Novel constraints on neutrino physics beyond the standard model from the CONUS experiment

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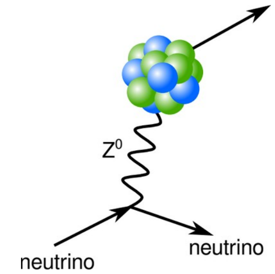
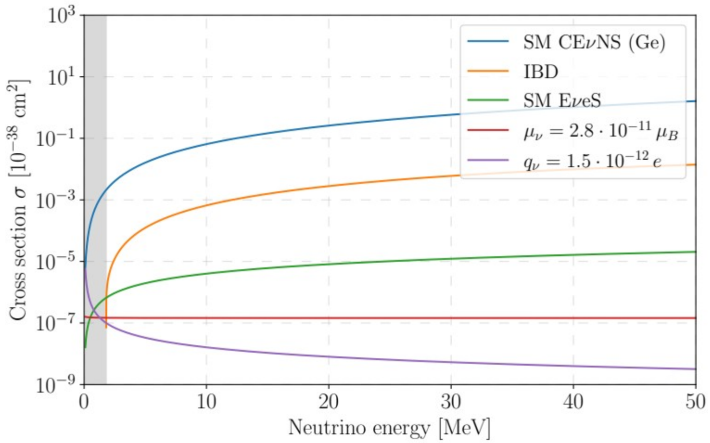
Max-Planck-Institut
für Kernphysik
Heidelberg

Coherent elastic neutrino-nucleus scattering (CEνNS)

CEνNS chronology:

- Daniel Freedman (1974): weak (SM) NC, flavor-blind, threshold-free!
- First detection with π-DAR ν's: COHERENT CsI (2017) & LAr (2021)
- Reactor experiments (2019 - ...): CONNIE (Si), CONUS (Ge), NCC-1701 (Ge), νGEN (Ge)
- Several running and future experiments: CCM (Ar), Miνer (Ge/Si), NEON (NaI[Tl]), ν-cleus ($CaWO_4$, Al_2O_3), RED100 (Xe), Ricochet (Ge/Zn), Texono (Ge)





[TR, 10.11588/heidok.00031274, 2022]

The Channel:

- Coherence = enhancement ~ N^2

Upper limit on neutrino energy:

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}[\text{MeV}]$$

- Observable = nuclear recoil energy T_A

$$\frac{d\sigma}{dT_A} = \frac{G_F^2 m_A}{4\pi}\left[(1-4\sin^2\theta_W)Z - N\right]^2\left(1-\frac{m_A T_A}{2E_\nu^2}\right)F^2(T_A)$$

→ detector material

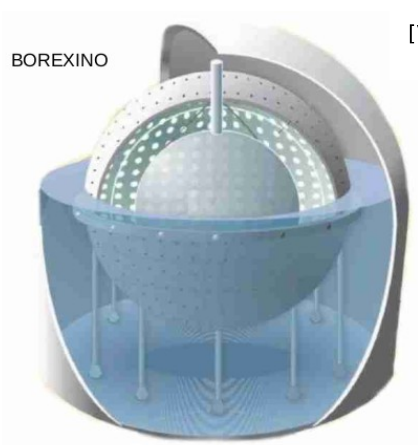
→ neutrino source

→ energy threshold / neutrino source

- Very low energy threshold needed:
  - $T_A \sim N^{-1}$
  - Quenching: T_A → "detectable" energy

Cross section σ
vs.
nuclear recoil T_A

[W. Maneschg, 2019]



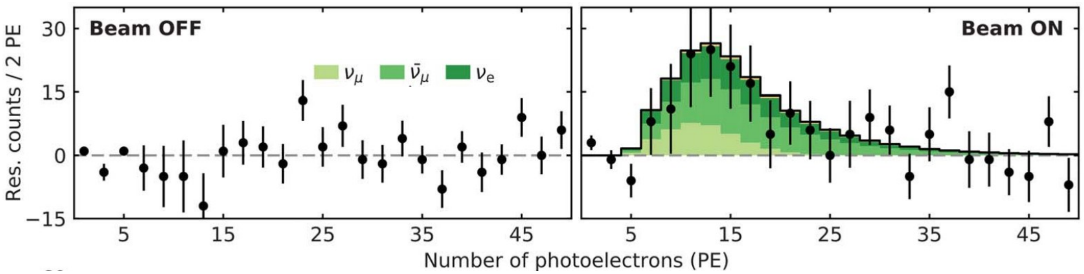
CEνNS observations and constraints

Observations:

COHERENT CsI[Na] (2017): 5 * 10[20] POT

obs. 134+-22, pred. 173+-48

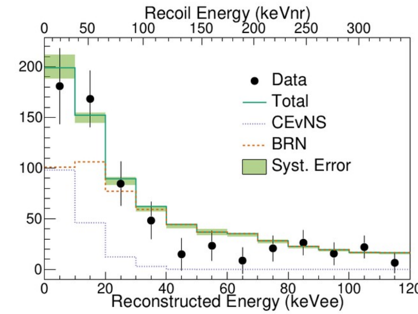
[Akimov et al., 10.1126/science.aao0990, 2017]

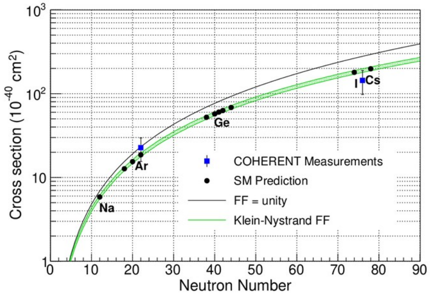


COHERENT LAr (2021): 13.7 * 10[22] POT

obs. 159+-43, pred. 128+-17

[Akimov et al., 10.1103/PhysRevLett.126.012002, 2021]





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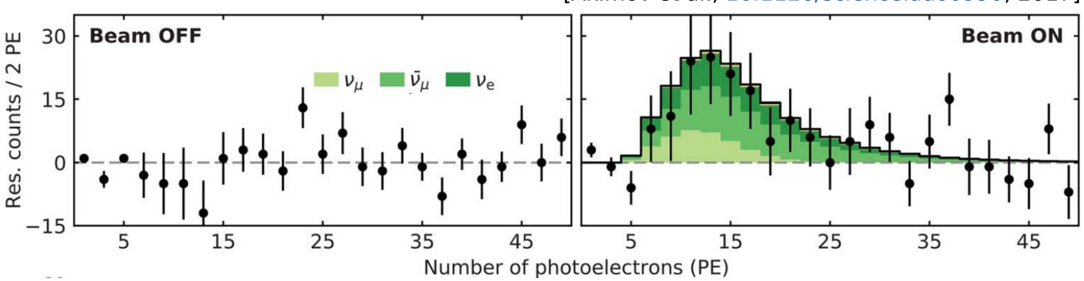

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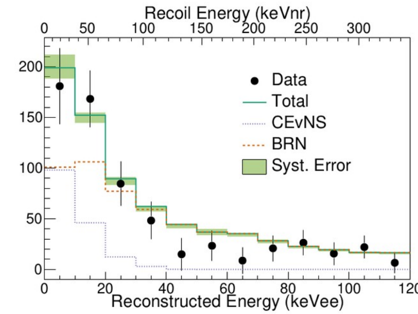
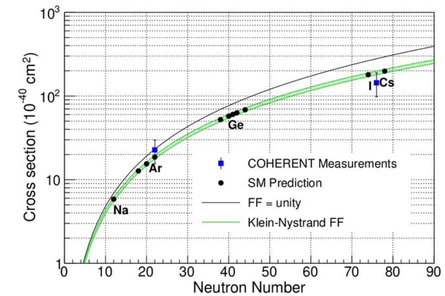
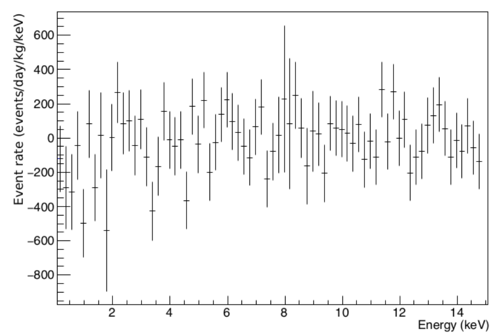




Limits:

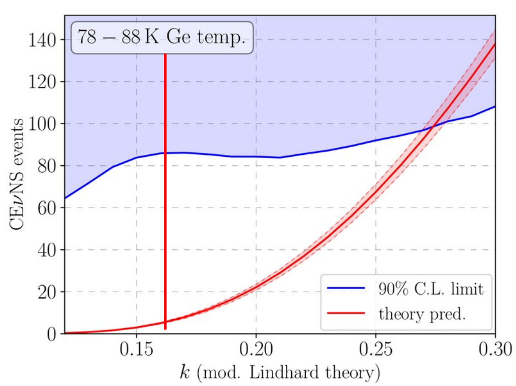
CONNIE Si (2019):
*R_{NP}<40*R_{SM} @ 95% C.L.*
2.1kg*d ON + 1.6kg*d OFF

[Aguilar-Arevalo et al., 10.1103/PhysRevD.100.092005, 2019]



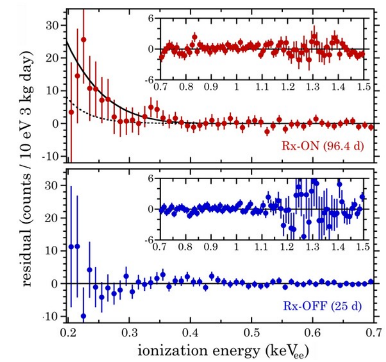
CONUS Ge (2020):
R_{SM}<0.4/kg/d @ 90% C.L.
(x17 lower then prediction)
249kg*d ON + 59kg*OFF

[Bonet et al., 10.1103/PhysRevLett.126.041804, 2020]



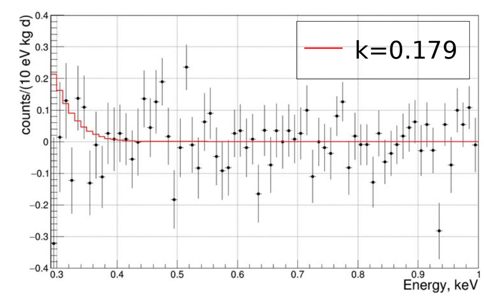
"Suggestive evidence …" [Colaresi et al., arXiv:2202.09672, 2022]

NCC-1701 Ge:
289kg*d ON + 75kg*d OFF



νGEN Ge (2022):
no excess,
k<0.177 @ 90% C.L.
133kg*d ON + 66kg*d OFF

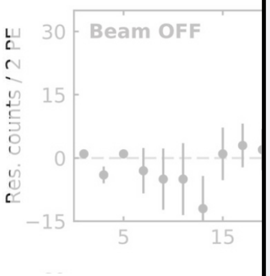
[Alekseev et al., arXiv:2205.04305, 2022]



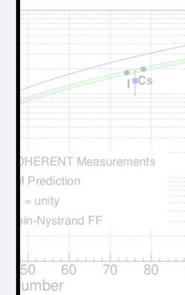
CEνNS observations and constraints

Observations:

COHERENT C...
obs. 134+-2...



...evLett.126.012002,



Coherent Neutrino Nucleus Scattering as a Probe of the Weak Neutral Current

Daniel Z. Freedman (Fermilab and SUNY, Stony Brook)

Oct, 1973

11 pages
Published in: *Phys.Rev.D* 9 (1974) 1389-1392
DOI: 10.1103/PhysRevD.9.1389
Report number: NAL-PUB-73-76-THY, FERMILAB-PUB-73-076-T
View in: OSTI Information Bridge Server, ADS Abstract Service

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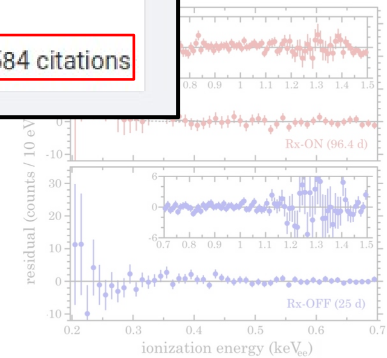

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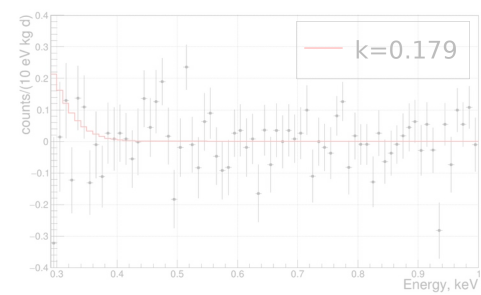
...305, 2022]



Experimental requirements at reactor site

Goal: Detecting CEνNS with high accuracy!

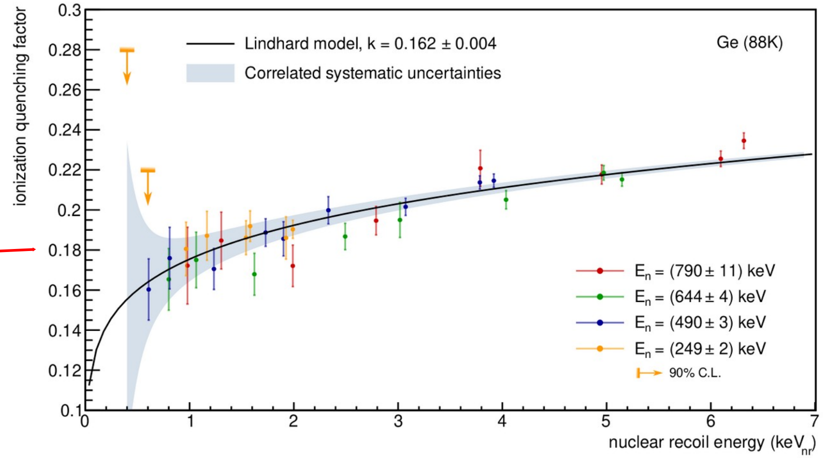
Several obstacles to overcome:

1) Beat $1/R^2$ factor
   → strong (= commercial) power plant, close to reactor core

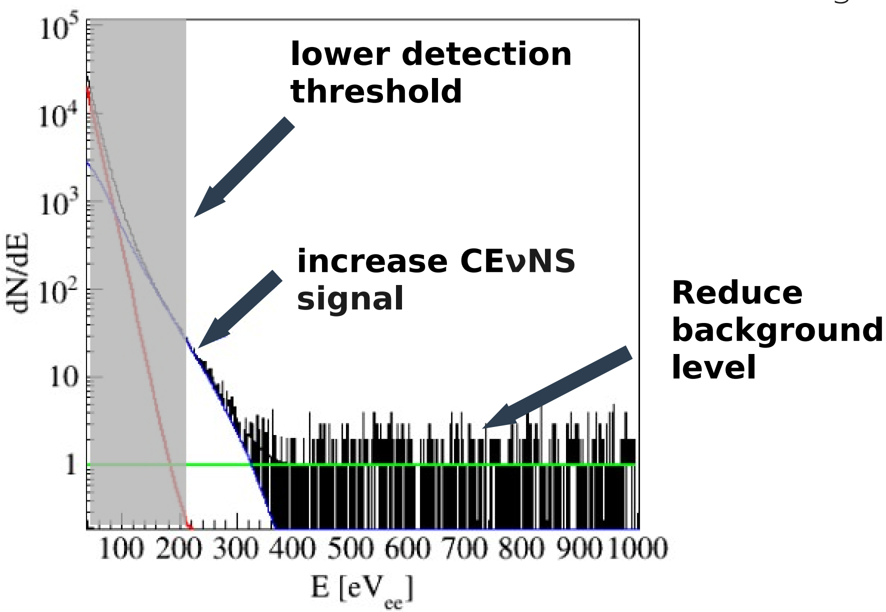
2) Compensate quenching (E_{recoil} → E_{ion})
   → lowest possible detection threshold

