Dark Matter,
Direct Searches
and the CRESST experiment

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

Johannes Rothe
Particle Physics School Colloquium
July 12, 2018

WHAT DO WE KNOW OF THE UNIVERSE?

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WHAT DO WE KNOW OF THE UNIVERSE?

Max-Planck-Tag am **14.9.2018**

Nicht viel.

Fünf Prozent des Universums besteht aus „normaler", sichtbarer Materie, wie wir sie auch von der Erde kennen.

Doch darüber hinaus ist der Kosmos gespickt mit Rätseln: Was ist Dunkle Materie,

NOT MUCH.

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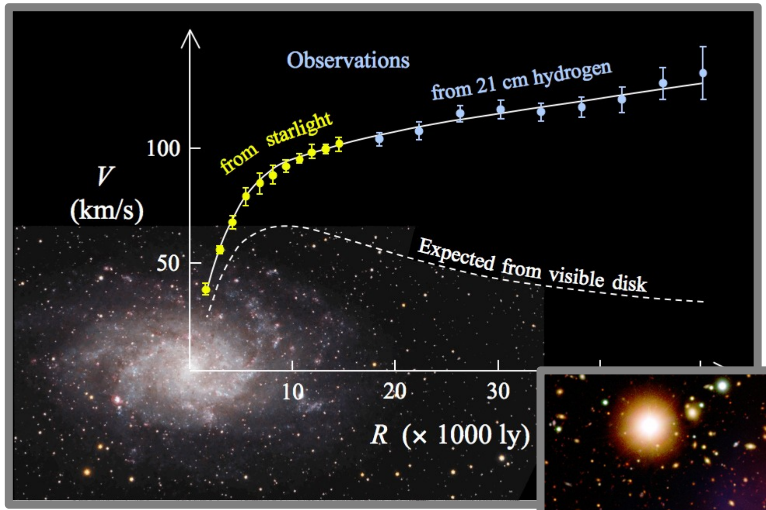
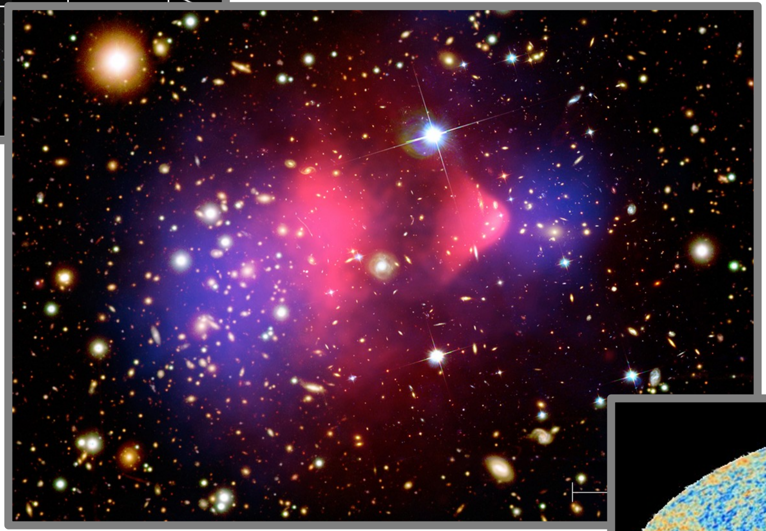
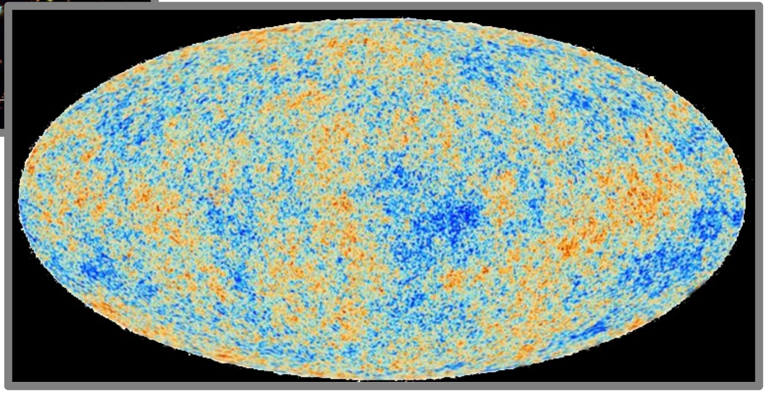
Dark Matter





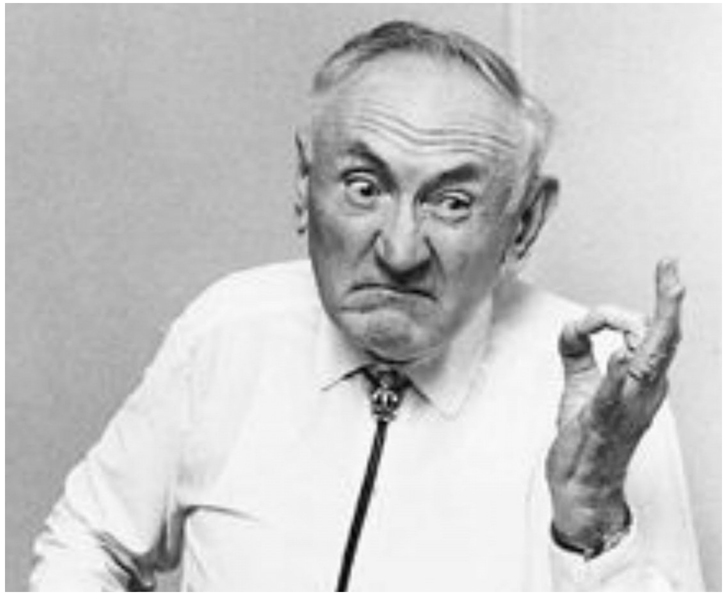


Compelling evidence for dark matter on various cosmological scales

...

Dark Matter – History

Dark Matter – History



Fritz Zwicky

Die Rotverschiebung von extragalaktischen Nebeln

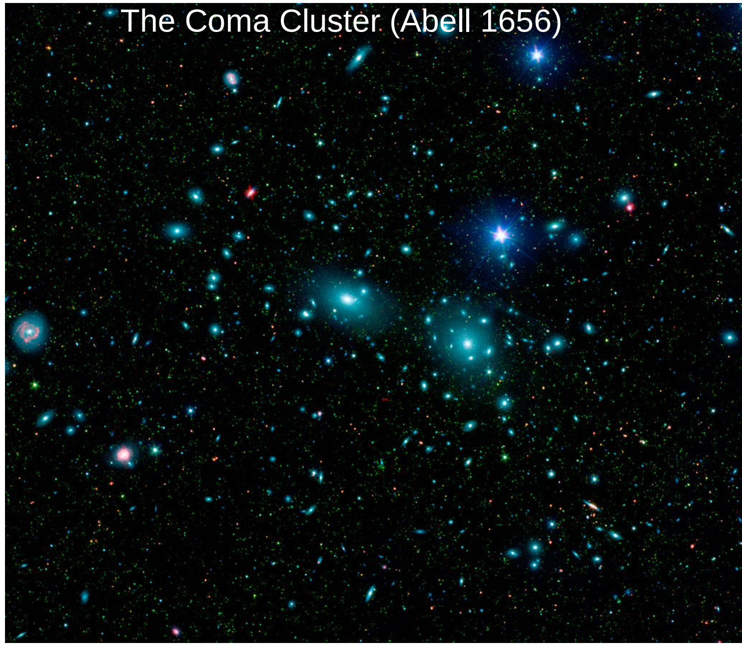
von **F. Zwicky.**

(16. II. 33.)

Scheinbare Geschwindigkeiten im Comahaufen.

v = 8500 km/sek	6900 km/sek
7900	6700
7600	6600
7000	5100 (?)

Zwicky, F. (1933) Helvetica Physica Acta, Vol. 6, p. 110-127



→ 400 x more dark matter!

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Dark Matter – History

Vera Rubin
& Kent Ford

ApJ, vol. 159, p.379, 02/1970

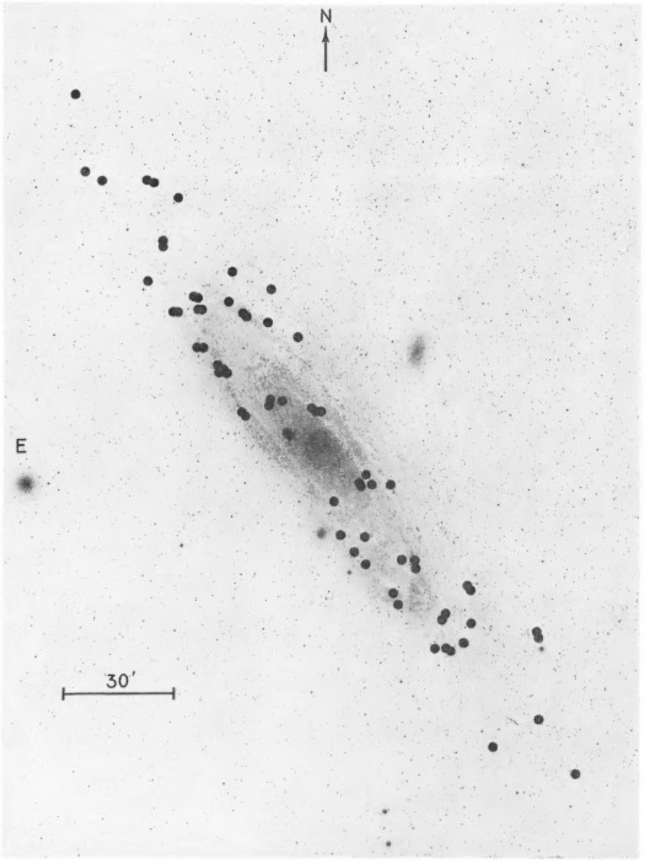
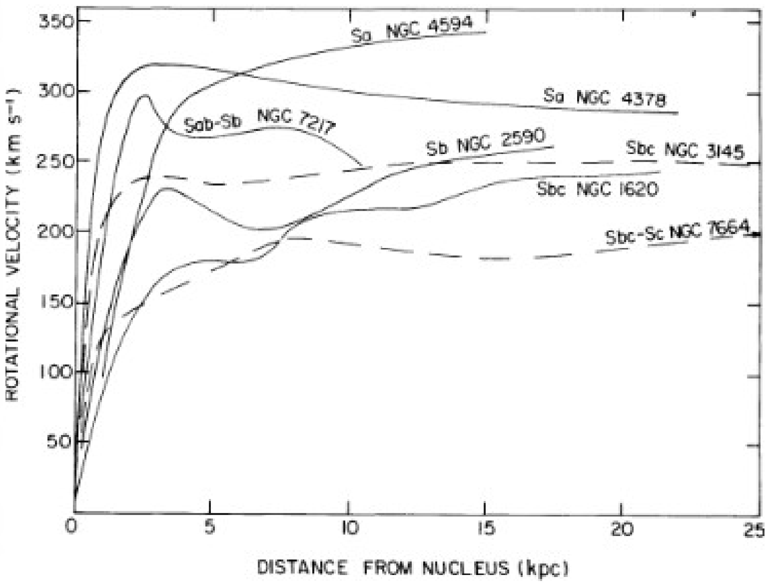


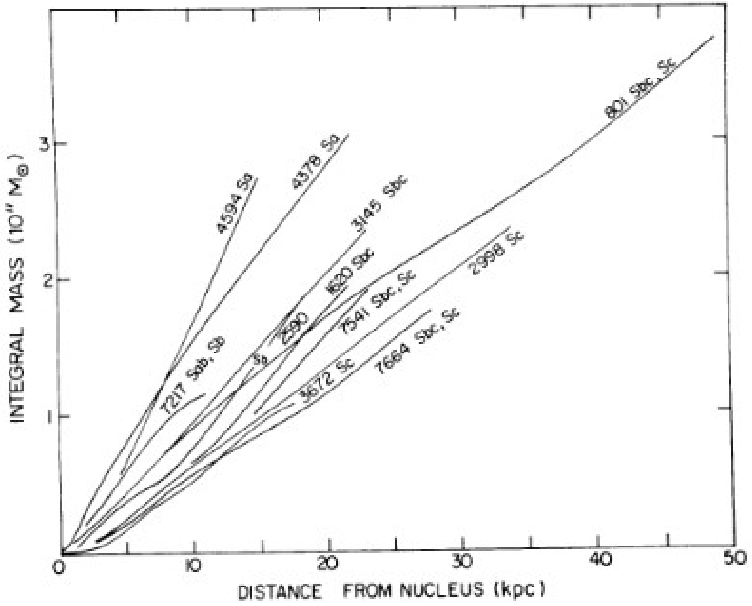
FIG. 1.—Identification chart for emission regions in M31 for which velocities have been obtained. Palomar 48-inch Schmidt ultraviolet photograph, 103aO plate + UG 1 filter, courtesy of Dr. S. van den Bergh.

EXTENDED ROTATION CURVES OF HIGH-LUMINOSITY SPIRAL GALAXIES. IV. SYSTEMATIC DYNAMICAL PROPERTIES, Sa→Sc

VERA C. RUBIN,*† W. KENT FORD, JR.,* AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1978 June 7; accepted 1978 July 18

ApJ, 225:L107-L111, 1978 Nov. 1



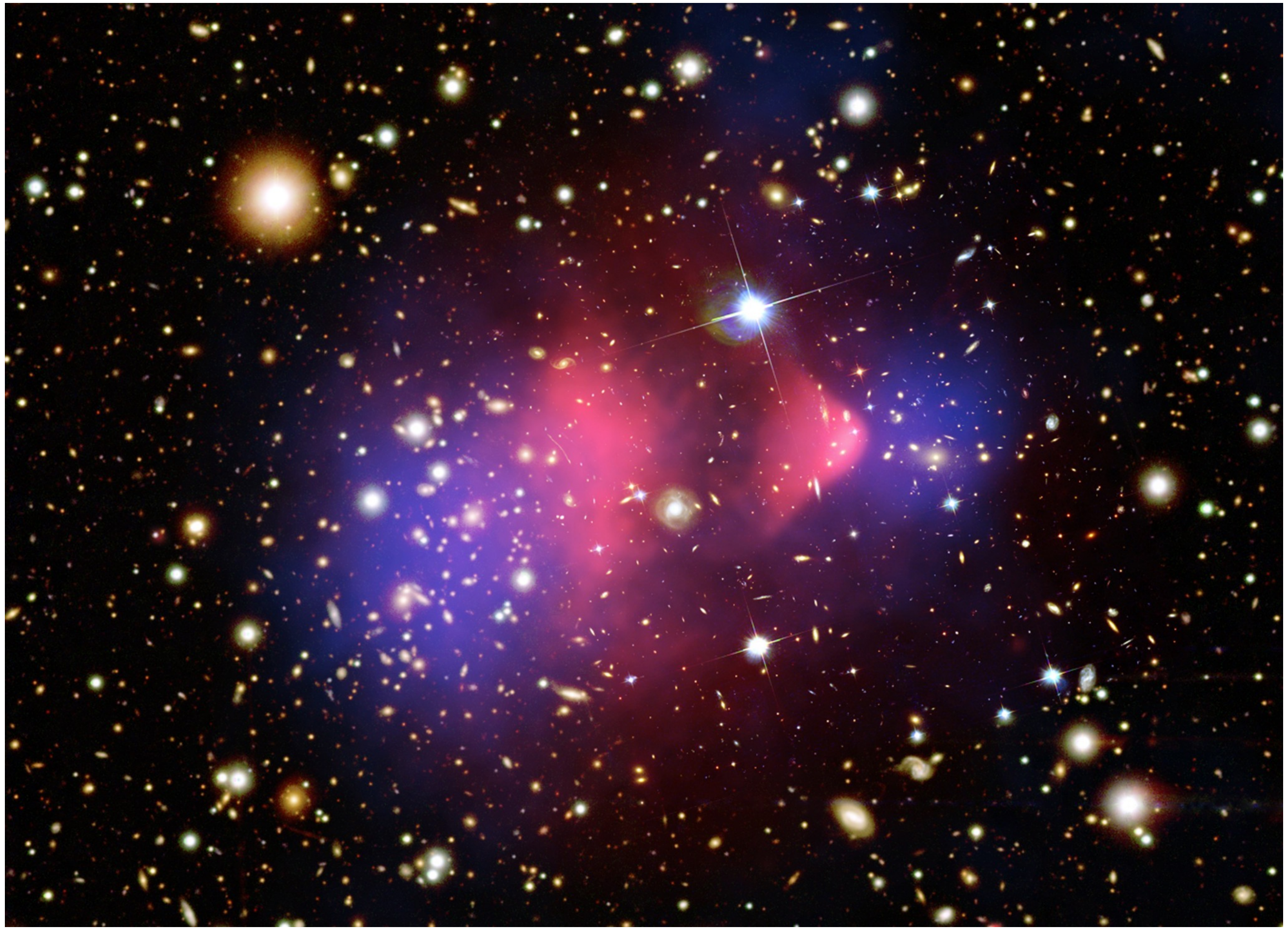


Dark Matter – History

The Bullet Cluster: “A Direct Empirical Proof of the Existence of Dark Matter”

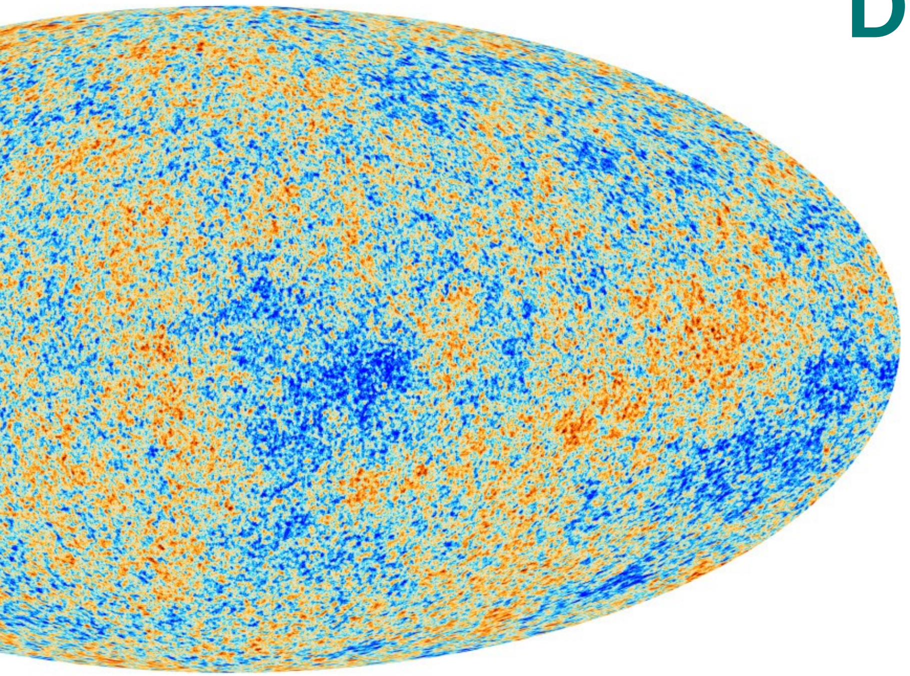
Red: x-ray ← gas ← matter

Blue: grav. lensing ← mass



Clowe D. et al. The Astrophysical Journal, Volume 648, Issue 2, pp. L109-L113. 09/2006

Dark Matter – History



Temperature map of the Cosmic Microwave Background (CMB)

Planck 2015 results XIII. Cosmological parameters A&A 594, A13 (2016)

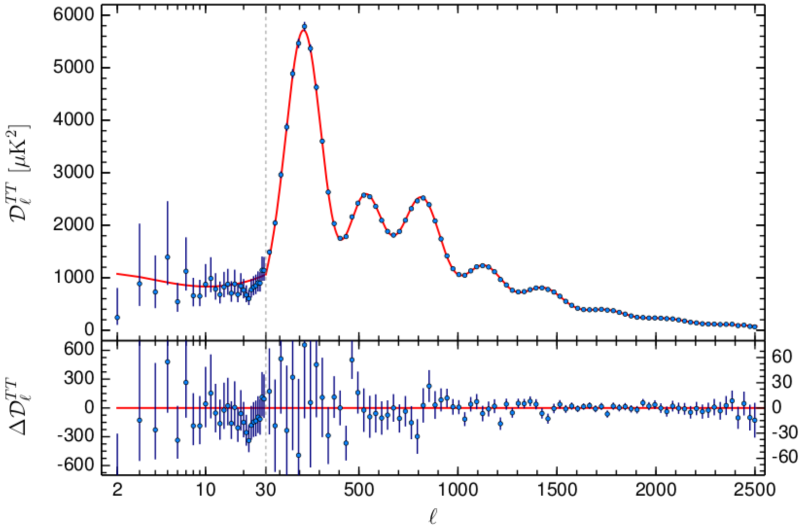
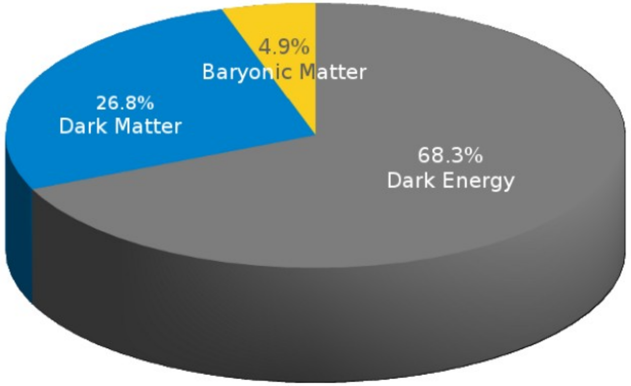


Fig. 1. *Planck* 2015 temperature power spectrum. At multipoles $\ell \geq 30$ we show the maximum likelihood frequency-averaged temperature spectrum computed from the Plik cross-half-mission likelihood, with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the Commander component-separation algorithm, computed over 94 % of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the *Planck* TT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ uncertainties.

Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

ΛCDM

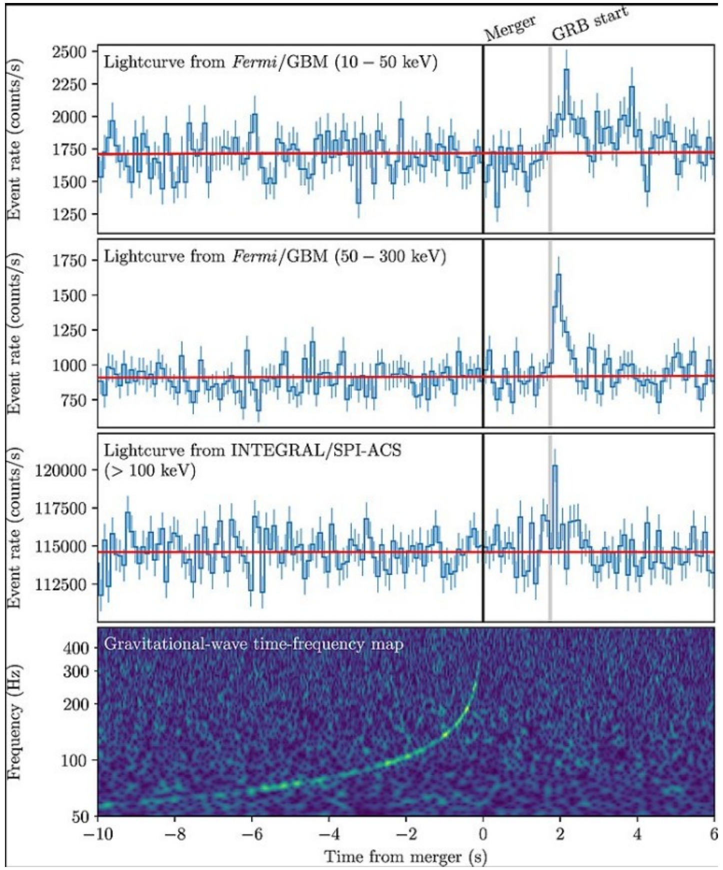


Dark Matter – what could it be?

Modified gravity?

- MOND works well for galaxy rotation curves,
  not so well on larger scales
- Community motivated by many topics other than DM
- Many theories under tension from GW170817

LIGO/VIRGO collaboration



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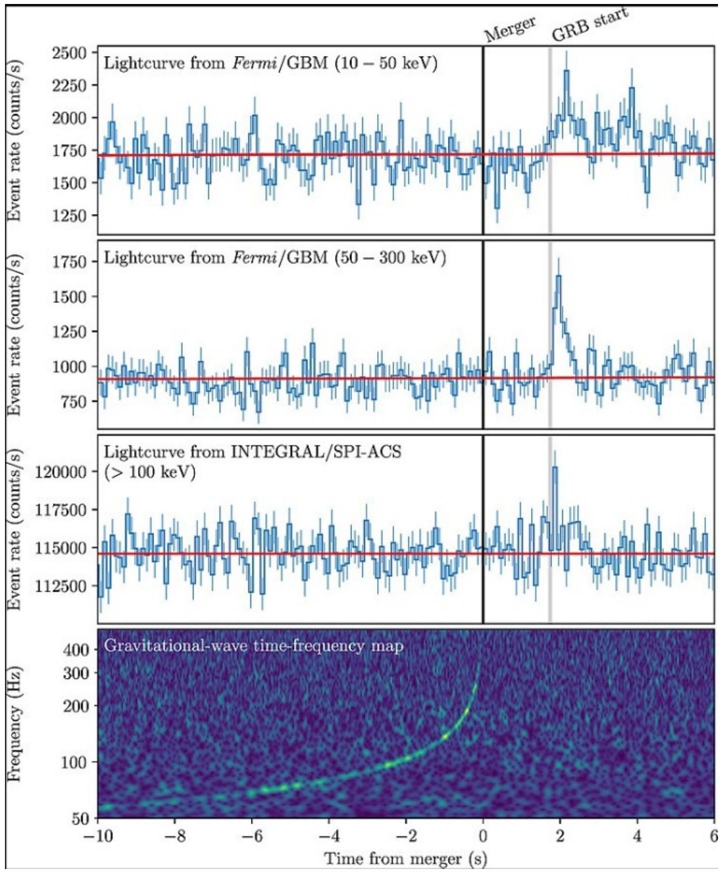

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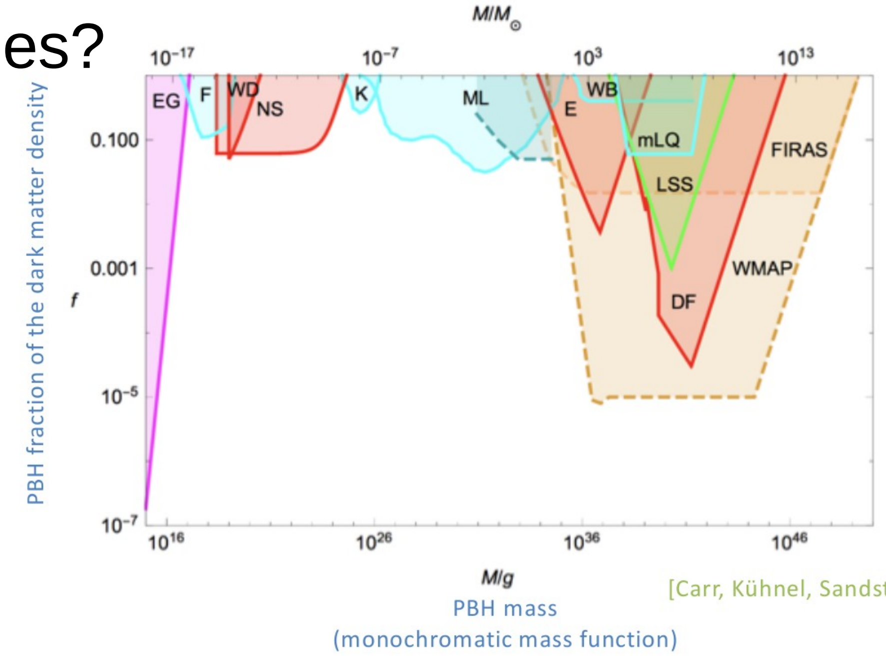
Primordial Black Holes?



[Carr, Kühnel, Sandstad (2016)]

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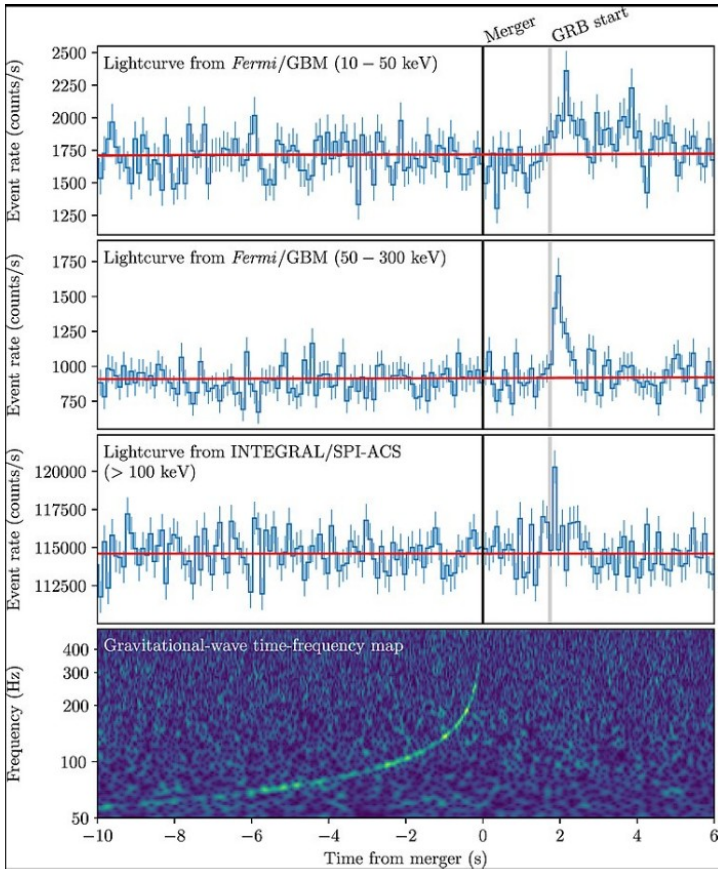

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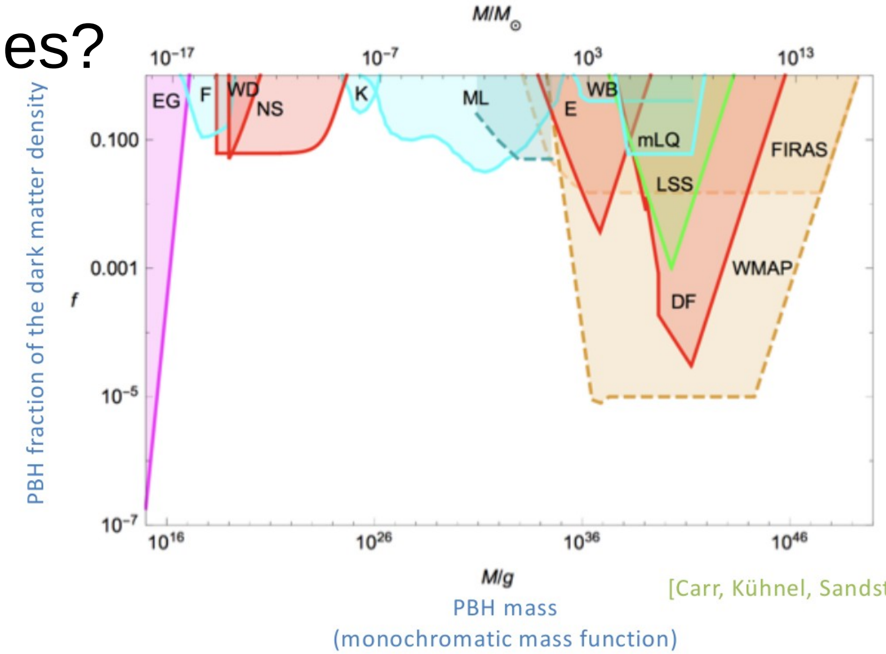
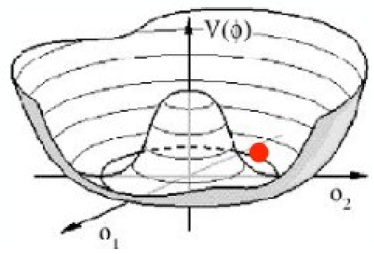


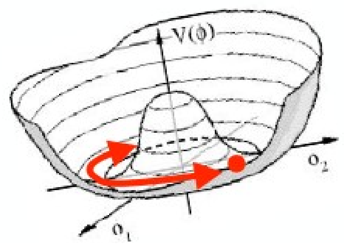
...an undiscovered elementary particle?

