Coherent Elastic Neutrino-Nucleus Scattering: Theory, Experiment, and Astrophysics

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@Beijing

CCEPP Summer School 2021 on Neutrino Physics

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

See the lectures by Prof. Kevin McFarland

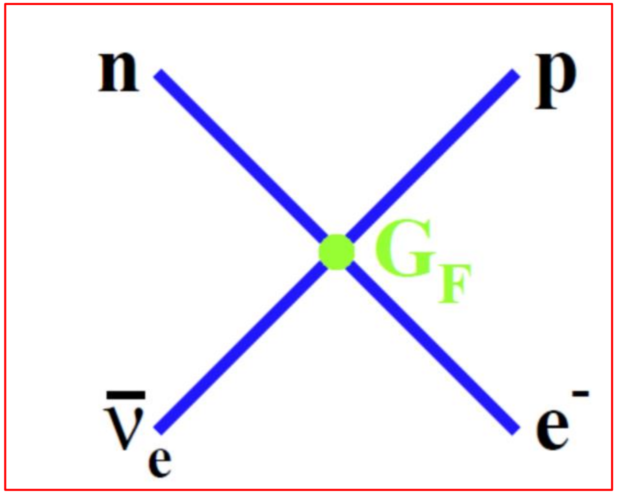
Part A: Some History

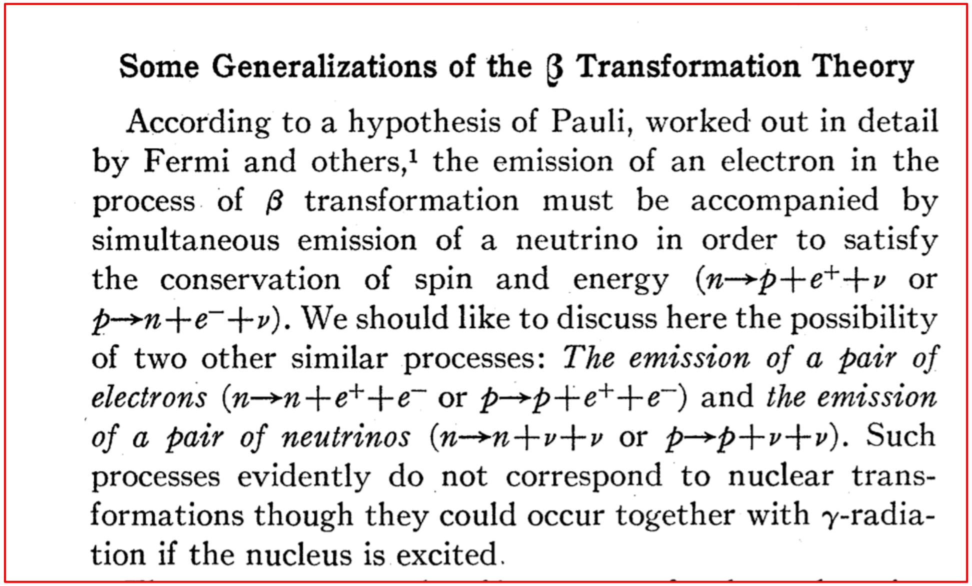
Neutral Current Weak Interaction

- **Neutral-Current (NC) Interaction is a natural prediction of the Standard Model of Particle Physics**

- **Fermi (1934) beta decay theory is the type of Charged-Current.**

- **The first idea (1937) of NC weak interaction was proposed by *Gamow and Teller, Kemmer, and Wentzel.***



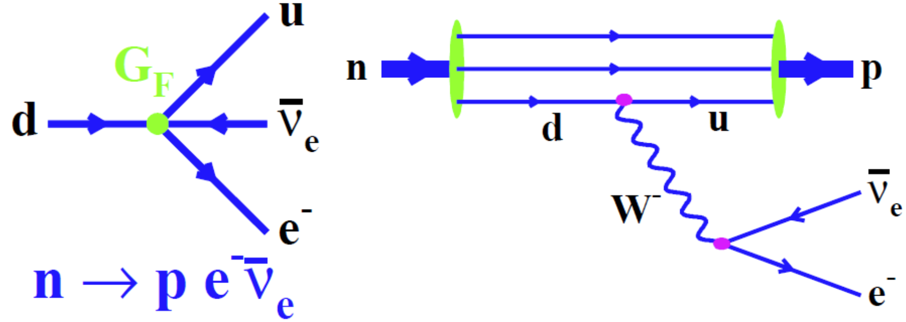


Some Generalizations of the β Transformation Theory

According to a hypothesis of Pauli, worked out in detail by Fermi and others,[1] the emission of an electron in the process of β transformation must be accompanied by simultaneous emission of a neutrino in order to satisfy the conservation of spin and energy ($n \to p + e^+ + \nu$ or $p \to n + e^- + \nu$). We should like to discuss here the possibility of two other similar processes: *The emission of a pair of electrons* ($n \to n + e^+ + e^-$ or $p \to p + e^+ + e^-$) and *the emission of a pair of neutrinos* ($n \to n + \nu + \nu$ or $p \to p + \nu + \nu$). Such processes evidently do not correspond to nuclear transformations though they could occur together with γ-radiation if the nucleus is excited.

Neutral Current Interactions in SM

- CC interaction is mediated by SU(2) Massive Gauge Boson $W^{+/-}$



- In 1958, Sidney Bludman suggested that there might be another arm of the weak force, the so-called "weak neutral current," mediated by an uncharged partner of the W bosons.
- The neutral Z boson was introduced by Glashow in 1961 in order to extend from SU(2) to SU(2)xU(1)
- Finally the gauge structure of SM was kept in Weinberg’s SM in 1967

Discovery of NC Interaction in 1973

- **Alternating neutral currents (忽隐忽现的中性流)**

- **Two neutrino experiments were running:**
  (A) Gargamelle at the CERN Proton Synchrotron
  (B) HPWF (Harvard, Pennsylvania, Wisconsin, Fermilab) counter at Fermi

- **To measure the NC & CC Interactions with muon neutrinos:**

Table 1

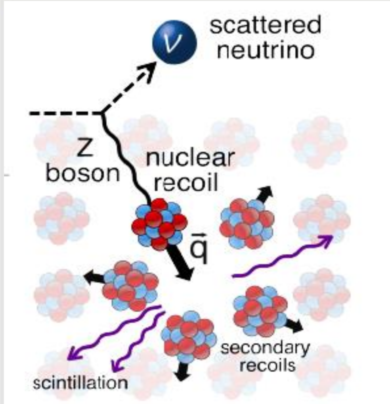
	ν-exposure	$\bar{\nu}$-exposure
No. of neutral-current candidates	102	64
No. of charged-current candidates	428	148

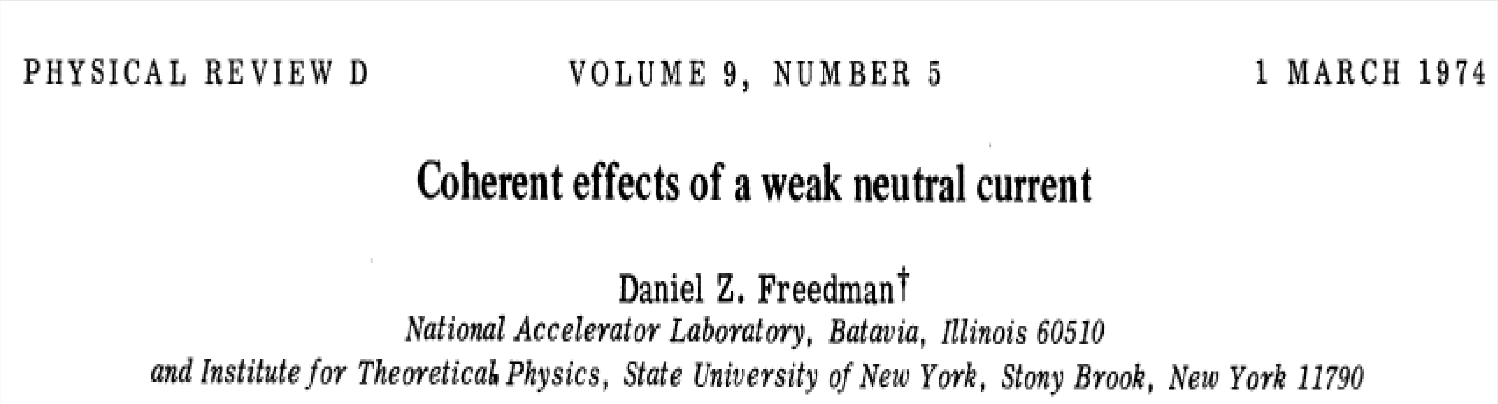
Fig. 1. The Gargamelle heavy-liquid bubble chamber, installed into the magnet coils, at CERN in 1970.

- **Long history of Fermi results (published in 1974) led by Carlo Rubbia.**

- **Rubbia discovered W&Z at CERN In 1983**

First prediction in 1974

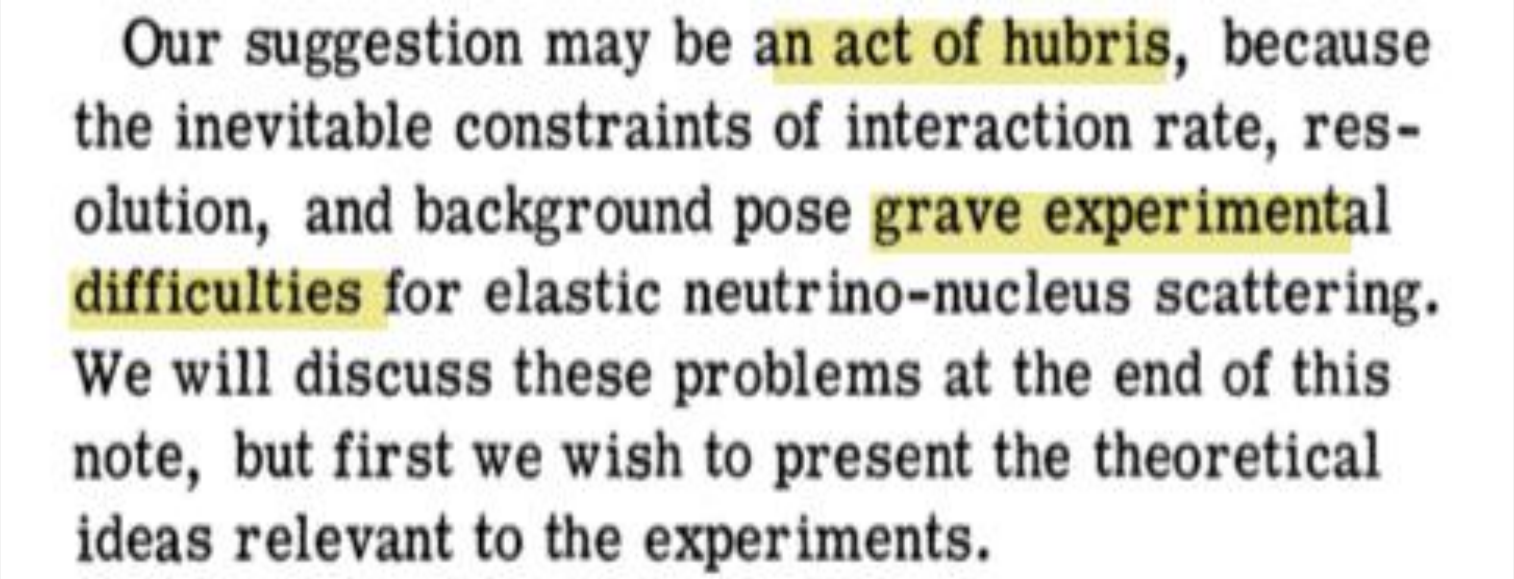




PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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



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.

In analogy to the coherent behavior of electron-nucleus scattering

First idea on the detection?

First idea on how to detect the neutrino coherent scattering process:

Superconducting-grain detector for (10-1000 eV) recoiled energies

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

direct detection of dark matter?

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 33, NUMBER 8 15 APRIL 1986

Possibility of detecting heavy neutral fermions in the Galaxy

Ira Wasserman
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853
(Received 22 May 1985; revised manuscript received 31 October 1985)

It is shown that heavy neutral fermions in the galactic halo could produce numerous detectable low-energy events in a "thermal" neutrino detector if the heavy-fermion—nucleon vector coupling is comparable in strength to the vector weak interaction. The conditions under which a detectable event rate could arise for fermions with purely axial-vector couplings are also discussed. In a silicon detector heavy-fermion events would be concentrated at low energies, and could be distinguished

First direct detection in 2017

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...
+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

Science

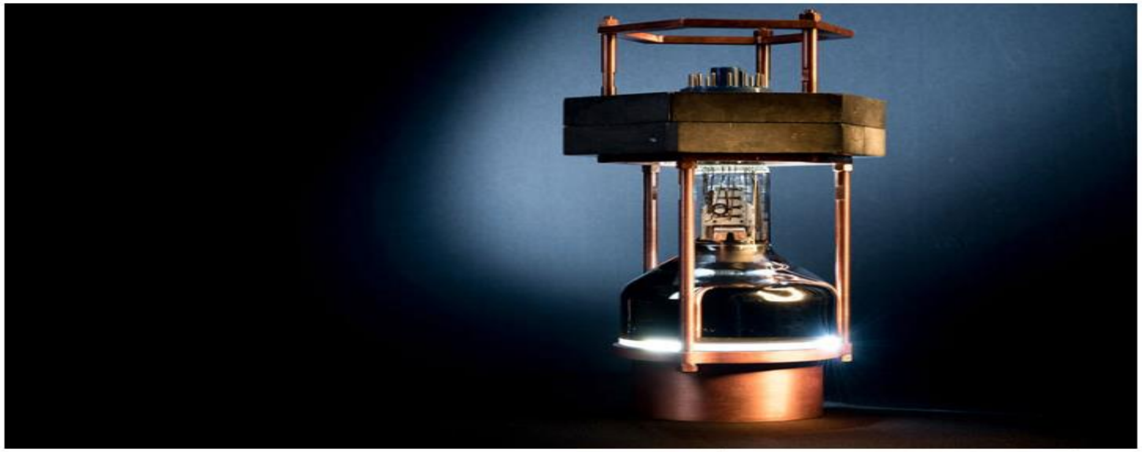
2017 BREAKTHROUGH OF THE YEAR

Cosmic convergence

RUNNERS-UP

- Life at the atomic level
- A tiny detector for the shiest particles
- Deeper roots for *Homo sapiens*
- Pinpoint gene editing
- Biology preprints take off
- A cancer drug's broad swipe
- A new great ape species
- Earth's atmosphere 2.7 million years ago
- Gene therapy triumph

A tiny detector for the shiest particles



A prototype of a detector that spotted coherent neutrino scattering for the first time. (JEAN LACHAT/UNIVERSITY OF CHICAGO)

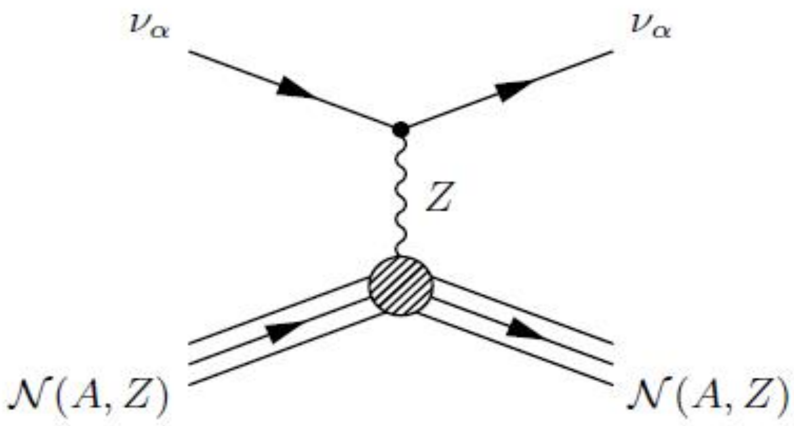
This year, physicists spotted the most elusive subatomic particles, neutrinos, pinging off atomic nuclei in a new way. The achievement fulfilled a 4-decade-long quest, and it didn't require the massive hardware usually used to detect neutrinos. Instead, the researchers pulled off the feat with a portable detector that weighs about as much as a microwave oven.

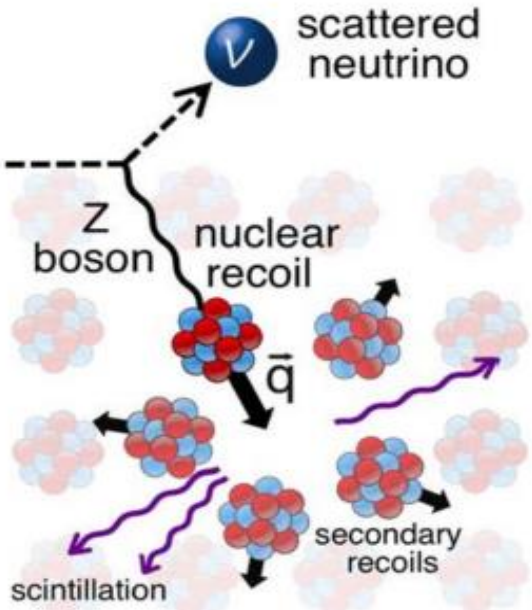
Part B: Fundamentals

Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced "sevens"
- Weak Neutral-Current (NC) interaction:

$$\boxed{\nu_\alpha + \mathcal{N}(A,Z) \to \nu_\alpha + \mathcal{N}(A,Z)}$$





- The nucleus $\mathcal{N}(A,Z)$ recoils as a whole!
- So what?

The CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W(Q^2)\right]^2$$

- Weak charge of the nucleus $\mathcal{N}$: $\boxed{|\vec{q}| = \sqrt{2\,M\,T}}$

$$Q_W(Q^2) = g_V^n\, N\, F_N(|\vec{q}|) + g_V^p\, Z\, F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

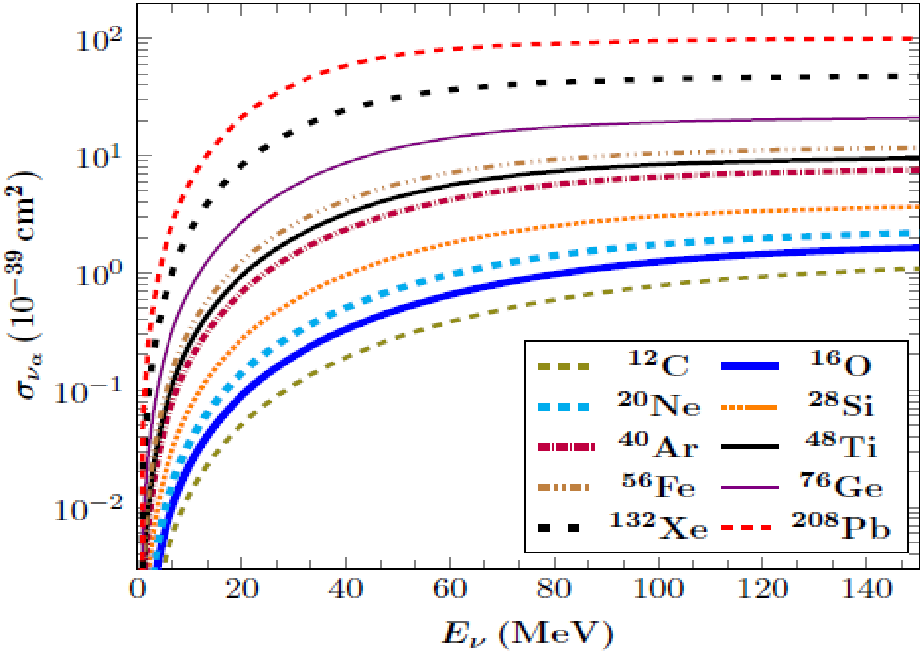
The neutron contribution is dominant! $\Longrightarrow$ $\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT} \propto N^2$

[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto N \Longrightarrow \sigma_{\mathrm{CE}\nu\mathrm{NS}}/\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto N$
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

The CEνNS Cross Section

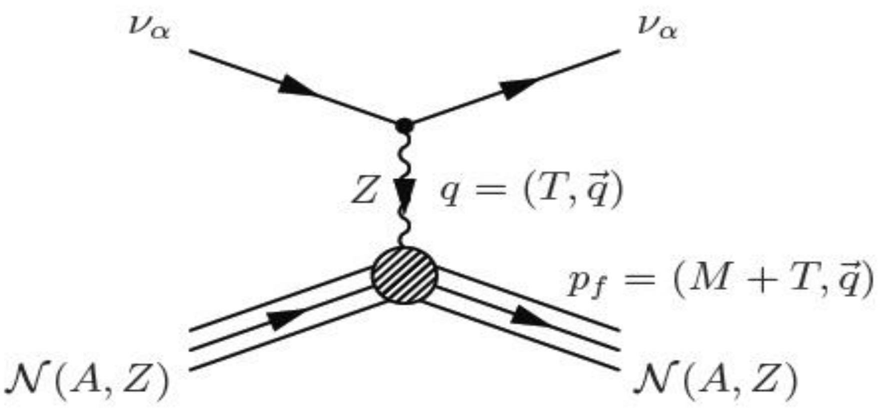
- Big cross section enhancement for heavy nuclei $\mathcal{N}(A, Z)$ with many nucleons N_i:
  - Incoherent scattering: $\sigma(\nu\mathcal{N}) \sim \sum_i |\mathcal{A}(\nu N_i)|^2 \propto A$
  - Coherent scattering: $\sigma(\nu\mathcal{N}) \sim \left|\sum_i \mathcal{A}(\nu N_i)\right|^2 \propto A^2$



[Papoulias, Kosmas, Kuno, arXiv:1911.00916]

The CEνNS kinematics

$$\boxed{|\vec{q}|\, R \lesssim 1}$$



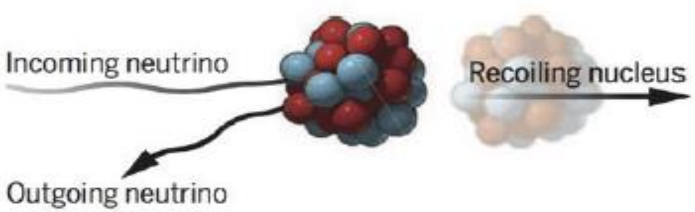
- Heavy target nucleus $\mathcal{N}(A, Z)$:

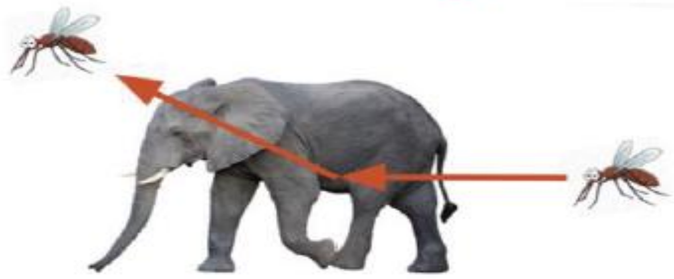
$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

$$R \approx 1.2\, A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$
- Non-Relativistic nuclear recoil:

$$|\vec{q}| \simeq \sqrt{2\,M\,T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$





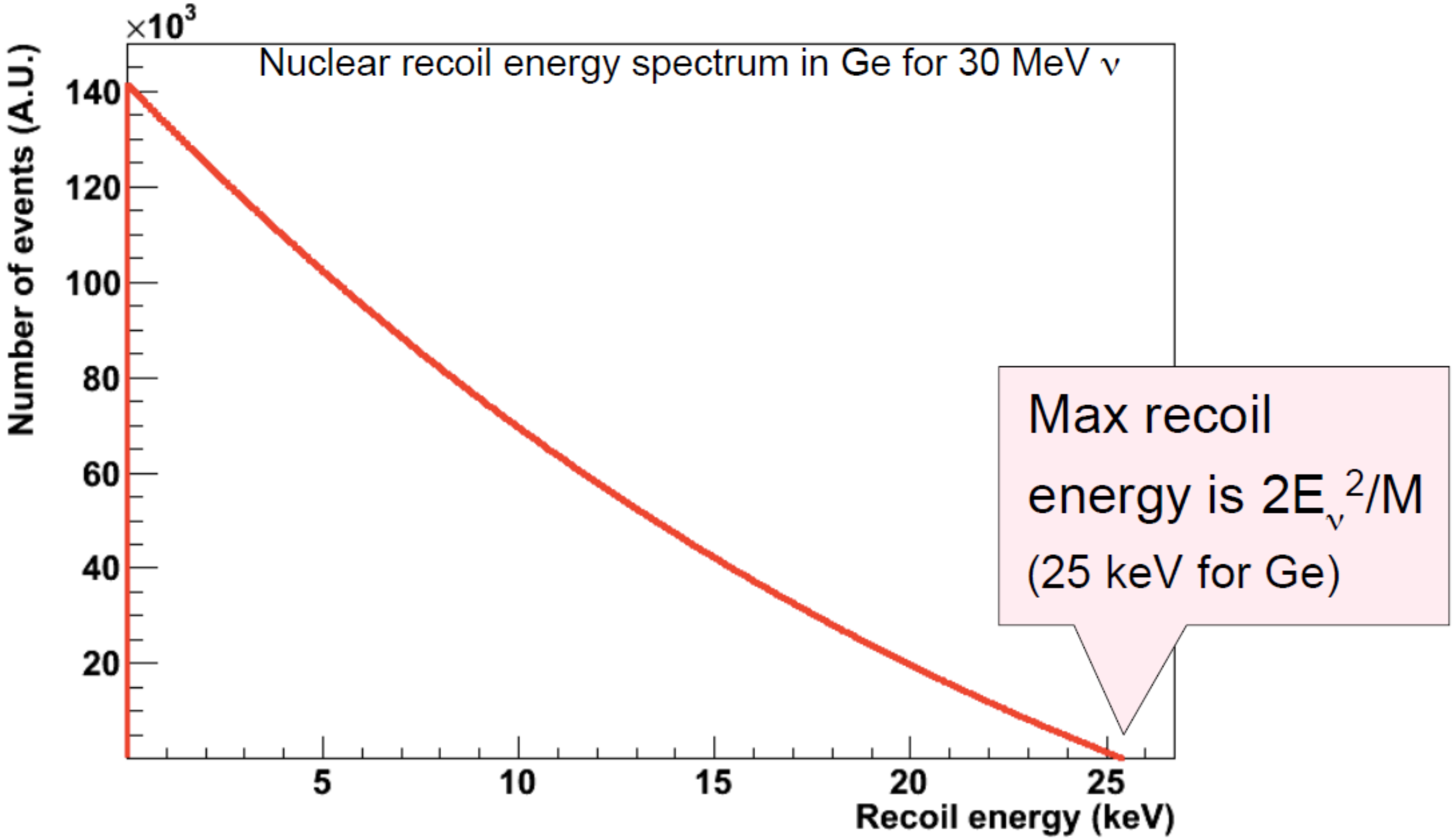
- Observable nuclear recoil kinetic energy:

$$T \simeq \frac{|\vec{q}|^2}{2\,M} \lesssim 10\,\text{keV} \quad \leftarrow \quad \text{Very Small!}$$

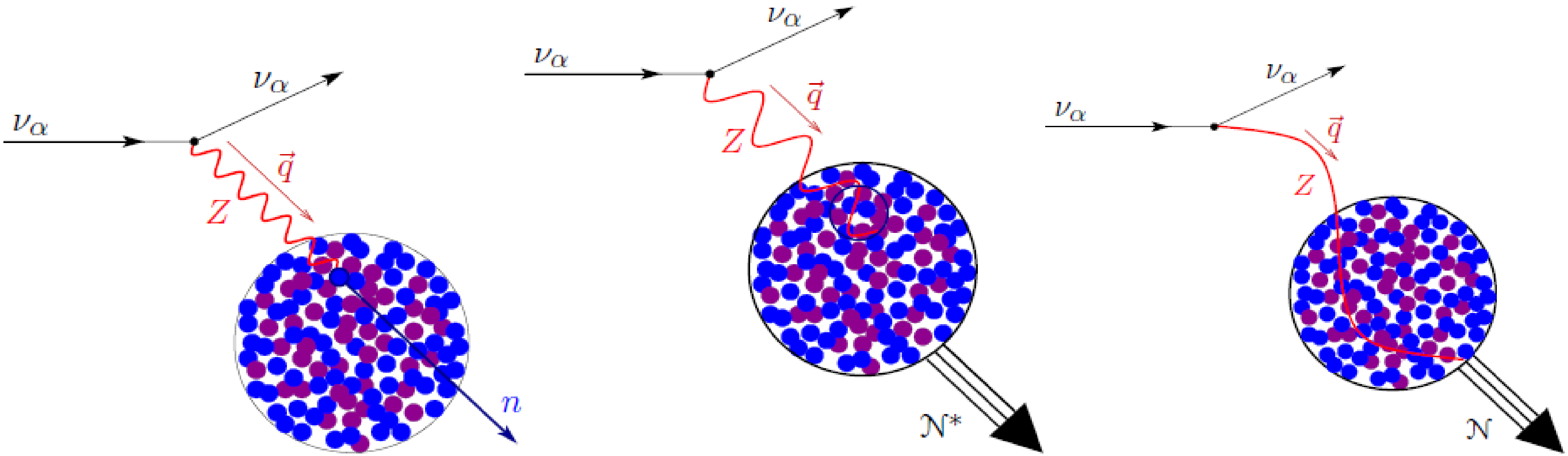
Why difficult?

(1) the only experimental signature: nuclear recoils

(2) tiny nuclear recoil energies



Why Coherent ?



Inelastic Incoherent	Elastic Incoherent	Elastic Coherent
$\lambda_Z \ll R$	$\lambda_Z \lesssim R$	$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|} \quad \Longrightarrow \quad \text{CE}\nu\text{NS for } |\vec{q}|\, R \lesssim \hbar$$

$$\boxed{|\vec{q}|\, R \lesssim 1} \quad \longleftarrow \quad \text{Natural Units}$$

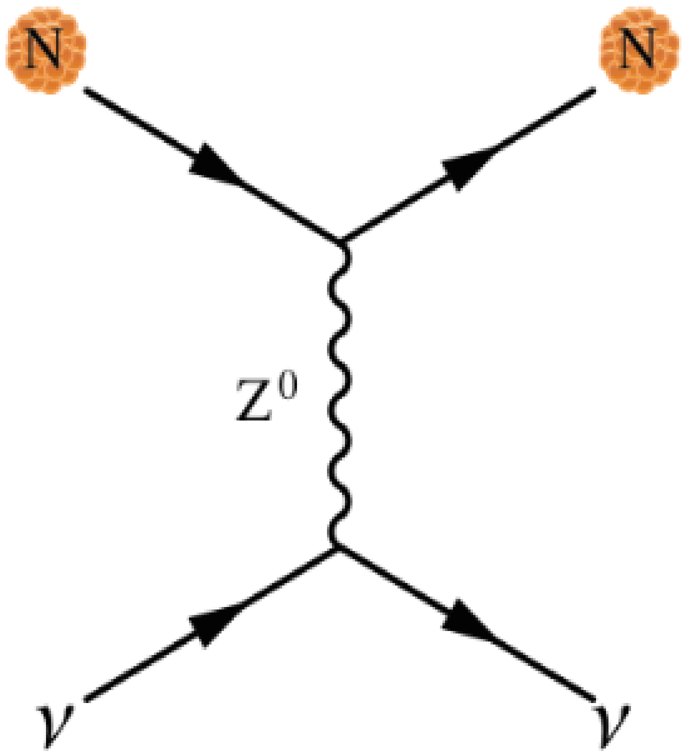
Why coherent?

Z-exchange of a neutrino with nucleus

- Neutrino wavelength larger than size of nucleus: QR<<1
- Nucleon wave-functions in the target nucleus are in phase with each other:

  nucleus recoils as a whole

- So the cross section should be proportional to A^2



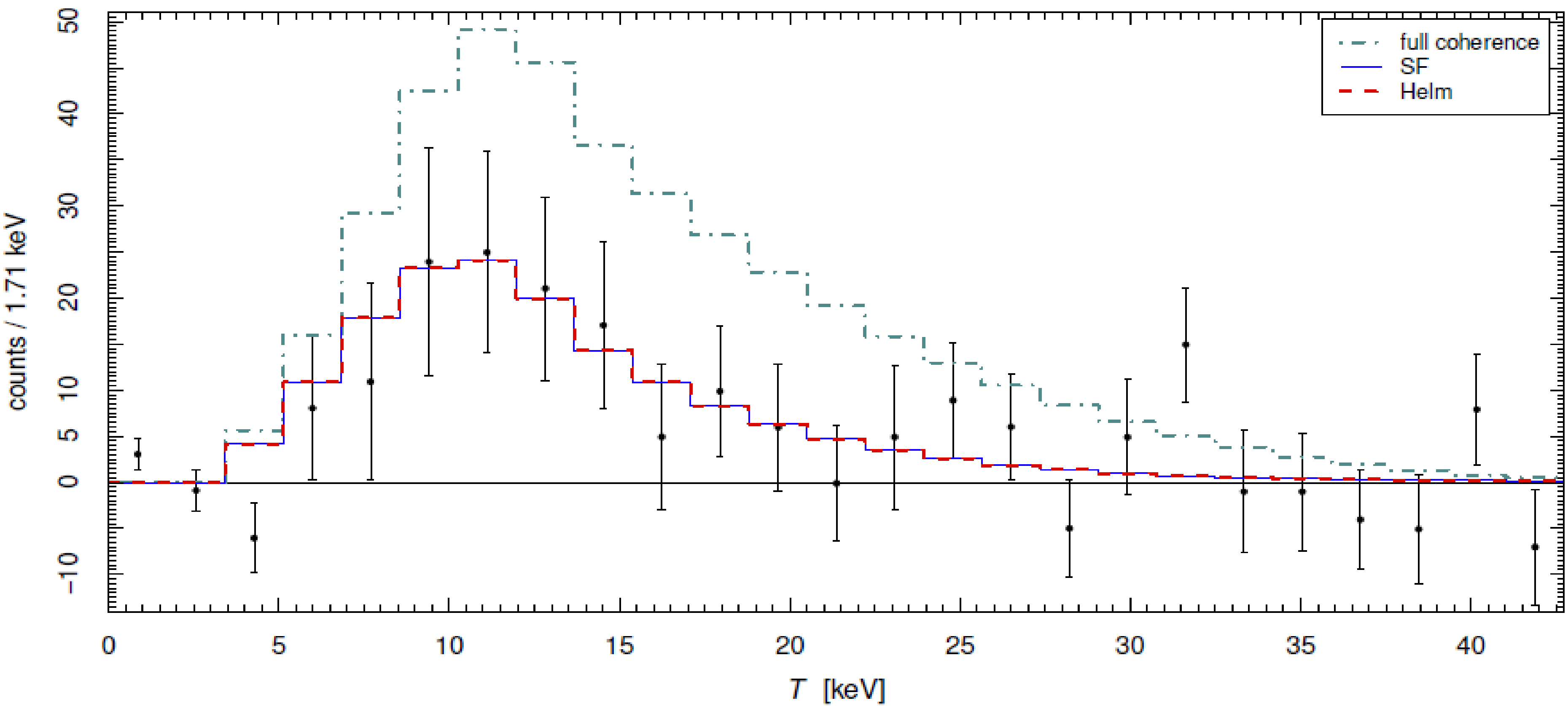
→ Enhanced cross section for heavy nuclei

Coherence hold up to ~ 50 MeV

Why Coherent ?

