Coherent elastic neutrino-nucleus scattering

First constraints / observations and future potential

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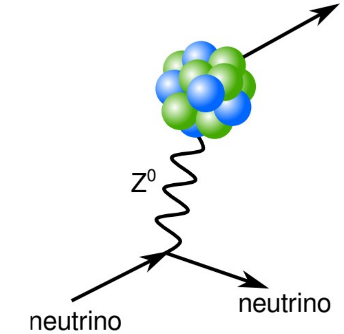
Max-Planck-Institut für Kernphysik Heidelberg

Coherent elastic neutrino-nucleus scattering (CEνNS)

CEνNS chronology:

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



The Channel:

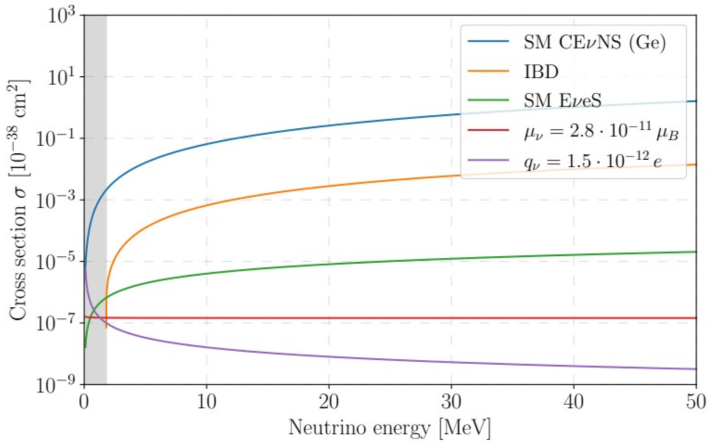
- Coherence = enhancement ~ N^2 $\quad E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}[\mathrm{MeV}]$
- Observable = nuclear recoil energy T_A

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

→ detector material

→ neutrino source

→ energy threshold / neutrino source



[TR, PhD thesis, 2022]

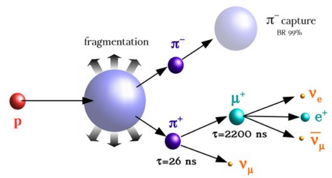
- Very low energy threshold needed:
  - $T_A \sim N^{-1}$
  - Quenching: T_A → "detection"

Cross section σ
vs.
nuclear recoil T_A

Element	N	E_ν [MeV]	T_A [keV]
Si	14	25.6	51.3
Ge	38 / 40 / 42	18.9	10.5
Xe	75 / 77 / 78	15.5	3.9
I / Cs	74 / 78	15.7 / 15.4	4.2 / 3.9

Two complementary paths

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

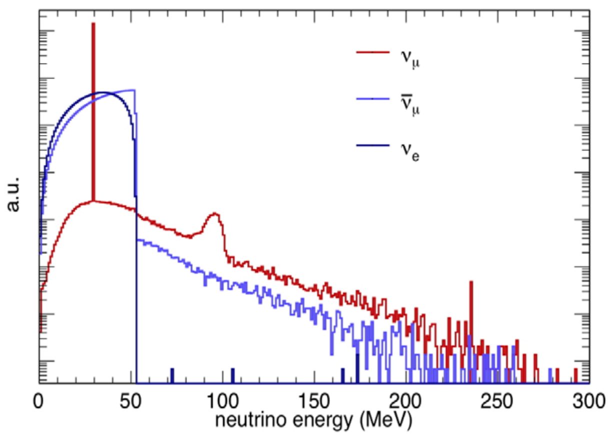
→ COHERENT, CCM, ESS...

Reactor antineutrinos:

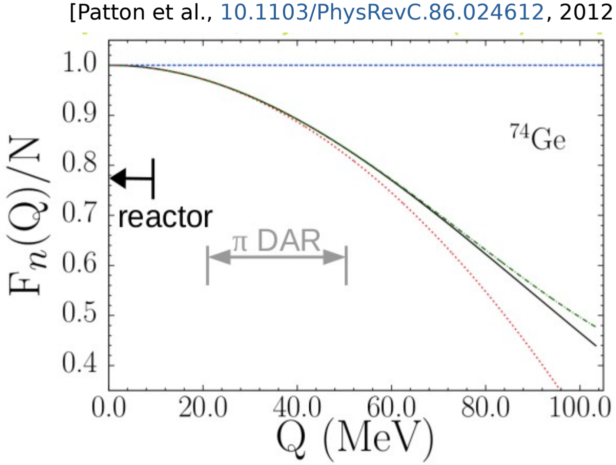
- β decays in nuclear reaction chains → only $\bar{\nu}_e$
- Strongest artificial ν source on earth: ~10^{20} $\bar{\nu}_e$'s/GW/s
- ν energies up to 10 MeV → coherent regime!
- Close to reactor core: no lab conditions! → no cryogenic liquids, no remote control

→ CONNIE, CONUS, NCC-1701, ...

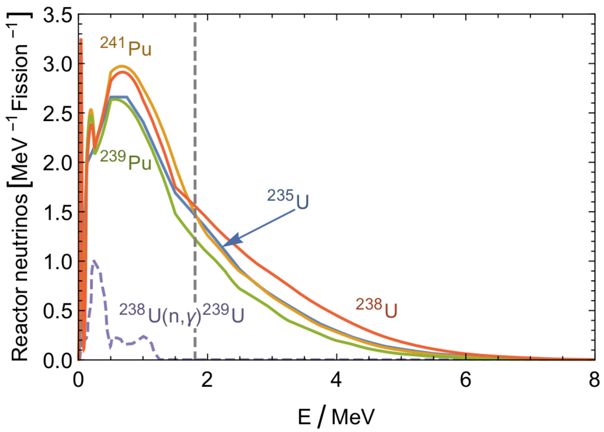
[Akimov et al., arXiv:1509.08702, 2015]



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



[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!

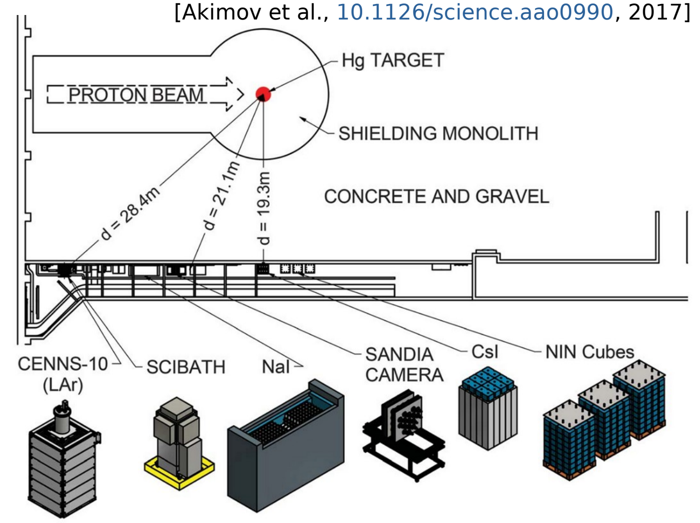
Experimental efforts

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

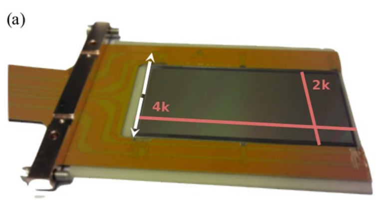
[Akimov et al., 10.1126/science.aao0990, 2017]

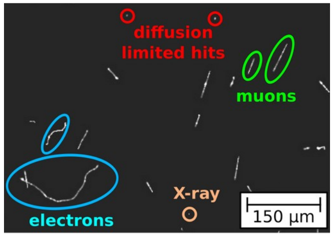


CONNIE (Brazil)

- 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]

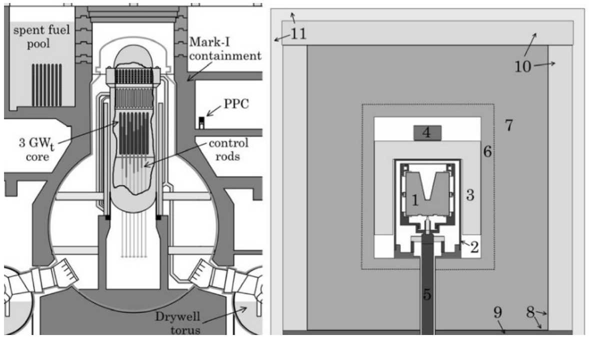




[Aguilar-Arevalo et al., 10.1088/1748-0221/11/07/P07024, 2016]

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]

The CONUS experiment

[Bonet et al., arXiv:2110.02174, 2021]

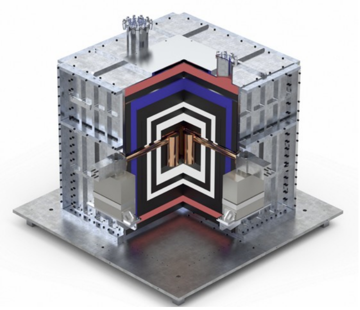
Reactor: Brokdorf nuclear power plant

- @17m to 3.9GW_{th} : inside reactor building!
- ν flux: 2.3 * 10^{13}/cm²/s
- Reactor information:
  fuel composition, thermal power

Background & shield

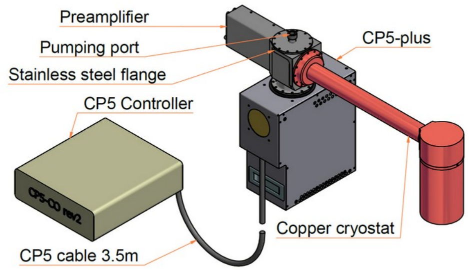
[Bonet et al., arXiv:2112.09585, 2021]

- 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

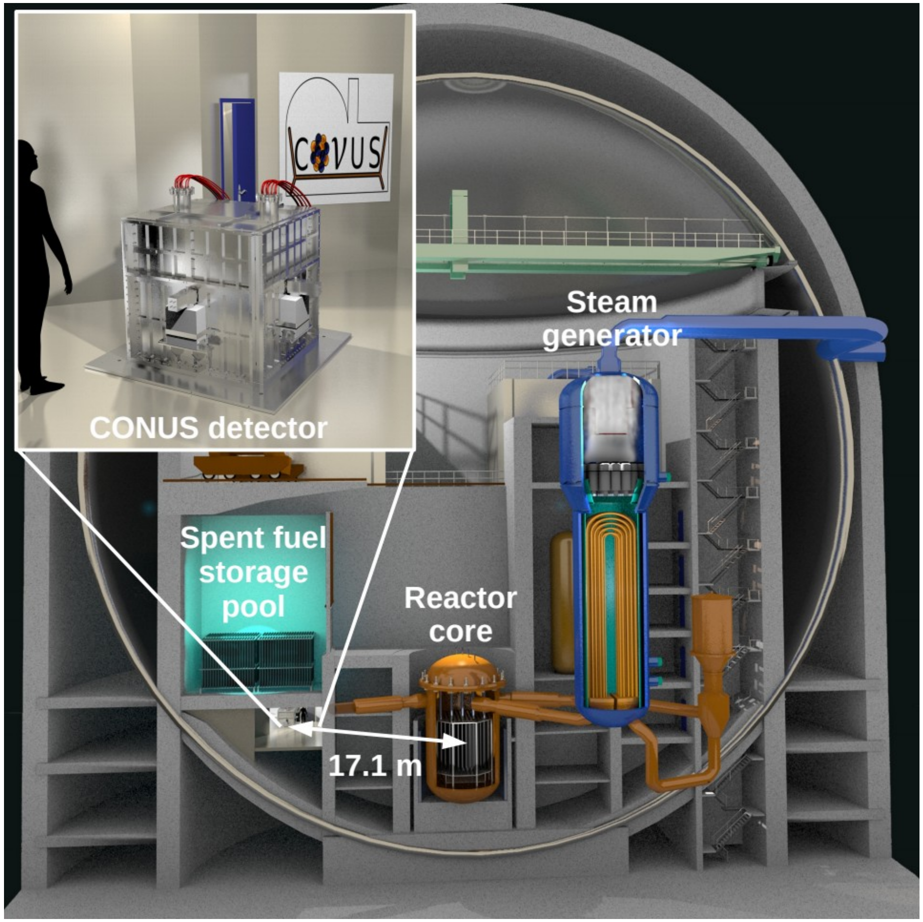


Detectors:

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



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



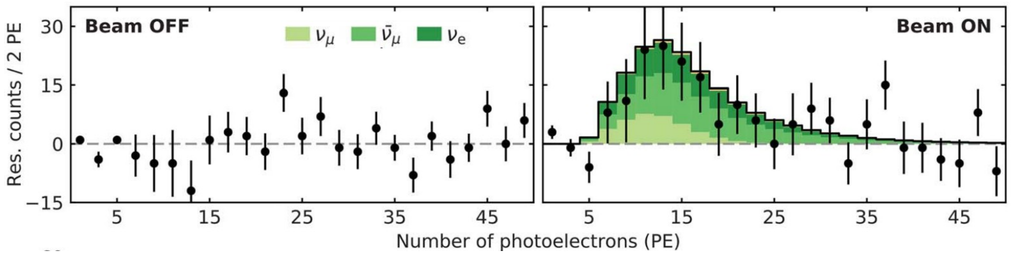
Close to reactor core:
lab conditions not easily realized
→ site monitoring crucial!

CEνNS observations and constraints

Observations:

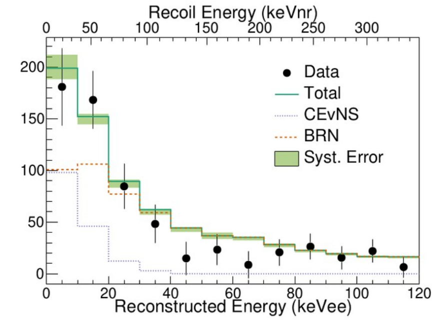
COHERENT CsI[Na] (2017): 5 * 10^{20} POT
134+-22 (pred. 173+-48)

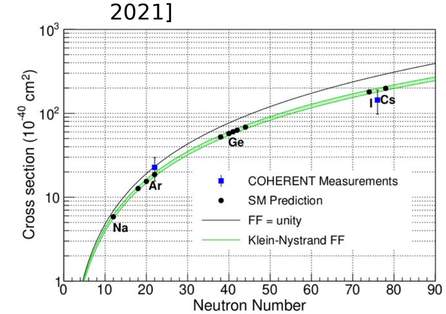
[Akimov et al., 10.1126/science.aao0990, 2017]



COHERENT LAr (2021): 13.7 * 10^{22} POT
159+-43 (pred. 128+-17)

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

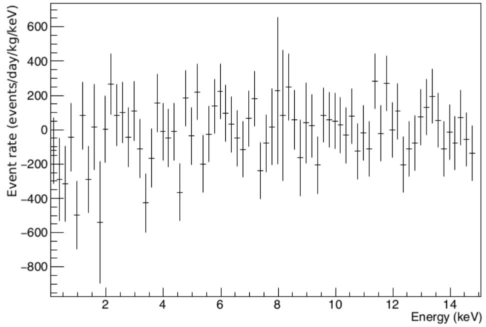




Limits:

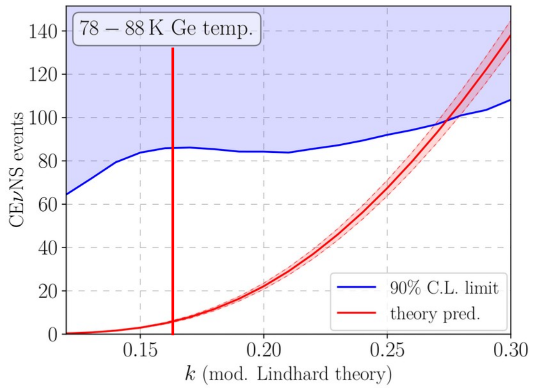
CONNIE Si (2019):
*R_{NP}<40*R_{SM} @ 95% C.L.*
2.1kg*d ON + 1.6kg*d OFF

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



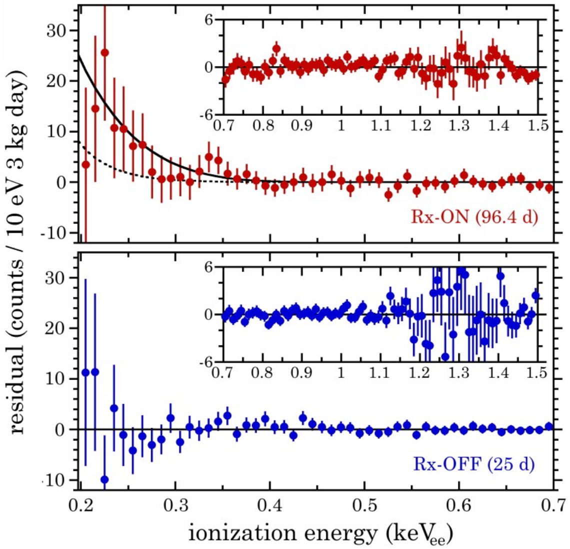
CONUS Ge (2020):
R_{SM}<0.4/kg/d @ 90% C.L.
(x17 lower then prediction)
249kg*d ON + 59kg*ON

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



"Suggestive evidence for Coherent Elastic Neutrino-Nucleus Scattering from reactor antineutrinos" [Colaresi et al., arXiv:2202.09672, 2022]

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

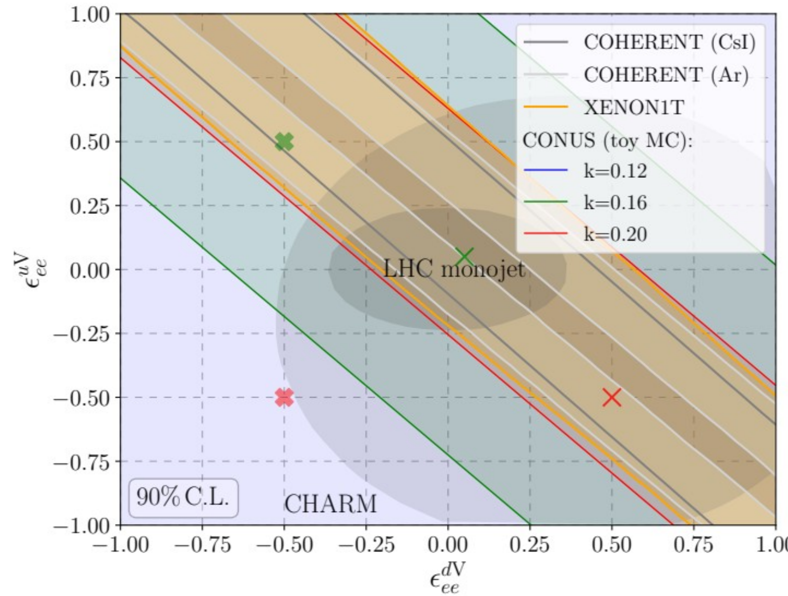


Non-standard interactions (NSIs)

Aim: Test for new (high-scale) neutrino interaction [Barranco et al., 10.1088/1126-6708/2005/12/021, 2005]

- Vector-type Interaction $\mathcal{O}^{qV}_{\alpha\beta} = (\bar{\nu_\alpha}\gamma^\mu P_L \nu_\beta)\,(\bar{q}\gamma_\mu P_{L/R} q) + \text{h.c.}$
  → New feature: destructive interference!
- Modified of weak nuclear charge
  $$\mathcal{Q}^V_{NSI} = \left(2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha} + g^V_p\right) Z + \left(\epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha} + g^V_n\right) N + \sum_{\alpha\neq\beta}\left[\left(2\epsilon^{uV}_{\alpha\beta} + \epsilon^{dV}_{\alpha\beta}\right) Z + \left(\epsilon^{uV}_{\alpha\beta} + 2\epsilon^{dV}_{\alpha\beta}\right) N\right]$$
- New couplings ε partially degenerate
  → different isotopes/targets at different sources

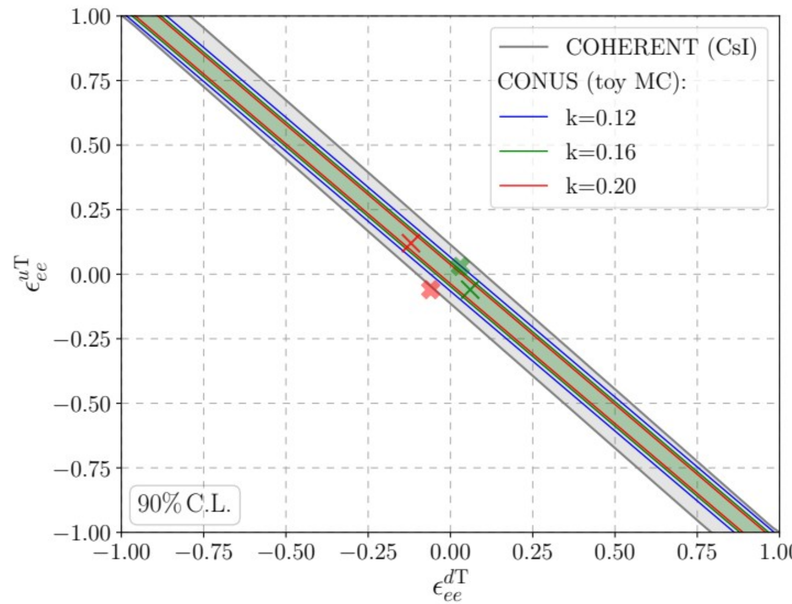
Λ_{NP}>100 GeV (CONUS, k=0.16)
Λ_{NP}>240 GeV (COHERENT, LAr)



[Bonet et al., arXiv:2110.02174, 2021]

- Tensor-type operator $\mathcal{O}^{qT}_{\alpha\beta} = (\bar{\nu}_\alpha\,\sigma^{\mu\nu}\nu_\beta)\,(\bar{q}\,\sigma_{\mu\nu}\,q) + \text{h.c.}$
  [Barranco et al., 10.1142/S0217751X12501473, 2012]
- 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

Λ_{NP}>360 GeV (CONUS, k=0.16)



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

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

Simplified models: light mediators at low-E

Aim: Test specific but simple mediator models that contribute to CEνNS [Cerdeño et al., 10.1007/JHEP05(2016)118, 2016]

Light scalar:

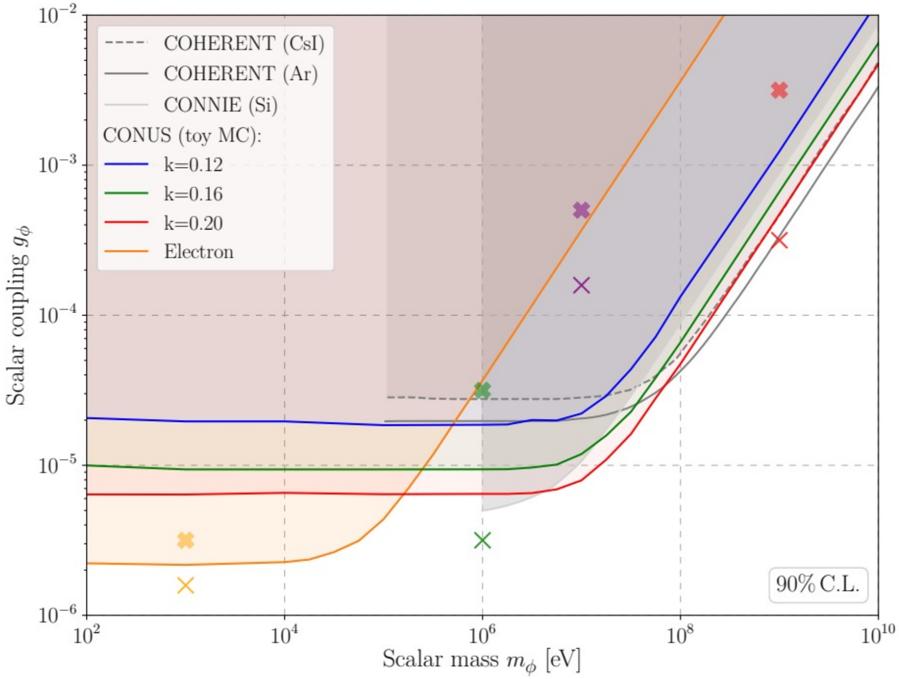
$$\mathcal{L}_\phi = \phi\left(g_\phi^{qS}\bar{q}q + g_\phi^{eS}\bar{e}e + g_\phi^{\nu S}\bar{\nu}_R\nu_L + \text{h.c.}\right) - \frac{1}{2}m_\phi^2\phi^2$$

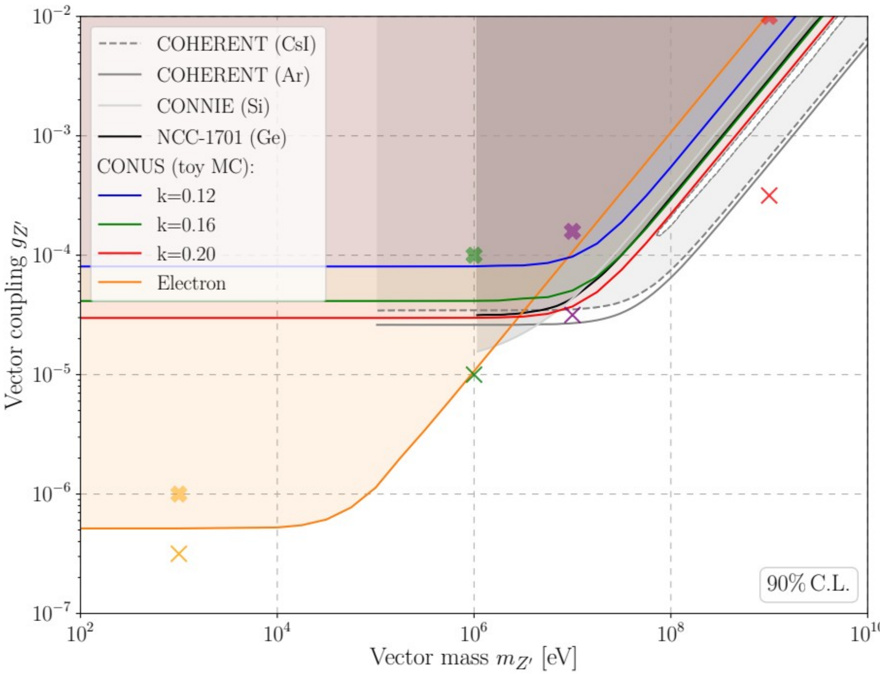
Light vector:

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

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

[Bonet et al., arXiv:2110.02174, 2021]

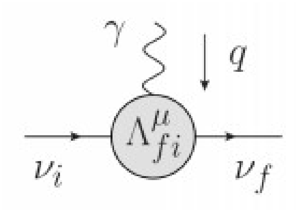




Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

Electromagnetic neutrino properties

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



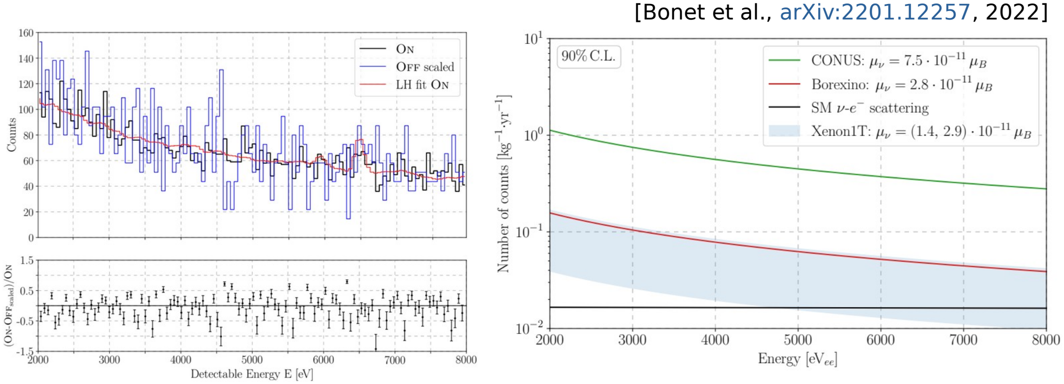
→ neutrino charge (radius), electric and magnetic dipole moment, anapole moment
→ characteristic dependence on neutrino's fermionic nature
→ test BSM physics!

νMM from electron scattering at reactor site:

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

- huge reactor ν flux
- low threshold energies!

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



$$\mu_{\nu_e} < 7.5 \cdot 10^{-11}\,\mu_B \;(90\%\;\mathrm{C.L.})$$

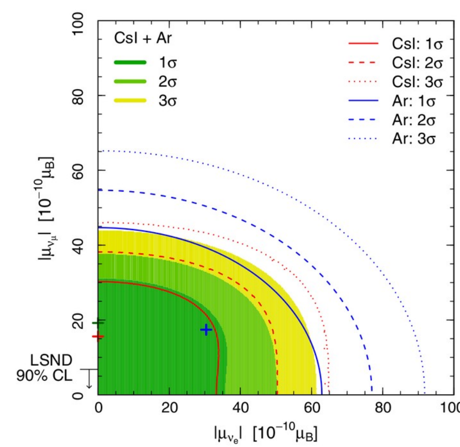
Assuming null result: convert to νMC bound

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

νMM from CEνNS at a π-DAR site:

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

- higher ν energy
- multiple flavors



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

νMC bounds from COHERENT:

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

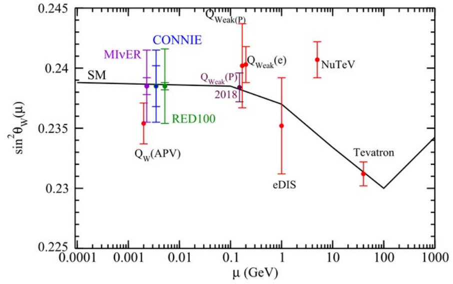
Future studies of transition moments, neutrino charge radii…, etc.

Opportunities for CEνNS experiments

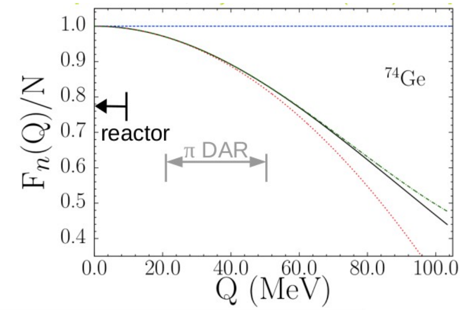
SM investigations:

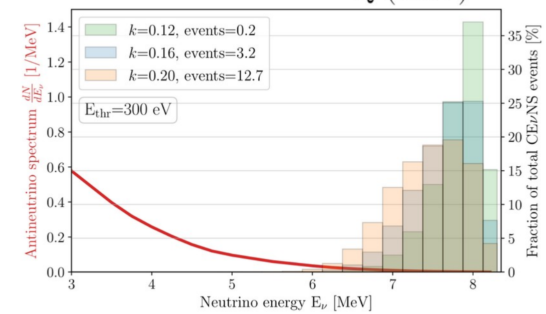
- **Weinberg angle at low-Q:**
  Test for deviations at low energy
  → light Z', neutrino charge radius
- **Nuclear form factors:**
  model-independent extraction of neutron density distributions
  → Beam-reactor complementarity
- **Measuring reactor antineutrino spectrum:**
  CEνNS sensitive to high-E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



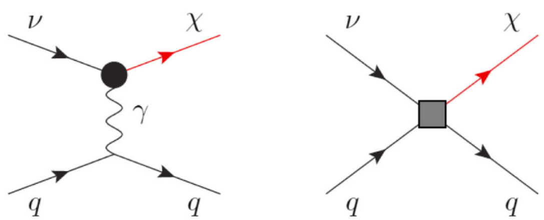


[TR, PhD thesis, 2022]

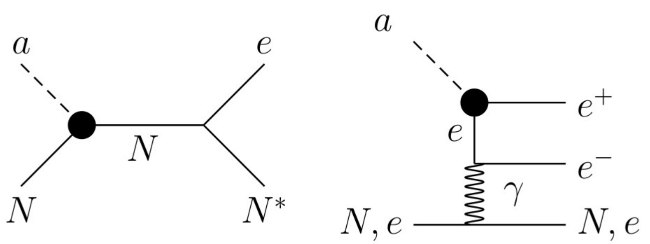
BSM investigations:

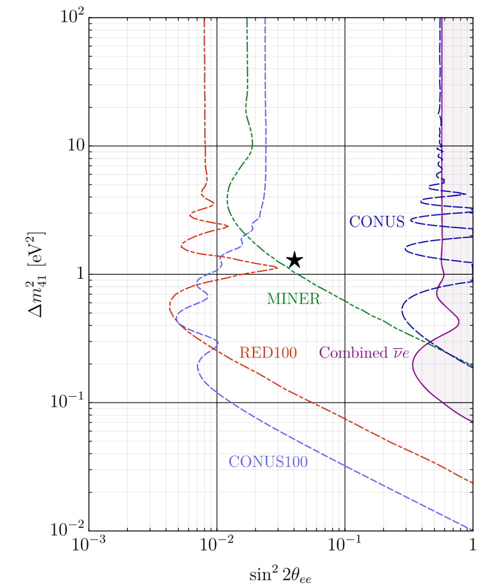
- **Light sterile neutrinos:**
  Use CEνNS for ν flux measurements
- **New fermion searches:**
  Test further ν interactions
  → ν mass, DM, ...
- **Probing portals:**
  ALPs, dark photons, etc.