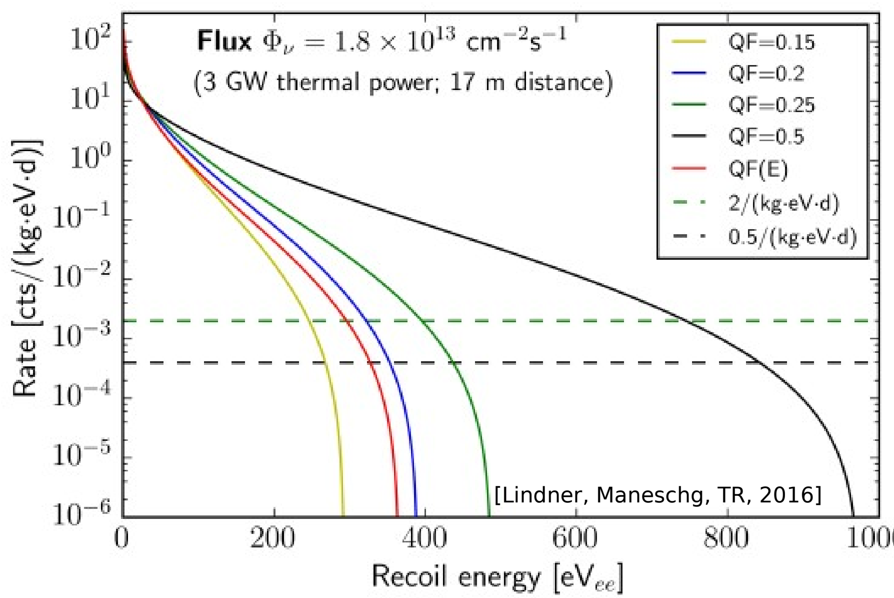
E_ν:	10MeV
max E_{Recoil}:	3keV
maxE_{ion}:	~600eV

[Bonhomme et al., arXiv:2202.03754, 2022]



3) Low background outside lab condition
   → moderate overburden & limited shielding capacities





[Lindner, Maneschg, TR, 2016]

The CONUS Collaboration

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Janina Hakenmüller, Janine Hempfling, Gerd Heusser, Thomas Hugle, Manfred Lindner,
Werner Maneschg, Thomas Rink, Edgar Sanchez Garcia, Josef Stauber, Herbert Strecker, Roland Wink

Max-Planck-Institut für Kernphysik Heidelberg

CONUS

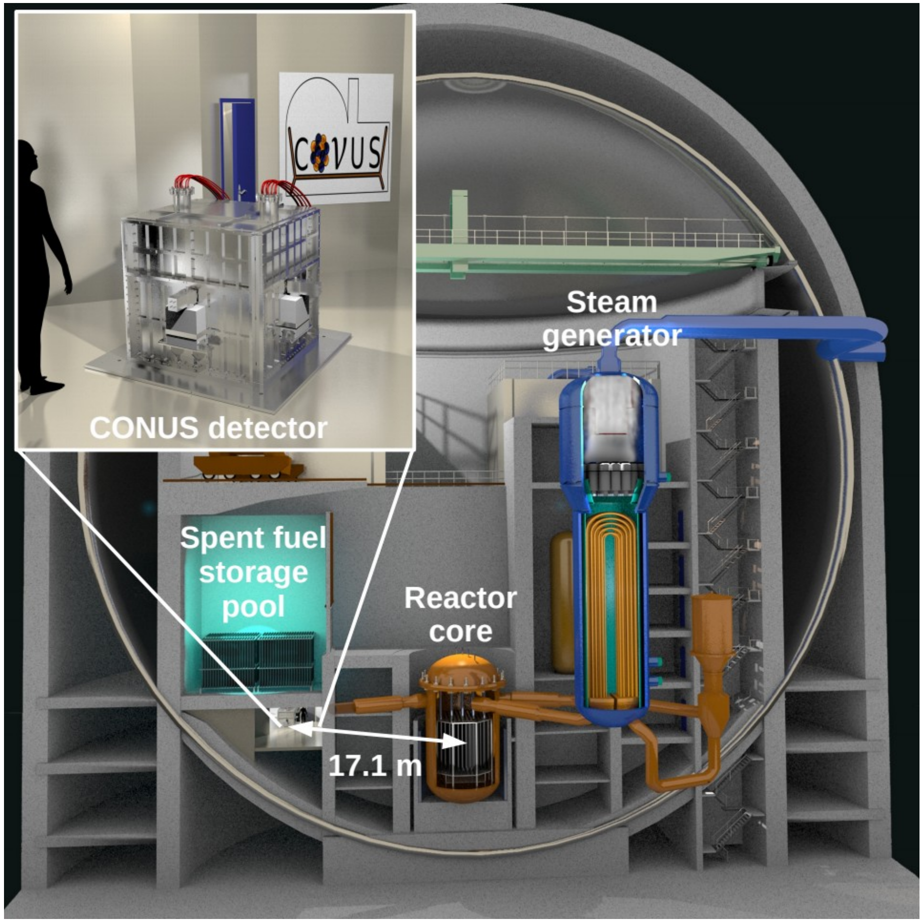
Preussen Elektra

The CONUS experiment

Reactor: Brokdorf nuclear power plant

- @17m to 3.9GW$_{th}$: inside reactor containment!
- ν flux: 2.3 * 10^{13}/cm²/s
- Access to reactor information: fuel composition, thermal power

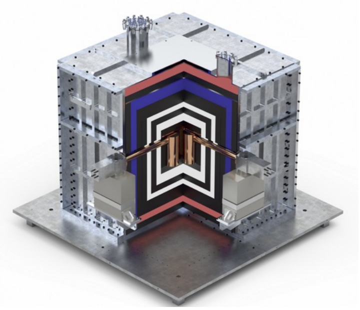
[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



Background & shield

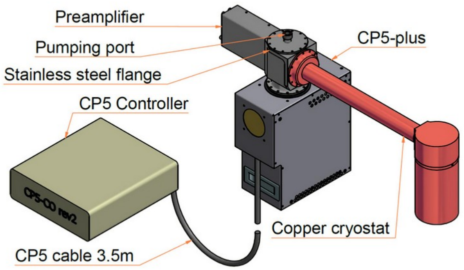
[Bonet et al., arXiv:2112.09585, 2021]

- Overburden: 10-45 m w.e.
- Active and passive components: bkg reduction x10^3-10^4
- Critical reactor-correlated bkg under control!
- Background level O(10)/keV/d/kg



Detectors:

- HPGe PPC: 4*1kg
- E^{thr}~300eV → T_A^{thr}~2keV$_{nr}$
- Low bkg design
- Electrical cryocooler



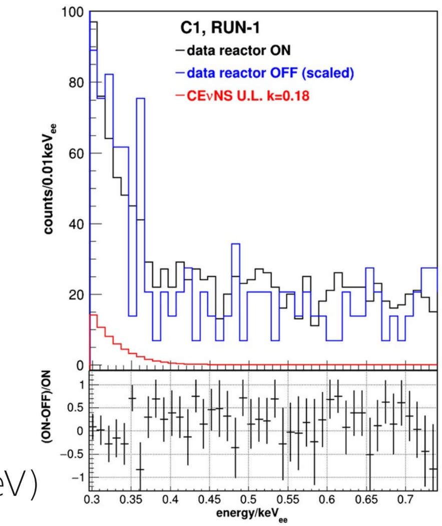
[Bonet et al., 10.1140/epjc/s10052-021-09038-3, 2021]

Close to reactor core:
lab conditions not easily realized
→ site monitoring crucial!

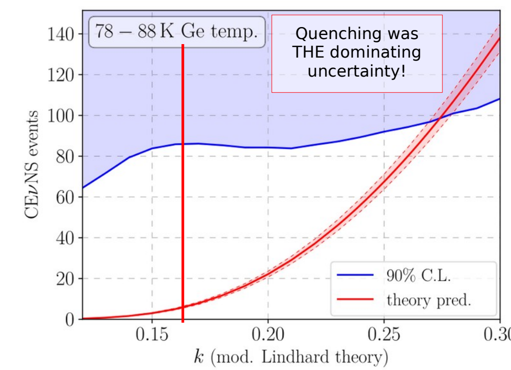
Data analyses of experimental data

(Binned log-) Likelihood function:

- ON and OFF data are fitted together:
  $$\log \mathcal{L} = \log \mathcal{L}_{\text{ON}} + \log \mathcal{L}_{\text{OFF}} + \text{pull terms}$$
  with $\log \mathcal{L}_{\text{ON}}(s, b, \Theta_{\text{thr}_1}, \Theta_{\text{thr}_2}, \Theta_{\text{rea}}, \Theta_{\text{det}}, \Theta_{\Delta\text{E}})$
  $\log \mathcal{L}_{\text{OFF}}(b, \Theta_{\text{thr}_1}, \Theta_{\text{thr}_2}, \Theta_{\text{det}}, \Theta_{\Delta\text{E}})$
- Parameter list:
  - s: signal strength (free), b: MC normalisation (free)
  - $\Theta_{\text{thr1/2}}$: electronic noise (free)
  - Θ_{rea} : reactor neutrino flux (~3%)
  - Θ_{det} : detector/DAQ (1-5%), $\Theta_{\Delta\text{E}}$: energy scale (10-20 eV)
- Compare signal to background-only hypothesis: **LH ratio**



CEνNS (SM):
248.7 kg d (ON)
58.8 kg d (OFF)



[Bonet et al., 10.1103/PhysRevLett.126.041804, 2020]

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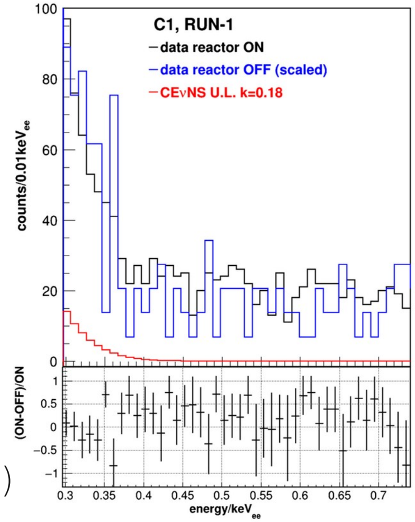

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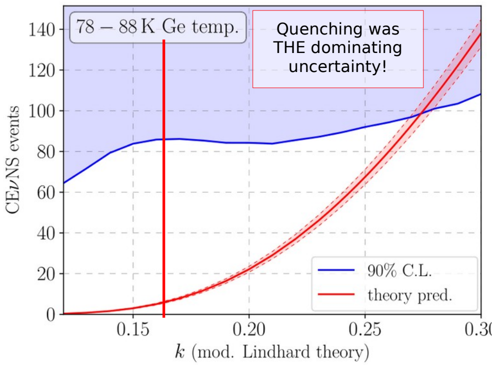

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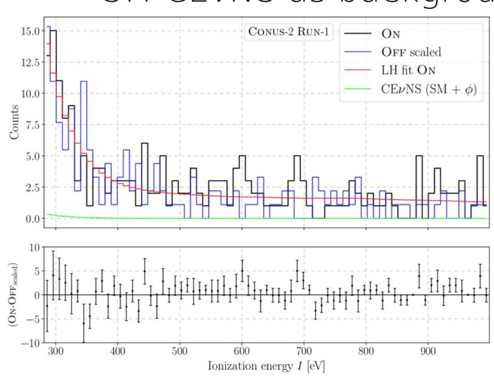
BSM investigations:

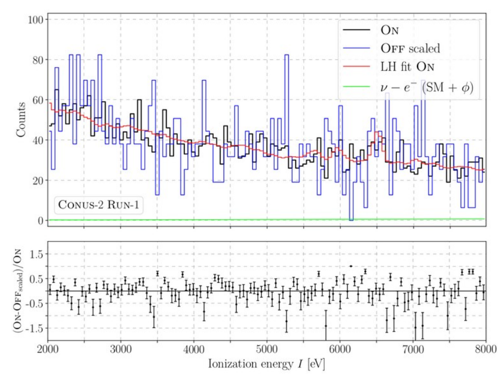
- Extend existing LH with BSM contributions
→ SM CEνNS as background



[Bonet et al., 10.1007/JHEP 05(2022)085, 2022]

CEνNS (BSM): 208.8 kg d (ON), 37.6 kg d (OFF)

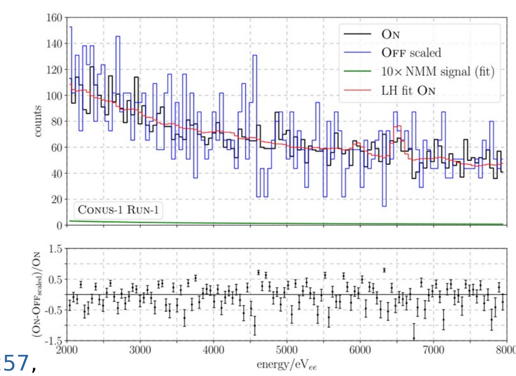
- Add. systematics within [2,8]keV
→ 5% shape uncertainty on bkg



[Bonet et al., arXiv:2201.12257, 2022]

EveS (BSM): 648.5 kg d (ON), 93.5 kg d (OFF)

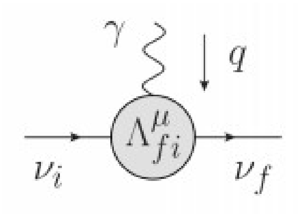
- BSM limits in terms of quenching factor!



EveS (νMM): 688.9 kg d (ON), 131.5 kg d (OFF)

Loop-induced electromagnetic properties:

[Giunti & Studenikin, 10.1103/RevModPhys.87.531, 2015]



→ neutrino charge (radius), electric and magnetic dipole moment, anapole moment
→ characteristic dependence on neutrino's fermionic nature
→ test for BSM physics!

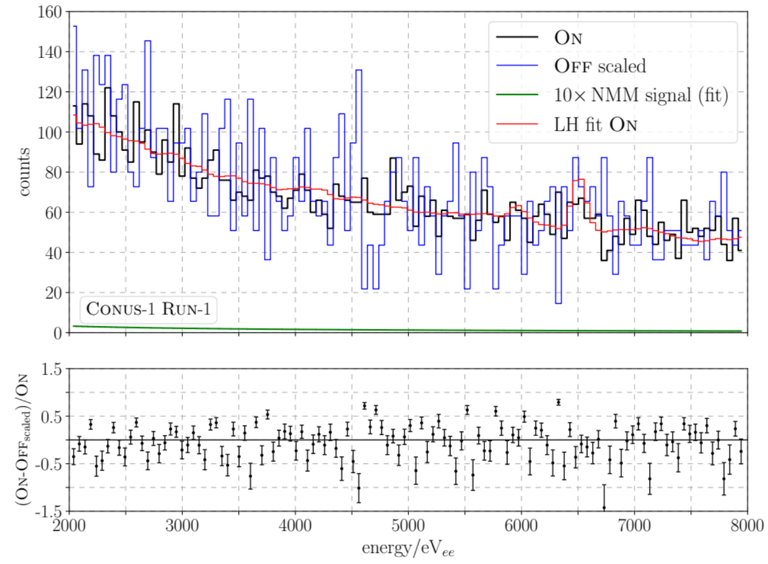
νMM from EνeS @ 2-8 keV:

$$\left(\frac{d\sigma}{dT}\right)^{e^-}_{\mu_\nu} = \frac{\pi\alpha^2_{em}}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2$$

- Model-independent bounds: [Bell et al., 10.1016/j.physletb.2006.09.055, 2006]

$$\mu^{\mathrm{D}}_{ll} \lesssim 3\cdot 10^{-15}\mu_B\left(\frac{m_l}{\mathrm{eV}}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \qquad \mu^{\mathrm{M}}_{ll'} \lesssim 4\cdot 10^{-9}\mu_B\left(\frac{M^{\mathrm{M}}_{ll'}}{\mathrm{eV}}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2\left|\frac{m_\tau^2}{m_l^2 - m_{l'}^2}\right|$$

- Extended CONUS data sets: $\mu_{\nu_e} < 7.5\cdot 10^{-11}\,\mu_B$ (90% C.L.)



