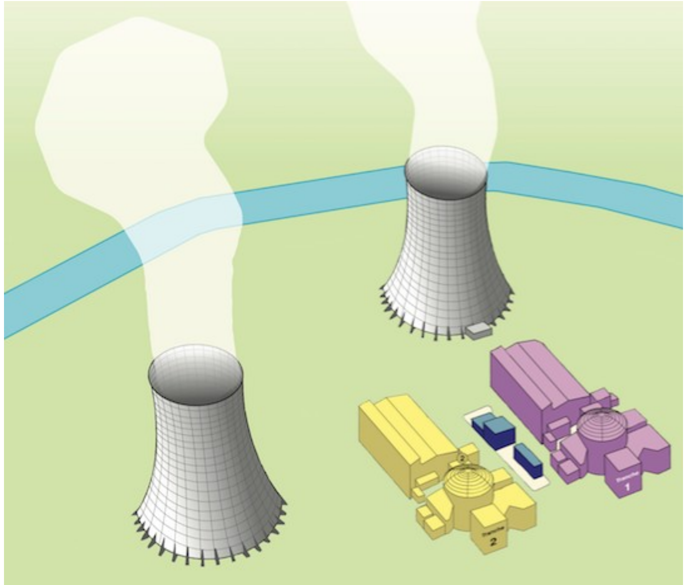
The Very-Near-Site @ Chooz:

a new Experimental Hall to Study Coherent Elastic Neutrino Nucleus Scattering



T. Lasserre[1,2], A. Langenkamper[3], G. Mention[1], Claudia Nones[1],
J. Rothe[4], R. Strauss[4], M. Vivier[1] and V. Wagner[1]

[1] CEA, Centre de Saclay, DRF/Irfu, 91191 Gif-sur-Yvette, France
[2] APC, AstroParticule et Cosmologie, Universite Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cite, 75205 Paris Cedex 13, France
[3] Physik-Department, Technische Universität München, D-85748 Garching, Germany
[4] Max-Planck-Institut für Physik, D-80805 München, Germany

GDR Neutrino Meeting , APC June 11-12 2018

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

- Well predicted SM cross-section:

$$\frac{d\sigma}{d\Omega}=\frac{G_F^2}{12\pi^2}Q_W^2 E_\nu^2(1+\cos\theta)F^2(Q^2)$$

with $Q_W=N+Z\cdot(1-4\cdot\sin^2\theta_W)$

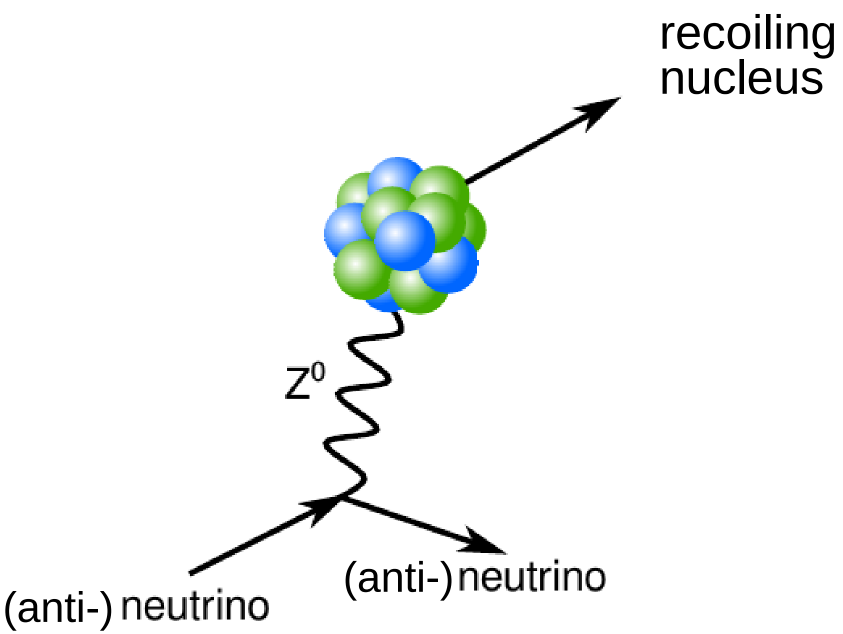
- Condition for coherence:

  fulfilled for $E_\nu < 50$ MeV

- Large cross-section with ~N^2
- In contrast to inverse beta decay (IBD):

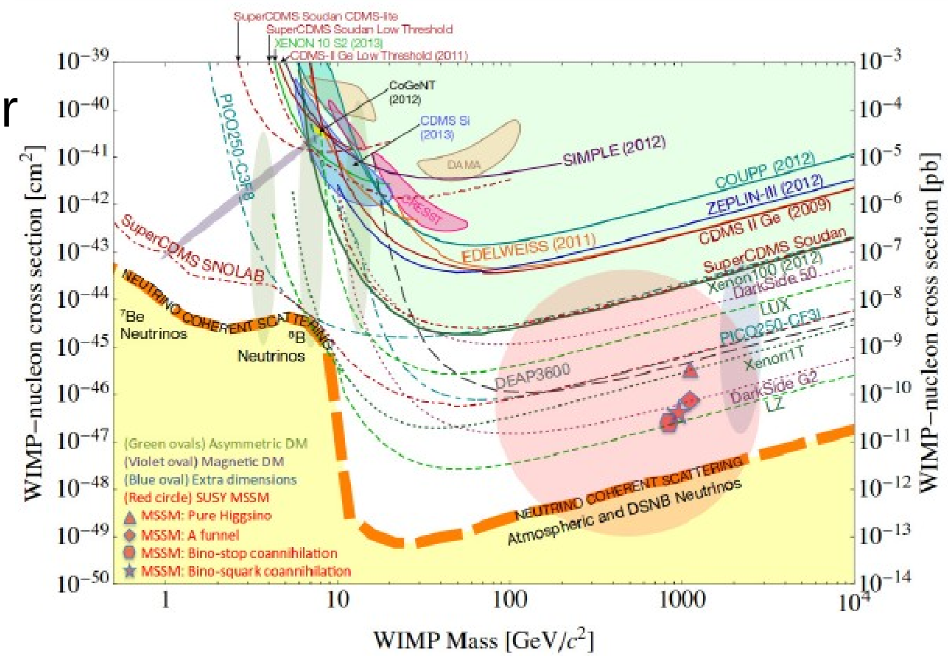
  - no energy threshold

  - flavor blind



Relevance of CEνNS

- Precision test of Standard Model (SM):
  - e.g. Weinberg angle at low energies
- Fundamental neutrino properties:
  - neutrino magnetic dipole-moment, sterile neutrinos
- Deviation from SM prediction may reveal **new physics beyond SM**:
  - new couplings, new bosons, etc.
- **Neutrino floor:** irreducible background for DM experiments from CEνNS
- Could have application in solar neutrino physics, nuclear physics, SN detection & nuclear reactor monitoring



P. Cushman et a., arXiv:1310.8327

Signature & Experimental Challenges

- Signal is a **nuclear recoil**

  - **sub keV-energy threshold detector**

  - quenching, high systematics

- **Strong CEνNS signal**:

  - high ν-flux

  - high kinetic ν-energy but in coherent regime

  - careful target (N) selection

- **Low background**:

  - ν-sources usually at shallow depth O(10 m.w.e.)

  → reduce cosmic background

nuclear recoil

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

vs

cross-section

$$\frac{d\sigma}{d\Omega} \sim N^2 \cdot E_\nu^2$$

Experimental Approaches

- Similar recoil of WIMPs and CEνNS → **WIMP detector technology**
- Many different approaches:

  - COHERENT (CsI[Na] & NaI[Tl] crystals, LAr TPC, HPGe)

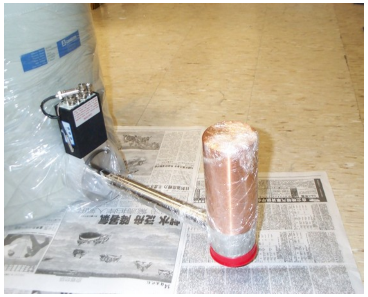
  - CONUS (HPGe)

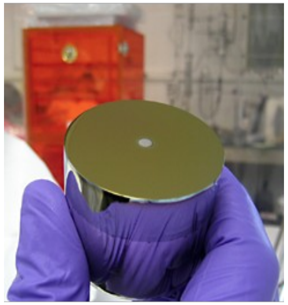
  - NU-CLEUS ($CaWO_4$ & Al_2O_3 bolometers)

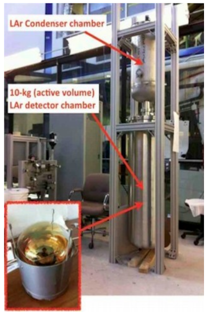
  - Ricochet (Zn & Ge bolometers)

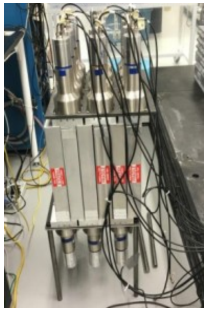
  - BASKET (Li_2WO_4 bolometers)

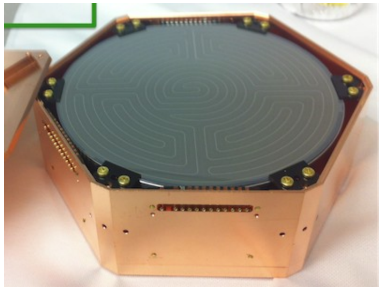
  - …

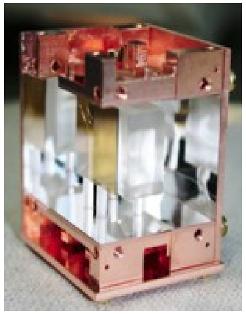












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  - Ricochet (Zn & Ge bolometers)
  - BASKET (Li_2WO_4 bolometers)
  - …

Cryogenic Bolometers

- Very low energy threshold (< 100 eV_{nr})

$\Delta T = \Delta E / C$ — thermometer & absorber material

weak thermal link

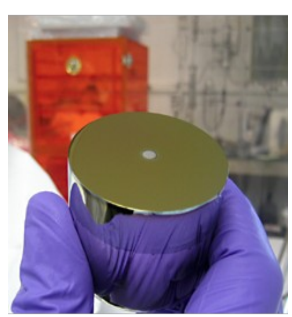
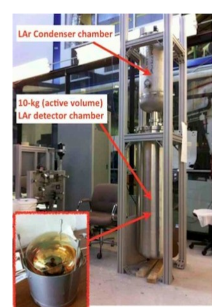
heat bath @ ~10mK

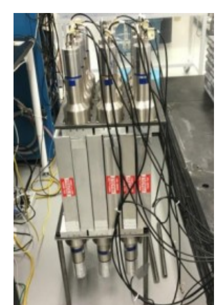
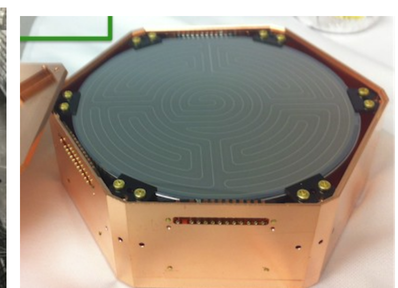
Bolometers At Sub KeV Energy Thresholds

