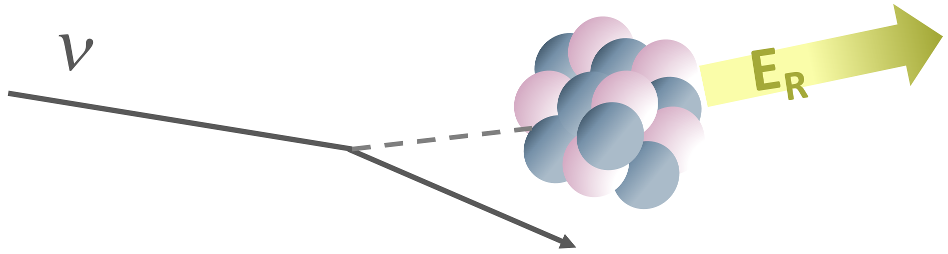


Coherent Elastic Neutrino-NUCLEUS Scattering

V. Wagner

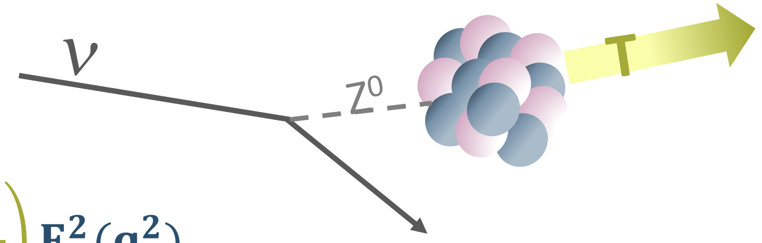
Technical University of München

IPA2022: Interplay between Particles and Astroparticle Physics 2022
Sept. 5th-9th 2022, Vienna

TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 Neutrinos Dark Matter Messengers

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)



- Well-predicted within Standard Model:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left[Z(1-4\sin^2\theta_w)-N\right]^2\left(1-\frac{MT}{2E_\nu^2}\right)F_w^2(q^2)$$

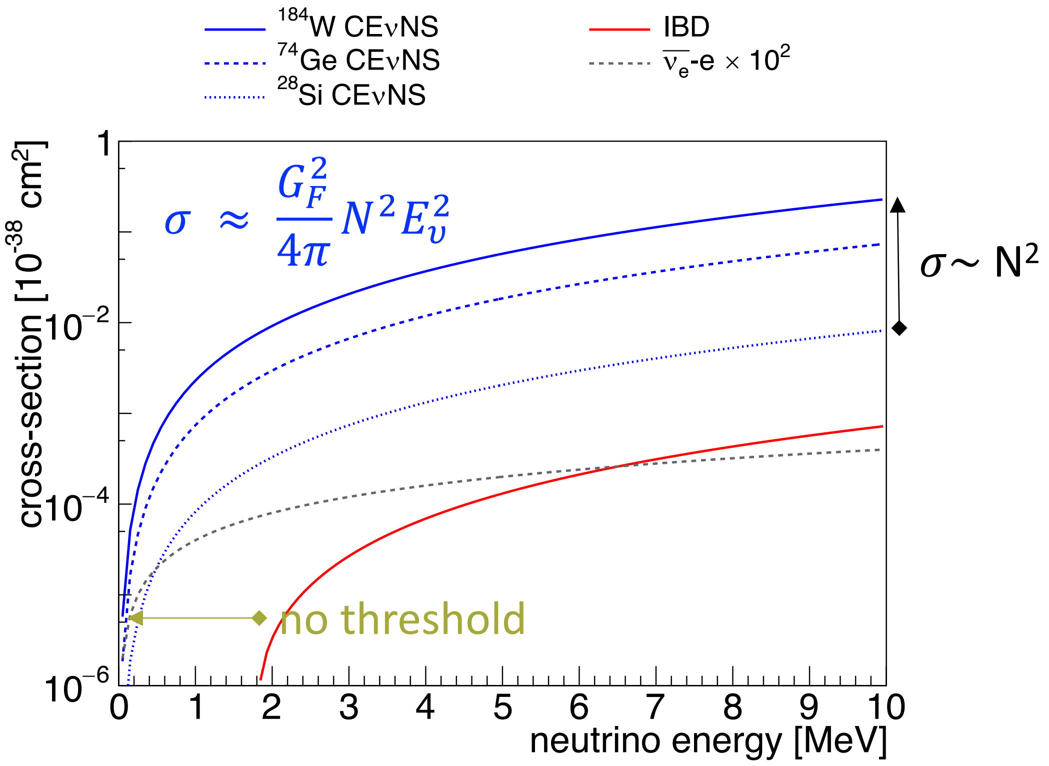
weak charge -> target nucleus

kinematics -> detection threshold & ν-source

weak form factor -> ν-source

- Large cross-section compared to other ν–interactions
- Coherent process for $q < 1/r_n$
- Flavor blind interaction

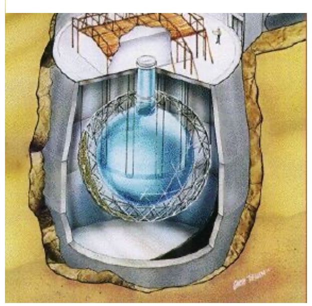
- **Dominant ν-scattering process for E_ν < 50 MeV**



CEvNS Potential - Application

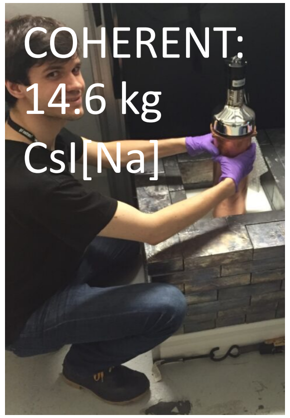
- New channel for sterile neutrino searches, solar physics and supernovae detection
- **Neutron floor**: (irreducible) background for Dark Matter experiments
- Miniaturization of neutrino detectors
- Reactor monitoring

SNO: 100 t heavy water

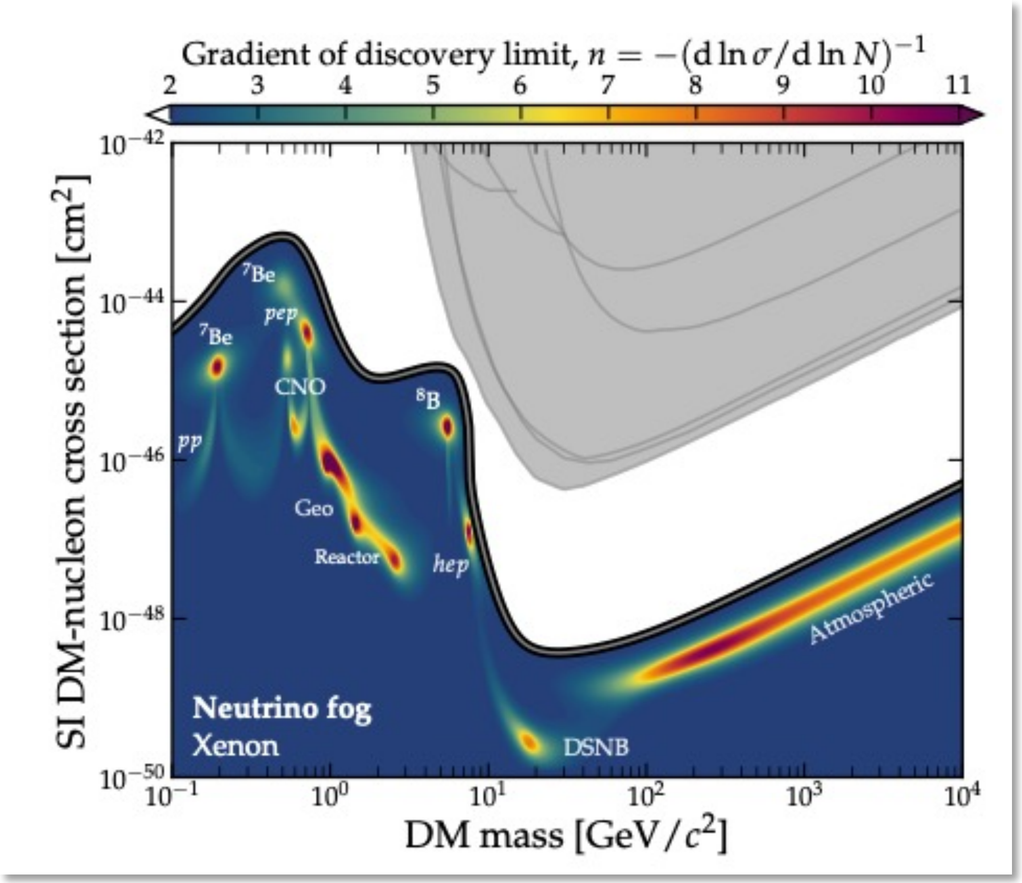


https://sno.phy.queensu.ca

vs



https://coherent.ornl.gov/the-coherent-detector-suite/



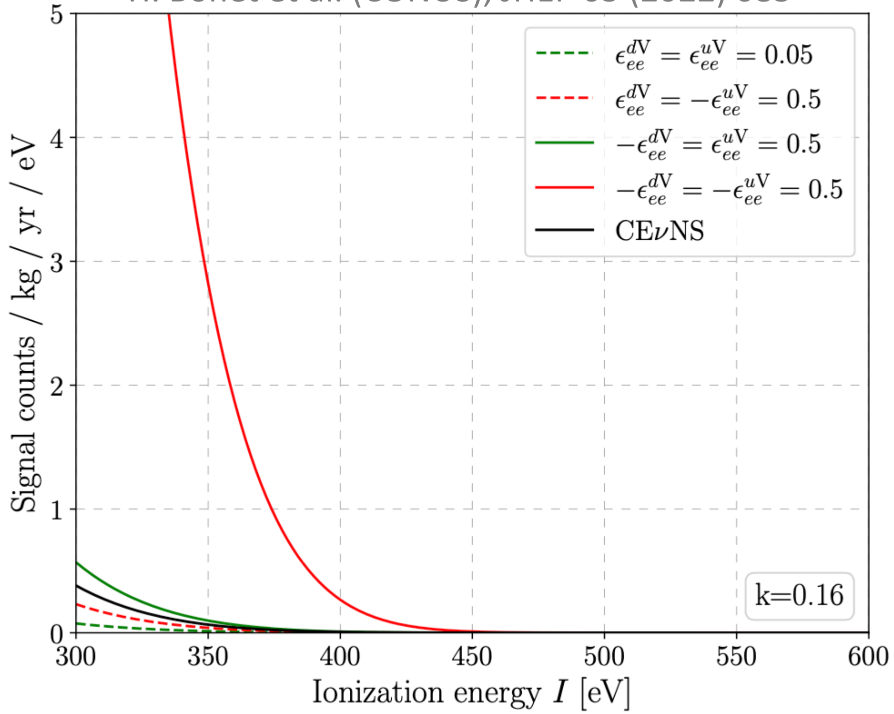
Plot from arXiv:2203.07361 [hep-ph],
Original work: C. A. J. O'Hare, Phys. Rev. Lett. 127, 251802 (2021)

