# NUCLEUS Experiment:
# Exploring Coherent Elastic Neutrino Scattering with Gram-Scale Cryogenic Detectors

V. Wagner

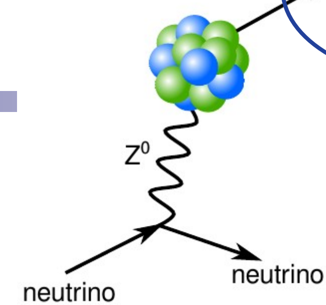
for the NUCLEUS collaboration

CEA-Saclay, DRF/Irfu

New Directions in the Search for Light Dark Matter Particles
Chicago, June 5th 2019

# Coheren Elastic Neutrino Nucleus Scattering (CE$\nu$NS)

exp. signature: sub-keV $E_R$

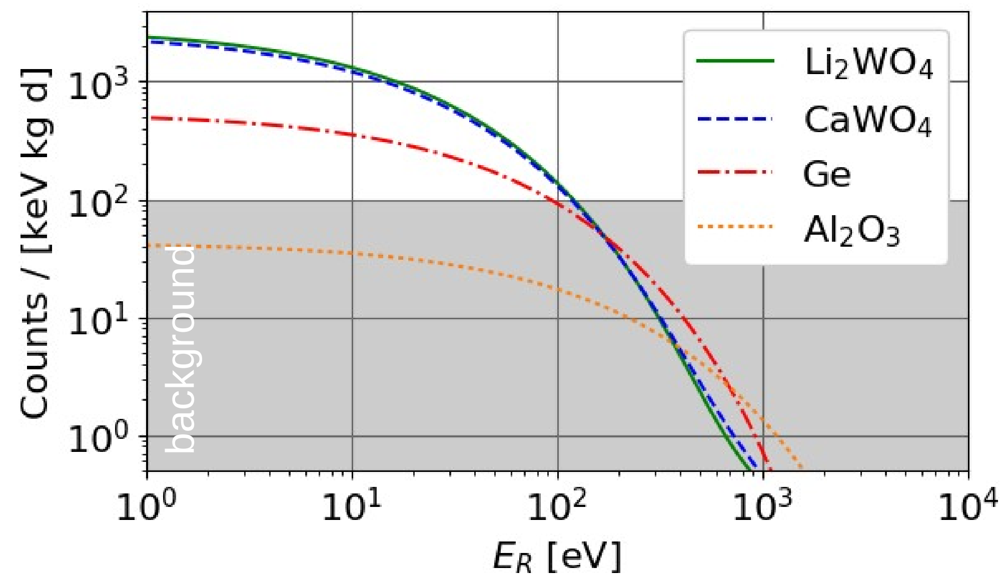



$$\sigma_{CE\nu NS} \propto \left(Z\left(4\sin\theta_W - 1\right) + \mathbf{N}\right)^2 F\left(q^2\right) E_\nu^2$$

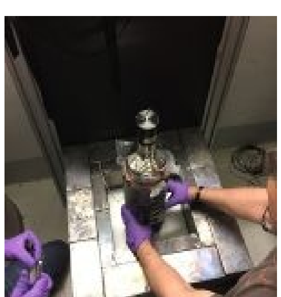
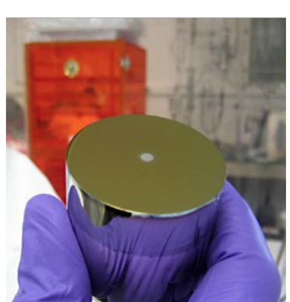
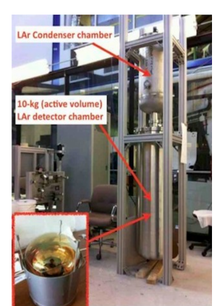
**Key parameters**:

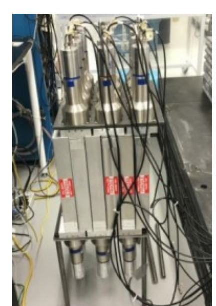
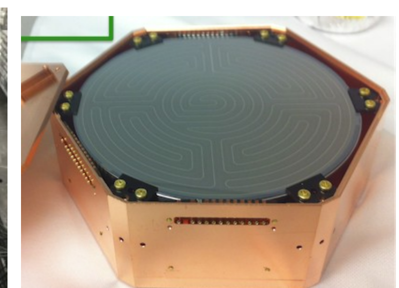
- Energy threshold < 100 eV
- Low background
- Different target materials to test $N^2$-dependence

**Synergies with detector R&D for light DM search**



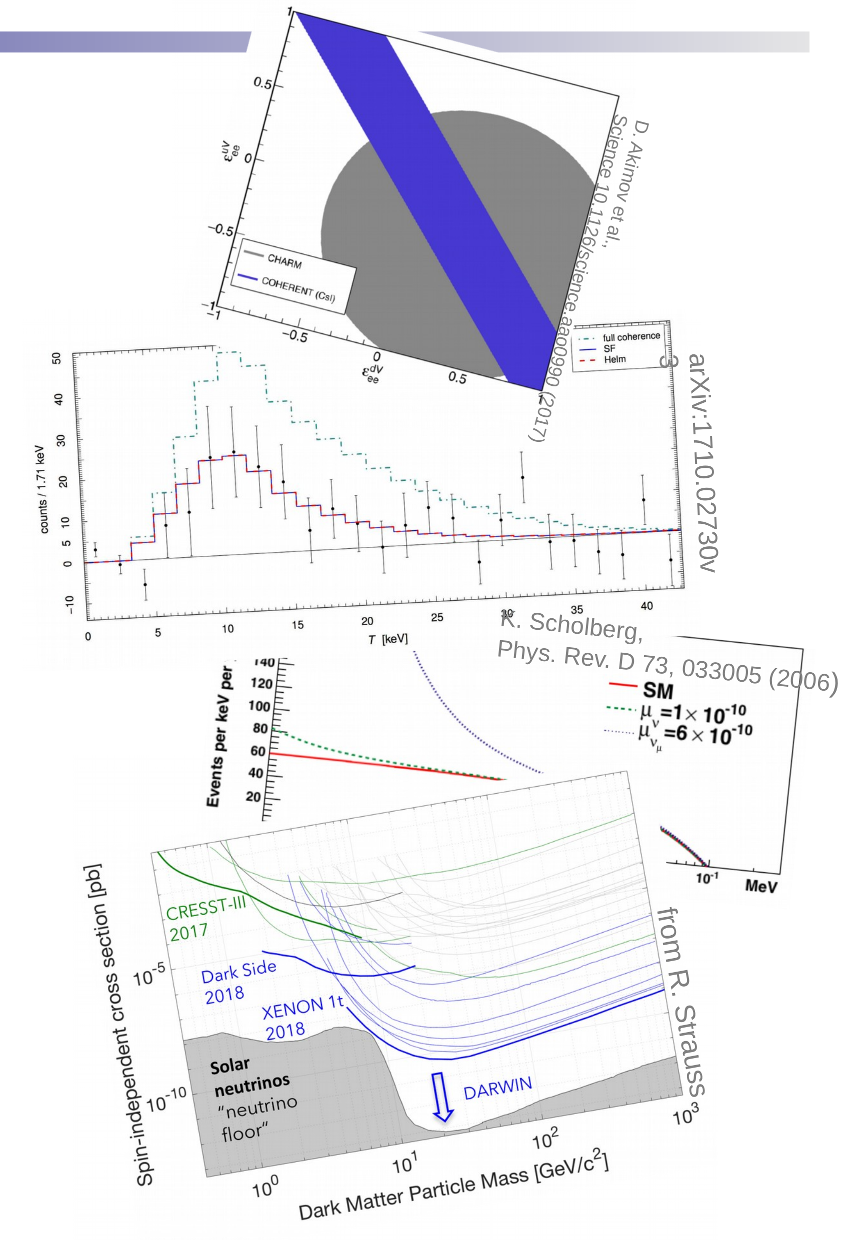


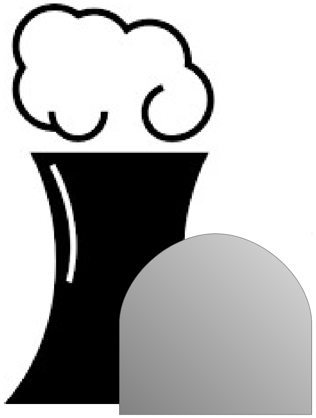



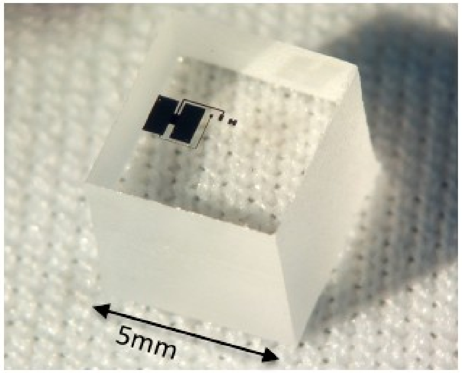

# Physics Potential of CEνNS

- Precision test of Standard Model (SM): e.g. **Weinberg angle at low momentum transfer**
- **New phsyics BSM & fundamental neutrino properties and interactions:** e.g. new q-ν couplings, neutrino magnetic dipole-moment, etc.
- New channel for **sterile neutrino** searches, **Supernovae** detection, **nuclear physics**
- Possible application in nuclear reactor monitoring
- **Neutrino floor:** irreducible background for DM experiments from CEνNS



# NUCLEUS Experiment






**Reactor anti-neutrinos**

- $E_\nu$ < 10 MeV
- High $\nu$-flux
- Experimental site at shallow depth < 10m.w.e.

