BULLKID a probe for CEvNS

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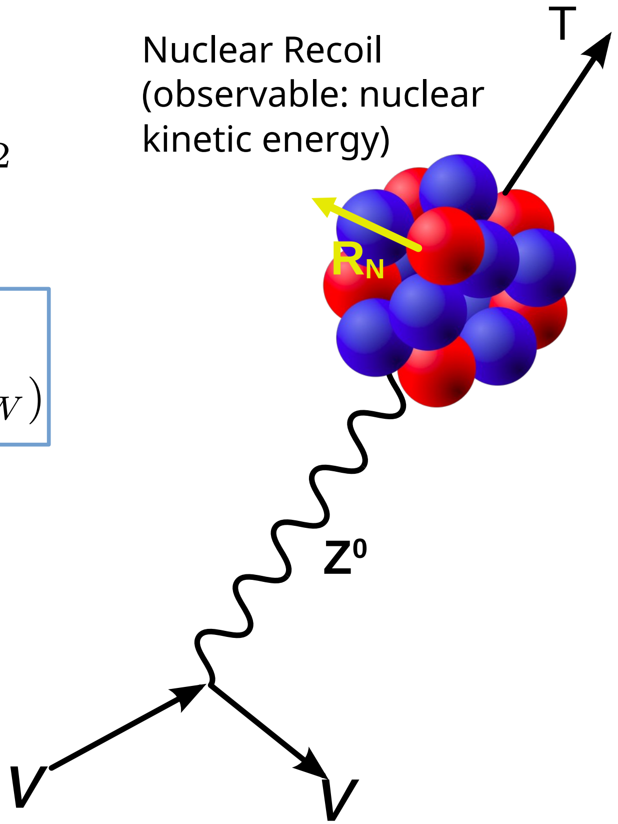
CEvNS: Coherent Elastic Neutrino Nucleus Scattering

What is CEvNS ?

$$\sigma_{CEvNS} = \frac{G_F}{4\pi}\boxed{E_\nu^2}\boxed{Q_W^2}\boxed{F(q^2)}$$

$$\sigma_{CEvNS} \leq 10^{-40}\mathrm{cm}^2$$



Neutrino Energy (see later)

$$E_\nu \approx O(\text{few MeVs})$$

Weak Force Charge

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

Nuclear Form Factor

$$F(q) = \frac{1}{Q_W}\int_0^{R_N} \rho_W(r)\frac{\sin(qr)}{qr}dr$$

$$\rho_W(r) = \rho_N(r) - (1 - 4\sin^2(\theta_W))\rho_P(r)$$

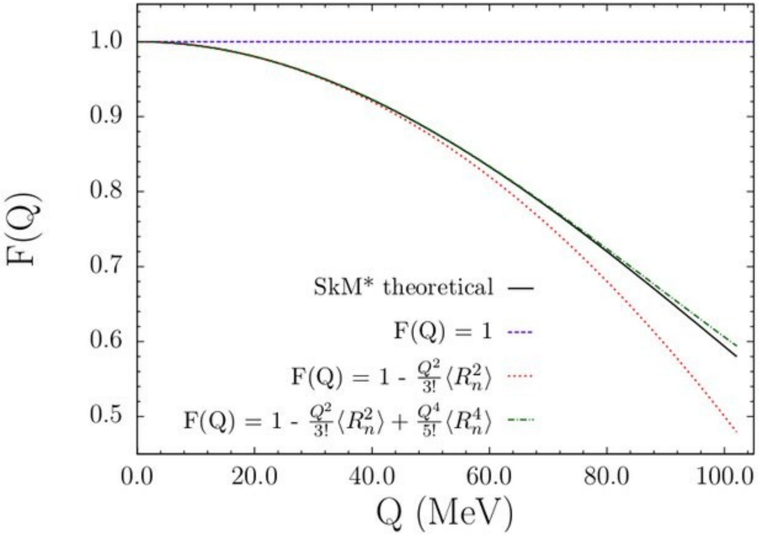
Fourier transform of the nucleon distribution

Coherent?

$$\sigma_{CE\nu NS} = \frac{G_F}{4\pi}\boxed{E_\nu^2}\boxed{Q_W^2}\boxed{F(q^2)}$$

Nuclear Form Factor

$$F(q) = \frac{1}{Q_W}\int_0^{R_N} \rho_W(r)\frac{\sin(qr)}{qr}dr$$



Coherency

Neutrino does not see the internal structure of the nucleus

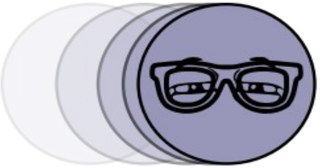
$$\text{Coherent:} F(q^2) \approx 1$$

$$\downarrow$$

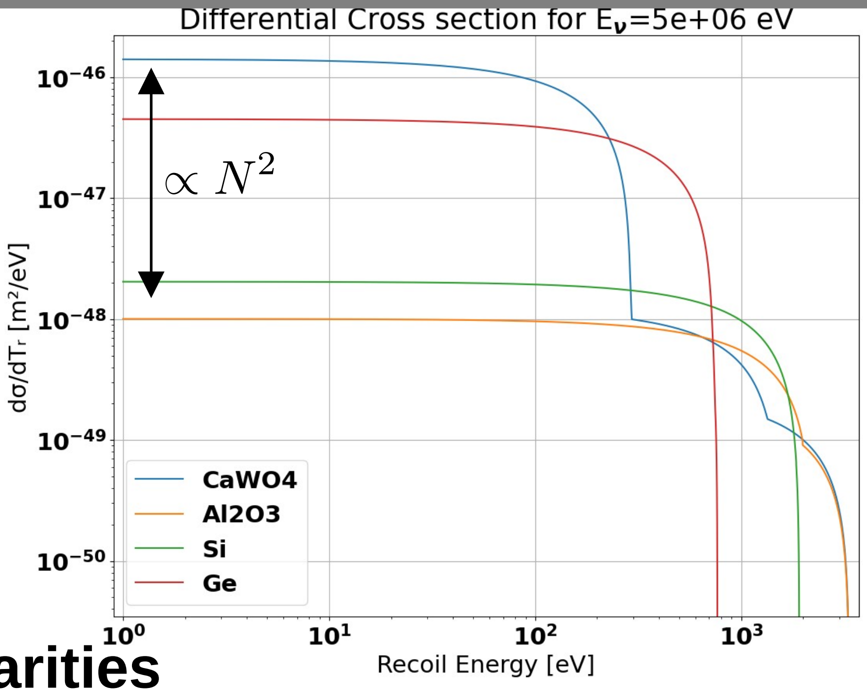
$$q \cdot R_N \ll 1$$

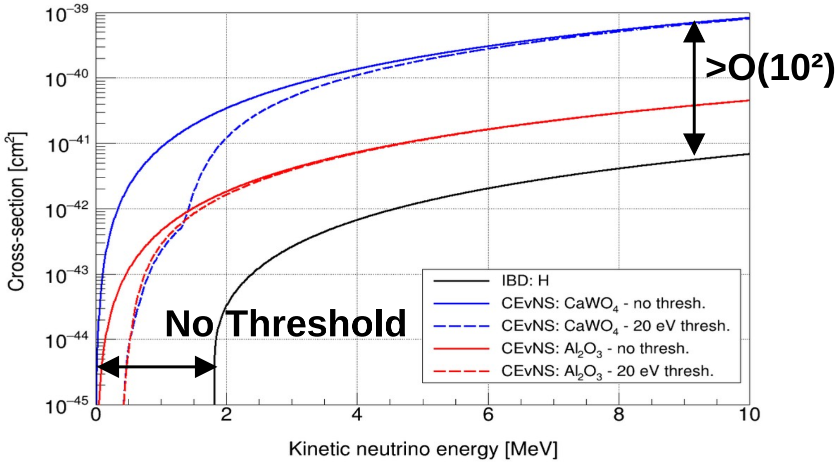
$$\downarrow$$

$$\boxed{E_\nu^{max} \approx 20\text{MeV [He]} \div 70\text{MeV [U]}}$$



Peculiarities





$$\sigma_{CE\upsilon NS} = \frac{G_F}{4\pi} \boxed{E_\nu^2} \boxed{Q_W^2} \boxed{F(q^2)}$$

