The CONUS coherent Neutrino scattering Experiment

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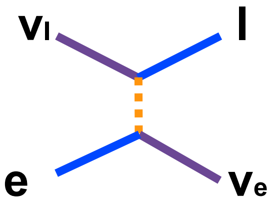
Bridging the Standard Model to New Physics with the Parity Violation Program at MESA

23 April 2018 to 4 May 2018

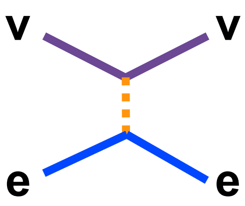
Coherent Neutrino Scattering

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

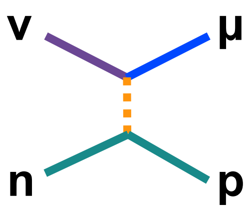
- **5 have already been detected**



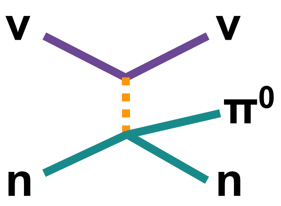
inverse muon (tau) decay



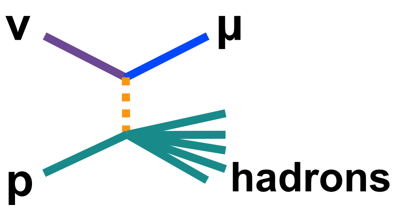
elastic electron scattering



(quasi) - elastic nucleon scattering

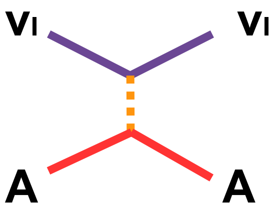


nuclear excitation and resonant production



Deep inelastic scattering and jet production

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



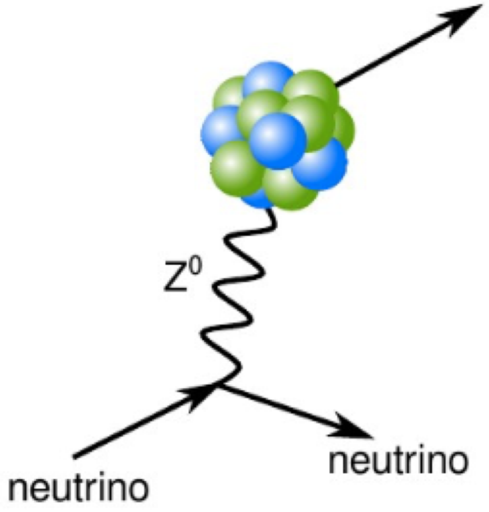
Coherent neutrino-nucleus scattering: CEνNS

➔ **conceptually important**
➔ **useful method 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



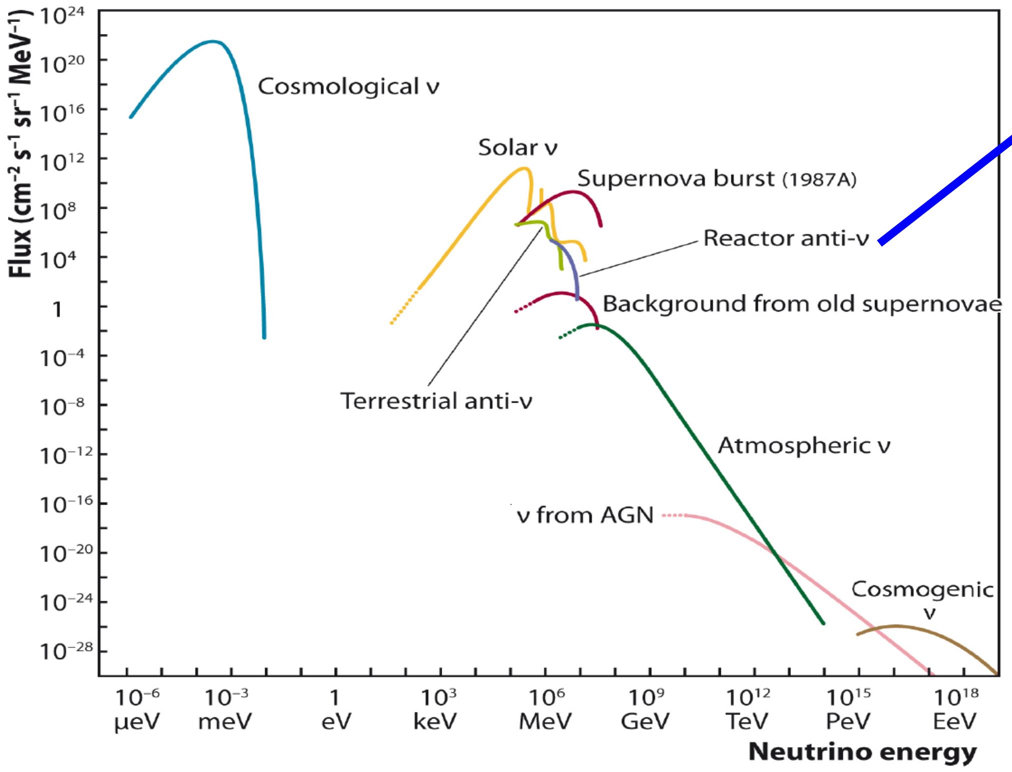
$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim \mathbf{N}$$

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

$N \simeq 40$ ➔ $N^2 = 1600$ ➔ 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



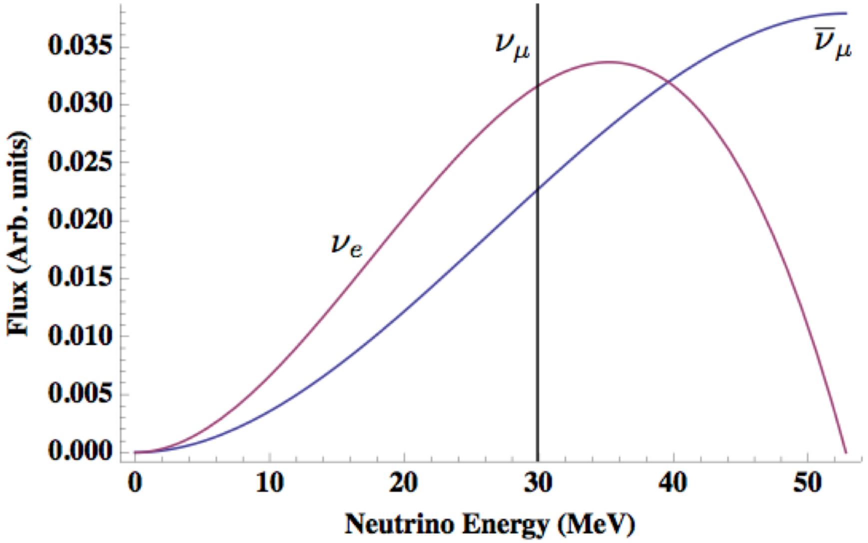
10 GW at a distance of 150 km

close to power reactors:
ca. 4% of the thermal power P
3.9 GW → ca. 150 MW in ν's
dilution by distance R
flux $\Phi \sim P/R^2$
ca. 150 kW/m² at 10m distance

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



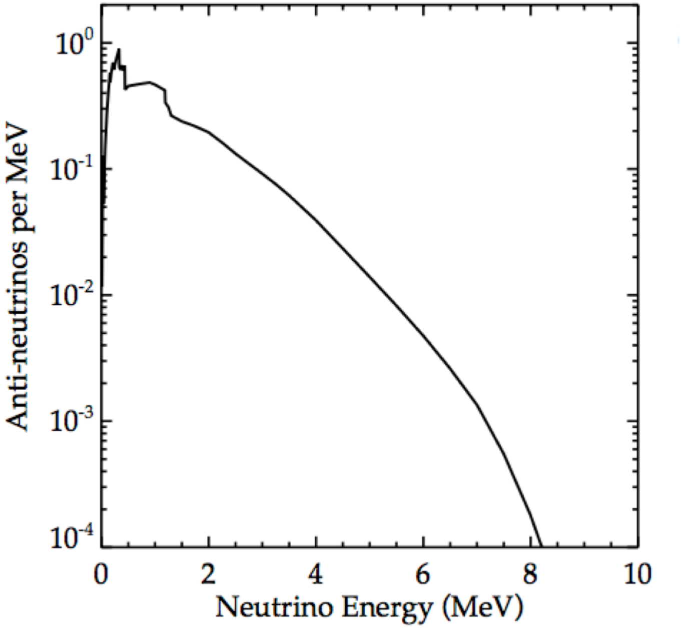
Low energy ν's from accelerators:

π-decay-at-rest (DAR) ν source

Different flavors produced

relatively high recoil energies

➔ close to de-coherence



Reactors:

Lower ν energies than accelerators

Lower cross section

Different flavor content

implications for probes of new physics

Vogel et al. 1981, Kopeikin 2012

First Observation of CEνNS

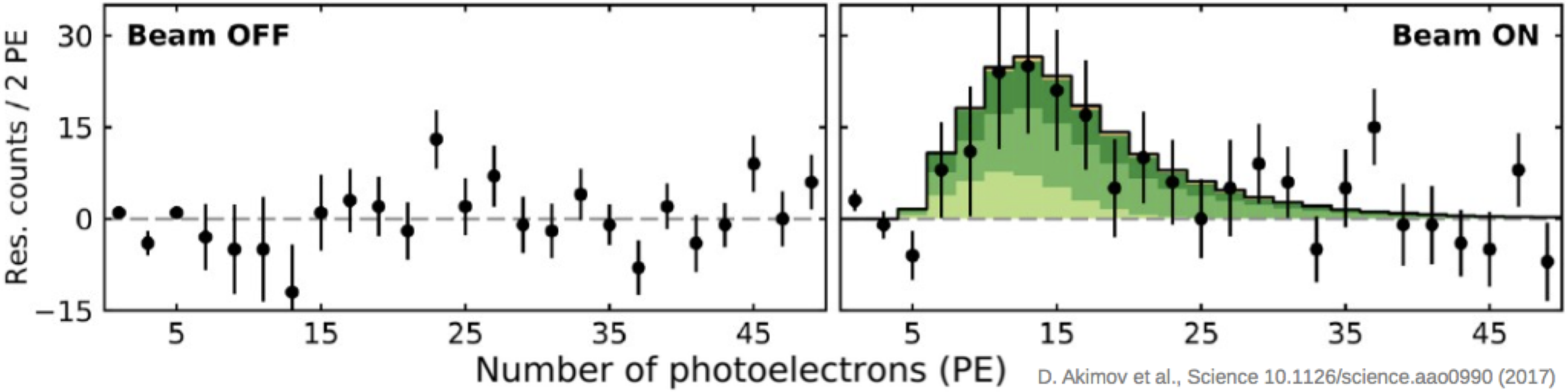
COHERENT experiment (stopped π beam 30-50 MeV neutrinos)

