The CONUS experiment and future potential of coherent neutrino scattering

Manfred Lindner

On behalf of the CONUS Collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Current Topics in Astroparticle Physics

Nov. 9-11, 2022
Max-Planck-Institut für Physik, Munich

Georg and I

Students at MPP in the early 80's

Georg: neutrinos... ⇔ I: BSM, colliders, ...

- very good friends
- together teaching assistants for lectures
- **training of young group members: supervisors & self-organization**

Back to Munich

Georg: MPP ←→ I: TUM

- my interests changing towards neutrinos...
  CP violation in ν oscillations
  power of reactor ν experiments, ...
- discussions, joint seminars, joint activities:
  → ISAPP school on astroparticle physics 2006
  → SFB375, TR27, IMPRS, ...
  → 2002 Neutrino Conference

Chairs:
F. v. Feilitzsch
N. Schmitz

Heavily involved:
Georg
M. Altmann
ML
...others

2006: Moving on...

Georg: MPP ⇔ I: MPIK, Heidelberg

- **ISAPP summer school on astroparticle physics @MPIK**
  - 2011: lectures by Georg
  - 2019: lectures by Georg
- **...**
- **my interests keept expanding:**
  - dark matter: XENON + theory
- **But neutrinos remain a top theme:**
  - theory ...
  - Double Chooz
  - Gerda / LEGEND200
  - STEREO
  - CONUS

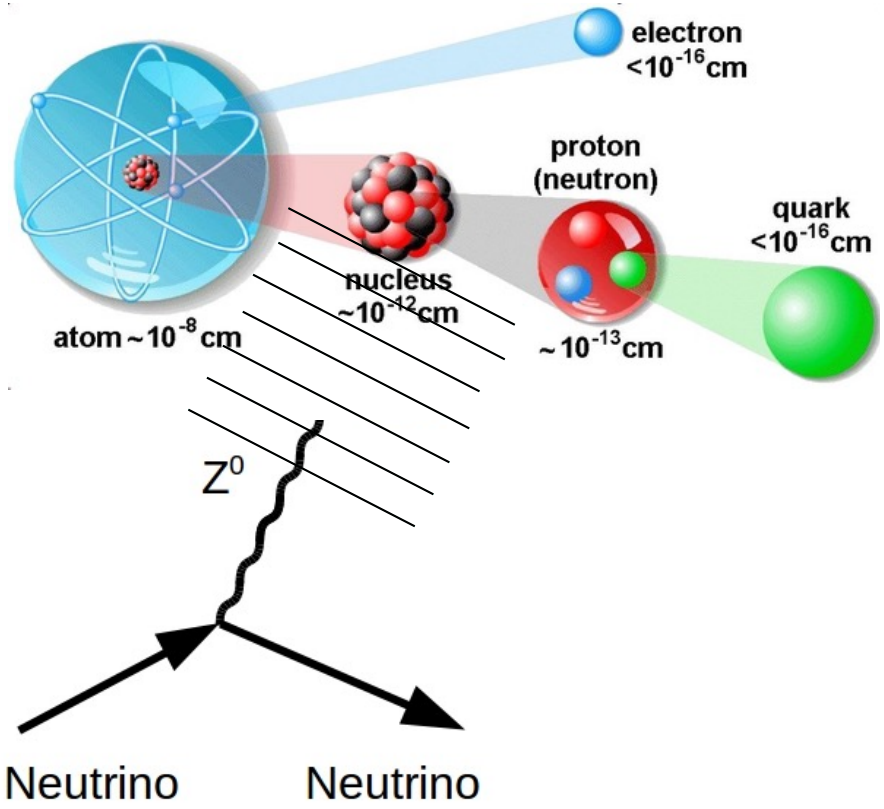
Coherent ν Scattering

Z-exchange of ν with nucleus

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

➔ mostly neutrons
momentum ←→ wavelength

Very low momentum
➔ nucleus recoils as a whole



Important: Coherence length ~ 1/E ➔ E_ν below O(50) MeV
➔ low energy E_ν ←→ lower cross sections ➔ very high flux!

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

N ≃ 40 ➔ N^2 = 1600 ➔ detector mass 10t ➔ few kg

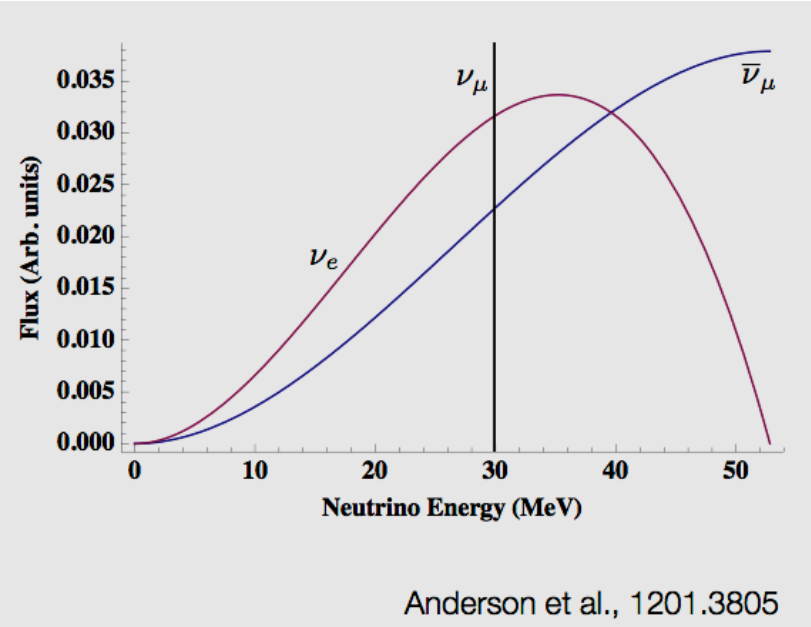
Different experimental Paths

Low energy ν's from accelerators:

- π-decay-at-rest (DAR) ν source
- different flavors produced
- relatively high recoil energies

➔ form factor & uncertainty

➔ **1st observation by COHERENT**

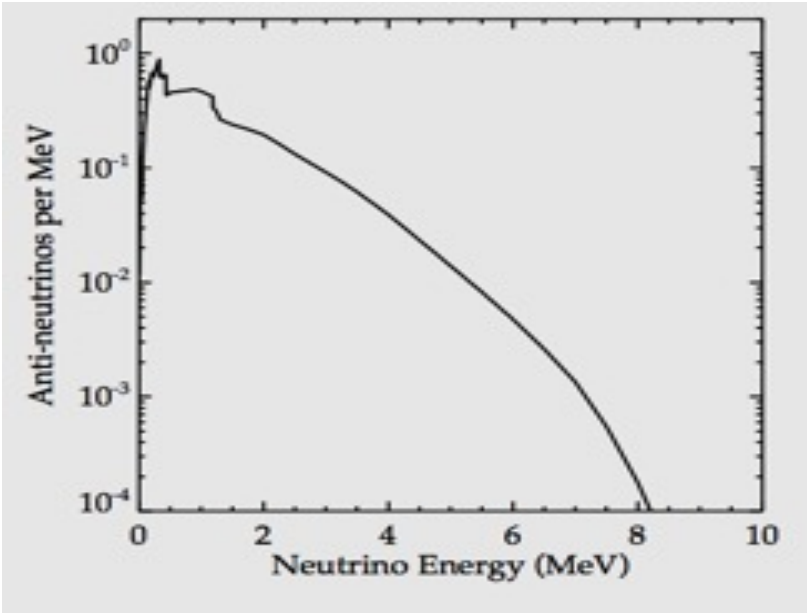


Anderson et al., 1201.3805

Reactors:

- lower ν energies than accelerators
- lower cross section → higher flux
- different flavor content implications for probes of new physics
- fully coherent ~no form factor

➔ **CONUS, ...**



Other: Solar ν's @ XENONnT, ...

Experimental Requirements

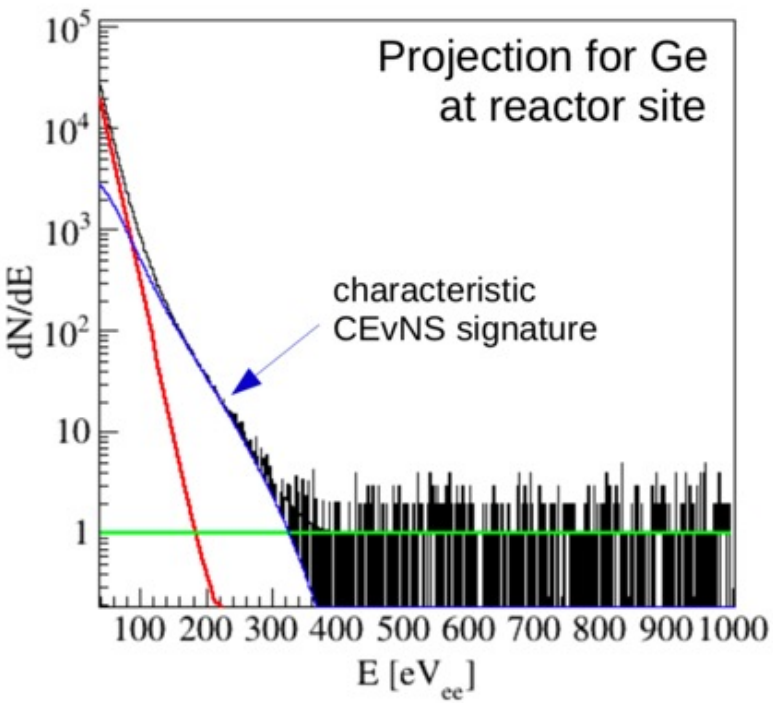
- measure nuclear recoil energy T

  for E_ν = 10 MeV ➔ $T_{max} \simeq$ 3 keV (in Ge)
- energy loss due to quenching (Lindhard)

  ➔ Quenching Factor (QF) at low energy

  ➔ include QF uncertainties

$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$



requirements of CEνNS detection:

- **very low background**

  - radio-pure materials

  - "virtual depth" shielding
- **low noise threshold (sub keV) + mass**
- **very high ν flux**

The CONUS Experiment

Combine:

- highest neutrino flux ➔ close to power reactor
- lowest detection threshold ➔ on-going R&D
- best background suppression ➔ "virtual depth"

