



# Light vector bosons and the weak mixing angle in the light of new reactor-based CEvNS experiments

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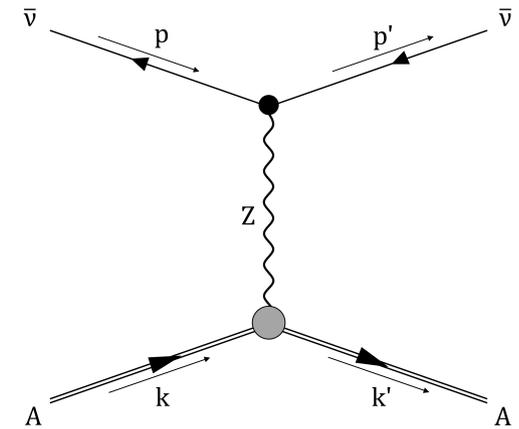
Magnificent CEvNS 2023 Munich  
22 to 29 March 2023



# Coherent elastic neutrino-nucleus scattering (CEvNS)

## CEvNS chronology:

- Daniel Freedman (1974): weak (SM) NC, flavor-blind, threshold-free!
- First detection with  $\pi$ -DAR  $\nu$ 's: COHERENT CsI (2017) & LAr (2021)
- Reactor experiments (2019 - ...):  
CONNIE (Si), CONUS (Ge), NCC-1701 (Ge),  $\nu$ GEN (Ge)
- Additional running and future experiments:  
CCM (Ar), Miver (Ge/Si), NEON (NaI[Tl]),  $\nu$ -cleus (CaWO<sub>4</sub>, Al<sub>2</sub>O<sub>3</sub>),  
RED100 (Xe), Ricochet (Ge/Zn), Texono (Ge), CONUS+ (Ge)



## The Channel:

- Coherence = enhancement  $\sim N^2$

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  $T_A$

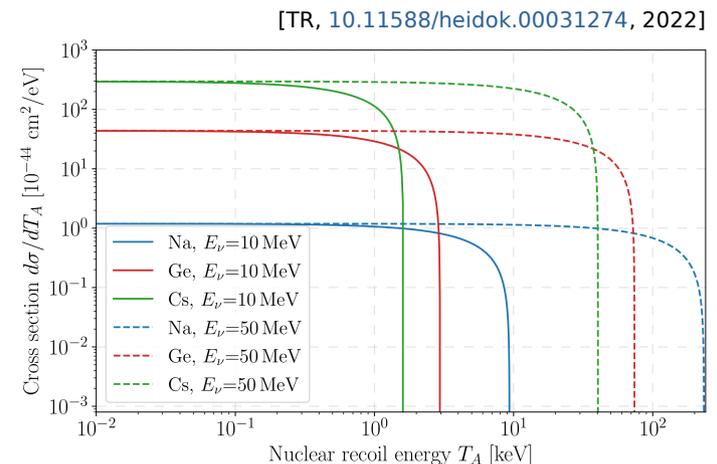
$$\frac{d\sigma}{dT_A} = \frac{G_F^2 m_A}{4\pi} \left[ (1 - 4\sin^2\theta_W)Z - N \right]^2 \left( 1 - \frac{m_A T_A}{2E_\nu^2} \right) F^2(T_A)$$

→ detector material
→ neutrino source  
→ energy threshold / neutrino source

- Very low energy threshold needed:

- $T_A \sim N^{-1}$
- Quenching:  $T_A \rightarrow$  "detectable" energy

Cross section  $\sigma$   
vs.  
nuclear recoil  $T_A$



# The weak mixing angle at low energy

- **SM:**  $SU(2)_L \times U(1)_Y$  + Higgs + renormalizability:

$$\sin^2 \theta_W^0 = e_0^2 / g_0^2 = 1 - m_W^2 / m_Z^2$$

→ respected by renorm. parameters (finite corrections)

- test SM @ quantum level / probe BSM physics

→ precision of  $O(\pm 0.1\%)$  desired!

- At low energy  $\gamma$ -Z interference introduces small degree of parity violation

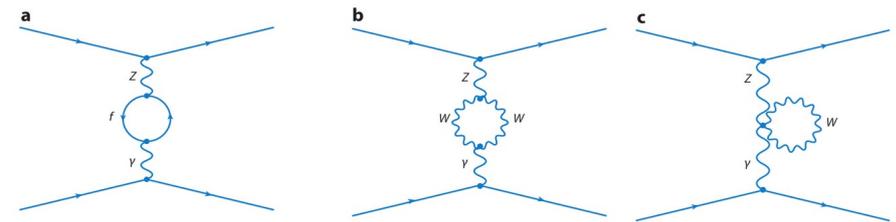
→ current experimental precision  $O(\pm 1\%)$

- Best precision achieved at Z pole:  $O(\pm 0.1\%)$

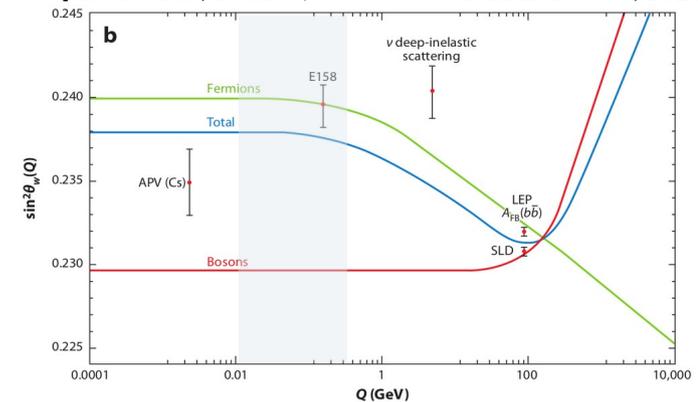
- **BUT** low- $Q^2$  measurements probe kinematic regions where Z pole measurements are insensitive to NP

→ **weakly-coupled light vector boson:**

dark parity violation / dark Z'



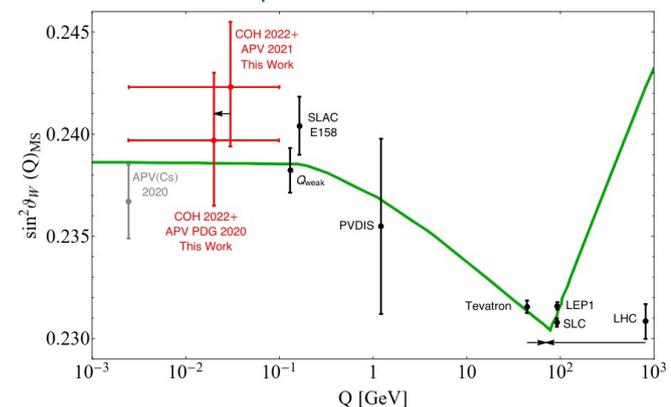
[Kumar et al., 10.1146/annurev-nucl-102212-170556, 2013]



$$\Delta \sin^2 \theta_W(Q^2) \simeq -0.42 \varepsilon \delta \frac{m_Z}{m_{Z_d}} \left( \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2} \right)$$

COHERENT  
(Cs+Ar)

[Cadeddu et al., 10.1103/PhysRevD.102.015030, 2020; Corona et al., 2303.09360, 2023]



# Assume a COvUS-like experiment

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

## Reactor: commercial nuclear power plant

- Experimental site  $\sim 20$  m to  $3.5 \text{ GW}_{\text{th}}$
- $\nu$  flux:  $\sim 1.5 \cdot 10^{13} / \text{cm}^2/\text{s}$  with 3% uncertainty
- Typical PWR fuel composition:  
56.1% U235, 7.6% U238, 30.7 Pu239, 5.6% Pu241

## Background

- No critical reactor-correlated bkg!
- Background levels:
  - 10 cnts/keV/d/kg for  $E_{\text{ion}} \leq 1 \text{ keV}$
  - 0.5 cnts/keV/d/kg for  $E_{\text{ion}} > 1 \text{ keV}$

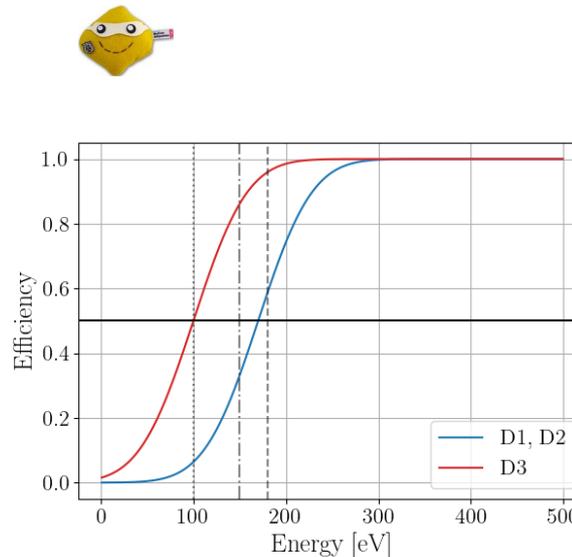
## Detectors:

- Data collection:  $t_{\text{OFF}} = 0.5 \cdot t_{\text{ON}}$

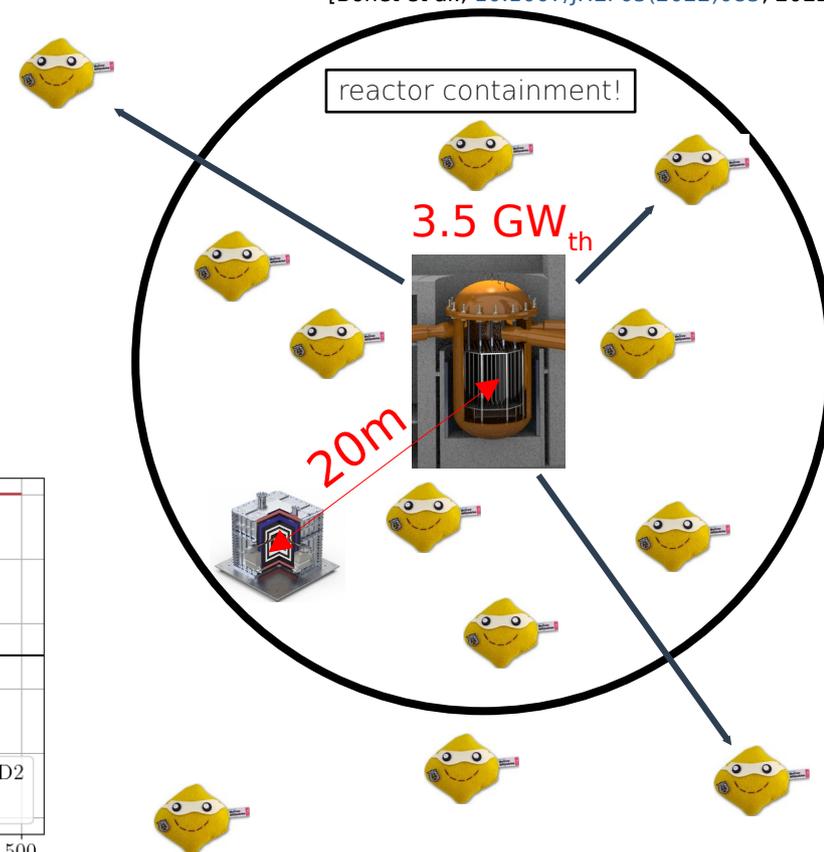
**R1** -  $\text{exp}_{\text{ON}} = 5 \text{ kg}\cdot\text{yr}$

**R2** -  $\text{exp}_{\text{ON}} = 50 \text{ kg}\cdot\text{yr}$

**R3** -  $\text{exp}_{\text{ON}} = 500 \text{ kg}\cdot\text{yr}$



[Bonhomme et al., 10.1140/epjc/s10052-022-10768-1, 2022]



- COvUS HPGe detectors with improved trigger efficiency:

$$E_{\text{thr}} \sim 3 \cdot \text{FWHM}_{\text{pulsar}}$$

- Quenching according to Lindhard model

Detector	Threshold $E_{\text{thr}}$
D1 (conservative)	180 eV
D2 (expected)	150 eV
D3 (optimistic)	100 eV



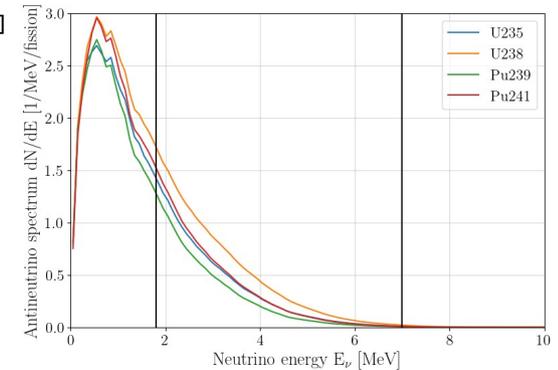
[particlezoo.net, 2023]

# Reactor antineutrino spectrum: data-driven approach

[Estienne et al., 10.1103/PhysRevLett.123.022502, 2019]

## 1) Low energy region $E < 1.8$ MeV:

Summation spectra of Estienne et al. (2019)



## 2) Intermediate energy $1.8 \text{ MeV} \leq E < 7 \text{ MeV}$

Daya Bay (2021):

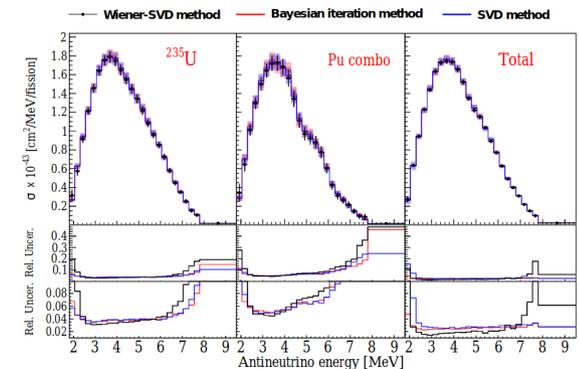
- unfolded IBD spectra of U235, (Pu239+ Pu241), total
- method to construct data-based predictions

$$S_{\text{pred}} = R \cdot \begin{pmatrix} S_{\text{total}} \\ S_{235} \\ S_{\text{combo}} \\ S_{238} \\ S_{241} \end{pmatrix} \quad R = \left( I_{25} \mid \Delta f_{235} I_{25} \mid \Delta f_{239} I_{25} \mid \Delta f_{238} I_{25} \mid (\Delta f_{241} - 0.183 \times \Delta f_{239}) I_{25} \right)$$

Difference in fission fractions

$\longrightarrow$  Mueller  
 $\longrightarrow$  Huber

Extend with bin-to-bin uncorrelated uncertainties: 10% Huber, 15% Mueller

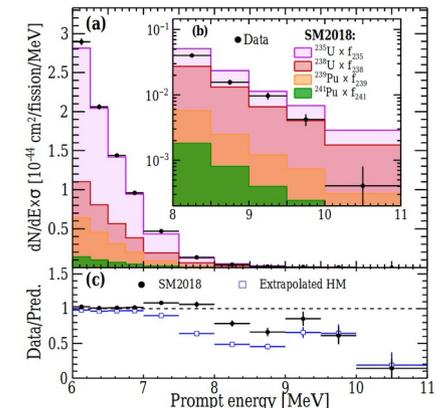


[An et al., 10.1088/1674-1137/abfc38, 2021]

## 3) High energy $E \geq 7$ MeV:

Daya Bay measurement of combined high energy spectrum (2022)

→ Application of Daya Bay data-based method with Estienne et al. spectra



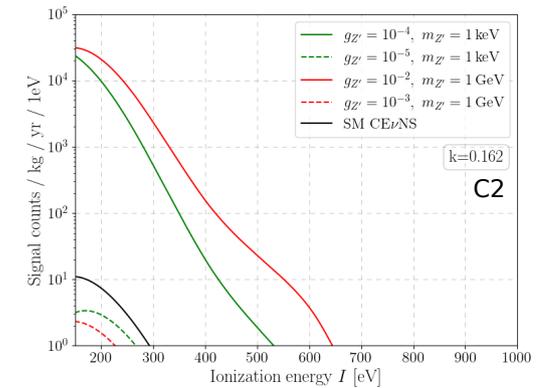
[An et al., 10.1103/PhysRevLett.129.041801, 2022]

Spectra also used in current COvUS analysis!

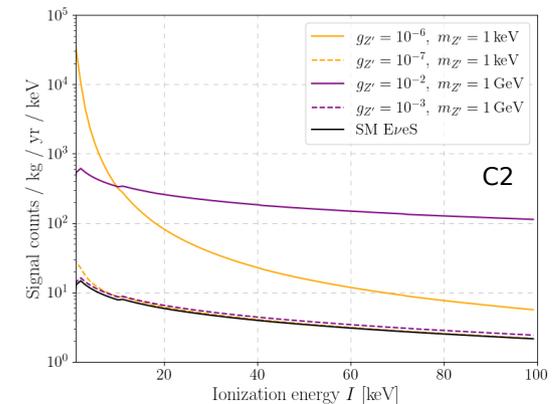
# Sensitivity determination

## (Binned log-) Likelihood function:

- ON and OFF data are fitted together:  
 $\log \mathcal{L} = \log \mathcal{L}_{\text{ON}} + \log \mathcal{L}_{\text{OFF}} + \text{pull term}$   
 with  $\log \mathcal{L}_{\text{ON}}(\sin^2 \theta_W, g_{Z'}, m_{Z'}; b_{\text{CE}\nu\text{NS}}, b_{\text{E}\nu\text{eS}}, \Phi_{\bar{\nu}}, k)$   
 $\log \mathcal{L}_{\text{OFF}}(b_{\text{CE}\nu\text{NS}}, b_{\text{E}\nu\text{eS}})$
- Parameter list:
  - Weinberg angle  $\sin^2 \theta_W$
  - Z' model parameters  $g_{Z'}, m_{Z'}$
  - bkg normalizations  $b_{\text{CE}\nu\text{NS}}, b_{\text{E}\nu\text{eS}}$
  - reactor neutrino flux ( $\sim 3\%$ )  $\Phi_{\bar{\nu}}$
  - parameter of Lindhard model ( $\sim 1\%$ )  $k$
- profile LH ratio for limits +  $\chi^2$ -distribution of test statistic
- Sensitivity estimates via two methods:
  - Asimov data set
  - MC sampling + median average of limits



CEvNS > 180eV -  $5.4 \cdot 10^2$  /kg/yr  
 CEvNS > 150eV -  $8.5 \cdot 10^2$  /kg/yr  
 CEvNS > 100eV -  $39 \cdot 10^2$  /kg/yr  
 EveS > 180eV -  $4.4 \cdot 10^2$  /kg/yr



