Neutrino Interactions with Matter

Artwork by Sandbox Studio, Chicago with Ana Kova

Kate Scholberg, Duke University,

Workshop on Gravity, Information, and Fundamental Symmetries

November 4, 2019

OUTLINE

- Neutrinos and why we love them
- Interactions of neutrinos with matter
- Interactions of neutrinos with nuclei
  and why we care
- Example 1: ~GeV neutrino interactions
  in long-baseline oscillation experiments
- Example 2: coherent elastic neutrino-nucleus scattering
- Summary

NEUTRINOS

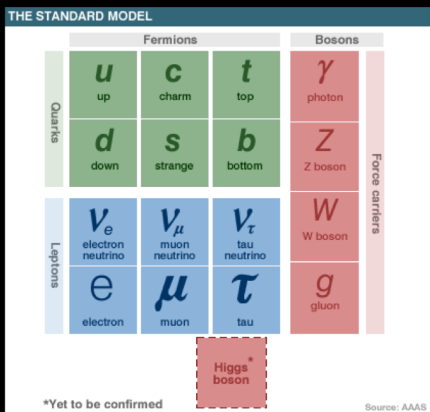
	~3	~1200	174,000	MeV/c^2
Quarks	u	c	t	
	d	s	b	
	~6	~100	~4200	MeV/c^2

	0.511	105.6	1778	MeV/c^2
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	

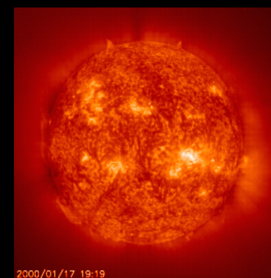
In the Standard Model of particle physics, neutral partners to the charged leptons

- Spin 1/2
- Zero charge
- 3 flavors (families)
- Interact *only* via ***weak interaction*** (& gravity)
- Tiny mass (< 1 eV)

Why do neutrinos matter?



fundamental particles and interactions

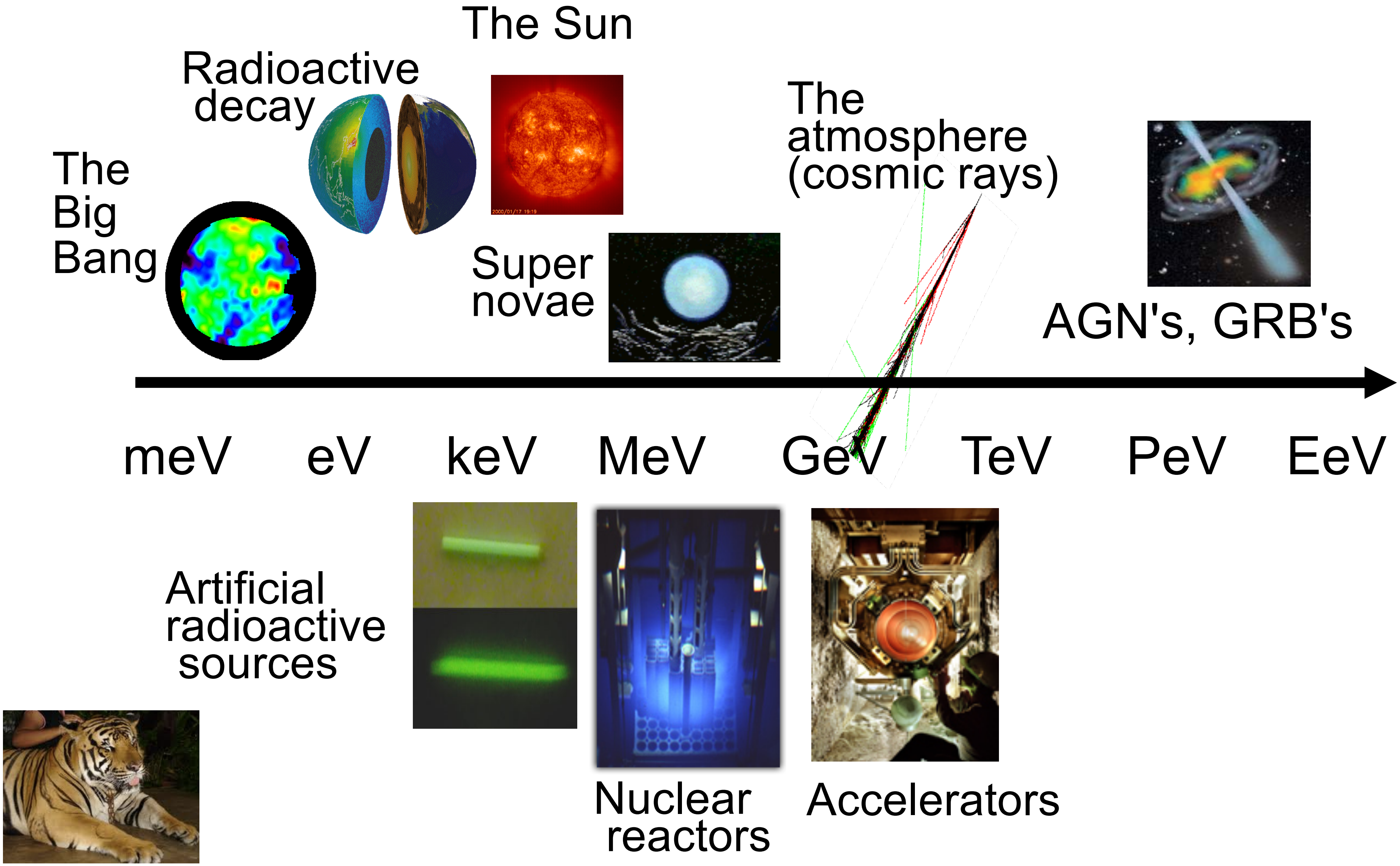



astrophysical systems

cosmology

nuclear physics

Wild and tame neutrinos



Neutrino Mass and Oscillations

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

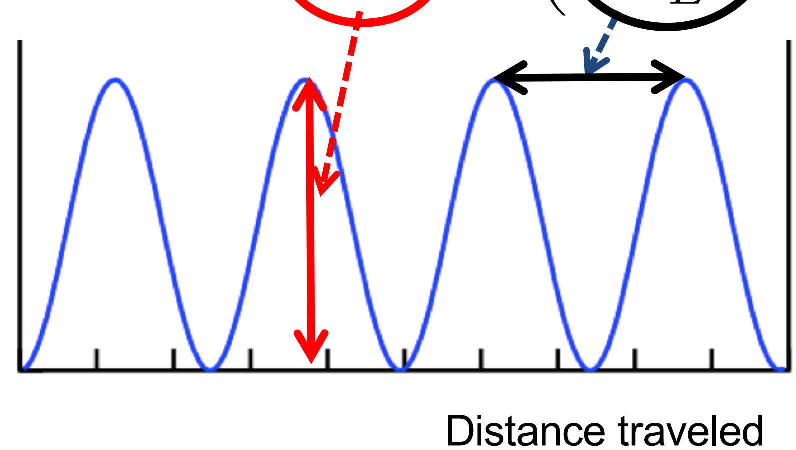
If mixing matrix is not diagonal, get *flavor oscillations:*

energy- and baseline-dependent flavor change

(essentially,interference between mass states)

2-flavor

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Neutrino Mass and Oscillations

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in we...

unitary mixing ...

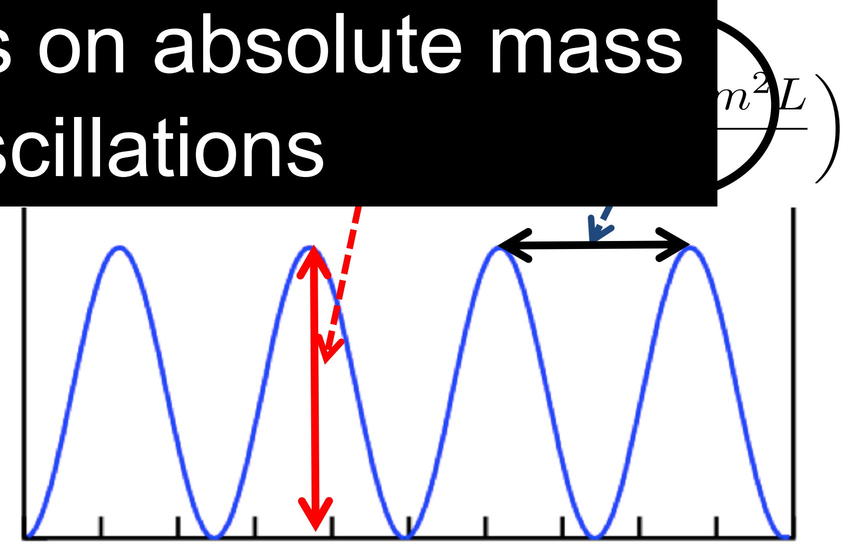
eigenstates of free ...

Later:
- Susanne Mertens on absolute mass
- Xianguo Lu on oscillations

If mixing ...
not diag...
get *flavor oscillations.*

energy- and baseline-dependent flavor change

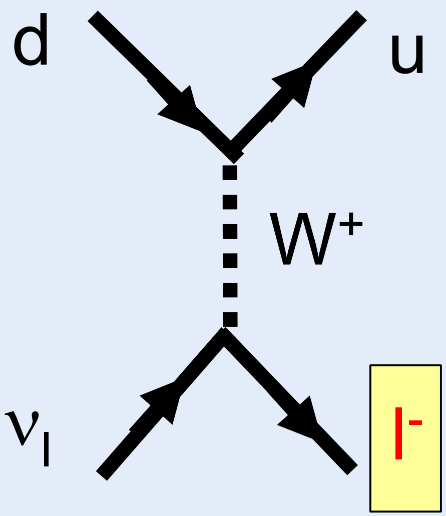
(essentially,interference between mass states)



Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

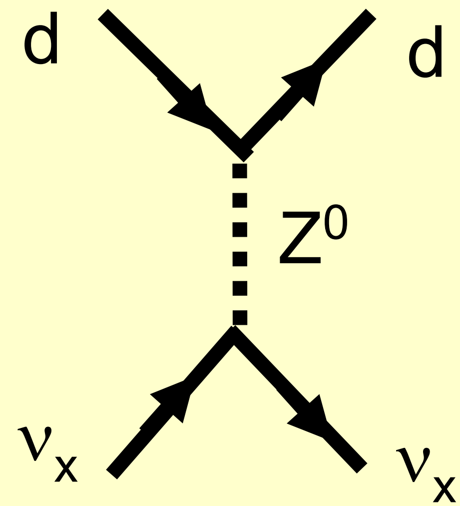


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)



Flavor-blind

Neutrino interaction rates in a detector material

Flux

Cross section

Number of targets

$$R = \Phi \, \sigma \, N_t$$

Cross sections (~16-17 orders of magnitude smaller than photon interaction cross sections!) are **neutrino-energy- and target-dependent**

Neutrino interaction rates in a detector material

Flux

Cross section

Number of targets

$$R = \Phi \, \sigma \, N_t$$

if you want to measure a flux...

Neutrino interaction rates in a detector material

Flux

Cross section

Number of targets

$$R = \Phi \sigma N_t$$

You need a well understood cross section

if you want to measure a flux...

Neutrino interaction rates in a detector material

$$R = \overbrace{\Phi}^{\text{Flux}} \overbrace{\sigma}^{\text{Cross section}} \overbrace{N_t}^{\text{Number of targets}}$$

If you want to measure a cross section...

Neutrino interaction rates in a detector material

Flux

Cross section

Number of targets

$$R = \Phi \, \sigma \, N_t$$

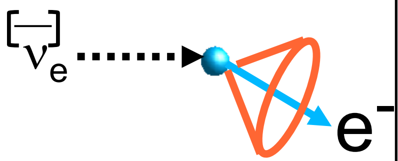
If you want to measure a cross section...

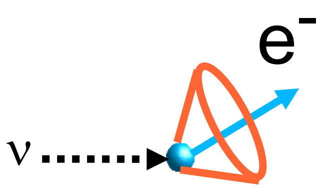
... you need a well known flux

Neutrino interactions with elementary particles

<table>
<tr><th></th><th>Electrons</th><th></th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering

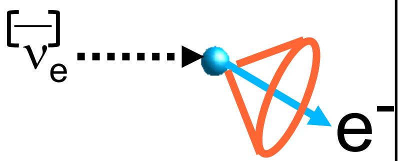
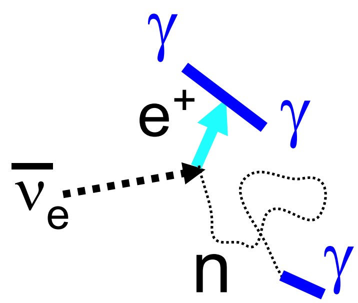
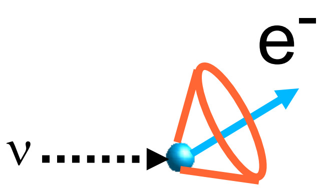
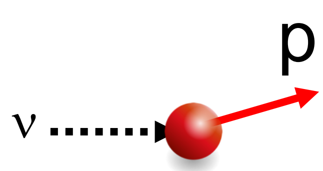
$\nu + e^- \rightarrow \nu + e^-$



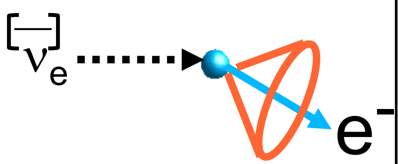
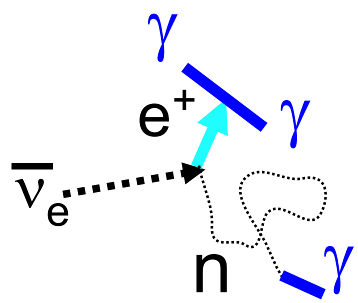
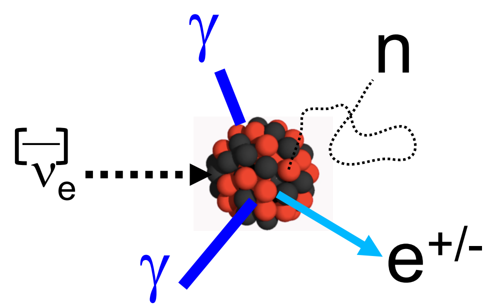
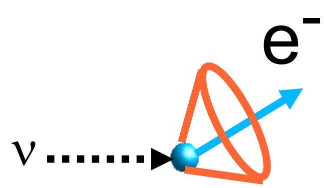
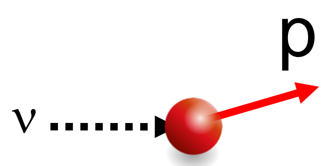
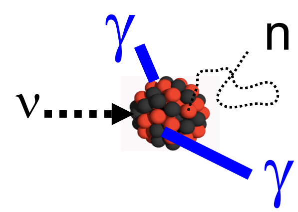
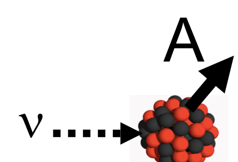


Useful
for pointing</td><td></td><td></td></tr>
<tr><td>Neutral current</td><td></td><td></td></tr>
</table>

Neutrino interactions with elementary particles

	Electrons	**Protons**	
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

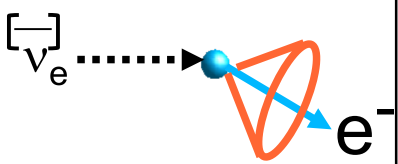
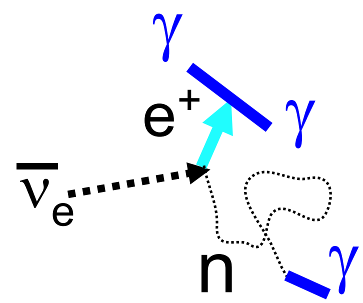
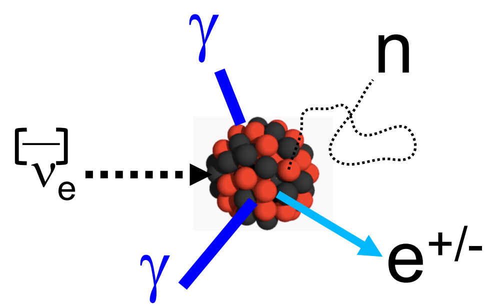
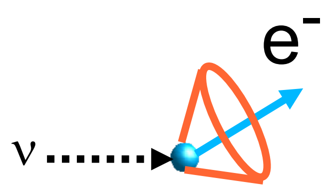
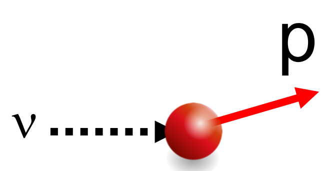
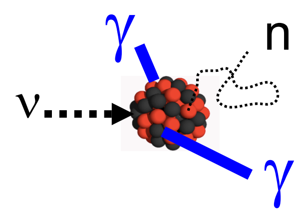
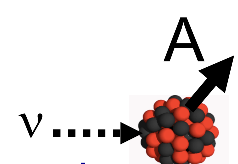
Neutrino interactions with elementary particles

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$   $\nu + A \to \nu + A$ Coherent elastic (CEvNS)

Various possible ejecta and deexcitation products

Simple targets… ~well understood

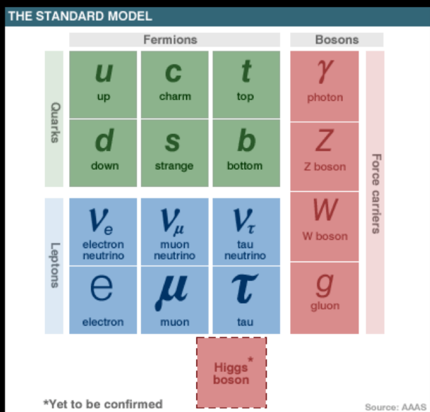
Neutrino interactions with elementary particles

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

Various possible ejecta and deexcitation products

Generally more complicated!

Why do we care about neutrino-nucleus interactions?



fundamental particles and interactions

cosmology

We need to understand the nature of the neutrino

- interpretation of neutrino oscillation... how do the flavors change?

- are there new interactions? beyond the Standard Model physics?

Why do we care about neutrino-nucleus interactions?

We need to unfold the fluxes from astrophysical systems (Sun, supernovae, blazars, mergers...) from detection on Earth

astrophysical systems

Why do we care about neutrino-nucleus interactions?

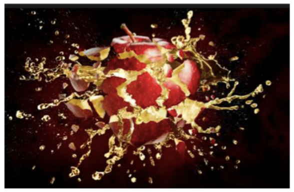
We can learn about
the structure of nuclei,
reactor processes,...

nuclear physics

Neutrino Interactions with Nuclei in Different Energy Regimes

Deep Inelastic Scattering

keV MeV GeV TeV PeV



Neutrino Interactions with Nuclei in Different Energy Regimes

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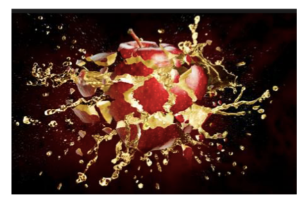


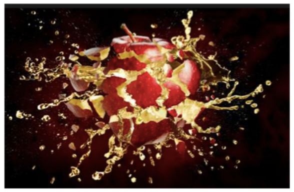
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino Interactions with Nuclei in Different Energy Regimes

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



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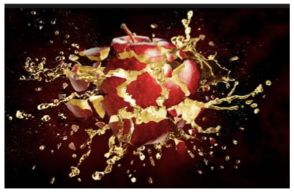


Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Example 1:
regime of
long-baseline oscillation experiments

Long-baseline beam experiments for oscillation physics

Past — Current — Future

K2K

KEK to Kamioka
250 km, 5 kW

MINOS (+)

FNAL to Soudan
734 km, 400+ kW

CNGS

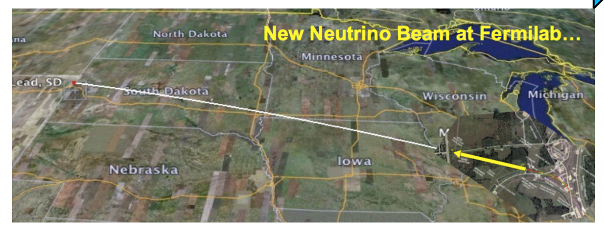
CERN to LNGS
730 km, 400 kW

NOνA

FNAL to Ash River
810 km, 400-700 kW

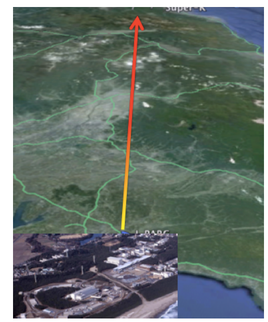
T2K (II)

J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW



LBNF/DUNE

FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)



Hyper-K

J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

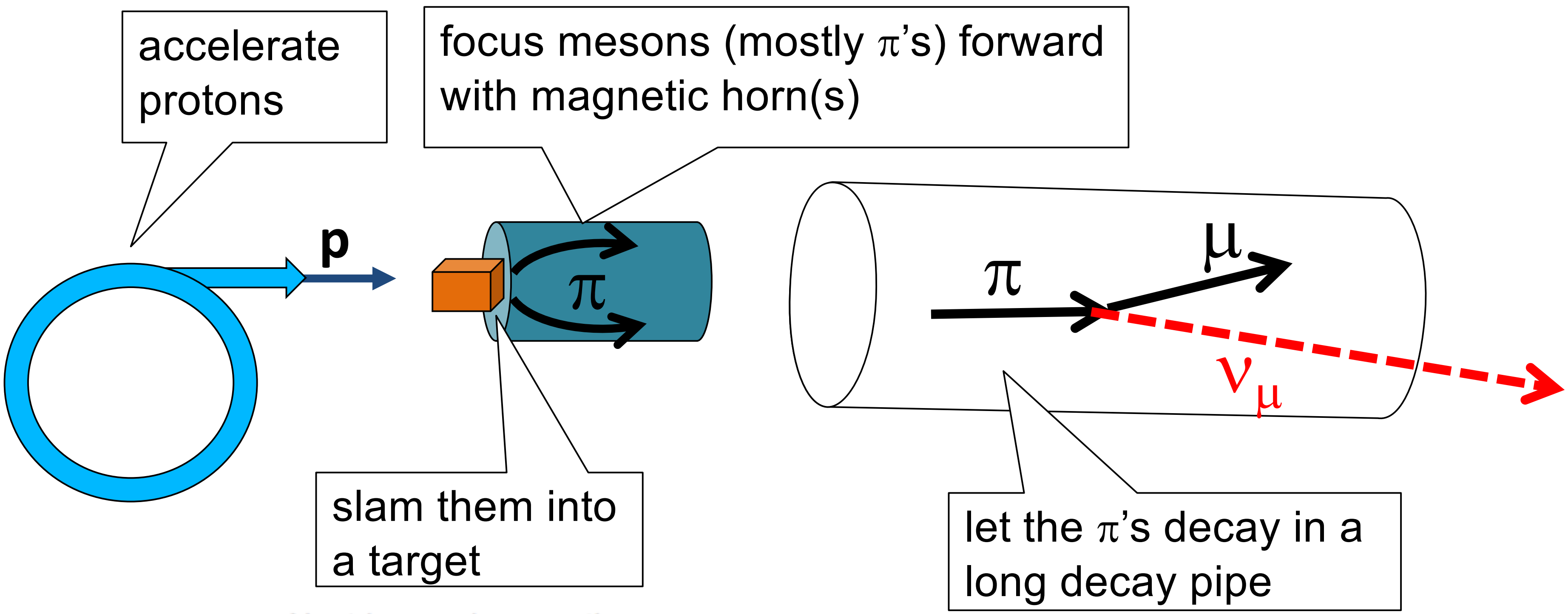
And beyond...

ESSnuB,
neutrino factories...

