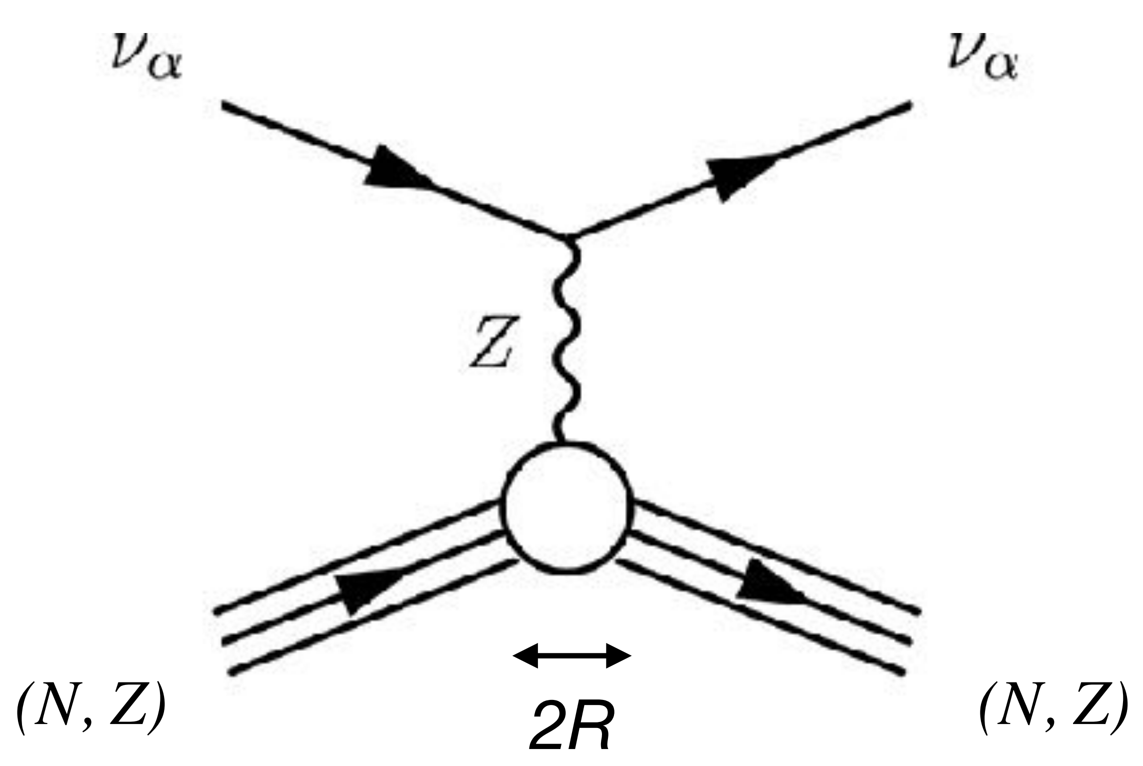
SAPIENZA
UNIVERSITÀ DI ROMA

INFN
Istituto Nazionale di Fisica Nucleare

CEνNS
coherent and elastic neutrino-nucleus scattering

Marco Vignati - 29 August 2023, TAUP 2023, Vienna

The process



Coherency:

$qR < 1,\ F(q^2) \to 1$

$E_\nu^{max}[\text{He}] \simeq 20$ MeV

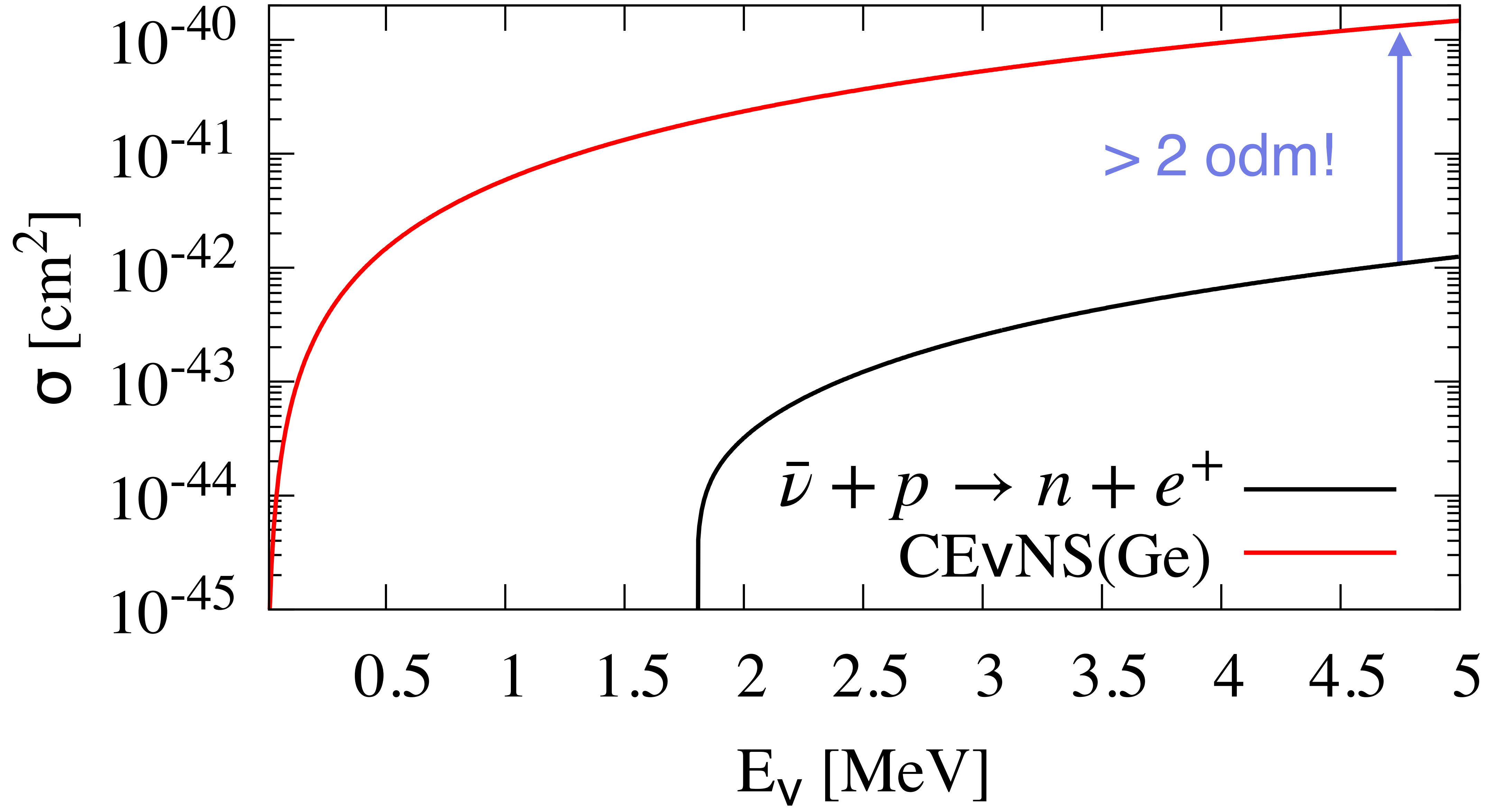
$E_\nu^{max}[\text{U}] \simeq 60$ MeV

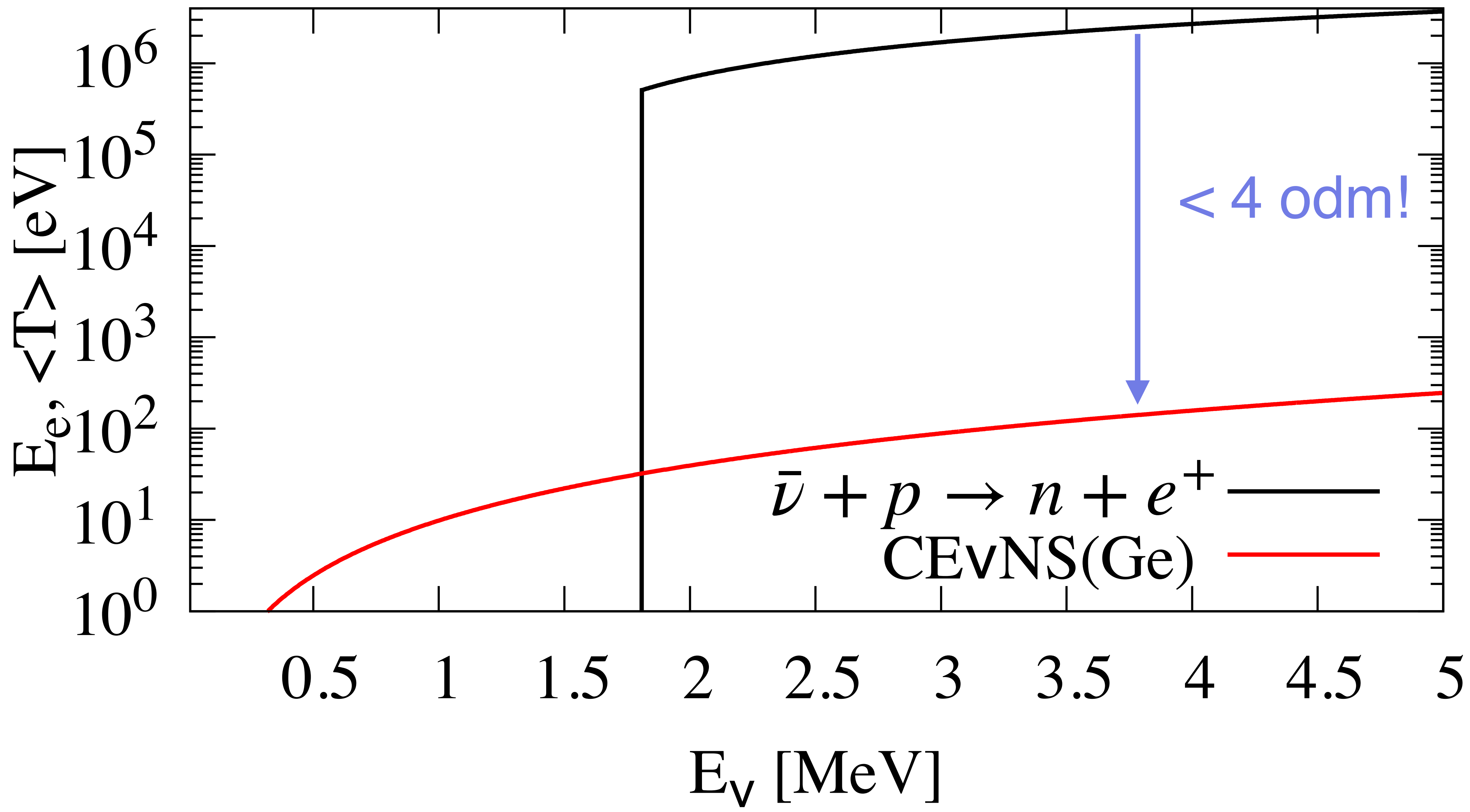
$$\sigma_{\text{CE}\nu\text{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

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

Observable: kinetic energy of nuclear recoil

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





History

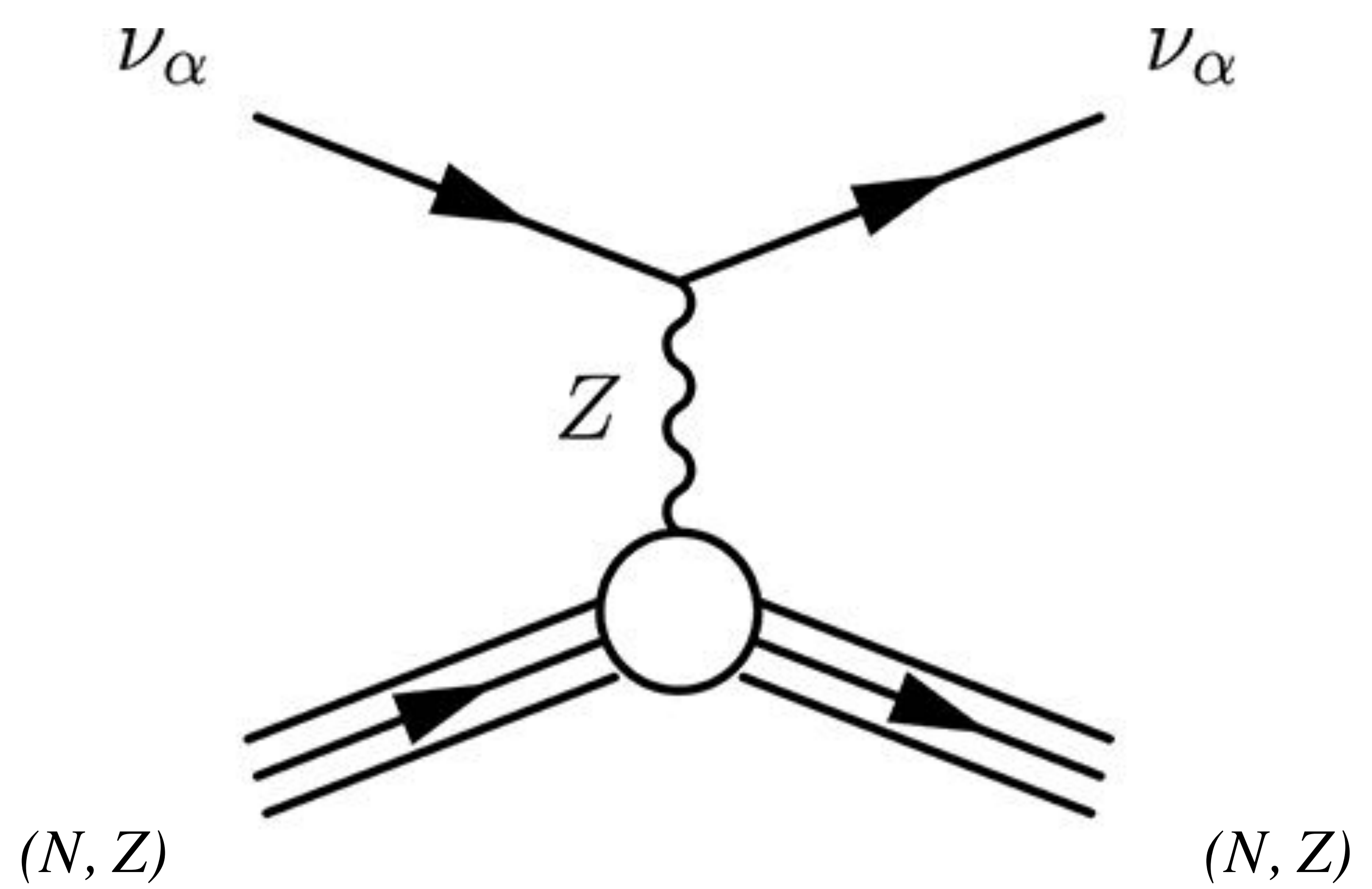
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ 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 $\nu + A \to \nu + A^*$ 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.



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

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.

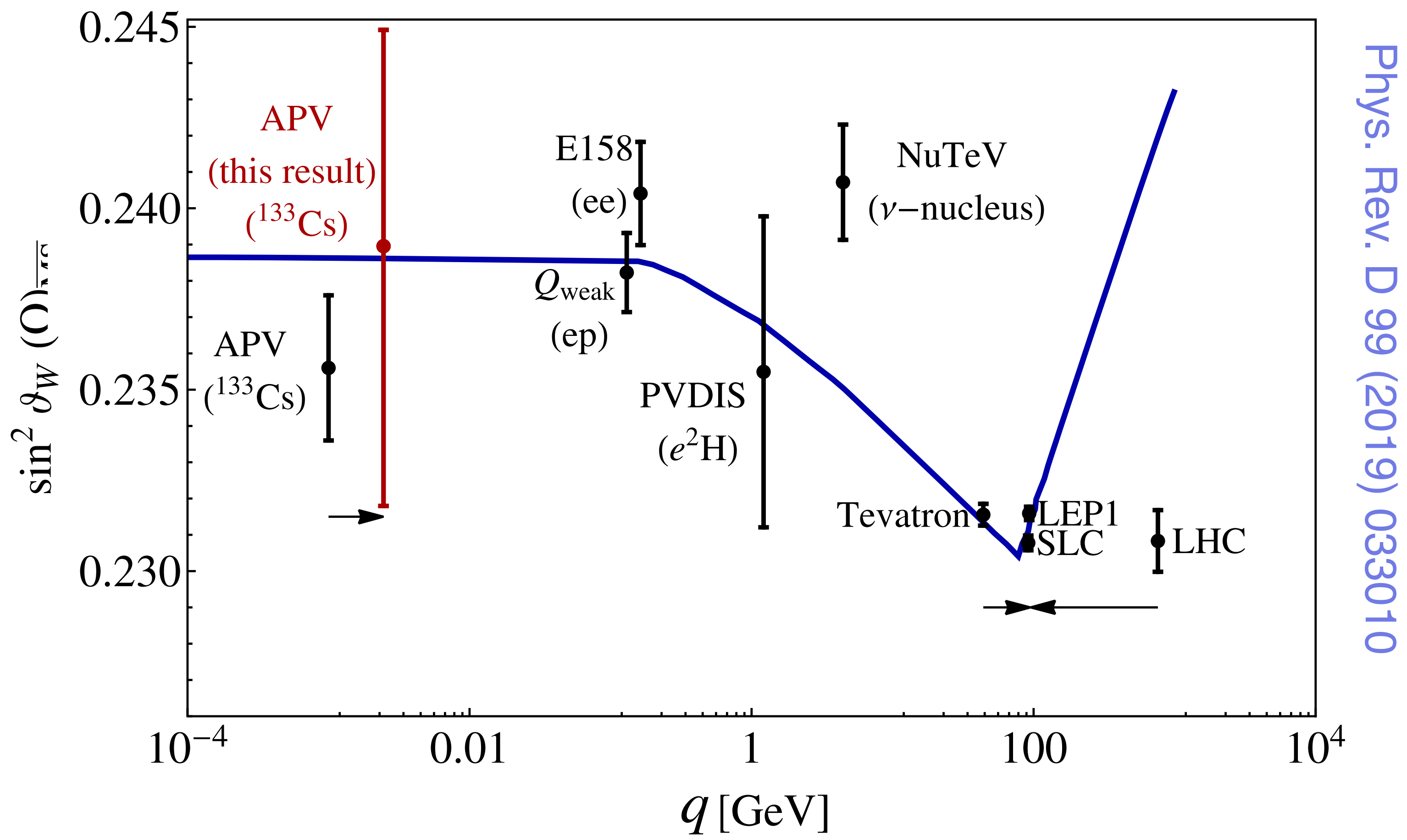
44 years for the discovery

Applications

$\sin^2\theta_W$ at low momentum transferred

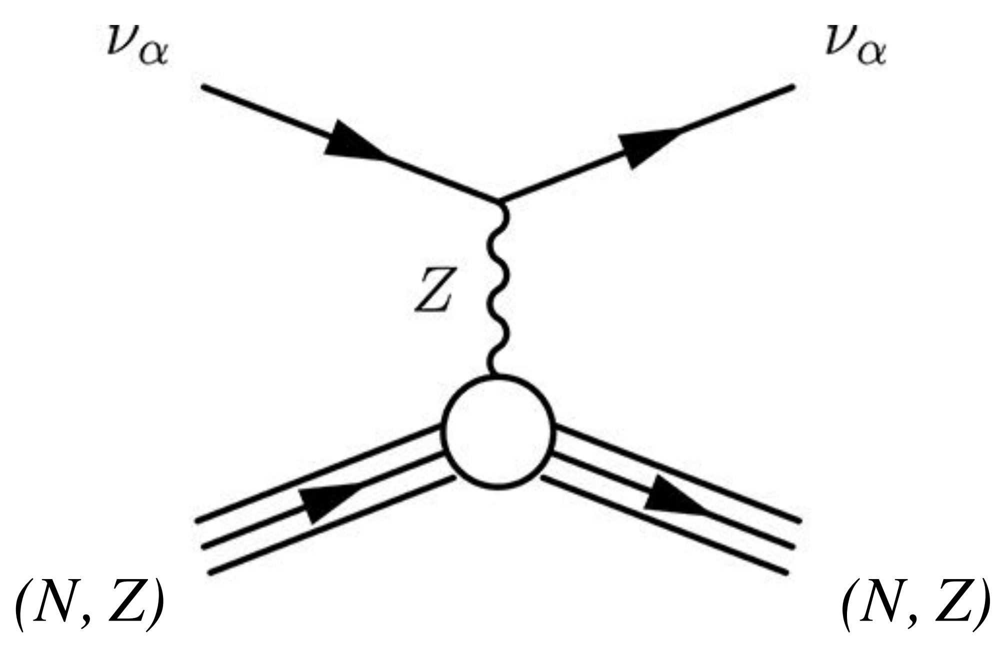
$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

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



Cadeddu, M and Dordei, F, Phys. Rev. D 99 (2019) 033010

T. Rink, Wednesday



Sanchez Garcia

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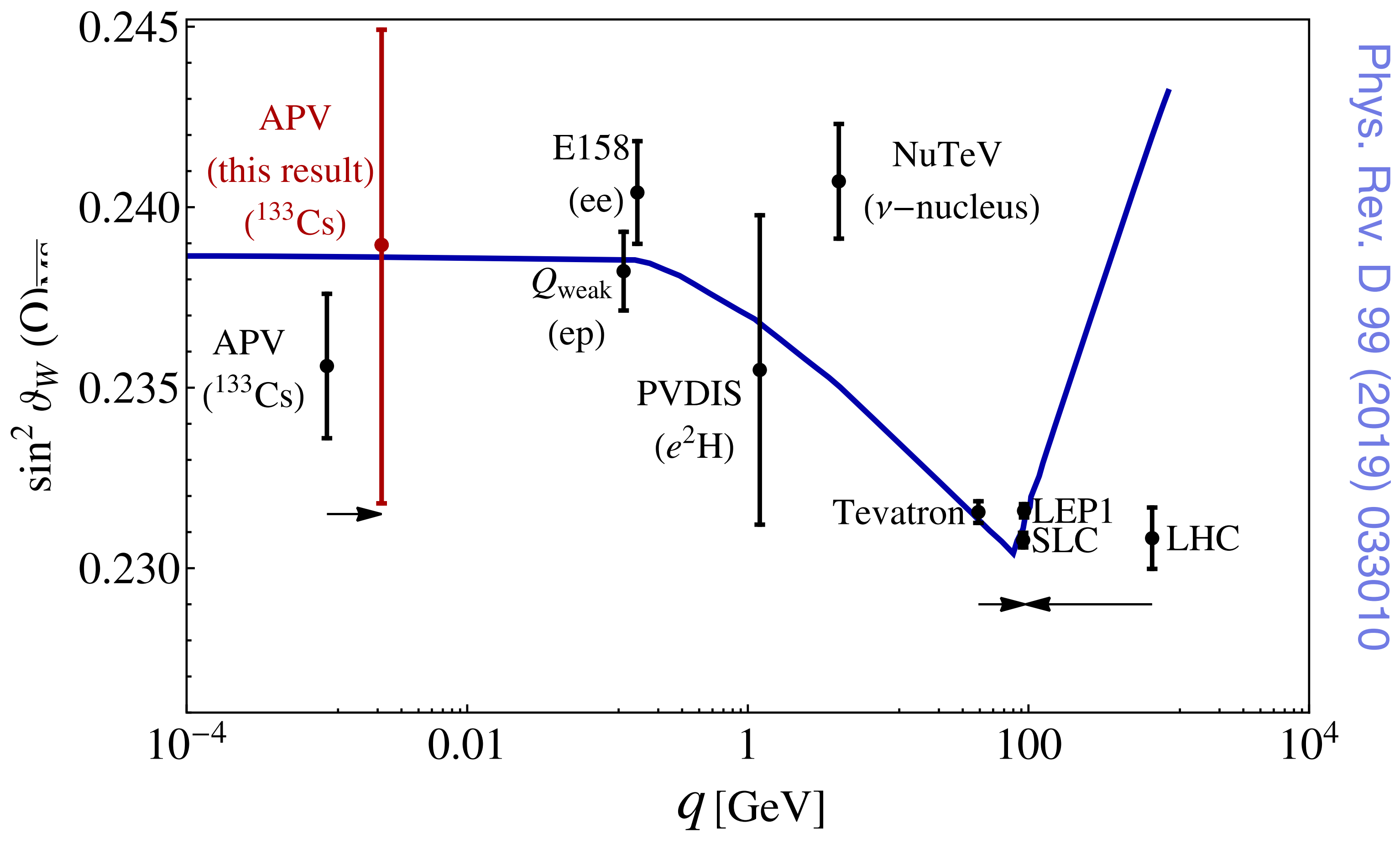

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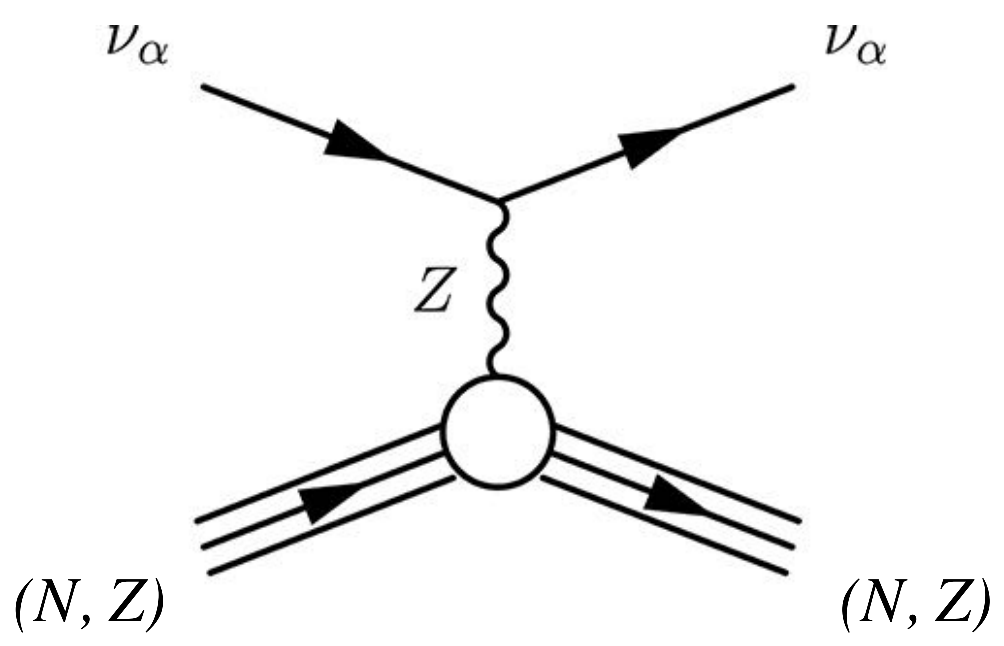
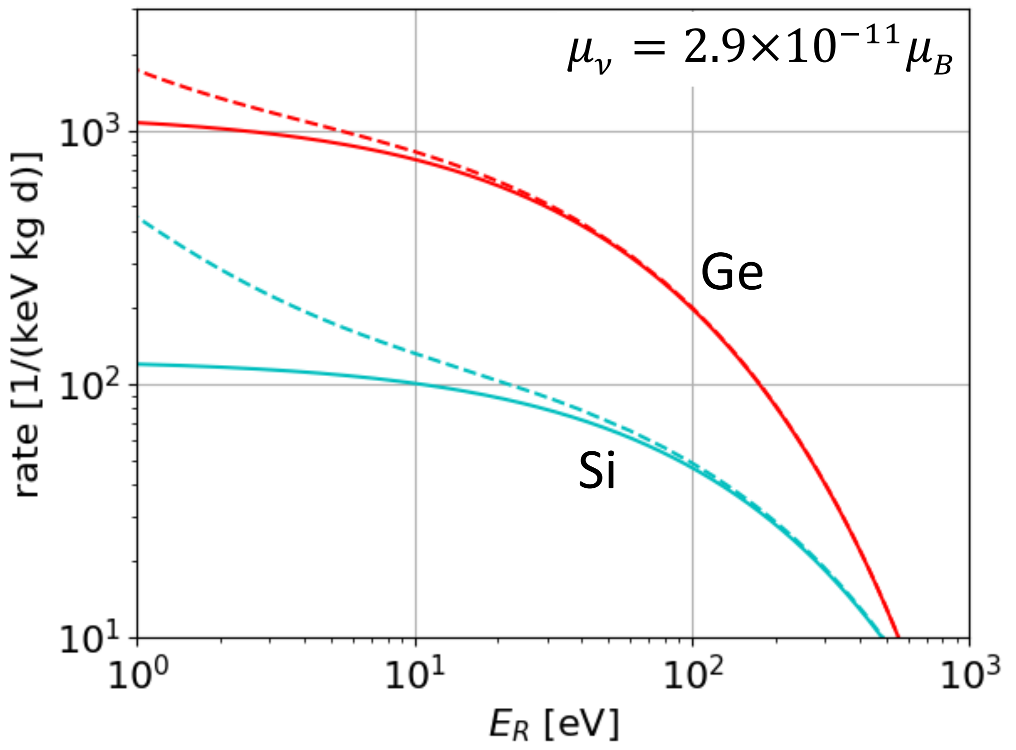


Sanchez Garcia

magnetic dipole moment of neutrino

Vign



Additive component to CNNS cross-section:

$$\frac{d\sigma_{EM}}{dE_R} \sim {\mu_\nu}^2 \left(\frac{1 - E_R/E_\nu}{E_\nu} + \frac{E_R}{4E_\nu^2} \right)$$

A.B. Balantekin, N. Vassh, Phys. Rev. D **89** (2014) no.7, 073013

M. Tórtola, today

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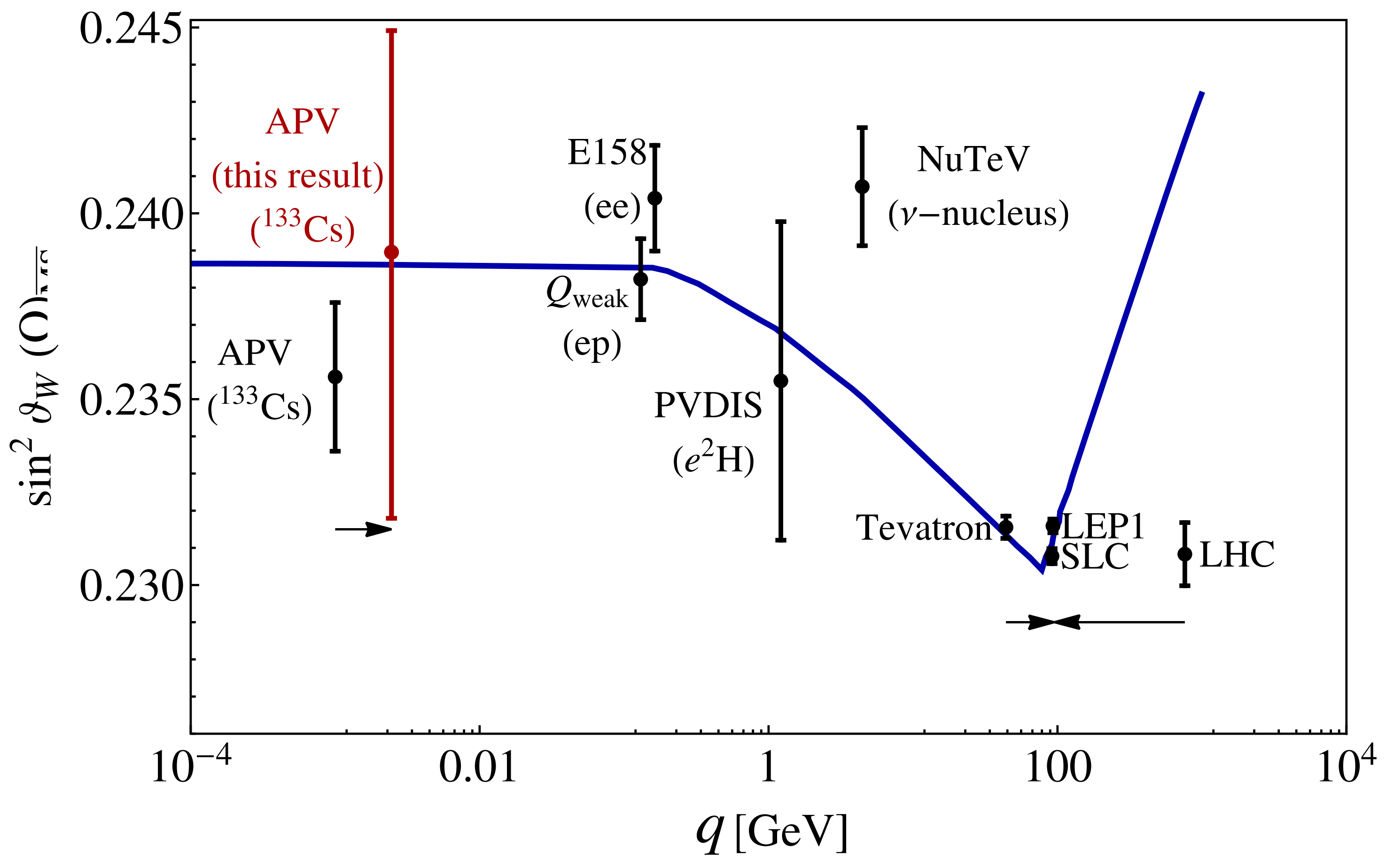
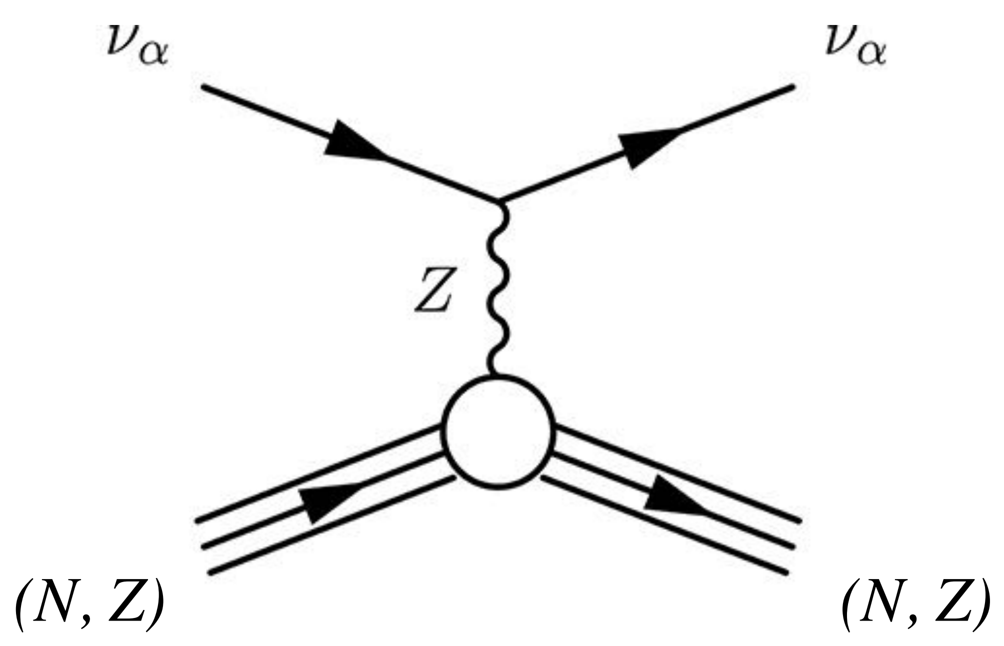


Cadeddu, M and Dordei, F, Phys. Rev. D 99 (2019) 033010

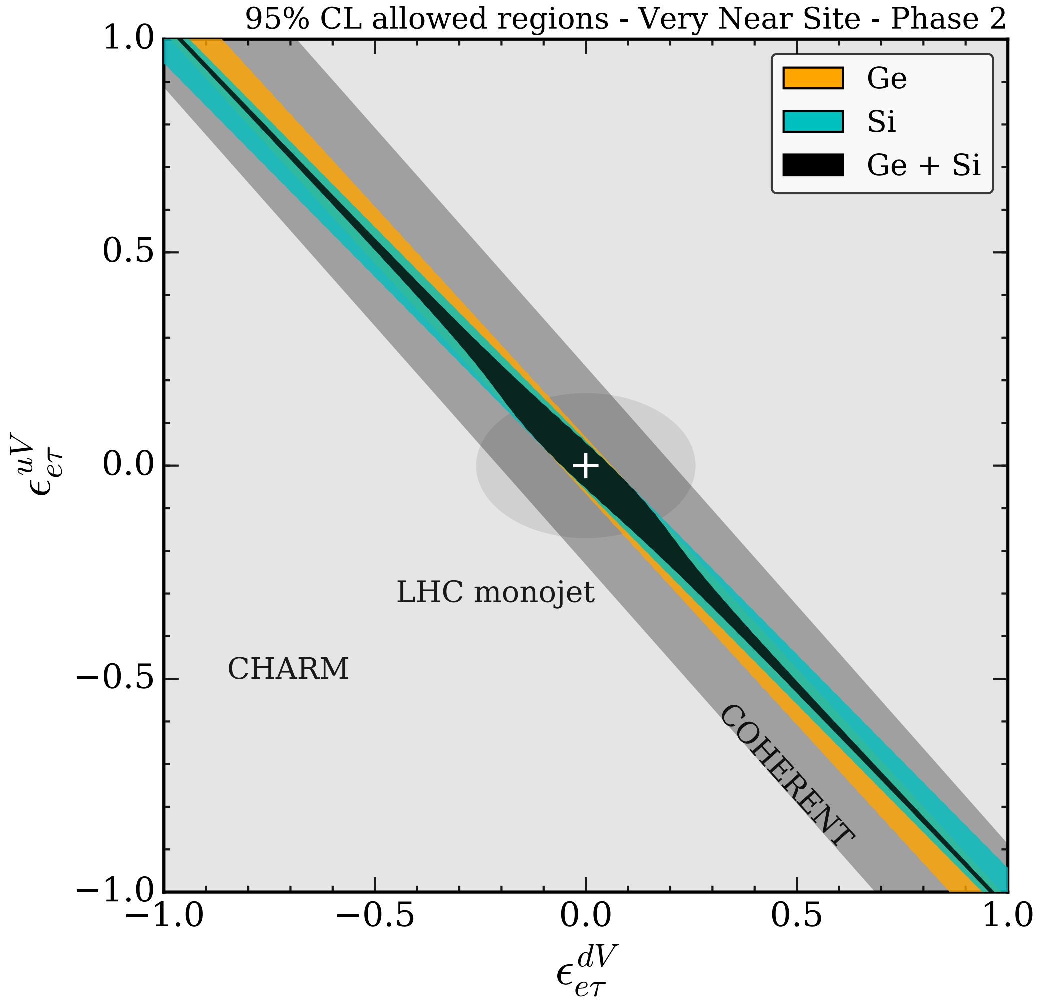
T. Rink, Wednesday



Sanchez Garcia

Non standard interactions (NSI)

$$\mathscr{L}^{\mathrm{NSI}} = -\epsilon_{\alpha\beta}^{qV}2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\mu\nu_\beta)(\bar{q}\gamma^\mu q)$$