Weak Force Charge

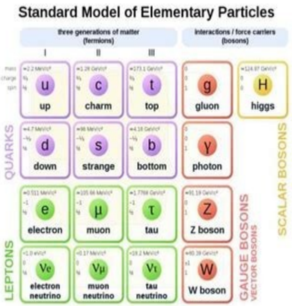
$$Q_W = N - P(1 - 4\sin^2\theta_W) \approx N$$

$$\boxed{\sigma_{CE\upsilon NS} \approx \frac{G_F}{4\pi} E_\nu^2 N^2}$$

Peculiarities

- No Energy Threshold!
- Scaling with N²
- Great enhancement due to coherency!
- ν-flavour independent (tree-level)

Why measure CEvNS ?

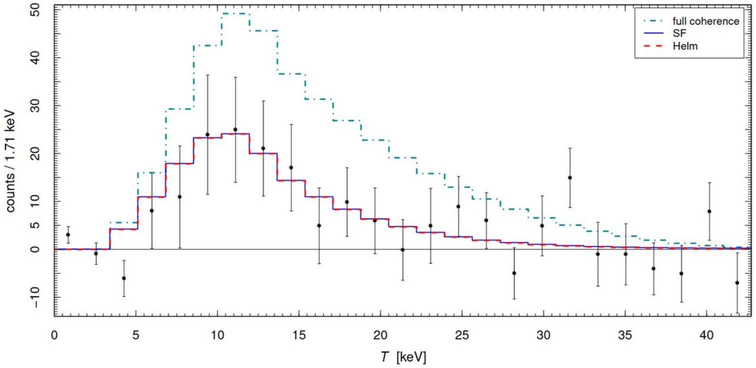


SM and BSM/NSI studies

- $\sin\theta_W$ at low momentum transfer
- Magnetic dipole moment of neutrino
- Non-standard interactions

Supernovae Collapse Models

Irreducible Background for WIMP experiments

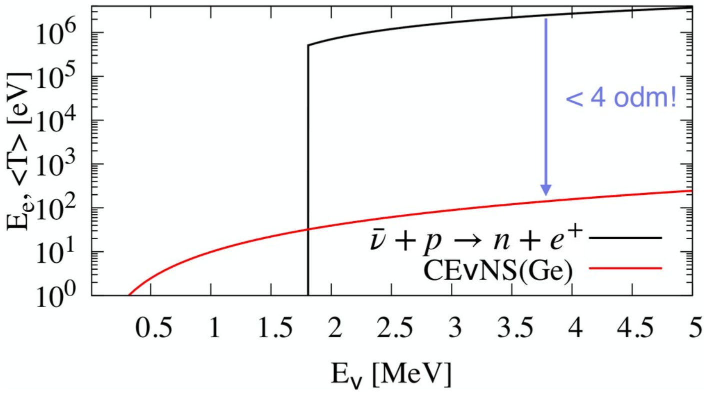


Studies on Nuclear Form Factor

Detector Miniaturization and non-invasive reactor and nuclear waste monitoring

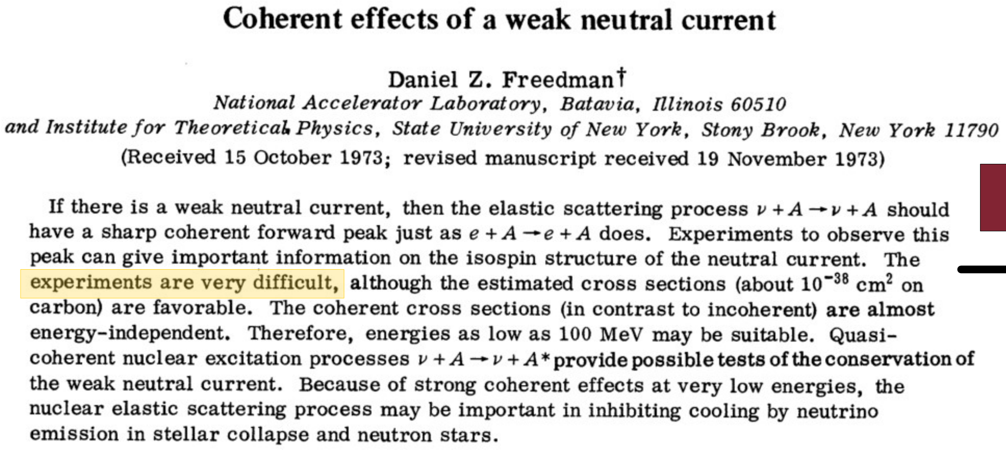
Measuring CEvNS

Experimental Challenges



$$E_\nu^{max} \approx 20\text{MeV [He]} \div 70\text{MeV [U]}$$

$$T_{max} = \frac{2E_\nu^2}{M_N} \approx O(10\text{keV})$$



Coherent effects of a weak neutral current

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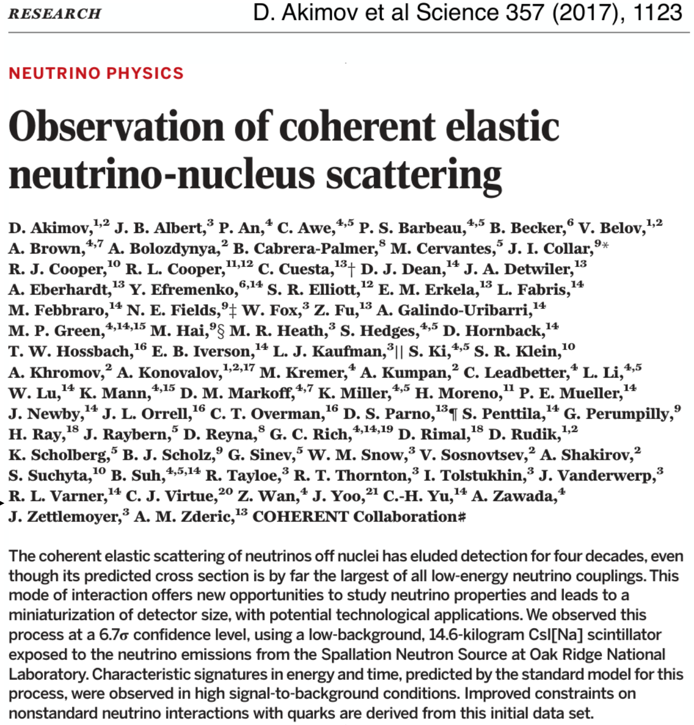
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

44 years!

