The dark Universe studied from deep underground: Exploring the low-mass frontier

University of Coimbra
20 June 2018

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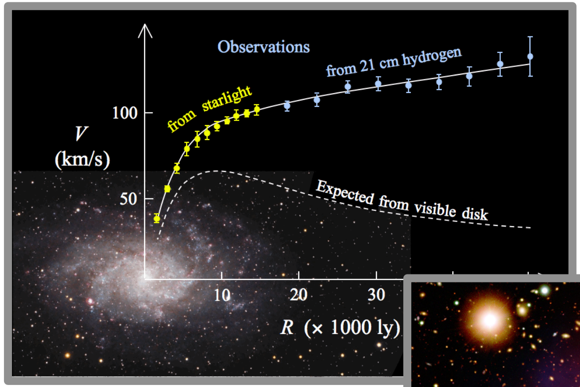
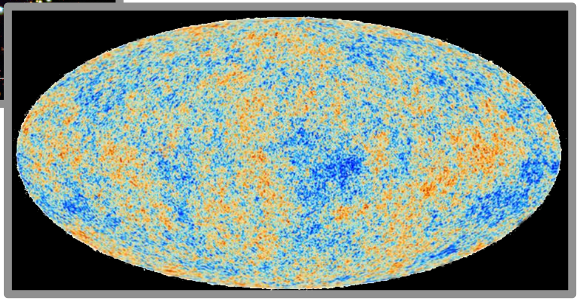
MPP Munich

for the CRESST collaboration

The dark matter problem

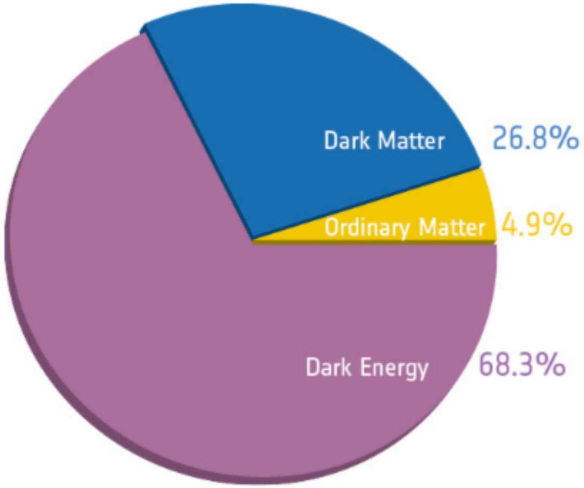




Compelling evidence for dark matter on various cosmological scales

The dark matter problem

One model fits all the observations...



Source: © European Space Agency / Planck

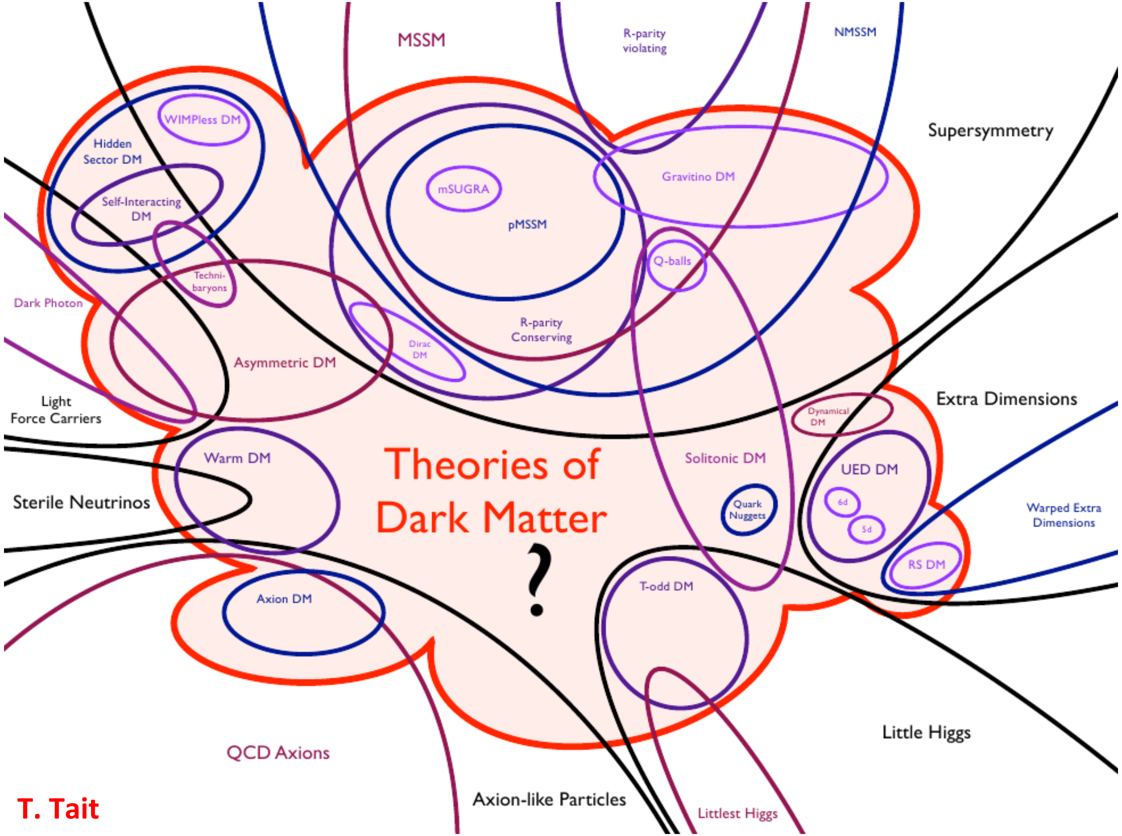
...but raises some fundamental questions:

What is dark matter?

What is dark energy?

After 80 years…

- **Non-baryonic**
  - Height of acoustic peaks in the CMB
  - Power spectrum of density fluctuations
  - Primordial nucleosynthesis
- **Cold (non-relativistic)**
  - Structure formation
- **Interacts via gravity and (maybe) some sub-weak scale force**
- **STILL HERE!**
  - Stable (or extremely long-lived)

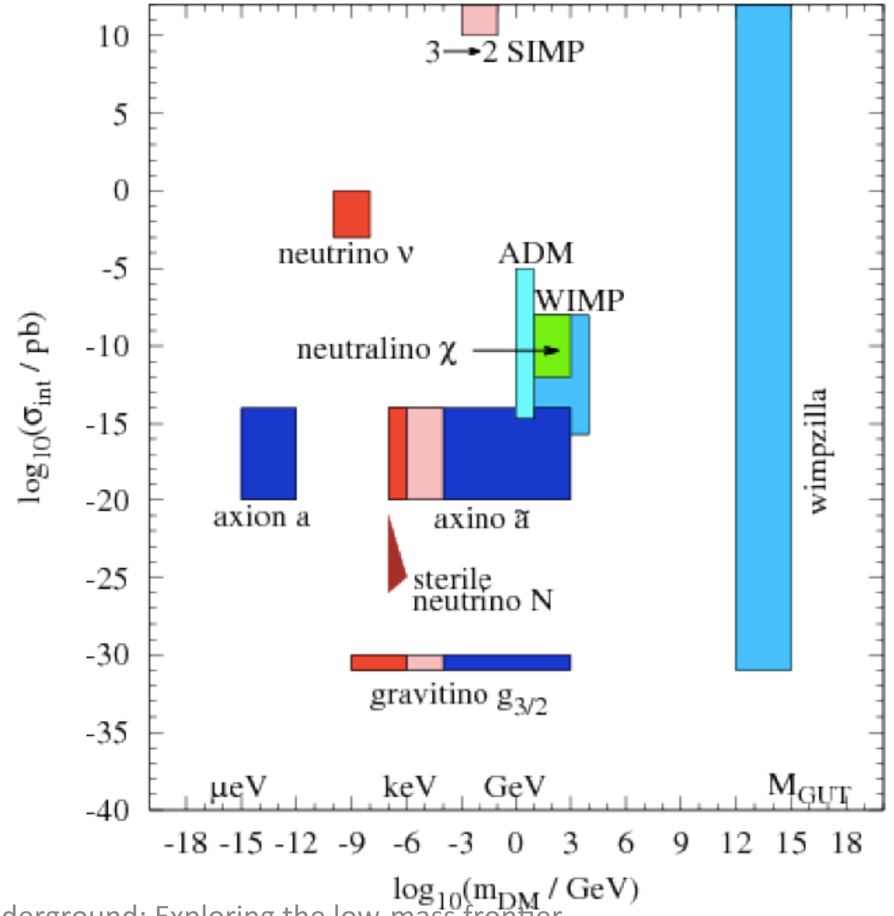


T. Tait

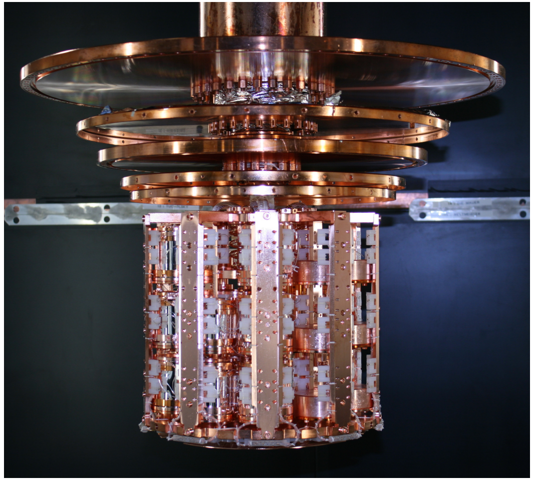
The nature of dark matter

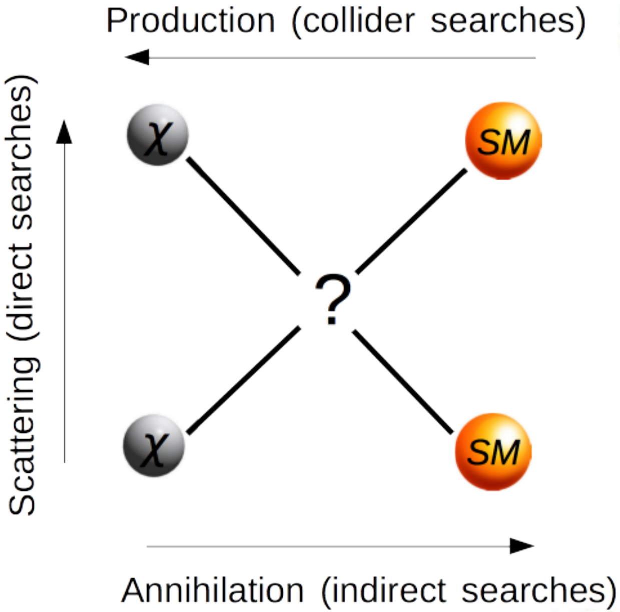
Once there was only the WIMP miracle...

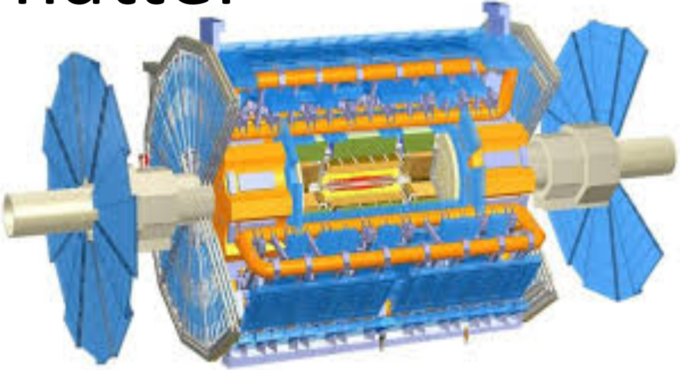
Now WIMP only one out of a range of theoretical motivated dark matter candidates with wide range of mass and cross section



The hunt for dark matter



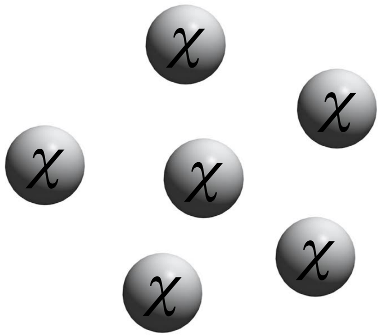




Direct dark matter detection

Basic idea

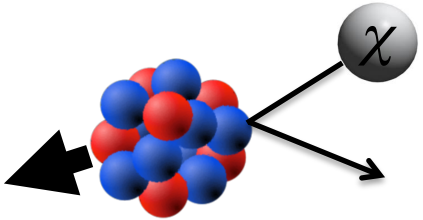
Dark matter is made of particles
which interact with Standard Model particles



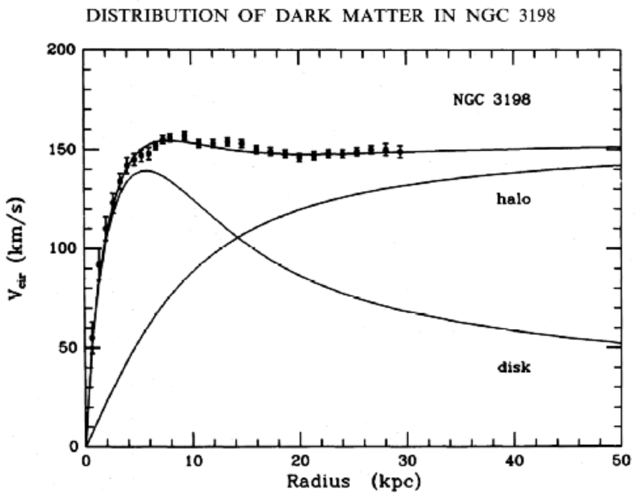
Most common scenario

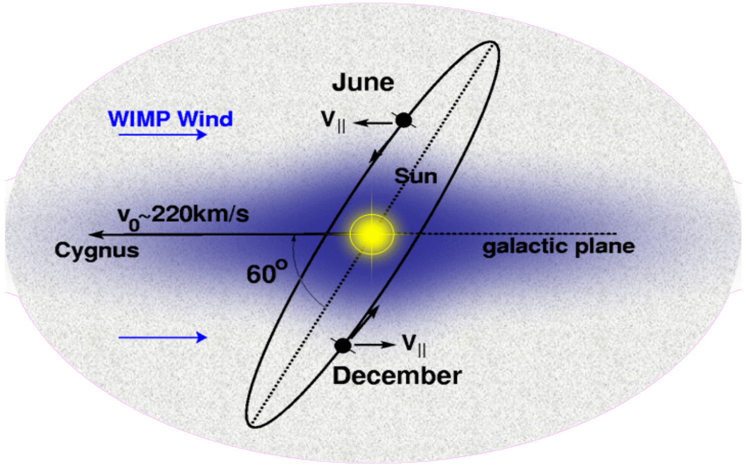
Dark matter particles scatter off nuclei:

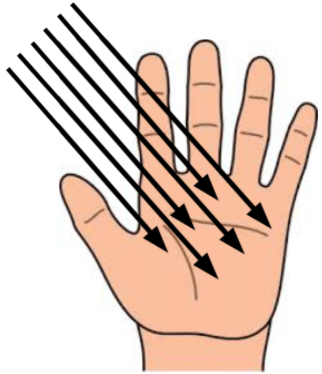
- elastically
- coherently: ~ A^2
- (spin-independent)



Dark matter in the Milky Way





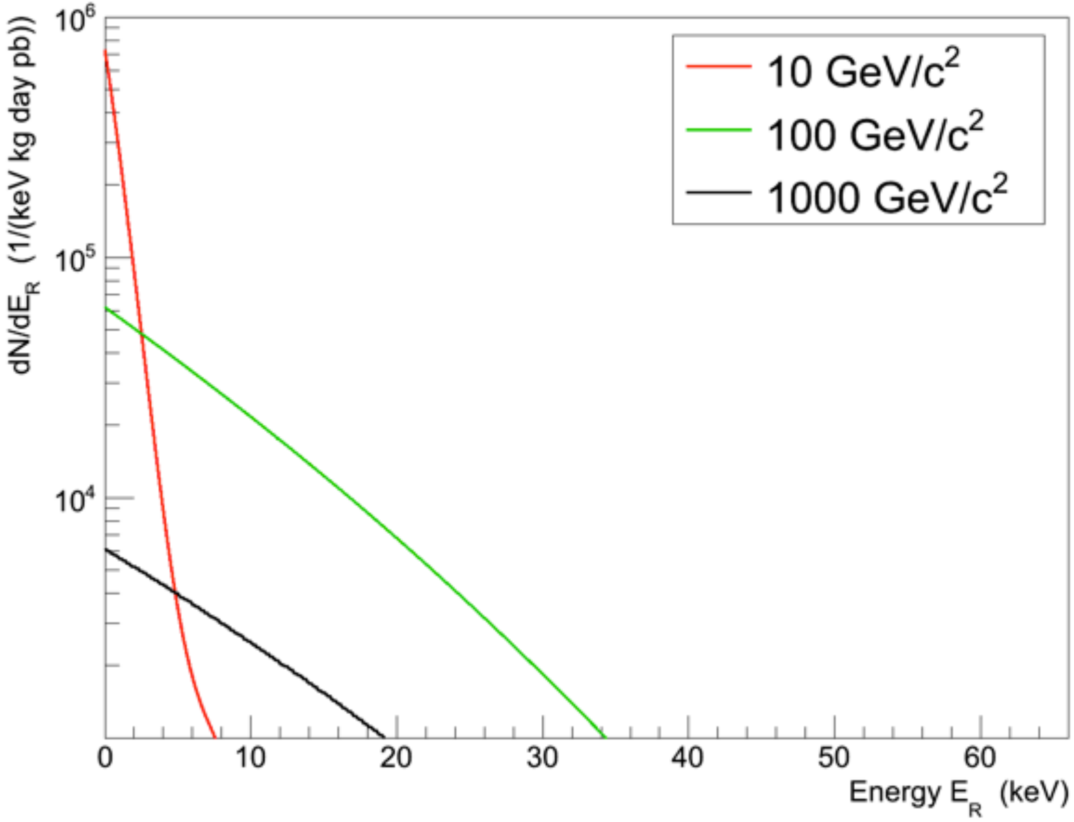


Standard assumptions:

- Maxwellian velocity distribution
- asymptotic velocity of 220 km/s
- galactic escape velocity of 544 km/s
- local dark matter density of 0.3 GeV/cm^3