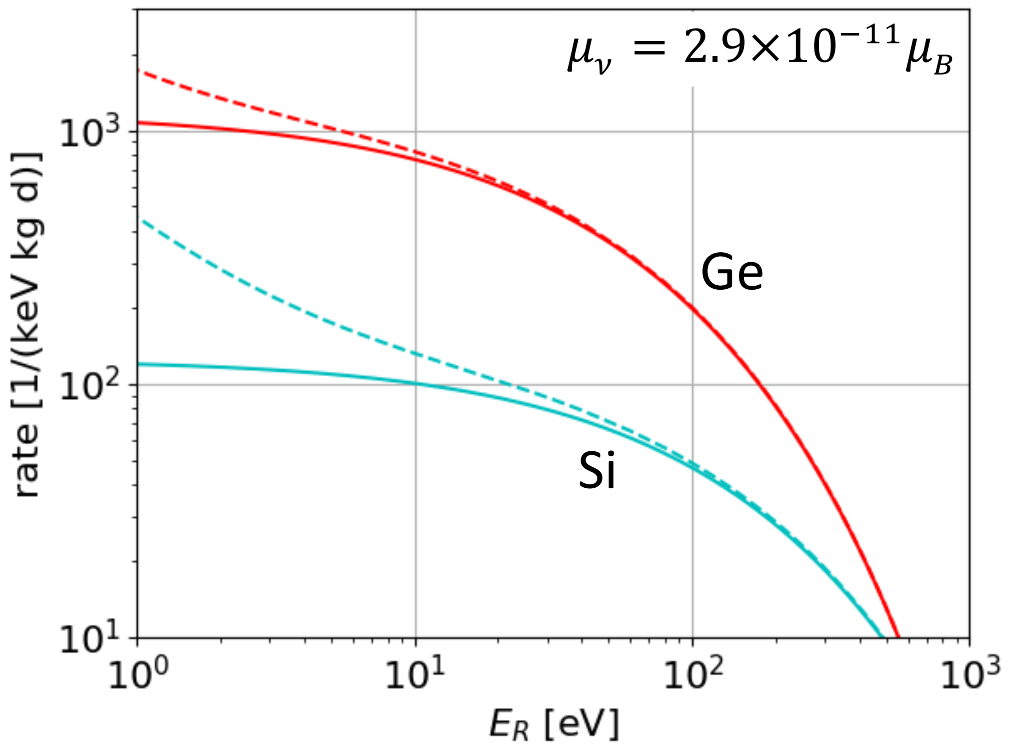


J. Billard, J. Johnston and B.J. Kavanagh, JCAP 1811 (2018) 016

V. Romeri, today

G. Sanchez-Garcia, Wednesday

magnetic dipole moment of neutrino



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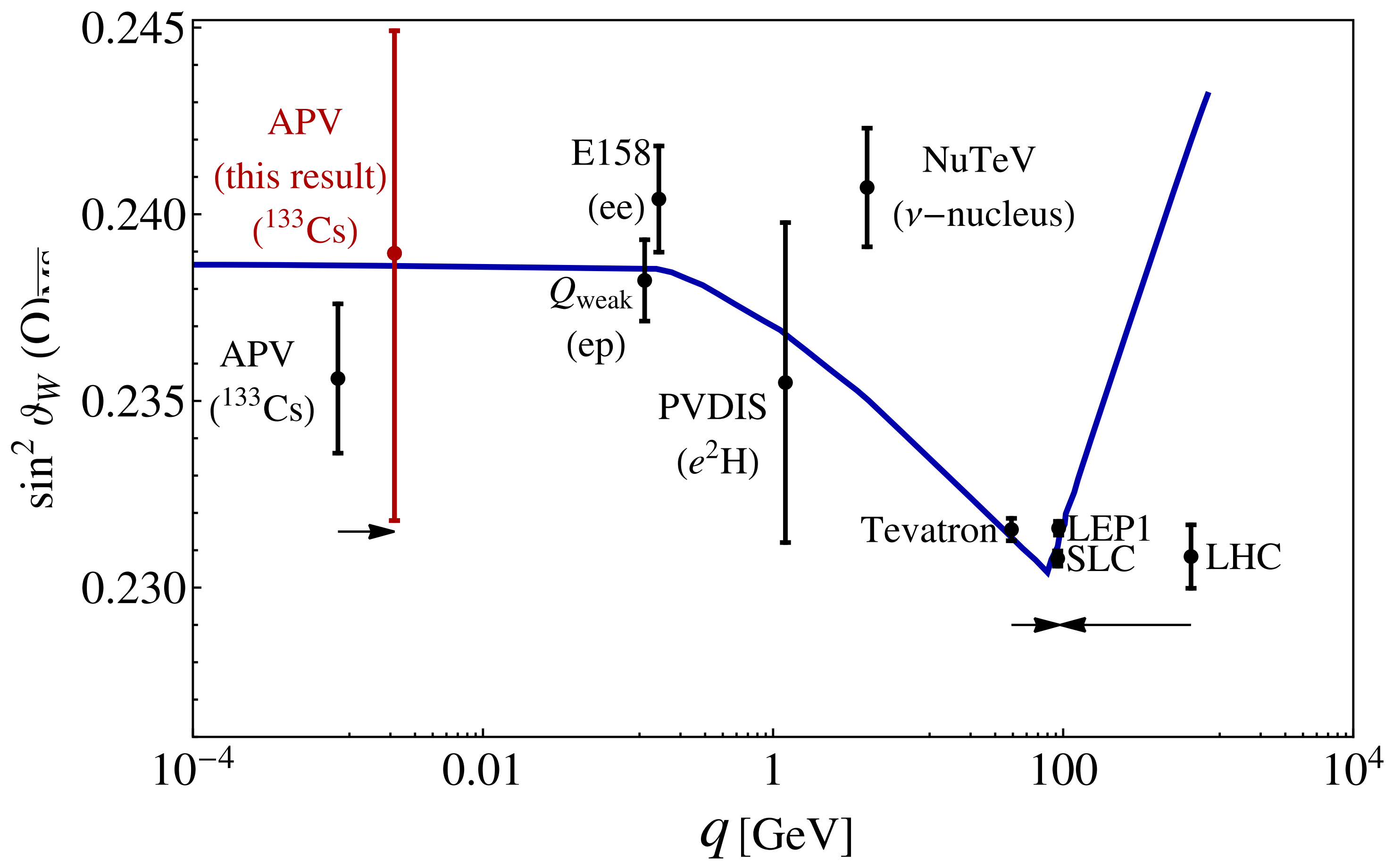

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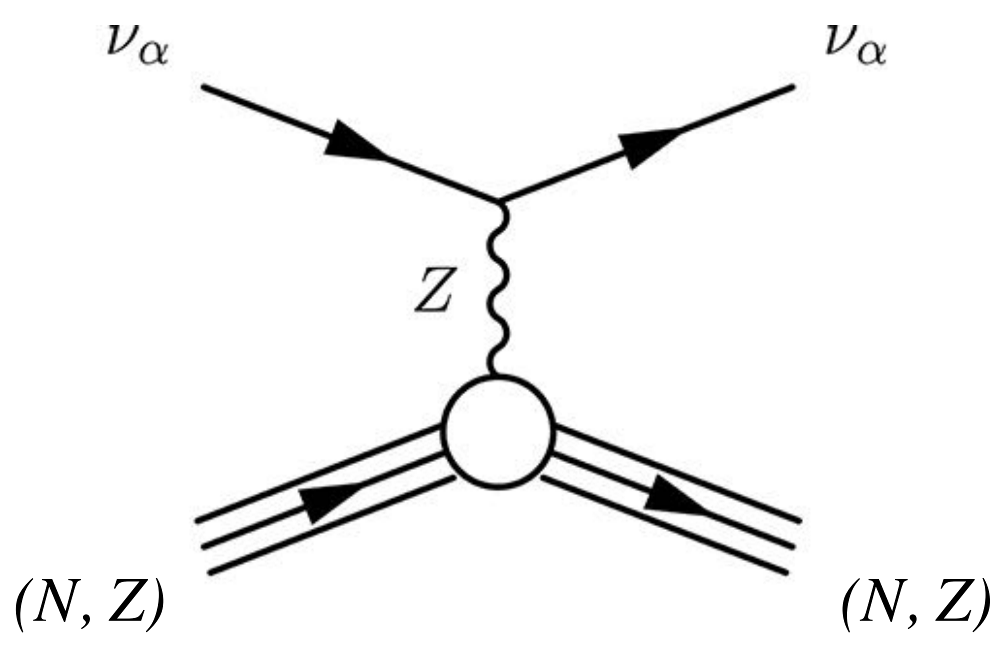

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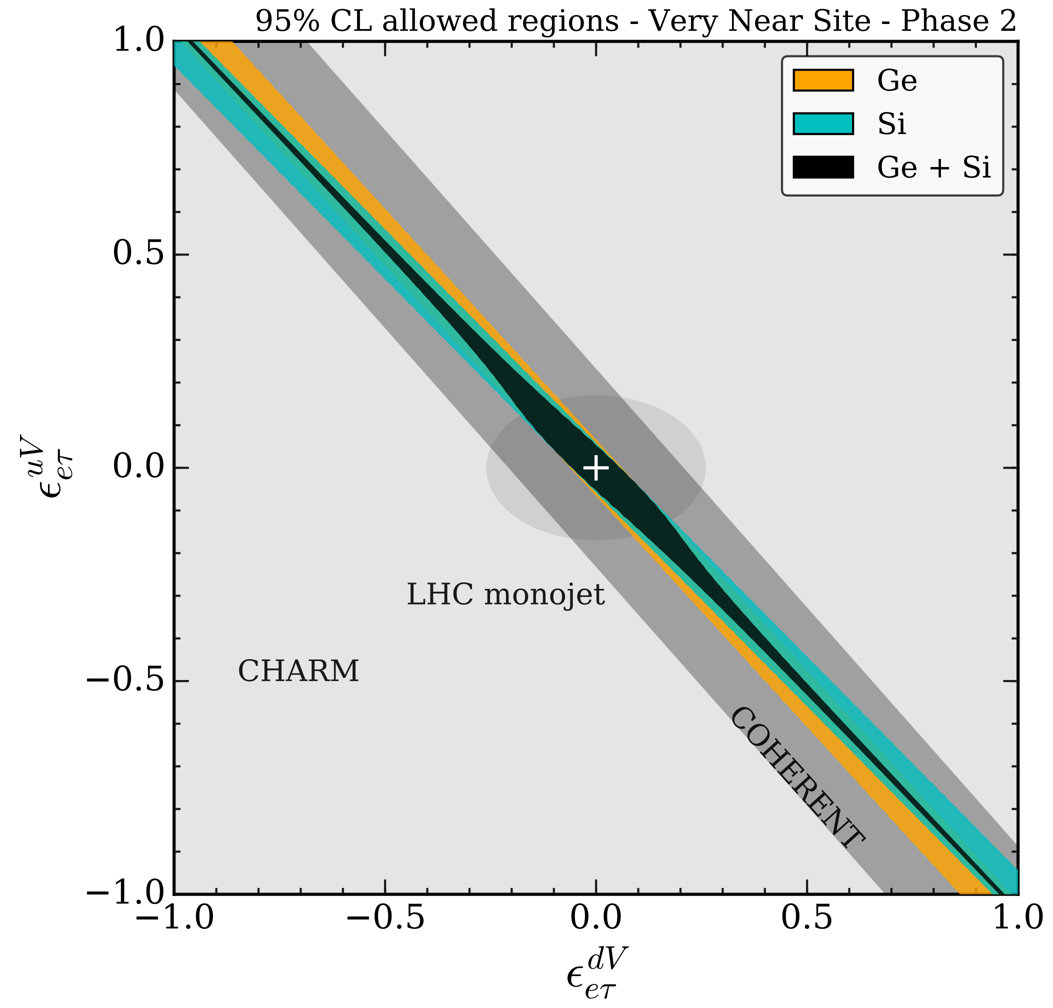

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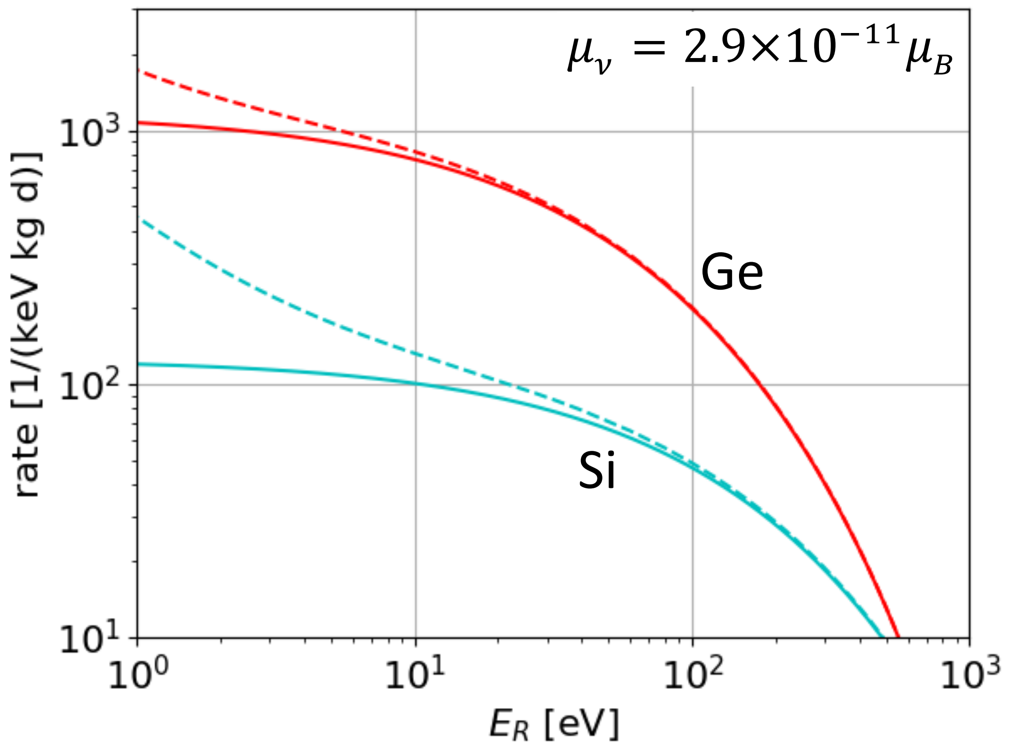

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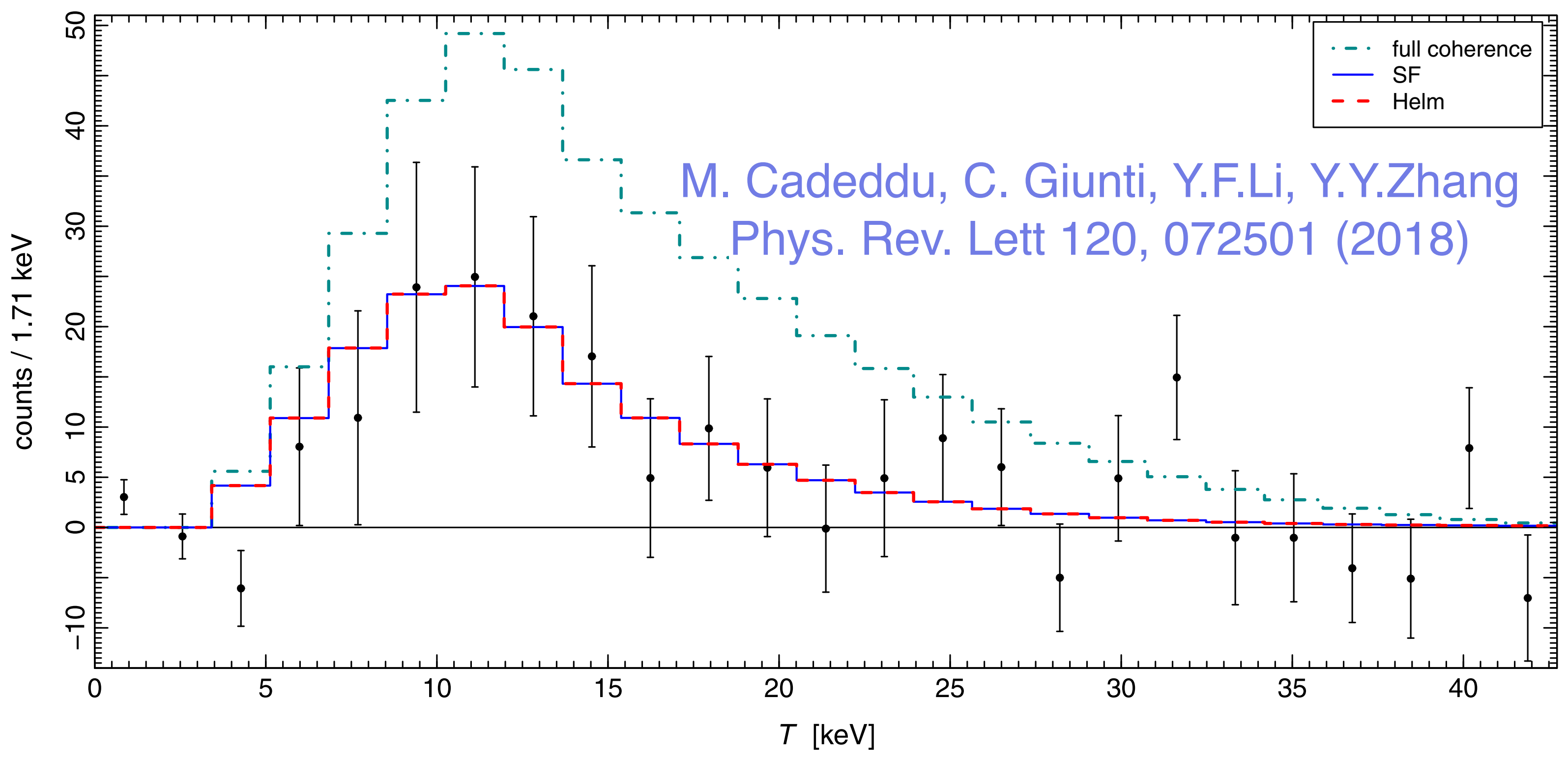
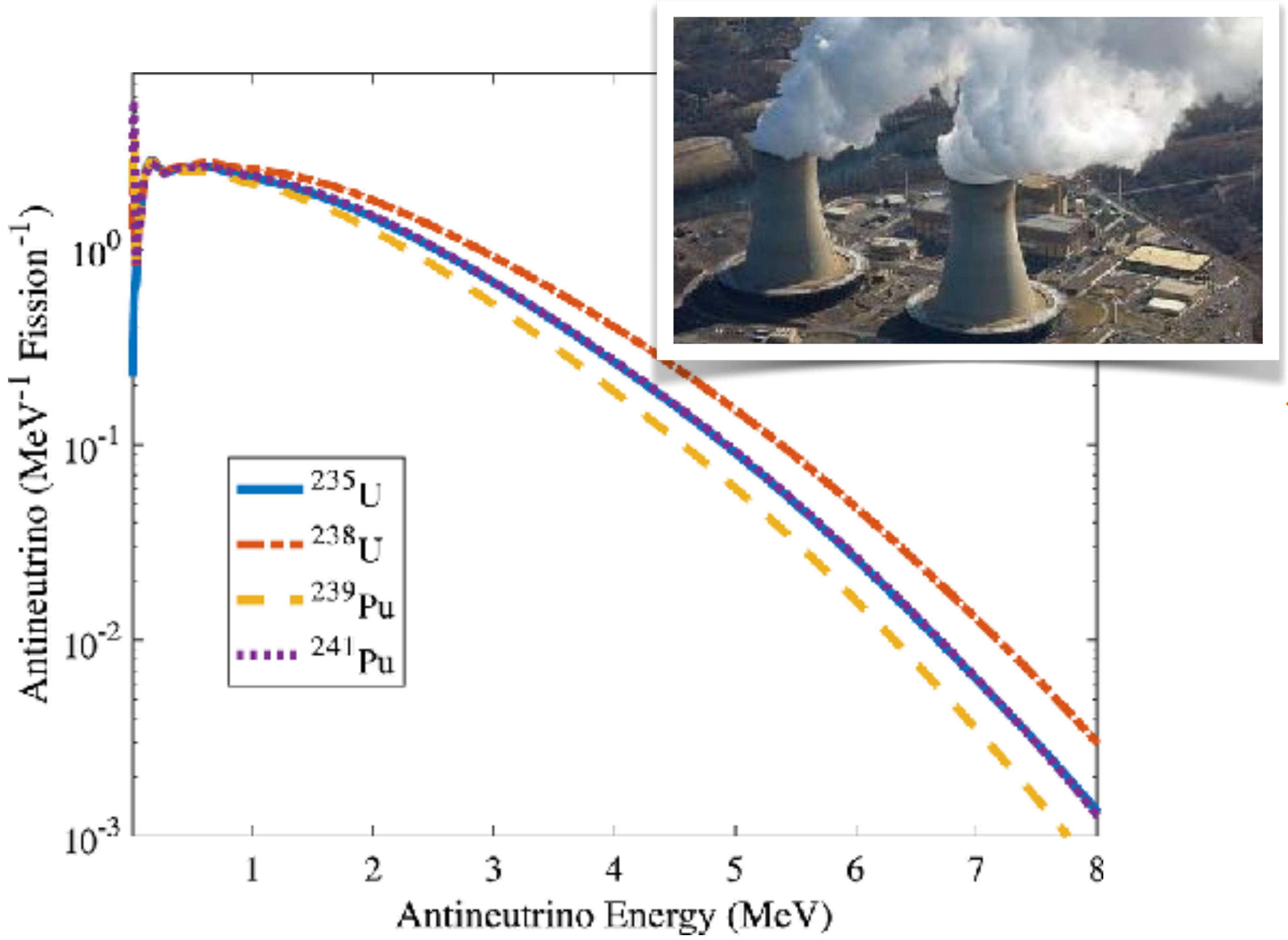
M. Tórtola, today

Form-factors / neutron radius

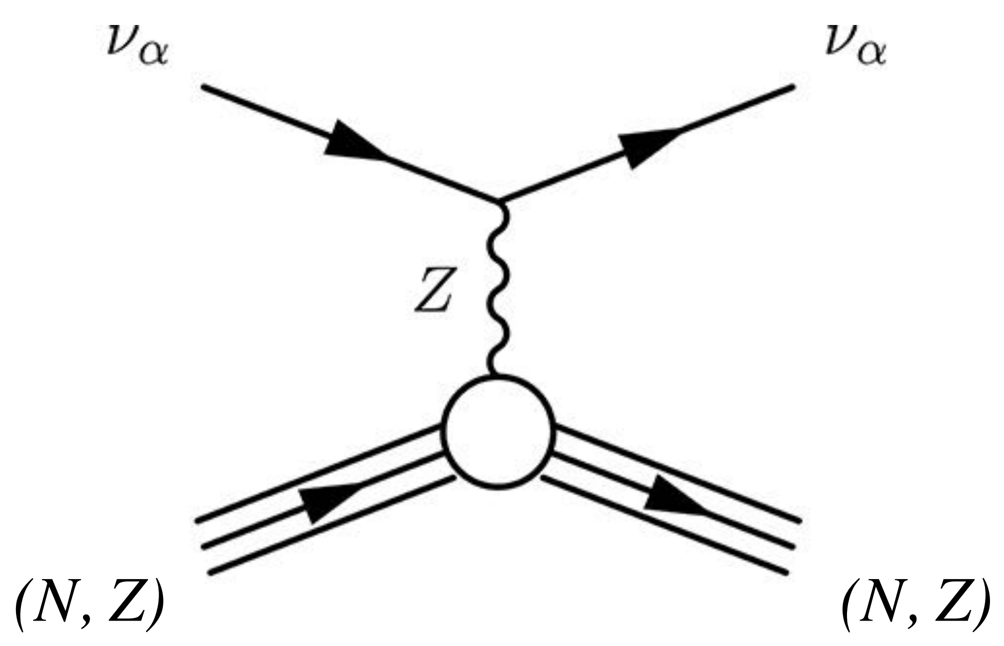


Applications

Monitor content of Pu in reactors



Adam Bernstein et al. Rev. Mod. Phys 92 (2020) 011003



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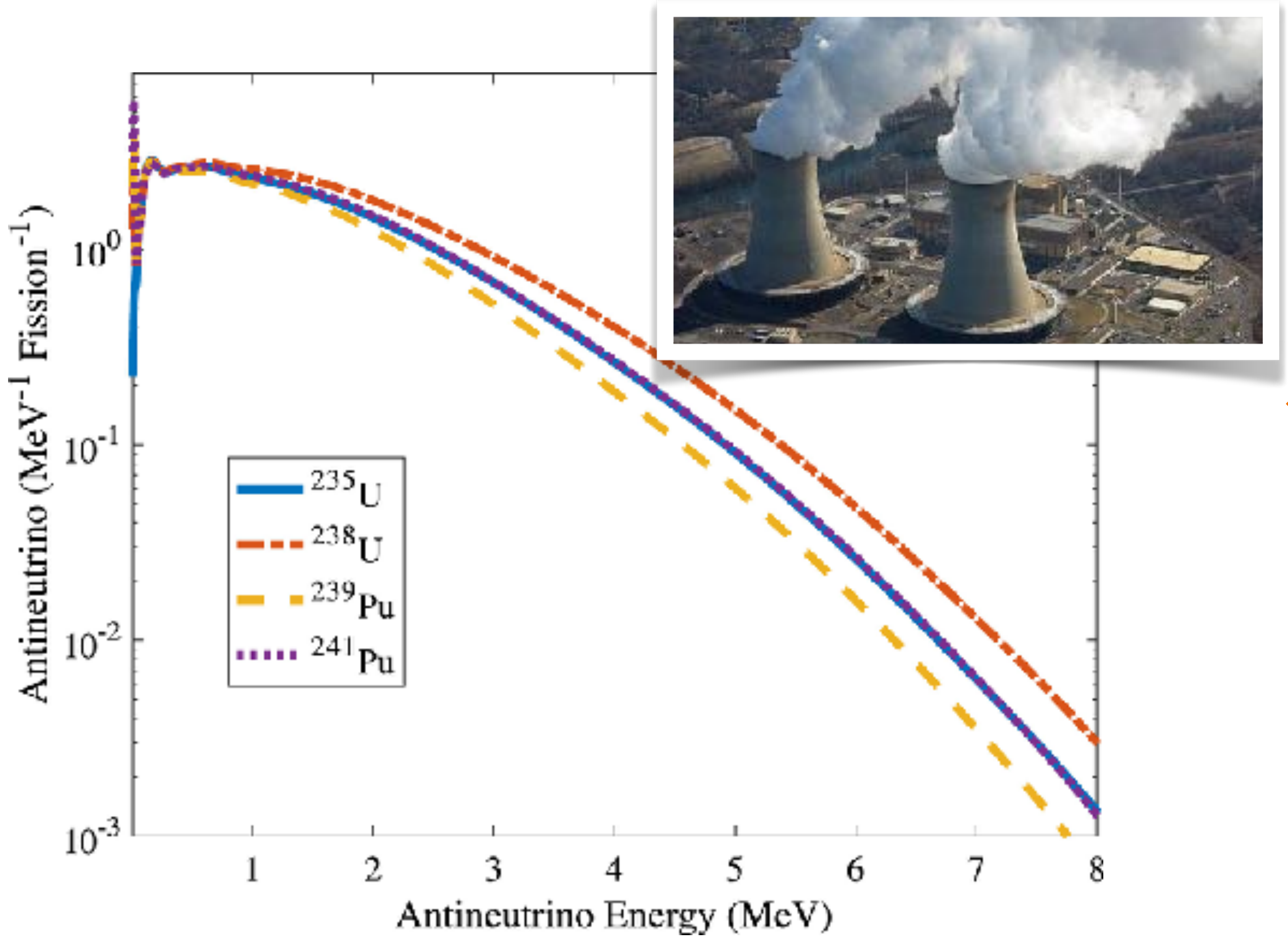

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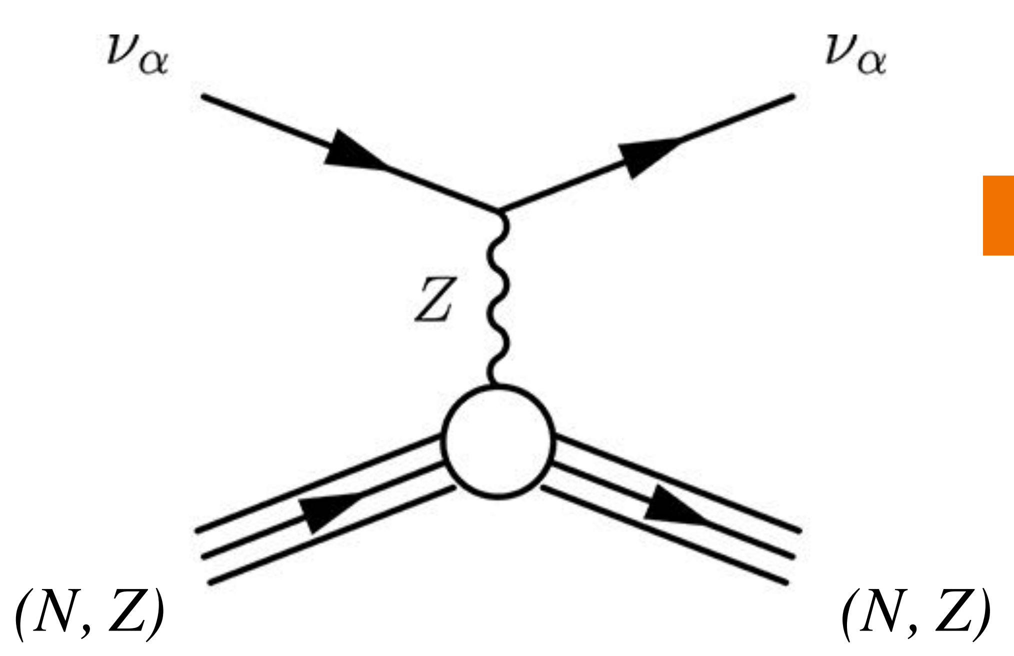
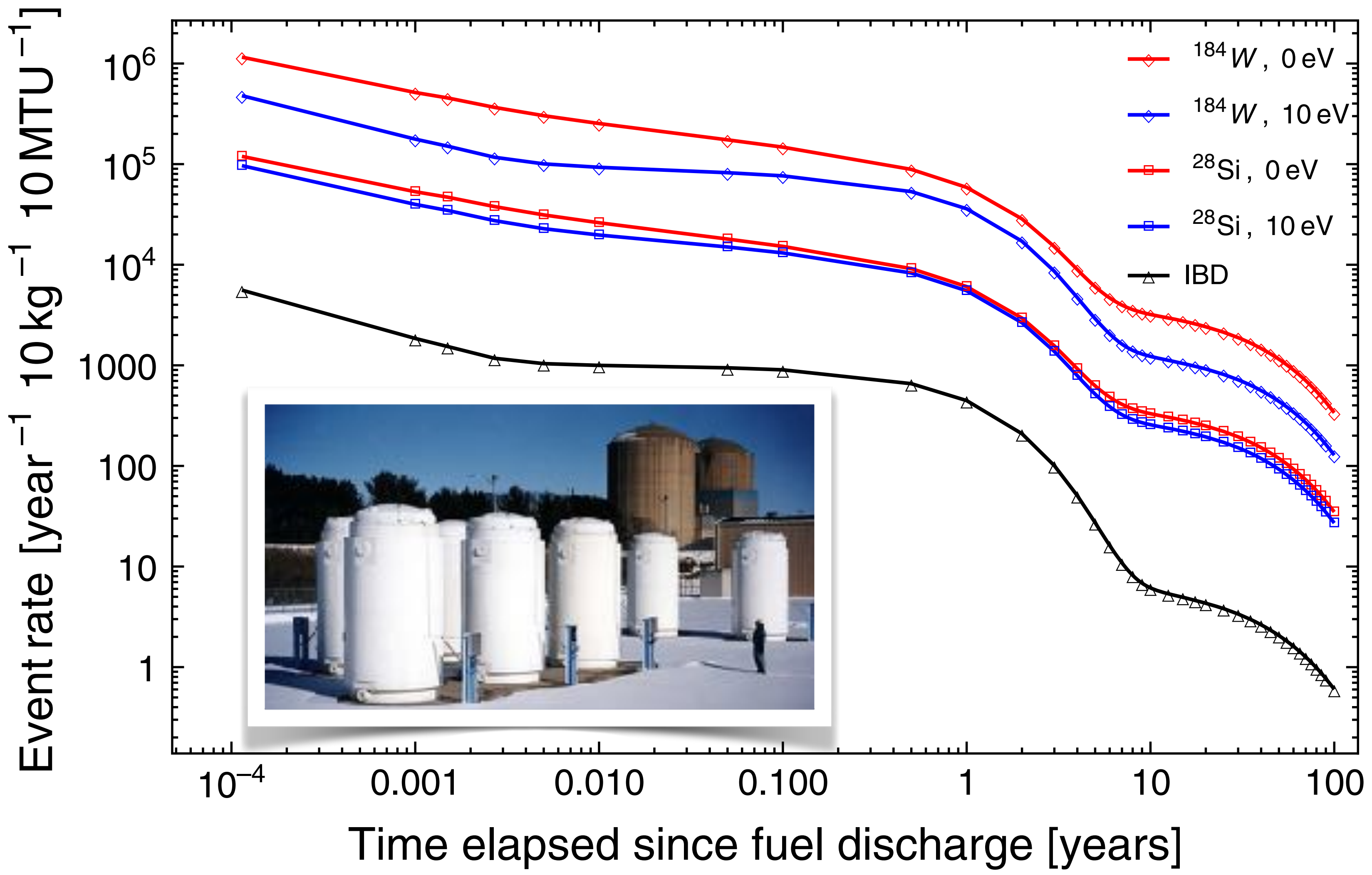


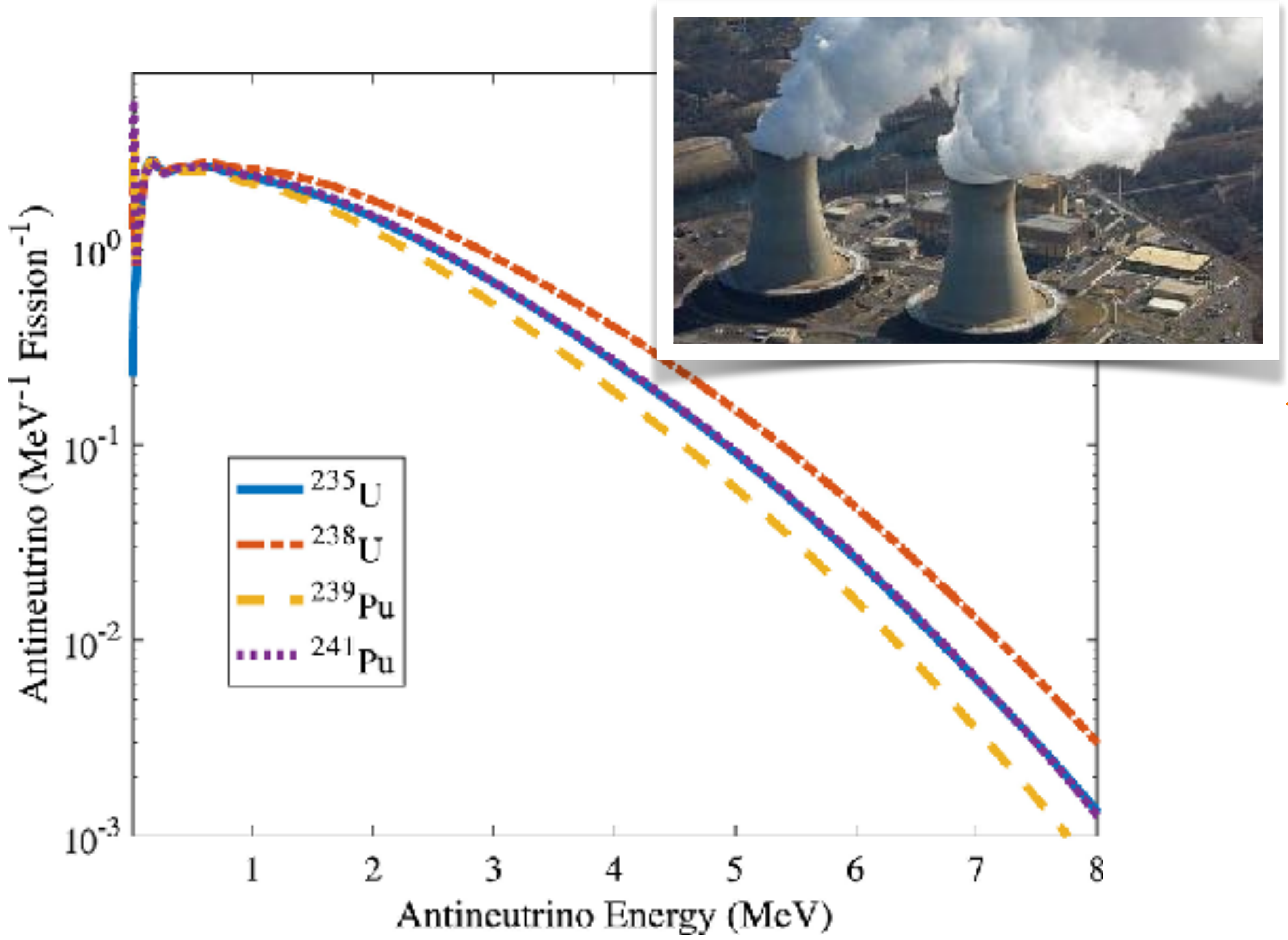
Monitor activity of nuclear waste



Raesfeld, C. and Huber, P.: Phys. Rev. D 105, (2022) 056002

Applications

Monitor content of Pu in reactors



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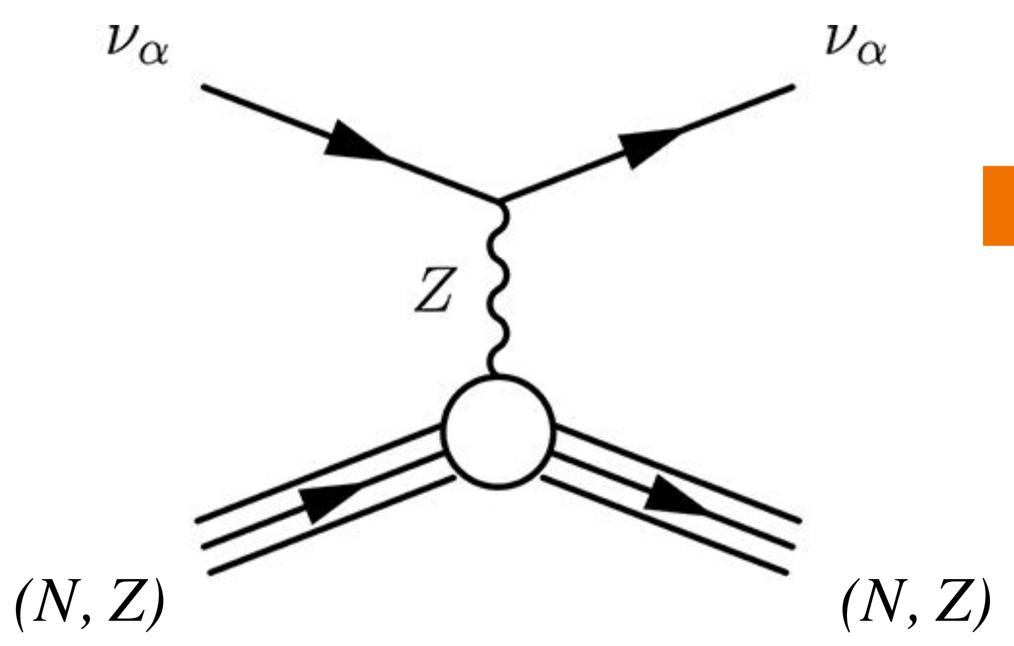