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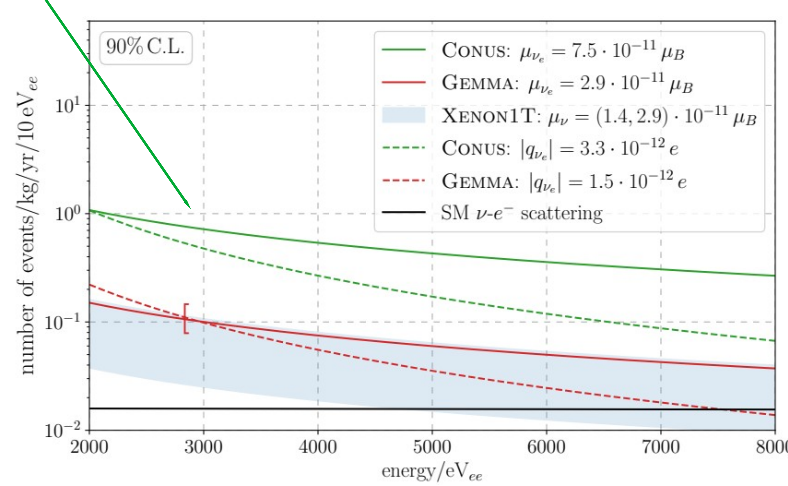

Neutrino magnetic moment & millicharge

Loop-induced electromagnetic properties:

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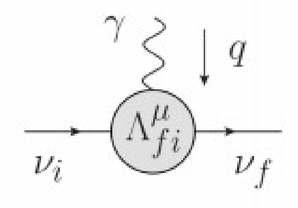

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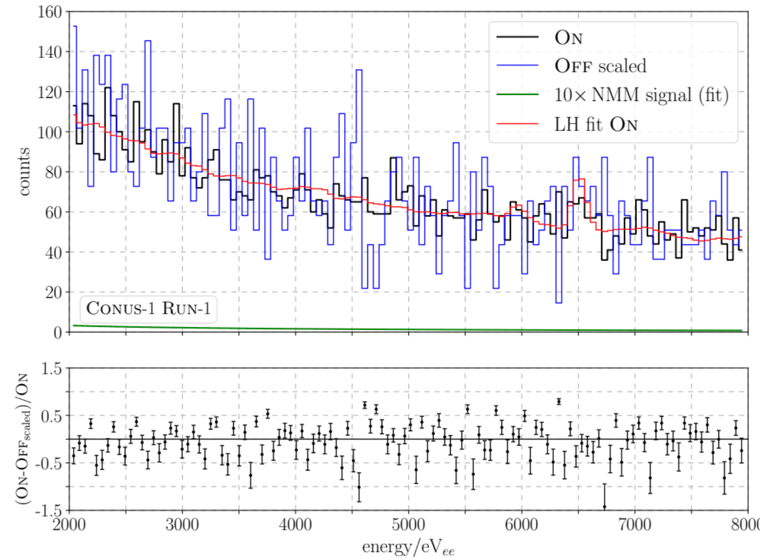

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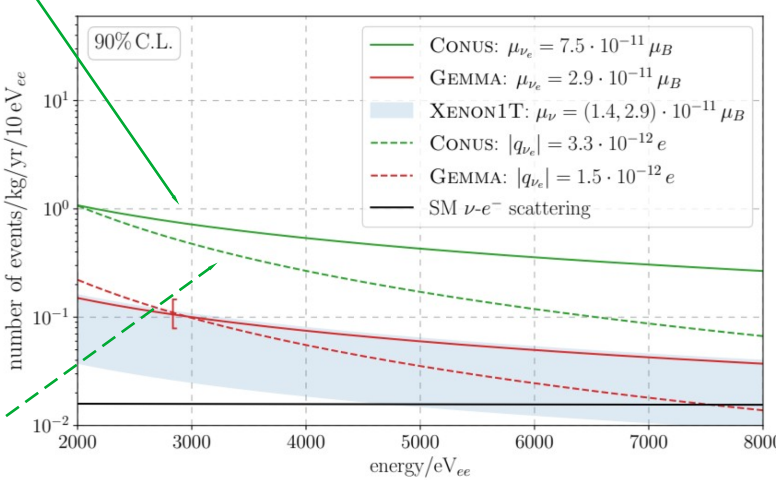
νMC limit from νMM limit:

[Giunti & Studenikin, 10.1103/RevModPhys.87.531, 2015]

$$\left(\frac{d\sigma}{dT}\right)^{e^-}_{q_\nu} \simeq \frac{2\pi\alpha^2_{\mathrm{em}}}{m_e T^2}\left(\frac{q_{\nu_e}}{e}\right)^2 \qquad \frac{(d\sigma/dT)^{e^-}_q}{(d\sigma/dT)^{e^-}_\mu} \simeq \frac{2m_e}{T}\left(\frac{(q_{\nu_e}/e)}{(\mu_{\nu_e}/\mu_B)}\right)^2 \leq 1$$

- νMC has different event shape!
- Assume null result within [2,8] keV: convert νMM into νMC

$$|q_{\nu_e}| < 3.3\cdot 10^{-12}\ e\ (90\%\ \mathrm{C.L.})$$



Non-standard interactions (NSIs)

Aim: Test for new (high-scale) neutrino interactions

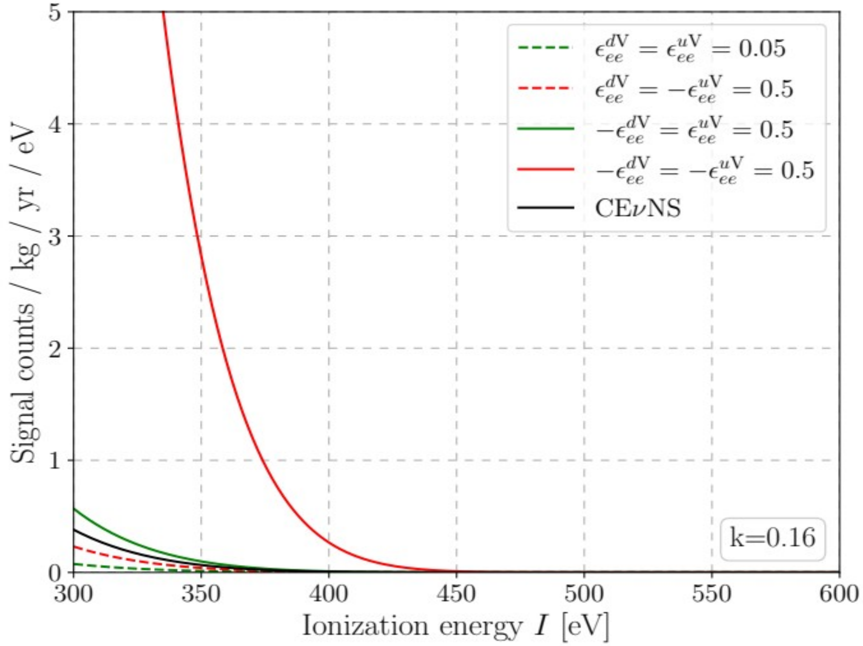
- Vector-type Interaction
  → New feature: destructive interference!
- Modified weak nuclear charge
- New couplings ε partially degenerate
  → different isotopes/targets at different sources

[Barranco et al., 10.1088/1126-6708/2005/12/021, 2005]

$$\mathcal{O}^{qV}_{\alpha\beta} = (\bar{\nu_\alpha}\gamma^\mu P_L \nu_\beta)\left(\bar{q}\gamma_\mu P_{L/R} q\right) + \text{h.c.}$$

$$\begin{aligned}\mathcal{Q}^V_{NSI} &= \left(2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha} + g^V_p\right) Z + \left(\epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha} + g^V_n\right) N \\ &+ \sum_{\alpha\neq\beta}\left[\left(2\epsilon^{uV}_{\alpha\beta} + \epsilon^{dV}_{\alpha\beta}\right) Z + \left(\epsilon^{uV}_{\alpha\beta} + 2\epsilon^{dV}_{\alpha\beta}\right) N\right]\end{aligned}$$

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



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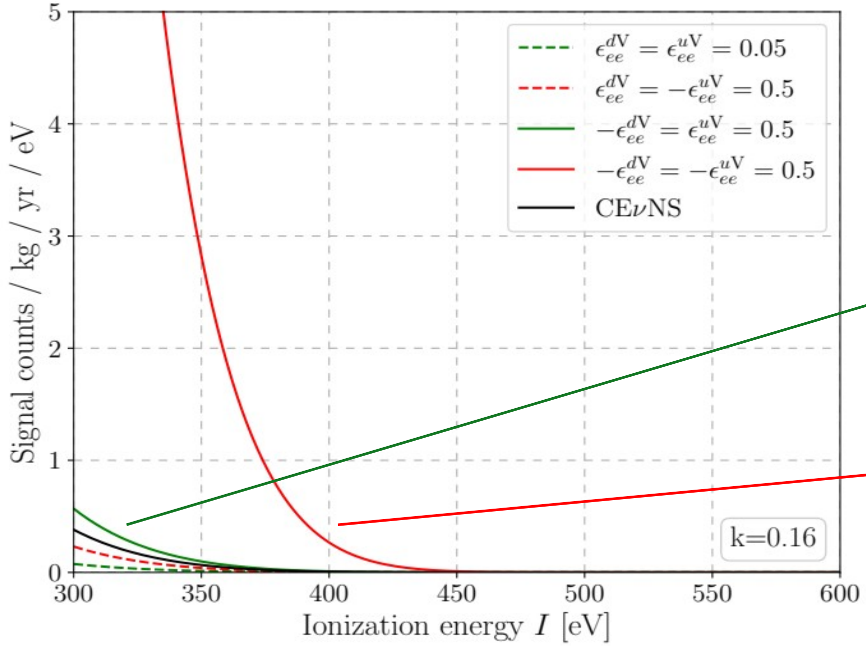
$$\mathcal{O}_{\alpha\beta}^{qV} = \left(\bar{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{q}\gamma_\mu P_{L/R} q\right) + \text{h.c.}$$

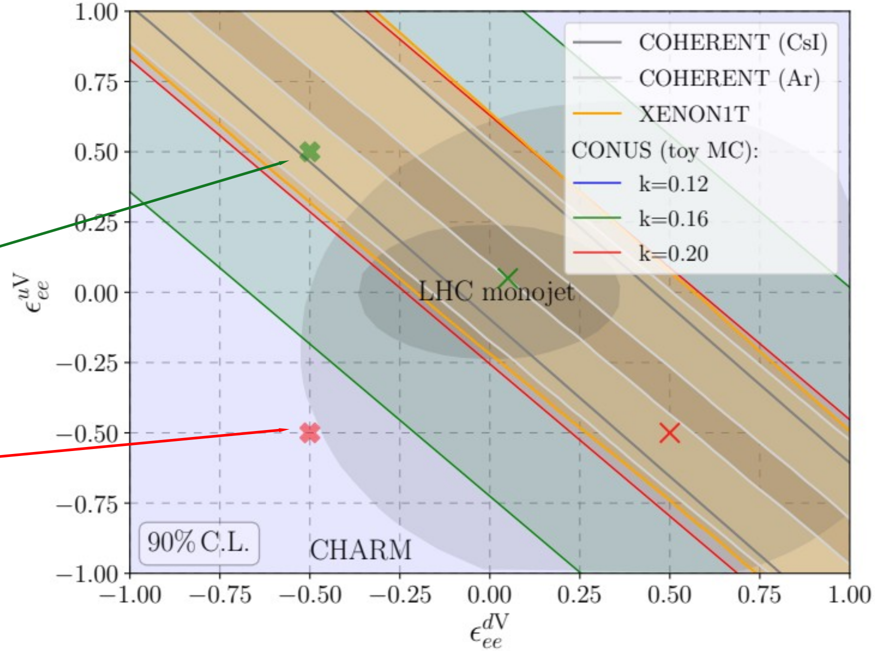
- Modified weak nuclear charge

$$\mathcal{Q}_{NSI}^{V} = \left(2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV} + g_p^V\right) Z + \left(\epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV} + g_n^V\right) N + \sum_{\alpha\neq\beta}\left[\left(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{dV}\right) Z + \left(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV}\right) N\right]$$

- New couplings ε partially degenerate
  → different isotopes/targets at different sources

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]





If sub-percent sensitivity on ε
→ probing **TeV-scale** physics!

[Lindner et al., 10.1007/JHEP03(2017)097, 2017]

$$\epsilon_{\alpha\beta}^{qX} \propto \frac{m_W^2}{\Lambda_{NP}^2}$$

Λ_{NP}>100 GeV (CONUS, k=0.16)

Λ_{NP}>240 GeV (COHERENT, LAr)

Non-standard interactions (NSIs)

Aim: Test for new (high-scale) neutrino interactions

[Barranco et al., 10.1142/S0217751X12501473, 2012]

- Tensor-type operator → exotic neutral currents!

$$\mathcal{O}^{qT}_{\alpha\beta} = (\bar{\nu}_\alpha\, \sigma^{\mu\nu} \nu_\beta)\,(\bar{q}\,\sigma_{\mu\nu}\, q) + \text{h.c.}$$

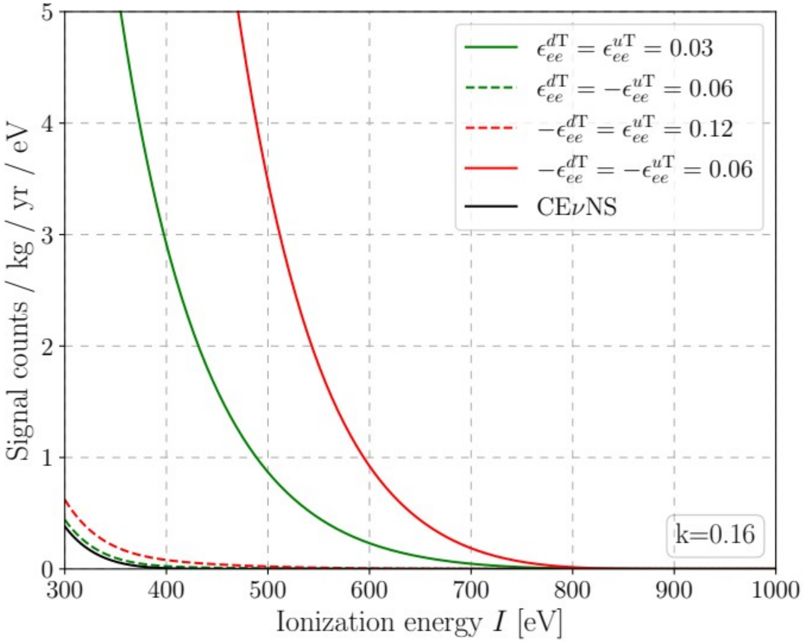
$$\mathcal{Q}^{T}_{NSI} = \left(2\epsilon^{uT}_{\alpha\beta} + \epsilon^{dT}_{\alpha\beta}\right) Z + \left(\epsilon^{uT}_{\alpha\beta} + 2\epsilon^{dT}_{\alpha\beta}\right) N$$

- Interaction with higher kinematic cut-off

$$\left(\frac{d\sigma}{dT_N}\right)^T_{NSI} = \frac{G_F^2 M}{\pi} \left(\mathcal{Q}^T_{NSI}\right)^2 \left(1 - \frac{M T_N}{4E_\nu^2}\right)$$