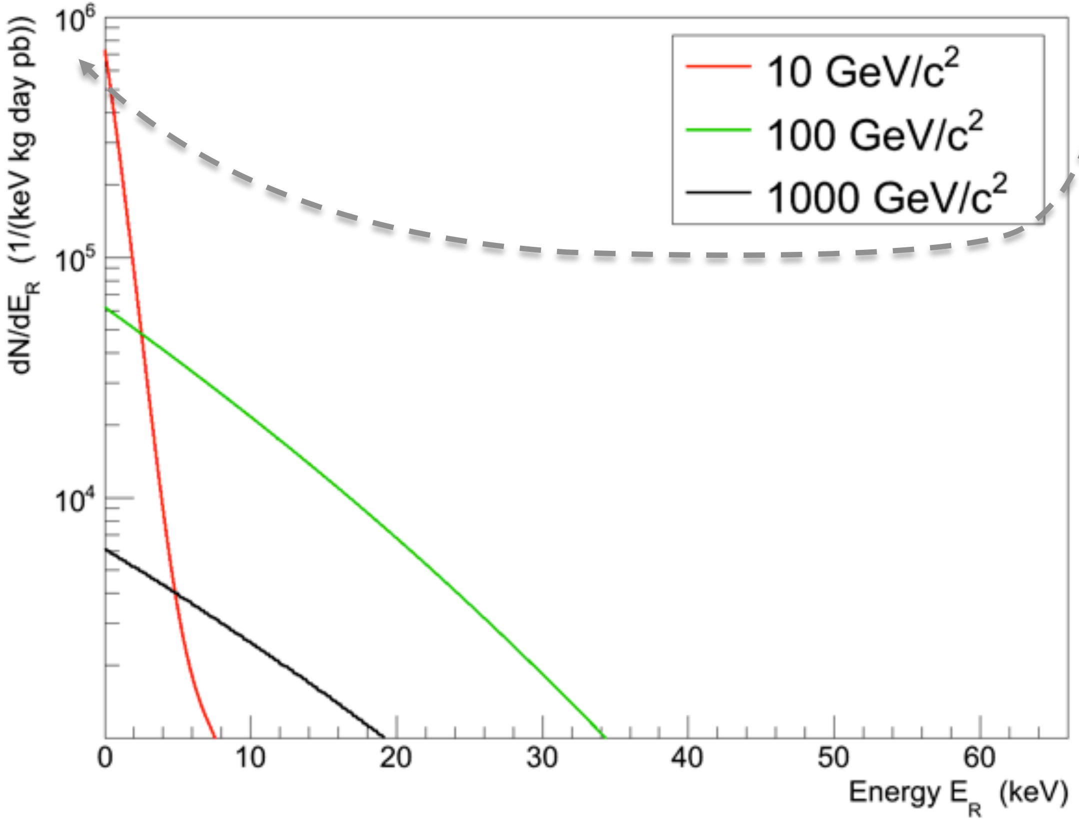
Experimental challenges

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



Experimental challenges

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



Very rare

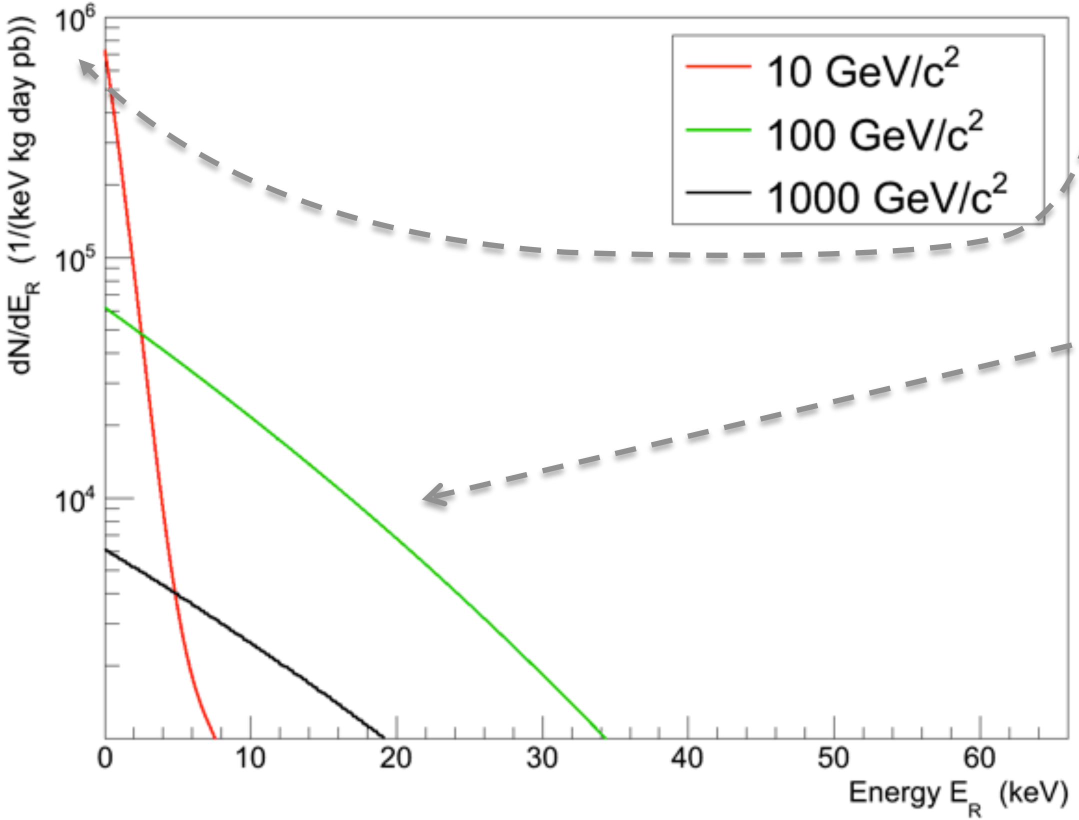
current limit*

$\mathcal{O}(0.01)$ counts/tonne day

* Xenon1T: arXiv:1805.12562

Experimental challenges

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



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Featureless spectrum

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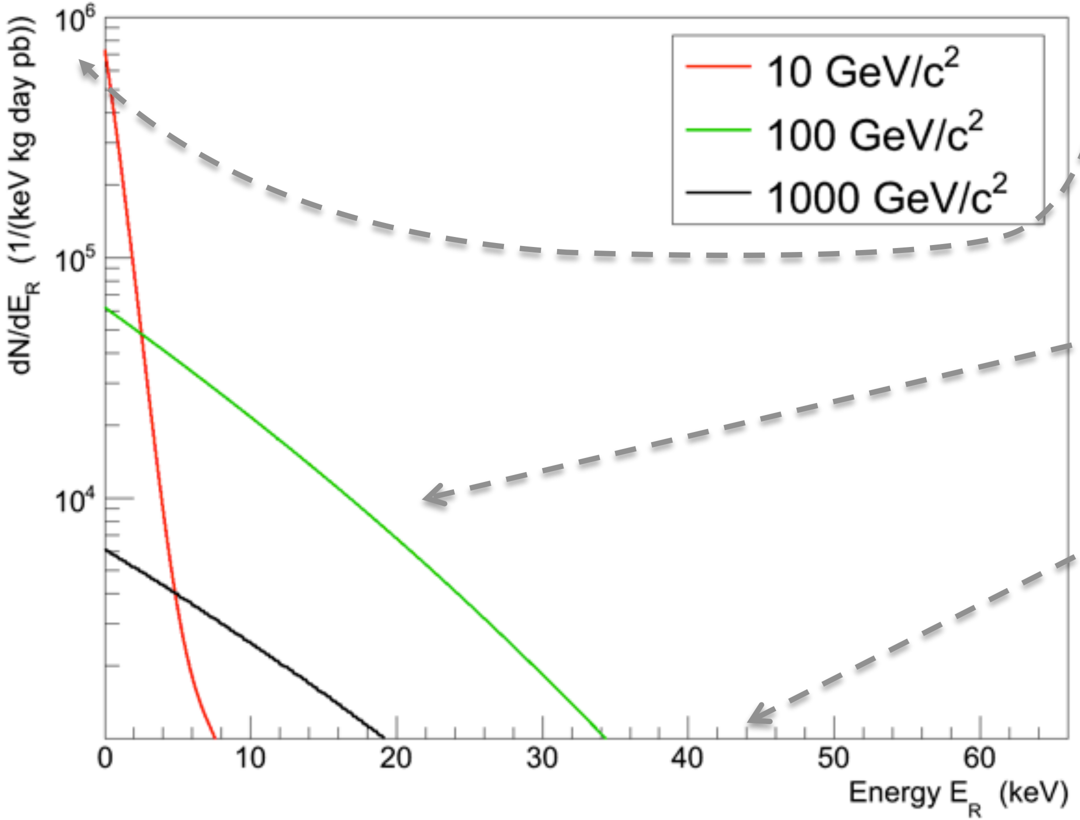
Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



Very rare

current limit*

$\mathcal{O}$(0.01) counts/tonne day

Featureless spectrum

Small recoil energies

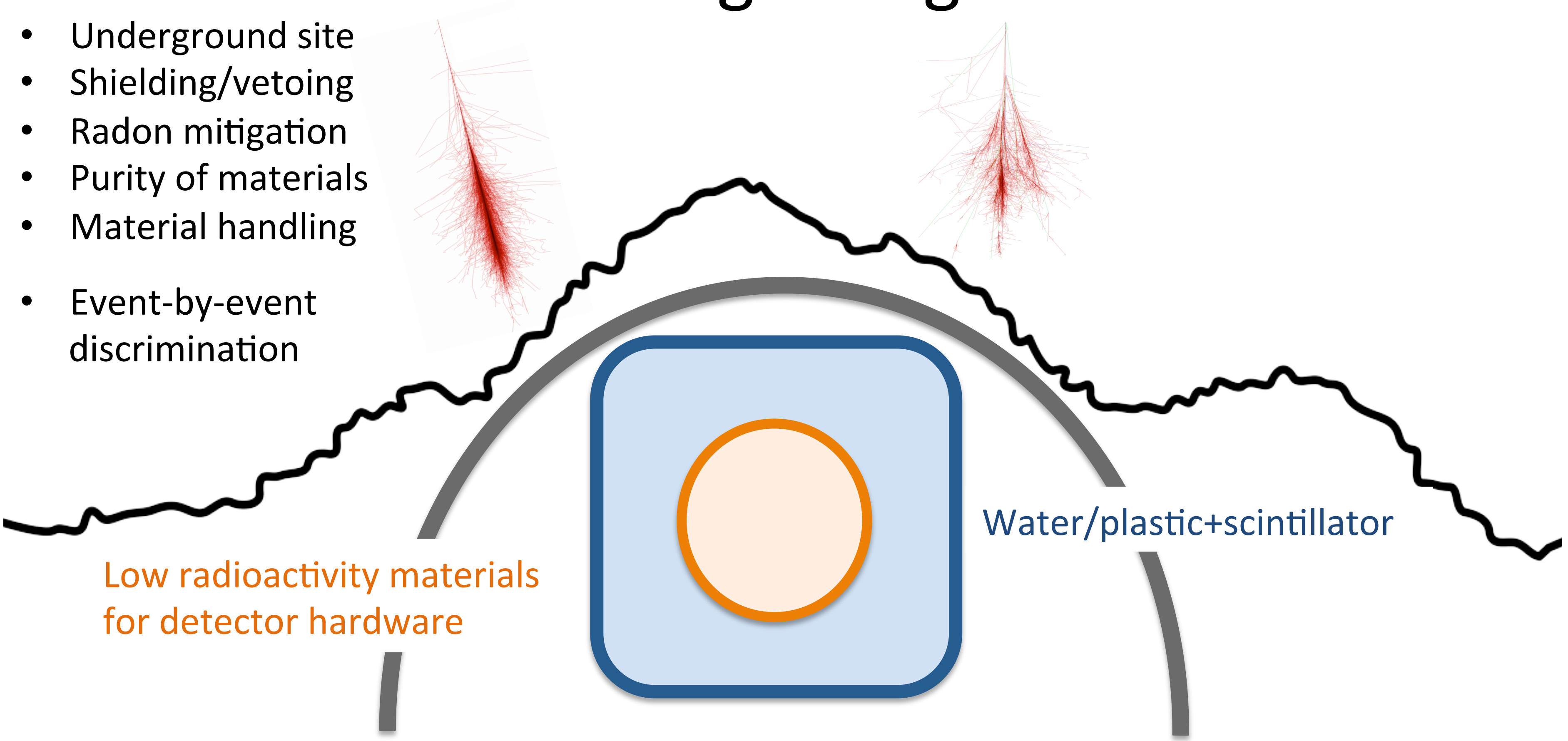
~ keV range

* Xenon1T: arXiv:1805.12562

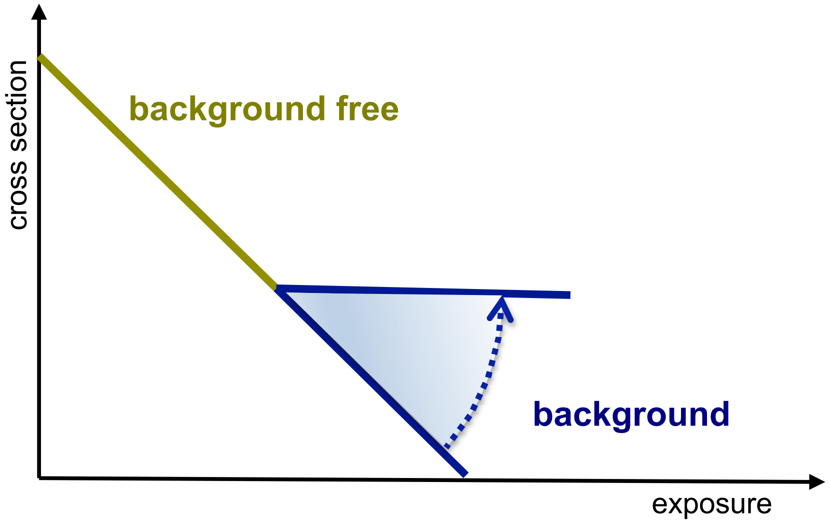
Minimising background

- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling

- Event-by-event discrimination



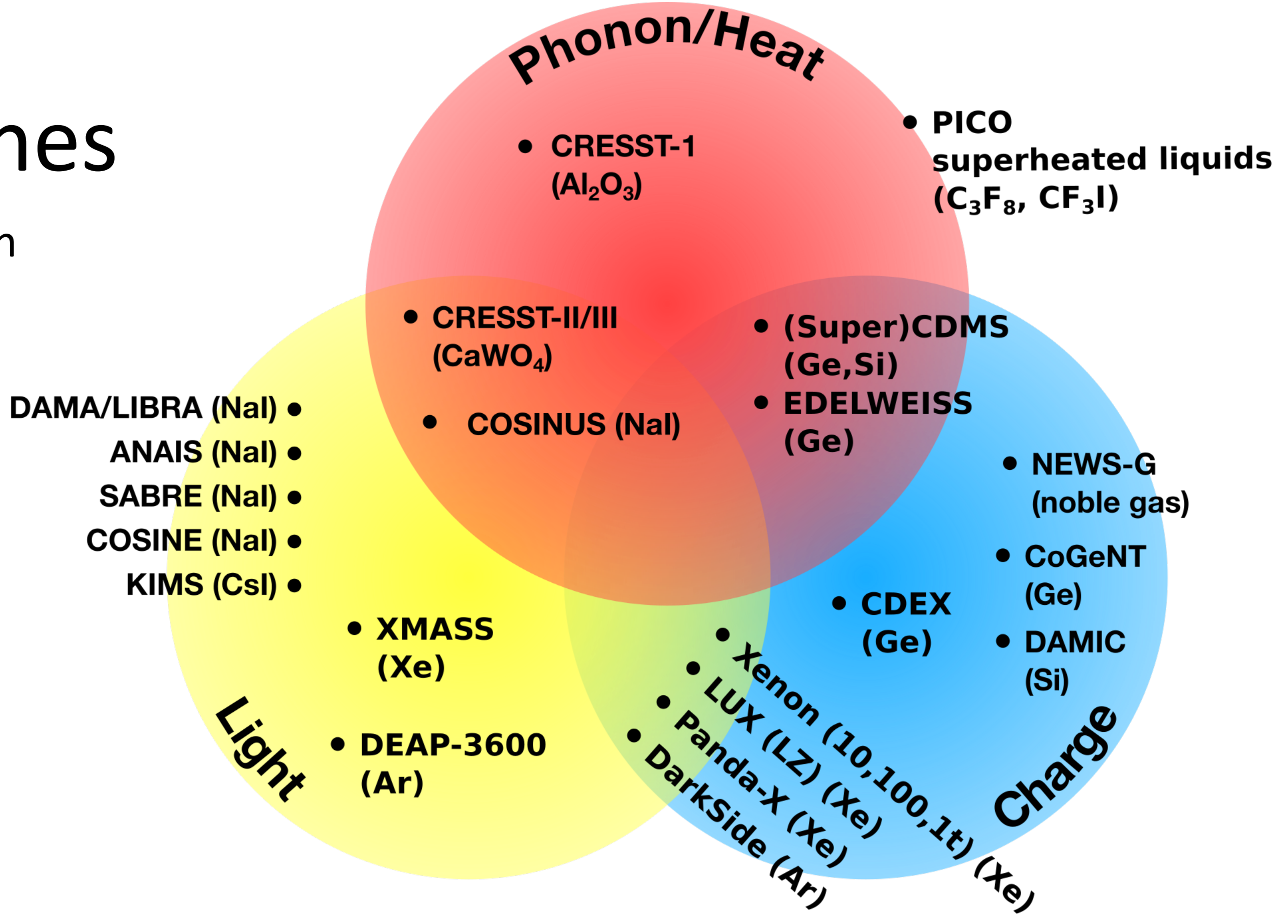
Minimising background



For a discovery:
understand residual background

Direct dark matter searches

An incomplete compilation



The CRESST collaboration

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Institut für Hochenergiephysik

Max-Planck-Institut für Physik
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TECHNISCHE UNIVERSITÄT MÜNCHEN

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LNGS
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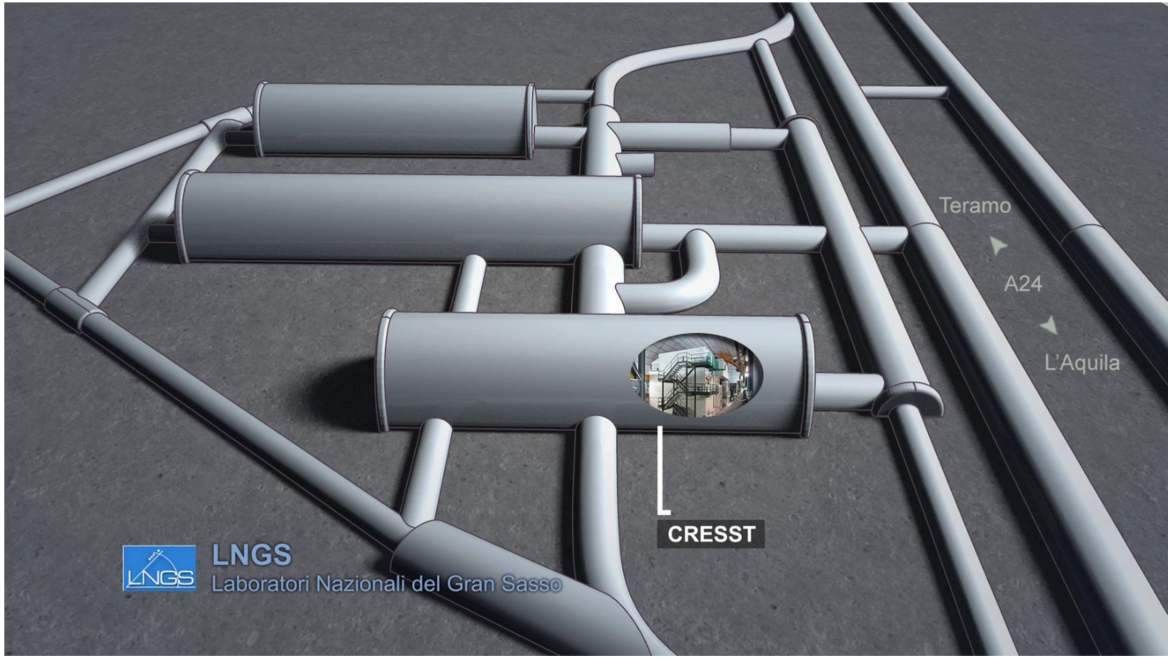
Laboratori Nazionali del Gran Sasso