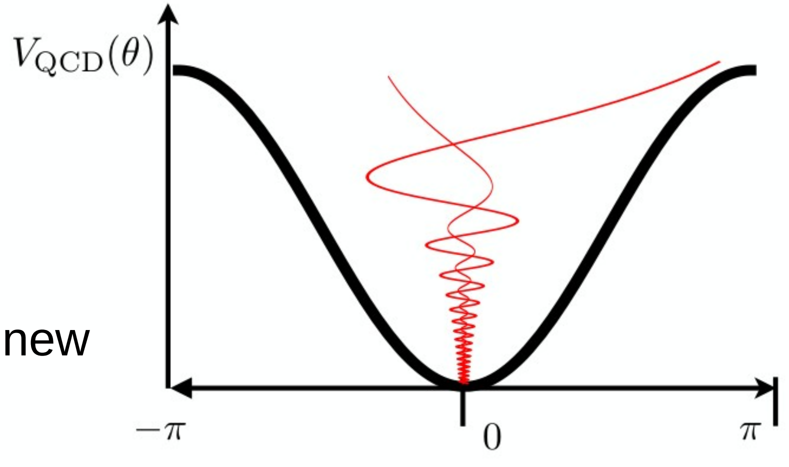
Some candidates from theory

J. Redondo, DSU2018

Axion



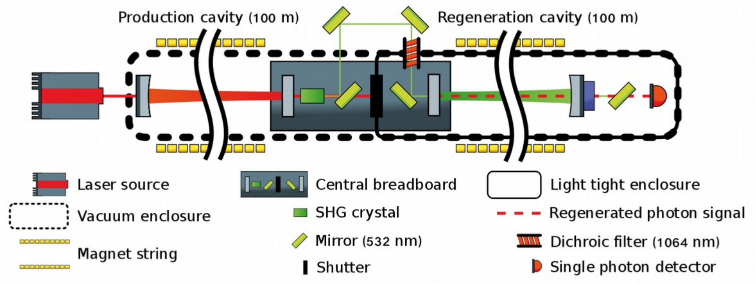




$\theta = \frac{A}{f_A}$

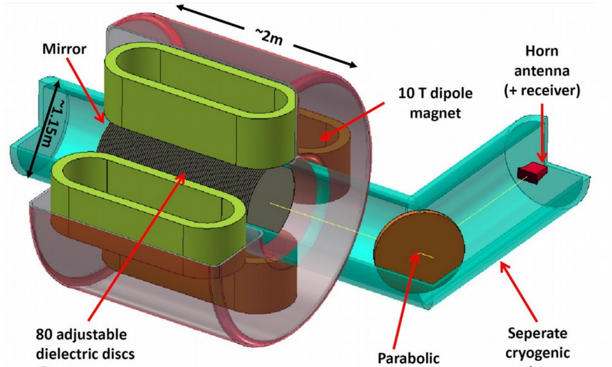
- (almost) massless Goldstone Bosons of a new spontaneously broken symmetry
- Axion DM: coherent oscillations of axion field → Coherent detection methods

Light shining through walls (e.g. ALPS II):



1611.05863 Figure 1: ALPS IIc simplified design.

Haloscopes (e.g. MADMAX):



1712.01062

Some candidates from theory

Axion

WIMP

Weakly Interacting Massive Particle

“WIMP miracle”:

New weak-scale particles with (sub-)weak interactions (like LSP)

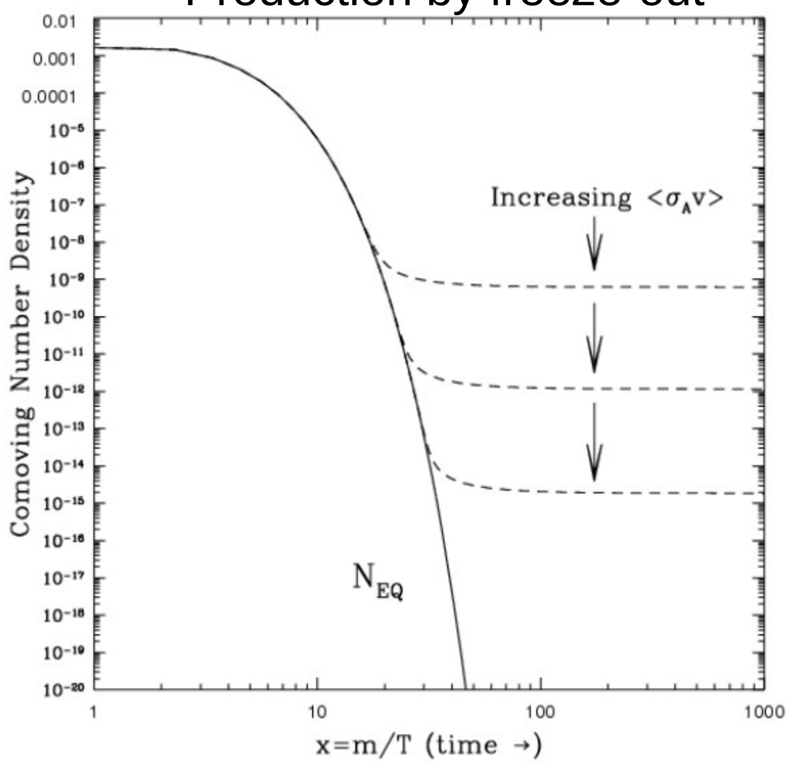
are thermally produced in the early universe at the right relic density!

→ Motivation coupled to SuSy

“Lee-Weinberg bound”

m_{DM} > 2-10 GeV (else overproduced)

Production by freeze-out

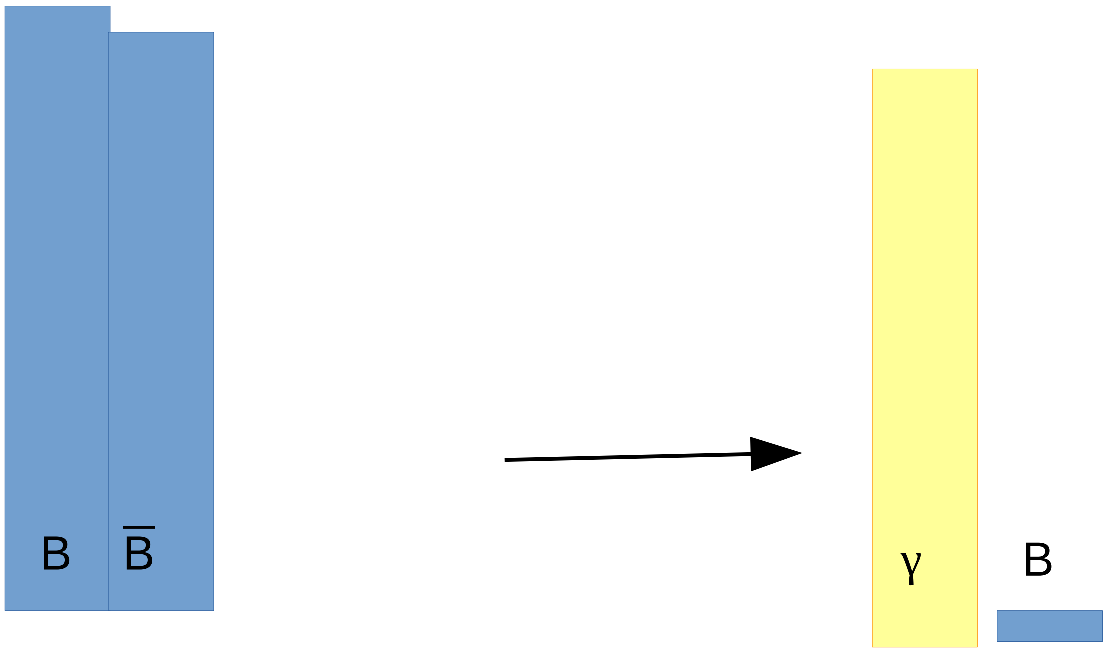


Some candidates from theory

Axion

WIMP

Asymmetric DM



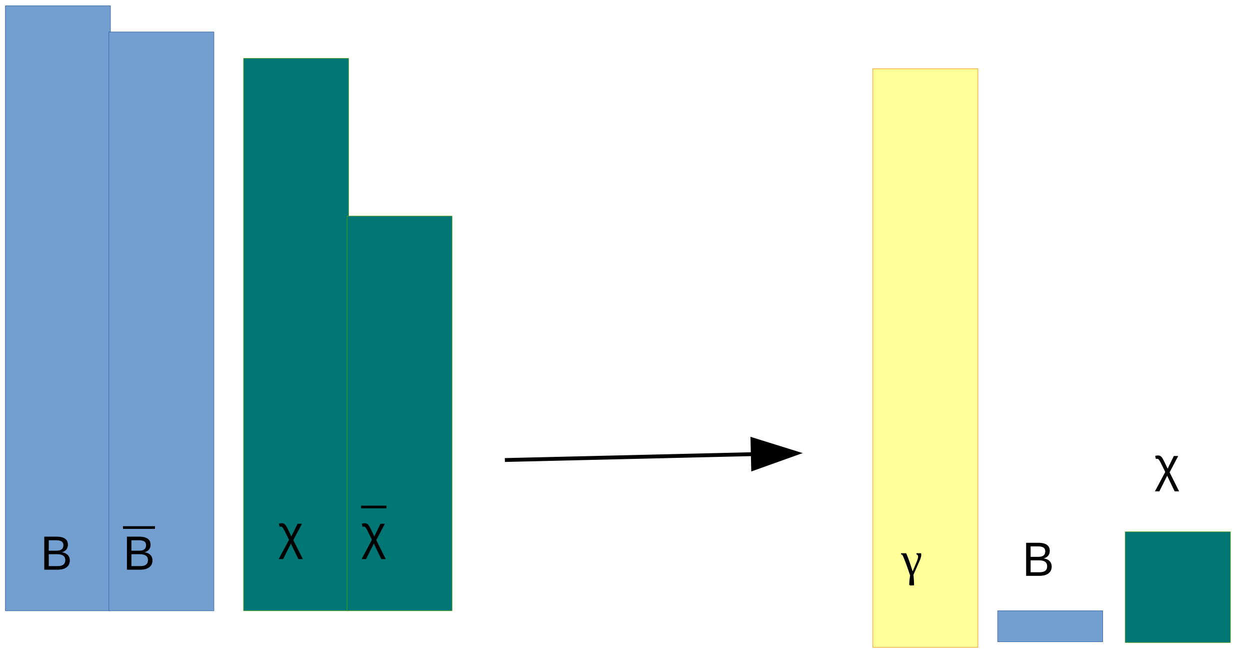
Baryon asymmetry in the early universe

Some candidates from theory

Axion

WIMP

Asymmetric DM



Baryon asymmetry in the early universe
Similar mechanism on the dark side

→ changes production mechanism
expected to be lighter than WIMP

Some candidates from theory

Axion

WIMP

Asymmetric DM

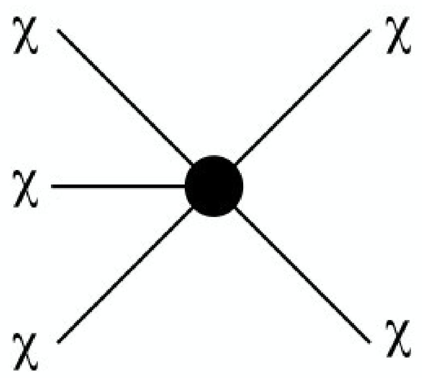
SIMP

Strongly Interacting Massive Particle

Self-interacting dark matter:
depleted by 3→2 annihilations

Can interact "stronger than weak"

Can be much lighter than WIMP (sub-GeV)



Some candidates from theory

Axion

WIMP

Asymmetric DM

SIMP

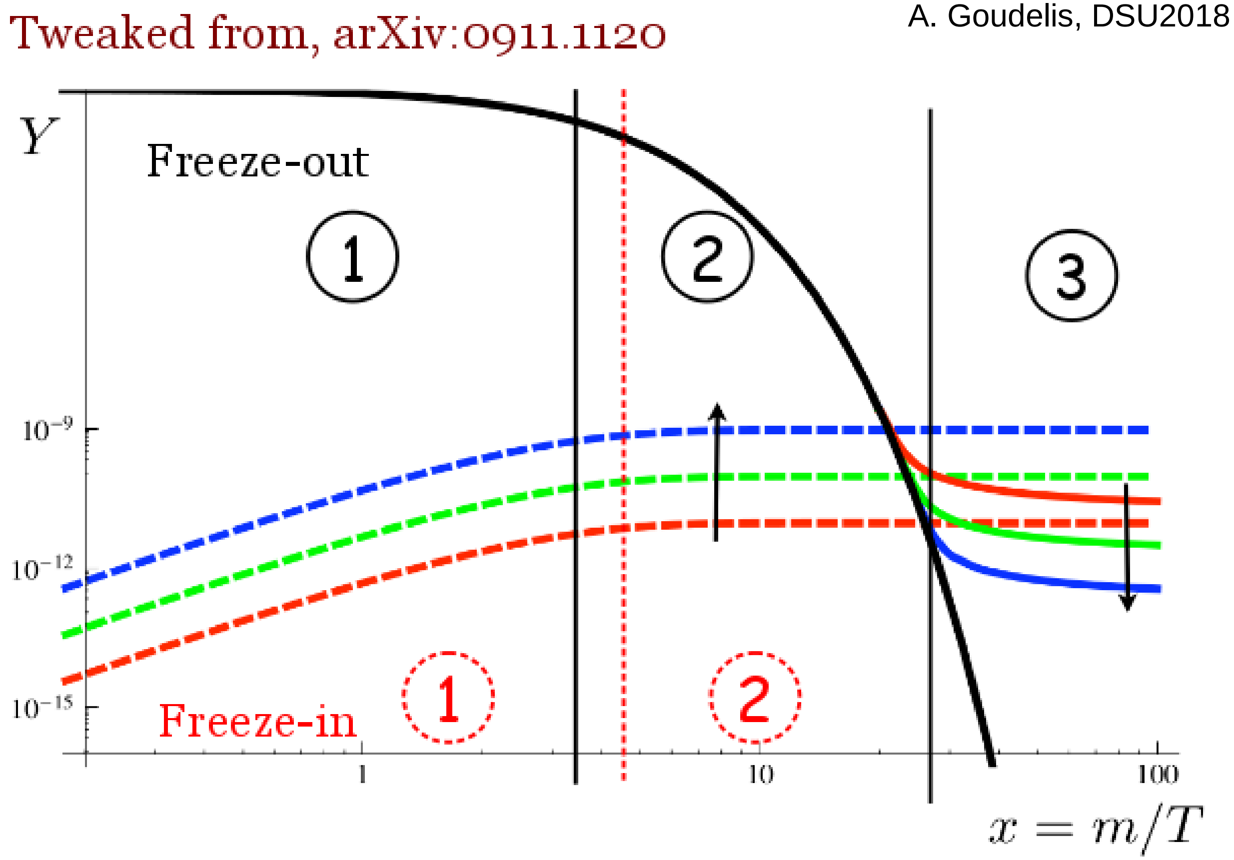
FIMP

Feebly Interacting Massive Particle

Never reaches thermal equilibrium

Production by "freeze-in"

A. Goudelis, DSU2018



Some candidates from theory

Axion

WIMP

Asymmetric DM

SIMP

FIMP

⋮

⋮

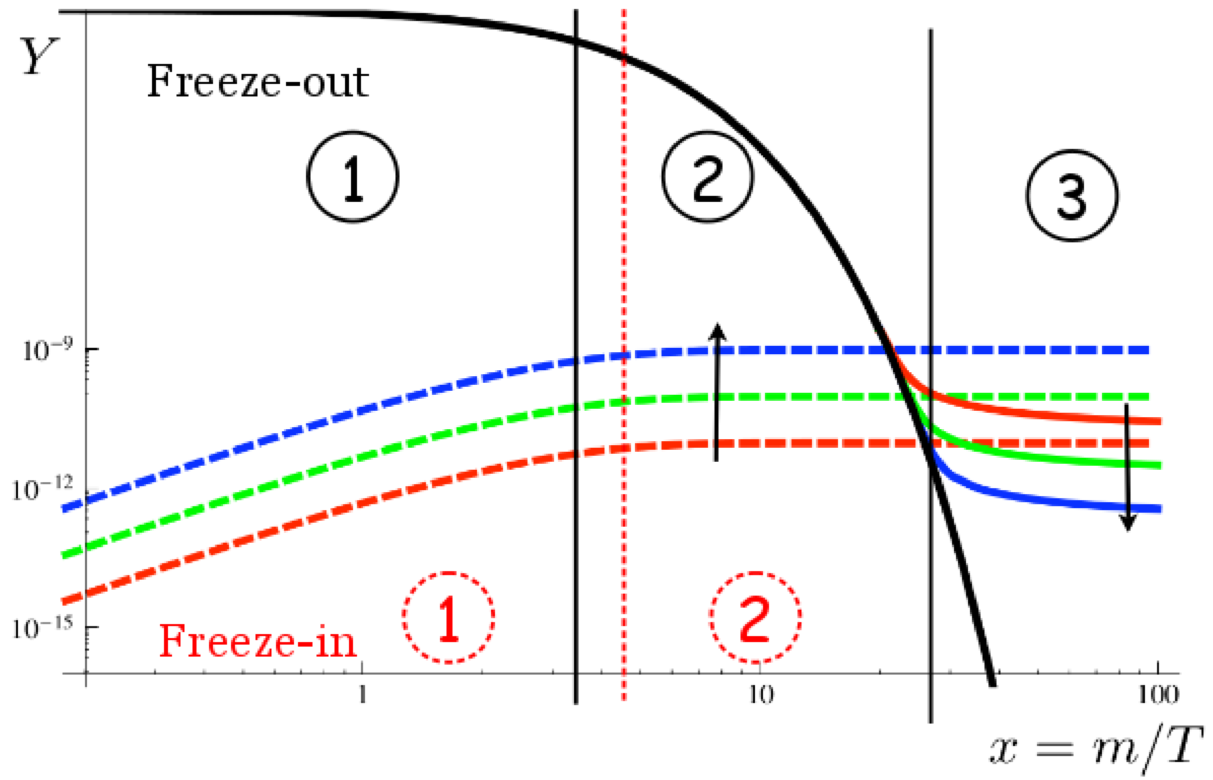
Feebly Interacting Massive Particle

Never reaches thermal equilibrium

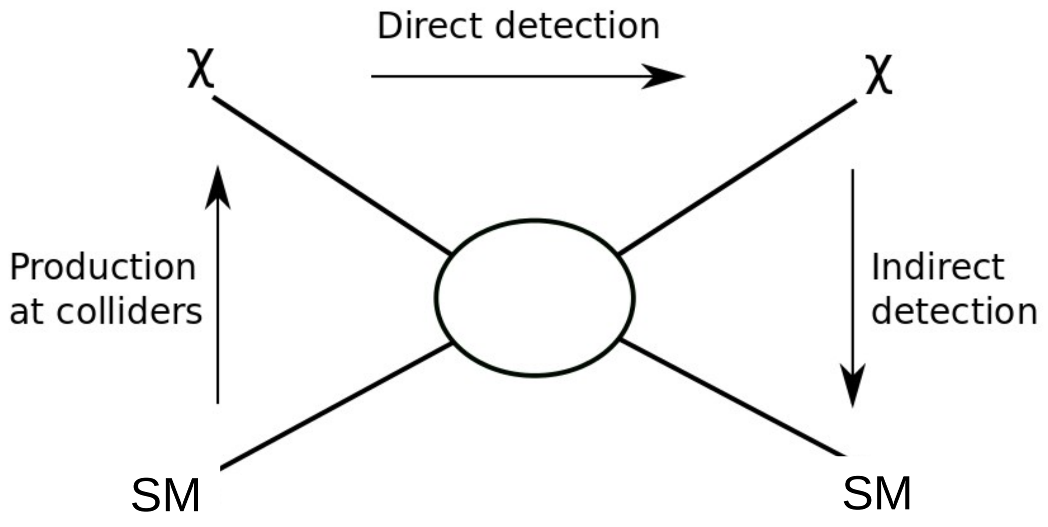
Production by "freeze-in"

A. Goudelis, DSU2018

Tweaked from, arXiv:0911.1120



Dark Matter Particles – so what?

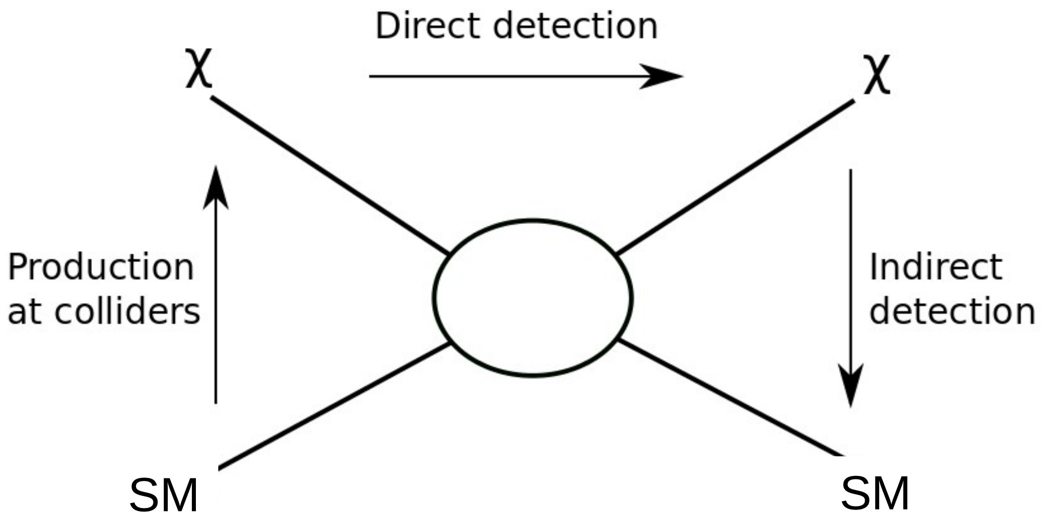


“triad” of detection possibilities

Dark Matter Particles – so what?

$M_\chi, \sigma_{\chi,n}$

$M_\chi, M_m, g_{m,\chi}, g_{\chi,SM}$



$M_\chi, <\sigma_{ann} \cdot v>$

“triad” of detection possibilities
but:
different measurable parameters
different kinematics in each process

Depending on the high-energy theory, each of these can be suppressed relative to the others.

Direct Detection – History

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

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

Detector concept (superconducting grains)
for coherent neutrino-nucleus scattering

Promise: extremely low energy threshold

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PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1–10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1–10^2 GeV; or strongly interacting particles of masses 1–10^{13} GeV.

This detector would be sensitive to DM particles in the halo!

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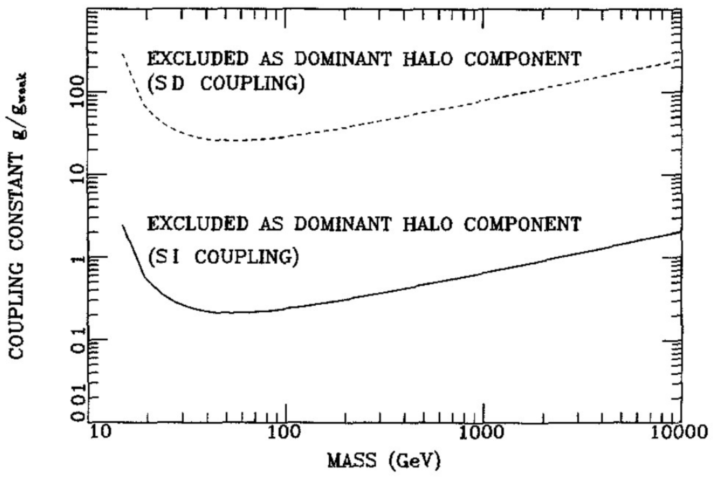
Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]



First dark matter exclusion plot using a Germanium detector

Direct Detection – Signal Rate

Local DM density

Halo integral: DM velocity distribution

Signal rate [1/keV/kg/d]

$$\frac{dN}{dE_R} = \frac{\rho_\chi}{2 m_\chi \mu_N^2} \sigma_0 F^2(E_R) \underbrace{\int_{v_{\min}(E_R)}^{v_\infty = v_{\mathrm{esc}}} d^3v \frac{f(\vec{v})}{v}}_{I(v_{\min})}$$

DM mass and (zero-momentum) cross-section

Nuclear response function (form factor)

v_{esc} galactic escape velocity

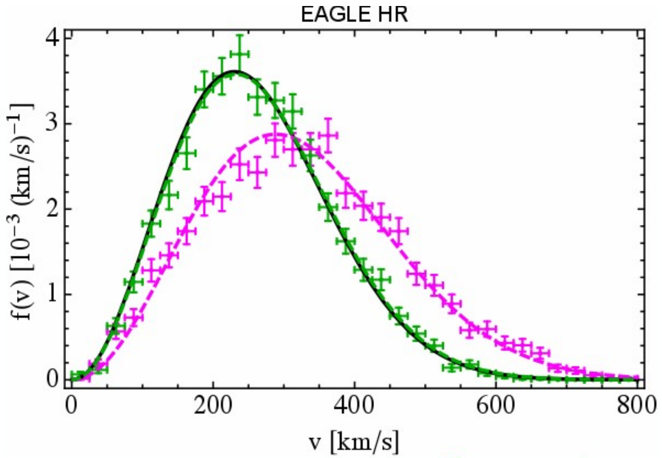
$$v_{\min} = \sqrt{(E_R m_N)/(2\mu_N^2)}$$

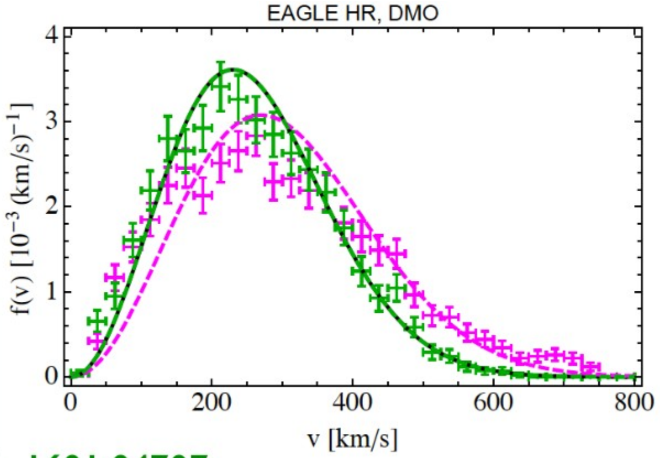
minimum velocity to deposit recoil energy E_R

nuclear-, particle- and astrophysics!

Astrophysical input

Halo Studies with n-body simulations





Bozorgnia et al., 1601.04707

DM+baryons

DM only

Local dark matter density

Global methods:

Fit a model of Milky Way + DM halo to astronomical observations

(0.2−0.6) GeV/cm³

Local methods:

Infer density from stellar velocity distributions in the solar neighborhood

(0.22−0.33) GeV/cm³

J.Phys. G44 (2017) no.8, 084001

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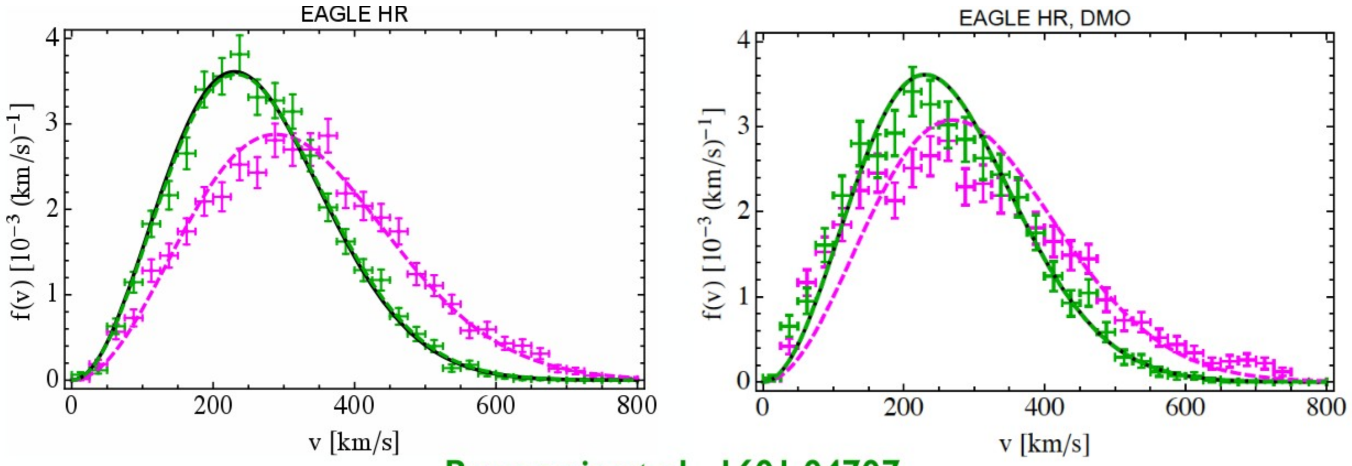

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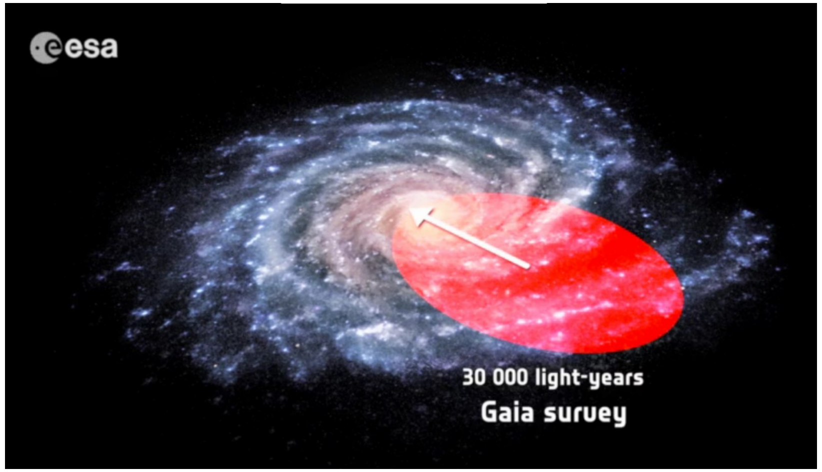

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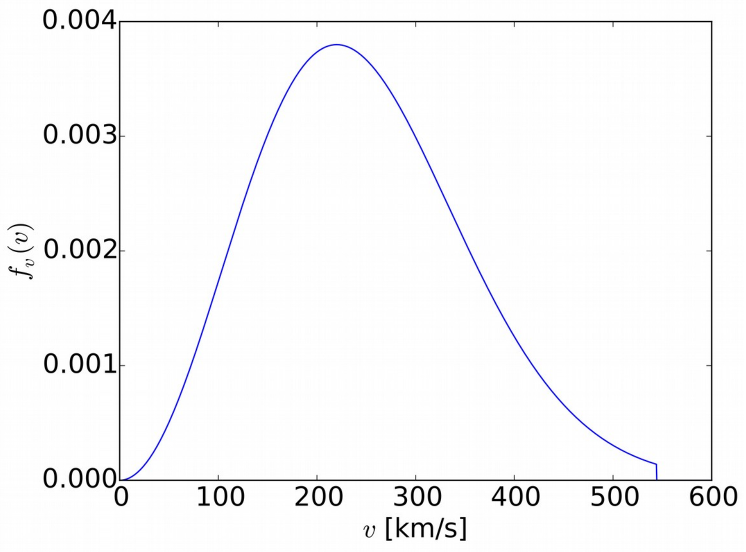
(0.22−0.33) GeV/cm³ J.Phys. G44 (2017) no.8, 084001

Near future: ESA's Gaia Astrometry mission will provide significant improvement

Some Simple Assumptions

Astrophysics:
"Standard Halo Model"

$$\rho_{dm} = 300\ \frac{\mathrm{MeV/c^2}}{\mathrm{cm^3}}$$
$$v_{rms} = 270\ \frac{\mathrm{km}}{\mathrm{s}}$$
$$v_{esc} = 544\ \frac{\mathrm{km}}{\mathrm{s}}$$
$$v_{sun} = 220\ \frac{\mathrm{km}}{\mathrm{s}}$$

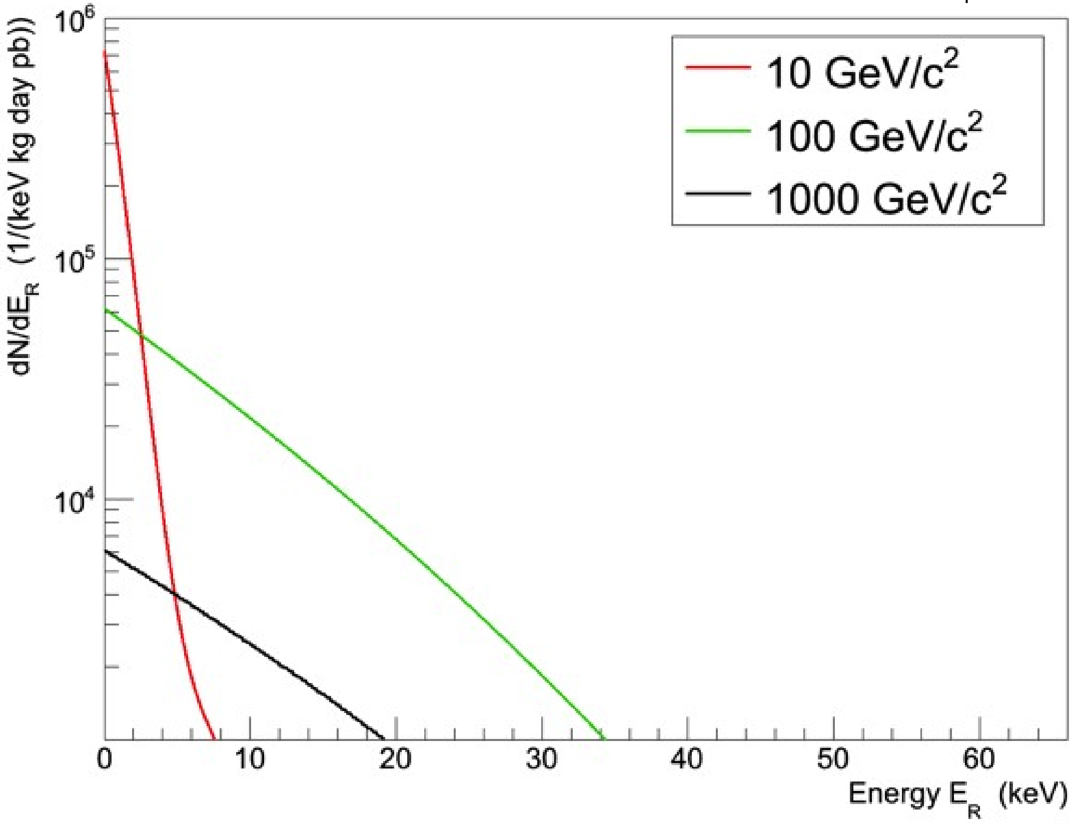


Maxwellian velocity distribution

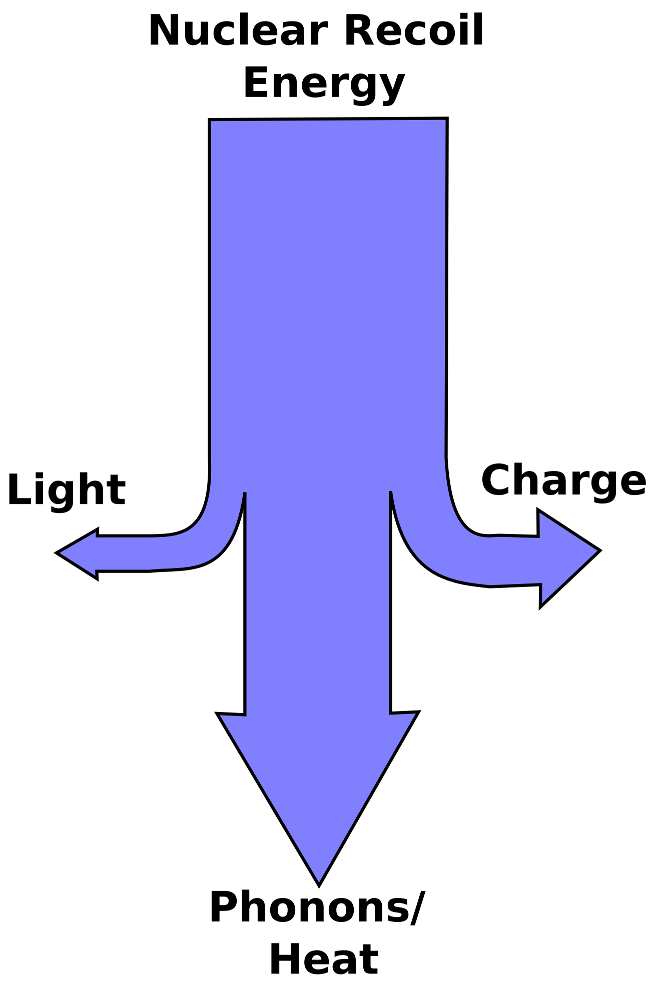
Nuclear/particle physics:
"Spin-Independent interaction"
(inspired by SuSy neutralino)

- DM interacts predominantly with nuclei
- DM couples to total nucleon content of the target ~A^2
- Nuclear response function becomes the Fourier Transform of the nucleon density

Dark matter nuclear recoil spectrum: $CaWO_4$ target



How to observe that?