Establishing **new experimental site, VNS @ Chooz Reactor (France) for NUCLEUS**
**G. Angloher et al. arXiv:1905.10258**

**Gram-scale cryogenic calorimeters based on CRESST technology:**

- Demonstrated energy threshold in 10eV-regime
- Operation above ground

**Detector Concept:**
**R. Strauss et al., Eur. Phys. J. C 77 (2017) 506**
**R. Strauss et al., Phys. Rev. D 96, 022009 (2017)**

# NUCLEUS Collaboration

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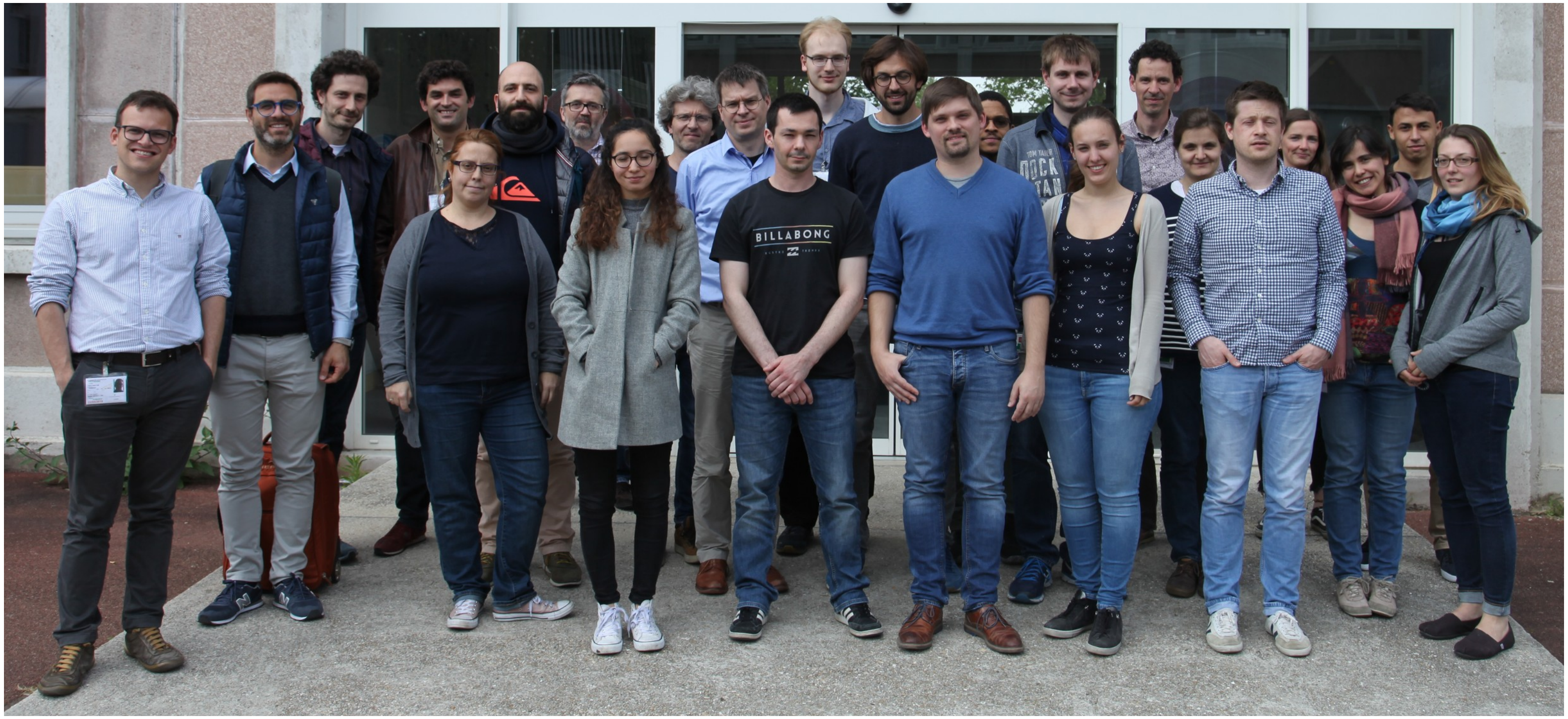



so far 5 institutes with ~30 members + strong interest from INFN groups

TECHNISCHE UNIVERSITÄT MÜNCHEN

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

DE LA RECHERCHE À L'INDUSTRIE cea

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

# The NUCLEUS Detector Concept

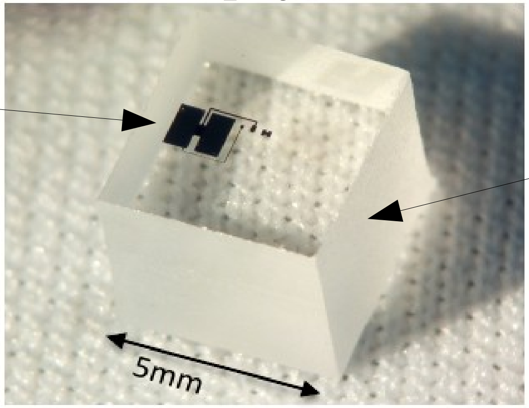
R. Strauss et al., Eur. Phys. J. C 77 (2017) 506

## Gram-scale cryogenic calorimeter

- Low systematics: energy scale well know (no significant quenching involved)
- Down-scaling of detector mass:
  - **$E_{th}$ ~ $M^{2/3}$** → predicts $E_{th} \leq 10$ eV
  - Achieved threshold so far: **$E_{th}$ = (19.7±0.8) eV**

0.5g $Al_2O_3$ prototype

Thermometer:
Transition-edge-sensor based on CRESST technology




Single $Al_2O_3$ or $CaWO_4$ cubic crystal

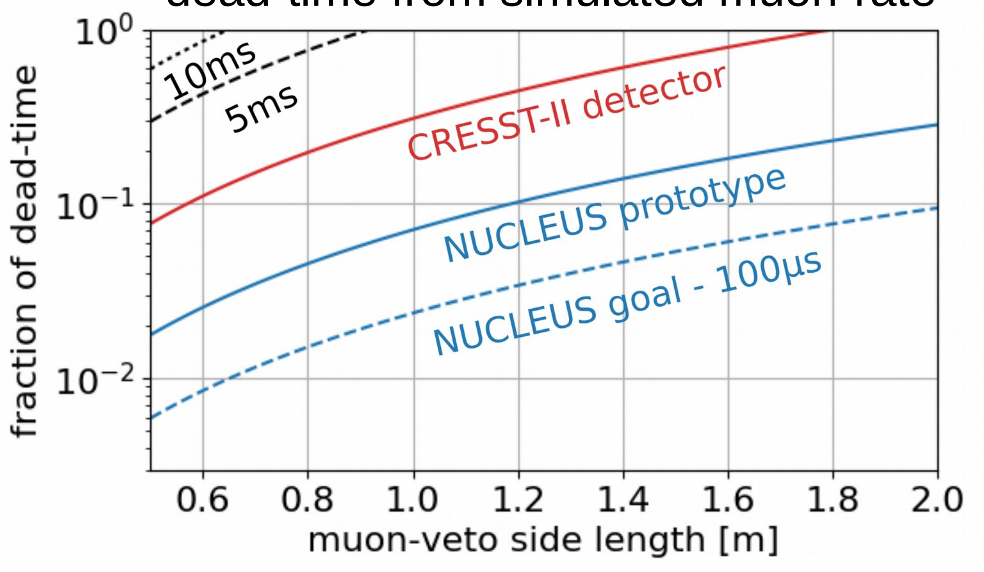
# The NUCLEUS Detector Concept

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

## Gram-scale cryogenic calorimeter

- Low systematics: energy scale well know (no significant quenching involved)
- Down-scaling of detector mass:
  - $E_{th} \sim M^{2/3} \rightarrow$ predicts $E_{th} \leq 10$ eV
  - **Operationable above ground**:
    - Low rate O(0.1Hz)
    - Fast pulses → critical for timing with veto detectors

dead-time from simulated muon-rate



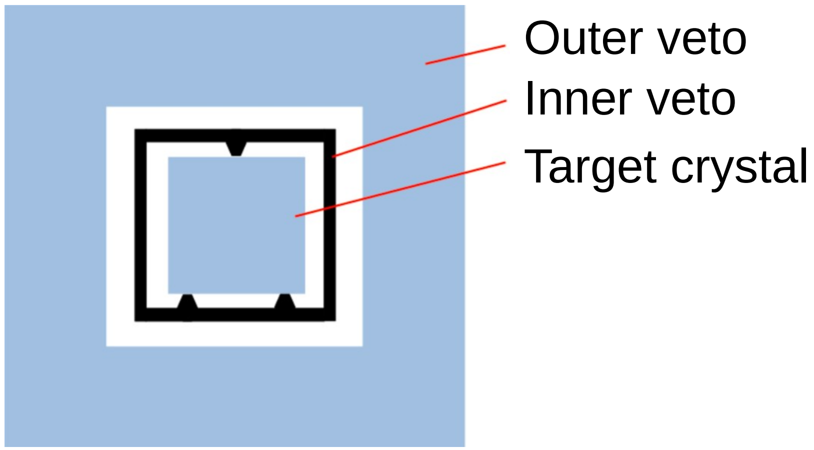

- Uncertainty of pulse on-set depends on pulse rise-time: $\sigma_\tau \sim \tau_r$
- Define a veto window of $\pm 5\sigma_\tau$

# The NUCLEUS Detector Concept

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

## Gram-scale cryogenic calorimeter

- Low systematics: energy scale well know (no significant quenching involved)
- Down-scaling of detector mass:
  - $E_{th} \sim M^{2/3} \rightarrow$ predicts $E_{th} \leq 10$ eV
  - Operationable above ground
  - **Fiducialization** of detector & new holder scheme for active background reduction:
    - Inner veto: holding force + $4\pi$ surface veto
    - Outer veto: reduction of external $\gamma$- and n-background
    - MC simulations show a **suppression factor of O(10$^3$)** can be reached



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

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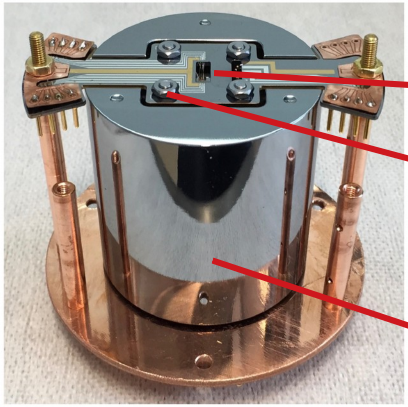
- Down-scaling of detector mass:
  - $E_{th} \sim M^{2/3} \rightarrow$ predicts $E_{th} \leq 10$ eV
  - Operationable above ground
  - **Fiducialization** of detector & new holder scheme for active background reduction:
    - Full demonstrator tested → analysis ongoing



