# Cryogenic Detectors for CEvNS and DM: Ideas and their Application

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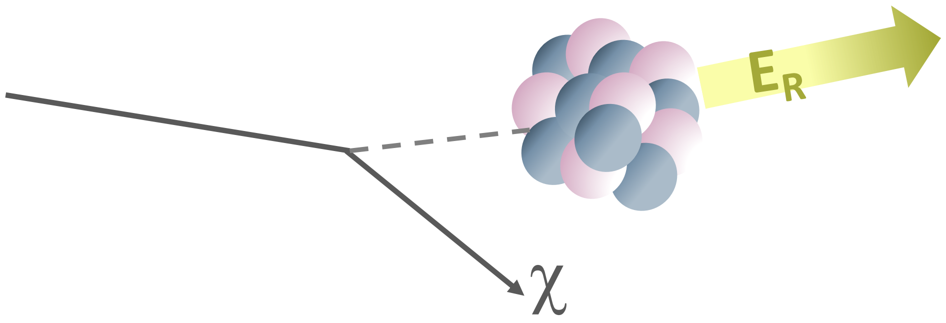
Technische Universität München

BSM-nu Workshop,
11. – 12.02.2012

# Direct Dark Matter Search

- For generic DM models: dark matter, $\chi$, interacts coherently with nucleus
- Experimental signature = nuclear recoil




- Featureless, smoothly decreasing spectrum

$$\frac{dR}{dE_R} = \frac{R_0}{E_0\mu} F^2(q) e^{-\frac{E_R}{E_0\mu}}$$

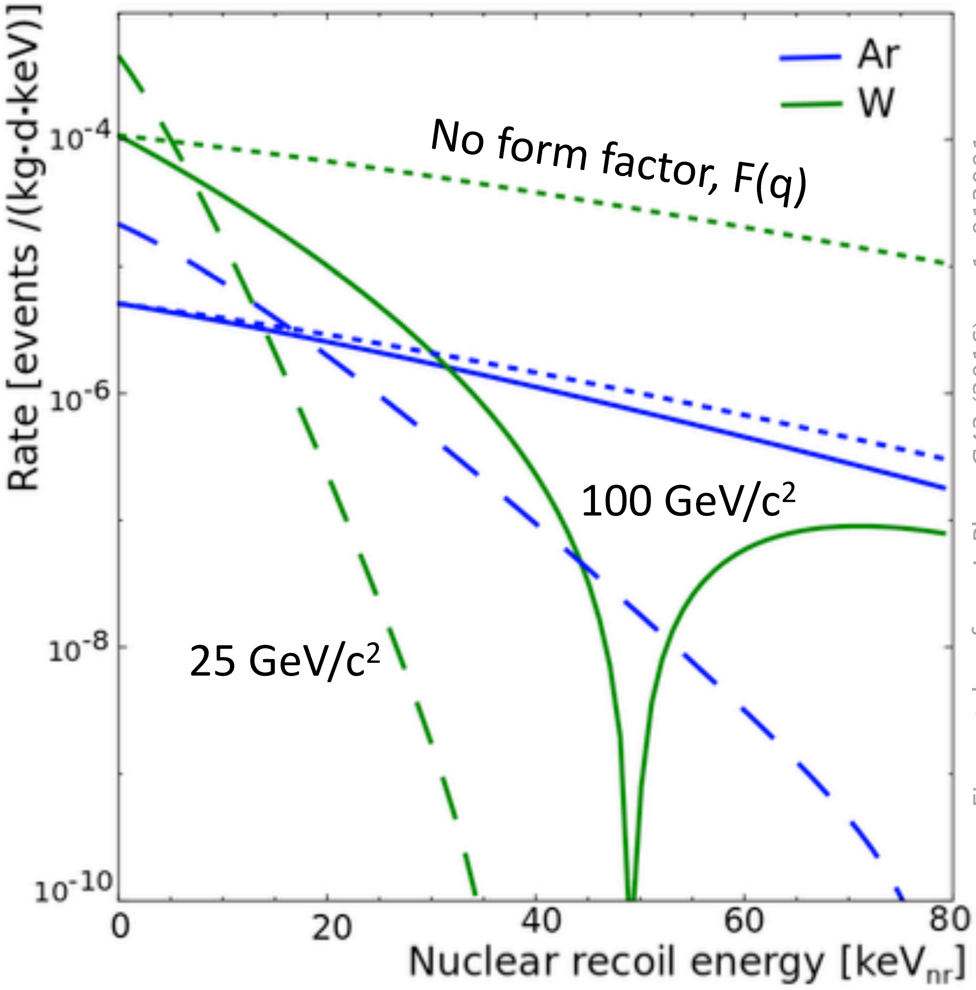



Figure taken from J. Phys. G43 (2016) no.1, 013001

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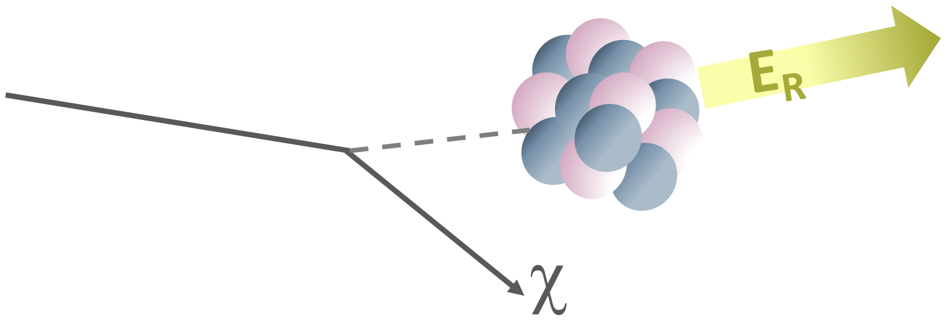


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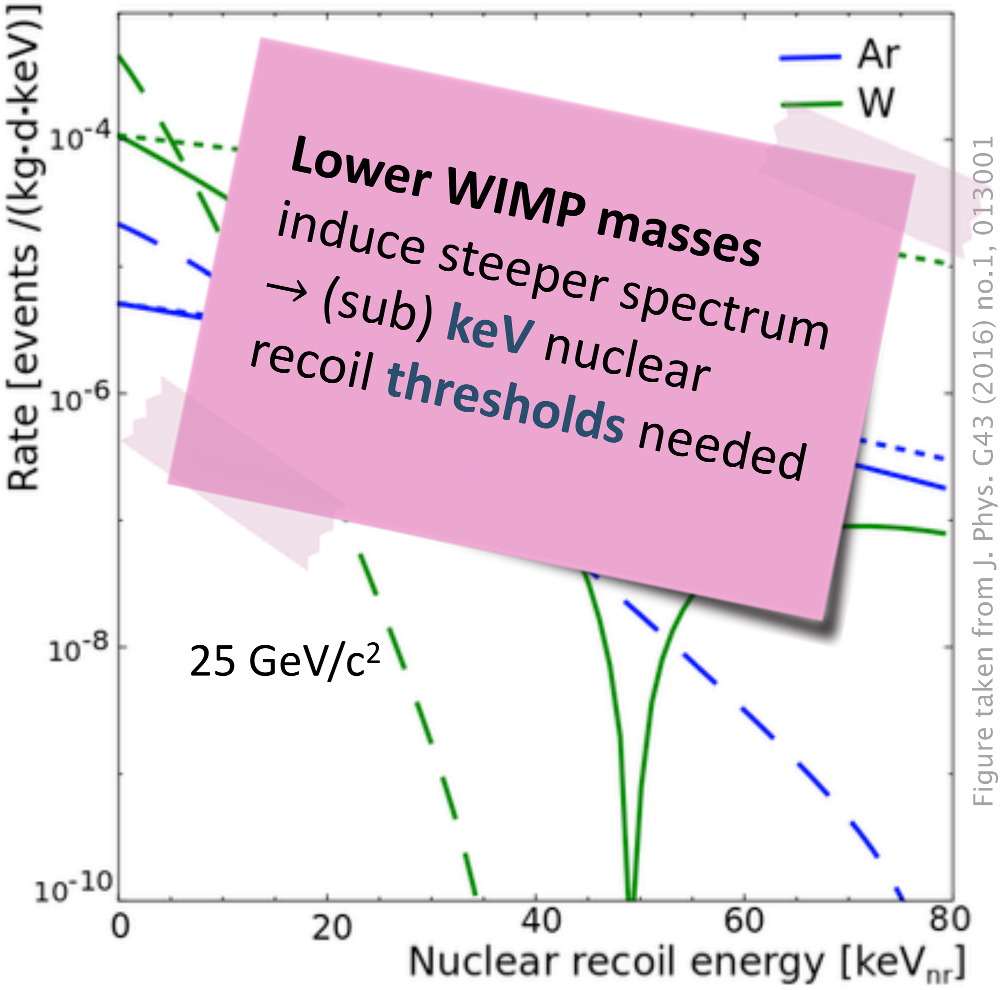
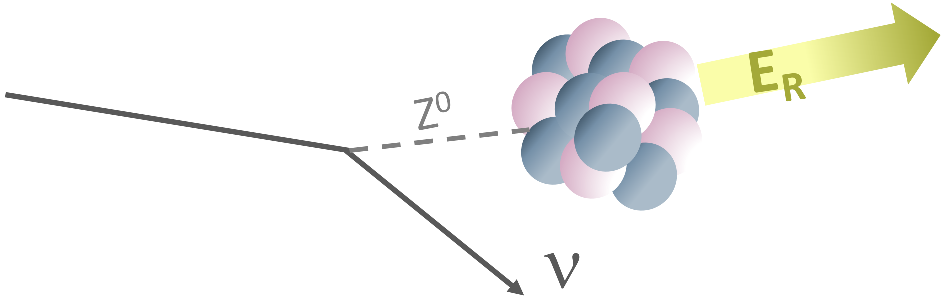
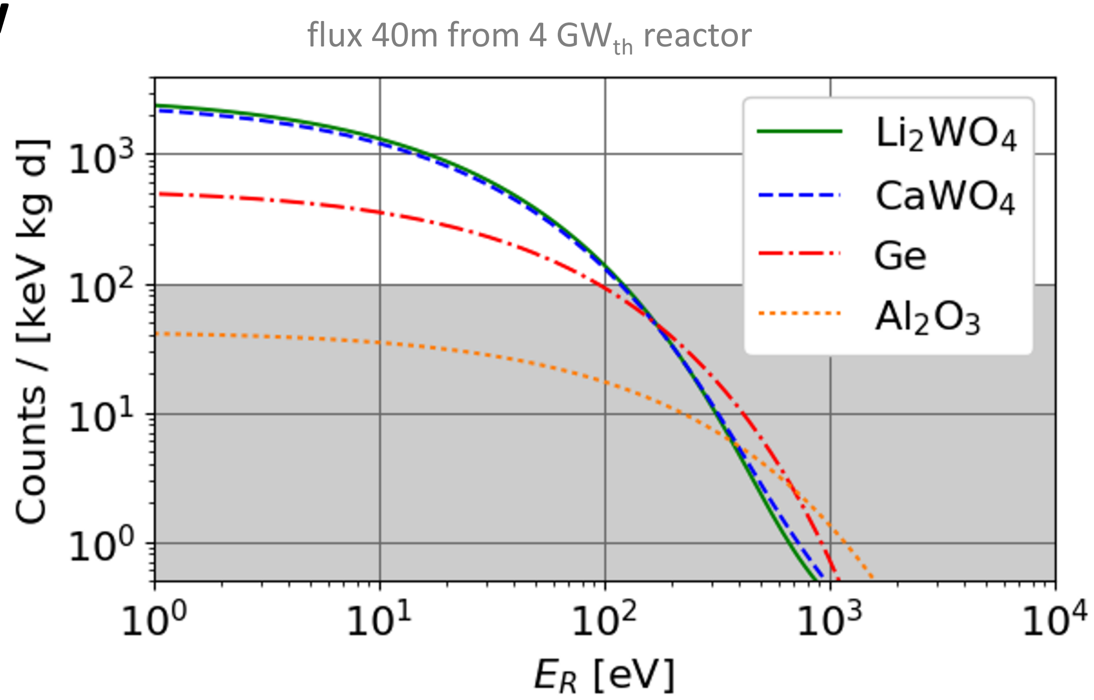


# Coherent Elastic n-Nucleus Scattering (CEvNS)

- Probe of SM predication & **search for new physics**
- Neutrino, ν, scattering off elastically a nucleus
- Experimental signature = nuclear recoil




- Coherent typically for $E_\nu < 30$ MeV
- Cross-section approximated by $$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

$$E_{nr}^{max} = \frac{2E_\nu^2}{m_n + 2E_\nu}$$

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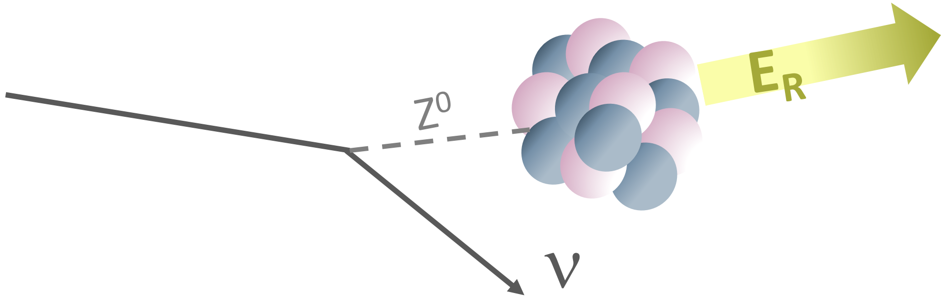


