



# Light vector bosons and the weak mixing angle in the light of new reactor-based CE $\nu$ NS experiments

Manfred Lindner, Thomas Rink and Manibrata Sen

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg

TAUP 2023 Vienna  
28 August to 1 September 2023





# 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

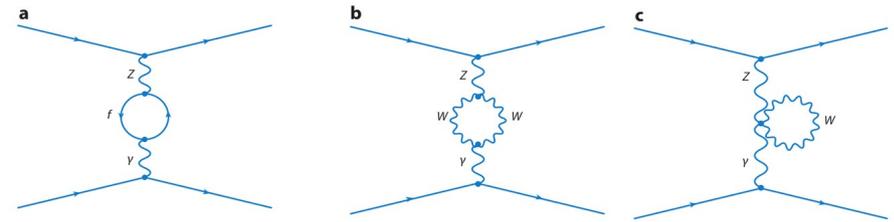
→ current experimental precision  $O(\pm 1\%)$

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

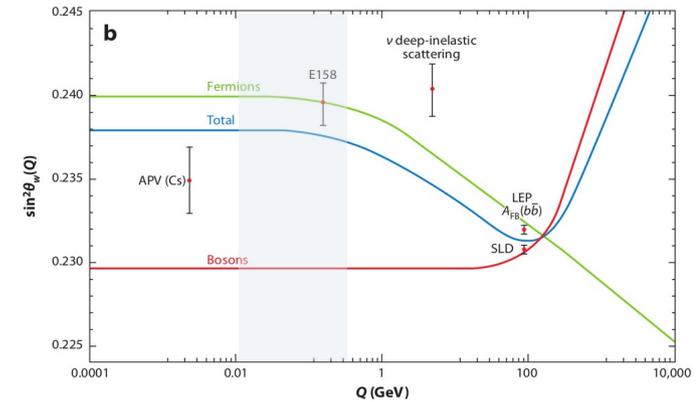
- **BUT** low- $Q^2$  measurements probe kinematic regions where Z pole measurements are insensitive to NP

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

dark parity violation / dark Z'



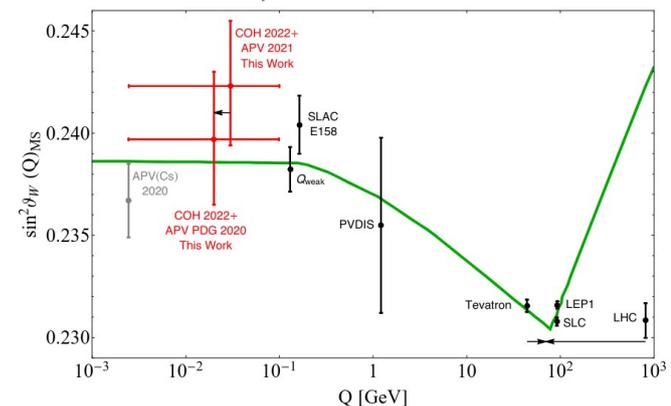
[Kumar et al., 10.1146/annurev-nucl-102212-170556, 2013]



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

COHERENT  
(Cs+Ar)

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



# Assume a CONUS-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:  $\sim 1.5 \cdot 10^{13} / \text{cm}^2 / \text{s}$  (3% uncertainty)
- Typical PWR fuel composition:  
56.1% U235, 7.6% U238, 30.7% Pu239, 5.6% Pu241

## Background

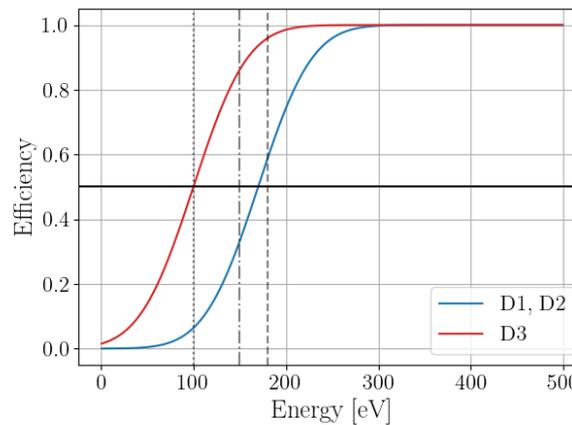
- No critical reactor-correlated bkg!
- Background levels:
  - 10 cnts/keV/d/kg for  $E_{\text{ion}} \leq 1 \text{ keV}$
  - 0.5 cnts/keV/d/kg for  $E_{\text{ion}} > 1 \text{ keV}$

## Detectors:

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

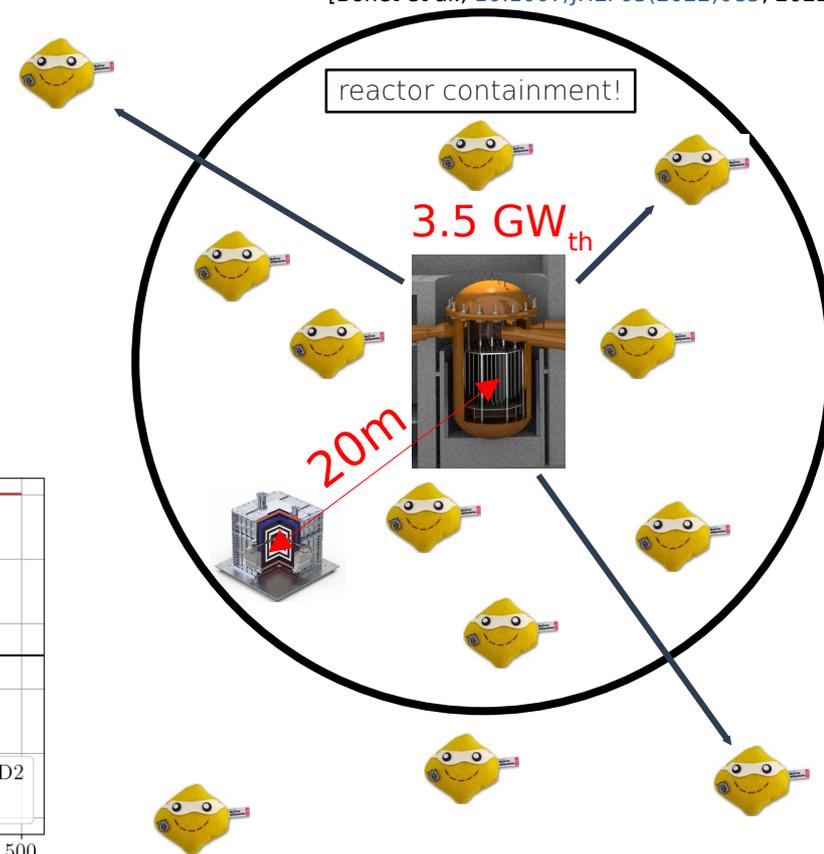
**R1** -  $\text{exp}_{\text{ON}} = 5 \text{ kg} \cdot \text{yr}$

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



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

- CONUS HPGe detectors with improved trigger efficiency:  
 $E_{\text{thr}} \sim 3 \cdot \text{FWHM}_{\text{pulser}}$
- Quenching according to Lindhard model (1% uncertainty)



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



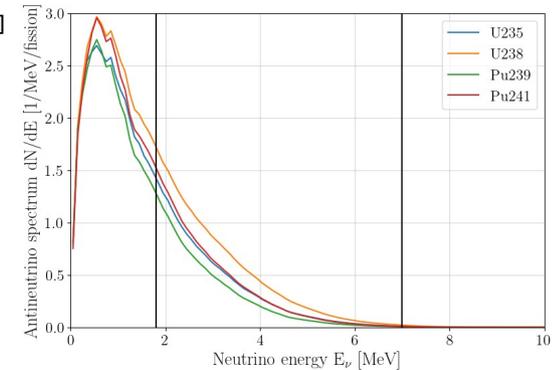
[particlezoo.net, 2023]

# 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):

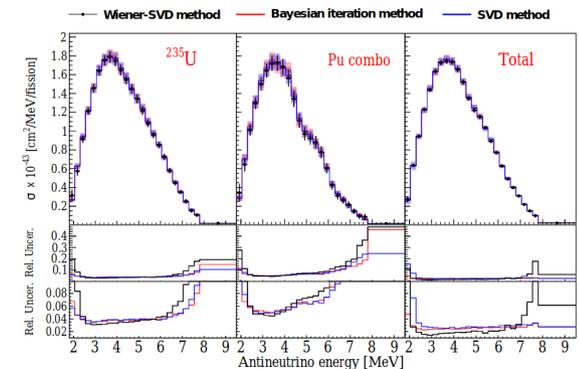
- unfolded IBD spectra of U235, (Pu239+ Pu241), total
- method to construct data-based predictions

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

Difference in fission fractions

$\longrightarrow$  Mueller  
 $\longrightarrow$  Huber

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

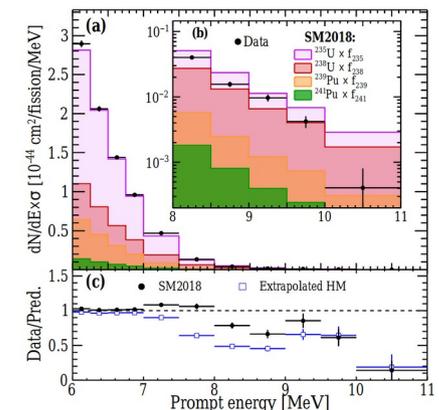


[An et al., 10.1088/1674-1137/abfc38, 2021]

