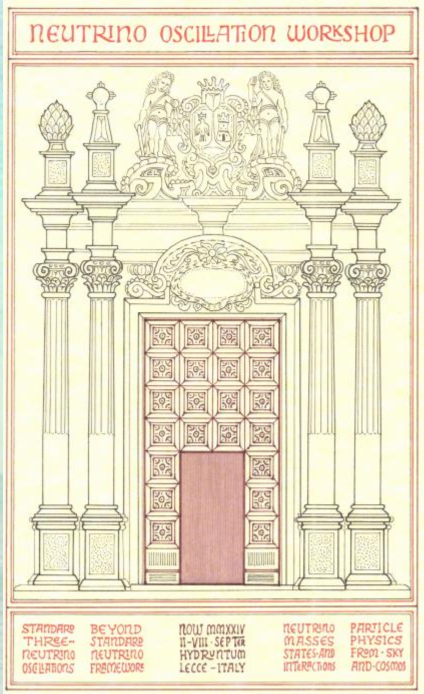
COHERENT and the future of CEvNS

Dan Pershey – Florida State University

NOW 2024 – Sep 6, 2024



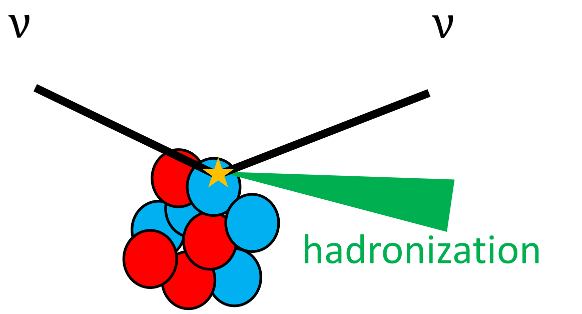
NC neutrino scattering with nuclei

What happens qualitatively during neutrino-nucleus interactions depends on the deBroglie wavelength involved, $\lambda = h/p$

E_ν~TeV E_ν~GeV E_ν~MeV

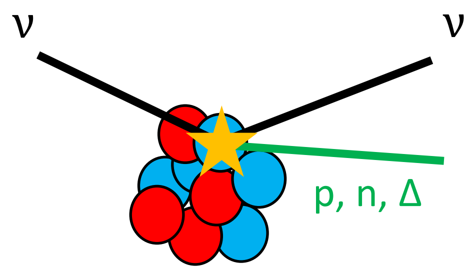
Decreasing Q^2

Increasing wavelength



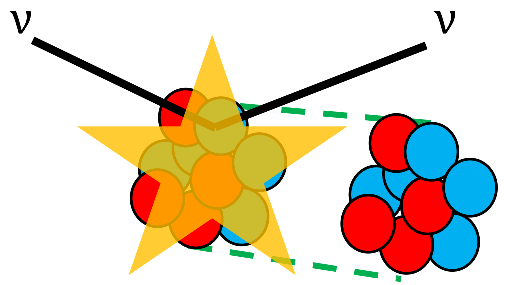
$\lambda = h/\sqrt{Q^2} \ll R_p$

Localized scattering on quarks with nuclear fragmentation
e.g. IceCube, FASERnu



$\lambda = h/\sqrt{Q^2} \approx R_p$

Scattering on nucleons with nucleon emission
e.g. NOvA, SK, DUNE



$\lambda = h/\sqrt{Q^2} \gg R_p$

Elastic scattering on nuclei with Q^2 so low, nucleus acts like point particle

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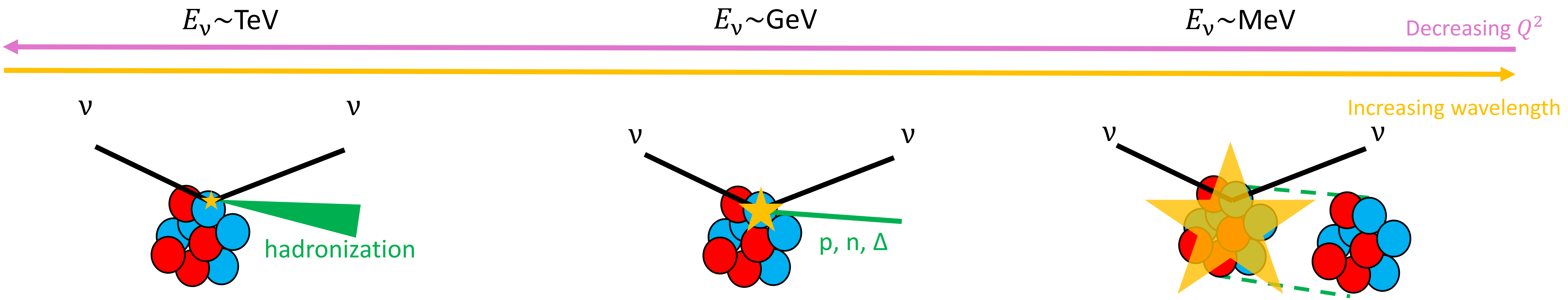

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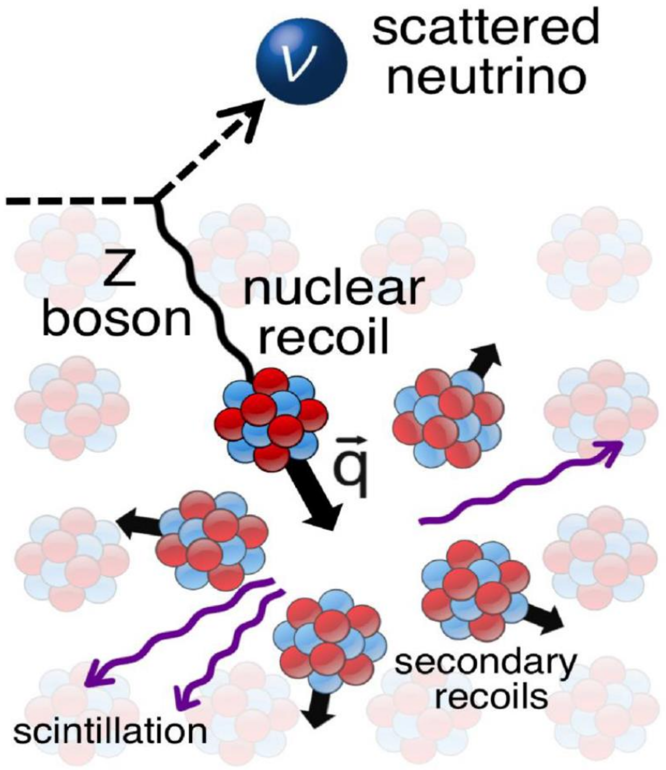
CEvNS – coherent, elastic neutrino-nucleus scattering.
Dominant interaction at energies below $E_\nu \approx 100$ MeV
Discovered by COHERENT in 2017 with CsI[Na] scintillator

Coherent-elastic neutrino nucleus scattering (CEvNS)



Low-energy neutrino scattering process whose only observable is O(keV) nuclear recoil

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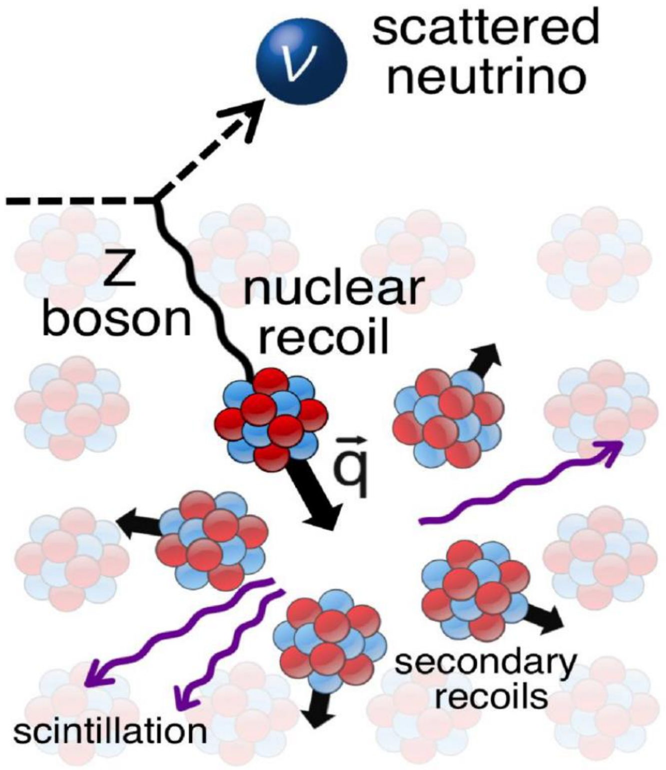
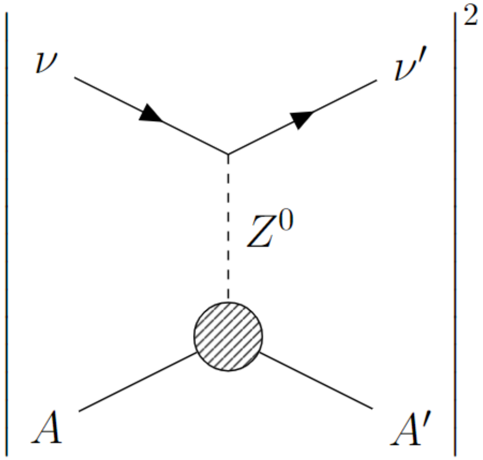


Low-energy neutrino scattering process whose only observable is O(keV) nuclear recoil

$$\sigma \propto |\mathcal{M}|^2 = \left| \quad \right|^2$$

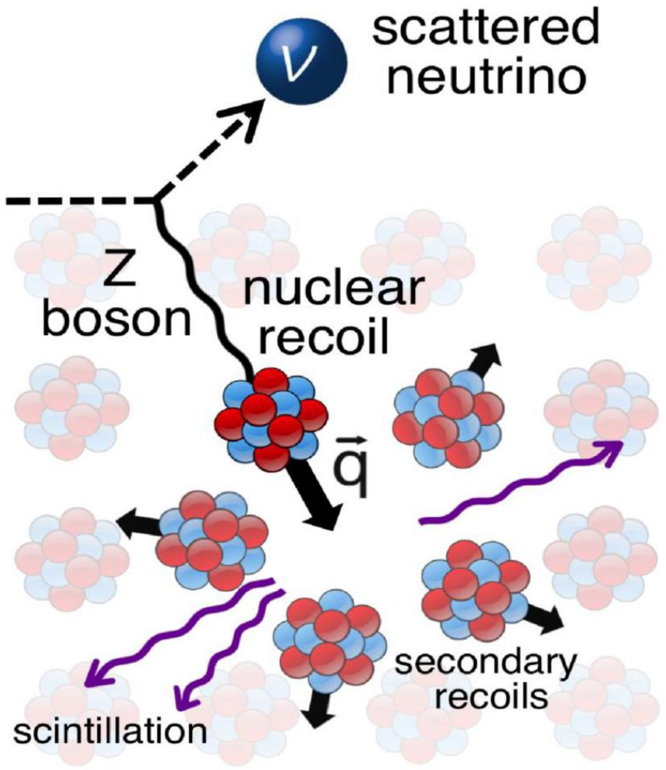


Scattering is <u>coherent</u>!

$$\sigma \propto Q_W^2$$

$$Q_W^2 = (g_p^V Z + g_n^V N)^2 = \big[\underbrace{(1 - 4\sin^2\theta_W)}_{\approx 0} Z - N)\big]^2$$

Coherent-elastic neutrino nucleus scattering (CEvNS)



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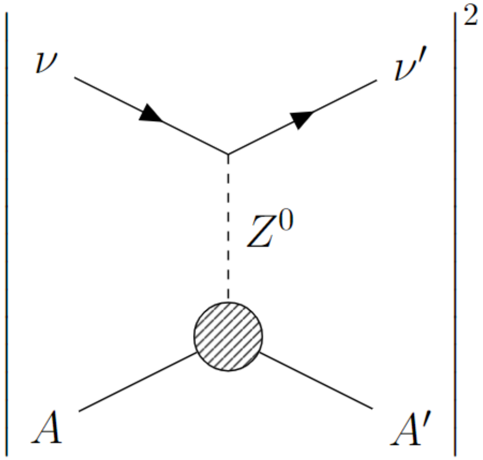

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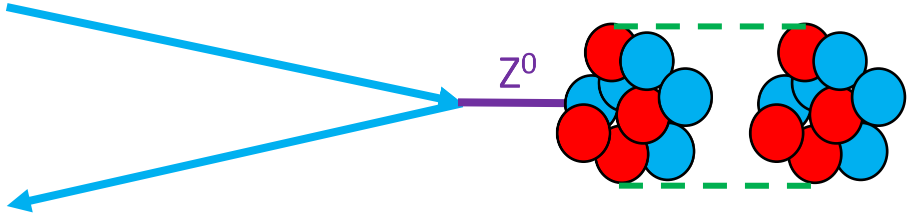
Scattering is elastic!



$$E_{\text{rec}} \approx \frac{p_{\text{Cs}}^2}{2m_{\text{Cs}}} = \frac{Q^2}{2m_{\text{Cs}}} \leq \frac{2E_\nu^2}{m_{\text{Cs}}} = 10.1 \text{ keV}$$

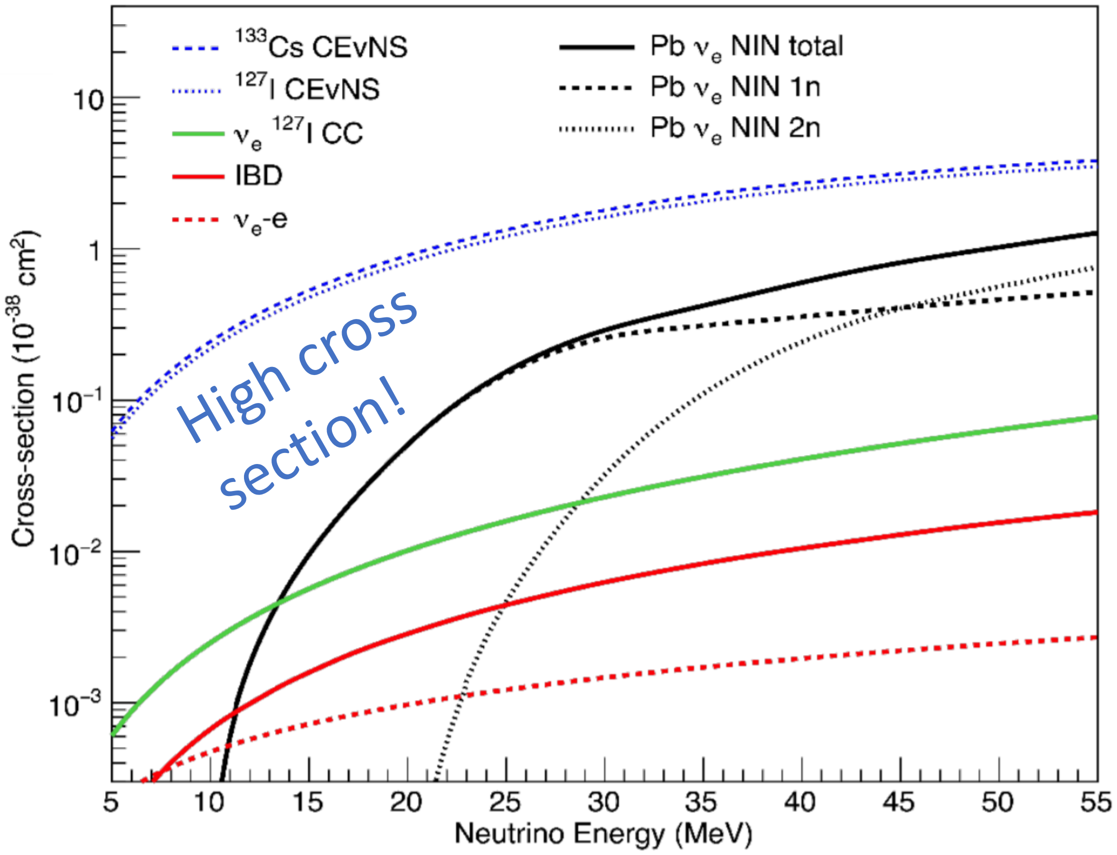
CEvNS cross section

$$\frac{d\sigma}{dE_{\rm rec}} = \frac{G_F^2}{2\pi} Q_W^2 m_{\rm nuc}\left(2 - \frac{m_{\rm nuc}E_{\rm rec}}{E_\nu^2}\right)|F(Q^2)|^2$$

Weak charge

Event kinematics

Nuclear physics



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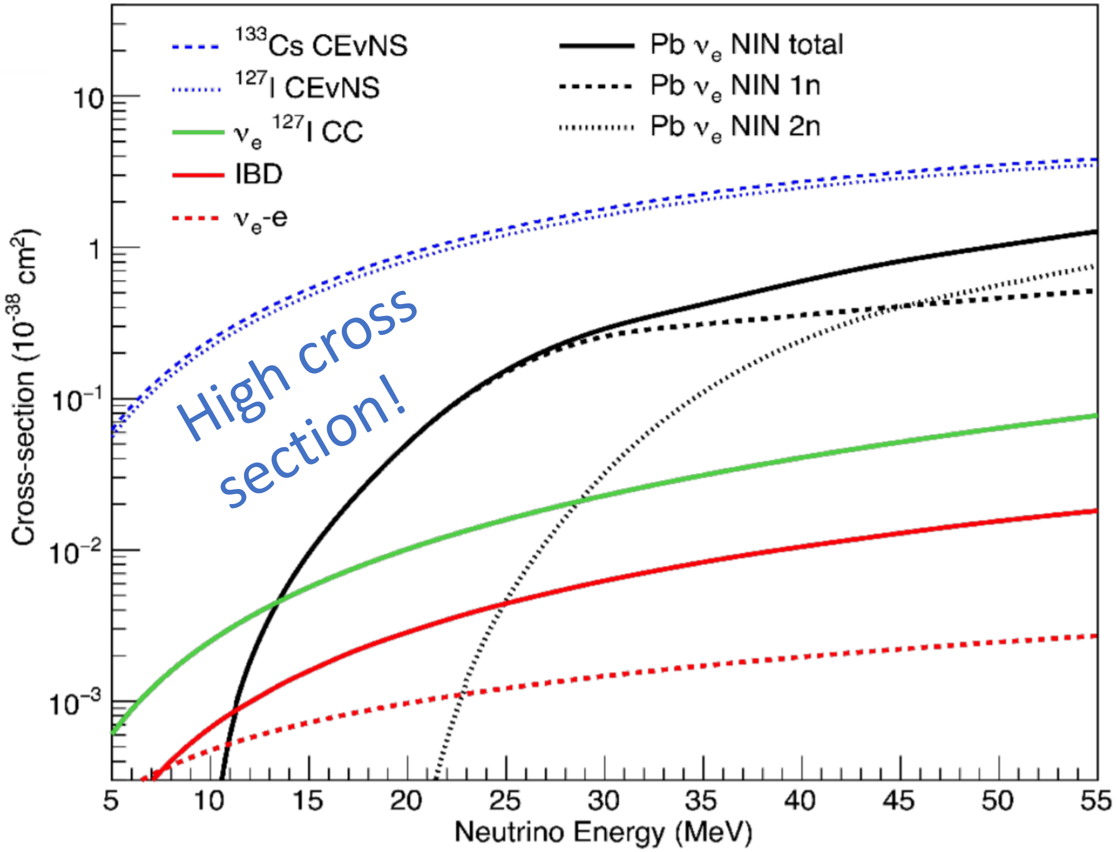
Weak charge | Event kinematics | Nuclear physics



Weak charge

$$Q_W = -\frac{1}{2}N + \left(\frac{1}{2} - 2\sin^2\theta_W\right)Z$$

– Neutrino-fermion couplings (NSI)