UNIVERSITY · OF · OXFORD

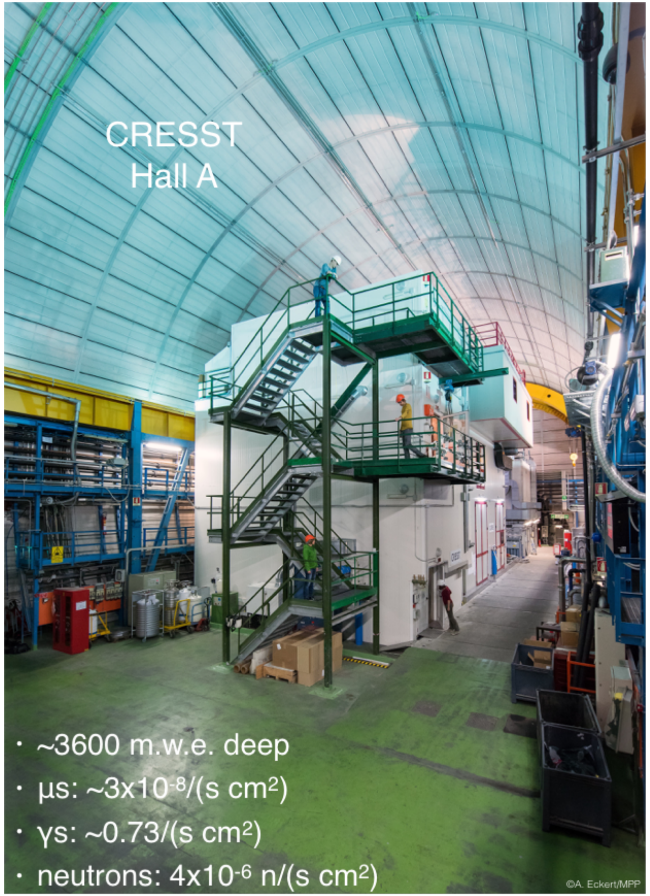
EBERHARD KARLS
UNIVERSITÄT TÜBINGEN

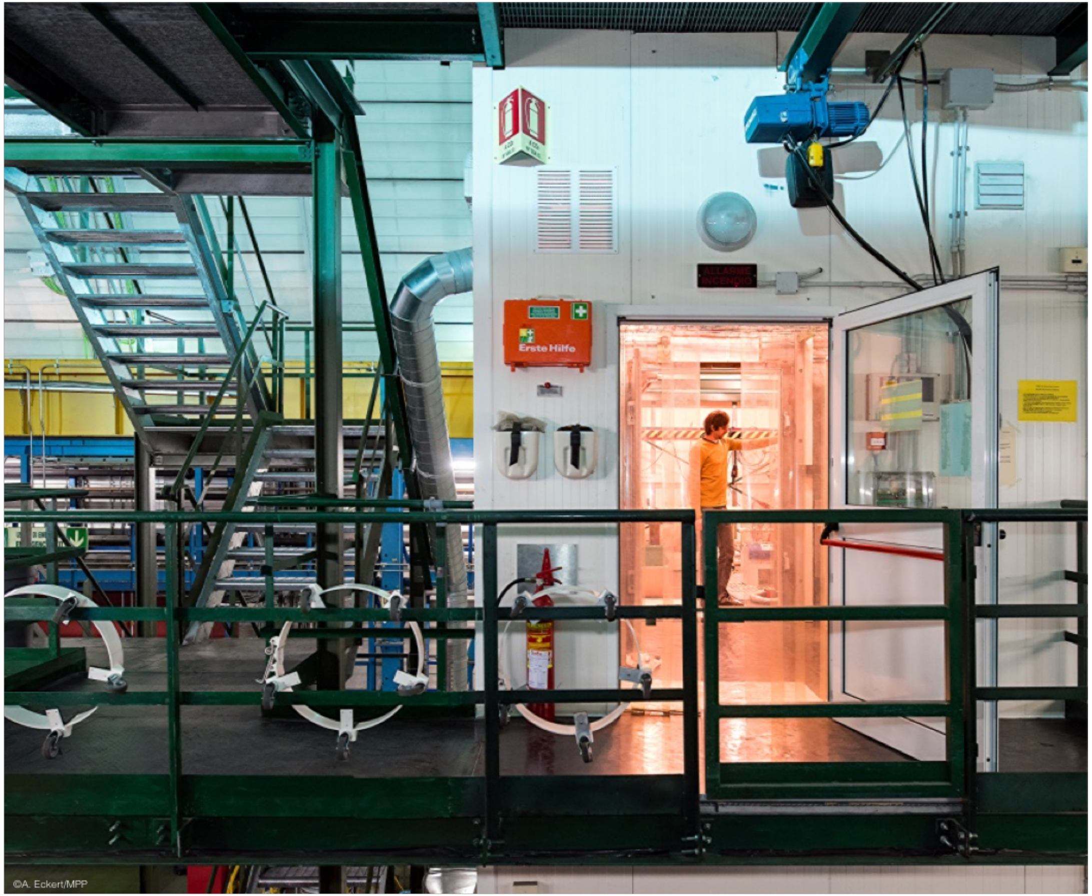
LNGS



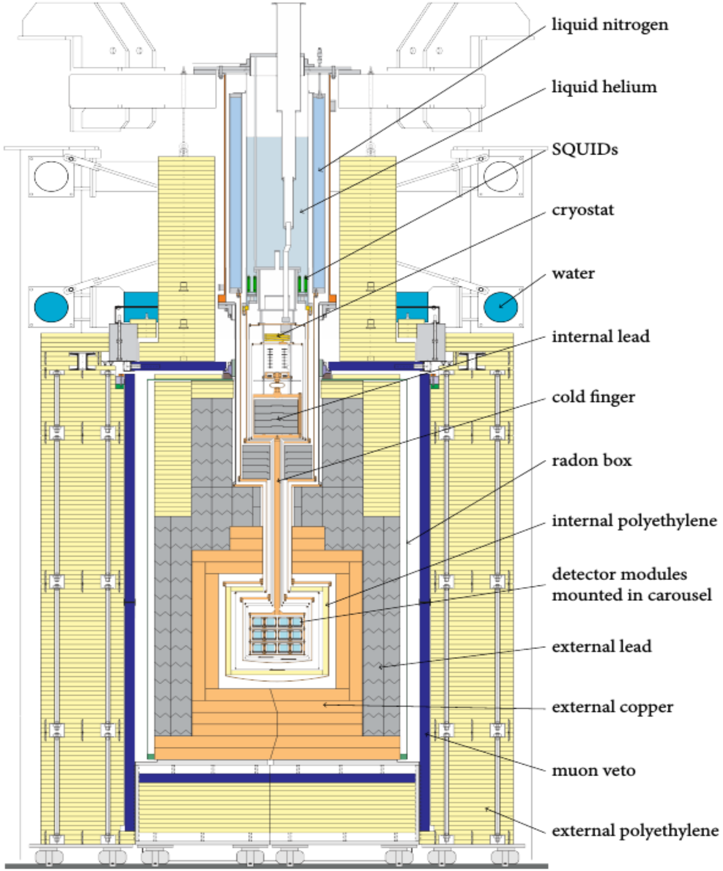
Teramo
A24
L'Aquila
CRESST
LNGS
LNGS
Laboratori Nazionali del Gran Sasso

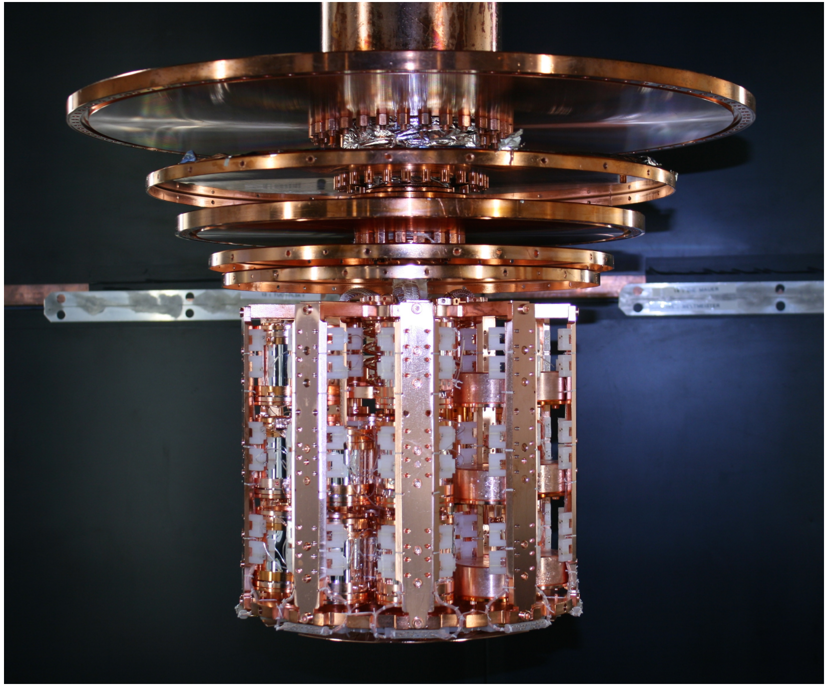
CRESST @ LNGS


CRESST
Hall A
• ~3600 m.w.e. deep
• μs: ~3x10-8/(s cm2)
• γs: ~0.73/(s cm2)
• neutrons: 4x10-6 n/(s cm2)
©A. Eckert/MPP


Erste Hilfe
©A. Eckert/MPP

The experimental setup

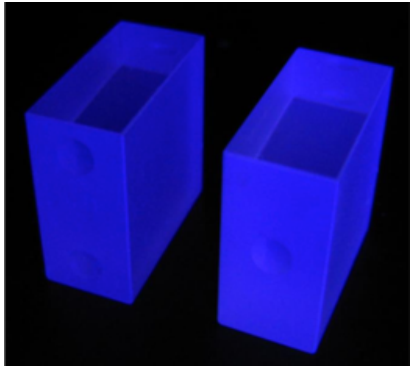




The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

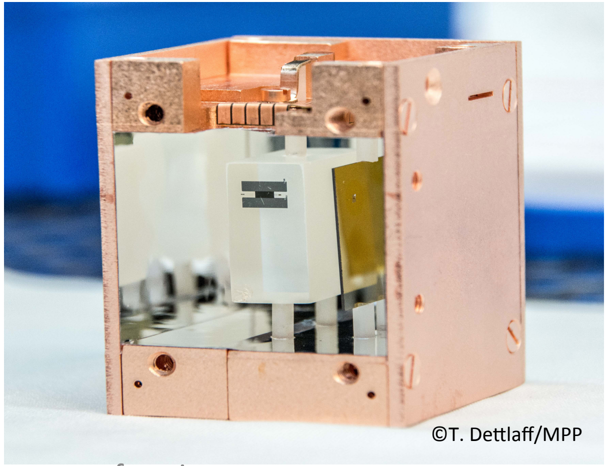
Direct detection of dark matter particles via their scattering off target nuclei



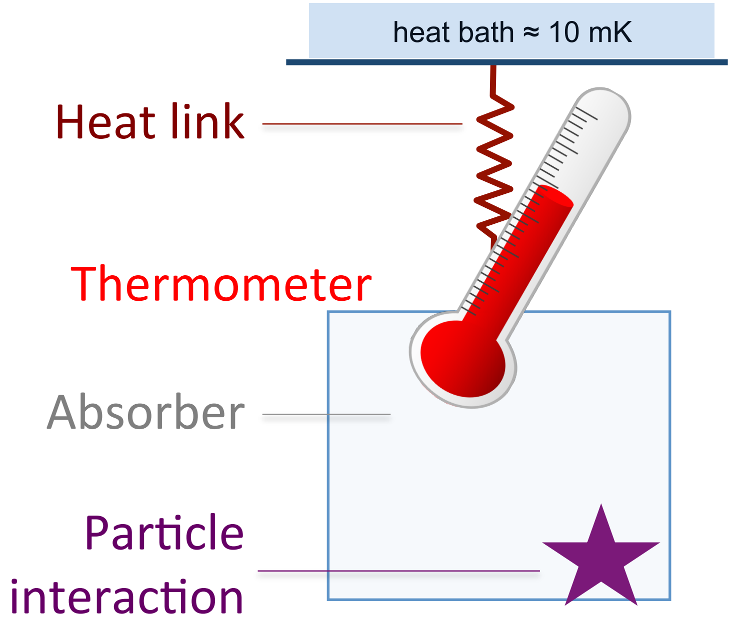
Scintillating $CaWO_4$ crystals as target

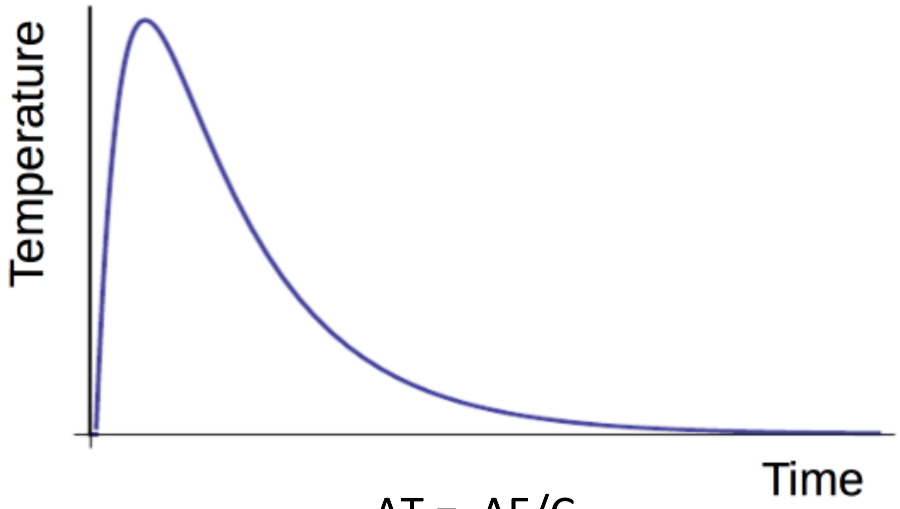
Target crystals operated as **cryogenic calorimeters** (~15mK)

Separate **cryogenic light detector** to detect the scintillation light signal



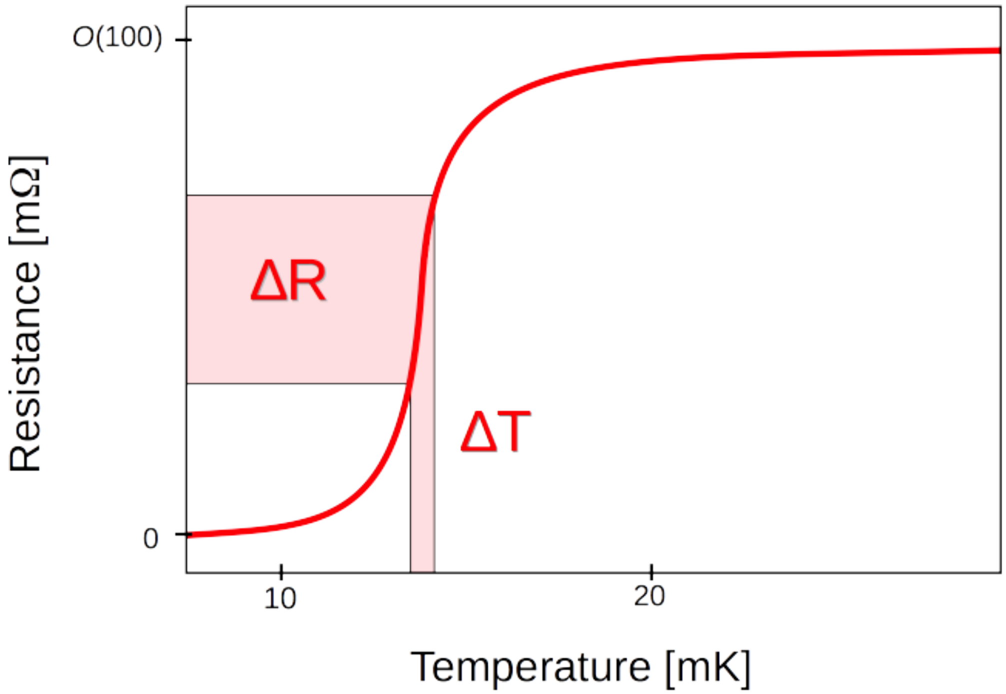
Cryogenic calorimeter





$\Delta T = \Delta E/C$

Transition edge sensor

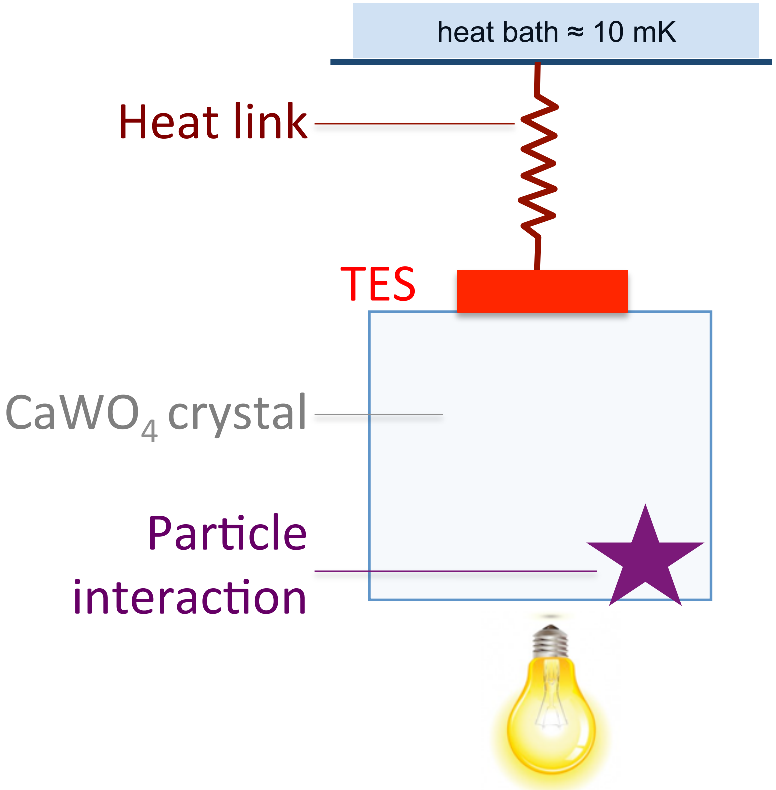


Energy deposition in absorber
~keV

Temperature rise in TES
~μK

Resistance change
~mΩ

Cryogenic detector

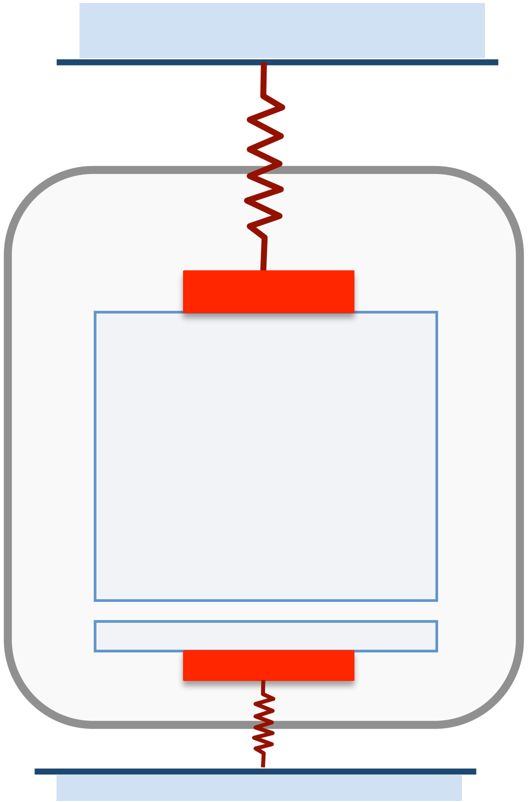


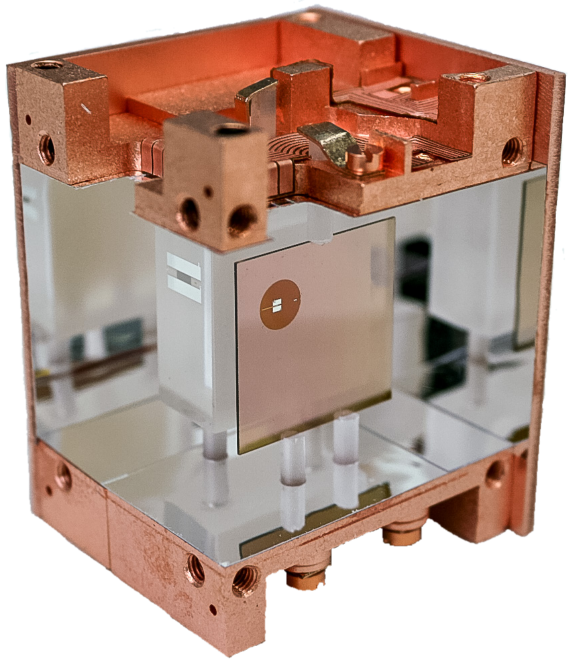
Phonon signal (≳90 %)
(almost) independent of particle type