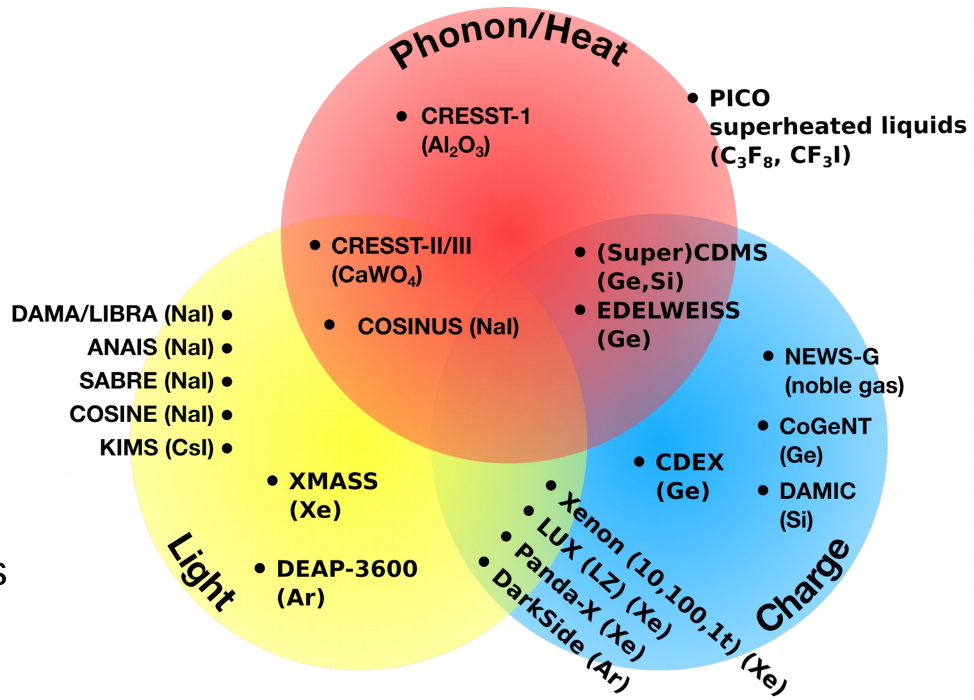
Possible excitations in matter:

Phonons/Heat
- largest signal (but hardest to detect)
- nearly full primary energy

Charge (e.g. in semiconductors)
- ~20% of primary energy in e-h pairs
- Particle dependent!

Light (in scintillators)
- ~few % of primary energy in photons
- Particle dependent!

An incomplete compilation



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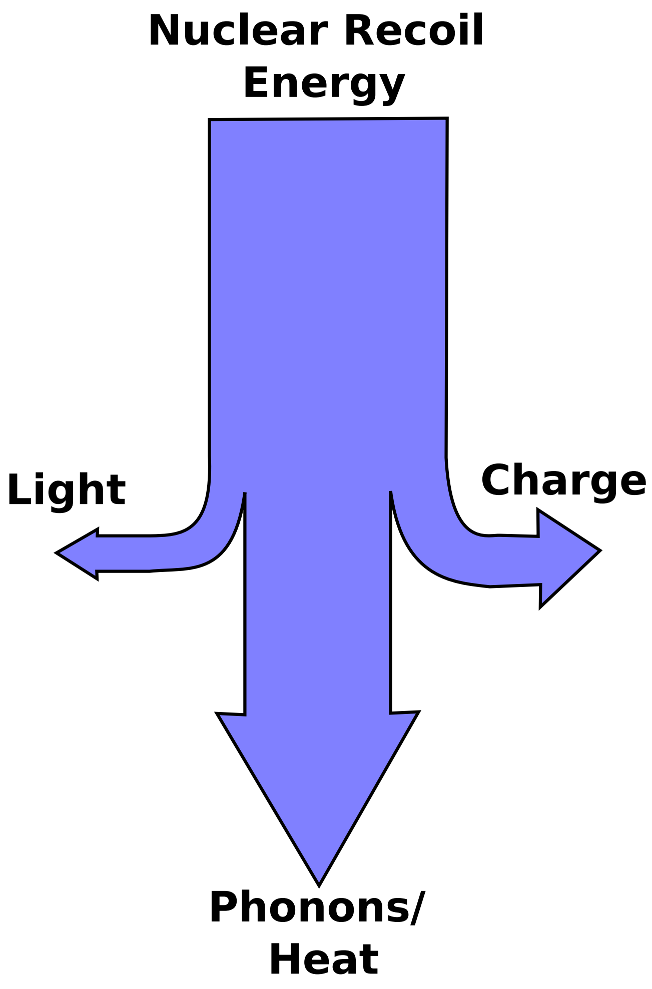


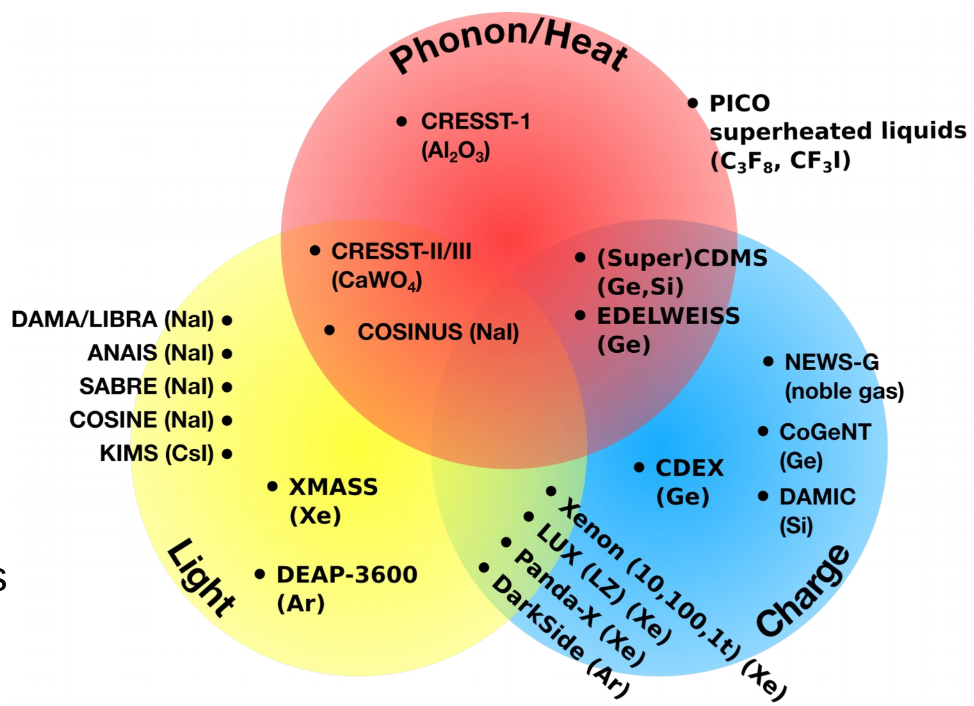
Possible excitations in matter:

Phonons/Heat
largest signal (but hardest to detect)
nearly full primary energy

Charge (e.g. in semiconductors)
~20% of primary energy in e-h pairs
Particle dependent!

Light (in scintillators)
~few % of primary energy in photons
Particle dependent!

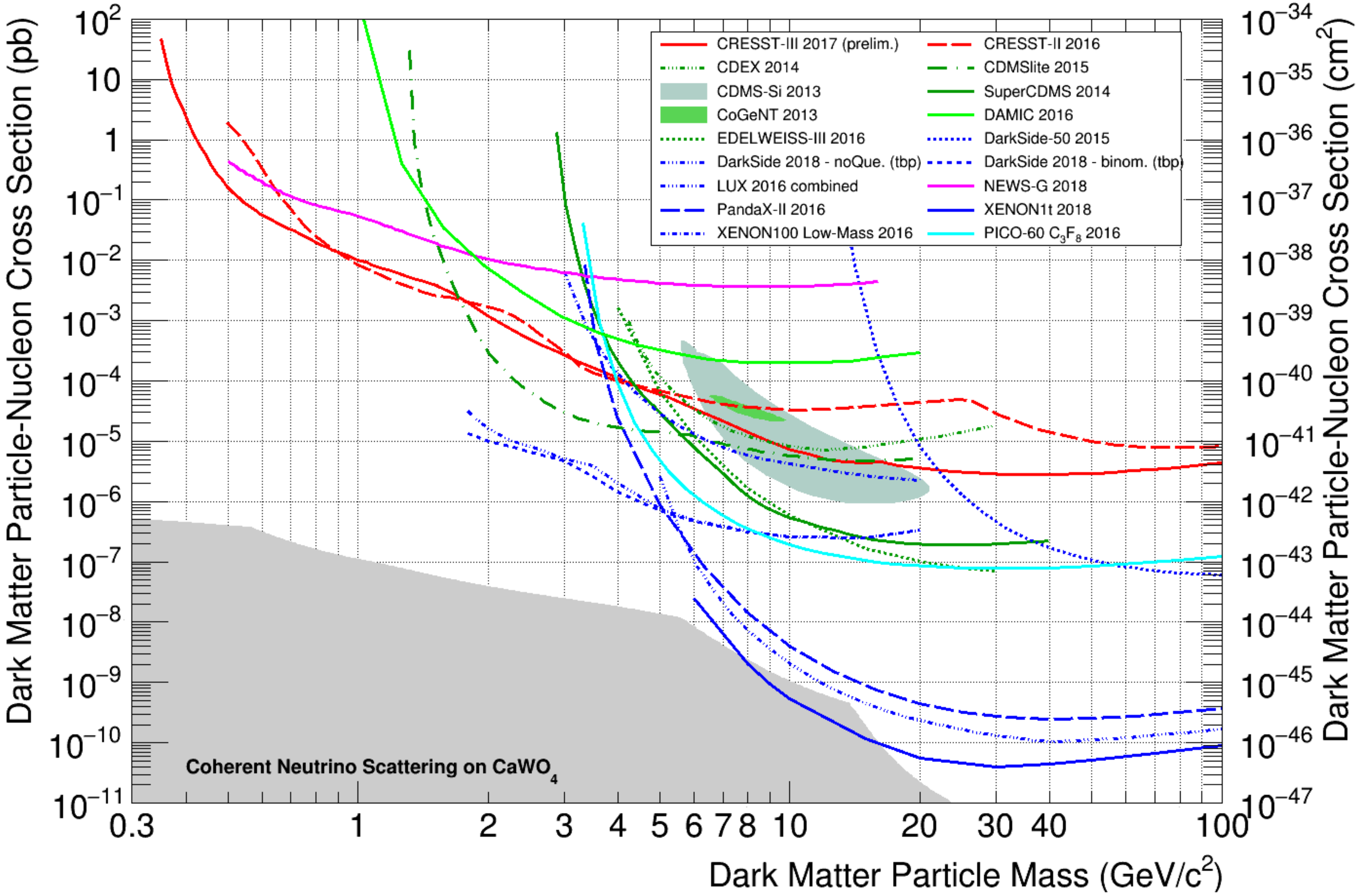
An incomplete compilation

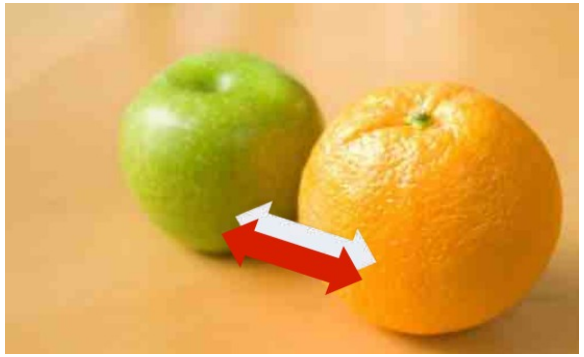


Direct Search Requirements

Small energies	High sensitivity
Low signal rates	Large exposures
Radiogenic backgrounds	Sophisticated shielding/ Particle Identification

The “playing field”





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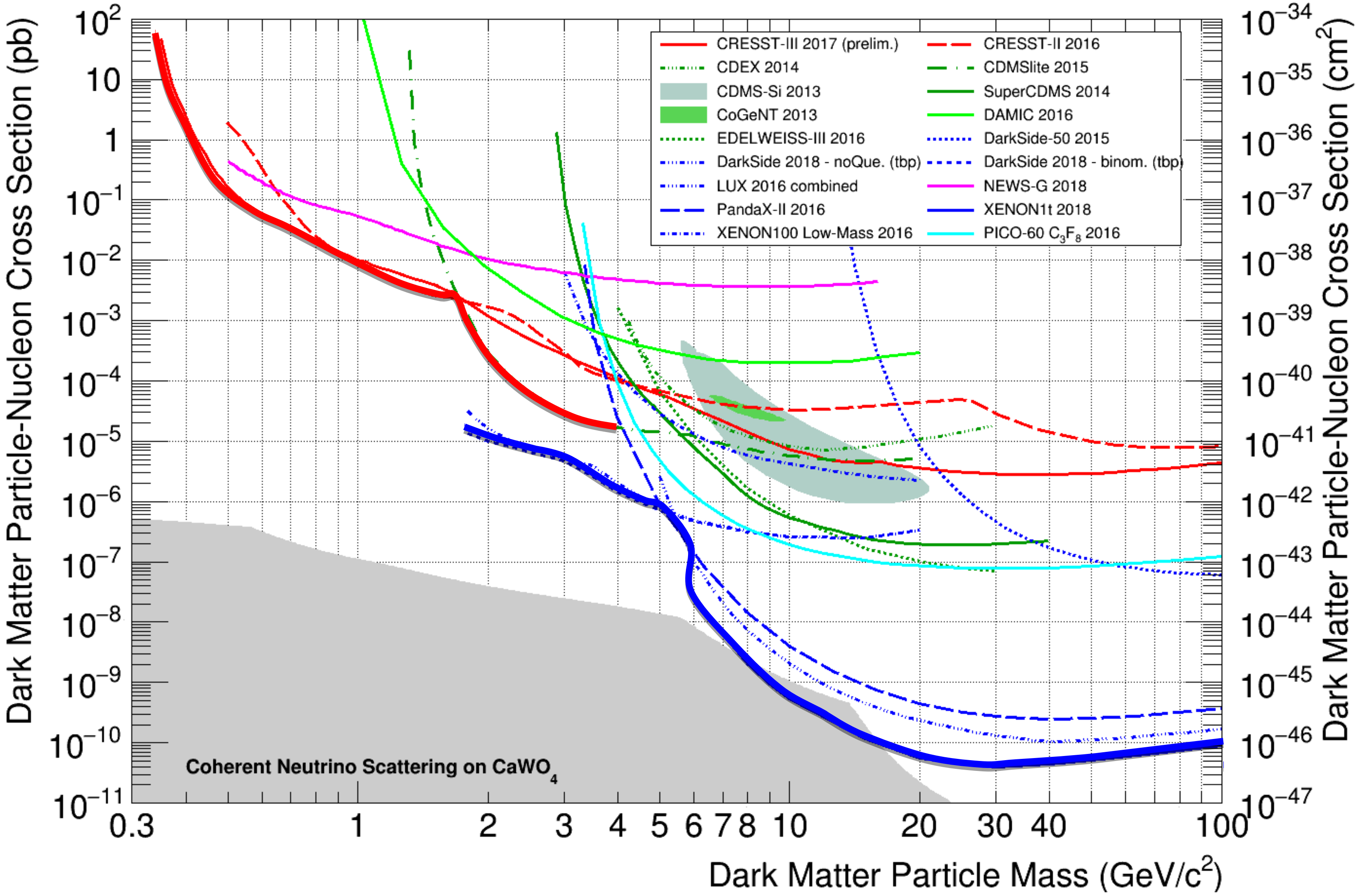
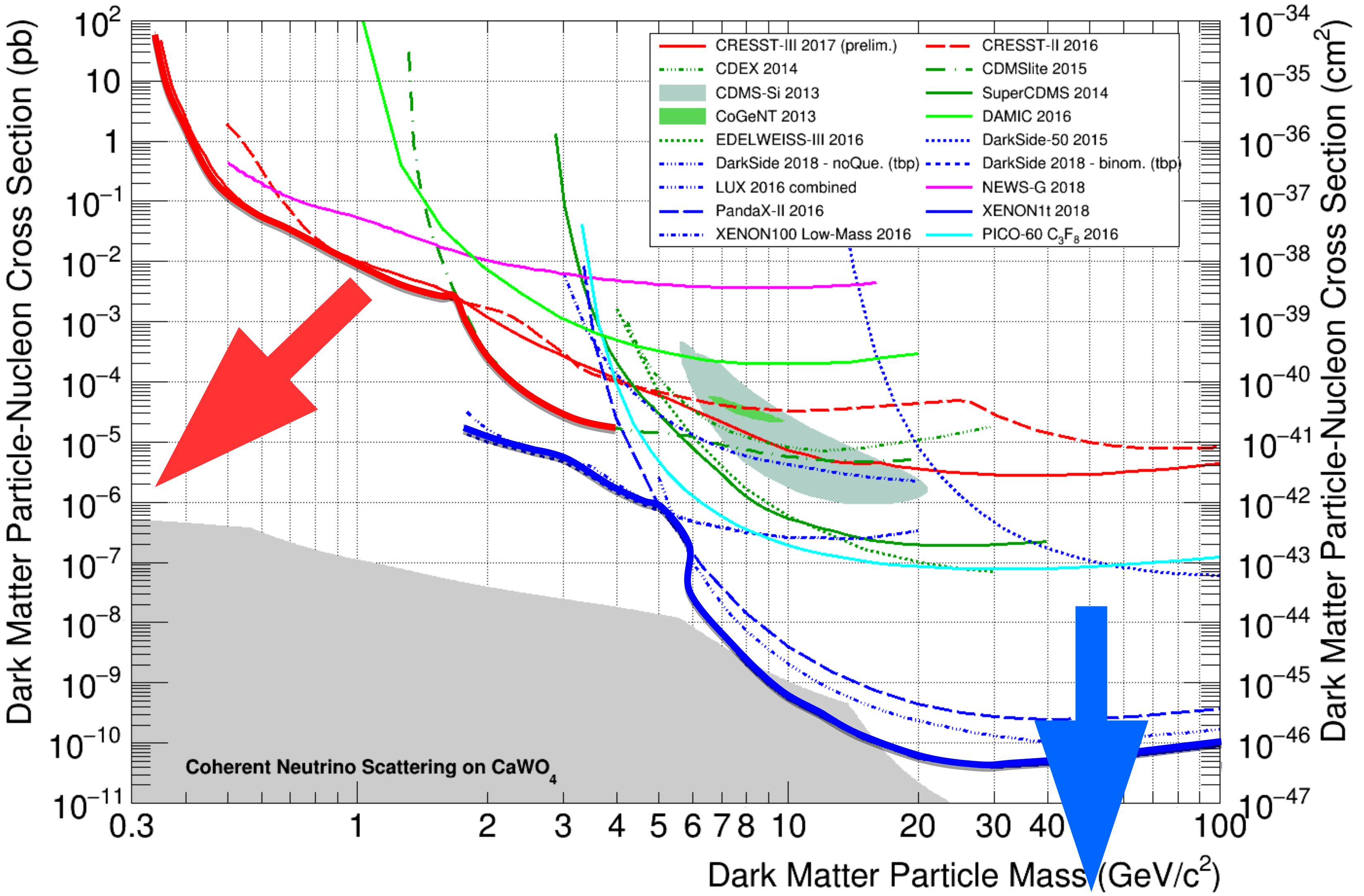
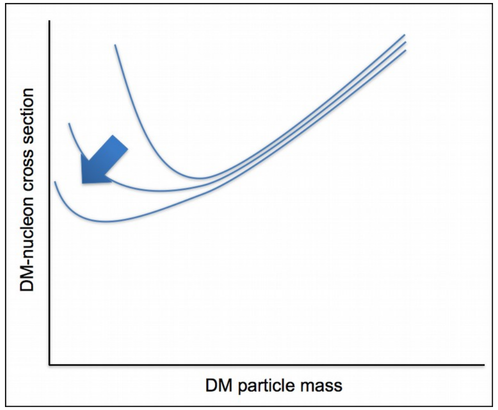


Cryogenic detectors

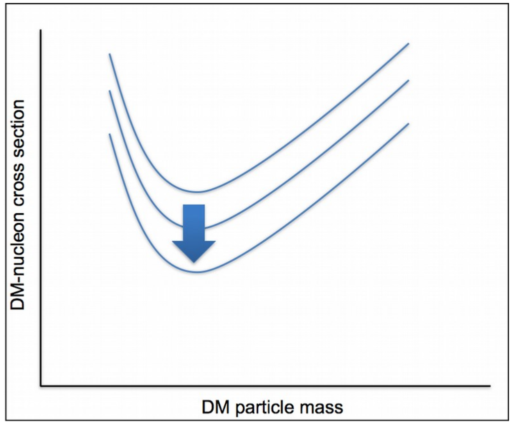
Dual-phase
liquid noble gas
TPCs

The “playing field”



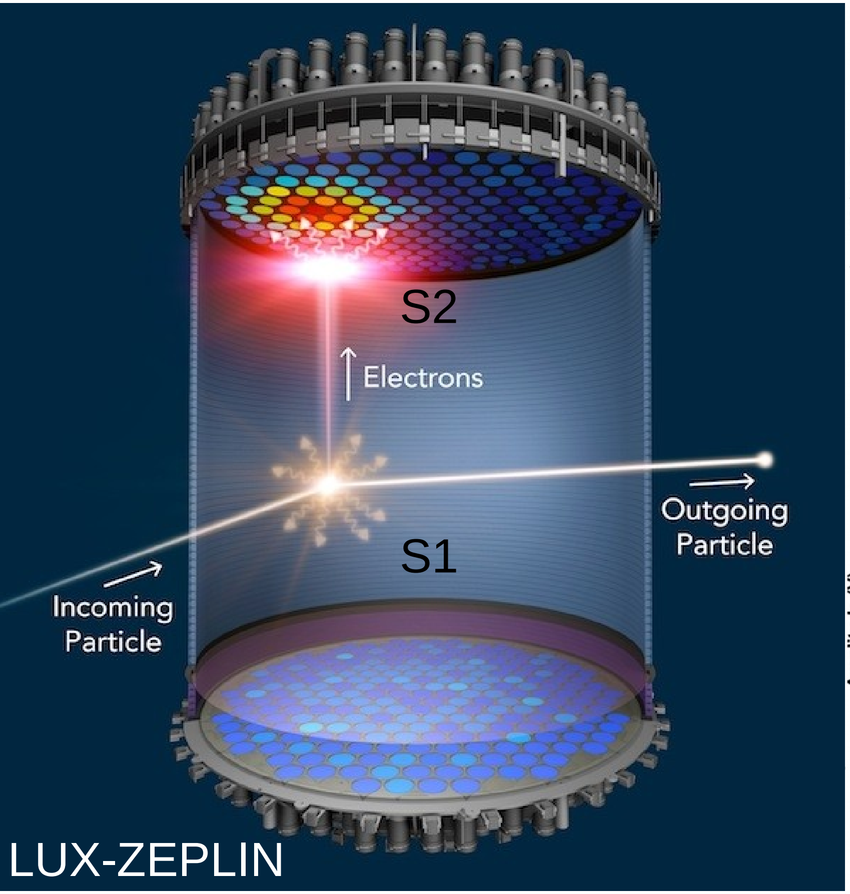


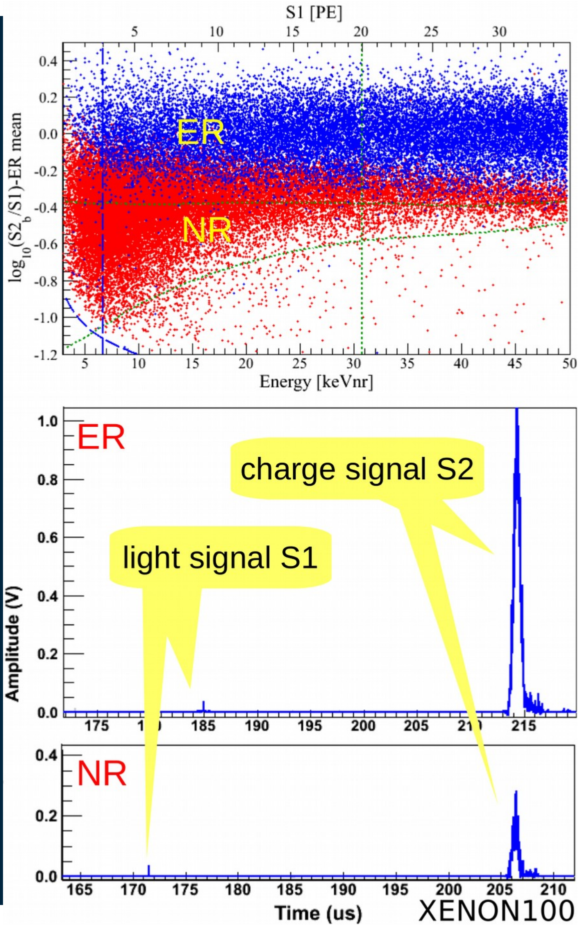
Detector performance (energy threshold)

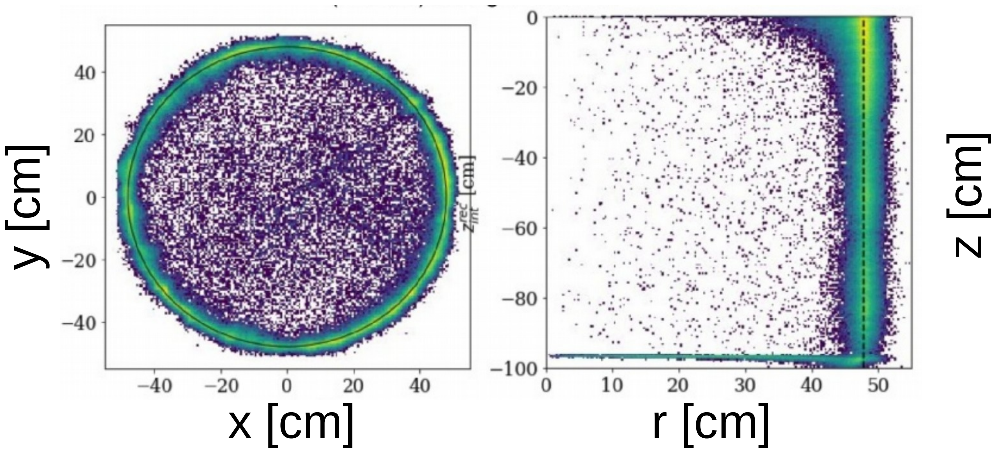


Exposure (Target mass + radiopurity)