CEvNS Potential - Physics

- Complementary measurement of the weak neutral current
- Precision test of the **Standard Model**
- Physics **beyond the Standard Model**, e.g.:
  - new ν-quark couplings
  - new mediators
  - magnetic neutrino moment,
  - sterile neutrino searches
- Important for stellar collapse physics (Type II SN)
- Application in nuclear physics

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} \mathbf{Q_w^2} \left(1 - \frac{MT}{2E_\upsilon^2}\right) \mathbf{F_w^2(q^2)}$$

H. Bonet et al. (CONUS), JHEP 05 (2022) 085

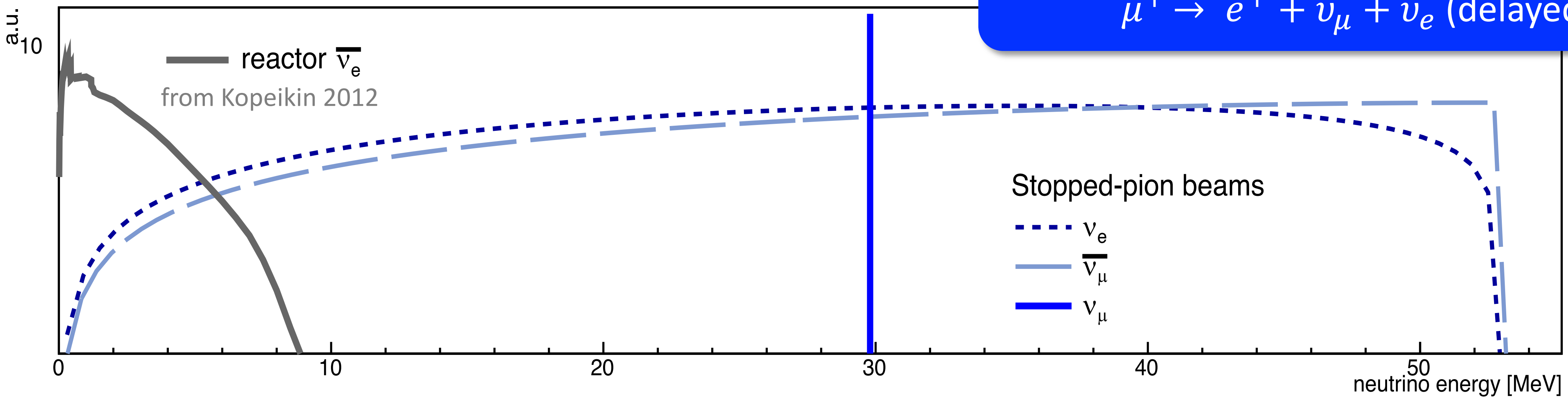


Neutrino Sources for CEvNS

used by experiments these days

$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$ (prompt)

$\mu^+ \rightarrow e^+ + \bar{\upsilon}_\mu + \upsilon_e$ (delayed)

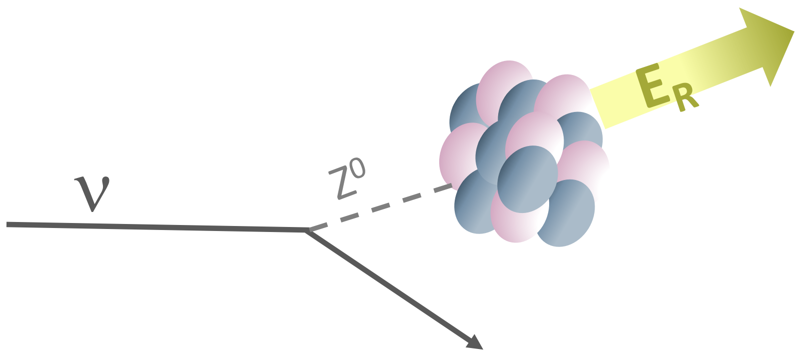


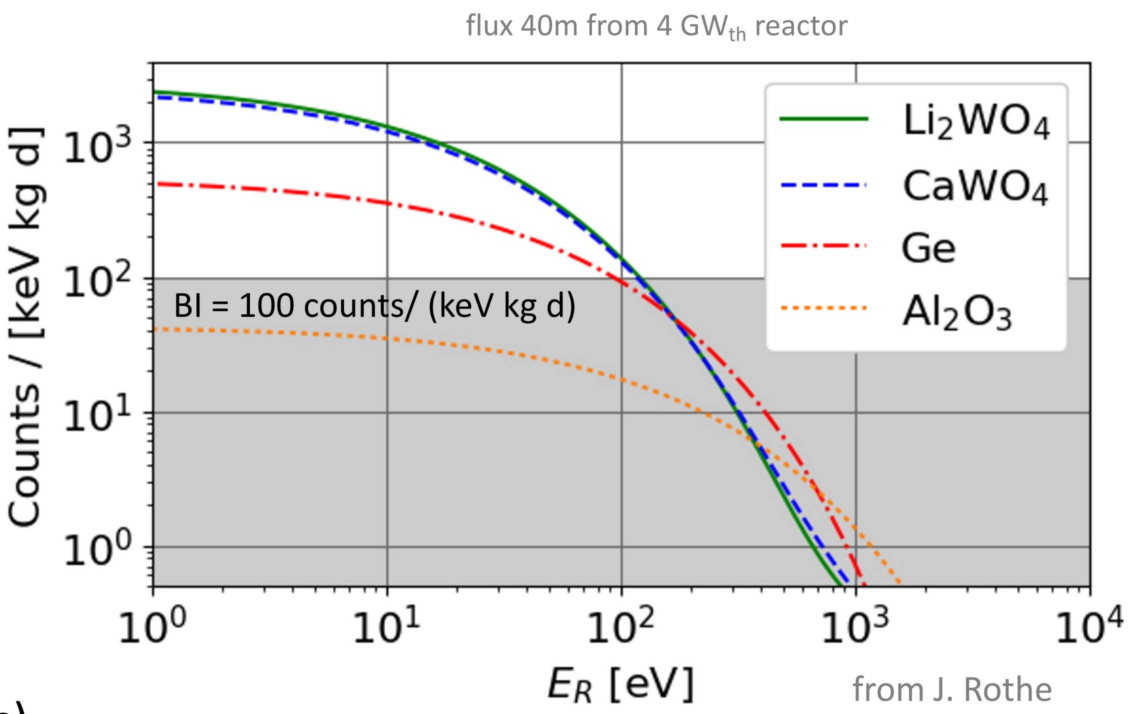
- **High flux**: O(10^{20} ν/s) @ power reactors
- Low neutrino energy: **coherency**
- Background suppression based on reactor-off time periods

- Flux at SNS in Oakridge (US): 4.3x10^7 ν/(cm^2 s)
- High neutrino energy: start of incoherent regime
- **Background suppressed**: pulsed beam

Overlap with DM searches

Wishlist for a CEvNS Experiment





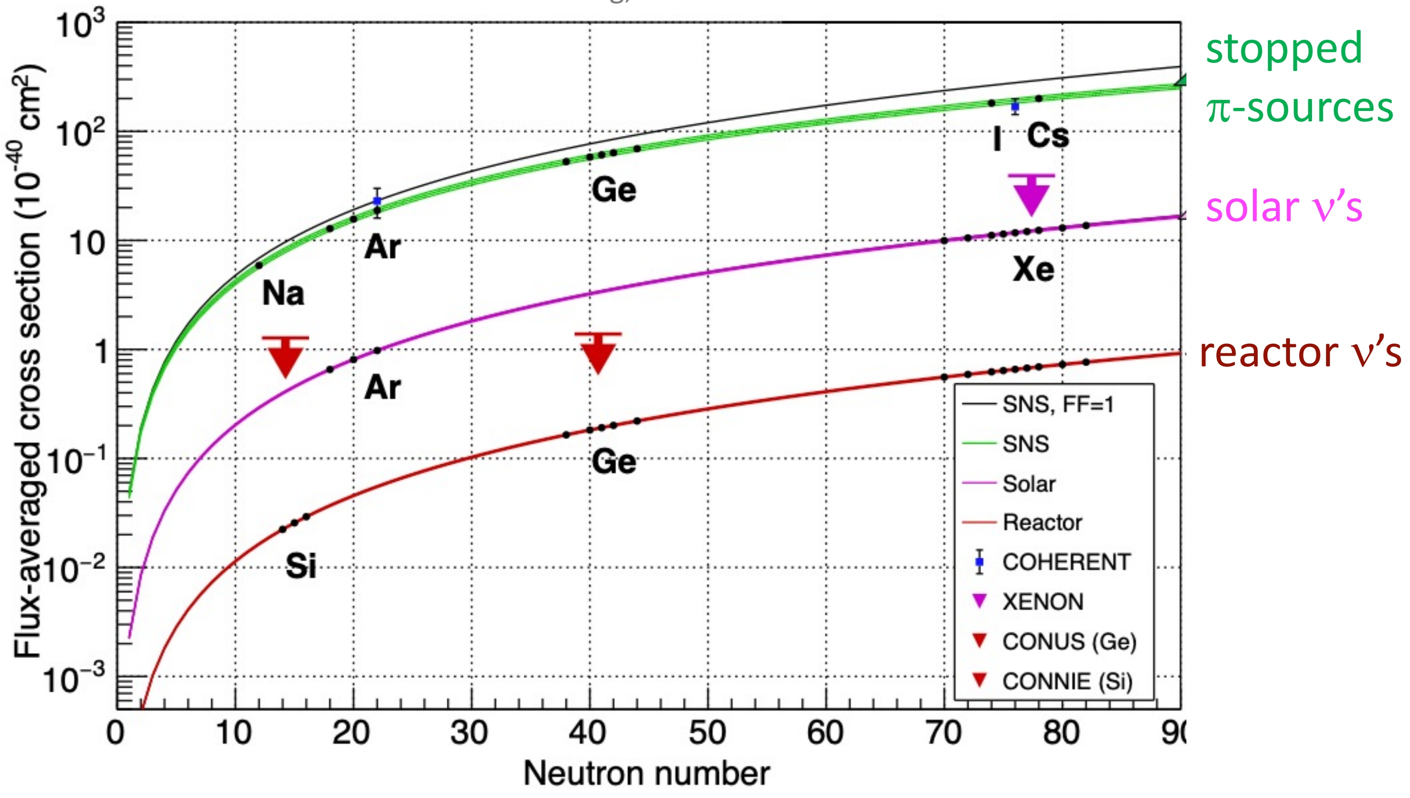
- Measure of (sub-)keV nuclear recoil signals:
  Low energy threshold
- Low signal rate expected, O(1 CEvNS event/ few days):
  Low background