→ quenching less relevant, overall background crucial

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



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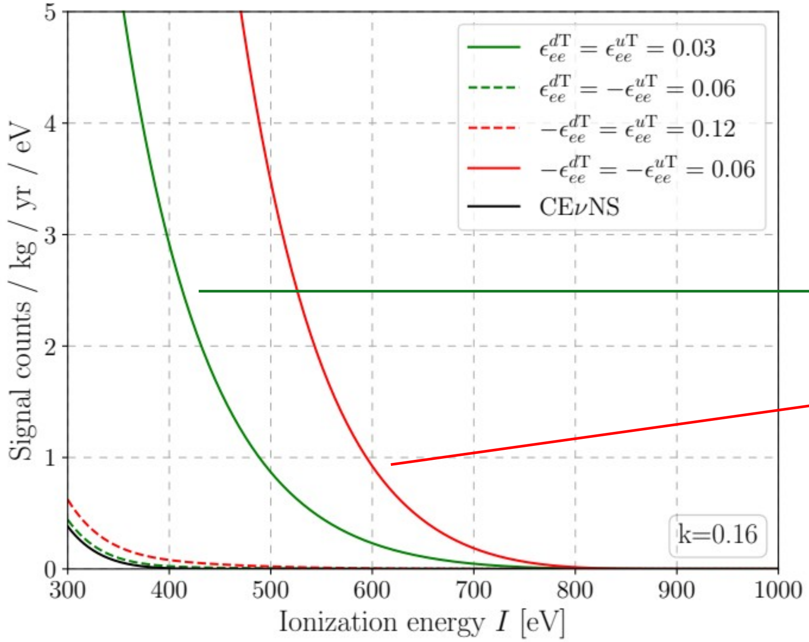
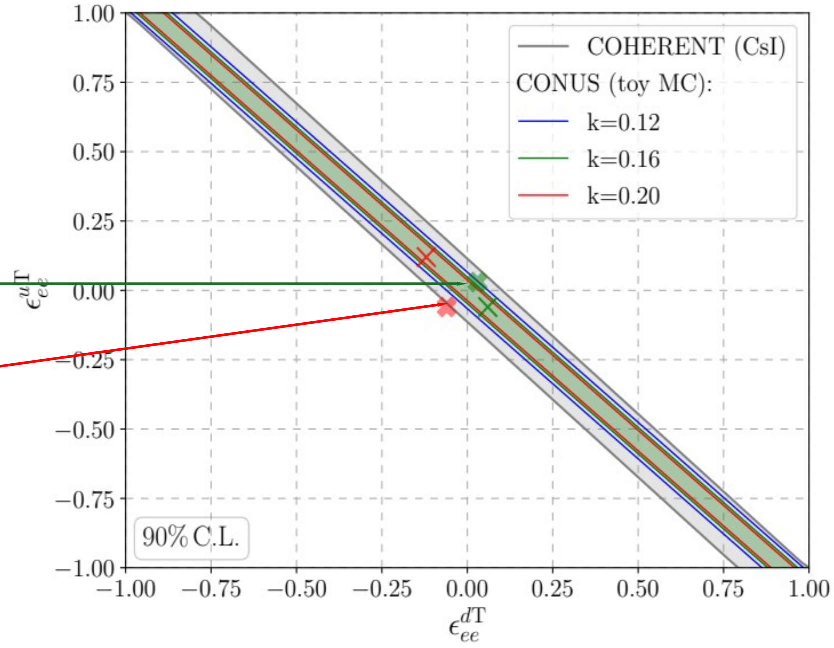


[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



→ CONUS data sets allow for competitive bounds with COHERENT!

Λ_{NP} >360 GeV (CONUS, k=0.16)

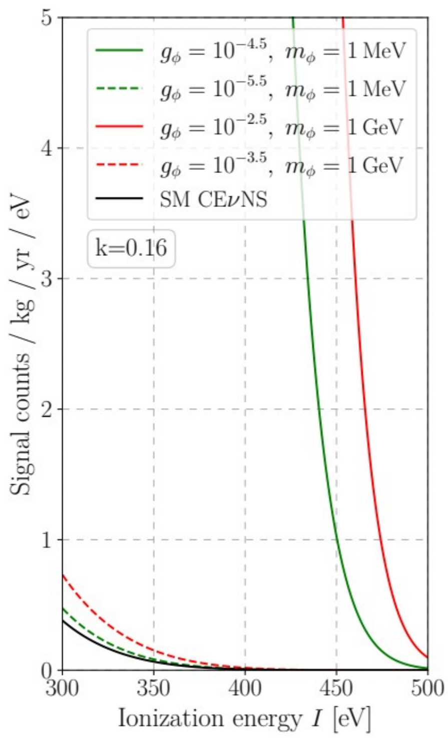
Simplified models: light scalar mediator

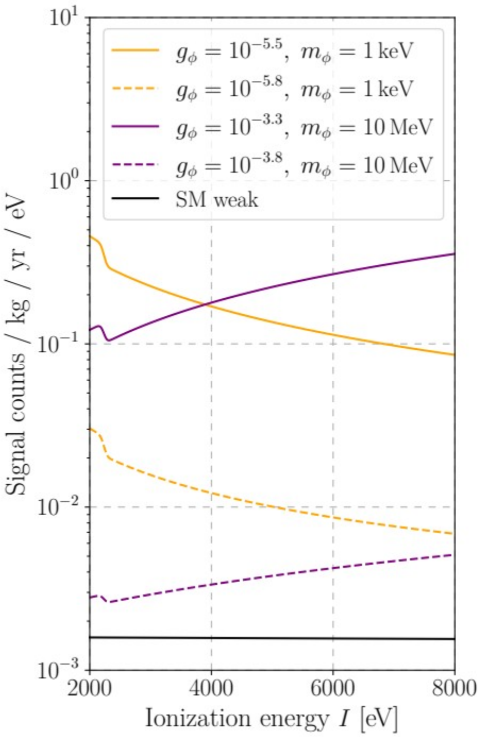
Aim: Test specific but simple mediator models that contribute to CEνNS / EνeS

[Cerdeño et al., 10.1007/JHEP05(2016)118, 2016]

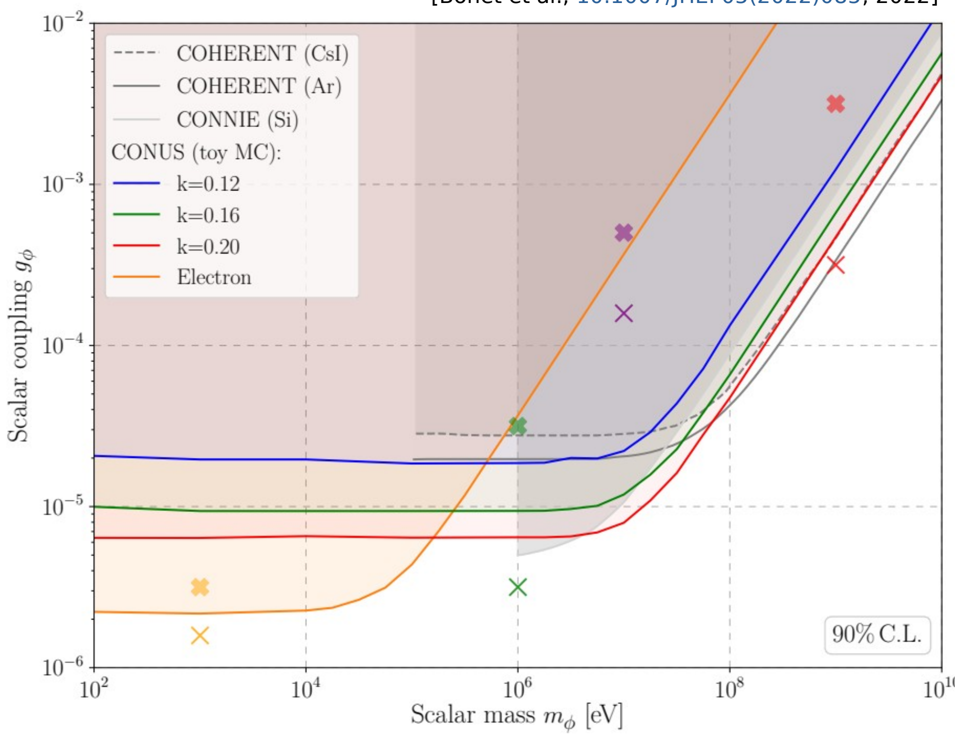
$$\mathcal{L}_\phi = \phi\left(g_\phi^{q\mathrm{S}}\bar{q}q + g_\phi^{e\mathrm{S}}\bar{e}e + g_\phi^{\nu\mathrm{S}}\bar{\nu}_R\nu_L + \mathrm{h.c.}\right) - \frac{1}{2}m_\phi^2\phi^2$$

- Assume: universal coupling to quarks / neutrinos: $(m_\phi,\, g_\phi)$
- Spectral distortions for **small recoil energies**





[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

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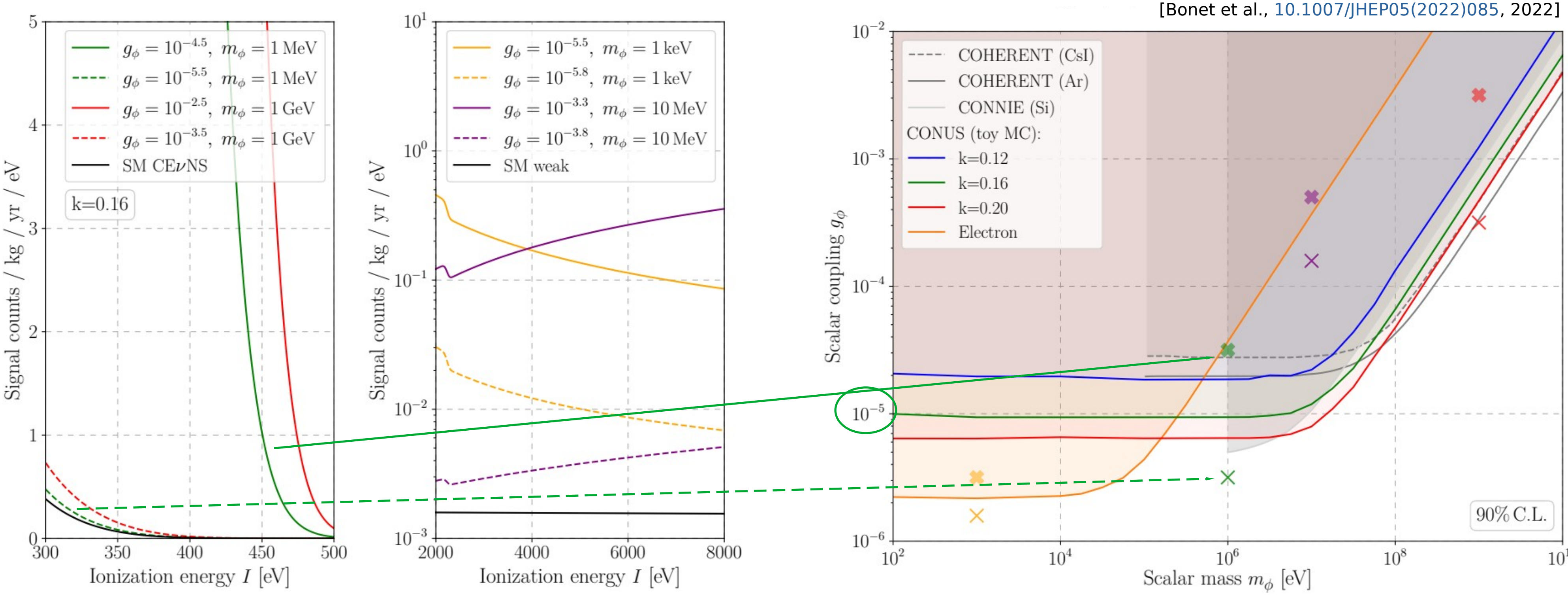
Limits from CEνNS

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



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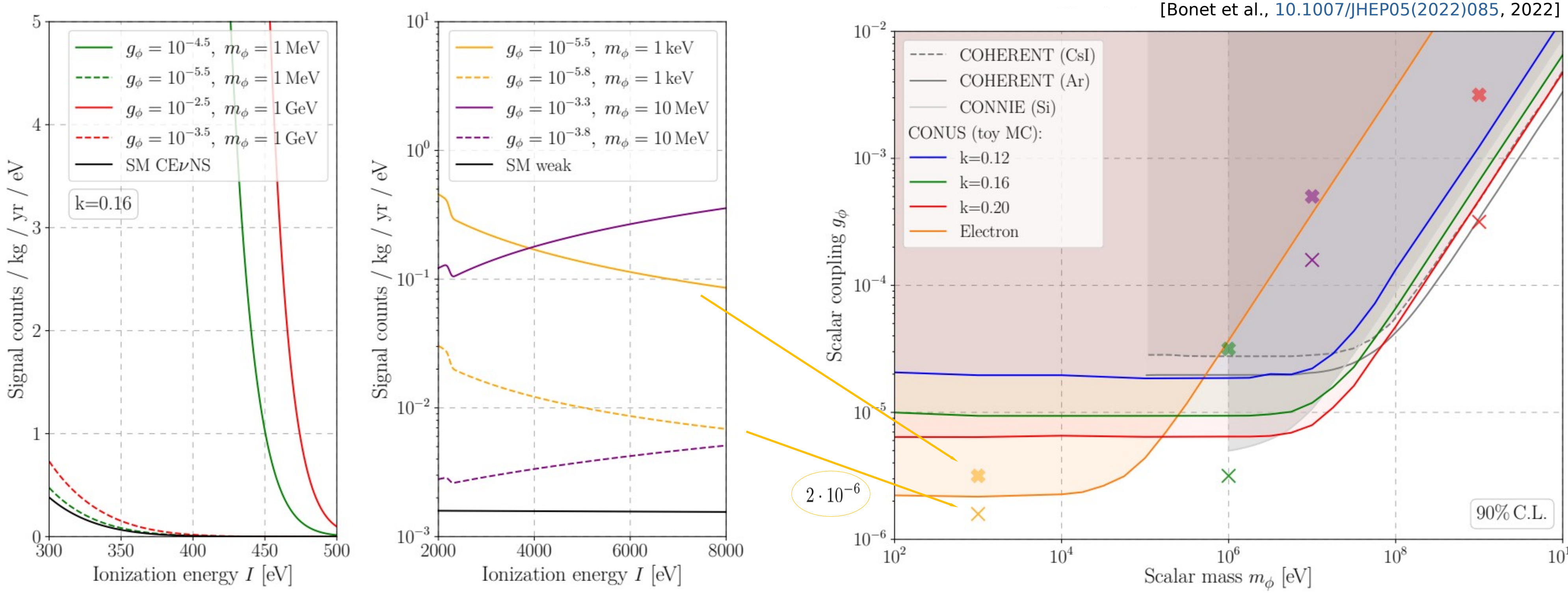
Limits from EνeS