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



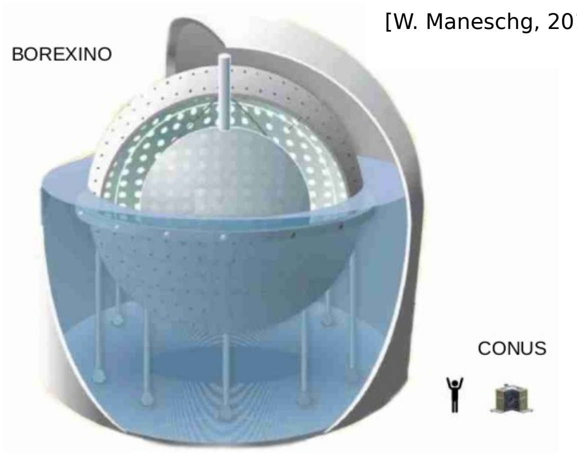
[Aristizabal Sierra et al., 10.1007/JHEP03(2021)294, 2021]





[Berryman, 10.1103/PhysRevD.100.023540, 2019]

Conclusion



- **CEνNS opens new path to high-statistics neutrino physics**
  → beams and reactors complement each other!
  → 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 the CONUS set-up:**
  → environmental stability, new DAQ (lower E_{thr}, pulse shapes)
  → analysis of new data in preparation

→ new experimental site under discussion!

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

[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., arXiv:2110.02174, 2021]
[Bonet et al., arXiv:2112.09585, 2021]
[Bonet et al., arXiv:2201.12257, 2022]
[Bonhomme et al., arXiv:2202.03754, 2022]

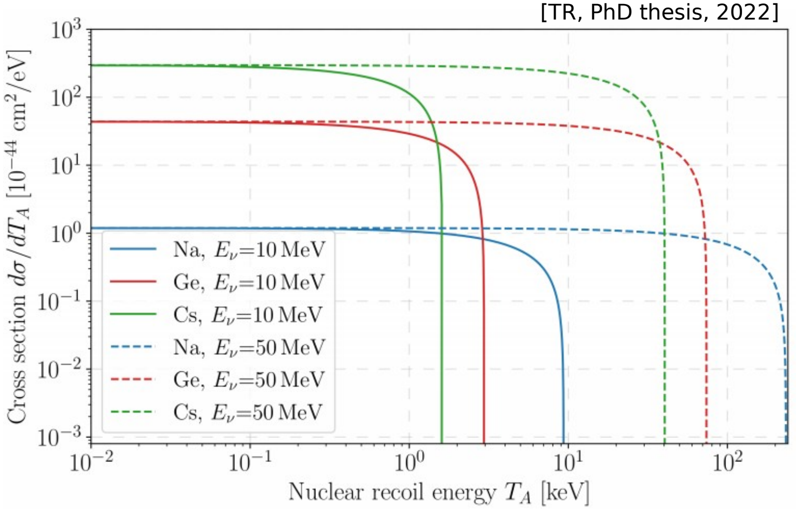
Next-generation experiments (π-DAR, reactors & DM DD) = huge playground for phenomenology

(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

CEνNS with different sources and targets

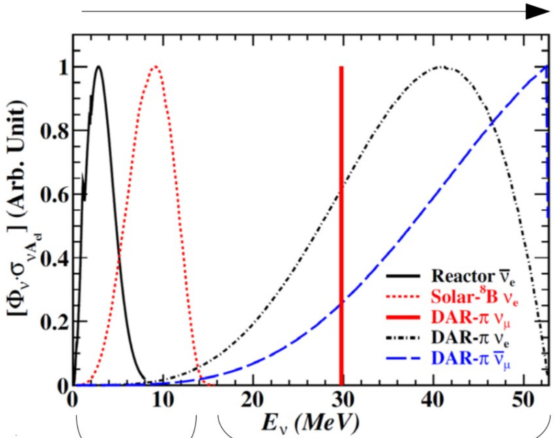
[TR, PhD thesis, 2022]



Element	N	r_A [fm]	E_ν^{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, PhD thesis, 2022]

Loss of coherency



Reactor $\bar{\nu}_e$: fully coherent

Pion decay at rest

4

[W. Maneschg, 2017]

Neutrino source	Target	T_A^{max} [keV]	E (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

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

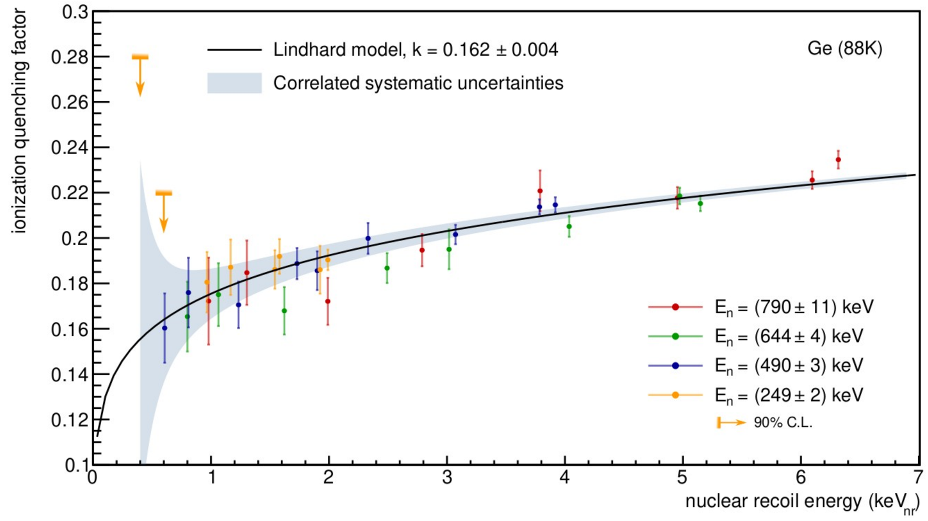
2) Compensate quenching ($E_{recoil} \rightarrow E_{ion}$)

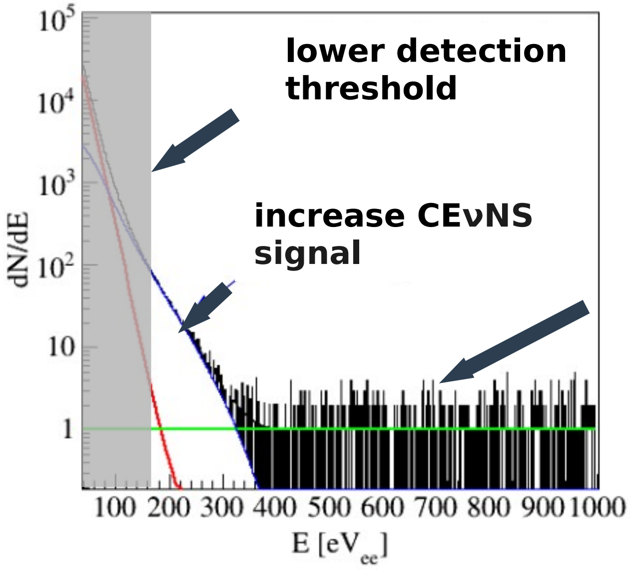
→ lowest possible detection threshold

3) Low background outside lab conditions

→ moderate overburden & limited shielding capacities

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

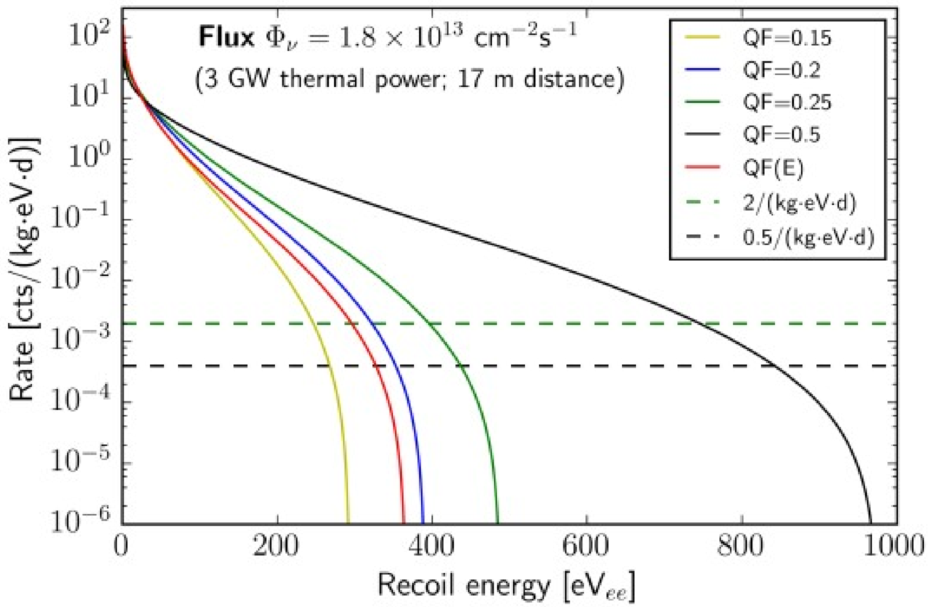




Reduce background level

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

[Lindner, Maneschg, Rink, 2016]

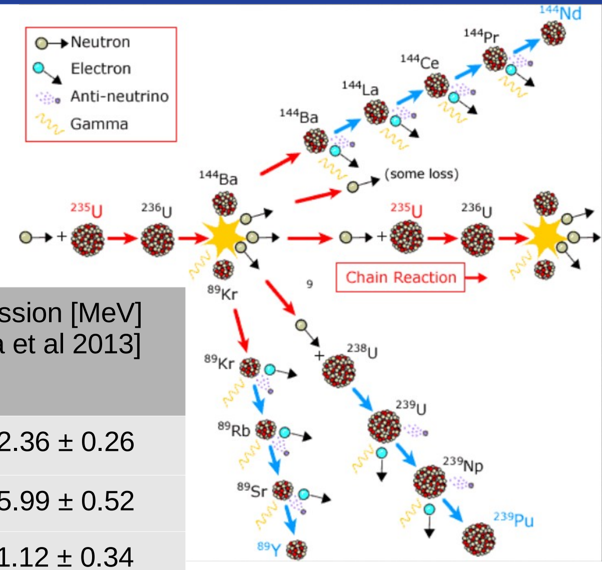


Antineutrinos from nuclear reactions

Antineutrino emission in β decays of fuel reaction chain

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

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

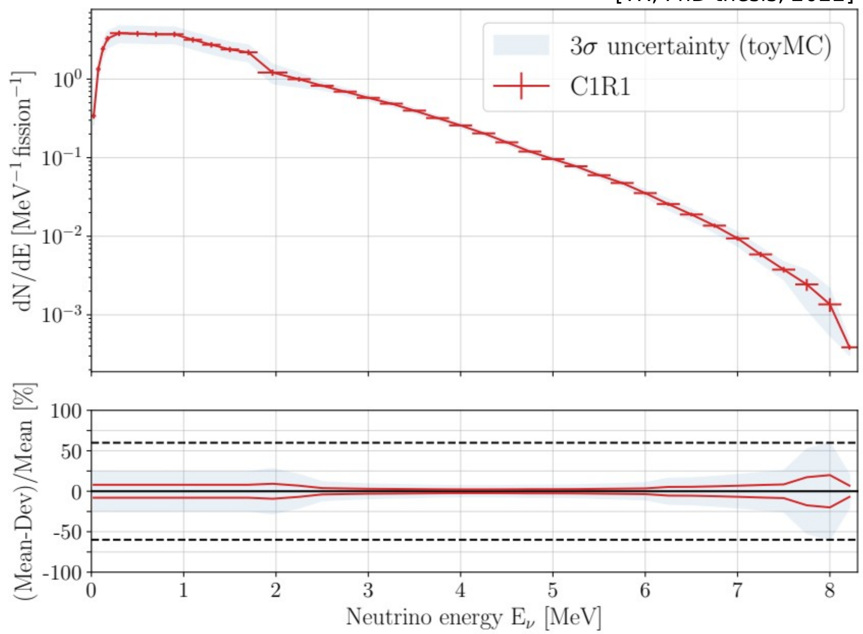


isotope	Fission fraction α (PWR)	E/fission [MeV] [Ma et al 2013]
235U	57%	202.36 ± 0.26
238U	8%	205.99 ± 0.52
239Pu	30%	211.12 ± 0.34
241Pu	5%	214.26 ± 0.33