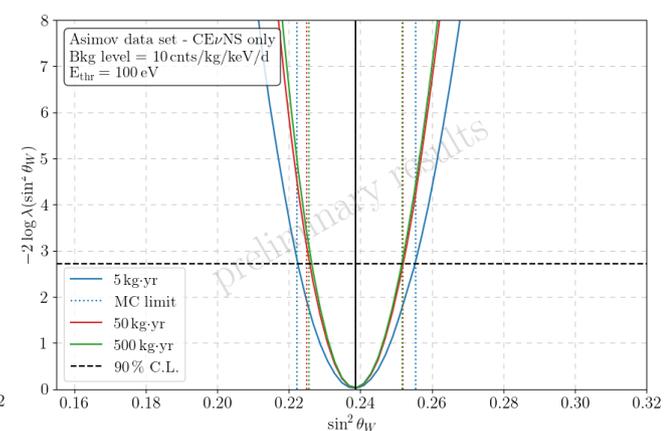
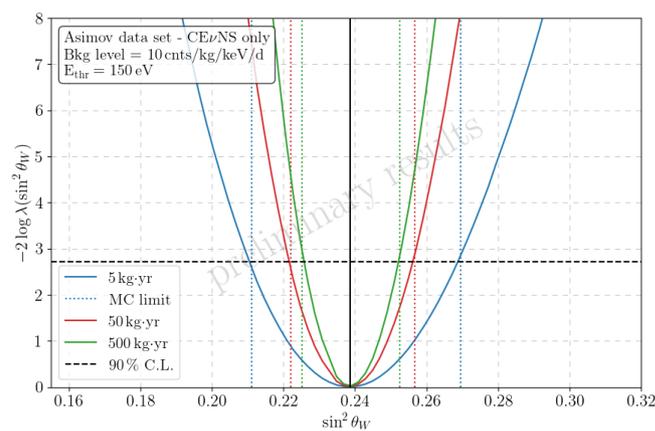
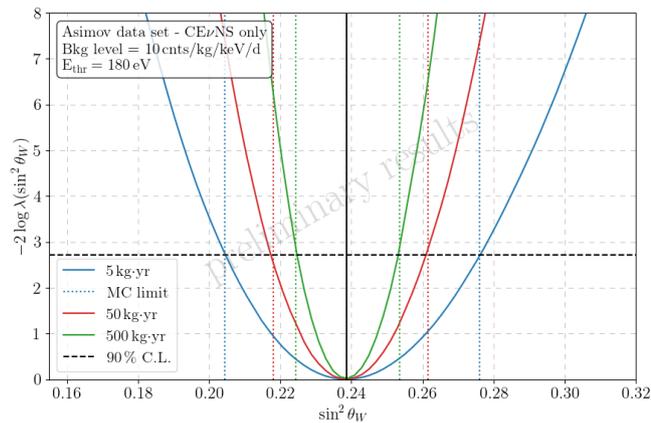
Sensitivity to the Weinberg angle  
 CEvNS -  $E_{\text{ion}} < 1\text{keV}$

Sensitivity to a light vector boson:  
 CEvNS -  $E_{\text{ion}} < 1\text{keV}$   
 EveS -  $E_{\text{ion}} < 100\text{keV}$

# Future Weinberg angle sensitivity

## $\Delta\chi^2$ contours for different mass and threshold configurations:

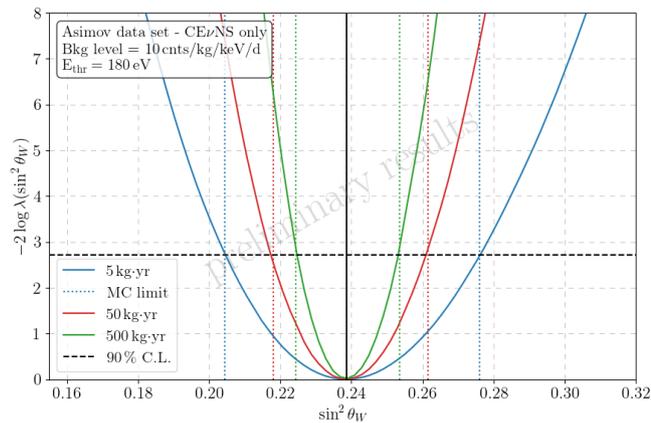
- EveS only is generally not competitive
- Combined analyses dominated by sensitivity below 1keV  $\rightarrow$  CE $\nu$ NS only
- 



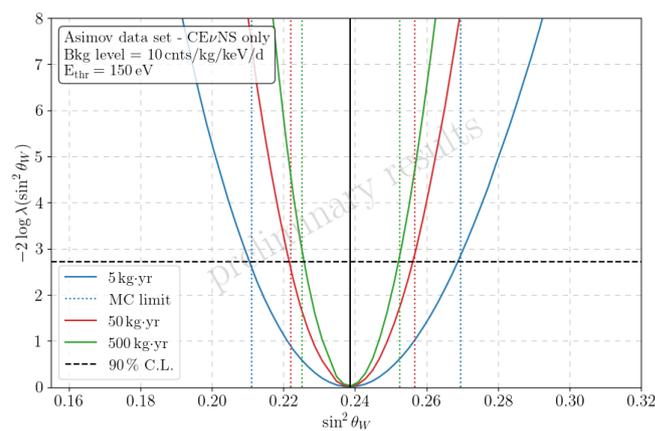
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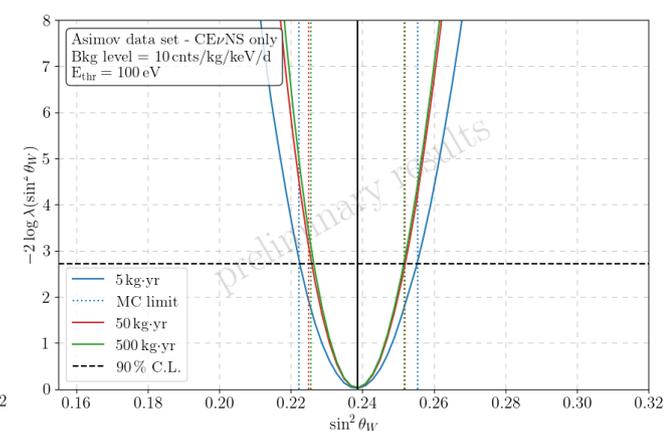
- EveS only is generally not competitive
- Combined analyses dominated by sensitivity below 1keV  $\rightarrow$  CEvNS only
- Sensitivity for current experimental configuration limited by systematics:  $\sim 5\%$  relative uncertainty



Exposure	Rel. uncertainty
5 kg*yr	(-14; +16) %
50 kg*yr	$\pm 9$ %
500 kg*yr	$\pm 6$ %



Exposure	Rel. uncertainty
5 kg*yr	(-12; +13) %
50 kg*yr	$\pm 7$ %
500 kg*yr	(-5; + 6) %



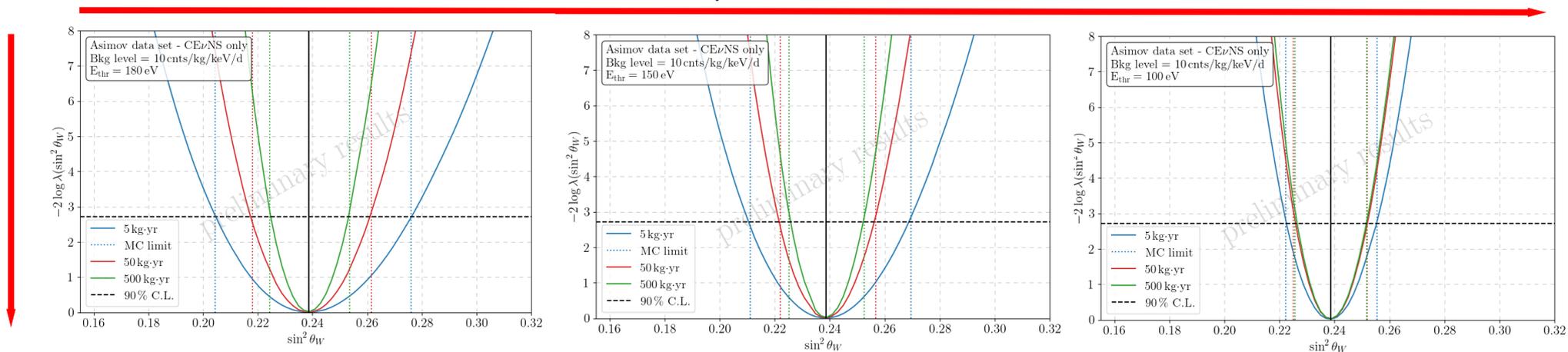
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- EveS only is generally not competitive
- Combined analyses dominated by sensitivity below 1keV  $\rightarrow$  CEvNS only
- Sensitivity for current experimental configuration limited by systematics:  $\sim 5\%$  relative uncertainty