- 4 different detector technologies
  - 14 kg of **CsI** scintillating crystals
  - 35 kg single phase LAr detector
  - 185 kg NaI scintillating crystal
  - 10 kg HPGe PPC detectors

- SNS source with $\bar{\nu}$ flux of $4.3 \cdot 10^7$ $\nu/\text{cm}^2/\text{s}$ @ 20m

First COHERENT result July 2017

- 15 month of live-time accumulated with CsI[Na]
- 6.7 σ significance for excess in events, with 1 σ consistency with the SM prediction



D. Akimov et al., Science 10.1126/science.aao0990 (2017)

see talk by K. Scholberg

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, H. Strecker, T. Schierhuber and V. Wagner
Max-Planck-Institut für Kernphysik, Heidelberg

K. Fülber and R. Wink
Preussen Elektra GmbH, Kernkraftwerk Brokdorf

Experimental Requirements

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

- measure nuclear recoil energy T

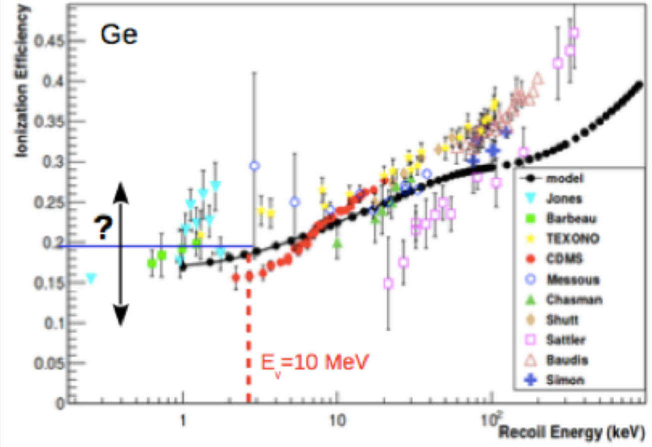
  for E_ν = 10 MeV ➔ $T_{max} \simeq$ 3 keV (in Ge)

- energy loss due to quenching (Lindhard)

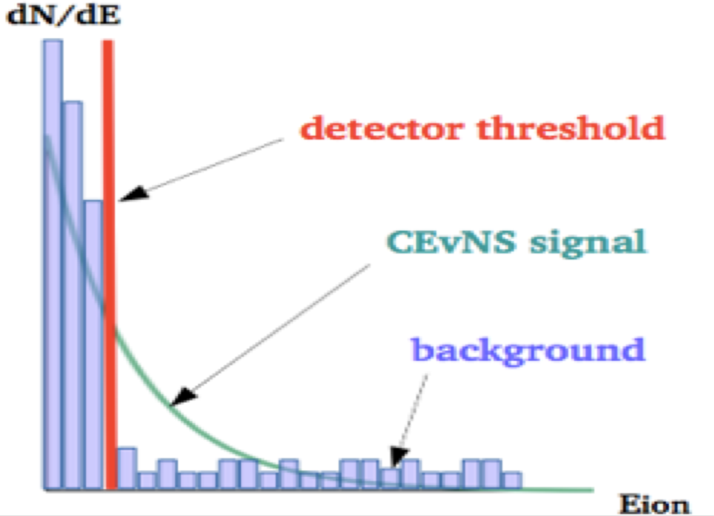
  ➔ Quenching Factor (QF)

  QF down to 0.2 in Ge → 600 eV

  ➔ include systematic uncertainty



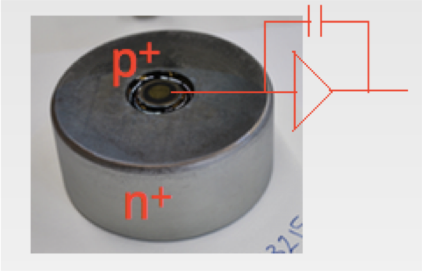
D. Barker, D.M. Mei, 2012 [1]



detection of CEνNS signal:

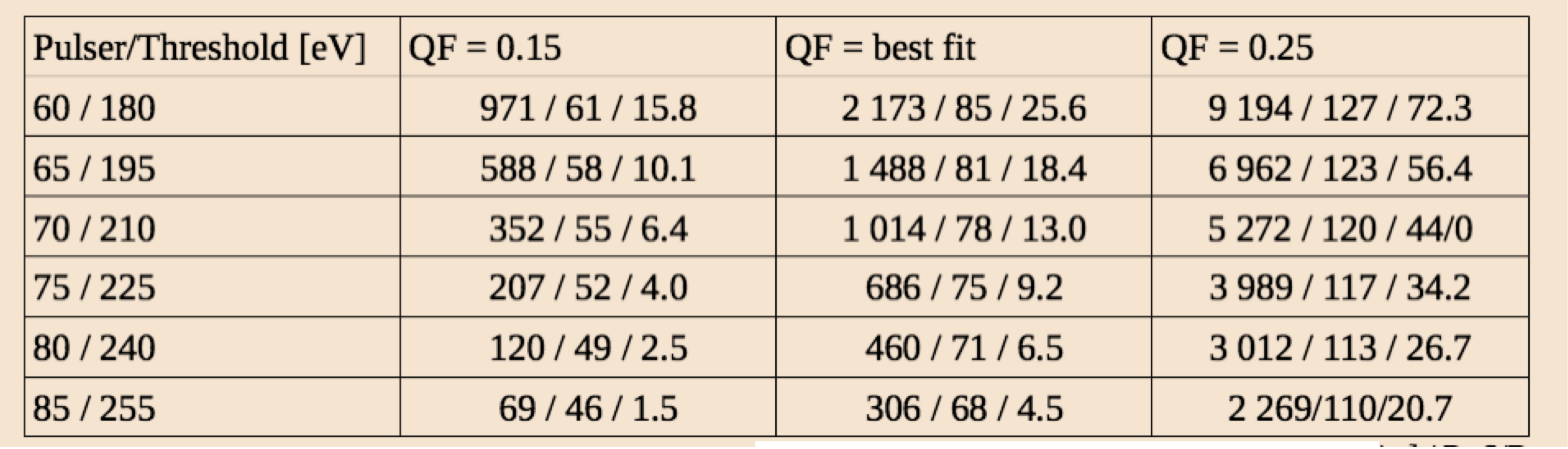
- high ν flux
- low threshold (sub keV)
- low background
  - radio-pure materials
  - "virtual depth" shielding

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

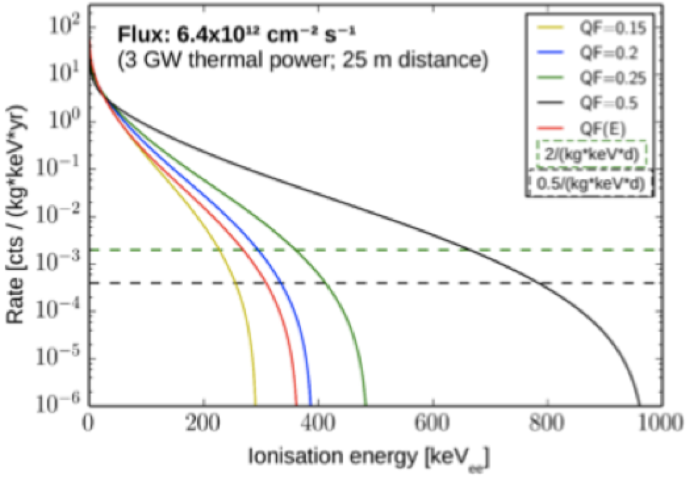
S[1/yr] / B[1/ye] / R=S/B



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 Source

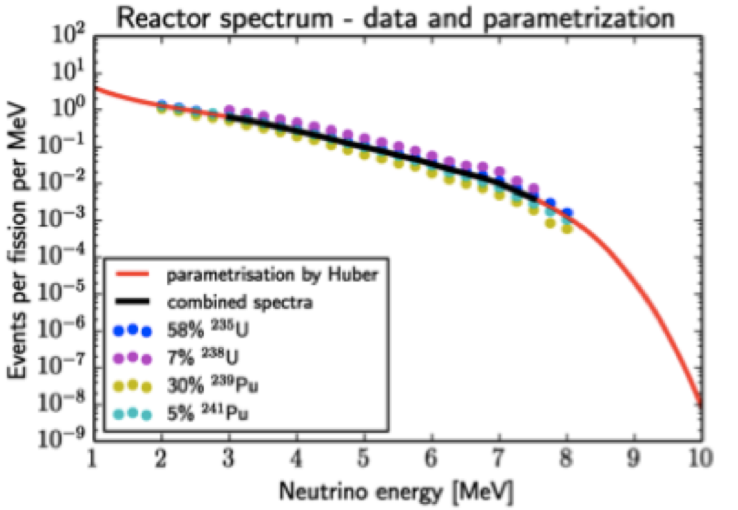
The Brokdorf (Germany) power plant:

thermal power 3.9GW_{th}
detector @ d=17m
➔ ν flux: $10^{14}/cm^2/s$
ca. 50 kW/m^2 in ν‘s
very high duty cycle

