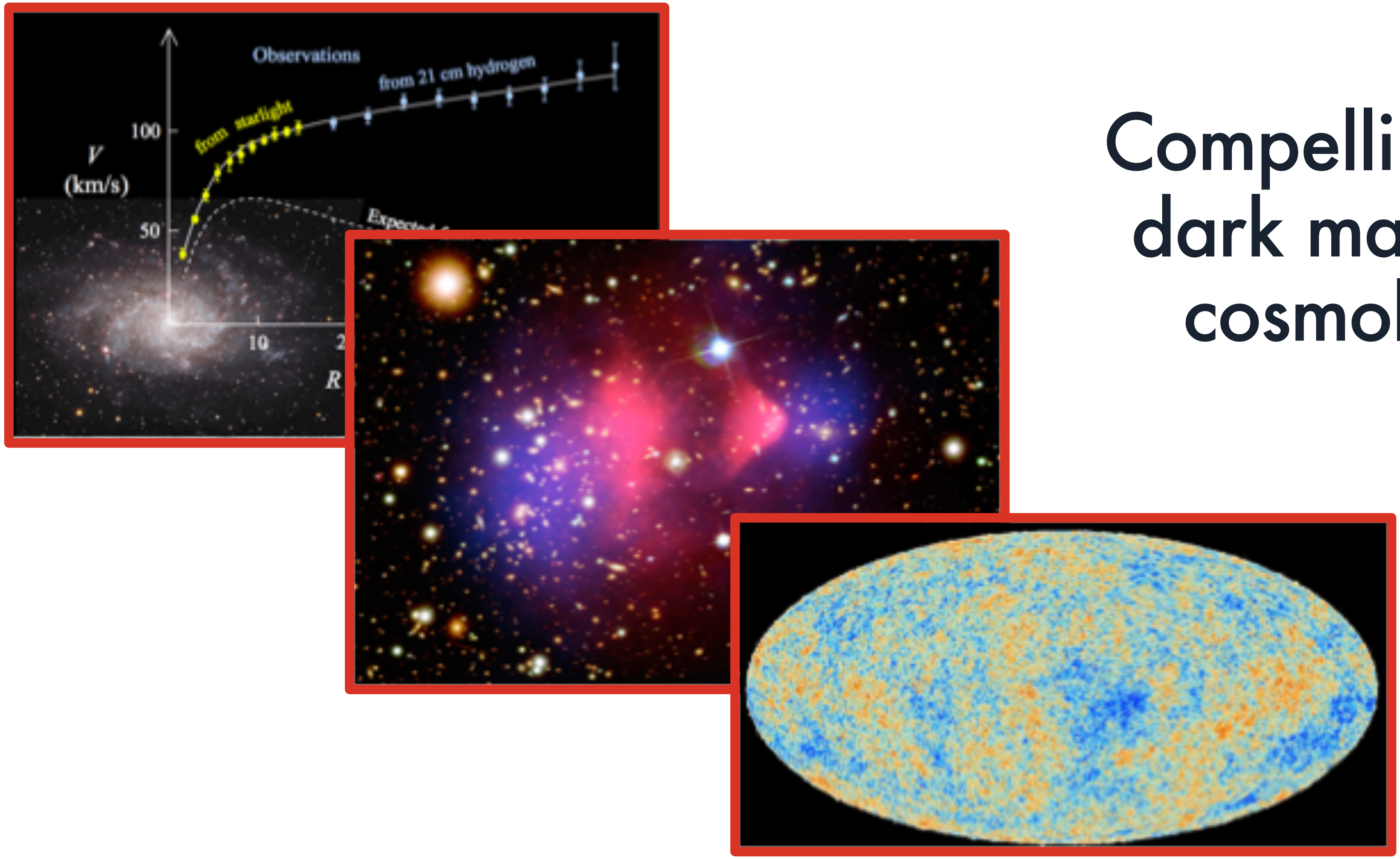
THE DARK UNIVERSE STUDIED FROM DEEP UNDERGROUND: EXPLORING THE LOW-MASS FRONTIER

Lisbon, 19 June 2018

Florian Reindl
HEPHY & TU Vienna

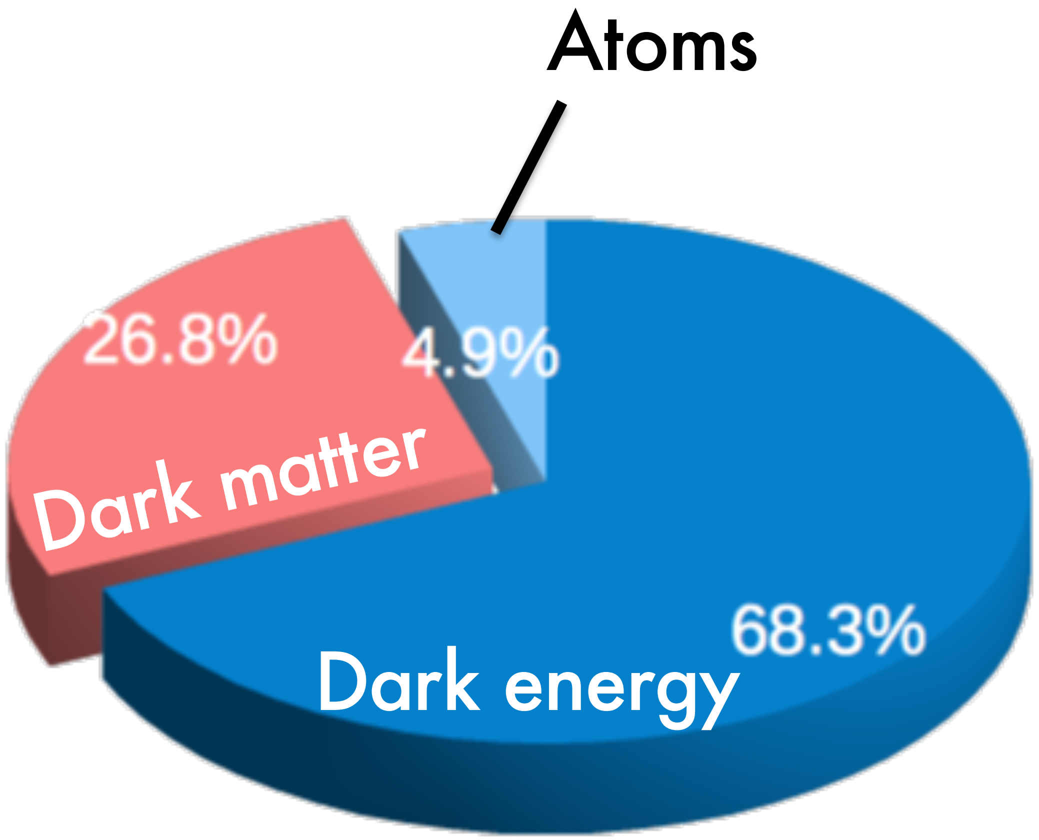
for the CRESST collaboration

EVIDENCE FOR DARK MATTER



Compelling evidence for dark matter on various cosmological scales

DARK MATTER



Astronomy

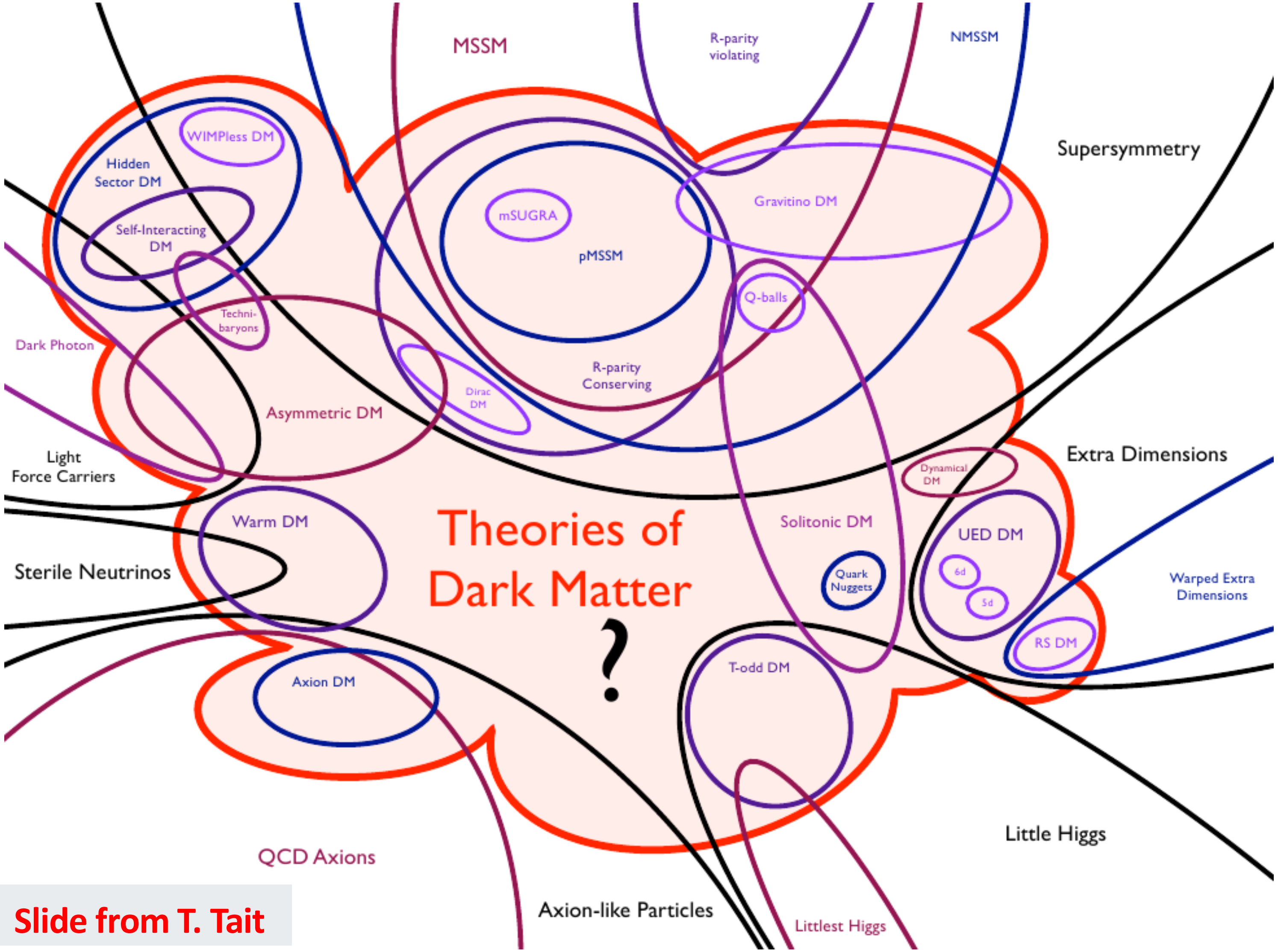
There is a lot of dark matter in the Universe!

(Astro-) Particle Physics

What is it made of?

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)

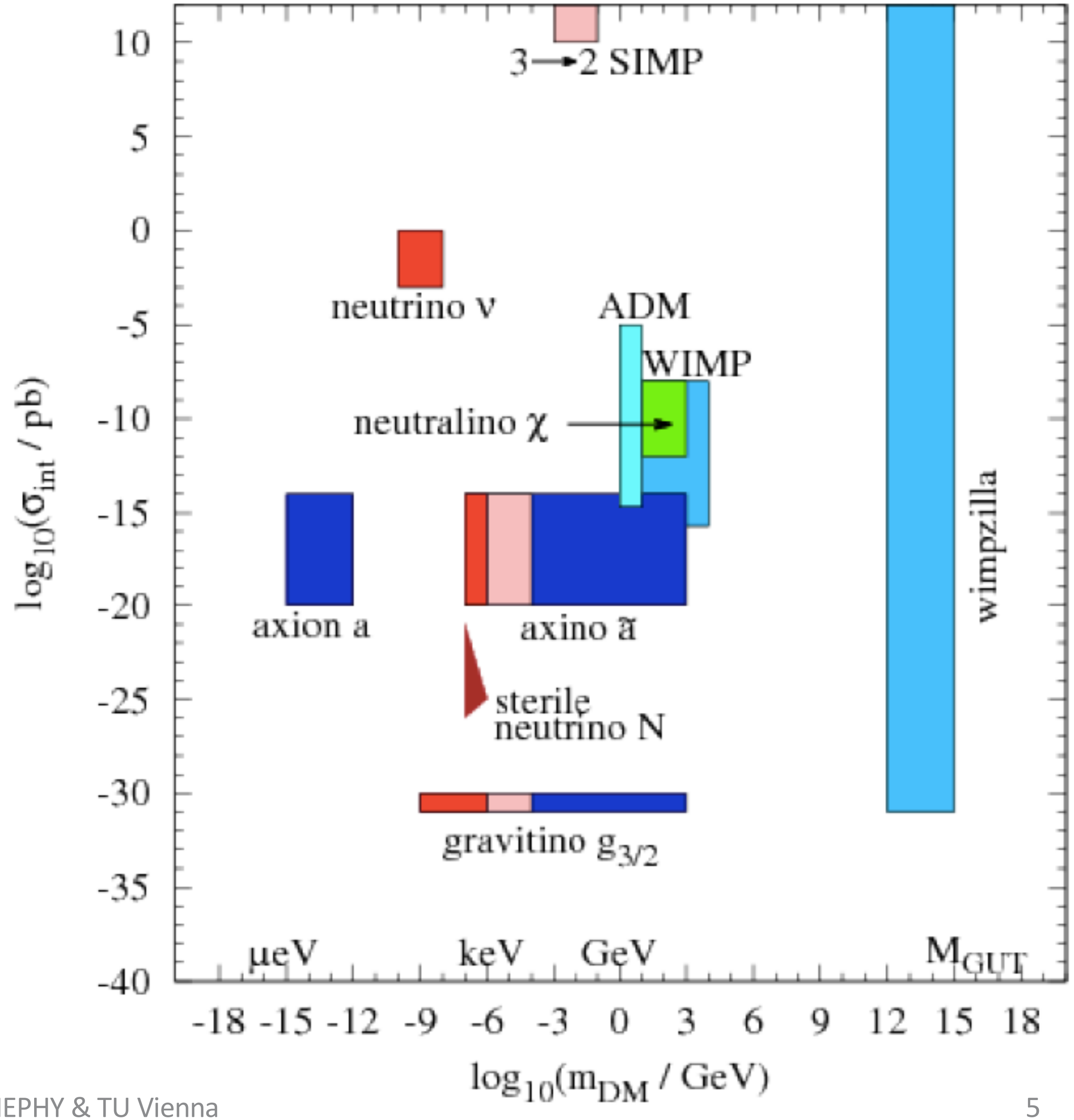


Slide from T. Tait

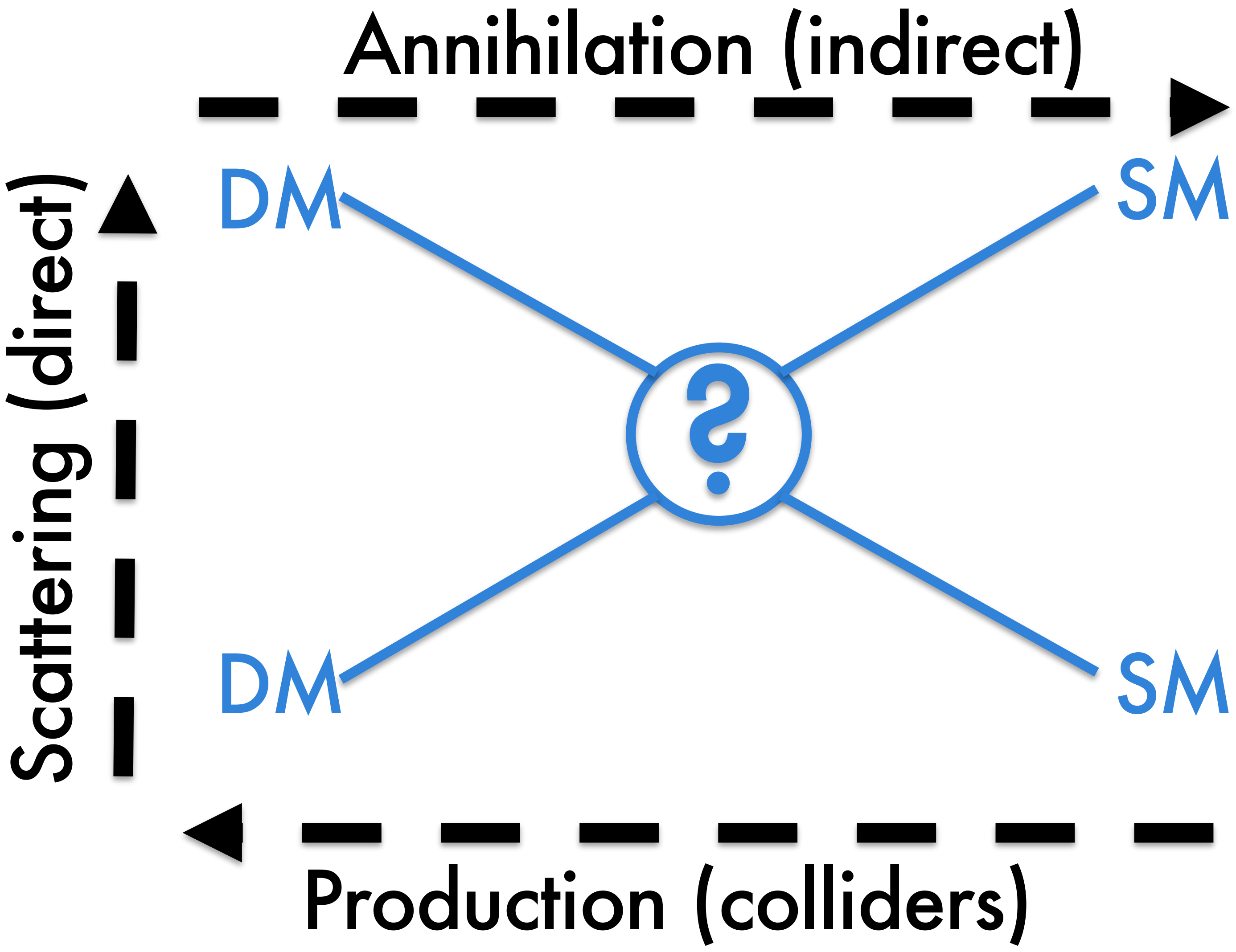
THE NATURE OF DARK MATTER

Once there was only the WIMP miracle…

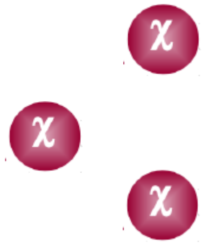
Now WIMPs are only one candidate out of a range of theoretical motivated dark matter particle candidates with a wide range of mass and cross section



DETECTION CHANNELS



DIRECT DETECTION OF DARK MATTER



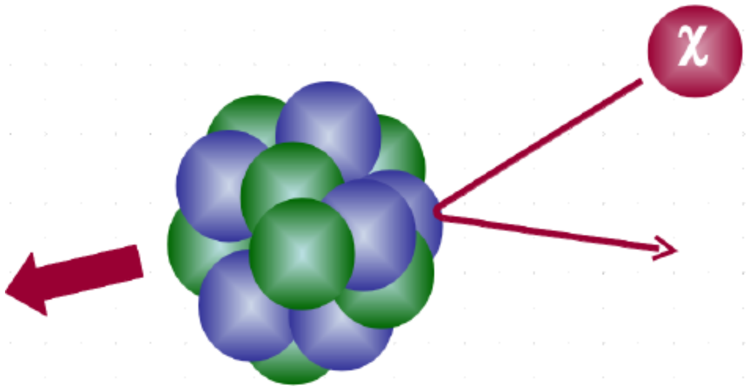
Basic idea

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

Most common

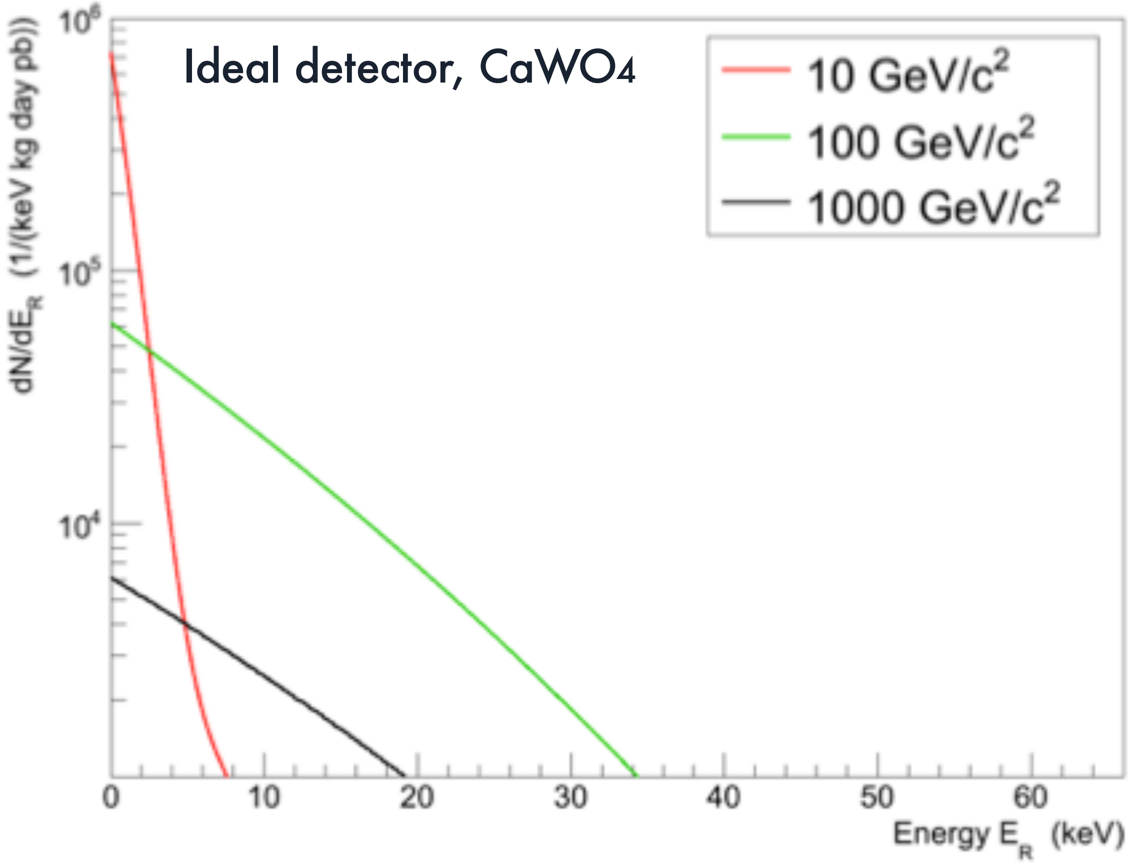
Dark matter particles scatter off nuclei:

- Elastic
- Coherent: ~A^2
- Spin-independent



EXPERIMENTAL CHALLENGES

THE DARK MATTER RECOIL SPECTRUM



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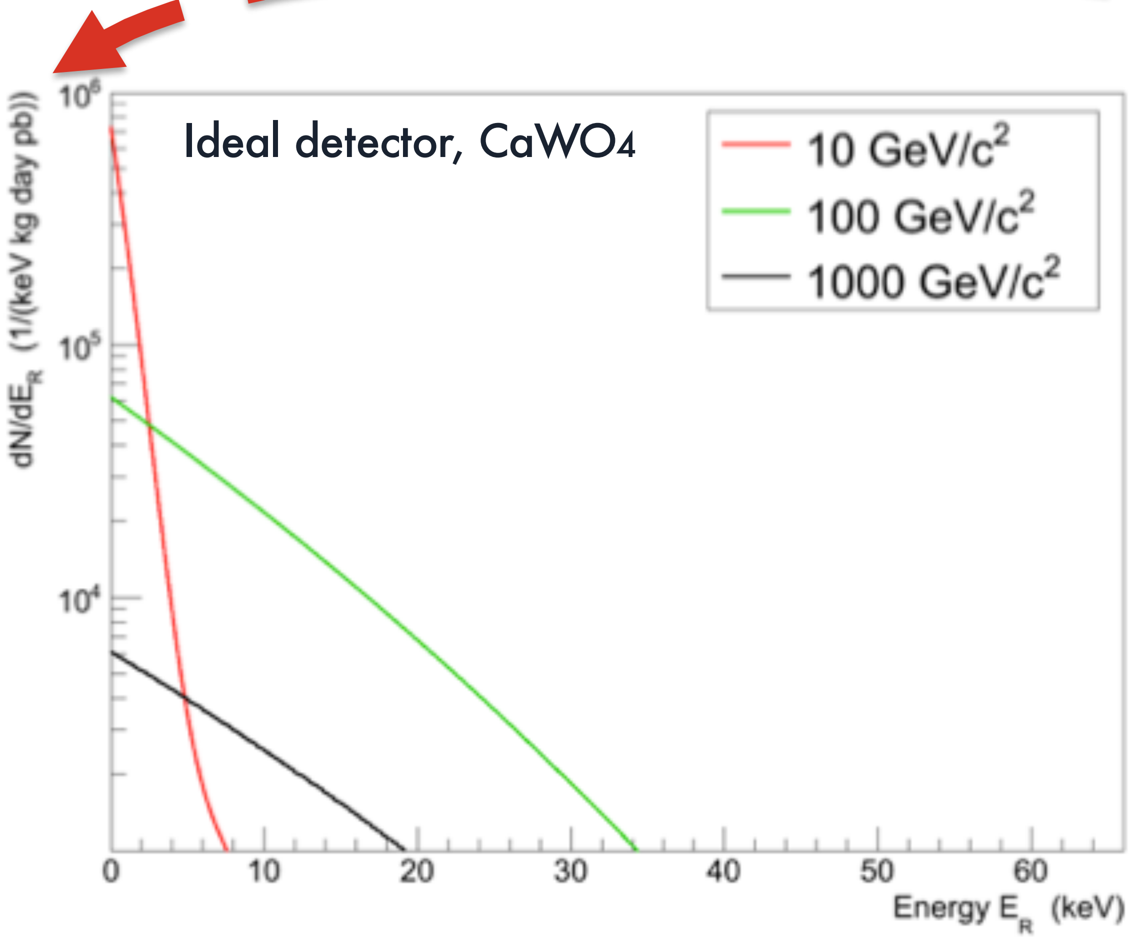