## 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



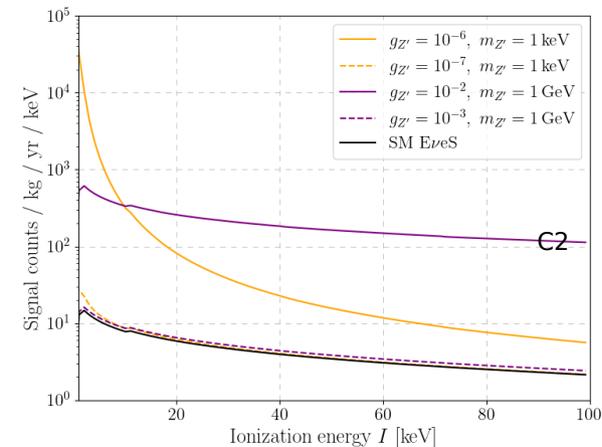
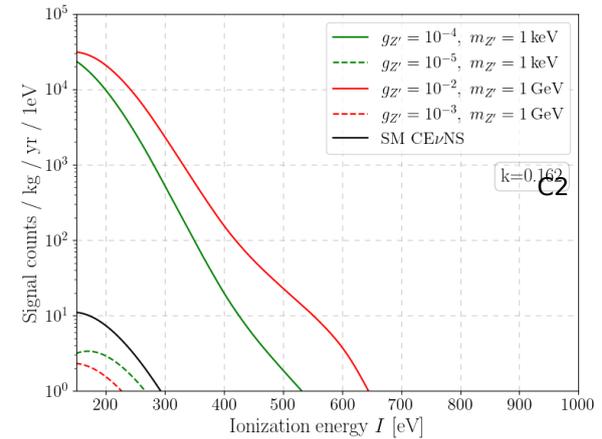
[An et al., 10.1103/PhysRevLett.129.041801, 2022]

Spectrum also used in current CONUS 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



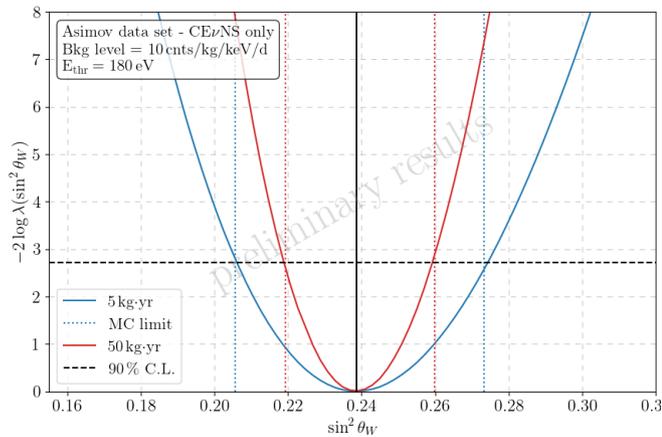
Sensitivity to the Weinberg angle  
 $\text{CE}\nu\text{NS} - E_{\text{ion}} < 1\text{keV}$

Sensitivity to a light vector boson:  
 $\text{CE}\nu\text{NS} - E_{\text{ion}} < 1\text{keV}$   
 $\text{E}\nu\text{eS} - E_{\text{ion}} < 100\text{keV}$

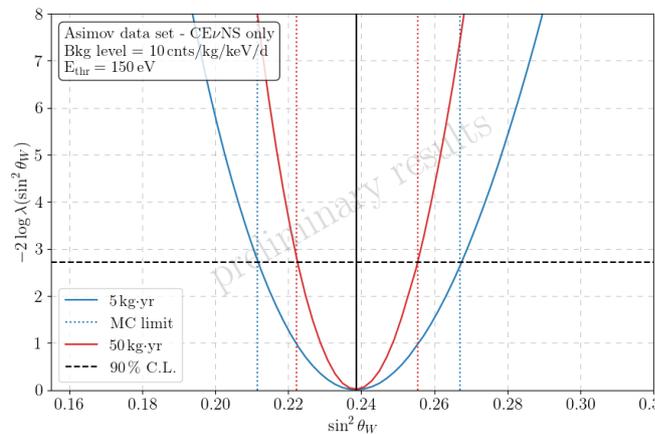
# Future Weinberg angle sensitivity

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

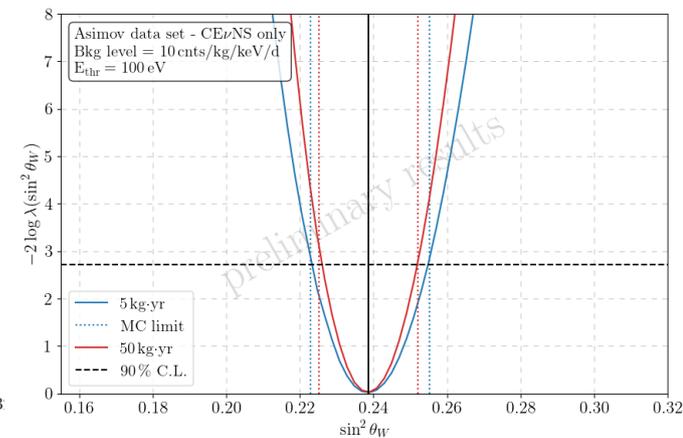
- EveS alone is generally not competitive
- Combined analysis dominated by contributions below 1keV  $\rightarrow$  CE $\nu$ NS only
- Sensitivity limited by systematics:  $\sim 5\%$  relative uncertainty



Exposure	Rel. uncertainty
5 kg*yr	(-14; +15) %
50 kg*yr	(-8; +9) %



Exposure	Rel. uncertainty
5 kg*yr	(-11; +12) %
50 kg*yr	$\pm 7$ %



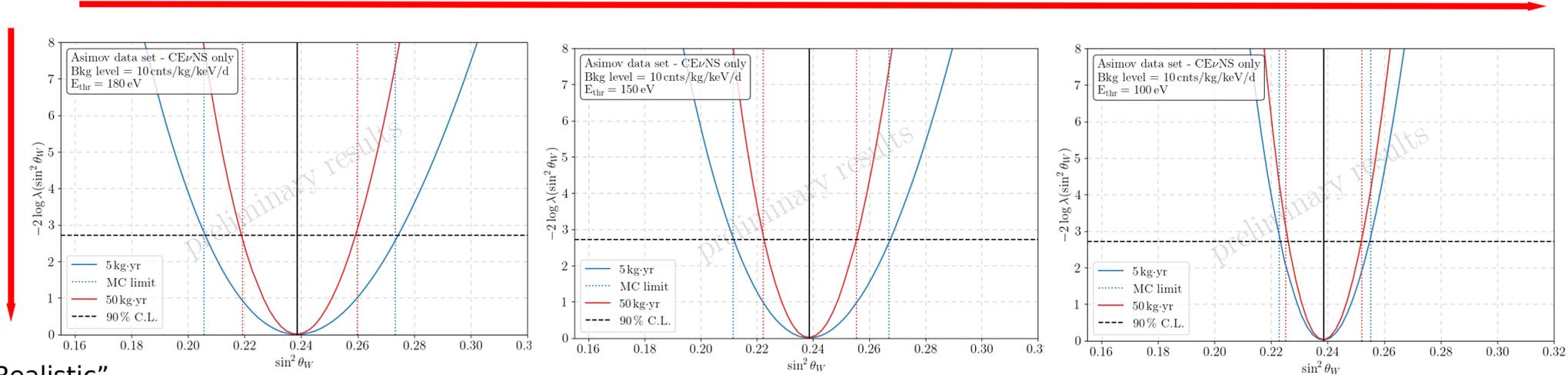
Exposure	Rel. uncertainty
5 kg*yr	(-6; +7) %
50 kg*yr	(-5; +6) %

# Future Weinberg angle sensitivity

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

- EveS alone is generally not competitive
- Combined analysis dominated by contributions below 1keV  $\rightarrow$  CE $\nu$ NS only
- Sensitivity limited by systematics:  $\sim 5\%$  relative uncertainty

“Realistic” improvement:  $\sim 3\text{-}8\%$  relative



“Realistic”  
improvement:  
 $\sim 1\text{-}6\%$  relative

Exposure	Rel. uncertainty
5 kg*yr	(-14; +15) %
50 kg*yr	(-8; +9) %

Exposure	Rel. uncertainty
5 kg*yr	(-11; +12) %
50 kg*yr	$\pm 7\%$

Exposure	Rel. uncertainty
5 kg*yr	(-6; +7) %
50 kg*yr	(-5; +6) %

# Future light vector sensitivity

## Simplified mediator model → contribution to CEνNS / EveS

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

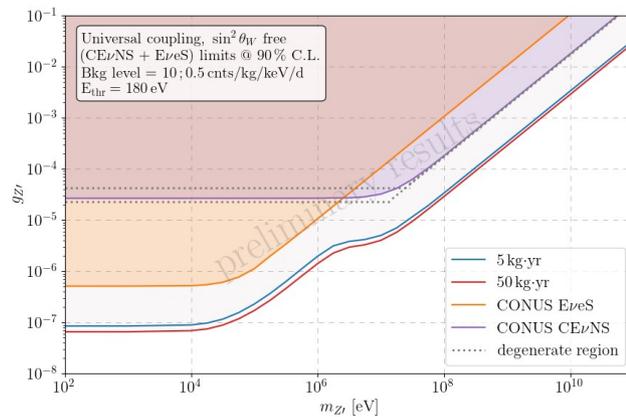
- Assume universal coupling to quarks / electron / neutrinos:  $(m_{Z'}, g_{Z'})$
- EveS more sensitive to lower mediator masses:  $m_e$  vs.  $m_{Ge}$
- CONUS benchmark points (keV, GeV): EveS -  $(5.2 \cdot 10^{-7}, 1.1 \cdot 10^{-2})$ ; CEνNS -  $(2.7 \cdot 10^{-5}, 1.8 \cdot 10^{-3})$

[Cerdeño et al., [10.1007/JHEP05\(2016\)118](https://arxiv.org/abs/10.1007/JHEP05(2016)118), 2016]

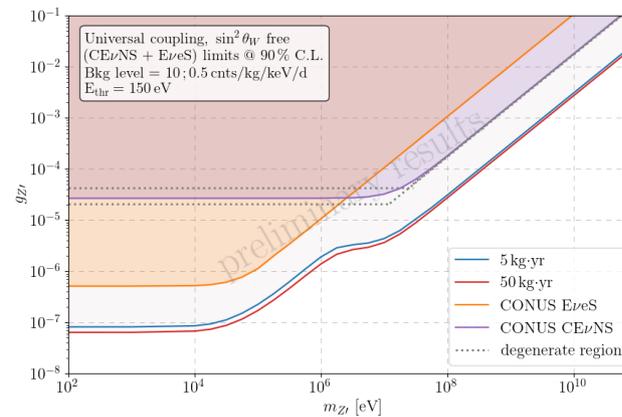
$$\frac{d\sigma}{dT} \propto \left[ Q_{SM} + \frac{3g_{Z'}^2}{\sqrt{2}G_F} \frac{Z+N}{|q|^2 + m_{Z'}^2} \right]^2$$