**NUCLEUS-1g**

target crystal: 0.5g $Al_2O_3$

inner cryogenic veto + holder: Si wafer

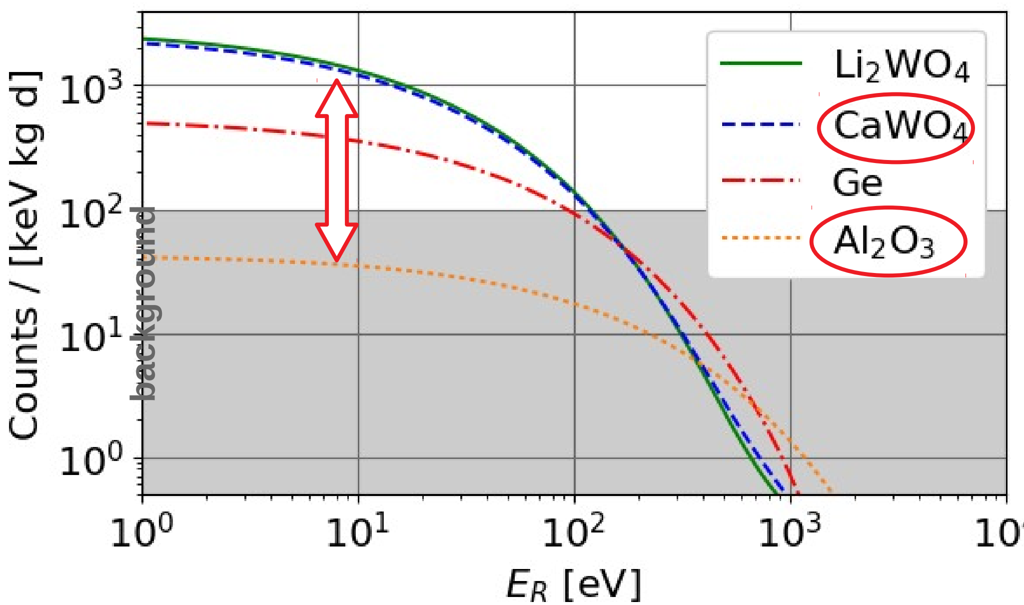
outer veto: 200g Si crystal

# The NUCLEUS Detector Concept

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

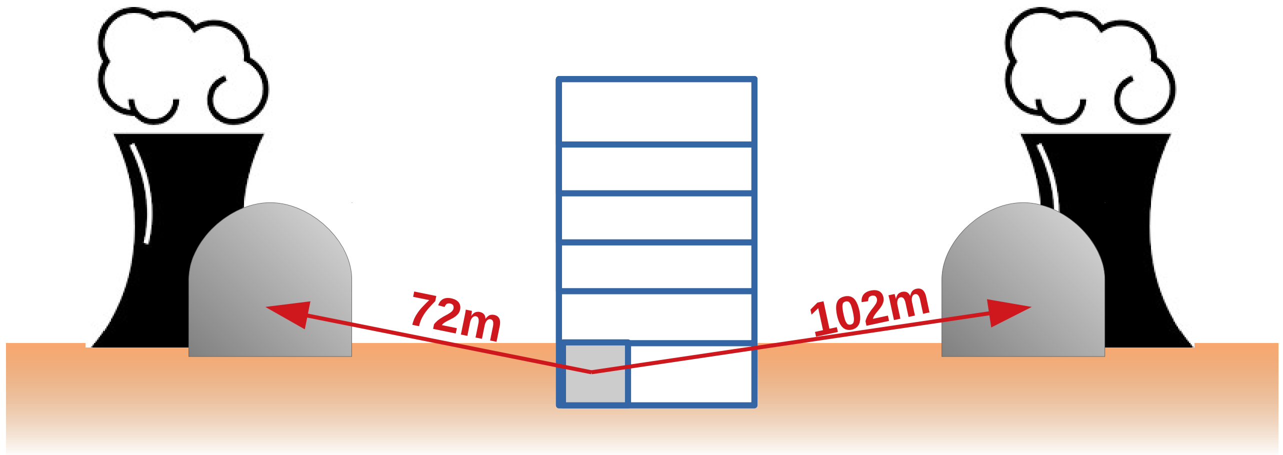
## Gram-scale cryogenic calorimeter

- Low systematics: energy scale well know (no significant quenching involved)
- Down-scaling of detector mass:
  - $E_{th} \sim M^{2/3} \rightarrow$ predicts $E_{th} \leq 10$ eV
  - Operationable above ground
  - Fiducialization of detector & new holder scheme for active background reduction
- **Multi-target approach**: CEνNS rate differs by a factor of ~10-100 → constrain background



# The Very Near Site (VNS) at Chooz

G. Angloher et al. arXiv:1905.10258




- **New experimental site** in a 24$m^2$ room in an administrative building
- In-between the two 4.25 $GW_{th}$ reactor cores
- Expected ν-flux: $10^{12}$ (s $cm^2$)$^{-1}$
- Muon rate attenuation measurements yield an overburden of 3 m.w.e. at the VNS

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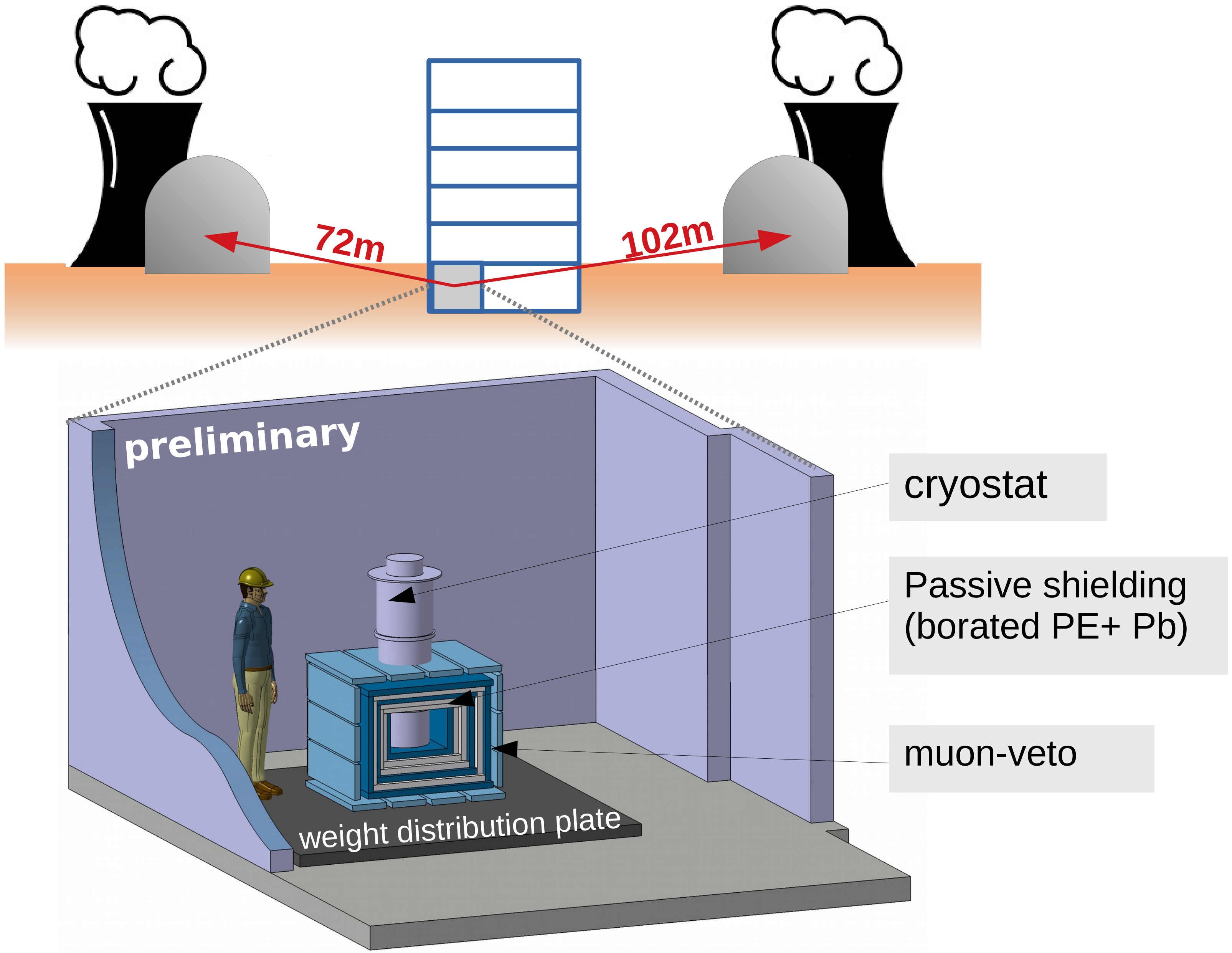
G. Anger et al. arXiv:1905.10258



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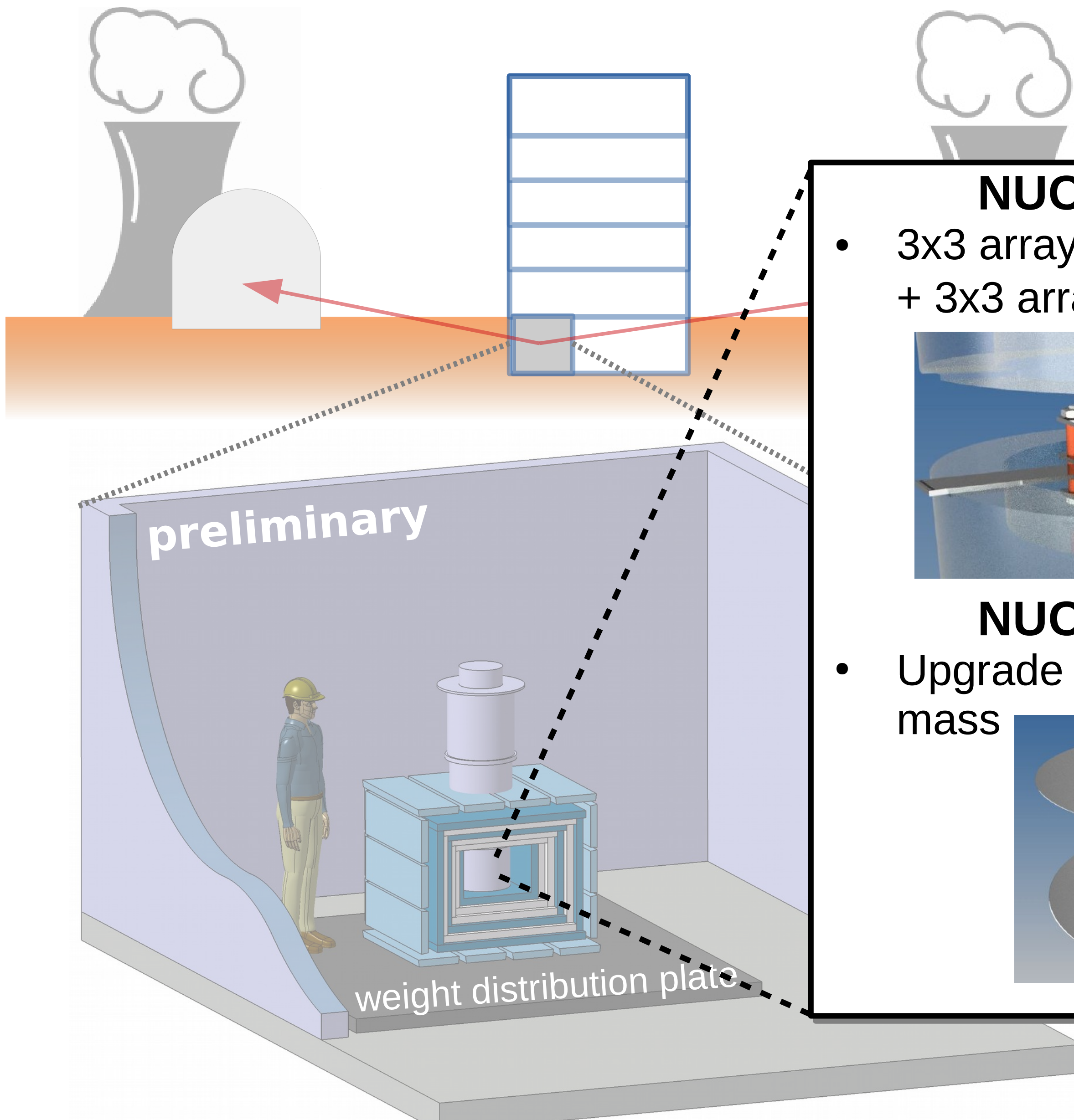
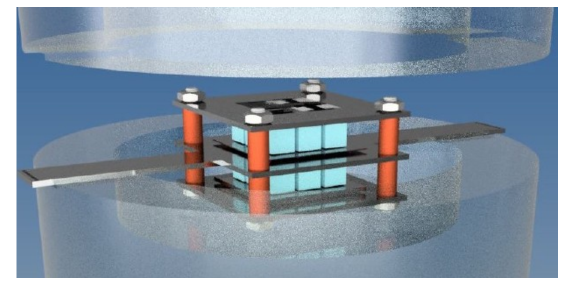


