Coherent Neutrino Scattering and the Status of CONUS

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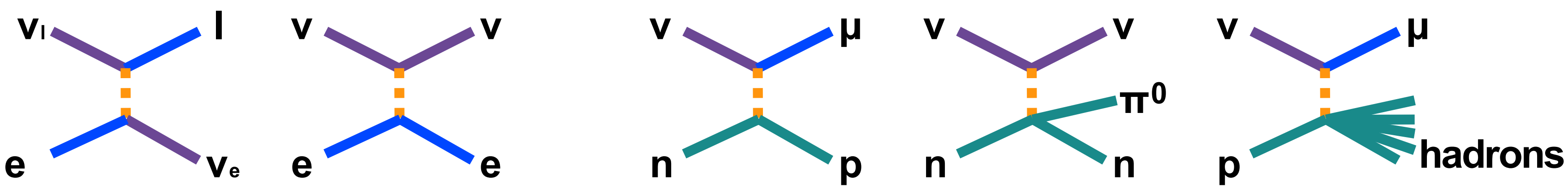
Coherent Neutrino Scattering

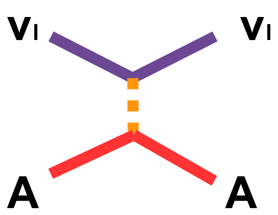
The Standard Model has six different interactions of neutrinos with matter:

- **5 have already been detected**



inverse muon (tau) decay | elastic electron scattering | (quasi) - elastic nucleon scattering | nuclear excitation and resonant production | Deep inelastic scattering and jet production

- **1 has so far not been detected:**



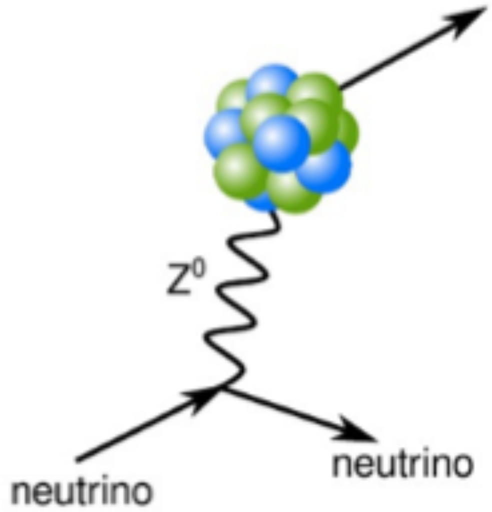
Coherent neutrino-nucleus scattering: CEνNS

➔ conceptually important
➔ very useful to test new physics

D.Z. Freedman, Phys.Rev. 9 (1974) 5
A. Drukier, Leo Stodolsky, Phys.Rev. D30 (1984) 2295 (1984), DOI: 10.1103/PhysRevD.30.2295

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
➔ nucleus recoils as a whole
➔ coherent up to $E_\nu \sim 50$ MeV



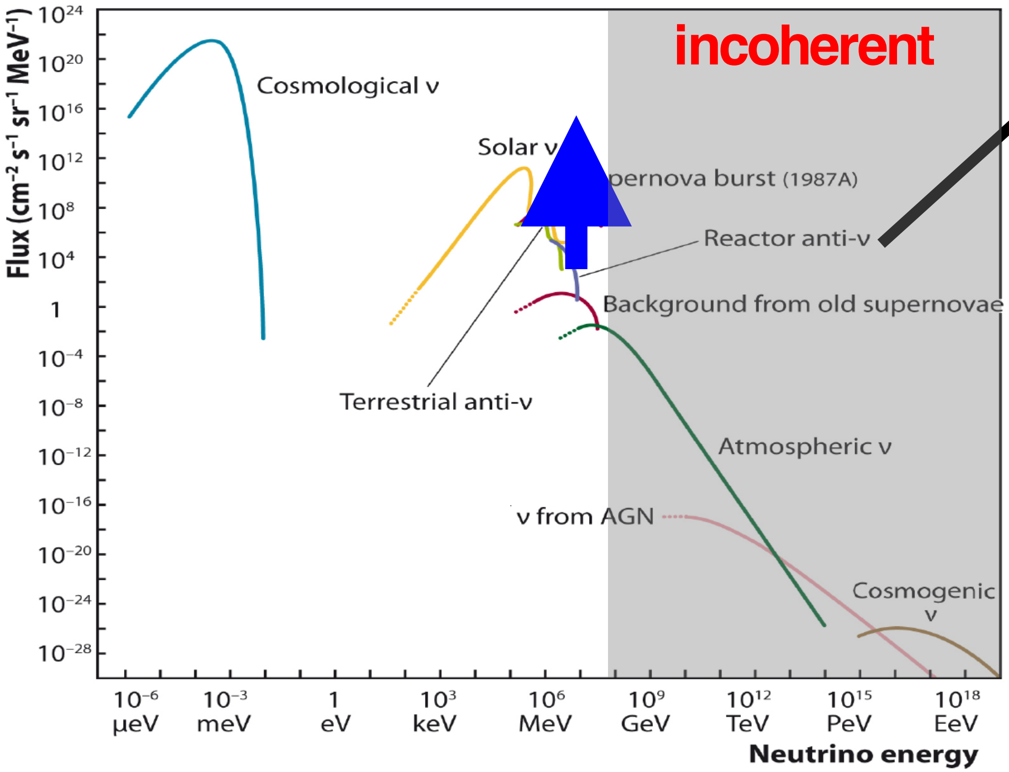
$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim N$$

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

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

Important: Coherence length ~ 1/E
→ need neutrinos below O(50) MeV for typical nuclei
→ low energy E_ν ←→ lower cross sections ←→ maximal flux!

The Neutrino Spectrum



~KamLAND:
10 GW at a distance of 150 km

ca. ~4% of the thermal power P
3.9 GW → ca. 150 MW in ν's

close to power reactors:
flux $\Phi \sim P/R^2$
ca. 150 kW/m² at 10m distance

+ beams
- cross section grows with neutrino energy

source	flux	
reactor neutrinos (3 GW, at 10m distance)	5 x 10^13	/cm^2/s
solar neutrinos (on Earth)	6 x 10^10	/cm^2/s
supernova (50 kpc Abstand, for O(10) seconds)	~ 10^9	/cm^2/s
geo-neutrinos (on the Earth's continental surface)	6 x 10^6	/cm^2/s

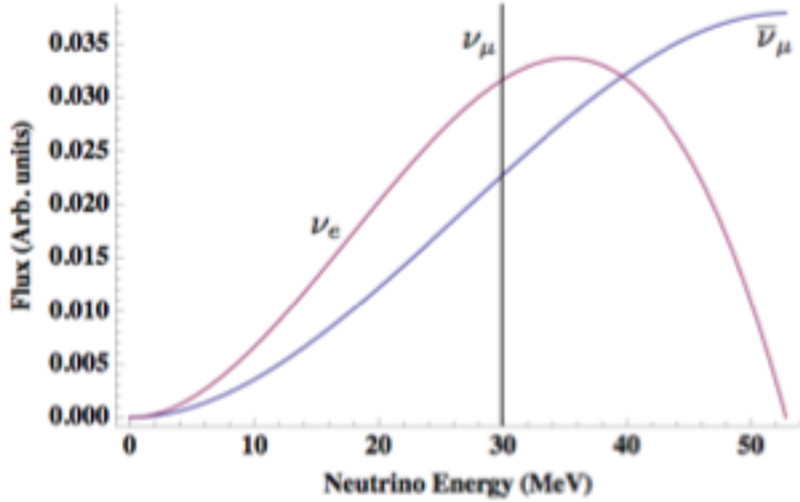
Two Paths

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 in 2017**

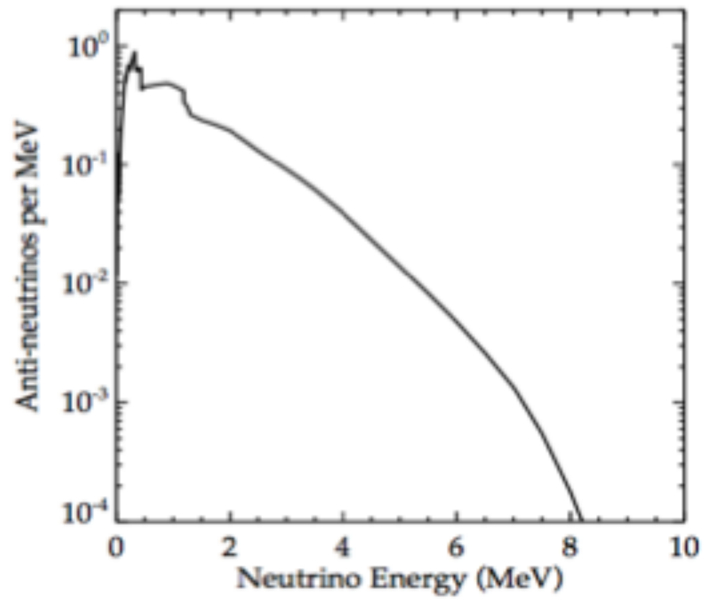


Anderson et al., 1201.3805

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

The CONUS Experiment

Combine:

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

➔ **COherent NeUtrino Scattering experiment**

C. Buck, J. Hakenmüller, G. Heusser, M. Lindner, W. Maneschg, T. Rink, T. Schierhuber, H. Strecker

- Max Planck Institut für Kernphysik (MPIK), Heidelberg

K. Fülber, R. Wink

- Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf

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Preussen Elektra

Experimental Requirements

- measure nuclear recoil energy T

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

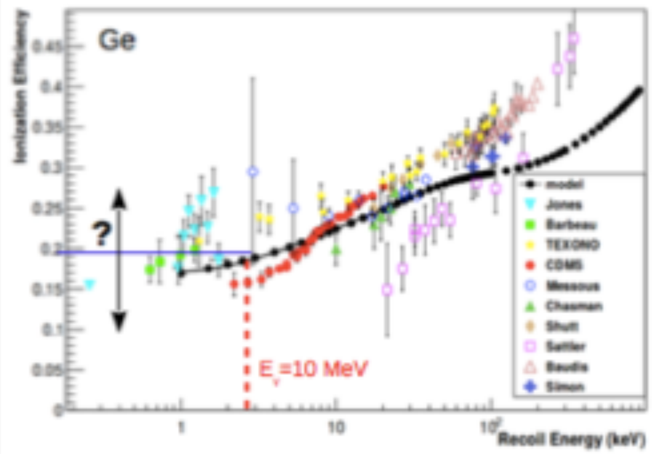
$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$

- energy loss due to quenching (Lindhard)

