

# CEvNS at the low-energy frontier with

## NU-CLEUS



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

**Johannes Rothe**

Max-Planck-Institute for Physics, Munich  
NOW 2018, Ostuni  
15.9.2018

SFB 1258

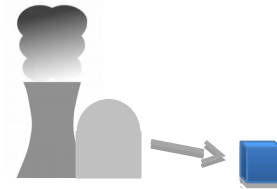
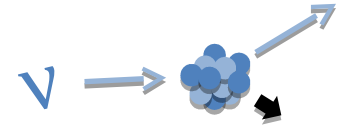
Neutrinos  
Dark Matter  
Messengers



# NU-CLEUS

## Key ingredients:

- Coherent neutrino-nucleus scattering
- Nuclear power reactor
- Ultra-low threshold detectors



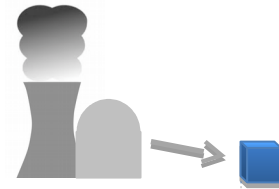
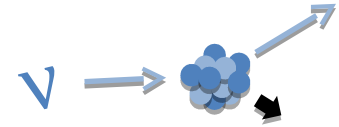
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## New Physics

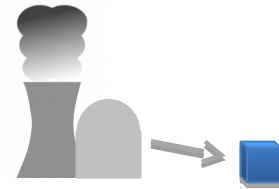
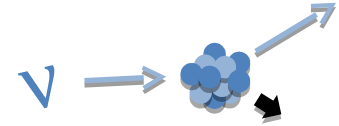
- Nature of neutrinos
- Fundamental neutrino interactions
- Precision tests of electro-weak theory



# NU-CLEUS





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- Coherent neutrino-nucleus scattering
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## New Physics

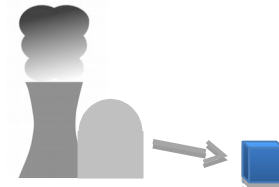
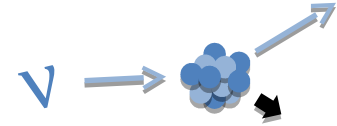
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- |   |                                 |
|---|---------------------------------|
|  | Reactor physics                 |
|  | Nuclear physics                 |
|  | Dark Matter, Solar Neutrinos    |
|  | Miniaturized neutrino detectors |

# NU-CLEUS

## Key ingredients:

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## New Physics

- Nature of neutrinos
- Fundamental neutrino interactions
- Precision tests of electro-weak theory

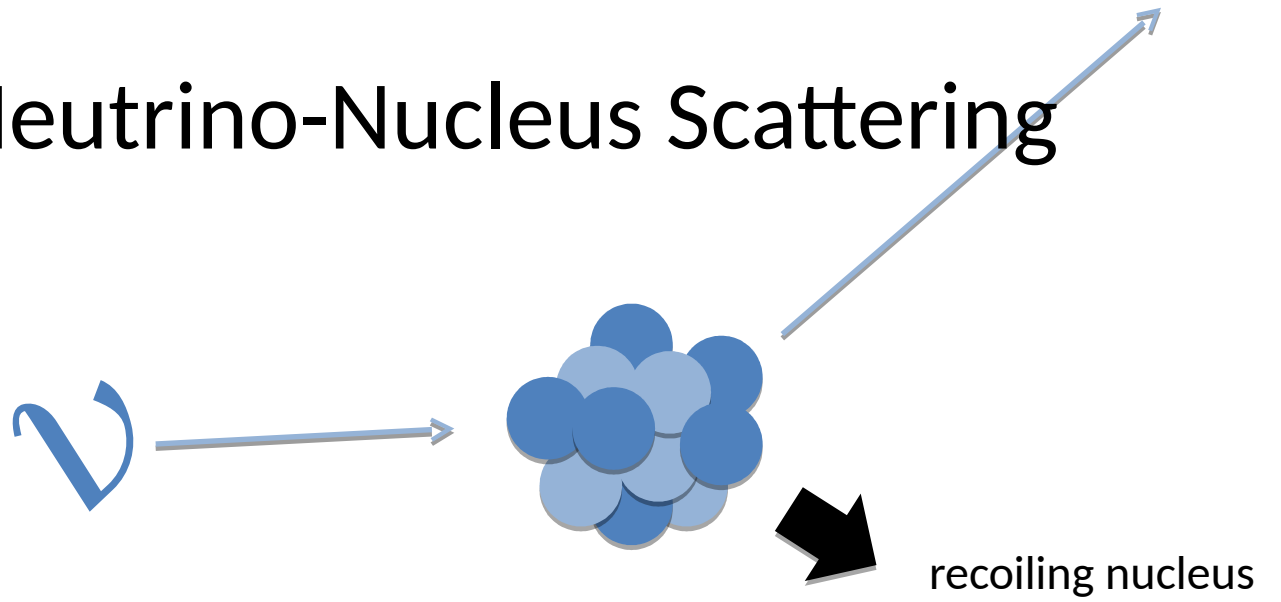
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- ➡ Dark Matter, Solar Neutrinos
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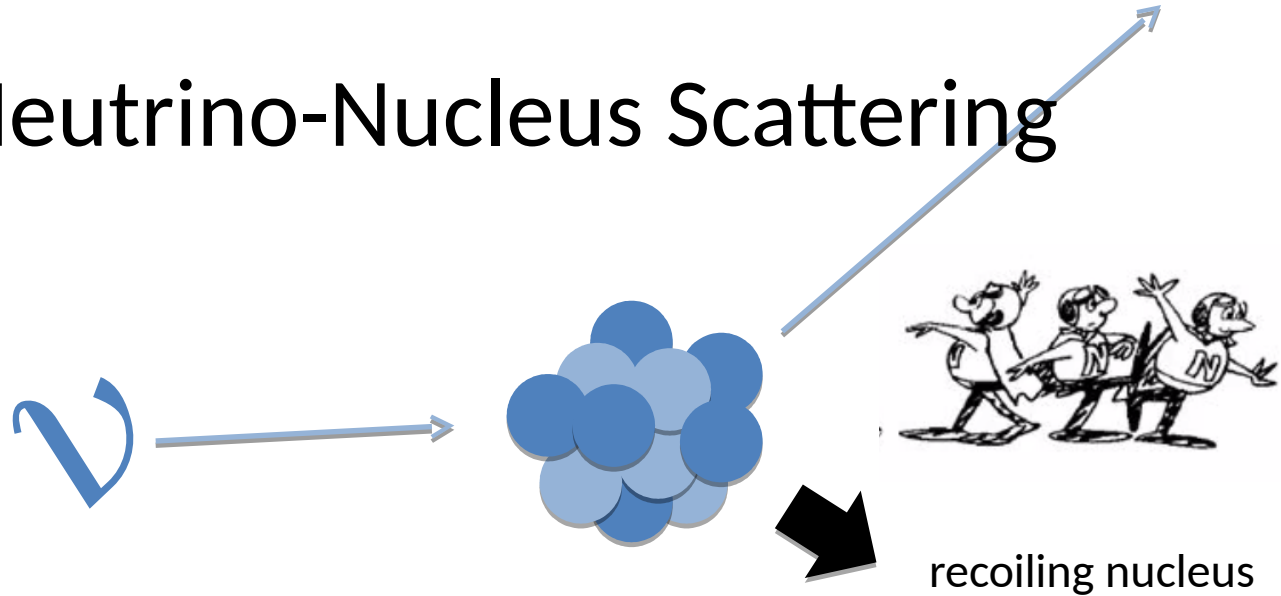
European Research Council

ERC Starting Grant 2018: NU-CLEUS  
Exploring coherent  
neutrino-nucleus scattering  
with gram-scale cryogenic calorimeters

# Coherent Neutrino-Nucleus Scattering



# Coherent Neutrino-Nucleus Scattering



R. Pynn

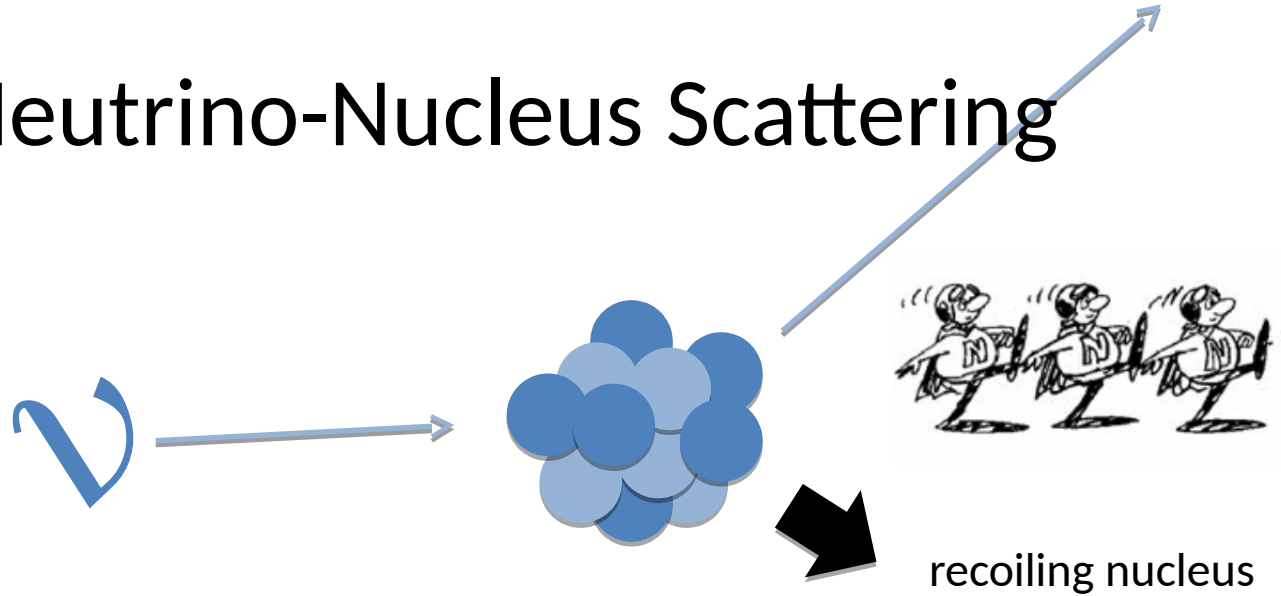
- Elastic **coherent** scattering

Superposition of individual scattering amplitudes:

$$F(\mathbf{q}) = \sum_{j=1}^A f_j(\mathbf{q}) \exp(i\mathbf{q}\mathbf{x}_j)$$

$$\frac{d\sigma}{d\Omega} = |F(\mathbf{q})|^2$$

# Coherent Neutrino-Nucleus Scattering



R. Pynn

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Superposition of individual scattering amplitudes:

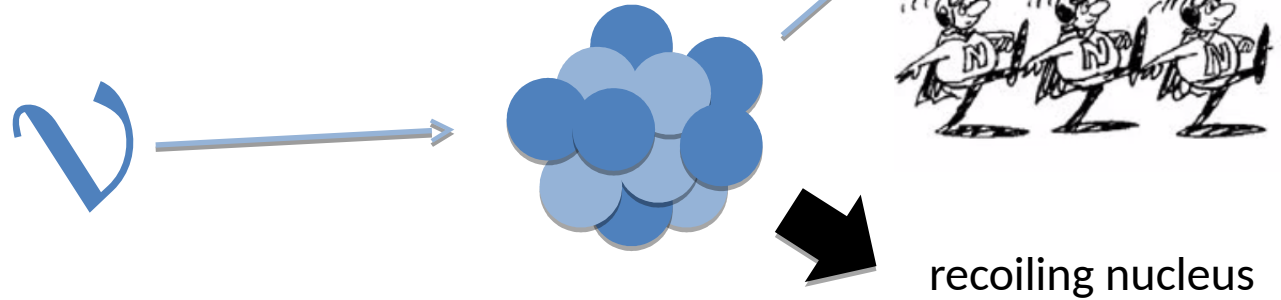
$$F(\mathbf{q}) = \sum_{j=1}^A f_j(\mathbf{q}) \exp(i\mathbf{q}\cdot\mathbf{x}_j)$$

$$\frac{d\sigma}{d\Omega} \cong N^2 |f_j(\mathbf{q})|^2$$

**coherence!**  
 $qR \ll 1$   
 $E_\nu < 20\text{MeV}$

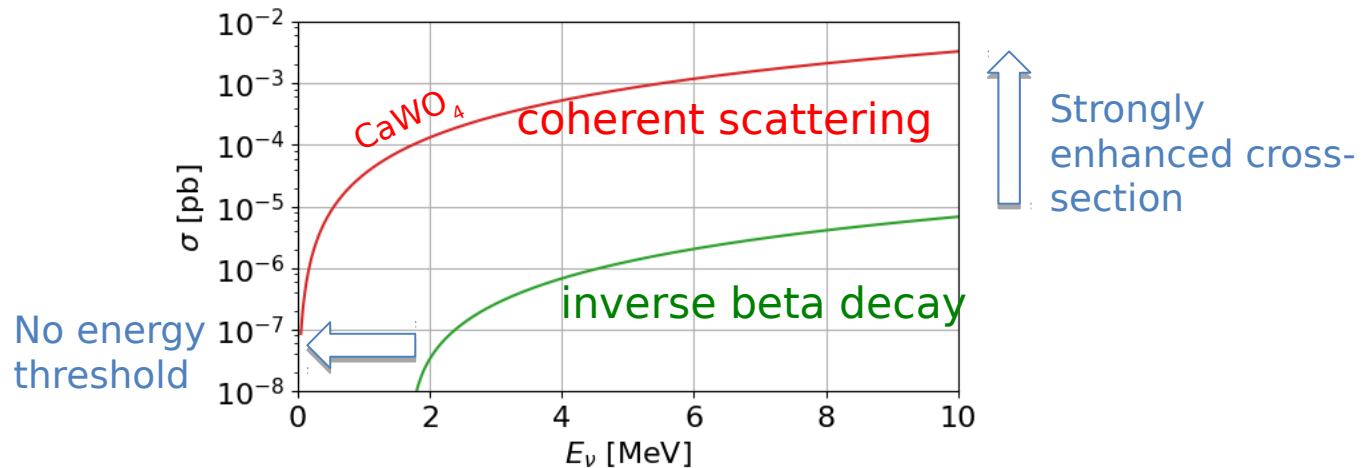
enhancement for heavy nuclei

# Coherent Neutrino-Nucleus Scattering

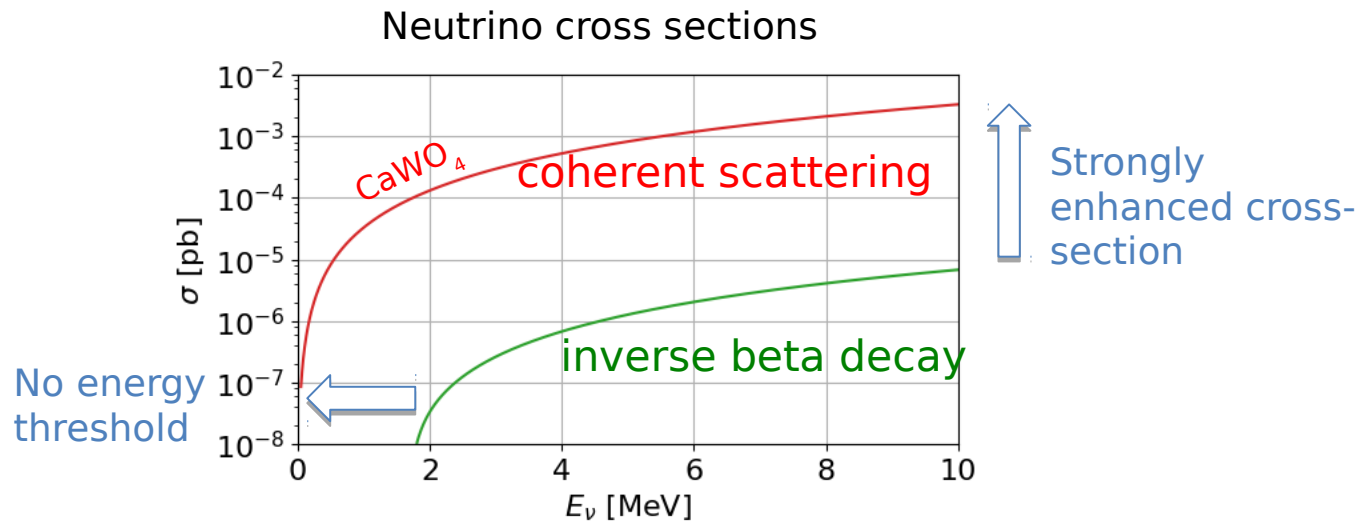
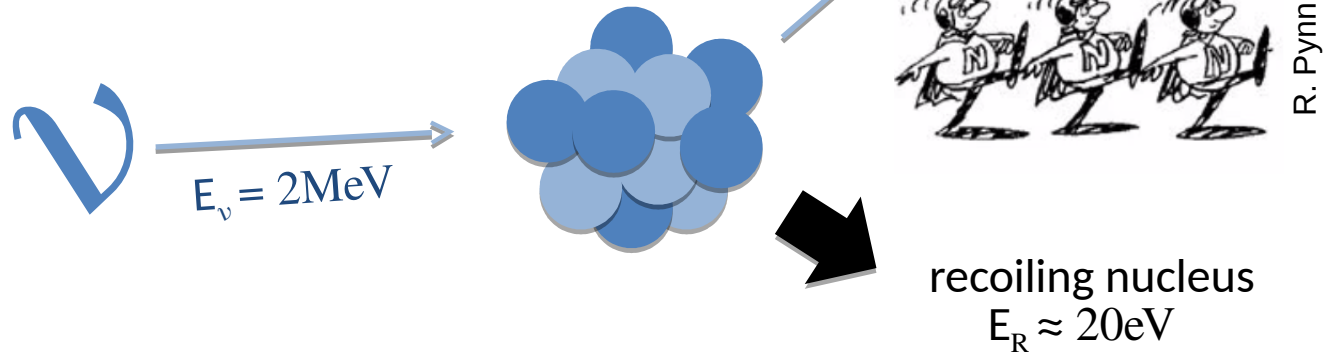


R. Pynn

Neutrino cross sections



# Coherent Neutrino-Nucleus Scattering



# Experiments - Overview

## COHERENT Experiment at the Spallation Neutron Source at Oak Ridge



First observation of CEVNS in Aug 2017!



## Other projects being planned or starting up:

- CONNIE (int.)
- CONUS (MPIK)
- MINER (US)
- V-GEN (RU)
- RICOCHET (US+FR)
- TEXONO (int.)
- RED-100 (RU)
- ...

## NU-CLEUS Experiment at a nuclear power reactor



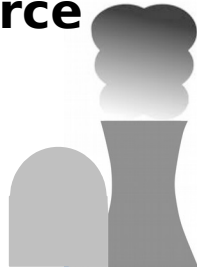
# Why **NU**-CLEUS ?

Neutrino physics at the **low energy** and **precision** frontier!

## **The neutrino source**

Antineutrinos from  
a nuclear reactor

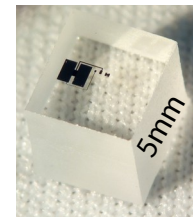
Low energy  
High intensity



## **The detector**

Gram-scale cryogenic  
calorimeters

Ultra-low threshold  
Low systematics



Picture: M. Mancuso, MPP

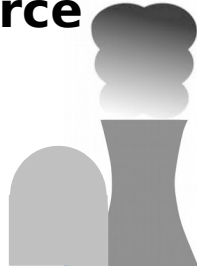
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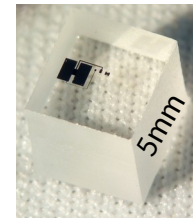
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## The detector

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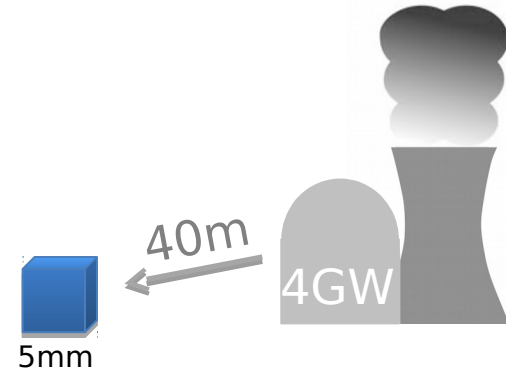


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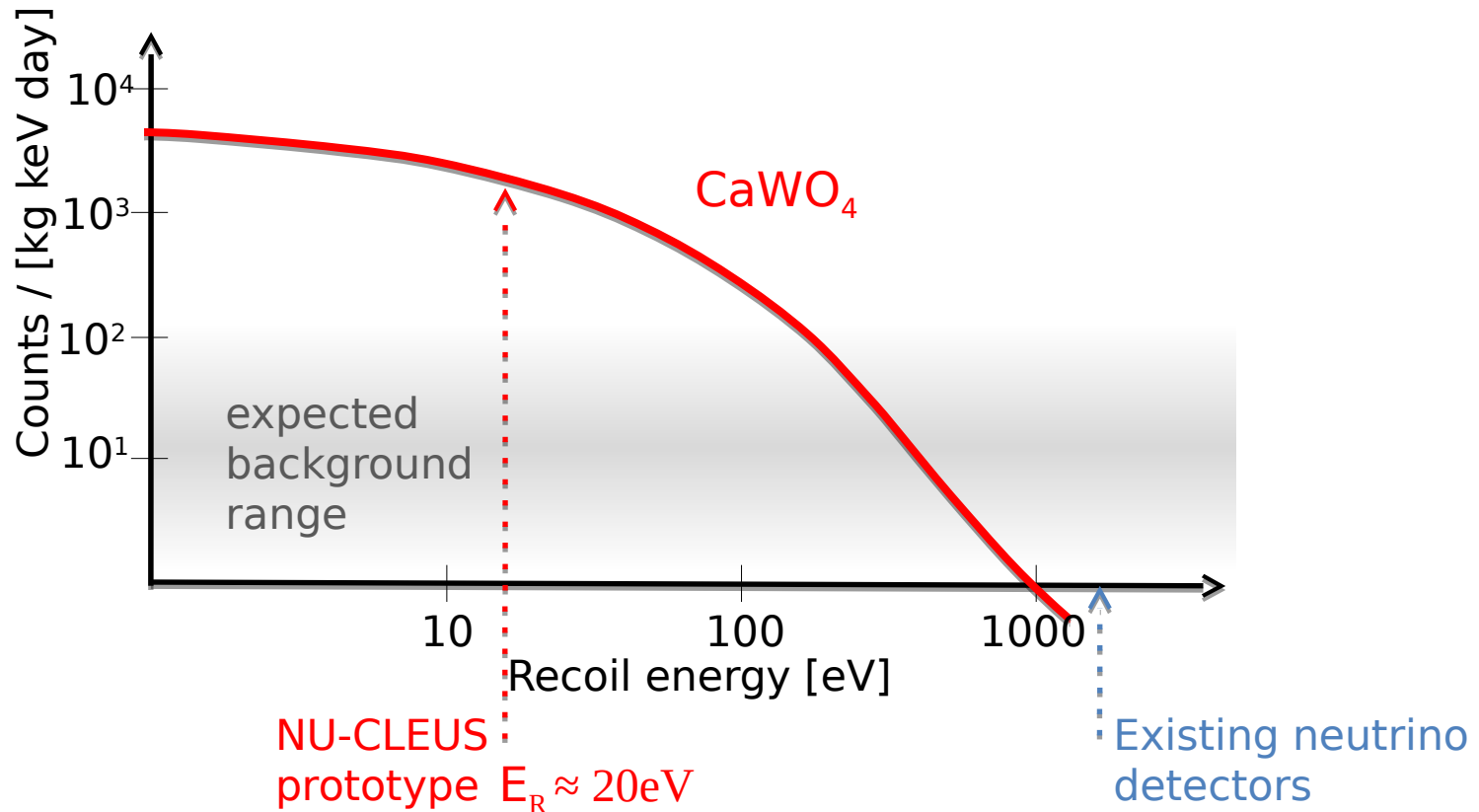
Two-phased approach:

- **Phase 1** NU-CLEUS *10g* ( $\text{CaWO}_4$  +  $\text{Al}_2\text{O}_3$  targets)
- **Phase 2** NU-CLEUS *1kg* (Ge + Si targets)

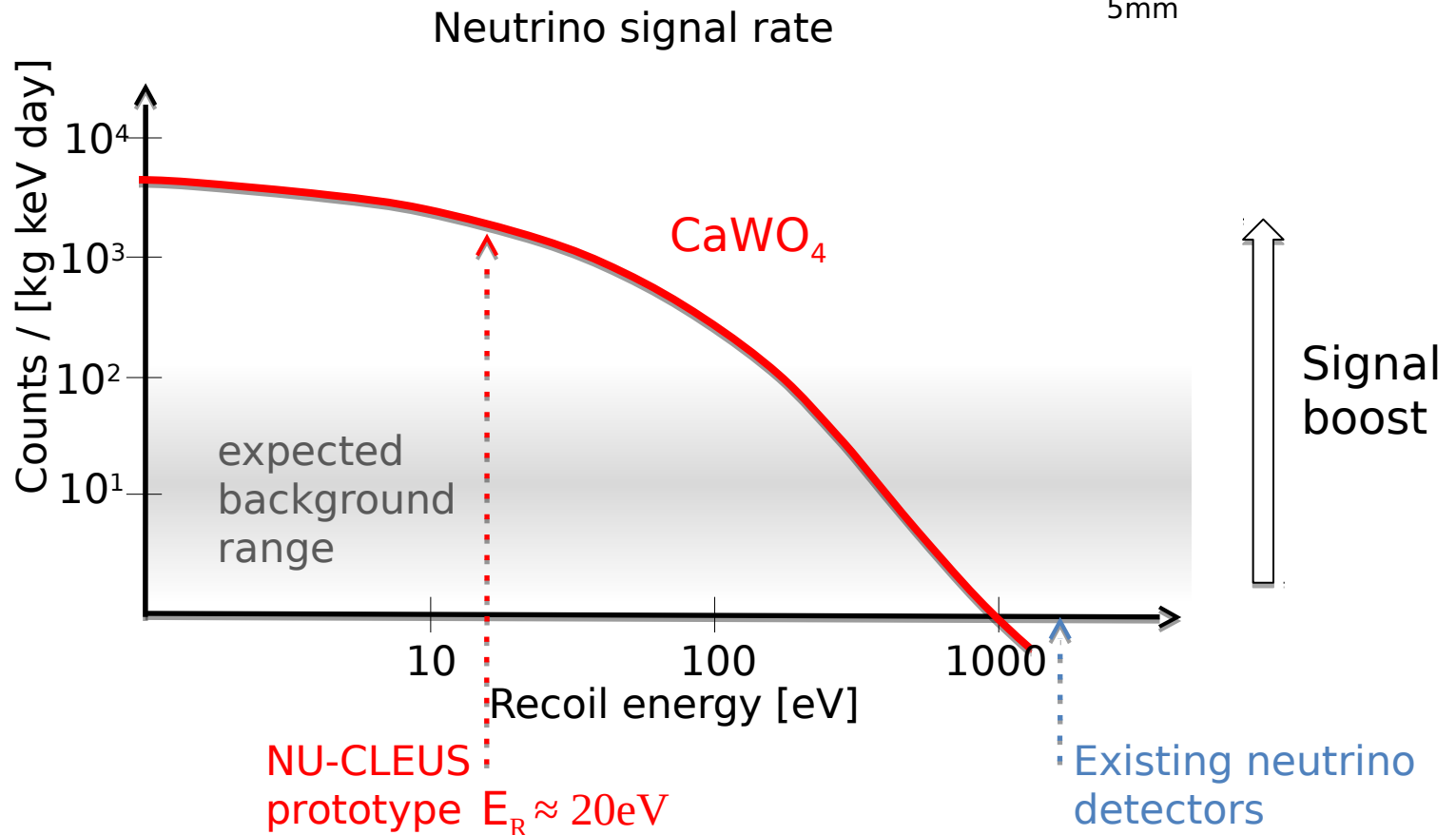
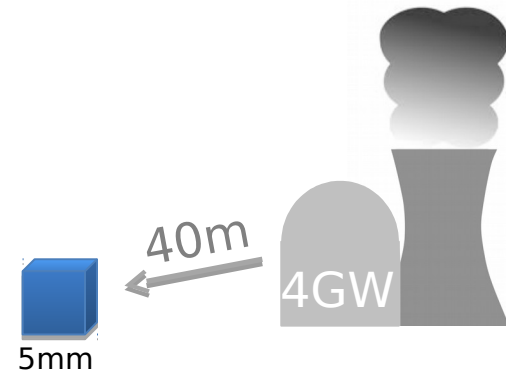
# NU-CLEUS Potential



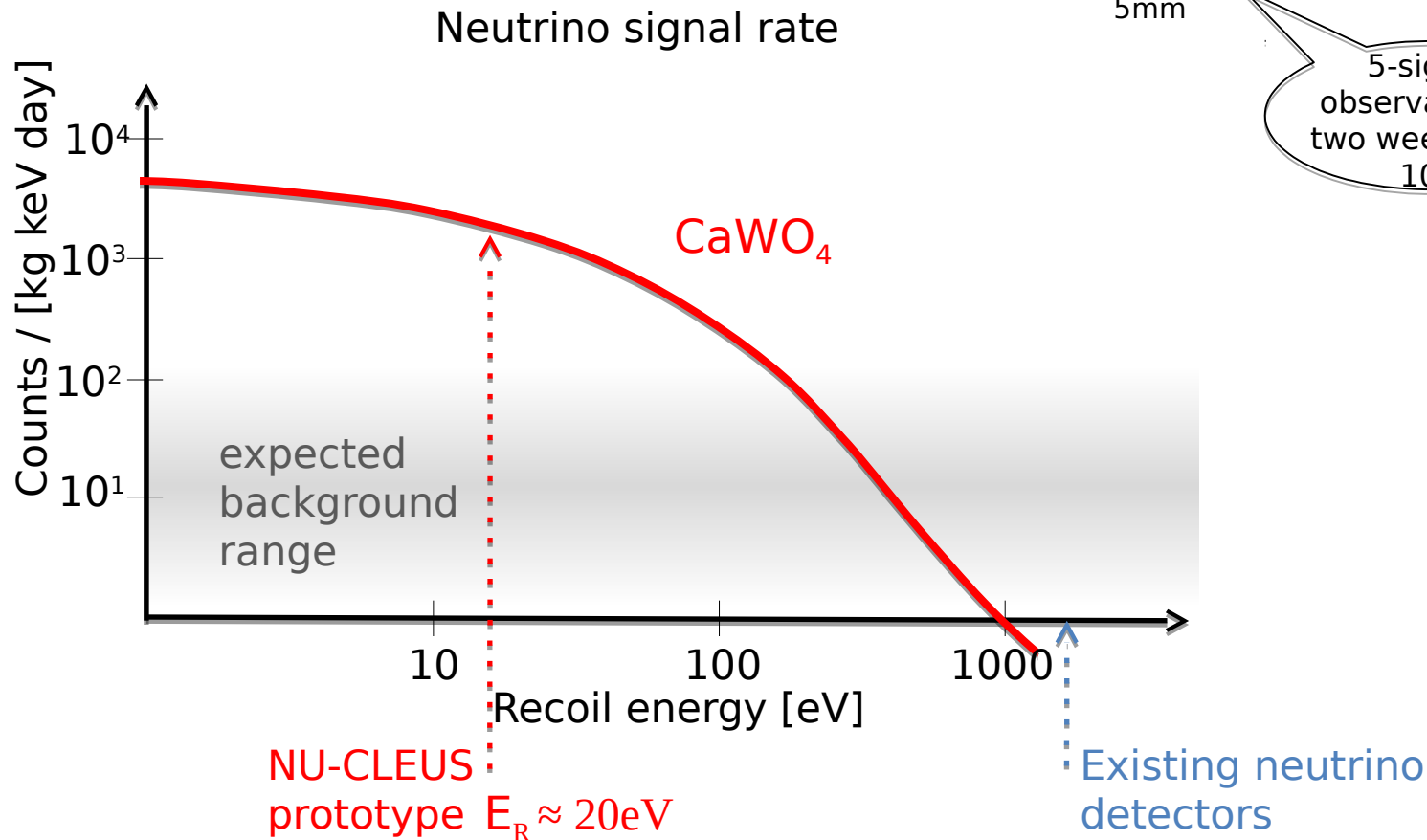
Neutrino signal rate



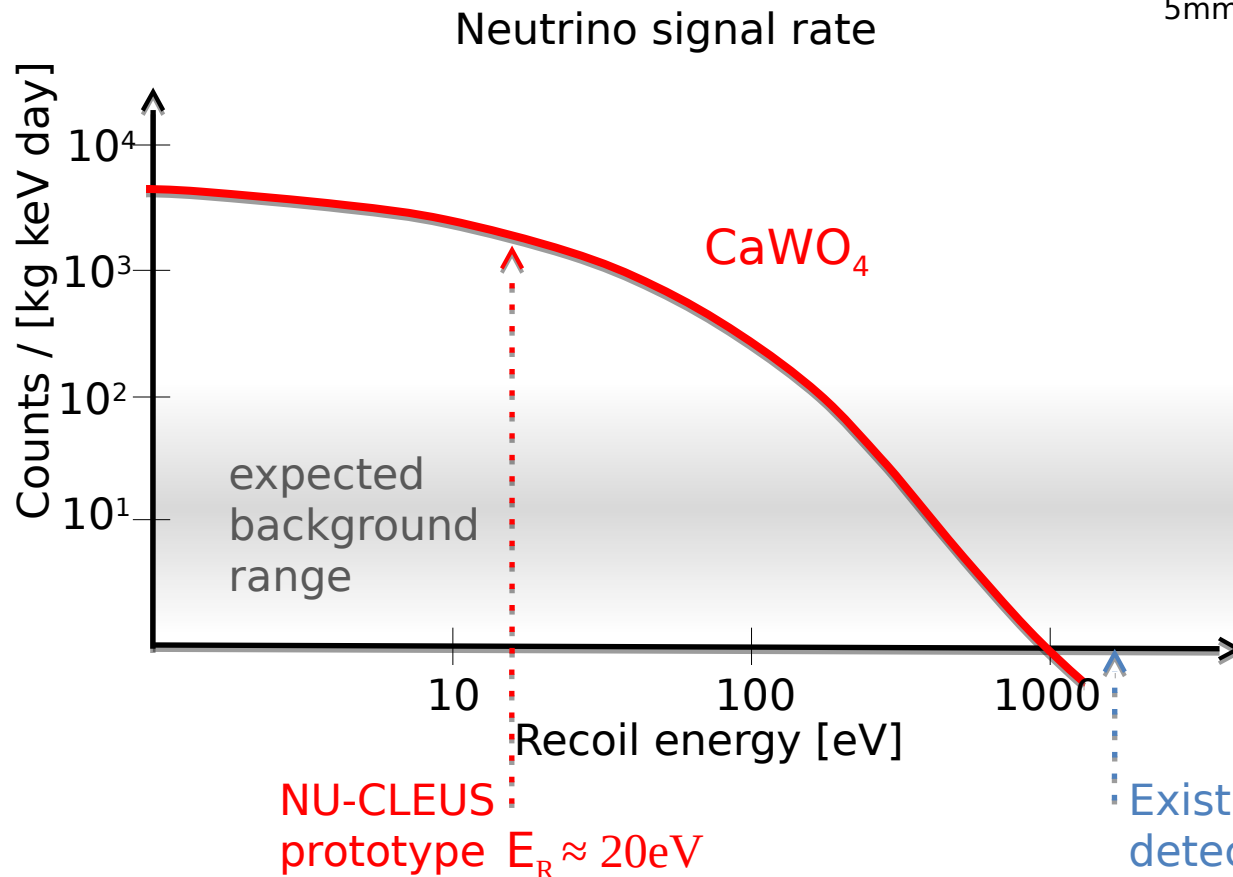
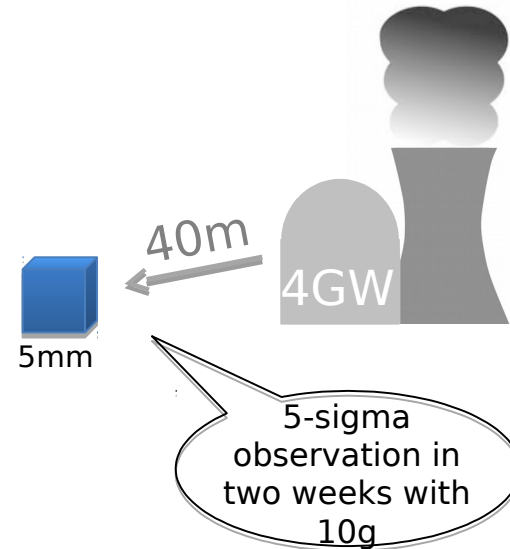
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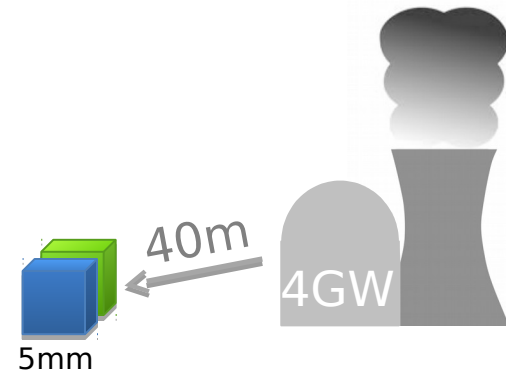
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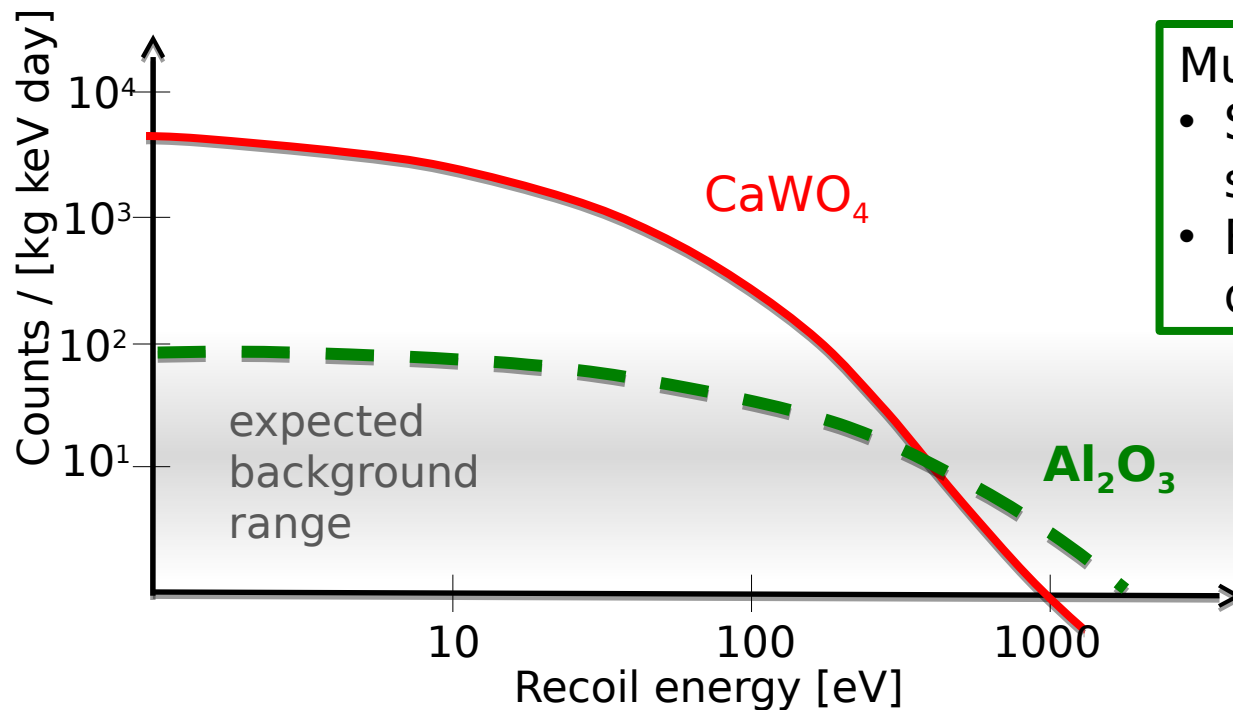
**Potential:**

- Low energies
- High S/B
- High rate

# NU-CLEUS Potential



Neutrino signal rate



Multi target:

- Smoking gun signal
- Background discrimination

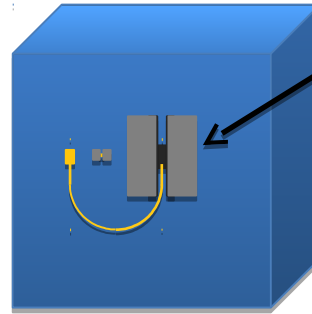
# THE U-CLEUS DETECTOR

# The **N**U-CLEUS Detector Concept

## Gram-Scale Cryogenic Calorimeters

Single crystal  
Si, Ge,  $\text{Al}_2\text{O}_3$ ,  
 $\text{CaWO}_4$

Operation at mK  
temperatures



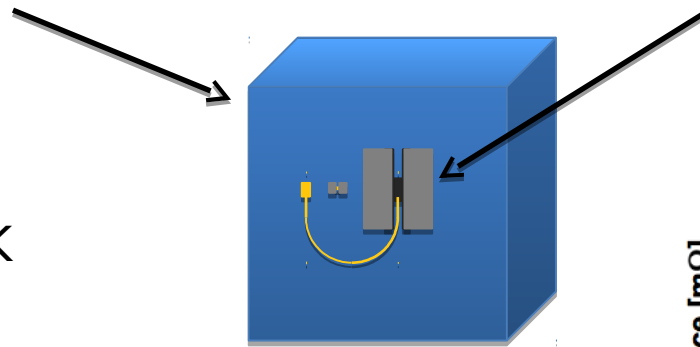
Thermometer  
Transition-edge-sensor

# The NU-CLEUS Detector Concept

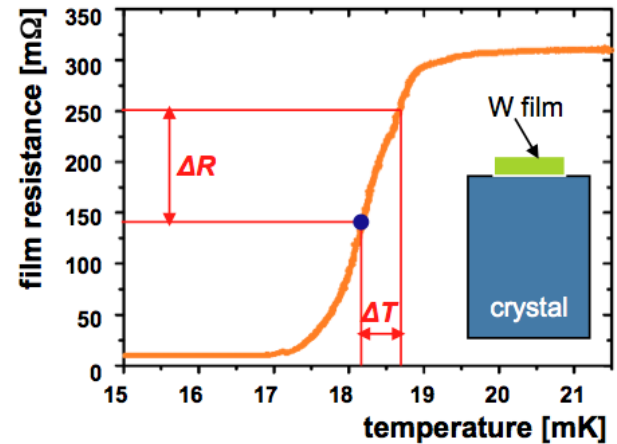
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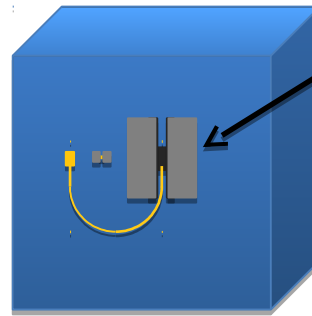


# The NU-CLEUS Detector Concept

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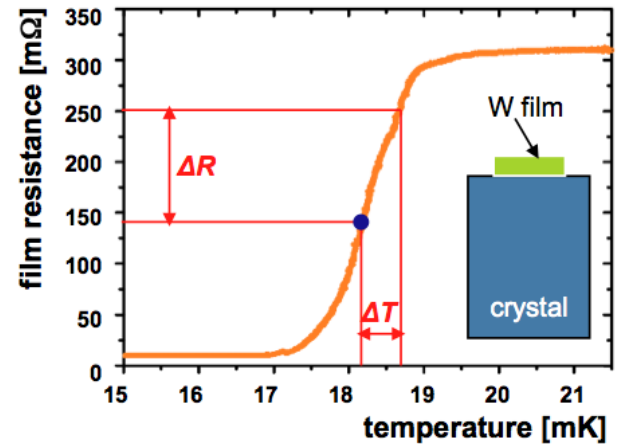


Thermometer  
Transition-edge-sensor

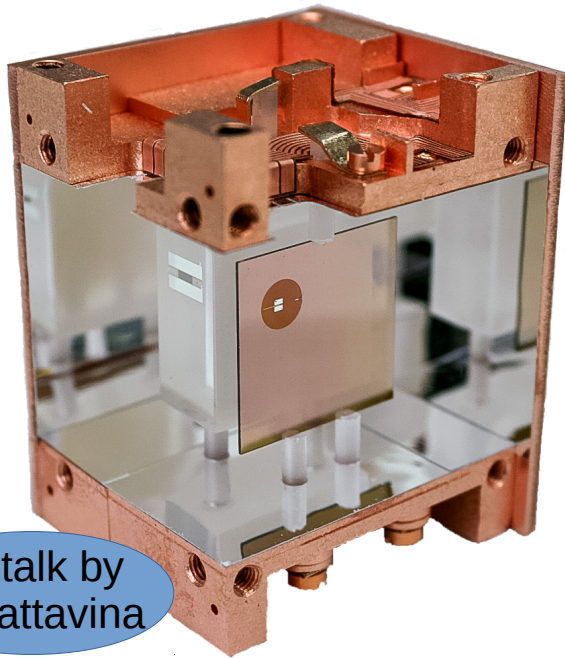
- **CRY**ogenics

+ thermal signal without quenching

$$100 \text{ eV}_{\text{ee}} = 100 \text{ eV}_{\text{nr}} = 100 \text{ eV}$$



# The NU-CLEUS Detector Concept



see talk by  
L. Pattavina

CRESST-III cryogenic calorimeter

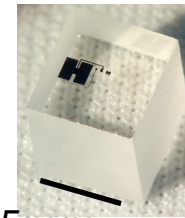
- Single crystal  $\text{CaWO}_4$
- Energy threshold  $< 100\text{eV}$
- Leading technology for low-mass dark matter searches

