First detection of coherent elastic neutrino-nucleus scattering of reactor-neutrinos with CONUS+

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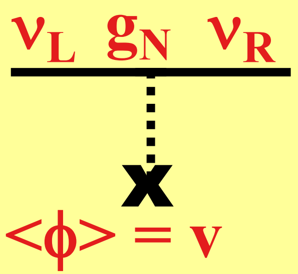
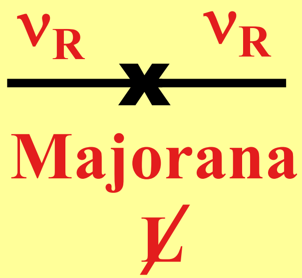
Adding Neutrino Masses to the SM

1) Simplest possibility: add 3 right handed neutrino fields





$$\rightarrow \quad \begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^{\mathbf{c}}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^{\mathbf{c}} \\ \nu_R\end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

significant NEW ingredients:

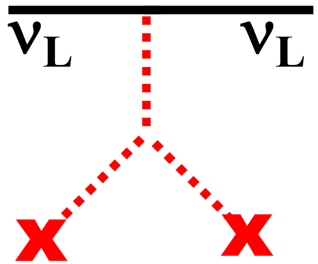
- SM=1-scale theory ➔ multi-scale theory
- modified global symmetries (L, henn – egg)
- 9 more parameters

➔ call it at least SM+

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

➔ **left-handed Majorana mass term:**



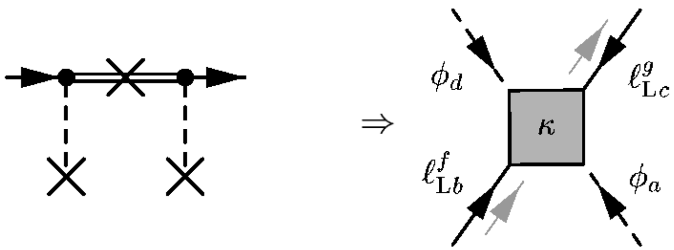
$$\rightarrow M_L \overline{L} L^c$$

3) Both ν_R and new Higgs triplets Δ_L:

➔ **see-saw type II**

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

4) Higher dimensional operators: d=5, …



$$\Leftrightarrow \quad \mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi \qquad \rightarrow M_L \overline{L} L^c$$

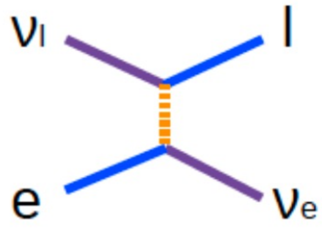
5-N) …

- mass mechanism & required extra fields are *NOT* known
- all BSM information so far encoded into 3 neutrino masses and mixings

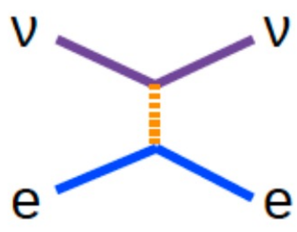
➔ **BSM physics can also show up in interactions!**

Beyond Masses & Mixings: ν Interactions + BSM

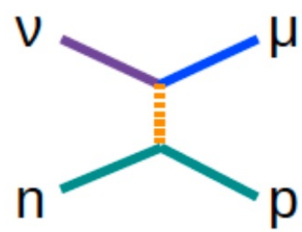
Exchange of W and Z bosons
→ NC and CC interactions with:
- **leptons**
- **quarks & protons/neutrons**



Inverese beta decay

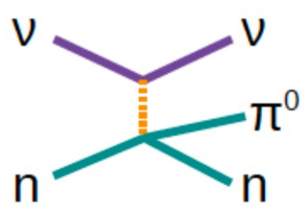


Elastic neutrino electron scattering

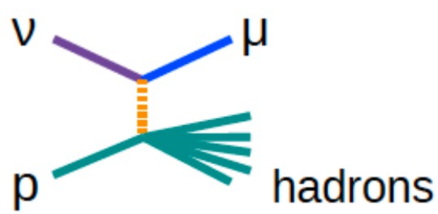


(Quasi-) elastic neutrino nucleon scattering

→ inelastic processes: **hadrons**

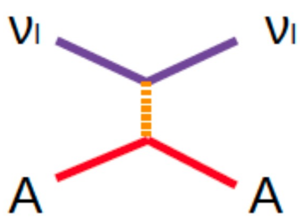


Nucleon excitation + resonance production



Deep inelastic scattering + jet production

Freedman 1974:
→ coherent scattering of neutrinos on the whole nucleus (CEνNS)
→ only via Z-exchange



Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

→ unique & powerful channel
- test the Standard Model
- search for new physics
- learn uniquely about sources

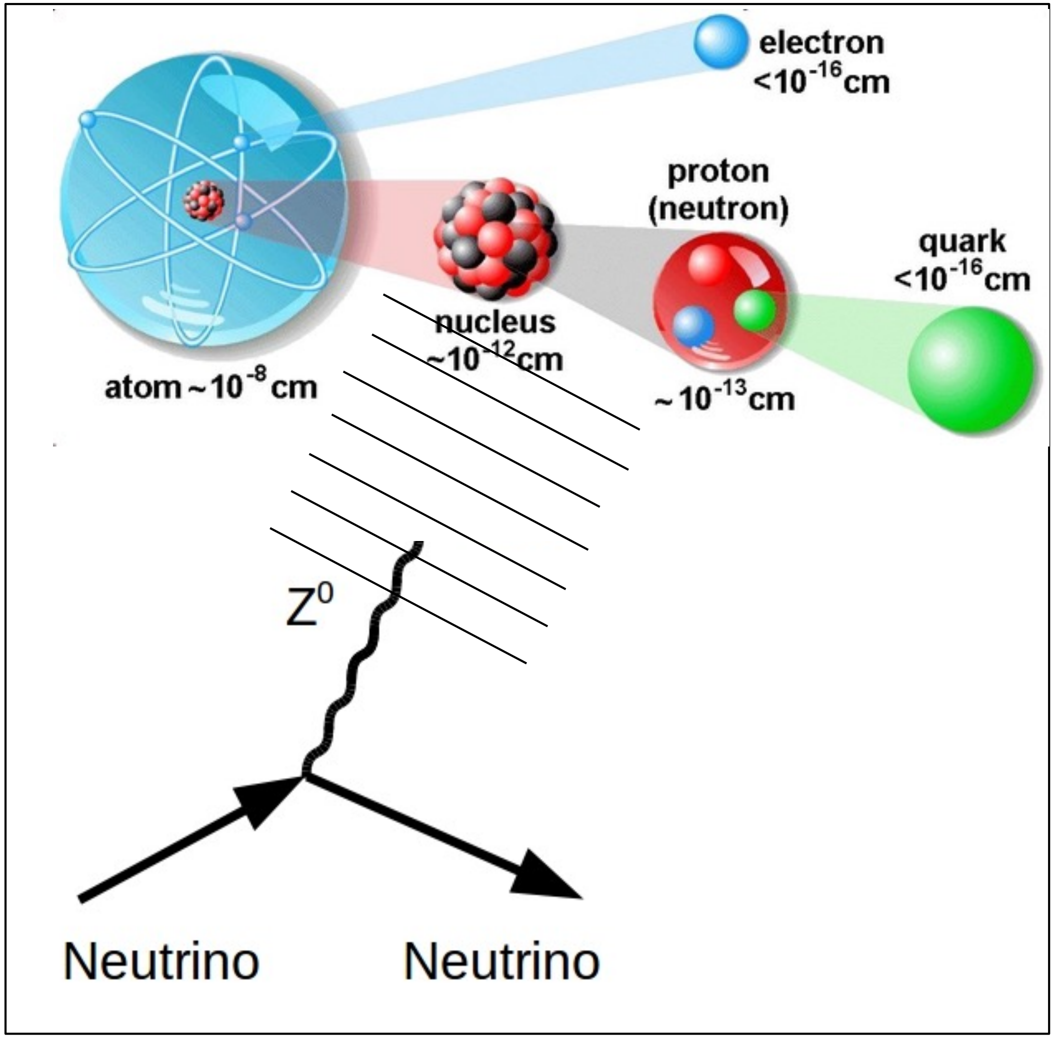
CEνNS: The simple Picture

1. ν-wavelength big enough
   → Z scattering @whole nucleus
2. small momentum transfer

   → **coherent scattering**

- Coherence length ~ 1/E
  - E_ν below O(50) MeV
  - lower for full coherence

- cross section $\sim (E_\nu)^2$
  → overcompensate:
  - very high ν flux
  - coherence ~ N^2



E.g. Germanium:
$N \simeq 40\text{-}44$ → $N^2 \simeq 1600\text{-}1900$ → conventional detector mass 10t ←→ few kg

Z-scattering of neutrinos with whole nucleus

$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$

$$Q_w = N - \underbrace{(1 - 4\sin^2\theta_w)}_{\simeq 0} Z \quad \sim \mathbf{N}$$

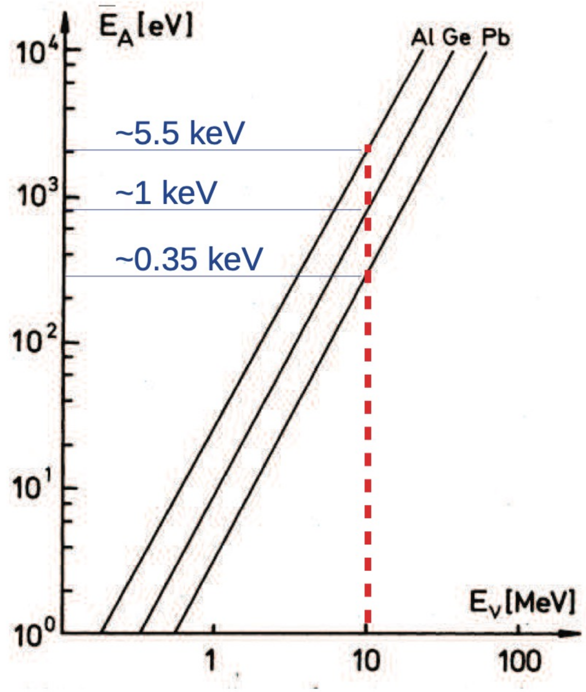
- neutrons dominate: $\sigma \sim N^2$ → enhancement
- form factor $F(Q^2)$ ←→ size of nucleus
- form factor matters for E_ν = 20-50 MeV
- $F(Q^2)$ → 1 for $E_\nu \ll 50$ MeV
- kinematics:

  M: mass of nucleus

  E_ν: neutrino energy

  T: nuclear recoil energy

  θ: scattering angle



A.Drukier, L.Stodolsky, Phys.Rev.D 30 (1984) 11

$$|\vec{q}| = \sqrt{2MT} = \sqrt{2E_\nu^2(1-\cos\theta)}$$

→ very small momentum transfer

What can be learned from CEνNS?

aim at the most precise measurement

nuclear uncertainties
➔ go to lowest q^2 where $F(q^2) = 1$

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\left(N - (1 - 4\sin^2\theta_W)Z\right)^2 F^2(q^2)\, m_A \left(1 - \frac{m_A T}{2E_\nu^2}\right)$$

+ new neutrino interactions⋯

Weinberg angle

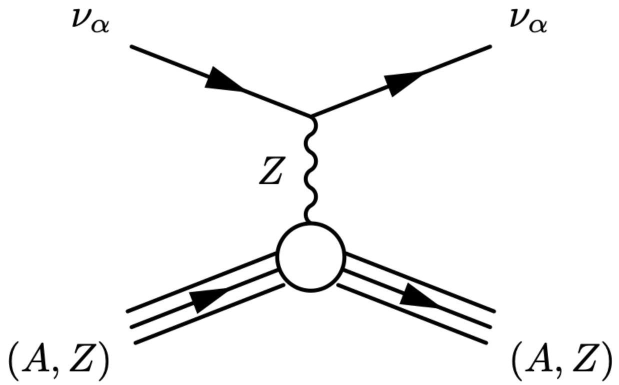
tests any new physics which modifies this relation

Inverted logic: If only SM ➔ CEνNS can be used to:

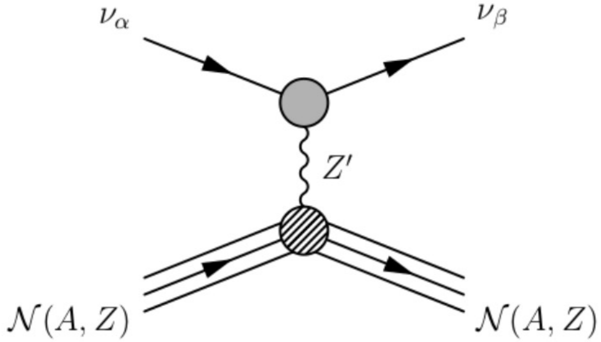
- test sources: the Sun, reactors, π@rest beams, ...
- unique tests of nuclear physics
- technological applications: reactor monitoring, safe-guarding,...