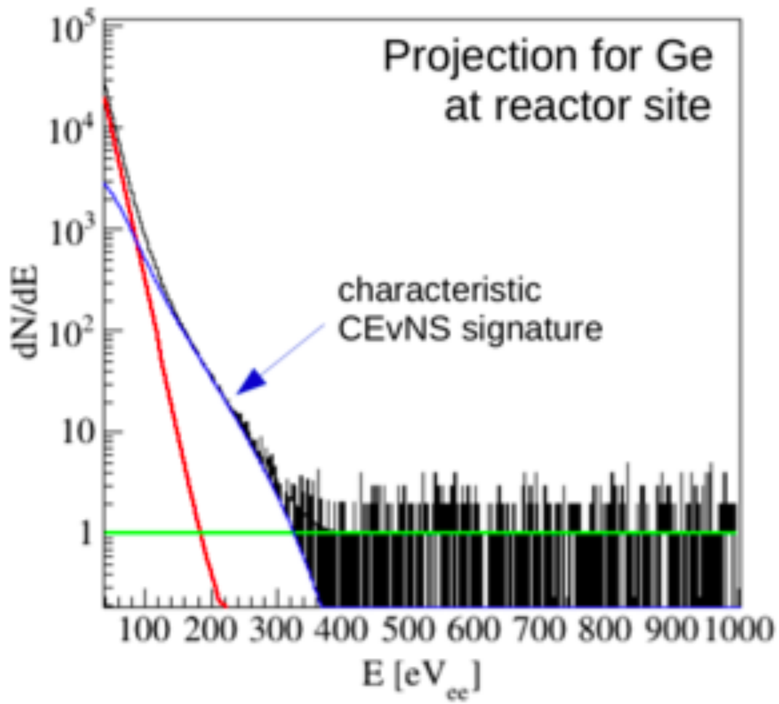
  ➔ Quenching Factor (QF)

  QF down to 0.2 in Ge → 600 eV

  ➔ include systematic uncertainty



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

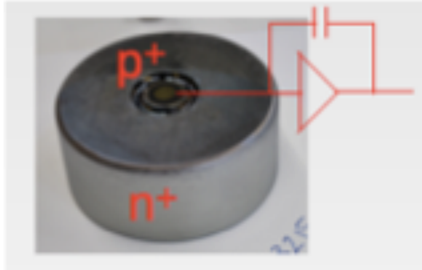


detection of CEνNS signal:

- highest ν flux
- low noise threshold (sub keV)
- low background
  - radio-pure materials
  - "virtual depth" shielding

Event Rates for a conceivable Experiment

1kg detector: BEGE or SAGE type germanium diode
Distance D=15 m; 3.9GW ←→ flux = 3.12*10^{13}/cm^2/s
Background ~ 1/kg/keV/day

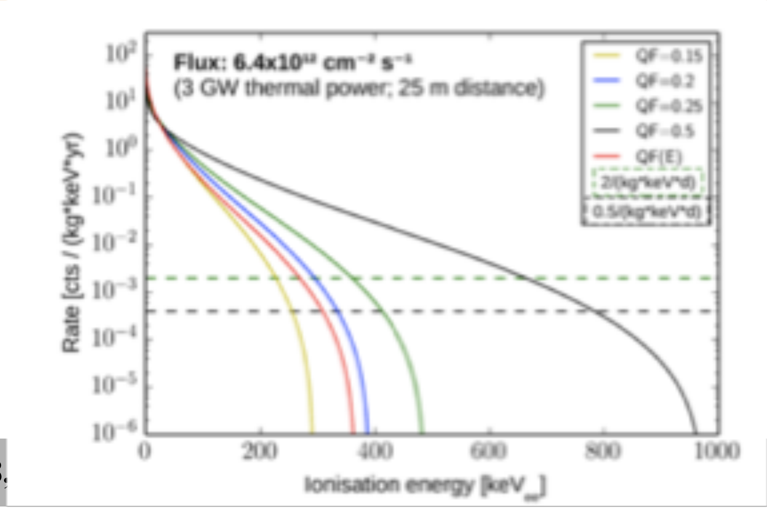


S[1/yr] / B[1/ye] / R=S/B

Pulser/Threshold [eV]	QF = 0.15	QF = best fit	QF = 0.25
60 / 180	971 / 61 / 15.8	2 173 / 85 / 25.6	9 194 / 127 / 72.3
65 / 195	588 / 58 / 10.1	1 488 / 81 / 18.4	6 962 / 123 / 56.4
70 / 210	352 / 55 / 6.4	1 014 / 78 / 13.0	5 272 / 120 / 44/0
75 / 225	207 / 52 / 4.0	686 / 75 / 9.2	3 989 / 117 / 34.2
80 / 240	120 / 49 / 2.5	460 / 71 / 6.5	3 012 / 113 / 26.7
85 / 255	69 / 46 / 1.5	306 / 68 / 4.5	2 269/110/20.7

- ➔ **Not trivial, but doable on a short time scale!**
- ➔ **Even a 1kg detector can detect CEνNS**
- ➔ **Upscaling…**

Maneschg, Rink, Salathe, ML



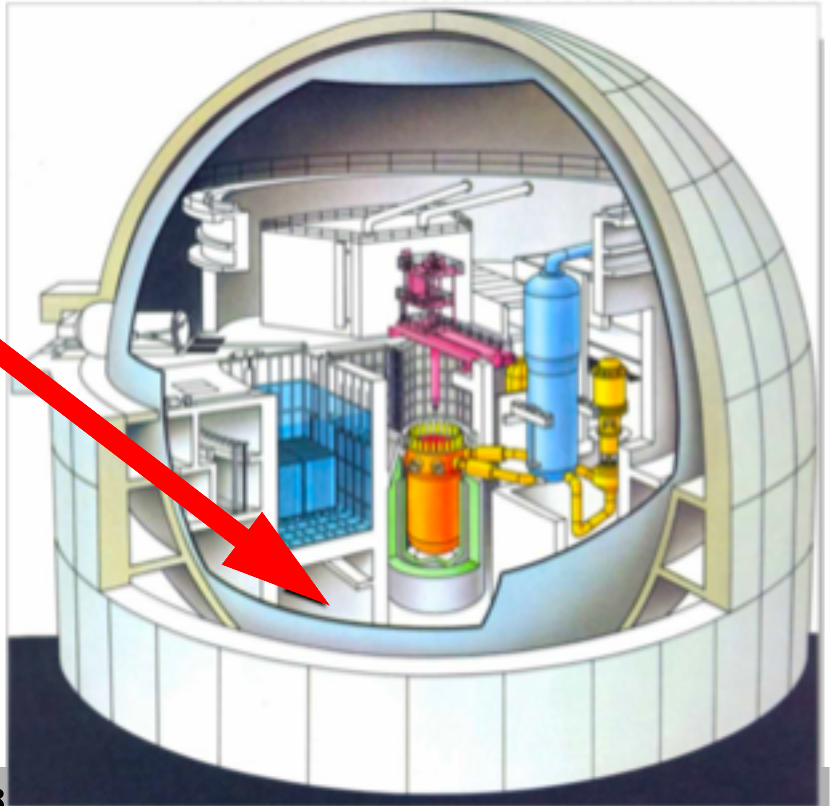
The CONUS Reactor Site

The Brokdorf (Germany) nuclear power plant:

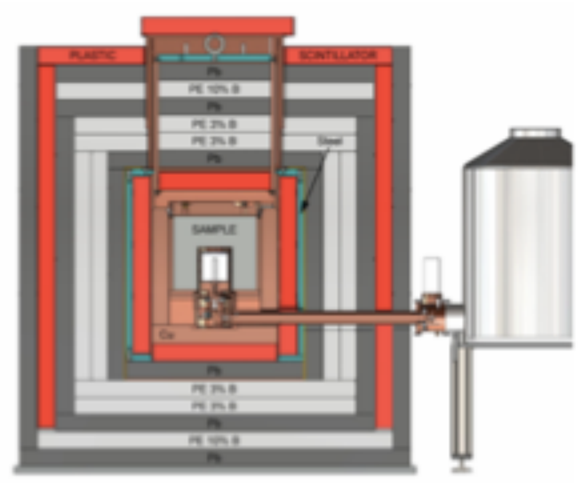
thermal power 3.9 GW_{th}
detector @ d=17m
➔ ν flux: 2.4 x 10^{13}/cm^2/s
very high duty cycle

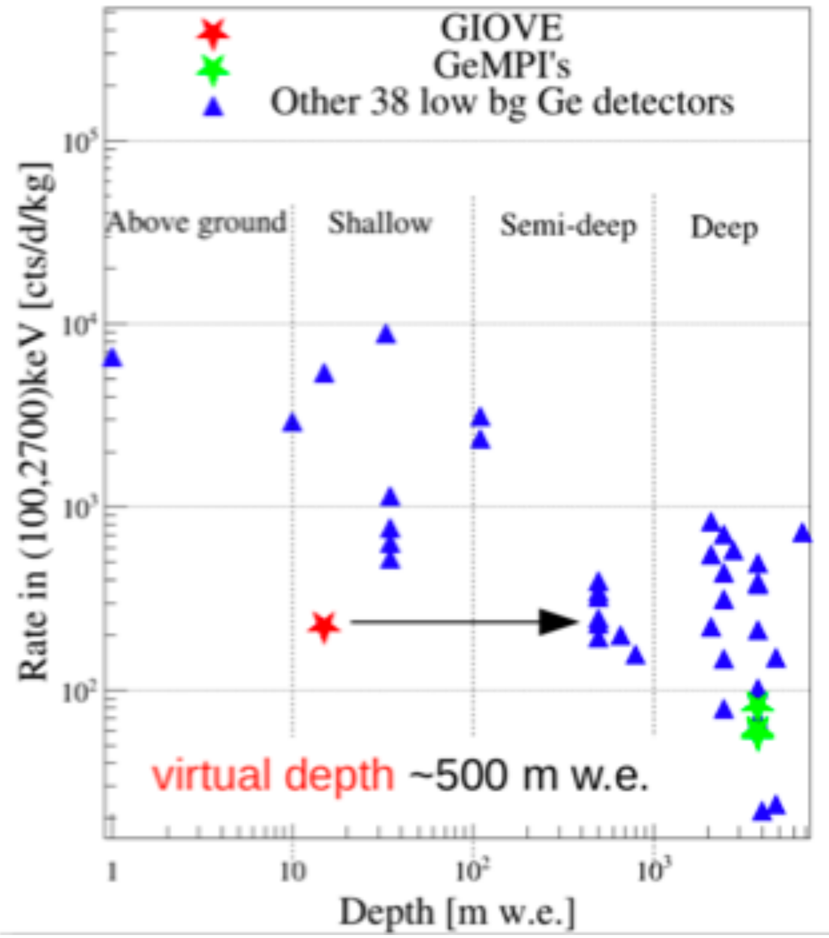
➔ very intense integral neutrino flux
$E_ν$ up to ~ 8 MeV → fully coherent