- In the COHERENT experiment the scattering is not completely coherent

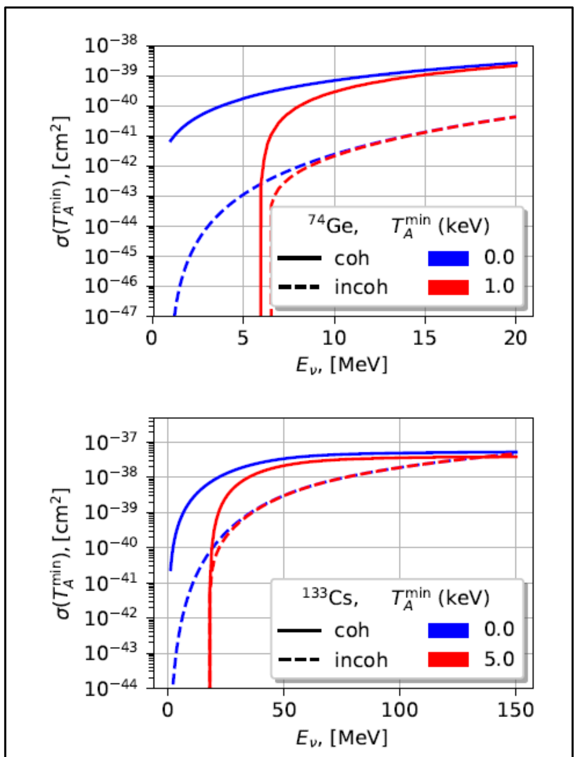
$$\text{CsI:}\ \left\{\begin{array}{l} |\vec{q}| \sim 30-80\,\text{MeV} \sim 0.1-0.4\,\text{fm}^{-1} \\ R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm} \end{array}\right\} \Longrightarrow |\vec{q}|R \sim 0.5-2$$



Where is the incoherence part?

Taken from Bednyakov, Naumov, arXiv:1806.08768

$$
\begin{aligned}
|\mathcal{A}|^2 &= |\mathcal{A}_0|^2 \left(A + G(\boldsymbol{q})A(A-1)\right) \\
&= |\mathcal{A}_0|^2 \left(A^2 G(\boldsymbol{q}) + A\left(1 - G(\boldsymbol{q})\right)\right)
\end{aligned}
$$



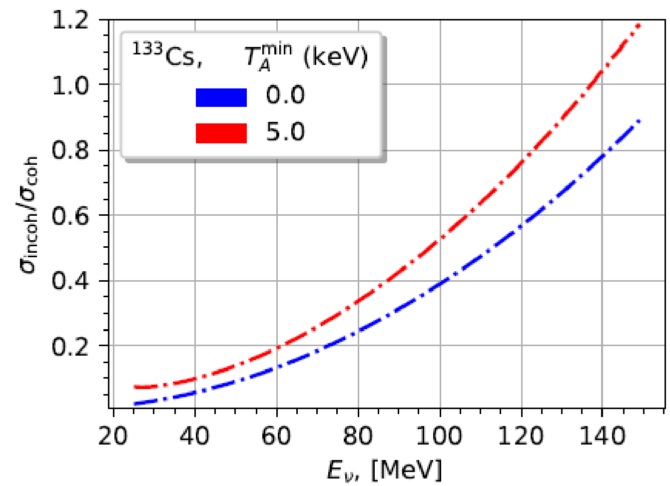
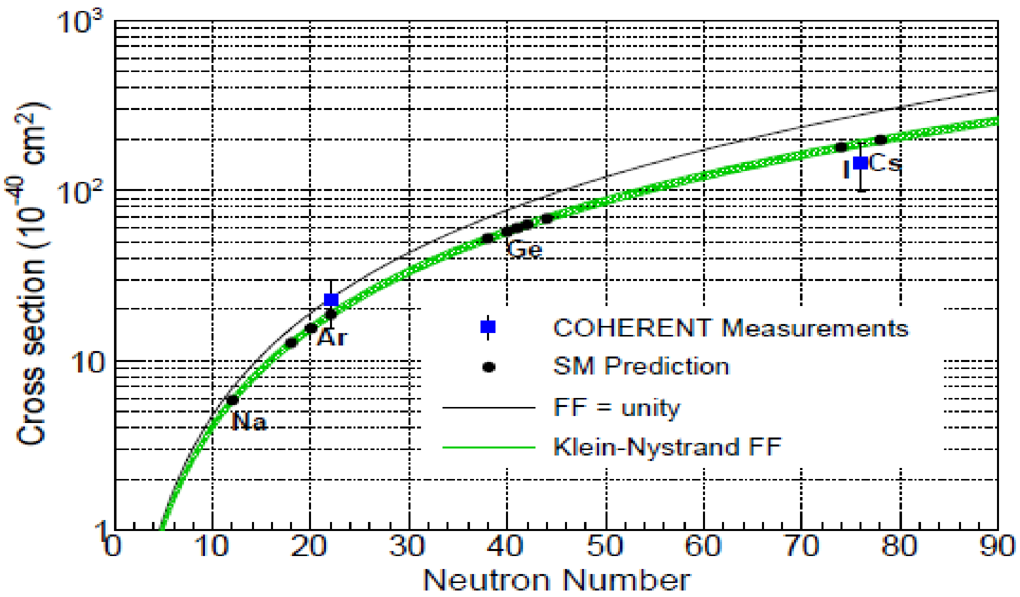


FIG. 8. Ratio $\sigma_{\mathrm{incoh}}/\sigma_{\mathrm{coh}}$ for neutrino scattering off of a ^{133}Cs nucleus as a function of E_ν. The two curves correspond to a $T_A^{\min} = 0\ (5)$ keV detection threshold.

Neutron Form Factor



[COHERENT, arXiv:2003.10630]

- Partial coherency is described by the nuclear neutron form factor $F_N(|\vec{q}|)$
- Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}}\,\rho_N(r)\,d^3r$$

- Measurable parameter: the radius R_n of the nuclear neutron distribution

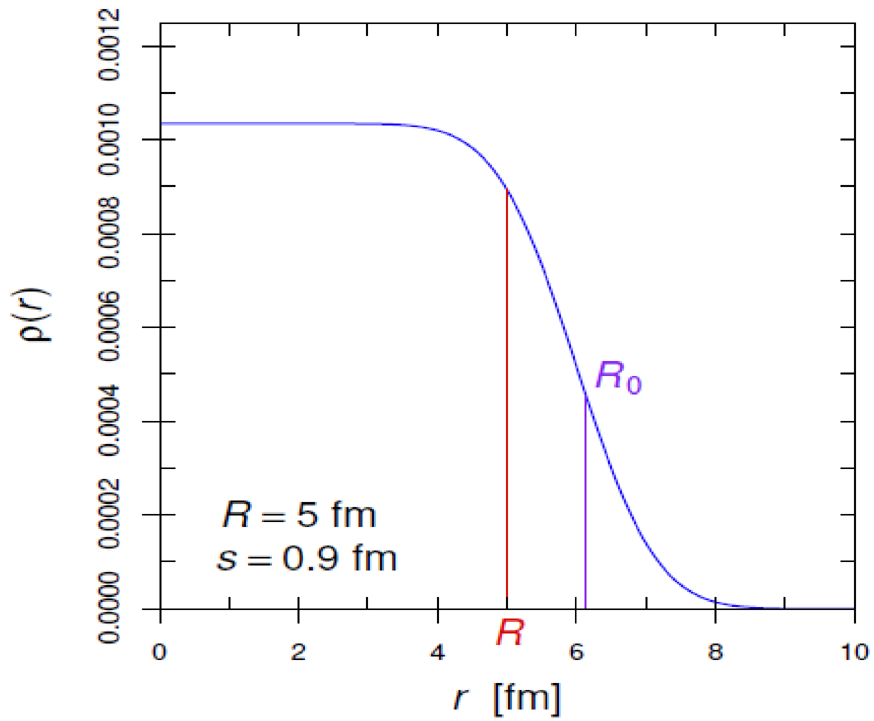
Neutron Form Factor

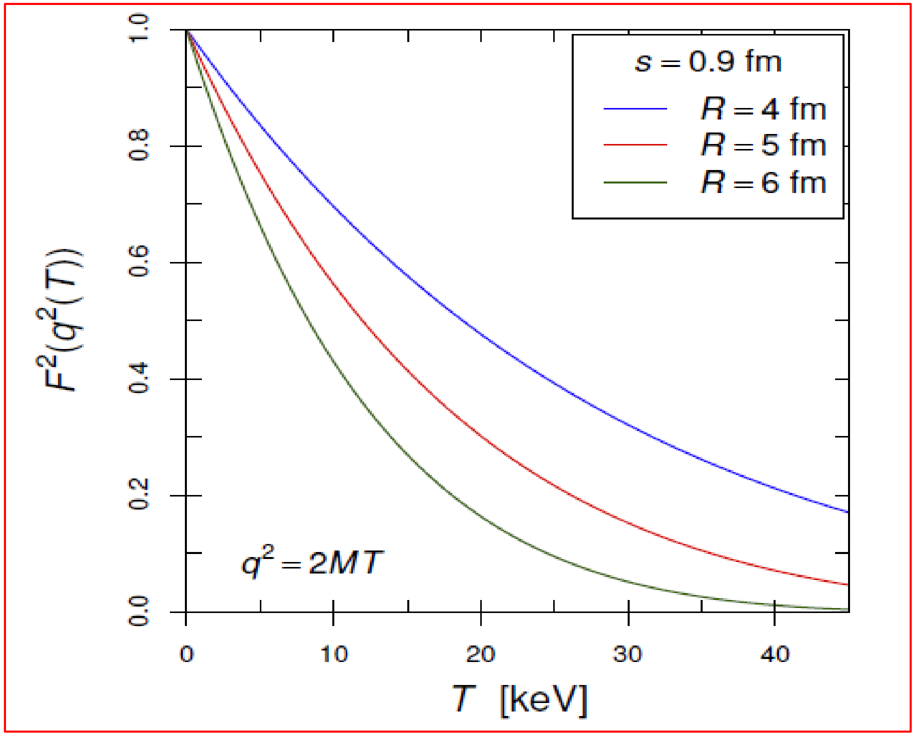
Helm form factor: $F_N^{\mathrm{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

Obtained from the convolution of a sphere with constant density with radius R_0 and a gaussian density with standard deviation s

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5} R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\mathrm{fm}$



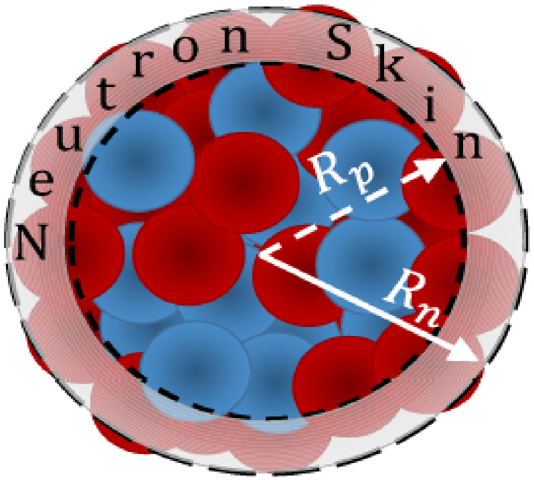


Nuclear Proton and Neutron Distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements.
  But they are more difficult.
- Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering:

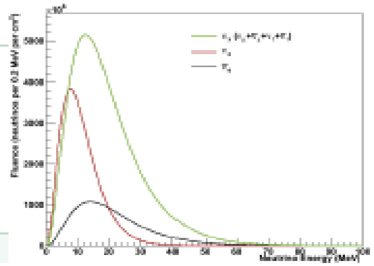
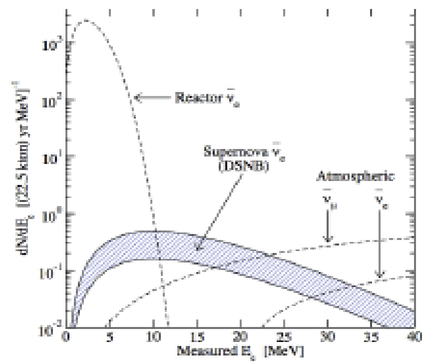
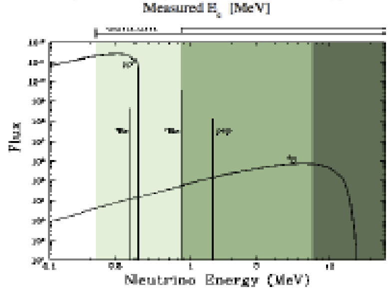
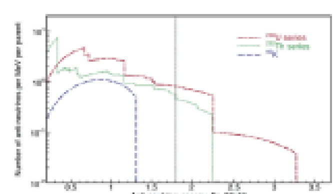
$$R_n(^{208}\mathrm{Pb}) = 5.78^{+0.16}_{-0.18}\ \mathrm{fm}$$

[PREX, PRL 108 (2012) 112502]



Part C: First Observation at SNS

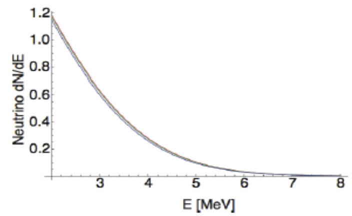
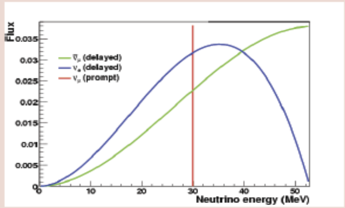
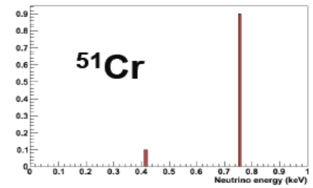
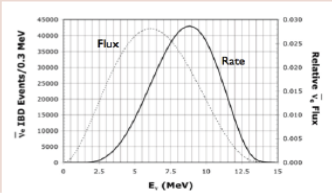
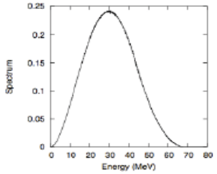
Natural sources of low-energy neutrinos

Supernova burst neutrinos		Every ~30 years in the Galaxy,~few 10's of sec burst, all flavors
Supernova relic neutrinos		All flavors, low flux
Atmospheric neutrinos		Some component at low energy
Solar neutrinos		Most flux below 1 MeV
Geoneutrinos		Very low energy

CEvNS eventually seen in DM expts

[Scholberg @ CNNP2017]

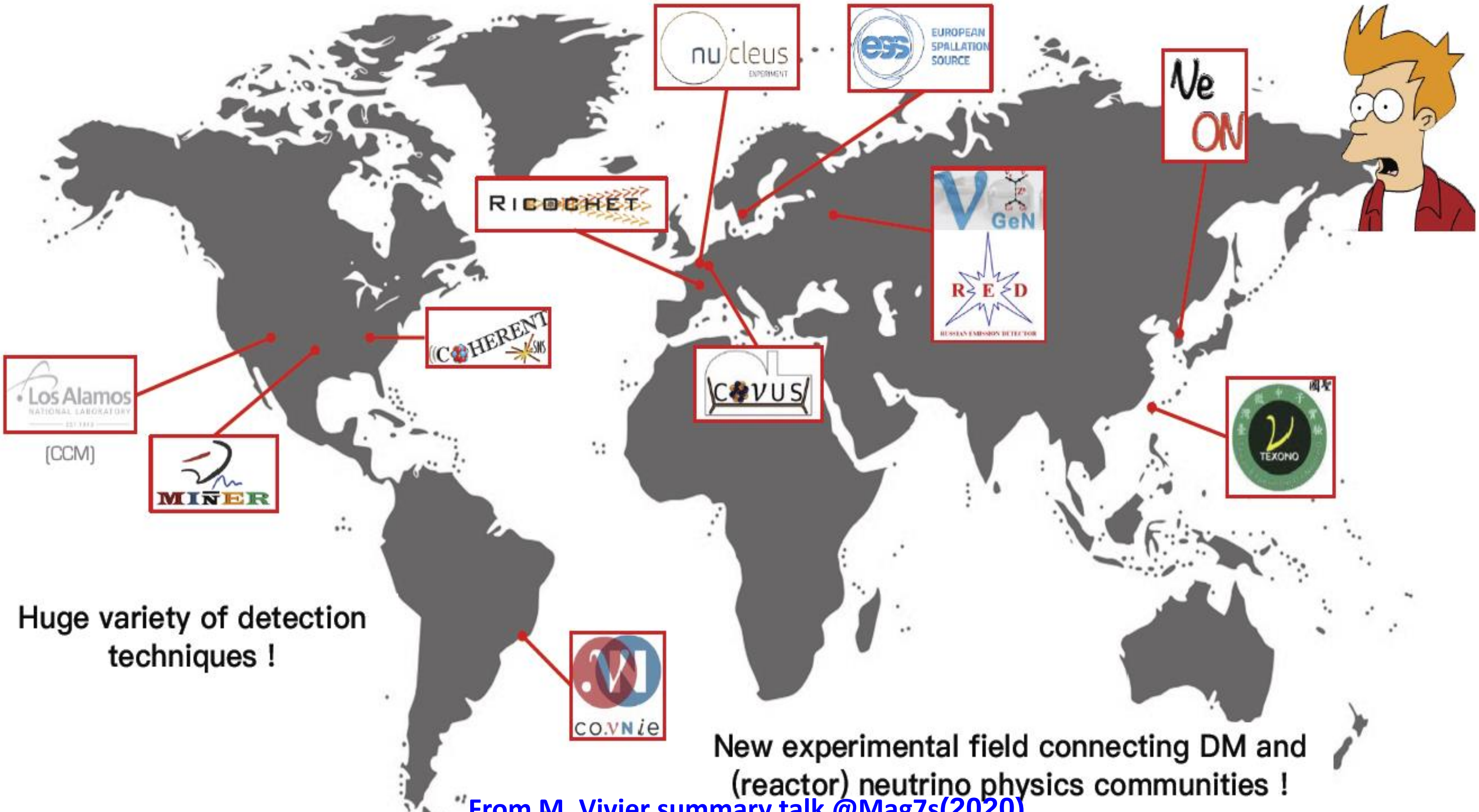
Artificial sources of low-energy neutrinos

Reactors		Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed
Stopped pions (decay at rest)		High energy, pulsed beam possible for good background rejection; possible neutron backgrounds
Radioactive sources (electron capture)		Portable; can get very short baseline, monochromatic **Low energy challenging**
Beam-induced radioactive sources (IsoDAR)		Relatively compact, higher energy than reactor; time structure not sharp **Does not exist yet**
Low-energy beta beams	 **γ=10 boosted ^{18}Ne ν_e**	Tunable energy, but not pulsed **Does not exist yet**

[Scholberg @ CNNP2017]

Exp. Program worldwide

Proliferation of experimental efforts worldwide !