BSM Physics with CEνNS

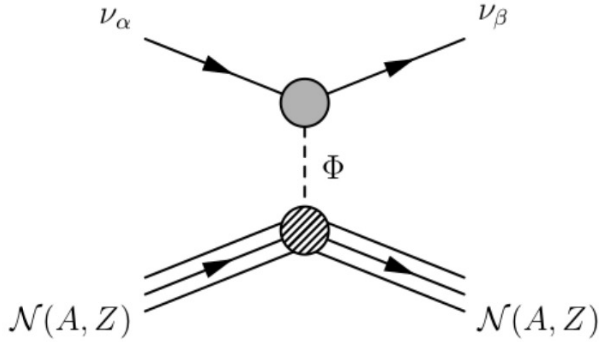
reference: SM neutral current



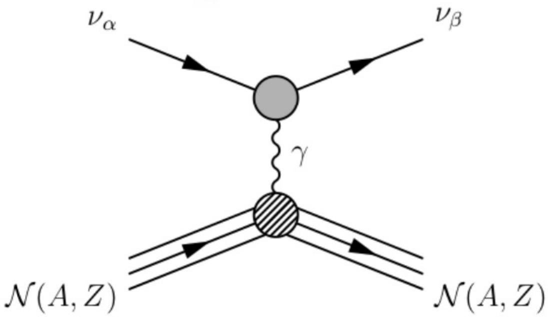
BSM Vector Mediator



BSM Scalar Mediator



Electromagnetic Interactions



milicharges
neutrino magnetic moments

modified low E running of $\sin^2\theta_W$

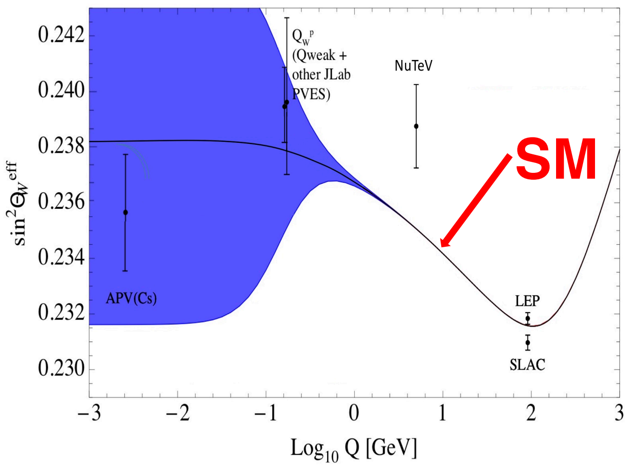
$\sigma \sim N - [(1- 4*\sin^2\theta_W)\, Z\,]^2$

←→ light dark sectors

dark matter candidates

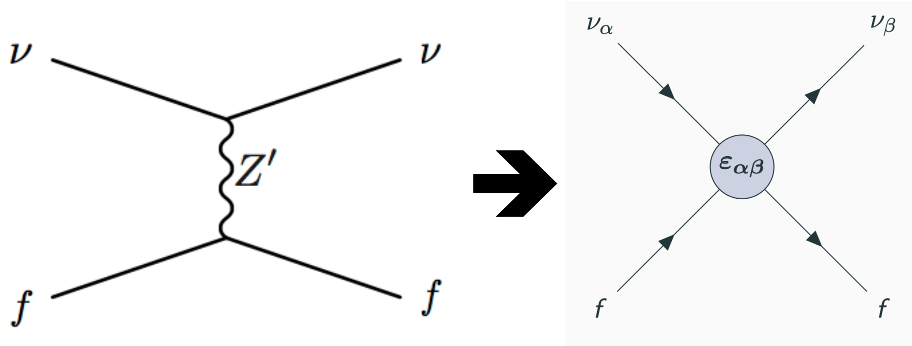
g-2

...



BSM Physics as NSI's

NSI's ←→ BSM at high scales
... which is integrated out
Z', new scalars, … → ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

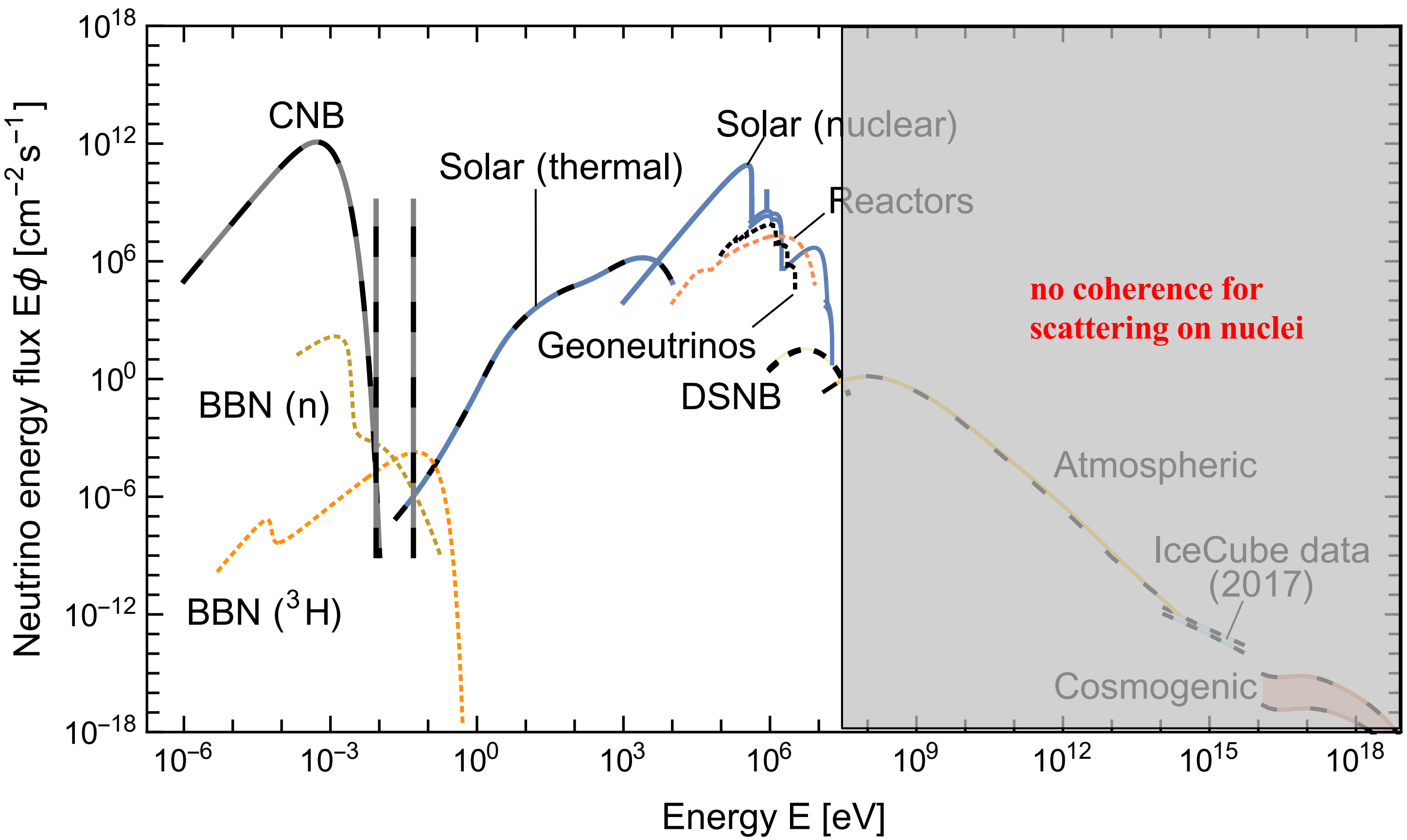
$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}$$

Barranco et al. 2005

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

→ **a powerful method to test new physics**
ε = 0.001 ←→ test multi TeV scales

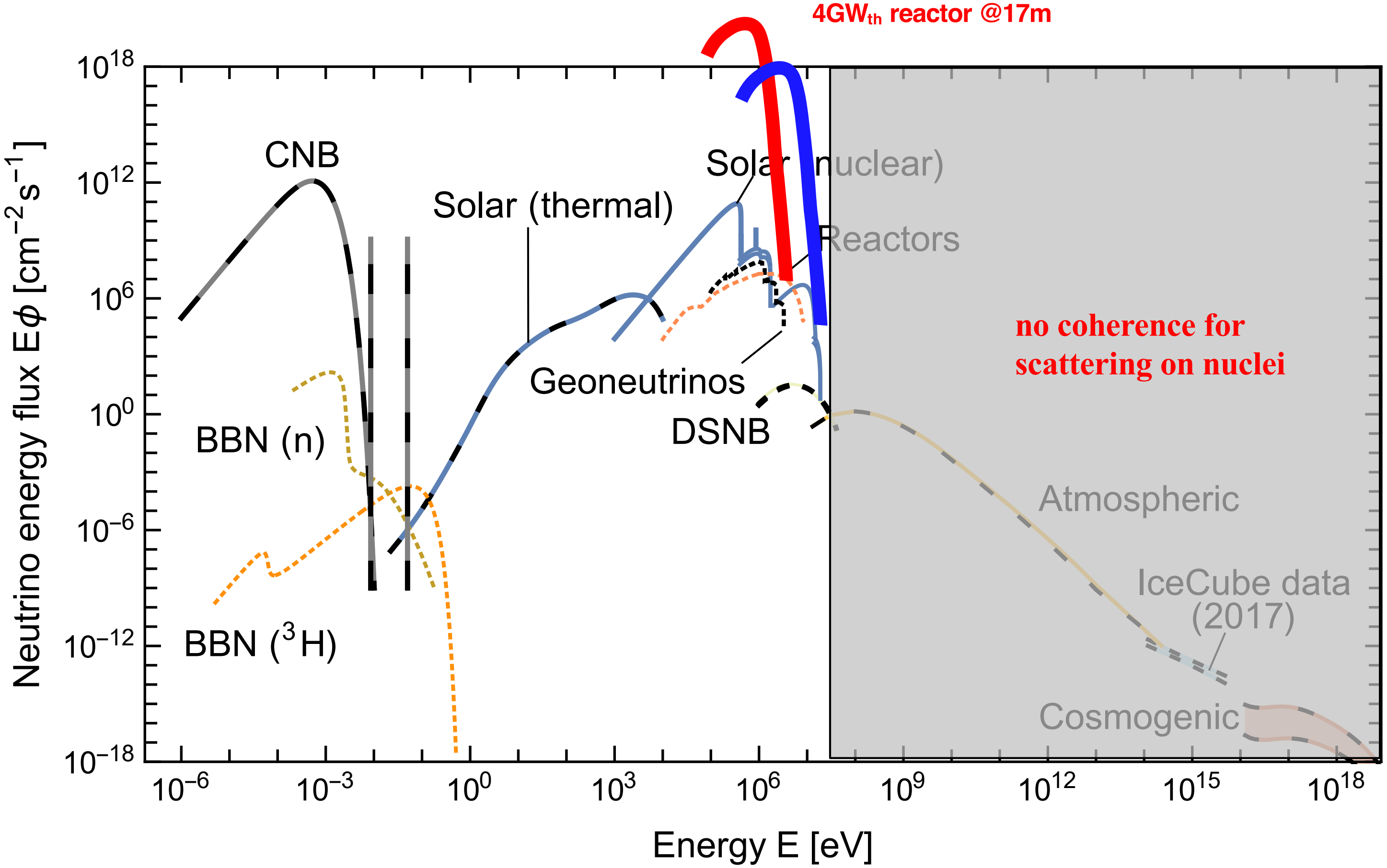
Neutrino Sources: Flux ⊗ Energy



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

Neutrino Sources: Flux ⊗ Energy

➔ very different close to a nuclear power reactor and in a stopped π-beam or a supernova