[Cadeddu et al., [10.1007/JHEP01\(2021\)116](https://arxiv.org/abs/10.1007/JHEP01(2021)116), 2021]

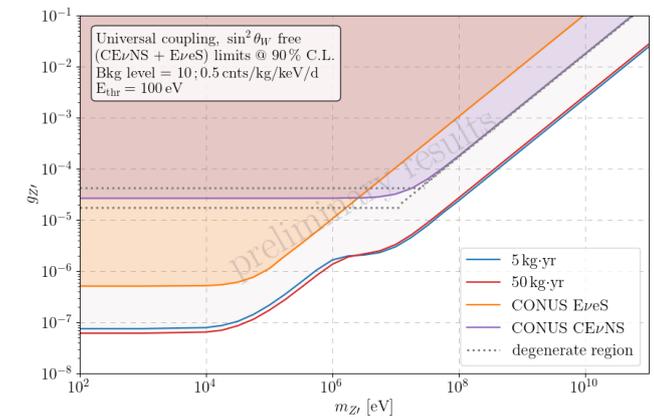
[Bonet et al., [10.1007/JHEP05\(2022\)085](https://arxiv.org/abs/10.1007/JHEP05(2022)085), 2022]



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.6 \cdot 10^{-8}$	$3.4 \cdot 10^{-4}$
50 kg*yr	$6.6 \cdot 10^{-8}$	$2.9 \cdot 10^{-4}$



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.2 \cdot 10^{-8}$	$3.1 \cdot 10^{-4}$
50 kg*yr	$6.4 \cdot 10^{-8}$	$2.7 \cdot 10^{-4}$



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.6 \cdot 10^{-8}$	$2.4 \cdot 10^{-4}$
50 kg*yr	$6.2 \cdot 10^{-8}$	$2.7 \cdot 10^{-4}$

# 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]

$$\frac{d\sigma}{dT} \propto \left[ Q_{SM} + \frac{3g_{Z'}^2}{\sqrt{2}G_F} \frac{Z+N}{|q|^2 + m_{Z'}^2} \right]^2$$

- Assume universal coupling to quarks / electron / neutrinos:  $(m_{Z'}, g_{Z'})$

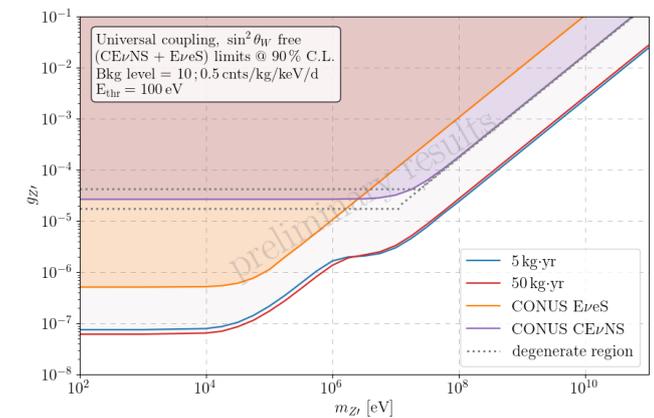
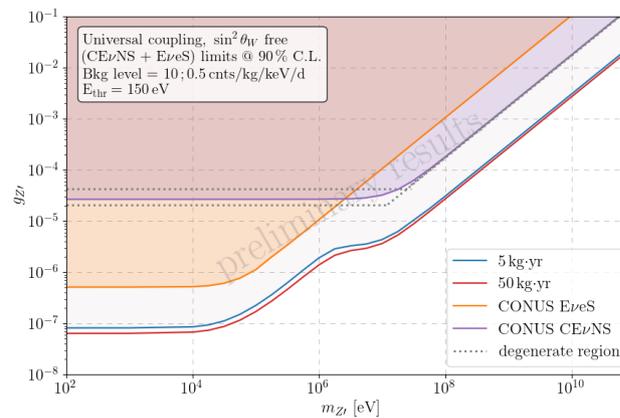
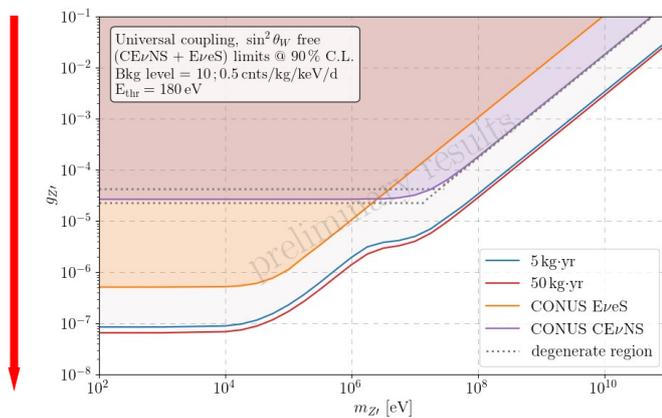
[Cadeddu et al., 10.1007/JHEP01(2021)116, 2021]

- EveS more sensitive to lower mediator masses:  $m_e$  vs.  $m_{Ge}$

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

- CONUS benchmark points (keV, GeV): EveS -  $(5.2 \cdot 10^{-7}, 1.1 \cdot 10^{-2})$ ; CEνNS -  $(2.7 \cdot 10^{-5}, 1.8 \cdot 10^{-3})$

“Realistic” improvements: CEνNS~7-29%, EveS~3-12%



“Real.” improv.:  
EveS~18-23%  
CEνNS~15%

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.6 \cdot 10^{-8}$	$3.4 \cdot 10^{-4}$
50 kg*yr	$6.6 \cdot 10^{-8}$	$2.9 \cdot 10^{-4}$

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.2 \cdot 10^{-8}$	$3.1 \cdot 10^{-4}$
50 kg*yr	$6.4 \cdot 10^{-8}$	$2.7 \cdot 10^{-4}$

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.6 \cdot 10^{-8}$	$2.4 \cdot 10^{-4}$
50 kg*yr	$6.2 \cdot 10^{-8}$	$2.7 \cdot 10^{-4}$

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

# Future light vector sensitivity

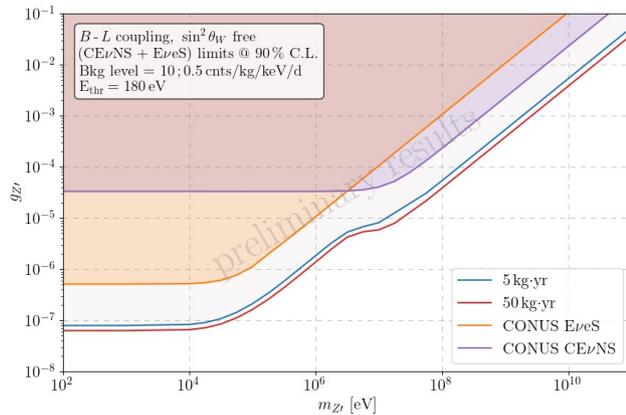
## THE benchmark (mediator) model $\rightarrow$ $U(1)_{B-L}$

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

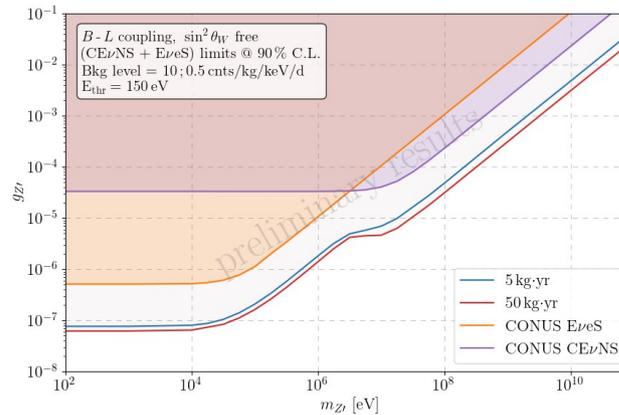
$$\frac{d\sigma}{dT} \propto \left[ Q_{SM} - \frac{g_{Z'}^2}{\sqrt{2}G_F} \frac{Z + N}{|q|^2 + m_{Z'}^2} \right]^2$$

[Cadeddu et al., [10.1007/JHEP01\(2021\)116](https://arxiv.org/abs/2010.116), 2021]

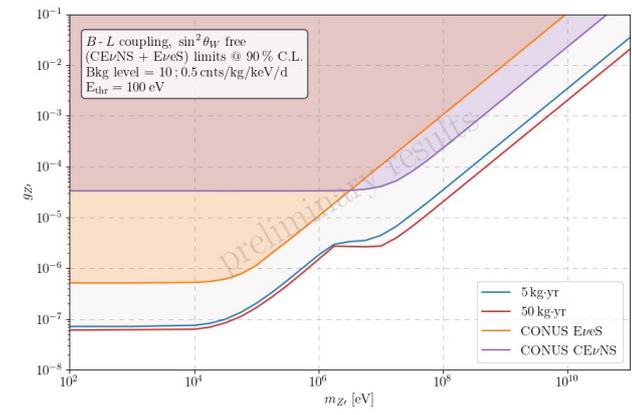
- Assume gauged B-L charge:  $(m_{Z'}, g_{Z'})$
- EveS more sensitive to lower mediator masses:  $m_e$  vs.  $m_{Ge}$
- CONUS benchmark points (keV, GeV): EveS -  $(5.2 \cdot 10^{-7}, 1.1 \cdot 10^{-2})$ ; CEvNS -  $(3.3 \cdot 10^{-5}, 2.3 \cdot 10^{-3})$



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.0 \cdot 10^{-8}$	$5.4 \cdot 10^{-4}$
50 kg*yr	$6.3 \cdot 10^{-8}$	$3.9 \cdot 10^{-4}$