– Precision EM parameters

Event kinematics

– Light mediators

– Dark matter

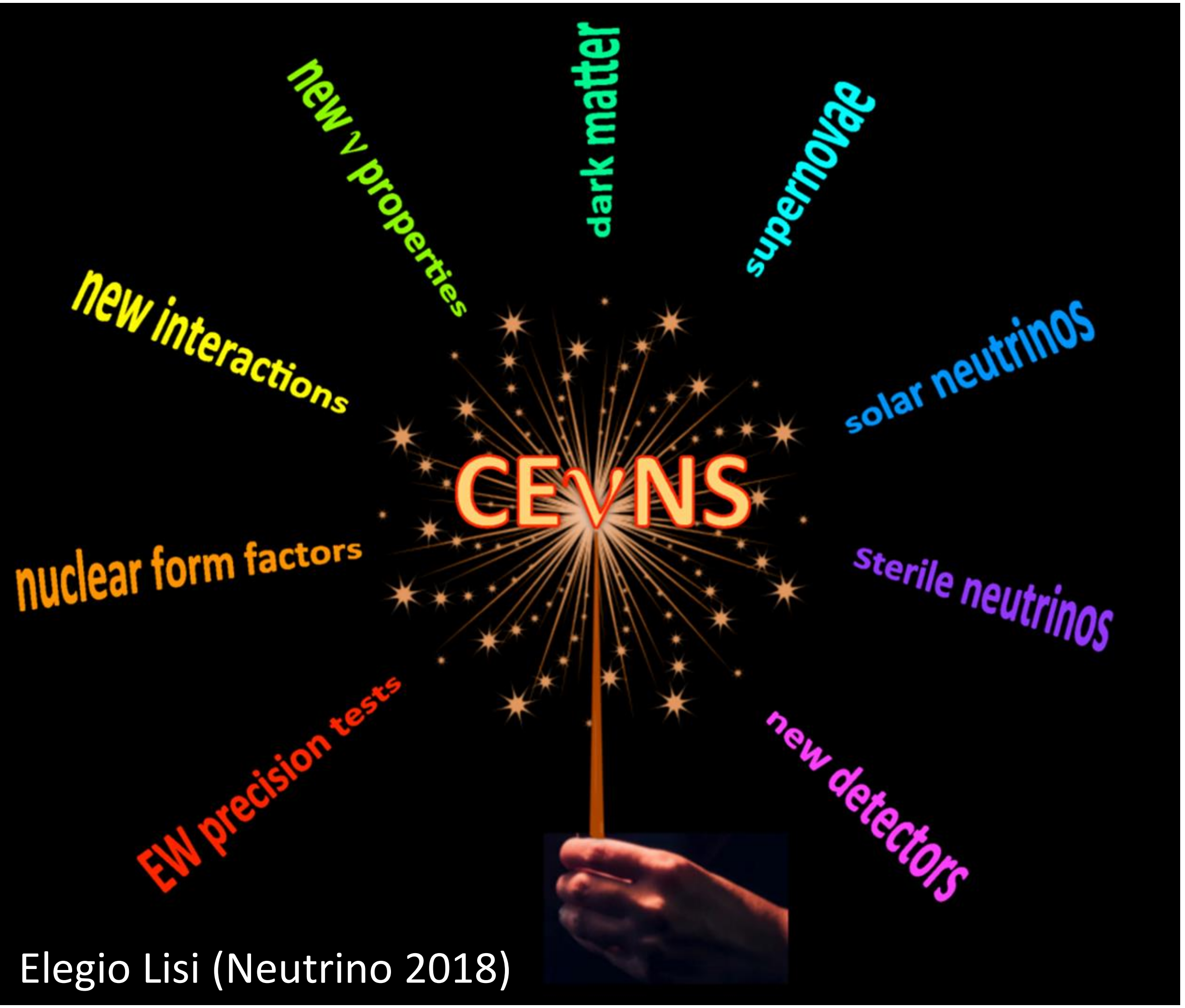
Nuclear physics

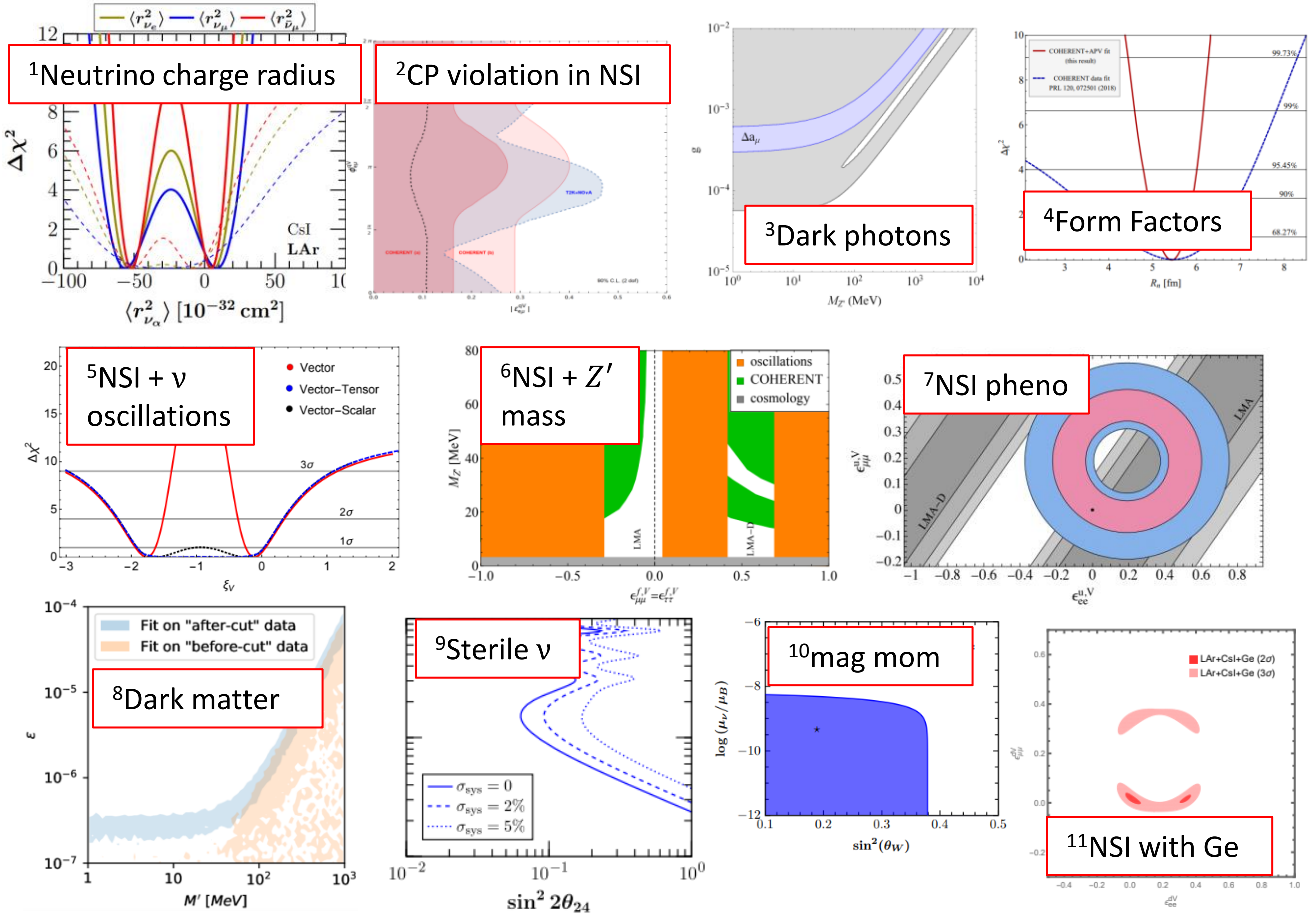
– Only uncertainty in cross section

– Nuclear neutron distribution

(See Matteo Cadeddu's talk)

Physics with CEvNS



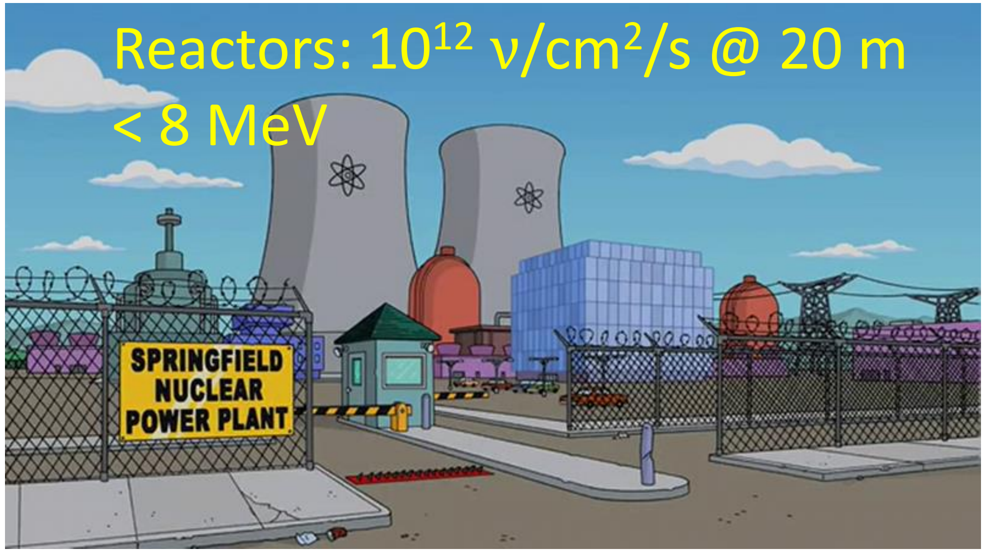


[1]Miranda et al., *JHEP* **05** 130 (2021)
[2]Khan et al., *PRD* **104** 015019 (2021)
[3]Liao/Marfatia, *PLB* **775** 54-57 (2017)
[4]Cadeddu/Dordei, *PRD* **99** 092003 (2019)
[5]Coloma et al., *PRD* **96** 115007 (2017)
[6]Denton/Gehrlein, *PRD* **106** 015022 (2022)
[7]Sierra et al., *PRD* **98** 075018 (2018)
[8]Dutta et al., *PRL* **124** 121802 (2019)
[9]Miranda et al., *PRD* **102** 113014 (2020)
[10]Papoulias/Kosmas, *PRD* **97** 033003 (2017)
[11]Liao/Marfatia/Zhang, arXiv:2408.06255 (2024)

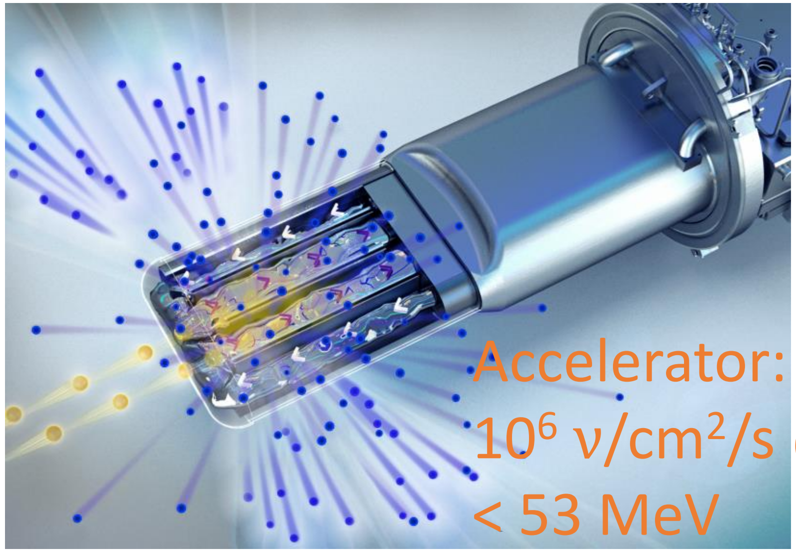
Low-energy neutrino sources

Steady | **Pulsed**

Artificial

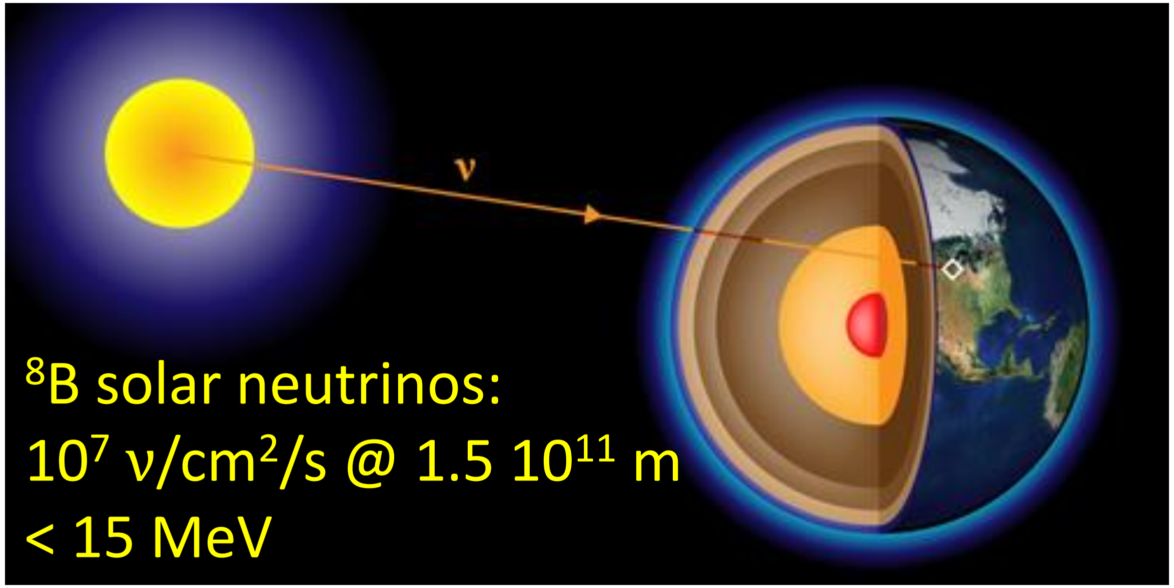


Reactors: 10^{12} ν/cm^2/s @ 20 m
< 8 MeV

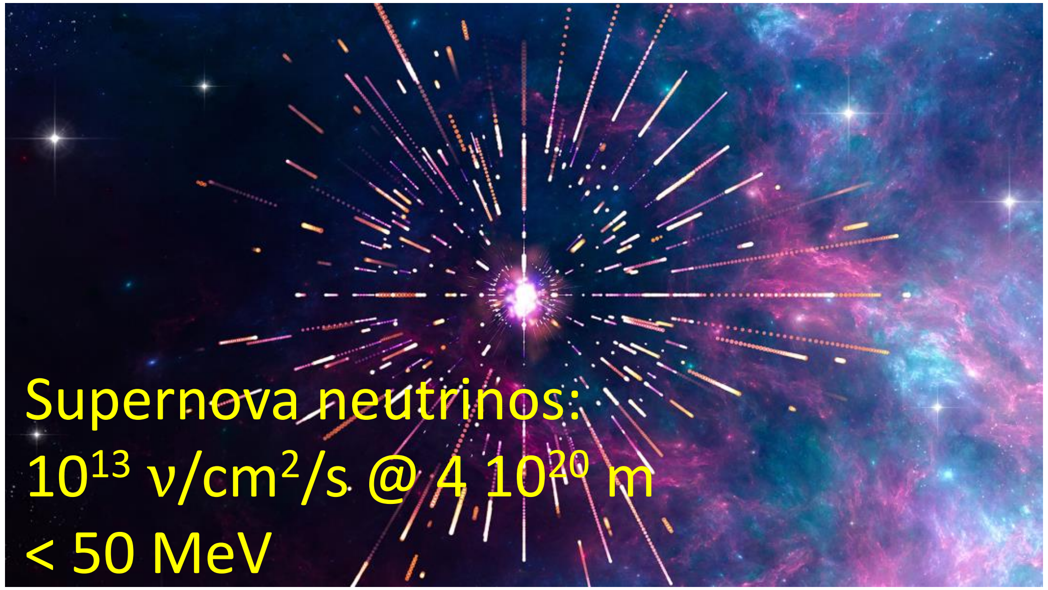


Accelerator:
10^{6} ν/cm^2/s @ 20 m
< 53 MeV

Natural



^{8}B solar neutrinos:
10^{7} ν/cm^2/s @ 1.5 10^{11} m
< 15 MeV

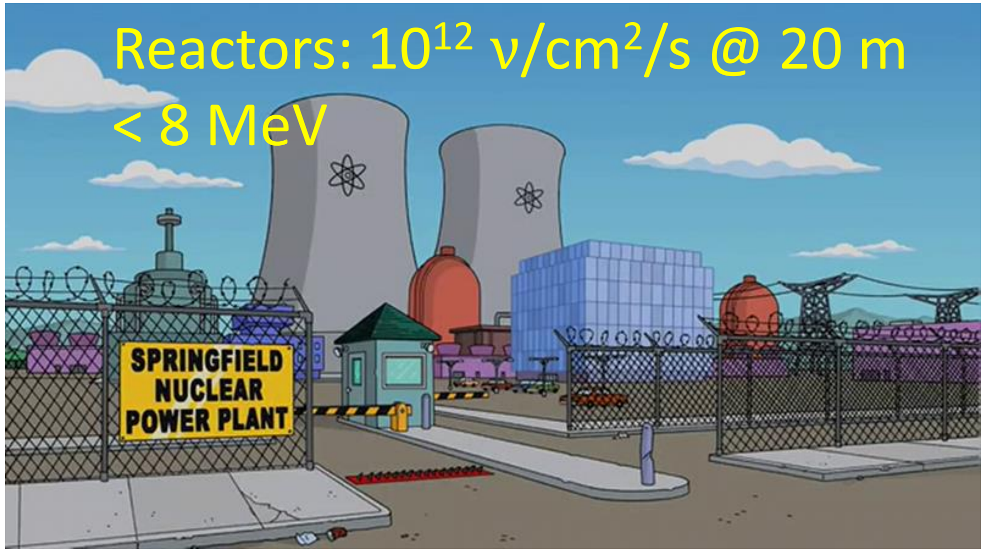


Supernova neutrinos:
10^{13} ν/cm^2/s @ 4 10^{20} m
< 50 MeV

Low-energy neutrino sources

Steady | Pulsed

Artificial



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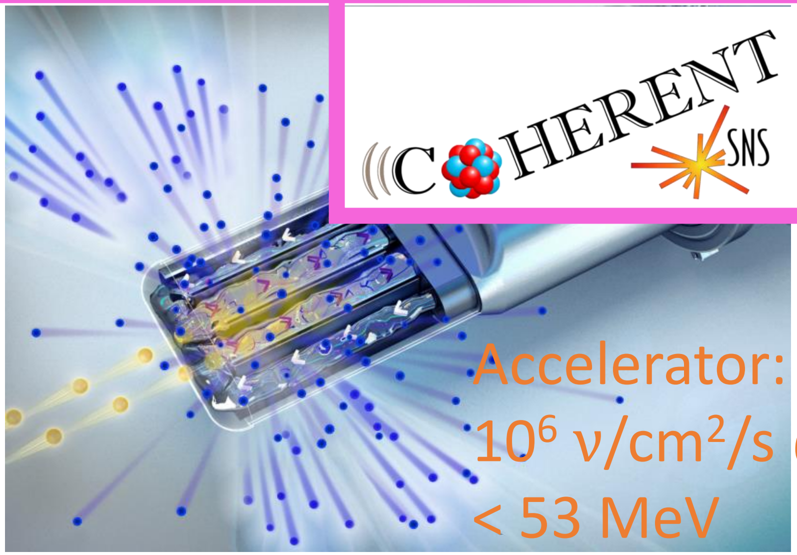