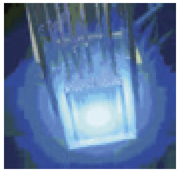


Huge variety of detection techniques !

New experimental field connecting DM and (reactor) neutrino physics communities !

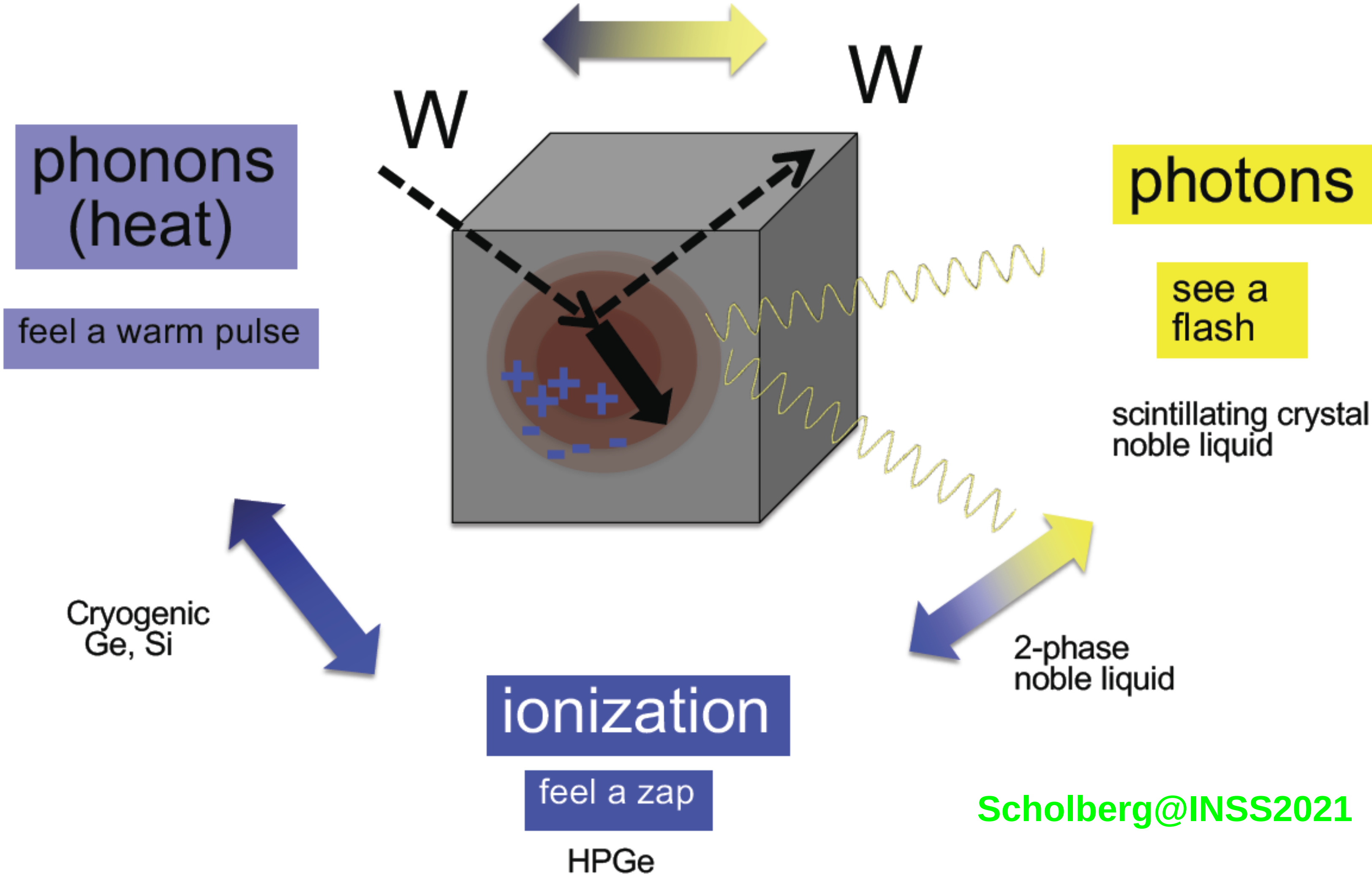
From M. Vivier summary talk @Mag7s(2020)

Reactor vs stopped-pion for CEvNS

Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor 	2e20 per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion 	1e15	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • multiple flavors	• lower flux • potential fast neutron in-time bg

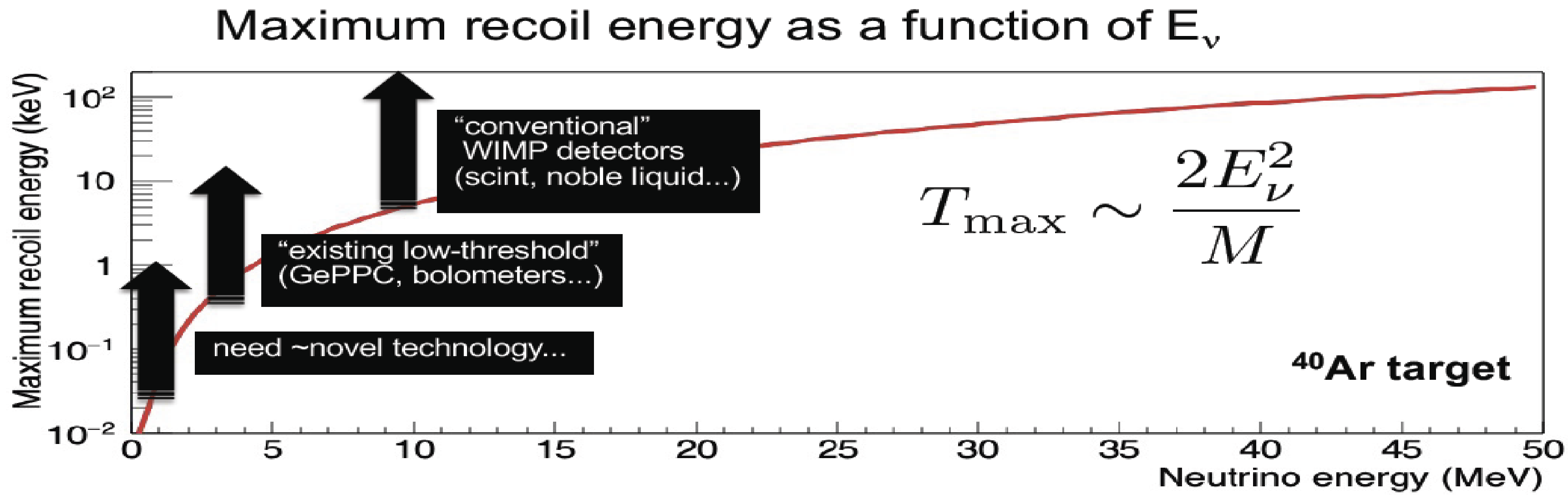
[Scholberg @ CNNP2017]

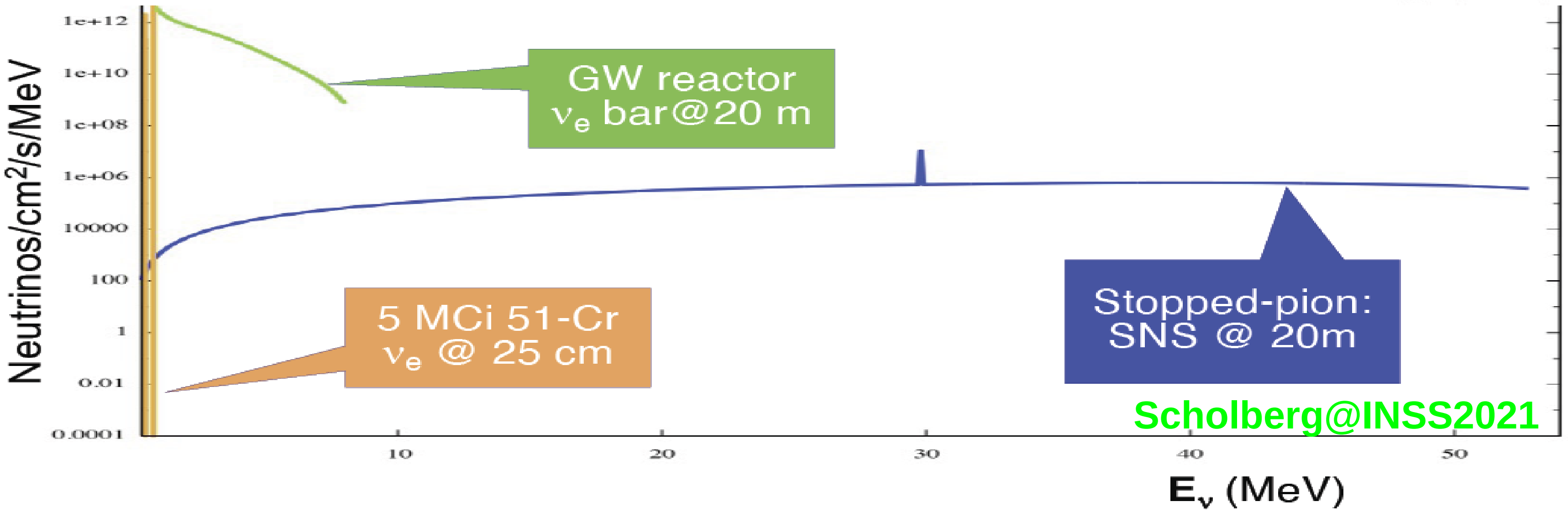
Low-energy nuclear recoil detection strategies



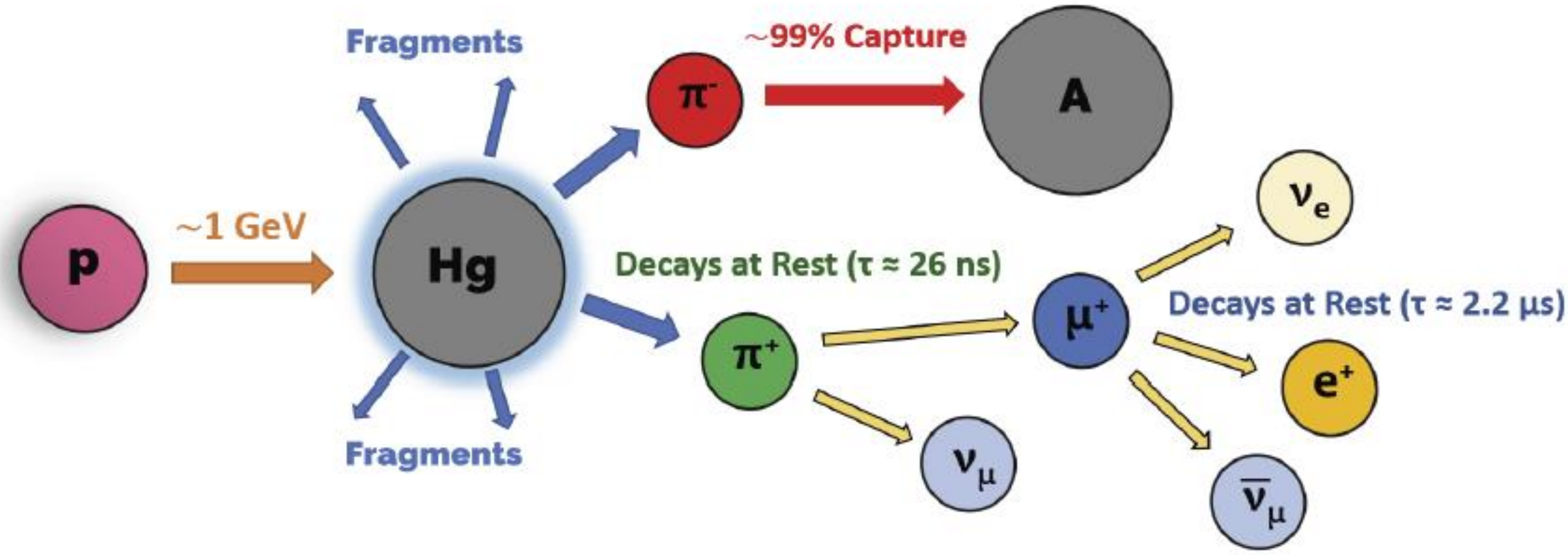
Scholberg@INSS2021

Detection of artificial sources





Stopped-Pion (πDAR) Neutrinos



[M. Green @ Magnificent CEvNS 2019]

Stopped-Pion Neutrino Spectrum

- Prompt monochromatic ν_μ from stopped pion decays:

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

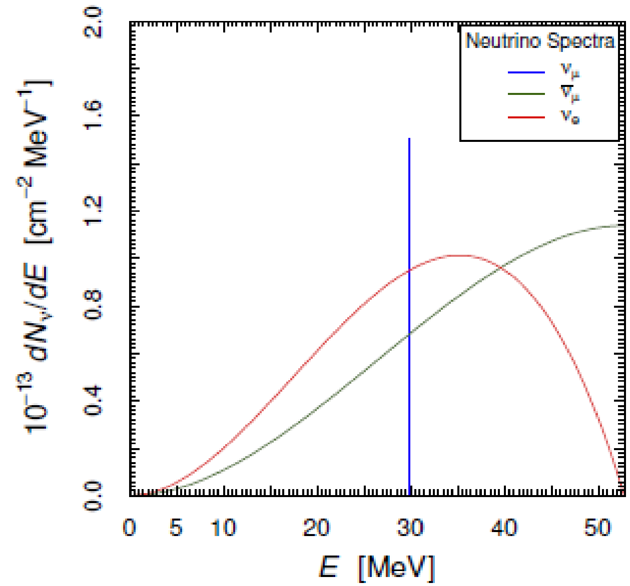
$$\frac{dN_{\nu_\mu}}{dE_\nu} = \eta\,\delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right)$$

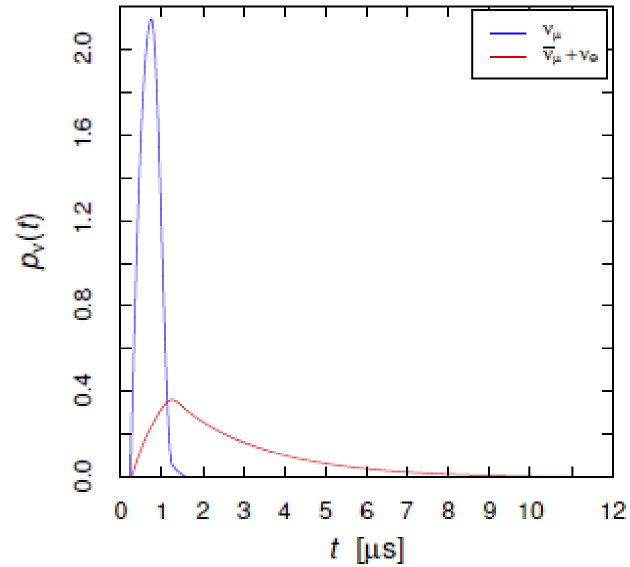
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

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

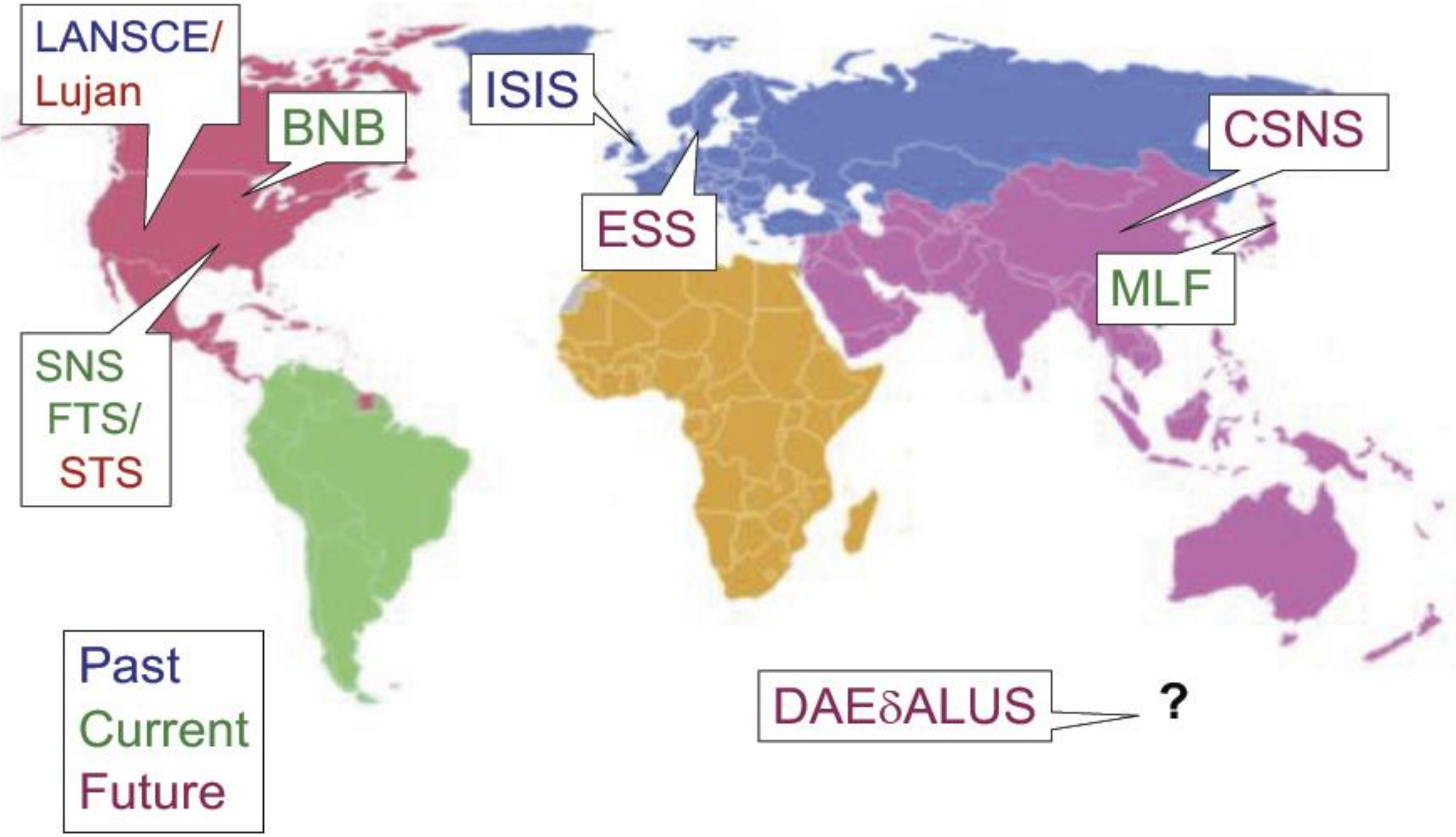
$$\frac{dN_{\nu_{\bar{\mu}}}}{dE_\nu} = \eta\,\frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)$$

$$\frac{dN_{\nu_e}}{dE_\nu} = \eta\,\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)$$



