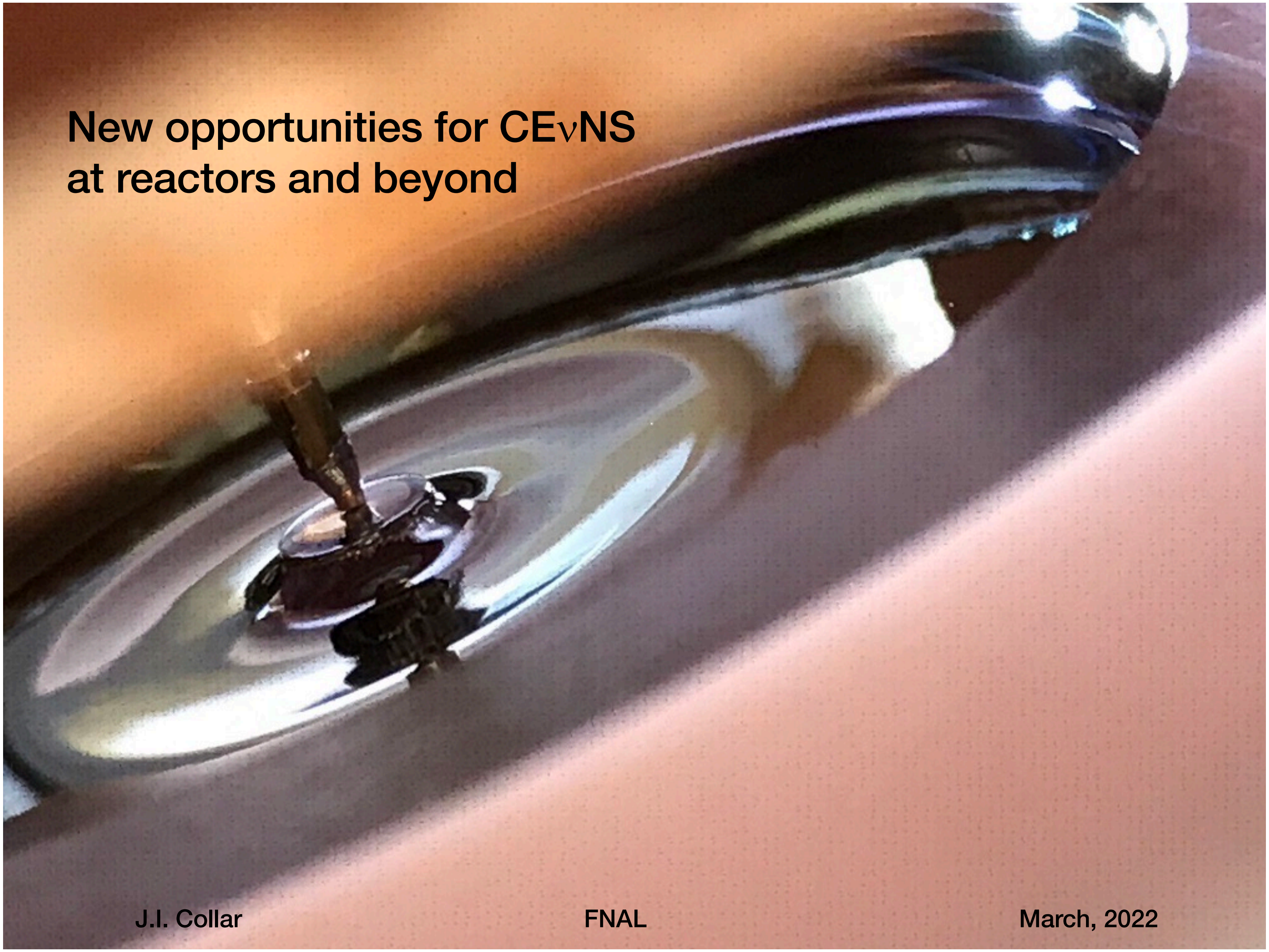


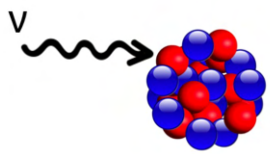
New opportunities for CEνNS at reactors and beyond

J.I. Collar

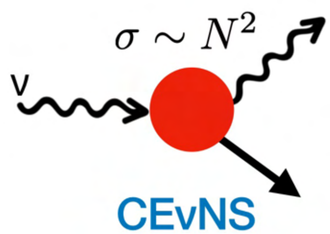
FNAL

March, 2022

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



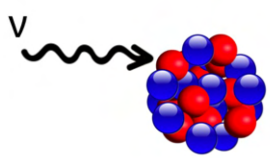
Long wavelength, “sees” all nucleons simultaneously



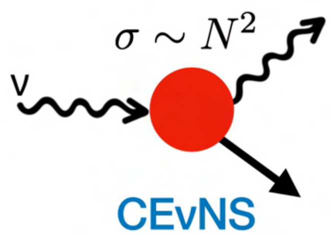
Cross section increases as N^2. (largest of all -> small detectors) CATCH: sub-keV to few keV recoils are only observable.

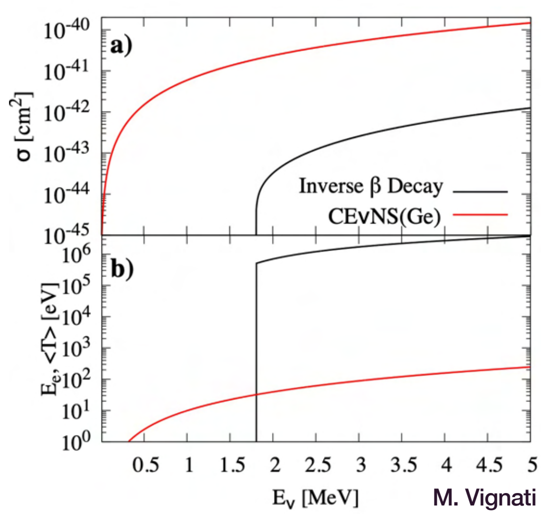
First measurement only 4 years ago (40 years after description)

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



Long wavelength, “sees” all nucleons simultaneously



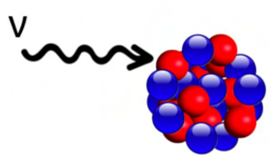


M. Vignati

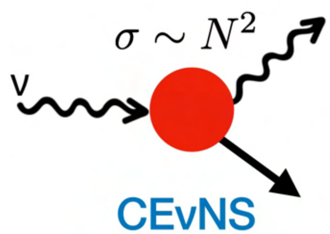
Cross section increases as N².
(largest of all -> small detectors)
CATCH: sub-keV to few keV recoils are only observable.

First measurement only 4 years ago (40 years after description)

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



Long wavelength, "sees" all nucleons simultaneously

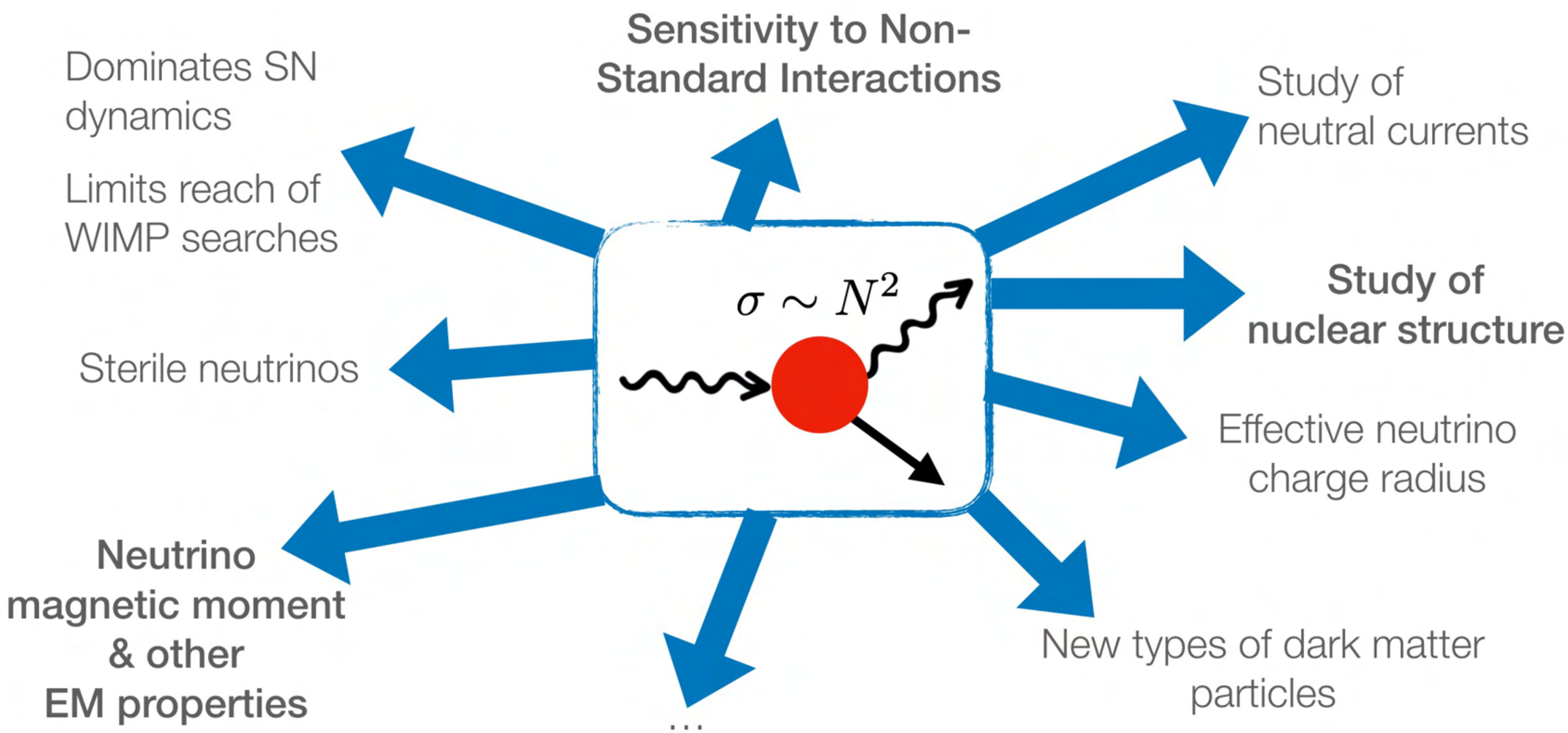


Cross section increases as N^2. (largest of all -> small detectors) CATCH: sub-keV to few keV recoils are only observable.

First measurement only 4 years ago (40 years after description)

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

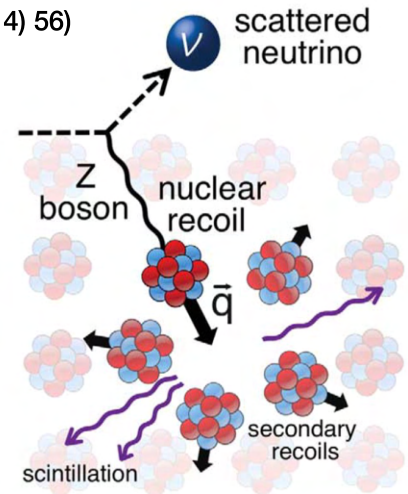
Rich phenomenology (45 years worth of it)

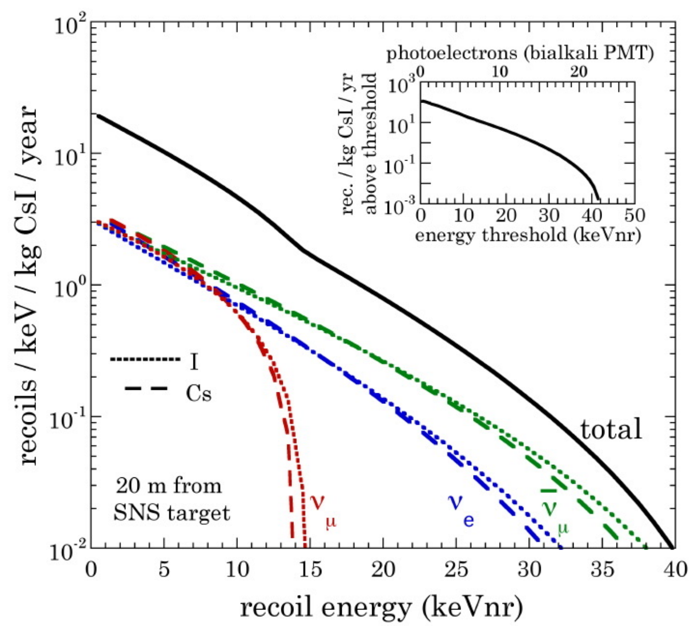


and counting
(~100 citations / year for 1st measurement)

Why CsI[Na]? (NIM A773 (2014) 56)

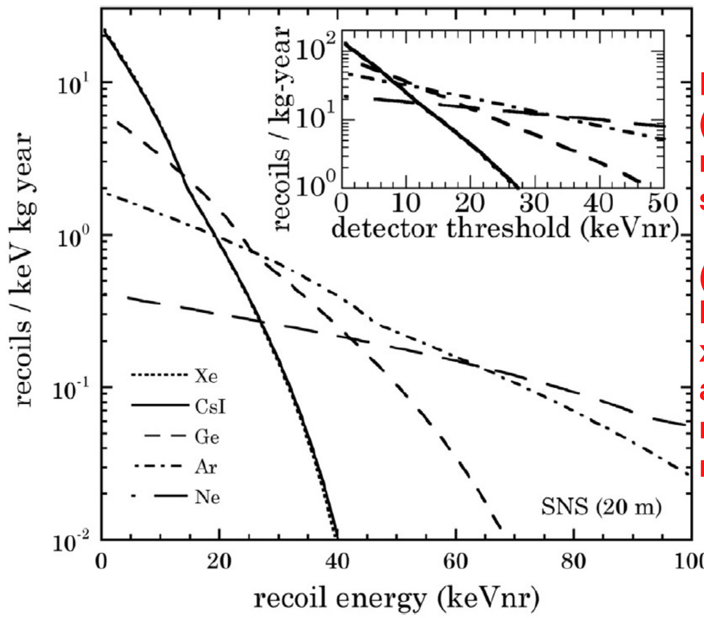
- Large N^2 => large x-section.
- Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.
- Quenching factor in energy ROI sufficient for ~5 keVnr threshold
- Statistical NR/ER discrimination may be possible at low-E (with large statistics).
- Sufficiently low in intrinsic backgrounds (U, Th ,K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicated we were ready)
- Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).
- Expected ~550 n recoils/year in 14 kg detector at SNS (before cuts).





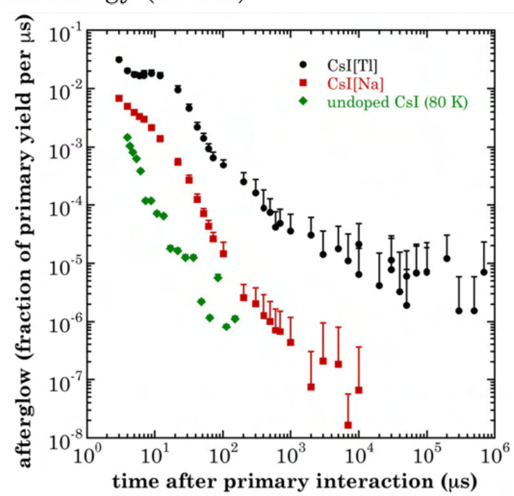
Why CsI[Na]? (NIM A773 (2014) 56)

- Large N² => large x-section.
- Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.
- Quenching factor in energy ROI sufficient for ~5 keVnr threshold
- Statistical NR/ER discrimination may be possible at low-E (with large statistics).
- Sufficiently low in intrinsic backgrounds (U, Th ,K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicated we were ready)
- Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).
- Expected ~550 n recoils/year in 14 kg detector at SNS (before cuts).



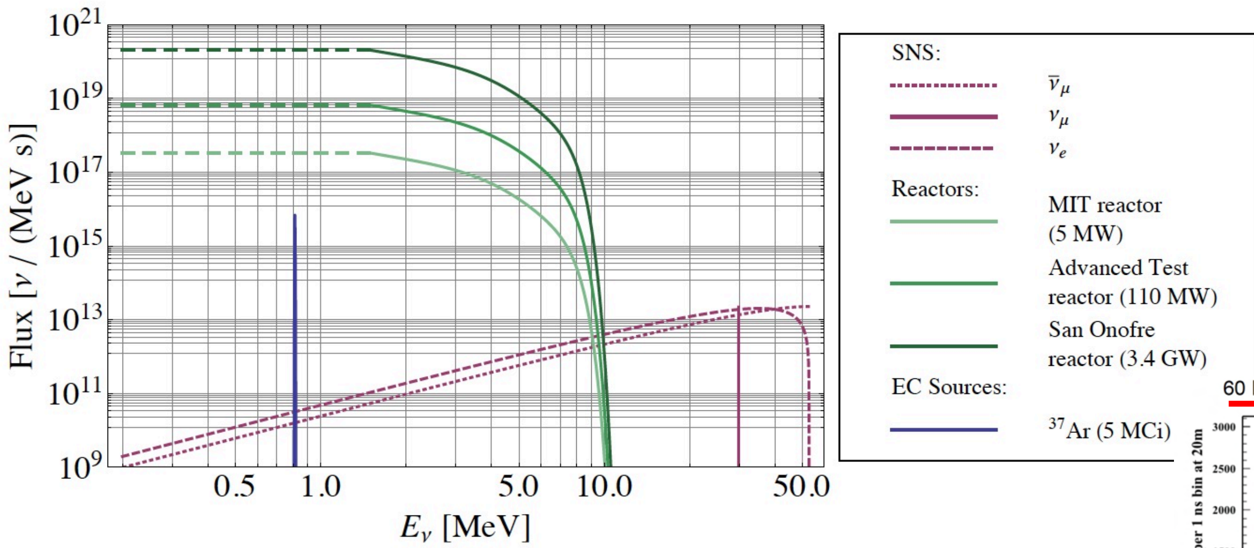
Brute force (large N²) not sufficient!