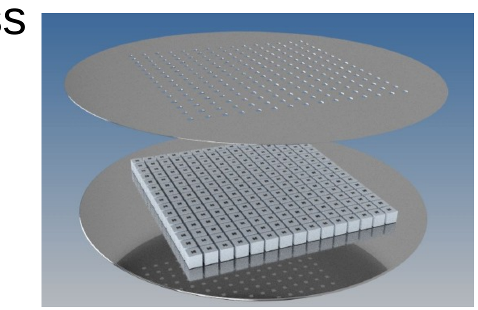

**NUCLEUS-10g**

- 3x3 array with $CaWO_4$ (6g) + 3x3 array with $Al_2O_3$ (4g)



**NUCLEUS-1kg**

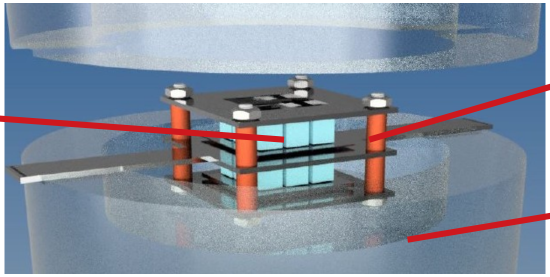
- Upgrade towards 1kg target mass



# NUCLEUS-10g

planned to start 2021

Target crystals:
3x3 array with $CaWO_4$ (6g)
+ 3x3 array with $Al_2O_3$ (4g)

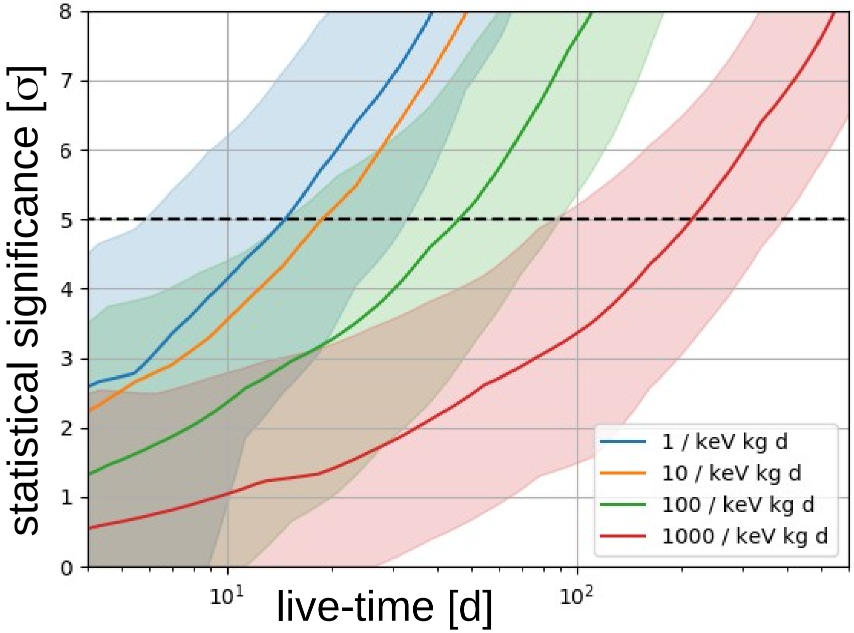


inner veto + holder

outer veto:
~1kg Ge/ $CaWO_4$

- First observation of CEνNS of lowest energy reactor neutrinos
- Signal observation after 2 weeks possible
- 10% measurement of CEνNS cross-section
- Worst case scenario: in case of signal-like background a 4σ-observation can be reached after one year → **unique to multi-target approach**

Exp. sensitivity (flat background)



# Conclusion & Outlook

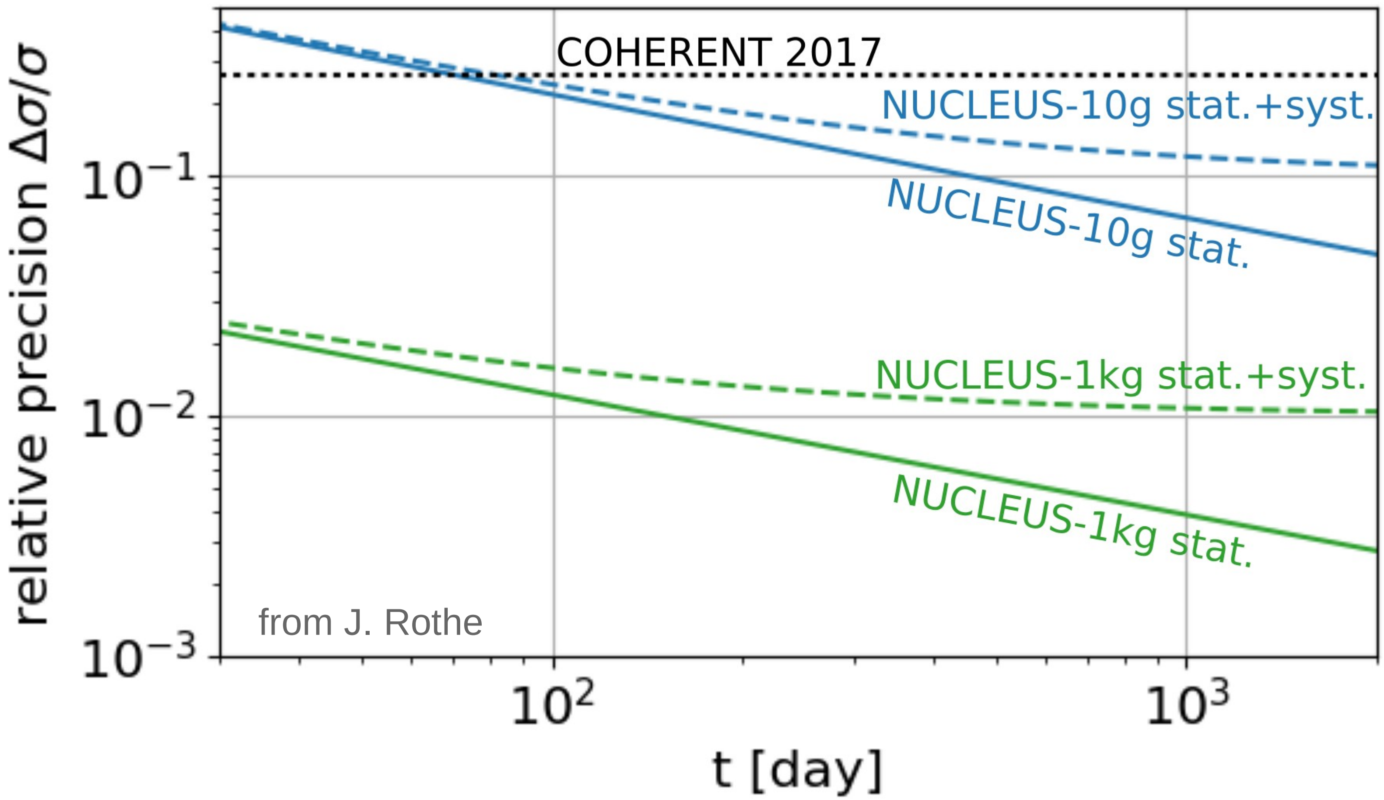
- **Gram-scale cryogenic calorimeters** are a very promising technology to measure CEνNS of reactor neutrinos:
  - Unprecedentedly low energy threshold **$E_{th}$ < 20 eV**
  - Operational above ground
  - Fiduzialisation of detector for background reduction
- Plan to install **NUCLEUS-10g at VNS** by 2021:
  - Observation of CEνNS of low energy neutrinos within 2 weeks
  - 10% precision after 1y → great potential for new physics
- **NUCLEUS-1kg** aims at a percent level measurement of CEνNS cross-section

- First publication of NUCLEUS at VNS:
  **G. Angloher et al. arXiv:1905.10258**

# Bonus Slides

# Statistical Precision of NUCLEUS

- NUCLEUS-10g dominated by statistics
- **NUCLEUS-1kg** envisions **precision measurement** of few percent for CEνNS