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



The GIOVE active Shield





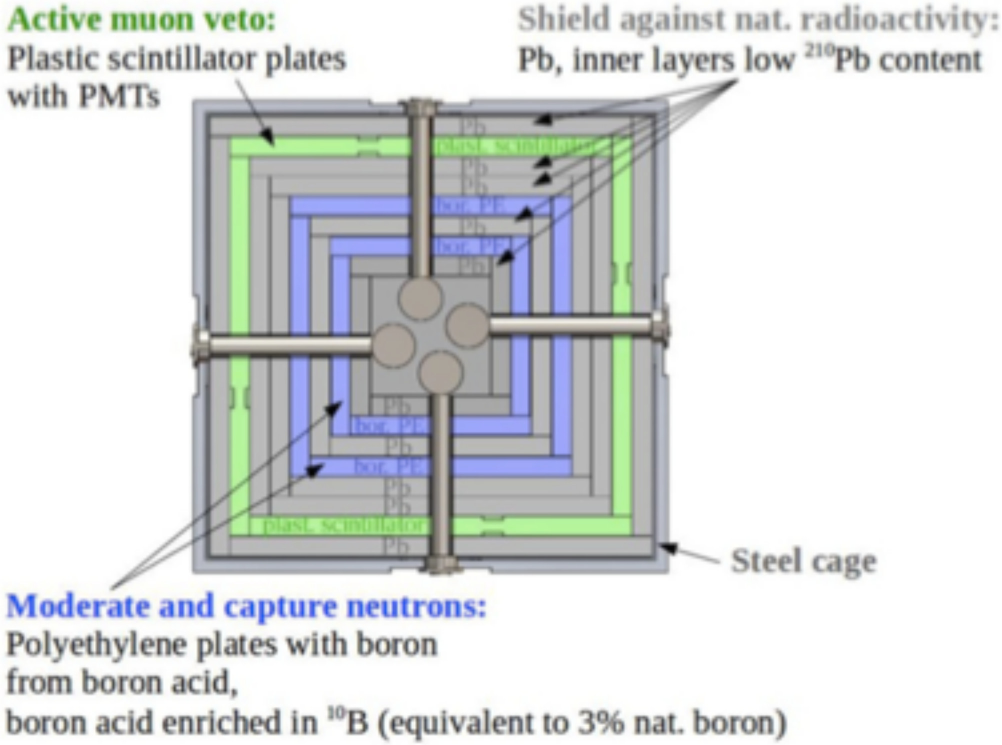
- R&D at MPIK
- main purpose: material screening @ shallow depth (15 mwe)
- coaxial HPGe detector (m_{act} = 1.8 kg)
- radio-pure passive shielding
  - Pb, B-doped PE, μ-veto, OFHC Cu
- active veto: optimized to reduce μ's and μ-induced signals
  - plastic scintillators with PMTs
  - 99% muon veto efficiency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

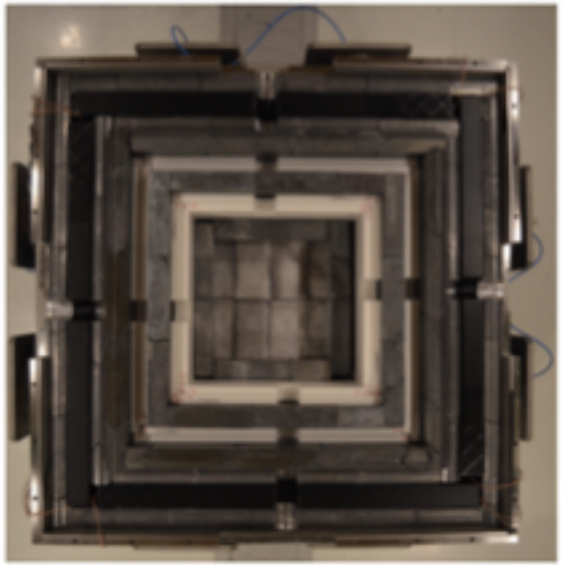
(^{226}Ra: 70μBq/kg, ^{228}Ra: 110μBq/kg, ^{228}Th 50μBq/kg)

``virtual depth" → UG projects close to surface

G.Heusseretal.,Eur.Phys.J. C(2015)75:531

The CONUS Shield





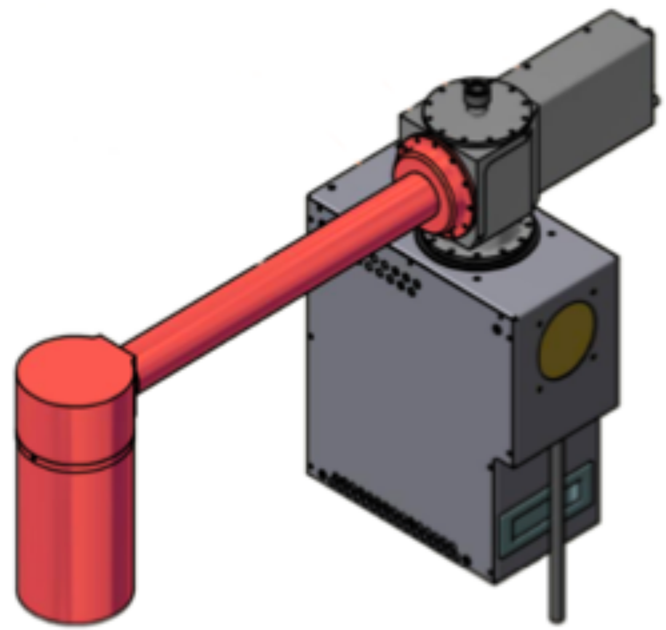
- **inner layer: Pb ⇒ suppress μ-induced bremsstrahlung continuum**
- **careful material selection (screening @MPIK & MPIK-GeMPIs@LNGS)**
- **radon mitigation without N2 flushing**
- **testing at Low Level Laboratory at MPIK (15 mwe):**

  - mechanical tests
  - muon veto performance (with coaxial high-purity detector CONRAD)
  - radiopurity of shield (with CONRAD)

Detectors

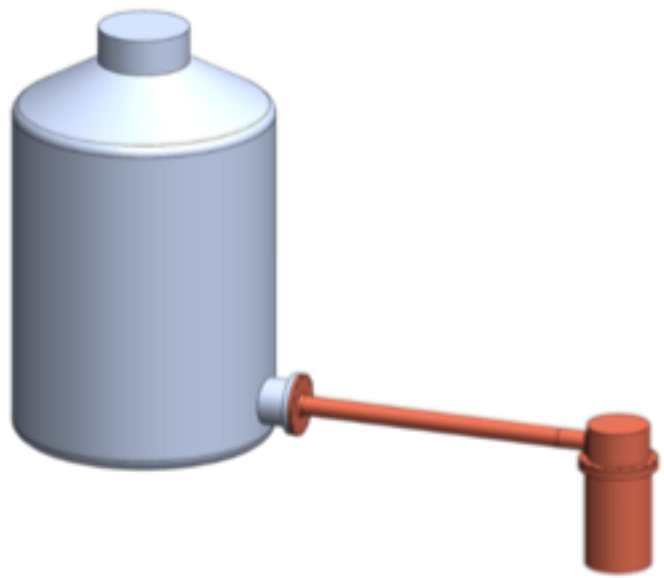
CONUS 1-4

- p-type point contact HPGe
- 4x 1kg – active mass 3.85kg
- Spec for pulser res. (FWHM) ≤ 85eV
  → noise threshold ≤ 300eV
- electriocal PT-cryocoolers
- very low bg components



CONRAD

- very low bg components
- p-type semi-coax HPGe
- 2.47kg, N2 cooling
- extremely low bg components



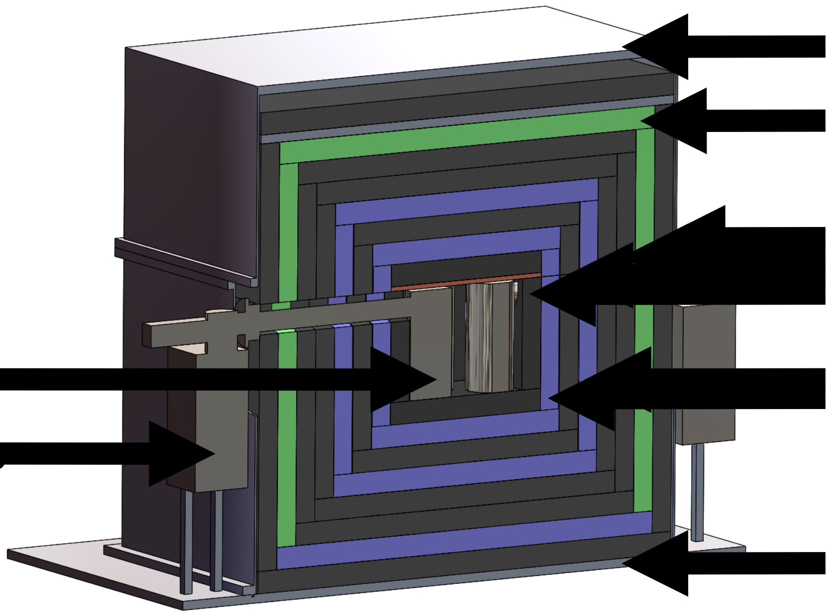
The CONUS Detector

Components:

- active/passive shielding
- 4 Germanium detectors
- 4kg ➔ smallest ν detector
- PT coolers

➔ all ultra low background
- electronics and DAQ rack

← about 1.2 m →



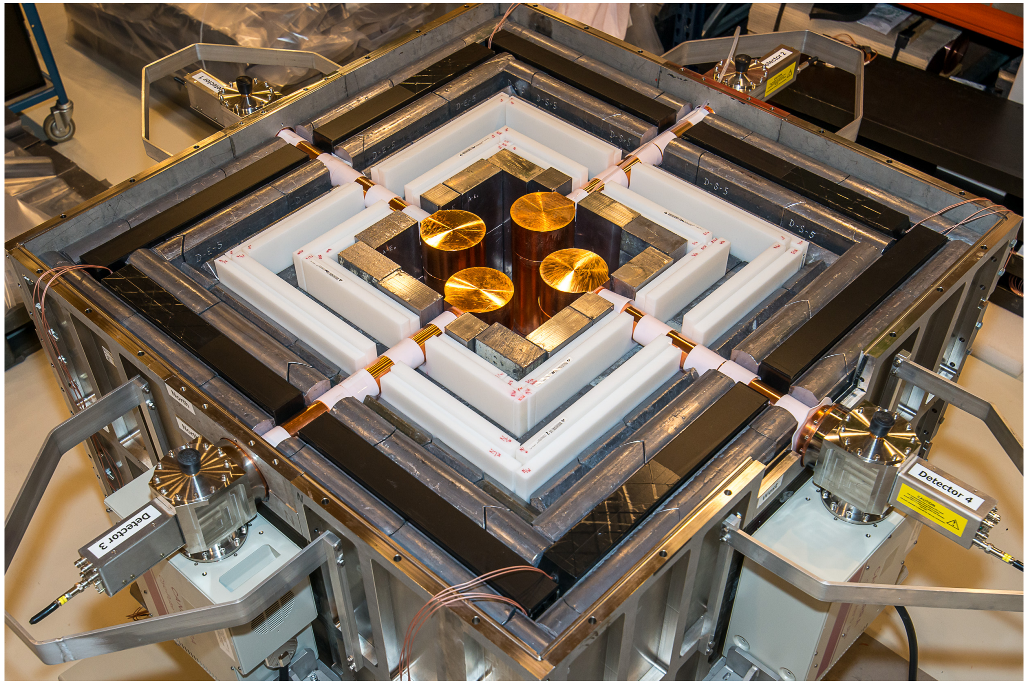
Successful combination of three essential improvements:
- new (best) active/passive shielding (GIOVE @ MPIK = "virtual depth")
- new detectors with very low thresholds
- site with highest neutrino flux