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

Simplified models: light vector mediator

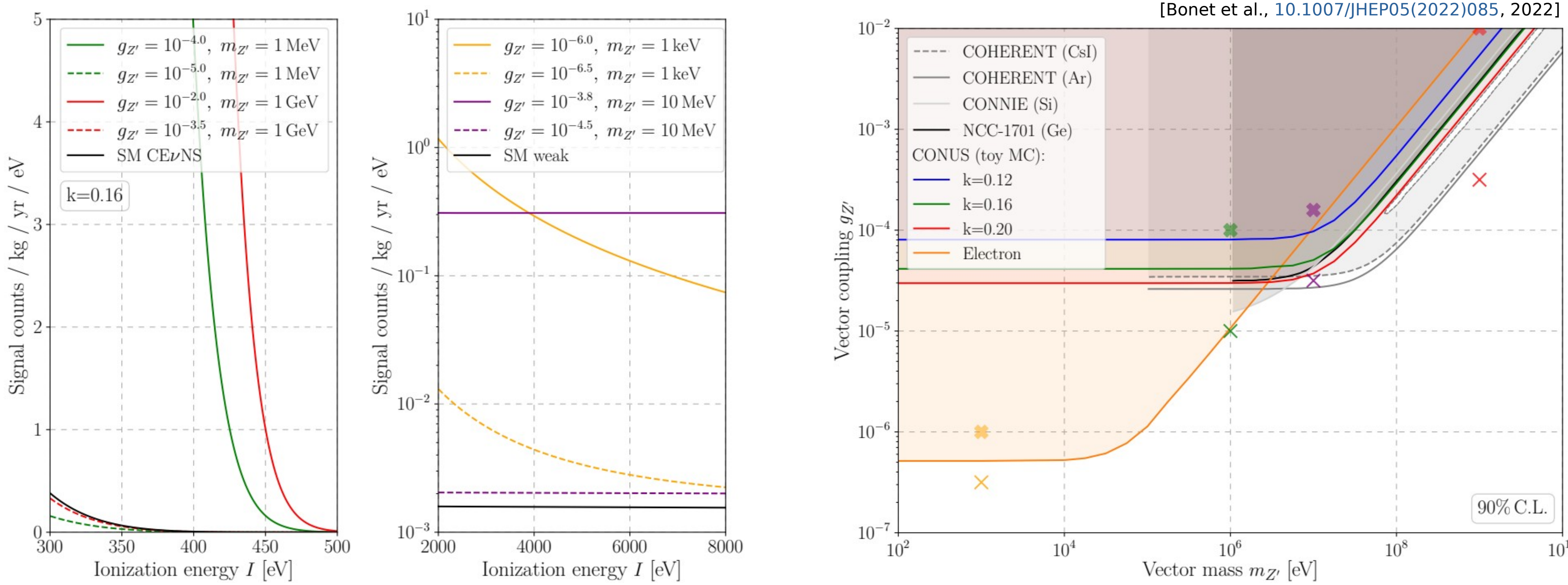
Aim: Test specific but simple mediator models that contribute to CEνNS / EνeS

[Cerdeño et al., 10.1007/JHEP05(2016)118, 2016]

$$\mathcal{L}_{Z'} = Z'_\mu \left(g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{qV} \bar{q} \gamma^\mu q \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

- Assume: universal coupling to quarks / neutrinos: $(m_{Z'}, g_{Z'})$
- Spectral distortions for **small recoil energies**

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



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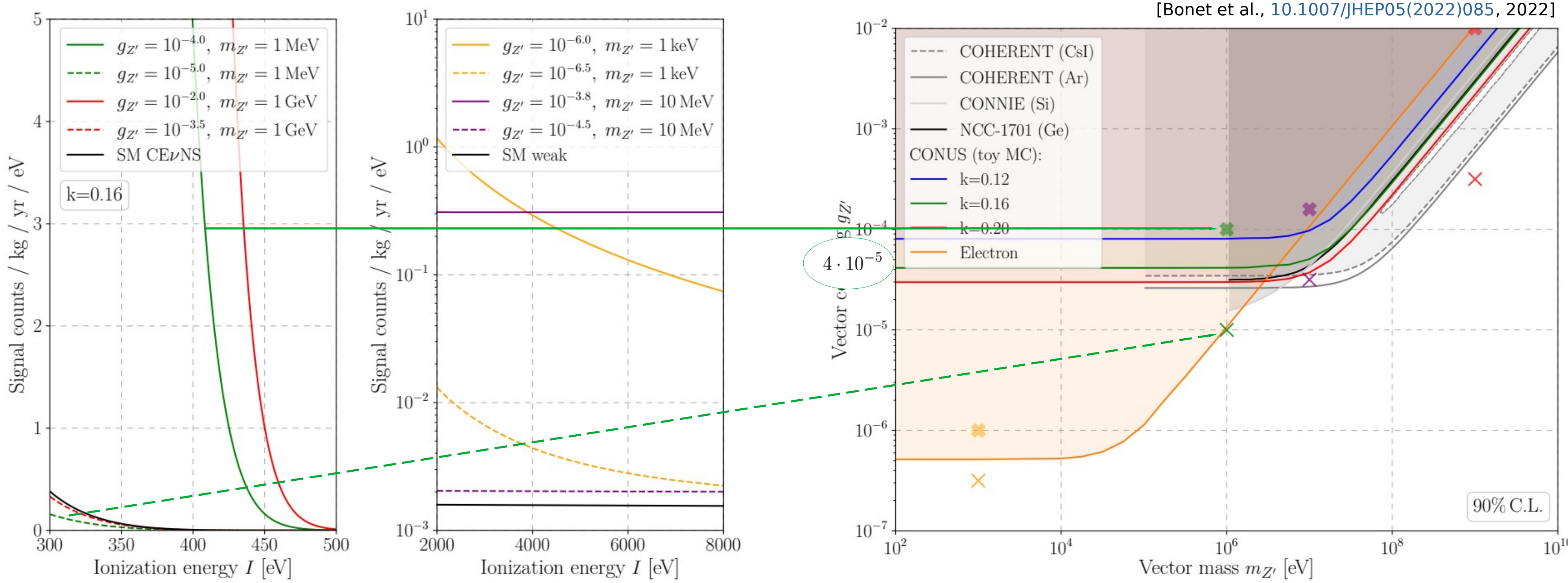

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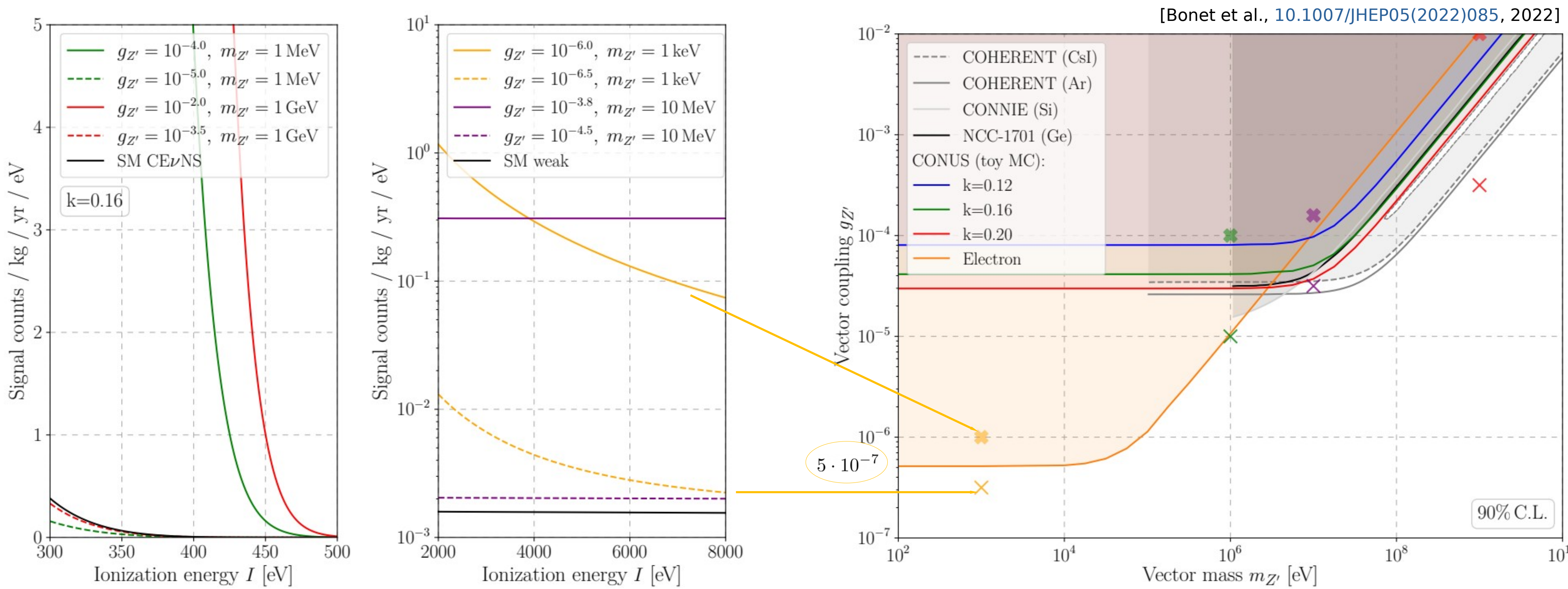
[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



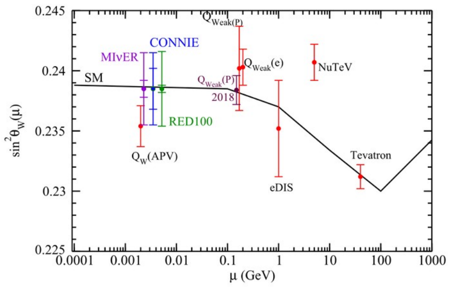
Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

Opportunities for CEνNS experiments

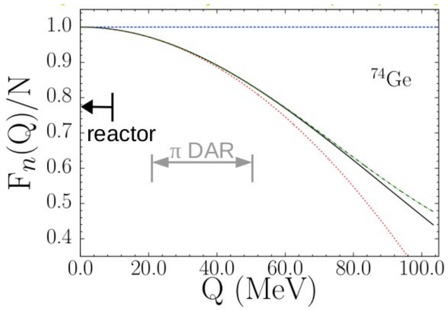
SM investigations with enhanced precision:

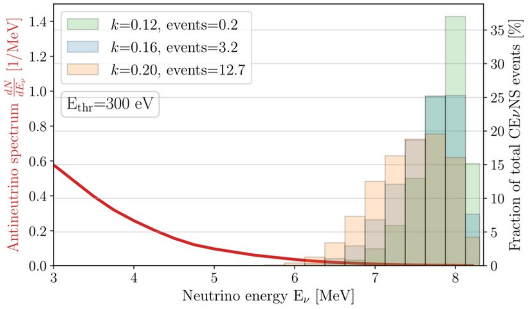
- **Weinberg angle at low-Q:**
  Test for deviations at low energy
  → light Z', neutrino charge radius
- **Nuclear form factors:**
  Model-independent extraction of neutron density distributions
  → Beam-reactor complementarity
- **Measuring reactor antineutrino spectrum:**
  CEνNS sensitive to high-E part where uncertainty is largest

[Cañas et al., 10.1016/j.physletb.2018.07.049, 2018]



[Patton et al., 10.1103/PhysRevC.86.024612, 2012]





[TR, 10.11588/heidok.00031274, 2022]

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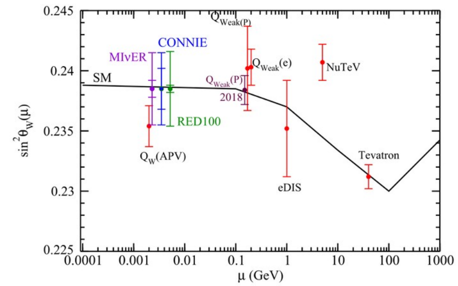

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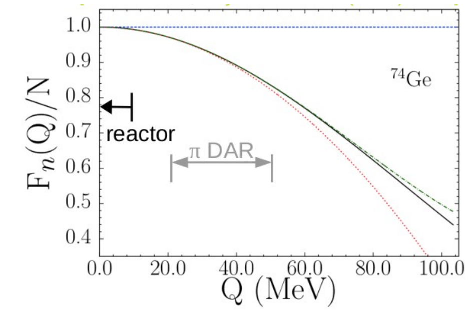
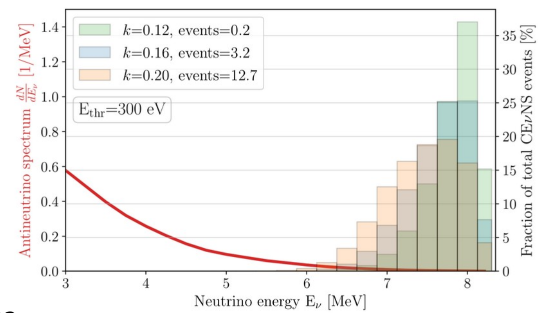


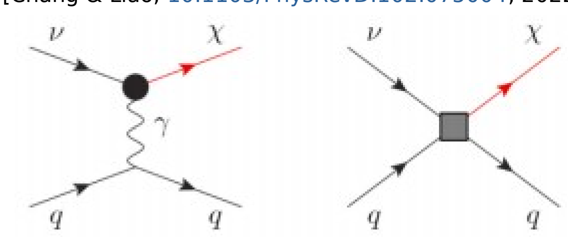


[TR, 10.11588/heidok.00031274, 2022]

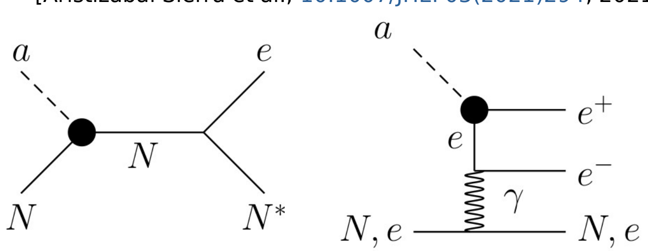
BSM investigations:

- **Light sterile neutrinos:**
  Use CEνNS for ν flux measurements
- **New fermion searches:**
  Test further ν interactions
  → ν mass, DM, ...
- **Probing portals:**
  ALPs, dark photons, etc.

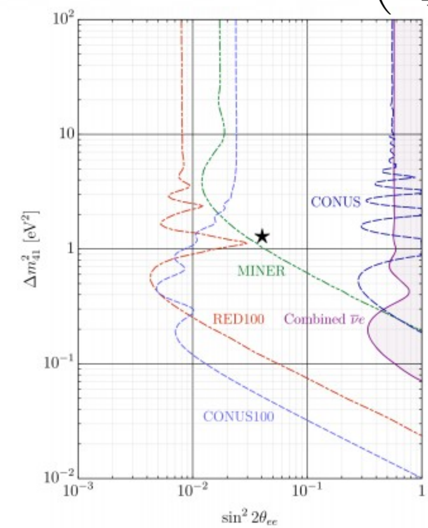
[Chang & Liao, 10.1103/PhysRevD.102.075004, 2022]



[Aristizabal Sierra et al., 10.1007/JHEP03(2021)294, 2021]



$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$



[Berryman, 10.1103/PhysRevD.100.023540, 2019]

Conclusion

- **CEνNS opens new path to high-statistics neutrino physics**
  - → beams and reactors go hand in hand!
  - → full spectrum of modern detection technologies
  - → "car-size" neutrino detectors!

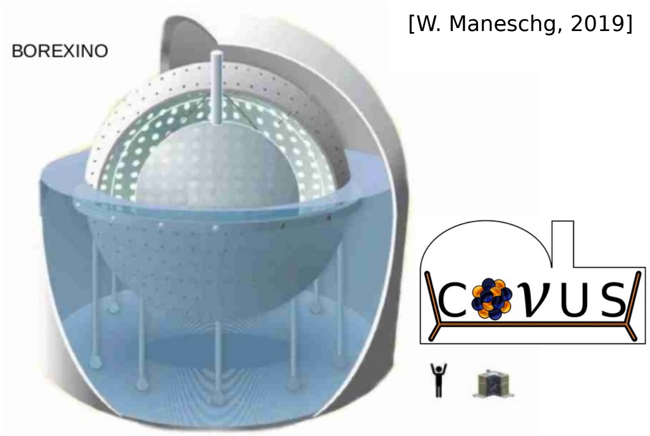
- **CEνNS data allow various SM & BSM investigations**
  - → Weinberg angle, nuclear form factors, ...
  - → *NSIs, light mediators, neutrino properties*, DM, ...

- **Several improvements of CONUS set-up:**
  - → environmental stability, new DAQ (lower E_{thr}, event shapes)
  - → pin down CEνNS → deduce more & stronger BSM limits!
  - → long run data collection ongoing

→ new experimental site under discussion!

- **Future: flavor-blind neutrino astronomy**
  - → supernovae, neutrino floor, ...