Improvement on systematics necessary: e.g. ν-flux, energy scale @ O(10 eV), …

# Low Energy Background

… measured with the NUCLEUS prototype at surface w/o shielding

Eur. Phys. J. C (2017) 77:637

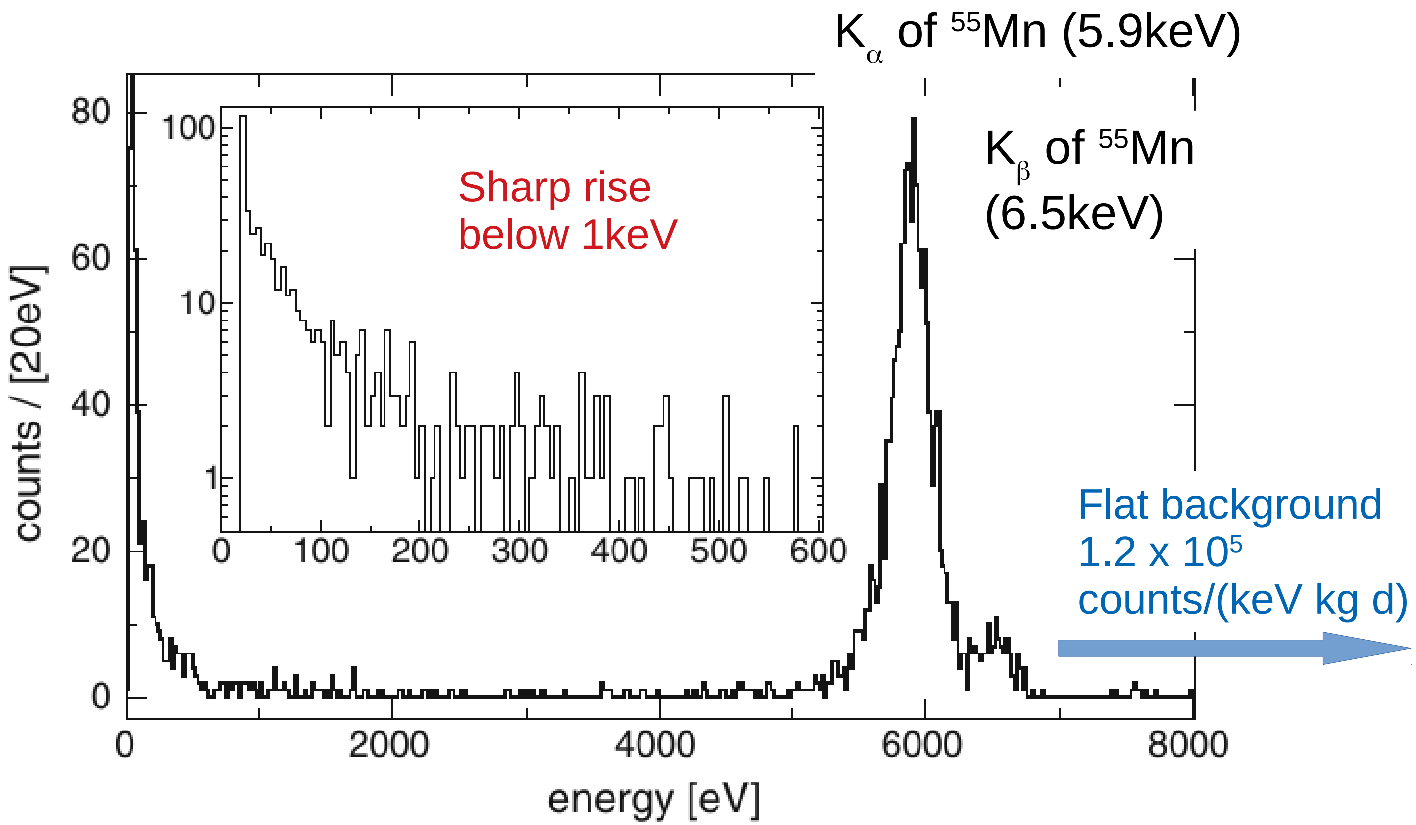
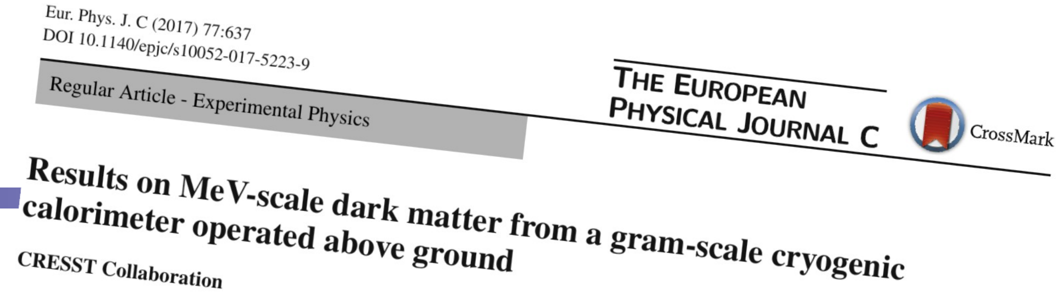



**Fig. 2** Total energy spectrum of the 5.3 h measurement in presence of the $^{55}$Fe X-ray source with peaks at 5.90 and 6.49 keV. The inset shows the events in the region-of-interest for DM search from the energy threshold of 19.7–600 eV (binning 5 eV). No data quality cuts are applied

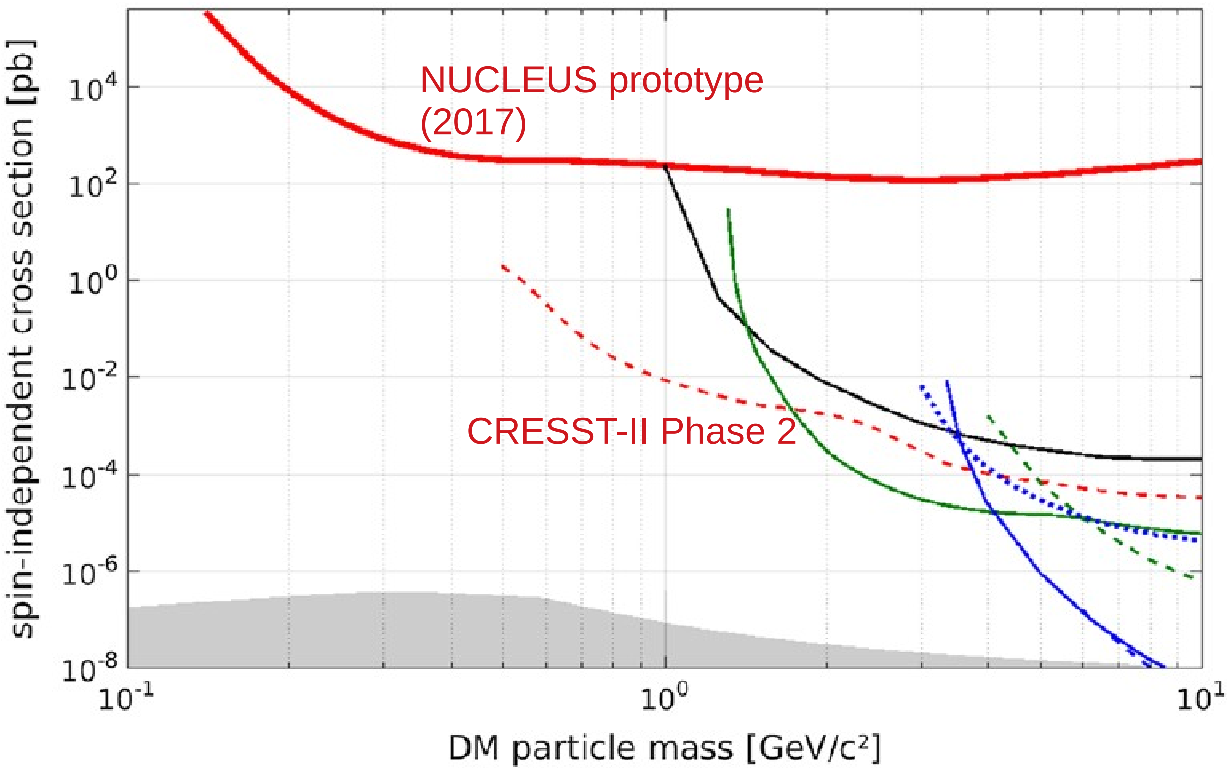
# Dark Matter Search with NUCLEUS Prototype

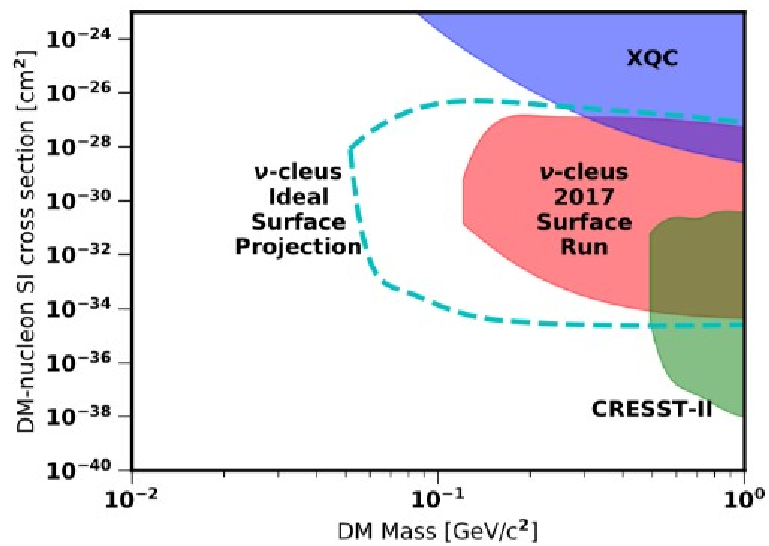

Eur. Phys. J. C (2017) 77:637
DOI 10.1140/epjc/s10052-017-5223-9
Regular Article - Experimental Physics
THE EUROPEAN PHYSICAL JOURNAL C

**Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground**

CRESST Collaboration

- 0.5 $Al_2O_3$ NUCLEUS prototype
- Operated **above ground** w/o significant shielding
- First limits in mass region **140 – 500 MeV/c²**




