The CONUS coherent Neutrino scattering Experiment

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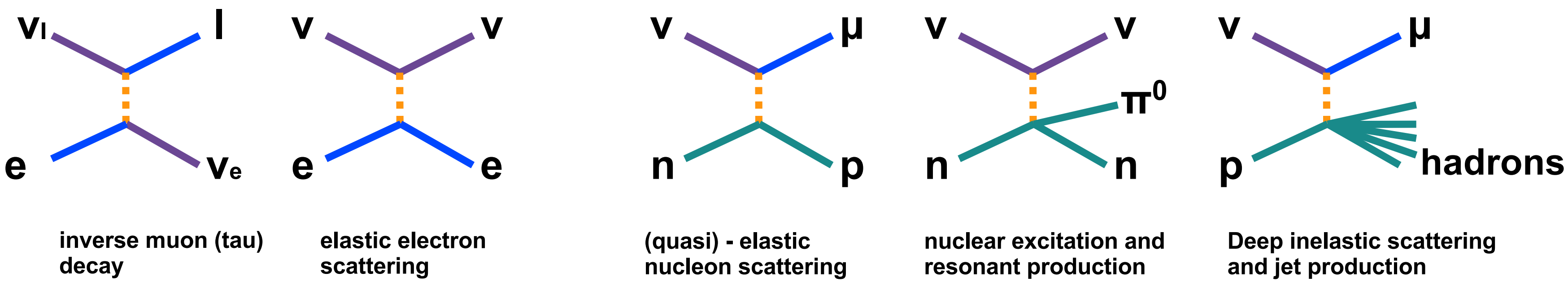
Conference on Neutrino and Nuclear Physics (CNNP2017)

15-21 October 2017 *Monastero dei Benedettini, University of Catania,*

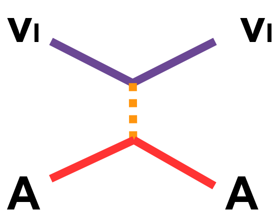
Coherent Neutrino Scattering

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

- **5 have already been detected**



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



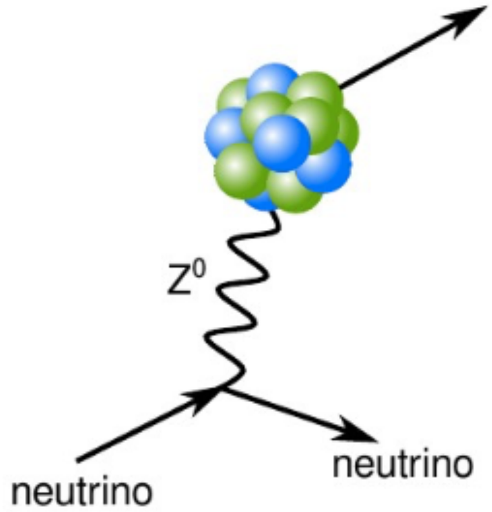
Coherent neutrino-nucleus scattering: CEνNS

➔ **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_ν~ 50 MeV



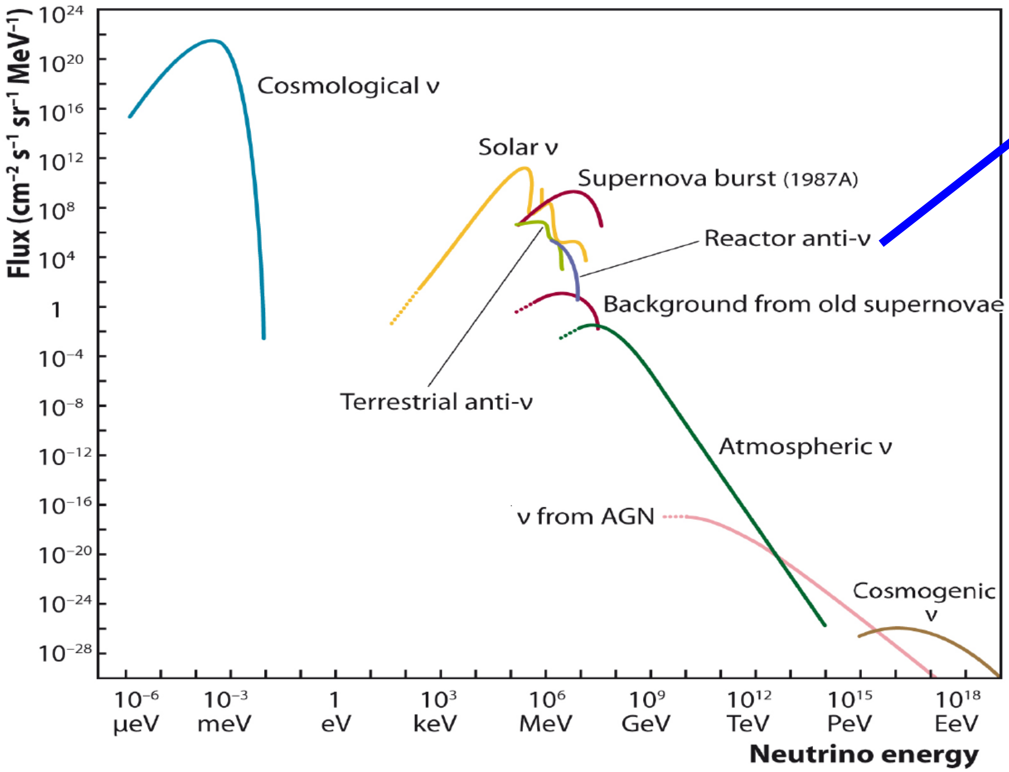
$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim N$$

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

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 ←→ flux!

The Neutrino Spectrum



10 GW at a distance of 150 km

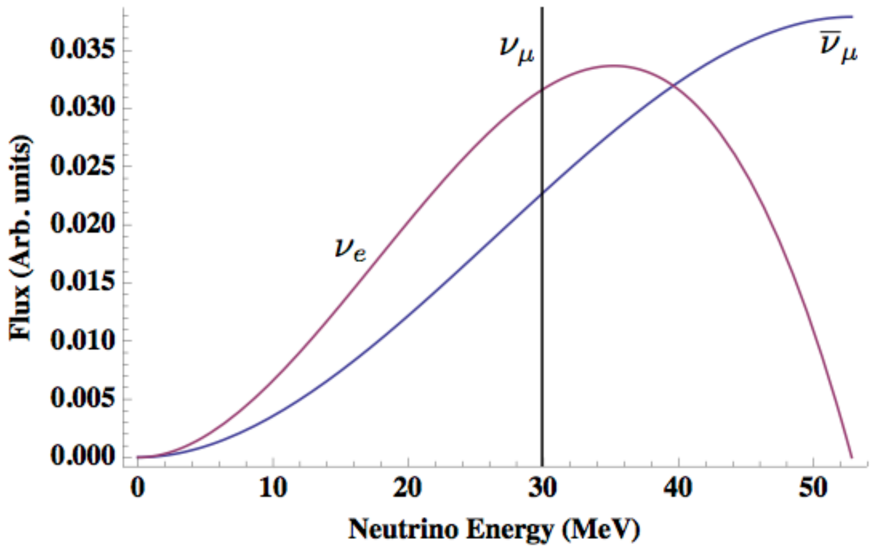
close to power reactors:
ca. 4% of the thermal power P
3.9 GW → ca. 150 MW in ν's
dilution by distance R
flux $\Phi \sim P/R^2$
ca. 150 kW/m² at 10m distance