D. Akimov et al Science 357 (2017), 1123



RESEARCH

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

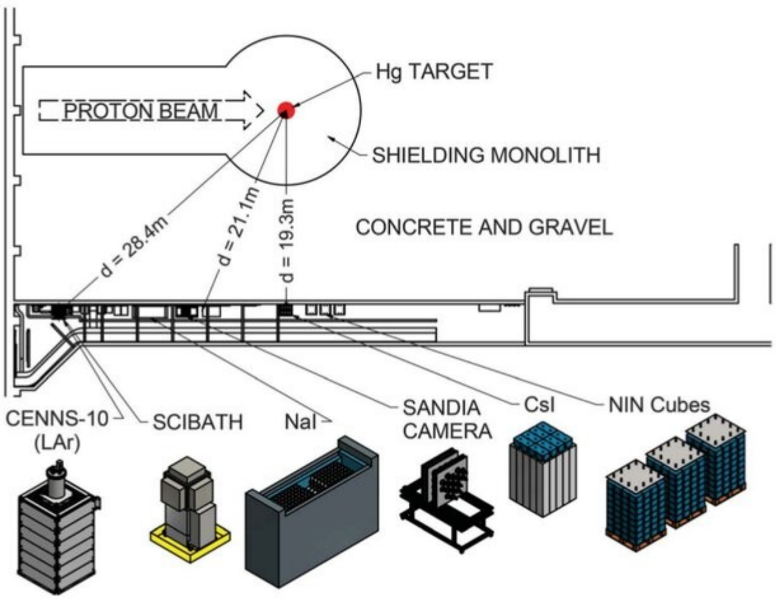
D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

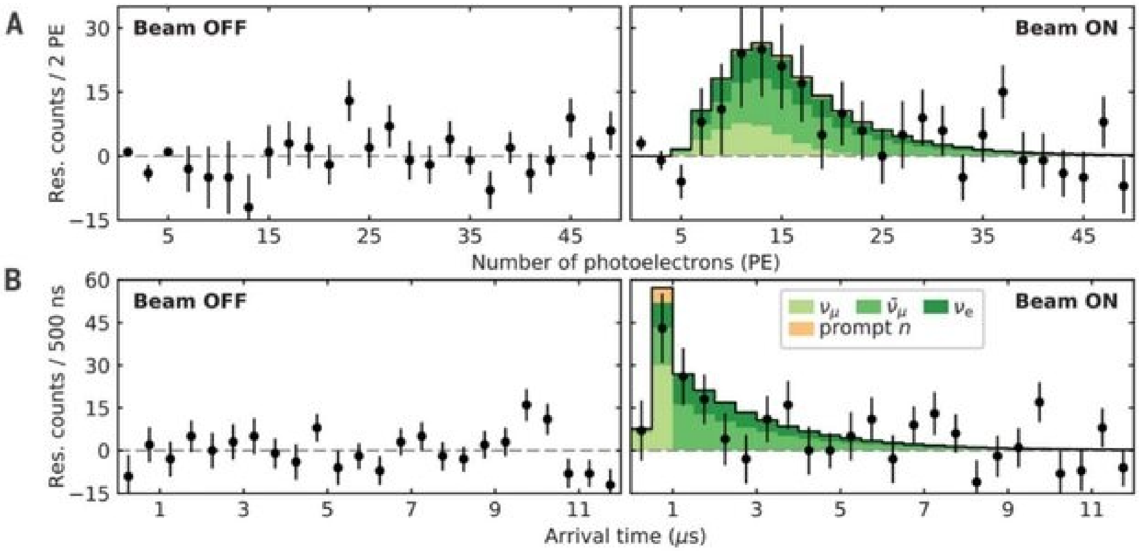
The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

First CEvNS observation

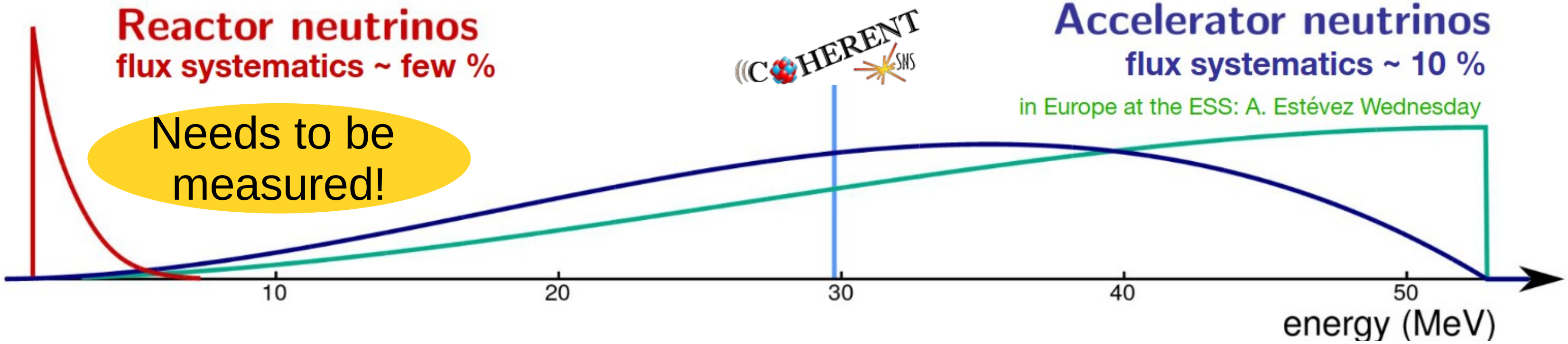
Observation from COHERENT in 2017 at Oak Ridge National Laboratory

Using shielded CsI[Na] scintillator





Where to measure CEvNS?

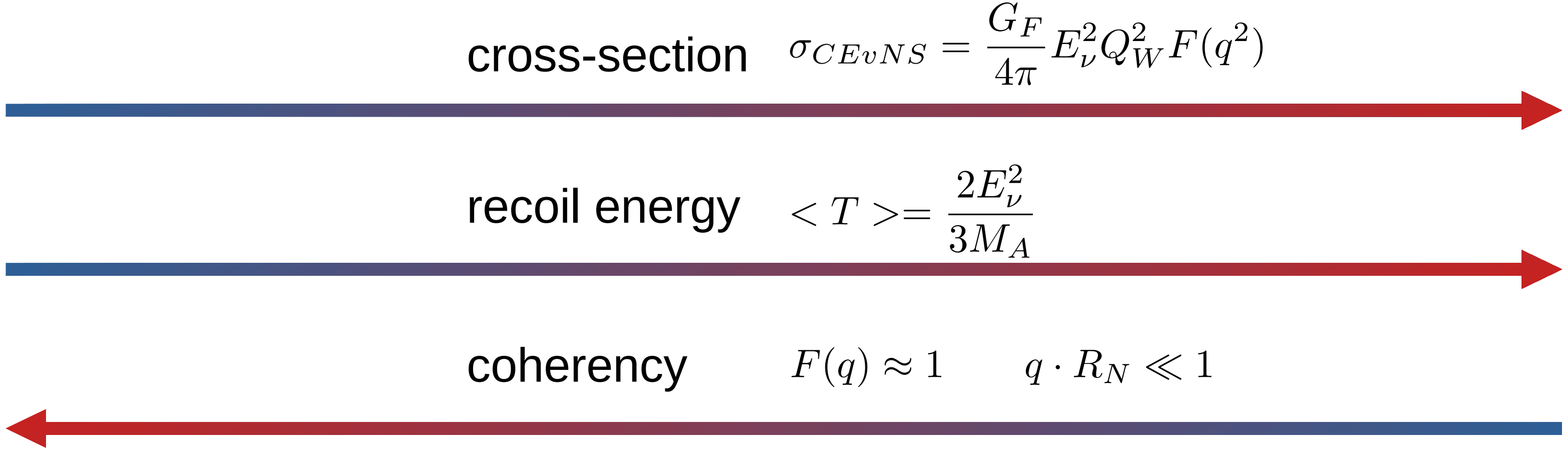


Reactor neutrinos
flux systematics ~ few %

Needs to be measured!