Wishlist for CEvNS Experiment(s)

- Complementary CEvNS measurements
  - At different ν energies
  - With different CEvNS targets ($\sigma \sim N^2$)

→ **large variety of neutrino experiments**

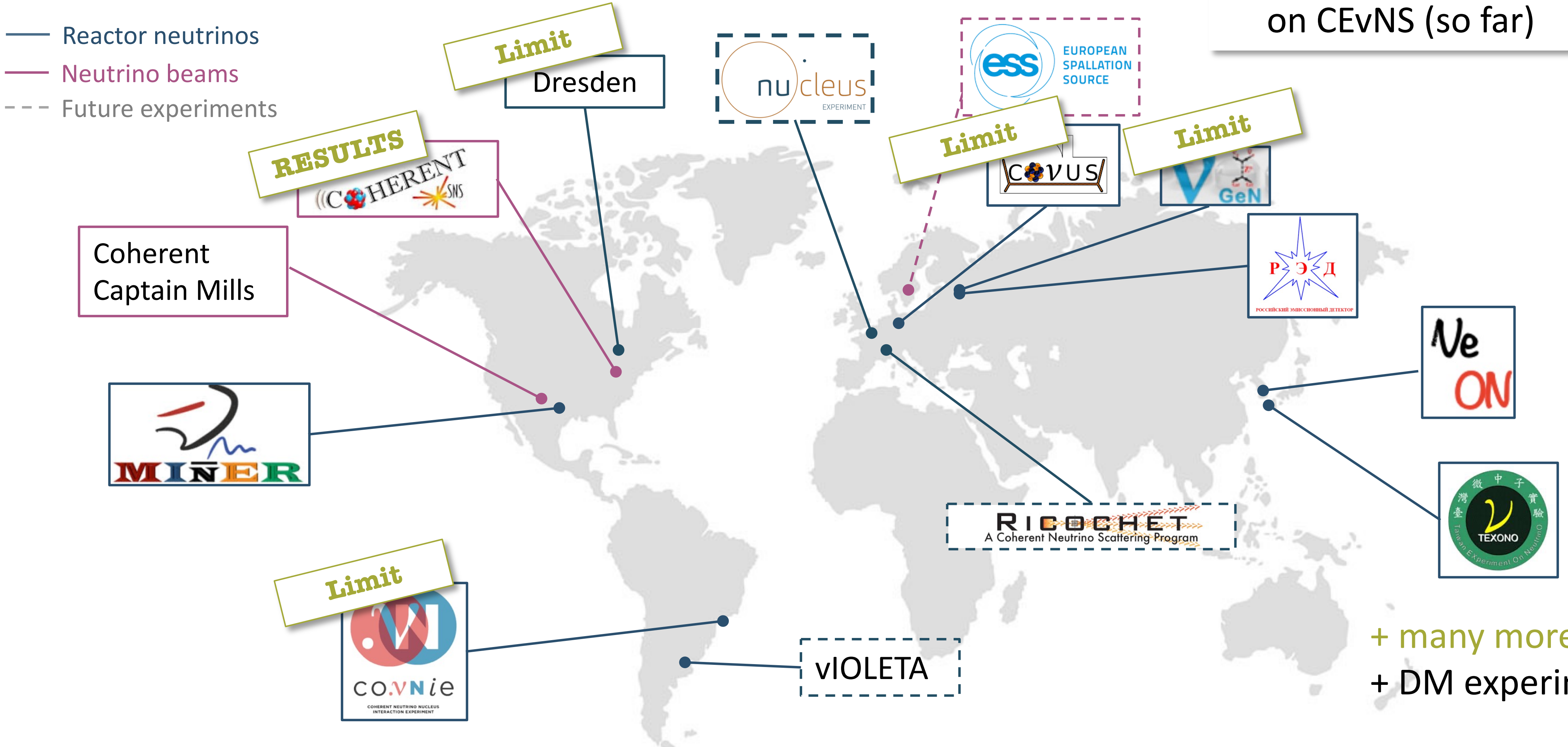
taken from K. Scholberg, talk at PANIC 2021



CEvNS Experiments

More complete list e.g. arXiv:2203.07361

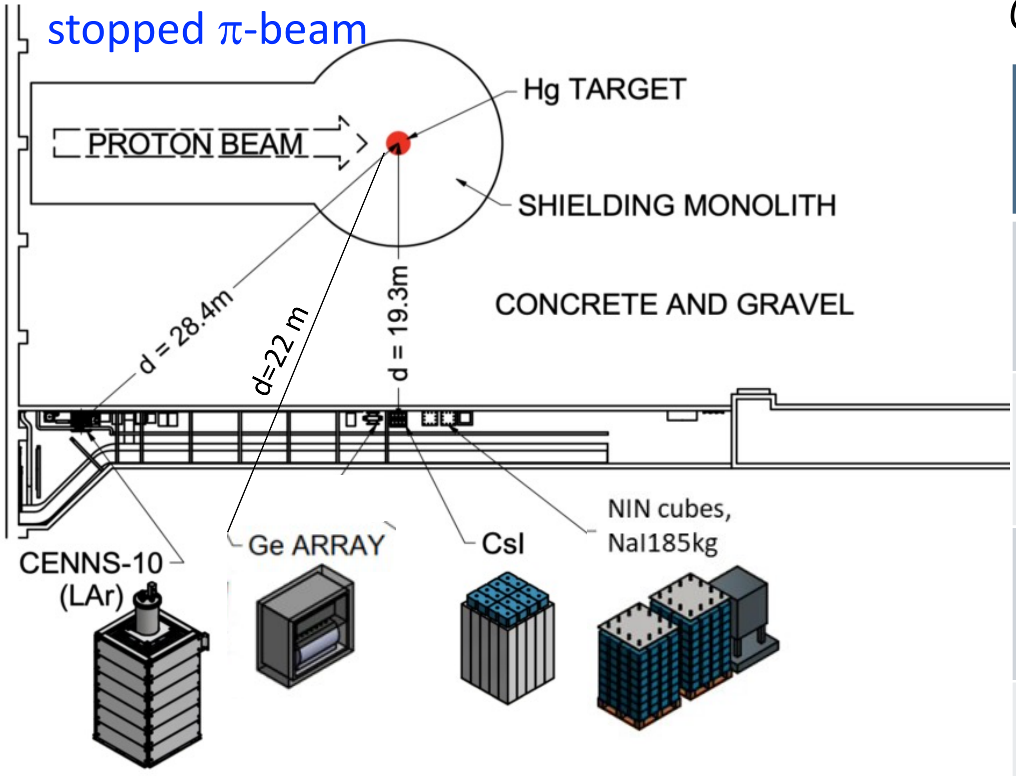
- ✓ COHERENT: results on CsI & Ar
- ⚙ Reactor experiment set limits on CEvNS (so far)



+ many more ideas
+ DM experiments

The COHERENT Experiment

modified from https://coherent.ornl.gov/the-coherent-detector-suite/



@Spallation Neutron Source (SNS) at Oakridge National Laboratory

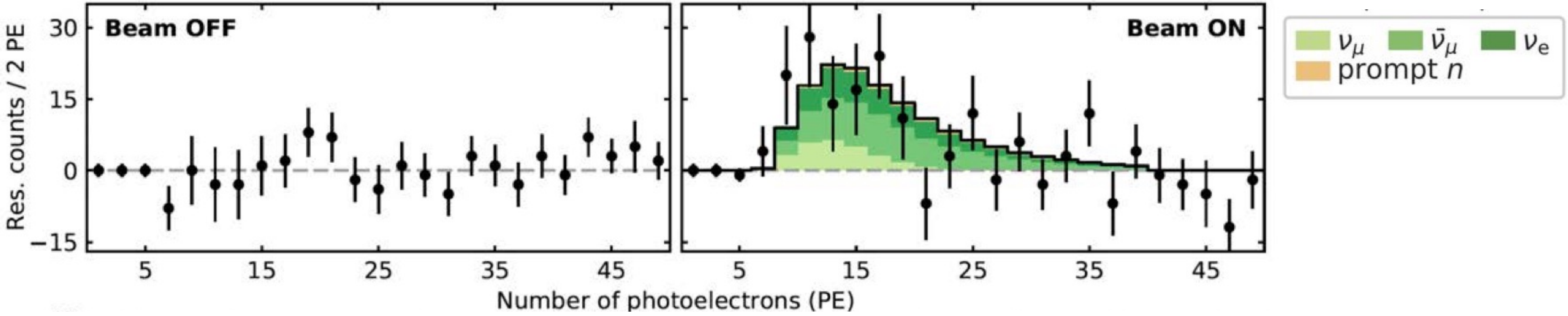
Target	technology	Mass [kg]	Threshold [keV_{nr}]	Status
CsI[Na]	Scintillation	14.6	6.5	Decommissioned
Ar	Scintillation Single phase LAr	24/ 610	20	Running Update 2024
Ge	Ionization HPGE PPC	18	< 5	Commissioning in 2022
NaI[Tl]	Scintillation	3388	13	Commissioning in 2022