[W. Maneschg, 2019]



[TR, 10.11588/heidok.00031274, 2022]

Vector NSI	CEνNS	$\Lambda_{\mathrm{NP}} \gtrsim 100\,\mathrm{GeV}$
Tensor NSI	CEνNS	$\Lambda_{\mathrm{NP}} \gtrsim 360\,\mathrm{GeV}$
Light scalar	CEνNS	$g_\phi \sim 1 \cdot 10^{-5}$
	EνeS	$g_\phi \sim 2 \cdot 10^{-6}$
Light vector	CEνNS	$g_{Z'} \sim 4 \cdot 10^{-5}$
	EνeS	$g_{Z'} \sim 5 \cdot 10^{-7}$
νMM	EνeS	$\mu_{\nu_e} < 7.5 \cdot 10^{-11}\,\mu_B$
νMC	EνeS	$\lvert q_{\nu_e}\rvert < 3.3 \cdot 10^{-12}\,e$

[Hakenmüller et al. 10.1140/epjc/s10052-019-7160-2, 2019]
[Bonet et al., 10.1103/PhysRevLett.126.041804, 2020]
[Bonet et al., 10.1140/epjc/s10052-021-09038-3, 2021]
[Bonet et al., 10.1007/JHEP05(2022)085, 2022]
[Bonet et al., arXiv:2112.09585, 2021]
[Bonet et al., arXiv:2201.12257, 2022]
[Bonhomme et al., arXiv:2202.03754, 2022]

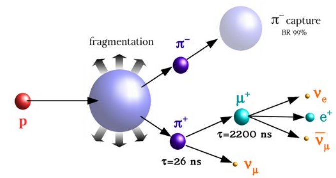
Next-generation experiments (π-DAR, reactors & DM DD!) = huge playground for phenomenology

(Neutrino magnetic moment, neutrino charge radius, vector NSI, tensor NSI, light scalars, light vectors, sterile neutrinos, dark matter, weak mixing angle, nuclear form factors, neutrino-electron-scattering, supernova neutrinos, antineutrino reactor spectra, neutrino floor, etc.)

Backup

Two complementary approaches

π-decay-at-rest neutrinos:



- Pulsed GeV-proton beam hitting heavy target → multiple ν flavors
- Time correlation of events → background suppression x(10^3-10^4)
- Higher ν energies → larger cross section, but reduced coherence

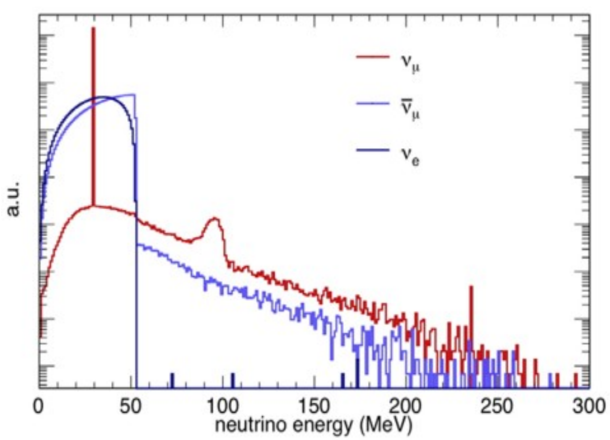
→ COHERENT, CCM, "CEνNS@ESS"...

Reactor antineutrinos:

- β decays in nuclear reaction chains → only $\bar{\nu}_e$
- Strongest artificial ν source on earth: ~10^{20} $\bar{\nu}_e$'s/GW/s
- ν energies up to 10 MeV → coherent regime!
- Close to reactor core: no lab conditions! → no cryogenic liquids, no remote control

→ CONNIE, CONUS, NCC-1701, νGEN ...

[Akimov et al., arXiv:1509.08702, 2015]



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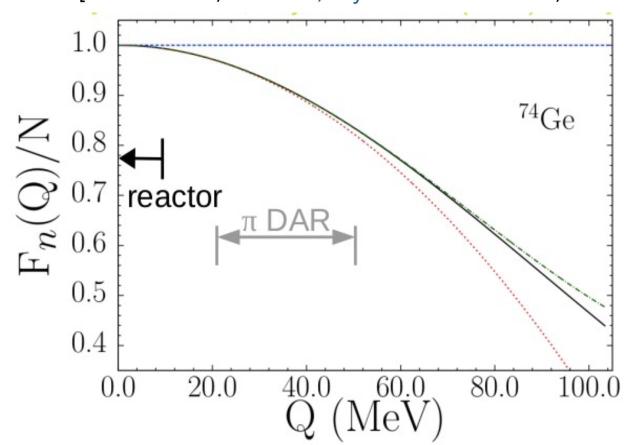
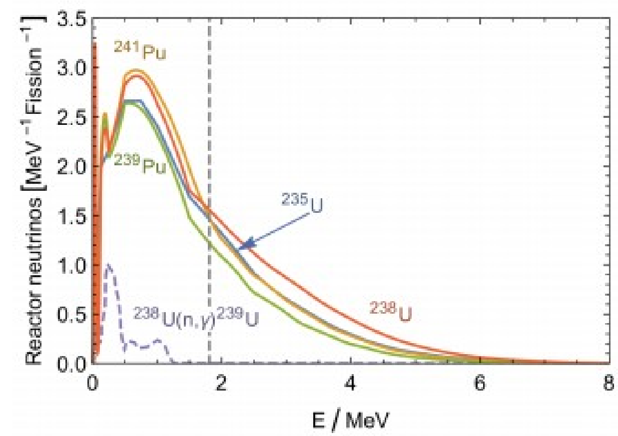


[Vitagliano et al., 10.1103/RevModPhys.92.045006, 2020]



Beam-reactor complementarity:
CEvNS at reactor site as high statistic baseline for multi-target and multi-flavored beam investigations!

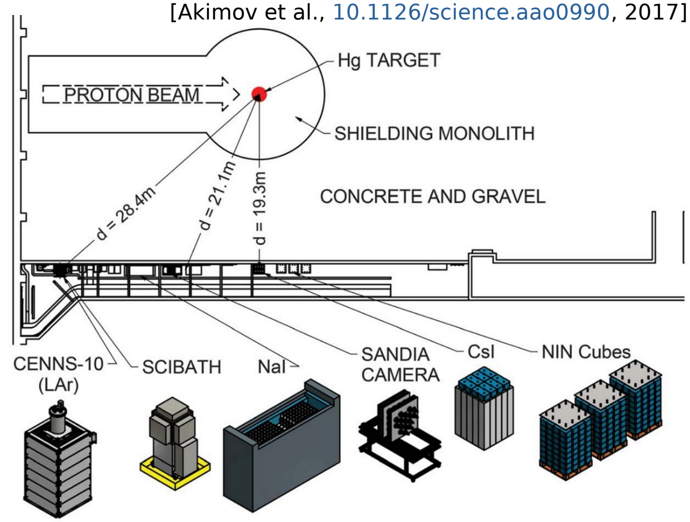
Experimental efforts with first results

COHERENT “neutrino alley” at Oak Ridge National Lab (USA)

- Overburden: 8m w.e.
- ν flux: $4.3 * 10^7$/cm²/s @ 20m
- Multiple targets @ different baselines

Target	N	Mass [kg]	T^{thr} [keV_{nr}]
CsI[Na]	78/74	14.6	~6.5
LAr	22	22	~20
NaI[Tl]	12/74	185	~13
Ge	38/40/42	10	~5

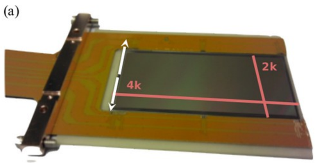
[Akimov et al., 10.1126/science.aao0990, 2017]

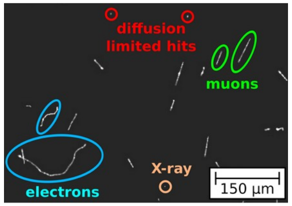


CONNIE (Brazil)

- CCDs (Si, ***N=14***) : 47.6g, T_A^{thr}~1keV_{nr}
- @30m to 3.8GW_{th} PWR:
  ν flux:$7.8 * 10^{12}$/cm²/s

[Aguilar-Arevalo et al., 10.1088/1742-6596/761/1/012057, 2016]

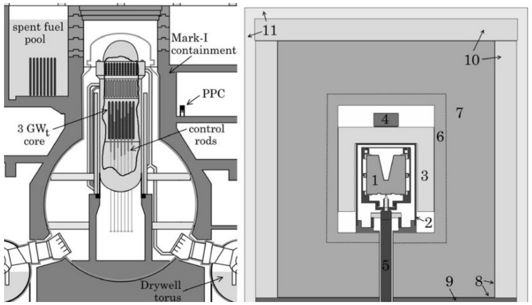




[Aguilar-Arevalo et al., 10.1088/1748-0221/11/07/P07024, 2016]

NCC-1701 (USA)

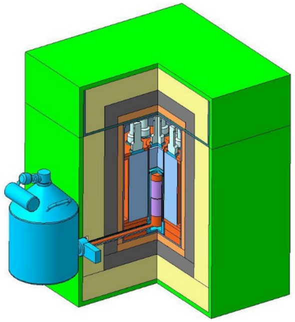
- Ge PPC (***N={38,40,42}***): 3kg, T_A^{thr}~1-2keV_{nr}
- @10.3m to 2.96GW_{th} BWR:
  ν flux: $5 * 10^{13}$/cm²/s



[Colaresi et al., 10.1103/PhysRevD.104.072003, 2021]

νGEN (Russia)

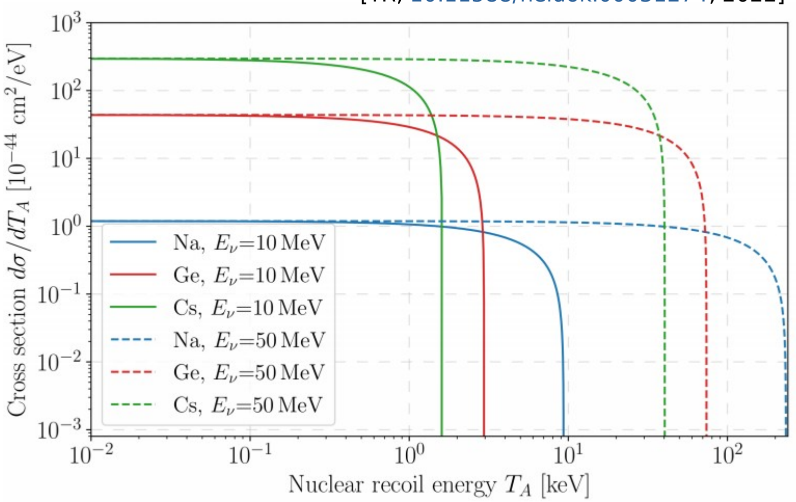
- Ge PPC (***N={38,40,42}***): 1.41kg, T_A^{thr}~1-2keV_{nr}
- @11.8m to 3.1GW_{th} PWR:
  ν flux: $3.9 * 10^{13}$/cm²/s



[Belov et al., 10.1088/1748-0221/10/12/P12011, 2015]

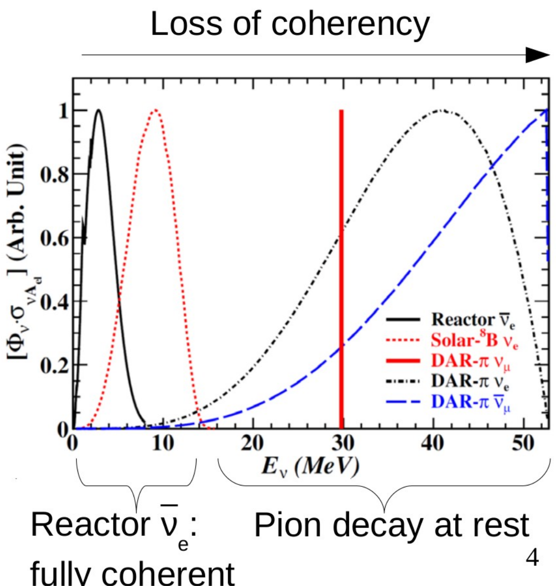
CEνNS with different sources and targets

[TR, 10.11588/heidok.00031274, 2022]



Element	N	r_A [fm]	$E_\nu^{\max}$ [MeV]	$T_A^{\max}$ [keV]
Na	12	3.6	27.7	71.5
Si	14	3.8	25.9	51.3
Ar	22	4.4	23.1	28.5
Ge	38/40/42	5.2	18.9	10.5
I	74	6.3	15.7	4.16
Xe	75/77/78	6.4	15.5	3.93
Cs	78	6.4	15.4	3.85

[TR, 10.11588/heidok.00031274, 2022]



[W. Maneschg, 2017]

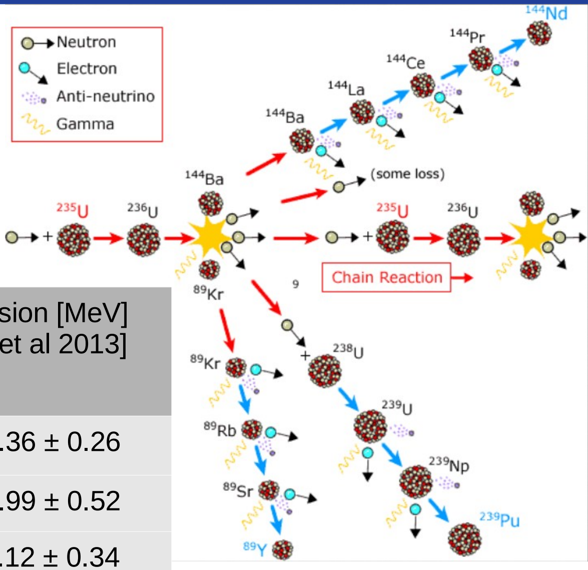
Neutrino source	Target	$T_A^{\max}$ [keV]	$E\,(\mathrm{QF} \in \{0.1, 0.15, 0.2\})$ [keV]
Nuclear reactor (10 MeV)	Na	9.33	0.93 / 1.40 / 1.87
	Si	7.64	0.76 / 1.15 / 1.53
	Ar	5.37	0.54 / 0.81 / 1.07
	Ge	2.96	0.30 / 0.44 / 0.59
	I	1.69	0.17 / 0.25 / 0.34
	Xe	1.64	0.16 / 0.25 / 0.33
	Cs	1.62	0.16 / 0.24 / 0.32
π-DAR source (50 MeV)	Na	232.4	23.2 / 34.9 / 46.5
	Si	190.4	19.0 / 28.6 / 38.1
	Ar	134.0	13.4 / 20.1 / 26.8
	Ge	73.8	7.38 / 11.1 / 14.8
	I	42.3	4.23 / 6.34 / 8.45
	Xe	40.9	4.09 / 6.13 / 8.17
	Cs	40.4	4.04 / 6.03 / 8.07

Antineutrinos from nuclear reaction products

Antineutrino emission in β decays of fuel reaction products

- Mainly from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu **→ >99%**
- ~ 6-7 ν's/fission up to 10MeV
- Spectral distribution

$$S(E_\nu) = \frac{1}{4\pi R^2} \frac{W_{th}}{\sum_i \alpha_i E_i} \sum_i \alpha_i \left(\frac{dN_i}{dE_\nu}\right)$$