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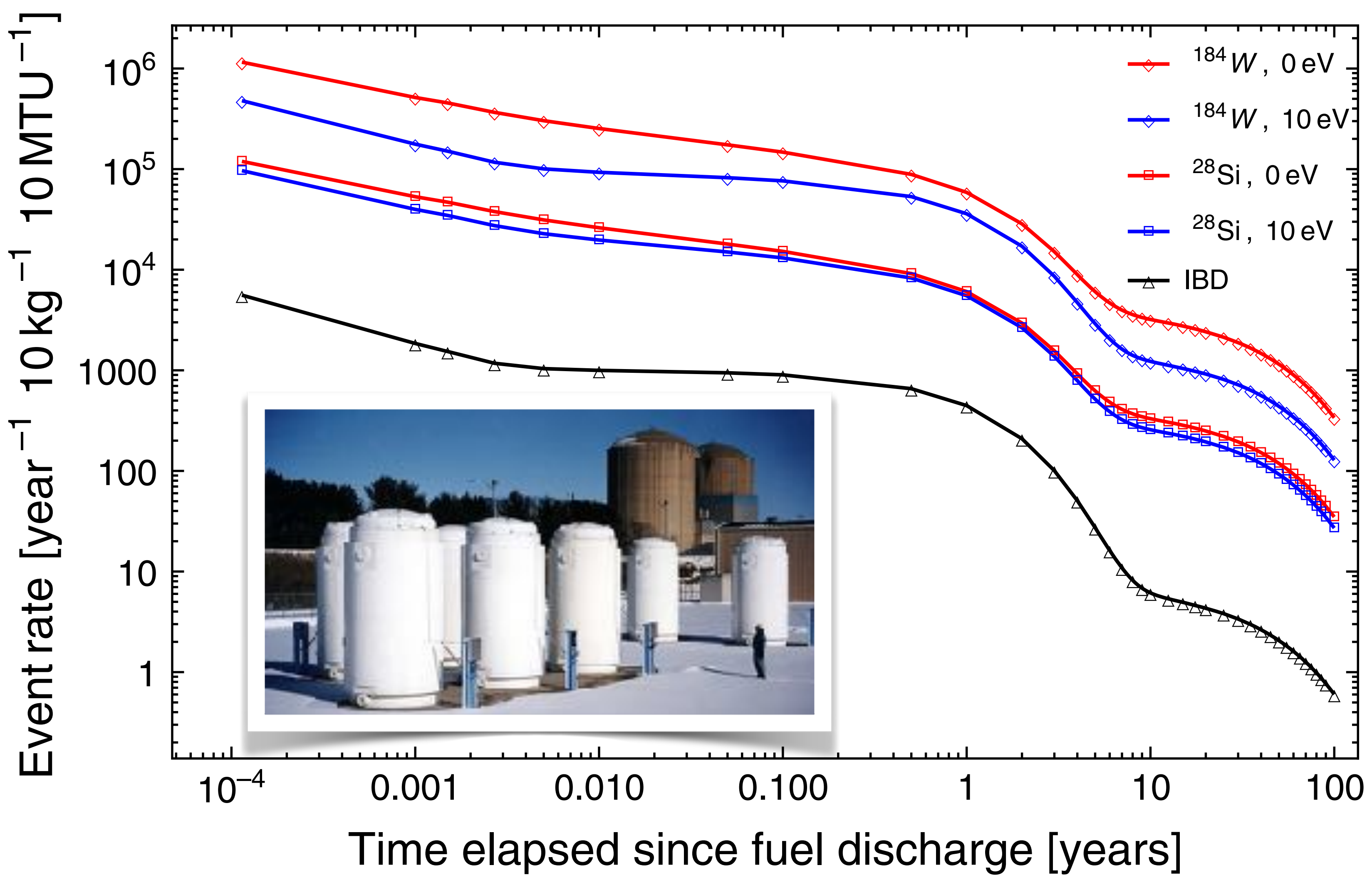
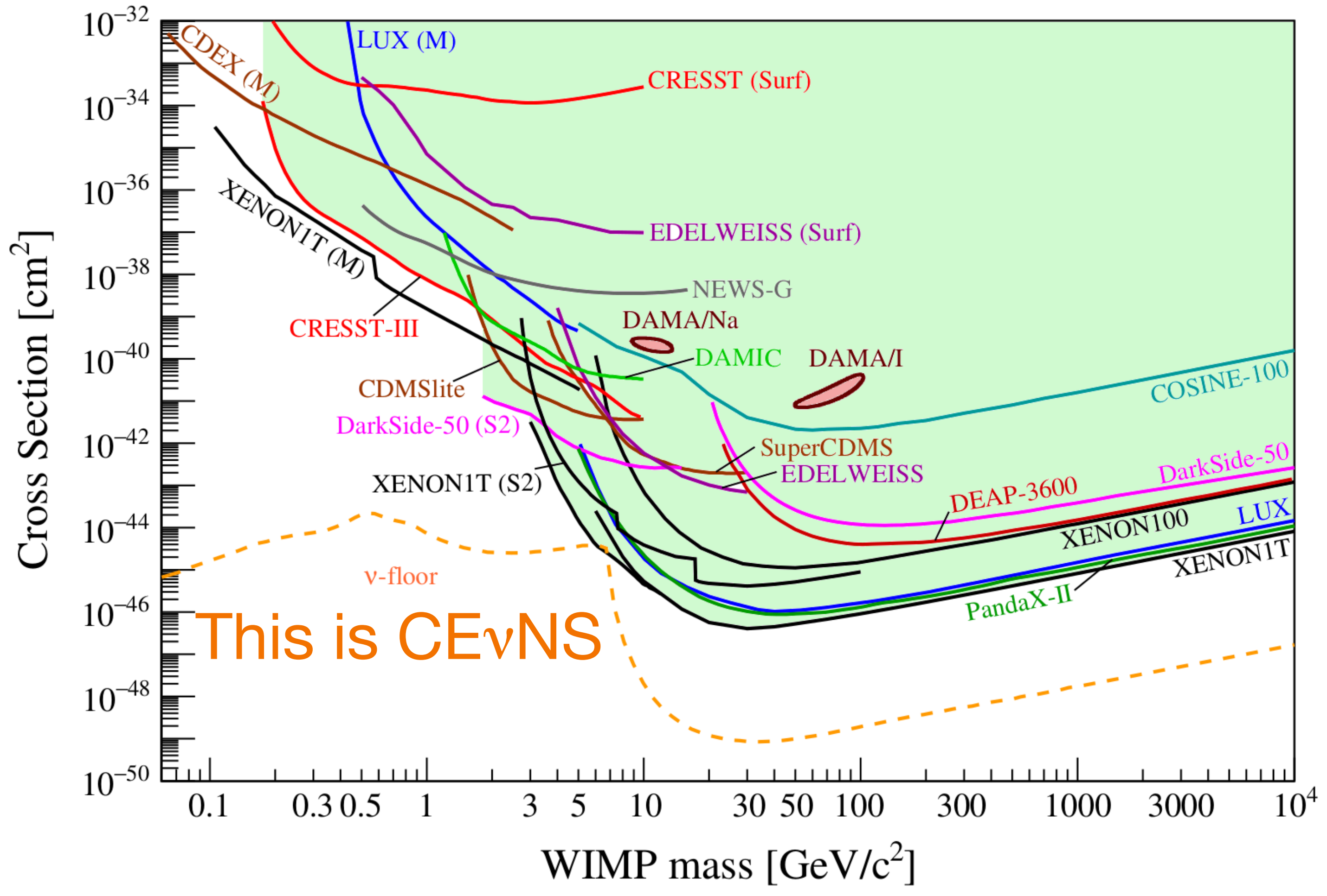


Raesfeld, C. and Huber, P.: Phys. Rev. D 105, (2022) 056002

The ultimate Dark Matter background



J. Billard, et al, APPEC Committee Report, arXiv:2104.07634

Q. Lin, yesterday
C. Wittweg, today

Applications

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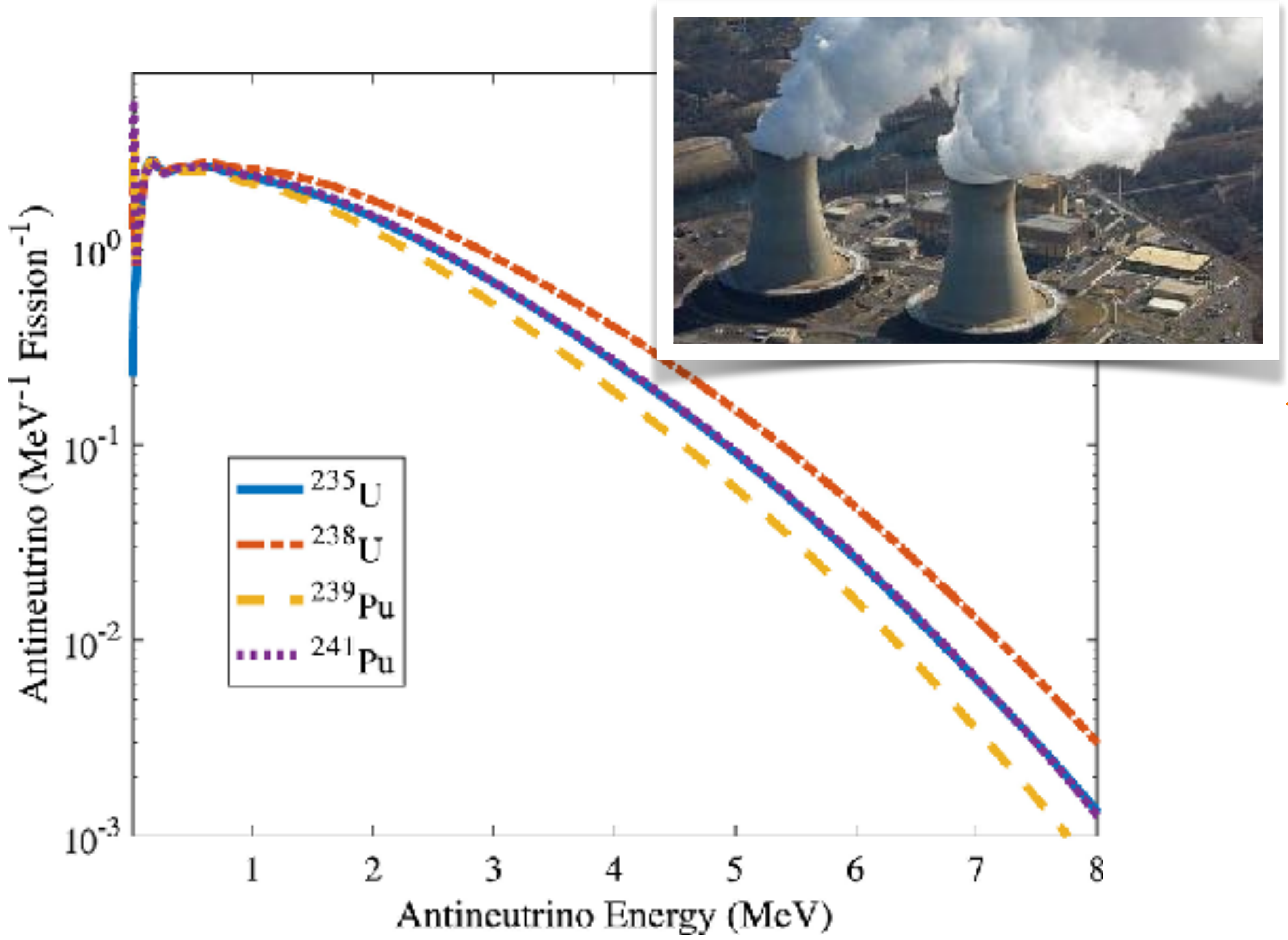

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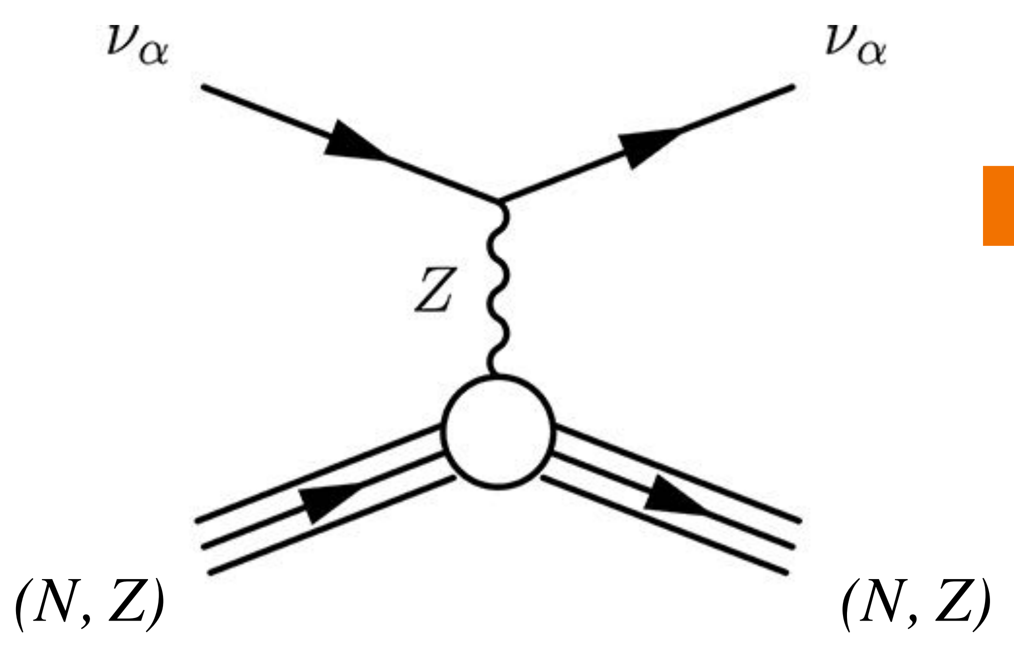

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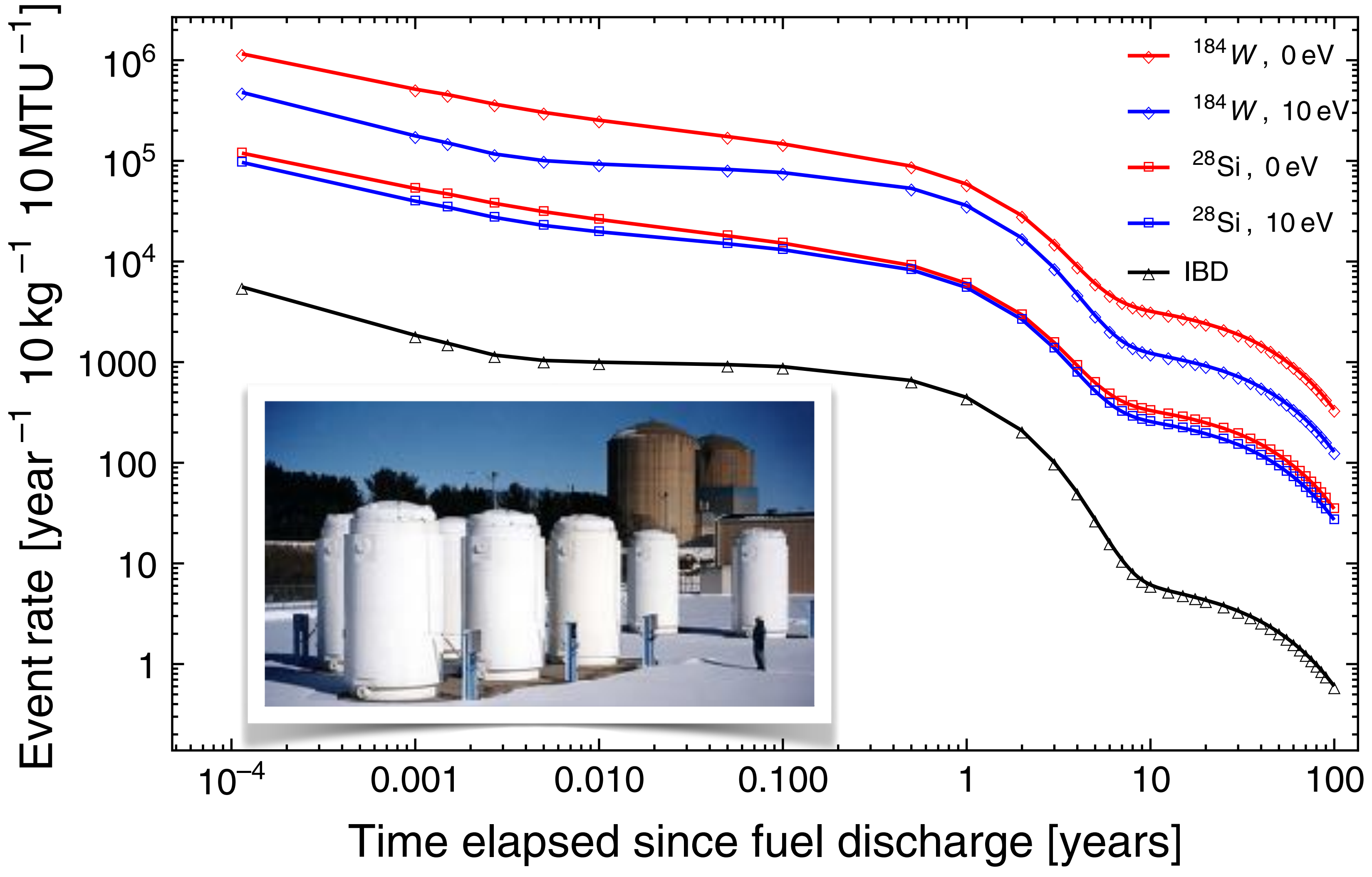

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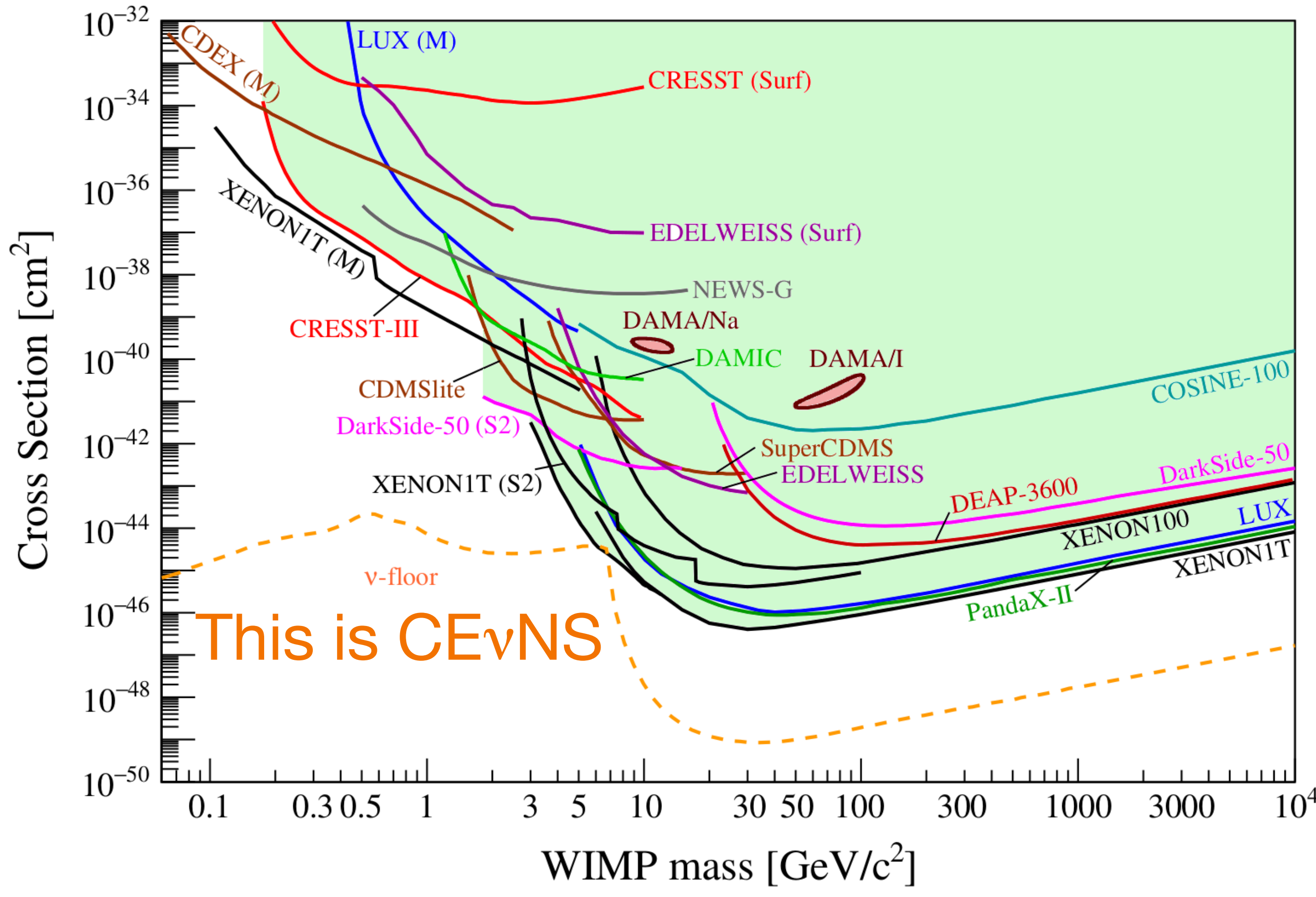
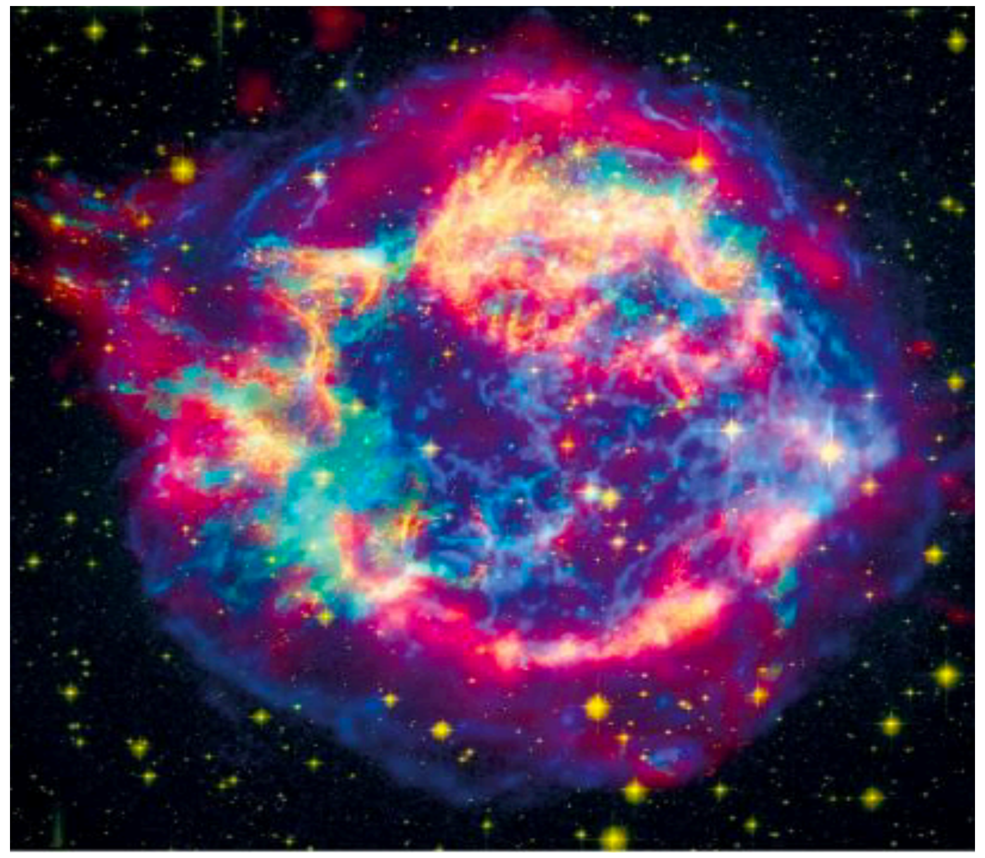


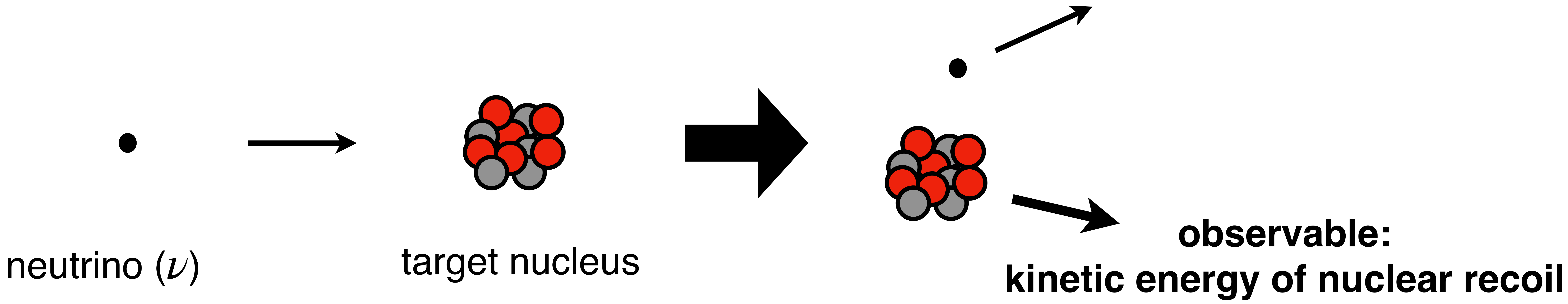
J. Billard, et al, APPEC Committee Report, arXiv:2104.07634

Supernova νs



S. Quitadamo, Wednesday

Experimental challenge



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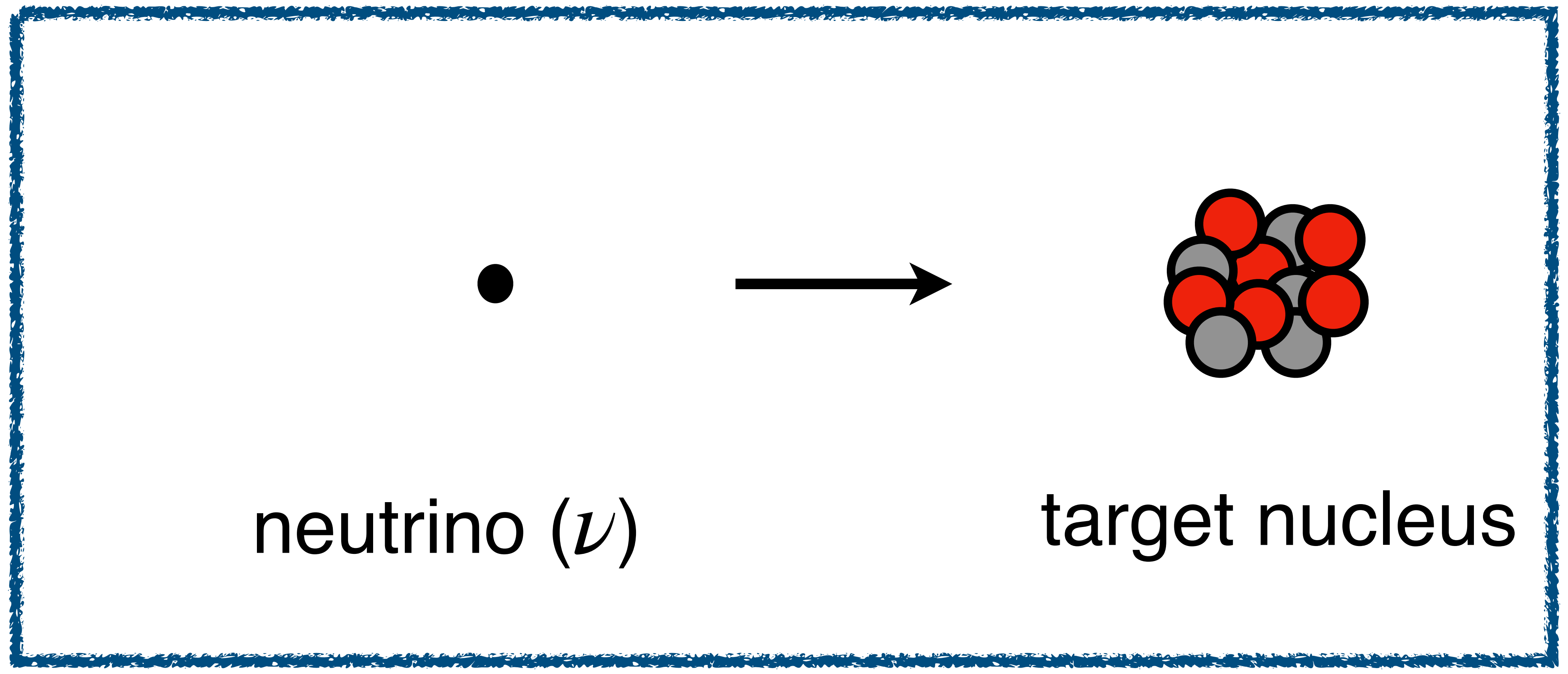
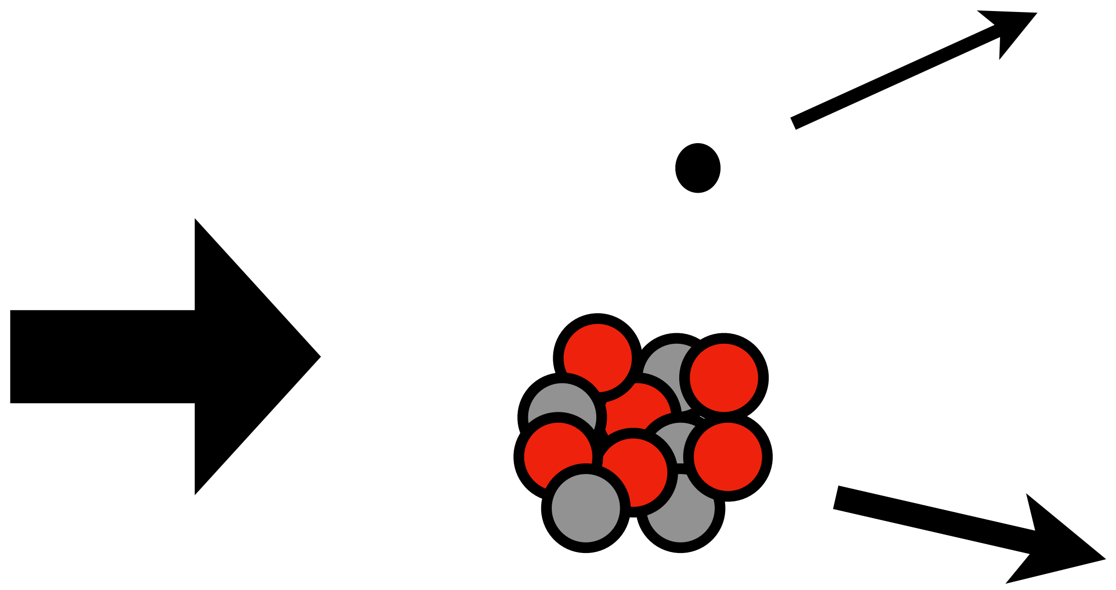
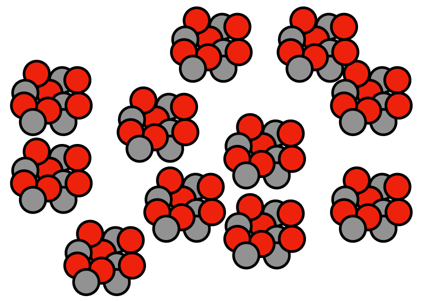




observable:
kinetic energy of nuclear recoil

cross section $\sigma \sim 10^{-40}\ \mathrm{cm}^2$

large number of targets
(large target mass)



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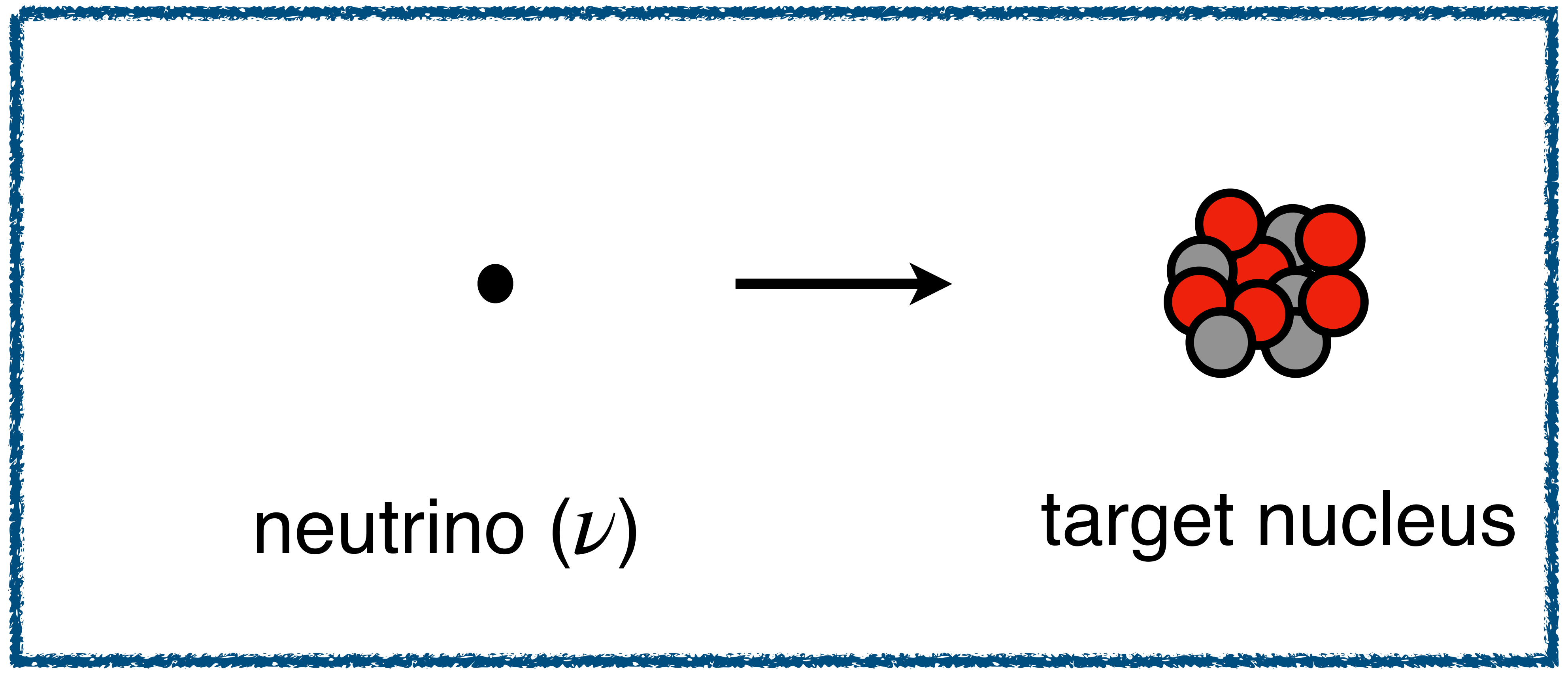
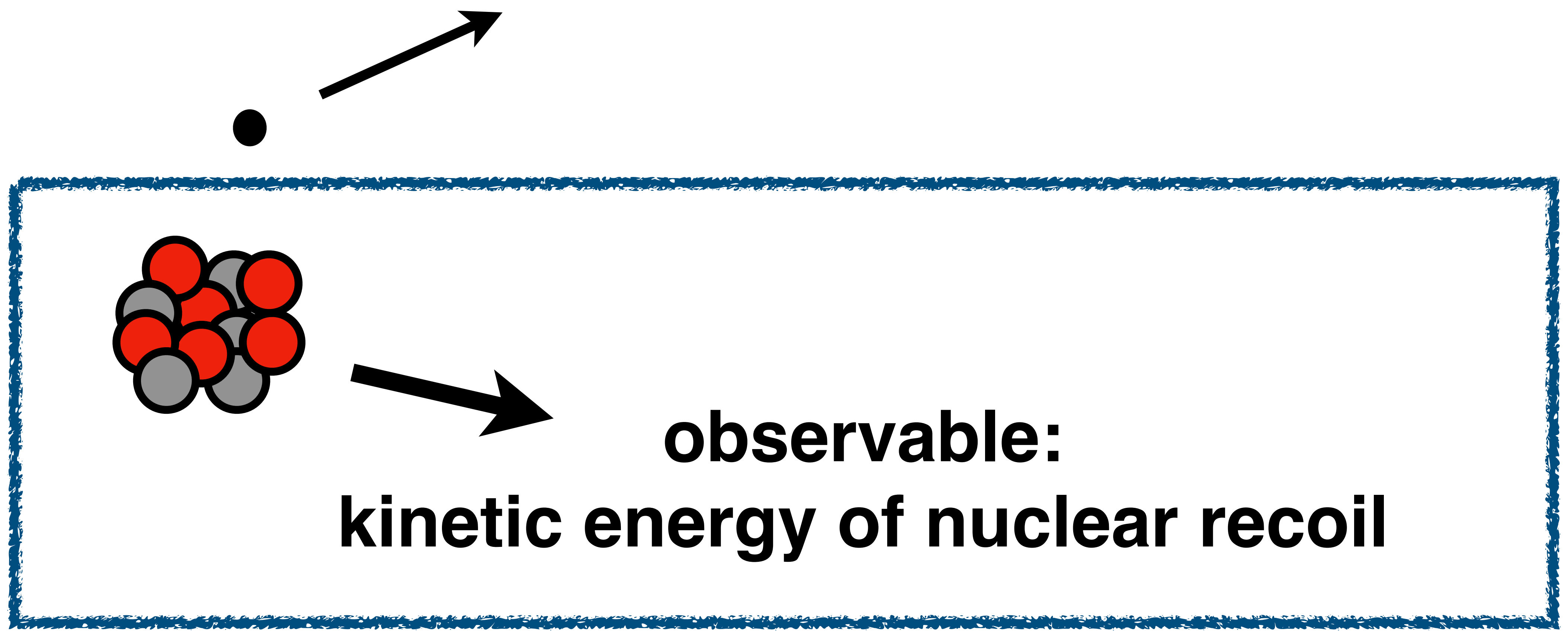
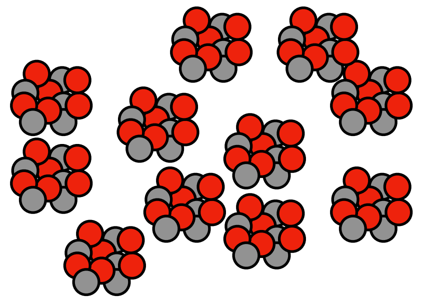


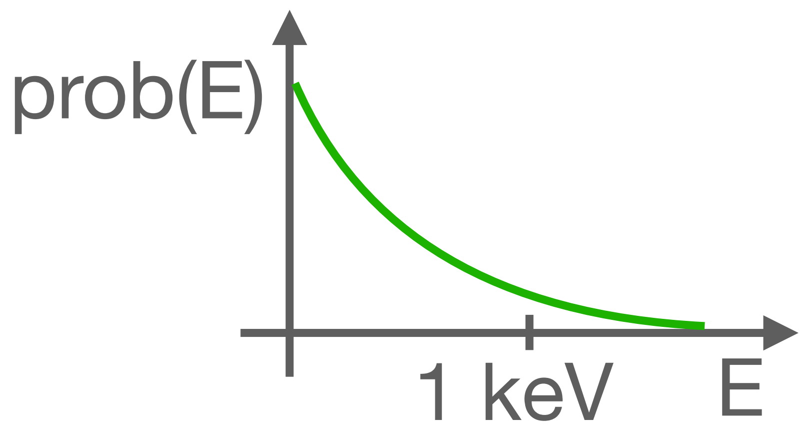


cross section $\sigma \sim 10^{-40}\ \mathrm{cm}^2$

keV or less

large number of targets
(large target mass)

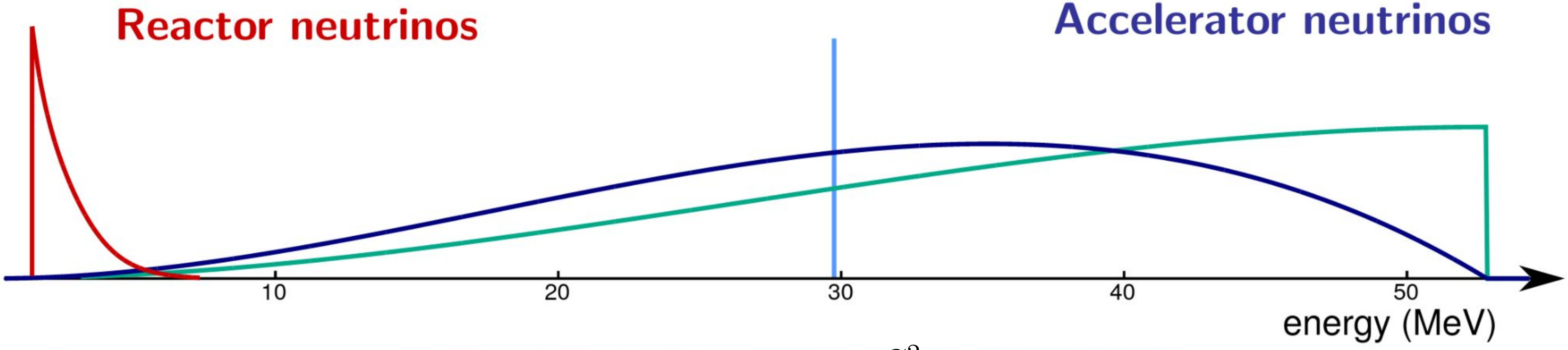




low-energy
detection threshold

Same challenge of Dark Matter experiments:
use same detector technologies!

