# Coherent Neutrino Scettering:
## The CONUS Experiment and future Potential

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*On behalf of the CONUS Collaboration*

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

**41st Course**
*Star Mergers, Gravitational Waves, Dark Matter and Neutrinos*
*in Nuclear, Particle and Astro-Physics, and in Cosmology*
**Erice-Sicily: September 16-24, 2019**

# Coherent ν Scattering

Z-exchange of ν with nucleus

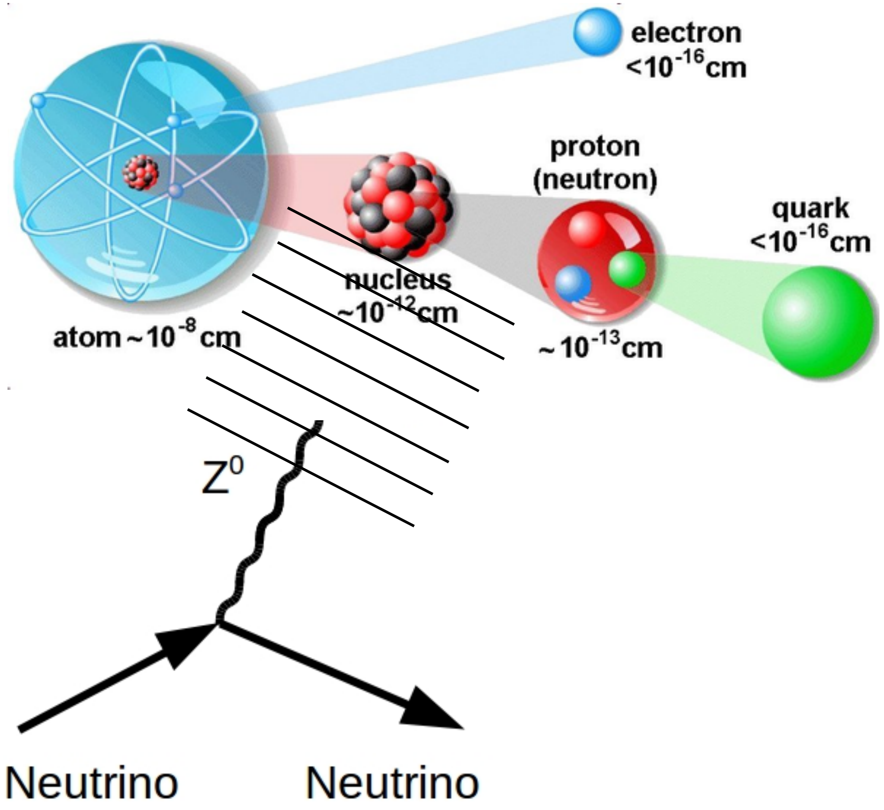
$Q_w = N - (1 - 4\sin^2\theta_w)Z$ ~ N

➔ mostly neutrons

momentum ←→ wavelength

Very low momentum

➔ nucleus recoils as a whole




Important: Coherence length ~ 1/E ➔ $E_\nu$ below O(50) MeV

➔ low energy $E_\nu$ ←→ lower cross sections ➔ very high flux!

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

N $\simeq$ 40 ➔ $N^2$ = 1600 ➔ detector mass 10t ➔ few kg

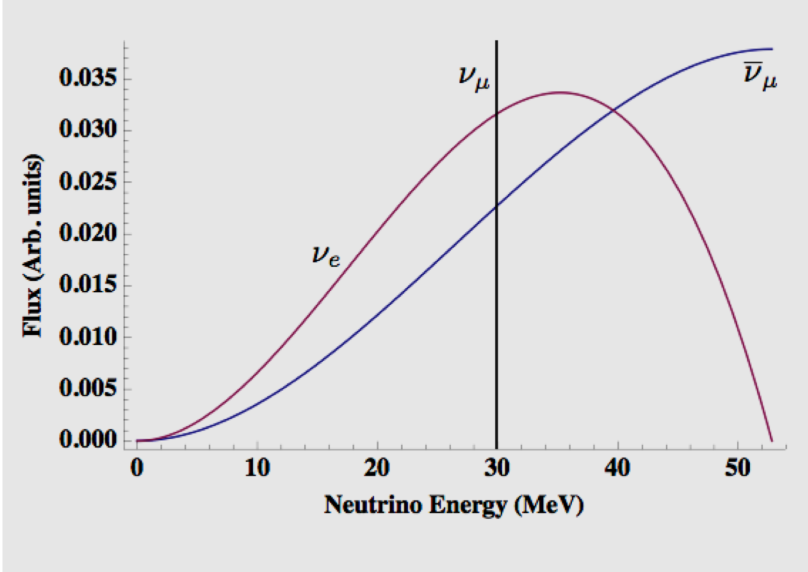
# Different experimental Paths

## Low energy ν's from accelerators:

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

➔ close to de-coherence

➔ **1st observation of CEνNS by COHERENT ➔ K. Scholberg**

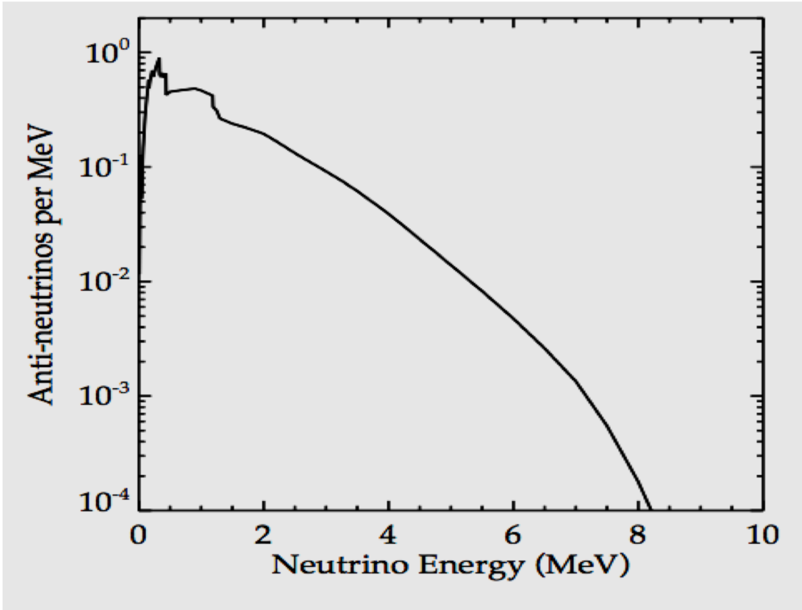



Anderson et al., 1201.3805

## Reactors:

- lower ν energies than accelerators
- lower cross section – higher flux
- different flavor content implications for probes of new physics

➔ **CONUS**




Vogel et al. 1981, Kopeikin 2012

## Others: individual & synergetic...

# Experimental Requirements

- measure nuclear recoil energy T

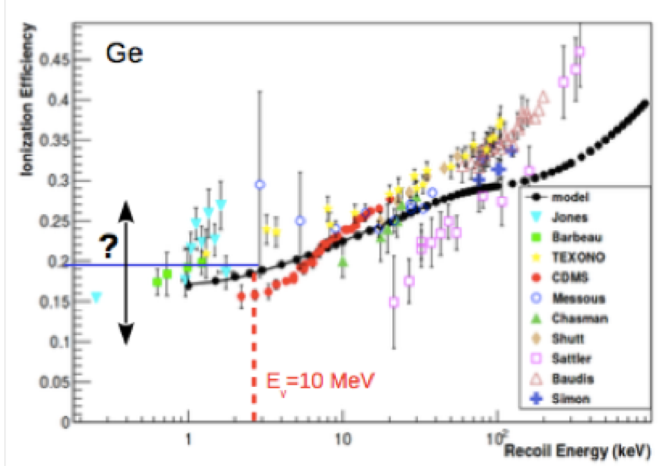
  for $E_\nu$ = 10 MeV ➔ $T_{max} \simeq$ 3 keV (in Ge)

- energy loss due to quenching (Lindhard)

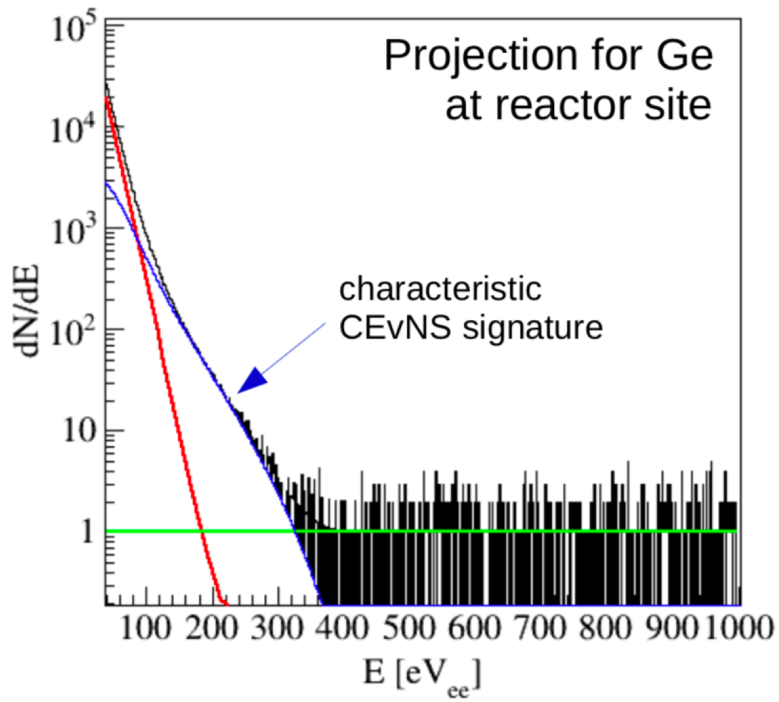
  ➔ Quenching Factor (QF) at low energy

  ➔ **include QF uncertainties**

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




D. Barker, D.M. Mei, 2012 [1]




**detection of CEνNS signal:**

- 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 ➔ R&D
- best background suppression ➔ “virtual depth”

➔ **COherent NeUtrino Scattering experiment**

C. Buck, A. Bonhomme, J. Hakenmüller, G. Heusser, M. Lindner, W. Maneschg, T. Rink, H. Strecker - Max Planck Institut für Kernphysik (MPIK), Heidelberg

K. Fülber, R. Wink - Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

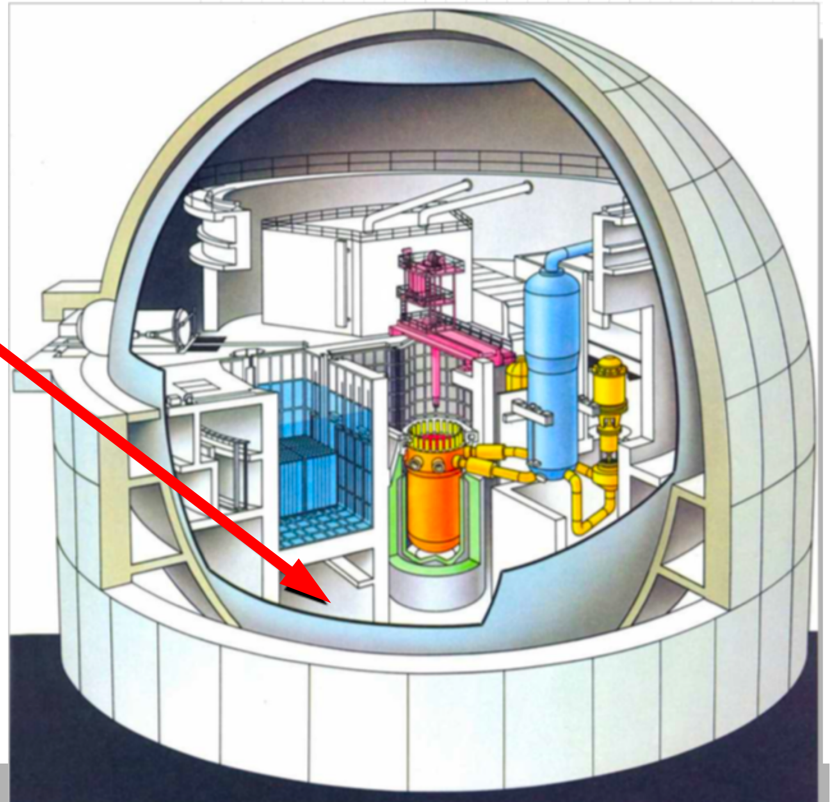
# The CONUS Reactor Site

**The 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

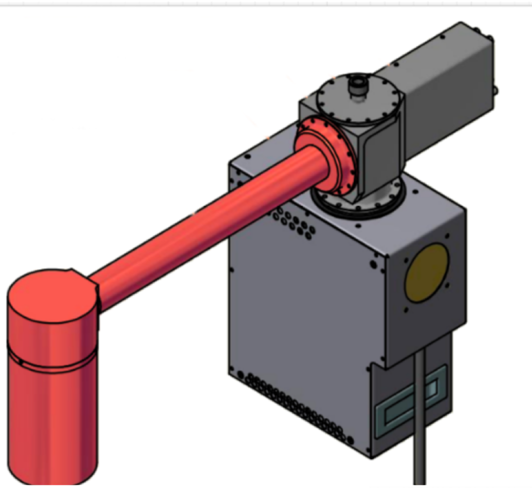
➔ very intense integral neutrino flux
$E_\nu$ up to ~ 8 MeV → fully coherent