(tradeoff between x-section and maximum recoil E)



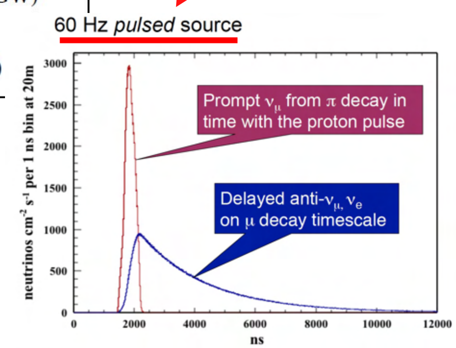
CsI[Tl] not an option due to excessive afterglow

Reactors: taking CEνNS to the next level



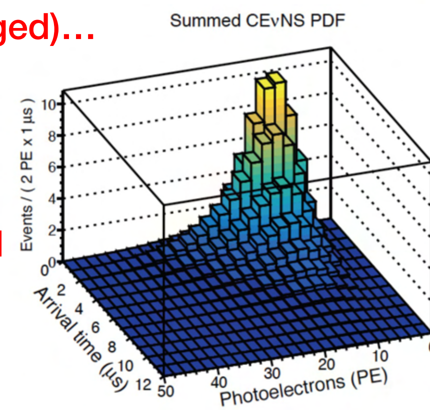
Enectali Figueroa-Feliciano / νMass 2013 / Milano

environmental background subtraction is possible for spallation sources



Many pros and cons:

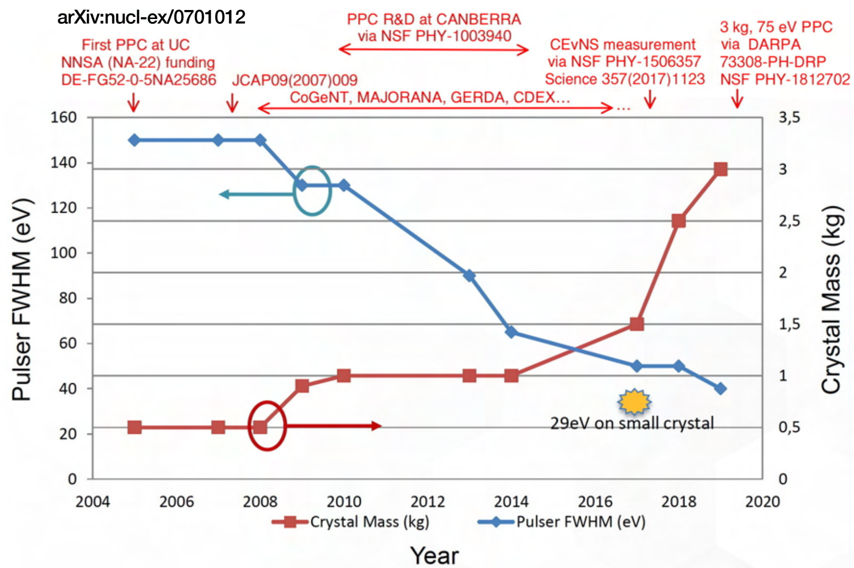
- Even lower recoil energies (scintillators discouraged)…
- … but much higher ν flux
- Rx-OFF periods are short (time is money)
- No background subtraction (steady-state source)
- Spallation sources produce x200 n per ν…
- … some reactor sites offer excellent bckg control



Spallation source CEνNS signal is characteristic in both energy and time

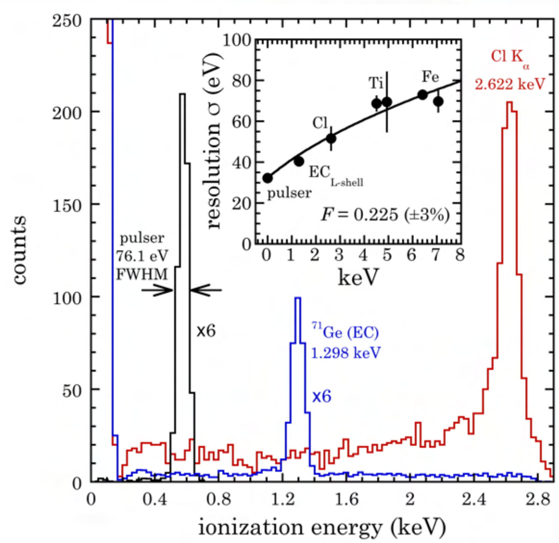
Almost a perfect quid pro quo. Very different game.

New CEνNS detector R&D at UC: PPCs

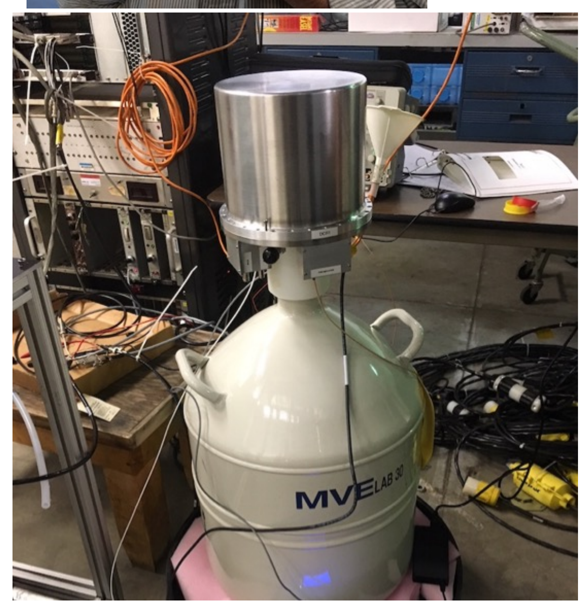


Inverted coax PPC
NIM A 665 (2011) 25

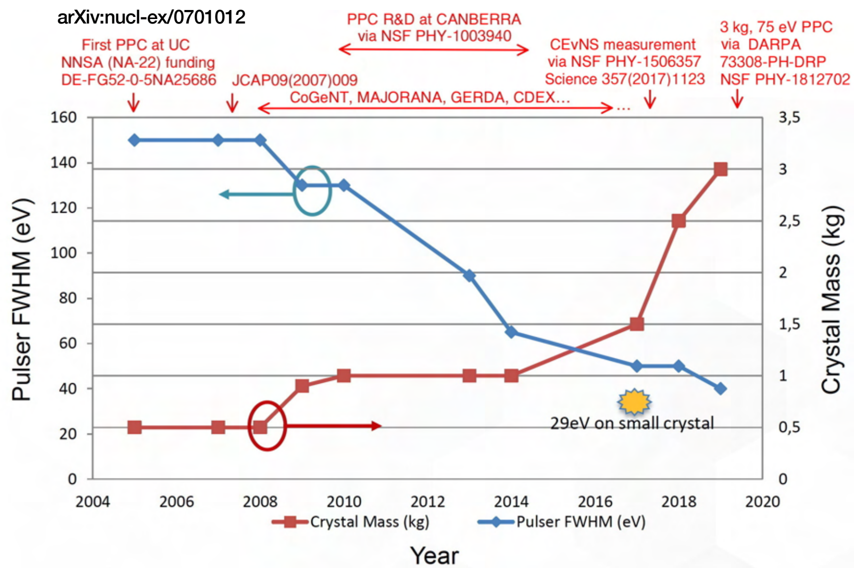
6kg
R&D
@
ORNL
(D. Radford)

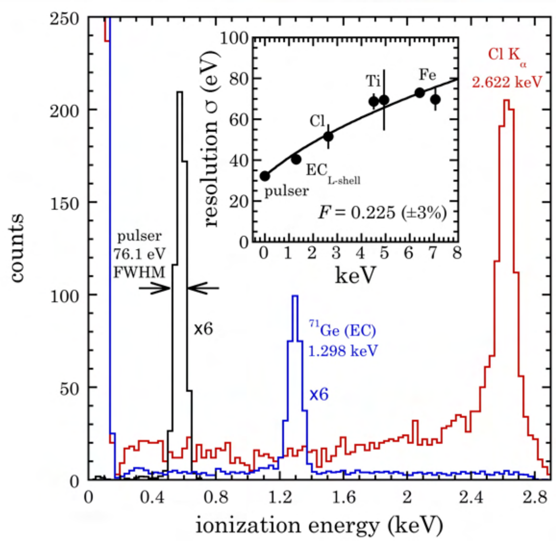


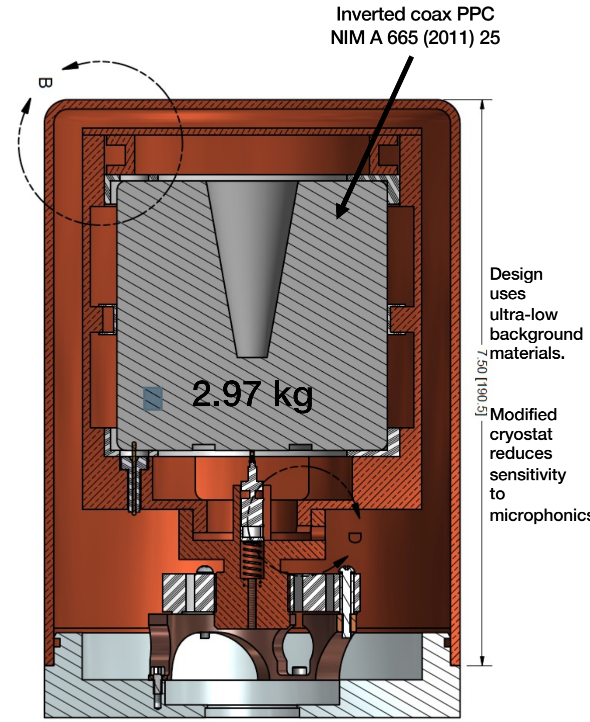
Ge PPC:
unique combination of mass, radiopurity, threshold and resolution provide ideal tool for precision CEnNS studies, and practical applications (reactor monitoring)



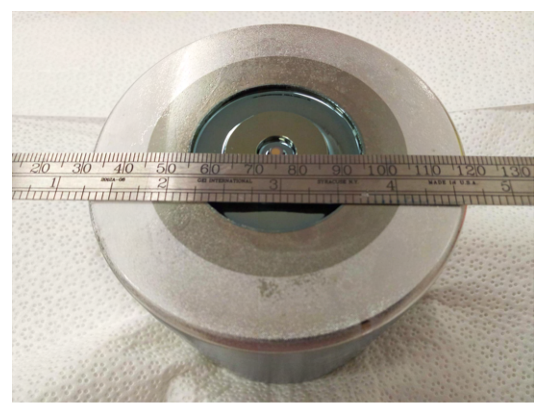
New CEνNS detector R&D at UC: PPCs



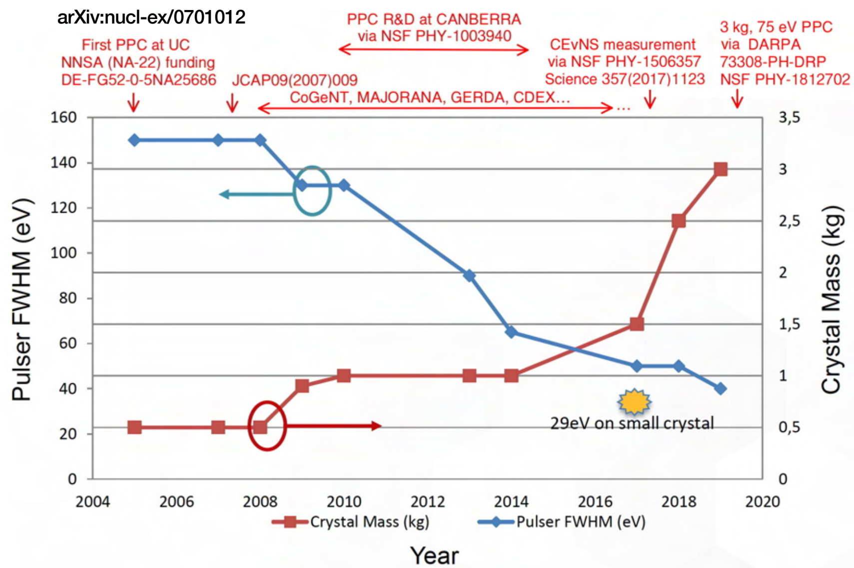


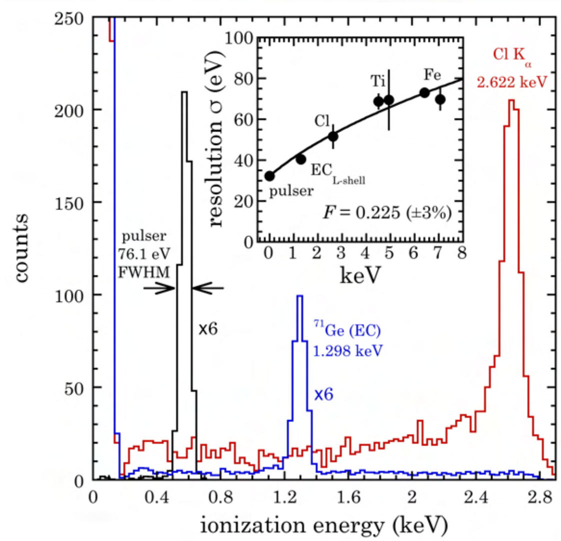


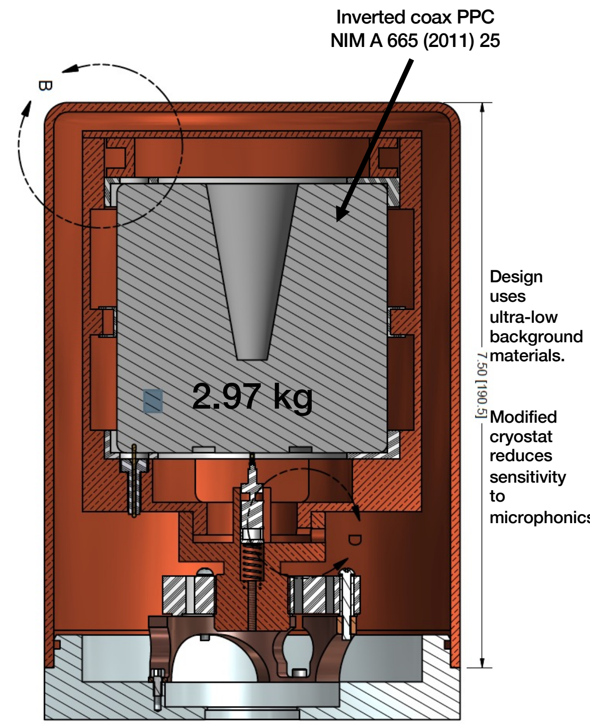
Ge PPC:
unique combination of mass, radiopurity, threshold and resolution provide ideal tool for precision CEnNS studies, and practical applications (reactor monitoring)



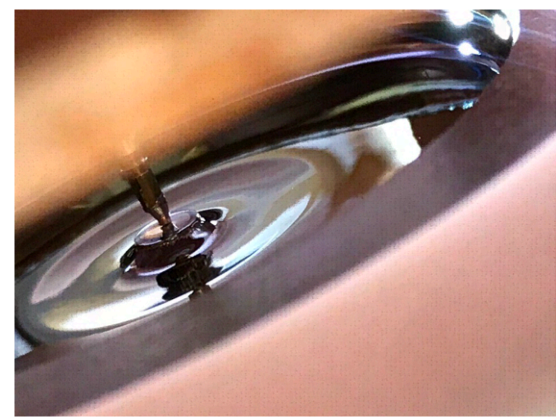
New CEνNS detector R&D at UC: PPCs



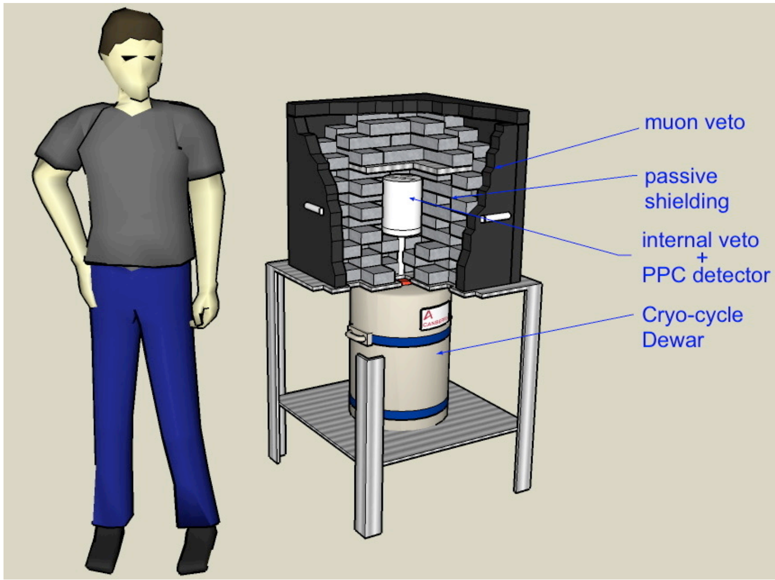


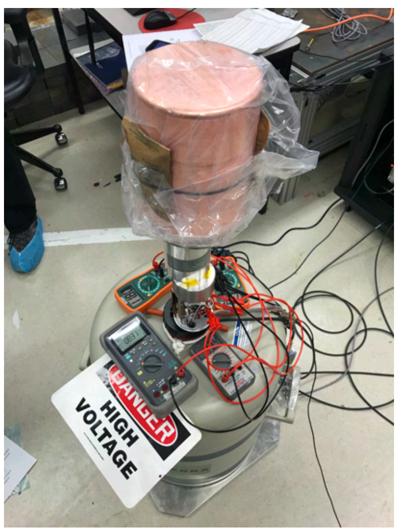


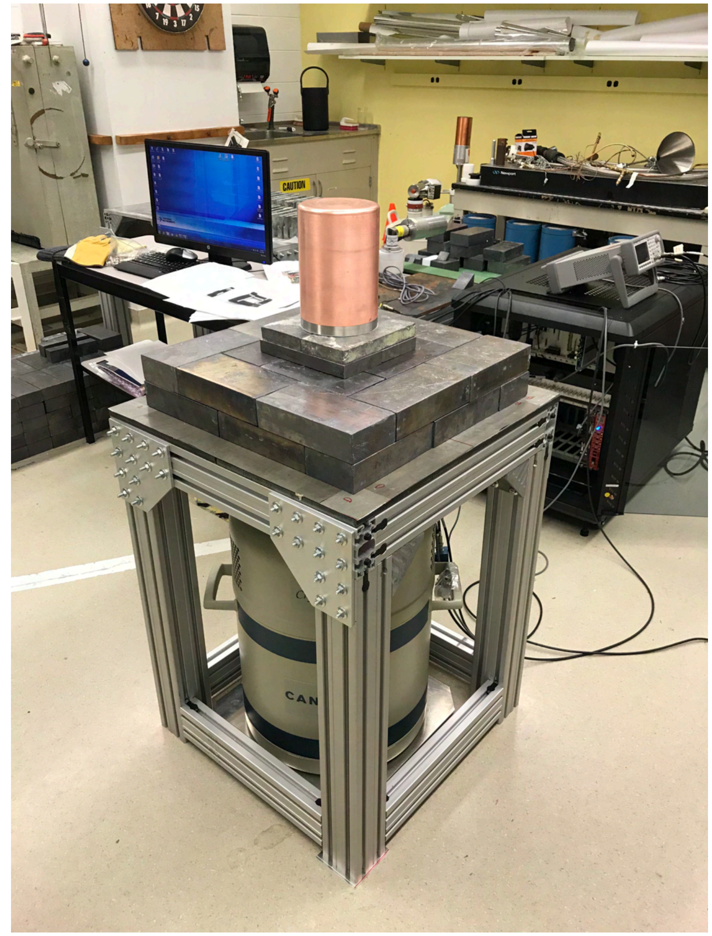
Ge PPC:
unique combination of mass, radiopurity, threshold and resolution provide ideal tool for precision CEnNS studies, and practical applications (reactor monitoring)



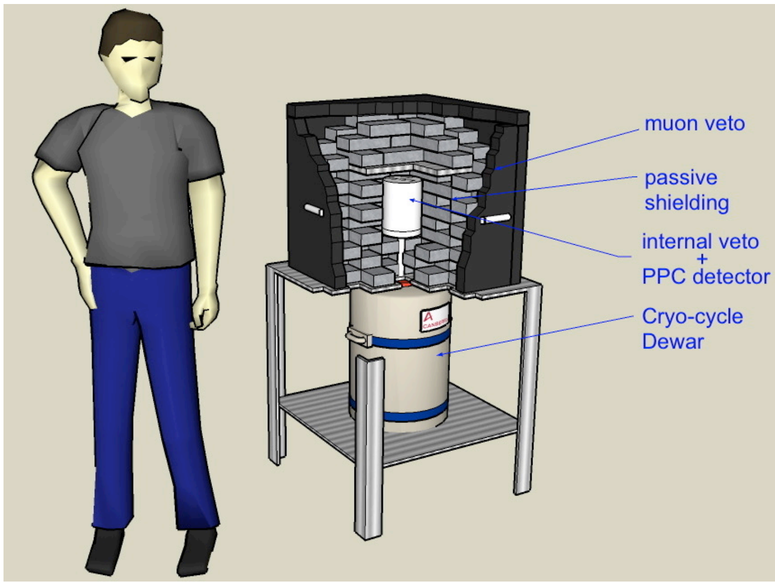
Turning a ~15 yr old sketch into a reality…