Very rare

current limit*

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

*Xenon1t: arXiv:1805.12562v1

EXPERIMENTAL CHALLENGES

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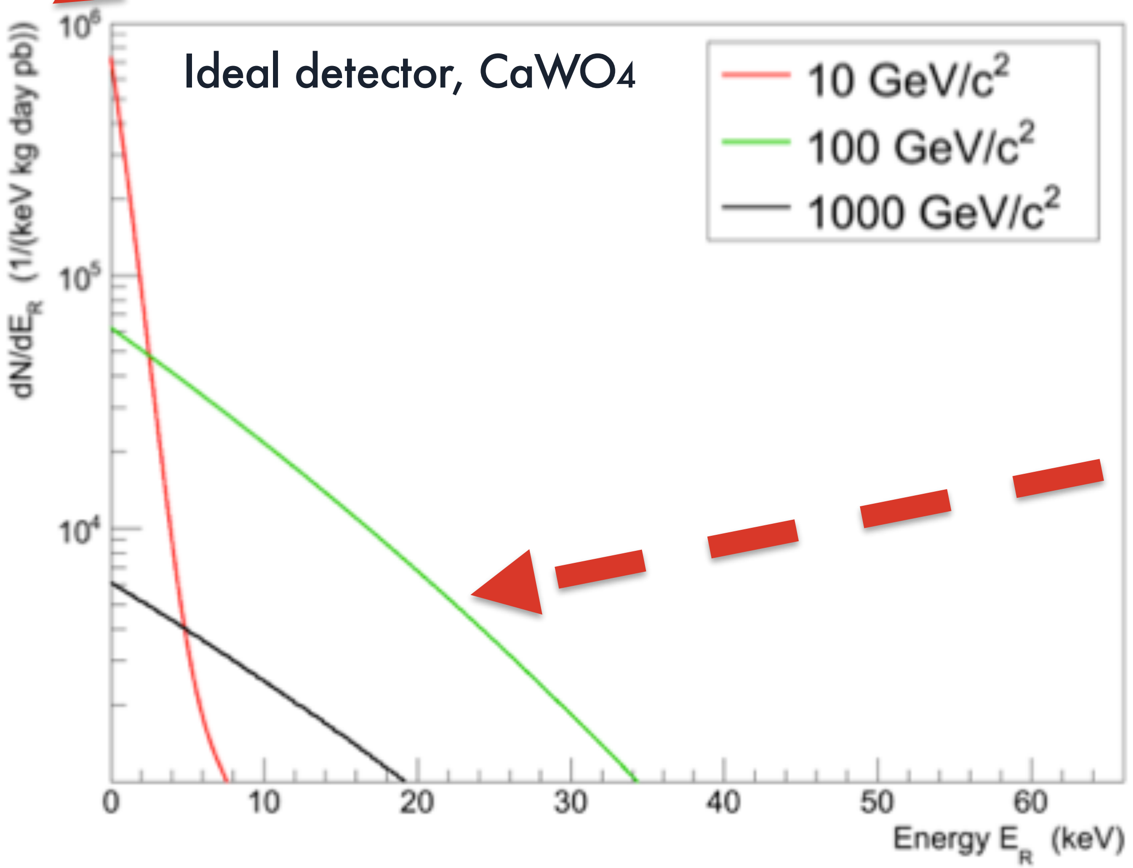

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Featureless spectrum

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EXPERIMENTAL CHALLENGES

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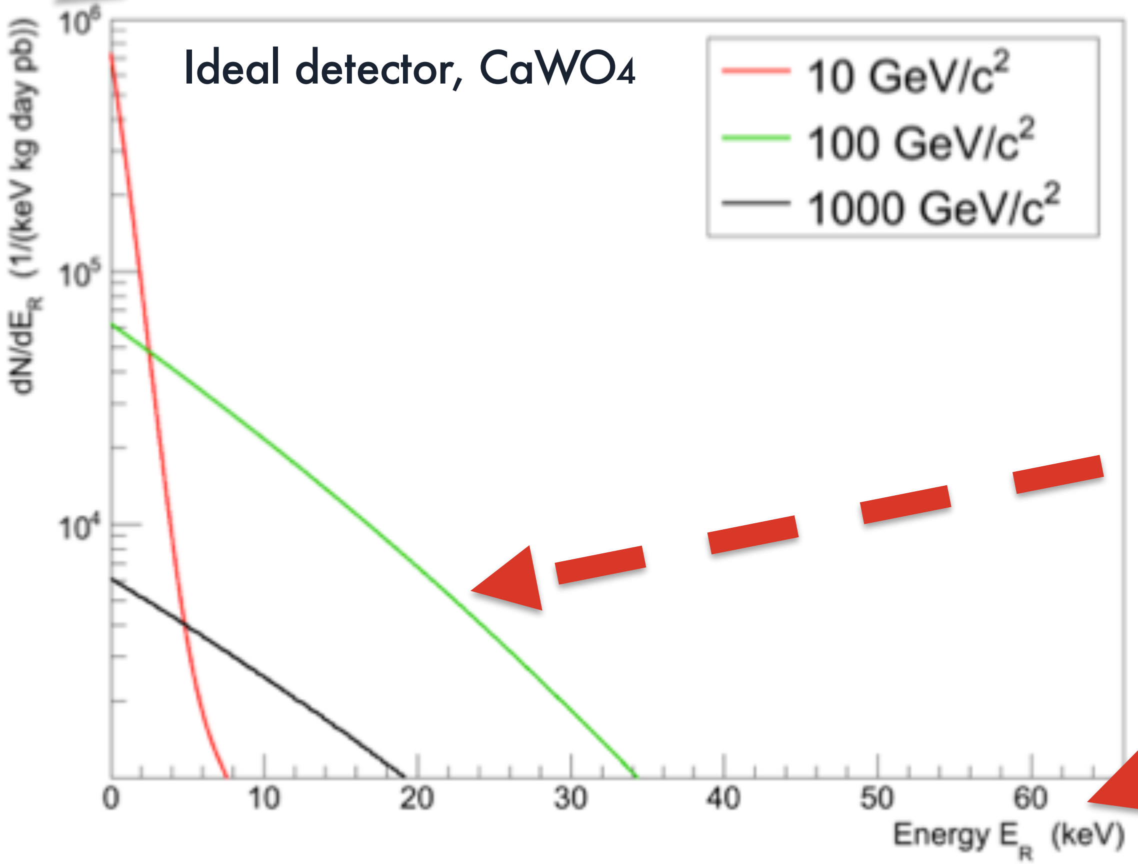


Very rare

current limit*

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

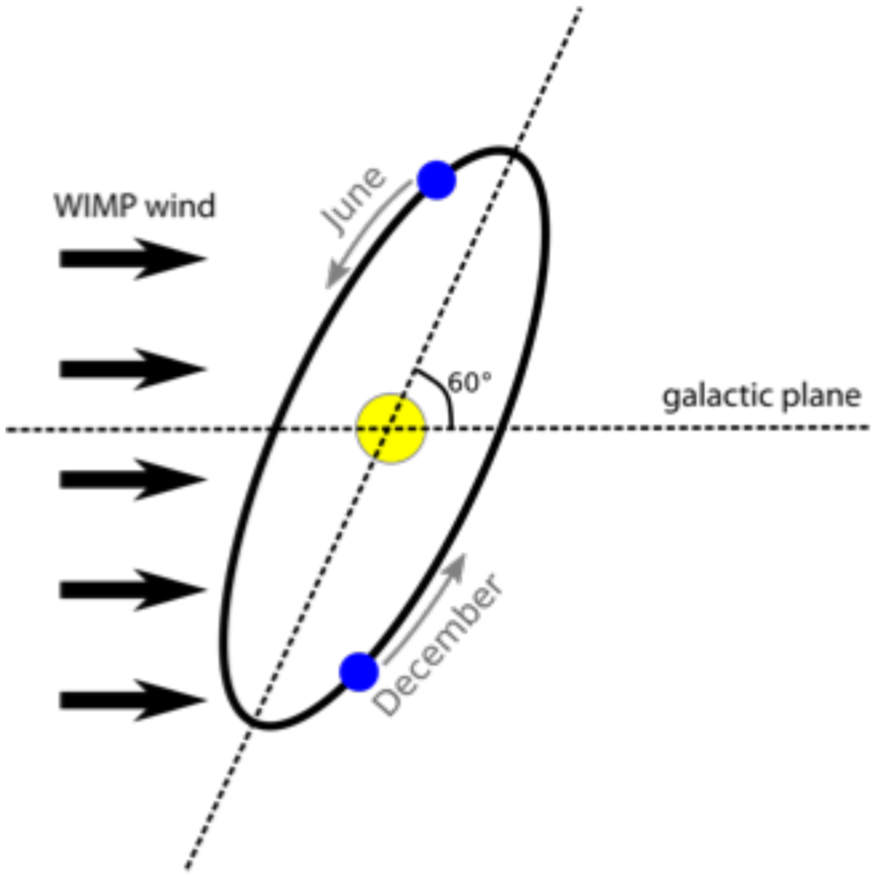
Featureless spectrum

Small recoil energies

~keV range

*Xenon1t: arXiv:1805.12562v1

THE RELATIVE VELOCITY MODULATES
AND SO SHOULD THE INTERACTION RATE

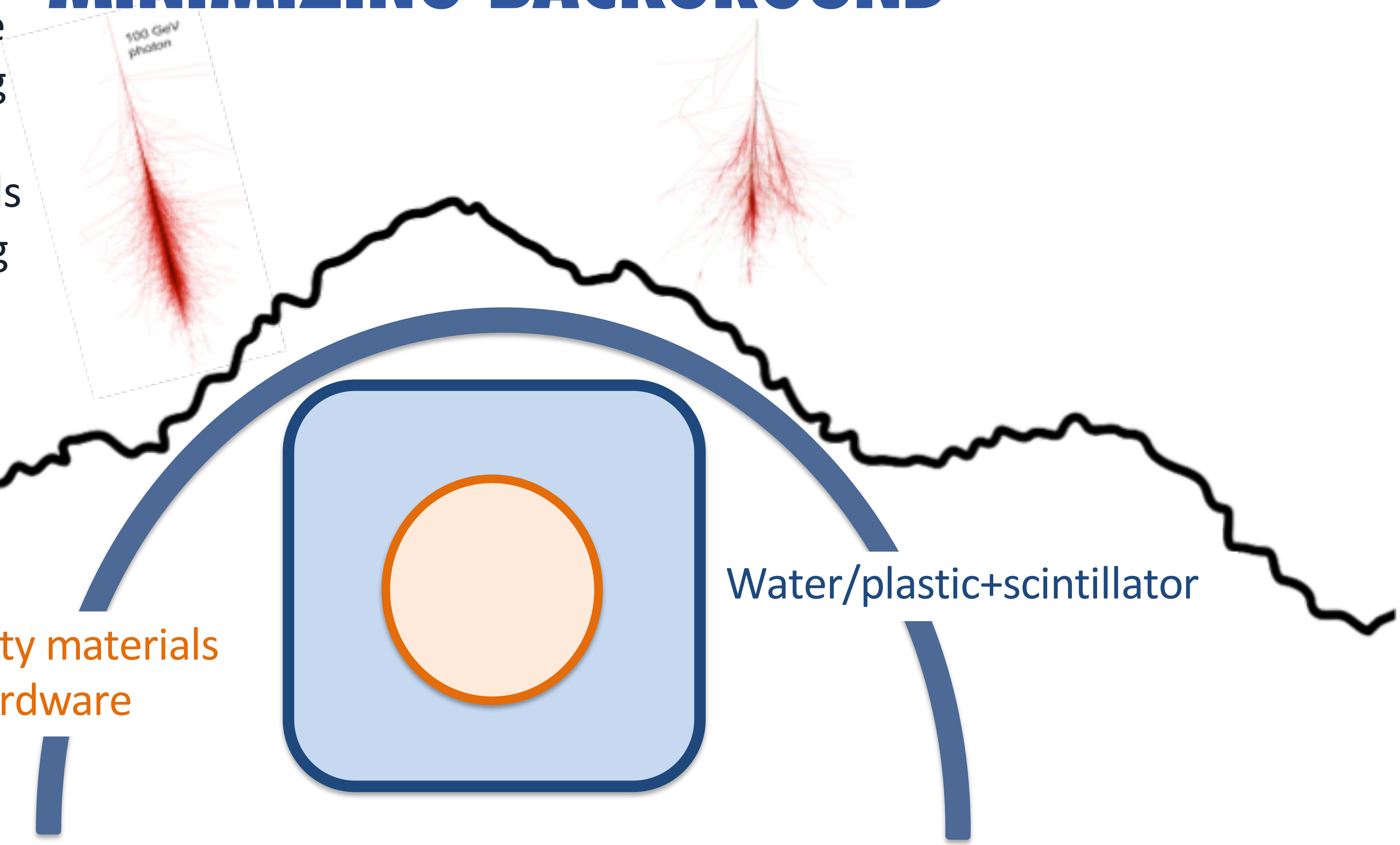


Period: 1 year
Phase: cosine peaking June 2nd

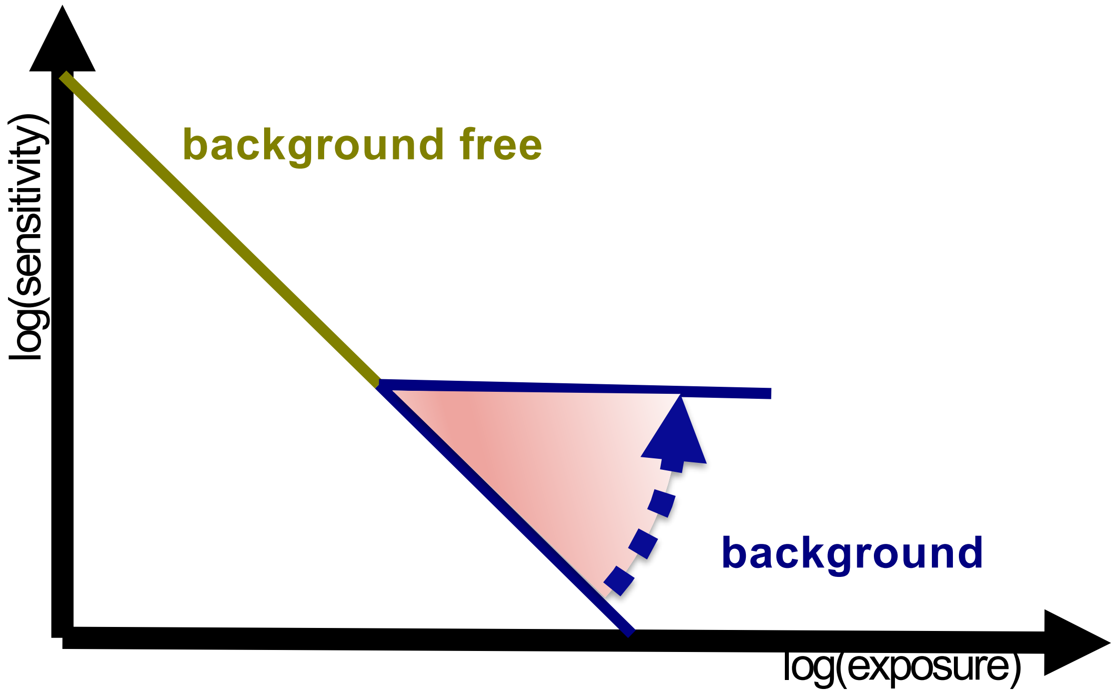
The smoking gun evidence?

MINIMIZING BACKGROUND

- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling
- Event-by-event discrimination



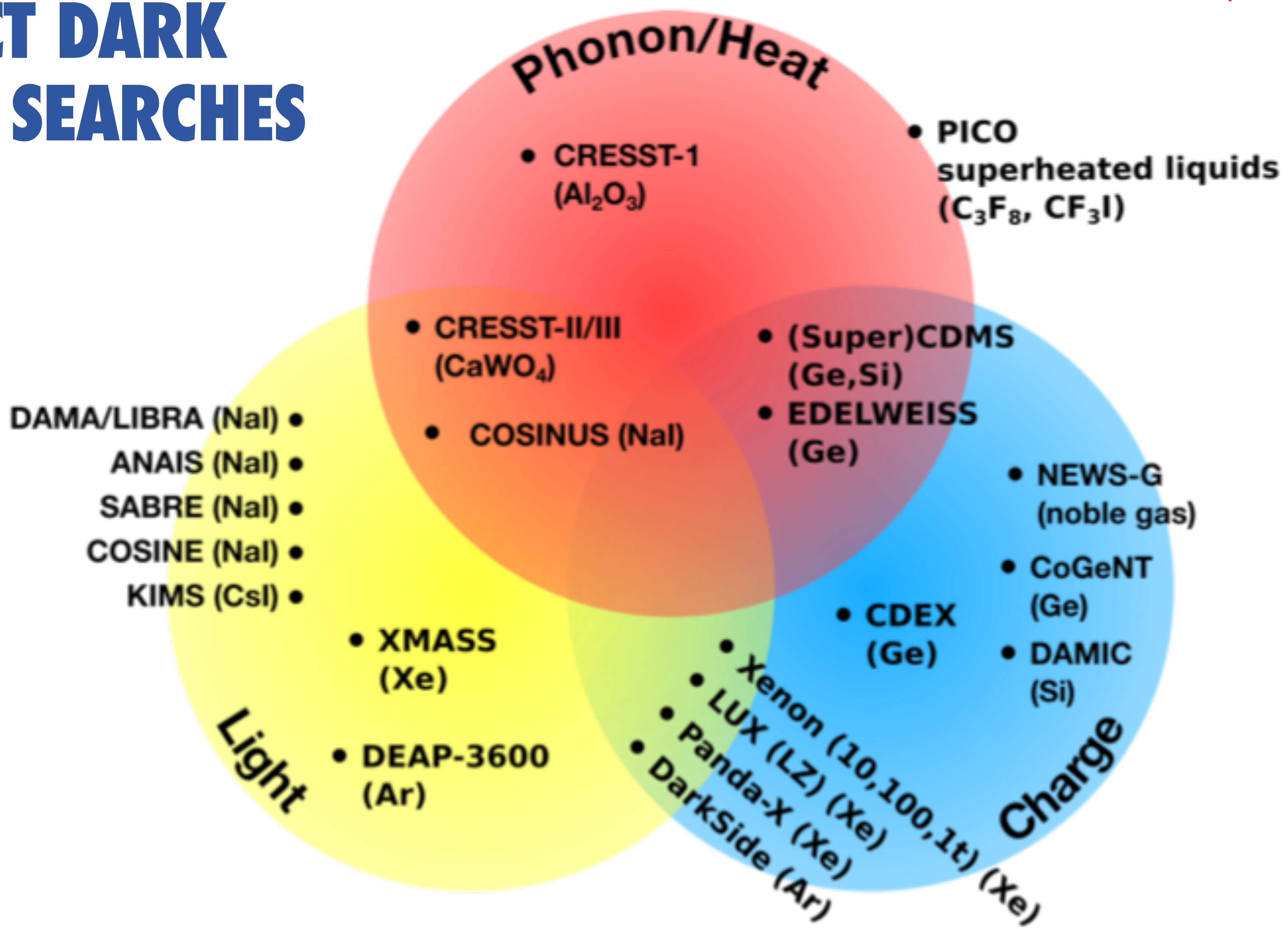
MINIMIZING BACKGROUND



For a discovery:
understand residual background

DIRECT DARK MATTER SEARCHES

Incomplete compilation!



THE CRESST COLLABORATION

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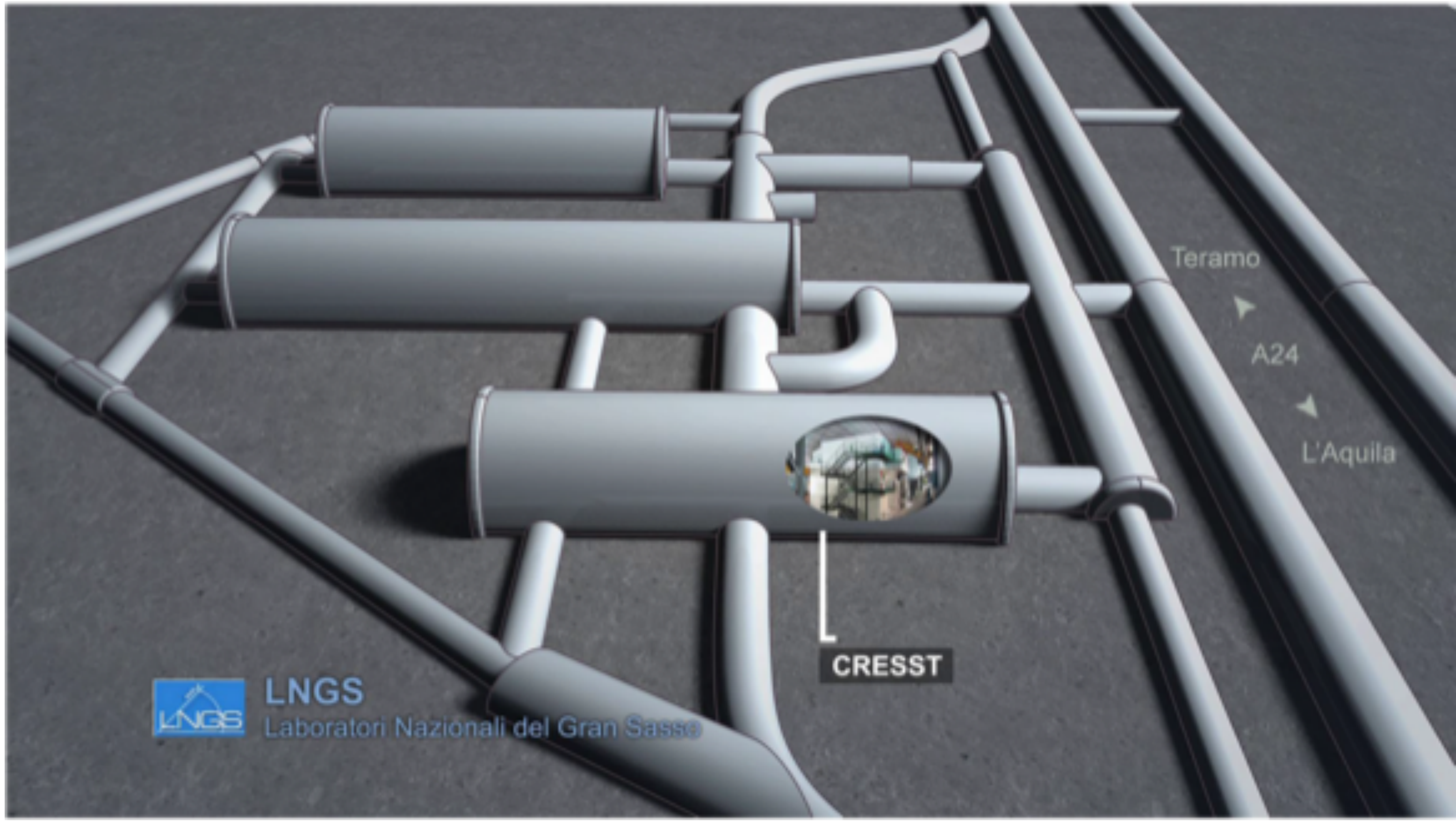
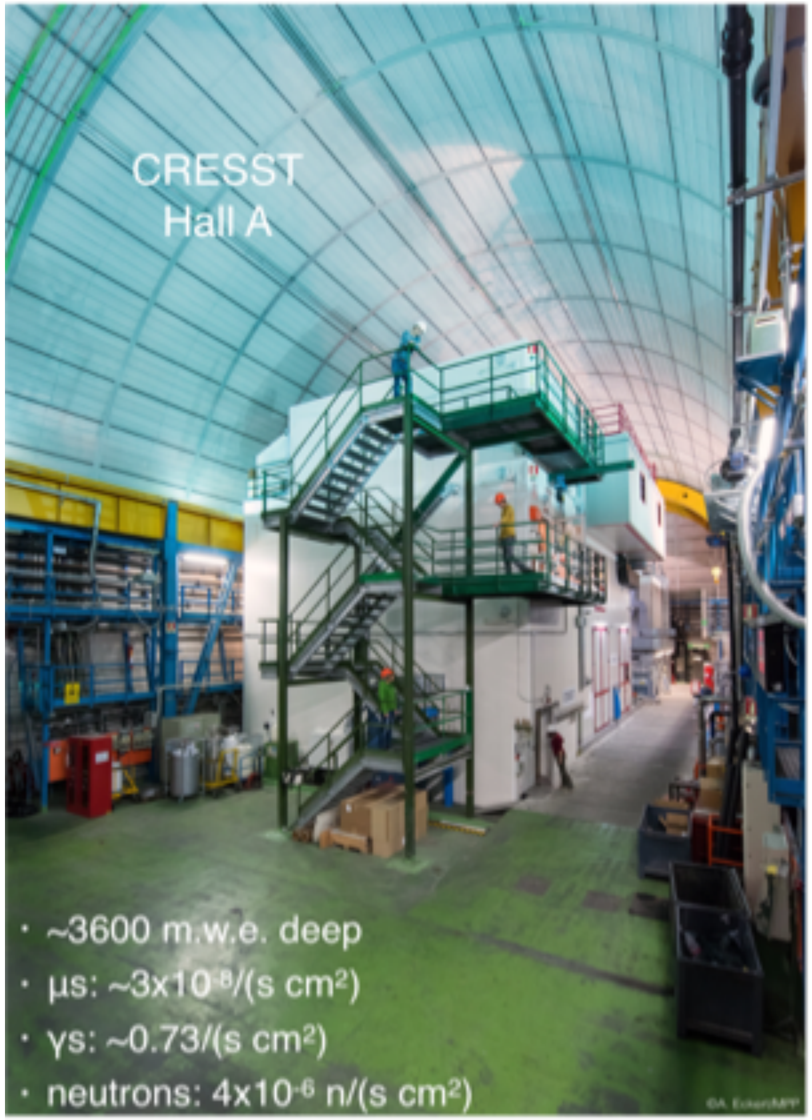
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

