The CONUS experiment and future potential of coherent neutrino scattering

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On behalf of the CONUS Collaboration

MAX-PLANCK-INSTITUT
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Neutrino & Nuclear Physics
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Coherent ν Scattering

Z-exchange of ν with nucleus

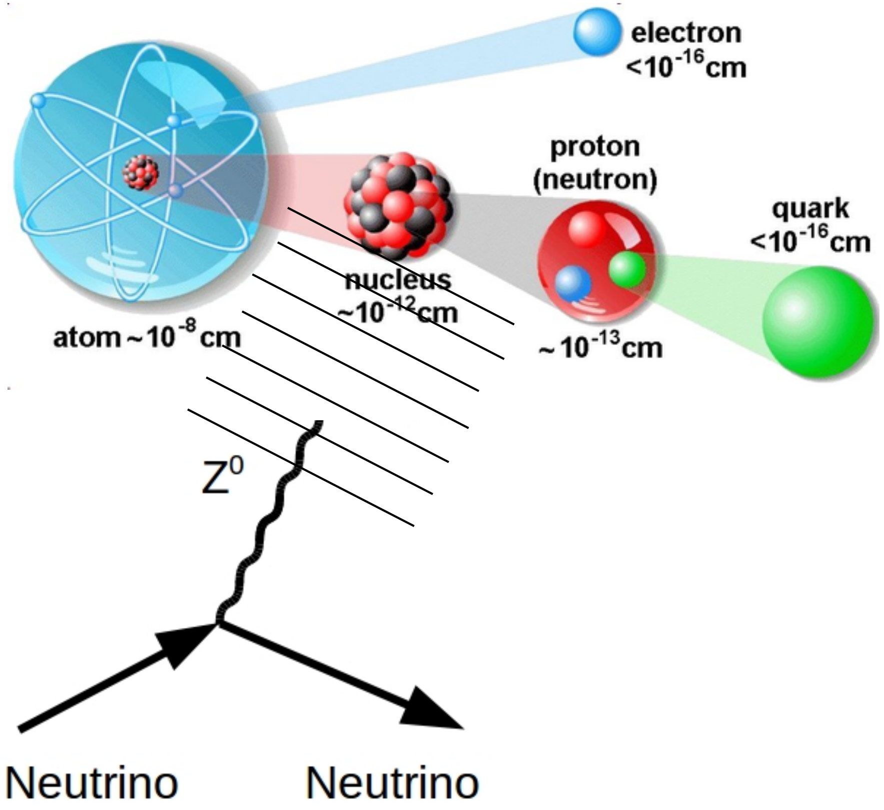
$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim N$$

➔ 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!

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

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

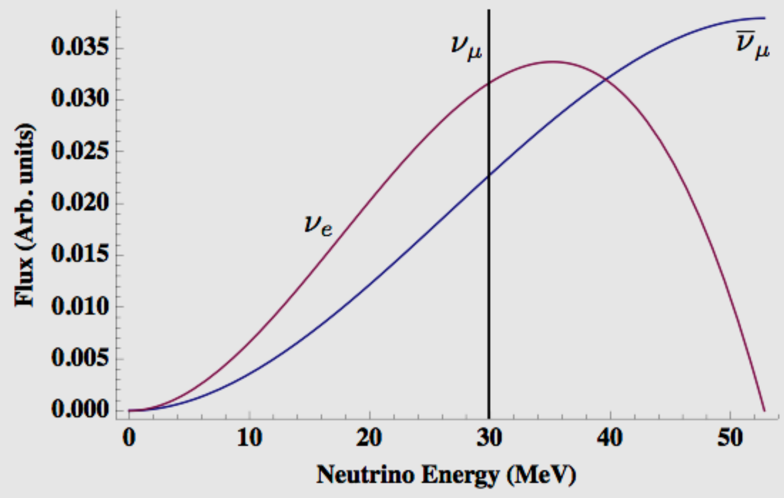
Different experimental Paths

Low energy ν's from accelerators:

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

➔ close to de-coherence

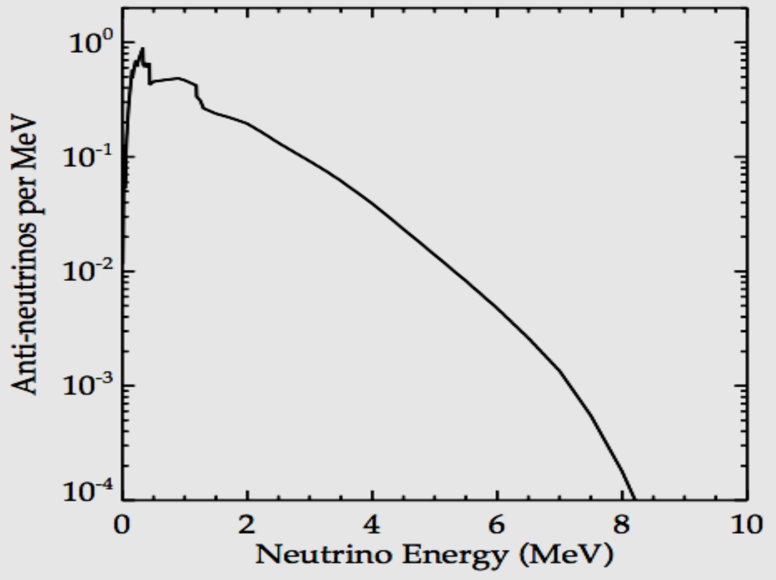
➔ **1st observation of CEνNS by COHERENT**



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



Vogel et al. 1981, Kopeikin 2012

➔ **Synergies between energies + more**

The CONUS Experiment

Combine:

1) lowest detection threshold ➔ R&D
2) best background suppression ➔ “virtual depth”
3) highest neutrino flux ➔ close to power reactor

➔ **COherent NeUtrino Scattering experiment**

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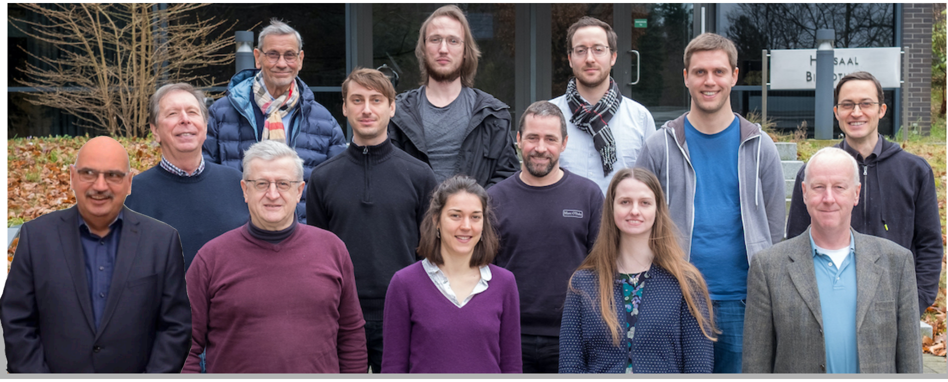


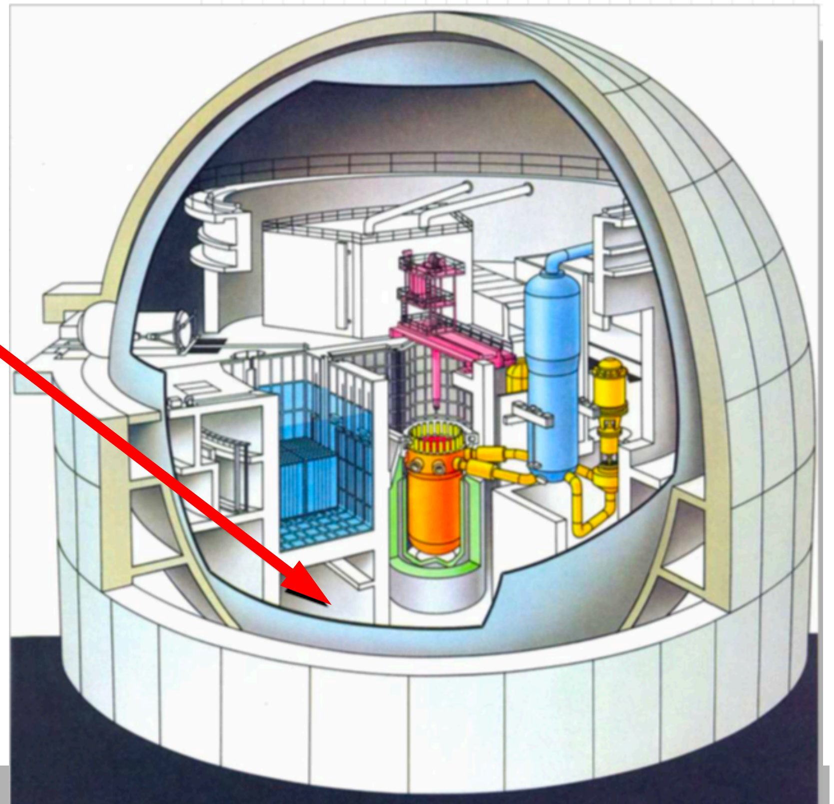
The CONUS Reactor Site

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

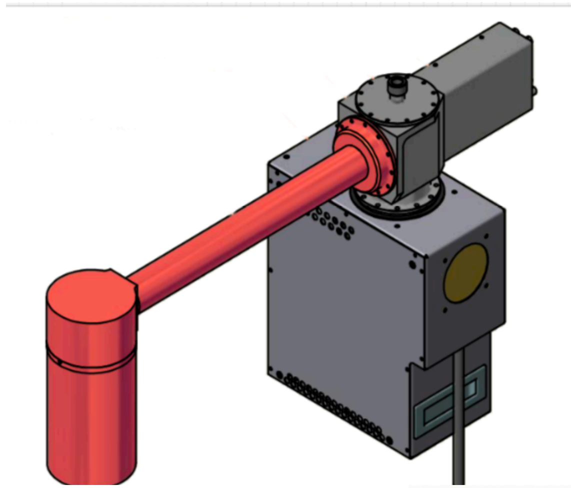
➔ very intense integral neutrino flux
E_ν up to ~ 8 MeV → fully coherent