“Realistic” improvement:  $\sim 4-7\%$  relative



“Realistic” improvement:  $\sim 5\%$  relative

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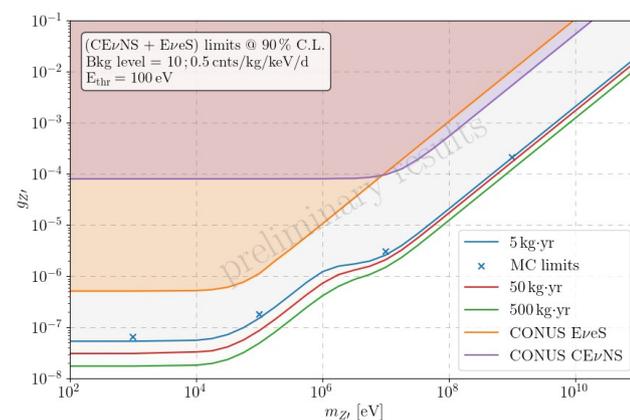
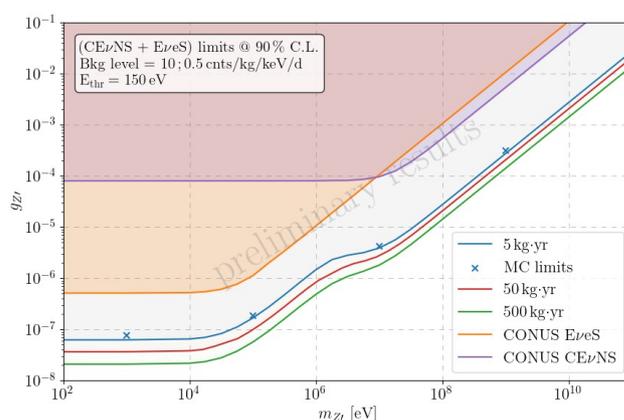
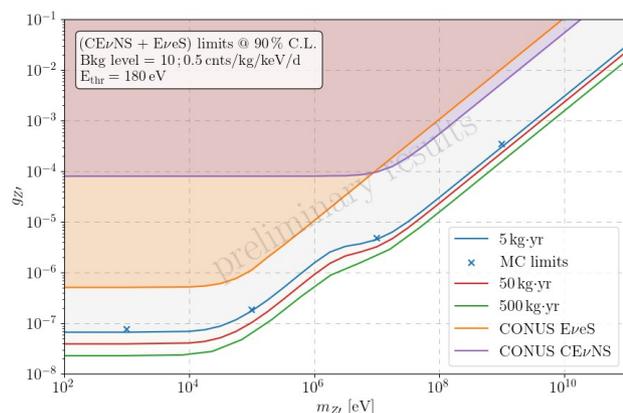
# Future light vector sensitivity

## Simplified mediator model → contribution to CEνNS / EveS

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

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

- Assume universal coupling to quarks / electron / neutrinos:  $(m_{Z'}, g_{Z'})$
- EveS more sensitive towards lowest mediator masses:  $m_e$  vs.  $m_{Ge}$  [Bonet et al., 10.1007/JHEP05(2022)085, 2022]
- COvUS benchmark points (keV, GeV): EveS -  $(5.2 \cdot 10^{-7}, 1.1 \cdot 10^{-2})$ ; CEνNS -  $(8.1 \cdot 10^{-5}, 5.4 \cdot 10^{-3})$



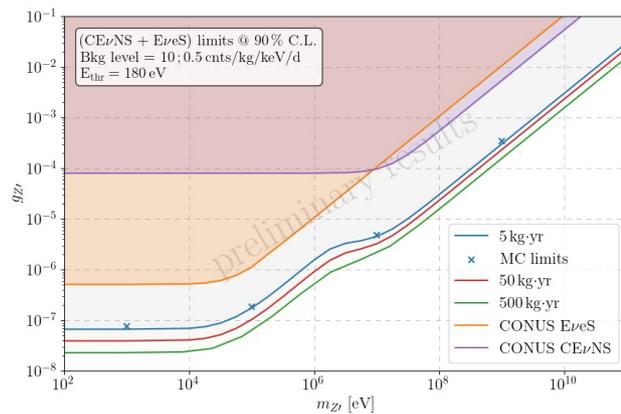
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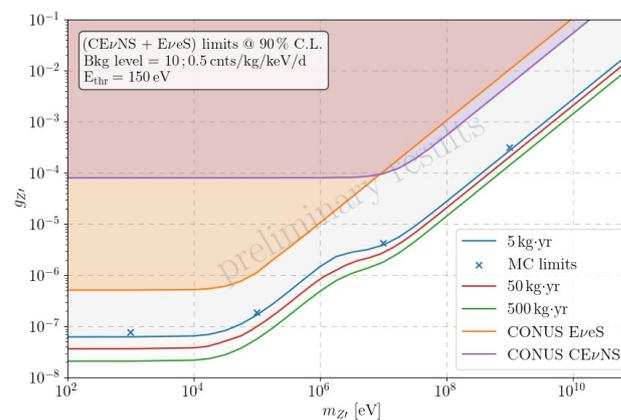
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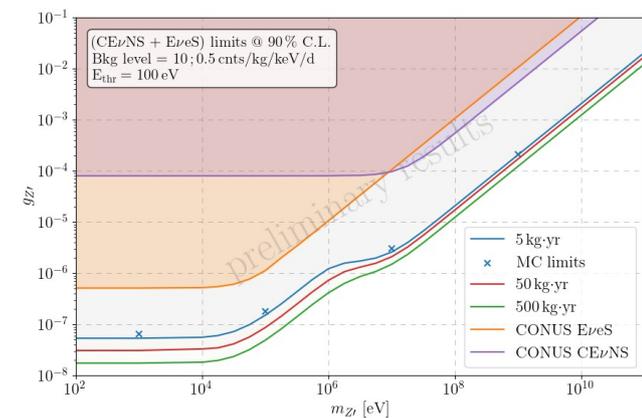
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Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$6.7 \cdot 10^{-8}$	$3.0 \cdot 10^{-4}$
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Exposure	Limit @ keV	Limit @ GeV
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50 kg*yr	$3.1 \cdot 10^{-8}$	$1.7 \cdot 10^{-4}$
500 kg*yr	$1.8 \cdot 10^{-8}$	$1.2 \cdot 10^{-4}$

# Future light vector sensitivity

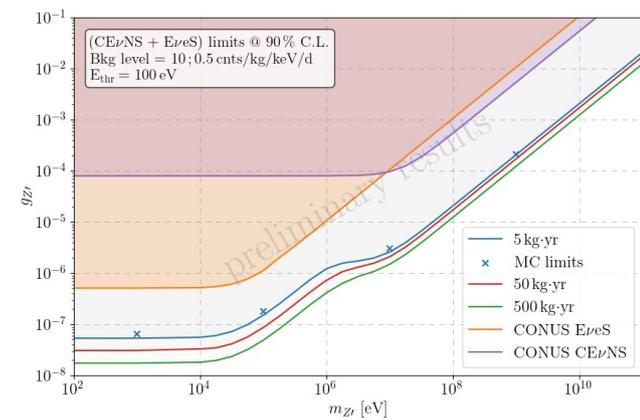
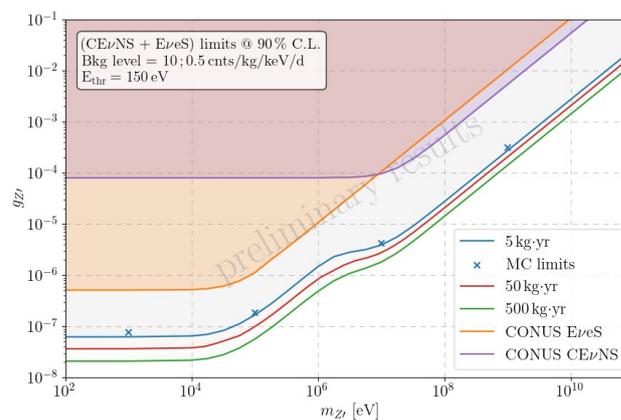
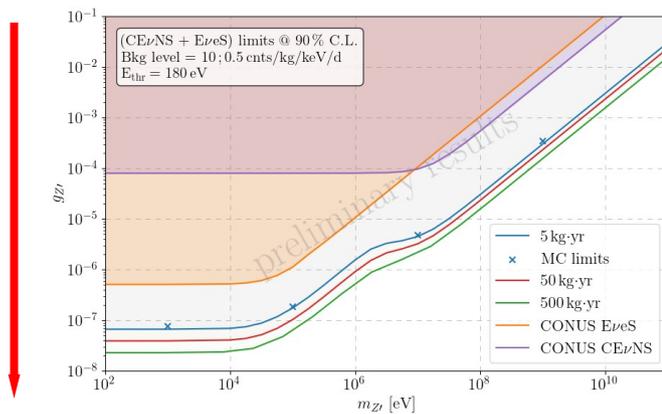
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“Realistic” improvements: CEνNS~25-30%, EνeS~20-22%



“Real.” improv.:  
EνeS~41%  
CEνNS~20-25%

Exposure	Limit @ keV	Limit @ GeV
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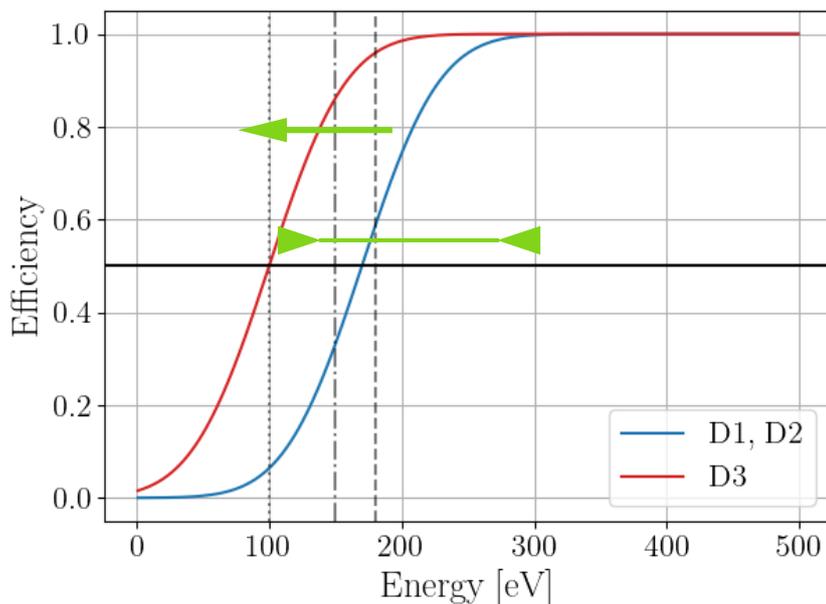
Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