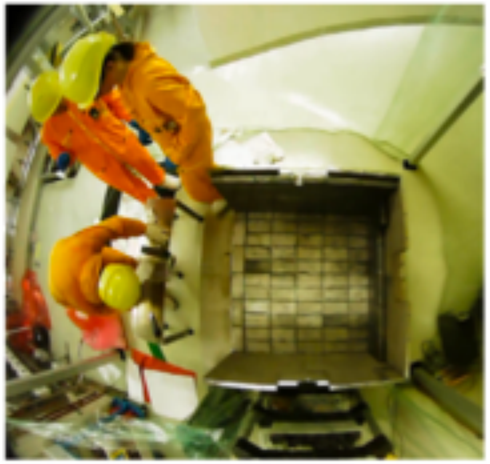
Start of the project summer 2016

Test Assembly and Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

installation @ Brokdorf
→ full assembly
→ commissioning



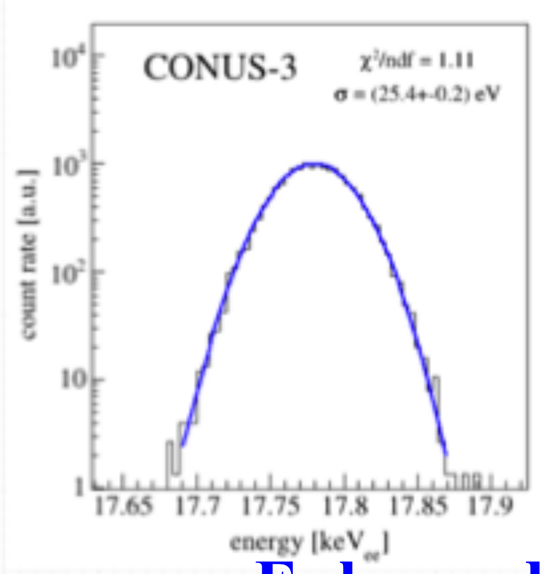


Energy Resolution

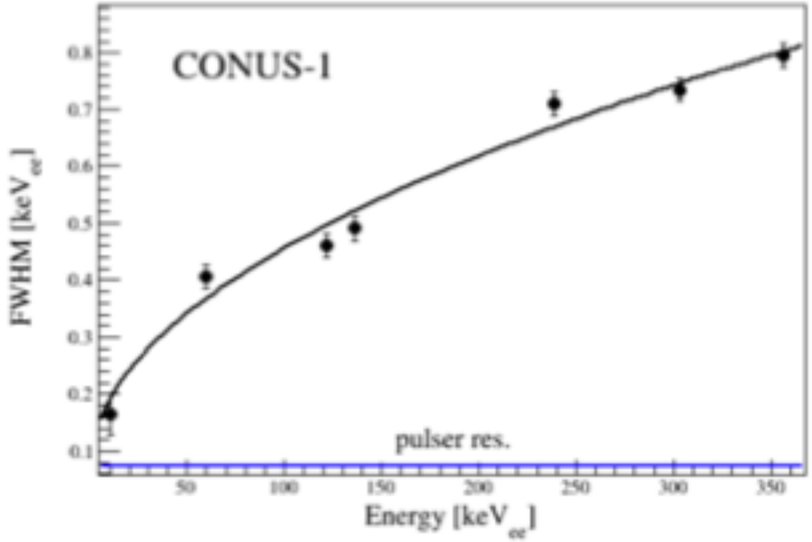
Commissioning @ MPIK

- pulser resolution

Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	74±1
CONUS-2	75±1
CONUS-3	59±1
CONUS-4	74±1



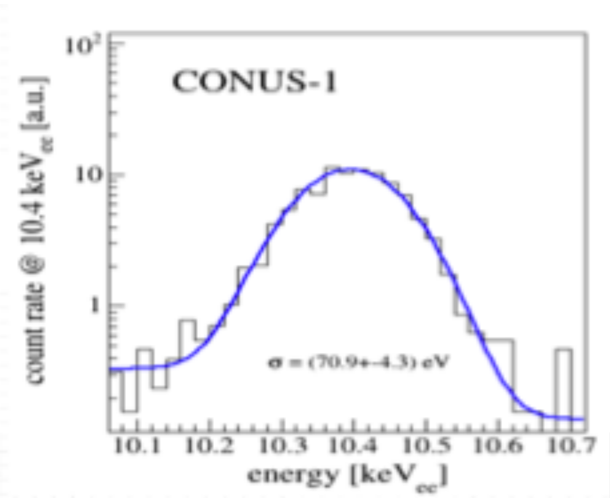
- energy resol. vs energy

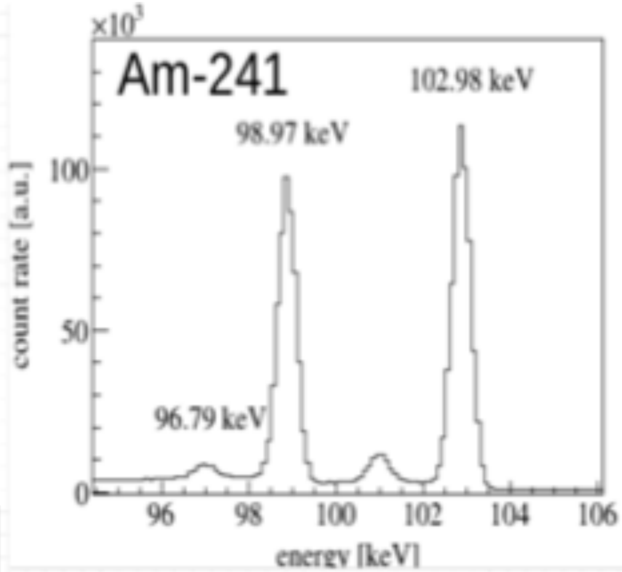


all within specs
moise edge ≈3xFWHMP

- Enhanced gamma-line separation

- X-ray peak resol. :

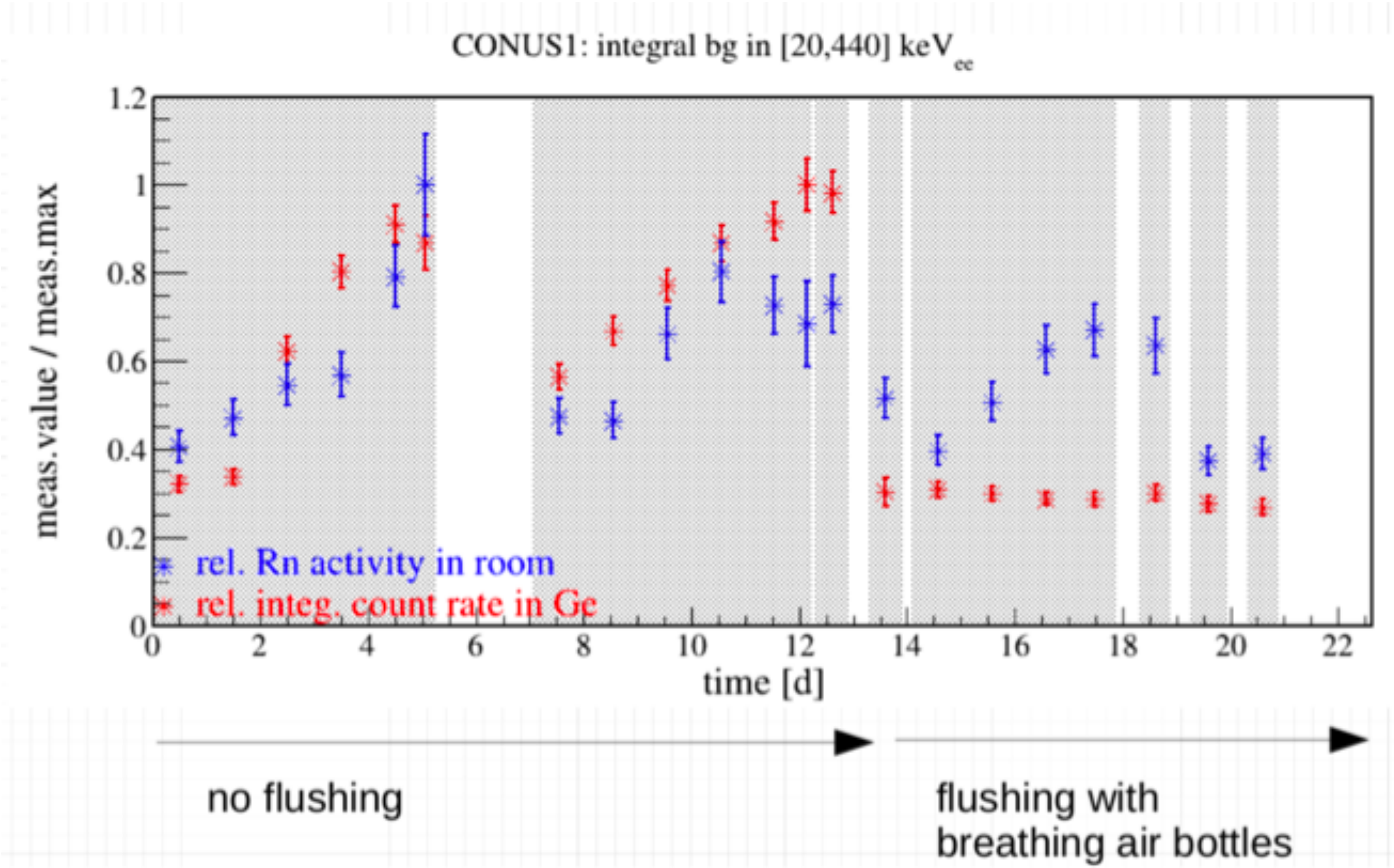




→ background analysis
→ detector characterisation
(e.g. active volume via
Am-241 source) ...
→ energy scale calibration

Radon Mitigation @ Reactor Site

radon at reactor site: closed room, thick concrete walls ➔ 100-300 Bq/m^3
counter measure: hermetical sealing + flush with breating air bottles ~1 l/min