- overburden 10-45 m.w.e
- access during reactor operation
- measurements of n background
- ON/OFF periods
  ➔ backgd. only measurement



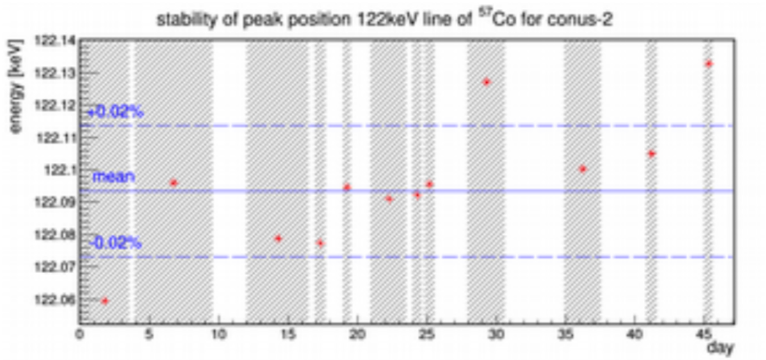
# Detectors: CONUS 1-4

- 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 collaboration with Canberra

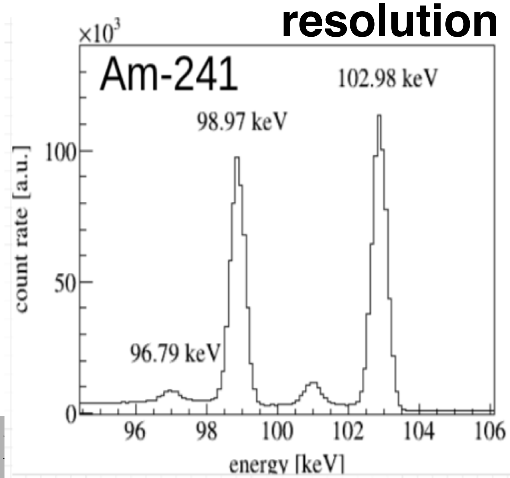


| Detector | Pulser FWHM$_P$ [eV$_{ee}$] |
|---|---|
| CONUS-1 | 69±1 |
| CONUS-2 | 77±1 |
| CONUS-3 | 64±1 |
| CONUS-4 | 68±1 |

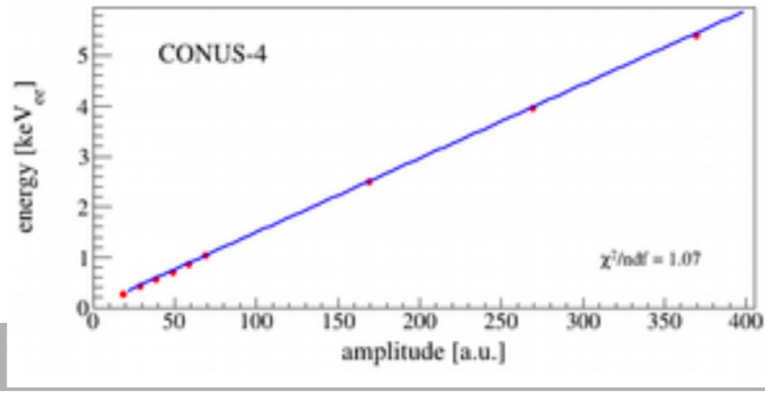
**Long term stability**
Under lab. Conditions:
stan. dev. of peak position:
+-15eV (+-0.02%)
(within 45 days)



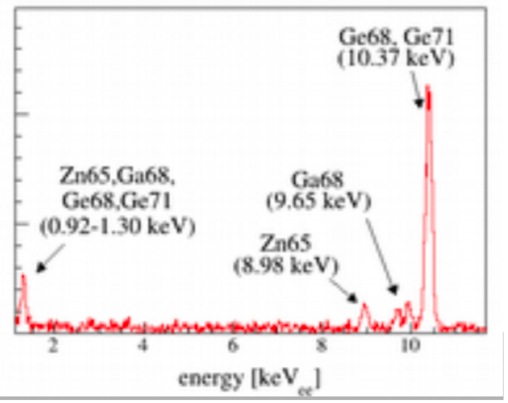

**resolution**



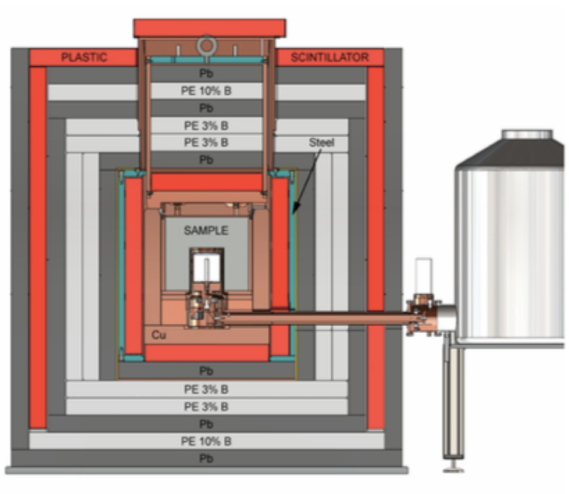

**Linearity of energy scale**




**activation lines: calibration**

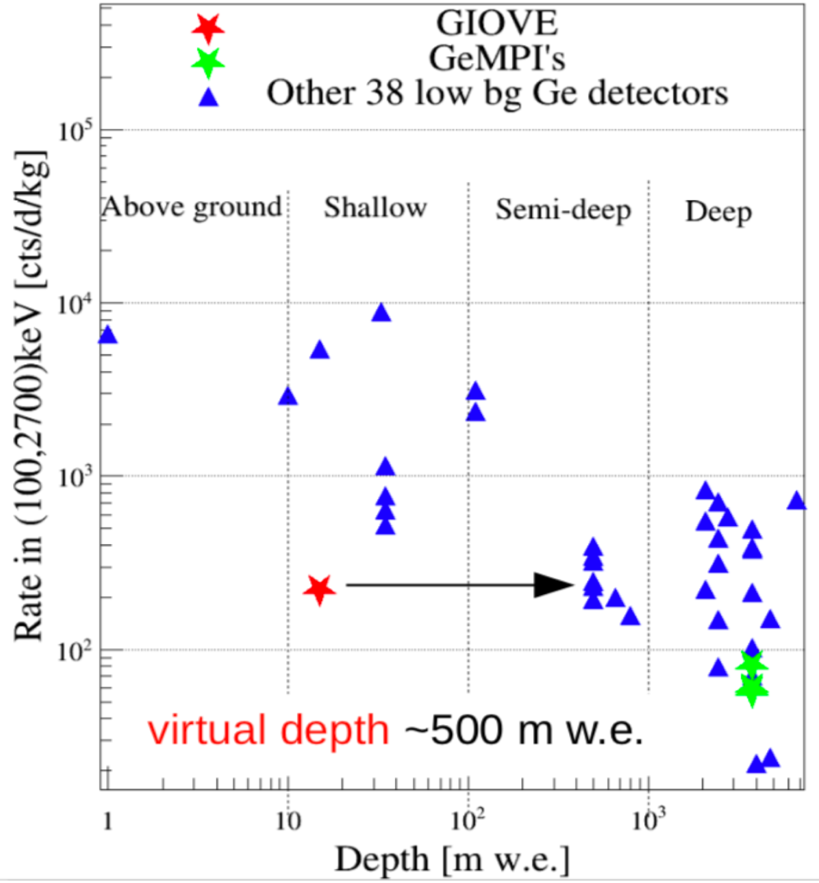


# ``Virtual Depth'': The GIOVE Shield




- 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''

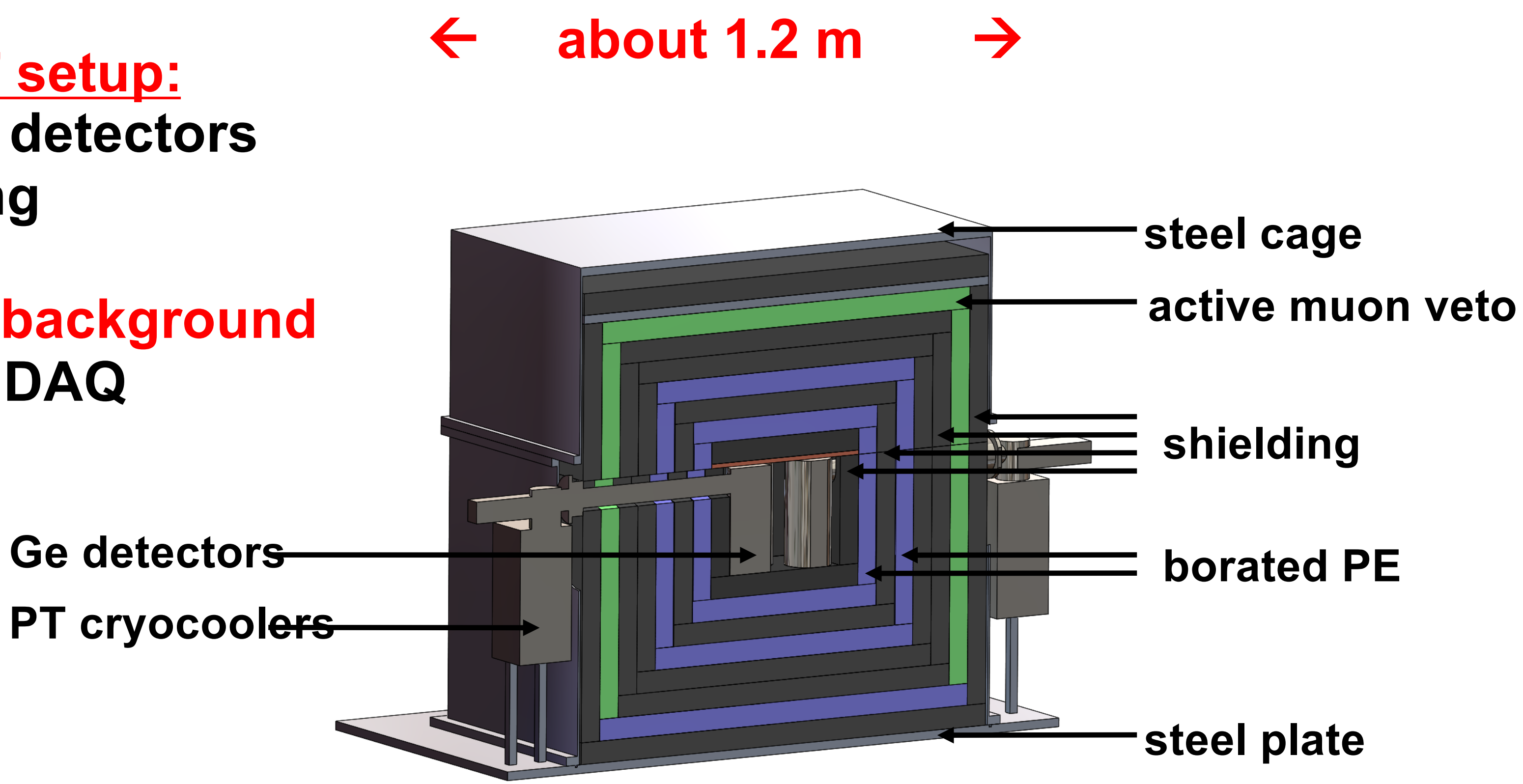
UG projects close to surface

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

# The CONUS Detector

``virtual depth" setup:
- 4 Germanium detectors
- PT cryocooling
- shielding

➔ all ultra low background
- electronics & DAQ




**Successful combination of three essential improvements:**

– excellent shielding (GIOVE @ MPIK = "virtual depth")