NU-CLEUS

RICOCHET — A Coherent Neutrino Scattering Program



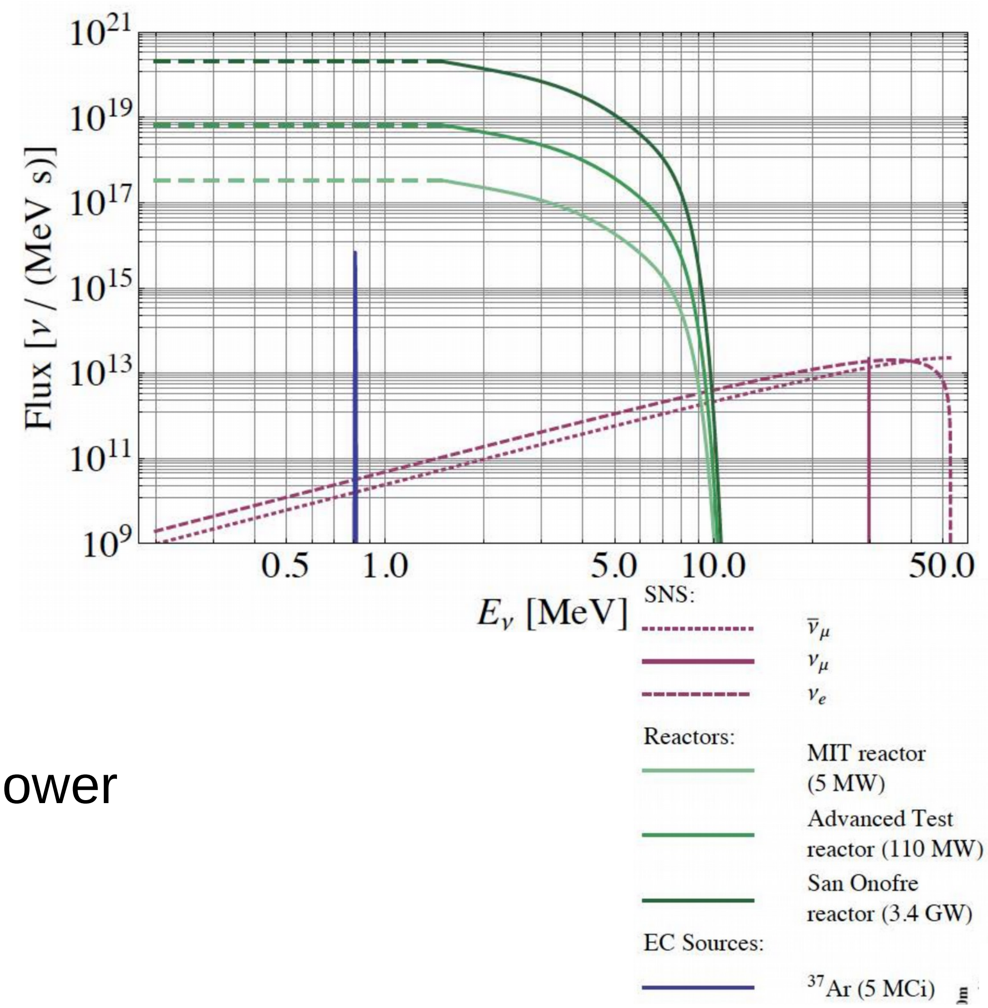




Neutrino Sources

- **Stopped π-decay at rest (DAR)** such as Spallation Neutron Source (SNS) @ Oak Ridge National Lab
  - **high E_ν** up to 50 MeV
  - ν-flux at SNS is 10^7 /s/cm^2 20 m from the mercury target
  - pulsed beam → bck rejection
  - but: possible neutron bck
- **Reactor ν's**:
  - low E_ν
  - very **high flux** (**10^{12} - 10^{13} ν/s/cm^2**)
  - CEνNS signal correlated to reactor power

taken from talk by J. Collar at NUINT 2017, Toronto



First Observation of CEνNS

… more than 40 years after its prediction

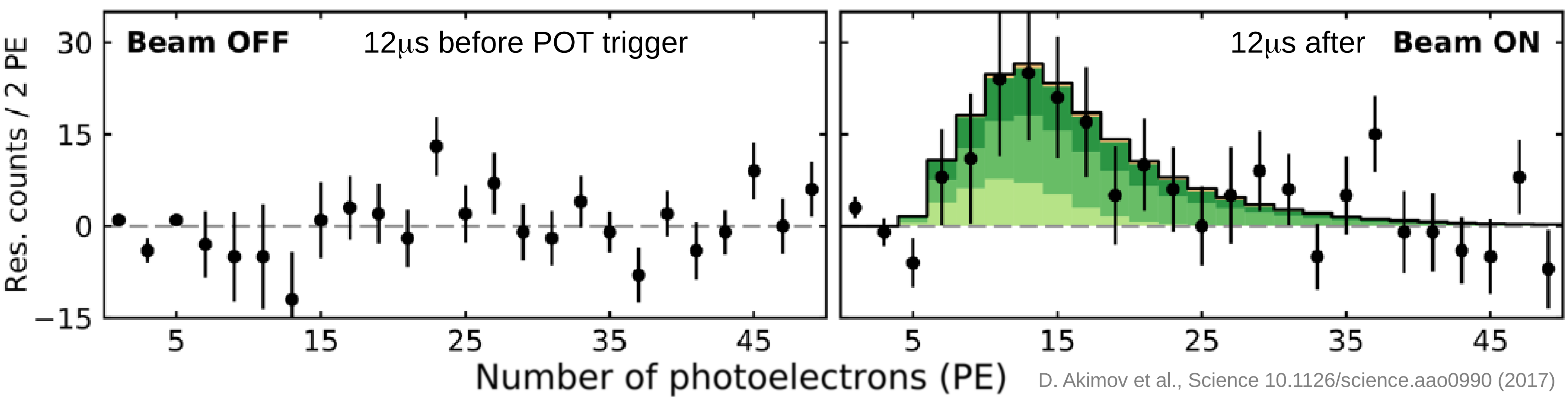
COHERENT Experiment

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

- 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

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)

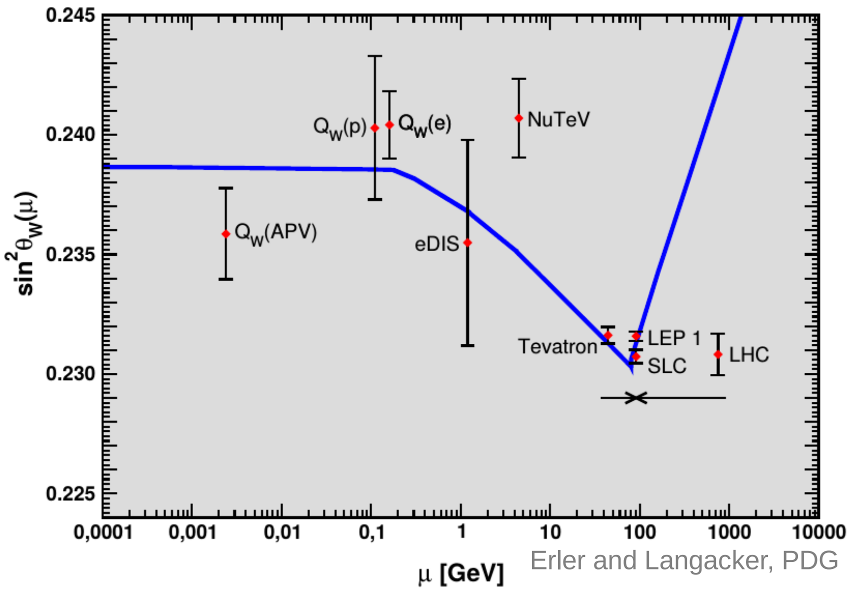
CEνNS @ Power Reactors

Reactor neutrino spectrum

- E_ν < 10 MeV

  → fully coherent

  → allows to probe SM @ low energies

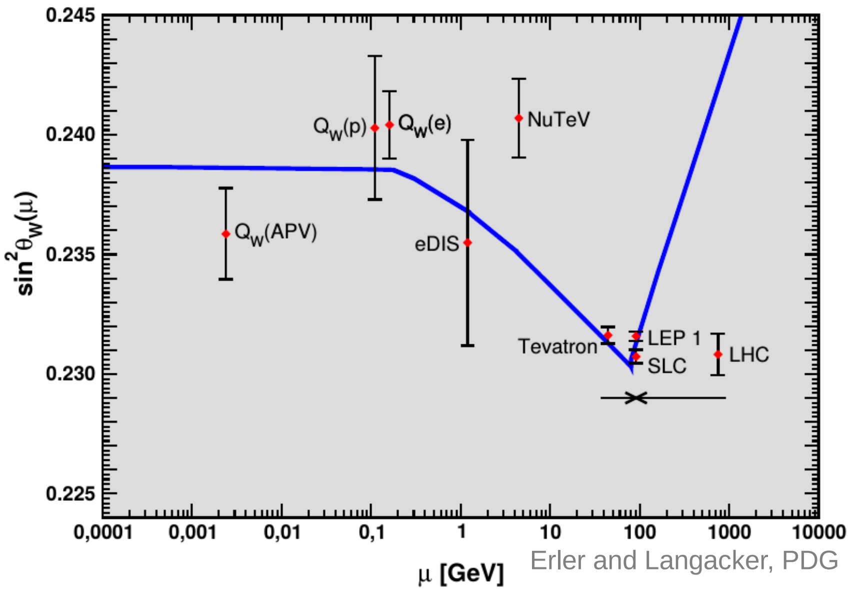


Erler and Langacker, PDG

First hint for CEνNS of reactor-ν :

- Presented @ Neutrino '18 by CONUS
- E_{th} ~ 300 eV_{ee} (→1-2 keV_{nr})
- 2.4 σ significance for excess in reactor ON over OFF data (statistics only) @

CEνNS @ Power Reactors



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Precision measurement of CEνNS @ low energies

- New gram-size bolometric detectors with extremely low threshold O(< 100 eV_{nr})
- New experimental site close (~100m) to reactors
- Active and passive shielding for background suppression

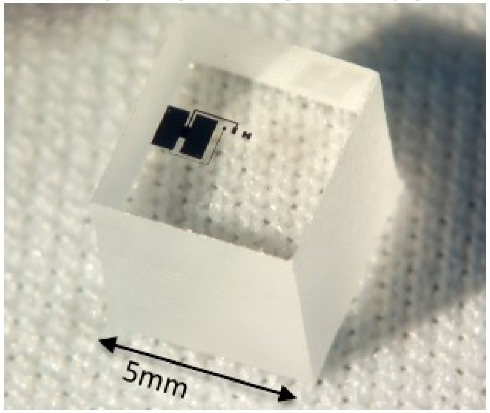
NU-CLEUS

technology concept (R. Strauss et al., Eur. Phys. J. C 77 (2017) 506)

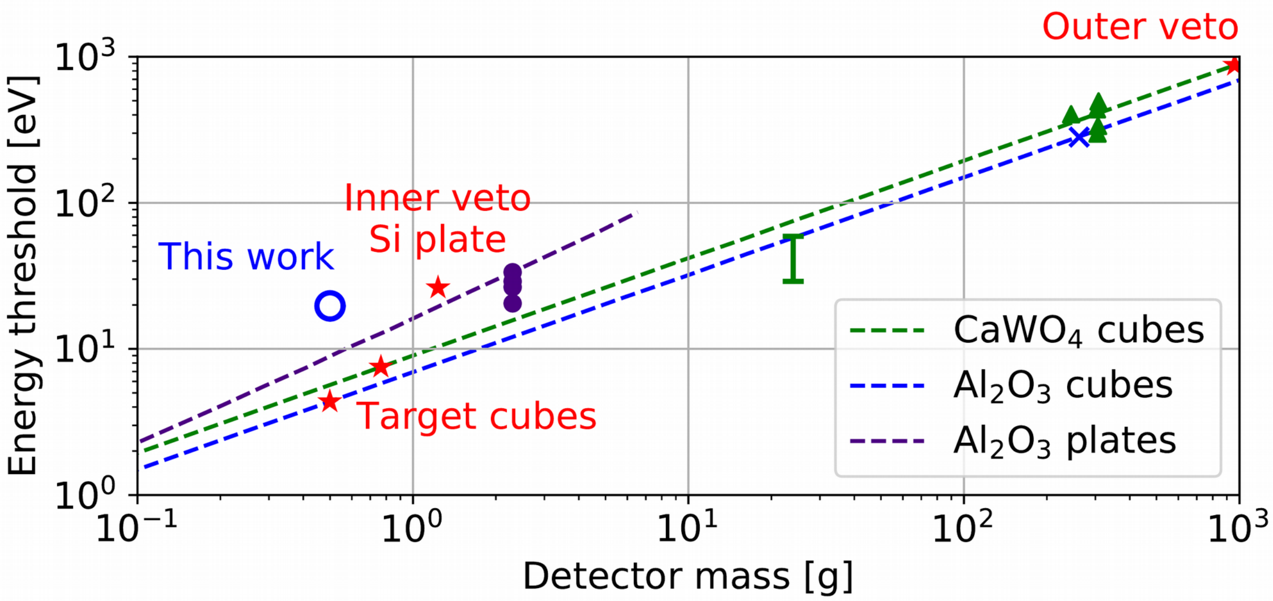
Gram-scale Cryogenic Calorimeter

- Based on CRESST technology
  - → $CaWO_4$, Al_2O3
  - → transition edge sensor (TES)
  - → $E_{th} \sim M^{2/3}$
  - → $E_{th} = (19.7 \pm 0.9)$ eV