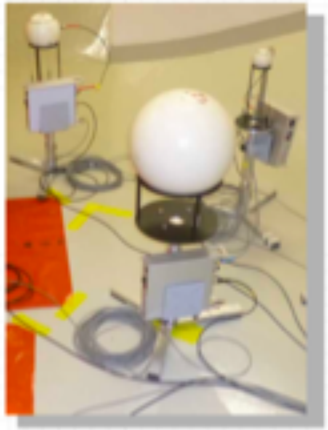
Neutron Spectroscoy @ Reactor Site

Potential neutron background: Ge recoils from fast neutrons mimic CEνNS signals

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

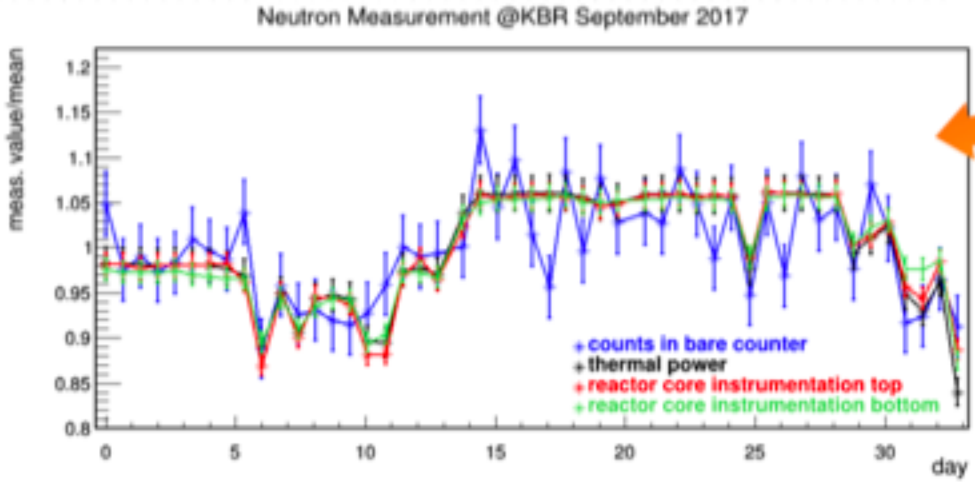
troublesome

} Outside CONUS shield →



Neutron spectrometry on-site with **NEMUS** by PTB [7]

Results from n measurements at experimental site:



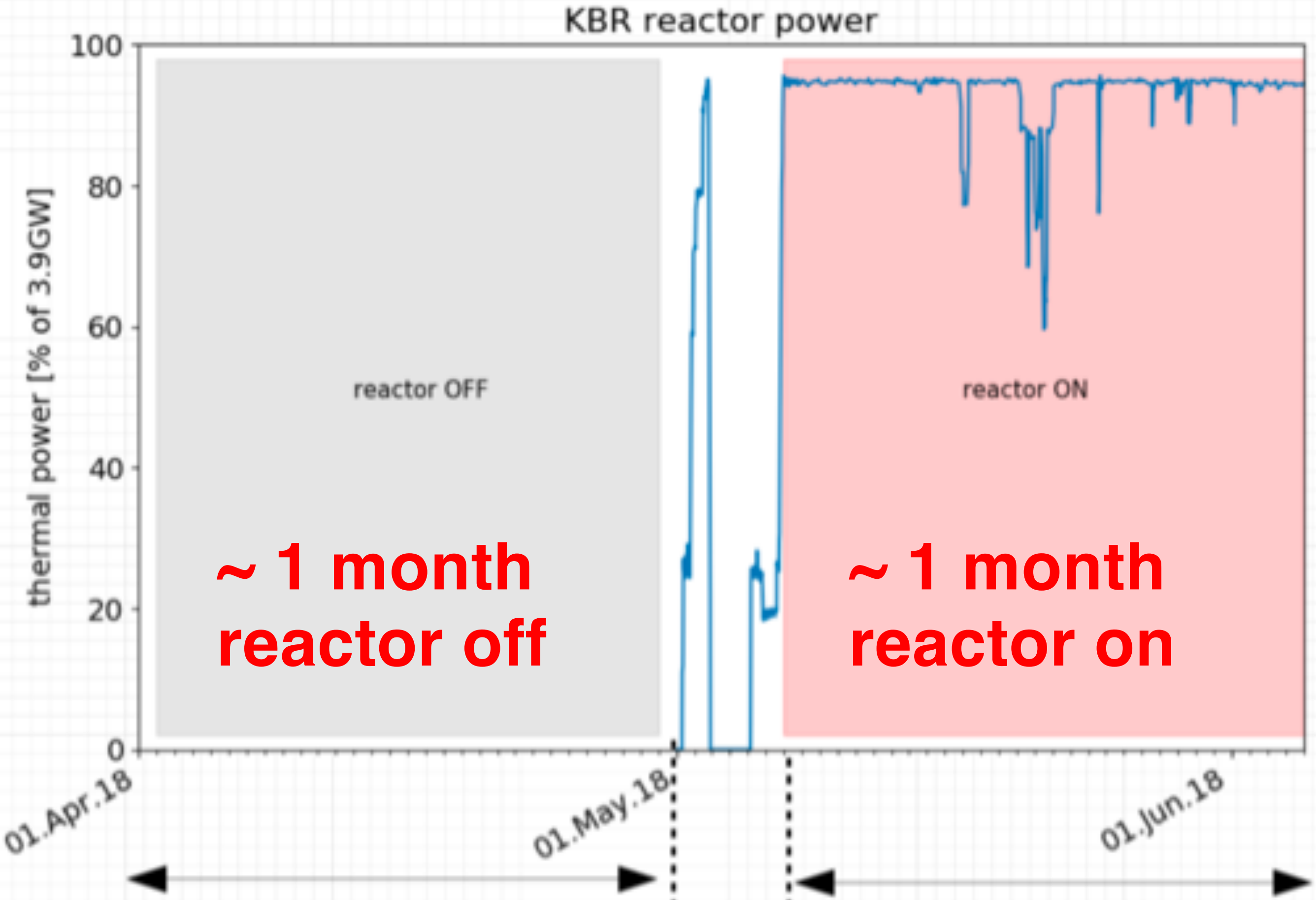
1. **Neutron field** highly thermalized (>80%), correlated with thermal power
   → fully absorbed by B-PE layers (MC)
2. Residual fluence:
   - if at all – epithermal from reactor
   - cosmic 100 MeV n: negligible

   → **reactor-correlated fast n** inside shield **negligible**

Data Taking

Begin of data collection: April 1, 2018

Reactor thermal power:

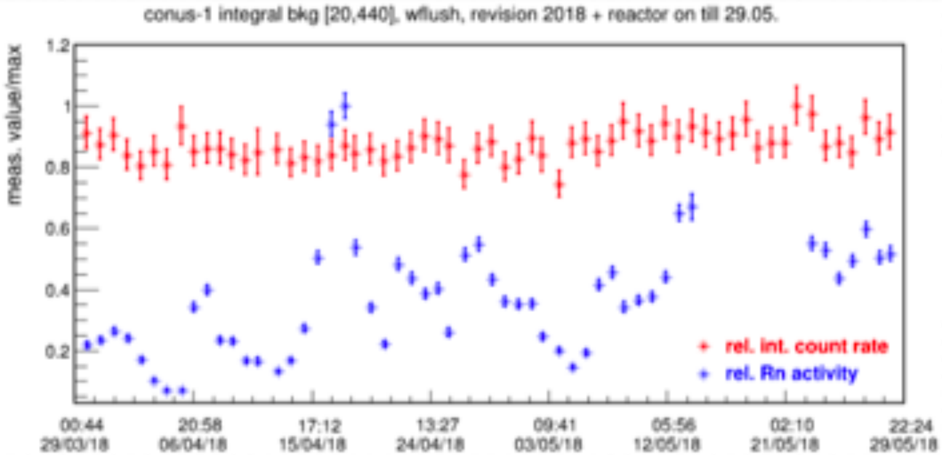


Datasets and exposure:

DS-1	DS-2
114.4 kg*d	~112.3 kg*d

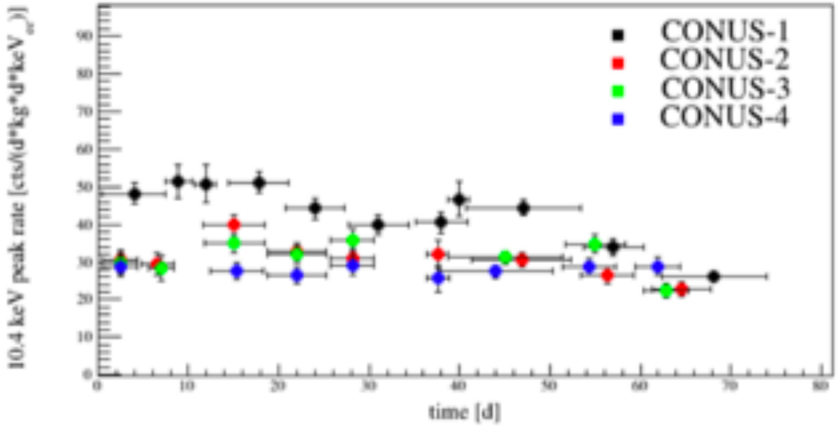
Background Stability in DS-1 & DS-2

1. Bg rate stability in [20,440] keV



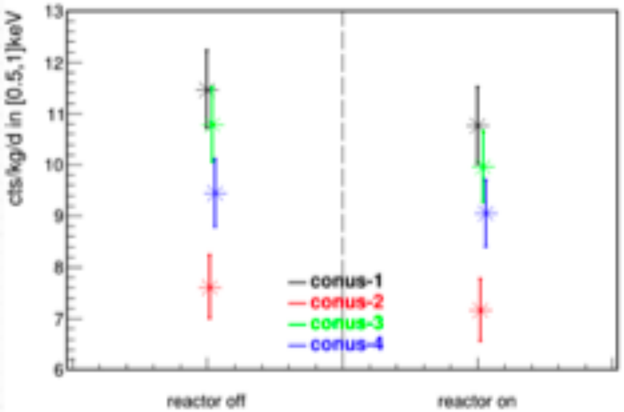
→ **Rn influence** at low energies: negligible

2. Rate stability of Ge line at 10.4 keV

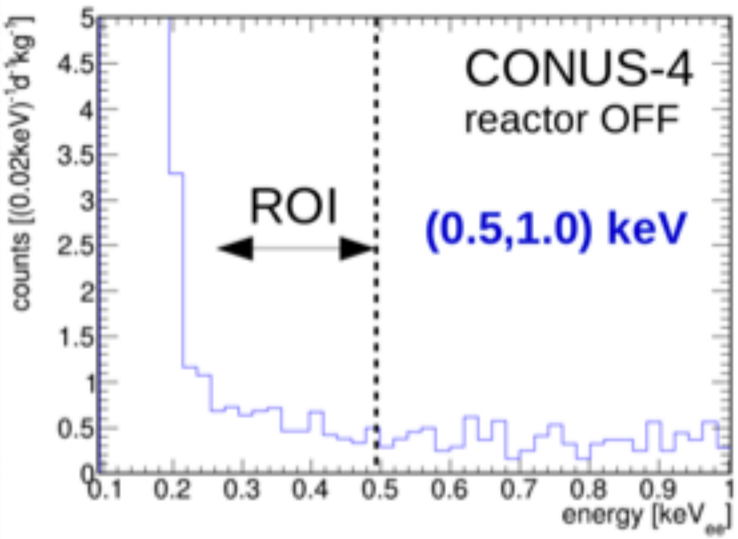


→ **Rate:** C2-C4 ~const, C1 small decrease

3. Bg stability in interval (0.5,1.0) keV



Due to slow pulses, Compton, ..