precise measurement of the deposited energy

Scintillation light (few %)
particle-type dependent
→ LIGHT QUENCHING

Detector module



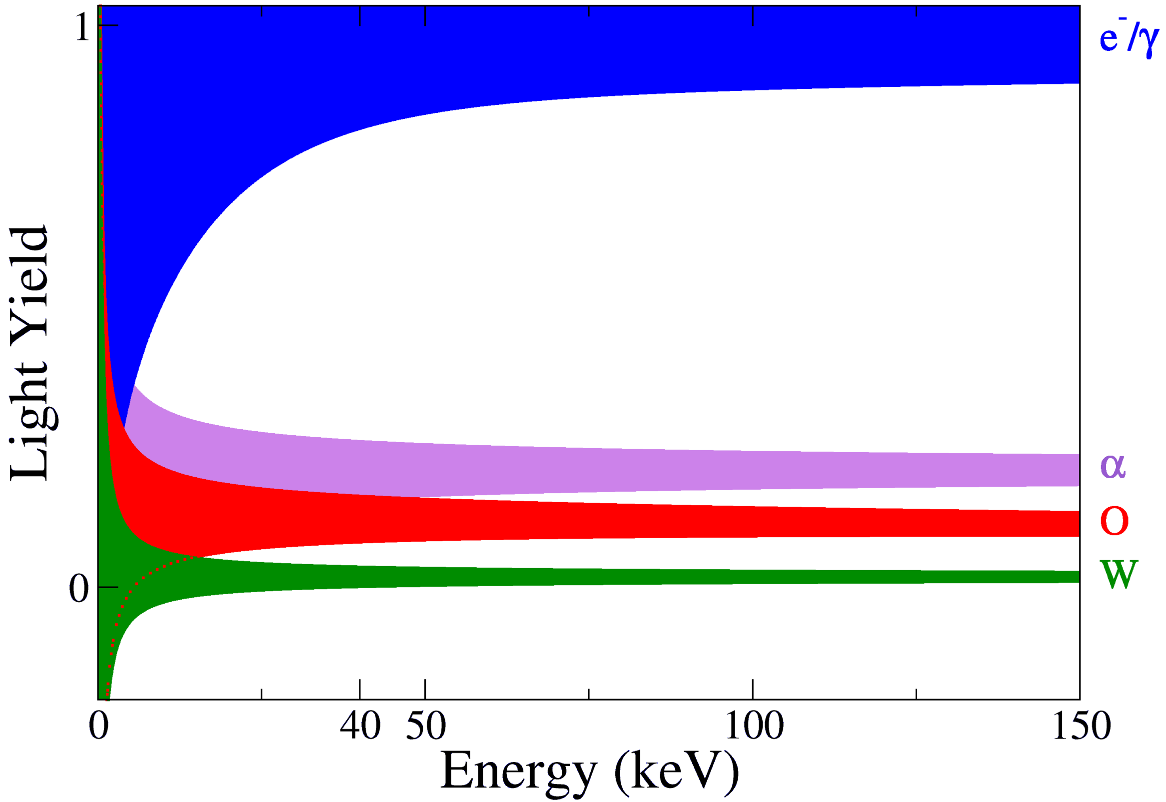


Simultaneous signals
from the transition edge sensors (TESs)

Event discrimination

Light Yield= $\frac{\text{Light signal}}{\text{Phonon signal}}$

Characteristic of the event type



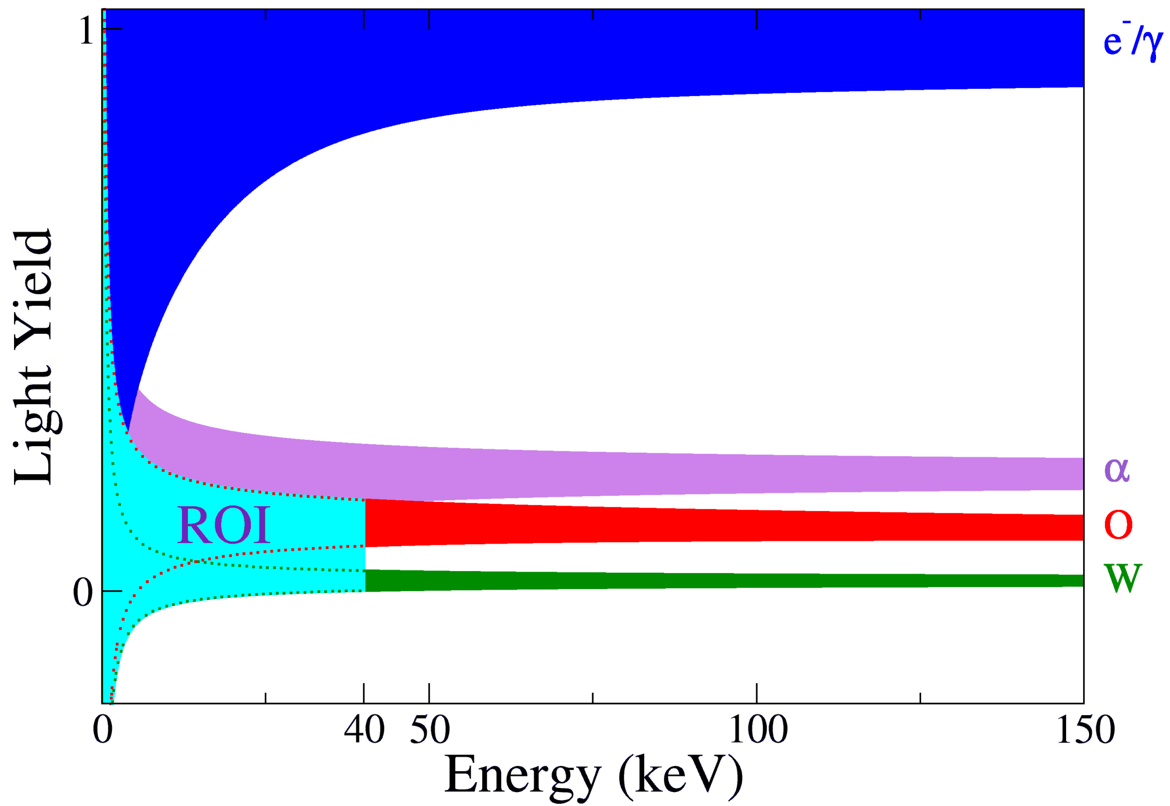
Excellent discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)

Event discrimination

Light Yield= $\dfrac{\text{Light signal}}{\text{Phonon signal}}$

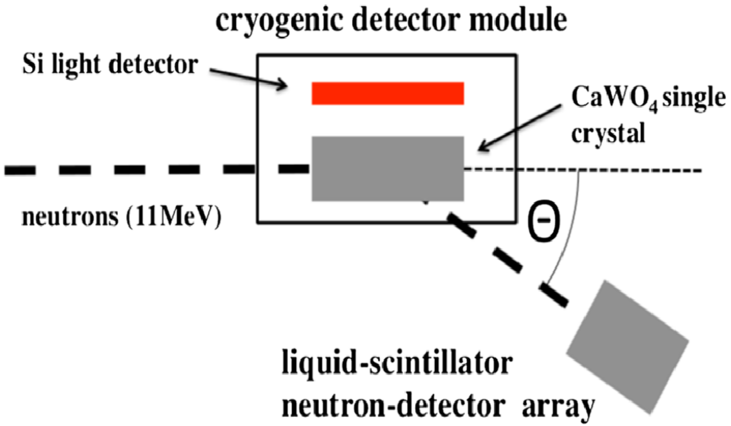
Characteristic of the event type

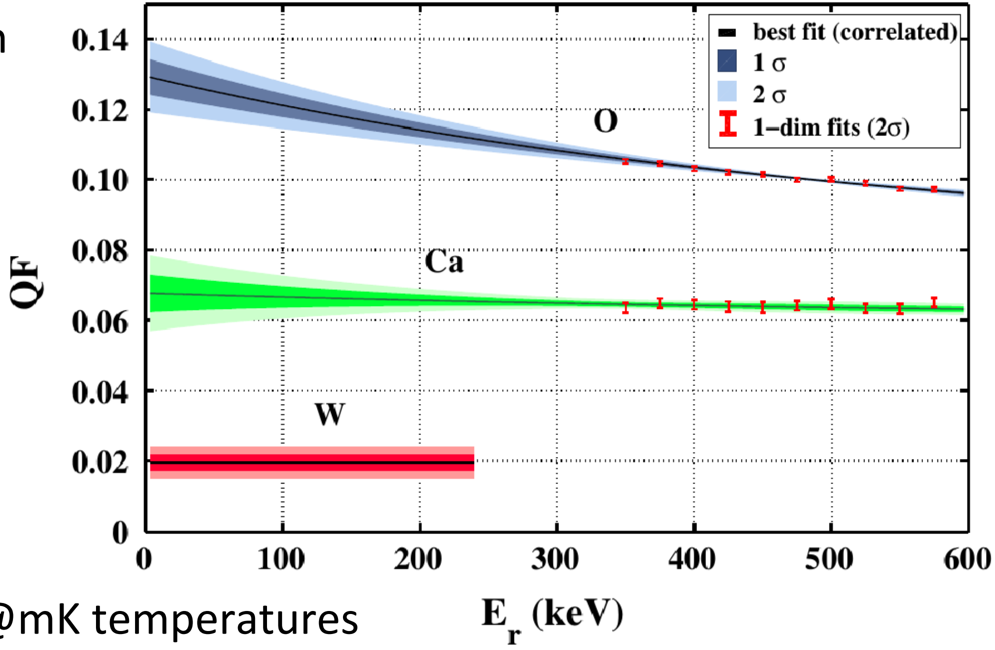
ROI : region of interest
for dark matter search



Quenching factor measurement

@ accelerator of Maier-Leibnitz-Laboratorium





Precise determination of QFs for O, Ca & W @mK temperatures

Values (in ROI)

- O: (11.2 ± 0.5)%
- Ca: (5.94 ± 0.49)%
- W: (1.72 ± 0.21)%

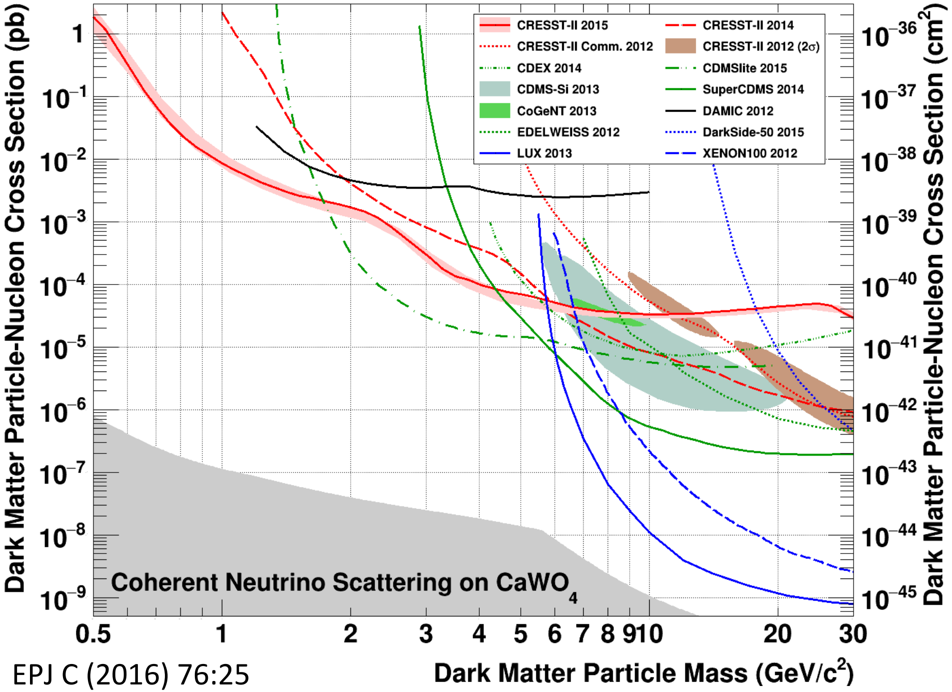
EPJ C (2014) 74:2957

CRESST-II results

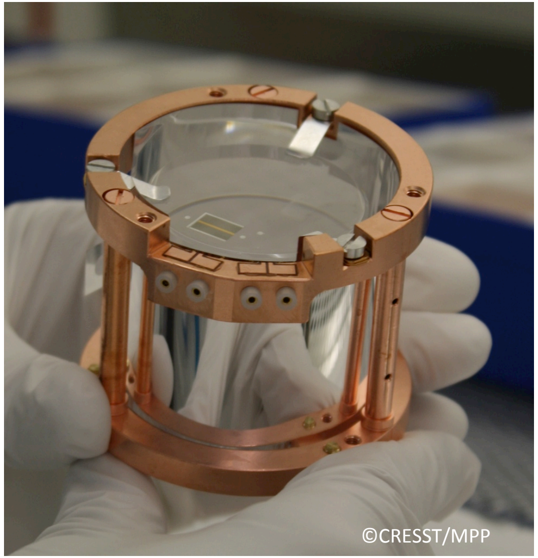
Crystal: Lise - background level ≈8.5 counts/(keV kg day)

Threshold: 307eV

Resolution: σ=62eV at zero energy



EPJ C (2016) 76:25

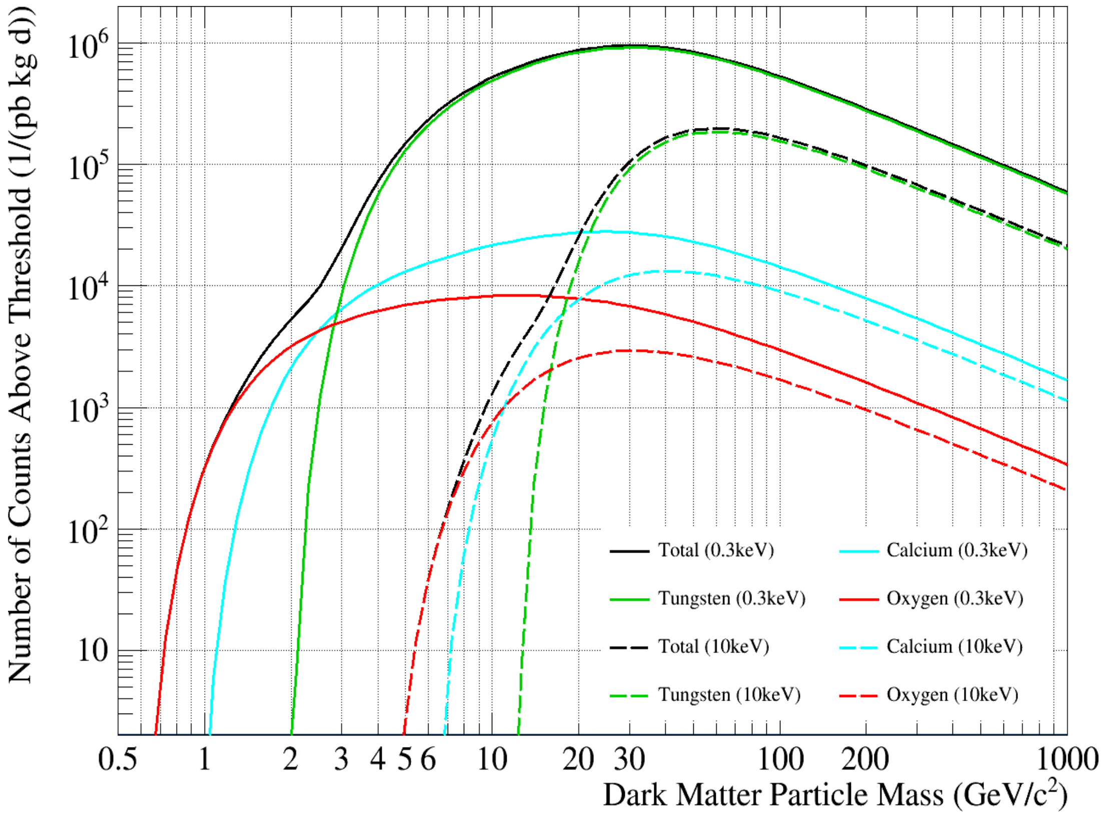


World-leading below 1.7GeV/c^2

Exploring new parameter space down to 0.5GeV/c^2

Hunting light dark matter requires a low threshold!

Low threshold detectors



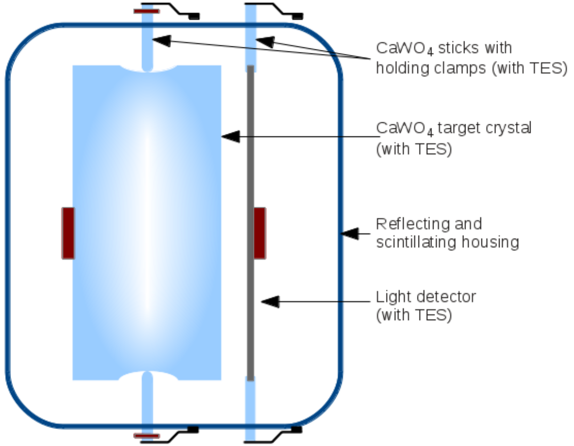
CRESST-III low-threshold detectors

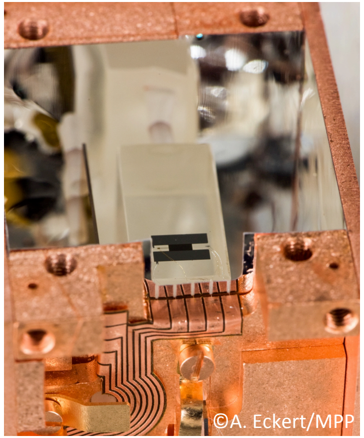
Detector layout optimized for low-mass dark matter

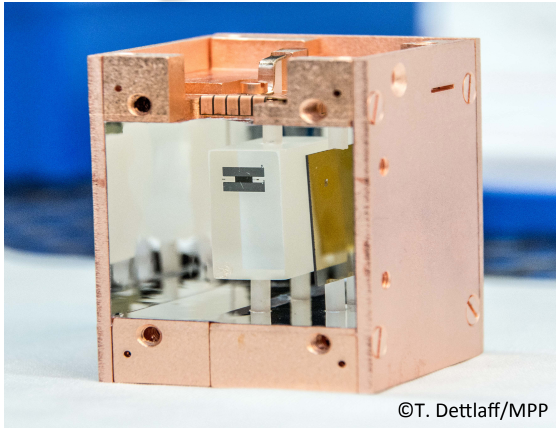
Radical reduction of dimension

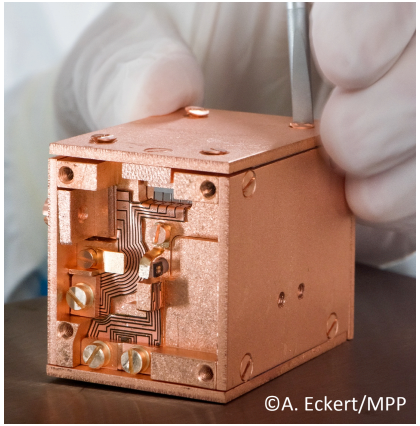
- Cuboid crystals of $(20\times20\times10)\mathrm{mm}^3$ (**≈24g**)
- Self grown crystals **≈3 counts/(keV kg day)**
- Threshold design goal **100 eV threshold**
- Fully scintillating housing
- Instrumented sticks