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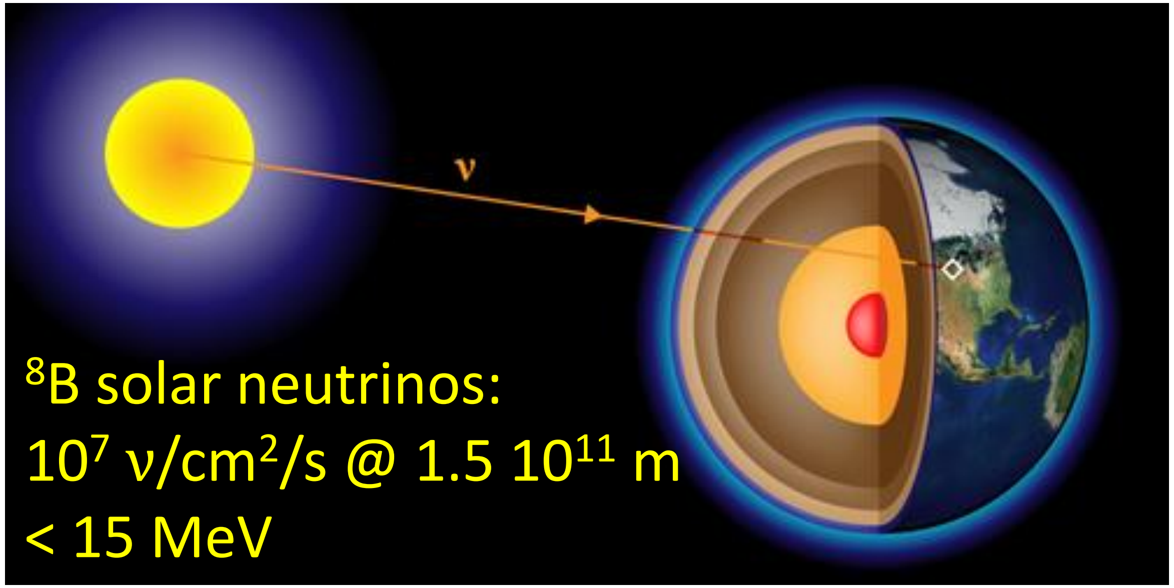

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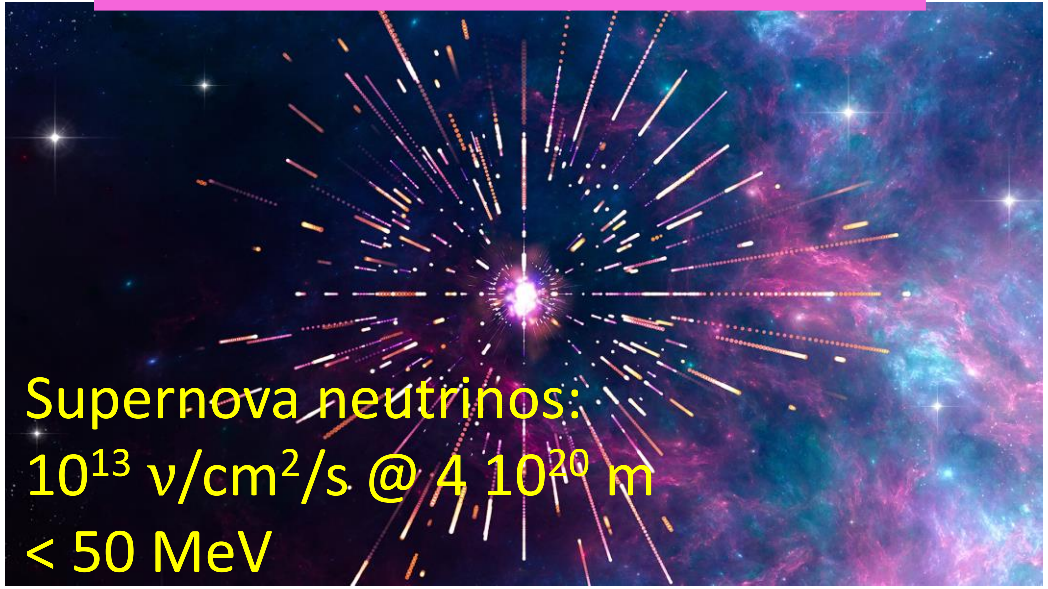

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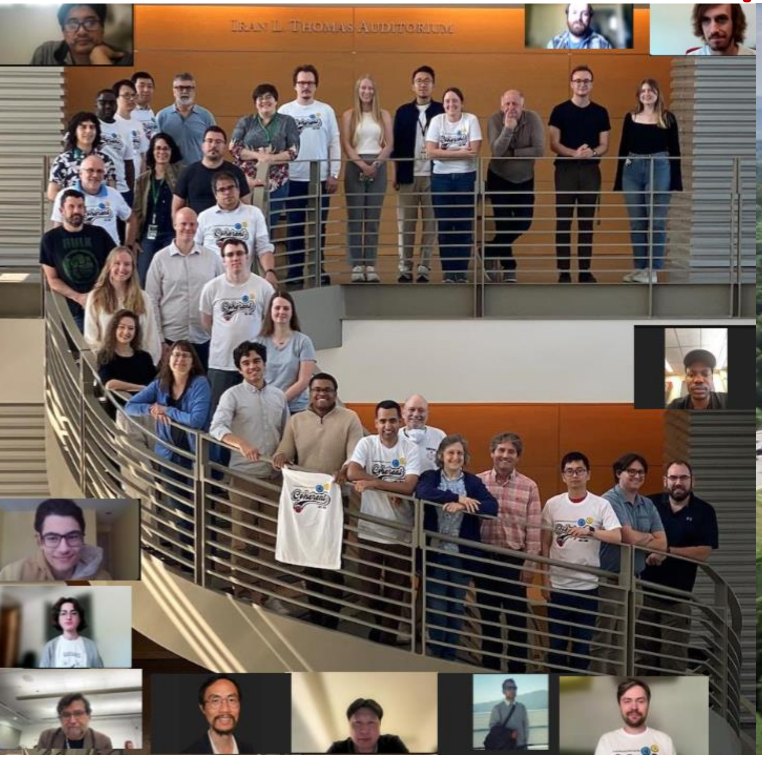
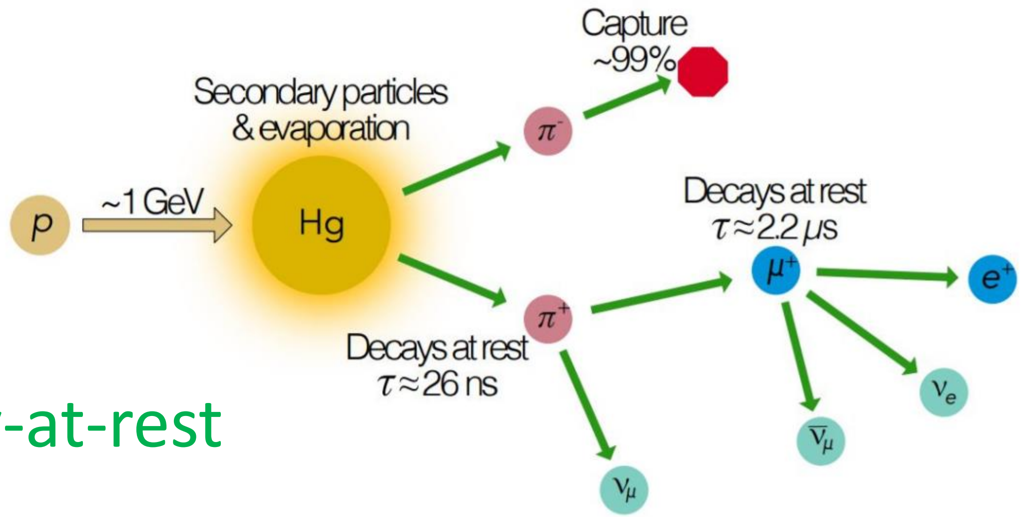
The COHERENT experiment



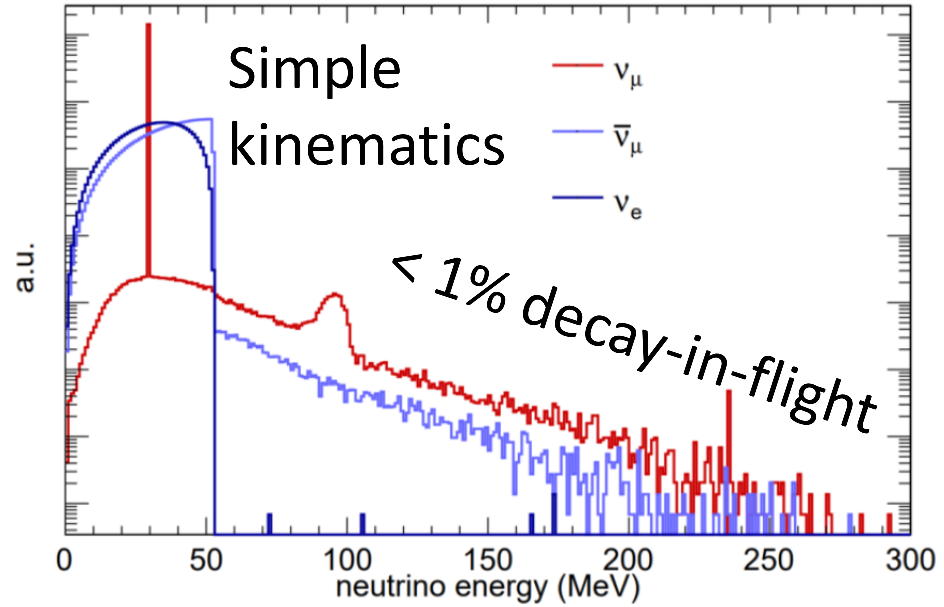
O(100) collaborators
28 institutions
6 countries

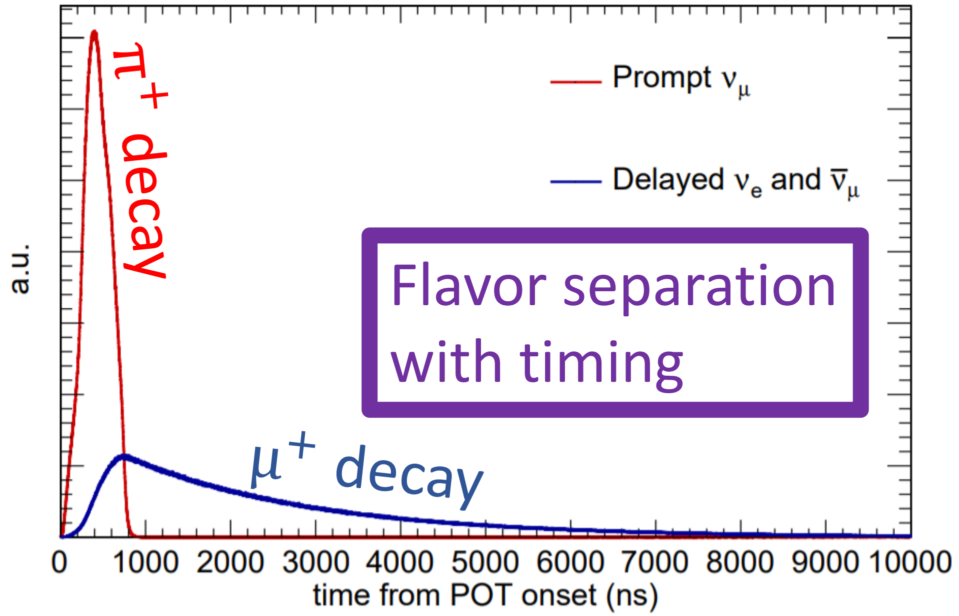
– Spallation neutron source – world leading source of neutrons and low-energy neutrinos
– 1.4 MW -> 2.0 MW (upgrade complete 2027)
– ≈ 1 GeV on Hg target at 60 Hz
– Narrow beam pulse (350 ns) -> 30000x bkg rejection
– Second target station planned in 2030s

Neutrino flux at the SNS



π decay-at-rest

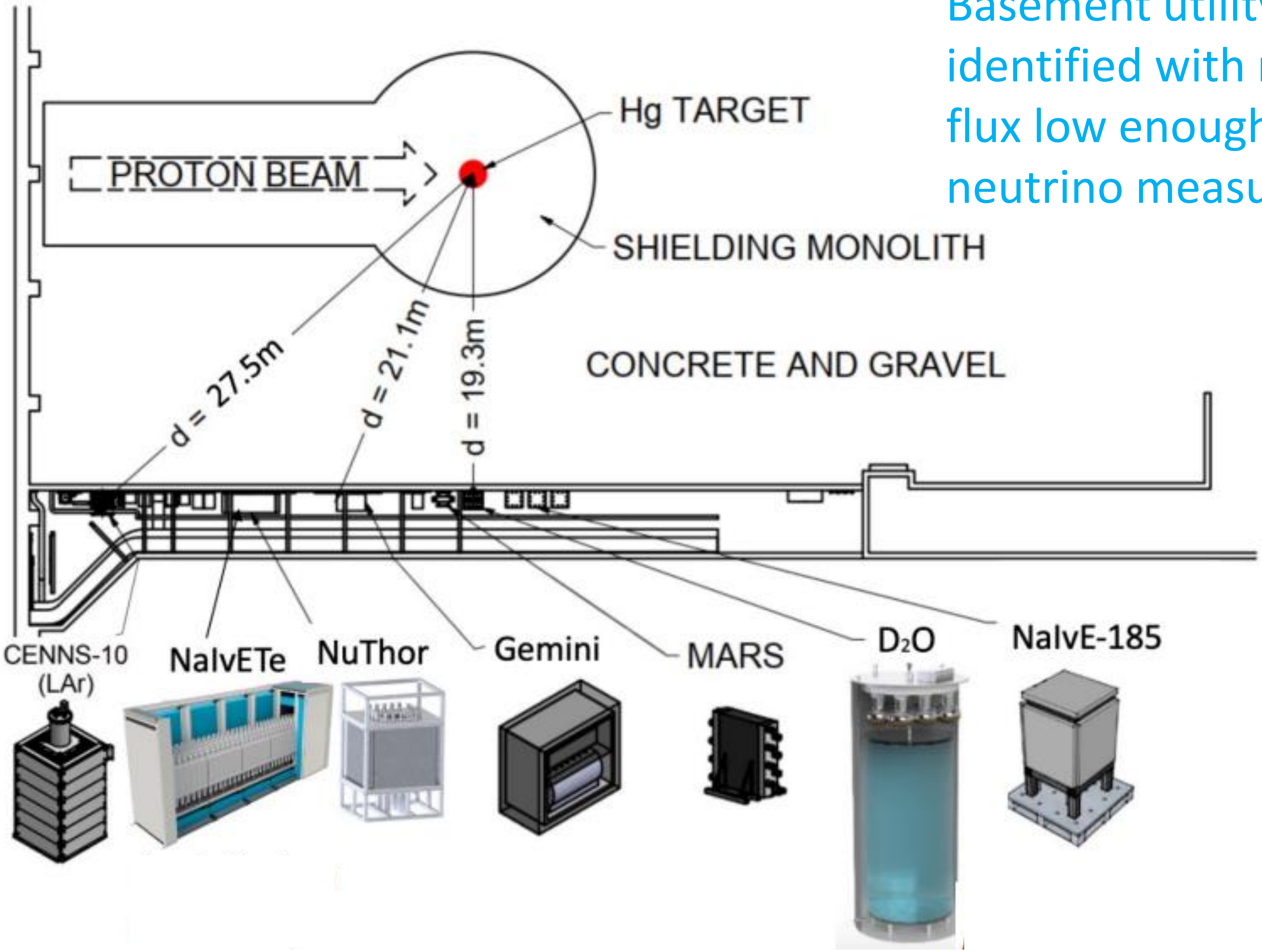




Making low-energy neutrinos at accelerators

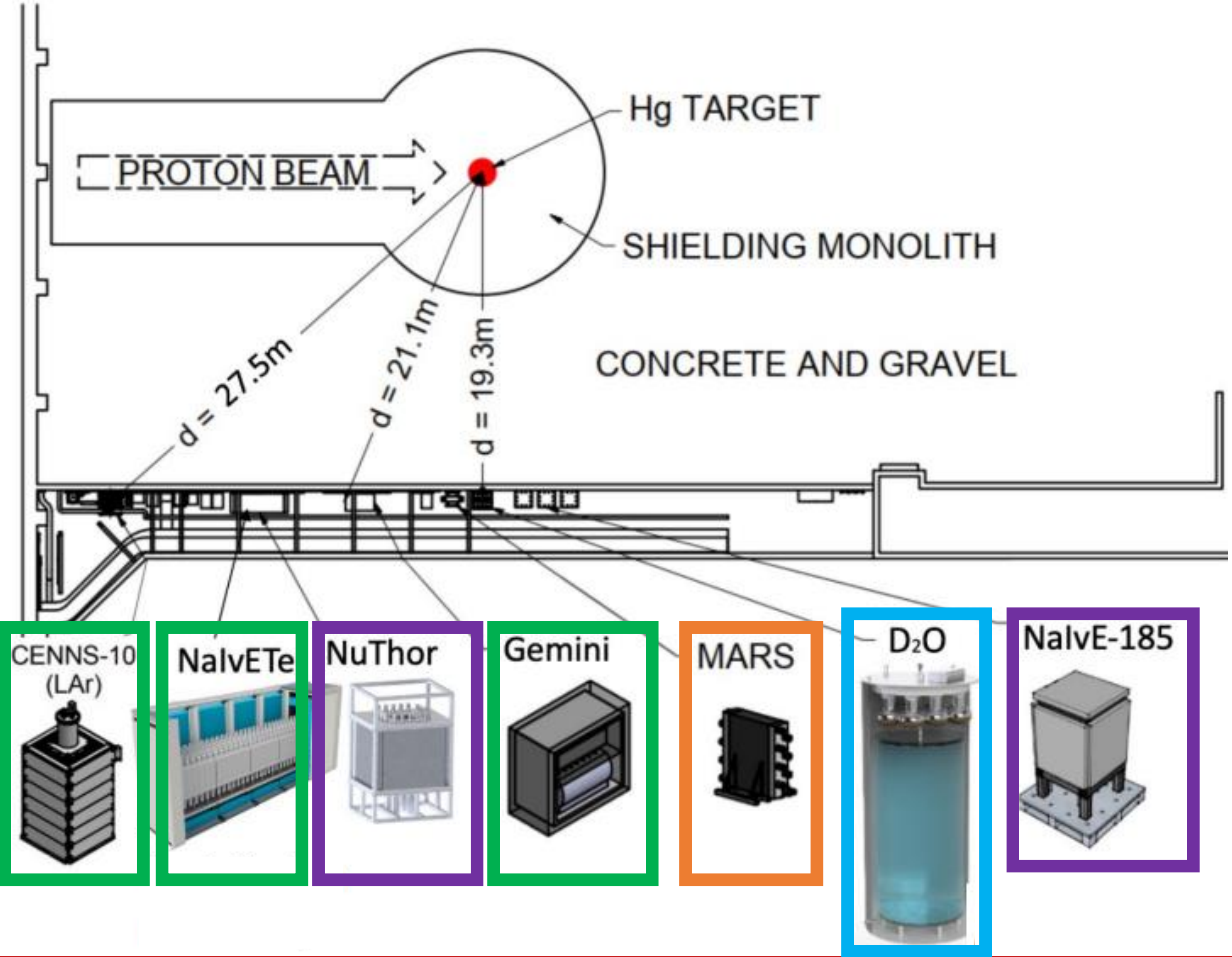
- Massive target and low energy → mesons decay at rest
- Well-understood energy and timing distribution
- No optics – isotropic angular distribution

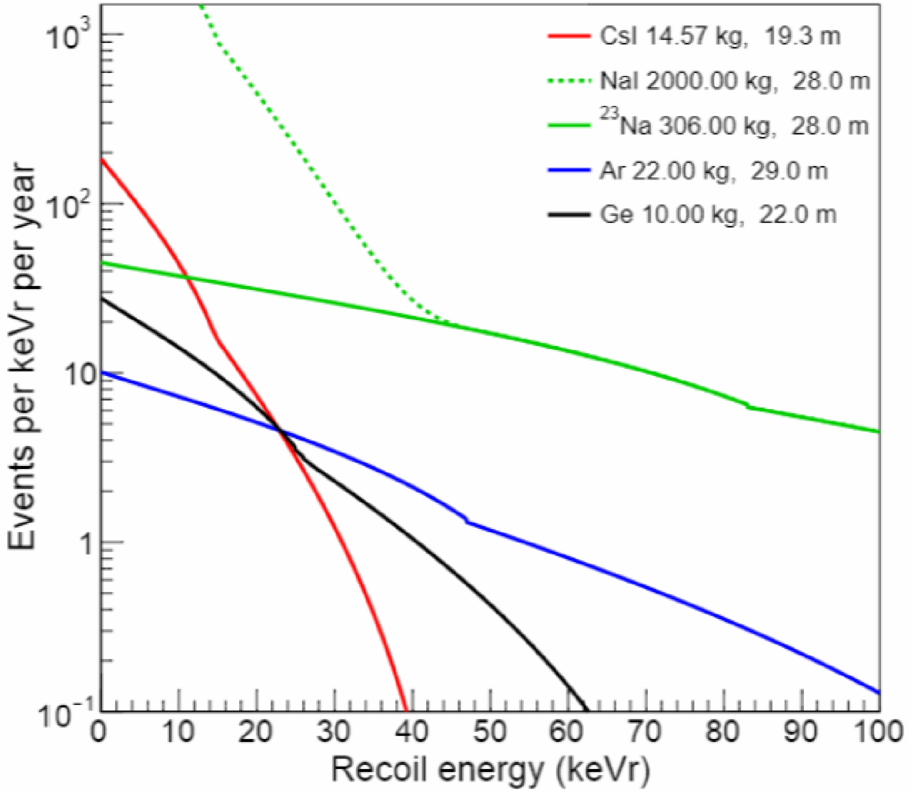
Finding an experiment hall: Neutrino alley



Basement utility hallway identified with neutron flux low enough for neutrino measurements!