Neutrino sources



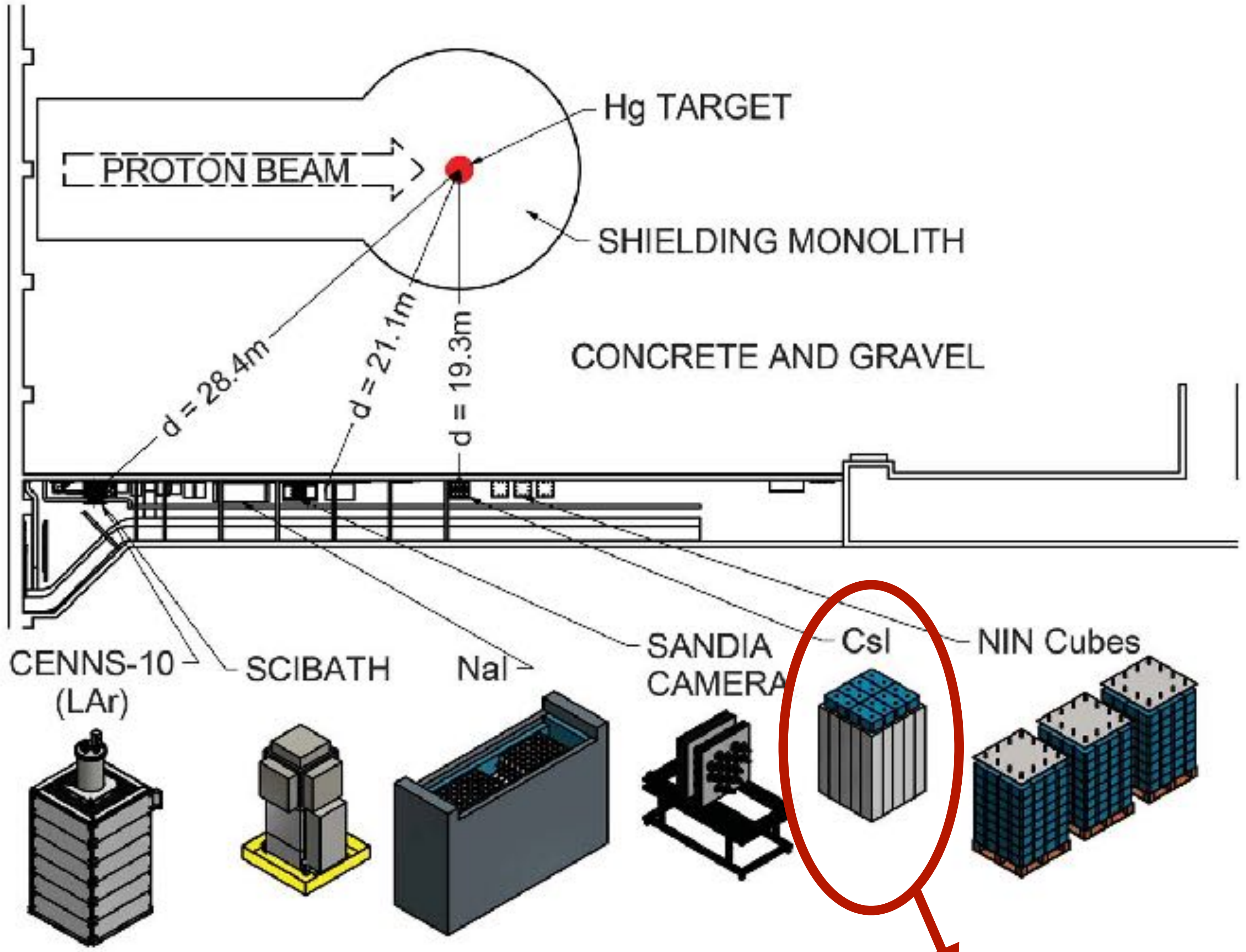
cross-section $\sigma_{\text{CE}\nu\text{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$

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

DISCOVERY

coherency $qR < 1 : \quad F(q^2) \rightarrow 1$

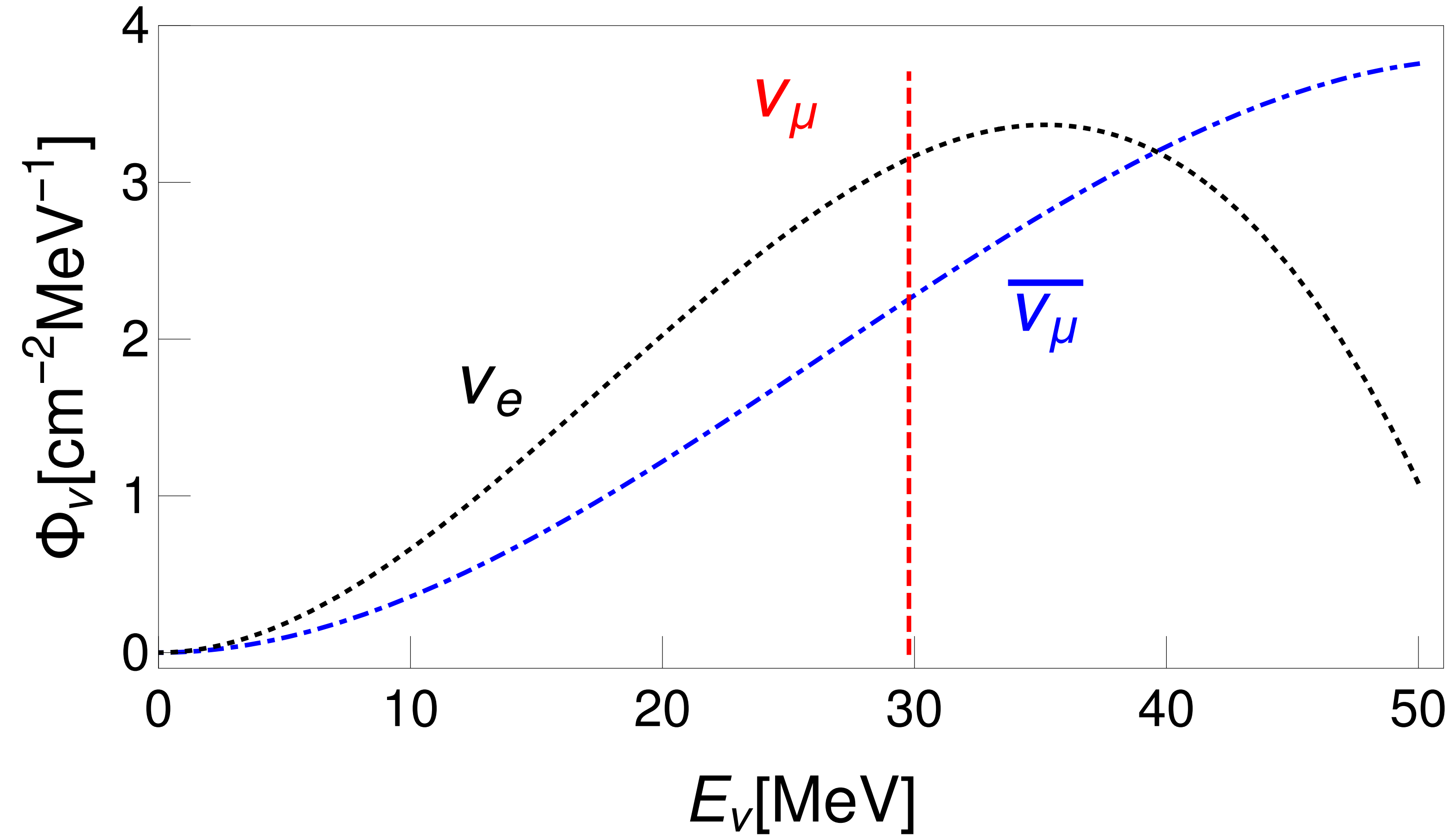
The discovery: COHERENT experiment



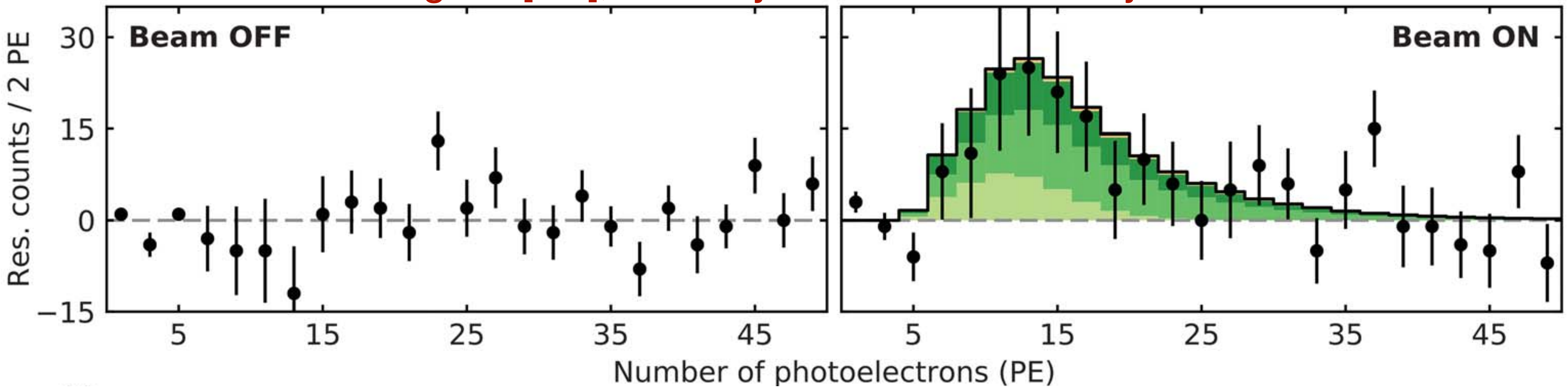
Spallation neutron source (SNS) at Oakridge:

5×10^{20} POT/day, 0.08 ν_μ/p,

60 Hz pulsed νs, 1 µs pulses of 1.7×10^{11} ν_μ/cm^2/s



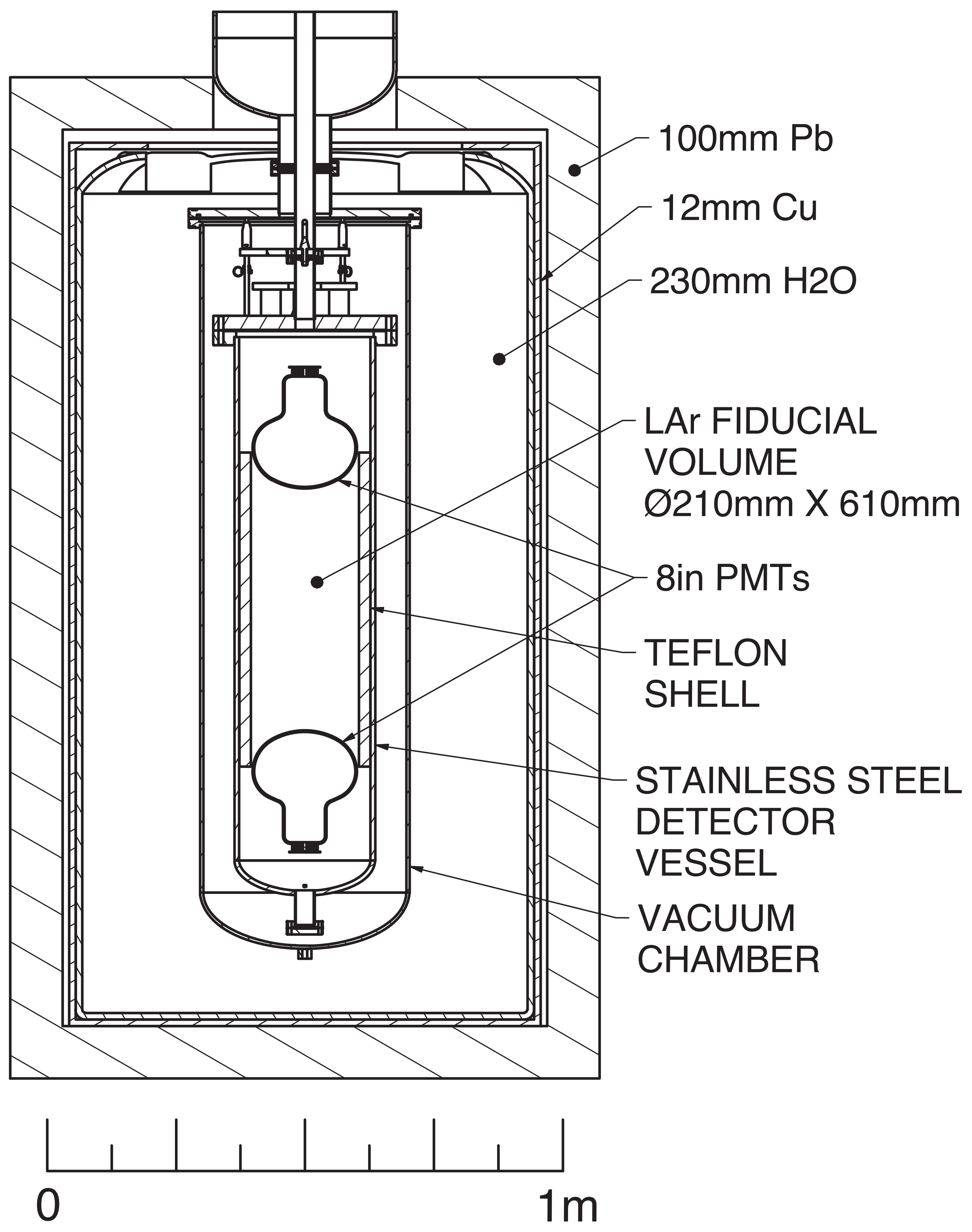
14.6 kg CsI[Na], 153 days beam off 308 days beam on

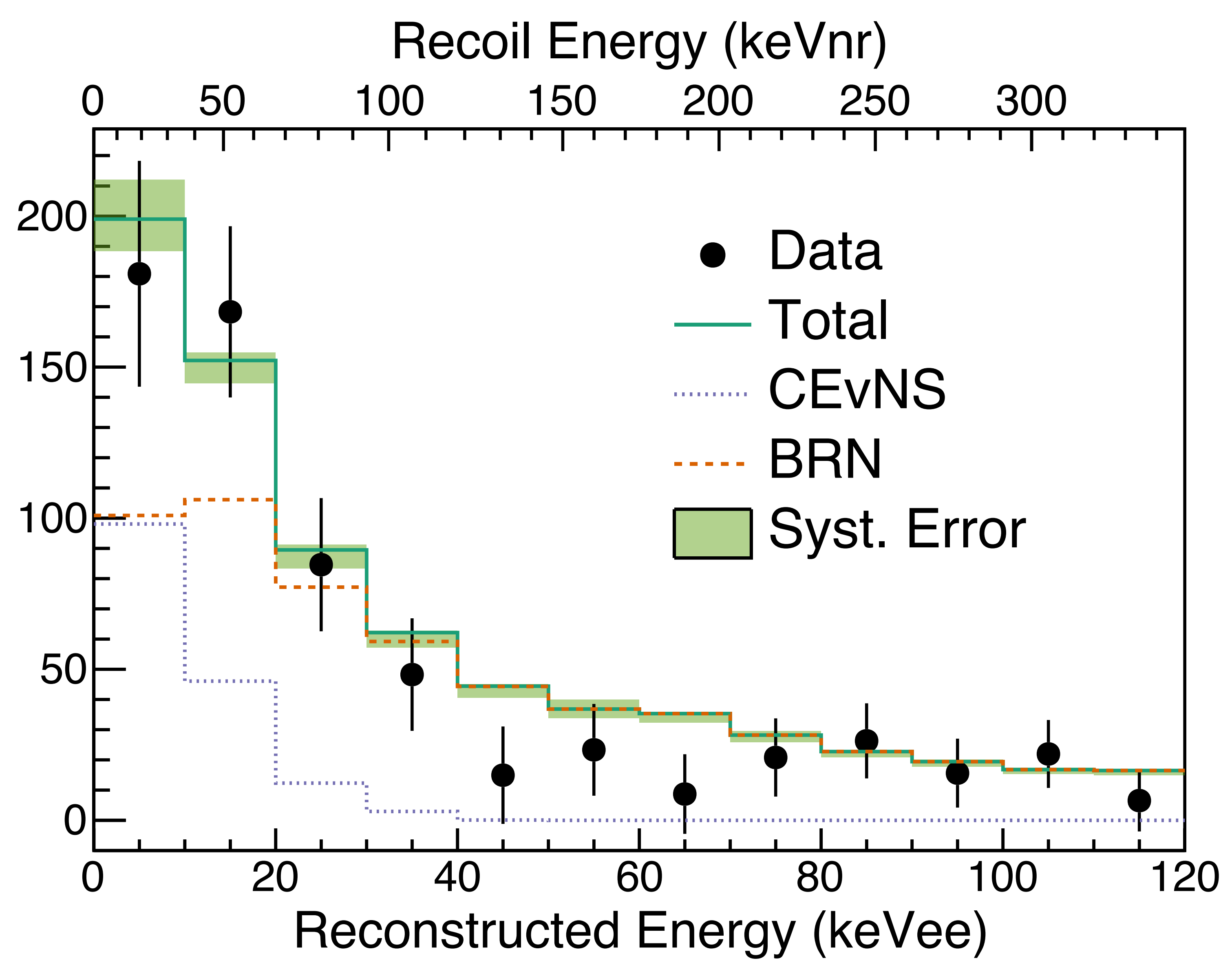


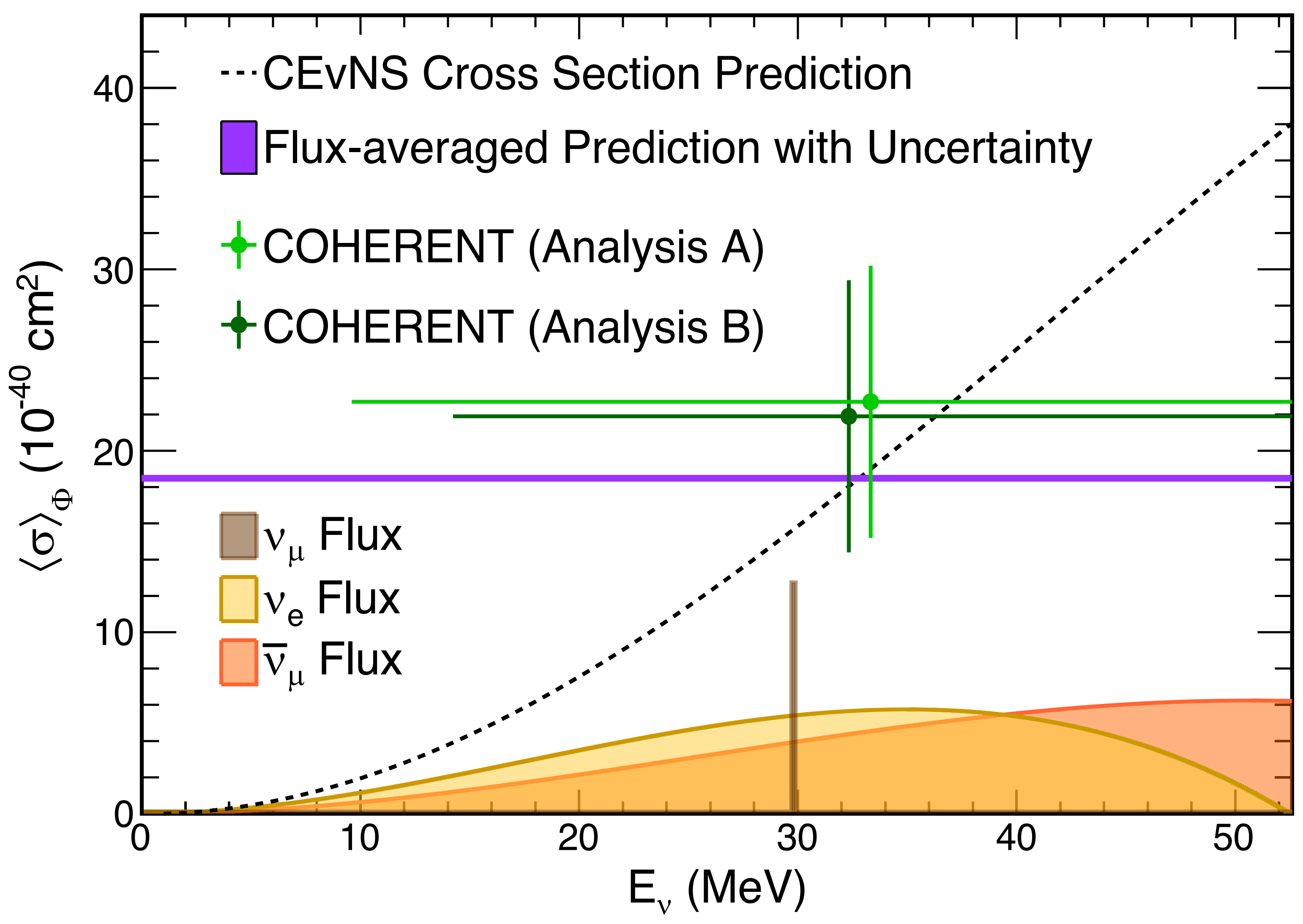
D. Akimov, et al, Science 357 (2017) 1123

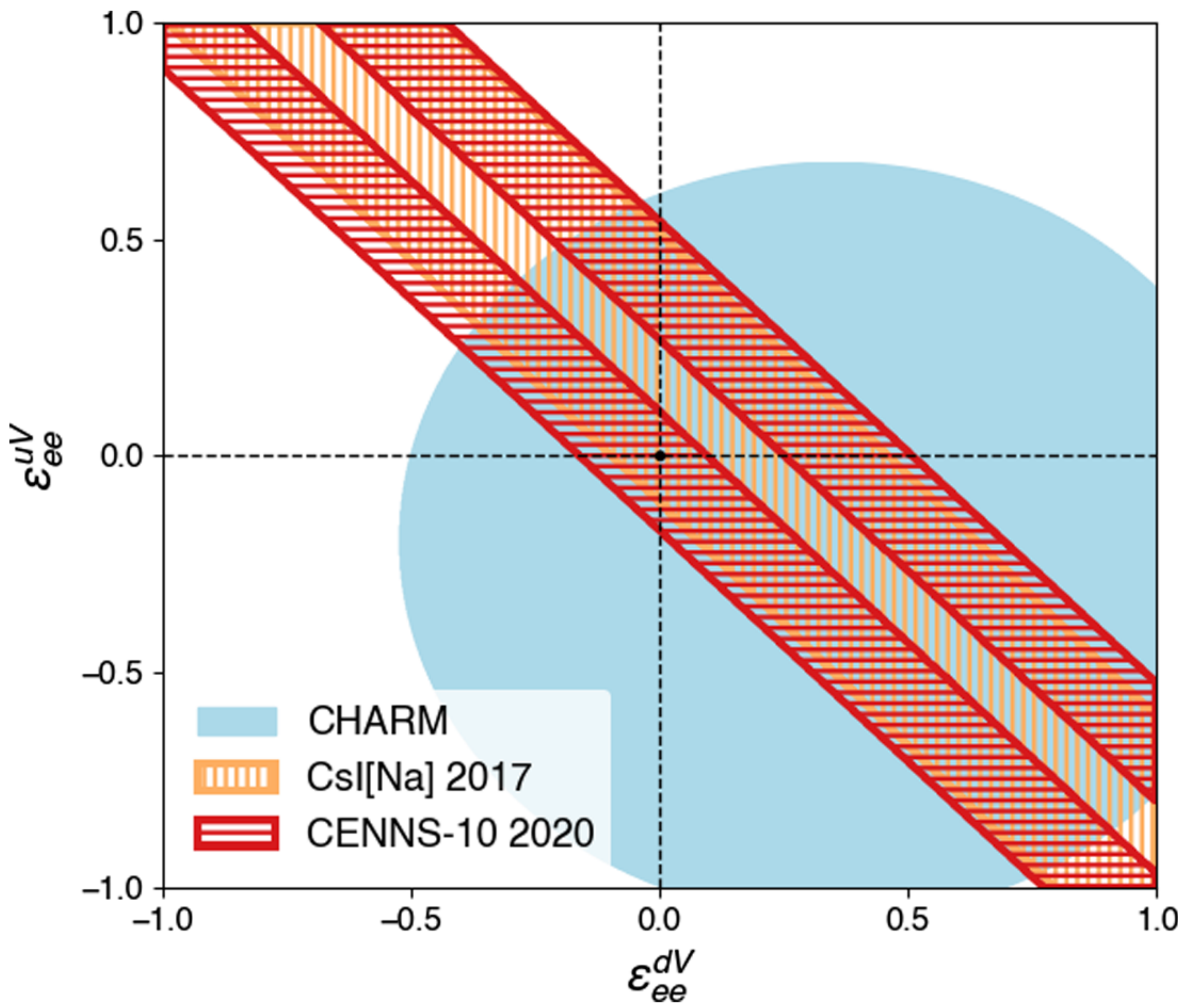
COHERENT (LAr)

24 kg of Liquid argon



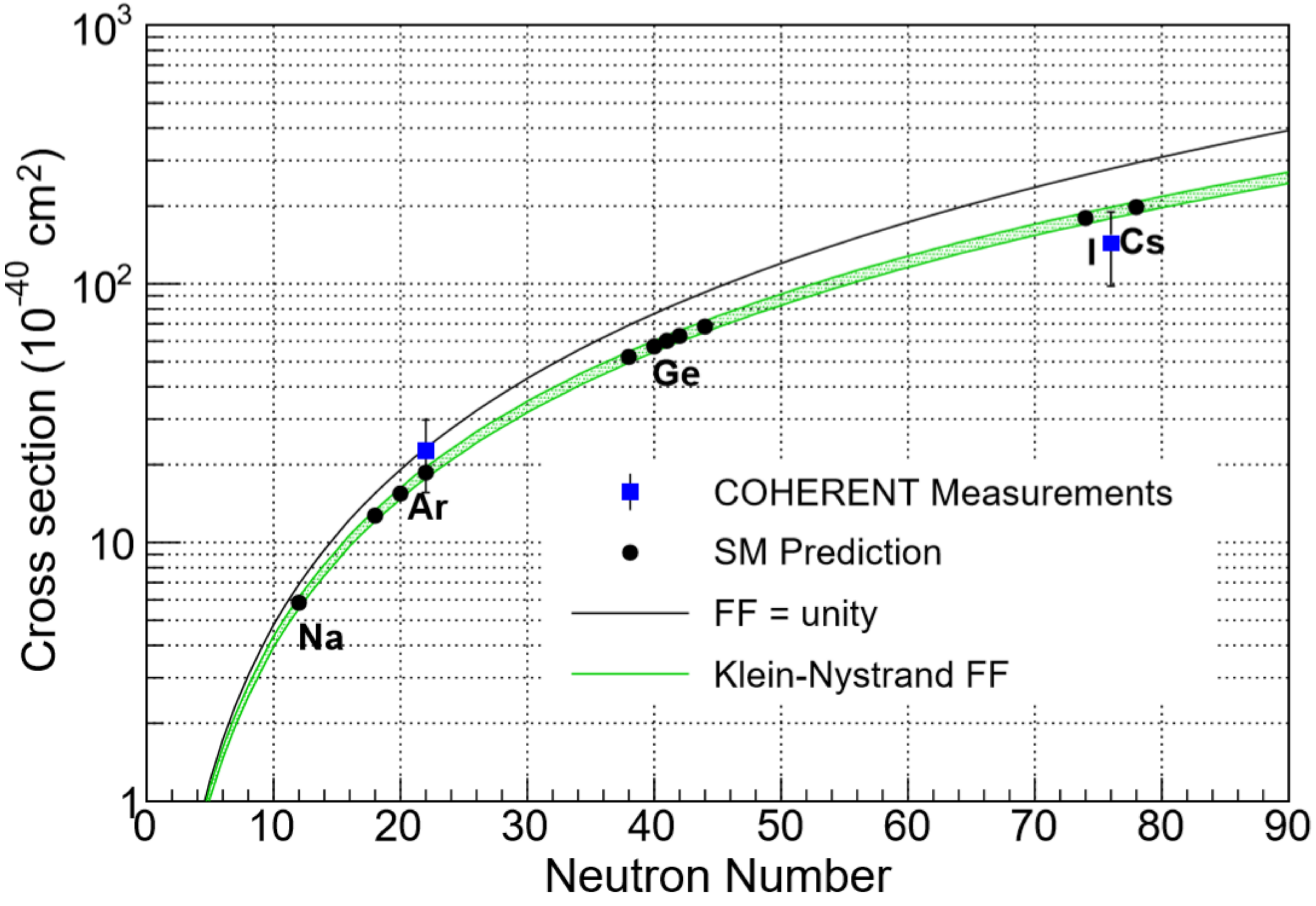


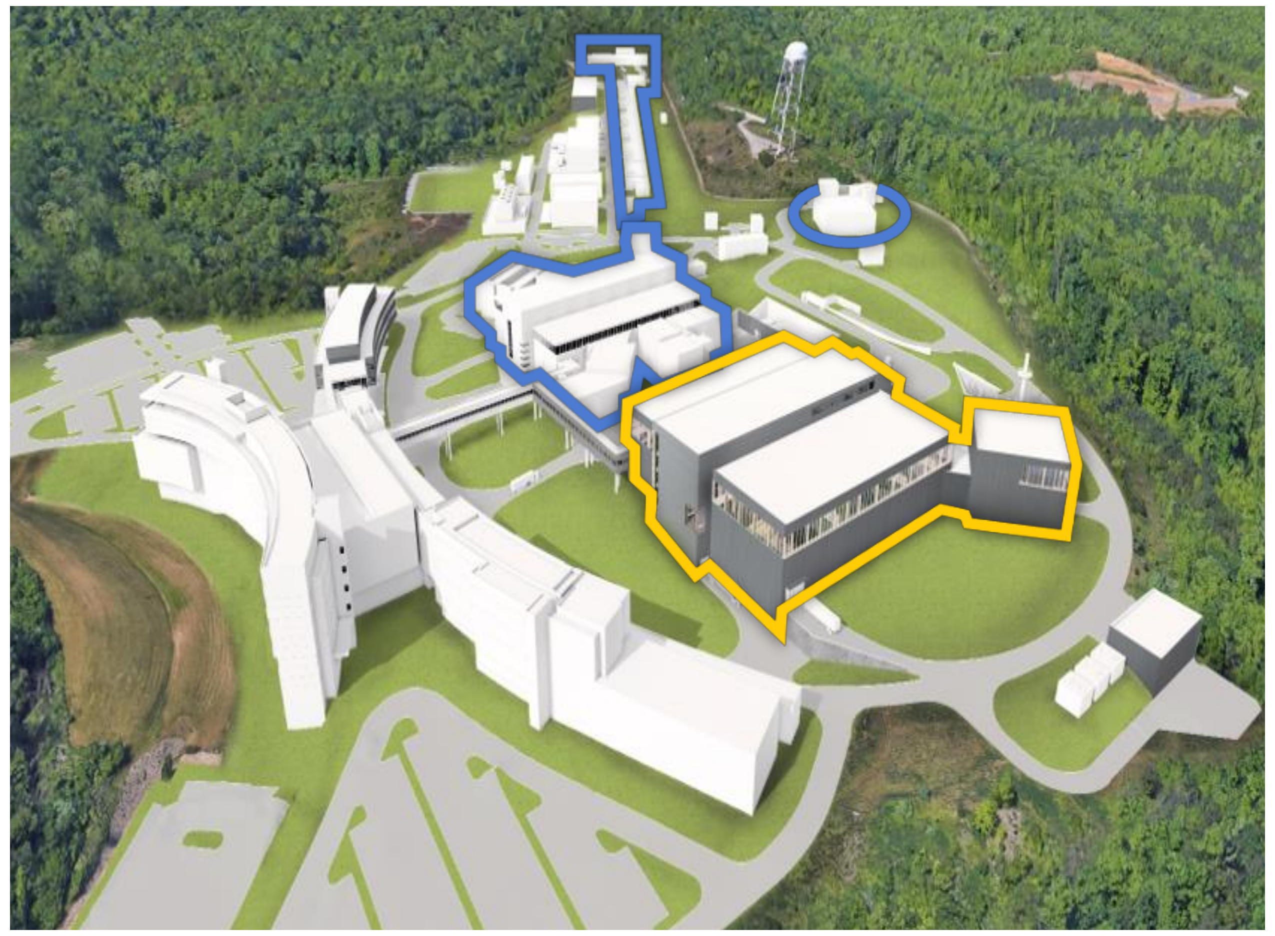




D. Akimov, et al, Phys. Rev. Lett 126 (2021) 012002

COHERENT future



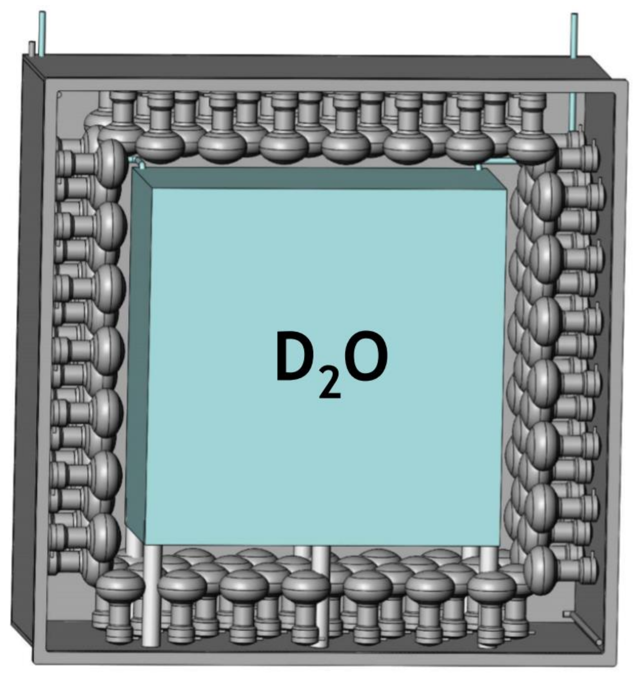


	2015	2023	2032
	First light	Precision at Neutrino Alley	STS
Ar	24 kg	610 kg	10000 kg
Ge		18 kg	
CsI	14 kg	10 kg*	700 kg*

*Cryogenic scintillator with sub-keV threshold

Modular NaI[Tl] Array

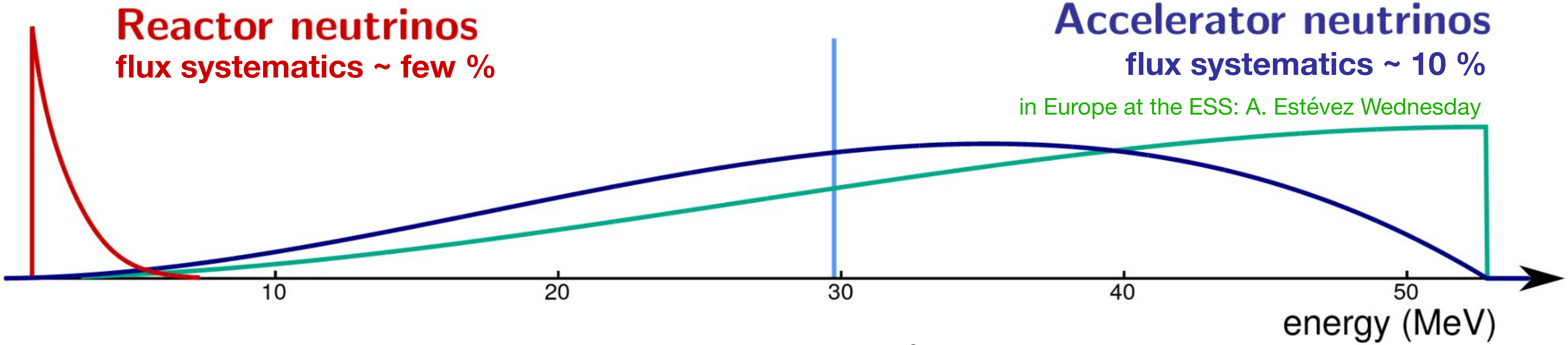
Ton-scale array to measure CEvNS on ^{23}Na and CC on ^{127}I cross sections.