0.5g saphire prototype



from R. Strauss



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→ fast rise-time: $\tau_{RT} = 0.1$ ms
+ precisely known pulse on-set

→ on-set critical for timing with muon-veto and resulting dead-time

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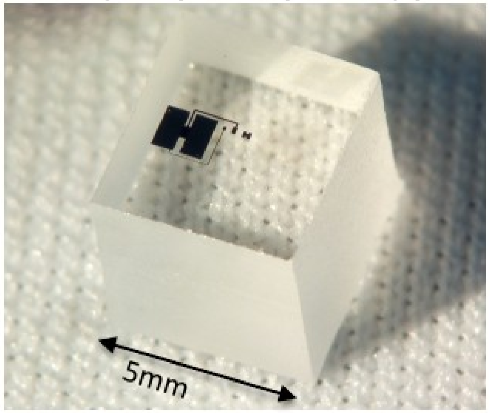
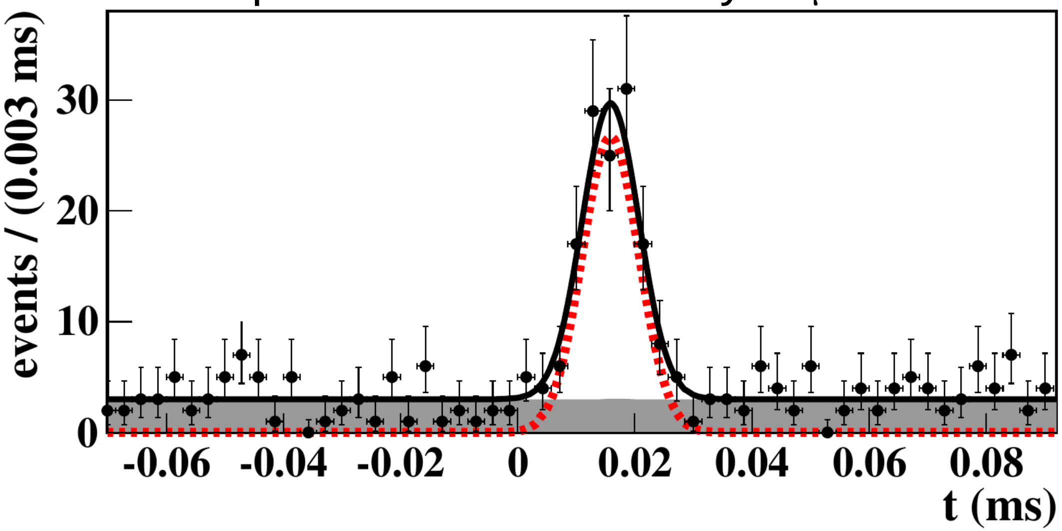


from R. Strauss

pulse onset uncertainty ±5μs



Eur. Phys. J. C 74(7), 2957 (2014).

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muon-veto and resulting dead-time

→ fiducial-volume cryogenic calorimeters
for **active background suppression**
of α/β-surface and external γ/n

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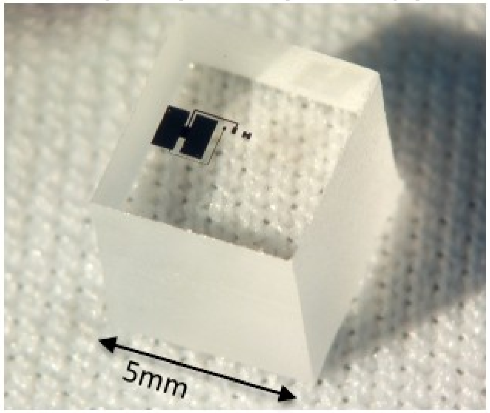

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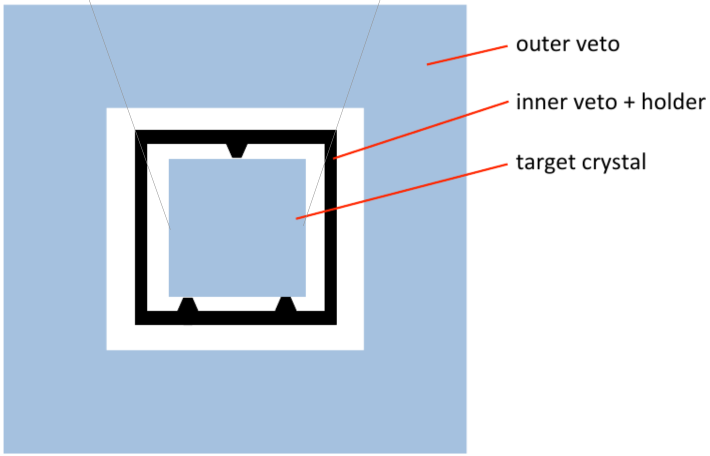
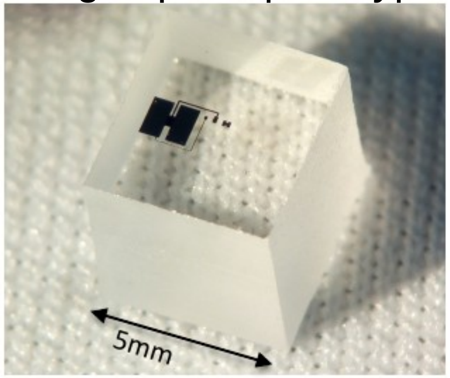


NU-CLEUS Status

- Prototype demonstrated that NU-CLEUS technology is suitable for next generation CEνNS experiment

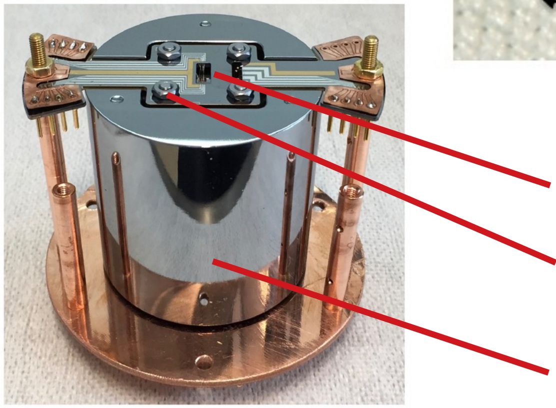
- **Next step**: 1g NU-CLEUS demonstrator fully commissioned in April 2018

0.5g saphire prototype



from R. Strauss

NU-CLEUS 1g



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NU-CLEUS Status

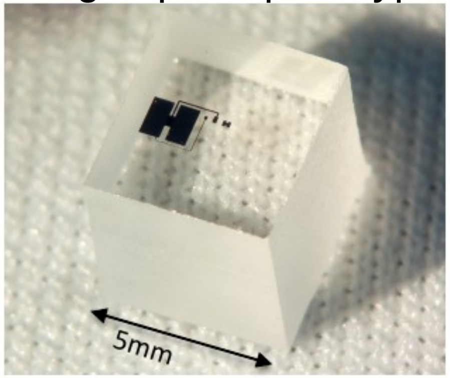
- Prototype demonstrated that NU-CLEUS technology is suitable for next generation CEνNS experiment

- **Next step**: 1g NU-CLEUS demonstrator fully commissioned in April 2018

- CEνNS measurement with 10g target array

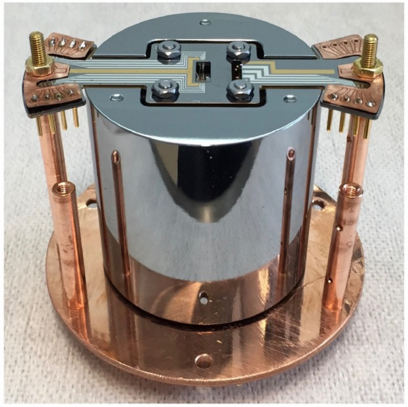
- Technology scalable to larger masses

0.5g saphire prototype



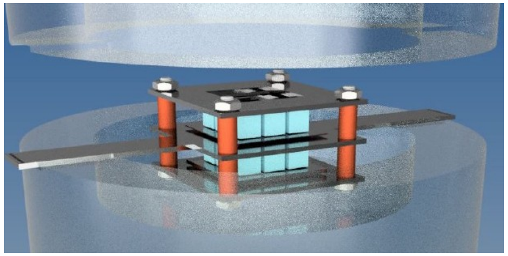
from R. Strauss

NU-CLEUS 1g

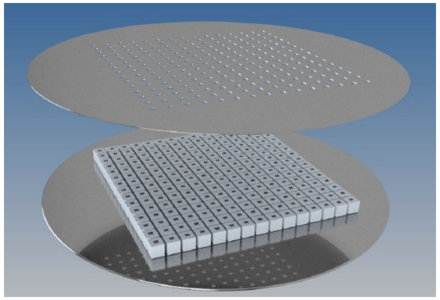


from R. Strauss

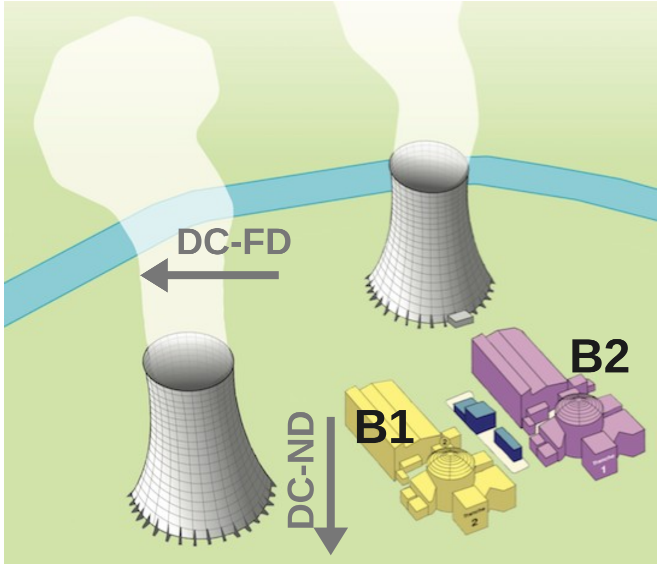
NU-CLEUS 10g



NU-CLEUS 10kg

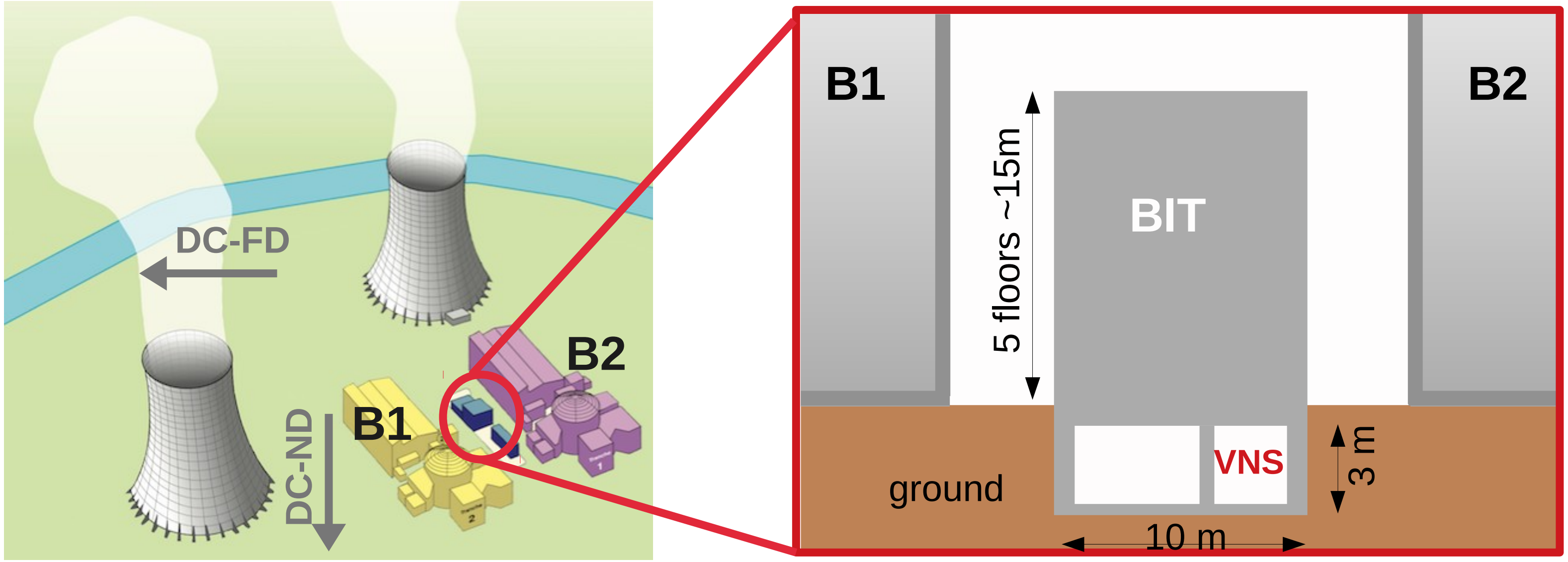


The Chooz Power Plant



- **Commercial nuclear power** plant in Chooz in the Ardennes region
- Operated by EdF
- 2 reactor cores with max. thermal power of **4.25 GW**
- Host of the Double Chooz experiment → CEA has good relation and experience with EdF
- Activities decoupled from Double Chooz → new agreement between CEA and EdF being drafted