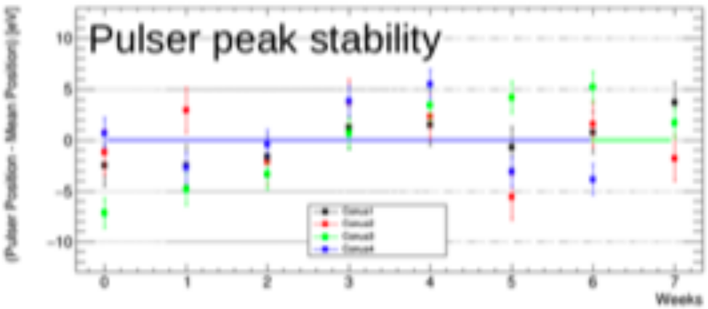
→ **Rate:** C2-C4 ~const, C1 small decrease

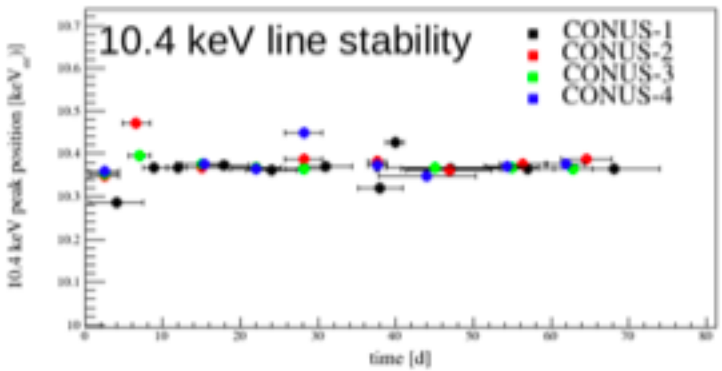
Detector Performance in DS-1 & DS-2

1. Pulser resolution

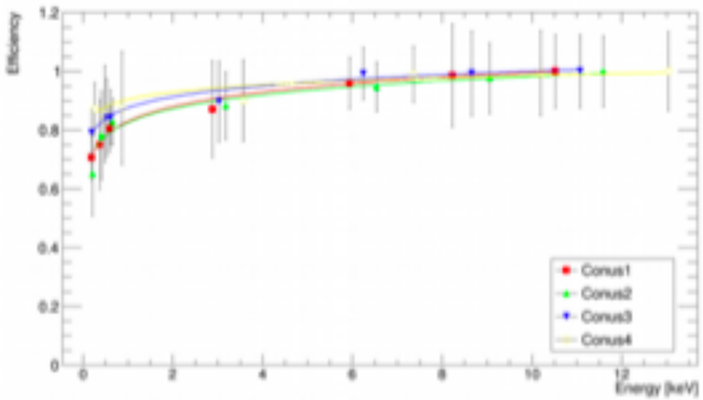
Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

2. Energy scale stability

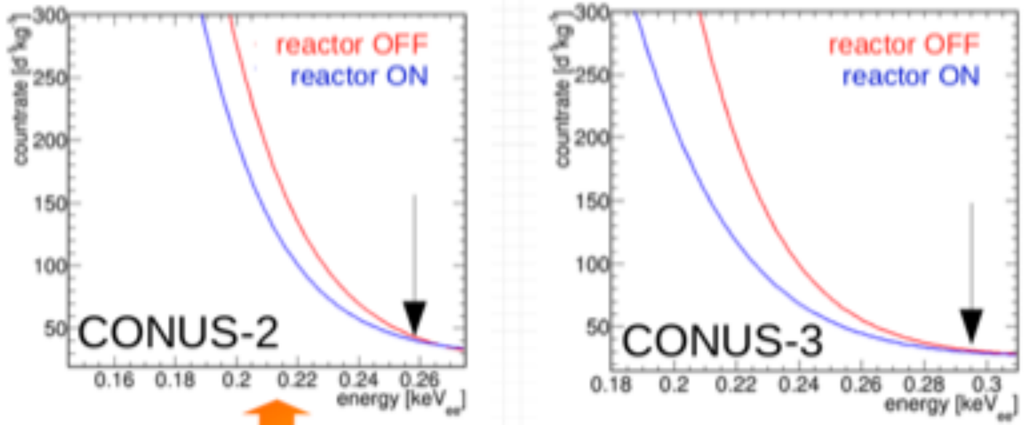




3. Trigger efficiency close to threshold



4. Noise threshold stability



CONUS-1/-4: similar shift for reactor ON/OFF

First quick Rate-Only Analysis

➔ **Talk by W. Maneschg @ NEUTRINO 2018**

Definition of cuts from reactor OFF time:
- energy scale calibration
- quality cuts (noise/spurious event red.)
- conservative ROI for CEνNS window
  (individual for every detector)

Definition of efficiencies:
- active volume: (96+-2)%
- muon AC ind. trg. Efficiency: (98+-1)%
- threshold trg. Efficiency
  (individual for every detector)

Rate comparison (all detectors):

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	2.4 σ	2.3 σ

Some systematics still under study

(*) Including stat. uncertainty and above efficiencies

➔ **observe excess which matches expected CEνNS range**

Future: CONUS100

Upscaling to 100kg ➔ very interesting Potential
high statistics ➔ precision ➔ 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	$2*10^{-3}$

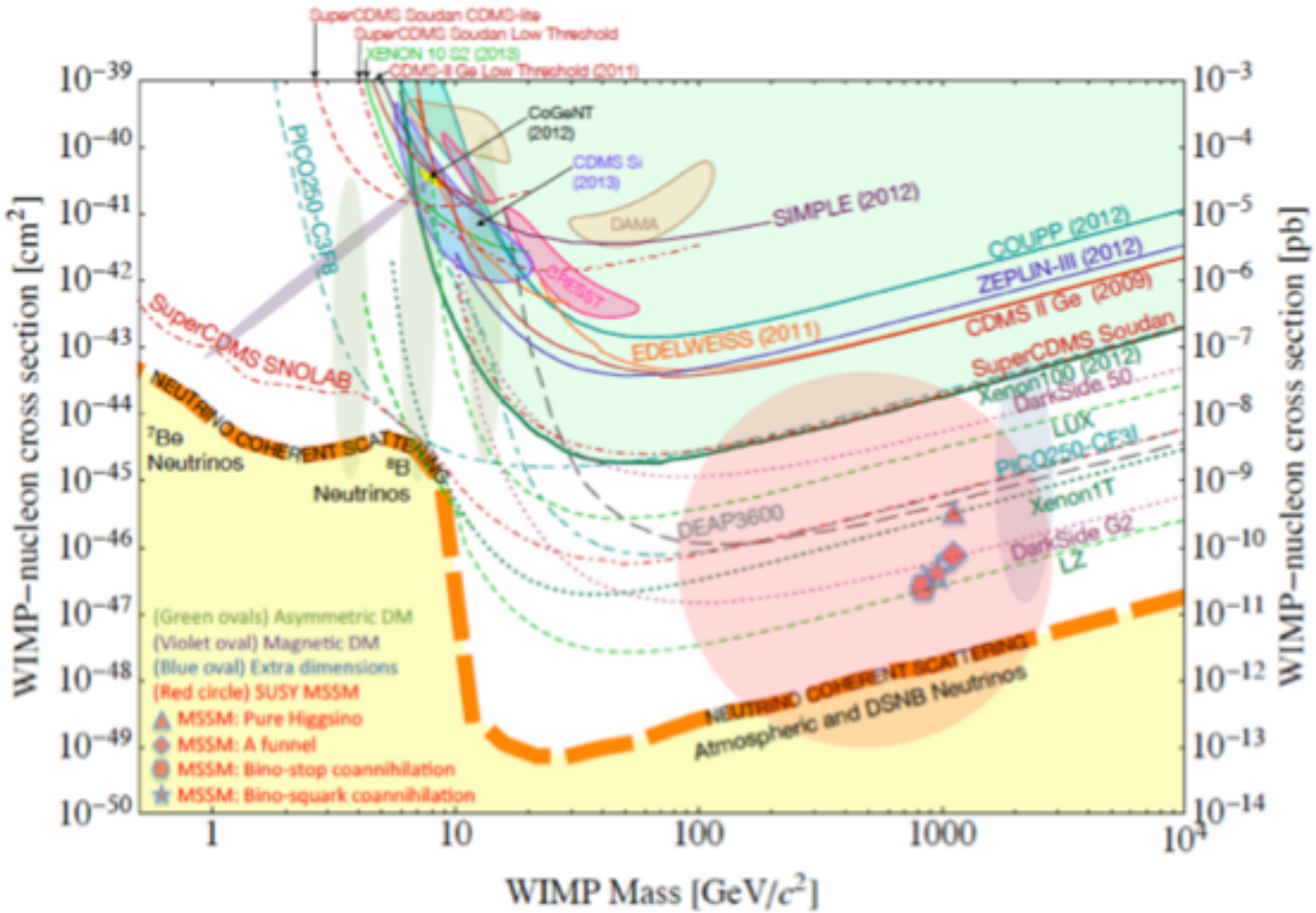
BSMsens=ΔS/S
S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

CEνNS becomes a Tool for other Topics

DM connection:

1) DM experiments assume coherent DM scattering → test of CνS
2) Neutrino floor of direct DM experiments *IS* due to CνS

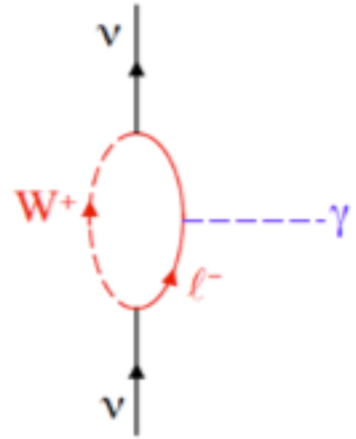


Searches for new Physics: Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:

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

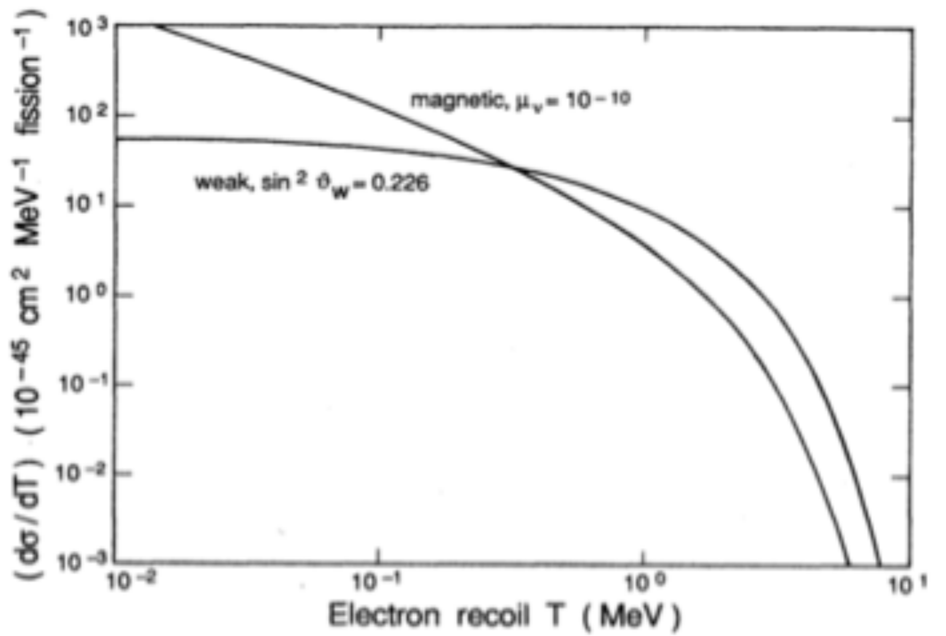
Majorana: $$\mu^M_{ll'} \lesssim 4 * 10^{-9} \mu_B \left(\frac{M^M_{ll'}}{\mathrm{eV}}\right) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \left|\frac{m_\tau^2}{m_l^2 - m_{l'}^2}\right|$$



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

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

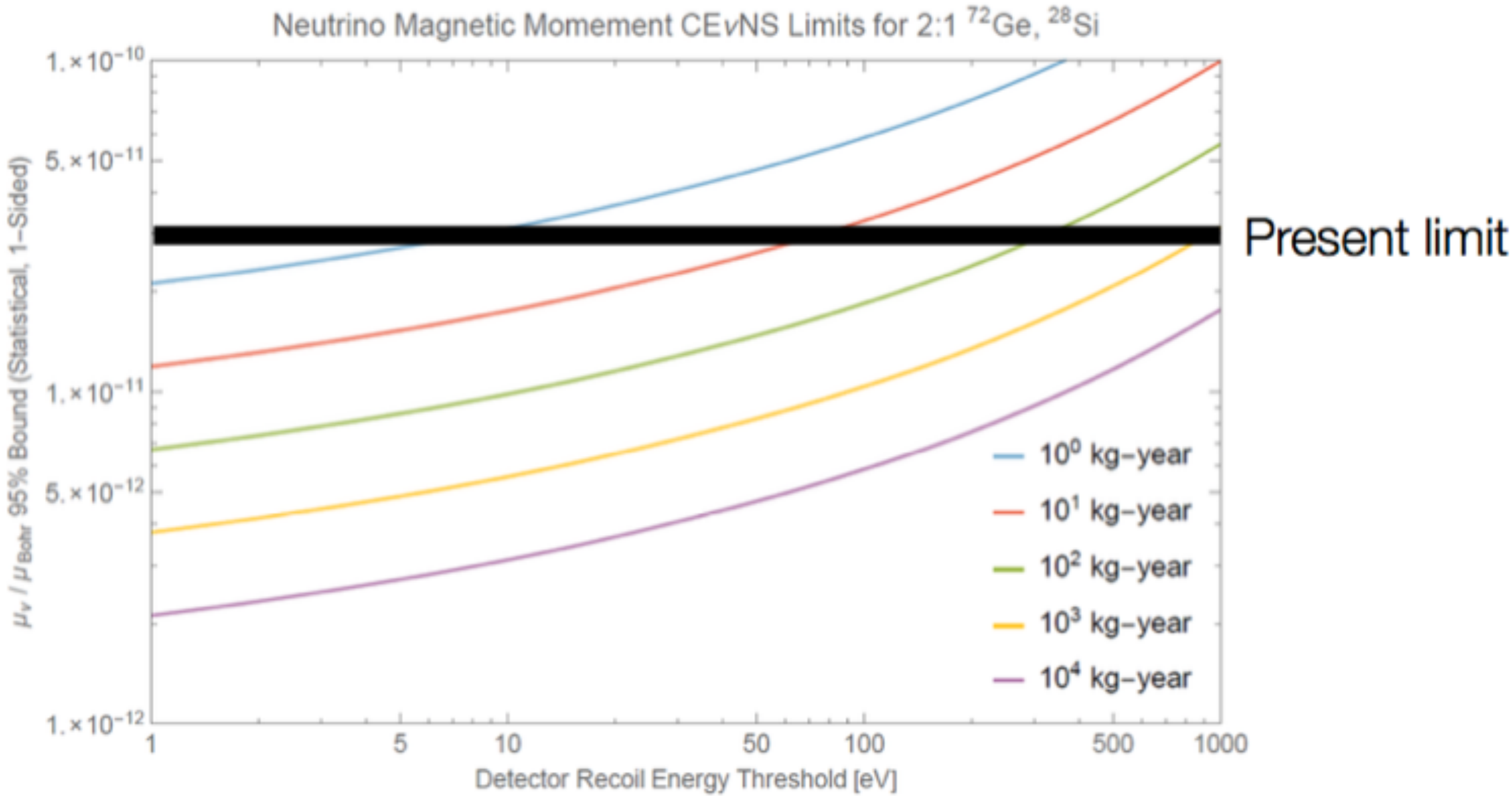
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$



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

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

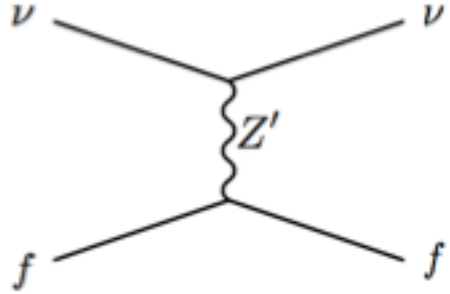
Potential for Magnetic Moments



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

Searches for new Physics: 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

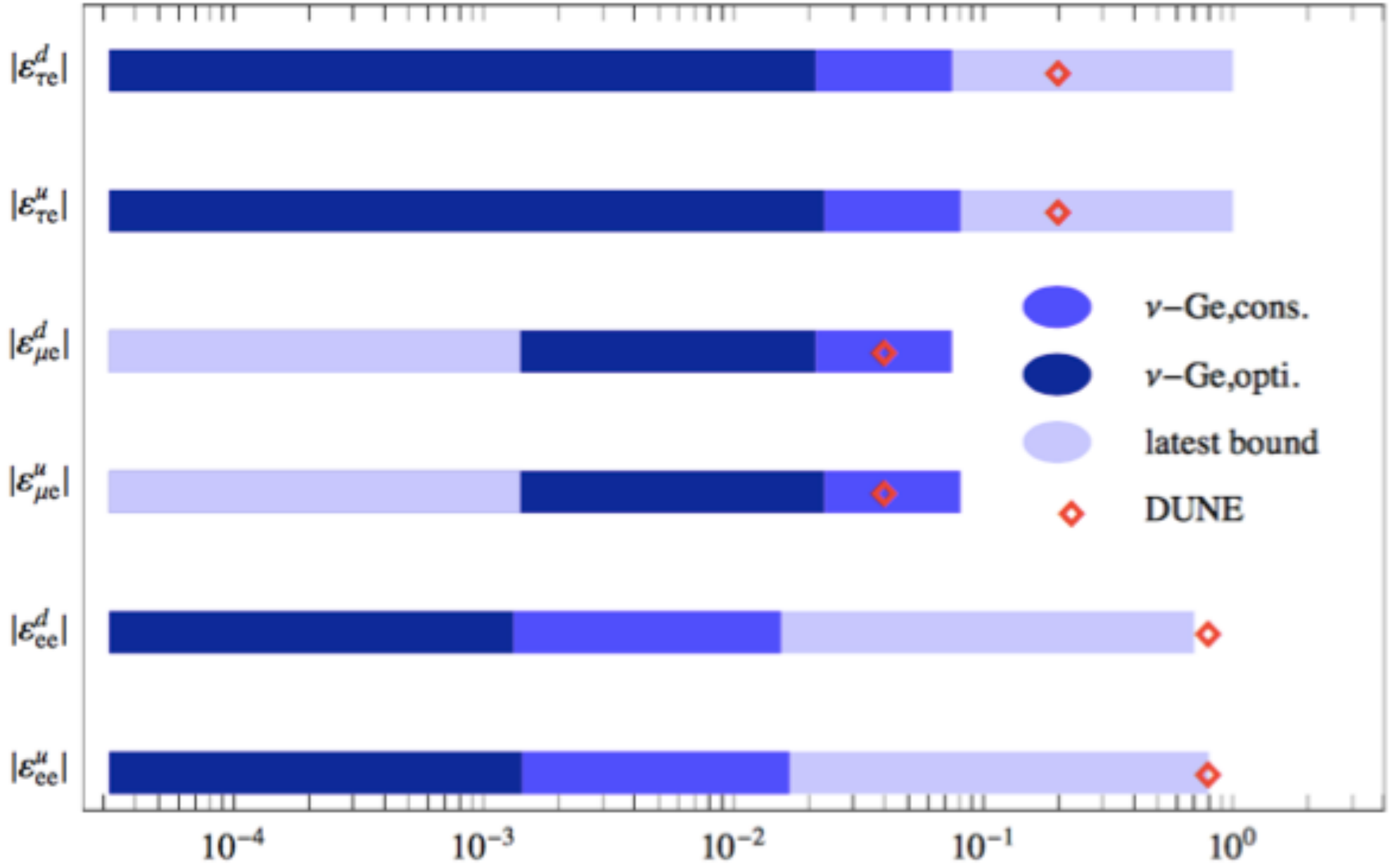
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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