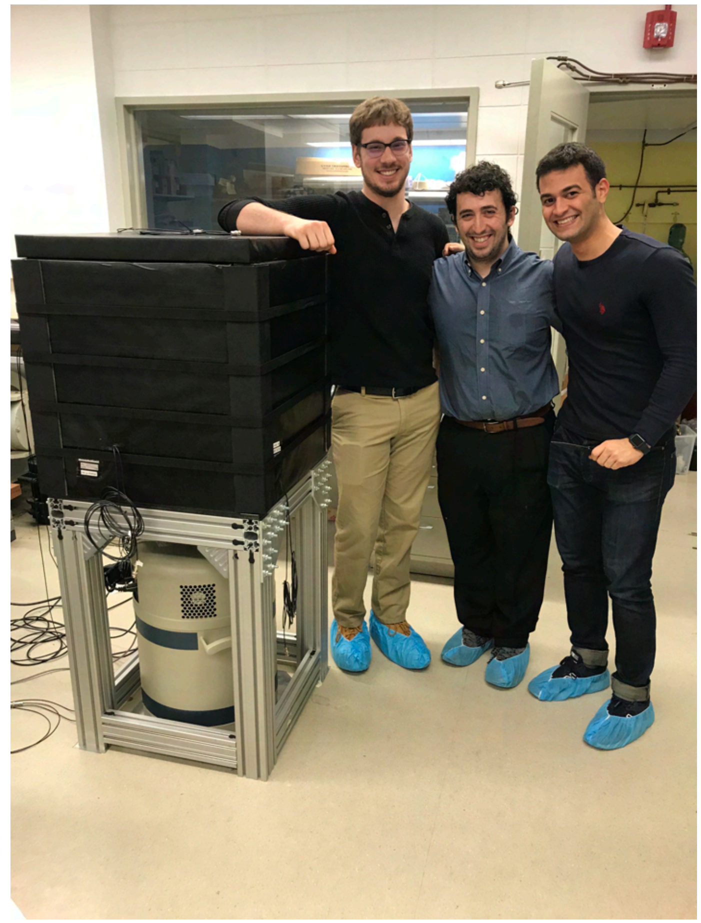


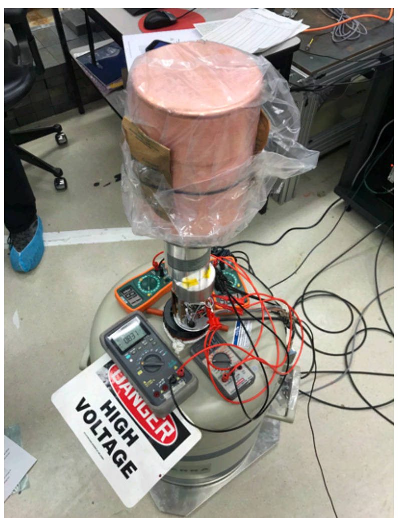


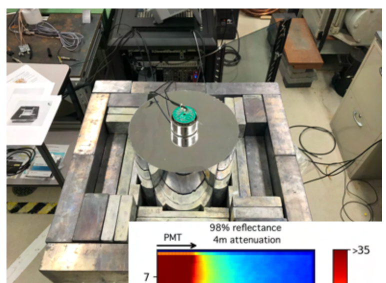


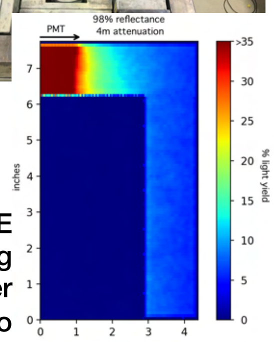
Turning a ~15 yr old sketch into a reality…











SPE
low-bckg
inner
neutron veto

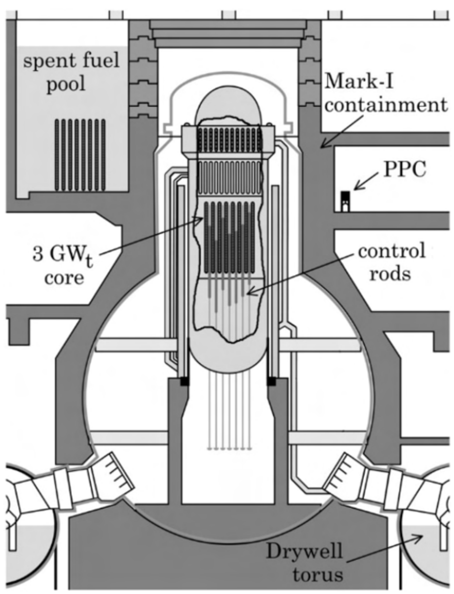
Turning a ~15 yr old sketch into a reality…

Fuel Elements 10.4 m away (7.5-13.3m)

4.8E13 ν/cm²s

60cm x 60cm footprint.

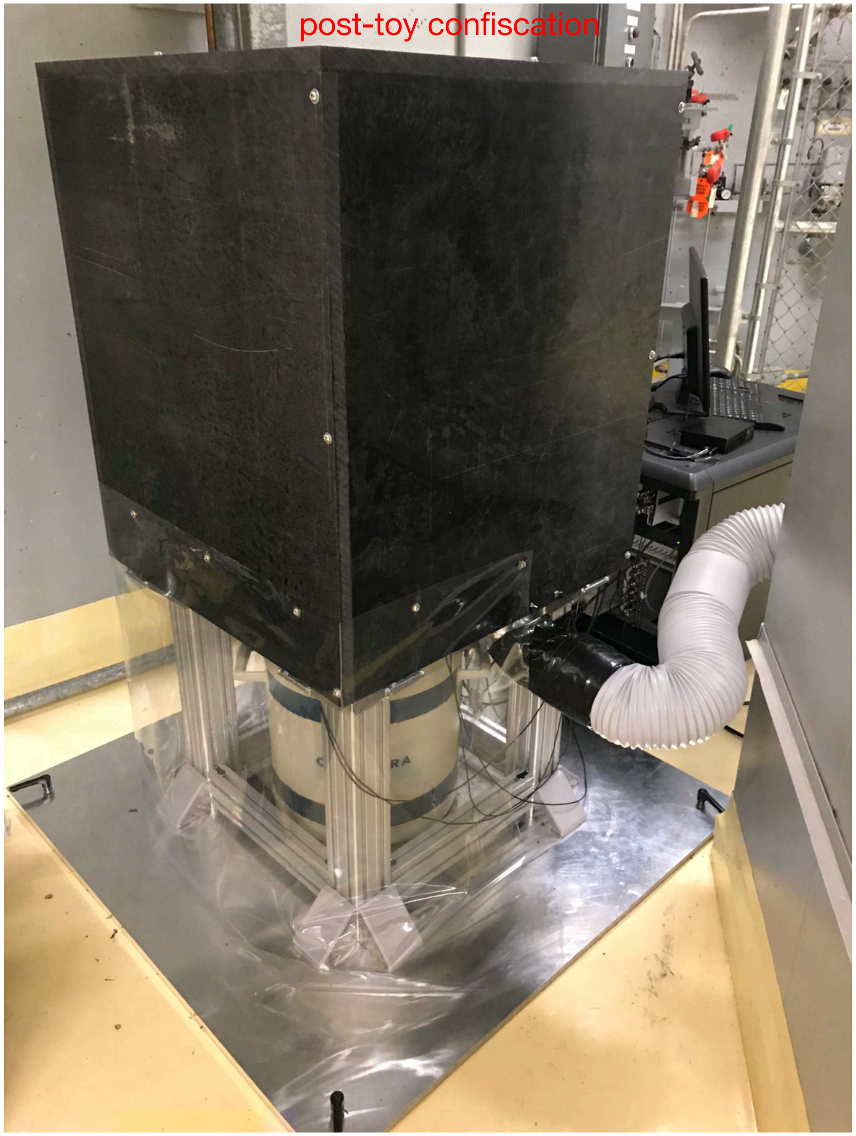
Assembled by 3 workers in one day.



Turning a ~15 yr old sketch into a reality…

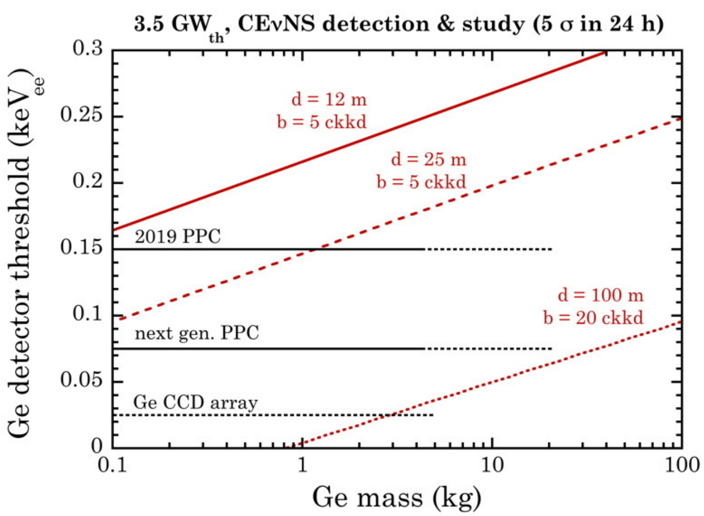
De rigueur selfie

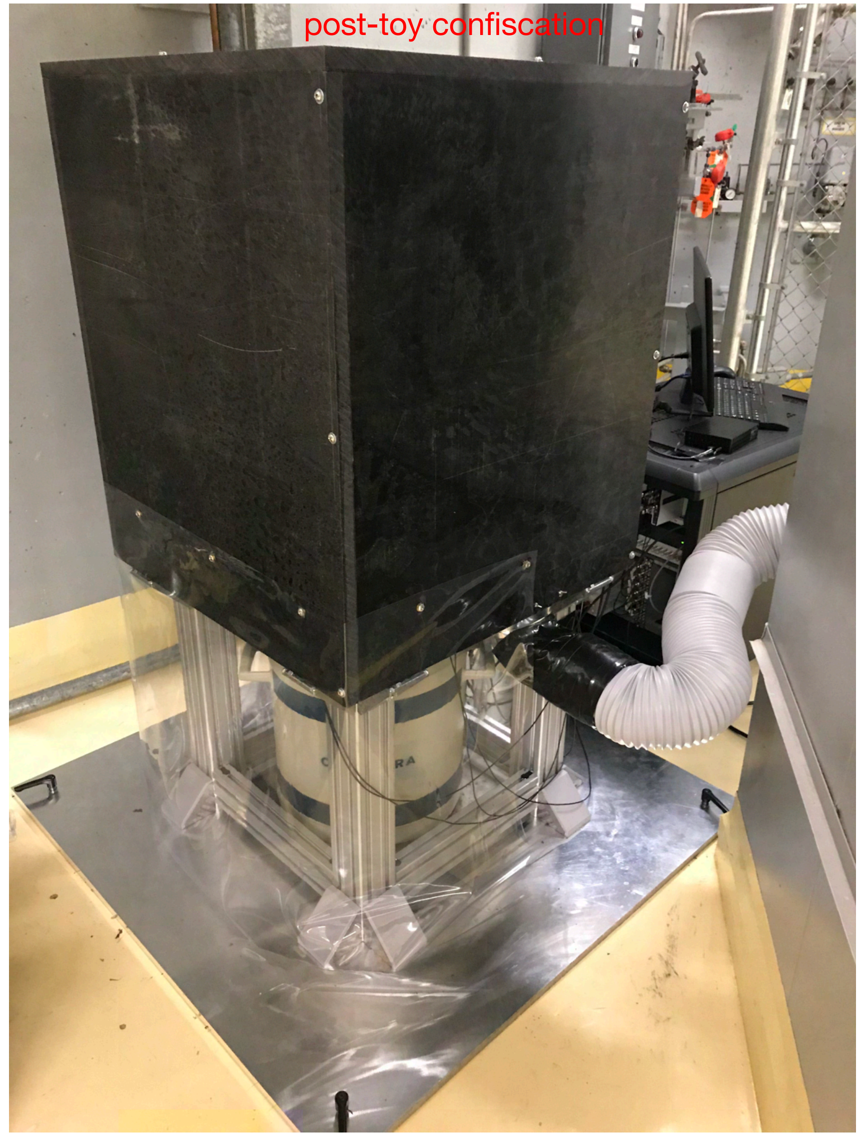
post-toy confiscation



Turning a ~15 yr old sketch into a reality…

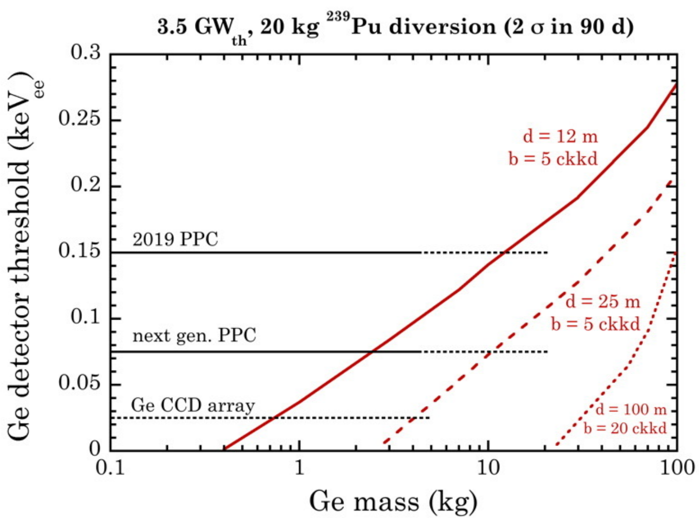
Not so far from a "ν technology"…

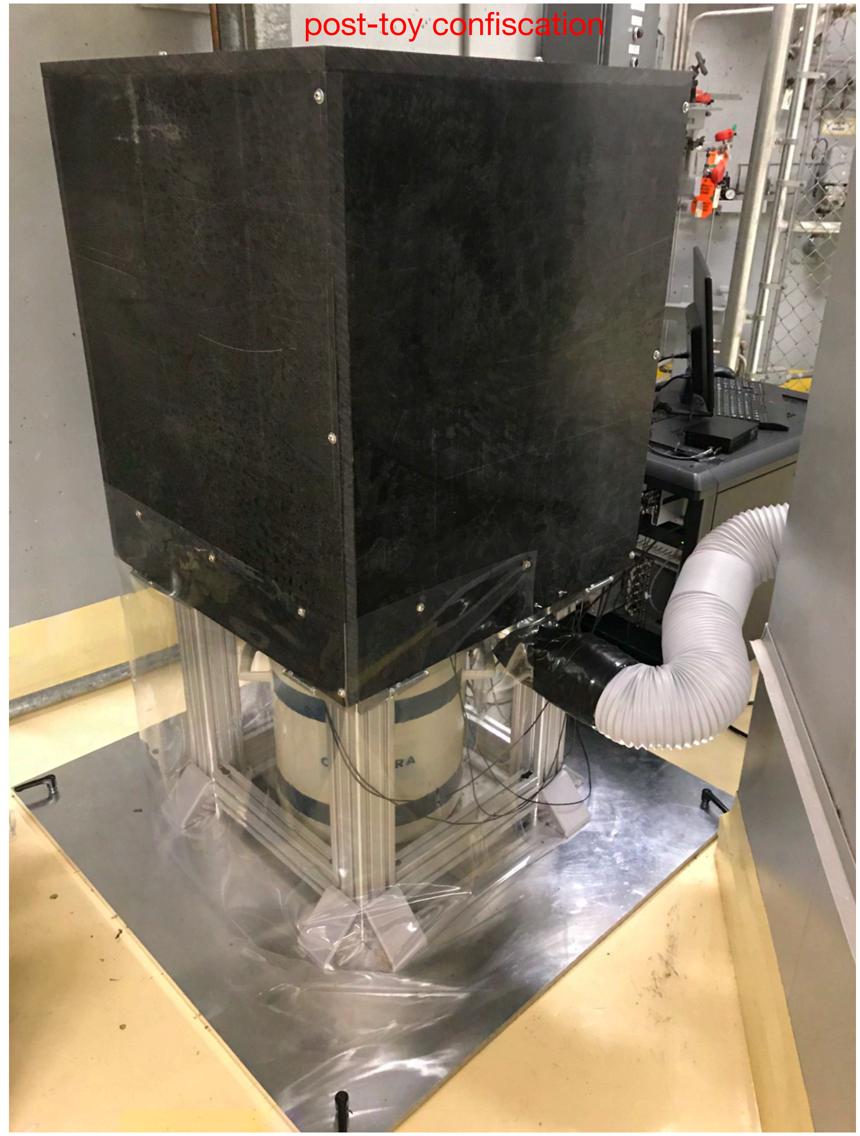




Turning a ~15 yr old sketch into a reality…

Not so far from a “ν technology”…

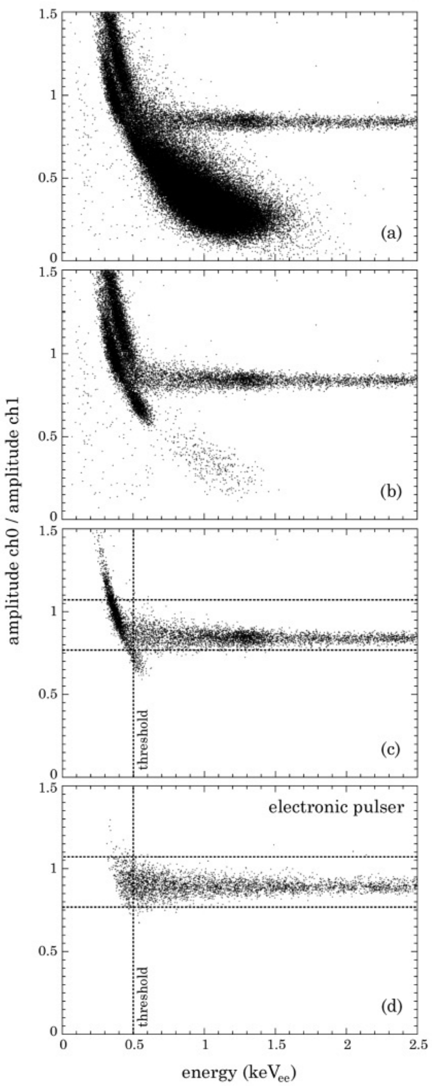




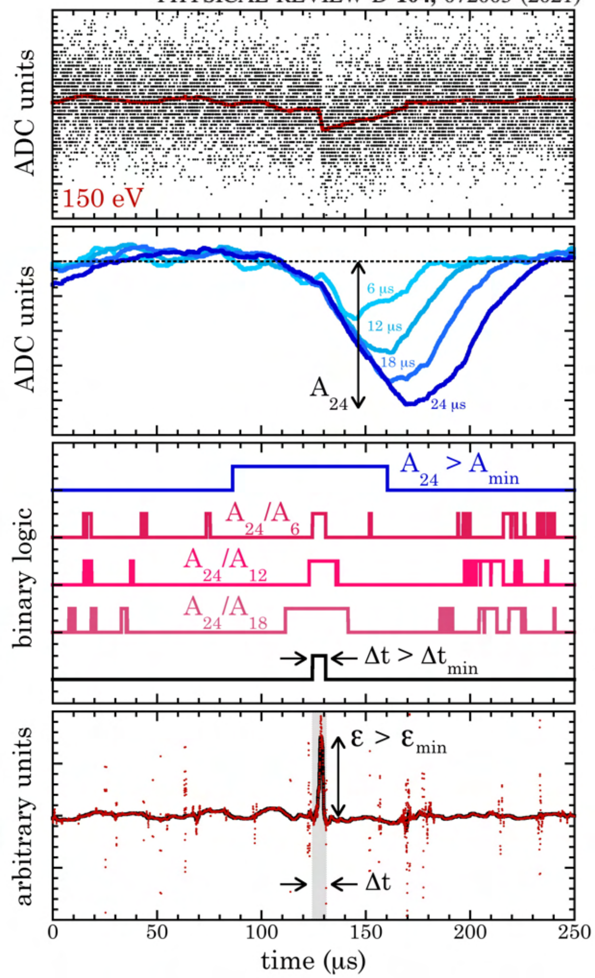
Secret sauce: FPGA DAQ

(something old, something new)

C.E. AALSETH *et al.* PHYSICAL REVIEW D **88,** 012002 (2013)

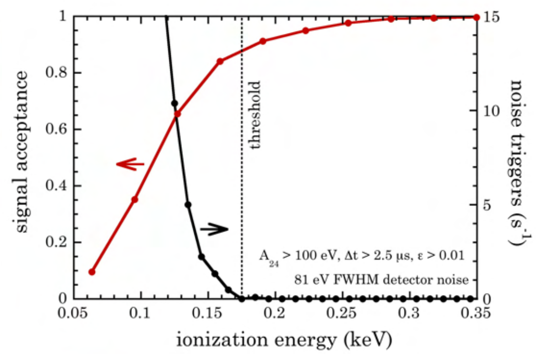


PHYSICAL REVIEW D **104,** 072003 (2021)



FPGA-based intelligent trigger algorithms implement old analog tricks in real-time, providing ultimate in low-threshold performance.