– new detectors with very low thresholds & PT cryocooling

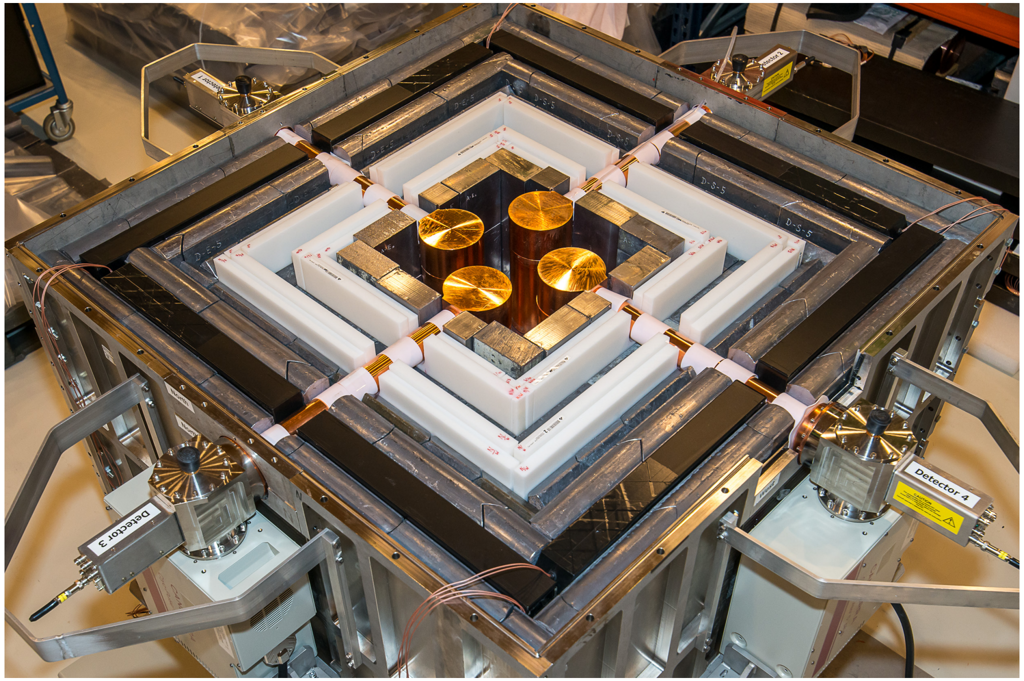
– site with very high neutrino flux

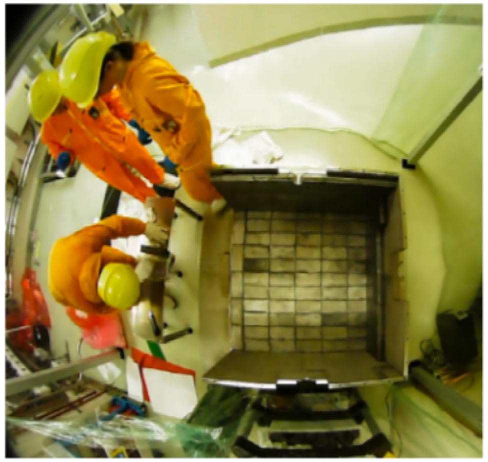
**Project start summer 2016 ➔ data taking spring 2018**

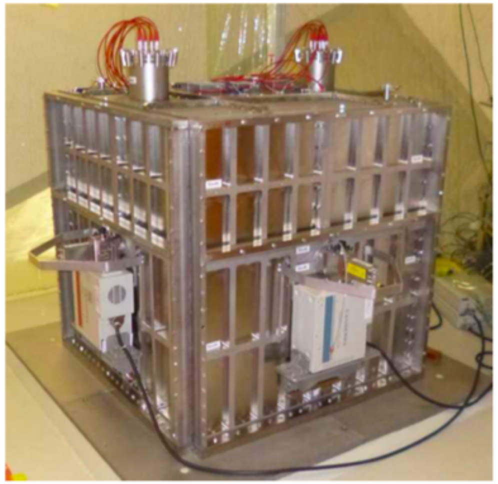
# Test Assembly and Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

installation @ Brokdorf
→ full assembly
→ commissioning

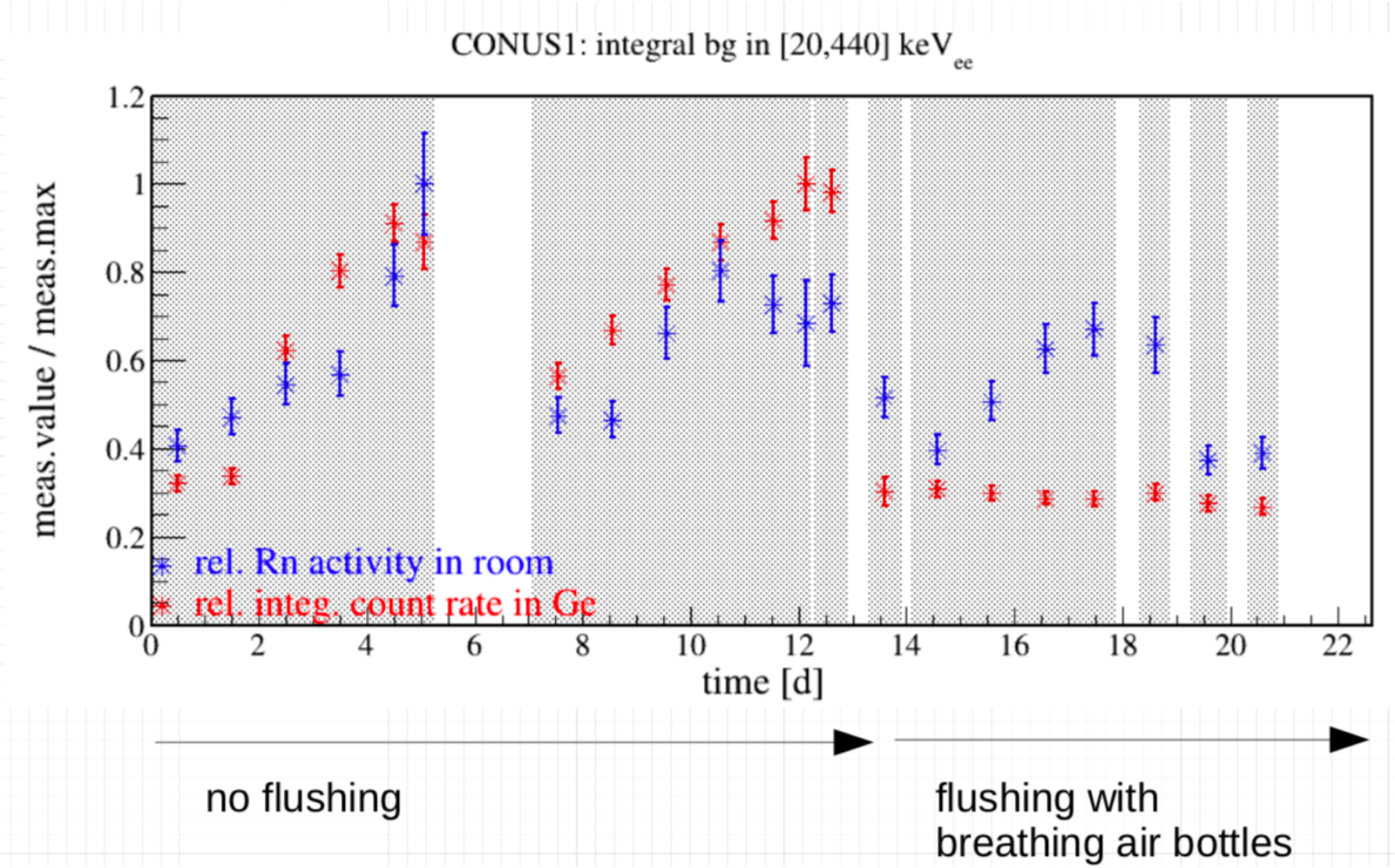




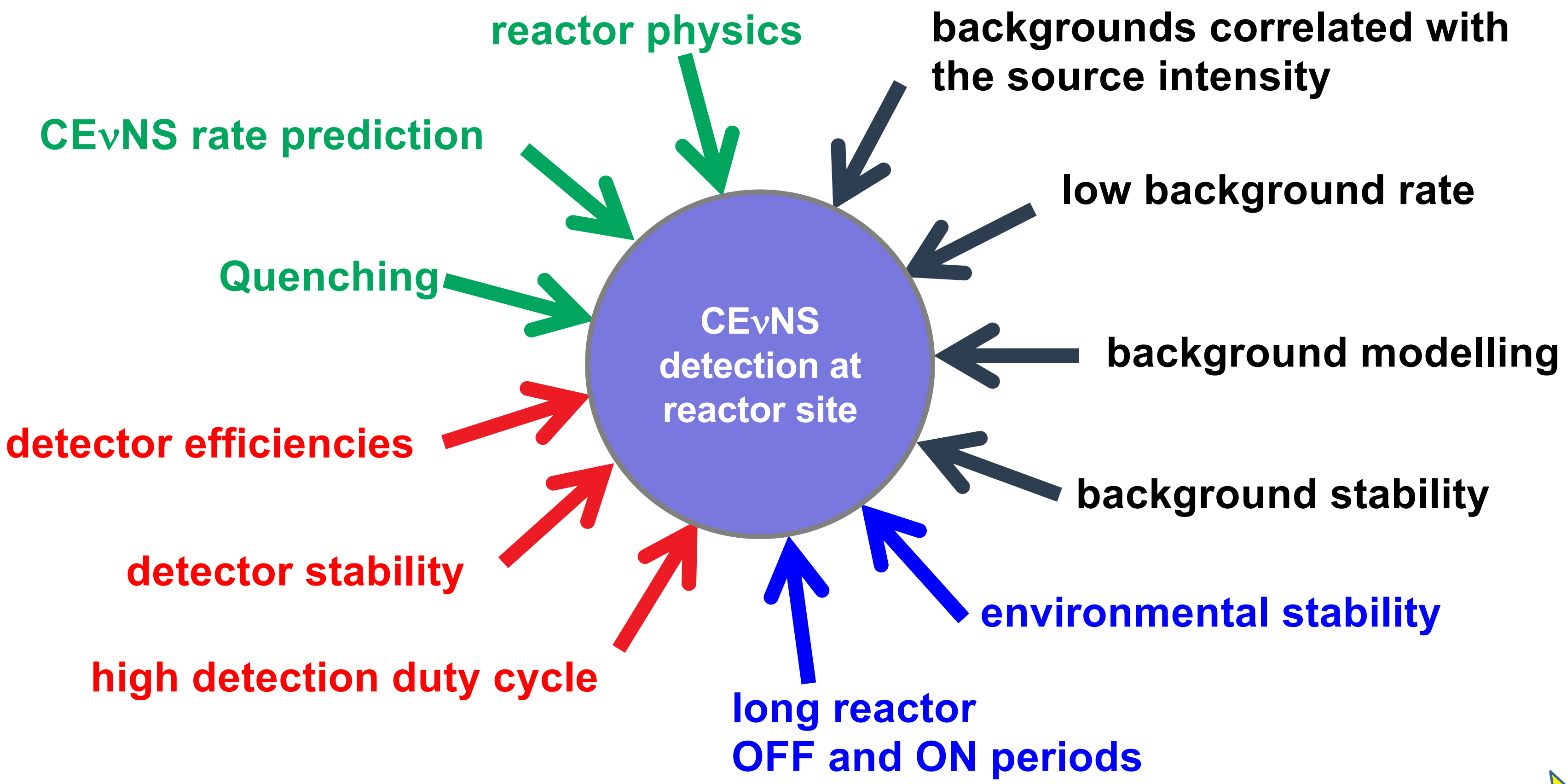
# Radon Mitigation @ Reactor Site

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:
hermetical sealing + flush with aged breating air bottles ~1 l/min