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

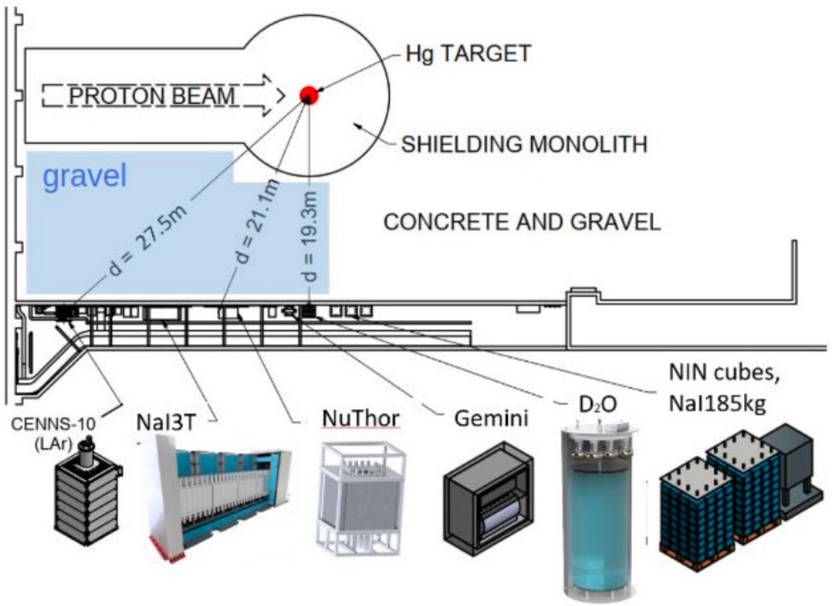
➔ event rates: neutrino flux ⊗ detector size ⬅➔ backgrounds

COHERENT: π-DAR Neutrino Beam

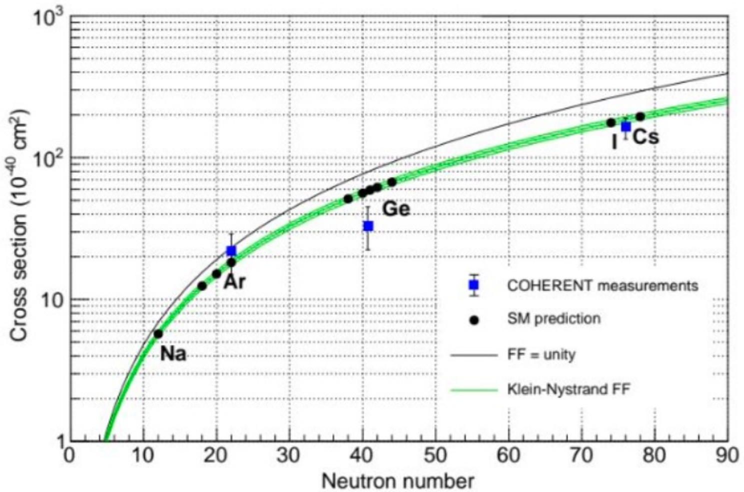
Located in Spallation Neutron Source, Oak Rigde National Laboratoy (USA).

Several detectors with different targets.

First detection of CEνNS with CsI[Na] in 2017.
Detection with Ar in 2020 and with Ge in 2024.



COHERENT collaboration 2021 JINST 16 P08048



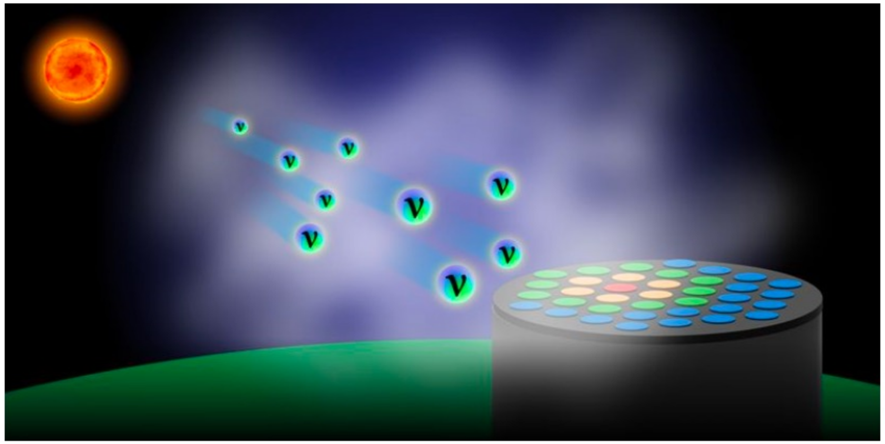
Credit: J. Hakenmüller @ AAP 2024

Dark Matter Experiments

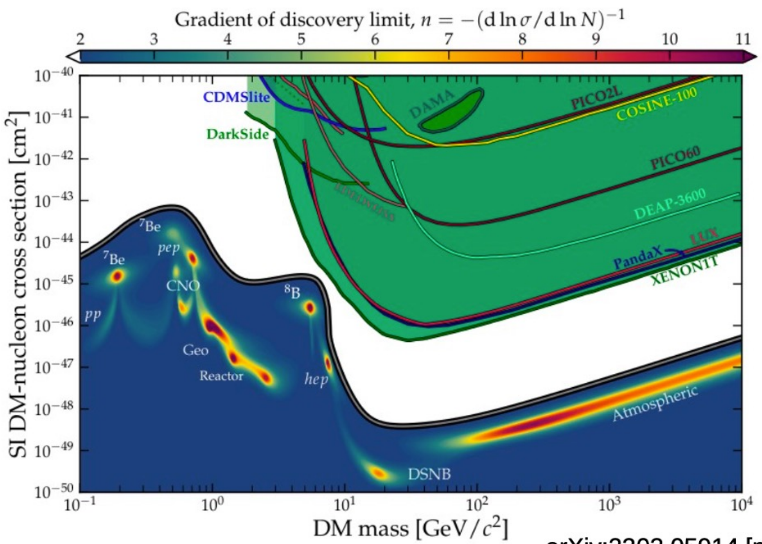
- neutrinos from the Sun and
- atmospheric neutrinos

➔ "neutrino fog"
in dark matter experiments

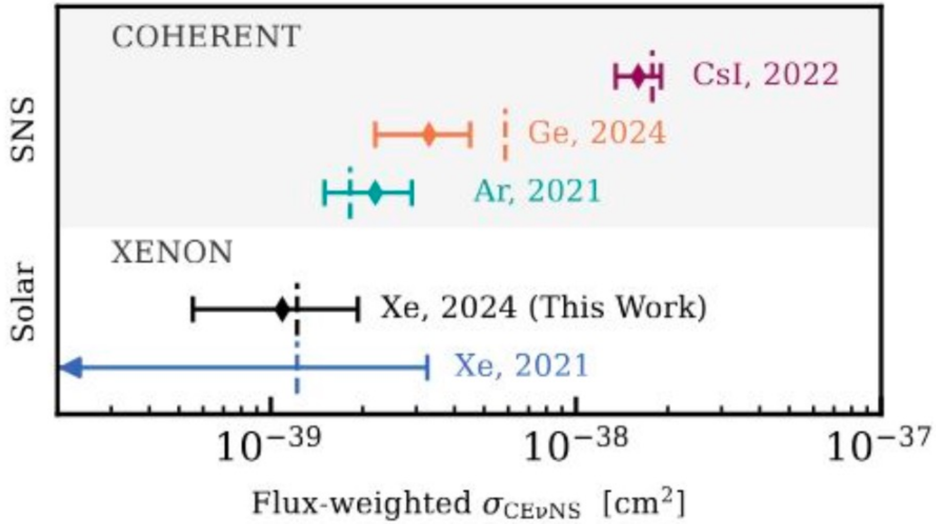
➔ dark matter like signature



APS/Alan Stonebraker



arXiv:2203.05914 [physics.ins-det]

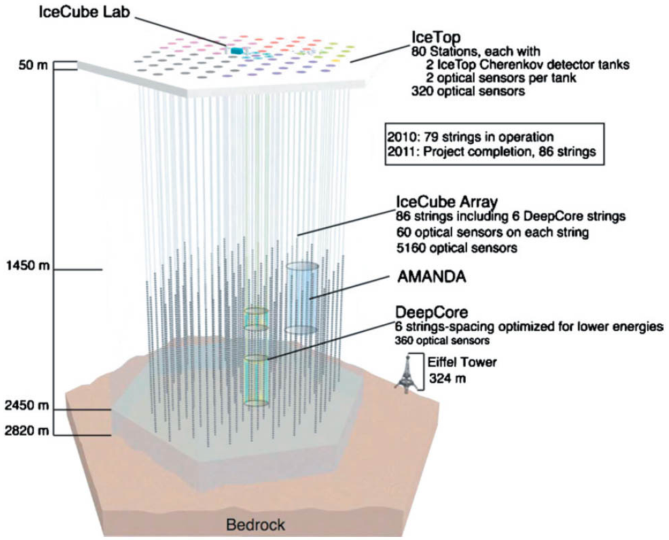


XenonNT 2.7 σ
Phys. Rev. Lett. 133, 191002 (2024)

PandaX 2.6 σ
Phys. Rev. Lett. 133, 191001 (2024)

Reactor Neutrino Experiments

IceCube experiment: km^3

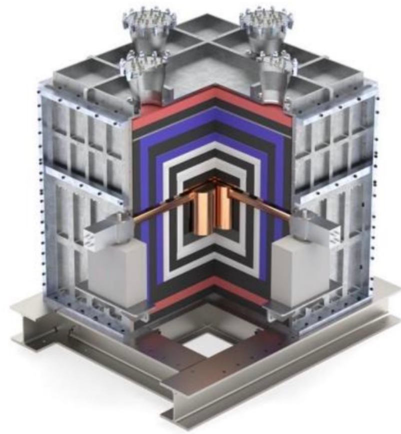


SuperKamiokande:
50.000 tons of water

neutrinos interact very weakly
🡐 huge experiments

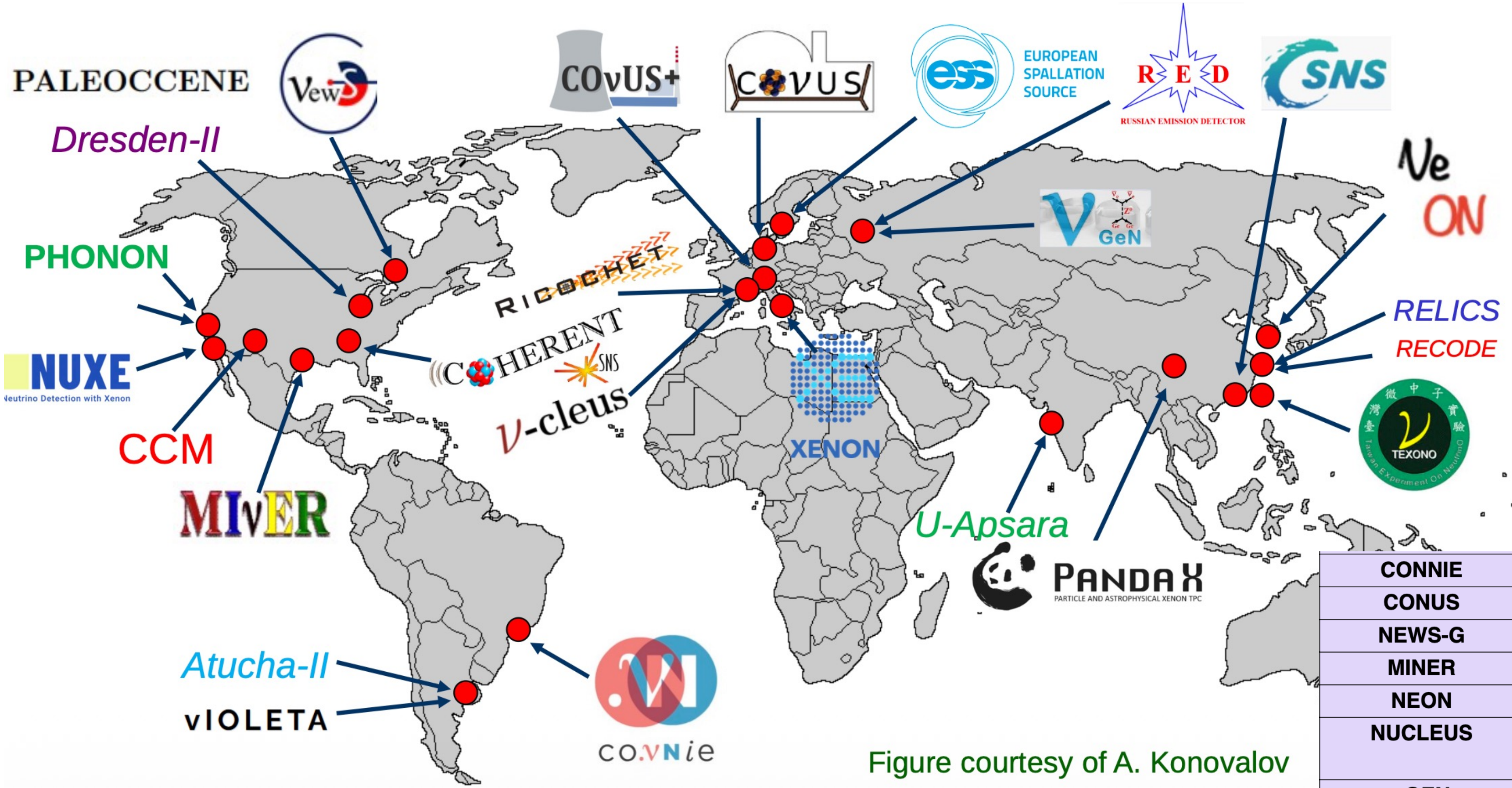
CEνNS + very high neutrino flux @commercial reactors
➔ small experiments

- **cost**
- **time**
- **potential**



CONUS+
- **size ~2m^3**
- **active mass ~4kg**

CEνNS Experiments in the World



CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
NEWS-G	Ar+2%CH4	Canada
MINER	Ge/Si cryogenic	USA
NEON	NaI(Tl)	Korea
NUCLEUS	$CaWO_4$, Al_2O_3 cryogenic	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn, Al, Sn cryogenic	France
TEXONO	p-PCGe	Taiwan
Dresden II	PCGe	USA

1974: prediction of CEνNS

...many attempts...