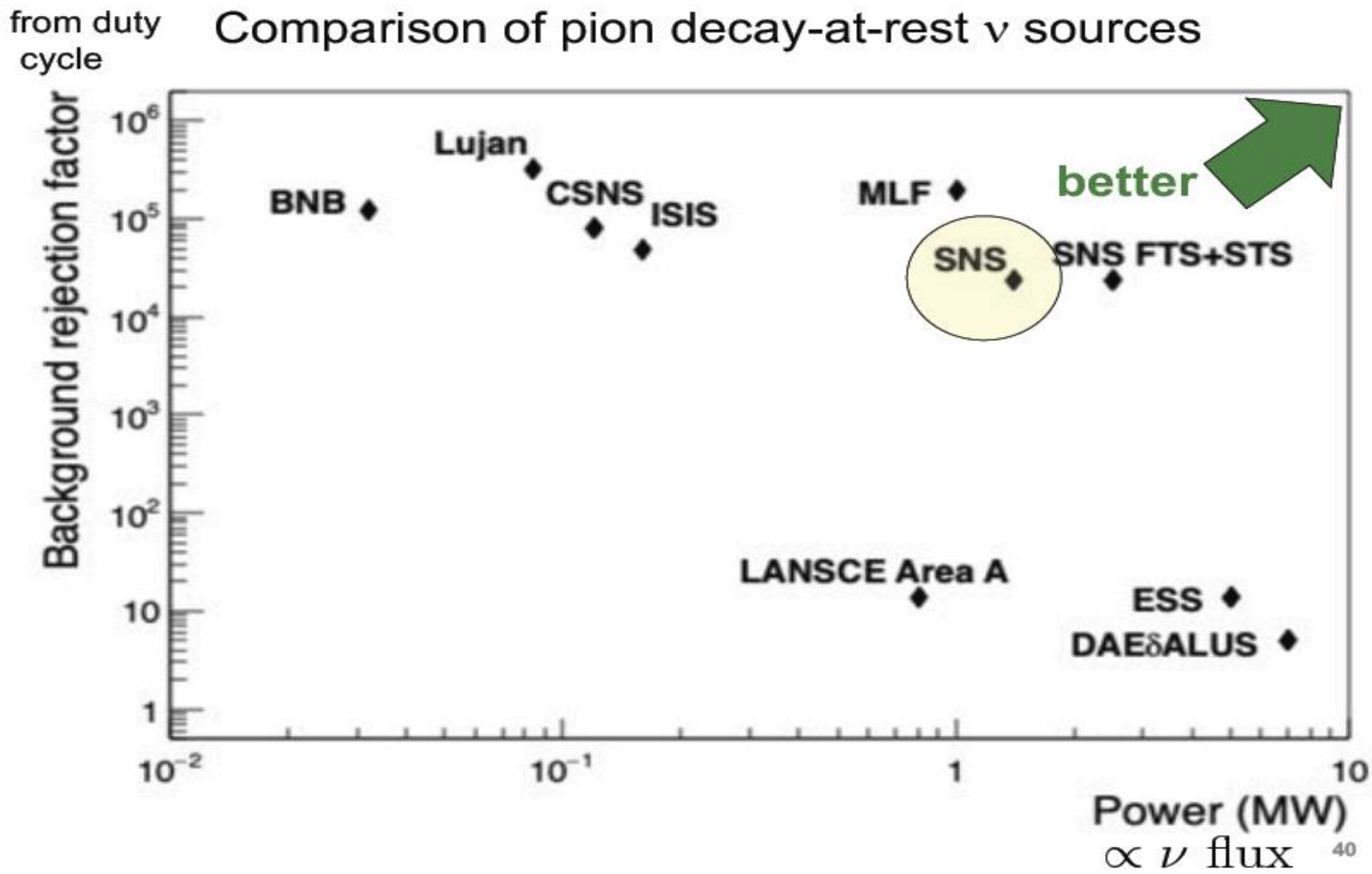


Stopped-Pion Neutrino Source Worldwide



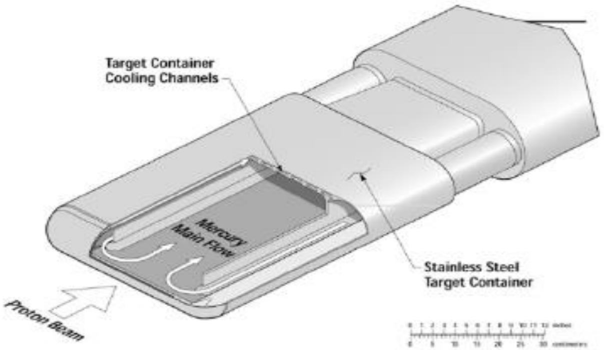
[Scholberg, GSSI Seminar 2020]

Stopped-Pion Neutrino Source Worldwide



[Scholberg, GSSI Seminar 2020]

Spallation neutron source at ORNL

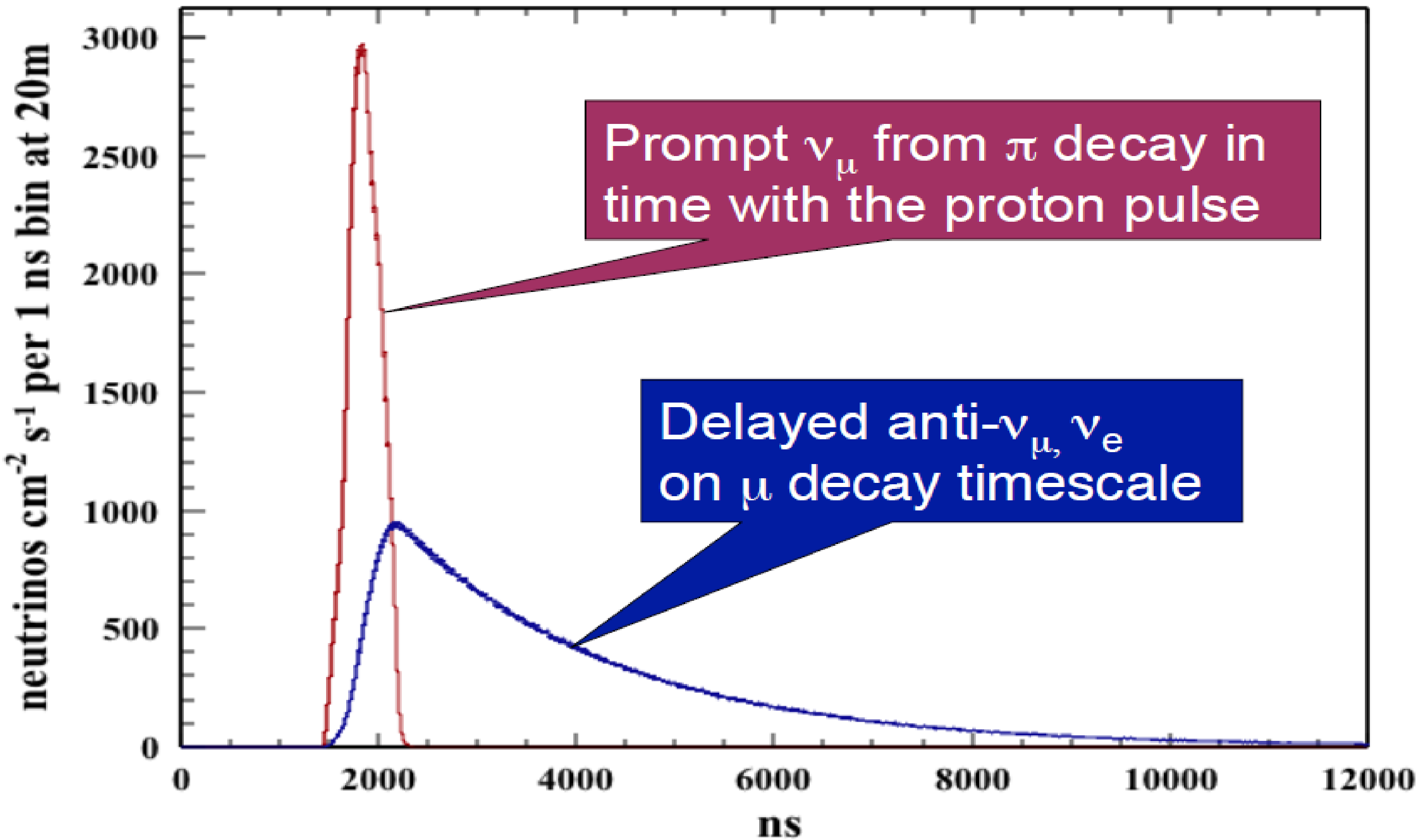


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

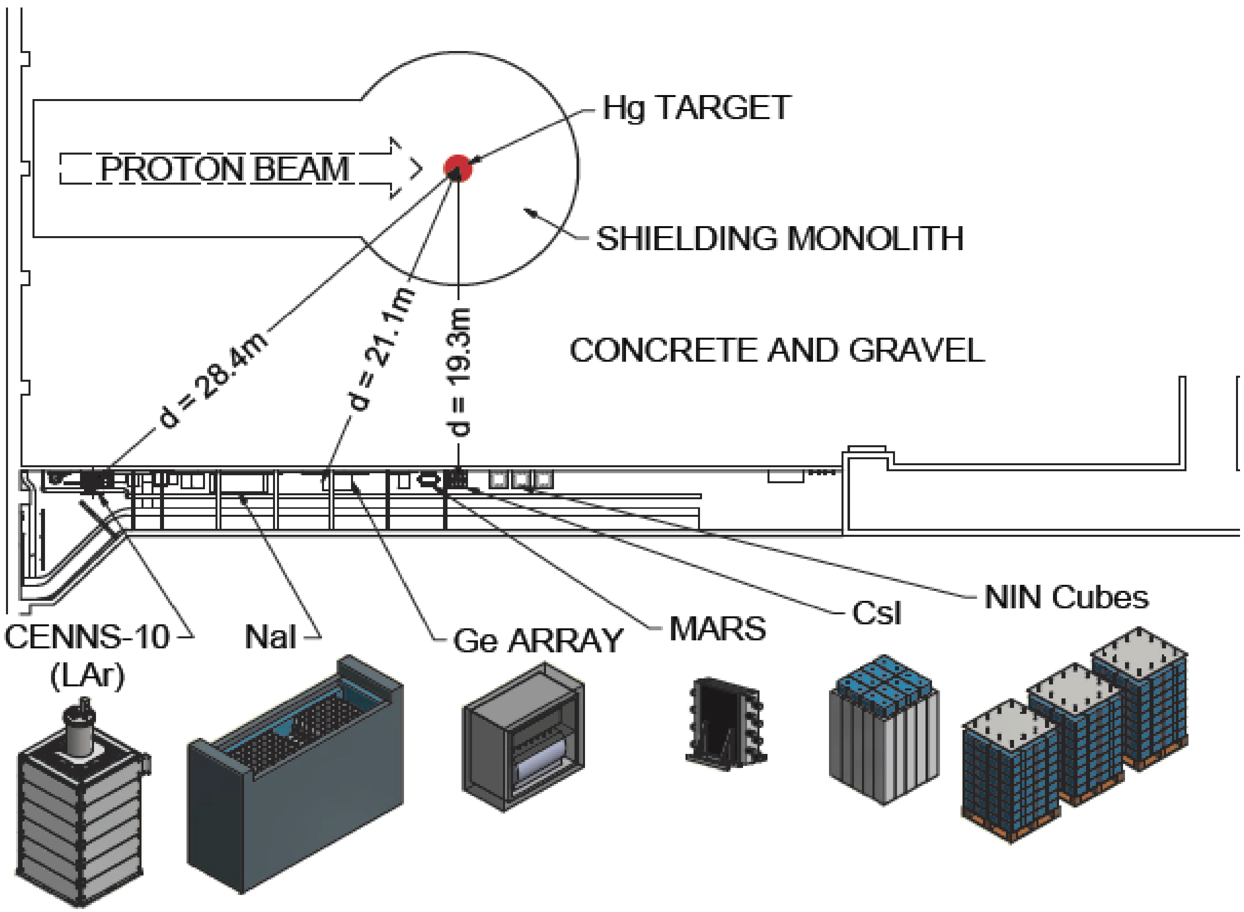
60 Hz *pulsed* source



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

The COHERENT experiment

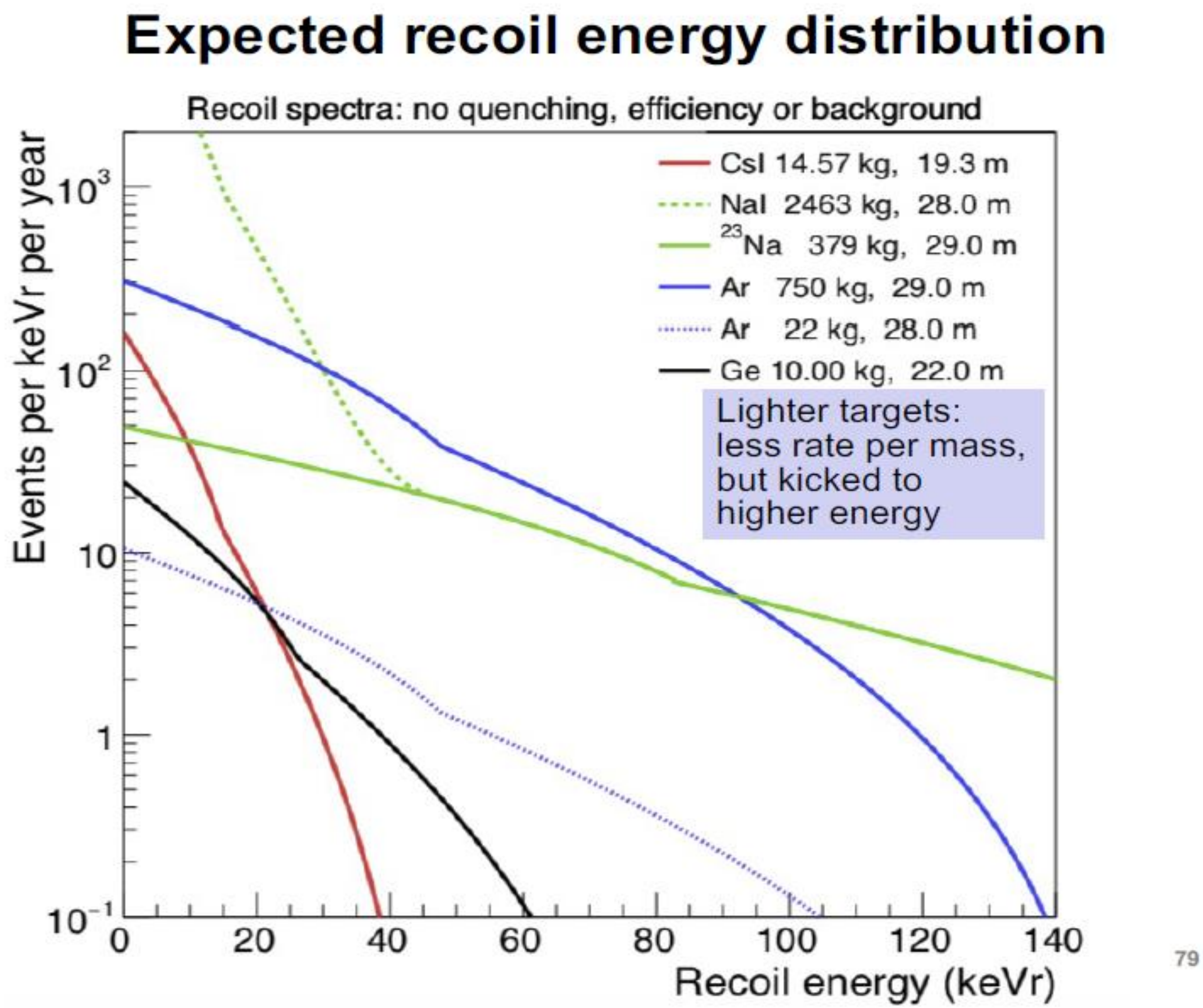
Oak Ridge Spallation Neutron Source



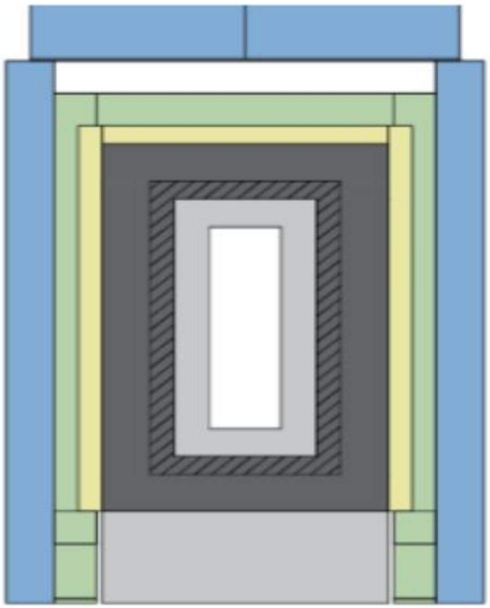
14.6 kg CsI
scintillating crystal

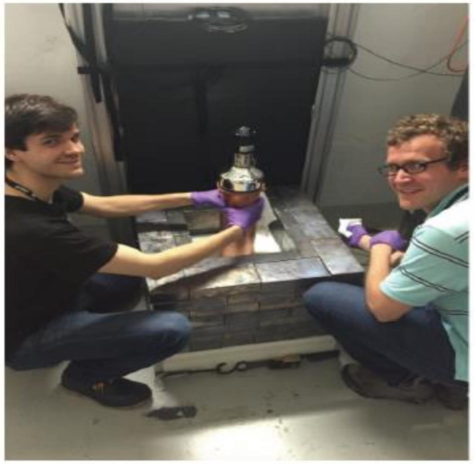
[COHERENT, arXiv:1803.09183]

Signals


Expected recoil energy distribution
Recoil spectra: no quenching, efficiency or background
CsI 14.57 kg, 19.3 m
NaI 2463 kg, 28.0 m
23Na 379 kg, 29.0 m
Ar 750 kg, 29.0 m
Ar 22 kg, 28.0 m
Ge 10.00 kg, 22.0 m
Lighter targets: less rate per mass, but kicked to higher energy
Events per keVr per year
Recoil energy (keVr)
79

CsI(Na) detector





A hand-held detector!