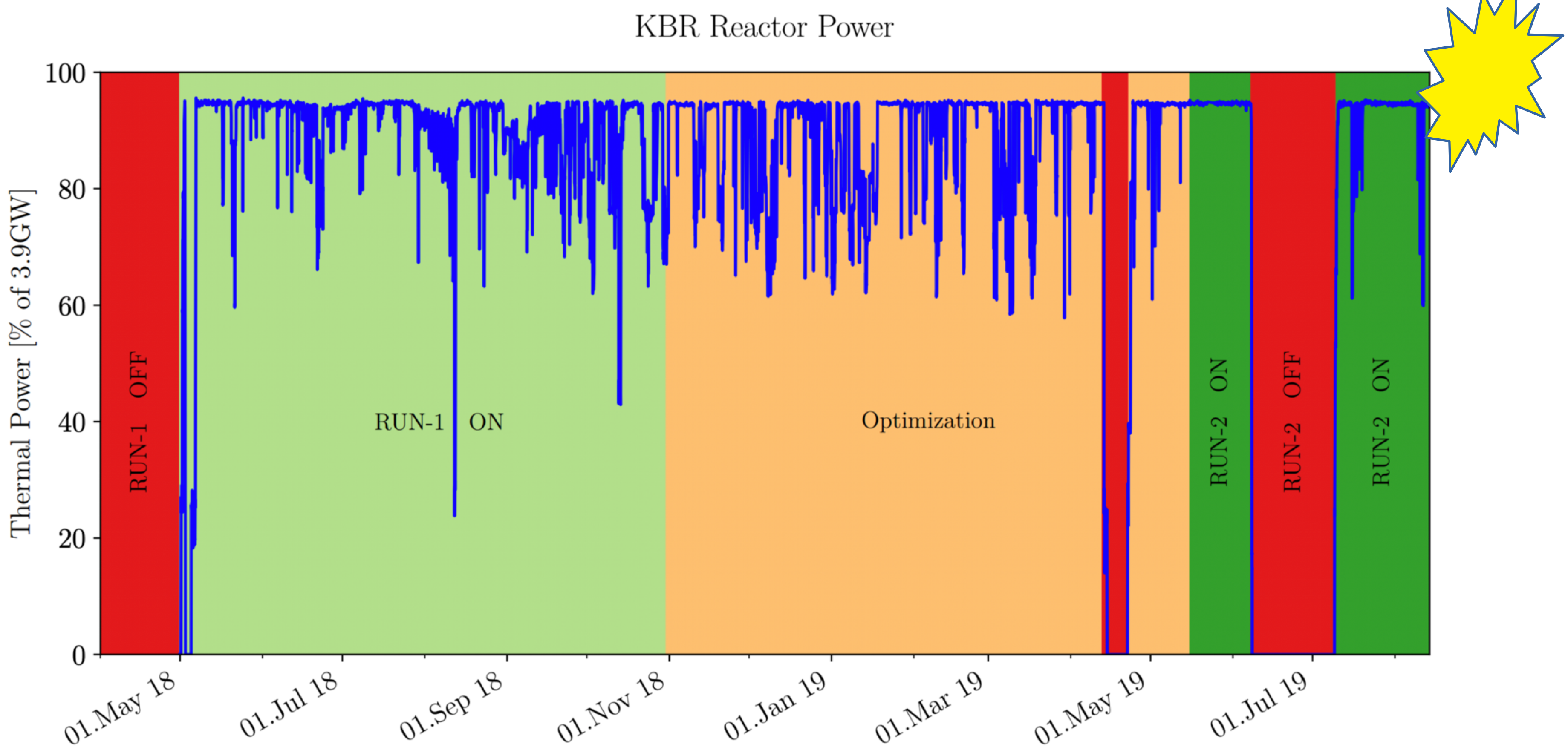
# Towards CEνNS Detection

**Simple: Compare ON versus OFF**
**To fully exploit the results:**



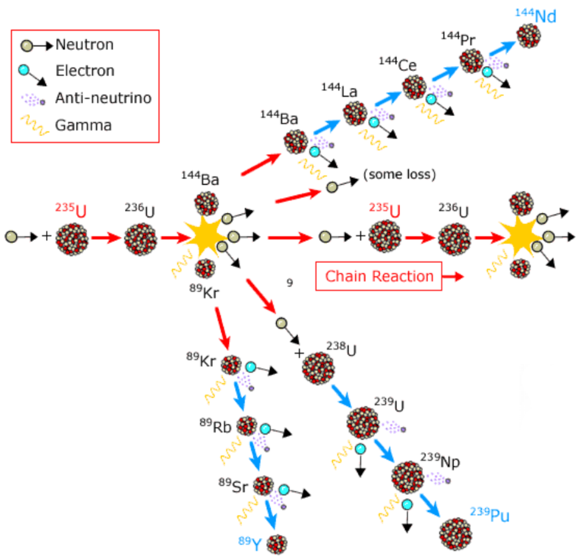

**→ important milestones achieved**
**new material highlighted on next slides**

# Exposure: Reactor ON/OFF periods




- **Smooth detector operation: reactor ON-OFF (thermal power)**
- **ON periods: reactor is operated at 95% of maximum 3.9 GW thermal power**
- **OFF periods: challenging due to environmental stability and less exposure**
- **Run 1 ended 10/2018 and Run 2 started in 05/2019 ➔ more OFF time!**

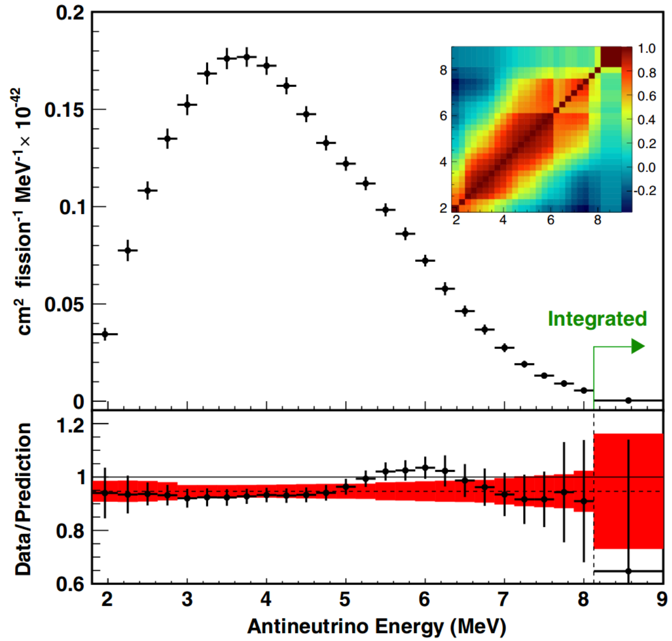
# Reactor Physics Implementation




**Antineutrino emission from β-decays in fuel reaction chain:**

- more than 99% from $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu
- ~ 6-7 ν's / fission
- energies up to ~10 MeV

Antineutrino Spectrum From Daya Bay:




Antineutrino Flux: $$\frac{dN^{\nu}(t)}{dt} \propto \frac{1}{L^2} \times \frac{P_{th}(t)}{<E_f>}$$

distance | # of fissions

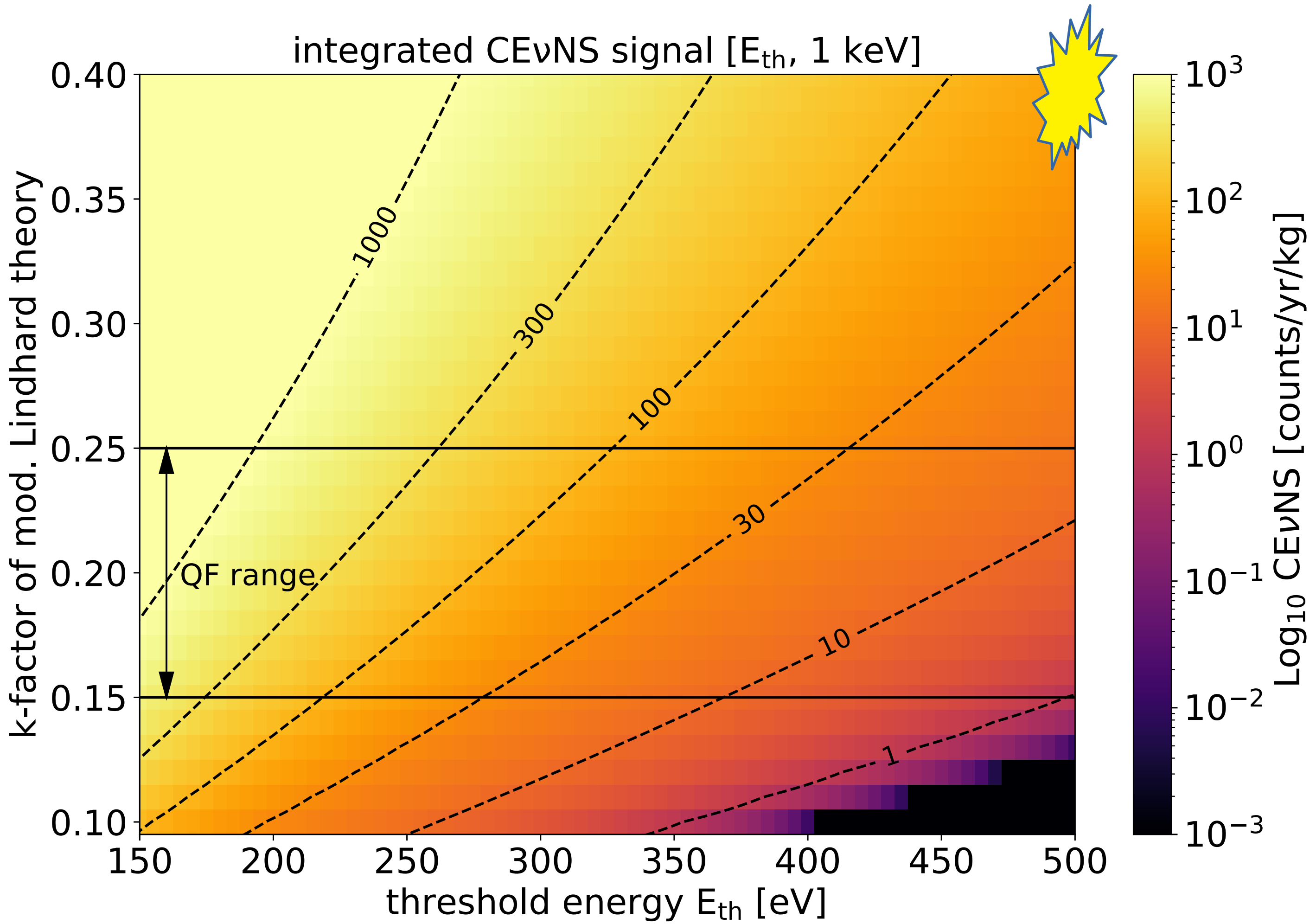
**Flux calculation for room A408 at KBR @17m from reactor core: ~$10^{13}$/(cm² s)**