Accelerator neutrinos
flux systematics ~ 10 %

in Europe at the ESS: A. Estévez Wednesday



cross-section $\sigma_{CE\upsilon NS} = \frac{G_F}{4\pi} E_\nu^2 Q_W^2 F(q^2)$

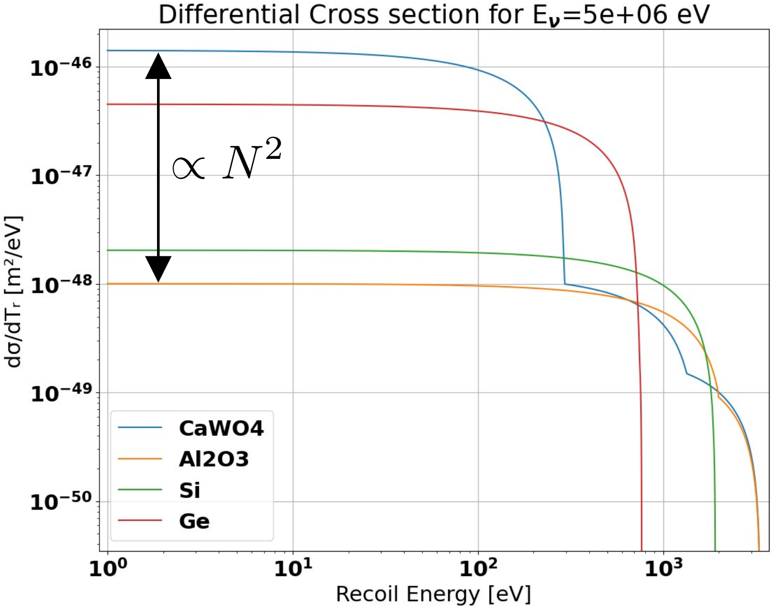
recoil energy $< T >= \frac{2E_\nu^2}{3M_A}$

coherency $F(q) \approx 1 \qquad q \cdot R_N \ll 1$

BULLKID for reactor CEvNS detection

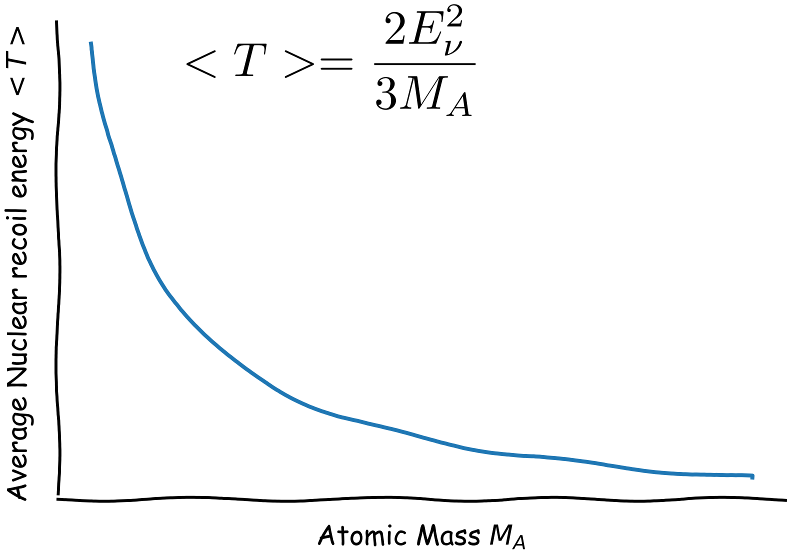
Detection Trade–off

N² Scaling



- Heavy Atoms Needed!

Nuclear Recoil Energy

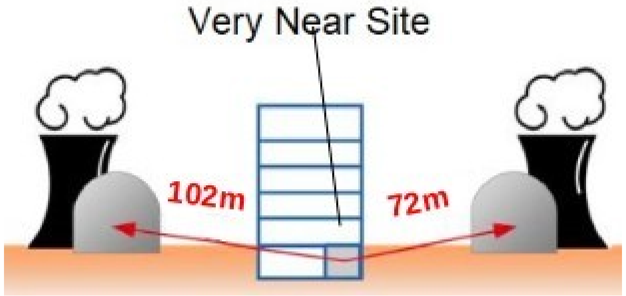


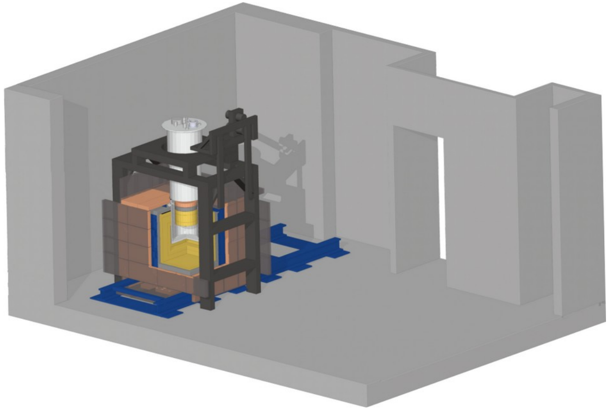
$$<T>=\frac{2E_\nu^2}{3M_A}$$

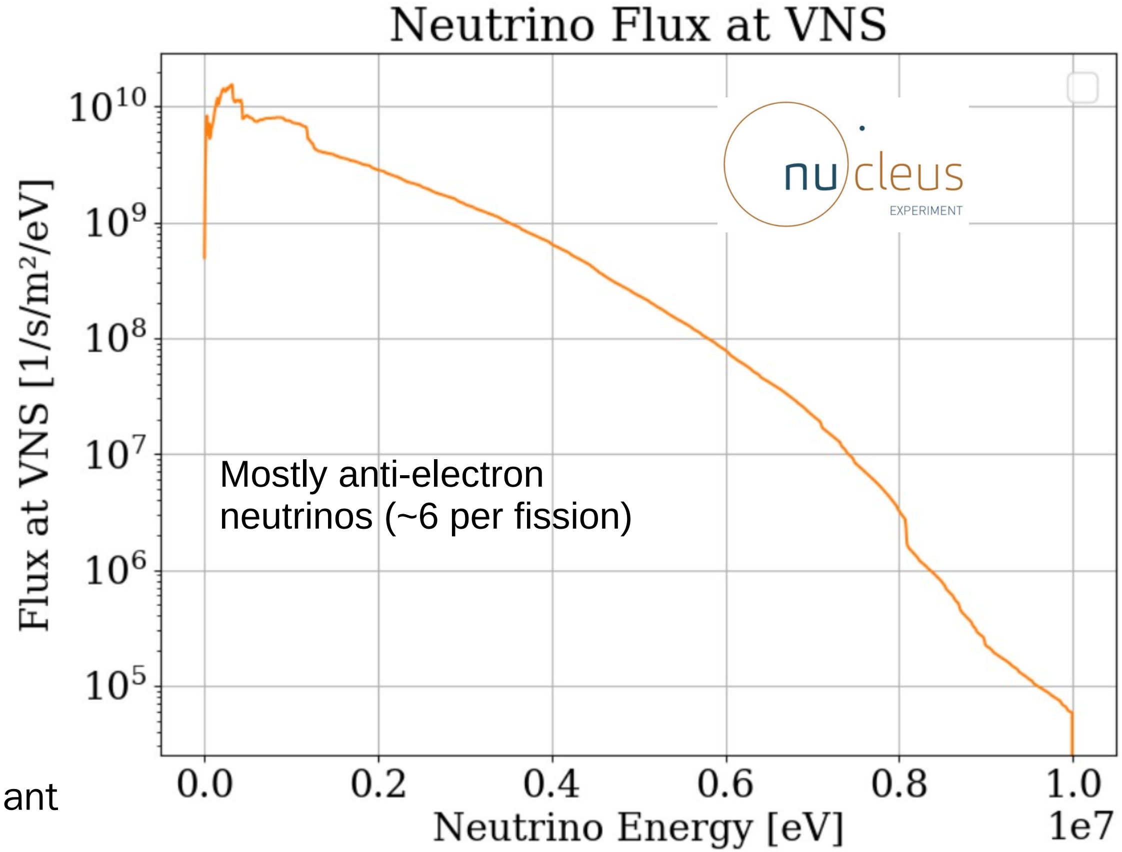
- Light Atoms Needed!