# Outlook: Future Ge detectors at reactor sites

## Progress for kg-size Ge detectors @ reactor sites

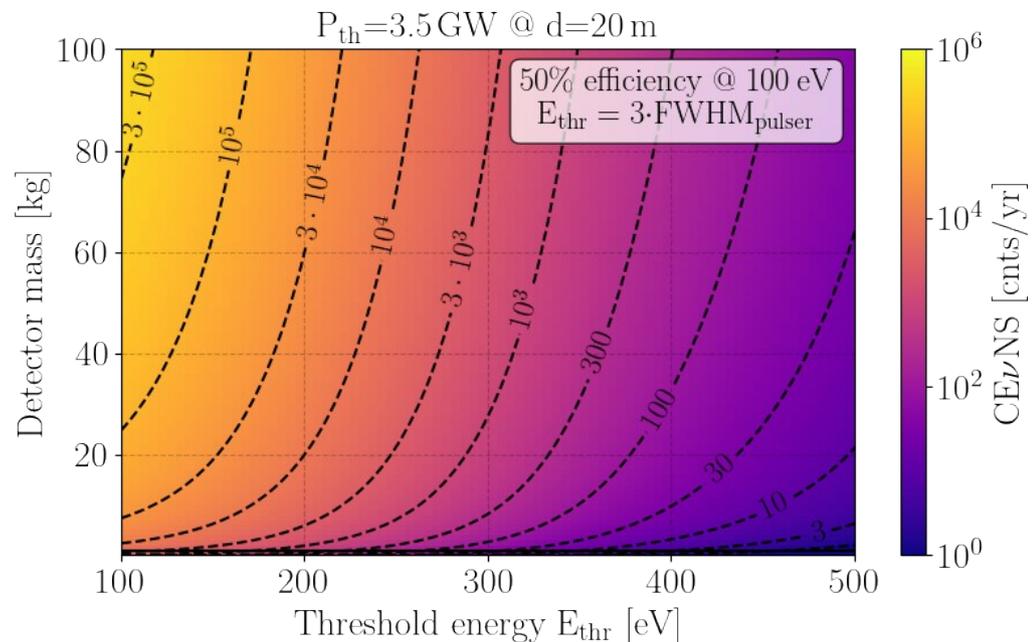
Experimental perspective (single diode):

- Improve pulser width  $\text{FWHM}_{\text{pulser}}$   
→ improves  $E_{\text{thr}} \sim 3 \cdot \text{FWHM}_{\text{pulser}}$  !
- Improve trigger efficiency  
→ record more events in critical region!
- Background and environmental stability at experimental site  
→ increases exposure



Theoretical perspective (whole set-up):

- Energy threshold and exposure are key for a strong CEvNS signal / BSM reach
- Trade-off between reactor flux and background
- Incorporate major uncertainties in SM and BSM studies!



# Conclusion

- **CEvNS 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!
- **Sensitivity estimates for the next-generation of Ge-based reactor experiments**
  - Weinberg angle:
    - ~**5% improved relative uncertainty** for improved threshold or increased exposure
    - limitation by **systematics!**
  - Light vector bosons (universal coupling): **→ More to appear soon!**
    - improved threshold: **EveS~20%, CEvNS~25-30%**
    - higher exposure: **EveS~41%, CEvNS~20-25%**
- **HPPC Ge detectors offer a scalable technology also in critical environments**
  - diode level: energy threshold **and** trigger efficiency are crucial!
  - experiment level: exposure via multiple diodes?
  - deviations in Ge **quenching (description)** needs to be resolved for reliable signal prediction!
- **Brace yourselves, CONUS RUN-5 SM & BSM analyses are coming!**

**Thank You!**

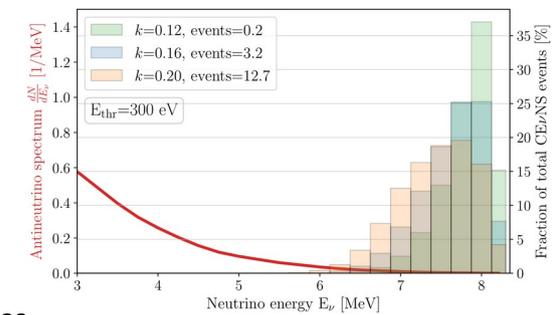
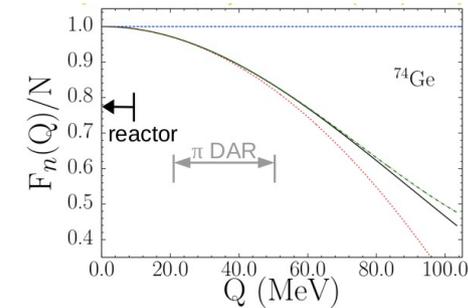
# Backup

# Opportunities for CEνNS experiments

## SM investigations with enhanced precision:

- **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

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

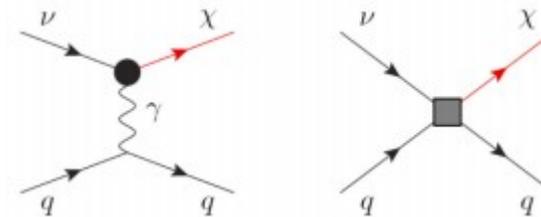


[TR, 10.11588/heidok.0031274, 2022]

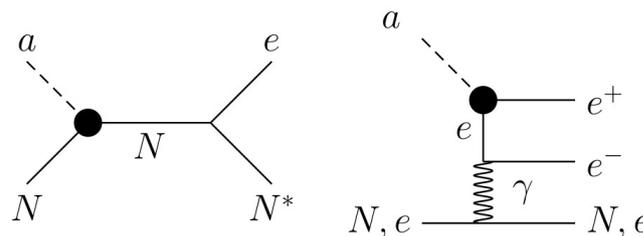
## BSM investigations:

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

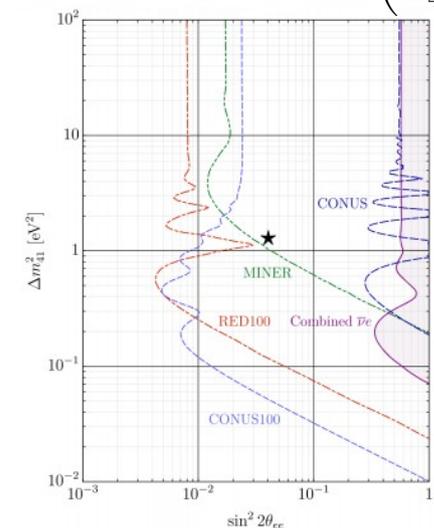
[Chang & Liao, 10.1103/PhysRevD.102.075004, 2022]



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

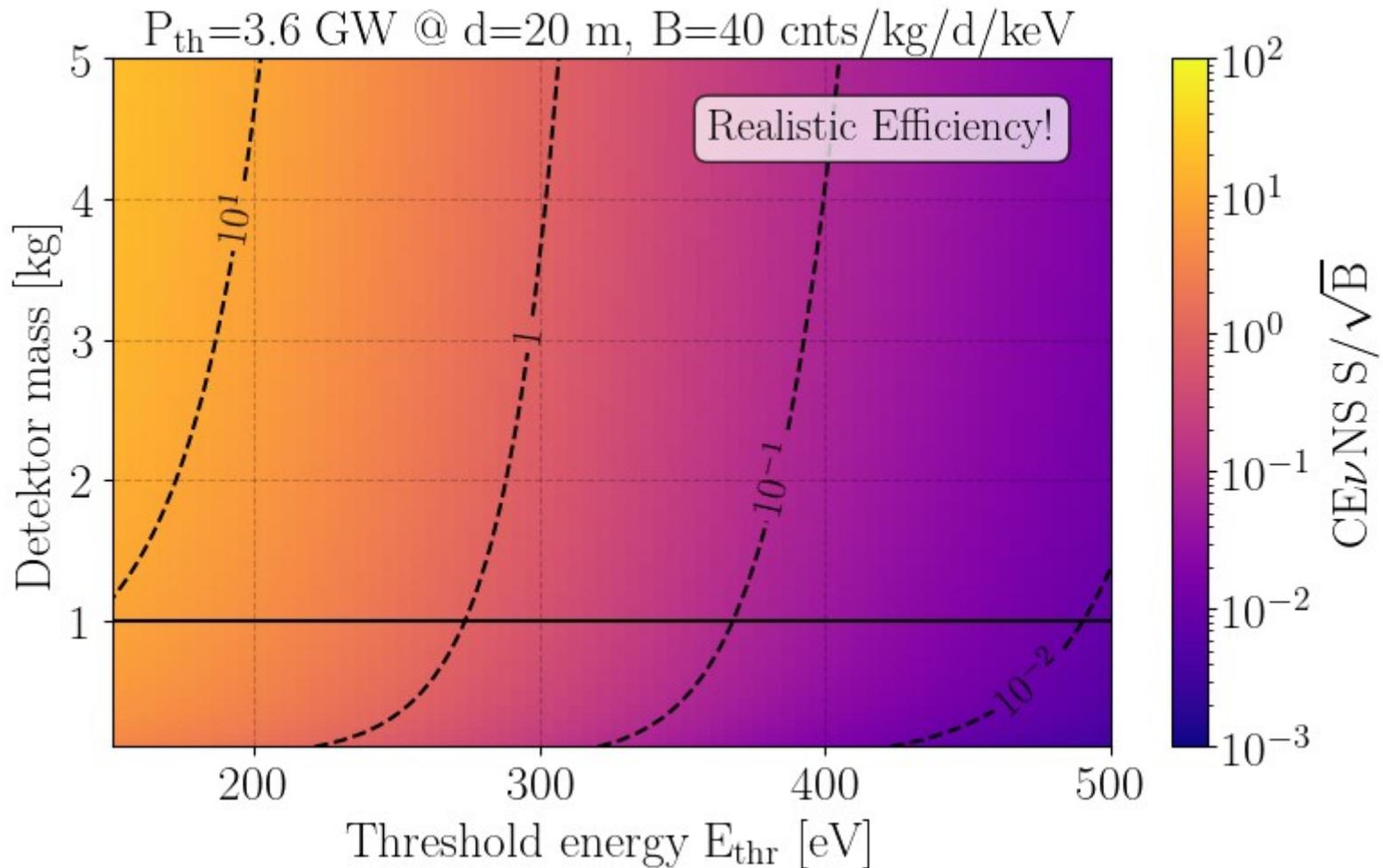


$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$



[Berryman, 10.1103/PhysRevD.100.023540, 2019]