$\Big\}$ Veto surface related background

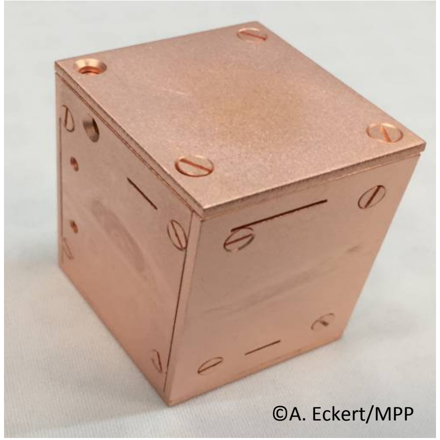


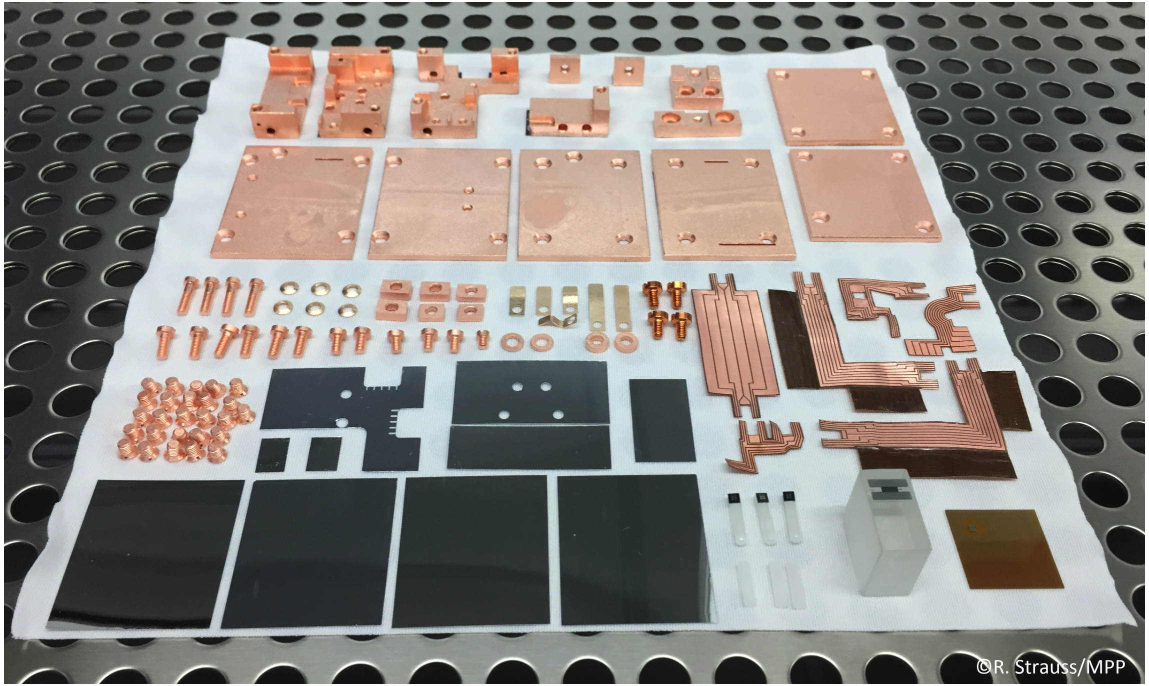


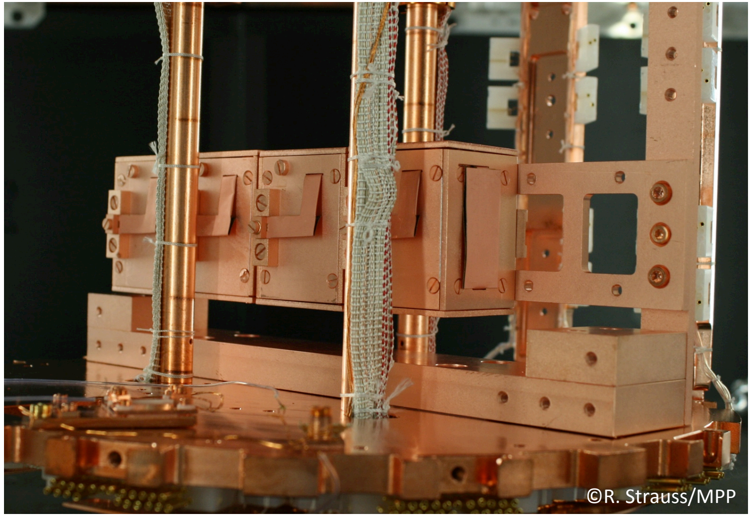




CRESST-III Phase 1





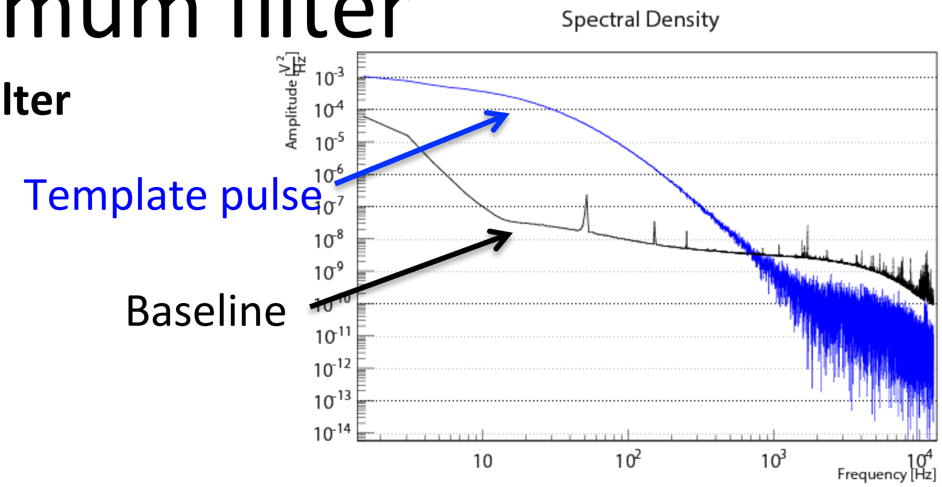


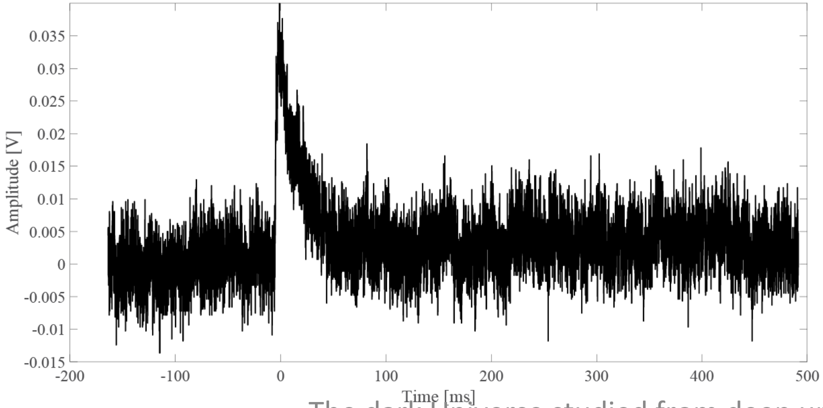
Data taking from July 2016 to February 2018

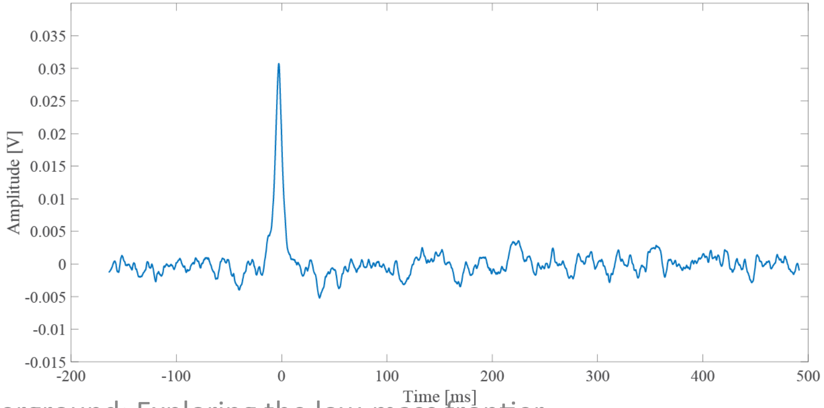
Optimum filter

Pulse-height evaluation with optimum filter

The **Gatti-Manfredi filter** is an optimum filter which maximizes the ratio between the amplitude of the treated pulse and the noise RMS







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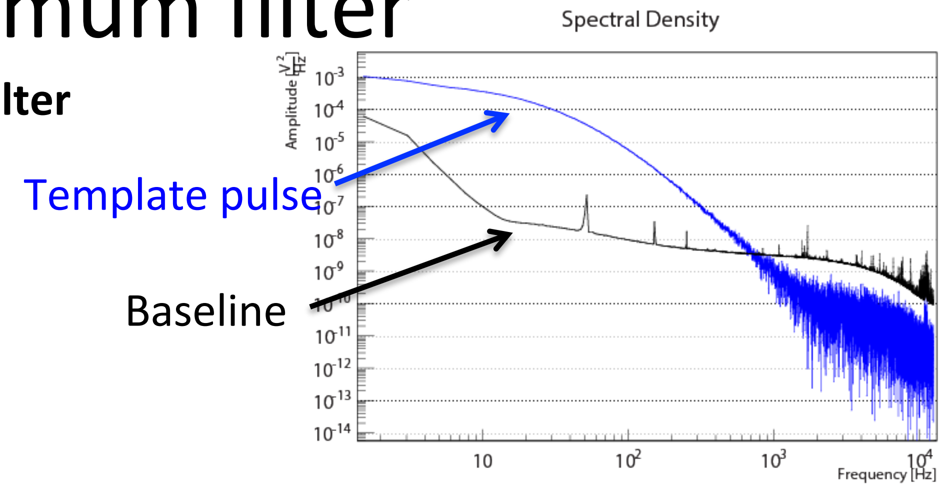
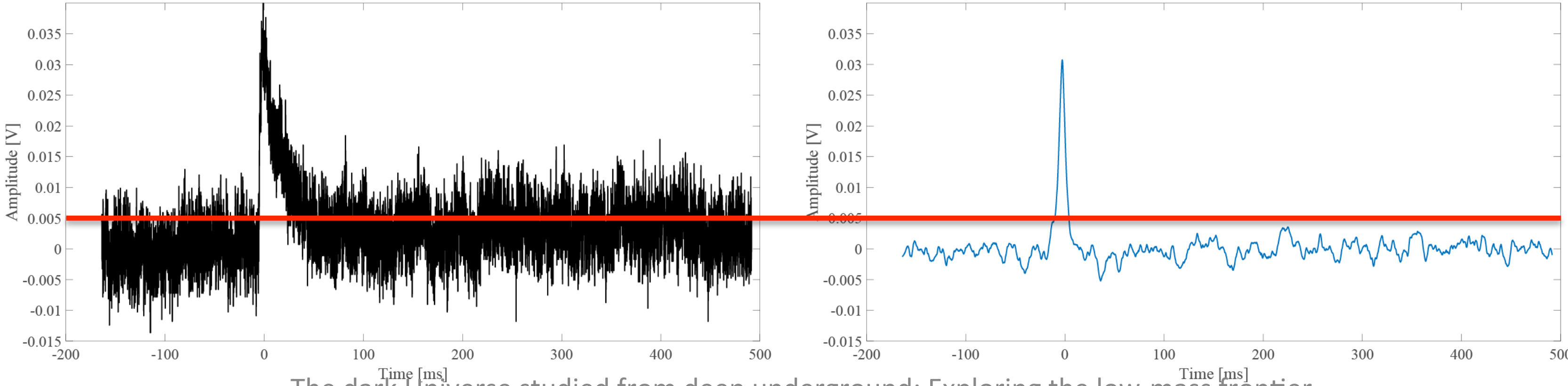
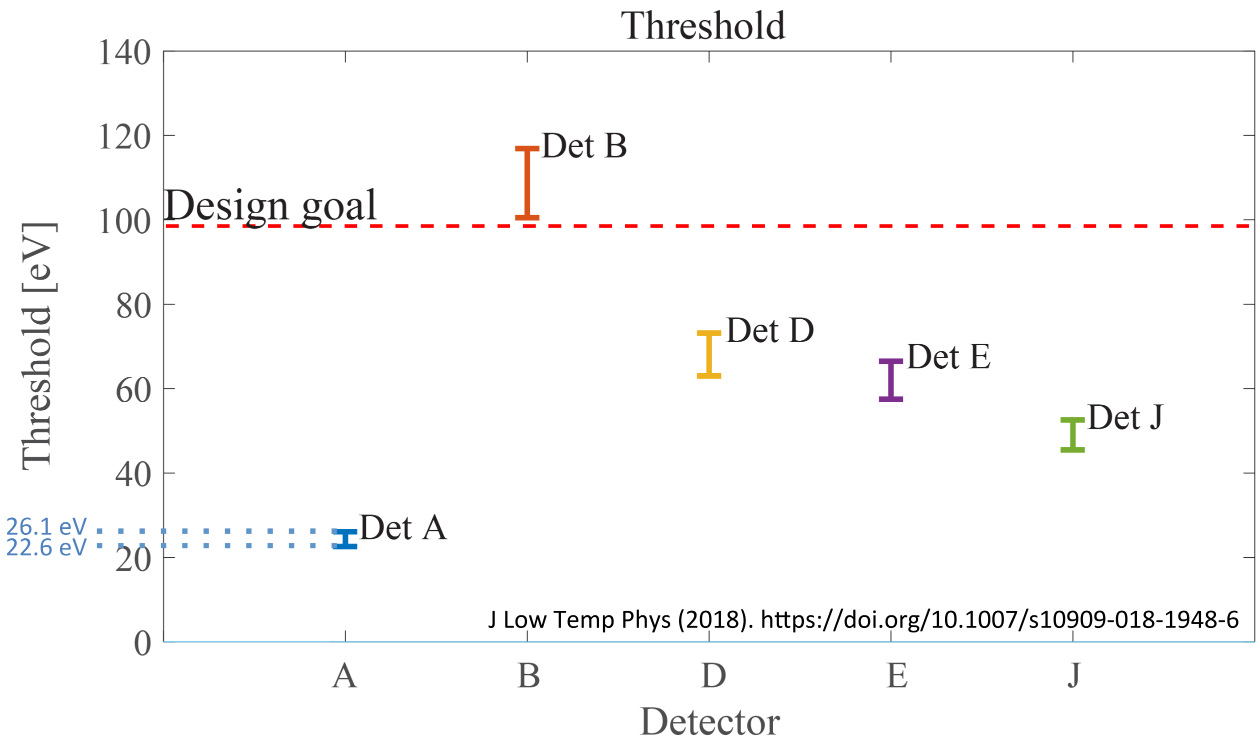


Typical improvement in resolution by using the optimum filter: factor 2-3



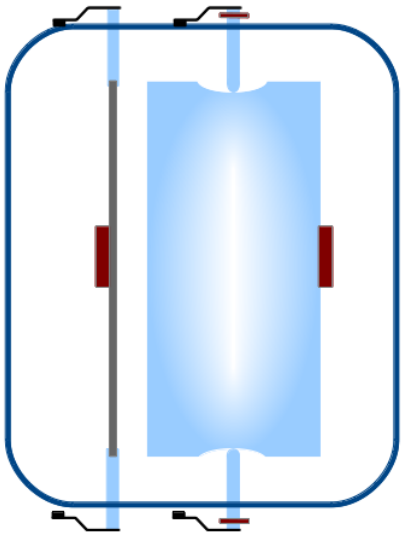
Optimum thresholds

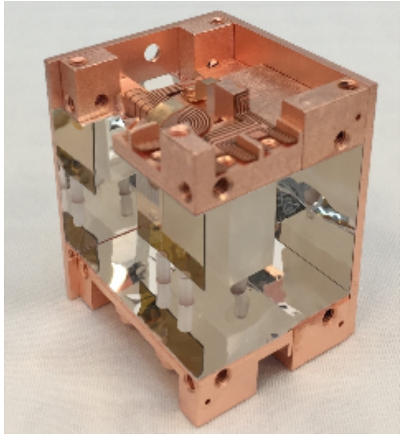
New frontier in direct dark matter detection



5 detectors reach/exceed the CRESST-III design goal

Detector A

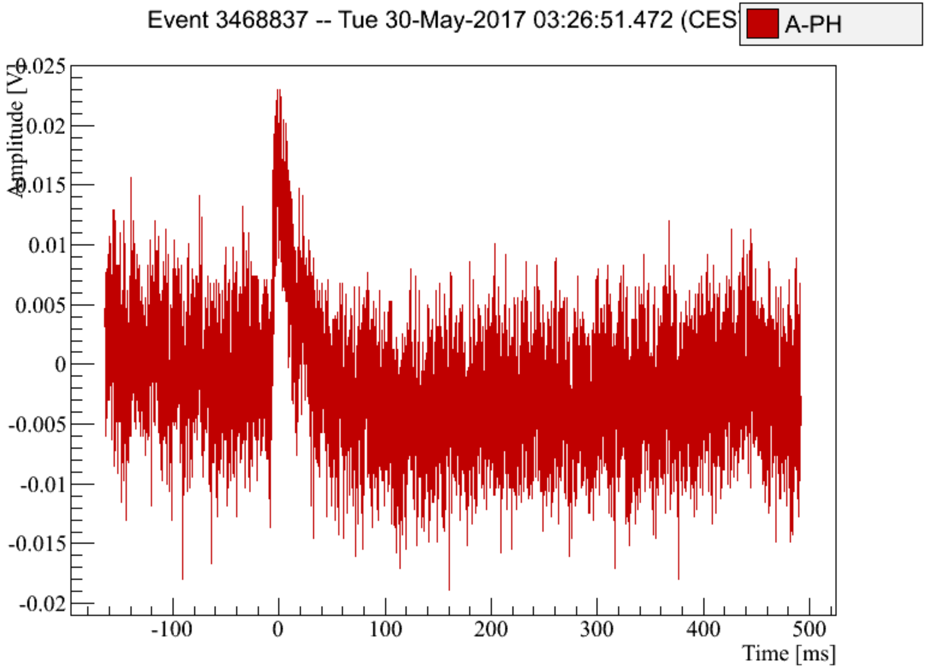


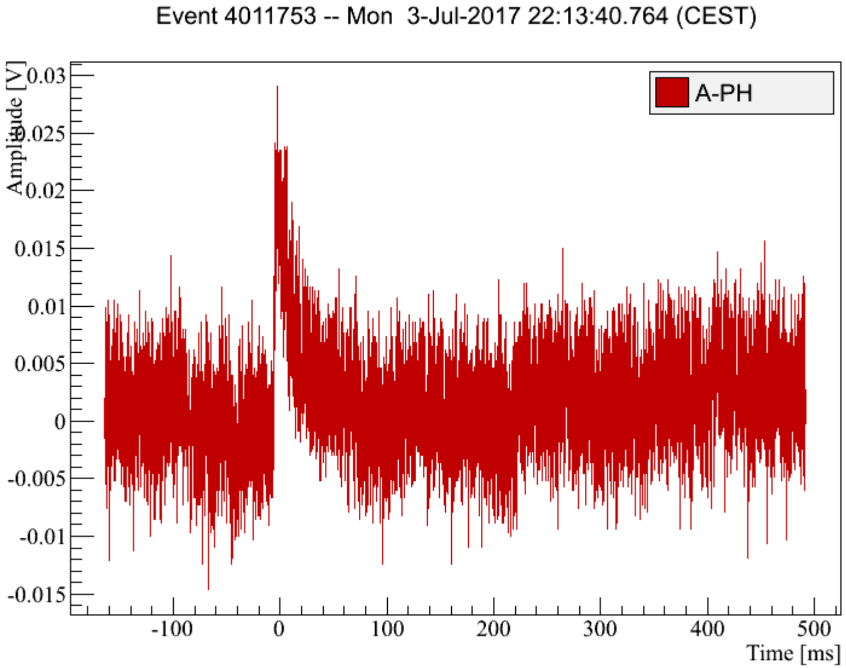


Data taking period for this analysis:	10/2016 – 05/2017
Non-blind data (dynamically growing):	20% randomly selected
Target crystal mass:	24g
Gross exposure (before cuts):	2.39 kg days
Analysis threshold:	100 eV

Det A - 100 eV pulses

Raw signals: no filtering, fitting etc.