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

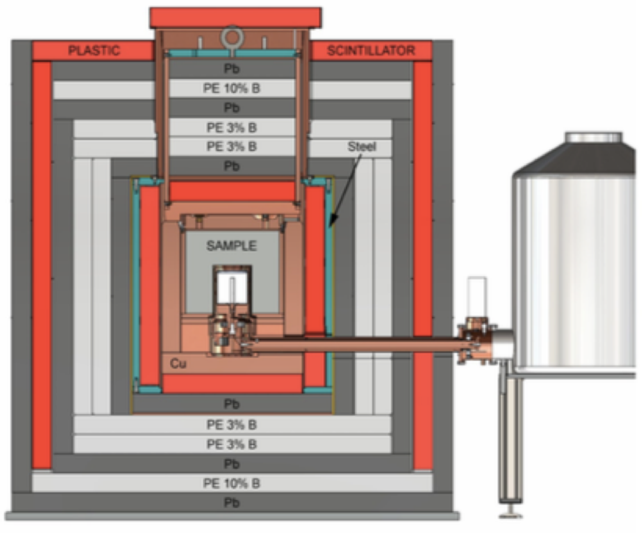
access during operation
overburden 10-45 m.w.e
measurements of neutron background
ON/OFF periods ➔ backgd. measurement

https://de.wikipedia.org/wiki/Kernkraftwerk_Brokdorf



Parametr./Data: from P. Huber [2] and N. Haag [3]

The GIOVE active Shield



coaxial HPGe detector (m_{act} = 1.8 kg)

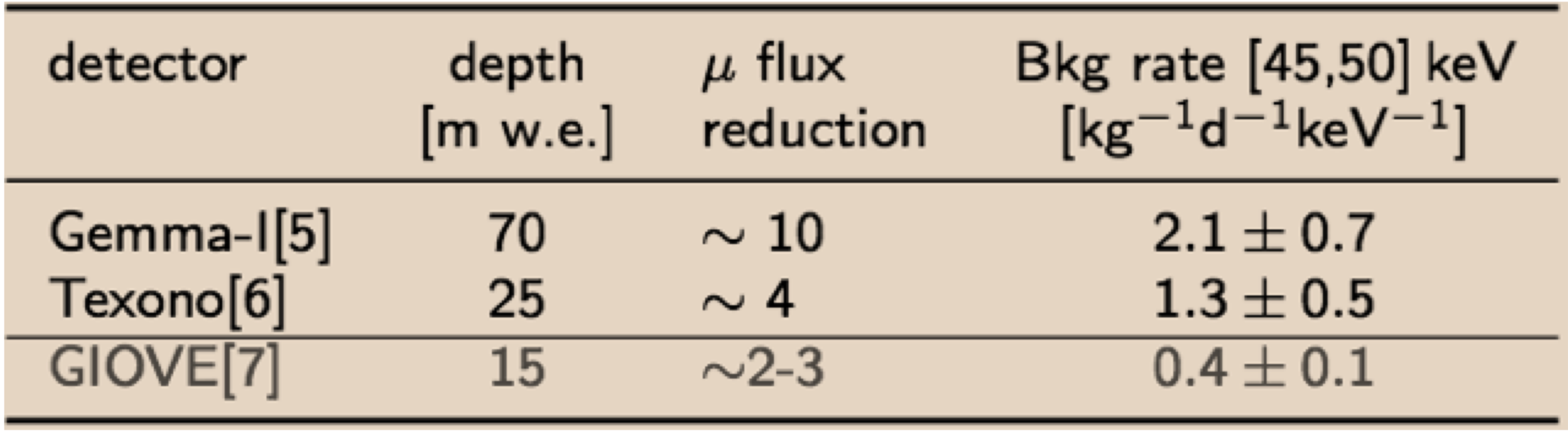
radio-pure passive shielding:

- Pb and Cu against external radioactivity
- borated PE to capture and moderate neutrons

active veto:

- plastic scintillators with PMTs
- 99% muon veto efficiency (dead time ~2%)

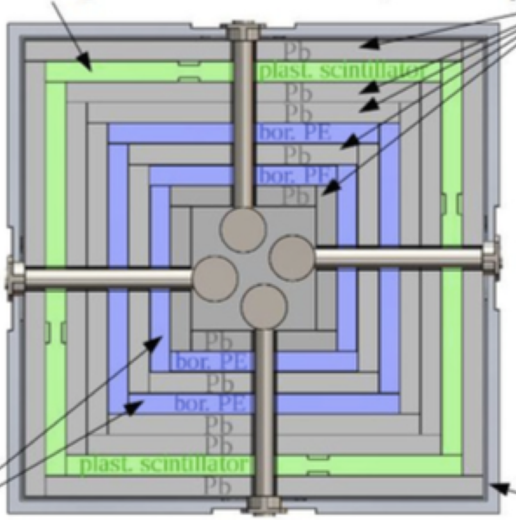
main purpose: material screening



detector	depth [m w.e.]	μ flux reduction	Bkg rate [45,50] keV [$kg^{-1}d^{-1}keV^{-1}$]
Gemma-I[5]	70	~ 10	2.1 ± 0.7
Texono[6]	25	~ 4	1.3 ± 0.5
GIOVE[7]	15	~2-3	0.4 ± 0.1

➔ GIOVE: ``virtual depth‘‘ of several hundred meter

The CONUS Shield

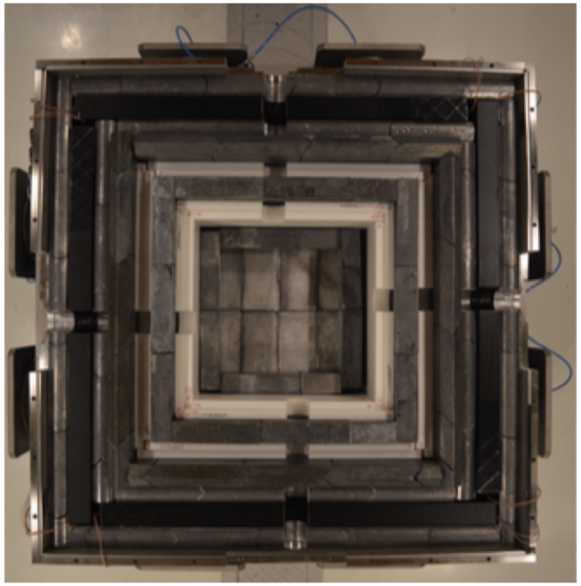


Active muon veto:
Plastic scintillator plates
with PMTs

Shield against nat. radioactivity:
Pb, inner layers low ^{210}Pb content

Steel cage

Moderate and capture neutrons:
Polyethylene plates with boron
from boron acid,
boron acid enriched in ^{10}B (equivalent to 3% nat. boron)



- **inner layer: Pb ⇒ suppress μ-induced bremsstrahlung continuum**
- **careful material selection (screening @MPIK & GeMPIs@LNGS)**
- **testing at Low Level Laboratory at MPIK (15 m w.e.):**
  - mechanical tests
  - muon veto performance (with coaxial high-purity detector CONRAD)
  - radiopurity of shield (with CONRAD)

Detectors

Low background - low threshold Ge detectors

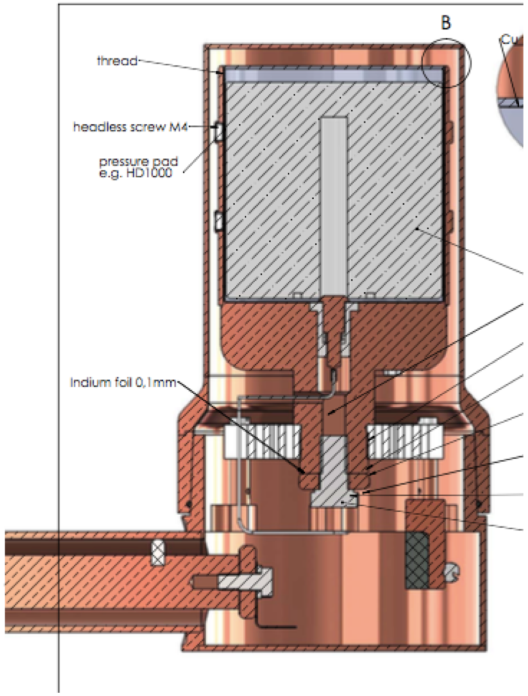
BEGe R&D @MPIK: Asterix & Obelix....