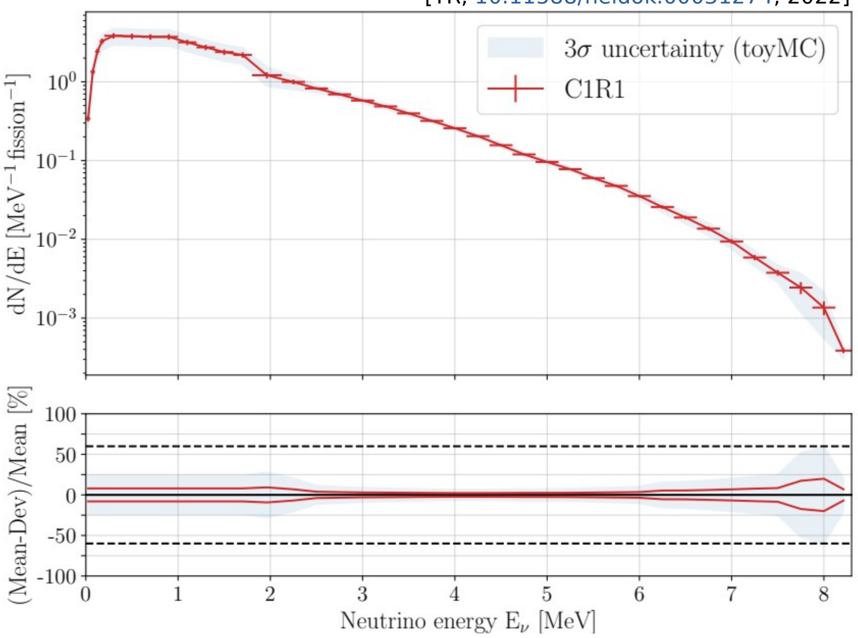


Isotope	Fission fraction α (PWR)	E/fission [MeV] [Ma et al 2013]
235U	57%	202.36 ± 0.26
238U	8%	205.99 ± 0.52
239Pu	30%	211.12 ± 0.34
241Pu	5%	214.26 ± 0.33

Knowledge about a reactors emission spectra

- Summation methods [Kopeikin et al. 10.1134/1.1825513, 2004]
  → summing β branches of all fission fragments
- Conversion methods [Haag et al., 10.1103/PhysRevLett.112.122501, 2014 Huber, 10.1103/PhysRevC.85.029901, 2011, Mueller et al., 10.1103/PhysRevC.83.054615, 2011]
  → measure β decay electron spectrum and convert into ν spectrum
- Direct measurements (IBD) [An et al., 10.1088/1674-1137/41/1/013002, 2017]

[TR, 10.11588/heidok.00031274, 2022]

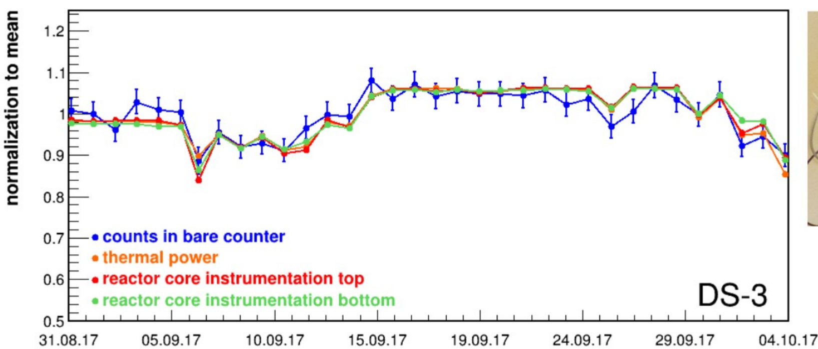


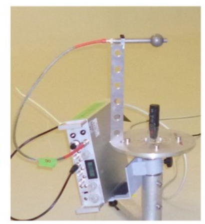
Reality much more complicated...
- Varying reactor power → **P(t)**
- Changing fuel composition → **α(t)**

Power-correlated reactor radiation

→ **Dedicated investigation of reactor-correlated background contributions:** [Hakenmüller et al. 10.1140/epjc/s10052-019-7160-2, 2019]

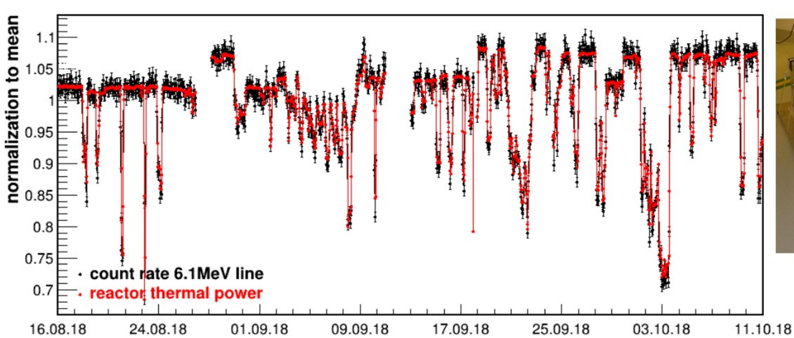
- Simulation and validation of neutrons emitted from reactor core (at CONUS site) → thermal neutron counter



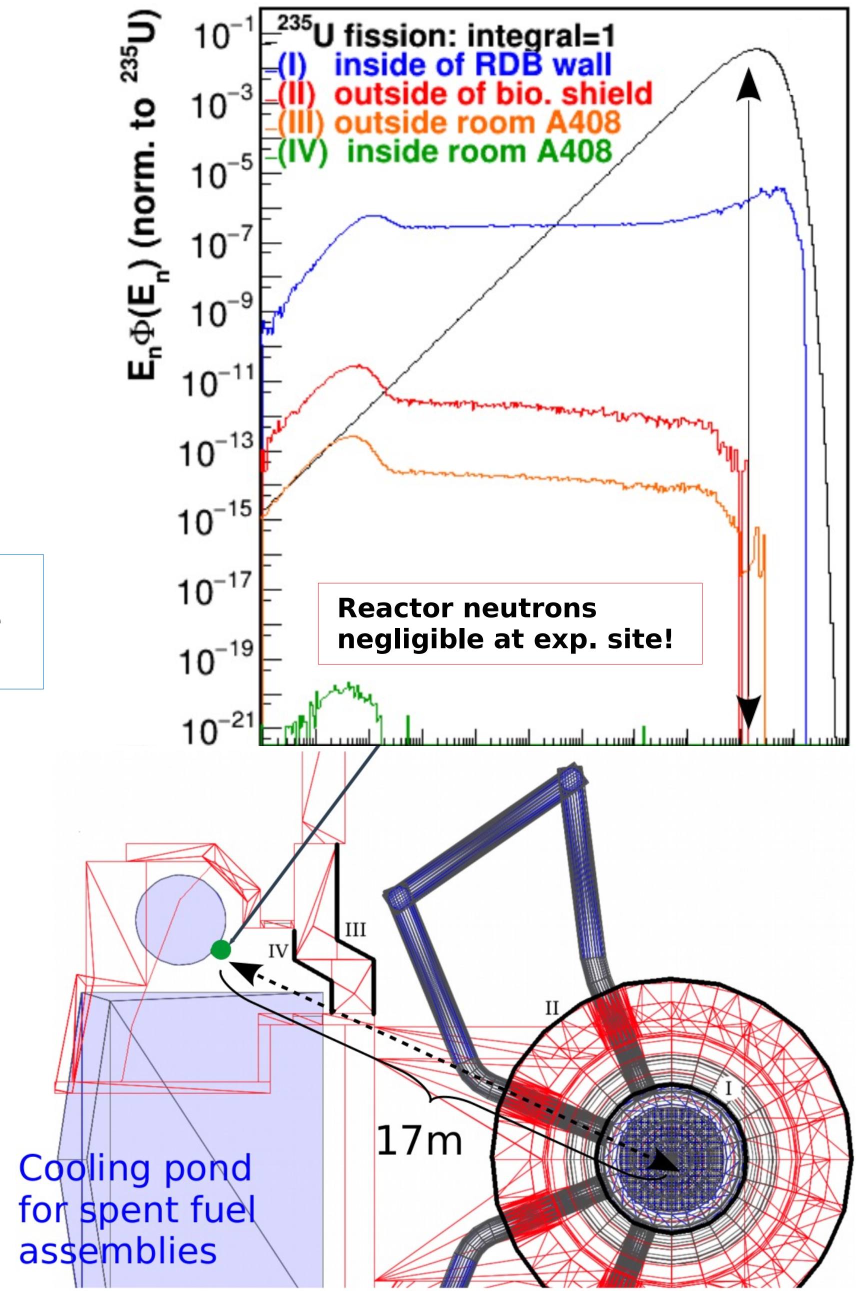


Correlation to incore and excore instrumentation

- γ radiation (6.1MeV from ^{16}N)

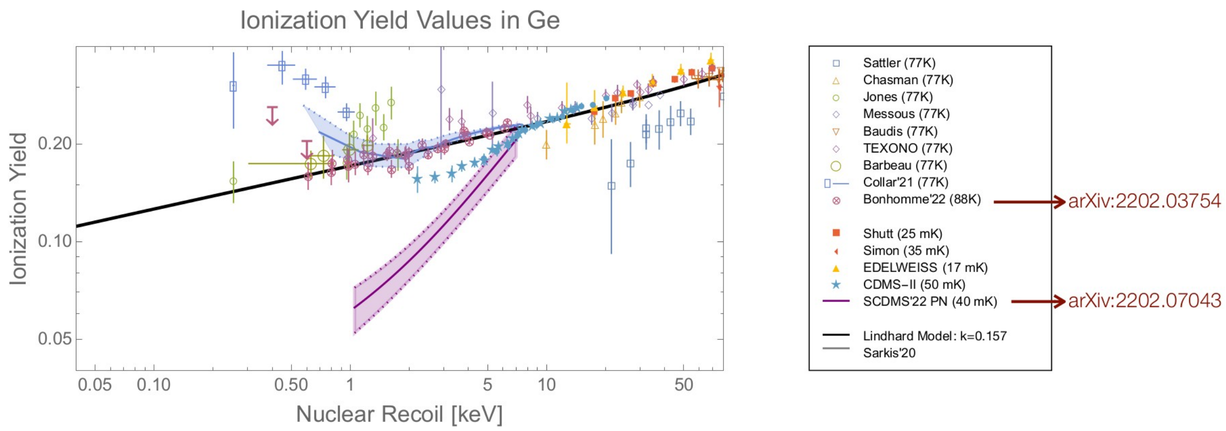


Unshielded HPGe detector



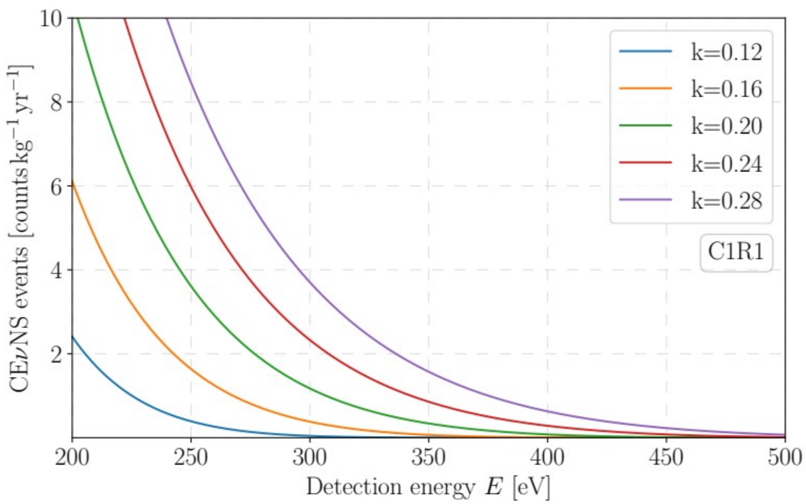
Impact of quenching at low energy

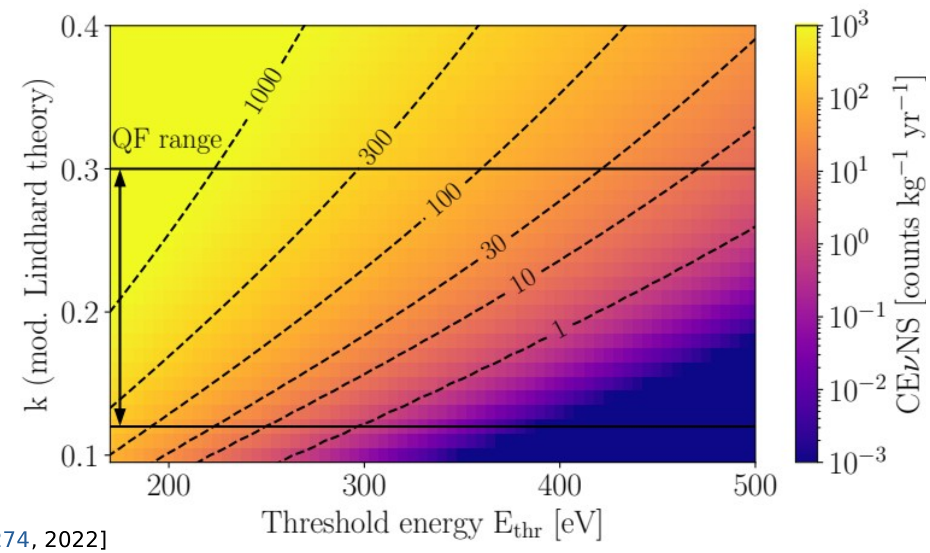
Overview of quenching measurements: T. Saab \ EXCESS 2022 \ February 16, 2022



Affects sensitivity of CEνNS and DM searches:
(Collar '21) used in arXiv:2202.09672
"Suggestive evidence for Coherent Elastic Neutrino-Nucleus Scattering from reactor antineutrinos"

Quenching according to mod. Lindhard model:

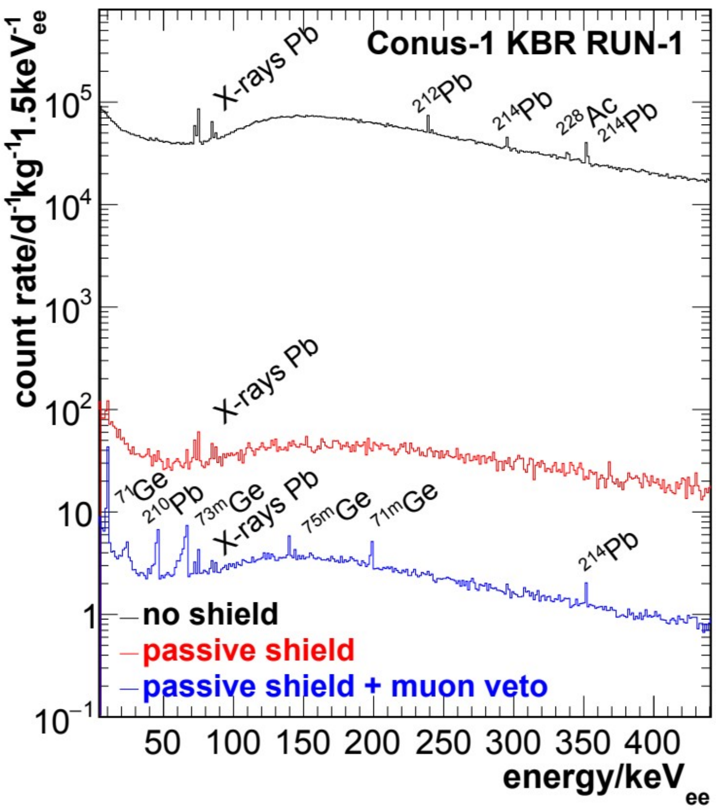


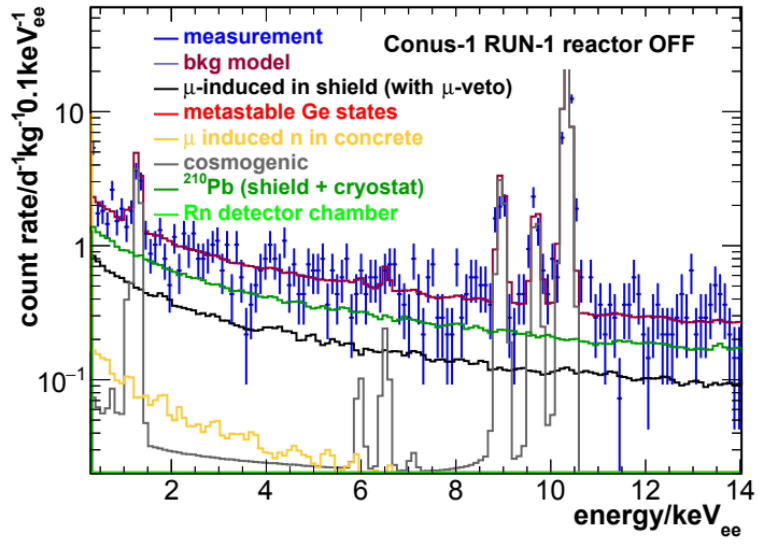


[TR, 10.11588/heidok.00031274, 2022]