COHERENT's lineup supporting diverse physics





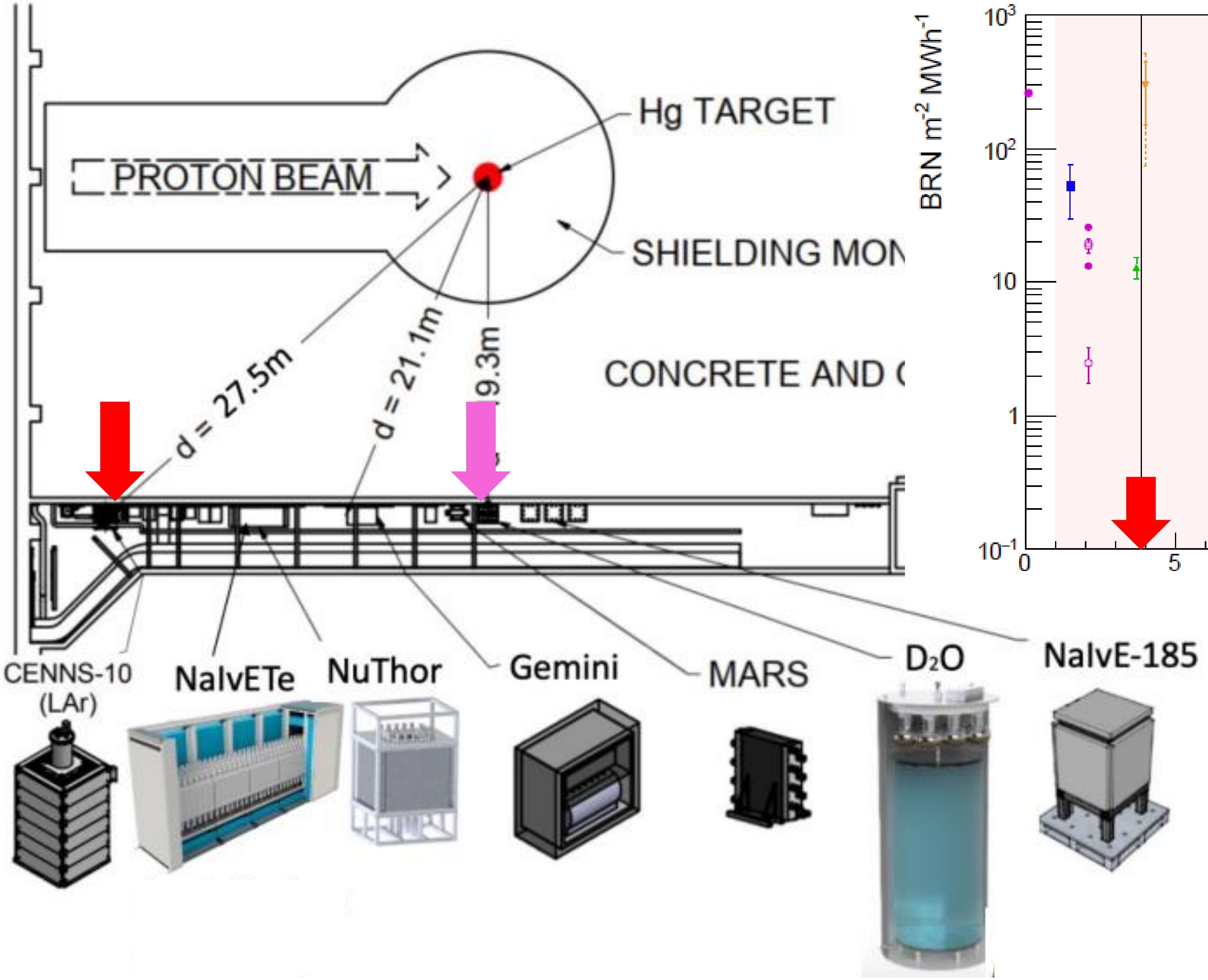
CEvNS on multiple nuclei

Inelastic cross sections

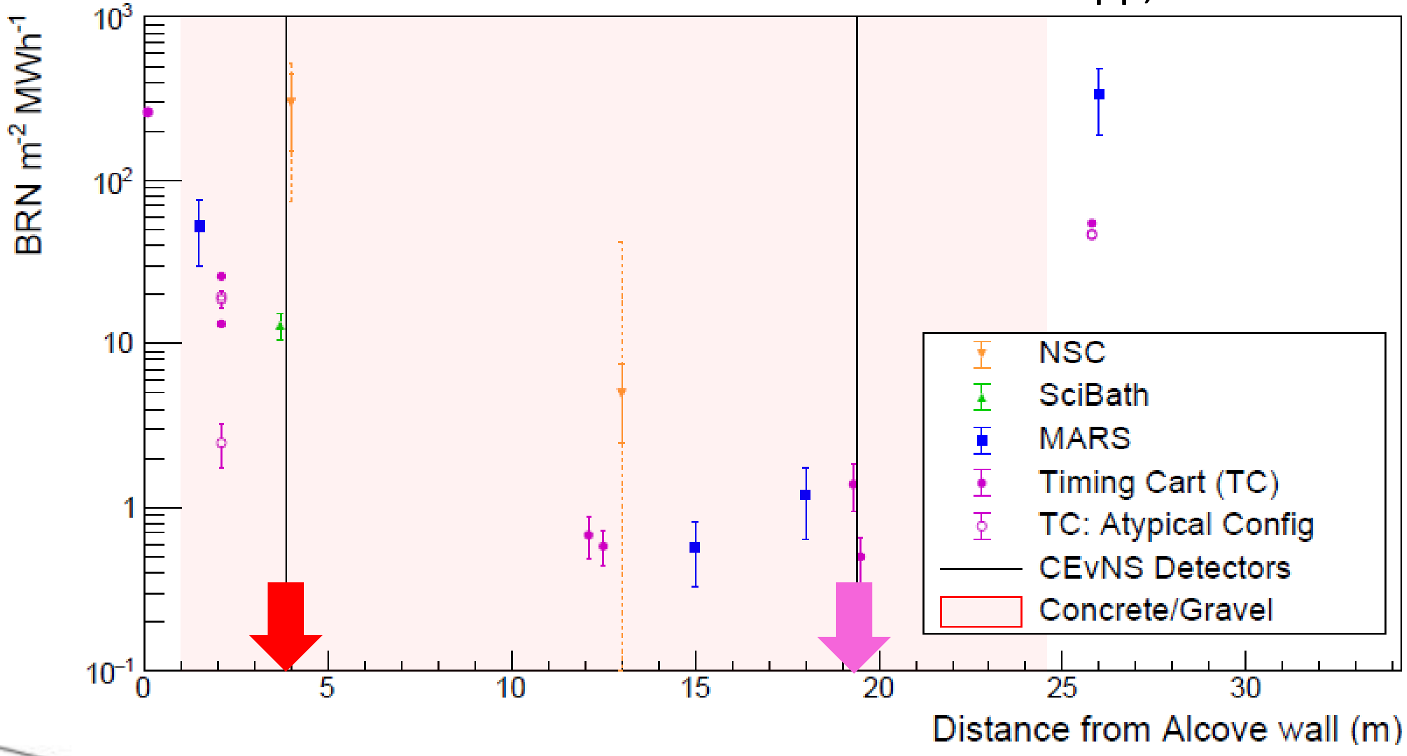
Background characterization

Flux calibration

Neutron flux through the alley

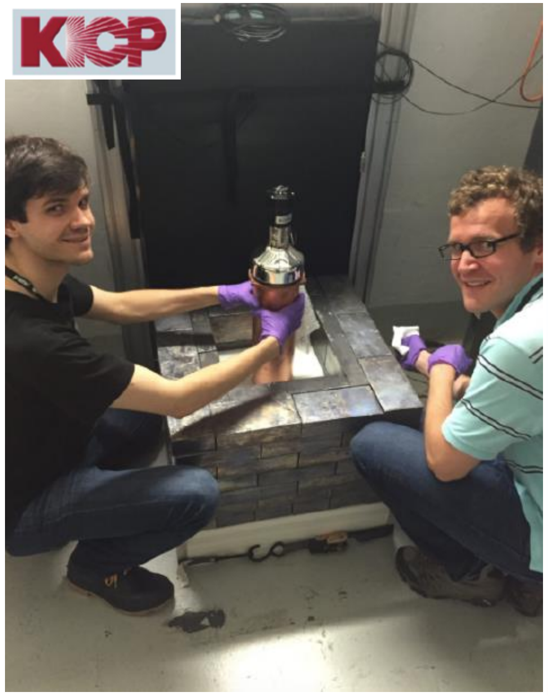


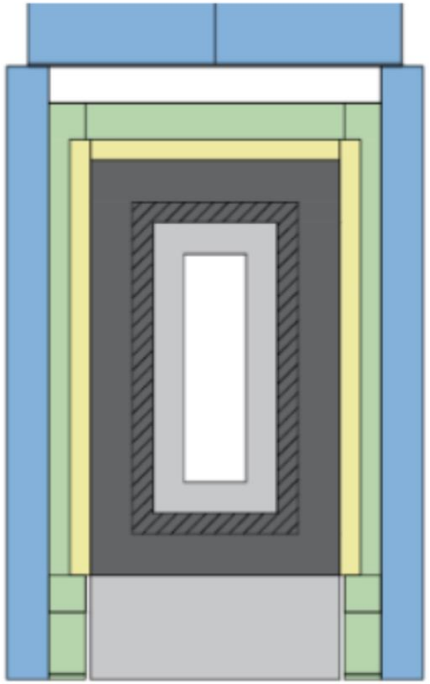
Rebecca Rapp, Ph.D. thesis



Dedicated neutron detectors to characterize and monitor backgrounds through the hall

First light – CsI[Na]





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

Hand-held 14.6-kg CsI[Na] detector
Single PMT readout
Composite background shielding

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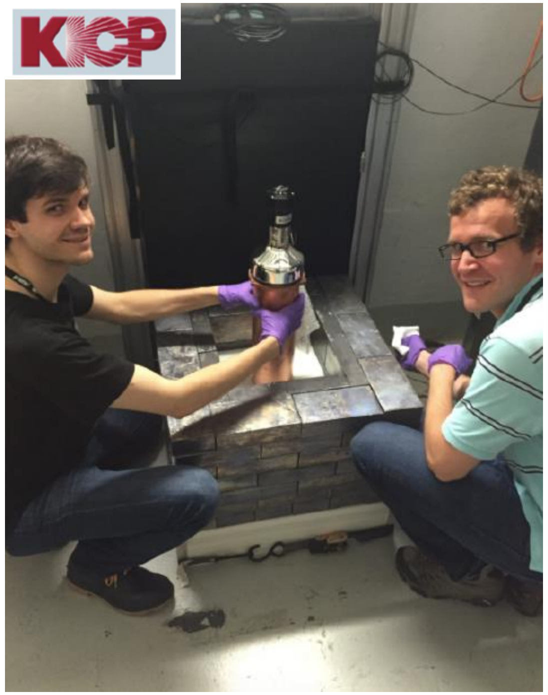

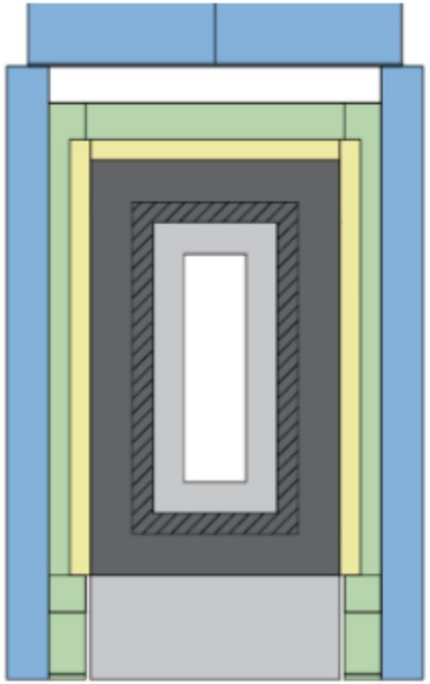

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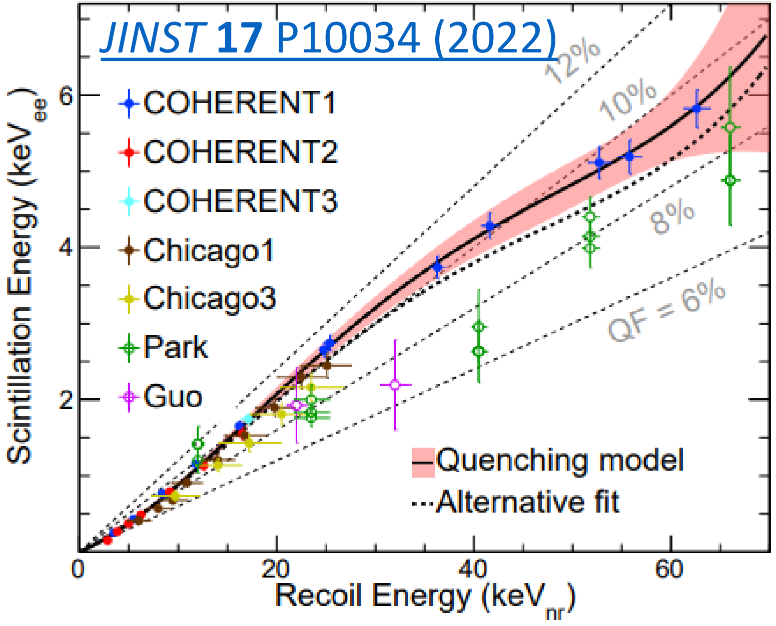

Major analysis challenge:
nuclear recoil quenching

Joint fit of five separate measurements

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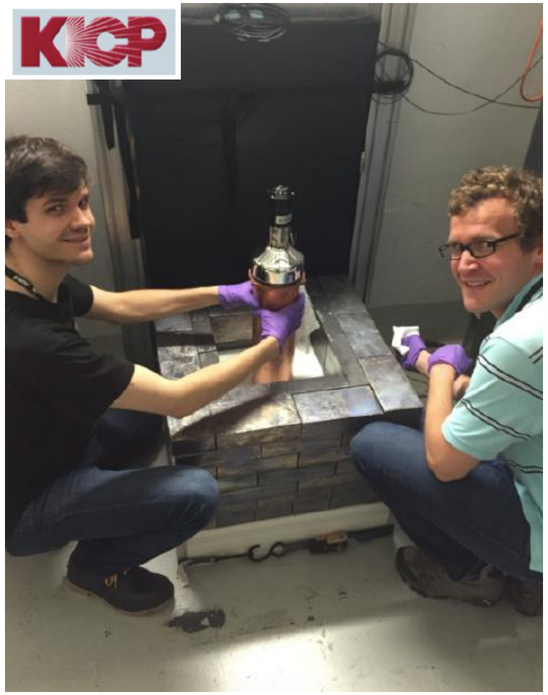

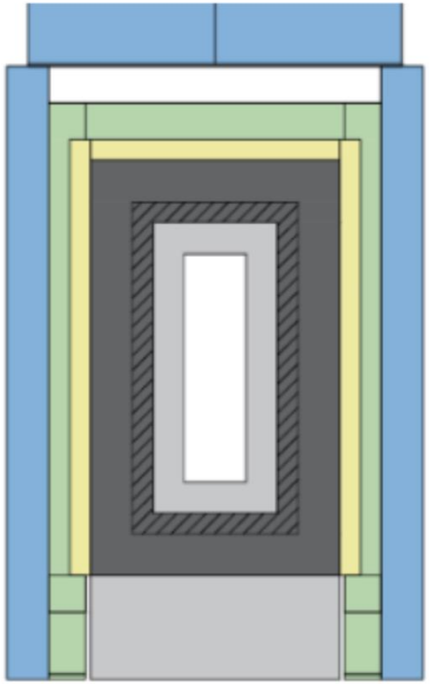

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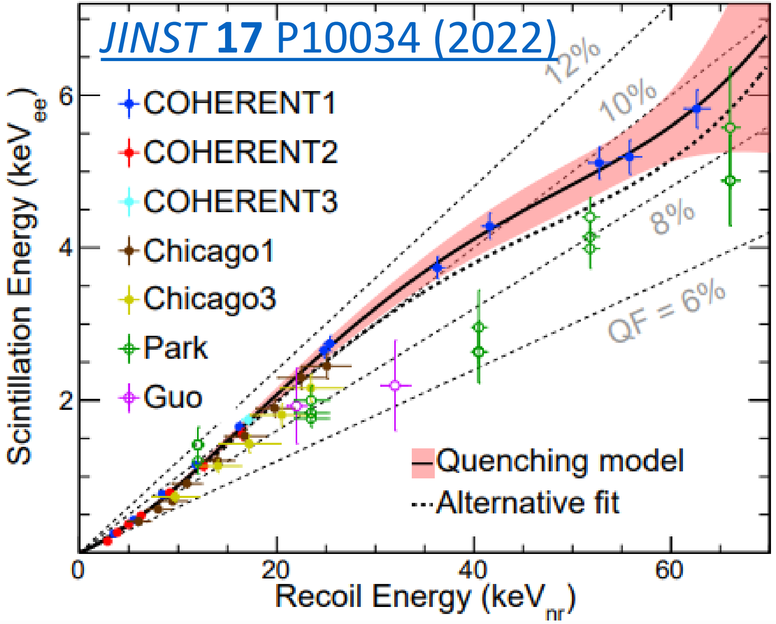