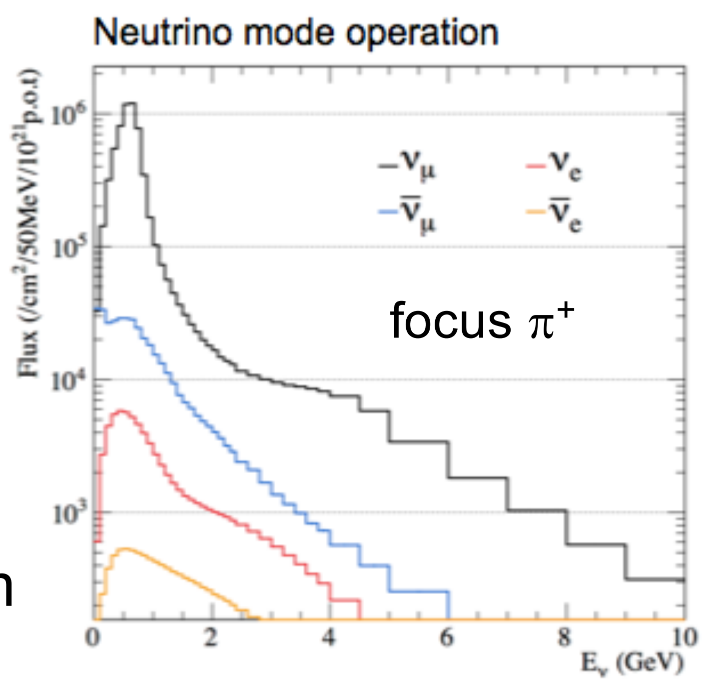




These make use of ~GeV neutrinos from π decay in flight



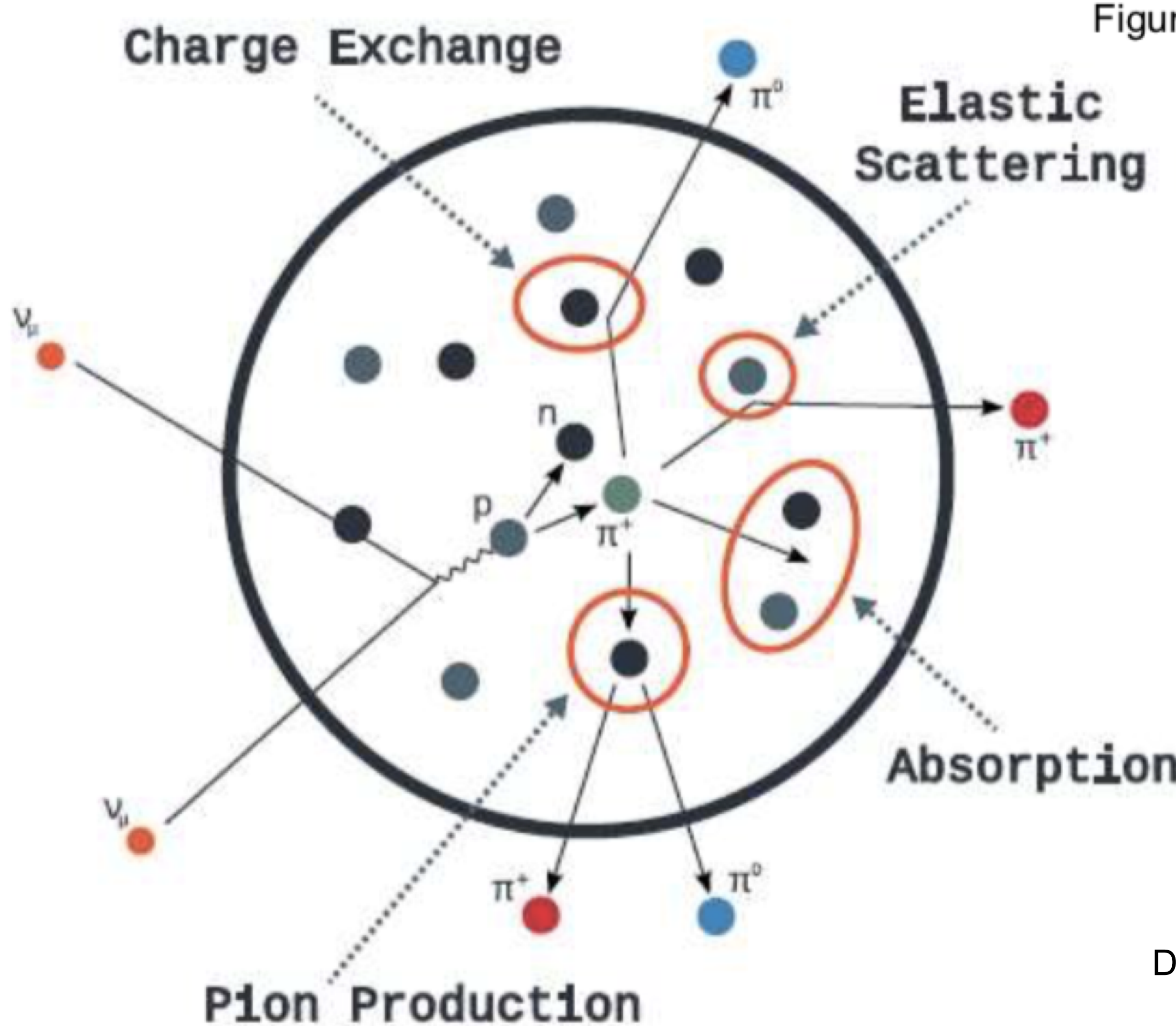
T2K beam



Non-negligible uncertainties on flux normalization and spectrum…

Neutrino-nucleus interactions in this regime have **complicated final states**

Figure by Tomasz Golan

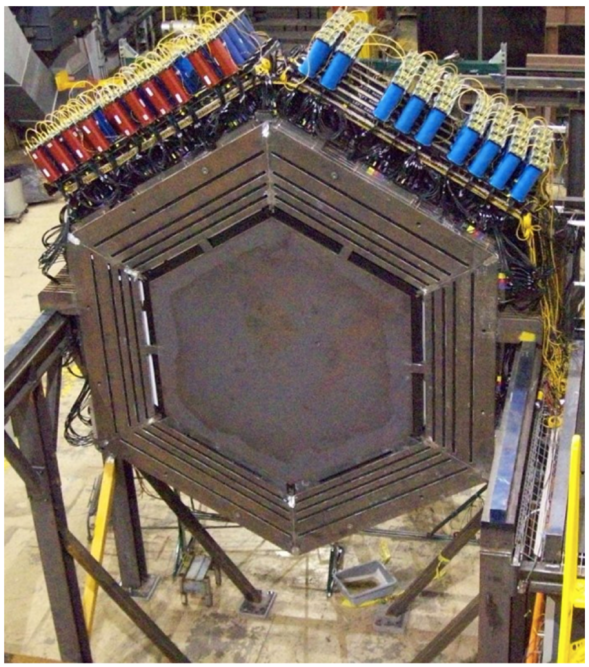


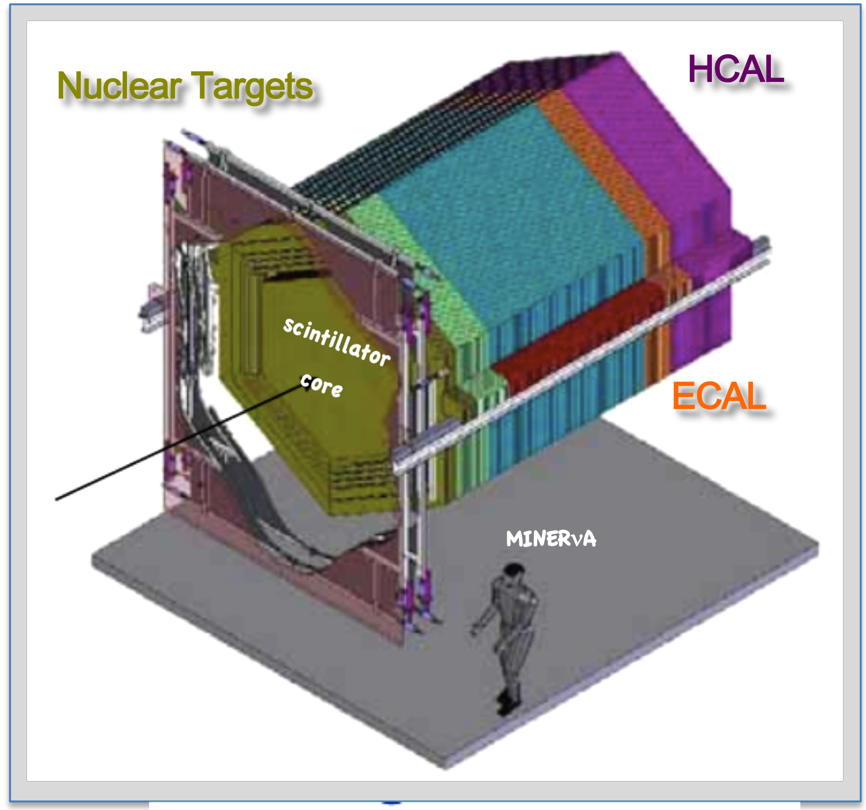
Need to unfold neutrino flavor, energy dependence for oscillation studies

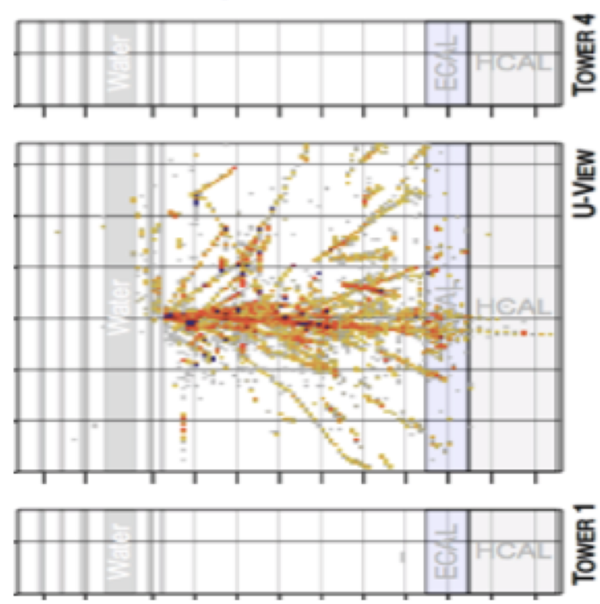
D. Ruterbories, Nu2018

MINERνA

Detector at NuMI (Fermilab)
to measure cross-sections of
~GeV neutrinos on nuclear targets
(finely-segmented scintillator
+ em & hadronic calorimeters)





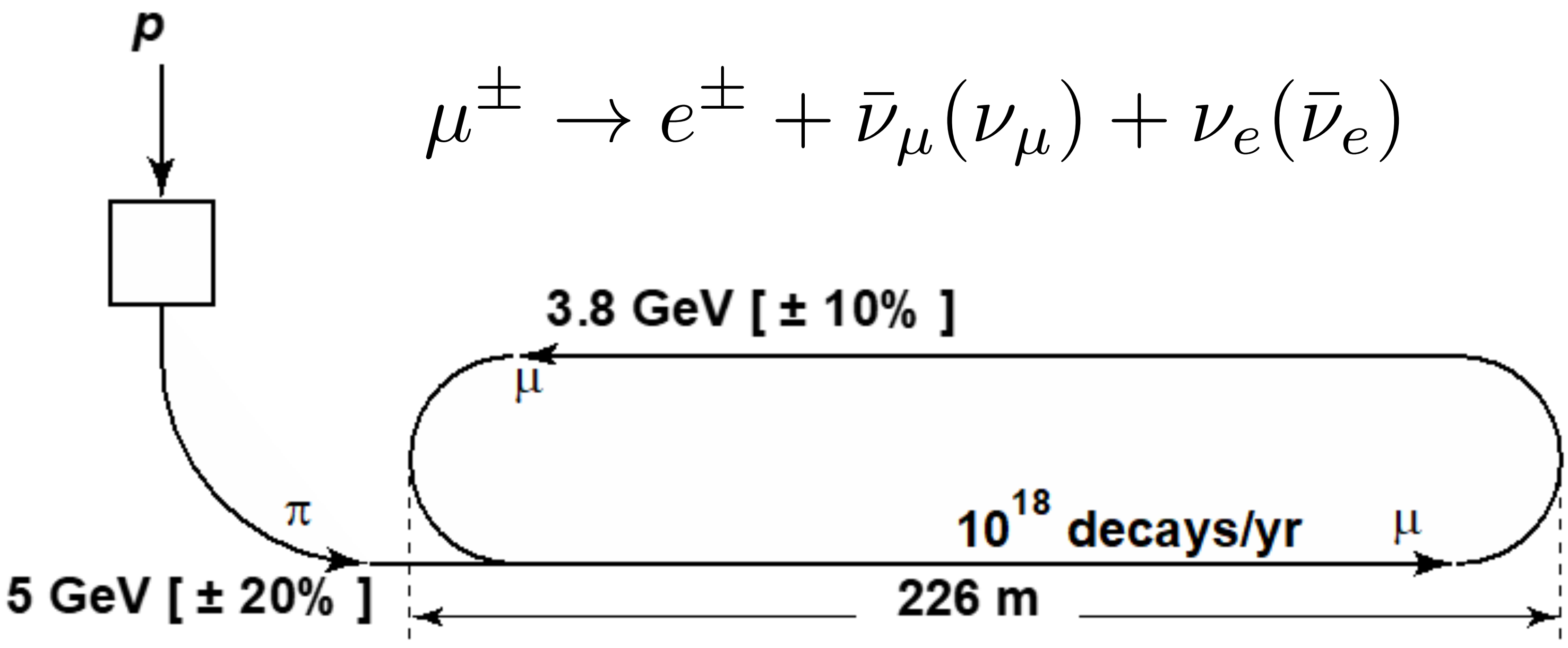


These challenging studies
are critical for interpretation of
neutrino oscillation experiments

Muon (or radioactive isotope) storage rings
are conceptually attractive
for **well-understood neutrino flux**
from muon decay in flight, tunable energy

➔ in principle good for
precision cross-section measurements

$$\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$$



e.g., NuSTORM

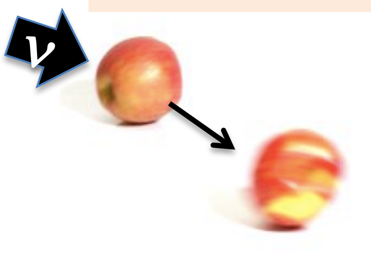
Now look at the low-energy regime and the *gentlest* interaction with nuclei

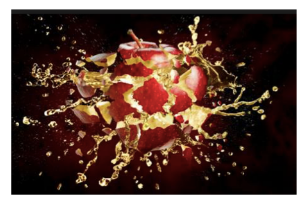
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV

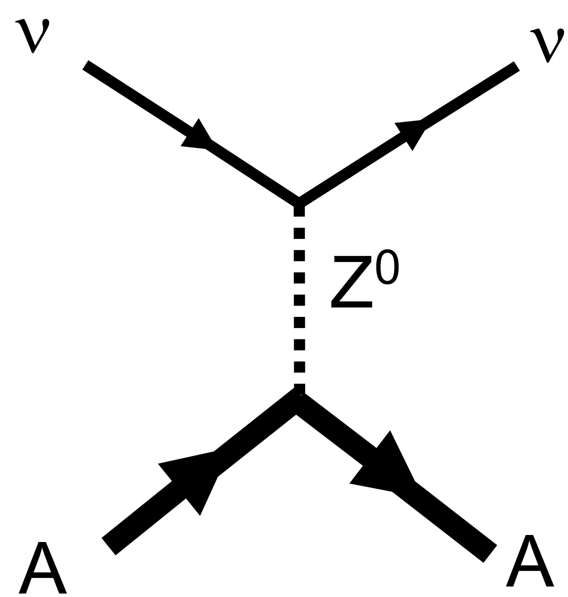




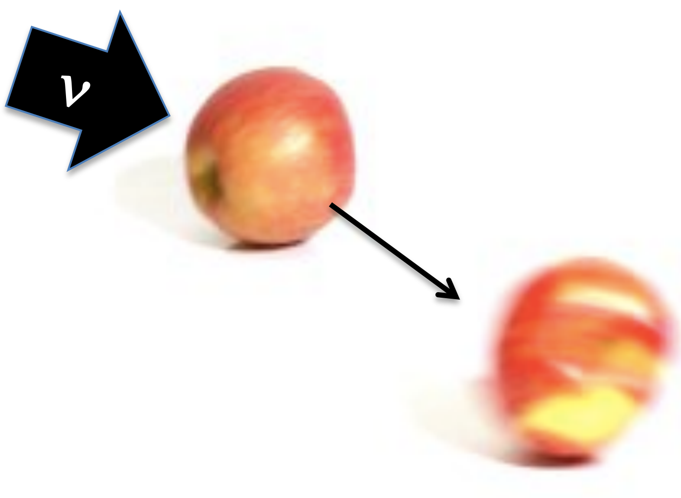
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Coherent elastic neutrino-nucleus scattering (CEvNS)

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



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



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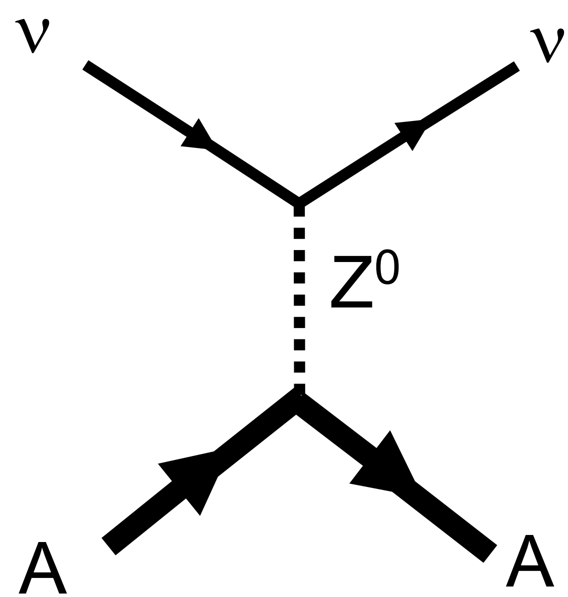

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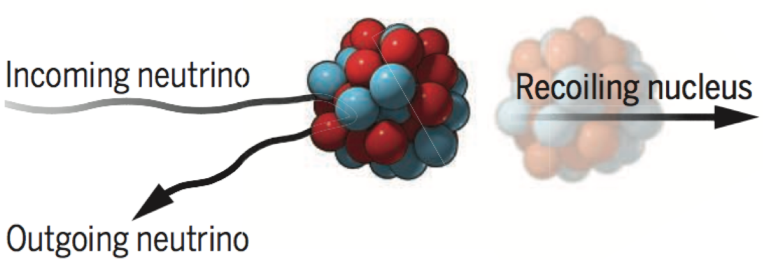


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

Image: J. Link *Science* Perspectives

A: no. of constituents

First proposed >4 decades ago!

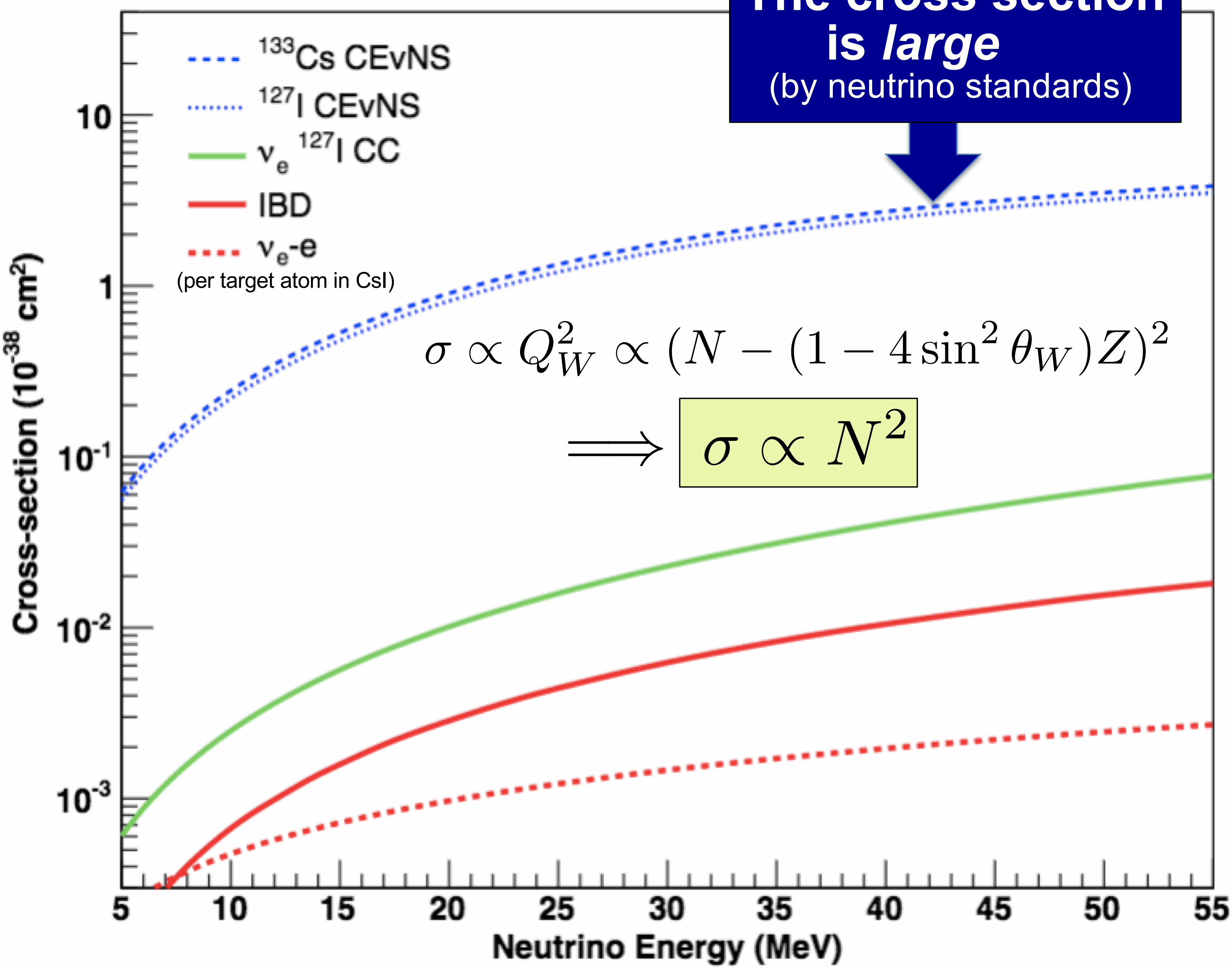
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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

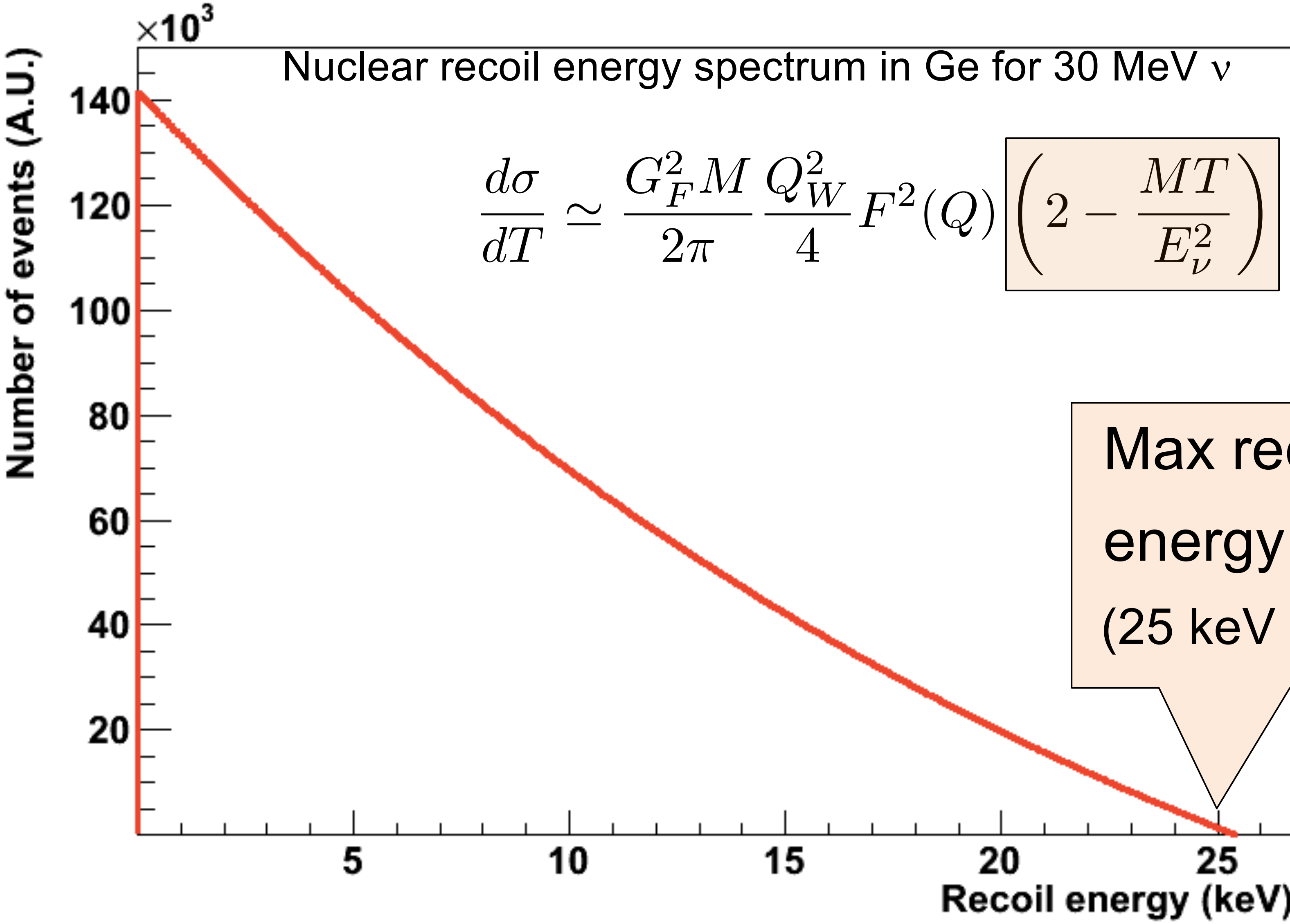


The cross section is *large*
(by neutrino standards)

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

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

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



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

Max recoil energy is ~$2E_\nu^2/M$

(25 keV for Ge)

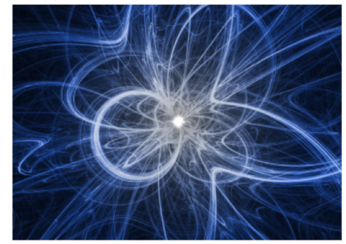
CEvNS: what's it good for?

1 So
2 Many
3 Things

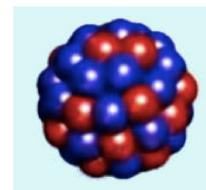
!

(not a complete list!)