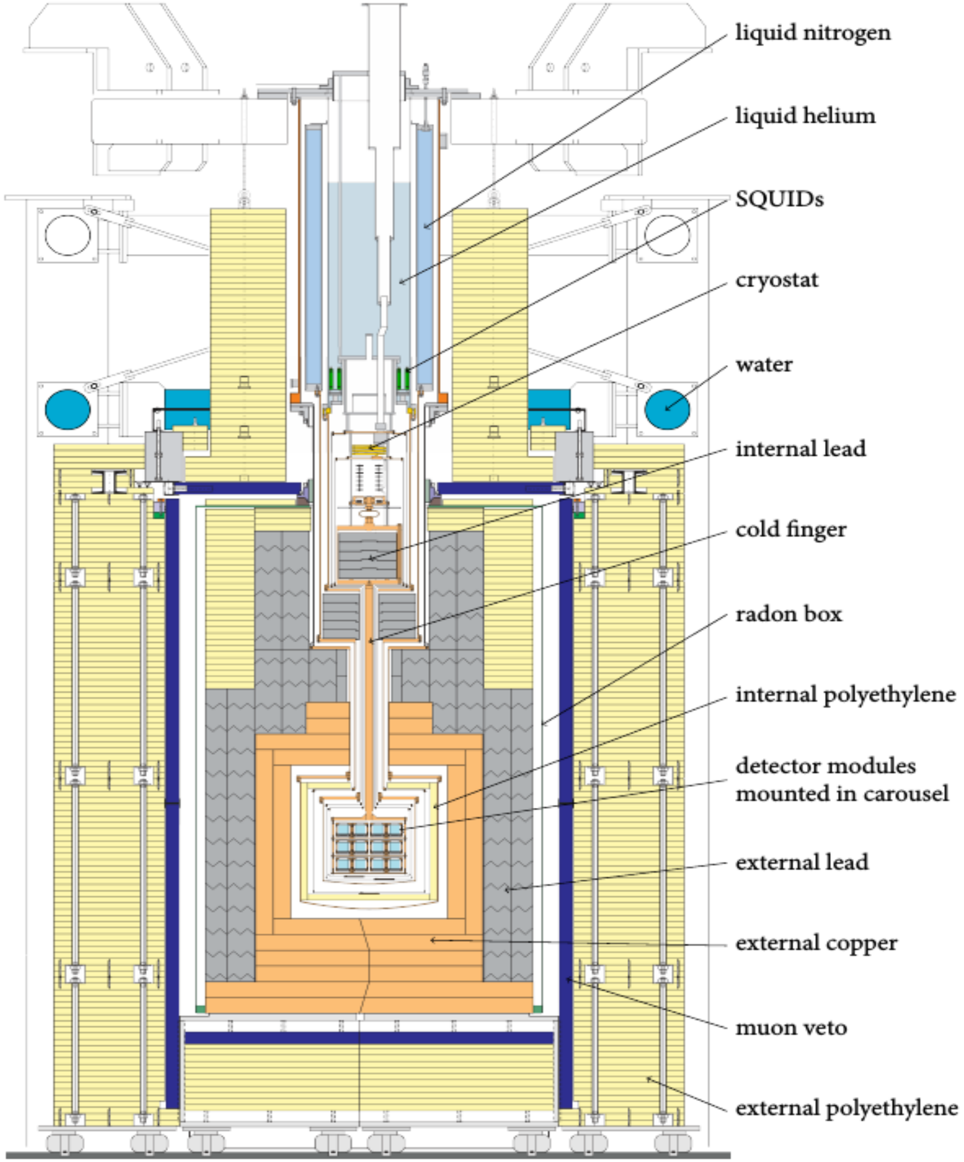
LABORATORI NAZIONALI DEL GRAN SASSO (LNGS)

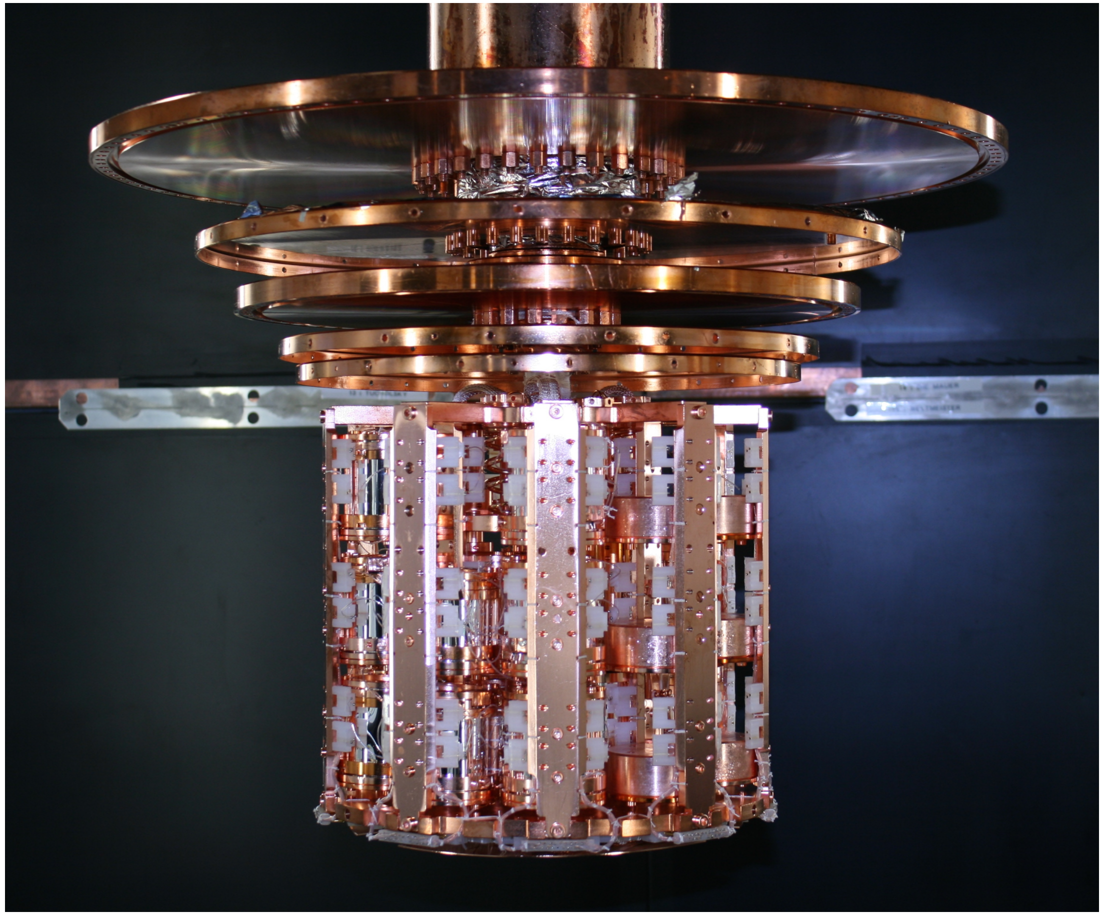


CRESST @ LNGS


CRESST
Hall A
• ~3600 m.w.e. deep
• μs: ~3x10^{-8}/(s cm^2)
• γs: ~0.73/(s cm^2)
• neutrons: 4x10^{-6} n/(s cm^2)

THE EXPERIMENTAL SETUP



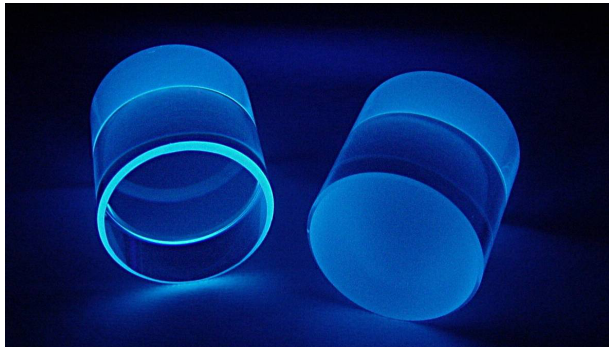


THE CRESST EXPERIMENT

Cryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers

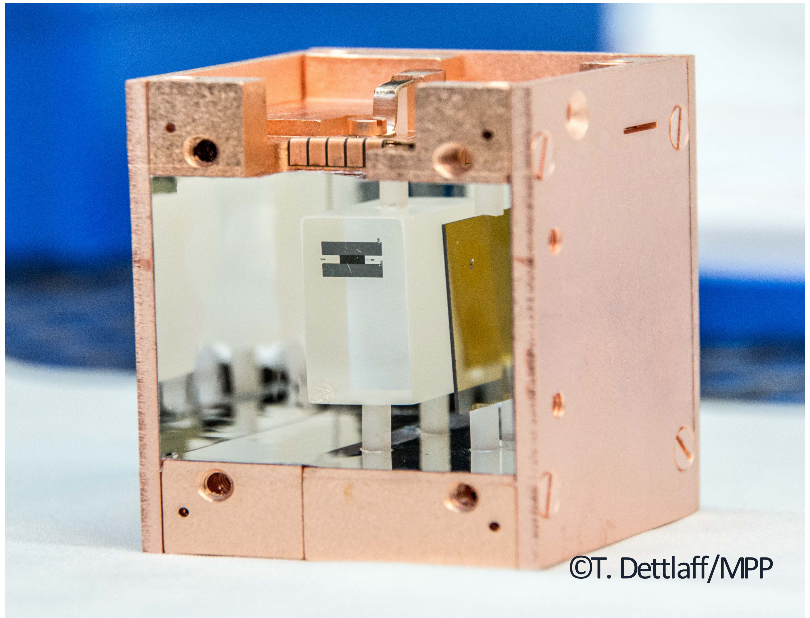
Direct detection of dark matter particles via their scattering off target nuclei

Scintillating $CaWO_4$ crystals as target

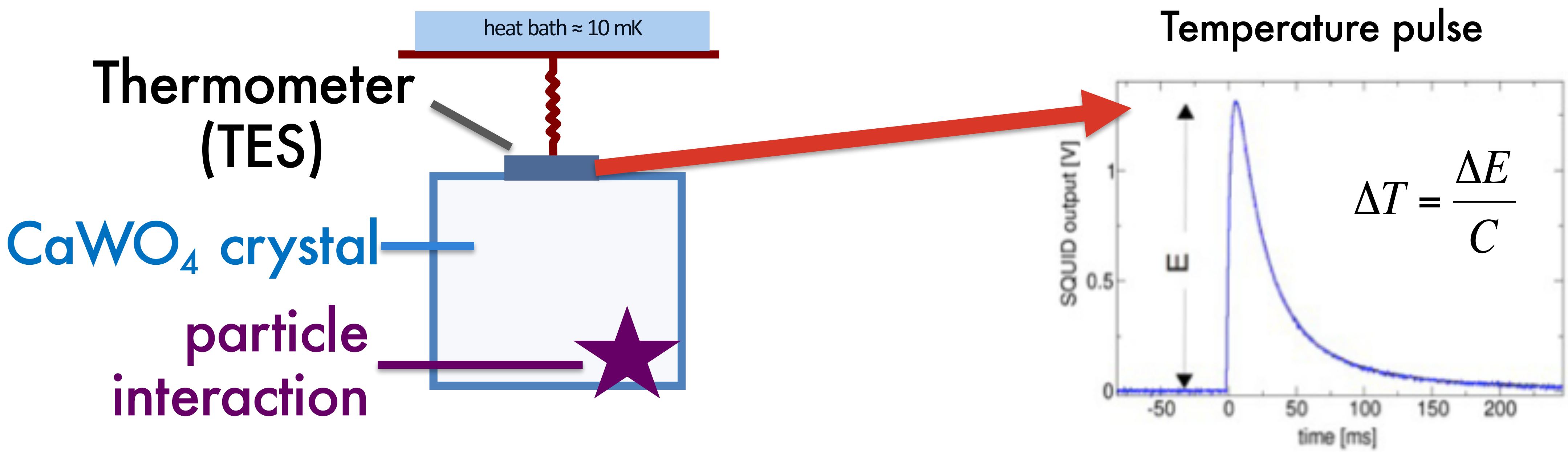


Target crystals operated as **cryogenic calorimeters** (~15mK)

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



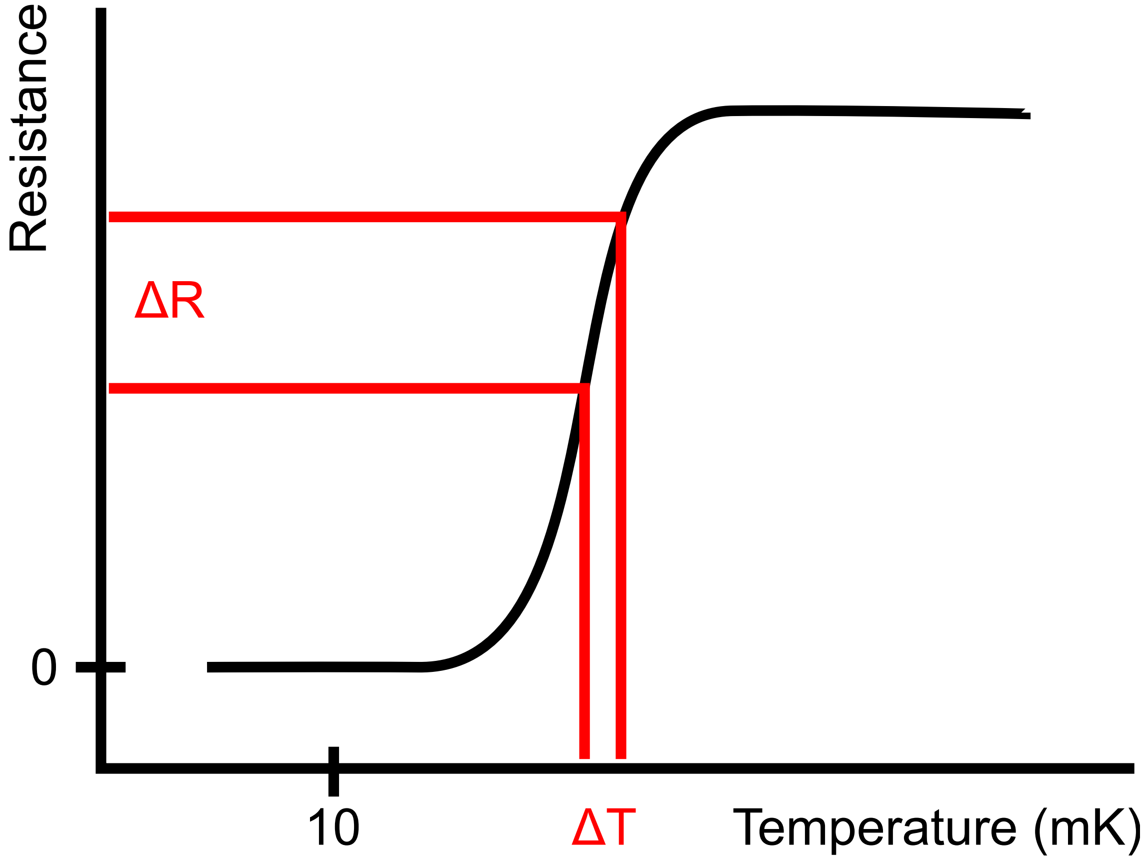
CRYOGENIC DETECTOR



Low temperature
Low heat capacity
} High sensitivity

TRANSITION EDGE SENSOR (TES)

WORKING PRINCIPLE



Energy deposition

~keV

↓

Temperature rise

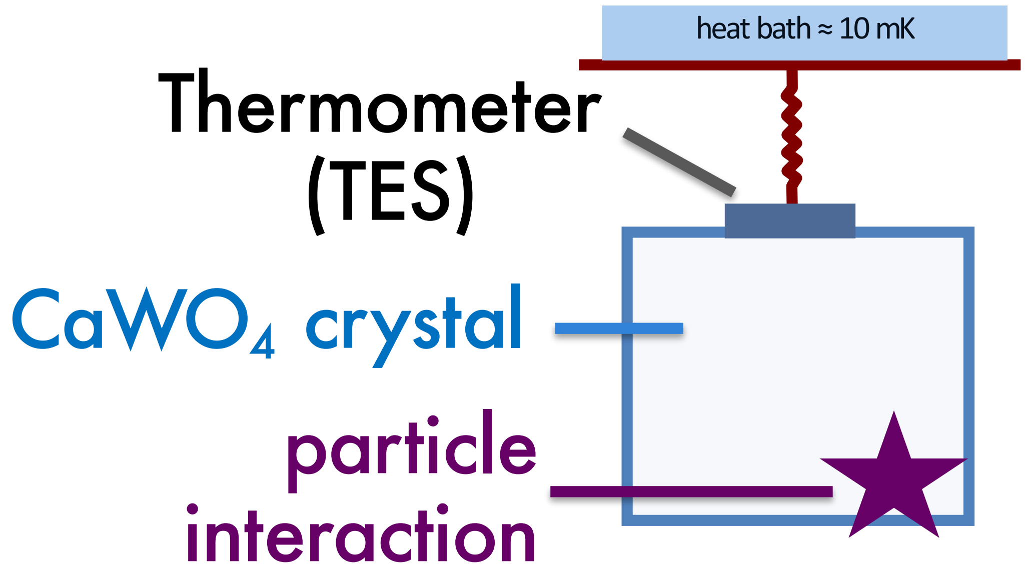
~µK

↓

Resistance change

~mΩ

CRYOGENIC DETECTOR

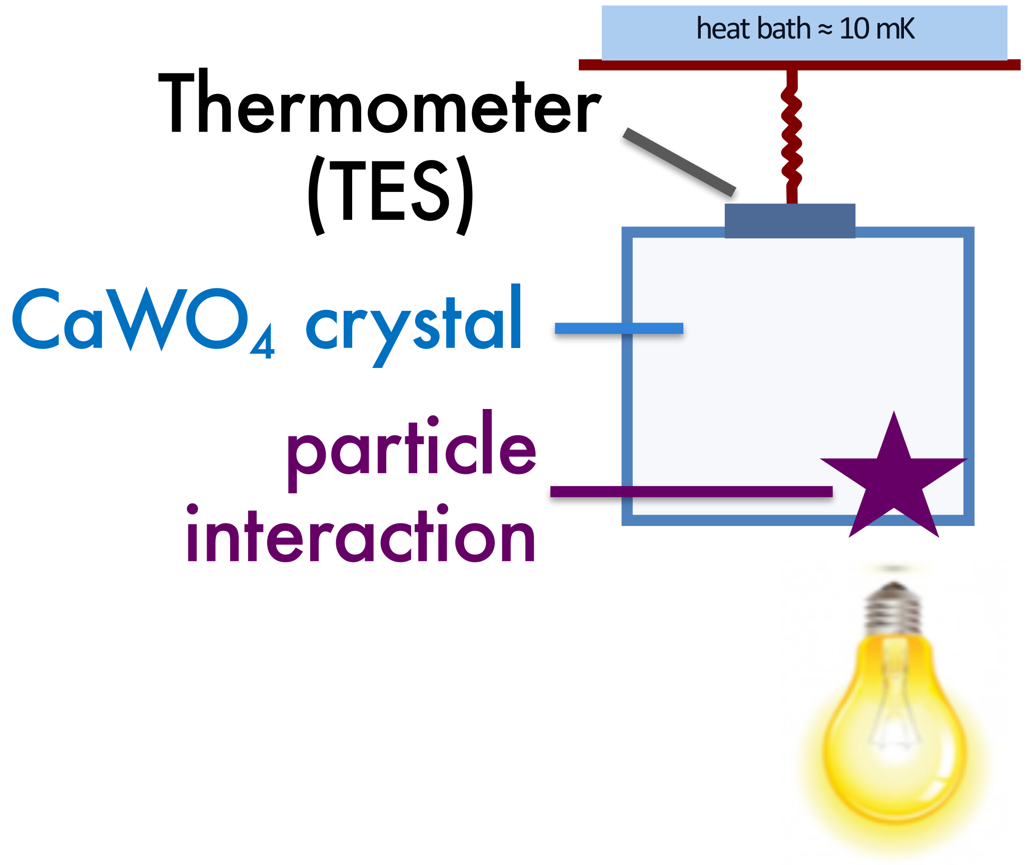


Phonon signal (≳90 %)

(almost) independent of particle type

precise measurement of the deposited energy

SCINTILLATING CALORIMETER



Phonon signal (≳90 %)

(almost) independent of particle type

precise measurement of the deposited energy

Scintillation light (few %)

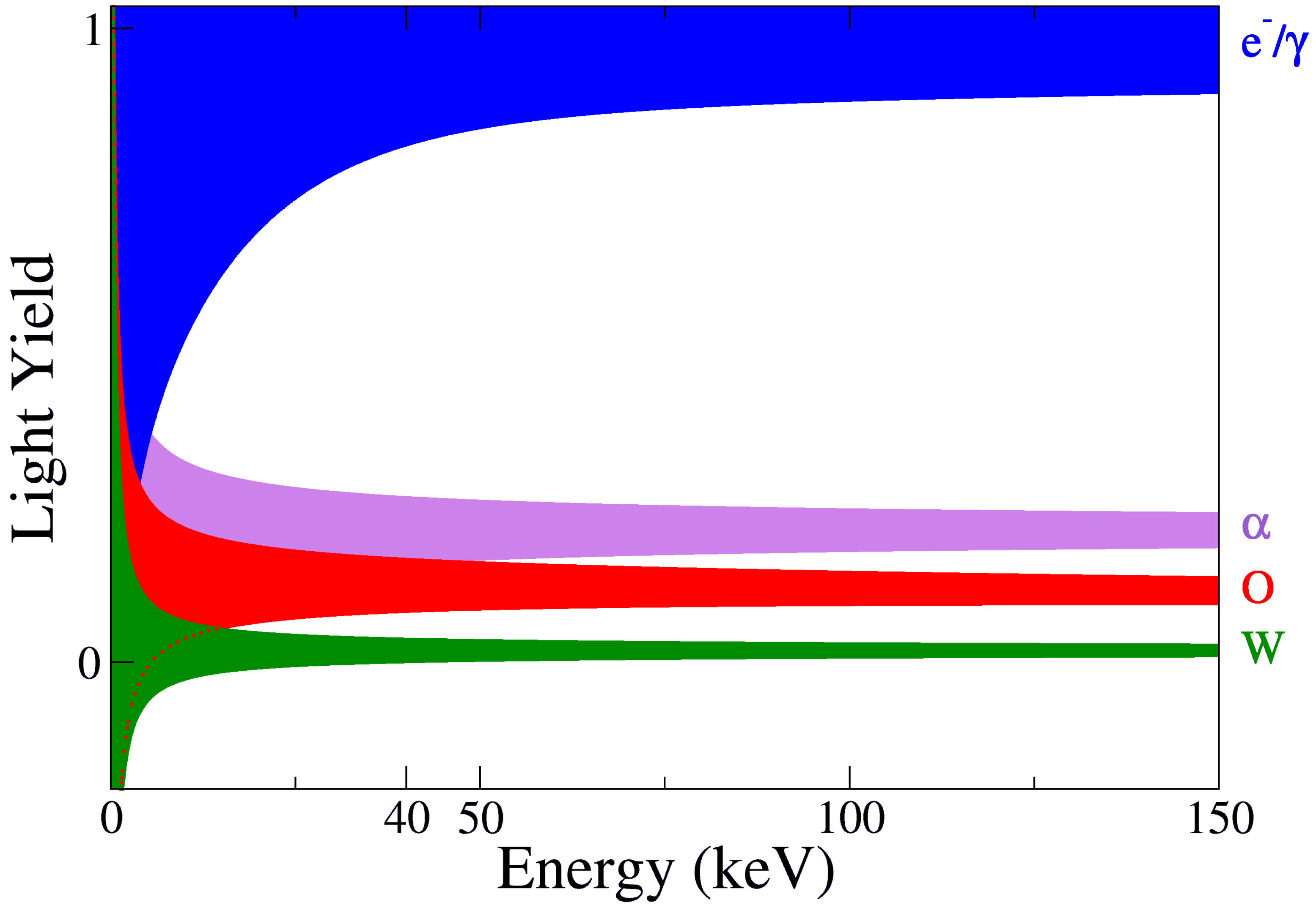
Particle-type dependent
→ LIGHT QUENCHING

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**)