Almost wrapped up…

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

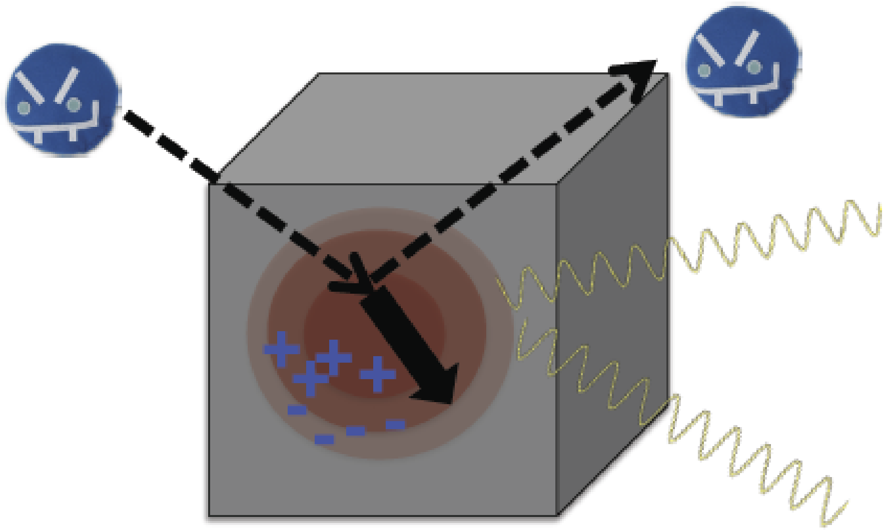
Why CsI (Na)?

Large N^2 →large cross section.
Cs and I surround Xe in Periodic Table.
Na-doping can reduce afterglow
High light yield

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

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Backgrounds

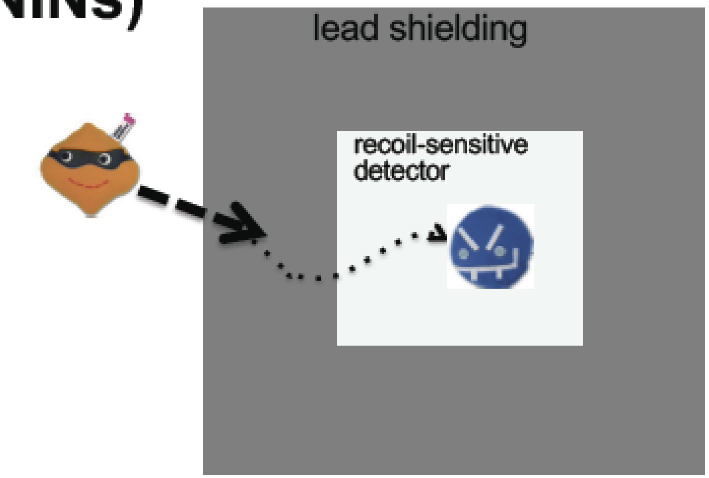
Neutrino Induced Neutrons (NINs)

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

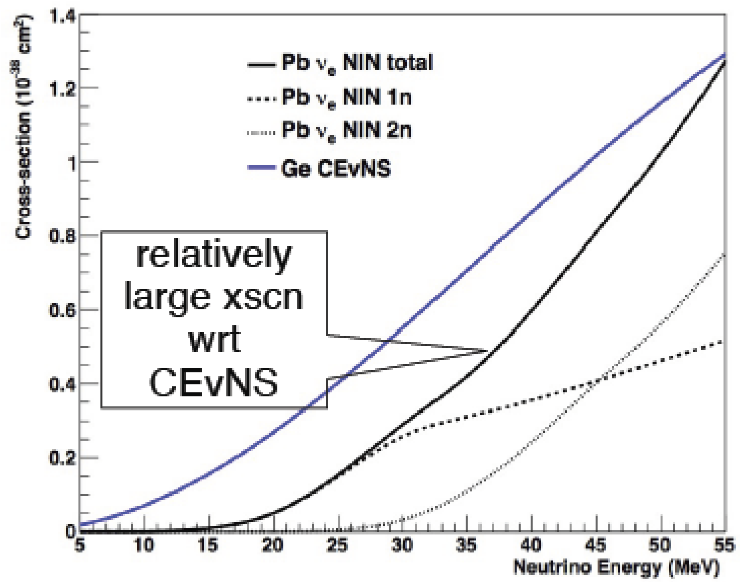
1n, 2n emission

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

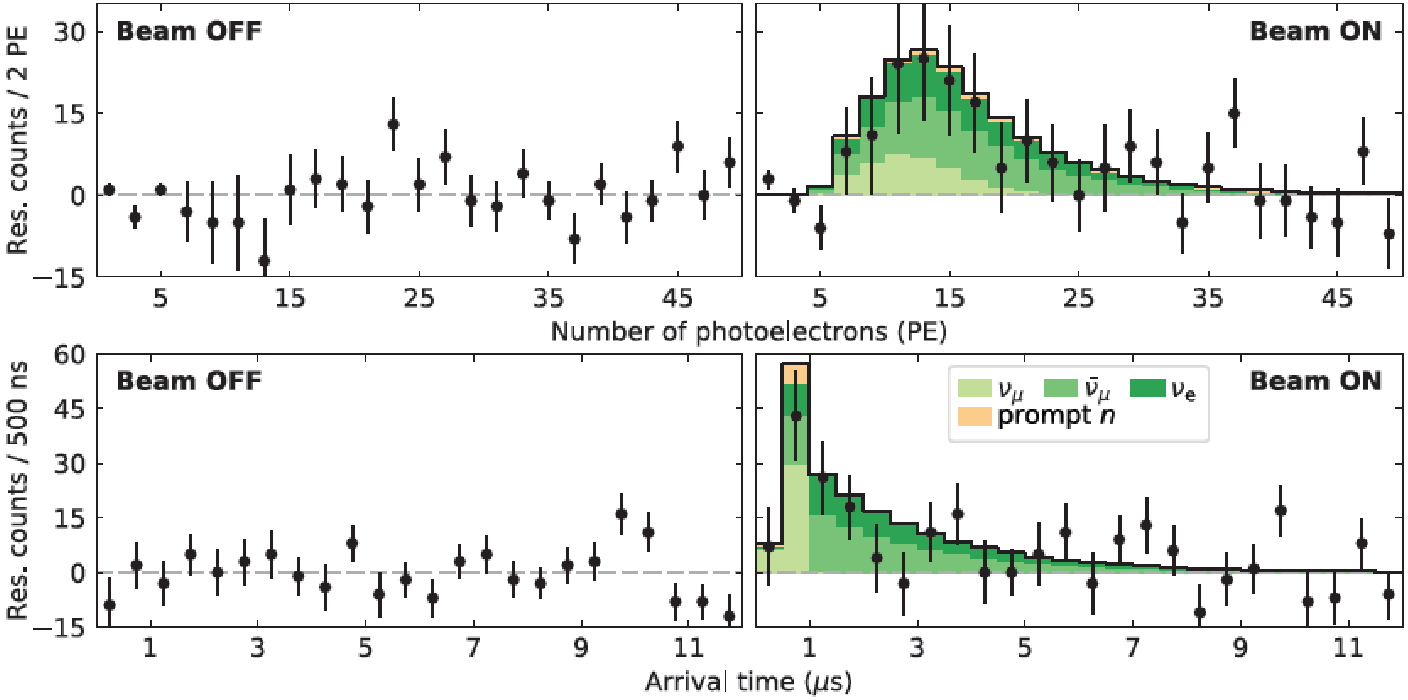
1n, 2n, γ emission



- 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]



First observation of CEvNS at CsI (2017)

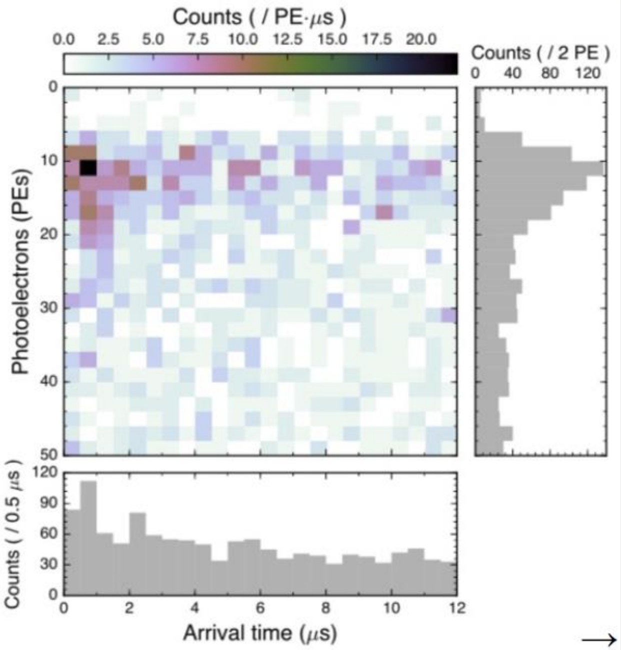


Akimov et al. *Science*
Vol 357, Issue 6356
15 September 2017

- Data are beam coincident and anti-coincident residuals during SNS operation, “On”, and during SNS shutdown periods, “Off”.
- Excess in light yield and timing distributions only for Beam on.

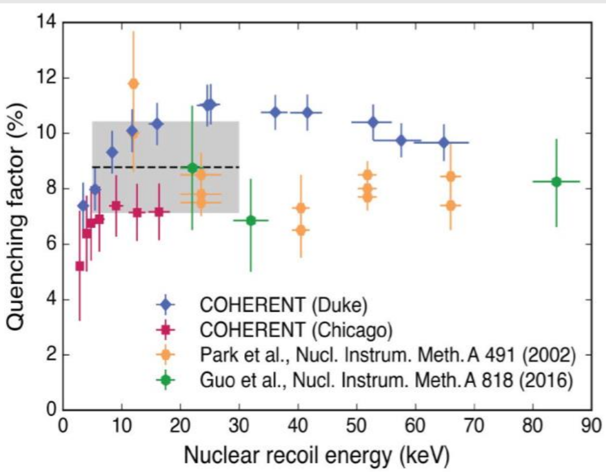
$^{133}_{55}\mathrm{Cs}_{78}$ and $^{127}_{53}\mathrm{I}_{74}$ $\leftarrow$ Heavy nuclei well suited for CEνNS

Comparison with SM (6.7sigma)

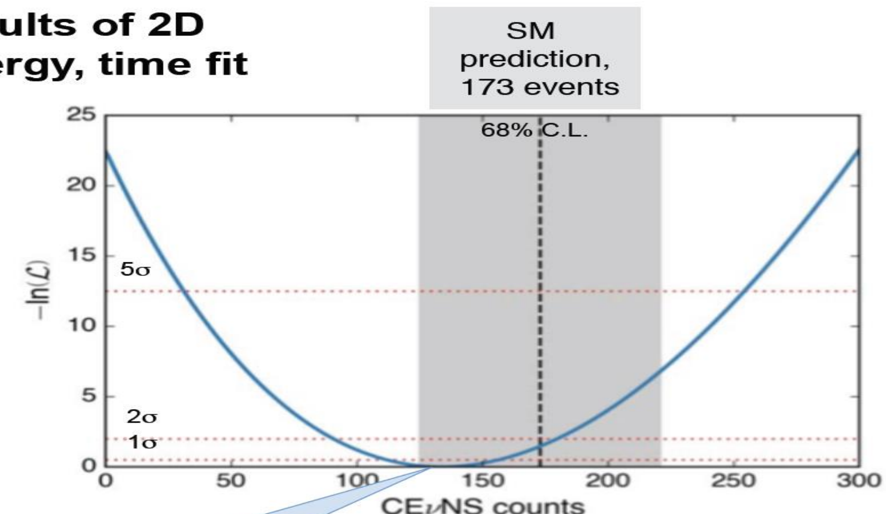


Breakdown of systematics

Source of systematic	Contribution
Form factor (in CEvNS cross-section)	5%
ν flux from SNS	10%
Quenching factor	25%
Det. efficiency	5%
Source-detector baseline	Negligible



Results of 2D energy, time fit



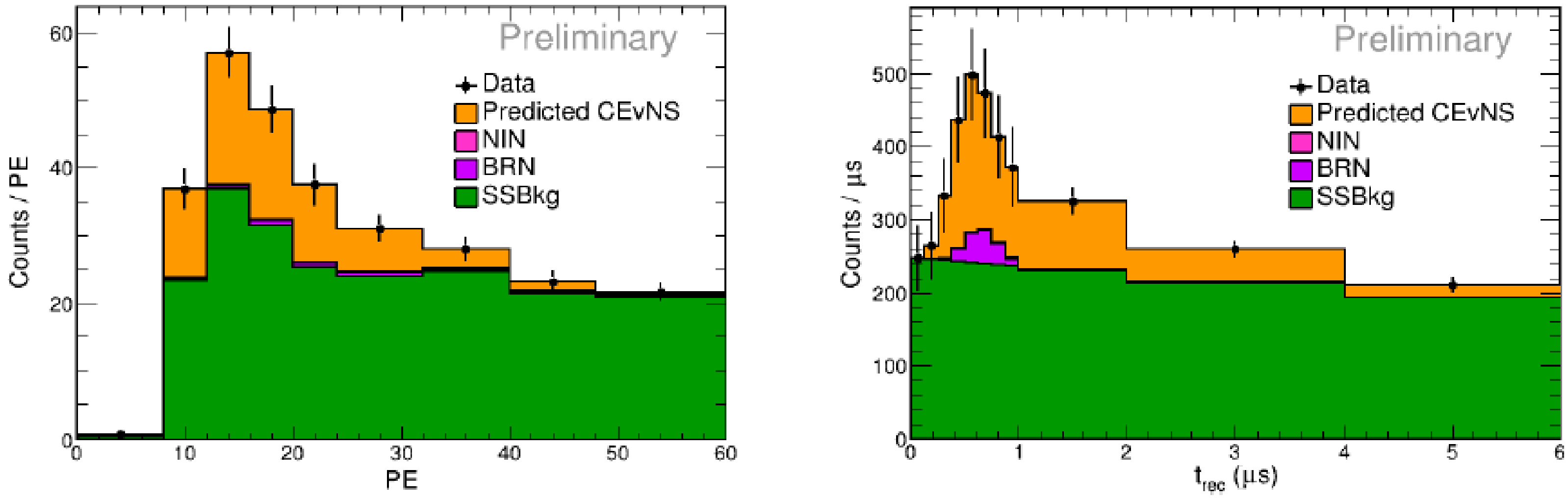
Best fit: **134 ± 22** observed events

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

New observation with CsI (2020)

Expected CEvNS in CsI

Pershey@@Mag7s(2020)



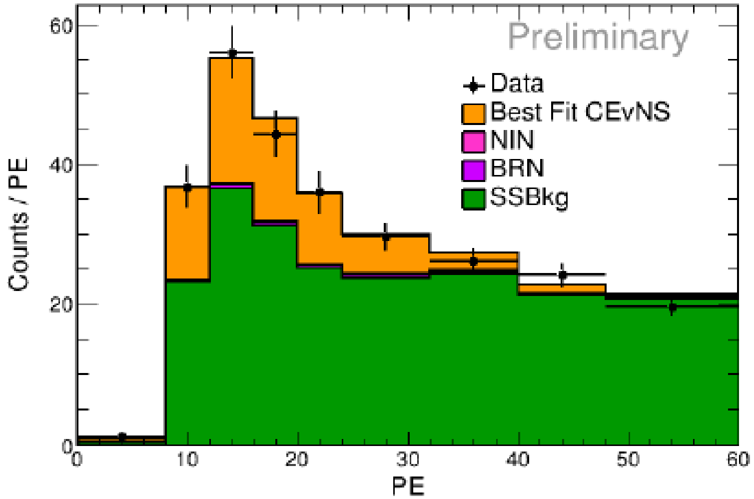
- Implemented many analysis improvements since first observation – see talk by A. Konovalov
  - Developed blind analysis to avoid biasing
- Perform 2D likelihood fit in PE and t_{rec}
- Beam-unrelated steady-state background measured in-situ with beam out-of-time data
- Beam-related neutron backgrounds small