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

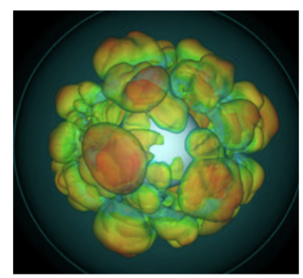


CEvNS as a **signal**
for understanding of "old" physics

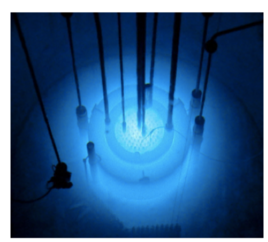


CEvNS as a **background**
for signatures of new physics

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



CEvNS as a **practical tool**



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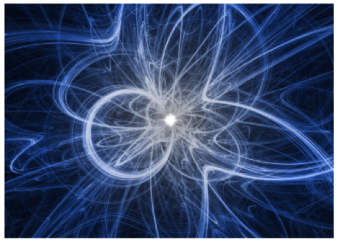

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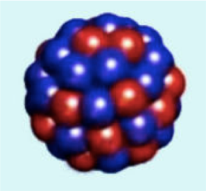
for understanding of "old" physics



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

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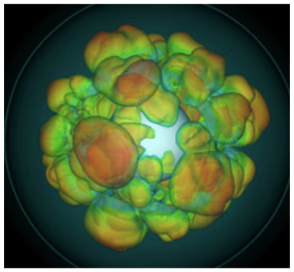

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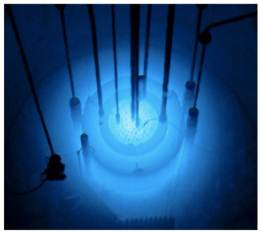
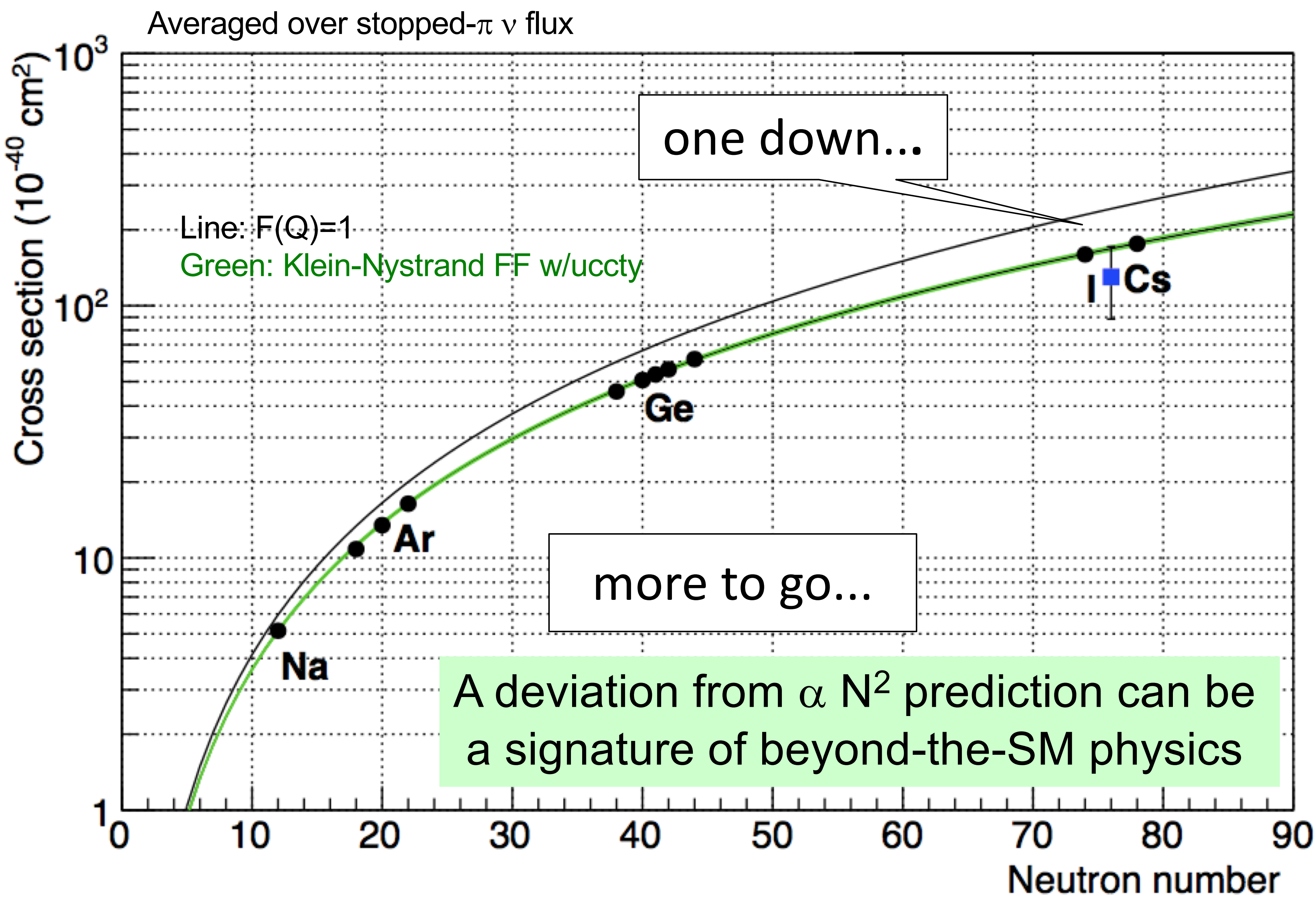


Need to measure **N² dependence** of the CEvNS xscn

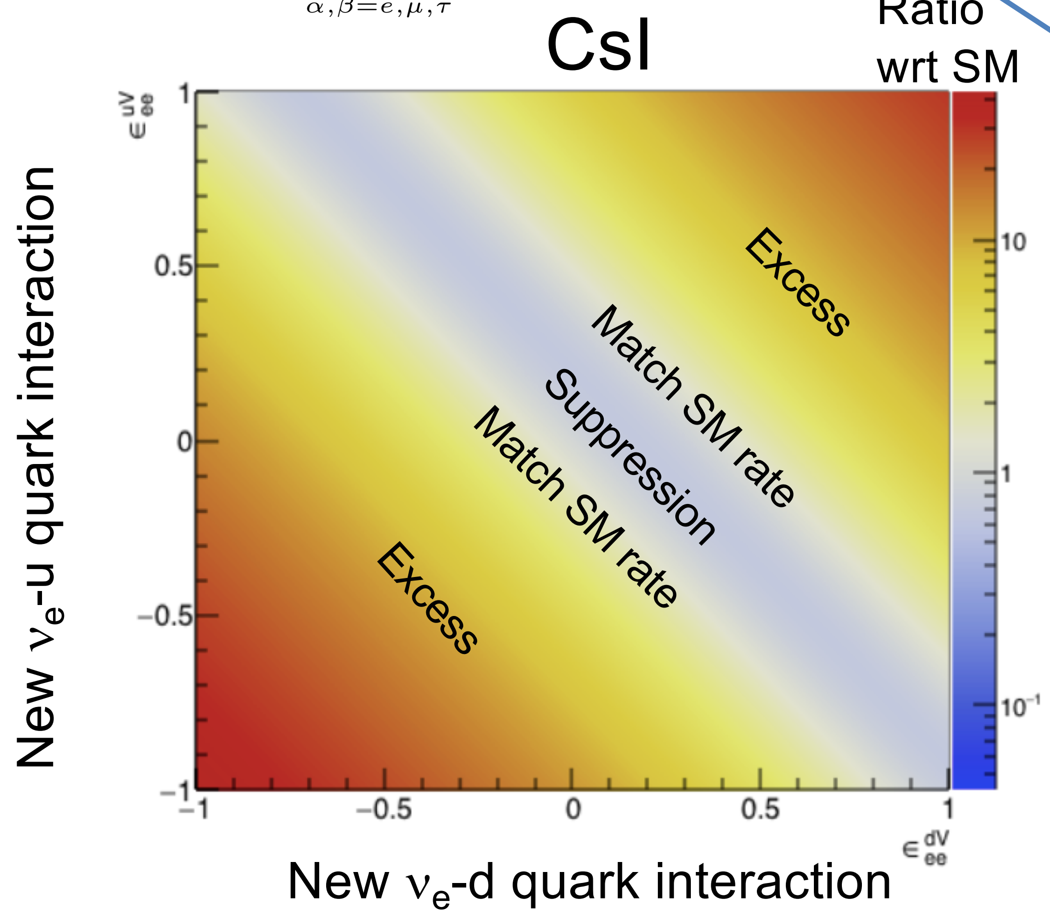


Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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

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



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

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

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

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

CEvNS: what's it good for?

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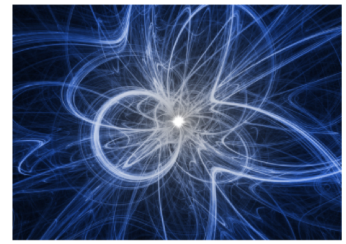

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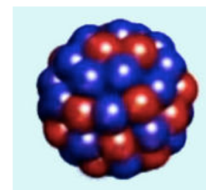
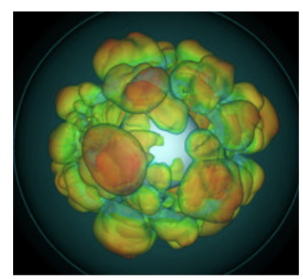
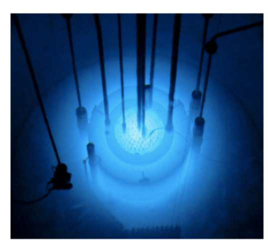


CEvNS as a **background**
for signatures of new physics (DM)

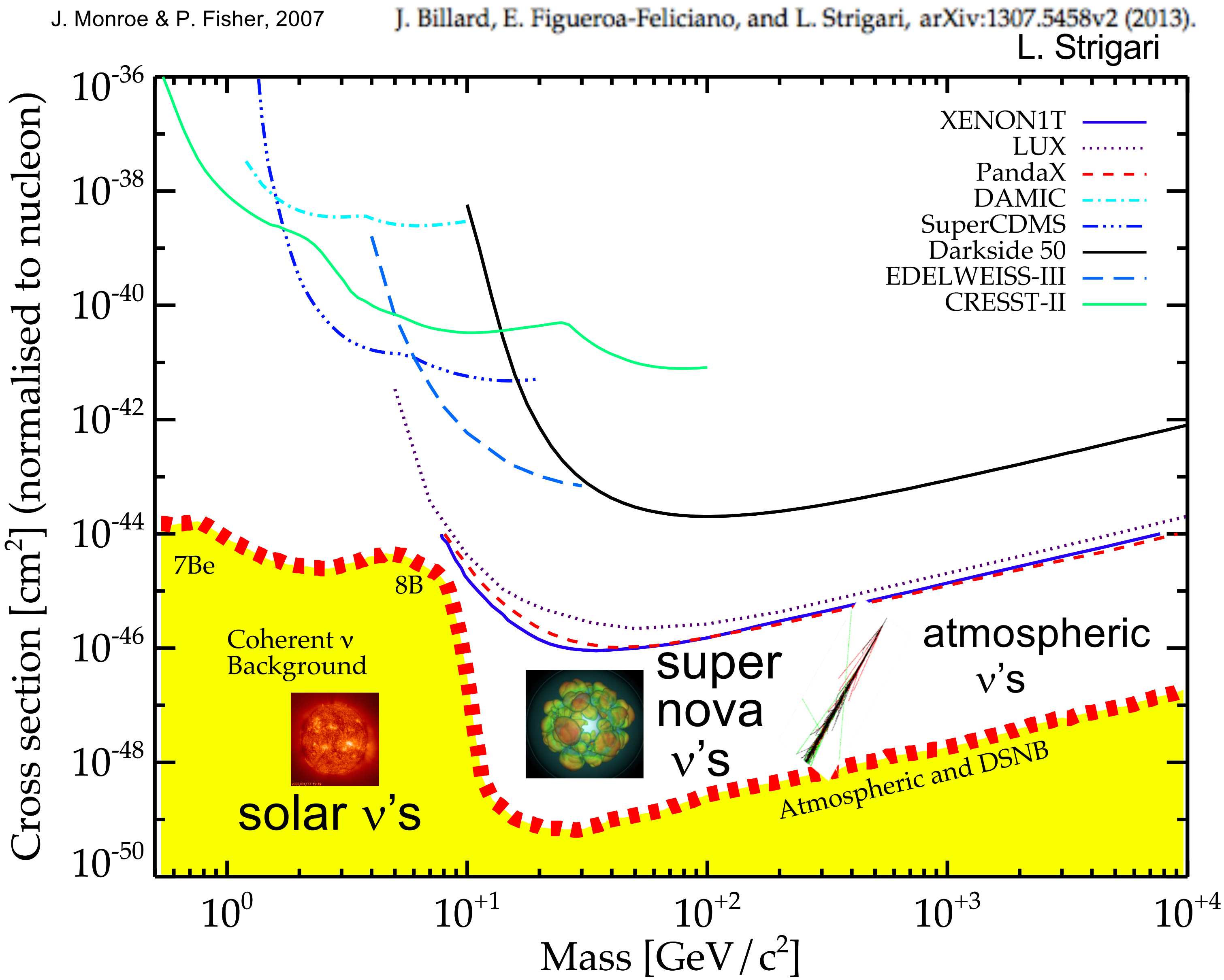
CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



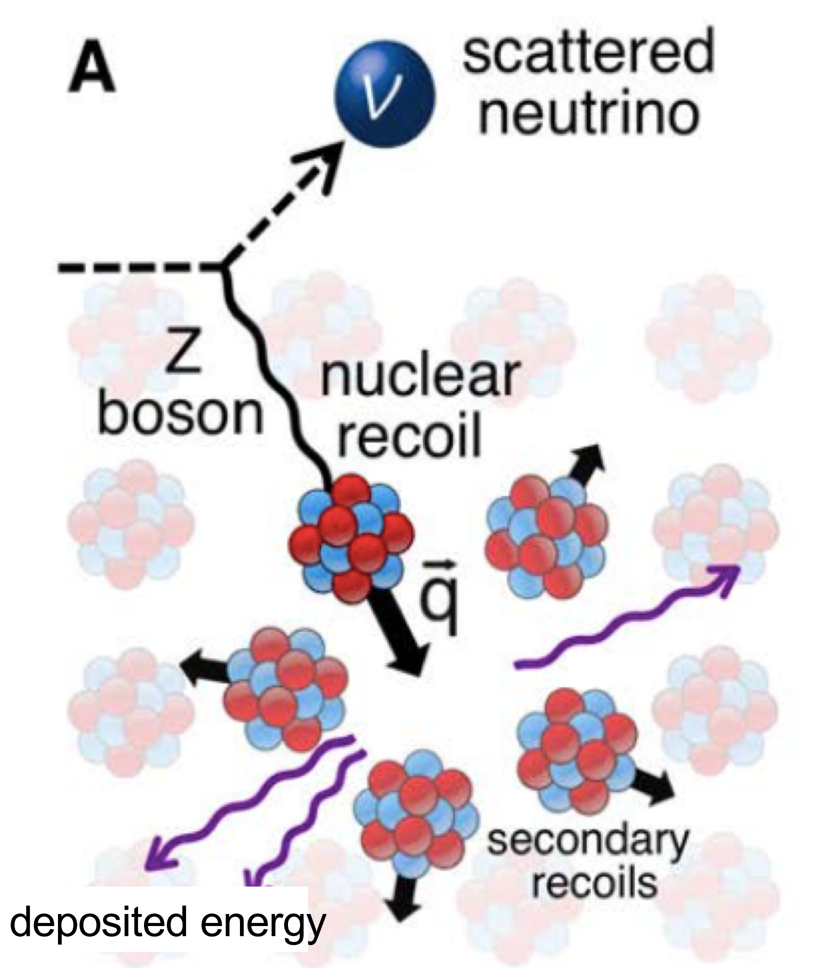
The so-called “neutrino floor” (**signal!**) for direct DM experiments



How to measure CEvNS

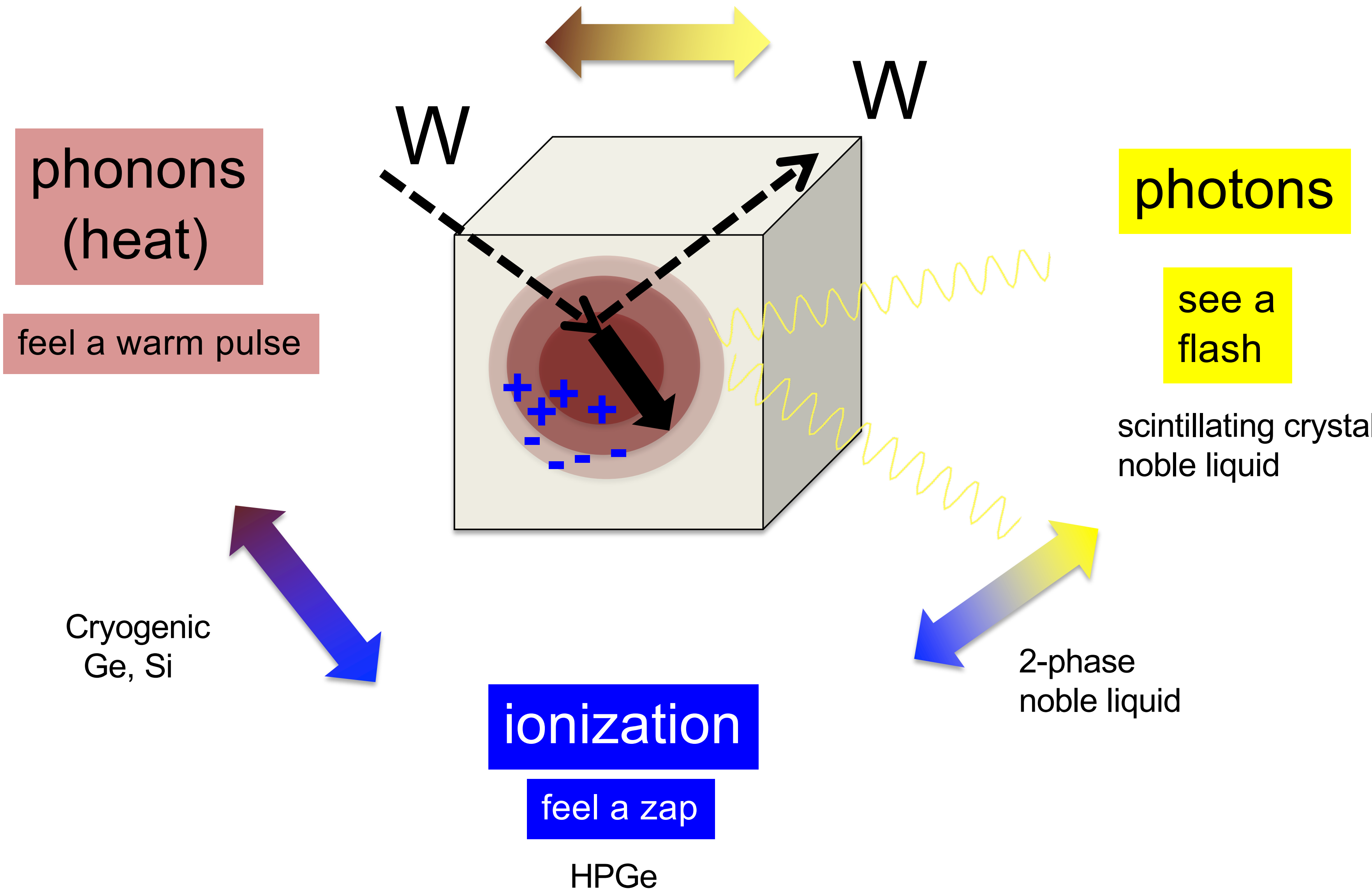
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



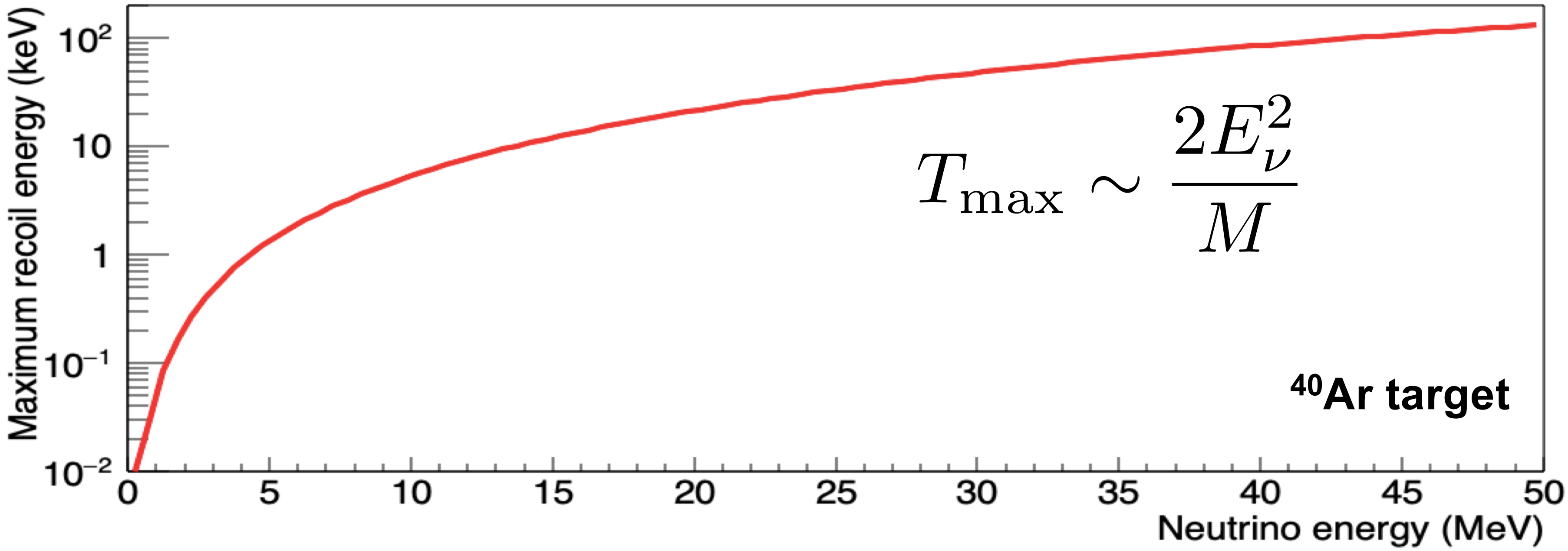
➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10's of keV recoils

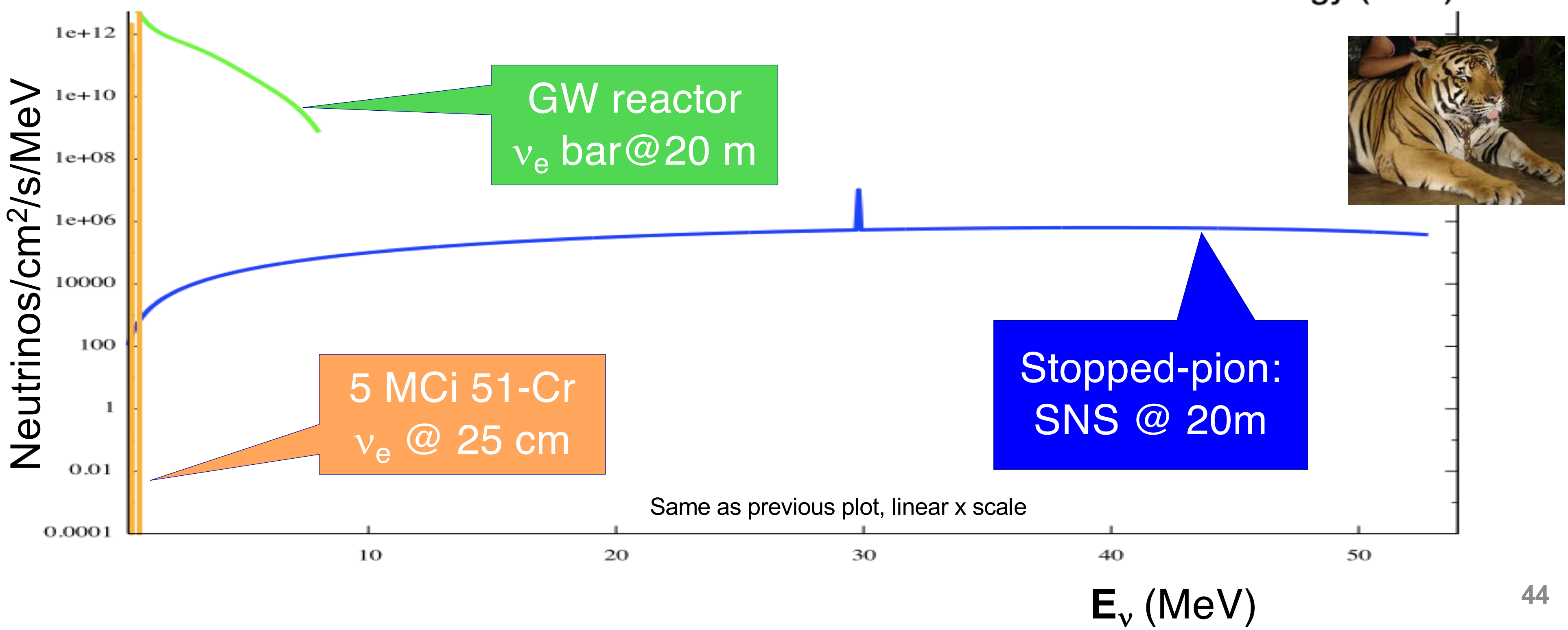
Low-energy nuclear recoil detection strategies



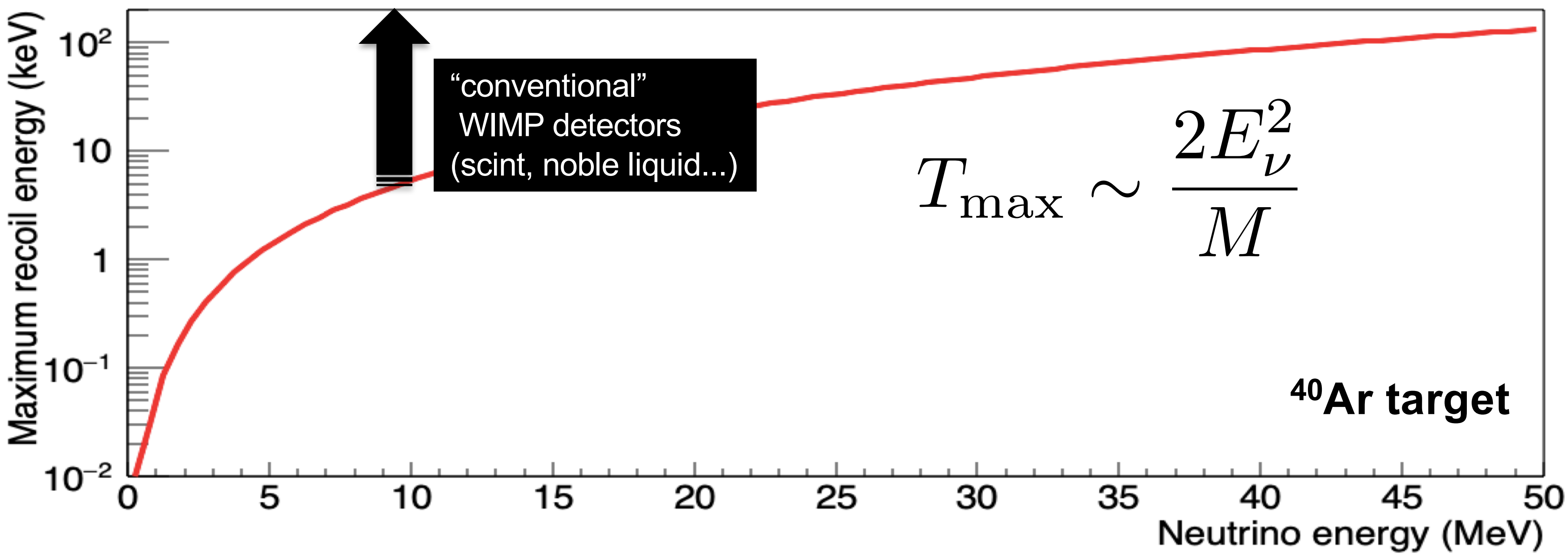
http://dmrc.snu.ac.kr/english/intro/intro1.html