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, PhD thesis, 2022]

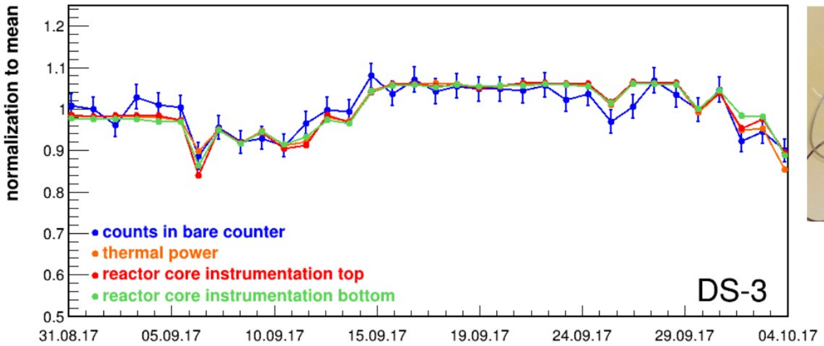


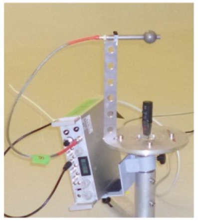
Reality much more complicated...
- Varying reactor power → **P(t)**
- Changing fuel composition → **α(t)**

Power-correlated reactor radiation

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

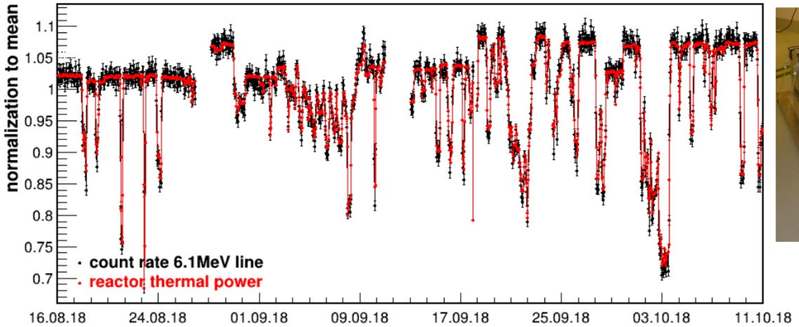
- Simulation and validation of neutrons emitted from reactor core (at CONUS site) → thermal neutron counter



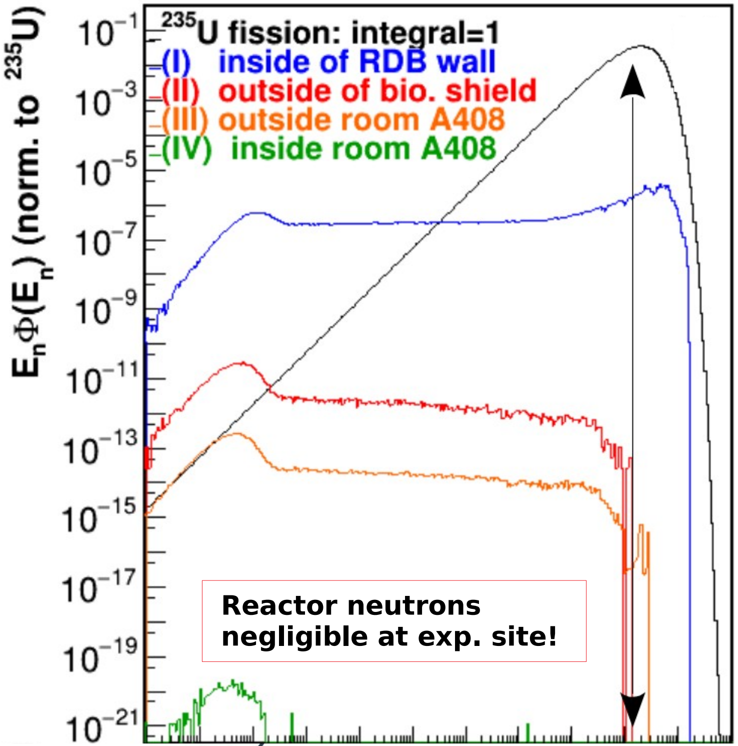


Correlation to incore and excore instrumentation

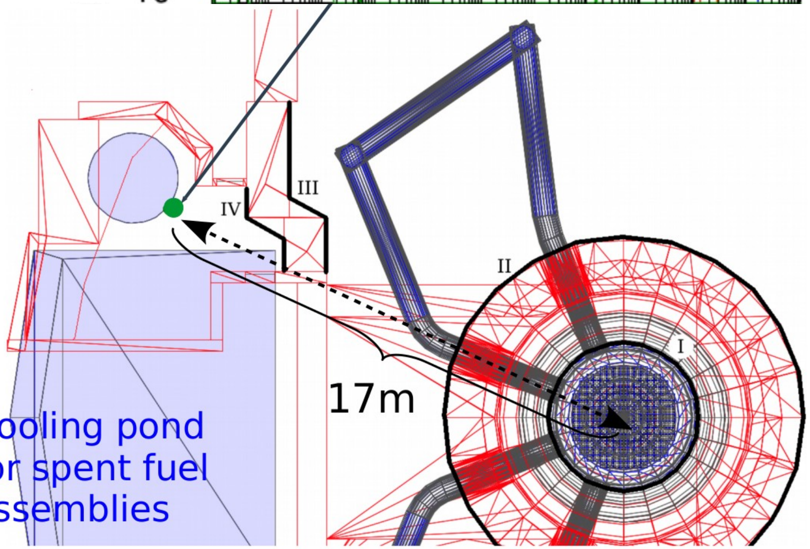
- γ radiation (6.1MeV from ^{16}N)



Unshielded HPGe detector



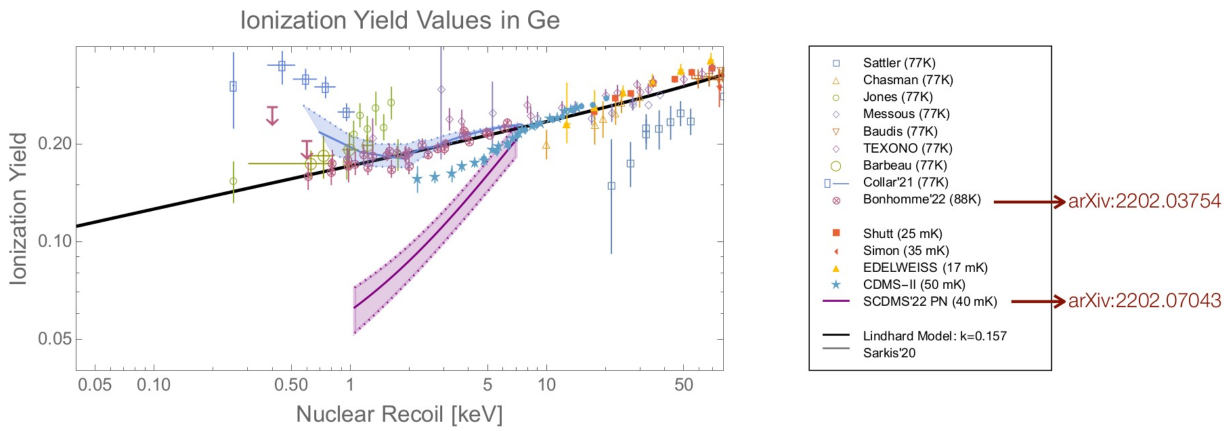
Reactor neutrons negligible at exp. site!



Cooling pond for spent fuel assemblies

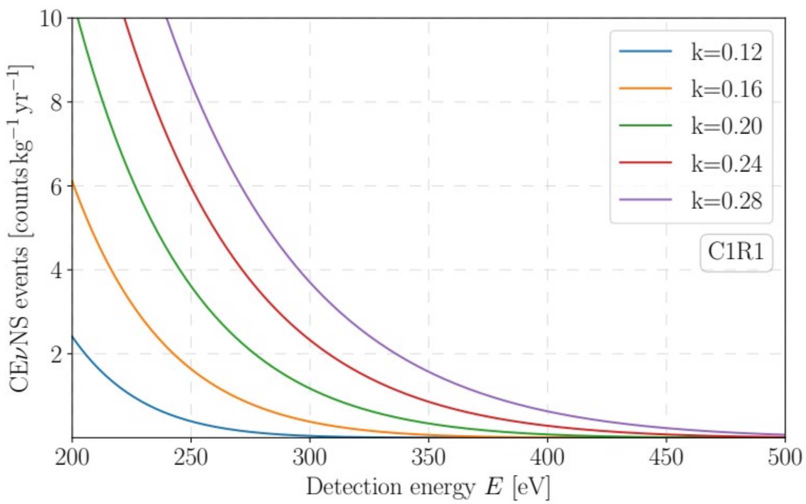
Impact of quenching at low energy

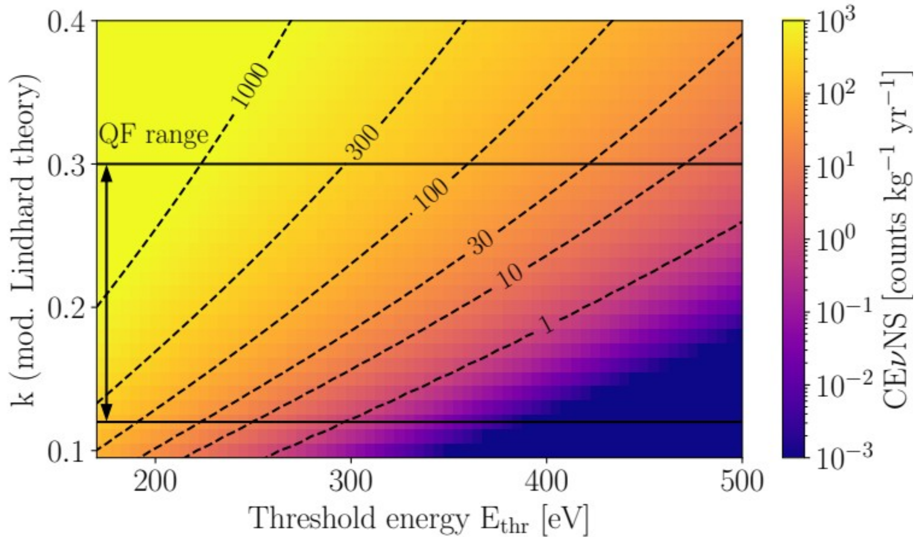
Overview of quenching measurements: T. Saab \ EXCESS 2022 \ February 16, 2022