➔ **CO**herent **N**e**U**trino **S**cattering experiment

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Preussen Elektra

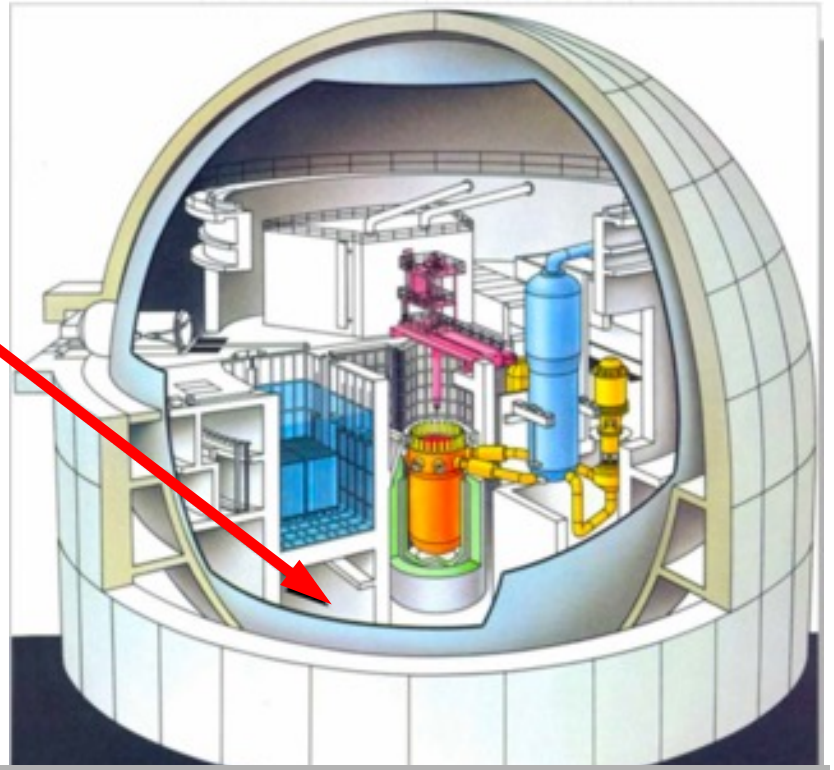
The CONUS Reactor Site

Brokdorf (Germany) nuclear power plant:

- thermal power 3.9 GW_{th}
- detector @ d=17m
- ν flux: 2.4 x $10^{13}/cm^2/s$
- very high duty cycle

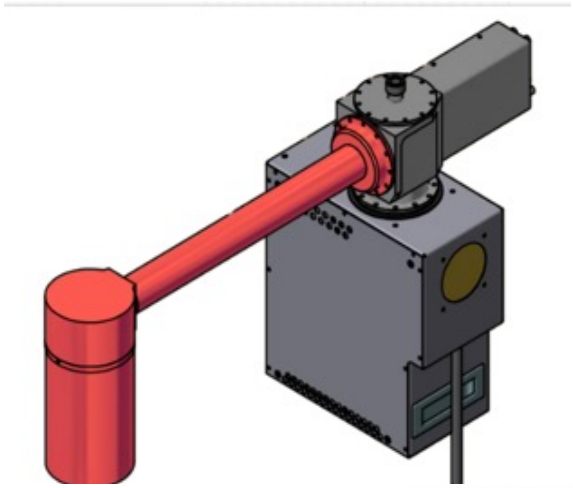
➔ very intense integral neutrino flux
E_ν up to ~ 8 MeV → fully coherent

- overburden 10 - 45 m.w.e
- access during reactor operation
- measurements of n bckgd with PTB
- ON/OFF periods
  - ➔ bckgd. only measurement
  - ➔ seismic detector



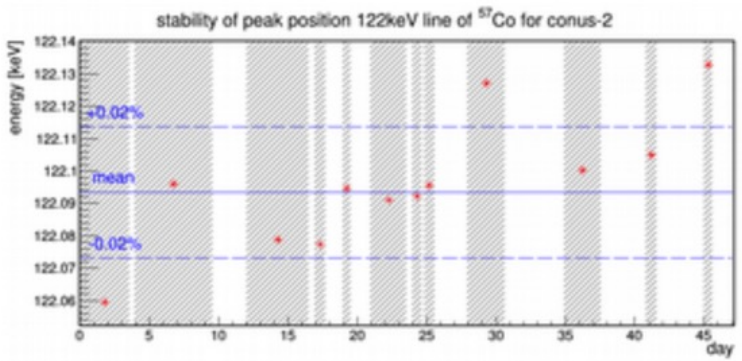
Detectors: CONUS 1-4

- p-type point contact HPGe
- 4x 1kg – **active mass 3.85kg**
- spec. for pulser res. (FWHM) **≤ 85eV**
  → noise threshold < 300eV
- **electrical PT-cryocoolers**
- ultra low background components
- close R&D collaboration with MIRION

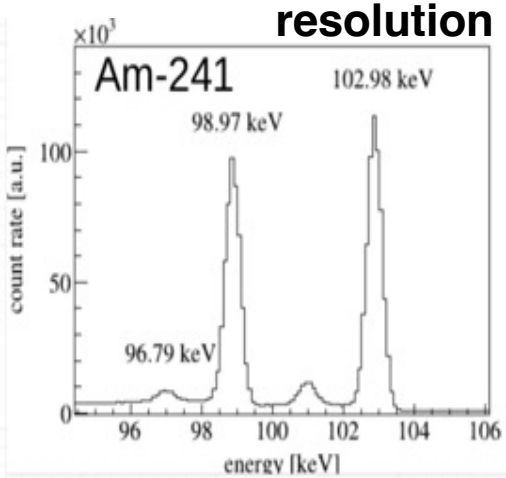


Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

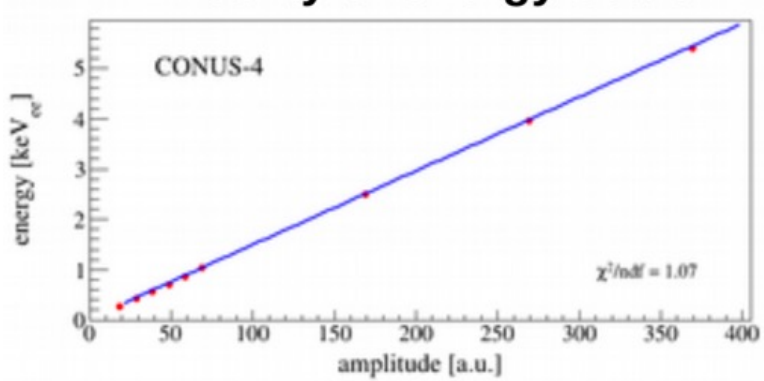
Long term stability
Under lab. Conditions:
stan. dev. of peak position:
+-15eV (+-0.02%)
(within 45 days)

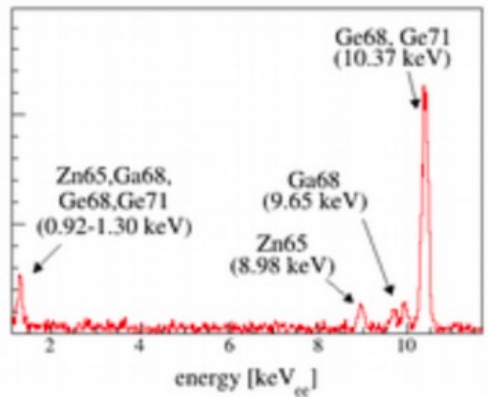


resolution

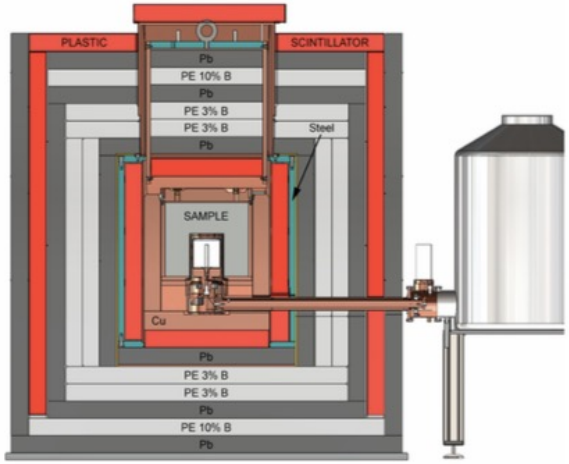


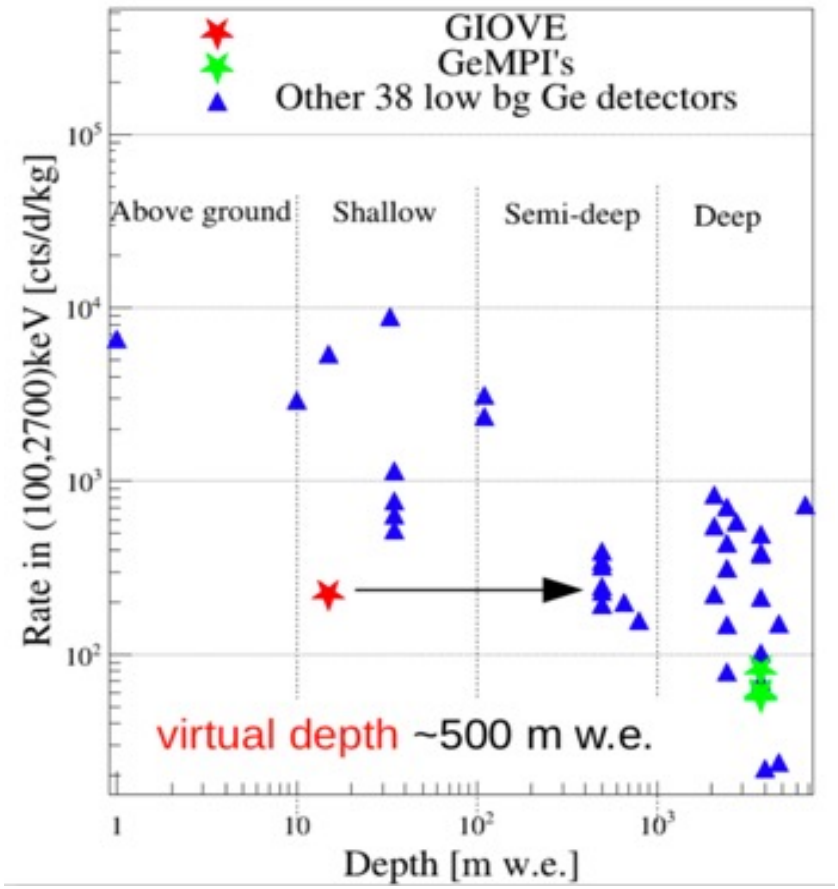
Linearity of energy scale **activation lines: calibration**





``Virtual Depth'': The GIOVE Shield





- R&D at MPIK
- main purpose: material screening @ shallow depth (15 mwe)
- coaxial HPGe detector (m_{act} = 1.8 kg)
- radio-pure passive shielding
  - Pb, B-doped PE, μ-veto, OFHC Cu
- active veto: optimized to reduce μ's and μ-induced signals
  - plastic scintillators with PMTs
  - 99% muon veto efficiency (dead time ~2%)

(^{226}Ra: 70μBq/kg, ^{228}Ra: 110μBq/kg, ^{228}Th 50μBq/kg)

➔ ``virtual depth''