100eV pulses are no challenge for amplitude determination

Det A – 100eV threshold analysis

Selection criteria

Objective

Keep only events where a correct determination of the amplitude (→energy) is guaranteed

Unbiased (blind) analysis

1. Design cuts on <u>non-blind</u> training set (≦20%, excluded from DM data set)
2. Apply without change to <u>blind</u> DM data set

Rate: noise conditions

Stability: Detector(s) in operating point

Data quality: Non-standard pulse shapes (e.g. i-Stick events and pileup)

Coincidences: with µ-veto and i-Sticks only (to be expanded to "with other detector modules")

Det A – 100eV threshold analysis

Efficiency of selection criteria

Rate, Stability:

92.5% survival = 2.21 kg days net exposure

Det A – 100eV threshold analysis

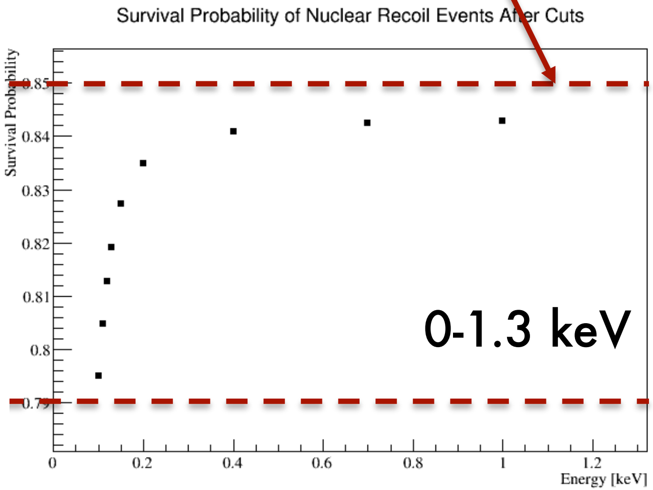
Efficiency of selection criteria

Rate, Stability:

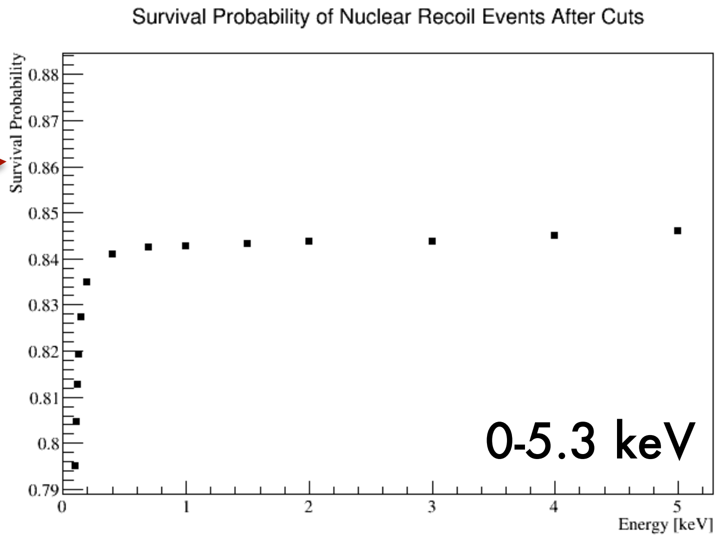
92.5% survival = 2.21 kg days net exposure

Data quality, Coincidences

85%



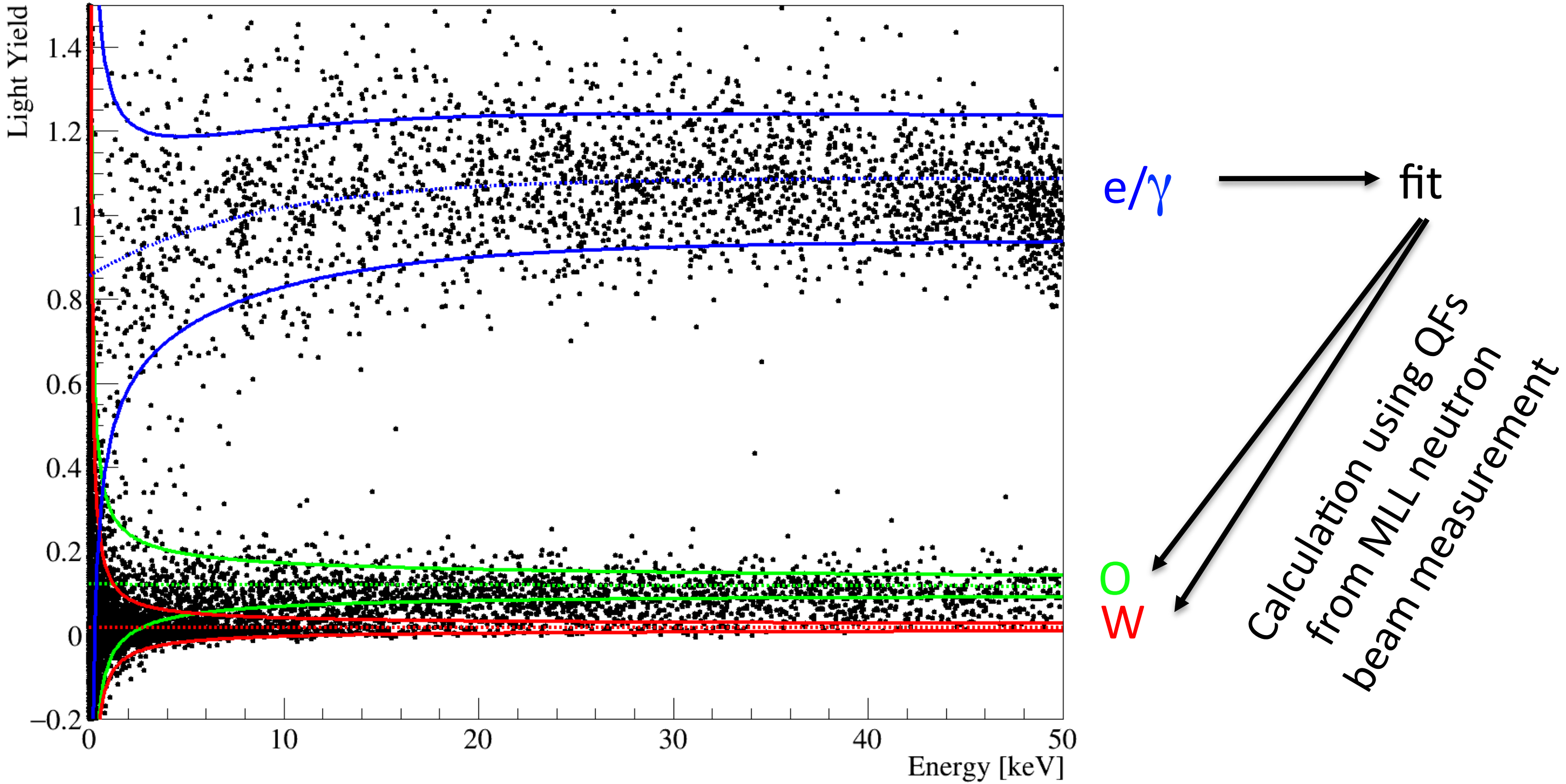
79%



79.5% at threshold of 100eV

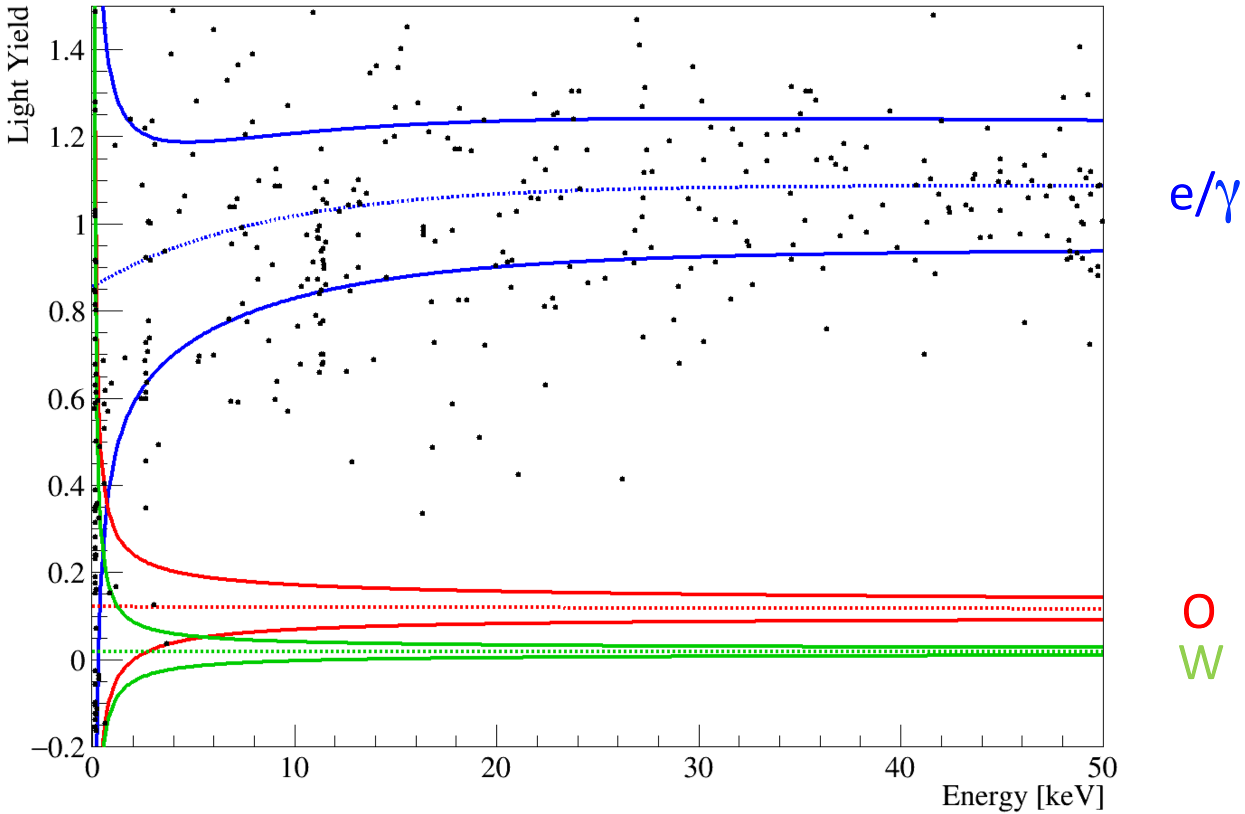
Det A – 100eV threshold analysis

Neutron calibration



Det A – 100eV threshold analysis

Dark matter data

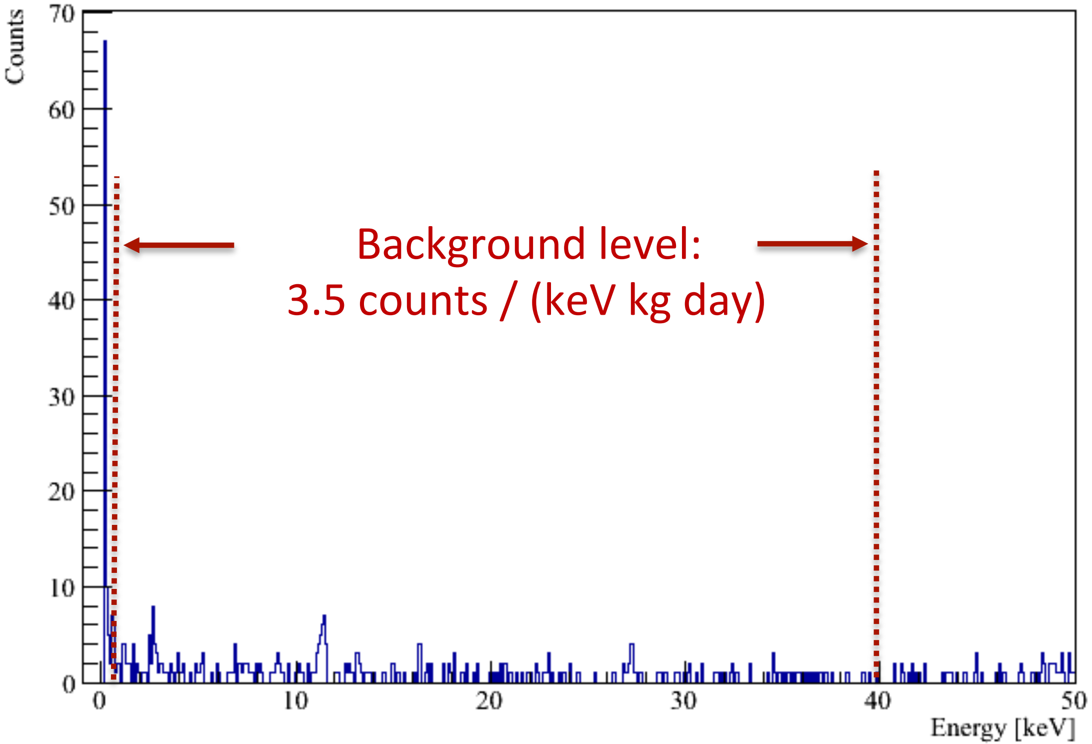


Unblinded:
Det A
E>100eV

Still blinded:
Det ≠ A
E<100eV

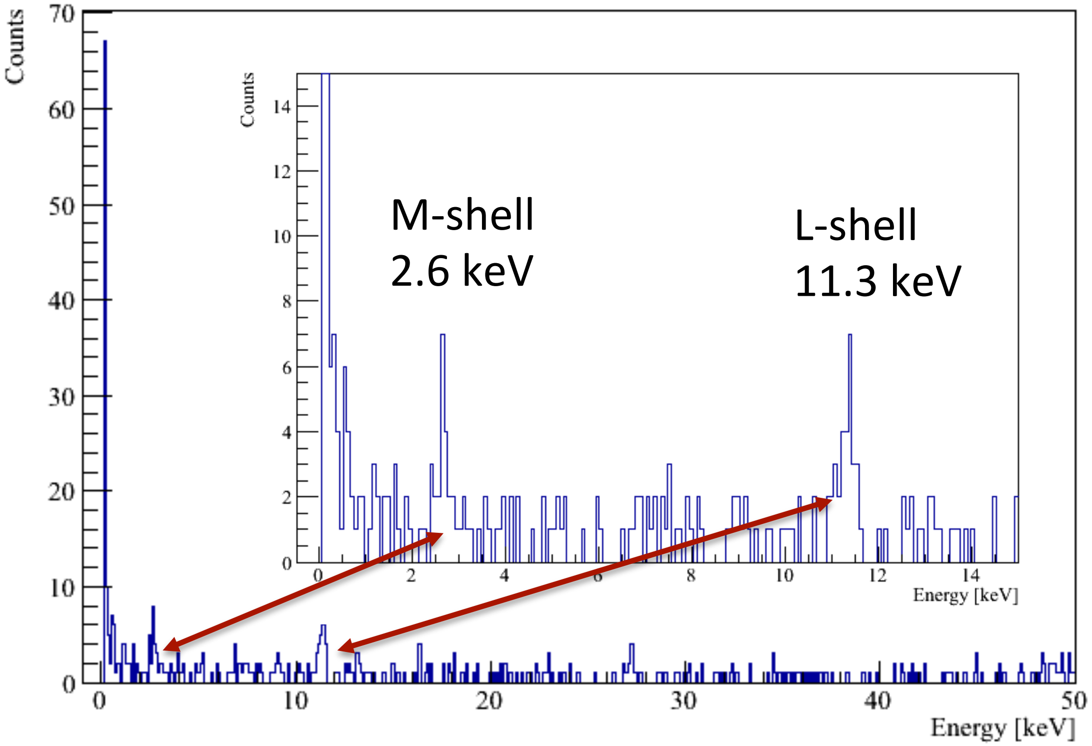
Det A – 100eV threshold analysis

Dark matter data – Energy spectrum



Det A – 100eV threshold analysis

Dark matter data – Energy spectrum

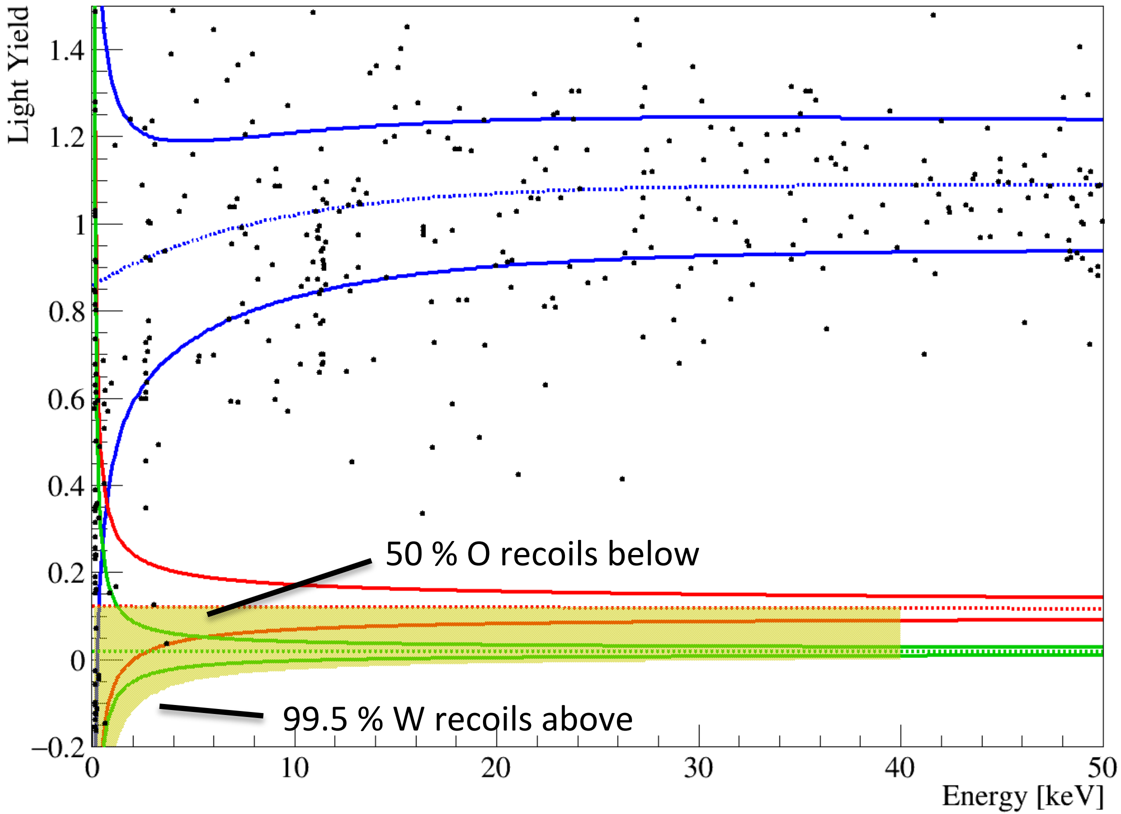


Cosmogenic activation

$^{179}Ta + e^{-} \rightarrow {}^{179}Hf + \nu_e$ (1.8y)

