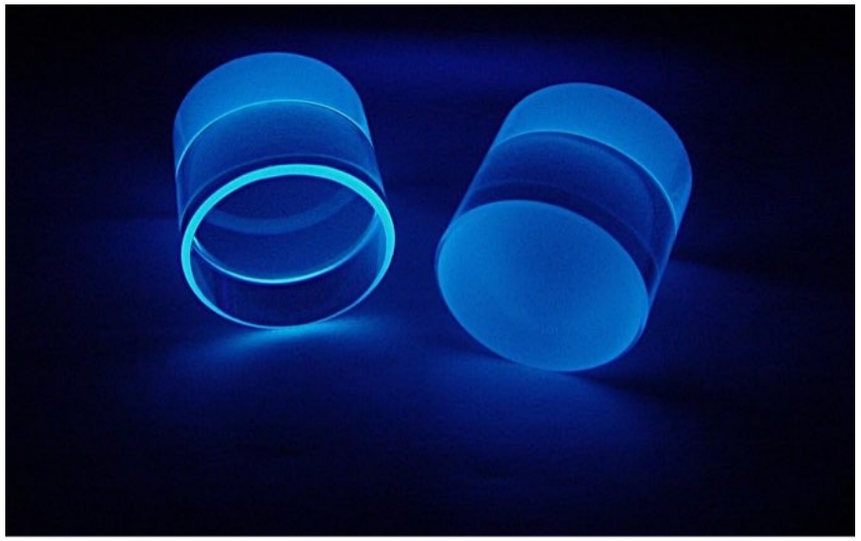


Direct Dark Matter Search with the CRESST III-Experiment & brief summary from other Dark Matter Experiments

Jochen Schieck
Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciences
and
Institute of Atomic and Subatomic Physics, TU Wien

for the CRESST collaboration

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

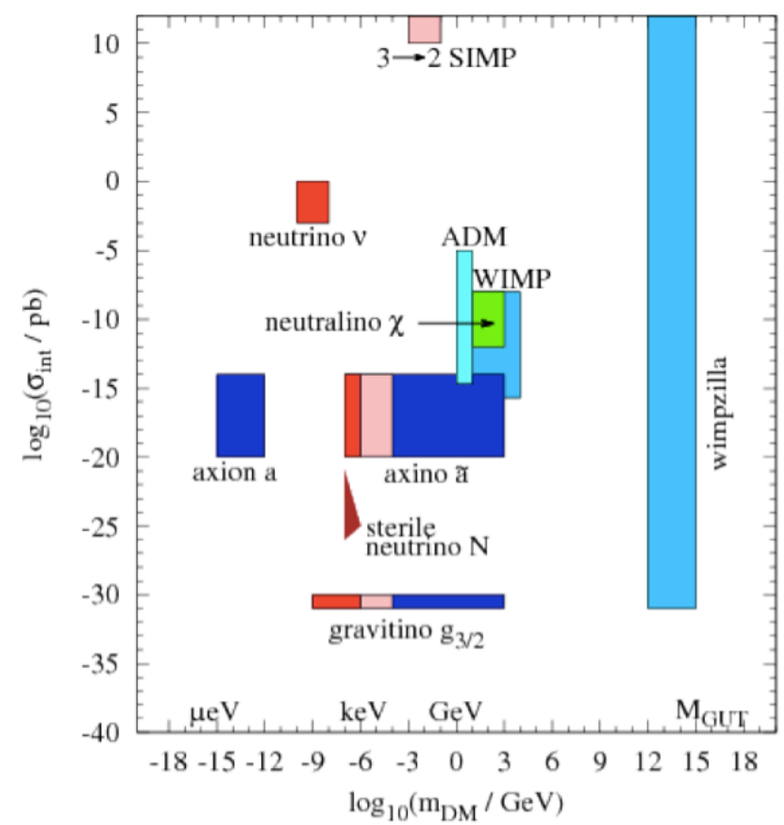
Outline

- brief introduction to direct detection of dark matter
- low mass dark matter - status and results of CRESST III
- search for Dark Matter with several GeV/c^2
  - liquid noble gas experiments - Xenon1T
- potential dark matter signals
  - directions towards a deeper understanding - COSINUS
- towards even lighter dark matter particles - DANAE