The Very-Near-Site @ Chooz

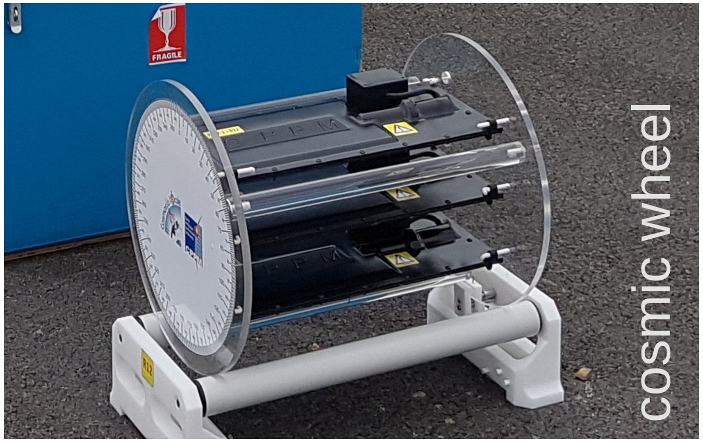


- 24m² room in an administrative building in-between the two reactors
- Distance to reactor core **72 m and 102 m**
- Expected ν flux O(**10^{12} ν/s/cm²**)
- ν energy up to **8 MeV** → fully coherent
- **< 5 m.w.e.** overburden

Site-Characterization started October 2017

Background Characterization Measurements

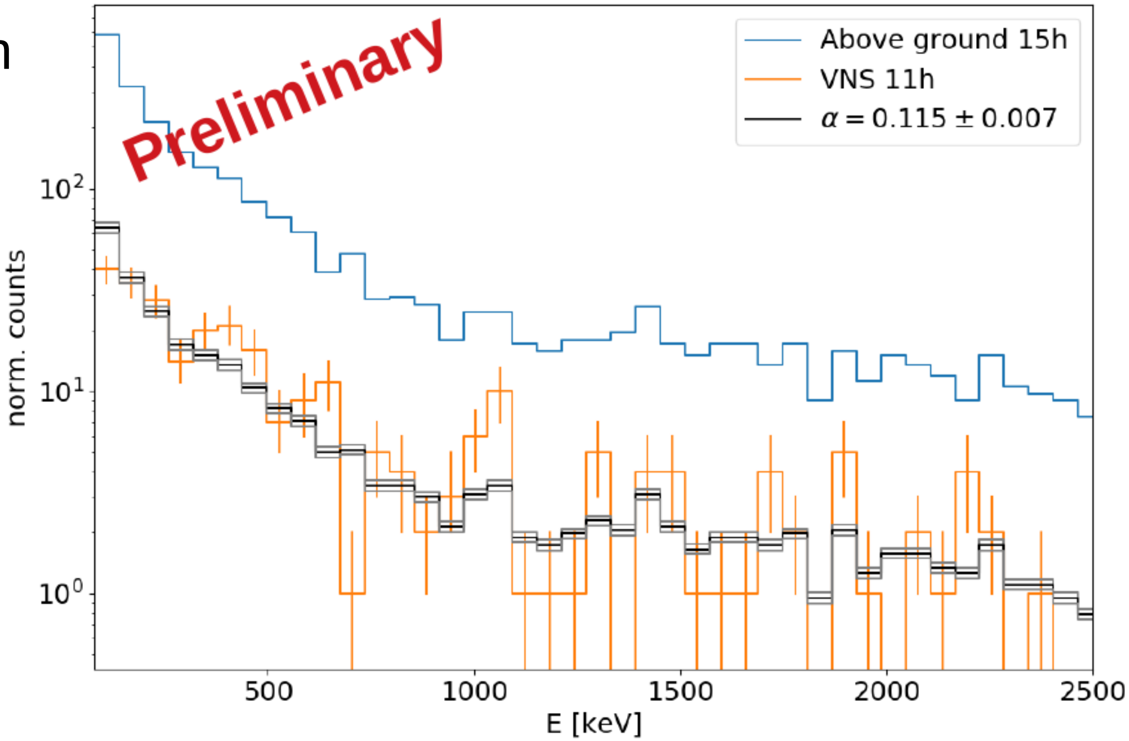
- Campaign to characterize neutron- and muon-background started
- Measurements performed at surface and VNS to determine the attenuation
- Results will be used to optimize the design of a compact shielding and evaluate the backgrounds in the detectors



Neutron Attenuation

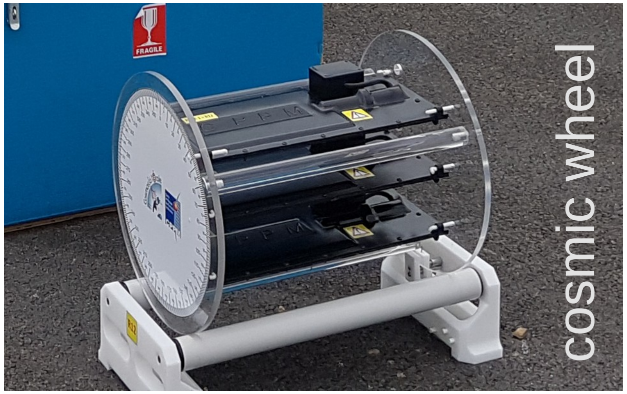
- Liquid scintillator cells from TUM
- Neutrons are expected to be most dangerous background
- Don’t expect neutrons from reactor cores, only muon induced neutrons
- Preliminary results give a neutron attenuation of factor of ~8
- No change in the spectrum observed with respect to surface

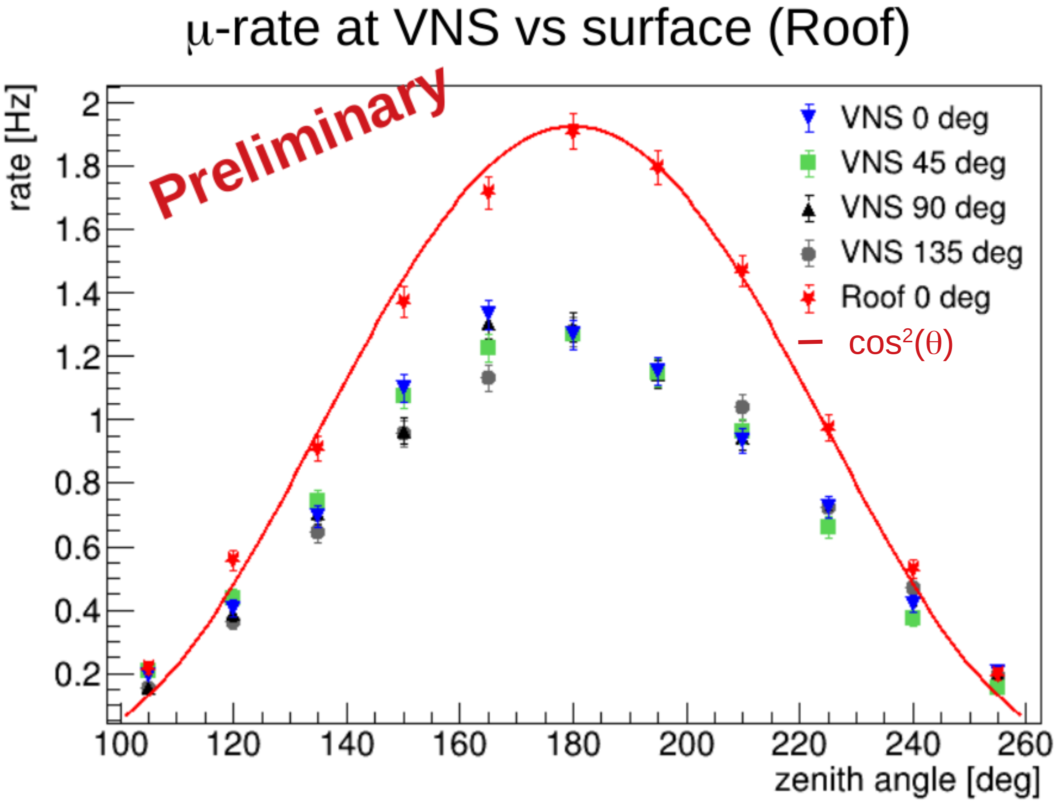
n-rate at VNS vs surface



Muon Attenuation

- Cosmic wheel from « Science à l'école » outreach program, developed by CPPM Marseille
- Preliminary results give a muon attenuation of factor of ~1.4
- Overburden ~ 3 m.w.e.





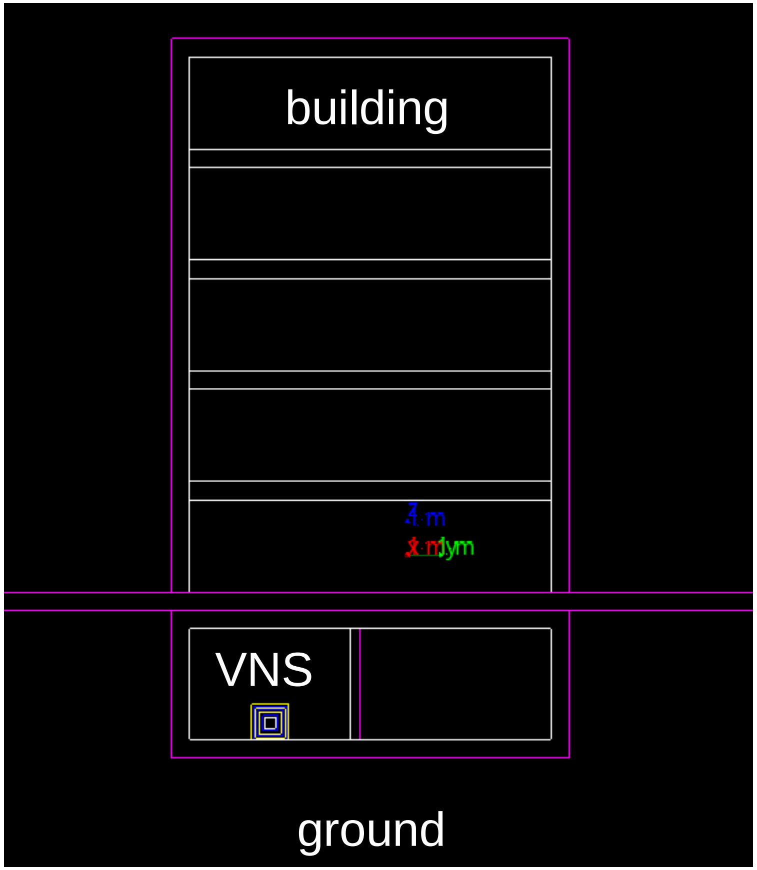
Muon MC Simulations

- Development of full MC simulation package on-going
- Results of background measurements taken as input
- Main goals of simulation studies:

  → attenuation of muons and neutrons from building

  → optimization of shielding: neutron/ gamma production in passive shielding

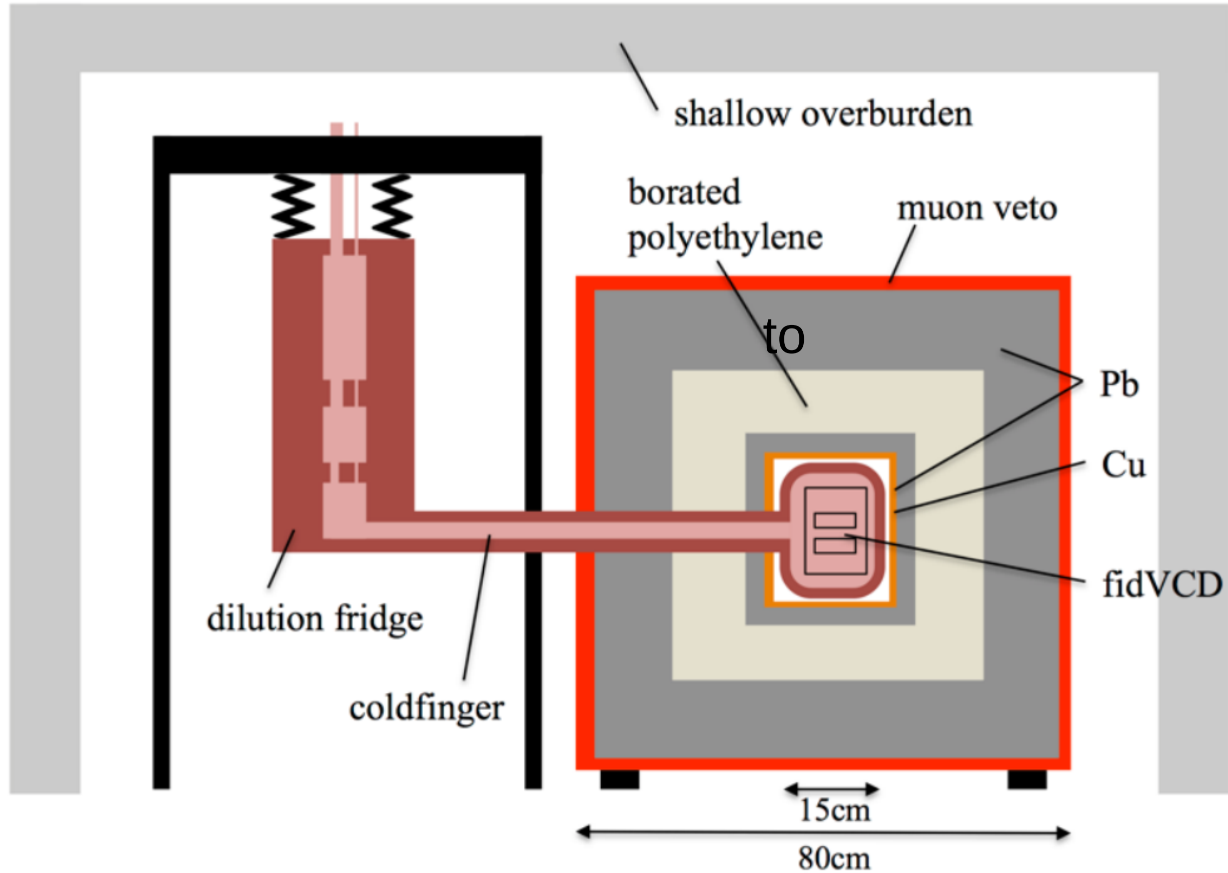
  → optimization of muon veto



Compact Shielding

Multi-layer active & passive shielding

- Outer active muon veto
- Borated polyethylen moderate and capture neutrons
- Lead to attenuate γ's



from R. Strauss

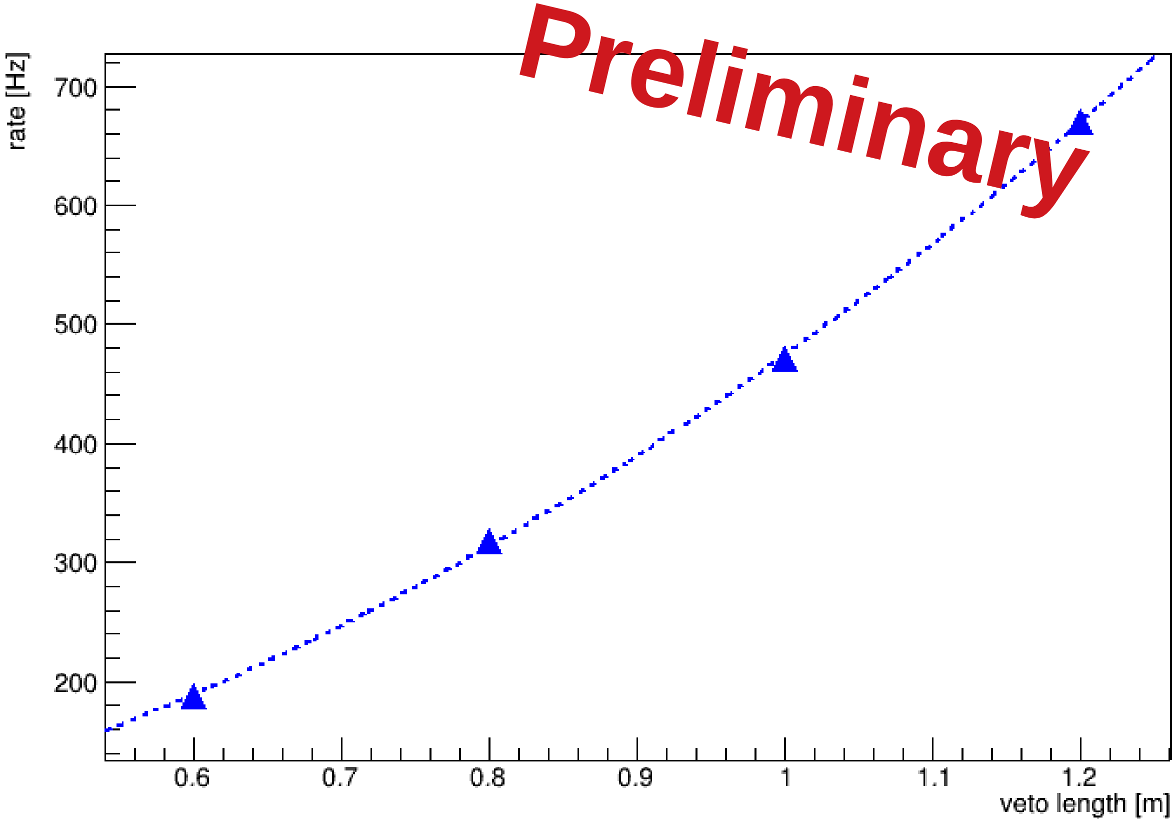
- Many examples that low background levels even at shallow depths are feasible with such a multi-layer design:

  → GIOVE detector @ MPIK: 0.4 counts/ keV/ kg/ day

  → Dortmund low-background facility 5 counts/ keV/ kg/ day

Muon-Veto Simulations

- Trade-off between size of passive shielding for large attenuation and size of muon-veto
- First MC simulation of the muon-veto yield an expected muon-trigger rate < 500 Hz for a 1m^3 shielding
- Fast rise-time of NU-CLEUS detectors implies a dead-time of 1%
- with NU-CLEUS a muon-veto up to the size of 2m x 2m x 2m is feasible
- Open question:
  muon veto efficiency needed

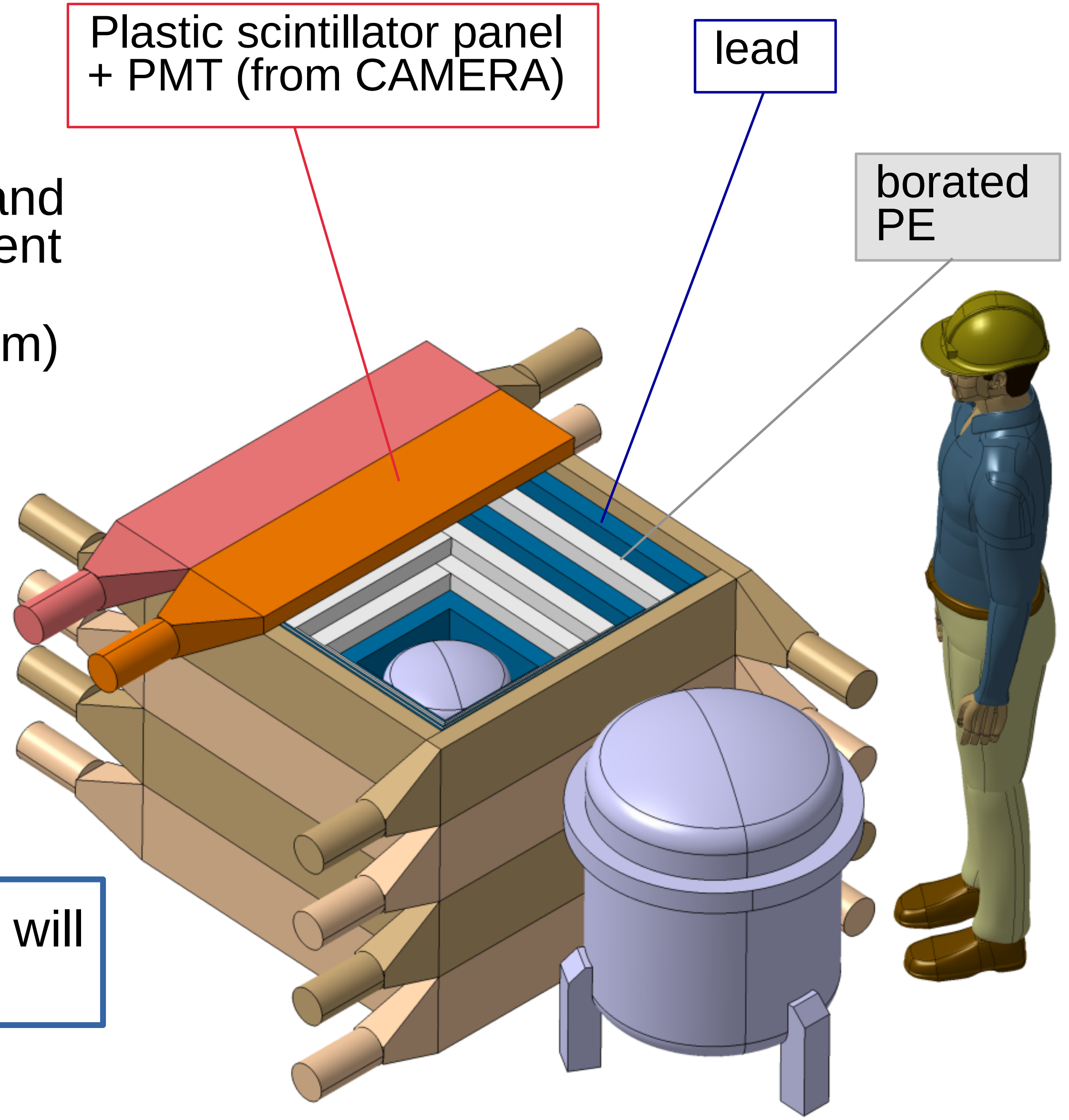


Muon Veto

- Compact active muon-veto ~1m^3
- Re-use plastic scintillator panels and PMTs from the CAMERA experiment
- Principle: scintillator thickness (5cm) large enough such that muons (2 MeV/cm) deposit energy well above 2.6 MeV

  → discrimination of muons from gamma's

- First prototype of scintillator panel will be tested in summer



First sketch by Loris SCOLA (CEA)

Summary and Outlook

- Precision measurement of coherent elastic neutrino nucleus scattering (**CEνNS**) may open the door to **new physics**
- **Very-Near-Site (VNS) at Chooz** is a promising experimental side for a new CEνNS experiment
- On-going background and simulation campaign to **fully characterize the VNS**
- EdF very supportive for project
- **NU-CLEUS** is a very promising detector technology:

  - based on well established CRESST technology

  - demonstrated to be able to run in above ground conditions like at VNS

  - first results from demonstrator will come soon
- Discussing possibility to join efforts with NU-CLEUS and Ricochet in a consortium