2017: COHERENT - 1st observation with (partially coherent) ν's from stopped π beam (from an accelerator)

2024: 1st observation of 8B neutrinos with CEνNS in dark matter experiments (XENONnT, PandaX)

2025: CONUS+ → 1st observation with reactor anti-neutrinos in the fully coherent regime

The CONUS Collaboration

N. Ackermann, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez Garcia, H. Strecker
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
K. Fülber, R. Wink
PreussenElektra GmbH, Kernkraftwerk Brokdorf (KBR), Germany
M. Rank, I. Stalder, J. Woenckhaus
Kernkraftwerk Leibstadt AG (KKL), Switzerland

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

Kernkraftwerk Leibstadt

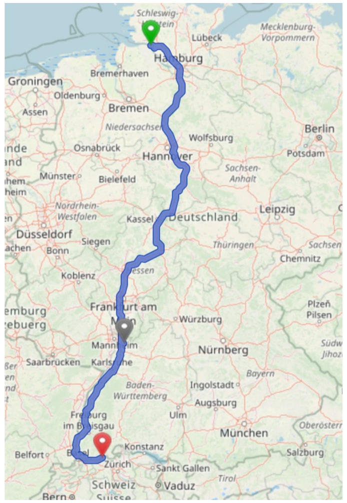
CONUS

COνUS+

1) **Most intense anti-neutrino flux from a commercial power reactor:**
➔ CONUS experiment at Brokdorf
➔ CONUS+ at Leibstadt (CH)

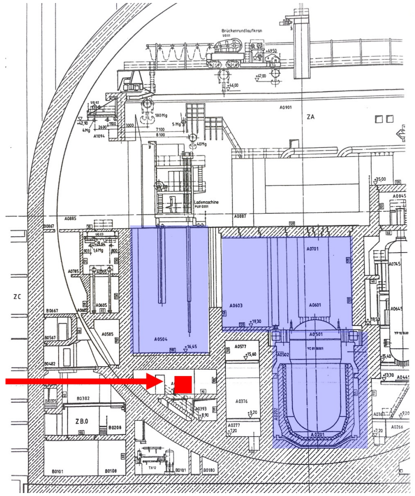
2) **Very sophisticated shield against all sort of backgrounds**

3) **Very low threshold Germanium detectors**



Experimental Sites

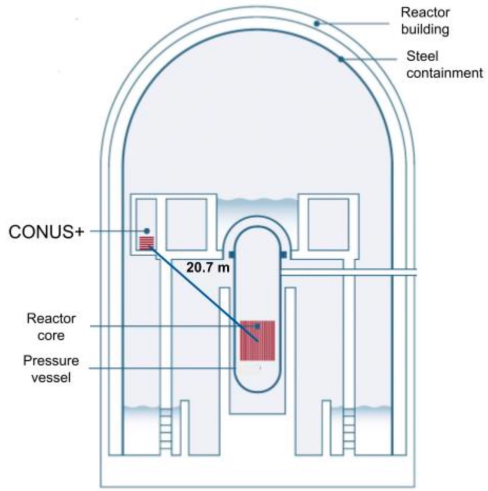
2018 – 2022 at power plant in Brokdorf (KBR)
3.9 GW_{th} reactor
CONUS @17m → **$2*10^{13}$ ν/cm^2/s**
→ Eur.Phys.J.C 79 (2019) 8, 699
→ Eur.Phys.J.C 83 (2023) 3



shutdown in 2021 → more off data
final result: factor 1.6 (90%CL) away from SM
→ Phys.Rev.Lett. 133 (2024) 25, 251802

➔ detector improvements → **CONUS+**

Since 2023 @Leibstadt, CH (KKL)
3.6 GW_{th} reactor
CONUS+ @20.7m → **$1.45*10^{13}$ ν/cm^2/s**
different overburden: 7-8 mwe → better veto
outage: drywell above detector +3.8cm steel

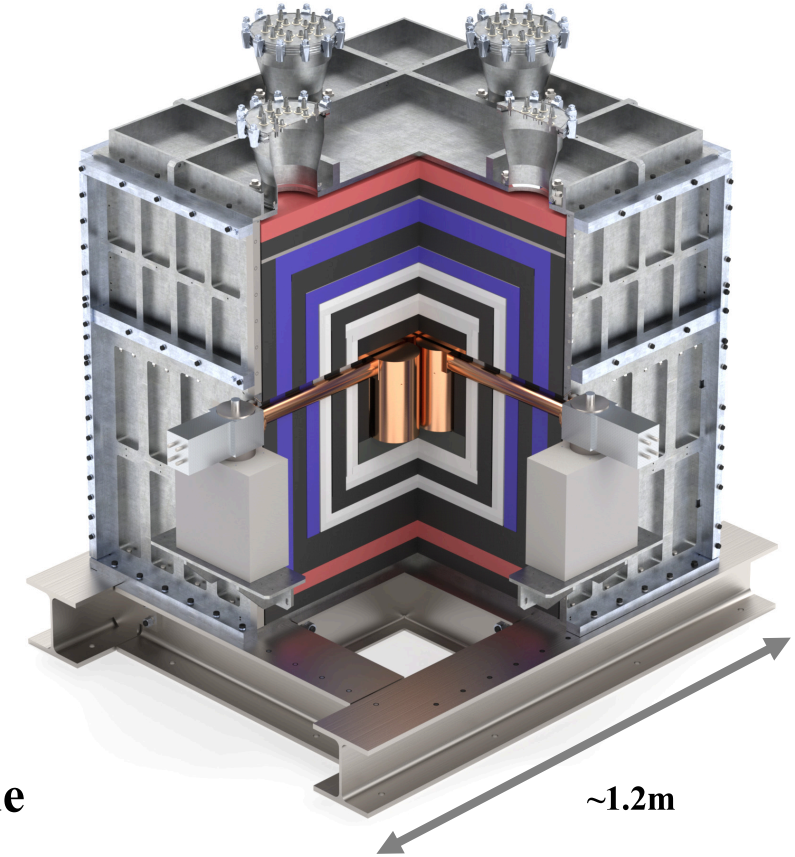


typical operation: 11 months per year ON, 1 month OFF for maintenance

The CONUS+ Setup: Shield

Shield for background suppression:

- stainless steel cage → safety (earthquakes)
- shield with active and passive layers:
  - outer and inner μ-veto layers
    → higher muon flux @KKL
  - lead for gamma suppression
  - PE (and borated PE) layers ←→ neutrons
- all materials carefully selected and screened
- flushing with radon-free air → remove ^{222}Rn
  → **background reduction by 4 orders of magnitude**
- 10 tons total mass



low background conditions like in UG labs

→ ``virtual depth"

CONUS: Eur. Phys J. C83 (2023) 195
CONUS+: Eur.Phys.J.C 85 (2025) 4, 465

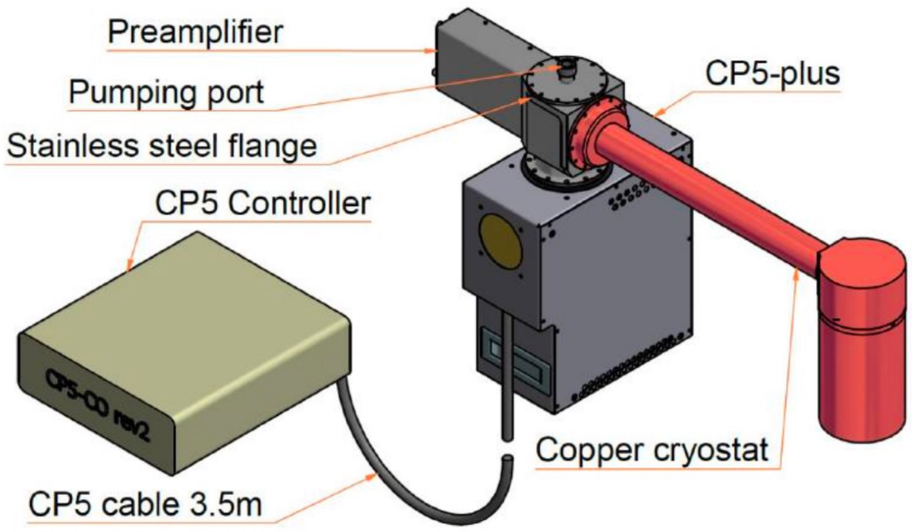
The CONUS+ Detectors

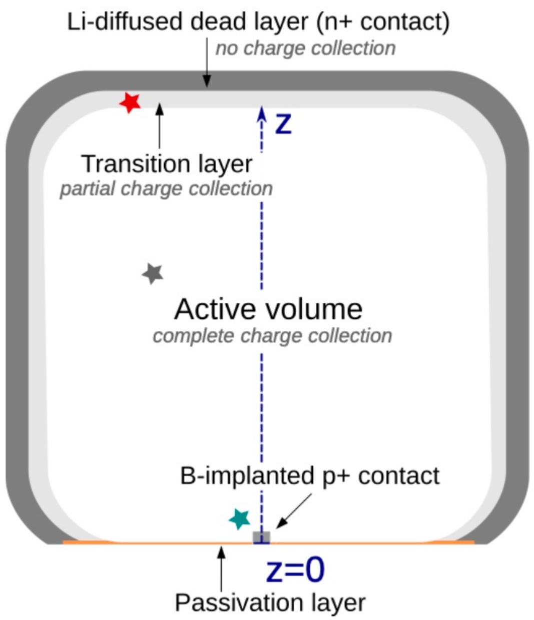
point-contact HPGe detectors

- point-contact HPGe detectors
  → diode in reverse direction, ~kV voltages
- 1kg crystals: C2,C3,C4,C5 plus C1@MPIK
  → active mass in CONUS: 3.74 kg
- electrical PT cryocoolers (LN not allowed)
- long cryostat arms
- intensive R&D cooperation with producer
- pulse shape discrimination (PSD ←→ slow pulses)
- ASIC based electronics
  → improved low E trigger efficiency
- reduced point contact size & bonding technology
  → reduced electronic noise
  → lower threshold: ~250 → 160 eV
  → improved energy resolution
- all components with very low background

Eur. Phys J. C81, 267 (2021)

Eur.Phys.J. C84, 1265 (2024)