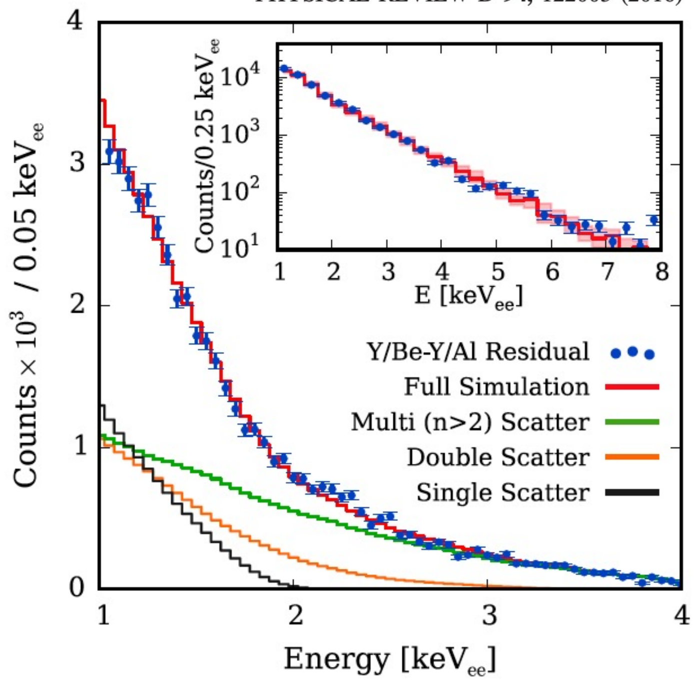
<u>Ultra-low threshold is posible without data throughput bottleneck.</u>

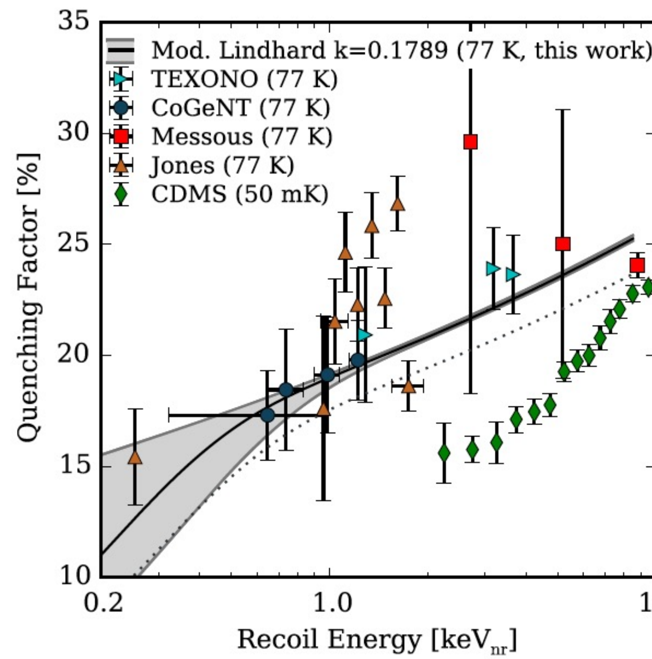


Digitize and you shall conquer

Quenching factor characterization: the key ingredient

PHYSICAL REVIEW D **94,** 122003 (2016)





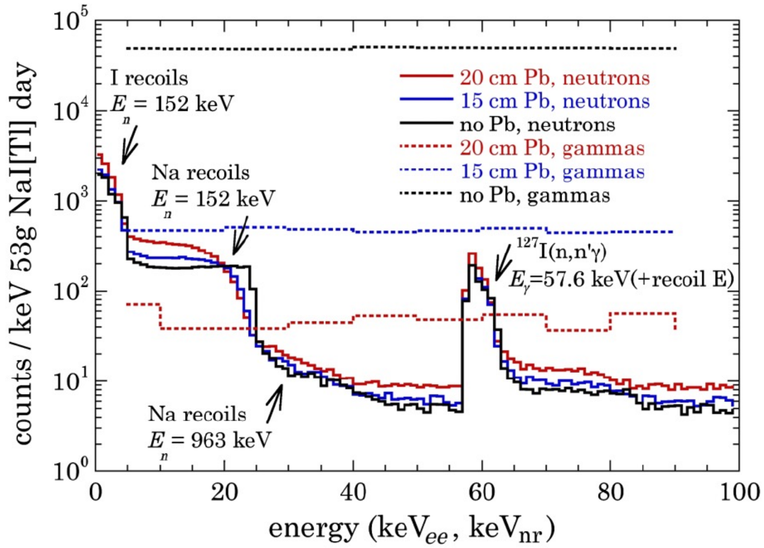
high threshold, large crystal (dominated by multiple scattering)

Quenching factor characterization: the key ingredient

PRL **110,** 211101 (2013)

Applications of an ^{88}Y/Be Photoneutron Calibration Source to Dark Matter and Neutrino Experiments

J. I. Collar*



convenient technique
(but you must trust your simulations)

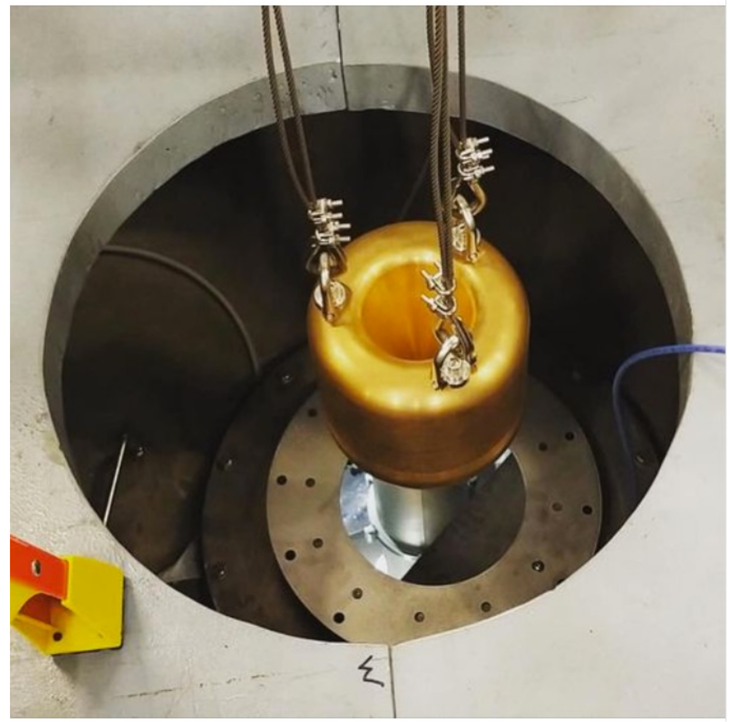
LZ added a new photo to the album: **A to Z of LZ**.
May 4, 2020 ·

Y is for YBe or Yttrium Beryllium!

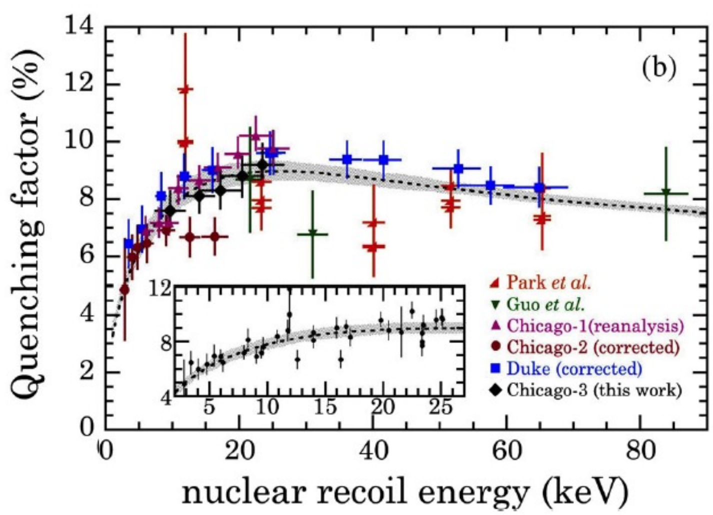
LZ has a special neutron source for calibrations made from the elements yttrium and beryllium that produces almost monoenergetic neutrons. The yttrium decays and releases a gamma ray, which interacts with the beryllium to produce a single neutron of around 200keV. These low energy neutrons are useful for calibrating nuclear recoils within the expected dark matter energy range.

The YBe source sits inside a tungsten shield (a mock up is shown in gold) to absorb the gamma rays, since we only want neutrons to get to the detector. This is lowered down to the top of the detector through a special port on top of the water tank.

Calibration sources like this are essential for understanding what dark matter looks like in LZ!



Quenching factor characterization: the key ingredient

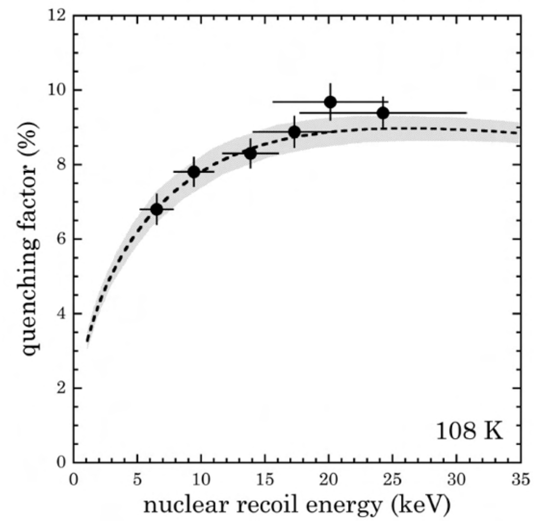


PHYSICAL REVIEW D **100**, 033003 (2019)

Response of CsI[Na] to nuclear recoils: Impact on coherent elastic neutrino-nucleus scattering

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

Went in hoping for a surprise…
(massive rise in low-E QF for α's)



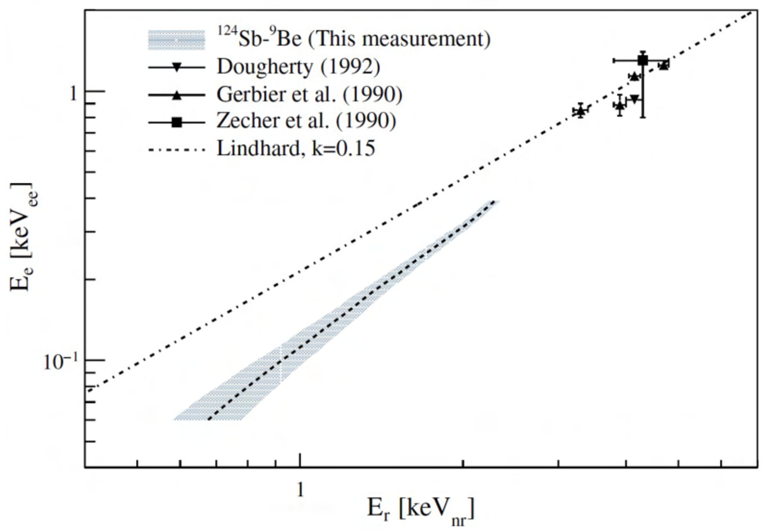
PHYSICAL REVIEW C **104**, 014612 (2021)

Response of undoped cryogenic CsI to low-energy nuclear recoils

C.M. Lewis* and J.I. Collar

Physics-based model (Birks + kinematic cutoff) works here (the exception)

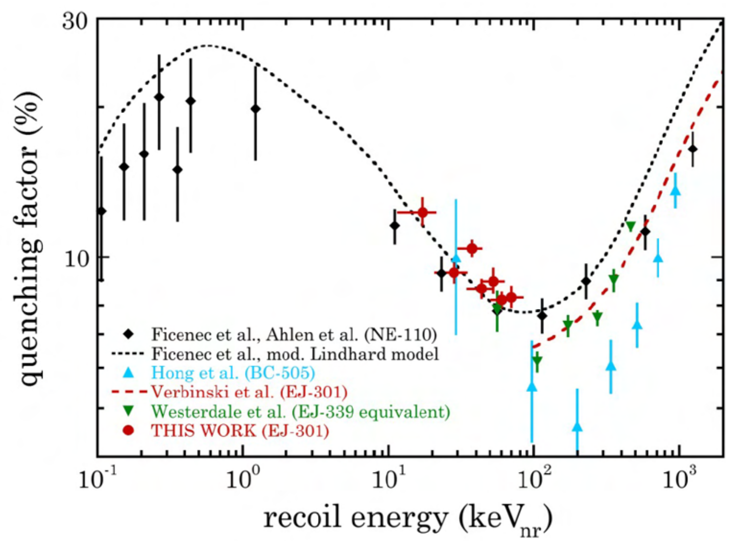
Quenching factor characterization: the key ingredient



PHYSICAL REVIEW D **94**, 082007 (2016)

Measurement of the ionization produced by sub-keV silicon nuclear recoils in a CCD dark matter detector

A. E. Chavarria,[1,*] J. I. Collar,[1] J. R. Peña,[1] P. Privitera,[1] A. E. Robinson,[1,2] B. Scholz,[1] C. Sengul,[1] J. Zhou,[1] J. Estrada,[2] F. Izraelevitch,[2] J. Tiffenberg,[2] J. R. T. de Mello Neto,[3] and D. Torres Machado[3]



PHYSICAL REVIEW C **98**, 045802 (2018)

Liquid scintillator response to proton recoils in the 10–100 keV range

C. Awe,[1] P. S. Barbeau,[1] J. I. Collar,[2,*] S. Hedges,[1] and L. Li[1]

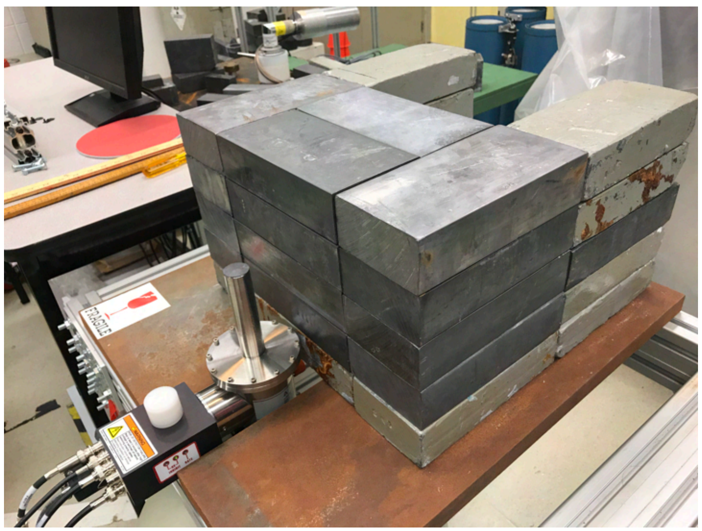
anything goes for the QF at sub-keV energies?