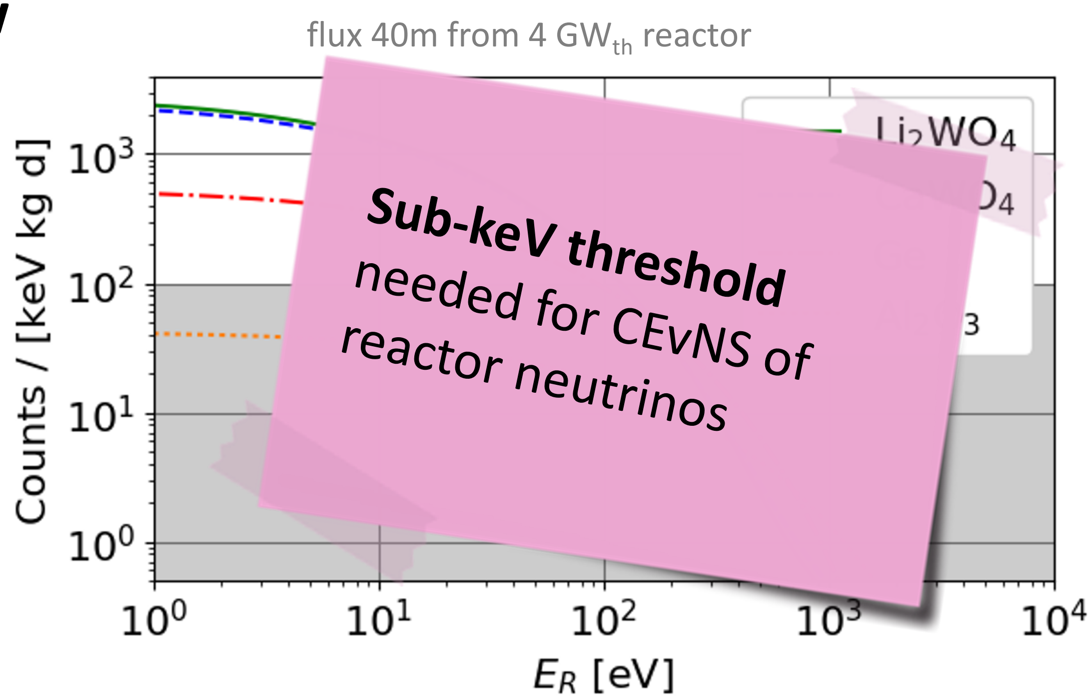


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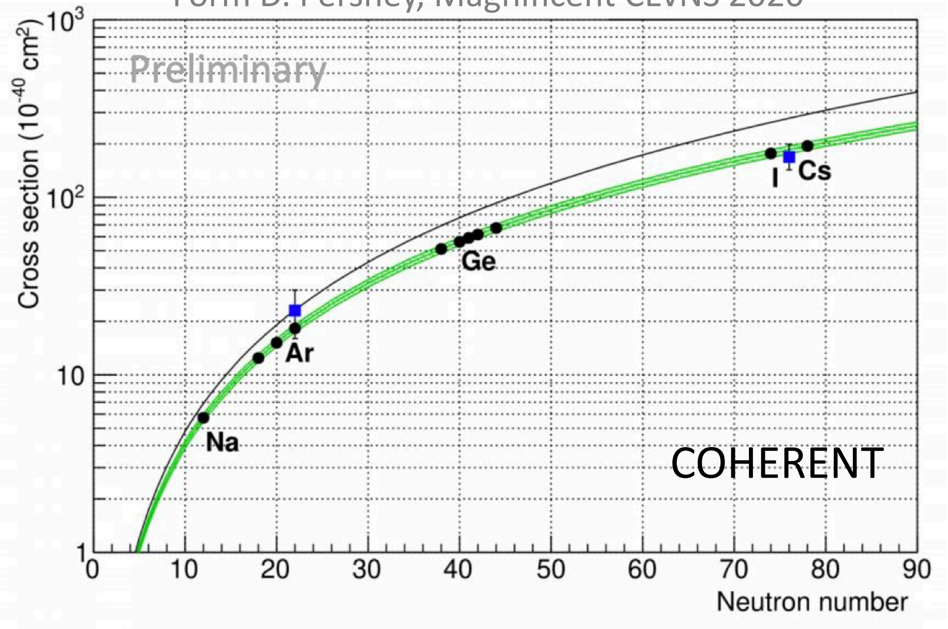
# Status CEvNS & Direct Dark Matter Search

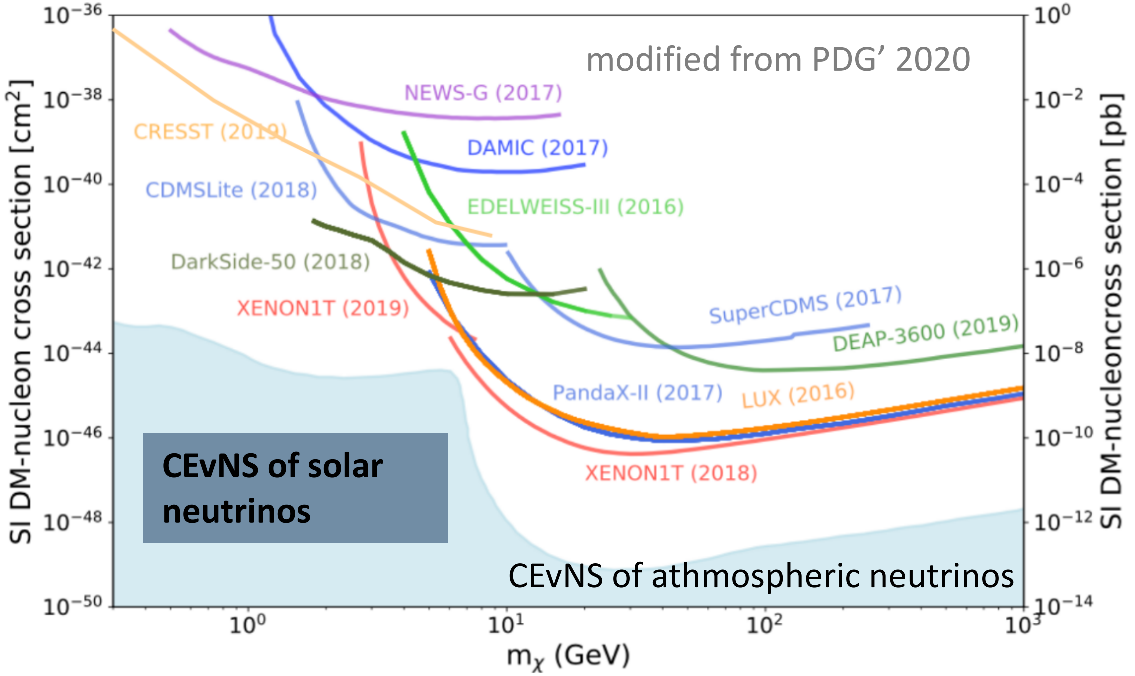
- First observation at $\pi$-DAR source with multiple detector types and keV thresholds