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.7 \cdot 10^{-8}$	$4.8 \cdot 10^{-4}$
50 kg*yr	$6.2 \cdot 10^{-8}$	$3.1 \cdot 10^{-4}$



Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.2 \cdot 10^{-8}$	$3.5 \cdot 10^{-4}$
50 kg*yr	$6.1 \cdot 10^{-8}$	$2.0 \cdot 10^{-4}$

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

# Future light vector sensitivity

## THE benchmark (mediator) model $\rightarrow$ $U(1)_{B-L}$

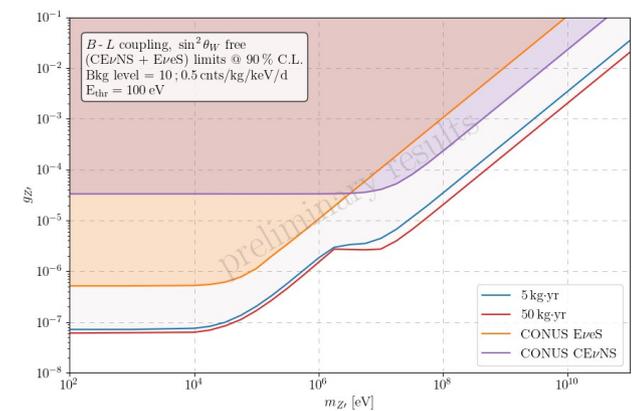
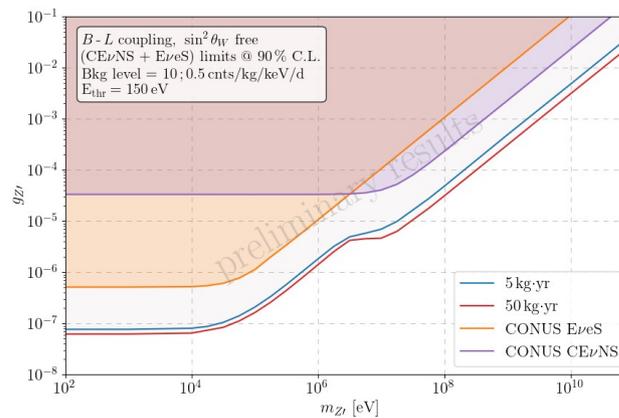
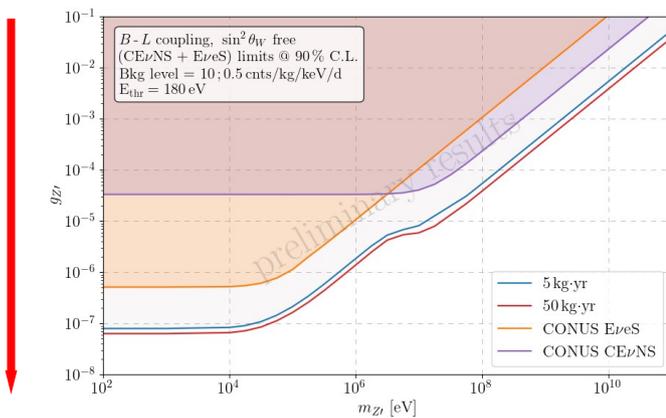
$$\mathcal{L}_{Z'} = Z'_\mu \left( g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{qV} \bar{q} \gamma^\mu q \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

$$\frac{d\sigma}{dT} \propto \left[ Q_{SM} - \frac{g_{Z'}^2}{\sqrt{2}G_F} \frac{Z + N}{|q|^2 + m_{Z'}^2} \right]^2$$

[Cadeddu et al., 10.1007/JHEP01(2021)116, 2021]

- Assume gauged B-L charge:  $(m_{Z'}, g_{Z'})$
- EveS more sensitive to lower mediator masses:  $m_e$  vs.  $m_{Ge}$
- CONUS benchmark points (keV, GeV): EveS -  $(5.2 \cdot 10^{-7}, 1.1 \cdot 10^{-2})$ ; CEvNS -  $(3.3 \cdot 10^{-5}, 2.3 \cdot 10^{-3})$

“Realistic” improvements: CEvNS~12-35%, EveS~2-10%



“Real.” improv.:  
EveS~15-21%  
CEvNS~27-43%

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.0 \cdot 10^{-8}$	$5.4 \cdot 10^{-4}$
50 kg*yr	$6.3 \cdot 10^{-8}$	$3.9 \cdot 10^{-4}$

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.7 \cdot 10^{-8}$	$4.8 \cdot 10^{-4}$
50 kg*yr	$6.2 \cdot 10^{-8}$	$3.1 \cdot 10^{-4}$

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.2 \cdot 10^{-8}$	$3.5 \cdot 10^{-4}$
50 kg*yr	$6.1 \cdot 10^{-8}$	$2.0 \cdot 10^{-4}$

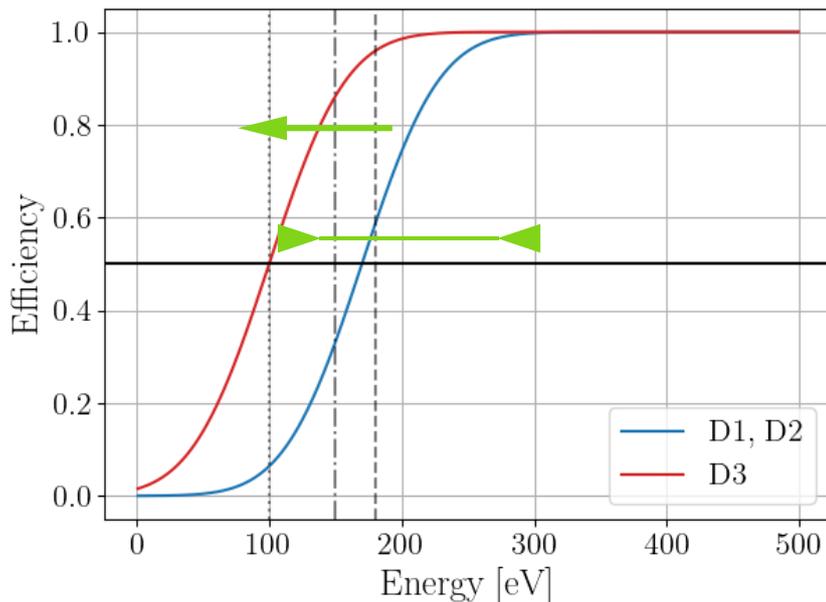
Reactor neutrinos for low masses  $\leftrightarrow$   $\pi$ -DAR neutrinos for higher masses

# Outlook: Future Ge detectors at reactor sites

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

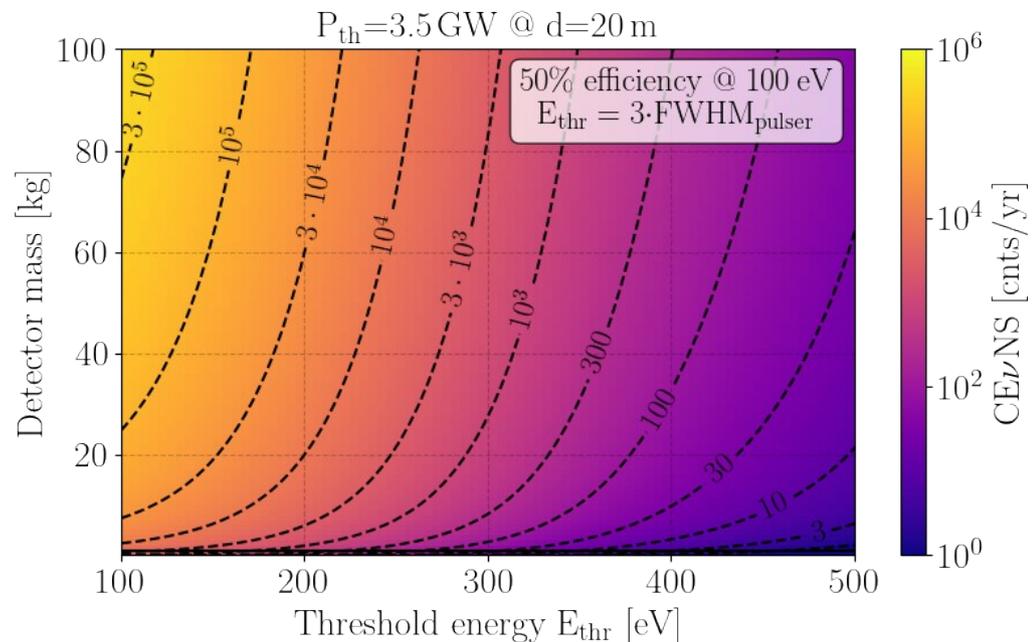
Experimental perspective (single diode):

- 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):

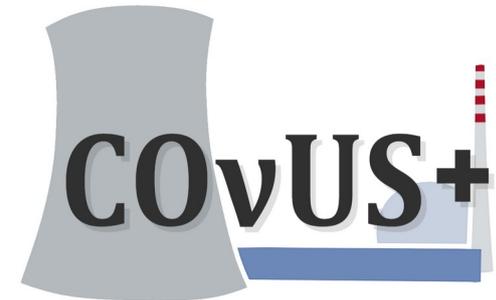
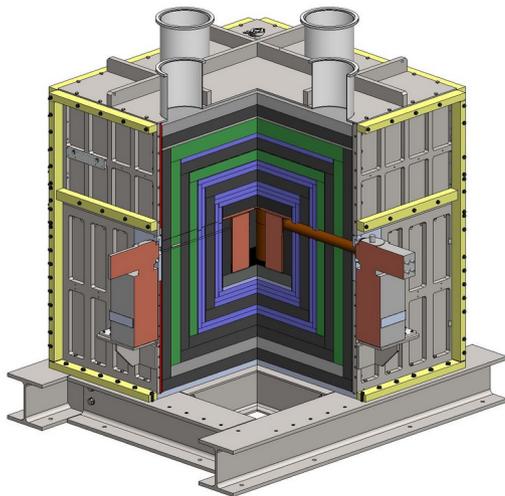
- Energy threshold and exposure are key for a strong CEvNS signal / BSM reach
- Trade-off between reactor flux and background
- Incorporate major uncertainties in SM and BSM studies!