Cross section grows with neutrino energy

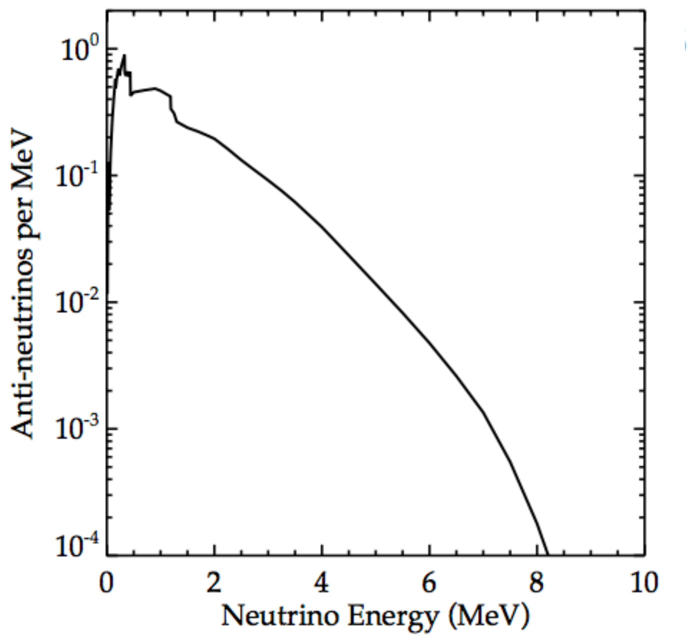
source	flux	
reactor neutrinos (3 GW, at 10m distance)	5 x 10^13	/cm^2/s
solar neutrinos (on Earth)	6 x 10^10	/cm^2/s
supernova (50 kpc Abstand, for O(10) seconds)	~ 10^9	/cm^2/s
geo-neutrinos (on the Earth's continental surface)	6 x 10^6	/cm^2/s

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

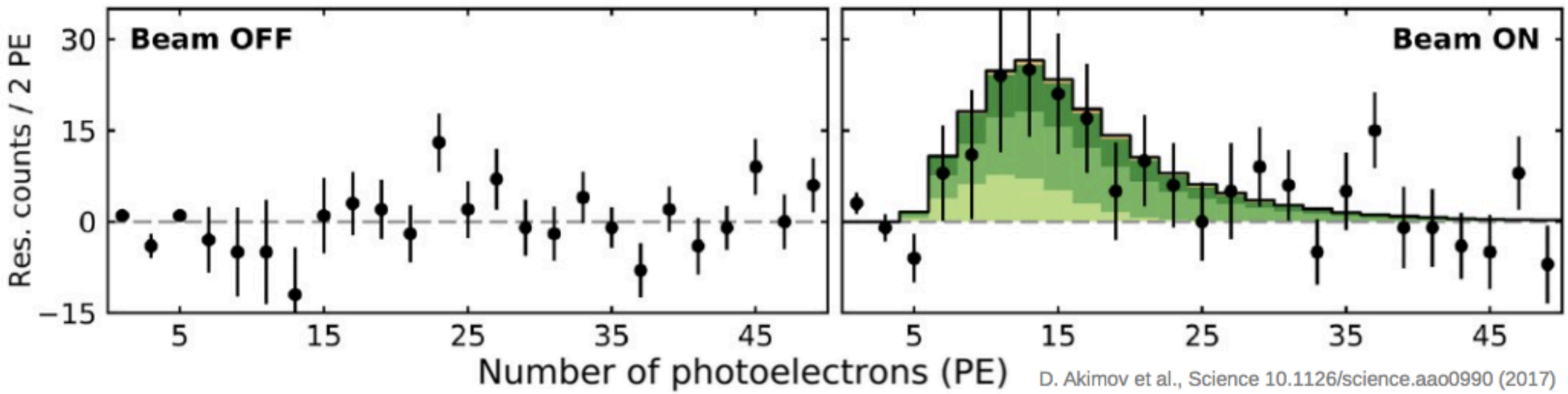
COHERENT experiment (stopped π beam 30-50 MeV neutrinos)

- 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 $4.3 \cdot 10^7$ $\nu/cm^2/s$ @ 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

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

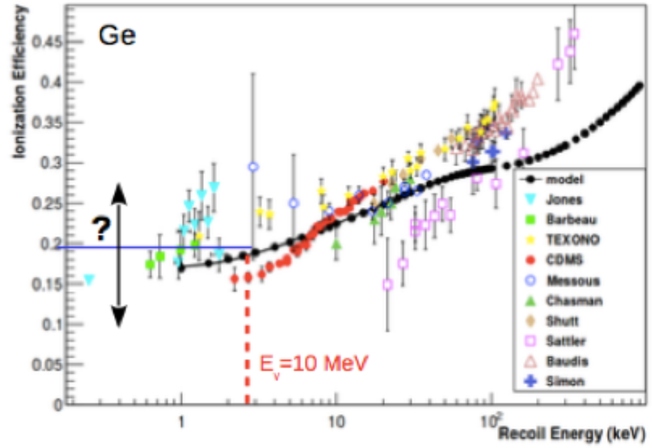
Experimental Requirements

- **measure nuclear recoil energy T**

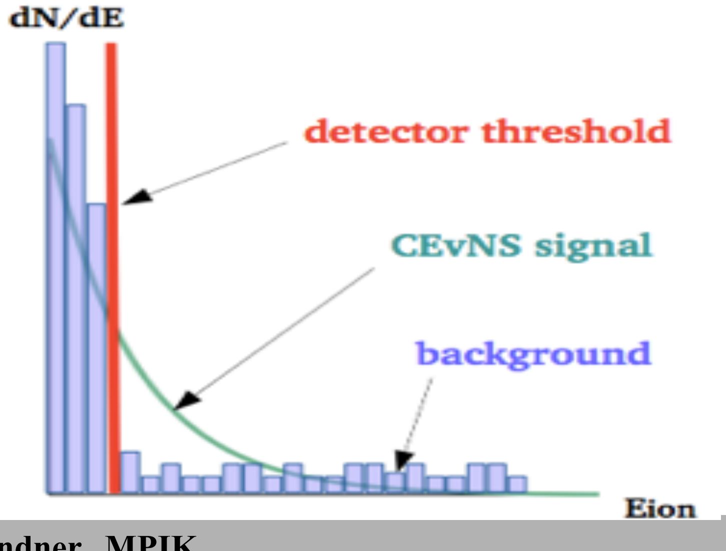
  for $E_\nu = 10$ MeV ➔ $T_{max} \simeq 3$ keV (in Ge)

- **energy loss due to quenching (Lindhard)**
  ➔ Quenching Factor (QF)
  QF down to 0.2 in Ge → 600 eV
  ➔ include systematic uncertainty

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



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

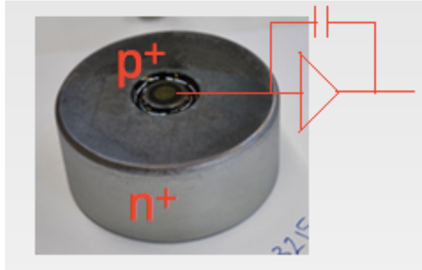


detection of CEνNS signal:

- **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

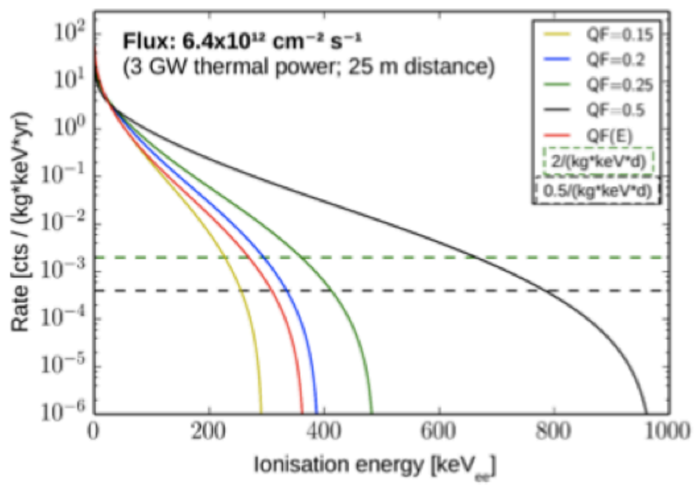
Pulser/Threshold [eV]	QF = 0.15	QF = best fit	QF = 0.25
60 / 180	971 / 61 / 15.8	2 173 / 85 / 25.6	9 194 / 127 / 72.3
65 / 195	588 / 58 / 10.1	1 488 / 81 / 18.4	6 962 / 123 / 56.4
70 / 210	352 / 55 / 6.4	1 014 / 78 / 13.0	5 272 / 120 / 44/0
75 / 225	207 / 52 / 4.0	686 / 75 / 9.2	3 989 / 117 / 34.2
80 / 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