UG projects close to surface

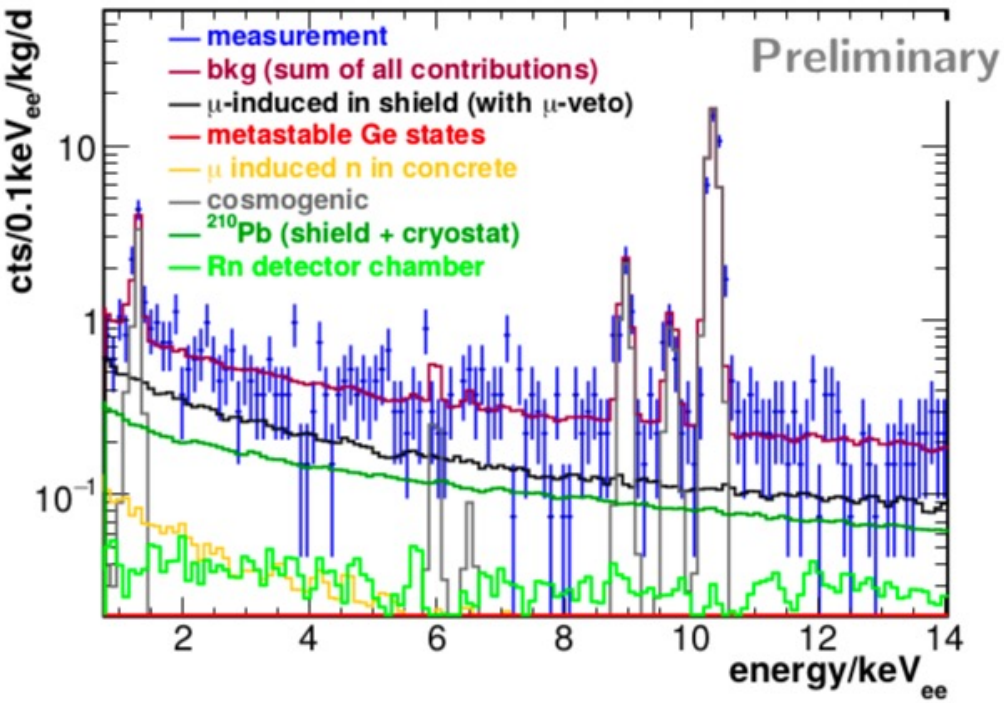
G.Heusser et al., Eur.Phys.J. C(2015)75:531

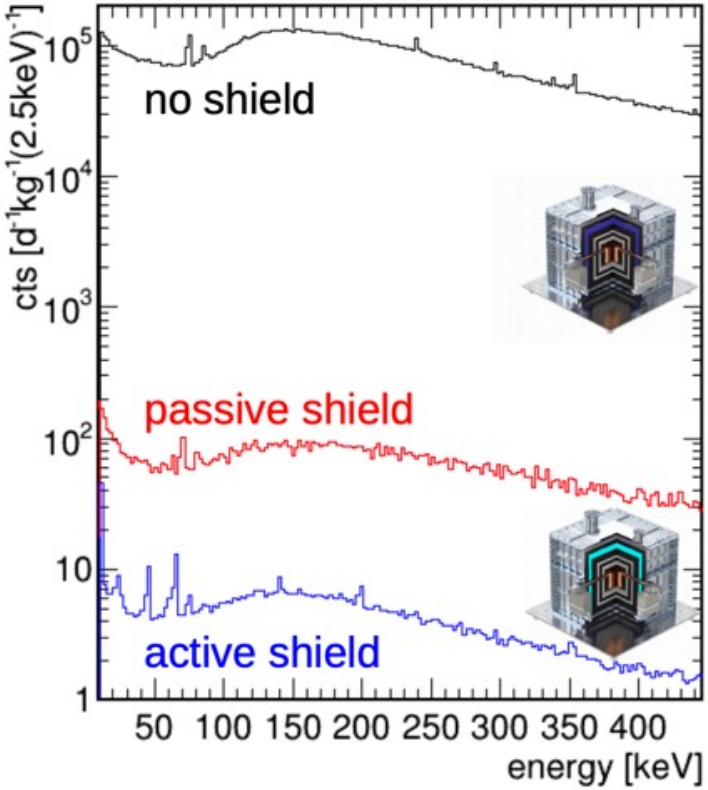
Background Suppression

- Suppression of external natural radioactivity and cosmogenic background by a factor of 10^4
- Residual background fully described by MC simulations

➡ stable background level in [0.5 – 1] keV_{ee}:
10 counts/kg/d/keV_{ee}

Eur. Phys. J. C 79, 699 (2019)
arXiv: 2112.09585 (2021)

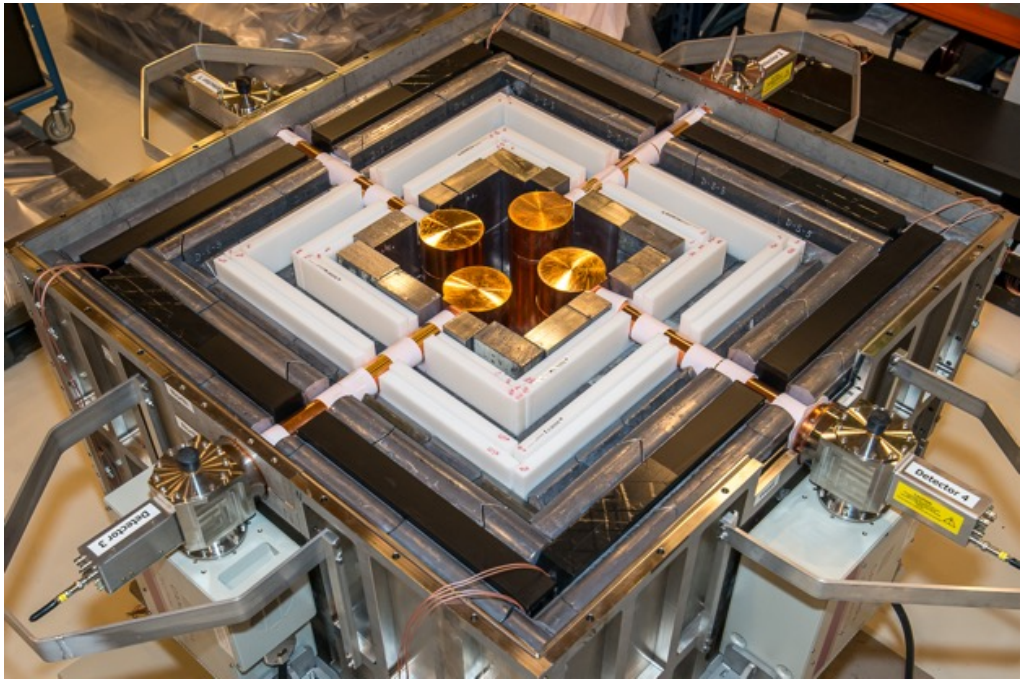


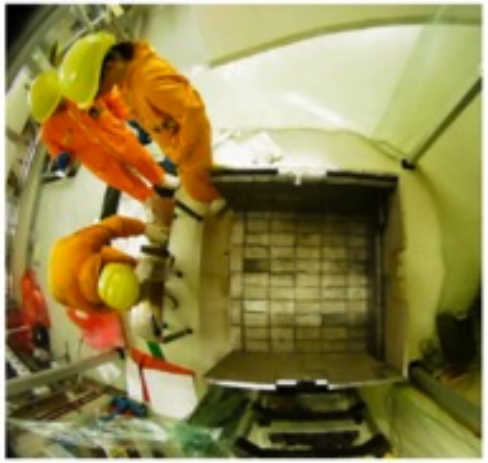


Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

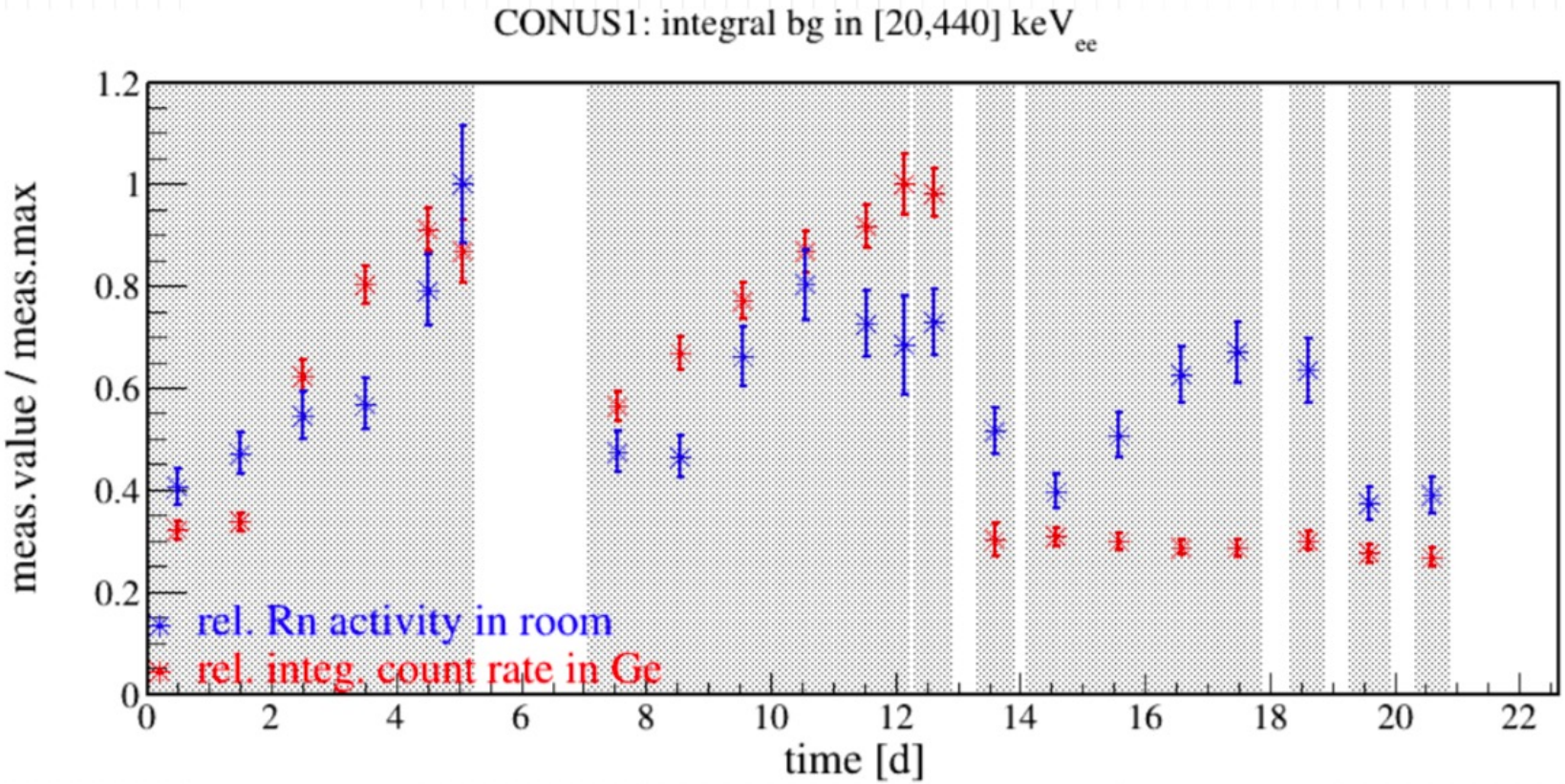
installation @ Brokdorf
→ full assembly
→ commissioning





Radon Mitigation @ Reactor Site

radon at reactor site: closed room, thick concrete walls ➔ 100-300 Bq/m^3
half-life of ^{222}Rn: 3.8d ➔ counter measure @reactor site: N not allowed
hermetical sealing + flush with aged breating air bottles ~1 l/min



no flushing

flushing with
breathing air bottles

Results

Ionization Quenching Factor

- Ionization quenching factor (IQF)