New parameter space excluded for SIMPs

J. Davis, *Phys. Rev. Lett.* **119**, 211302 (2017)

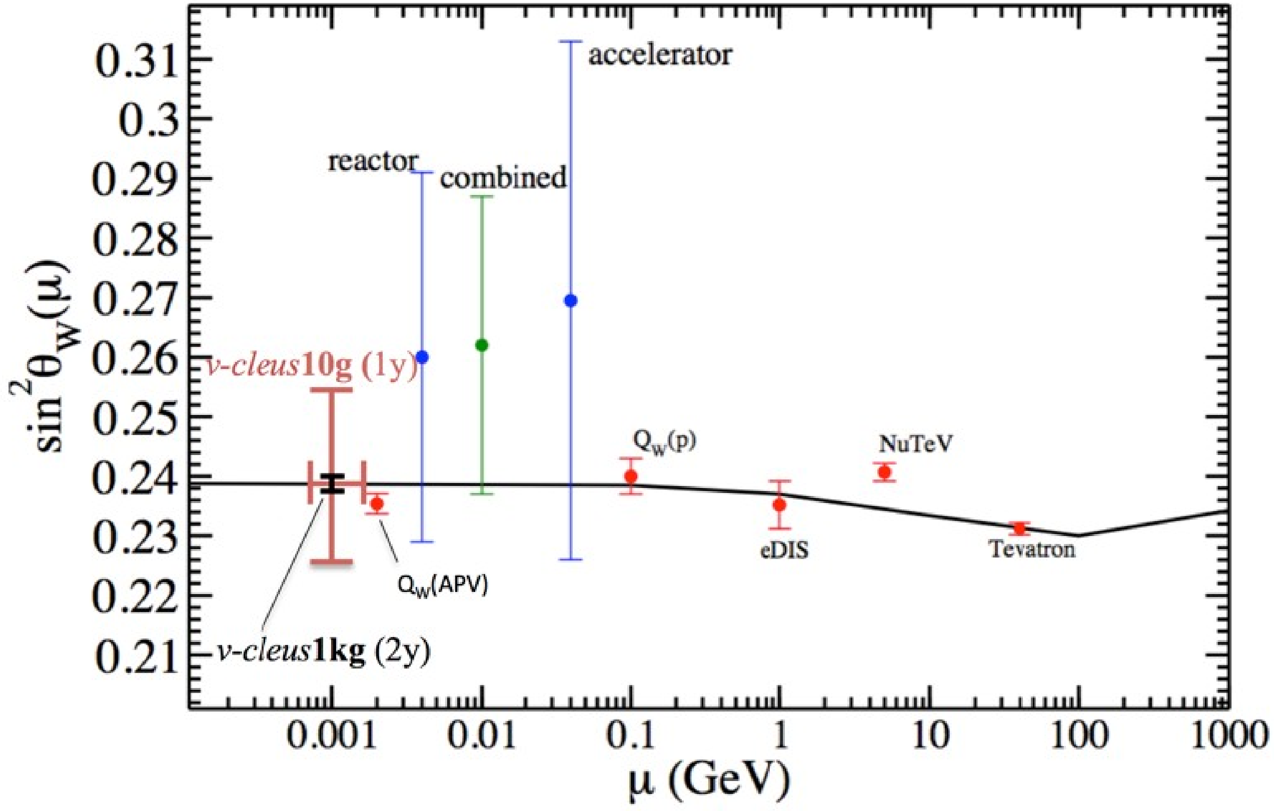
# Testing the SM with NUCLEUS-10g

## Measuring the Weinberg angle at low momentum transfer

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$

$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$

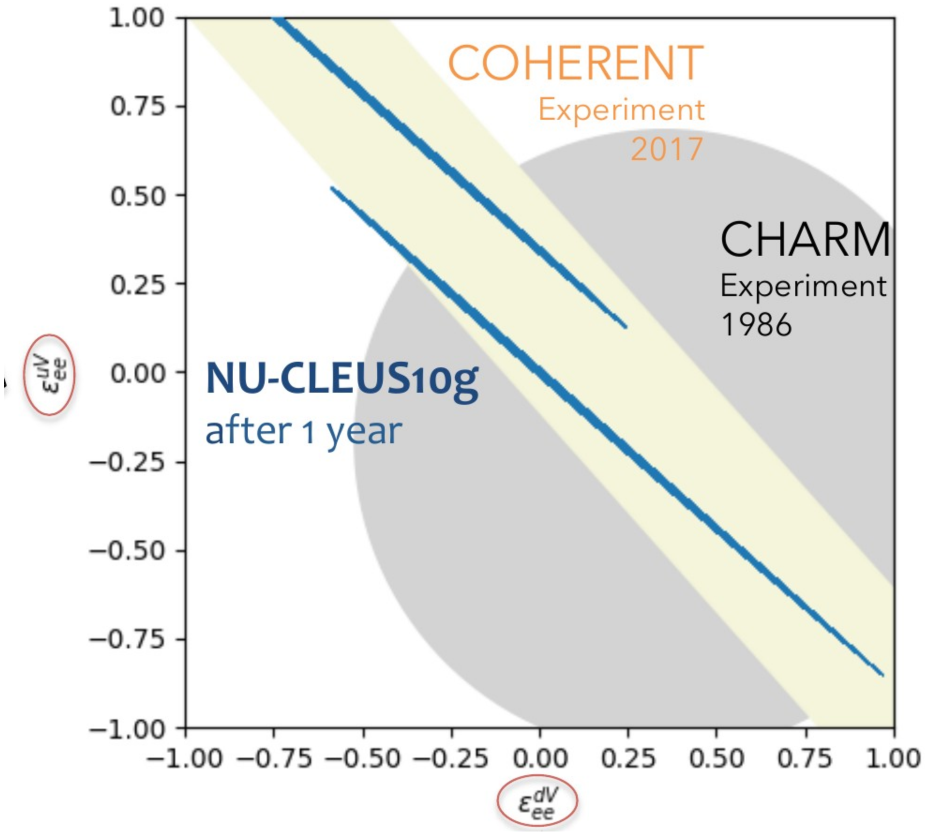
With $g_V^p = (\frac{1}{2} - 2\sin^2\theta_W)$ and $g_V^n = -\frac{1}{2}$



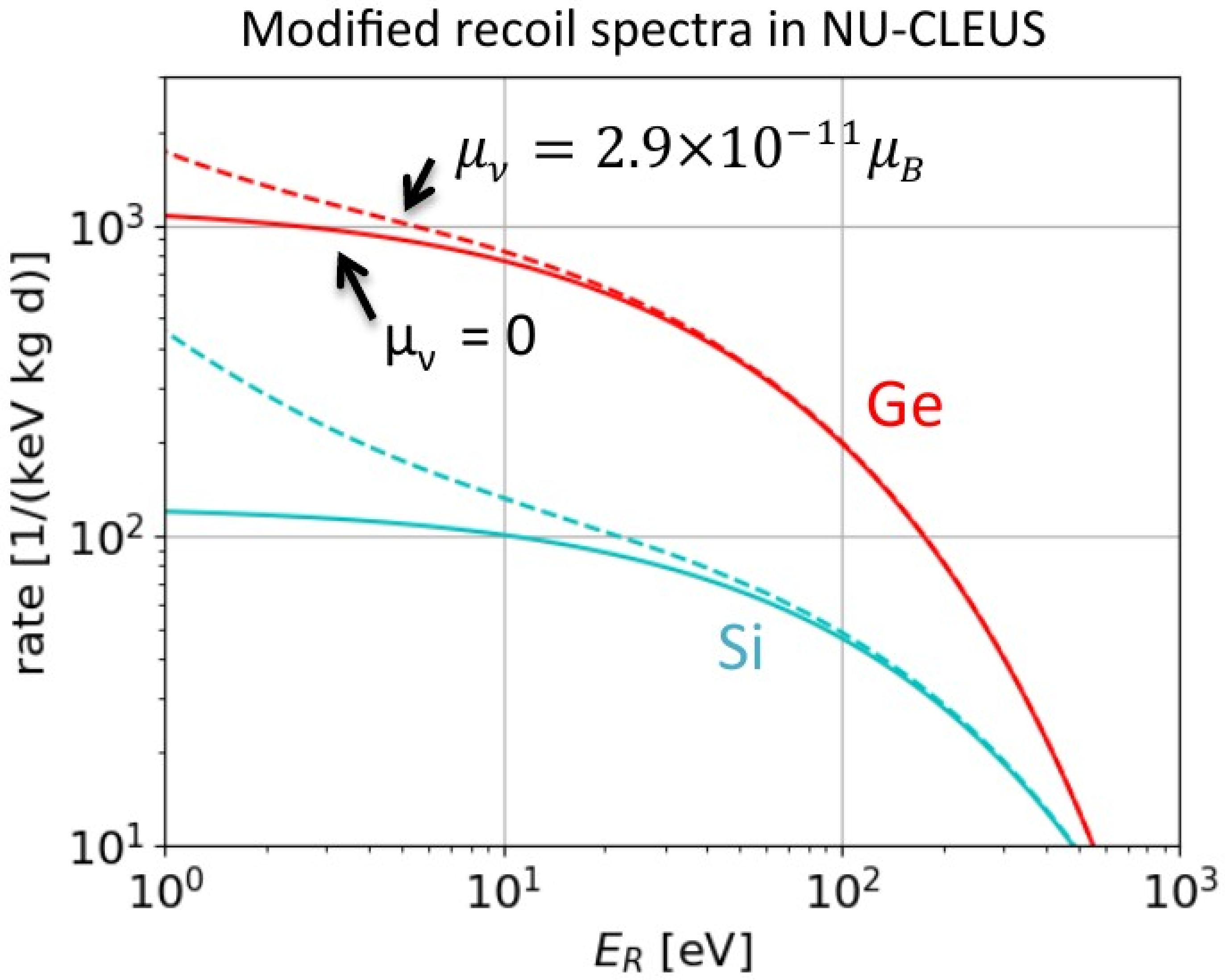
# Searching for BSM with NUCLEUS-10g

## Non-standard neutrino interactions

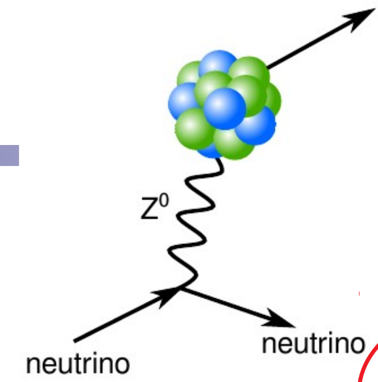
$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$