COHERENT Experiment - CsI

- By now > 3 years of data
- Final result: CEvNS observation on CsI at 11.6 σ
  flux averaged cross section of $\langle\sigma\rangle_\phi = (165^{+30}_{-25})\times 10^{-40}\mathrm{cm}^2$
- Consistent within 1 σ with the SM prediction

First observation of CEvNS in July 2017

D. Akimov et al., Science
10.1126/science.aao0990 (2017)



Latest COHERENT Results on CsI

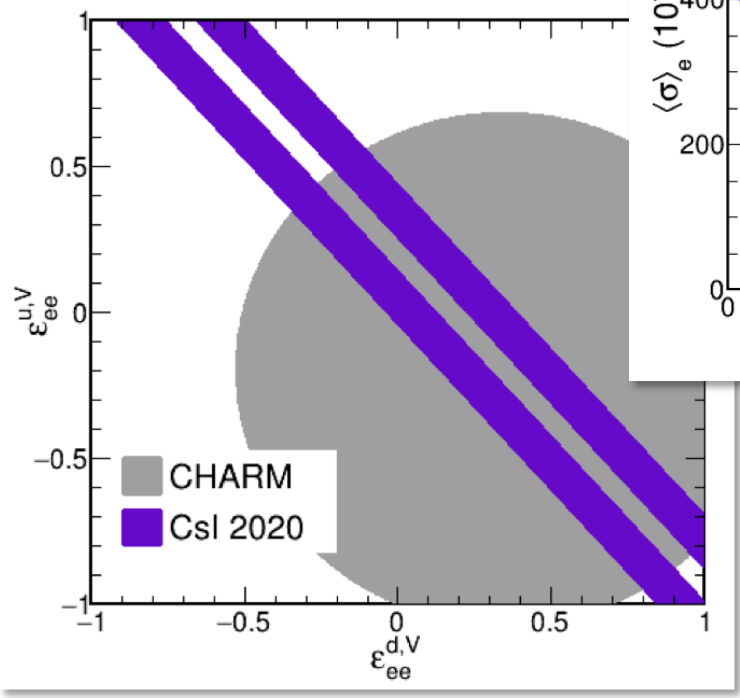
D. Akimov, et al. (COHERENT Collaboration), Phys.Rev.Lett. 129 (2022) 8, 081801

$$\sigma \sim \left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2$$

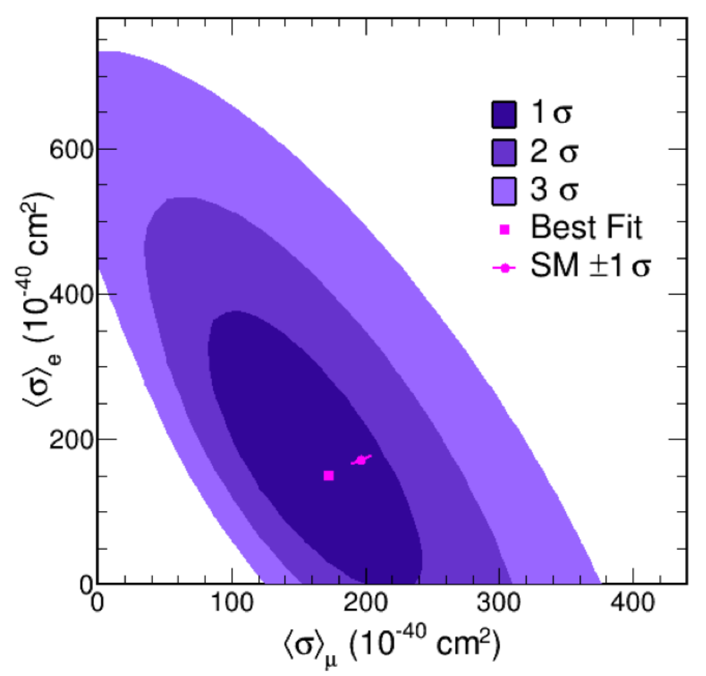
$$g_V^p = +\frac{1}{2} - 2\sin^2\theta_W$$

- Measurement of the weak mixing angle $\sin^2\theta_W = 0.220{+}0.028$ at $Q^2 \approx (50\ \mathrm{MeV})^2$
- Improvements on CEvNS constraints on **neutrino-quark NSI** scenarios
- Measurement of flavored CEvNS cross-section by neutrino timing

New ν-q couplings



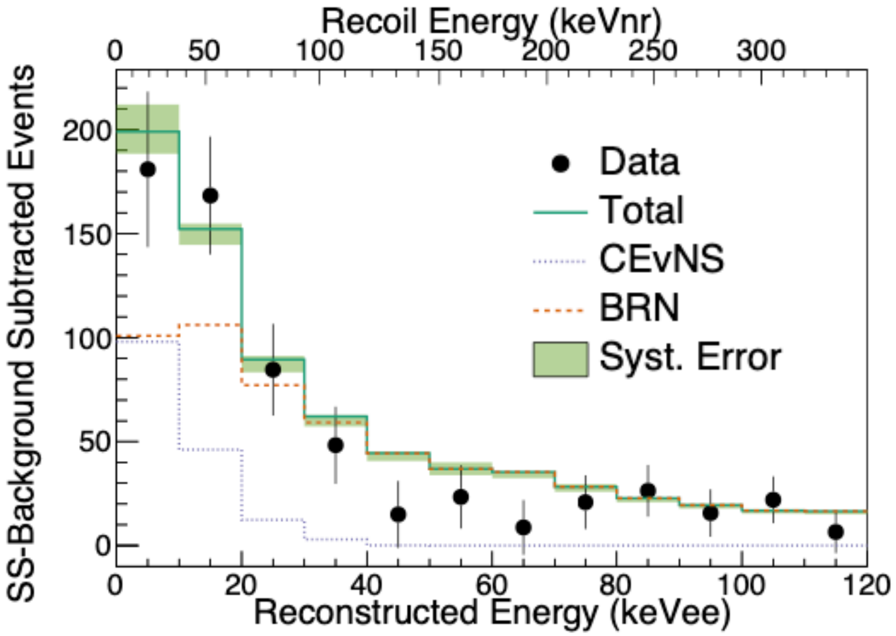
"Flavored" CEvNS cross-section



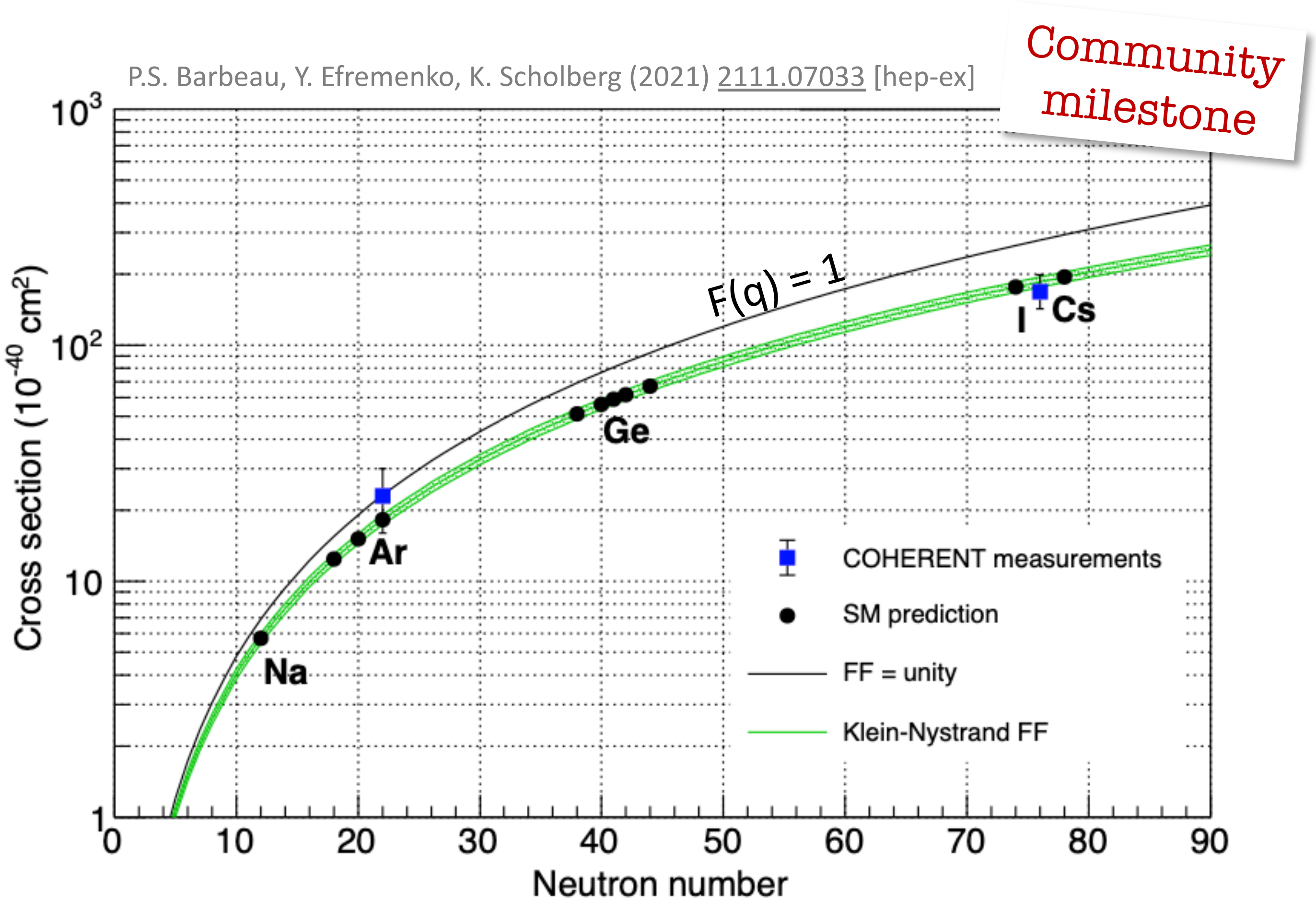
Latest COHERENT Results on Ar

D. Akimov, et al. (COHERENT Collaboration), Phys.Rev.Lett. 126 (2021) 1, 012002

- Data set: July 2017 – Dec. 2018
- CEvNS observation on Ar with > 3σ



P.S. Barbeau, Y. Efremenko, K. Scholberg (2021) 2111.07033 [hep-ex]



Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	$O(1keV_{nr})$	Running
TEXONO	Ge ionization	$O(1keV_{nr})$	Finished
Nu-GEN	Ge ionization	$O(1keV_{nr})$	Running
Dresden	Ge ionization	$O(1keV_{nr})$	Running
NEON	NaI(Tl) ionization	$O(1keV_{nr})$	Running
RED-100	Liquid Xe TPC	$O(1keV_{nr})$	Construction
CONNIE	CCD (Si)	~$300eV_{nr}$	Running
MINER	Cryogenic (Ge, Si)	$O(100eV_{nr})$	Commissioning
RICOCHET	Cryogenic (Ge, Zn)	$55eV_{nr}$	Construction
NUCLEUS	Cryogenic ($CaWO_4$)	$20eV_{nr}$	Construction

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
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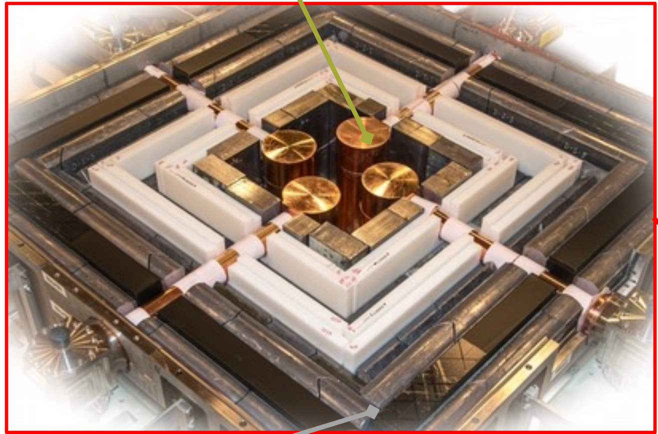
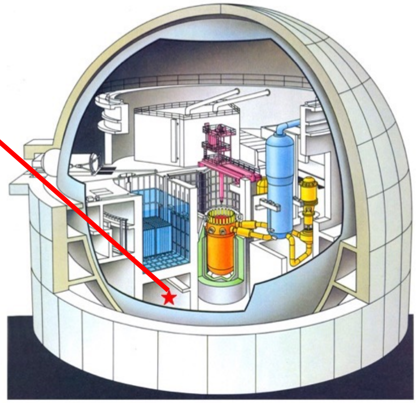
RICOCHET	Cryogenic (Ge, Zn)	55eV$_{nr}$	Construction
NUCLEUS	Cryogenic ($CaWO_4$)	20eV$_{nr}$	Construction

Physics data: 2018 – 2021
Background data: since 2022

Commercial p-type point-contact **HPGe** detectors (m≈4kg)
Threshold: 300eV$_{ee}$



Multi-layer passive shielding + efficient muon veto



Reactor Sites

Brokdorf, Germany

Power	3.9GW$_{th}$
Cores	1
Baseline	17m
ν-flux	2.2×10^{13} cm^{-2}s^{-1}

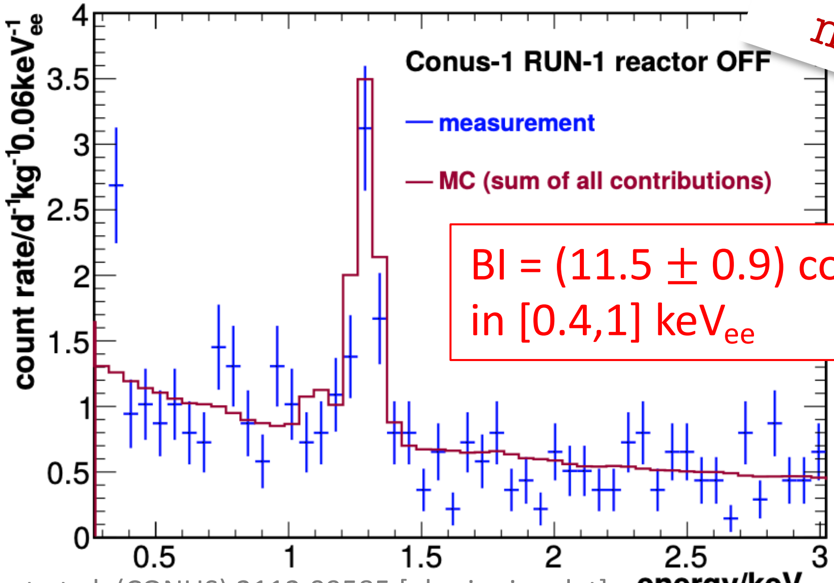
Slide adopted from R. Strauss

CONUS Results

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

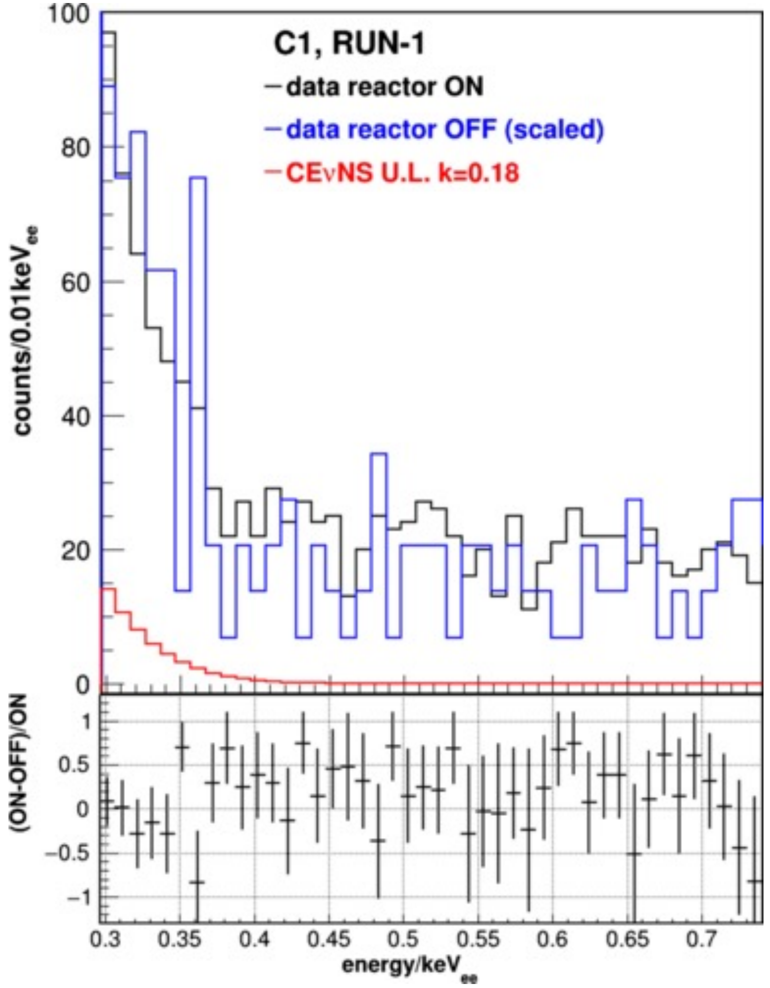
- Low background achieved
- Upper limit on CEvNS, factor 17 above SM expectations

Community milestone



BI = (11.5 ± 0.9) counts/ (kg d) in [0.4,1] keV_{ee}

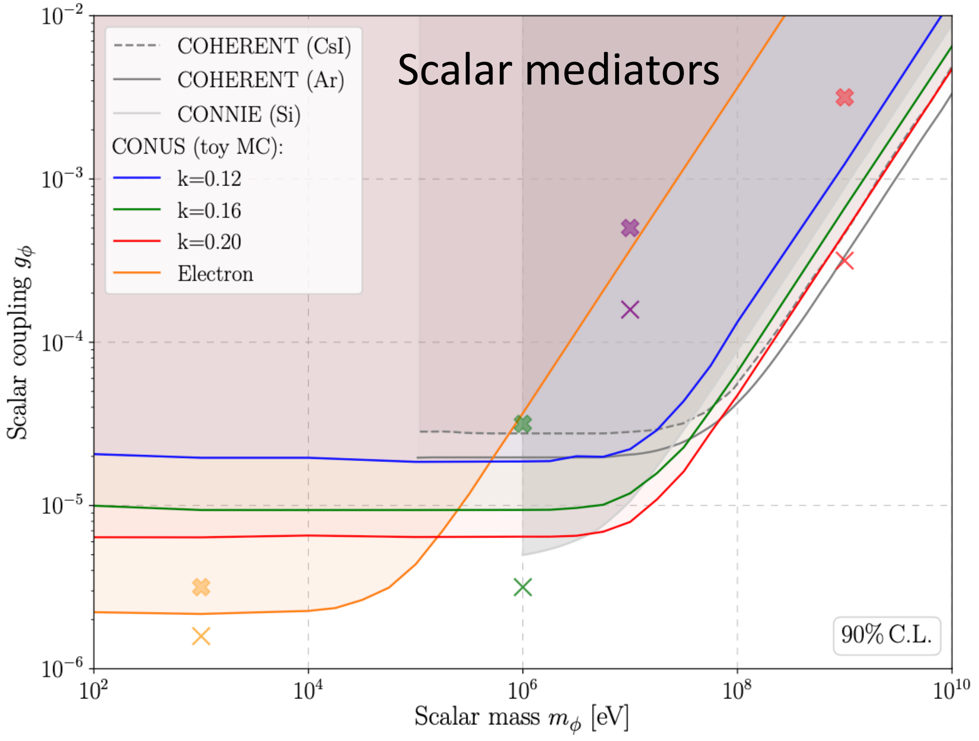
H. Bonet et al. (CONUS) 2112.09585 [physics.ins-det]