Scaling down:

$$E_{th} = (\text{const.}) \times M^{2/3}$$

Phys. Rev. D96 (2017) no.2, 022009

Picture: M. Mancuso, MPP



5mm

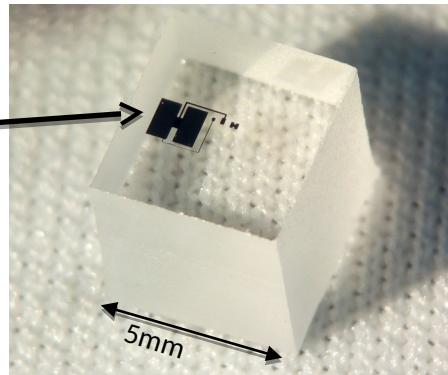
Gram-scale cryogenic calorimeter

- $\text{Al}_2\text{O}_3$ ,  $\text{CaWO}_4$ , Si, Ge...
- Threshold expectation (fully optimized):  $< 10\text{eV}$

# The NU-CLEUS Detector Concept

A first prototype detector

Optimized  
thermometer



## Innovations:

Low threshold

Above-ground  
operation

Fiducialisation

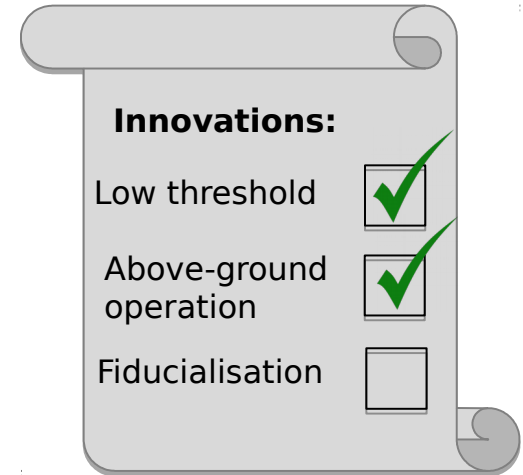
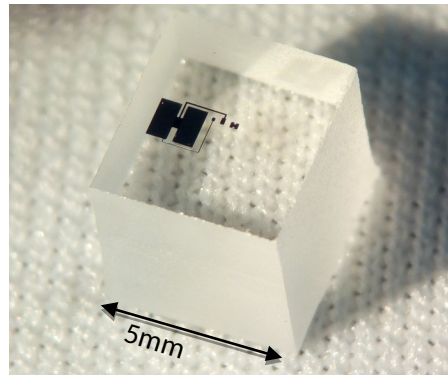
## Technology for neutrino detector demonstrated

R. Strauss et al., *Phys. Rev. D* **96**, 022009 (2017)

- World-best energy threshold for nuclear recoils,  
 **$E_{\text{th}} = (19.7 \pm 0.8) \text{ eV}$**
- Low systematics - precise knowledge of energy scale

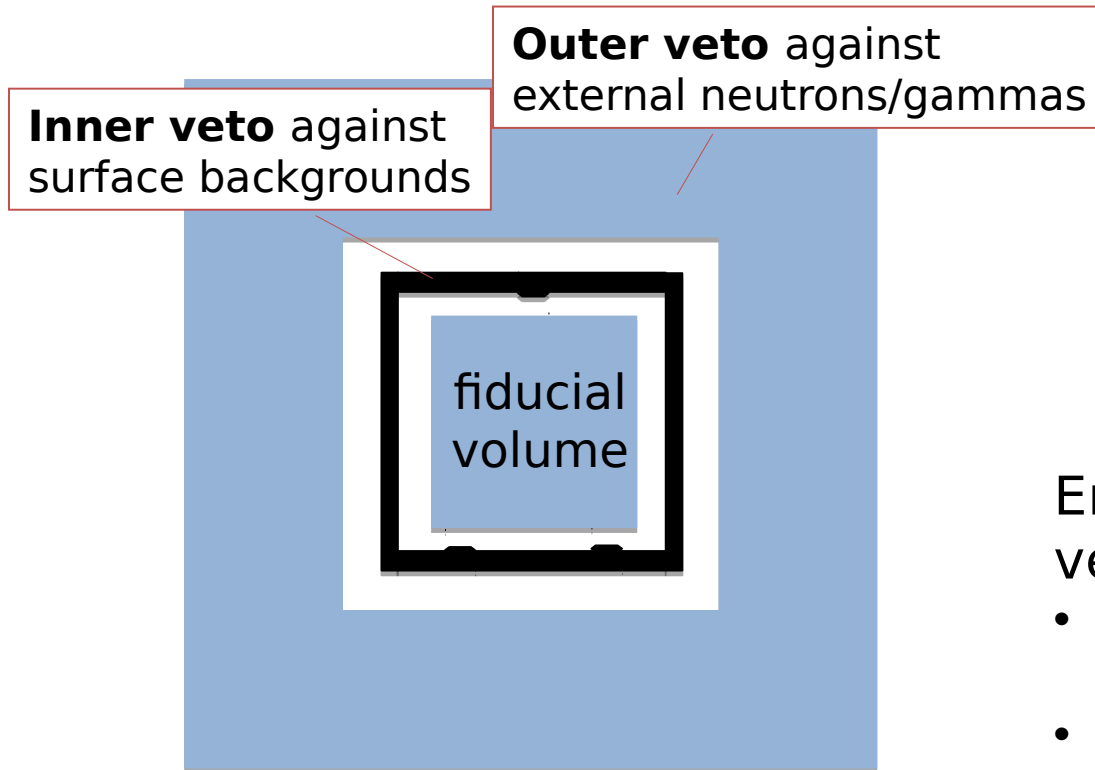
# The **NU**-CLEUS Detector Concept

A first prototype detector

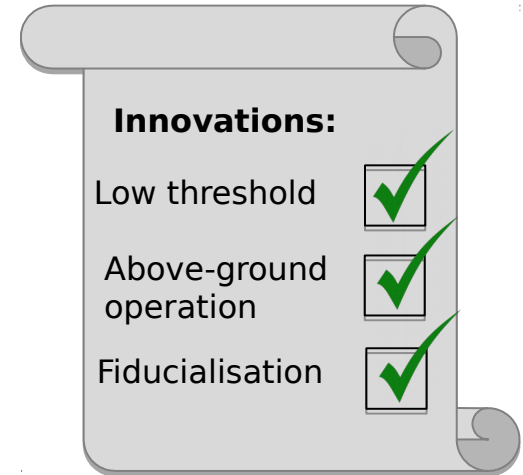


- Rate sufficiently low for operation in high-background environments
- Fast pulses: **anti-coincidence with muon-veto** of kHz count rate (for above ground setup)

# The **NU**-CLEUS Detector Concept



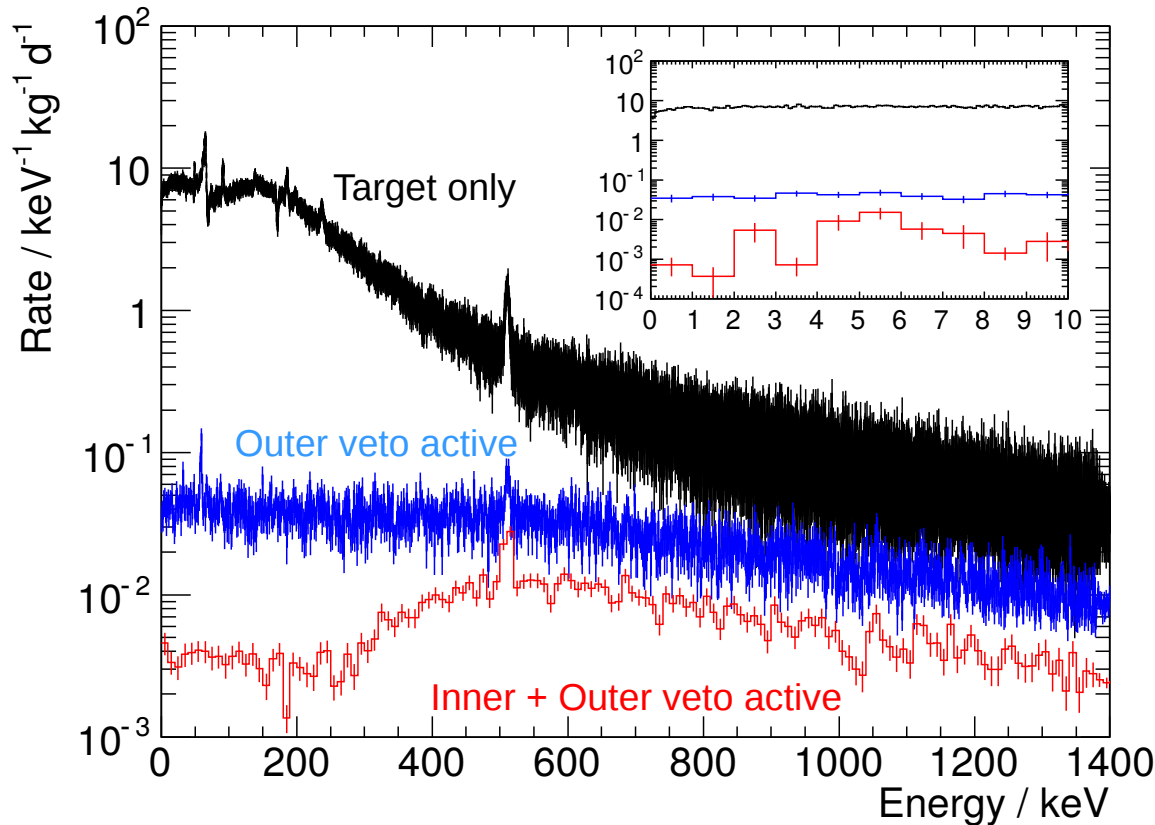
→ Fiducial-volume cryogenic detector



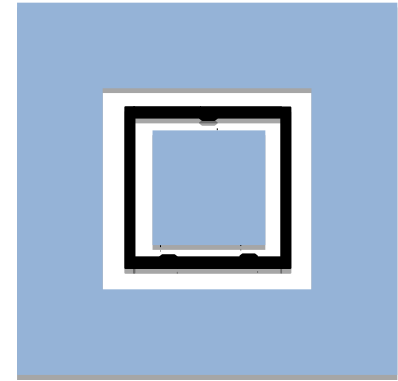
Encapsulation by cryogenic veto detectors:

- Crucial background reduction
- Dedicated MC studies: 2-3 orders of magnitude improvement

# Veto Simulations



Fiducial-volume detector



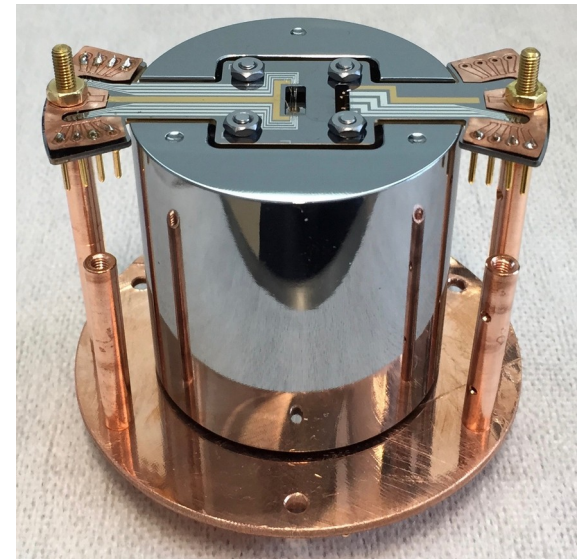
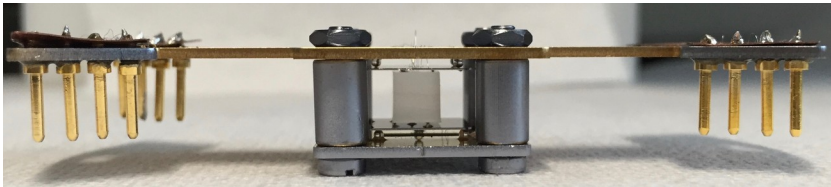
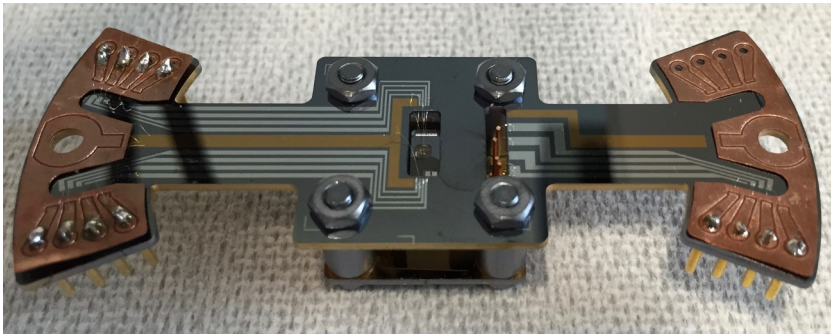
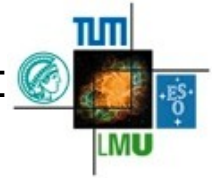
RS, et al.. Eur. Phys. J., C77(8):506  
(2017) arXiv: 1704.04320

- External / muon-induced gammas negligible compared to intrinsic radiopurity
- Dedicated MC study needed for neutrons

# NEWS: Recent Measurements

## NU-CLEUS 1g demonstrator

Seed money project

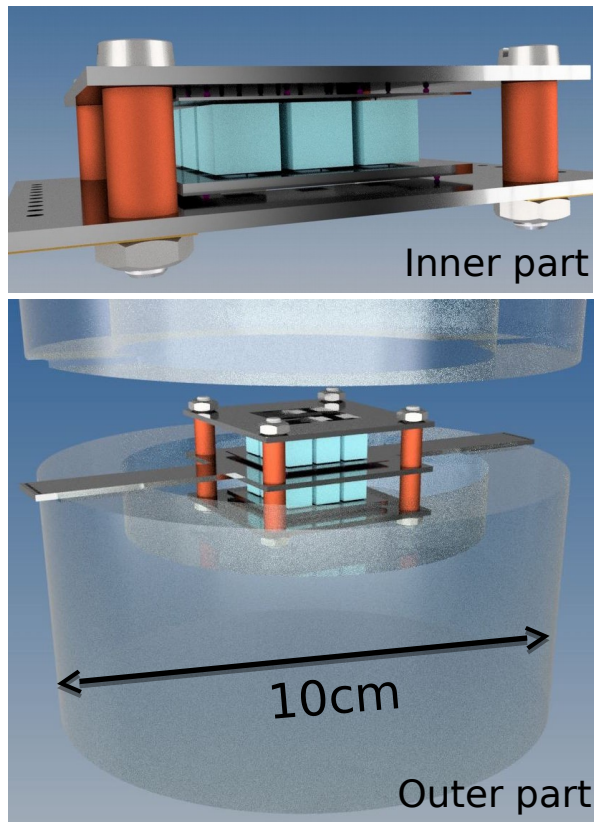


Si outer veto prototype

- Sapphire and  $\text{CaWO}_4$  crystals
- Flexible Si wafers as inner veto detectors

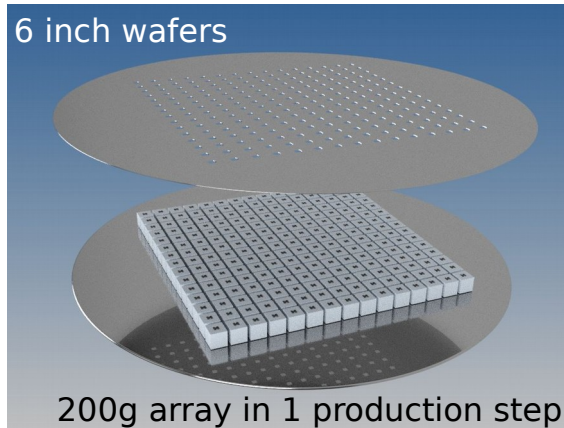
# NU-CLEUS 10g and 1kg

## NU-CLEUS 10g



## NU-CLEUS 1kg

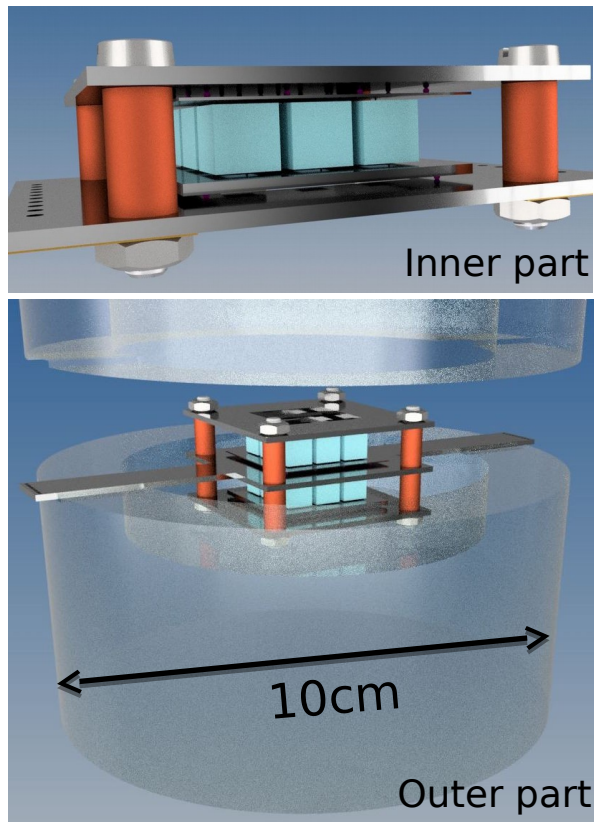
A scalable cryogenic detector



- Exploit semiconductor technology
- SQUID multiplexing

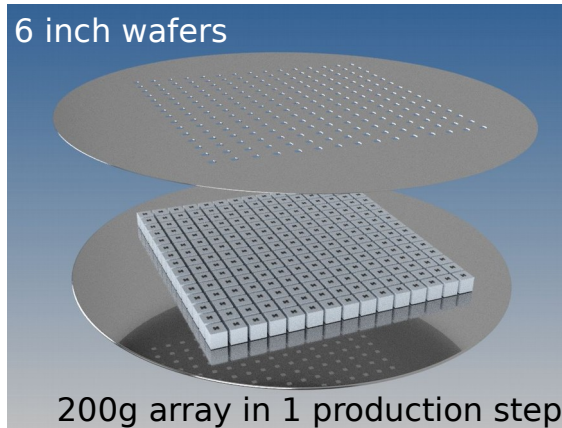
# NU-CLEUS 10g and 1kg

## NU-CLEUS 10g



## NU-CLEUS 1kg

A scalable cryogenic detector



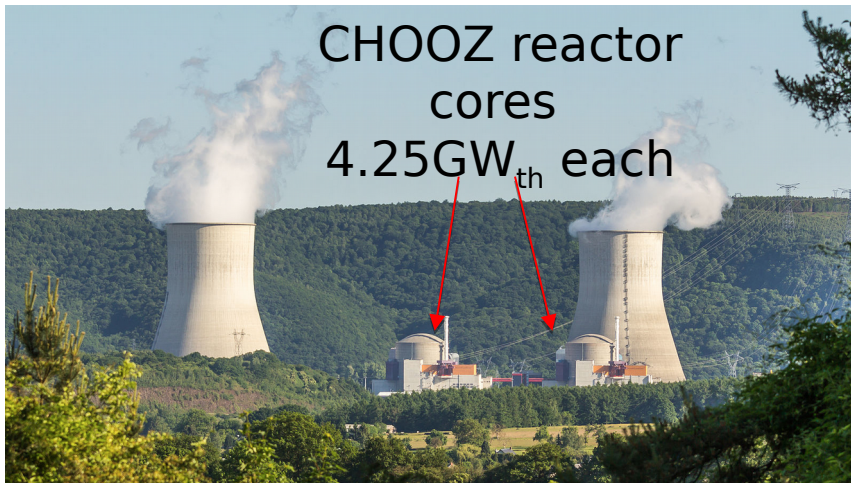
- Exploit semiconductor technology
- SQUID multiplexing

- Multi-year R&D program
- New approach for rare-event search and small precision  $\nu$  experiments

Background studies at CHOOZ

# **The Nuclear Reactor**

# The CHOOZ Power Plant in France



Th. Lasserre (CEA)  
**M. Vivier (CEA)**  
V. Wagner (CEA)  
**G. Munch (EDF)**  
J. Molina (EDF)  
R. Strauss (MPP)  
A. Langenkämper (TUM)



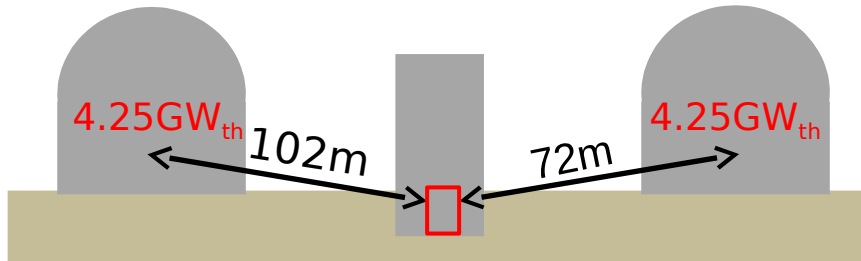
Established relation to reactor company (EDF)

Since March 2018:

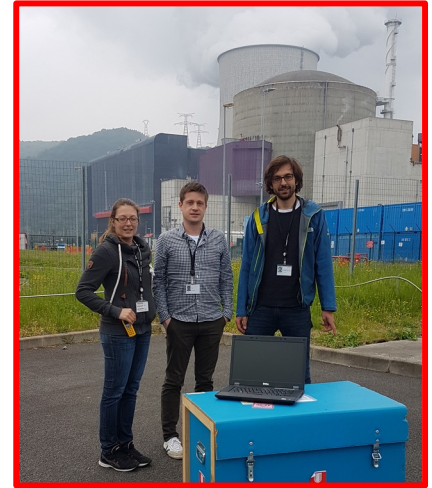
- Full access to inner zone of power plant
- Support from engineers on-site for infrastructure and safety
- Permission for background measurements on-site
- Convention (CEA-EDF) for NU-CLEUS in preparation



# The Very-Near-Site at CHOOZ



Full access to a  
24m<sup>2</sup> basement  
room



We aim for a compact setup for  
NU-CLEUS

## Background measurements ongoing:

Cosmic **muons**: attenuation by 1.5  
Fast **neutrons**: attenuation by factor  $\sim 8$