**➔ expected event rates (w/o new physics)**

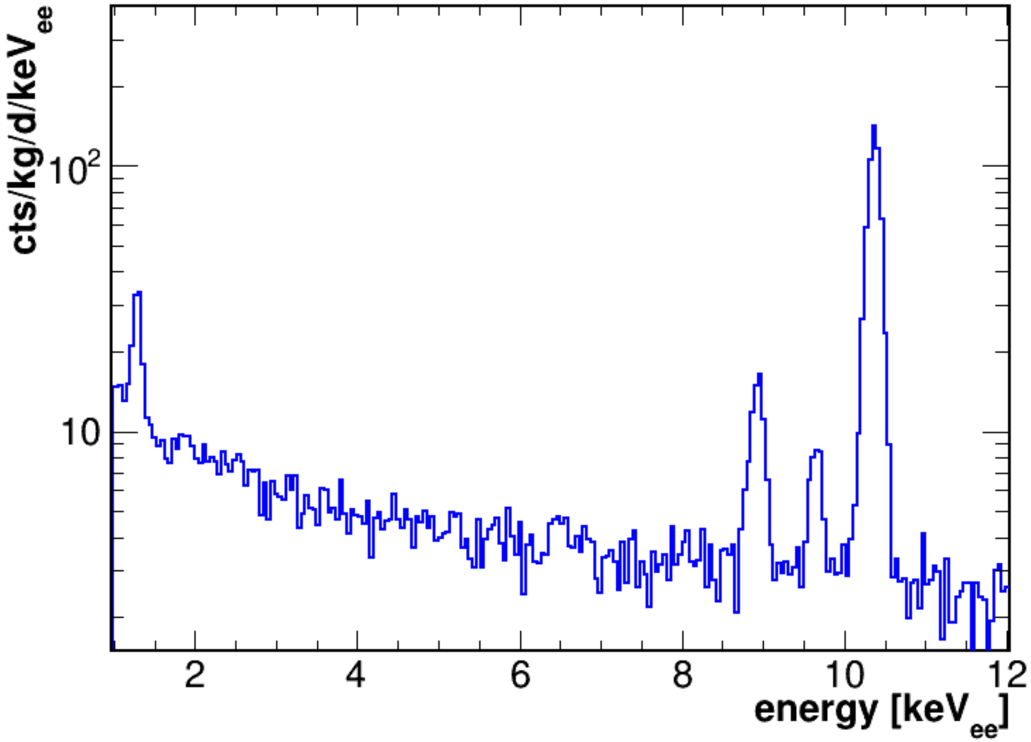
# Expected Signal

**Updated prediction including new reactor information:**

- **Daya Bay covariance matrix,…**
- **thermal power total uncertainty: +-2.5%**
- **Quenching factor is largest systematic error (as for all CEvNS experiments)**



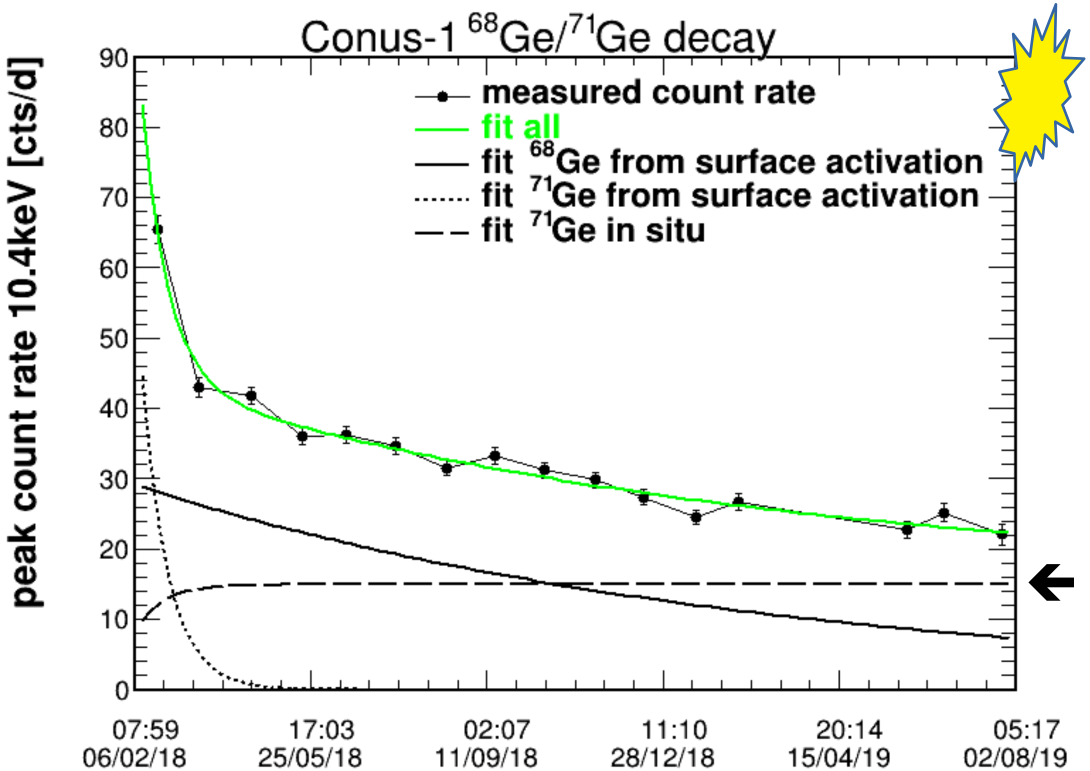
# Background Level




Conus-2:
214 days of live time

- **"virtual depth" works: bg rates of 10 (1) cts/d/kg below 1 keV (above 2 keV)**
- **1yr of operation: only 4 lines visible below 12keV: $^{71}Ge$, $^{68}Ge$, $^{65}Zn$, $^{68}Ga$**
- **no hints for other lines: $^{55}Fe$, $^{56}Fe$, $^{49}V$, $^{73}As$, $^{74}As$, $^{51}Cr$, $^{56}Ni$, $^{56}Co$, $^{58}Co$**
  **(less than what has been achieved by several other DM experiments)**
- **Very low bg shield at reactor site possible w/o contamination!**

# Background Stability




half lifes:

$^{68}$Ge: 270.95(16) d

$^{71}$Ge: 11.43(2) d

← in-situ production of $^{71}$Ge: ~15cts/d/kg

- **radon under control, little variation has no impact on low energy regime**
- **decaying Ge isotope bg rate can be well corrected in spectral fit for all ON/OFF periods**
- **hadronic showers close to surface at few m.w.e. fully negligible**
  **(non-trivial and not true for all other experiments...)**
- **Muon flux variations have a negiligible impact**

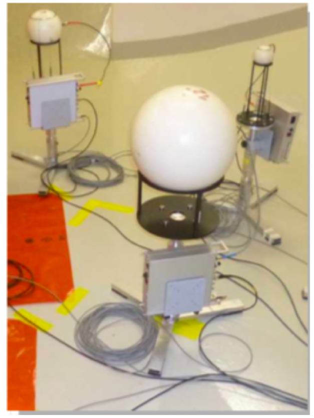
# Neutron Spectroscoy @Reactor Site

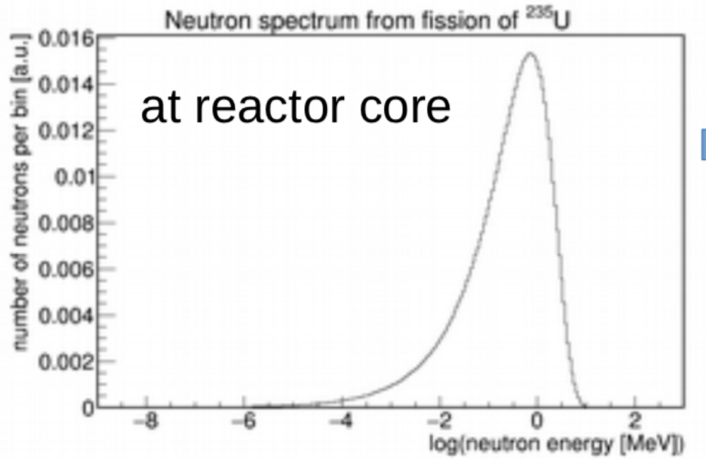
**Ge recoils from fast neutrons can mimic CEνNS**

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

outside of shield

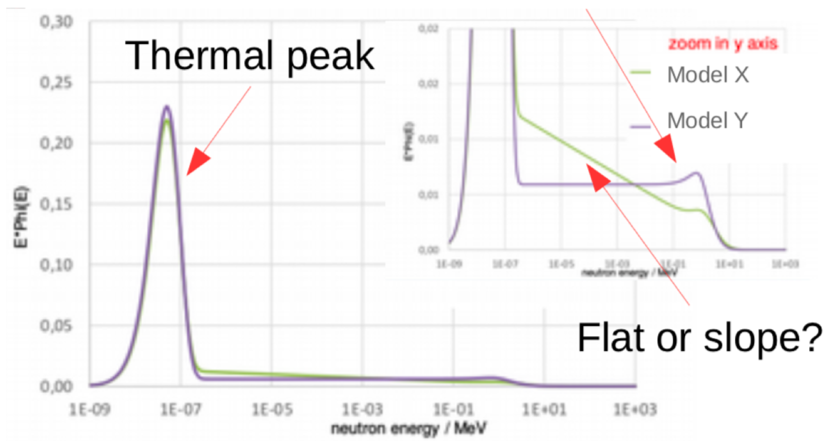
➔ **NEMUS**
setup by PTB
➔ on-site neutron spectroscopy






propagation
water
Steel
Concrete
…

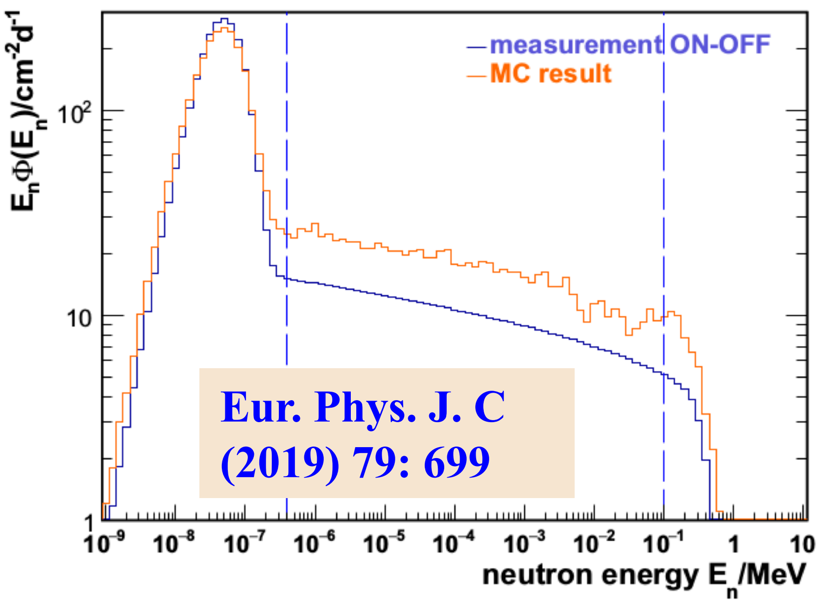
Remaining fast neutrons?