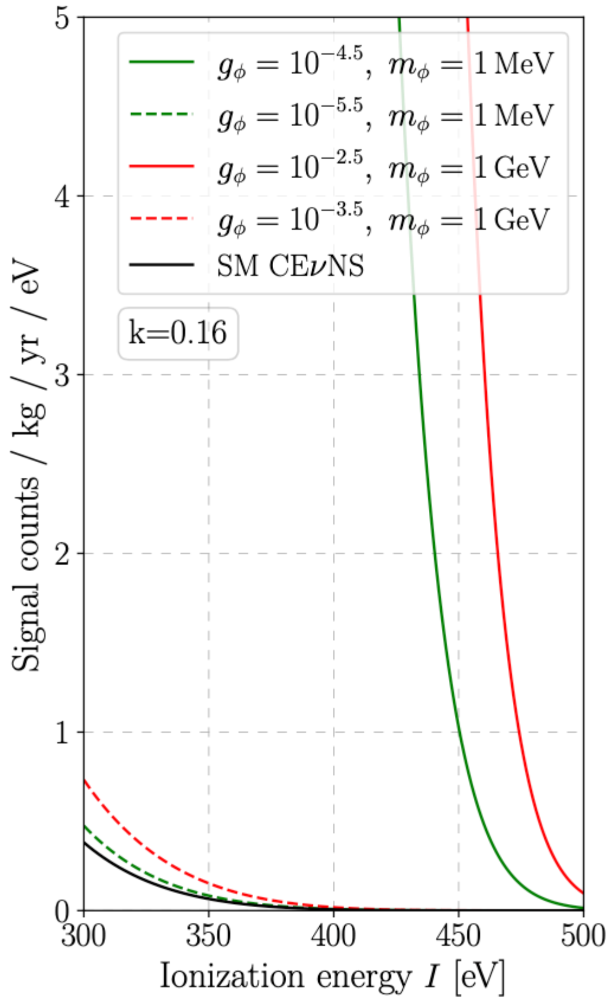


CONUS Results on BSM Physics

H. Bonet et al. (CONUS), JHEP 05 (2022) 085

- New constraints on different NSI models
  - new light bosons
  - new ν-q couplings





+ results on neutrino magnetic moment from neutrino-electron scattering

Reactor Experiment

as a next generation example

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Finished
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	Running
Dresden	Ge ionization	O(1keV$_{nr}$)	Running
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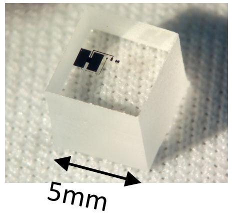
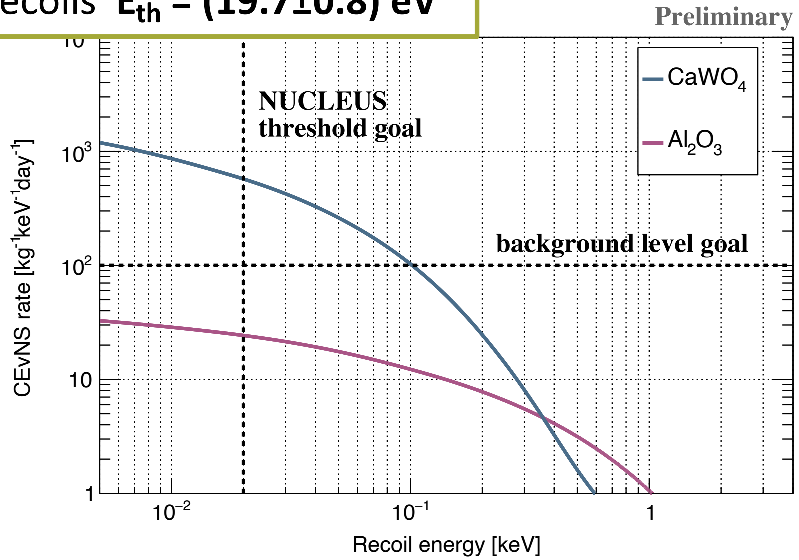
RICOCHET	Cryogenic (Ge, Zn)	55eV$_{nr}$	Construction
NUCLEUS	Cryogenic ($CaWO_4$)	20eV$_{nr}$	Construction

Multi-layer passive shielding
+ efficient veto systems

Lowest energy threshold for nuclear recoils **E_{th} = (19.7±0.8) eV**

$CaWO_4$ + Al_2O_3





Reactor Sites

CHOOZ, France

Power	4.25GW$_{th}$
Cores	2
Baseline	72 , 102m
ν-flux	2×10^{12} cm^{-2}s^{-1}

Prospects for CEvNS

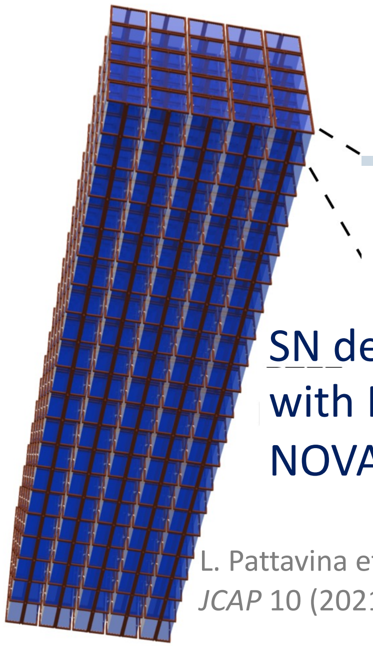
Much more on CEvNS than can be covered in a short summary talk …

Rich physics program with CEvNS

- Precision measurement of CEvNS provides many interesting SM and BSM physics

CEvNS is a very active field, with great advances

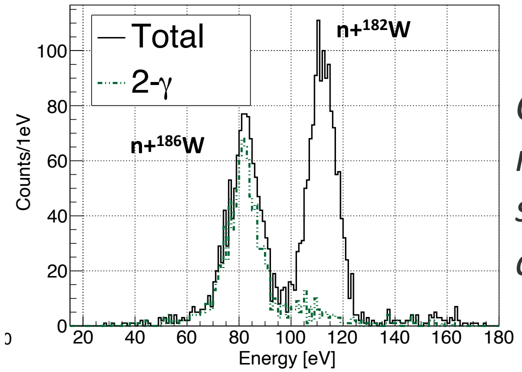
- Many different CEvNS experiments currently running or under way
- New detector ideas
- Challenges addressed in community: (↔ DM)
  - Low energy excess
  - Calibration of nuclear recoil in sub-keV
  - Quenching factor measurement at sub-keV
  - Scalability of detector read-out (↔ 0νββ)



SN detection with RES-NOVA

L. Pattavina et al. *JCAP* 10 (2021) 064

L. Thulliez *et al*,. 2021 *JINST* 16 P07032



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

Save the Date!

More will follow soon

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Carl Friedrich von Siemens Stiftung