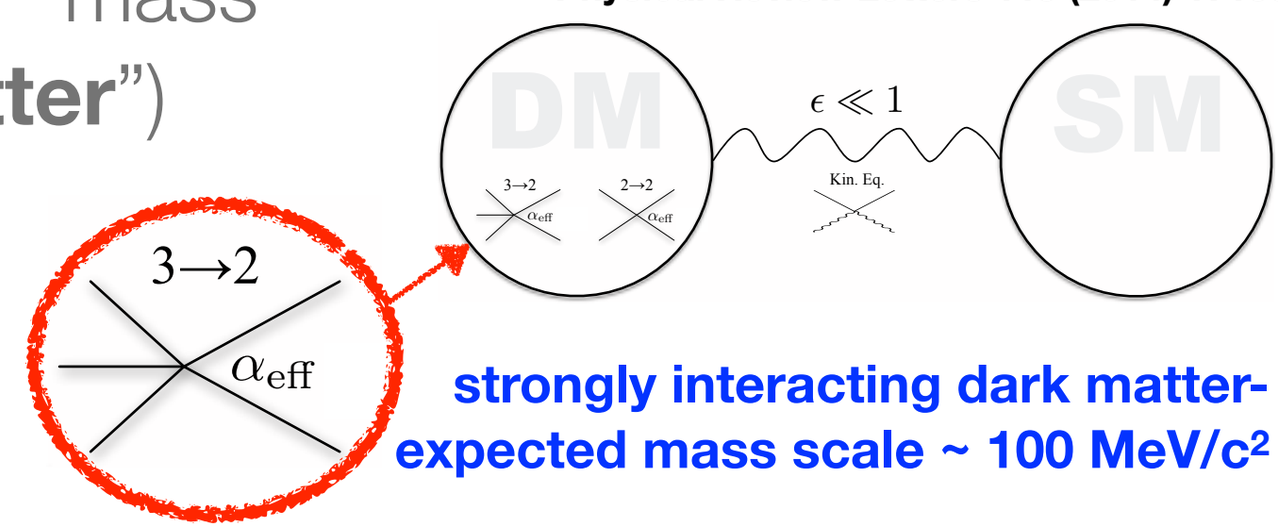
Unraveling the Particle Character of Dark Matter

- clear evidence for dark matter on different scales
  - observation of dark matter based on gravitational pull only
- undiscovered new particles well motivated candidate for dark matter
- mass region below the WIMP mass scale (“**low mass dark matter**”) recently gained a lot of theoretical interest

Physics Reports 555 (2015) 1–60



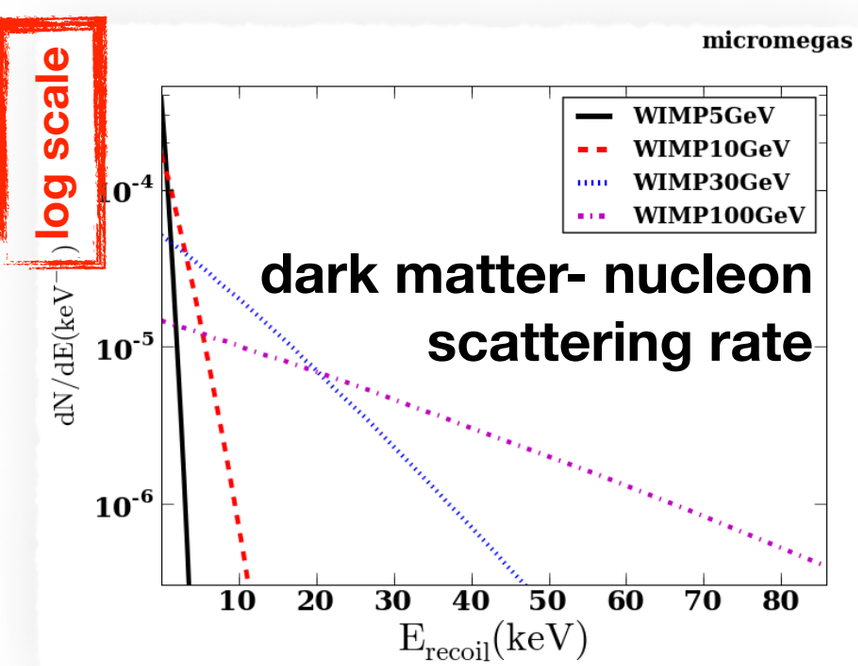
Physical Review Letters 113 (2014) 171301