Usual targets are: Si, Ge, $CaWO_4$, Al_2O_3, CsI[Na], NaI[Tl], Xe,Ar

Reactor CEvNS: Neutrino Spectrum at VNS



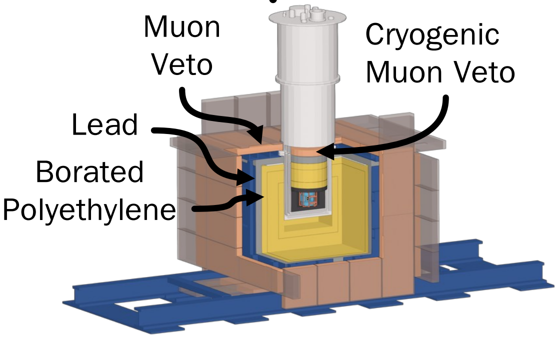




Mostly anti-electron neutrinos (~6 per fission)

- 24 m^2 basement room (~3 m.w.e)
- 2x4.25 GW$_{th}$ nuclear reactors at the Chooz Power Plant
- Baselines of 72 m and 102 m
- At experimental site expected antineutrino flux of 1.7x10^{12} ν/(s cm^2)

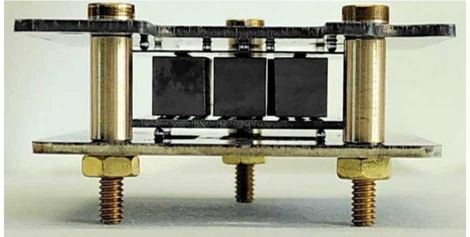
BULLKID vs NUCLEUS



NUCLEUS External Shielding

CryoVeto (ambient γ)

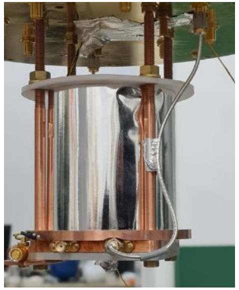
- 4π Germanium Coverage
- Different Readout



CryoCubes

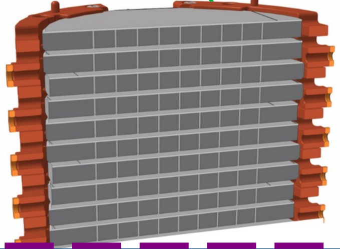
- Resoluton < 6 eV
- Dense Crystals (CaWO$_4$)
- 10 g Detector (18 cubes)

- 4π BGO Coverage (*)
- Same Readout (KID based)

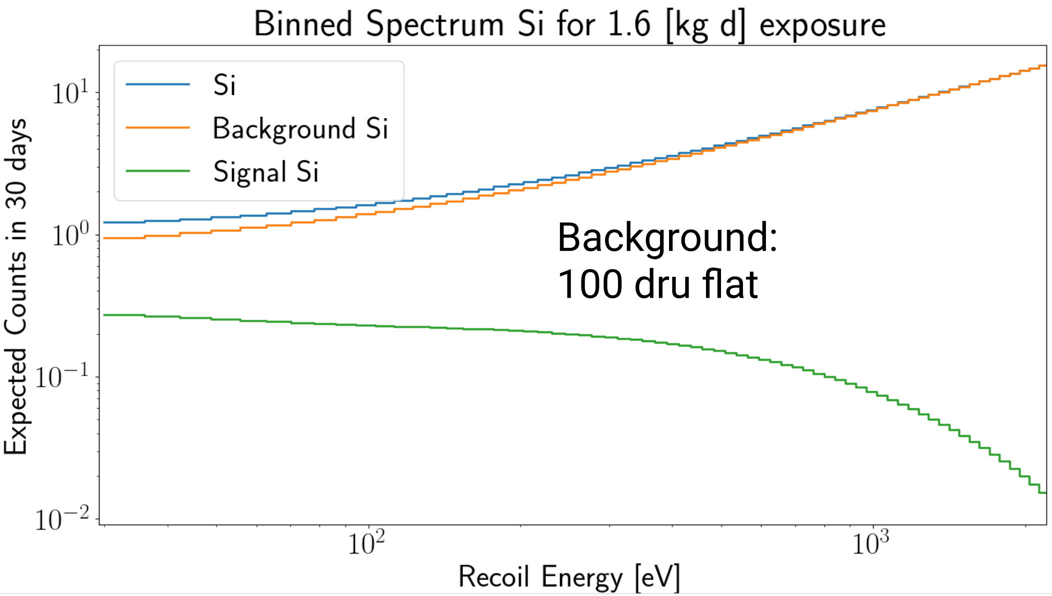


*see M. del Gallo’s talk tomorrow

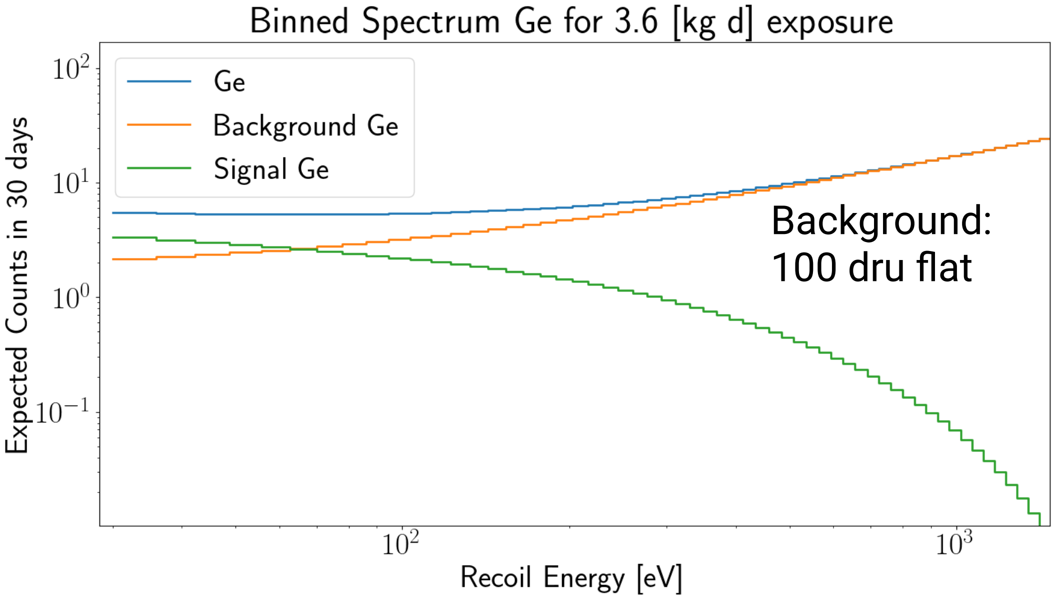
- Resolution ~ 25 eV
- Needs Germanium MKIDs
- O(1 kg) Detector (>100 cubes)