SFB 1258 Neutrinos Dark Matter Messengers

erc

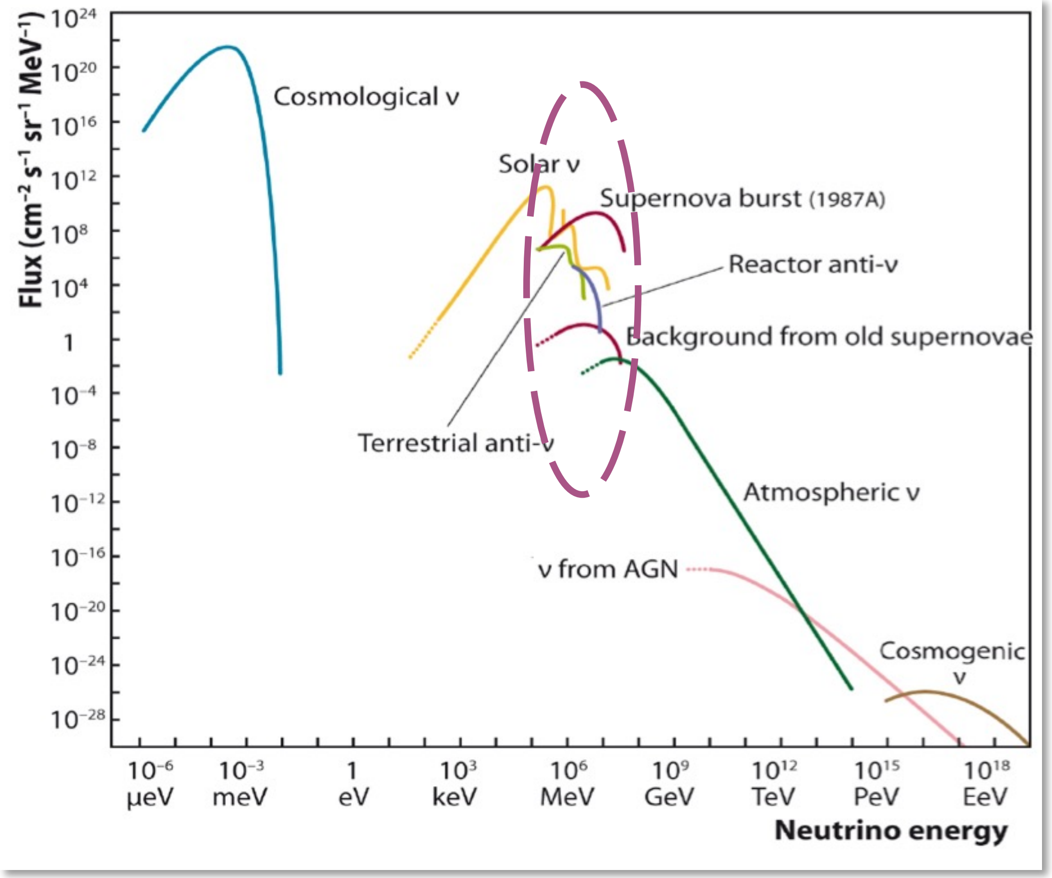
MUNICH

March 22-24 2023

BONUS SLIDES

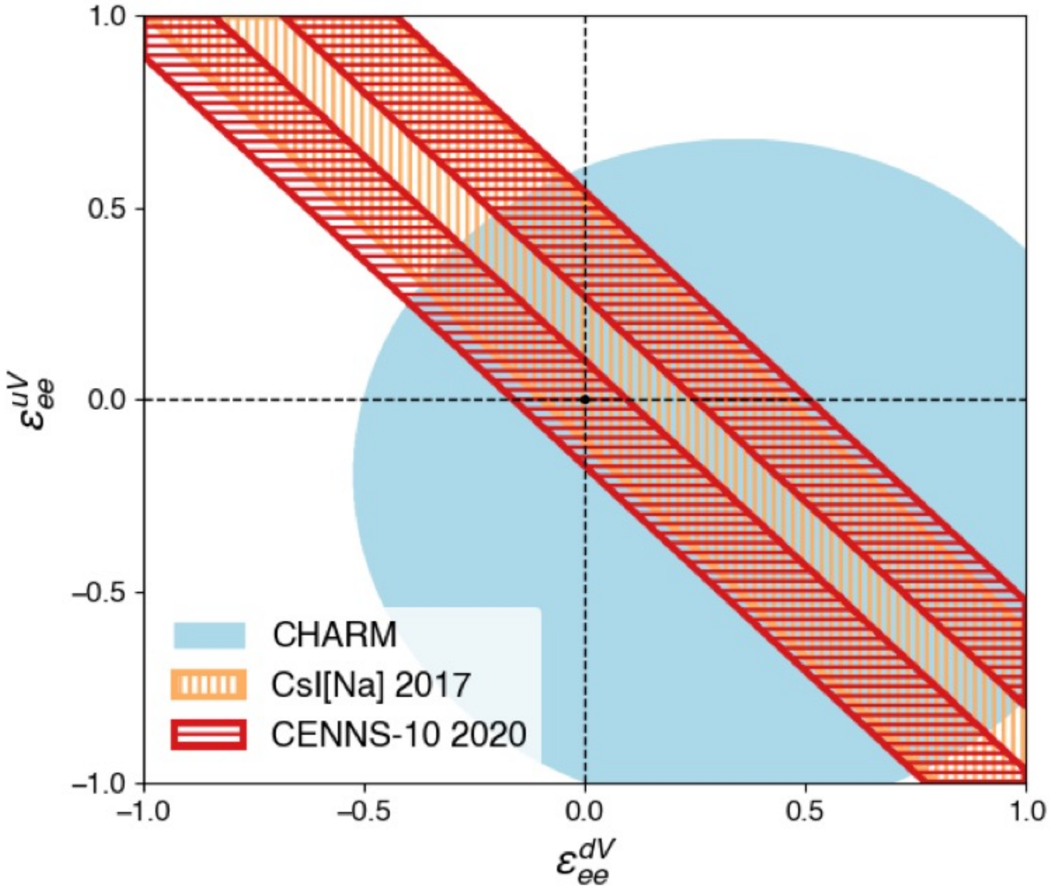
Neutrino Sources for CEvNS

from U. F. Katz and Ch. Spiering, *Prog.Part.Nucl.Phys.* 67 (2012) 651-704

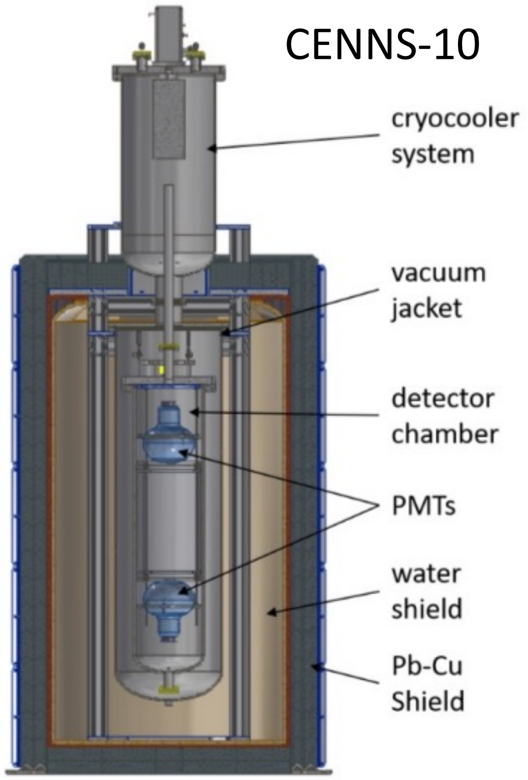


- Radioactive sources, e.g. Cr-51
- Stopped pion decay at rest sources

COHERENT – Ar Results



https://sites.duke.edu/coherent/detectors/



CONUS Results

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

- Low background achieved

Community milestone

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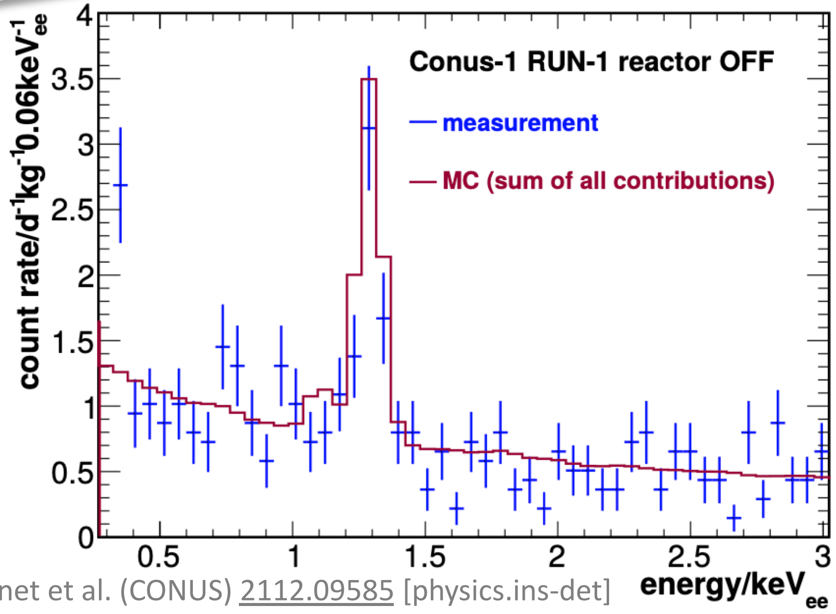
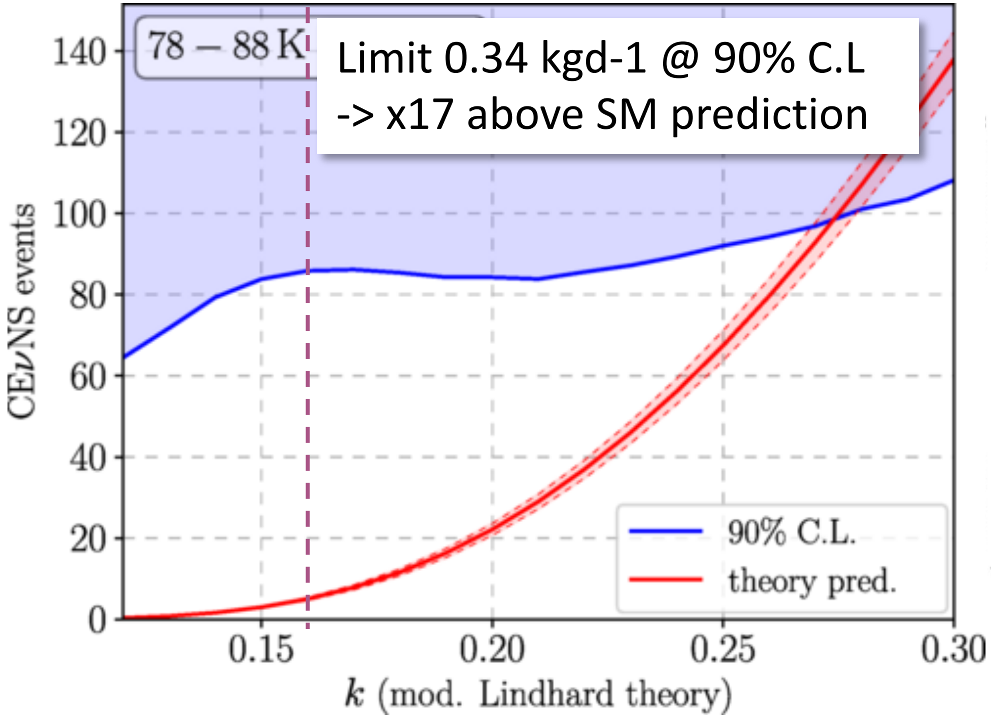


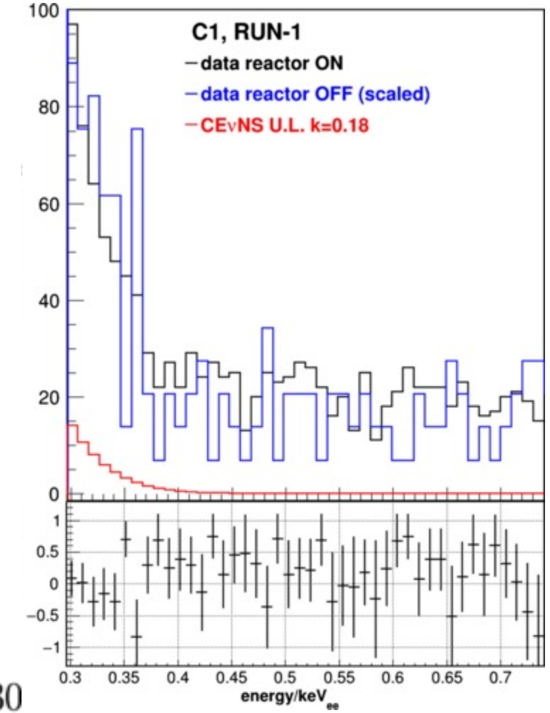
H. Bonet et al. (CONUS) 2112.09585 [physics.ins-det]