➔ kg-size SAGe detectors

PT-cooled (no LN; optimally adjustable T)

pulser resolution 70-85 eV, $E_{th} \simeq 240$ eV

CONUS: 4kg = 4x 1kg



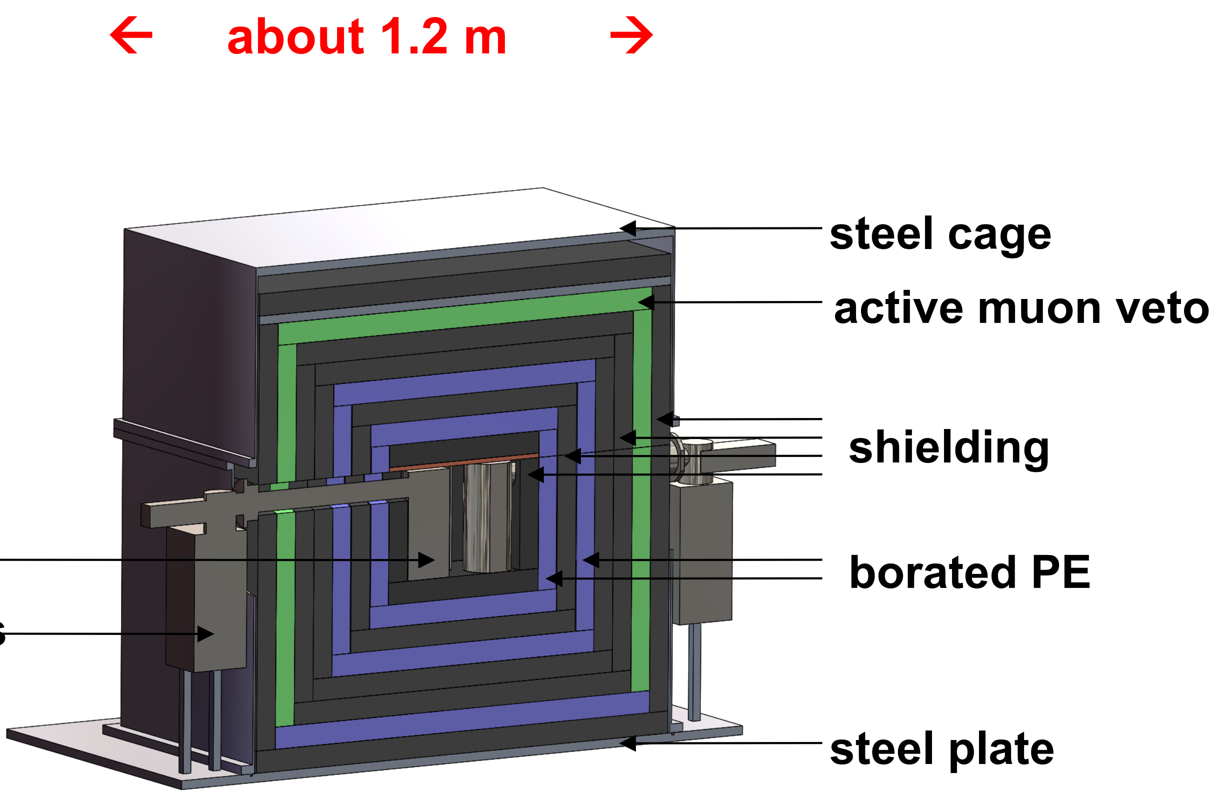
The CONUS Detector

Components:

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

➔ all ultra low background

- electronics and DAQ rack

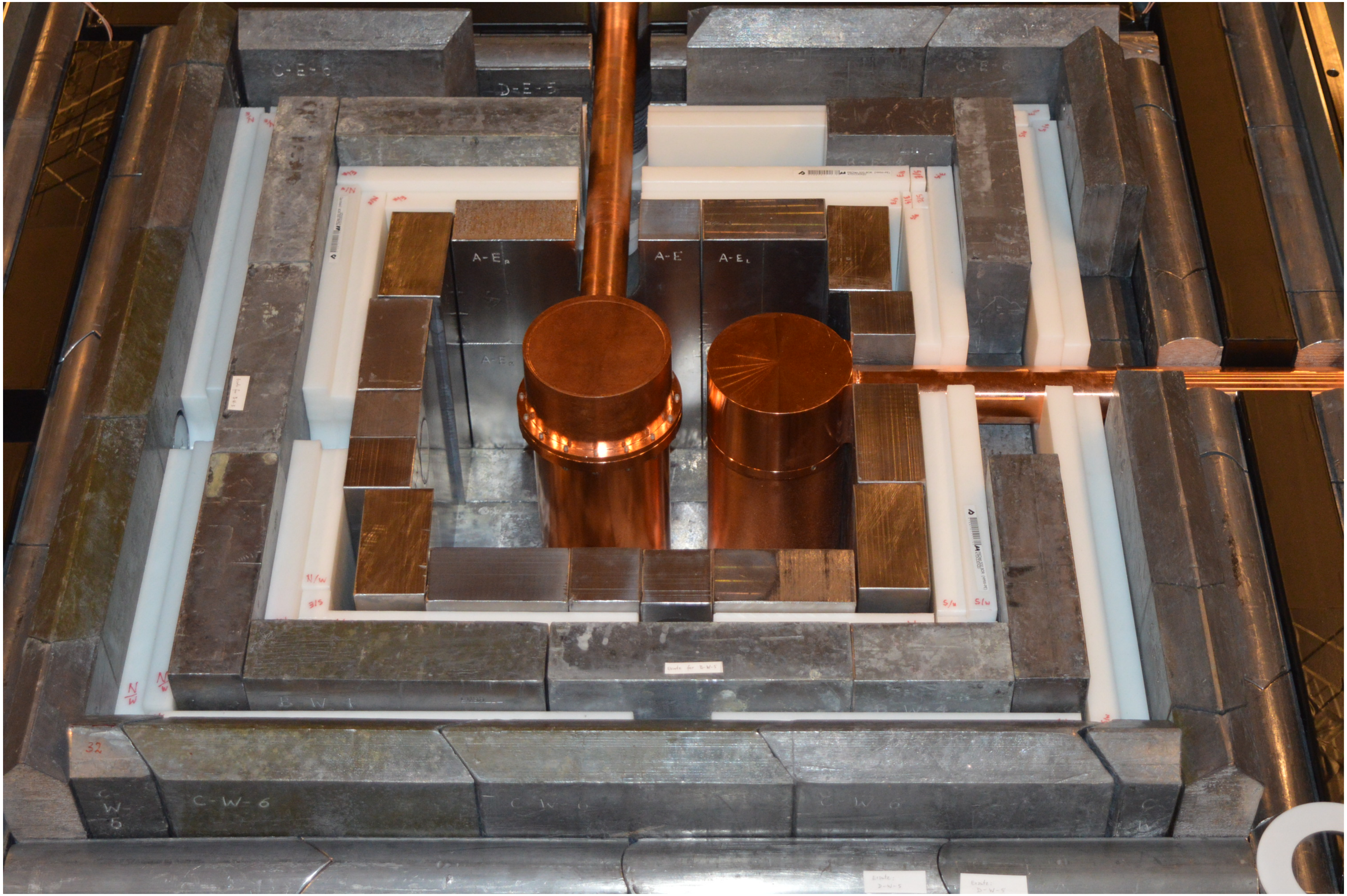


Successful combination of three essential improvements:

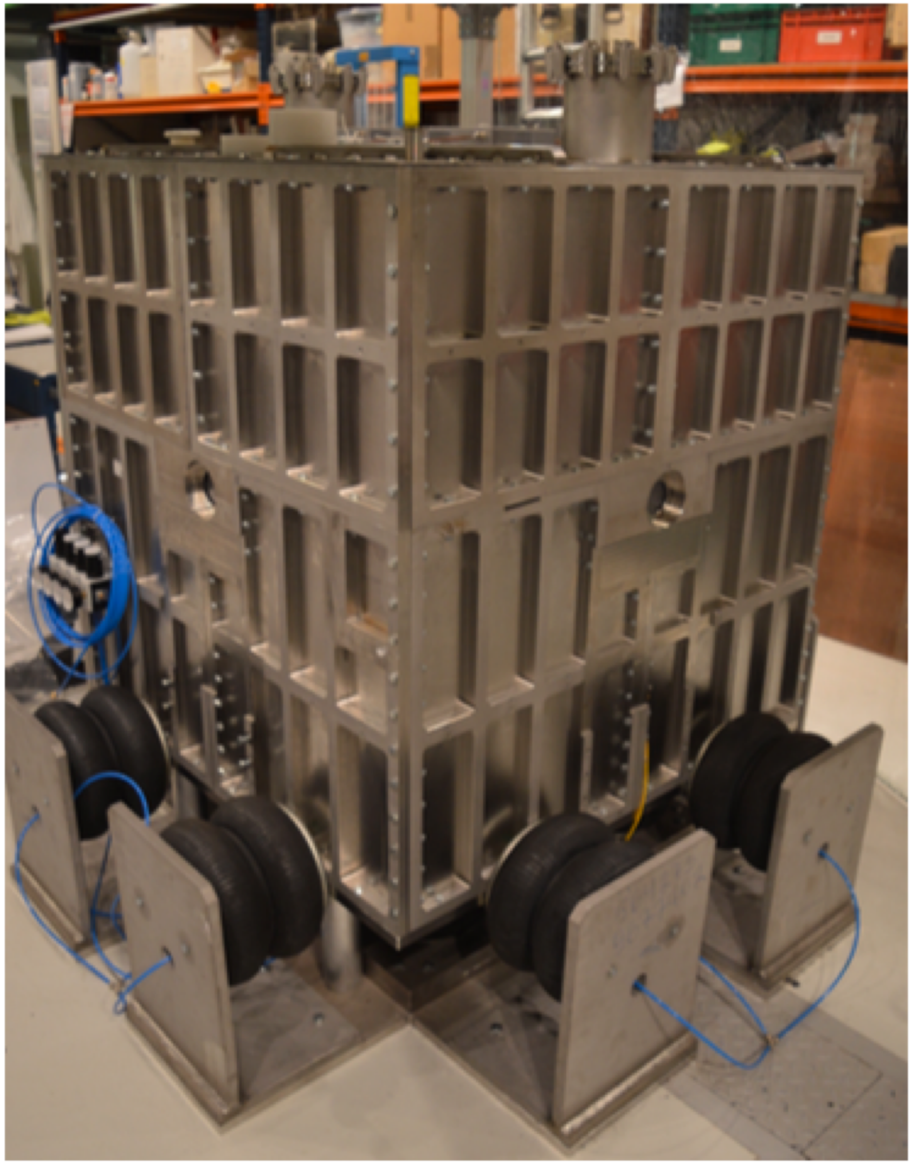
- new (best) active/passive shielding (GIOVE @ MPIK = “virtual depth”)
- new detectors with very low thresholds
- site with highest neutrino flux