# New experiment at new site: CONUS+

## Aim: First CEvNS detection @ reactor-site!

- Installation in Leibstadt (Switzerland) this summer  
→ @ **20 m** distance to the 3.5 GW<sub>th</sub> reactor core
- Refurbishment of existing COvUS Ge detectors  
→ energy threshold < **200 eV**!
- Increased muon rejection efficiency via additional plastic scintillator layer
- **Full background characterization** at experimental site already performed  
→ array of Bonner spheres + liquid scintillator cell



**Future:** Results from / upgrades of NCC-1701 (Ge), vGEN (Ge) and Texono (Ge)?

# 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!

**Large playground for BSM pheno:**

see talks by  
Valentina De Romeri 29/8 16:00  
Mariam Tórtola 29/8 17:45  
Gonzalo Sanchez Garcia 30/8 17:30

- **Sensitivity for the next-gen. of Ge-based reactor experiments**

- Weinberg angle:
  - relative uncertainty  $\lesssim 10\%$
  - systematics become crucial!
- Light vector bosons (universal coupling & B-L):
  - probing the next order of magnitude
  - improved threshold critical for CEvNS-dominated limit regions

**Paper to  
appear soon!**

- **HPPC Ge detectors offer a scalable technology also in critical environments**

- energy threshold and trigger efficiency are crucial! exposure via multiple diodes?
- quenching (description) strongly affects CEvNS prediction

- **CONUS RUN-5 SM results presented on this conference!**

→ **BSM analyses are coming!**

See talk by Edgar  
Sanchez Garcia  
Tue 29/8 16:45

**Thank You!**

# Backup

# Opportunities for CEνNS experiments

## SM investigations with enhanced precision:

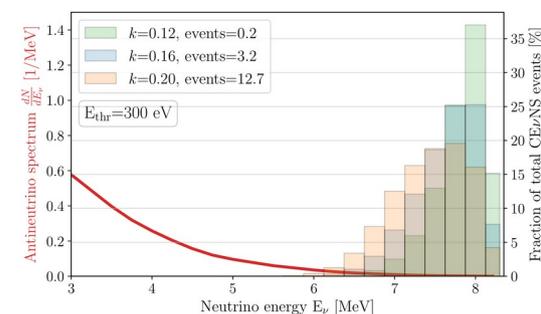
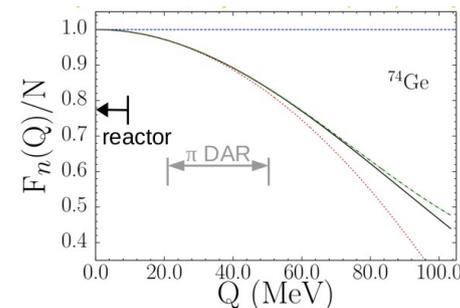
- **Nuclear form factors:**

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.00031274, 2022]

## BSM investigations:

- **Light sterile neutrinos:**

Use CEνNS for  $\nu$  flux measurements

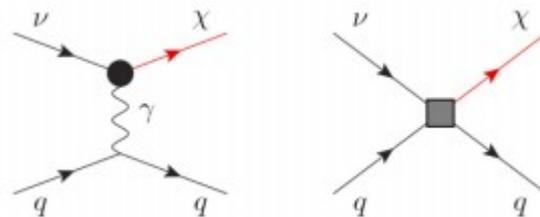
- **New fermion searches:**

Test further  $\nu$  interactions  
 →  $\nu$  mass, DM, ...

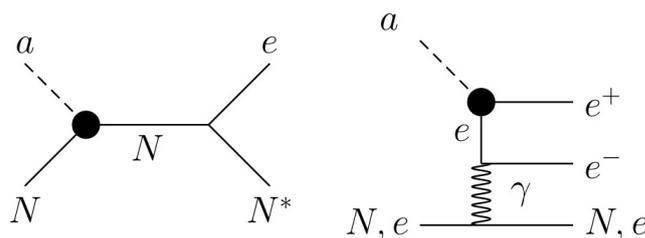
- **Probing portals:**

ALPs, dark photons, etc.

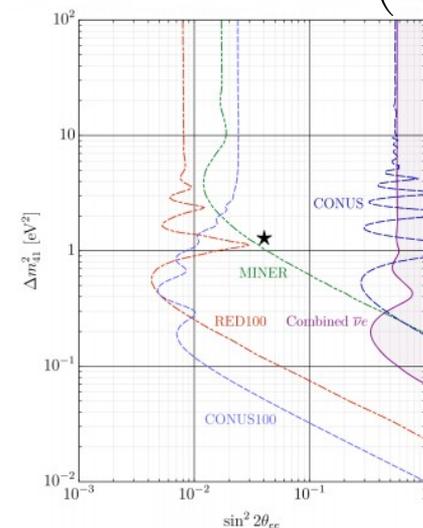
[Chang & Liao, 10.1103/PhysRevD.102.075004, 2022]



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



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



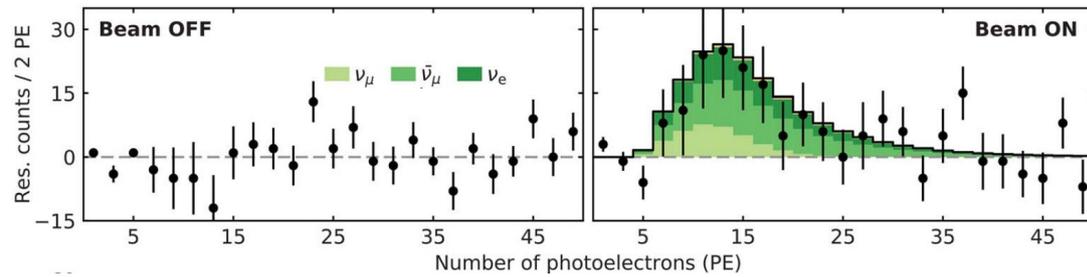
[Berryman, 10.1103/PhysRevD.100.023540, 2019]

# CEvNS observations and constraints

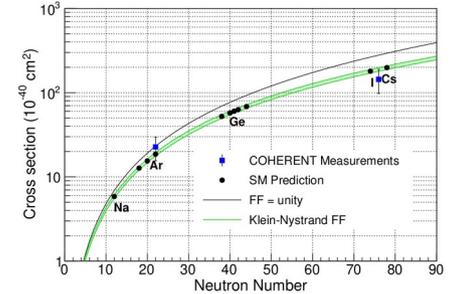
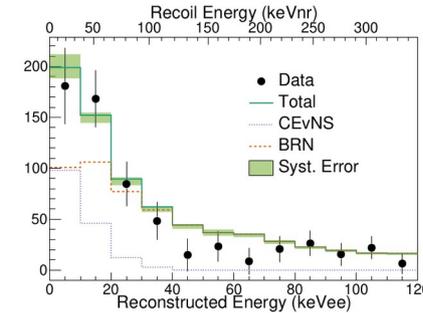
## Observations:

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

[Akimov et al., [10.1126/science.aao0990](https://doi.org/10.1126/science.aao0990), 2017]

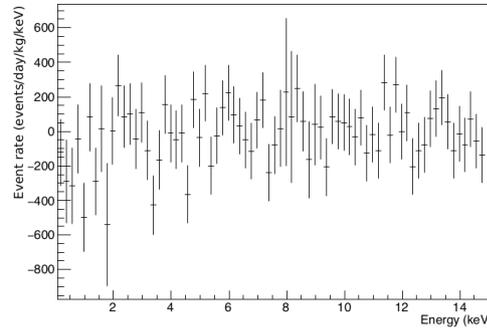


COHERENT LAr (2021):  $13.7 * 10^{22}$  POT  
*obs. 159+-43, pred. 128+-17*  
 [Akimov et al., [10.1103/PhysRevLett.126.012002](https://doi.org/10.1103/PhysRevLett.126.012002), 2021]

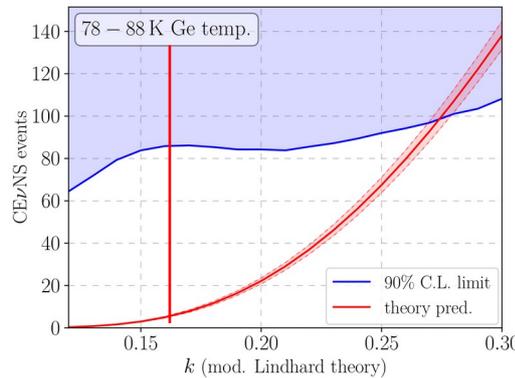


## Limits:

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](https://doi.org/10.1103/PhysRevD.100.092005), 2019]



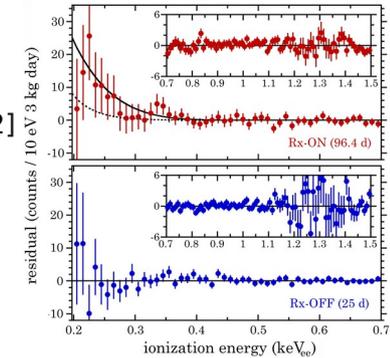
CONUS Ge (2020):  
 $R_{SM} < 0.4/kg/d$  @ 90% C.L.  
 (x17 lower than prediction)  
 249kg\*d ON + 59kg\*d OFF  
 [Bonet et al., [10.1103/PhysRevLett.126.041804](https://doi.org/10.1103/PhysRevLett.126.041804), 2020]



## “Measurement [...] Reactor Antineutrinos”

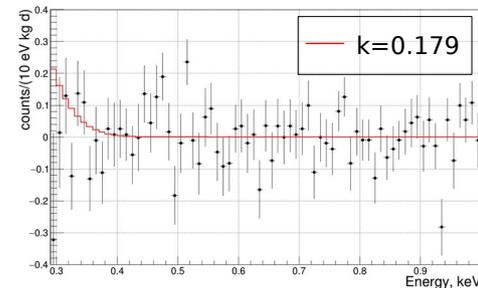
[Colaesi et al., [10.1103/PhysRevLett.129.211802](https://doi.org/10.1103/PhysRevLett.129.211802), 2022]