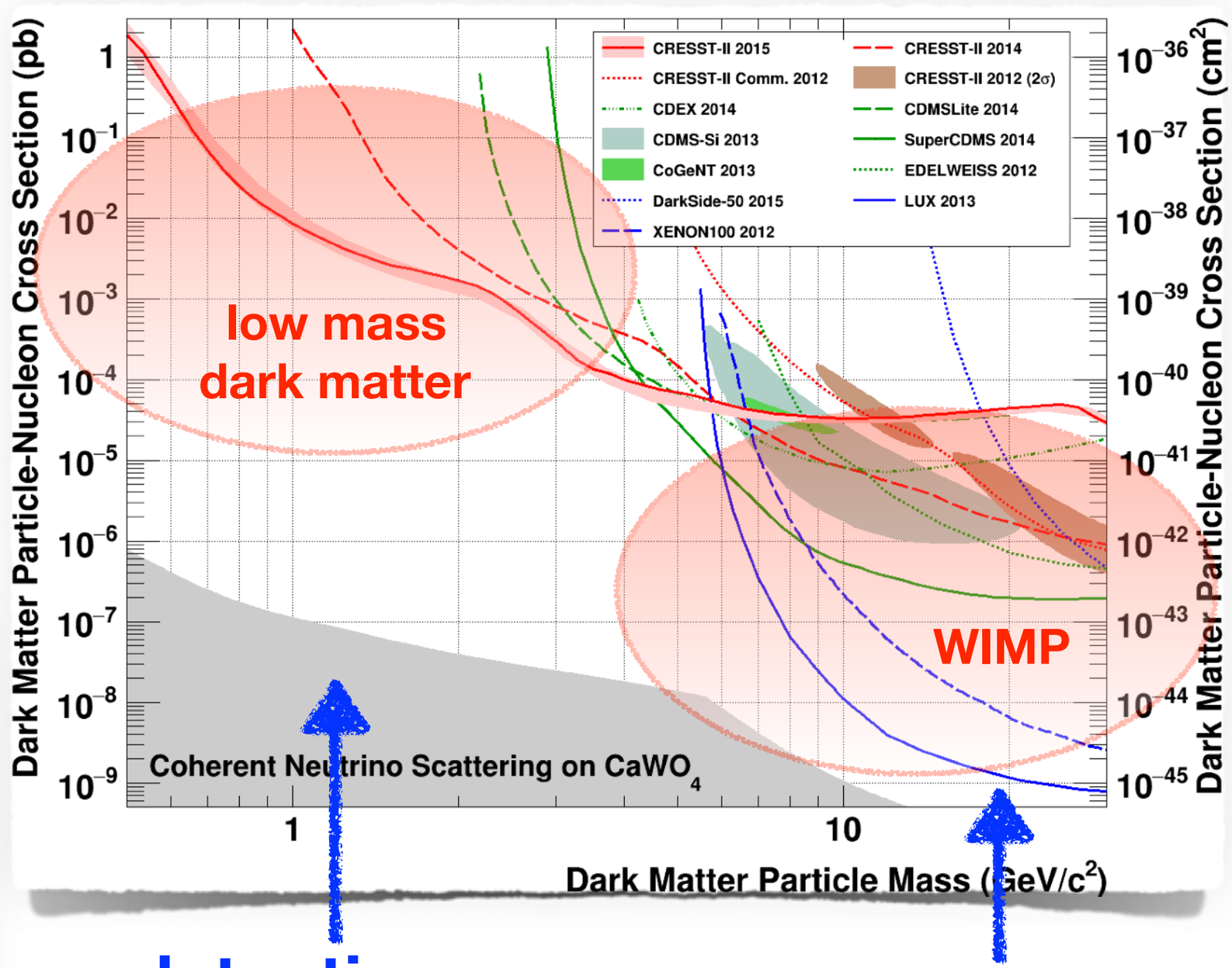


strongly interacting dark matter-expected mass scale ~ 100 MeV/c²

The Dark Matter Landscape - Detector Challenge

- different mass regions require different detector technologies
- low mass dark matter requires **low detection threshold**
- detection of larger dark matter masses depend **on exposure**