Liquid Xenon Time Projection Chambers

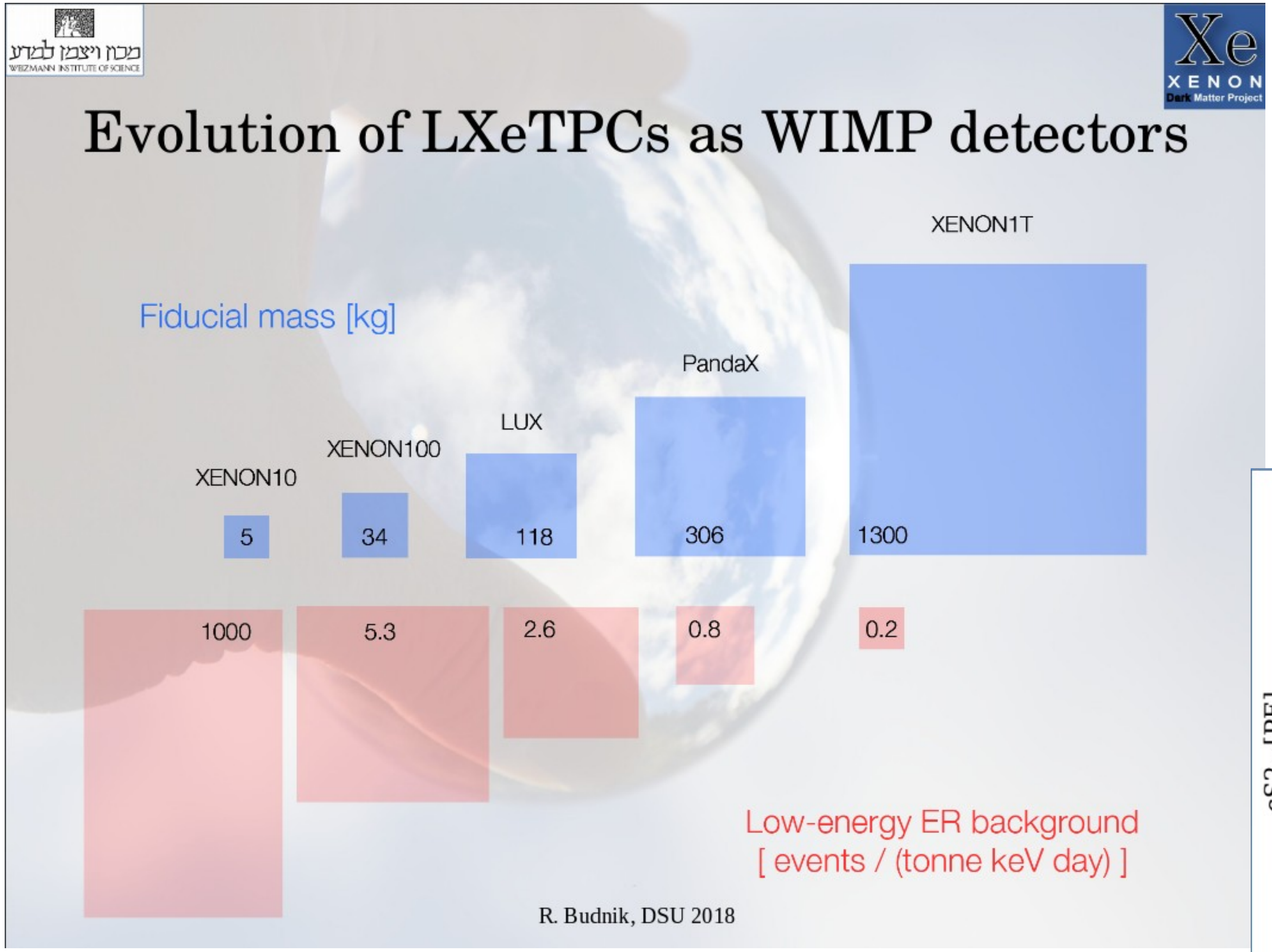






- S2/S1 different for nuclear recoils and electrons recoils
- XY from top PMT array (few mm)
- Z from timing difference (fraction of mm)

Liquid Xenon Time Projection Chambers

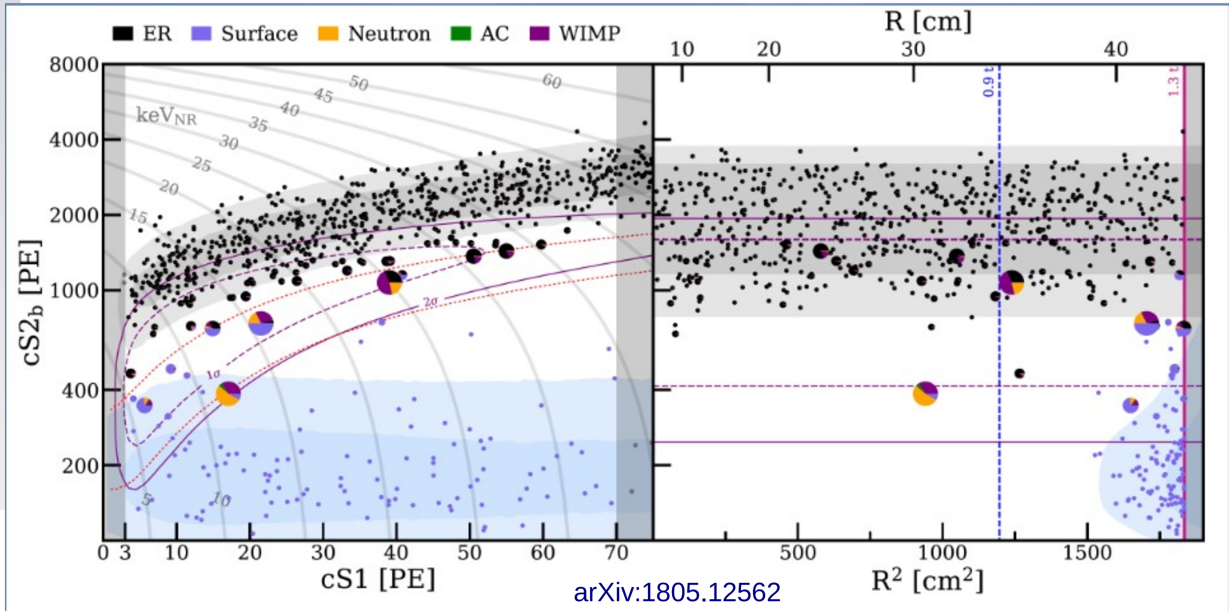


Pros:

- Fiducialization (self-shielding via event location)
- Scalable to large target masses
  - long attenuation length
  - long charge drift length
- Constant purification

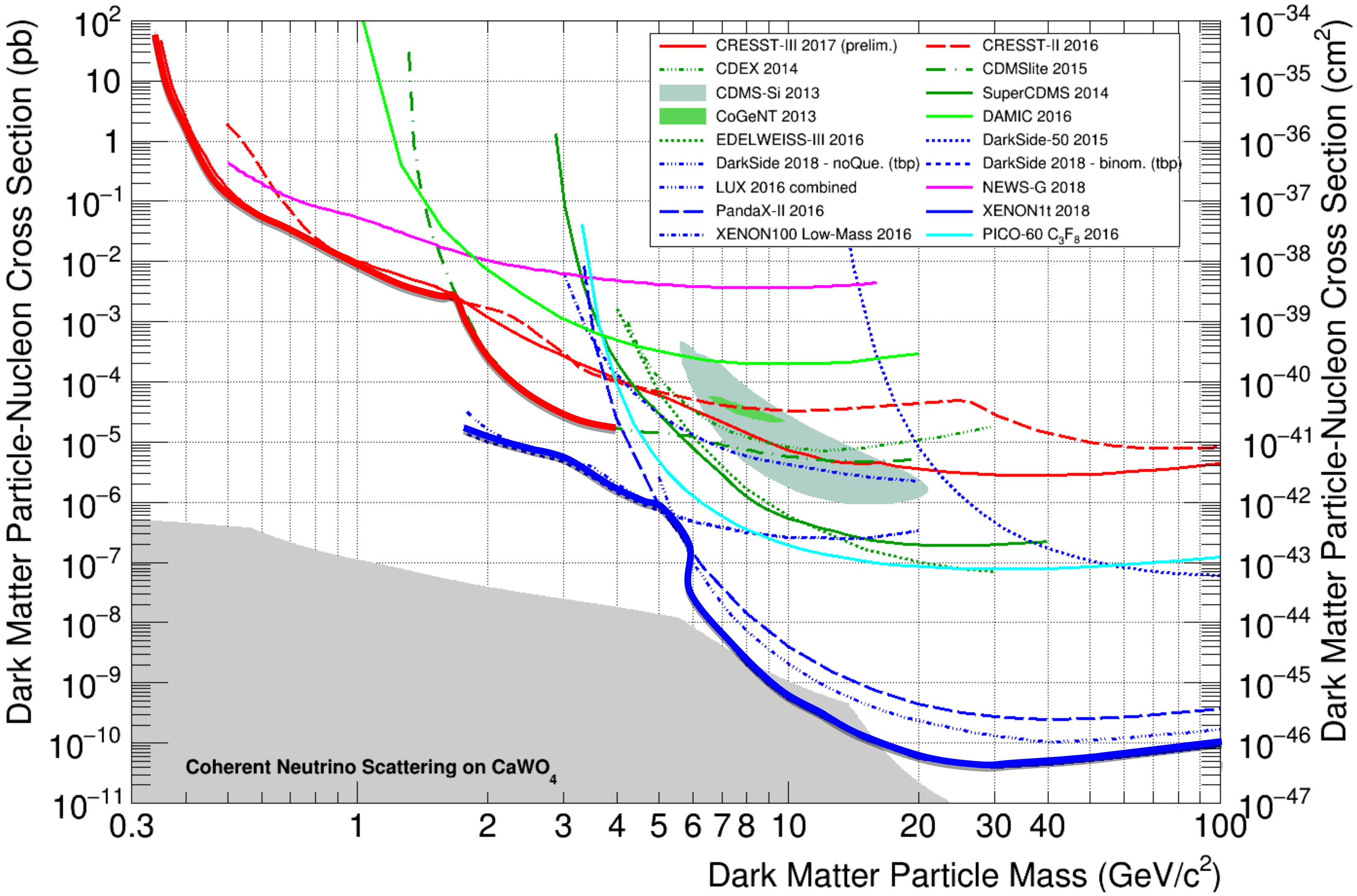
Cons:

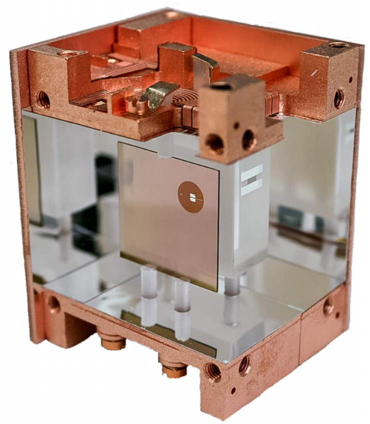
- “Rather high” energy thresholds (few keV for nuclear recoils)
- Calibration
  - energy scale for nuclear recoils derived from S1 using an independently measured scintillation efficiency



arXiv:1805.12562

The "playing field"



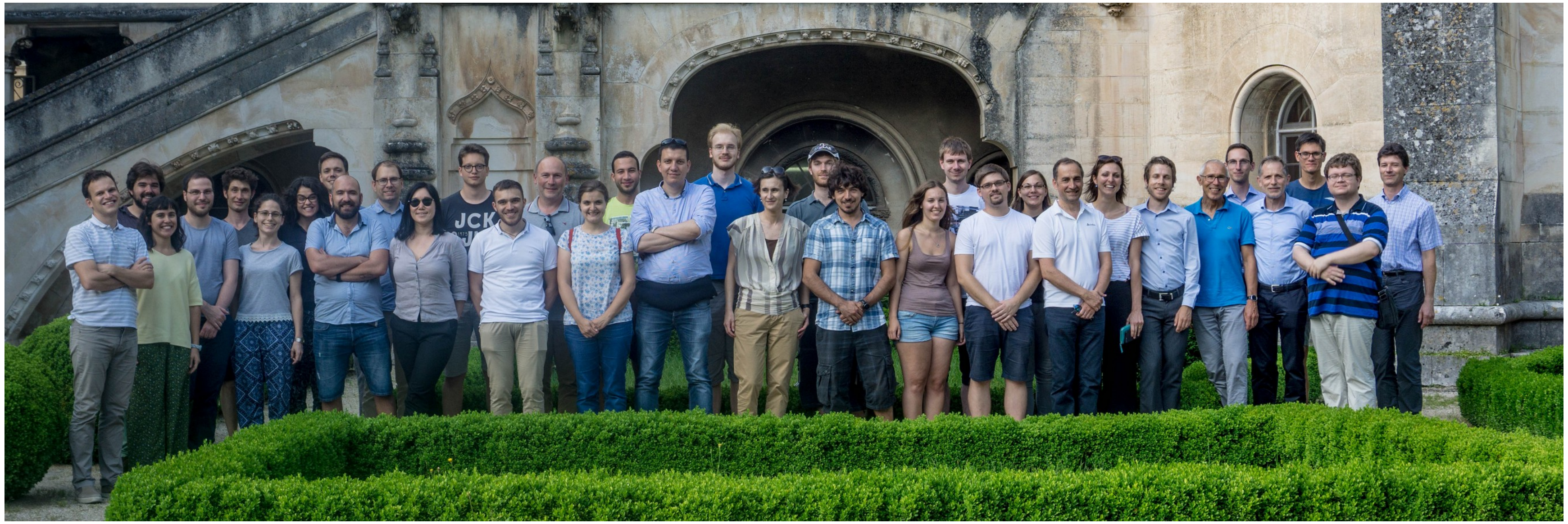


Cryogenic detectors

Dual-phase
liquid noble gas
TPCs

The CRESST collaboration

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



HEPHY
Institut für Hochenergiephysik

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

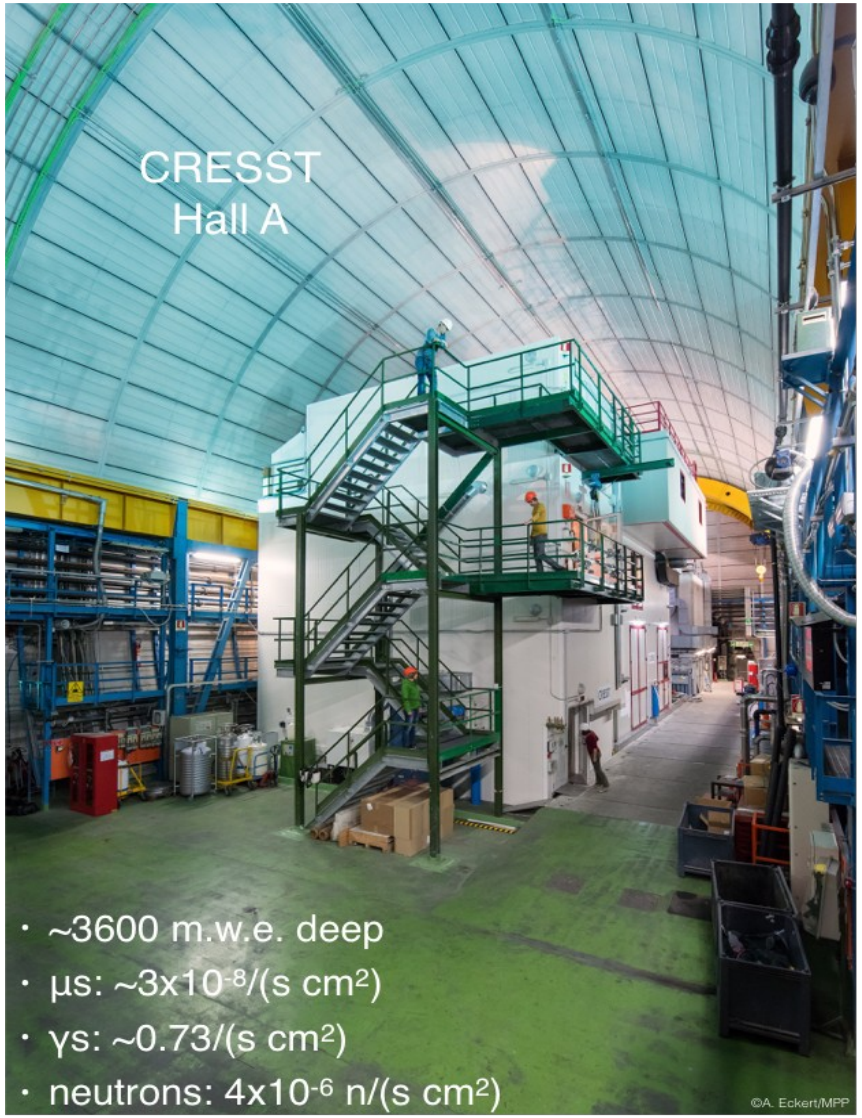
TUM
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

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

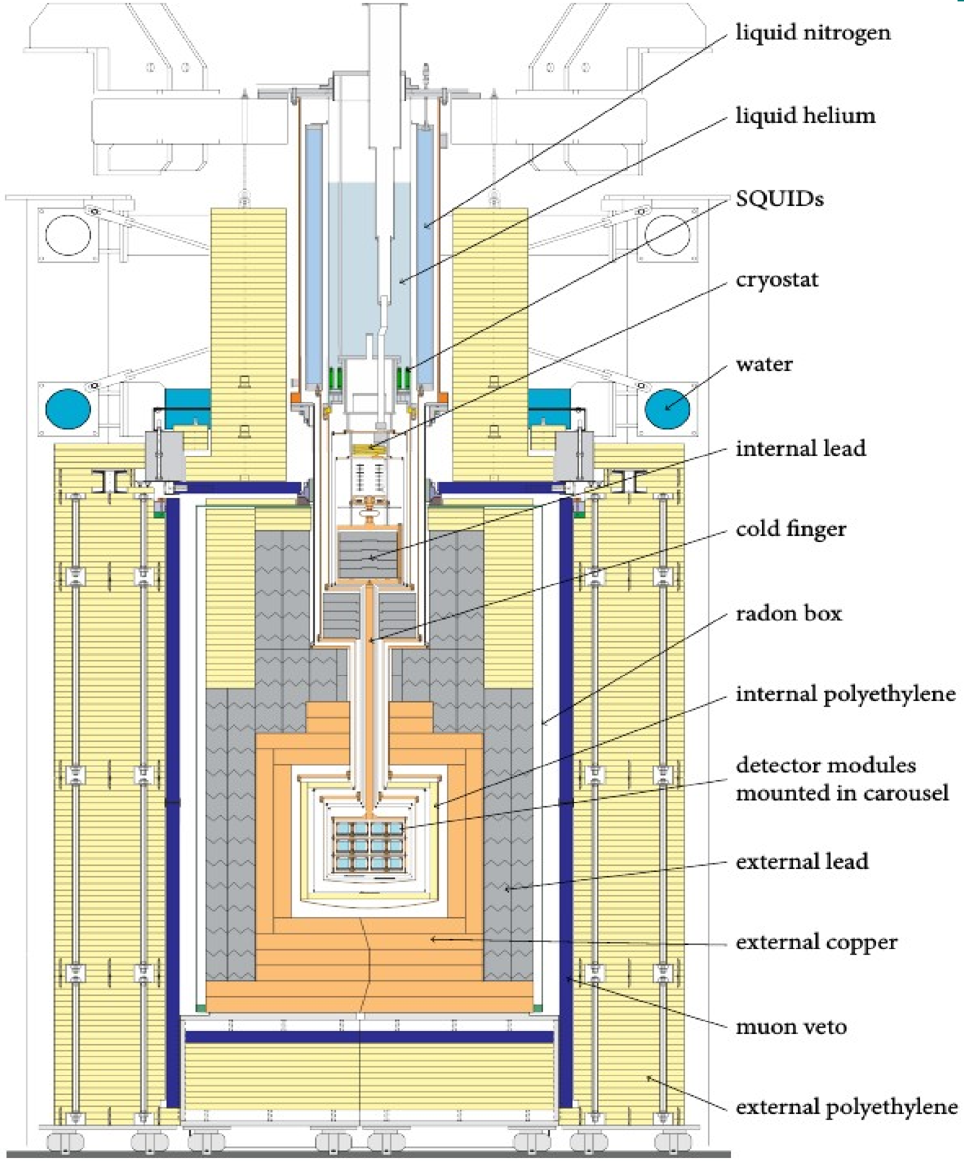
INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

UNIVERSITY OF OXFORD

CRESST @ Laboratori Nazionali del Gran Sasso (LNGS)



The experimental setup



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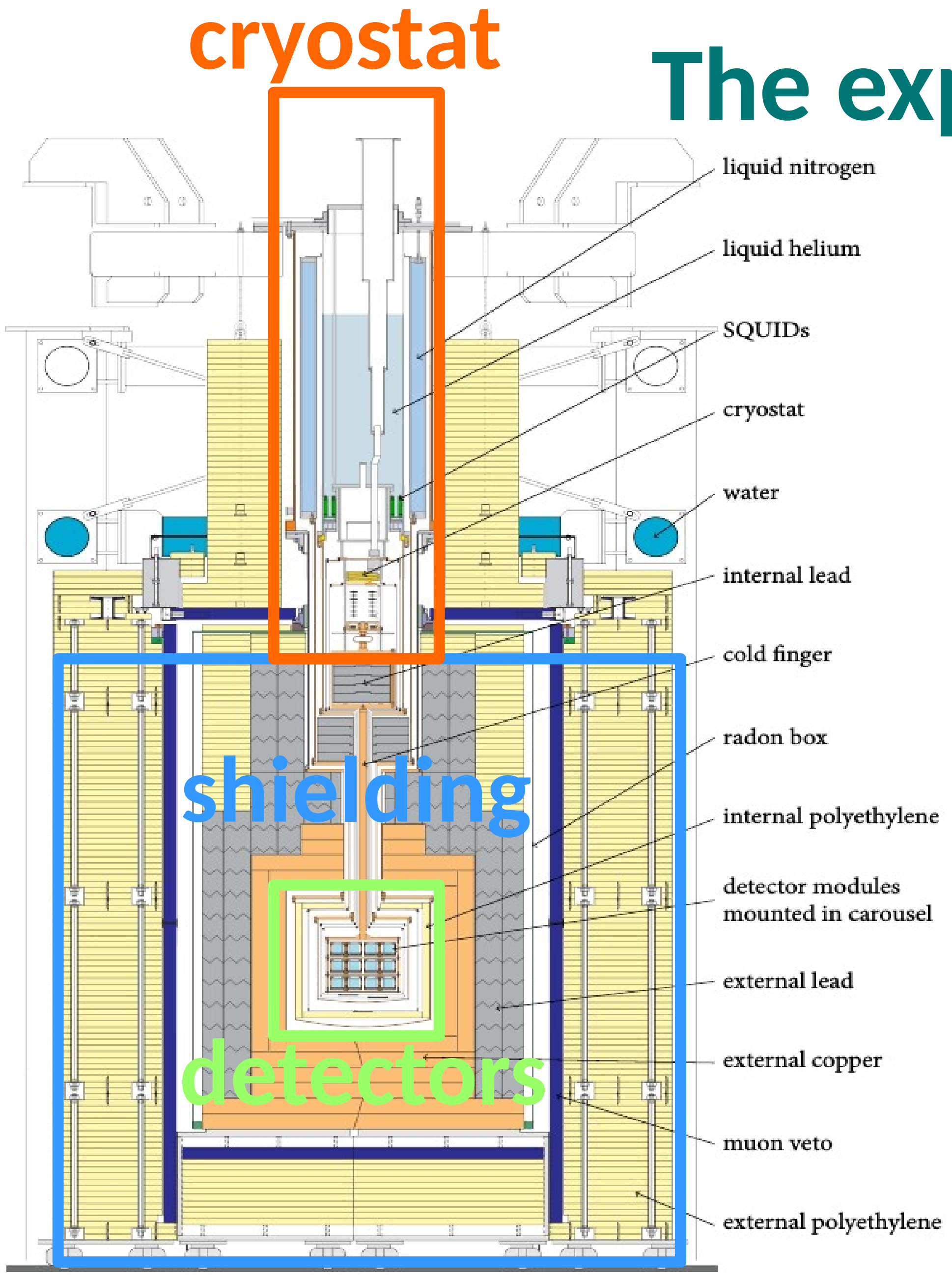

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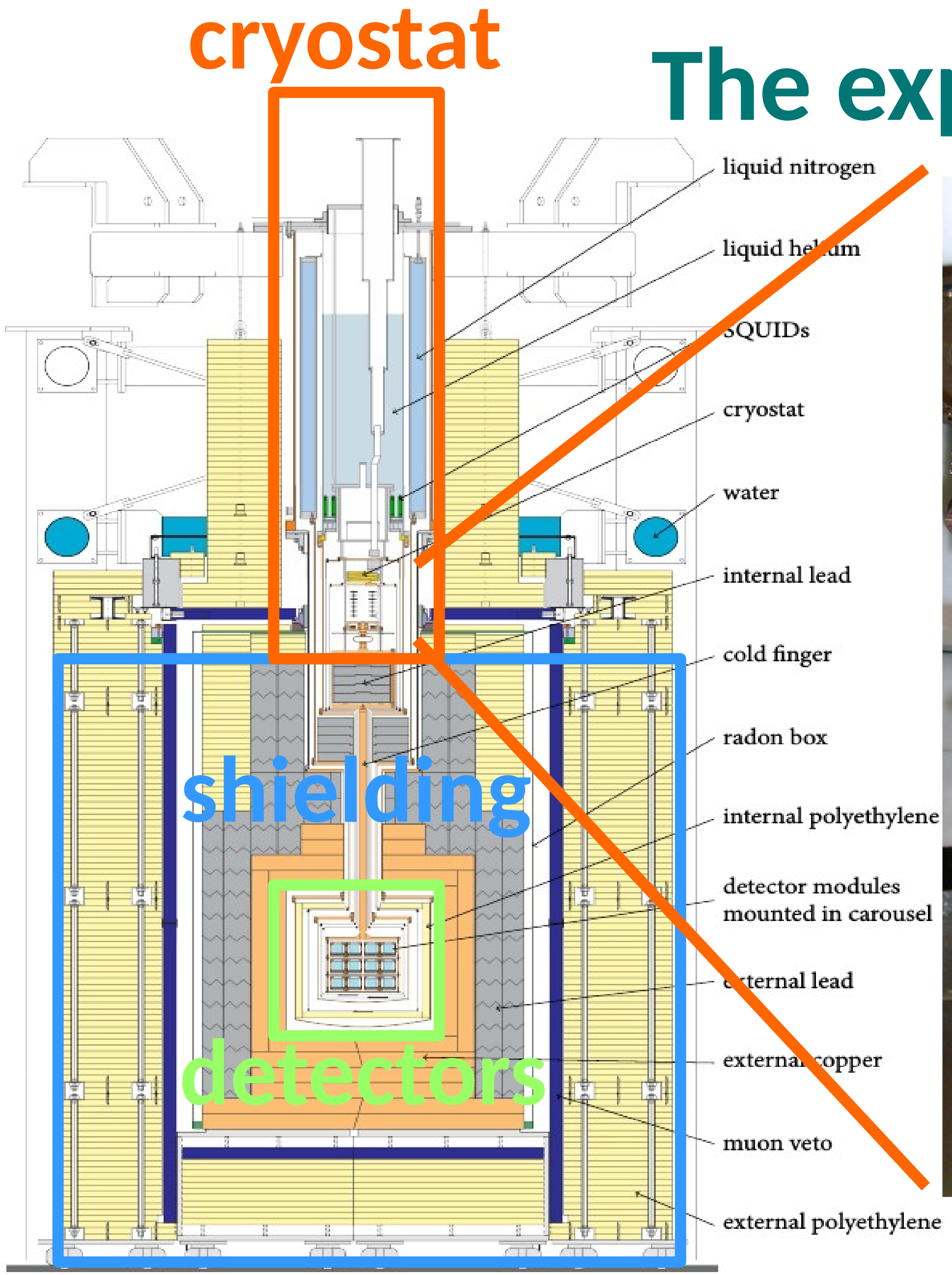
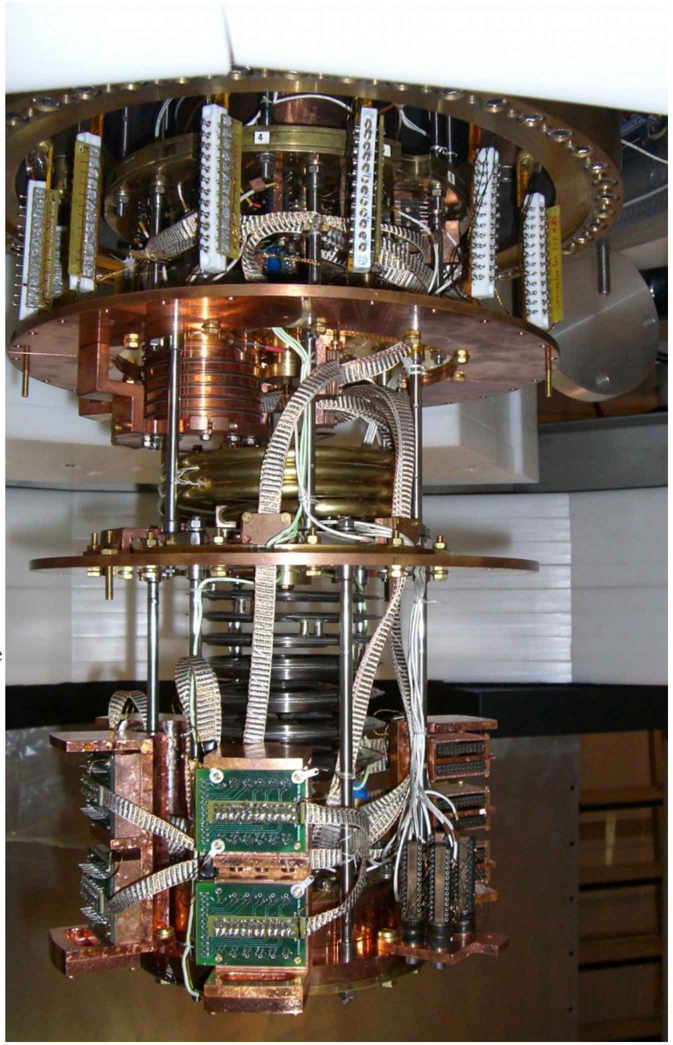
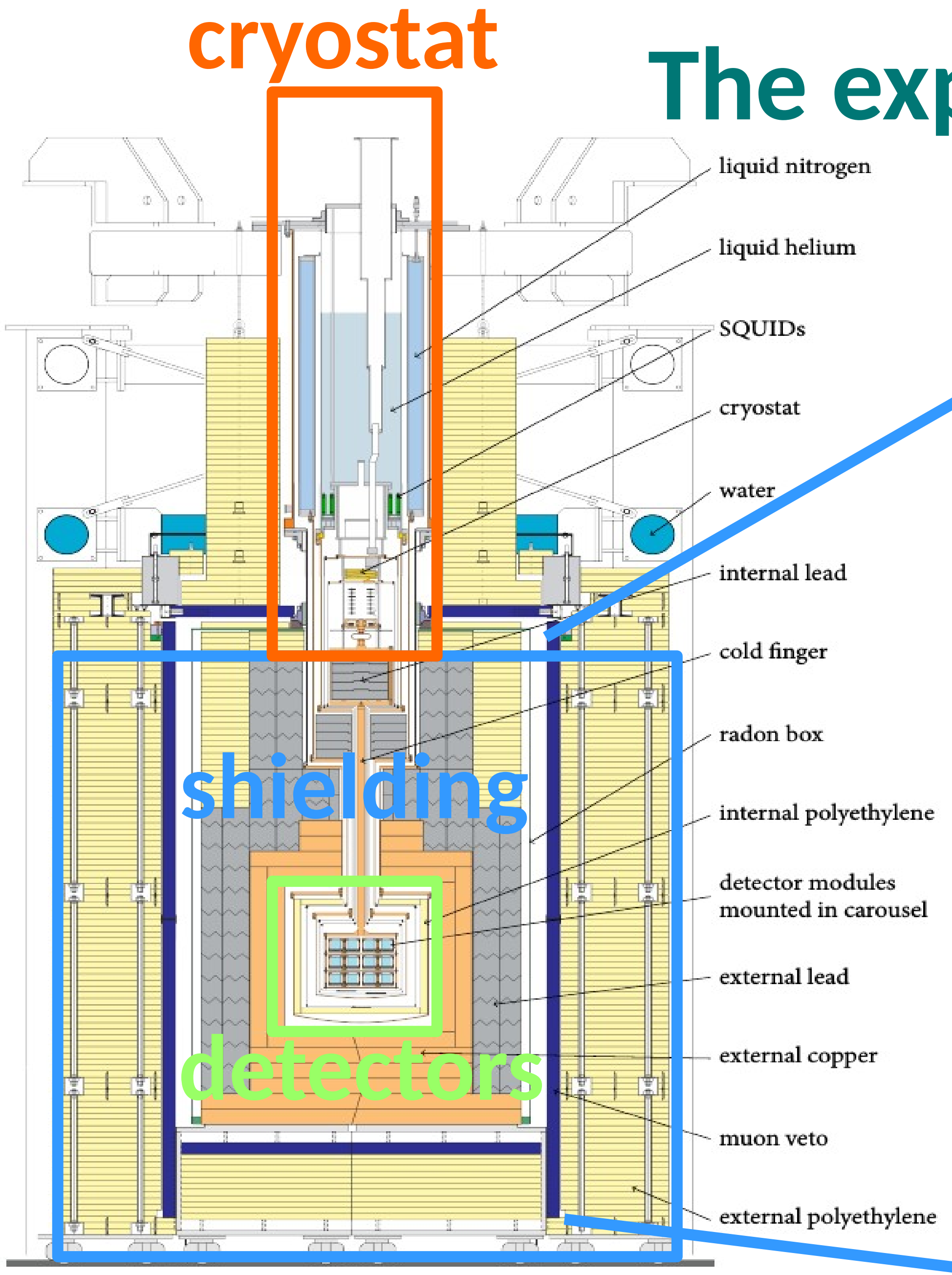




^{3}He-^{4}He dilution refrigerator

- lowest indefinitely sustainable temperatures (<10mK)
- no moving parts at the cold end