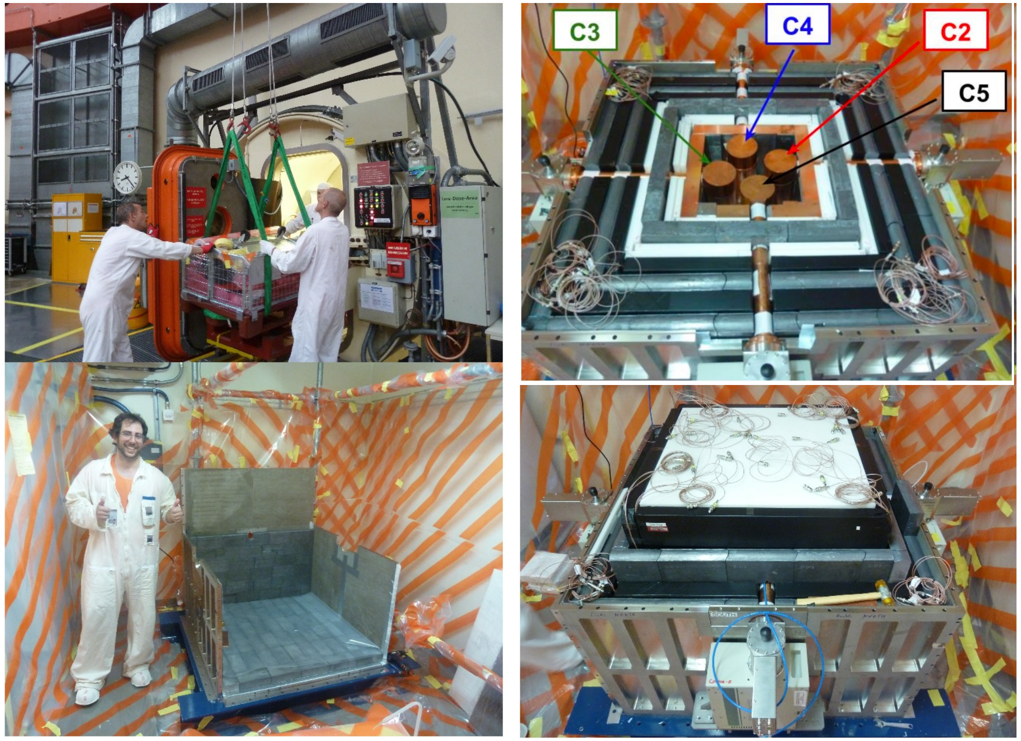


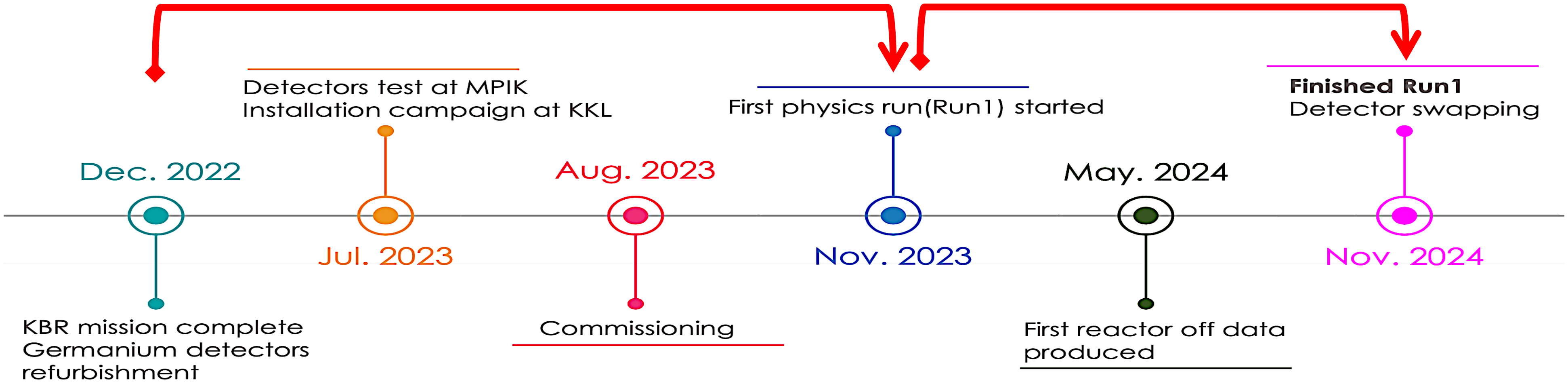


Timeline of CONUS+

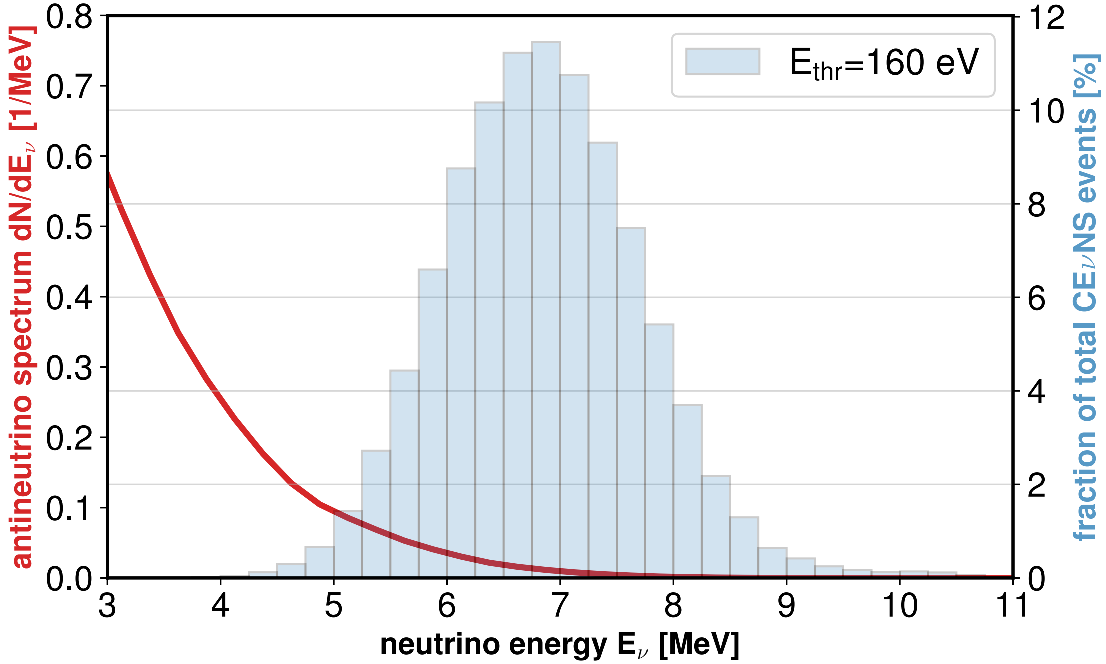
- dismantling
- transport
- improvements
- installation
- data taking
- analysis

➔





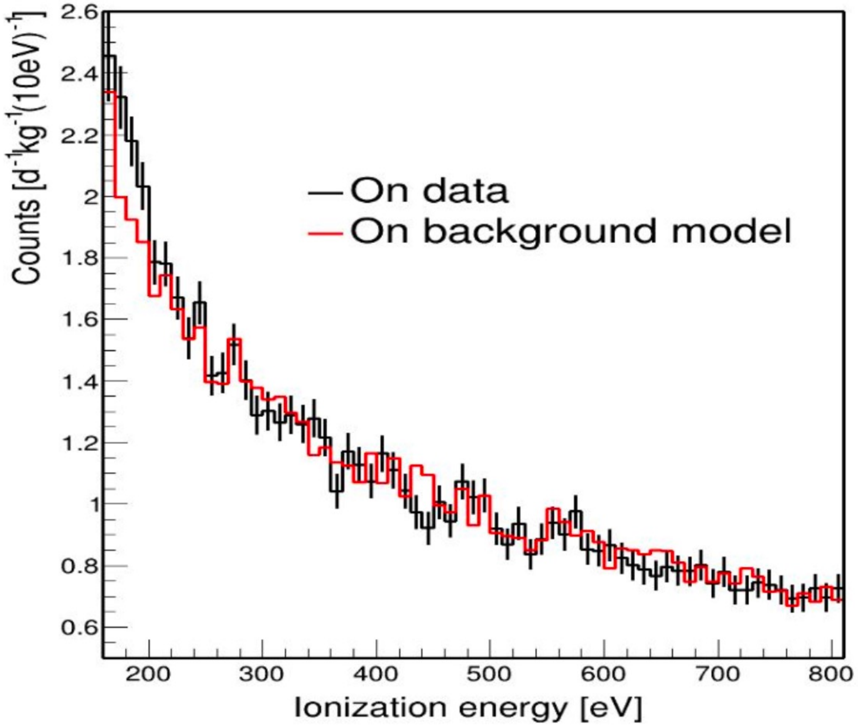
Signal Prediction

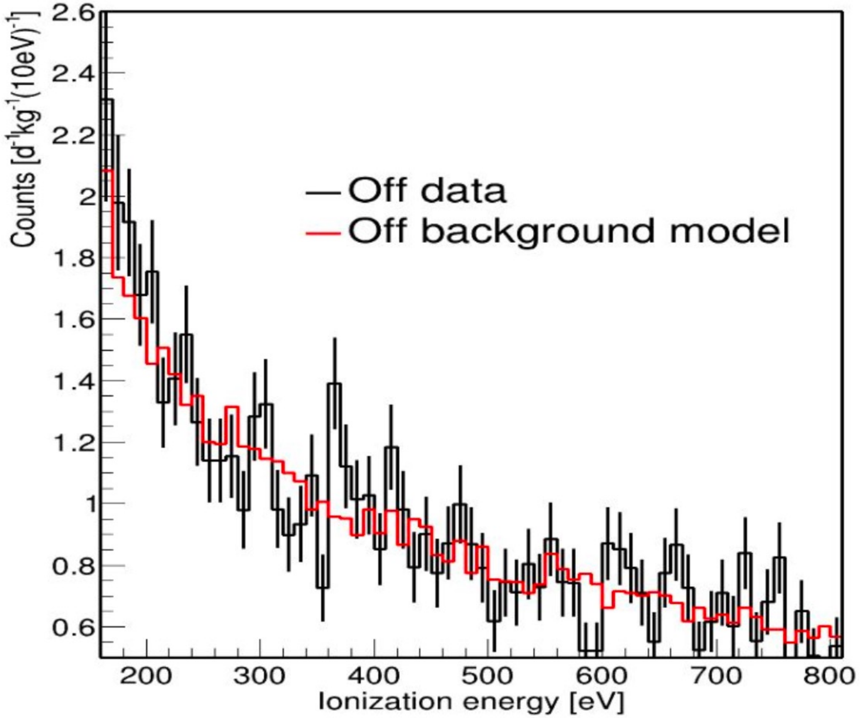


Detector	Threshold [eV_{ee}]	Predictetd CEvNS counts
C5	170	116 (+20/-18)
C2	180	96 (+16/-14)
C3	160	135 (+23/-20)
COMBINED	-	345 (+34/-30)