detection threshold

exposure

The CRESST Experiment

The CRESST Collaboration

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

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

UNIVERSITY OF OXFORD

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

TECHNISCHE UNIVERSITÄT MÜNCHEN

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

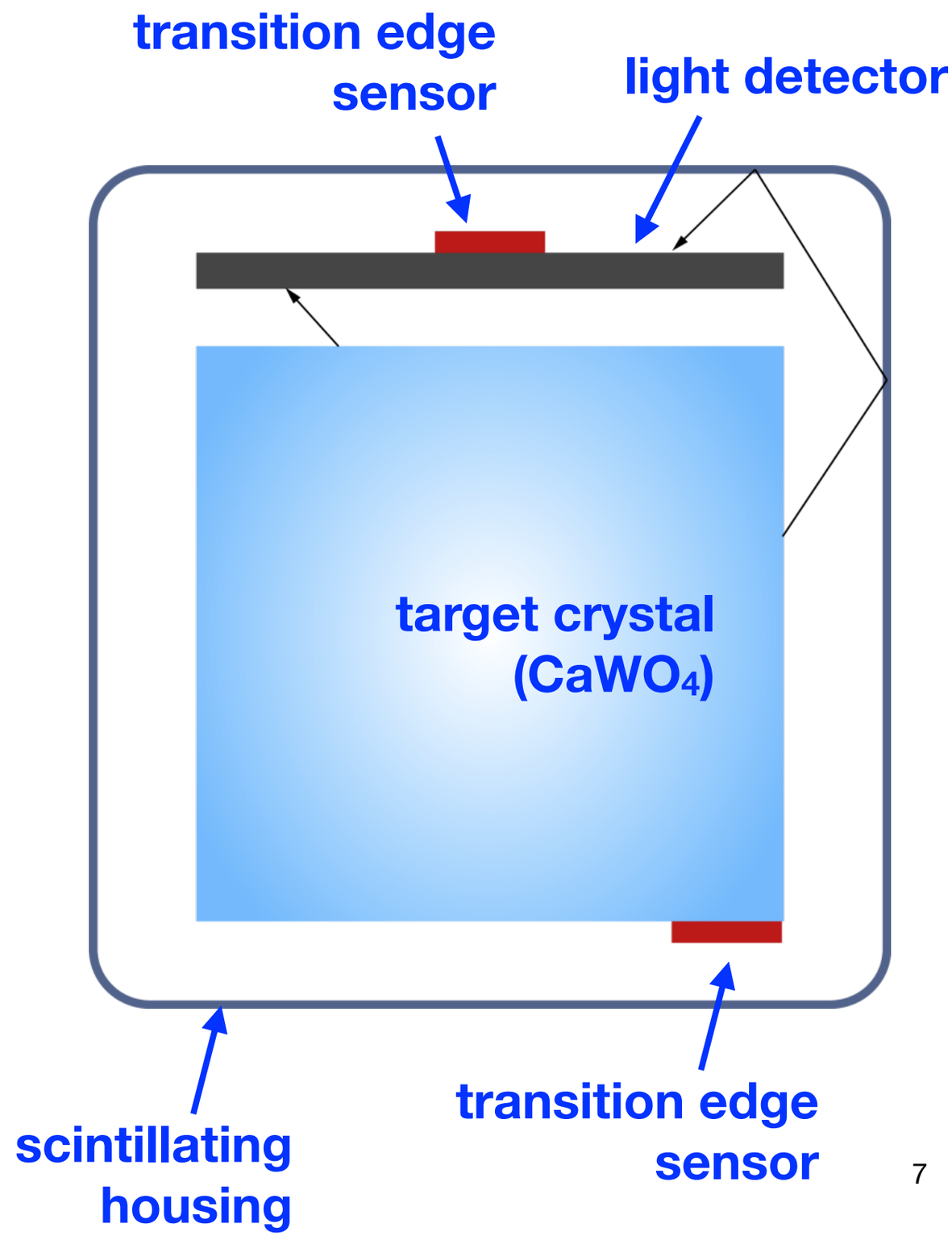
TU WIEN

About 40-50 scientists from 6 institutions and 4 countries

CRESST - Detection Principle I

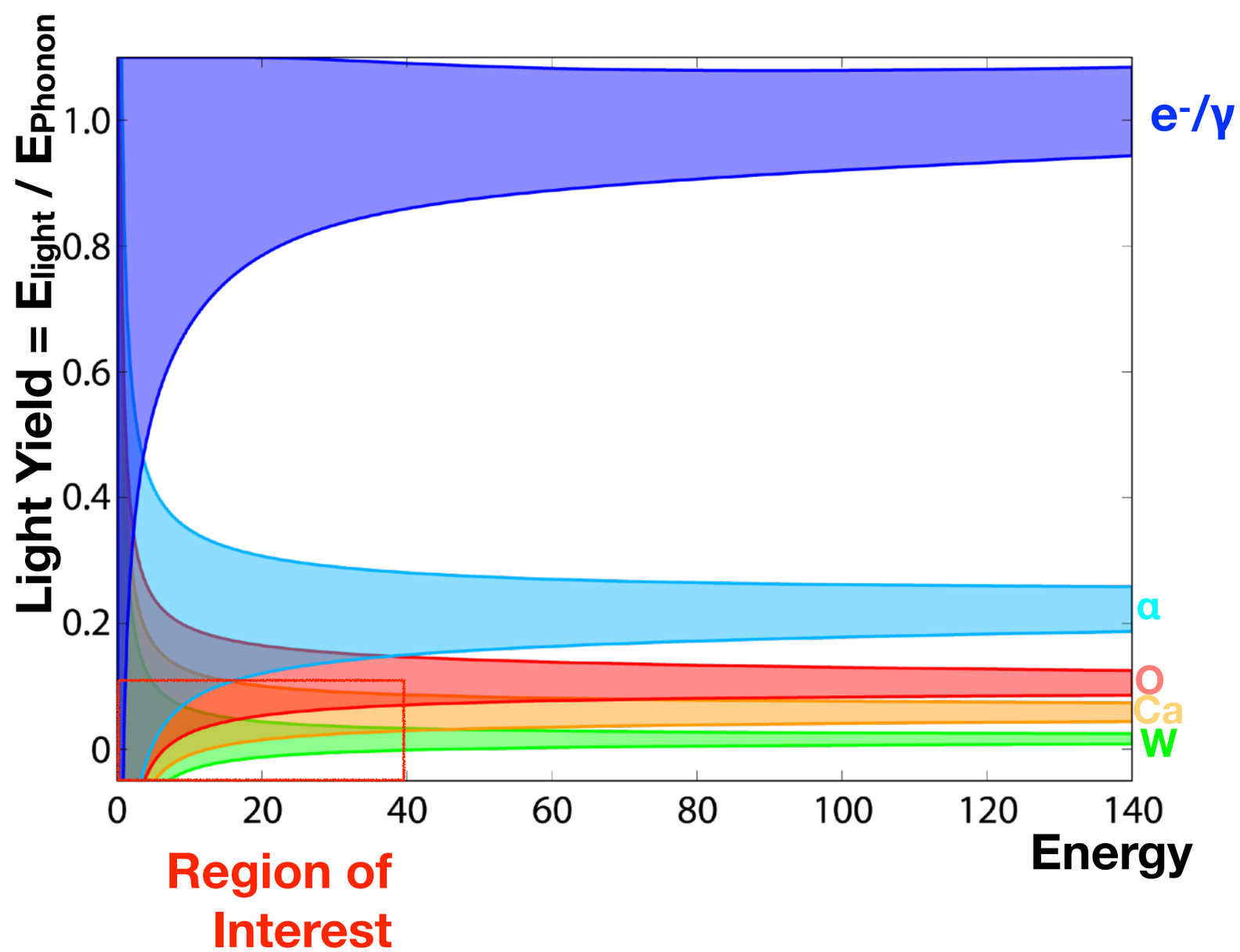
simultaneous read-out of two signals

- **phonon channel:** particle independent measurement of total deposited energy