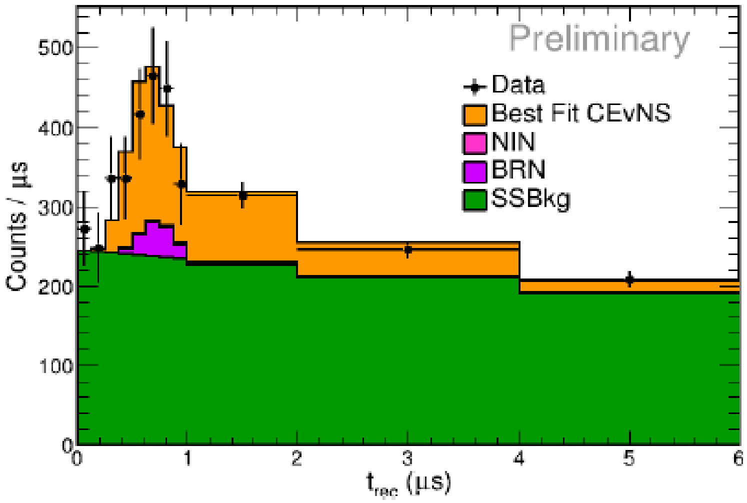
Expected events

Steady-state background	1286
Beam-related neutrons	18
Neutrino-induced neutrons	6
CEvNS	333

New observation with CsI (2020)

Observed CEvNS





- Data in our CsI[Na] detector match our best-fit predicted spectra very well
- Best-fit CEvNS slightly low, but consistent with expected statistical error

Best fit results

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

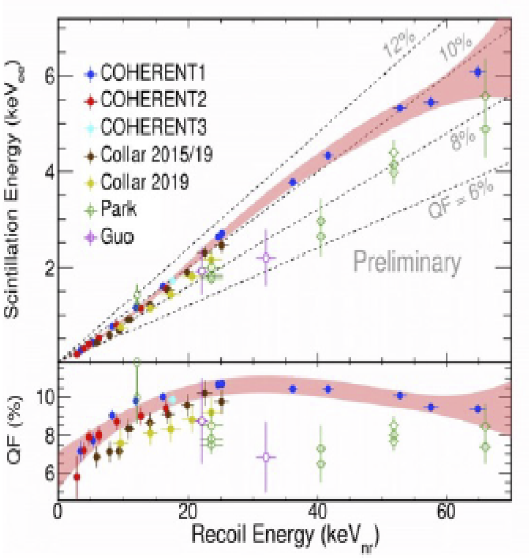
New observation with CsI (2020)

- Continued data collection up to June 2019 → increased statistics by a factor > 2
- Refinements in the SSB characterization and beam power determination

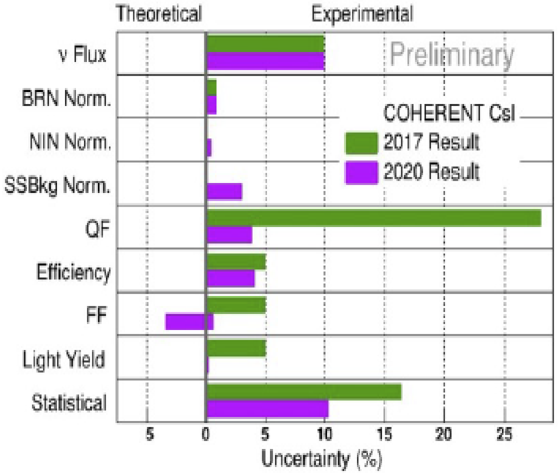
See A. Konovalov's talk

- Big work on re–measuring and understanding the QF

→ Unc. reduced to 3.6% in the new analysis !



- Updated measurement of CEvNS on CsI with new unc. budget !



No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\mathrm{th}) \pm 42(\mathrm{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

+ various searches of BSM physics…

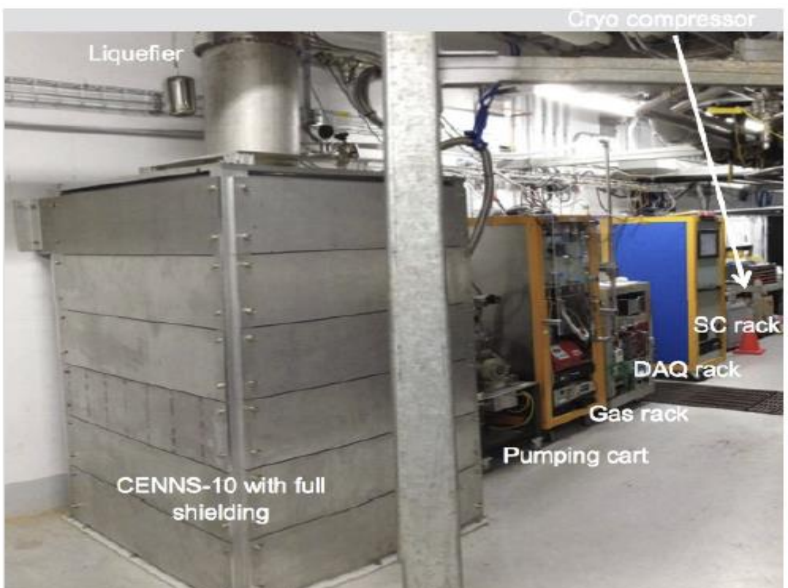
See D. Pershey's talk

From M. Vivier summary talk @Mag7s(2020)

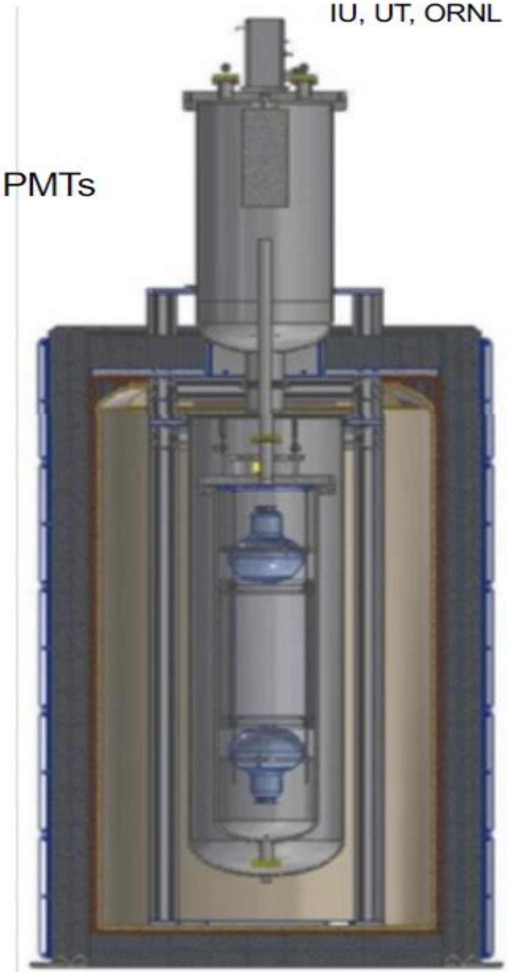
Single-Phase Liquid Argon

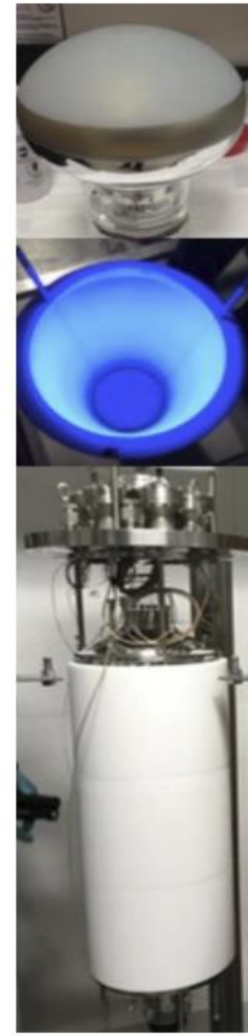
Single-Phase Liquid Argon

- ~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



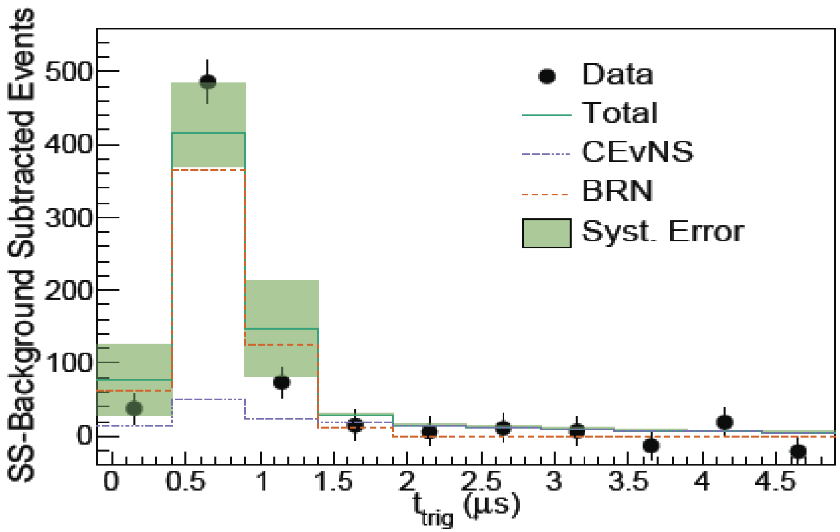


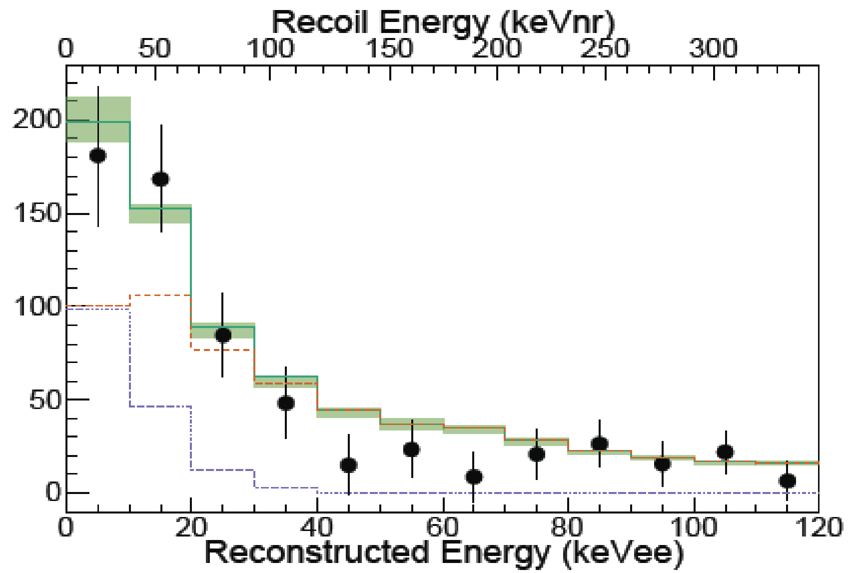
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

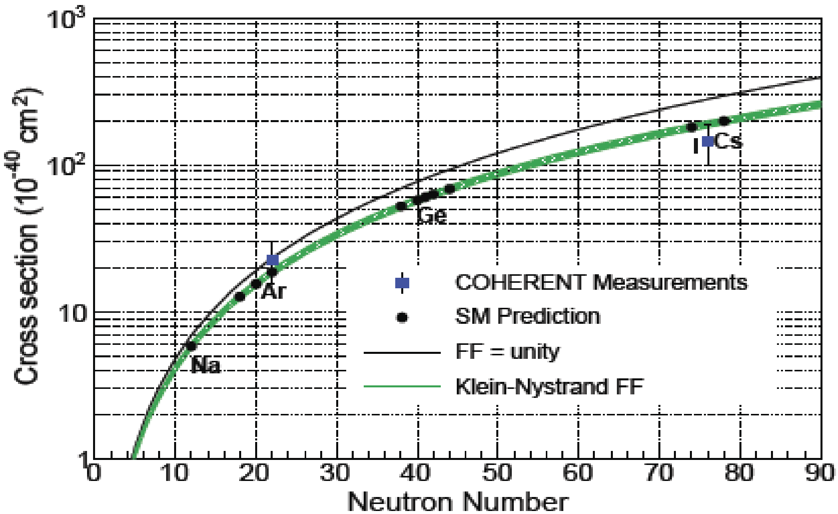
90

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]







$^{40}_{18}Ar_{22}$ not so heavy

Verified theoretical $\boxed{\sigma \propto N^2}$

Near Future-I

High-Purity Germanium Detectors

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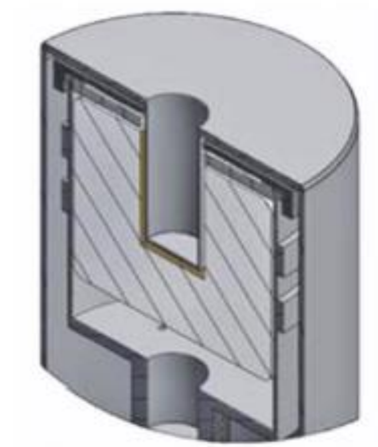
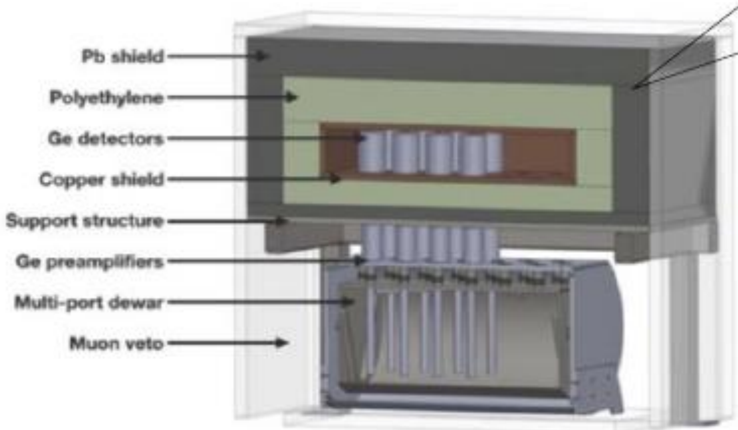
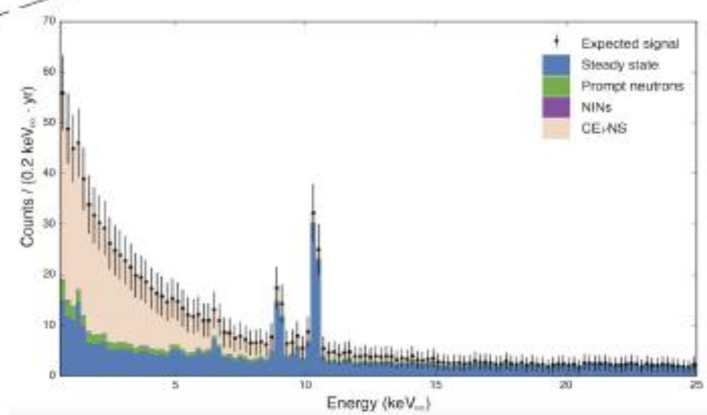
P-type Point Contact



- 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





Near Future-II

Tonne-scale LAr Detector

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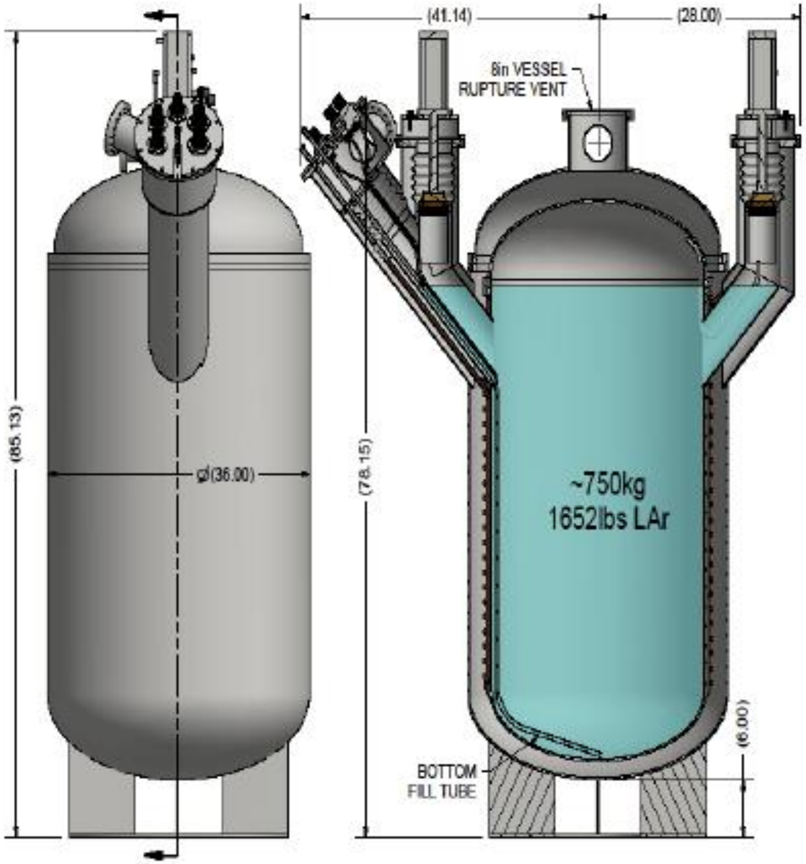
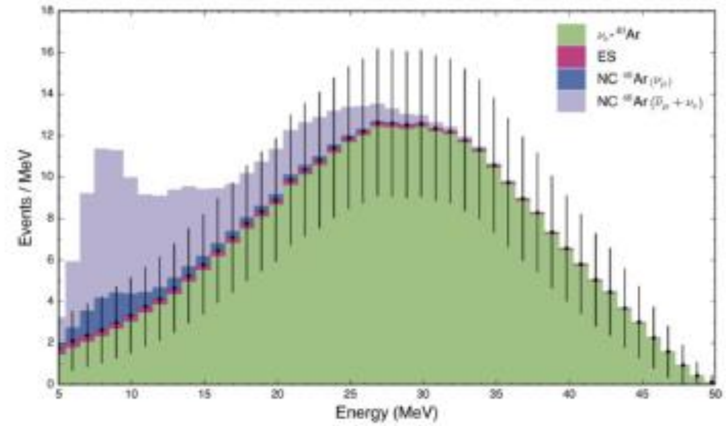