Det A – 100eV threshold analysis

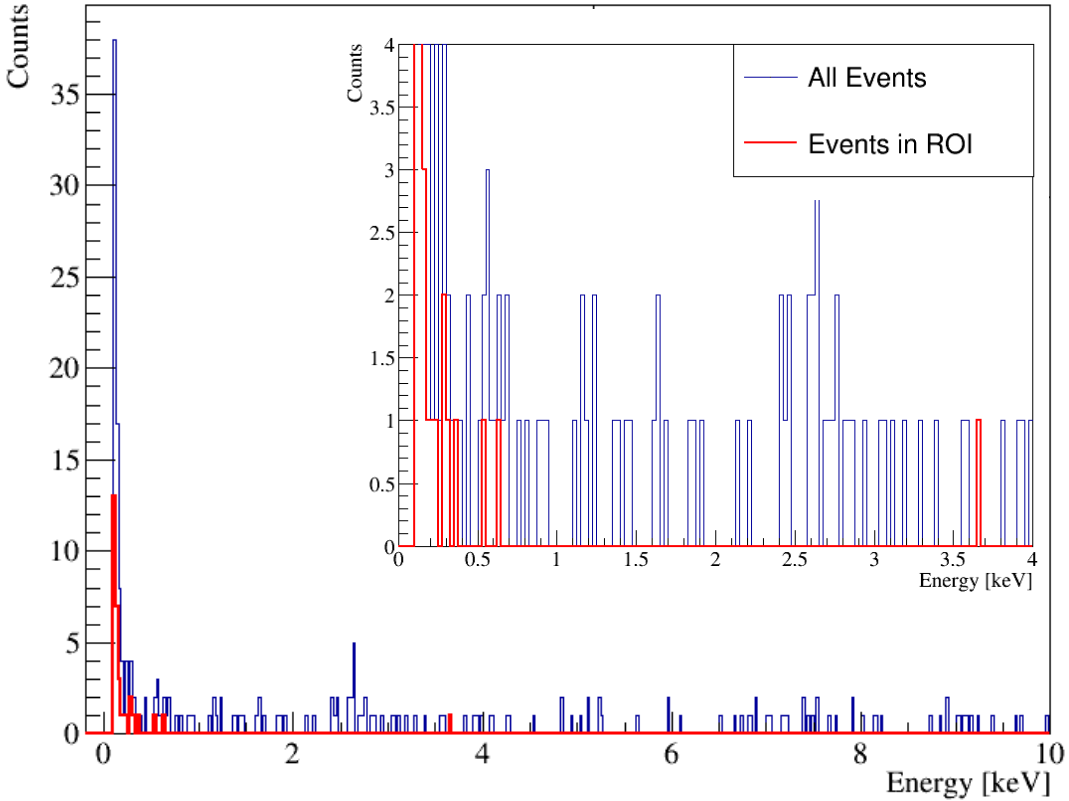
Dark matter data – Acceptance region



Acceptance region fixed before unblinding

Det A – 100eV threshold analysis

Dark matter data – Accepted events



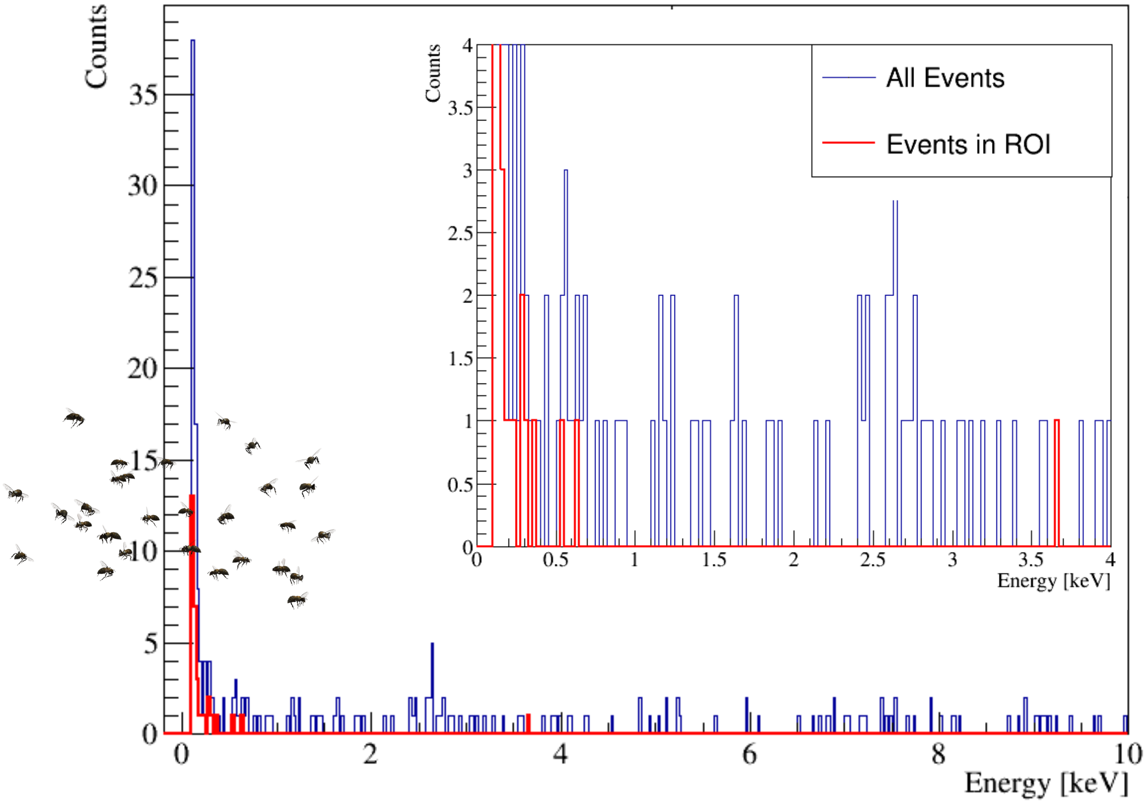
Accepted events (red)

→ Yellin's optimal interval method

→ limit on dark matter-nucleon cross-section

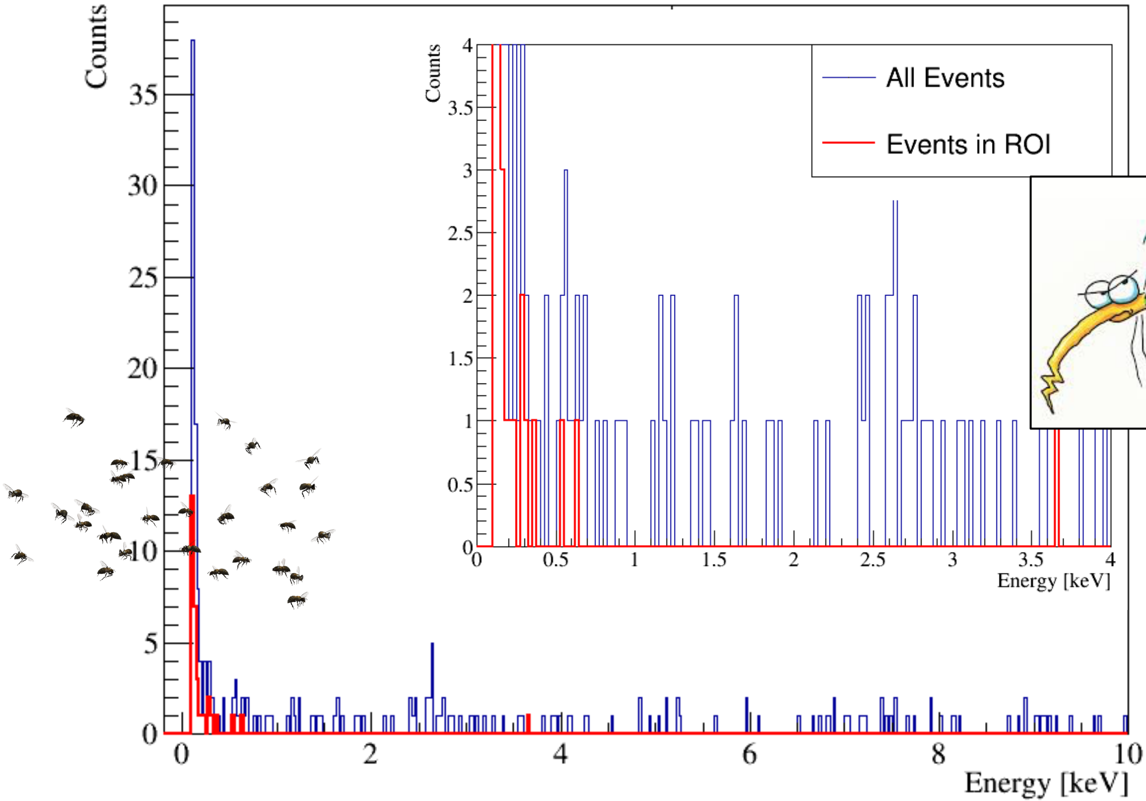
Det A – 100eV threshold analysis

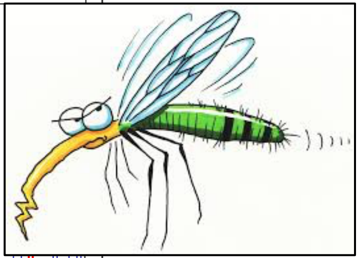
Dark matter data – Accepted events



Det A – 100eV threshold analysis

Dark matter data – Accepted events



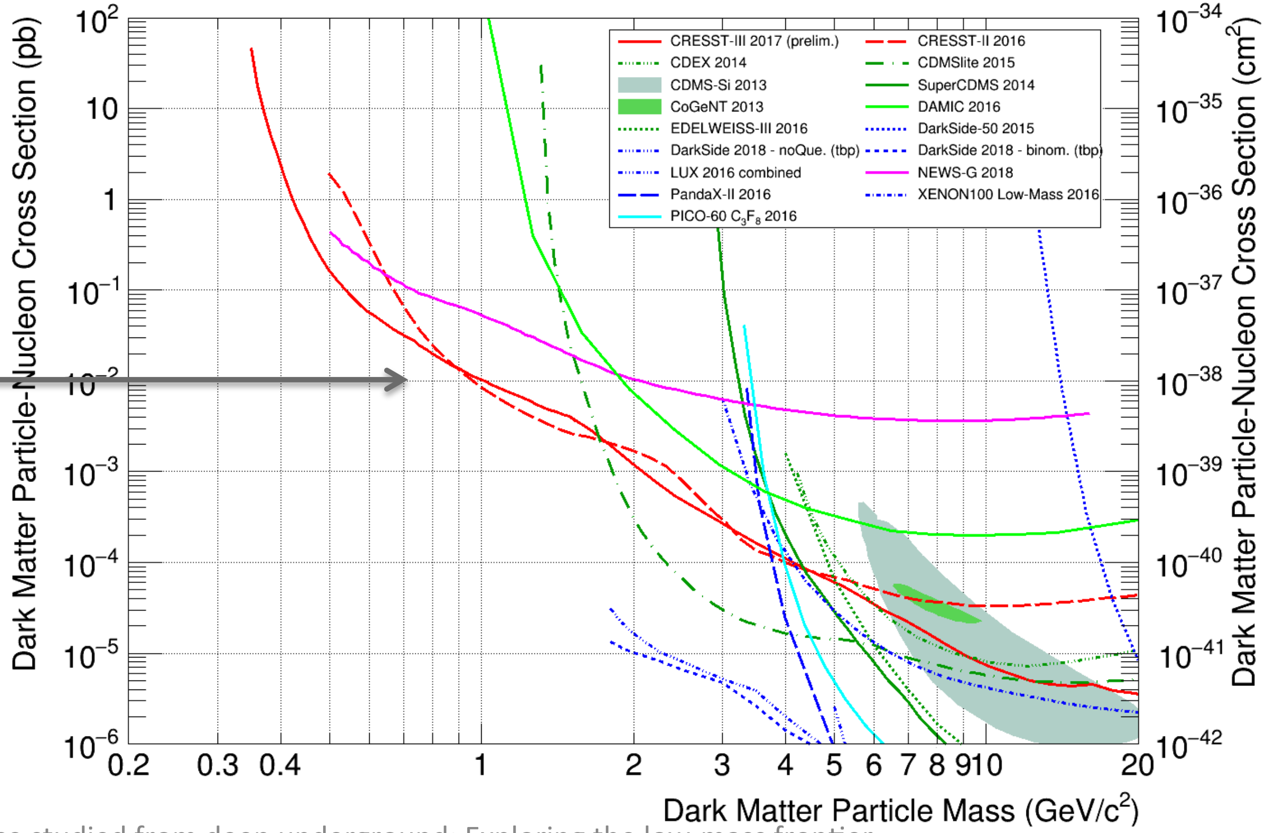


From accepted events to dark matter limits

Energy spectrum of accepted events

Yellin one dimensional optimum interval method

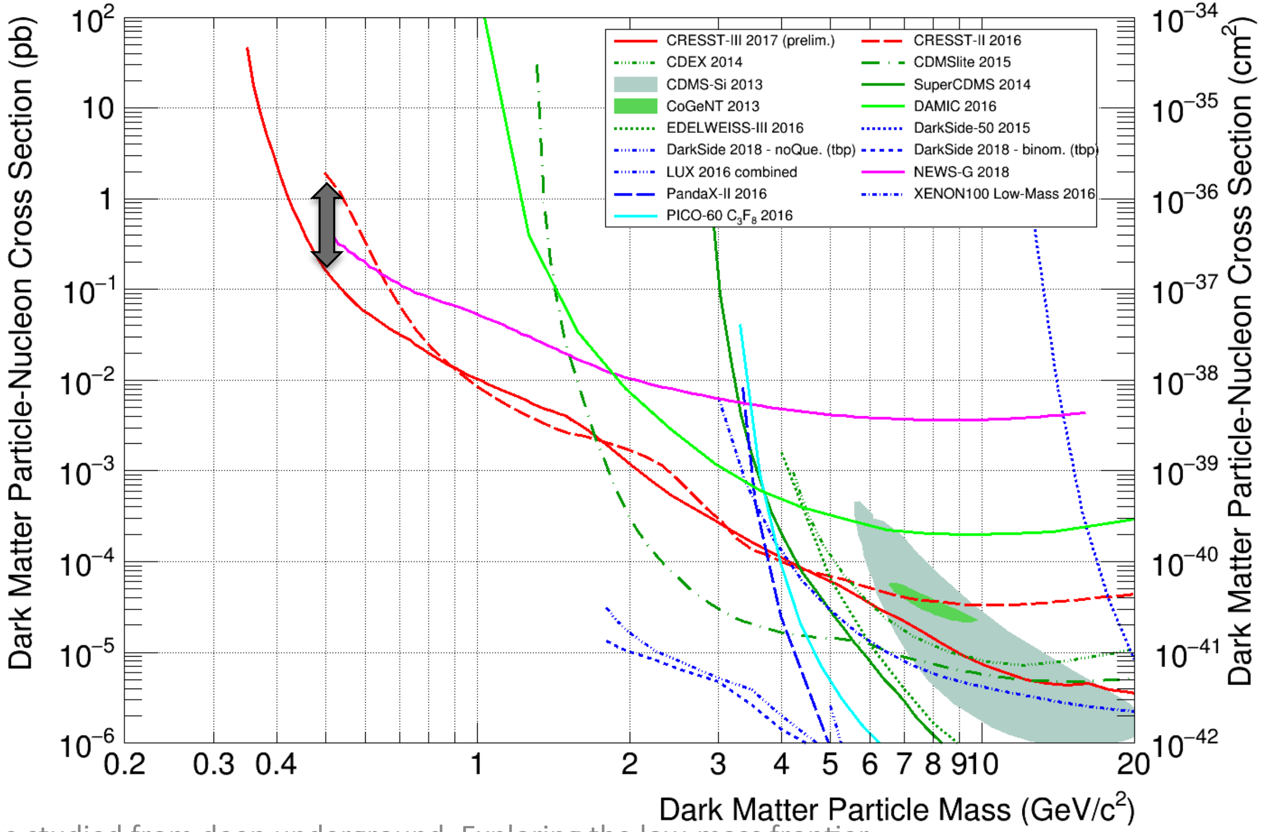
Expected energy spectrum for dark matter



Det A – 100eV threshold analysis

Results

One order of magnitude improvement at 0.5 GeV/c^2

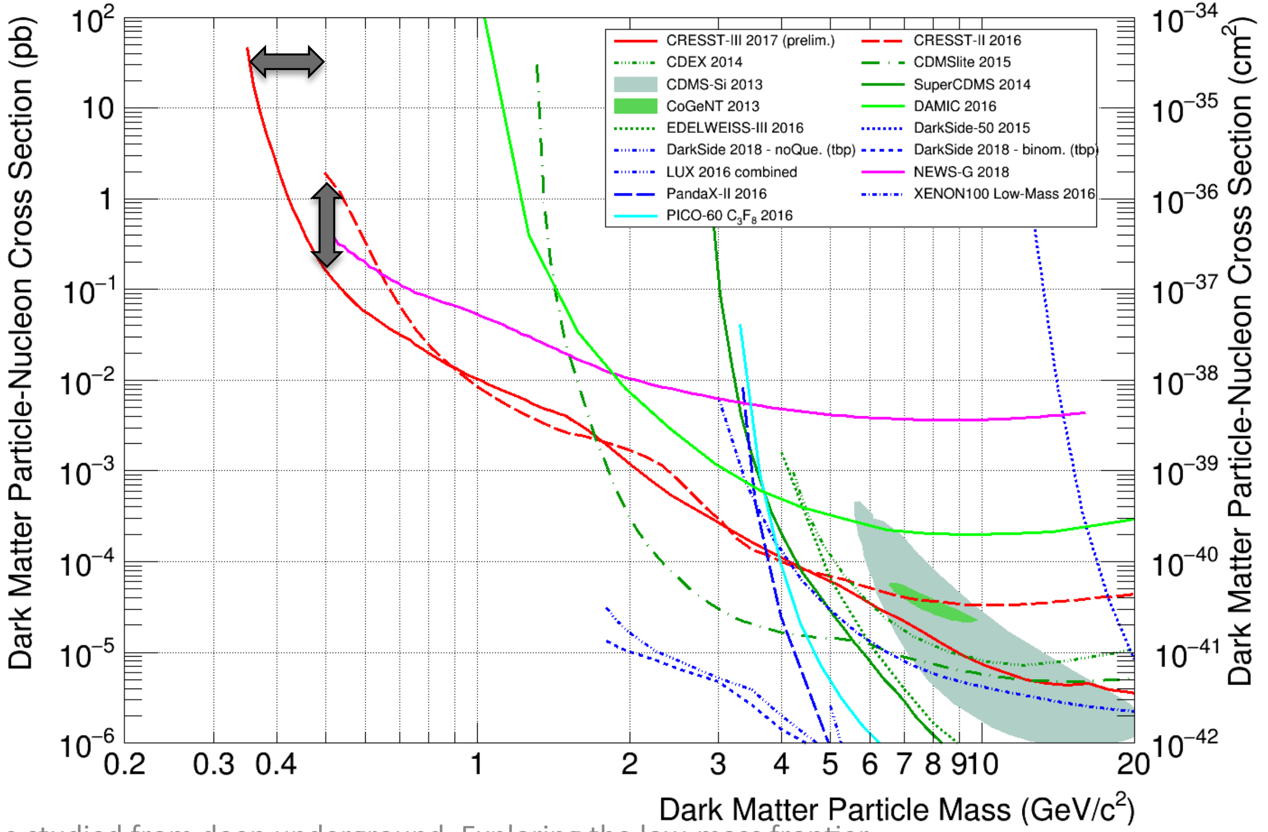


Det A – 100eV threshold analysis

Results

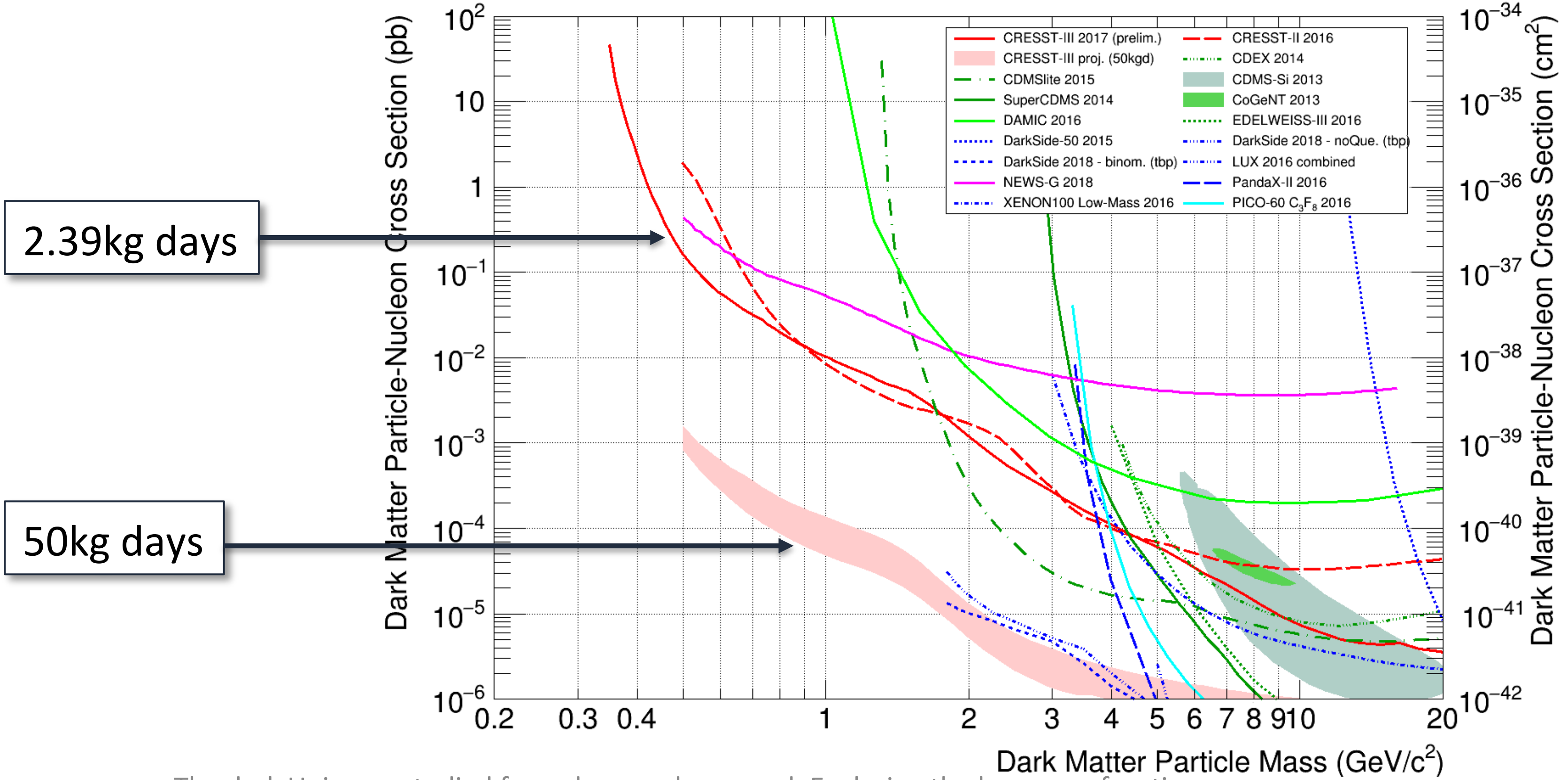
Reach of direct dark matter experiments extended to 0.35 GeV/c^2