- **(scintillation) light:** different response for signal and background events for background rejection ("quenching")



Signal-Background Separation

- simultaneous readout of light and phonon channel allows background reduction
- less scintillation light from dark matter-nucleus scattering
  - clear separation between signal and background at large Energy
  - significant overlap of bands at low energies (= **low mass dark matter**)



CRESST - Detection Principle II

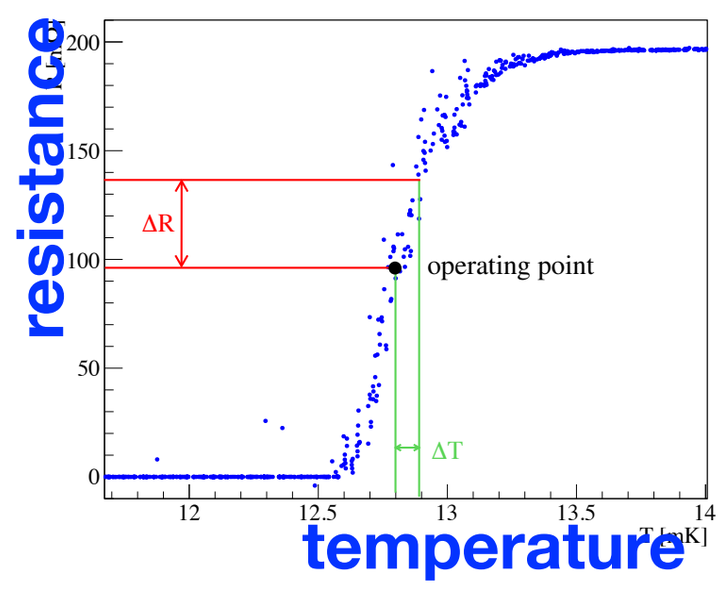
- experiment operated at cryogenic temperature (<10 mK)
- nuclear recoil will deposit energy in the crystal leading to a temperature rise proportional to energy