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



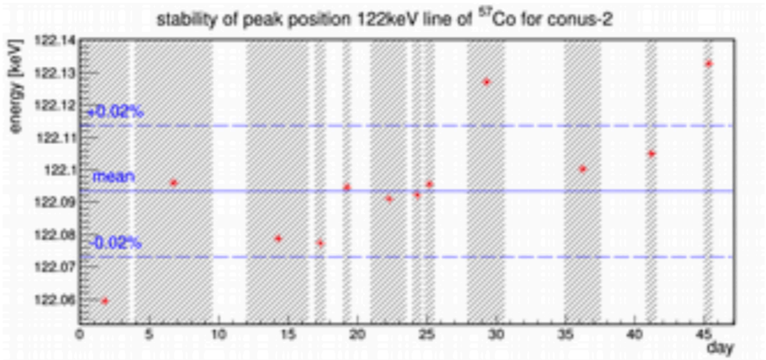
Detectors: CONUS 1-4

- 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

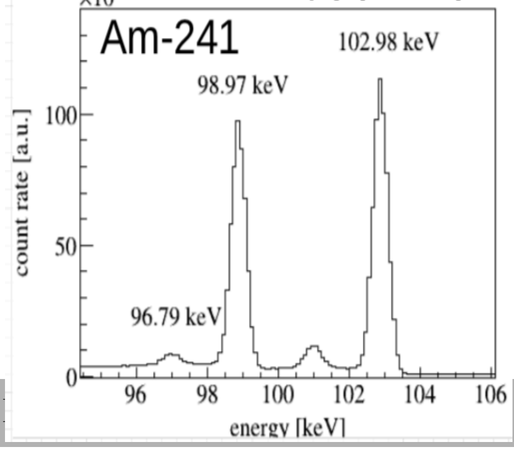


Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

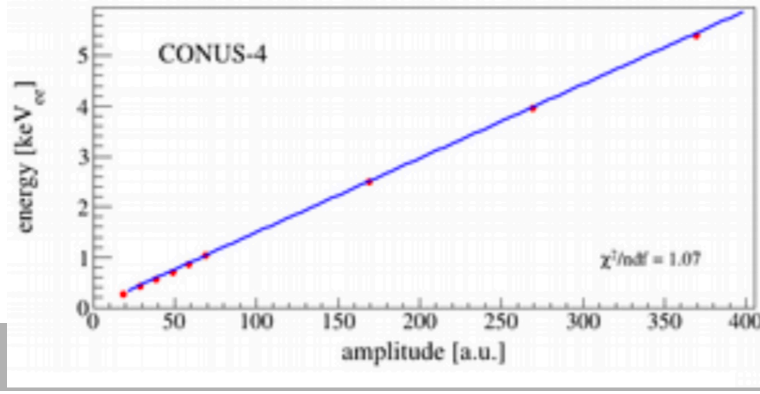
Long term stability
Under lab. Conditions:
stan. dev. of peak position:
+-15eV (+-0.02%)
(within 45 days)



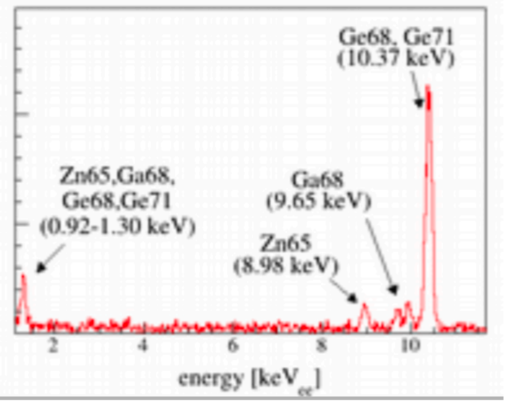
resolution



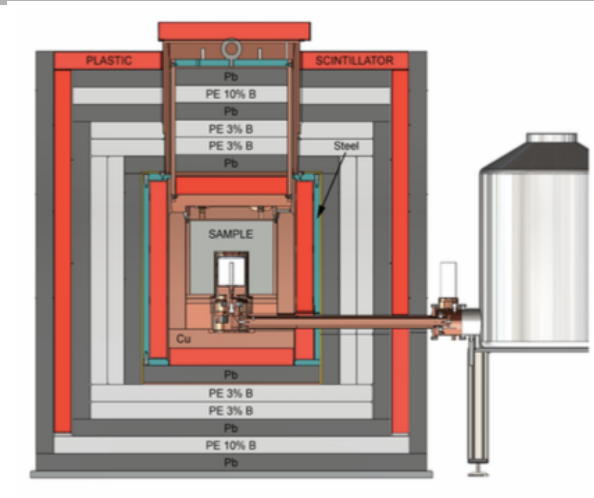
Linearity of energy scale



activation lines: calibration

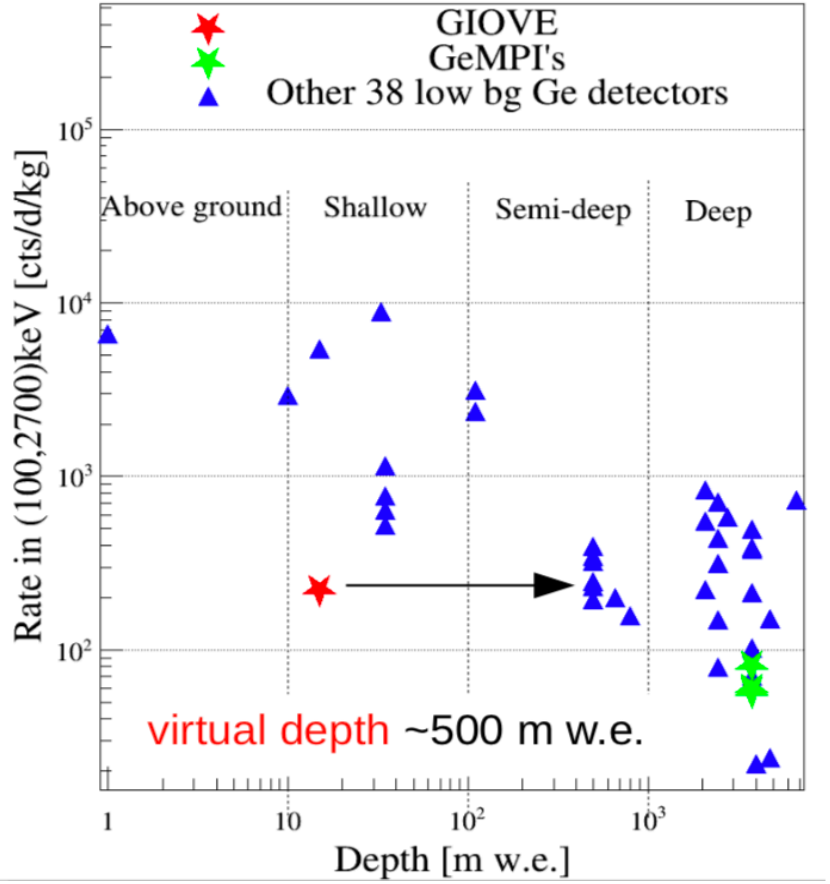


``Virtual Depth'': The GIOVE Shield



- 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)



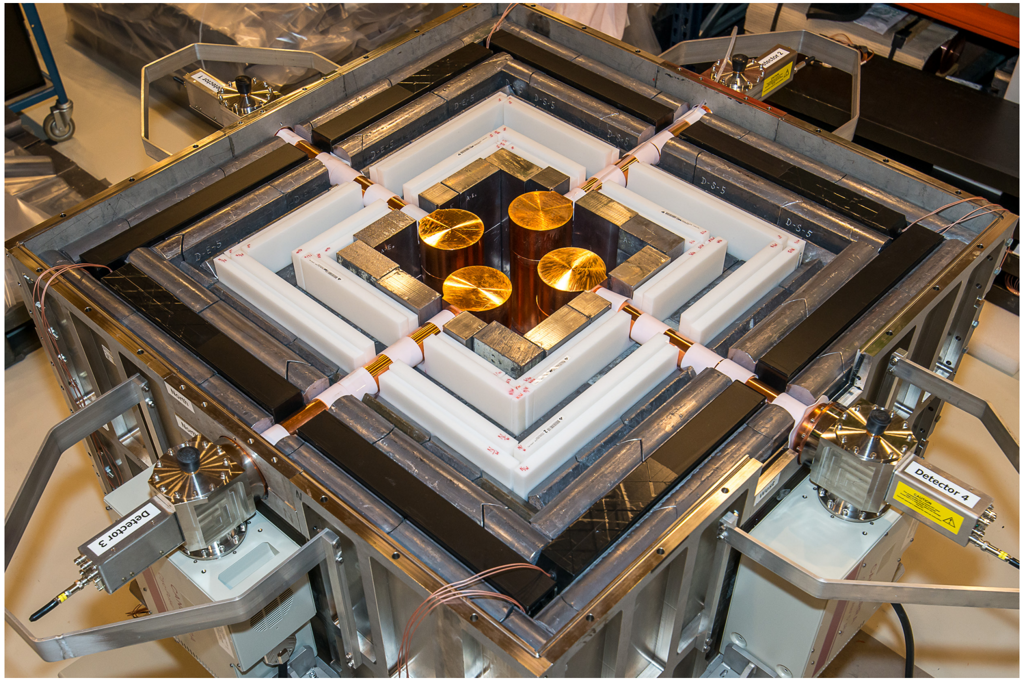
➔ ``virtual depth"
UG projects close to surface

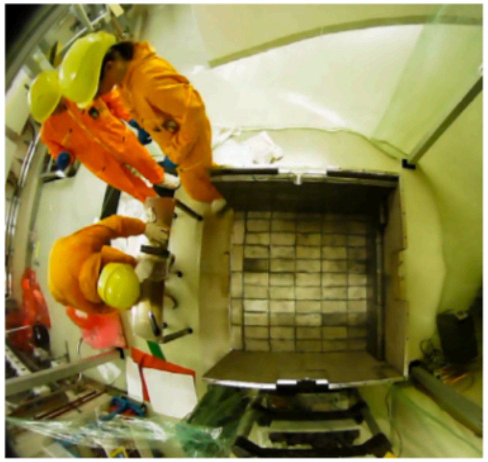
G.Heusser et al.,Eur.Phys.J. C(2015)75:531