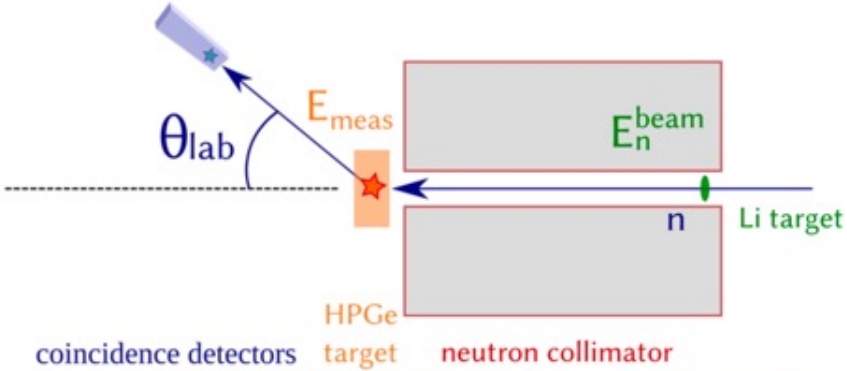
$$IQF = \frac{E_{ionization}}{E_{nuclear\ recoil}}$$

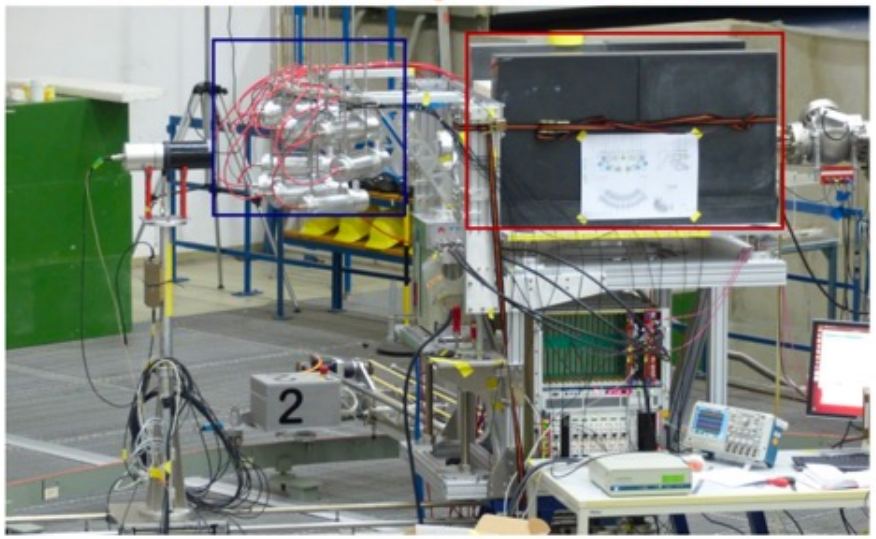
arXiv:2202.03754 (2022)

- Extensively measured from 10-100keV, data lacking in keV range → Conus ROI

Measurement of IQF in Ge:

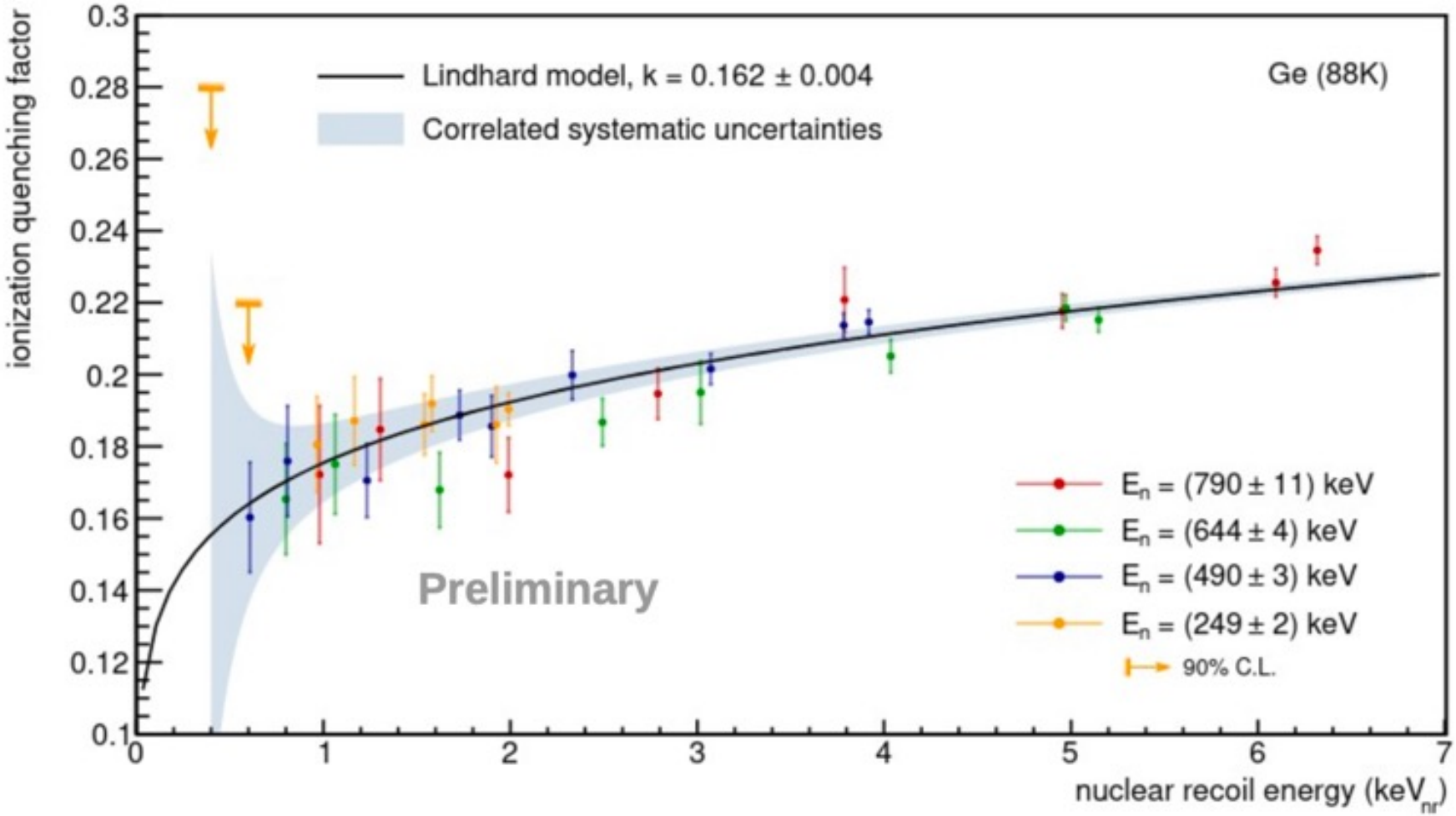
- direct, model-independent using neutrons
- scientific cooperation with PTB:
  - pulsed proton beam
  - mono-energetic neutrons via Li(p,n) reaction
- Experimental setup:
  - neutron collimator
  - thin HPGe target
  - liquid scintillator (LS) array





- Model-independent analysis of data (~16h beam exposure)
- All major systematic uncertainties included

➡ Data compatible with Lindhard model: $k = 0.162 \pm 0.004\,(stat + syst)$

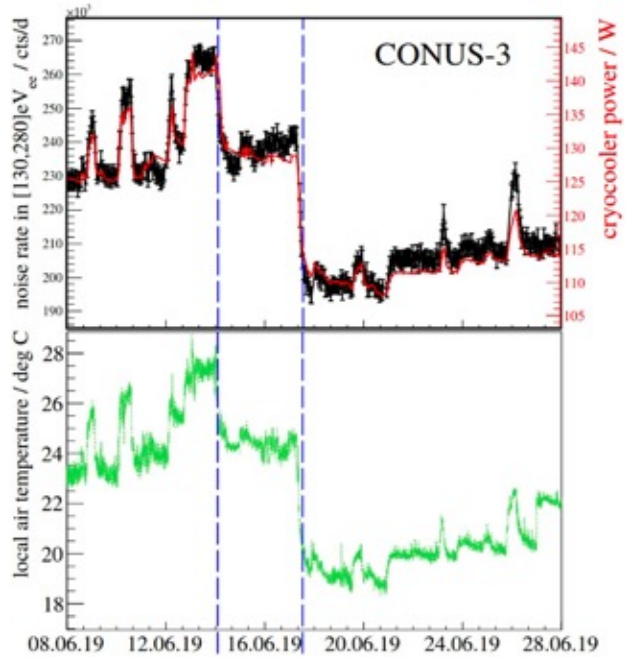


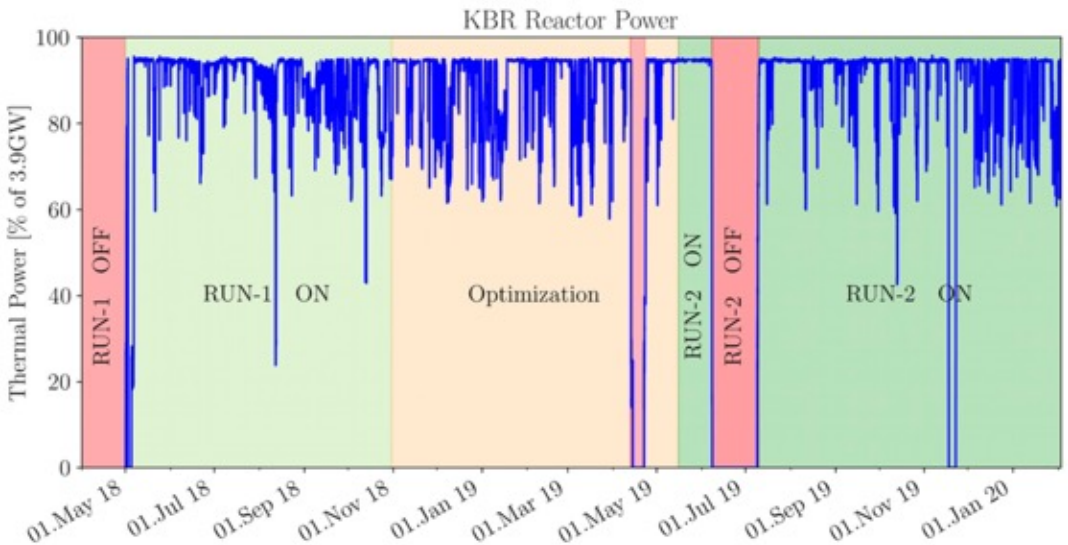
CEνNS Analysis: Data Selection & Noise Cuts

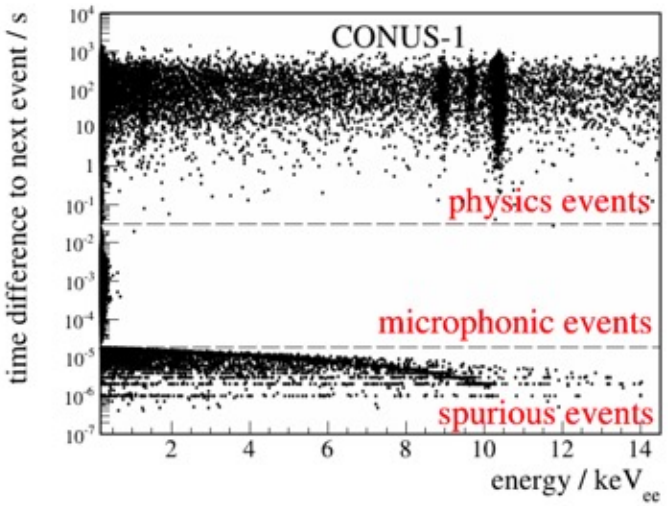
- Noise-temperature correlation cut
- Reject microphonic and spurious events with time-difference distribution cut

➡ Run-1+2 exposure after all cuts:
- 248.7 kg d (reactor-on)
- 58.8 kg d (reactor-off)