NSI-Potential

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu



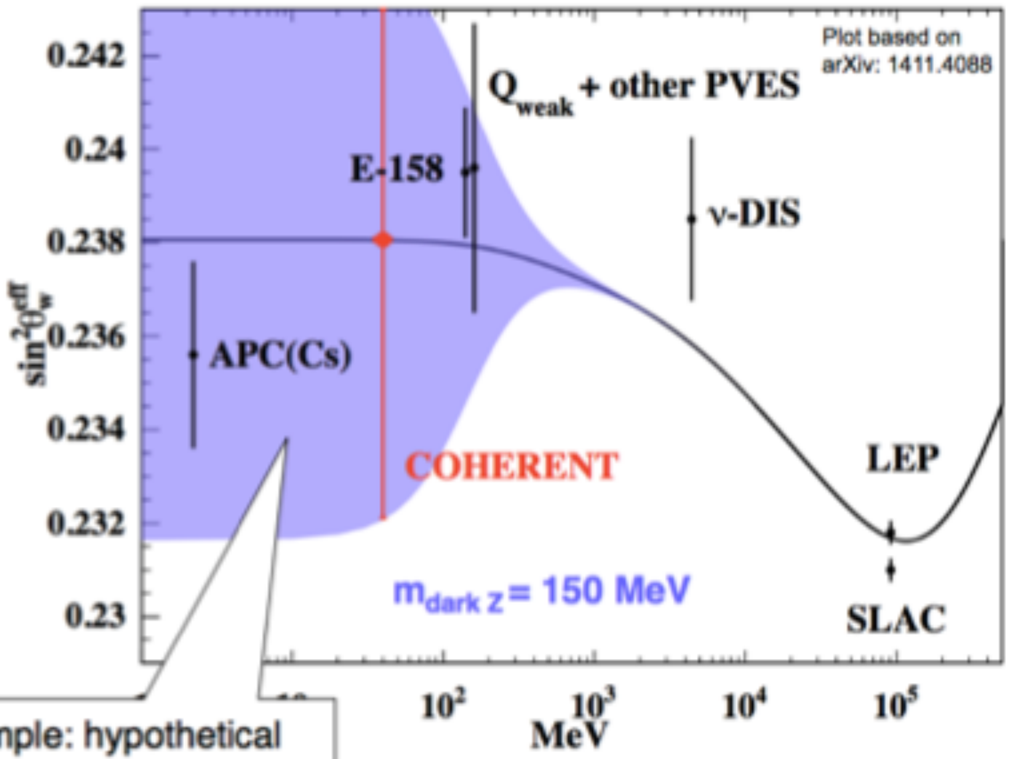
~10 TeV

~TeV

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

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ; **deviation probes new physics**

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}\left(N - (1 - 4\sin^2\theta_W)Z\right)^2$$



Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

BSMsens =

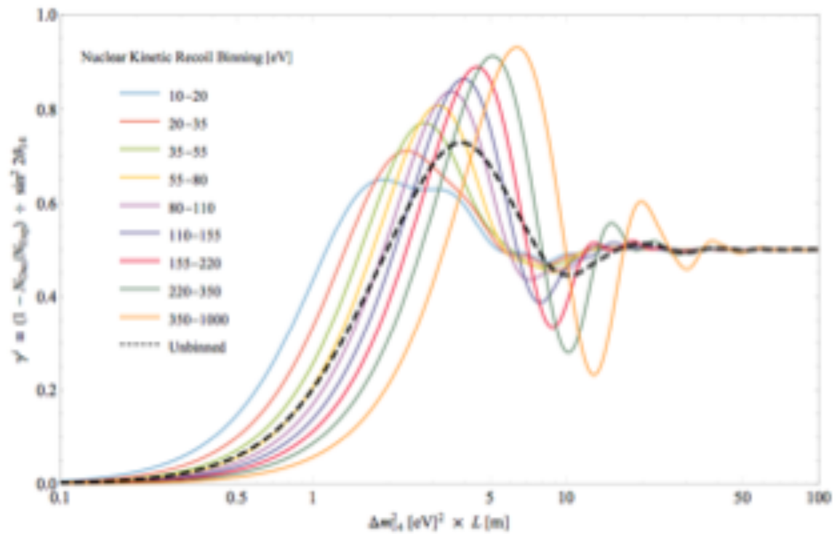
10^{-3} ➔ $\Delta\sin^2\theta_W = 0.006$

10^{-4} ➔ $\Delta\sin^2\theta_W = 0.0006$

slide adopted from K. Scholberg

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…

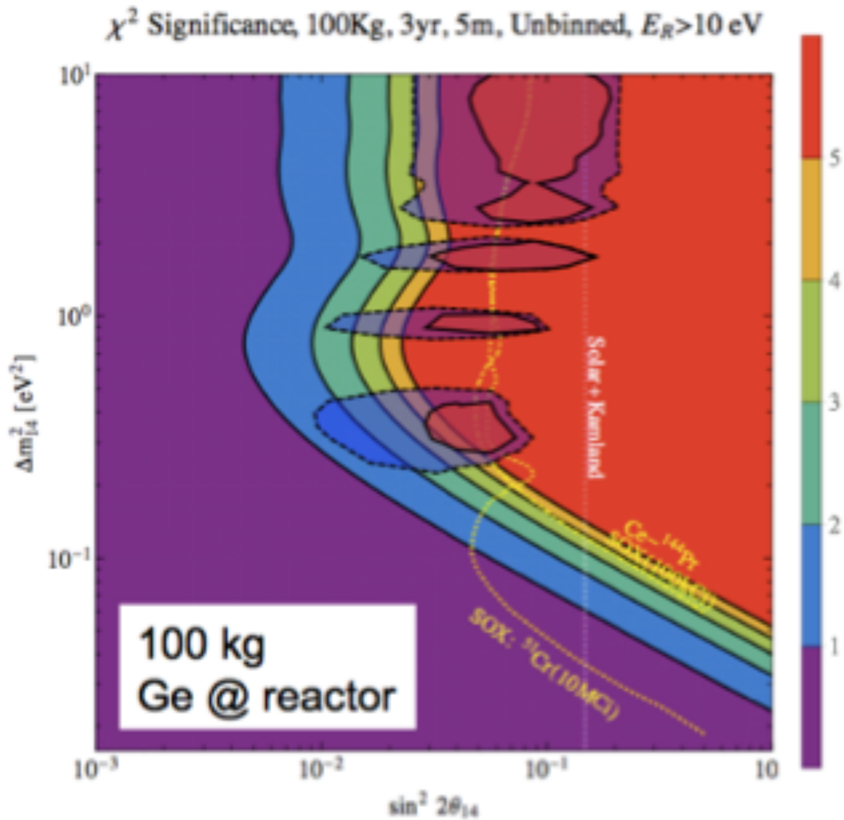


Dutta et al. 1511.02834

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

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

➔ time scales compared to other projects



B. Dutta et al, arXiv:1511.02834

Nuclear Physics with coherent Scattering

Remember: DAR sources close to decoherence ↔ combine with reactor measurements

we can start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105

K. Patton et al., PRC86 (2012) 024612

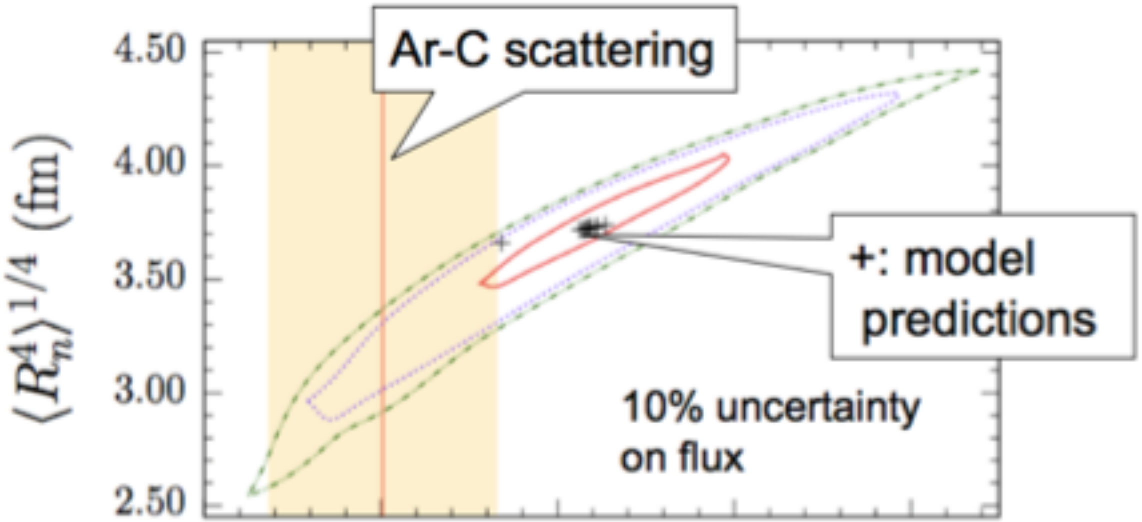
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

Form factor: encodes information about nuclear (primarily neutron) distributions

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

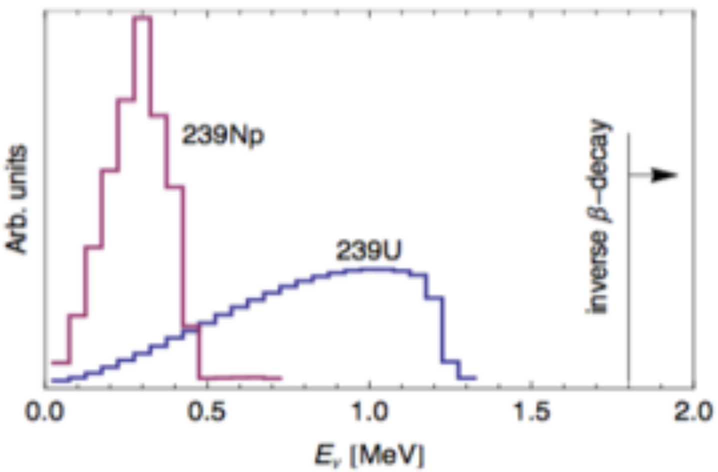


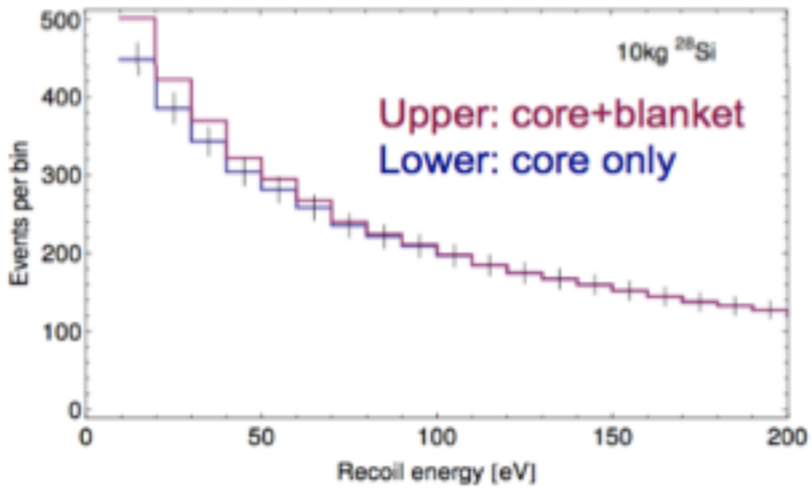
Nuclear Safeguarding

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

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

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





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

Summary

- **CEνNS was 1st observed by COHERENT at E_ν ~ 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**