Heavy Water Cerenkov

Use known ν_e – d cross section (2-3%) to constrain ν–flux normalization at SNS

Neutrino sources: precision at reactors



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

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

PRECISION

coherency $qR < 1 : \quad F(q^2) \rightarrow 1$

DRESDEN result

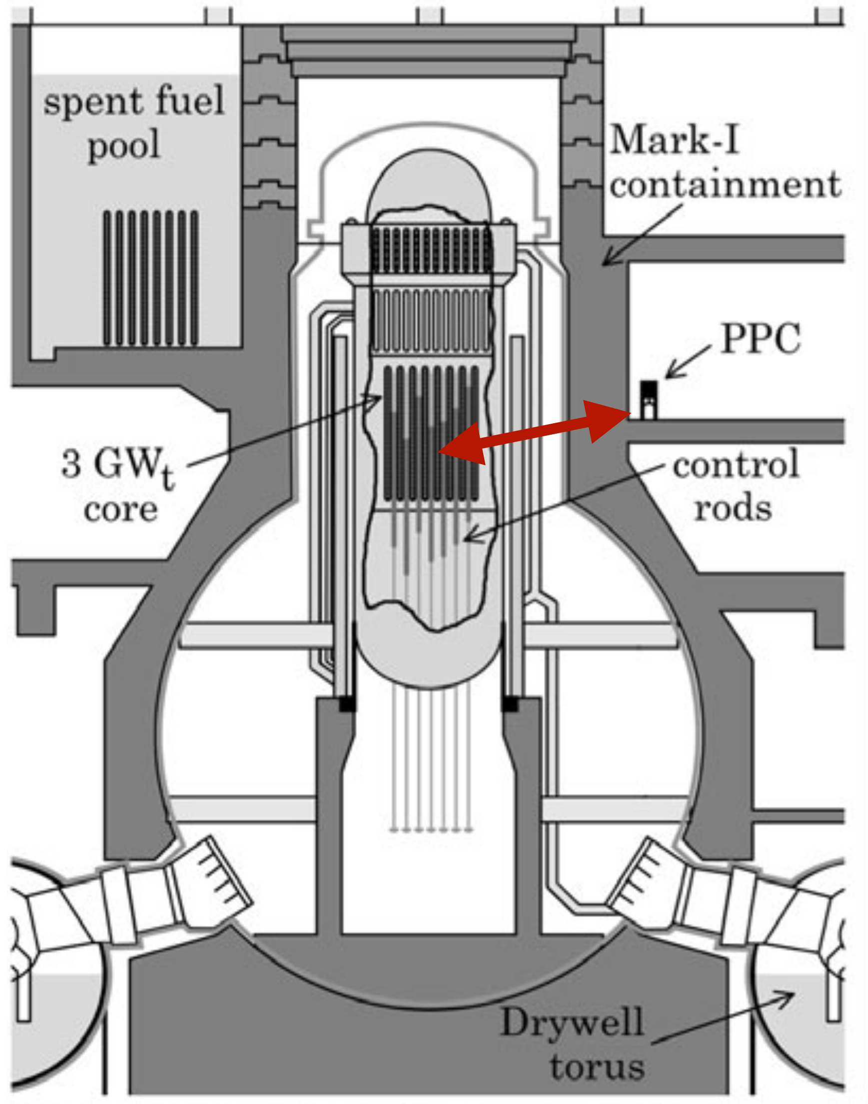
PHYSICAL REVIEW LETTERS **129,** 211802 (2022)

Measurement of 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, Connecticut 06450, USA*
[2]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Pacific Northwest National Laboratory, Richland, Washington 99354, USA*

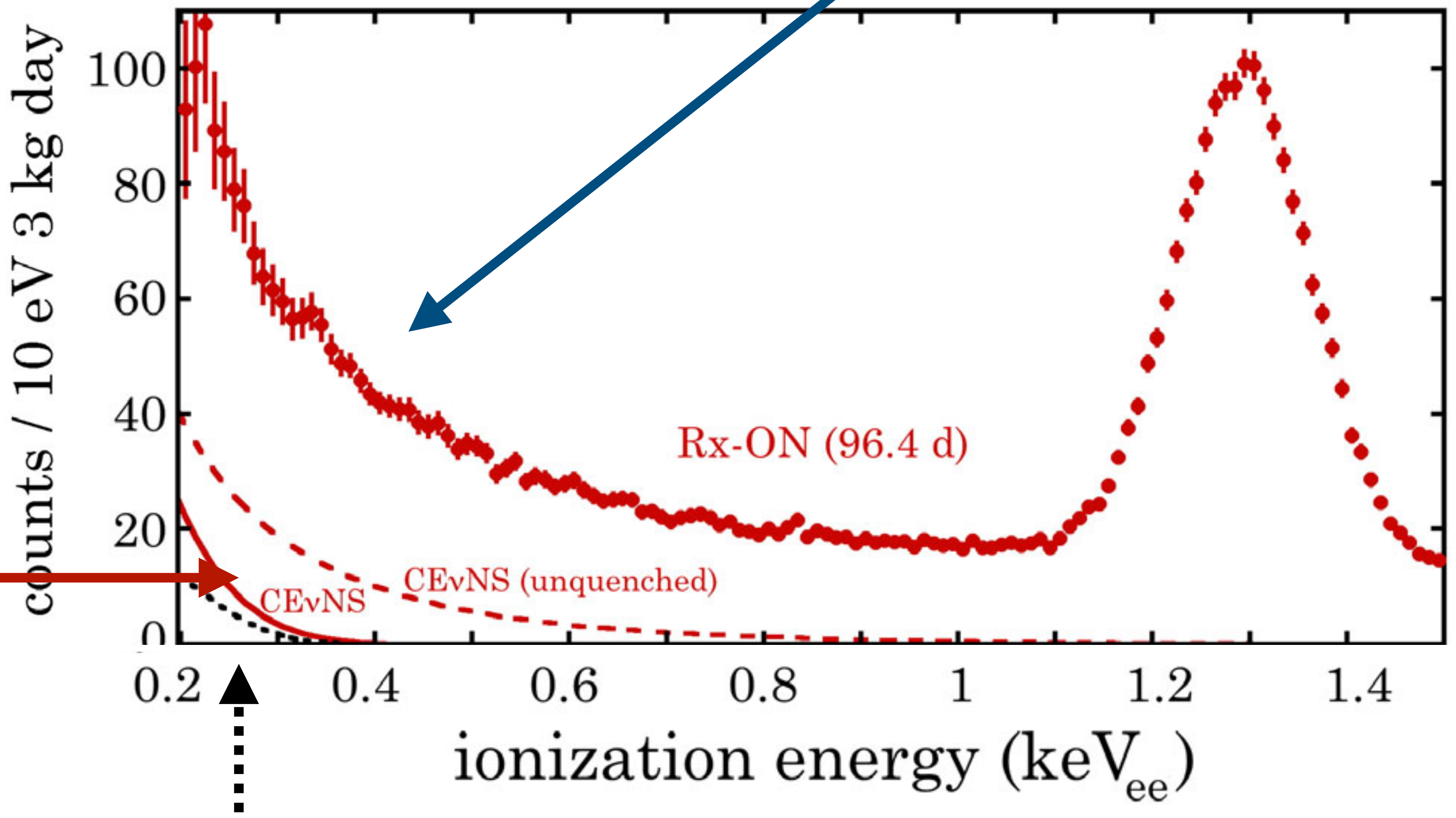
(Received 29 November 2021; revised 21 March 2022; accepted 20 September 2022; published 17 November 2022)

The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEνNS signal is in good agreement with expectations based on a recent characterization of germanium response to sub-keV nuclear recoils. Deviations of order 60% from the standard model CEνNS prediction can be excluded using present data. Standing uncertainties in models of germanium quenching factor, neutrino energy spectrum, and background are examined.



Detector baseline: 10.4 m
$4.8 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$

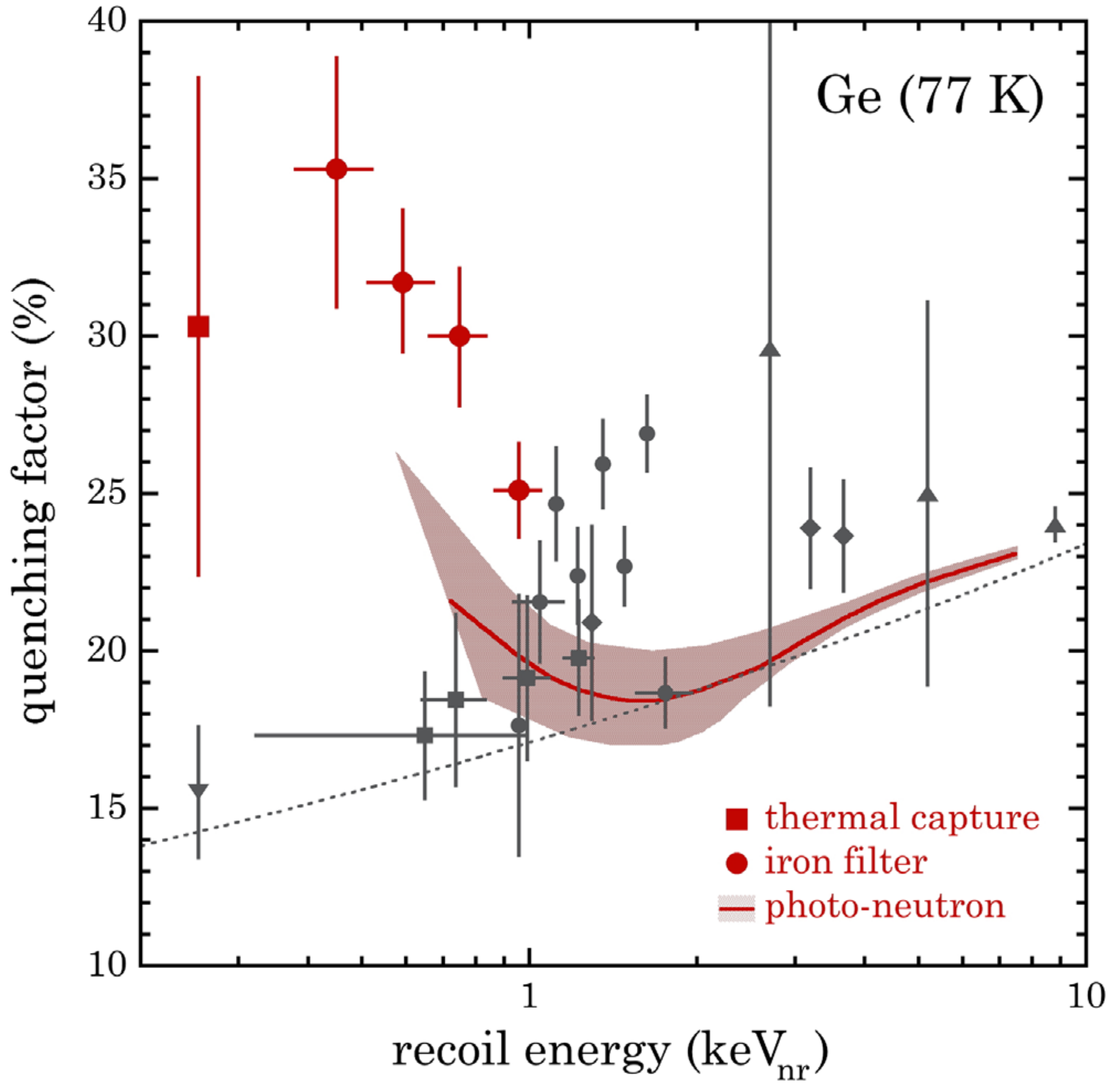
Reactor-induced background from epithermal neutrons



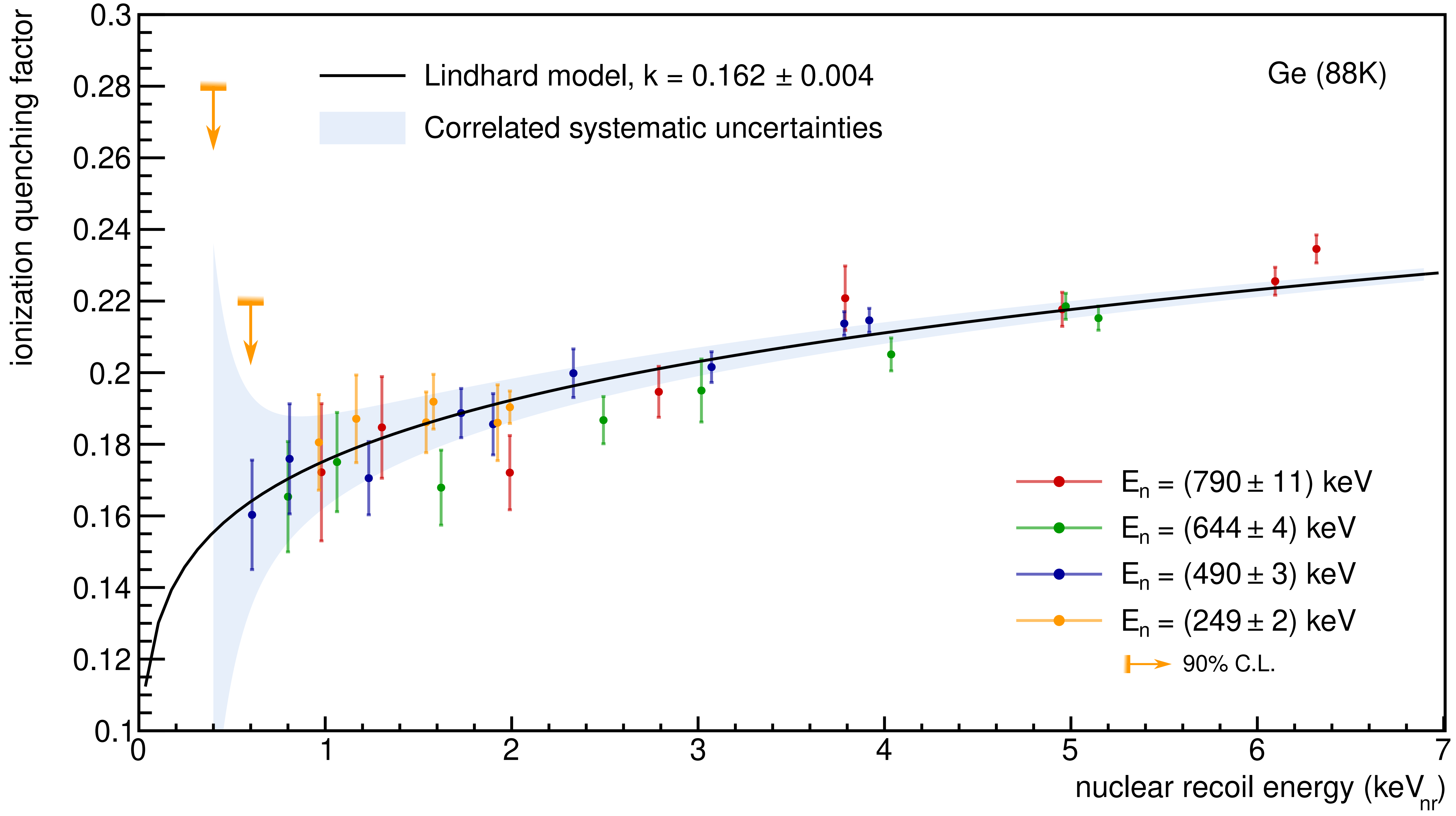
CEvNS signal with newly measured quenching factors (2x higher than other literature)

Derived background from ^{71}Ge M-Shell EC

Controversy on quenching factors

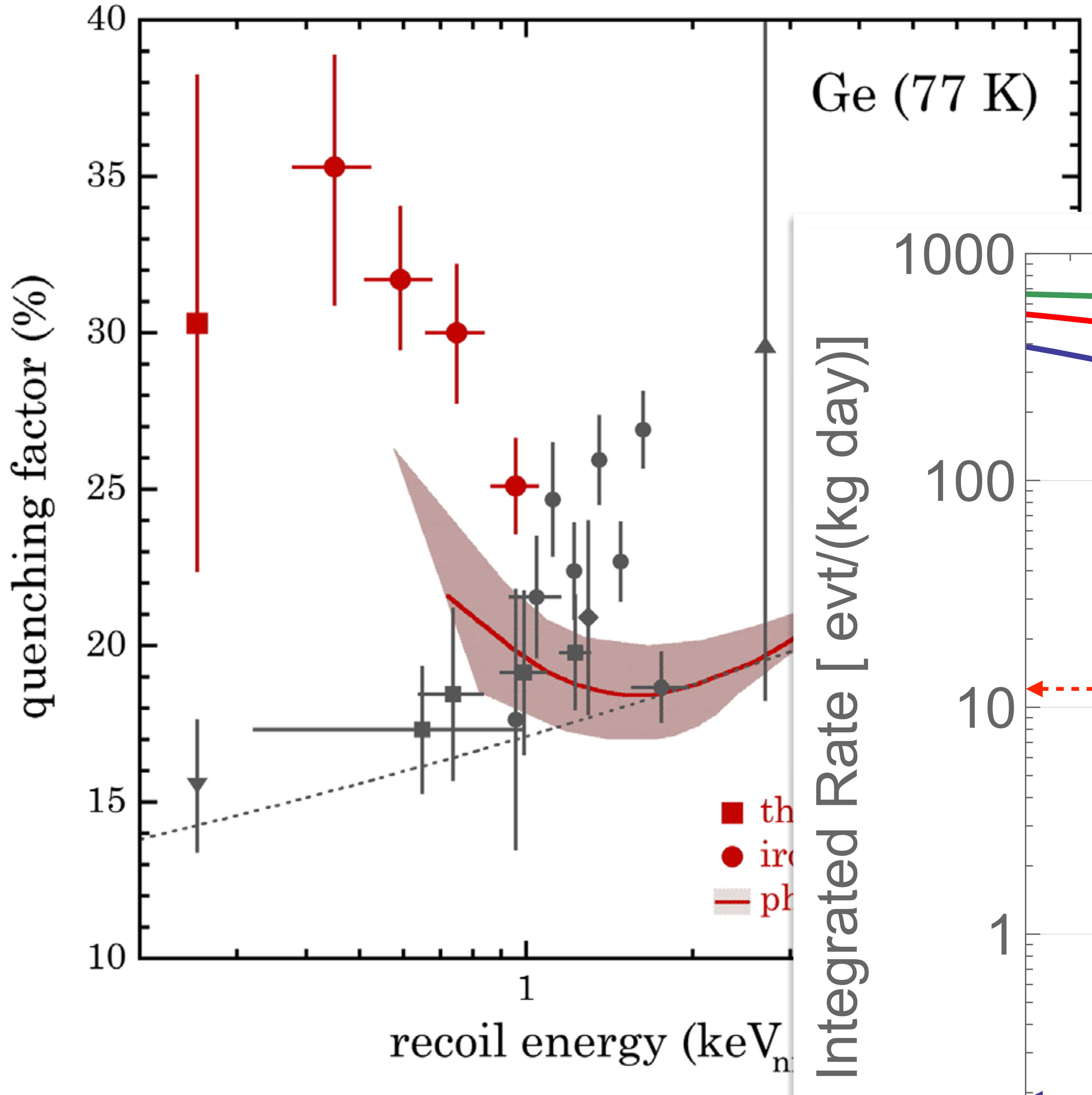


J. I. Collar, A. R. L. Kavner, and C. M. Lewis, Phys. Rev. D 103, 122003 (2021)

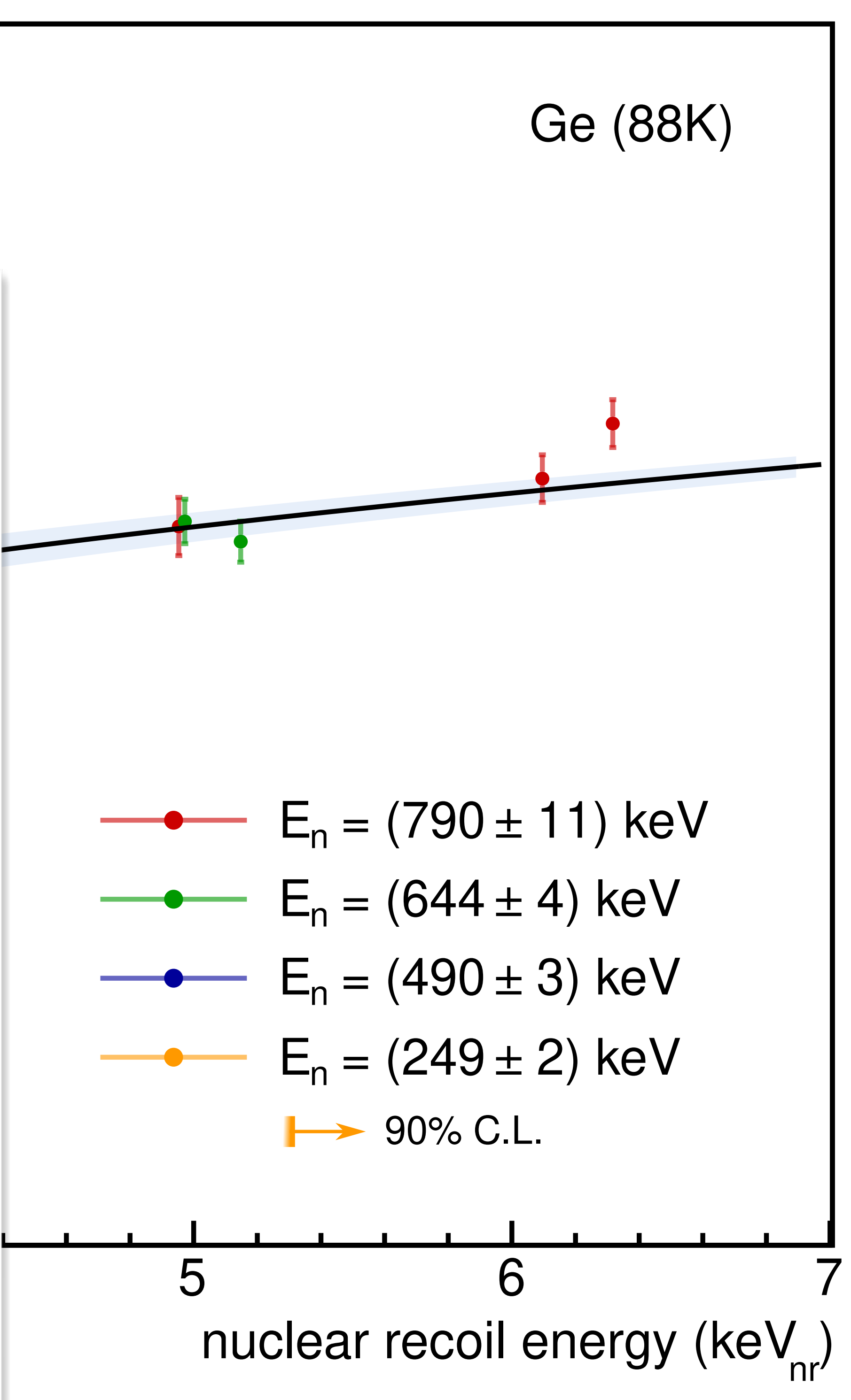


A. Bonhomme, et al, Eur. Phys. J. C 82, 815 (2022)

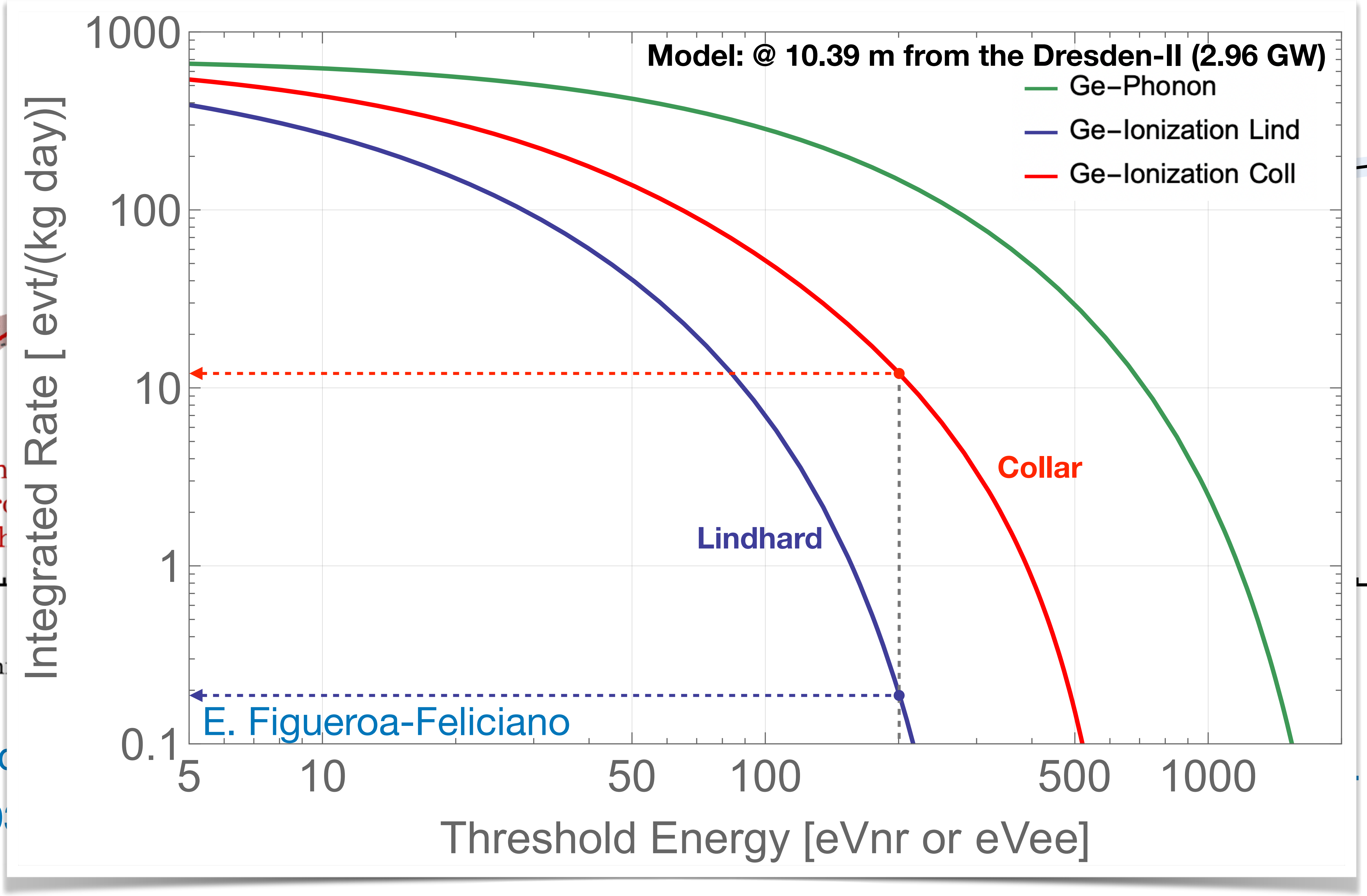
Controversy on quenching factors



J. I. Collar, A. R. L. Kavner, and
Phys. Rev. D 103, 12200

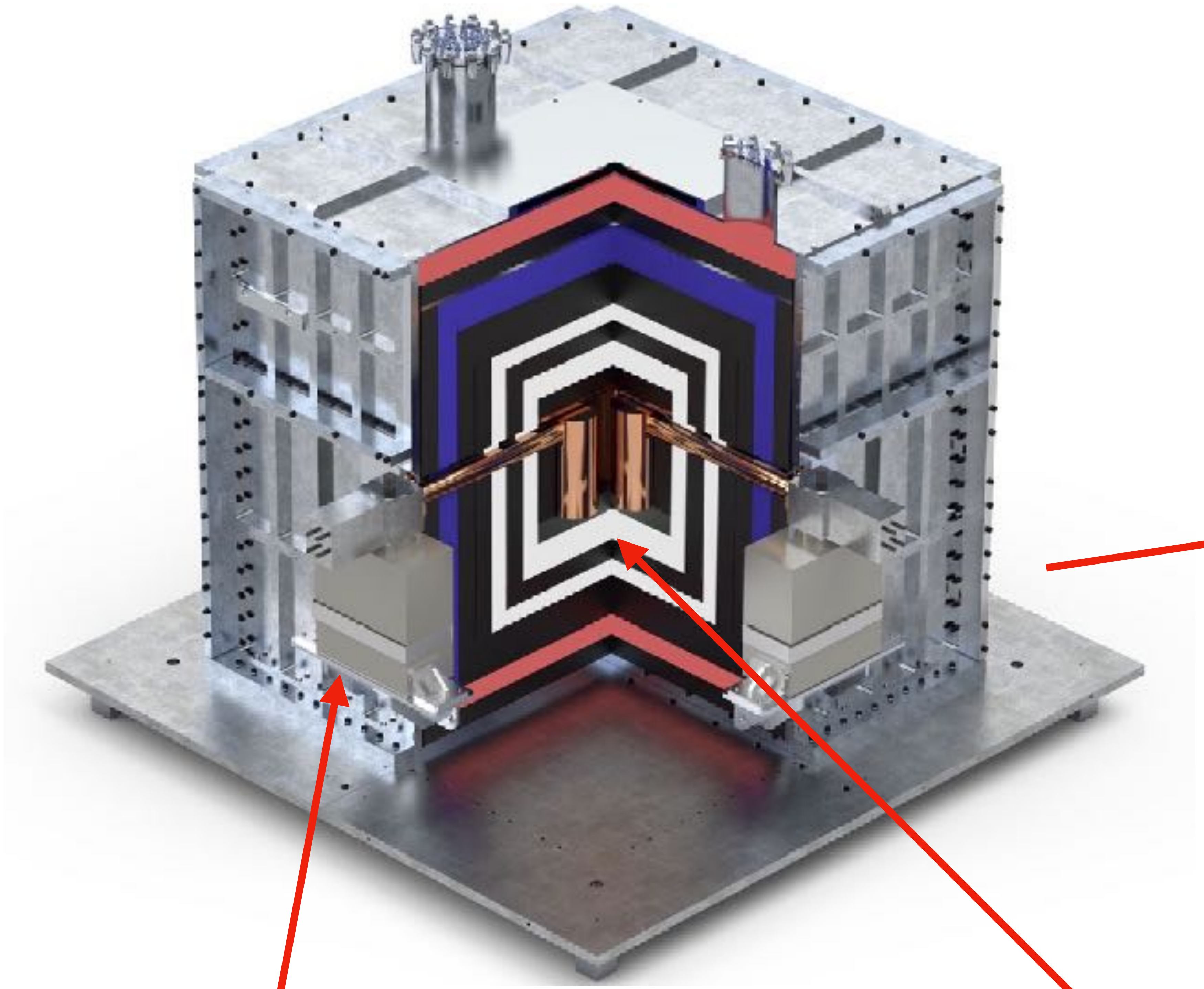


C 82, 815 (2022)



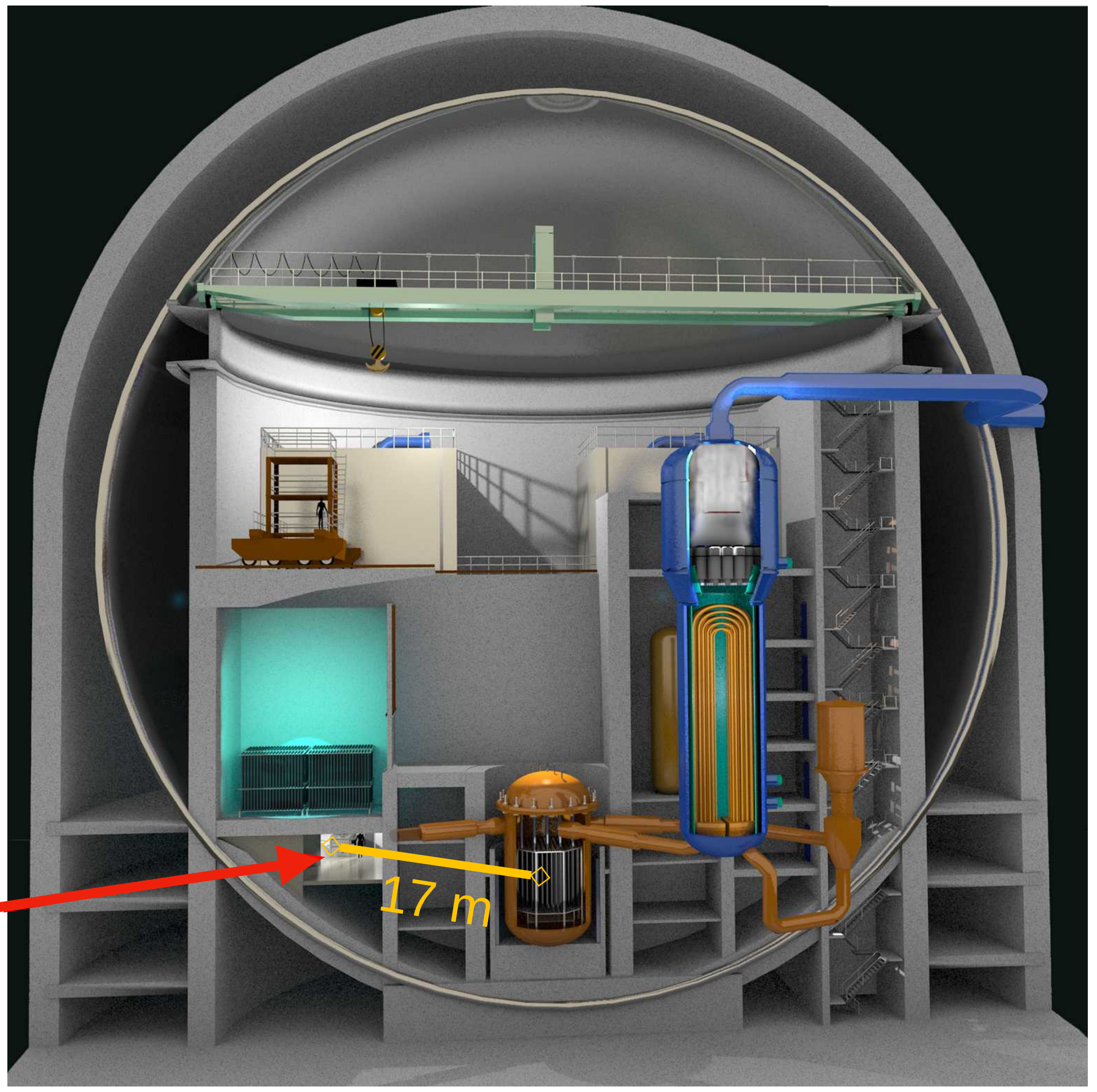
the signal observed by DRESDEN
depends on the true value of the quenching

CONUS

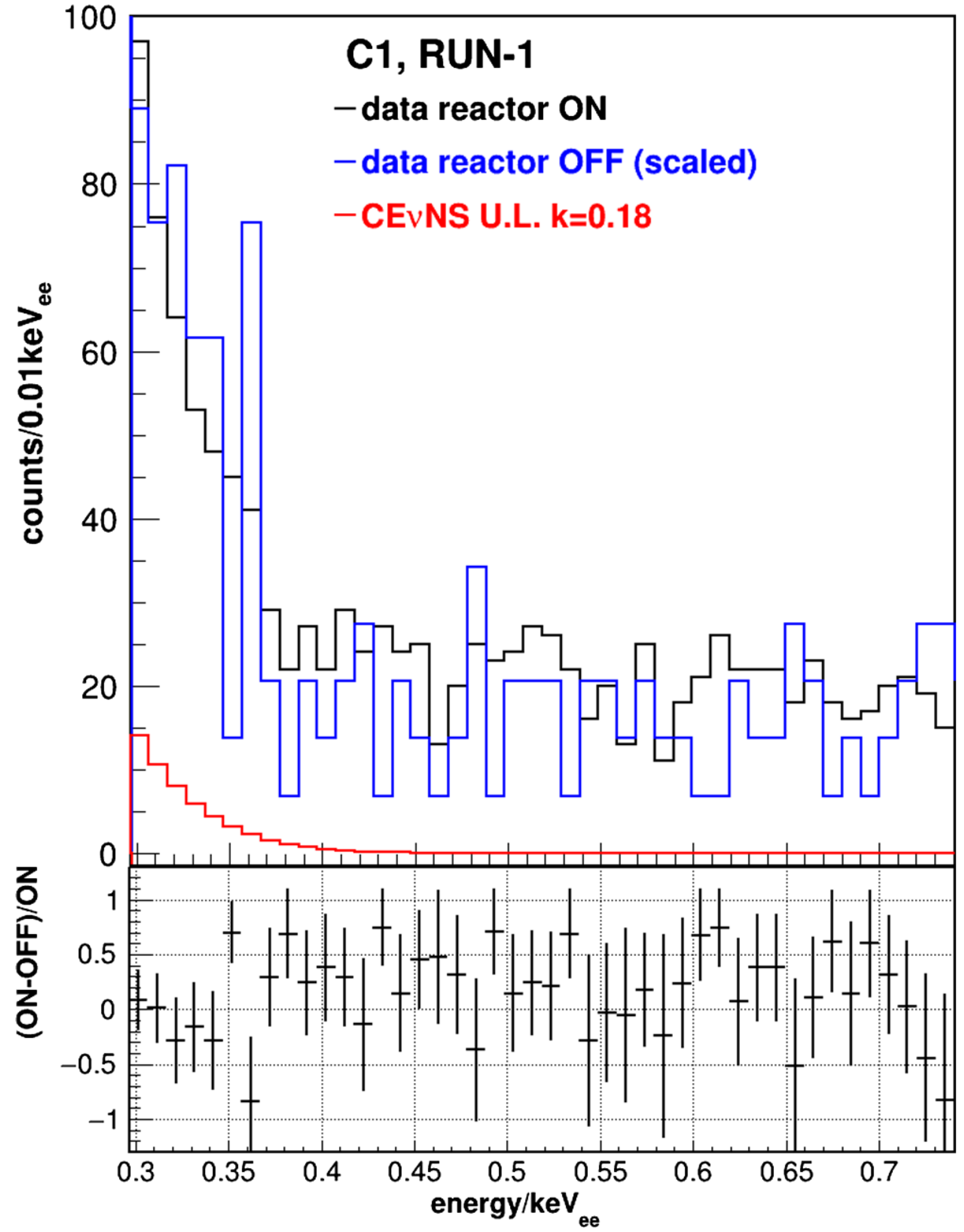


Shielding (~10 counts / keV kg d):
- Steel / Pb (black)
- Polyethilene (Red)
- B-doped PE (white)
- Plastic scintillator (blue)