lower detector thresholds
➔ increased impact
of lower energy neutrinos

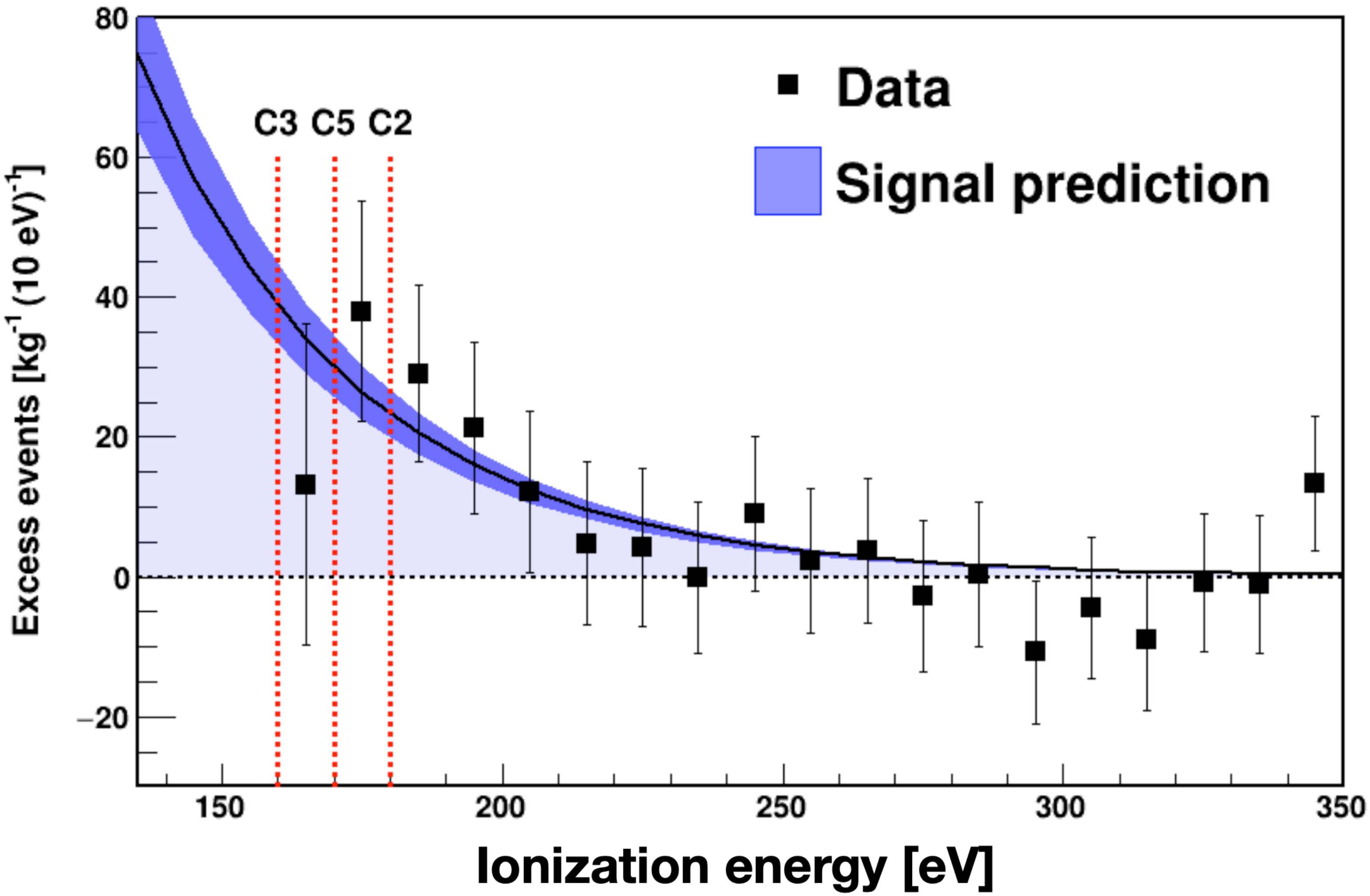
Background Model and Off-Data





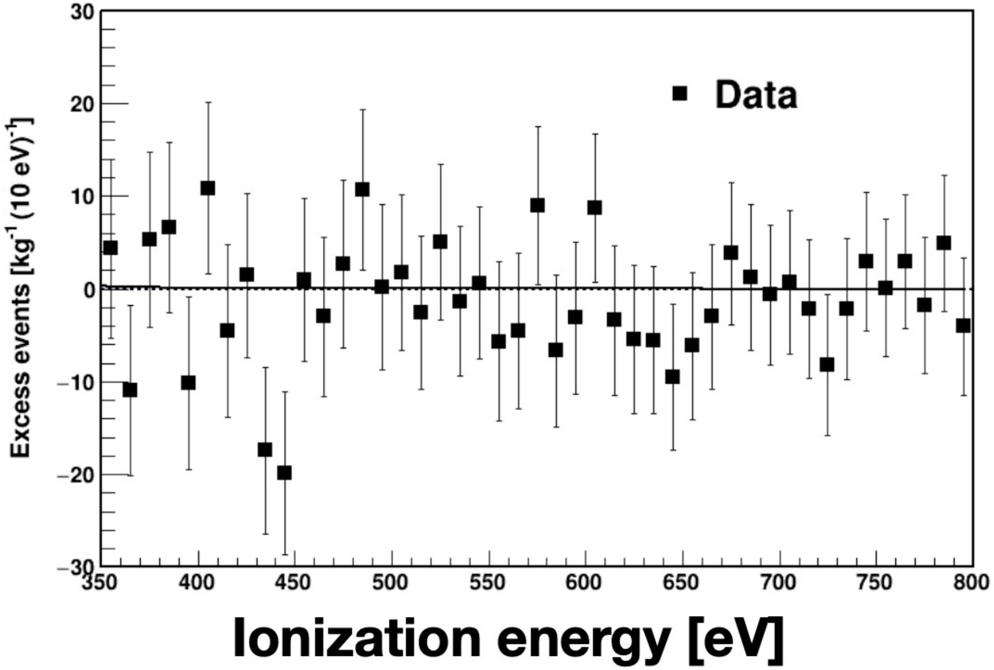
The run 1 result predominantly from On-data versus very well understood background
Upcoming runs: Combination of On-Off and On-background

Excess Events (below 350 eV_{ee})

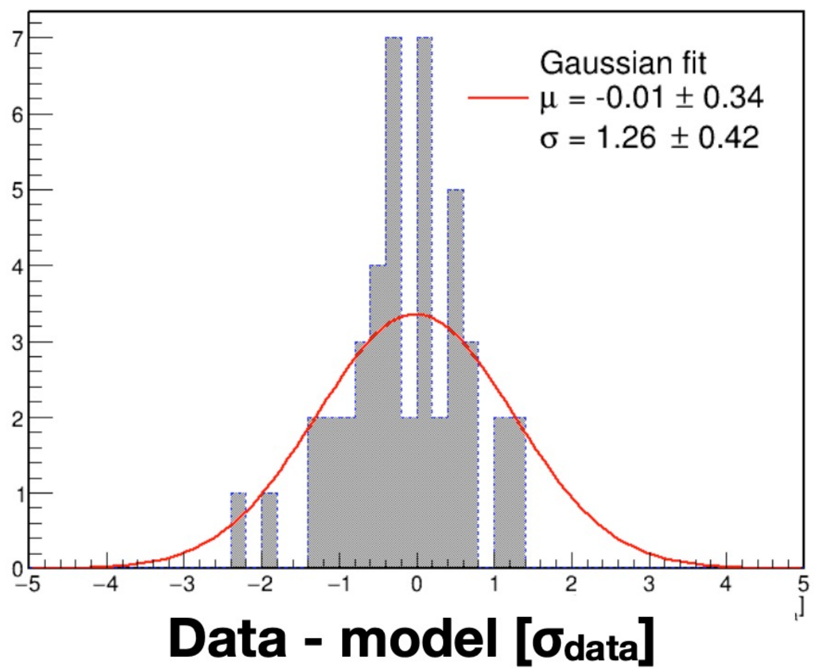


- difference between 119 days of reactor on to the background model scaled to the total detector mass
- vertical lines indicate the energy thresholds of the three detectors used in the analysis
- Nature 643, 1229–1233 (2025)

No Excess above 350 eV_{ee}



agreement between data and background model above the signal region from 350−800 eV



spread of the data points around the model

Comparison to Other CEνNS Results

Experiment	Target	Source	Neutrino energy	Flux [$cm^{-2}s^{-1}$]	Data [counts]	Data/ SM prediction	Significance of null hypothesis rejection
COHERENT	Cs	Accelerator	10 – 50 MeV	$5 * 10^7$	306^{+20}_{-20}	$0.90^{+0.14}_{-0.14}$	$11.6\,\sigma$
COHERENT	Ar	Accelerator	10 – 50 MeV	$5 * 10^7$	140^{+40}_{-40}	$1.22^{+0.49}_{-0.49}$	$3.5\,\sigma$
COHERENT	Ge	Accelerator	10 – 50 MeV	$5 * 10^7$	21^{+7}_{-6}	$0.59^{+0.26}_{-0.24}$	$3.9\,\sigma$
XENONnT	Xe	Sun (^8B)	< 15 MeV	$5 * 10^6$	11^{+4}_{-2}	$0.90^{+0.65}_{-0.67}$	$2.73\,\sigma$
PandaX-4T	Xe	Sun (^8B)	< 15 MeV	$5 * 10^6$	4^{+1}_{-1}	$1.25^{+0.69}_{-0.69}$	$2.64\,\sigma$
CONUS+	Ge	Reactor	< 10 MeV	$1.5 * 10^{13}$	395^{+106}_{-106}	1.14^{+036}_{-036}	$3.7\,\sigma$

→ CONUS+ has detected the lowest energy neutrinos via the CEνNS channel (down to 4 MeV)

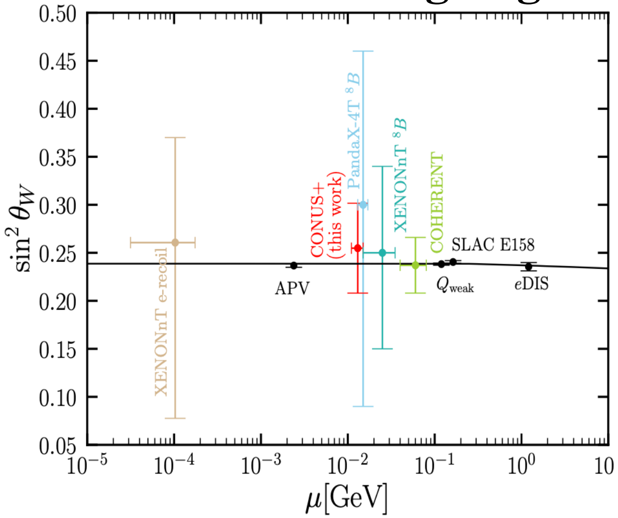
→ CONUS+ has accumulated the highest number of CEνNS counts in one single isotope (low threshold + high flux)

Some Studies based on CONUS+ Signal

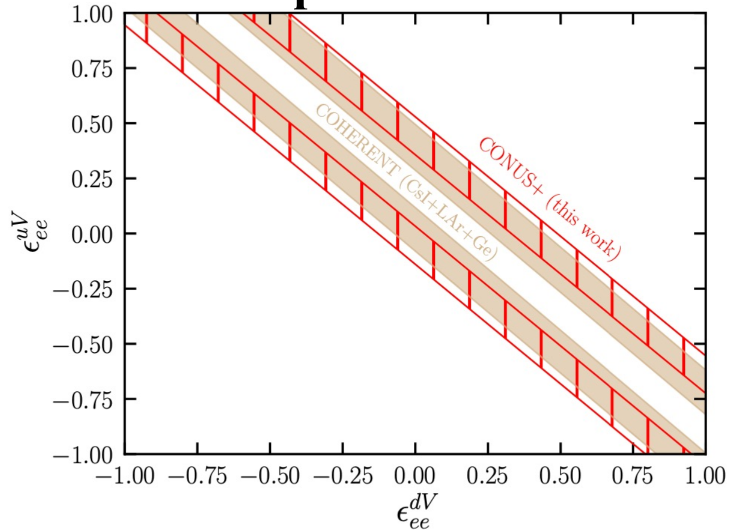
M. Alpízar-Venegas et al., arXiv:2501.10355

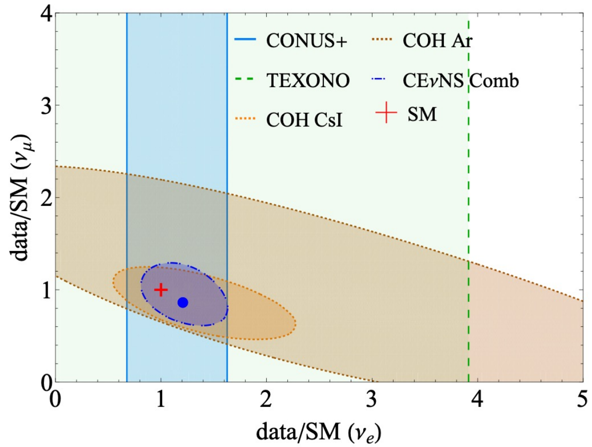
Corona, Cadeddu, Cargioli, Dordei, Giunti, arXiv: 2501.18550