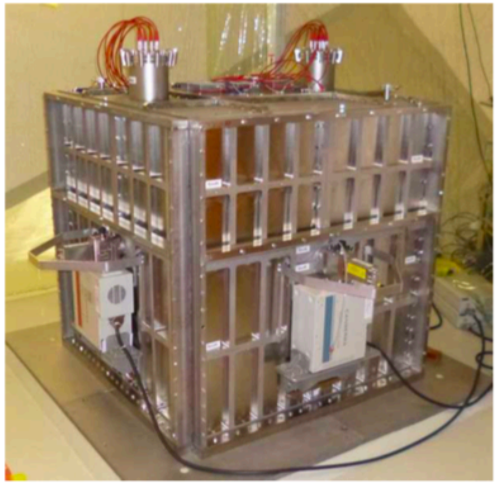
Test Assembly and Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

installation @ Brokdorf
→ full assembly
→ commissioning

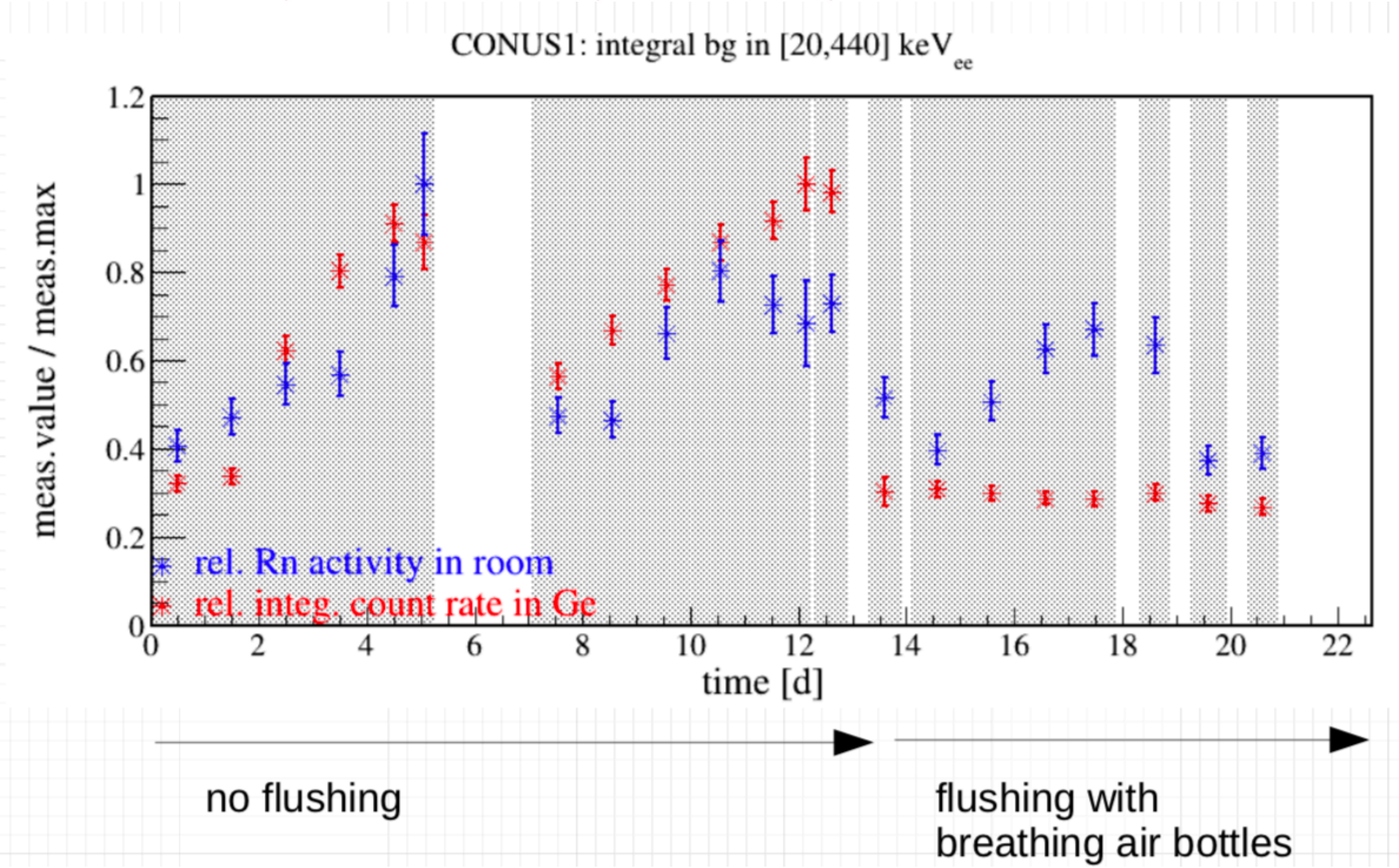






Radon Mitigation @ Reactor Site

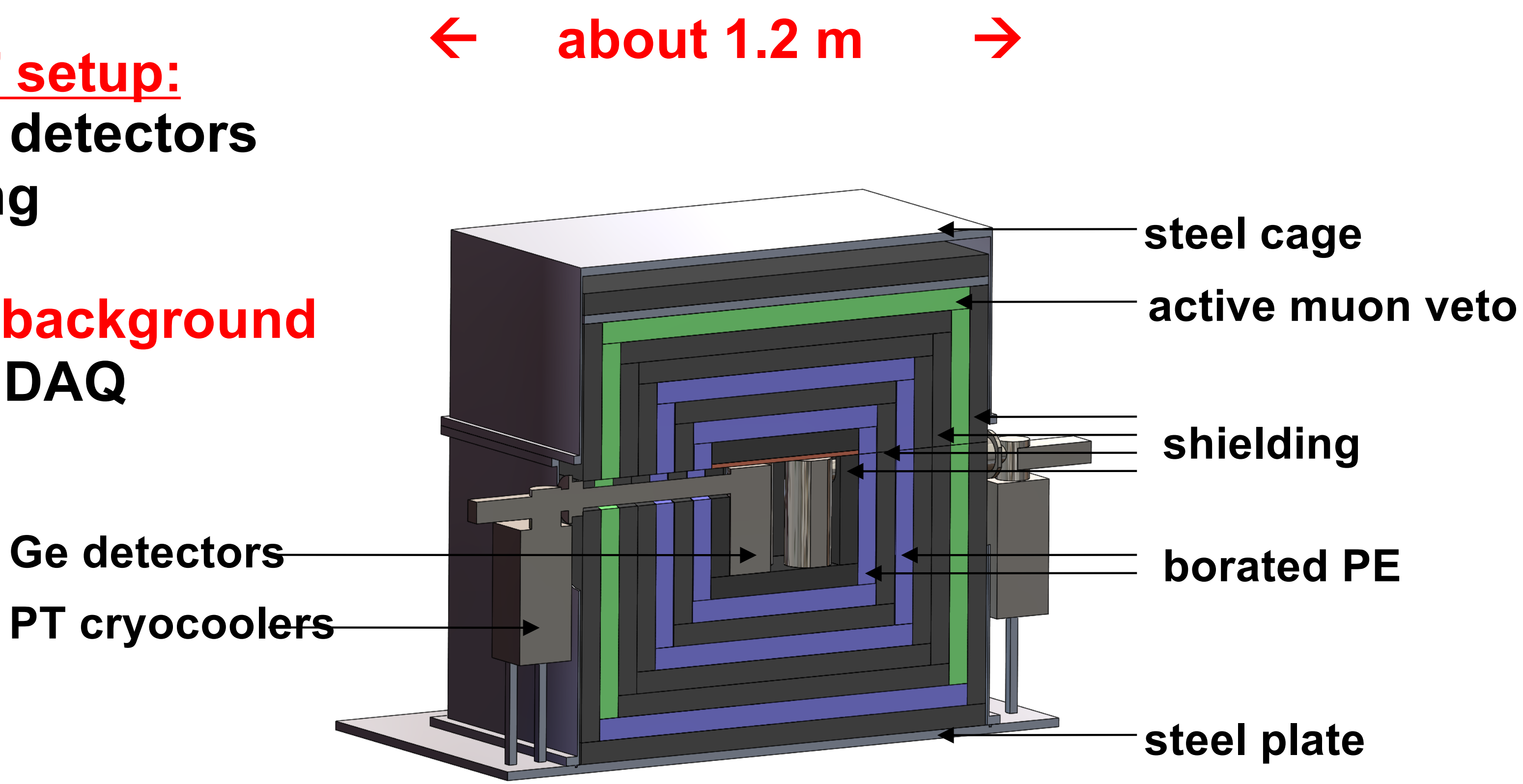
radon at reactor site: closed room, thick concrete walls ➔ 100-300 Bq/m^3
half-life of ^{222}Rn: 3.8d ➔ counter measure @reactor site:
hermetical sealing + flush with aged breating air bottles ~1 l/min