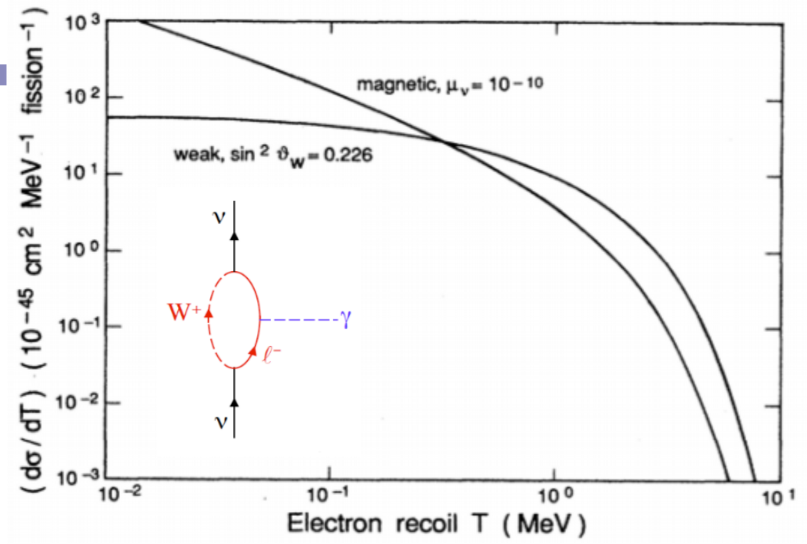
Bonus Slides

BSM with CEνNS

from M. Lindner @ CNNP2017

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{12\pi^2} Q_W^2 E_\nu^2 (1+\cos\theta) F^2(Q^2)$$

$$Q_W = N - (1 - 4\cdot\sin^2\theta_W)$$



Search for BSM

- Neutrino magnetic moment
  → adds term to CEνNS cross section and changes recoil spectrum
- Non-Standard ν-Interactions (many possible channels)
  → changes Q_W and, thus, magnitude of cross-section and recoil spectrum
- Sterile Neutrinos
  → CeνNS flavor blind, thus, insensitive to active flavor oscillations → measure $1/R^2$ flux dependence

Precision Test of SM

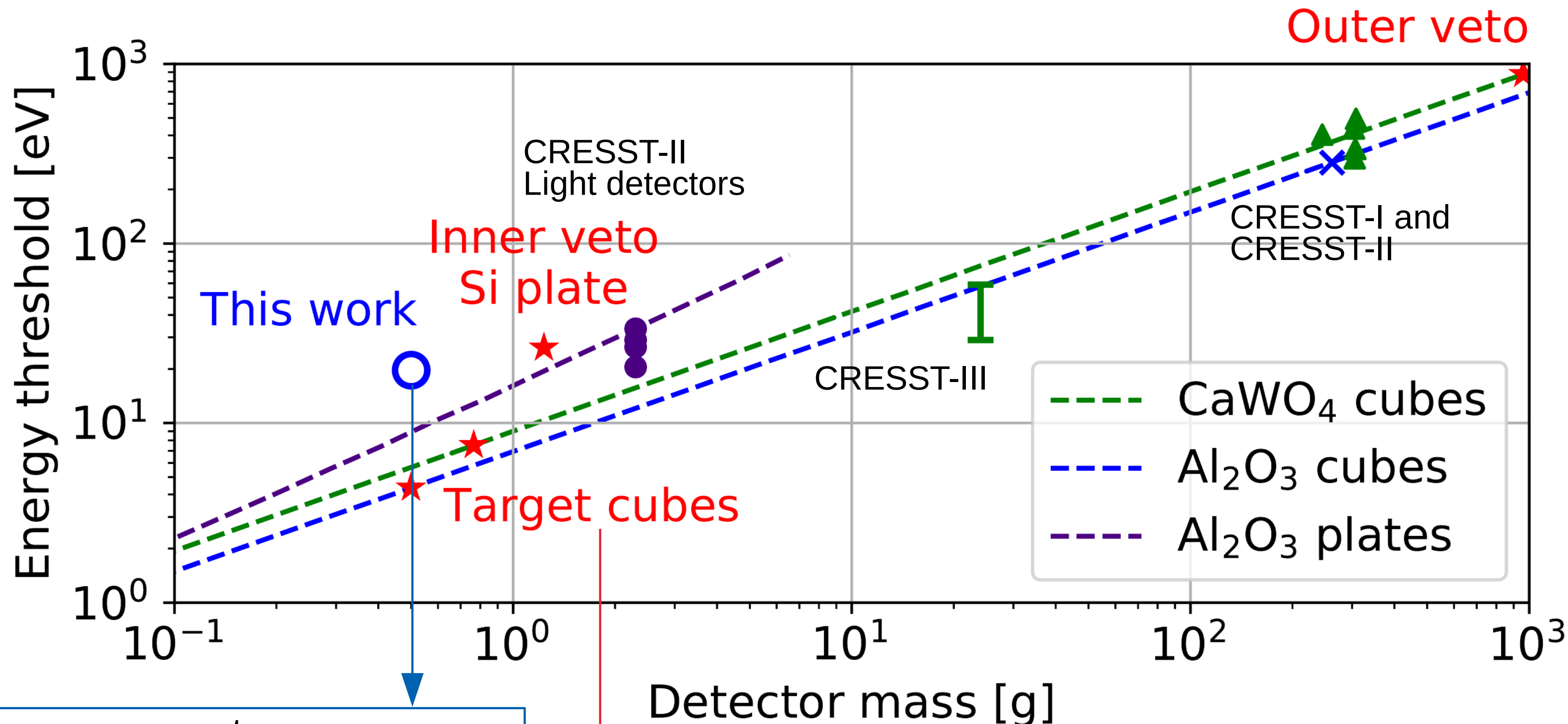
- Measurement of $\sin^2\theta_W$ at low energies
  → $Q_W = Q_W(\sin^2\theta_W)$, thus, cross-section / recoil spectrum

Nuclear Physics

- Measurement of form factor $F(Q^2)$

Energy Threshold of ν-cleus Detectors

R. Strauss et al., Eur. Phys. J. C 77 (2017) 506

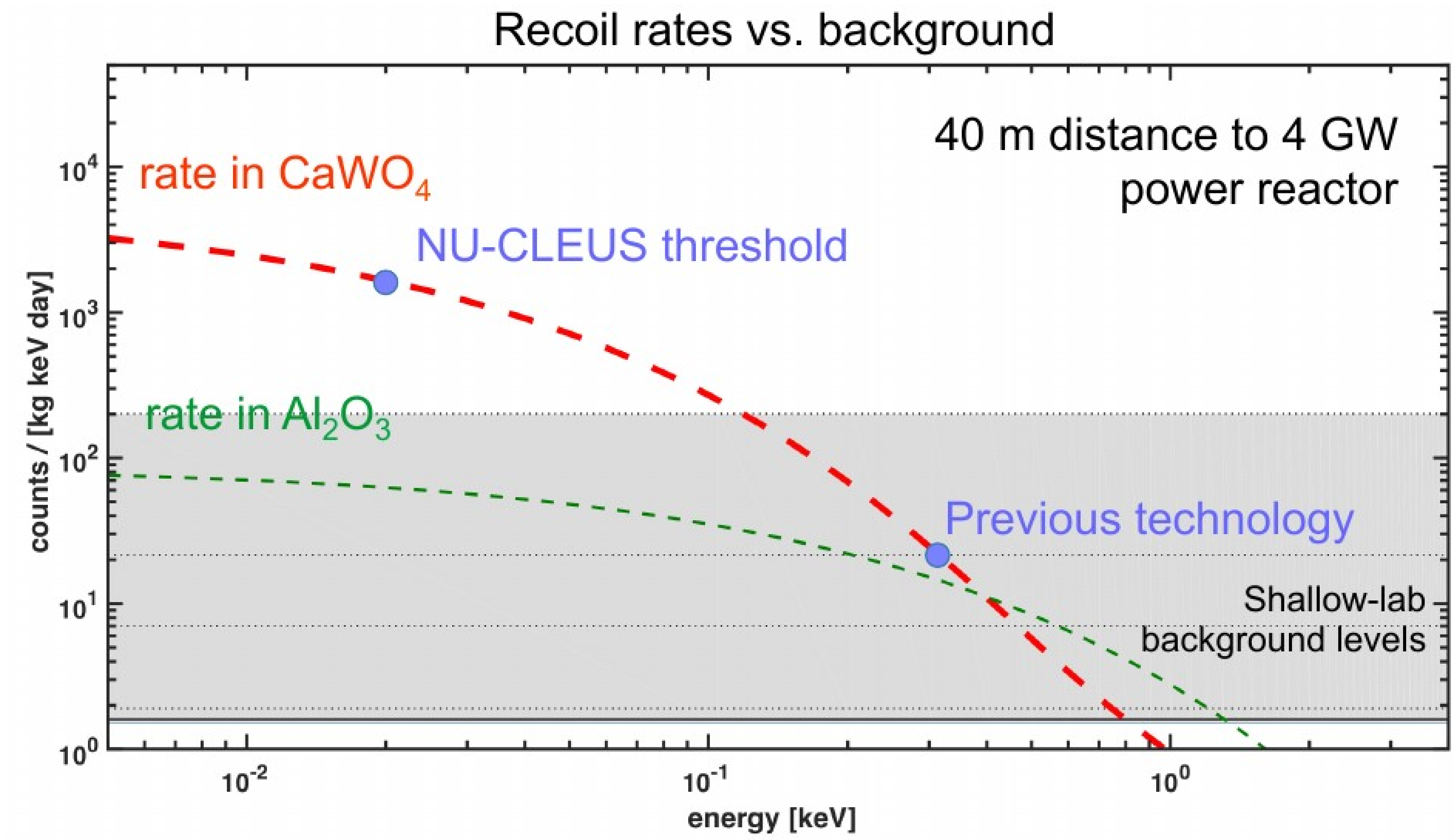


measurement:
E_{th} = (19.7 ± 0.9) eV (Al_2O_3)
non-optimized noise

Model: E_{th} ~ 4 keV (Al_2O_3)
E_{th} ~ 7 keV ($CaWO_4$)

CENNS Recoild Rates in NU-CLEUS

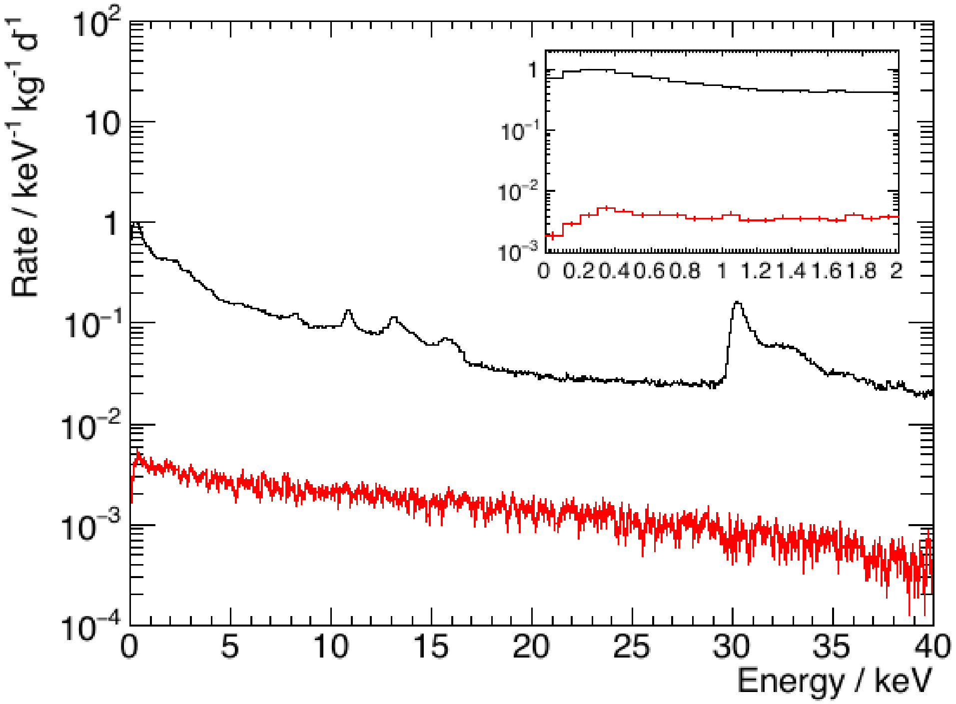
Eur. Phys. J. C, C77(8):506, 2017 arXiv:1704.04320