- 750-kg LAr will fit in the same place, will reuse part of existing infrastructure
- Could potentially use underground argon



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

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

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

Near Future-III

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

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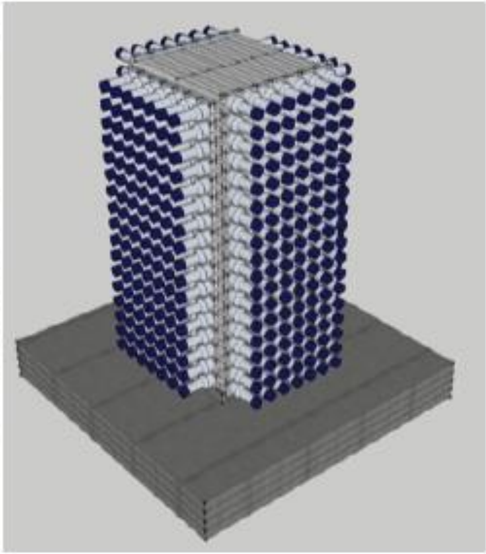
- up to 9 tons available, 2 tons in hand
- QF measured
- require PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement
- development and instrumentation tests underway at UW, Duke

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}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	$284 \pm 91(\text{stat}) \pm 25(\text{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

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

Near Future-IV

Heavy water detector in Neutrino Alley

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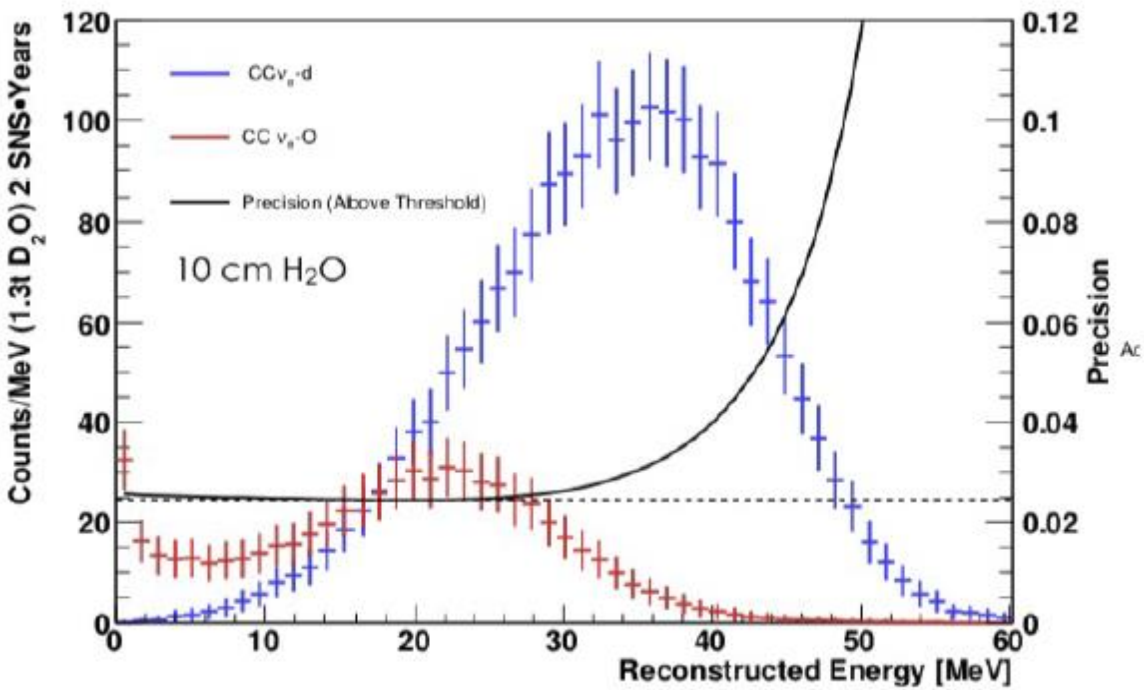
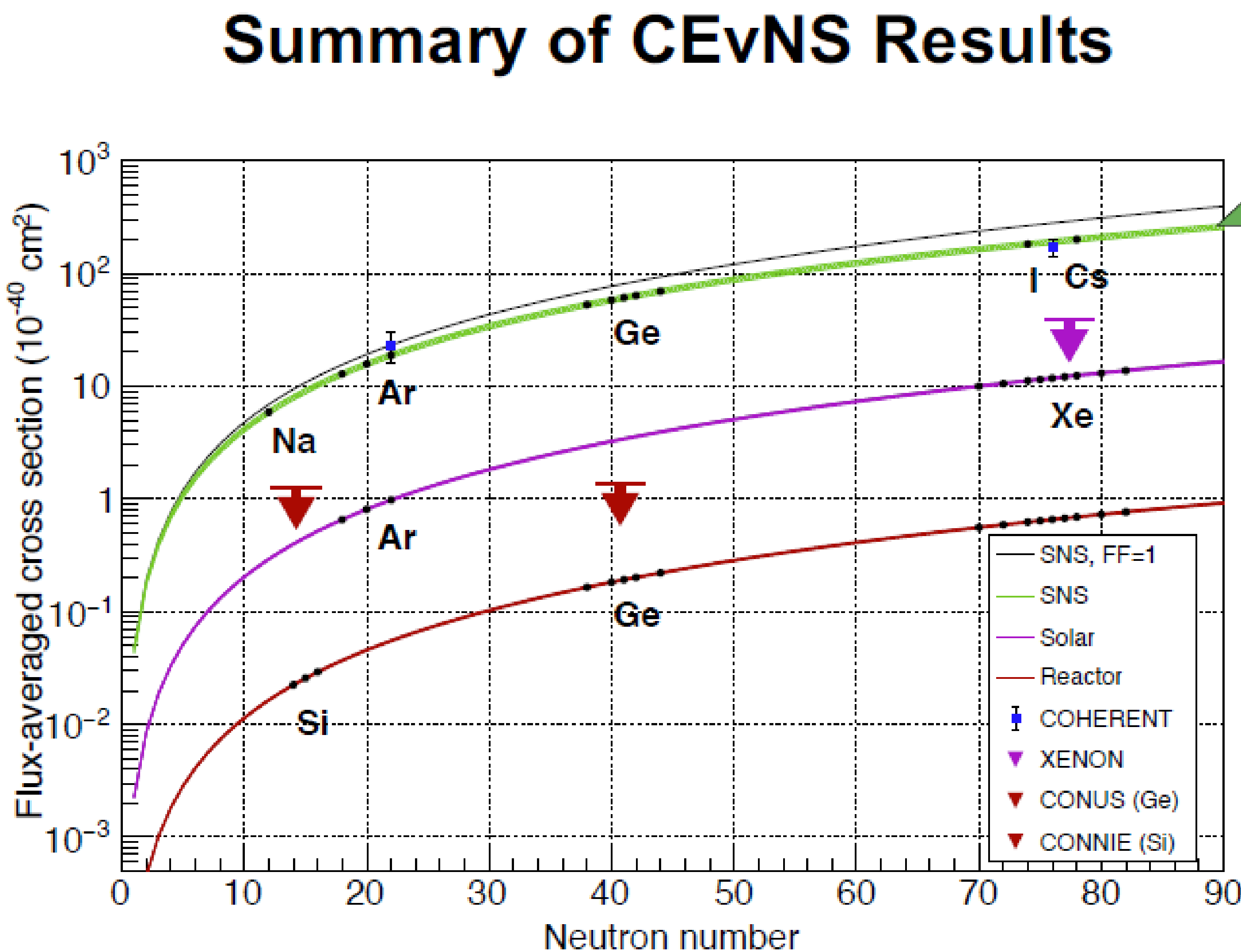
Measurement Precision with 2 SNS years at 1.4 MW

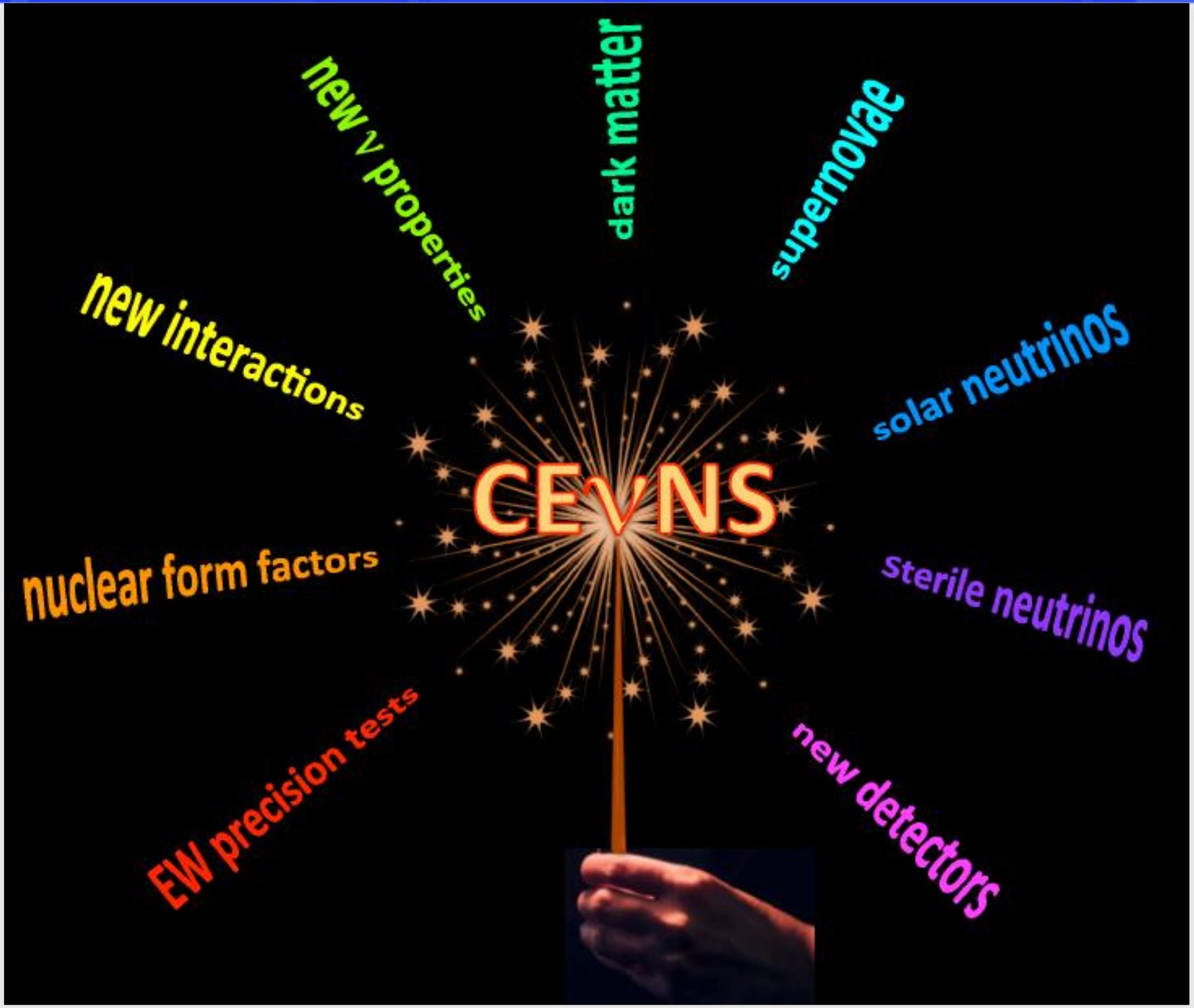


➔ ~few percent precision on flux normalization

What is for tomorrow?



What is for tomorrow?



E. Lisi@Neutrino 2018

Backup

How to detect this process?

- **How to detect the CEνNS process:**
- **We need an intensive source and a sensitive detector.**
- **Natural sources versus Man-Made sources:**

(a) Solar neutrinos, atmospheric neutrinos, supernova neutrinos
(b) Reactor neutrinos, accelerator neutrinos

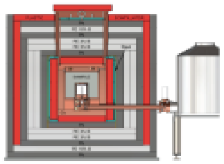
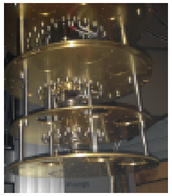
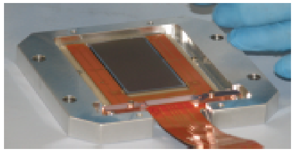
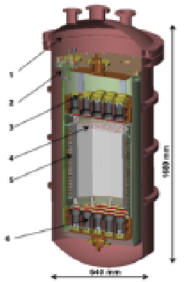
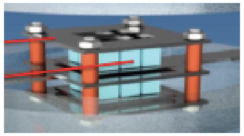
- **Sensitive detectors:**

(a) Thanks to thirty years developments of dark matter detection techniques, we are approaching to the low threshold frontier of the keV level.

Promising prospective for the CEνNS detection !

CEνNS Experiments at Reactors

Experiment	Technology	Location
CONUS	HPGe	Germany
Ricochet	Ge, Zn bolometers	France
CONNIE	Si CCDs	Brazil
RED	LXe dual phase	Russia
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
MINER	Ge iZIP detectors	USA


Novel low-background, low-threshold technologies

Implications: overview

- What can we do using the new CEνNS measurements:
- Testing the coherency
- Neutron radius measurements
- Testing properties of neutrino interactions

  Nonstandard interactions,
  Neutrino electromagnetic properties

- New physics at low threshold frontiers,

  Z prime, 1708.04255, 1803.01224, 1812.04067, 1903.10666, etc.
  scalar mediator, 1802.05171, 1804.03660, etc.
  dark photon, 1710.10889, 1906.10745, etc.
  Neutrino floor, 1710.10889, 1809.06385, 1904.11214 etc.
  and many other aspects

Why study the neutron radius?

(a) The neutron radius and neutron skin are strongly correlated to the nuclear Equation of State (EOS), the slope of bulk symmetry energy, and other nuclear quantities.

(b) A larger neutron skin would suggest a stiffer EOS and imply a larger neutron star radius, which is related to the gravitational binding energy of core collapse supernovae.

(c) With the first observation of binary neutron star inspiral at Advanced LIGO and Advanced Virgo, one can infer the tidal deformability parameter, which is also related to the neutron star EOS and to the neutron skin.

(d) Information on the nuclear neutron density radius is also important for a precise determination of the background due to coherent elastic neutrino-nucleus scattering in dark matter detectors (e.g., 133Cs and 127I have similar atomic and mass numbers to that of Xenon).

Nuclear Form Factors

- **Form factor** describes the interaction of extended objects beyond the point-like particles.

- Taking the charge distribution (Coulomb scattering) as an example:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{point-like}} |F(q^2)|^2$$

$$F(q^2) \equiv \frac{1}{Ze} \int e^{\frac{-i\mathbf{q}.\mathbf{R}}{\hbar}} \rho(\mathbf{R}) d\tau \Rightarrow F(q^2) = \frac{4\pi\hbar}{Zeq} \int R\rho(R) \sin\left(\frac{qR}{\hbar}\right) dR$$

- Here for weak interaction of protons and neutrons:

$$F_Z(q^2) = \frac{4\pi}{Z} \int \rho_p(r)\, j_0(qr)\, r^2 dr$$

- How to obtain the form of form factors:

  a) calculated with nuclear structure models *arXiv:1502.02928*

  b) using analytical expressions with effective parameters

  c) directly taken from experimental data

Nuclear Form Factors

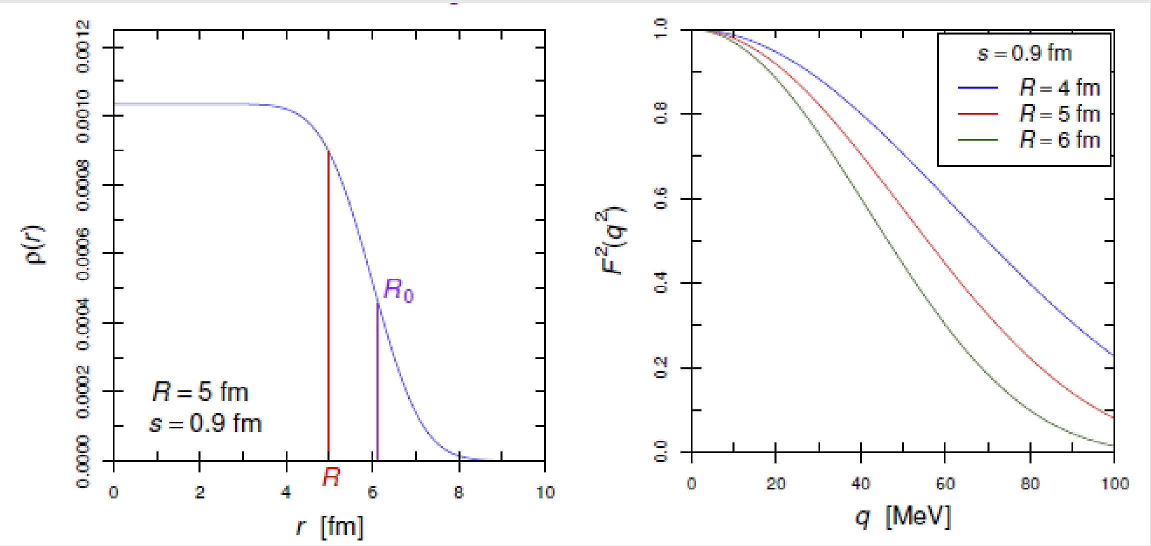
➢ **Analytical expressions of form factors:**

a) **symmetrized Fermi form factor** ***Phys. Rev. C94, 034316 (2016)***
b) **Helm form factor** ***Phys. Rev. 104, 1466 (1956)***
c) **Klein-Nystrand form factor** ***Phys. Rev. C60, 014903 (1999)***

➢ **We choose the Helm form factor:**

$$F_N^{\mathrm{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$$

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5}R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\mathrm{fm}$



Helm form factor:

Obtained from a convolution of a sphere with constant density with radius R_0 and a Gaussian density with standard deviation *s*.