The experimental setup

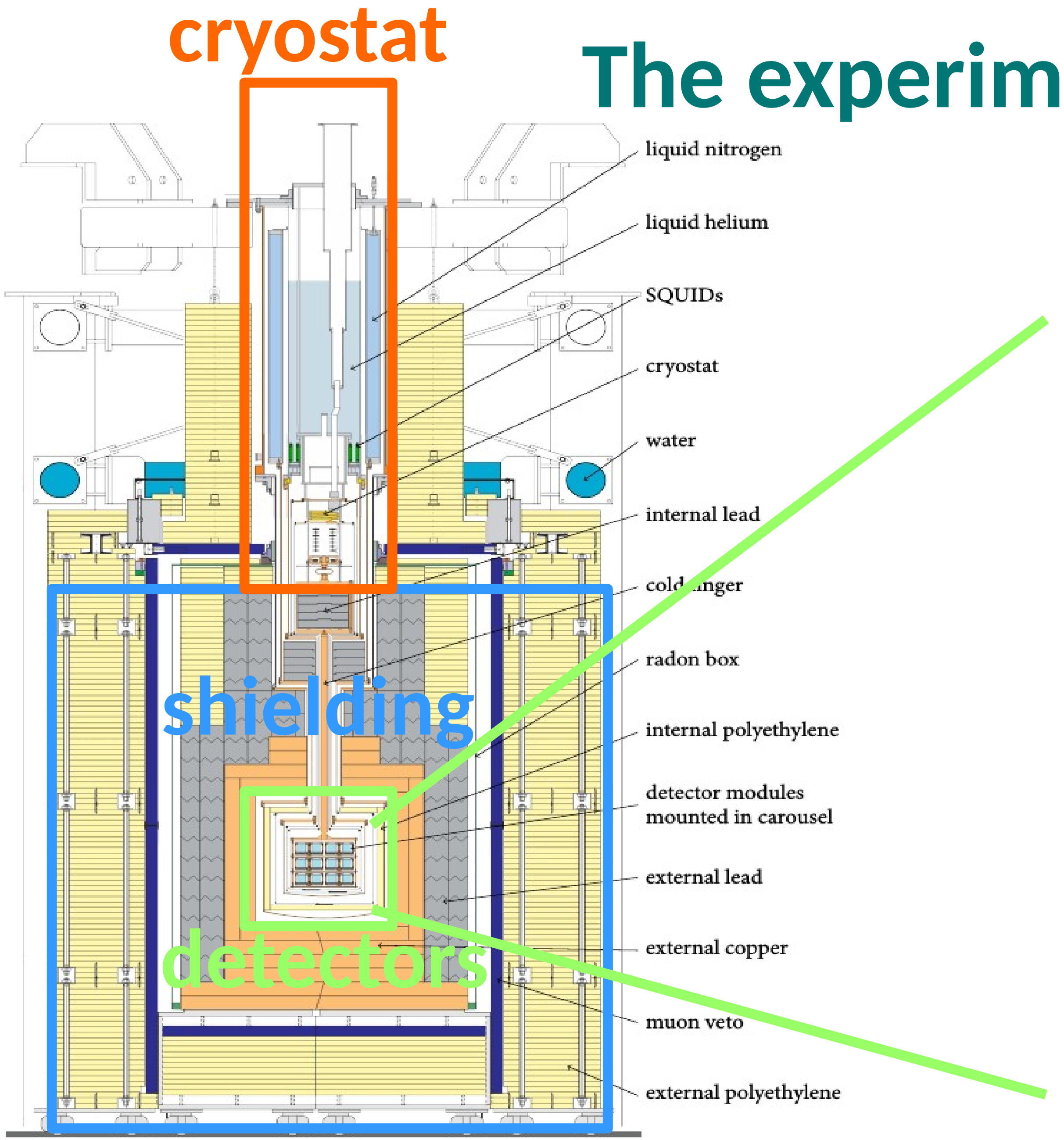


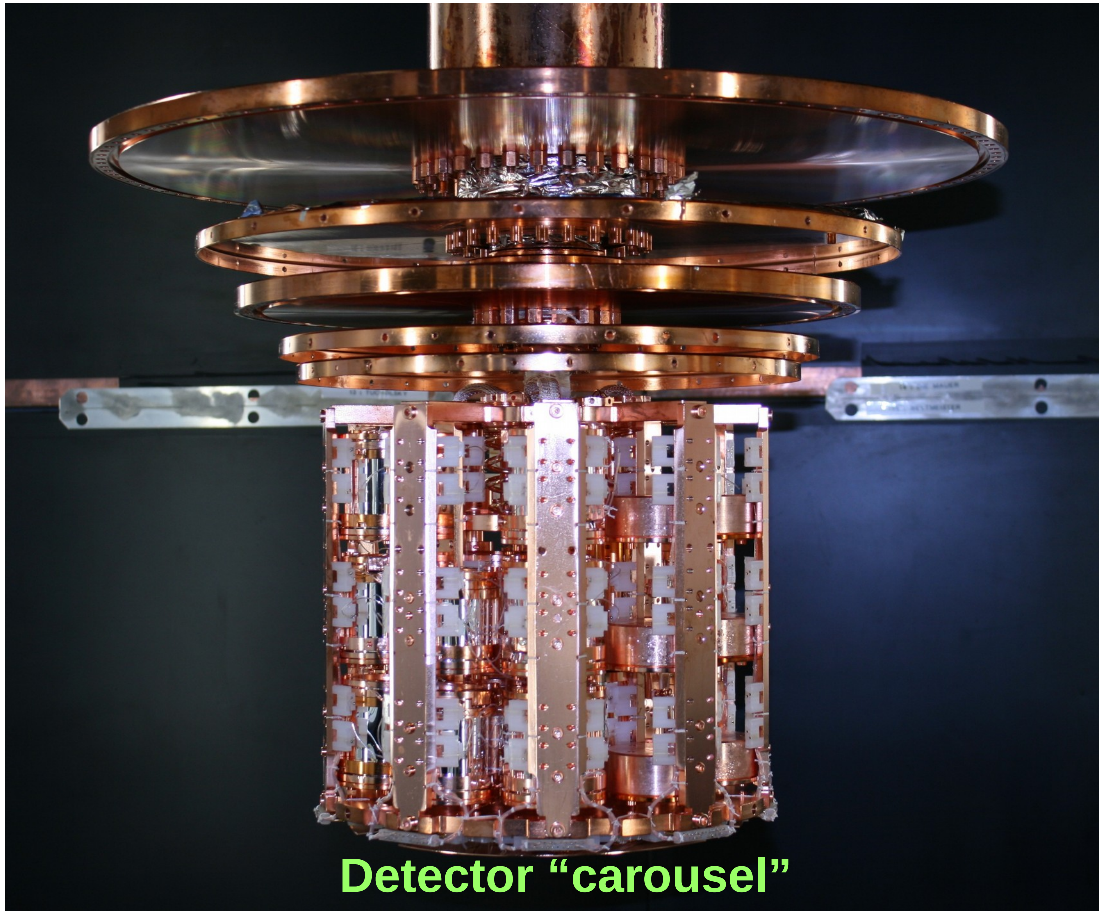
outer polyethylene (n moderator)

lead shielding (high Z)

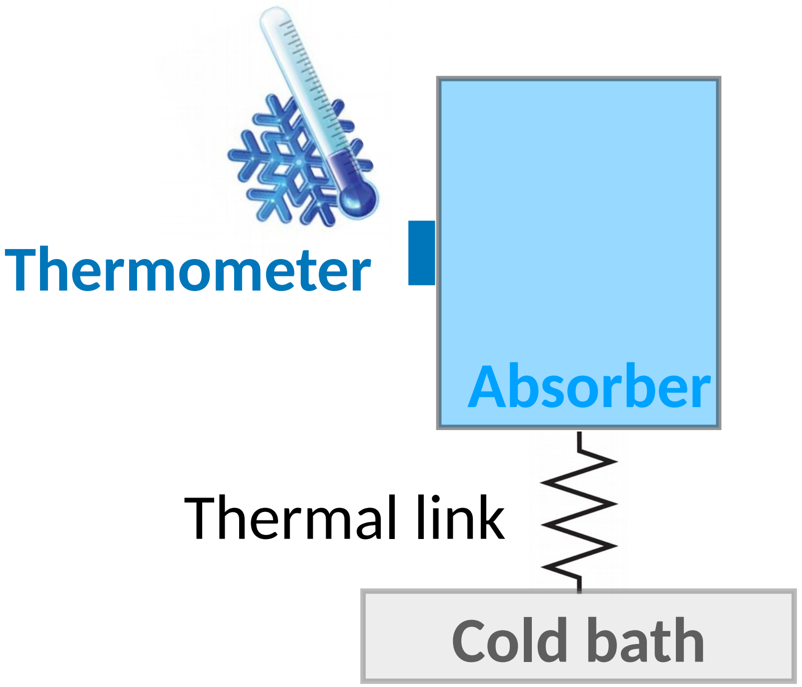
clean inner copper

The experimental setup





Cryogenic Calorimeters



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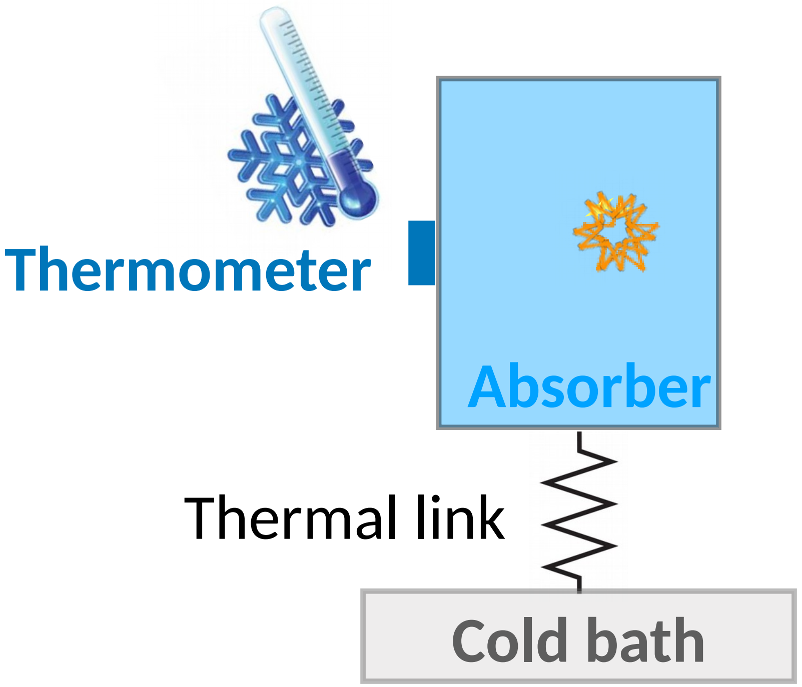
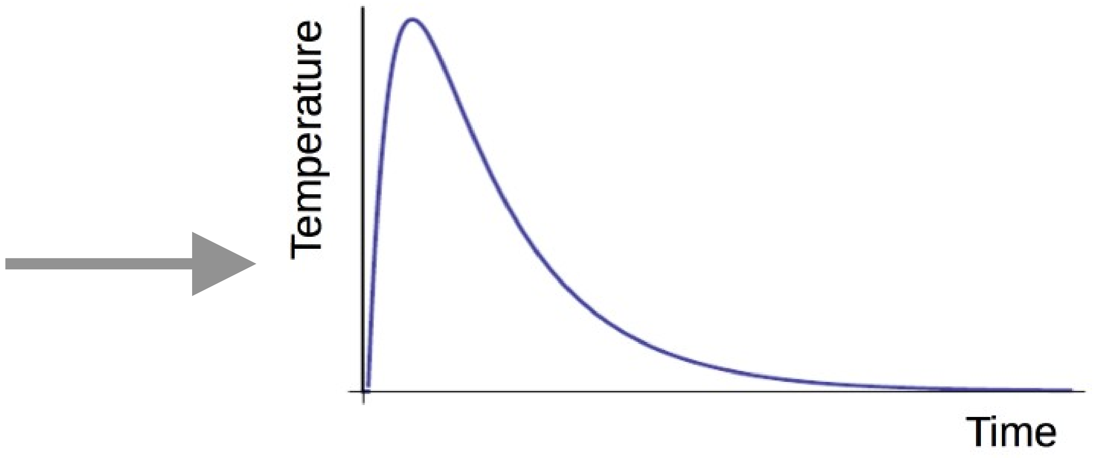
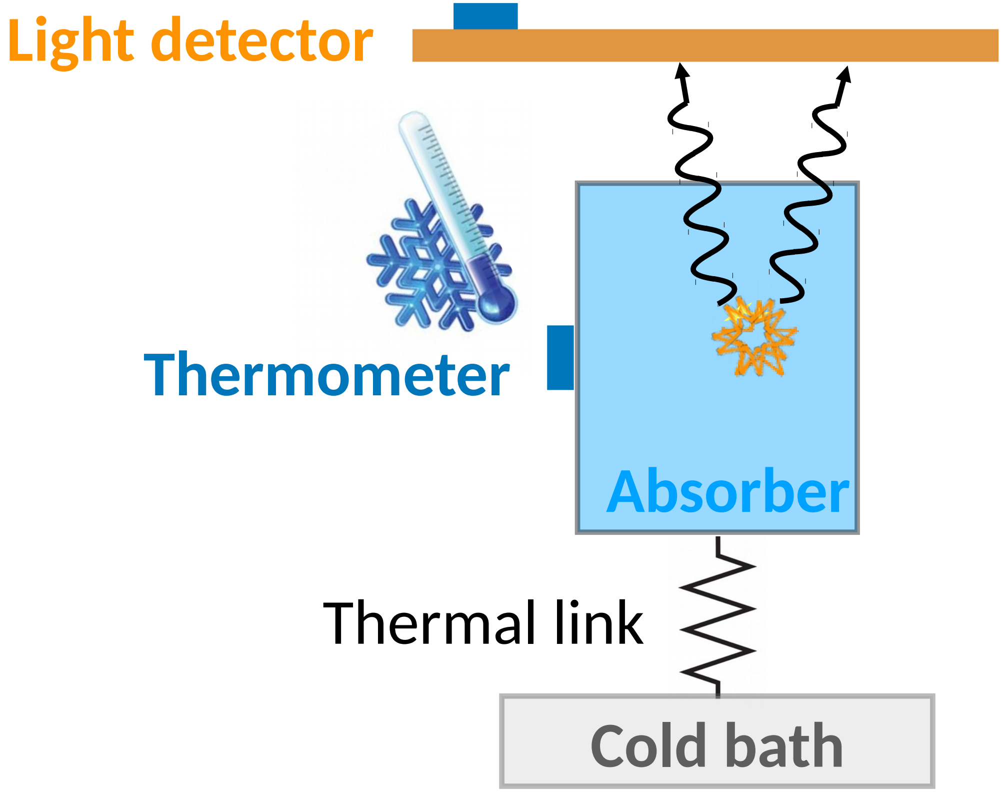
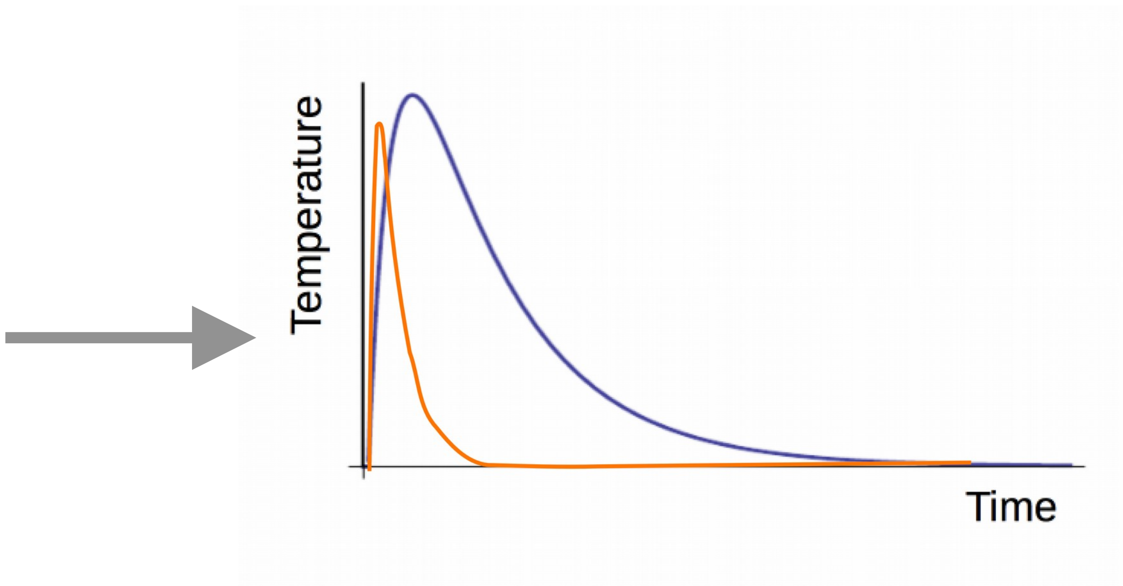




- Measurement of total deposited **energy** (~particle independent).

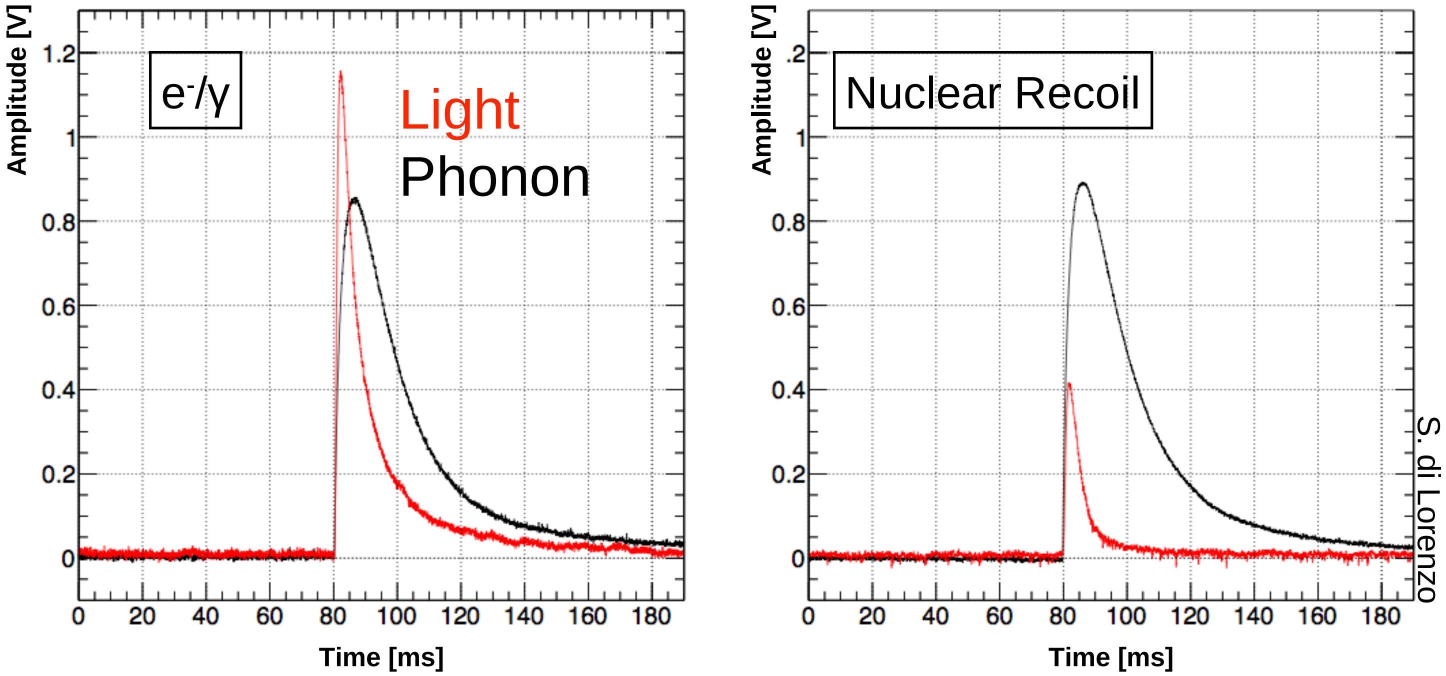
Scintillating Cryogenic Calorimeters





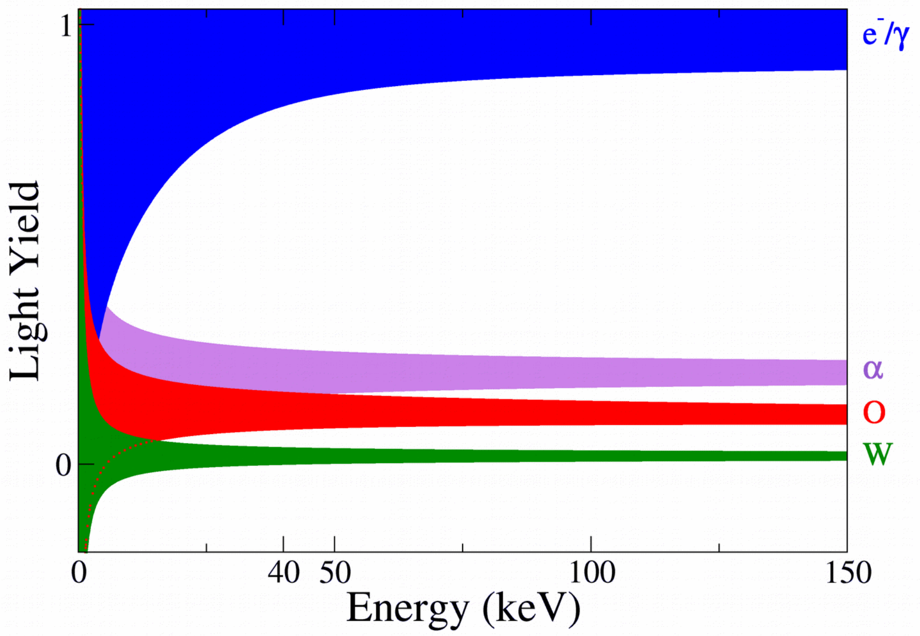
- Measurement of total deposited **energy** (~particle independent).
- **Particle identification** given by the measurement of the scintillation light (Light yield).

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**)

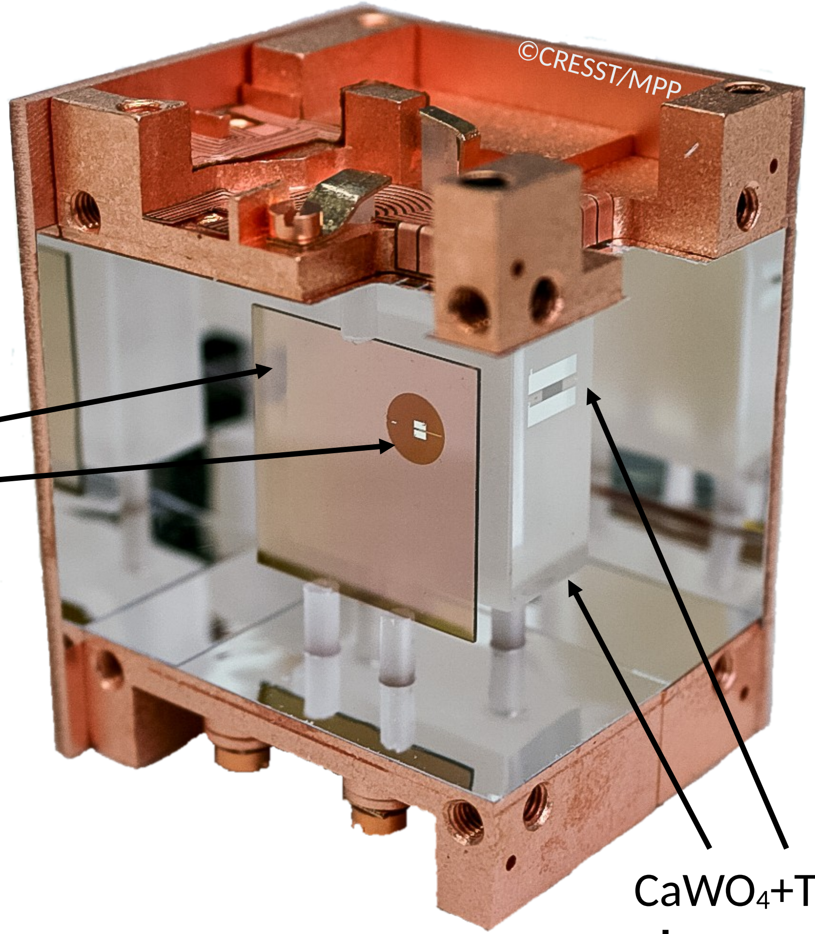
CRESST Modules: scintillating cryogenic calorimeters

Crystals operated as
cryogenic calorimeters (~15mK)

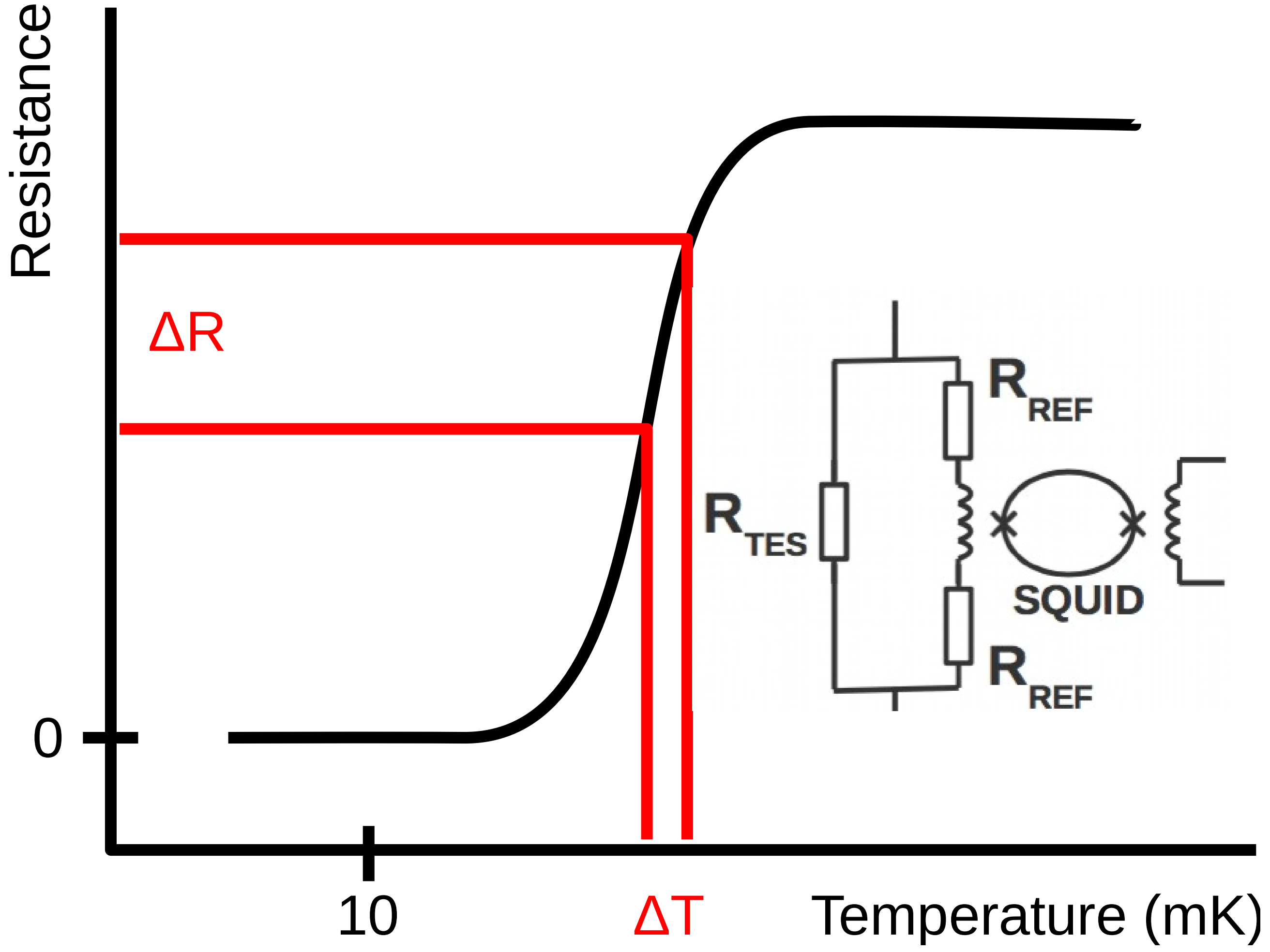
Target crystal (phonon signal):
Scintillating $CaWO_4$, 2x2x1 cm^3

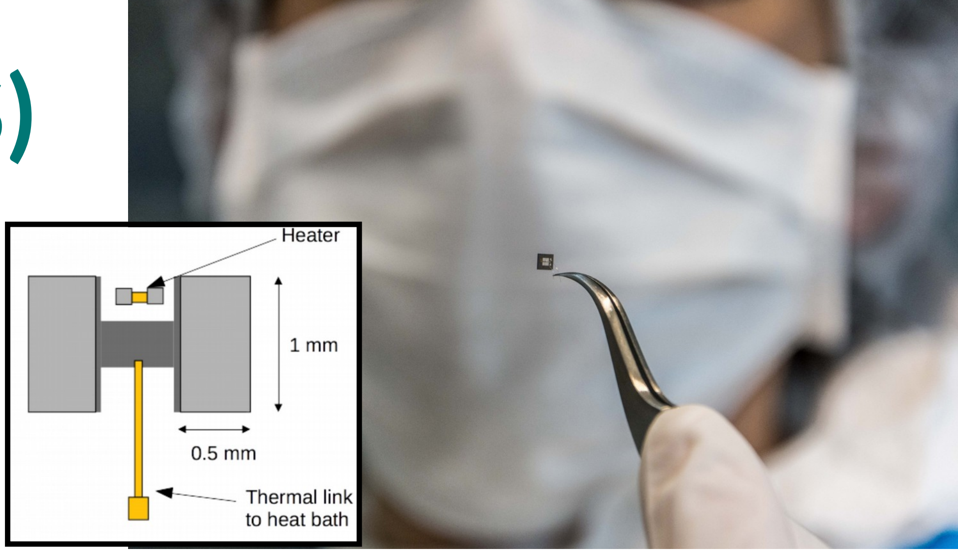
Light detector:
Silicon on Sapphire (SOS)
detects scintillation light signal

Tungsten **Transition Edge Sensors** (TES)
detect temperature fluctuations



Transition edge sensor (TES)
Working principle

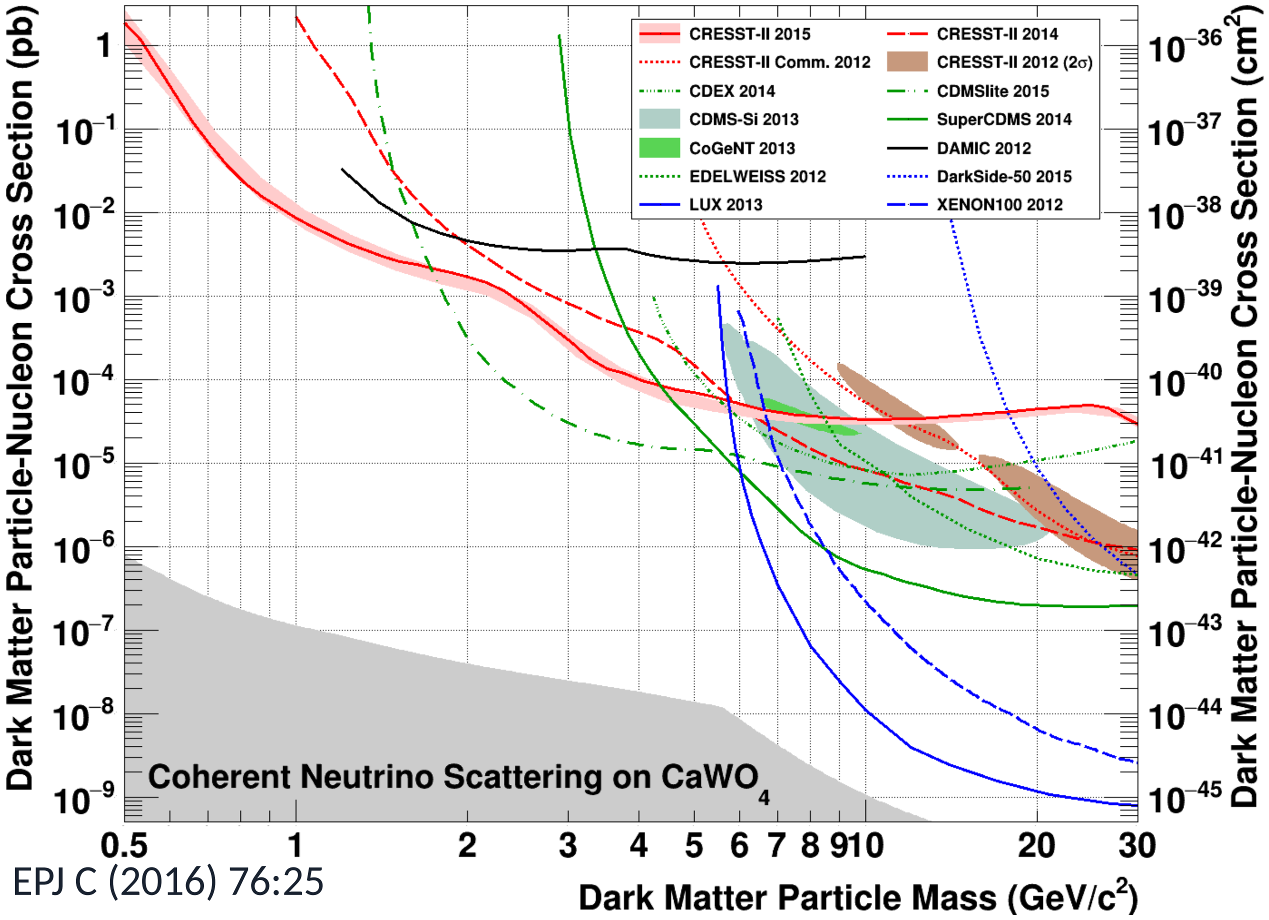




Energy deposition
~keV
↓
Temperature rise
~μK
↓
Resistance change
~mΩ

CRESST-II results (2015)

Most sensitive module **(Lise)**:
Detector mass: **300g** $CaWO_4$
Phonon detector threshold: **307eV**
Background level: **~8.5 cts/ (keV kg d)**
Exposure: **52 kg d**

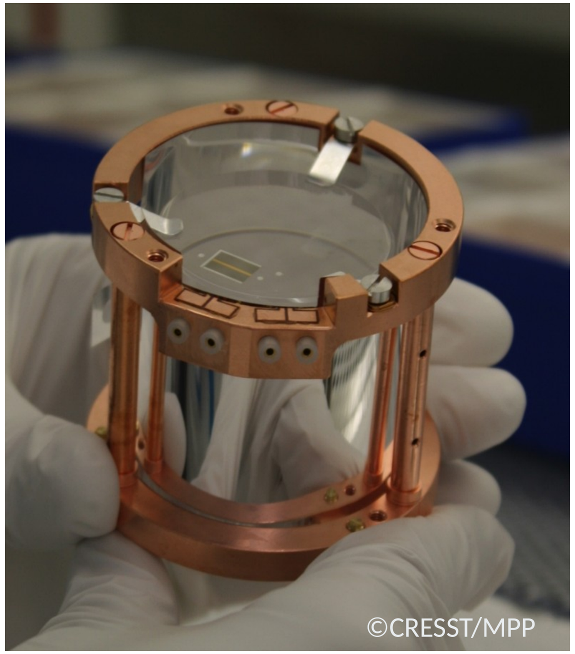


EPJ C (2016) 76:25

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!