$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

$$c \propto (T/\theta_D)^3$$

Θ_D:Debye temperature

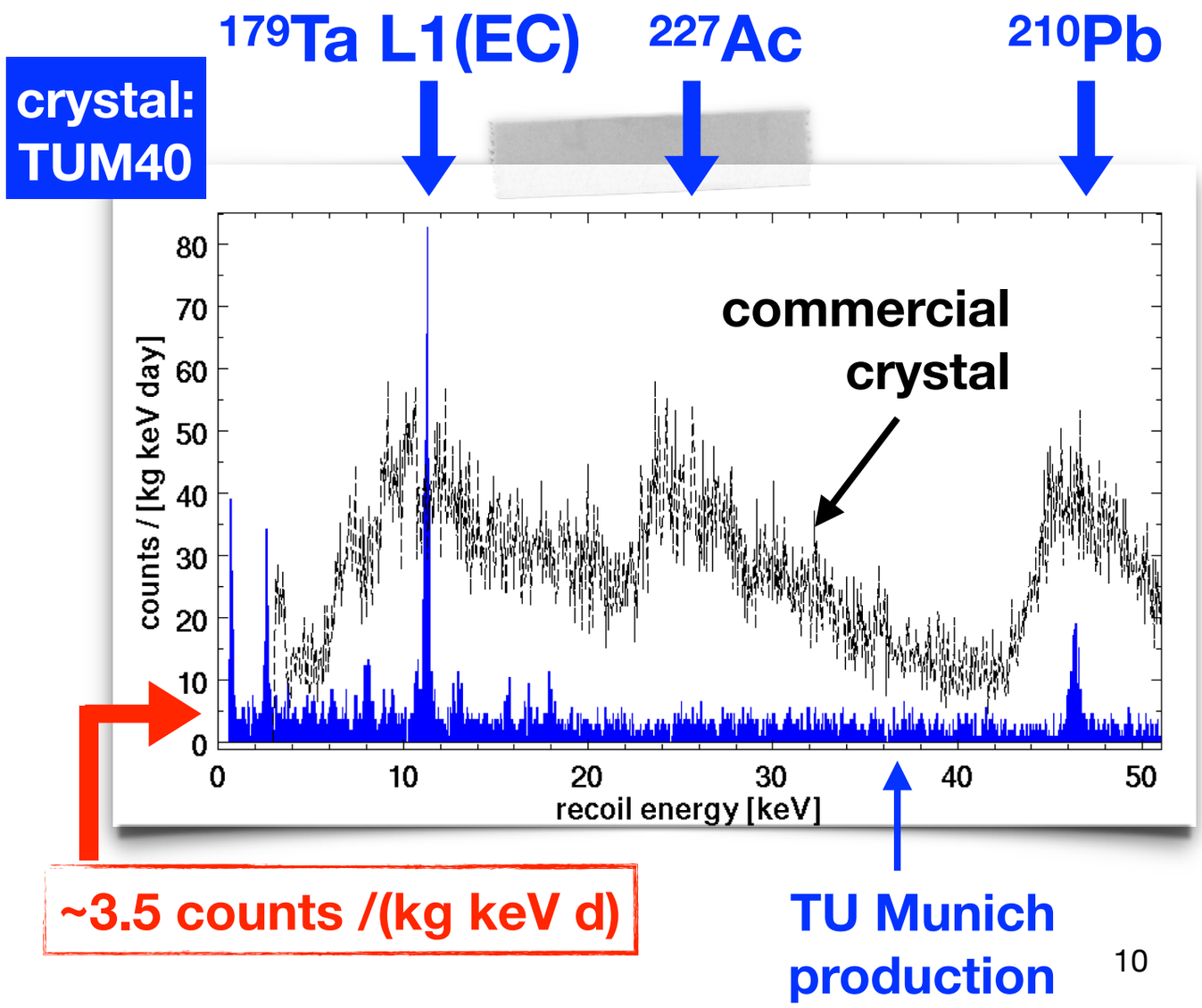
- detection of small energy depositions requires very small heat capacity c
- detection of temperature rise with superconductor operated at the phase transition from normal to superconducting