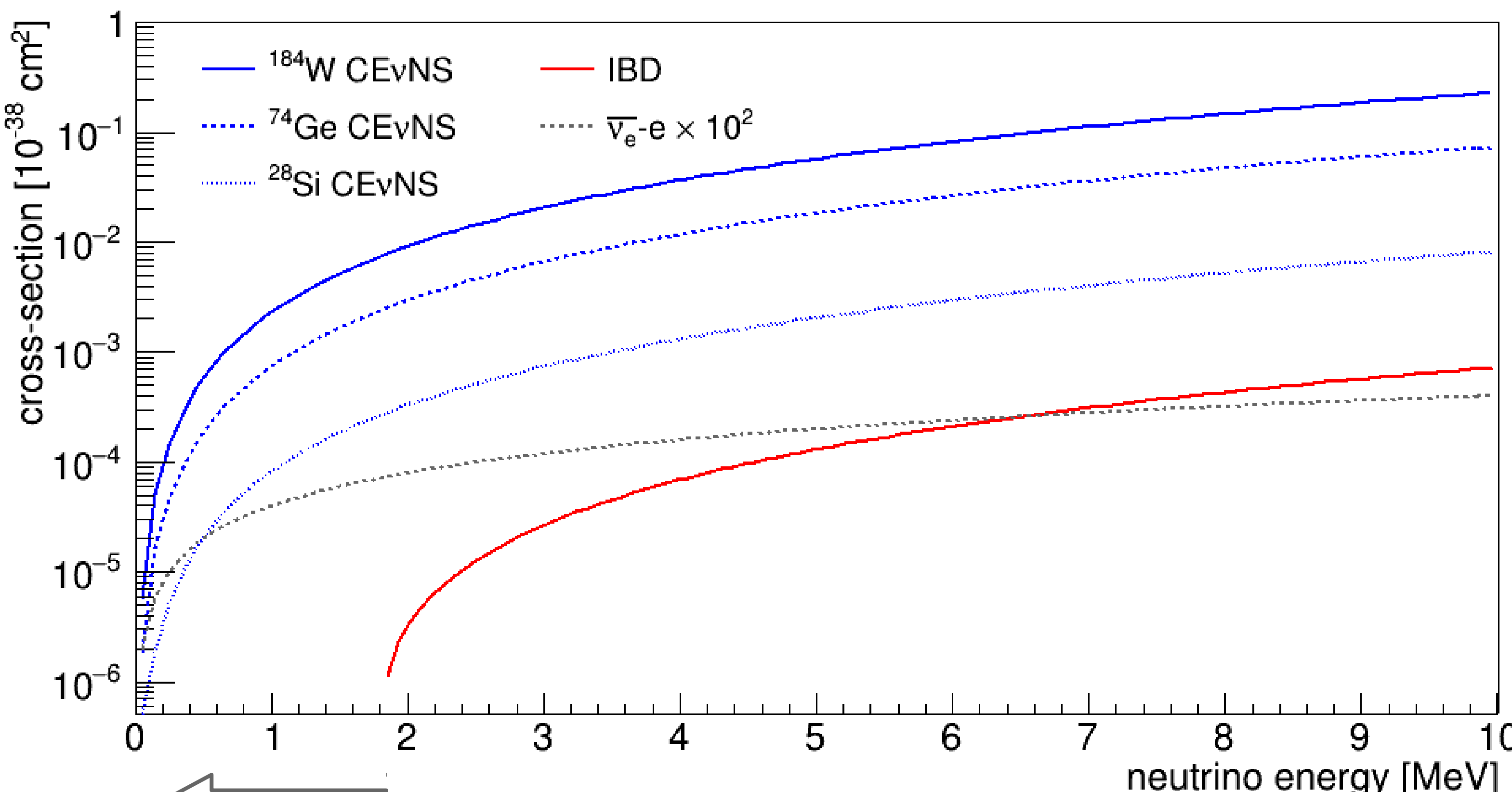
# Neutrino Magnetic Dipole Moment



# CEνNS vs IBD




**flavor blind process**

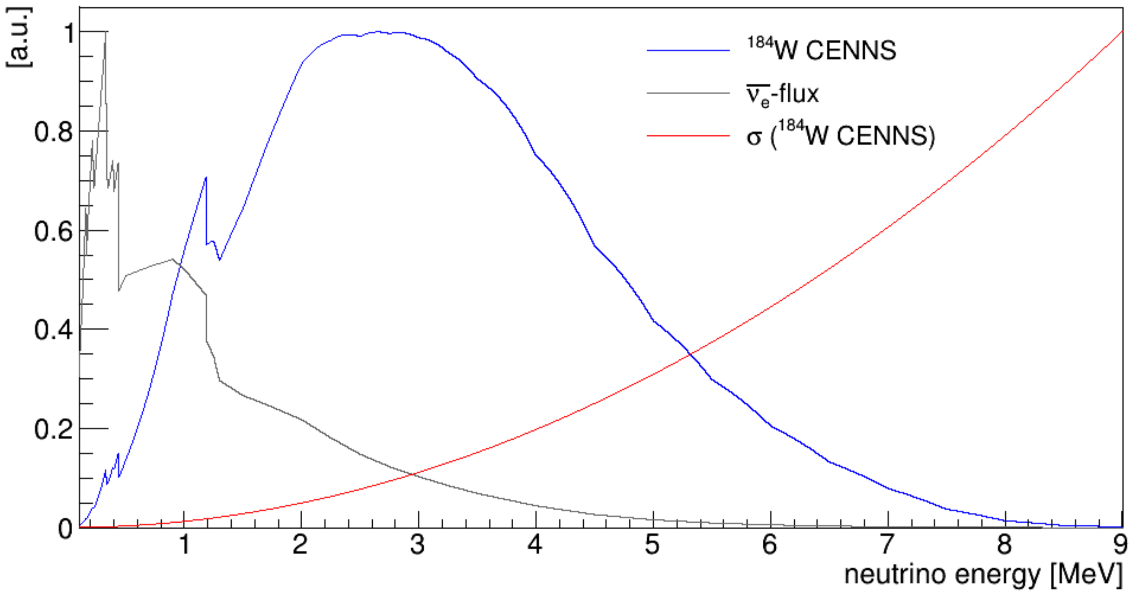



**enhancement of CEνNS cross section**

**no energy threshold for CEνNS**

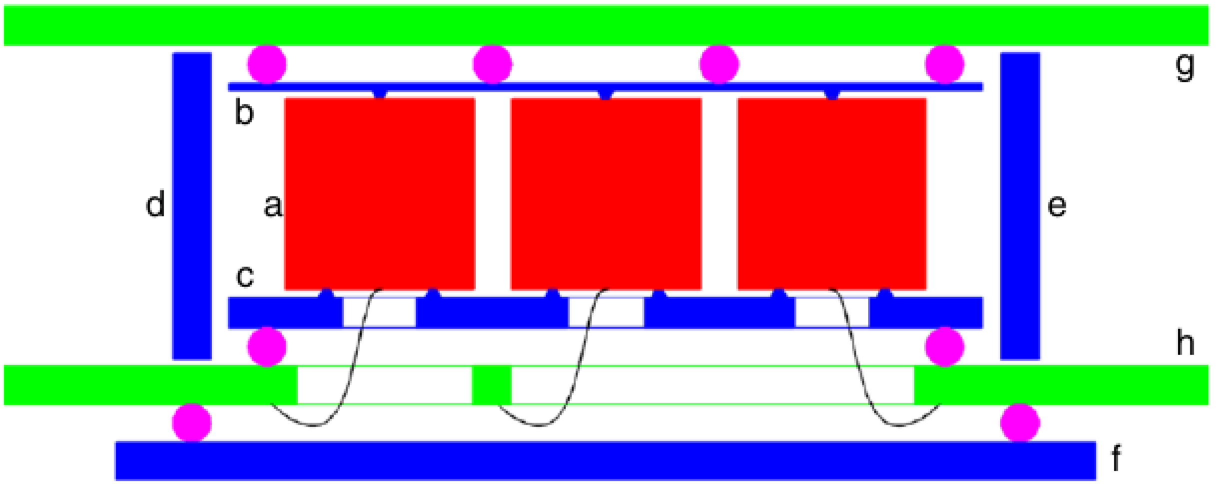
# Nuclear Reactor as Neutrino Sources

- **Reactor (anti-)neutrinos**
  - high $\nu$-flux $10^{12}$-$10^{13}$ $s^{-1}cm^{-2}$
  - $E_\nu$ < 10 MeV → full coherence
    → test SM @ low energies
  - correlation with reactor power



# NUCLEUS Detector Array

(a) Target:
(5x5x5)mm³ calorimeter
read out with TES




(g-h) passive components:
2mm thick Si slaps

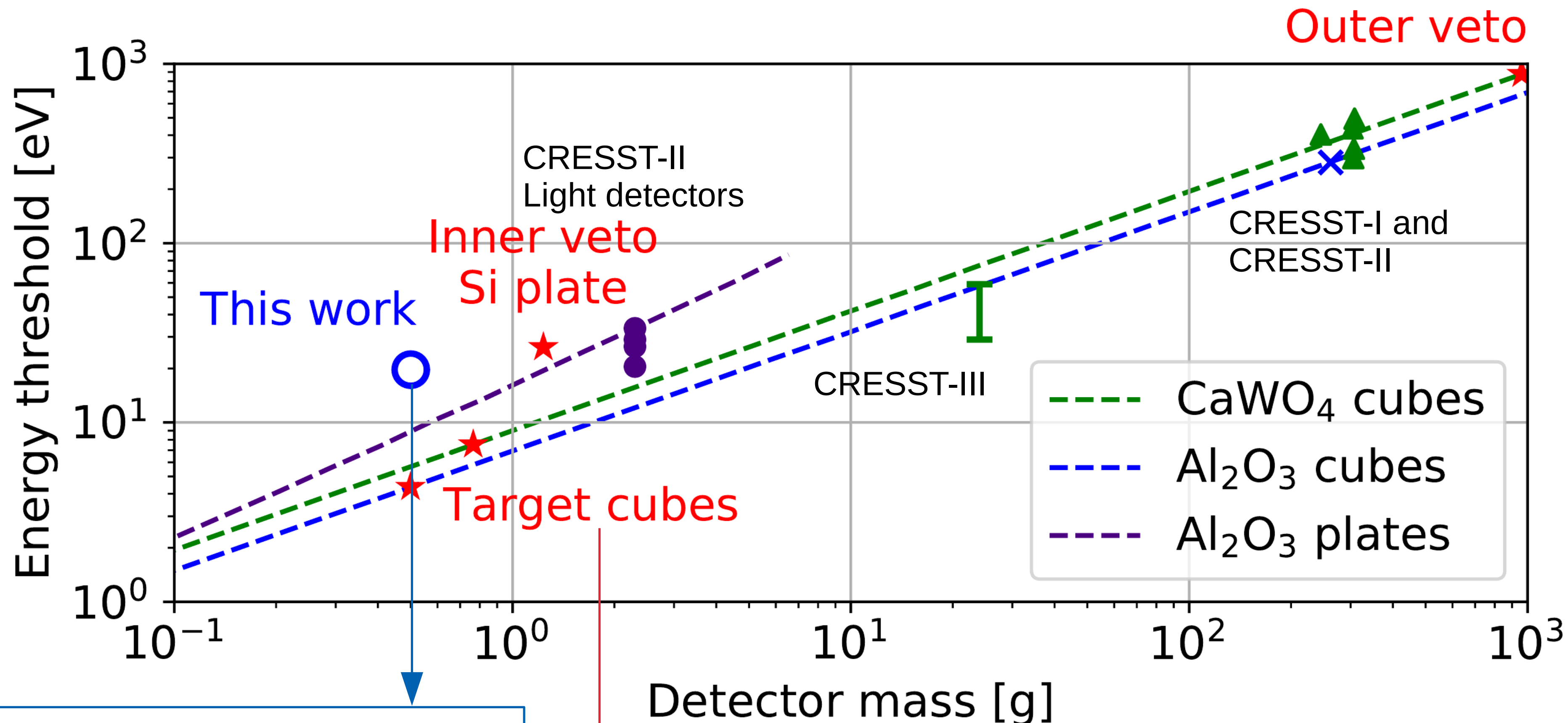
- support structures
- (h) equipped with Al (Au) wiring for electrical (thermal) connections of (a-f)

(b-f) active components:
Si wafers read out by TES

- $4\pi$ veto against surface events
- (b) & (c) hold target with Si pyramids
- (b) 200mm thick $\rightarrow$ acts as a spring & compensates for thermal contraction
- Events induced by e.g. thermal-stress relaxation vetoed as they induce signals in (b) & (c)

