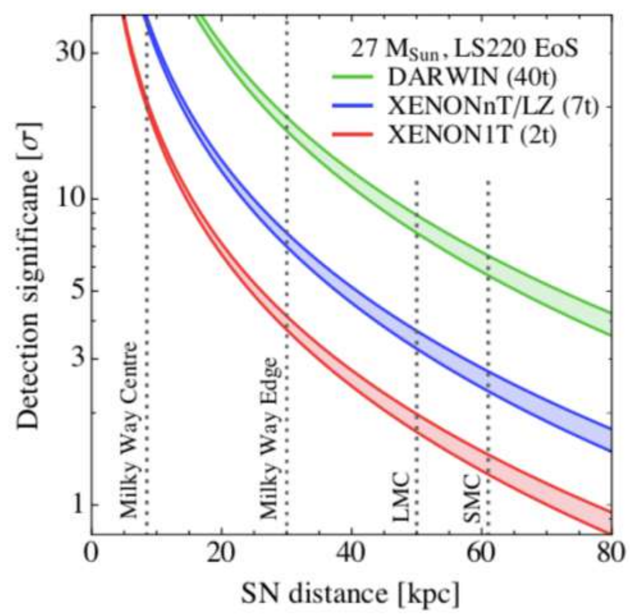
- dual-phase xenon time projection chambers











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

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

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