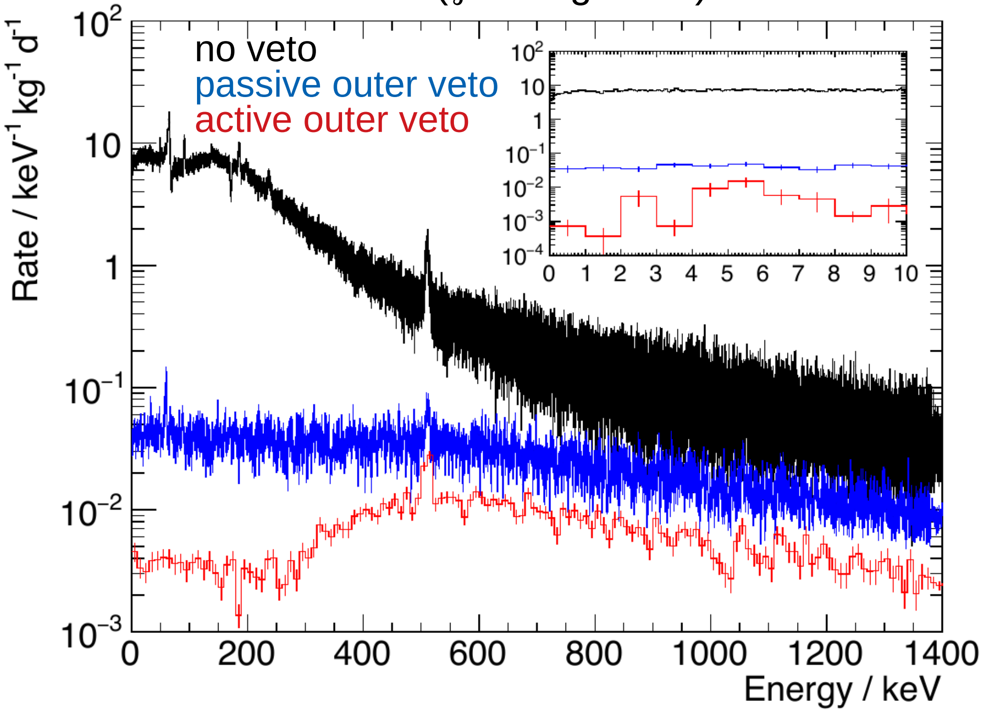
Fiducial-Volume Cryogenic Detector

R. Strauss et al., Eur. Phys. J. C 77 (2017) 506

MC simulation (β-background Po-210) - inner veto

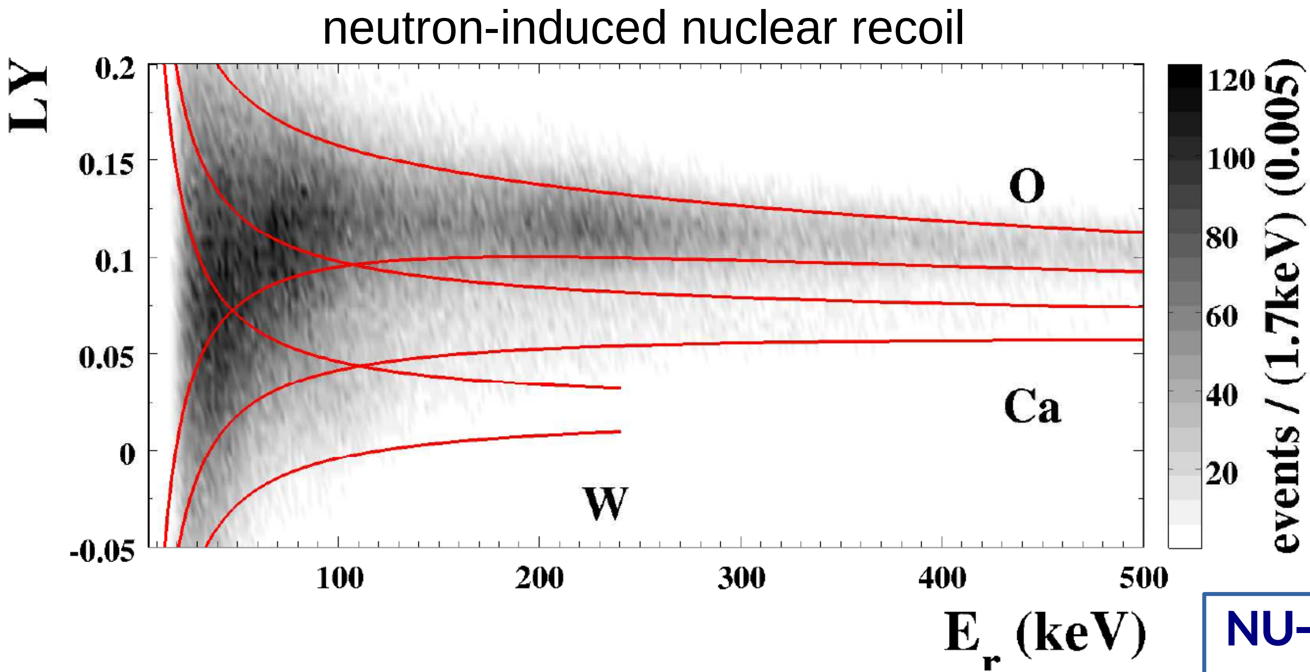


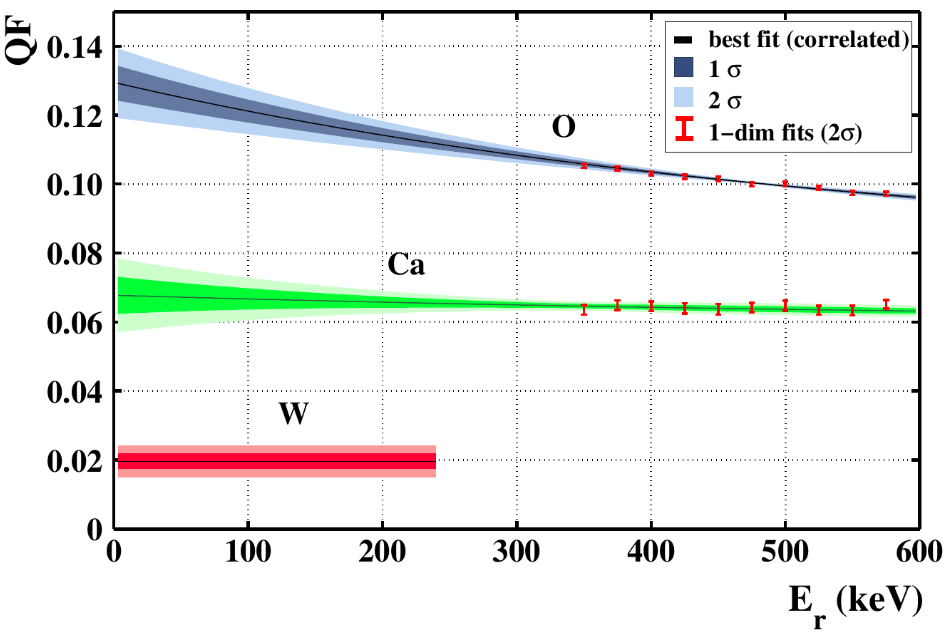
MC simulation (γ-background) - outer veto



Quenching

arXiv:1401.3332v2 & 1410.1753

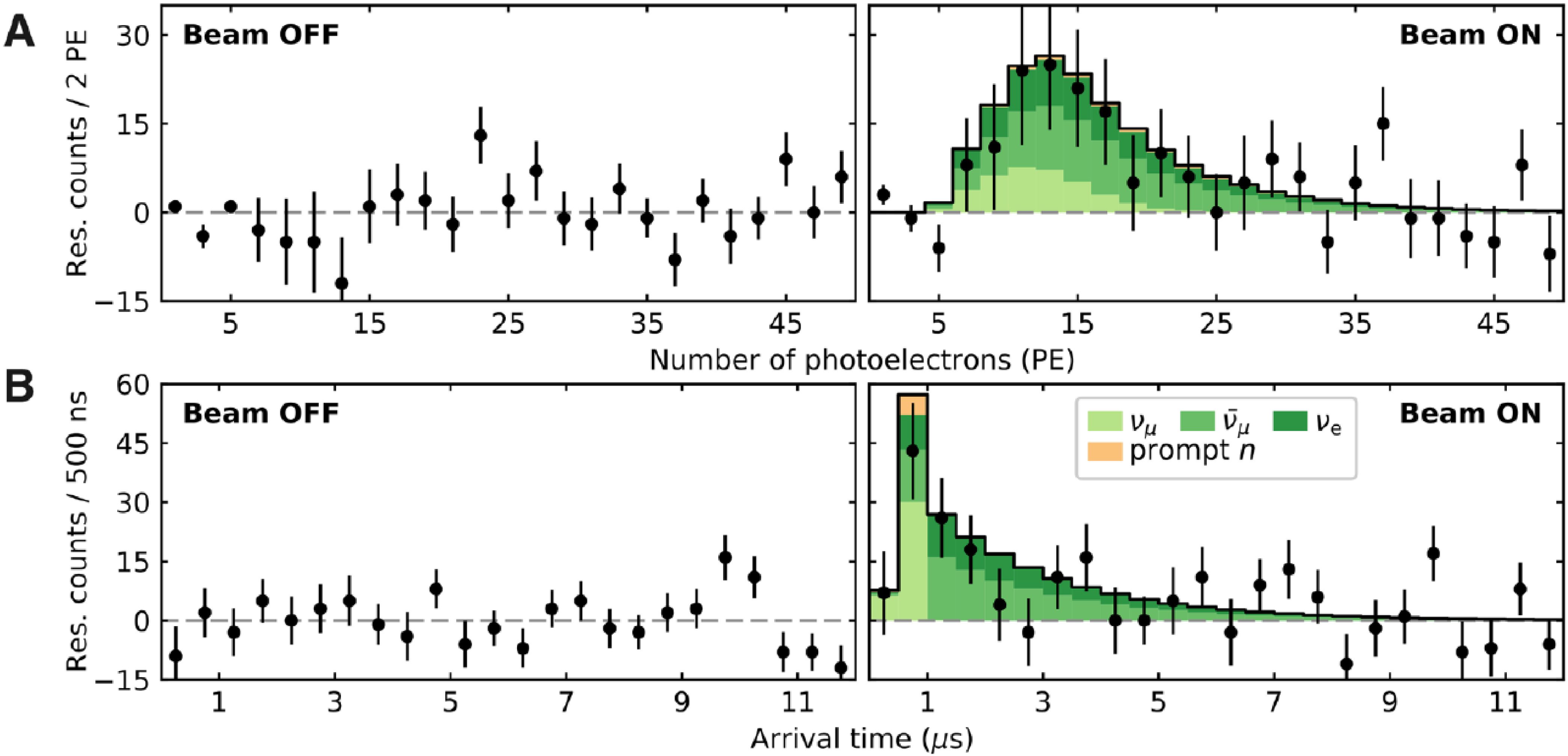




NU-CLEUS detectors

- Nuclear recoils have an O(5%) higher phonon signal compared to electron recoils of the same energy
- (Light) quenching is well measured for CRESST detectors → used to correct phonon energy for heat quenching