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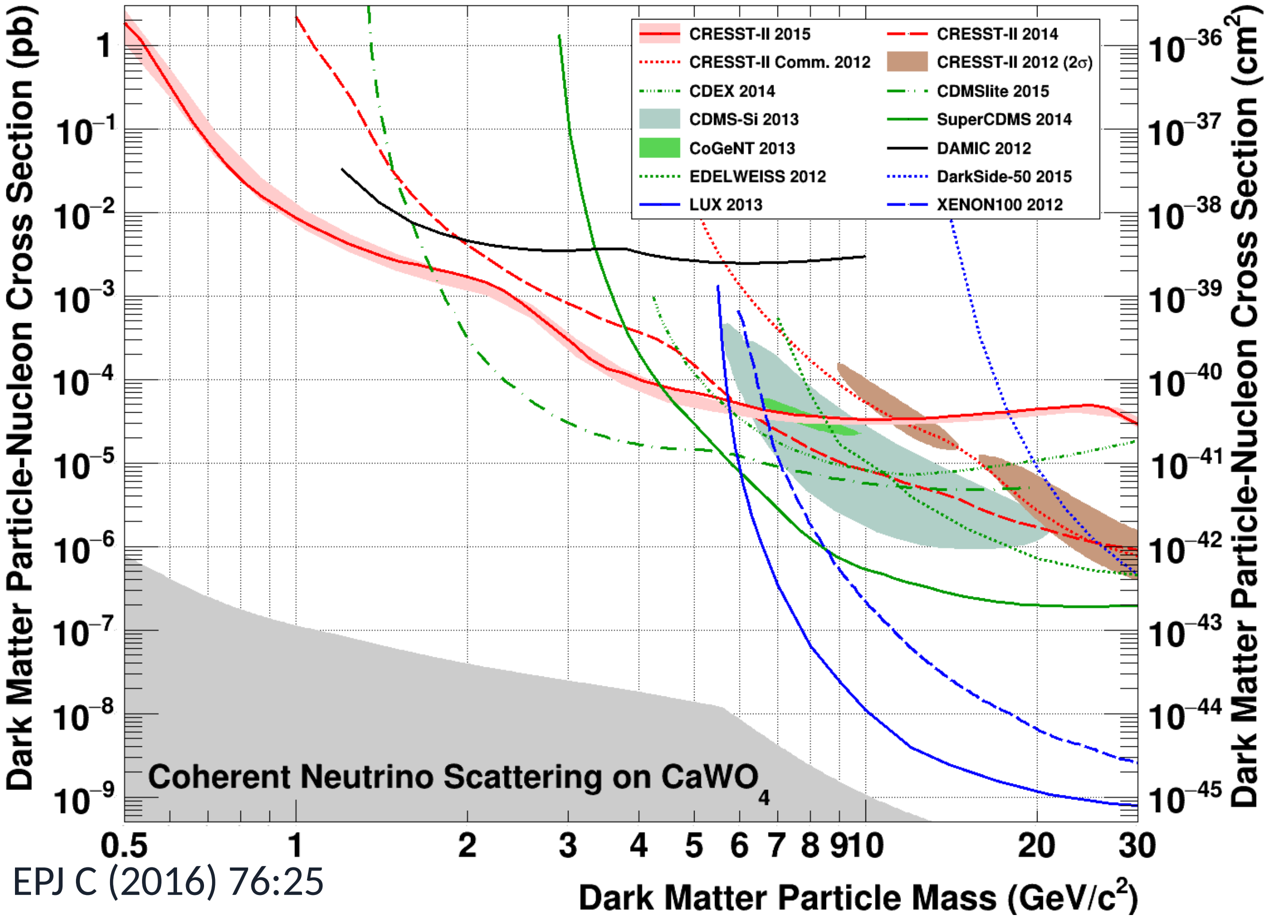

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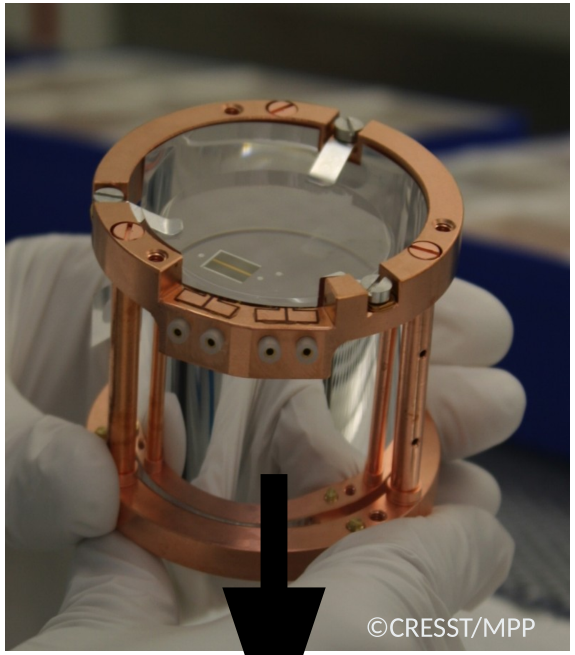
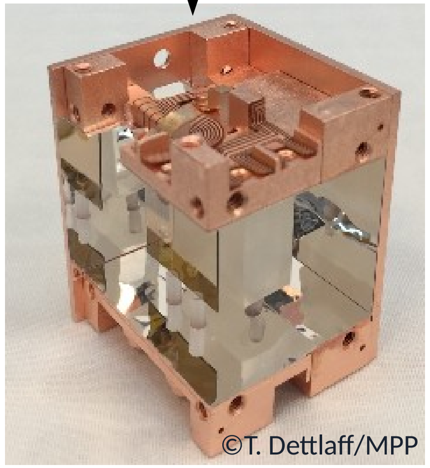


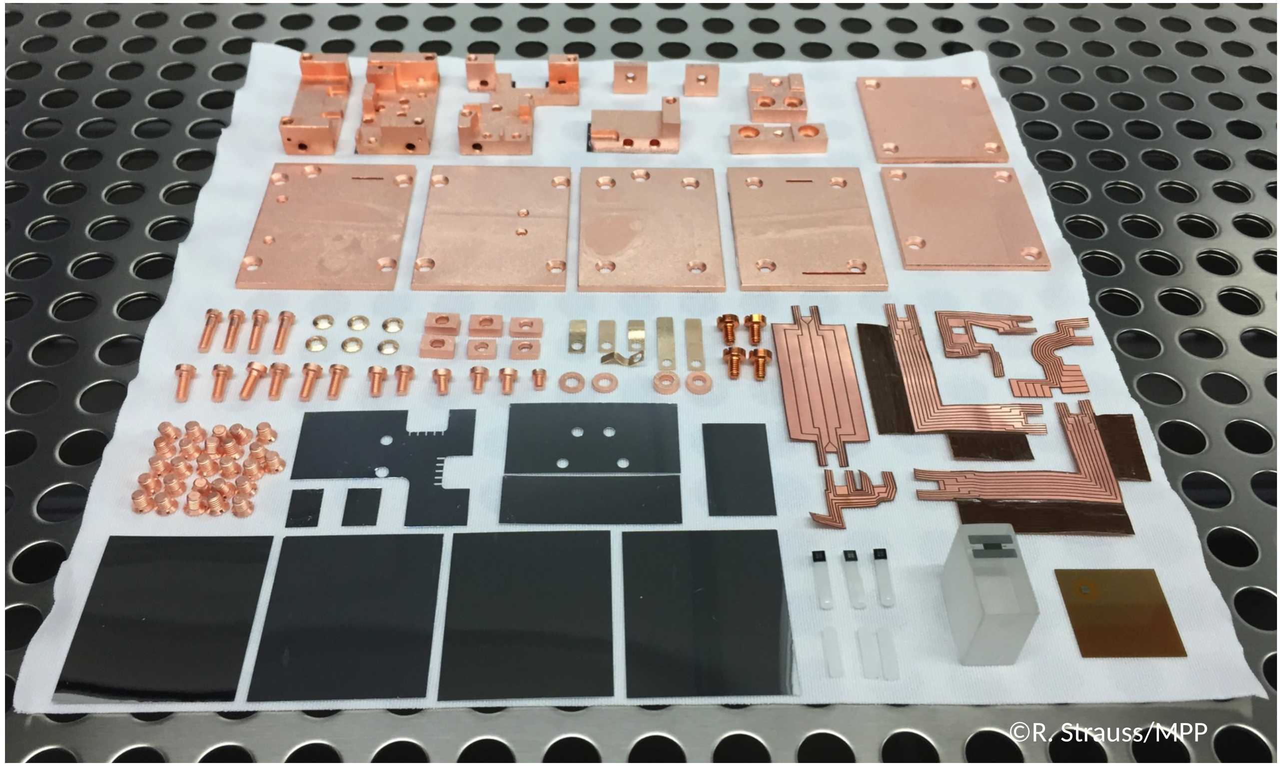
Layout optimized for low-mass dark matter

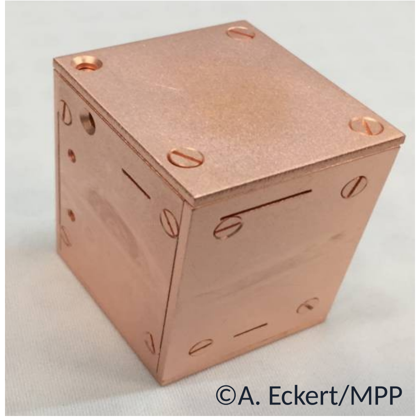
Radical reduction of dimension (300g → 24g)

Threshold design goal **100 eV**

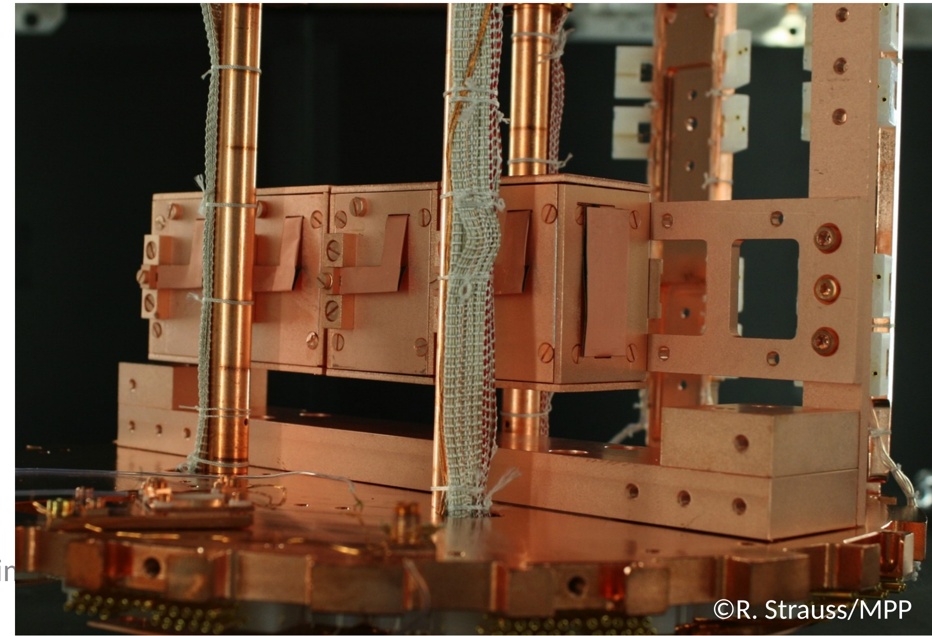


First Run of CRESST-III





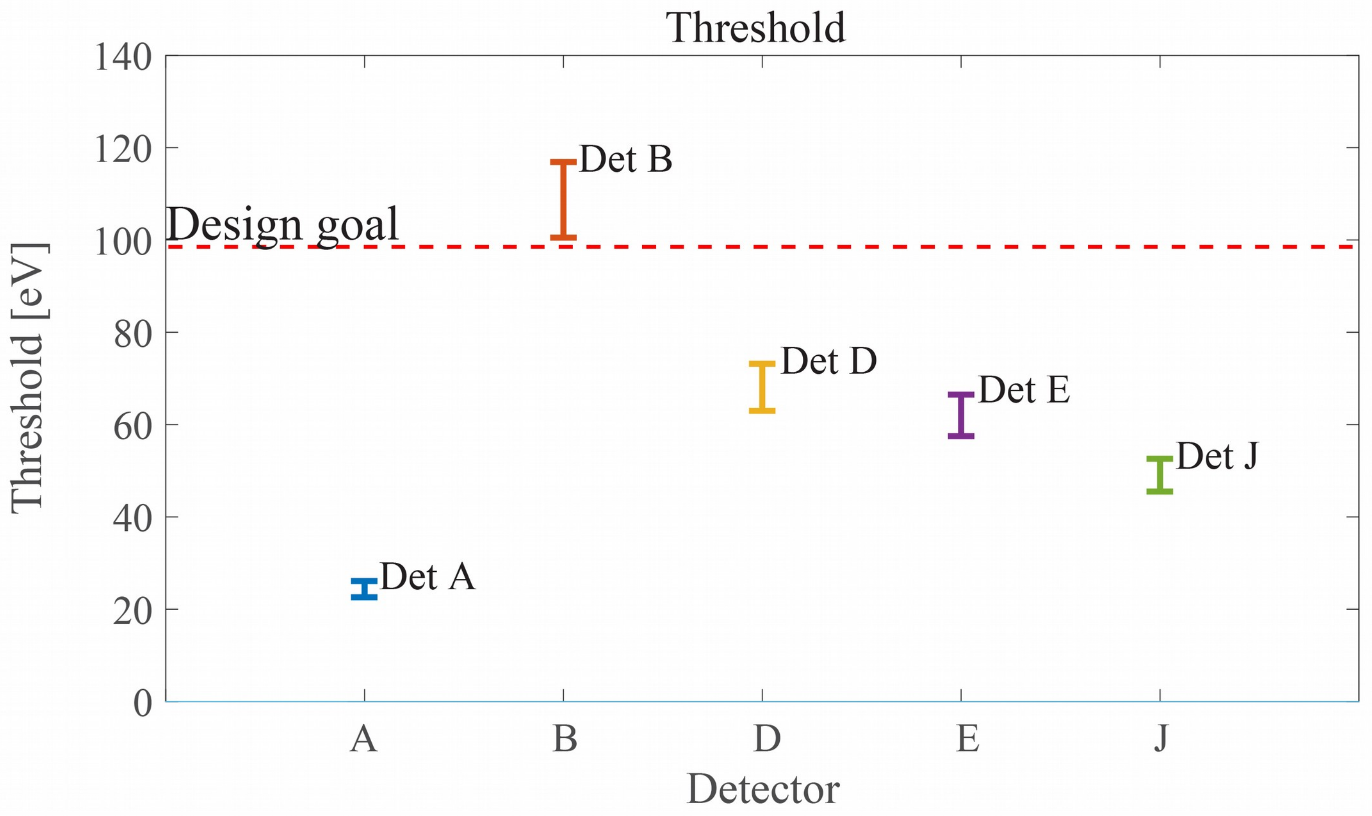
x10



Data taking from July 2016 to February 2018

- Gamma calibration (350h)
- Neutron calibration (840h)

Detector thresholds



Threshold set as a function of accepted noise trigger rate

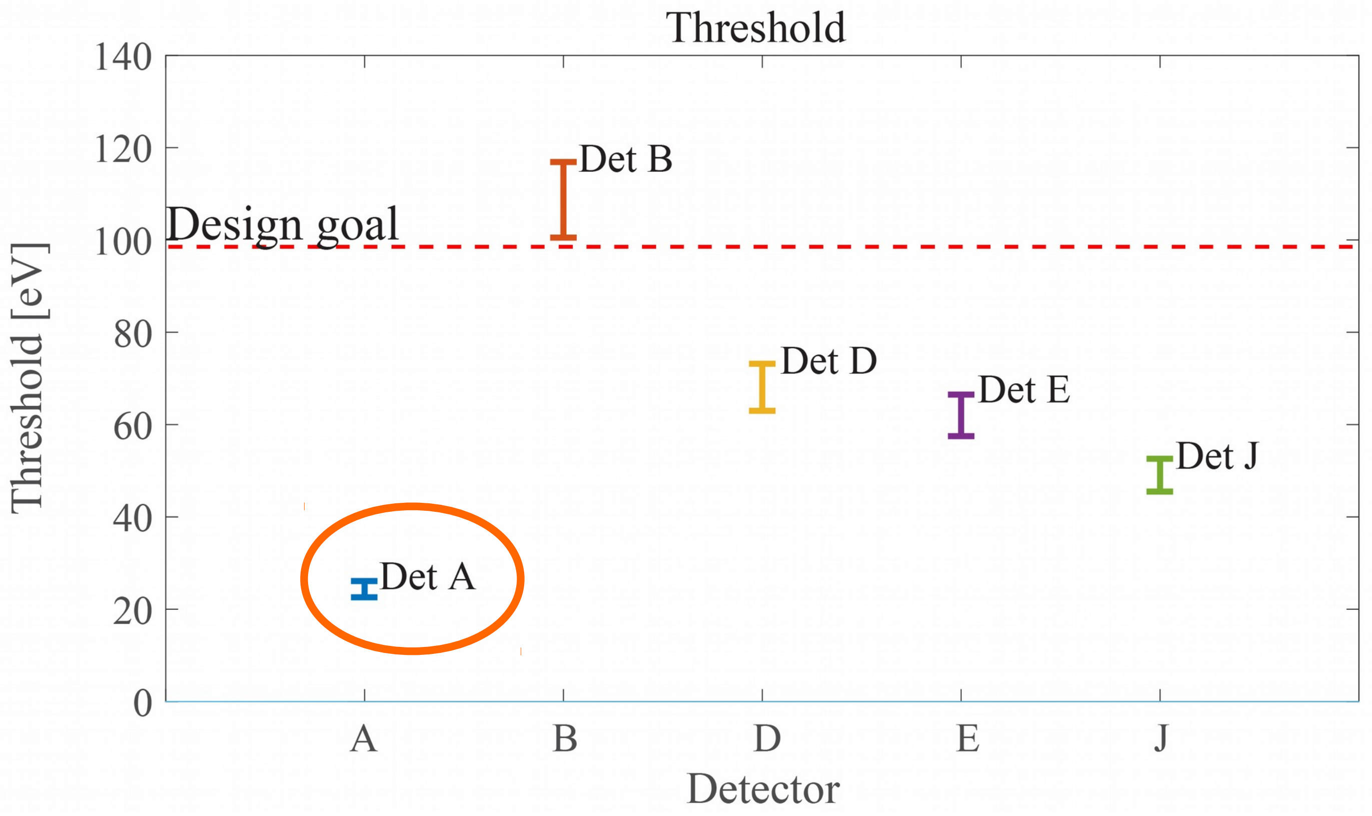
5 detectors reach/exceed the CRESST-III design goal

accepted noise trigger rate {

Threshold[eV]	Det A	Det B	Det D	Det E	Det J
100 cts/keV/day	22.6	100.5	63.0	57.5	45.5
1 count/keV/day	26.1	116.9	73.2	66.5	52.6

Mancuso, M. et al. (CRESST collaboration)
J Low Temp Phys (2018).
https://doi.org/10.1007/s10909-018-1948-6

Detector thresholds



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accepted noise trigger rate {

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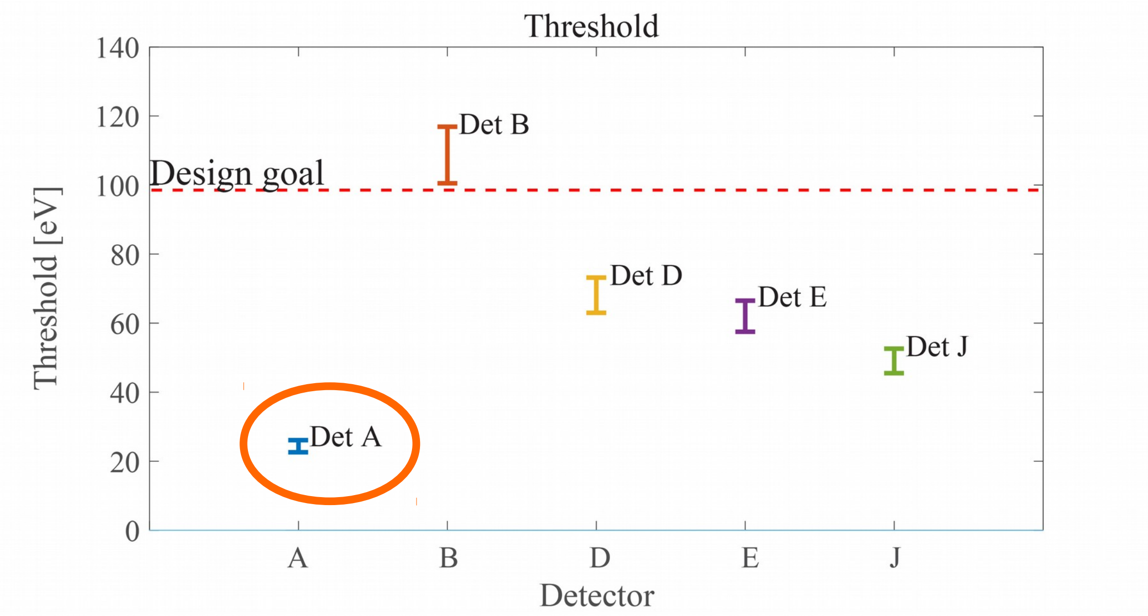
First Data Analysis: Detector A

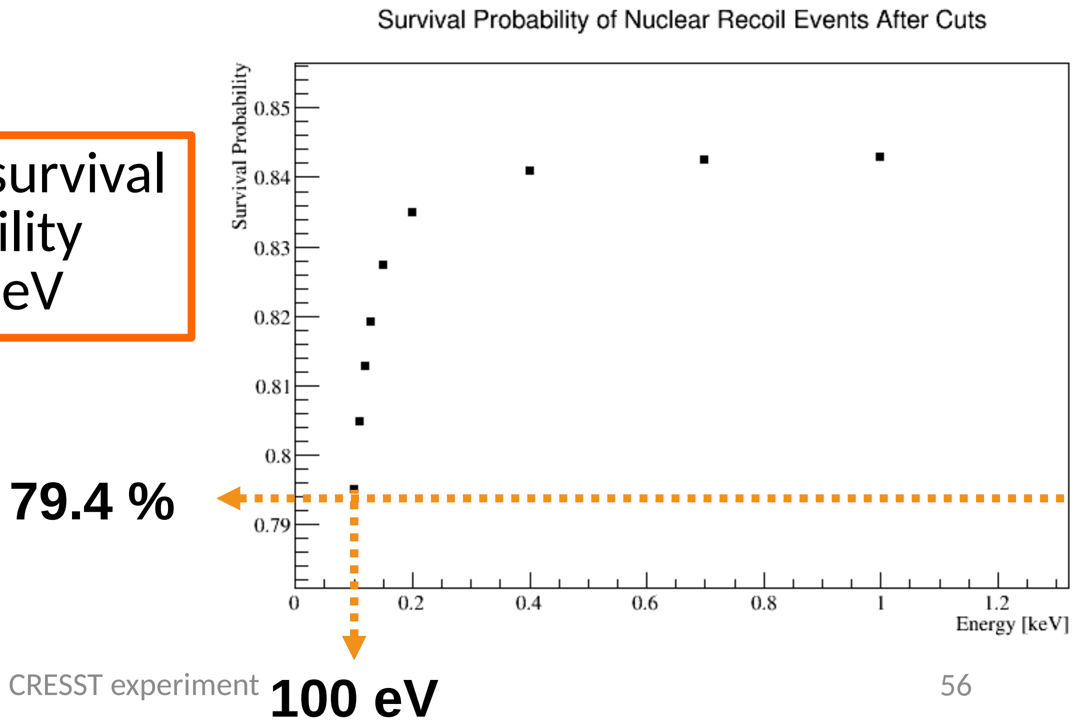


- **Data taking period**: 31/10/16 to 05/07/17
- **Detector mass**: 24 g
- **Total exposure**: 2.39 kg days
- **Analysis Threshold**: 100 eV

Data Selection Criteria

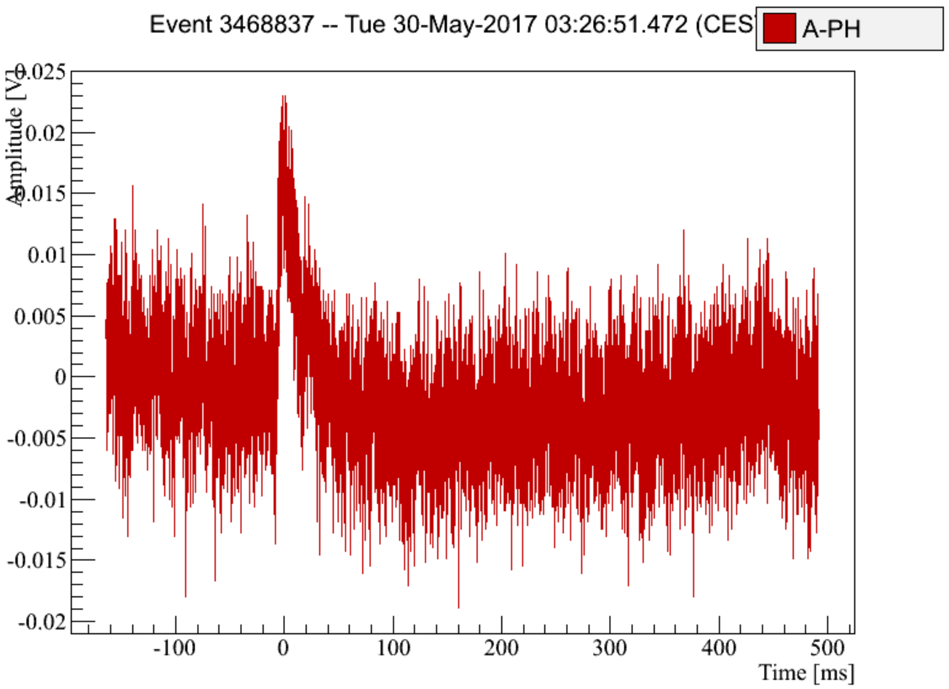
- Stable noise conditions
- Detector temperature
- Pulse shape
- Coincidences

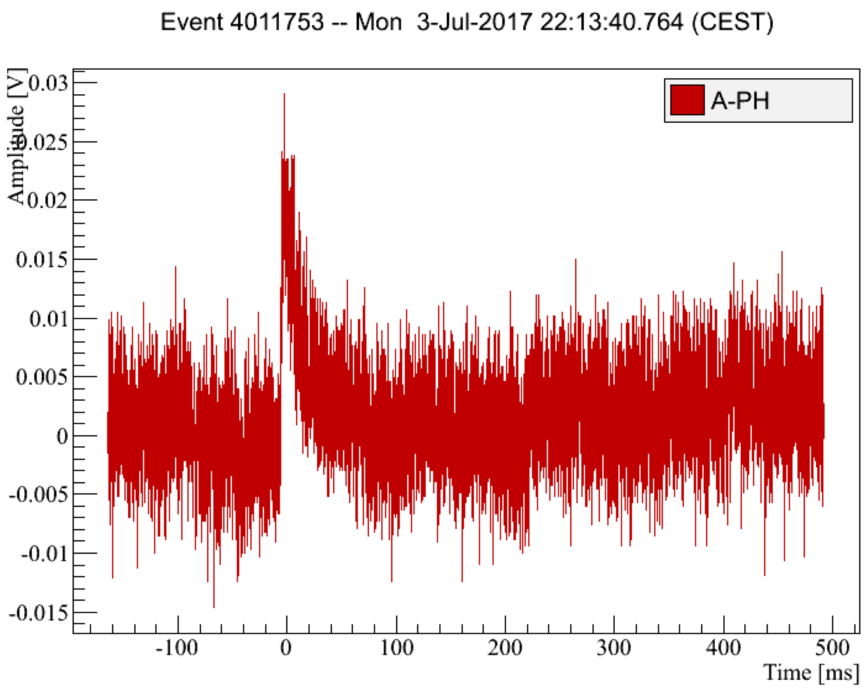
79.4% survival probability at 100 eV



Detector A – 100 eV events

Raw signals: no filtering, fitting etc.