The CONUS Detector

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

➔ all ultra low background
- electronics & DAQ



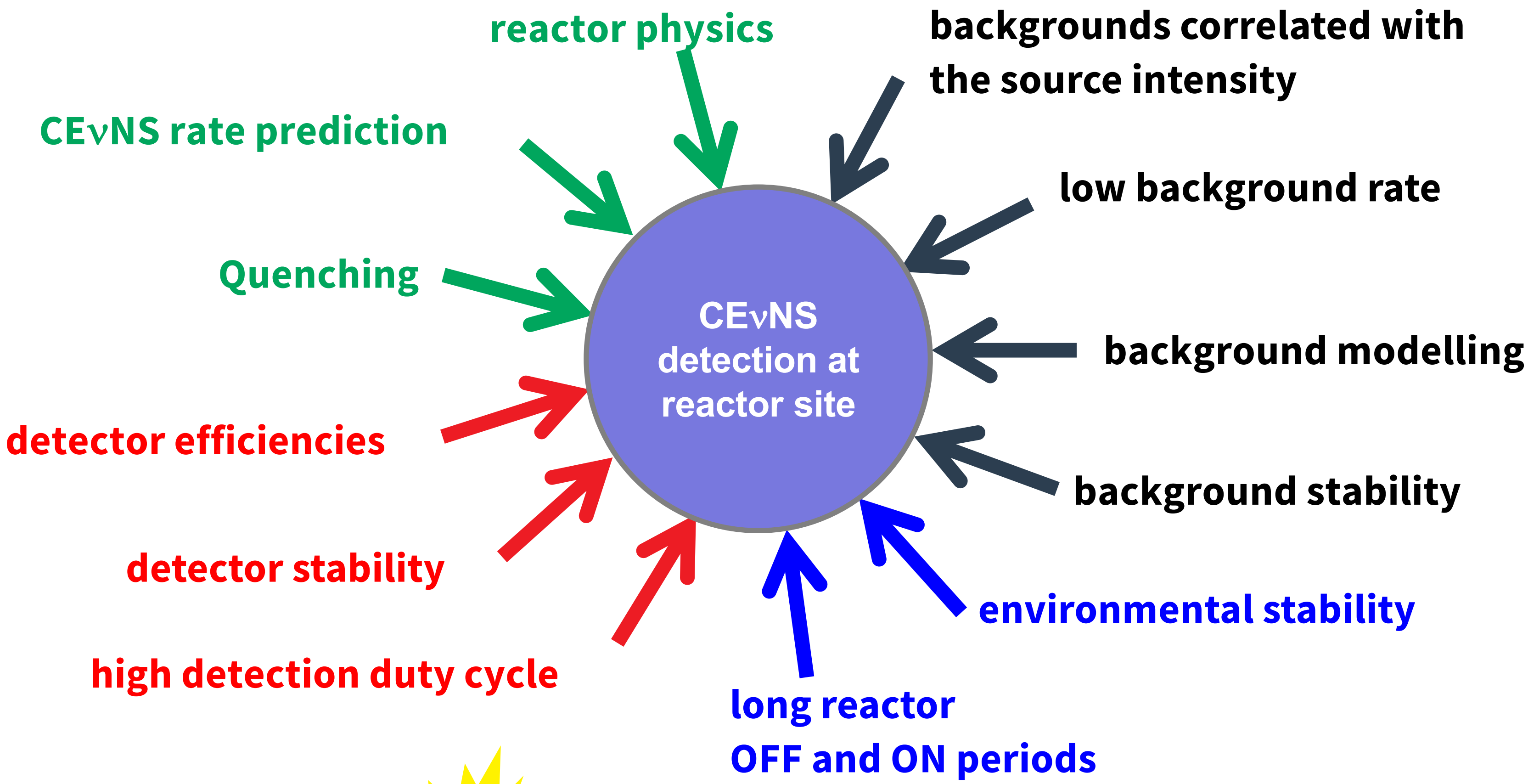
Successful combination of three essential improvements:

– 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

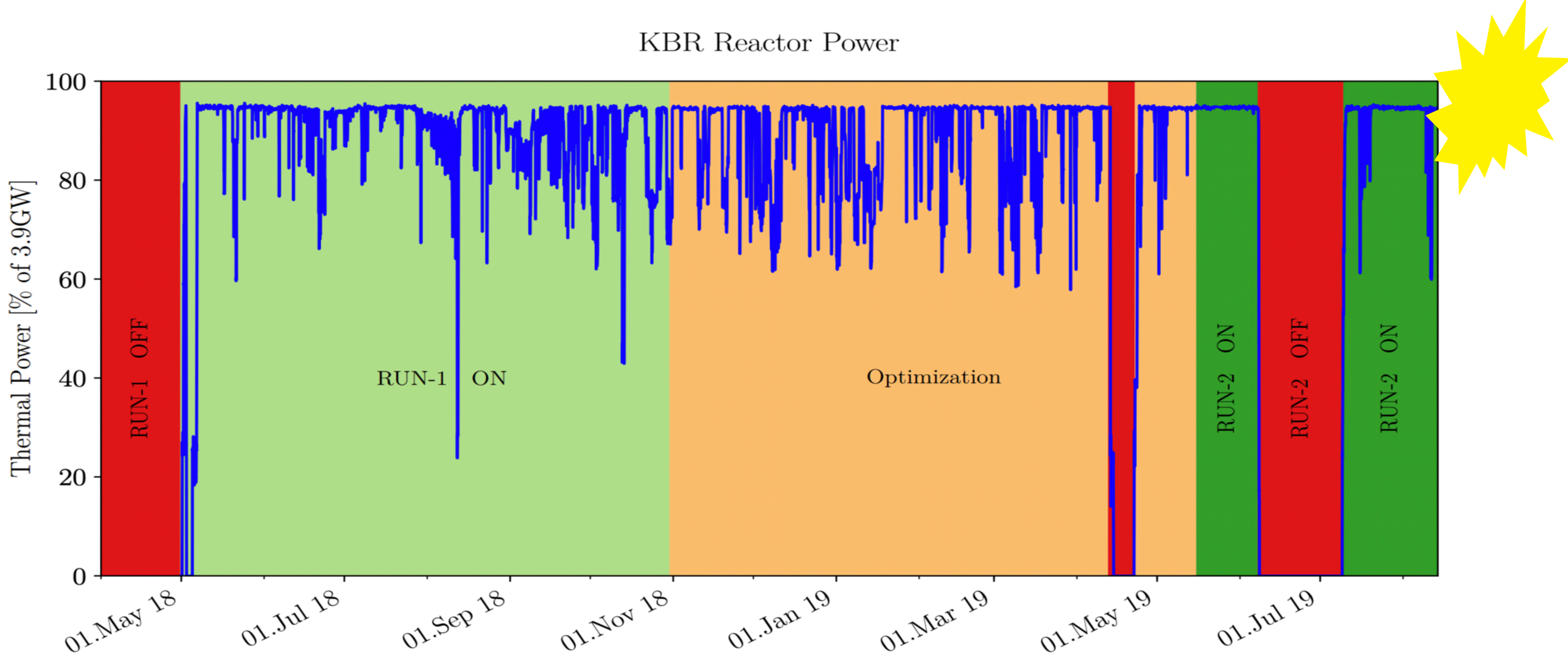
Towards CEνNS Detection

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



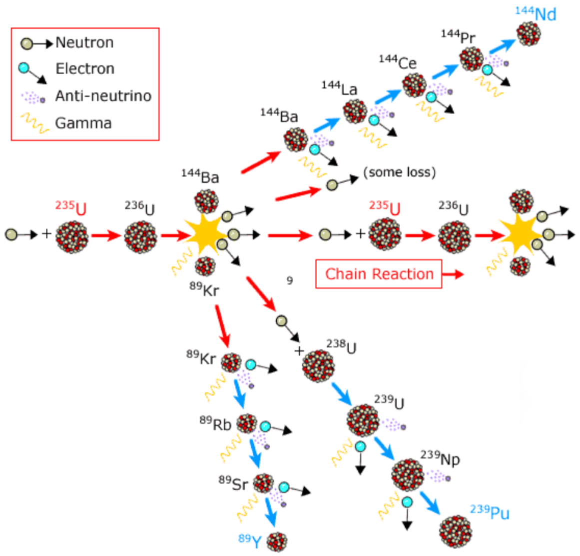
important milestones achieved → see next slides