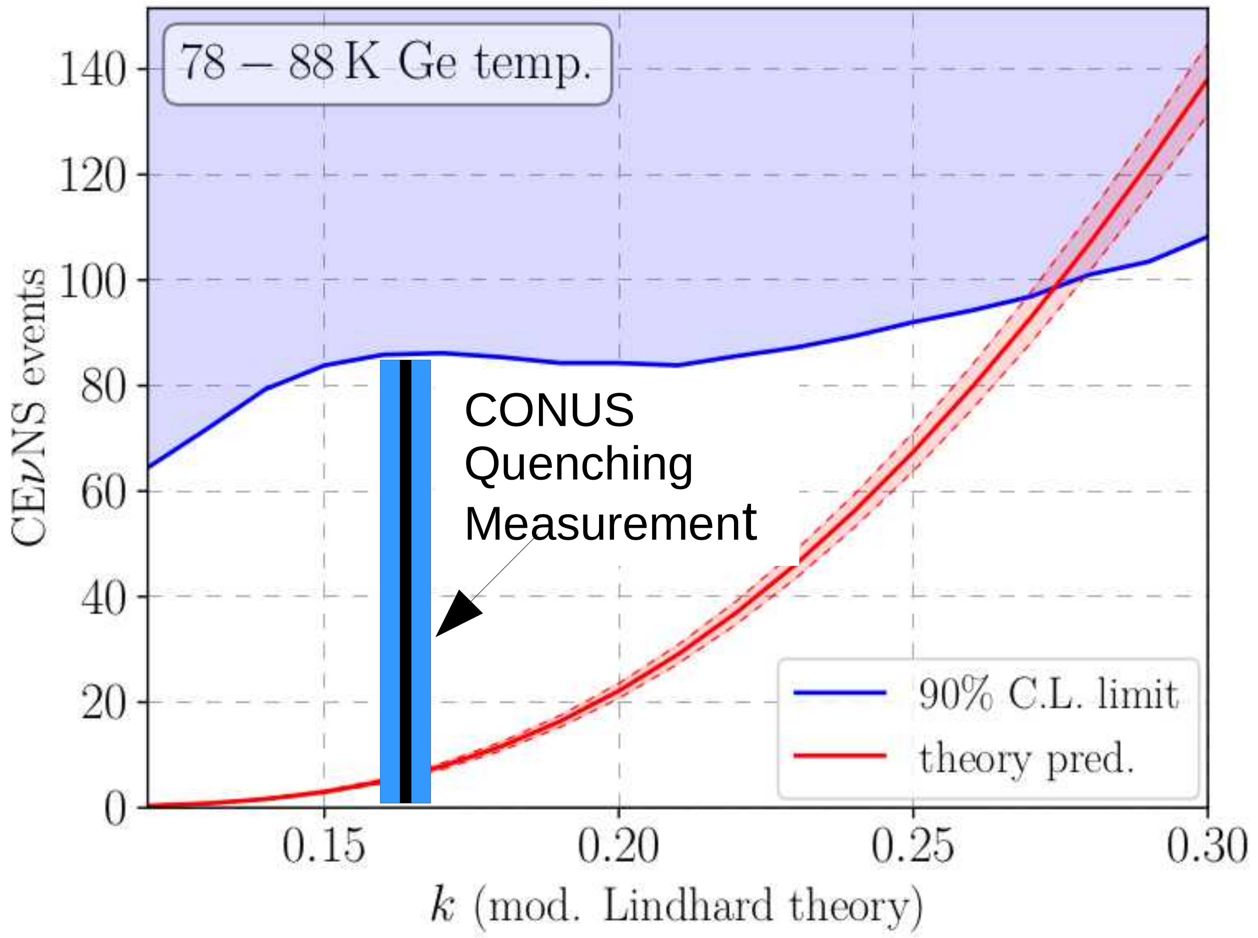
Germanium detector
Mass: 3.72 kg
baseline: 17 m
$2.3 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$



Brokdorf reactor in Germany
3.9 GWth
Operated until 12/2021

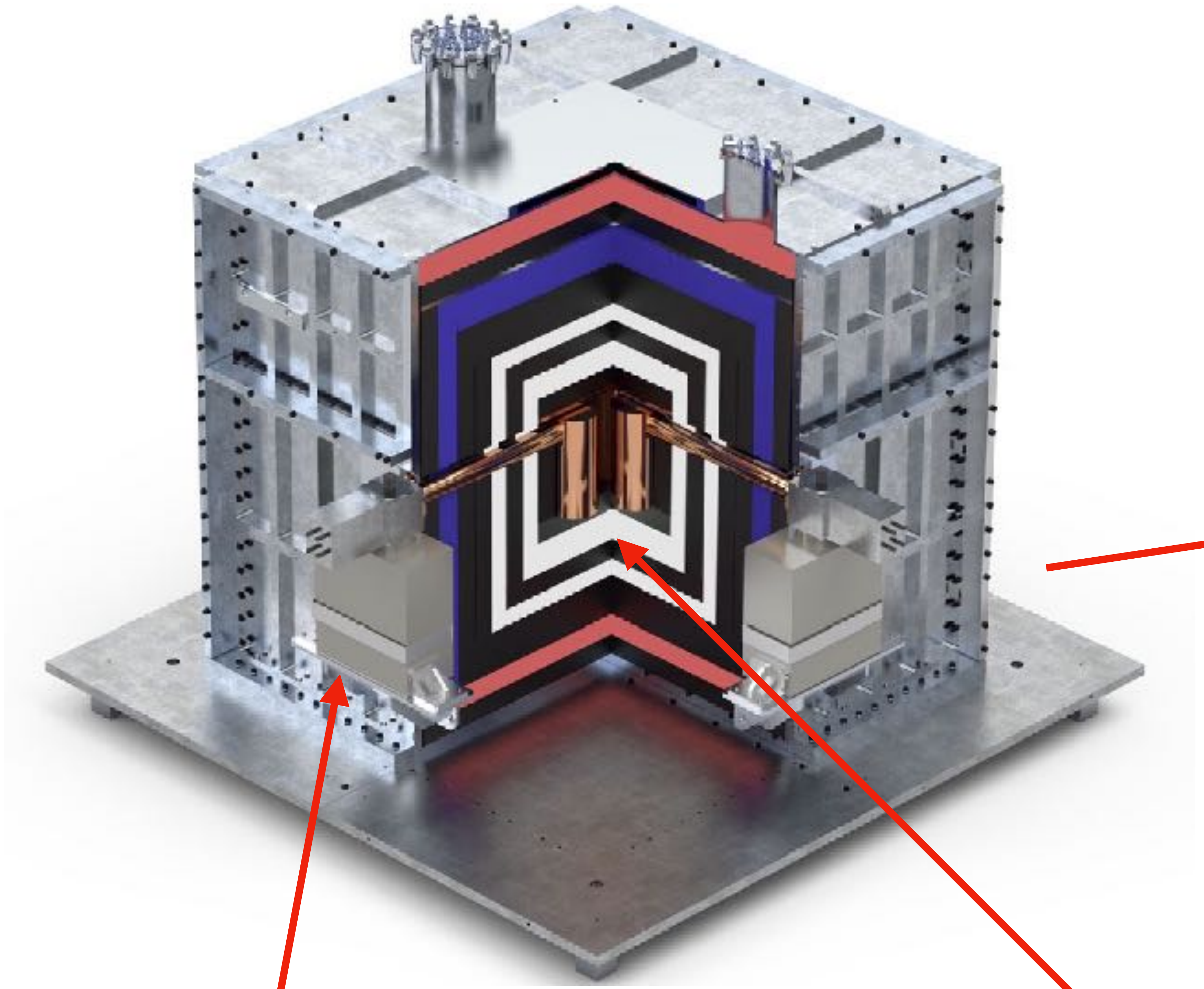


ON: 59 kg*d OFF: 249 kg*d



H. Bonet, et al, Phys. Rev. Lett. 126 (2021) 041804

CONUS



Shielding (~10 counts / keV kg d):
- Steel / Pb (black)
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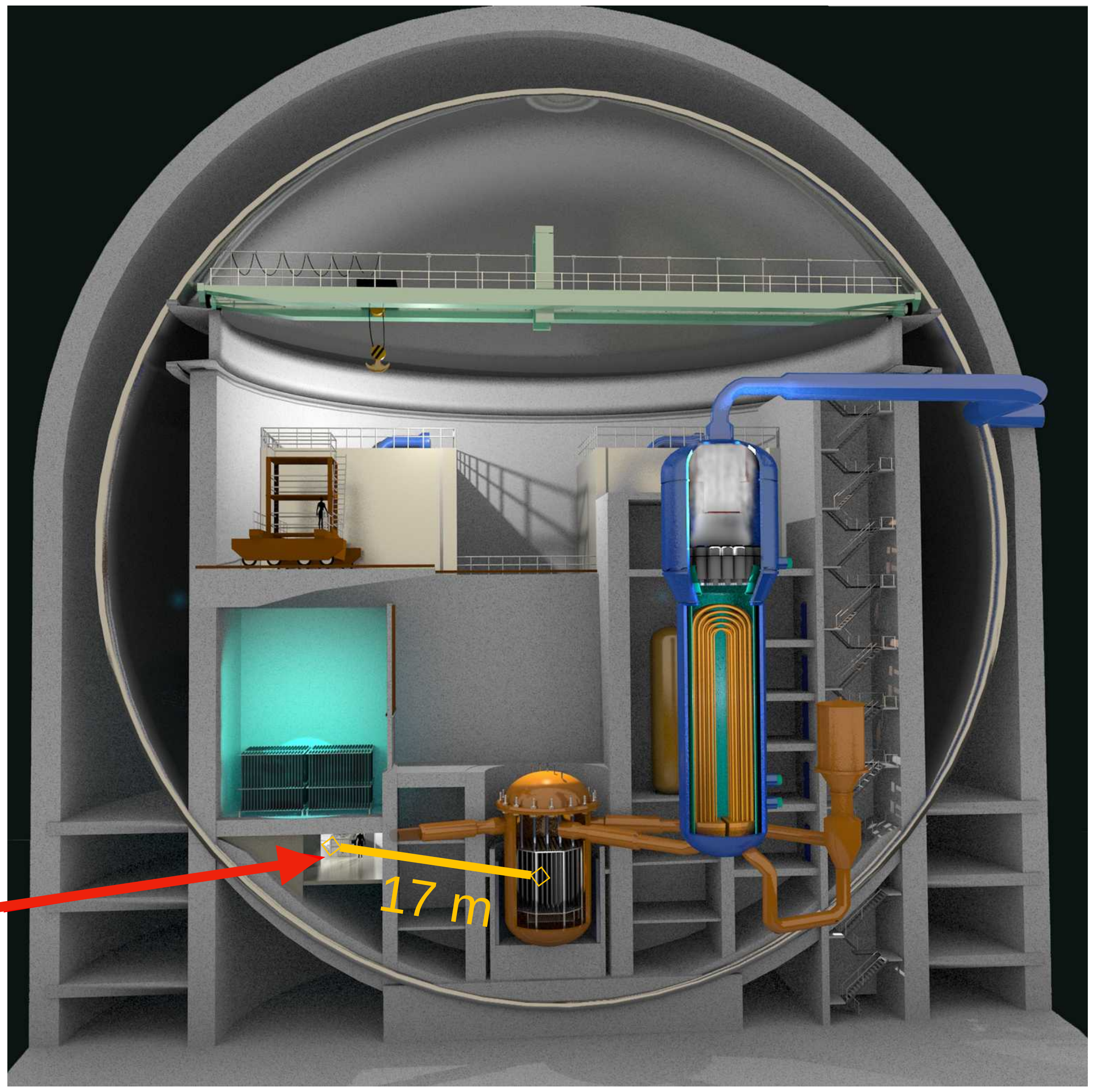
- Plastic scintillator (blue)

Germanium detector
Mass: 3.72 kg
baseline: 17 m
$2.3 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$



Brokdorf reactor in Germany
3.9 GWth
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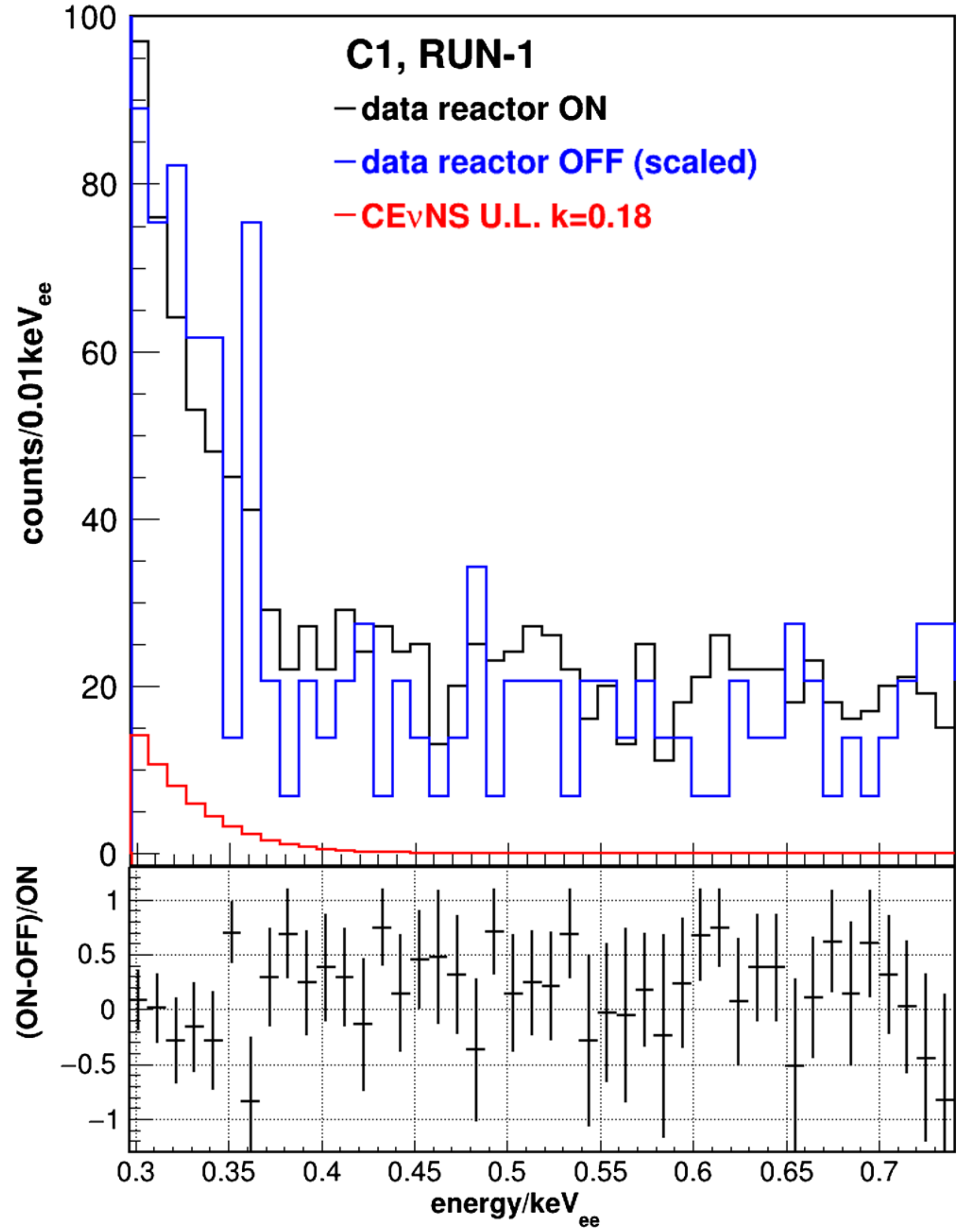
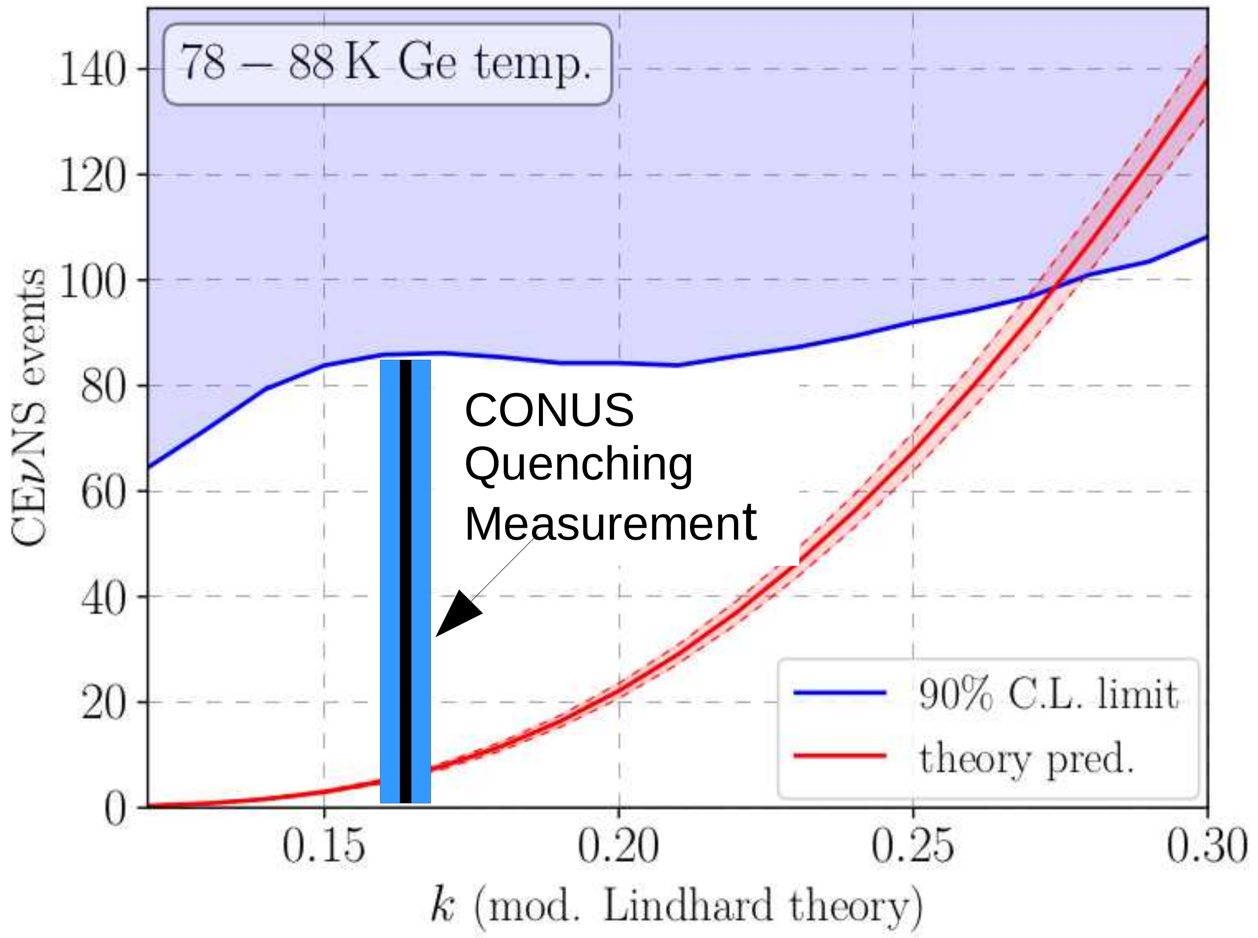


ON: 59 kg*d OFF: 249 kg*d

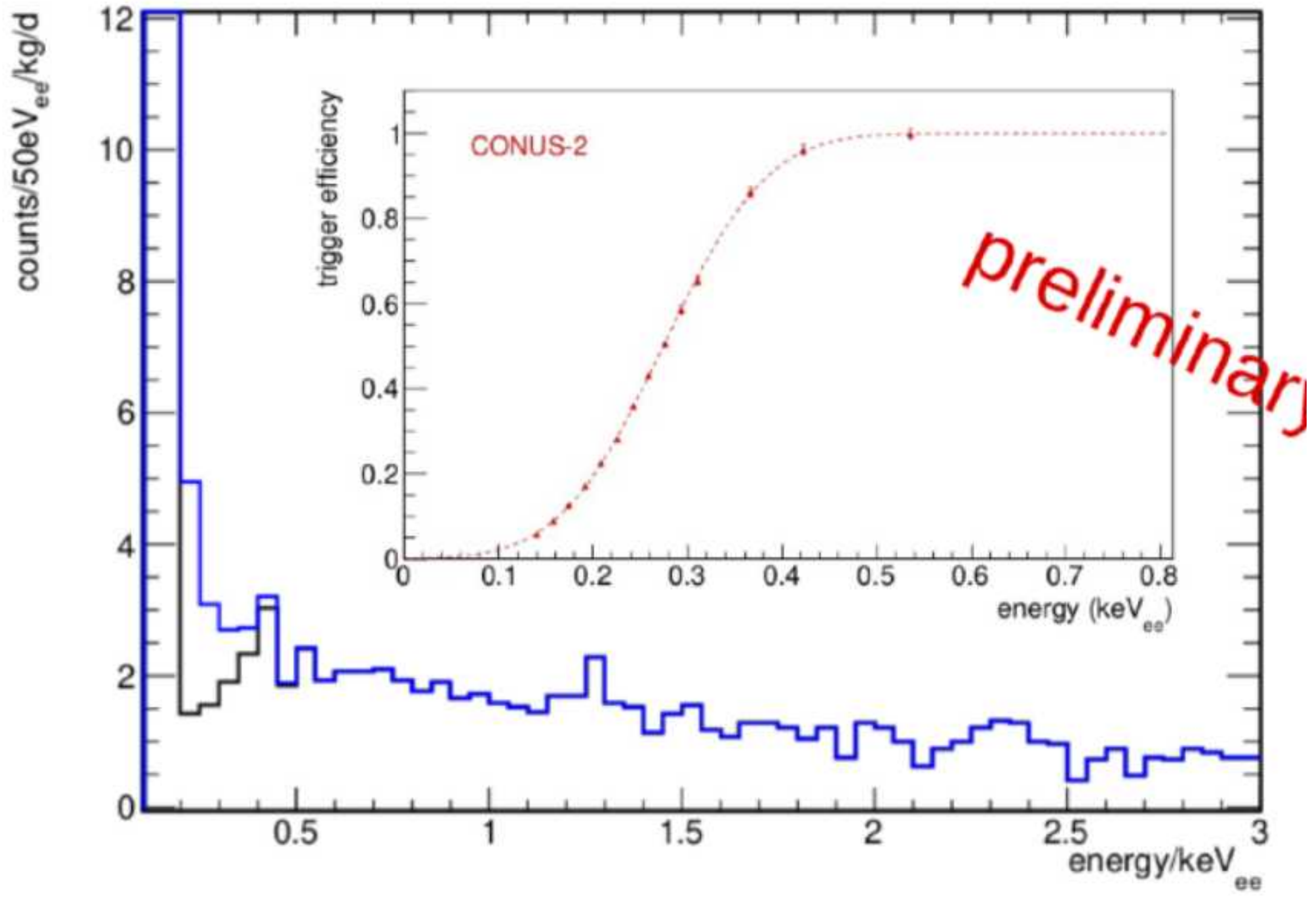


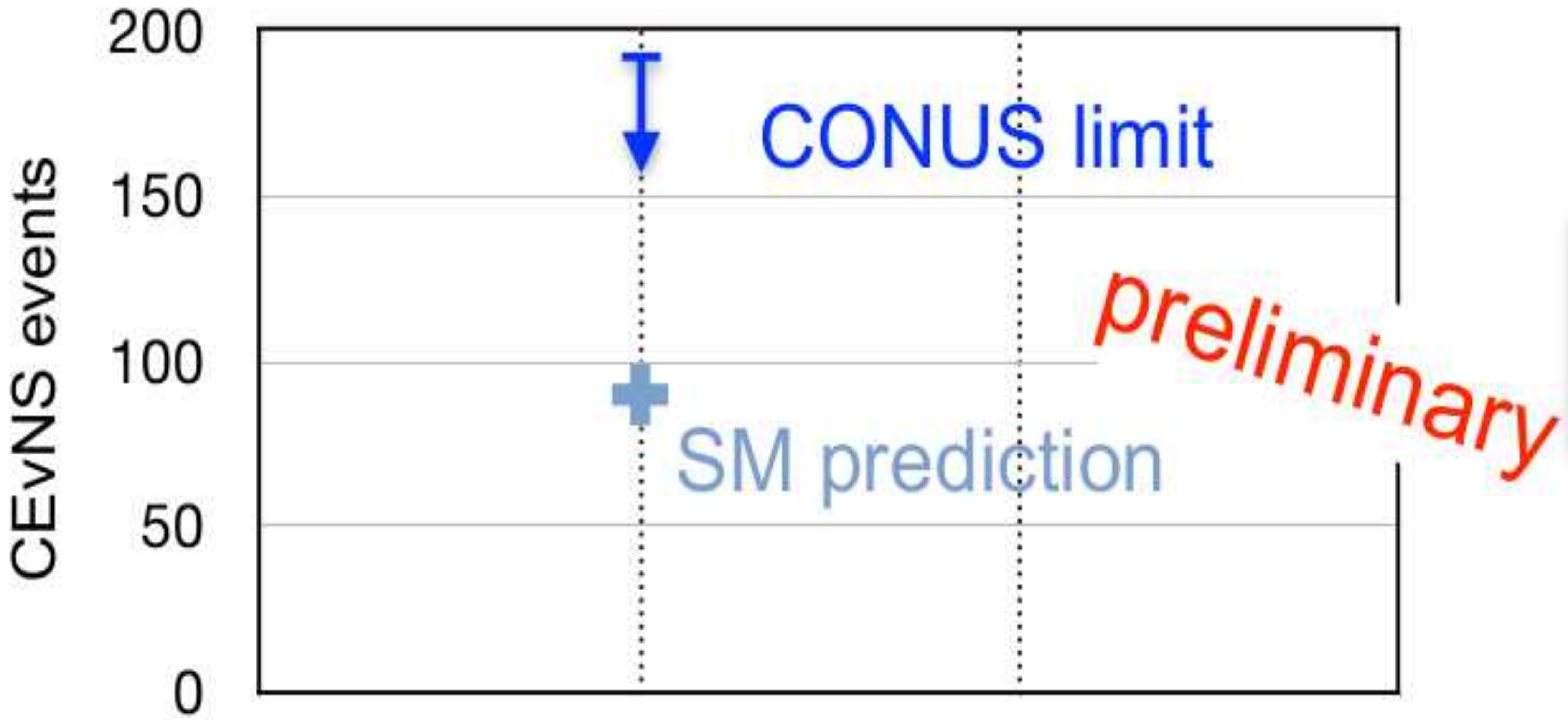
null result

CEvNS < 0.4 c / kg d

H. Bonet, et al, Phys. Rev. Lett. 126 (2021) 041804

CONUS Update, threshold from 300 to 200 eV





Limit 2x higher than SM

E Sanchez, today afternoon

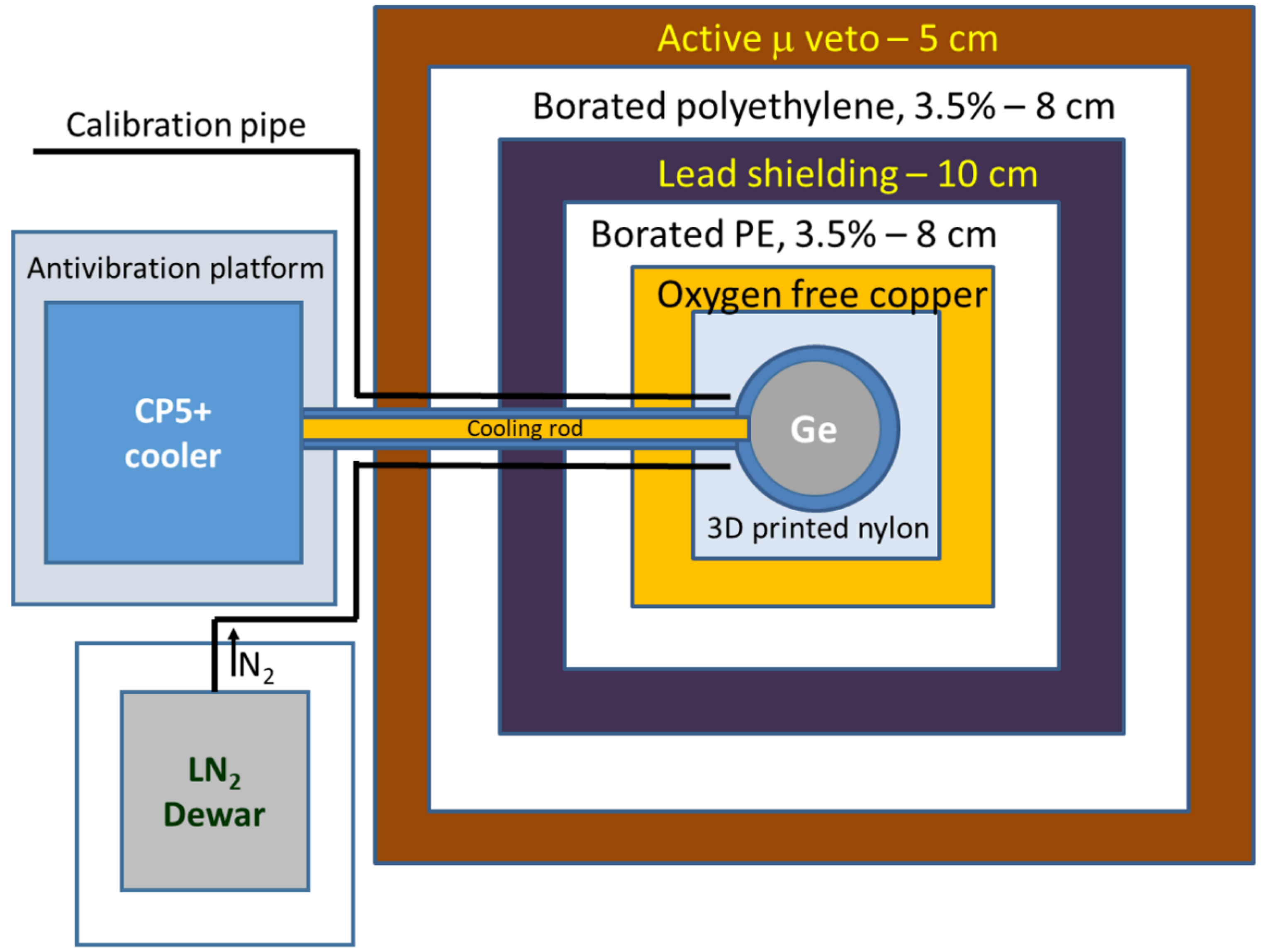
CONUS+

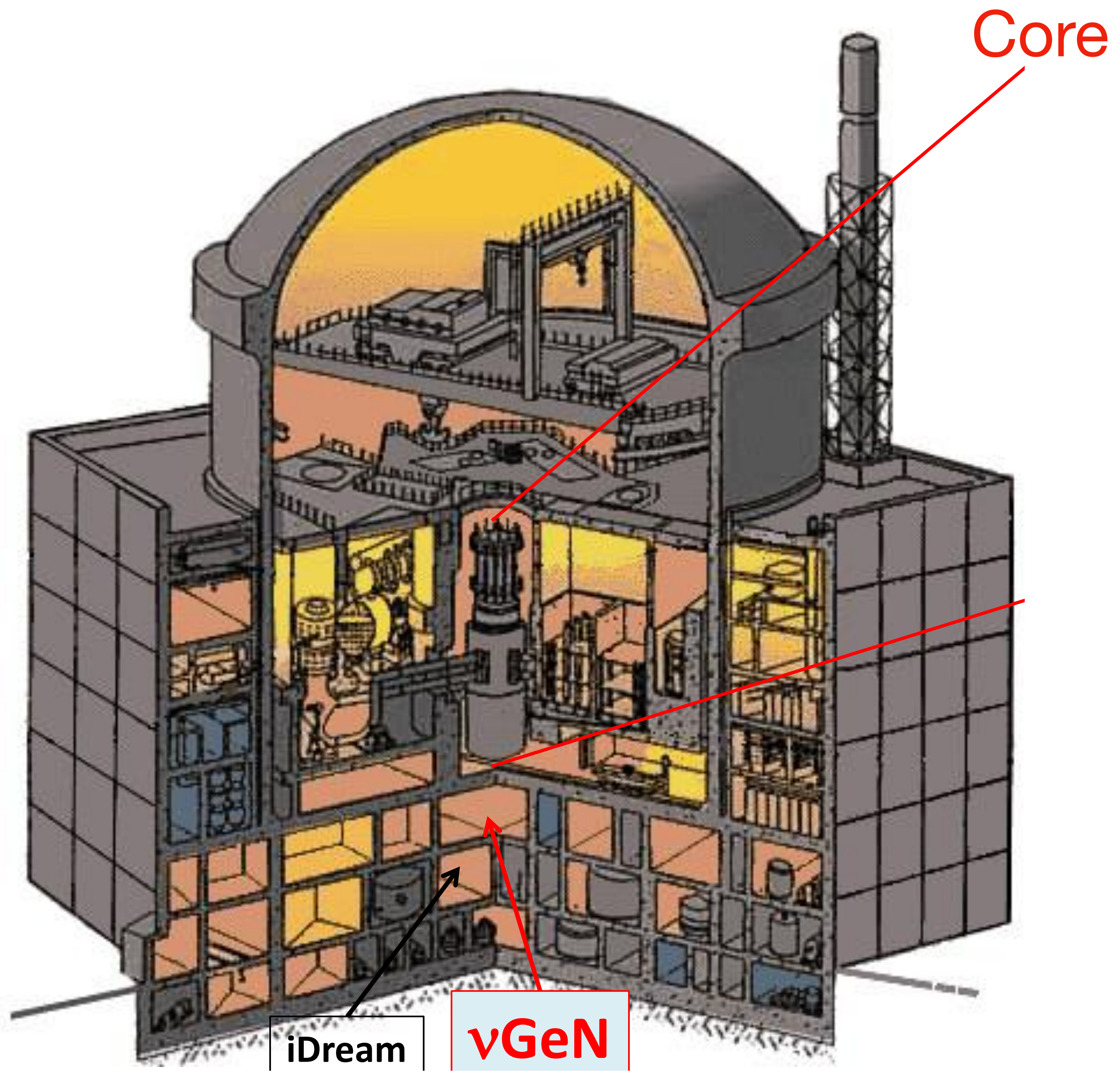
Leibstadt nuclear power plant in Switzerland

- 3.6 GW_{th}
- 21 m baseline
- $1.5 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$
- Target threshold < 200 eV
- Better muon-veto

Installation this year

νGEN



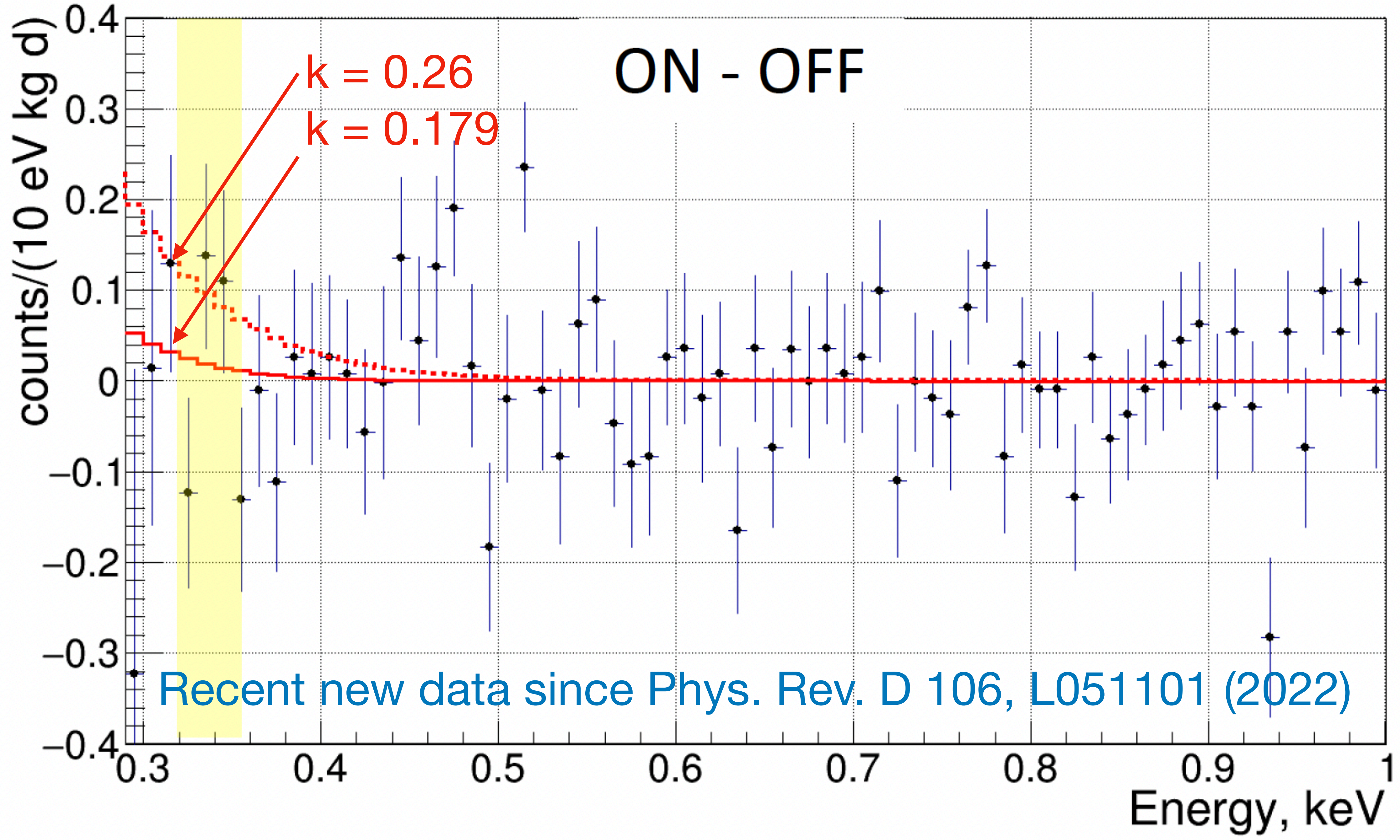


KNPP reactor in Russia
3.1 GWth

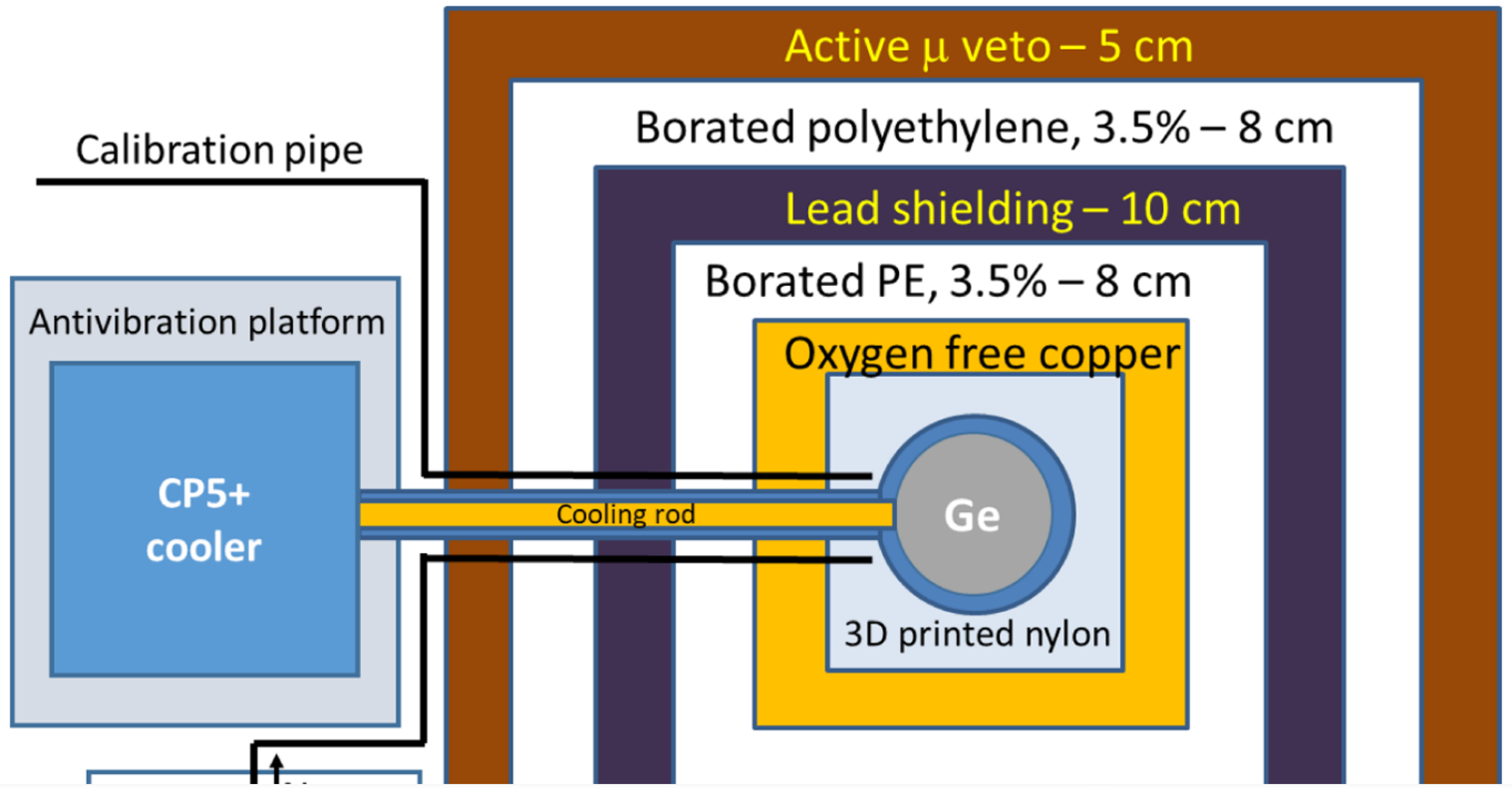
Shielding (~50 counts / keV kg d):