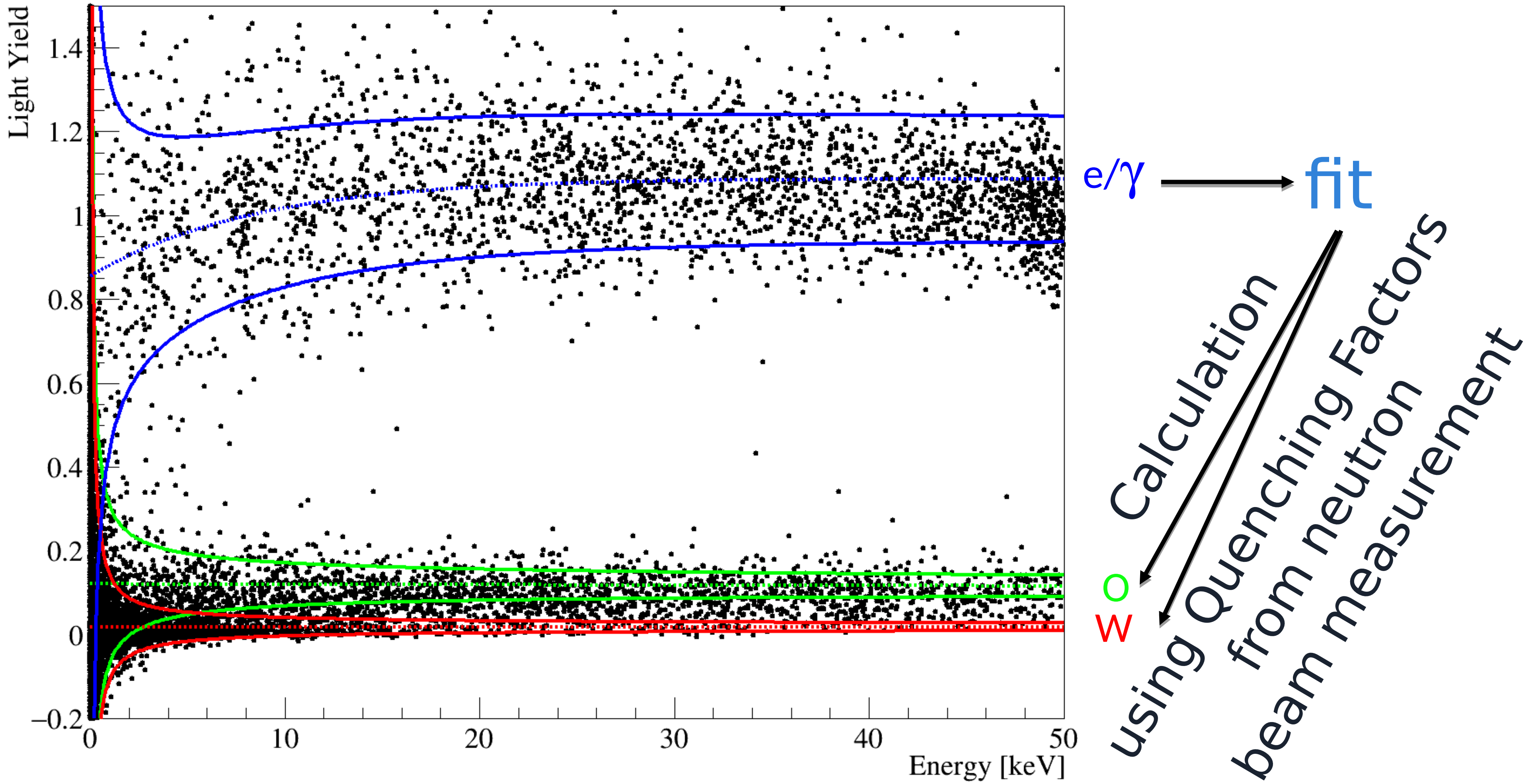




100eV pulses are no challenge for amplitude determination

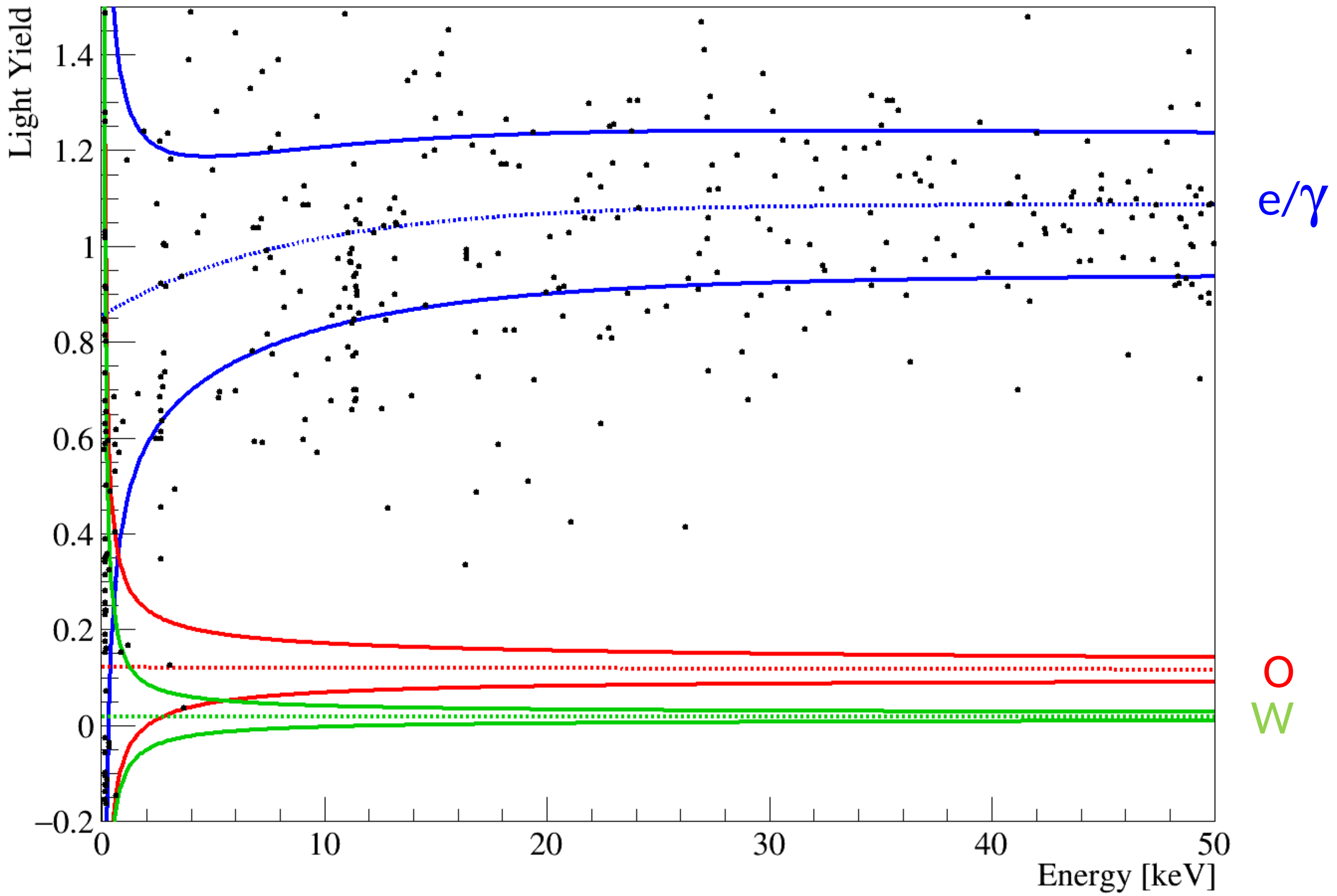
Detector A – 100eV threshold analysis

Neutron calibration data



Detector A – 100eV threshold analysis

Dark Matter data

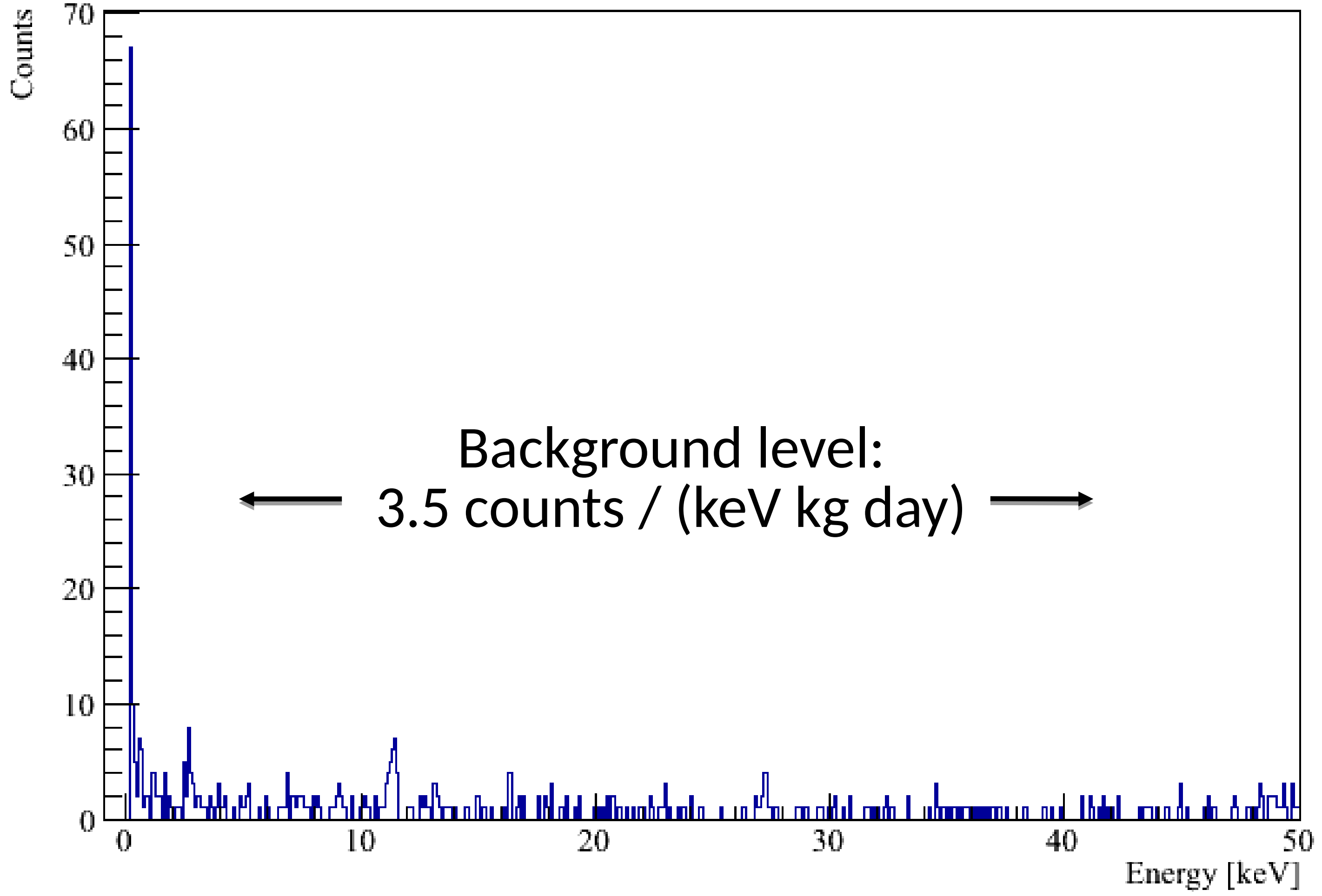


Unblinded:
Det. A
E>100eV

Still blinded:
Det. A <100eV
Other detectors

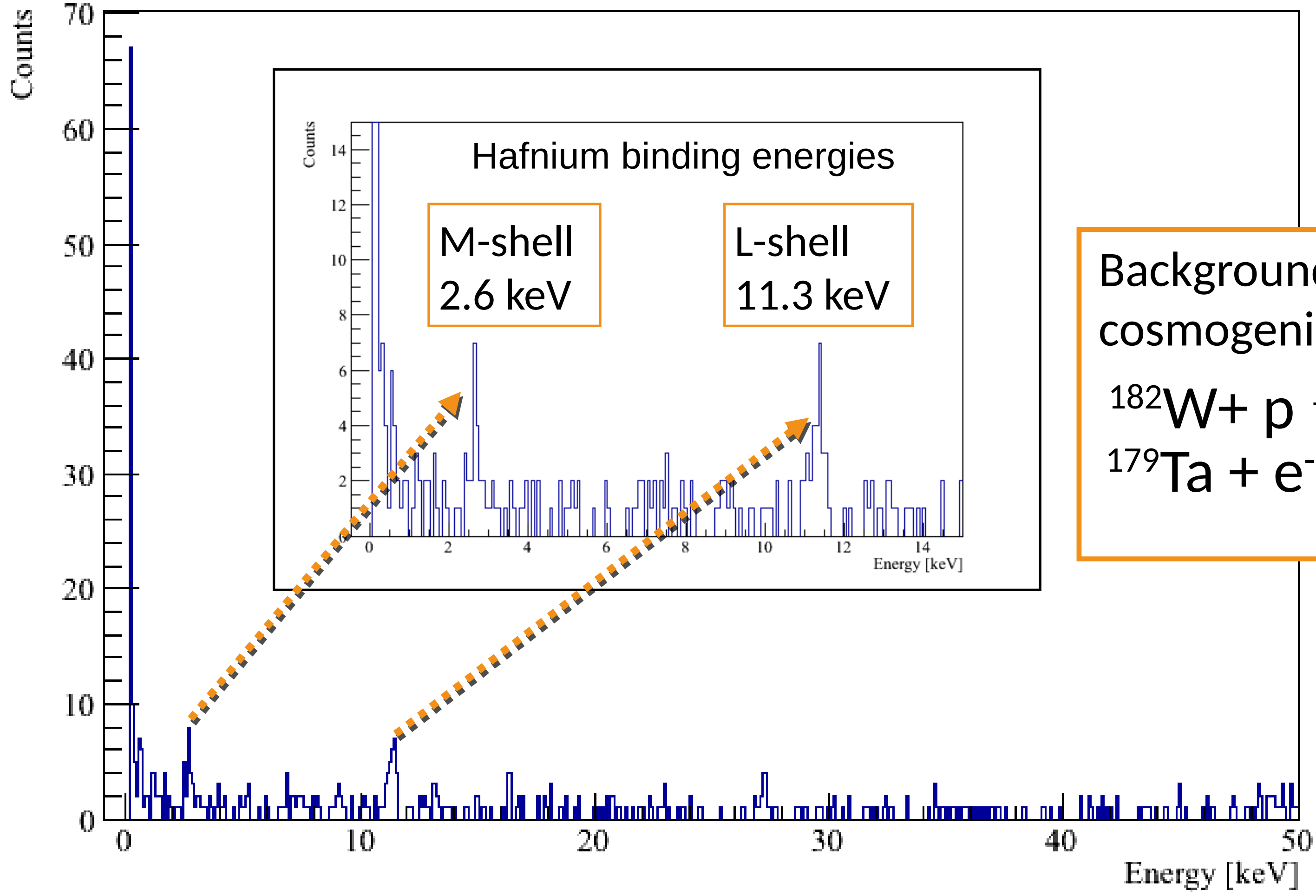
Detector A – 100eV threshold analysis

Dark Matter data – Energy spectrum



Detector A – 100eV threshold analysis

Dark Matter data – Energy spectrum



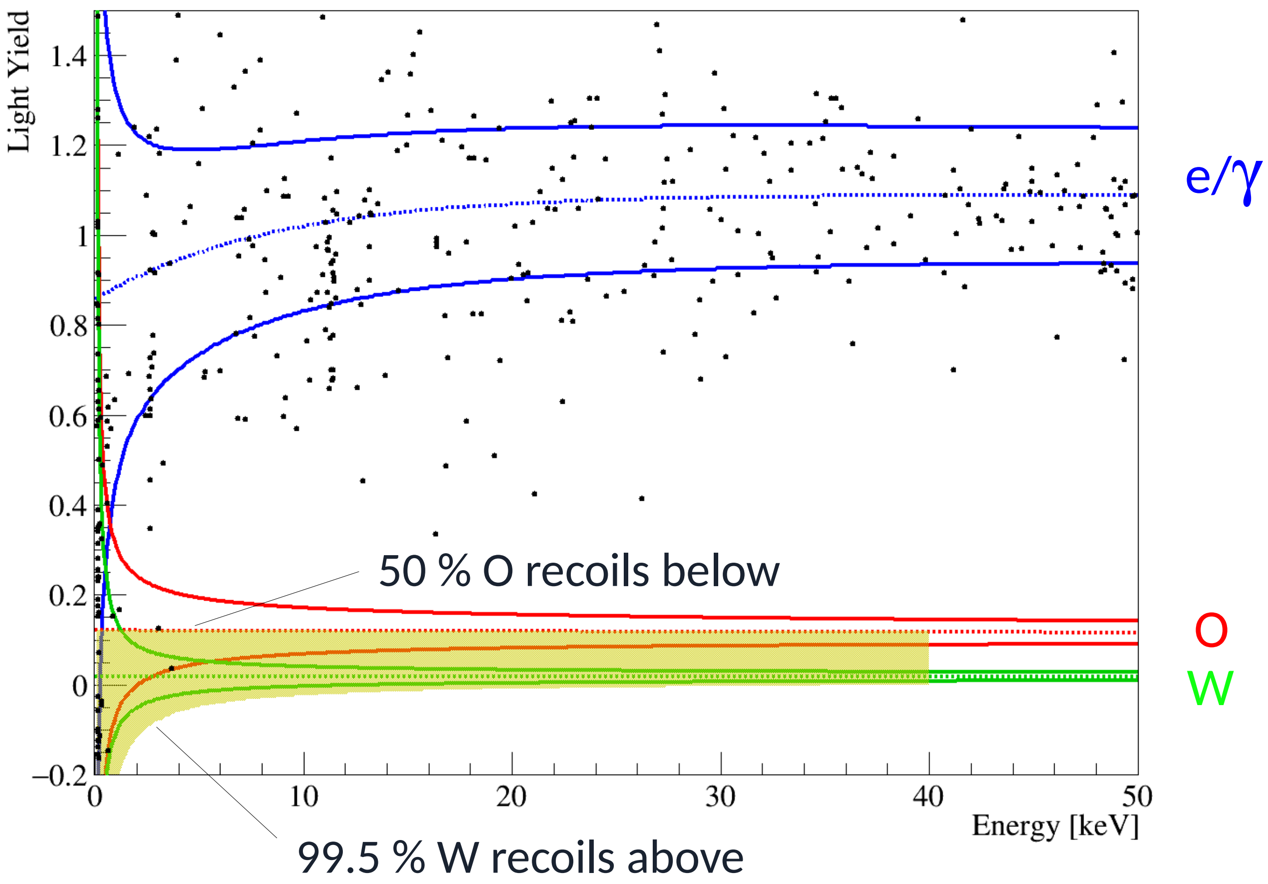
Background events from cosmogenic activation

$^{182}W + p \longrightarrow {}^{179}Ta + \alpha$

$^{179}Ta + e^{-} \longrightarrow {}^{179}Hf + \nu_e$

Detector A – 100eV threshold analysis

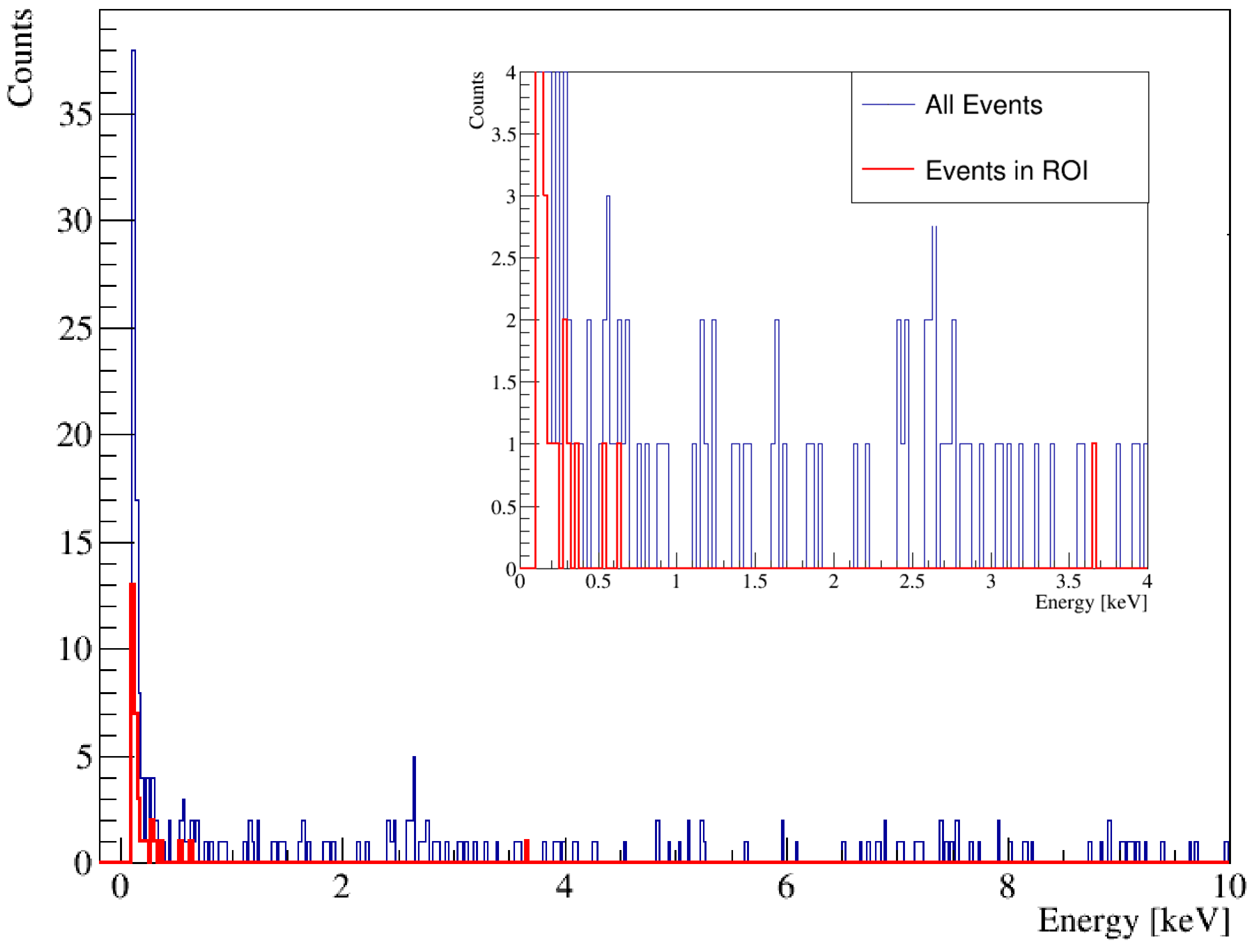
Dark Matter data – Energy spectrum



Acceptance region fixed before unblinding

Detector A – 100eV threshold analysis

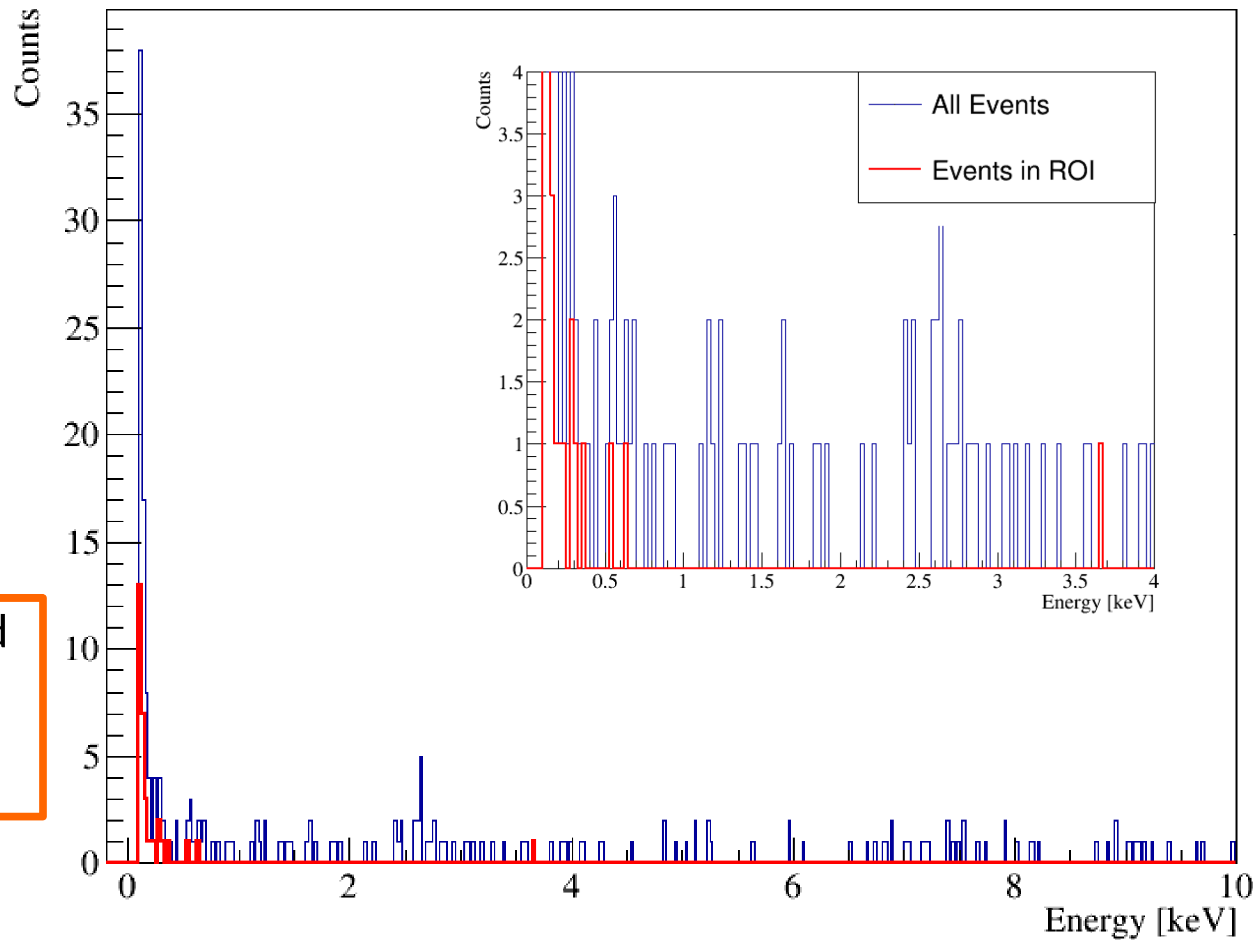
Dark Matter data – Accepted Events



Detector A – 100eV threshold analysis

Dark Matter data – Accepted Events

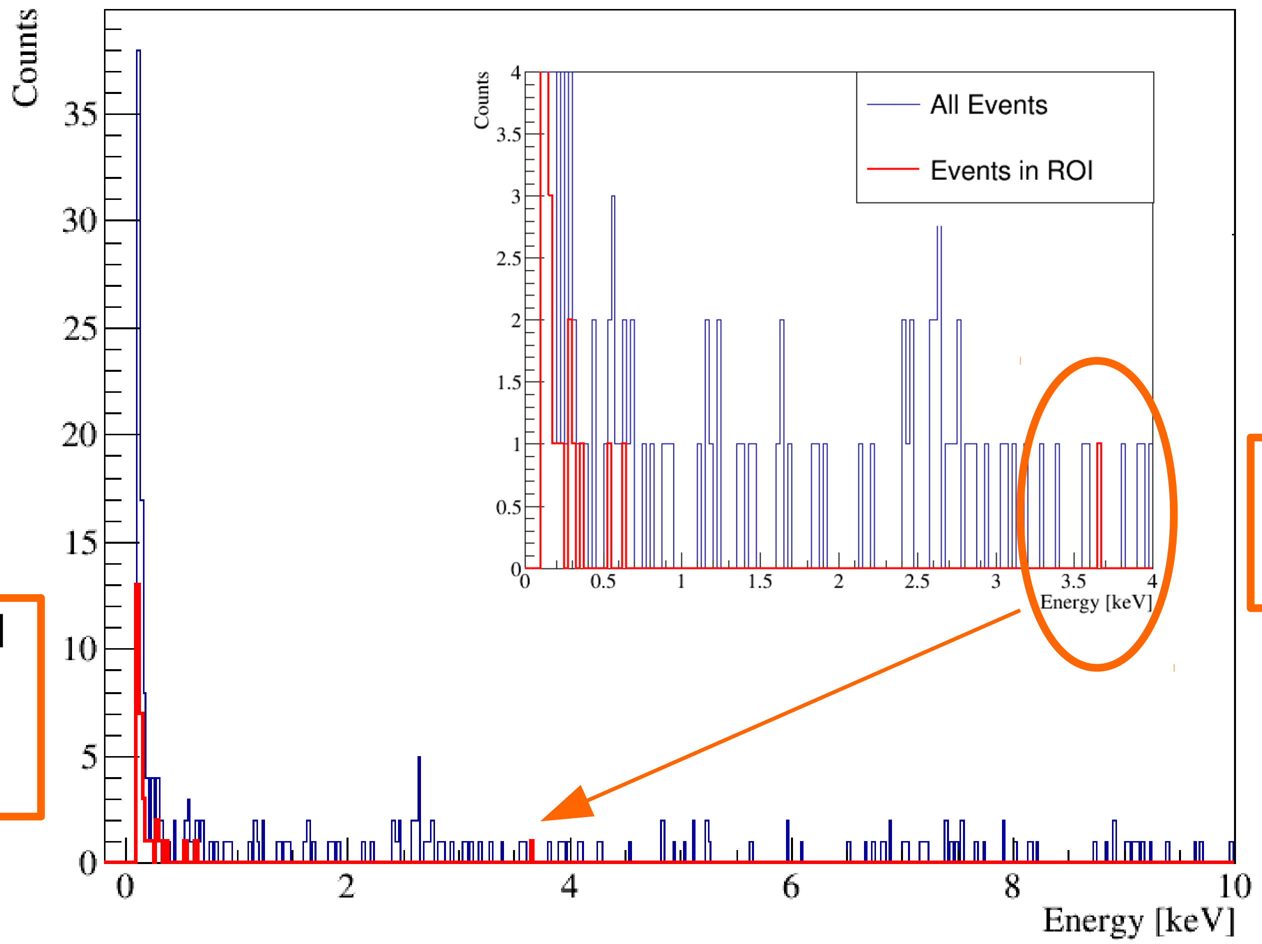
Background rising towards threshold



Detector A – 100eV threshold analysis

Dark Matter data – Accepted Events

Background rising towards threshold



Single accepted event at higher energies

Statistical analysis – Yellin method

"Finding an Upper Limit in the Presence of Unknown Background"

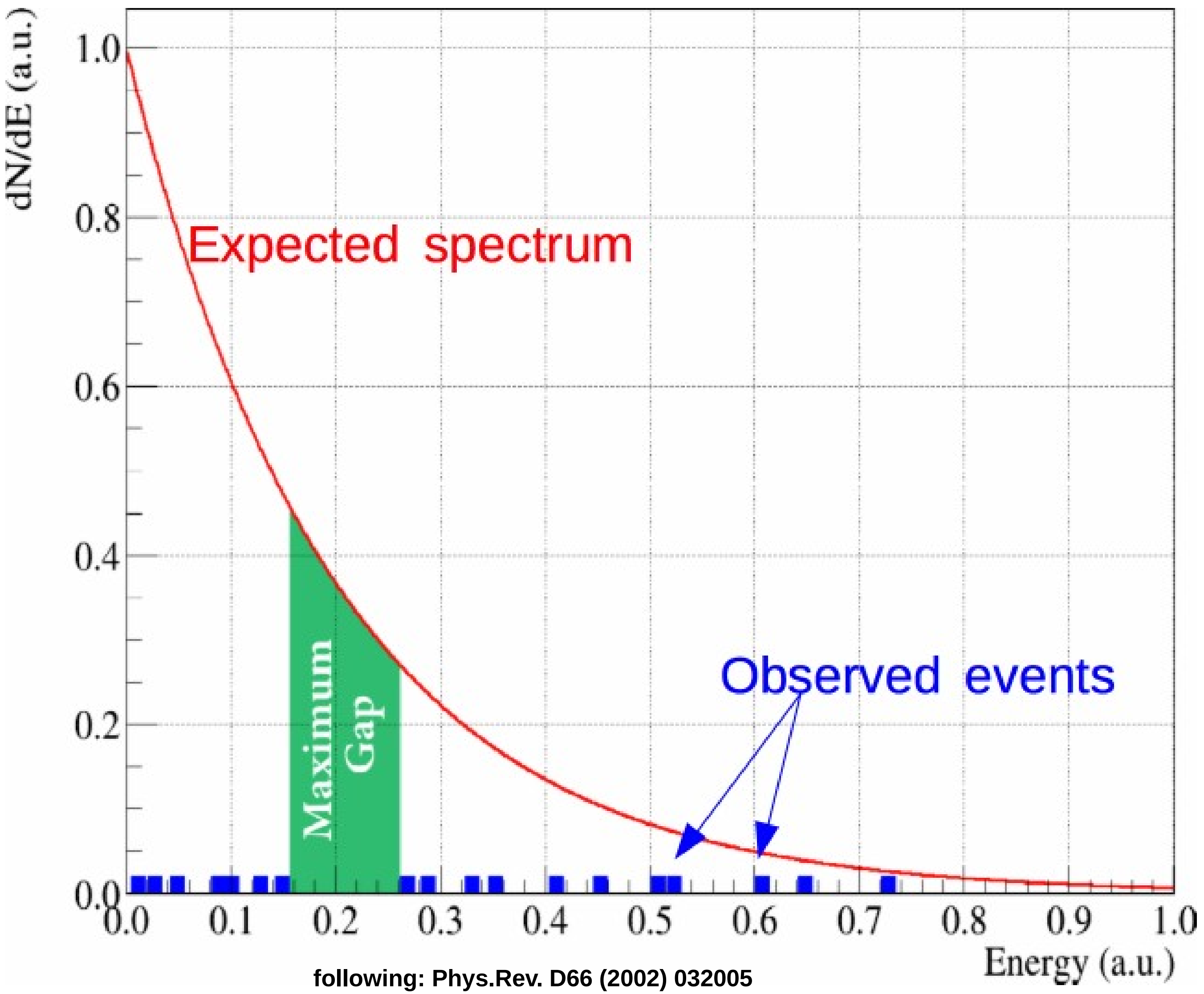
- Conservative approach:
  all events are considered DM candidates

- Maximum Gap: Search for largest gap without events (N = 0)

- Find largest signal normalization statistically compatible with observed largest gap (at 90% C.L.)