Phys. Rev. Lett. 126, 041804 (2021)



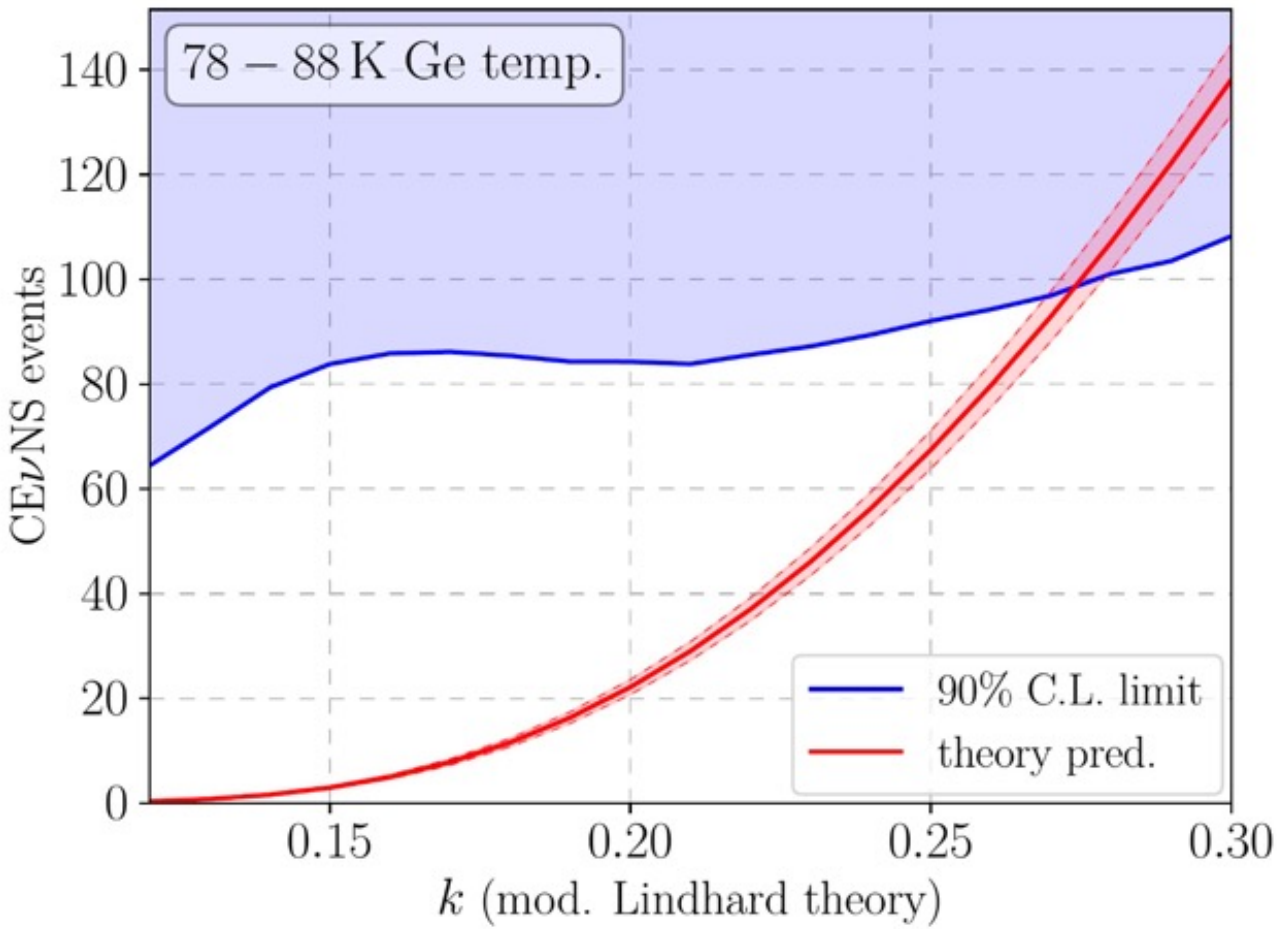




First Results

- **Best CEνNS limit at reactor:** < 0.4 d^{-1} kg^{-1} (90 % C.L.)
- Signal expectation depends on quenching factor

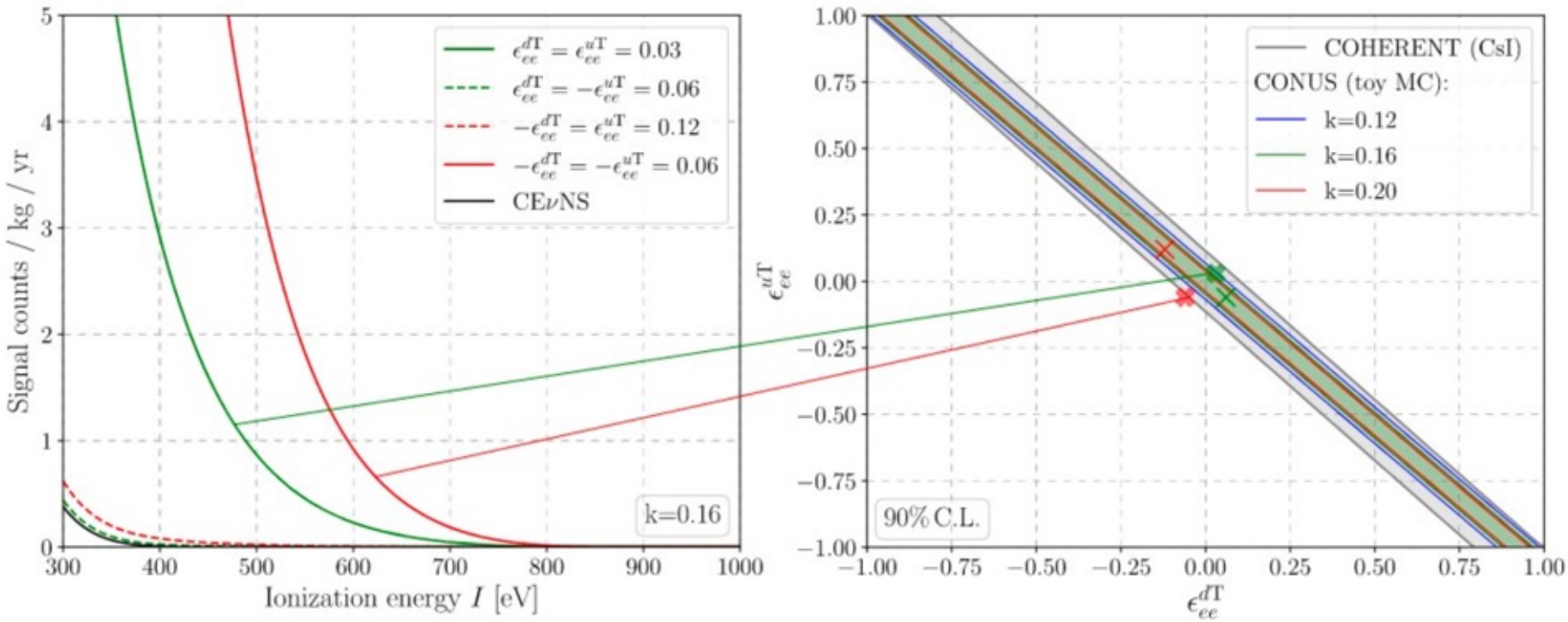
➡ For k=0.16: expected CEνNS signal 17x below CONUS upper limit



BSM: NSI Limits

- Non Standard Interactions (NSIs):
  - effective vector/tensor operators
  - ➡ new couplings $Q_W \rightarrow Q_{NSI}(\{\epsilon^q_{\alpha\beta}\})$
  - Tensor case: $\left(\frac{d\sigma}{dT_N}\right) = \left(\frac{d\sigma}{dT_N}\right)_{CE\nu NS} + \frac{4G_F^2 M}{\pi} Q_{NSI}^{T\,2}\left(1 - \frac{MT}{4E_\nu^2}\right)$

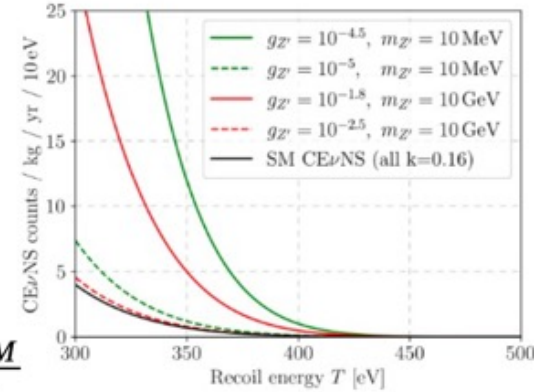
ROI for BSM Analysis: [2 – 8] keV_{ee}



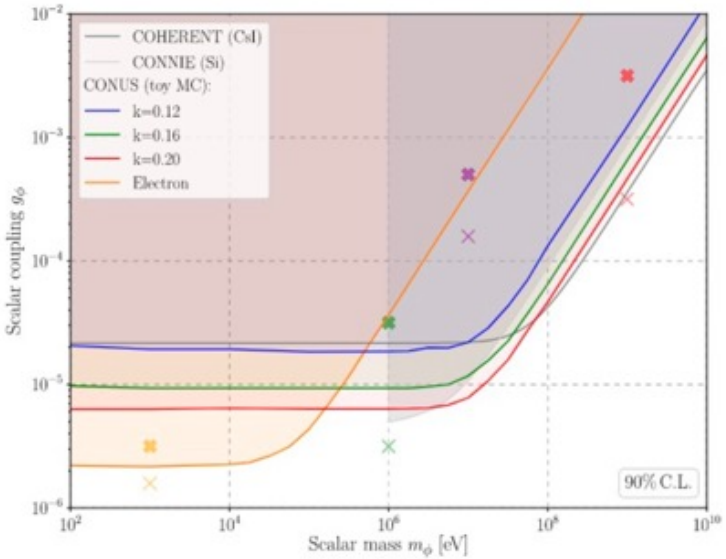
BSM: Simplified Models

- Simplified models:
  - new light scalar/vector mediators
  - universal couplings
  - light scalar boson ϕ : $\frac{d\sigma_\phi}{dT} = \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$
  - light vector boson Z': $\frac{d\sigma_{Z'}}{dT} = \left(1 - \frac{3 g_Z^{\nu\prime} g_Z^{q\prime} (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_{Z'}^2)}\right)^2 \frac{d\sigma_{SM}}{dT}$

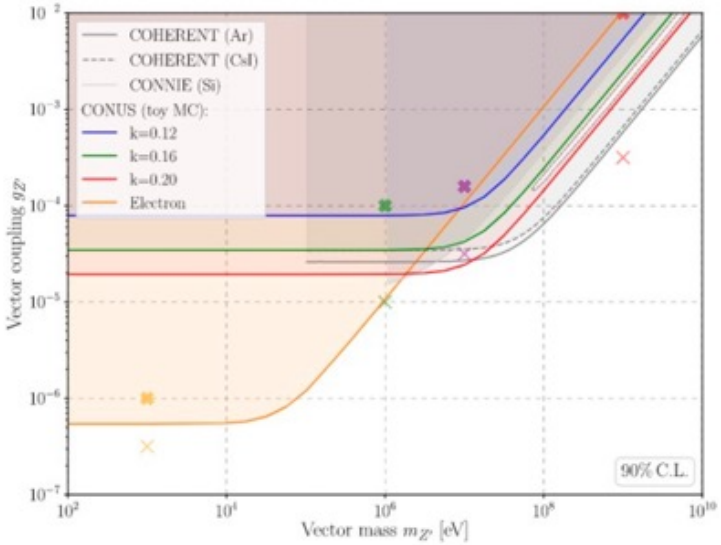
ROI for BSM Analysis: [2 – 8] keV_{ee}



Light scalar boson ϕ



Light vector boson Z'