Reactor CEvNS: Threshold and Target



Background:
100 dru flat



Background:
100 dru flat

Reactor CEvNS:

- Most of the flux < 5 MeV:

  $\langle T_{Si} \rangle \leq 700$ eV

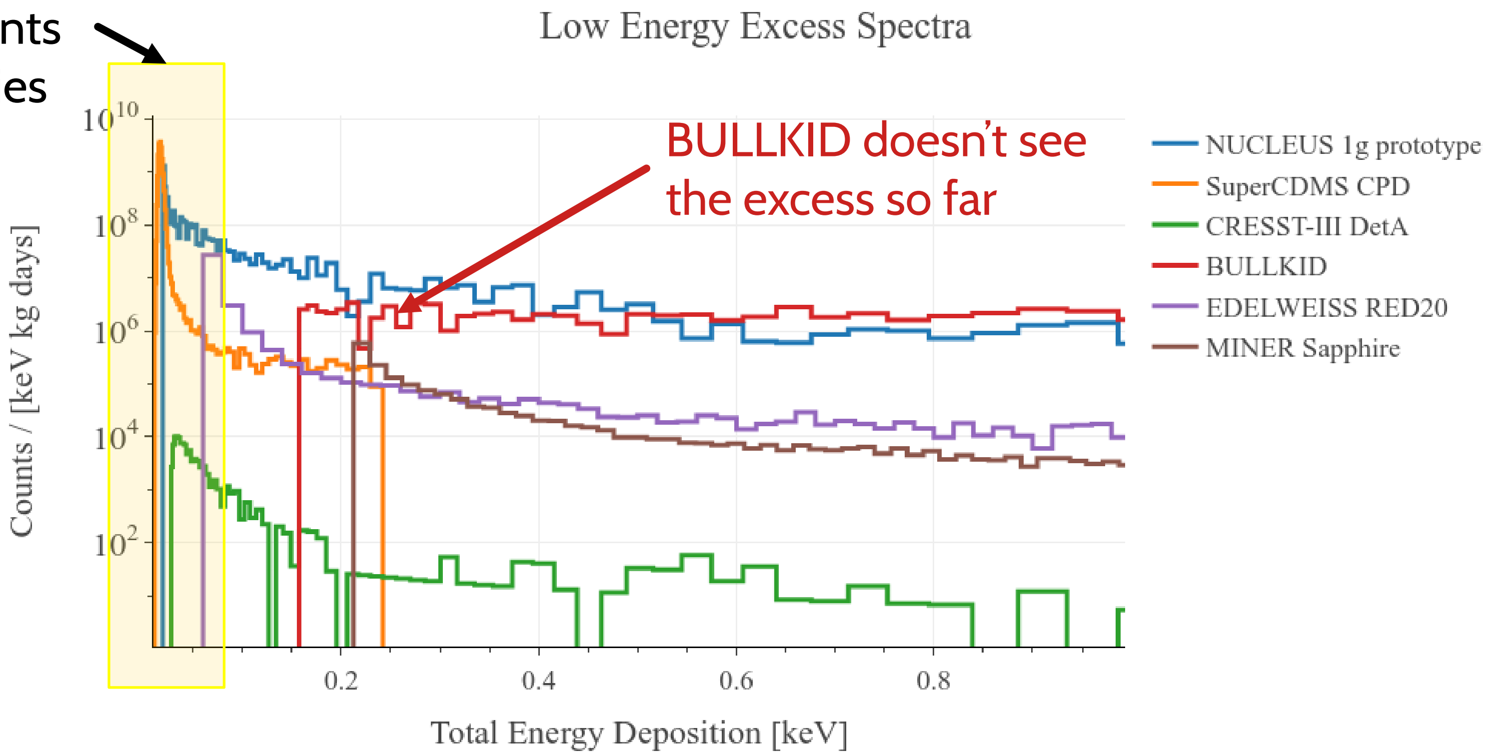
  $\langle T_{Ge} \rangle \leq 300$ eV

Requires:
- Exposure
- Heavy Materials
- Low Resolutions!
- Low Background!

BULLKID: Background

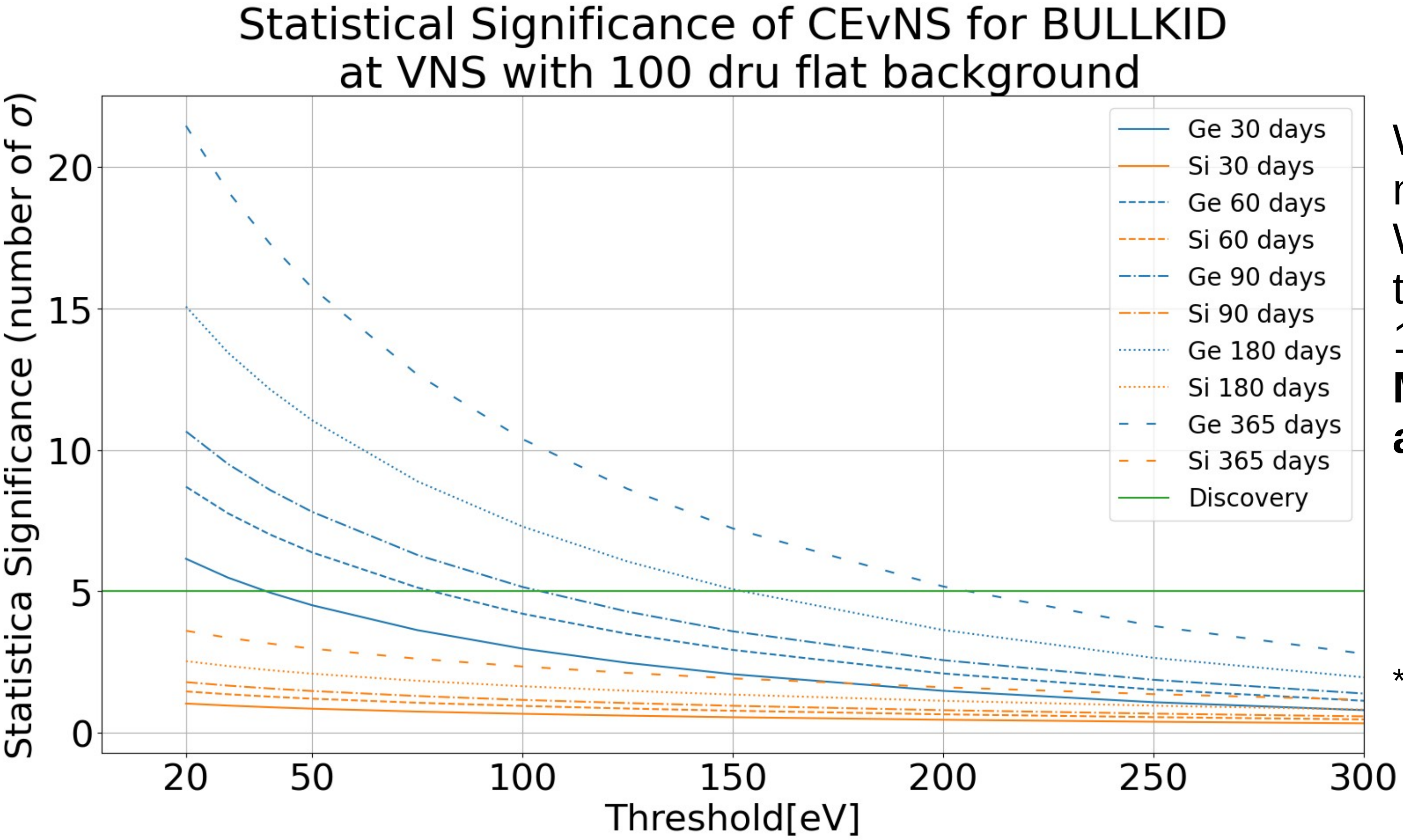
The EXCESS is seen in both CCDs and CryoDetectors and makes you blind to most of the reactor neutrino spectrum