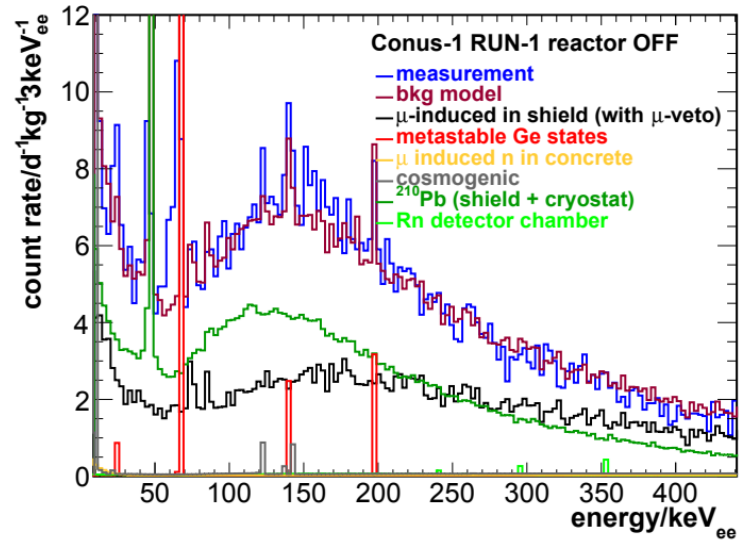
Background (model) at reactor site

[Bonet et al., arXiv:2112.09585, 2021]





Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
(α,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes



Data analyses of experimental data

(Binned log)-Likelihood in the SM case:

- ON and OFF data are fitted together:

$$\log \mathcal{L} = \log \mathcal{L}_{ON} + \log \mathcal{L}_{OFF} + \text{pull terms}$$

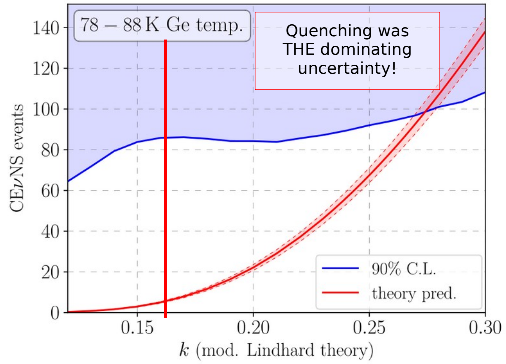
with $\log \mathcal{L}_{ON}(s, b, \Theta_{thr_1}, \Theta_{thr_2}, \Theta_{rea}, \Theta_{det}, \Theta_{\Delta E})$

$\log \mathcal{L}_{OFF}(b, \Theta_{thr_1}, \Theta_{thr_2}, \Theta_{det}, \Theta_{\Delta E})$

- Parameter list:
  - s: signal strength (free), b: MC normalisation (free)
  - $\Theta_{thr1/2}$: electronic noise (free)
  - Θ_{rea} : reactor neutrino flux (~3%)
  - Θ_{det} : detector/DAQ (1-5%), $\Theta_{\Delta E}$: energy scale (10-20 eV)
- Compare signal to background-only hypothesis: **LH ratio**

Data sets: 5 detectors (in 2 runs)

Data set	ON [kg d]	OFF [kg d]	ROI [keV]
C1R1	96.7	13.8	0.296 - 0.75
C2R1	14.6	13.4	0.311 - 1.00
C3R1	97.5	10.4	0.333 - 1.00
C1R2	19.6	12.1	0.348 - 0.75
C3R2	20.2	9.1	0.343 - 1.00
All	248.7	58.8	



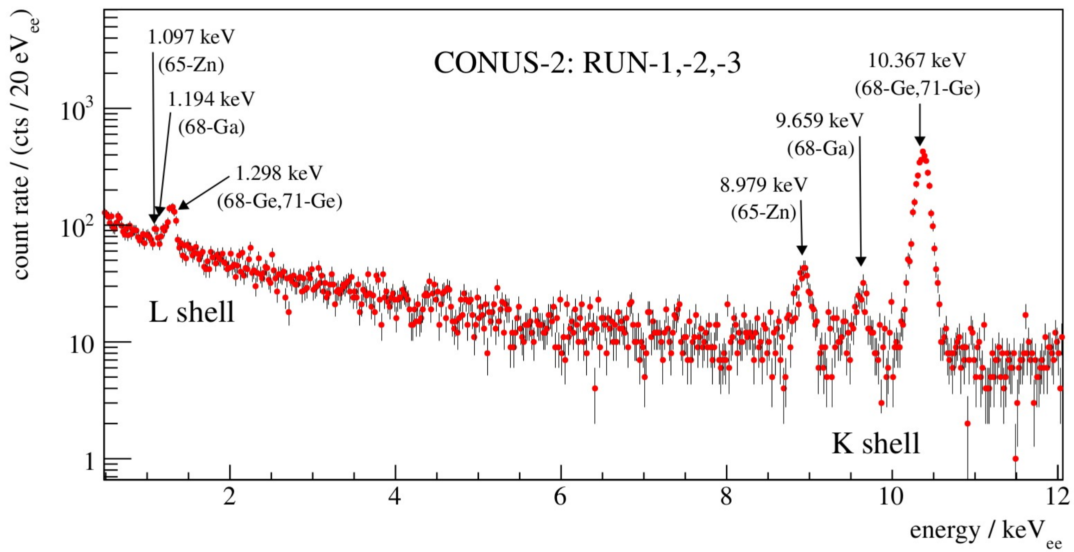
BSM investigations:

- Extend existing LH with BSM contributions
  → CEνNS now additional background
- Additional systematic due to elastic ν-e- scatterings *(EνeS)* @[2,8]keV
  → 5% shape uncertainty on background model
- BSM limits in terms of quenching factor!

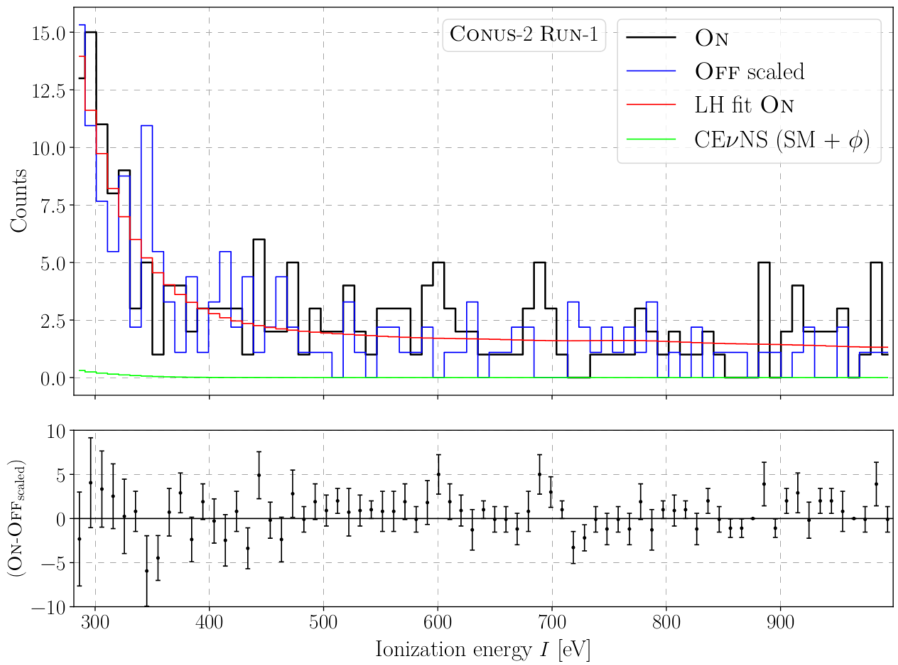
Analysis	Data set	ON [kg d]	OFF [kg d]	ROI [keV]
BSM	C1R1	96.7	13.8	0.276 - 0.741
$(\bar{\nu}_e + A(Z,N))$	C2R1	14.6	13.4	0.281 - 0.999
	C3R1	97.5	10.4	0.333 - 0.991
	all	208.8	37.6	
BSM + νMM	C1R1	215.4	29.6	2.013 - 7.968
$(\bar{\nu}_e + e)$	C2R1	184.6	32.2	2.006 - 7.990
	C3R1	248.5	31.7	2.035 - 7.989
	all	648.5	93.5	
νMM	C1R2	19.6	18.5	2.010 - 7.955
$(\bar{\nu}_e + e)$	C3R2	20.8	19.0	2.007 - 7.991
	all	688.9	131.5	

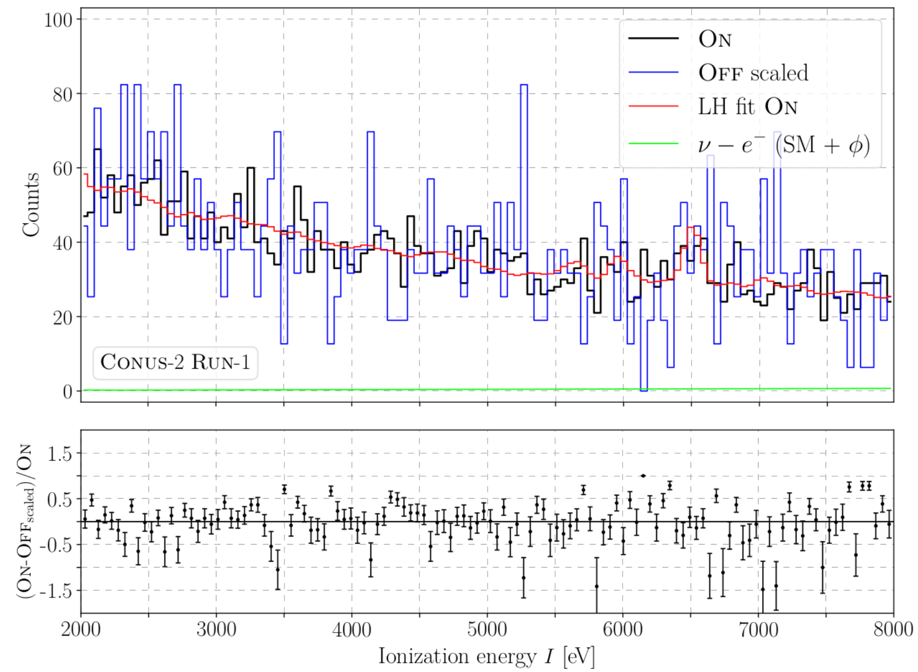
Exemplary spectra: CONUS-2 RUN-1

[Bonet et al., 10.1140/epjc/s10052-021-09038-3, 2021]



[Bonet et al., 10.1007/JHEP05(2022)085, 2022]





Sensitivity of next and future data

Estimate for recent data collection period

- Bkg stability → exposure 2.7 kg*yr
- Quenching factor known! → CONUS measurement
- New DAQ → lower threshold
- PSD → background reduction of ~20%

[TR, 10.11588/heidok.00031274, 2022]

E_{thr} [eV]	CONUS [counts]	Z	V
300	30	0.15	42
275	49	0.25	16
250	99	0.50	4.1
225	178	0.88	1.3
200	286	1.40	0.5

→ naive counting estimate: no shape, no systematics

s: signal events
b: background events

$Z = s/\sqrt{b}$

$V = (s+b)/s^2$

Theoretical CONUS upgrade

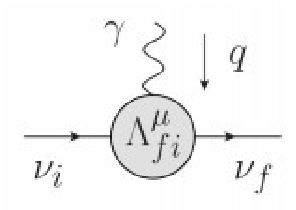
- New experimental site similar to KBR
- Same bkg and detector specifications
- Exposure: 500 kg*yr

→ precision neutrino physics with CEνNS!

E_{thr} [eV]	CONUS-100 [counts]	Z	V
300	$5.5 \cdot 10^3$	2.1	$227 \cdot 10^{-3}$
275	$9.1 \cdot 10^3$	3.4	$85 \cdot 10^{-3}$
250	$18 \cdot 10^3$	6.8	$22 \cdot 10^{-3}$
225	$33 \cdot 10^3$	12.0	$7 \cdot 10^{-3}$
200	$53 \cdot 10^3$	19.0	$3 \cdot 10^{-3}$

Electromagnetic neutrino properties

Loop-induced electromagnetic properties: [Giunti & Studenikin, 10.1103/RevModPhys.87.531, 2015]



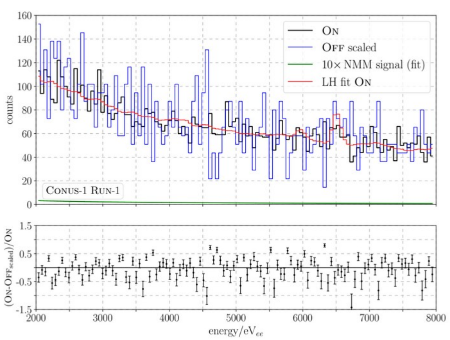
→ neutrino charge (radius), electric and magnetic dipole moment, anapole moment
→ characteristic dependence on neutrino's fermionic nature
→ test for BSM physics!

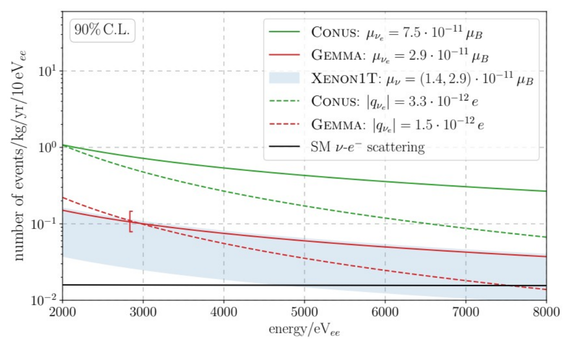
νMM from electron scattering at reactor site:

$$\left(\frac{d\sigma}{dT_e}\right)_{\nu\mathrm{MM}} = \frac{\pi\alpha^2_{\mathrm{em}}}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2$$

- huge reactor ν flux
- low threshold energies!

[Bonet et al., arXiv:2201.12257, 2022]





$$\mu_{\nu_e} < 7.5\cdot10^{-11}\,\mu_B\ (90\%\ \mathrm{C.L.})$$

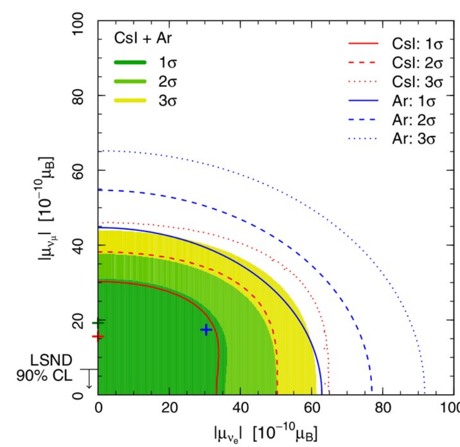
Assuming null result: convert to νMC bound

$$|q_{\nu_e}| < 3.3\cdot10^{-12}\ e\ (90\%\ \mathrm{C.L.})$$

νMM from CEνNS at a π-DAR site:

$$\left(\frac{d\sigma}{dT_A}\right)_{\nu\mathrm{MM}} = \frac{\pi\alpha^2_{\mathrm{em}}}{m_e^2}Z^2\left(\frac{1}{T_A}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2F^2(T_A)$$

- higher ν energy
- multiple flavors



[Cadeddu et al., 10.1103/PhysRevD.102.015030, 2020]

νMC bounds from COHERENT:

$$|q_\nu| \sim \mathcal{O}(10^{-8})e$$

Future studies of transition moments, neutrino charge radii..., etc.