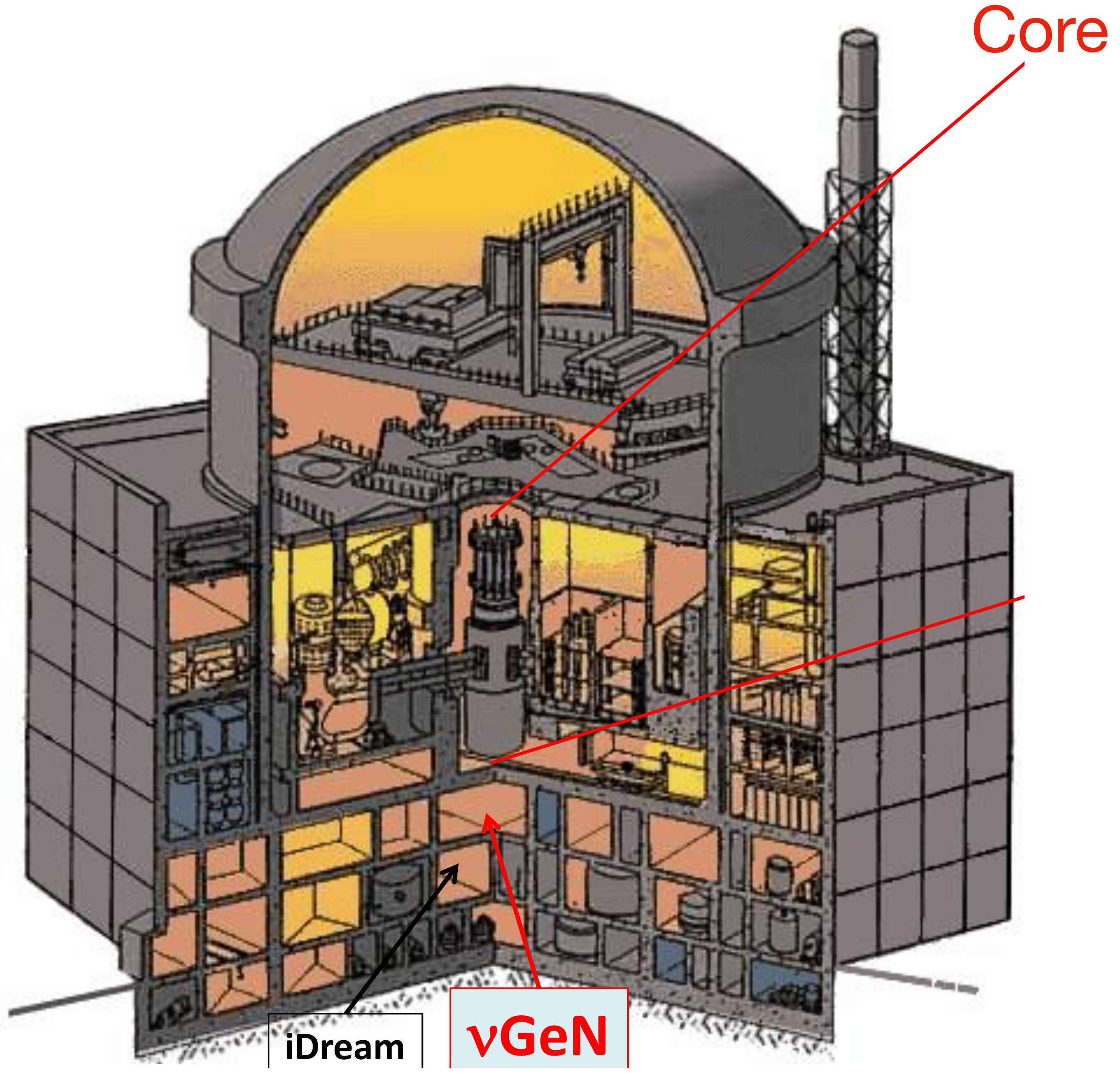
- Pb (black)
- B-doped PE (white)
- muon-veto (brown)
- Copper (yellow)

Germanium detector
Mass: 1.4 kg
baseline: 11 m
$4 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$

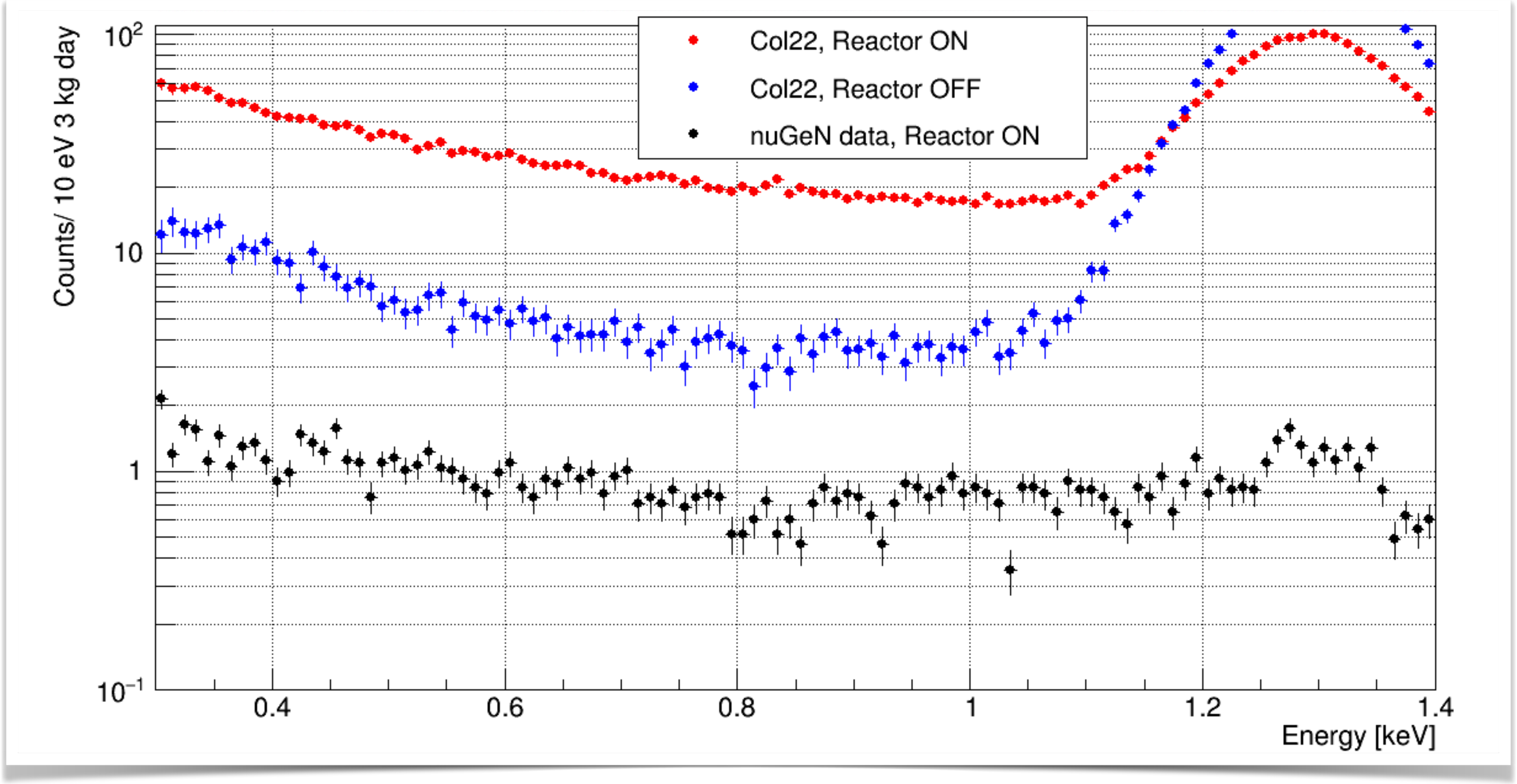


νGEN



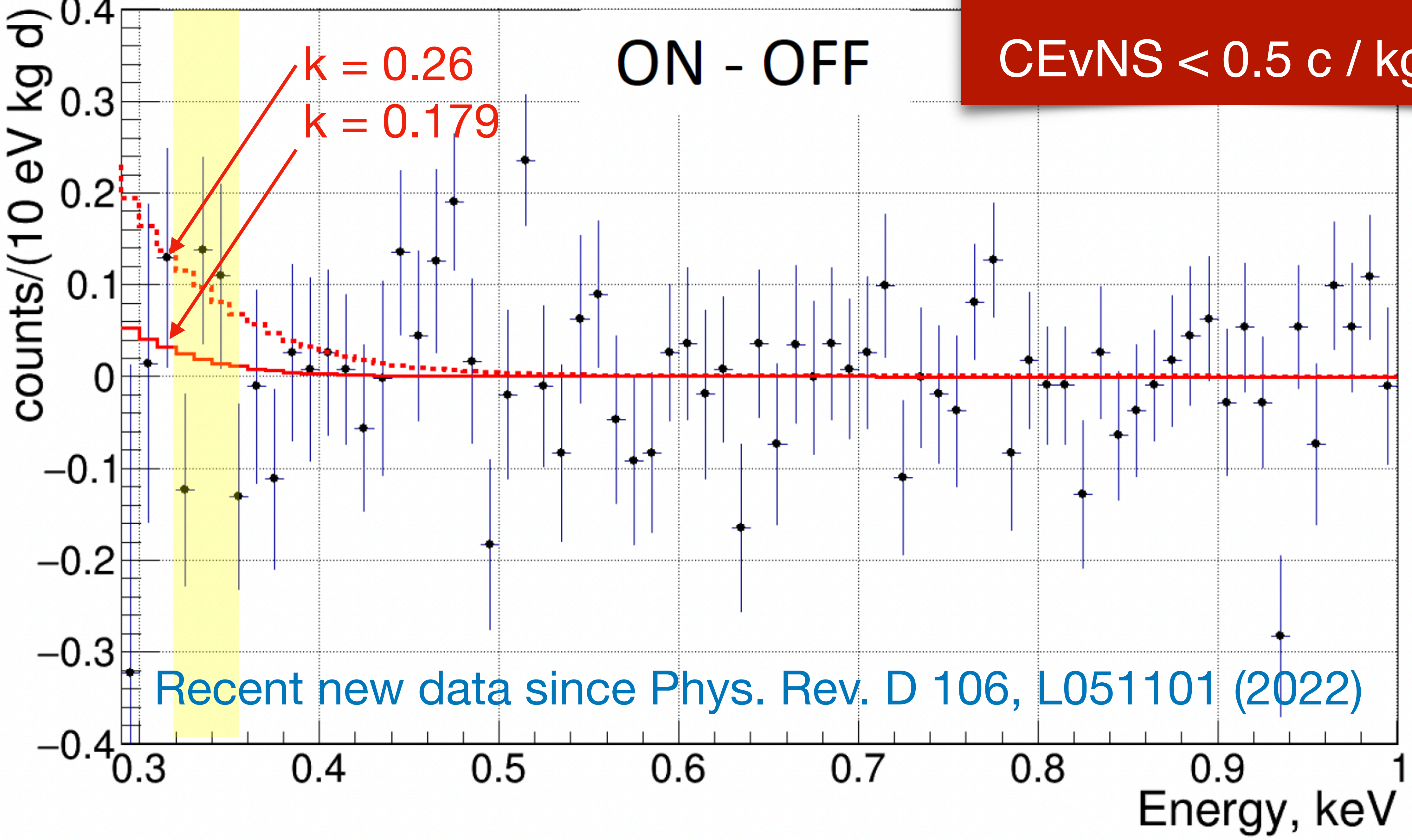


KNPP reactor in Russia
3.1 GWth



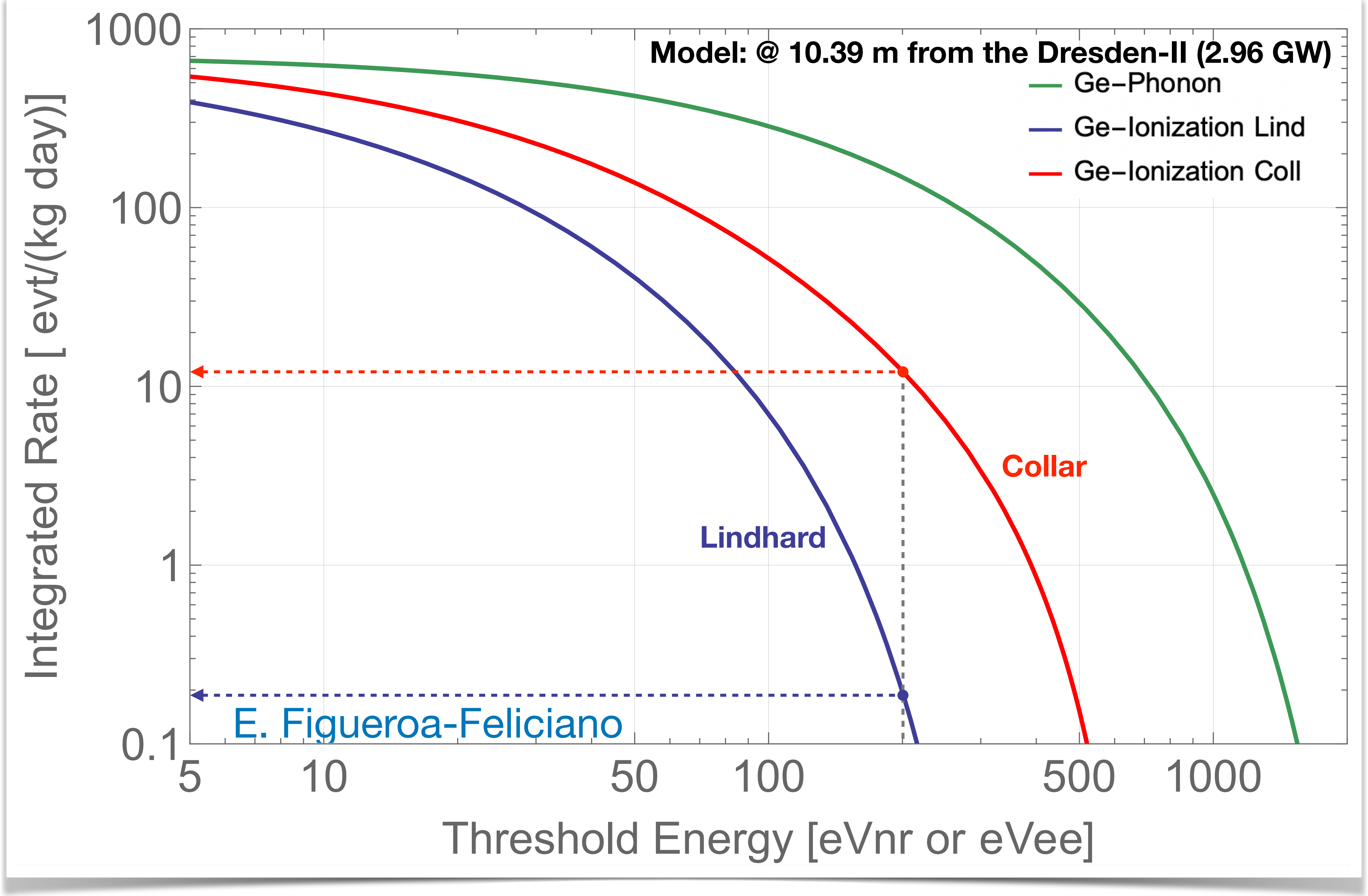
null result

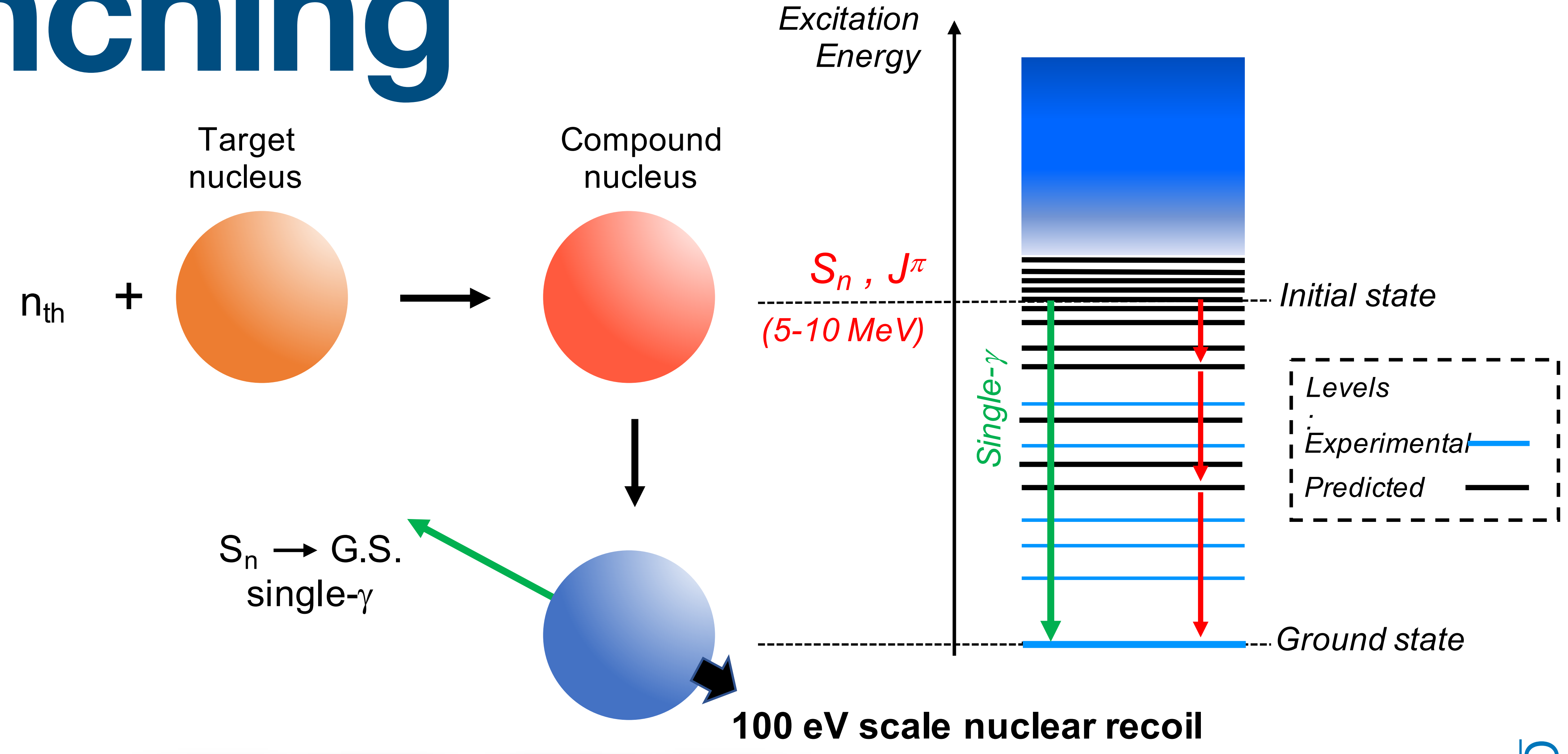
CEvNS < 0.5 c / kg d



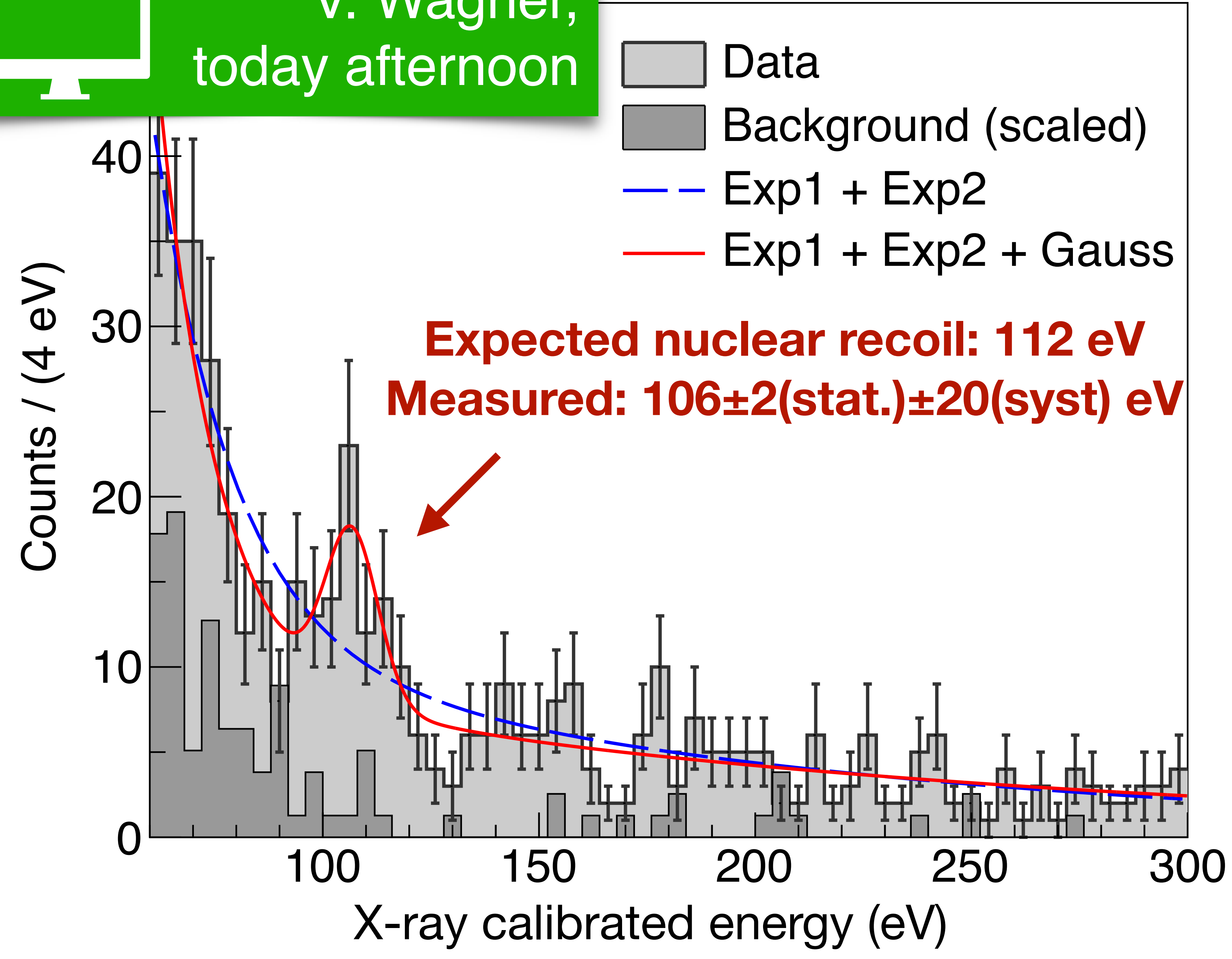
Cryodetectors: no quenching

+) Low energy thresholds
+) Small uncertainty on energy scale
–) Complicated operation
–) Small targets





V. Wagner, today afternoon



CRAB & NUCLEUS Colls, PRL 130 (2023) 211802

Cryodetectors: RICOCHET

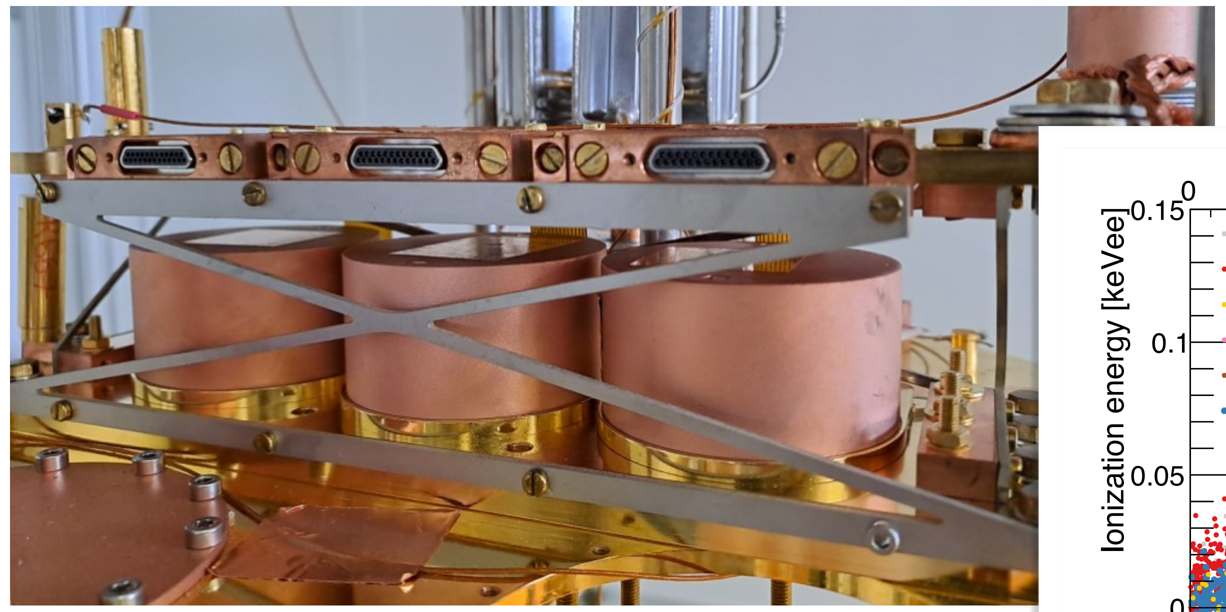
Data taking foreseen in 2024

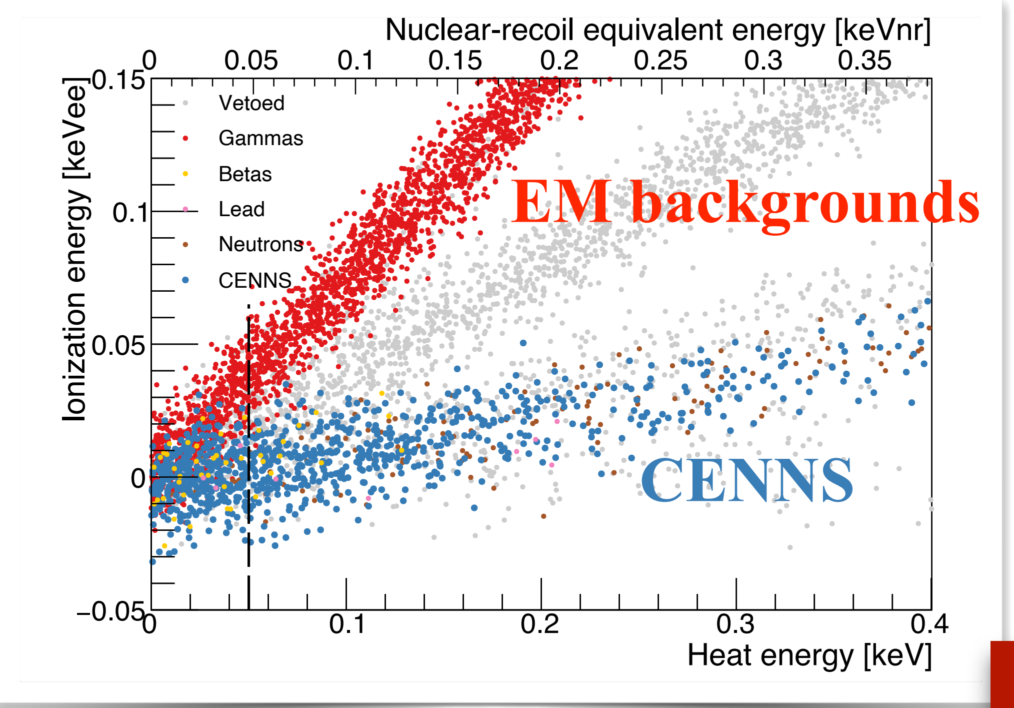
Ge detectors (heat + ionisation)

Target Mass: 42 g x 18/27

baseline: 8.8 m

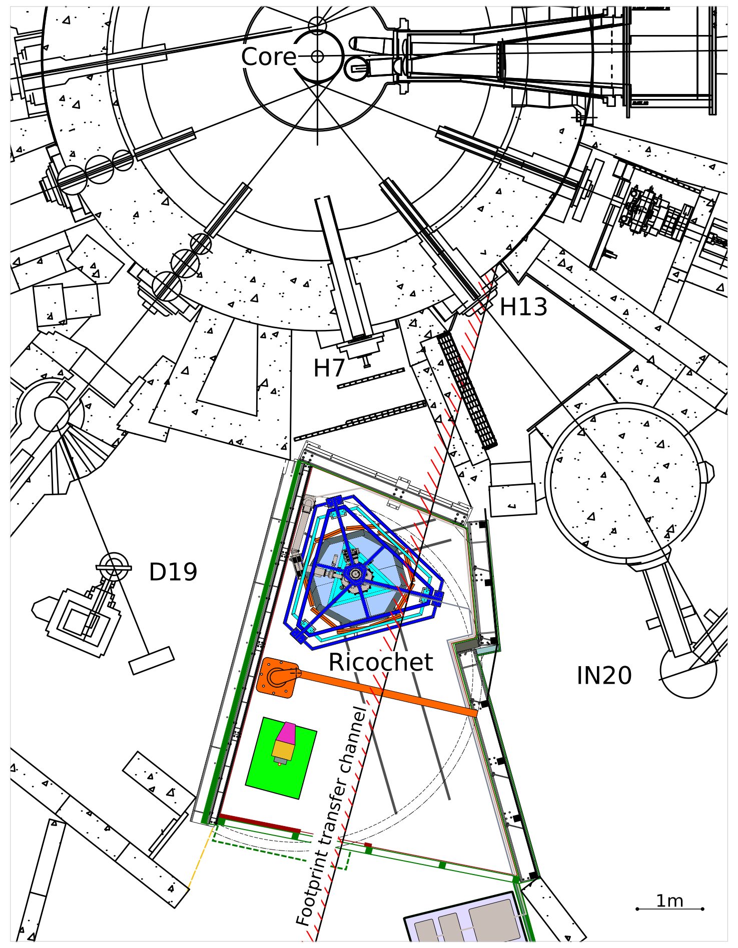
$1.1 \times 10^{12}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$





ILL Research reactor in Franche

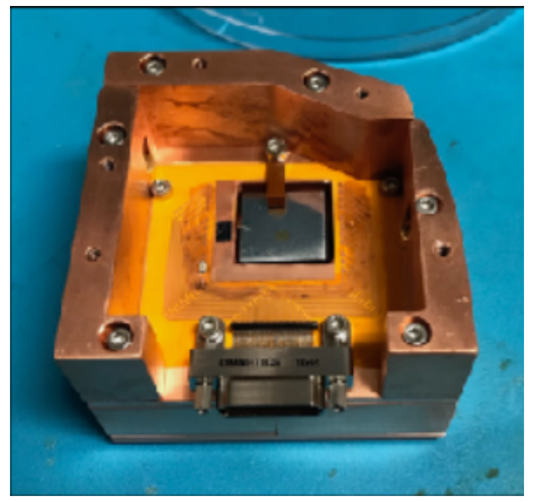
58 $\mathrm{MW_{th}}$

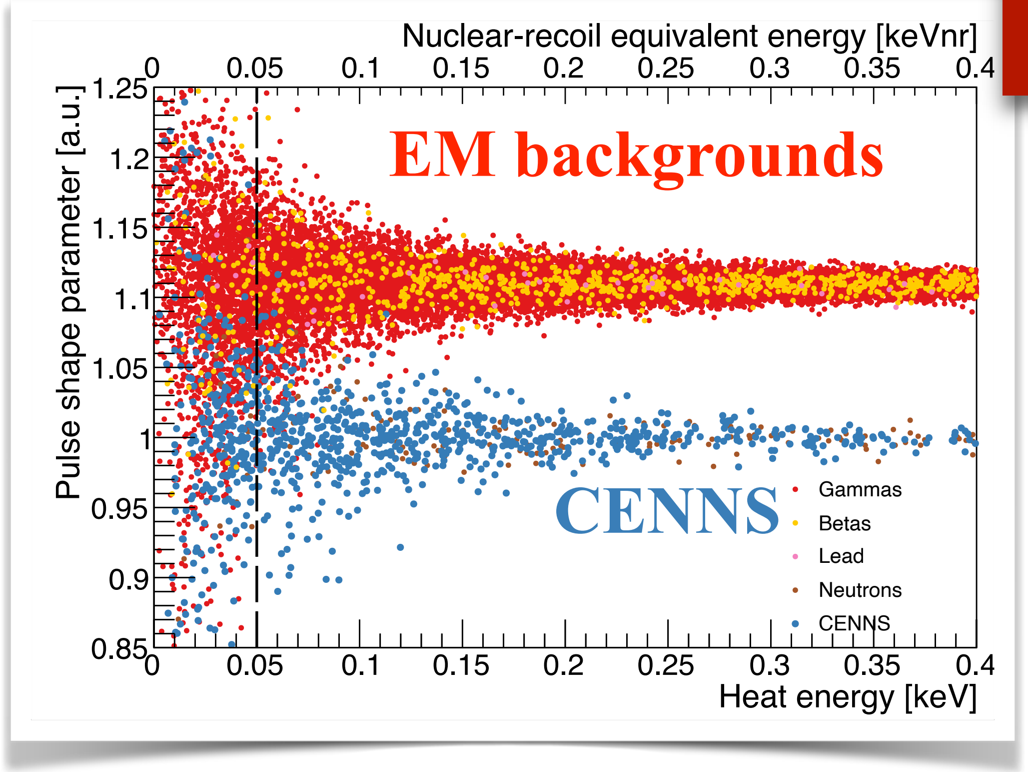


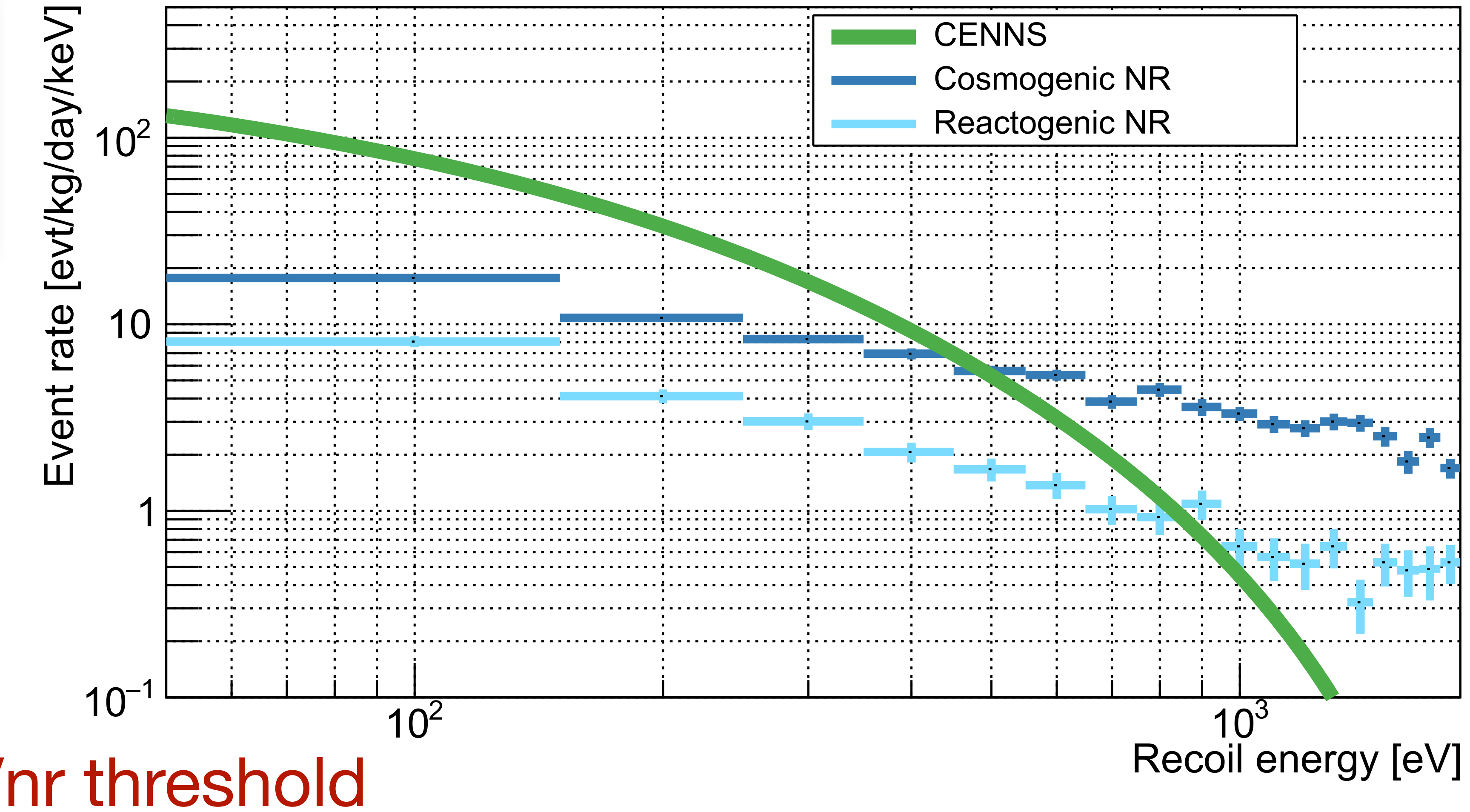
Particle ID @ < 100 eV

Zn detectors (heat only)