low E Weinberg angle



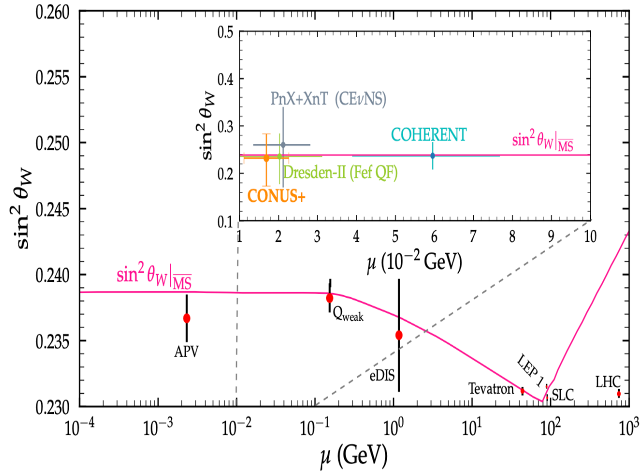
NSI operators



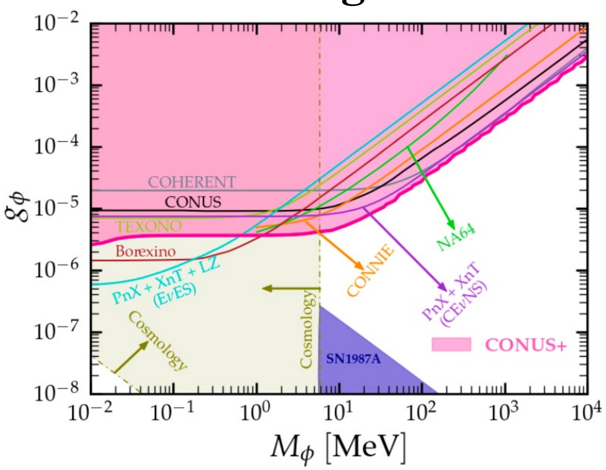


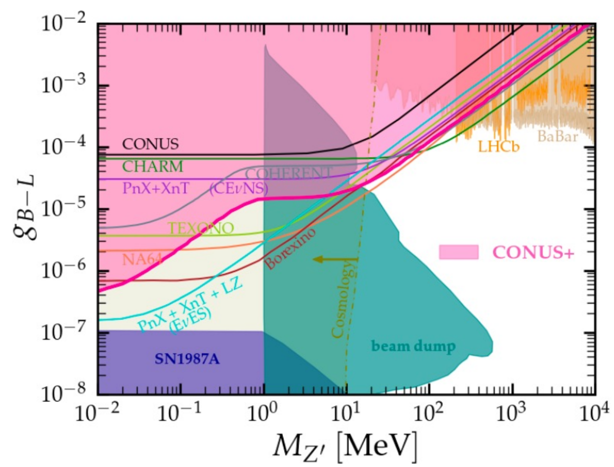
A. Chattaraj, et al., arXiv:2501.12441

low E Weinberg angle

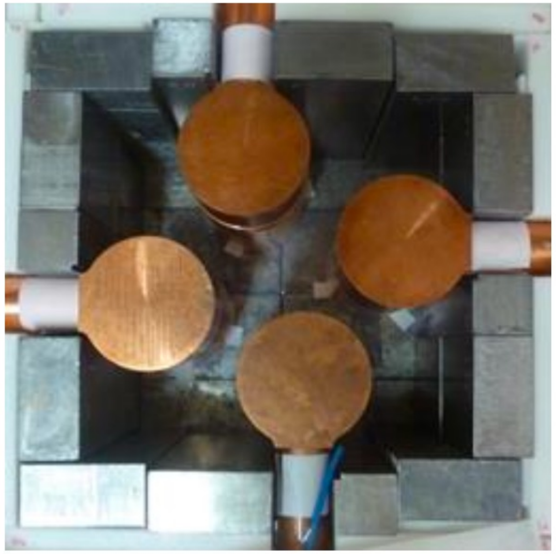


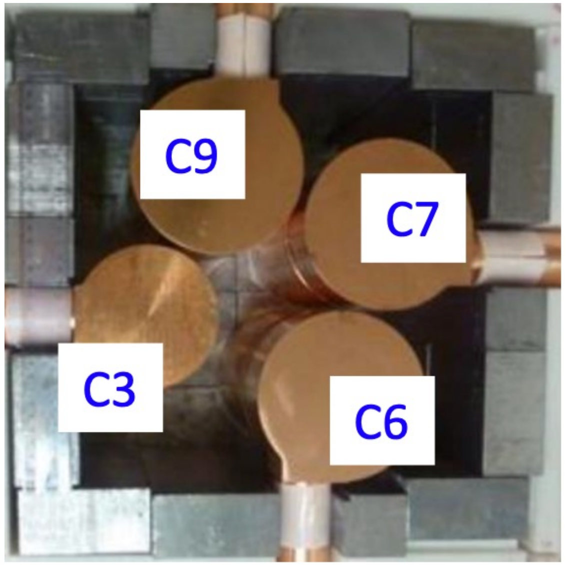
new light scalar or vector B-L mediator





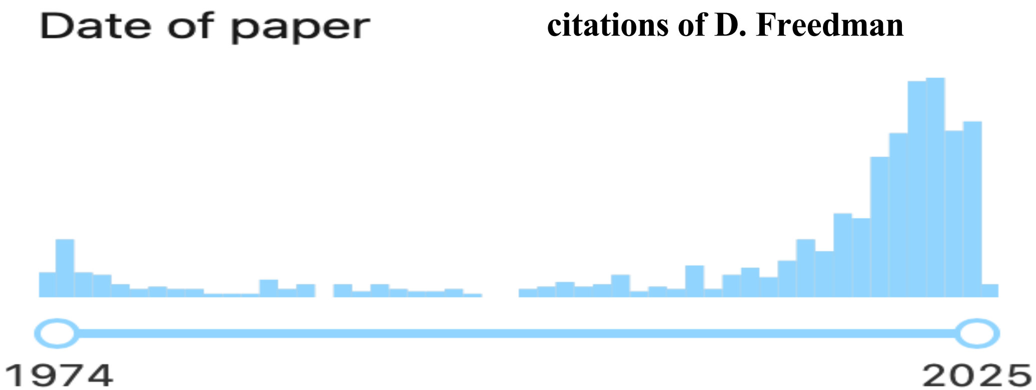
Short Term Outlook





- 3 new 2.4 kg PPC Ge detectors: C9, C7 and C6
  Crystal mass: 3 kg → 1 + 3*2.4 = 8.2 kg
- better cryocooler stability with new coolant
- slight background improvement in new detectors
- thresholds at least as low as in previous detectors
  ➔ installed in 11/2024
- commissioning finished → data taking has started
  ➔ expect significantly improved results O(1yr)

- **CEνNS is becoming a hot topic:**



Longer Term (few years) Prospects

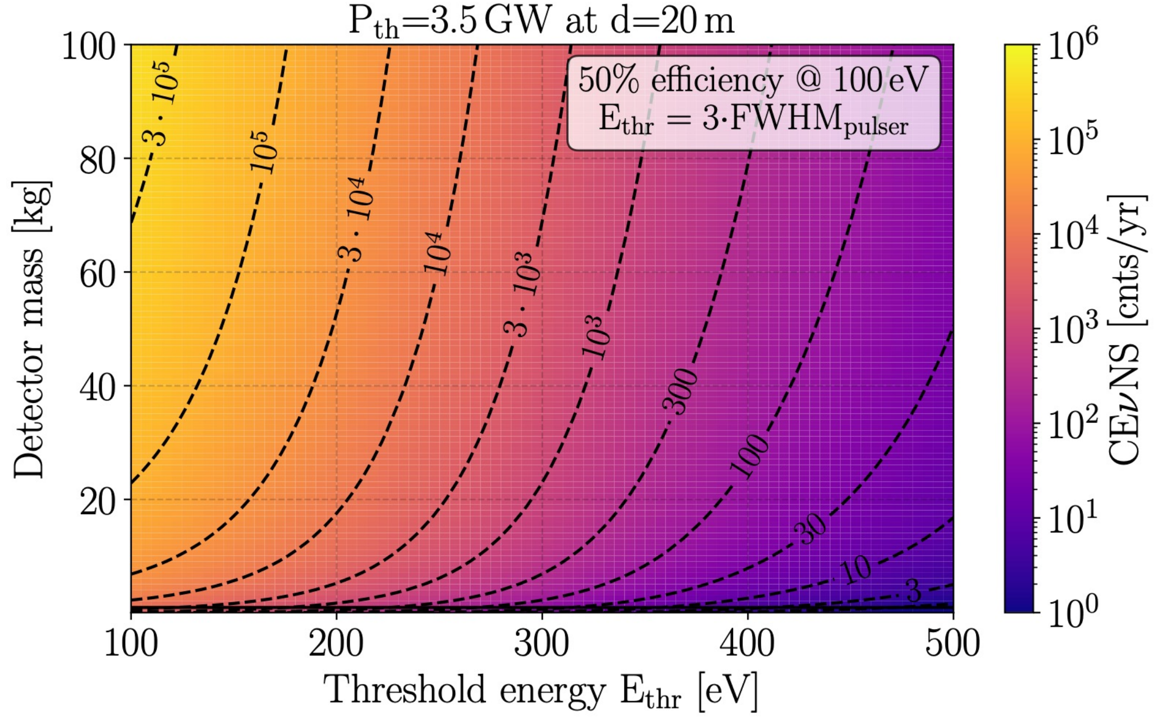
technology for moderate size high statistics experiments established:

- O(100kg) possible
- 100 eV threshold feasible

ML, T. Rink, M. Sen, JHEP 08 (2024) 171

➔ 500.000 events in 5y
➔ plans for CONUS100
with enlarged collaboration

- other technolgies @reactors



in addition:

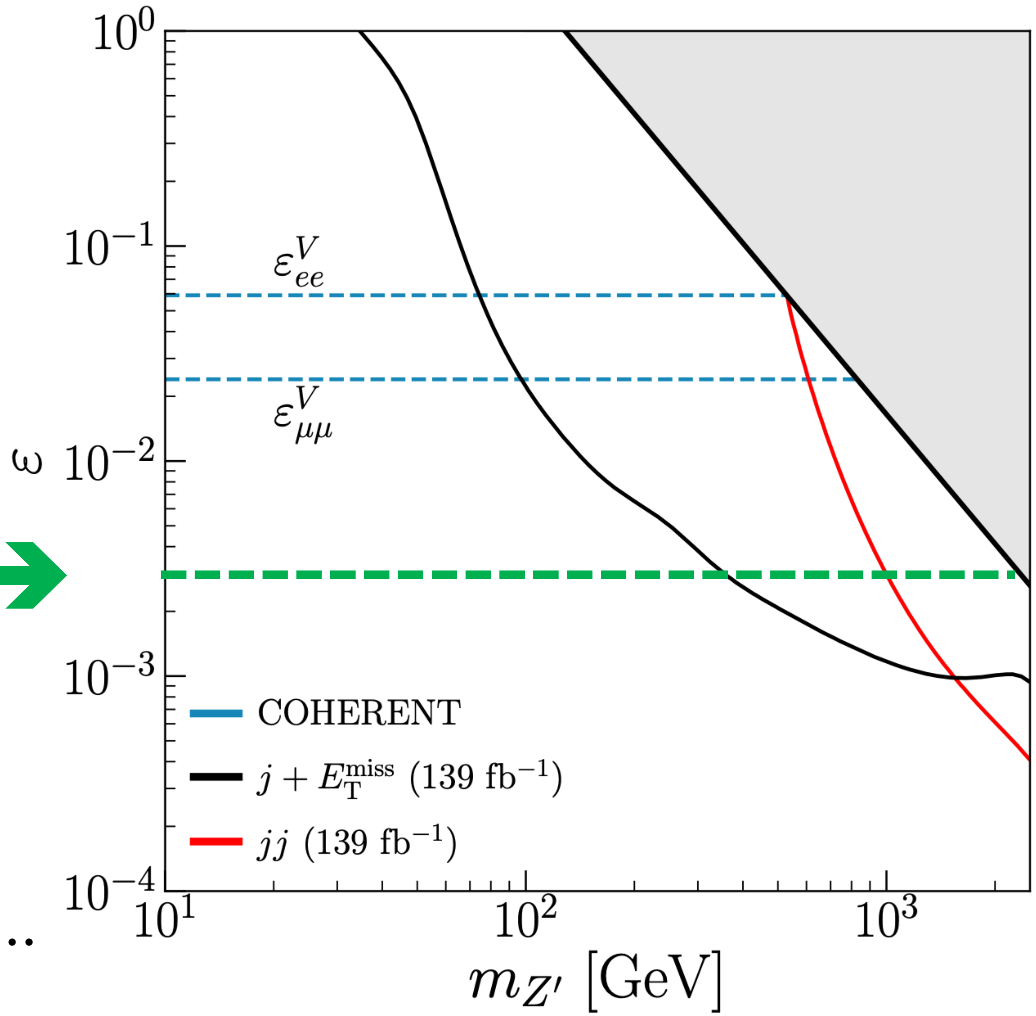
- upgrades of COHERENT
- next generation LXe dark matter (XLZD, ...)

➔ **precision CEνNS physics with excellent potential within a few years...**

One projection of the Phyiscs Implications

projected sensitivity
to a new Z' gauge boson

500k events →



"scoping" → know early what to expect (or not to expect) at a next big collider...