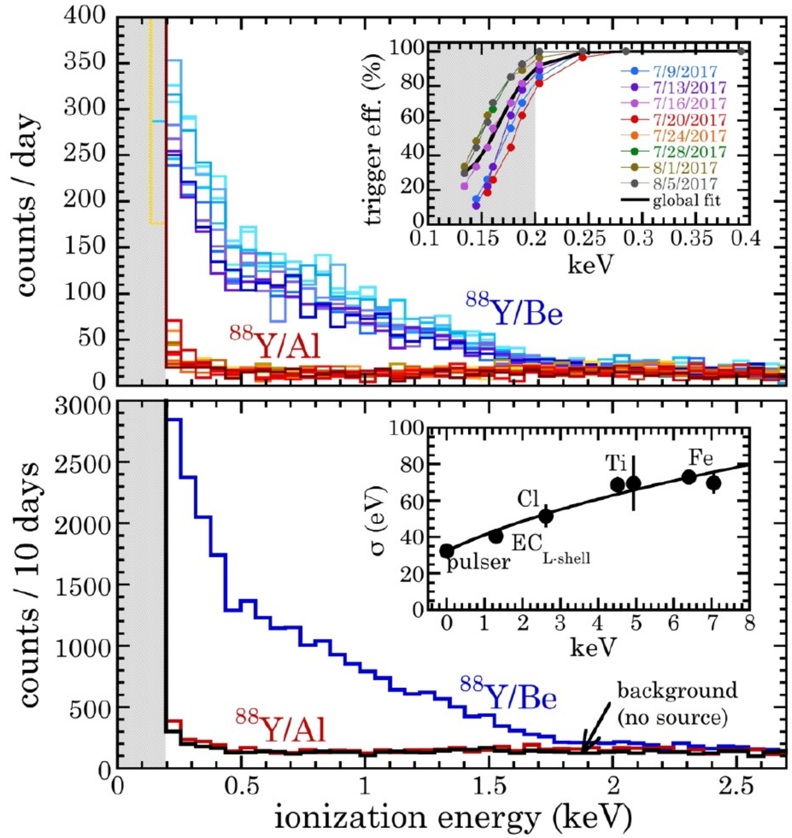
Quenching factor characterization: the key ingredient

PHYSICAL REVIEW D **103,** 122003 (2021)

Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis





Improved detector:

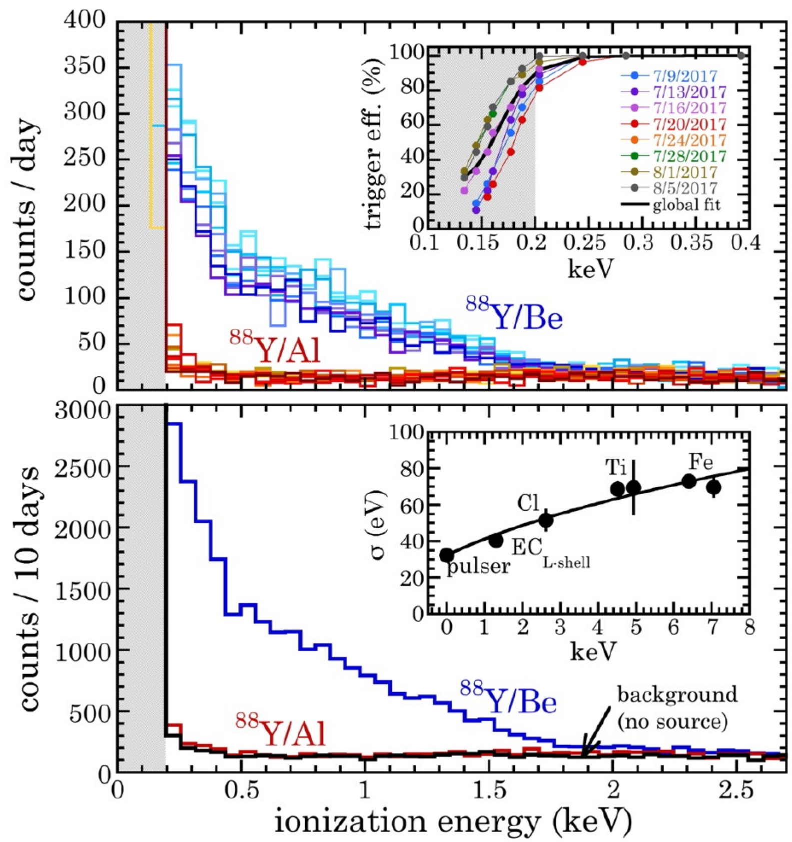
- x5 lower threshold
- excellent E resolution
- 1 cm^3 → dominated by single recoils
- n-type (no dead + transition layers)

1) photoneutron sources

PHYSICAL REVIEW D **103**, 122003 (2021)

Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

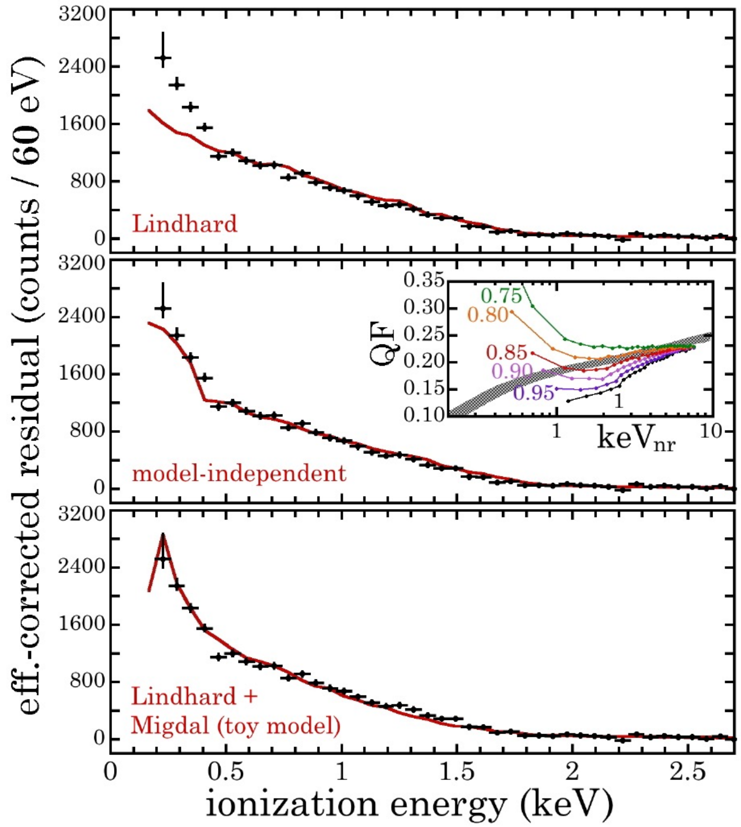


1) photoneutron sources

PHYSICAL REVIEW D **103**, 122003 (2021)

Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

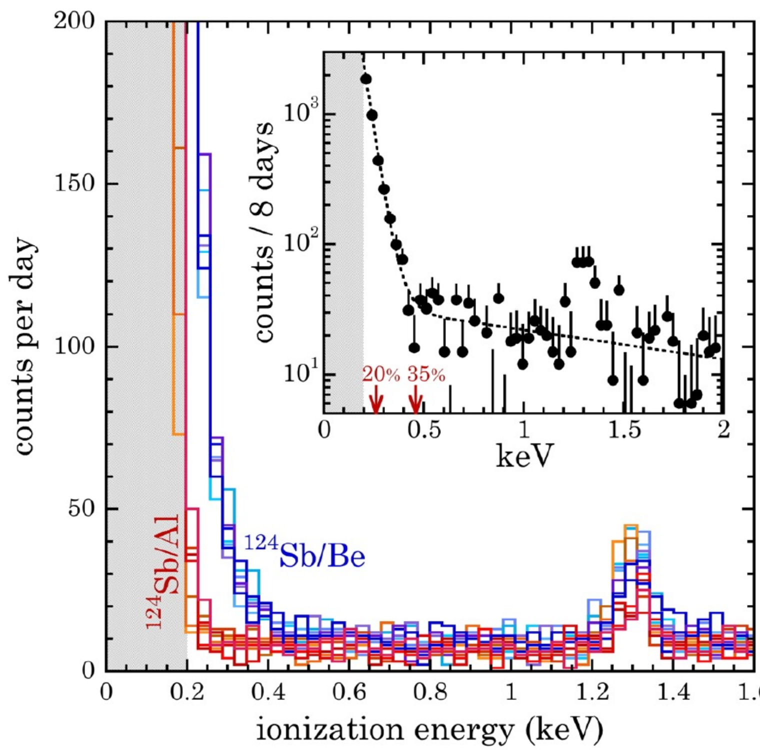


1) photoneutron sources

PHYSICAL REVIEW D **103,** 122003 (2021)

Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis



2) recoils from n_{th} capture

PHYSICAL REVIEW D **103,** 122003 (2021)

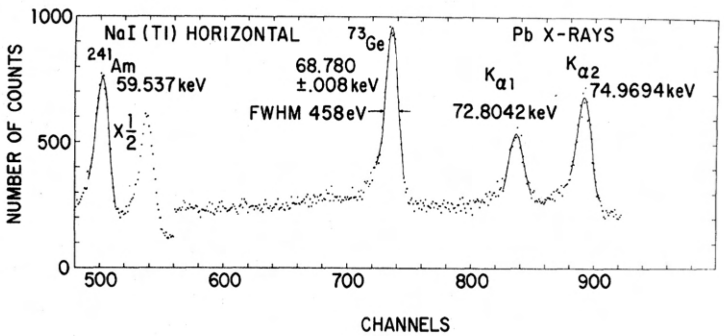
Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

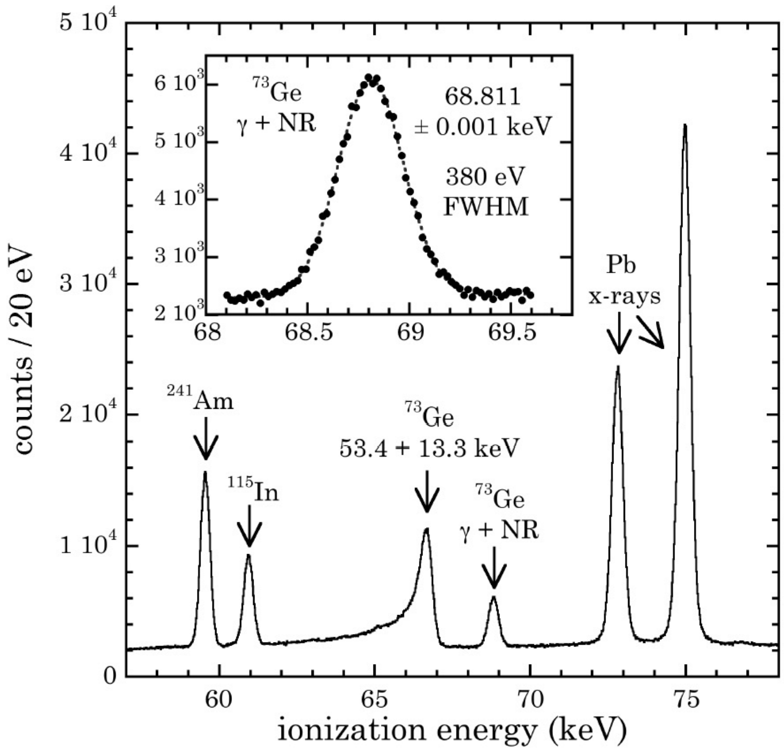
PHYSICAL REVIEW A VOLUME 11, NUMBER 4 APRIL 1975

Energy lost to ionization by 254-eV ^{73}Ge atoms stopping in Ge†

K. W. Jones and H. W. Kraner



notice two orders of magnitude difference
in statistics of calibration peaks,
tails in Ge(Li) peaks…

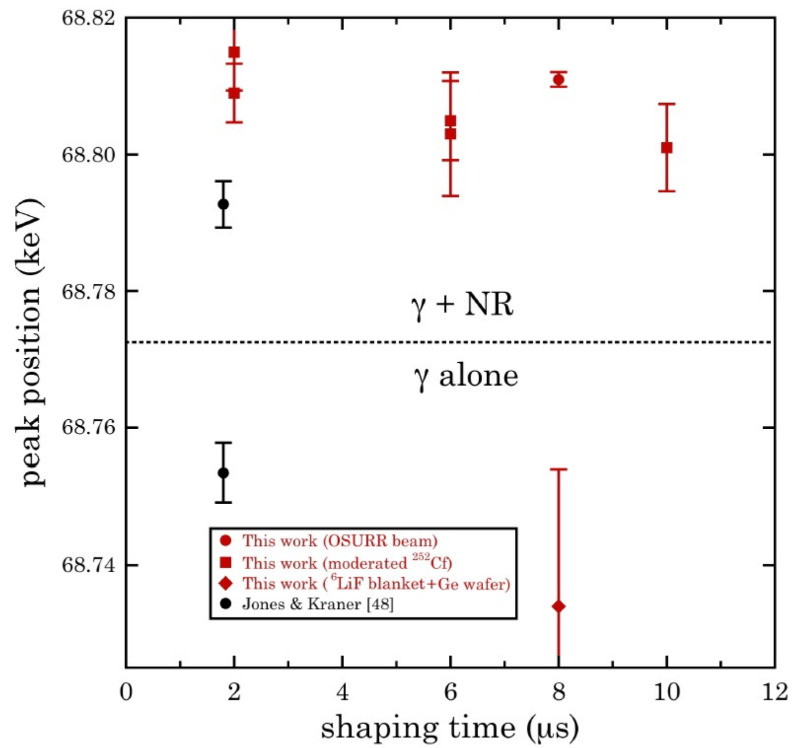


2) recoils from n_{th} capture

PHYSICAL REVIEW D **103,** 122003 (2021)

**Germanium response to sub-keV nuclear recoils:
A multipronged experimental characterization**

J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

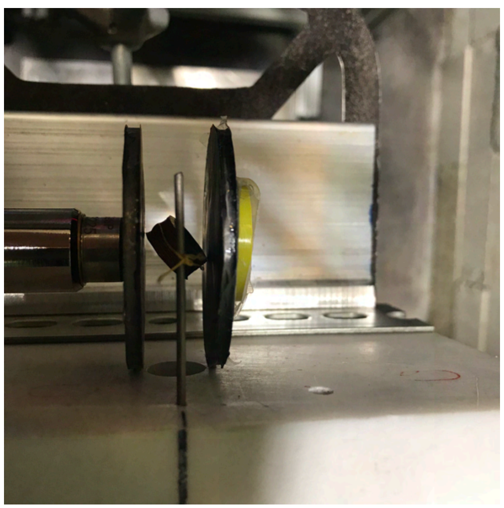


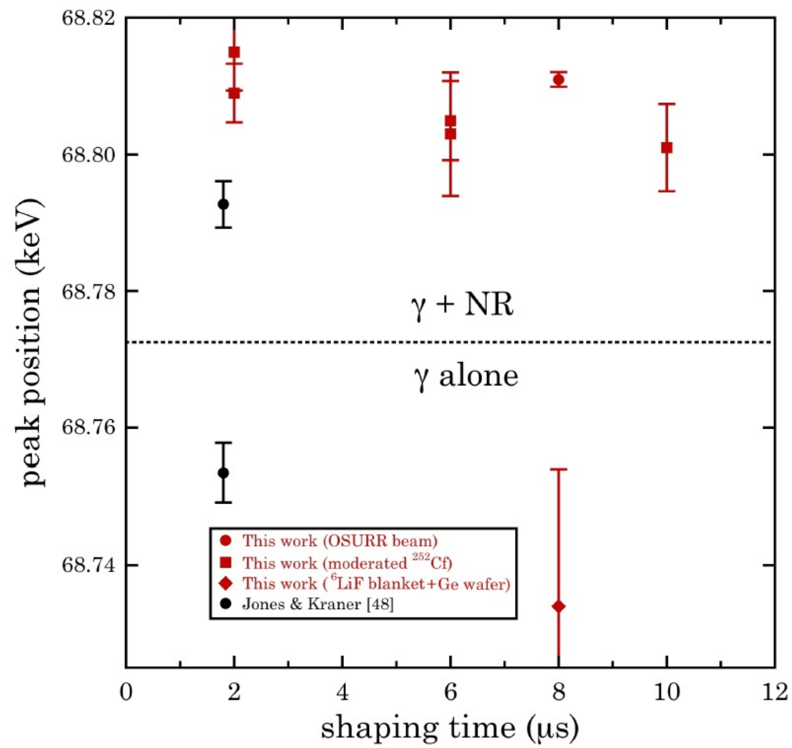
2) recoils from n_{th} capture

PHYSICAL REVIEW D **103,** 122003 (2021)

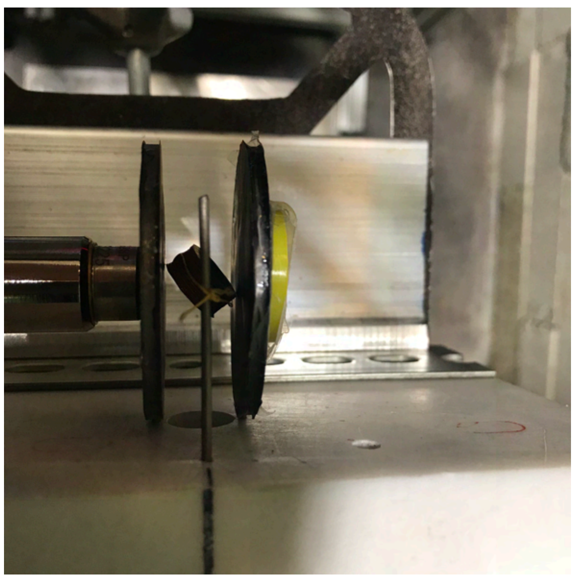
**Germanium response to sub-keV nuclear recoils:
A multipronged experimental characterization**

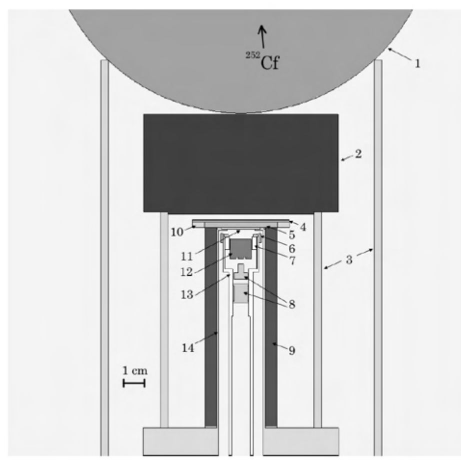
J. I. Collar,* A. R. L. Kavner, and C. M. Lewis

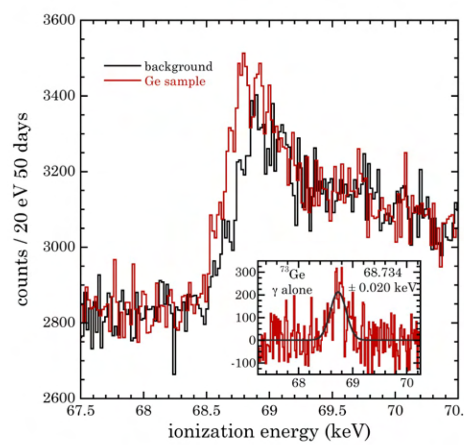




2) recoils from n_{th} capture





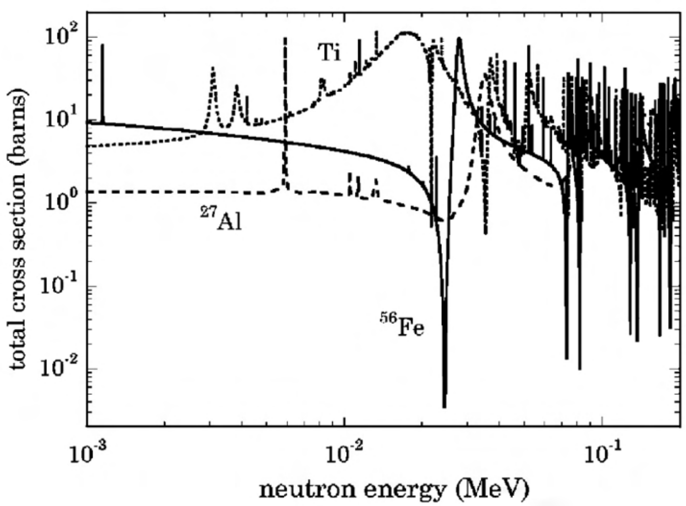


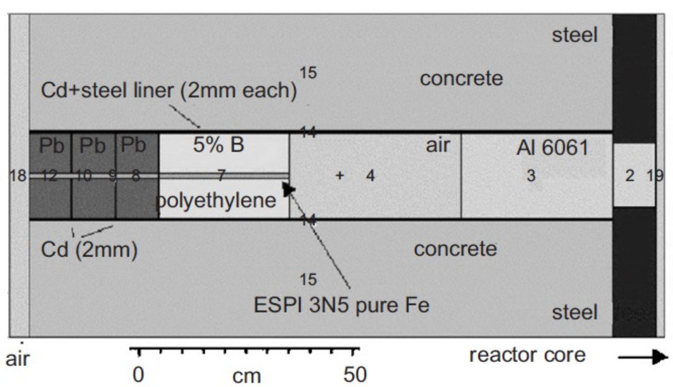
3) recoils from Fe filter

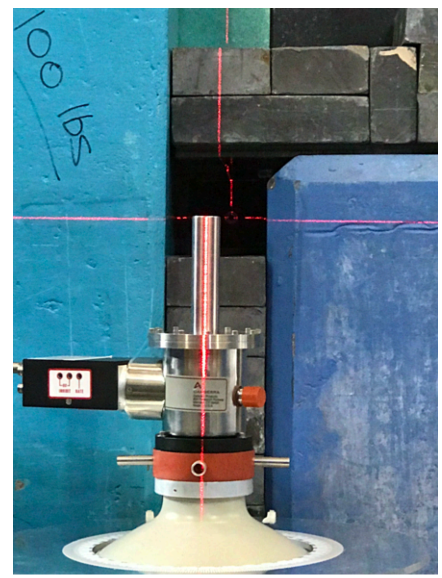
Nuclear Instruments and Methods in Physics Research A 574 (2007) 385–391