Target Mass: 32 g x 9







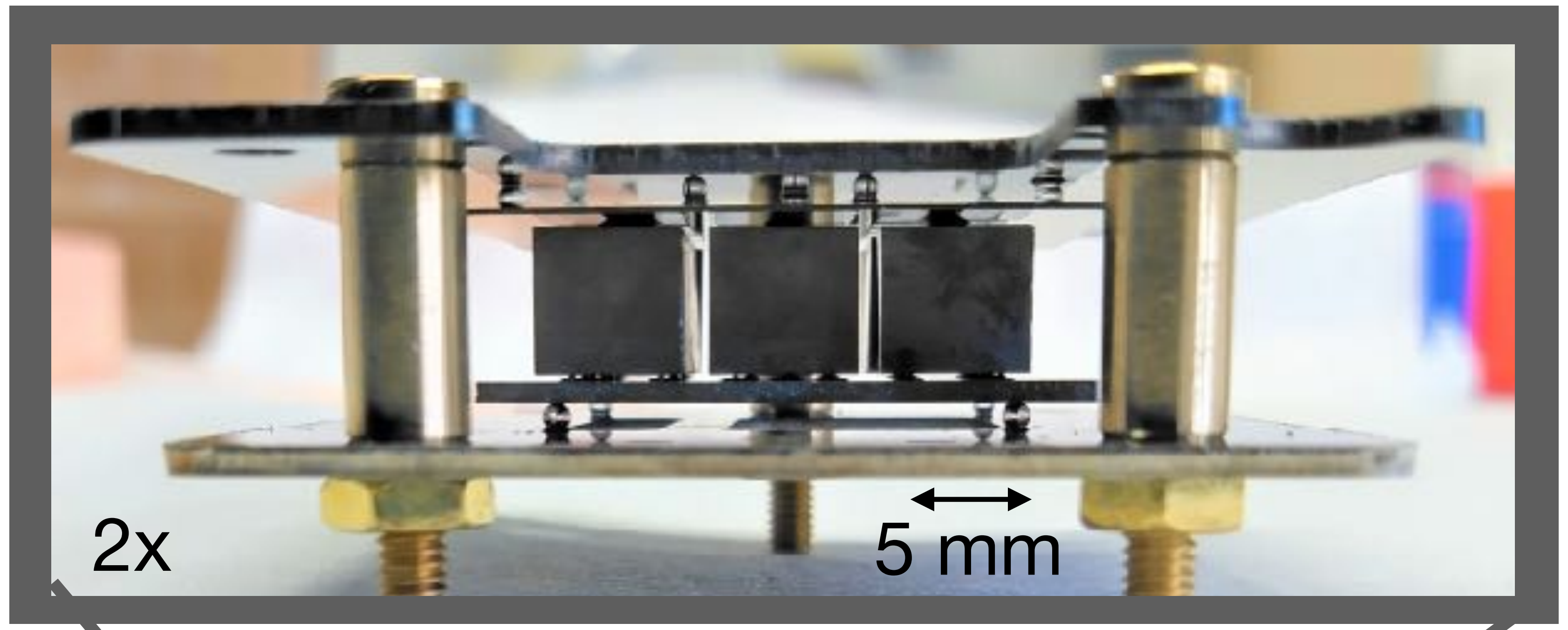
50 eVnr threshold

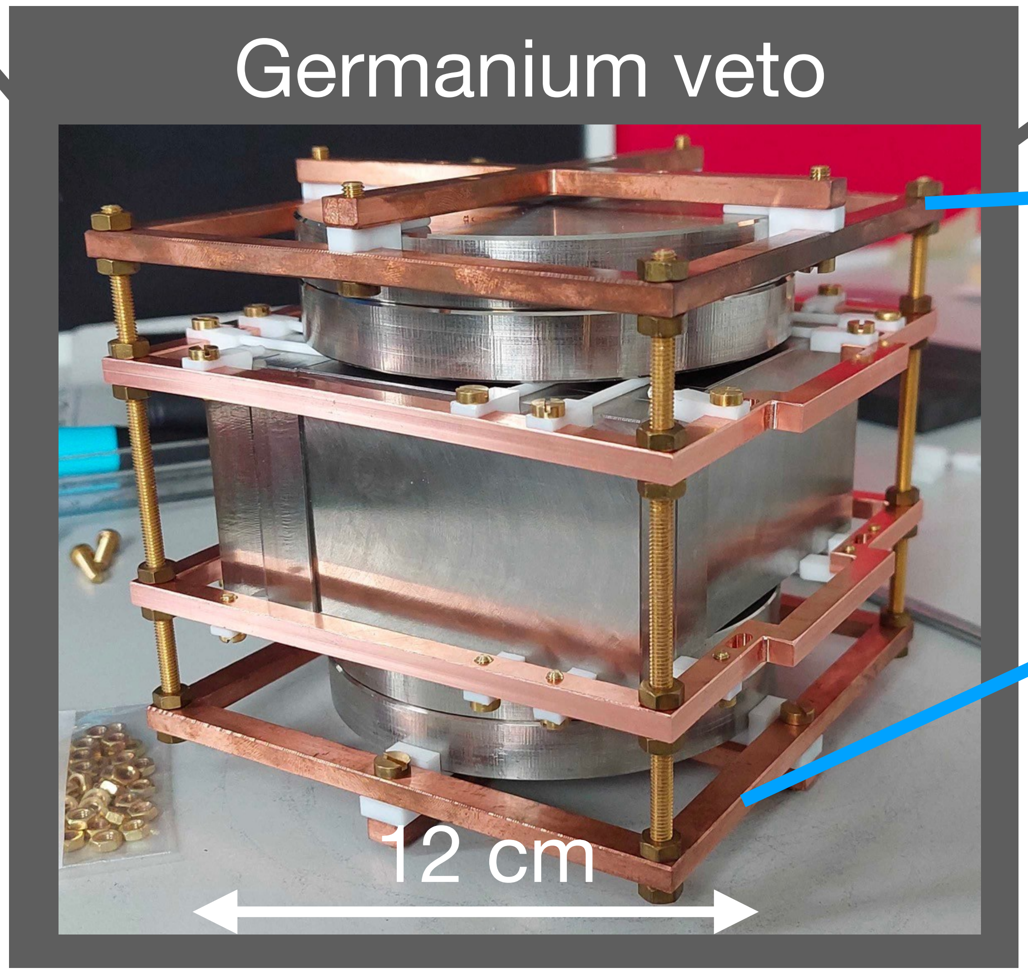
C. Augier, et al, Eur. Phys. J. C 83 (2023) 20

Cryodetectors: NUCLEUS

T. Lassere,
today afternoon

Neutrino target: crystals 5x5x5 mm^3
9 Al_2O_3 (4 g) and 9 $CaWO_4$ (6 g)
20 eVnr threshold





Cryostat 10 mK
Shielding Pb+PE+B_4C:
100 counts / kg keV d

Now: Phase 1 - 10 g
Future: Phase 2 - 1 kg

Neutrino source: Chooz nuclear plant
1.7×10^{12} $\nu/cm^2\,s$

20% precision on $\sigma_{CE\nu NS}$
(1 year of data taking)

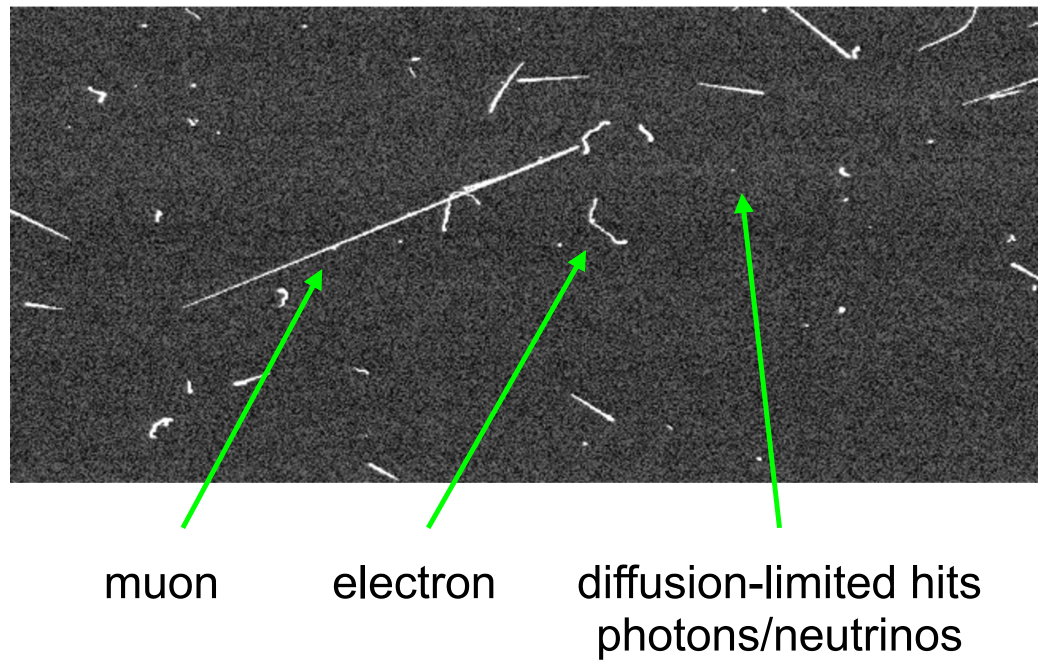
G. Angloher et al., Eur. Phys. J. C, 79 (2019) 1018

https://nucleus-experiment.org

Other experiments (reactors)

CONNIE
Skipper CCD
(Limit 70x SM)

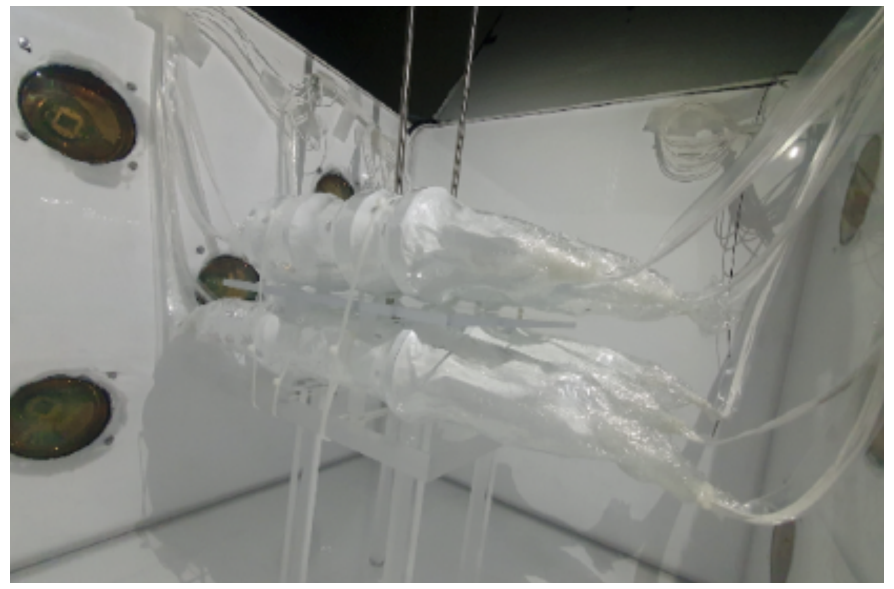
A.Aguilar-Arevalo, today



RED-100
LXe / LAr
(Results soon)

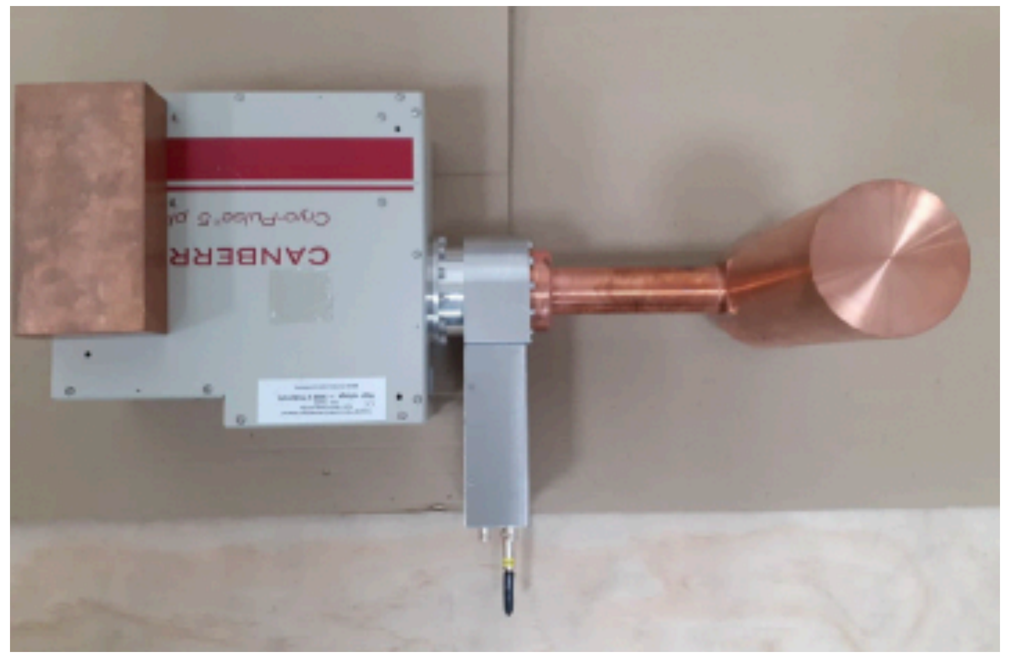
NEON
NaI(Tl)
(taking/analysing data)

H. Ha, today

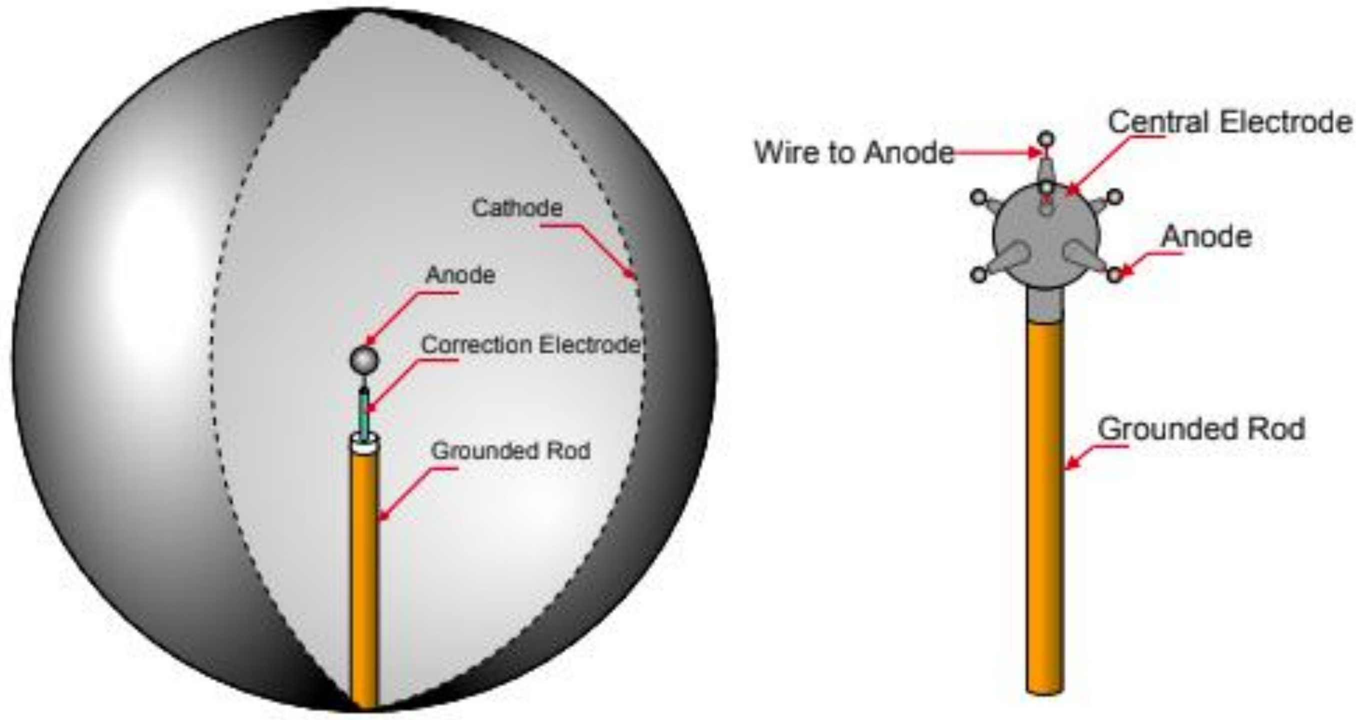


TEXONO
Ge

M. Singh, today

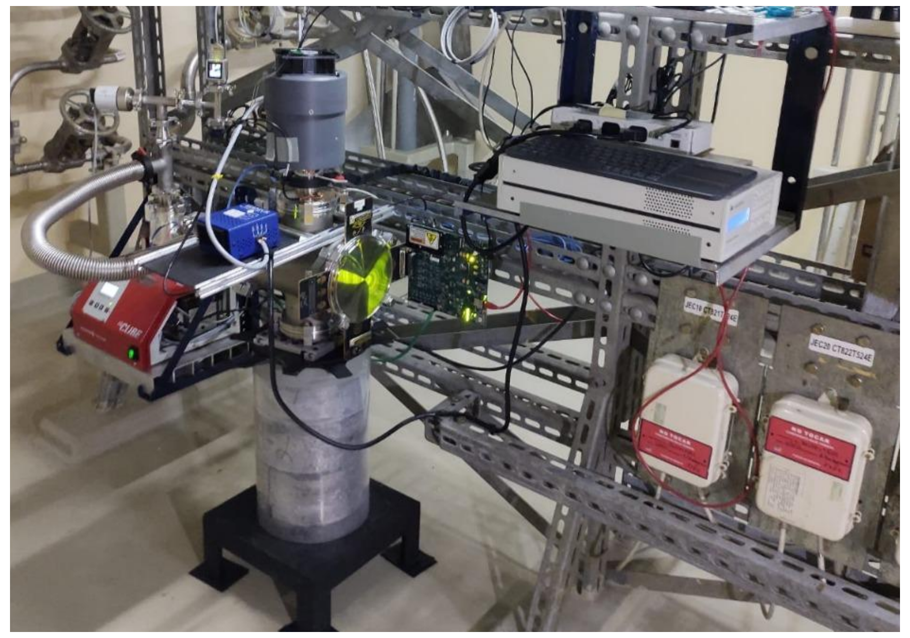


NEWS-G3
Proportional counters
(design finalization)

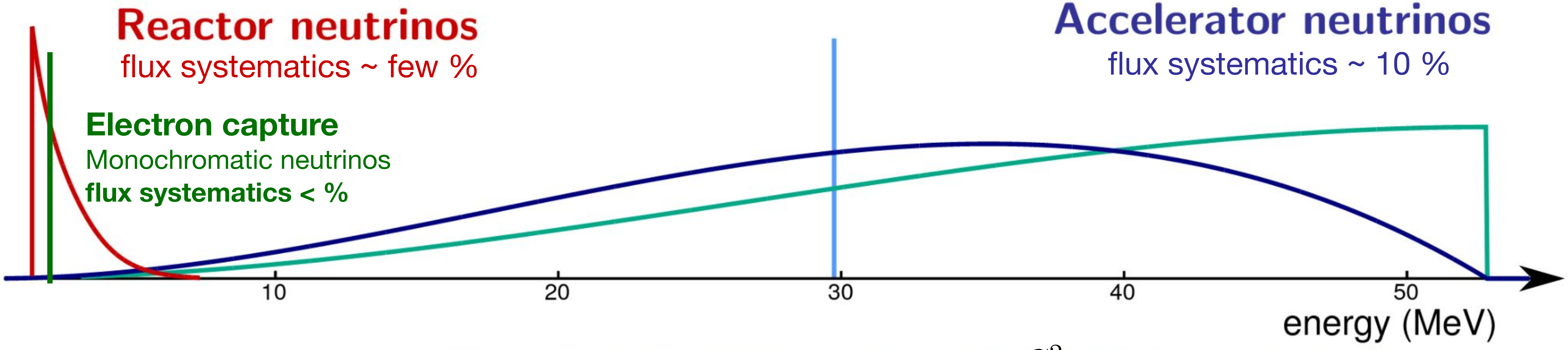


Skipper CCD@Atucha2
Commissioning/
data taking

M. Cabbie, Wednesday



Source (Future)^2: Electron capture



^{37}**Ar:** Formaggio, Figueroa, Anderson, Phys. Rev D 85, 013009 (2012)

^{51}**Cr:** C. Bellenghi, et al, Eur. Phys. J. C 79 (2019) 727

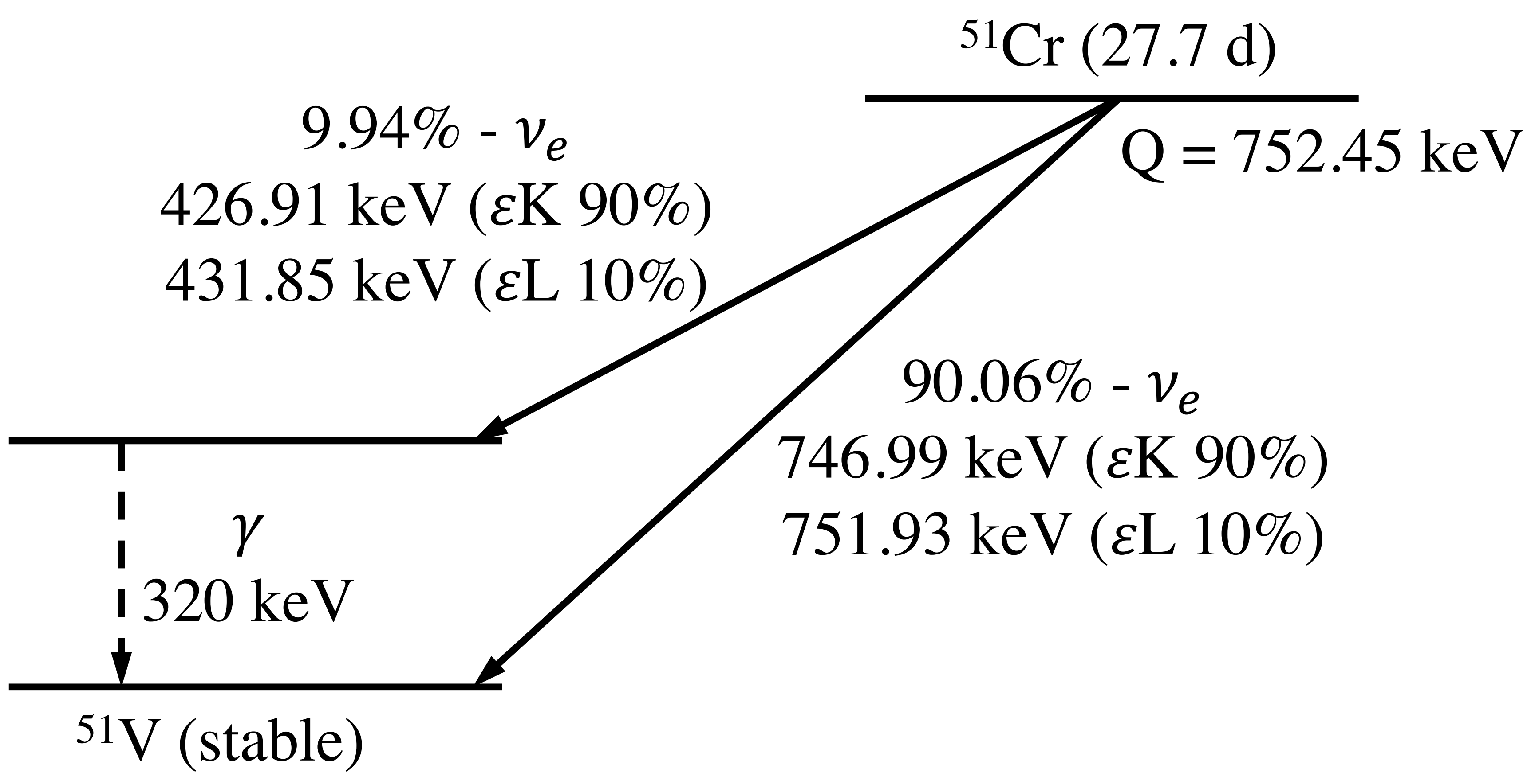
cross-section $\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$

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

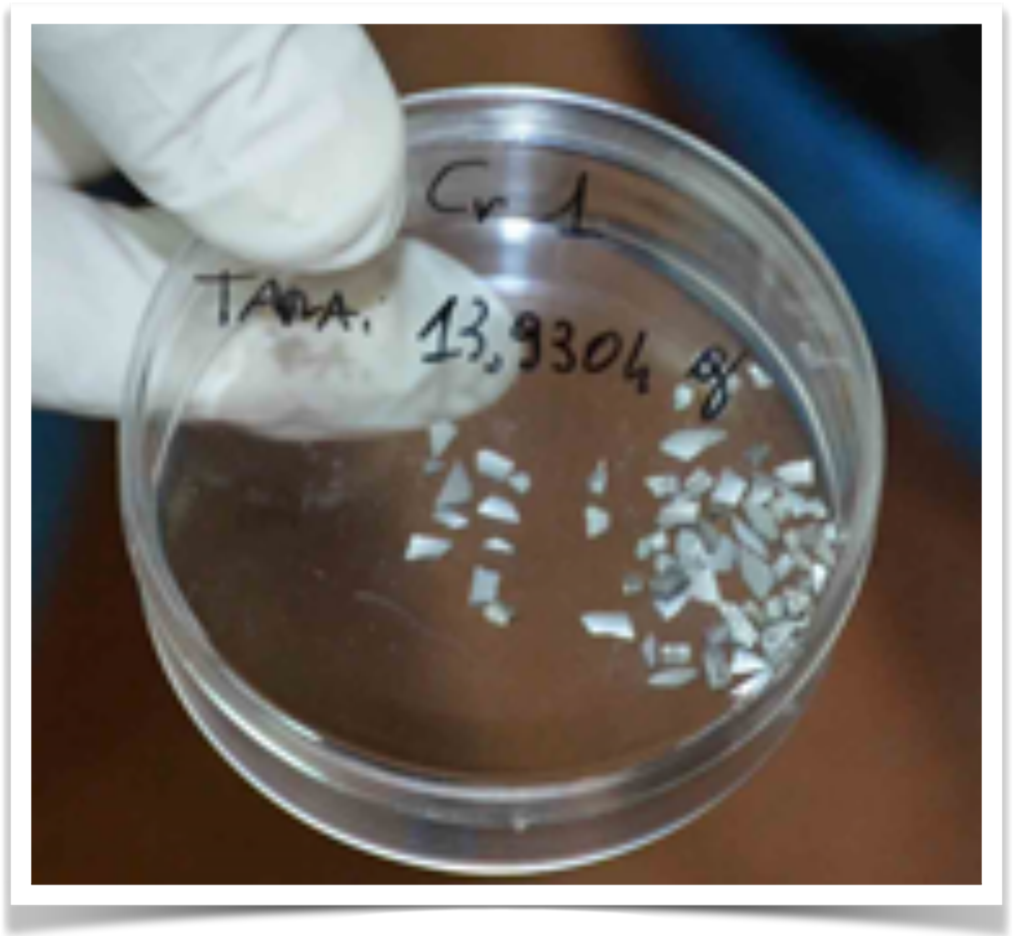
coherency $qR < 1 : \quad F(q^2) \to 1$

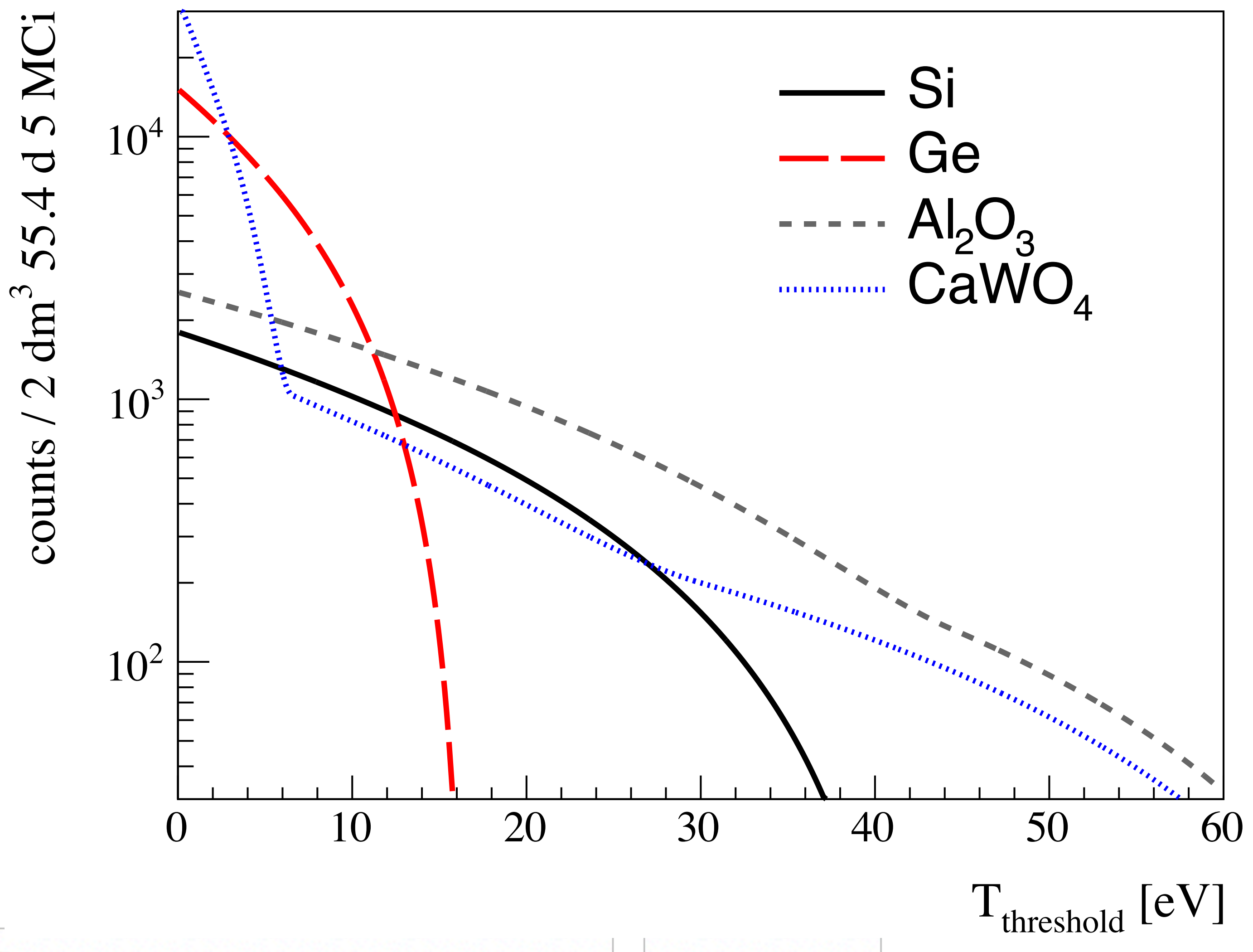
PRECISION

^{51}Cr

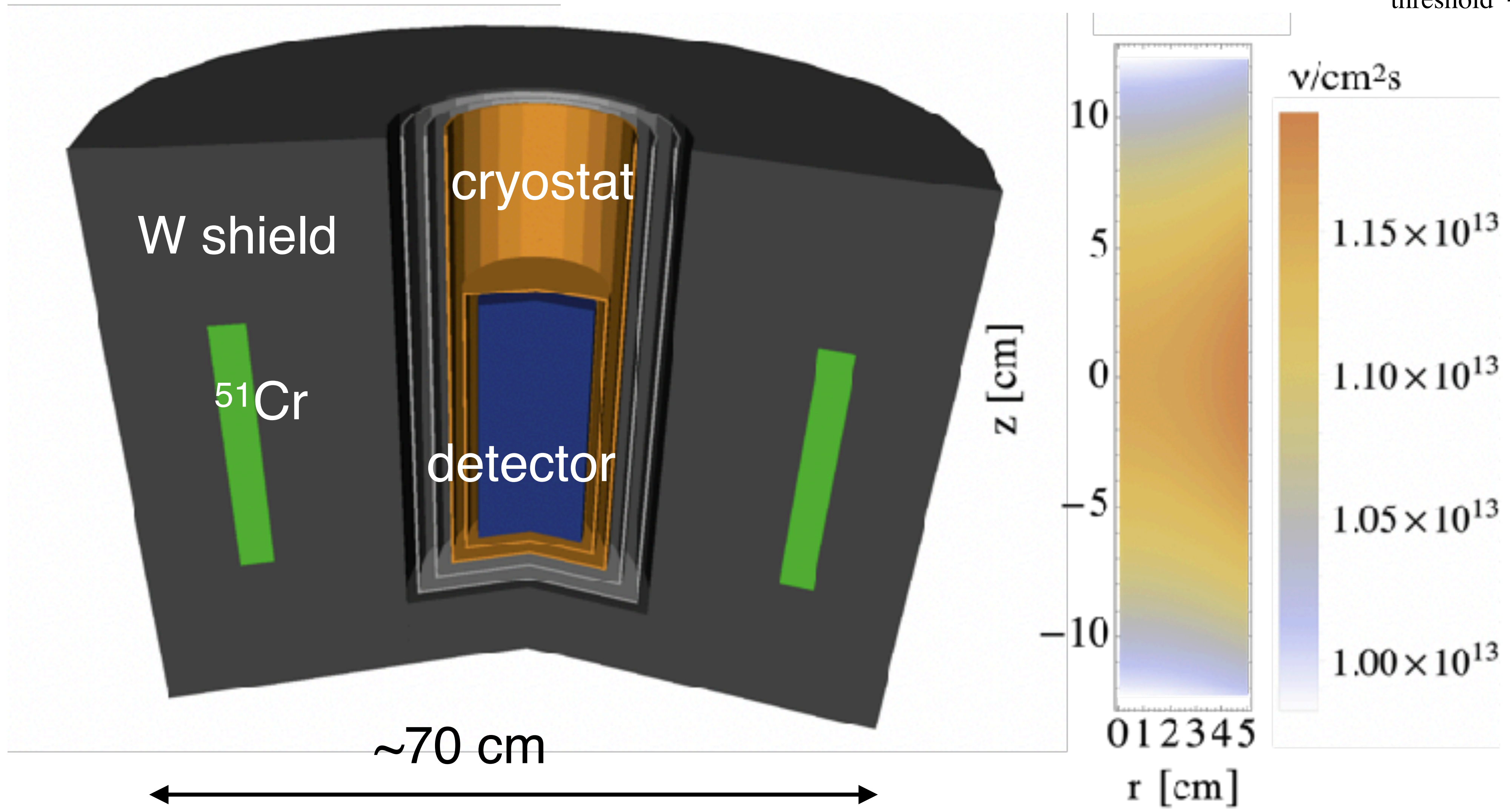


C. Bellenghi, et al, Eur. Phys. J. C 79 (2019) 727





- ✓ Activity monitored with calorimeter < 1 % precision (SOX experience)
- ✓ INFN owns a 36 kg source (GALLEX)

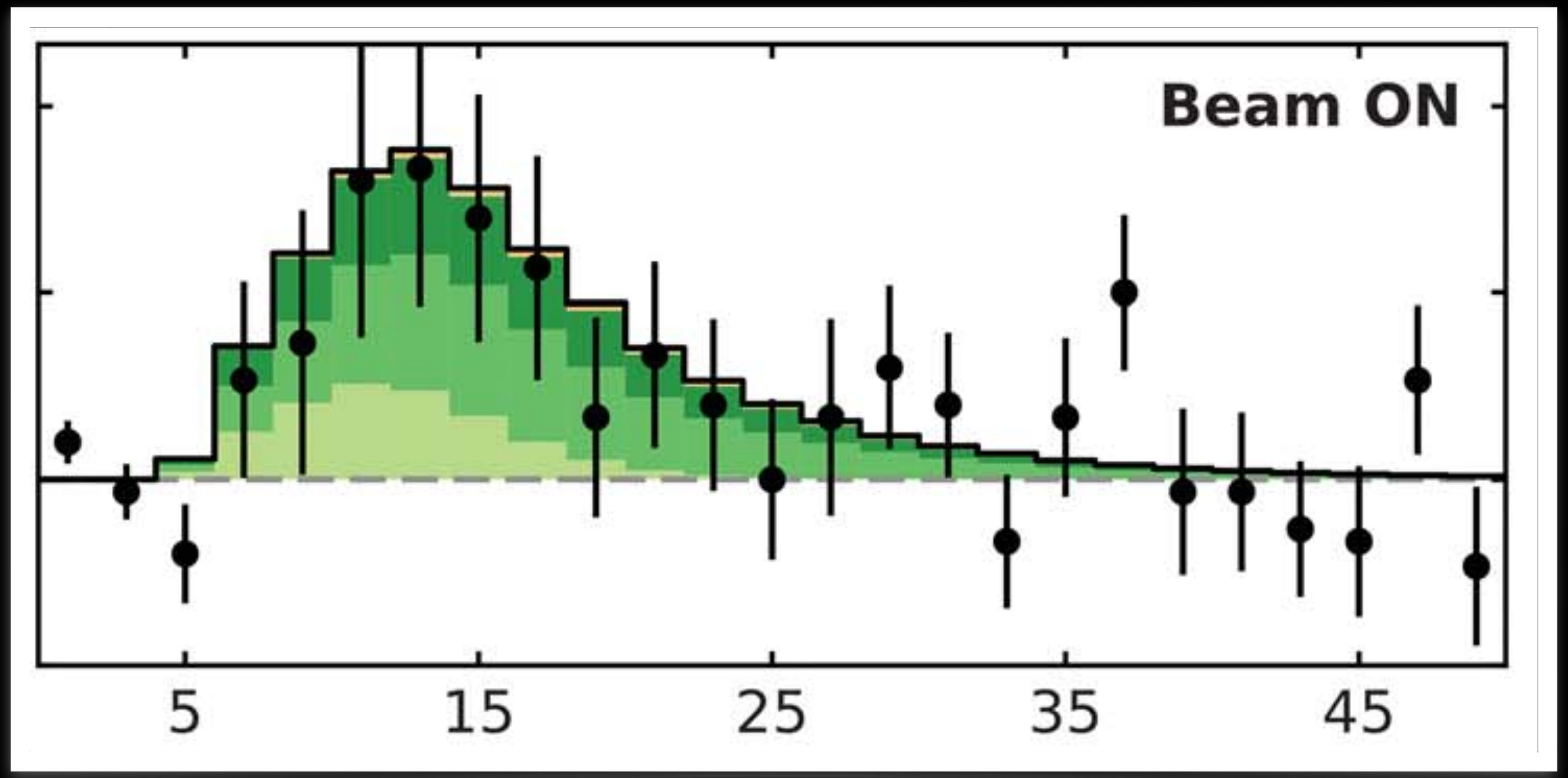


Challenges:

- activation up to 5 MCi
- even lower threshold than reactors

1% precision with 10 kg Ge target in 2 months, but extremely challenging!

Summary



Present and future challenge is precision:
Source and detector wise:

+ mass
+ neutrinos
- threshold
- backgrounds
- systematics

From the point of view of an experimentalist:
Difficult but **doable and time-limited!**