One order of magnitude improvement at 0.5 GeV/c^2



Det A – 100eV threshold analysis

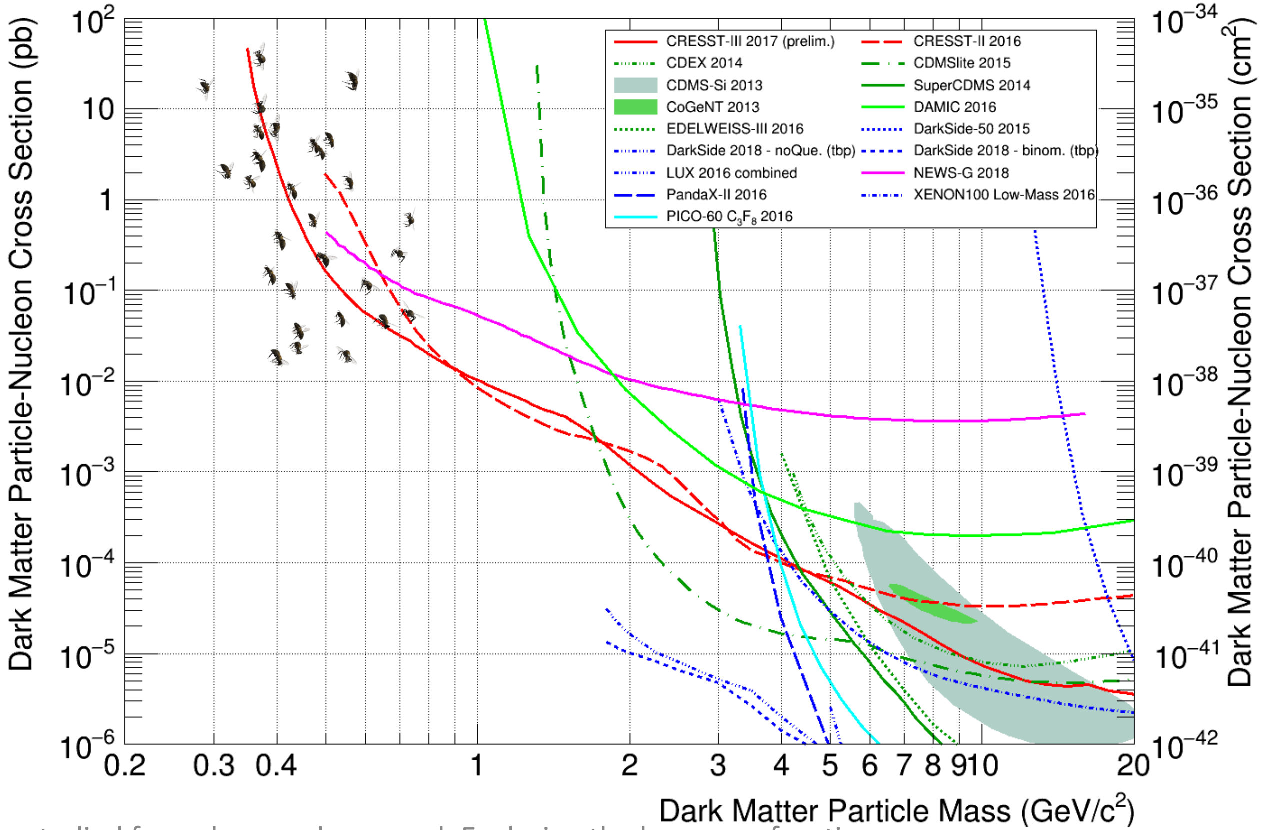
Results



Det A – 100eV threshold analysis

Results

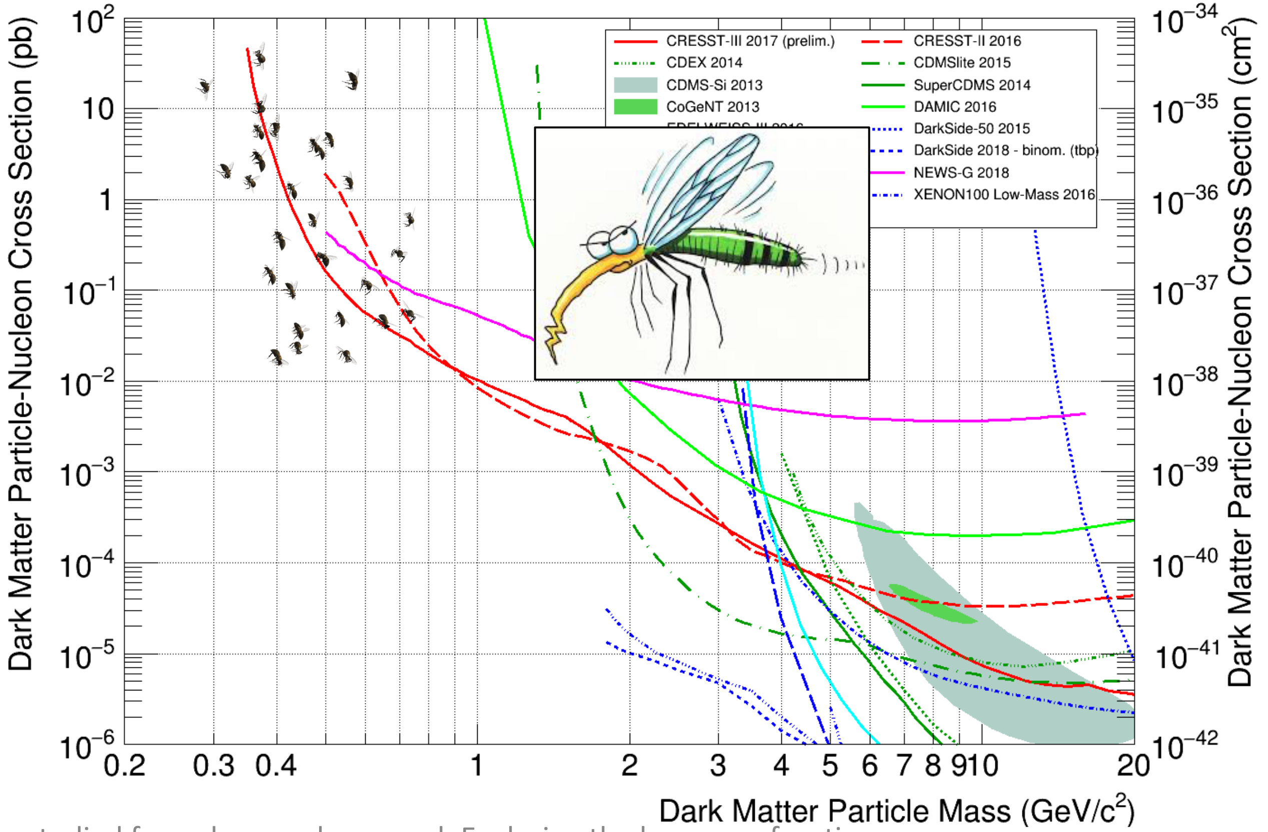
Non-flat background at 100eV



Det A – 100eV threshold analysis

Results

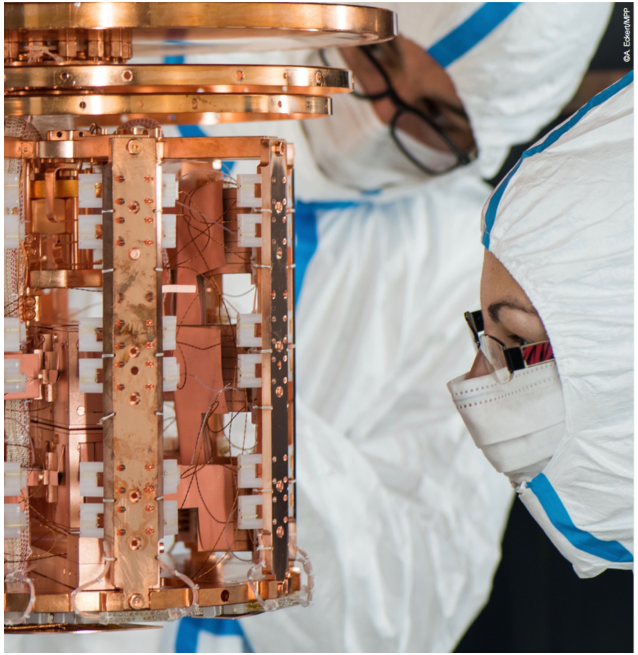
Non-flat background at 100eV



Conclusions

~~Conclusions~~

This is just the beginning



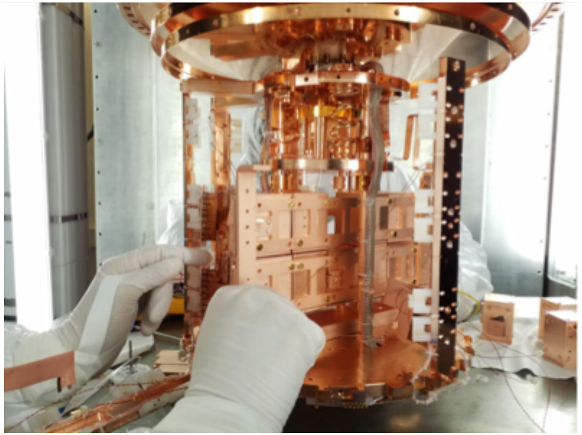
First CRESST-III run 07/2016 - 02/2018: Analysis ongoing

3 times lower optimum threshold for detector A

3 other detectors with thresholds << 100eV

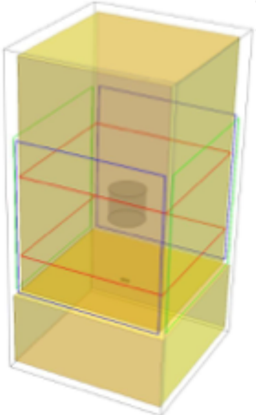
3 times more statistics → deeper understanding of backgrounds

Second CRESST-III run just starting



Key innovation

Upgraded detector modules with dedicated hardware changes to understand backgrounds



Additional upgrade

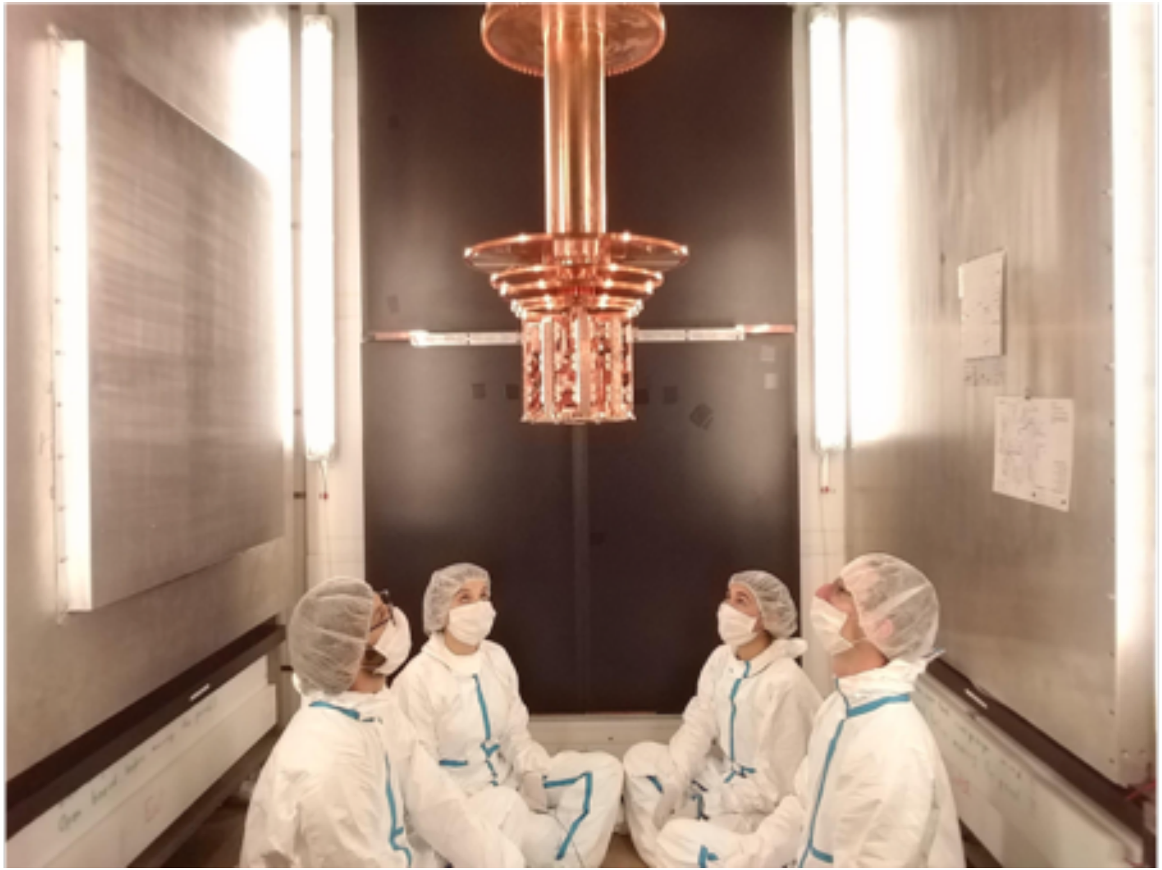
Active magnetic field compensation with three pair of coils for x,y & z-axes

Waiting for dark matter

The cryostat is cold

First pulses measured

Commissioning phase

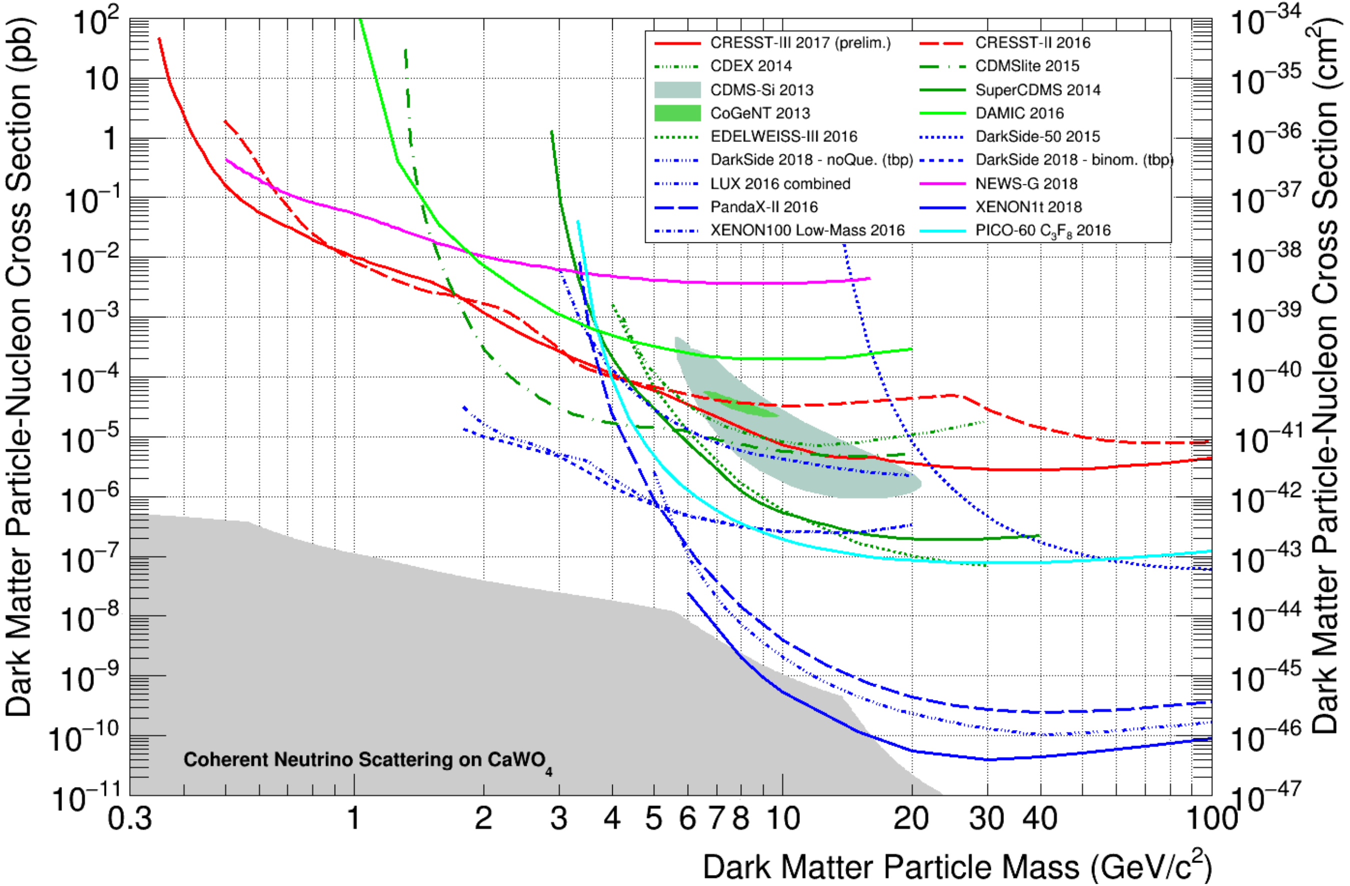



New frontiers ...
... new potentials ...
... new challenges!


New frontiers ...
... new potentials ...
... new challenges!

Backup slides to follow

Wide range and up-to-date



Rate Xenon1T

From arXiv: 1805.12562

TABLE I: Best-fit expected event rates with 278.8 days live-time in the 1.3 t fiducial mass, 0.9 t reference mass, and 0.65 t core mass, for the full ($cS1$, $cS2_b$) ROI and, for illustration, in the NR signal reference region. The table lists each background (BG) component separately and in total, the observed data, and the expectation for a 200 GeV/c^2 WIMP prediction assuming the best-fit $\sigma_{SI} = 4.7 \times 10^{-47}$ cm^2.

Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
$\mathrm{WIMP}_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

278.8 days * 1.3 t / 3.56 counts
= 101days t/count
→ 0.01 counts/day t