Design and characterization of a neutron calibration facility for the study of sub-keV nuclear recoils

P.S. Barbeau[a], J.I. Collar[a,*], P.M. Whaley[b]





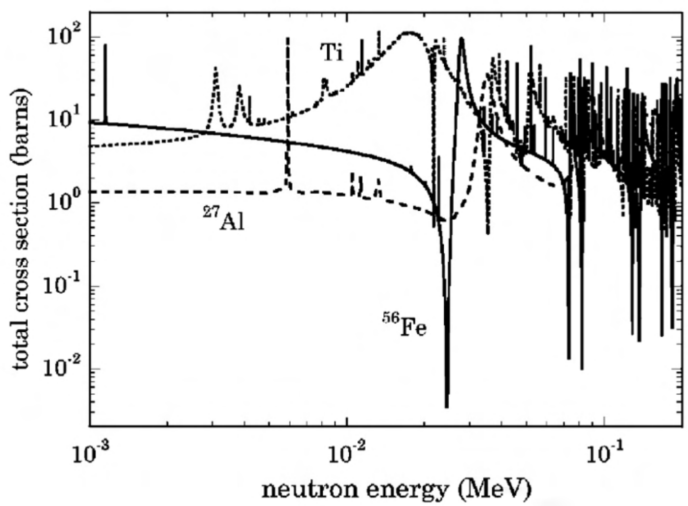


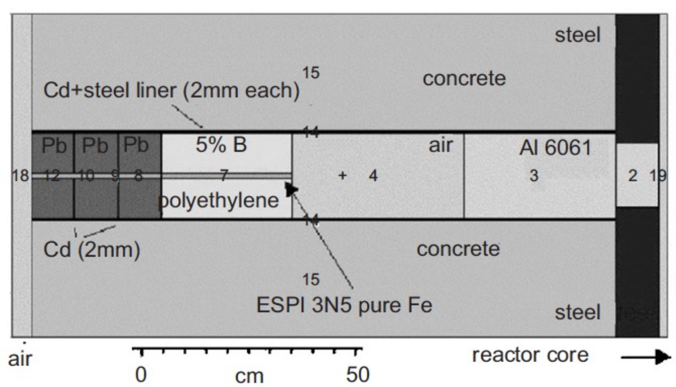
3) recoils from Fe filter

Nuclear Instruments and Methods in Physics Research A 574 (2007) 385–391

Design and characterization of a neutron calibration facility for the study of sub-keV nuclear recoils

P.S. Barbeau[a], J.I. Collar[a,*], P.M. Whaley[b]



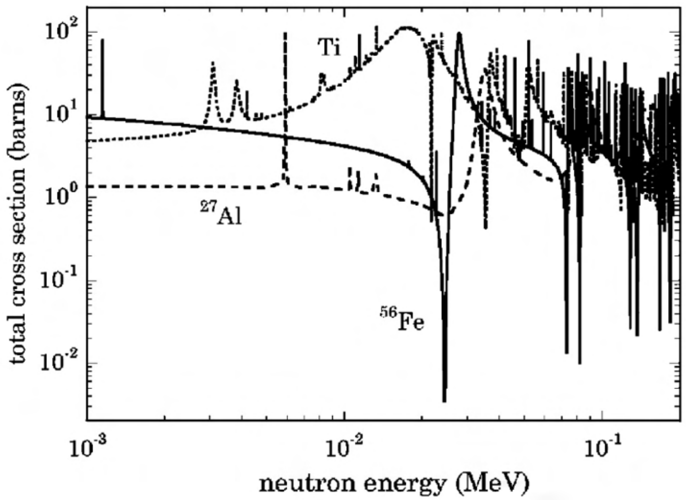


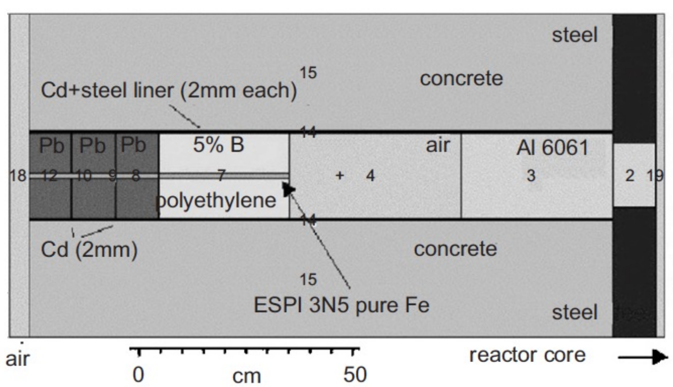
3) recoils from Fe filter

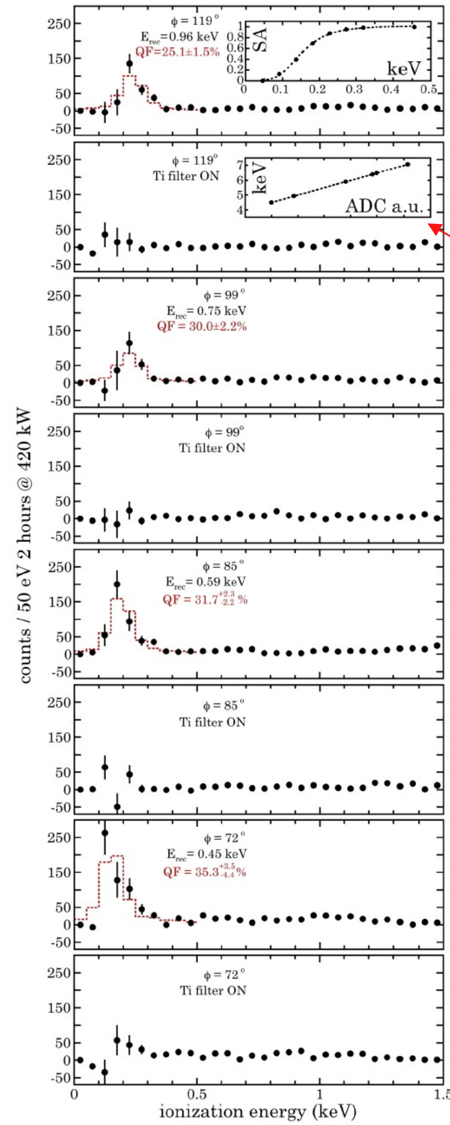
Nuclear Instruments and Methods in Physics Research A 574 (2007) 385–391

Design and characterization of a neutron calibration facility for the study of sub-keV nuclear recoils

P.S. Barbeau[a], J.I. Collar[a,*], P.M. Whaley[b]



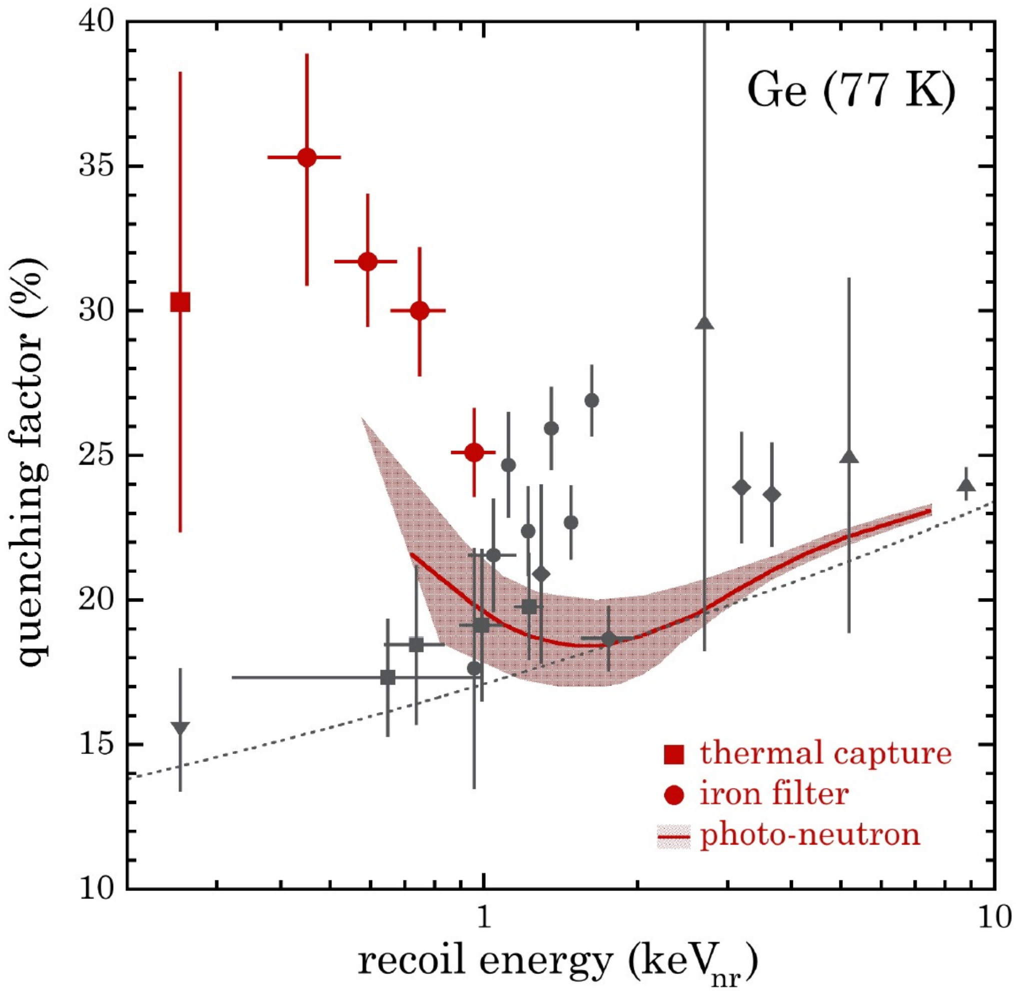




Due attention paid to energy calibration (α PIXE)

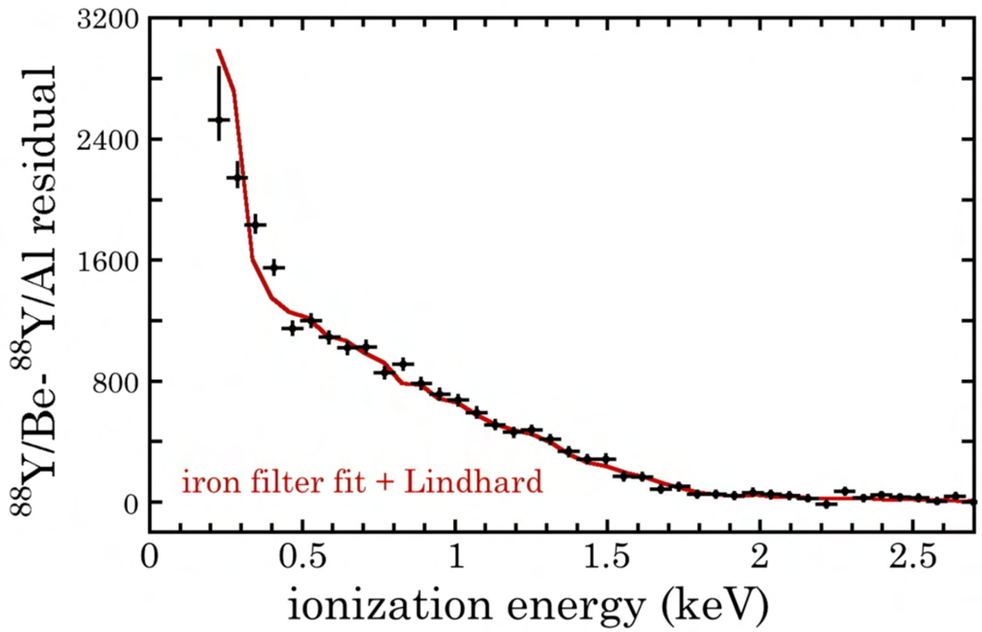
This is critical, and not always done…

Et voila



Ge (77 K)
thermal capture
iron filter
photo-neutron
quenching factor (%)
recoil energy (keV$_{nr}$)
40
35
30
25
20
15
10
1
10

Internal consistency x-checks



(going back full-circle to "that ain't Lindhard")

Also tested against earlier result with higher (x 5) threshold

Paging Mr. Migdal?

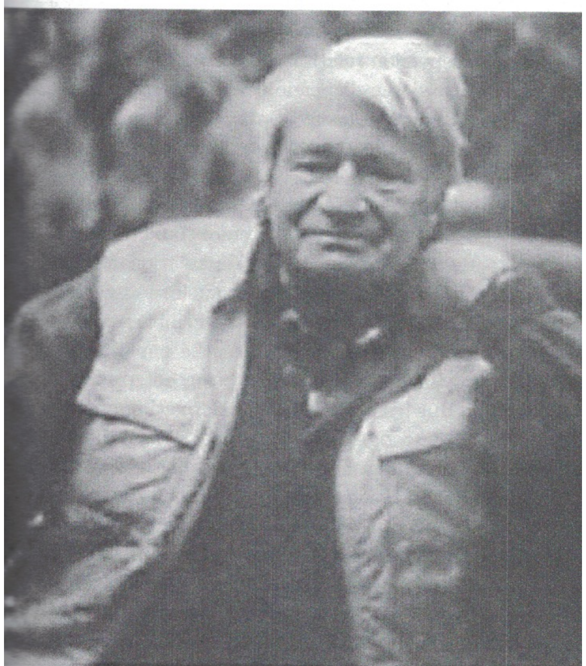
1941: A.B. Migdal, J. Phys. USSR 4 449

1958: Landau and Lifshitz Vol. 3: Quantum Mechanics, sec. 41:

PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

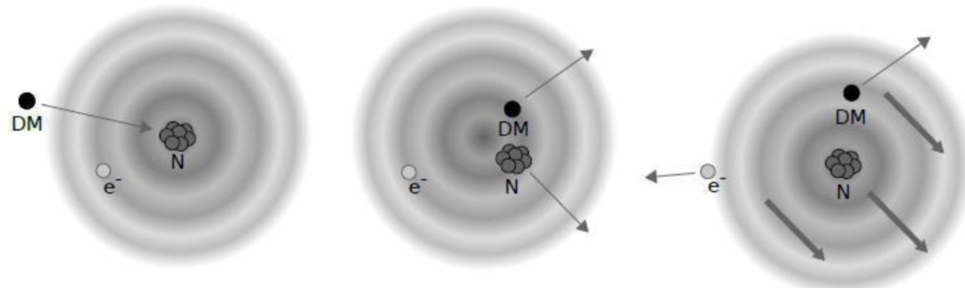
~2000: DAMA invokes Migdal, "Migdal" becomes a dirty word.

"Migdal may be late, but Migdal never lets you down"



A.B. Migdal

From B. Ioffe "Atom Projects: Events and People"



(it would not come as a big surprise...)

PRL 108, 243201 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

First Measurement of Pure Electron Shakeoff in the β Decay of Trapped $^6He^+$ Ions

C. Couratin,[1] Ph. Velten,[1] X. Fléchard,[1,*] E. Liénard,[1] G. Ban,[1] A. Cassimi,[2] P. Delahaye,[3] D. Durand,[1] D. Hennecart,[2] F. Mauger,[1] A. Méry,[2] O. Naviliat-Cuncic,[1,4] Z. Patyk,[5] D. Rodríguez,[6] K. Siegień-Iwaniuk,[5] and J-C. Thomas[3]

PHYSICAL REVIEW A 97, 023402 (2018)

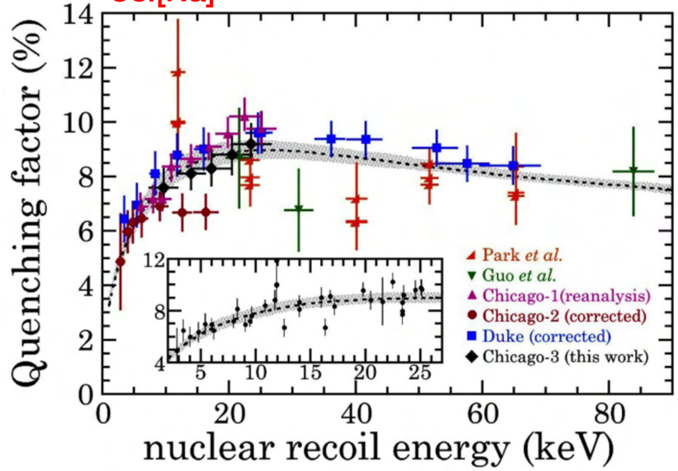
Electron shakeoff following the β^+ decay of $^{19}Ne^+$ and $^{35}Ar^+$ trapped ions

X. Fabian,[1,*] X. Fléchard,[1,†] B. Pons,[2] E. Liénard,[1] G. Ban,[1] M. Breitenfeldt,[3,‡] C. Couratin,[1] P. Delahaye,[4] D. Durand,[1] P. Finlay,[3] B. Guillon,[1] Y. Lemière,[1] F. Mauger,[1] A. Méry,[5] O. Naviliat-Cuncic,[1,6] T. Porobic,[3] G. Quéméner,[1] N. Severijns,[3] and J.-C. Thomas[4]

Toto, we’re not in Kansas anymore:

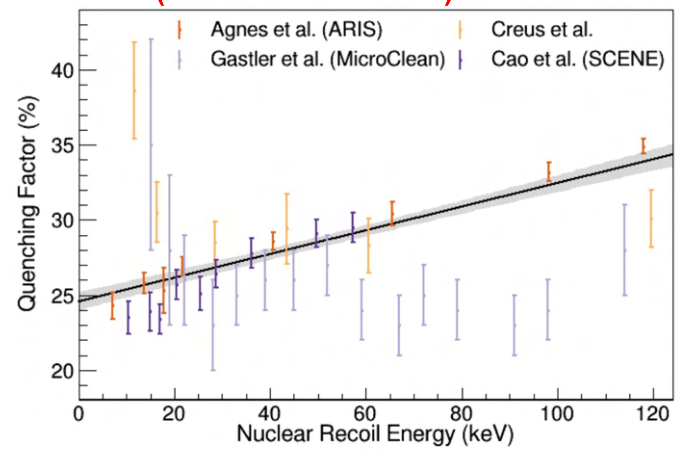
for CEνNS studies, the QF is the crux

CsI[Na]



5% uncertainty in 5-25 keV ROI
Physics-based model (Birks + kinematic threshold)

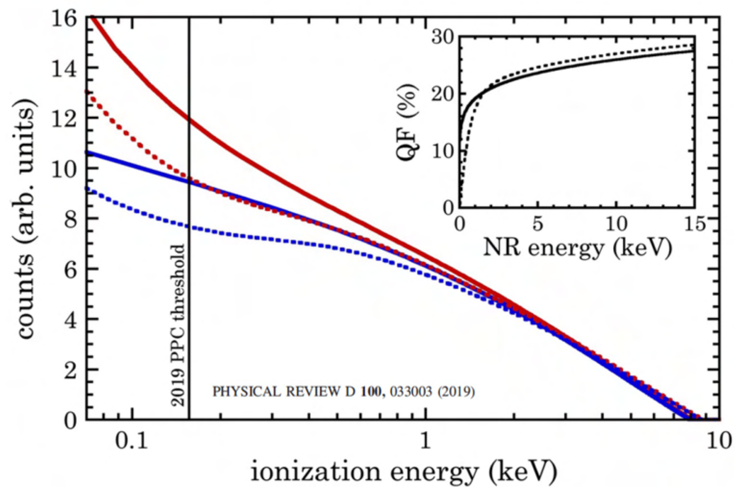
LAr (COHERENT collab.)