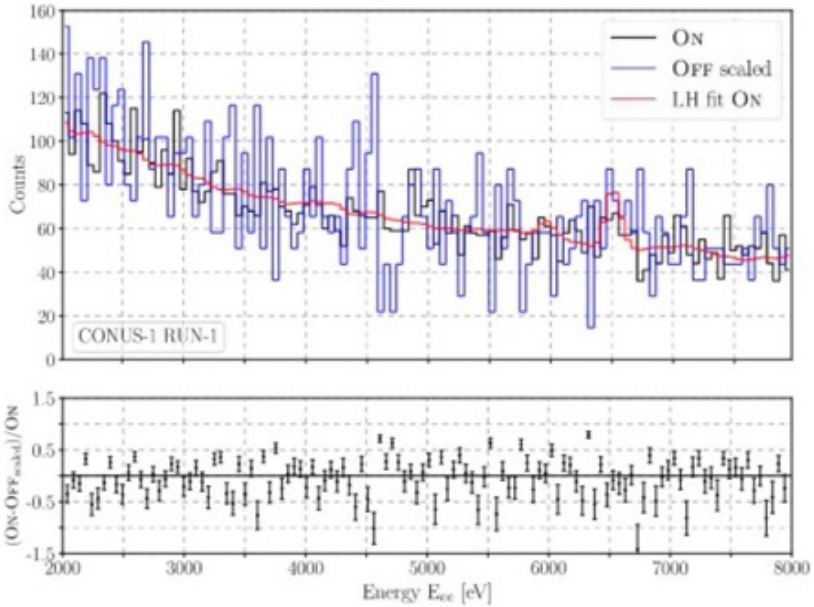
Electro-magnetic Properties

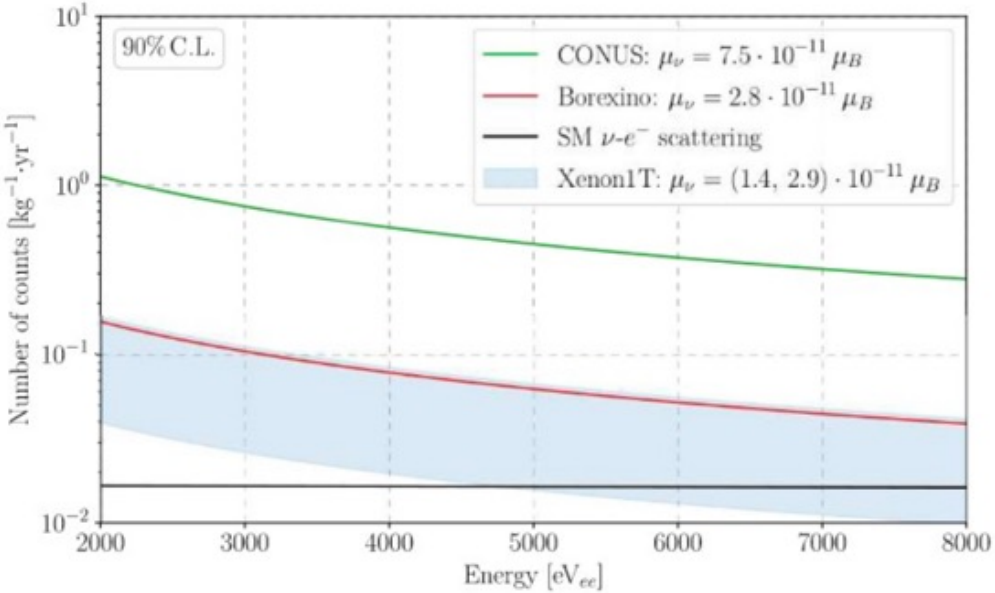
arXiv:2201.12257 (2022)

- Neutrino electron scattering channel:

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

ROI for BSM Analysis: [2 – 8] keV_{ee}





magnetic moment $\mu_\nu < 7.5 \cdot 10^{-11}\ \mu_B\ (90\%\ C.L.)$

millicharges $q_\nu < 3.3 \cdot 10^{-12}\ e_0\ (90\%\ C.L.)$

19/20

Soon (plus next Years)

- Brokdorf shut down January 2022 → more off data
- Run-5 analysis (pulse shape analysis) on-going → stay tuned
- Identified a new reactor site: Leibstadt (CH)
  - similar distance & neutrino flux
  - closer position may be possible...
- move upgraded CONUS → CONUS+
  - * improved detectors (even lower threshold)
  - * optimized shielding & veto (W,...)
  - * aim at increased detector mass
  - * installation planned for next spring

- goals:
  - * observe CEvNS signal
  - * improve BSM sensitivity
  - * demonstrate scalability to O(100)kg

Longer Term Potential

Upscaling of a working technology to 100kg ➔ very interesting potential
high statistics ➔ precision ➔ potential for various interesting topics…

assume:
100 kg detector
4GW @ 15m
flux ~$3*10^{13}/cm^2/s$
background 1/kg/day

BSMsens=ΔS/S

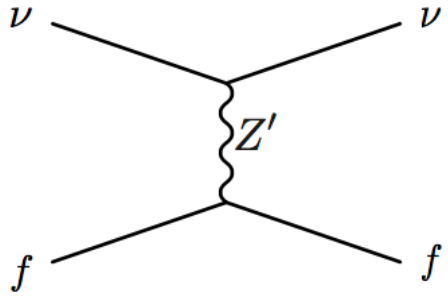
Puler/Thresh [eV]	QF=0.15	**BSMsens**	QF=BF	**BSMsens**	QF=0.25	**BSMsens**
40 / 120	647 474/ 8291 / 78.1	$1*10^{-3}$	965 999/ 10 775/89.7	$1*10^{-3}$	$2.9*10^{6}$/ 15 158 / 189	$6*10^{-4}$
45 / 135	407 092/ 8 036 / 50.7	$2*10^{-3}$	664 316/ 10 519/63.2	$1*10^{-3}$	$2.1*10^{6}$/ 14 866 / 144	$7*10^{-4}$
50 / 150	254 745/ 7780 / 32.7	$2*10^{-3}$	458 072/ 1 0264/44.6	$1*10^{-3}$	$1.6*10^{6}$/ 14 574 / 84.9	$8*10^{-4}$
55 / 165	158 109/ 7 524 / 21.0	$3*10^{-3}$	315 843/ 9 971/31.7	$2*10^{-3}$	$1.2*10^{6}$/ 14 318 / 84.9	$9*10^{-4}$
60 / 180	97 066/ 7 305 / 13.3	$3*10^{-3}$	217 277/ 9 716/22.4	$2*10^{-3}$	919 435/ 13 026 / 65.6	$1*10^{-3}$
65 / 195	58 827/ 7 049 / 8.3	$4*10^{-3}$	148 848/ 9 460/15.7	$3*10^{-3}$	696 196/ 13 770 / 50.6	$1*10^{-3}$
70 / 210	35 154/ 6 830 / 5.1	$5*10^{-3}$	101 386/ 9 204/11.0	$3*10^{-3}$	527 204/ 13 514 / 39.0	$1*10^{-3}$
75 / 225	20 711/ 6 575 / 3.2	$7*10^{-3}$	68 573/ 8 949/7.7	$4*10^{-3}$	398 867/ 13 222 / 30.2	$2*10^{-3}$
80 / 240	12 042/ 6 355 / 1.9	$9*10^{-3}$	46 008/ 8 730/5.27	$5*10^{-3}$	301 231/ 12 966 / 23.2	$2*10^{-3}$
85 / 255	6 924/ 6 136 / 1.1	$1*10^{-2}$	30 598/ 8 474/3.6	$6*10^{-3}$	226 910/ 12 711 / 17.9	$2*10^{-3}$

BSMsens=ΔS/S S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales
Which are integrated out
Z', new scalars, … ➔ ε_{ij}