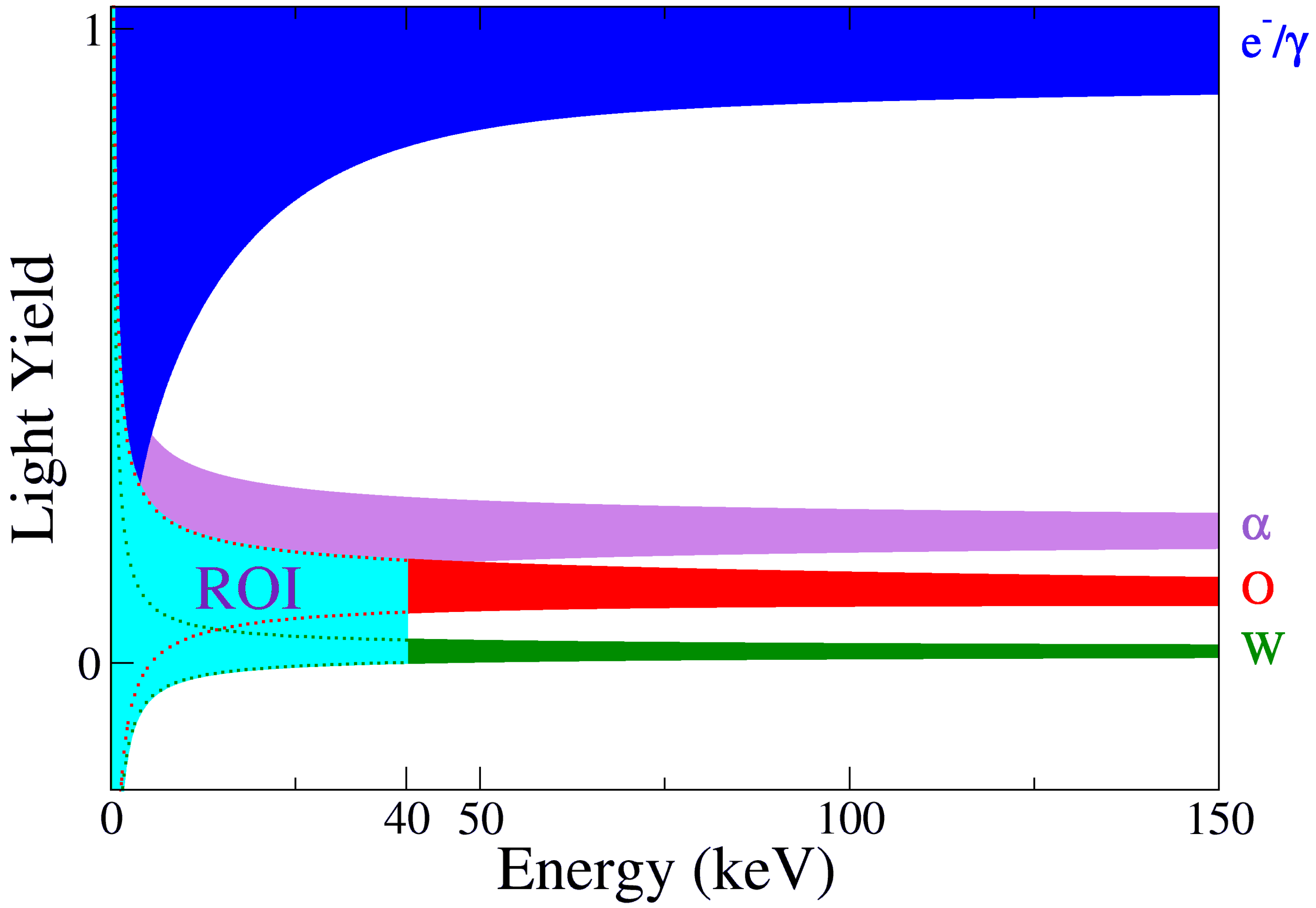


EVENT DISCRIMINATION

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

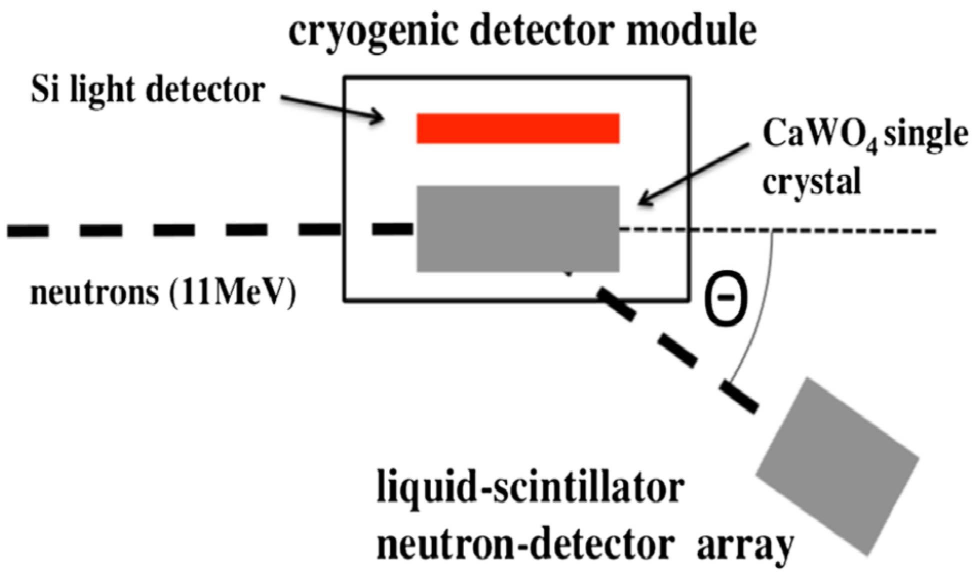
Characteristic of the event type

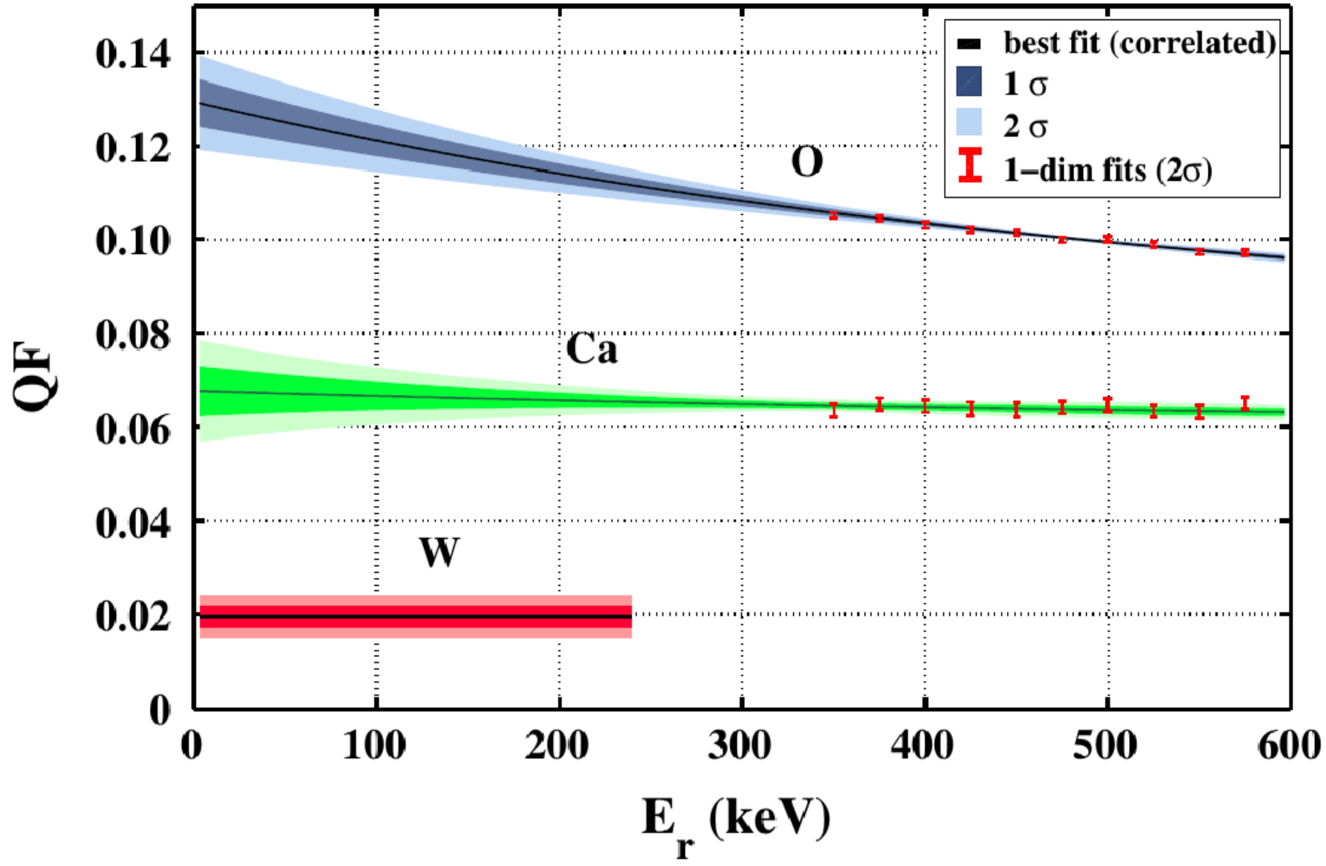
ROI : region of interest
for dark matter search



QUENCHING FACTOR MEASUREMENT

@ accelerator of Maier-Leibnitz-Laboratorium



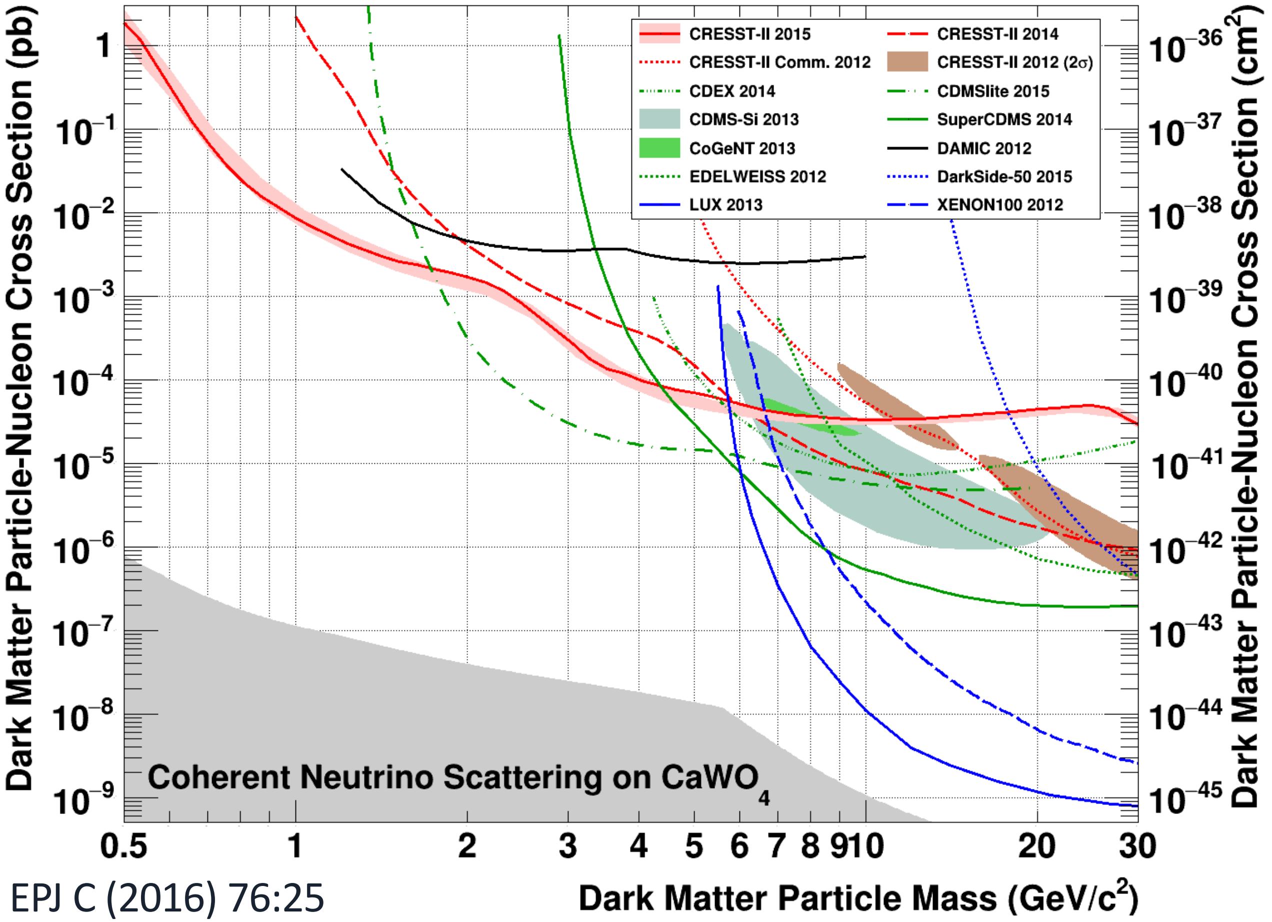


Precise determination of QFs for O, Ca & W **@mK temperatures**

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

CRESST-II RESULTS

Lise: Background level ≈8.5 counts/(keV kg day)
Threshold: 307eV



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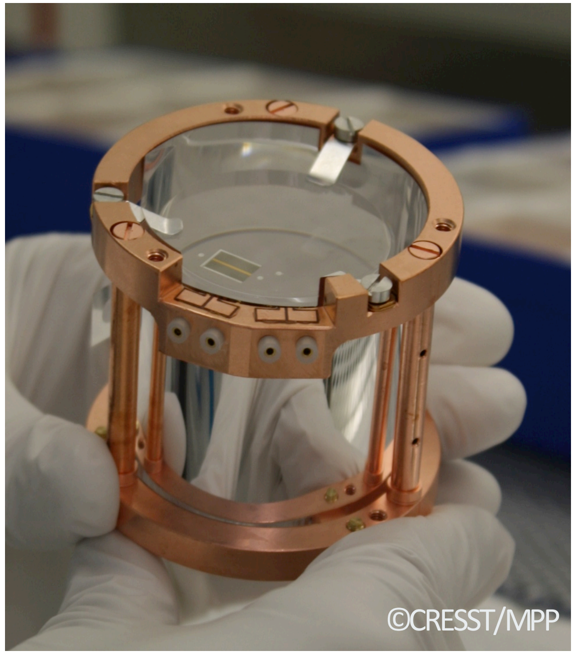
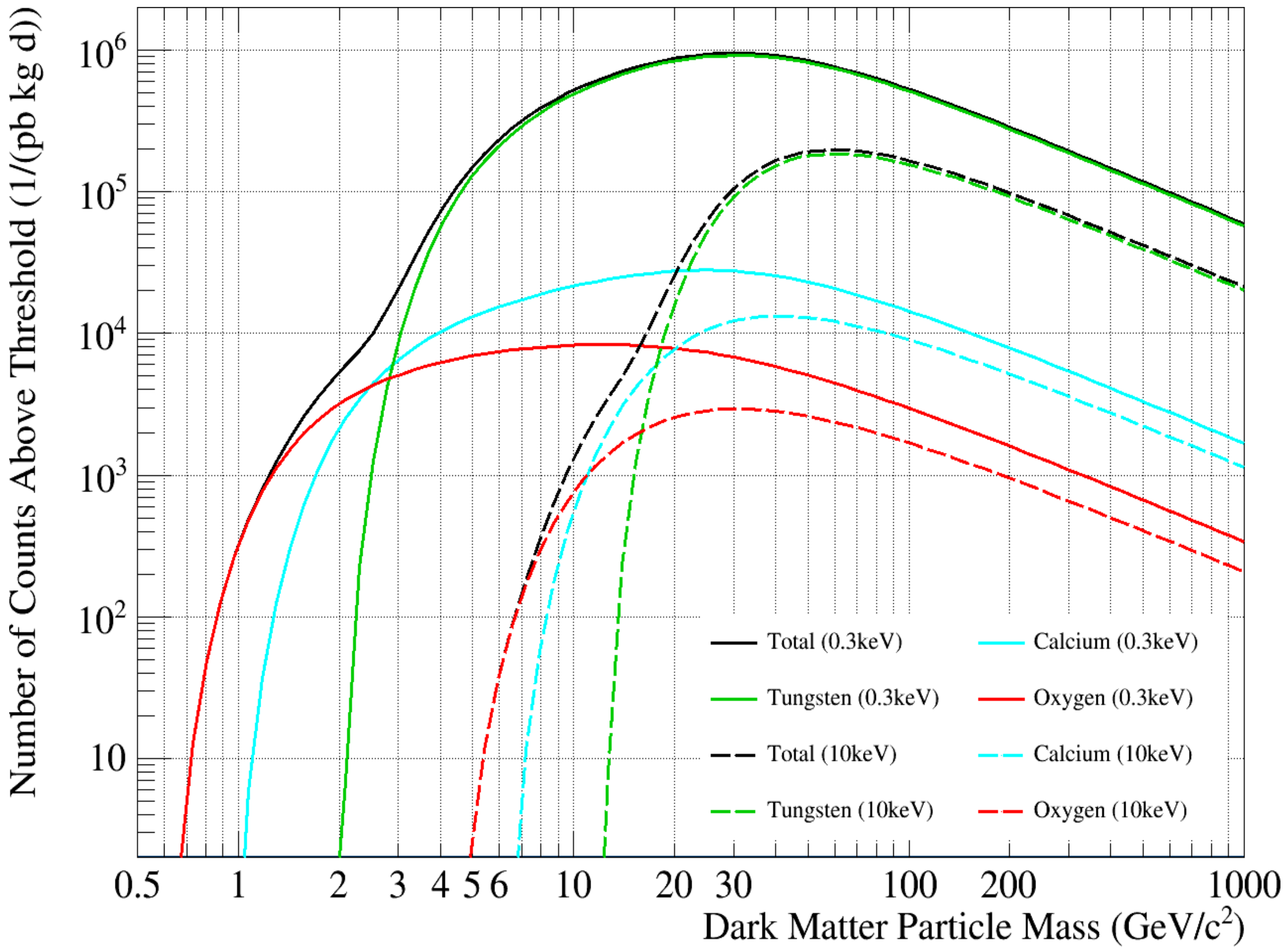


World-leading below $1.7 GeV/c^2$

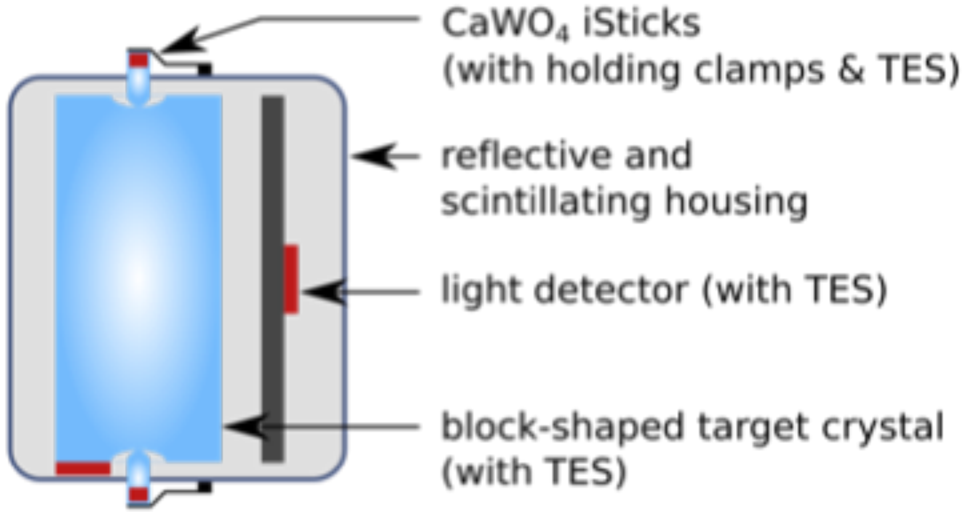
Exploring new parameter space down to $0.5 GeV/c^2$

Hunting light dark matter requires a low threshold!

LOW THRESHOLD DETECTORS



CRESST-III LOW-THRESHOLD DETECTORS



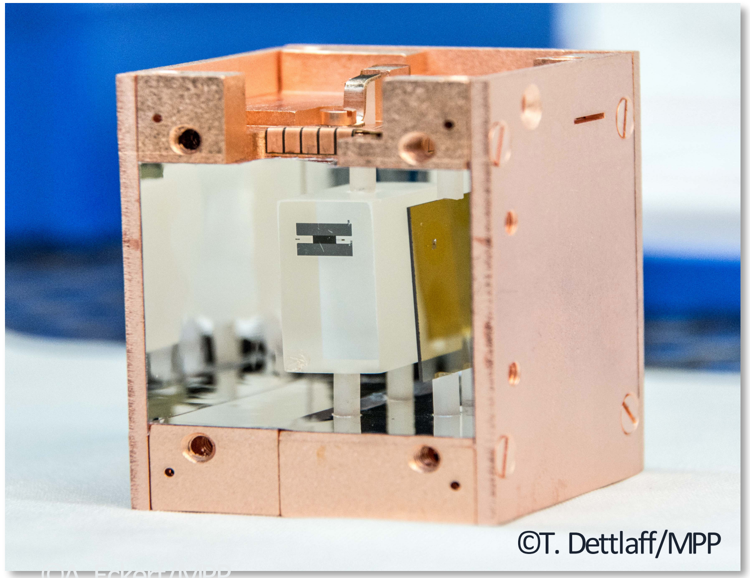
Detector layout optimized for low-mass dark matter

Radical reduction of dimension (250g → 24g)

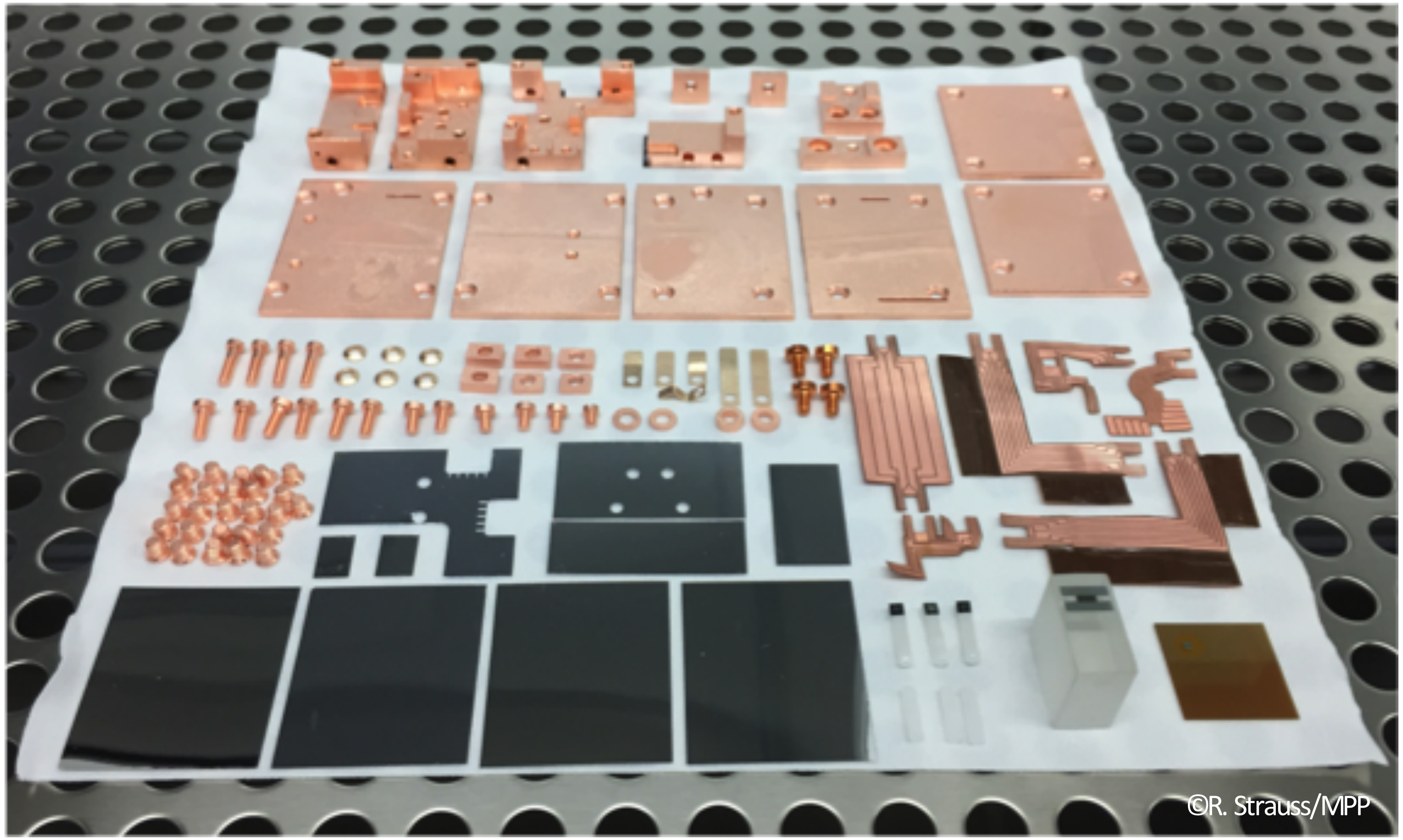
- Cuboid crystals of $(20\times20\times10)\text{mm}^3$ (≈**24g**)
- Threshold design goal **100 eV threshold**

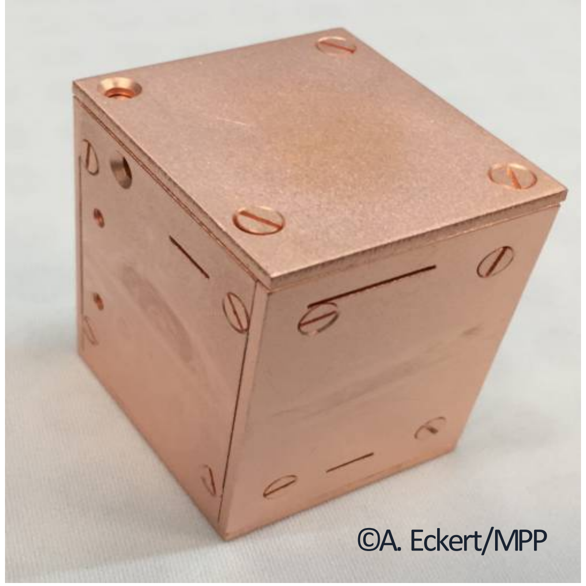
- Fully scintillating housing
- Instrumented sticks