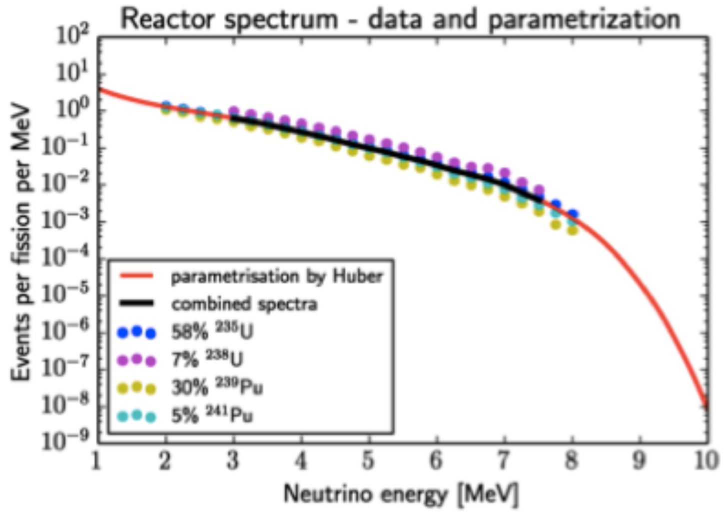
The Source

The Brokdorf (Germany) power plant:

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

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



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

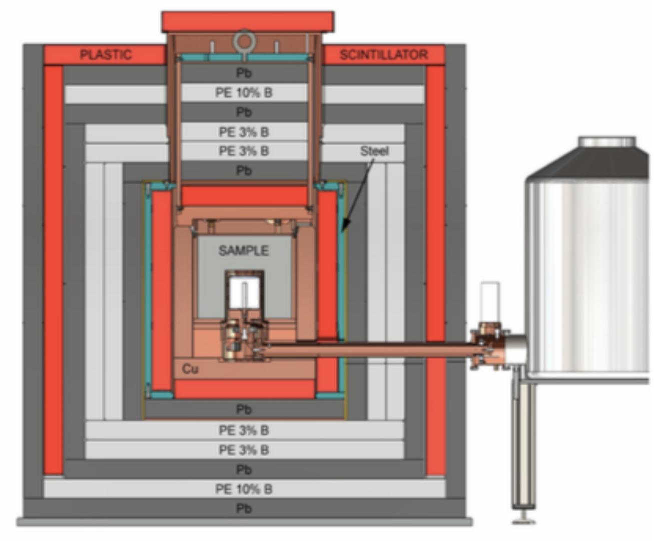
access during operation
overburden 10-45 m.w.e
measurements of neutron background
ON/OFF periods ➔ backgd. measurement

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%)

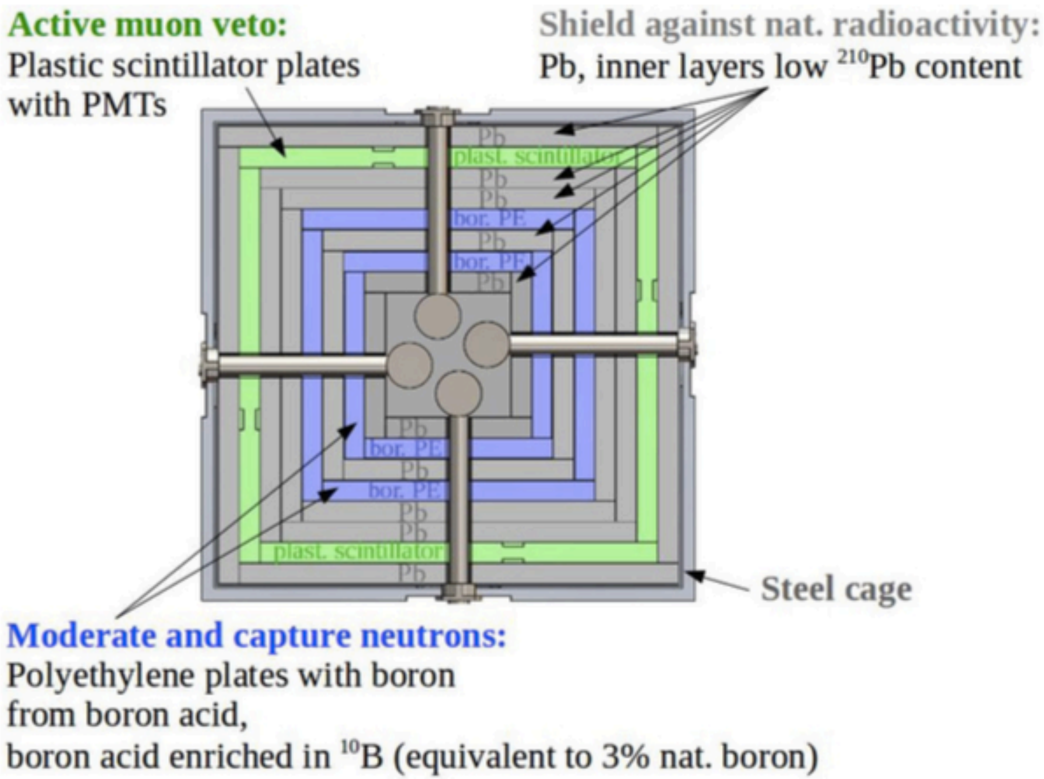
main purpose: material screening

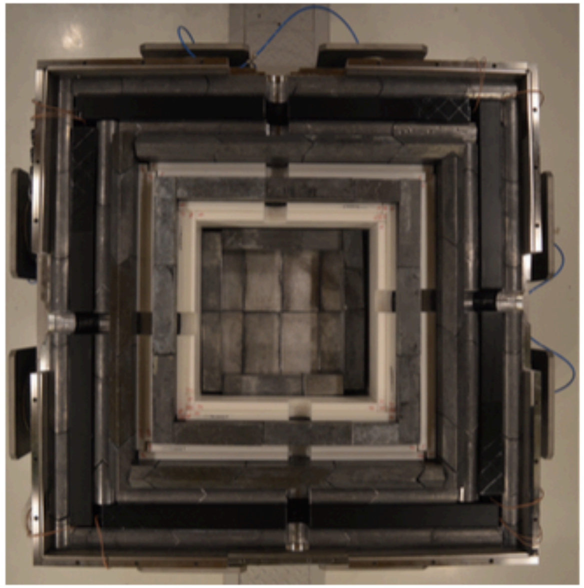


detector	depth [m w.e.]	μ flux reduction	Bkg rate [45,50] keV [$kg^{-1}d^{-1}keV^{-1}$]
Gemma-I[5]	70	$\sim$ 10	2.1 ± 0.7
Texono[6]	25	$\sim$ 4	1.3 ± 0.5
GIOVE[7]	15	~2-3	0.4 ± 0.1

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

The CONUS Shield





- **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

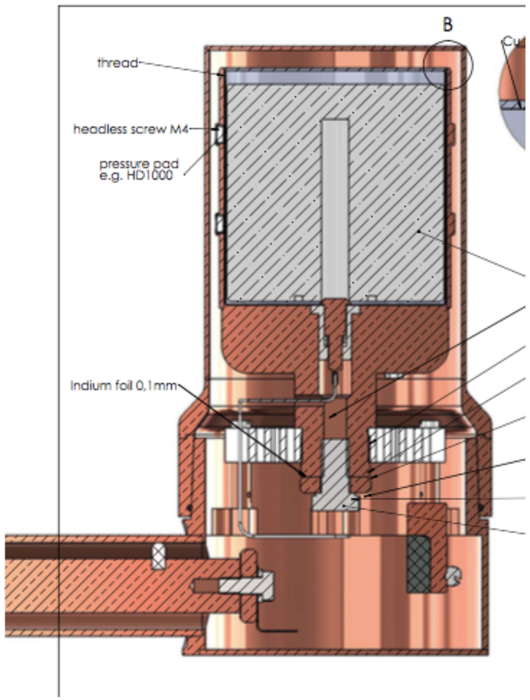
BEGe R&D @MPIK: Asterix & Obelix....