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

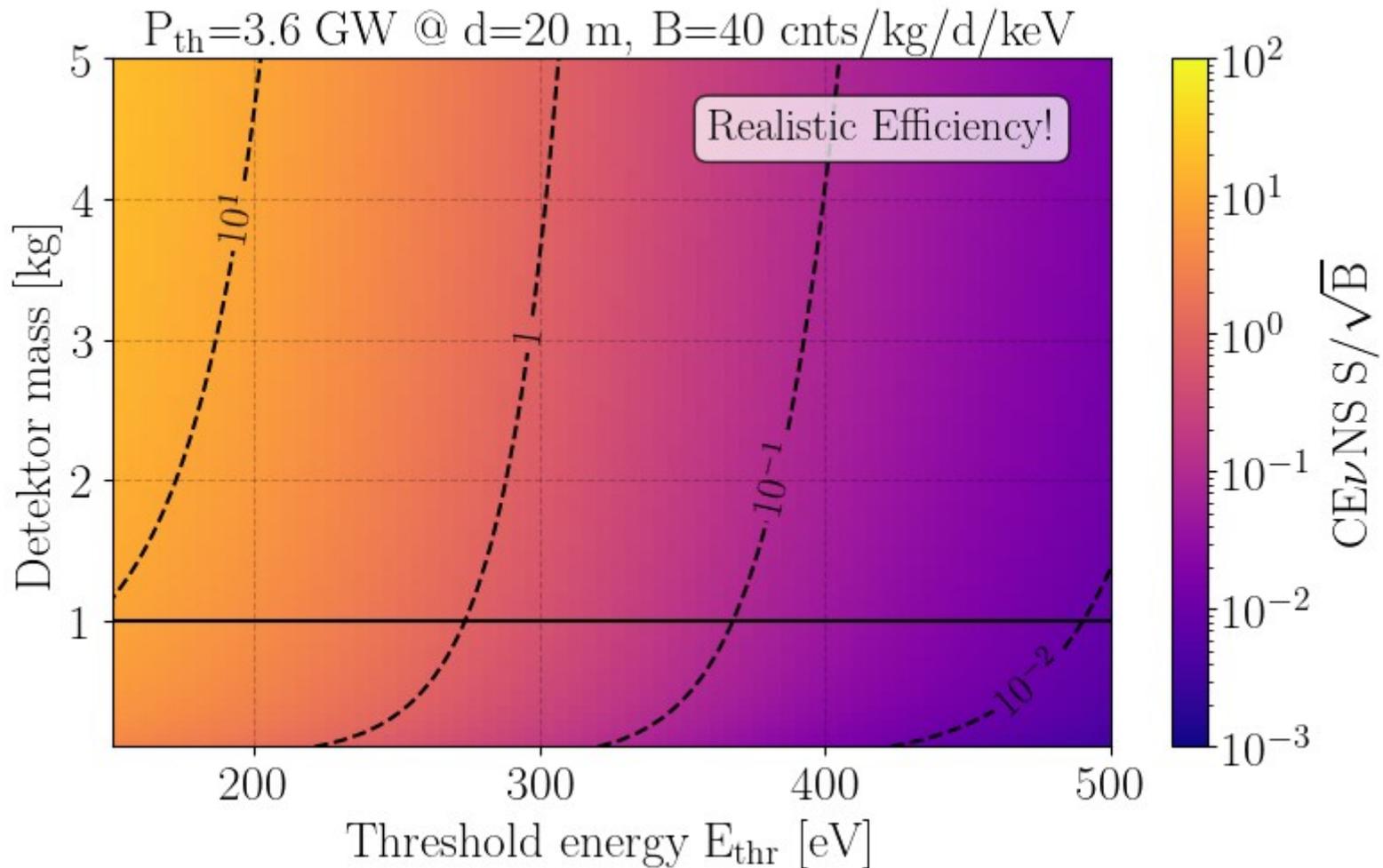


$\nu$ GEN Ge (2022):  
*no excess,*  
 $k < 0.177$  @ 90% C.L.  
 133kg\*d ON + 66kg\*d OFF

[Alekseev et al., [10.1103/PhysRevD.106.L051101](https://doi.org/10.1103/PhysRevD.106.L051101), 2022]



# CE $\nu$ NS signal-to-noise



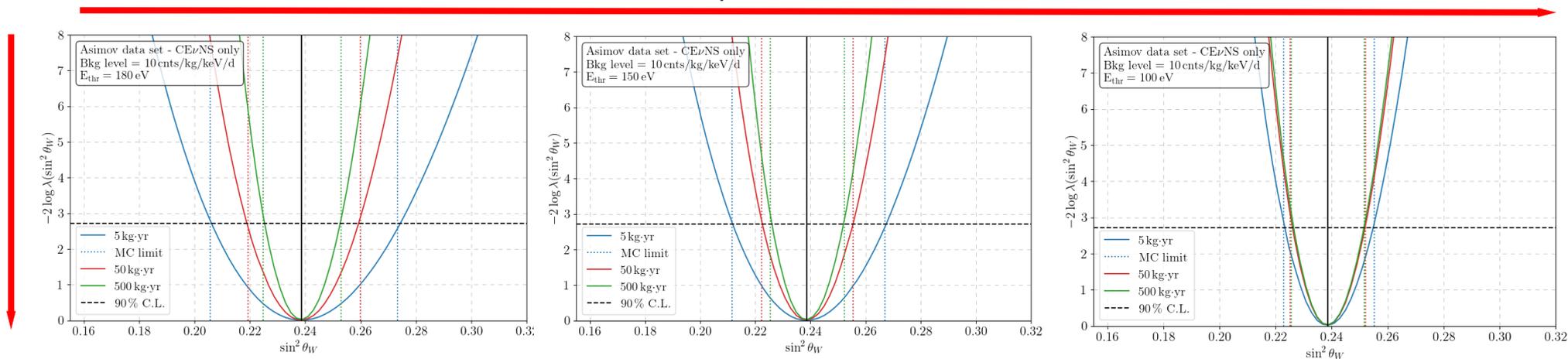
**Caution:** No direct comparison to above possible!  
(E.g. exp. specifications, different detector resolution)

# 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
- Sensitivity for current experimental configuration limited by systematics:  $\sim 5\%$  relative uncertainty

“Realistic” improvement:  $\sim 3-8\%$  relative



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

Exposure	Rel. uncertainty
5 kg*yr	(-14; +15) %
50 kg*yr	(-8; +9) %
500 kg*yr	$\pm 6$ %

Exposure	Rel. uncertainty
5 kg*yr	(-11; +12) %
50 kg*yr	$\pm 7$ %
500 kg*yr	(-5; +6) %

Exposure	Rel. uncertainty
5 kg*yr	(-6; +7) %
50 kg*yr	(-5; +6) %
500 kg*yr	(-5; +6) %

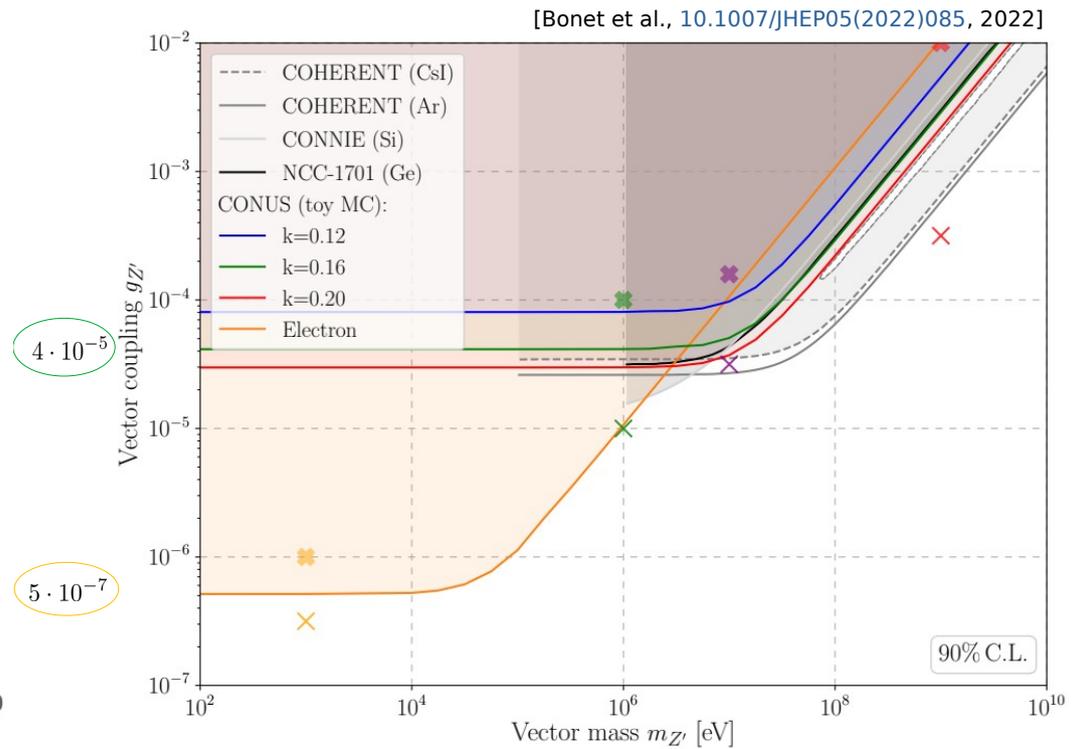
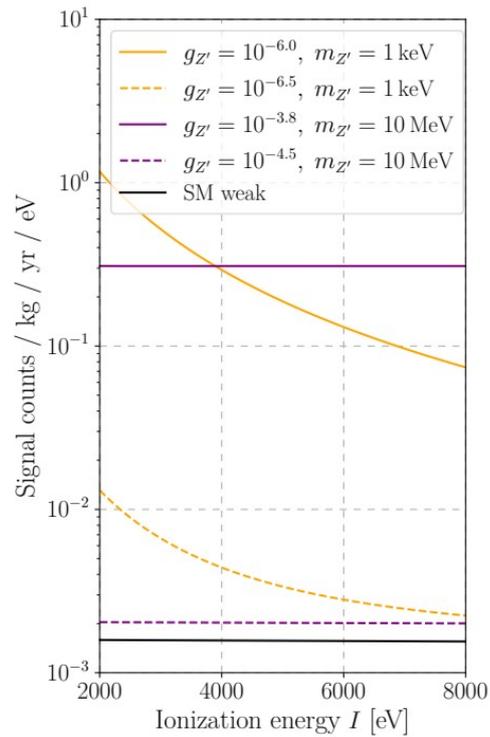
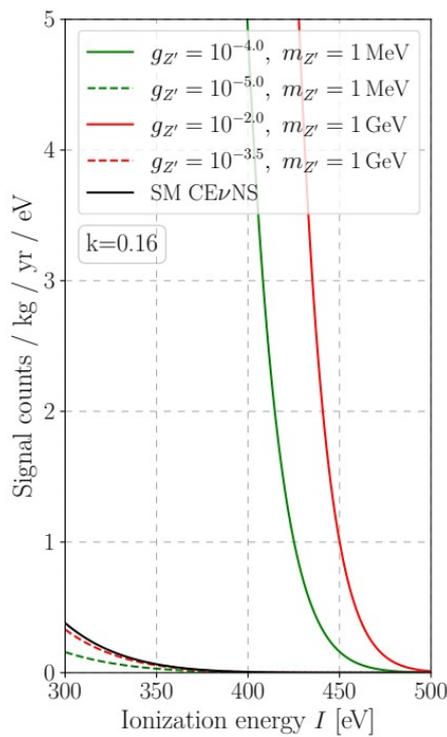
# Simplified models: light vector mediator