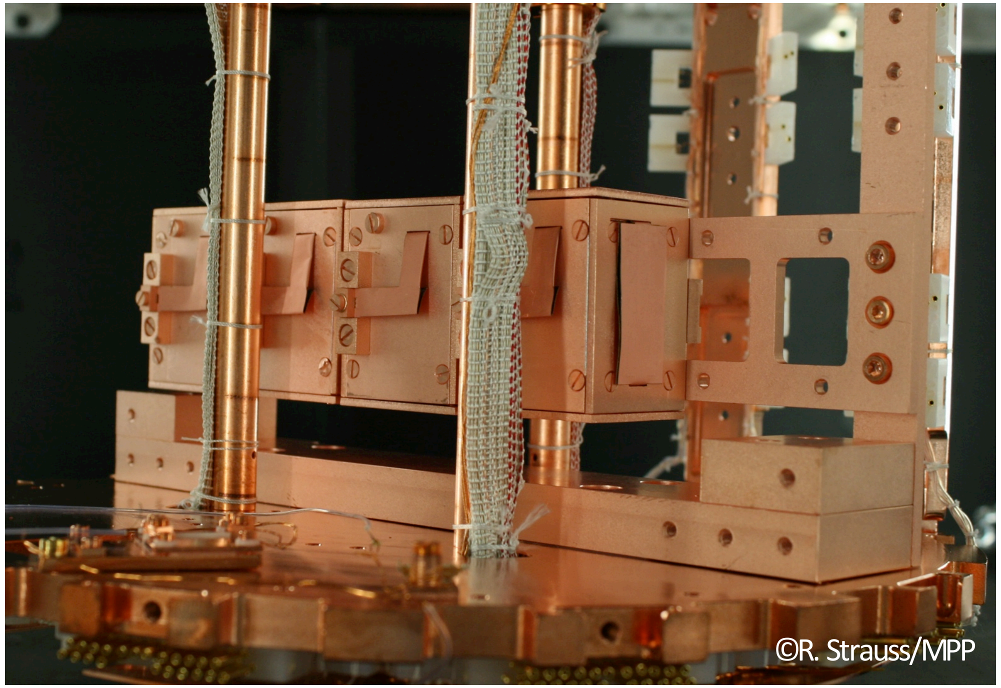
} Veto surface-related background



CRESST-III PHASE 1





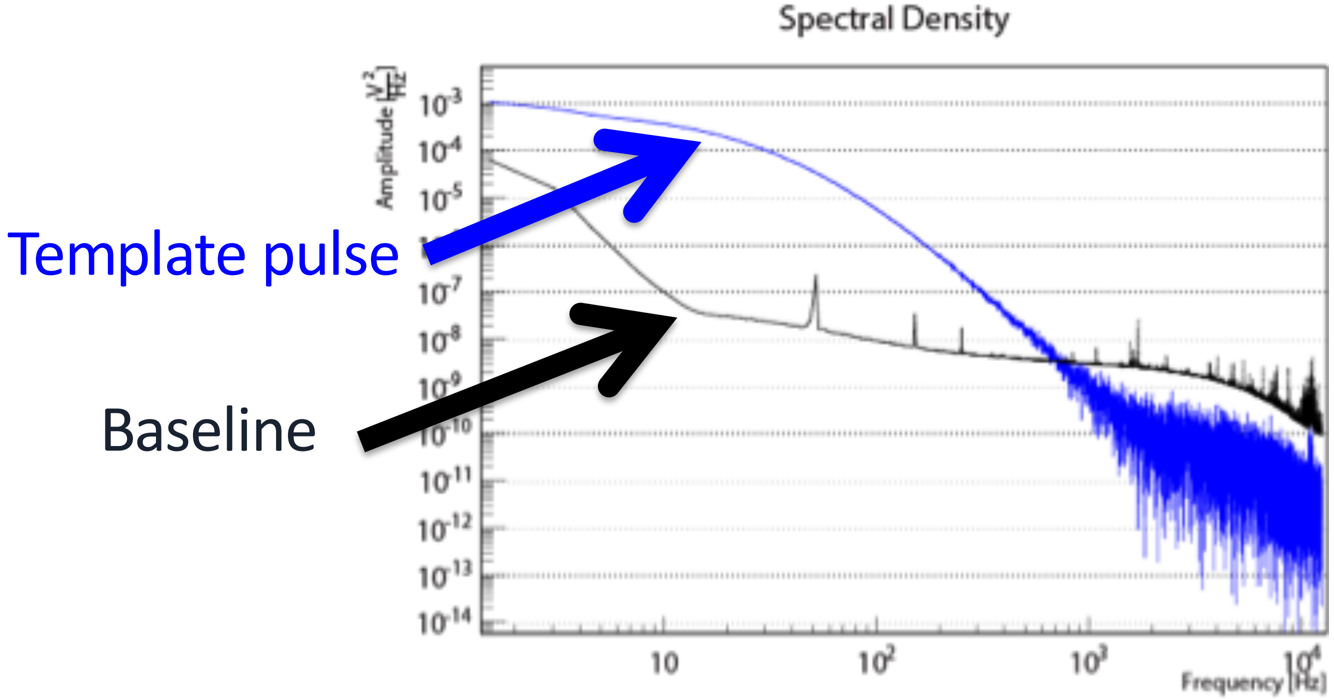


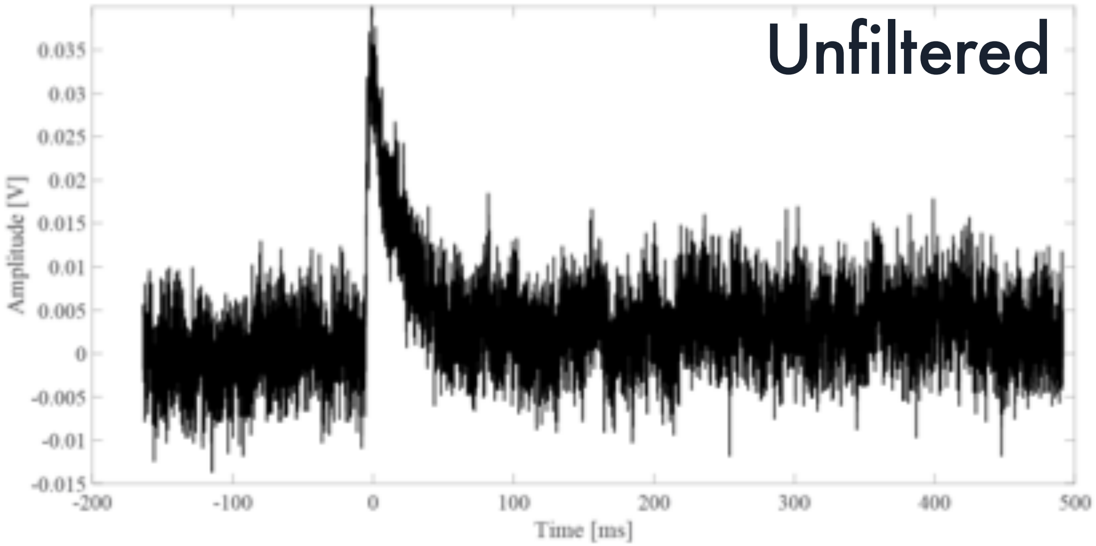
Data taking from July 2016 to February 2018

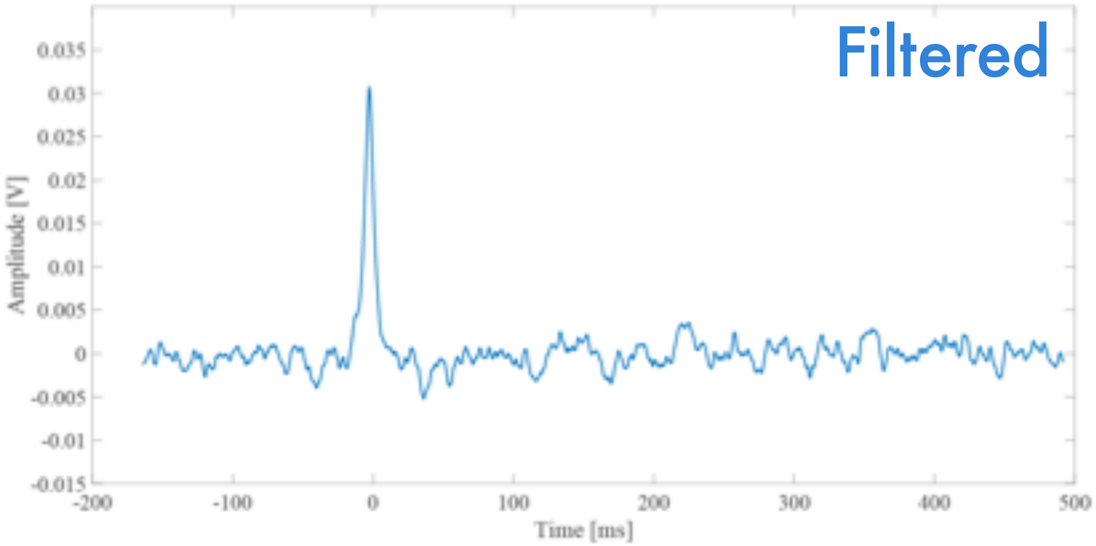
OPTIMUM FILTER

Maximizes signal-to-noise ratio (in frequency space)

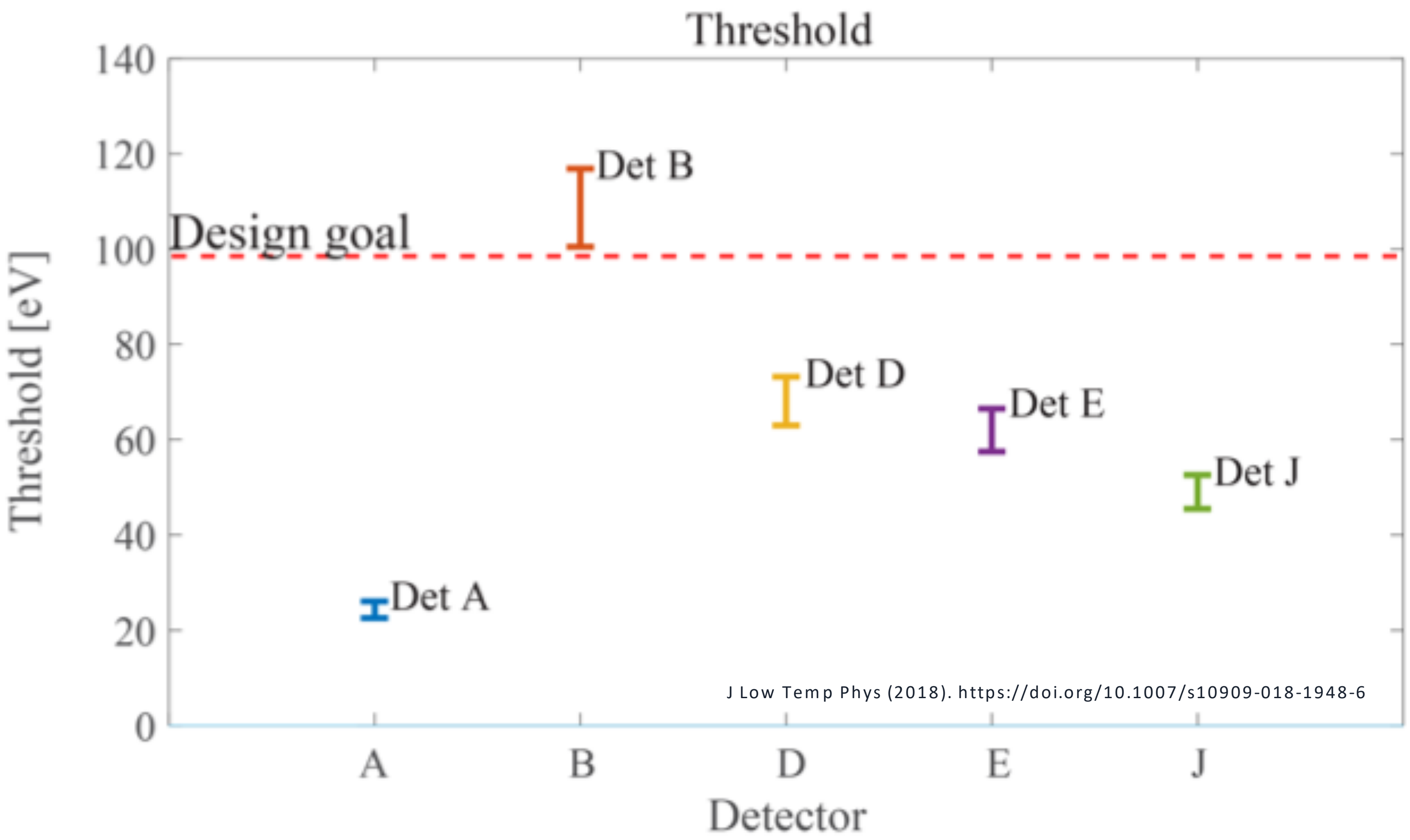
Factor 2-3 typical improvement in resolution





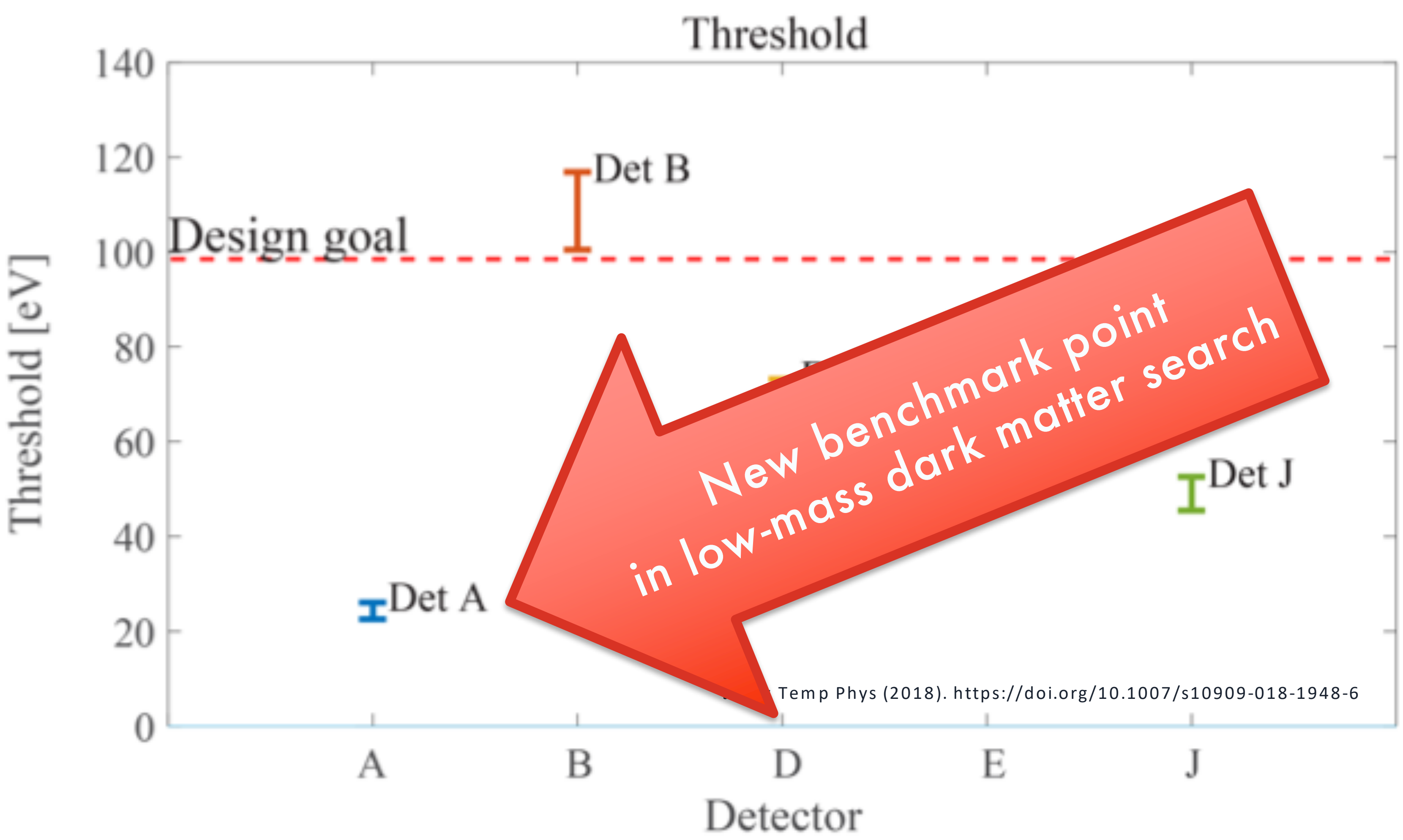


OPTIMUM THRESHOLDS: NEW FRONTIER IN DIRECT DM DETECTION



5 detectors reach/exceed the CRESST-III design goal

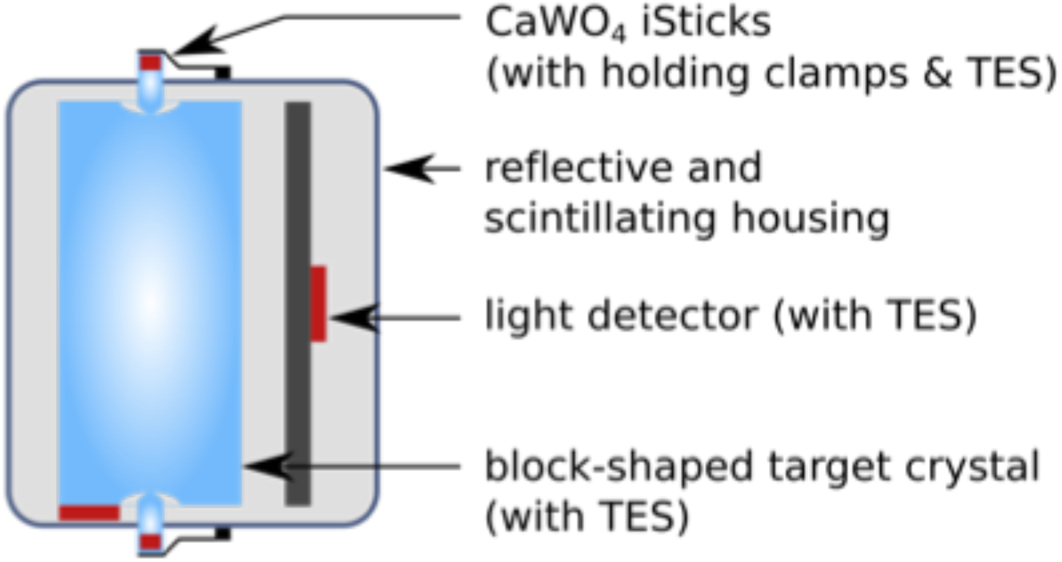
OPTIMUM THRESHOLDS: NEW FRONTIER IN DIRECT DM DETECTION

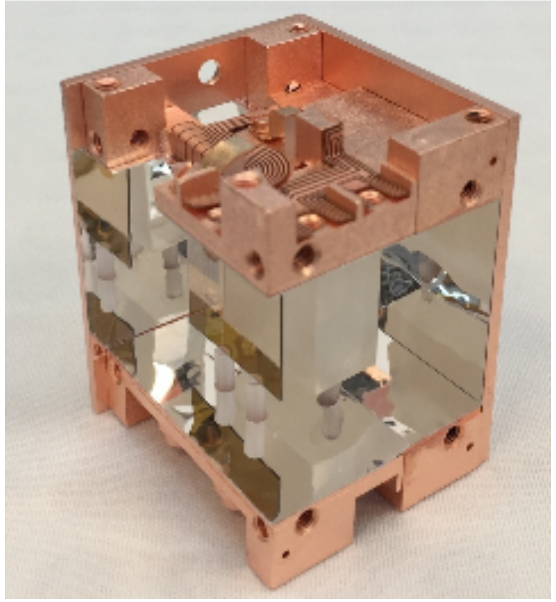


5 detectors reach/exceed the CRESST-III design goal

DETECTOR A

= LOWEST THRESHOLD IN CRESST-III PHASE 1

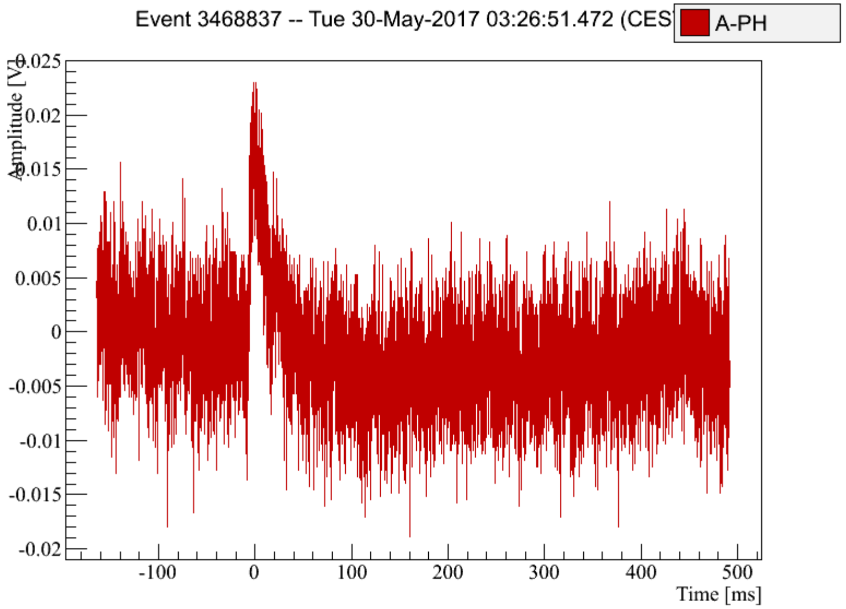


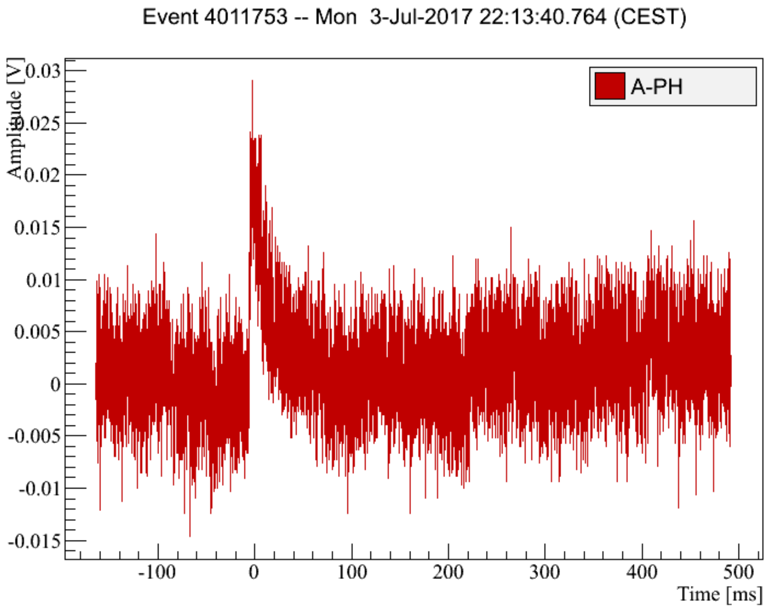


Data taking period:	10/2016 – 05/2017
Non-blind data (dynamically growing):	20% randomly selected
Target crystal mass:	24g
Gross exposure (before cuts):	2.39 kg days
Analysis threshold:	100 eV

DET. A – 100eV EVENT EXAMPLES

Raw signals: no filtering, fitting etc.





100eV pulses are no challenge for amplitude determination

DET. A – 100eV THRESHOLD ANALYSIS

SELECTION CRITERIA (AKA "CUTS")

Objective

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

Unbiased (blind) analysis

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

DET. A – 100eV THRESHOLD ANALYSIS

SELECTION CRITERIA (AKA "CUTS")

Rate: noise conditions

Stability: Detector(s) in operating point

Data quality: Non-standard pulse shapes (in particular iStick events and pileup)

Coincidences: with muon veto and iSticks only (will be expanded to "with other detector modules")

DET. A – 100eV THRESHOLD ANALYSIS

EXPOSURE AFTER RATE AND STABILITY CUT

Rate, Stability:

92.5% survival = 2.21 kg days net exposure

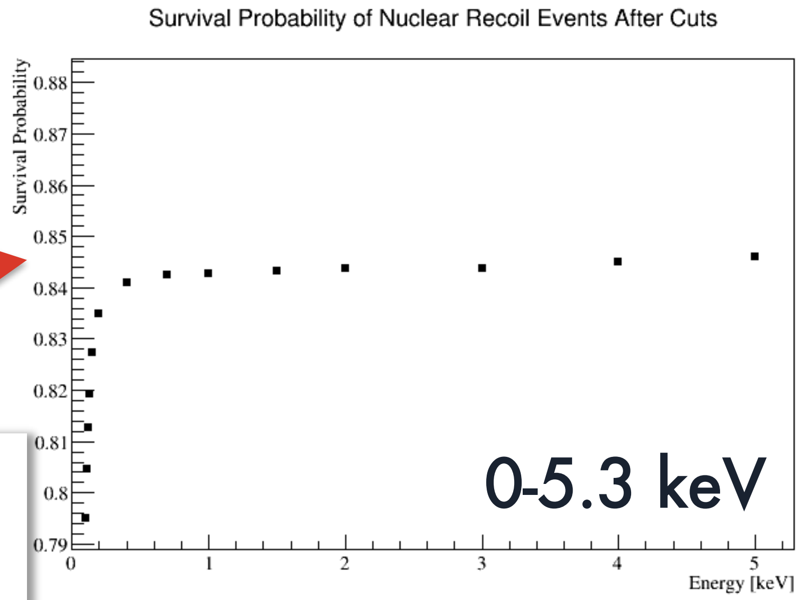
DET. A – 100eV THRESHOLD ANALYSIS

EFFICIENCY OF DATA QUALITY CUTS

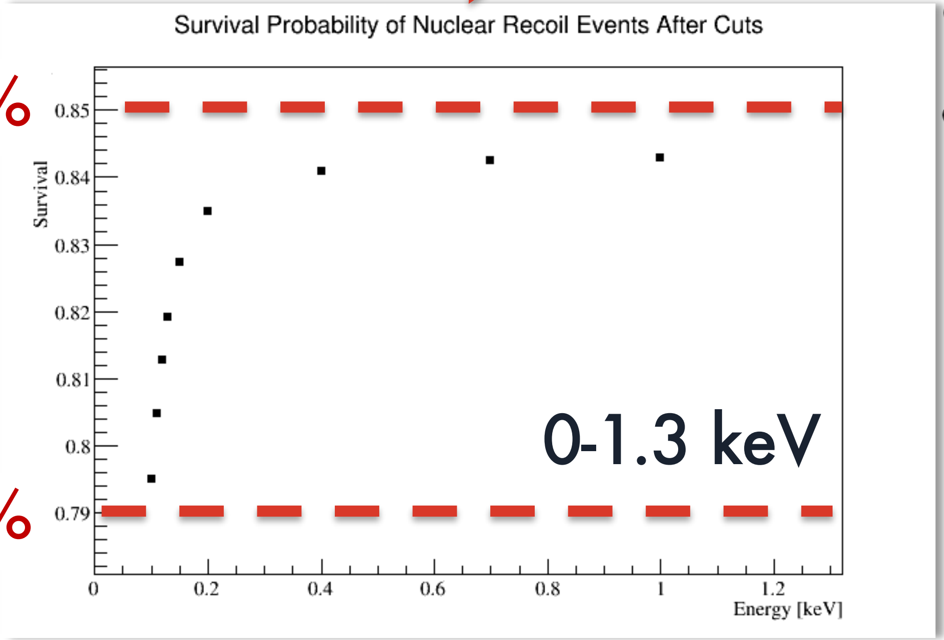
Rate, Stability:

92.5% survival = 2.21 kg days net exposure

Data quality, Coincidences



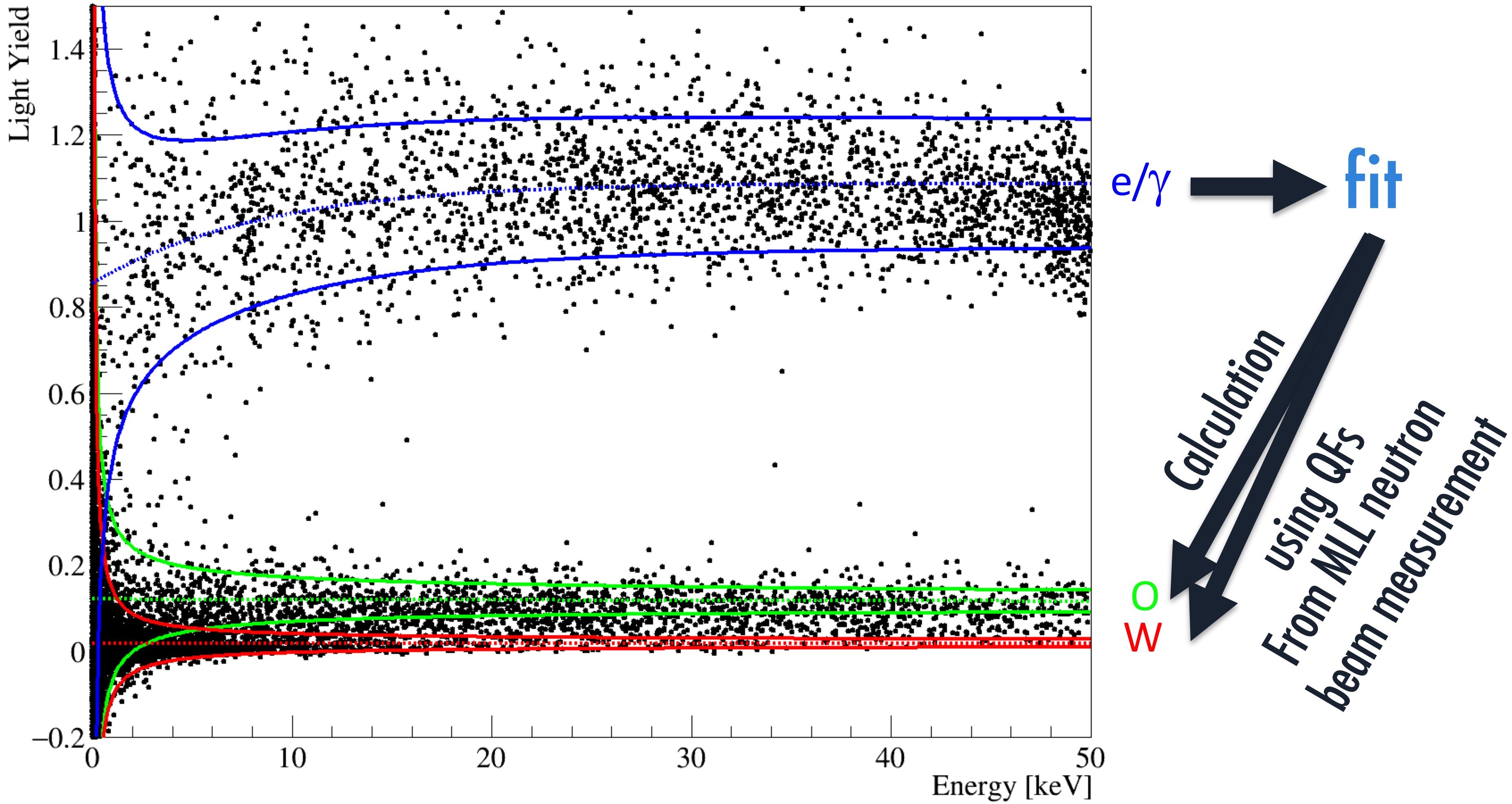
85%



79%

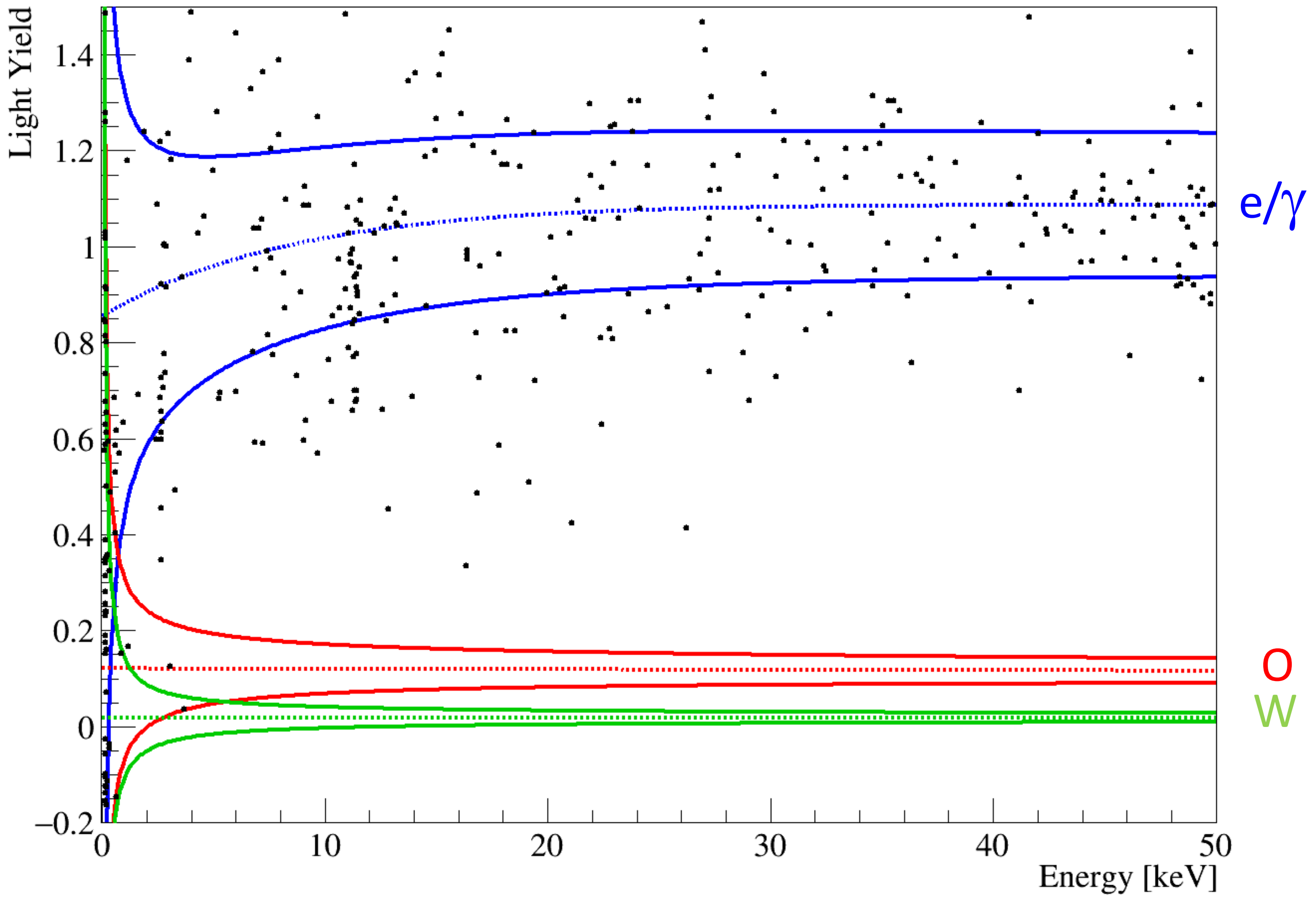
79.5% at threshold of 100eV

DET. A – 100eV THRESHOLD ANALYSIS
NEUTRON CALIBRATION DATA



DET. A – 100eV THRESHOLD ANALYSIS

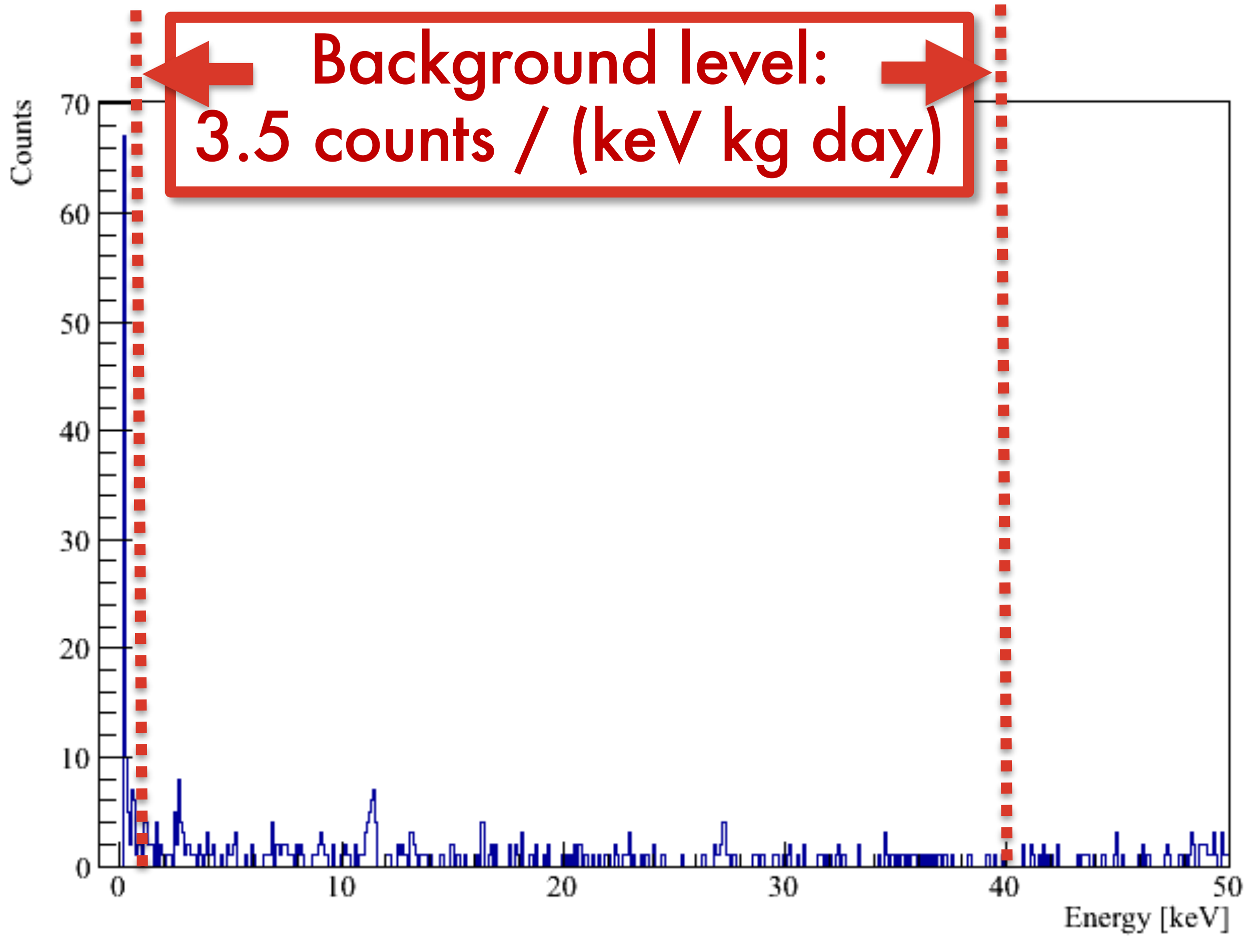
DARK MATTER DATA – LIGHT YIELD



Unblinded:
Det. A
E>100eV

Still blinded:
Det. ≠ A
E<100eV

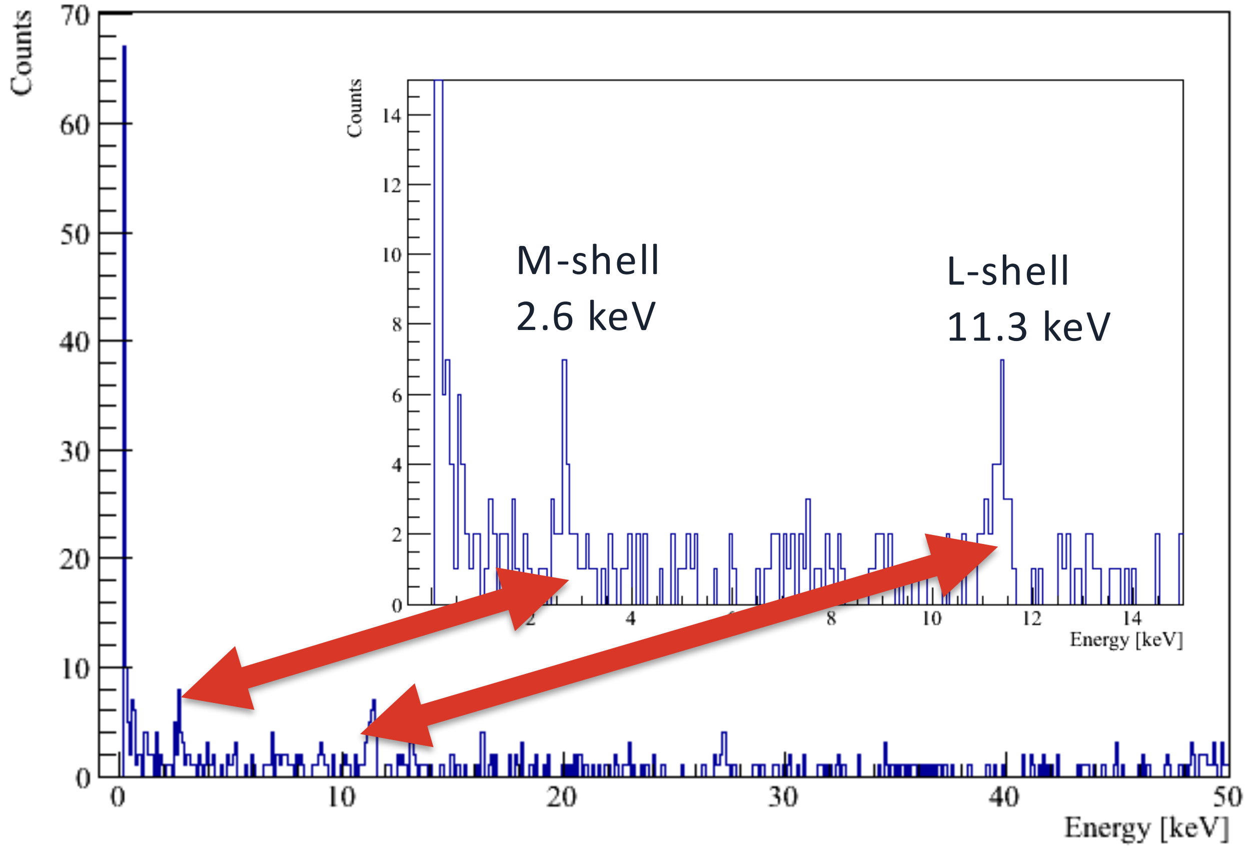
DET. A – 100eV THRESHOLD ANALYSIS
DARK MATTER DATA – ENERGY SPECTRUM



DET. A – 100eV THRESHOLD ANALYSIS

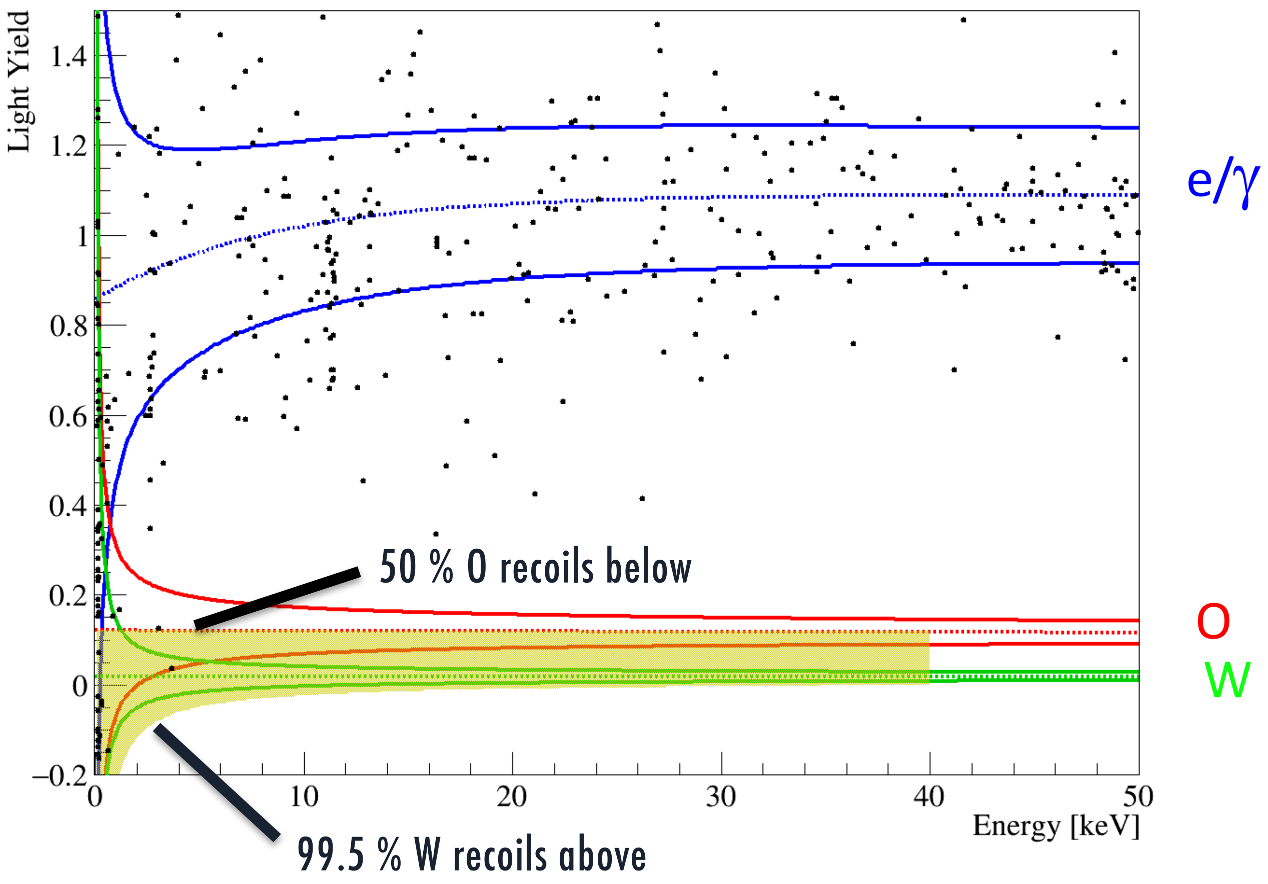
DARK MATTER DATA – ENERGY SPECTRUM

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



DET. A – 100eV THRESHOLD ANALYSIS

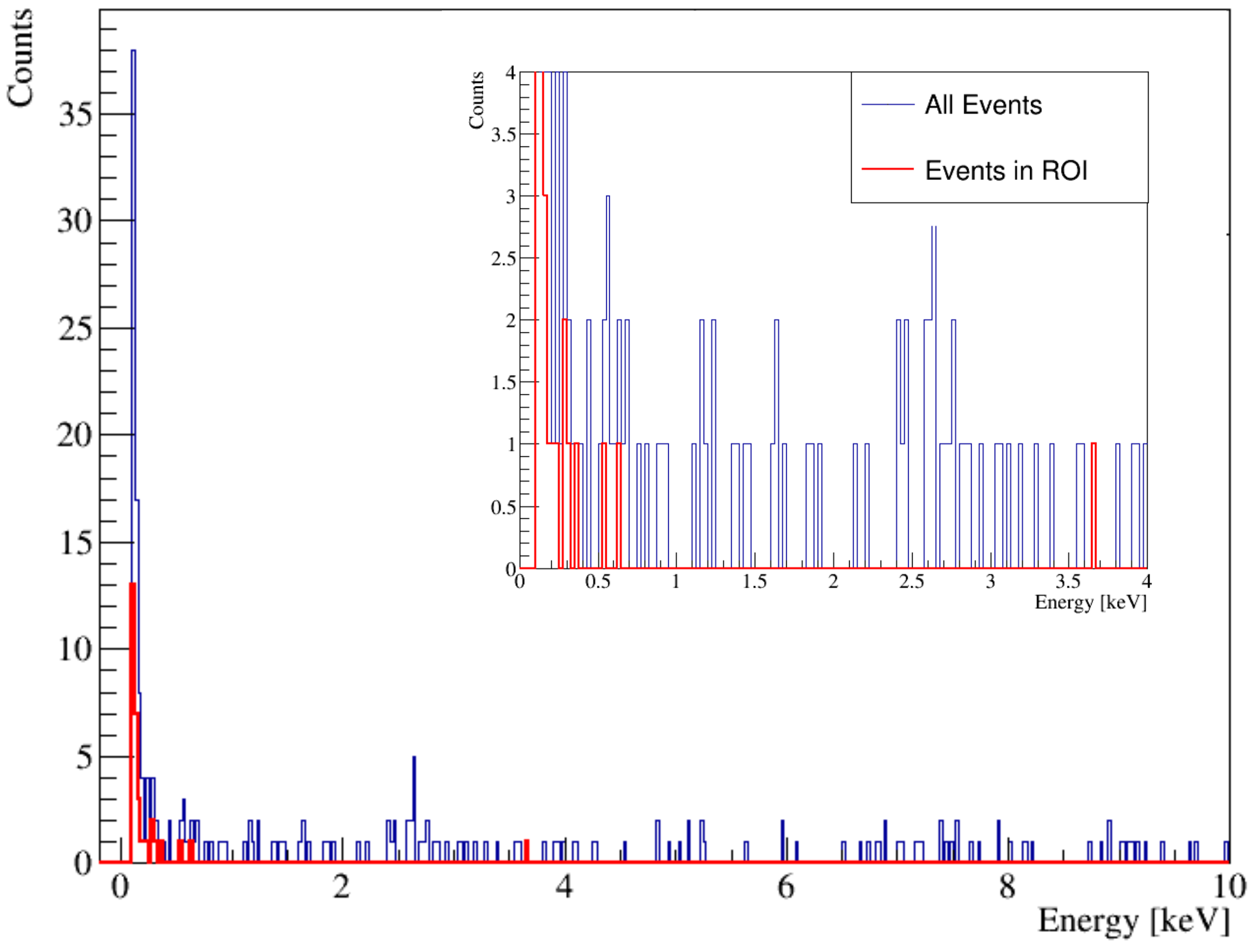
DARK MATTER DATA → DARK MATTER LIMIT



Acceptance region fixed before unblinding

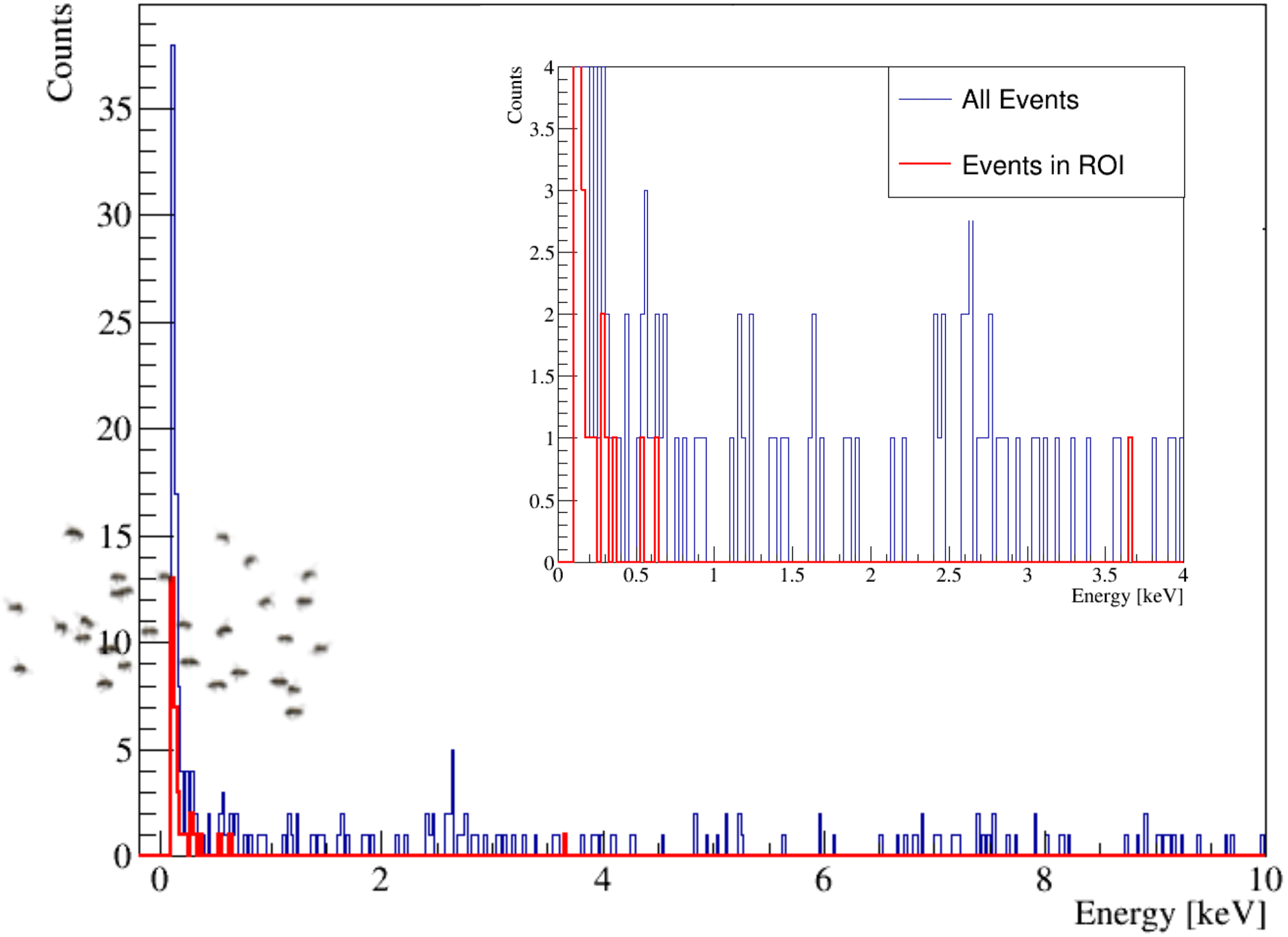
DET. A – 100eV THRESHOLD ANALYSIS
DARK MATTER DATA – ACCEPTED EVENTS

Accepted events (red) → Yellin's optimal interval method → limit on DM-nucleon cross-section



DET. A – 100eV THRESHOLD ANALYSIS
DARK MATTER DATA – ACCEPTED EVENTS

Accepted events (red) → Yellin's optimal interval method
→ limit on DM-nucleon cross-section