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!
- Power variations

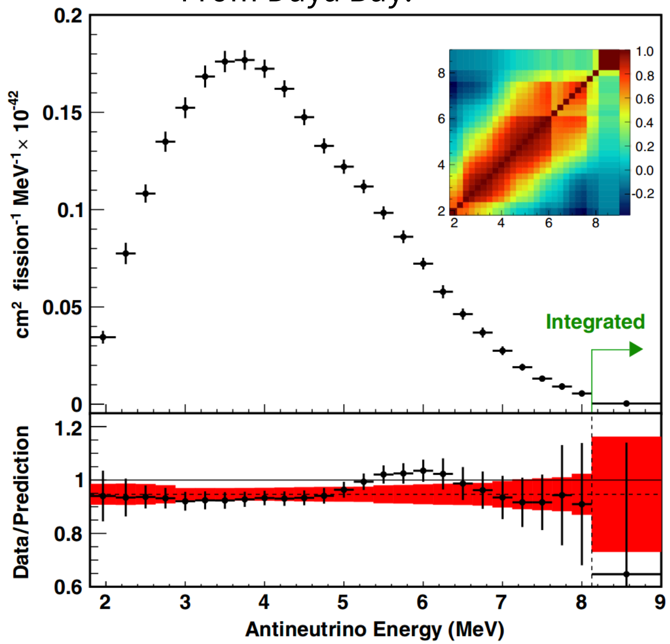
Reactor Physics Implementation



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

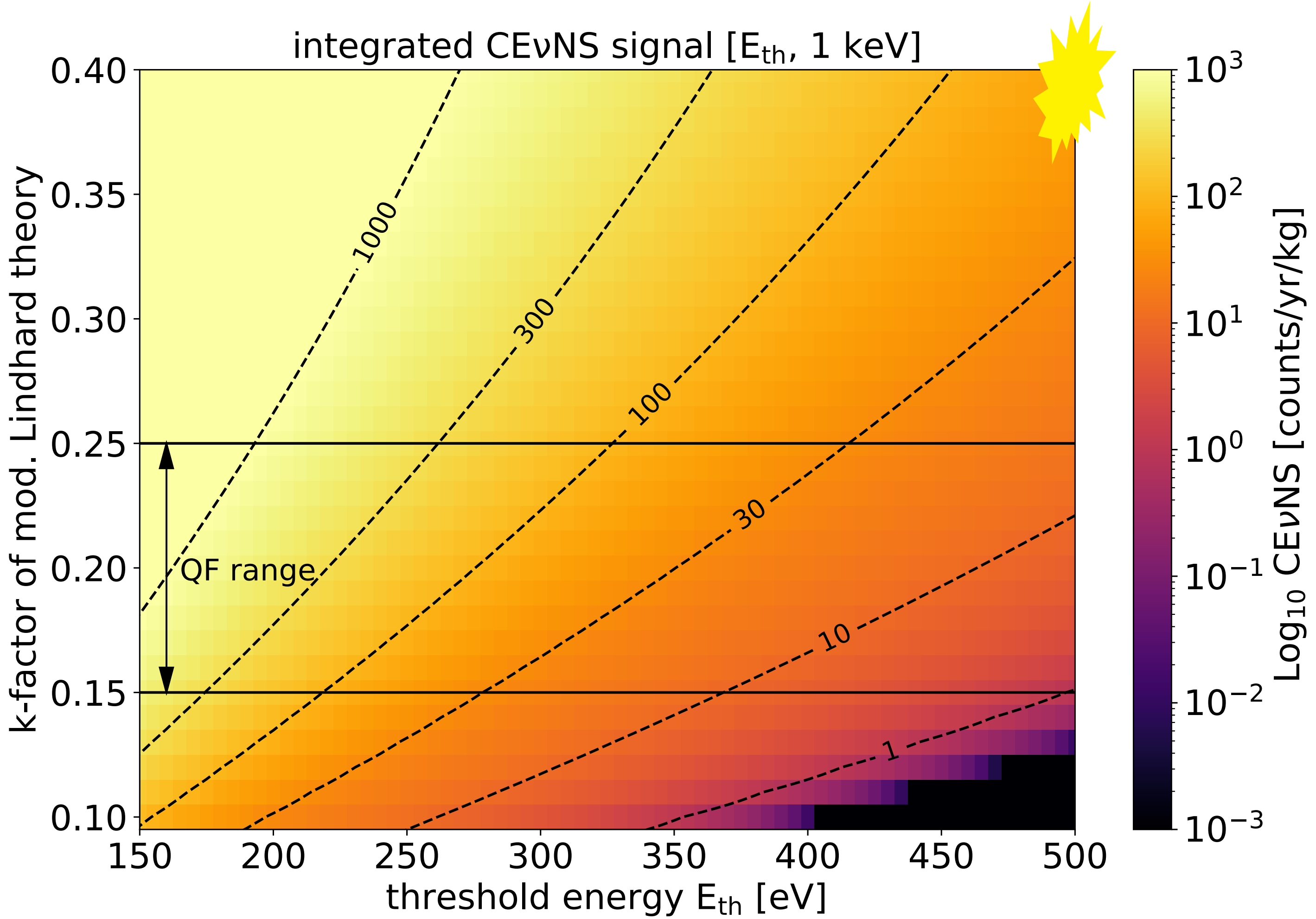
➔ **flux calculation for room A408 at KBR @17m from reactor core: ~10^{13}/(cm^2 s)**

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

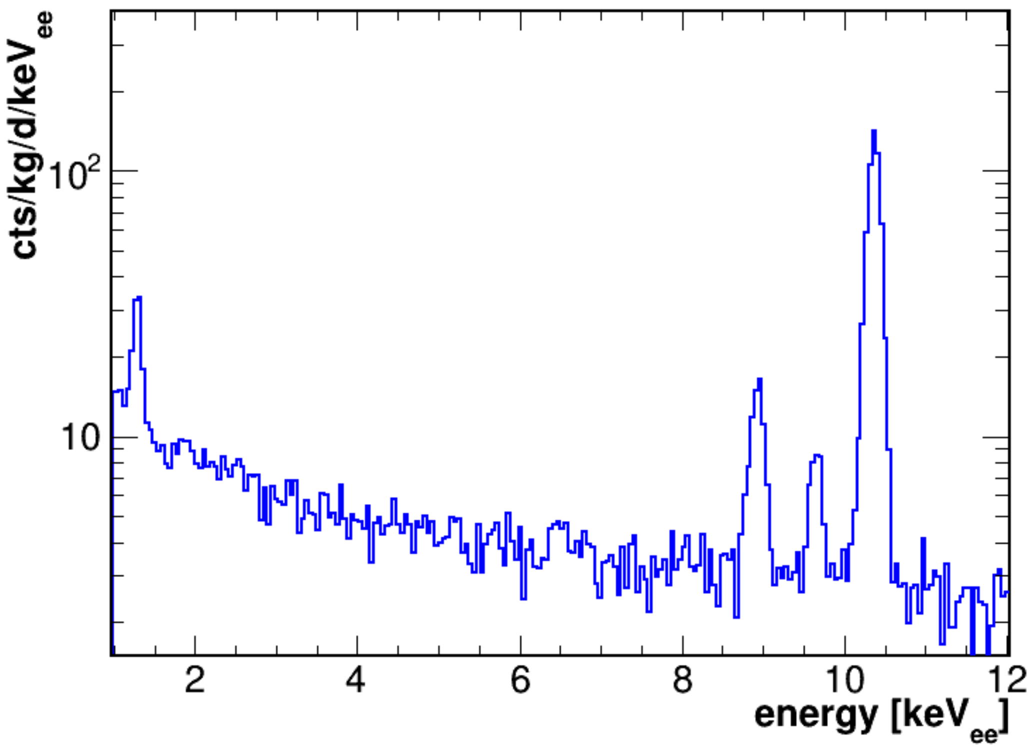
Expected Signal

Updated prediction including all reactor information:

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



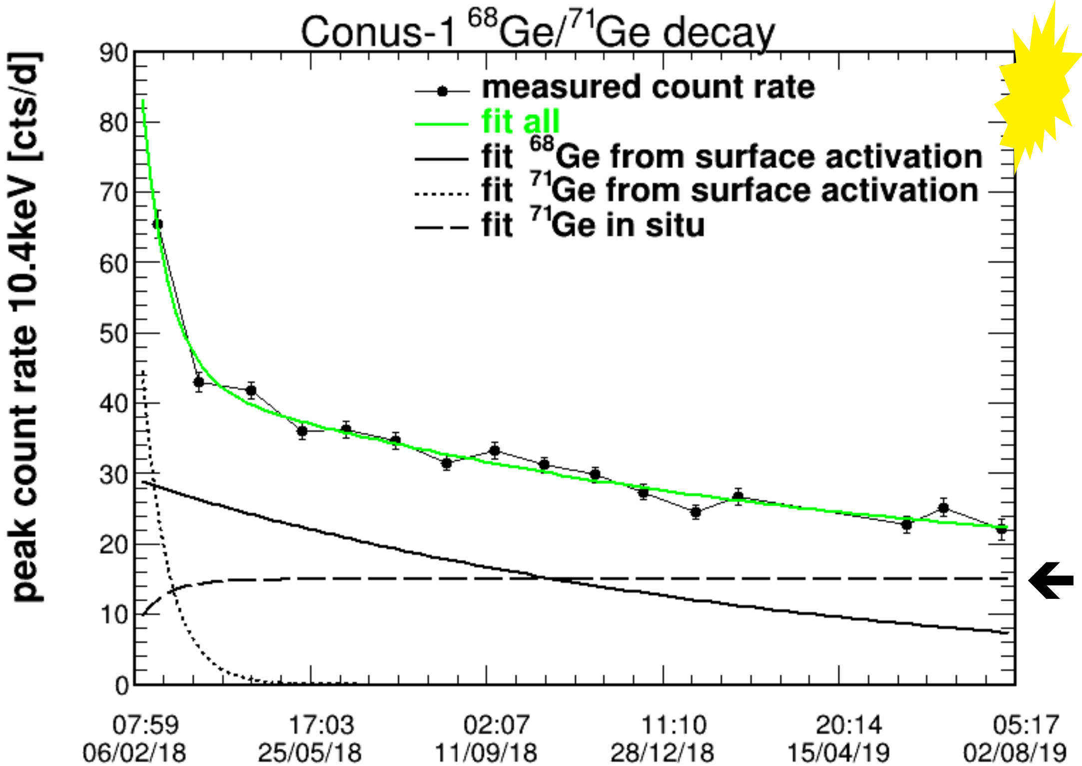
Background Level



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
  (lower than what has been achieved by several other DM experiments)
- **Very low bg shield at reactor site possible w/o contamination!**

Background Stability



<u>half lifes:</u>

^{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

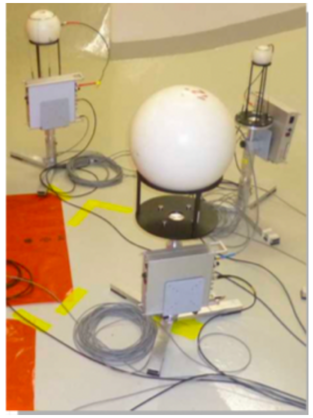
Ge recoils from fast neutrons can mimic CEνNS