CONUS BSM Results: Run 1-4 @KBR

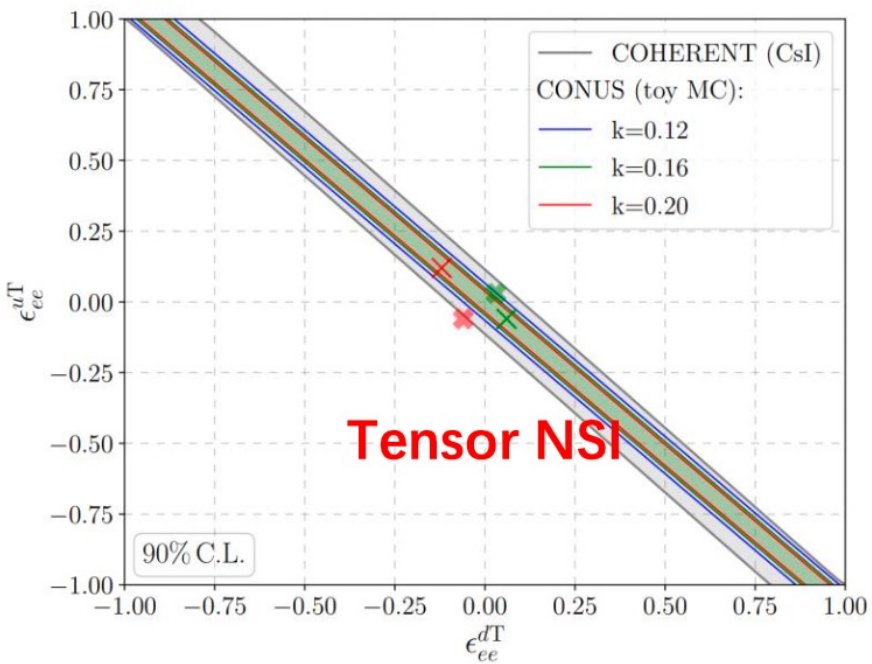
Fully coherent regime → any deviation form SM = new physics:

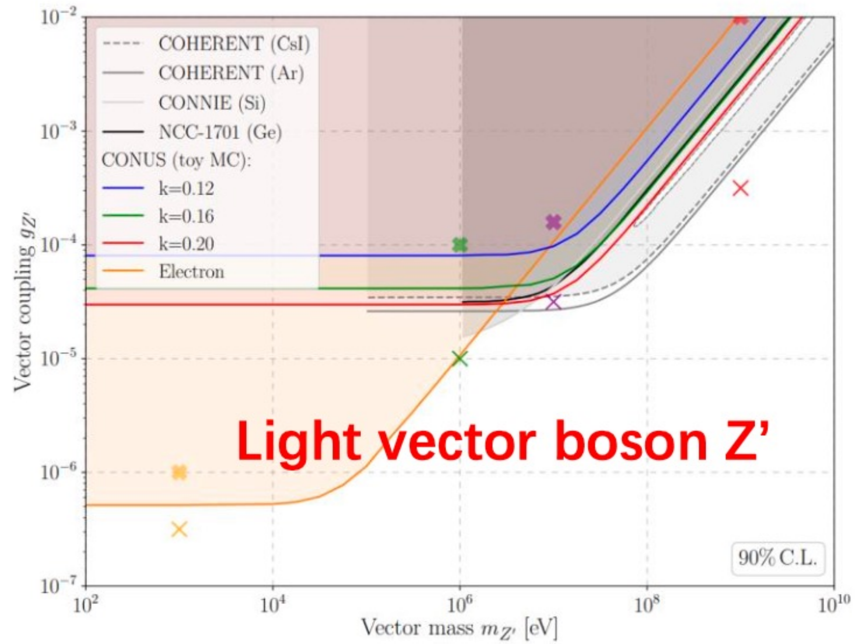
Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space

Light vector boson: limits the mass-coupling parameter space

Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$

Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$





JHEP 05 (2022) 085

Nuclear Structure with CEνNS

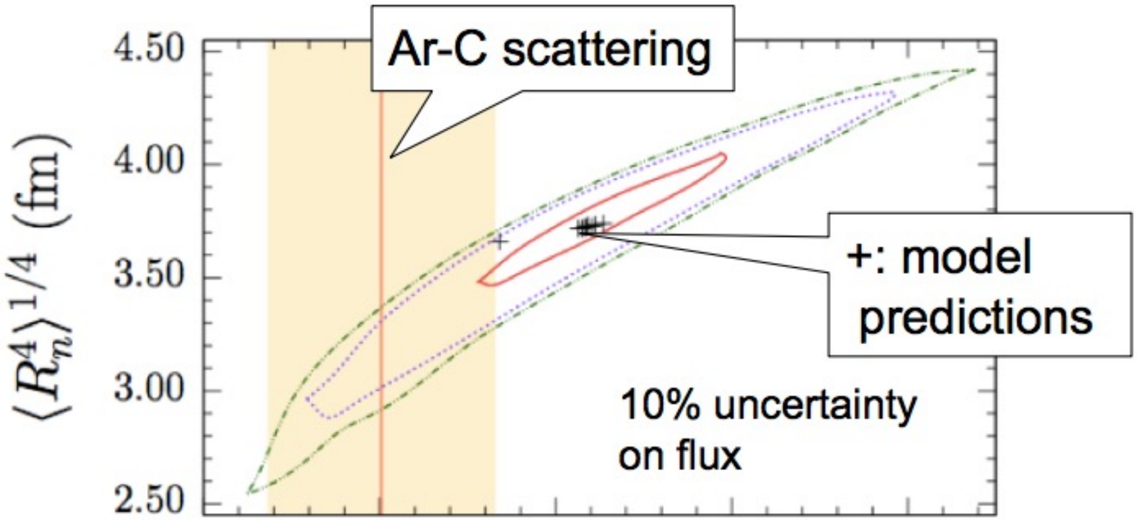
DAR sources partially coherence ←→ combine with reactor measurements

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right)\left[N F_N(q^2) - Q_W Z F_Z(q^2)\right]^2$$

Nuclear form factors $F_{N,Z}(q)$ ~ Fourier transforms of N & P densities
→ resolve nuclei (neutrons) in neutrino light

Fit recoil ***spectral shape*** to determine the F(Q²) moments
(requires very good energy resolution,good systematics control)

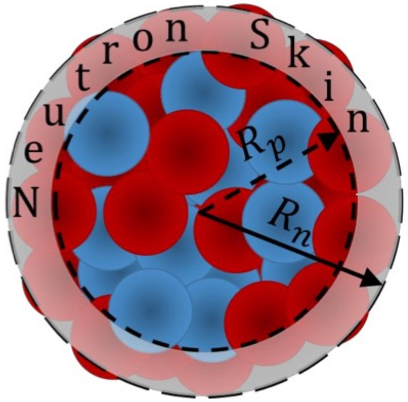
Example:
tonne-scale
experiment
at πDAR source



Nuclear Models and NSI's

Klein-Nystrand form factor

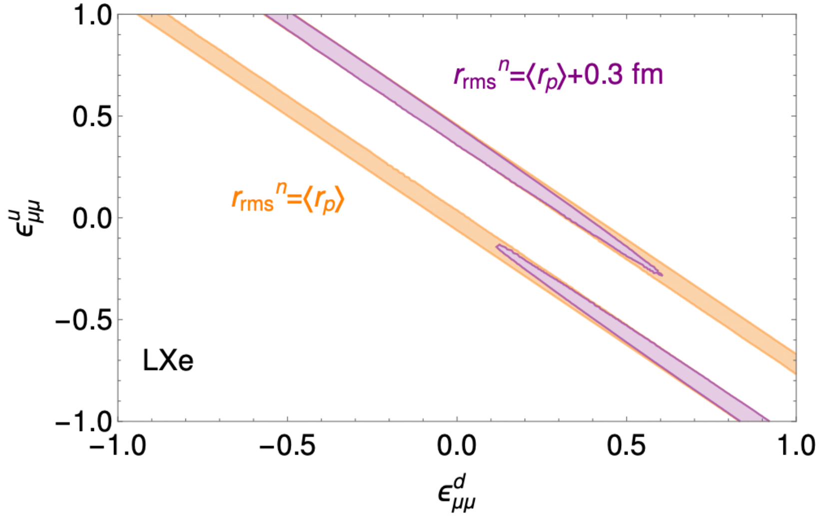
$$F_W(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2a_k^2}\right)$$

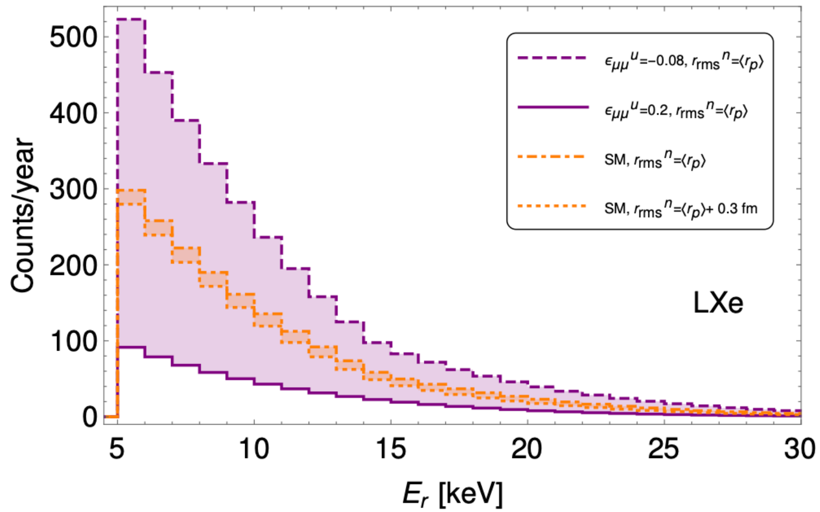


➔ **relies on a surface-diffuse distribution**
folding a short-range Yukawa potential with range a_k
over a hard sphere distribution with radius R_A

$$\langle r^2\rangle_{\mathrm{KN}} = \frac{3}{5}R_A^2 + 6a_k^2$$

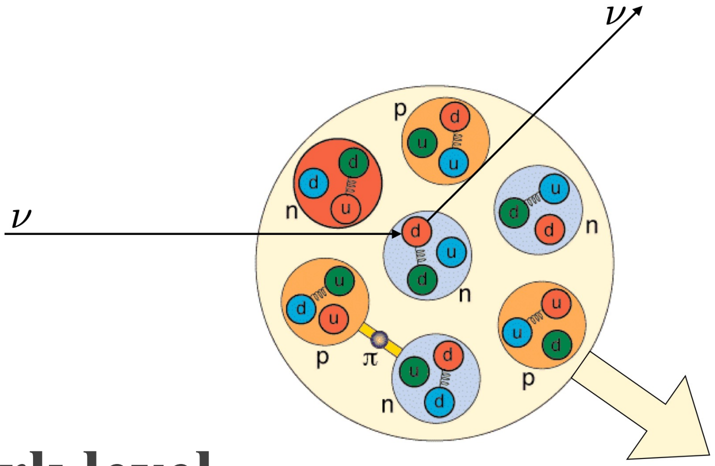
Aristizabal Sierra, Liao, Marfatia, JHEP 06 (2019) 141
allowed regions in the NSI case and for two choices of the rms neutron radius





On the more fundamental level...

Elementary reaction: neutrinos interact with quarks via Z exchange



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requirements:
absence of individual recoil
scattering in phase

- **Form factors and x-sections ←→ quark level**
  ←→ limitations of factorization σ ⊗ F(q^2)
- **CEνNS in QFT ➔ conceptually very interesting questions**
  see e.g. **Akhmedov, Arcadi, ML, Vogl, JHEP 1810 (2018) 045, arXiv:1806.10962**
  - role of the recoil of constituents in quantized picture
  - semi-classical factorization of QFT process into (cross-section) * F(q^2) ?
- **coherence length in QFT approach**
  Egorov, Volobuev: 1902.03602

What is CEvNS good for?

CEvNS relates to many interesting topics:

- Large cross sections → small neutrino detectors → faster progress, applications
- Clean SM predictions for cross sections → BSM sensitivity
- Sensitivity to neutrino magnetic moment and $\langle r_\nu^2 \rangle$ → BSM sensitivity
- Possibility to measure $\sin^2\theta_W$ at low energies → BSM sensitivity
- Masurements of neutron formfactors (nuclear structure) → unique
- Nuclear reactor monitoring (non-proliferation) → applications
- Precision flavor-independent neutrino flux measurements for oscillation experiments → synergy with other experiments
- Sterile neutrino searches → BSM
- Energy transport in supernovae → important for next SN
- SN neutrino detection → SNEWS, pointing, ...
- Input for dark matter direct detection (neutrino floor) → solar neutrinos
- dark matter physics → BSM

Summary

With 119 days of reactor ON and 19 days of reactor OFF data:

CONUS+ sees an excess of physics events in reactor ON data, which is consistent with:

• Standard model prediction of CEνNS cross section

• Lindhard model of quenching (verified by dedicated measurement)

• Precise knowledge about reactor ν flux, fissile fuel burning and thermal power

The excess is not:

• Due to a non-considered reactor-correlated background component

• A statistical fluctuation or a not considered artifact

Null hypothesis is rejected at 3.7σ

→ First observation of CEνNS on reactor anti-neutrinos!

→ First observation of CEνNS in the fully coherent regime (form factor 1)

→ next data release with more mass*exposure ...

- **Interesting and competitive BSM results and excellent future potential**
  - BSM physics
  - sources