DET. A – 100eV THRESHOLD ANALYSIS

DARK MATTER DATA – ACCEPTED EVENTS

Accepted events (red) → Yellin's optimal interval method
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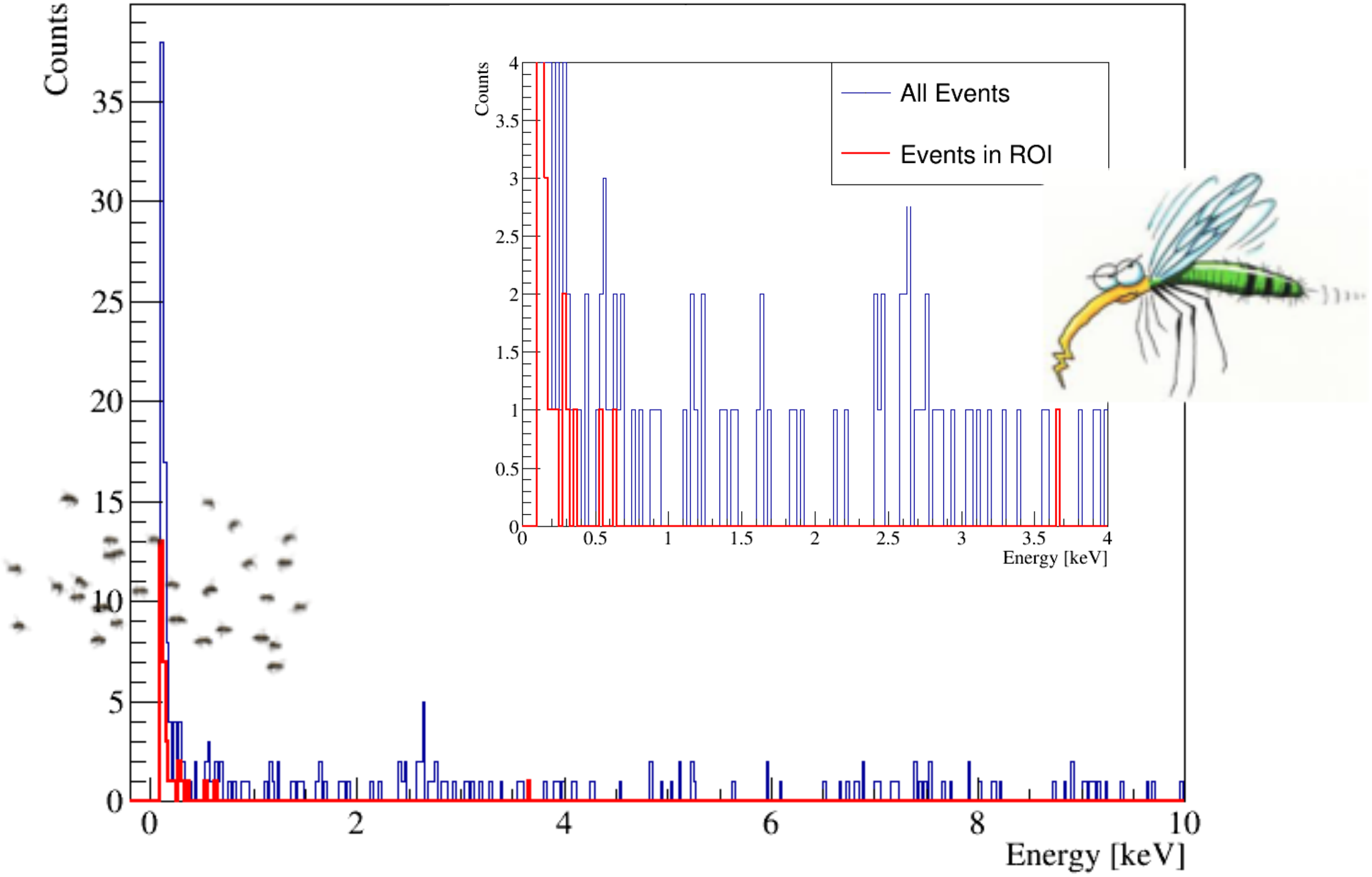
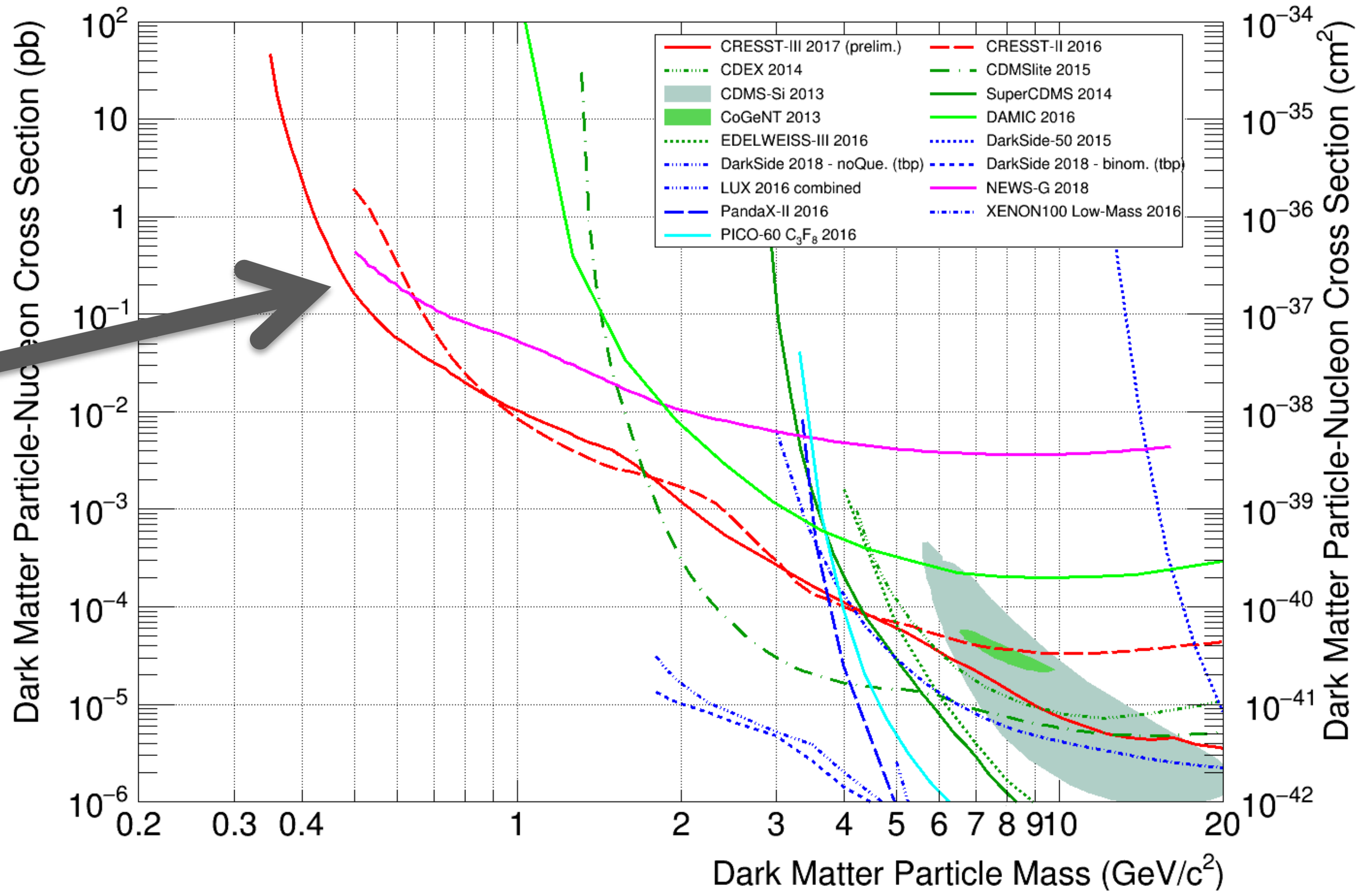


FROM ACCEPTED EVENTS TO DARK MATTER LIMITS

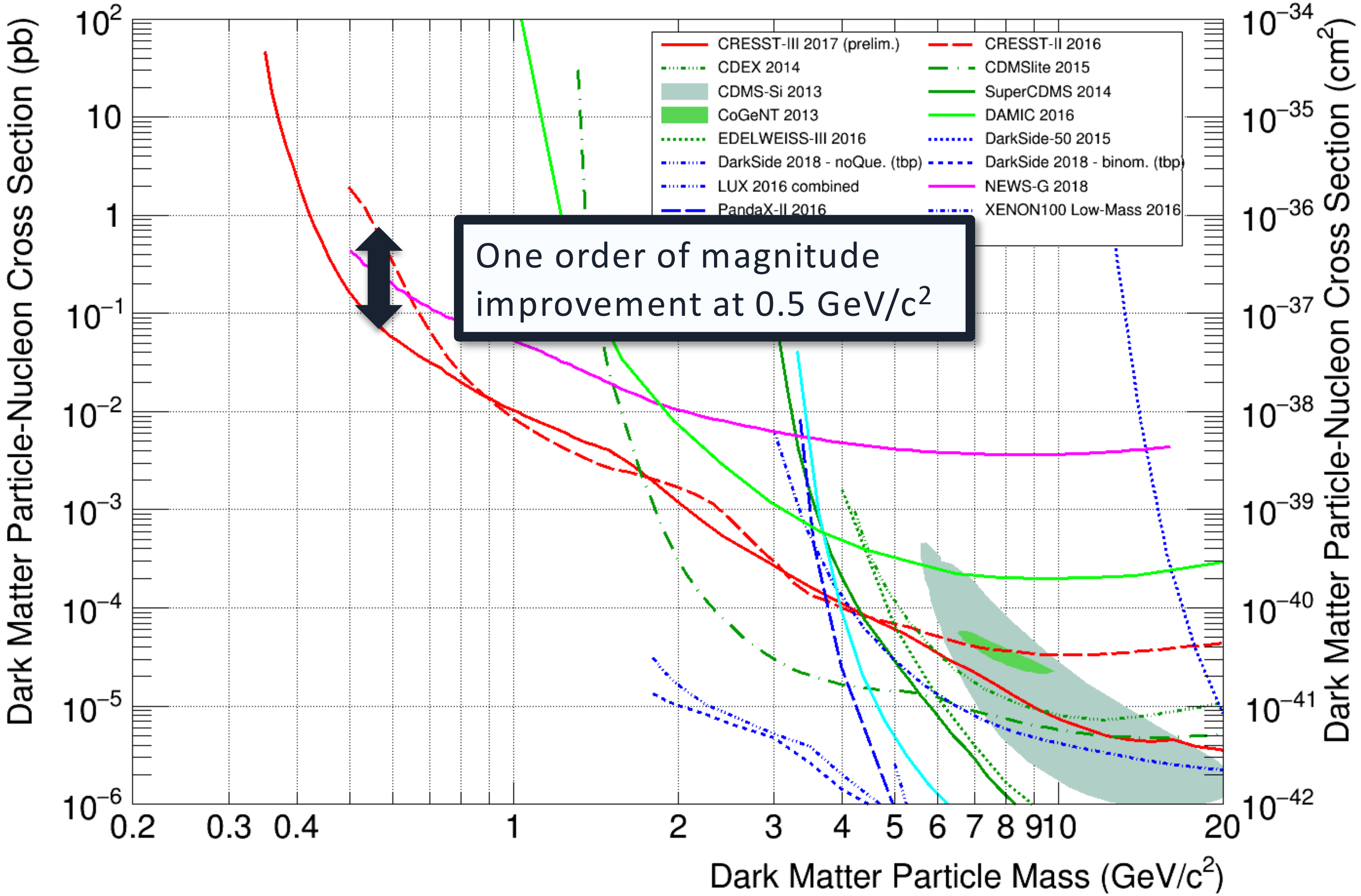
Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM



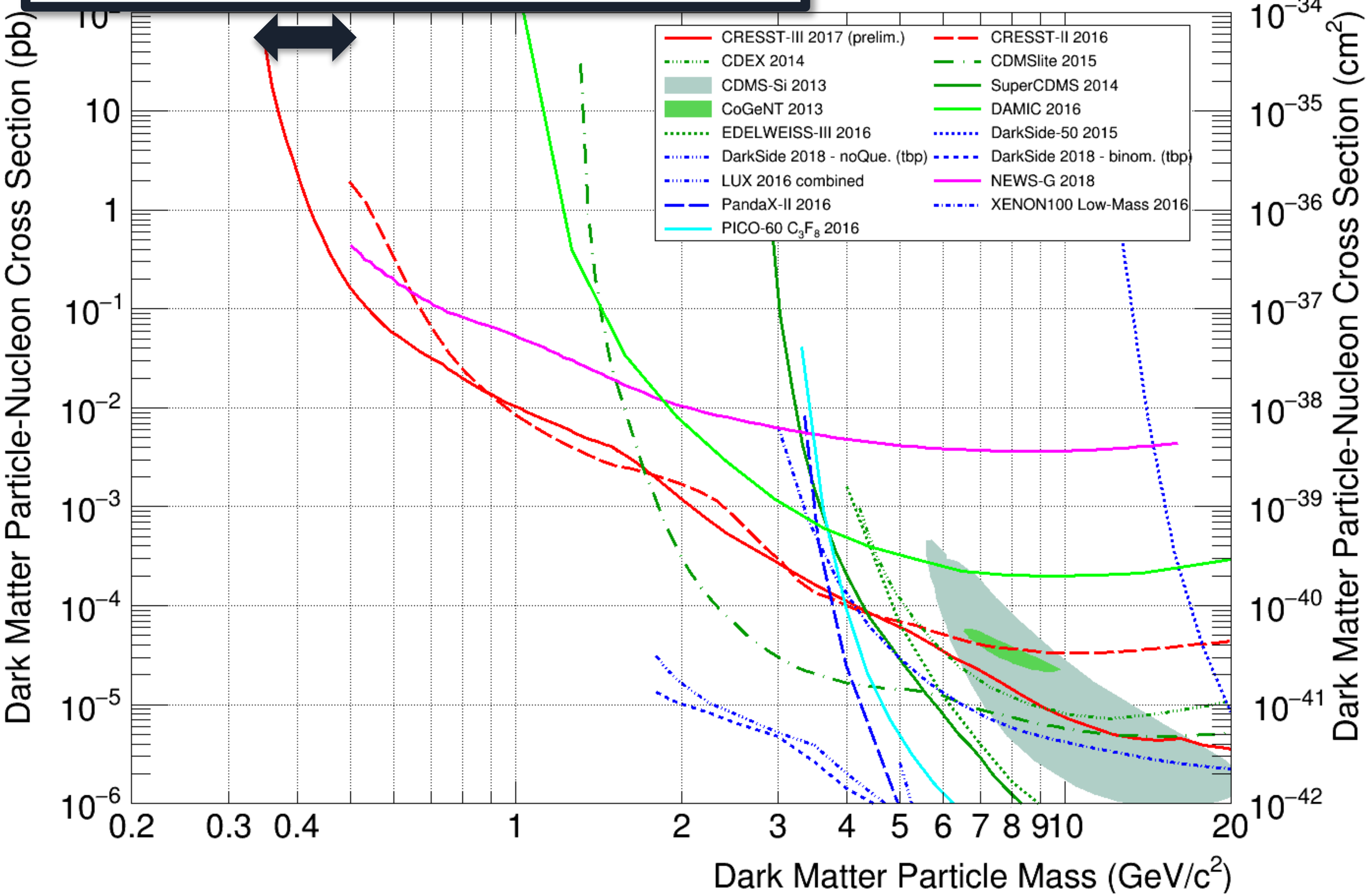
DET. A – 100eV THRESHOLD ANALYSIS
RESULT



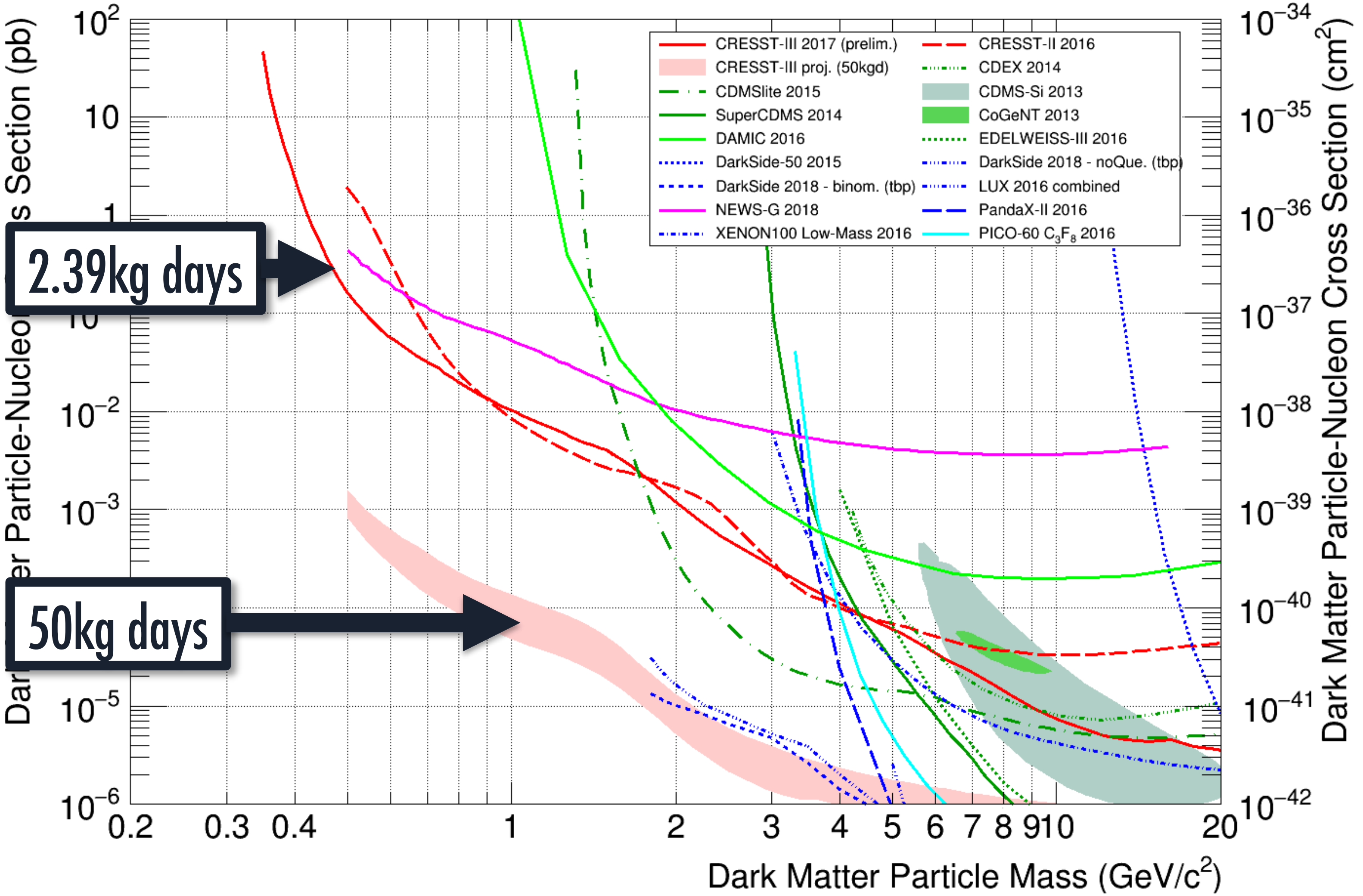
DET. A – 100eV THRESHOLD ANALYSIS

RESULT

Extend reach from 0.5 GeV/c² to 0.35GeV/c²

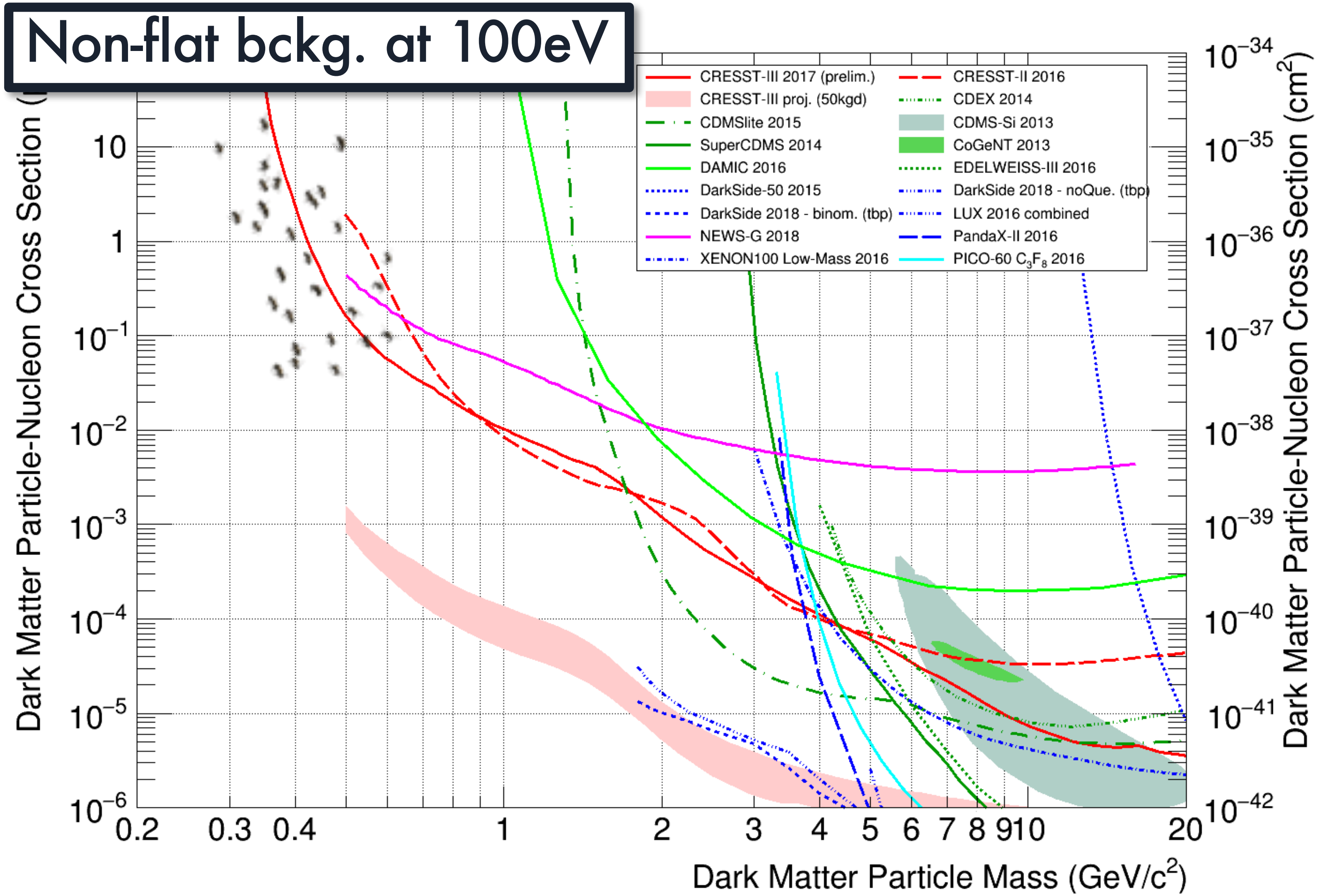


DET. A – 100eV THRESHOLD ANALYSIS
RESULT



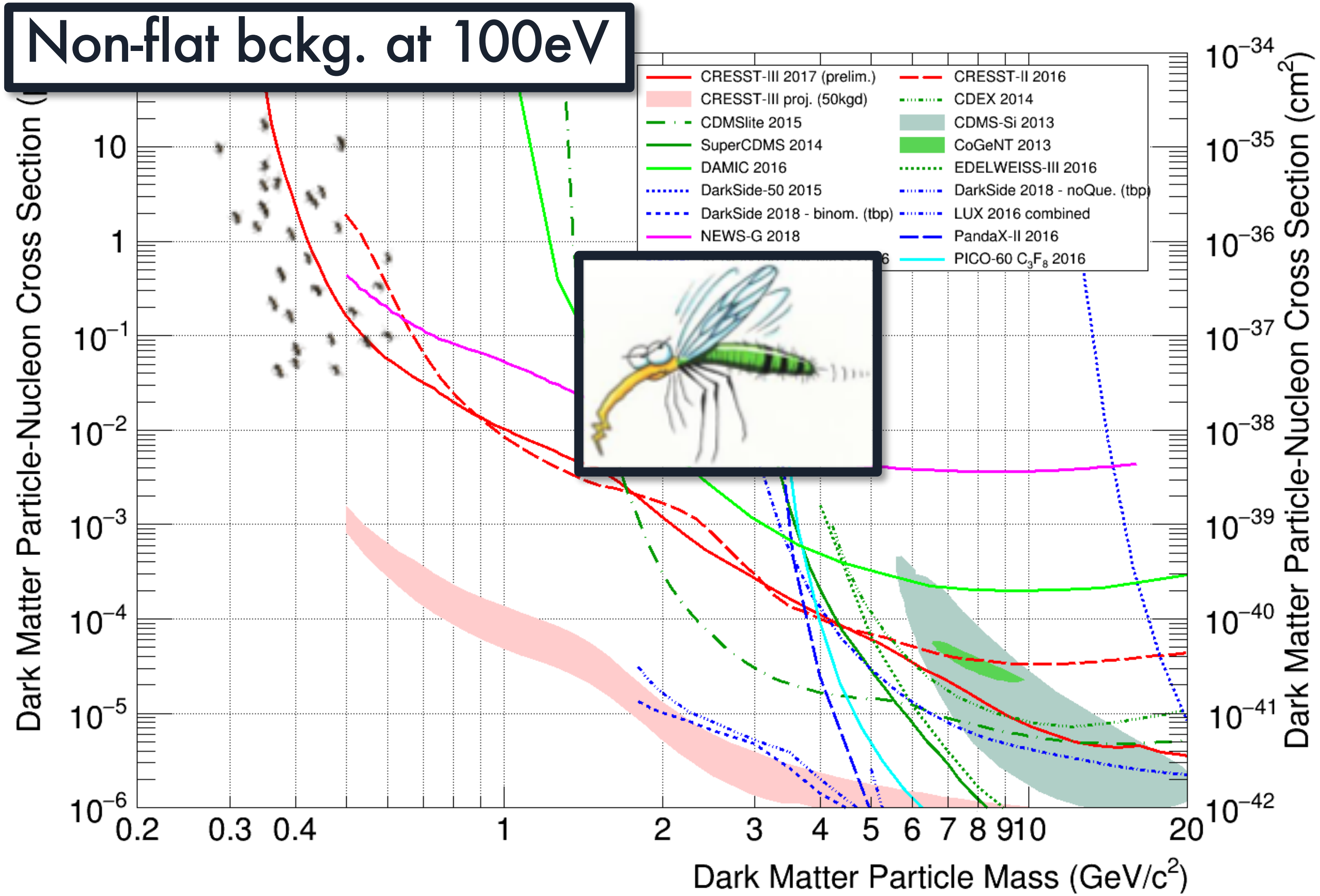
DET. A – 100eV THRESHOLD ANALYSIS

RESULT



DET. A – 100eV THRESHOLD ANALYSIS

RESULT



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

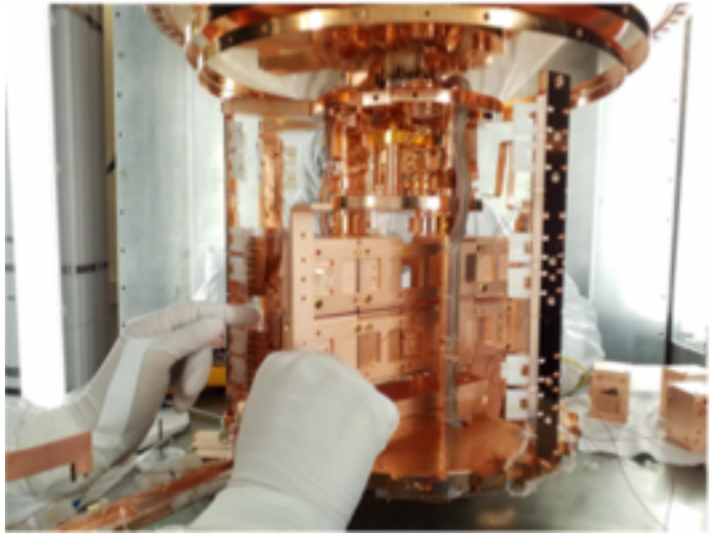
3 other detectors with thresholds << 100eV