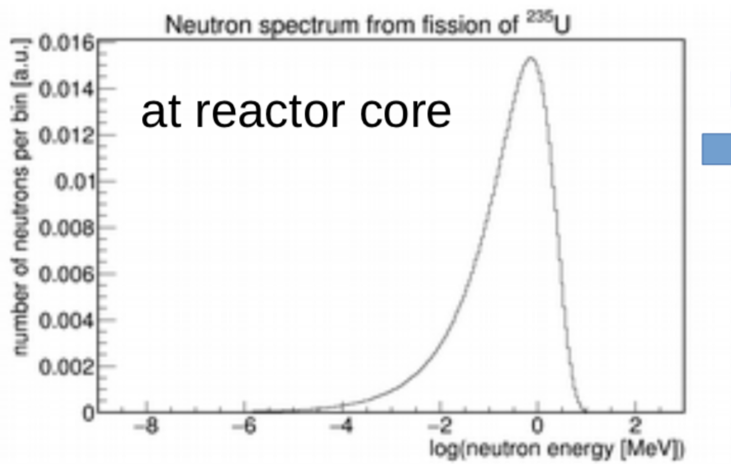
Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
(α,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes

outside of shield

→ **NEMUS**

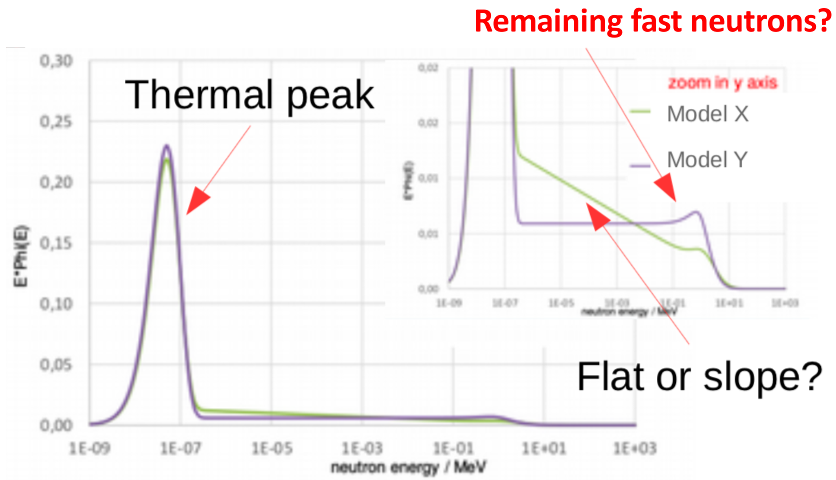
setup by PTB
➔ on-site neutron spectroscopy





propagation

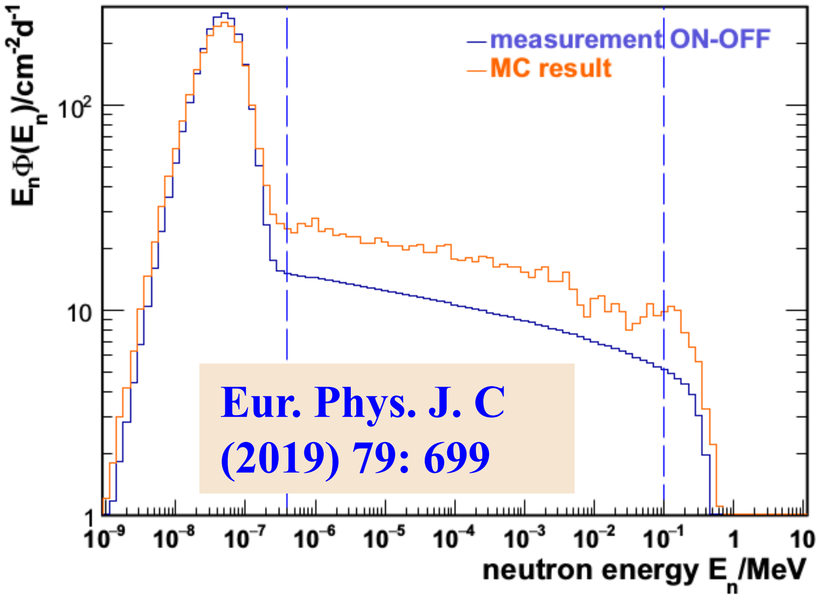
water
Steel
Concrete
…

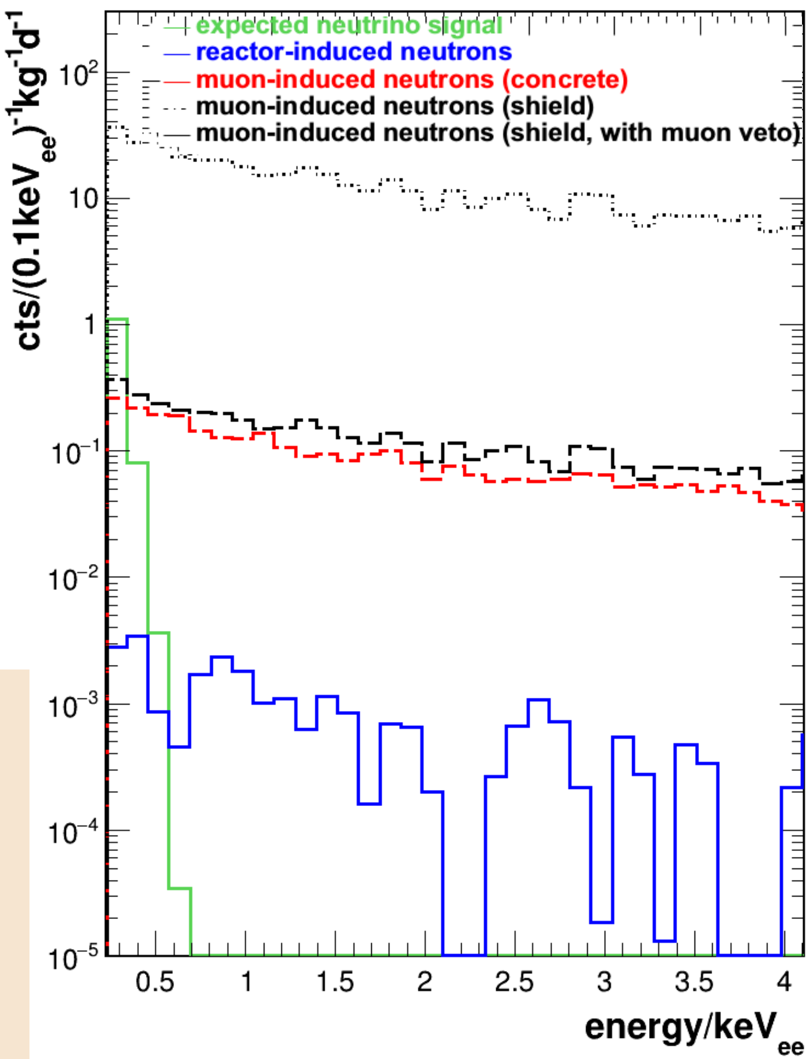


1. **Neutron field highly thermalized (>80%), correlated with thermal power**
→ fully absorbed by B-PE layers (MC)
2. **Residual fluence: if at all – epithermal from reactor - cosmic 100 MeV n: negligible**
→ reactor-correlated fast n inside shield ~ negligible

Thermal Power correlated Background

Bonner Sphere measurement with PTB

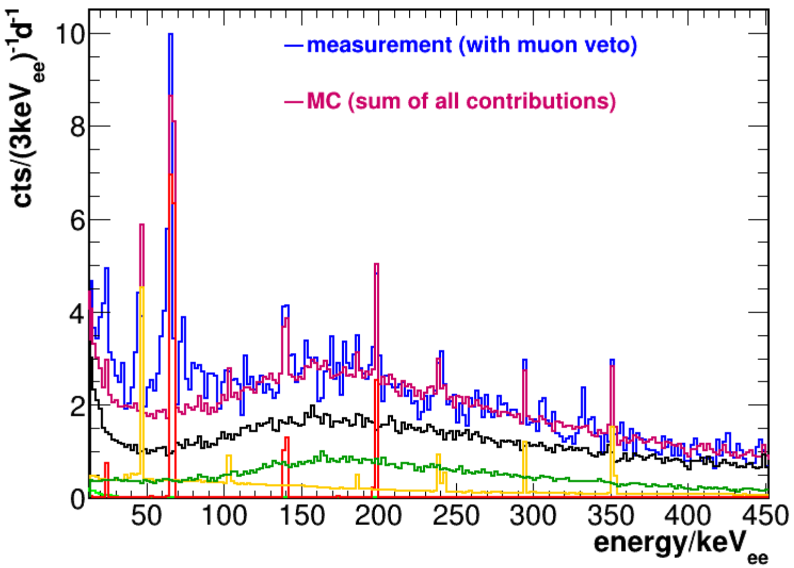




- neutron field inside A408 highly thermalized, but inhomogeneous → mapping; lession:
  ➔ should be done for all reactor experiments
- MC demonstrates that almost no reactor neutrons arrive at diodes inside shield; at least ten times less then the expected signal
- μ-induced neutrons dominant, but at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

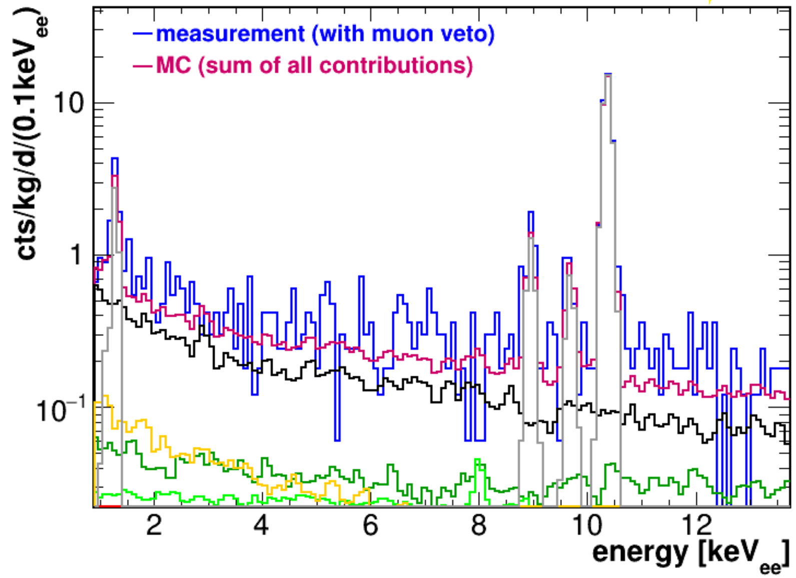
Background Model

high energy



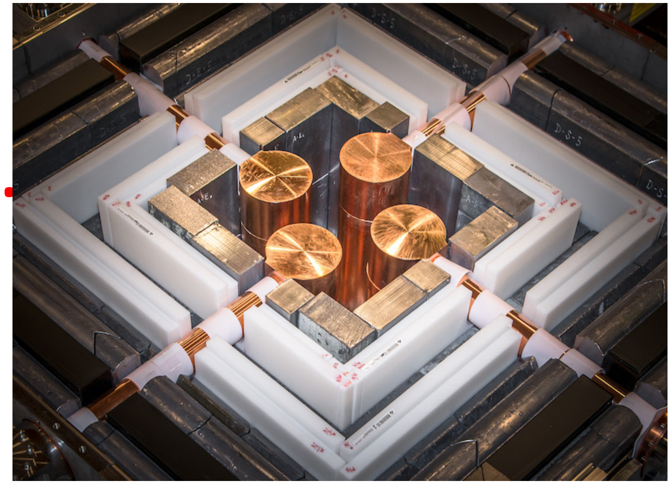
Prompt Muon-induced
^{210}Pb
Metastable Ge states
Cosmic activation
Muon-induced neutrons in concrete
Residuals