- Constraints on CEvNS on Ge, in dependence of QF
- Followed by quenching factor measurement down to 400 eV_{nr} A. Bonhomme et al., 2202.03754 [physics.ins-det]

k = 0.162 ± 0.004

Limit 0.34 kgd-1 @ 90% C.L
-> x17 above SM prediction



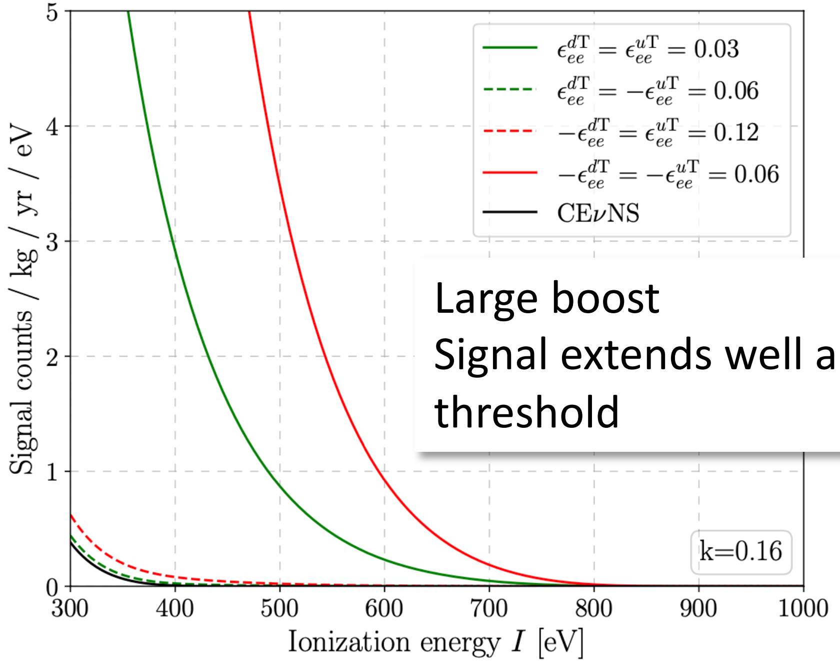


Tensor-type NSI

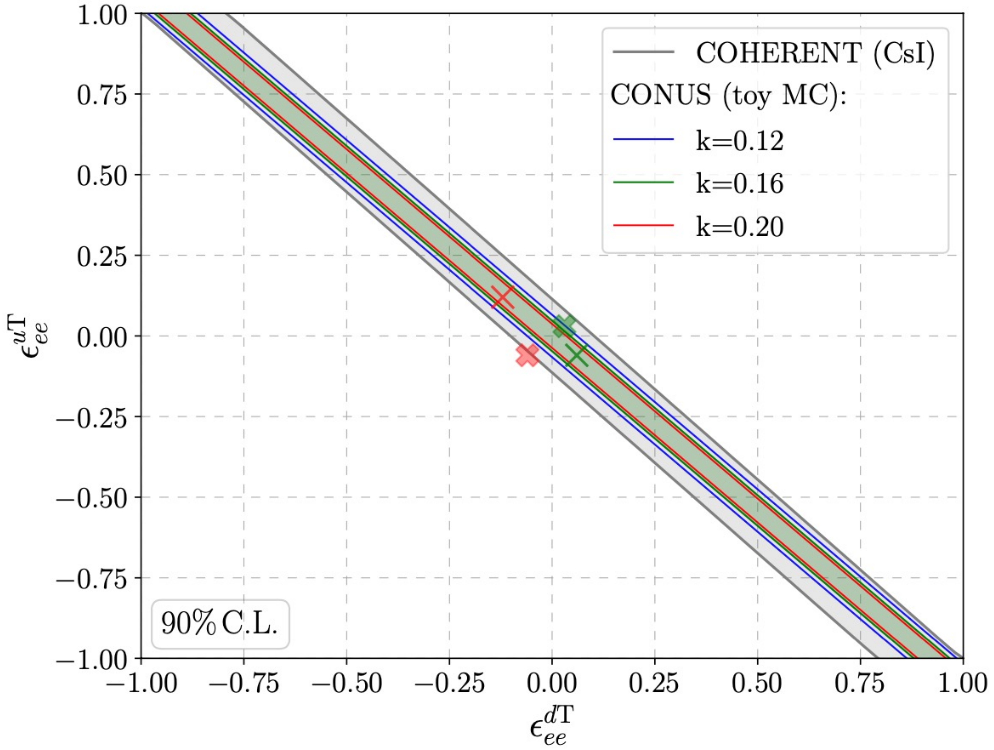
H. Bonet et al. (CONUS), JHEP 05 (2022) 085

$$\left(\frac{d\sigma}{dT_A}\right) = \left(\frac{d\sigma}{dT_A}\right)_{CE\nu NS} + \frac{4G_F^2}{\pi} {Q_{NSI}^T}^2 m_N \left(1 - \frac{m_A T_A}{4E_\upsilon^2}\right)$$

with $Q_{NSI}^T (2\epsilon_{\alpha\beta}^{uT} + \epsilon_{\alpha\beta}^{dT})\mathrm{Z} + (\epsilon_{\alpha\beta}^{uT} + 2\epsilon_{\alpha\beta}^{dT})\mathrm{N}$

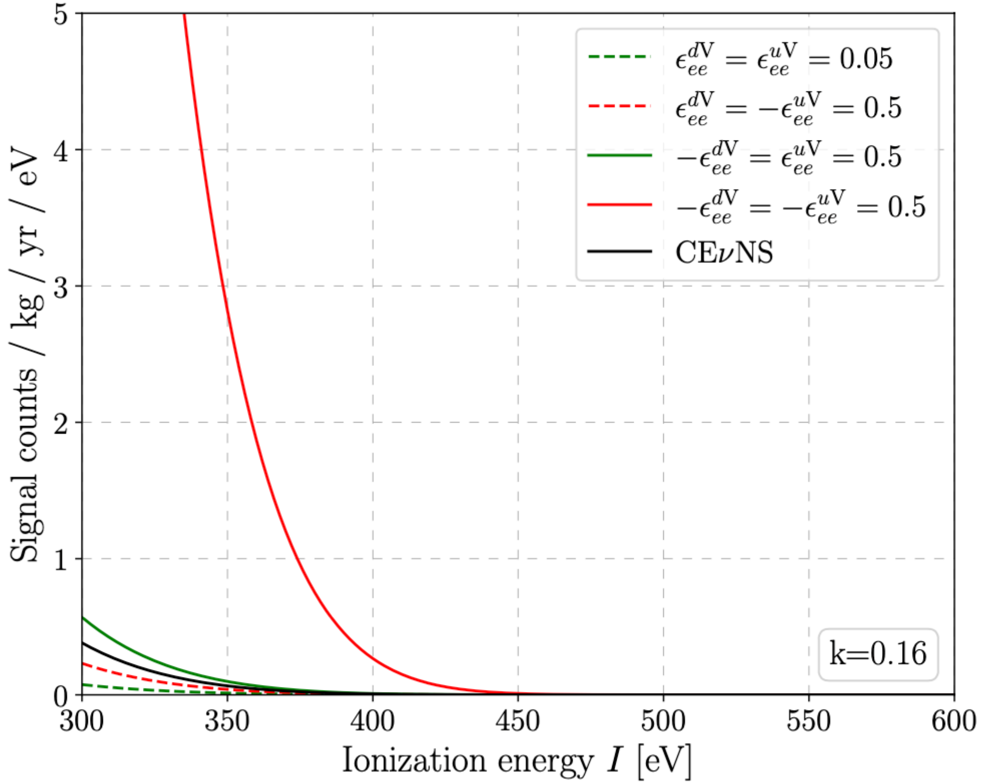


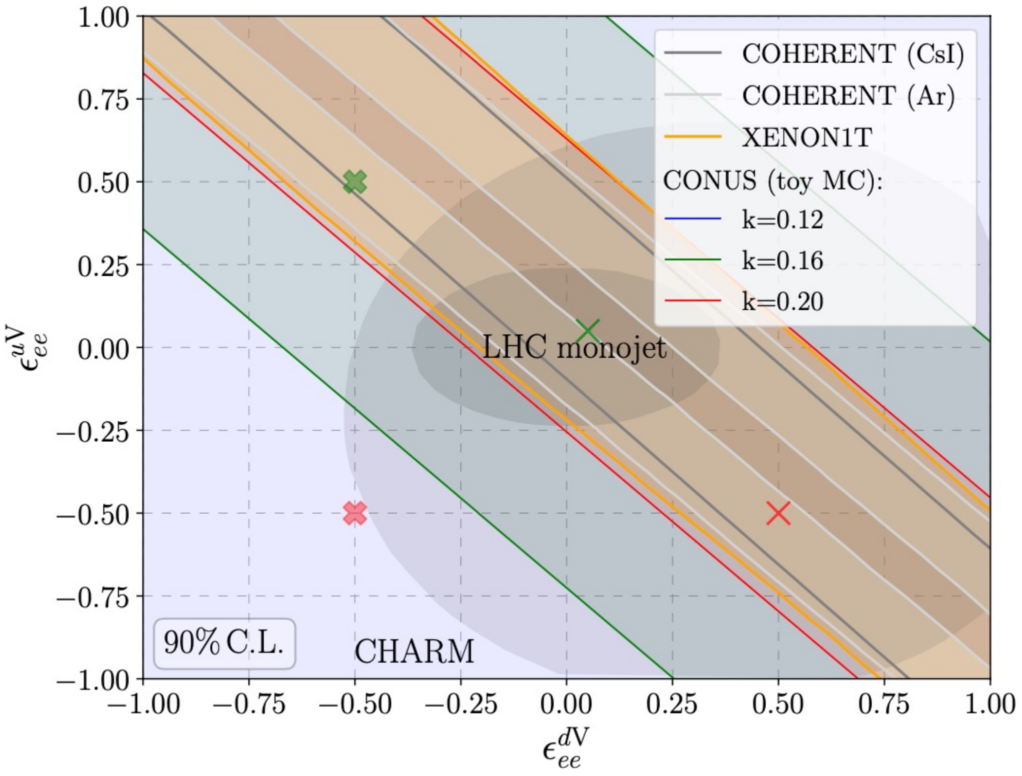
Large boost
Signal extends well above threshold



Vector-type NSI

H. Bonet et al. (CONUS), JHEP 05 (2022) 085





Light vector bosons

H. Bonet et al. (CONUS), JHEP 05 (2022) 085