➔ 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



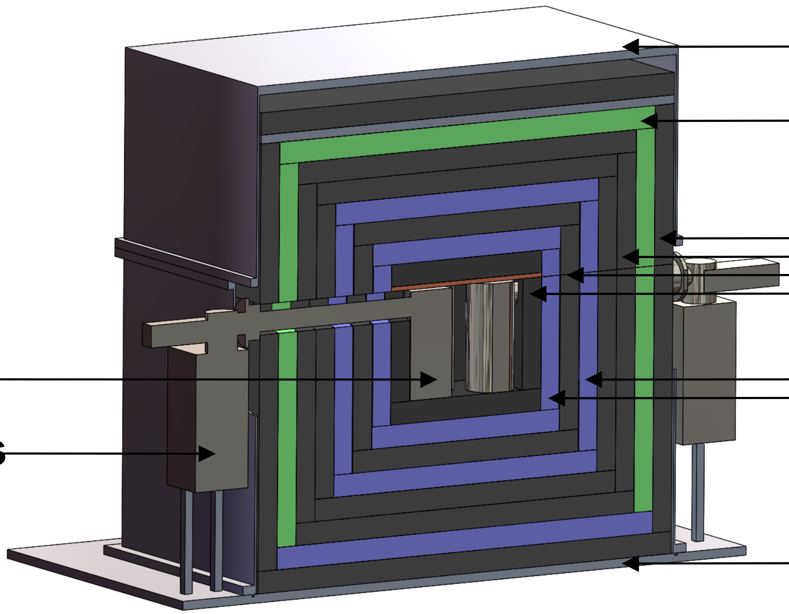
The CONUS Detector

Components:

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

➔ all ultra low background

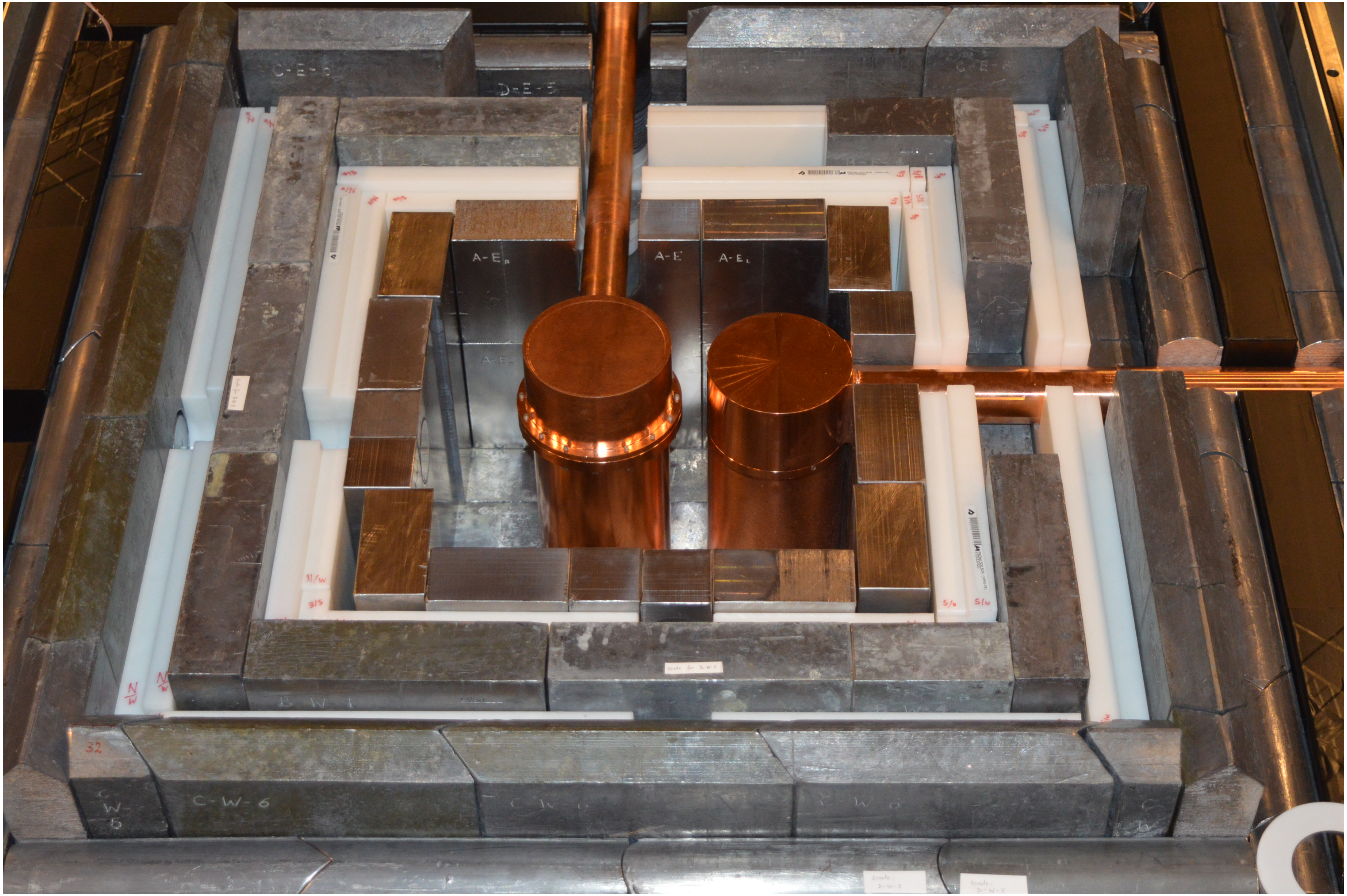
- electronics and DAQ rack

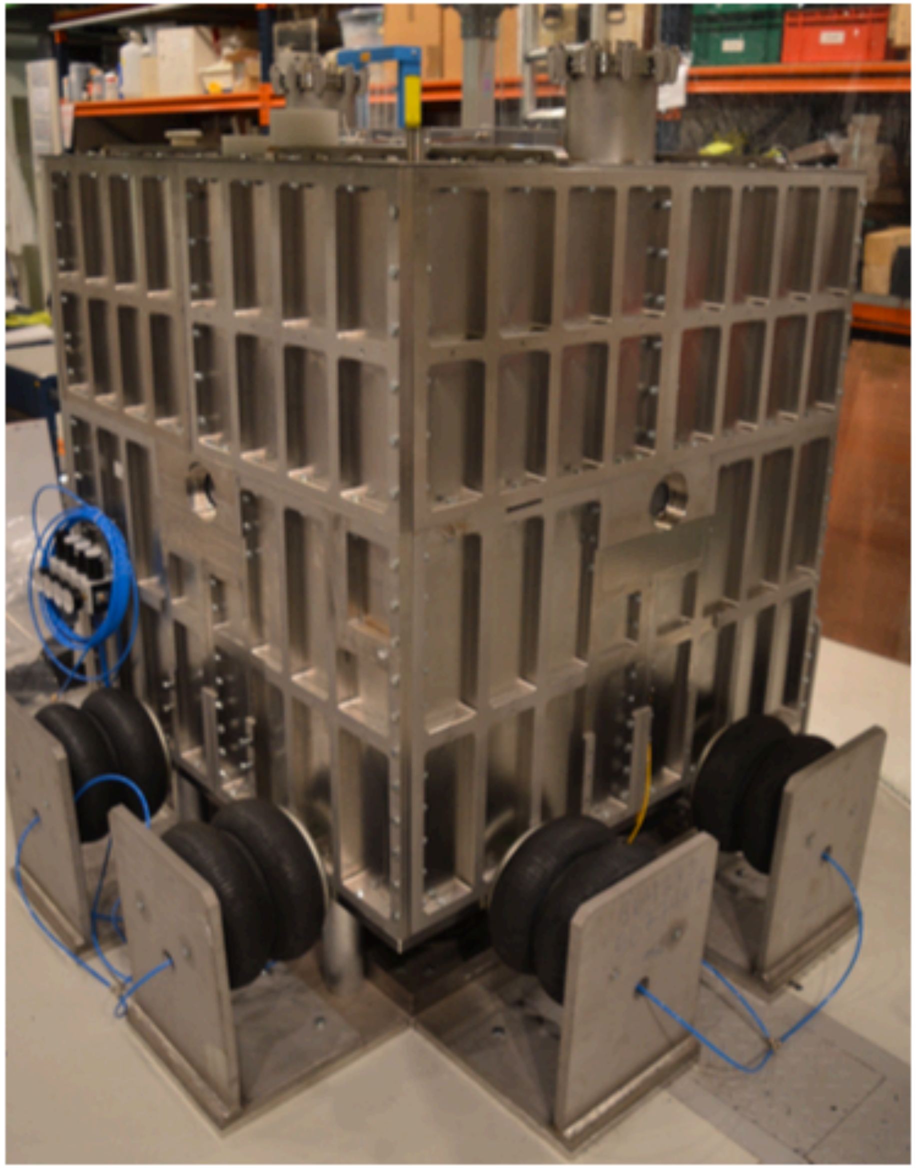


Successful combination of three essential improvements:

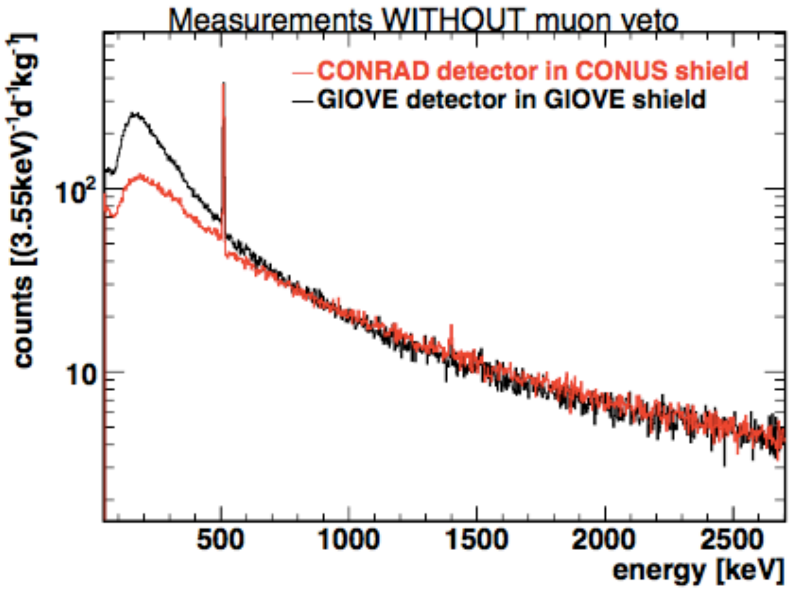
- new (best) active/passive shielding (GIOVE @ MPIK = "virtual depth")
- new detectors with very low thresholds
- site with highest neutrino flux

Start of the project summer 2016
Data taking starts 2017 (6 months delay due to unexpected reactor stop)





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

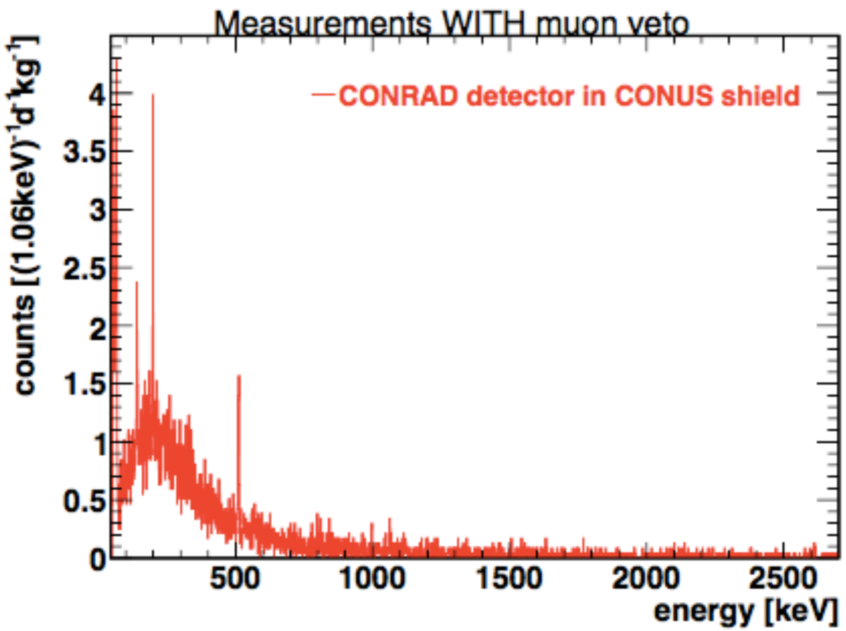
* detector characterization in progress, only stat. uncertainty on meas. data given

Muon Veto Performance

Muon veto efficiency:

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

➔ design goals achieved



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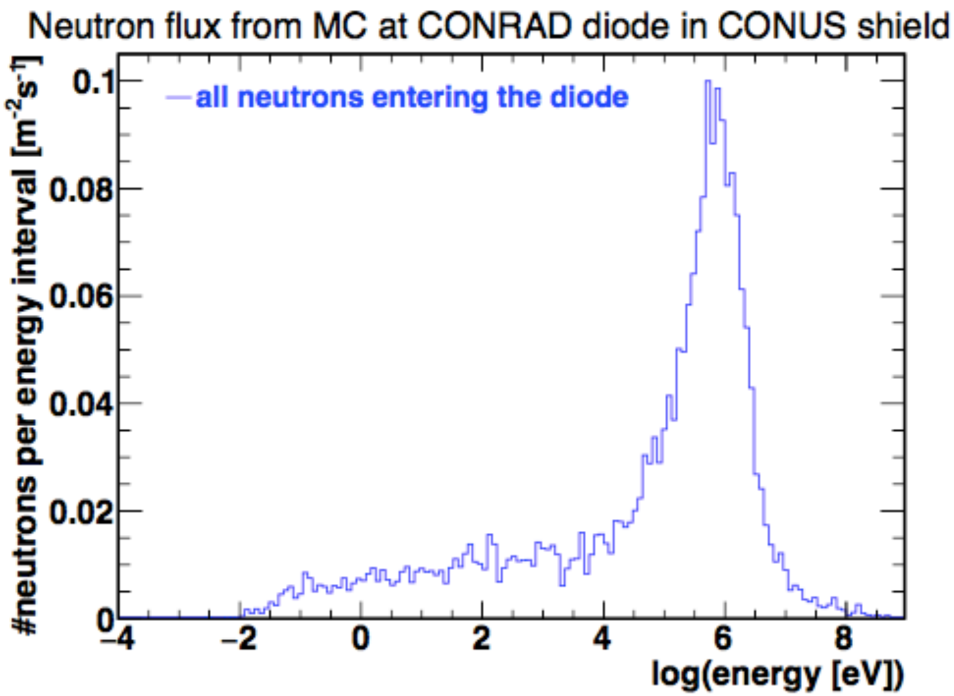
GIOVE[7]	15	$\sim$2-3	0.4 ± 0.1
CONRAD	15	$\sim$2-3	0.7 ± 0.1

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

Neutron Background

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

- Cosmic ray background: a bit 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	$2*10^{-3}$