Form D. Pershey, Magnificent CEvNS 2020




- CEvNS of reactor neutrinos unobserved so far
- Need of sub keV threshold

- Much of the WIMP parameter space already excluded




- To explore $m_\chi$ < GeV/c2 need to lower threshold

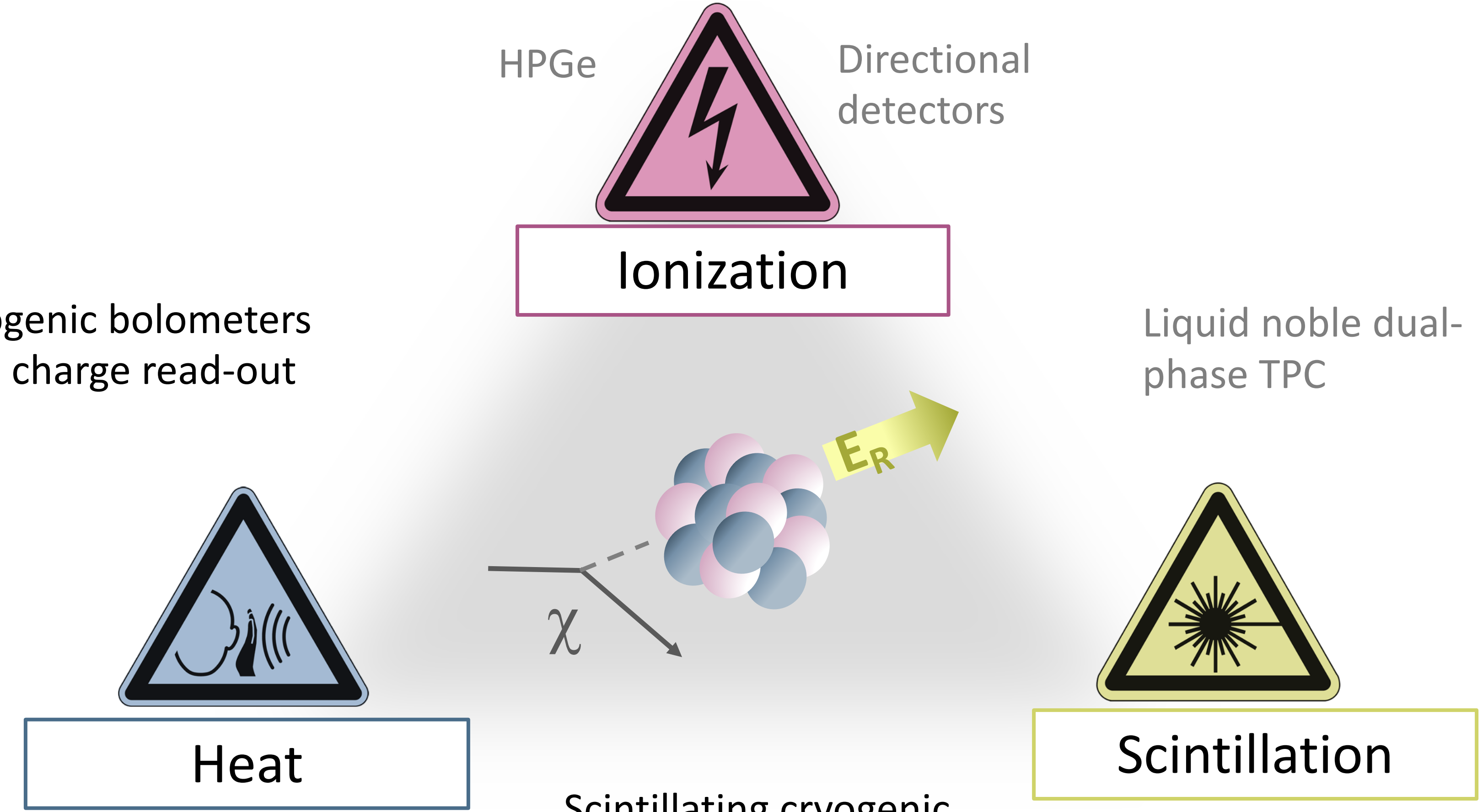
# Observables

HPGe

Directional detectors

Cryogenic bolometers with charge read-out

Liquid noble dual-phase TPC




Cryogenic bolometers

Liquid noble gas detectors

Superheated liquids

Scintillating cryogenic bolometers

Scintillating crystals

# Principle of Bolometer

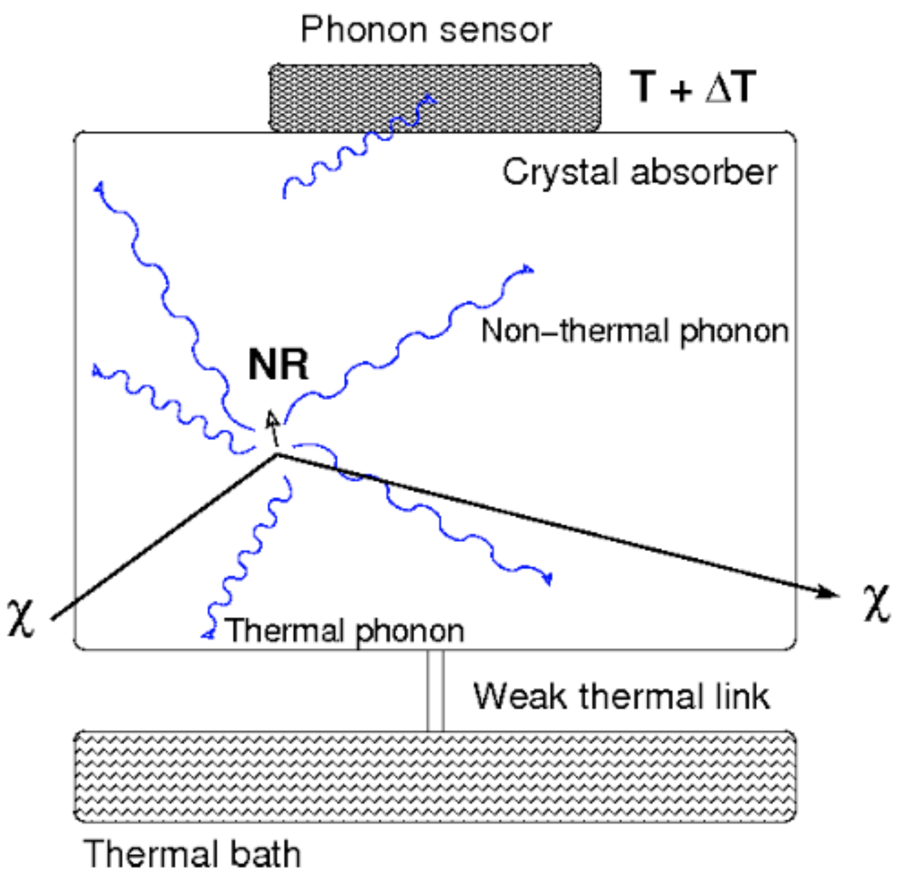
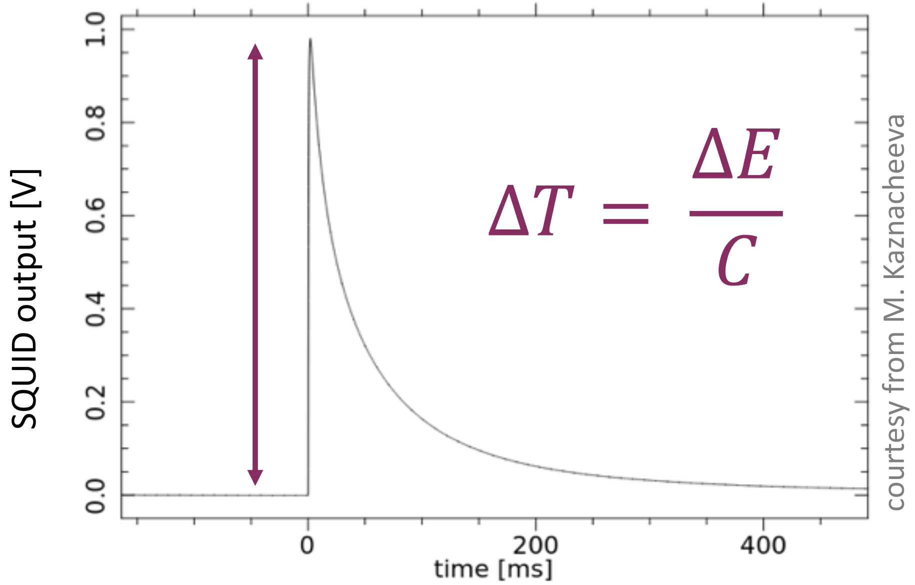



Figure taken from J. Phys. G43 (2016) no.1, 013001

Heat pulse measured with W-TES



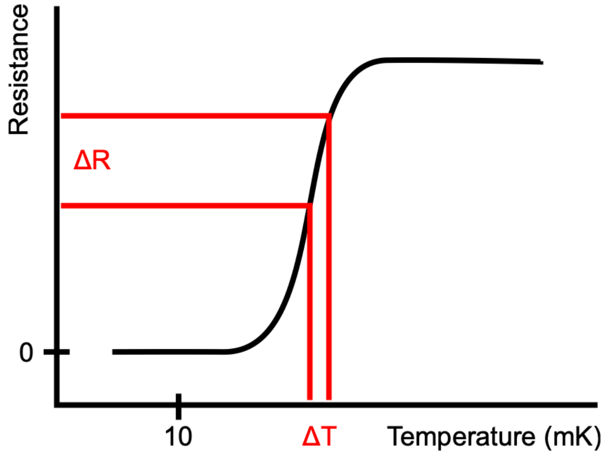

$$\Delta T = \frac{\Delta E}{C}$$

- ✓ Measurement of full recoil energy
- ✓ Achieve very low thresholds & excellent energy resolution
- ✓ Wide range of target materials
- ✗ Operation at (10—100) mK
- ✗ Limited scalability of detectors

Synergy of CEvNS and dark matter

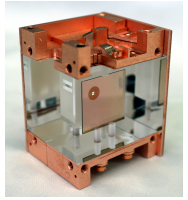
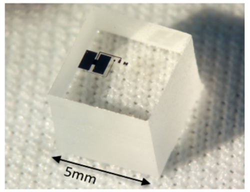
# Thermometers

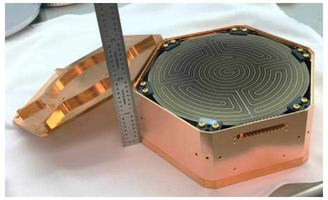
## Transition Edge Sensor (TES)



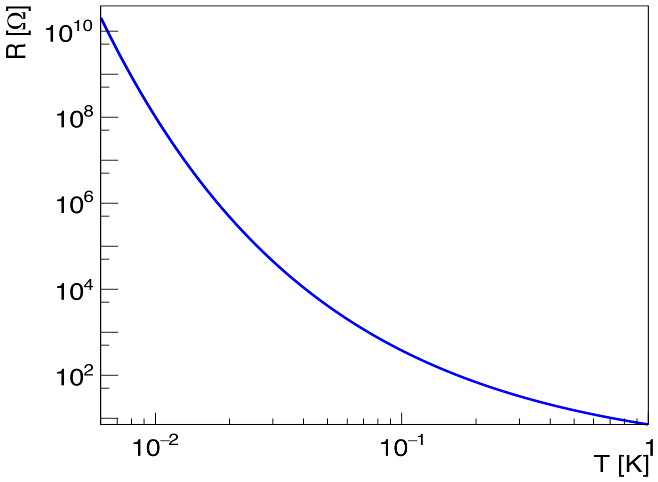

$\Delta T = O(100\ \mu K)$ → $\Delta R = O(100\ m\Omega)$

- SQUID read-out
- Fast response O(μs)
- Narrow temperature range

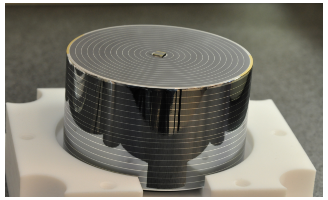
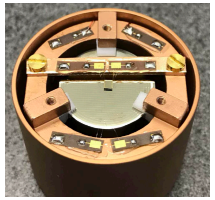


## Neutron Transmutation Doped (NTD) Ge




$\Delta T = O(100\ \mu K)$ → $\Delta R = O(8\ M\Omega)$

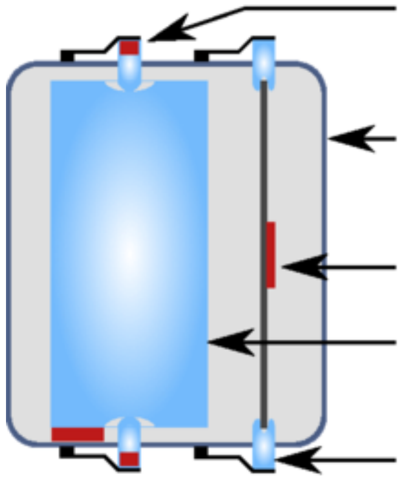
- Voltage amplifier read-out
- Slow response O(ms)
- Wider temperature range

# CRESST-III

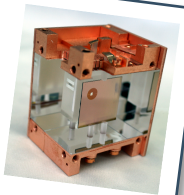
CRESST, PhysRevD.100.102002

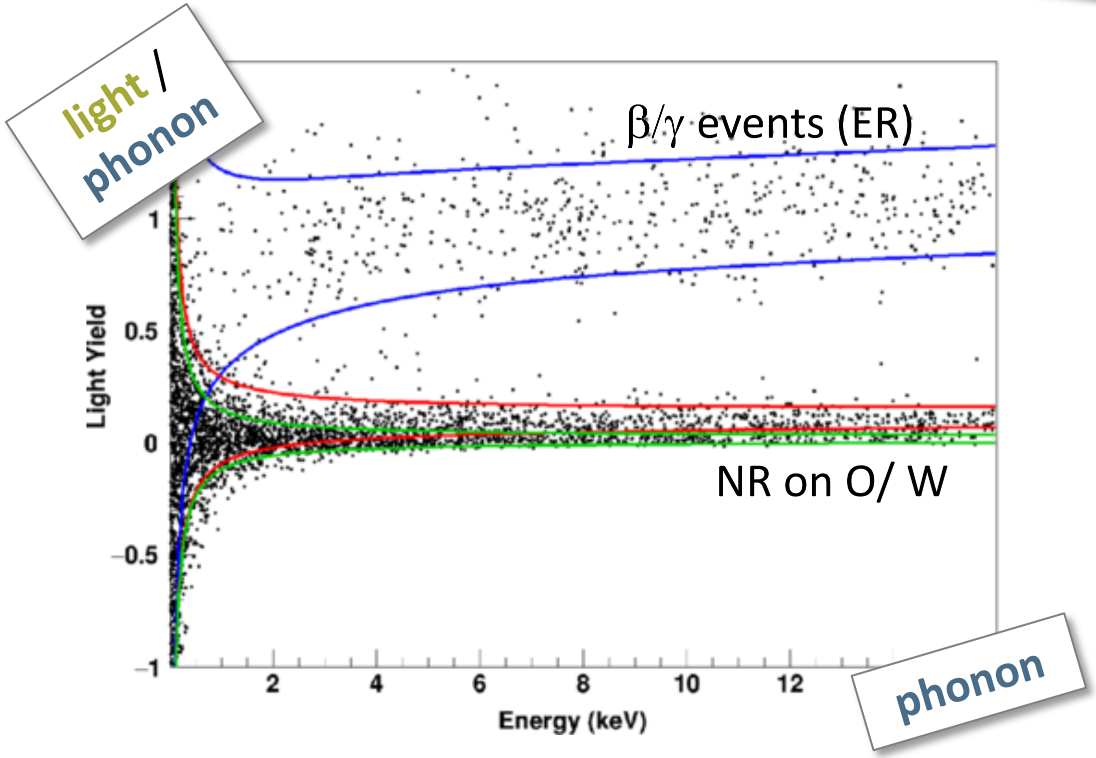
- Optimized for low-mass dark matter
- Scintillating **$CaWO_4$** target crystals
- Dimensions: $(20x20x10)mm^3 \approx$ **24g**
- Achieved threshold: **$30.1\ eV_{nr}$**




CRESST-III

Target: $CaWO_4$
Mass: 10x 24 g, 3x 220g
Location: LNGS
Status: running





# Towards 10 $eV_{nr}$ Thresholds

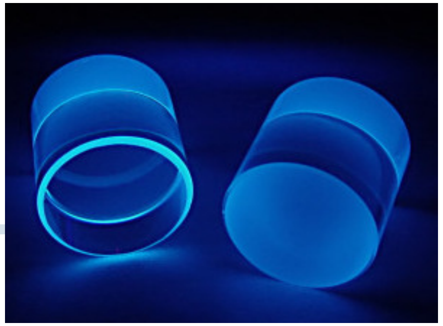
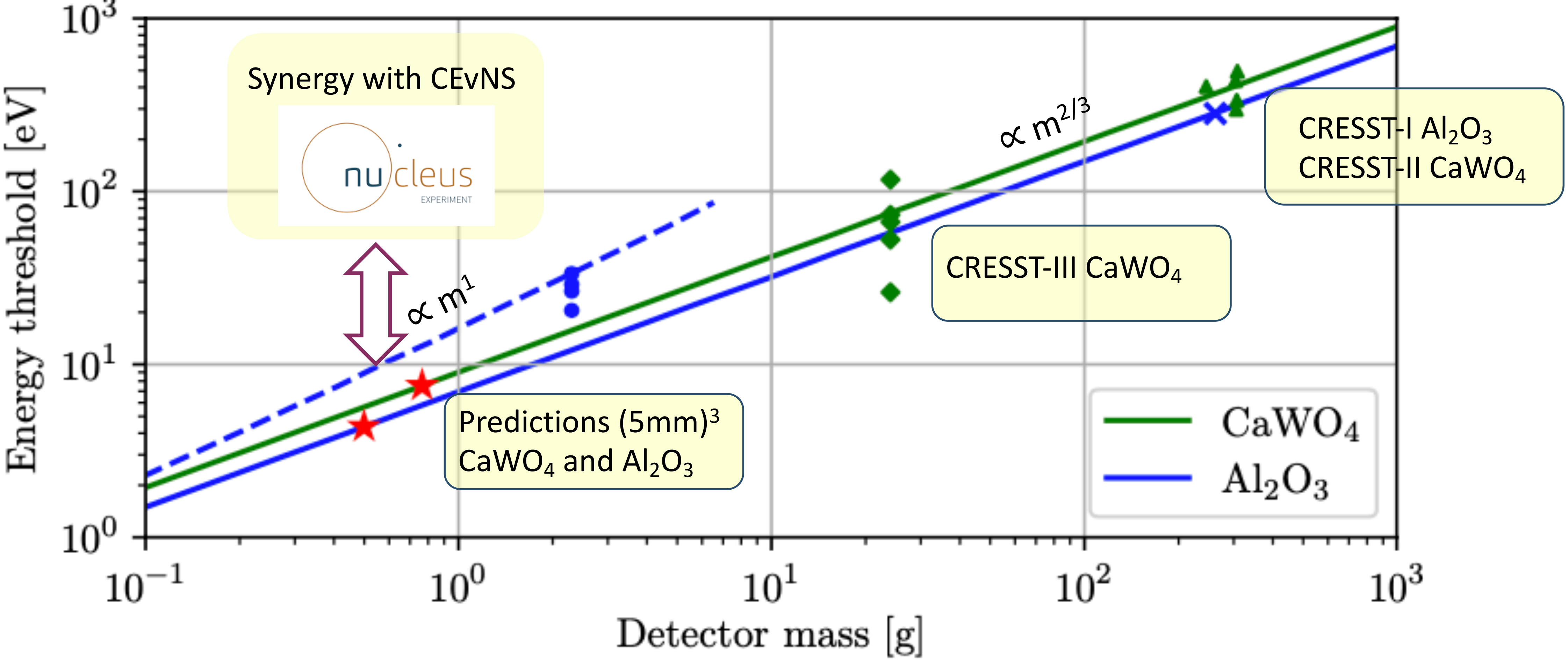