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

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

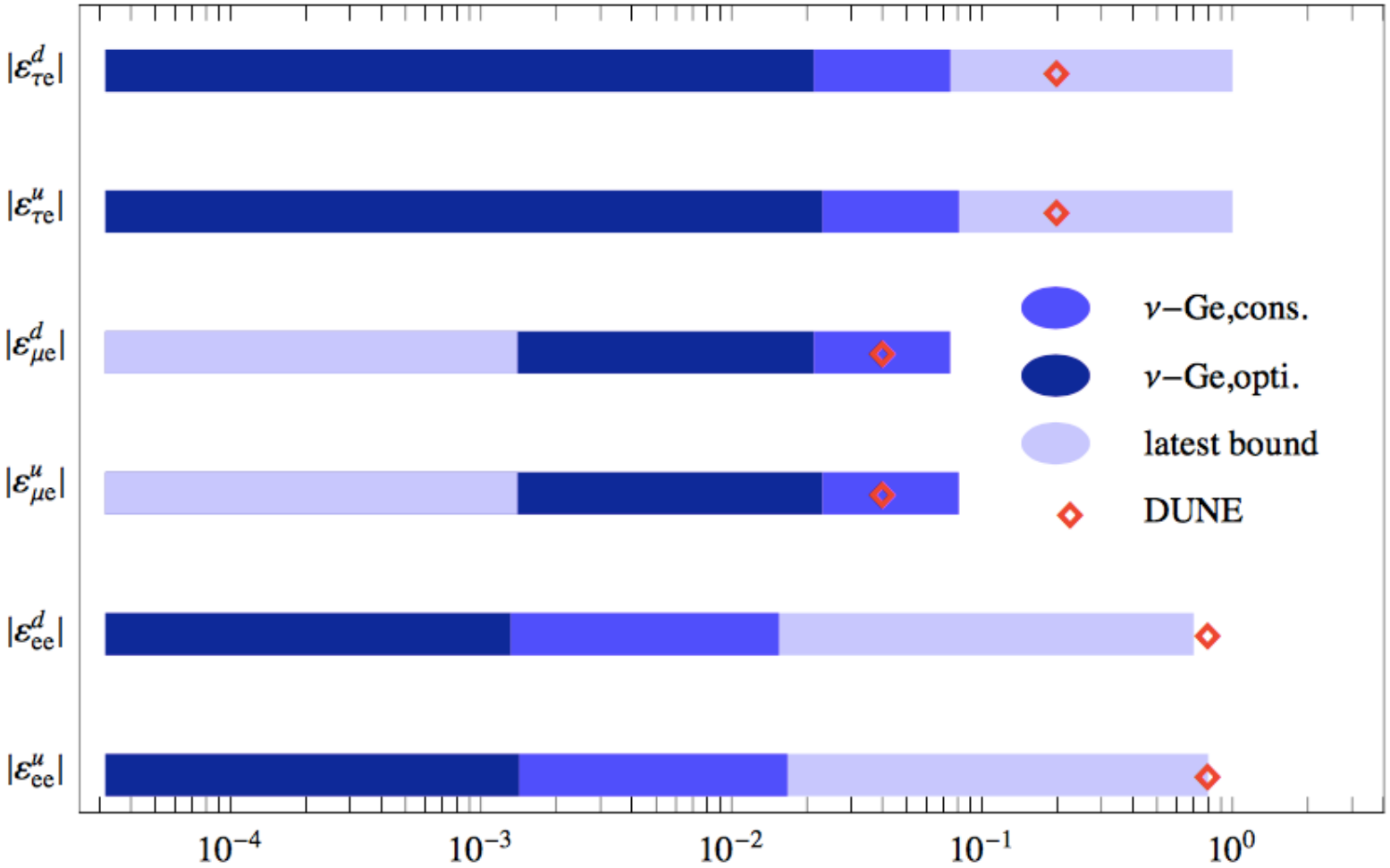
Barranco et al. 2005

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

➔ Competitive method to test TeV scales
$\varepsilon = 0.01$ ←→ TeV scales

NSI-Potential

100kg detector, 5 years operation @ 4GW **ML, W. Rodejohann, X.Xu**



~10 TeV **~TeV**

Precise Measurement of $\sin^2\theta_W$ at low E

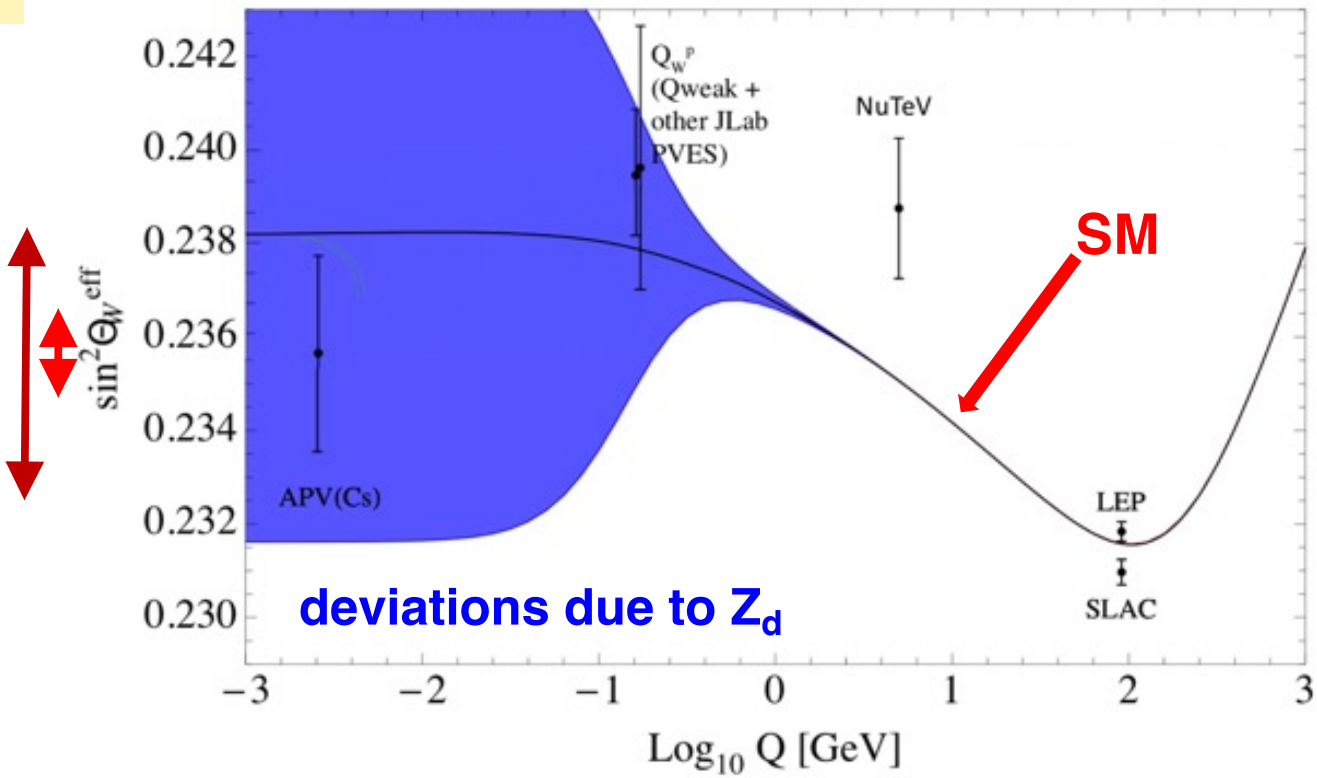
$\sin^2\theta_W$ precisely known in SM
SM quantum corrections
→running $\sin^2\theta_W^{eff}$

CEνNS cross-section:
$\sigma \sim N - [(1- 4*\sin^2\theta_W)\ Z\ ]^2$

$\simeq 0$
→ enhanced sensitivity

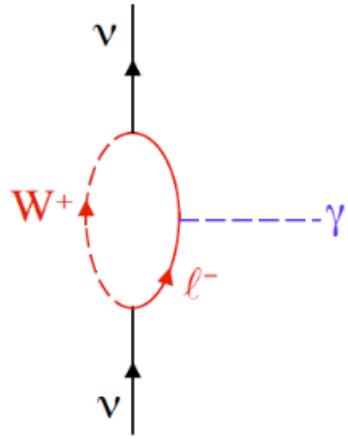
BSMsens:
10^{-3} → $\Delta\sin^2\theta_W = 0.006$
10^{-4} → $\Delta\sin^2\theta_W = 0.0006$

potential problem: (g-2) anomaly
→ Light dark sector?
Z_d ; M=150 MeV; ...other parameters
See e.g. 1411:4088
many models lead to similar effects...



Searches for new Physics: Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:



Dirac: $$\mu^D_{kk} \simeq 3.2 * 10^{-19} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_B$$

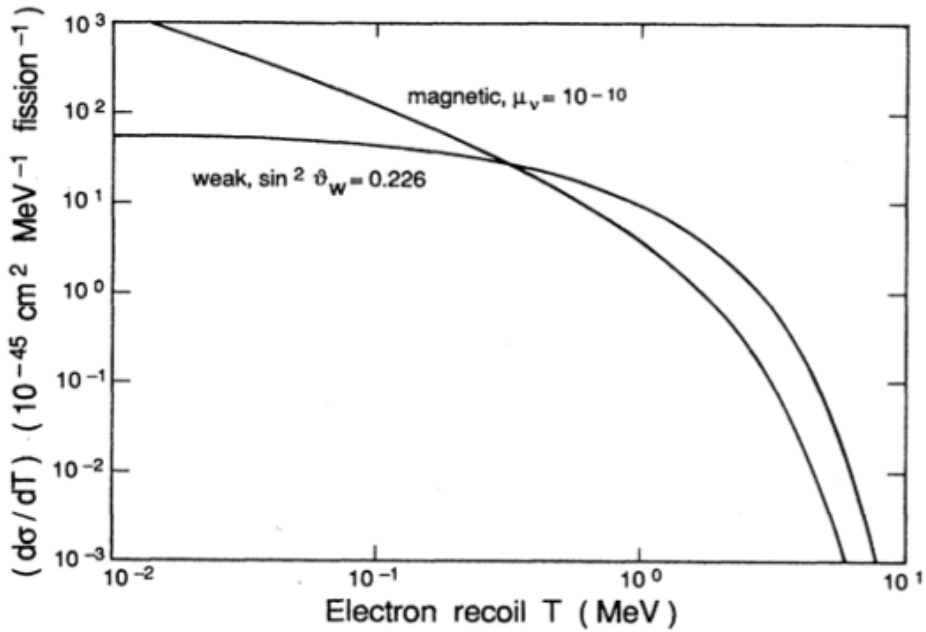
Majorana: $$\mu^M_{ll'} \lesssim 4 * 10^{-9} \mu_B \left(\frac{M^M_{ll'}}{\mathrm{eV}}\right) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \left|\frac{m_\tau^2}{m_l^2 - m_{l'}^2}\right|$$

New physics ➔ detectable enhancements due to new physics:
SUSY, extra dimensions, …

At least new best limits:
e-scattering (GEMMA) and astrophysics:

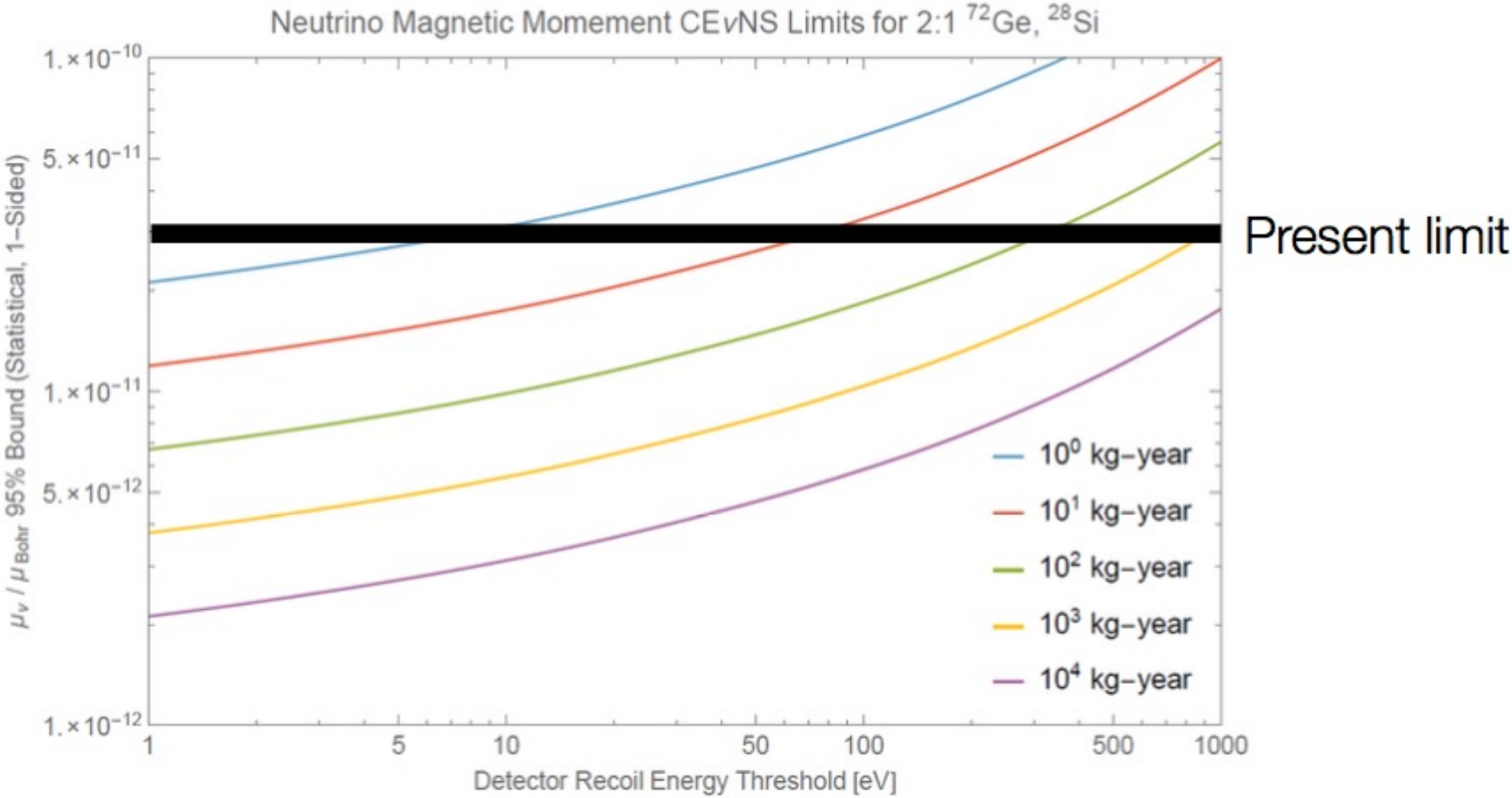
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$