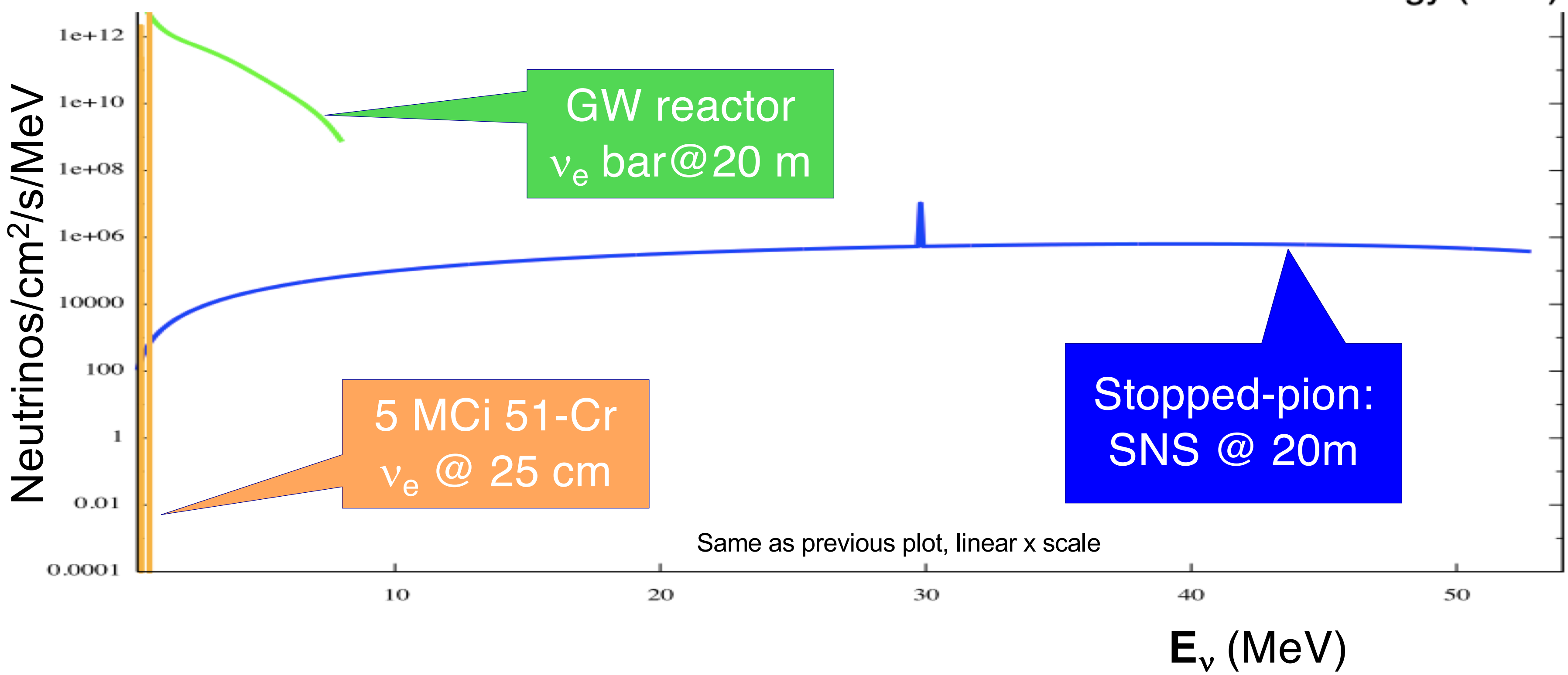
Maximum recoil energy as a function of E_ν





Maximum recoil energy as a function of E_ν





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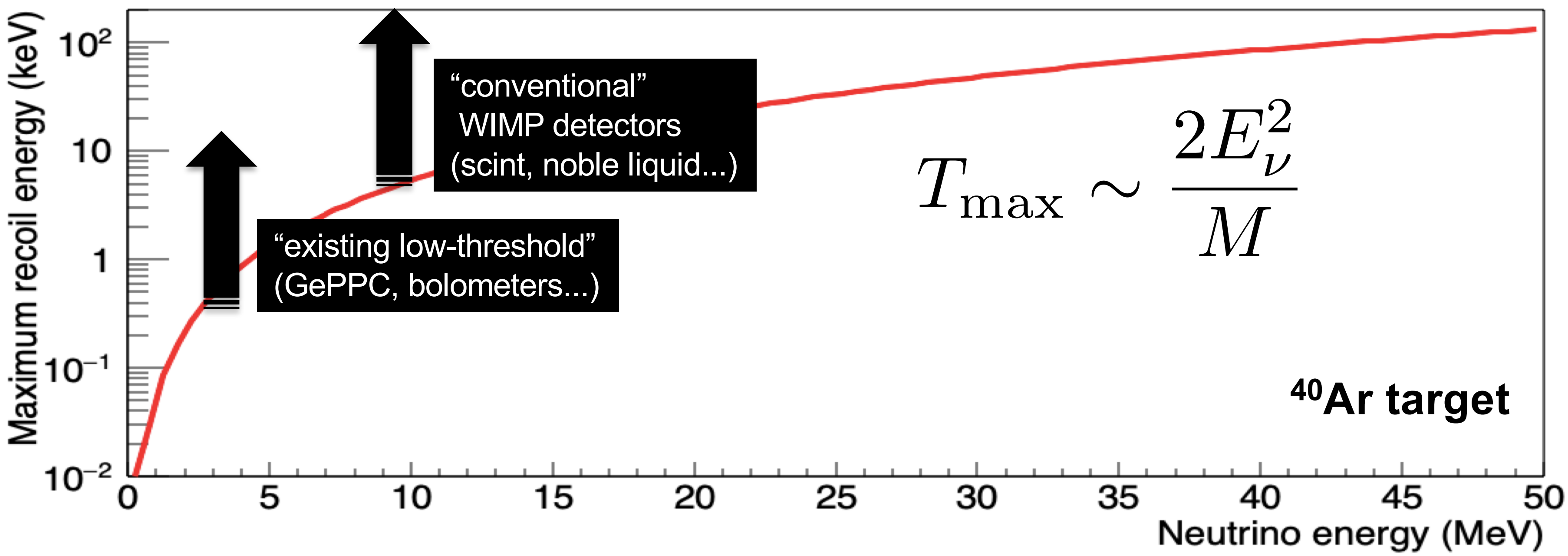
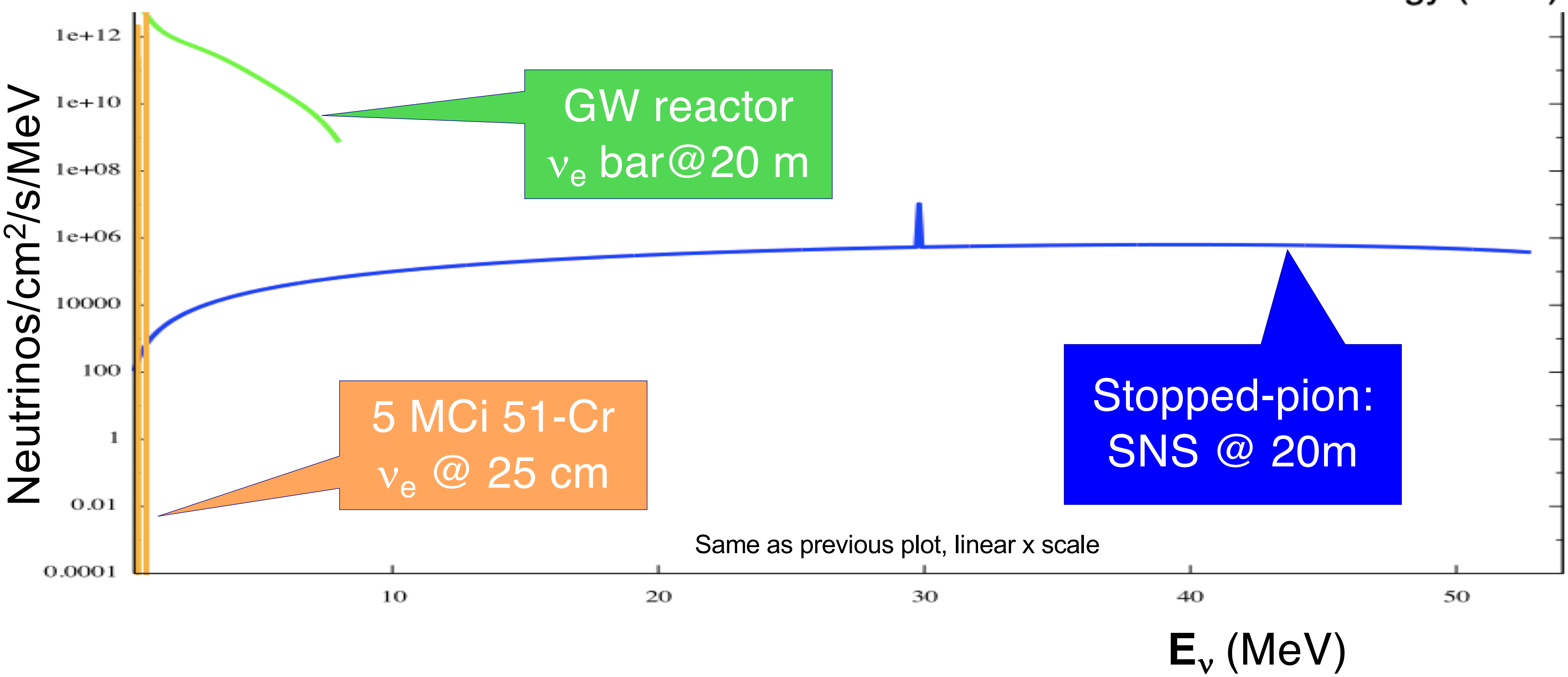
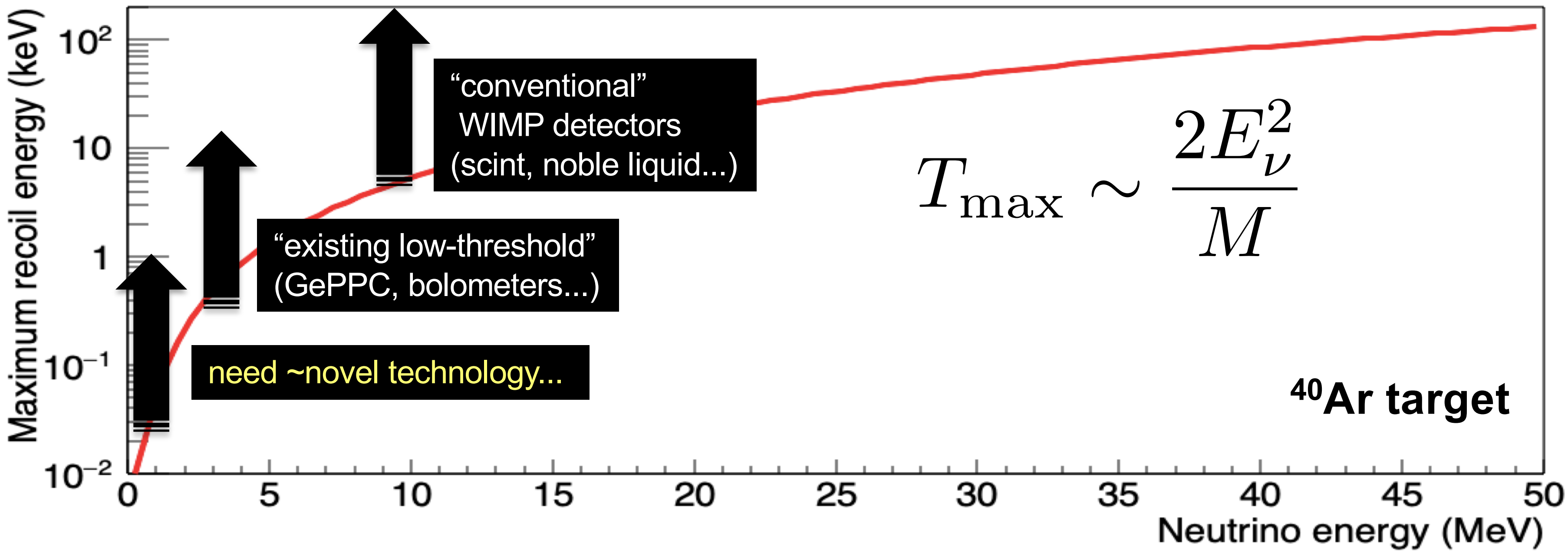
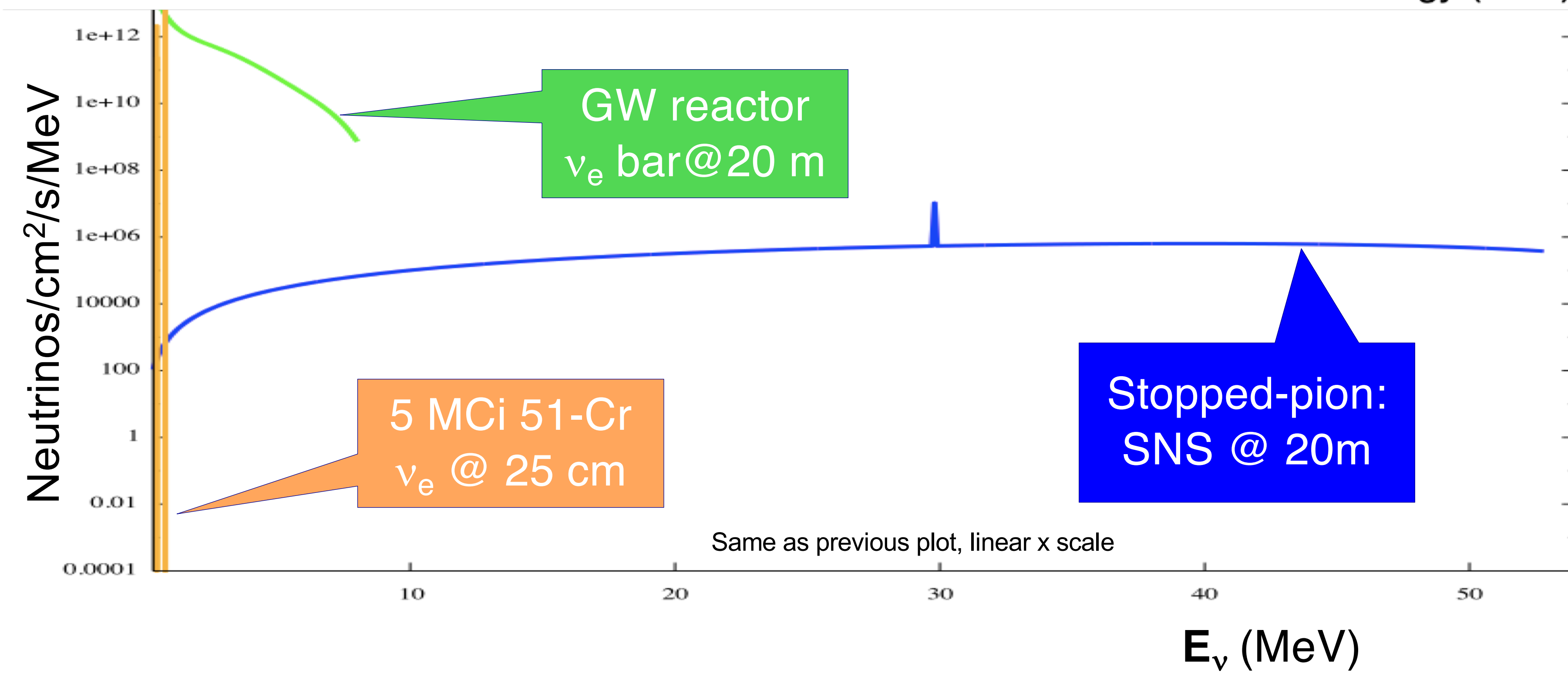


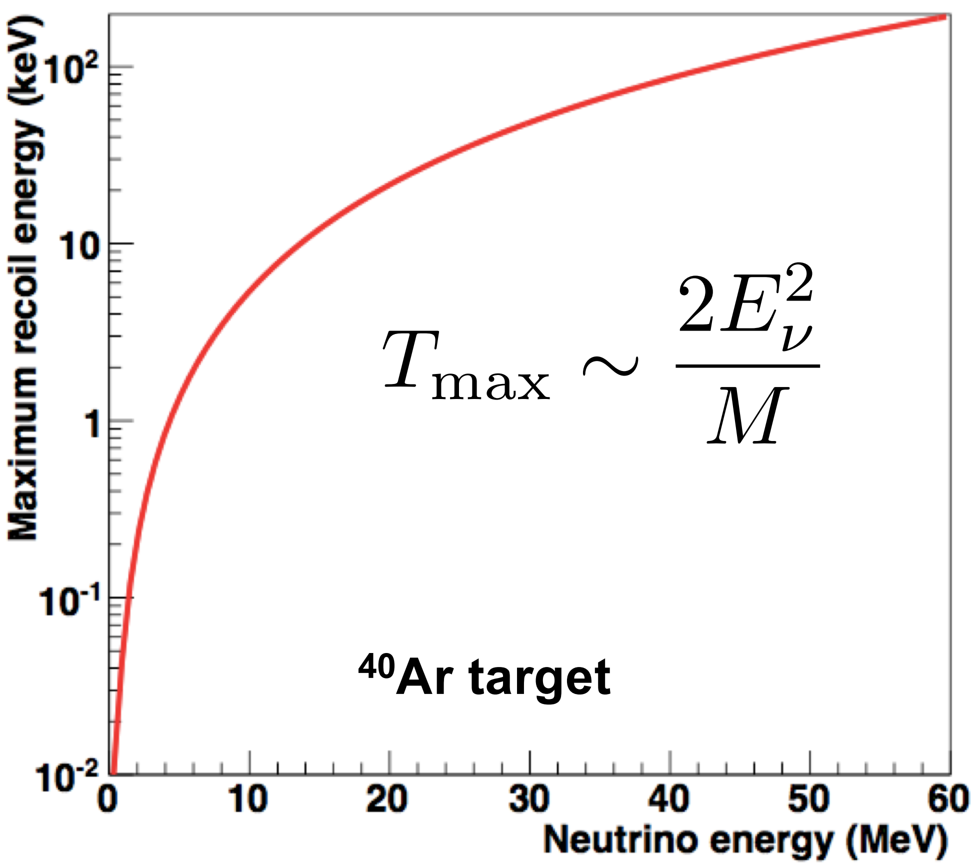


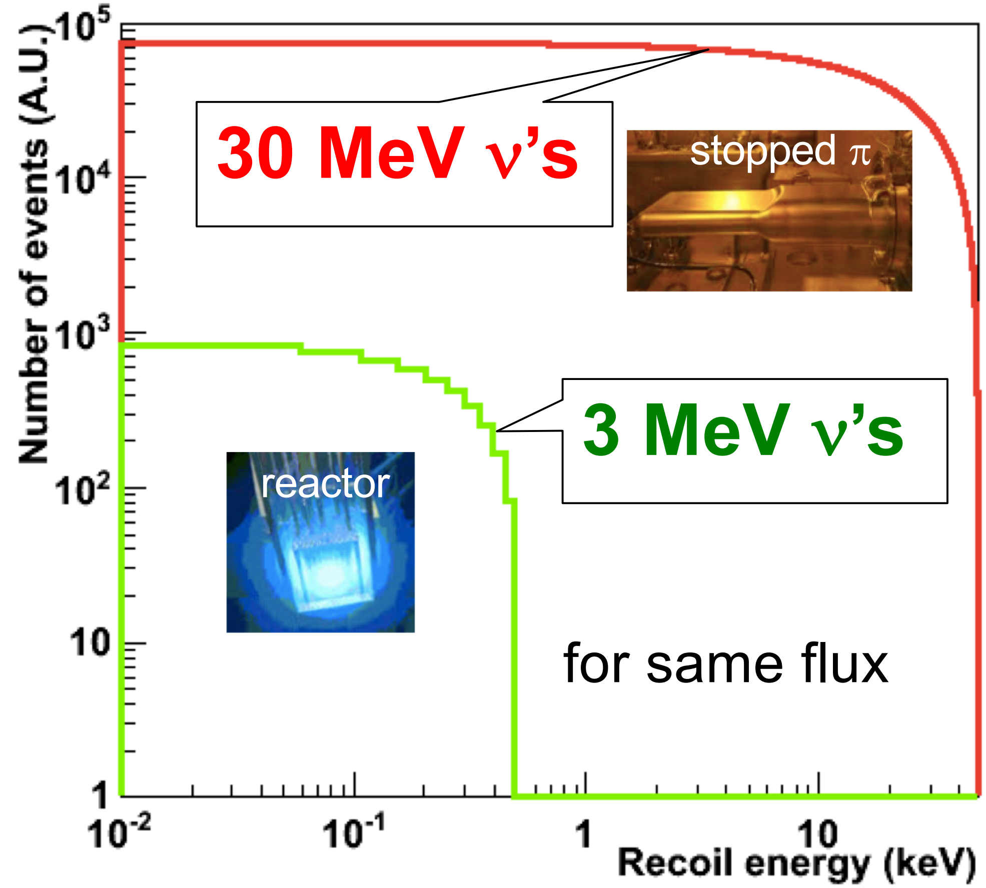
Maximum recoil energy as a function of E_ν





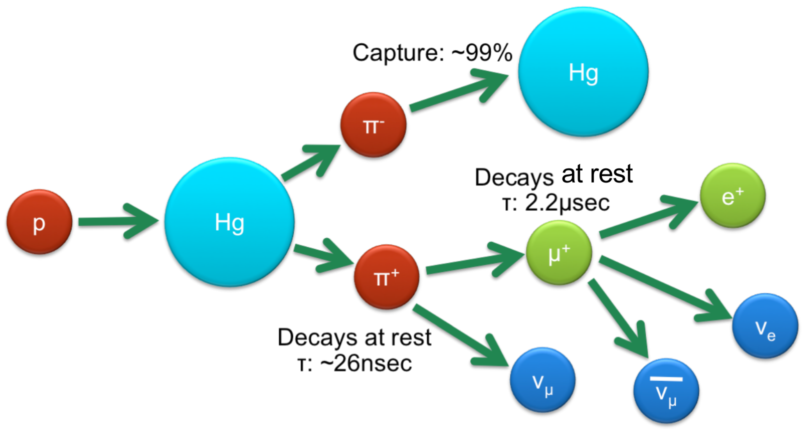
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

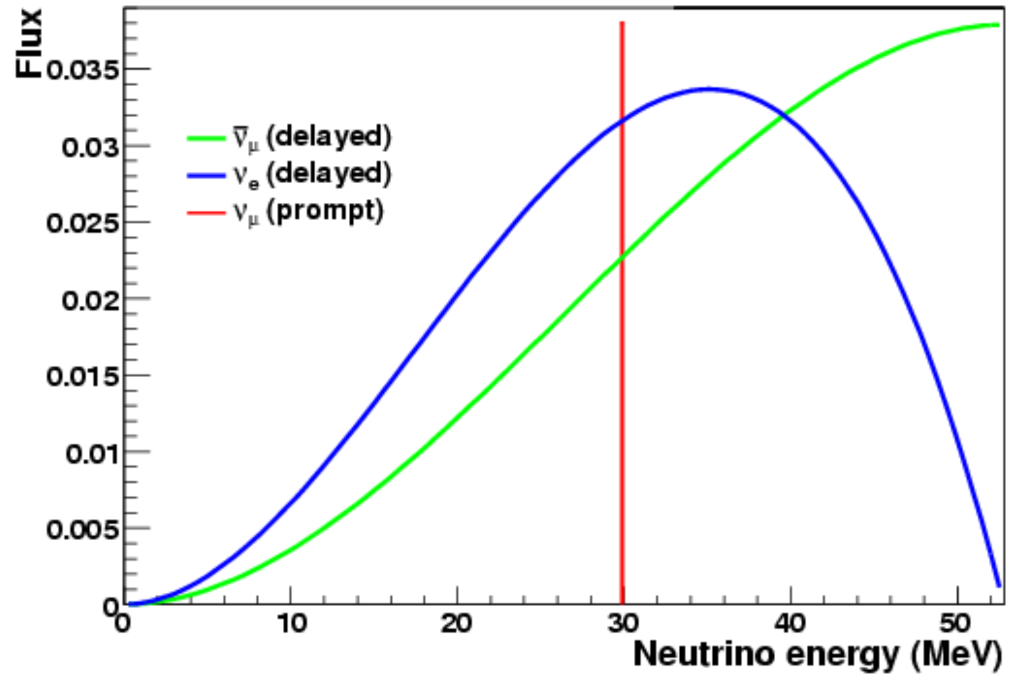




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

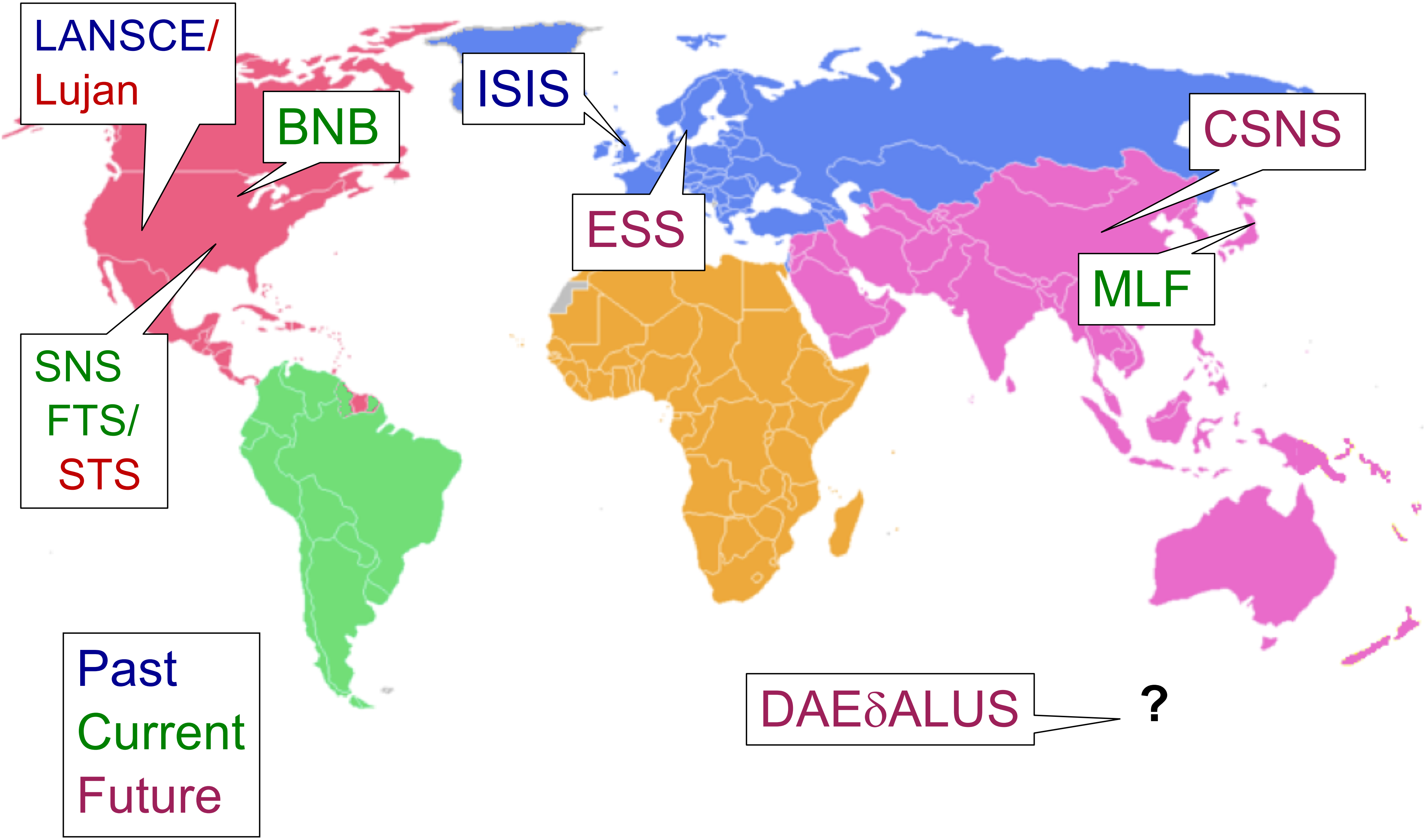
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

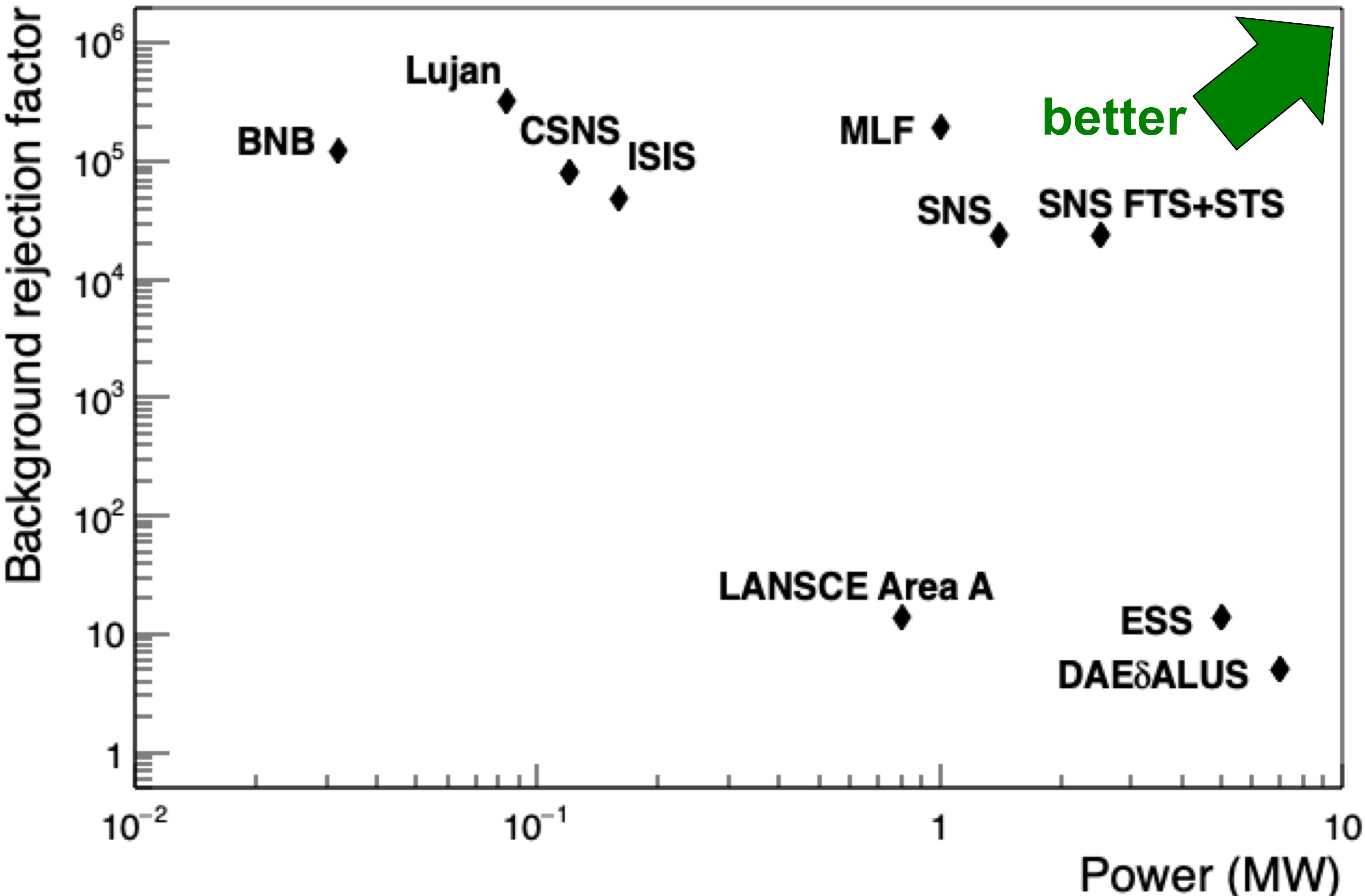
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Neutrino Sources Worldwide



Comparison of pion decay-at-rest ν sources

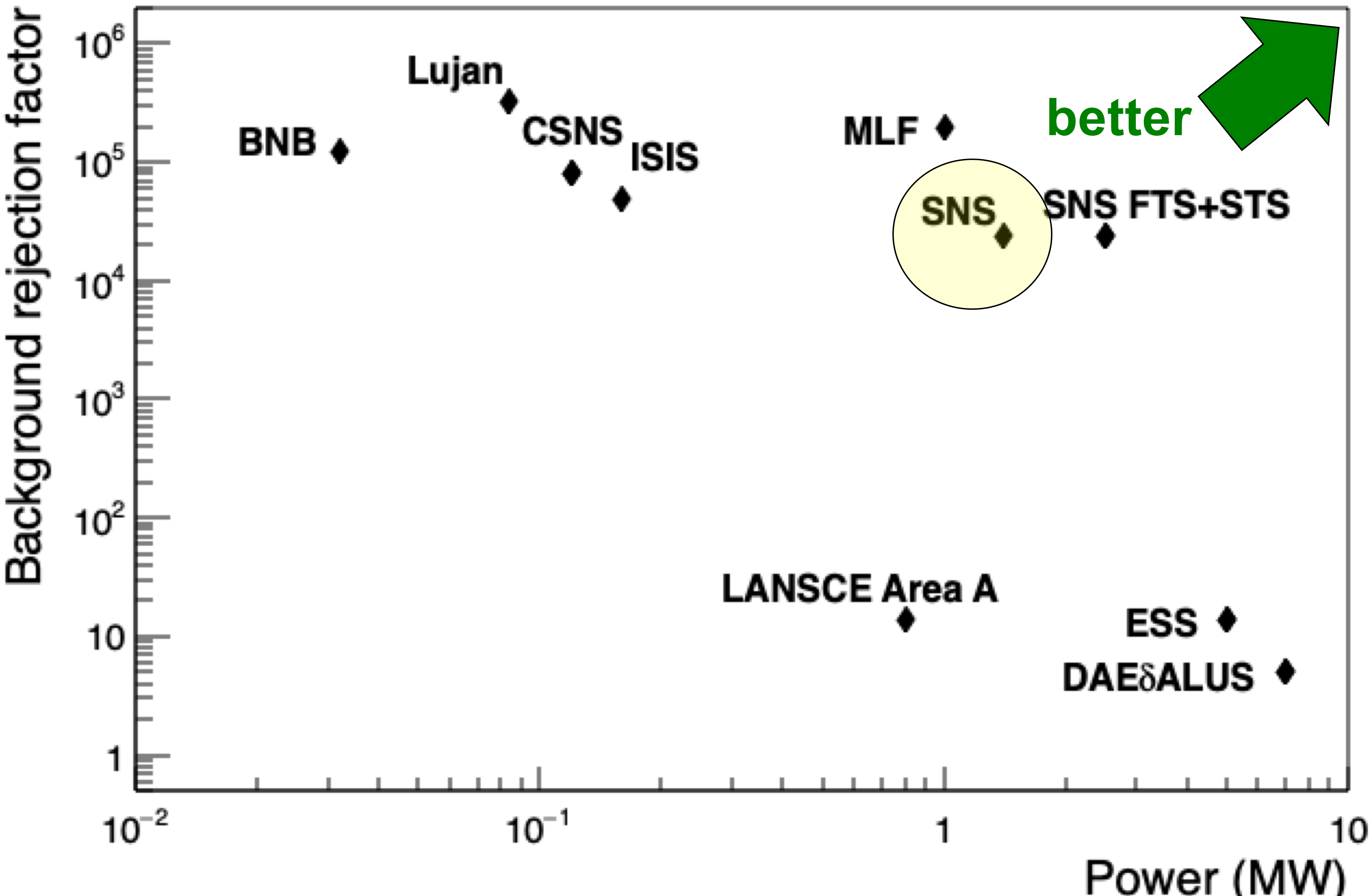
from duty cycle



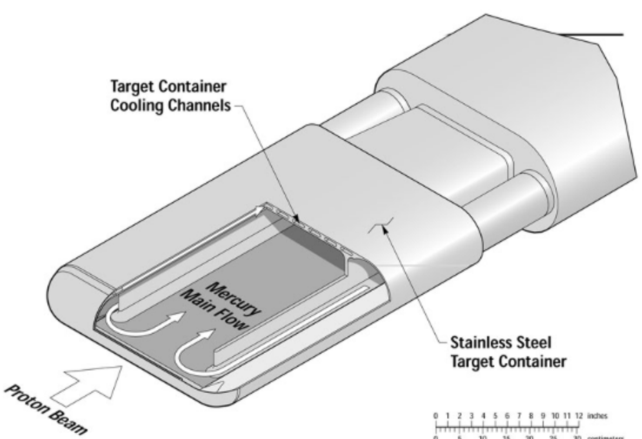
$\propto \nu$ flux

Comparison of pion decay-at-rest ν sources

from duty cycle



$\propto \nu$ flux

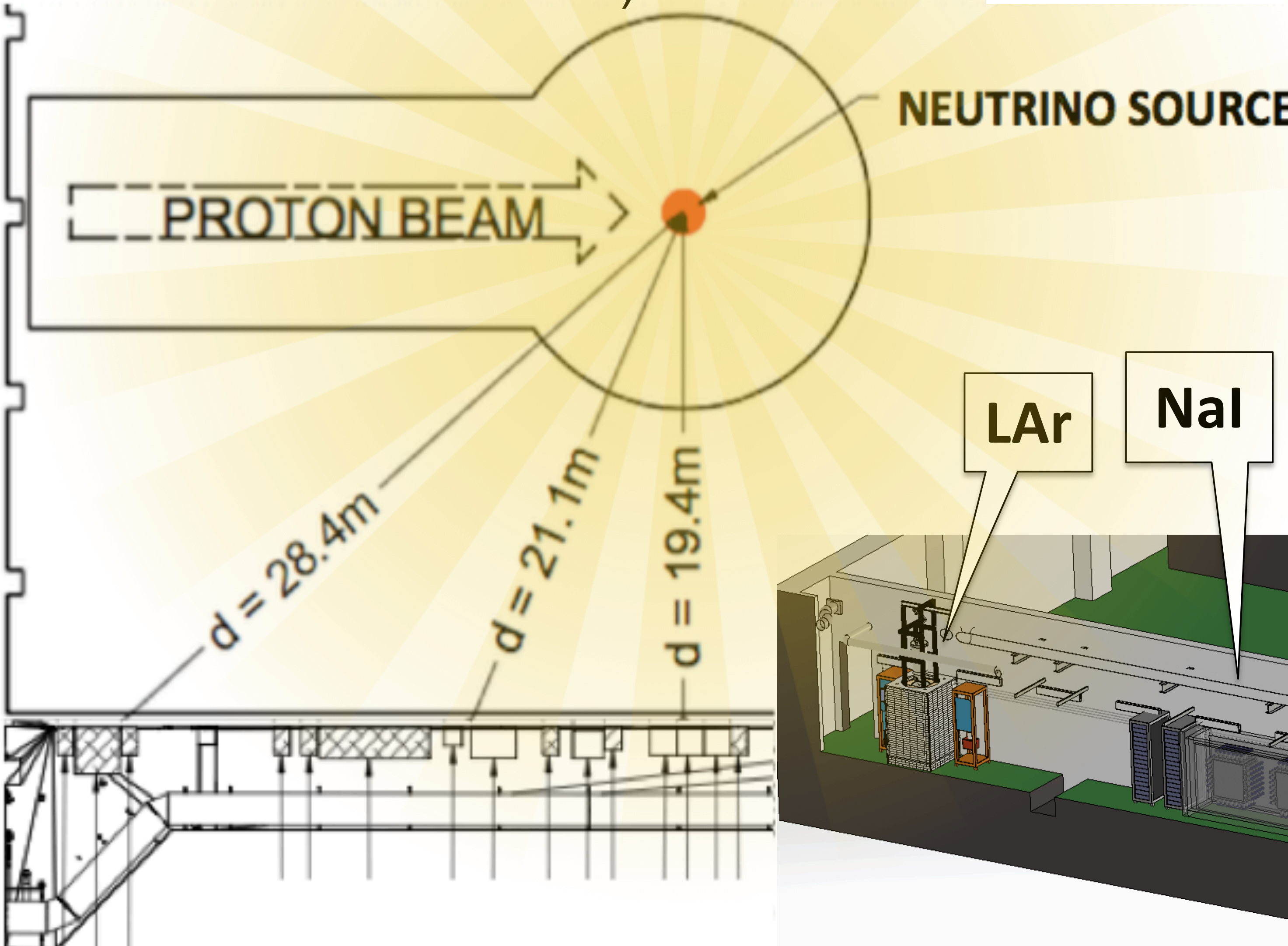


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

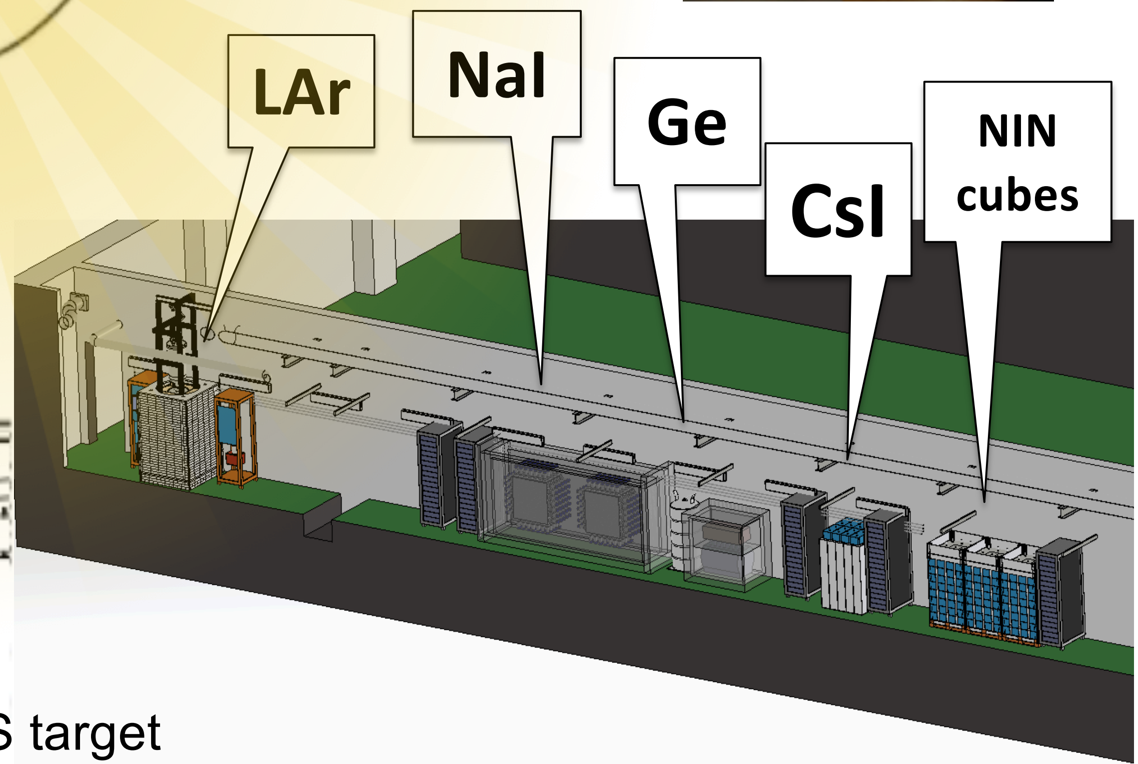
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)



Isotropic ν glow from Hg SNS target

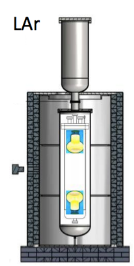
View looking
down "Neutrino Alley"

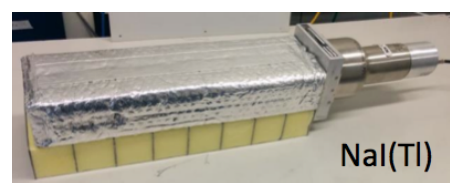


COHERENT CEvNS Detectors

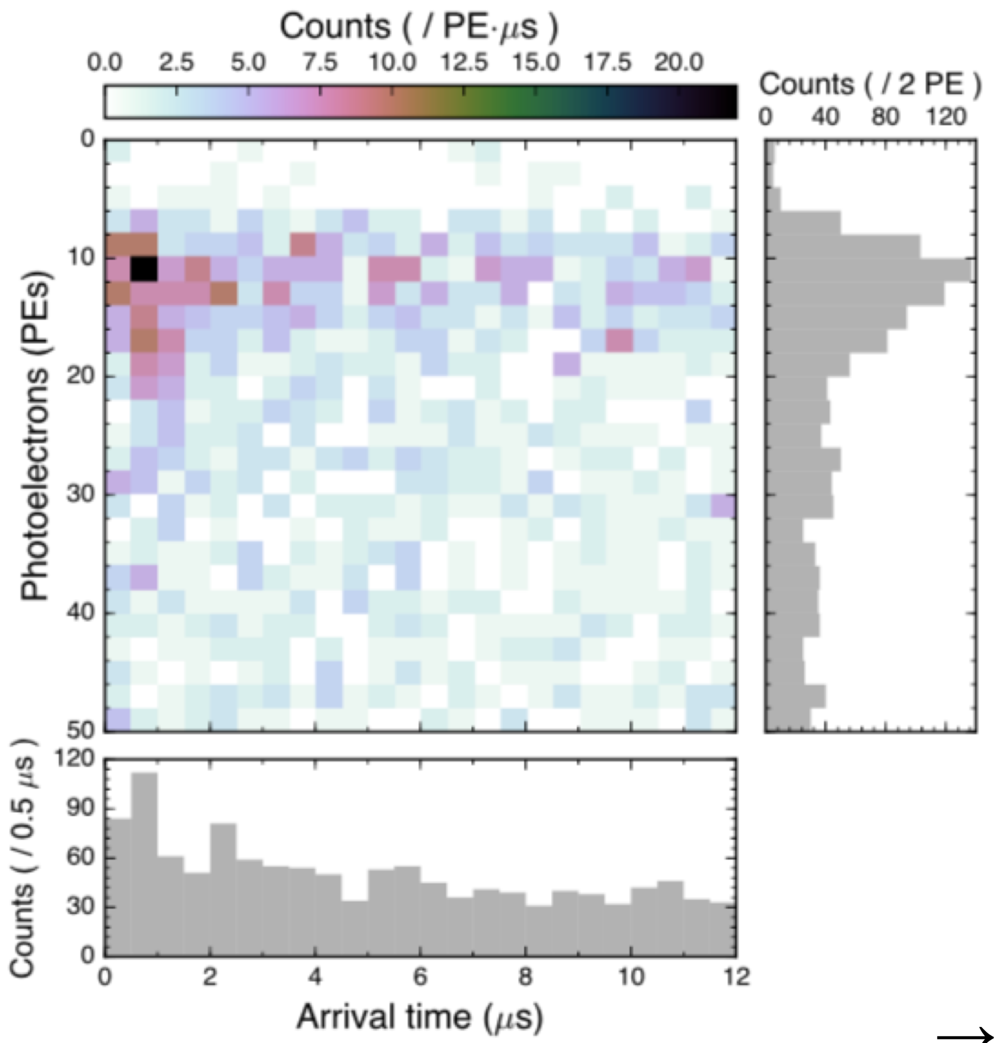
Nuclear Target	Technology		Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal	flash	14.6	19.3	6.5
Ge	HPGe PPC	zap	16	20	<few
LAr	Single-phase	flash	22	29	20
NaI[Tl]	Scintillating crystal	flash	185*/3338	28	13

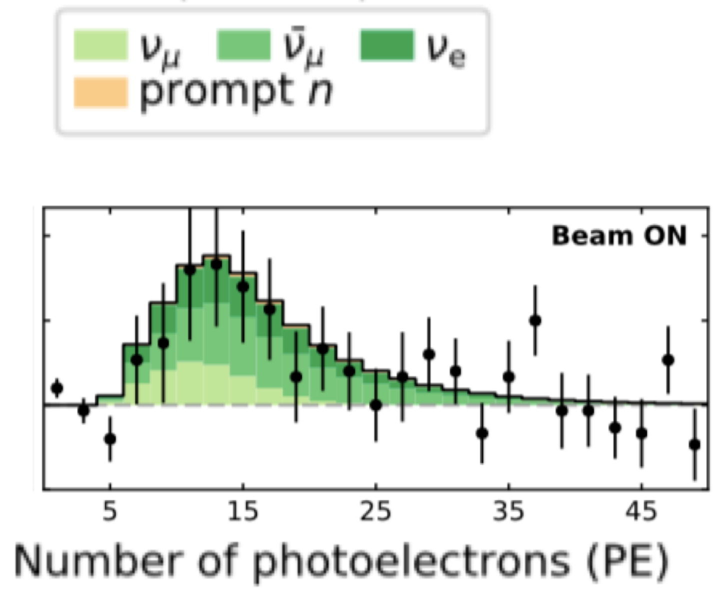
Multiple detectors for N^2 dependence of the cross section





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





Background-subtracted and integrated over time

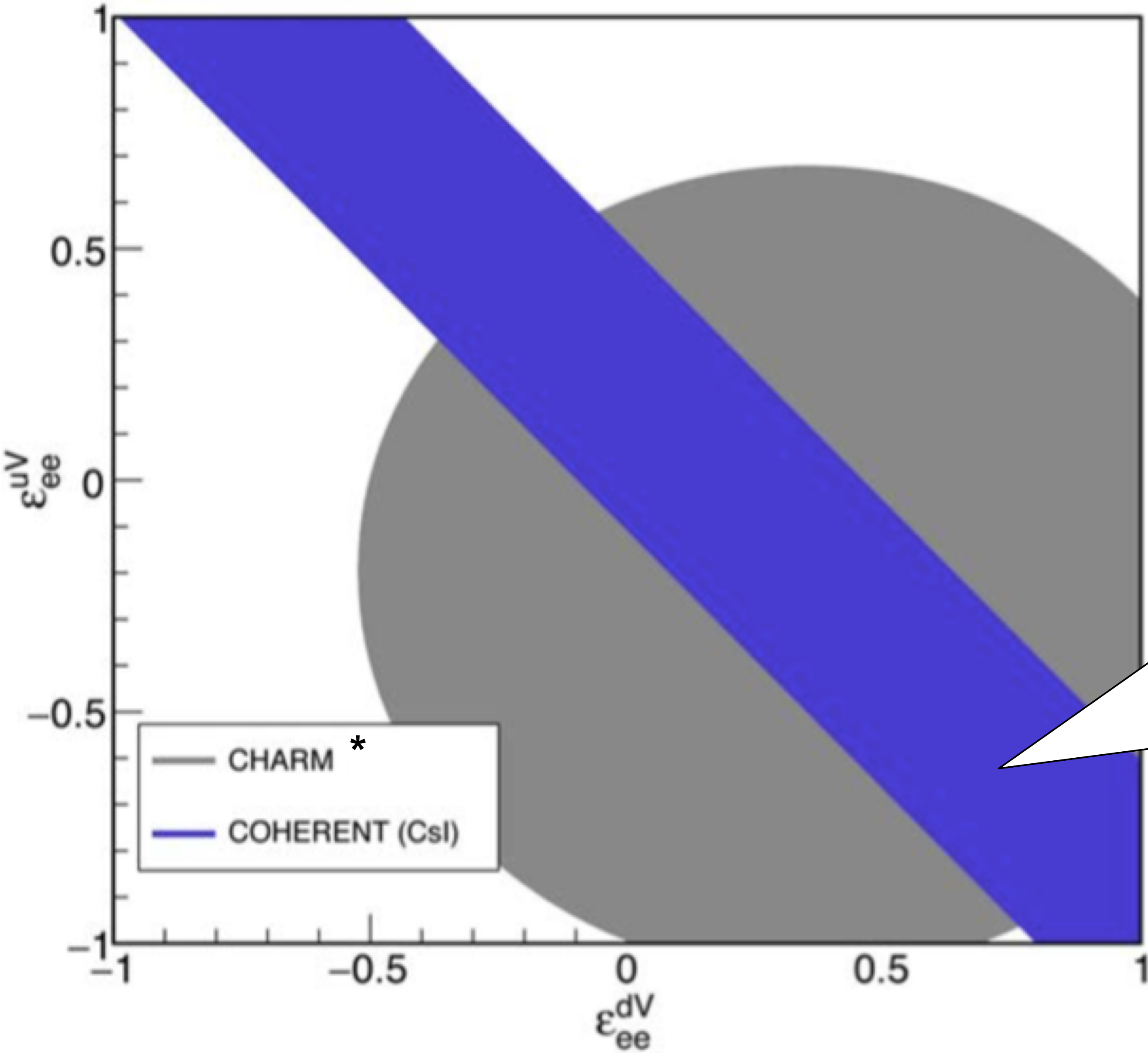
$$\mathrm{PE} \propto T \propto Q^2$$

→ 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:



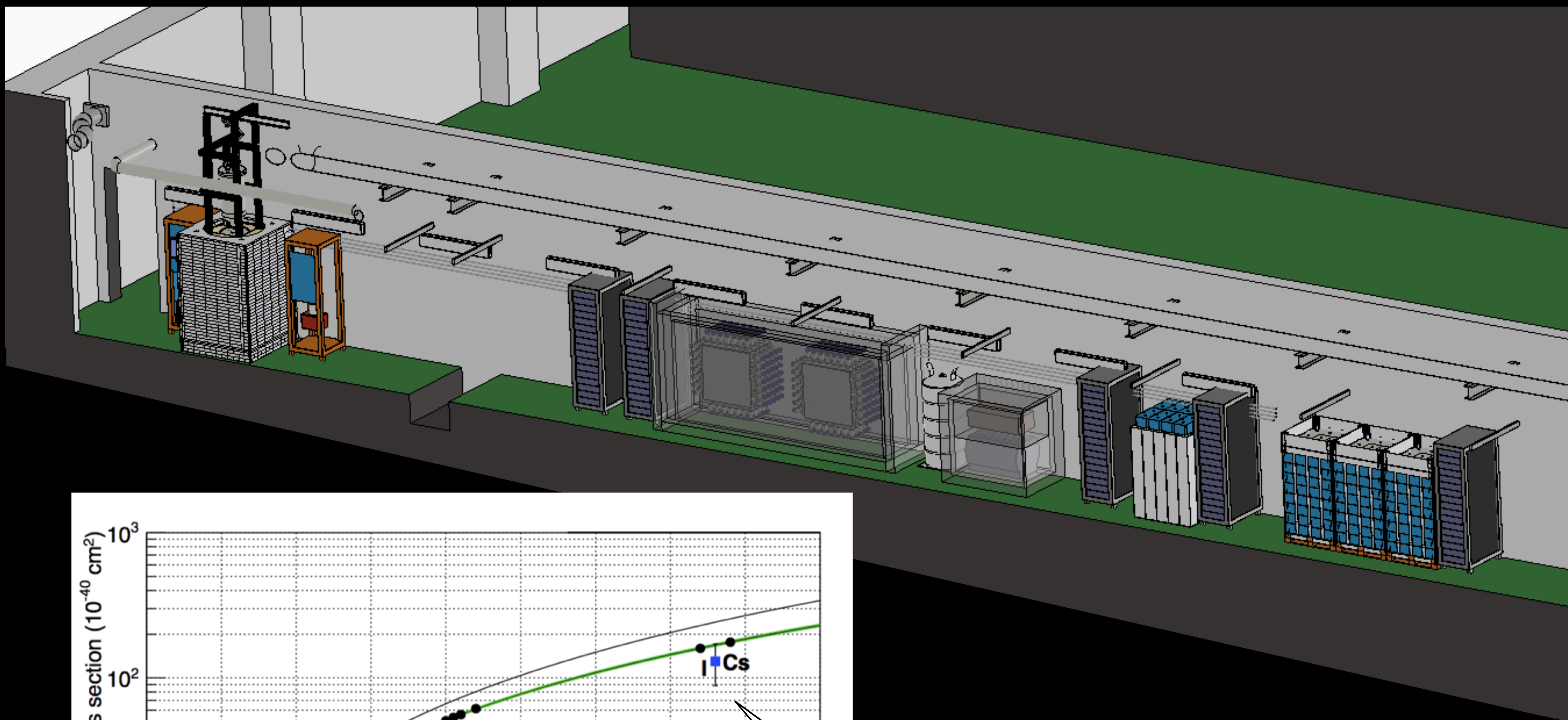
- Assume all other ε's zero

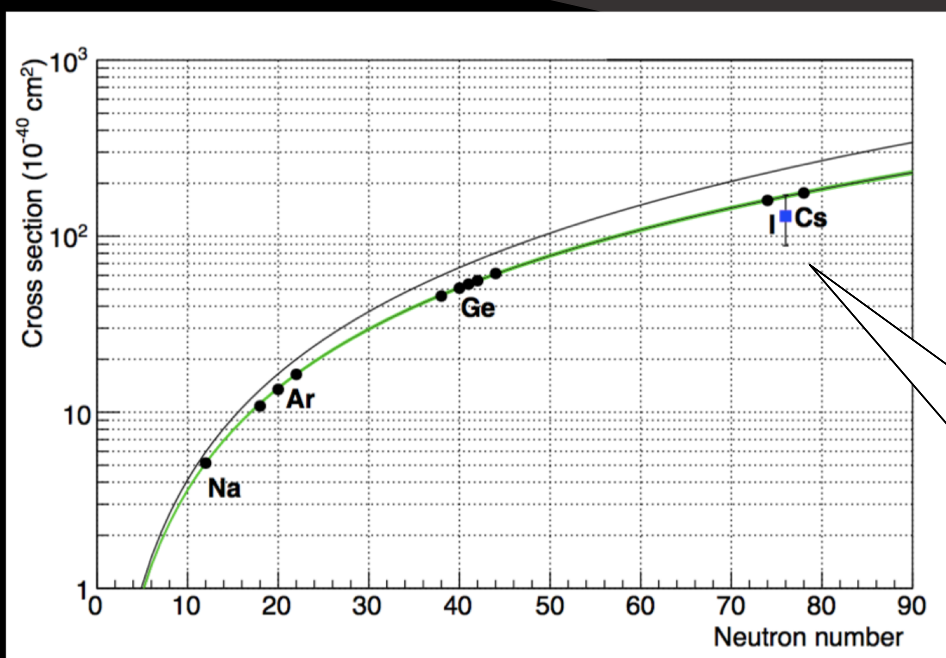
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

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

*CHARM constraints apply only to heavy mediators

What's Next for COHERENT?

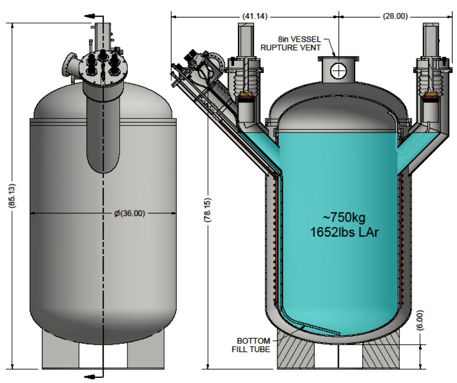


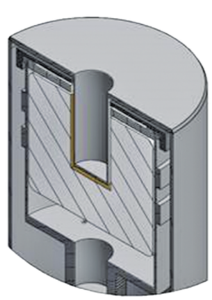


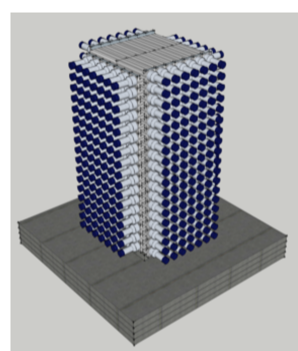
One measurement so far! Want to map out N^2 dependence

COHERENT **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



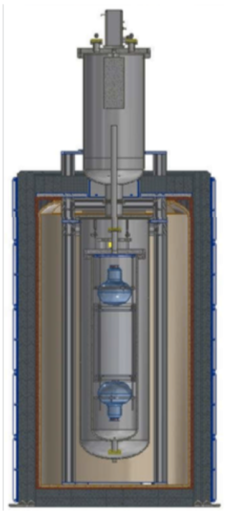


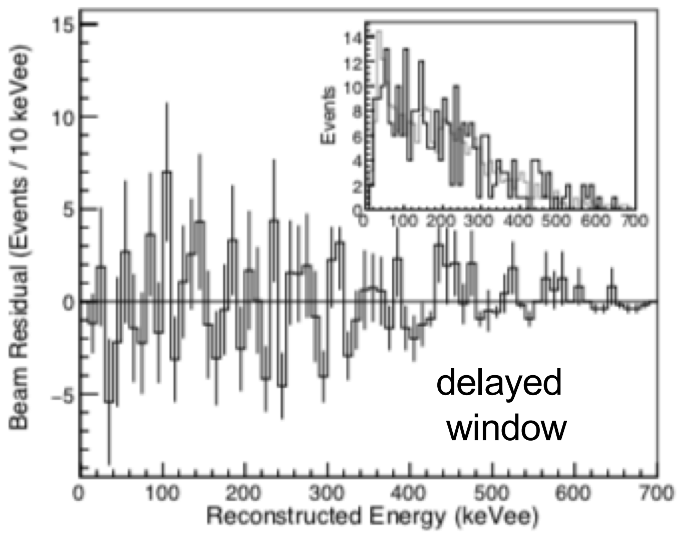


+D_2O for flux normalization

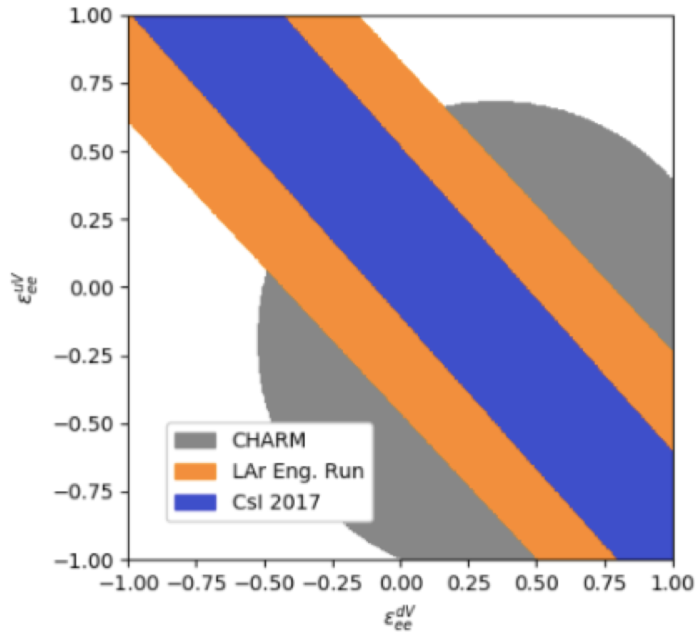
+ concepts for other targets...

COHERENT LAr Engineering Run Result





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

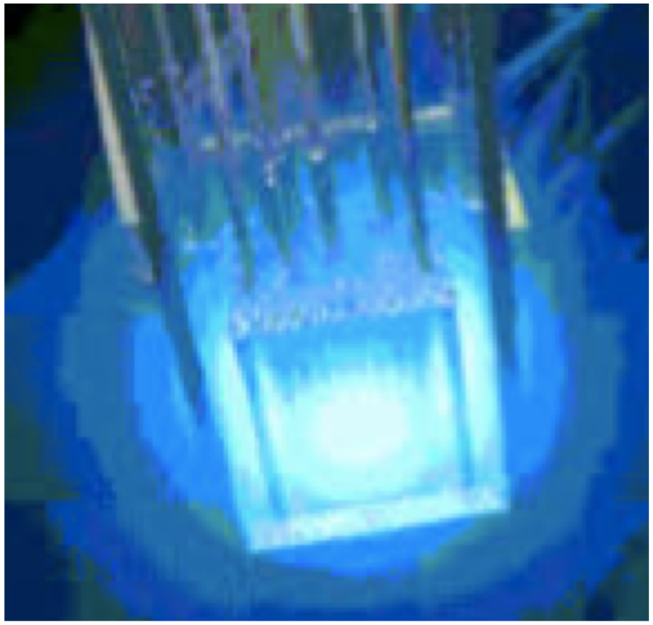


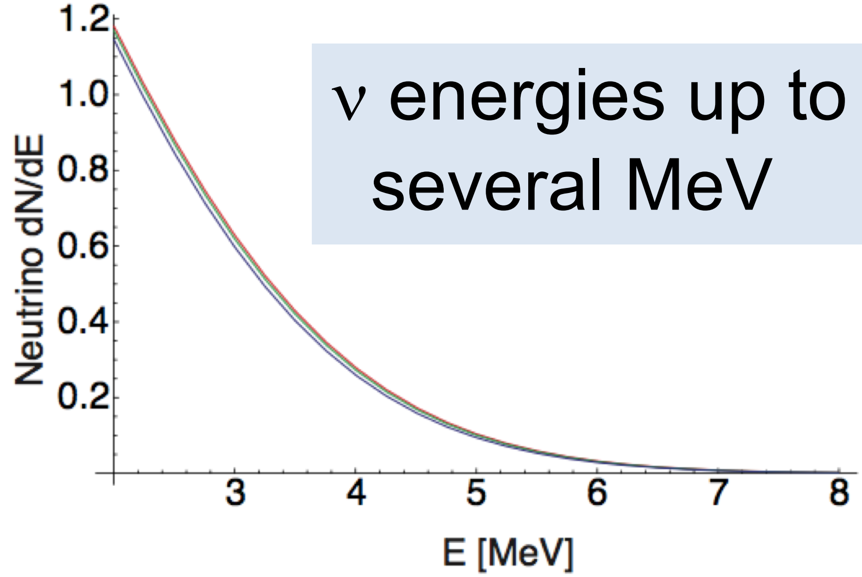
measure 1 ± 4 (stat), expect <1

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

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

Neutrinos from nuclear reactors

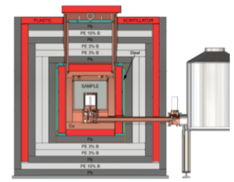


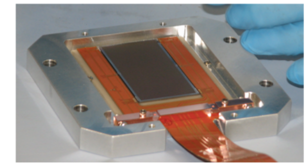


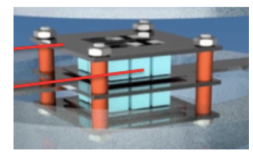
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging
- F~1, so even smaller nuclear effects than stopped-π

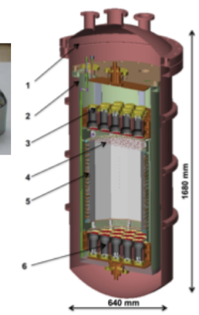
Reactor CEvNS Efforts Worldwide

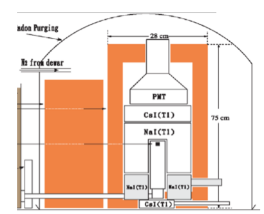
Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
MINER	Ge/Si cryogenic	USA
NuCleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn bolometers	France
TEXONO	p-PCGe	Taiwan











Many novel low-background, low-threshold technologies

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

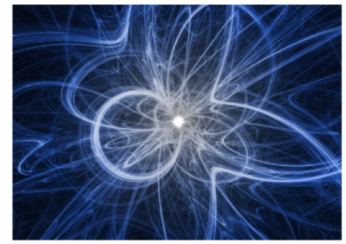
CEvNS: what's it good for?

(1) So
(2) Many
(3) Things

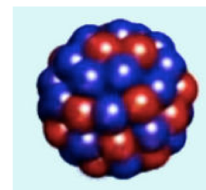
!

(not a complete list!)

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

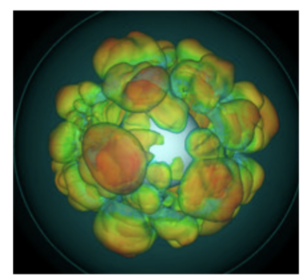


CEvNS as a **signal**
for understanding of "old" physics

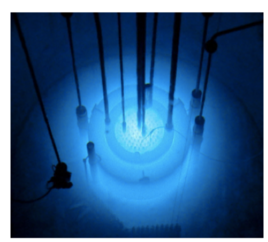


CEvNS as a **background**
for signatures of new physics (DM)

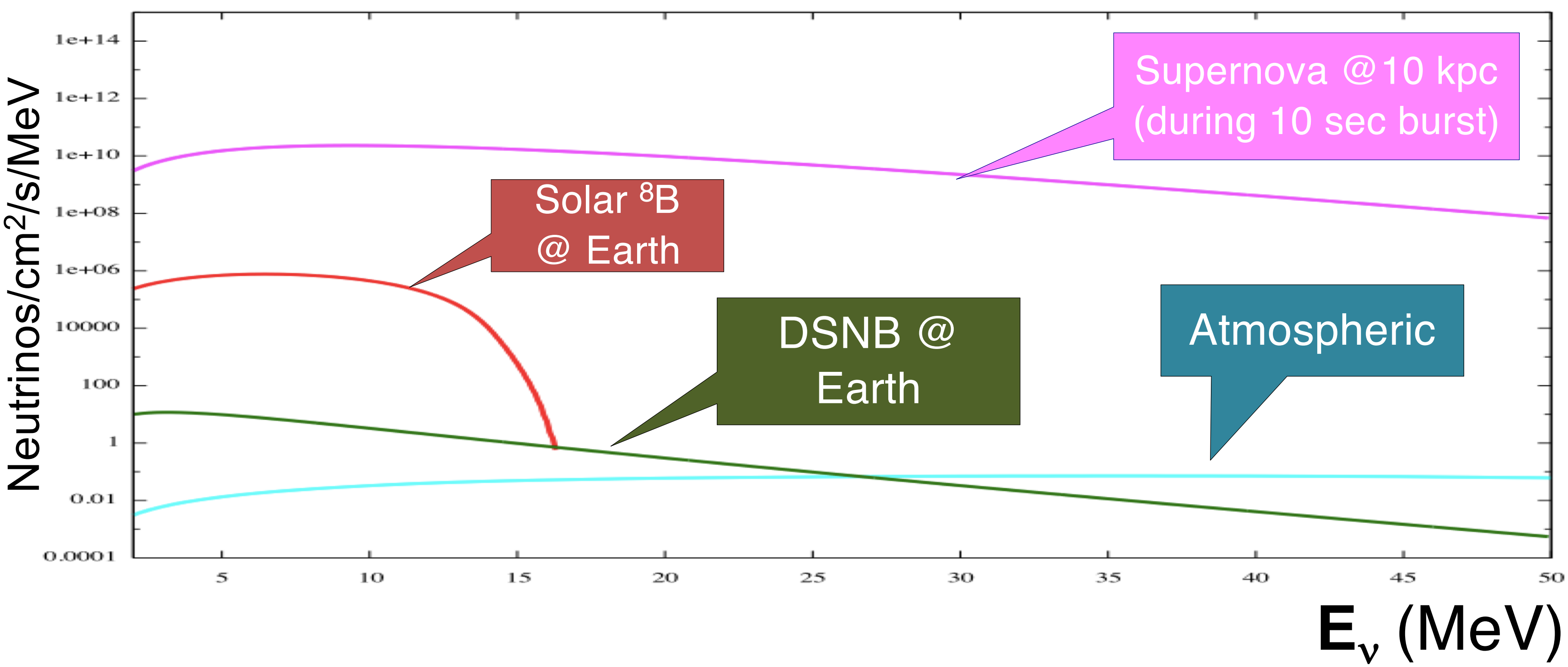
CEvNS as a **signal** for *astrophysics*



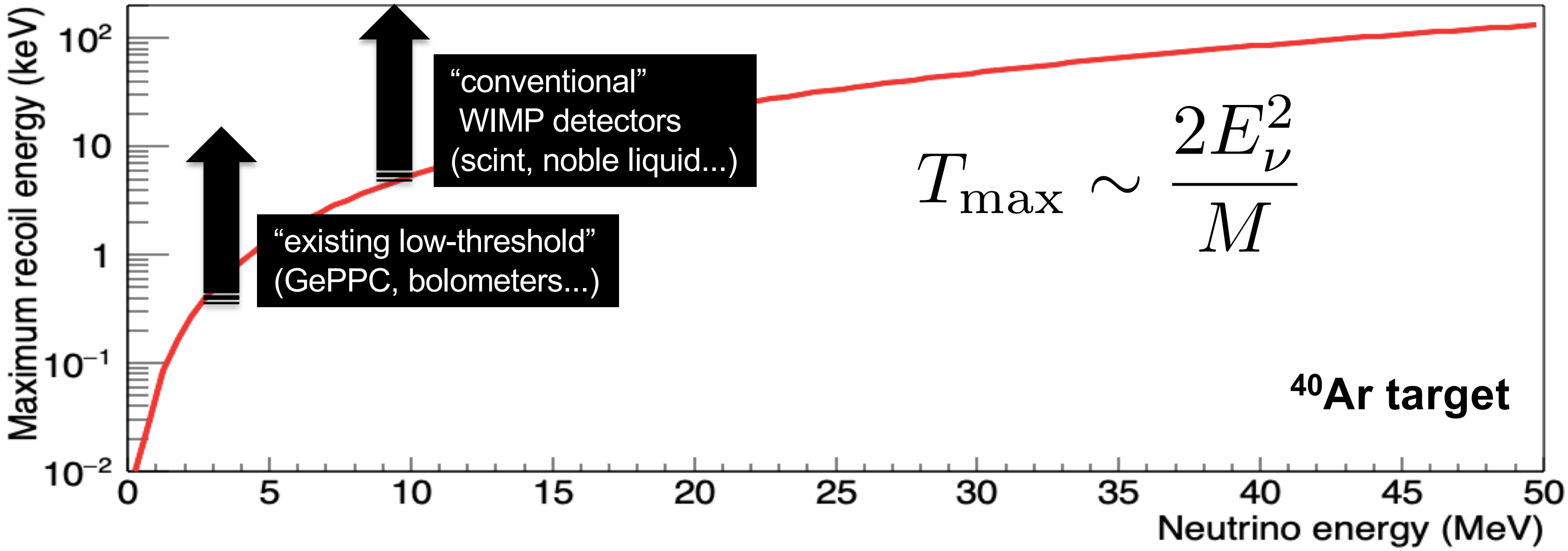
CEvNS as a **practical tool**

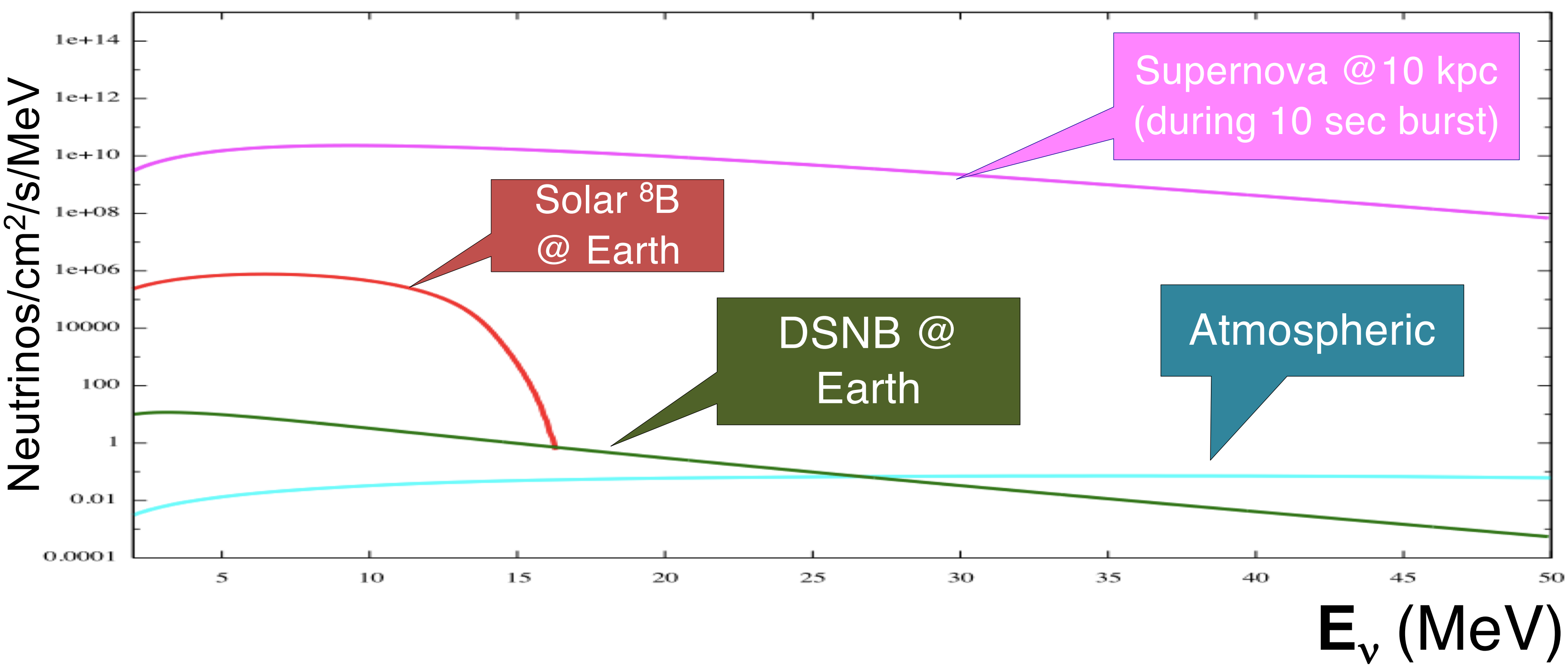


Natural neutrino fluxes



Natural neutrino fluxes

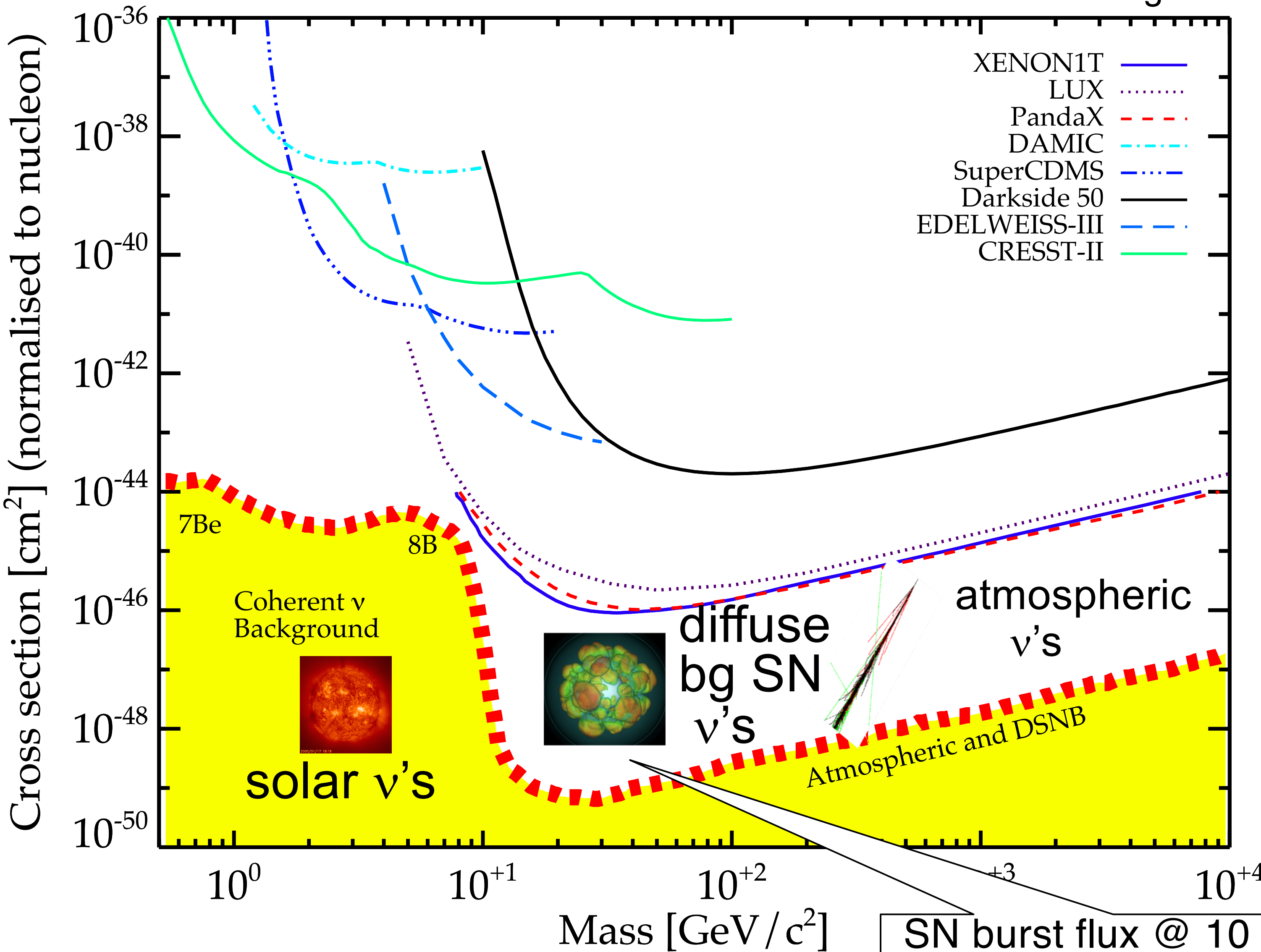




The so-called "**neutrino floor**" for DM experiments

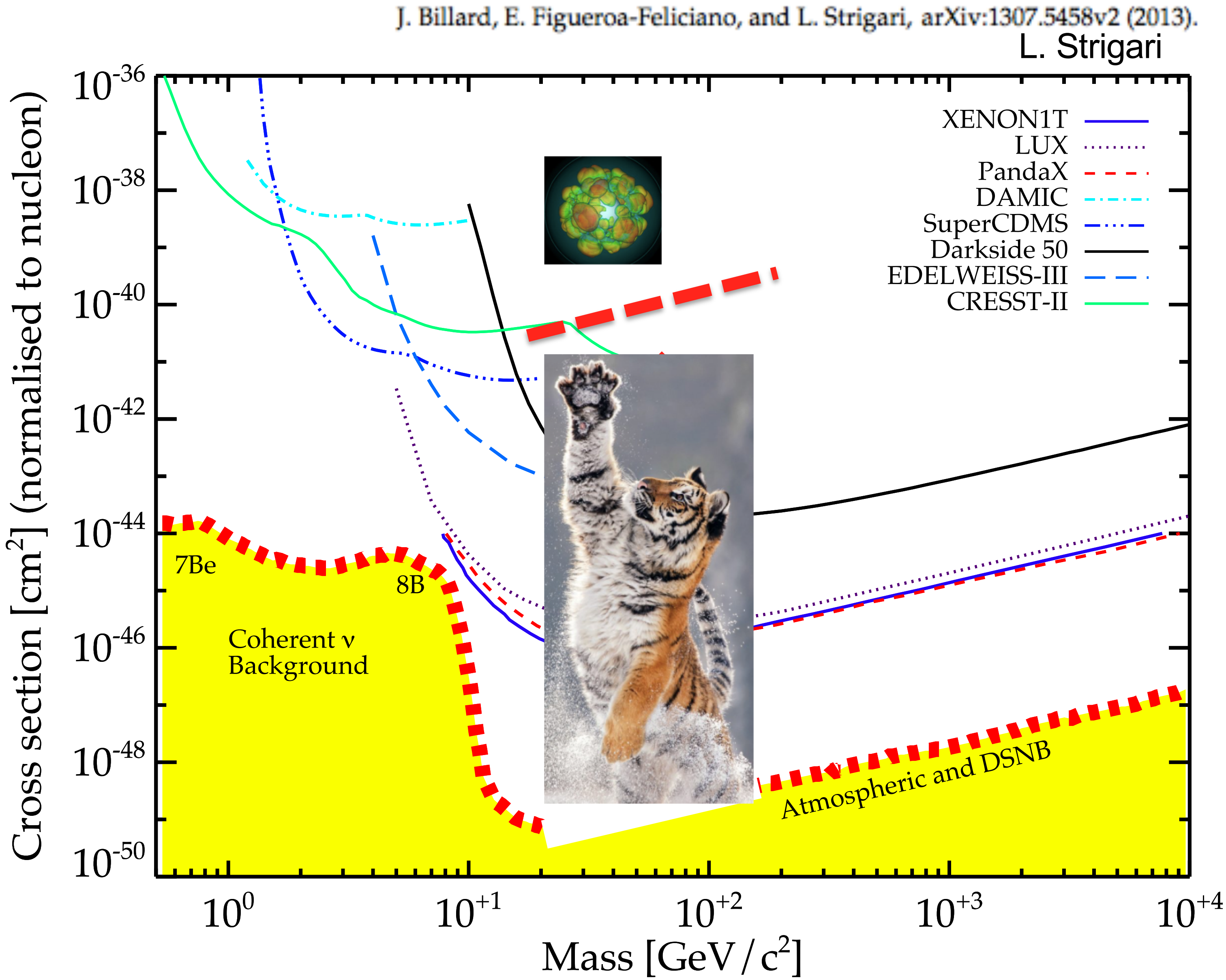
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

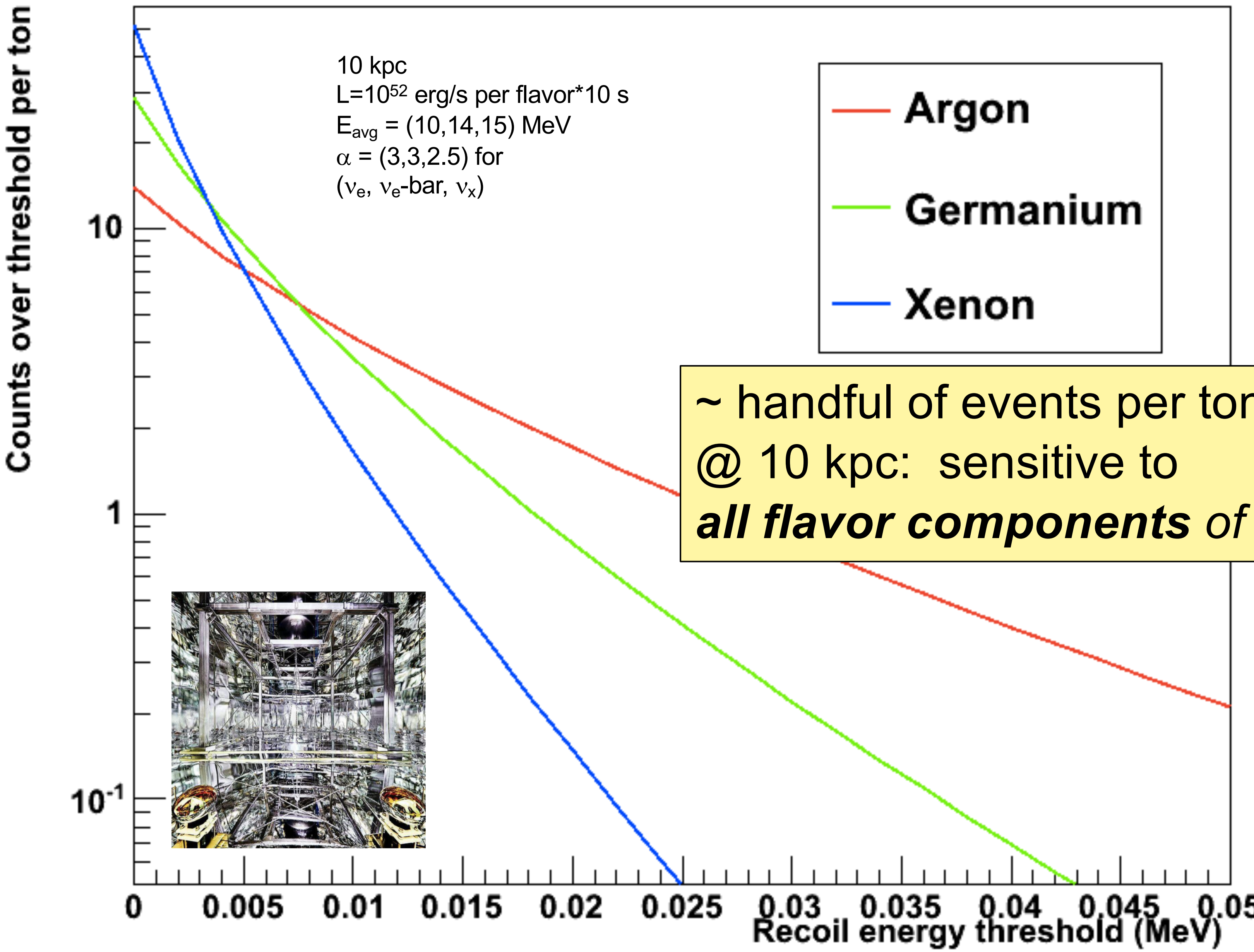


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux over ~10 sec

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



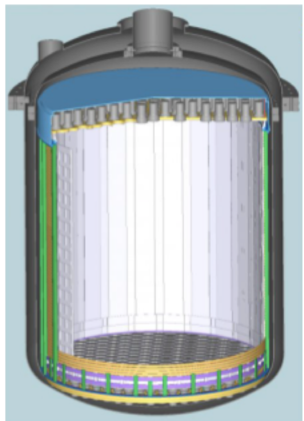
Supernova neutrinos in tonne-scale DM detectors

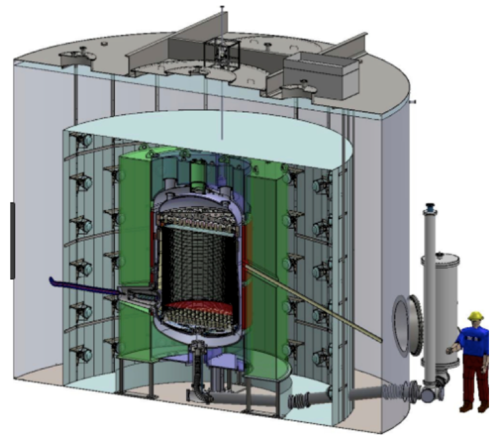


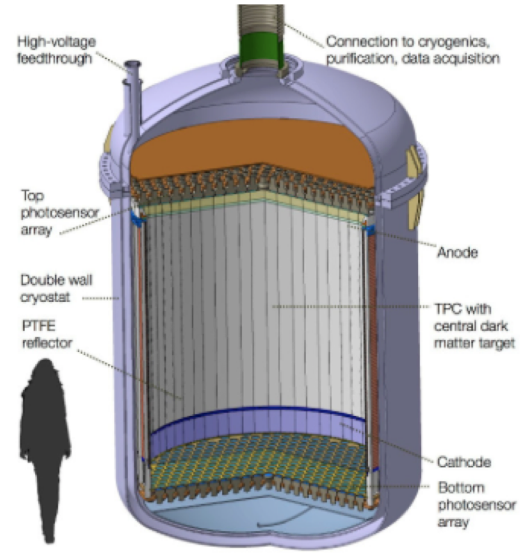
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

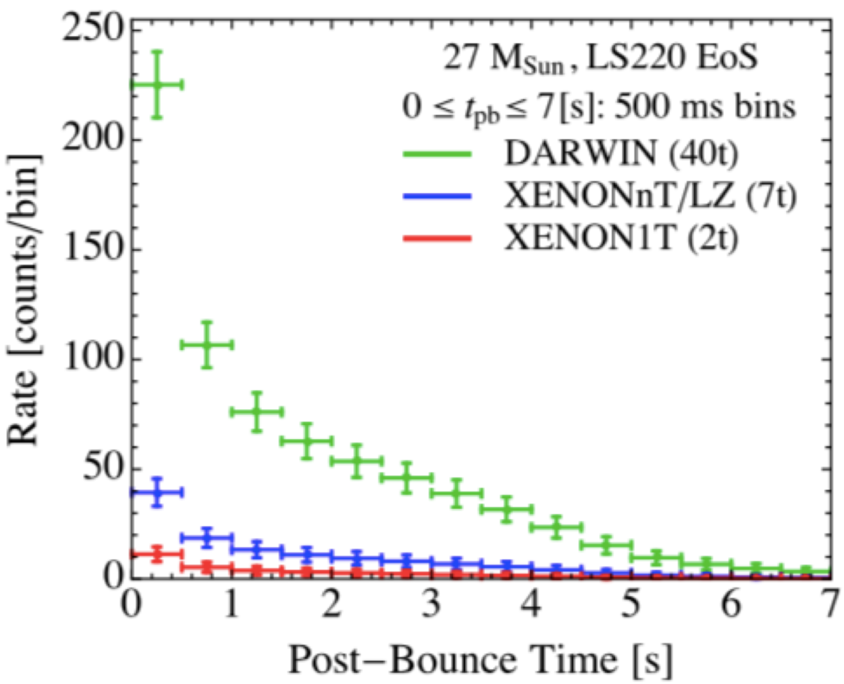
Detector example: **XENON/LZ/DARWIN**

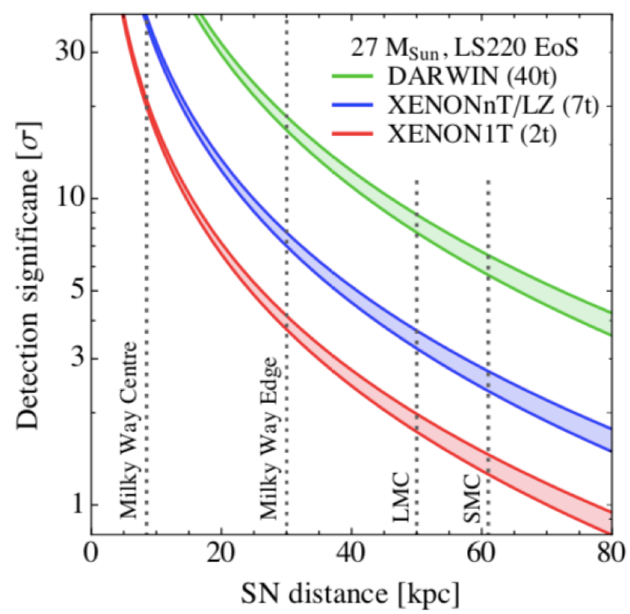
- dual-phase xenon time projection chambers









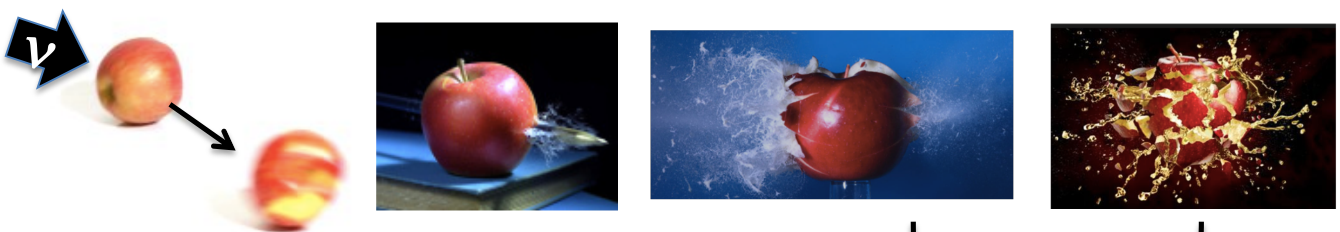


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Take-Away Messages

- **Neutrinos** matter:
  - tiny (but emphatically non-zero) mass, weakly interacting...
  - but strong in physics! particle physics, cosmology, astrophysics, nuclear physics

- Understanding of **neutrino interactions with nuclei** matters:
  - interpretation of neutrino experiments (oscillation, astrophysical)
  - search for beyond-the-SM physics
  - understanding of the nuclei themselves

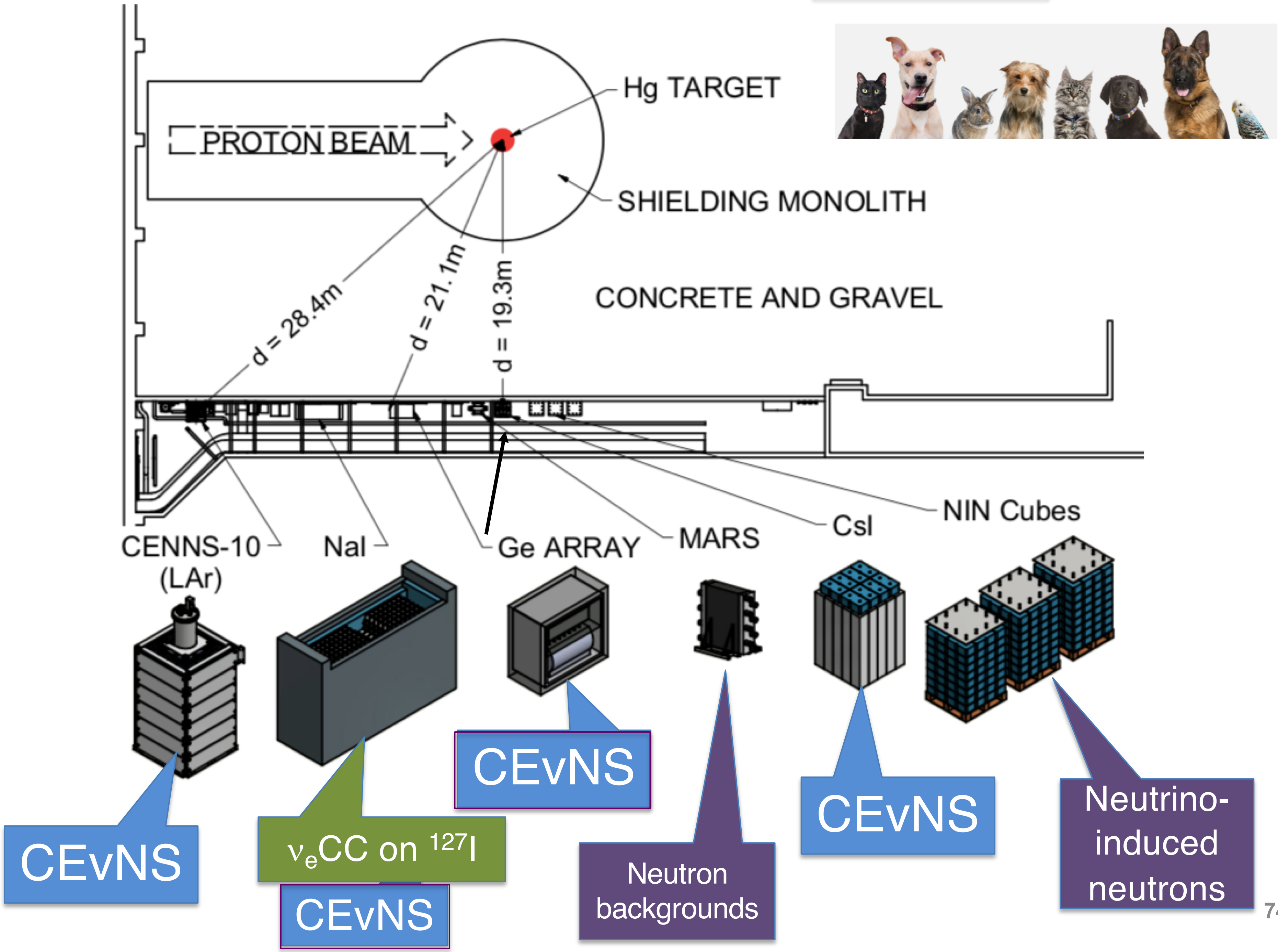


CEvNS at low energy…
first light @ SNS, but
low-energy detection frontier
Is exciting for the future!

High-energy neutrino
Interactions are another critical
direction for oscillation physics
(Xianguo later today)

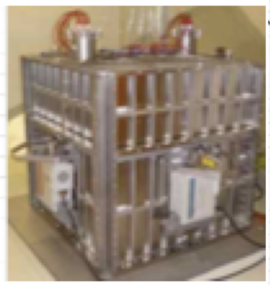
Extras/Backups

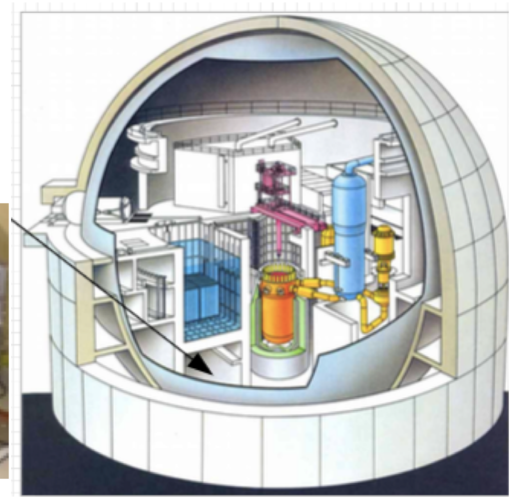
Neutrino Alley Deployments: current & near future

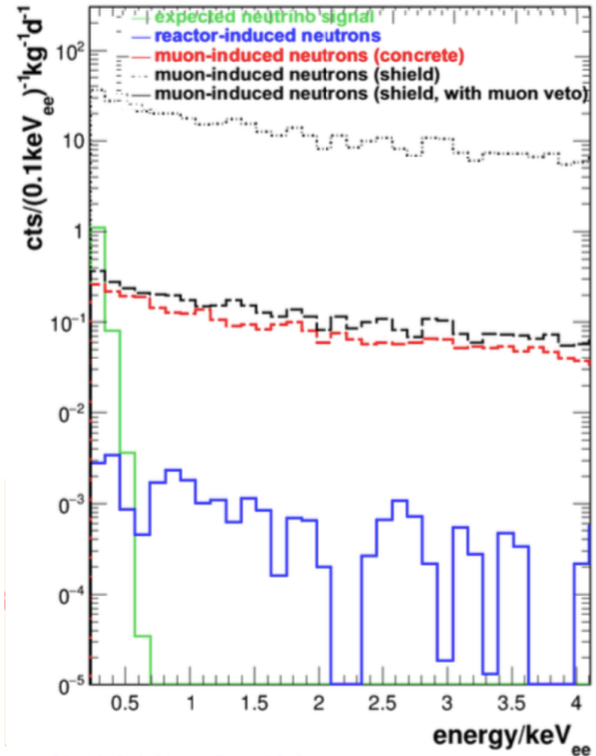


CONUS

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







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

Rate comparison (all detectors):

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

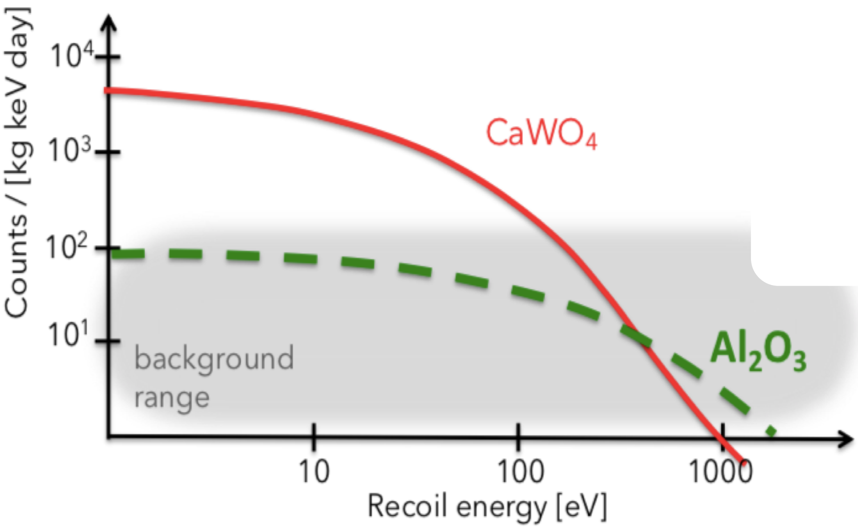
Some systematics still under study

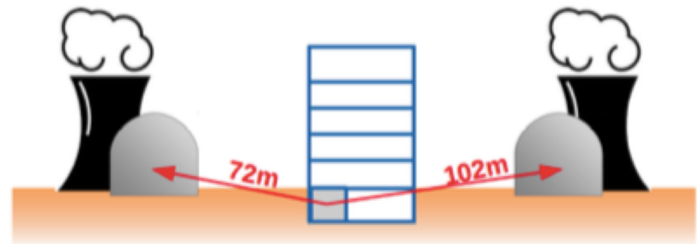
(*) Including stat. uncertainty and above efficiencies

W. Maneschg, Nu2018

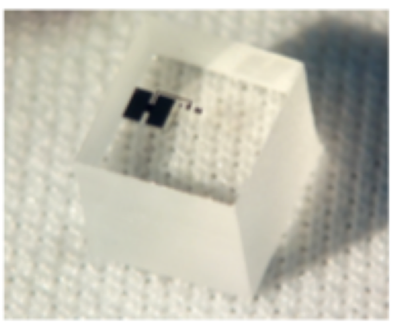
NUCLEUS

"gram-scale cryogenic calorimeters"





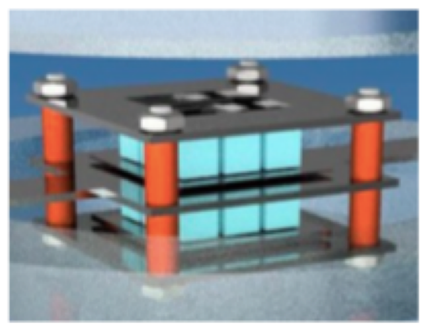
NUCLEUS 1g



2017-2019

straight
forward

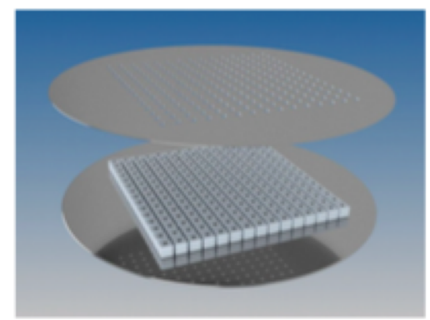
NUCLEUS 10g



2020-2022

major
R&D

NUCLEUS 1kg



>2024

The COHERENT collaboration

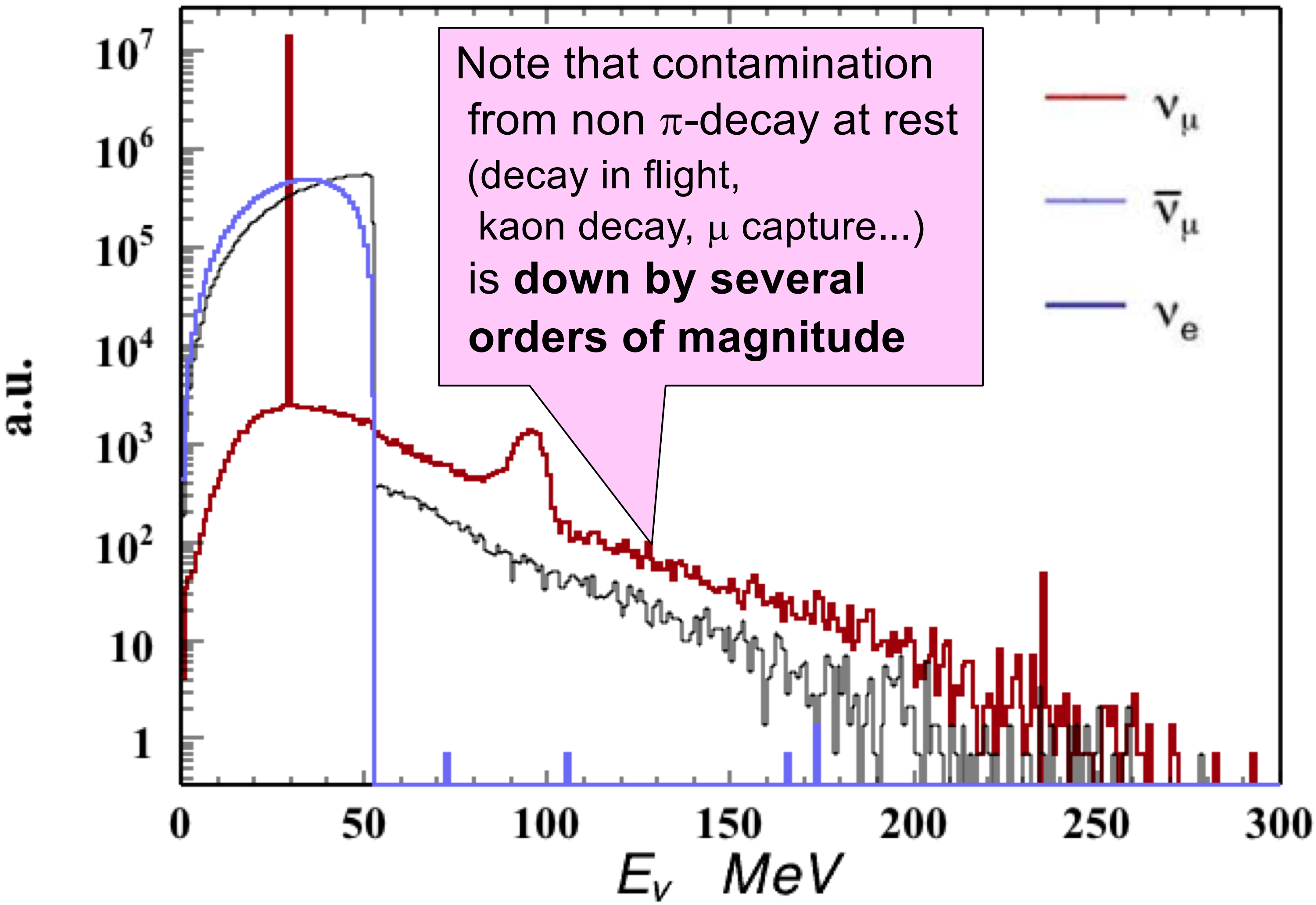
http://sites.duke.edu/coherent

~90 members,
20 institutions
4 countries

arXiv:1509.08702

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

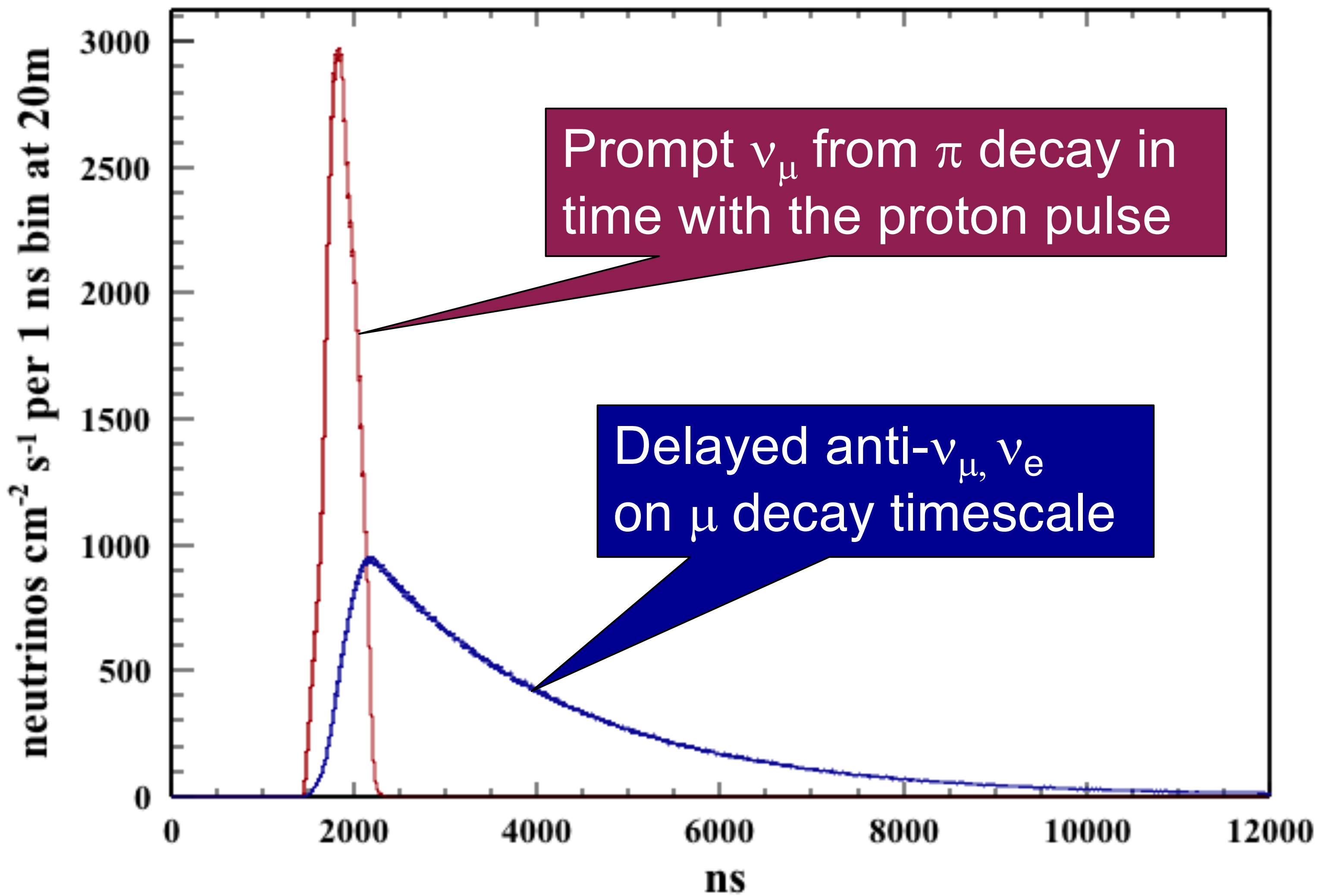
0.08 neutrinos per flavor per proton on target



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

Time structure of the SNS source

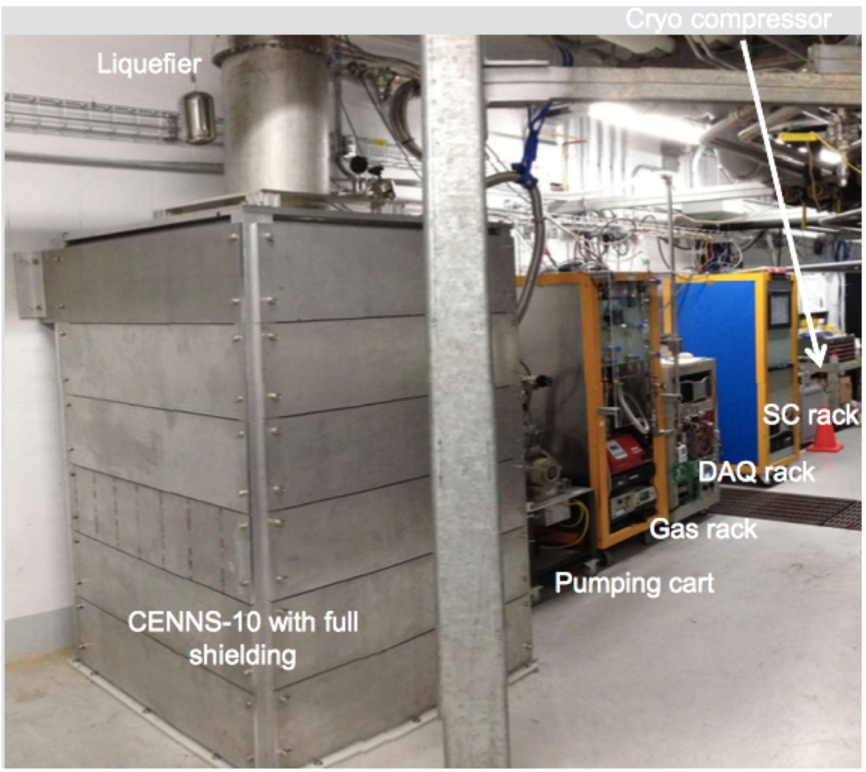
60 Hz *pulsed* source



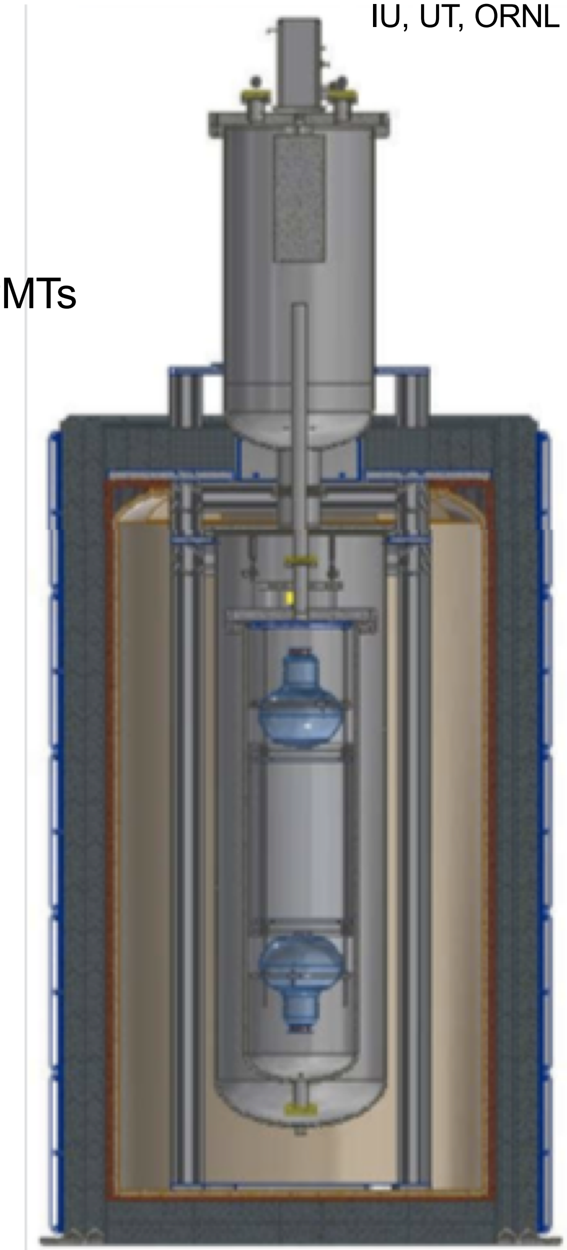
Background rejection factor ~few x 10^{-4}

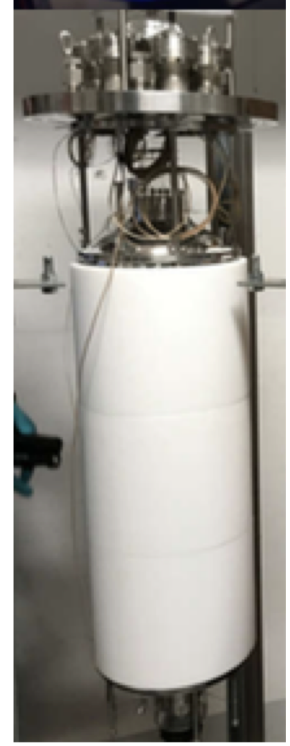
Single-Phase Liquid Argon

- ~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



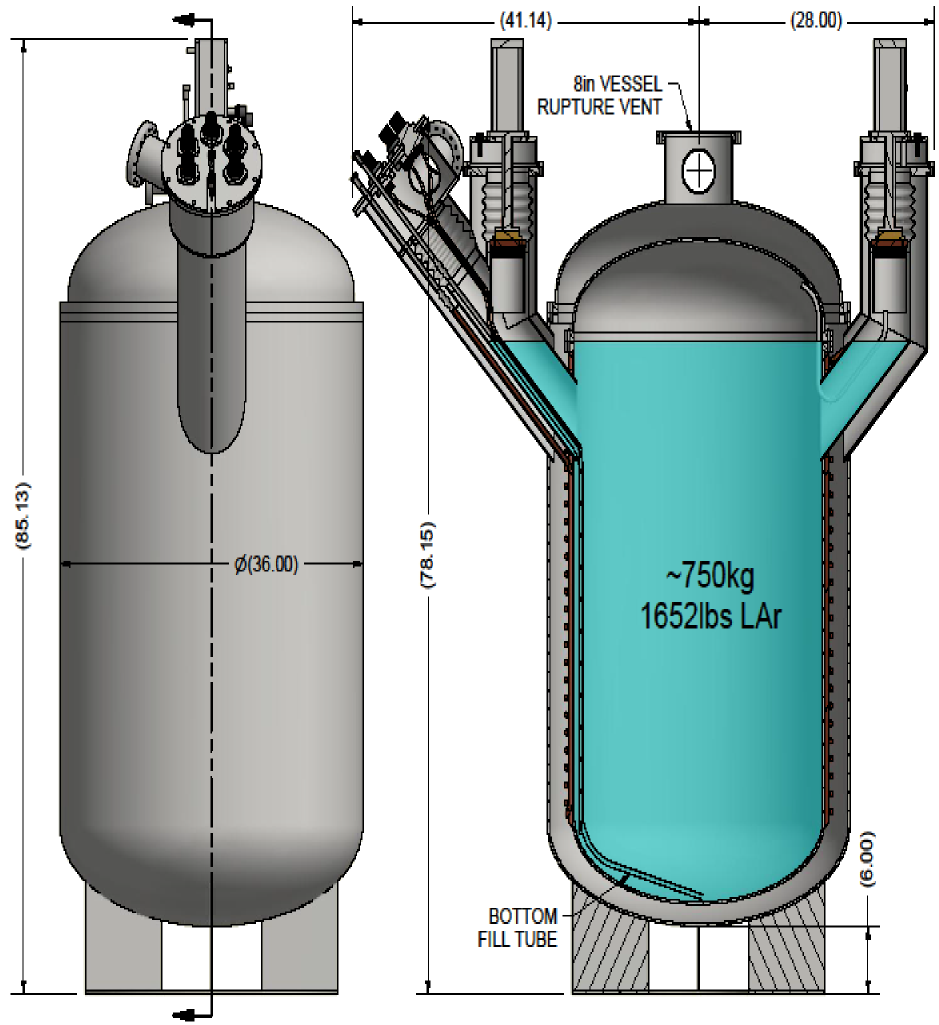
IU, UT, ORNL



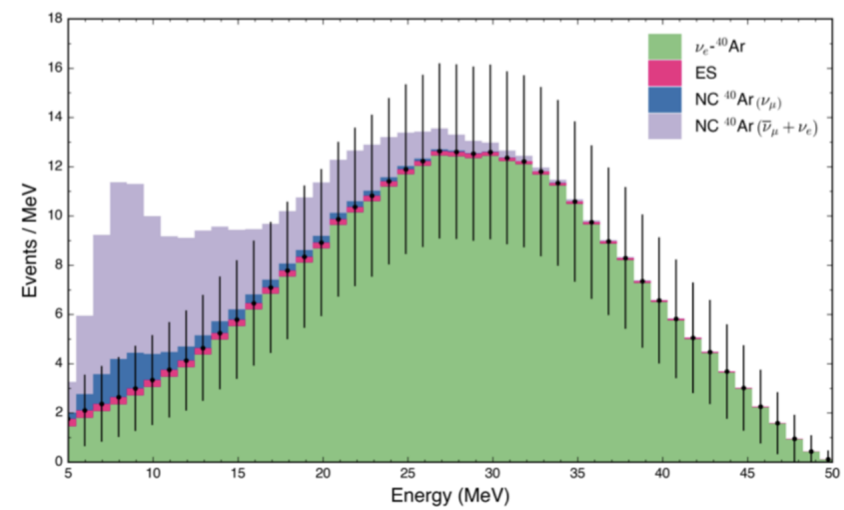


Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

Tonne-scale LAr Detector



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



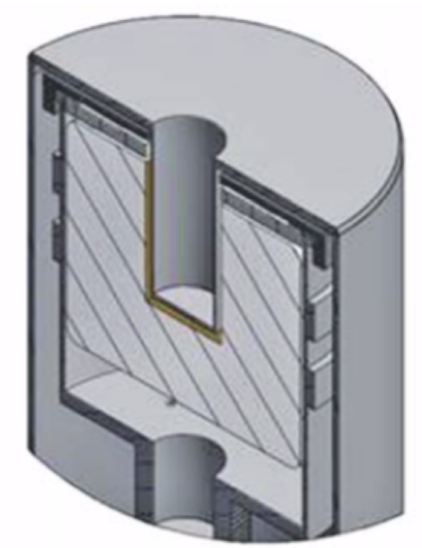
CC/NC **inelastic** in argon of interest for supernova neutrinos

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

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

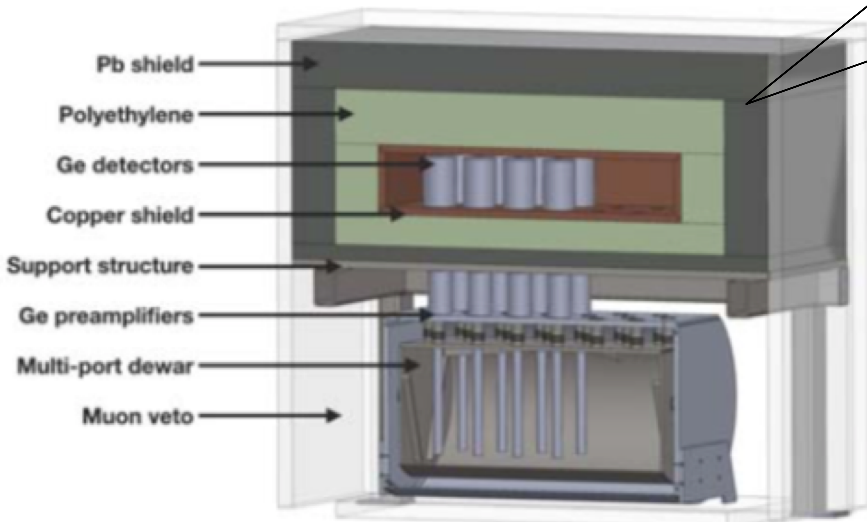
High-Purity Germanium Detectors

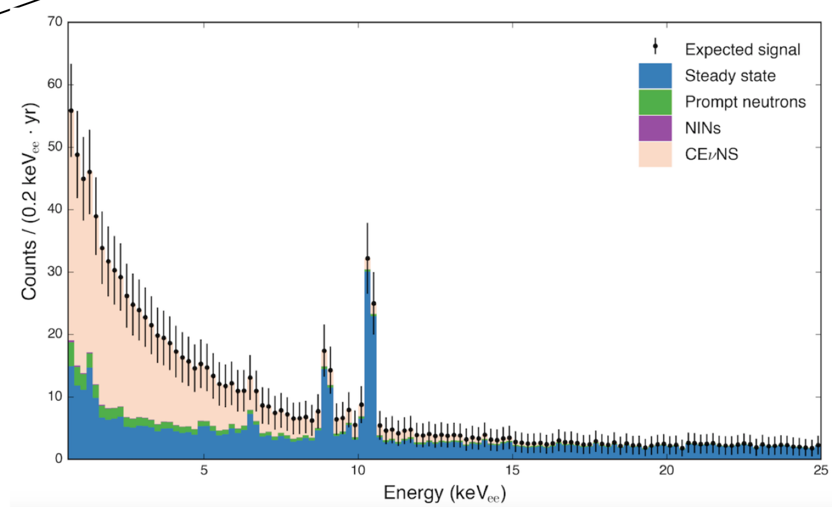
P-type Point Contact



- 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

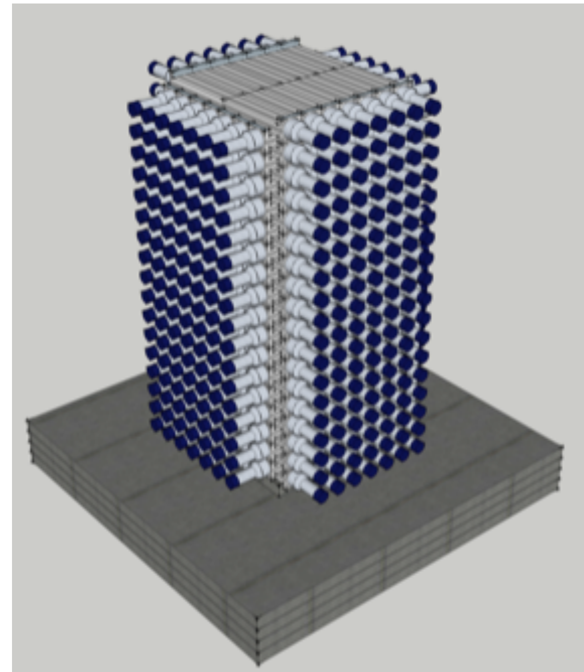




Sodium Iodide (NaI[Tl]) Detectors (NaIvE)

- 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 ν_e**CC on ^{127}I**

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

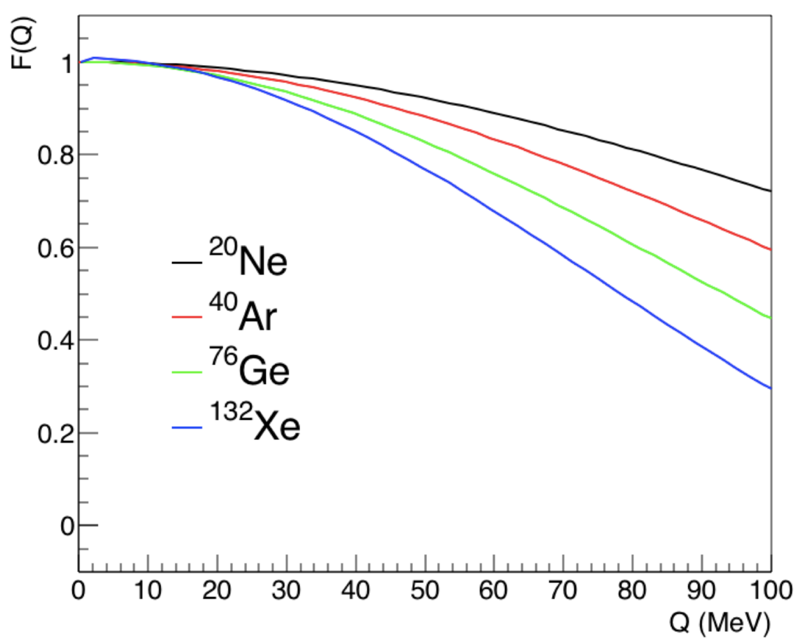
J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

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