Crystal Intrinsic Background

crystal production at TU Munich

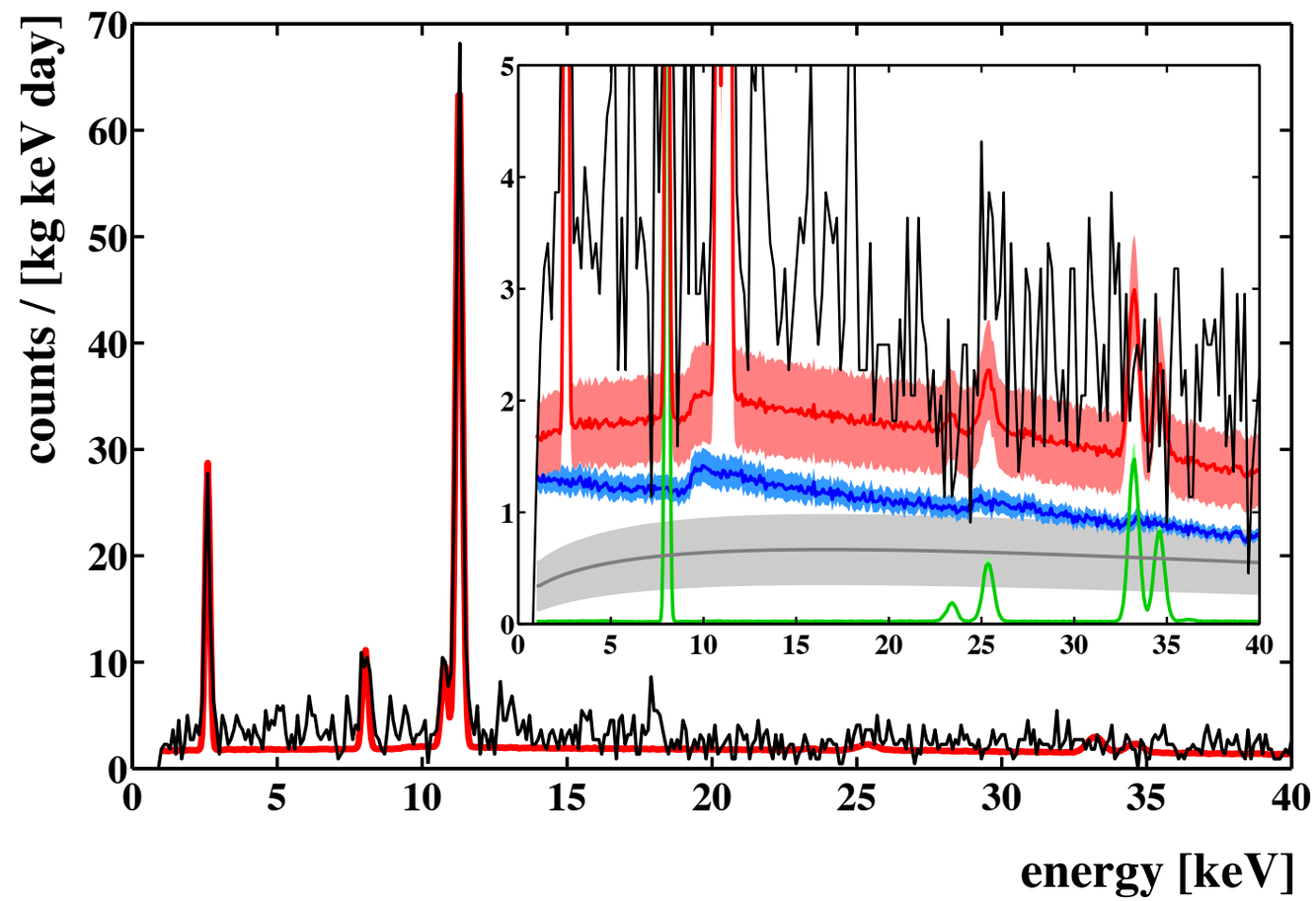
- experimental sensitivity limited by background
  - CRESST dominated by crystal-intrinsic radioactive contaminations
- in-house production of $CaWO_4$ crystals improves radio purity significantly



Background Simulation of CRESST Data

- understanding of background crucial
- Geant4 based simulation to estimate intrinsic background
- use measured α-activity as input for Geant4 to determine intrinsic β/γ radiation