Low energy



- 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**
  ➔ **more studies...**
- **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 on-going...**

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 ~$3*10^{13}/cm^2/s$
background 1/kg/day

BSMsens=ΔS/S

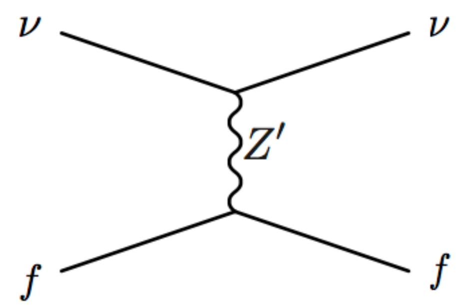
Puler/Thresh [eV]	QF=0.15	**BSMsens**	QF=BF	**BSMsens**	QF=0.25	**BSMsens**
40 / 120	647 474/ 8291 / 78.1	$1*10^{-3}$	965 999/ 10 775/89.7	$1*10^{-3}$	$2.9*10^{6}$/ 15 158 / 189	$6*10^{-4}$
45 / 135	407 092/ 8 036 / 50.7	$2*10^{-3}$	664 316/ 10 519/63.2	$1*10^{-3}$	$2.1*10^{6}$/ 14 866 / 144	$7*10^{-4}$
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

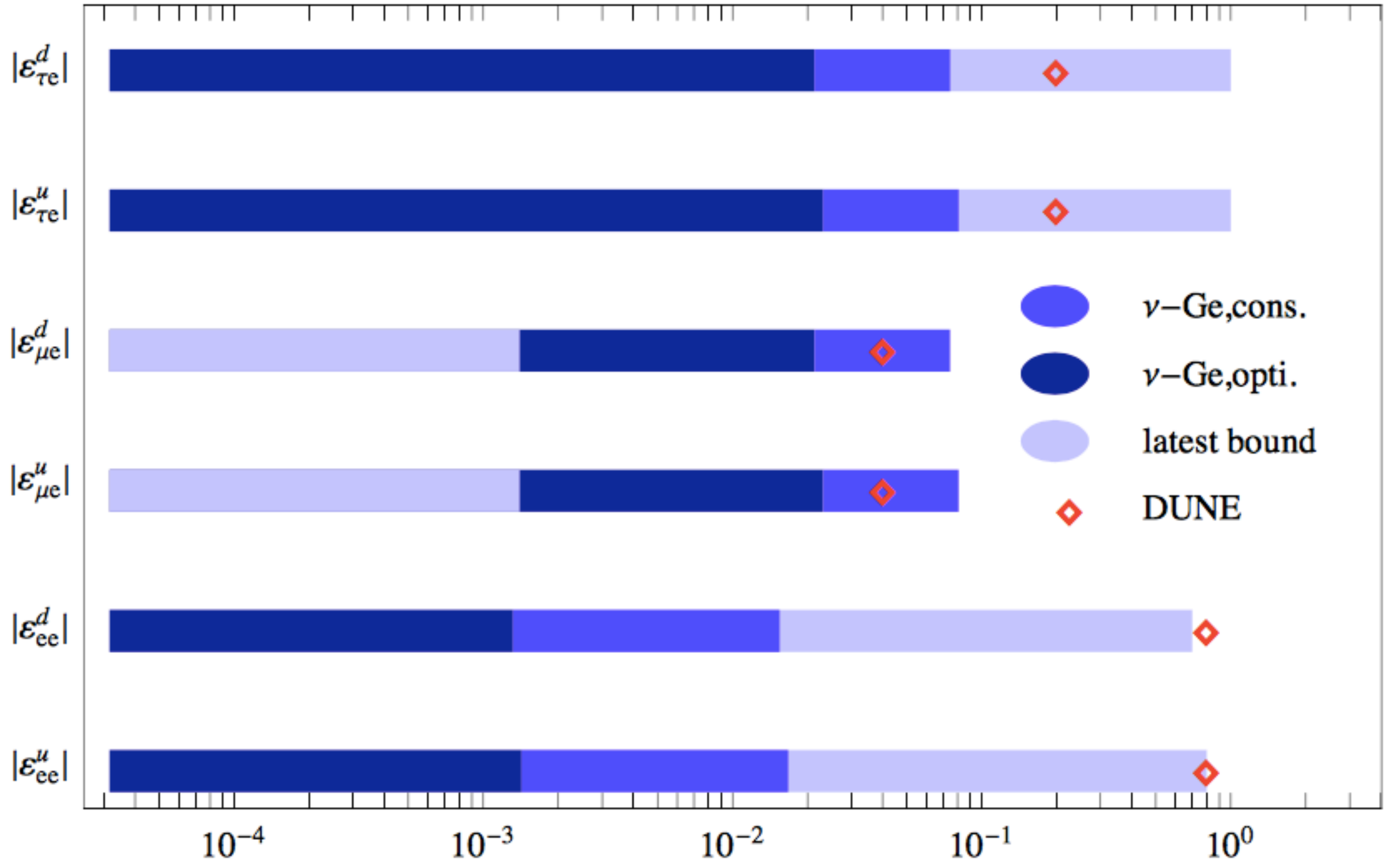
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ **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

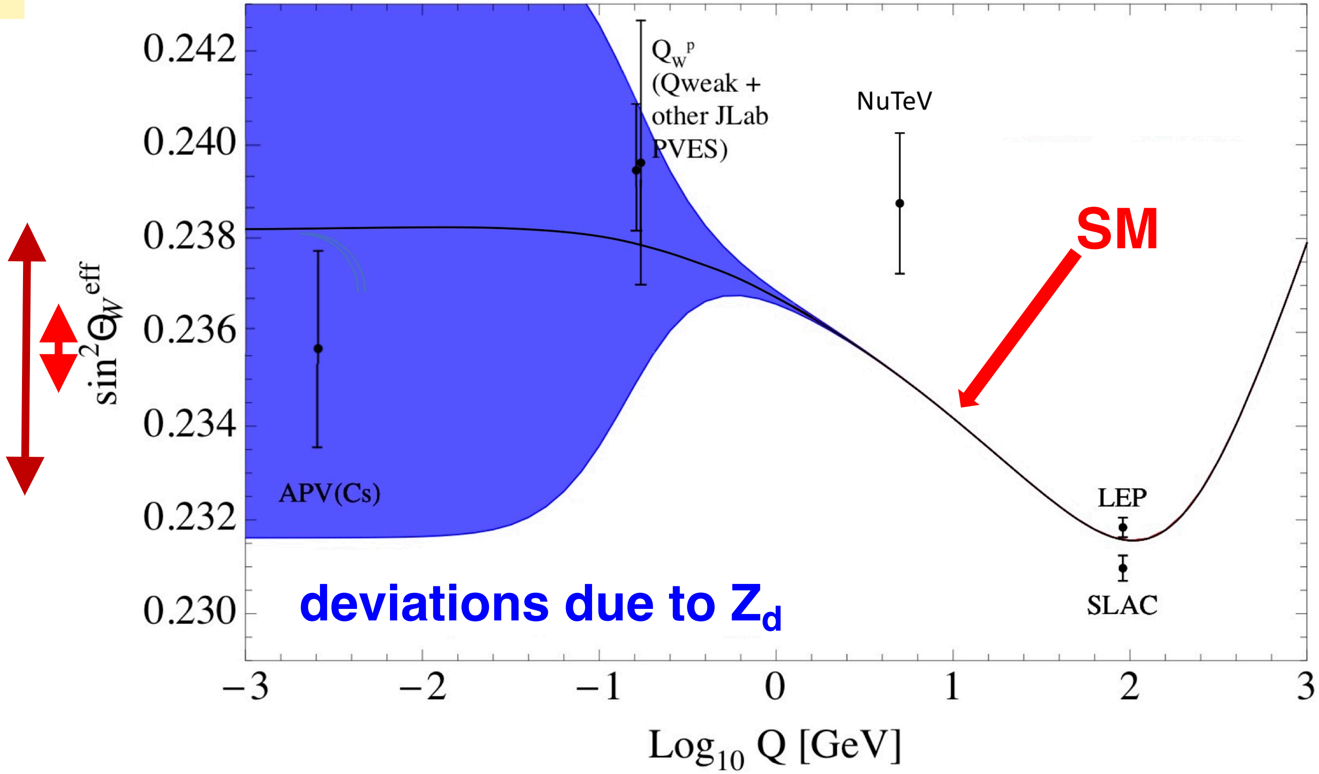
$\sin^2\theta_W$ precisely known in SM
SM quantum corrections
→running $\sin^2\theta_W^{eff}$

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

$(1- 4*\sin^2\theta_W) \simeq 0$
➔ 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...