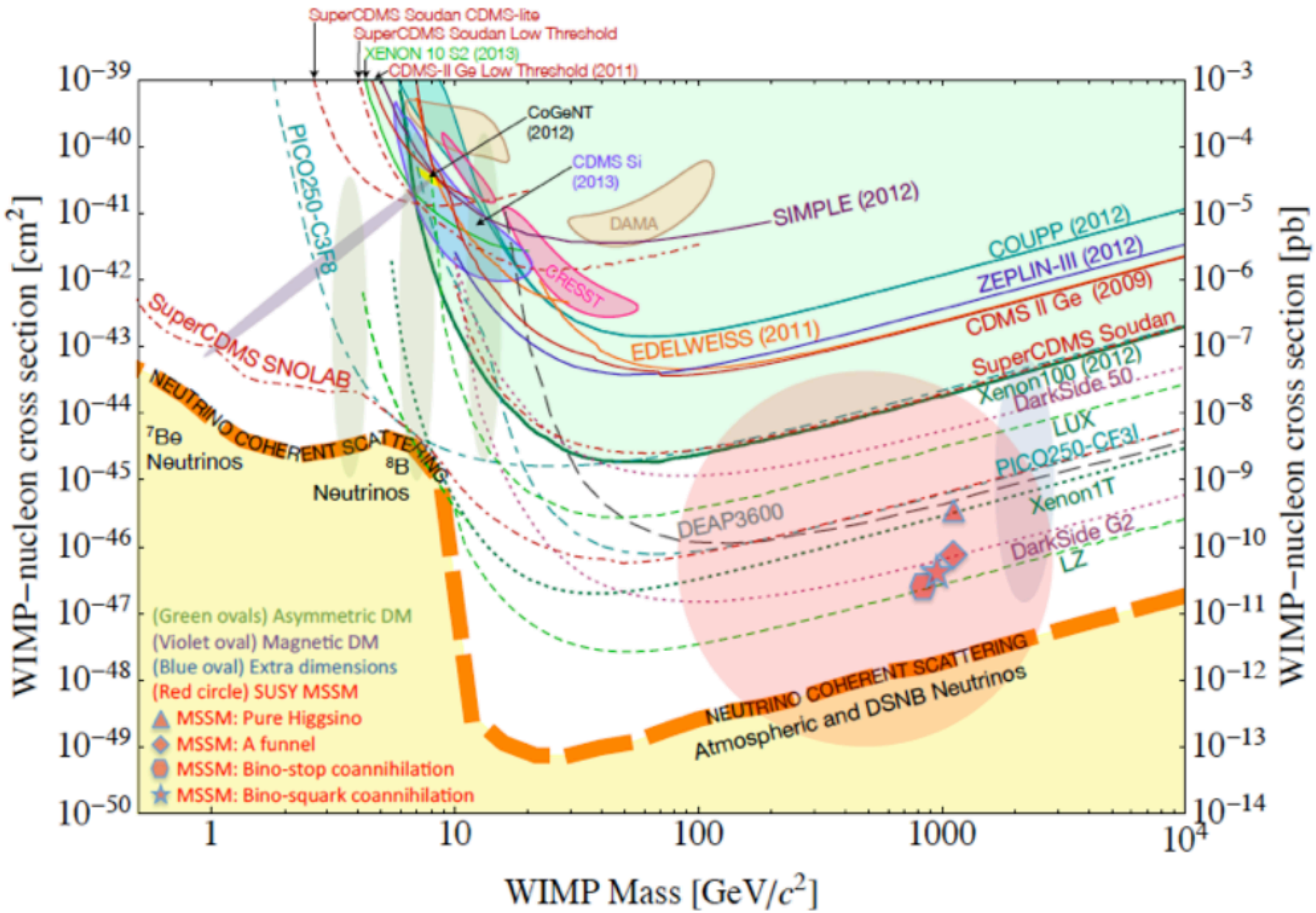
BSMsens=ΔS/S S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

CEνNS becomes a Tool for other Topics

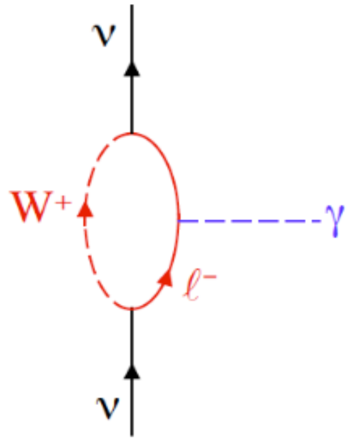
DM connection:

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

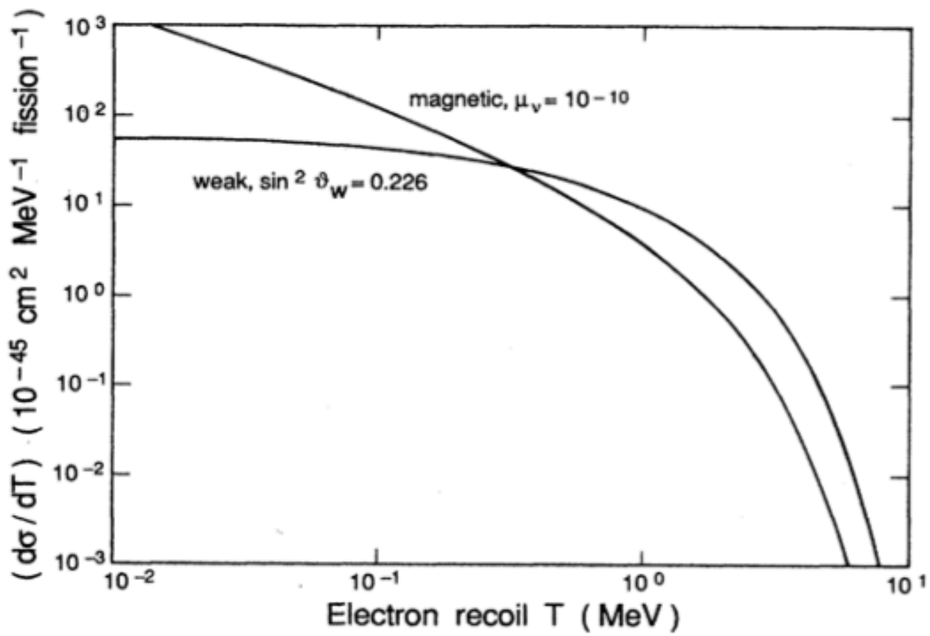
Magnetic moment for minimal ν masses are very tiny:



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

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

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



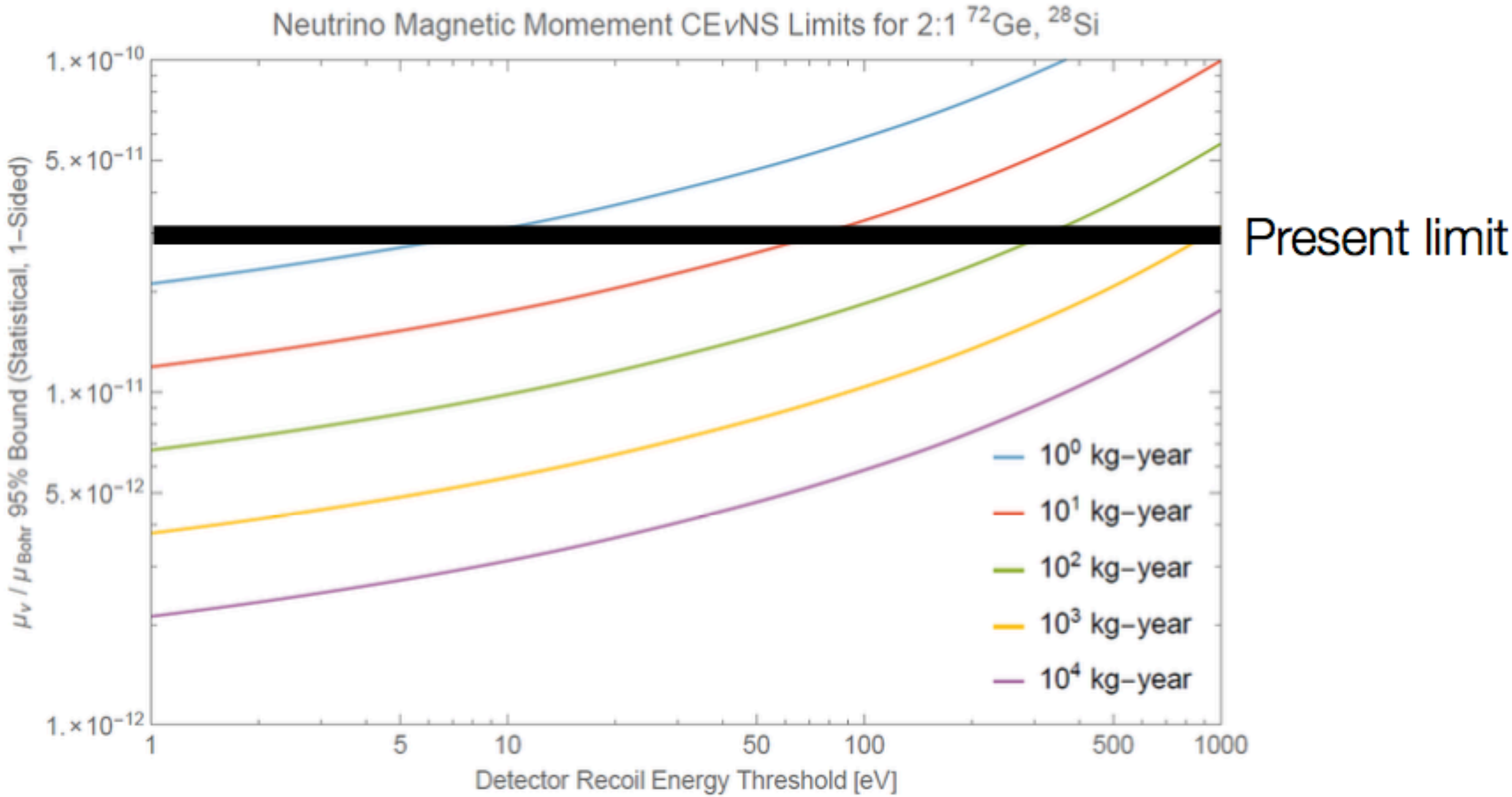
At least new best limits:
e-scattering (GEMMA) and astrophysics:

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

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

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

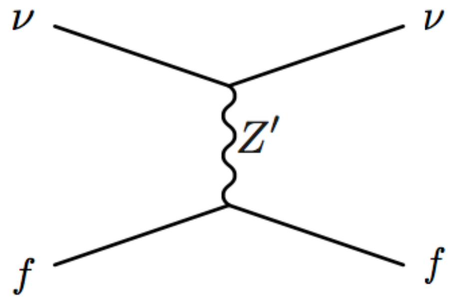
Potential for Magnetic Moments



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

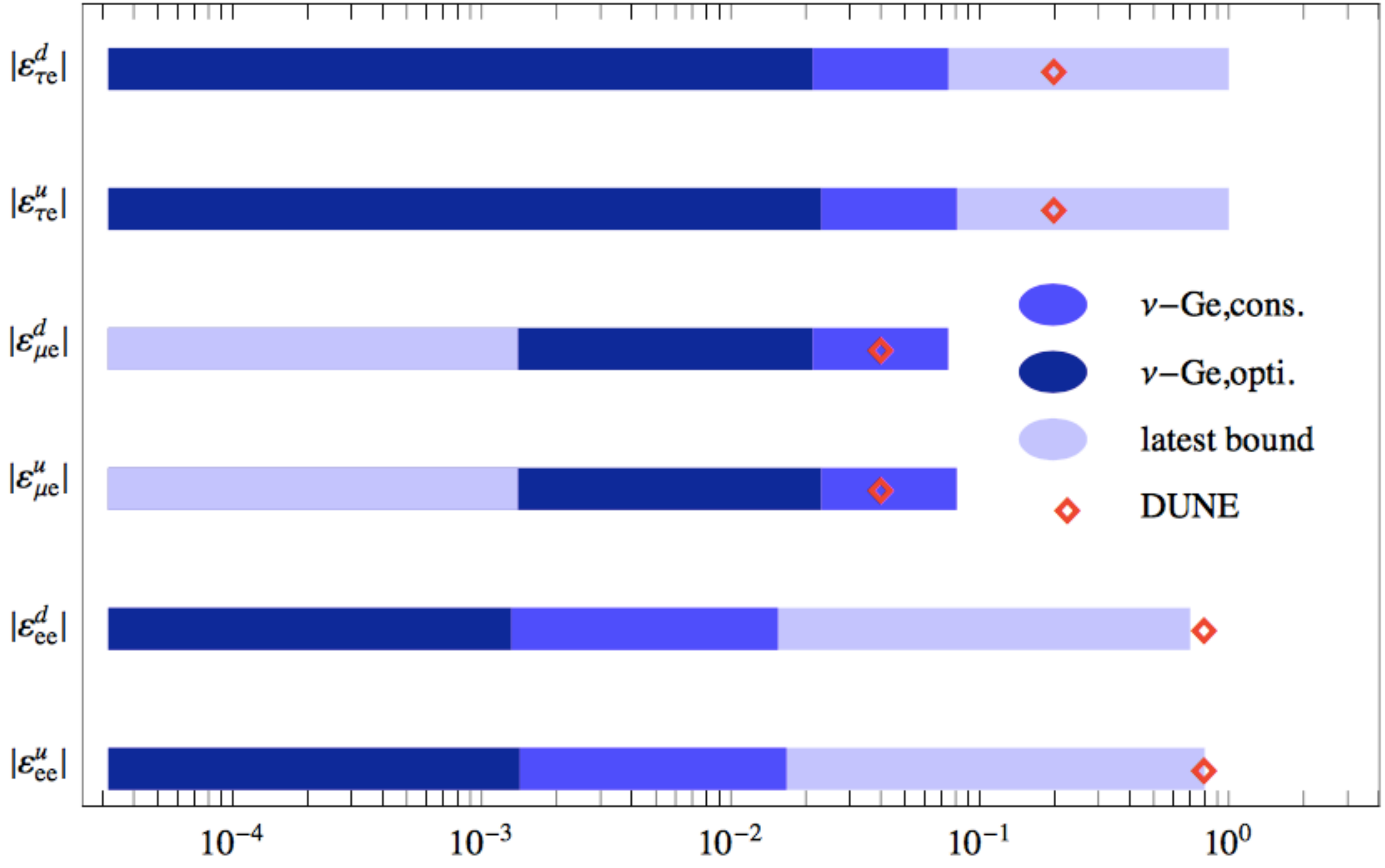
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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