First results presented at *NEUTRINO2018*  
Publication in preparation



Coherent Neutrino-Nucleus Scattering

# **Potential for New Physics**

# Neutrino Non-Standard Interactions

**Standard parametrization of modified CEvNS cross-section:**

K. Scholberg, *Phys. Rev. D* **73**, 033005 (2006)

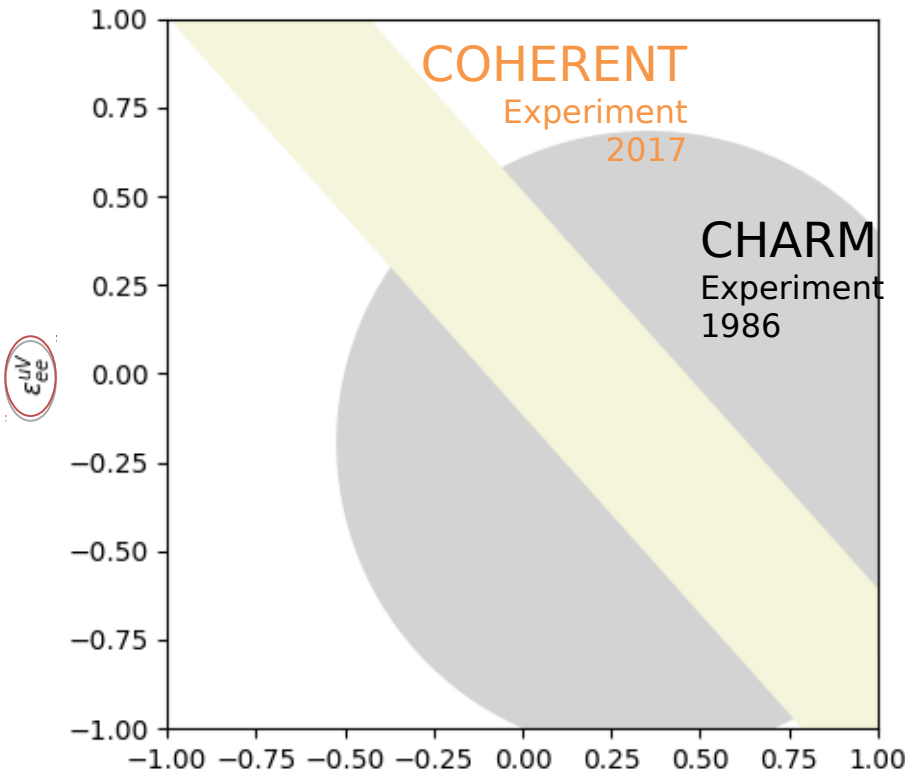
$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME) \left[1 - \frac{ME}{2k^2}\right] \times \quad (4)$$

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

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

and  $g_V^n = -\frac{1}{2}$

Additional coupling to u-quark



Additional coupling to d-quark

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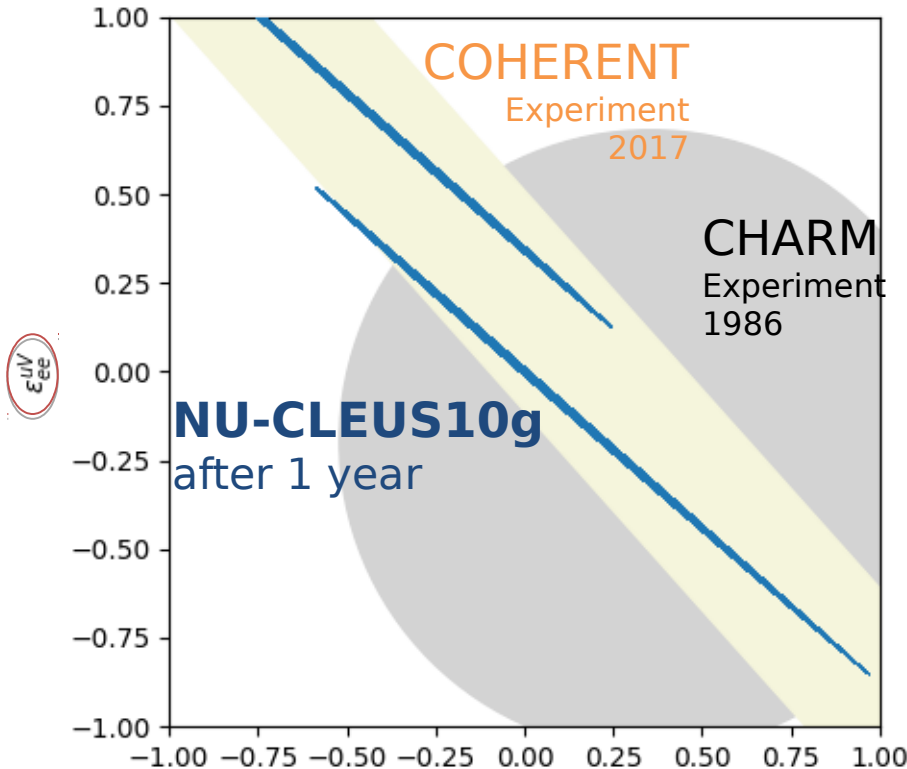
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With  $g_V^p = (\frac{1}{2} - 2 \sin^2 \theta_W)$   
 and  $g_V^n = -\frac{1}{2}$

Improve upon existing constraints after few months.

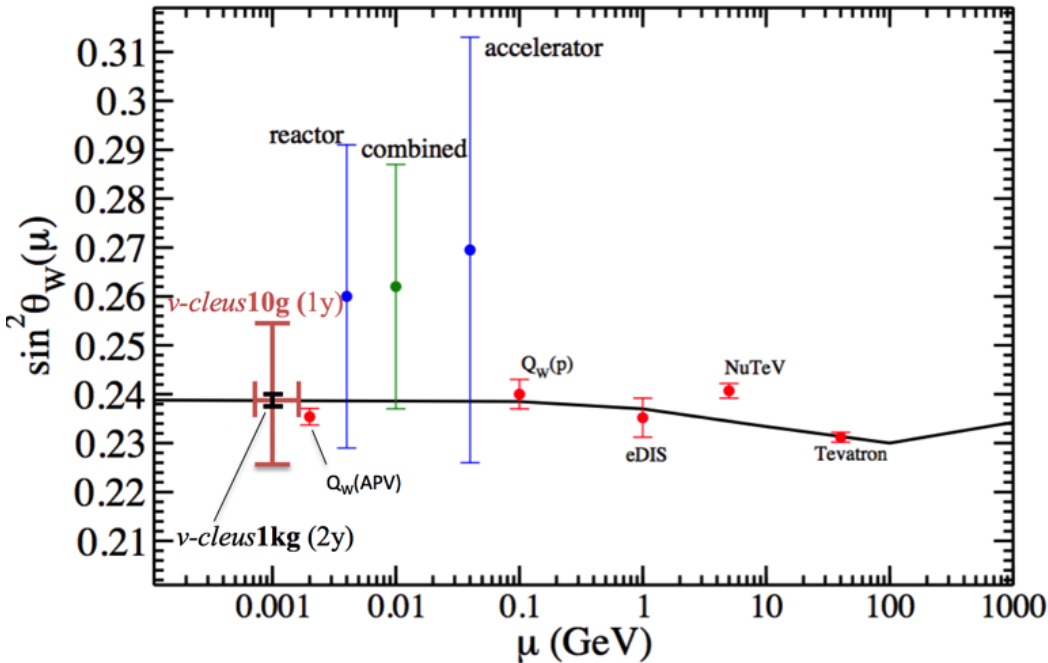
Additional coupling to u-quark



Additional coupling to d-quark

# Weak mixing angle

Running of weak mixing angle



adapted from Phys.Lett. B761 (2016) 450-455

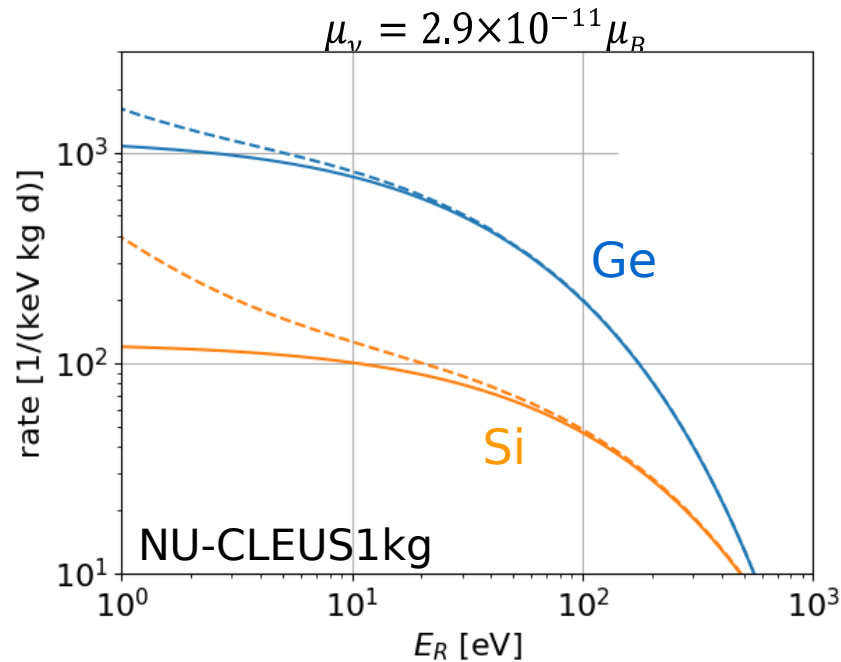
$$\left(\frac{d\sigma}{dE}\right)_{\nu_{\alpha}A} = \frac{G_F^2 M}{\pi} F^2(2ME) \left[1 - \frac{ME}{2k^2}\right] \times \left\{ [Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2 \right.$$

$$\text{With } g_V^p = \left(\frac{1}{2} - 2 \sin^2 \theta_W\right), \quad g_V^n = -\frac{1}{2}$$

First determination of the weak mixing angle at  $q = 1\text{MeV}/c$

CEvNS measurement can provide most stringent neutrino constraint

# Neutrino magnetic dipole moment ( $\nu$ MDM)



$\nu$ MDM can be written as  
(minimally extended SM):

$$\mu_\nu \approx 3.2 \times 10^{-19} (m_\nu / 1\text{eV}) \mu_B$$

$\nu$ MDM in SM extensions:

M. Fukugita *et al.*, PRL **58** (1987) 1807  
Phys.Lett. B642 (2006) 377-383

→  $10^{-12}$ - $10^{-10} \mu_B$  (Majorana)

Additive component to CNNS cross-section:

$$\frac{d\sigma_{EM}}{dE_R} \sim \mu_\nu^2 \left( \frac{1 - E_R/E_\nu}{E_\nu} + \frac{E_R}{4E_\nu^2} \right)$$

A.B. Balantekin, N. Vassh, Phys. Rev. D **89** (2014) no.7, 073013

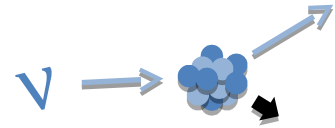
NU-CLEUS can improve  
presently best limit on  $\nu$ MDM  
to  $10^{-12} \mu_B$

→ Study nature of neutrinos

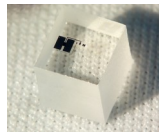
→ Indications for new physics

# Conclusions

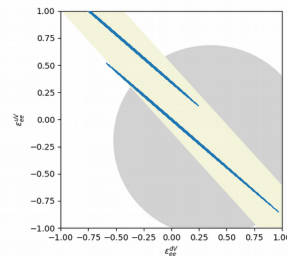
Coherent neutrino-nucleus scattering:  
**Portal to new physics**



Gram-scale cryogenic calorimeters:  
**Miniaturization of neutrino detectors**

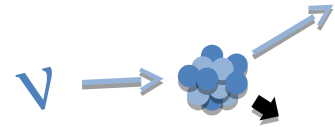


**NU-CLEUS** at a nuclear reactor:  
**Explore low-energy neutrino frontier**

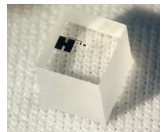


# Conclusions

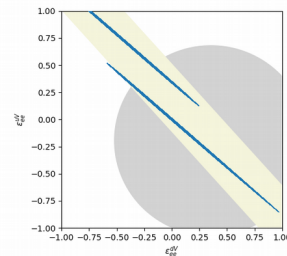
Coherent neutrino-nucleus scattering:  
**Portal to new physics**



Gram-scale cryogenic calorimeters:  
**Miniaturization of neutrino detectors**



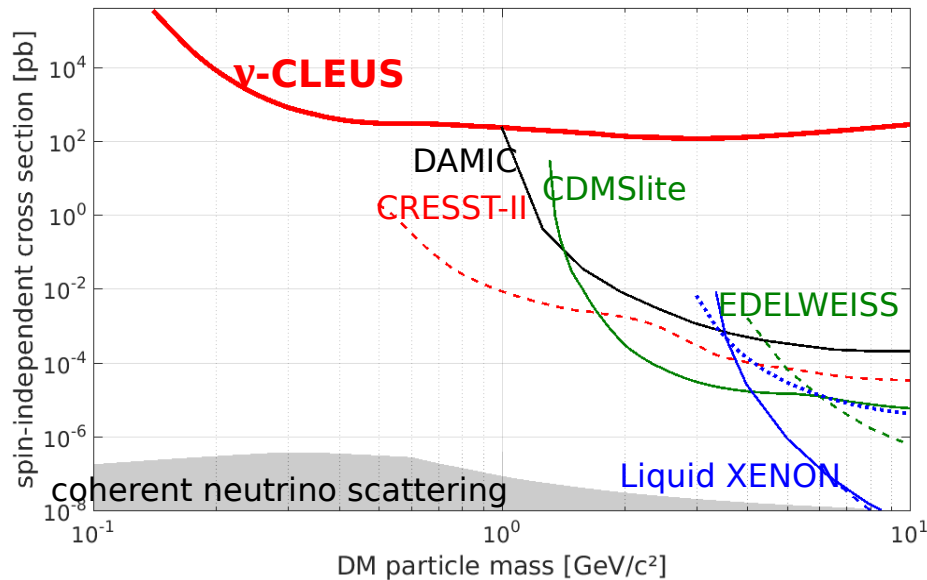
**NU-CLEUS** at a nuclear reactor:  
**Explore low-energy neutrino frontier**



Thank you!

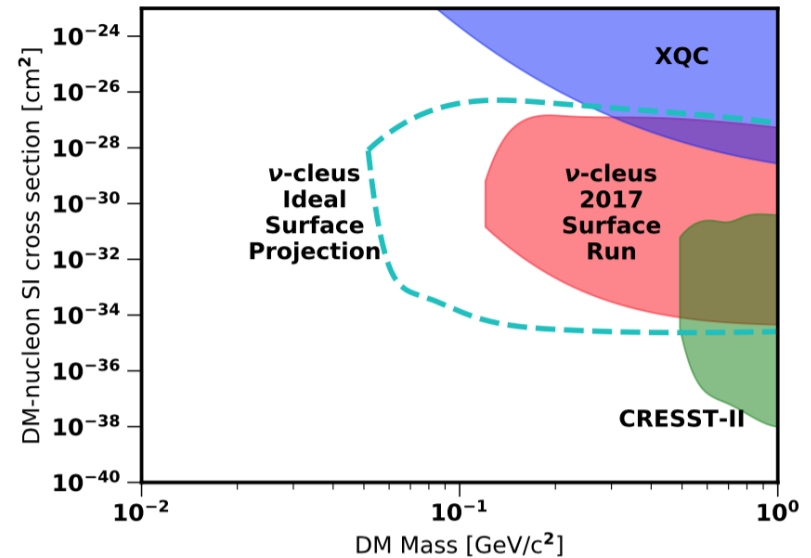
# **Backup Slides**

# NU-CLEUS: Dark Matter Results



First limit for dark matter particle masses below  $500\text{MeV}/c^2$  via NR

G. Angloher et al. (CRESST Collab.), *Eur. Phys. J. C* **77** (2017) no.9, 637

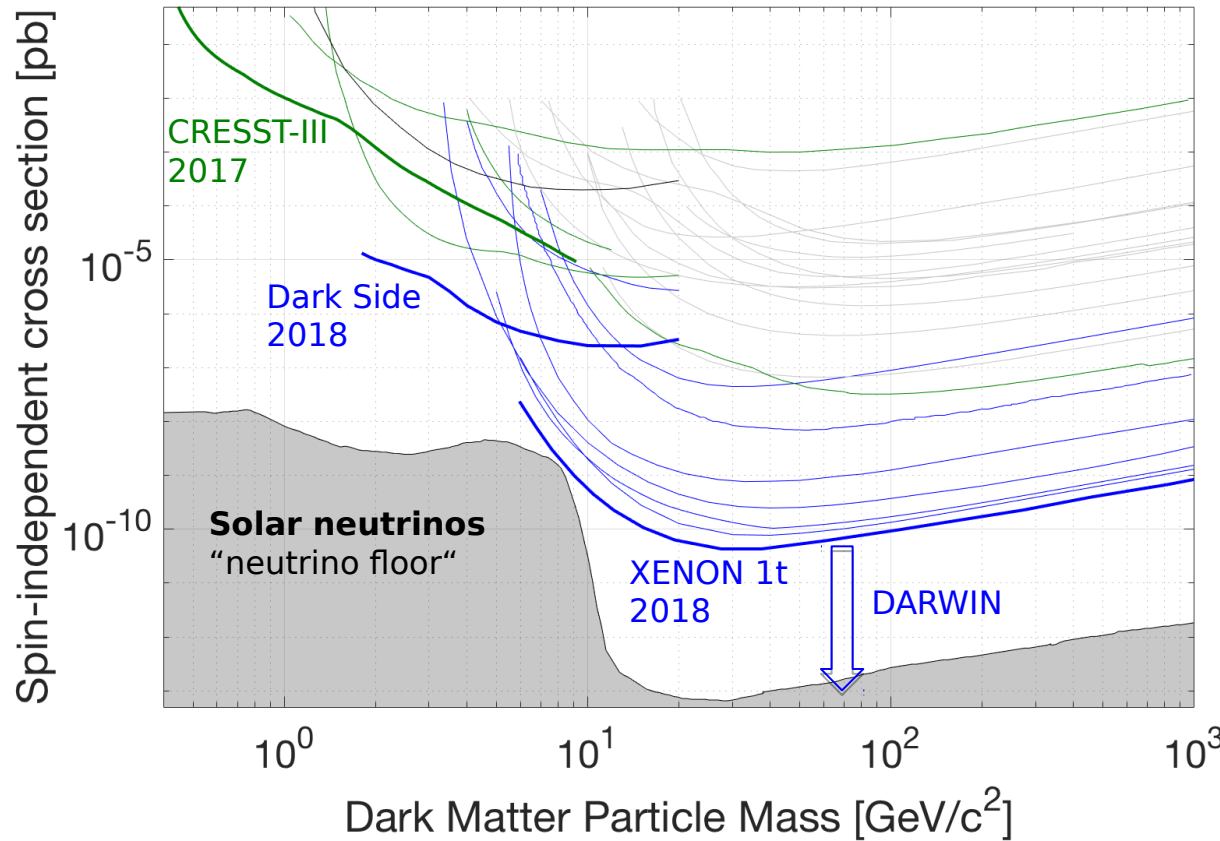


New parameter space excluded for SIMPs

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

# Cross-Disciplinary: Dark Matter Search

Current experimental limits on Dark Matter

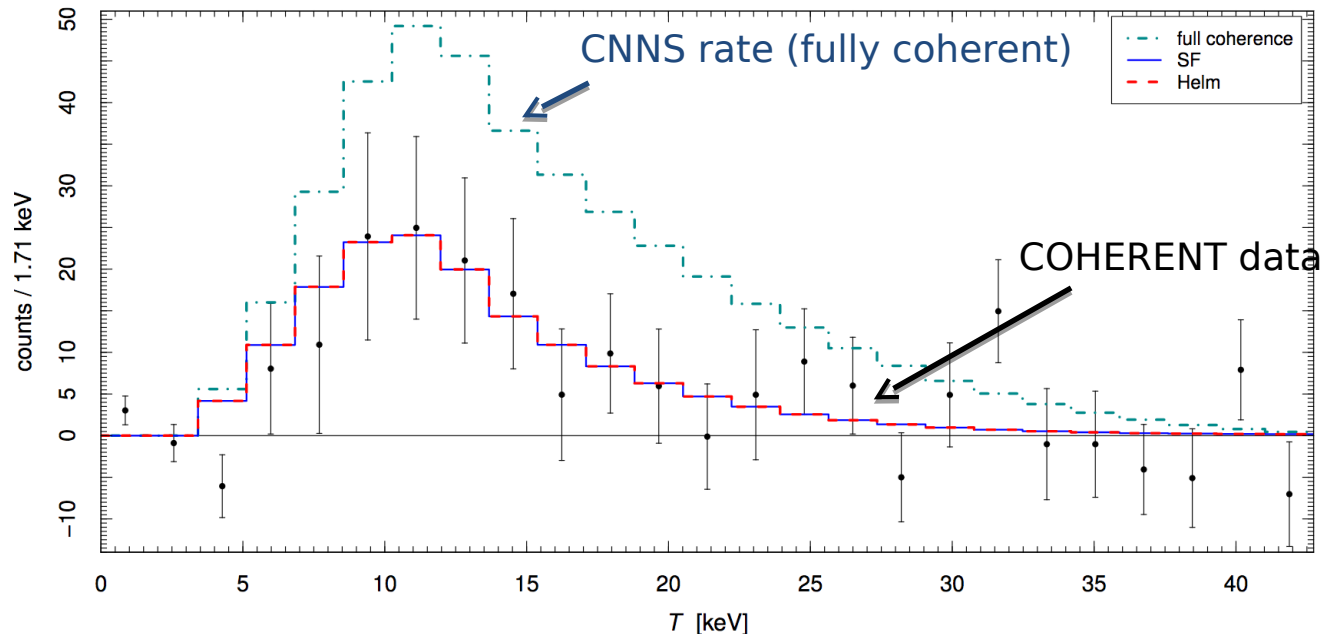


Coherent scattering of **solar neutrinos** as ultimate background for Dark Matter searches (?)