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:

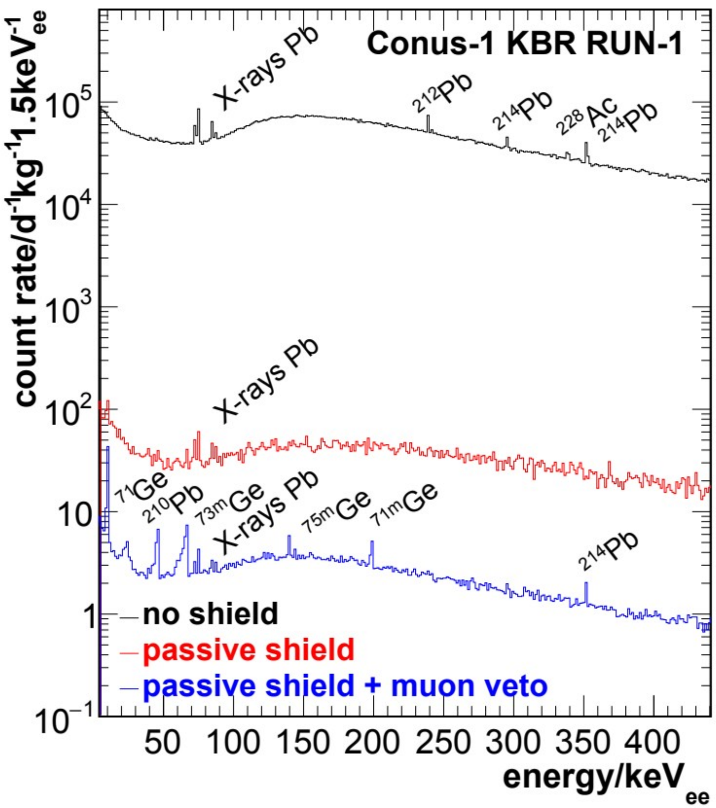


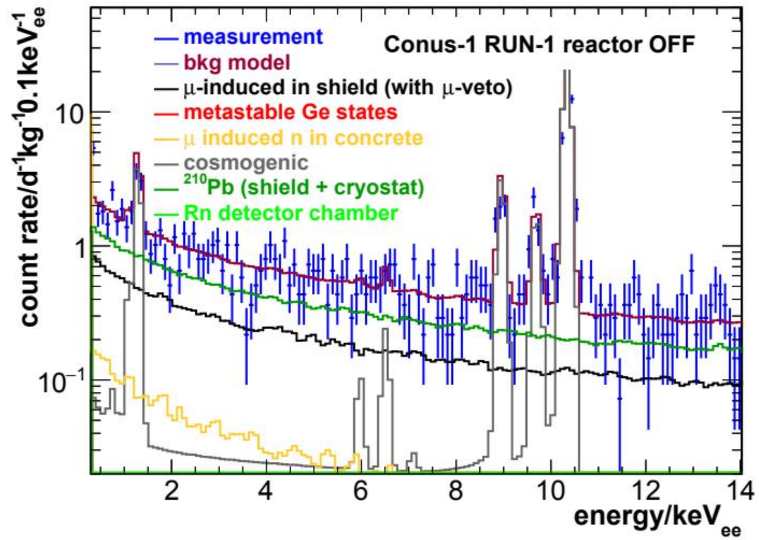


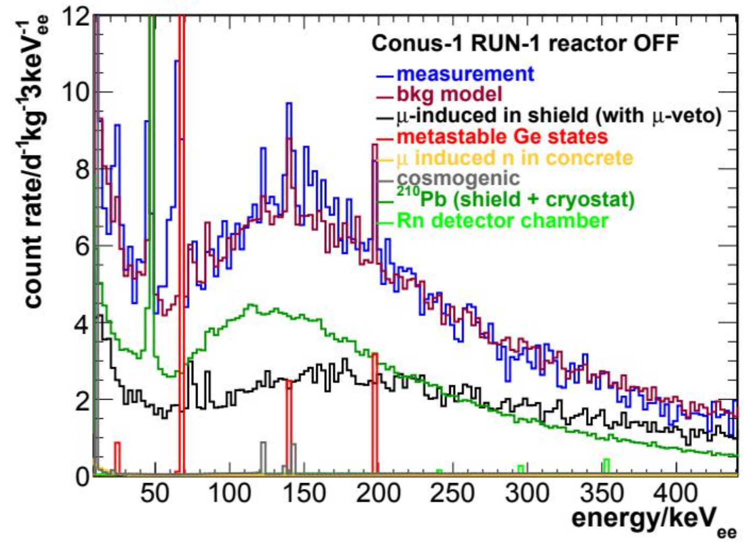
[TR, PhD thesis, 2022]

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:

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

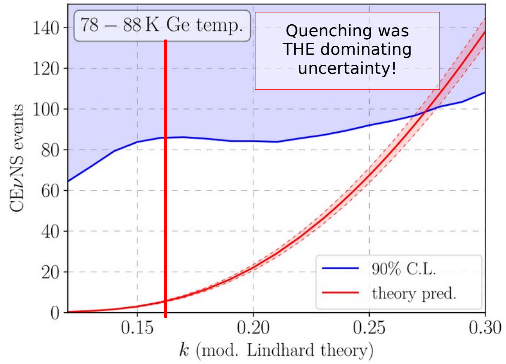
with

$$\log \mathcal{L}_{\mathrm{ON}}(s, b, \Theta_{\mathrm{thr}_1}, \Theta_{\mathrm{thr}_2}, \Theta_{\mathrm{rea}}, \Theta_{\mathrm{det}}, \Theta_{\Delta\mathrm{E}})$$
$$\log \mathcal{L}_{\mathrm{OFF}}(b, \Theta_{\mathrm{thr}_1}, \Theta_{\mathrm{thr}_2}, \Theta_{\mathrm{det}}, \Theta_{\Delta\mathrm{E}})$$

- Parameter list:
  - s: signal strength (free), b: MC normalisation (free)
  - $\Theta_{\mathrm{thr1/2}}$: electronic noise (free)
  - Θ_{rea} : reactor neutrino flux (~3%)
  - Θ_{det} : detector/DAQ (1-5%), $\Theta_{\Delta\mathrm{E}}$: energy scale (10-20 $\mathrm{eV_{ee}}$)

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	



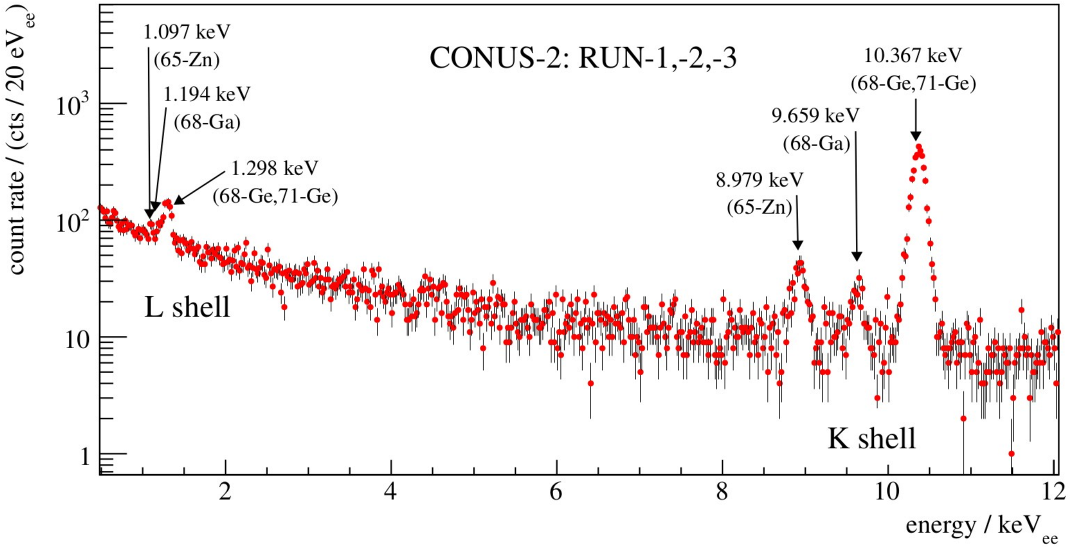
BSM investigations:

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

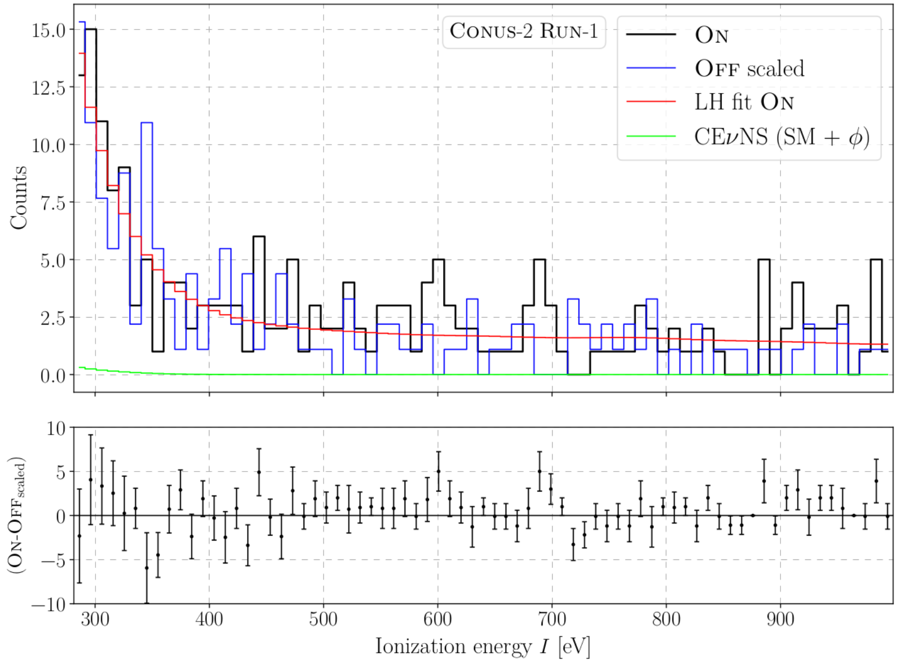
Analysis	Data set	ON [kg d]	OFF [kg d]	ROI [keV]
BSM	C1R1	96.7	13.8	0.276 - 0.741
$(\bar{\nu}_e + A(Z,N))$	C2R1	14.6	13.4	0.281 - 0.999
	C3R1	97.5	10.4	0.333 - 0.991
	all	208.8	37.6	
BSM + νMM	C1R1	215.4	29.6	2.013 - 7.968
$(\bar{\nu}_e + e)$	C2R1	184.6	32.2	2.006 - 7.990
	C3R1	248.5	31.7	2.035 - 7.989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