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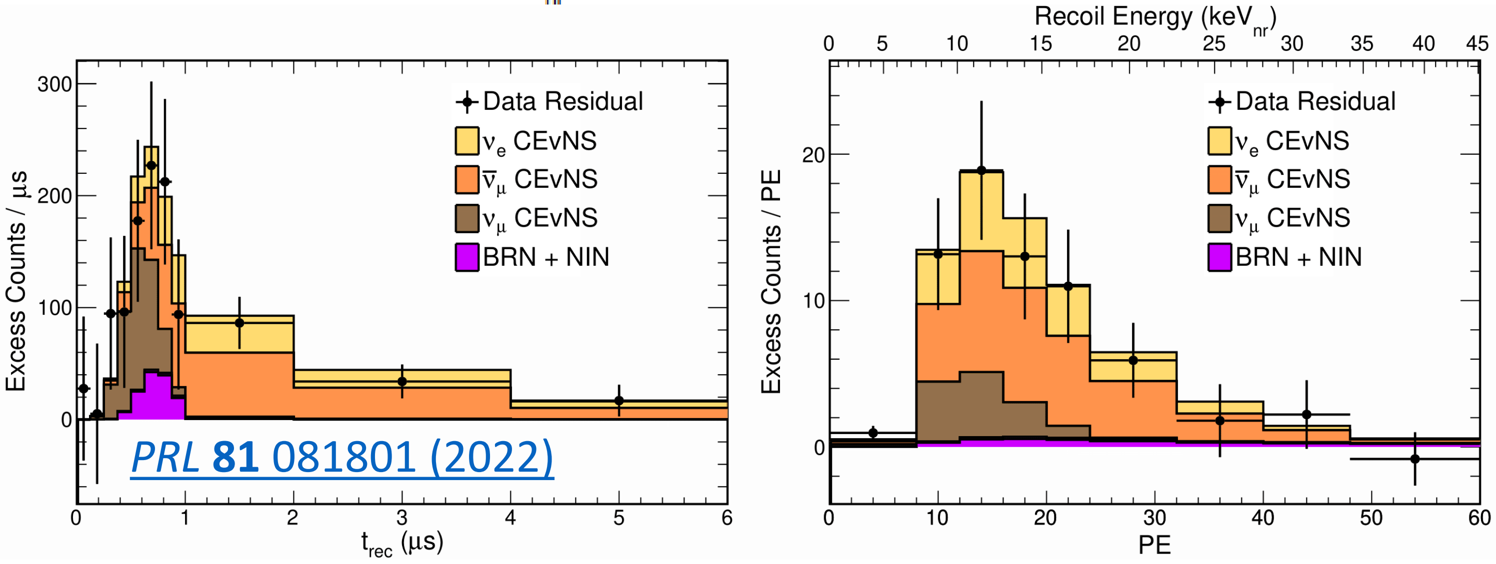
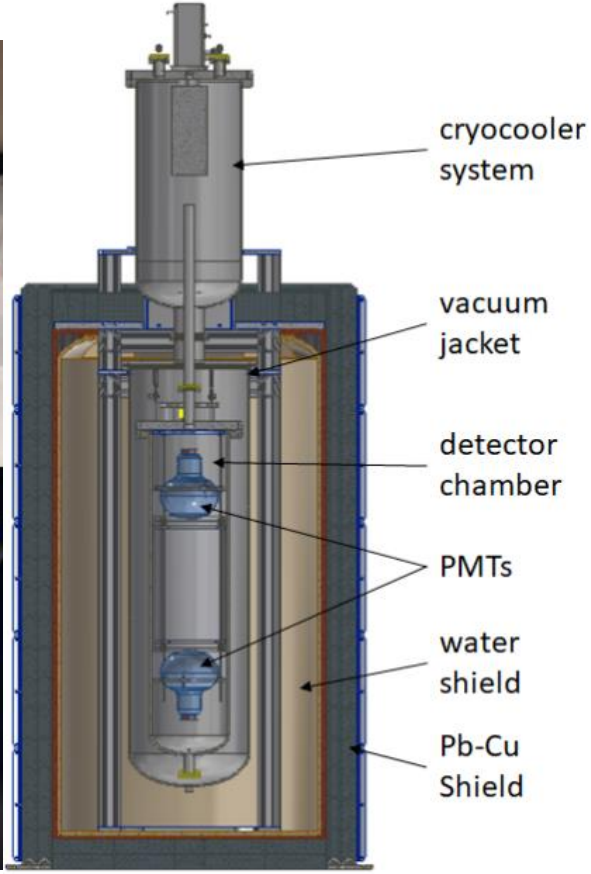
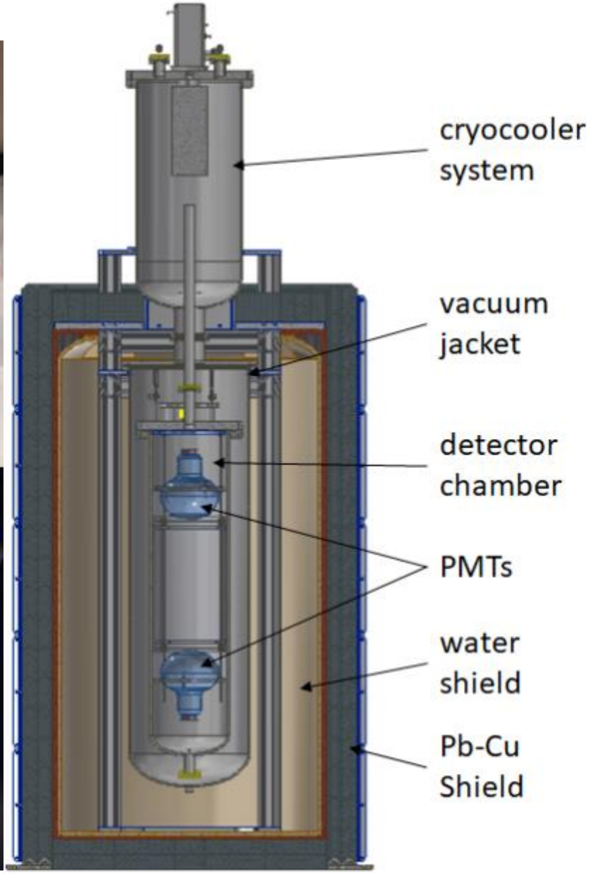


First light – argon

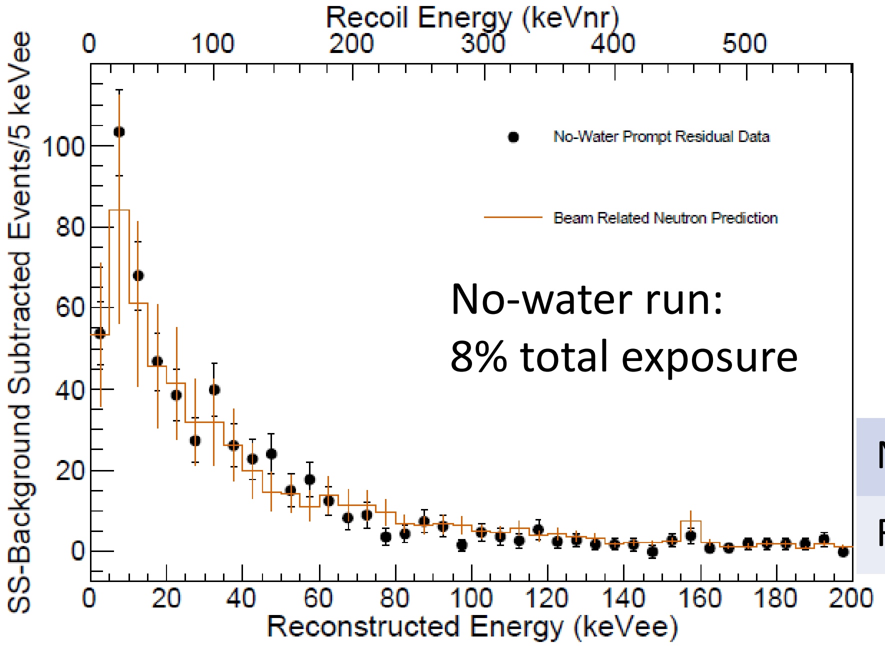


24-kg argon scintillating calorimeter
Dual PMT readout
Drainable water tank – neutron bkg

First light – argon



Jacob Zettlemoyer, Ph.D. thesis



Major analysis challenge:
beam-correlated neutrons

No-water running

	$N_{neutrons}$	Exposure
No water	580 ± 25	0.54 GWhr
Full shielding	553 ± 34	6.12 GWhr

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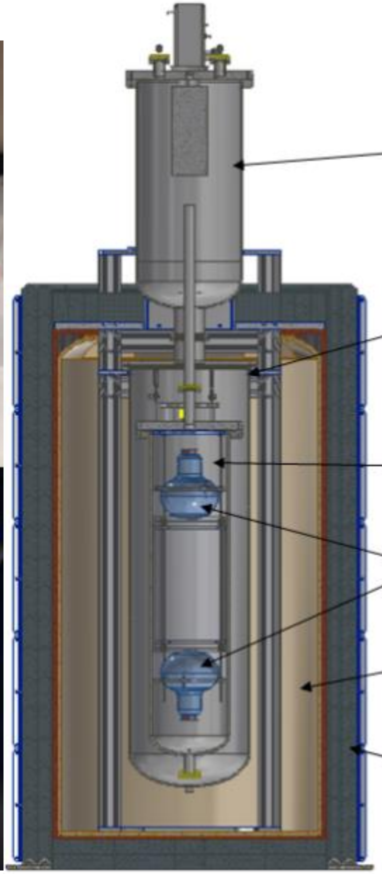

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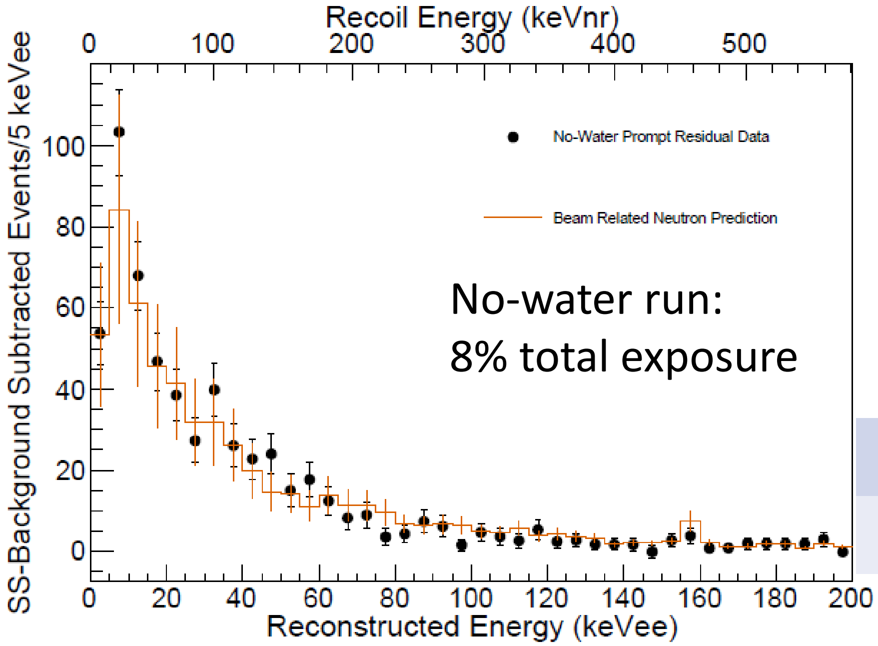

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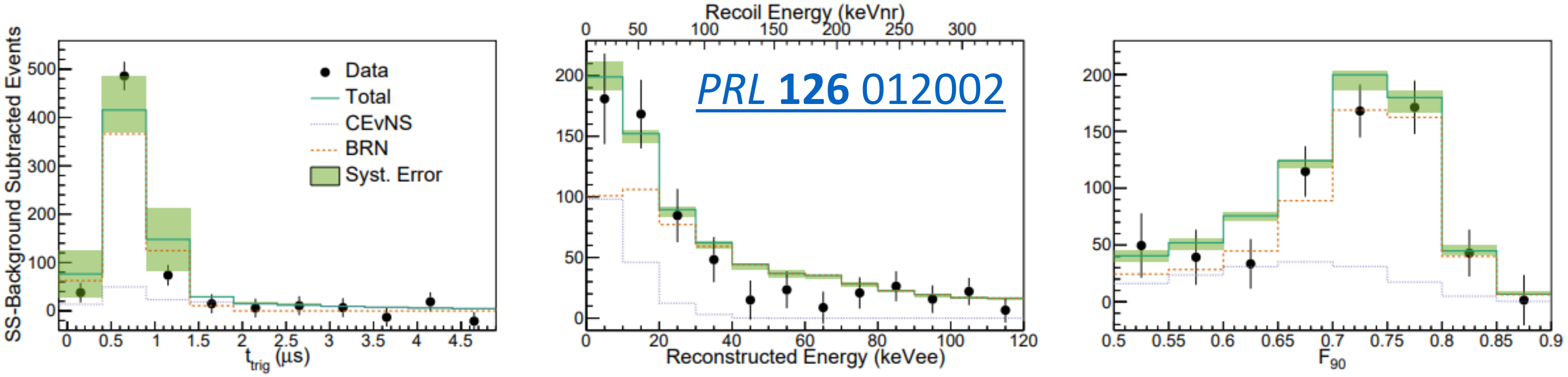
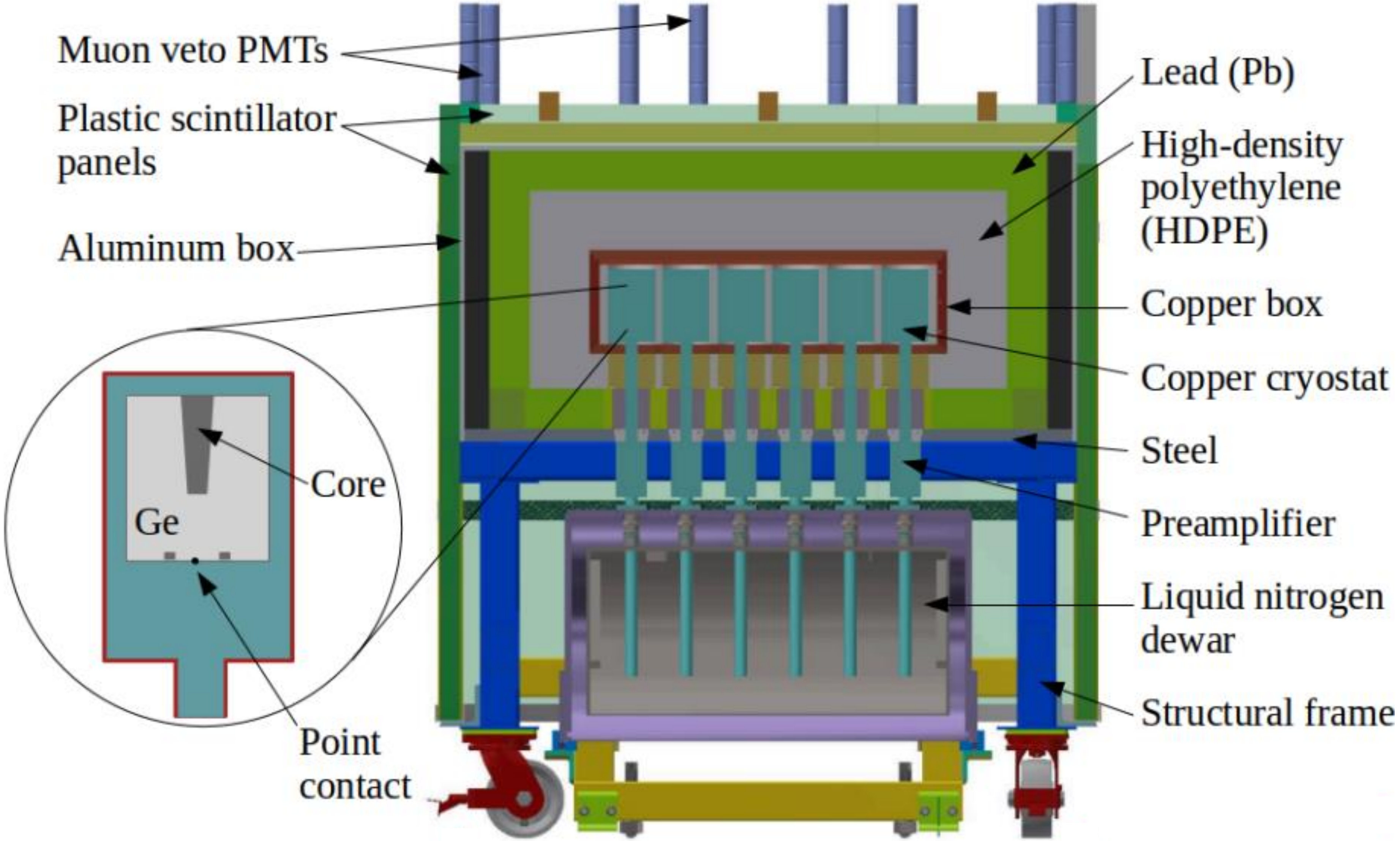
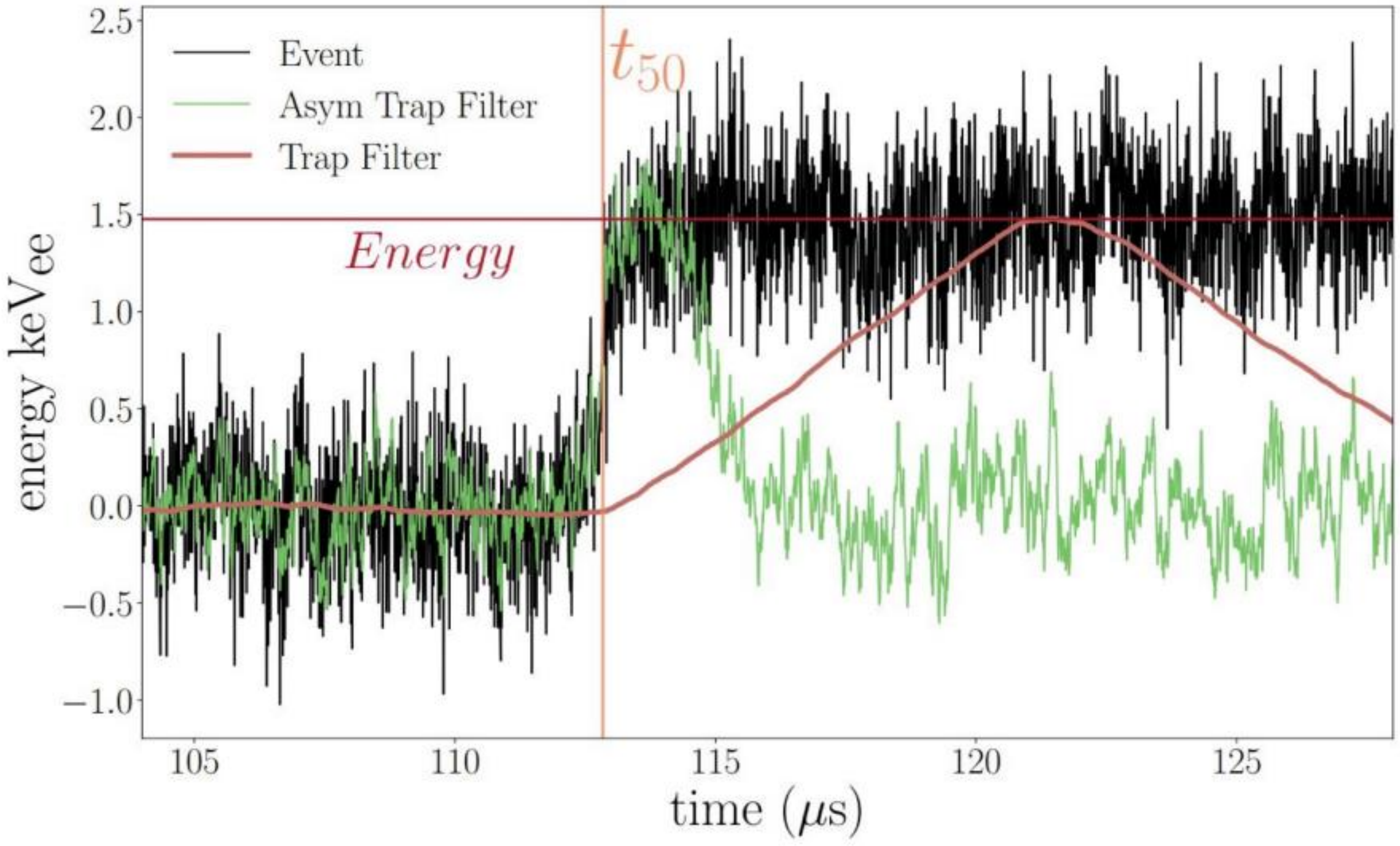