Start of the project summer 2016

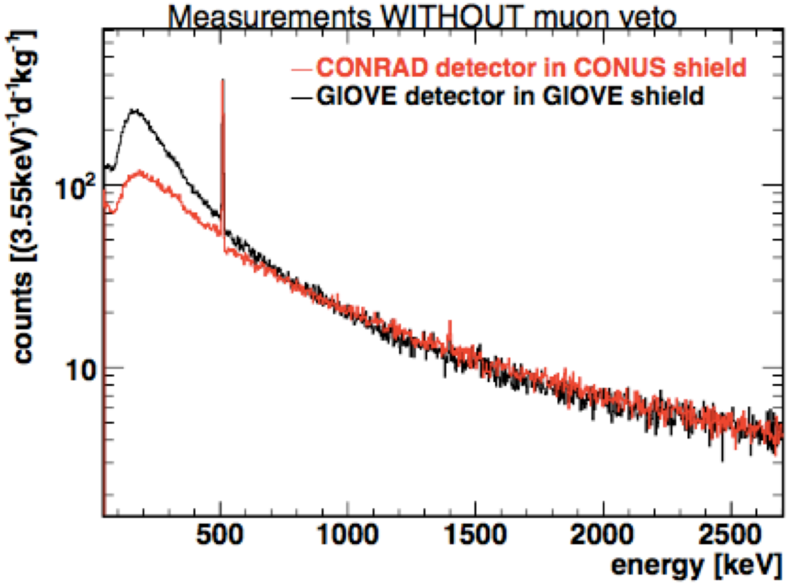
Data taking starts 2017 (6 months delay due to unexpected reactor stop)


C-E-6
D-E-5
A-E
A-E
A-E
C-W-6
C-W-5
32


A-E
A-E
A-E

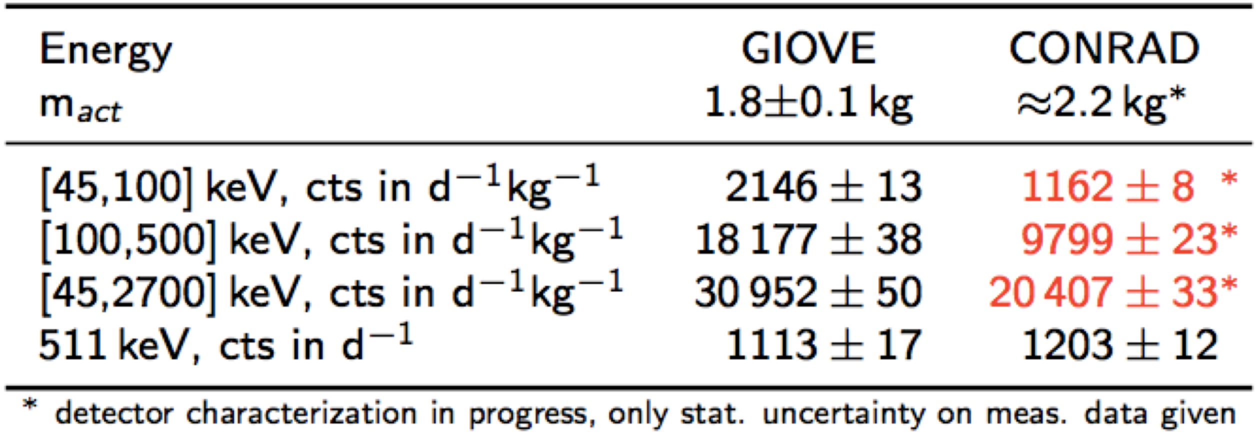


Muon induced Background in CONUS Shield



Continuum of bremsstrahlung:

- **Pb has more bremsstrahlung than Cu (~Z^2)**
- **but better self-shielding in Pb (~Z^5)**
  ➔ in total: lower count rate at low energies



Energy m_{act}	GIOVE 1.8±0.1 kg	CONRAD ≈2.2 kg*
[45,100] keV, cts in $d^{-1}kg^{-1}$	2146 ± 13	1162 ± 8 *
[100,500] keV, cts in $d^{-1}kg^{-1}$	$18\,177 \pm 38$	9799 ± 23*
[45,2700] keV, cts in $d^{-1}kg^{-1}$	$30\,952 \pm 50$	$20\,407 \pm 33$*
511 keV, cts in d^{-1}	1113 ± 17	1203 ± 12

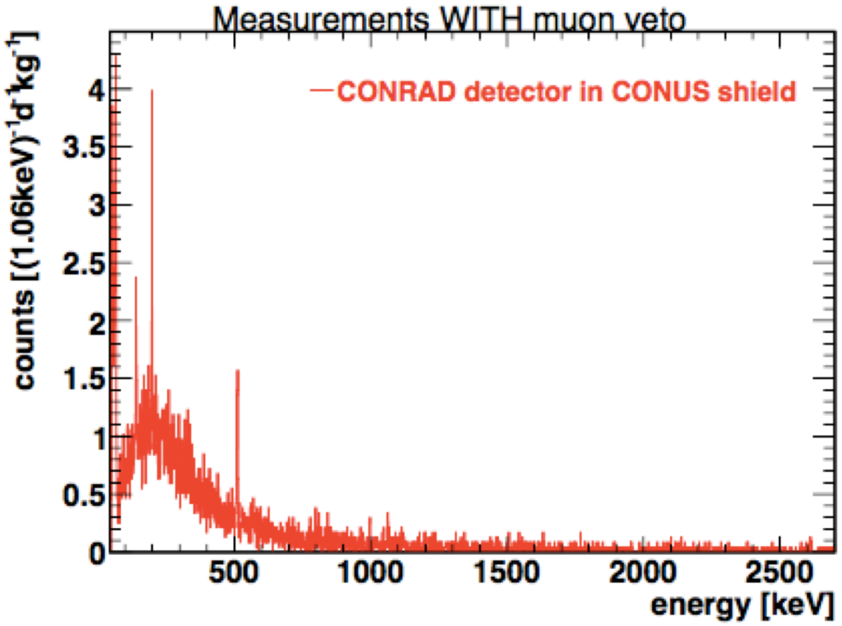
* detector characterization in progress, only stat. uncertainty on meas. data given

Muon Veto Performance

Muon veto efficiency:

- around 99% (comparible to GIOVE) almost no line background of radioactive contamination
- in ROI [45,50] keV: < $1 kg^{-1} d^{-1} keV^{-1}$

➔ design goals achieved



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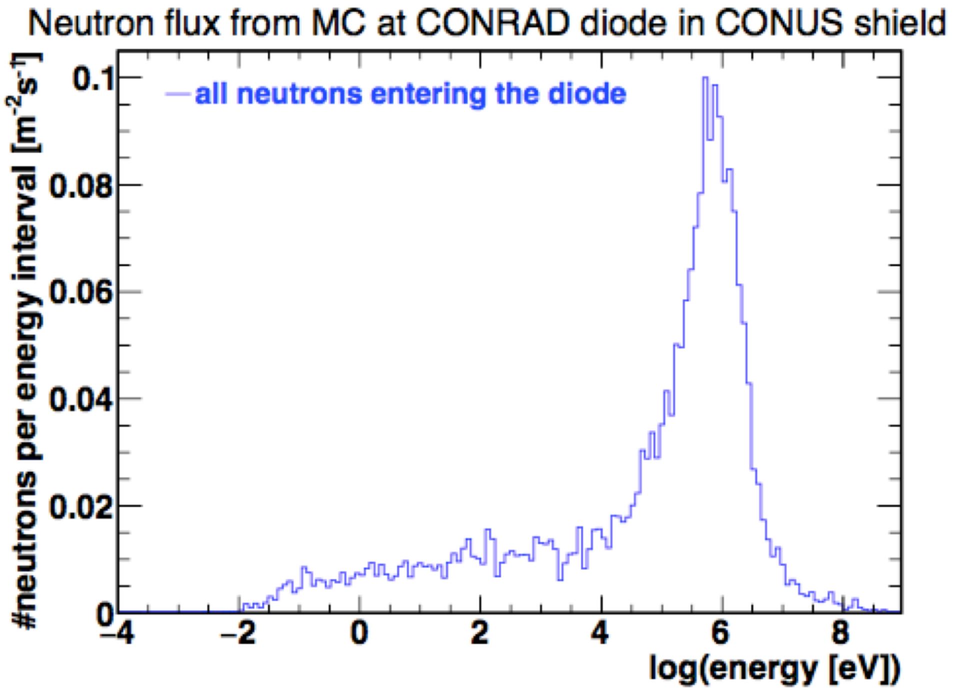
GIOVE[7]	15	~2-3	0.4 ± 0.1
CONRAD	15	~2-3	0.7 ± 0.1

$\Rightarrow$ "virtual depth" of several 100 m w.e. achieved!

Neutron Background

Neutron background at reactorsite (10-45 m.w.e. overburden)

- **Cosmic ray background: more overburden than at MPIK**
  - similar conditions: μ-induced neutrons in shield dominate
  - background understood and acceptable
- **Neutrons from reactor**
  - measured by PTB Braunschweig (German National Metrology Institute)
  - MC simulations from reactor core to experimental site in progress
  - outcome:
    - ➢ mostly thermal neutrons arrive at experimental site
    - ➢ thermal neutrons are shielded well
    - ➢ within shield: mostly muon-induced neutrons in lead