NSI-Potential

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu

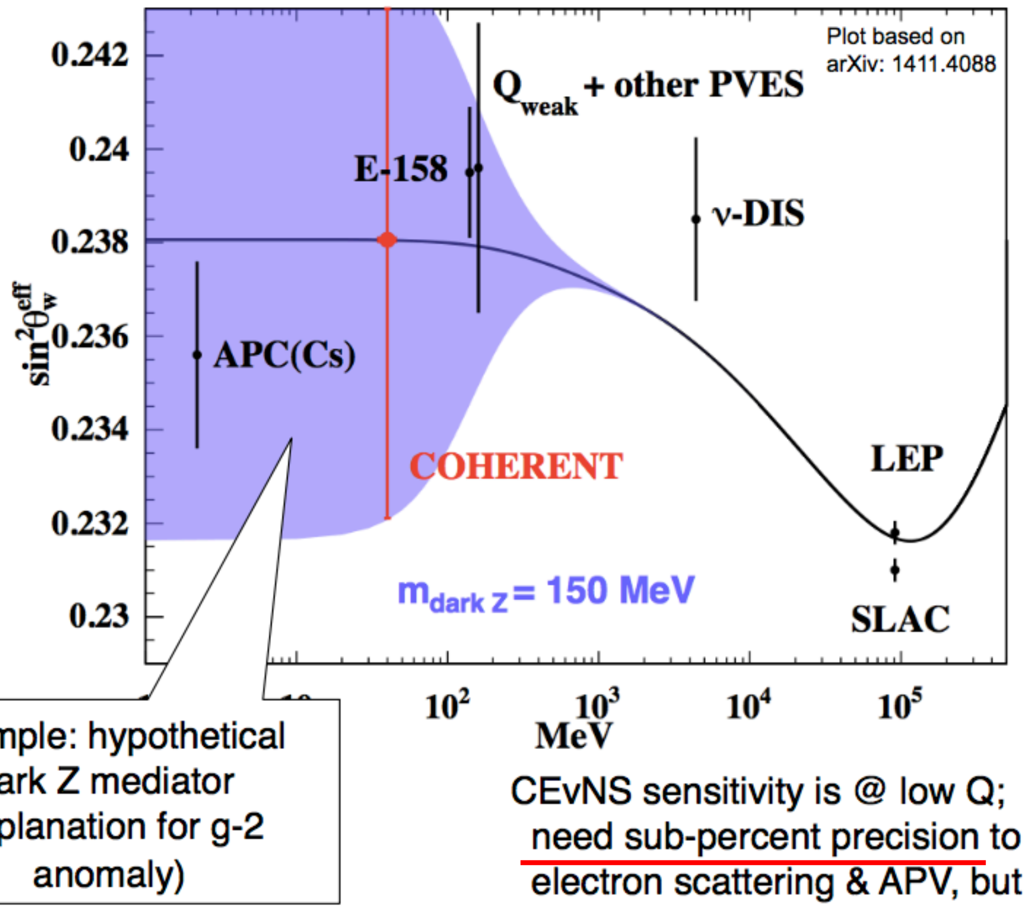


~10 TeV ~TeV

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**

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



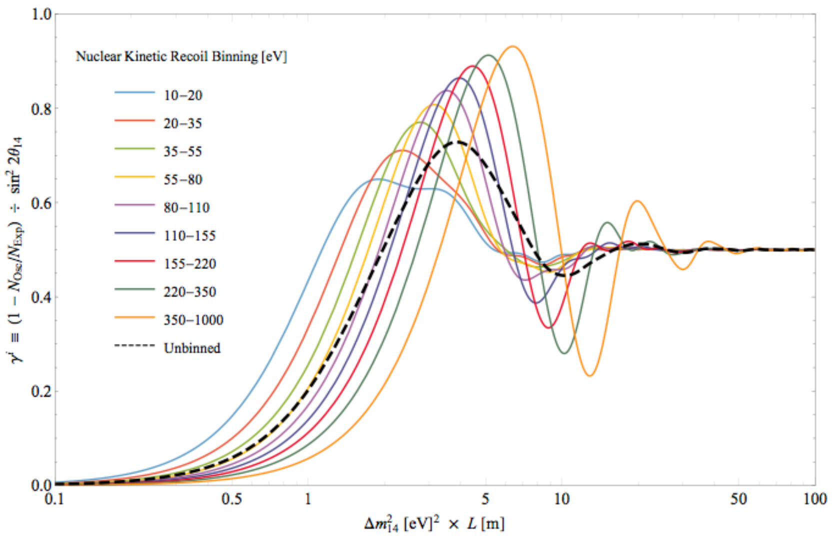
BSMsens =
10^{-3} ➔ $\Delta\sin^2\theta_W = 0.006$
10^{-4} ➔ $\Delta\sin^2\theta_W = 0.0006$

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

slide adopted from K. Scholberg

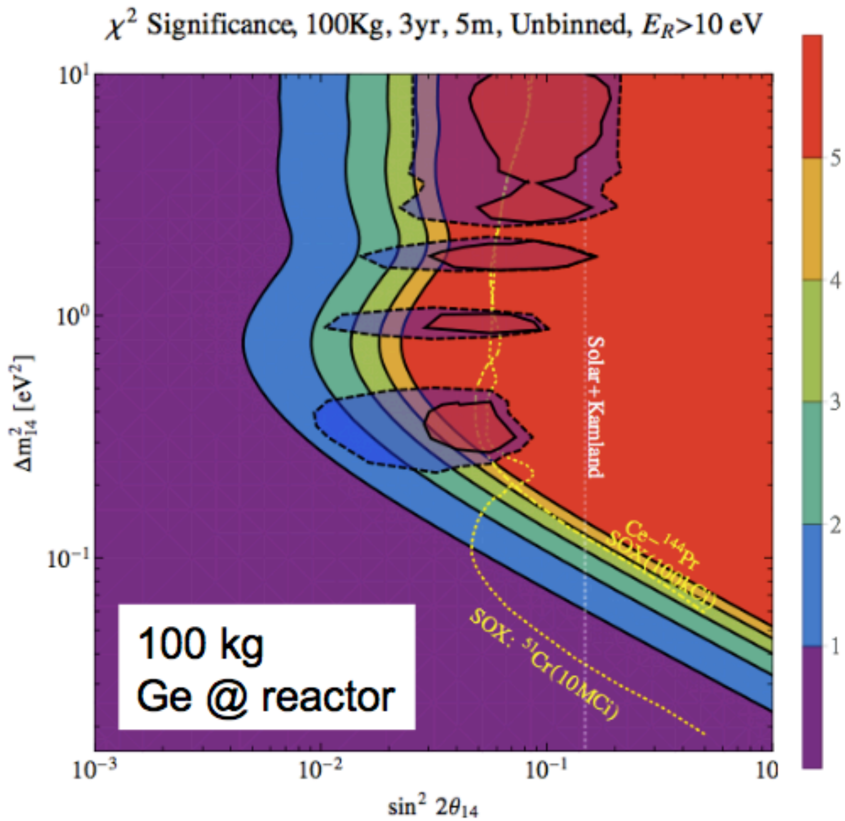
Searches for new Physics: Sterile ν's

- **Various indications / hints for sterile neutrinos**
- **Tensions with cosmology?**
- eV hints with small mixing
- keV warm dark matter with tiny mixing ≤ 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/R²**

➔ **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

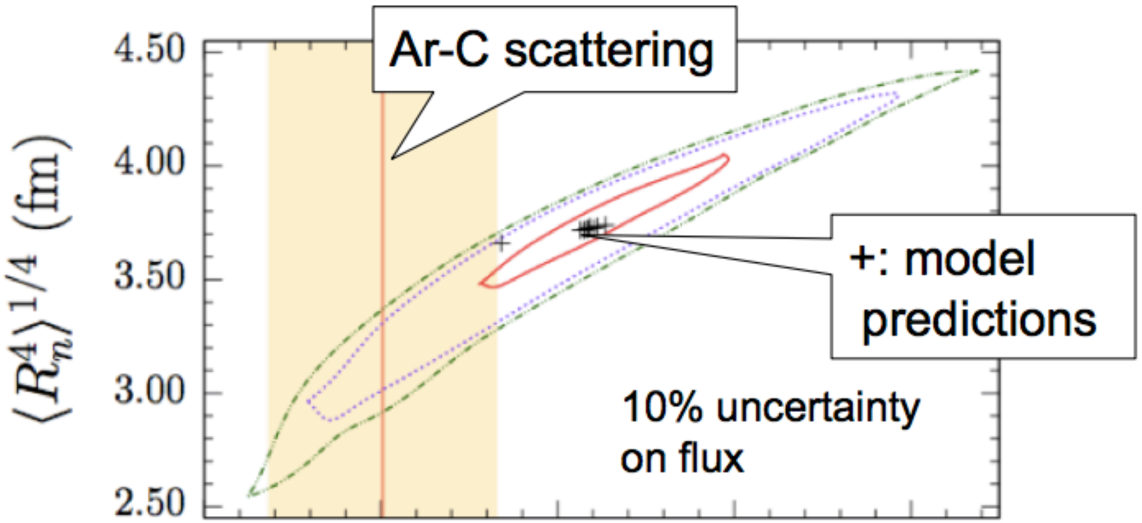
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

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

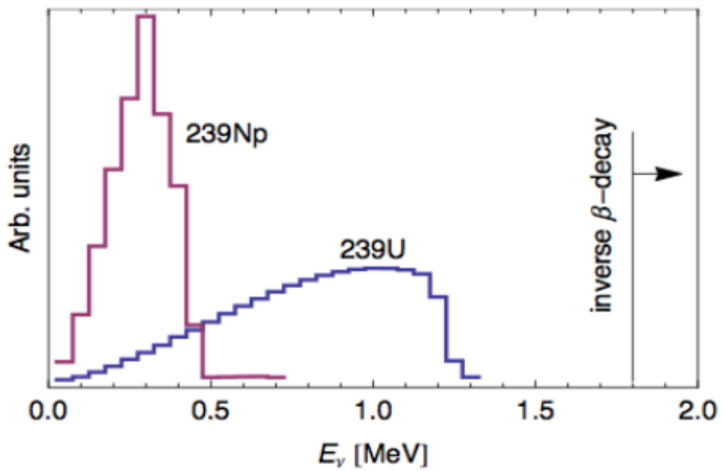


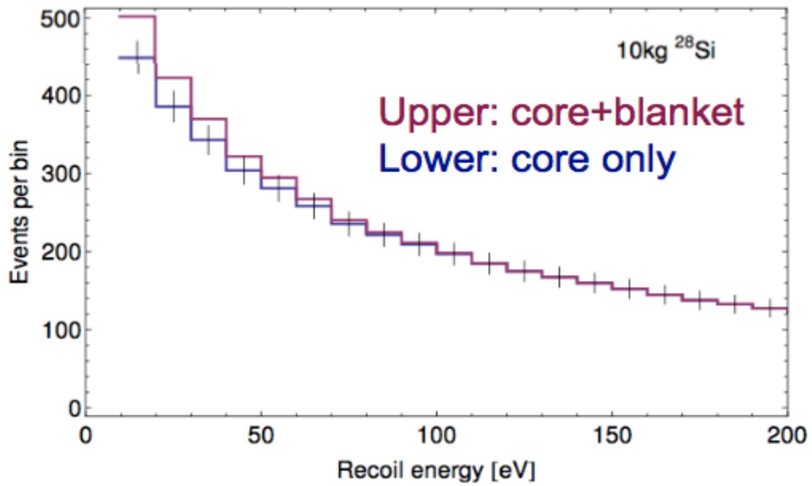
Nuclear Safeguarding

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