Precise knowledge of **coherent neutrino scattering cross-section** and **Form factors** necessary!  
Phys. Rev. Lett. 120, 072501 (2018)

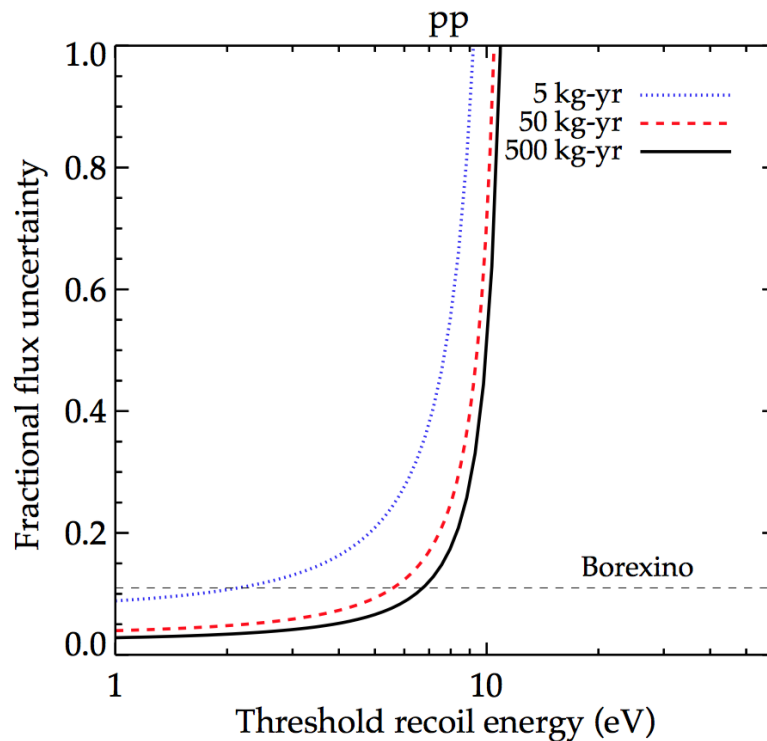
# Nuclear physics: Neutron rms radius

Phys. Rev. Lett. **120** 071501, arXiv:1710.02730

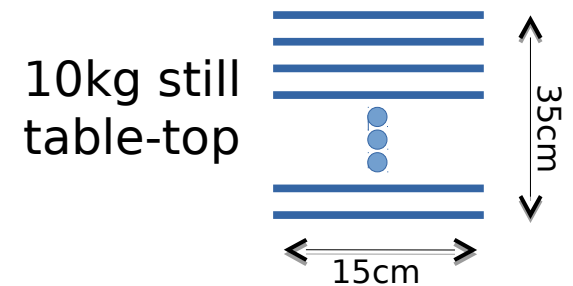
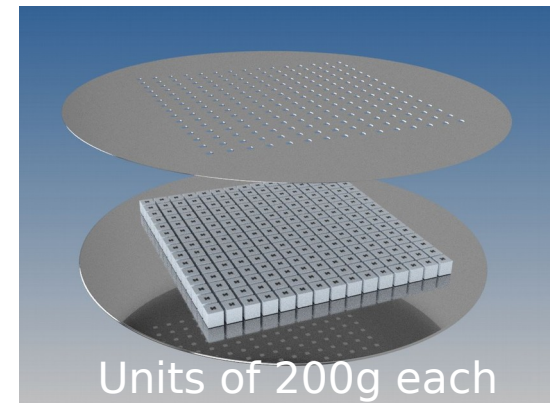


Coherence valid for neutrino energies  $< 20$  MeV  
(e.g. for CsI)  
→ Measurement at low energy breaks  
degeneracy (cross-section vs. decoherence)

# Solar neutrinos with a table-top experiment

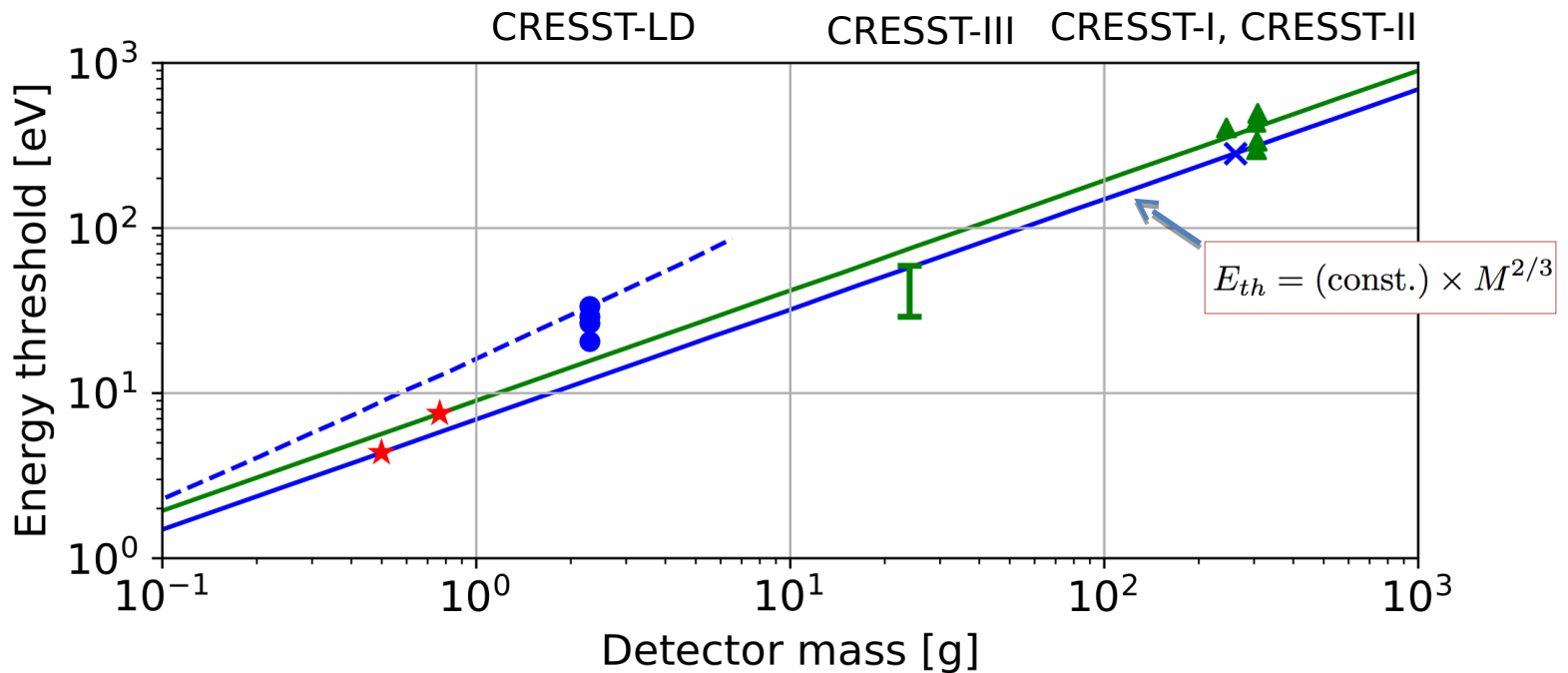


L.E. Strigari, Phys. Rev. D 93, 103534 (2016)



NU-cleus 1kg could get sensitive to pp neutrinos!

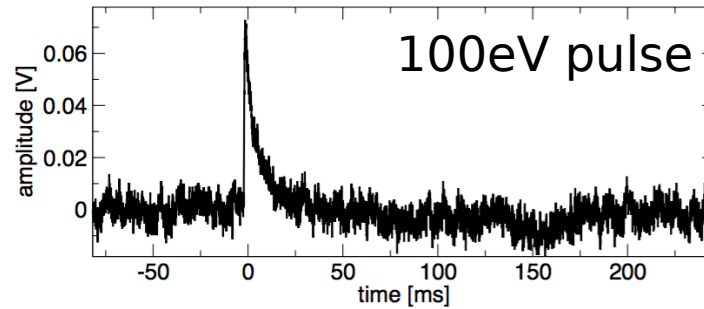
# Modeling NU-CLEUS Detectors



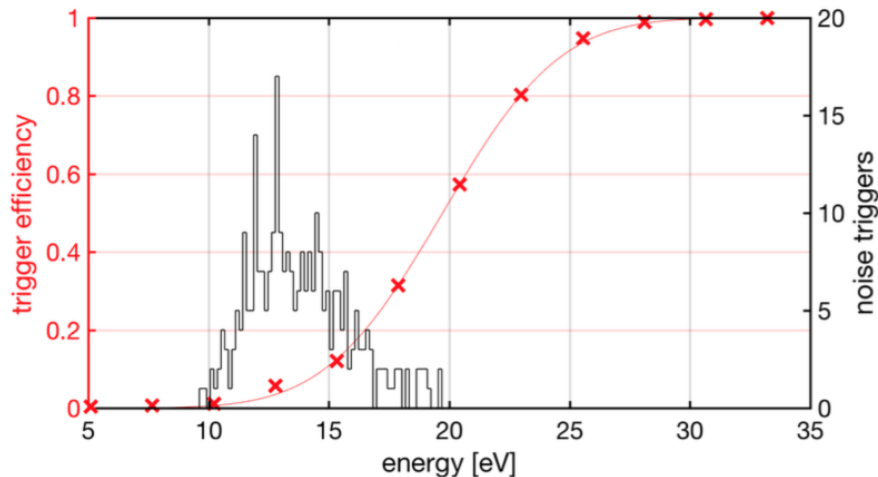
Eur. Phys. J., C77(8):506 (2017)  
arXiv: 1704.04320

- Predict performance of calorimeters
- Threshold expectation: **4-10eV regime**

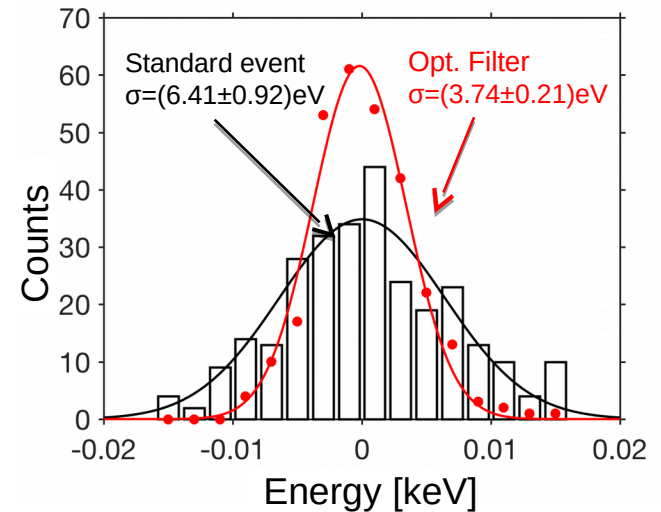
# NU-CLEUS Detector Prototype



## Trigger Efficiency



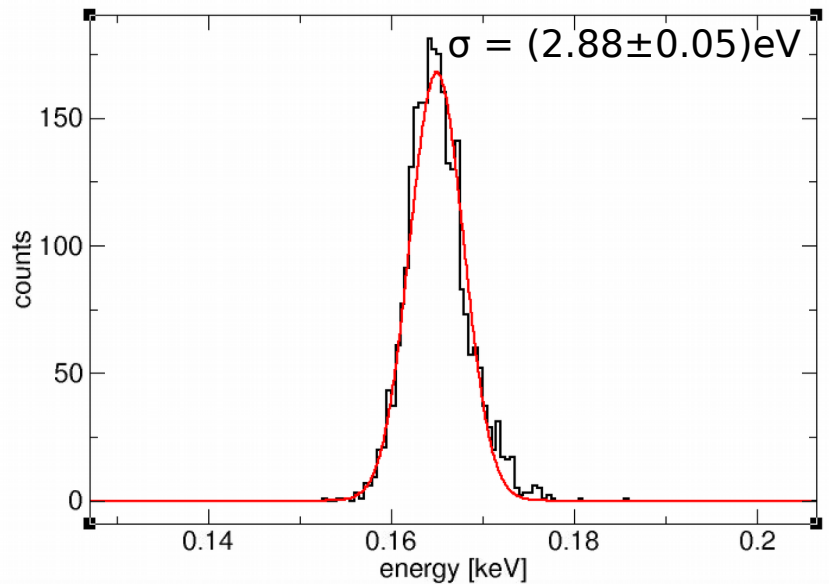
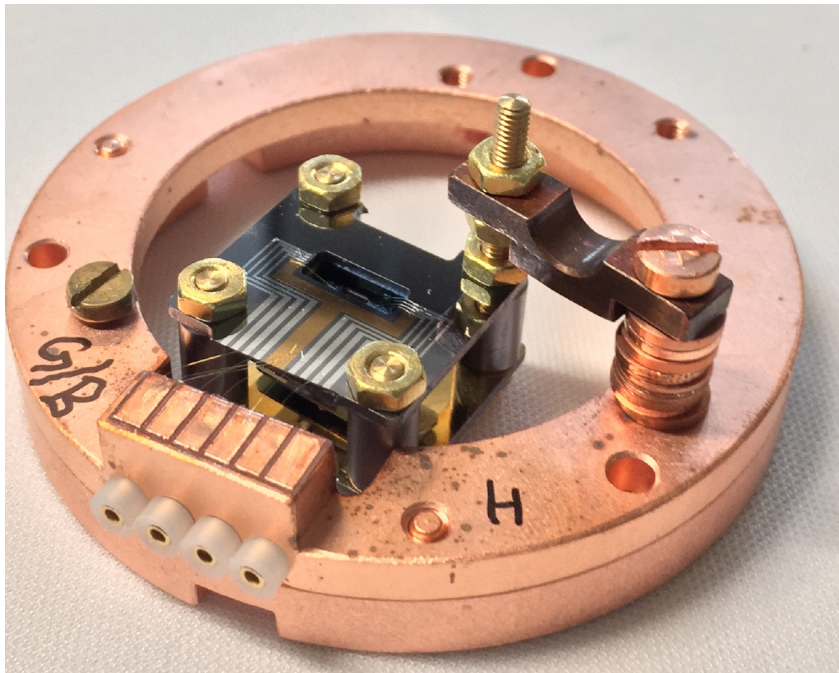
## Baseline Resolution



RS et al., Phys. Rev. D **96**, 022009 (2017) arXiv: 1704.04317

# NU-CLEUS Detector Prototype

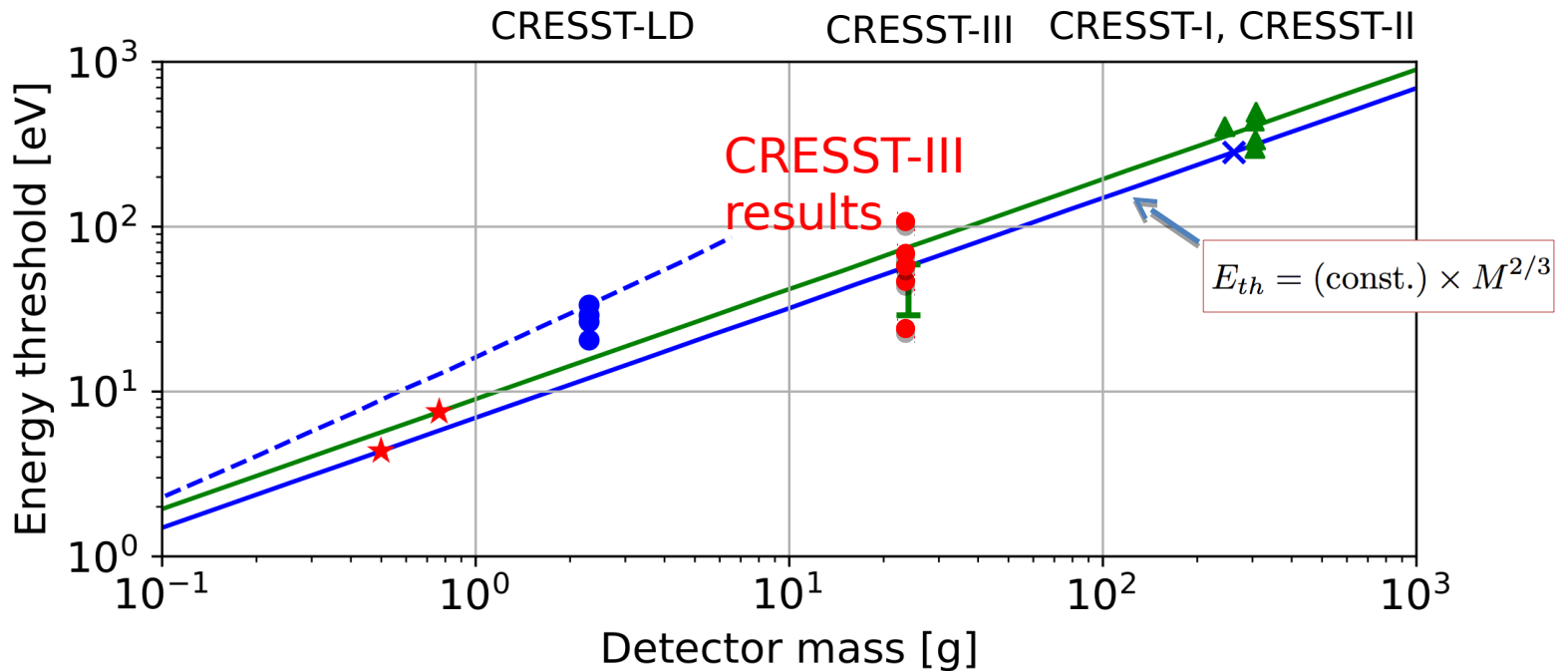
New results from May 2018



→  $E_{\text{th}} \approx 14.4 \text{eV}$

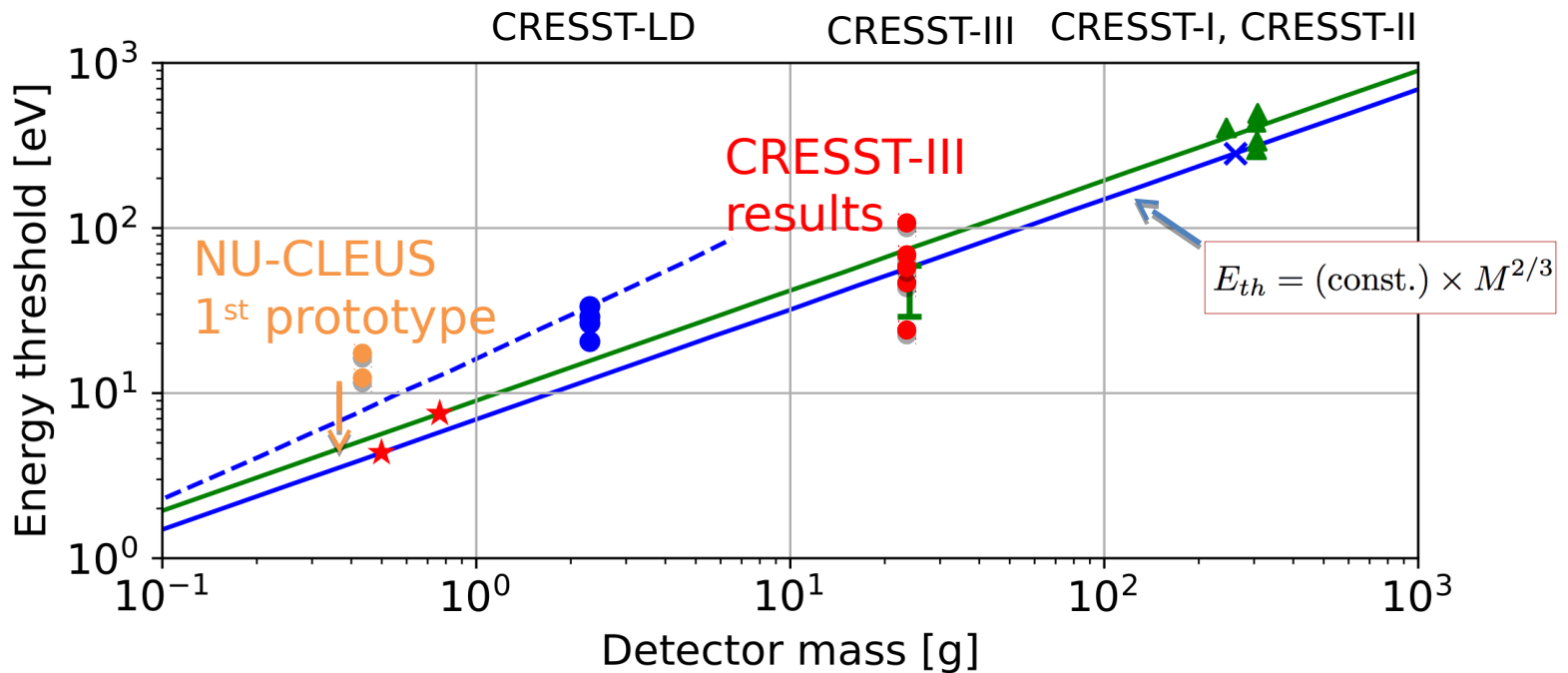
0.5g NU-CLEUS detector in new Si holder and different TES

# Modeling NU-CLEUS Detectors



RS, et al.. Eur. Phys. J., C77(8):506  
(2017) arXiv: 1704.04320

# Modeling NU-CLEUS Detectors



RS, et al.. Eur. Phys. J., C77(8):506  
(2017) arXiv: 1704.04320

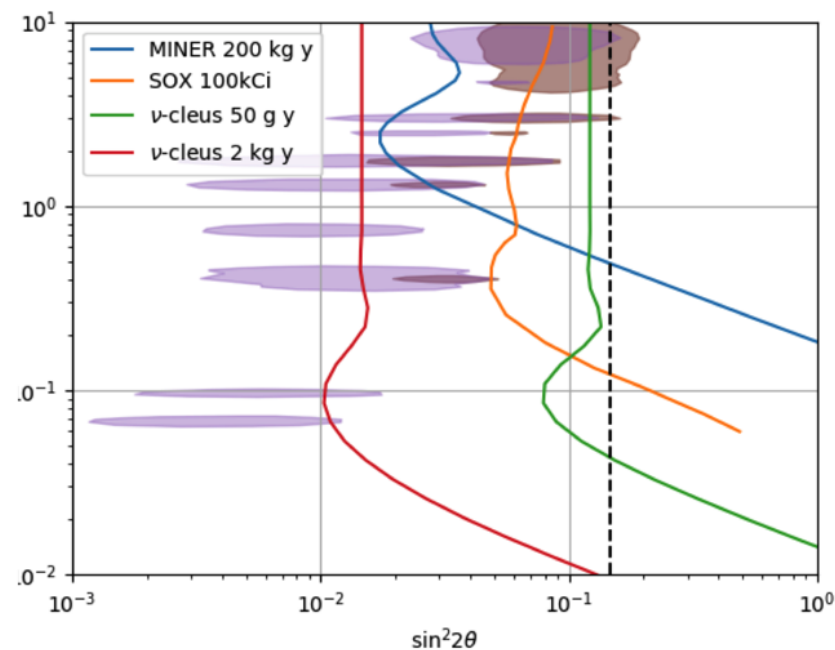
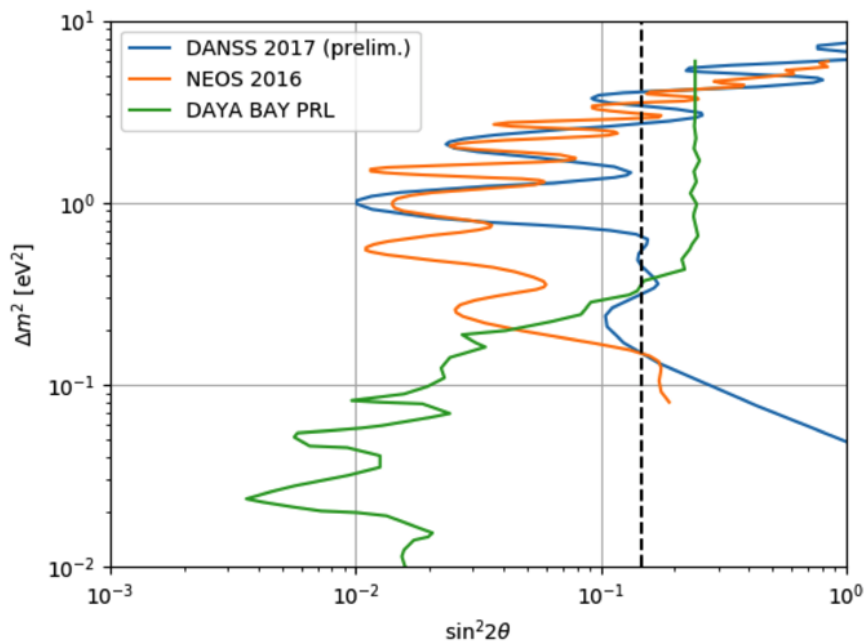
Noise level of setup factor 2-3 worse compared to CRESST benchmark setup