2% uncertainty in >20 keV ROI claimed (?)
Linear fit (because “it isn’t completely unreasonable”)

We are not looking for WIMPs: we have predictable signals, from particles known to exist.

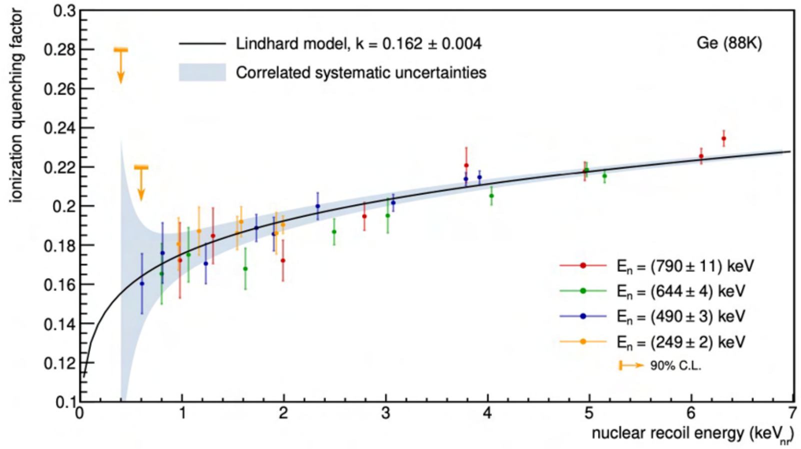
Time to start taking this subject seriously… it can make the difference between discoveries and embarrassment.



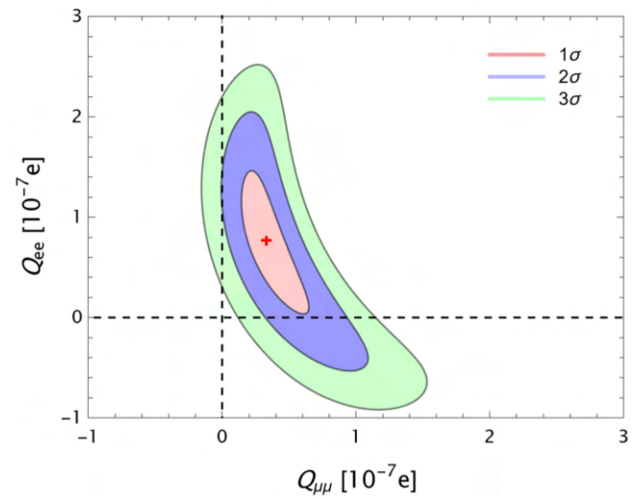
HPGe

Recent developments

arXiv:2202.03754v1



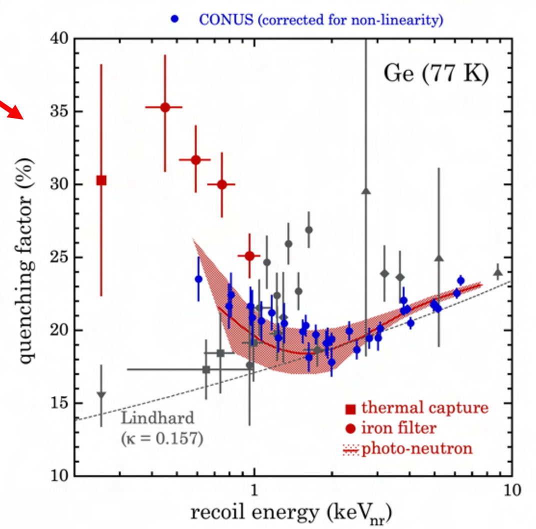
arXiv:2201.10578v1



→ underestimated uncertainty in energy scale.

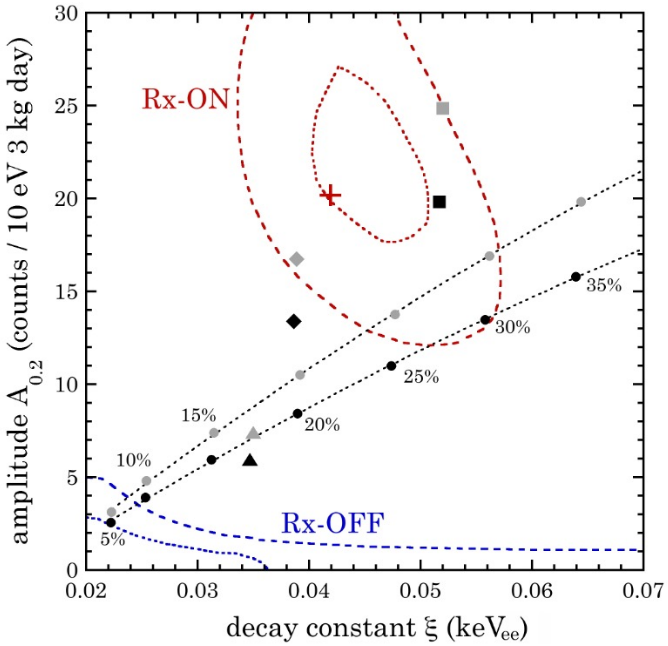
→ negative non-linearity (50% @ 100 eV_{ee}) unaccounted for.

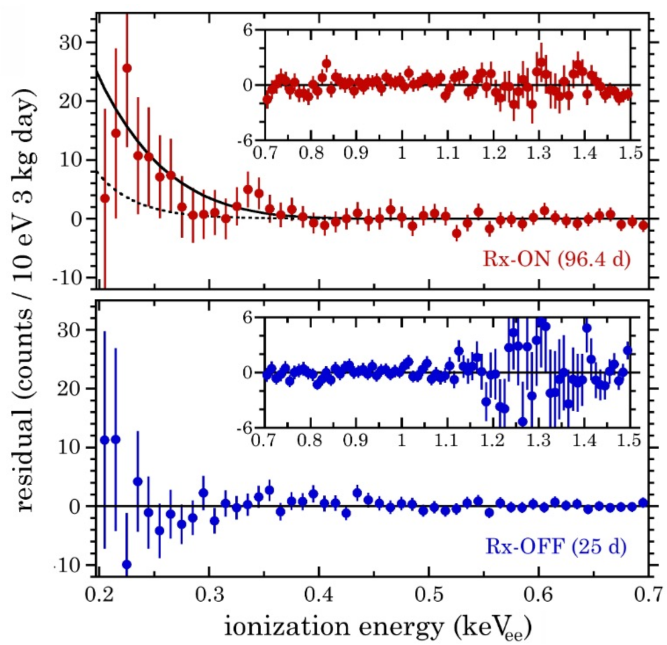
See arXiv:2203.00750v2



3.5 σ for millicharged ν's or use of a biased QF?

Returning to Dresden-II





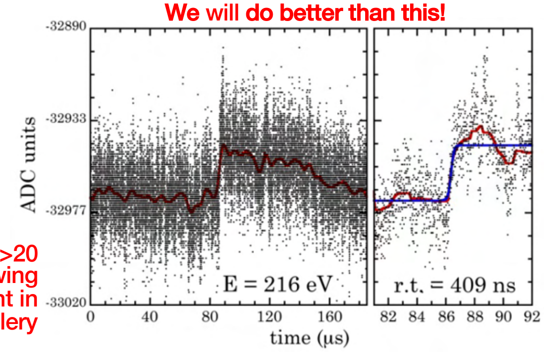
arXiv:2202.09672v1

Suggestive evidence for coherent elastic neutrino-nucleus scattering from reactor antineutrinos

J. Colaresi[1], J.I. Collar[2,*], T.W. Hossbach[3], C.M. Lewis[2], and K.M. Yocum[1]
[1]*Mirion Technologies Canberra, 800 Research Parkway, Meriden, CT, 06450, USA*
[2]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA and*
[3]*Pacific Northwest National Laboratory, Richland, Washington 99354, USA*

(Dated: February 22, 2022)

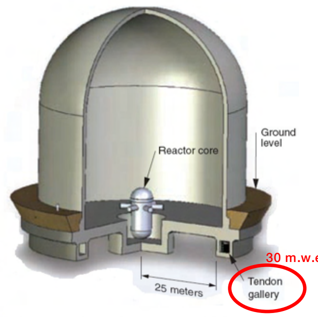
We will do better than this!

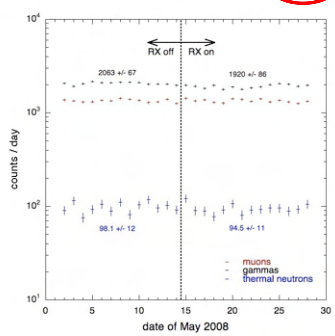


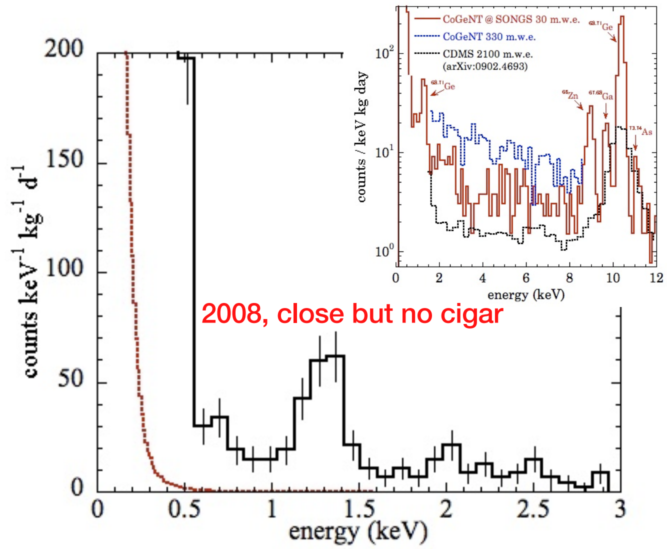
signal/bckg >20 expected following redeployment in tendon gallery

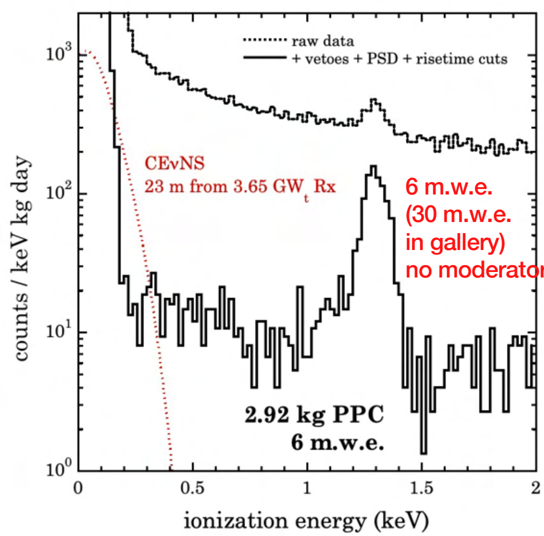
Towards a *precision* measurement of reactor CEνNS

Vandellòs deployment approved by Spanish ENUSA
Braidwood deployment also TBD









Negligible risk following Dresden-II and 2008 SONGS PPC deployment in ***identical*** tendon gallery.

A signal-to-background of > × 20 (present is ¼) is firmly expected.

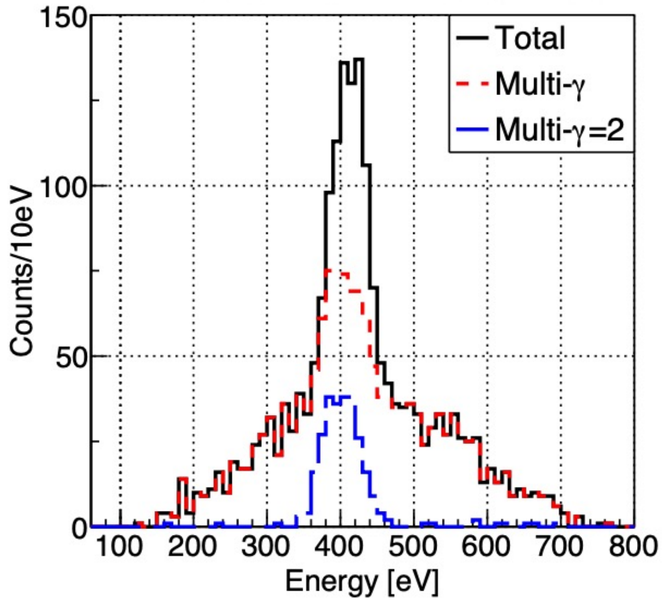
There is no peace for the living

(upcoming QF work at OSURR thermal beam)

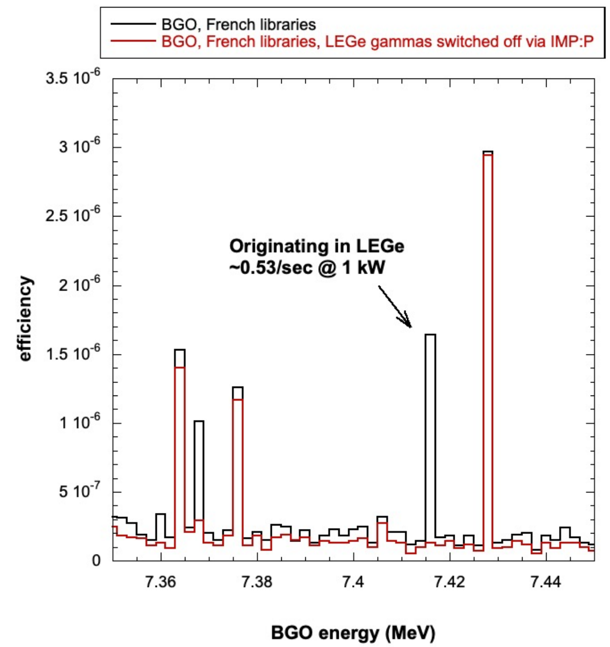
Calibration of nuclear recoils at the 100 eV scale using neutron capture

L. Thulliez,[a] D. Lhuillier,[a,*] F. Cappella,[b] N. Casali,[b] R. Cerulli,[c,d] A. Chalil,[a] A. Chebboubi,[e] E. Dumonteil,[a] A. Erhart,[f] A. Giuliani,[g] F. Gunsing,[a] E. Jericha,[h] M. Kaznacheeva,[f] A. Kinast,[f] A. Langenkämper,[f] T. Lasserre,[a,f] A. Letourneau,[a] O. Litaize,[e] P. de Marcillac,[g] S. Marnieros,[g] T. Materna,[a] B. Mauri,[a] E. Mazzucato,[a] C. Nones,[a] T. Ortmann,[f] L. Pattavina,[d,i] D.V. Poda,[g] R. Rogly,[a] N. Schermer,[f] O. Serot,[e] G. Soum,[a] L. Stodolsky,[j] R. Strauss,[f] M. Vignati,[b,k] M. Vivier,[a] V. Wagner[f] and A. Wex[f]

2021 JINST 16 P07032



(should be possible w/ Si as well)

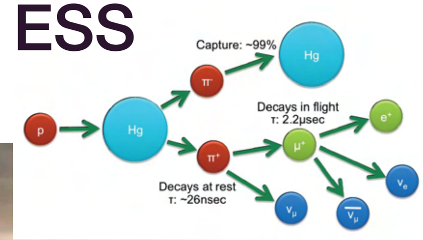


Will provide dramatic test of Lindhard in HPGe at 0.4 keVnr

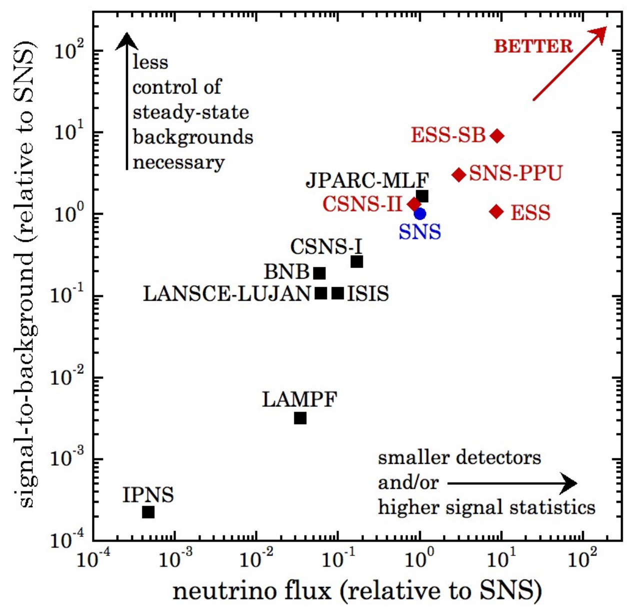
In addition to this:

→ attempt to reduce error bar in 0.25 keVnr datapoint
→ improved analysis of Y/Be data with MCMC

Looking at the future: CEνNS @ ESS



- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!