First charge – germanium in the GeMini detector *(new in 2023)*



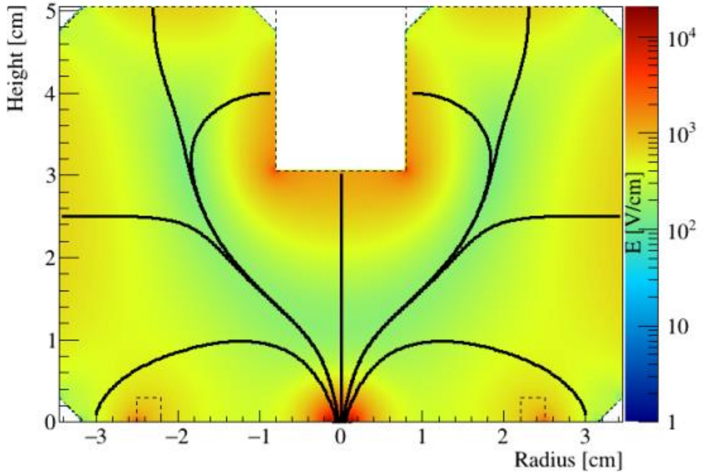
GeMini waveform analysis



Convolve waveform with a trapezoidal kernel to reconstruct energy and time of each event

GeMini timing calibration

Li, Liu, Kooi, *EPJC* **80** 3 (2020)



Major analysis challenge:

non-trivial electron drift time through germanium diode

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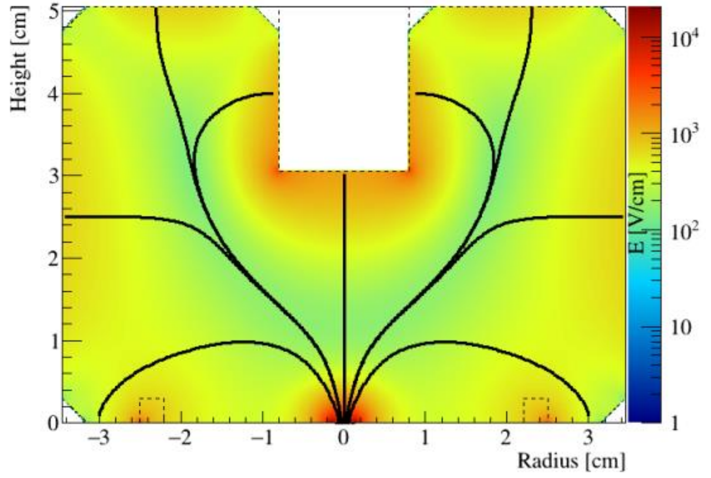

Major analysis challenge:
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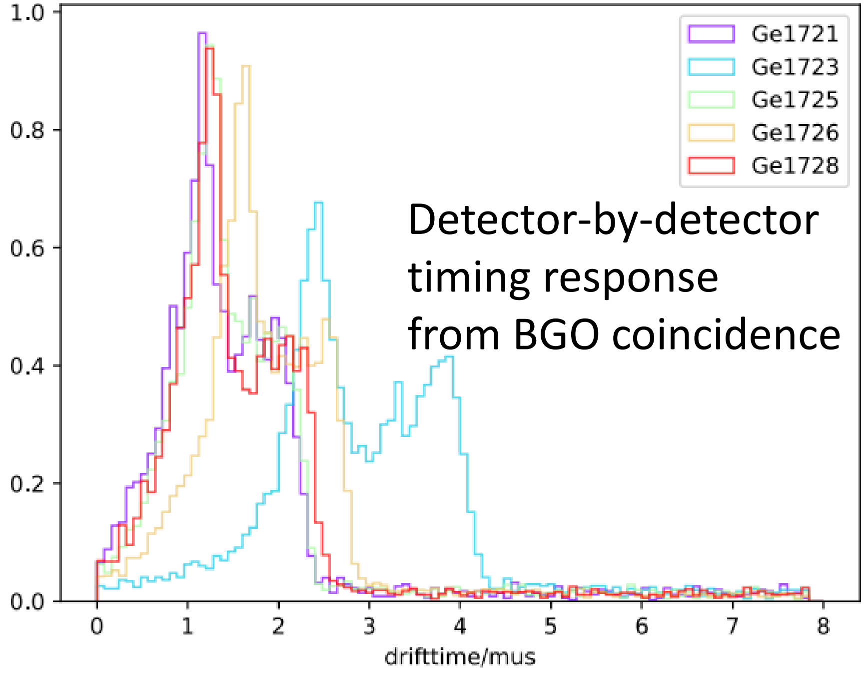
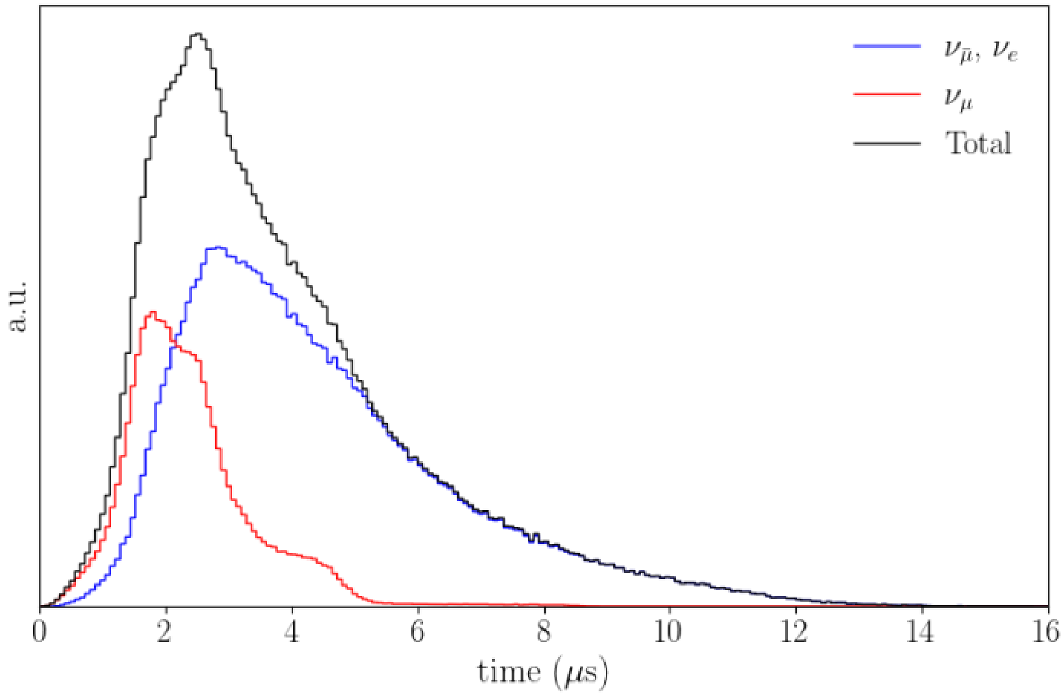
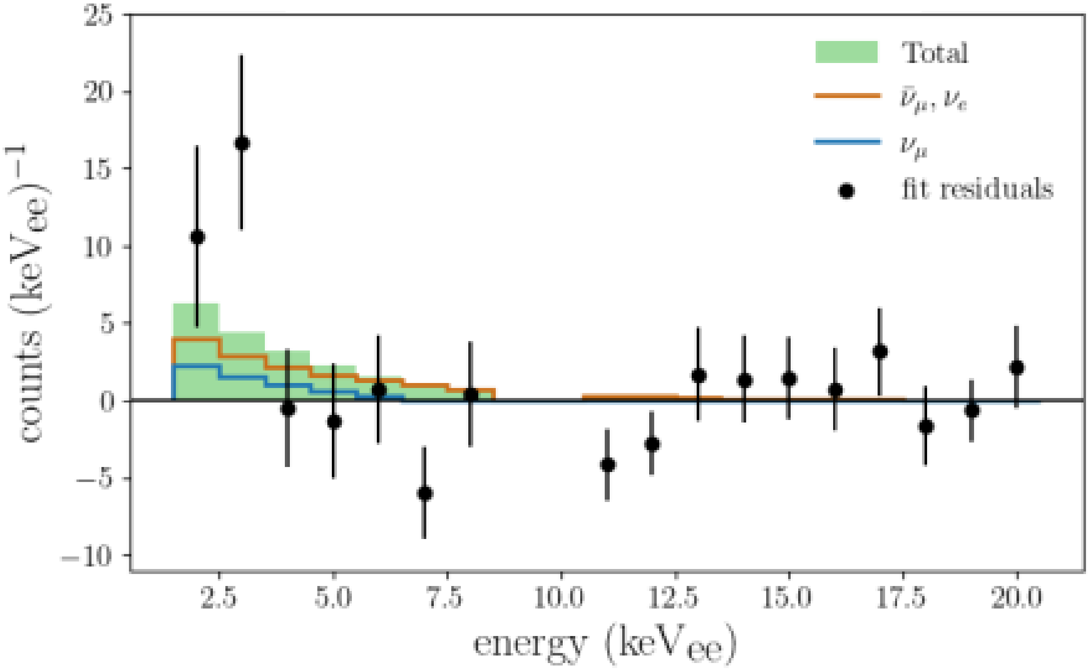
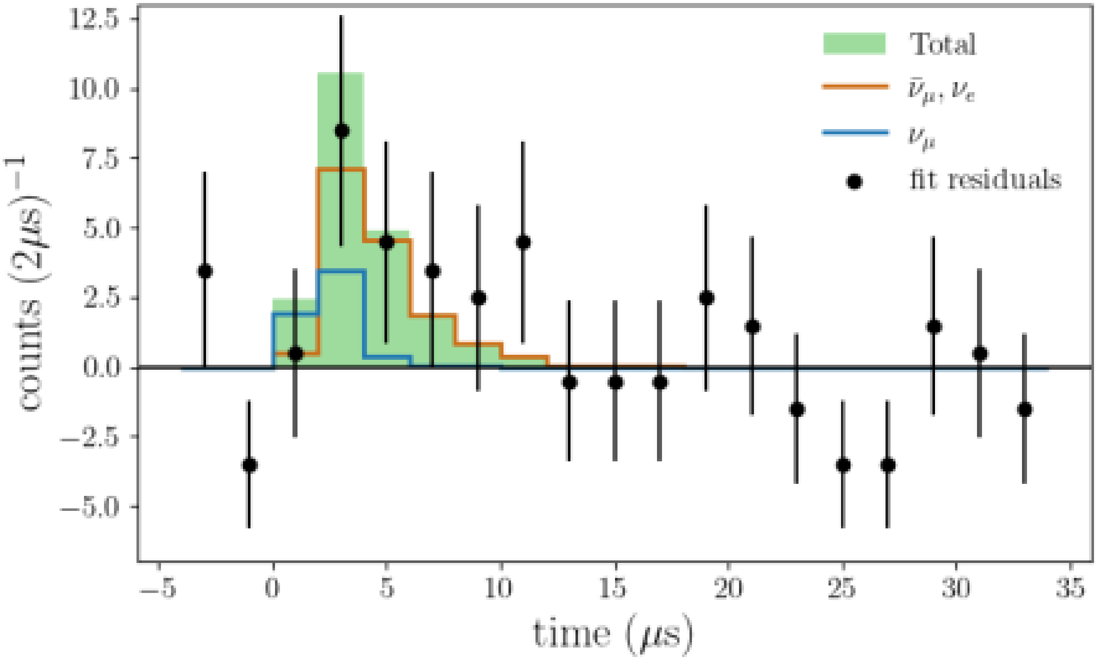
Coincidence of gamma rays from ^{228}Th source measured in BGO crystal and Ge crystals to calibrate *O(μs)* resolution





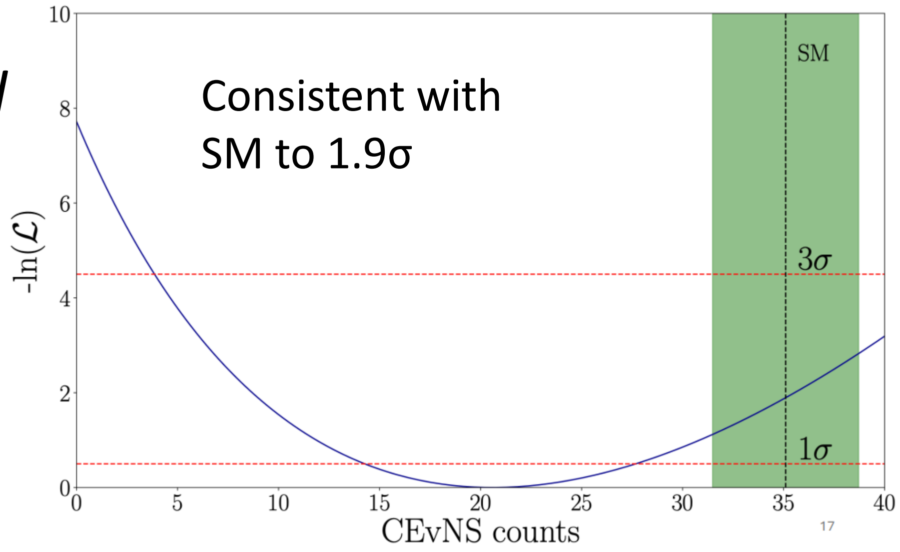
GeMini results



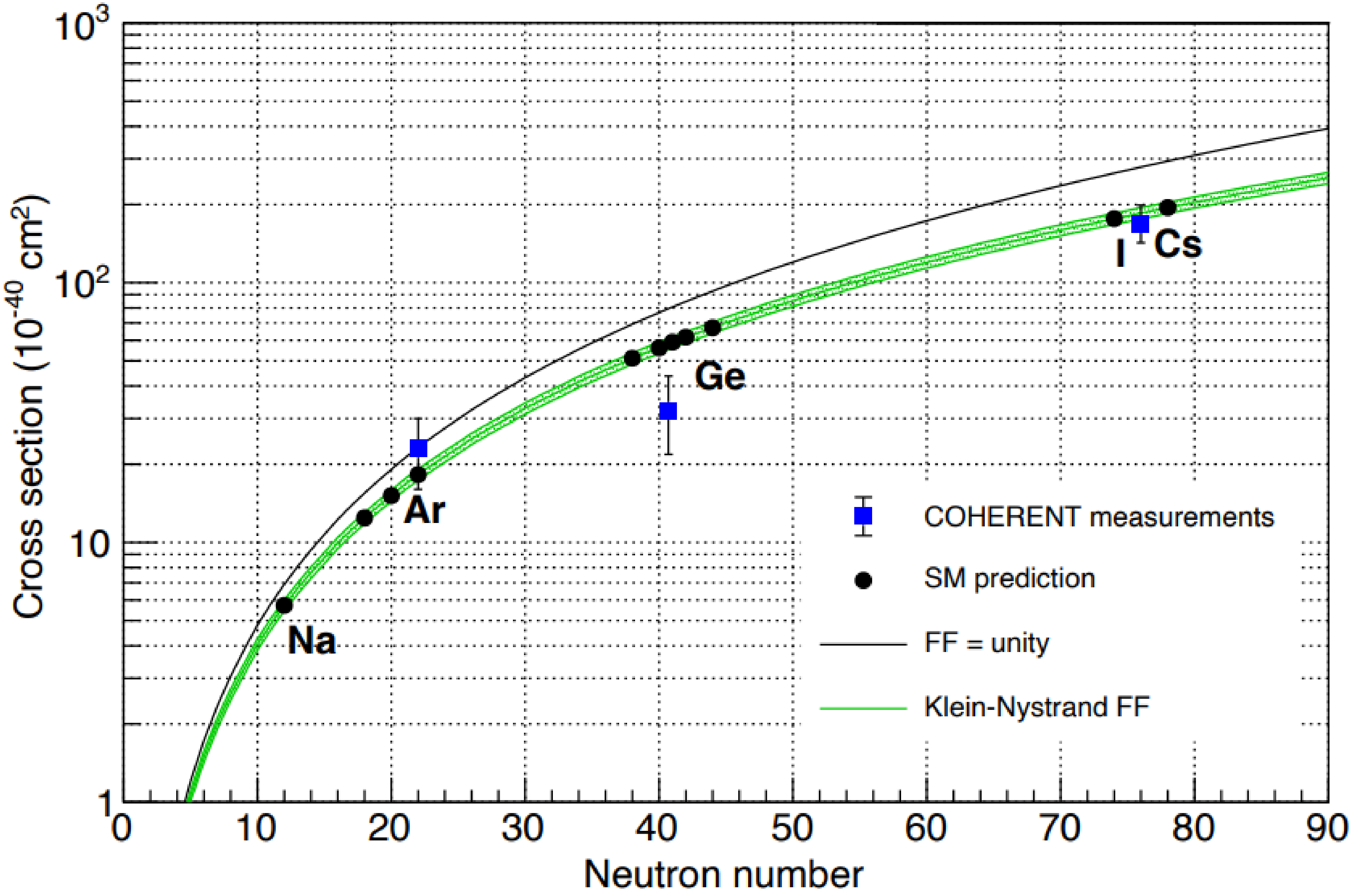


2D unbinned likelihood fit with 1-to-1 signal to background

Fitted event counts	20.6+7.1-6.3
Prediction	35.1
Systematic error on pred	10.3%
No-CEvNS rejection	3.9σ



Summary of current *COHERENT* CEvNS results

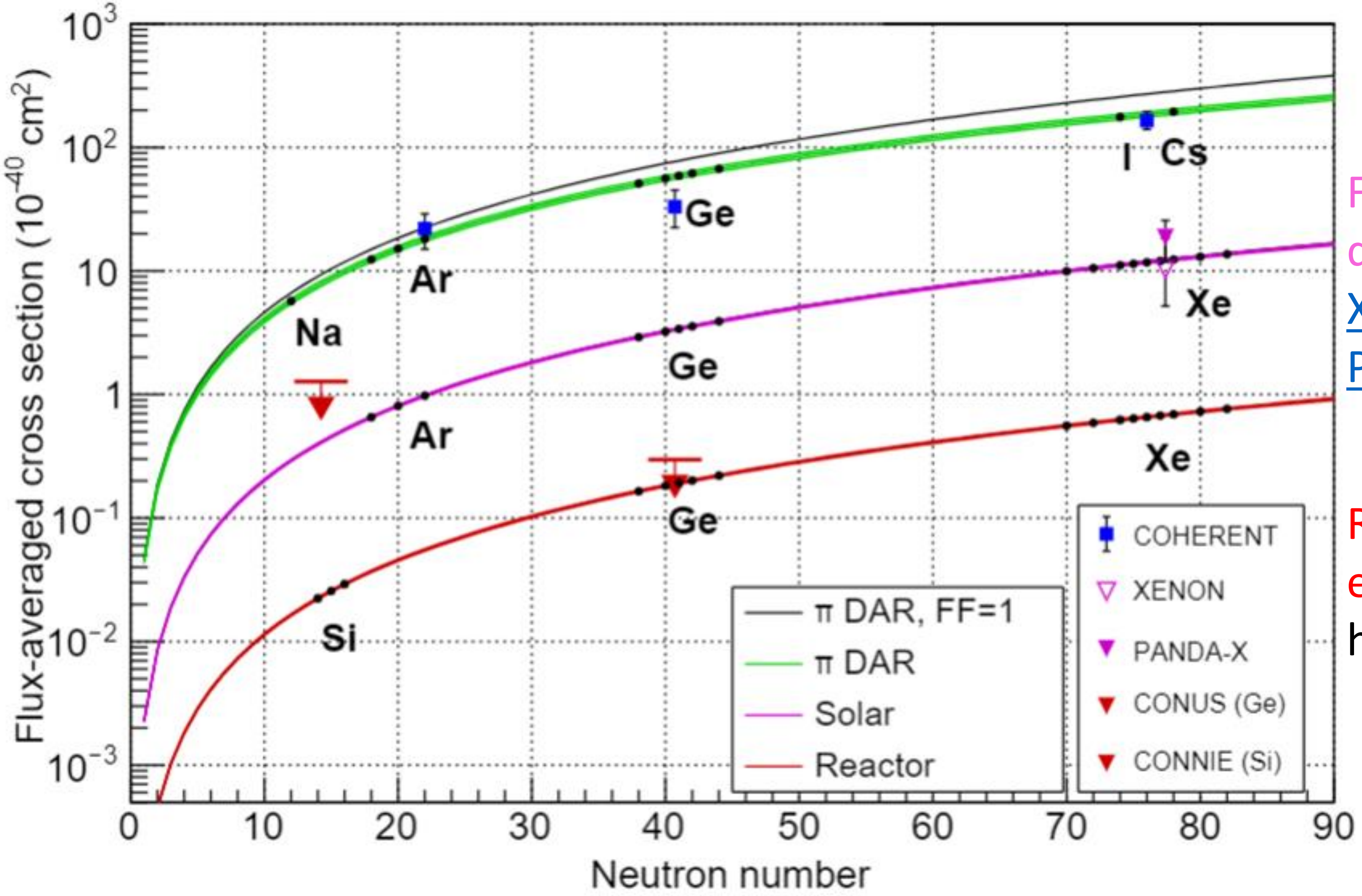


With three measurements, $\sigma \propto N^2$ becoming clear but more data needed for precision tests