# Sensitivity Study on Sterile Neutrinos

3+1 neutrino model:  $P_{e \rightarrow s} = 1 - \sin^2(2\theta_{14}) \sin^2\left(1.27 \frac{\Delta m_{14}^2 d}{E_\nu}\right)$  for  $\frac{\Delta m_{14}^2 d}{E_\nu}$  in units of  $\left[\frac{\text{eV}^2 \text{m}}{\text{MeV}}\right]$

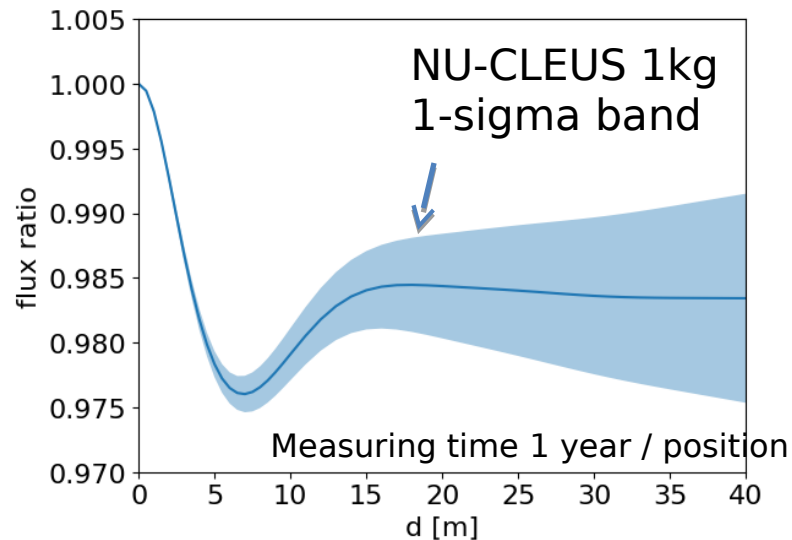
Oscillation maximum at reactor:  $d [\text{m}] \approx 4 / \Delta m_{14}^2 [\text{eV}^2]$

→ Extend searches to lower  $\Delta m_{14}^2$



# Sterile Neutrino Search at Reactors

Neutrino flux for global best fit to eV sterile neutrino [JHEP 11 (2017) 099]



Benchmark case:  
 $\Delta m_{14}^2 = 0.4 \text{eV}^2$   
 $\sin^2 2\theta = 0.035$

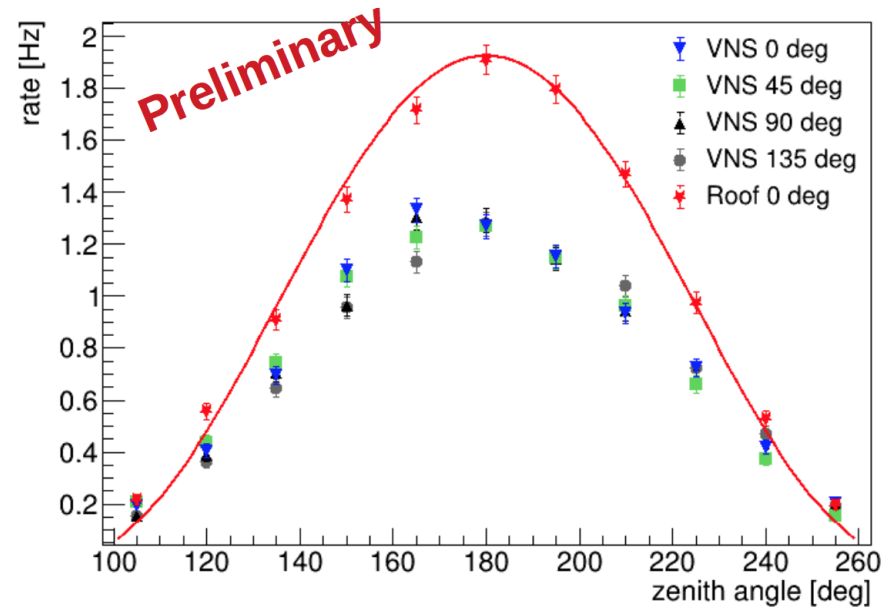
For ultimate precision (<5%):

- New evaluation of neutrino fluxes at reactors (e.g. NeNuFar @ CEA)
- add near(er) detector for flux normalization

# Measurements at the Very-Near-Site



## Muon measurements on-site at CHOOZ

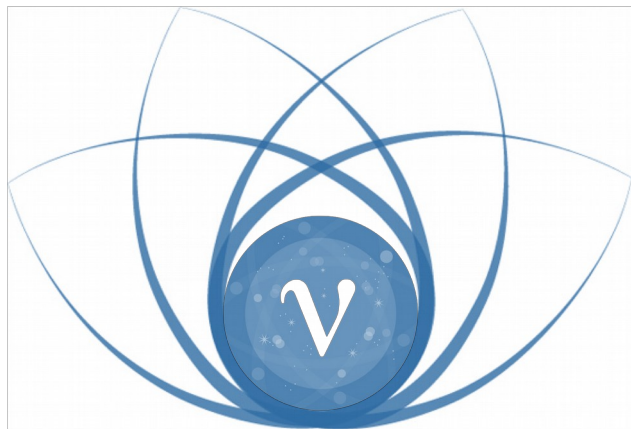


Average  
attenuation by a  
factor of 1.4  
→ Input for MC  
simulations



# The NEVFAR project:

## New Evaluation of $\nu$ Fluxes At Reactors



Project motivated by anomalies and discrepancies in latest reactor  $\nu$  experiments:

- § Reactor antineutrino anomaly: deficit in the total measured fluxes with respect to predictions
- § Reactor shape anomaly: distortion in the measured energy spectra
- § Evolution of measured reactor fluxes with reactor core isotopic composition do not agree with model predictions

Refined reactor  $\nu$  spectrum calculations along with revised uncertainty budgets. Will include:

- § details of reactor physics yet unaccounted for in the calculations
- § refined treatment of  $\beta$  branch spectra modeling
- § extension of the predictions to low energy regime ( $E_\nu \leq 1.8$  MeV) for CEvNS
- § comparison to existing experimental data to address anomalies



Cross-disciplinary project involving people working in various fields at CEA:

- § Matthieu Vivier (PI)/Alain Letourneau (particle & nuclear experimental physics)
- § Davide Mancusi (simulation for reactor physics)
- § Xavier Mougeot (nuclear theoretical physics and nuclear database evaluation)

Funded by CEA for a 2-yr post-doc (Anthony Onillon) + a 3-yr PhD (Lorenzo Perisse)  
Project started in April 2018

Courtesy: M. Vivier (CEA)

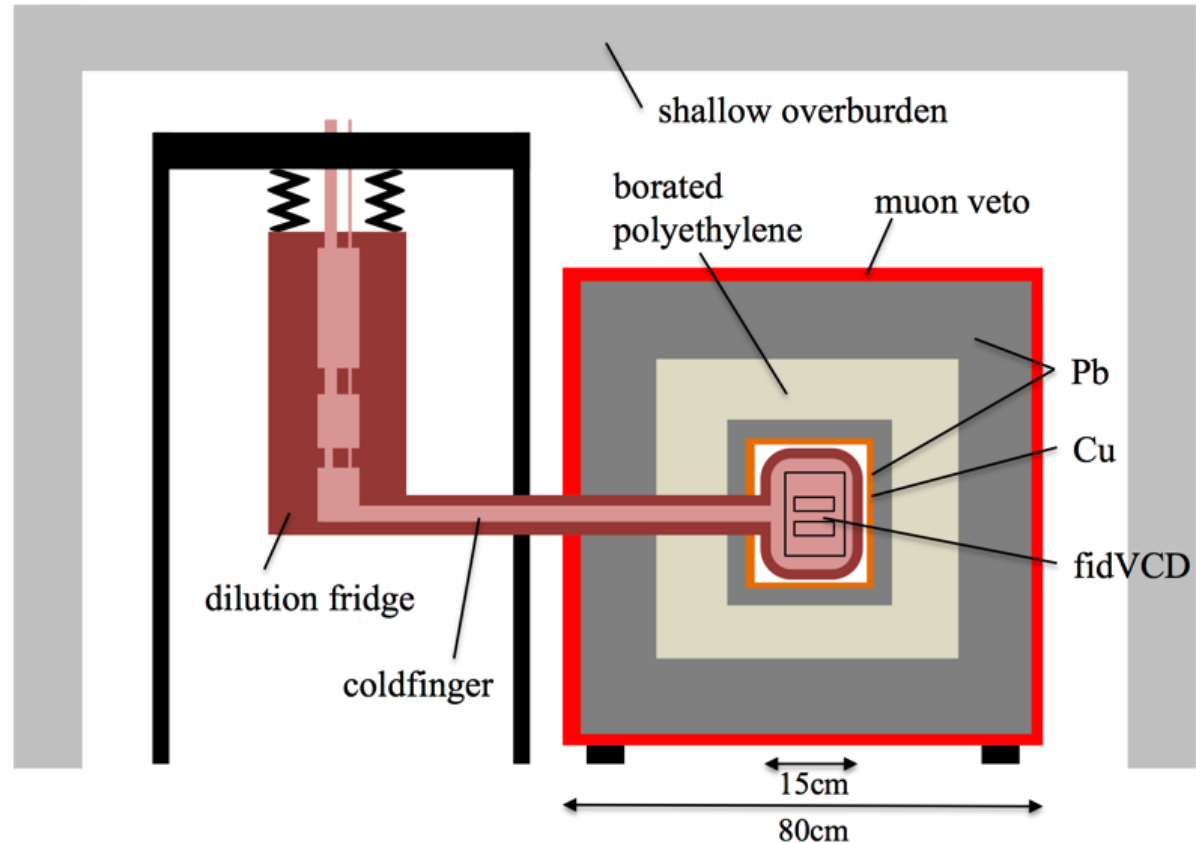
# NU-CLEUS: Setup

## Cryogenic infrastructure

requested in ERC proposal as major equipment (350k€)

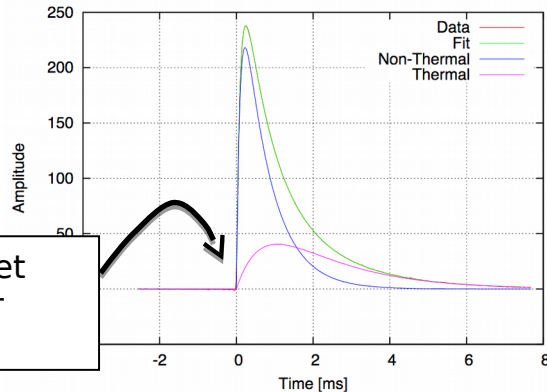
**Shielding and muon veto** will be provided by CEA

**Data acquisition** will be provided by HEPHY



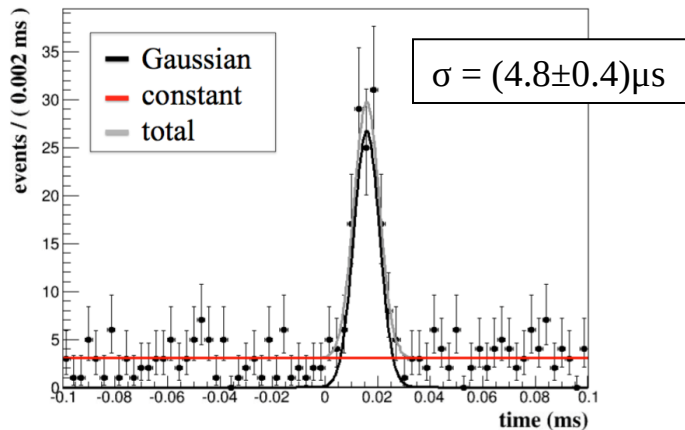
# Muon Veto and Dead Time

Pulse of CaWO<sub>4</sub> cryogenic detector



Pulse onset critical for timing

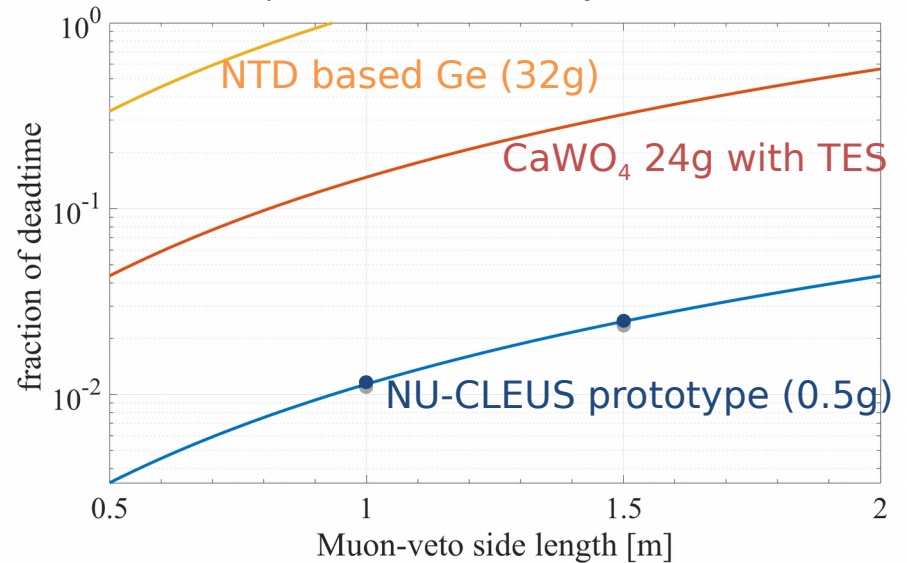
Measurement of pulse onset with a pulsed accelerator beam



□ NU-CLEUS: 5-sigma timing of 24μs

- Rise time governs the onset determination
- Measure rise-times:
  - CaWO<sub>4</sub> (this):  $\tau_{\text{rise}} = 0.1 \text{ ms}$
  - Al<sub>2</sub>O<sub>3</sub> (NU-CLEUS):  $\tau_{\text{rise}} = 0.1 \text{ ms}$
  - CaWO<sub>4</sub> (24g):  $\tau_{\text{rise}} = 1.3 \text{ ms}$
  - Ge (NTD based):  $\tau_{\text{rise}} \approx 10 \text{ ms}$

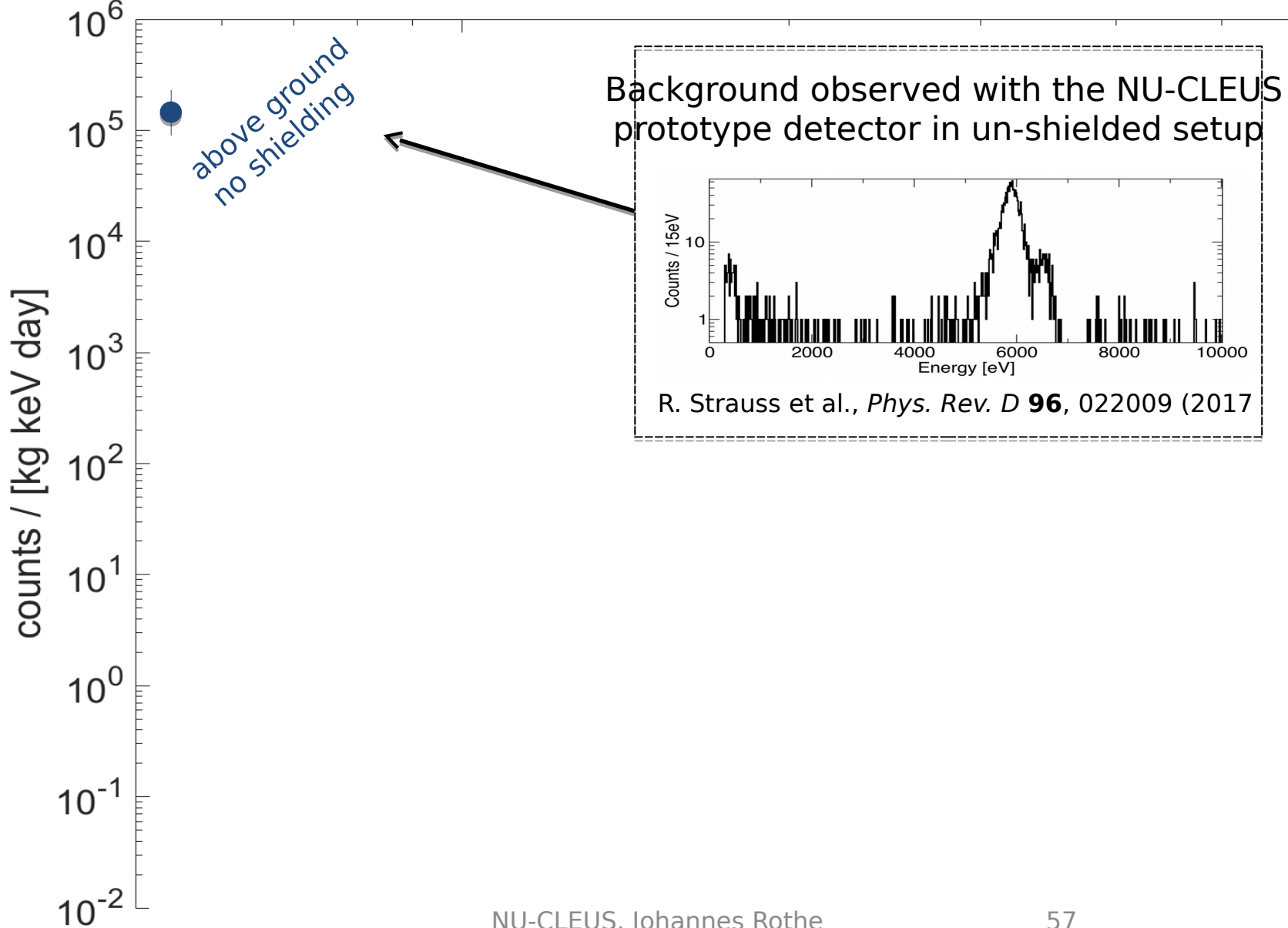
Dead-time expectation at the Very-Near-Site at CHOOZ



- Trigger rate of muon veto at the Very-Near-Site derived from dedicated simulation (V. Wagner, CEA)
- Onset-Rise time relation from accelerator experiment  
 → **NU-CLEUS detector fast enough for operation in compact shielding** (e.g. ~1% deadtime for (1m)<sup>3</sup> veto)

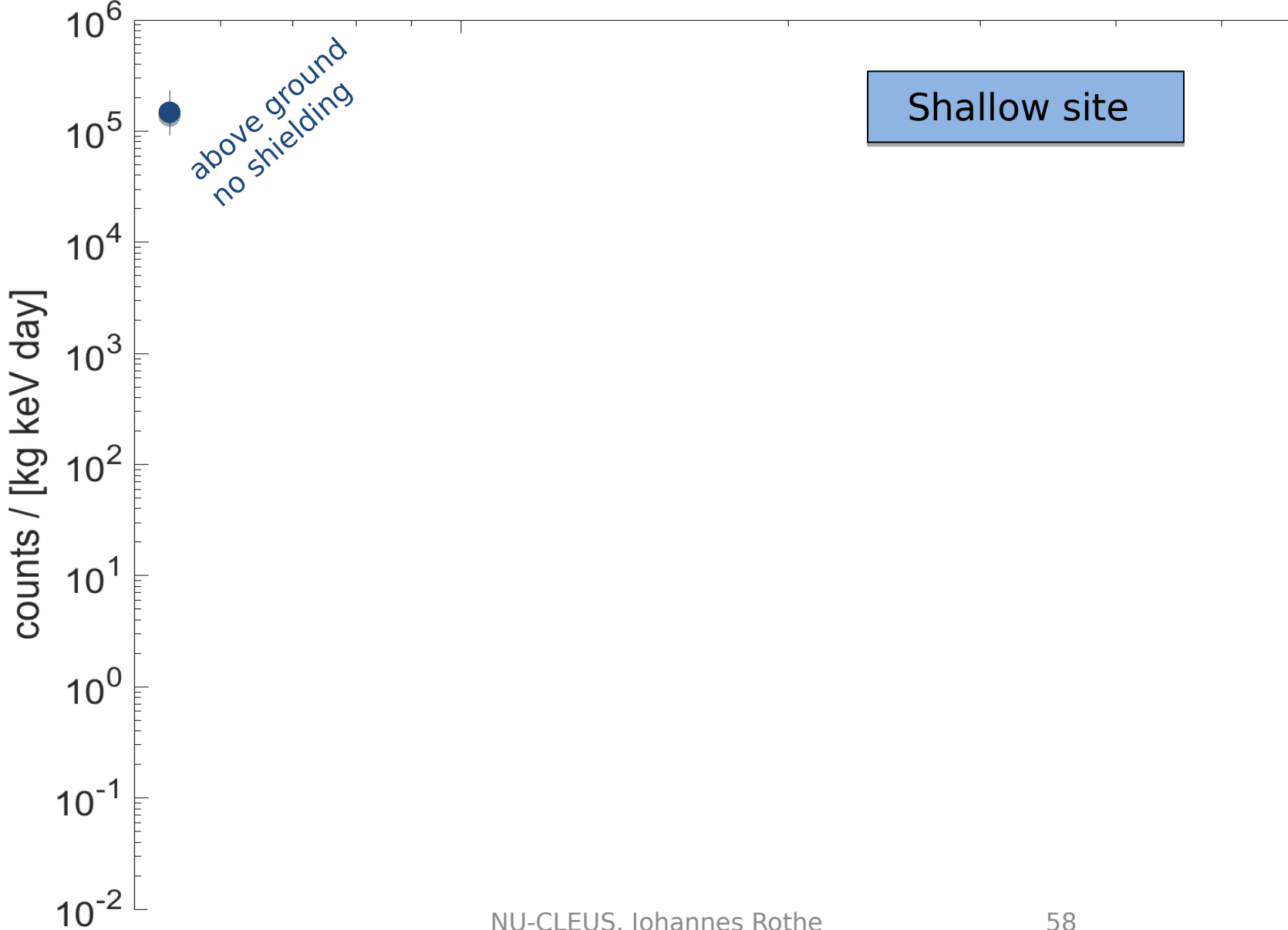
# Fighting Backgrounds

Background level



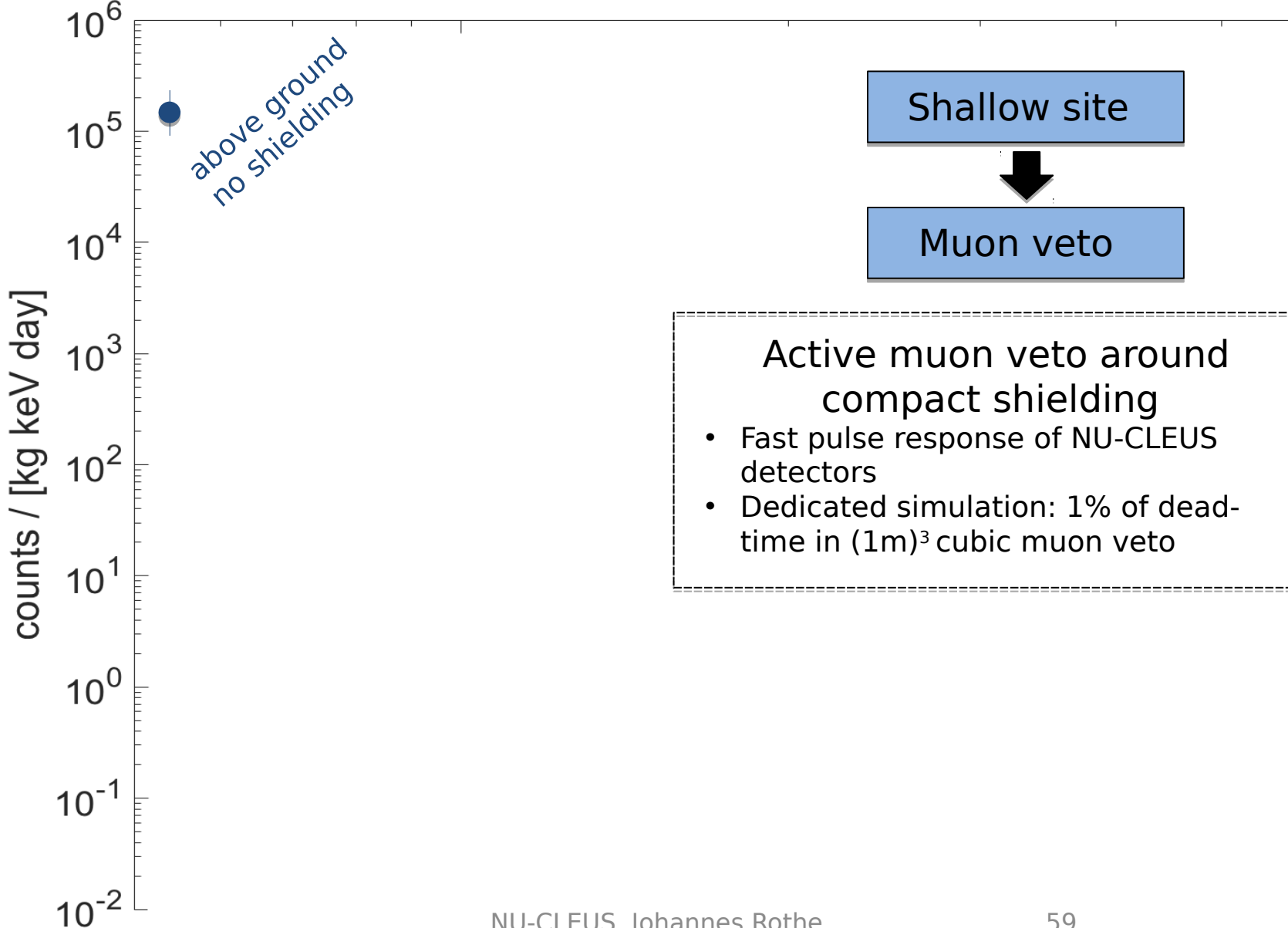
# Fighting Backgrounds

Background level



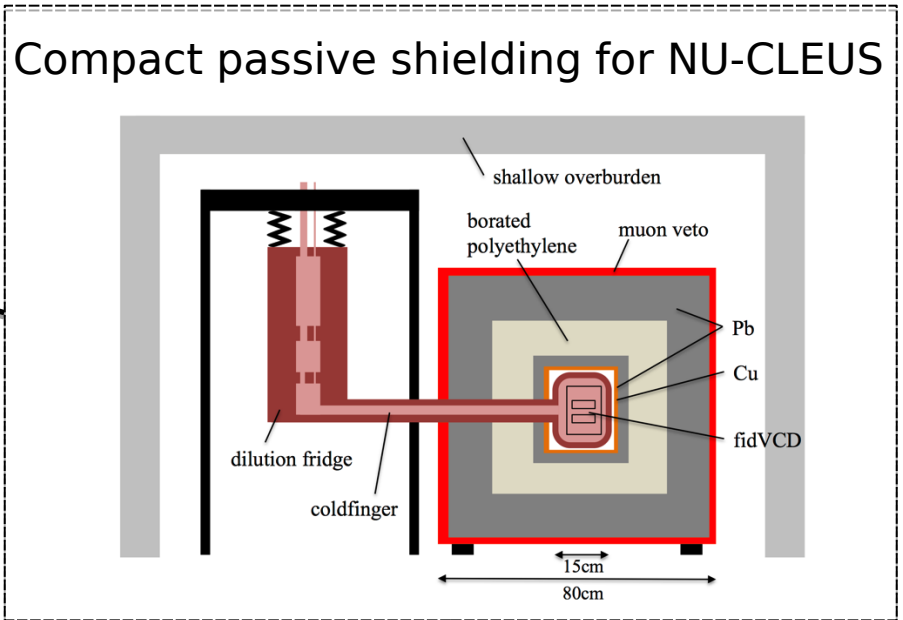
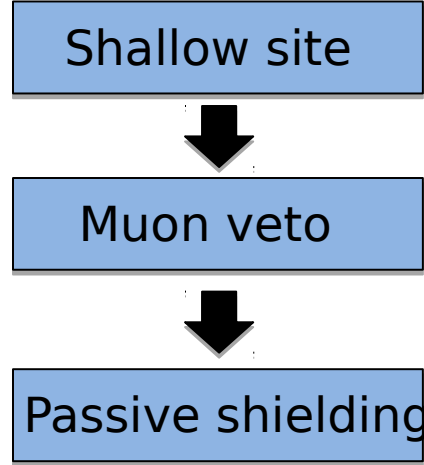
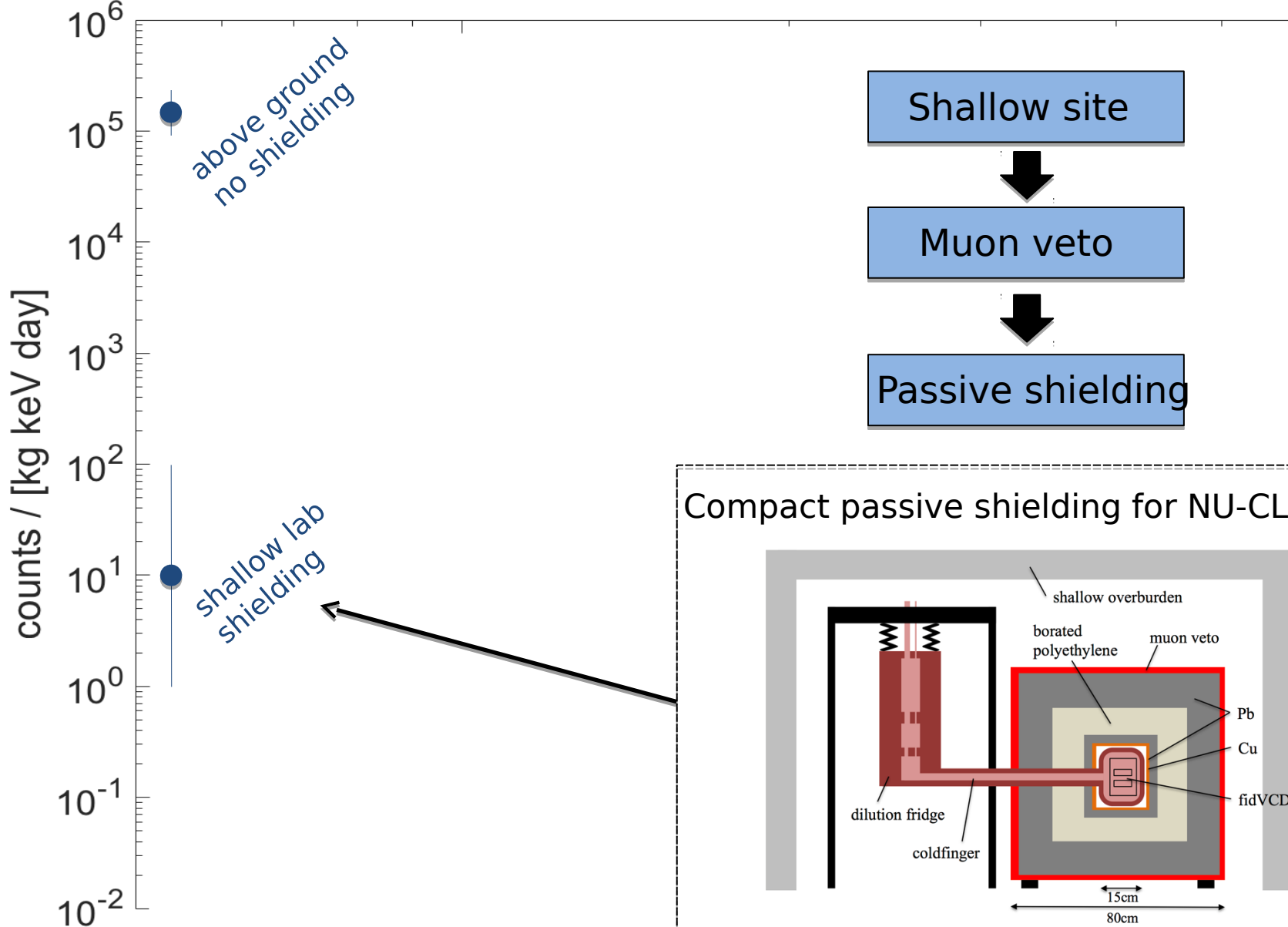
# Fighting Backgrounds

Background level



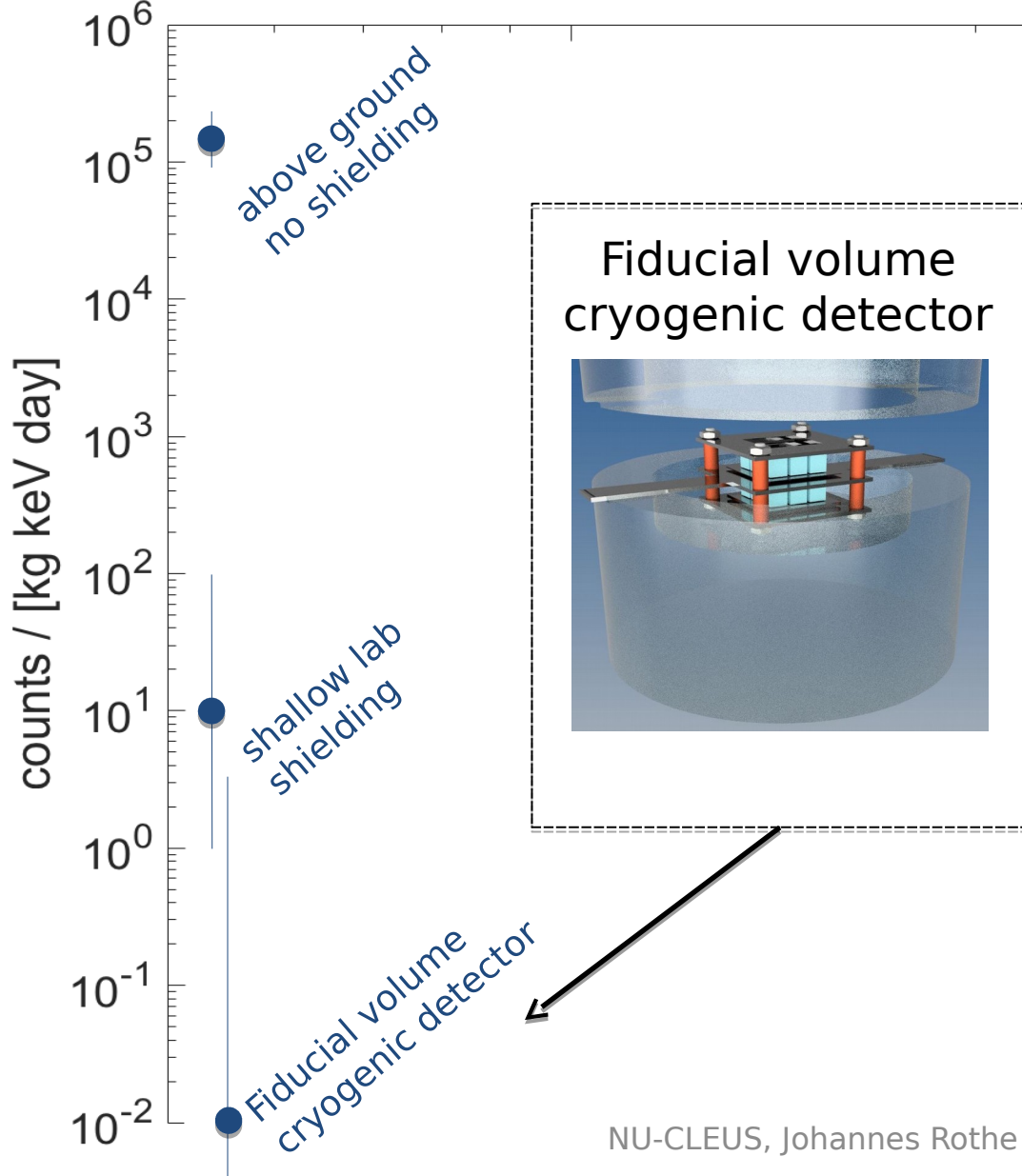
# Fighting Backgrounds

Background level



# Fighting Backgrounds

Background level



Shallow site



Muon veto



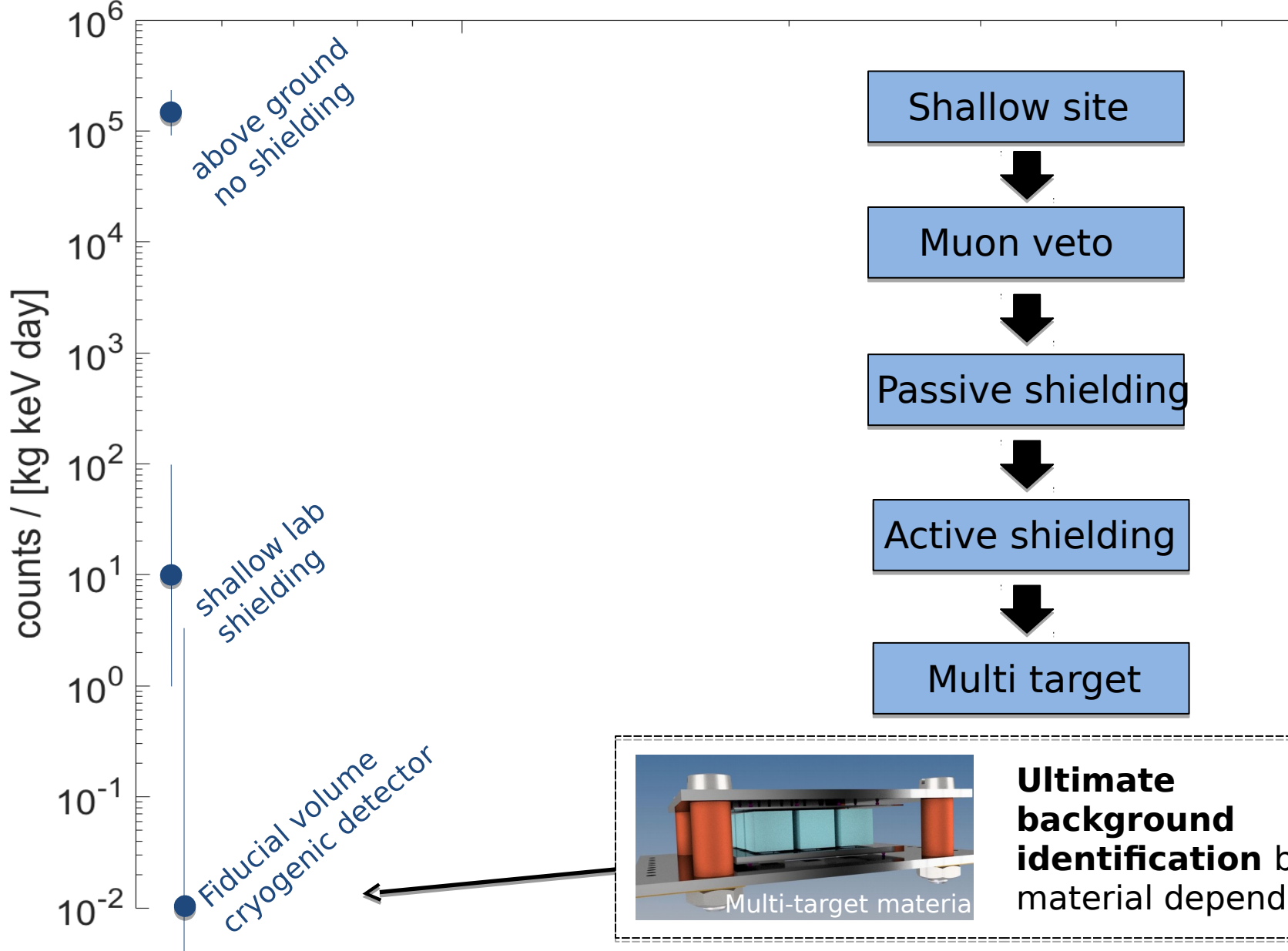
Passive shielding



Active shielding

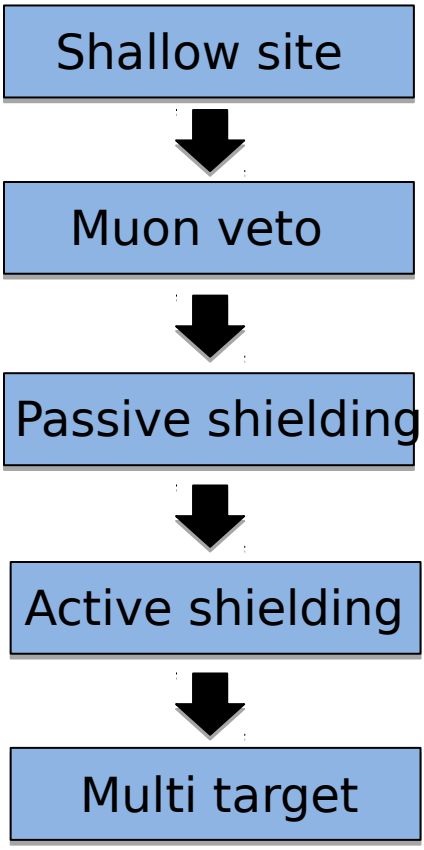
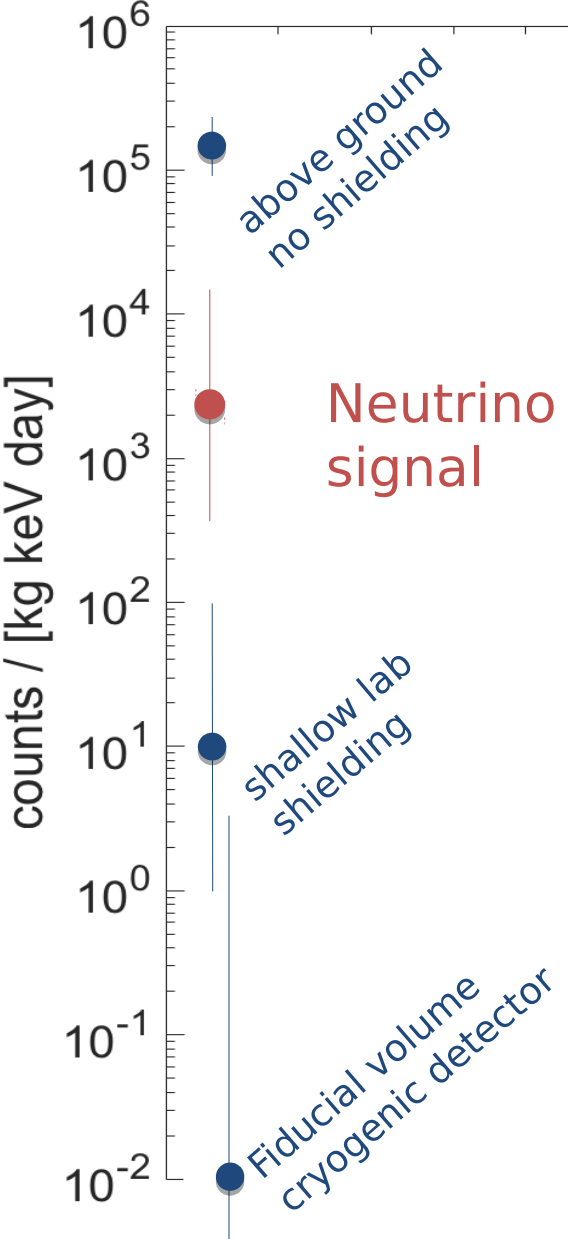
# Fighting Backgrounds

Background level



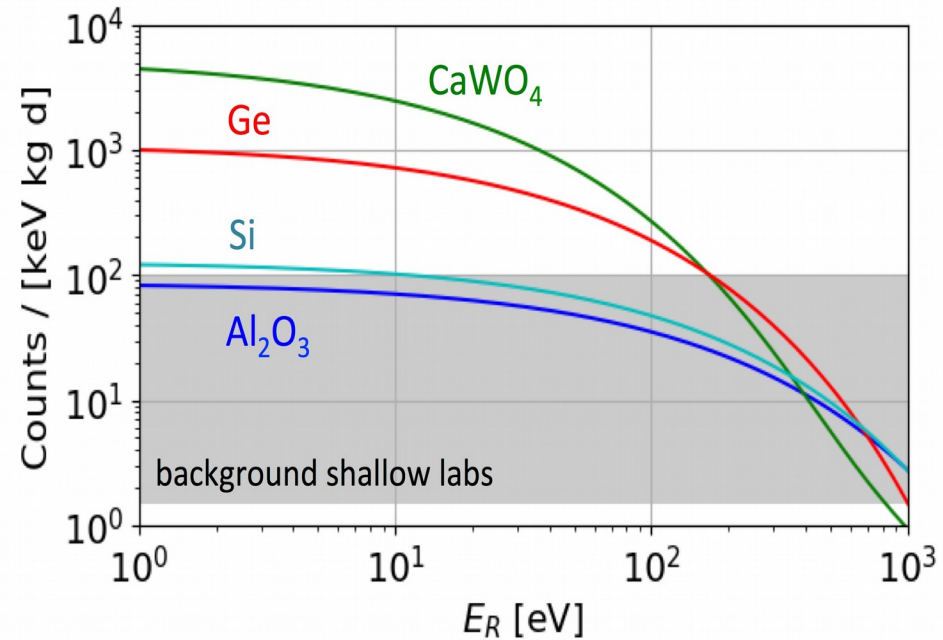
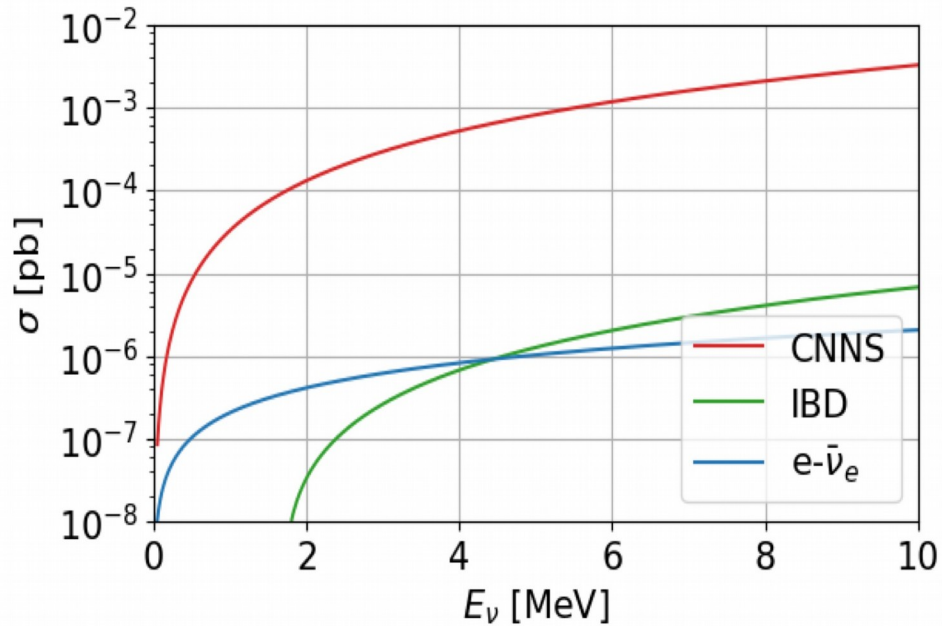
# Fighting Backgrounds