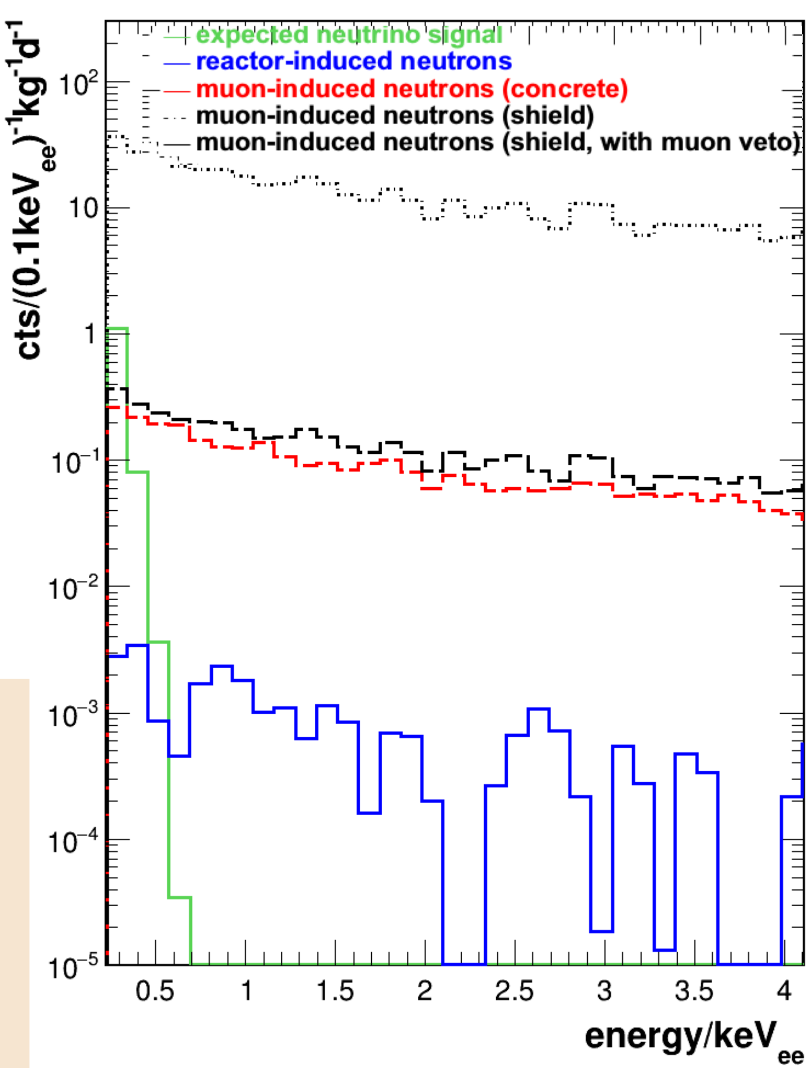



1. **Neutron field highly thermalized (>80%), correlated with thermal power**
**→ fully absorbed by B-PE layers (MC)**
2. **Residual fluence: if at all – epithermal from reactor - cosmic 100 MeV n: negligible**
**→ reactor-correlated fast n inside shield ~ negligible**

# Thermal Power correlated Background

Bonner Sphere measurement with PTB

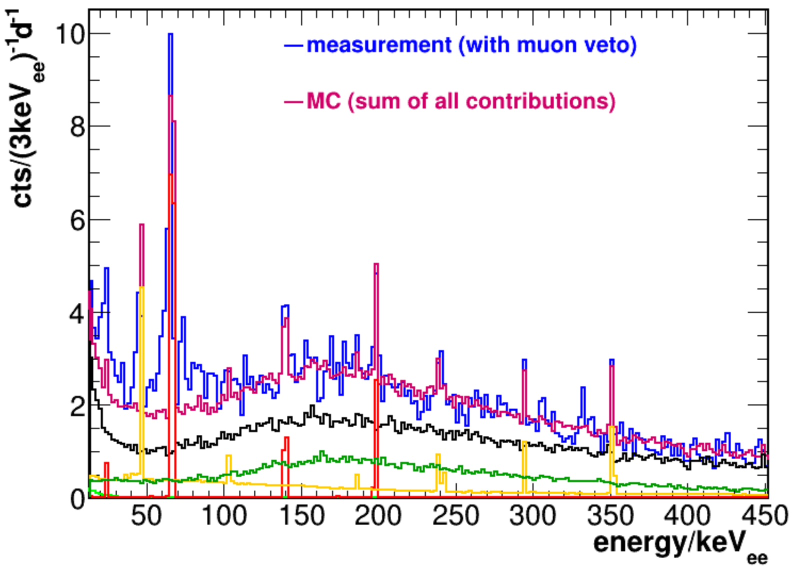


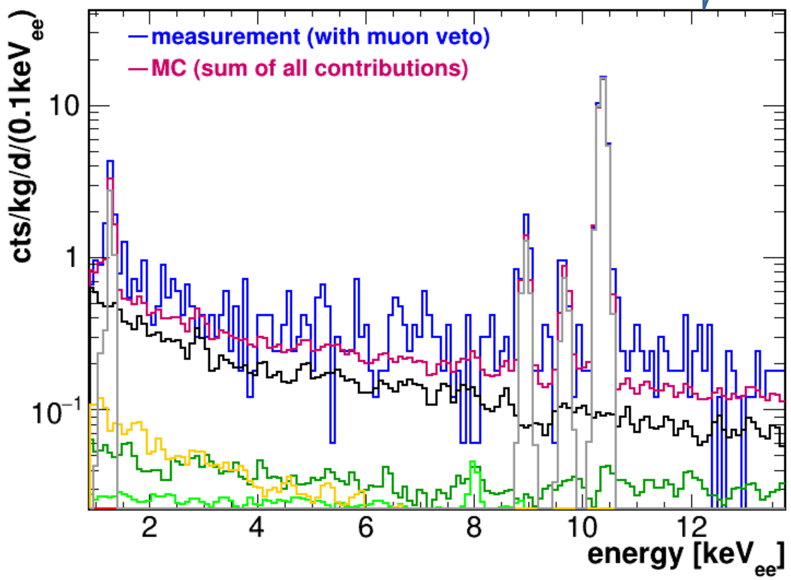

- **neutron field inside A408 highly thermalized, but inhomogeneous → mapping; lession: ➔ should be done for all reactor experiments**
- **MC demonstrates that almost no reactor neutrons arrive at diodes inside shield; at least ten times less then the expected signal**
- **$\mu$-induced neutrons dominant, but at constant rate ←→ non ON/OFF effect**

# Background Model

high energy



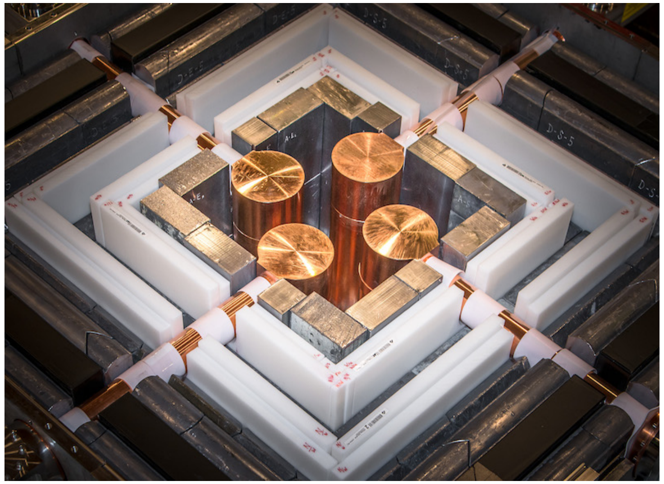

Low energy




Prompt Muon-induced
$^{210}$Pb
Metastable Ge states
Cosmic activation
Muon-induced
neutrons in concrete
Residuals

- **background MC includes detailed knowledge from material screening and neutron measurements**
- **the main left-over components are μ-induced and from Pb210 in the shield**
- **Consistency between:**
  **commissioning at MPIK at 15 m.w.e. ←→ operation at KBR at 24 m.w.e.**
- **fully consistent background understanding, no surprises**

# The Status of CONUS



- **KBR Brokdorf: Very strong ν-source;**
  **$W_{th}$ = 3.9GW @17m ➔ ~$10^{13}$ ν/($cm^2$ s);**
  **detailed information on flux, spectrum, ...**
- **CONUS: Very low threshold HPGe detectors**
  **``virtual depth"; very low bg demonstrated**
- **Comprehensive campaign to understand remaining backgrounds**
  **➔ very detailed study (neutrons): Eur. Phys. J. C (2019) 79: 699**
  **➔ reactor correlated background inside shield neligible**
- **Detailed background modelling and stability studies**
- **NEUTRIN0-2018: 114/112 kg*d of OFF/ON data → 2.4 σ stat. excess**
- **More data (OFF data!) ; very detailed analysis nearing completion**

# The Future: CONUS100

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

**assume:**
**100kg detector**
**4GW @ 15m**
**flux ~3*$10^{13}$/cm²/s**
**background 1/kg/day**

**BSMsens=ΔS/S**

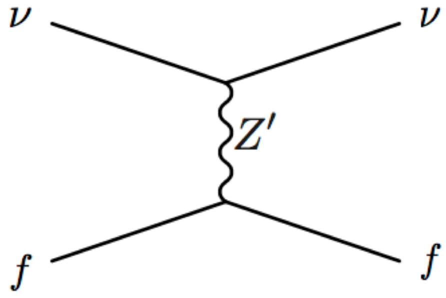
| Puler/Thresh [eV] | QF=0.15 | **BSMsens** | QF=BF | **BSMsens** | QF=0.25 | **BSMsens** |
|---|---|---|---|---|---|---|
| 40 / 120 | 647 474/ 8291 / 78.1 | 1*$10^{-3}$ | 965 999/ 10 775/89.7 | 1*$10^{-3}$ | 2.9*$10^{6}$/ 15 158 / 189 | 6*$10^{-4}$ |
| 45 / 135 | 407 092/ 8 036 / 50.7 | 2*$10^{-3}$ | 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, … ➔ $\varepsilon_{ij}$**




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

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

Barranco et al. 2005

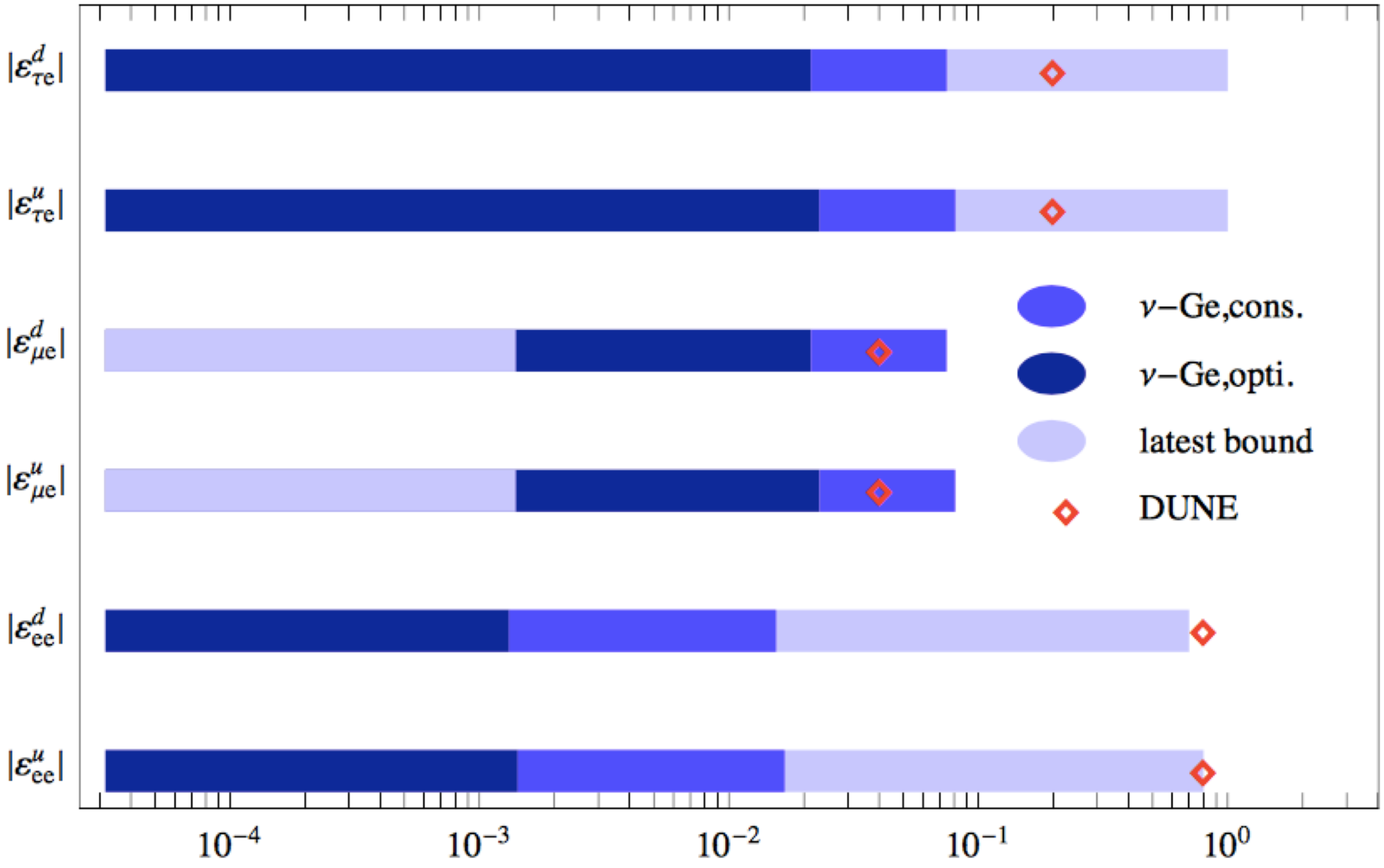
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