# Energy Threshold of NUCLEUS Detectors

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

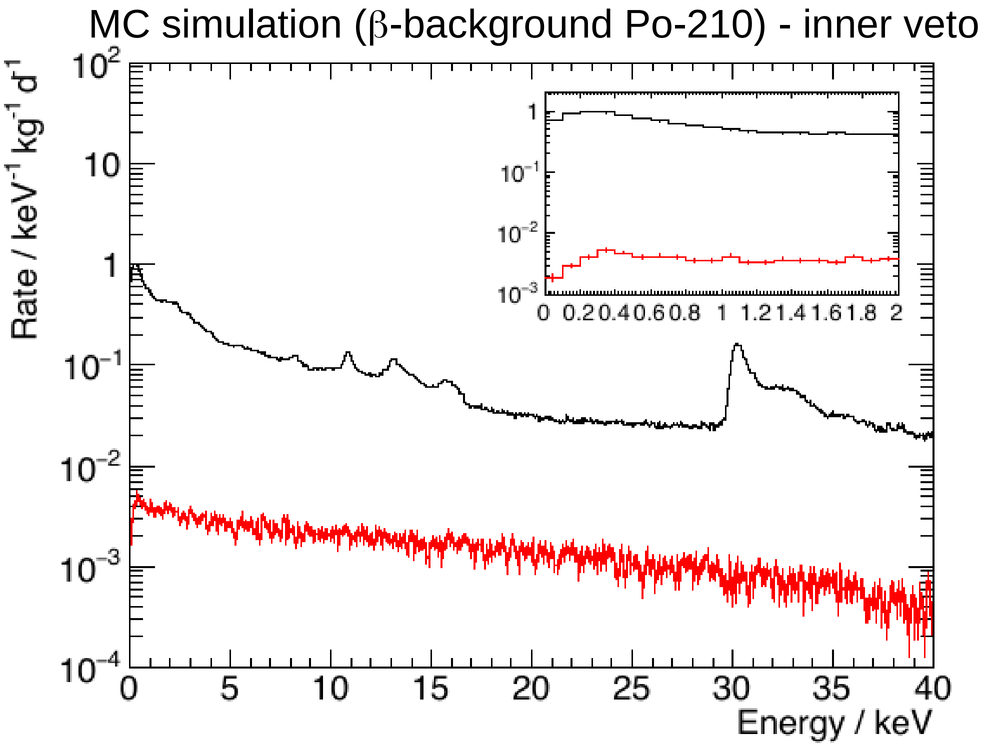


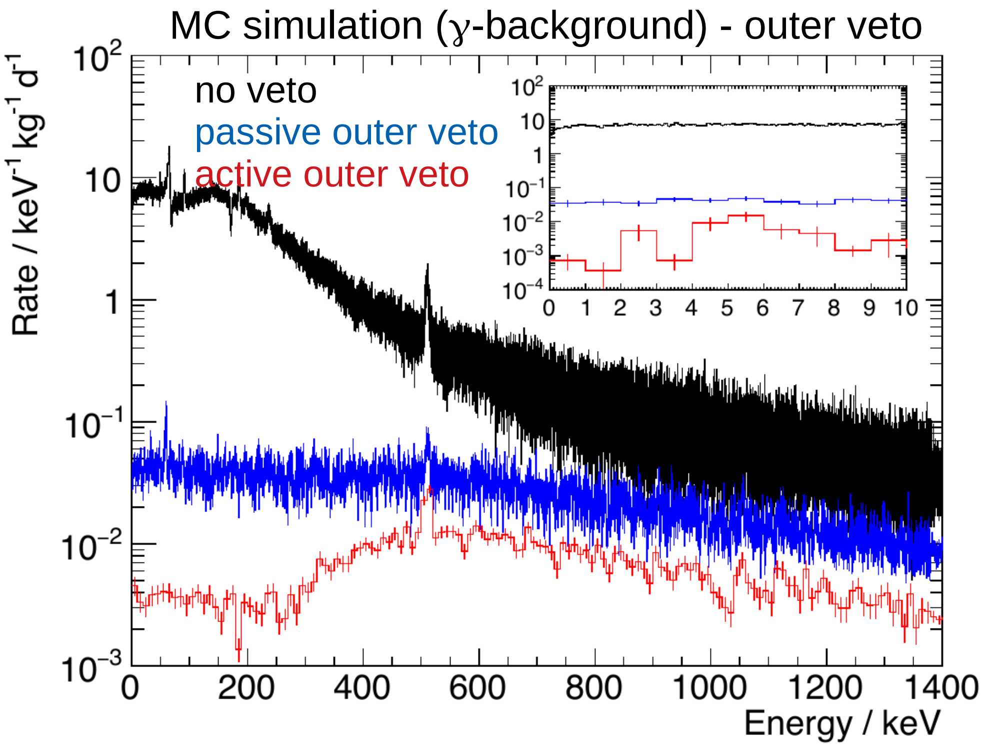

measurement:
$E_{th}$ = (19.7 ± 0.9) eV ($Al_2O_3$)
non-optimized noise

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

# Fiducial-Volume Cryogenic Detector

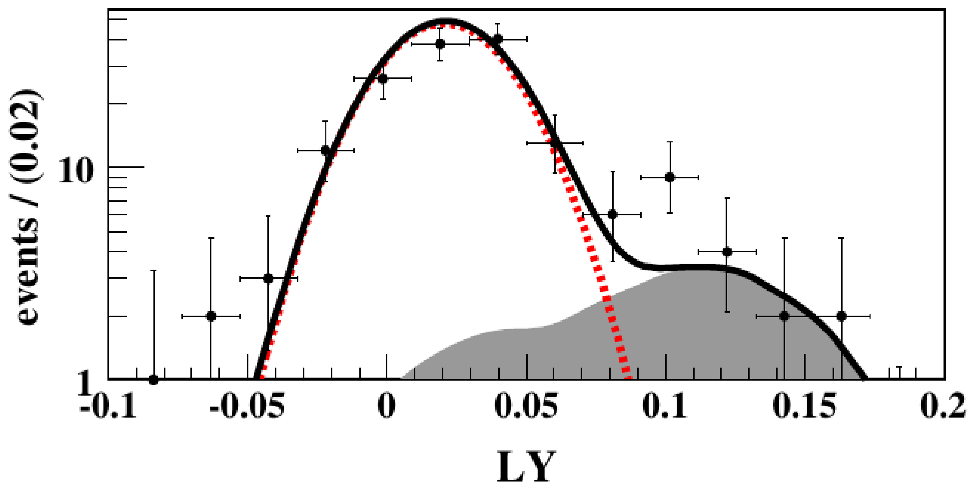
R. Strauss et al., Eur. Phys. J. C 77 (2017) 506

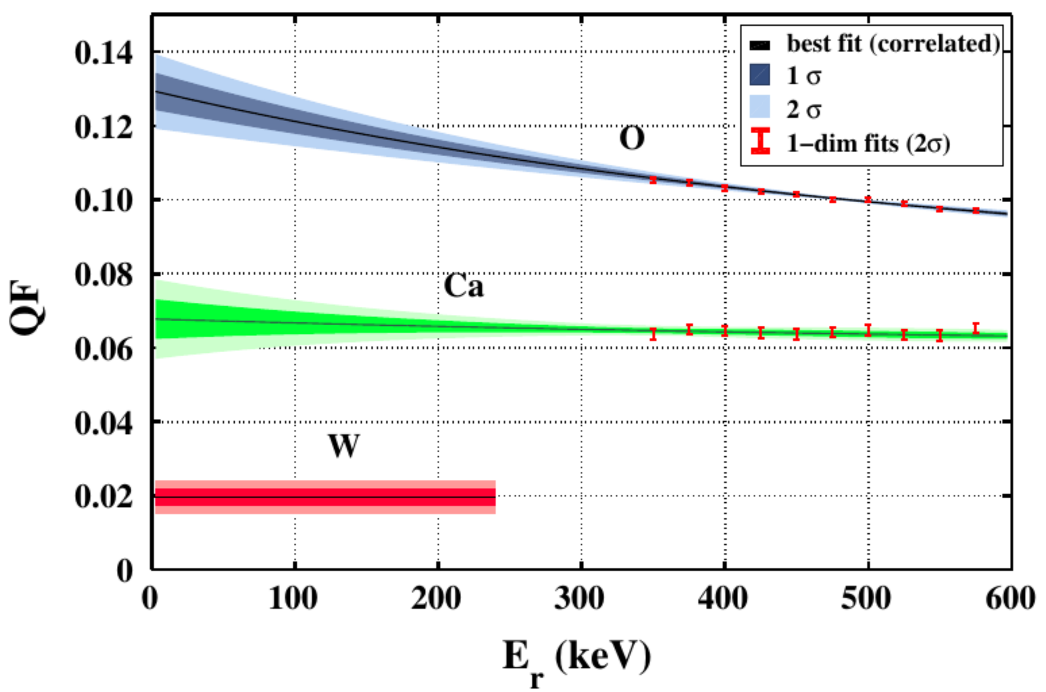


# Quenching Factor

Eur. Phys. J. C (2014) 74:2957

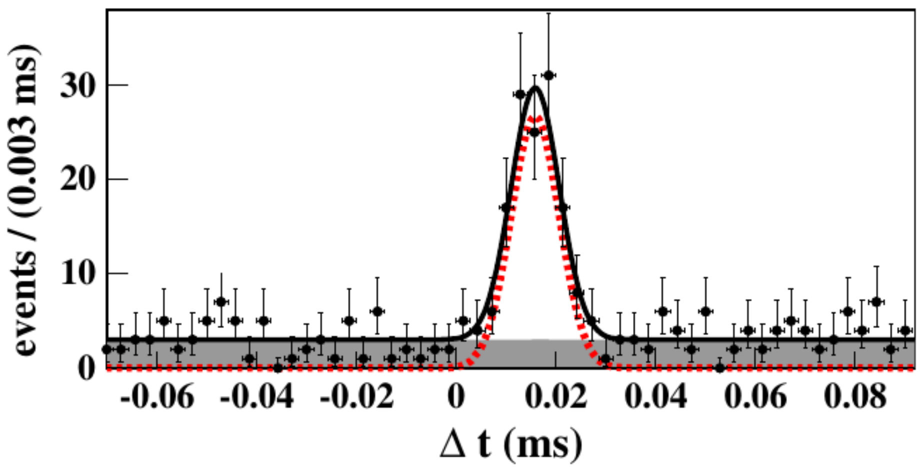


# Muon-induced Dead-Time at the VNS

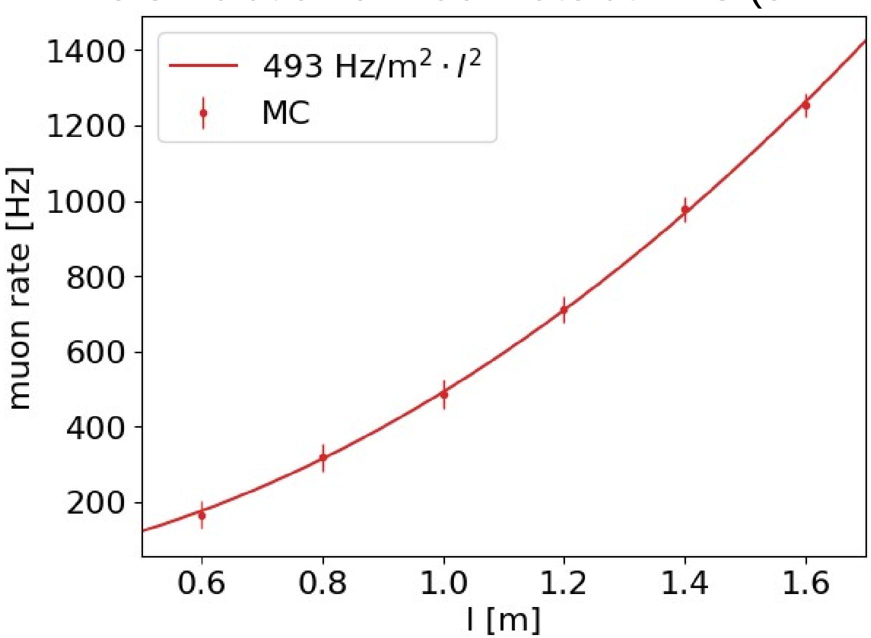
Eur. Phys. J. C (2014) 74:2957 & arXiv:1905.10258

Pulse on-set




- Pulse on-set well measured for CRESST detectors with uncertainty $\sigma_\tau$ = 4.8μs
- Uncertainty on pulse on-set proportional to rise-time $\tau_r$
- Define veto window of $\pm 5\sigma_\tau$

MC simulation of muon-rate at VNS (3 m.w.e.)




dead-time from simulated muon-rate