# CEvNS signal-to-noise



**Caution:** No direct comparison to above possible!  
(E.g. exp. specifications, different detector resolution)

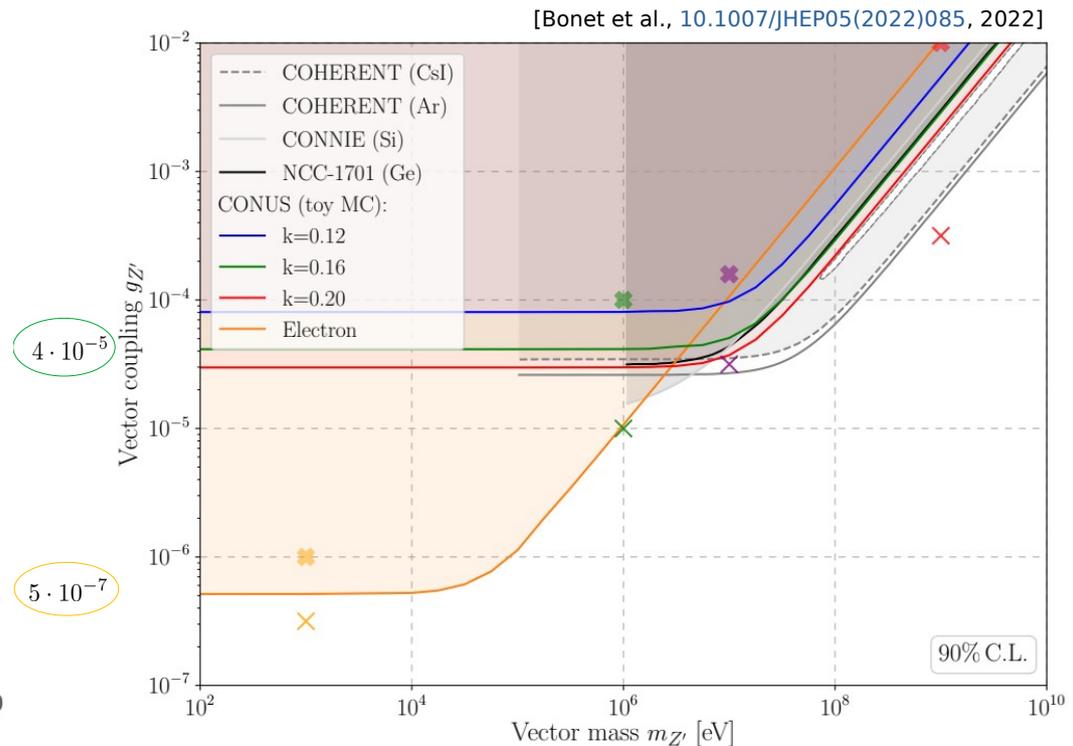
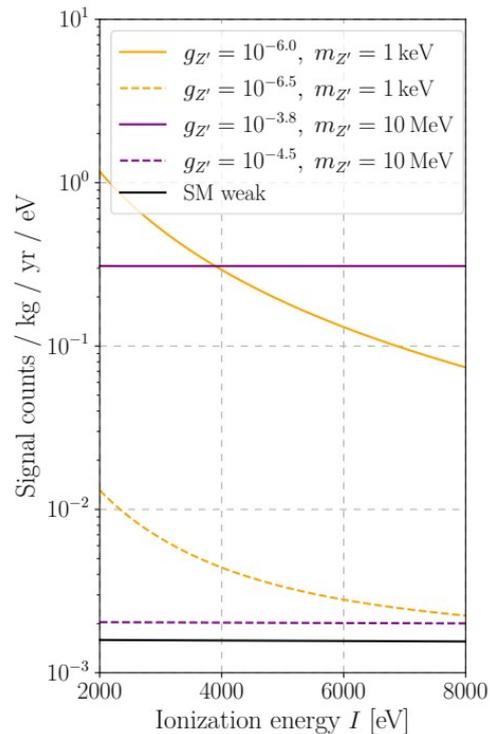
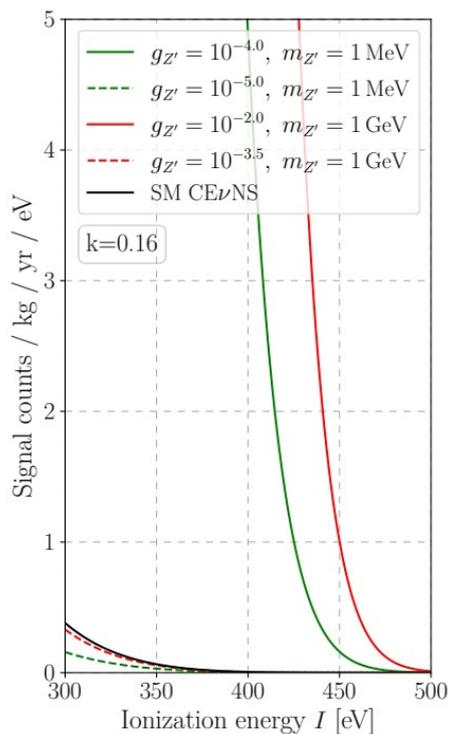
# Simplified models: light vector mediator

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

[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**



Reactor neutrinos for low masses  $\leftrightarrow$   $\pi$ -DAR neutrinos for higher masses

# Experimental requirements at reactor site

**Goal:** Detecting CEvNS with high accuracy!

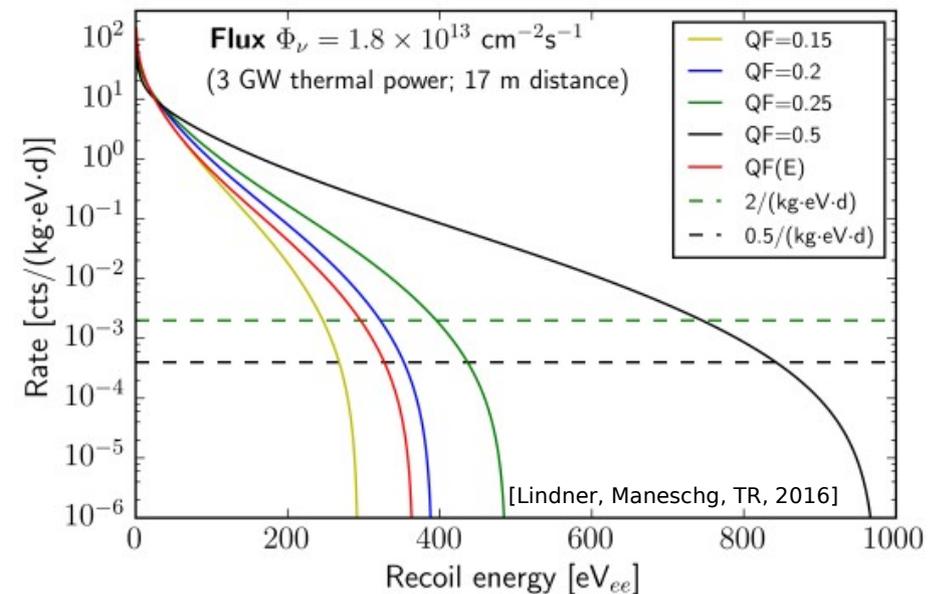
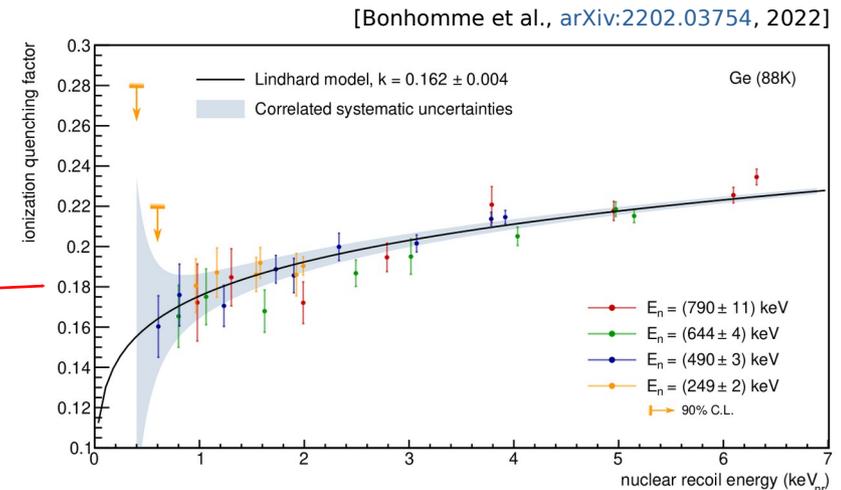
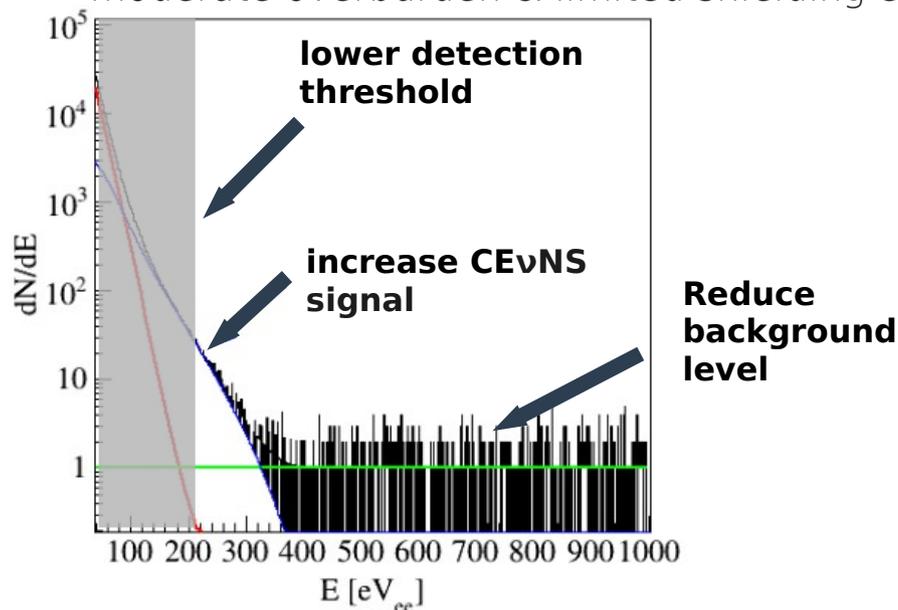
**Several obstacles to overcome:**