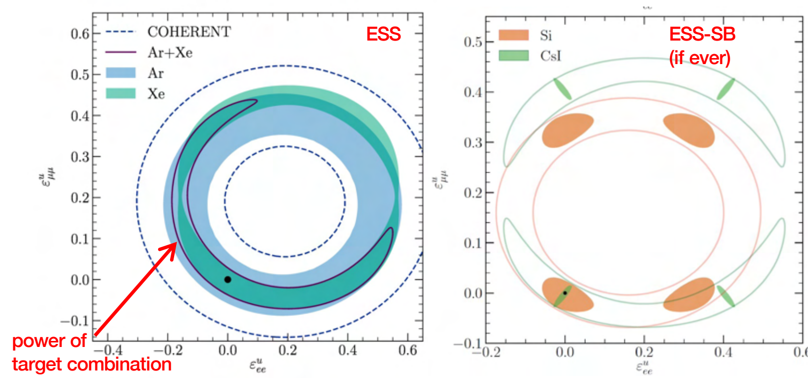
Looking at the future: CEνNS @ ESS

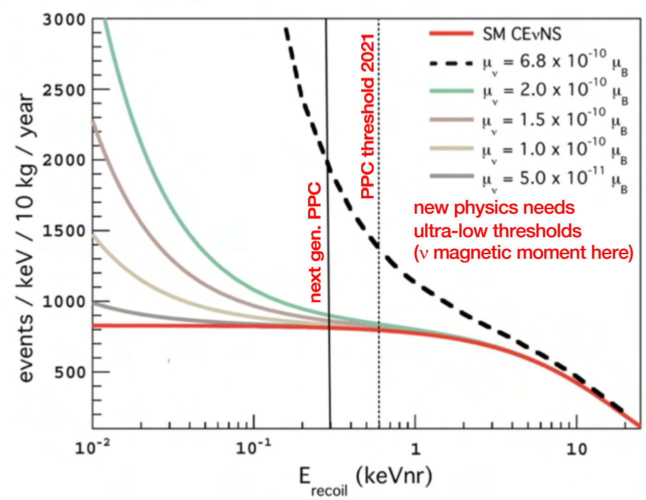
- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

JHEP 02 (2020) 123

Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

D. Baxter,[1] J.I. Collar,[1,*] P. Coloma,[2,†] C.E. Dahl,[3,4] I. Esteban,[5,‡] P. Ferrario,[6,7,§] J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1] F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]



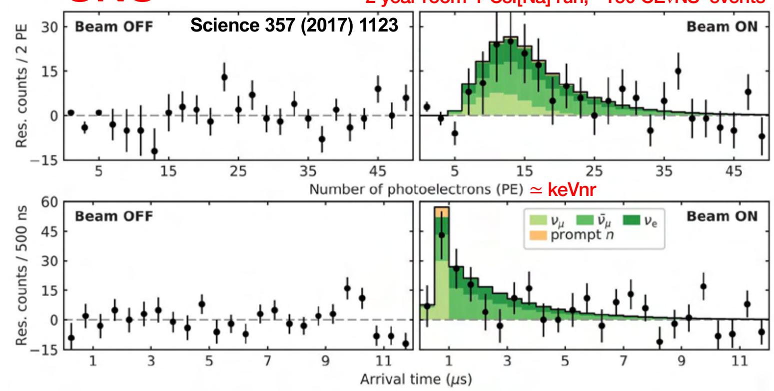


Looking at the future: CEνNS @ ESS

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV$_{nr}$ thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

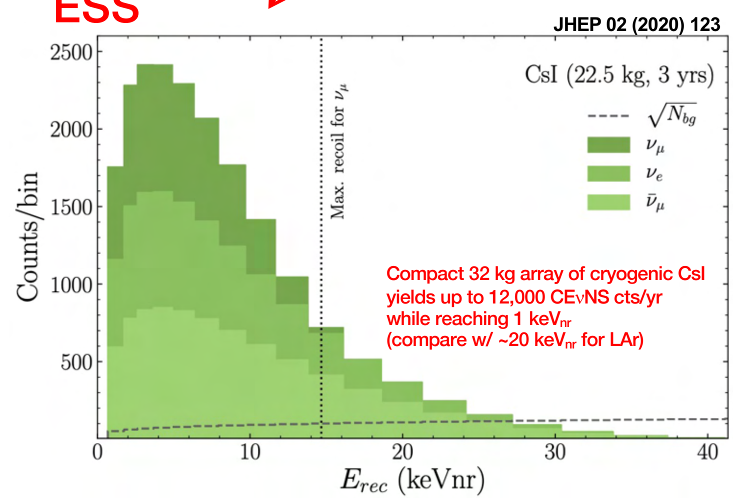
SNS

2 year room-T CsI[Na] run, ~150 CEνNS events



~×10 ν flux
~×10 low-E signal acceptance

ESS

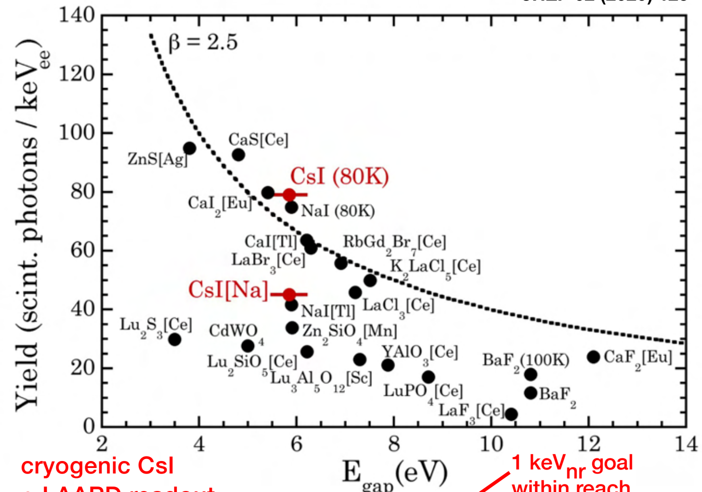


Looking at the future: CEνNS @ ESS

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance ($1\ \mathrm{keV_{nr}}$ thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

cryo CsI

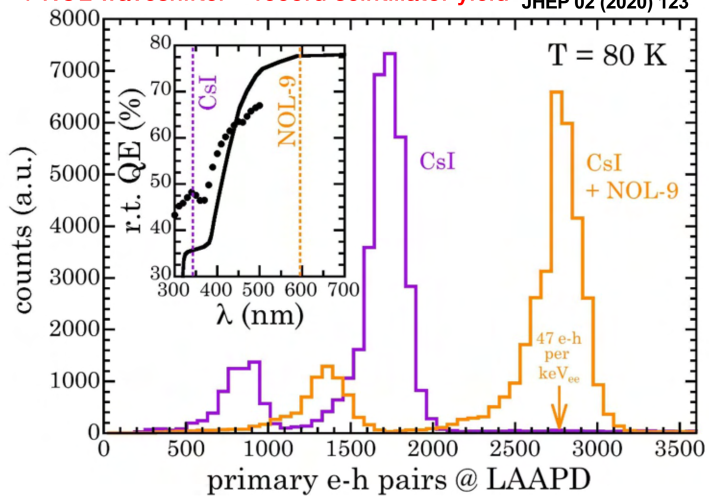
JHEP 02 (2020) 123



cryogenic CsI
+ LAAPD readout
+ NOL waveshifter = record scintillator yield

$1\ \mathrm{keV_{nr}}$ goal within reach

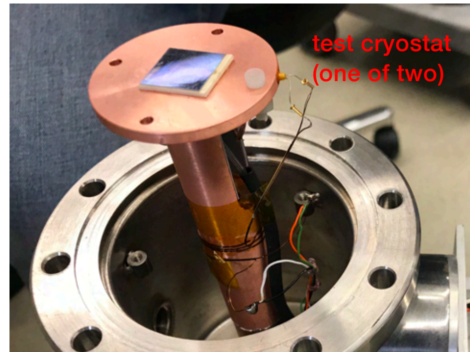
JHEP 02 (2020) 123

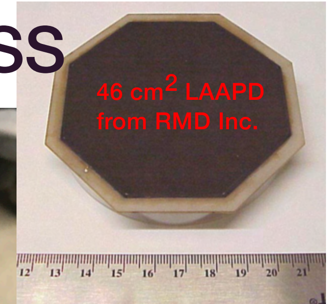


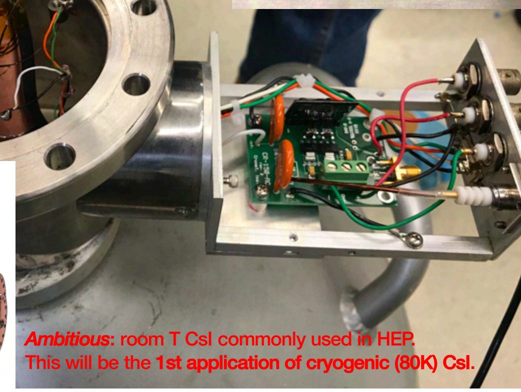
Looking at the future: CEνNS @ ESS

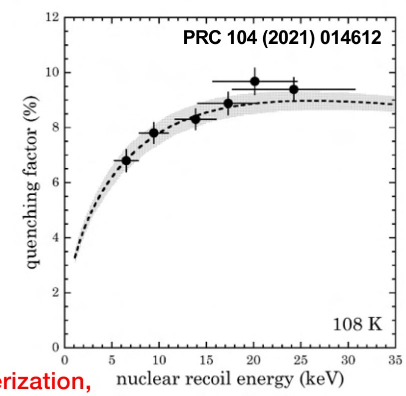
- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

cryo CsI

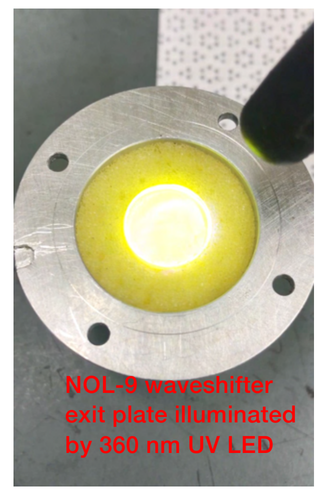








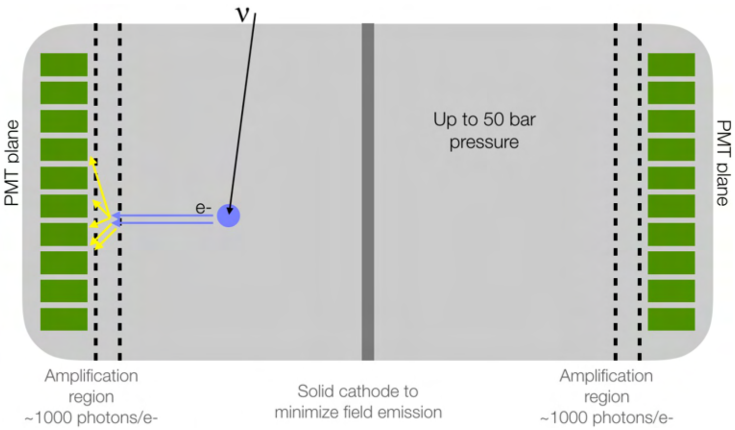
full characterization,
long-term stability,
low-E QF, already studied
(but **A LOT** more work planned)



Looking at the future: CEνNS @ ESS

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

HP Gas



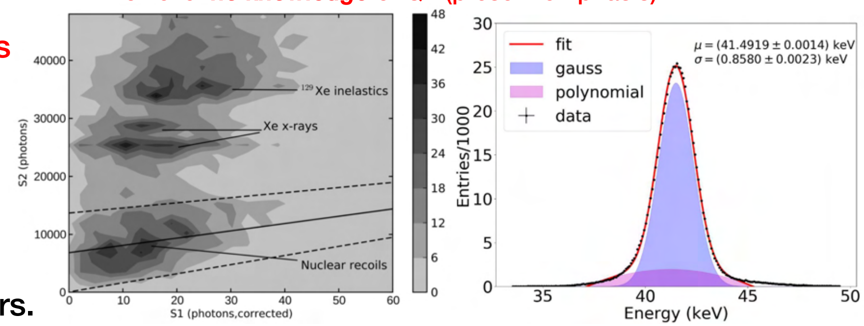
HP gas funding already secured via Ikerbasque Foundation and ERC Horizon (GaνESS) + Marie Curie (νPESS) proposals

Looking at the future: CEνNS @ ESS

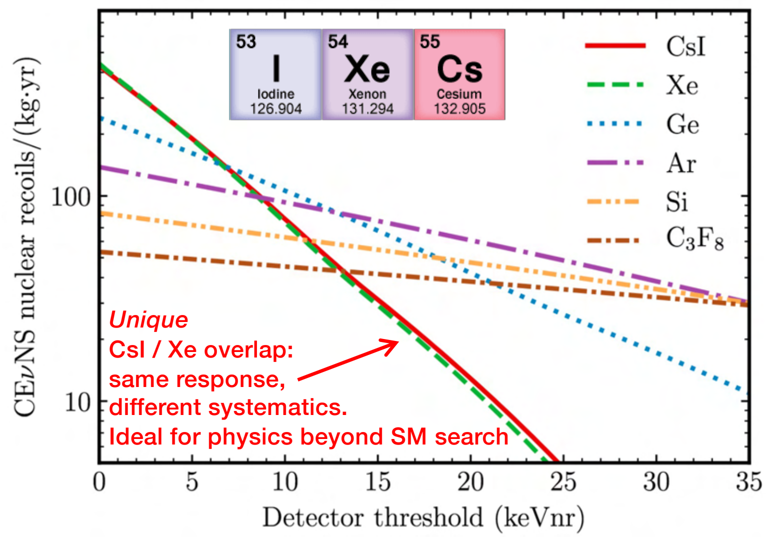
- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

HP Gas

Excellent promise of HP gas in this new area:
possible ER discrimination, E resolution, ability to swap targets.
However ***no knowledge*** of QF (present emphasis)



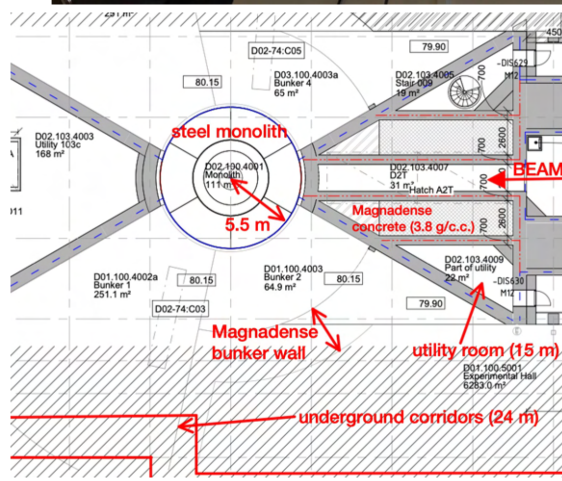
JHEP 02 (2020) 123



Looking at the future: CEνNS @ ESS

Close collaboration with ESS personnel vis-a-vis specific issues (site selection, neutron simulations, official approval process, timing). Eight ESS personnel co-signers of 61-author LOI under review. Strong support from Directorate. Part of upcoming White Paper on Fundamental Physics at the ESS.

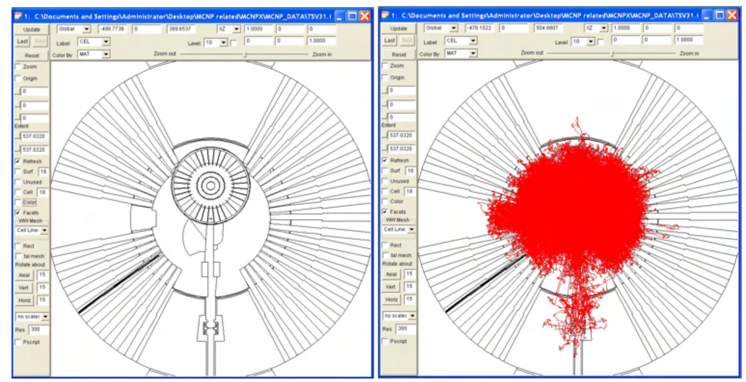
- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 $\mathrm{keV_{nr}}$ thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!



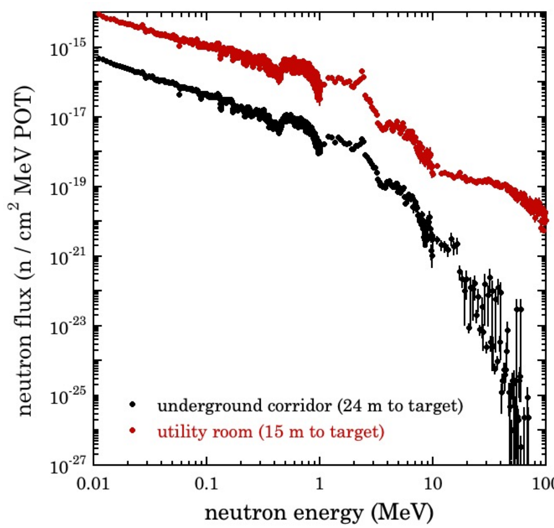
Looking at the future: CEνNS @ ESS

Close collaboration with ESS personnel vis-a-vis specific issues (site selection, neutron simulations, official approval process, timing). Eight ESS personnel co-signers of 61-author LOI under review. Strong support from Directorate. Part of upcoming White Paper on Fundamental Physics at the ESS.

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!



MCNPX/GEANT
massively-parallel neutron transport simulations
(Ben Gurion / Chicago / DIPC / ESS / Lund paper in preparation)



Looking at the future: CEνNS @ ESS

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.
- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors.
- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors.
- Concentrate instead on device performance (1 keV_{nr} thresholds) and understanding of their response (QF, quenching factor).
- Develop ***multiple*** technologies to meet challenge. Benefit from their synergies.
- Perfect timing vis-à-vis ESS start.
- Enthusiastic reception. Work (and flow of funding) has started!

Close collaboration with ESS personnel vis-a-vis specific issues (site selection, neutron simulations, official approval process, timing). Eight ESS personnel co-signers of 61-author LOI under review. Strong support from Directorate. Part of upcoming White Paper on Fundamental Physics at the ESS.

EUROPEAN SPALLATION SOURCE

Coherent Elastic Neutrino-Nucleus Scattering at the ESS

Expression of Interest

J.I. Collar,[e] J.J. Gomez-Cadenas,[d,g] F. Monrabal,[d,g] P. Privitera,[e] A. Algora,[j] L. Arazi,[m] F. Ballester,[k] D. Baxter,[e] C. Blanco,[e] M. Blennow,[q] F. Calviño,[n] G. Carlsson,[t] J. Cederkall,[t] P. Coloma,[j] C.E. Dahl,[c,f] D. Di Julio,[t,u] C. Domingo-Pardo,[j] T.J.C. Ekelöf,[x] I. Esteban,[b] R. Esteve,[k] M. Fallot,[s] E. Fernandez-Martinez,[p] P. Ferrario,[d,g] H.O.U. Fynbo,[v] P. Golubev,[t] M.C. Gonzalez-Garcia,[a,b,h] A.M. Heinz,[w] J. A. Hernando,[i] P. Herrero,[d] V. Herrero,[k] P. Huber,[o] A.R.L. Kavner,[e] E.B. Klinkby,[u] C.M. Lewis,[e] M. Lindroos,[u] N. Lopez-March,[k] E. Lytken,[t] P.A.N. Machado,[f] M. Maltoni,[p] J. Martin-Albo,[j] T.M. Miller,[u] F.J. Mora,[K] G. Muhrer,[u] J. Muñoz-Vidal,[d] E. Nacher,[J] T. Nilsson,[w] P. Novella,[j] C. Peña-Garay,[l] K. Ramanathan,[e] J. Renner,[i] J. Rodriguez,[k] B. Rubio,[j] J. Salvado,[b] V. Santoro,[u] T. Schwetz,[r] J.L. Tain,[j] A. Takibayev,[u] A. Tarifeño-Saldivia,[n] J.F. Toledo,[k] U. Uggerhøj,[v] and L. Zanini[u]

[a] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook NY 11794-3849, USA*

[b] *Departament de Fisica Quàntica i Astrofisica, Institut de Ciències del Cosmos, Universitat de Barcelona, E-08028 Barcelona, Spain*

[c] *Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*

[d] *Donostia International Physics Center (DIPC), 20018 San Sebastián / Donostia, Spain*

[e] *Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*

[f] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

[g] *Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain*

[h] *Institucio Catalana de Recerca i Estudis Avancats (ICREA), Barcelona, Spain*

[i] *Instituto Gallego de Física de Altas Energías, Univ. de Santiago de Compostela, Santiago de Compostela, E-15782, Spain*

[j] *Instituto de Física Corpuscular (IFIC), CSIC & Universitat de Valencia, Paterna, E-46980, Spain*

[k] *Instituto de Instrumentación para Imagen Molecular (I3M), Centro Mixto CSIC - Universidad Politécnica de Valencia, Valencia, E-46022, Spain*

[l] *Laboratorio Subterráneo de Canfranc, Canfranc Estación, Huesca, E-22880, Spain*

[m] *Nuclear Engineering Unit, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer-Sheva, 8410501, Israel*

[n] *Universitat Politecnica de Catalunya, UPC, Intstitut de Tecniques Energetiques (INTE). Av. Diagonal 647, Barcelona, Spain*

[o] *Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*

[p] *Departamento de Fisica Teorica and Instituto de Fisica Teorica, IFT-UAM/CSIC, Universidad Autonoma de Madrid, Cantoblanco, 28049, Madrid, Spain*

[q] *Department of Physics, KTH Royal Institute of Technology, AlbaNova University Center, SE–106 91 Stockholm, Sweden*

[r] *Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany*

[s] *SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France*

[t] *Physics Department, Lund University, PO Box 118, 221 00 Lund, Sweden*

[u] *European Spallation Source, PO Box 176, SE-221 00 Lund, Sweden*

[v] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*

[w] *Department of Physics, Chalmers University of Technology, S-41296 Gothenburg, Sweden*

[x] *Department of Physics and Astronomy, Uppsala University, SE-752 37 Uppsala, Sweden.*