3 times more statistics → deeper understanding of backgrounds

SECOND CRESST-III RUN 06/2018: JUST STARTING

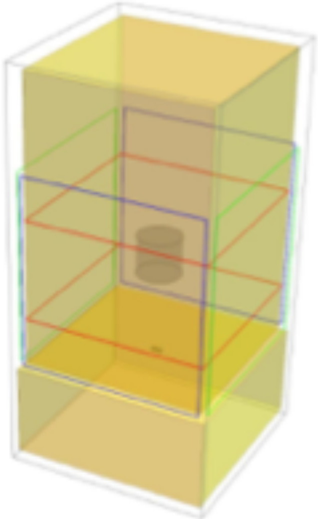
Key innovation

Upgraded detector modules with dedicated hardware changes to understand backgrounds



Additional upgrade

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

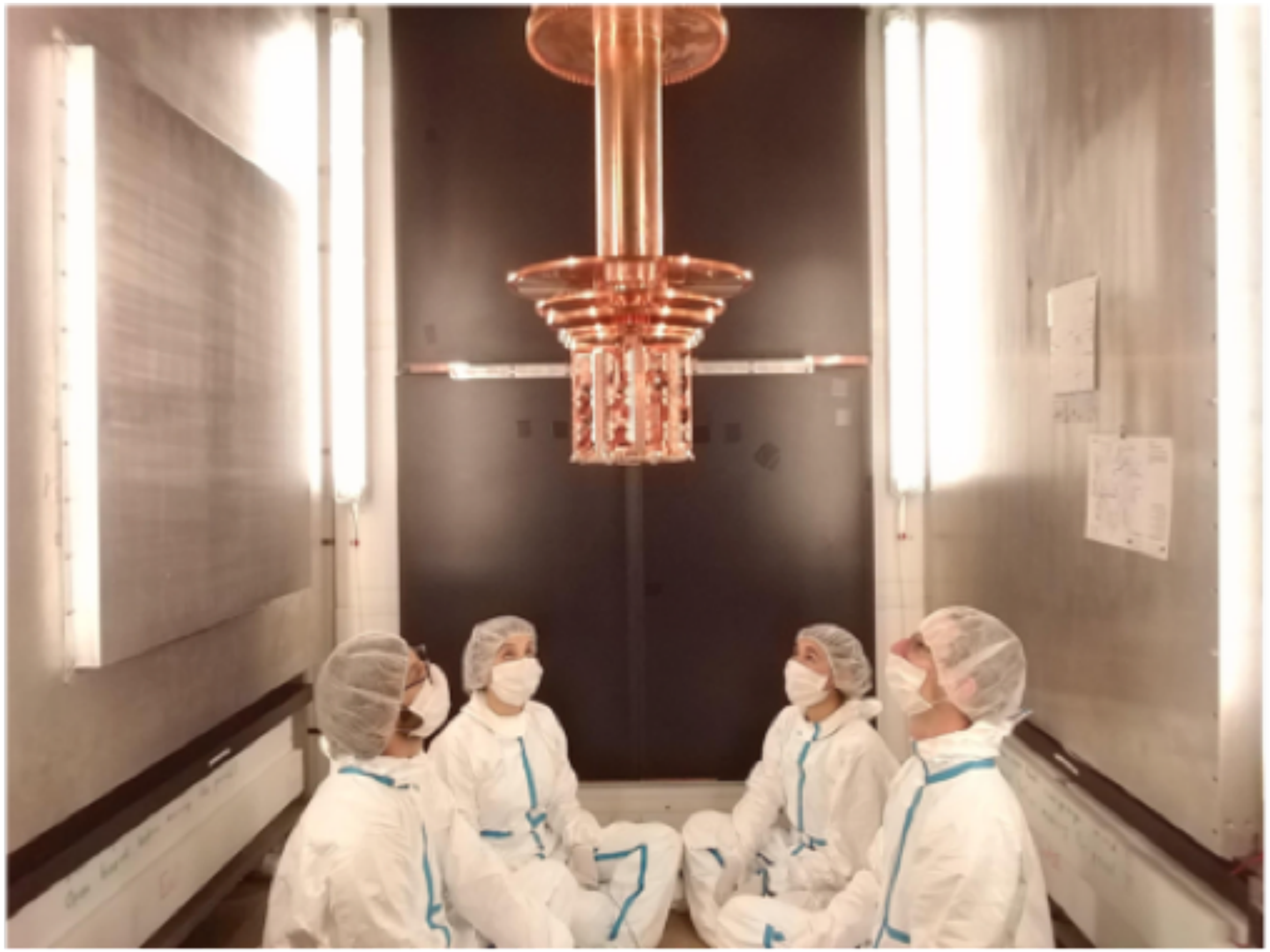


WAITING FOR DARK MATTER

The cryostat is cold

First pulses measured

Commissioning phase



ONE MORE THING ...

LIMIT

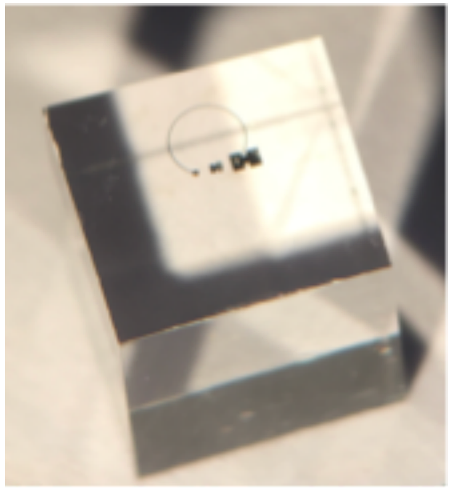
ONE MORE ~~THING~~ ...

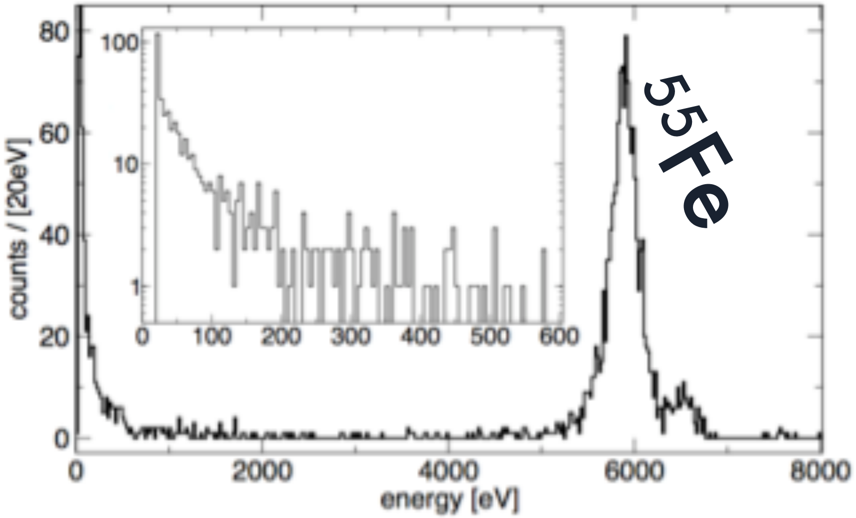
GRAM-SCALE DETECTOR

Al_2O_3 0.49g 5x5x5mm^3

E_{th} = (19.7 ± 0.9) eV

Measured above ground



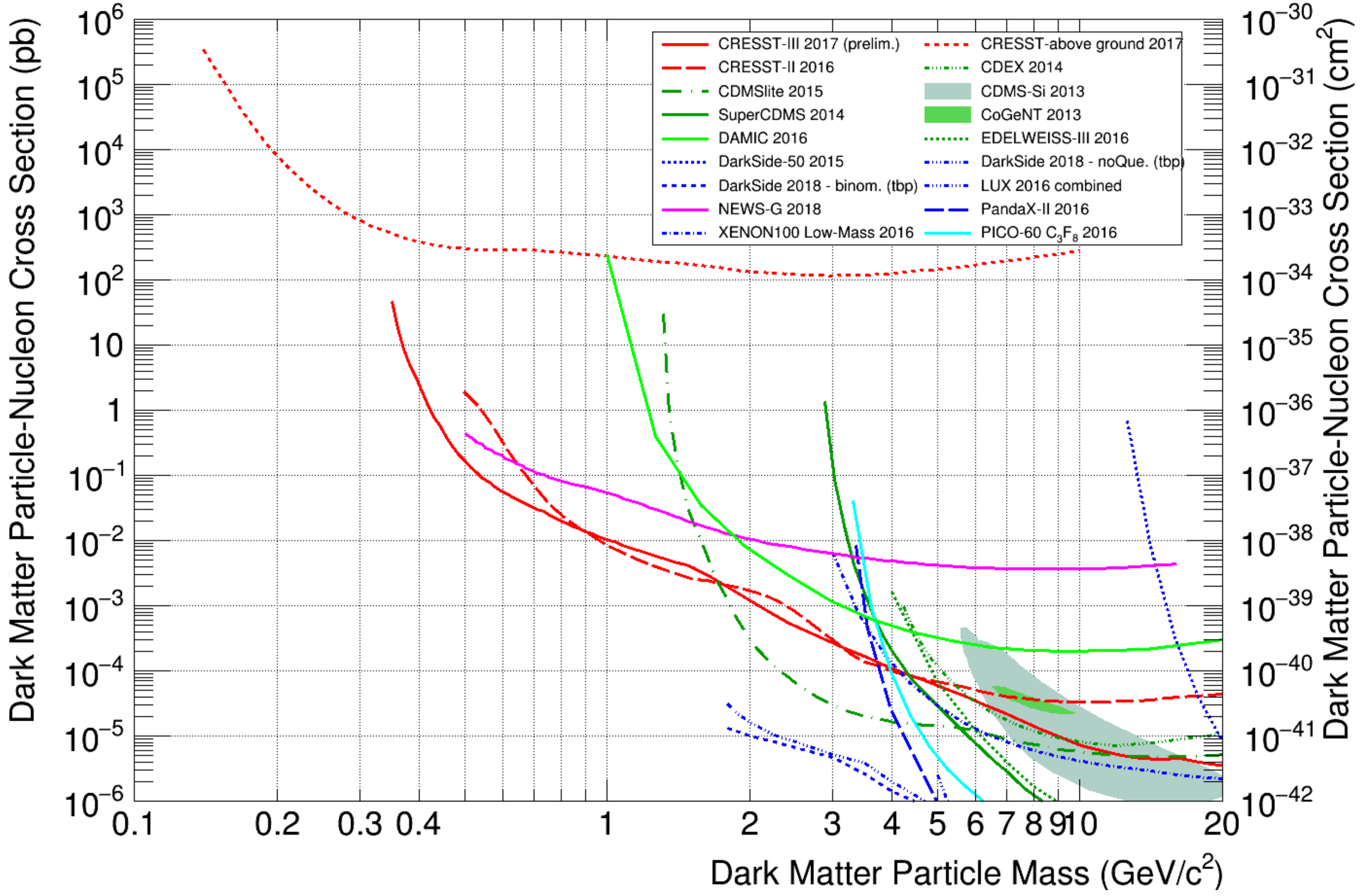


Measuring time 5.3h

No data quality cuts

EPJ C (2017) 77:637

GRAM-SCALE DETECTOR



GRAM-SCALE DETECTOR: THEORISTS LOVE IT 😻

ABOVE GROUND: SENSITIVITY FOR STRONGLY INTERACTING DM

1) Search for a Non-Relativistic Component in the Spectrum of Cosmic Rays at Earth. By J.I. Collar., [arXiv:1805.02646 [astro-ph.CO]].

2) Constraints on Dark Matter with a moderately large and velocity-dependent DM-nucleon cross-section. By M. Shafi Mahdawi, Glennys R. Farrar., [arXiv:1804.03073 [hep-ph]].

3) SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run. By SENSEI Collaboration (Michael Crisler et al.)., [arXiv:1804.00088 [hep-ex]].

4) Mapping The Neutrino Floor For Dark Matter-Electron Direct Detection Experiments. By Jason Wyenberg, Ian M. Shoemaker., [arXiv:1803.08146 [hep-ph]].

5) Supernova 1987A Constraints on Sub-GeV Dark Sectors, Millicharged Particles, the QCD Axion, and an Axion-like Particle. By Jae Hyeok Chang, Rouven Essig, Samuel D. McDermott., [arXiv:1803.00993 [hep-ph]].

6) Probing sub-GeV Dark Matter-Baryon Scattering with Cosmological Observables. By Weishuang Linda Xu, Cora Dvorkin, Andrew Chael., Phys.Rev. D97 (2018) no.10, 103530.

7) How blind are underground and surface detectors to strongly interacting Dark Matter?. By Timon Emken, Chris Kouvaris., [arXiv:1802.04764 [hep-ph]].

8) Robust Constraints and Novel Gamma-Ray Signatures of Dark Matter That Interacts Strongly With Nucleons. By Dan Hooper, Samuel D. McDermott., Phys.Rev. D97 (2018) 115006.

9) CNO Neutrino Grand Prix: The race to solve the solar metallicity problem. By David G. Cerdeno, Jonathan H. Davis, Malcolm Fairbairn, Aaron C. Vincent., JCAP 1804 (2018) 037.

10) Earth-Scattering of super-heavy Dark Matter: updated constraints from detectors old and new. By Bradley J. Kavanagh., [arXiv:1712.04901 [hep-ph]].

11) Looking for the WIMP Next Door. By Jared A. Evans, Stefania Gori, Jessie Shelton., JHEP 1802 (2018) 100.

12) A method to define the energy threshold depending on noise level for rare event searches. By M. Mancuso, A. Bento, N. Ferreiro Iachellini, D. Hauff, F. Petricca, F. Pröbst, J. Rothe, R. Strauss. [arXiv:1711.11459 [physics.ins-det]].

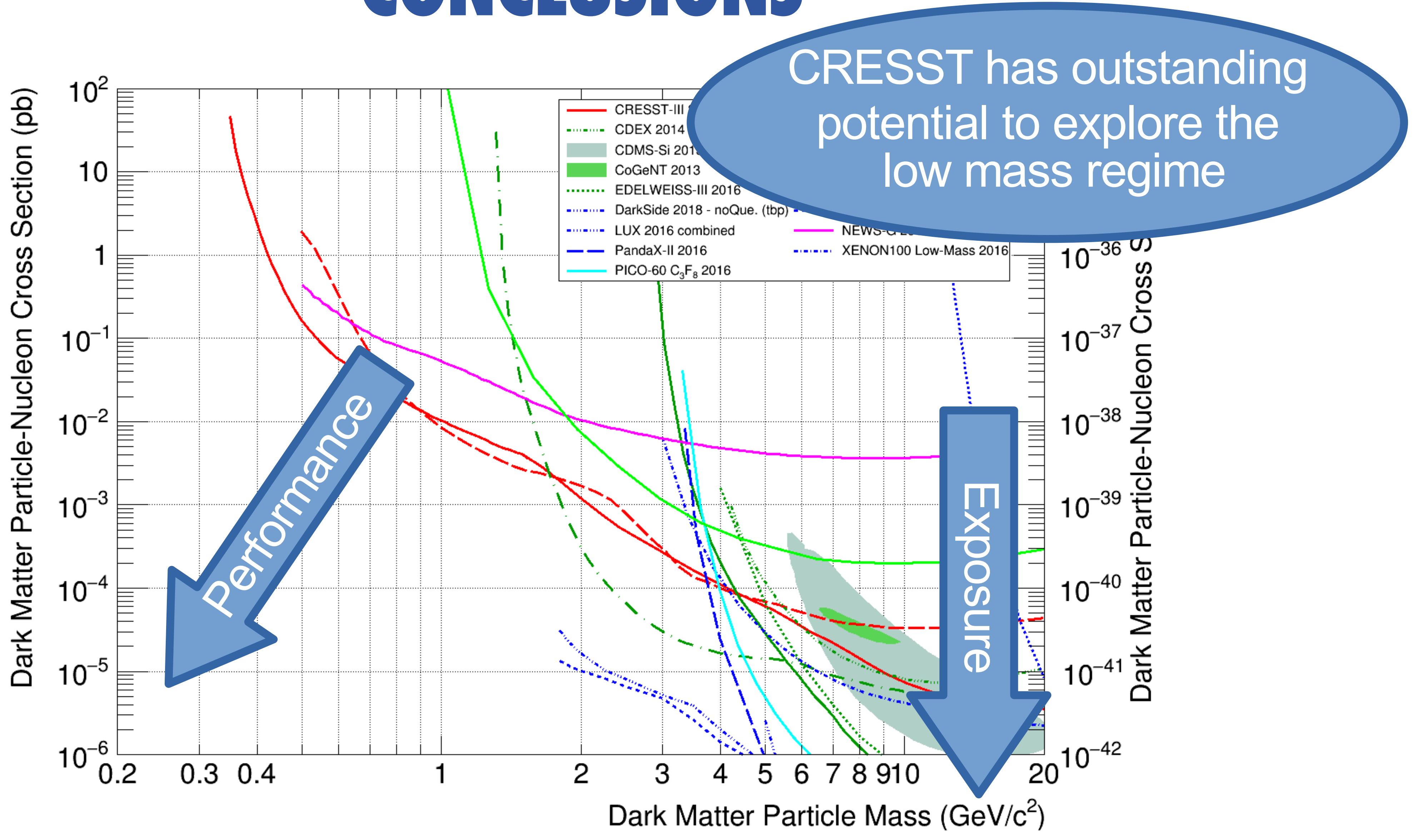
13) Direct Detection of sub-GeV Dark Matter with Electrons from Nuclear Scattering. By Matthew J. Dolan, Felix Kahlhoefer, Christopher McCabe., [arXiv:1711.09906 [hep-ph]].

14) Probing Sub-GeV Mass Strongly Interacting Dark Matter with a Low-Threshold Surface Experiment. By Jonathan H. Davis., Phys.Rev.Lett. 119 (2017) no.21, 211302.

15) Gram-scale cryogenic calorimeters for rare-event searches. By R. Strauss et al.., Phys.Rev. D96 (2017) no.2, 022009.

Source: inspire-hep (11/06/2018), paper on arXiv since 07/2018

CONCLUSIONS




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

BACKUP

RATE STATEMENT XENON 1T

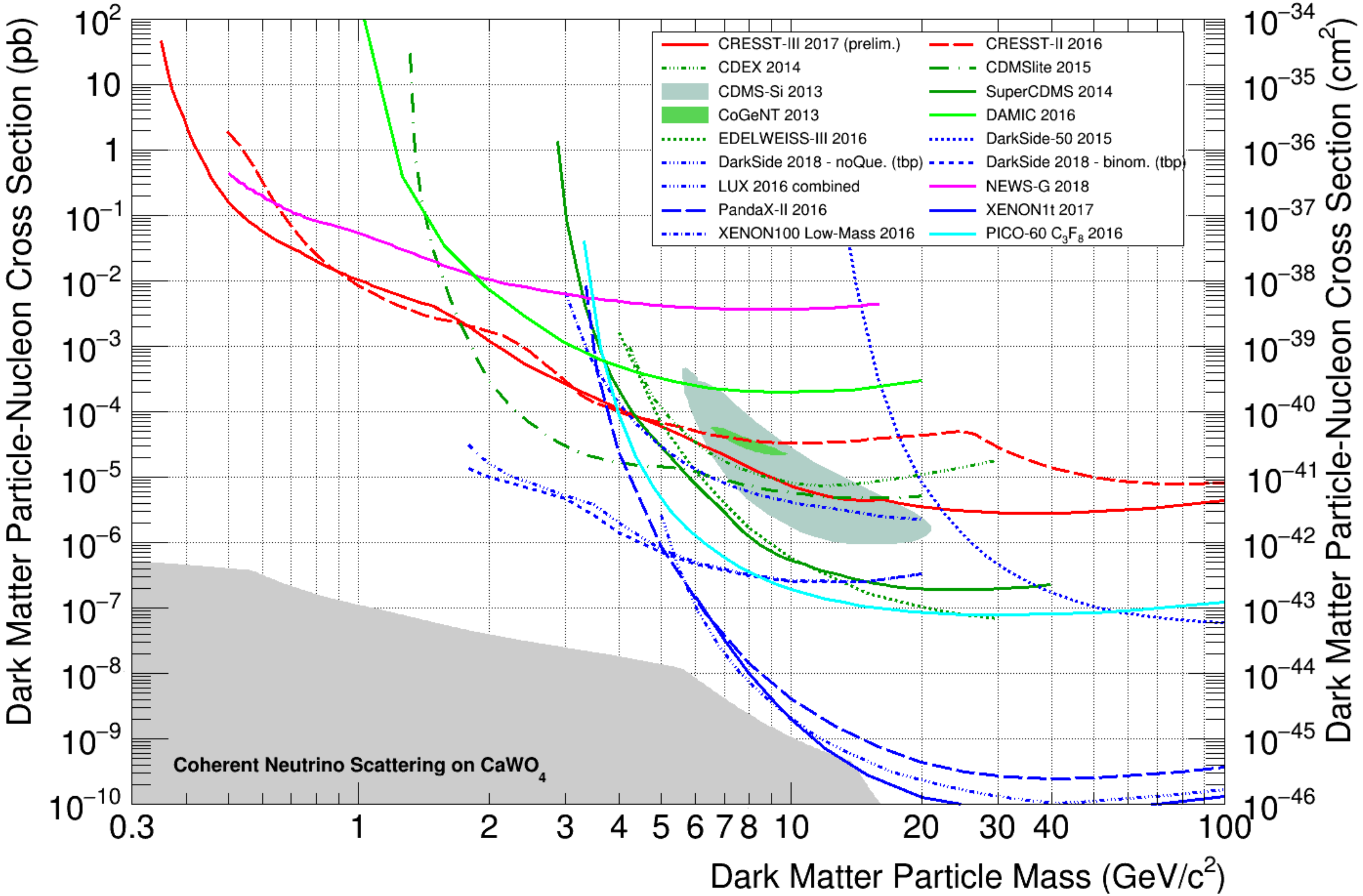
From arXiv: 1805.12562v1

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/count → 0.01 counts/(day tonne)

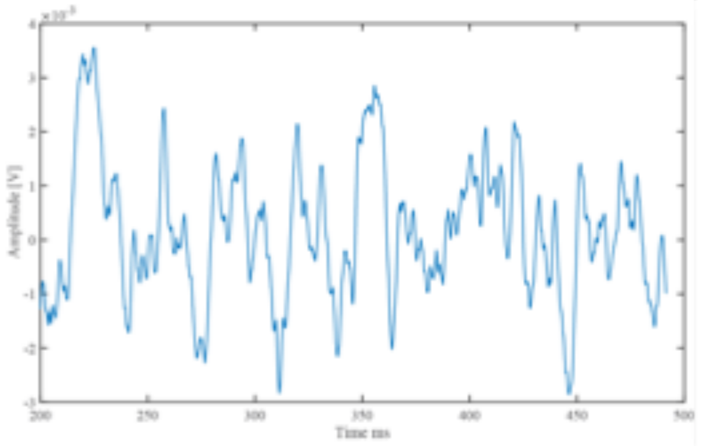
SENSITIVITY PLOT – ZOOMED OUT

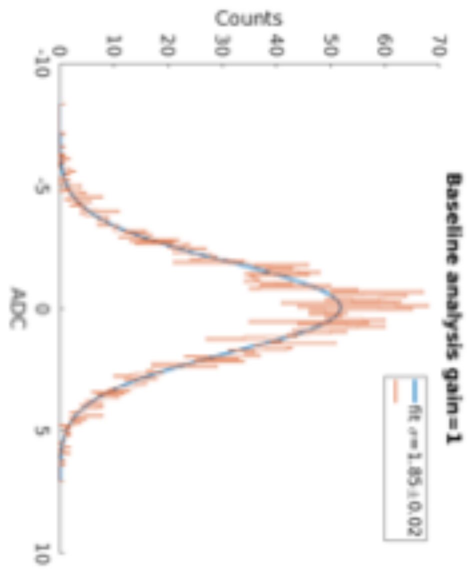


OPTIMUM TRIGGER – DETECTOR A

Optimum filter for threshold analysis

Empty base line trace

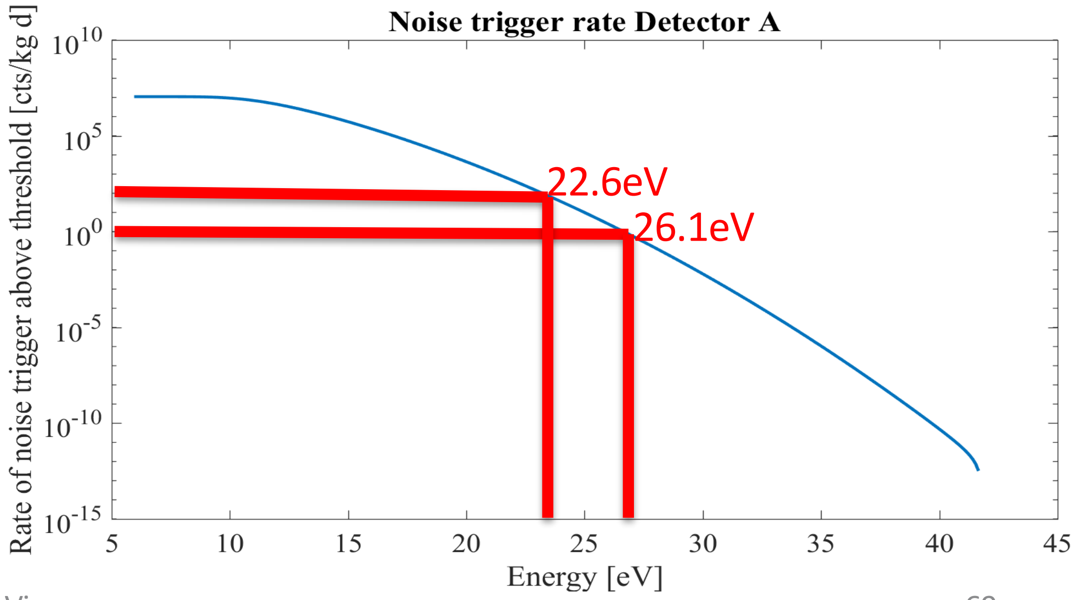




Histogram of a typical baseline trace

- Continuous sampling of raw data
- Study the noise distribution after optimum filter in order to set the threshold

Analytical description of amplitude distribution in empty baselines



DETECTOR STABILITY

W-TES equipped with heaters

- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold