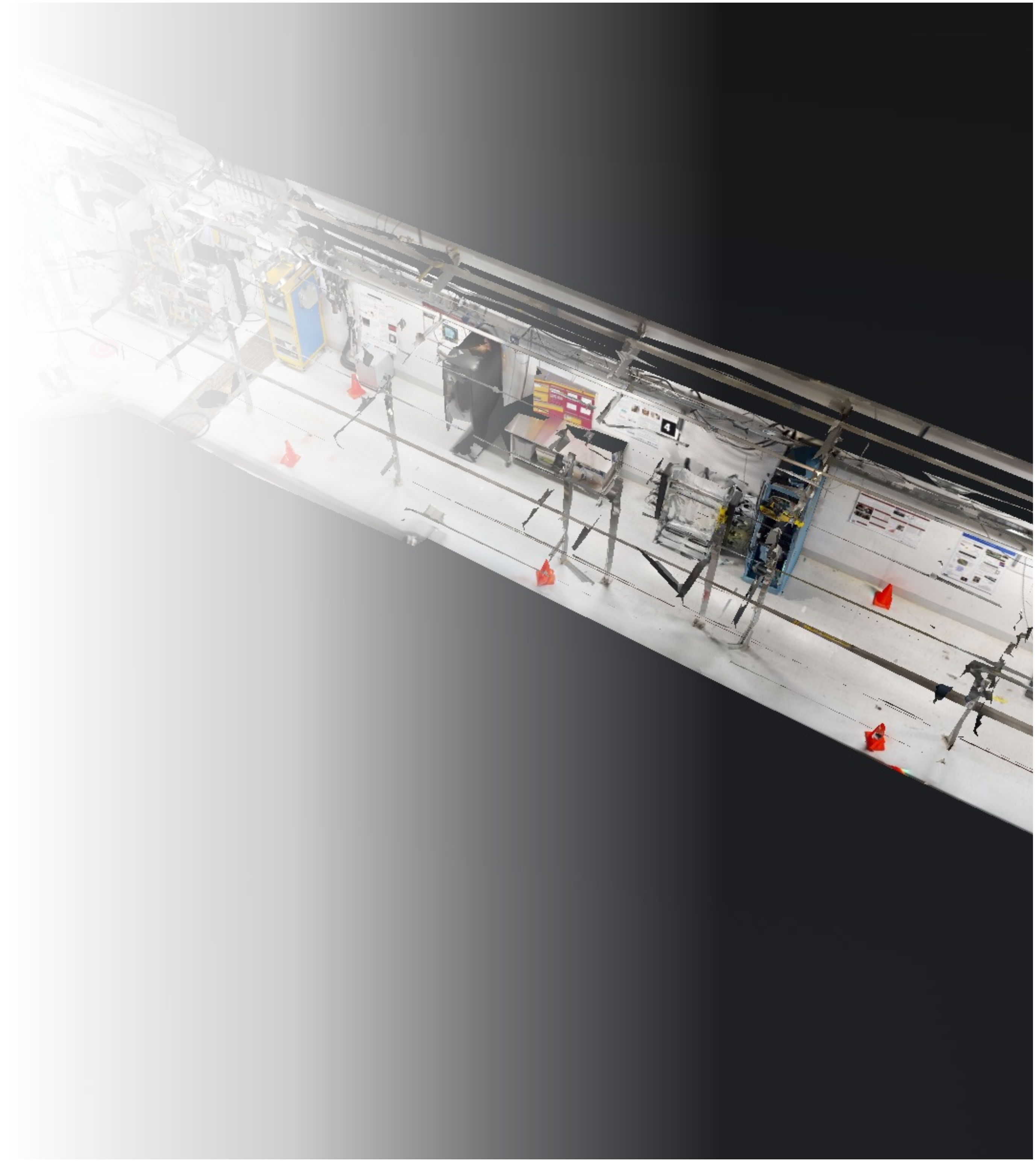
Neutrino-Nucleus Interactions



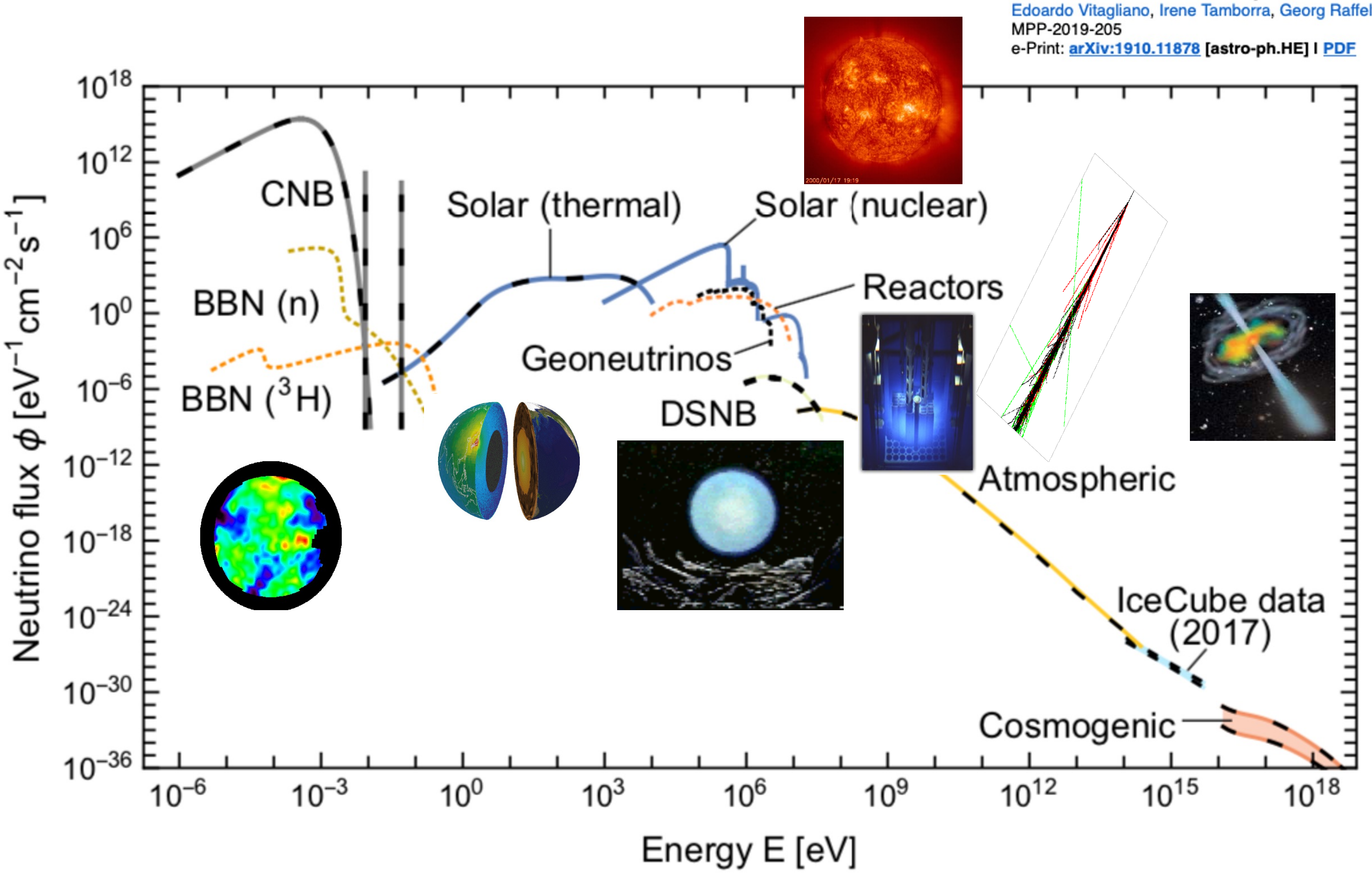
Kate Scholberg,
Duke University

International School of Physics
Enrico Fermi 2023

Villa Monastero, Varenna
July 1, 2023

Energy spectrum of neutrino sources

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] I PDF



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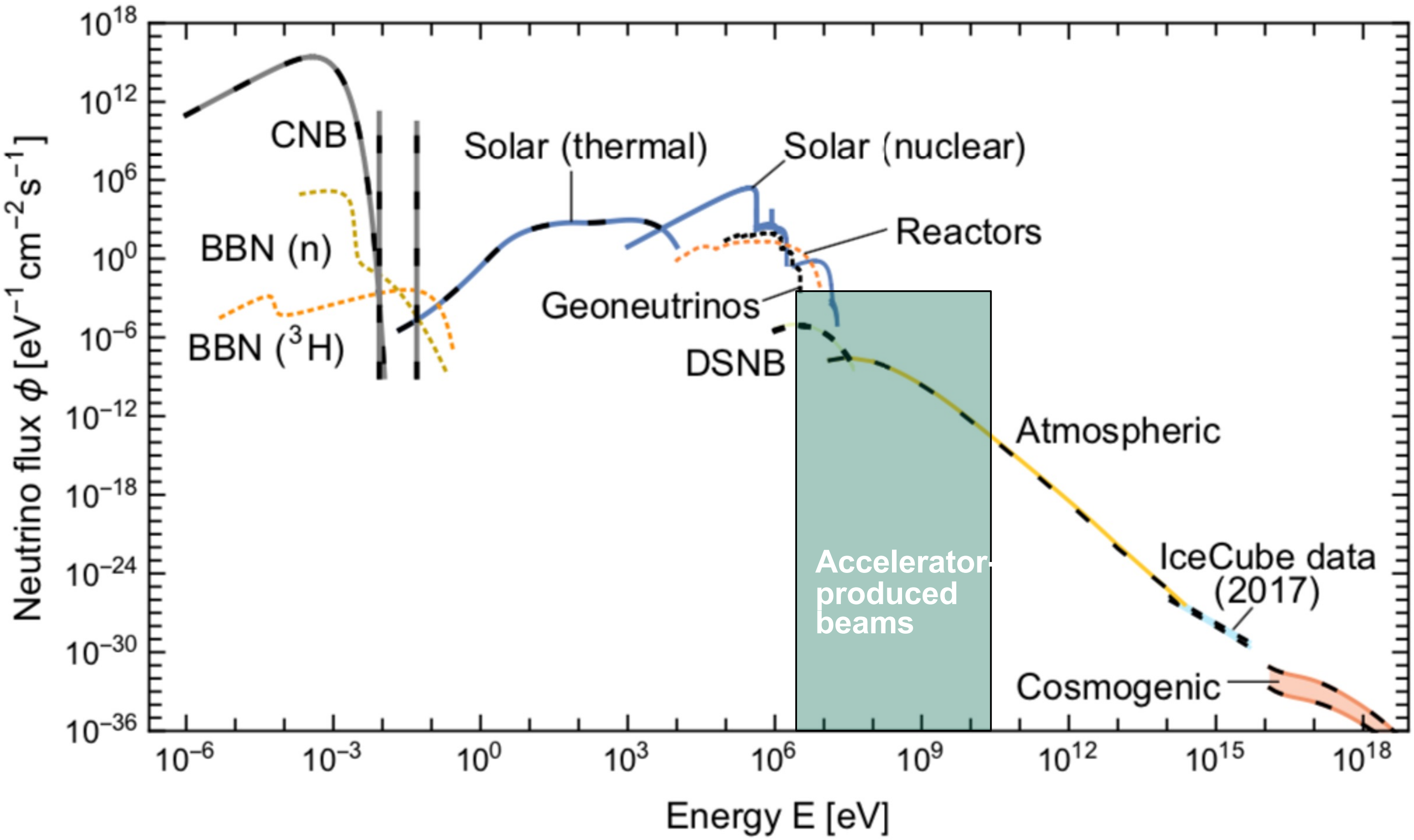

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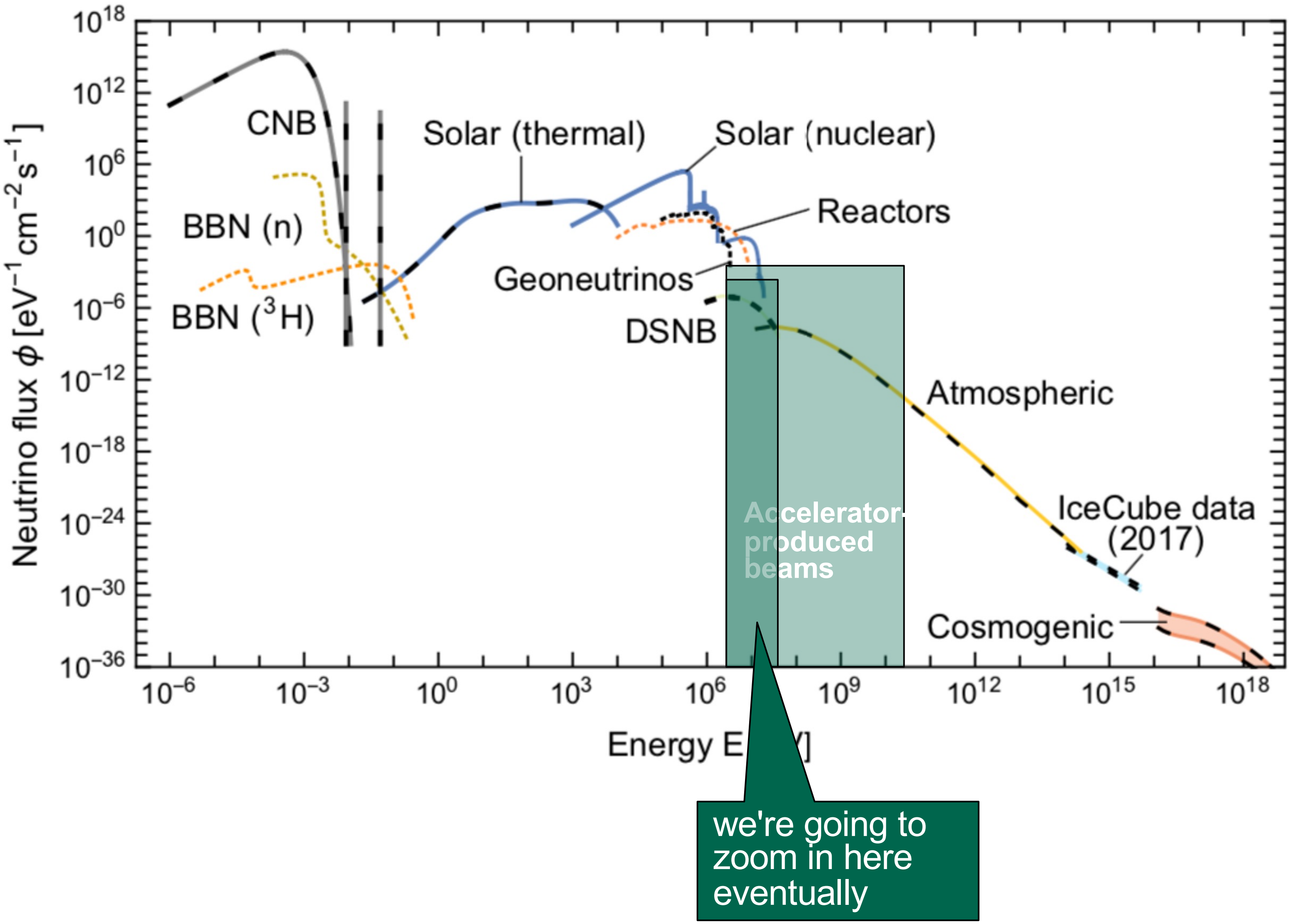
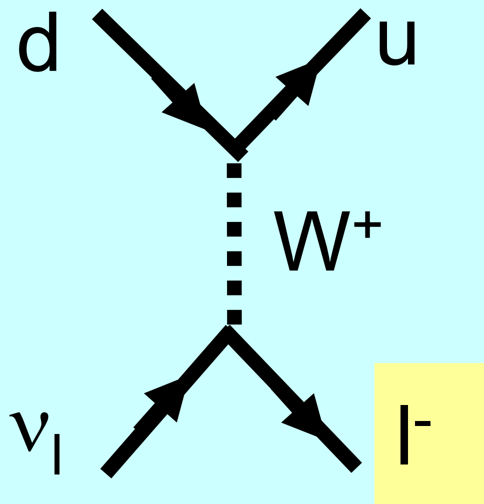


Neutrino interactions with matter

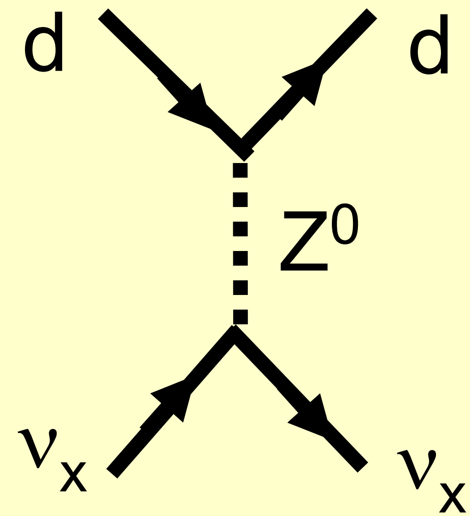
Charged Current (CC)



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

Produces lepton
with **flavor corresponding to neutrino flavor**
(must have enough energy to make lepton)

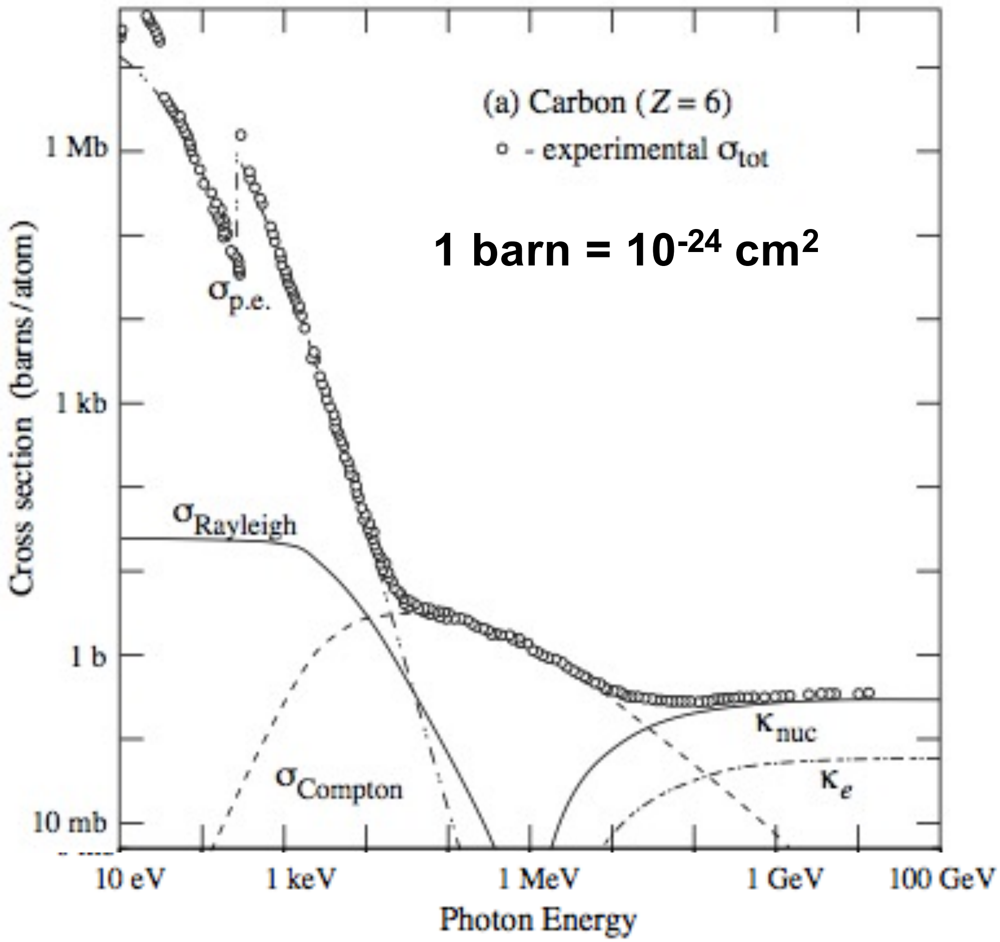
Neutral Current (NC



Flavor-blind

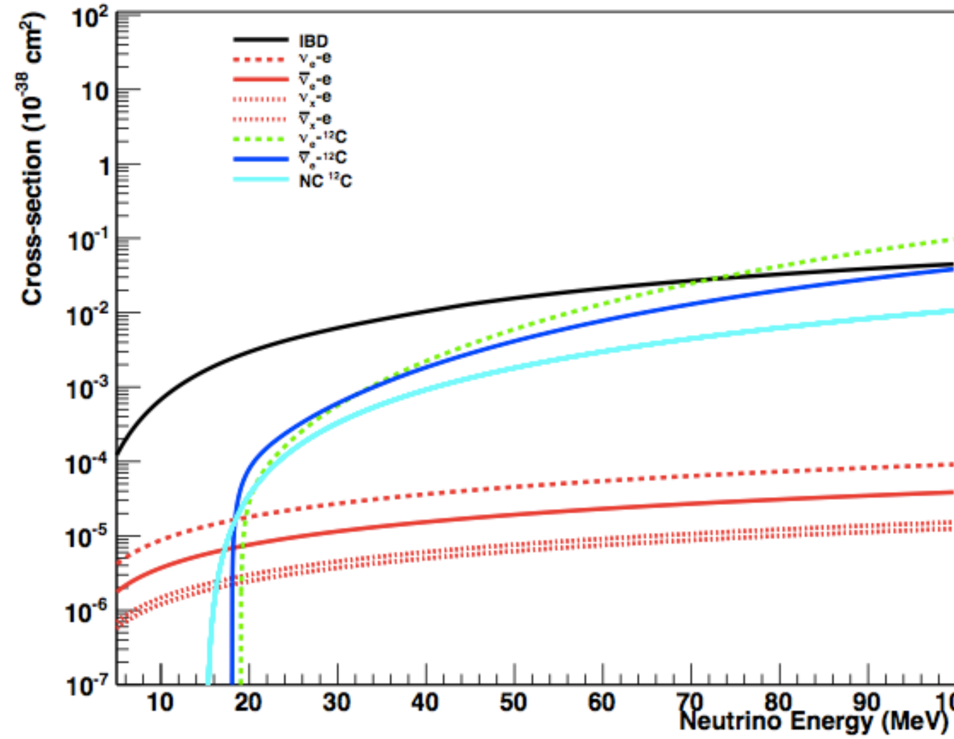
It’s called the weak interaction for a reason

Photon-matter cross-sections



~10^{-24} cm^2

Neutrino-matter cross-sections



~10^{-40} cm^2

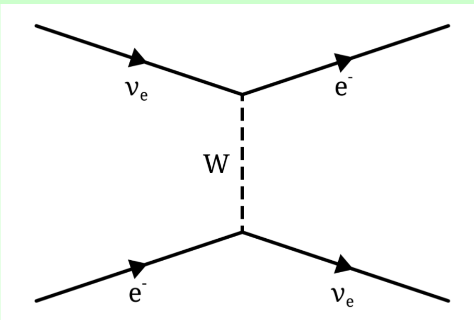
~16-17 orders of magnitude smaller

For astrophysics, the weakness of the interaction is both a blessing and a curse...

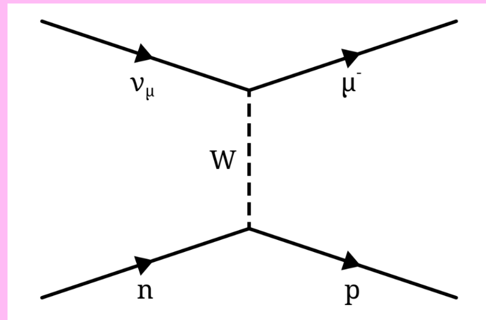
- neutrinos bring information from deep inside objects, from regions where photons are trapped

- but they require heroic efforts to detect!

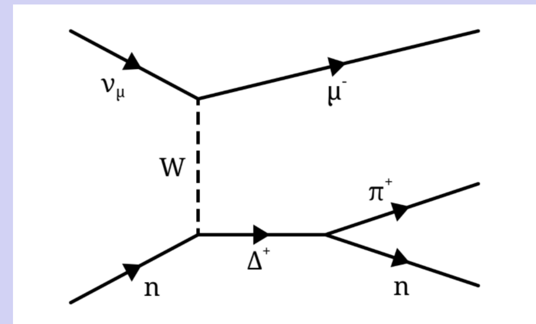
Common nomenclature for neutrino interactions



“Elastic”
same particles in as out



“Quasi-elastic”
different final-state particles but same number of particles



“Inelastic”
energy converted to new particles

Interaction rates in a detector material

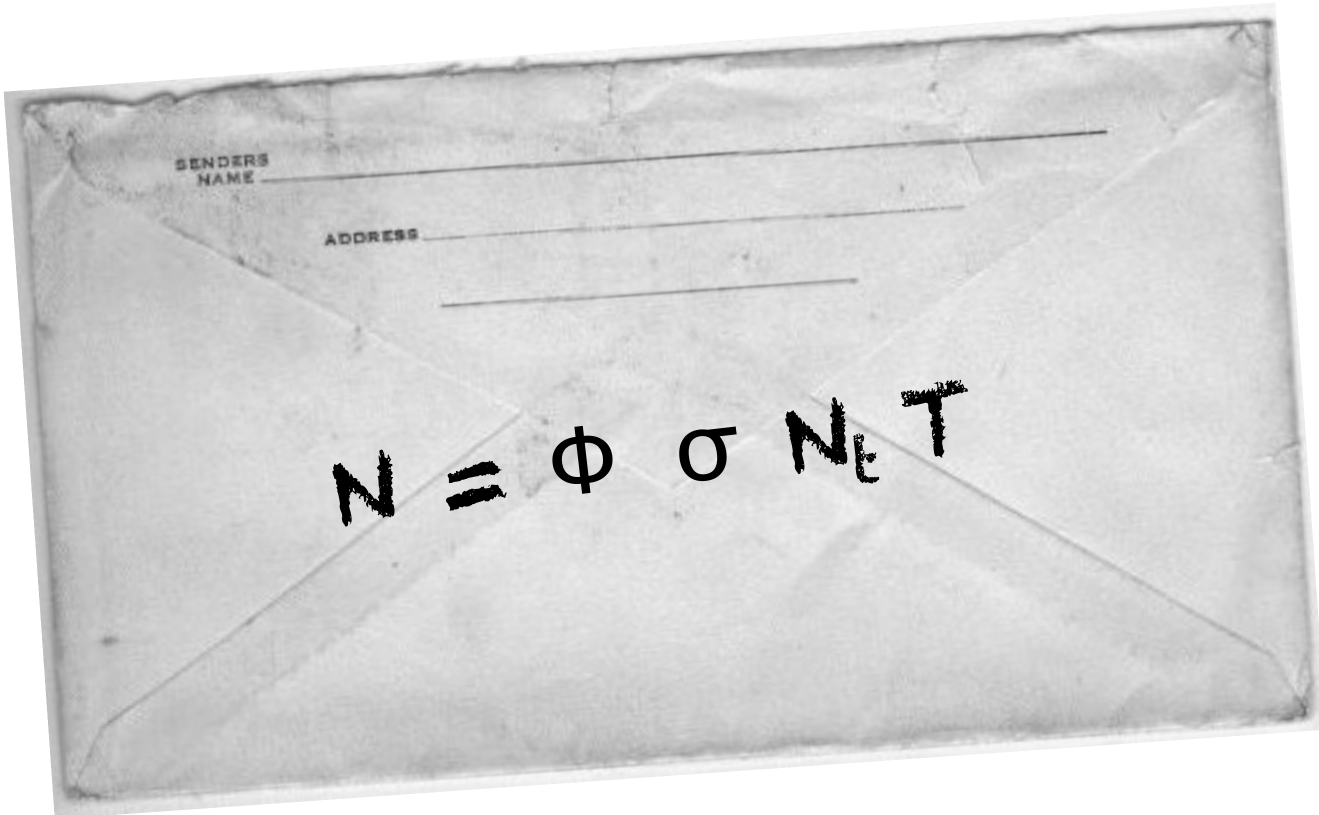
Flux Cross section Number of targets

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

$$\propto \text{detector mass}, 1/D^2$$

(Note: fluxes, cross-sections are E_ν dependent)

In fact this may be the neutrino experimentalist's most useful back-of-the-envelope expression...



How many solar neutrinos will interact in your body during your lifetime?

$\sigma \sim 5 \times 10^{-44}$ cm^2 (electron scattering cross-section above a few MeV)
$\phi \sim 2 \times 10^6$ cm^{-2}s^{-1} (flux above a few MeV, mostly from ^{8}B neutrinos)

How many solar neutrinos interact in your body during your lifetime?

A. 10^-6

B. 10^-3

C. 10

D. 10^3

E. 10^6

What do we want from a neutrino detector?

depends on the source and the physics:

Geordi La Forge’s special visor that can see neutrinos

What do we want from a neutrino detector?

depends on the source and the physics:

Geordi La Forge’s special visor would tell us:

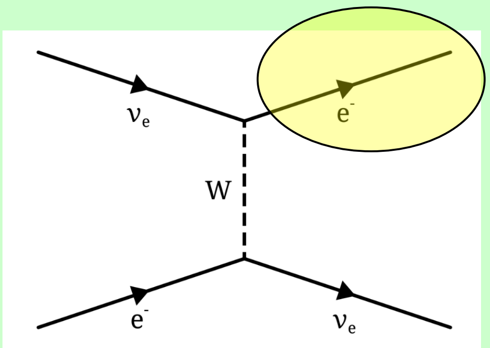
- flavor/CP state [nu vs antinu]
- energy
- direction
- time of interaction
- position of interaction

plus pretty much always want:

- high statistics (mass,efficiency)
- low background

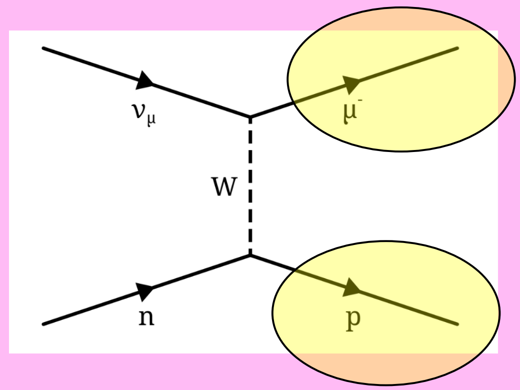
What you actually ***detect*** is the **secondary(ies)**... (and tertiaries...)

scattered particle, newly created particles, ejected nuclei, showers...



"Elastic"

same particles in as out



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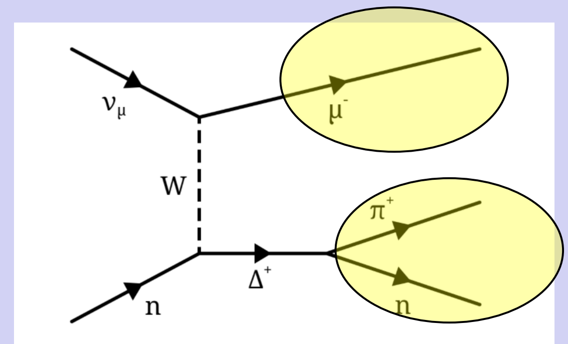


"Inelastic"

energy converted to new particles

Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
can be categorized as:

A. charged-current elastic

B. charged-current quasi-elastic

C. charged-current inelastic

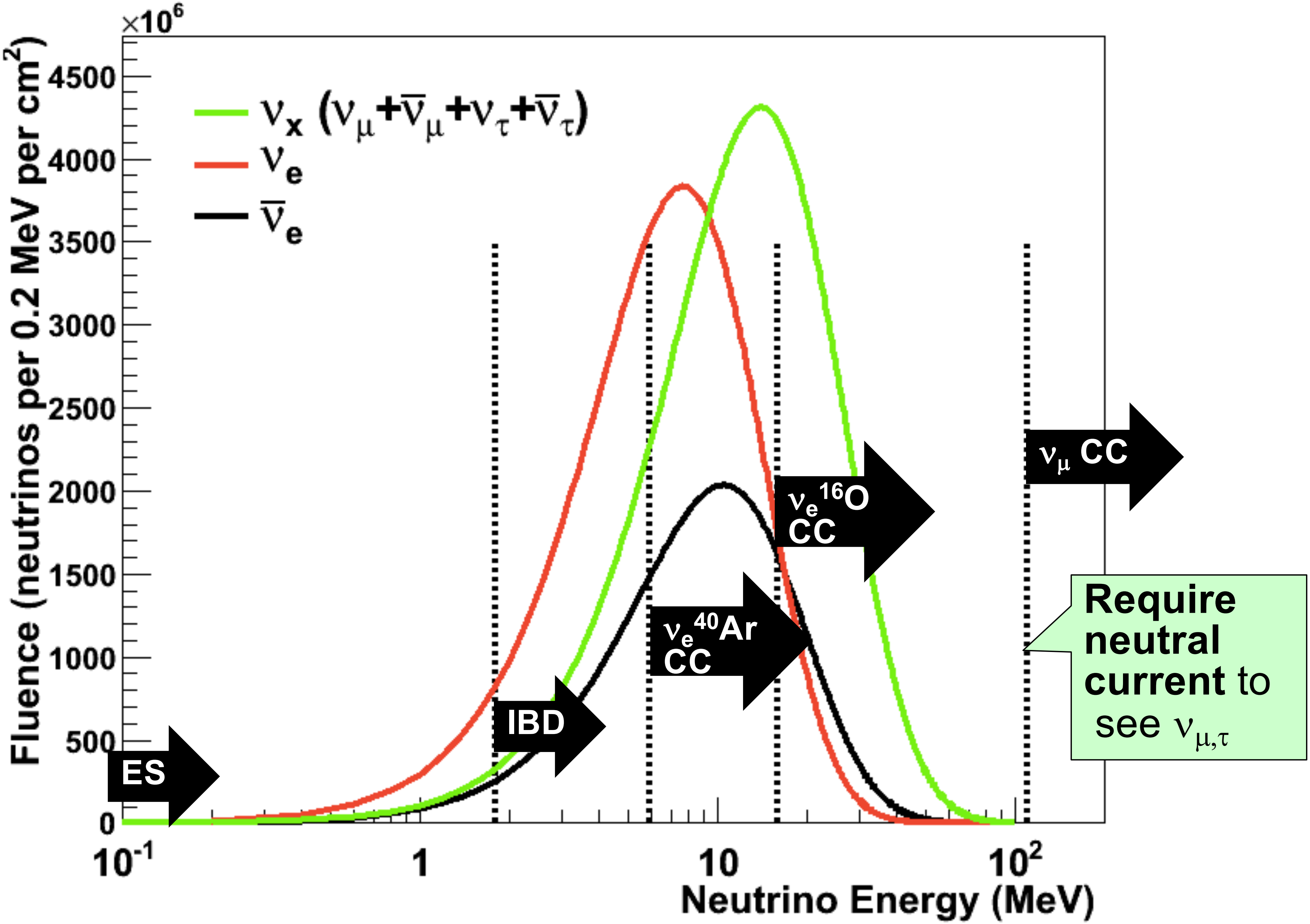
D. neutral-current elastic

E. neutral-current inelastic

Supernova neutrinos range up to about ~50 MeV, and arrive in a burst containing neutrinos and antineutrinos of all flavors

Why are only electron-flavor neutrinos visible via charged-current?

Neutrino interaction thresholds



Event spectrum as a function of observed energy E', for a realistic detector

$$\text{flux} \otimes \text{xscn} \otimes \text{interaction products} \otimes \text{detector response}$$

Flux

Cross section

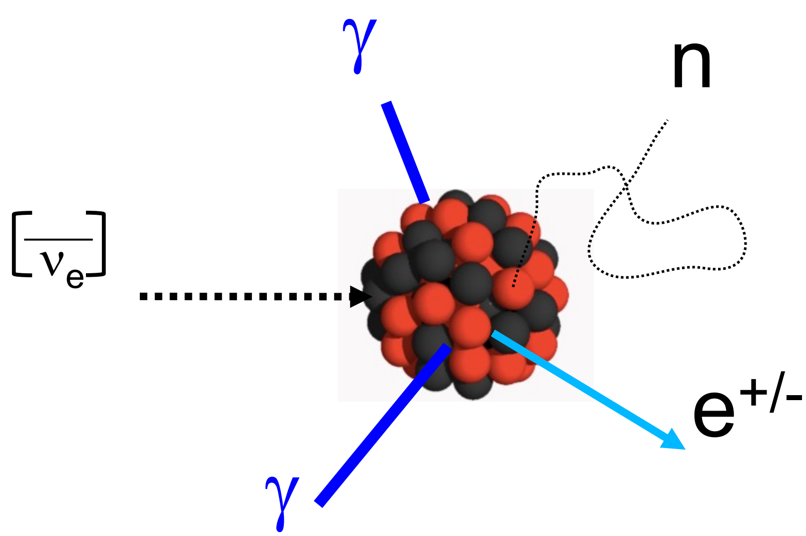
$$\frac{dn}{dE'} = N \int_0^\infty \int_0^\infty dE\, d\hat{E}\, \Phi(E)\, \sigma(E)\, k(E - \hat{E})\, T(\hat{E})\, V(\hat{E} - E')$$

Interaction products (physics)

Detector response (detector simulation)

E': observed energy
k: observed energy for given neutrino energy
T: detector efficiency
V: detector resolution

Neutrino detection physics
is actually **physics of electromagnetic-**
or strongly-interacting particle detection



- charged particles
  - “heavy” (μ, π, p, ...)
  - e^+, e^-
- photons
- neutrons

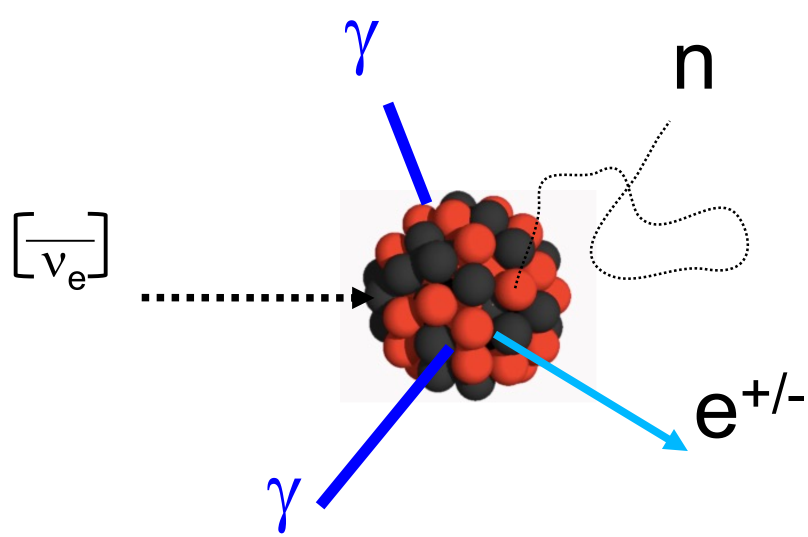
Take-away points so far

- Neutrino sources:
  - natural and artificial sources over many orders of magnitude in energy

- Neutrino interactions:
  - CC, NC; elastic, QE, inelastic
  - How to calculate neutrino event rates

$$R = \Phi \; \sigma \; N_t$$

- Neutrino detection:
  - Neutrinos are observed via secondaries/tertiaries



Neutrino interactions over a range of energies

Deep Inelastic Scattering

keV MeV GeV TeV PeV

Neutrino interactions over a range of energies

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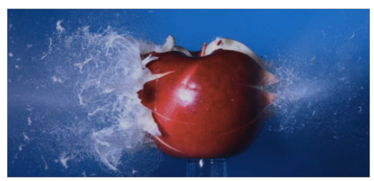
keV MeV GeV TeV PeV



Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino interactions over a range of energies

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

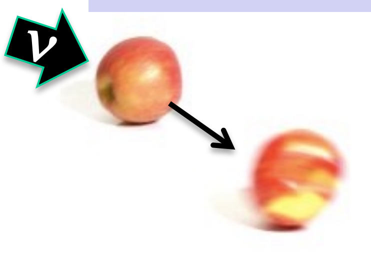
Neutrino interactions over a range of energies

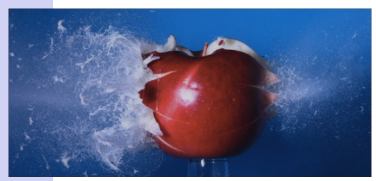
Coherent elastic neutrino-nucleus scattering

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

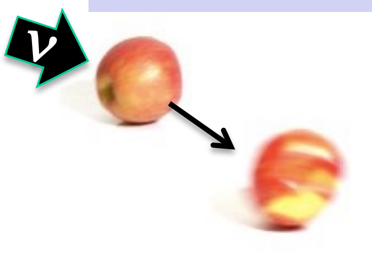
This is the ***gentlest*** interaction of a neutrino with a nucleus

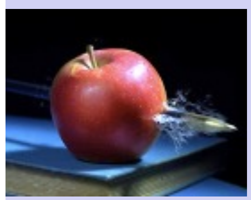
Coherent elastic neutrino-nucleus scattering

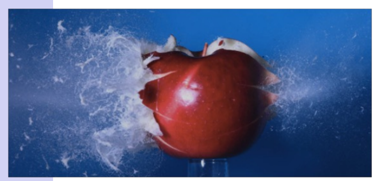
Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV

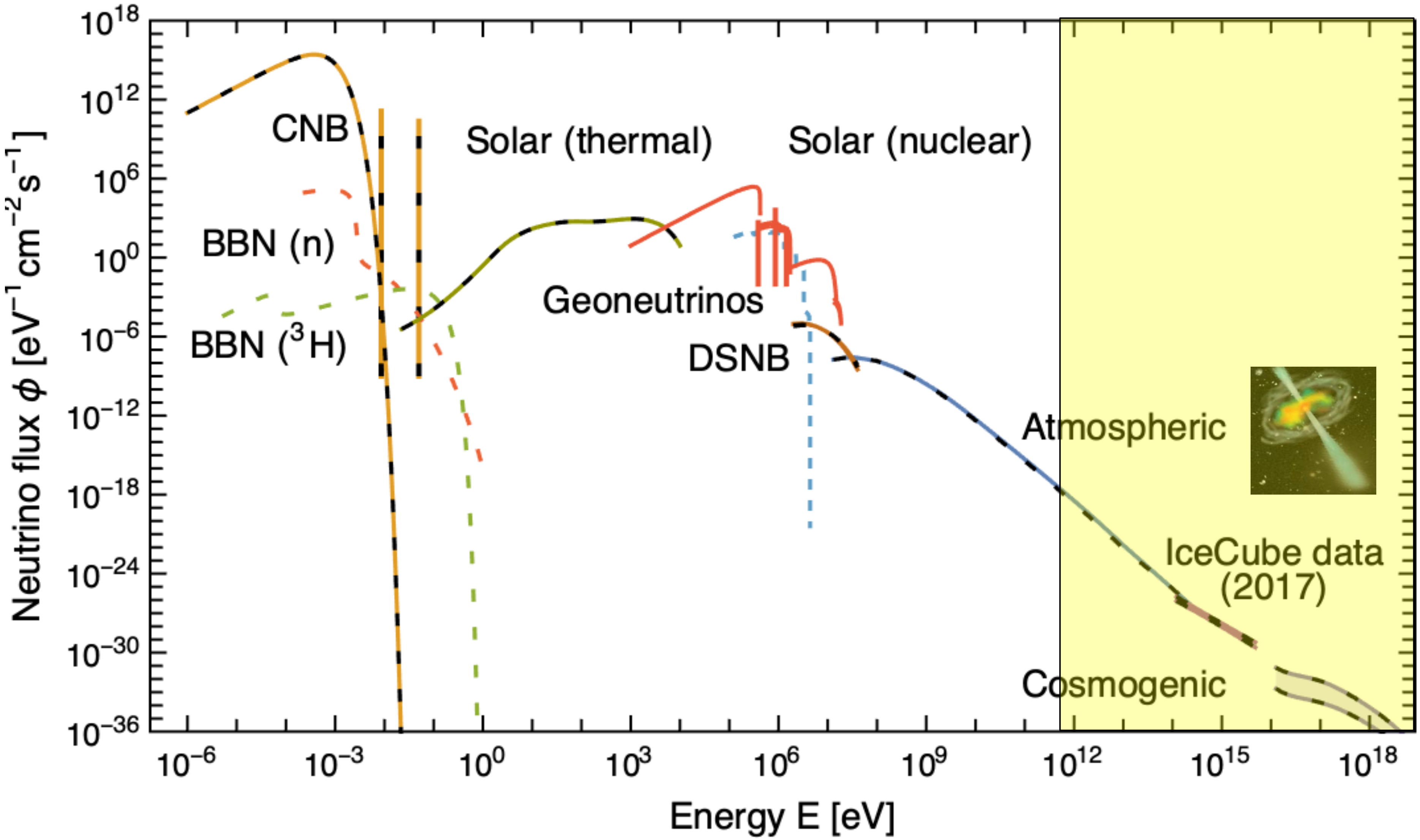






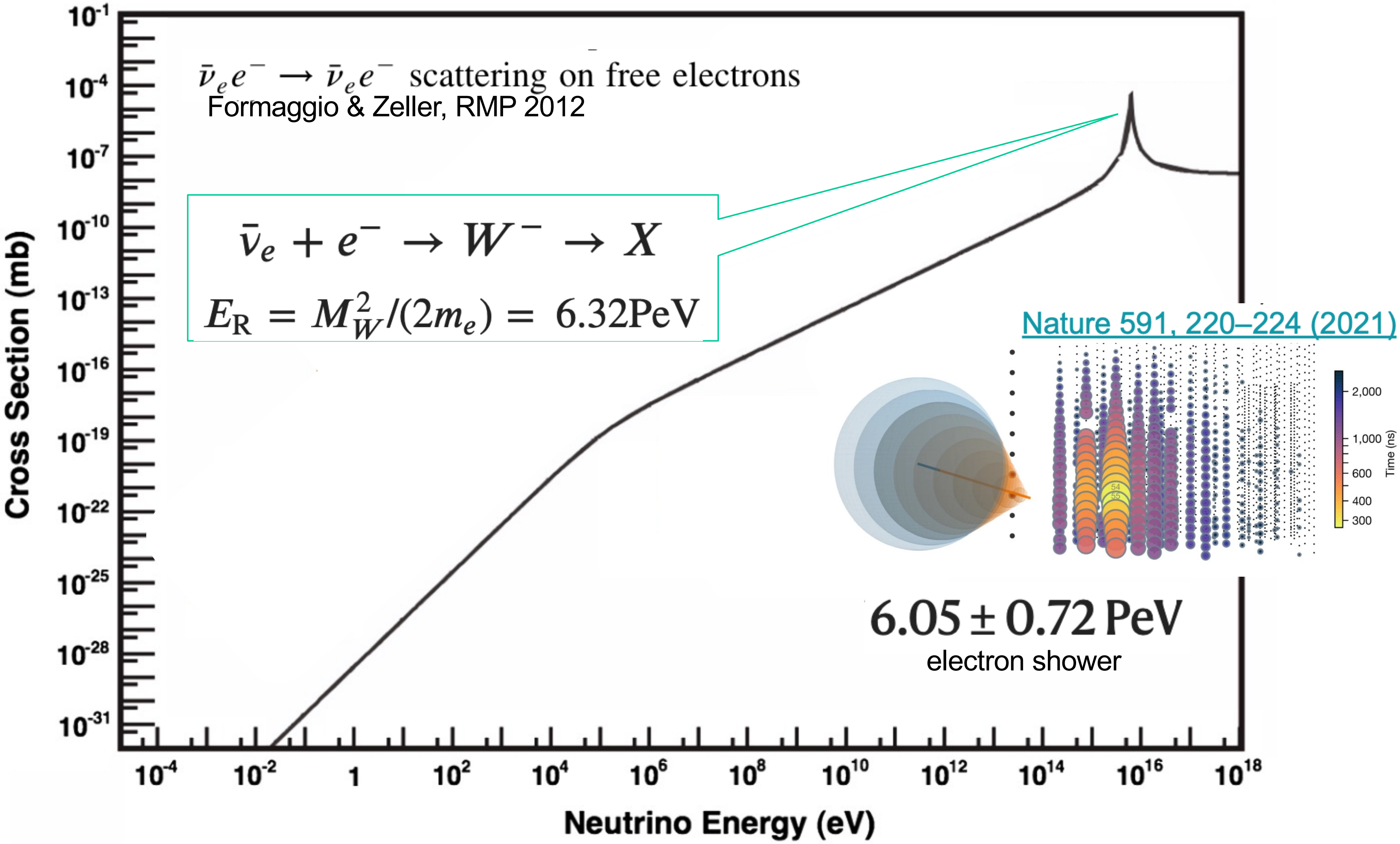
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

A tour by neutrino energy scale, of some highlights...



start at the high end

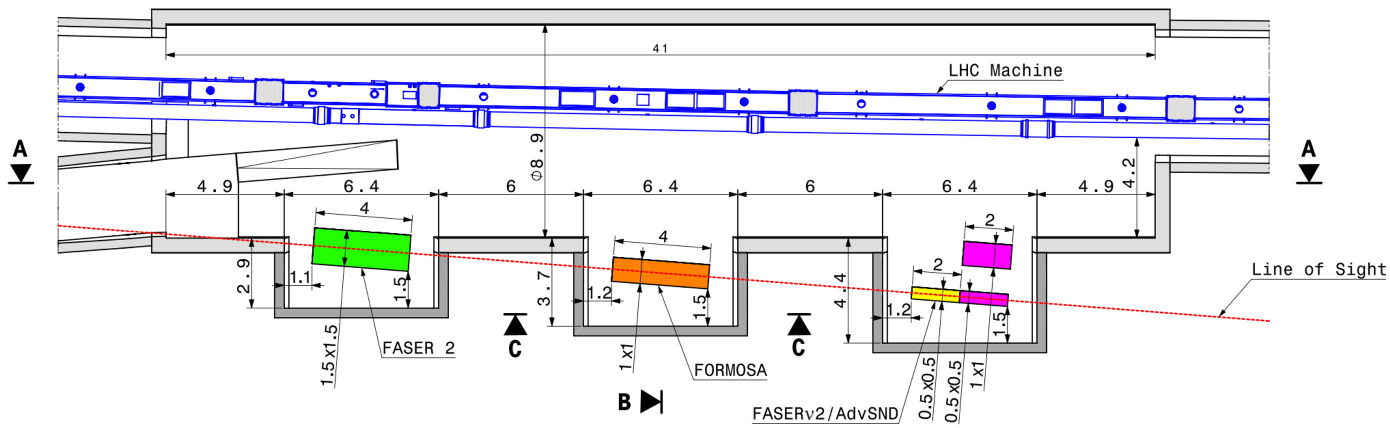
IceCube Glashow Resonance

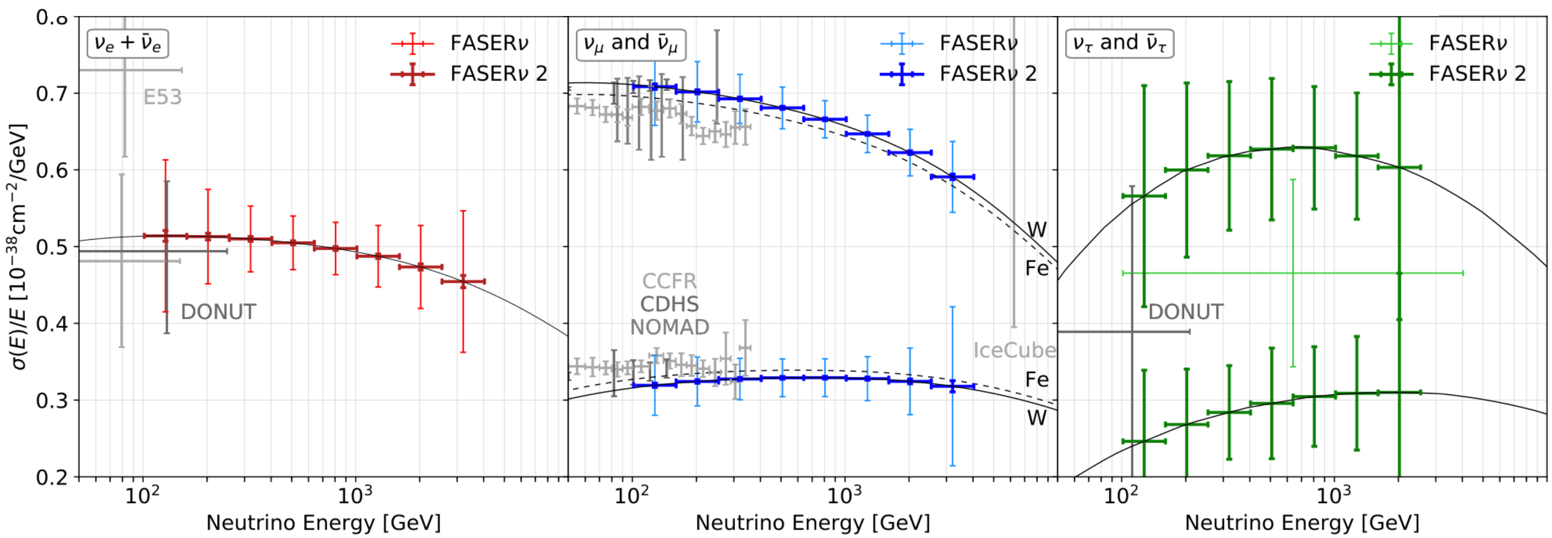


$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^- \to \bar{\nu}_e + e^-} \frac{s/M_W^2}{(s - M_W^2)^2 + \Gamma_W^2 M_W^2}$$

Hard to study very high energies in the laboratory...

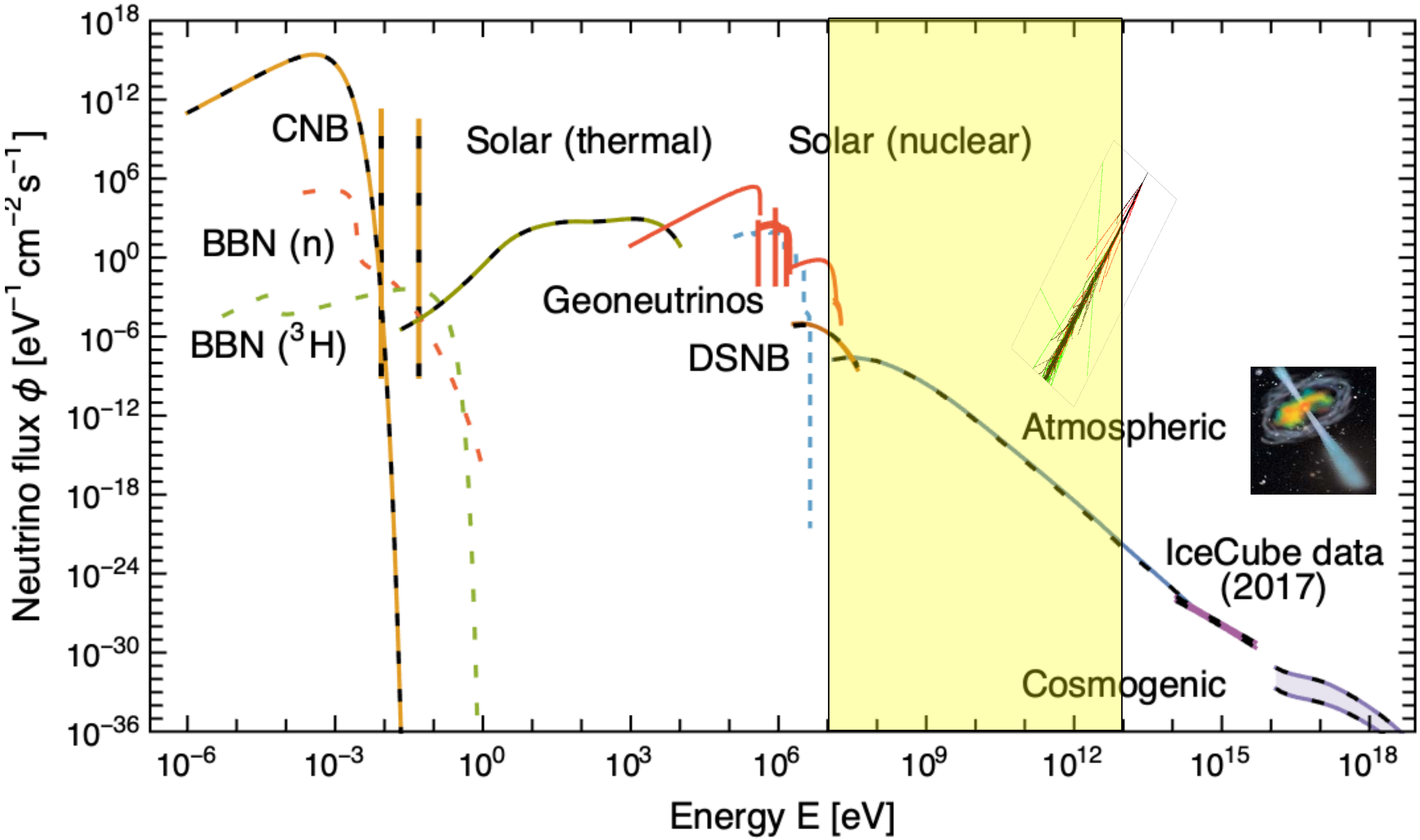
Some interesting future prospects for ν interaction in the ~TeV range at the **Forward Physics Facility at the LHC**





https://arxiv.org/pdf/2109.10905.pdf

Going down a little lower, to few 100 MeV-10 GeV scale



Long-baseline beam experiments for oscillation physics

Past → **Current** → **Future**

K2K
KEK to Kamioka
250 km, 5 kW

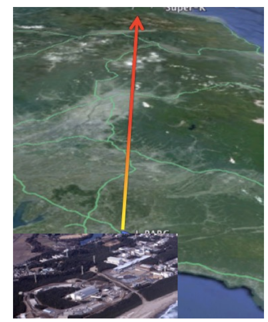
MINOS (+)
FNAL to Soudan
734 km, 400+ kW

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)



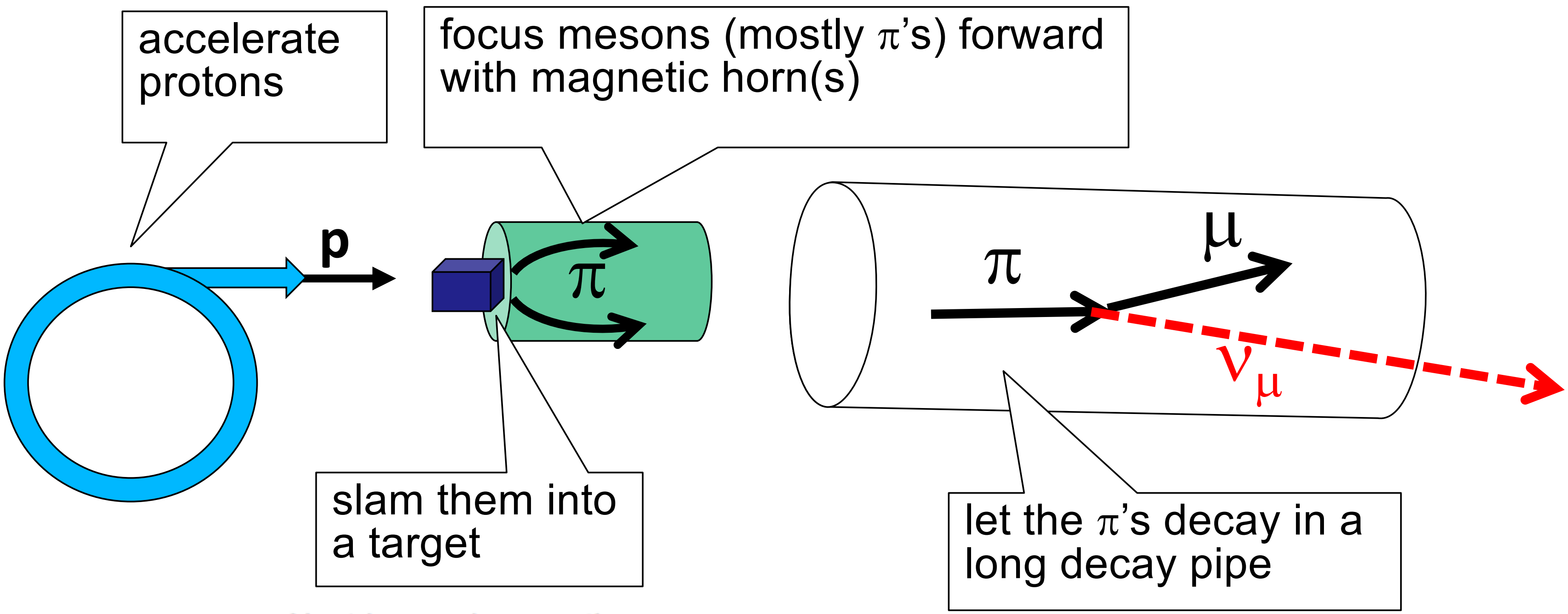
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

And beyond...
ESSnuB,
neutrino factories...

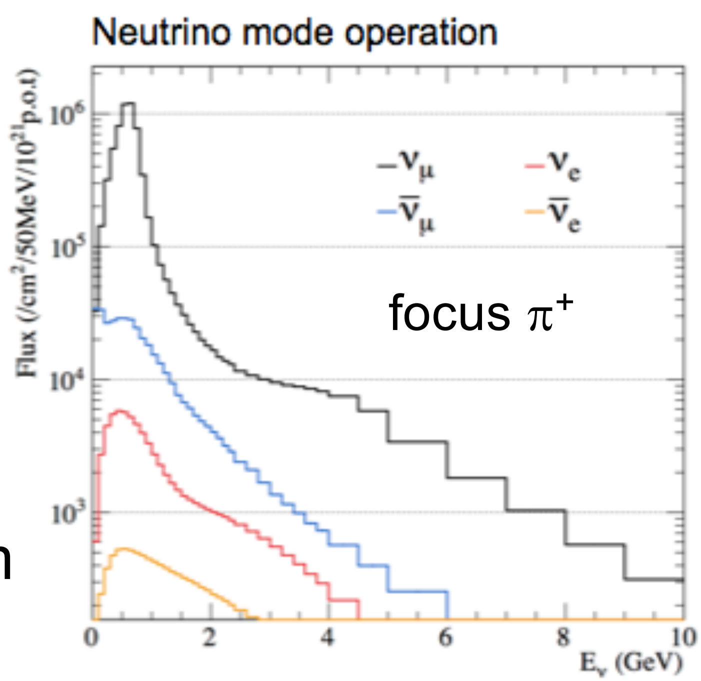




These make use of ~GeV neutrinos from π decay in flight



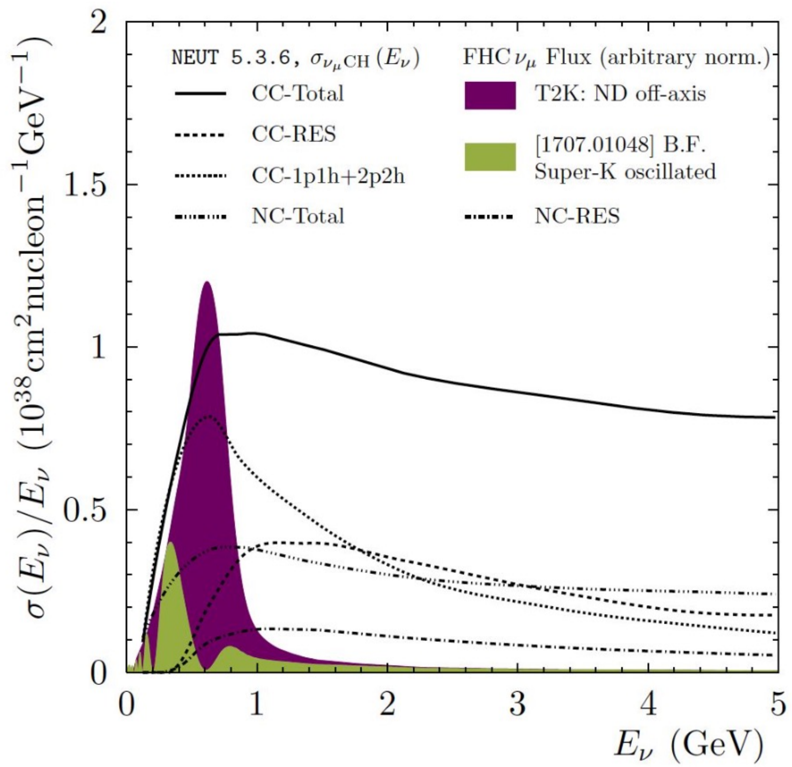
T2K beam



Non-negligible uncertainties on flux normalization and spectrum…

It's *critically important* to understand neutrino interactions with nuclei for interpretation of oscillation experiments

The game is to compare observed ν flavor and energy spectrum at
near and far sites
(observable is wiggles as a function of L and E)



K. Mahn, Snowmass Neutrino Colloquium

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true};E_{reco})$$

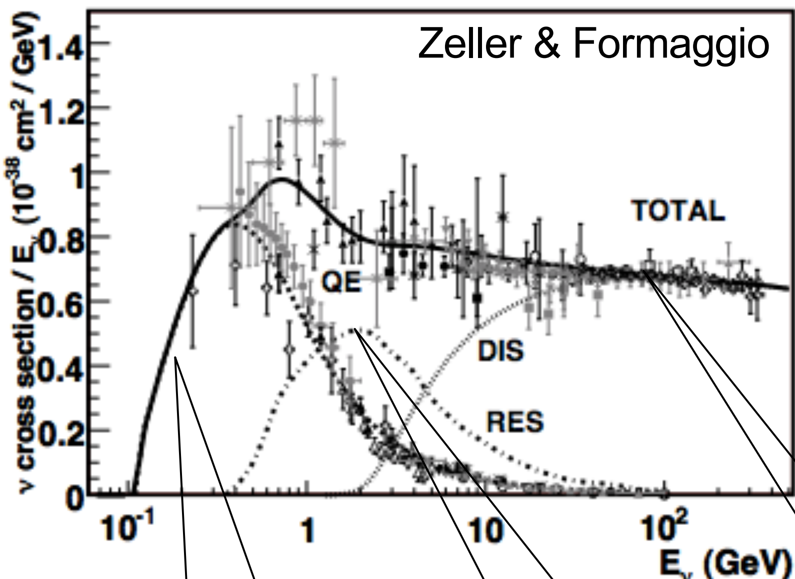
Oscillation depends on true ν energy...
→ **must reconstruct ν energy from observed final state particles**

(there are near detector tricks to mitigate uncertainties, but it's hard to get away from needing good understanding)

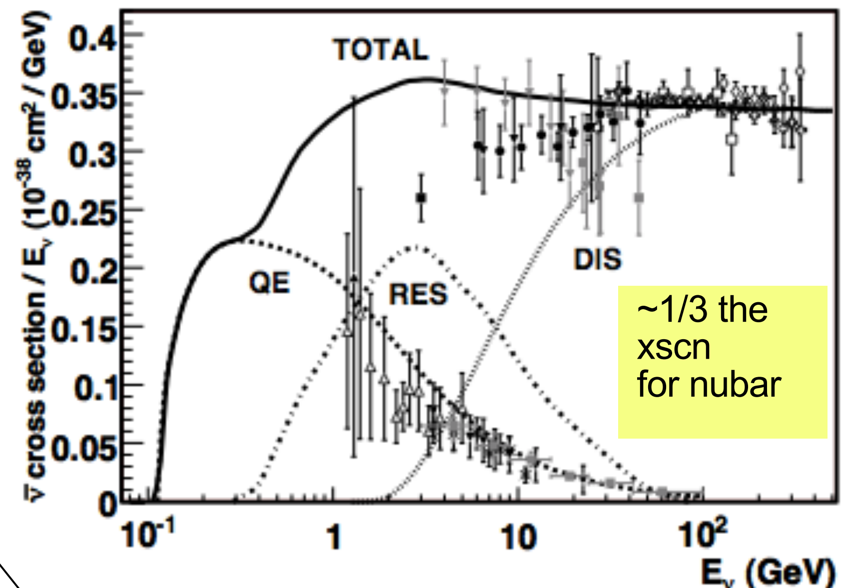
Interactions of neutrinos in the few-GeV range

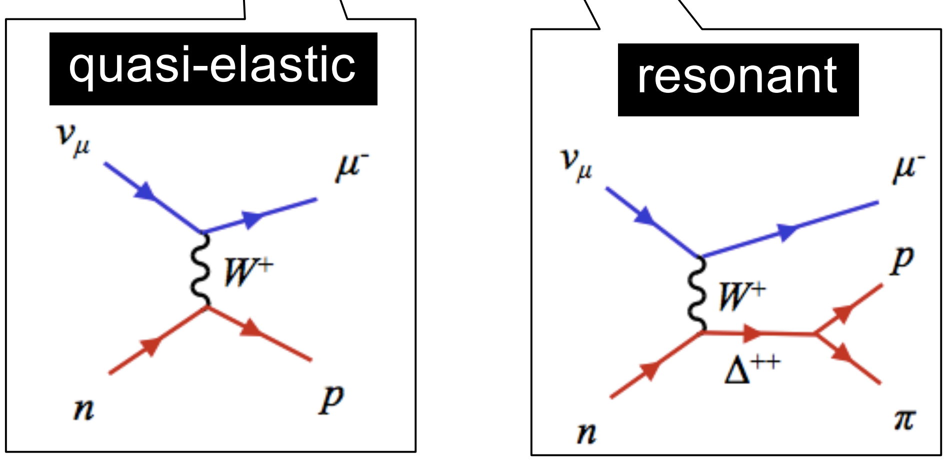
scattering off nucleons, but can blow up the nucleus & create new particles

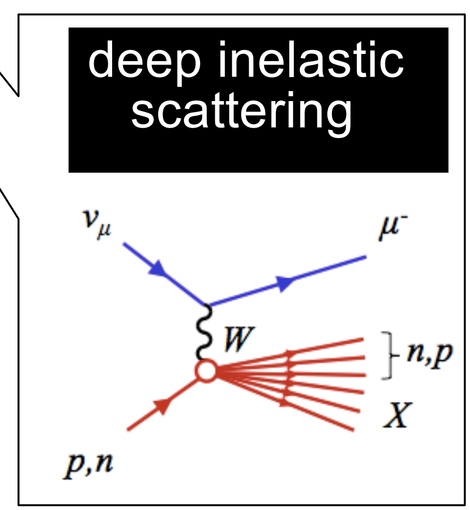
Neutrinos



Antineutrinos

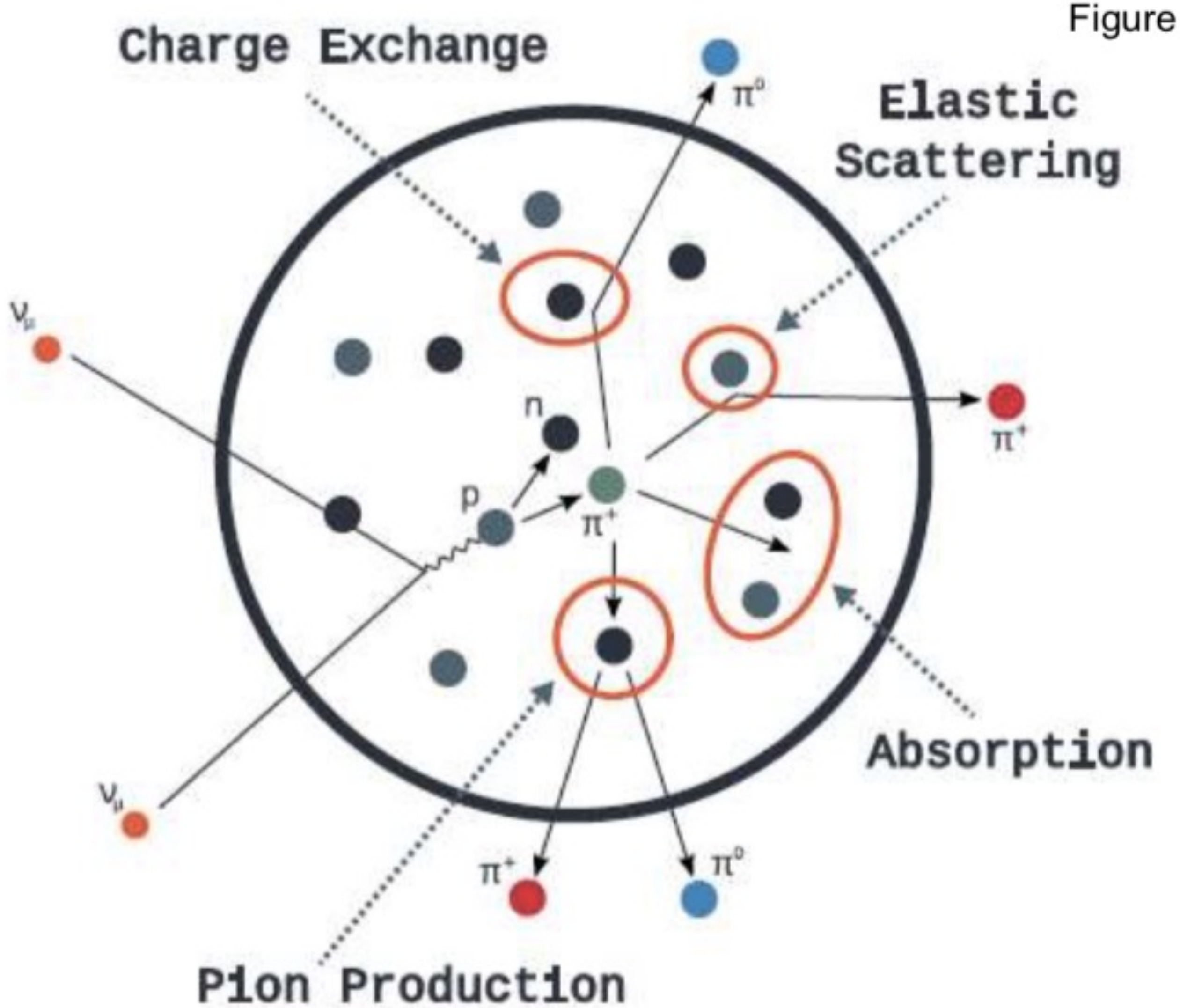






Neutrino-nucleus interactions in this regime
have **complicated final states...** final-state interactions matter

Figure by Tomasz Golan



D. Ruterbories, Nu2018

Dedicated measurements in process and proposed, + theory, to understand interactions in this regime

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

ANNIE

annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

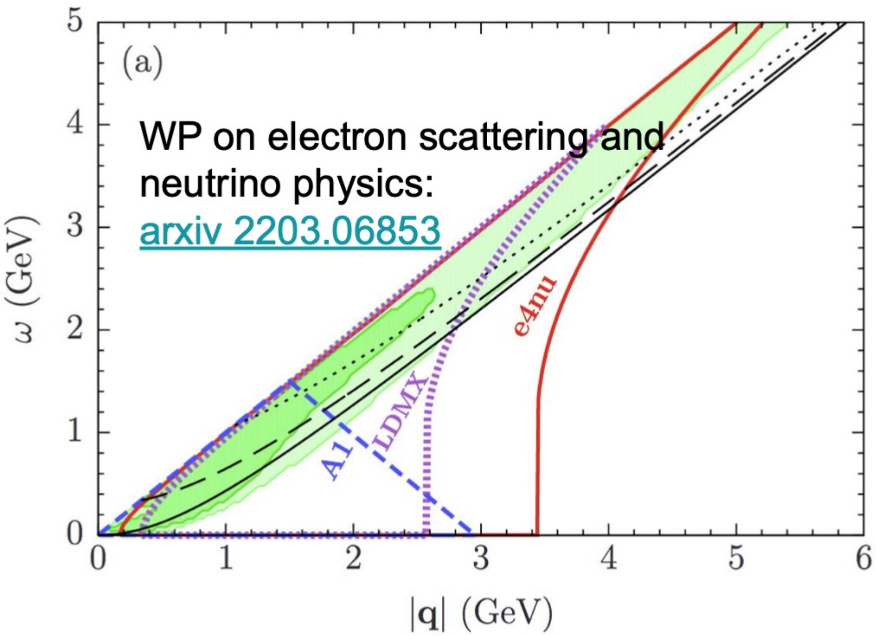
NINJA

Recent: Phys. Rev. D 102, 072006

K. Mahn, Snowmass Neutrino Colloquium

+T2K, NOvA, DUNE, HK near detectors

Electron scattering measurements can help to constrain neutrino scattering models



Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\lesssim E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Semi inclusive, exclusive electron scattering measurements constrain vector piece of cross section

- Measurements critical where ND constraints are not applicable (e.g. BSM)
- High multiplicity final state characterization, range of targets (nuclear effects)

Exciting new experimental programs focused on this problem; complementary to ND

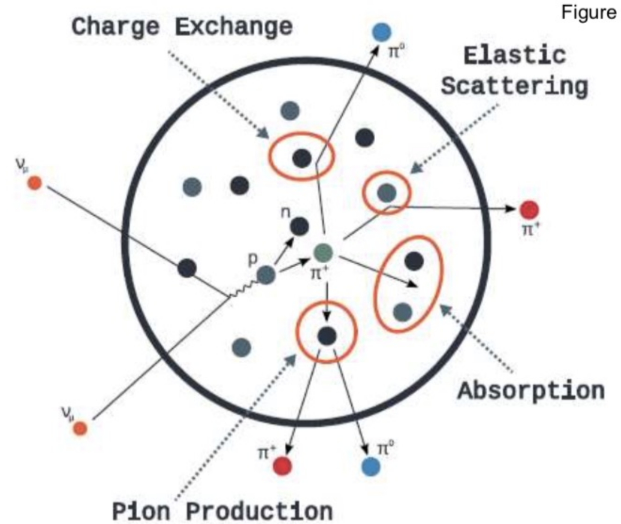
Next take-away points

- High-energy (GeV scale) neutrino interactions important for long-baseline experiments

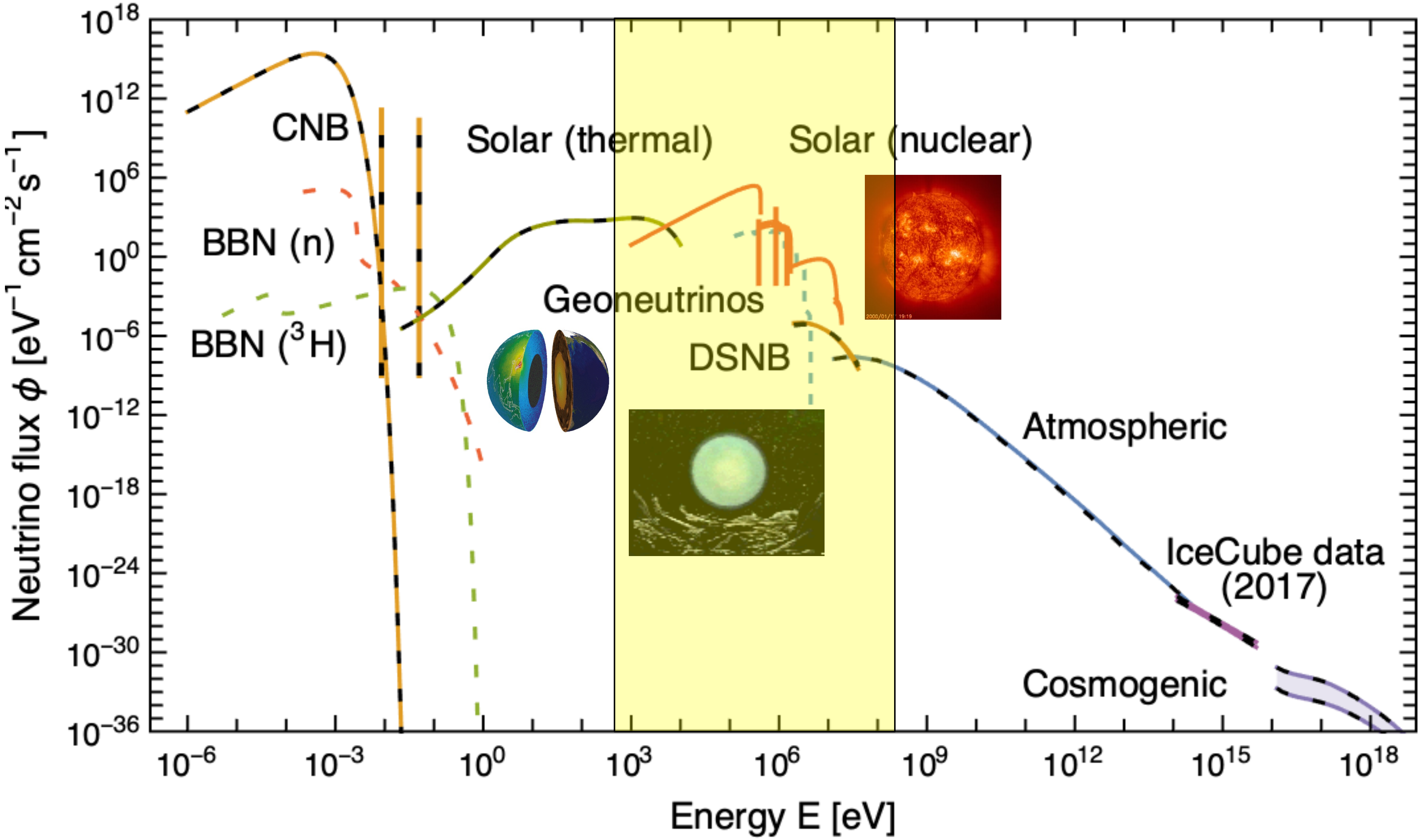
- Nuclei are goopy, complicated places...

- Dedicated measurements + theory needed

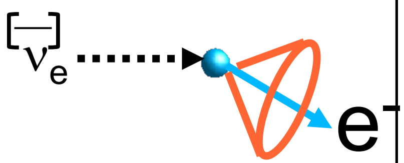
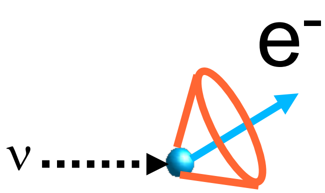
Figure by Tomasz Golan



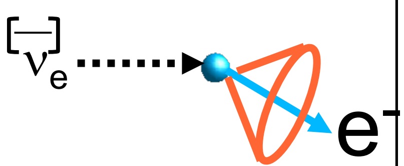
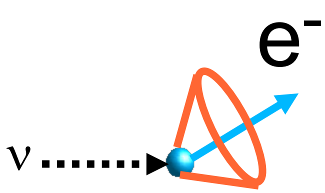
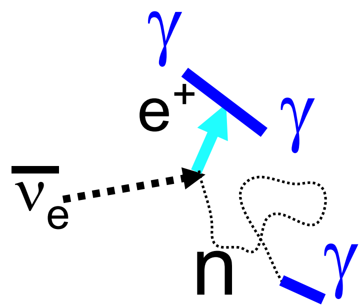
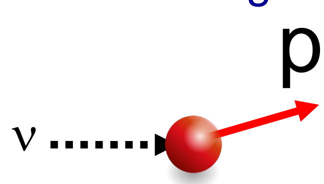
Now moving down in energy to the few-100 MeV scale



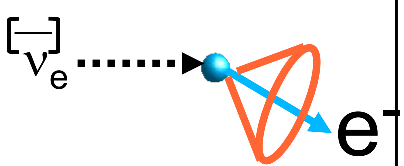
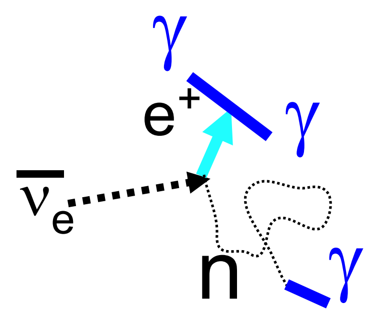
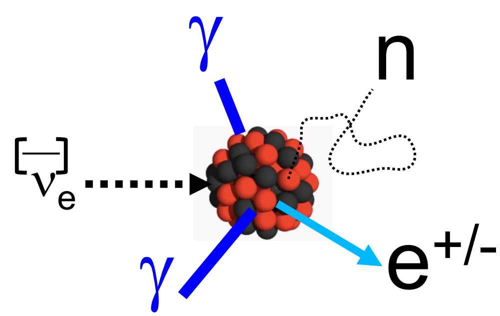
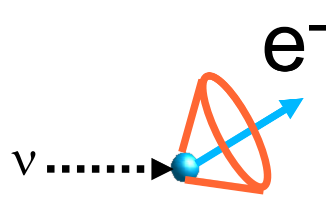
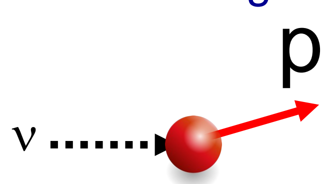
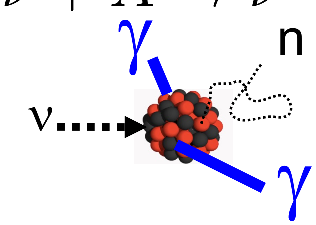
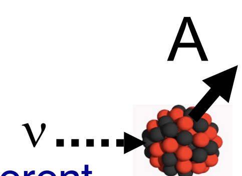
Neutrino interactions with elementary particles

	Electrons		
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 		
Neutral current	 Useful for pointing		

Neutrino interactions with elementary particles

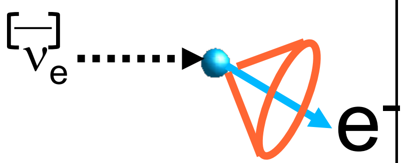
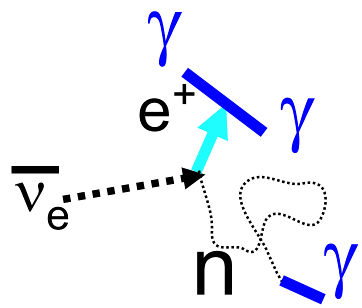
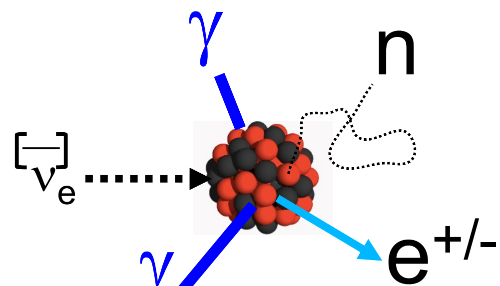
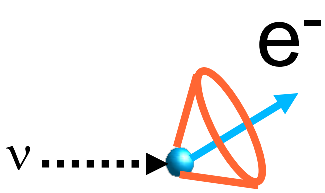
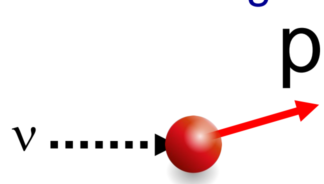
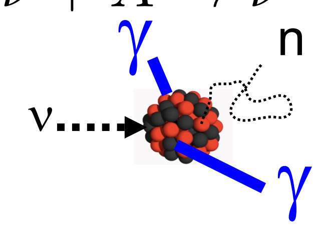
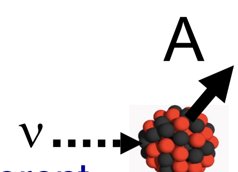
<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering
$\nu + e^- \to \nu + e^-$


Useful for pointing</td><td>Inverse beta decay
$\bar{\nu}_e + p \to e^+ + n$
</td><td></td></tr>
<tr><td>Neutral current</td><td>Elastic scattering

very low energy recoils</td><td></td></tr>
</table>

Neutrino interactions with elementary particles

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

Simple targets… ~well understood

Neutrino interactions with elementary particles

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

Generally more complicated!

Low-energy neutrino detector types

Water

$\bar{\nu}_e + p \to e^+ + n$

$\bar{\nu}_e$

Water, long-string

$\bar{\nu}_e + p \to e^+ + n$

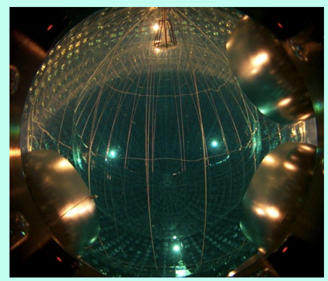
$\bar{\nu}_e$

Argon

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

ν_e

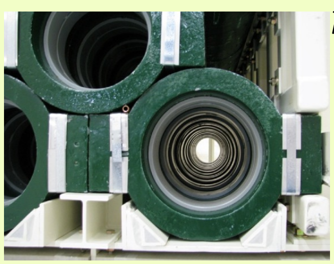
Scintillator



$\bar{\nu}_e + p \to e^+ + n$

$\bar{\nu}_e$

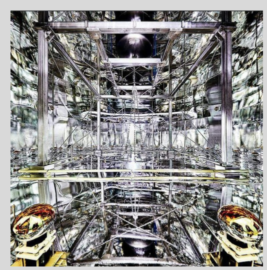
Lead



$\nu_e + {}^{208}\mathrm{Pb} \to e^- + {}^{208}\mathrm{Bi}^*$

ν_e

DM (Noble liquid)



$\nu_x + \mathrm{A} \to \nu_x + \mathrm{A}$

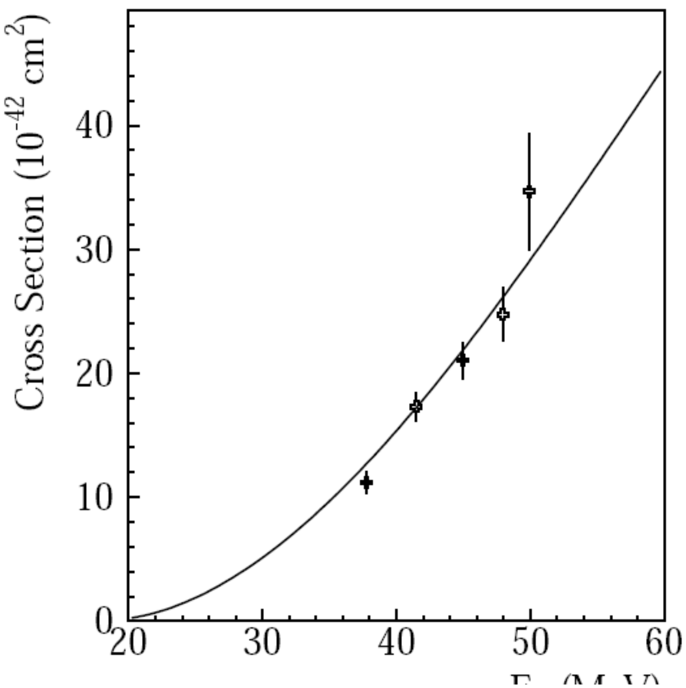
ν_x

Very little experimental information on inelastic neutrino-nucleus interactions in this regime!

.. previously ^{12}**C was the *only* "heavy" nucleus** with ν interaction x-sections well (~10%) measured in the tens of MeV regime

LSND

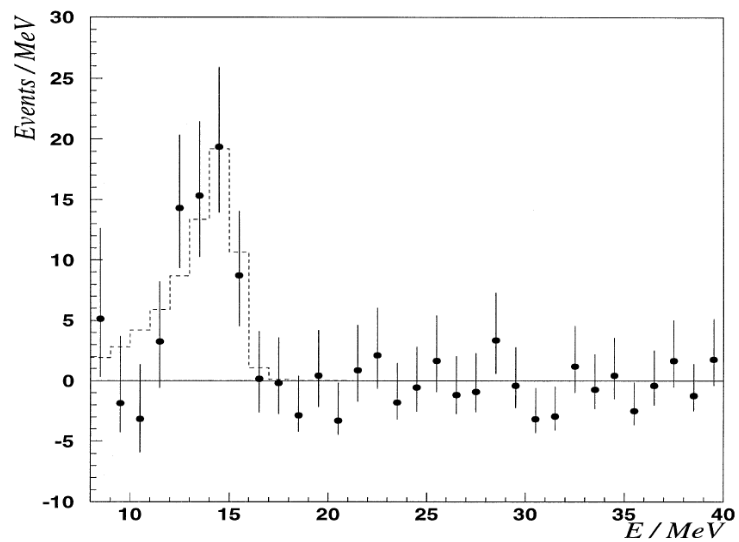
Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen

Phys. Lett. B 423 (1998) 15-20



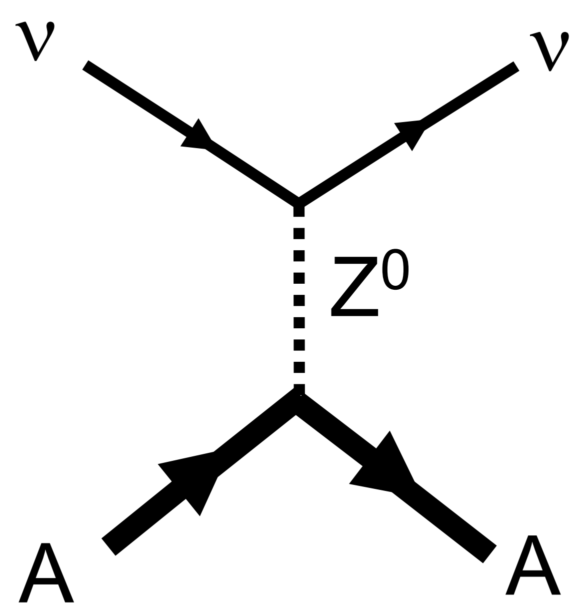
$$^{12}\mathrm{C}(\nu_\mu \nu_\mu')\,^{12}\mathrm{C}^*(1^+,1;15.1\ \mathrm{MeV})$$

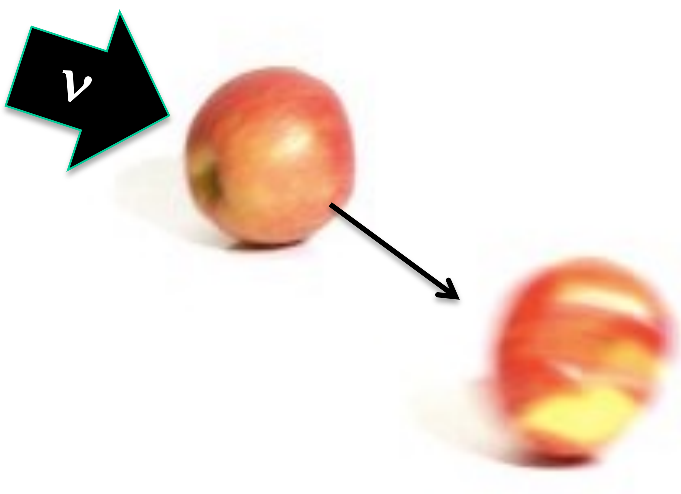
Need: oxygen (water), lead, argon, ...

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





Coherent elastic neutrino-nucleus scattering (CEvNS)

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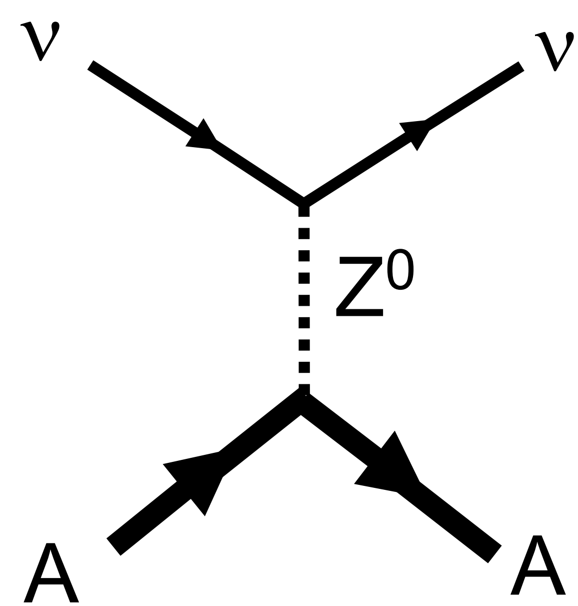
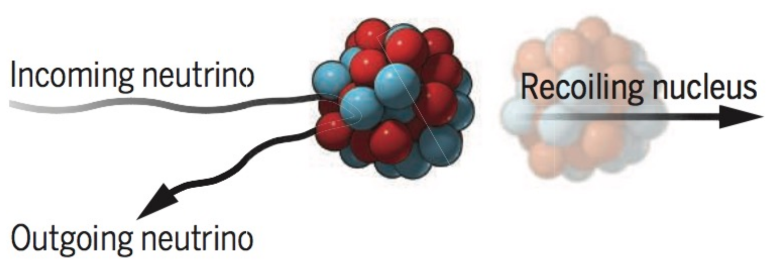


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



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

First proposed >47 years ago!

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

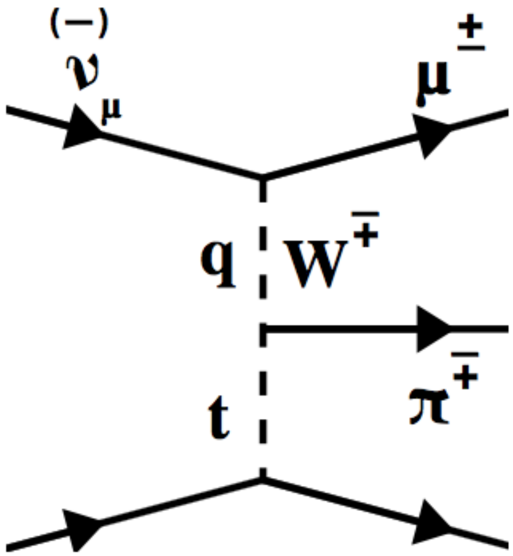
Coherent effects of a weak neutral current

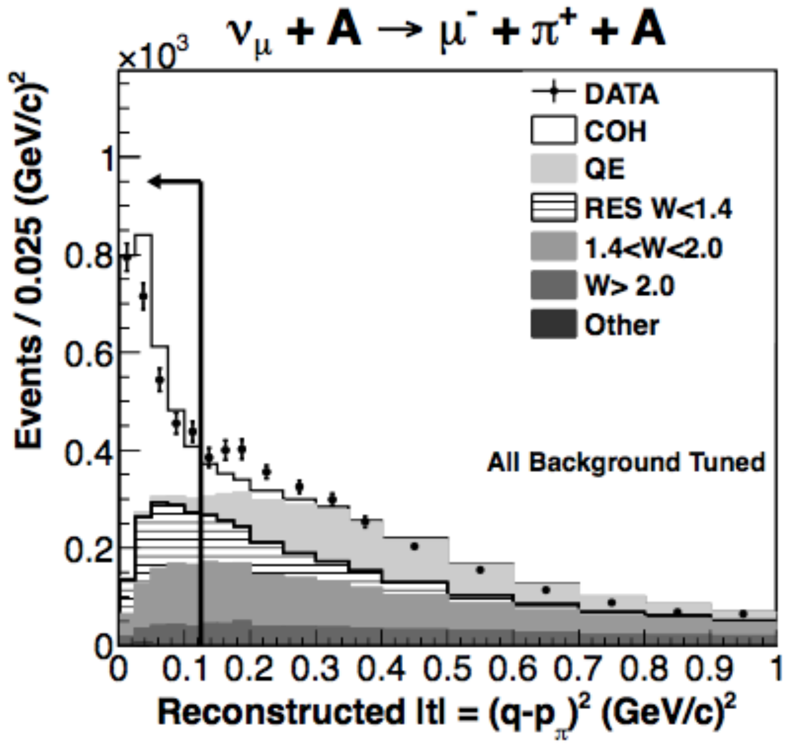
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

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

This is ***not*** coherent pion production, a strong interaction process ***(inelastic)***





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

How do you pronounce "CEvNS"?

A. "KEVENS"

B. "KENZ"

C. "KENSE"

D. "SEVENS"

E. "SENSE"

F. "SENZ"

\begin{aside}

Literature has CNS, CNNS, CENNS, ...

- I prefer including “E” for “elastic”... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I’m told “NN” means “nucleon-nucleon” to nuclear types
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced “sevens”...

spread the meme!

\end{aside}

Standard Model prediction for CEvNS differential cross section

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

(probability of kicking a nucleus with recoil energy T)

Fermi constant (SM parameter)

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

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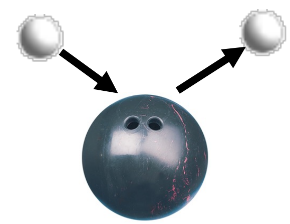
kinematics:
ping-pong ball hits bowling ball



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Form factor: F=1 ➔ full coherence

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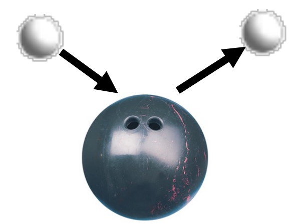

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weak nuclear charge

Form factor: F=1 ➔ full coherence

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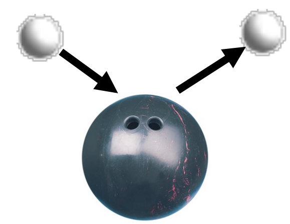
ping-pong ball hits bowling ball



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

Standard Model prediction for differential cross section

(probability of kicking a nucleus with recoil energy T)

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

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

weak nuclear charge

No. of protons

No. of neutrons

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

$\sin^2\theta_W = 0.231$,

so protons unimportant

$$\Longrightarrow \quad Q_W \propto N$$

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

E_ν: neutrino energy
T: nuclear recoil energy
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weak nuclear charge

Form factor: F=1 ➔ full coherence

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Q = √ (2 M T):
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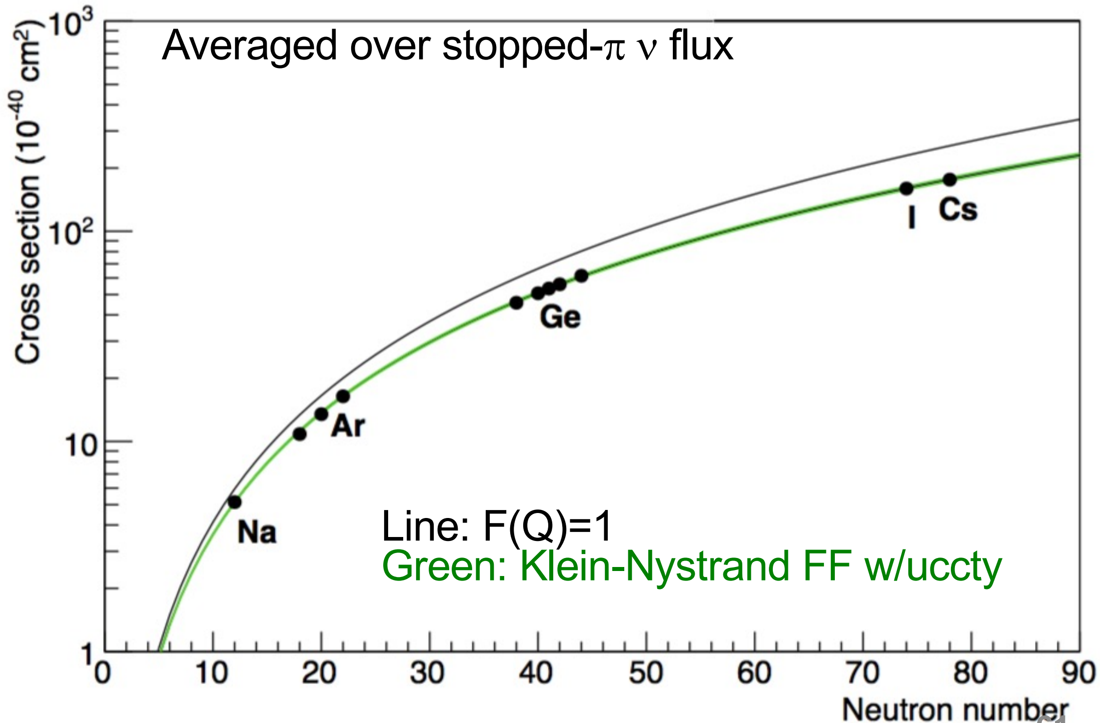
weak nuclear charge

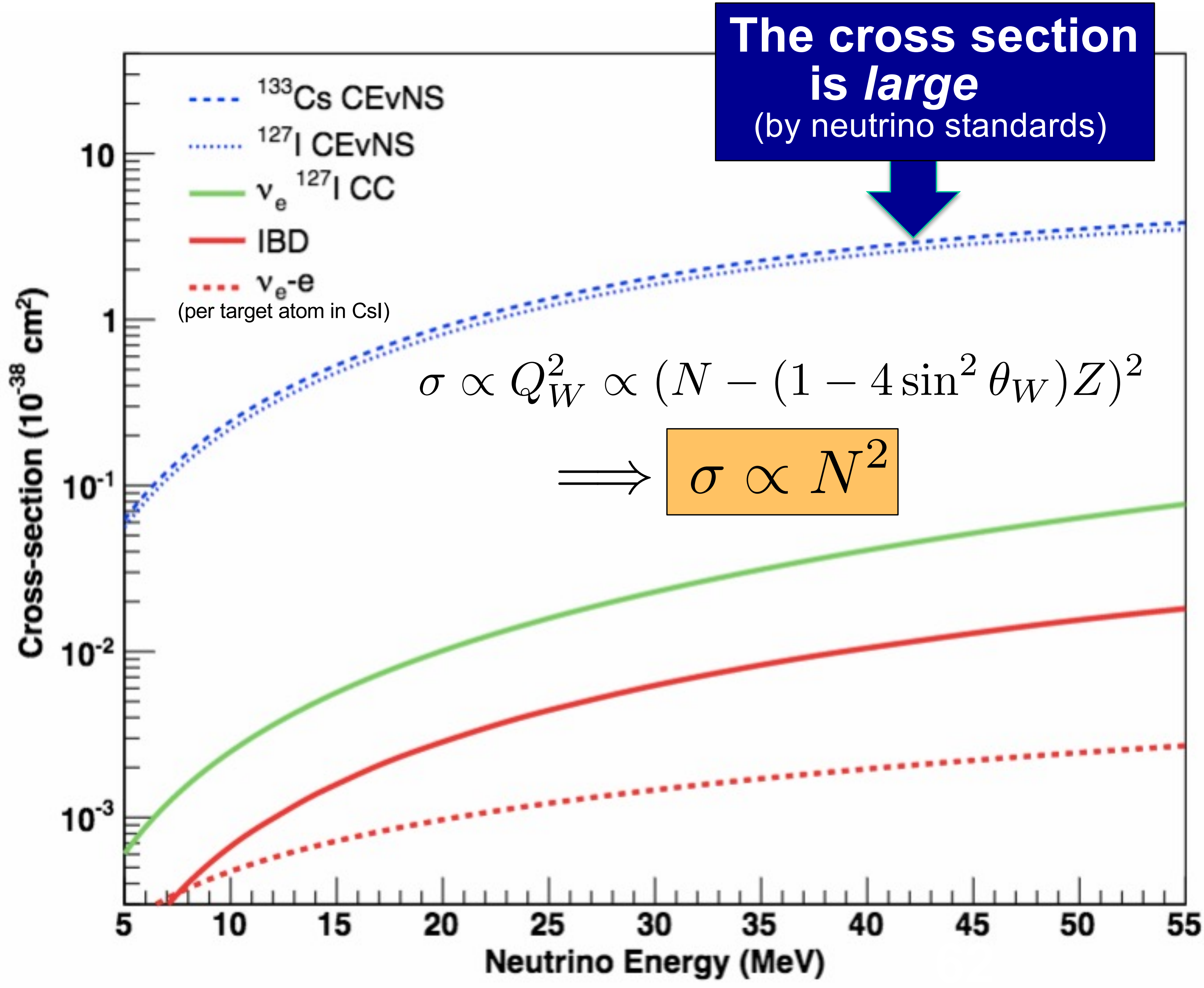
Form factor: F=1 ➔ full coherence

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

$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$



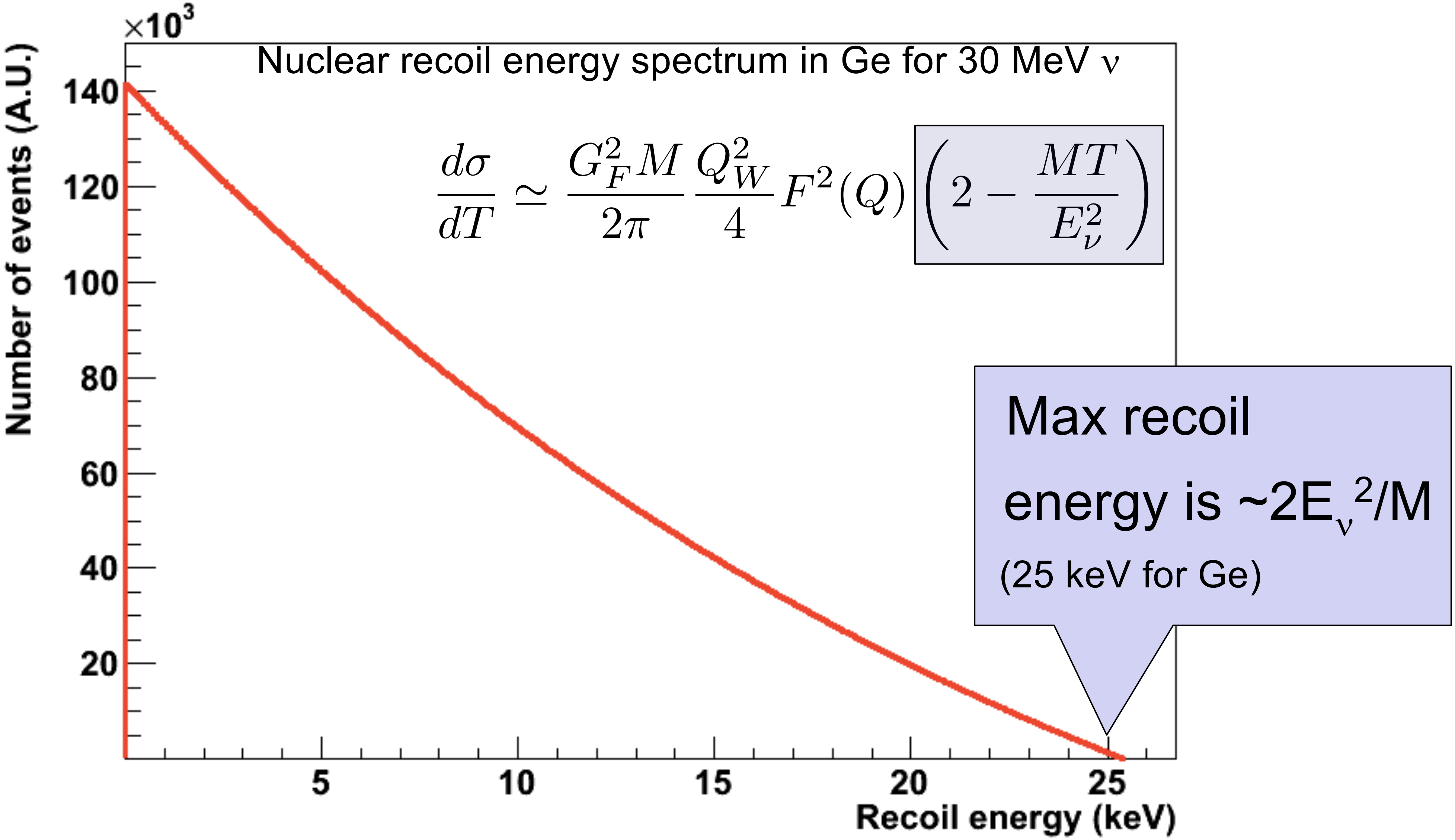
The cross section is *large*
(by neutrino standards)



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

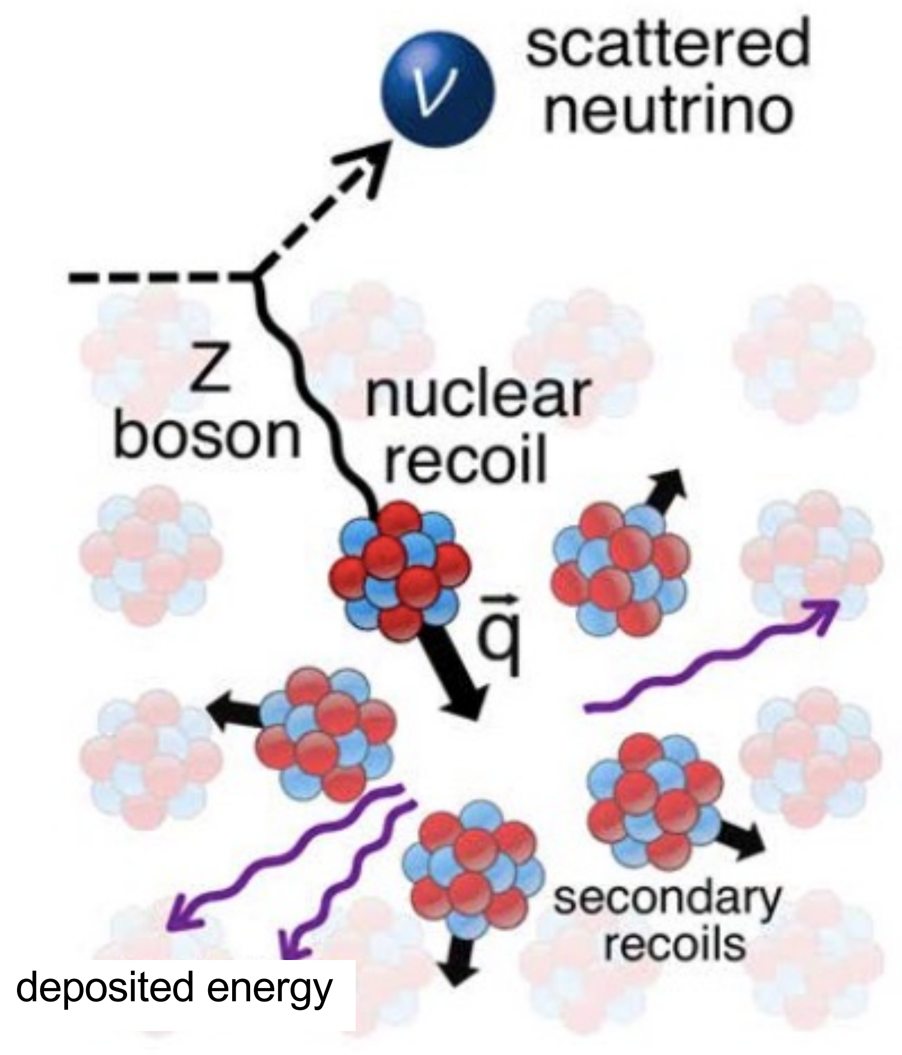
$$\Longrightarrow \boxed{\sigma \propto N^2}$$

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



The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



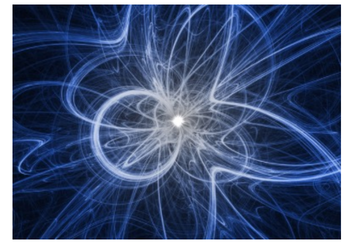
➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

CEvNS: what's it good for?

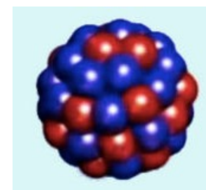
1. So
2. Many
3. Things

! (not a complete list!)

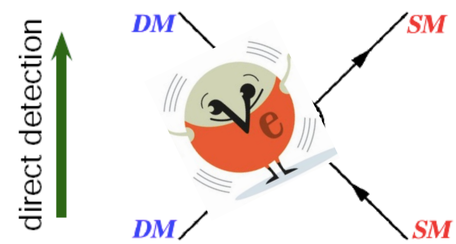
CEvNS as a **signal**
for signatures of *new physics*



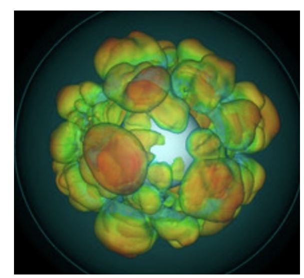
CEvNS as a **signal**
for understanding of "old" physics



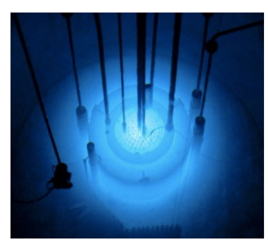
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**

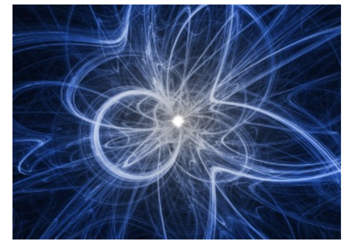


CEvNS: what's it good for?

1 So
2 Many
3 Things

! (not a complete list!)

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



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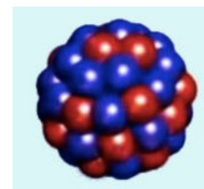
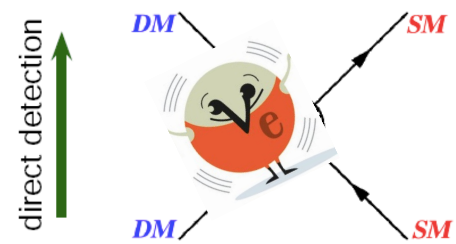


CEvNS as a **background**
for signatures of new physics



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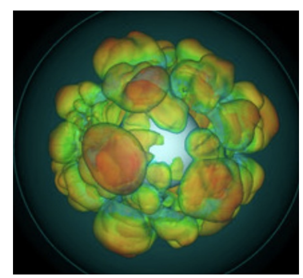

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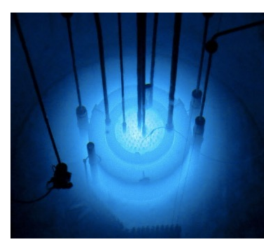


The cross section is cleanly predicted in the Standard Model

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

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (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

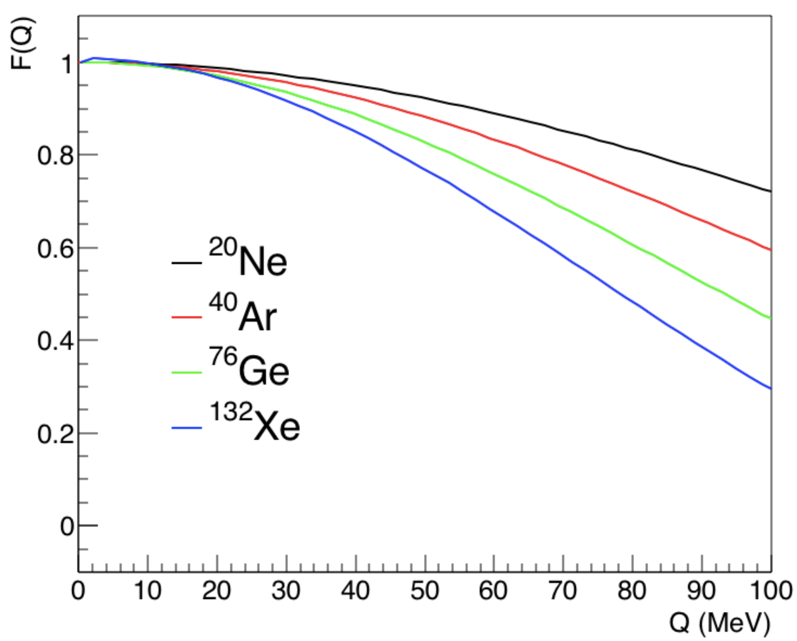
$$\boxed{\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}}$$

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
$Q = \sqrt{(2 M T)}$: momentum transfer

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

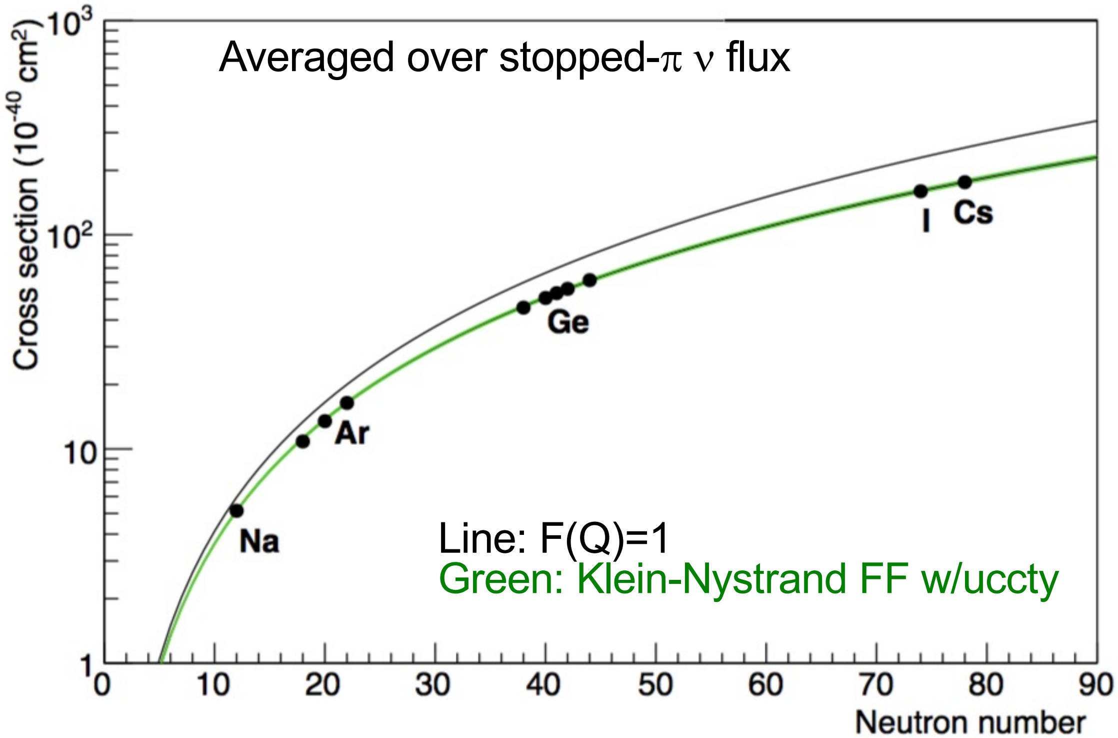


form factor suppresses cross section at large Q

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

Searching for BSM Physics with CEvNS

A first example: simple counting to constrain **non-standard interactions (NSI)** of neutrinos with quarks

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

"Model-independent" parameterization

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

ε's parameterize new interactions

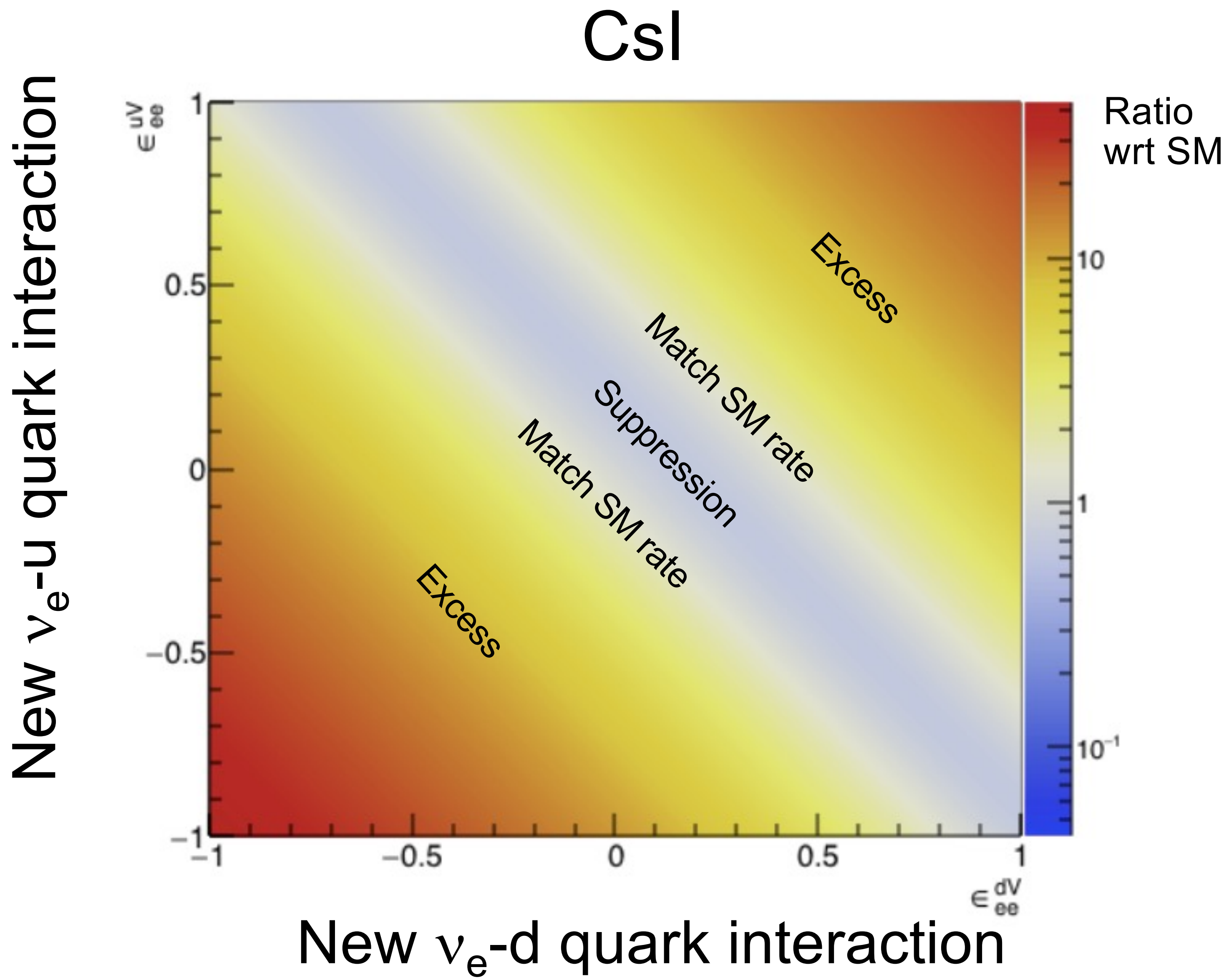
"Non-Universal": ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha \neq \beta$

$\Rightarrow$ some are quite poorly constrained (~unity allowed)

Signatures of **Beyond-the-Standard-Model Physics**

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



Other new physics results in a *distortion of the recoil spectrum* (Q dependence)

BSM Light Mediators

SM weak charge

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

Effective weak charge in presence of light vector mediator Z'

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

specific to neutrinos and quarks

e.g. arXiv:1708.04255

Neutrino (Anomalous) Magnetic Moment

e.g. arXiv:1505.03202, 1711.09773

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right)$$

Specific ~1/T upturn at low recoil energy

Sterile Neutrino Oscillations

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

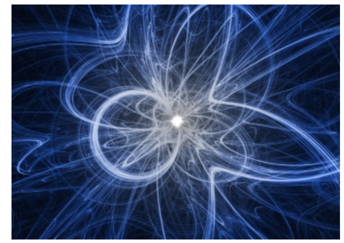
"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

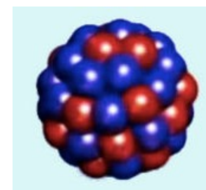
CEvNS: what's it good for?

! (not a complete list!)

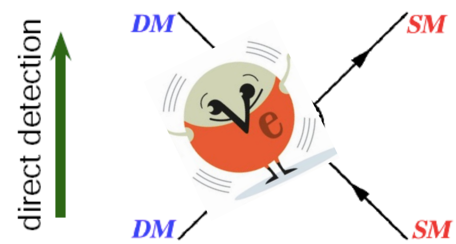
CEvNS as a **signal**
for signatures of *new physics*



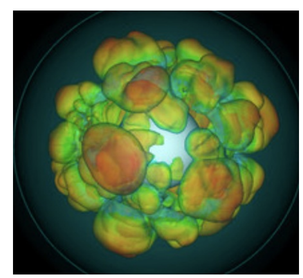
CEvNS as a **signal**
for understanding of "old" physics



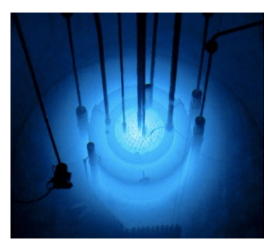
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



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

Nuclear neutron form factor from neutrino–nucleus coherent elastic scattering

P S Amanik and G C McLaughlin

Department of Physics, North Carolina State University, Raleigh, NC 27695-8202, USA

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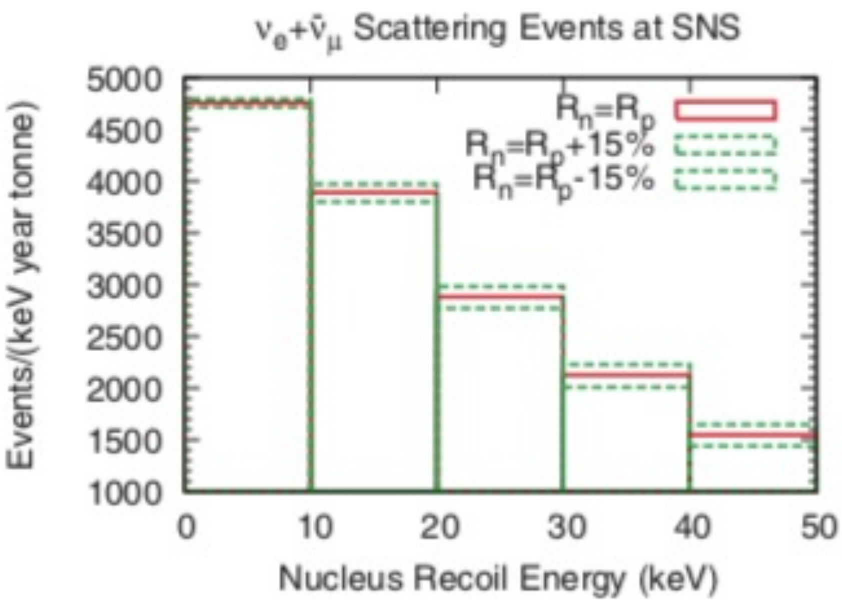
Published 30 October 2008
Online at stacks.iop.org/JPhysG/36/015105

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



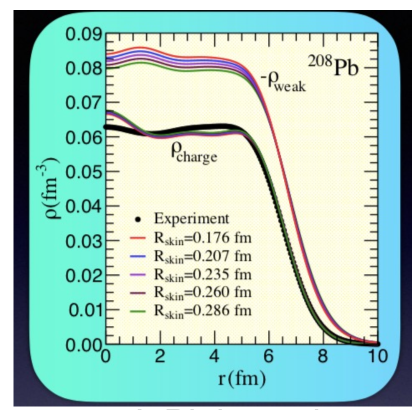
Neutrino-nucleus coherent scattering as a probe of neutron density distributions

Kelly Patton[1,*] Jonathan Engel[2,†] Gail C. McLaughlin[1,‡] and Nicolas Schunck[3§]
[1] *Physics Department, North Carolina State University, Raleigh, North Carolina 27695, USA*
[2] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599, USA*
[3] *Physics Division, Lawrence Livermore Laboratory, Livermore, California 94551 USA*
(Dated: July 4, 2012)

Neutrino-nucleus coherent elastic scattering provides a theoretically appealing way to measure the neutron part of nuclear form factors. Using an expansion of form factors into moments, we show that neutrinos from stopped pions can probe not only the second moment of the form factor (the neutron radius) but also the fourth moment. Using simple Monte Carlo techniques for argon, germanium, and xenon detectors of 3.5 tonnes, 1.5 tonnes, and 300 kg, respectively, we show that the neutron radii can be found with an uncertainty of a few percent when near a neutrino flux of 3×10^7 neutrinos/cm^2/s. If the normalization of the neutrino flux is known independently, one can determine the moments accurately enough to discriminate among the predictions of various nuclear energy functionals.

Observable is **recoil spectrum shape**

Neutron radius and "skin" (R_n-R_p) relevant for understanding of neutron stars

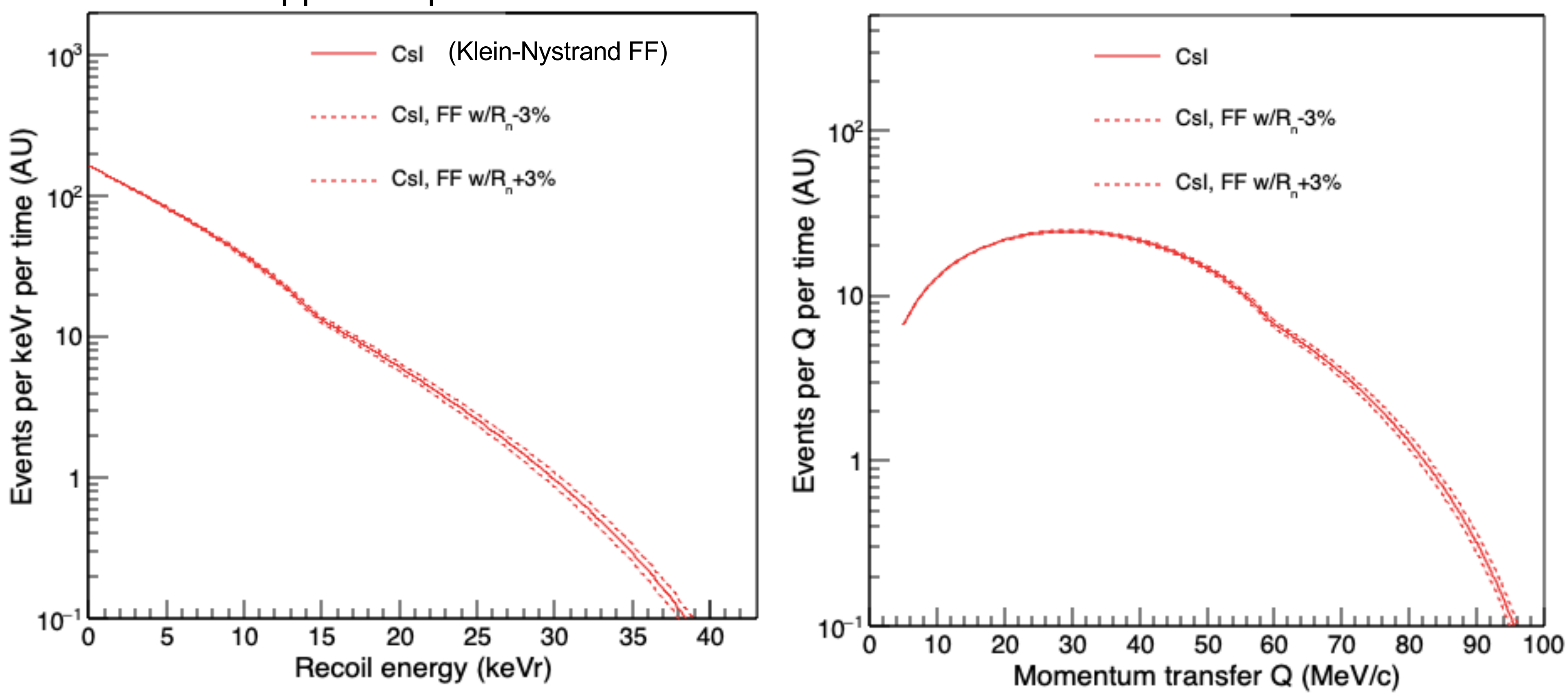


J. Piekarewicz

Effect of form-factor *uncertainty* on the recoil spectrum: estimate as R_n +/- 3%

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

Stopped-π spectrum



At current level of experimental precision, form factor uncertainty is small effect

So: if you are hunting for BSM physics as a distortion of the recoil spectrum

… uncertainties in the form factor are a nuisance!

There are degeneracies in the observables between "old" (but still mysterious) physics

and "new" physics

We will need to think carefully about how to disentangle these effects and understand uncertainties, for the longer term

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

Summary of what we can get at experimentally

Observables:

Event rate
Recoil spectrum ($T=Q^2/2M$)
[In principle: scattering angle... hard]

Spectral shape systematics are hard!

Knowable/controllable parameters:

Neutrino flavor, via source, and timing

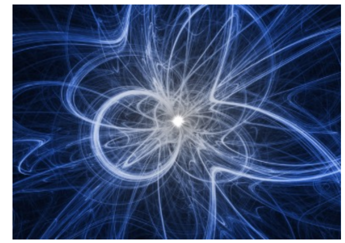
(reactor: ν_e-bar, stopped-π: ν_e, ν_μ-bar, ν_μ)

N, Z via nuclear target type
Baseline
Direction with respect to source

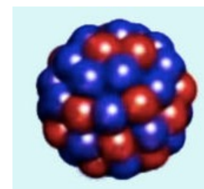
CEvNS: what's it good for?

! (not a complete list!)

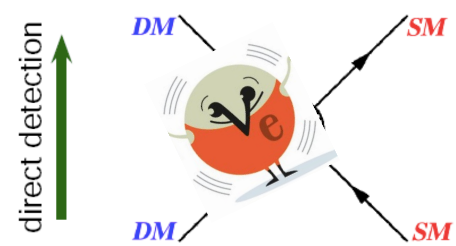
CEvNS as a **signal**
for signatures of *new physics*



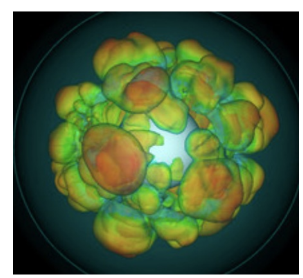
CEvNS as a **signal**
for understanding of "old" physics



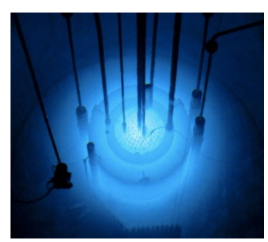
CEvNS as a **background**
for signatures of new physics (DM)



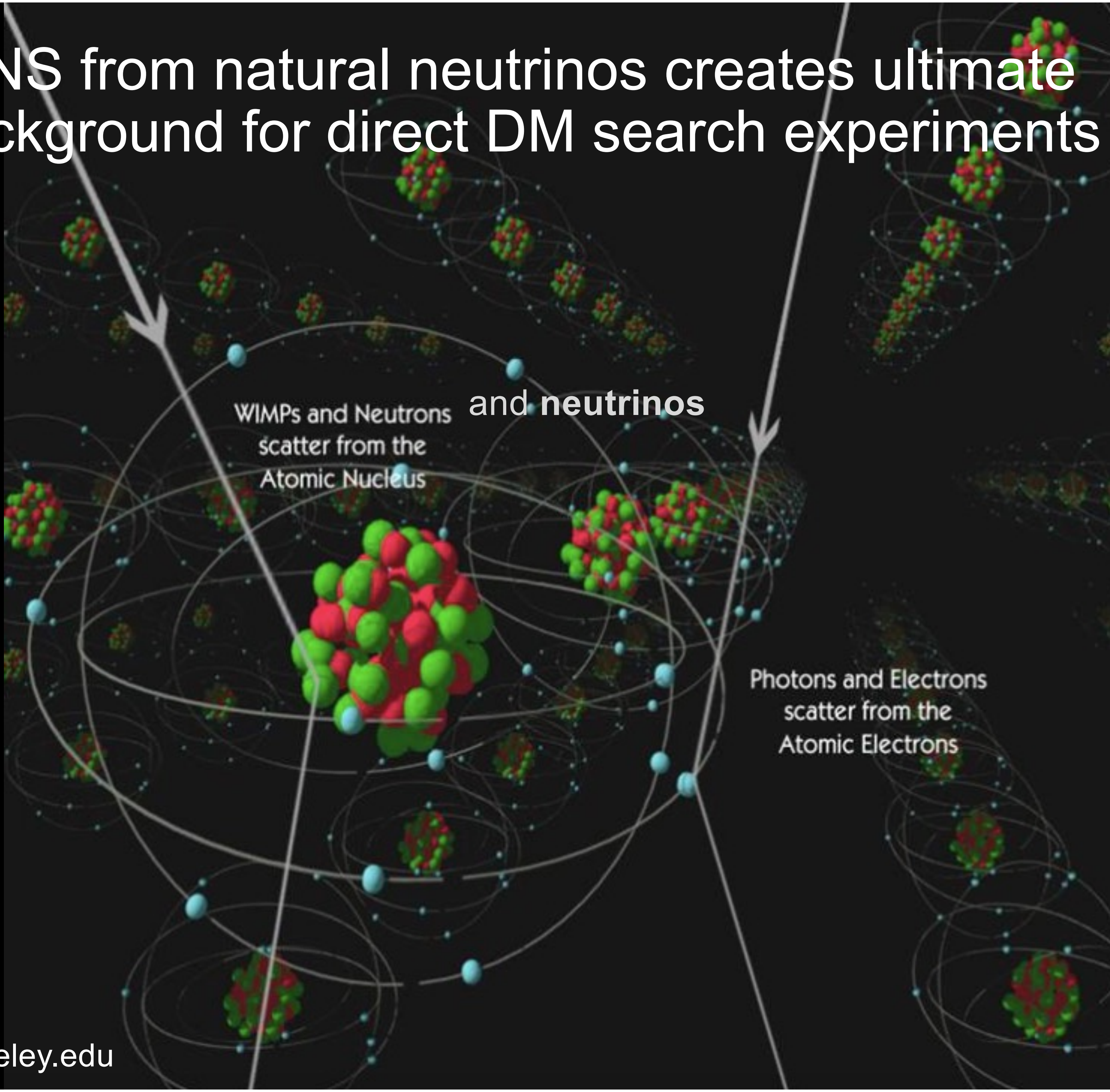
CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**

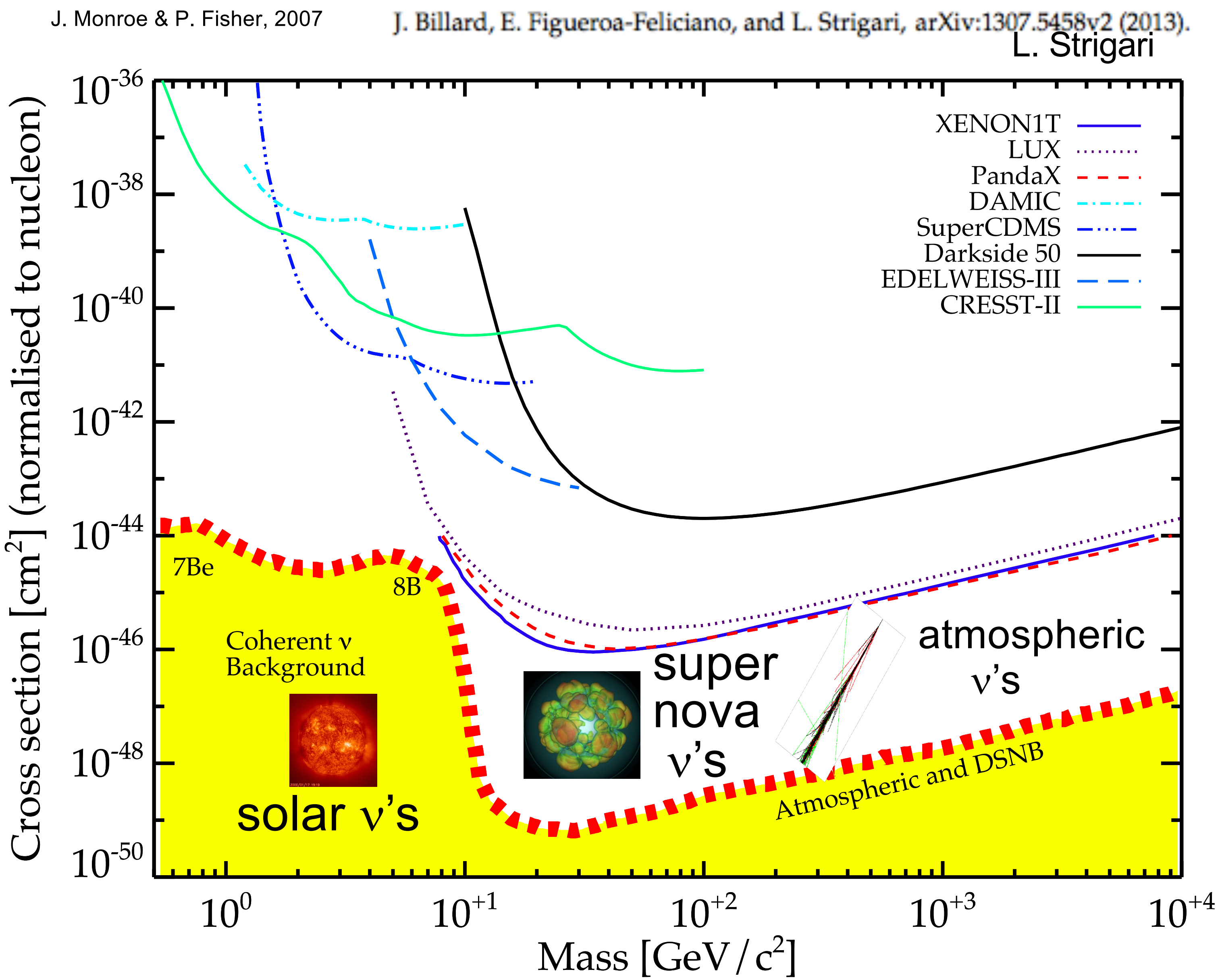


CEvNS from natural neutrinos creates ultimate background for direct DM search experiments



cdms.berkeley.edu

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



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

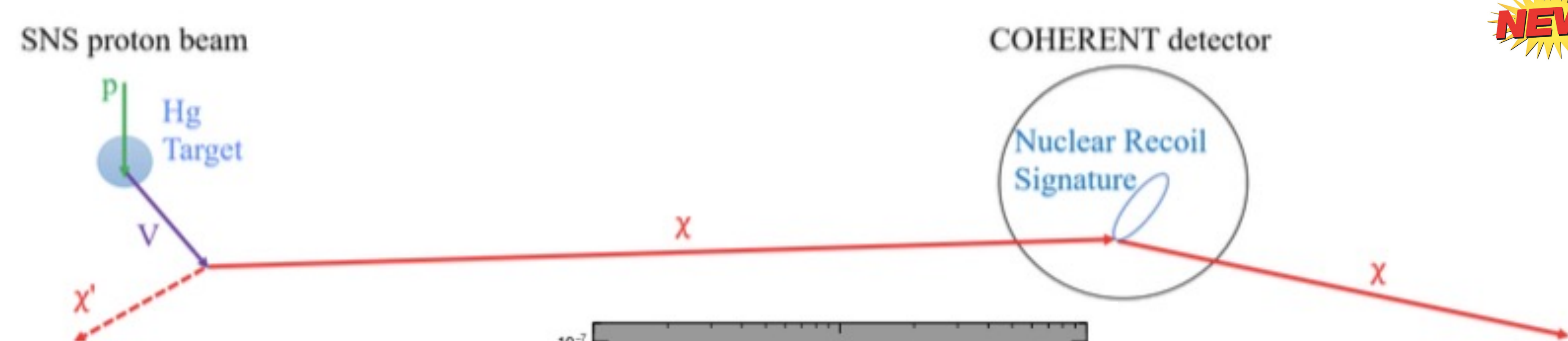
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

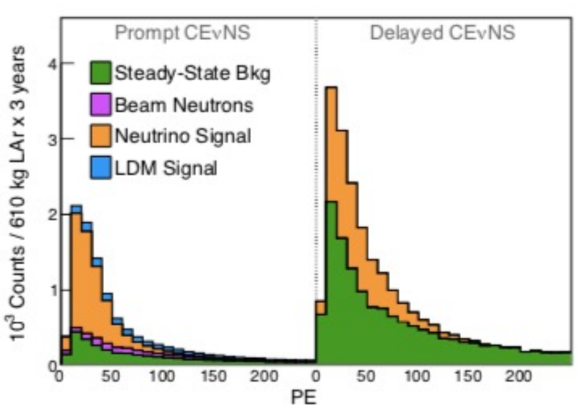
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

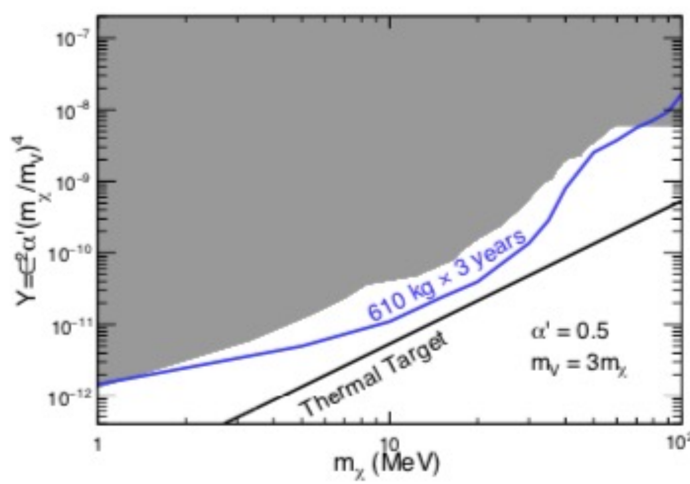
B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)

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

NEW!







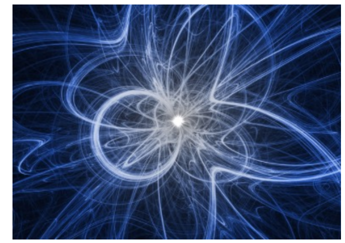
Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

CEvNS: what's it good for?

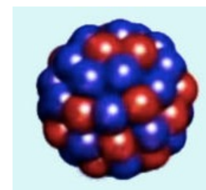
!

(not a complete list!)

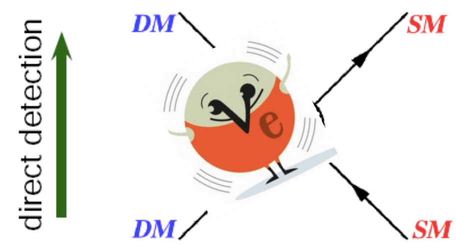
CEvNS as a **signal**
for signatures of *new physics*



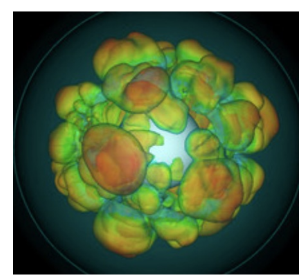
CEvNS as a **signal**
for understanding of "old" physics



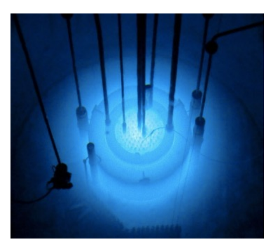
CEvNS as a **background**
for signatures of new physics (DM)



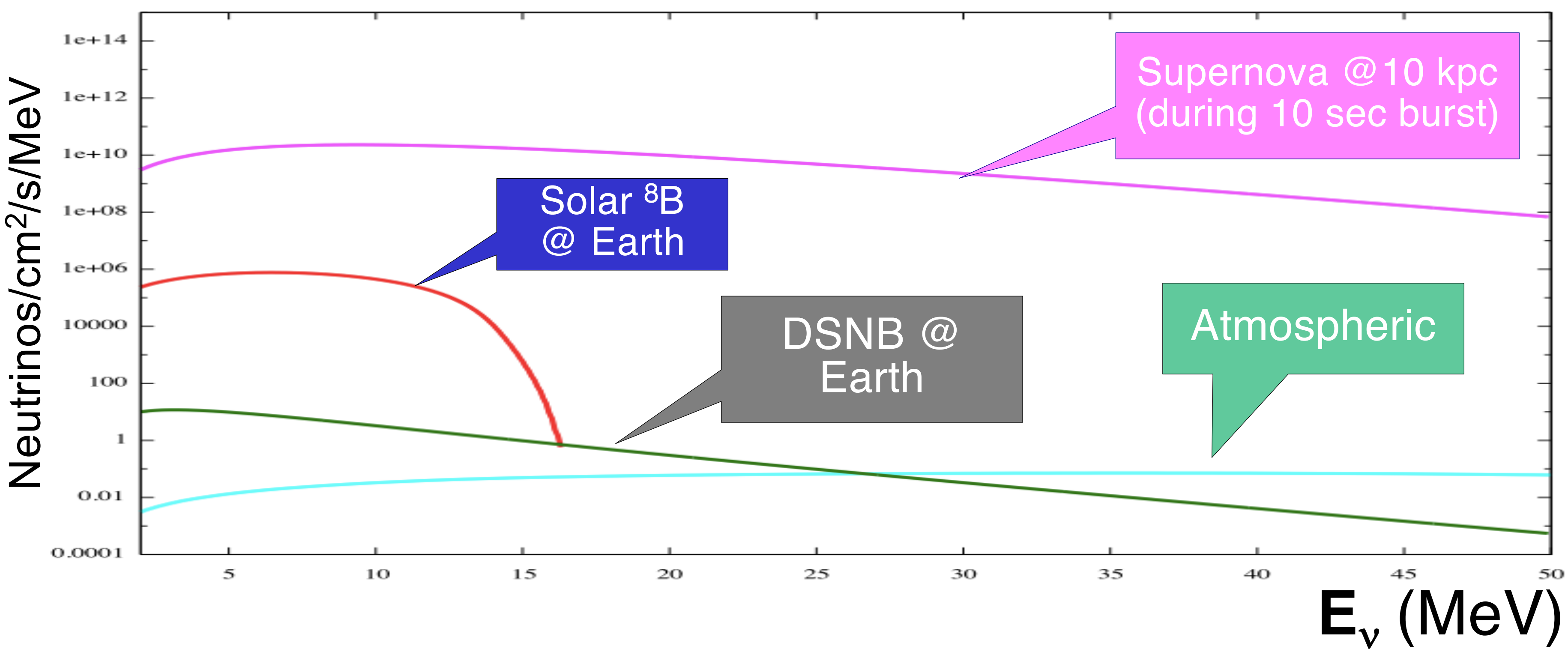
CEvNS as a **signal** for *astrophysics*



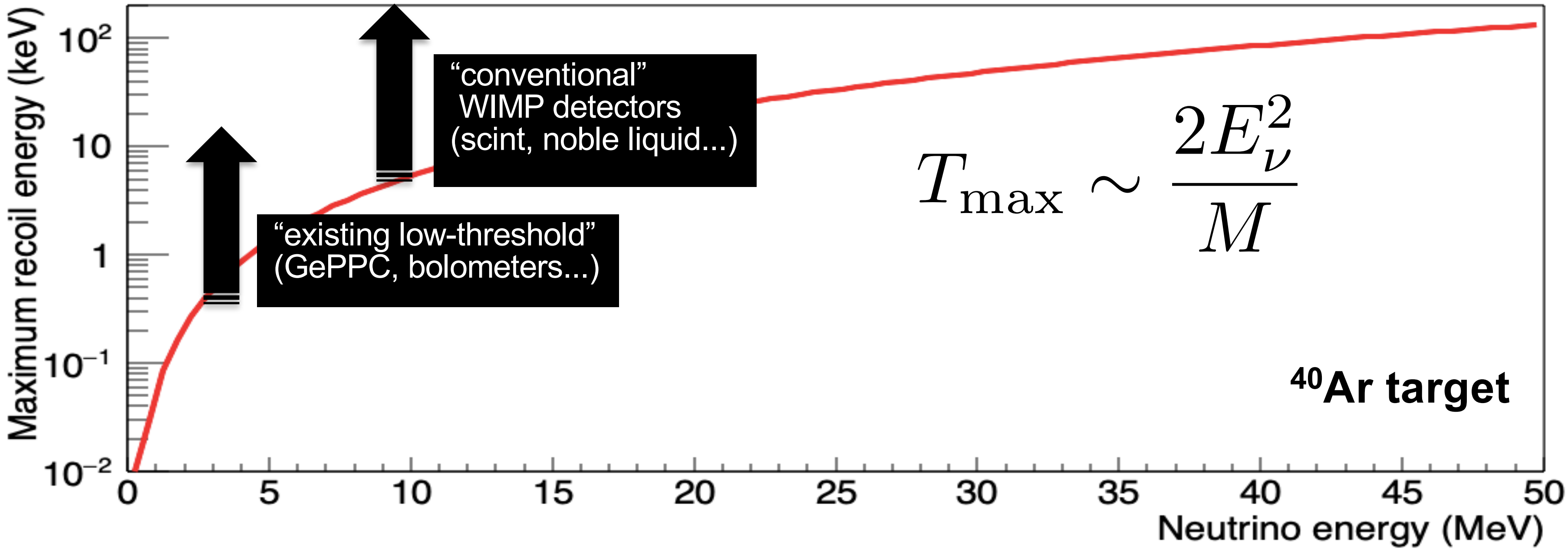
CEvNS as a **practical tool**

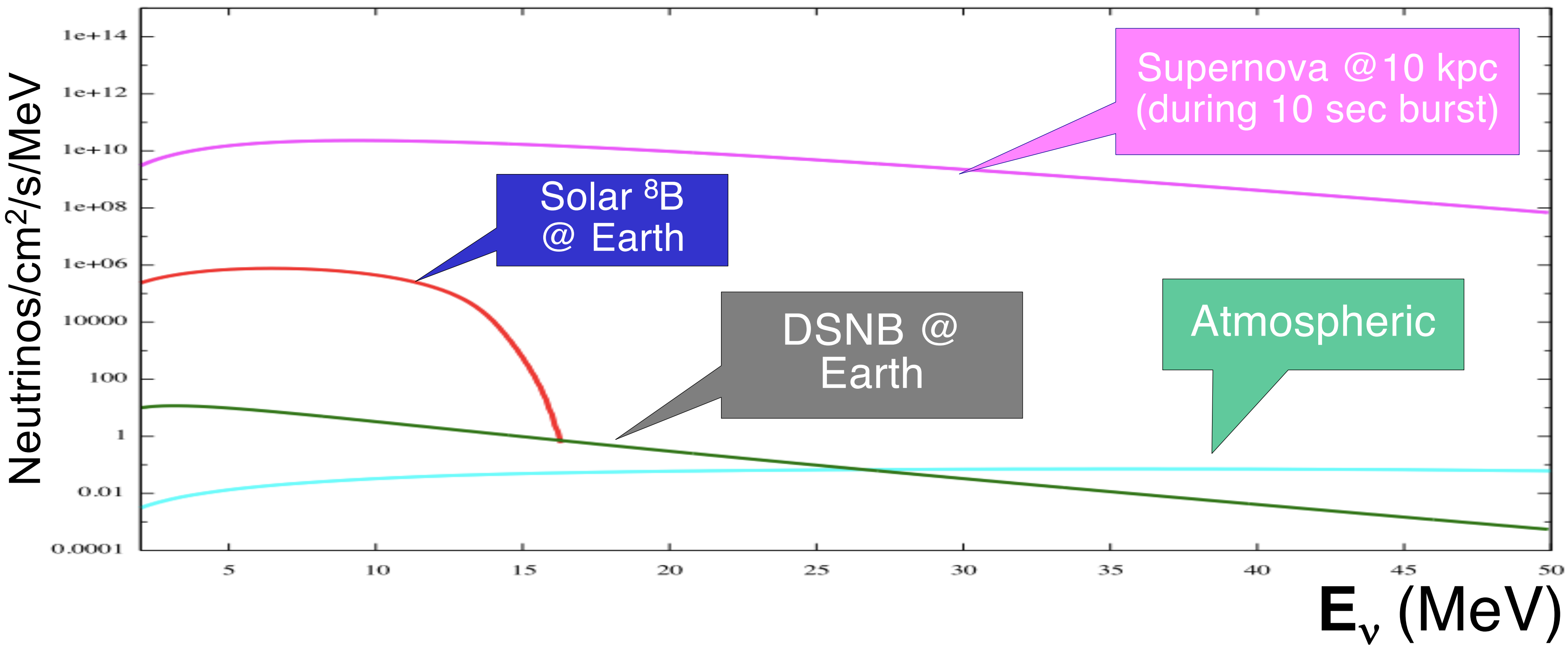


Natural neutrino fluxes



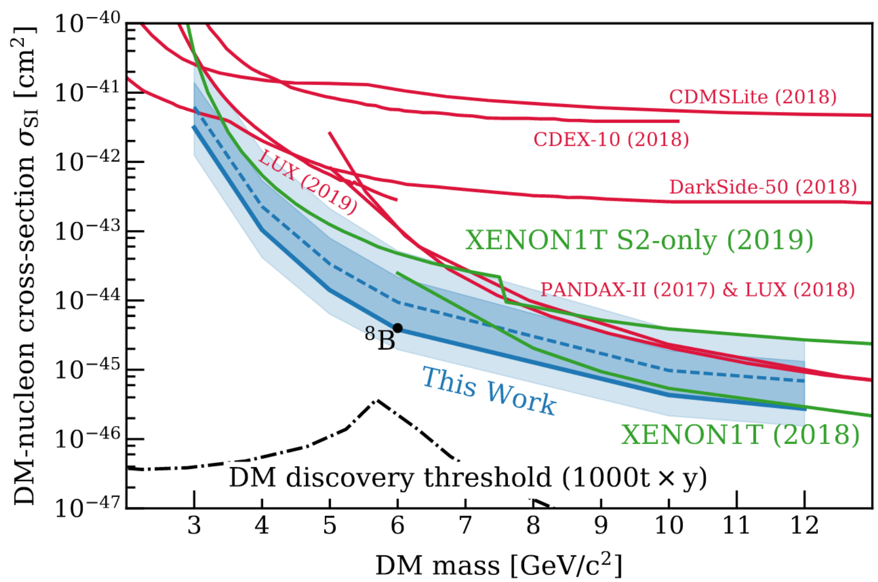
Natural neutrino fluxes



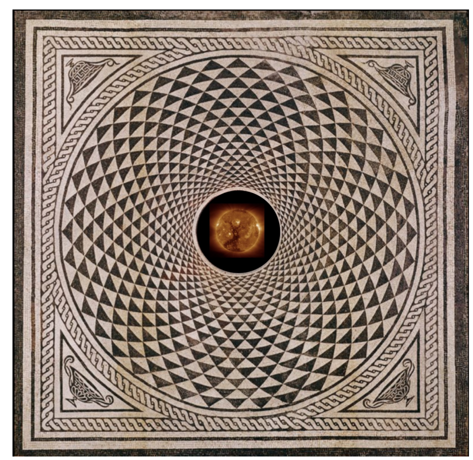


Search for CEvNS from solar neutrinos with the XENON-1T experiment

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...

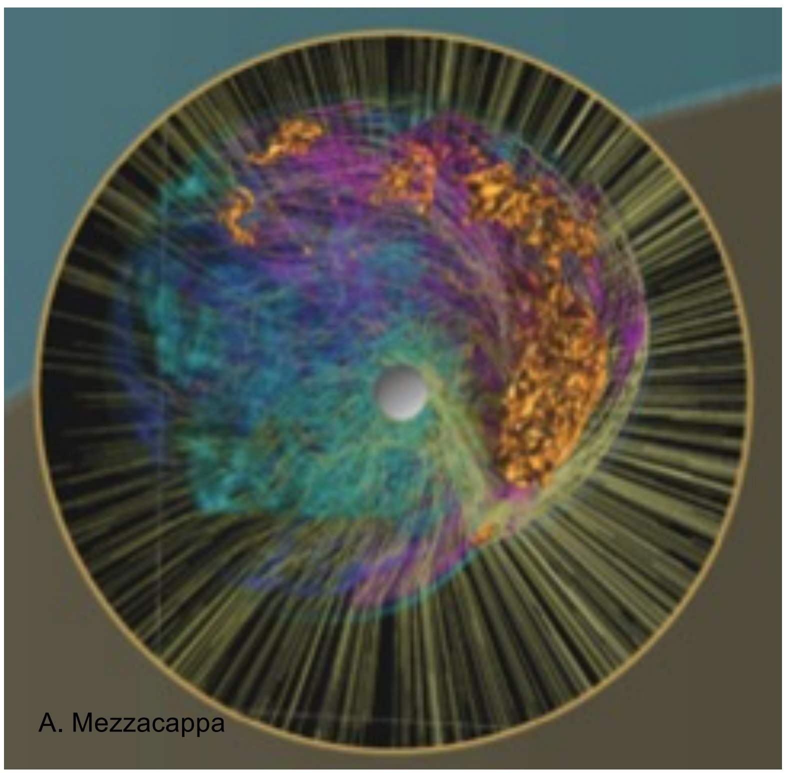


Neutrinos from core-collapse supernovae

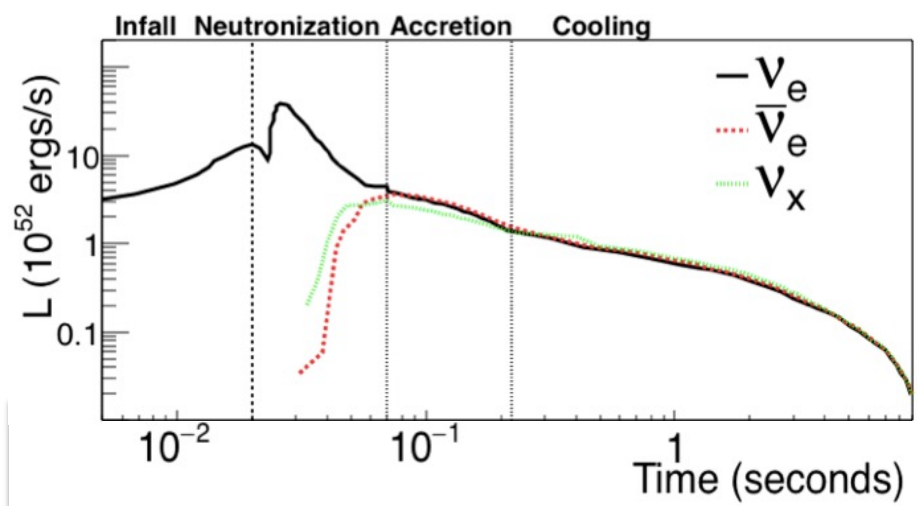
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

Energy *can* escape via ν's

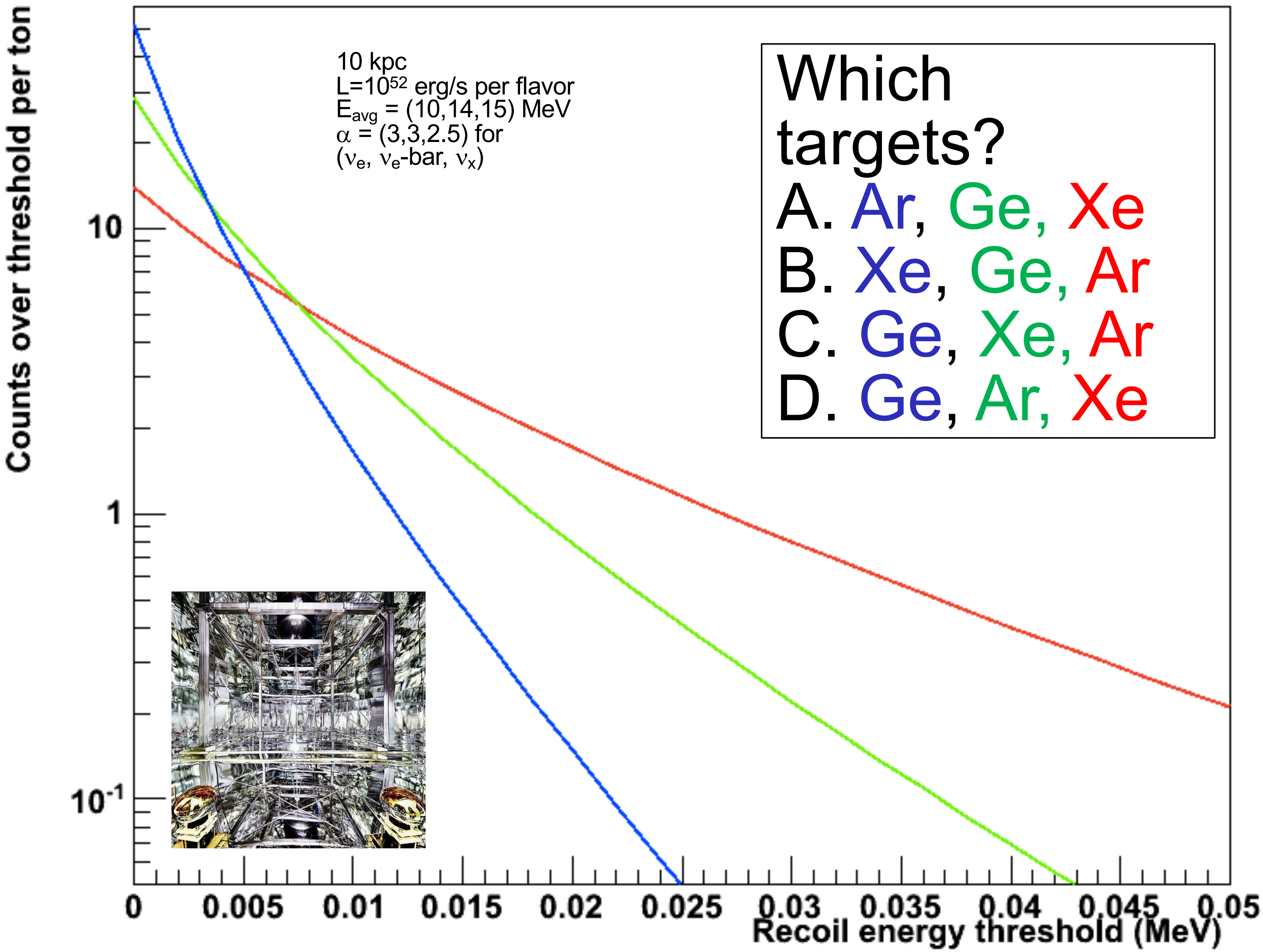
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



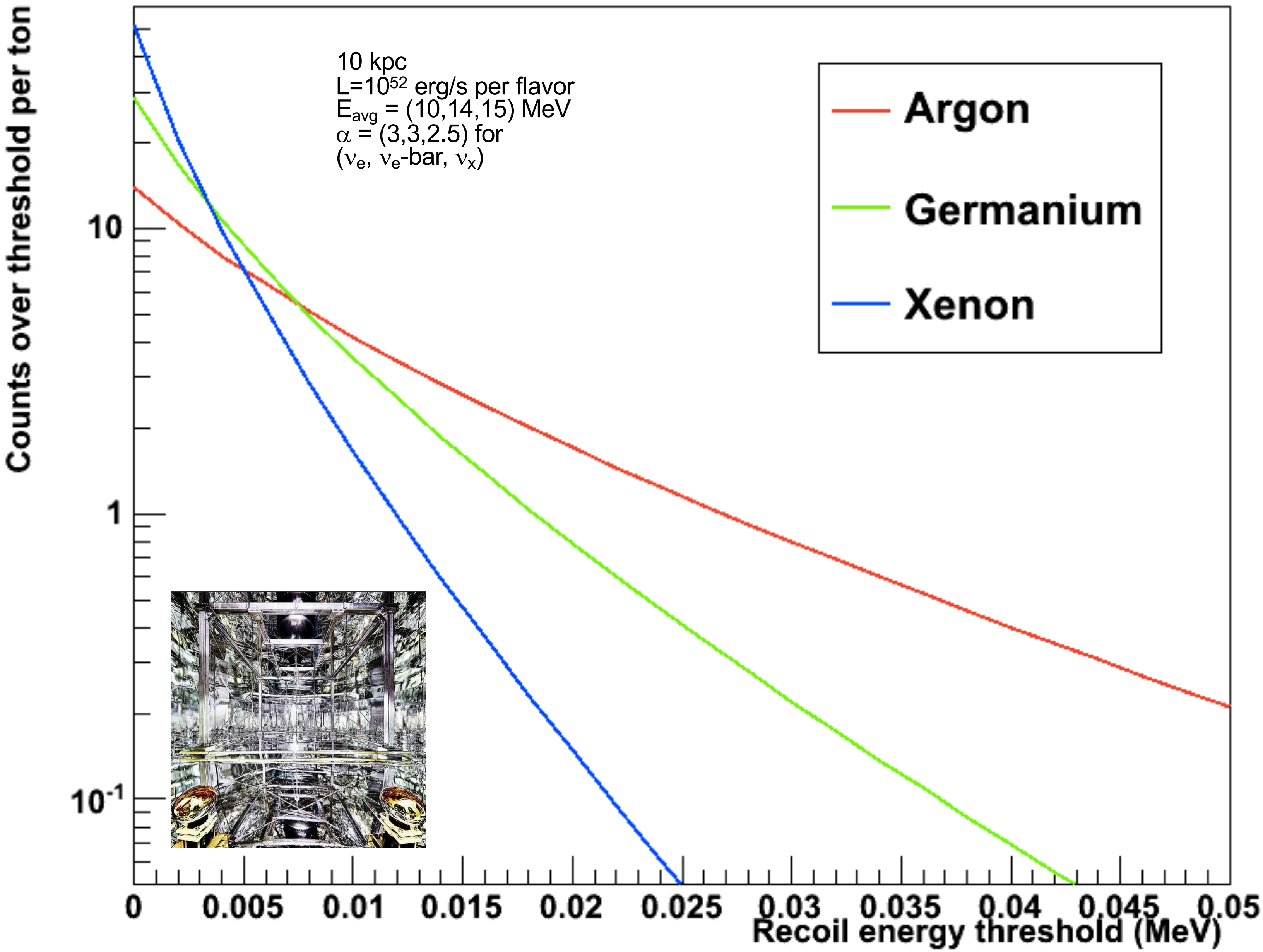
Timescale: *prompt* after core collapse, overall Δt~10's of seconds



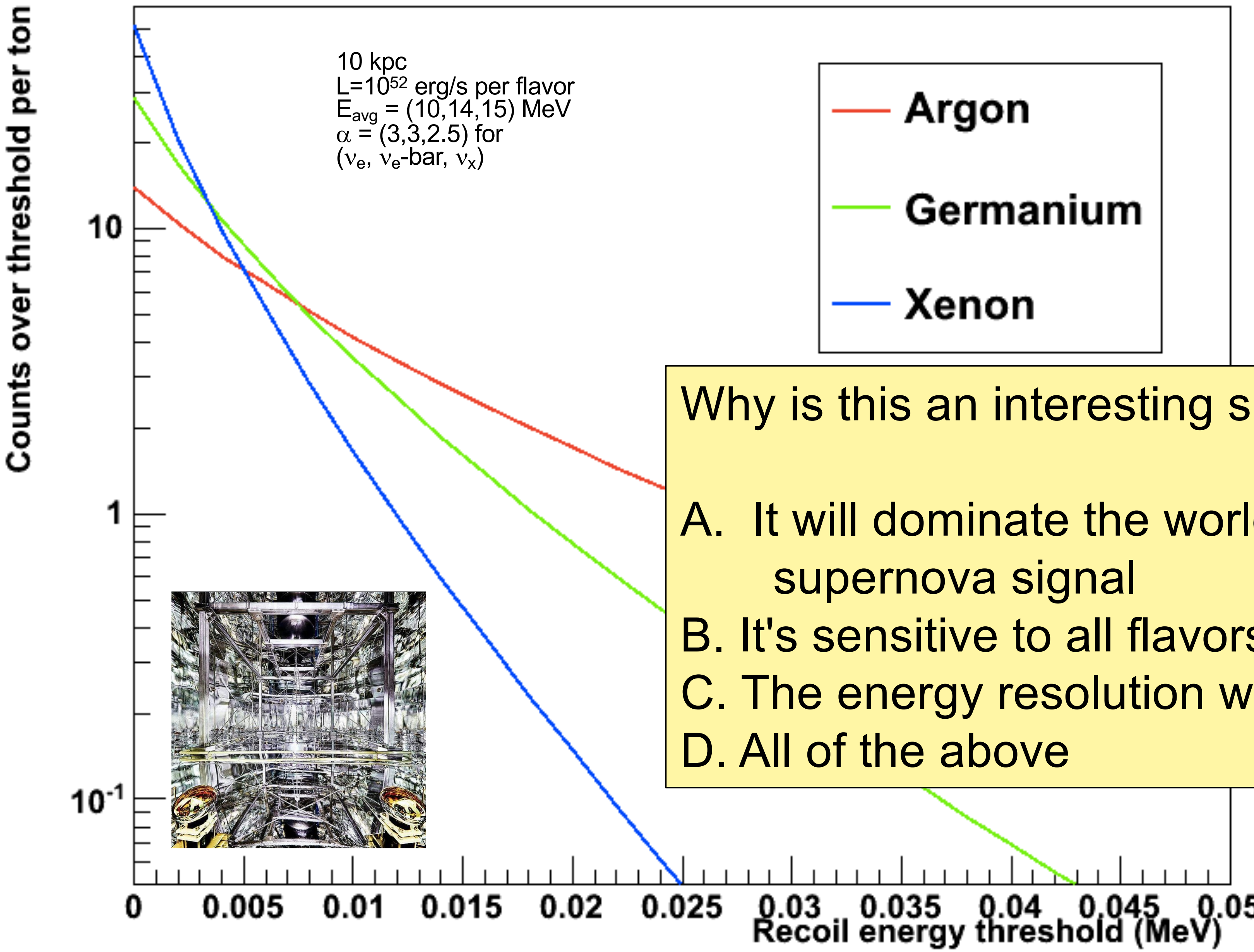
Supernova neutrinos in tonne-scale DM detectors



Supernova neutrinos in tonne-scale DM detectors



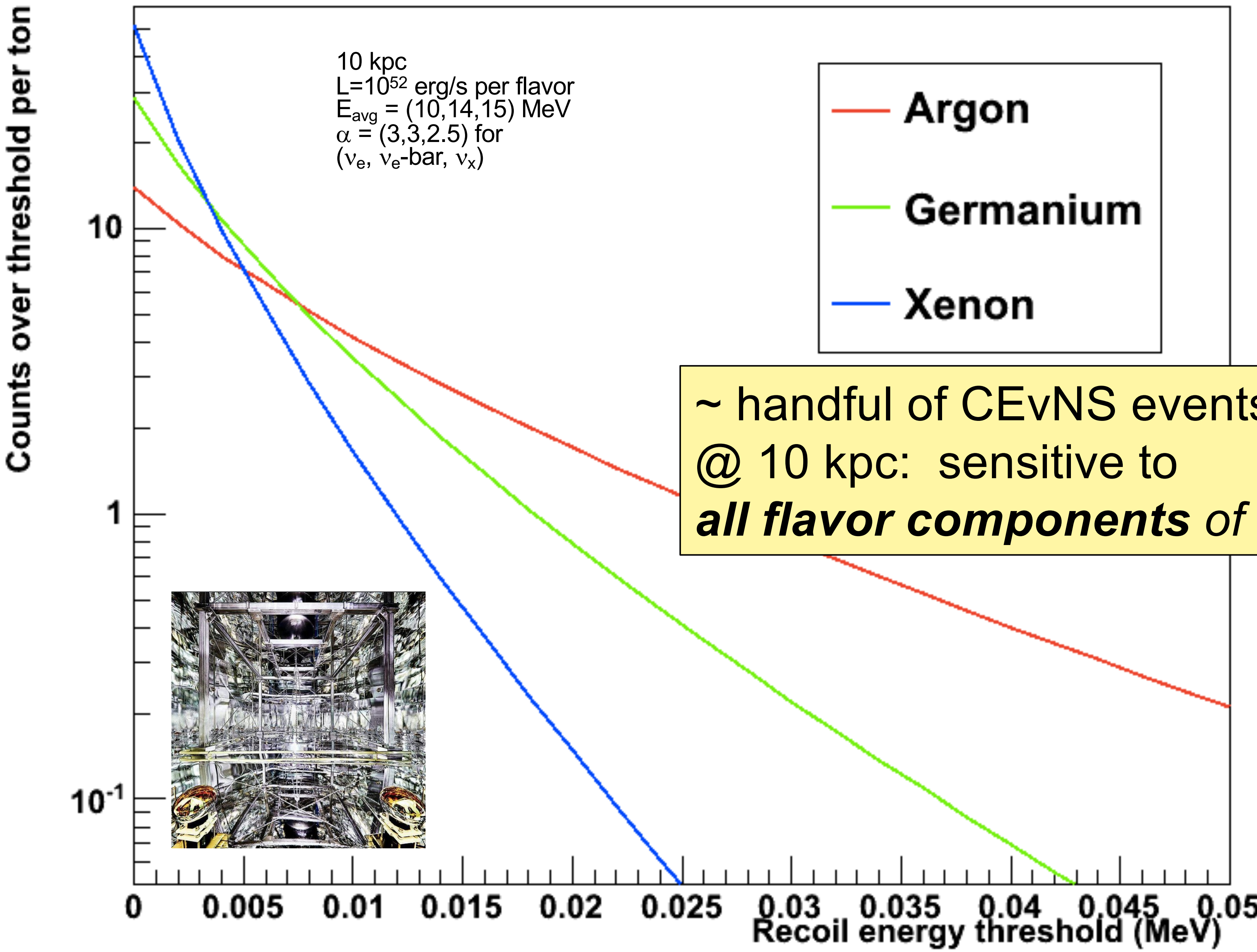
Supernova neutrinos in tonne-scale DM detectors



Why is this an interesting signal?

A. It will dominate the worldwide supernova signal
B. It's sensitive to all flavors of the burst
C. The energy resolution will be good
D. All of the above

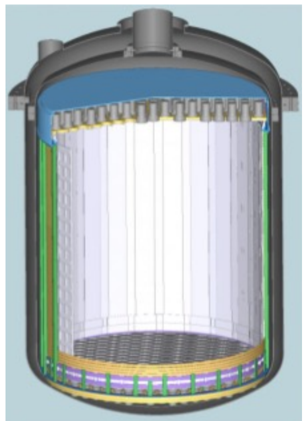
Supernova neutrinos in tonne-scale DM detectors

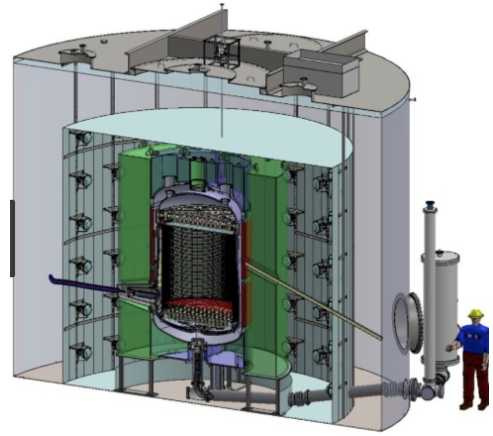


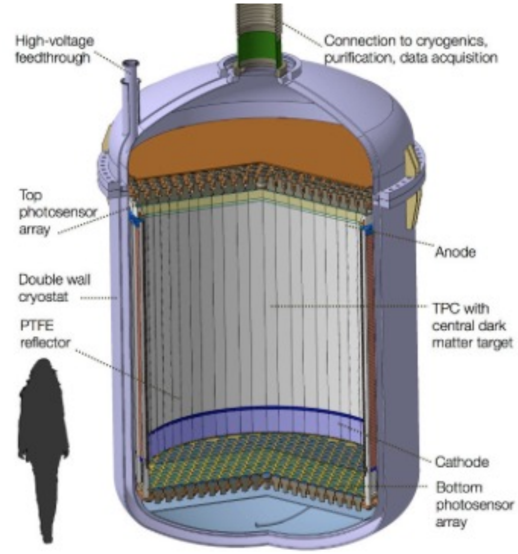
~ handful of CEvNS events per tonne @ 10 kpc: sensitive to ***all flavor components*** *of the flux*

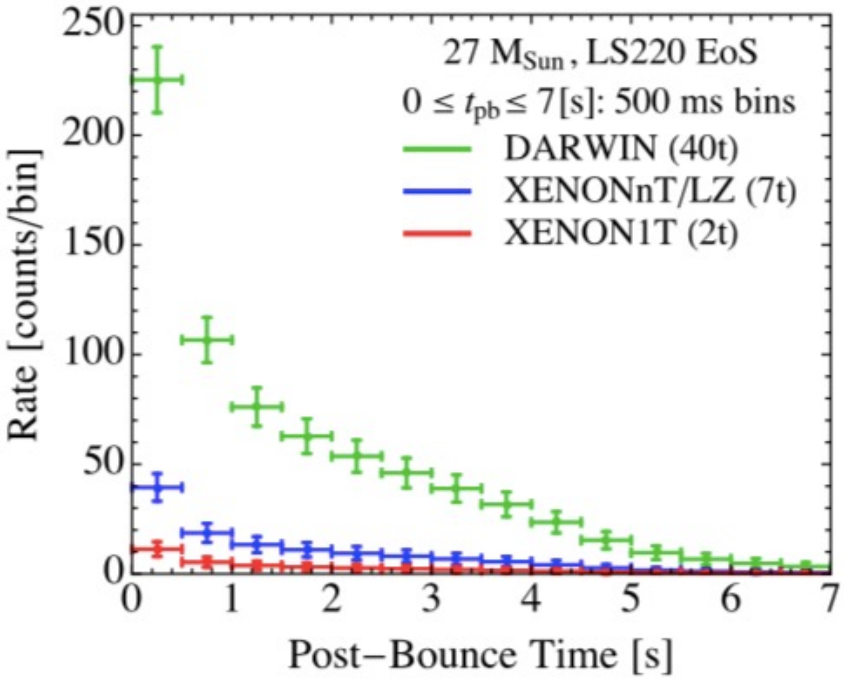
Detector example: **XENON/LZ/DARWIN**

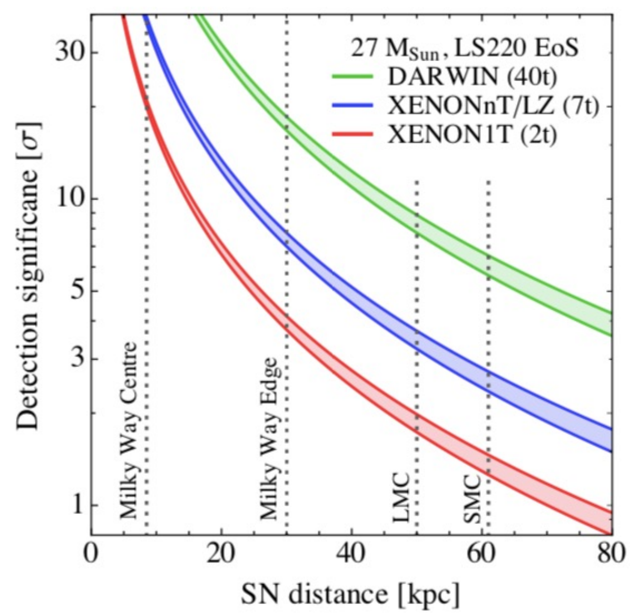
- dual-phase xenon time projection chambers









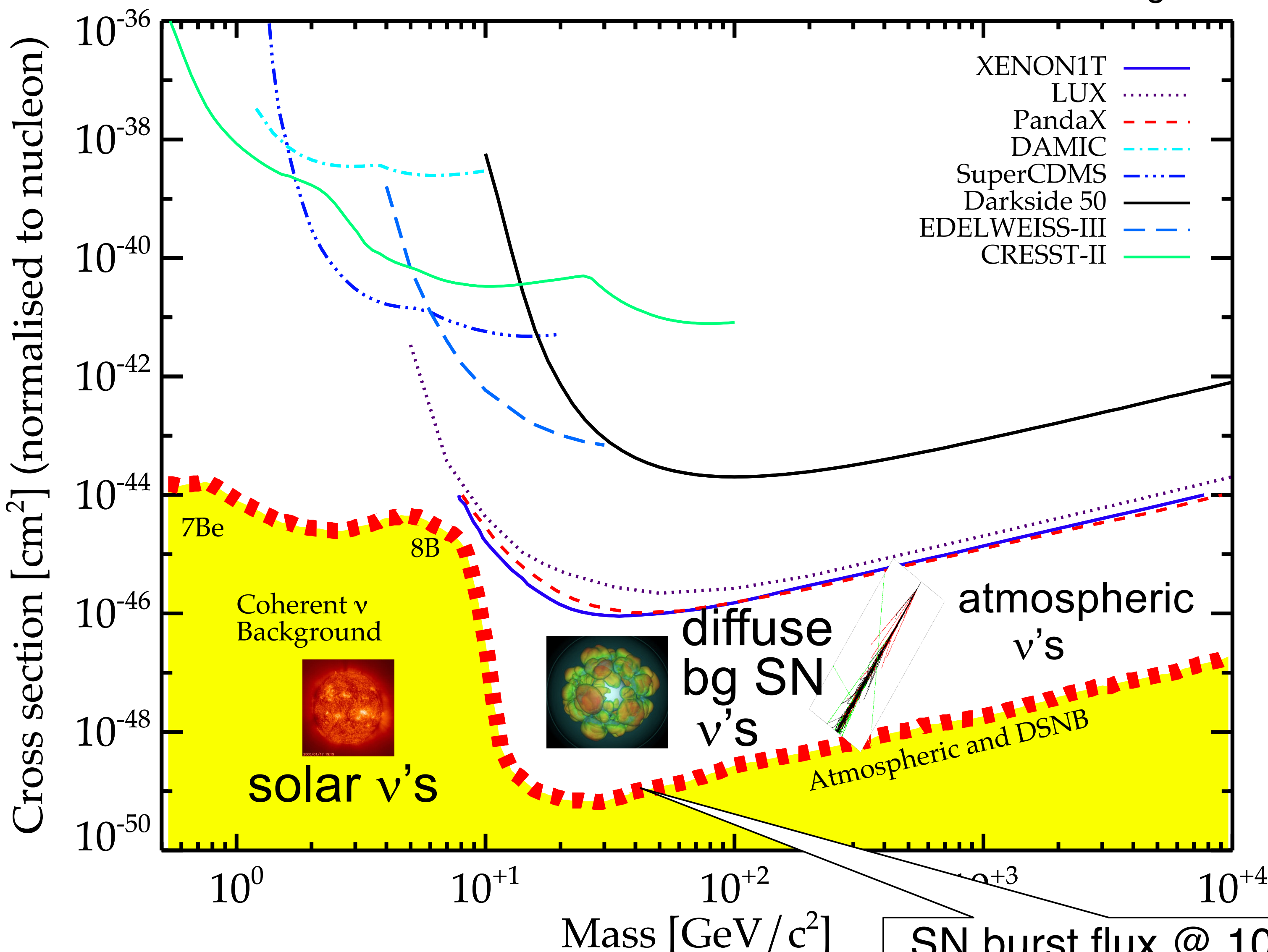


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

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

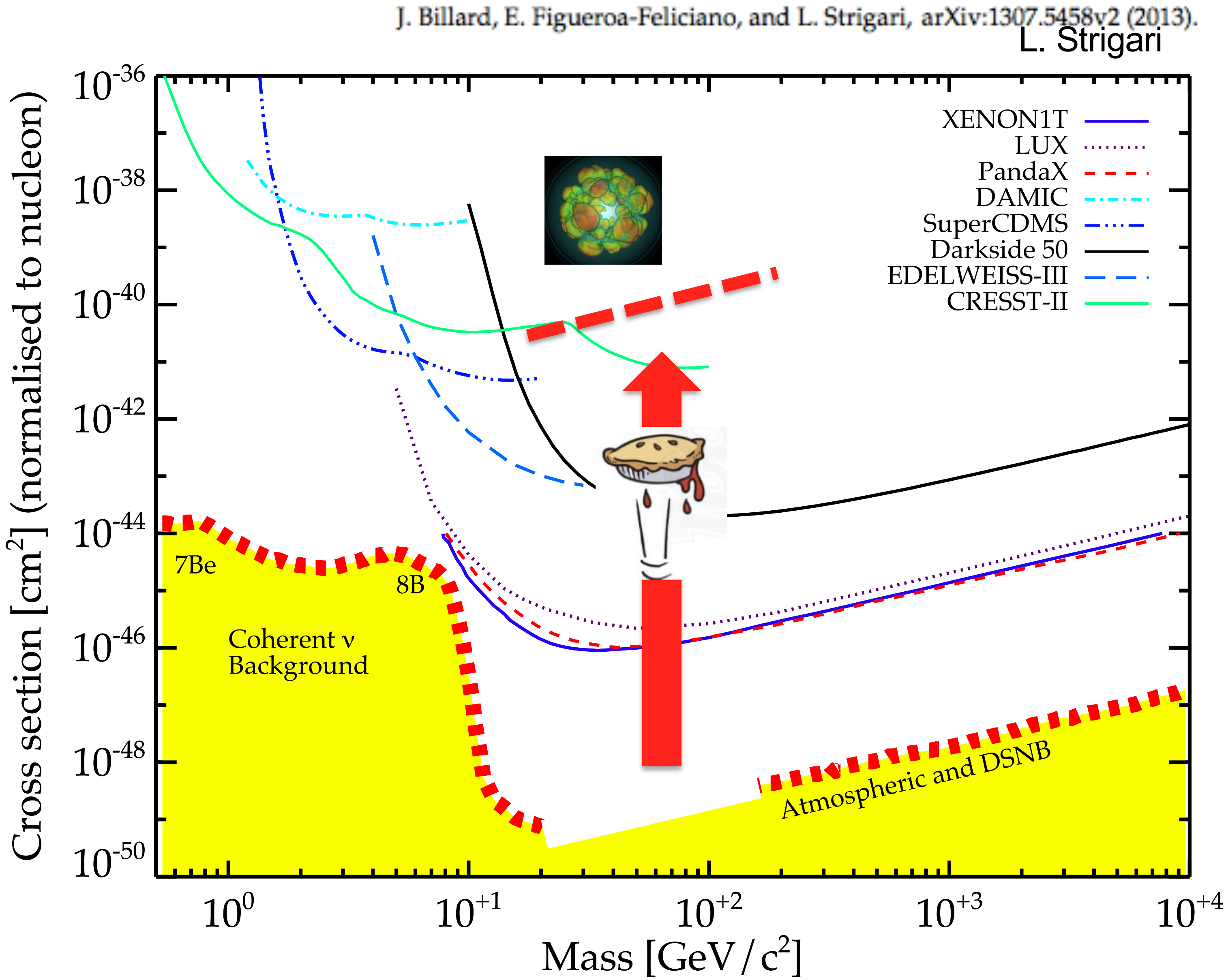
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



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

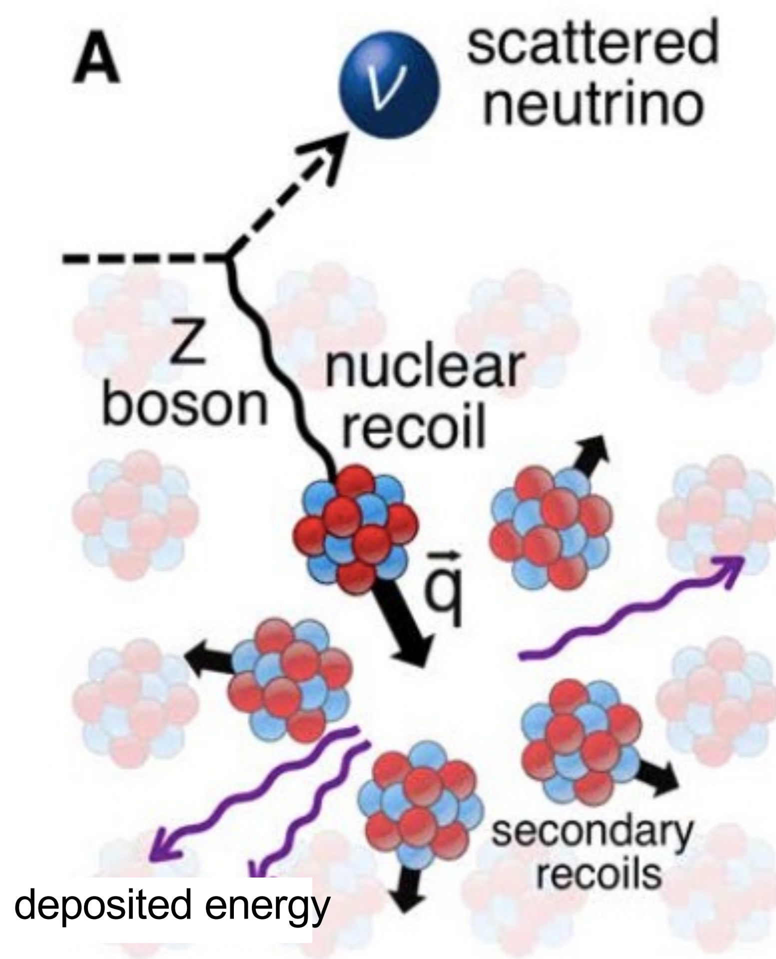
Think of a SN burst as “**the ν floor coming up to meet you**”



How to measure CEvNS

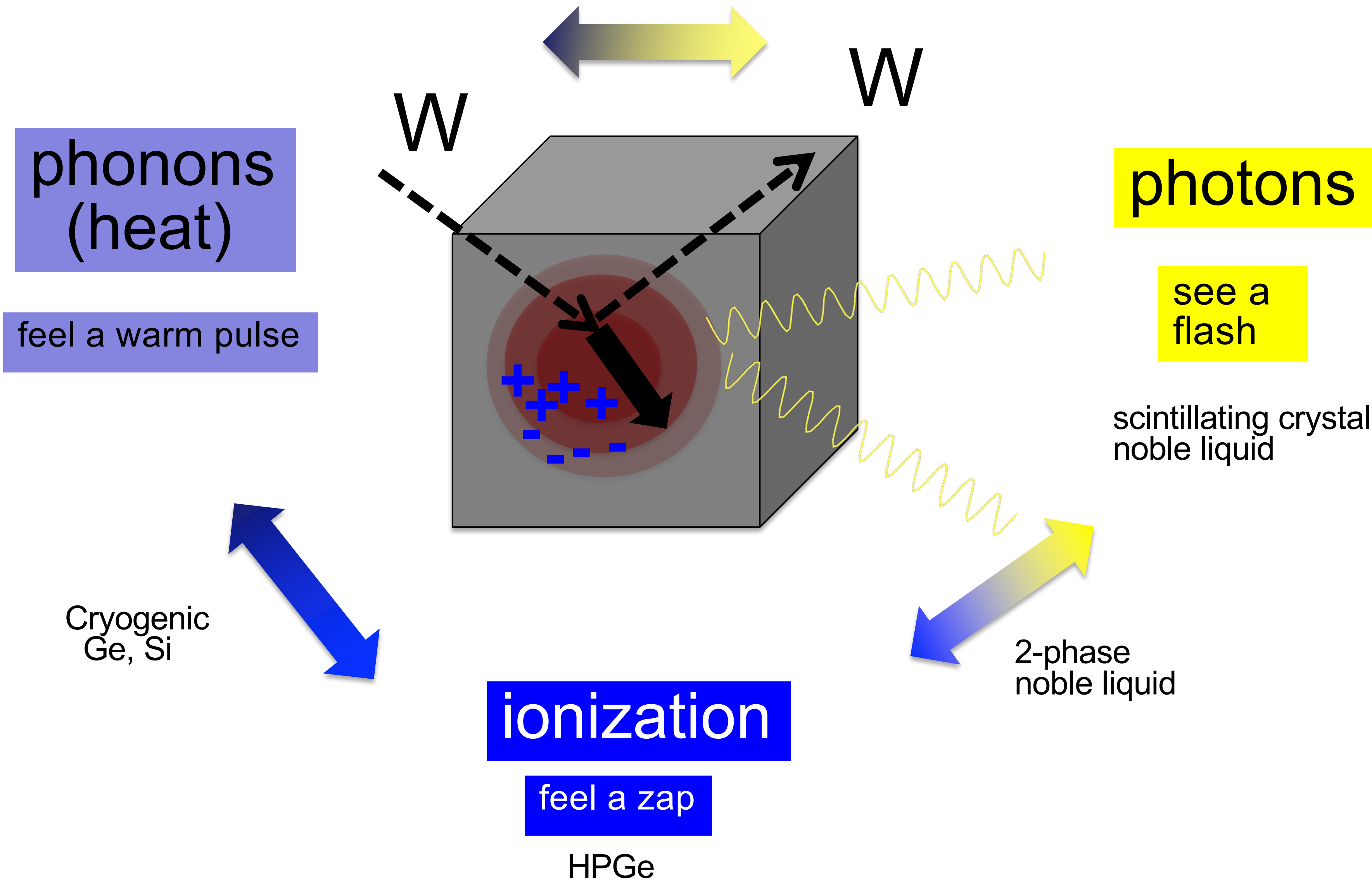
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



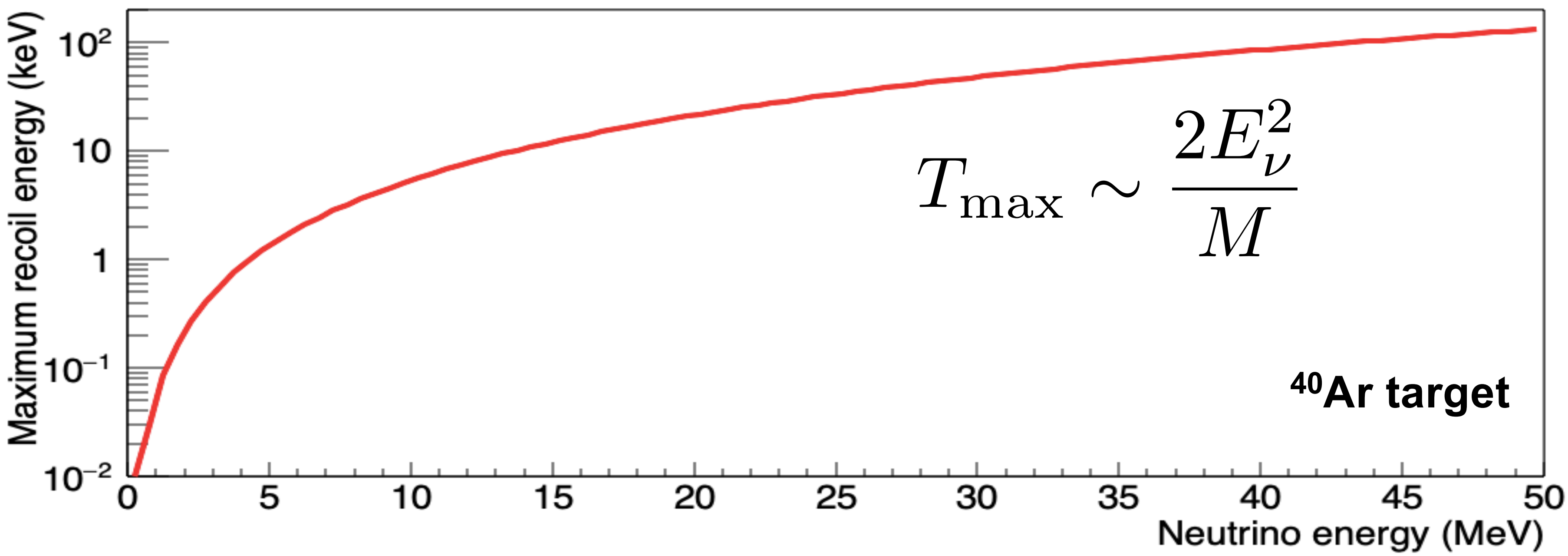
➔ detectors developed over the last ~few decades are sensitive to ~ keV to 10’s of keV recoils

Low-energy nuclear recoil detection strategies

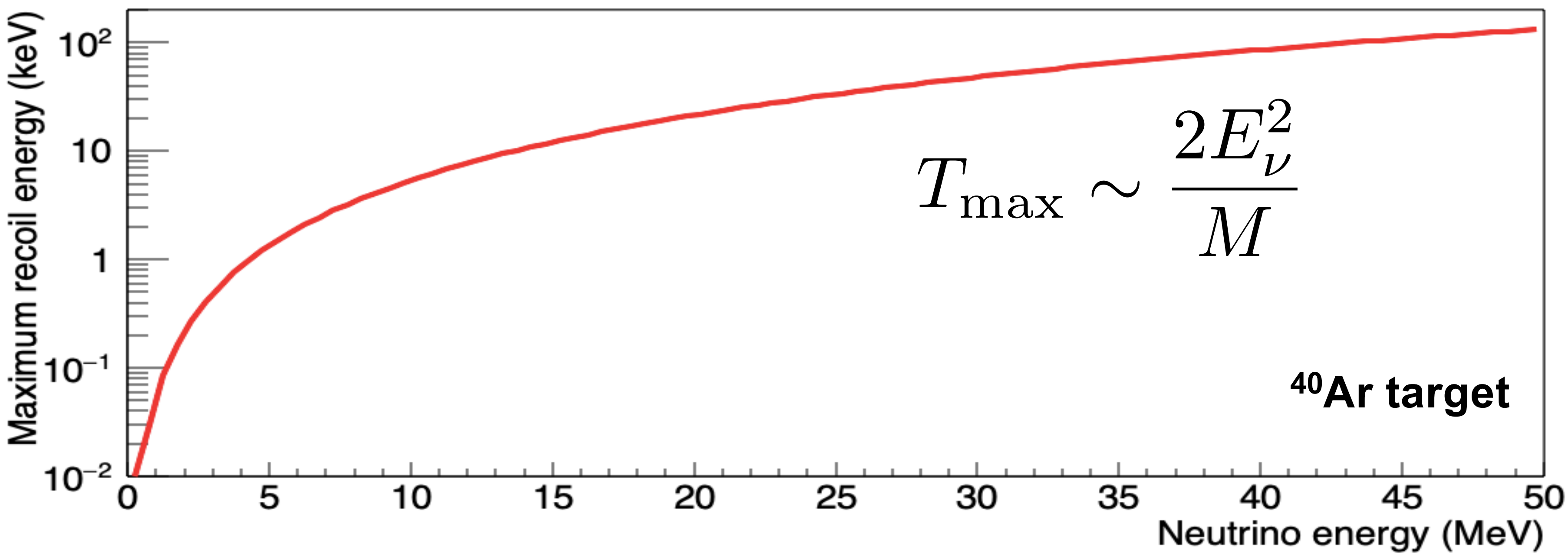


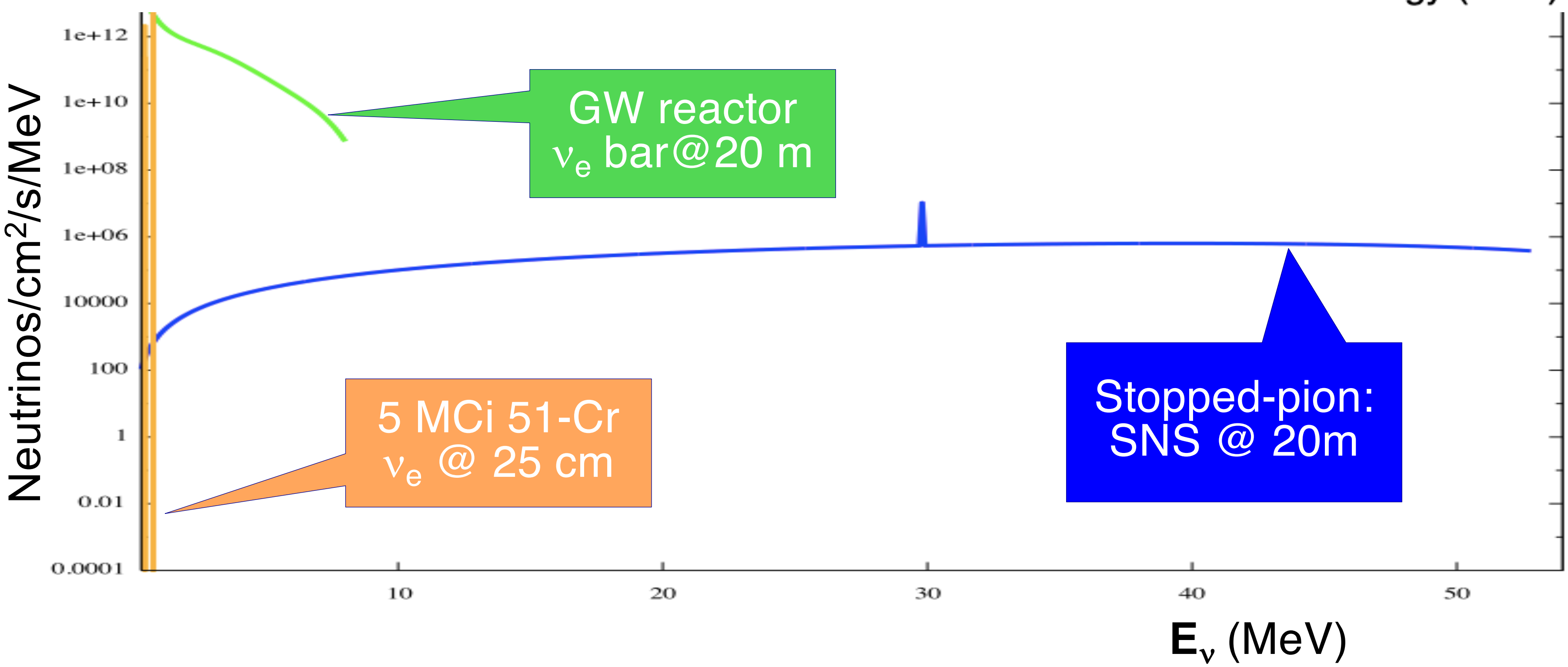
http://dmrc.snu.ac.kr/english/intro/intro1.html

Maximum recoil energy as a function of E_ν

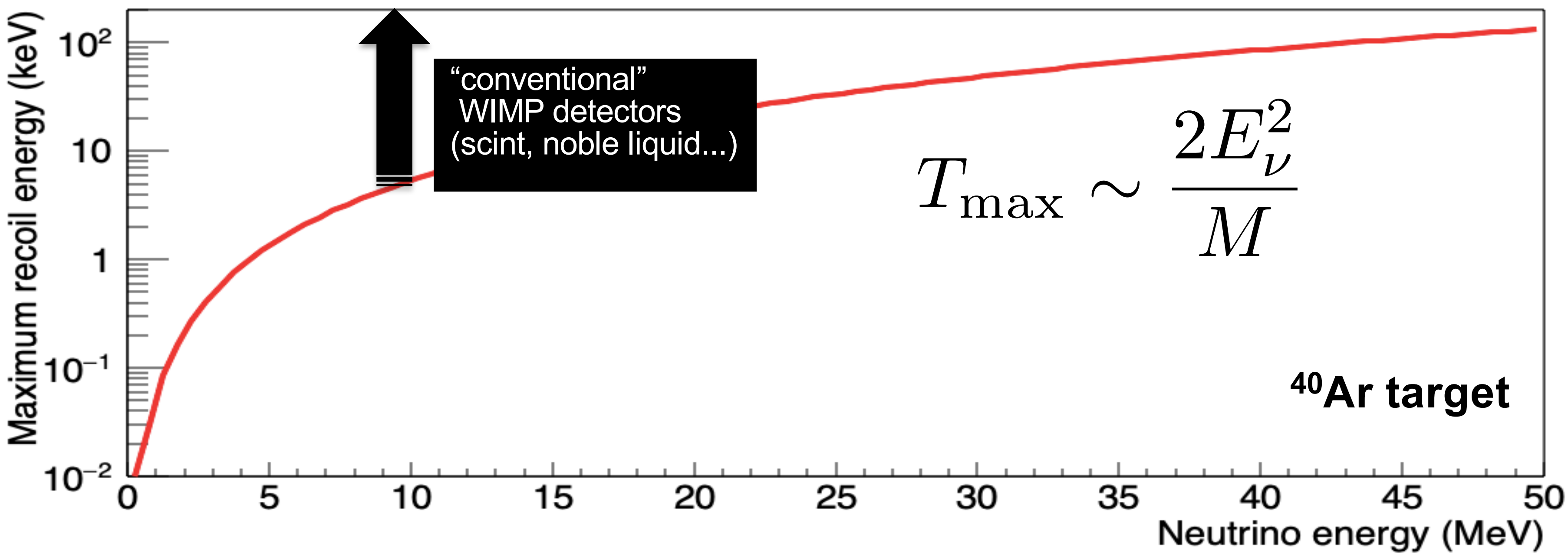


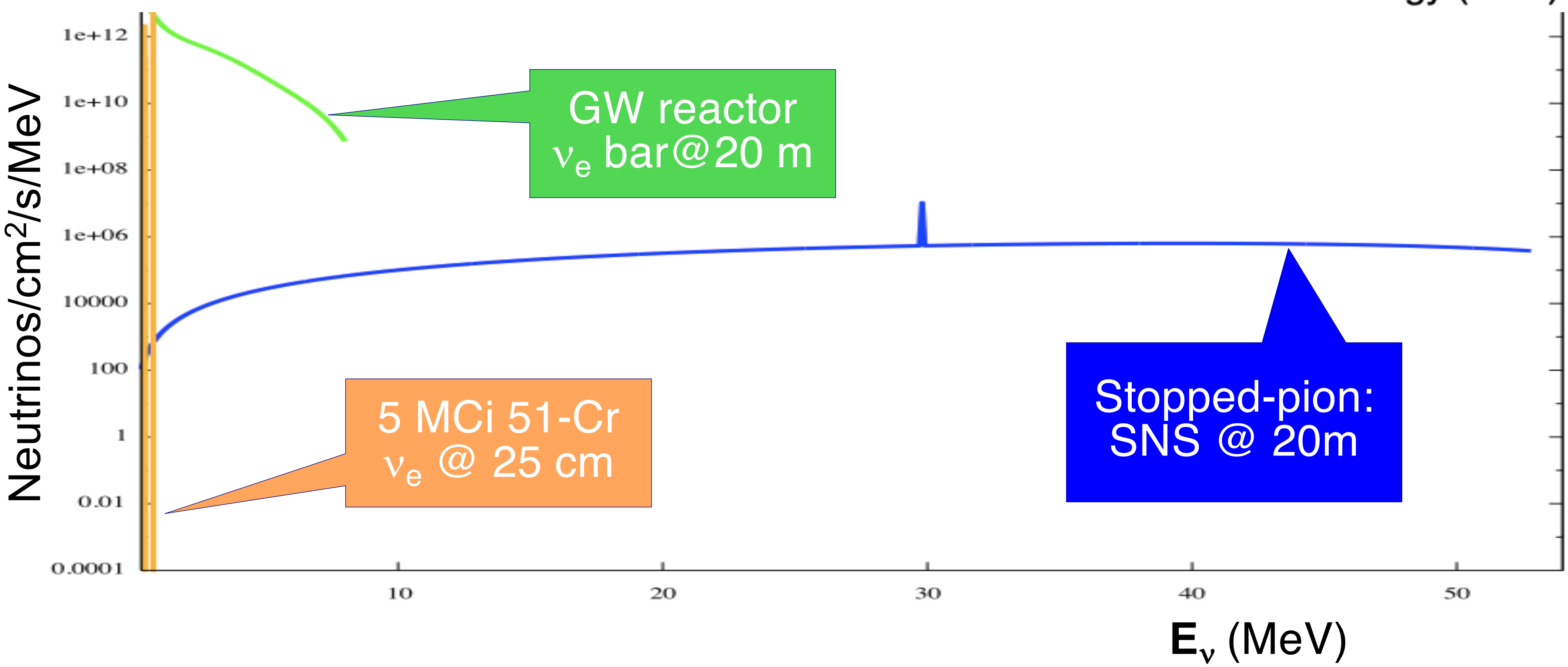
Maximum recoil energy as a function of E_ν



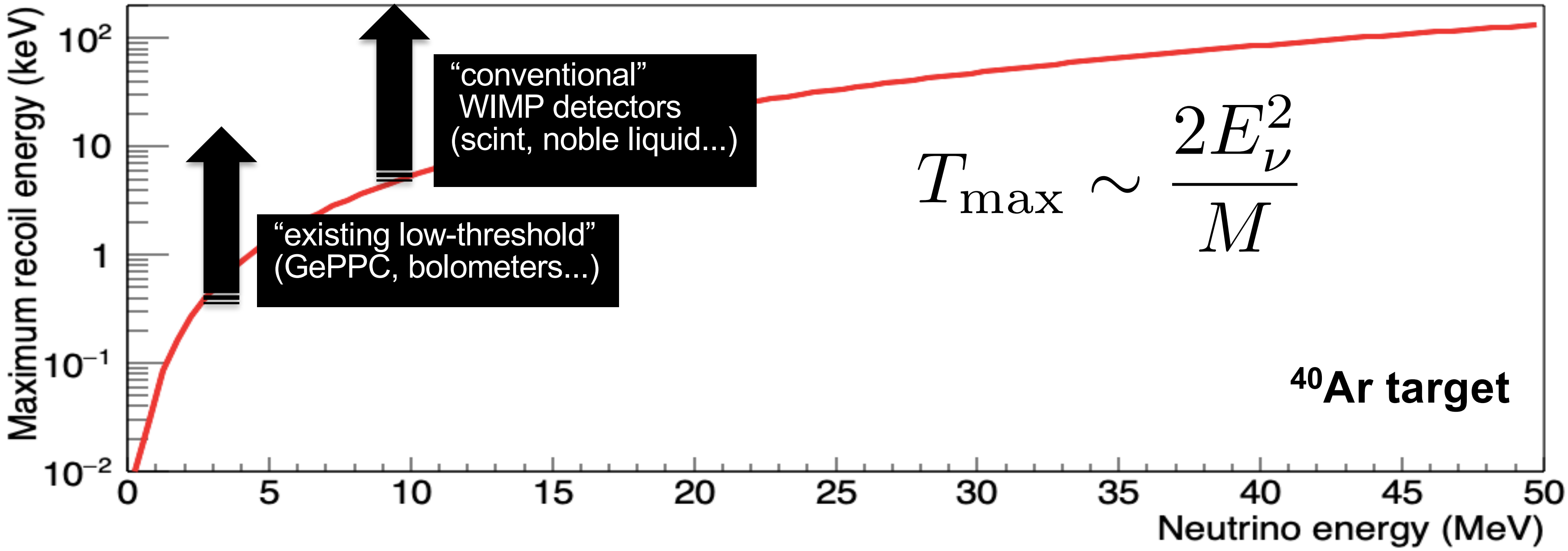


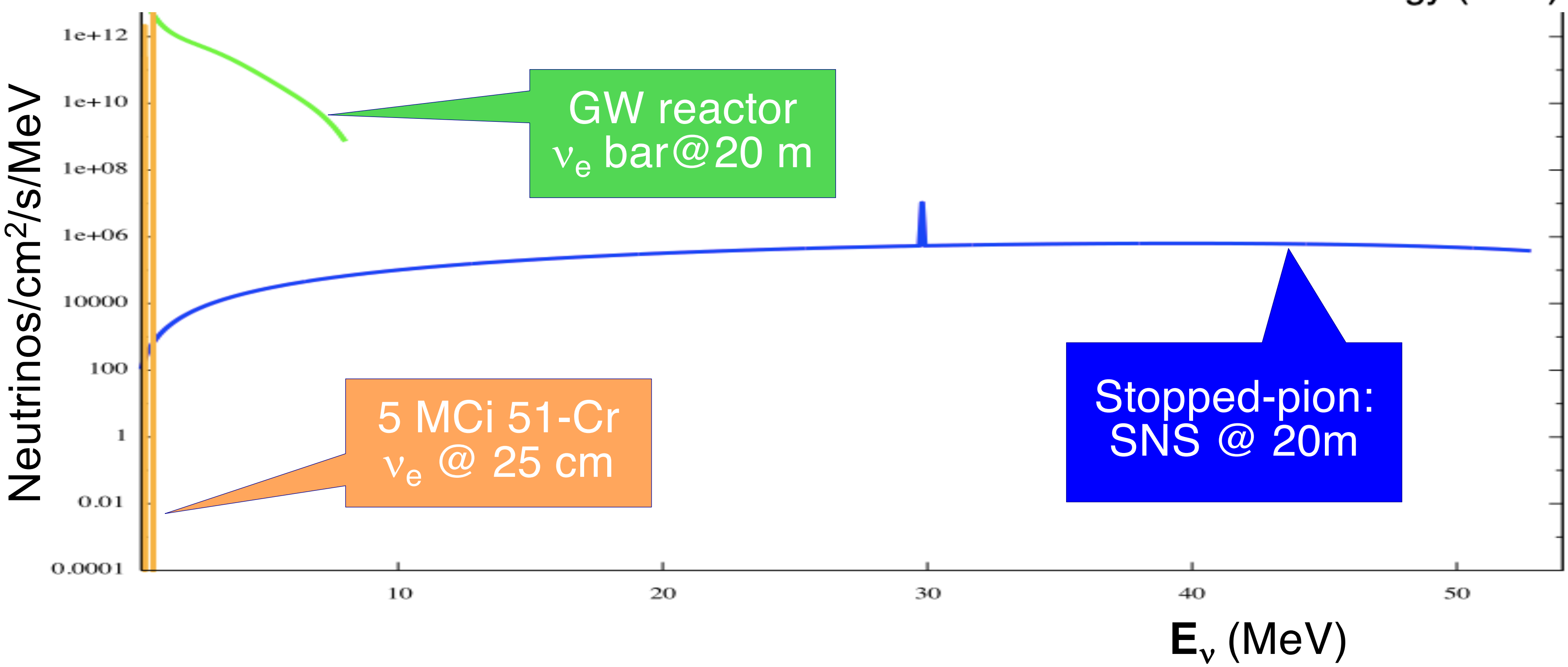
Maximum recoil energy as a function of E_ν



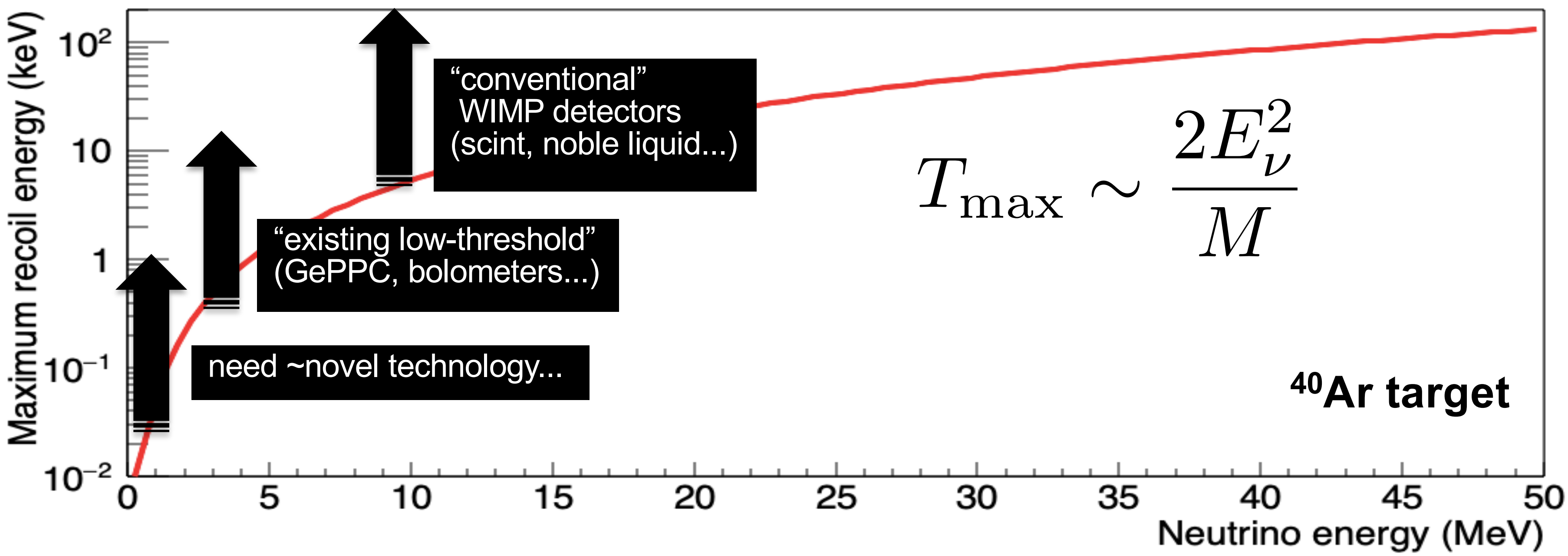


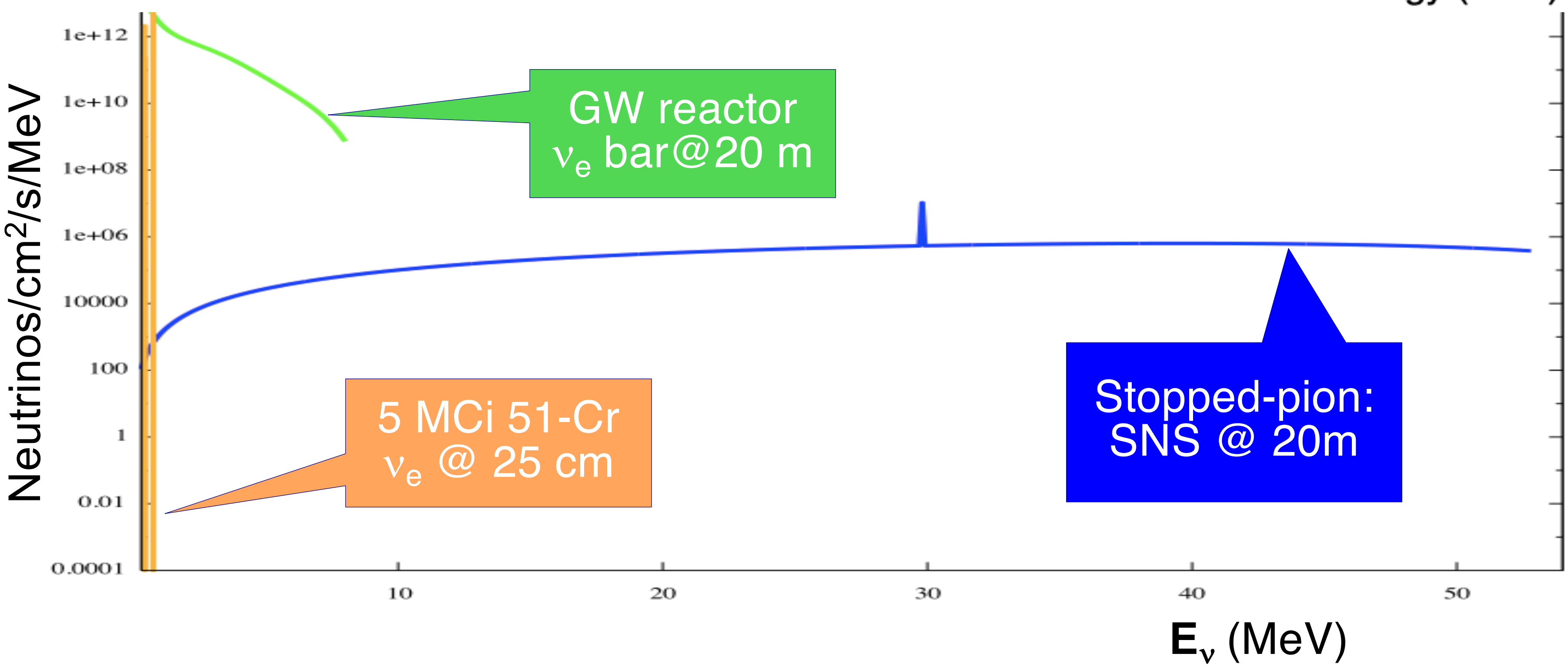
Maximum recoil energy as a function of E_ν





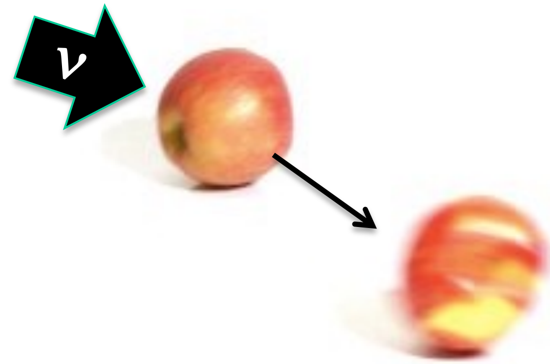
Maximum recoil energy as a function of E_ν





How to detect CEvNS?

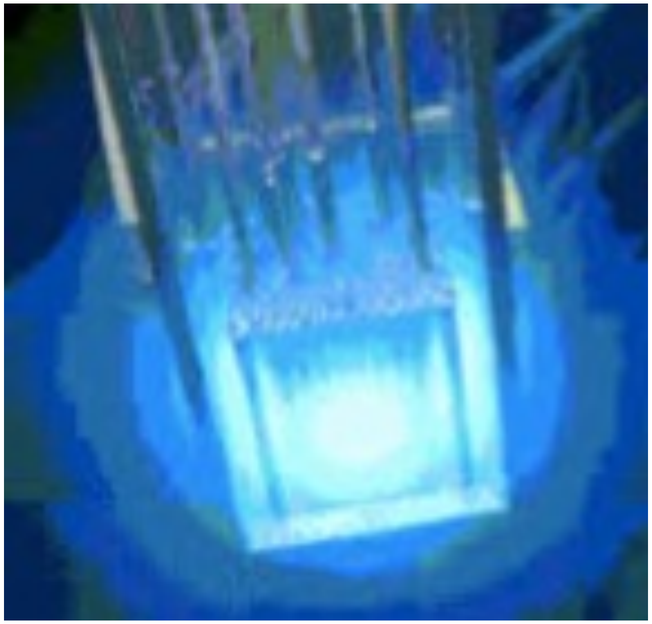
You need a neutrino source
and a detector

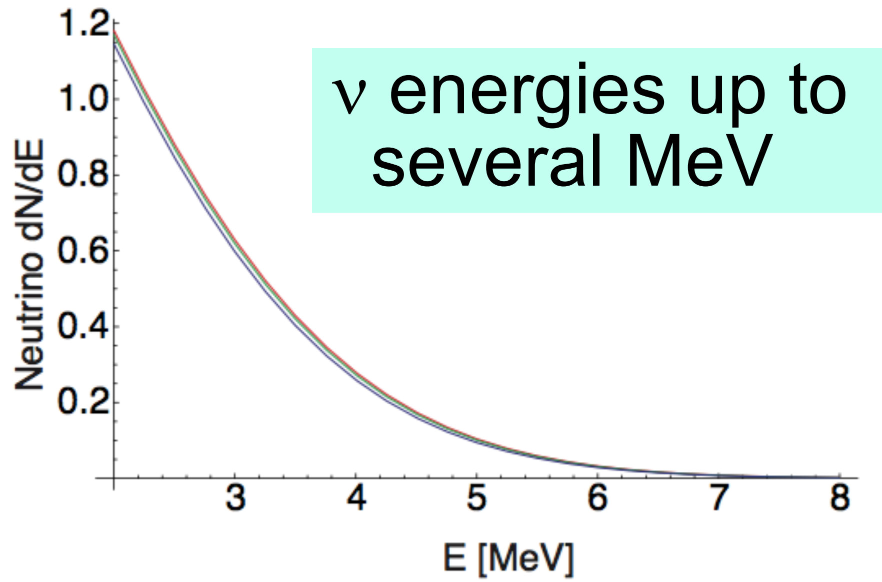


What do you want for your ν source?

- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

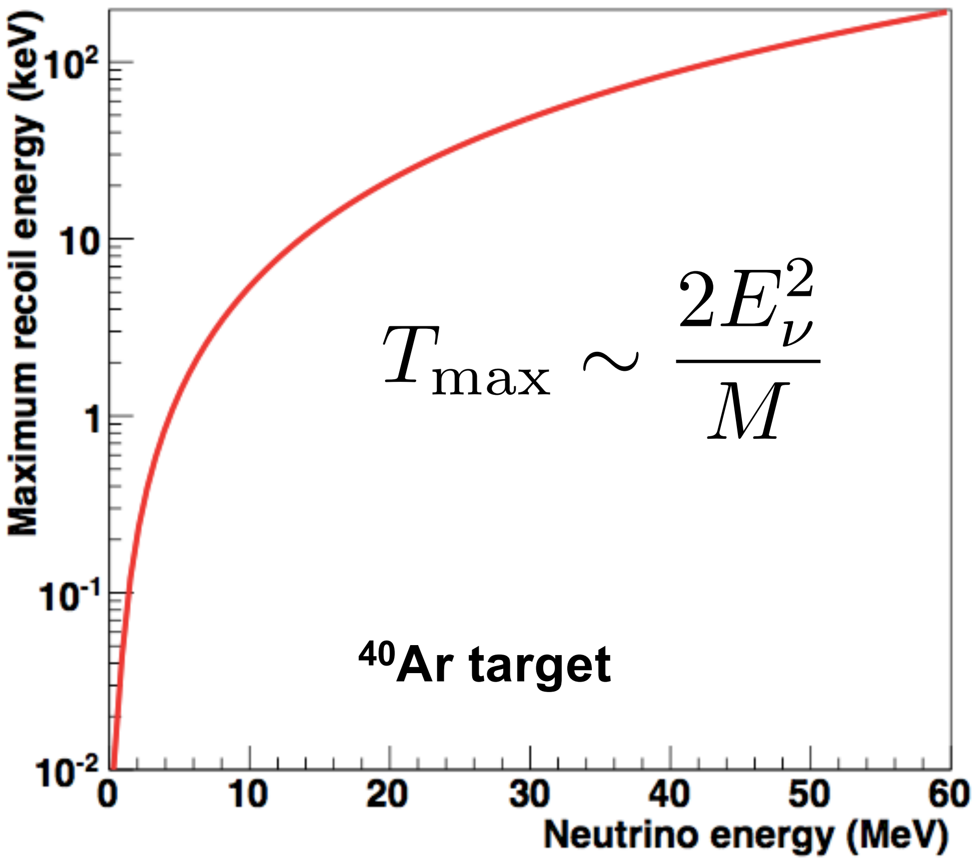
Neutrinos from nuclear reactors

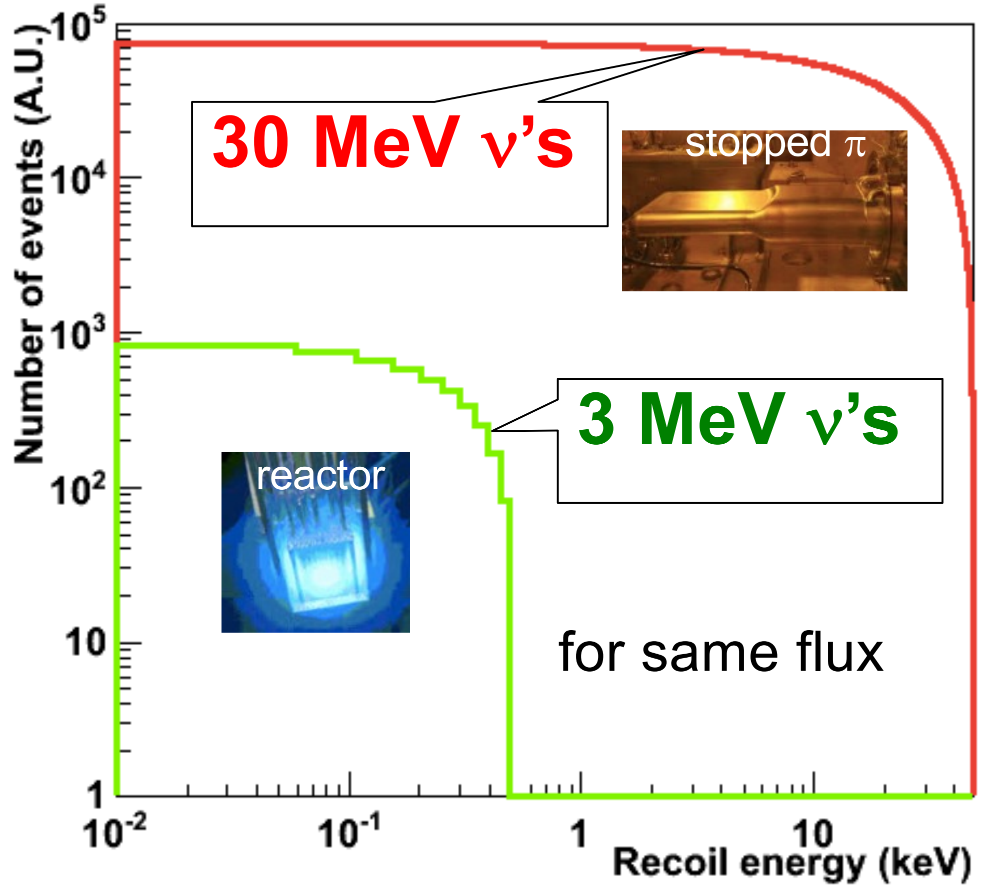




- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

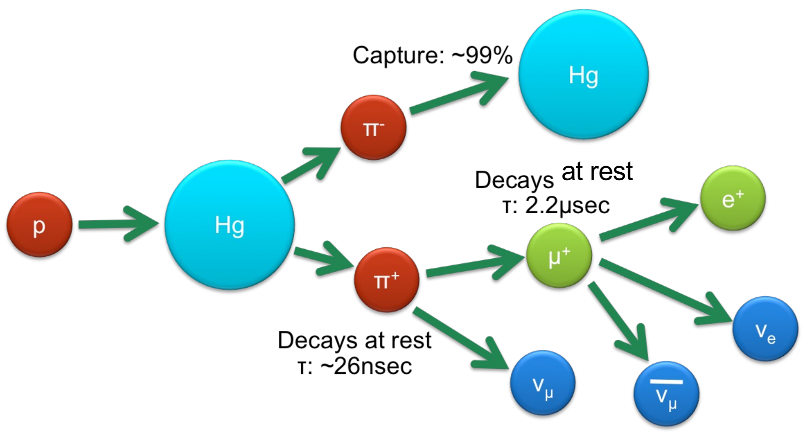
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

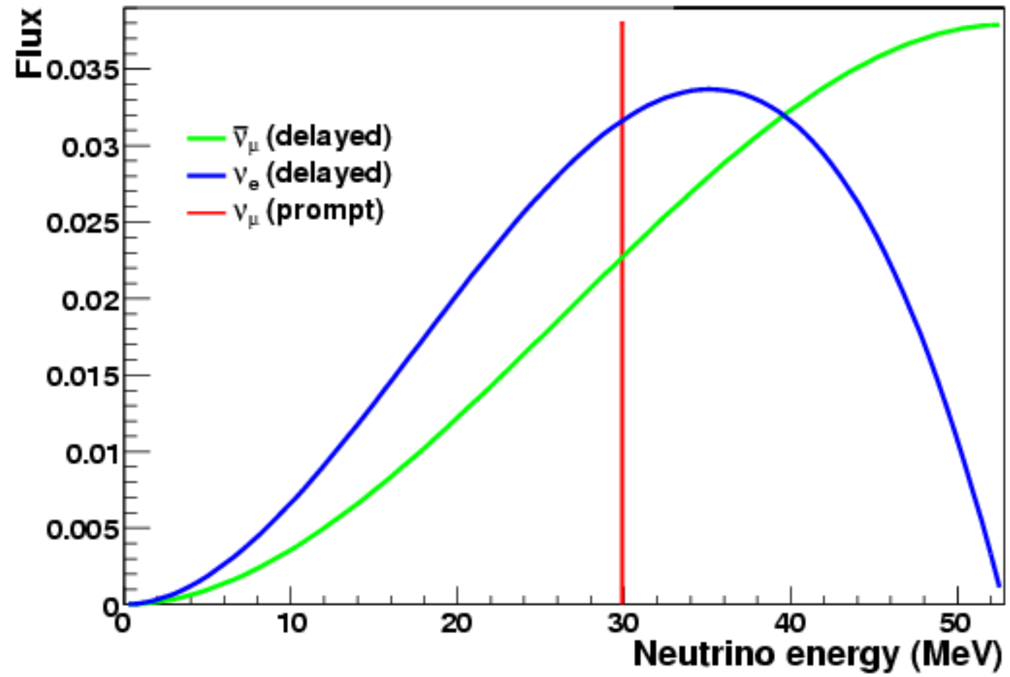




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

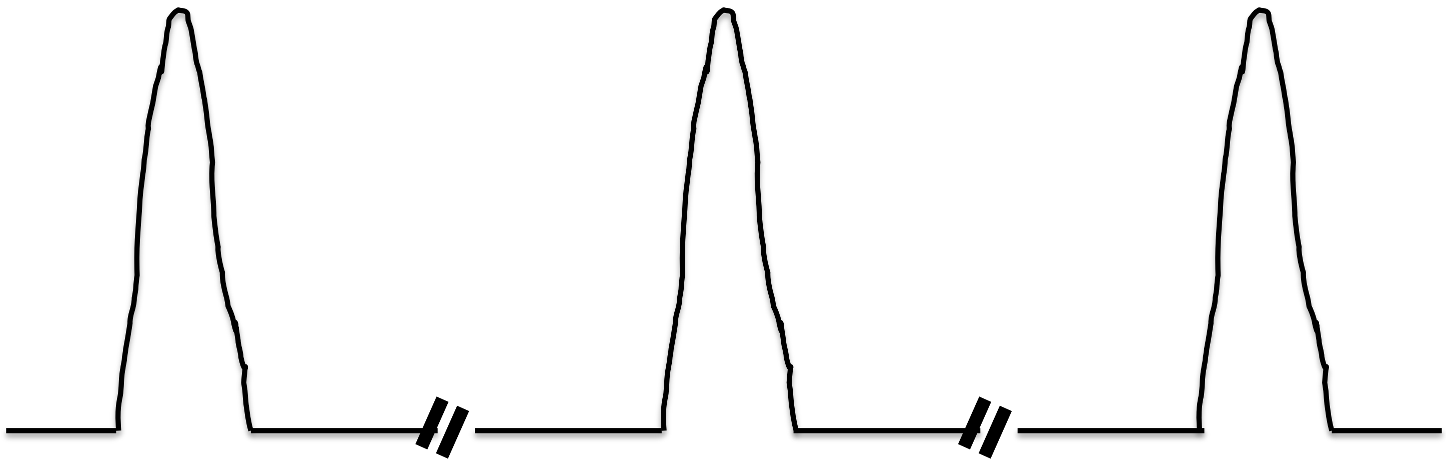
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

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

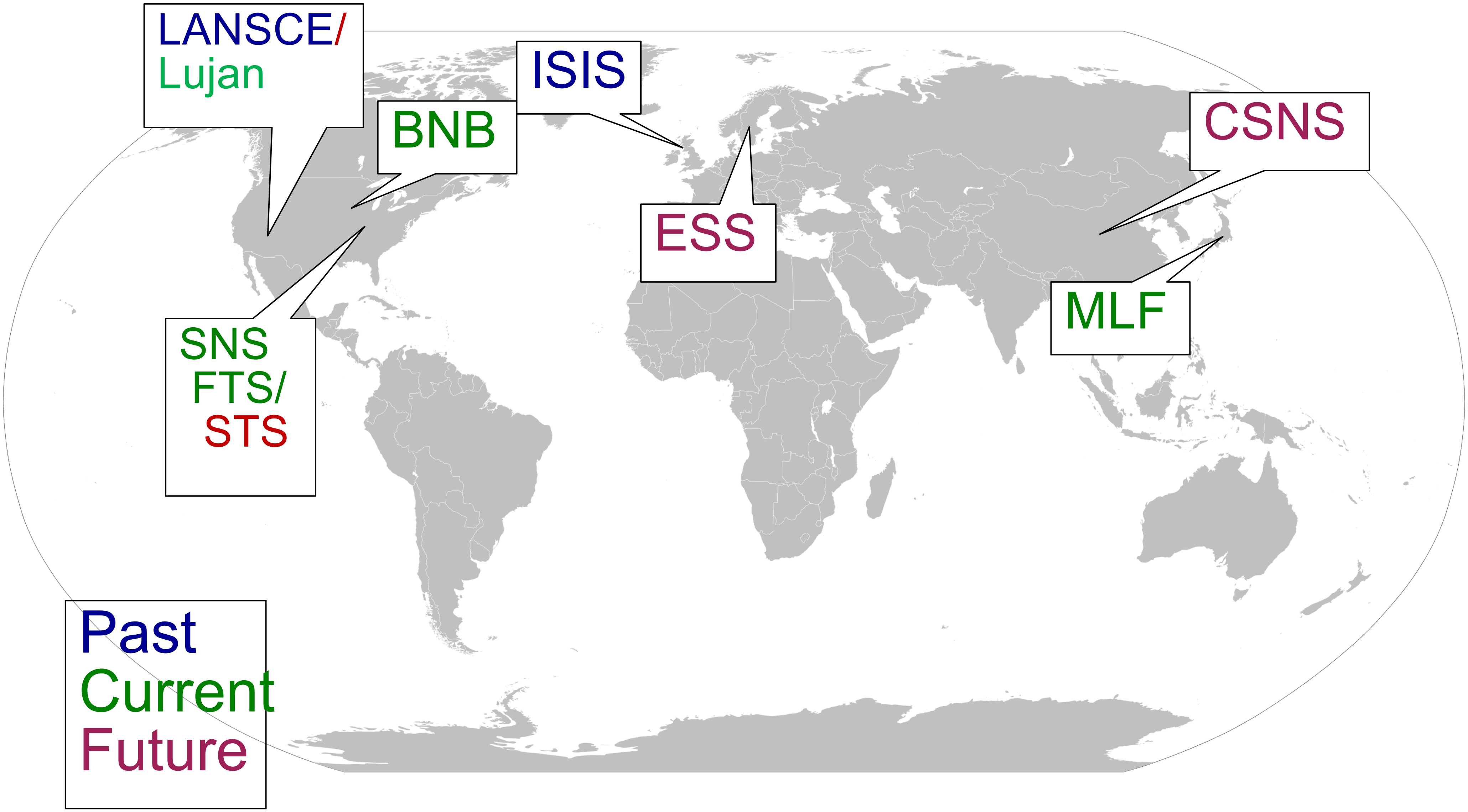
When the beam is **pulsed**, make use of the time structure to reject background



- Only look for stopped-π ν's within few μs of proton pulse
- ***Measure*** the steady-state background off-pulse
- You only care about sqrt of steady-state bg...
- (Beam-related bg is more pernicious... )

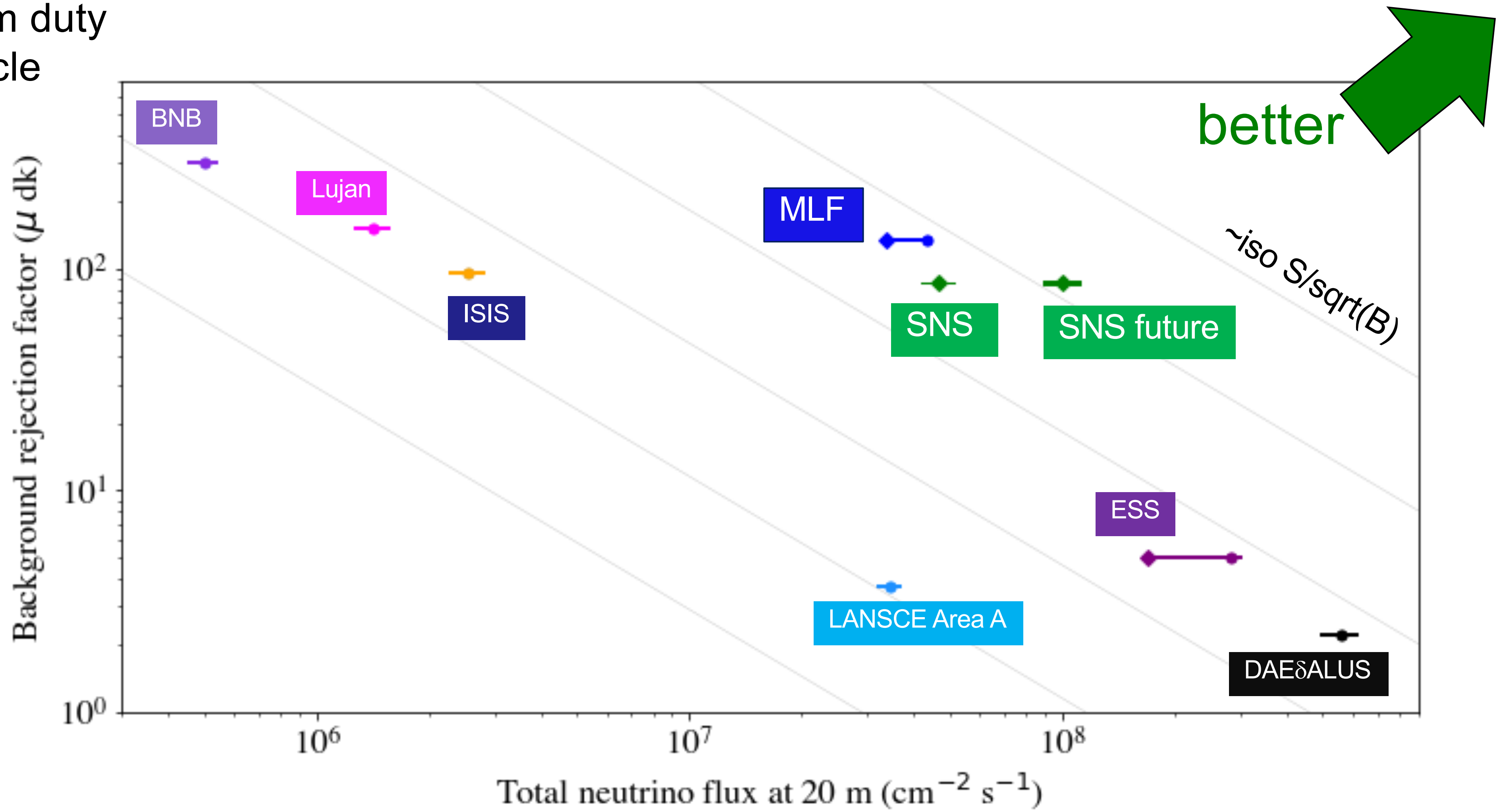
  - "Duty factor" or "duty cycle" = fraction of time beam is on
  - Inverse duty factor $\rightarrow$ "background rejection factor"

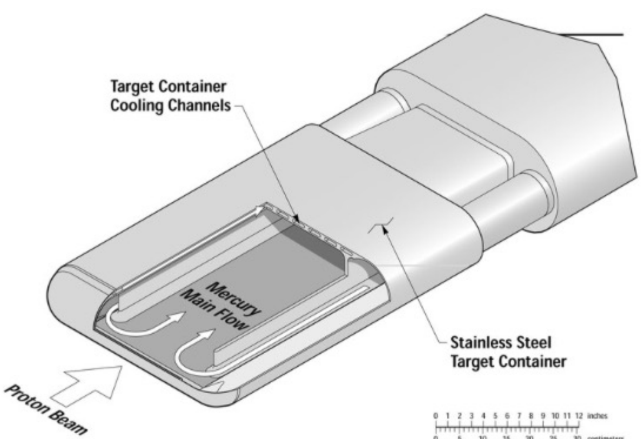
Stopped-Pion Neutrino Sources Worldwide



Comparison of stopped-pion ν sources

from duty cycle



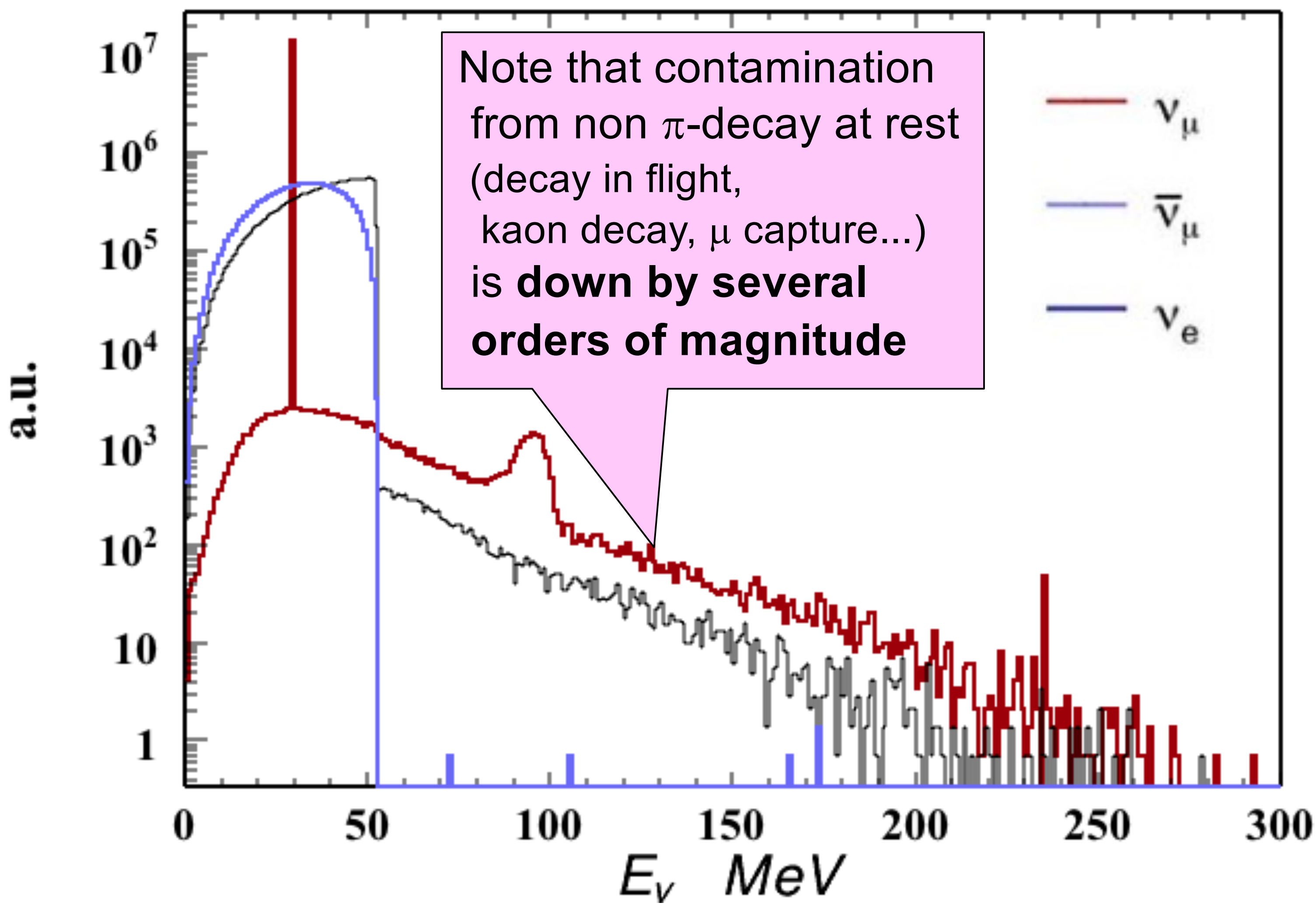


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

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

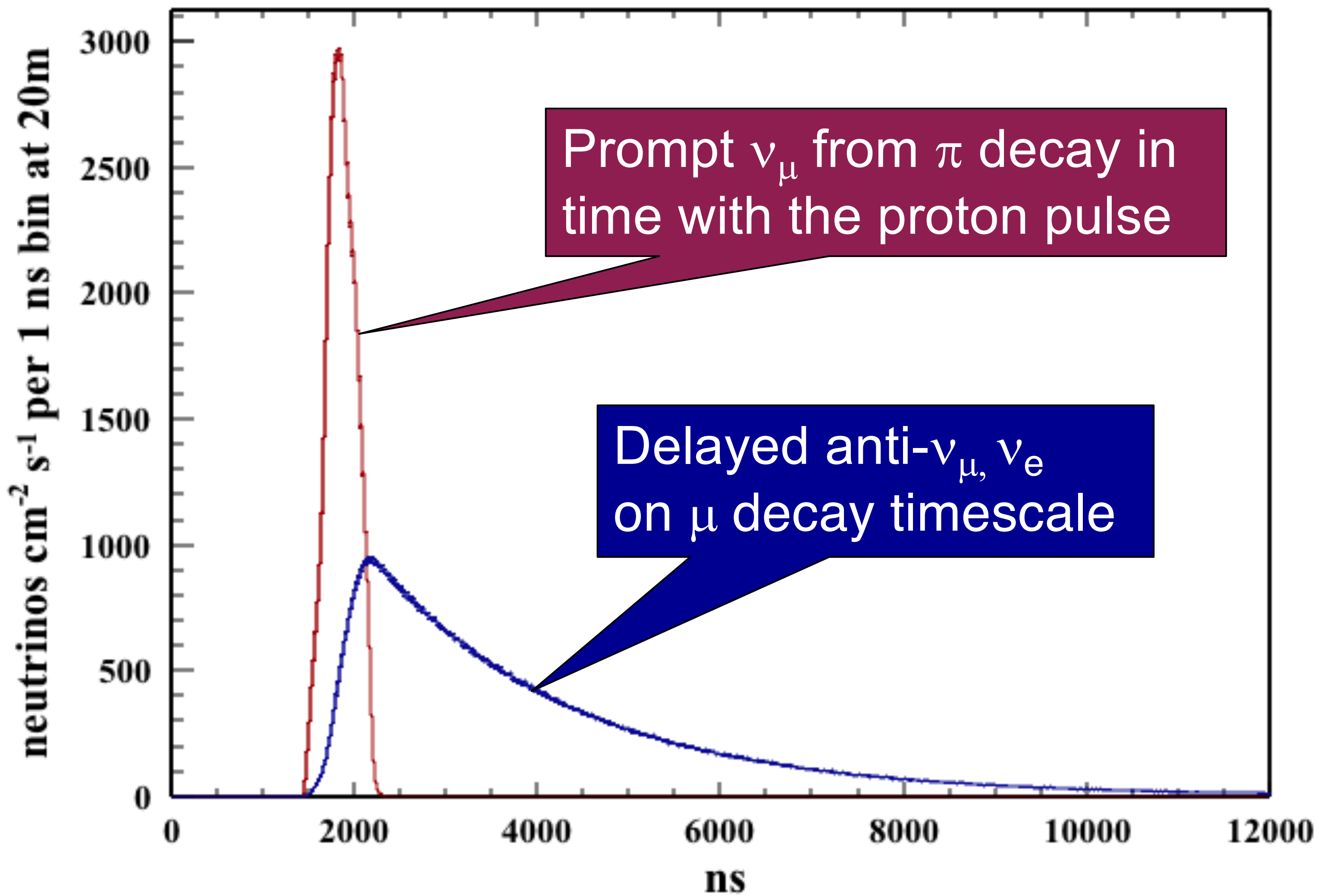
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

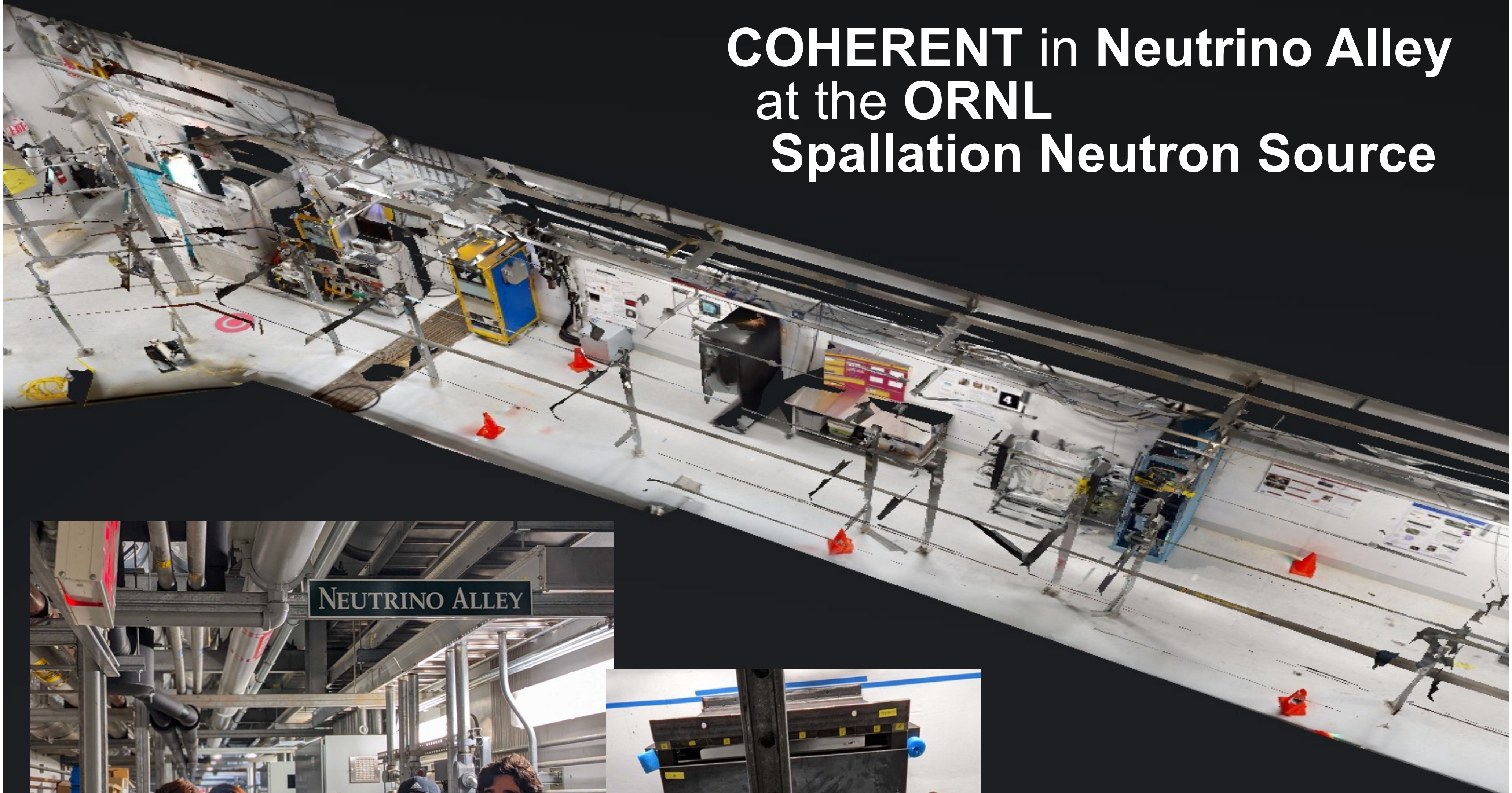
Time structure of the SNS source

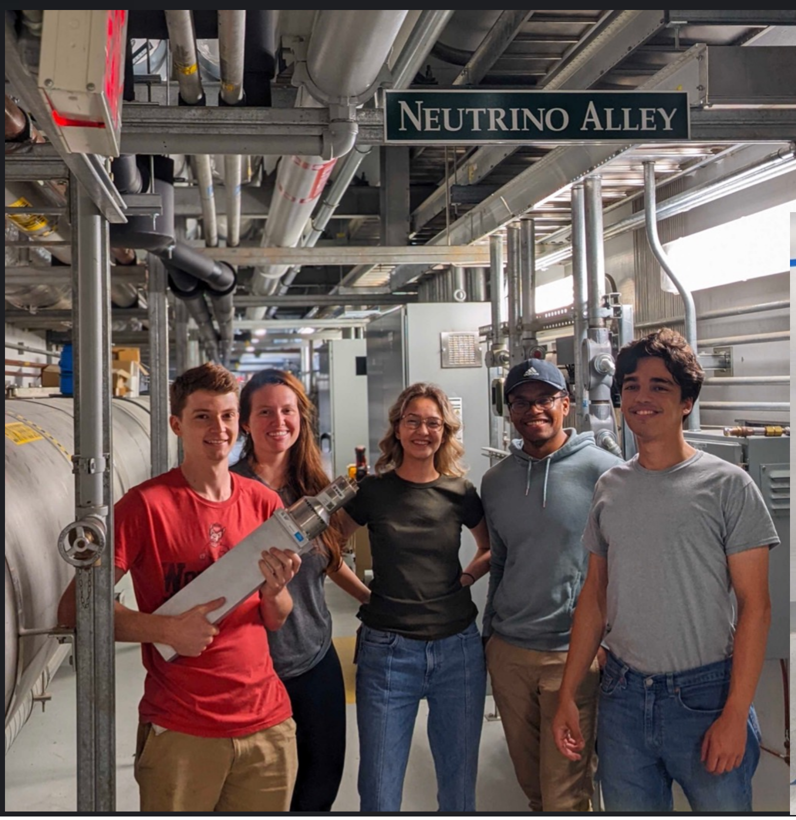
60 Hz *pulsed* source



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

COHERENT in Neutrino Alley at the ORNL Spallation Neutron Source





COHERENT
SNS
SPALLATION NEUTRON SOURCE

The COHERENT collaboration

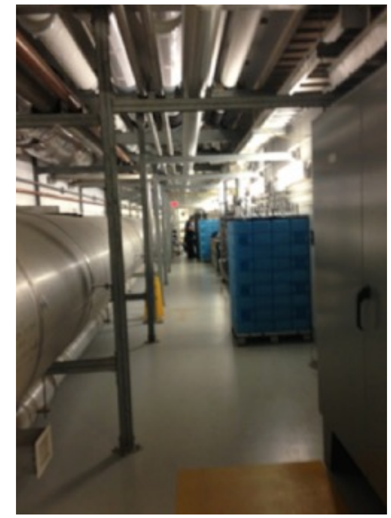
http://sites.duke.edu/coherent

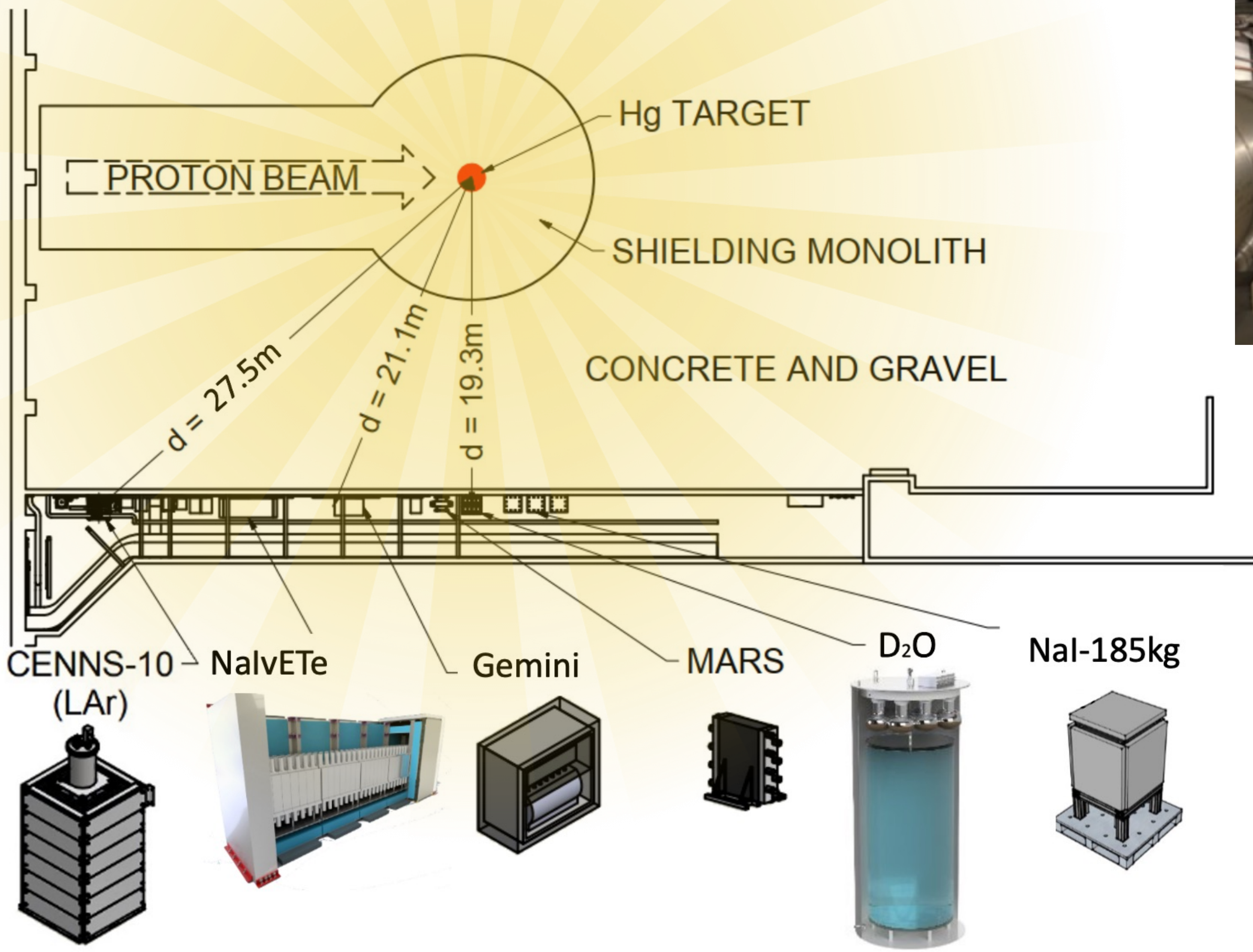
~90 members,
23 institutions
4 countries

Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

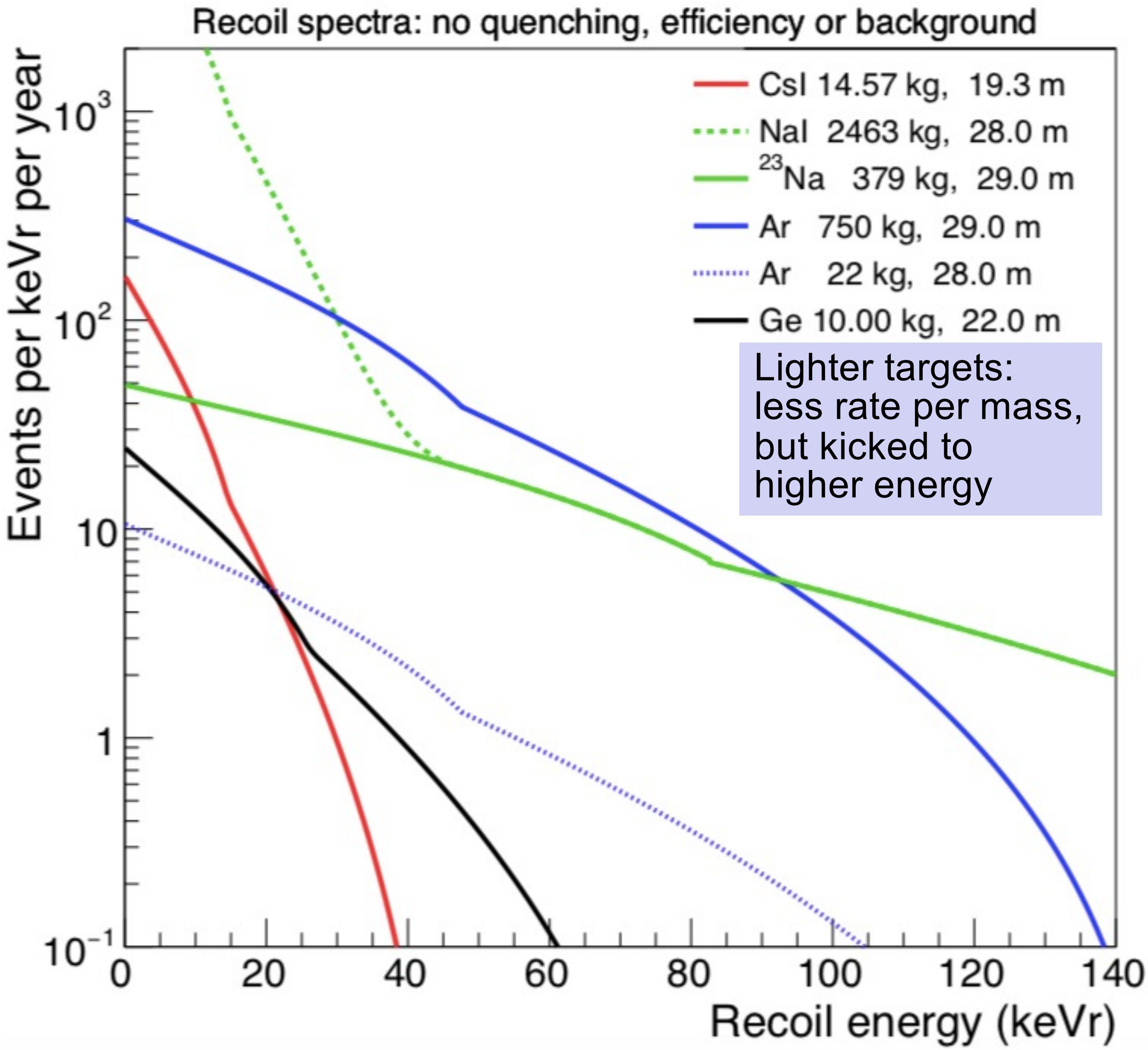
View looking
down “Neutrino Alley”





Isotropic ν glow from Hg SNS target

Expected recoil energy distribution



If 100 counts are expected in 10 kg of argon at 20 m, how many are expected in 100 kg at 40 m?

A. 2.5

B. 25

C. 100

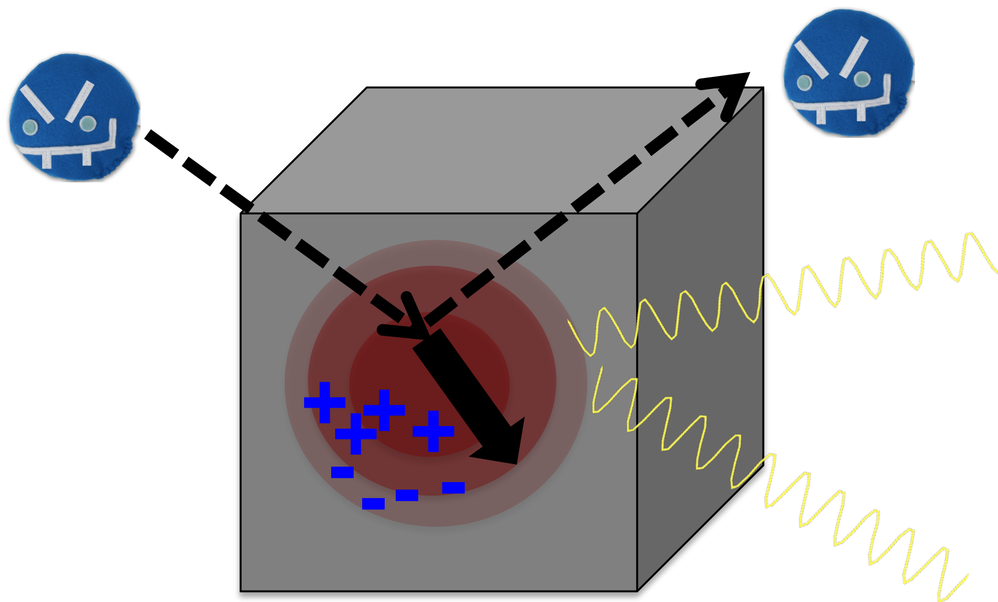
D. 250

E. 2500

Backgrounds

Usual suspects:
- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not your friends*



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

*Thanks to Robert Cooper for the "mean neutron"

A "friendly fire" in-time background:

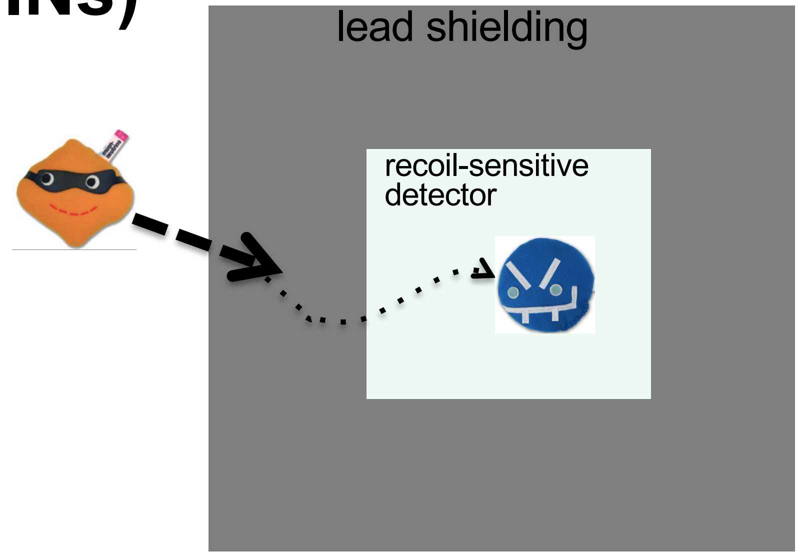
Neutrino Induced Neutrons (NINs)

$$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^- \quad \text{CC}$$

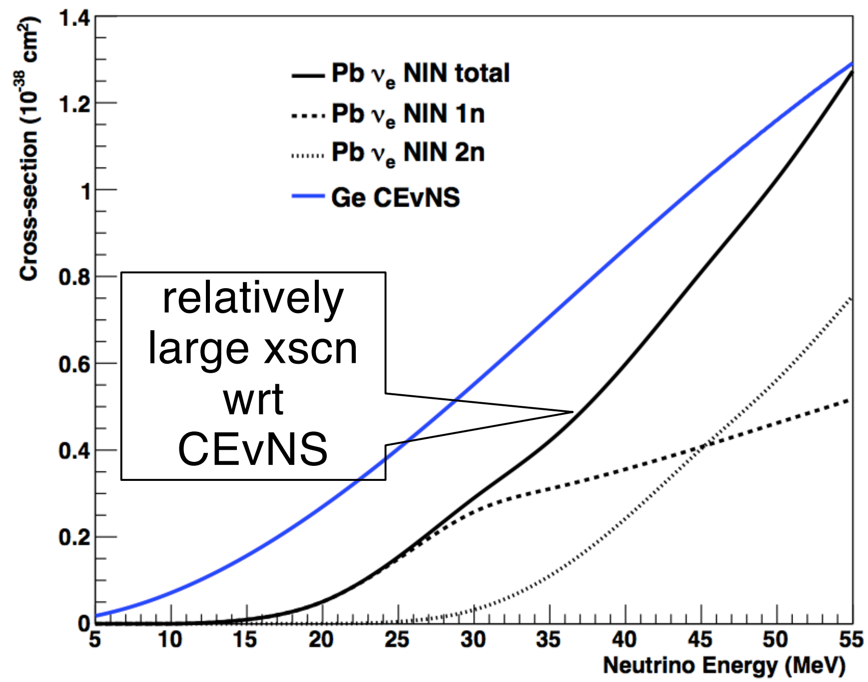
1n, 2n emission

$$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x \quad \text{NC}$$

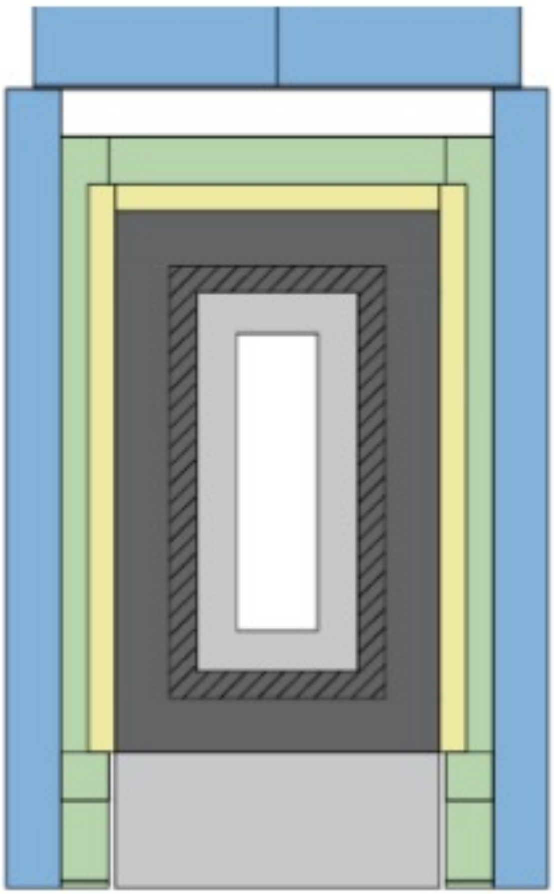
1n, 2n, γ emission

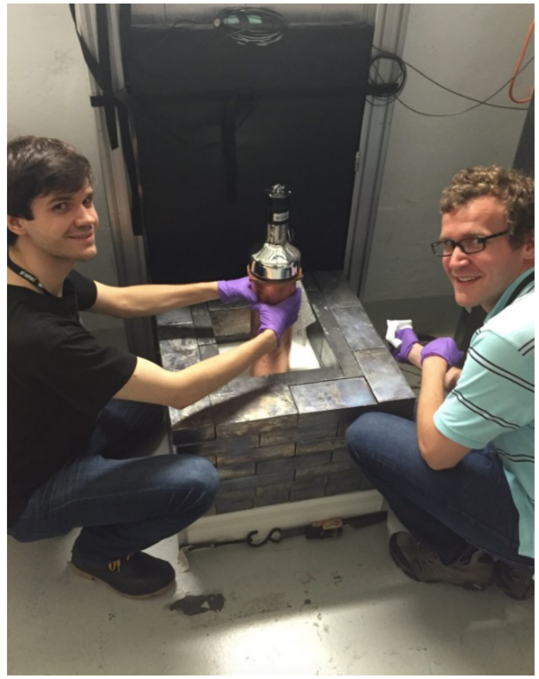


- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in xscn calculation
- [Also: a signal in itself, e.g, HALO SN detector]

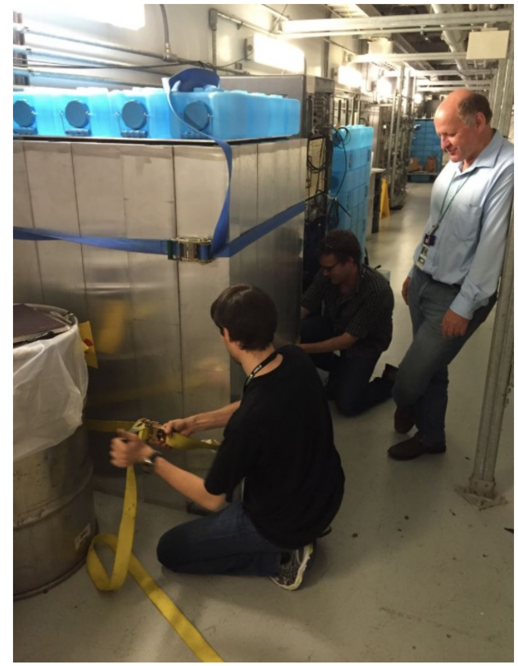


The CsI Detector in Shielding in Neutrino Alley at the SNS





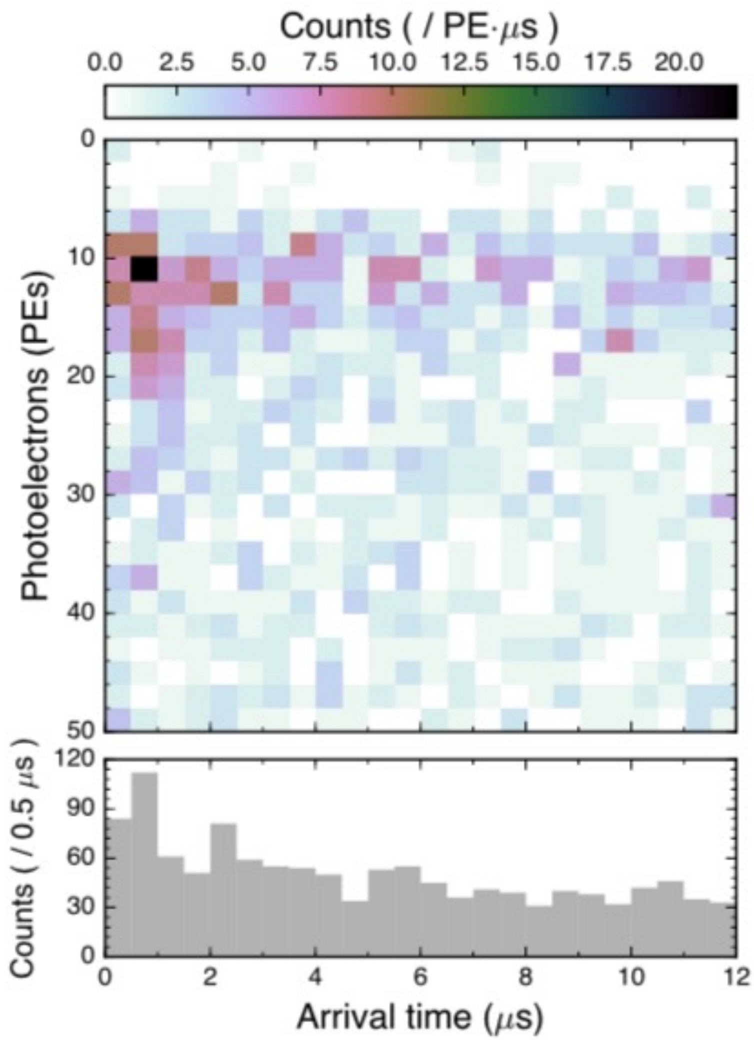
A hand-held detector!

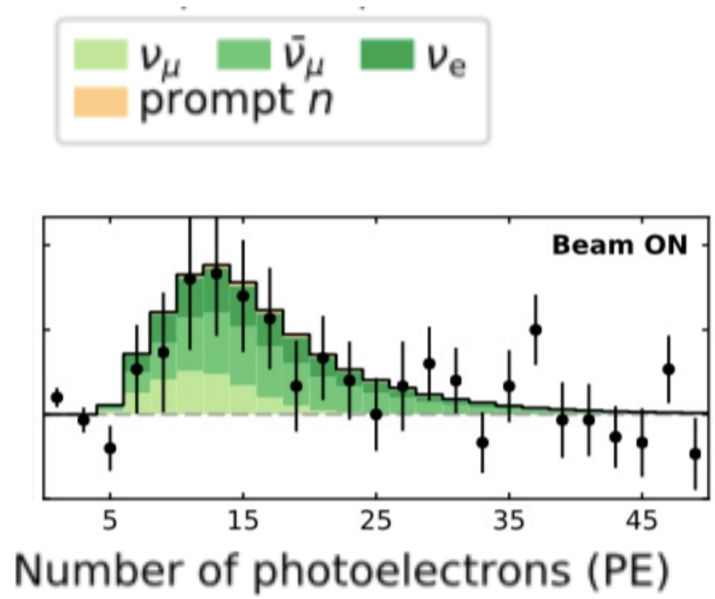


Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3''	2''	4''	2''	4''
Colour					

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





Background-subtracted and integrated over time

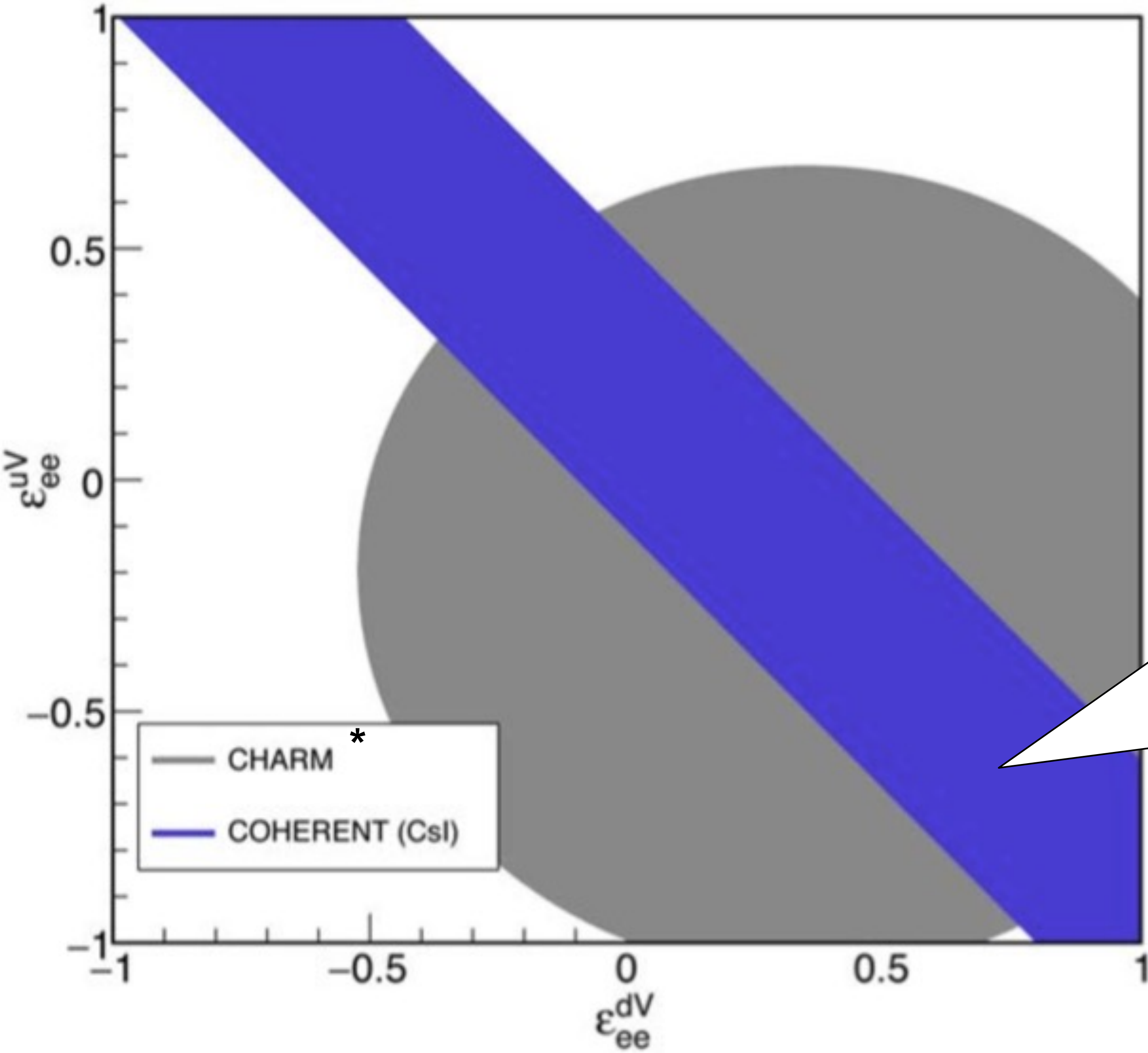
$$\mathrm{PE} \propto T \propto Q^2$$

→ 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:

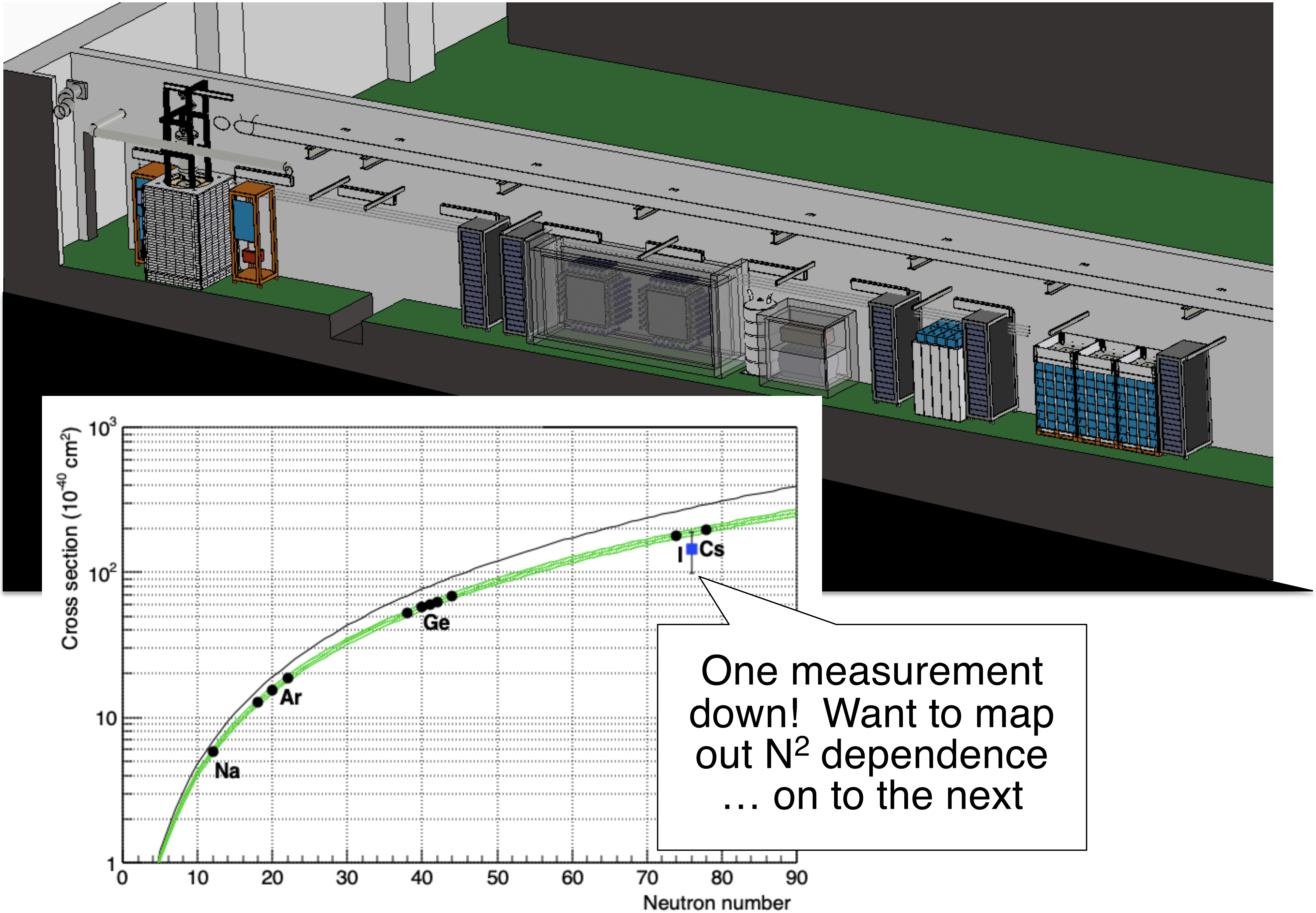


- Assume all other ε's zero

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

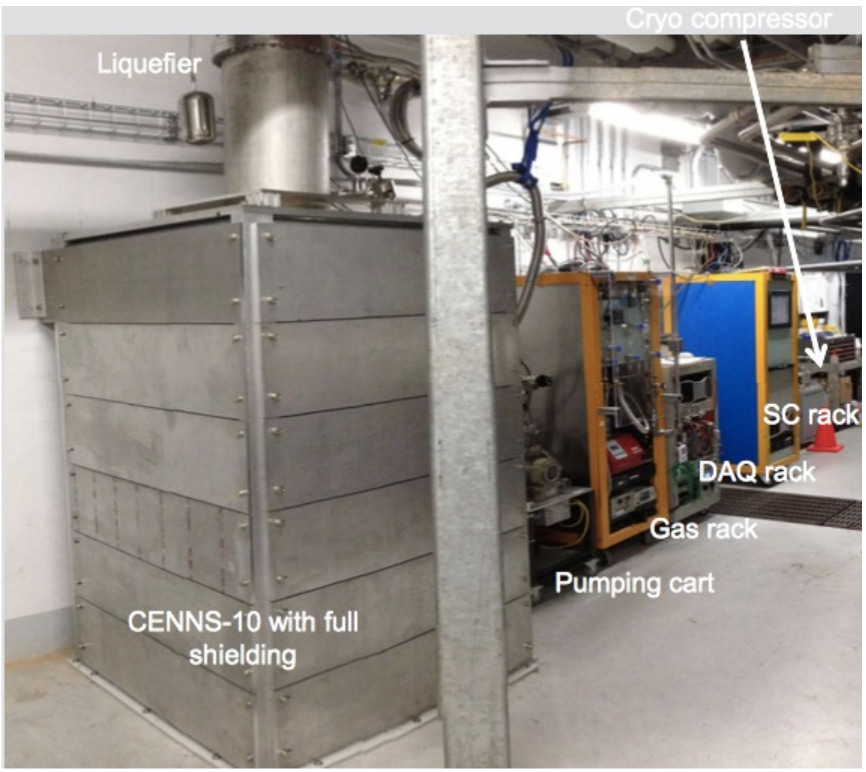


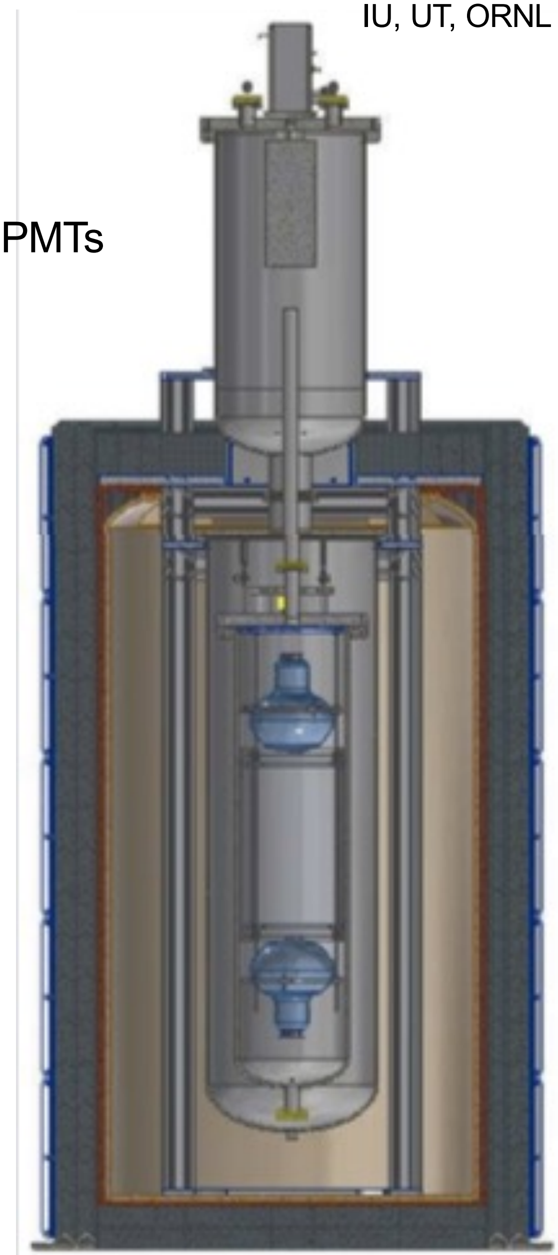
One measurement down! Want to map out N^2 dependence … on to the next

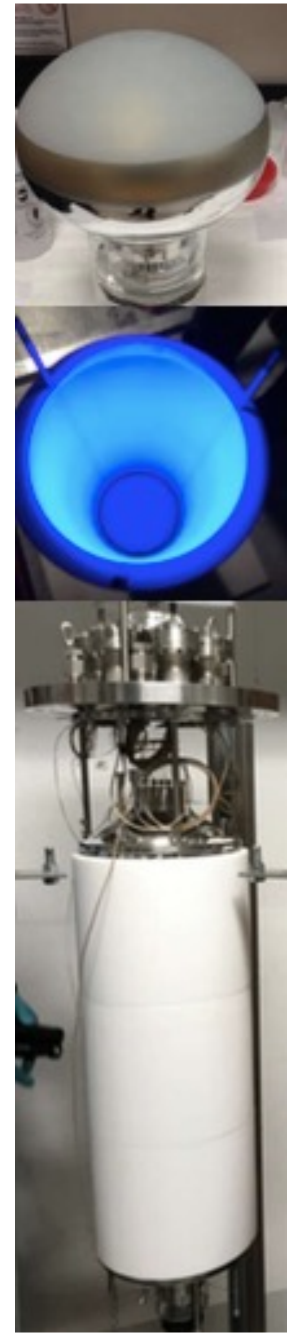
Single-Phase Liquid Argon

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

IU, UT, ORNL



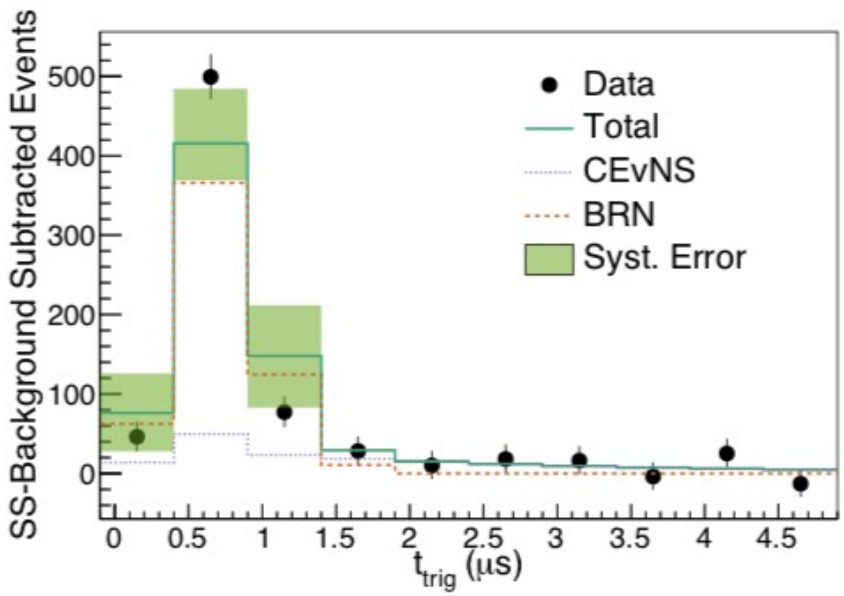


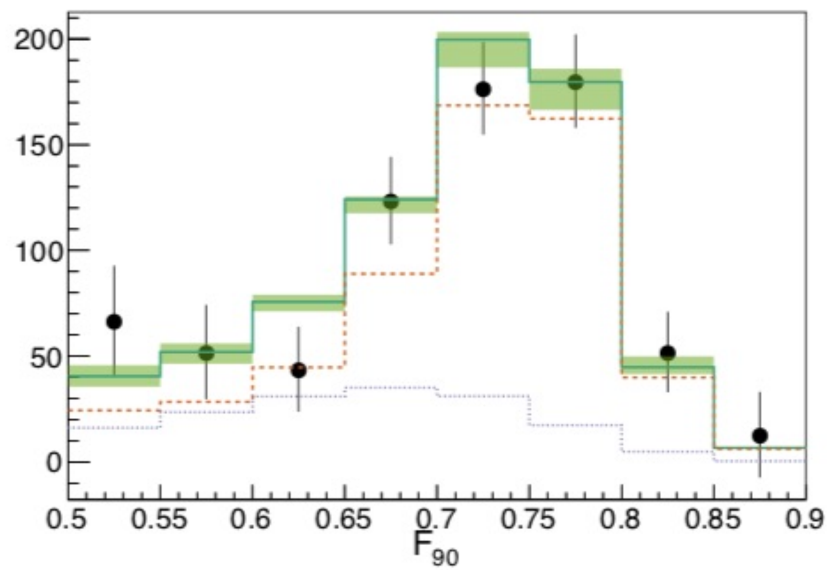


Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

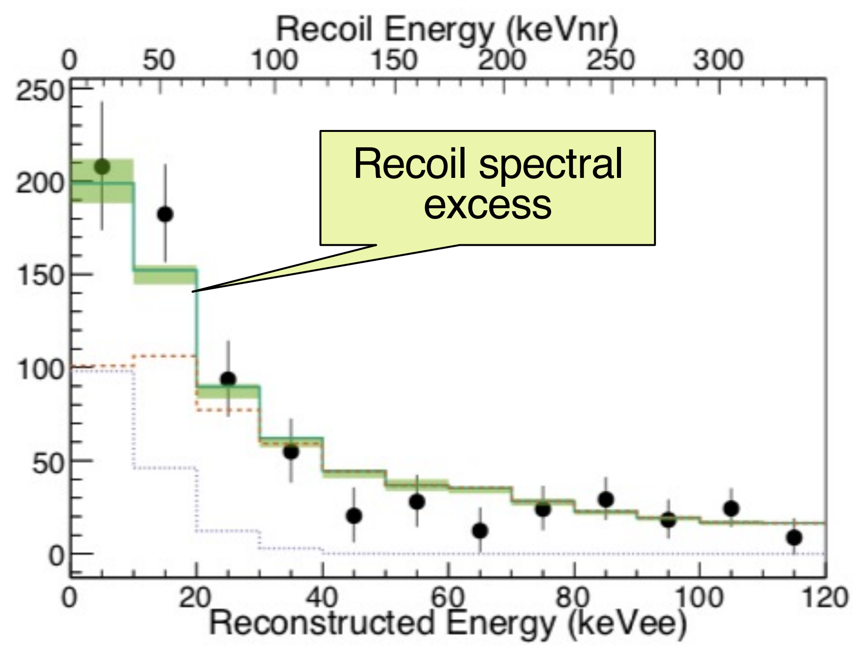
Likelihood fit in time, recoil energy, PSD parameter

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

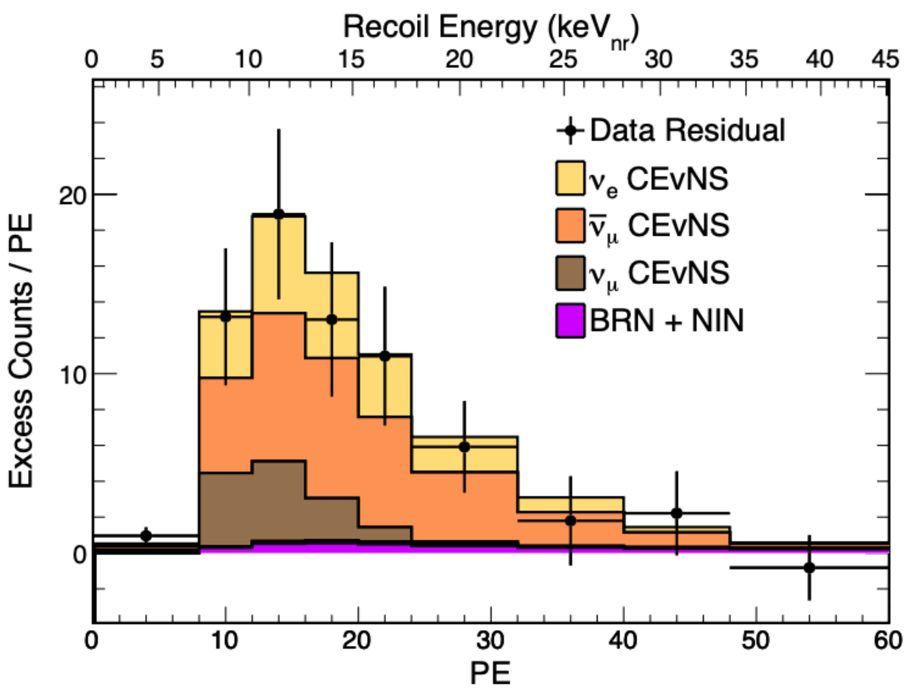


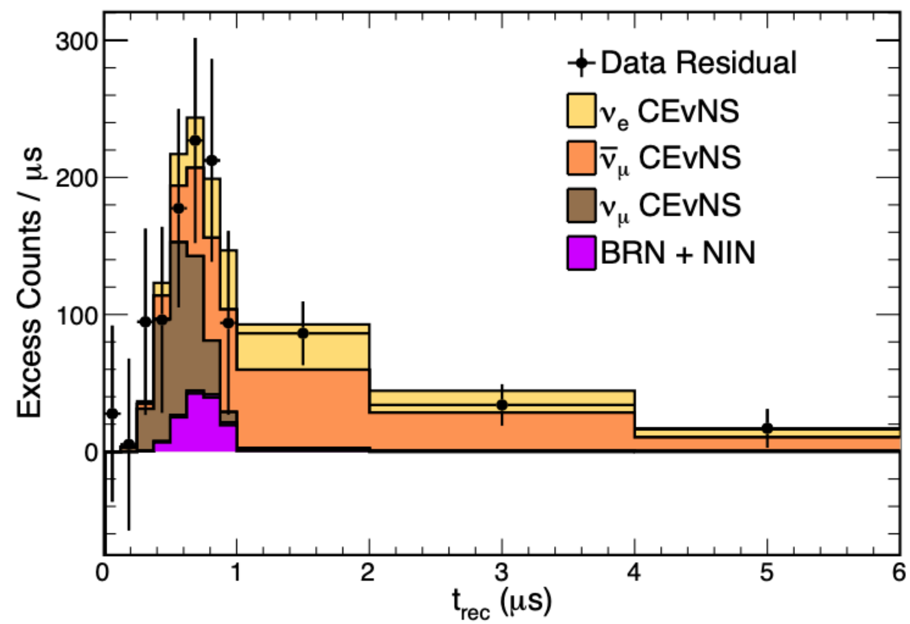


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

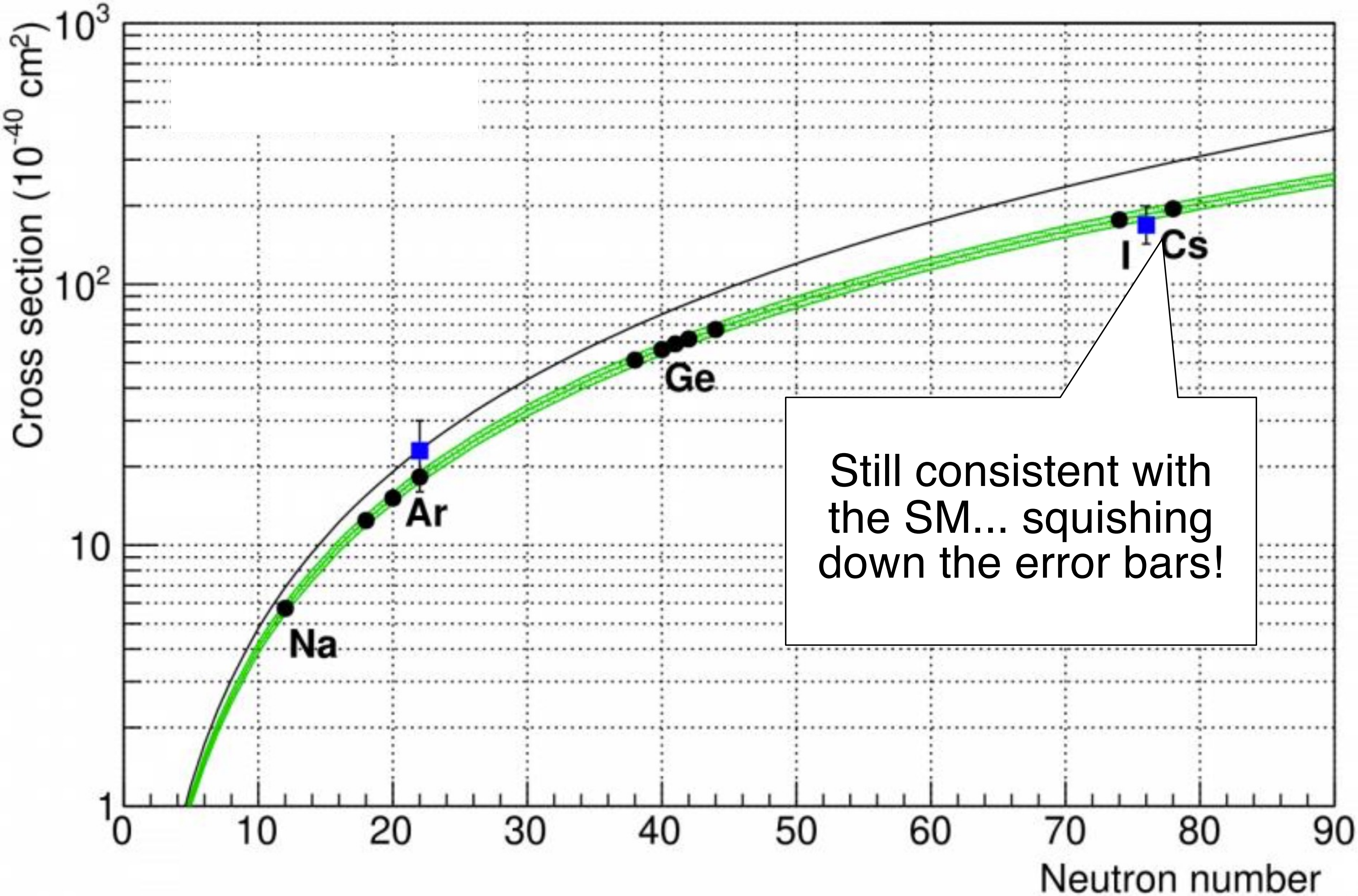


Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis



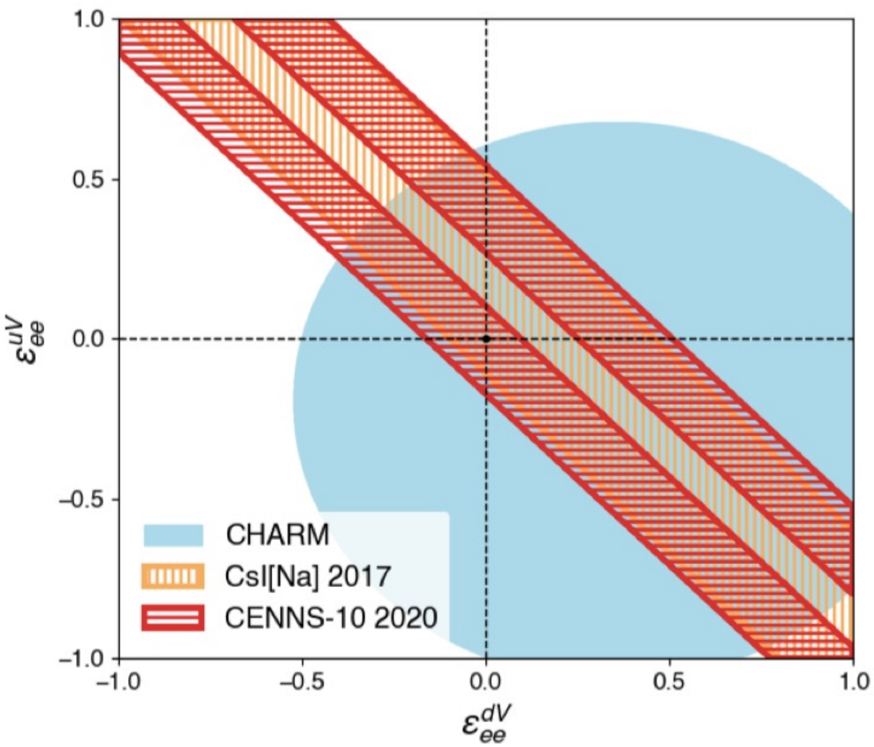


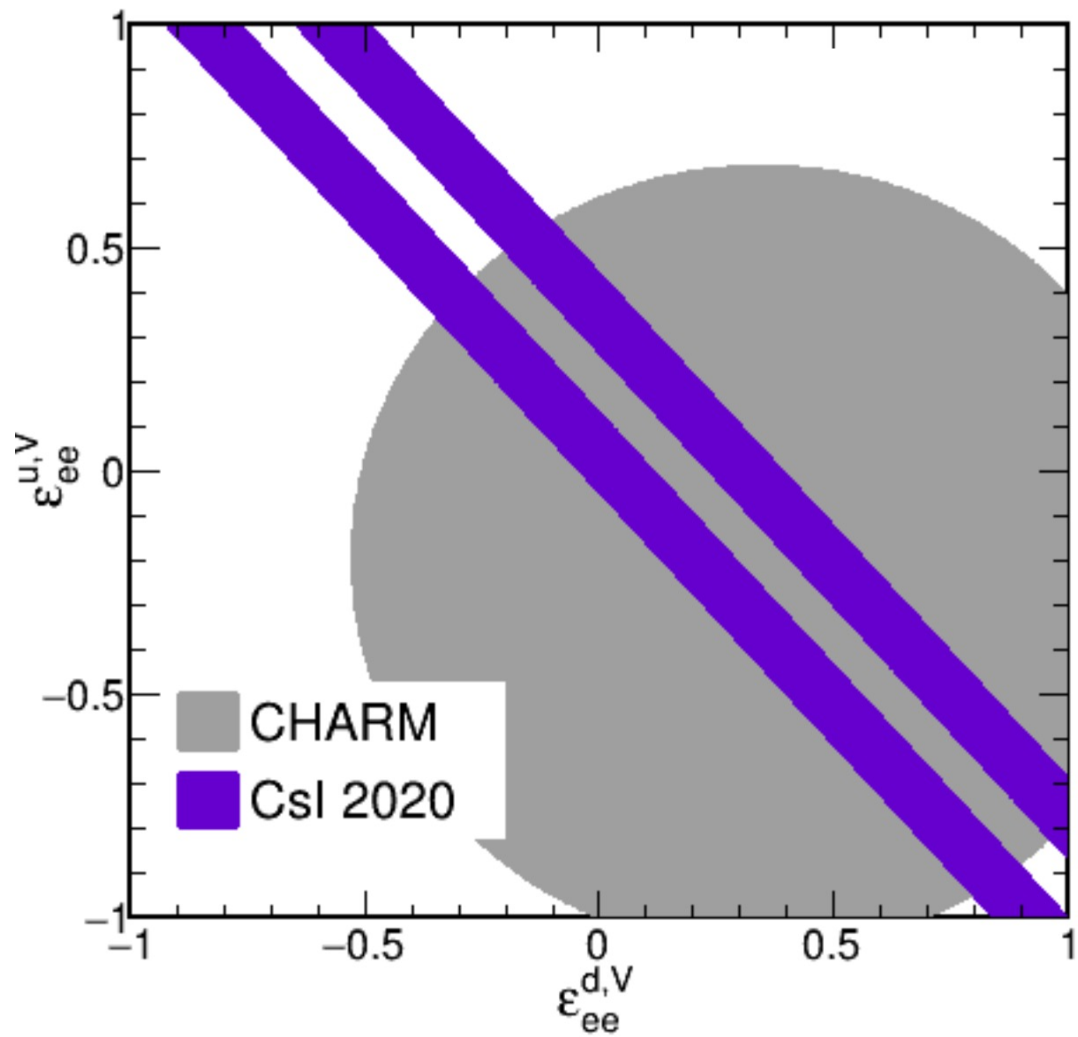
arXiv: 2110.07730



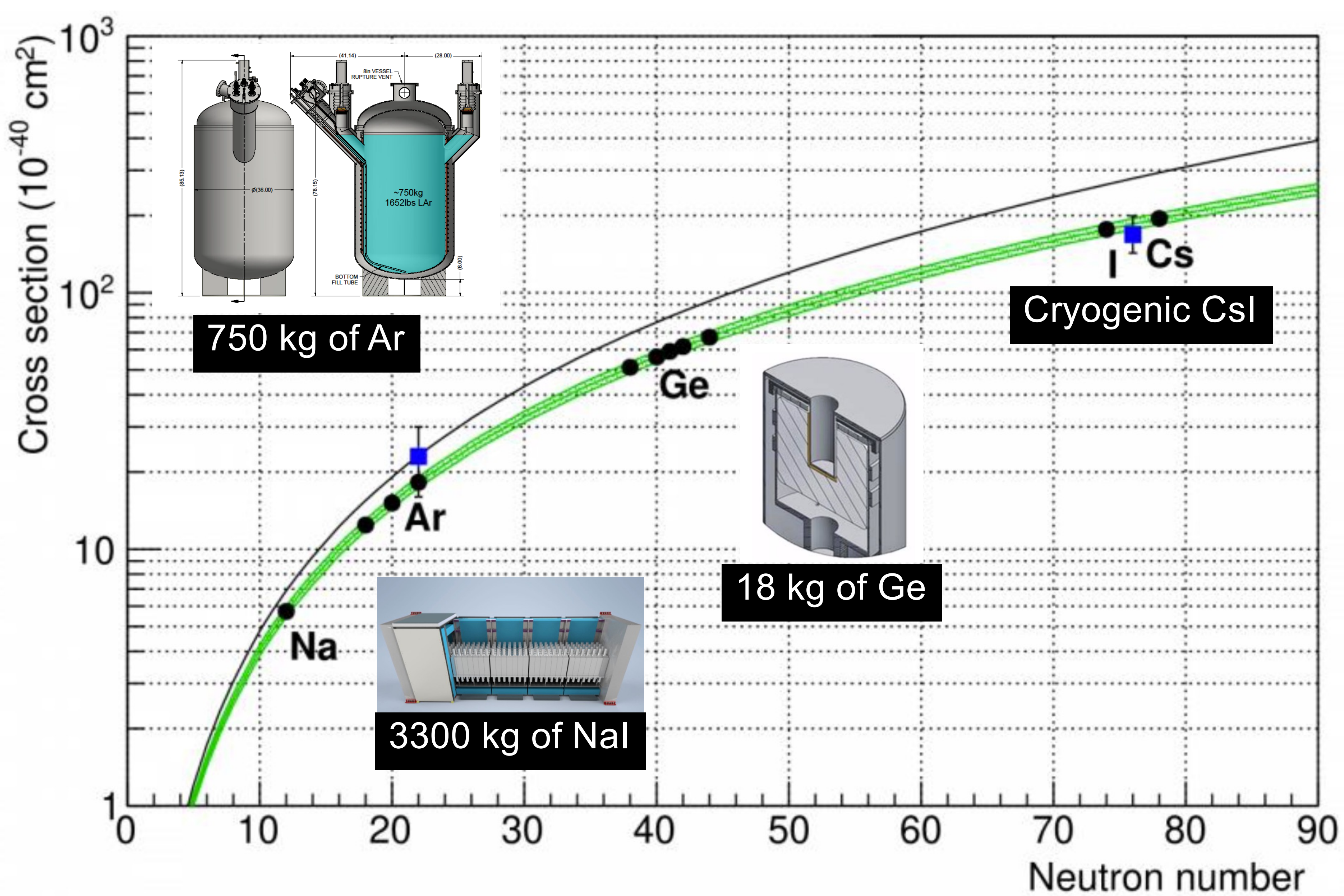
Cross section (10^{-40} cm²)
Neutron number
Na
Ar
Ge
I
Cs
Still consistent with the SM... squishing down the error bars!

And squeezing down the possibilities for new physics...



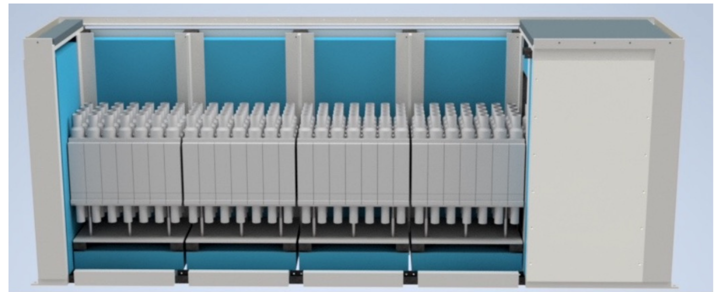


COHERENT future CEvNS deployments in Neutrino Alley



Sodium Iodide (NaI[Tl]) Detectors

- 3.3 tons, 5 modules
- QF measured
- PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement



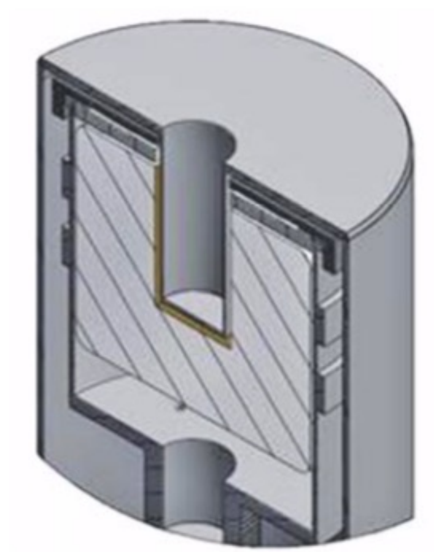
NaIvE: 185 kg deployed at SNS to go after ν_eCC on ^{127}I

NaIVETE: 3.3 tonnes for CEvNS + ν_eCC on ^{127}I

- first commissioning data from first module 22/23
- **second module now deployed**

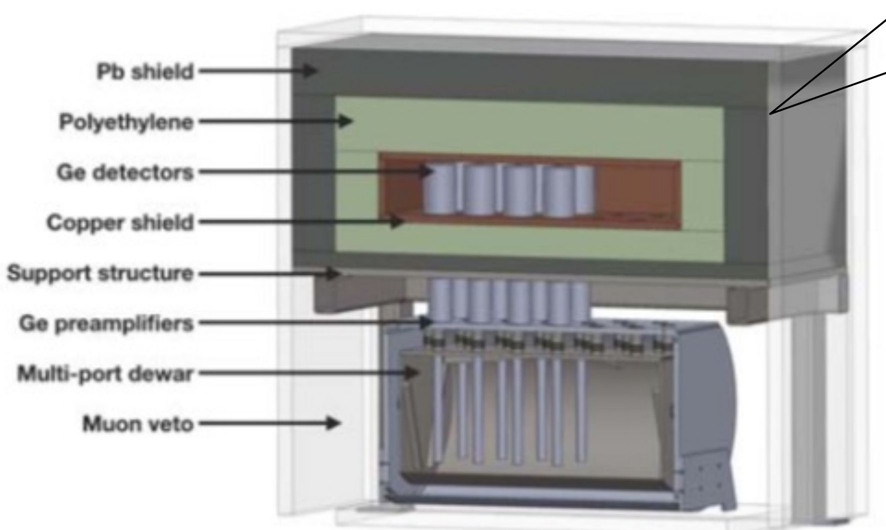
High-Purity Germanium Detectors

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

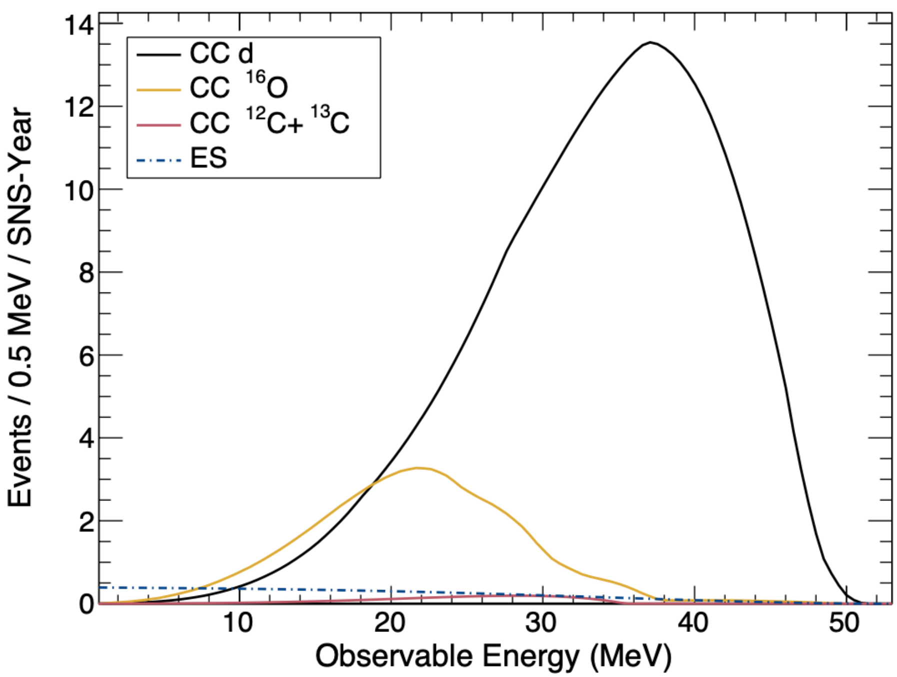


- first commissioning data
  22/23
- **campaign-2 now with
  6/8 detectors**

Heavy water detector in Neutrino Alley

Dominant current uncertainty is ~10%, on neutrino flux from SNS

$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ cross section known to ~1-2%



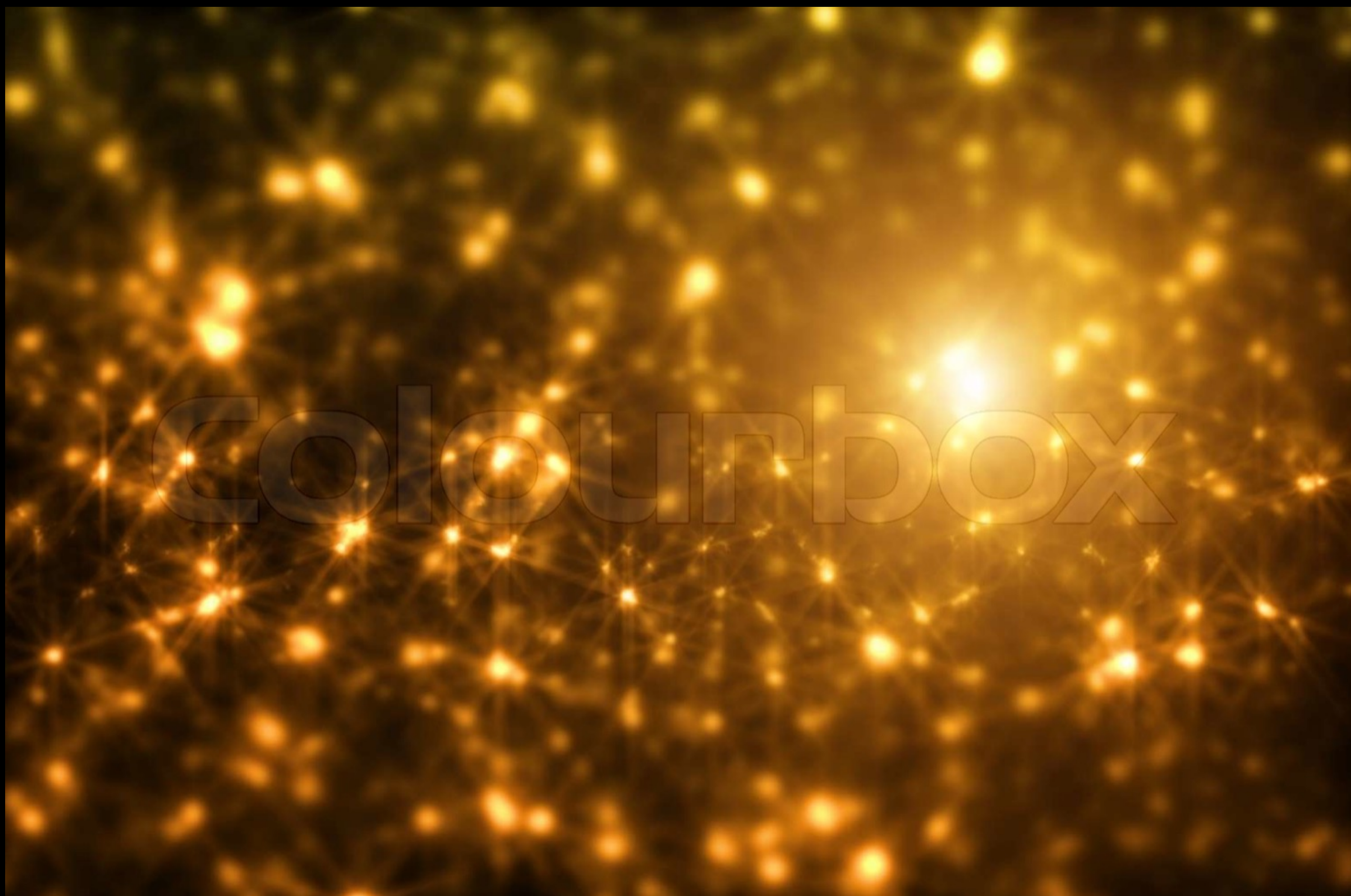
- Measure electrons to determine flux normalization
- Inelastics on ^{16}O [studying dedicated light water detector]

- commissioning w/light water 22/23
- **nearly ready for D_2O fill**

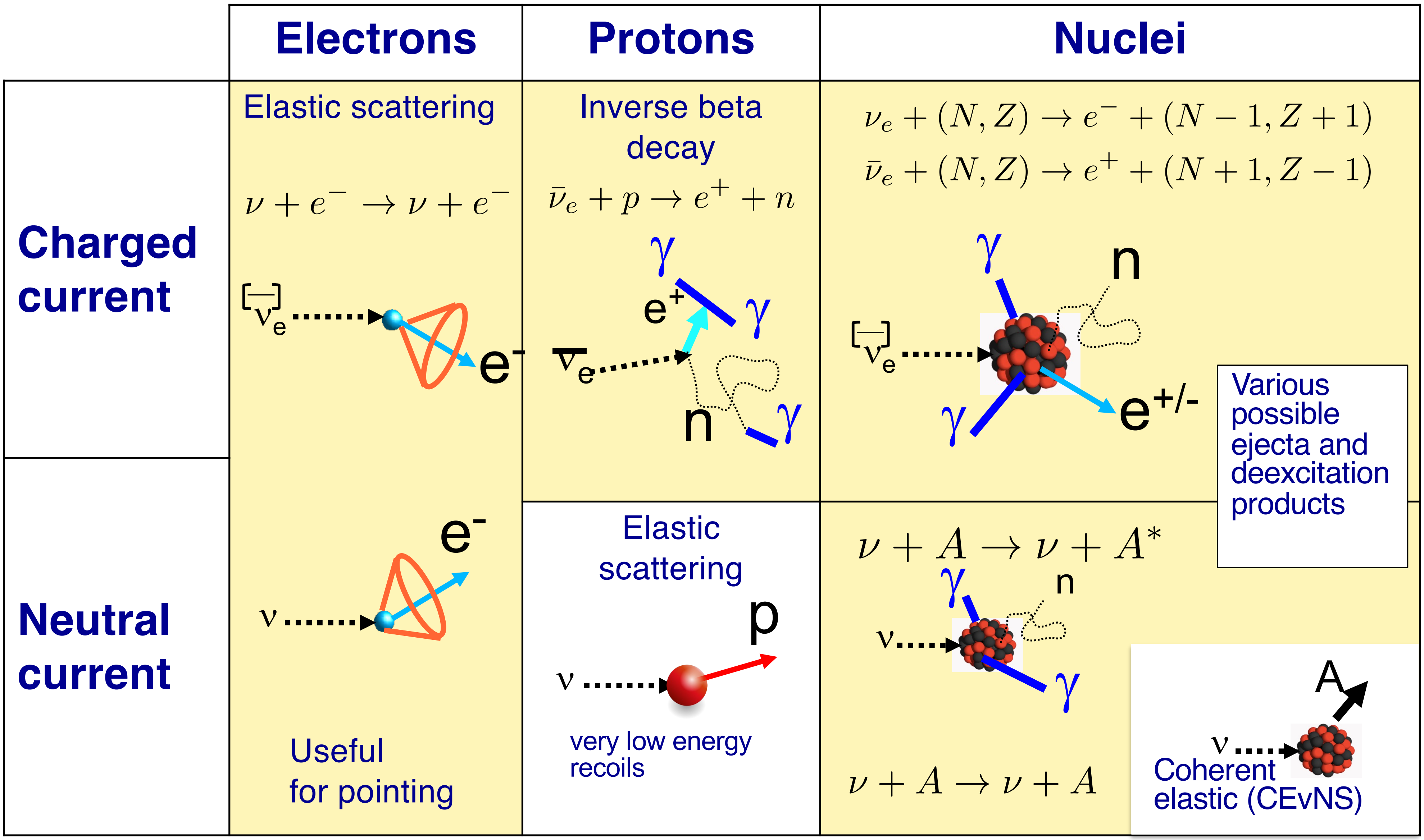
So far considered signal from faint recoils...

bright signals are possible too...

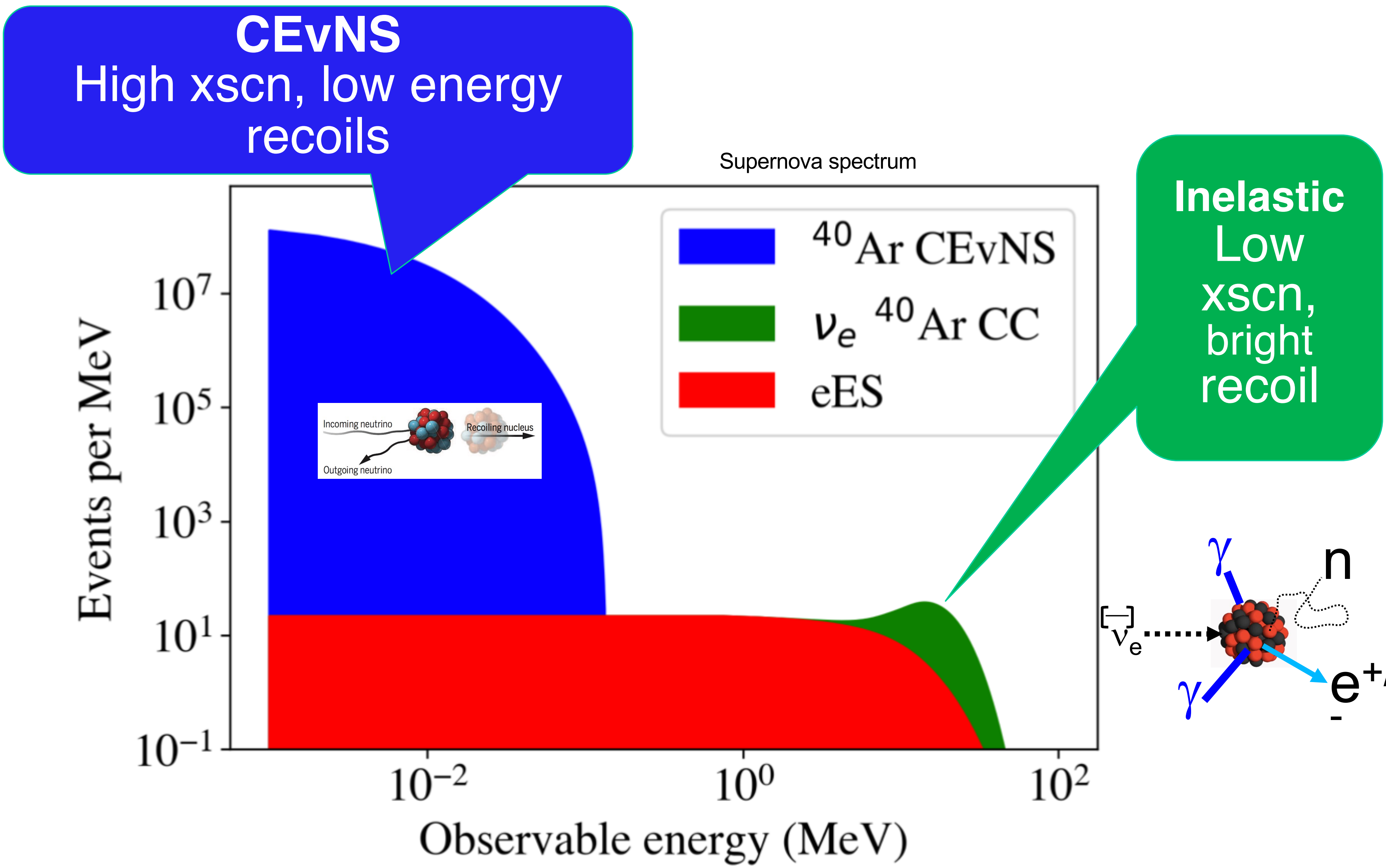
Neutrinos: eES, inelastic neutrino-nucleus interactions,
[inelastic DM interactions, axions...]



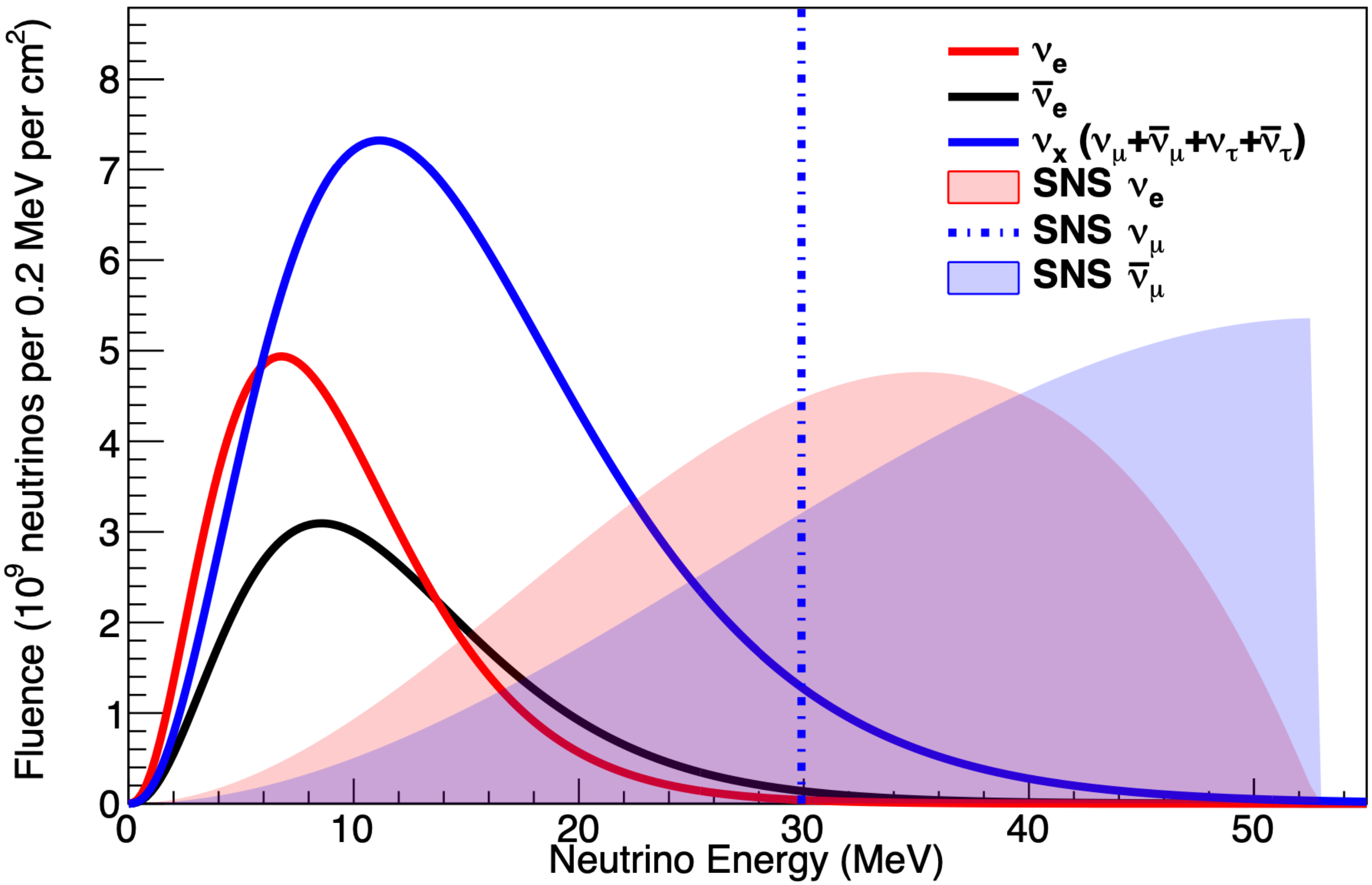
Low-energy neutrino interactions



Neutrino interaction signals in the few to few-tens of MeV range



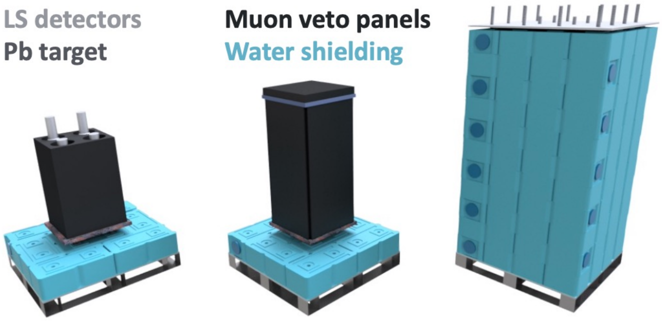
Stopped-pion neutrinos relevant for supernova burst regime

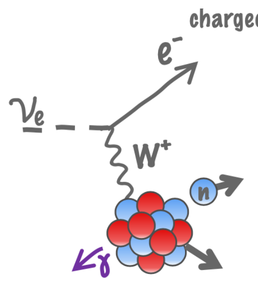


- understanding of SN processes & detection
- understanding of weak couplings (g_A quenching) & nuclear transitions

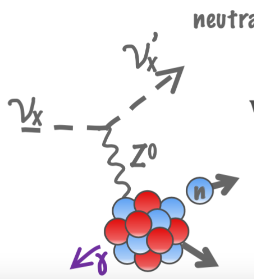
See:Workshop on Neutrino Interaction Measurements for Supernova Neutrino Detection
https://indico.phy.ornl.gov/event/217/

COHERENT results for **neutrino-induced neutrons (NINs)** on Pb



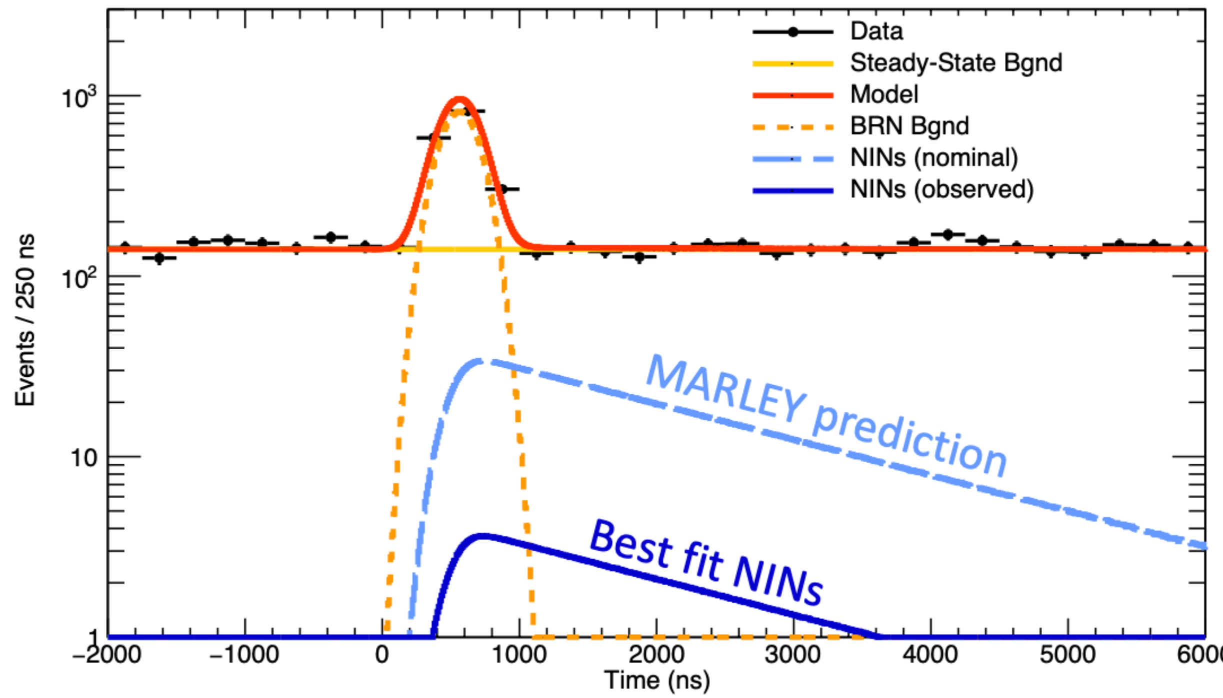


$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$$
$$\Downarrow$$
$$^{208-y}\mathrm{Bi} + x\gamma + yn$$



$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x'$$
$$\Downarrow$$
$$^{208-y}\mathrm{Pb} + x\gamma + yn$$

Sam Hedges talk



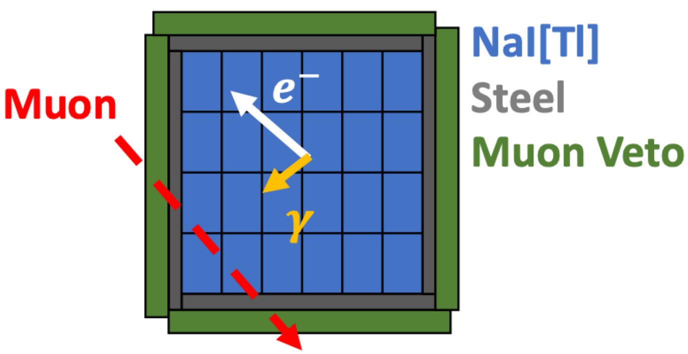
Combined fit yields MARLEY cross section suppressed by a factor of $0.29^{+0.17}_{-0.17}$

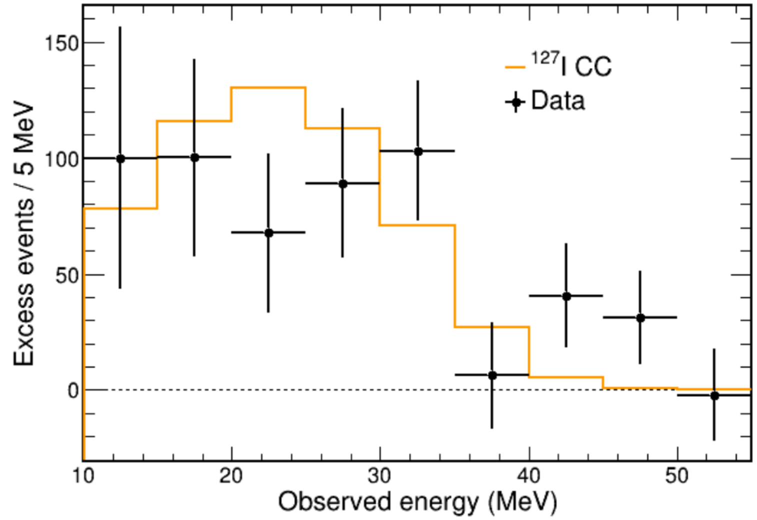
- 1.8σ significance, $>4\sigma$ disagreement with MARLEY model

Lower than expectation

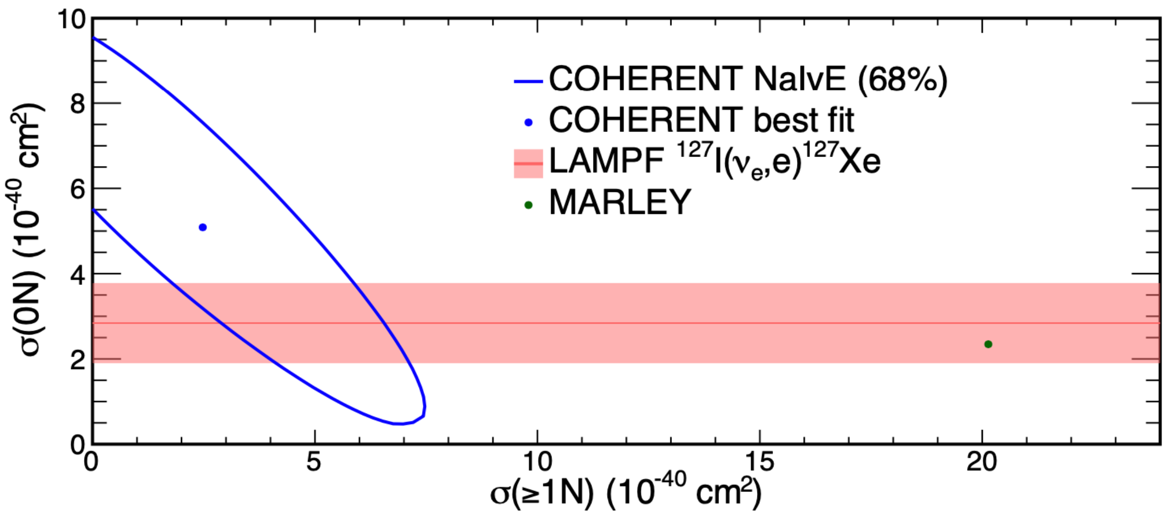
COHERENT results for **CC ν_e on ^{127}I**

NEW!





Preliminary



- $0n$ cross section: $\mathbf{5.2^{+3.4}_{-3.1} \times 10^{-40} cm^2}$
  - Compare to LAMPF measured value: $\mathbf{2.84 \pm 0.91(\mathit{stat}) \pm 0.25(\mathit{sys})}$×10^{-40} cm^2
- $1n$ cross section: $\mathbf{2.4^{+3.3}_{-2.4} \times 10^{-40} cm^2}$

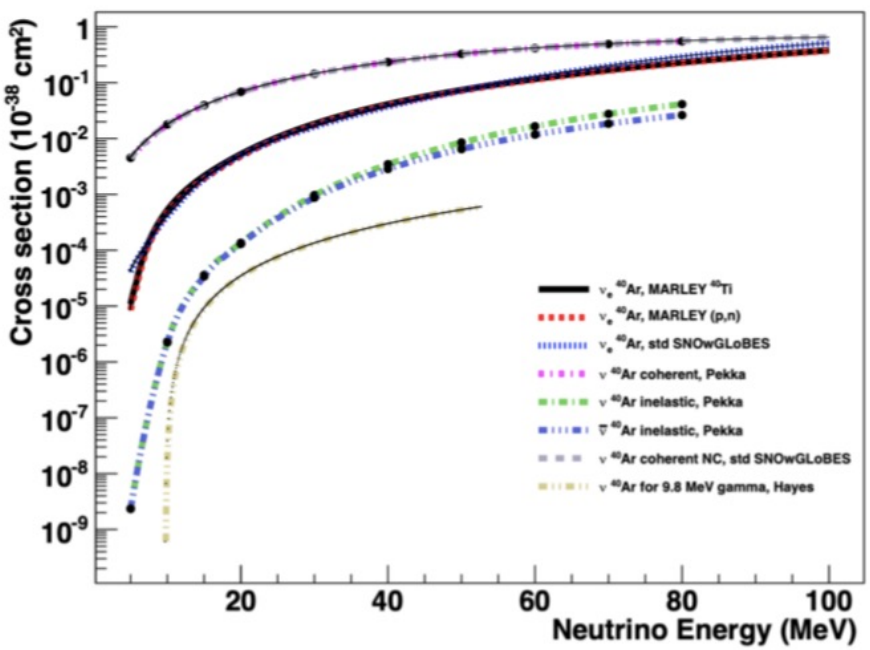
Also low!

Especially interesting to measure **electron neutrino interactions on on argon in the few tens of MeV range**

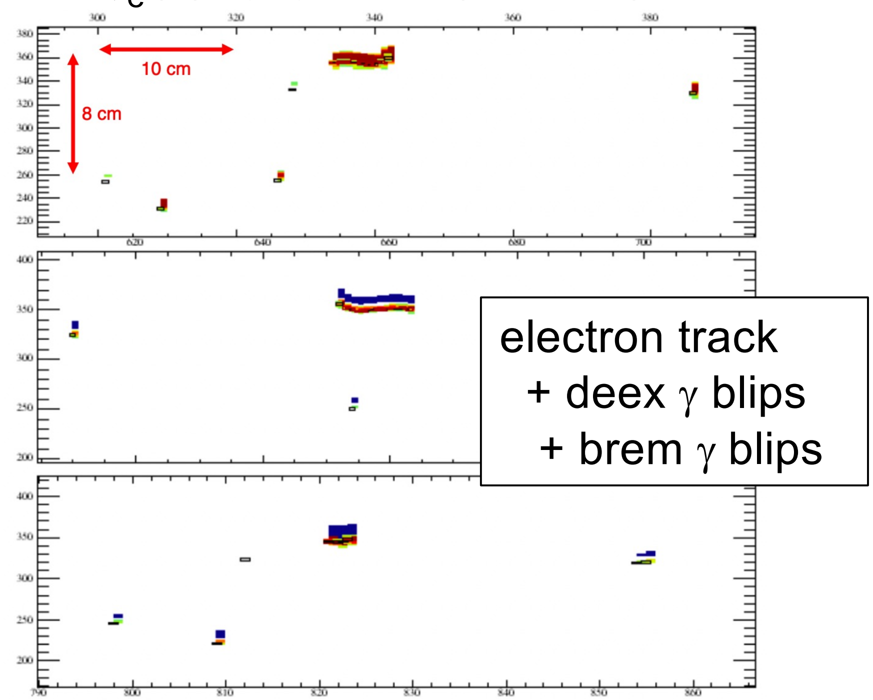
$$\text{CC} \quad \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

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

- critical to understand (differential) cross sections for supernova physics in DUNE
- large theoretical uncertainties on cross sections
- **no** existing measurements



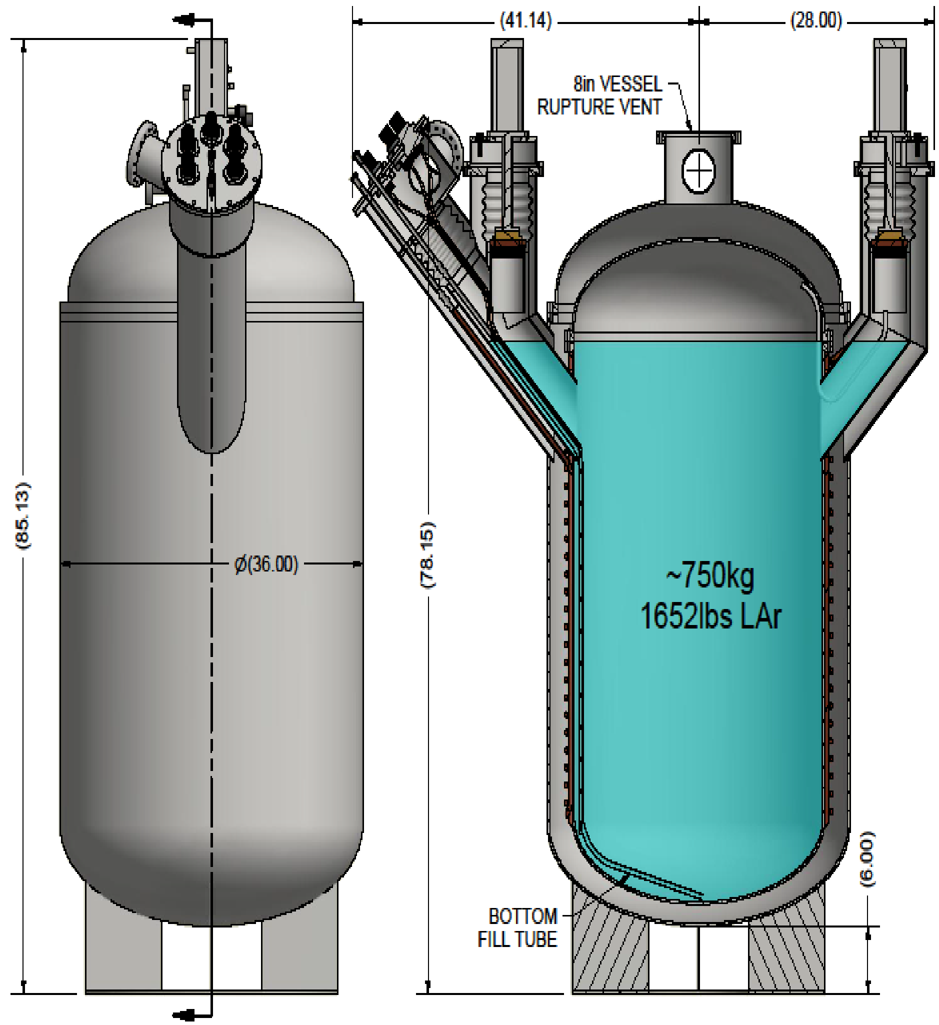
ν_eCC event in DUNE TPC



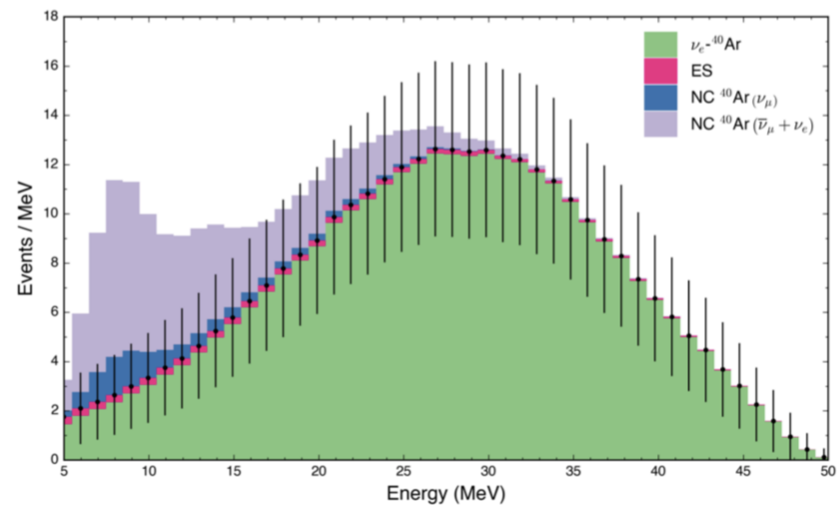
Impact on SNB in DUNE arXiv:2303.17007

More soon from COHERENT!

Tonne-scale LAr Detector



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



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

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

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

If ~7000 CEvNS interactions per year are detected in 1 ton of argon at the SNS, about how many ν_eCC events would be expected?

A. 70000

B. 3000

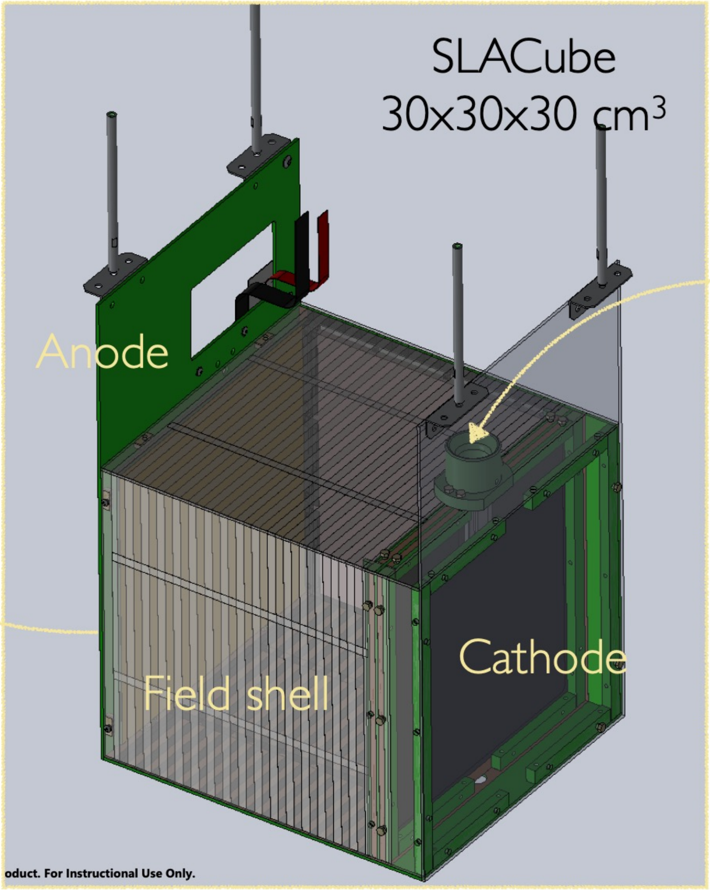
C. 300

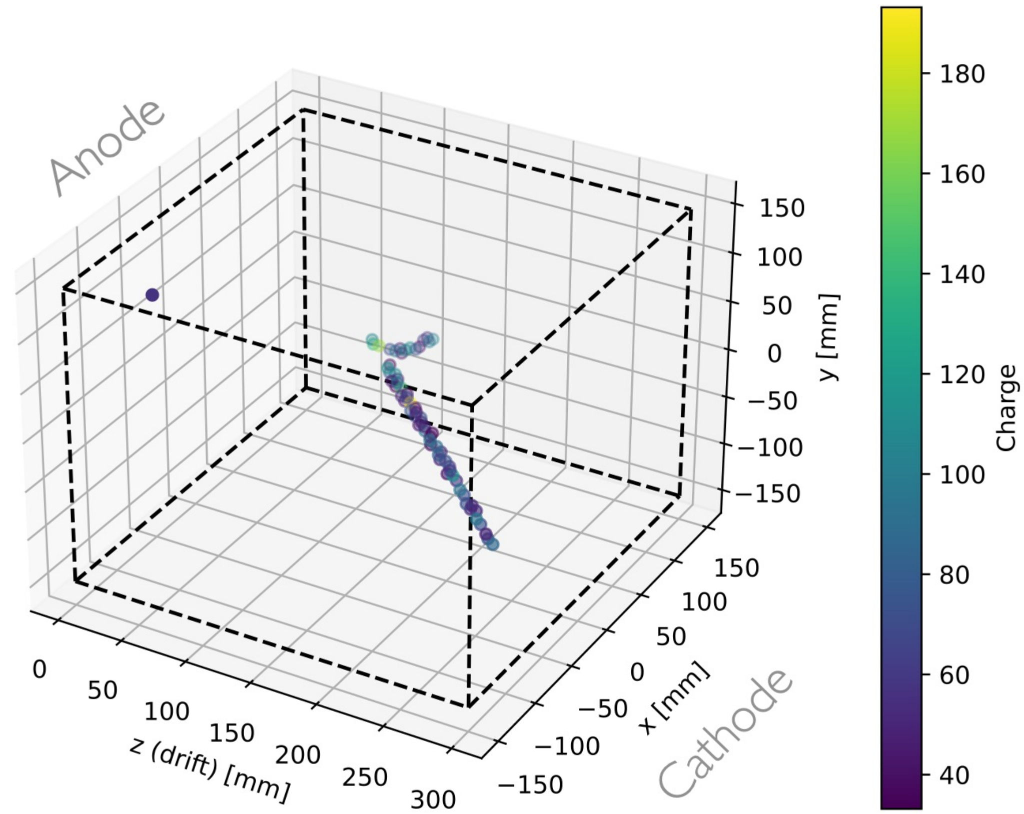
D. 70

E. 3

F. 0.1

Future LArTPC





Yun-tse Tsai, SLAC

- Proposed: 250 kg Ar (50x60x60 cm^3) [larger for STS]
- DUNE-like, relevant for SN burst & solar detection
- R&D test bed (e.g. pixelated readout, photon detectors, ...)

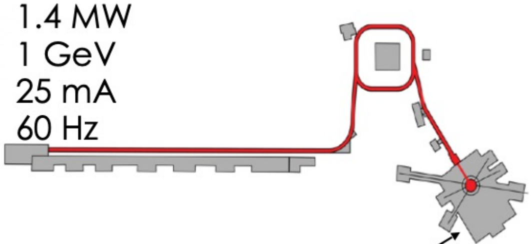
SNS upgrades: Beam Power and Second Target Station

PPU and STS upgrades will ensure SNS remains the world’s brightest accelerator-based neutron source

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

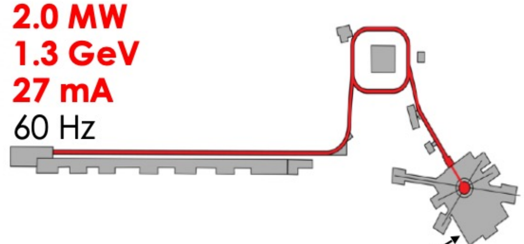


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



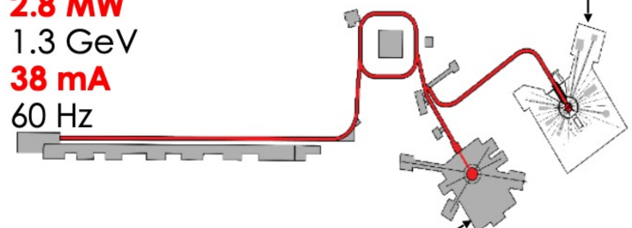
FTS
2 MW
60 Hz

early 2030's

- **2000+** users
- Hierarchical materials, time-resolution and small samples

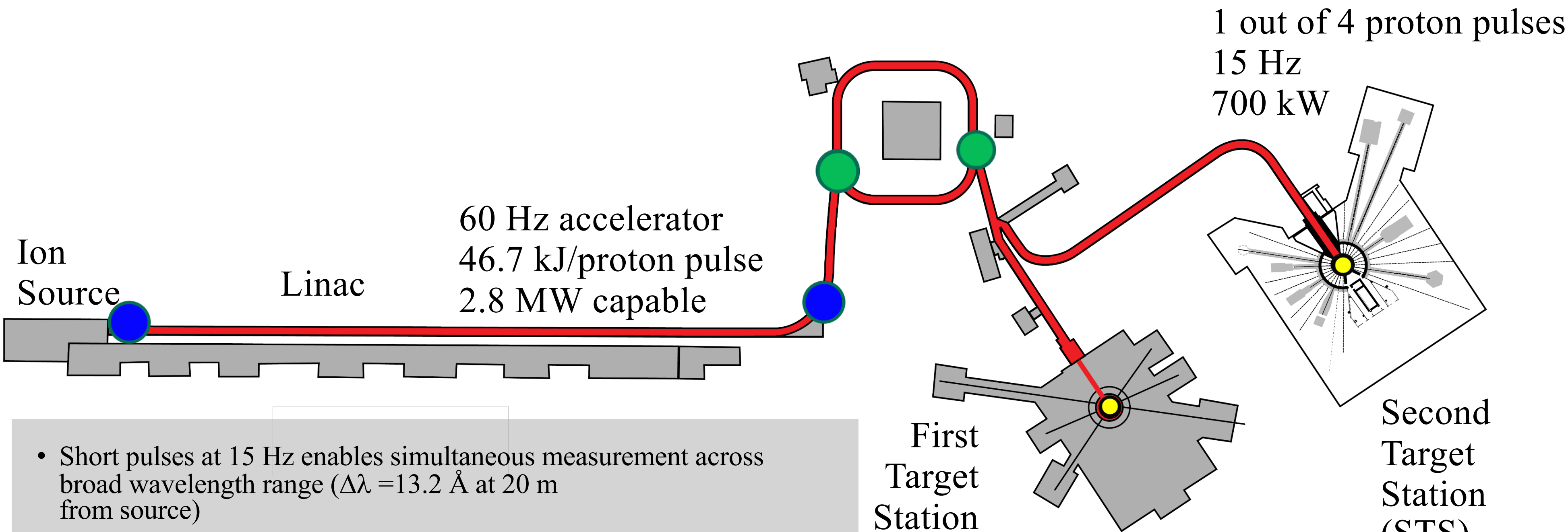
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec

STS will make optimal use of the SNS accelerator capability

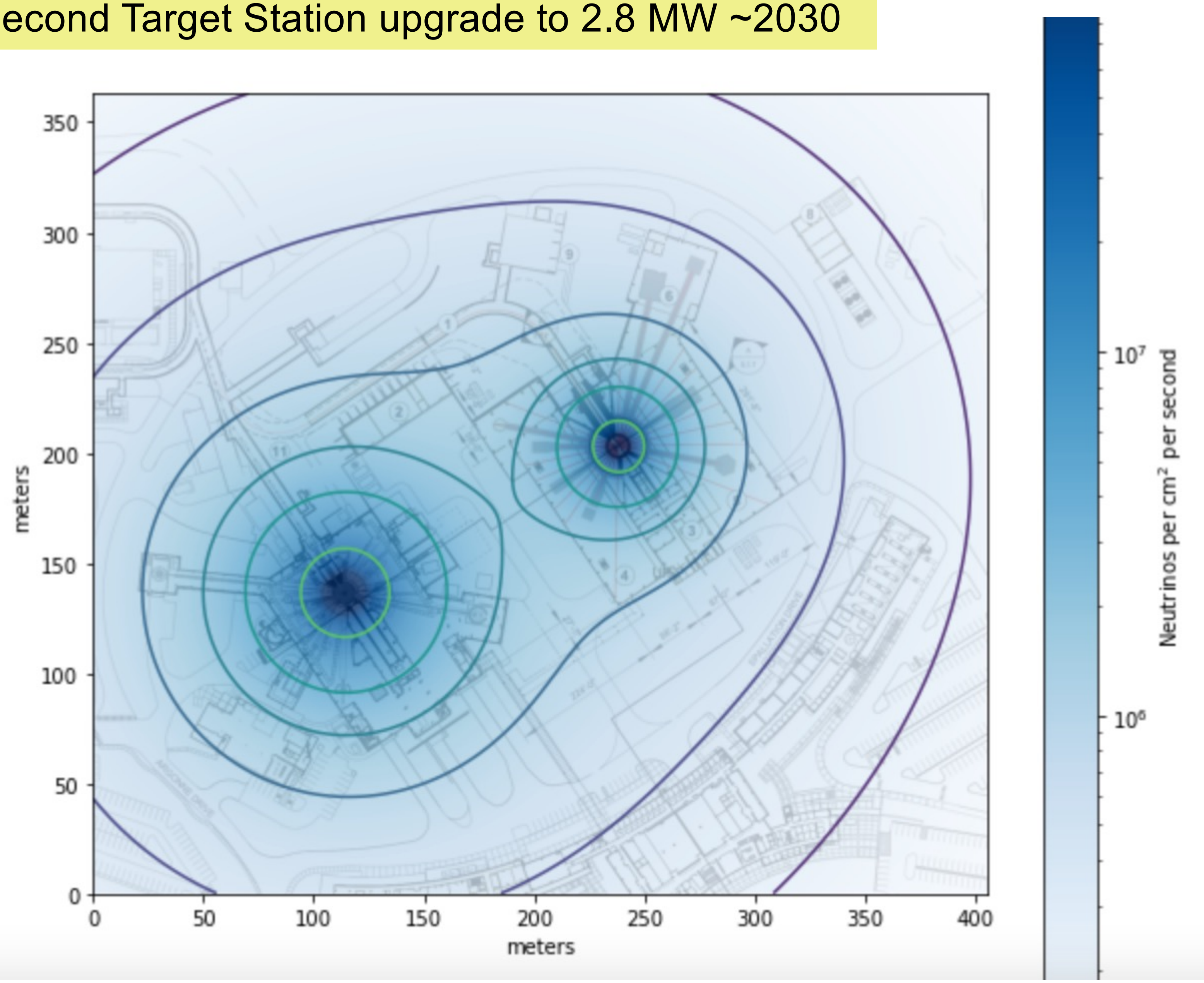


- Short pulses at 15 Hz enables simultaneous measurement across broad wavelength range ($\Delta\lambda$ =13.2 Å at 20 m from source)
- Complementarity with FTS – uses all available accelerator capability provided by PPU
- Flexibility will be provided to operate both FTS and STS at the same time or separately if either is shutdown

*animation courtesy of Matt Stone

From Ken Herwig

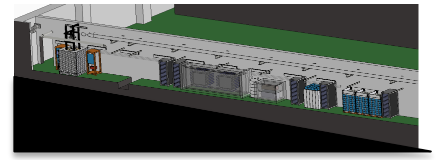
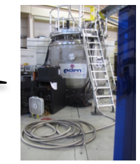
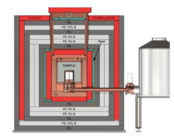
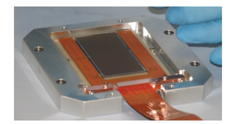
SNS power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030

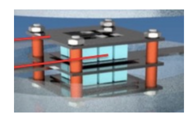


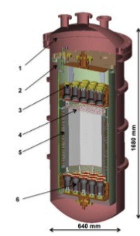
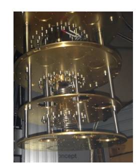
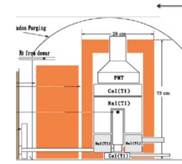
Many exciting possibilities for ν's + DM!

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

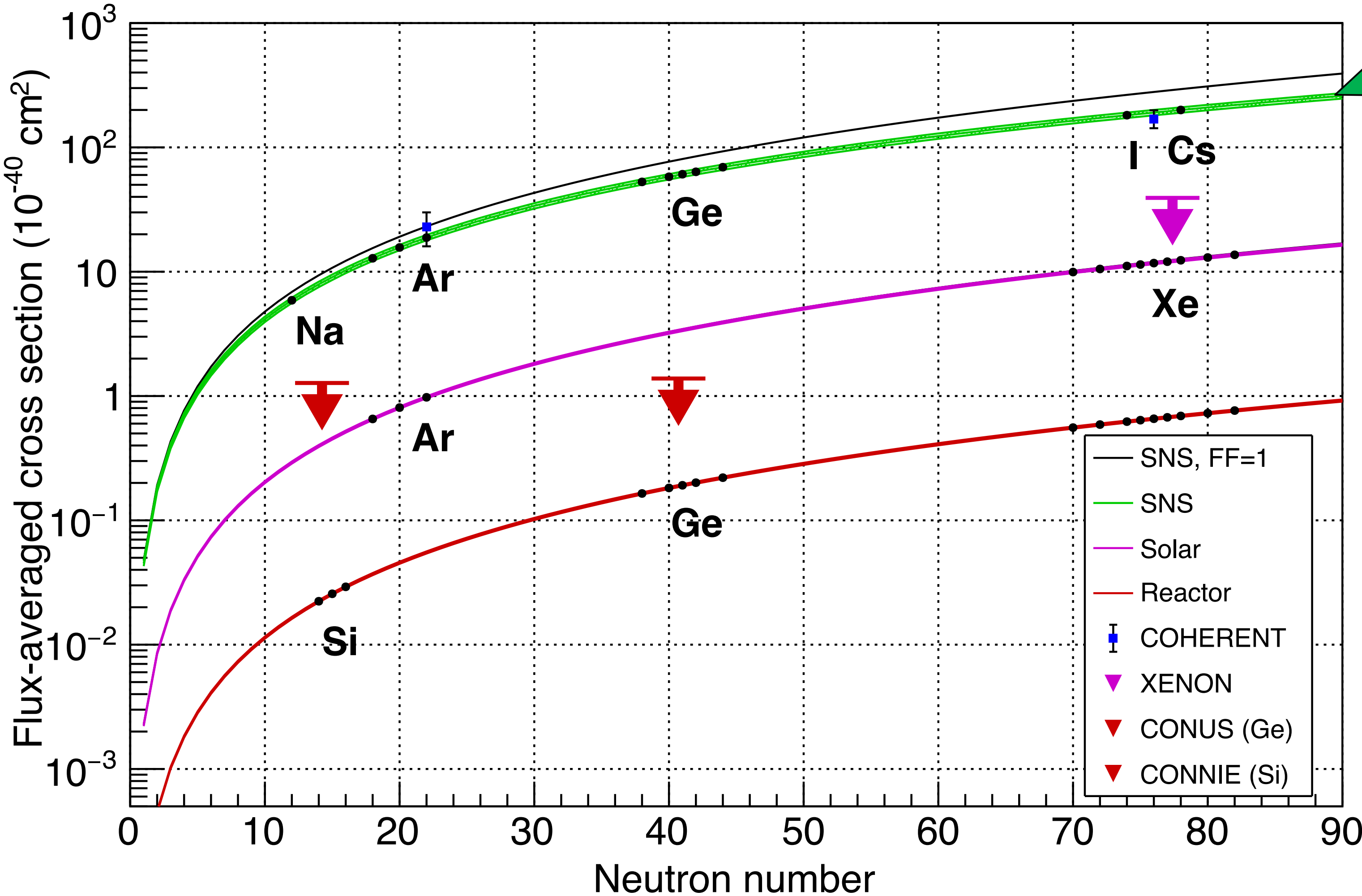


+ DM detectors, +directional detectors +more...

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

Summary of CEvNS Results



So far: measurements in CsI, Ar from COHERENT
... looking forward to more soon!

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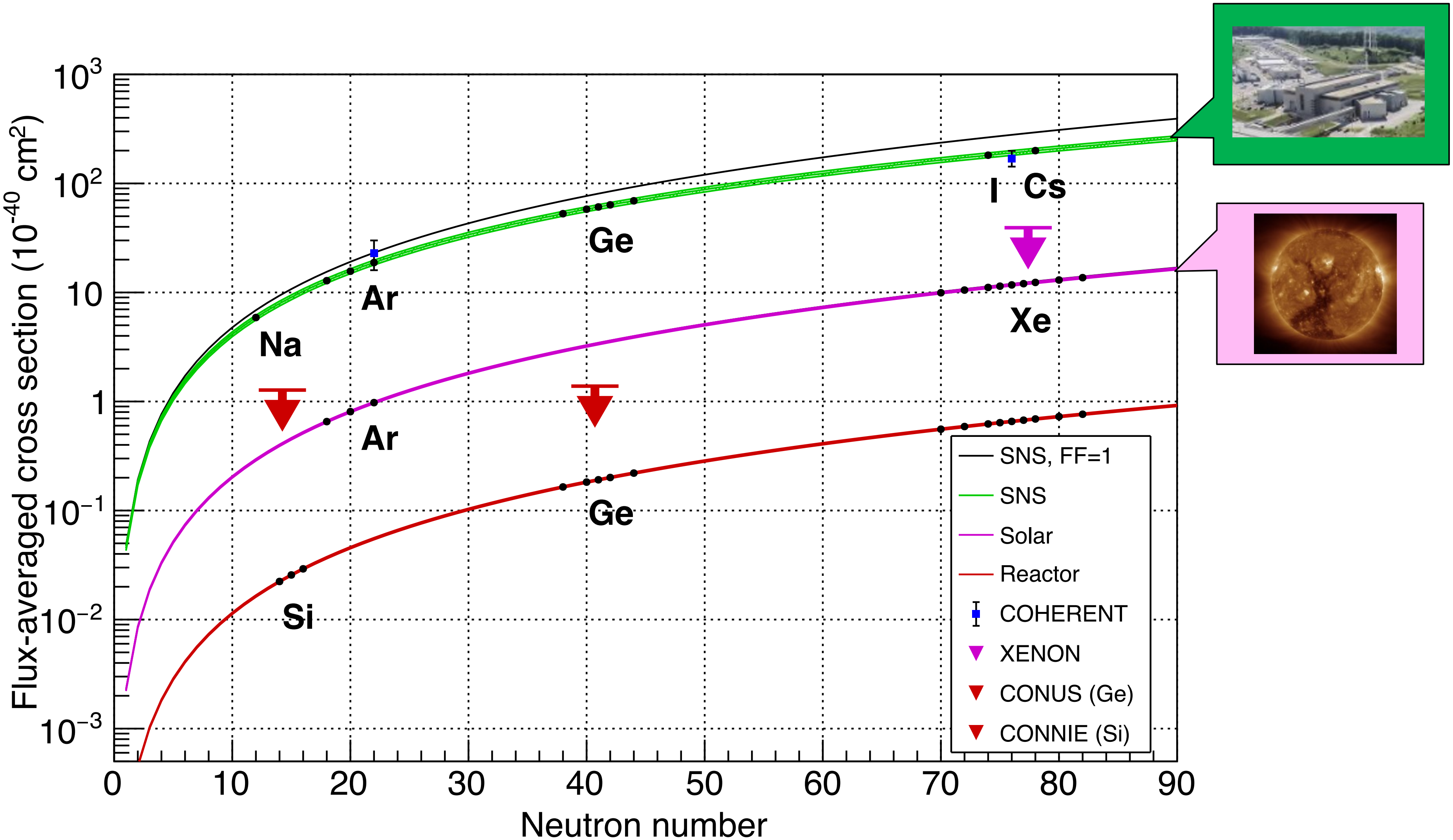

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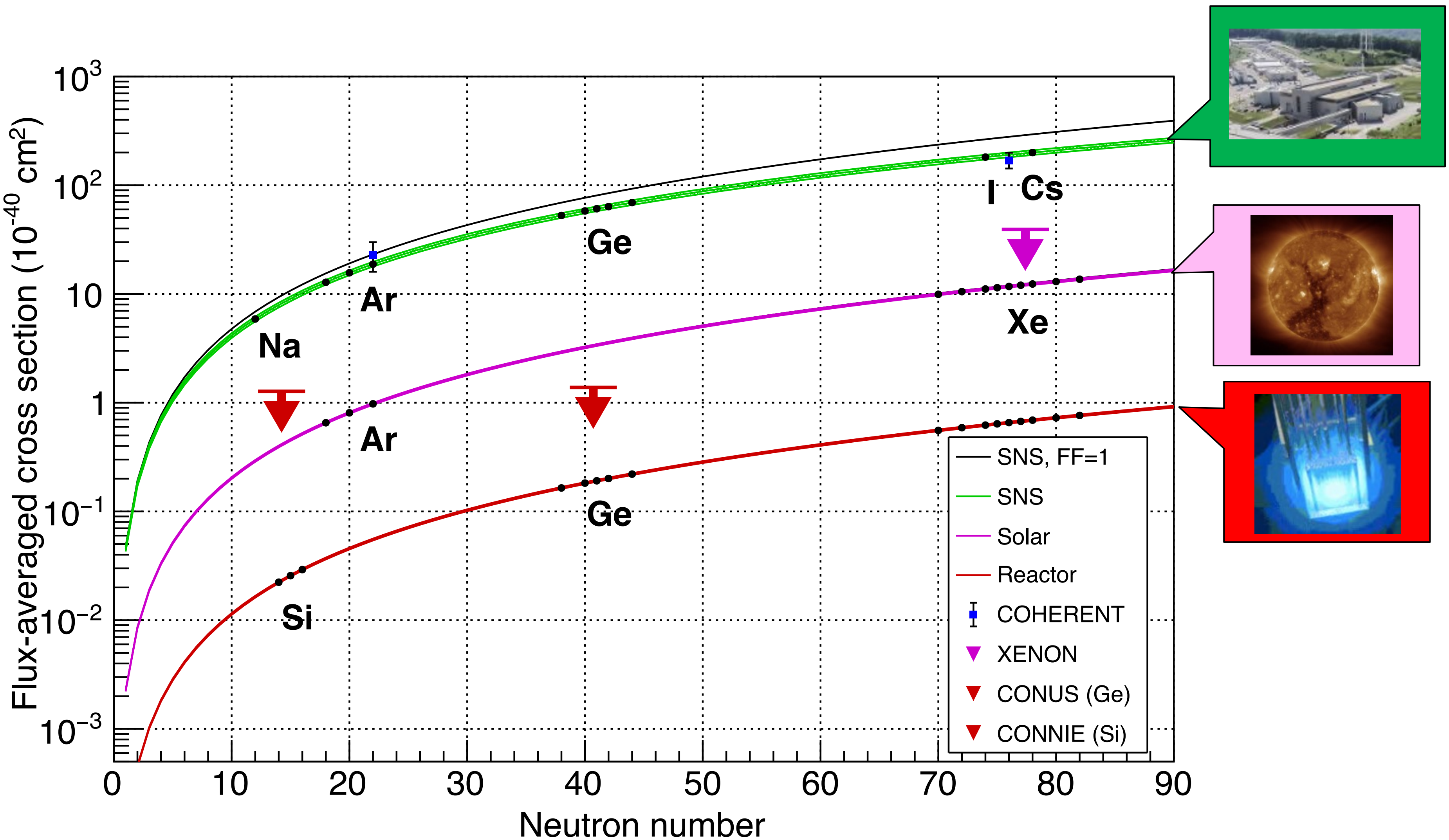

So far: measurements in CsI, Ar from COHERENT
... looking forward to more soon!

Final set of take-away points

- **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**

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

- **Inelastics in tens of MeV regime:**
  - fewer but brighter, important for SN & solar