**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!

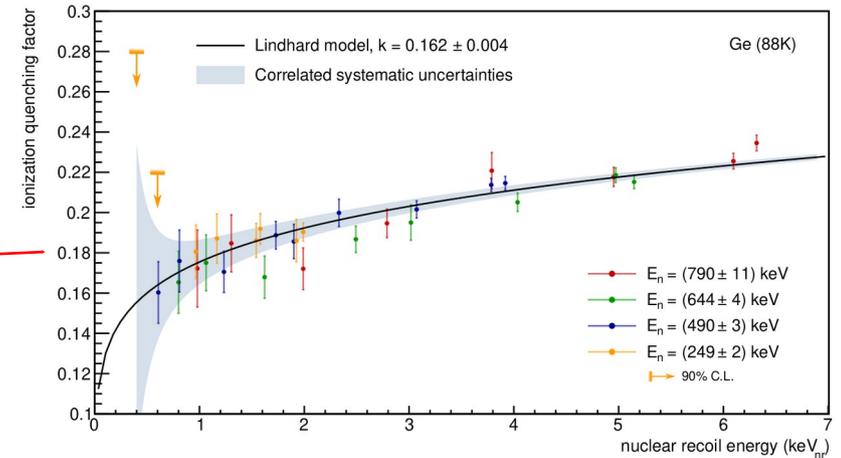
**Several obstacles to overcome:**

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

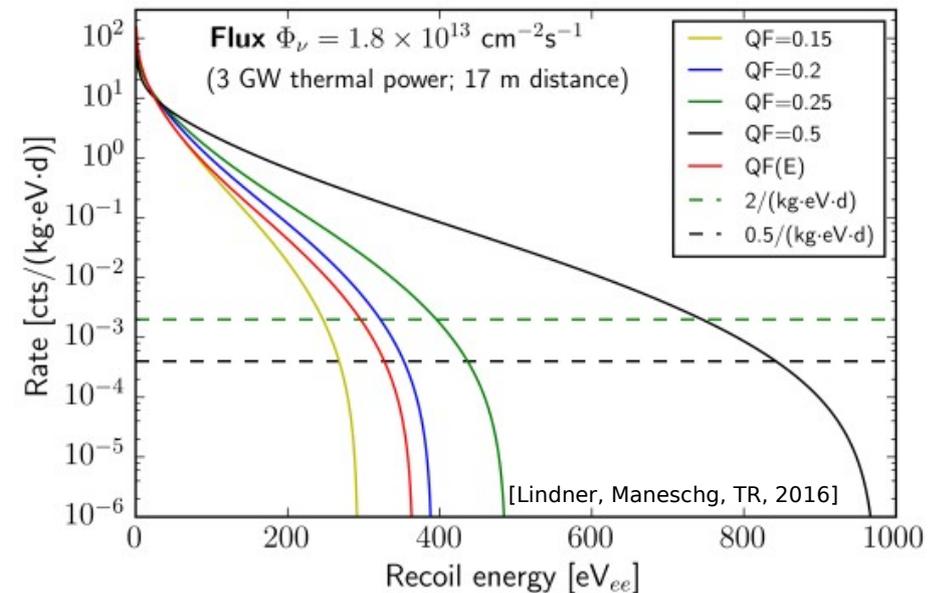
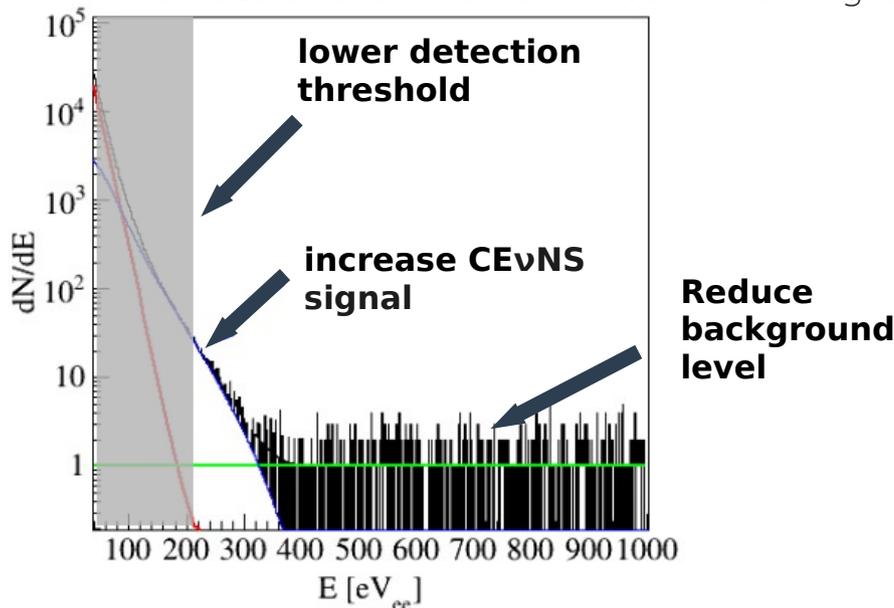
2) Compensate quenching ( $E_{\text{recoil}} \rightarrow E_{\text{ion}}$ )  
 → lowest possible detection threshold

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

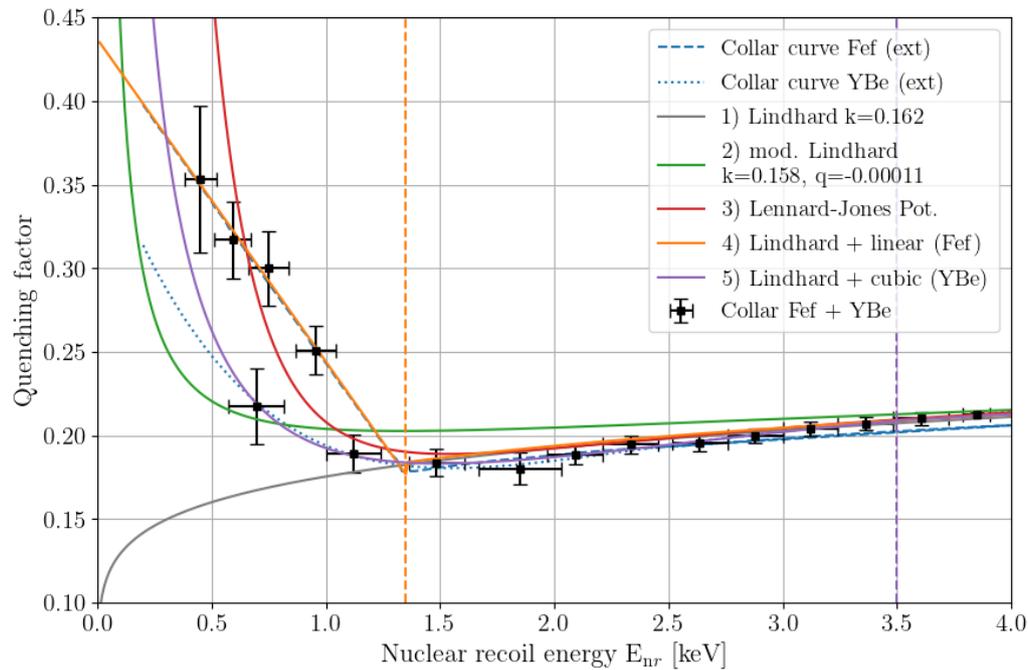
[Bonhomme et al., arXiv:2202.03754, 2022]



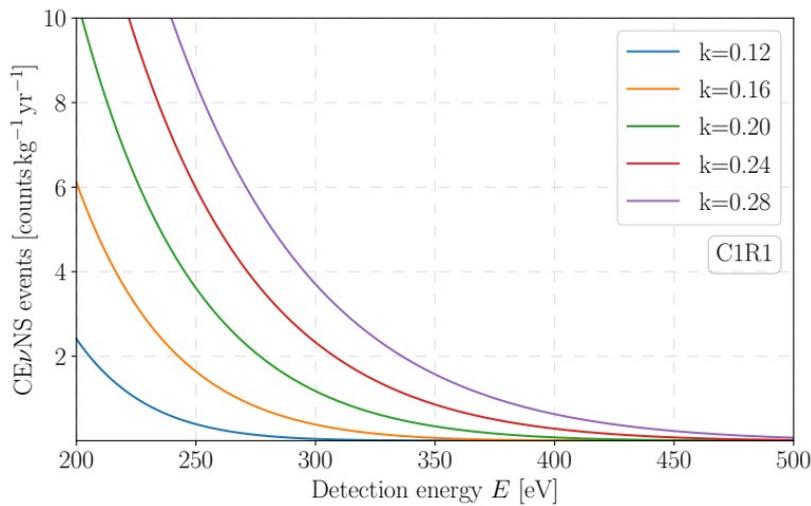
3) Low background outside lab condition  
 → moderate overburden & limited shielding capacities