→ no background model needed

→ still makes use of known spectral shape of signal



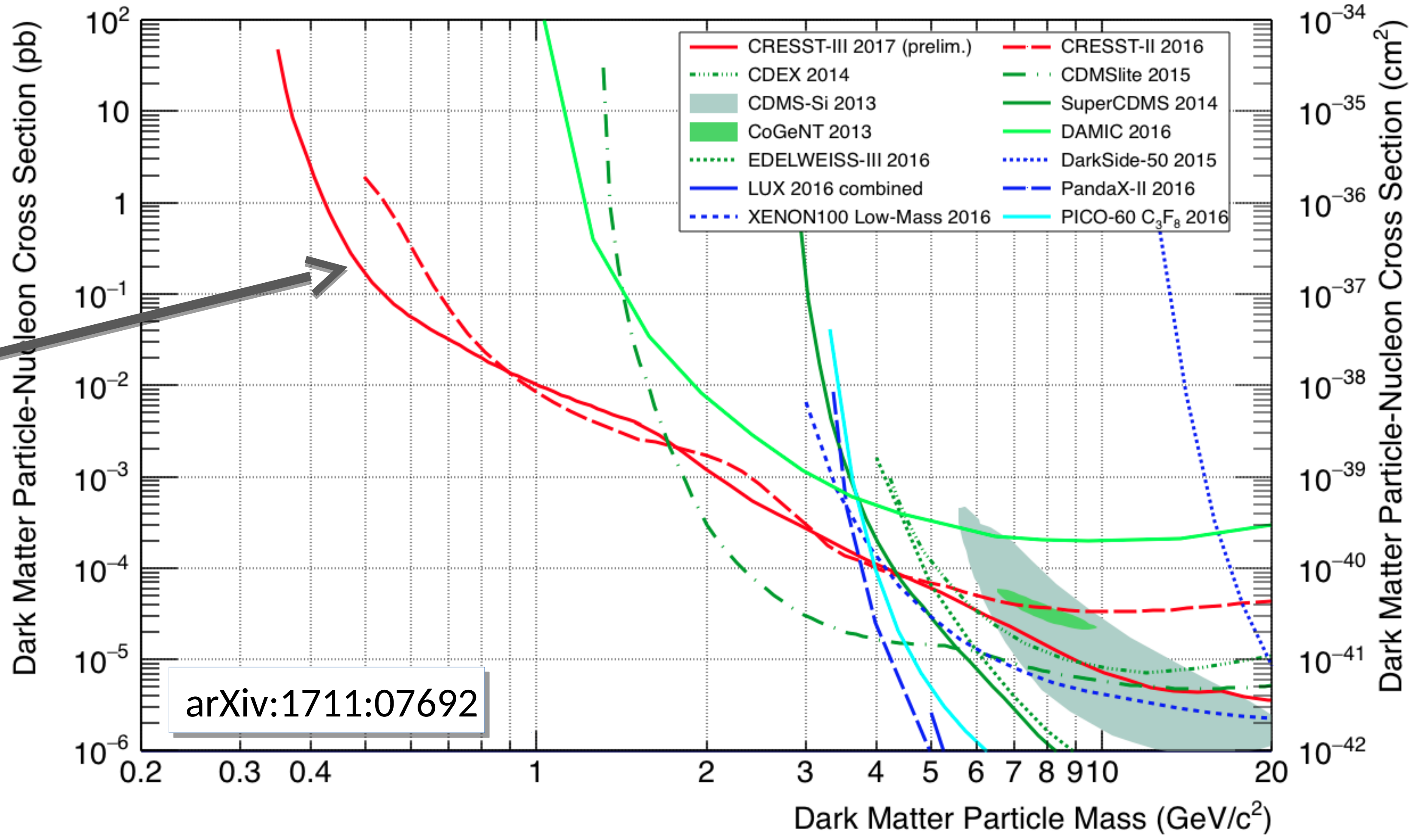
following: Phys.Rev. D66 (2002) 032005

Detector A – 100 eV threshold – Dark Matter limit

Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM

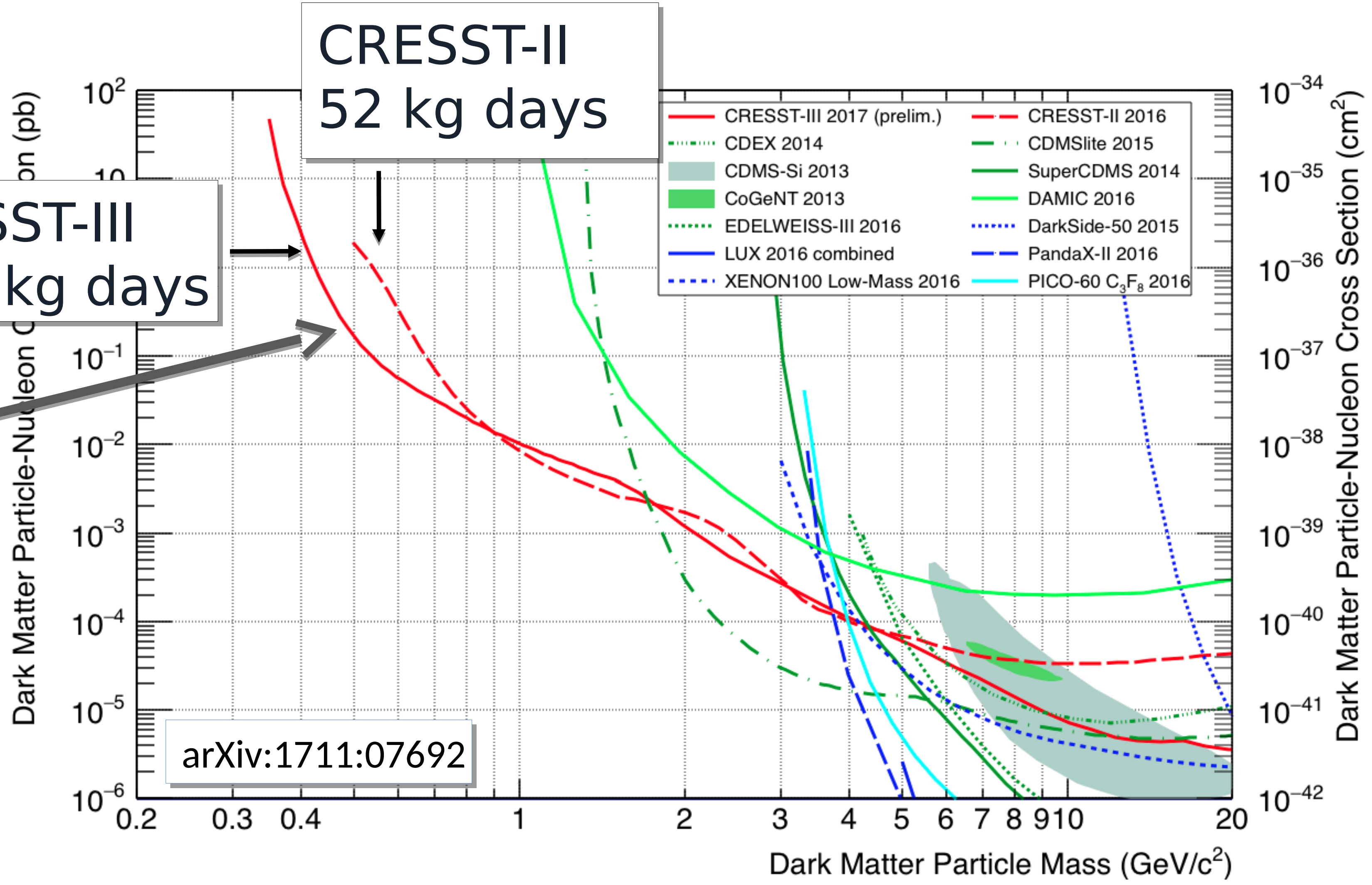


Detector A – 100 eV threshold – Dark Matter limit

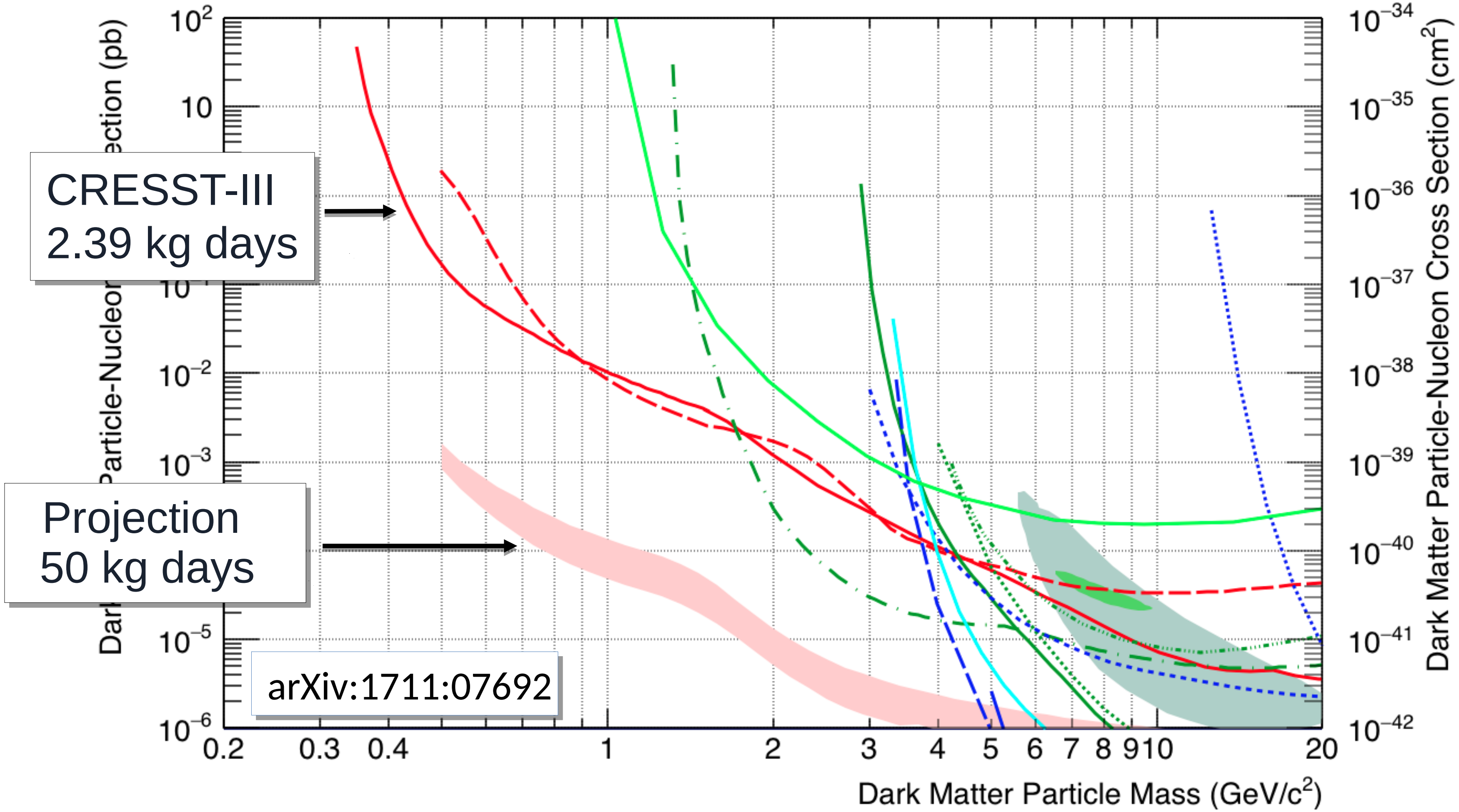
Energy spectrum of accepted events

Yellin 1D optimum interval method

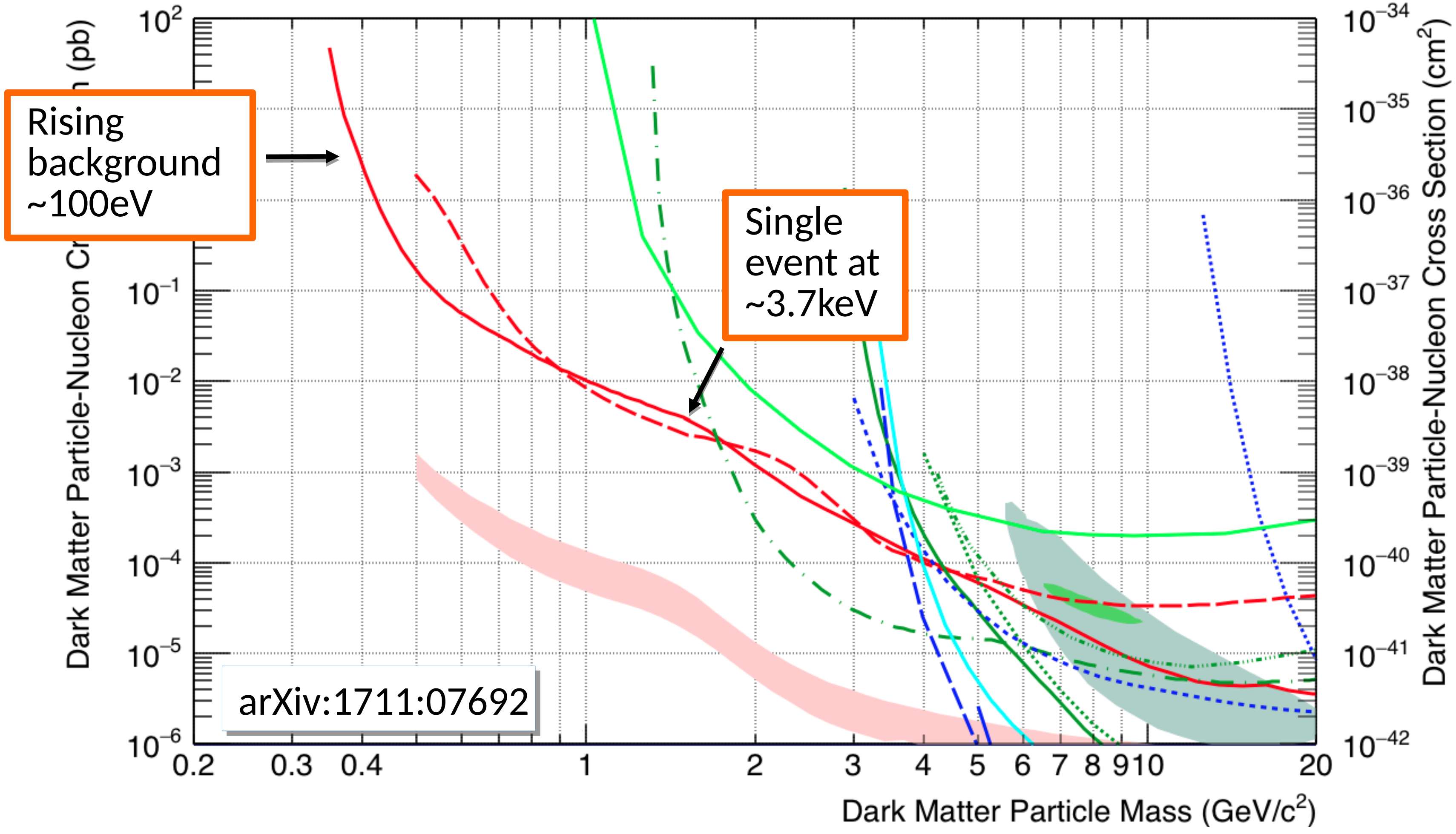
Energy spectrum expected for DM



Detector A – 100 eV threshold – Dark Matter limit



Detector A – 100 eV threshold – Dark Matter limit



First CRESST-III Run: Analysis ongoing

3 times lower optimum threshold for detector A

3 other detectors with thresholds << 100eV

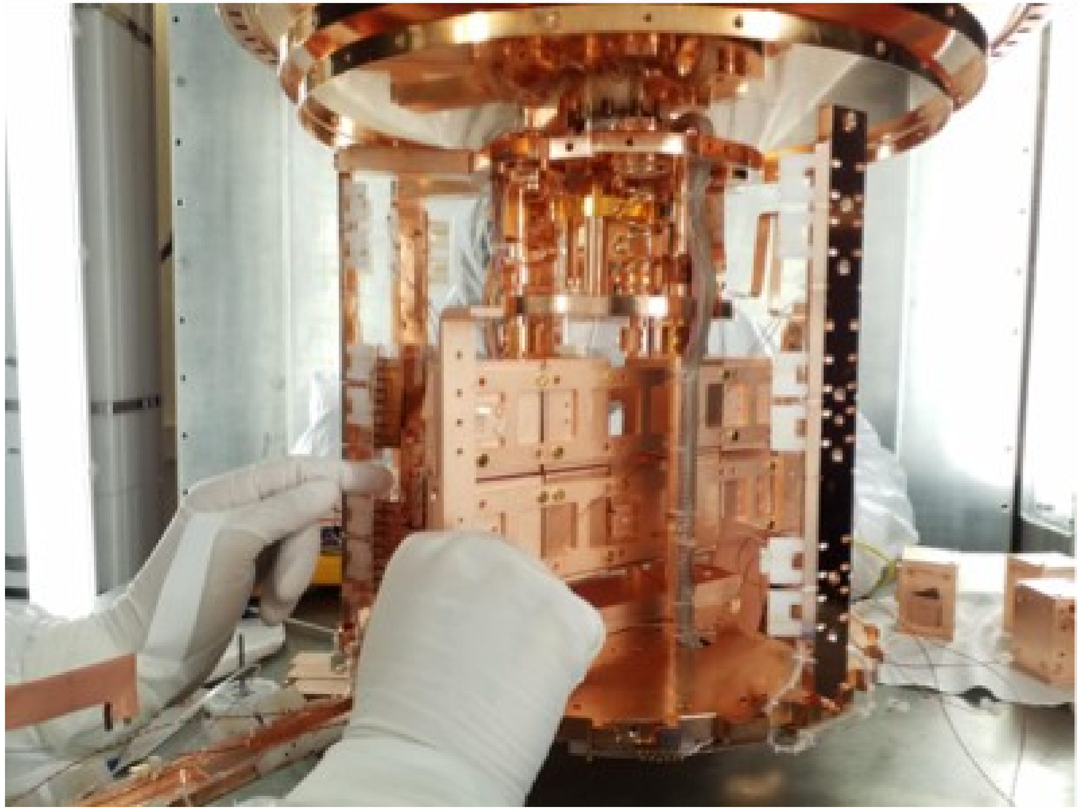
3 times more statistics → deeper understanding of backgrounds

Second CRESST-III run 07/2018: starting now

Key innovation

Dedicated hardware changes to understand backgrounds:

- Target materials
- Supporting structures
- Surrounding material



CRESST-III: waiting for signals from the dark universe

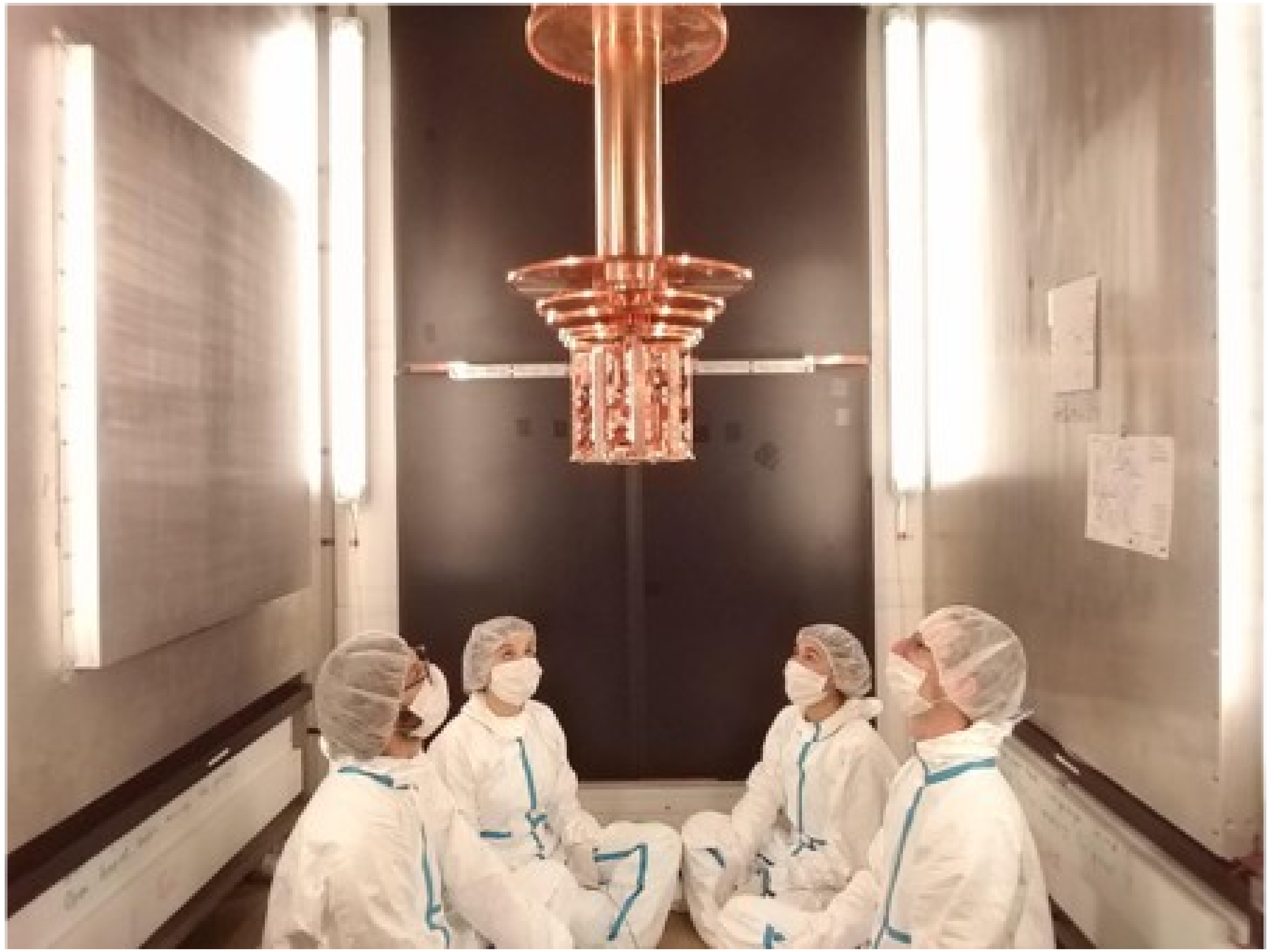
Key innovation

Dedicated hardware changes to understand backgrounds:

- Target materials
- Supporting structures
- Surrounding material

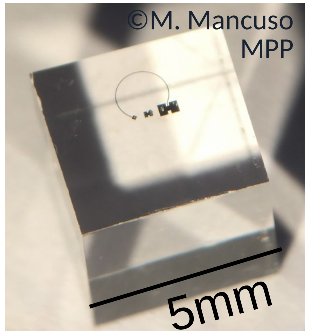
Status

- The cryostat is cold
- First pulses measured
- Commissioning phase

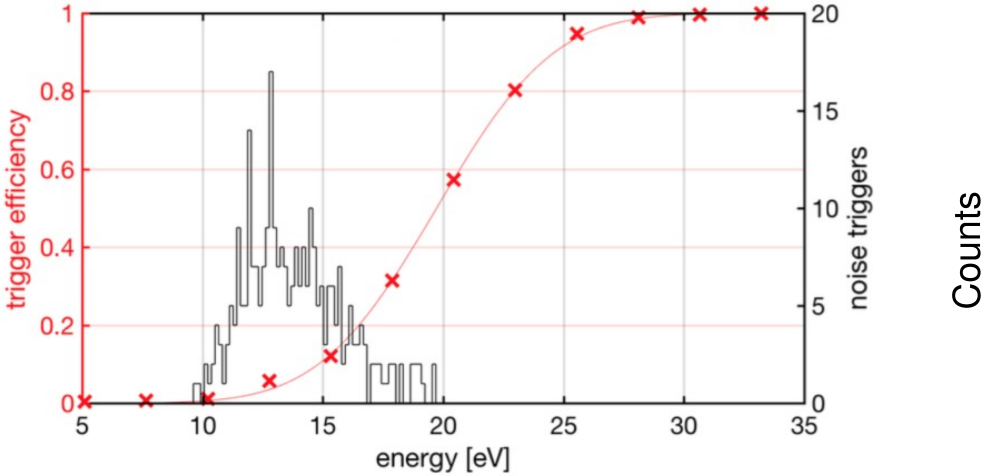


How small can we go: gram-scale detector

Al_2O_3 0.49g 5x5x5mm^3



Trigger Efficiency



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

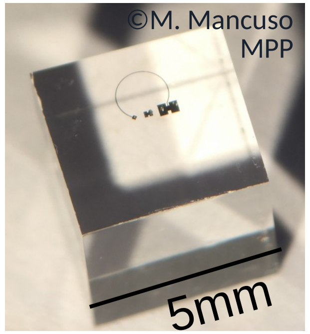
Measured above ground

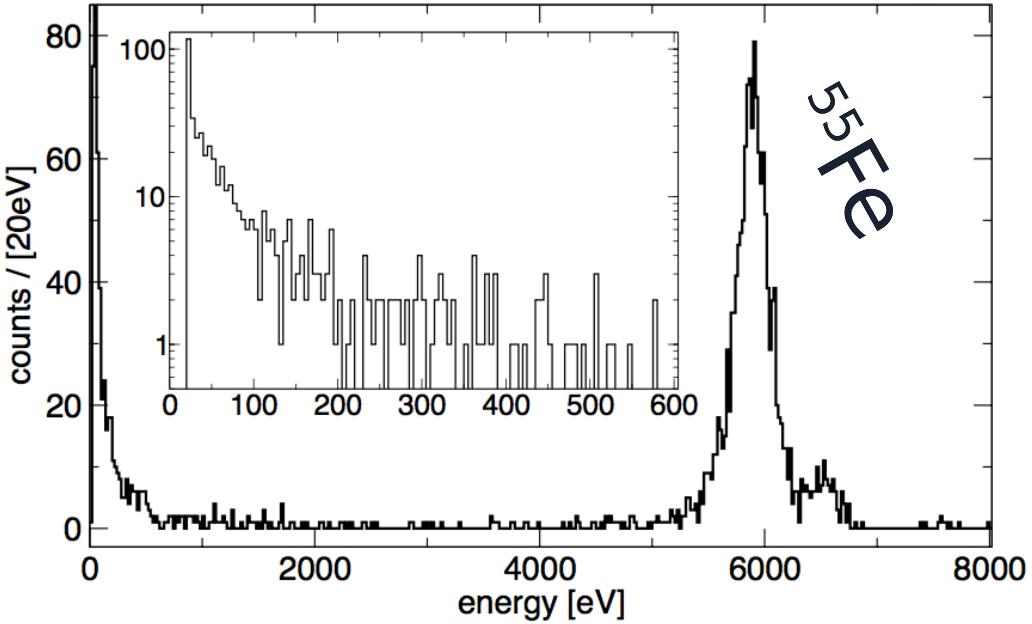
Energy threshold: E_{th} = (19.7 +- 0.9) eV

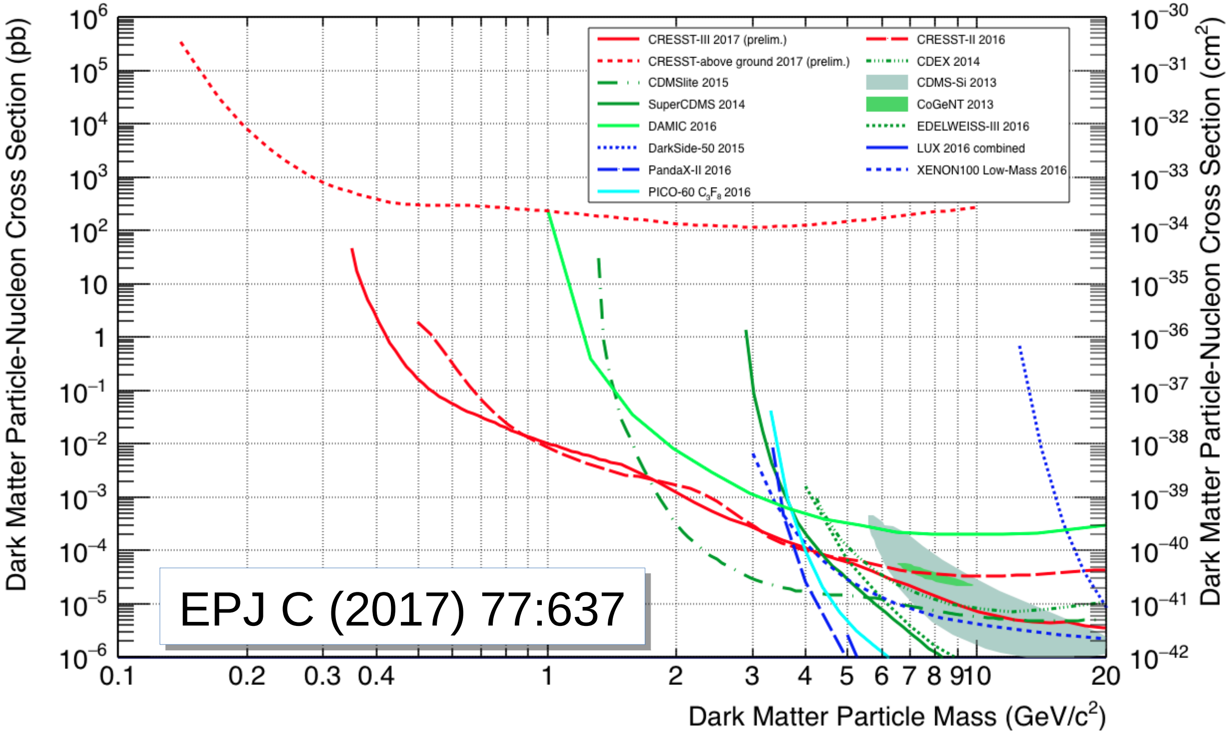
Lowest threshold for nuclear recoils in the field

How small can we go: gram-scale detector

Al_2O_3 0.49g 5x5x5mm^3







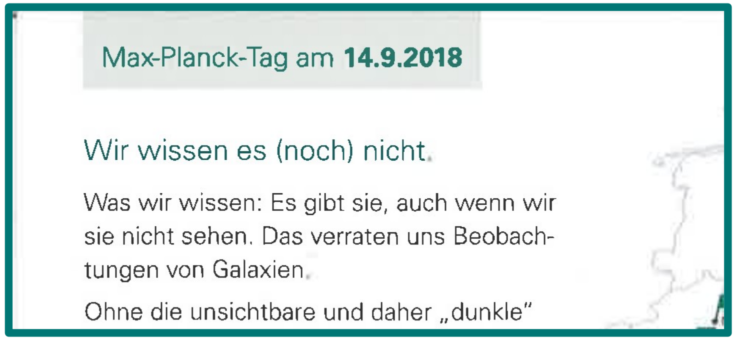
Measuring time 5.3h, no data quality cuts

WHAT IS DARK MATTER?

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

Johannes Rothe
IMPRS Colloquium July 12, 2018

WHAT IS DARK MATTER?


Max-Planck-Tag am **14.9.2018**

Wir wissen es (noch) nicht.

Was wir wissen: Es gibt sie, auch wenn wir sie nicht sehen. Das verraten uns Beobachtungen von Galaxien.

Ohne die unsichtbare und daher „dunkle“

WE DO NOT KNOW (YET).

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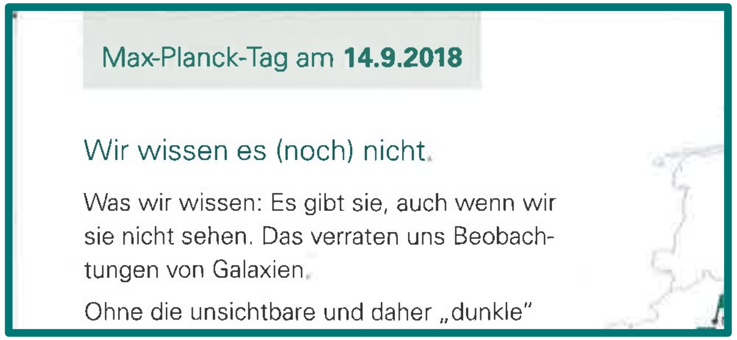
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Ohne die unsichtbare und daher „dunkle"

WE DO NOT KNOW (YET).

WE'RE WORKING ON IT.

THANK YOU

Johannes Rothe

IMPRS Colloquium July 12, 2018

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