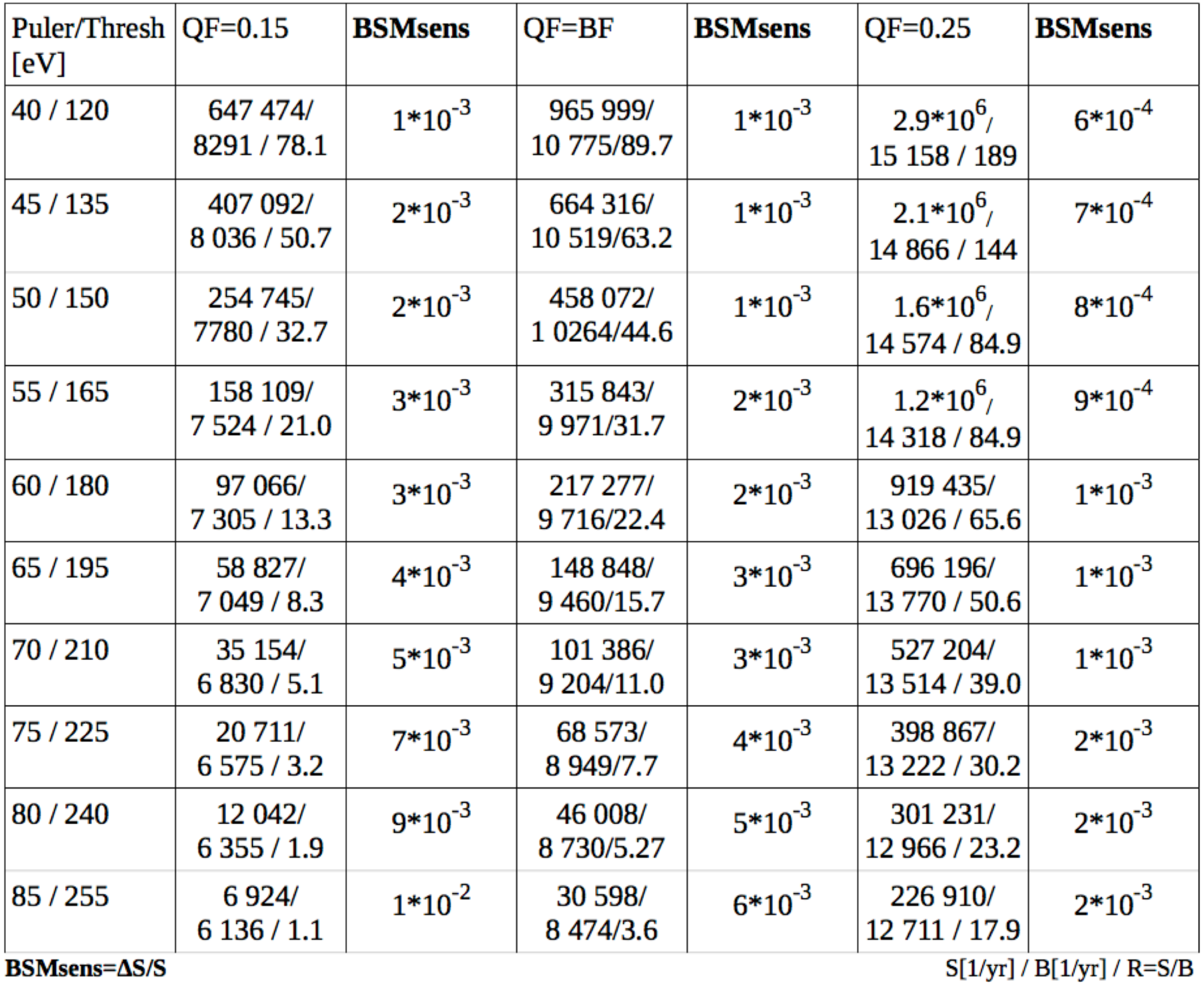


CONUS100

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	$2*10^{-3}$

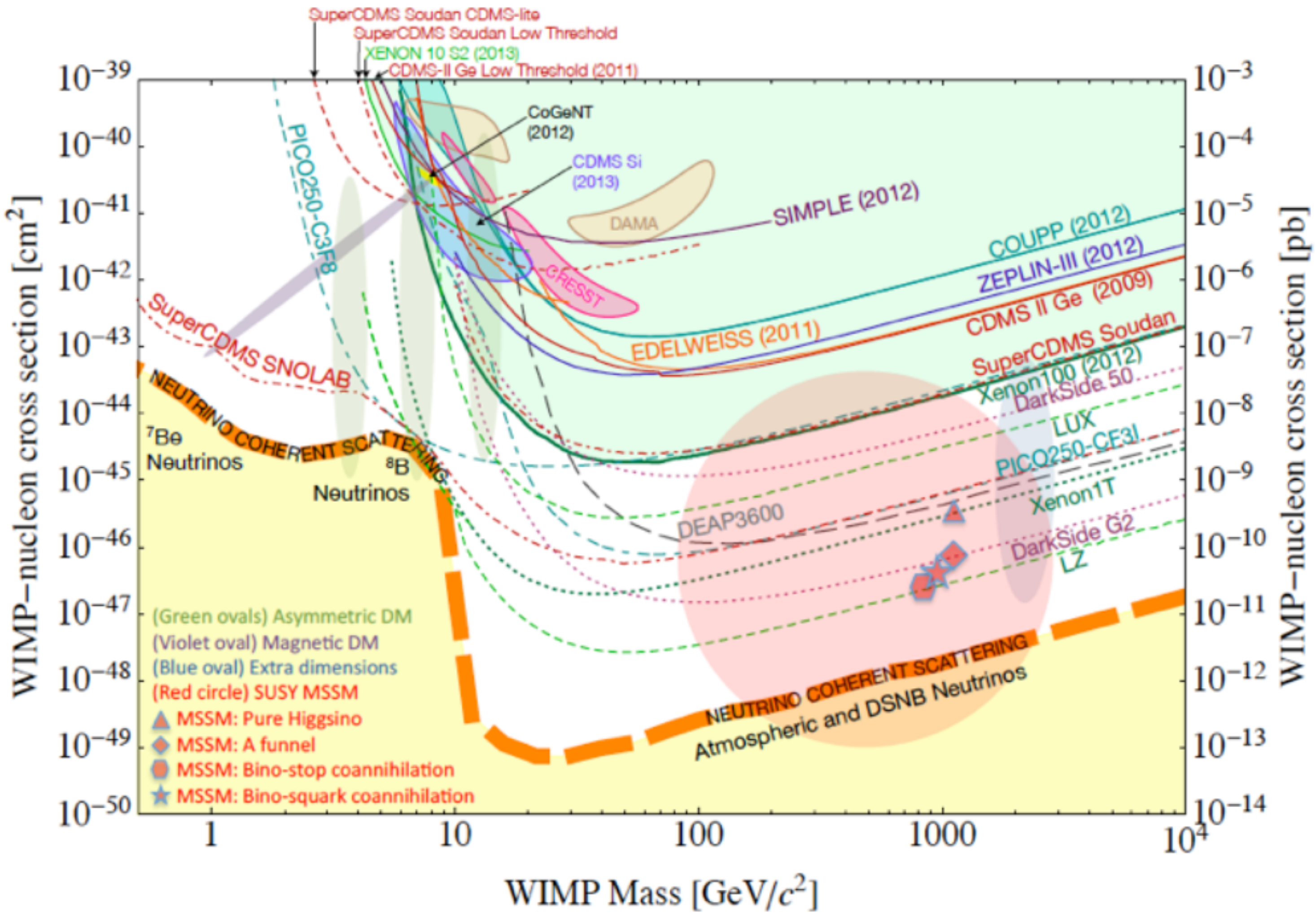
BSMsens=ΔS/S S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

CEνNS becomes a Tool for other Topics

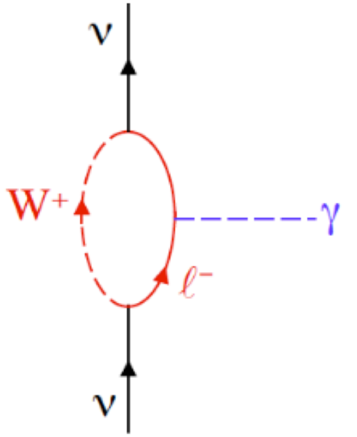
DM connection:

1) DM experiments <u>assume</u> 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:

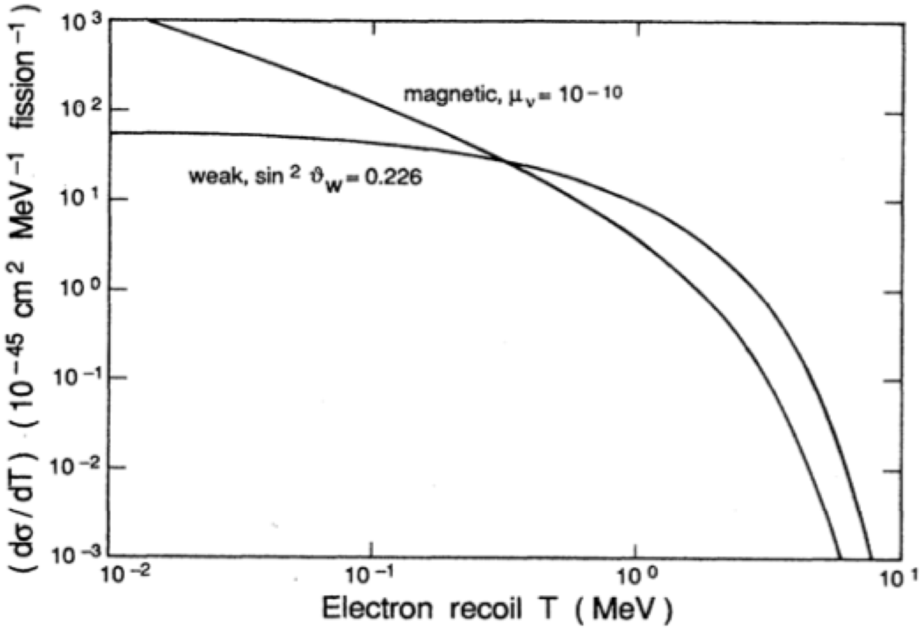
SUSY, extra dimensions, …

At least new best limits:

e-scattering (GEMMA) and astrophysics:

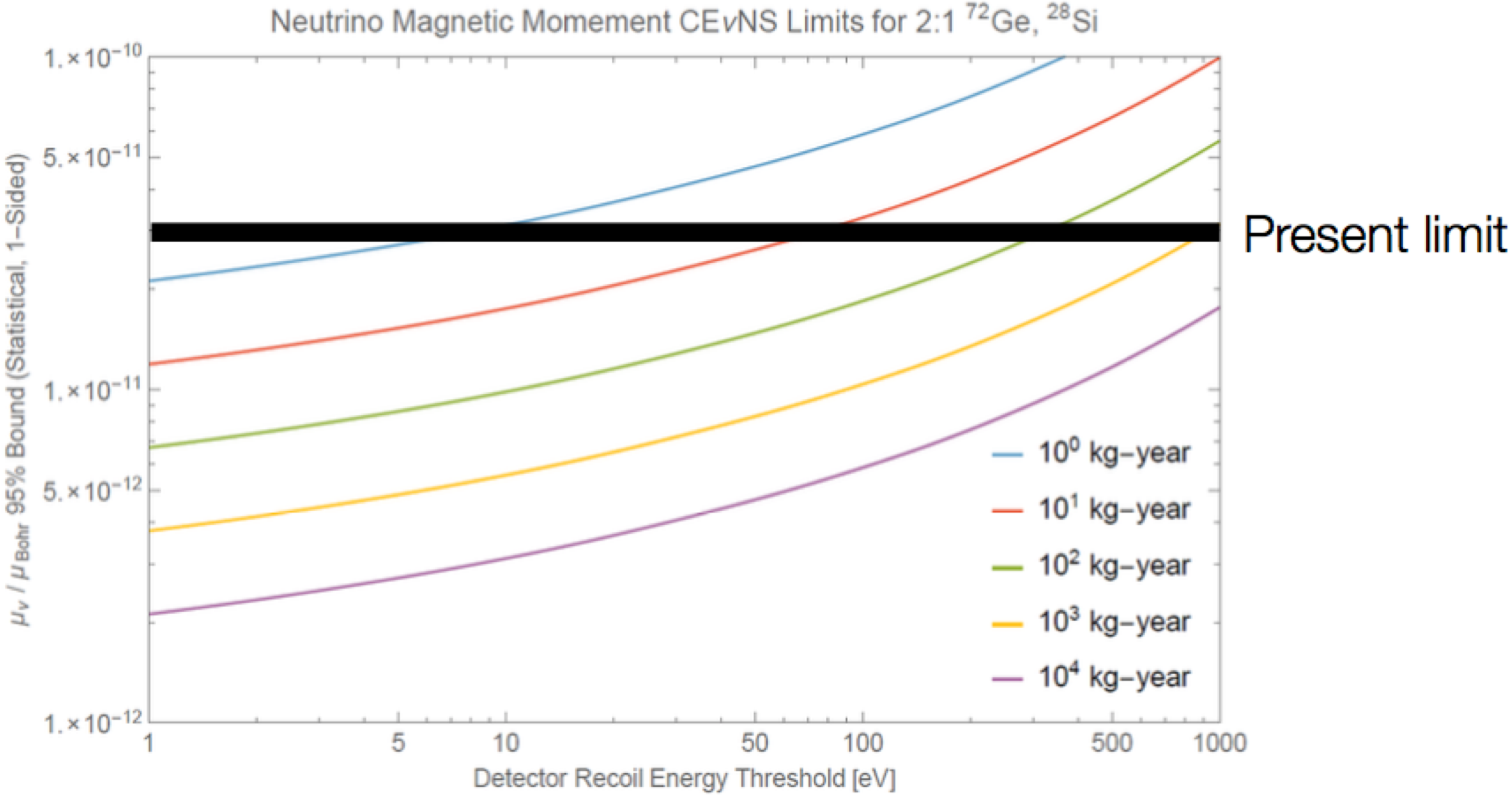
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$

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



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

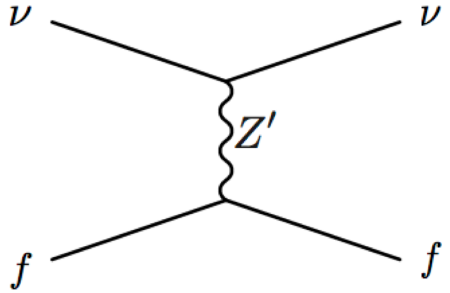
Potential for Magnetic Moments



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

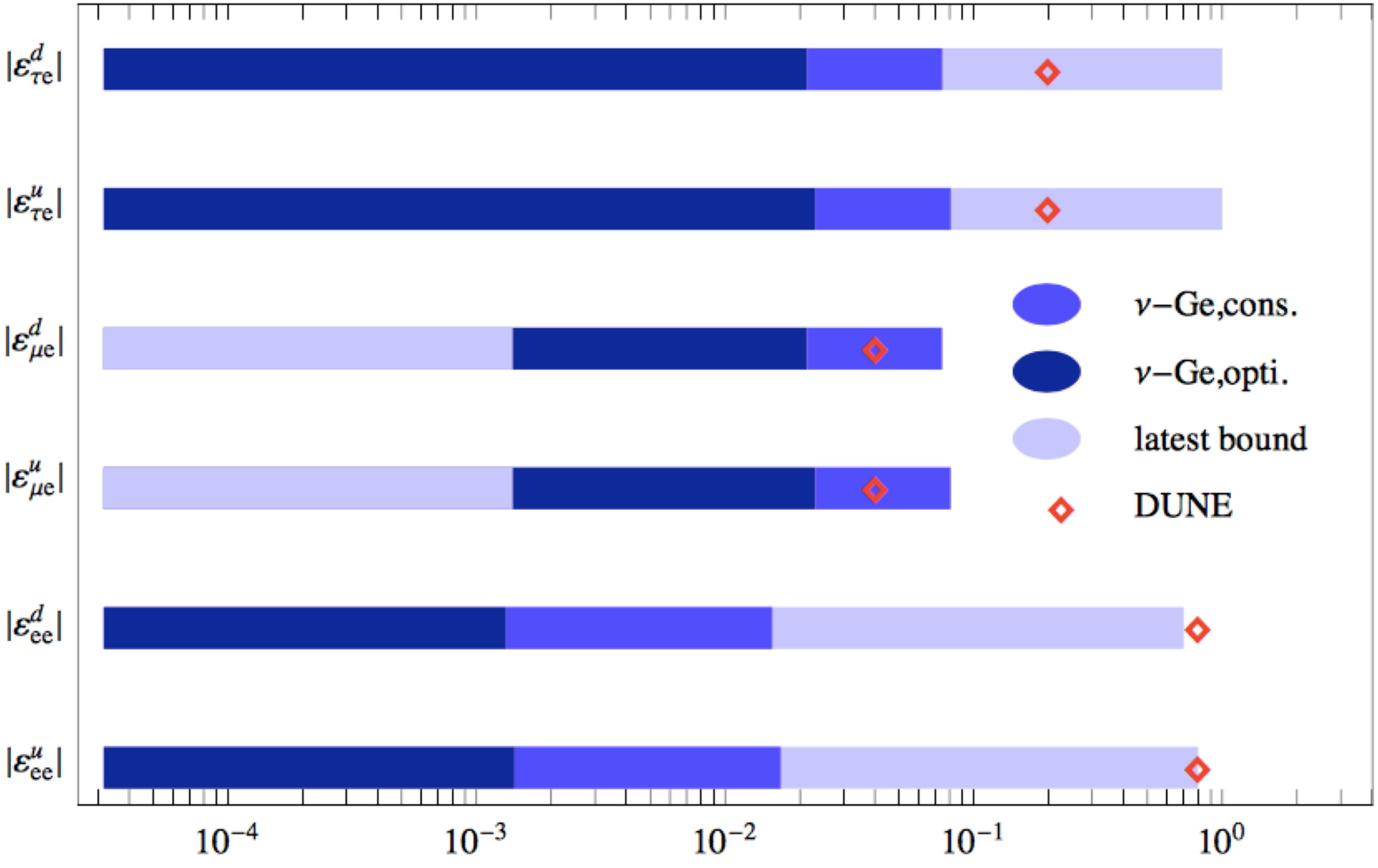
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ Competitive method to test TeV scales
ε = 0.01 ←→ TeV scales