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

2) Compensate quenching ( $E_{\text{recoil}} \rightarrow E_{\text{ion}}$ )  
 → lowest possible detection threshold

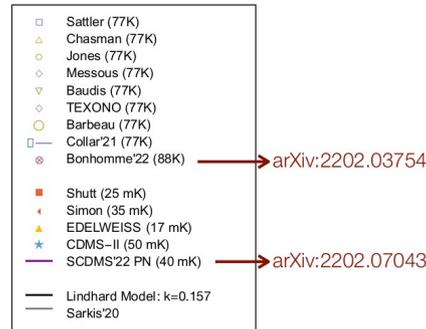
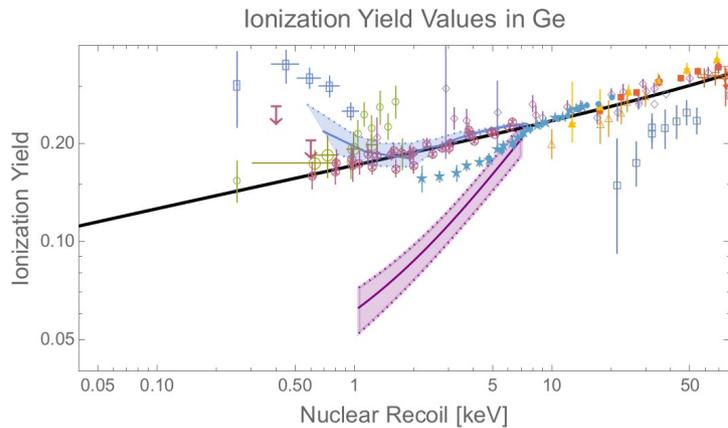
$E_\nu$ : 10MeV  
 max  $E_{\text{Recoil}}$ : 3keV  
 max  $E_{\text{ion}}$ : ~600eV

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



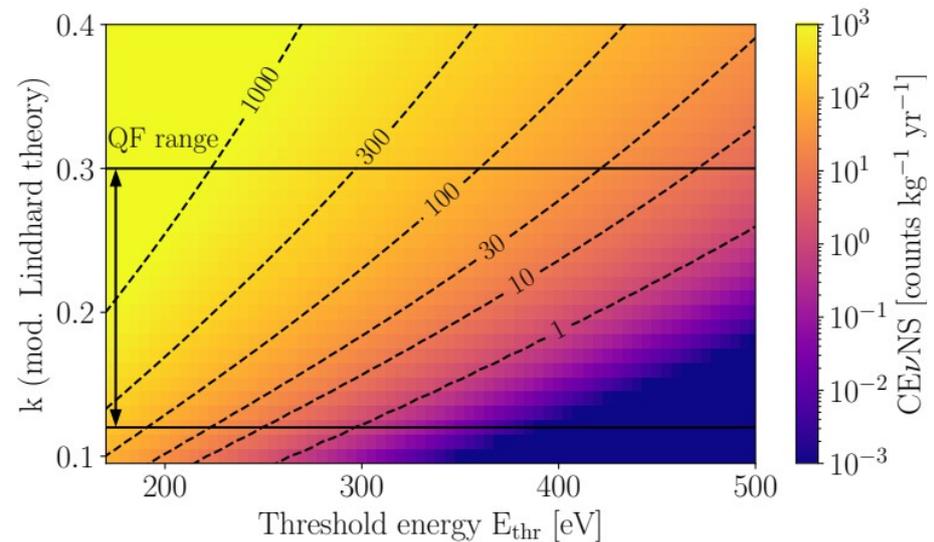
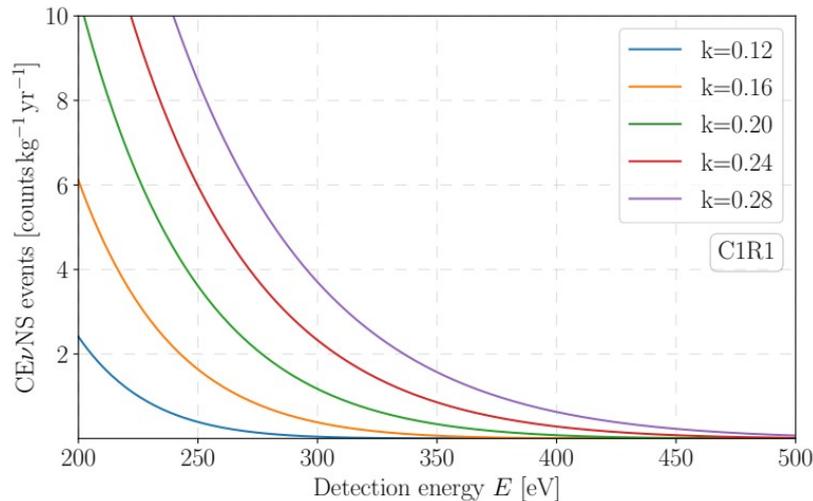
# Impact of quenching at low energy

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](https://arxiv.org/abs/2202.09672)  
 "Suggestive evidence for Coherent Elastic Neutrino-Nucleus Scattering from reactor antineutrinos"

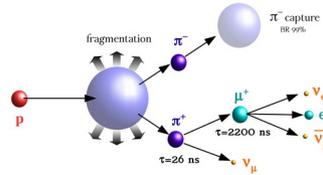
Quenching according to mod. Lindhard model:



[TR, PhD thesis, 2022]

# Two complementary approaches

## $\pi$ -decay-at-rest neutrinos:



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

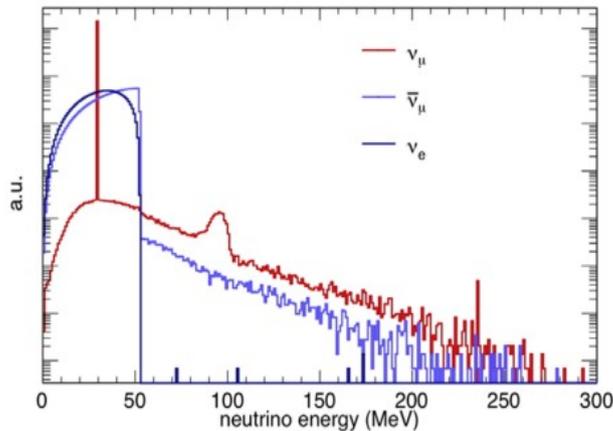
→ **COHERENT, CCM, “CE $\nu$ NS@ESS”...**

## Reactor antineutrinos:

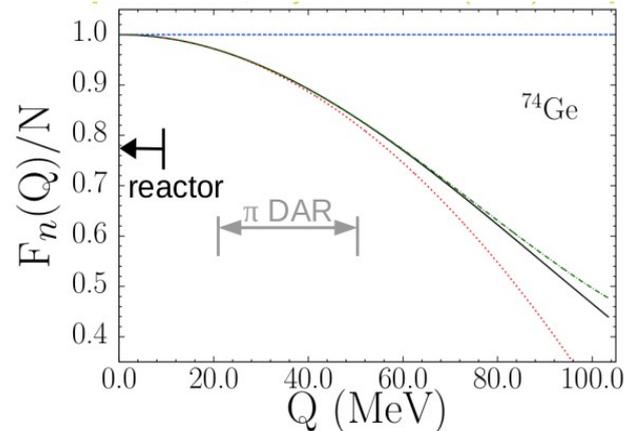
- $\beta$  decays in nuclear reaction chains → only  $\bar{\nu}_e$
- Strongest artificial  $\nu$  source on earth:  
 $\sim 10^{20}$   $\bar{\nu}_e$ /s/GW/s
- $\nu$  energies up to 10 MeV → coherent regime!
- Close to reactor core: no lab conditions!  
→ no cryogenic liquids, no remote control