Figure taken from PhD thesis J. Rothe, TUM, 2020



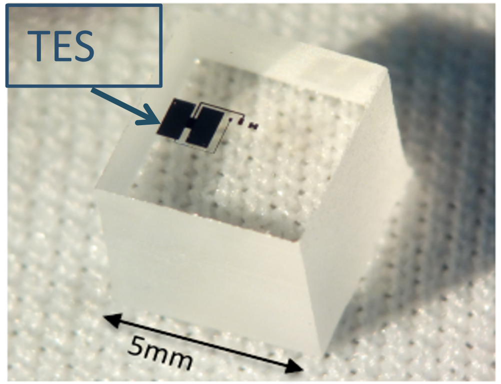
# NUCLEUS

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

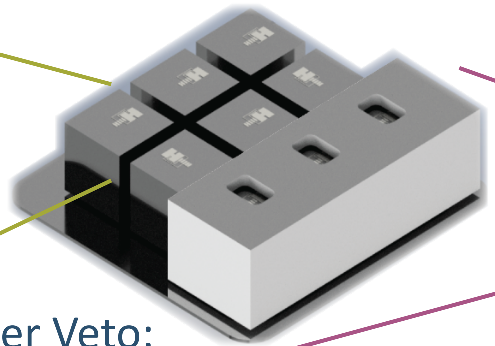
- Based on CRESST technology
- Demonstrated 20 $eV_{nr}$ threshold
- 2 arrays of gram-scale cryogenic calorimeters
- Multitarget approach for $N^2$ dependence of CEνNS
- Cryogenic veto system for background rejection

**NUCLEUS-10g**

Target: $CaWO_4$, $Al_2O_3$
Mass: 6.8g + 4.4g
Location: Chooz, France
Status: Construction

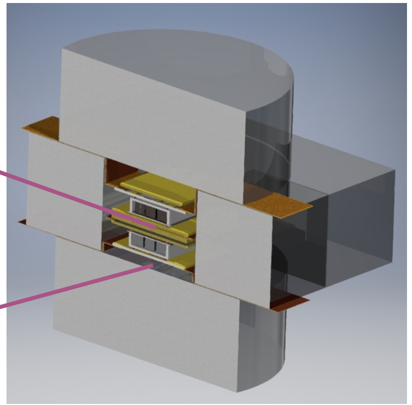


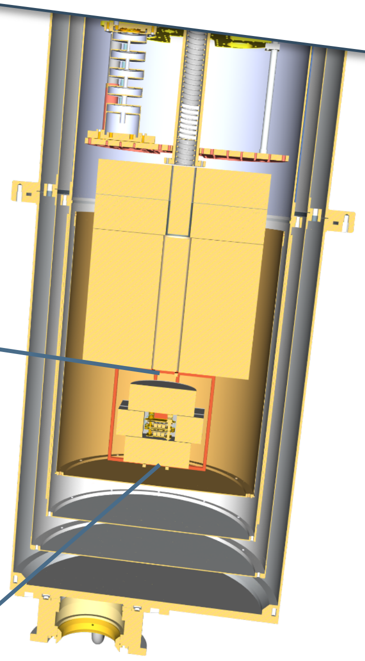

$0.5g\ Al_2O_3$ prototype



Inner Veto:
Instrumented holder

Outer Veto:
O(kg) Ge detector





# EDELWEISS-III

E. Armengaud *et al* 2017 *JINST* **12** P08010

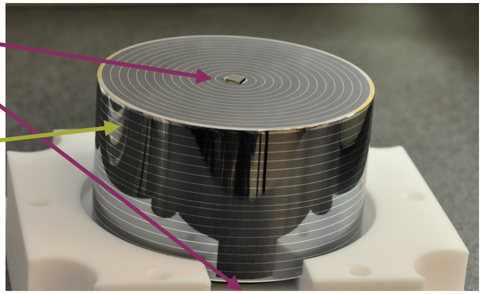
- 800g Ge detectors
- Heat & ionization readout
- Ionization energy resolution < 0.7 $keV_{ee}$ (FWHM)
- Heat energy resolution < 1.5 keV (FWHM)

EDELWEISS-III

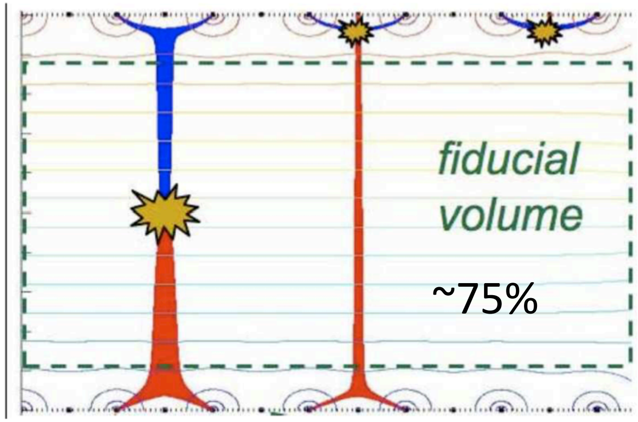
Target: Ge
Mass: 24 x 800g
Location: LSM
Status: Running

Ge-NTD

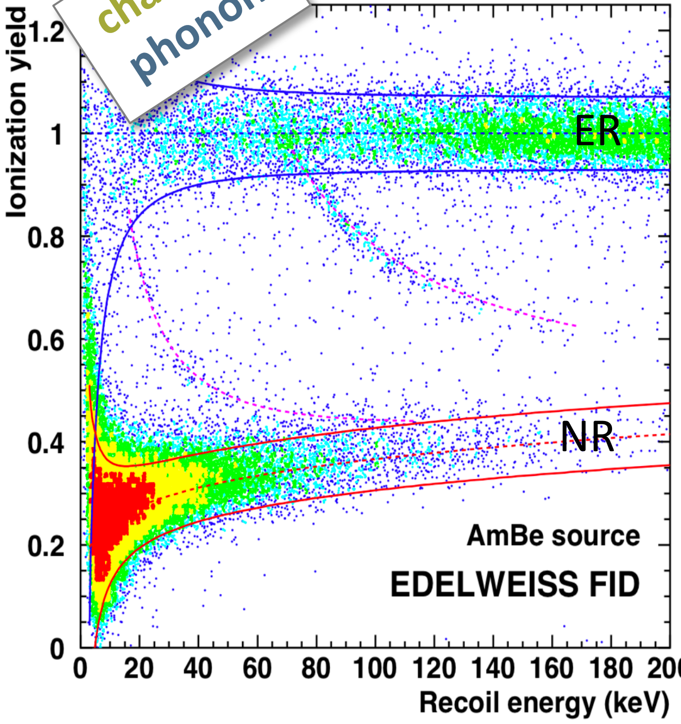
Interleaved electrodes



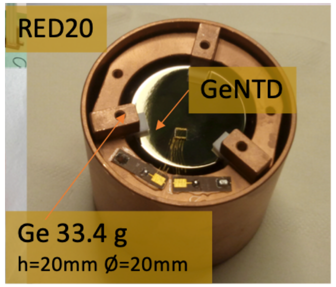
Surface background




http://dx.doi.org/10.3204/DESY-PROC-2010-03/gerbier gilles



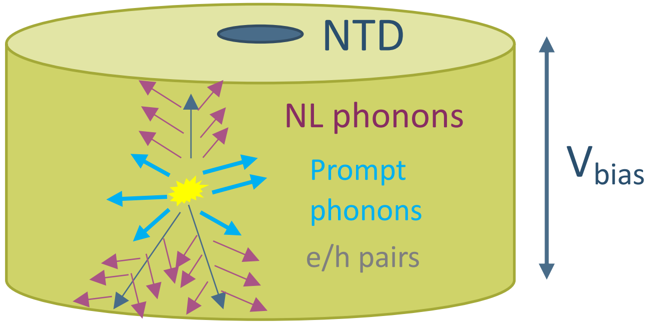
# Towards low Threshold with EDELWEISS-III



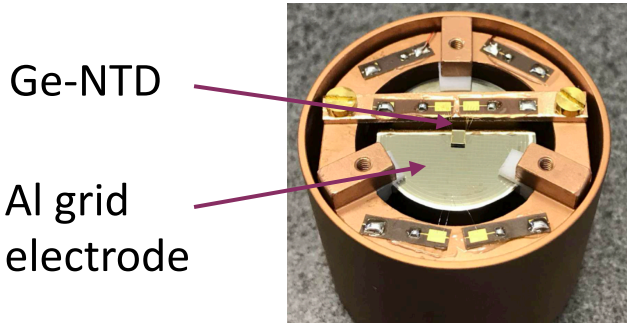

## EDELWEISS-Surf

*E. Armengaud et al., Phys. Rev. D 99, 082003 (2019)*

- Mass reduced to **33 g**
- Analysis threshold reduced to **55 eV$_{nr}$**
- No ionization channel




Neganov-Luke Effect




## High voltage R&D

- Single e-/h sensitivity
- Use Neganov-Luke effect

## Low Voltage R&D:

- Goal: 10 eV (20 eV) heat (ionization) resolution
- R&D on front-end electronics with HEMT preamplifier

Synergy with CEvNS

RICOCHET
A Coherent Neutrino Scattering Program

# RICOCHET

J Billard *et al* 2017 *J. Phys. G: Nucl. Part. Phys.* **44** 105101

- O(kg) cryogenic detector array with 10 eV threshold to measure CEvNS
- Mixed array of Ge and Zn target detectors

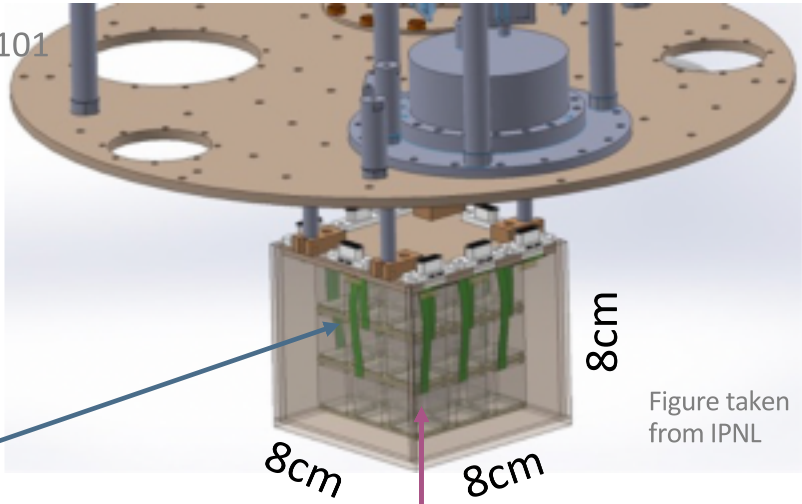



Figure taken from IPNL

RICOCHET

Target: Ge, Zn
Mass: 27 x 32g
Location: ILL, Grenoble
Status: Construction

### Ge semiconductors

- Well known technique with proven 55 eV threshold

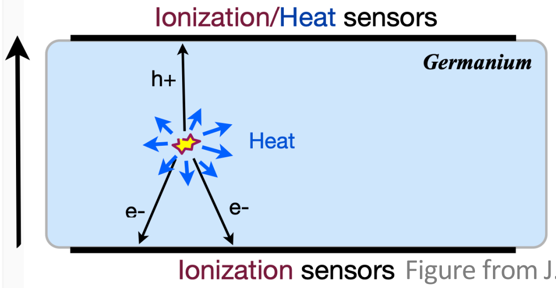



Figure from J. Billard, IPPP, 2019

### Zn superconducting metal

- NEW technology
- Prompt vs delayed heat signal depend on particle type

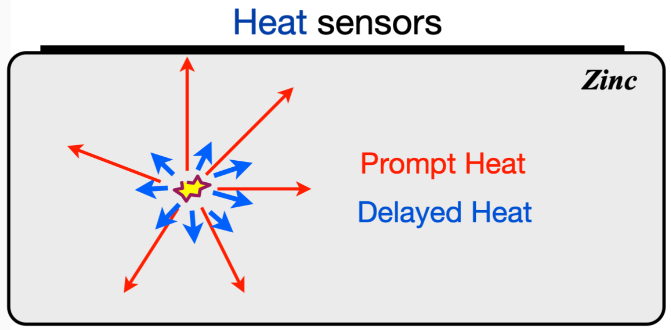



Figure from J. Billard, IPPP, 2019

# SuperCDMS

SuperCDMS Collaboration, Phys. Rev. D **95**, 082002

SuperCDMS

Target: Ge, Si

Mass: 10kg

Location: SNOLAB

Status: construction

1.4 kg Ge and 0.6 kg Si detectors with two designs

## iZIP Detector

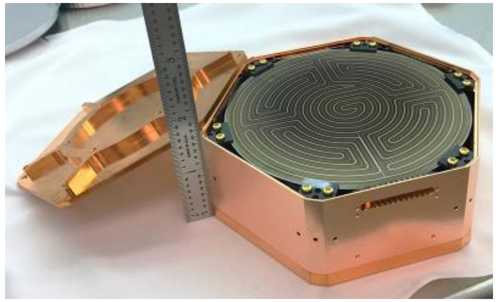
- Focus on background, $m_\chi$ ~ 5 GeV/c$^2$
- Interleaved phonon and ionization sensors
- Surface event discrimination
- ER/NR discrimination down to 2 keV$_{nr}$

## HV detector

- Focus on low threshold to explore $m_\chi$ < 5 GeV/c$^2$
- ~100V bias to increase of phonon signal:

$$E_{total} = E_{recoil} + n_{eh} e\Delta V = E_{recoil}\left(1 + \frac{Ye\Delta V}{\langle E_{eh}\rangle}\right)$$

- Only (TES-)based phonon sensors



| Anticipated | iZIP | | HV | |
|---|---|---|---|---|
| | Ge | Si | Ge | Si |
| Number of detectors | 10 | 2 | 8 | 4 |
| Total exposure (kg·yr) | 56 | 4.8 | 44 | 9.6 |
| Phonon resolution (eV) | 50 | 25 | 10 | 5 |
| Ionization resolution (eV) | 100 | 110 | – | – |
| Voltage Bias (V) | 6 | 8 | 100 | 100 |

From R. Mahapatra, Magnificent CEvNS 2020

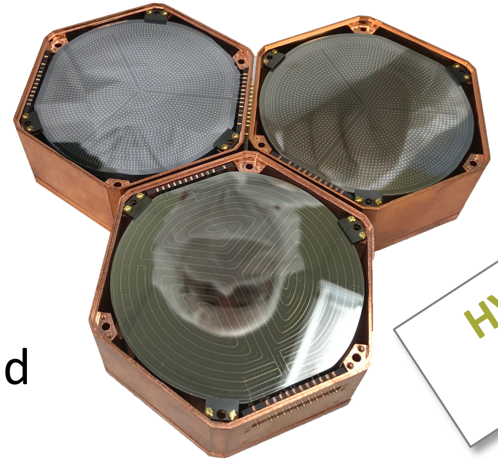
Synergy with CEvNS

MINER

# MIνER

Phys. Rev. D 94, 093002 (2016)

http://people.tamu.edu/~mahapatra/miner.html



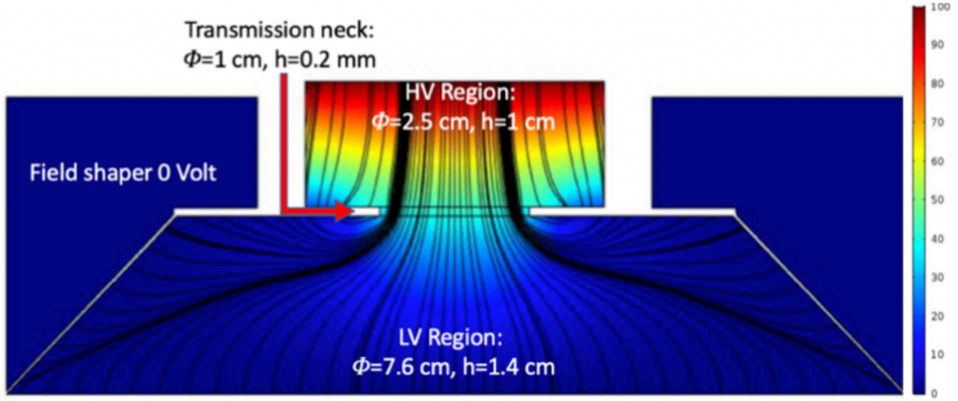
MIνER

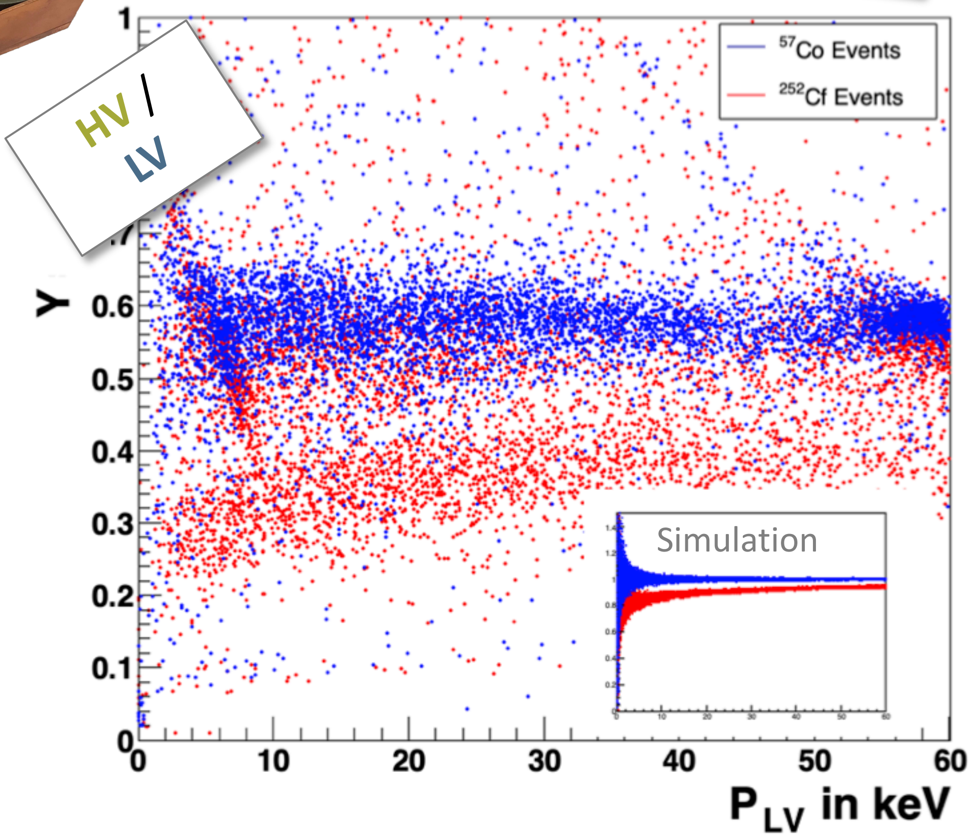
Target: Ge, Si
Mass: 10kg
Location: TAMU, Texas
Status: running

- Phase 1:
  - 3 Si HV detectors (single e/h sensitive) for CEvNS
  - 1 new Si Hybrid in-situ background measurement

## Hybrid HV Detector arXiv:2006.13139v1

- Combine single e/h sensitivity & background discrimination
- LV: measurement of primary phonons (iZIP-like)
- HV: measurement of Neganov-Luke phonons



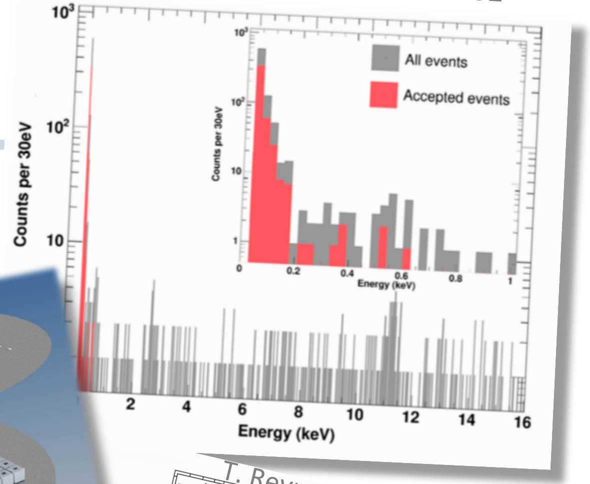



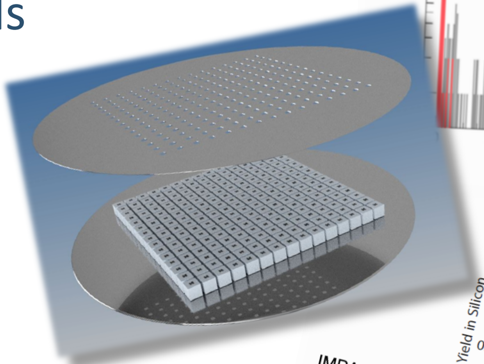
# Summary Conclusion

- Low mass dark matter search & CEνNS are very active fields
- Many new ideas under way

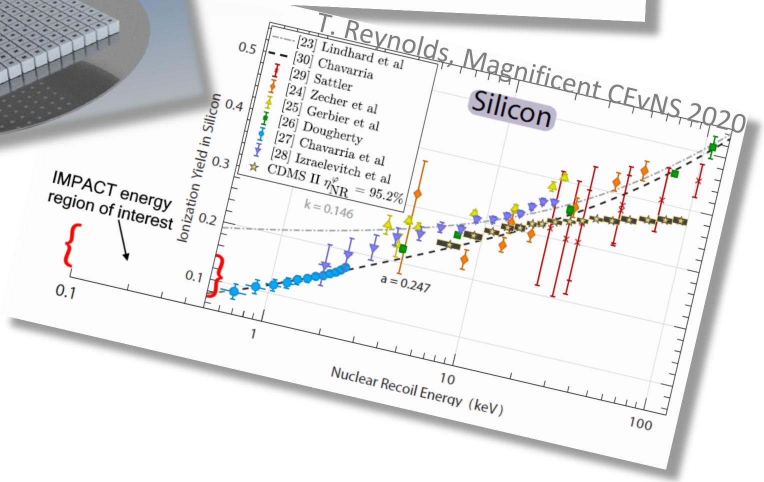
- Challenges
  - Low energy background
  - Calibration of nuclear recoil
  - Measurement of quenching factors
  - Scalability of read-out

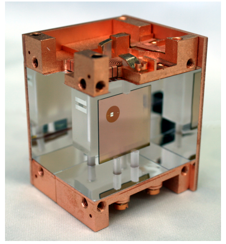
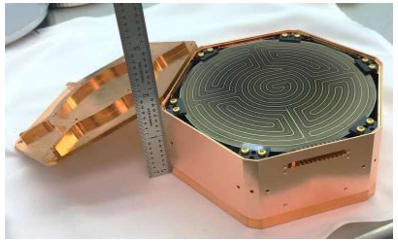
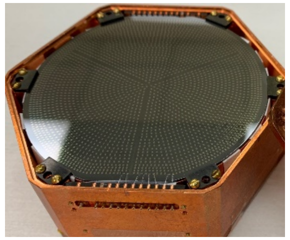
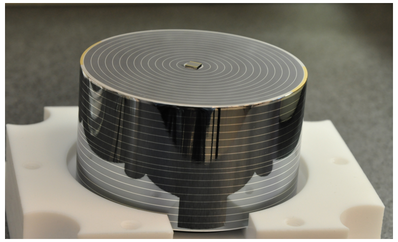
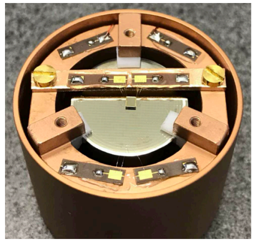
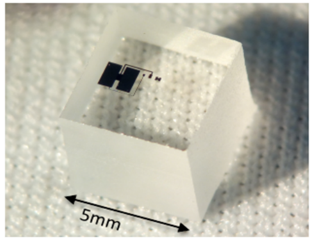
CRESST, PhysRevD.100.102002

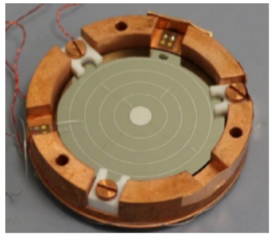


T. Reynolds, Magnificent CEvNS 2020



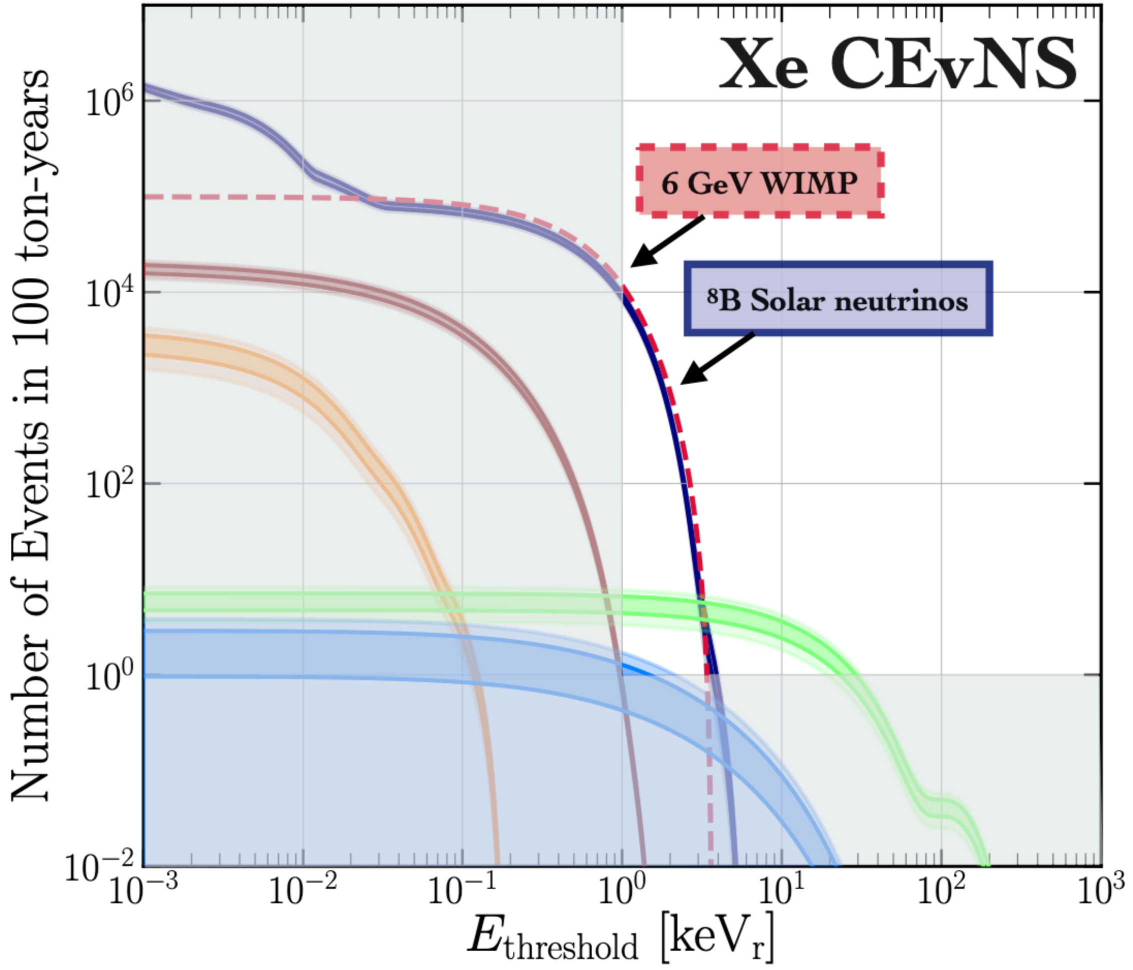



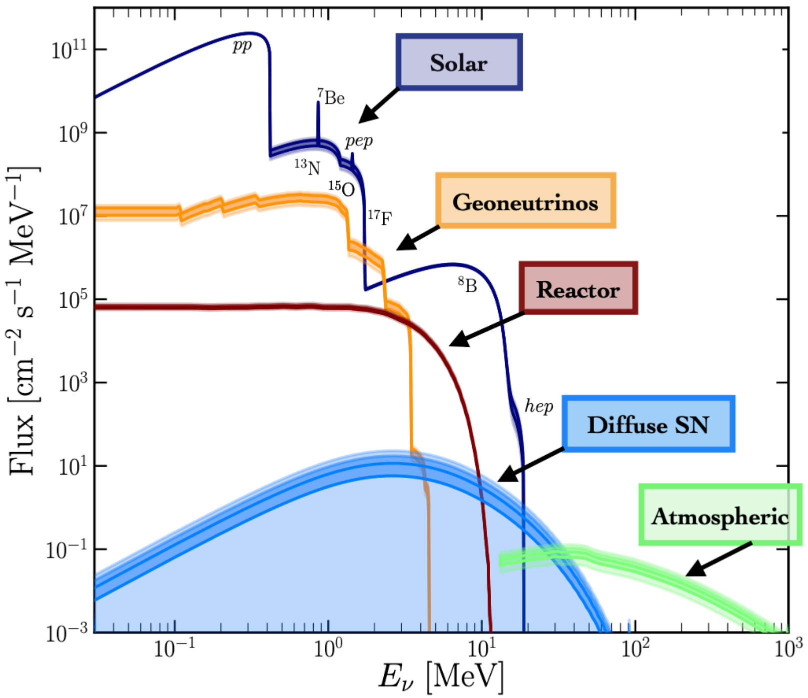
MUNICH
Oct 5-7 2021

# Thank you for your attention

# Neutrino Floor

C. O'Hare, Magnificent CEvNS 2020

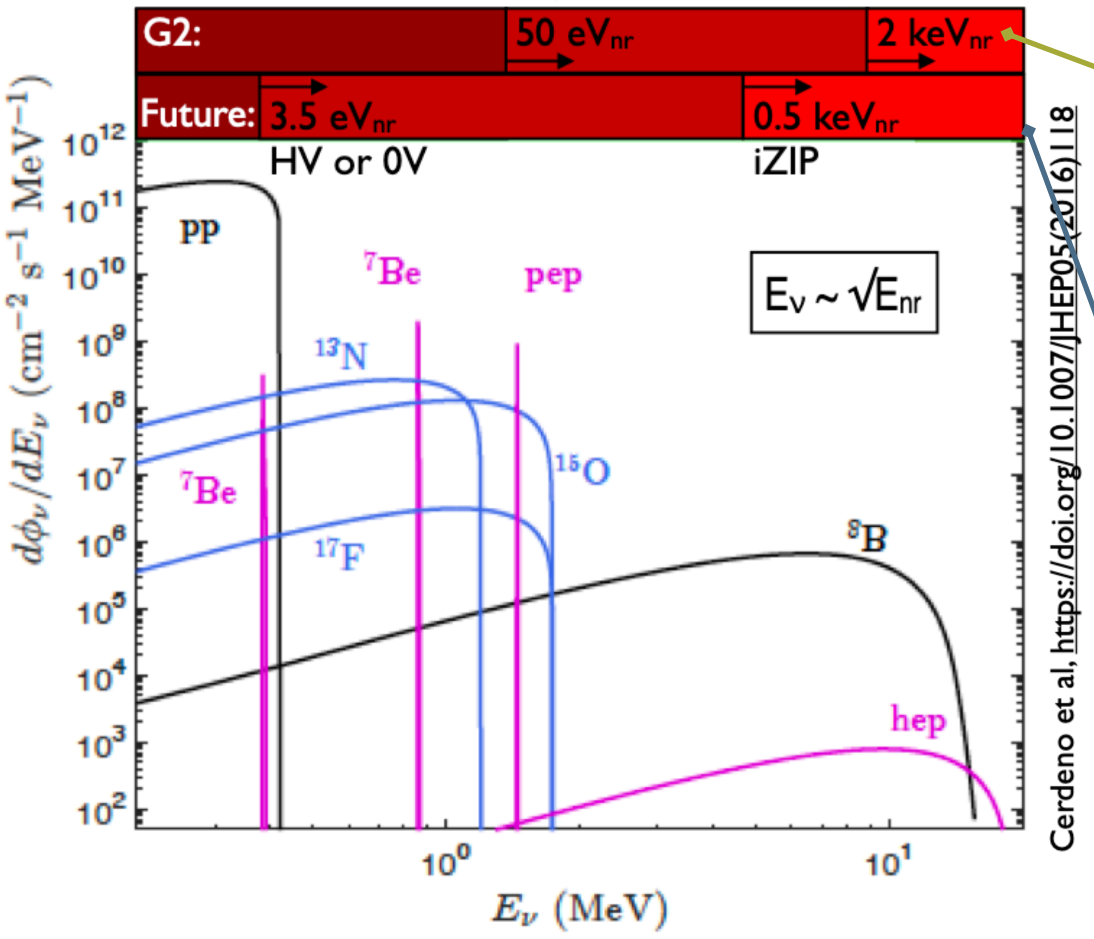



- Discrimination by
  - Annual modulation
  - Complementary targets
  - Directional detectors
  - Improved energy resolution

# CEvNS with SuperCDMS

S. Golwala, Magnificent CEvNS 2020




**iZIP detectors:**

Few $^8$B w/ discrimination, O(50) down to 350 eV$_{nr}$ w/o discrimination

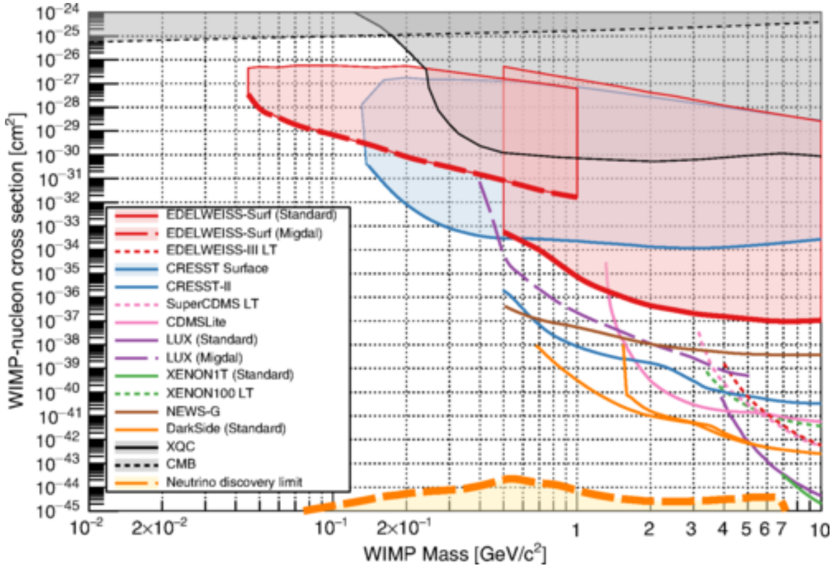
Discrimination down to 0.5 keV$_{nr}$

Few more $^8$B w/ discrimination

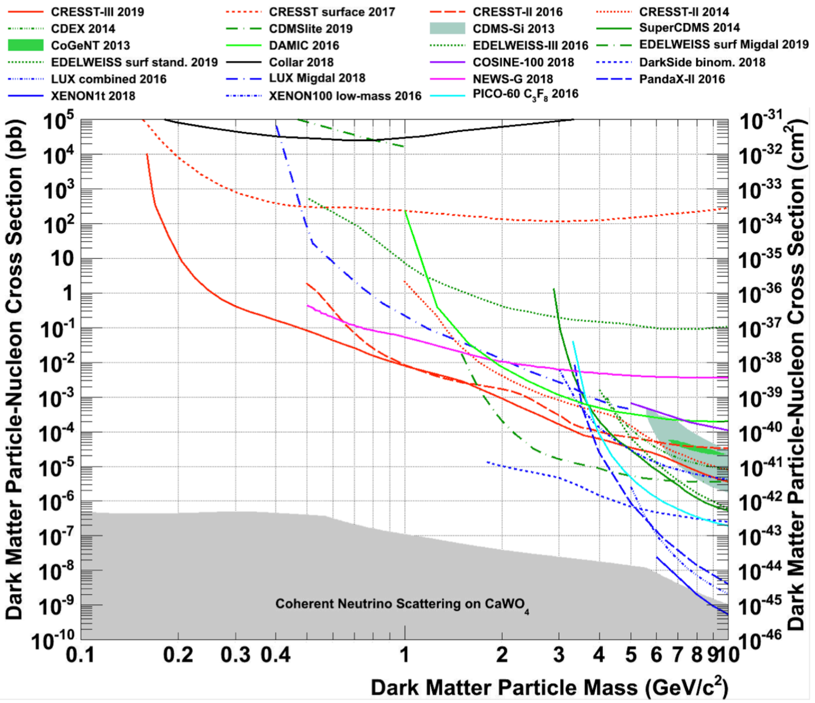
HV detectors:
- No discrimination
- neutrinos << background

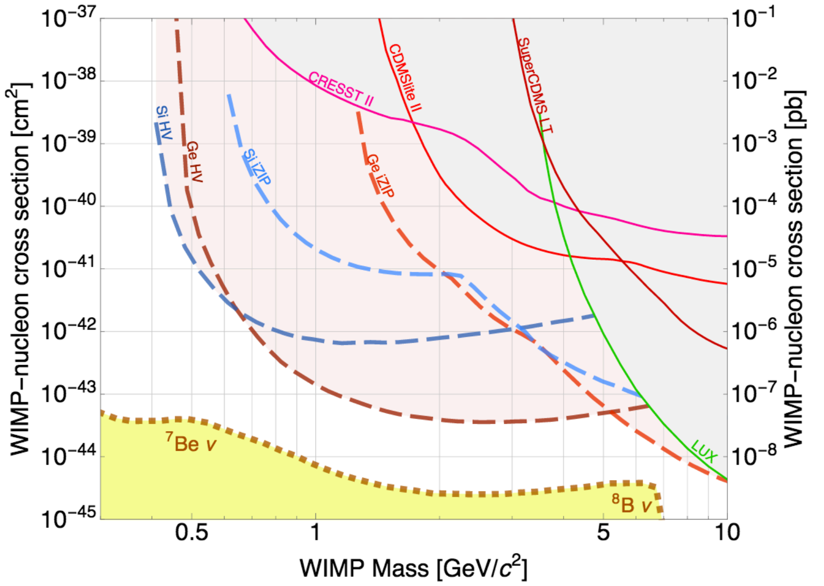
# Perspective Dark Matter

- Cryogenic experiments optimized for low-mass DM
- Can probe masses down to 0.2 GeV/c2
- Future phases will probe cross sections down to $10^{-43} – 10^{-44}$ cm$^2$




Phys. Rev. D **99**, 082003

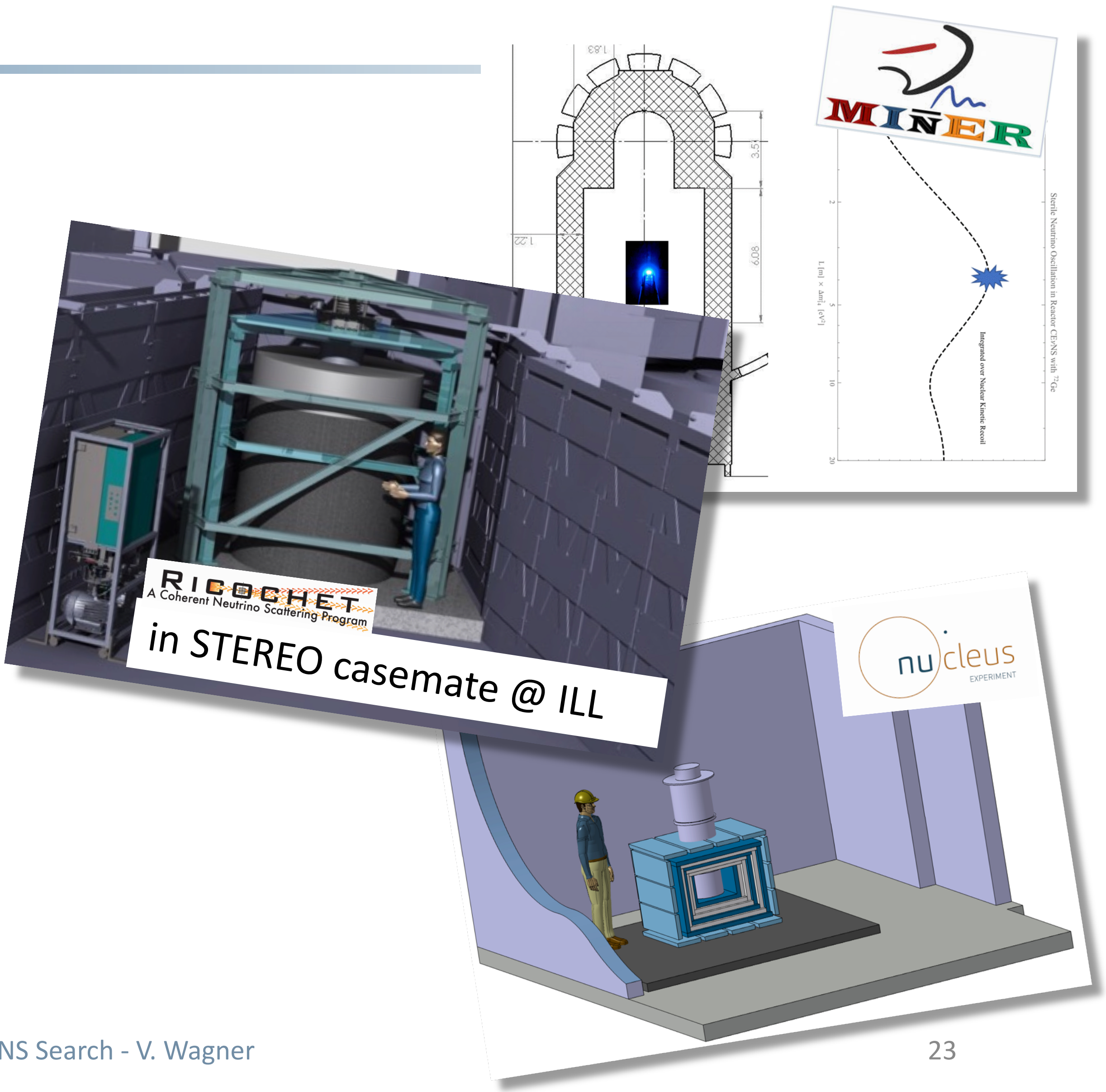



R. Agnese et al., Phys. Rev. D 95, 082002 (2017)
R. Agnese et al., arXiv:1707.01632v1

# Reactor CEvNS Experiments with Cryogenic Detectors

| Experiment | Target | Threshold | $\nu$-flux [$cm^{-2}s^{-1}$] |
|---|---|---|---|
| MI$\nu$ER | Ge, Si | O(100 $eV_{nr}$) | $4x10^{11}$ |
| RICOCHET | Ge, Zn | 55 $eV_{nr}$ | $9x10^{11}$ |
| NUCLEUS | $CaW0_4$, $Al_2O_3$ | 20 $eV_{nr}$ | $2x10^{12}$ |



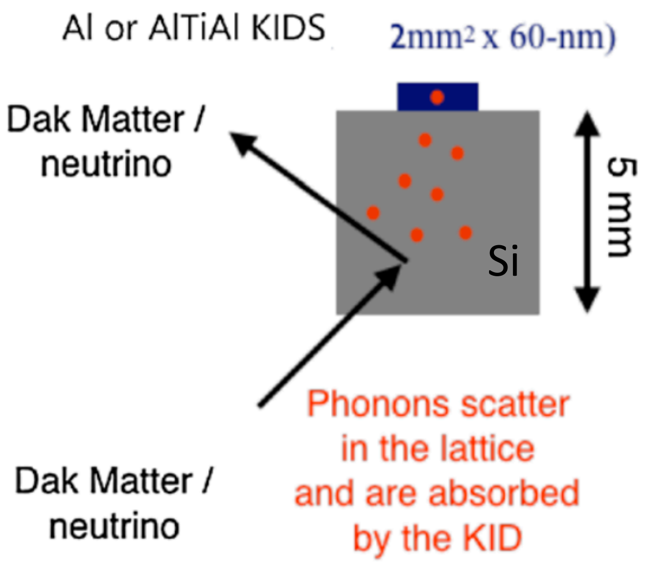
# BULLKID

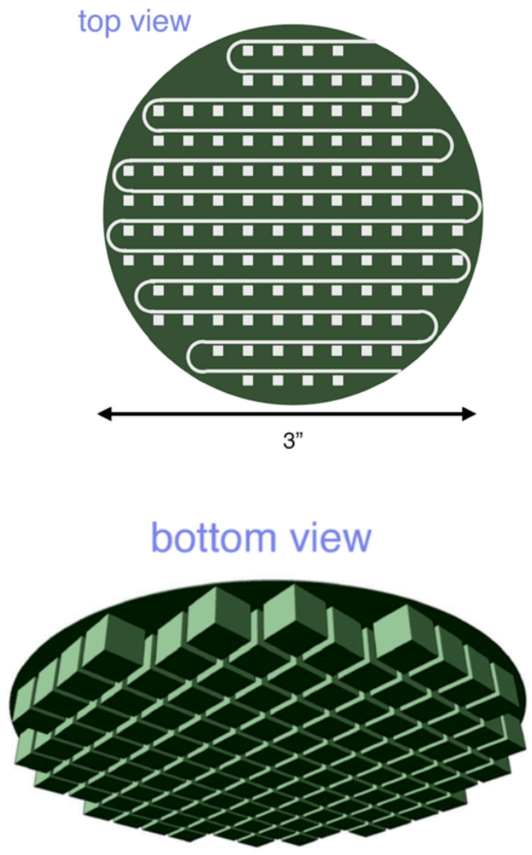
Journal of Low Temperature Physics (2020) 199:593–597

- New detector concept addressing **scalability** of existing cryogenic technologies

- Goal:
  - energy threshold **< 100 $eV_{nr}$** and
  - **O(1kg)** target mass

- Low phonon efficiency O(10%)
- Different KID materials under study:
  - Al, AlTiAl (25 eV resolution with CALDER[1])
  - W + Al and Hf