Unexplained excess of events at low energies



BULLKID doesn't see the excess so far

BULLKID Sensitivity

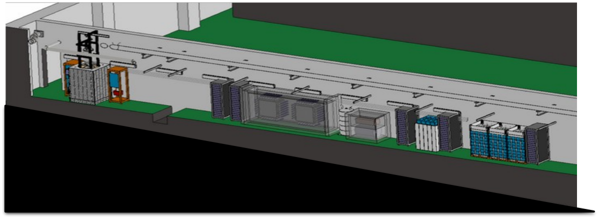


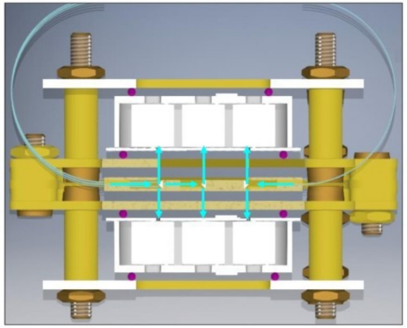
With a demonstrator made of Ge*
With 150 eV trigger threshold
100 dru flat background
Measure reactor CEvNS at 5σ!

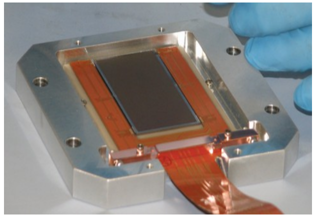
*see D.Delicato’s talk tomorrow

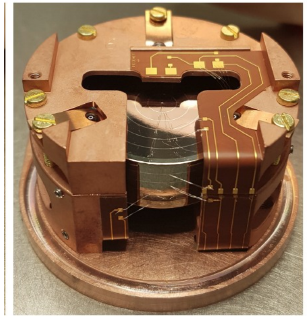
Other Experiments

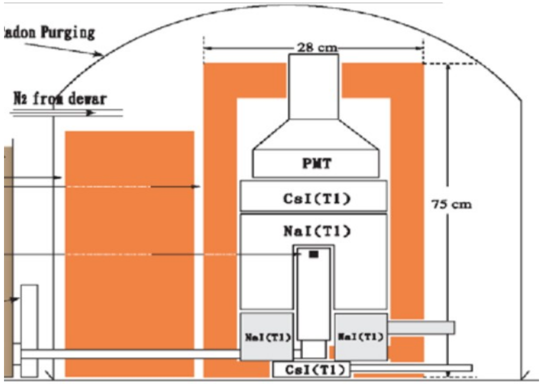
Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
BULLKID	Si/Ge	Italy	Reactor
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
NEWS-G	Ar+2%CH4	Canada	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NEON	NaI(Tl)	Korea	Reactor
NUCLEUS	$CaWO_4$, Al_2O_3 cryogenic	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn, Al, Sn cryogenic	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
Dresden II	PCGe	USA	Reactor
SBC	Scintillating Bubble Chamber	Fermilab (R&D)	Reactor