→ **CONNIE, CONUS, NCC-1701,  $\nu$ GEN ...**

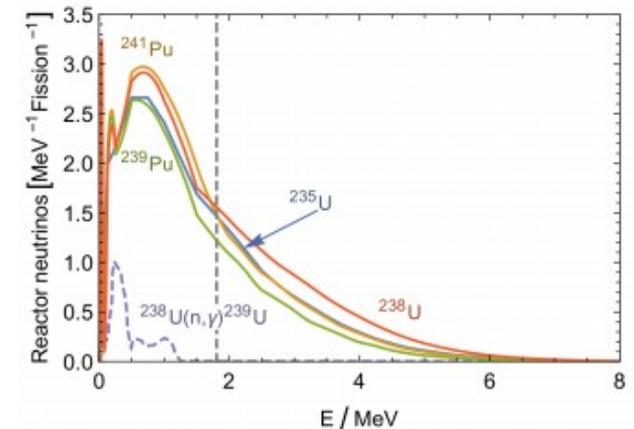
[Akimov et al., arXiv:1509.08702, 2015]



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



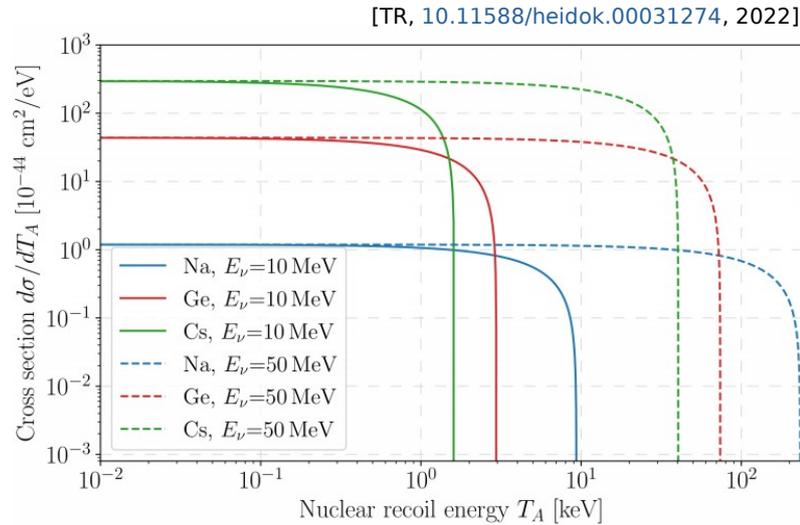
[Vitagliano et al., 10.1103/RevModPhys.92.045006, 2020]



## Beam-reactor complementarity:

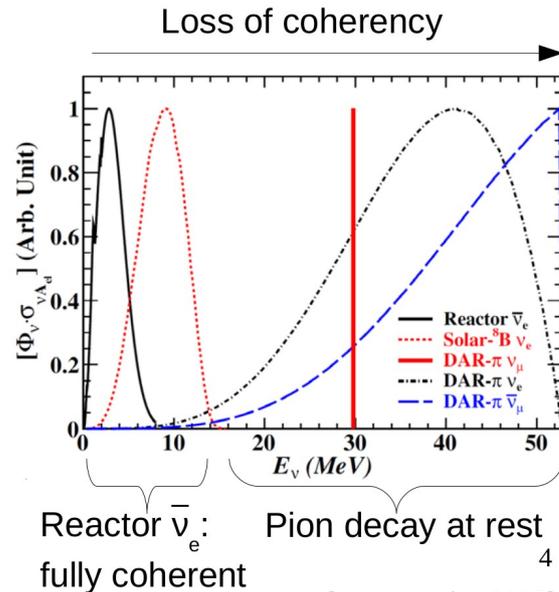
CE $\nu$ NS at reactor site as high statistic baseline for multi-target and multi-flavored beam investigations!

# CEvNS with different sources and targets



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]	$E$ (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
$\pi$ -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 $\beta$ decays of fuel reaction products

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

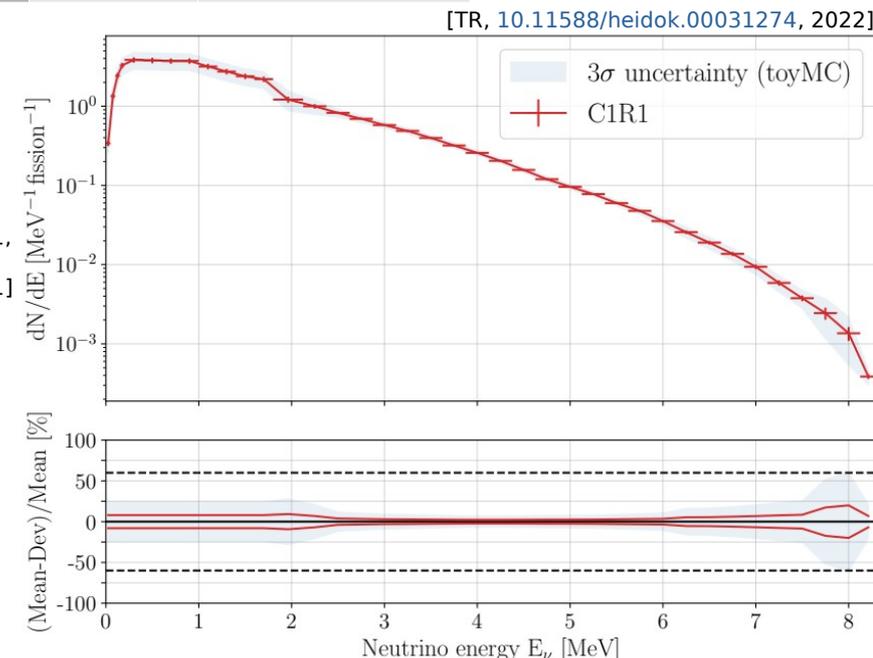
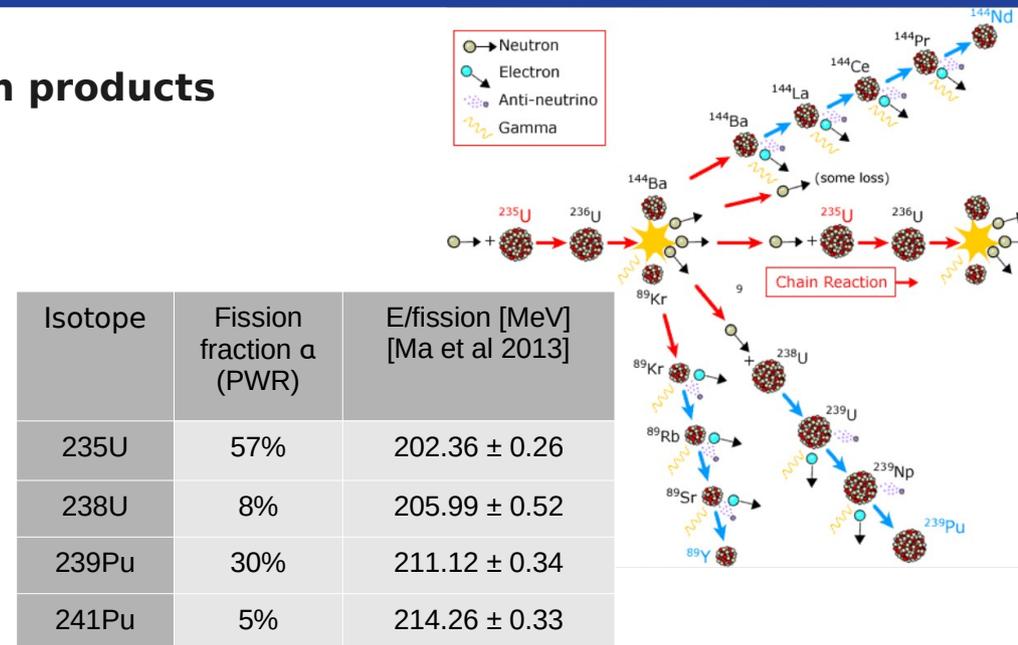
$$S(E_\nu) = \frac{1}{4\pi R^2} \frac{W_{th}}{\sum_i \alpha_i E_i} \sum_i \alpha_i \left( \frac{dN_i}{dE_\nu} \right)$$

## Knowledge about a reactors emission spectra

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

Reality much more complicated...

- Varying reactor power  $\rightarrow \mathbf{P(t)}$
- Changing fuel composition  $\rightarrow \mathbf{\alpha(t)}$



# Reminder: Reactor antineutrino spectra for CEvNS

“Weight CEvNS cross section with neutrinos per energy”:

$E_{\max} \sim 10\text{MeV}$ , depending on assumptions

$$\frac{d\bar{\sigma}}{dT_A}(T_A) = \int_{E_{\min}}^{E_{\max}} dE_\nu \left( \frac{dN}{dE_\nu}(E_\nu) \right) \left( \frac{d\sigma}{dT_A}(T_A, E_\nu) \right)$$

CEvNS cross section

$$E_{\nu,\text{thr}} = \frac{1}{2} \left( \sqrt{2MT_{\text{th}} + T_{\text{th}}^2} + T_{\text{th}} \right) \approx \sqrt{\frac{M}{2}} T_{\text{th}}$$

$E_{\text{thr}}$  determined by  
target, quenching and energy threshold

Full reactor antineutrino spectrum:  
(Summation method,  
conversion method,  
direct IBD measurement)