**➔ 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

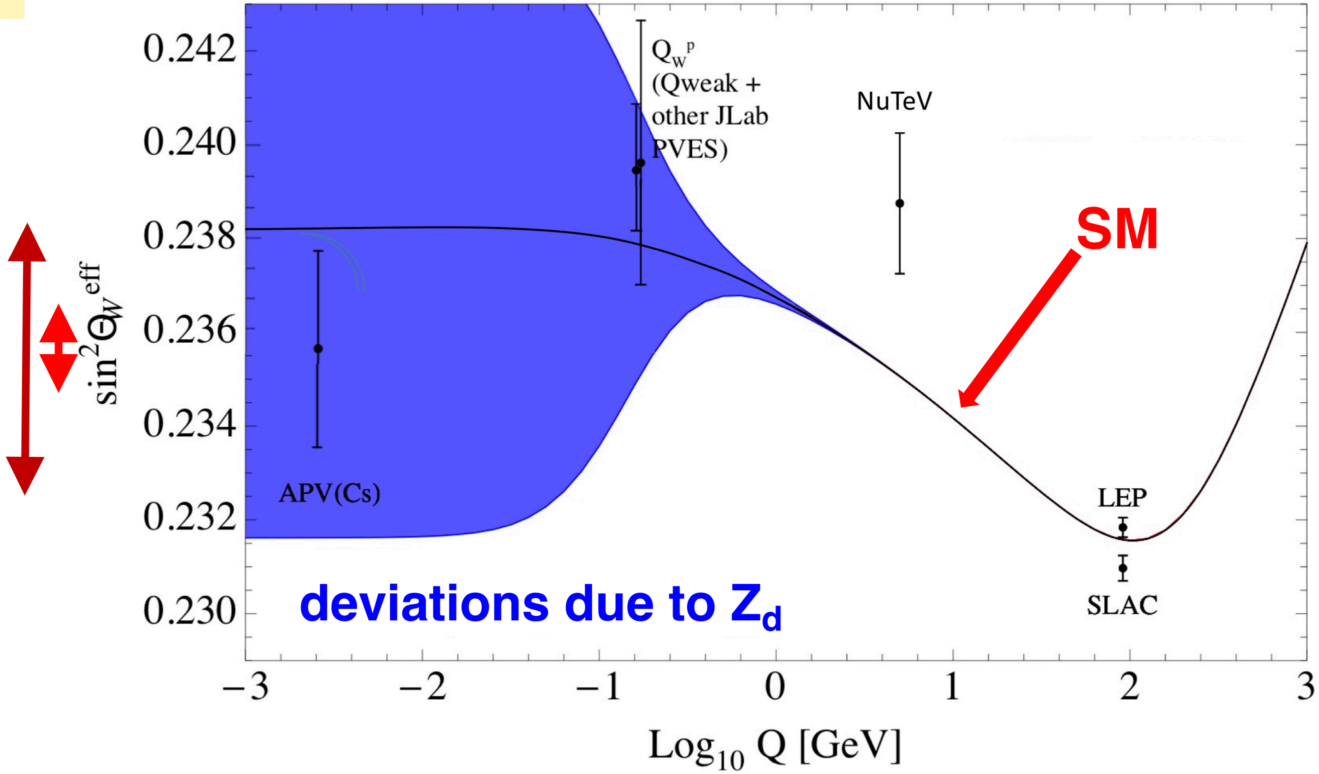
$\sin^2\theta_W$ precisely known in SM
SM quantum corrections
→running $\sin^2\theta_W^{eff}$

**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...

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

$\simeq 0$
➔ enhanced sensitivity

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

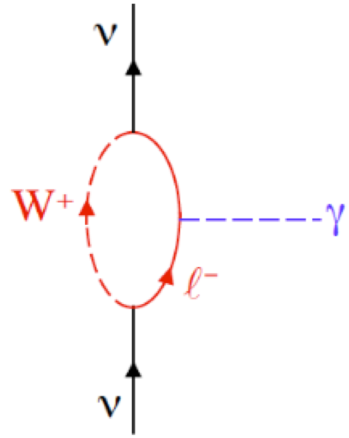


# Searches for new Physics: Magnetic Moments

**Magnetic moment for minimal ν masses are very tiny:**

**Dirac:** $$\mu_{kk}^{D} \backsimeq 3.2 * 10^{-19} \left(\frac{m_k}{\text{eV}}\right) \mu_B$$

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

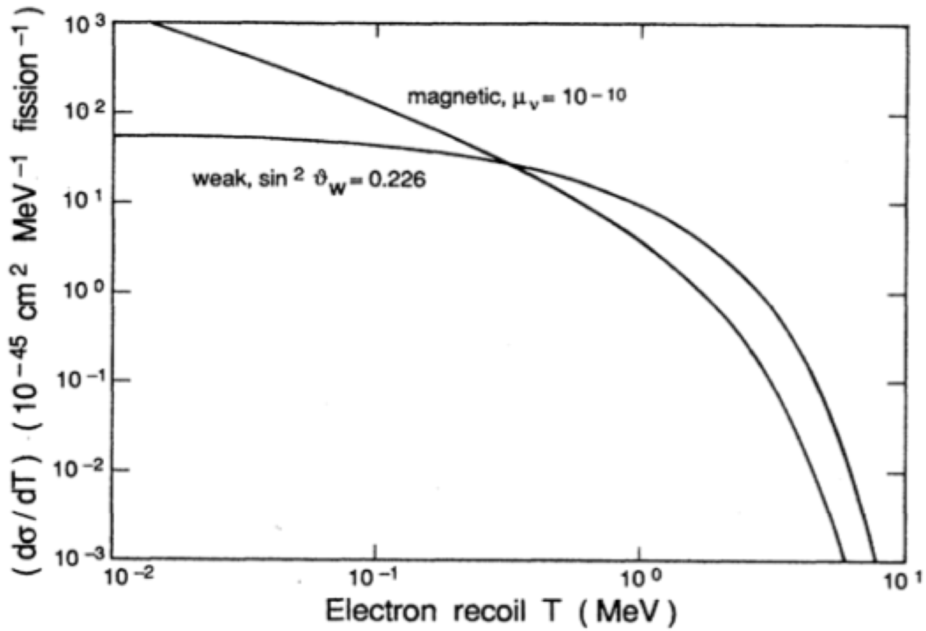



**New physics ➔ detectable enhancements due to new physics:**
**SUSY, extra dimensions, …**

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

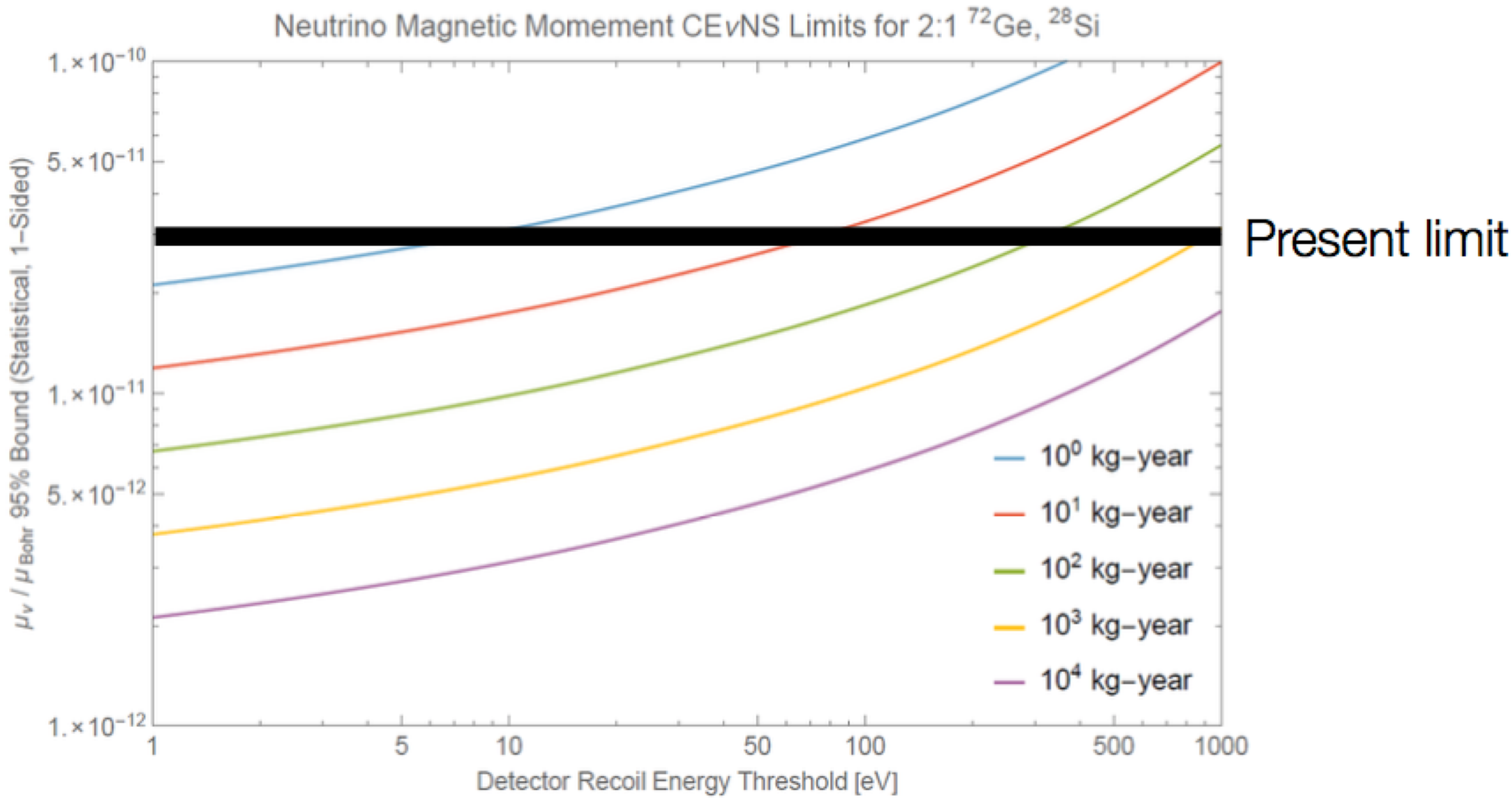
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$

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




$$\left.\frac{d\sigma}{dT_R}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1 - T_R/E_\nu}{T_R} + \frac{T_R}{4E_\nu^2}\right]$$