Nuclear form factor effects evident, see slides from Matteo Cadeddu

Construction of 2.5-t NaI NaIvETe detector will measure lightest target

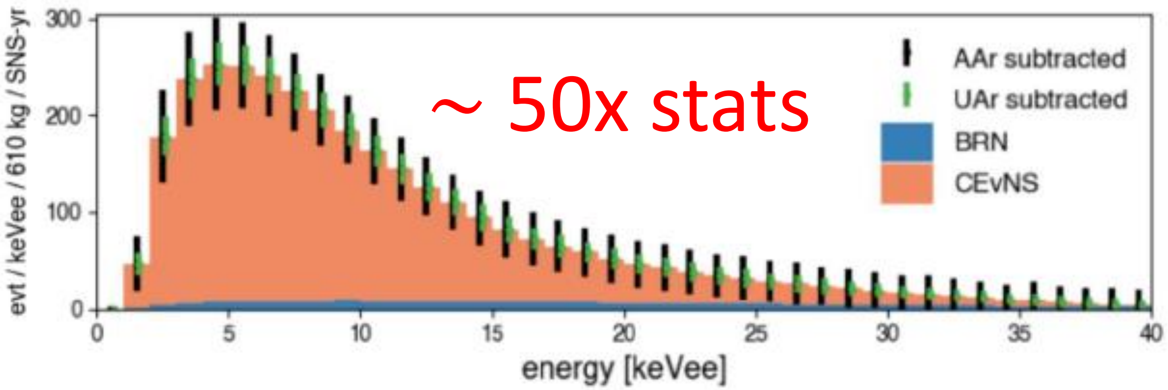
Summary of current *global* CEvNS results



First results on xenon from dark matter experiments
[XENONnT arXiv:2407.02877]
[PandaX-4T arXiv:2407.10892]

Reactor measurements expected soon – CONUS has leading limit at 2xSM

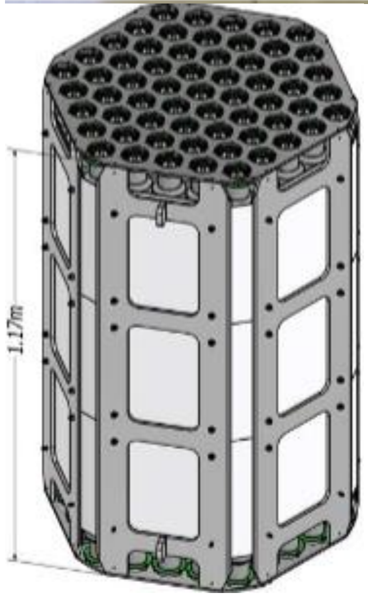
Future: upgraded ton-scale argon detector

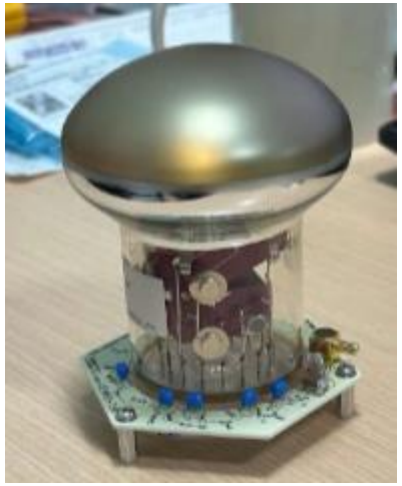


610-kg // 122-PMT argon calorimeter

~ 20 keV_{nr} threshold

CEvNS + inelastics





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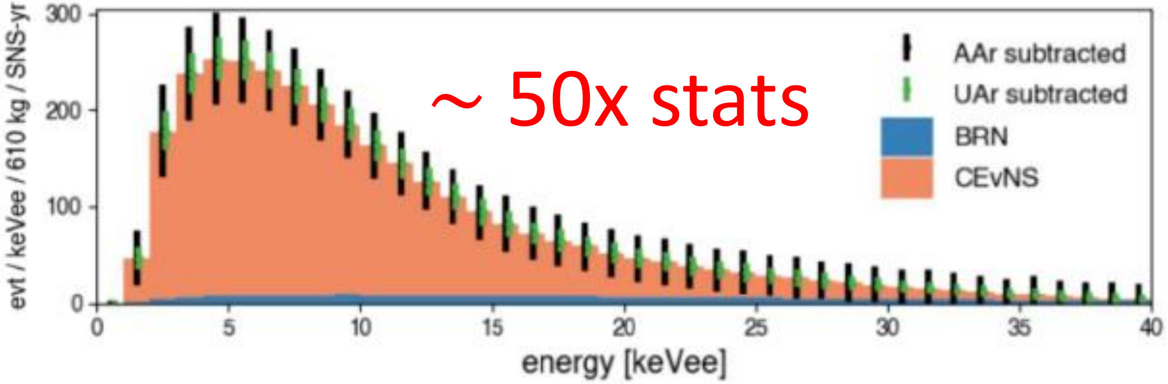

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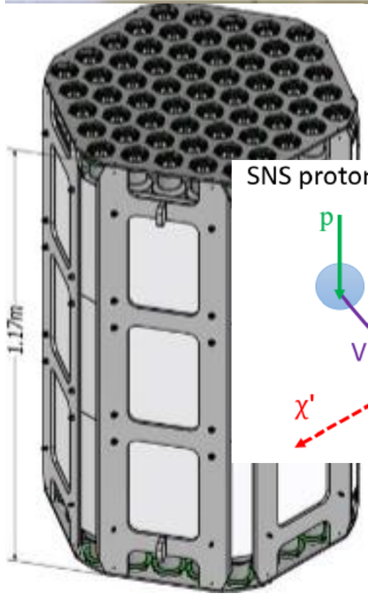
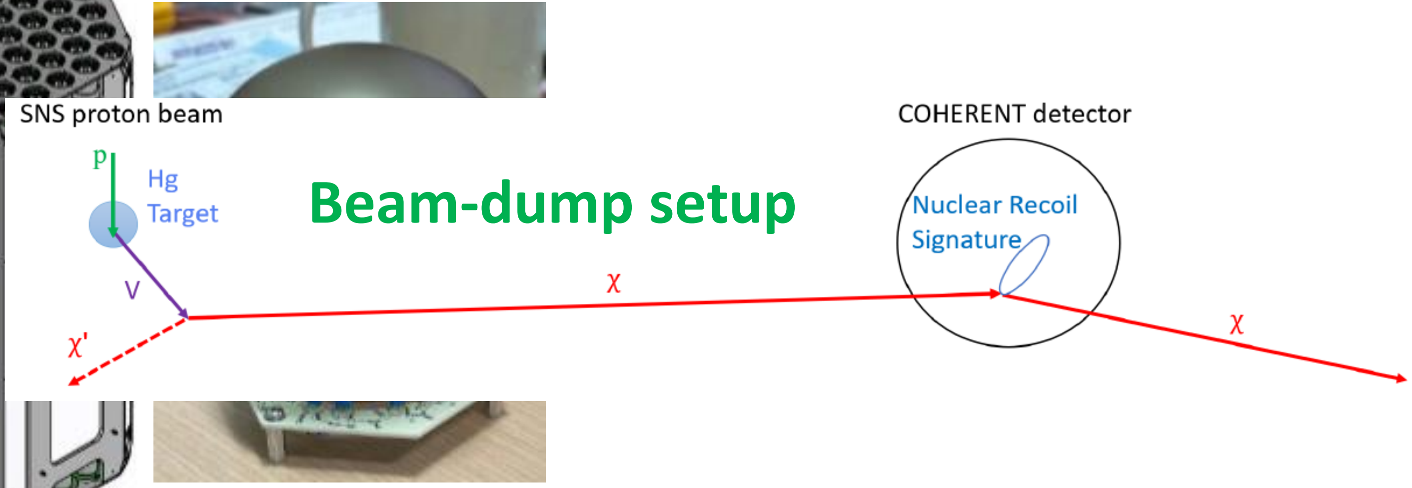
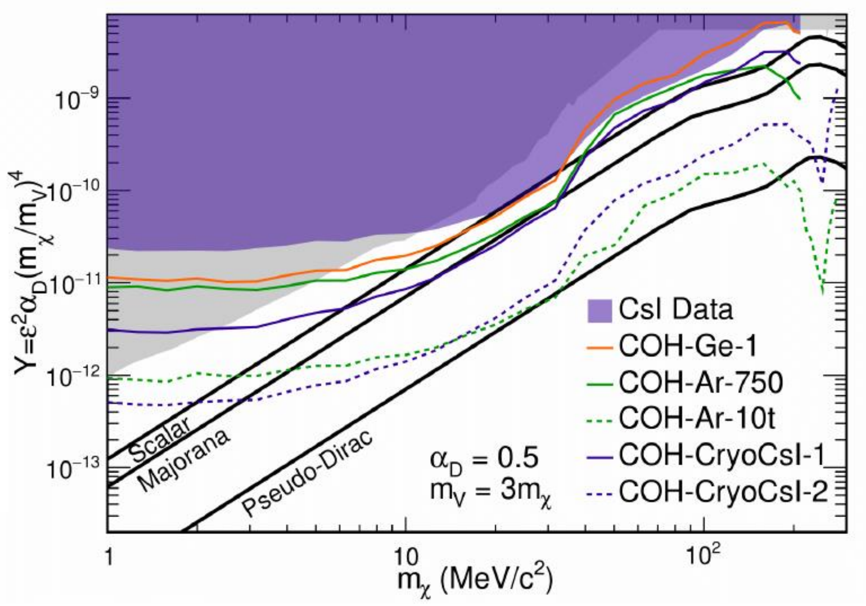
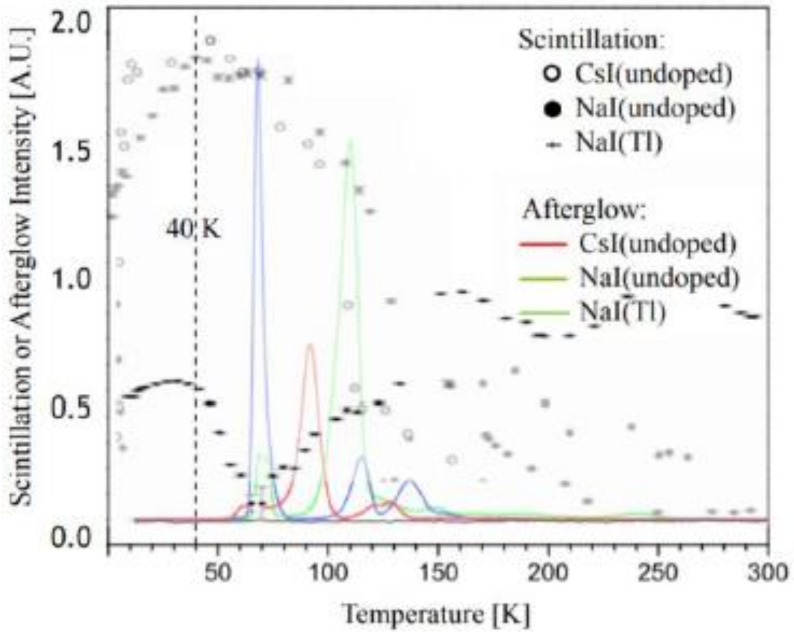






Future: cryogenic undoped CsI scintillator

Chernyak et al., EPJ C80 547 (2020)

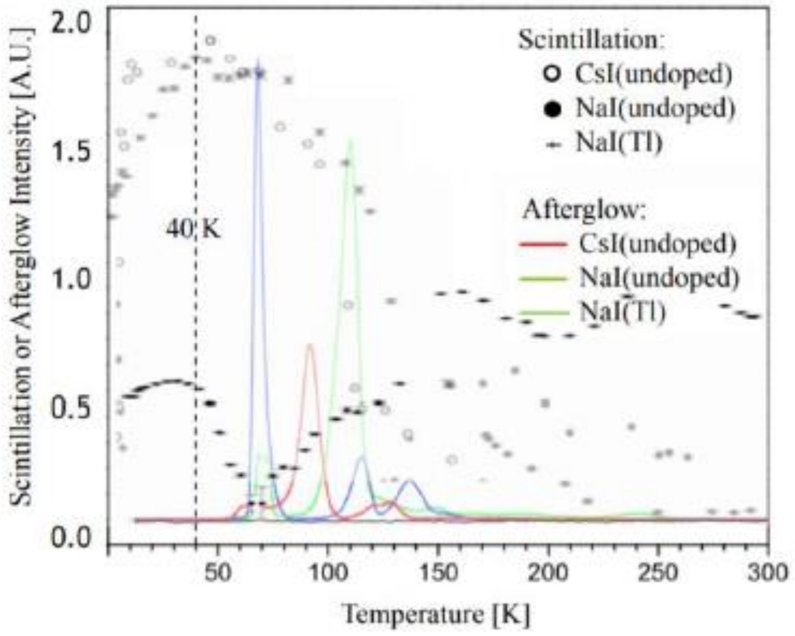


– Light yield of undoped CsI dramatically increases at low temperature, peaks at 40 K

– Also mitigates afterglow scintillation

Future: cryogenic undoped CsI scintillator

Chernyak et al., EPJ C80 547 (2020)



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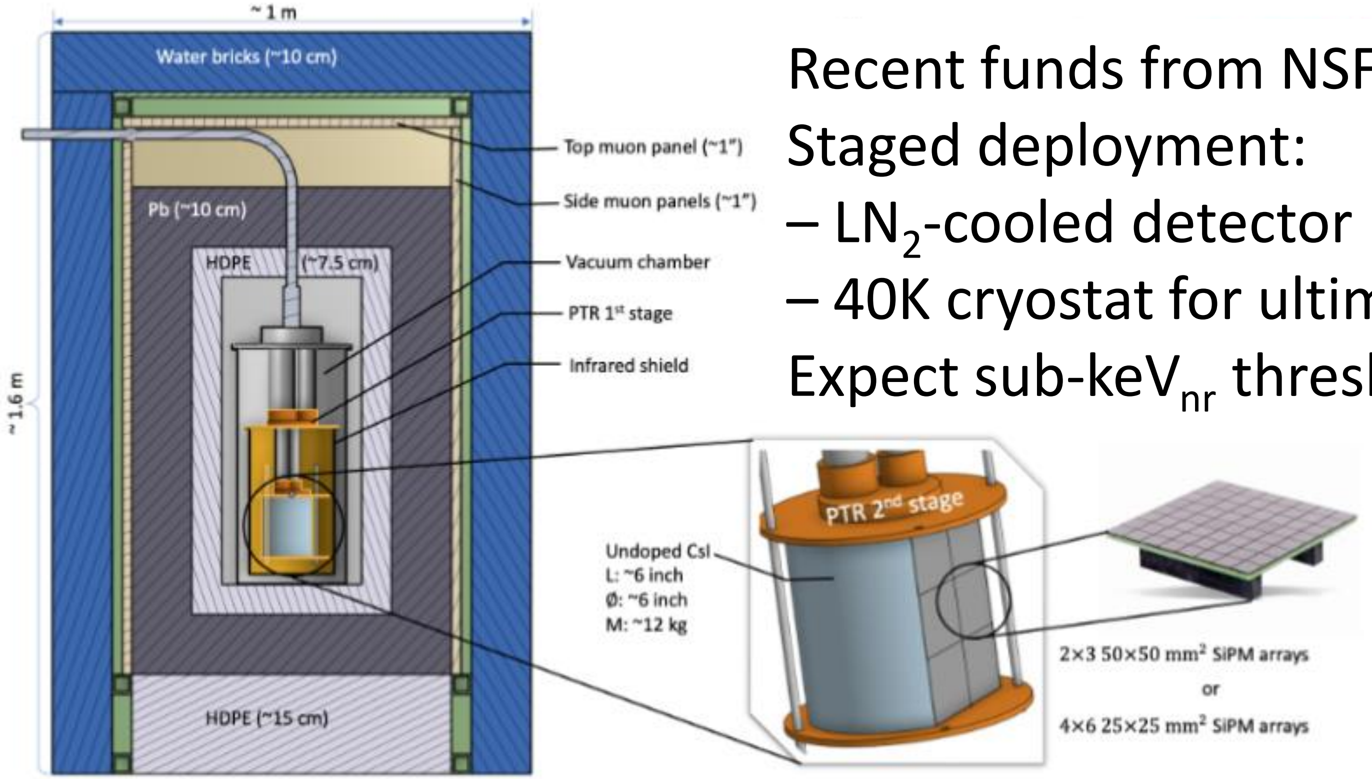
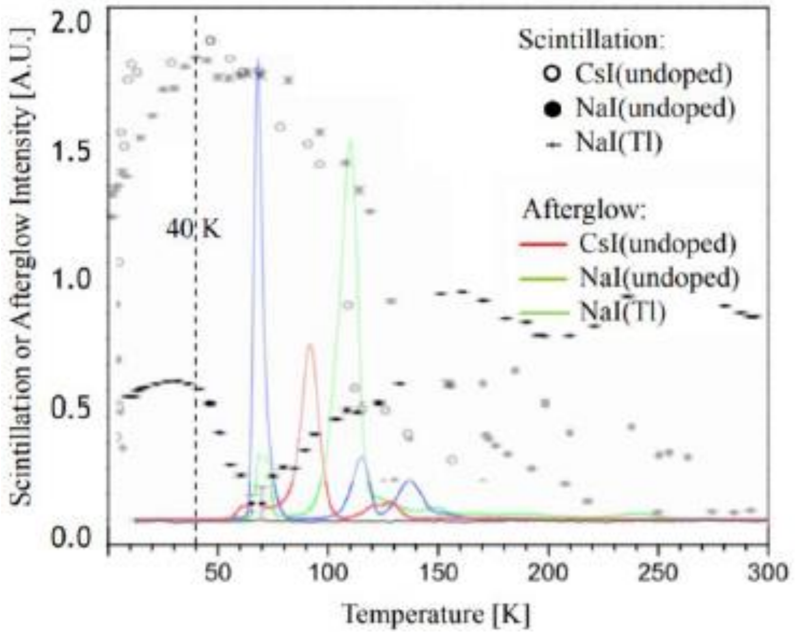


Recent funds from NSF + China
Staged deployment:
– LN_2-cooled detector
– 40K cryostat for ultimate reach
Expect sub-keV_{nr} threshold

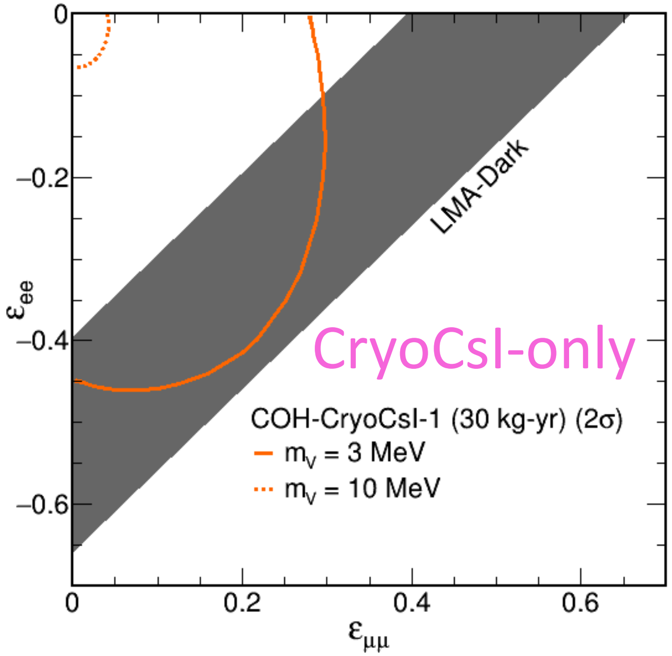
Future: cryogenic undoped CsI scintillator