Scattering on protons coherently enhanced: ➔ detectable at low energy (Vogel & Engel 1989)



$$\frac{d\sigma}{\ldots} = \frac{\pi\alpha^2\mu_\nu^2}{\ldots}\left[1 - T_R/E_\nu + \frac{T_R}{\ldots}\right]$$

Potential for Magnetic Moments

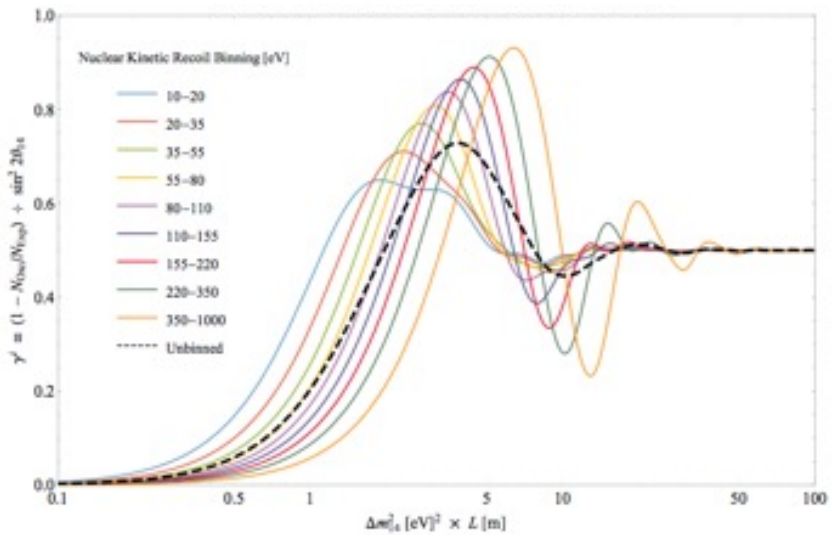


100kg * 5y = 500 kg-year ; low threshold ➔ one order of magnitude better

Searches for new Physics: Sterile ν's

- **Various indications / hints for sterile neutrinos ?**

- eV sterile ν's with small mixing
- keV warm dark matter with tiny mixing
- …different mass ranges
- any sterile state would motivate more…

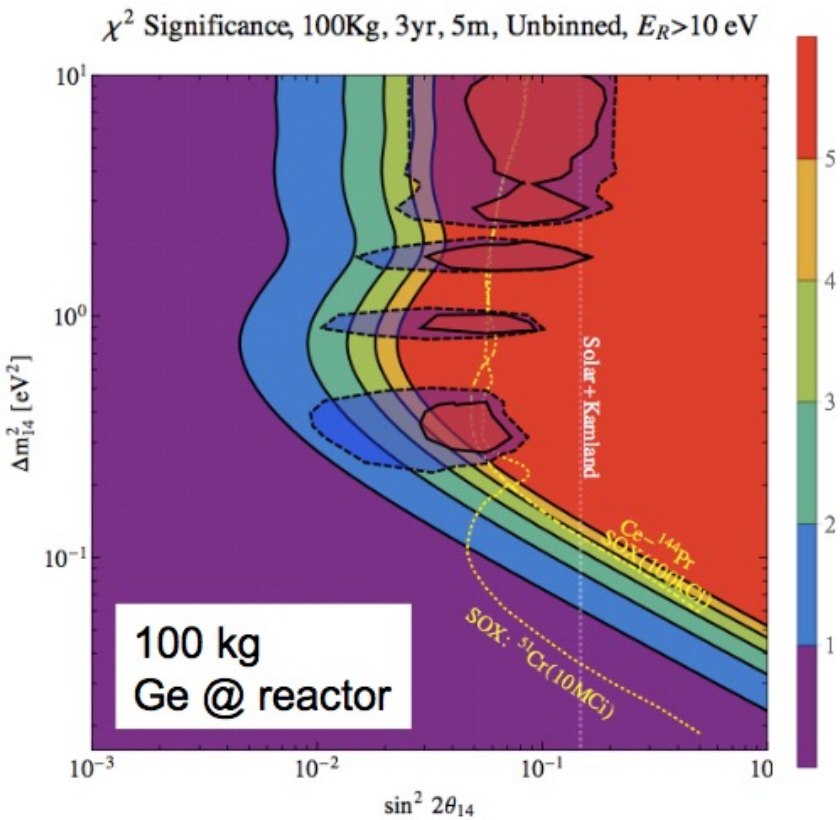


Dutta et al. 1511.02834

$$P(\nu_\alpha \to \nu_\alpha) = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\sin^2(1.27\Delta m^2_{41}L/E)$$

➔ **test if / how flux deviates from $1/R^2$**

➔ **time scales compared to other projects**



B. Dutta et al, arXiv:1511.02834

Nuclear Structure with coherent Scattering

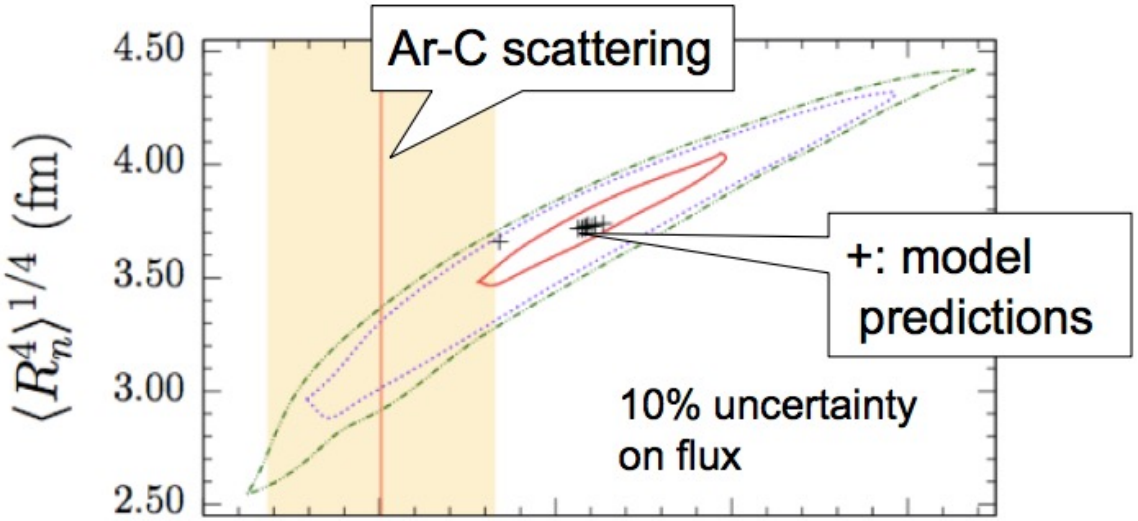
Remember: DAR sources close to de-coherence ⇔ combine with reactor measurements

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

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

Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments
(requires very good energy resolution,good systematics control)

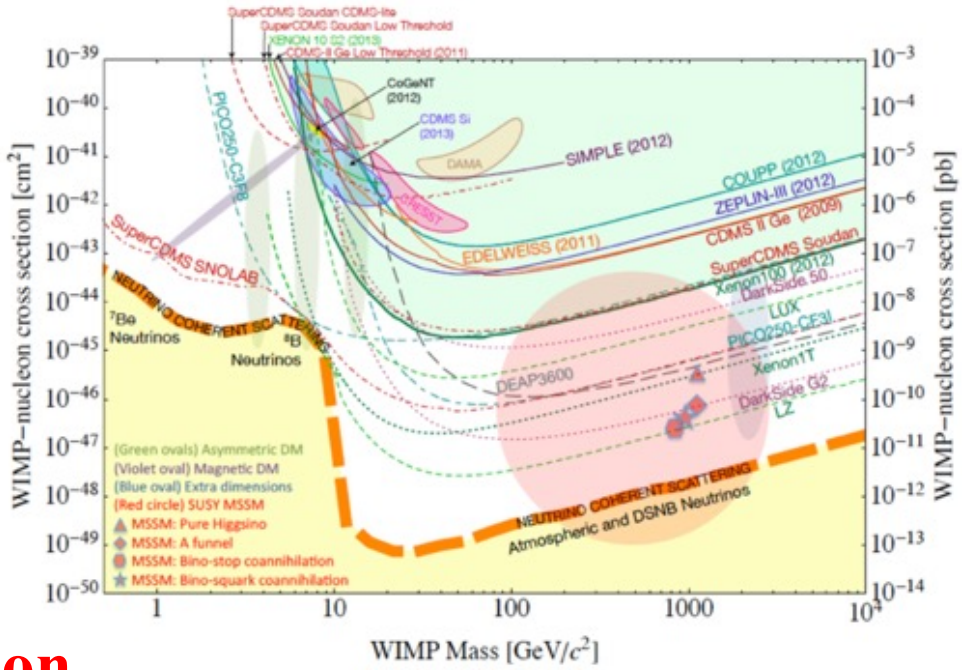
Example:
tonne-scale
experiment
at πDAR source



CEνNS Connections to more Topics...

DM connection:

1) DM experiments <u>assume</u> coherent DM scattering → test with ν's
2) Neutrino floor of direct DM experiments will measure CEνNS
   → combine different measurements



CEνNS cross-section

3) Important for astrophysical applications: supernovae, ...
4) ...

More Phenomenology / Theory / Applications

- **coherent ν's ➔ conceptually very interesting questions**
  see e.g. Akhmedov, Arcadi, ML, Vogl, JHEP 1810 (2018) 045, arXiv:1806.10962
  - can coherent scattering occur at macroscopic scales?
  - role of the recoil of constituents in quantized picture
  - semi-classical factorization of QFT process into (cross-section) * $F(q^2)$?
  - ...
- **coherence length in QFT approach**
  Egorov, Volobuev: 1902.03602
- **many connections to dark matter models**
- **producing new fermion in CEνNS** **Brdar, Rodejohann, Xu: 1810.03626**
- **effects of CP violating parameters on CEνNS processes**
  see e.g. Sierra, De Romeri, Rojas: arXiv:1906.01156
- **Safeguarding...**
- **...**

Summary

- **CEνNS was 1st observed by COHERENT at $E_\nu \simeq$ 30-50 MeV**
- **CONUS**
  - close to signal ←→ lower QF than expected ➔ run-5 analysis on-going
  - strong BSM limits ←→ fully coherent → deviations are BSM
  - improvement: detailed pulse shape analysis – analysis of run 5 ongoing
  - on-going upgrade to CONUS+ at new reactor site
    * lower threshold * increased detector mass

- **Longer term future: CEνNS will become an interesting tool**
  - upscaling of existing technology to O(100kg) ➔ physics topics:
  - coherent ν scattering ←→ DM & WIMP scattering, neutrino floor
  - BSM: ν magnetic moments, NSIs, steriles, $\sin^2\theta_W$, sterile oscillation
  - nuclear form factors with neutrinos $F(q^2)$
  - reactor ν spectrum & anomalies

  ➔ **very interesting potential of demonstrated technology**