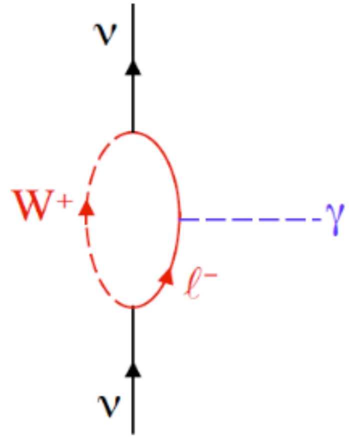


Searches for new Physics: Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:

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

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

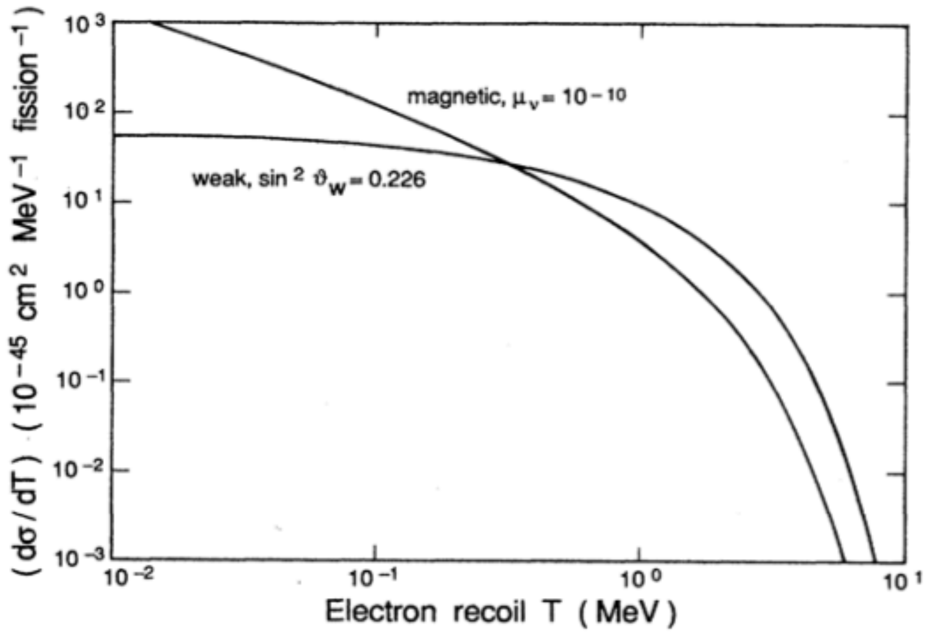


New physics ➔ detectable enhancements due to new physics:
SUSY, extra dimensions, …

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

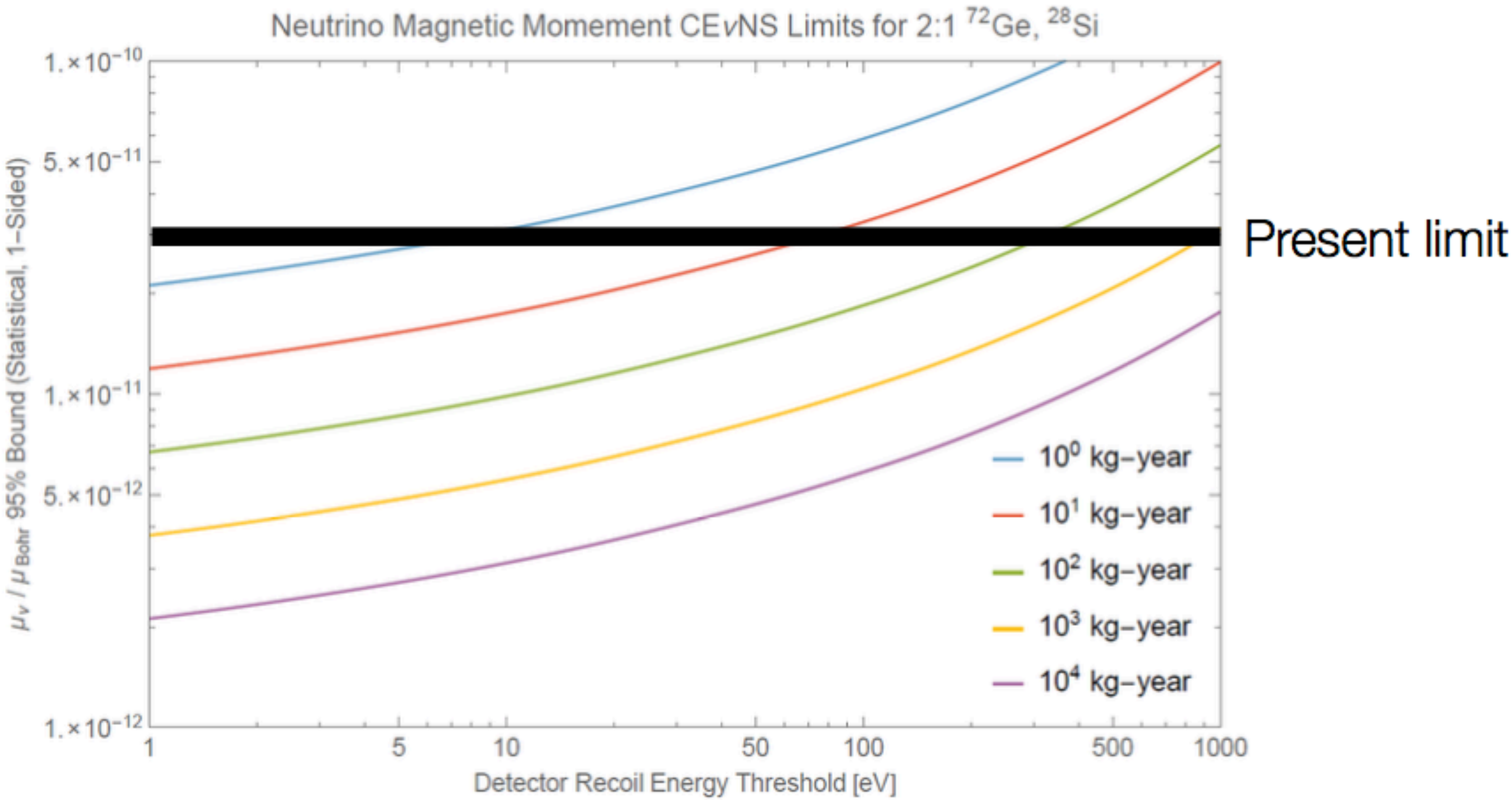
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$

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

Nuclear Structure with coherent Scattering

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

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

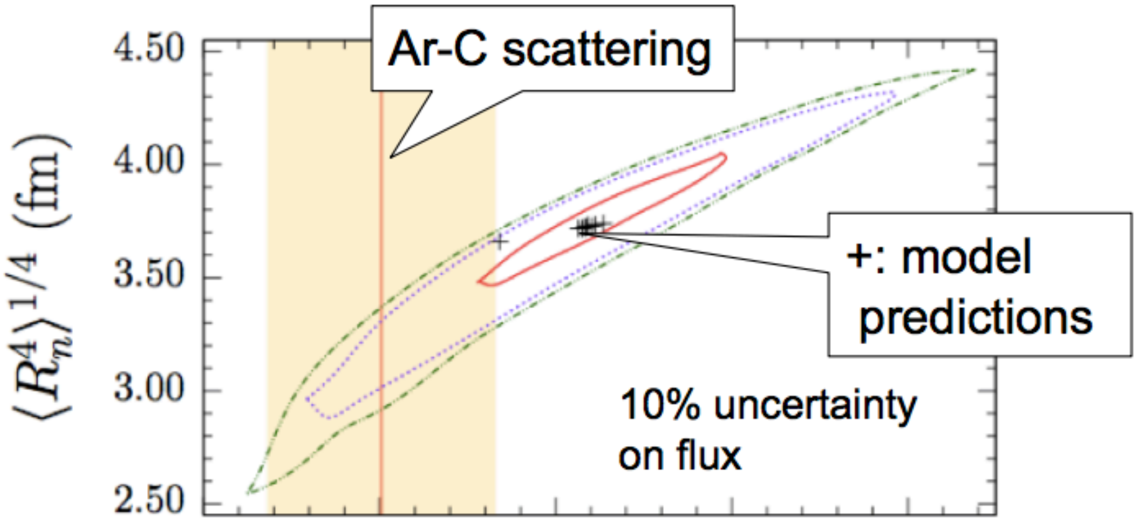
Nuclear form factors $F_{N,Z}(q)$ are Fourier transforms of N & P densities

➔ 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)

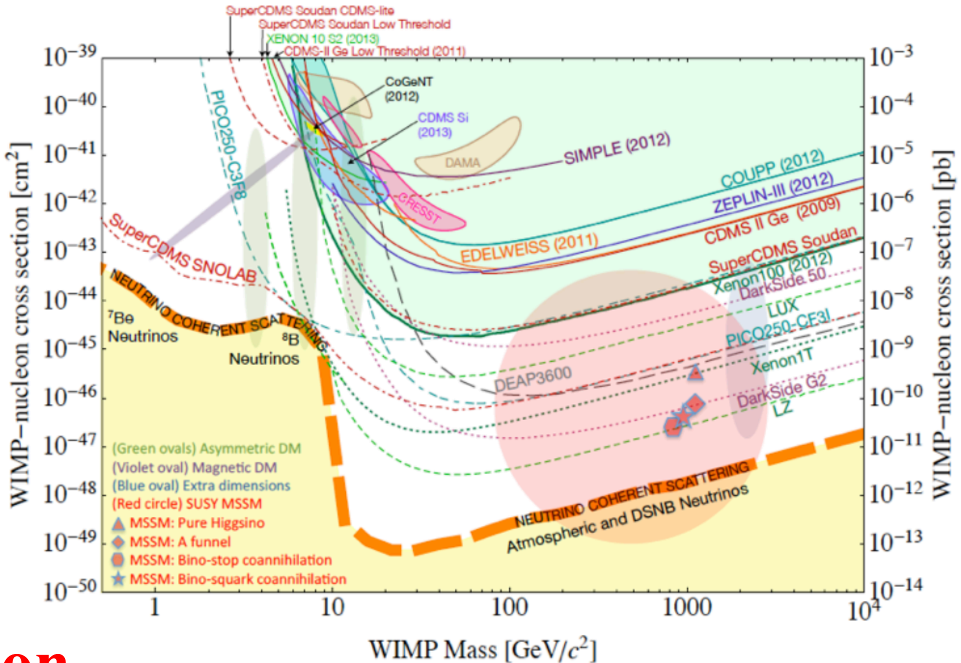
Example:
tonne-scale
experiment
at πDAR source



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) ...

More Phenomenology / Theory of CEνNS

- **Sterile neutrino searches...**
- **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
- **Safe-guarding + reactor neutrino spectra, +...**

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**