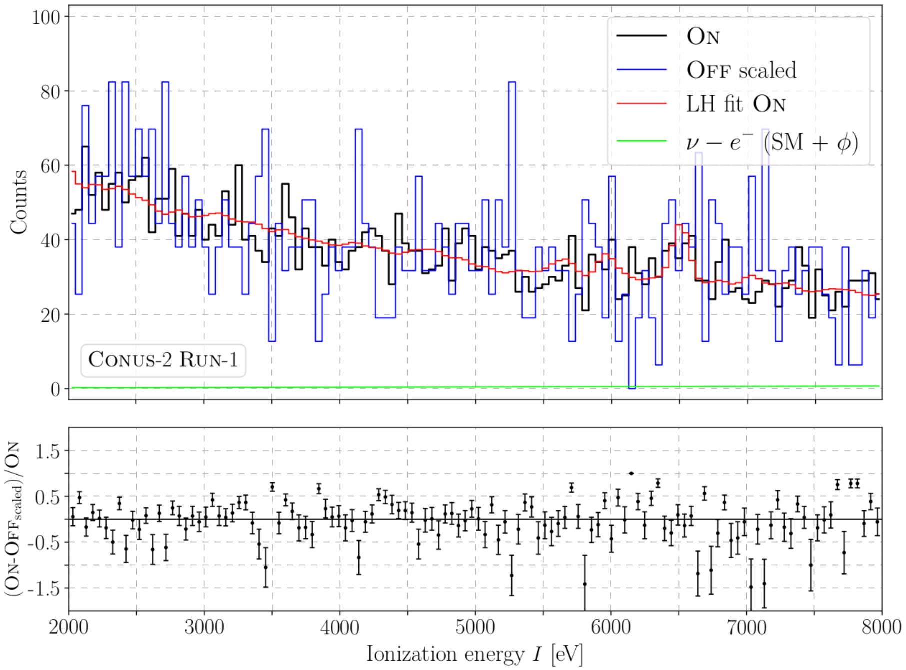
Exemplary spectra: CONUS-2 RUN-1

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



[Bonet et al., arXiv:2110.02174, 2021]





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, PhD thesis, 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!

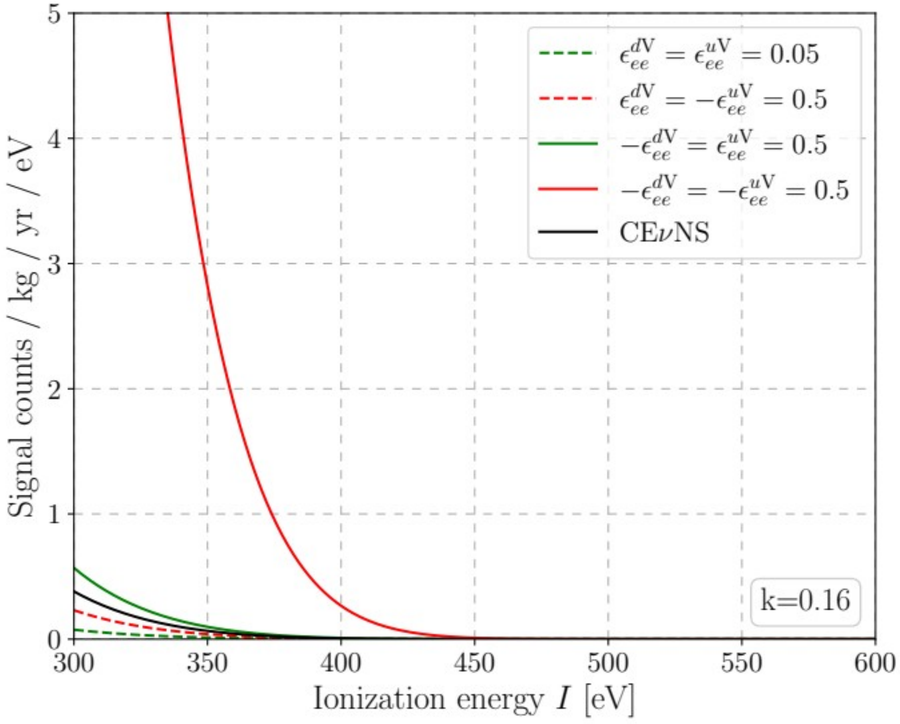
E_{thr} [eV]	CONUS-100 [counts]	Z	V
300	$5.5 \cdot 10^3$	2.1	$227 \cdot 10^{-3}$
275	$9.1 \cdot 10^3$	3.4	$85 \cdot 10^{-3}$
250	$18 \cdot 10^3$	6.8	$22 \cdot 10^{-3}$
225	$33 \cdot 10^3$	12.0	$7 \cdot 10^{-3}$
200	$53 \cdot 10^3$	19.0	$3 \cdot 10^{-3}$

Vector-type NSIs

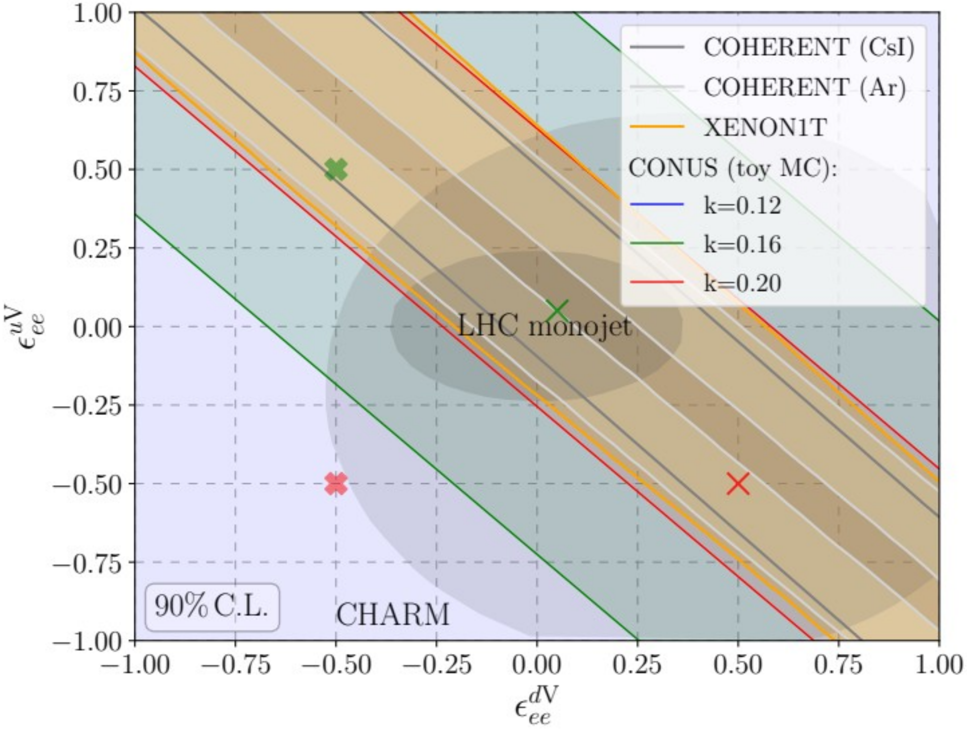
$$\mathcal{O}^{qV}_{\alpha\beta} = (\bar{\nu_\alpha}\gamma^\mu P_L \nu_\beta)\left(\bar{q}\gamma_\mu P_{L/R} q\right) + \text{h.c.}$$

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

Expectation for C1R1



Limits of combined data sets

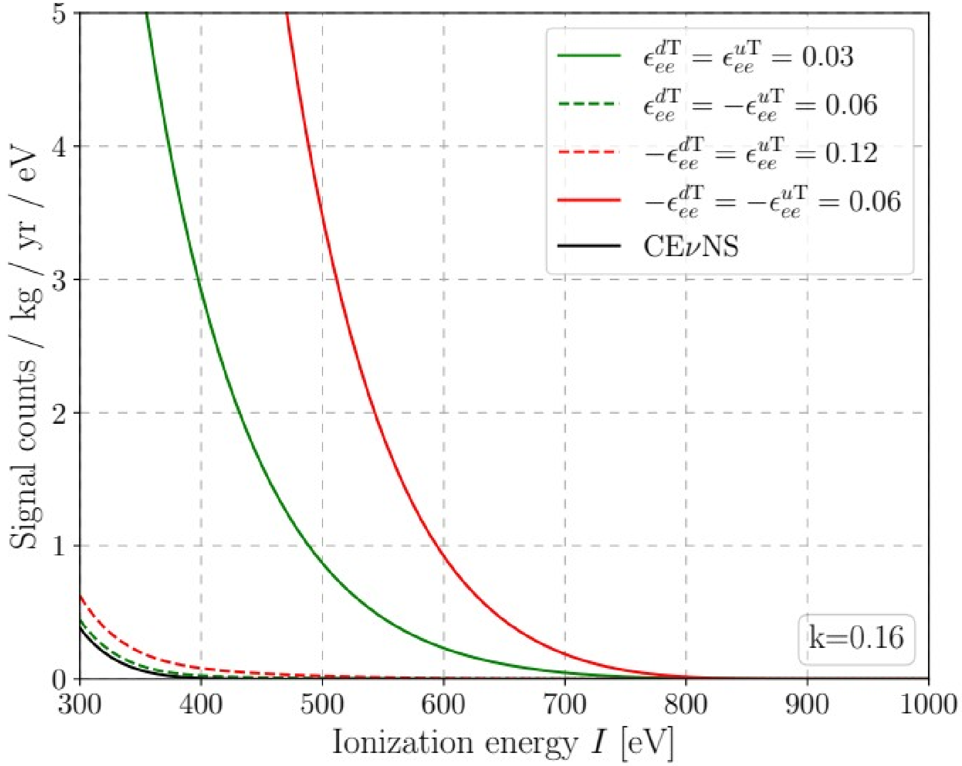


[Bonet et al., arXiv:2110.02174, 2021]