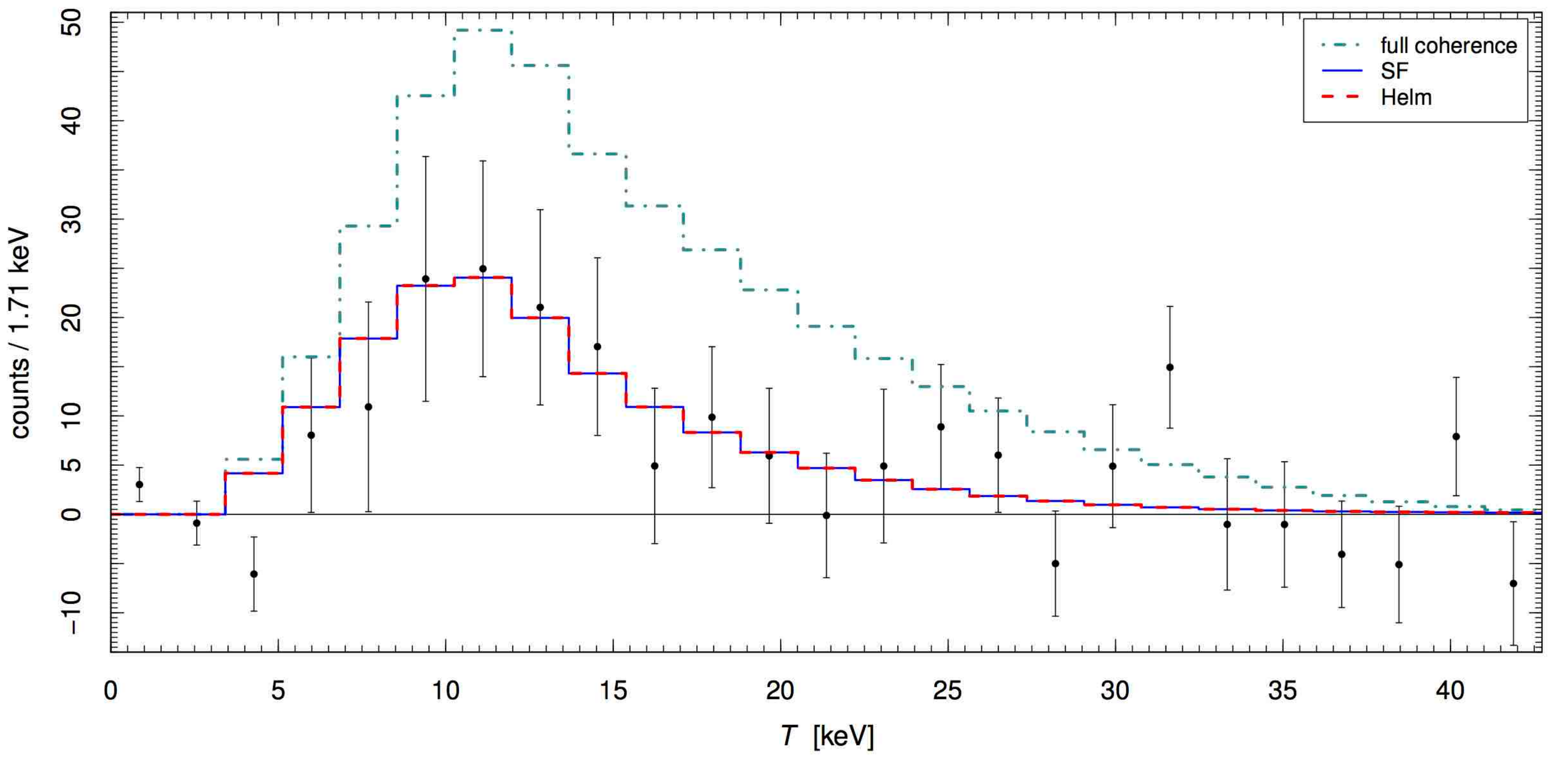
Cite as: D. Akimov *et al*., *Science*
10.1126/science.aao0990 (2017).



residual differences between signals in the 12 μs following POT triggers, and 12-μs before

Suppression of Coherence

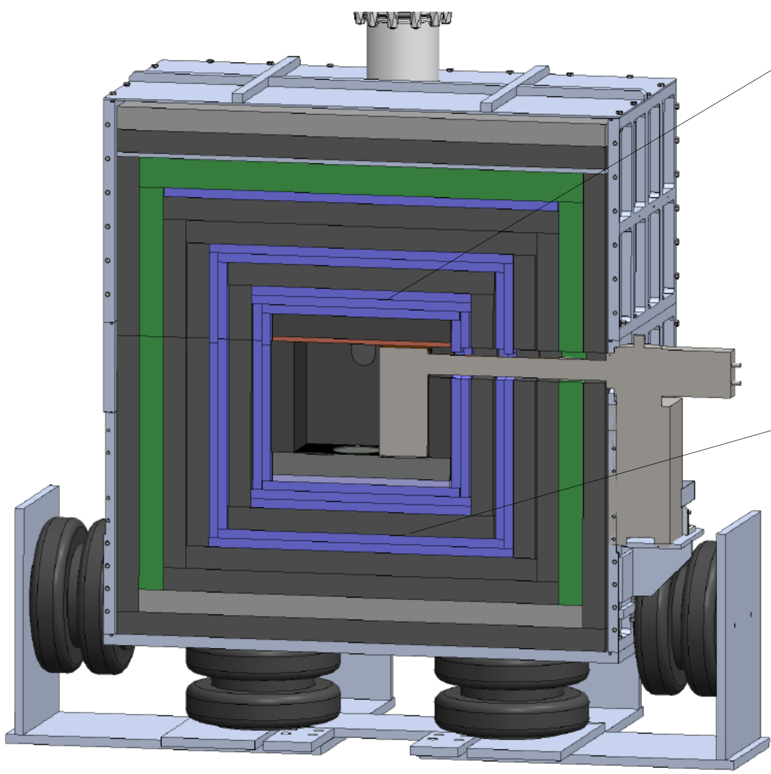
2.3σ evidence of nuclear structure suppression of coherence

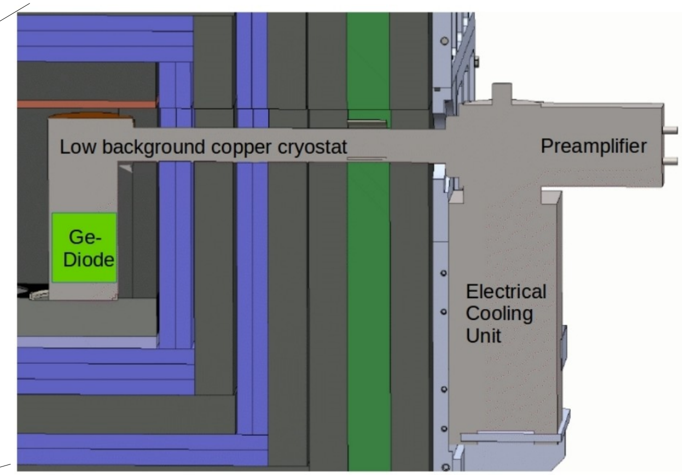


arXiv:1710.02730v3

The CONUS Project @ MPIK

- **low threshold point contact HPGe** in novel **active and passing shielding** for background reduction





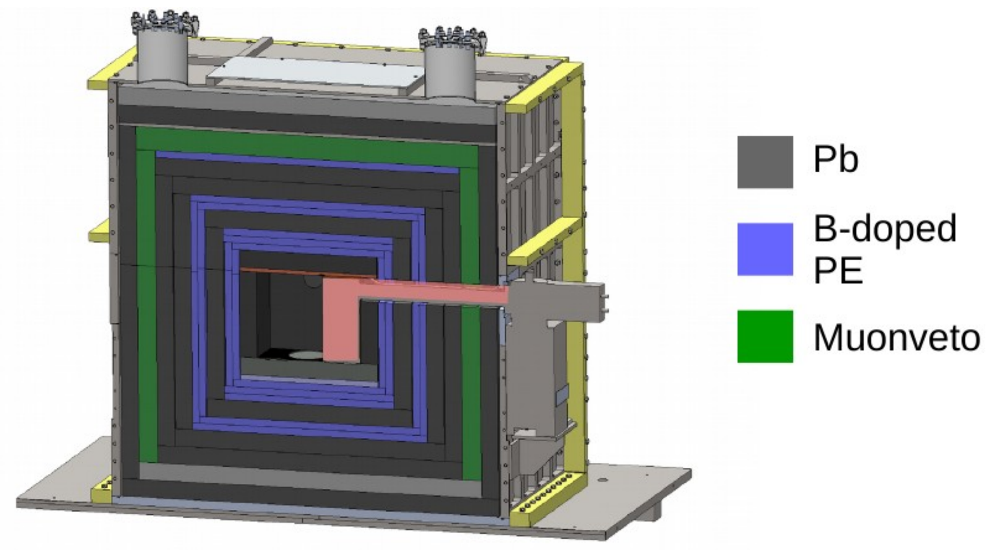
- **4 kg target mass**
- **low background**
  - screening of internal parts
  - close cooperation with manufacturer for Cu cryostat
  - underground storage
- detector threshold ~ **300 eV**

Latest News from CONUS

presented @ Neutrino '18 by W. Maneschg

CONUS Experiment

- Nuclear power plant Brokdorf, Germany with $2.4 \cdot 10^{13}$ ν/cm²/s @ 17m
- 4 x 1kg p-type point contact HPGe detectors in a compact multi-layer shielding
- Pulser resolution of ~70 eV
- E_{th} ~300 eV_{ee}
- Bck rate ~ 10 counts/ kg/ day in [0.5-1.0] keV



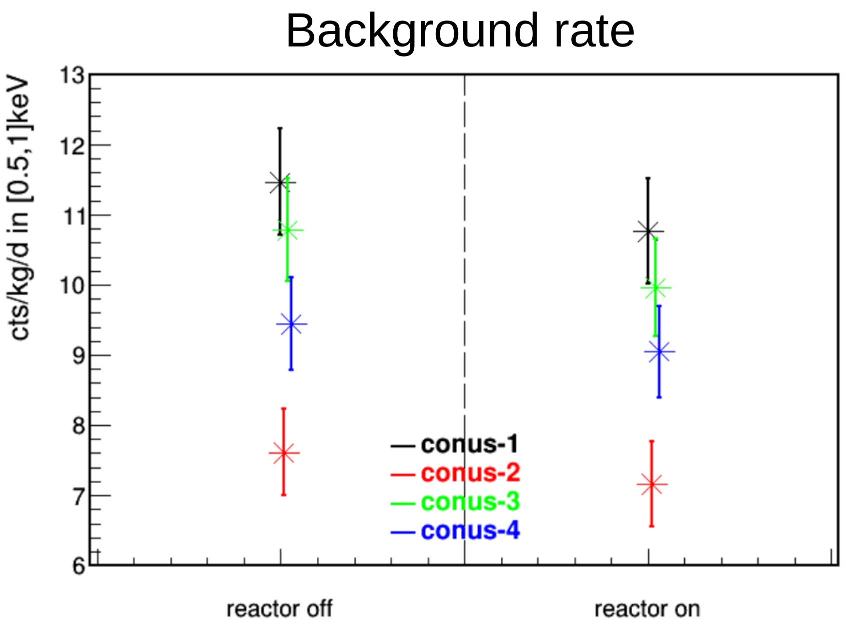
First hint for CEνNS of reactor-ν :

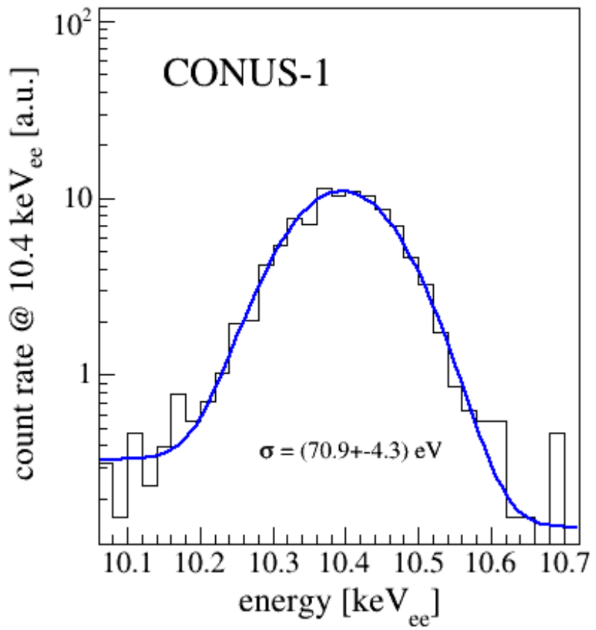
- 114 kg days of reactor OFF data
- 112 kg days reactor ON data
- 2.4 σ significance for excess in reactor ON over OFF data (statistics only)

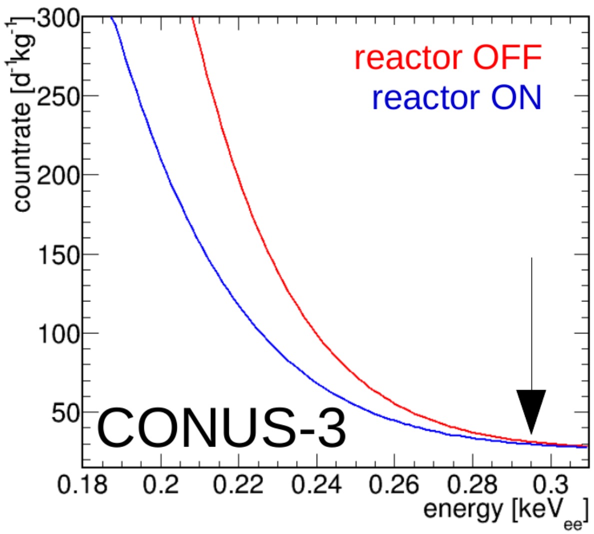
CONUS: Latest Results

presented @ Neutrino '18 by W. Maneschg

X-ray peak resolution:







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

→ **Observed excess of events is consistent with expected CEνNS signal range**