[1]Casali et al., EPJ C 79 724

# MKID

Energy deposition

↓

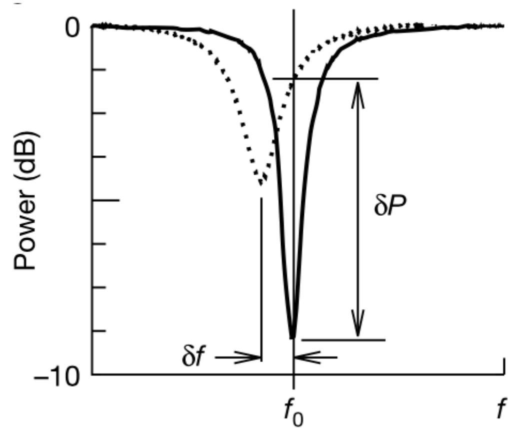
Breaking of Cooper pairs

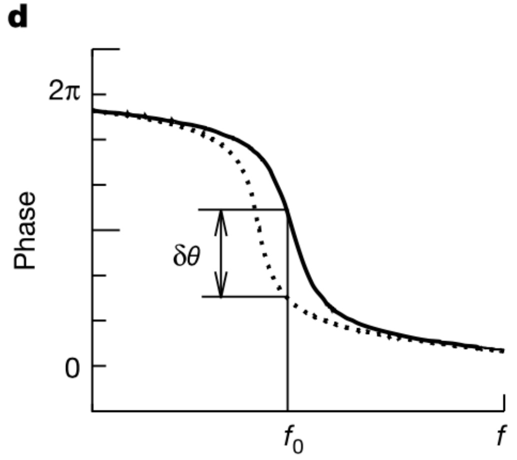
↓

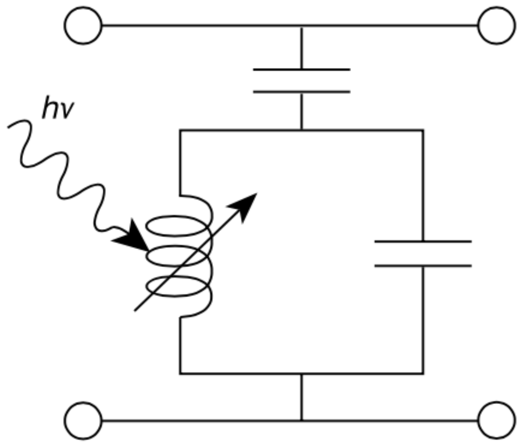
Change in kinetic inductance

↓

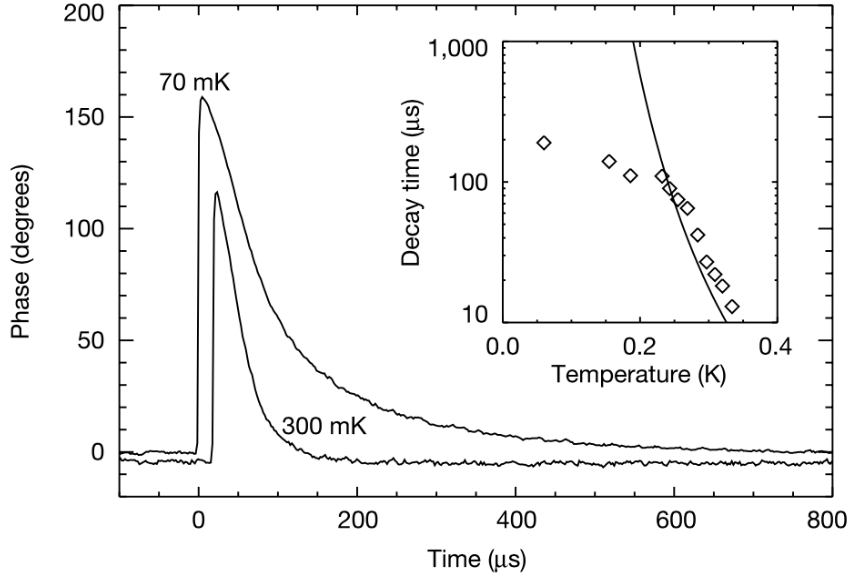
Change of resonance frequency $f_0$



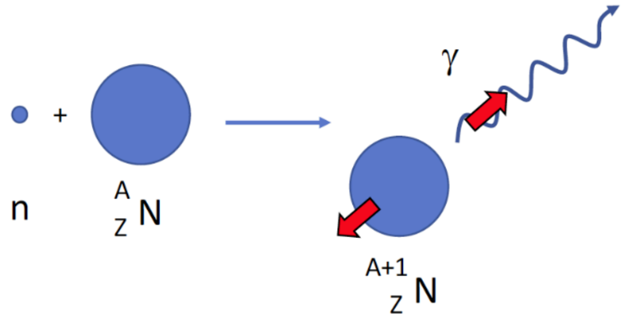




Fine-tune $f_0$ for multiplexing in GHz range



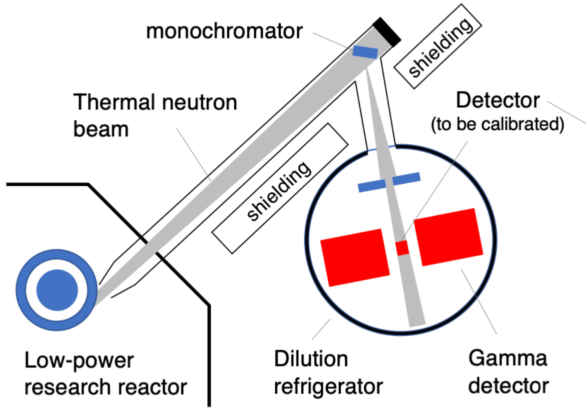

From nature02037

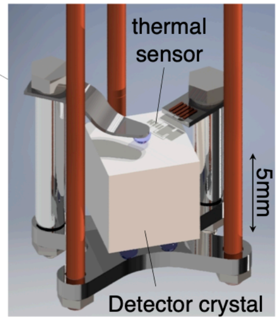
# CRAB




L. Thuillier arXiv: 2011.13803

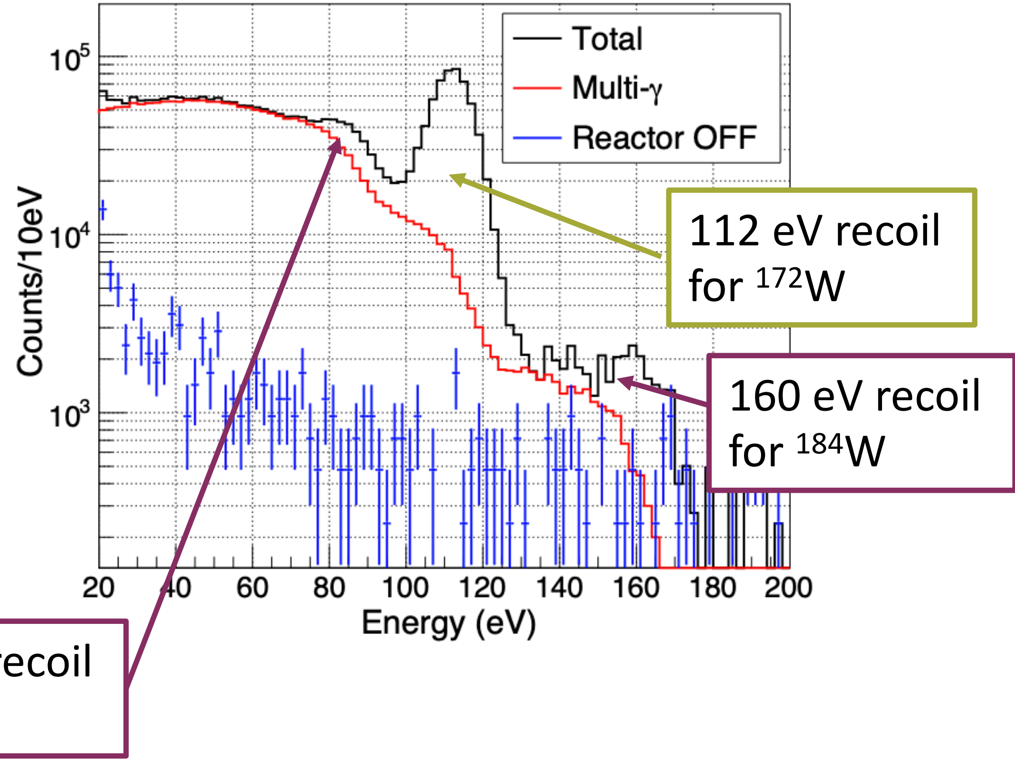
- Calibration at the 100 eV scale using neutron-induced nuclear recoils
- Idea: nuclear recoils from gamma emission
- γ-emission can be used for background reduction
- Suggested experiment at low power TRIGA reactor




(not on scale)

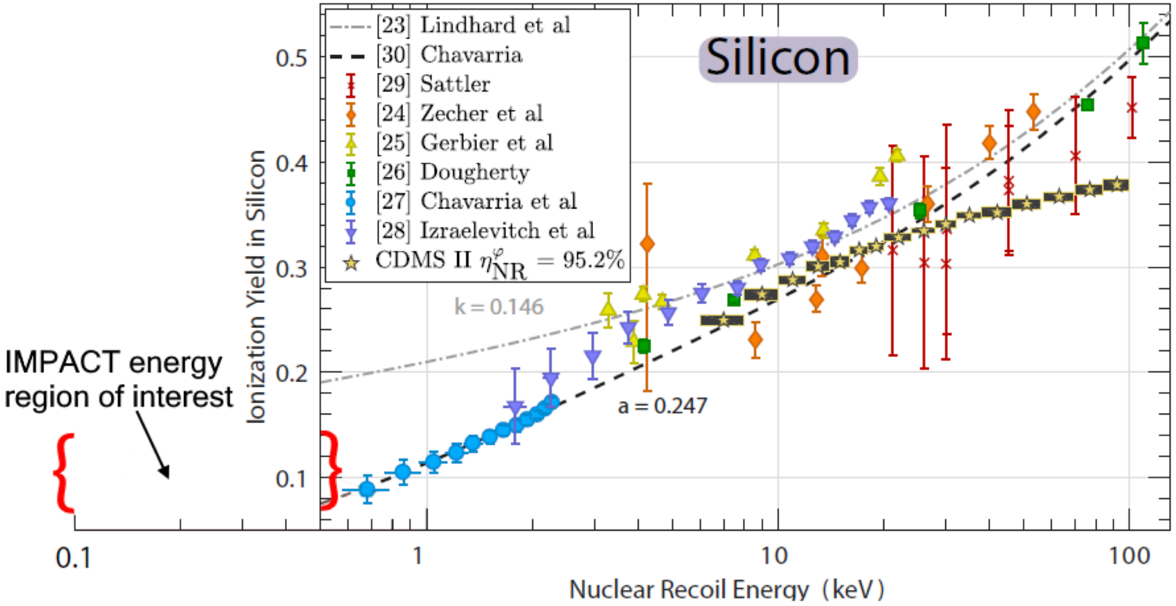
Simulation for 0,76g CaWO4 crystal and
5 eV energy resolution



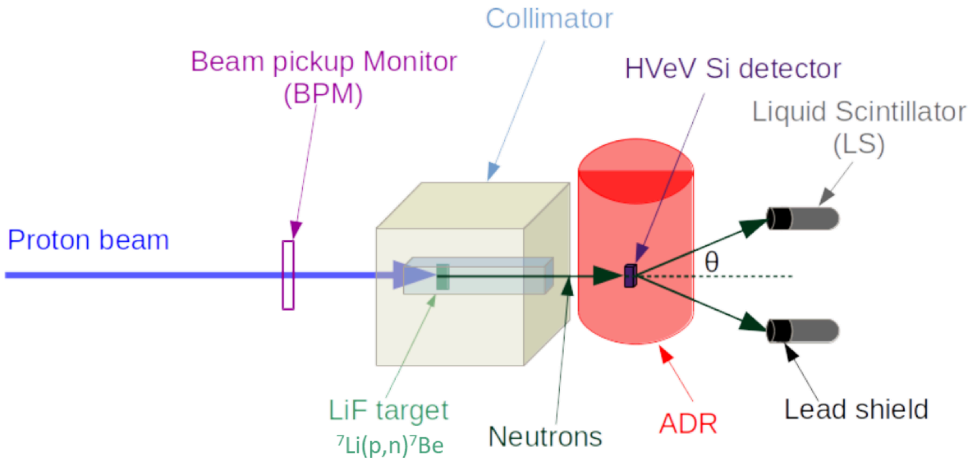
# SuperCDMS Ionization Yield Measurement

T. Reynolds, Magnificent CEvNS 2020

$$E_{total} = E_{recoil} + n_{eh} e\Delta V = E_{recoil}\left(1 + \frac{Ye\Delta V}{\langle E_{eh}\rangle}\right)$$



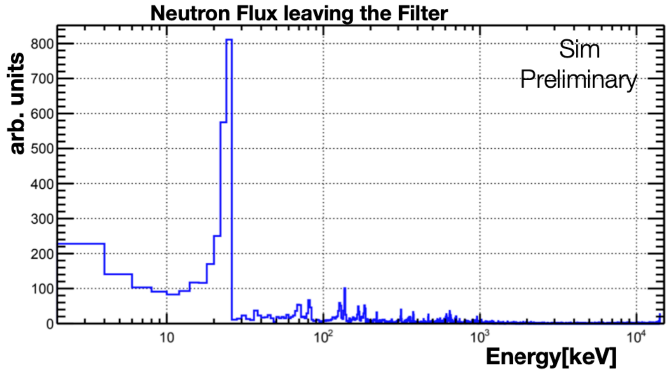

IMPACT@TUNL, results expected soon

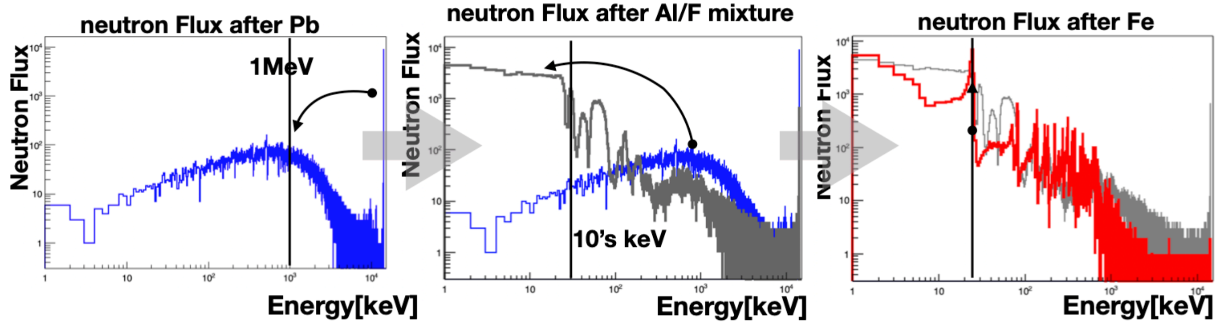


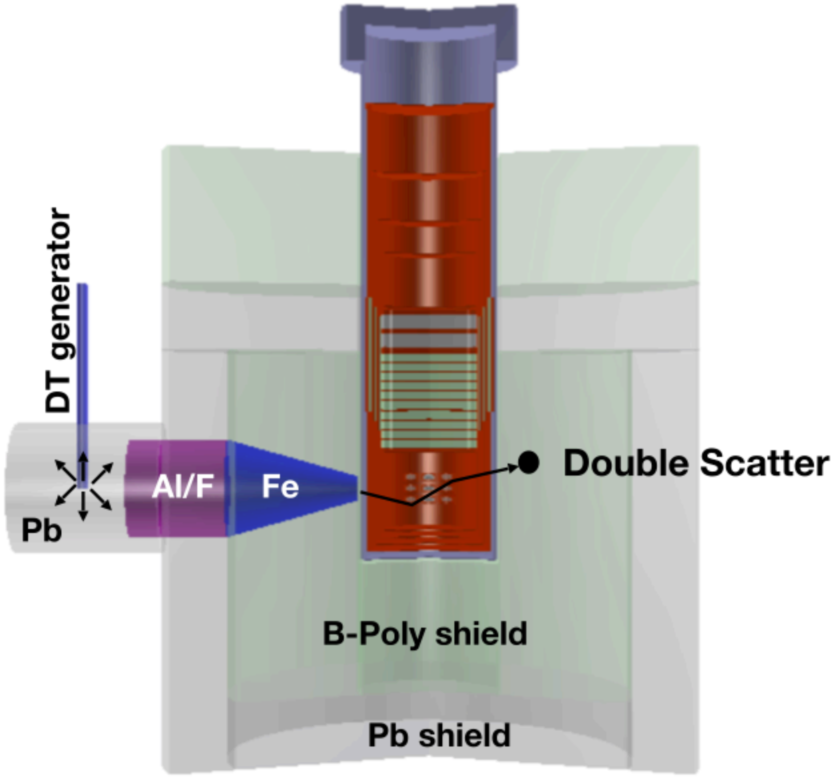
# keV Neutron Source

- For < 100 eV nuclear recoil need keV neutron source
- Ideally portable, to measure at experimental side
- Fe-filtered DT generator for RICOCHET:

P. Patel, Magnificent CEvNS 2020




T. Salanac, Magnificent CEvNS 2020