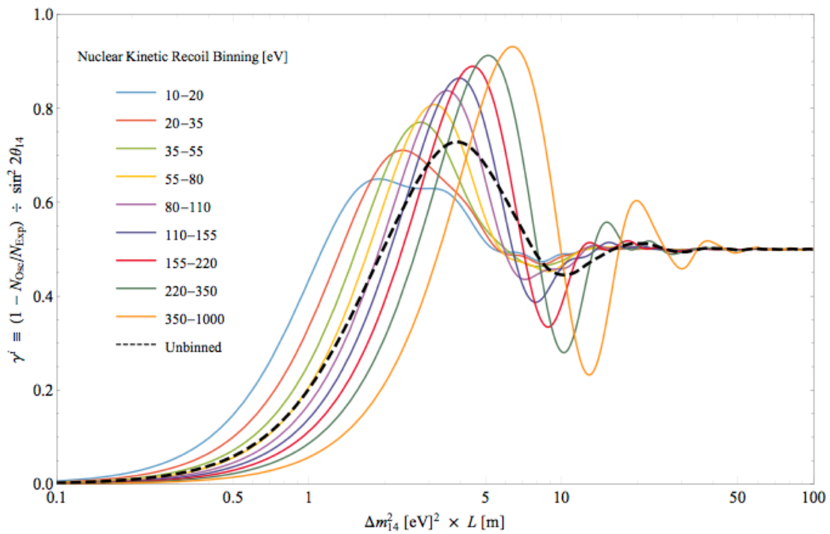
# Potential for Magnetic Moments




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

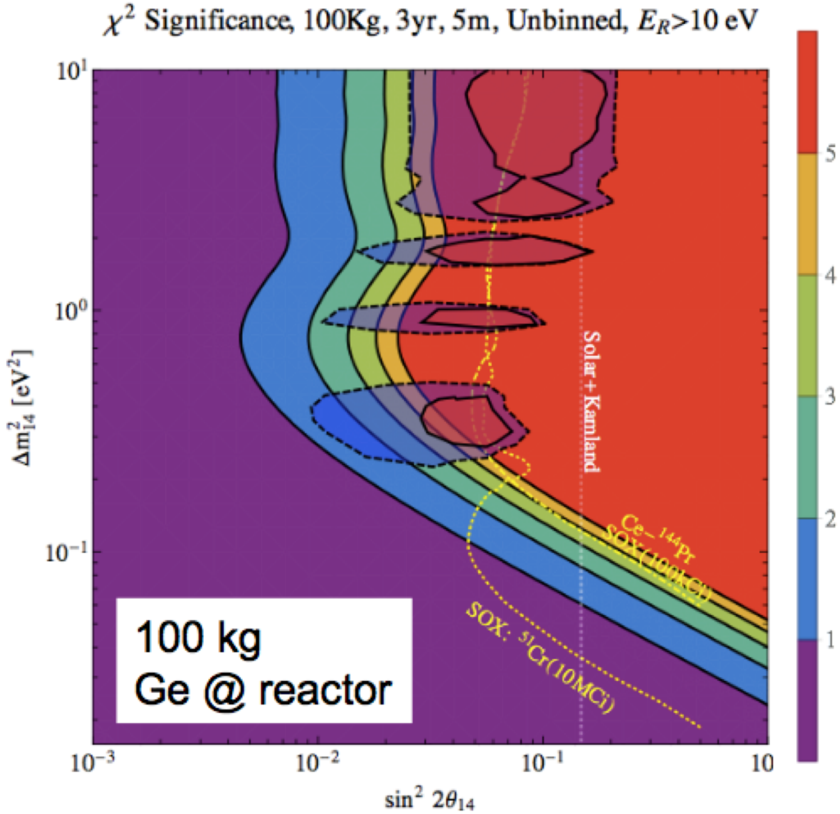
# Searches for new Physics: Sterile ν's

- **Various indications / hints for sterile neutrinos**
- **Tensions with cosmology?**
- eV hints with small mixing
- keV warm dark matter with tiny mixing $\leq 10^{-8}$x
- …different mass ranges
- any sterile state would motivate more…




Dutta et al. 1511.02834

$$P(\nu_\alpha \to \nu_{\not\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2(1.27\Delta m^2_{41} L/E)$$




B. Dutta et al, arXiv:1511.02834

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

➔ **time scales compared to other projects**

# Nuclear Structure with coherent Scattering

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

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

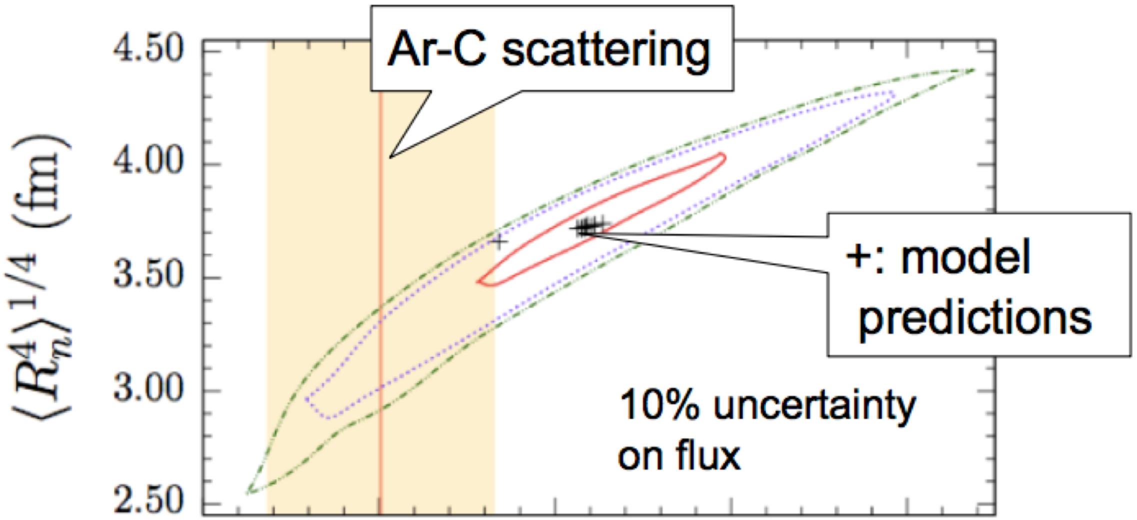
**Nuclear form factors $F_{N,Z}(q)$ are Fourier transforms of N & P densities**

**➔ resolve nuclei (mostly neutrinos) in neutrino light**

Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments

(requires very good energy resolution,good systematics control)

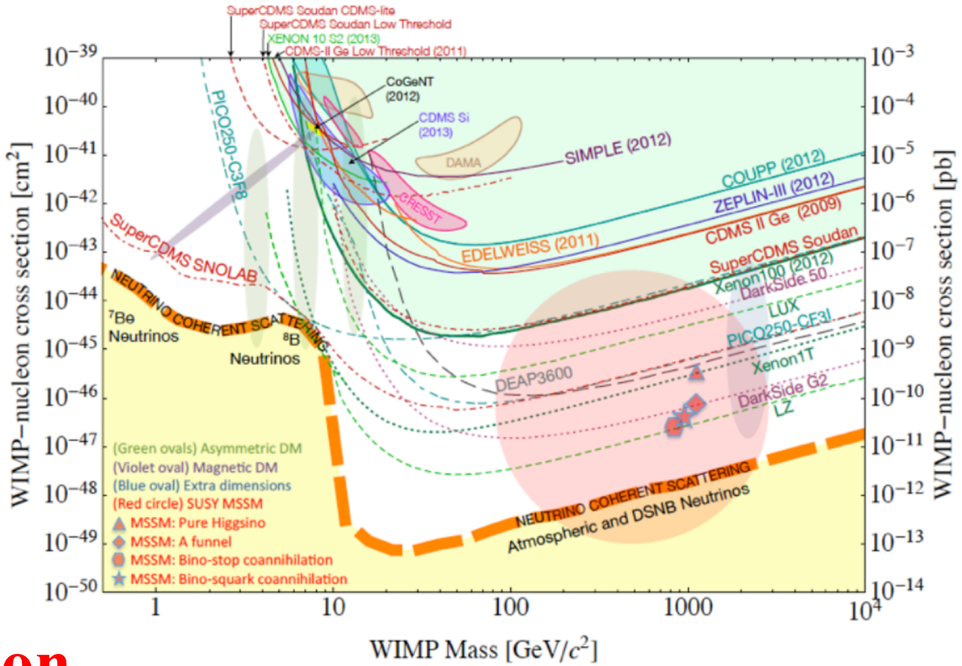
Example:
tonne-scale
experiment
at πDAR source



# 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

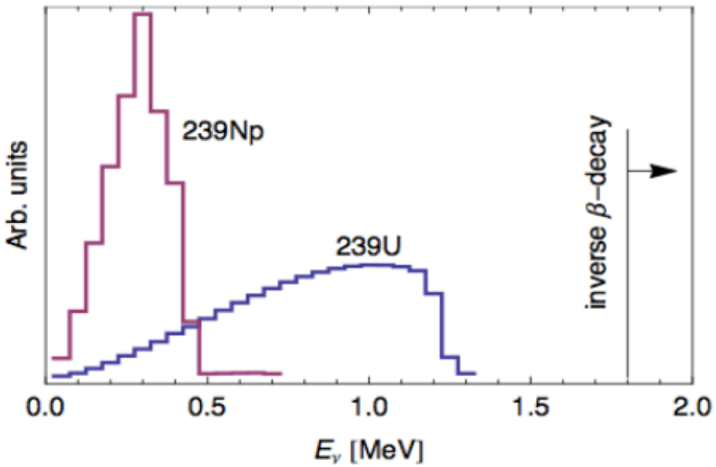
3) Important for astrophysical applications: supernovae, ...
4) ...

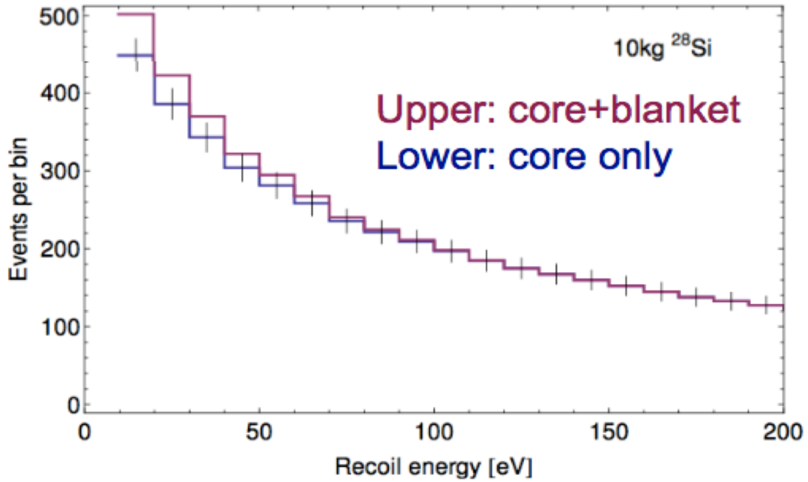
# Nuclear Safeguarding

P. Huber, talk at NA/NT workshop, Manchester, May 2015

Presence of **plutonium breeder blanket** in a reactor has ν spectral signature

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$




ν spectrum is below IBD threshold

➔ accessible with CEvNS, but require low recoil energy threshold

a) Of interest to IAEA

b) Could be used as an extra "sensor" in reactors (close to core ←→ $1/R^2$)

➔ safety, optimal burn-up = neutrino technology

# More Phenomenology / Theory of CEνNS

- 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

- connections to dark matter models (many...)

- 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

- ....

# Summary

- **CEνNS was 1st observed by COHERENT at $E_\nu \simeq$ 30-50 MeV**

- **CONUS starts to see CEνNS with reactor neutrinos (few MeV)**
  - 1st rate only results from one month of reactor on
  - shape... ➔ more significant ➔ to be published soon
  - detector & reactor are running ➔ more statistics soon

- **CEnNS will become an interesting tool**
  - upscaling of existing technology to O(100kg)

  **various physics topics:**
  - coherent ν scattering ←→ DM & WIMP scattering, neutrino floor
  - search / limits for magnetic moments
  - search for new physics: NSIs, steriles, $\sin^2\theta_W$, sterile osc. searches
  - nuclear form factors with neutrinos $F(q^2)$
  - reactor ν spectrum & anomalies
  - reactor monitoring: safe-guarding, optimization

➔ **very interesting potential of CEνNS**