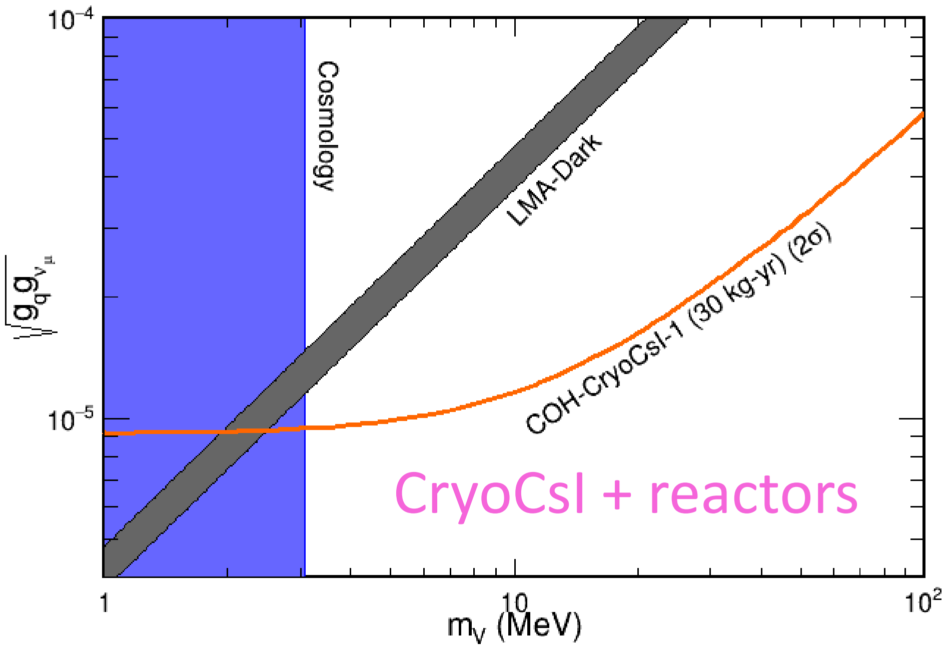
Chernyak et al., EPJ C80 547 (2020)



– Light yield of undoped CsI dramatically increases at low temperature, peaks at 40 K
– Also mitigates afterglow scintillation

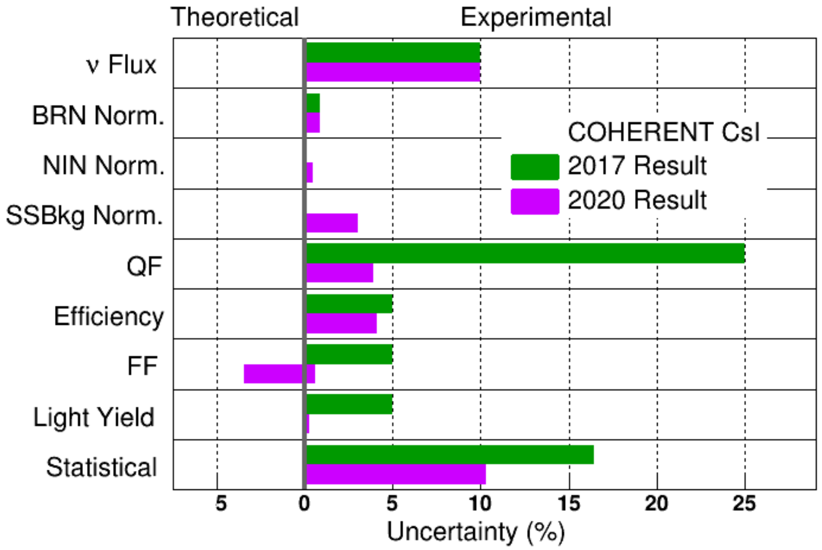
Detector will resolve NSI-oscillations ambiguity!





Reducing flux uncertainties

Purple – error budget for latest CsI result

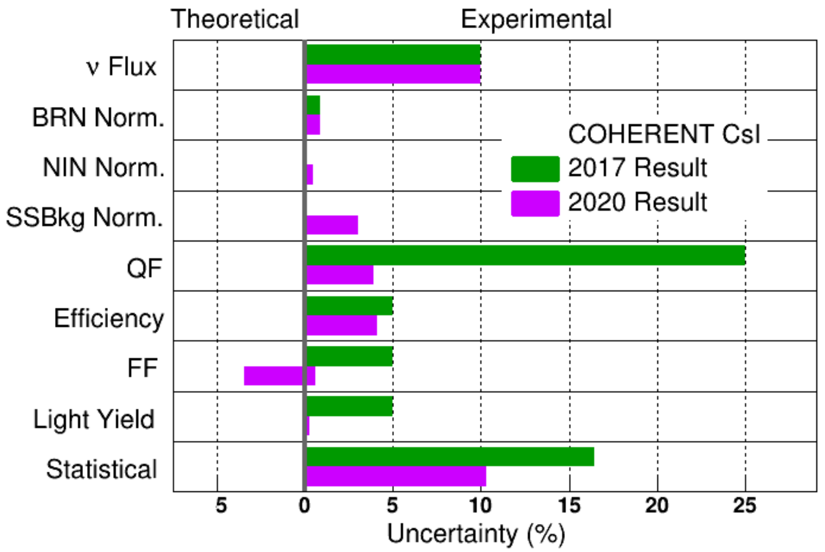


Neutrino flux uncertainty will soon dominate COHERENT cross section measurements

Need strategy to calibrate

Reducing flux uncertainties – the R^2D_2O program

Purple – error budget for latest CsI result



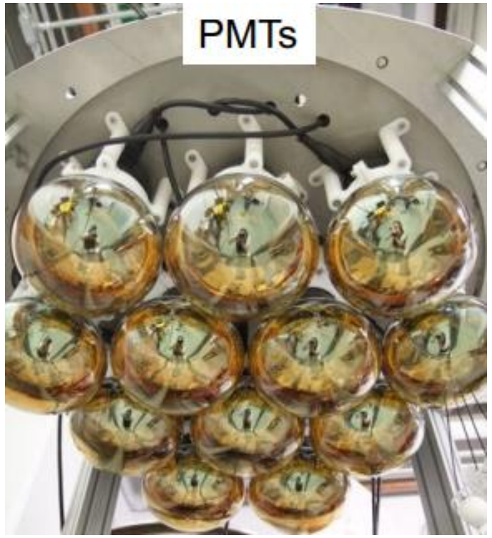
Neutrino flux uncertainty will soon dominate COHERENT cross section measurements

Need strategy to calibrate

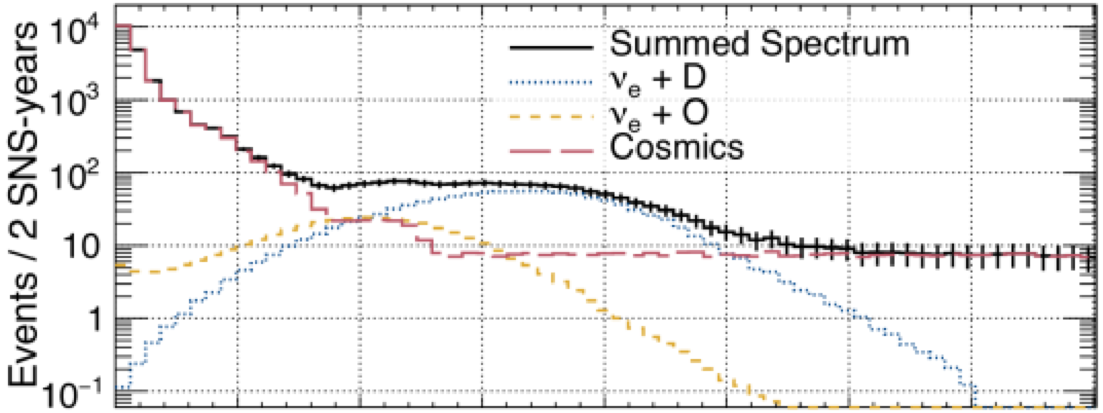
d_2O Cherenkov detector uses theoretically well-understood process

$$\nu_e + d \rightarrow e + p + p$$

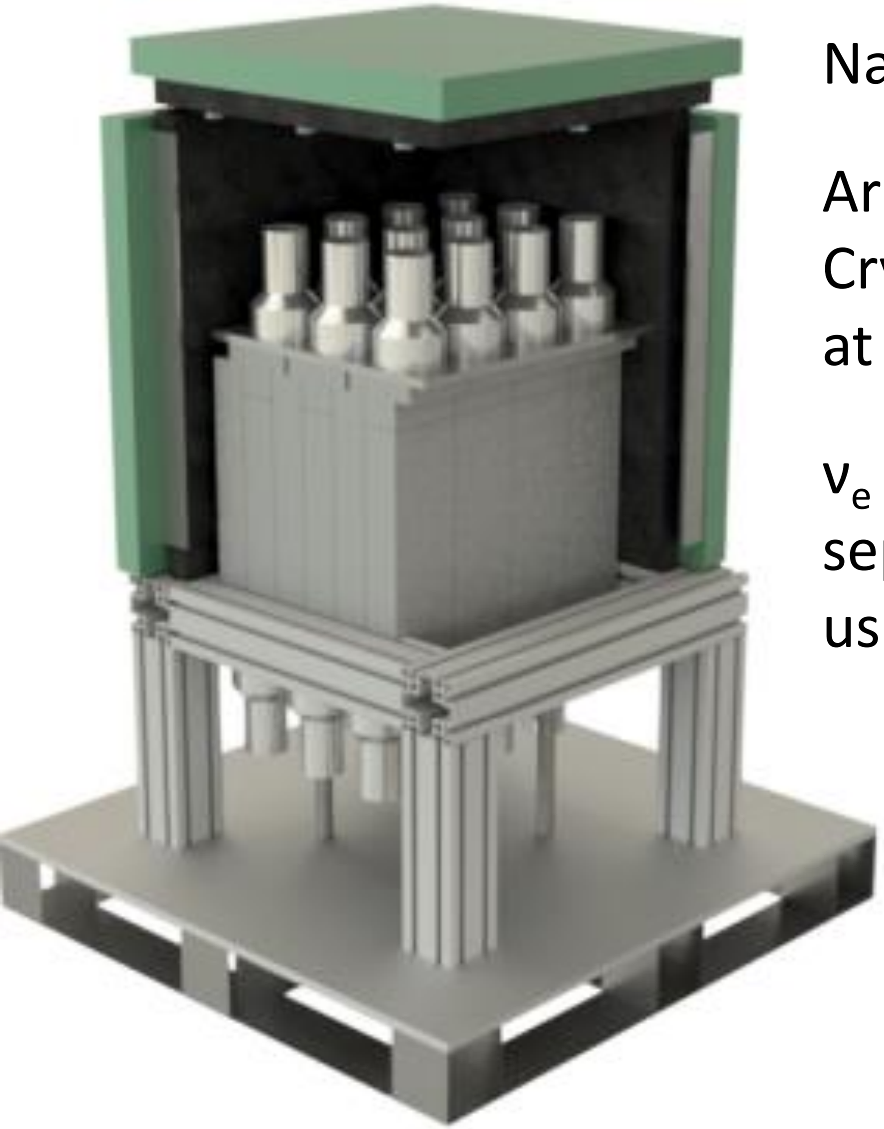
To translate between event rate and ν_e flux



1 module commissioned, second being deployed



Bonus: ν_e CC inelastics on iodine



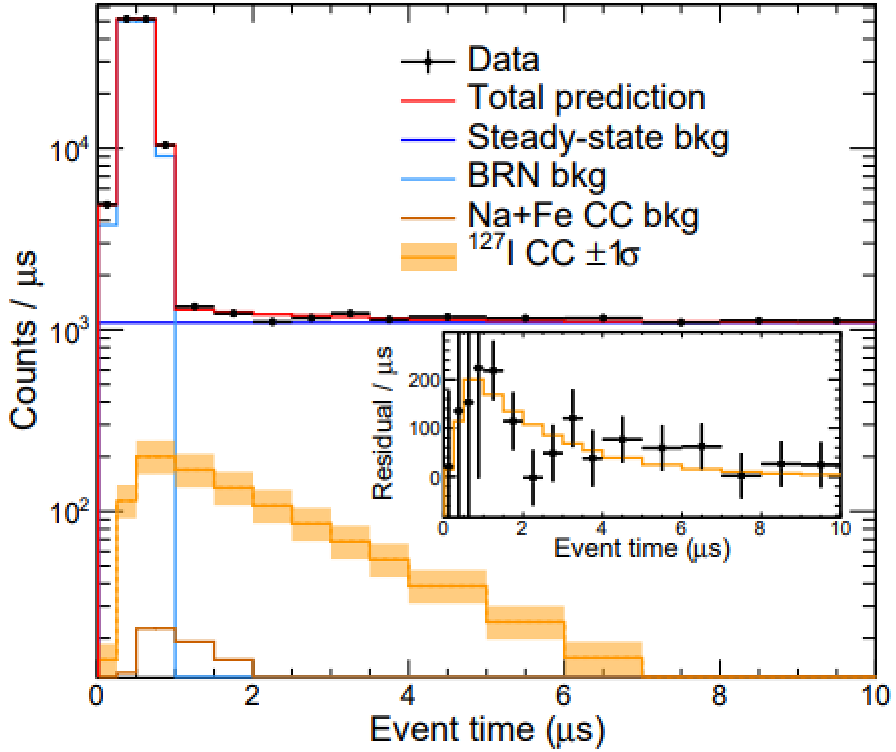
NaIvE COHERENT detector

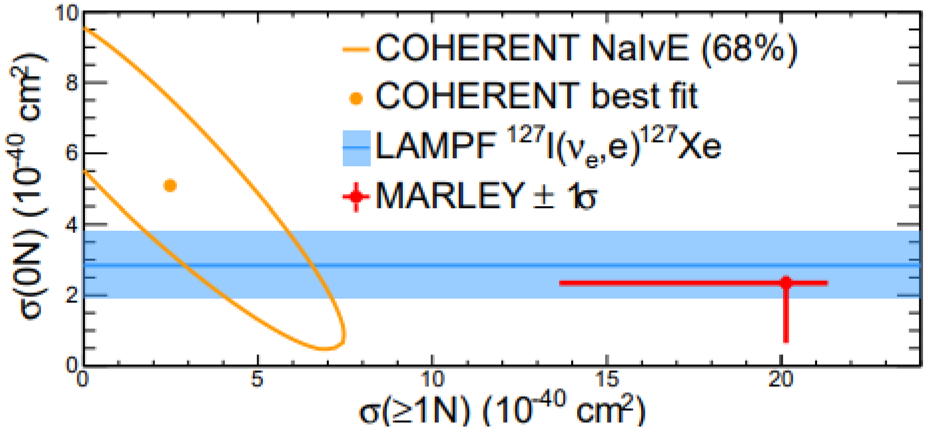
Array of 24 7.7-kg NaI[Tl] Crystals in Neutrino alley at the SNS

ν_e CC signal on ^{127}I separated from background using timing information

Distinguish between interactions that spit out a neutron using energy information

Best fit 41% MARLEY prediction





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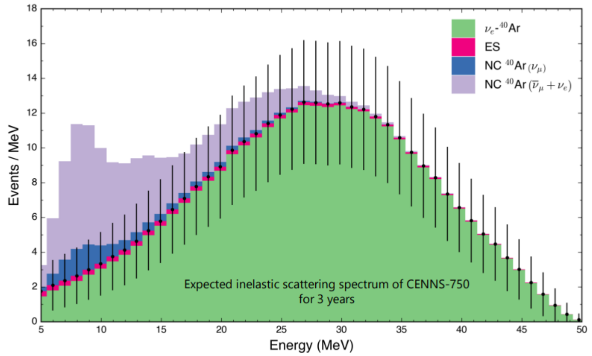
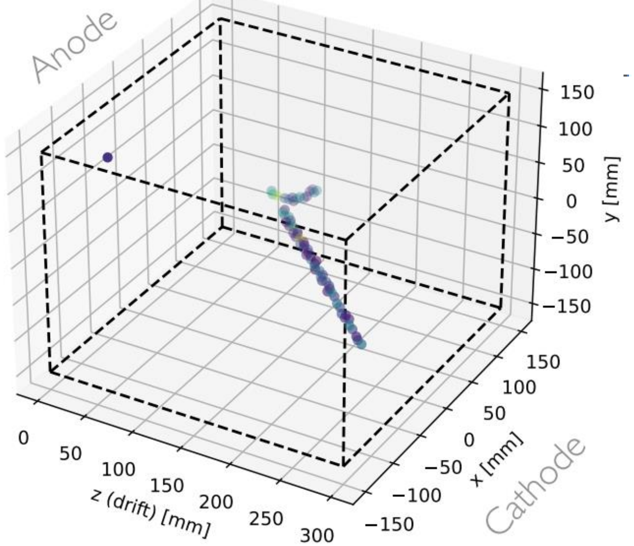
Full inelastic scattering program

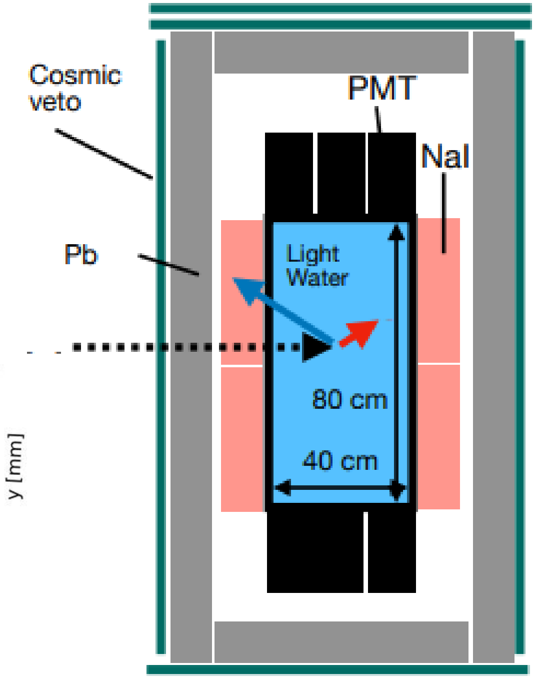
Ton-scale argon



Pixelated LArTPC (Proposed)

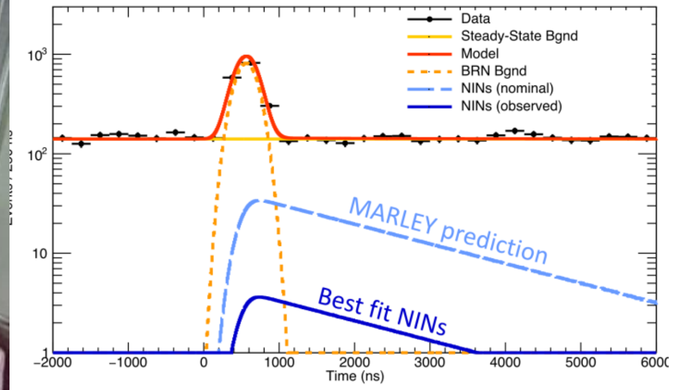


Water Cherenkov



NuThor – search for neutrino-induced fission

n emission in ν-Pb interactions



+ Pb-doped scintillating glass for inclusive meas.

Summary

- Excellent physics potential with small-scale scattering experiment
- Nearing completion of first-light measurements (3/4 target nuclei)!
- Upgraded Ar + CsI along with Ge detectors will blaze the trail for precision measurements
- CEvNS activity beyond COHERNET continuously maturing
- Multiple targets for inelastic measurements critical