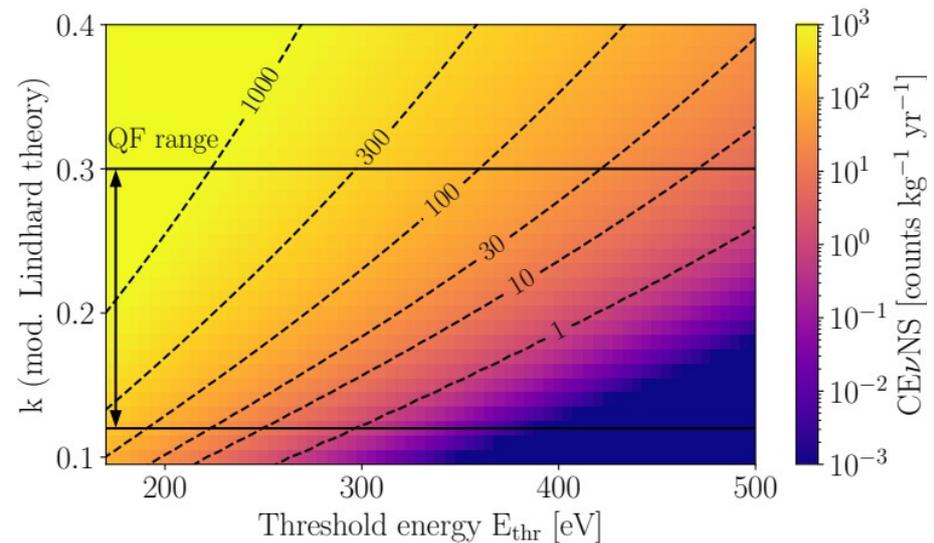
# Impact of quenching at low energy



## Quenching according to mod. Lindhard model:

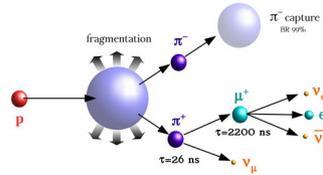


[TR, PhD thesis, 2022]



# 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

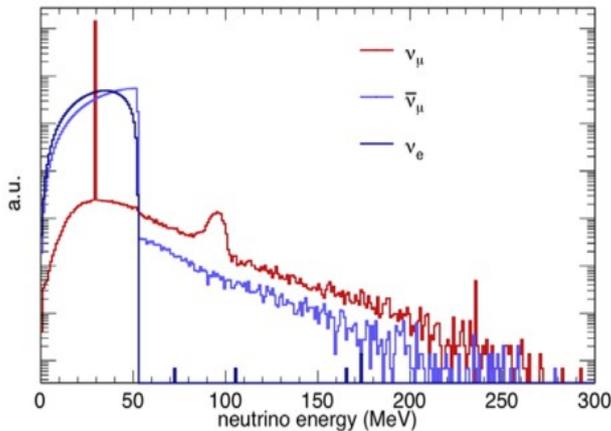
→ **COHERENT, CCM, "CE $\nu$ NS@ESS"...**

## Reactor antineutrinos:

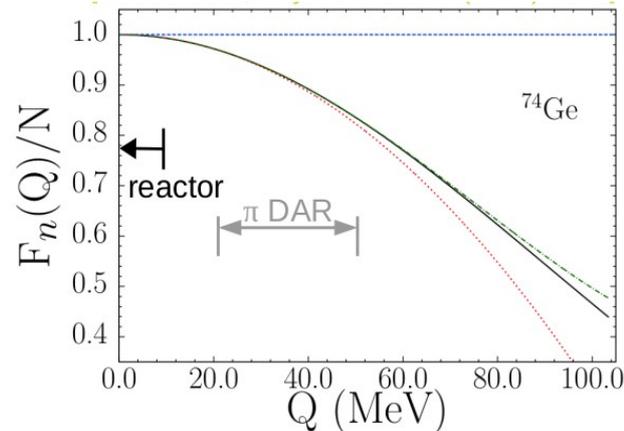
- $\beta$  decays in nuclear reaction chains → only  $\bar{\nu}_e$
- Strongest artificial  $\nu$  source on earth:  
 $\sim 10^{20}$   $\bar{\nu}_e$ 's/GW/s
- $\nu$  energies up to 10 MeV → coherent regime!
- Close to reactor core: no lab conditions!  
→ no cryogenic liquids, no remote control

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

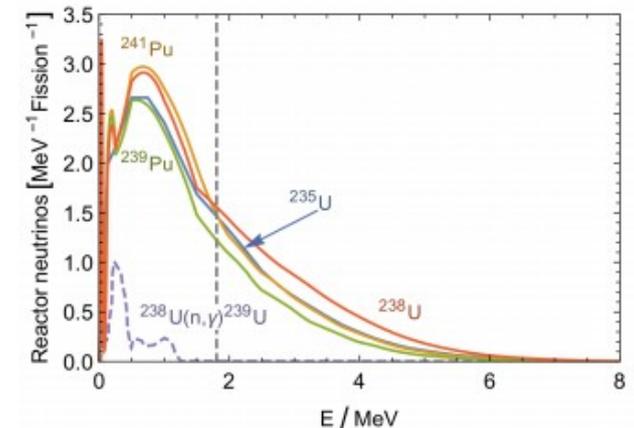
[Akimov et al., arXiv:1509.08702, 2015]



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



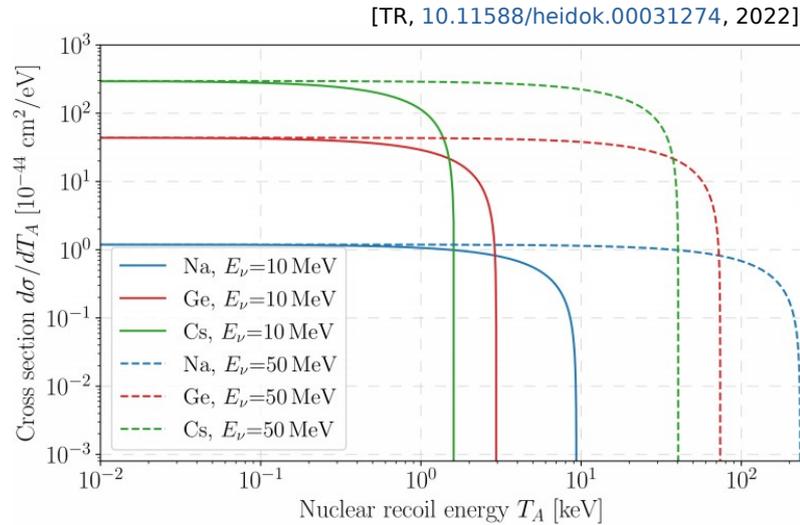
[Vitagliano et al., 10.1103/RevModPhys.92.045006, 2020]



### Beam-reactor complementarity:

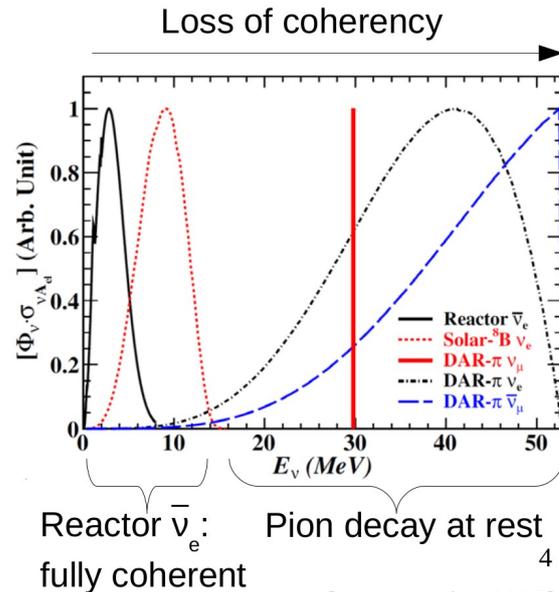
CE $\nu$ NS at reactor site as high statistic baseline for multi-target and multi-flavored beam investigations!

# 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
$\pi$ -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

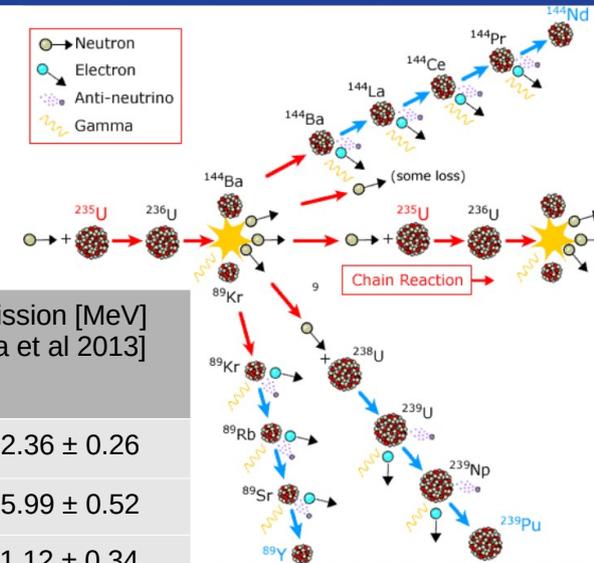
$$S(E_\nu) = \frac{1}{4\pi R^2} \frac{W_{th}}{\sum_i \alpha_i E_i} \sum_i \alpha_i \left( \frac{dN_i}{dE_\nu} \right)$$

## 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  $\rightarrow \mathbf{\alpha(t)}$



Isotope	Fission fraction $\alpha$ (PWR)	E/fission [MeV] [Ma et al 2013]
$^{235}\text{U}$	57%	$202.36 \pm 0.26$
$^{238}\text{U}$	8%	$205.99 \pm 0.52$
$^{239}\text{Pu}$	30%	$211.12 \pm 0.34$
$^{241}\text{Pu}$	5%	$214.26 \pm 0.33$