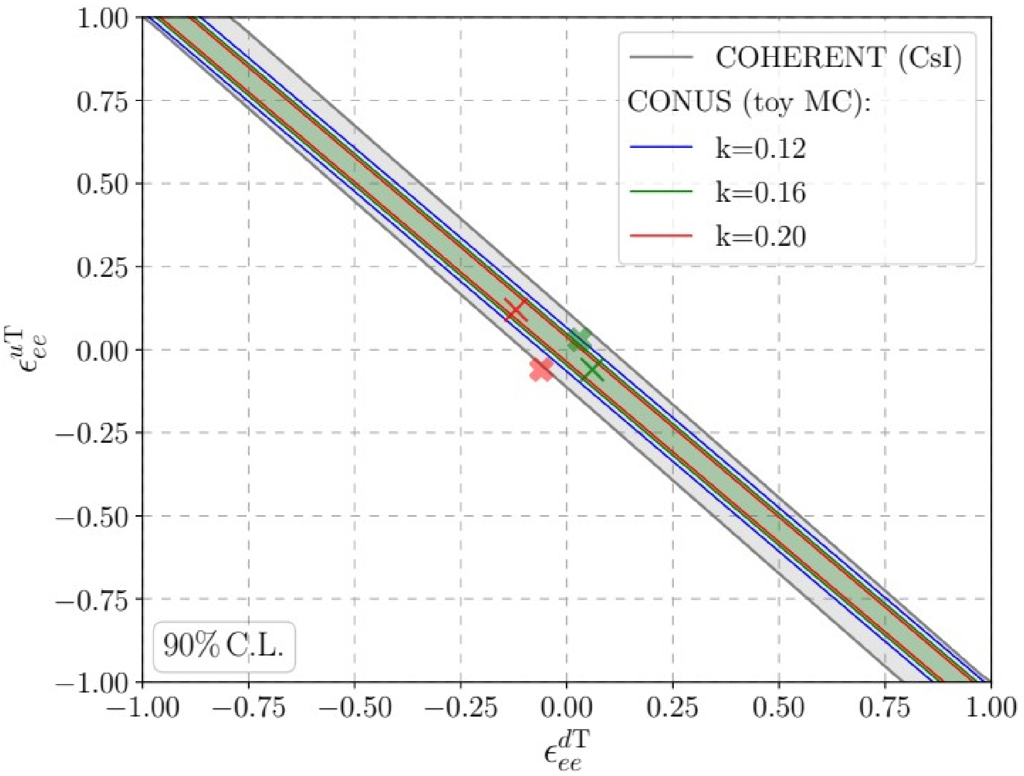
Tensor-type NSIs

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

Expectation for C1R1



Limits of combined data sets

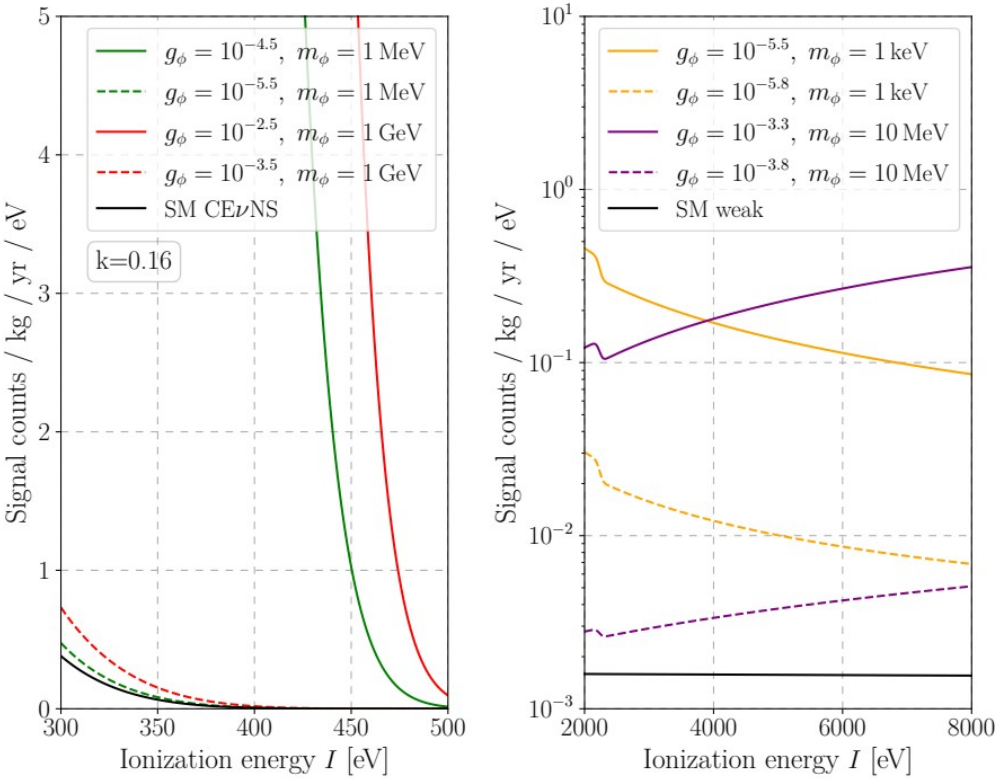


[Bonet et al., arXiv:2110.02174, 2021]

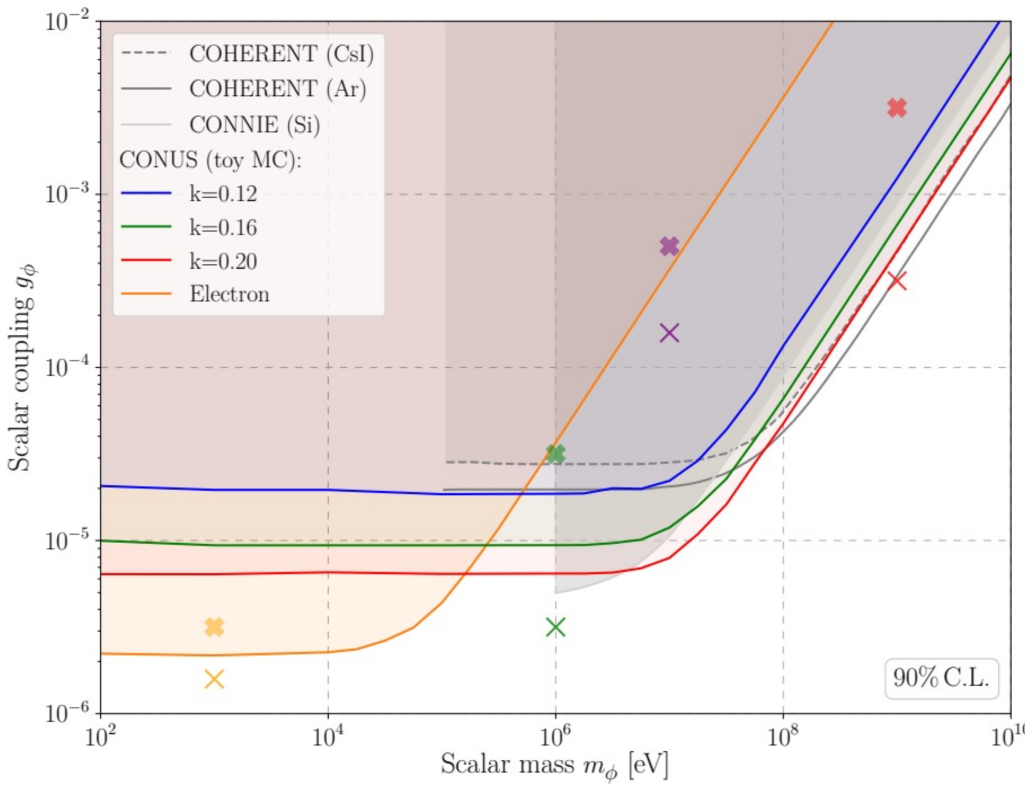
Light scalar mediator

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

Expectation for C1R1



Limits of combined data sets

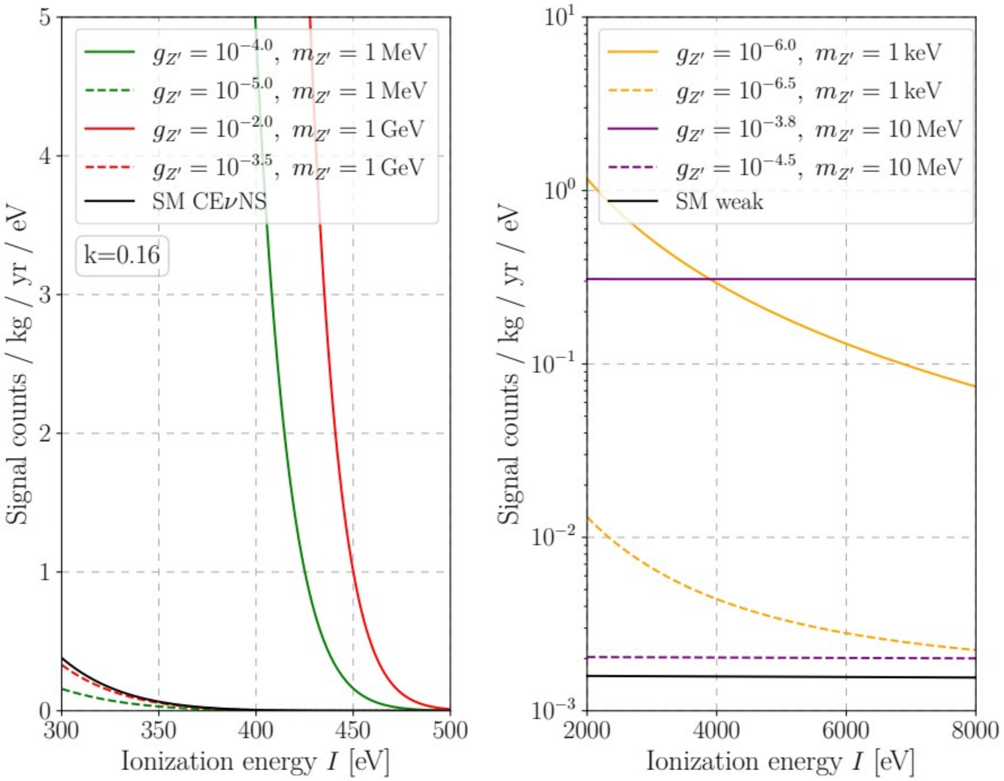


[Bonet et al., arXiv:2110.02174, 2021]

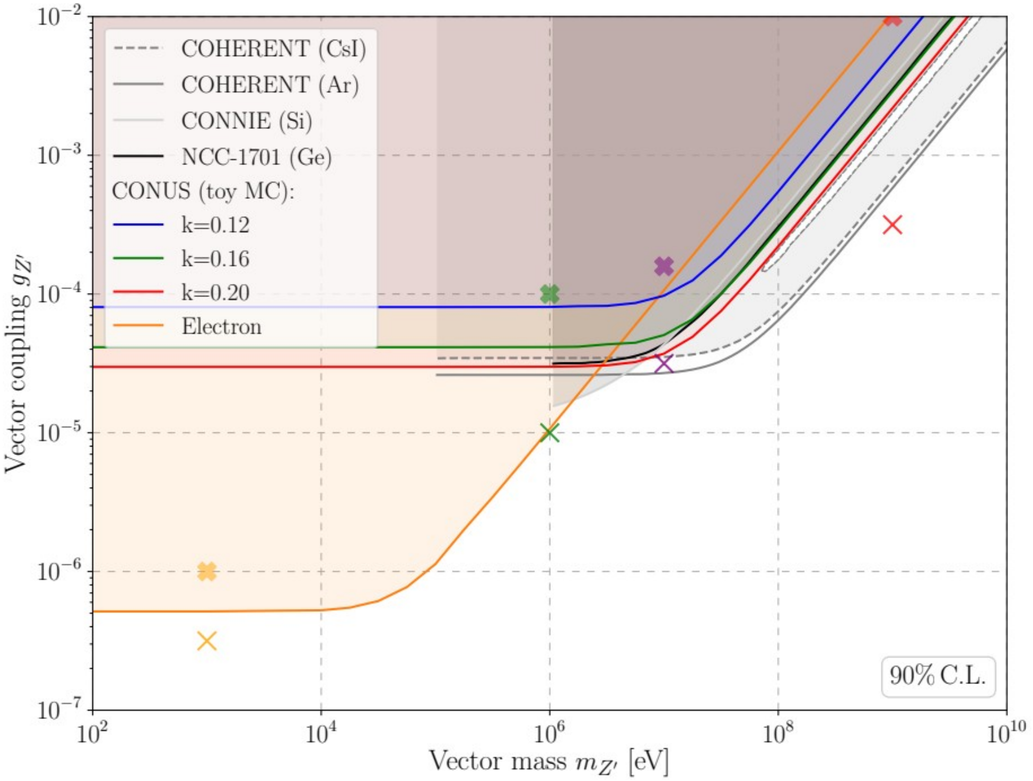
Light vector mediator

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

Expectation for C1R1



Limits of combined data sets



[Bonet et al., arXiv:2110.02174, 2021]