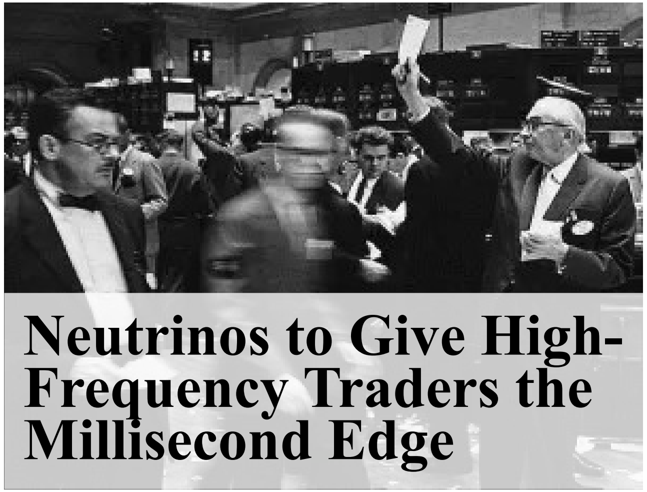




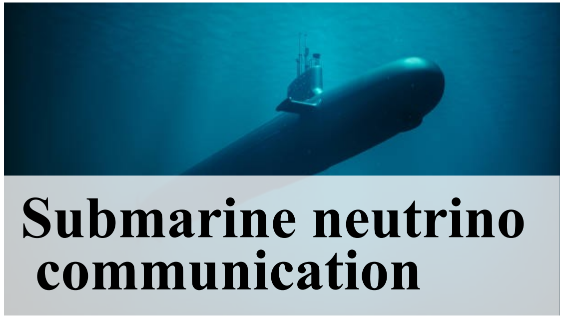


Slide from Enectali Figueroa-Feliciano

Exotic CEvNS and Bibliography

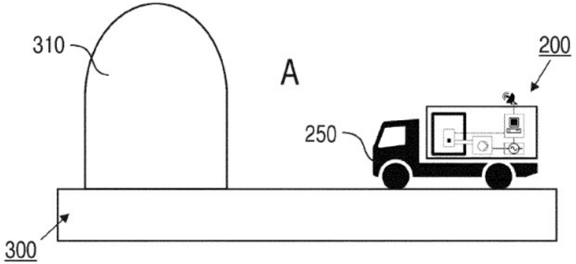


Neutrinos to Give High-Frequency Traders the Millisecond Edge



Submarine neutrino communication

Neutrino-Based Tools for Nuclear Verification

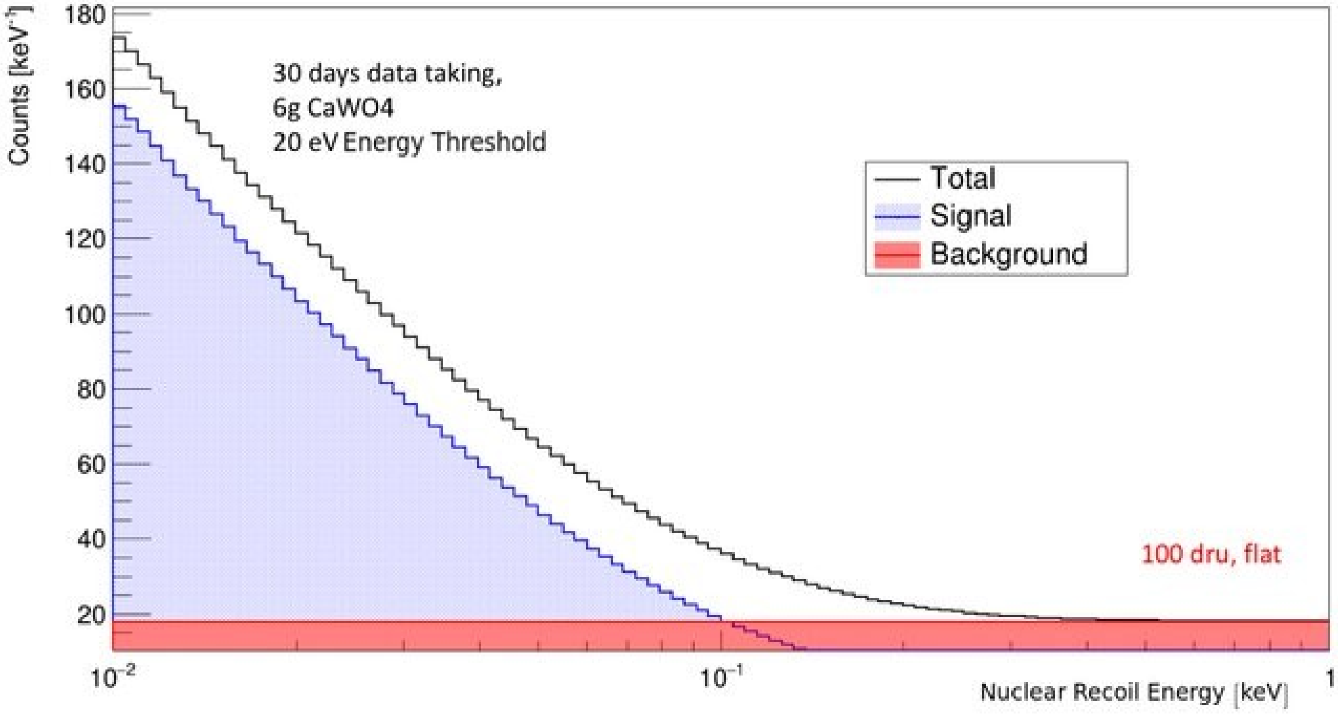


Neutrino detector device, neutrino detector system and method for detecting neutrinos

1. Coherent effects of a weak neutral current, Daniel Z. Freedman, Phys. Rev. D 9, 1389
2. Coherent Neutrino-Nucleus Scattering and new Neutrino Interactions,M. Lindner et al. , Journal of High EnergyPhysics 2017.3 (Mar. 2017)
3. Magnificent CEvNS 2023 Experimental Summary, Enectali Figueroa-Feliciano
4. CevNS coherent and elastic neutrino-nucleus scattering, M.Vignati Taup 2023
5. EXCESS workshop: Descriptions of rising low-energy spectra
6. Latest observations on the low energy excess in CRESST-III
7. Exploring CEvNS with NUCLEUS at the Chooz nuclear power plant

Backup

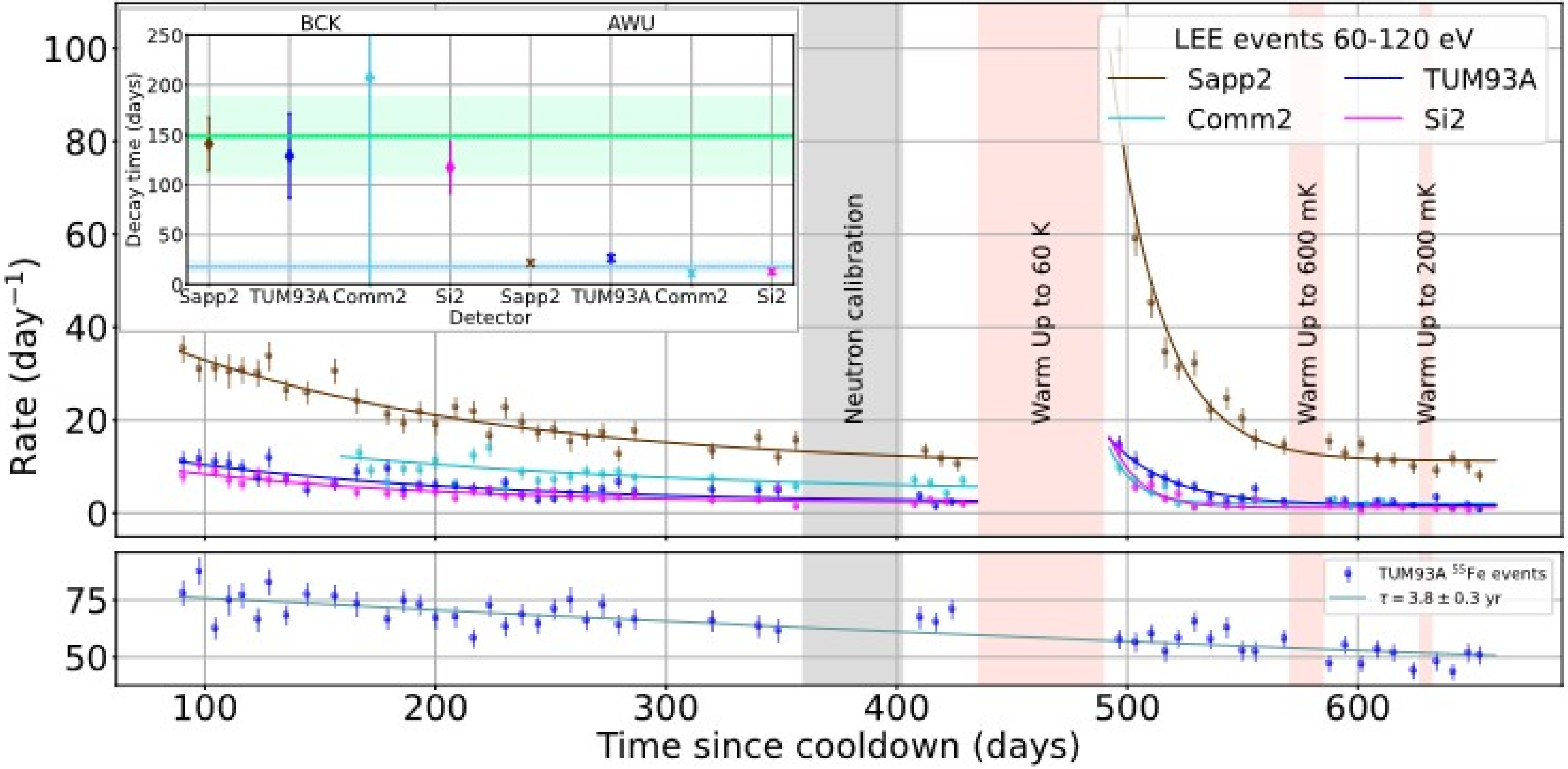
More on EXCESS



Low Energy Excess has similar signature to CEvNS

Difficult signal to background discrimination

EXCESS time dependence



Asimov Statistics

Calculate directly from the expected background and CEvNS rate the significance without any montecarlo simulations

$$-\log(\mathcal{L}(\beta,\sigma)) = \sum_{t\in isotopes}\left[\mu_t(\beta,\sigma) - \sum_{i,\ldots,n_t} n_i \log(\mu_i(\beta,\sigma))\right]$$

$$\sigma = \text{Signal Strength} \qquad \beta = \text{Background Strength}$$

$$f_{null}(\beta) = -\log\left(\mathcal{L}(\beta,0)\right) \qquad f_{free}(\beta,\sigma) = -\log\left(\mathcal{L}(\beta,\sigma)\right)$$

$$\min\left[f_{null}(\beta)\right] = f_{null}(\beta_0) \qquad \min\left[f_{free}(\beta,\sigma)\right] = f_{free}(\beta_1,\sigma_1)$$

$$Z = \sqrt{2\left(f_{null}(\beta_0) - f_{free}(\beta_1,\sigma_1)\right)}$$

"Development of energy calibration and data analysis systems for the NUCLEUS experiment", G. Del Caste