Background level

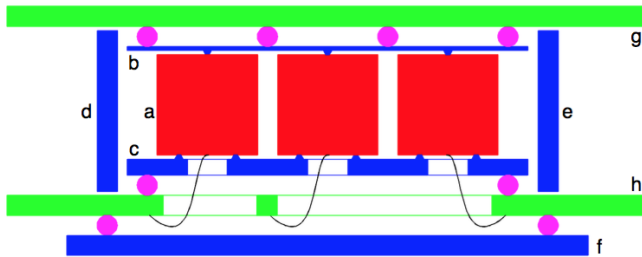
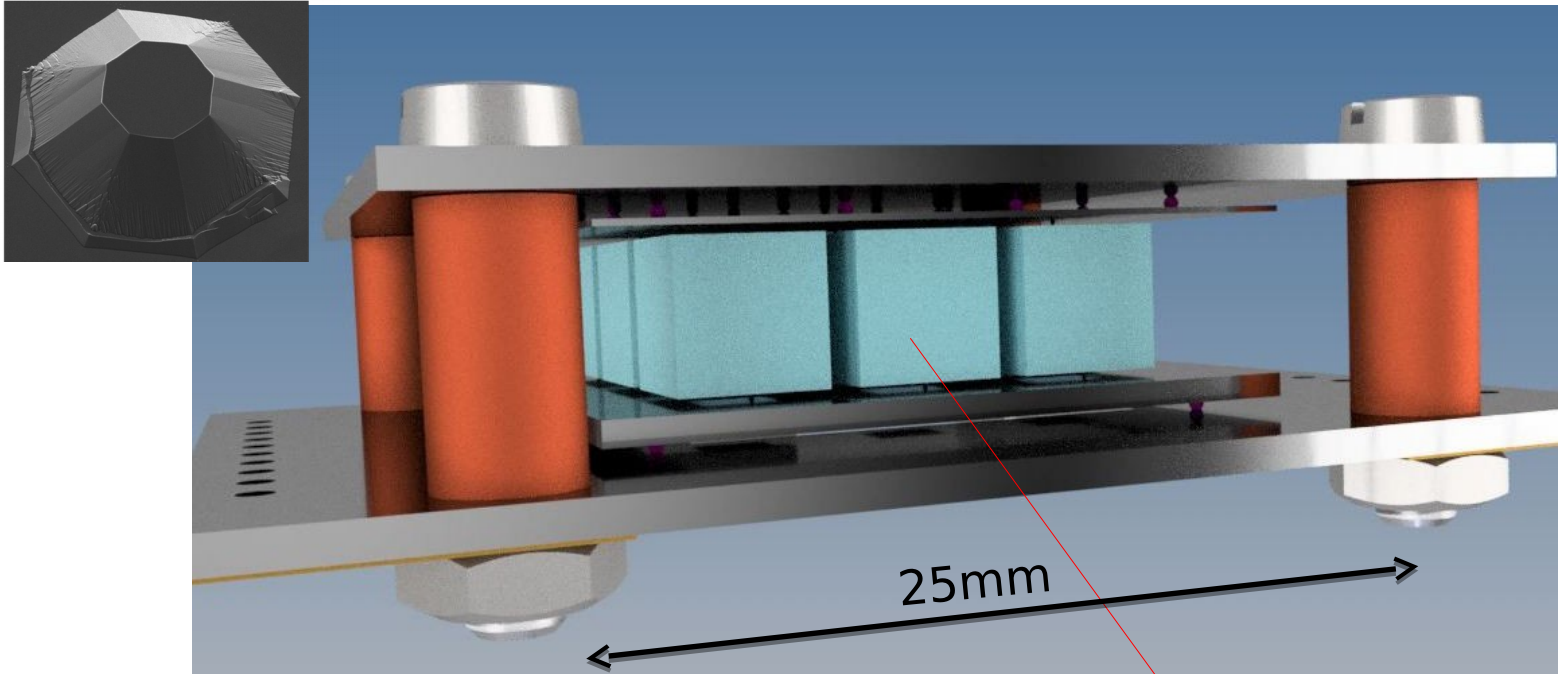


# Multi-Target Aspect

Coherent neutrino-nucleus scattering rate at 40m to a 4GW reactor

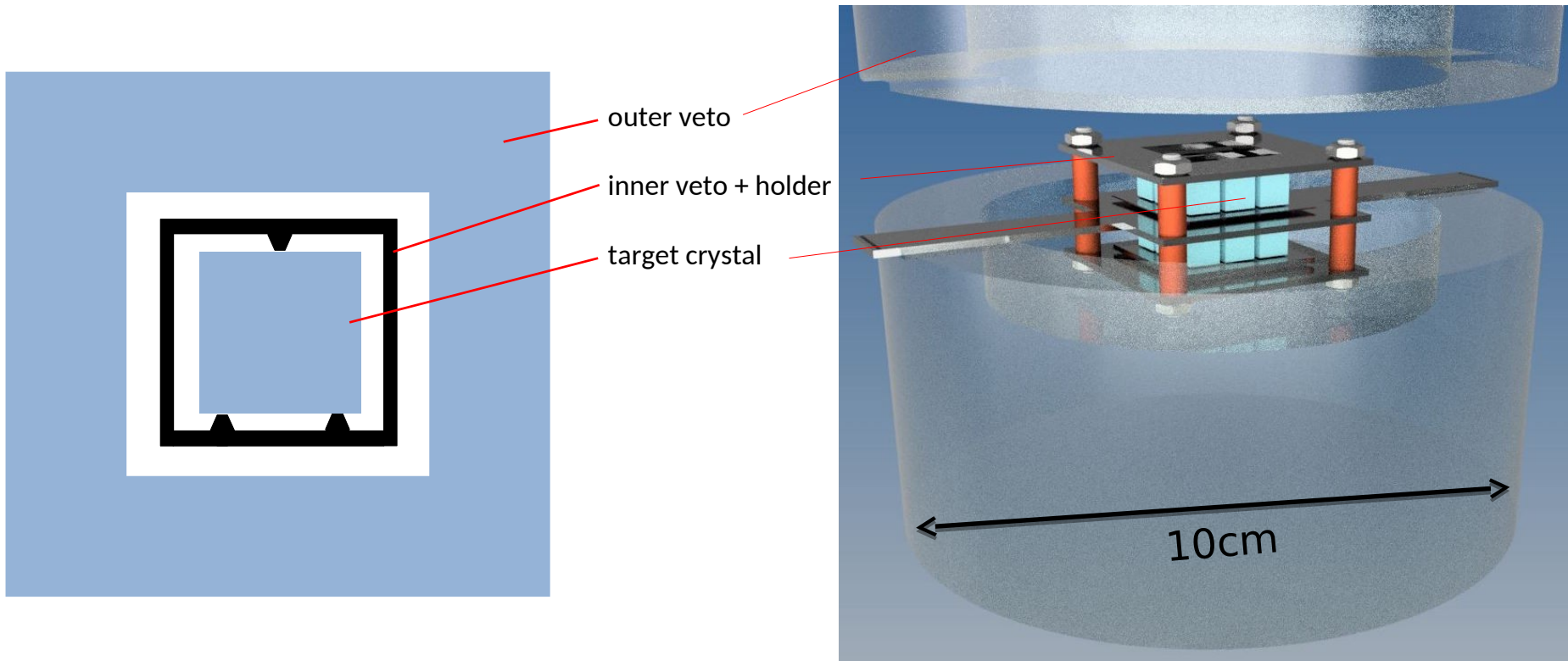


# NU-CLEUS Detector: Inner Part



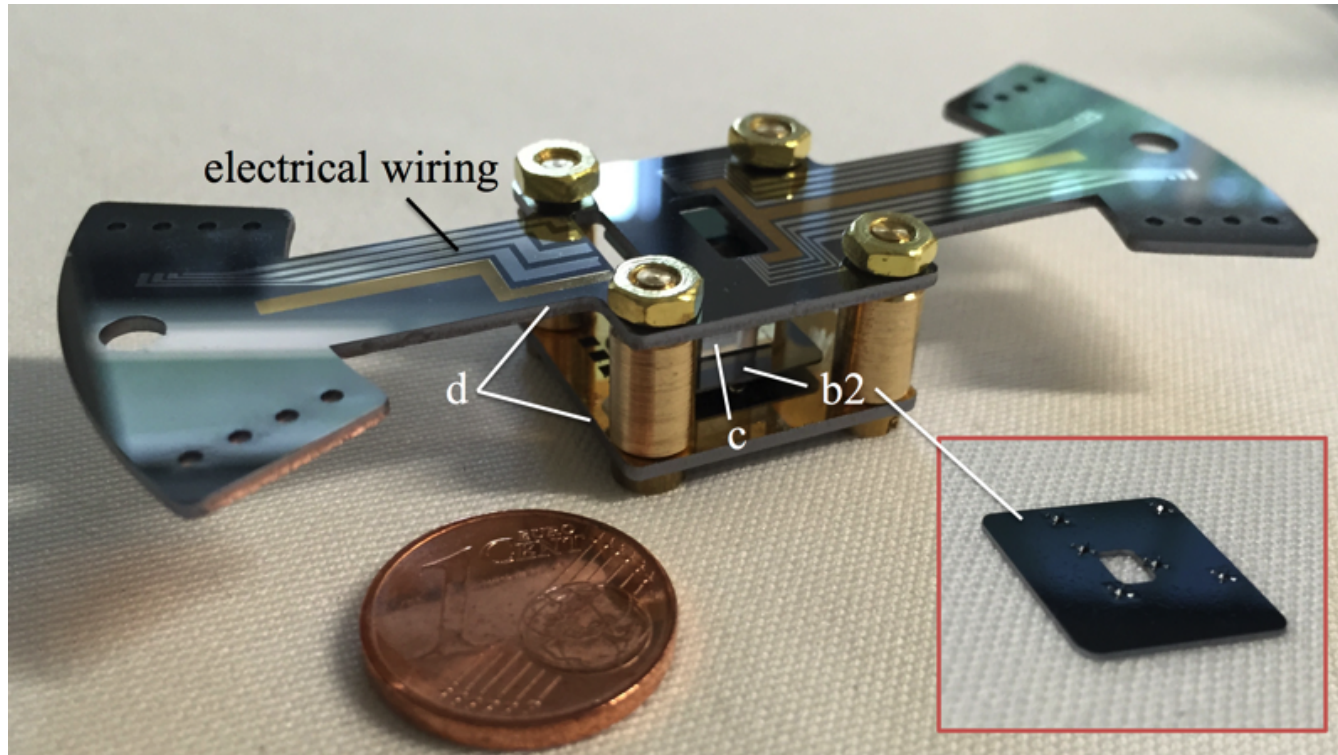
Segmented detector array of cubic  $\text{Al}_3\text{O}_3$  and  $\text{CaWO}_4$  crystals

# A fiducial-volume cryogenic detector



Fits into standard commercial cryostat!

# First 1g Demonstrator



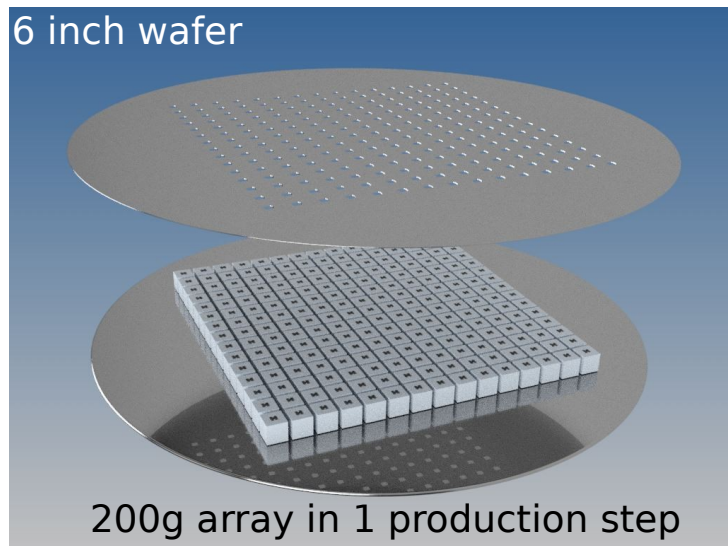
seed money  
Projects R. Strauss  
2017 + **2018**  
**20k€**



# Designed to be LARGE

Second stage of NU-CLEUS:

## Detector unit for NU-CLEUS 1kg

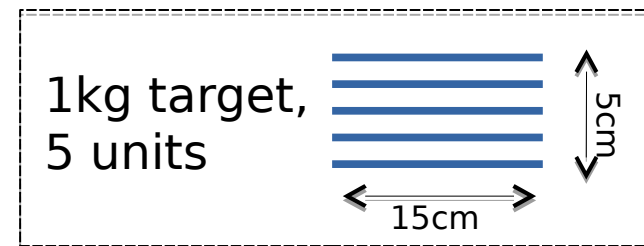


## A scalable cryogenic detector!

Exploiting semiconductor techniques!

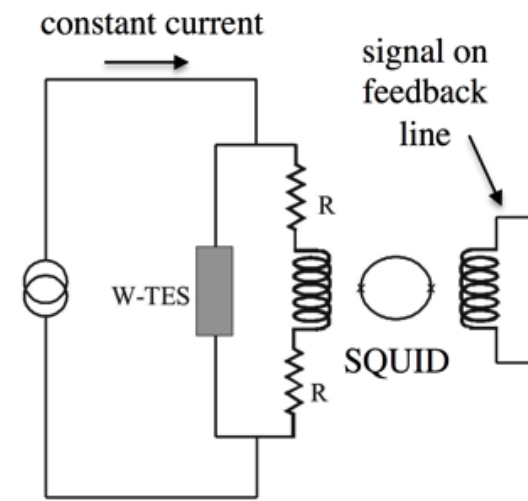
Using Si and Ge wafers

Multiplexed SQUID readout.



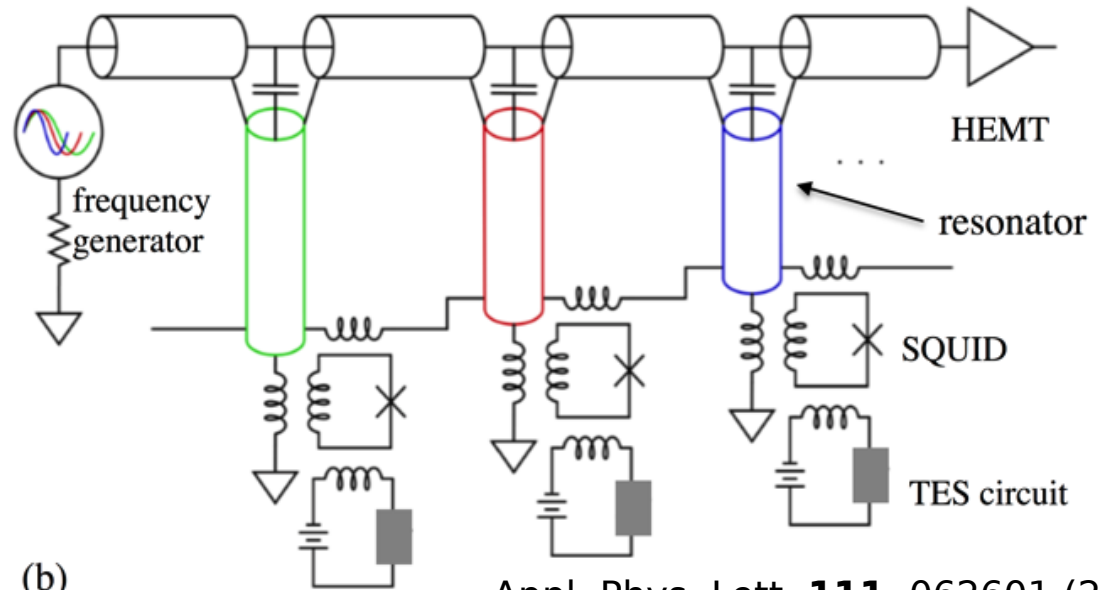
# Microwave SQUID Multiplexing

CRESST-type single readout



(a)

NIST: 128 channel multiplexer



(b)

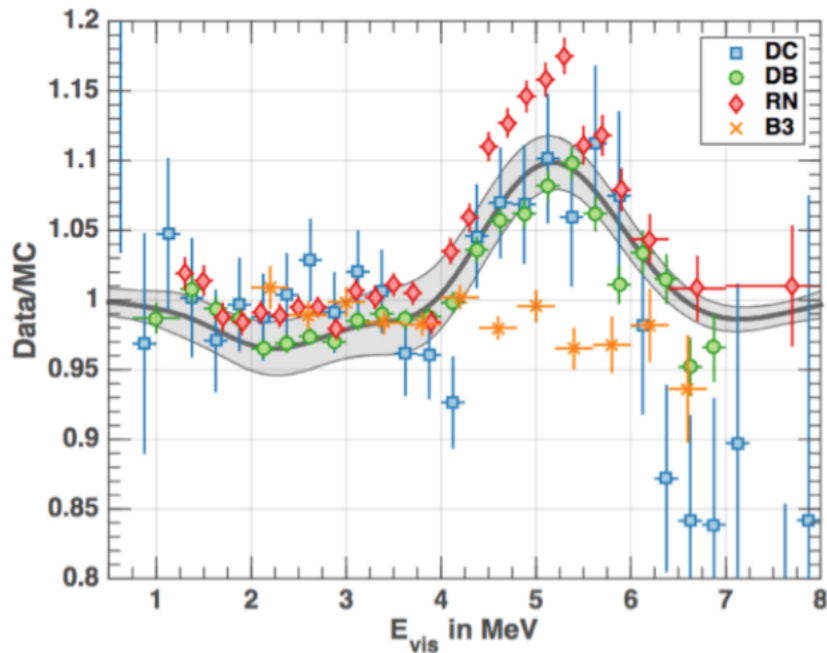
Appl. Phys. Lett. **111**, 062601 (2017)

- Simultaneous readout of 128 channels (bandwidth 300kHz)
- Available bandwidth sufficient for ~1000 channels

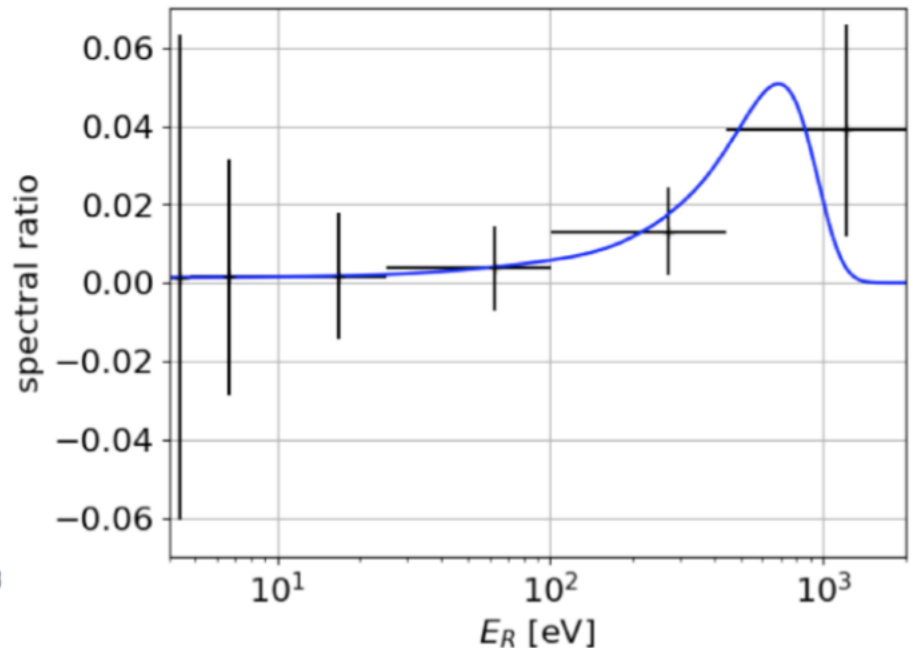
+Contact established with group of L. Gastaldo in Heidelberg (ECHO experiment)

# Reactor Physics: 5 MeV bump

Observation in reactor neutrino experiments:



Signature in NU-CLEUS **1kg** recoil spectrum



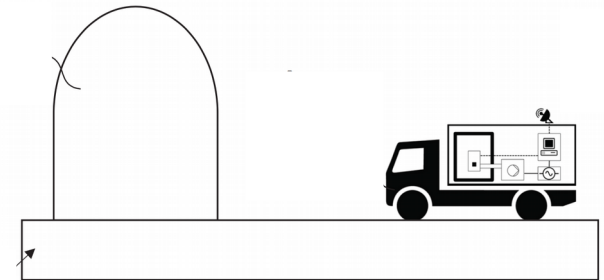
- Independent, complementary probe of the bump
- Clear signature in recoil spectrum

# Application of NU-CLEUS Technology

Mobile cryogenic detector

Use neutrinos to monitor nuclear reactors

Surveillance of power plants world-wide



Nuclear non-proliferation



**IAEA**

International Atomic Energy Agency

*Atoms for Peace*

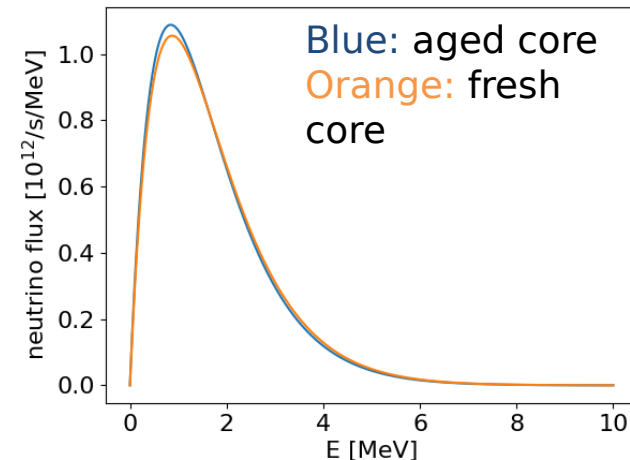
e.g. Phys. Rev. Lett. 113, 042503 (2014)

# Nuclear Non-Proliferation

Fuel content modifies antineutrino spectrum



<http://www.lefigaro.fr/assets/pdf/AIEA-neutrino.pdf>



Following the scenario of  
Phys. Rev. Lett. 113, 042503 (2014)

At 40m distance:  
Significance for  
diversion of fuel  
elements after 8  
days (90%conf.)