NSI-Potential

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu



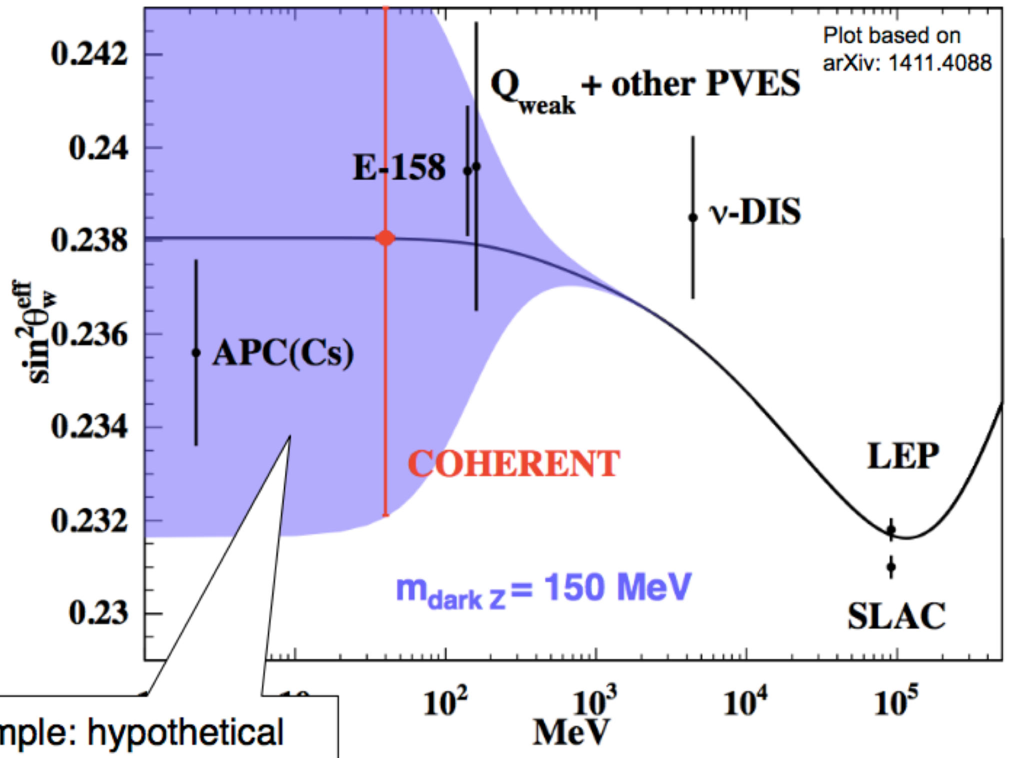
~10 TeV ~TeV

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

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



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

BSMsens =

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

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

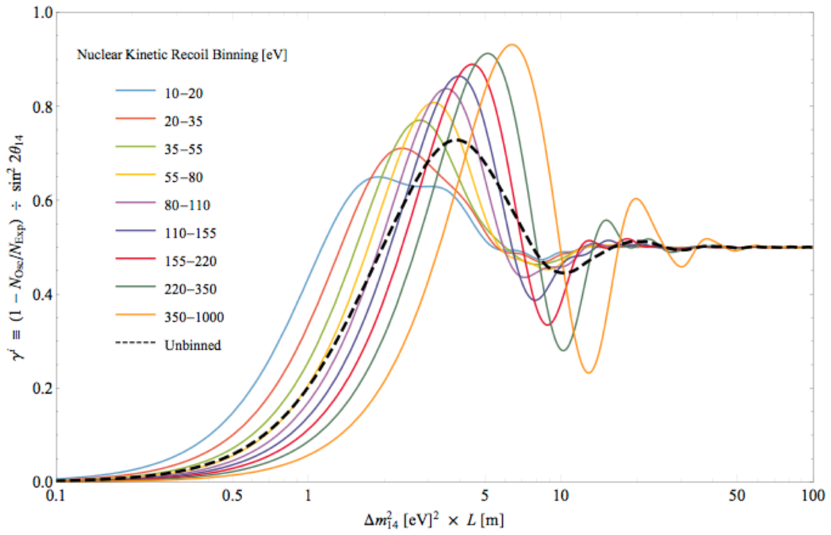
CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

slide adopted from K. Scholberg

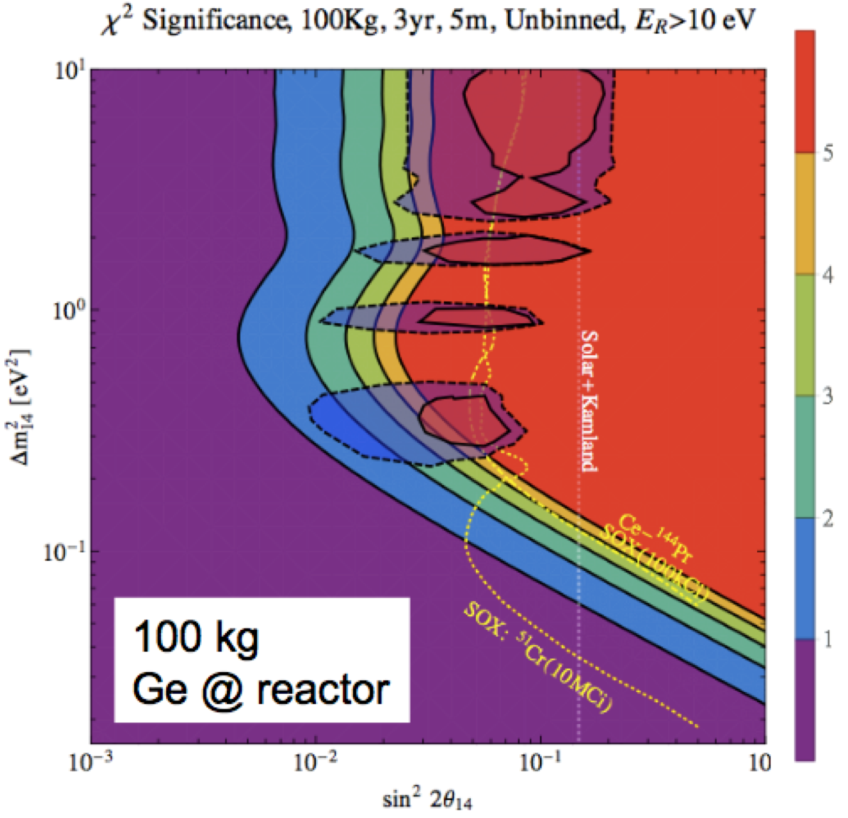
Searches for new Physics: Sterile ν's

- 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



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

B. Dutta et al, arXiv:1511.02834

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

➔ time scales compared to other projects

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

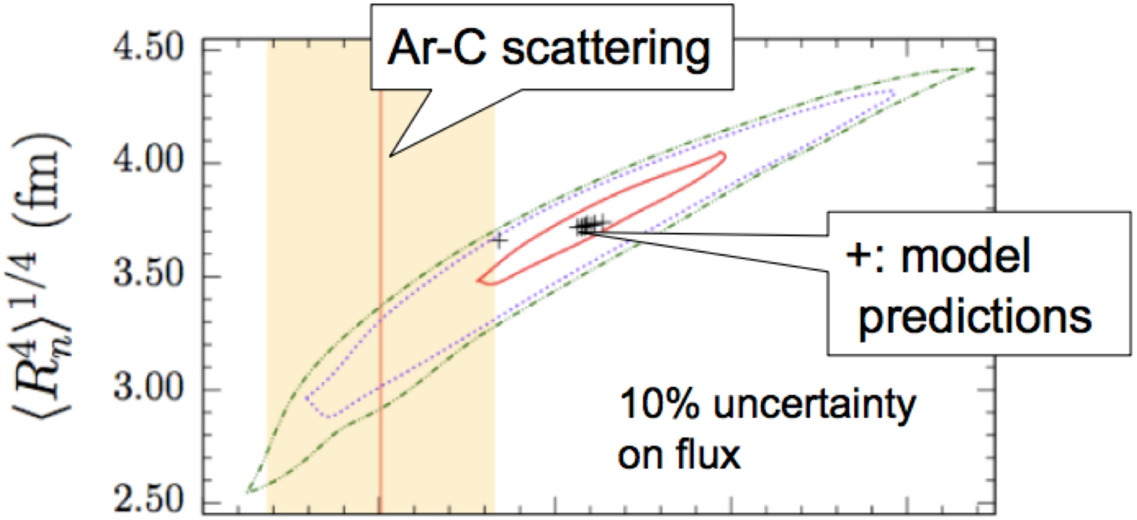
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2)$$

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



Ar-C scattering

+: model predictions

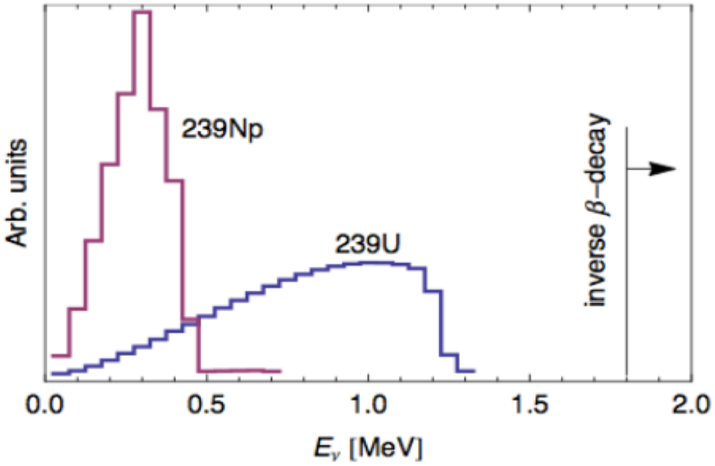
10% uncertainty on flux

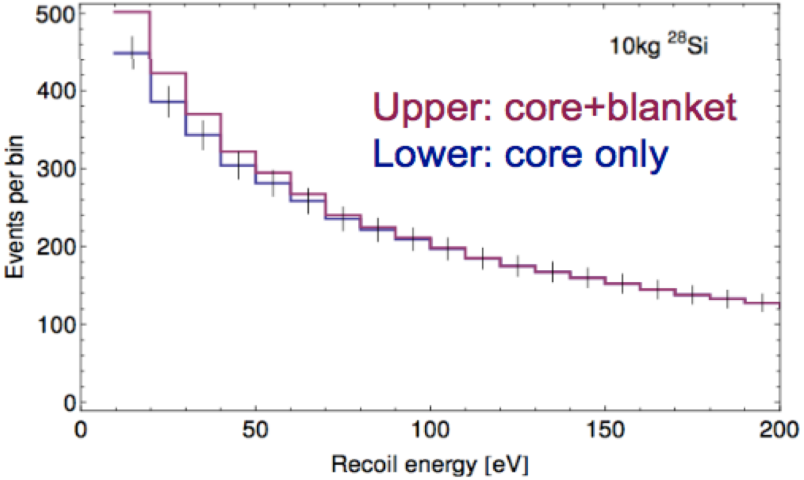
Nuclear Safeguarding

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

Summary

- **CEνNS recently observed by COHERENT at $E_\nu \simeq$ 30-50 MeV**
- **CONUS will see CEνNS of reactor neutrinos (few MeV)**
  - detector ready and tested ; reactor re-started
  - final approval for operation of CONUS @ Brokdorf
  - move detector in place → data taking in 2017
- **CEnNS will become an interesting tool**
  - discussed upscaling of existing technology to O(100kg)
  - will contribute / make use of better β-spectra
  - coherent ν scattering ←→ DM & WIMP scattering, neutrino floor
  - search / limits for magnetic Moments
  - search for new physics: NSIs, steriles, $\sin^2\theta_W$, sterile oscillation searches
  - nuclear form factors with neutrinos $F(q^2)$
  - supernova physics
  - reactor ν spectrum & anomalies
  - reactor monitoring: safe-guarding, optimization

→ very interesting potential of CEνNS