JCAP, 2015(06), 030

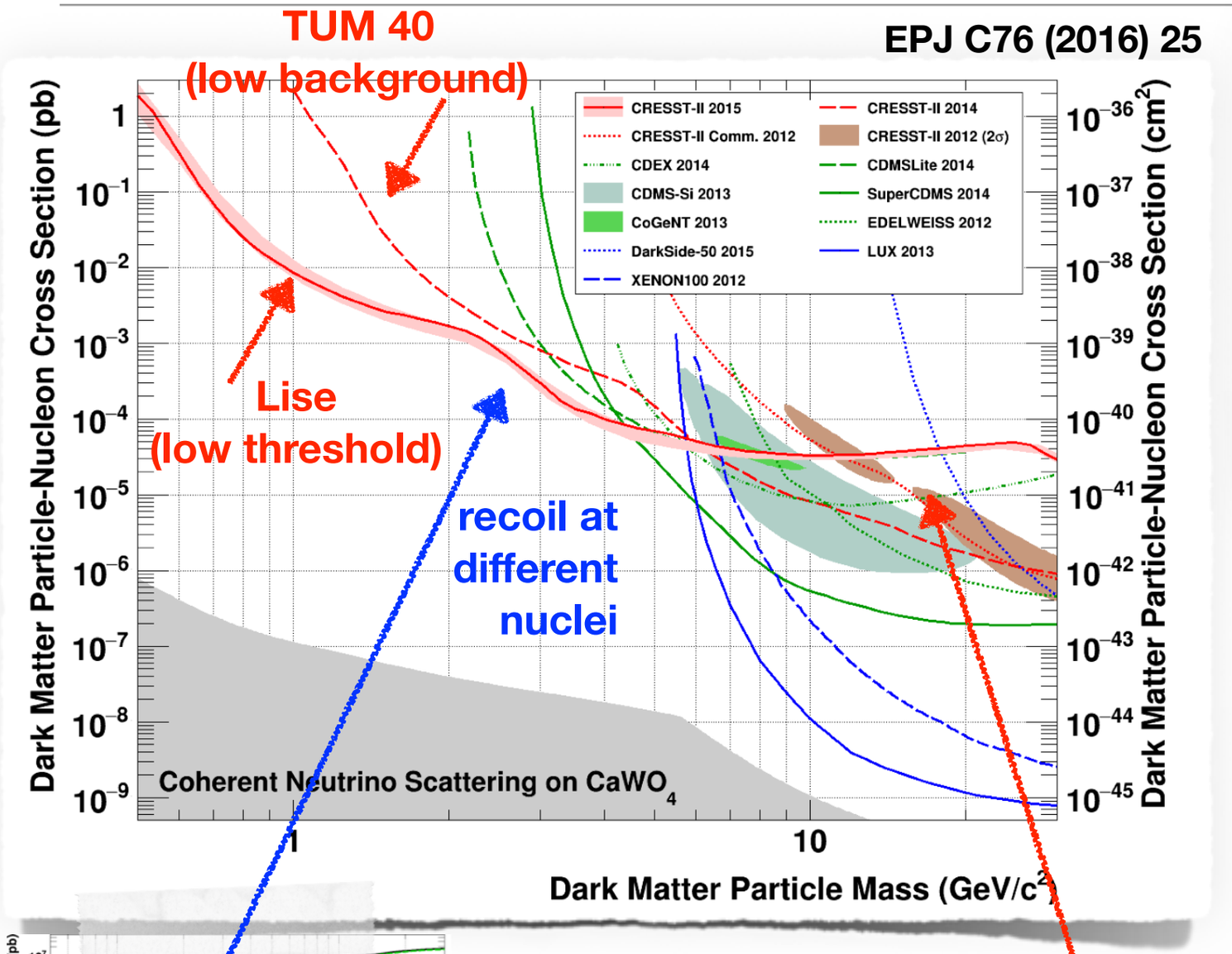


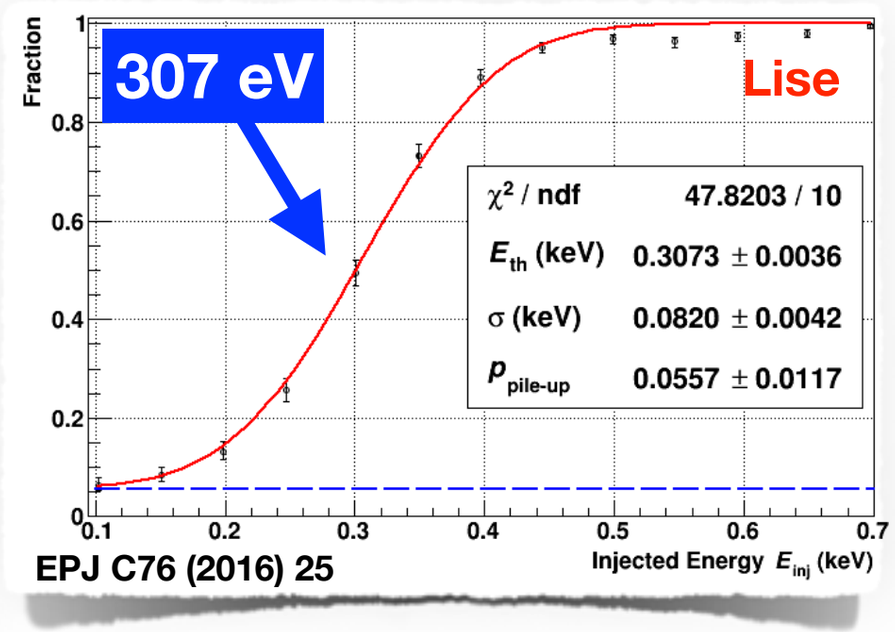
green: external gamma radiation
gray: external betas
blue: intrinsic β/γ radiation from natural decay chains
red: sum + cosmogenic activation

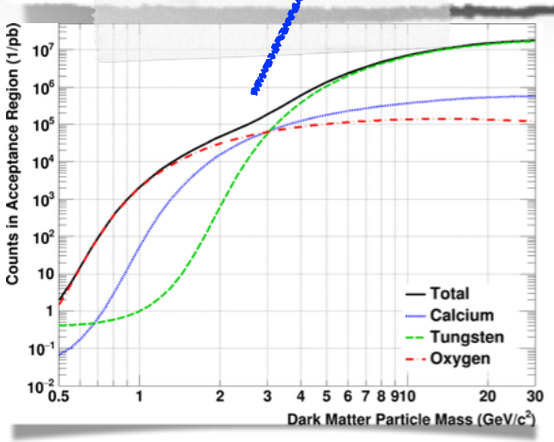
crystal: TUM40

CRESST - Status before Summer 2017

Final Result of CRESST II







reduced sensitivity due to surface ^{55}Fe

expected number of counts for $\sigma_{\chi\text{-}n}$=1pb in the acceptance region

- energy threshold at 307 eV for nuclear recoil
  resolution 62 eV (at zero energy)
- background level
  ~ 8.5 counts / (keV·kg·d)
- best sensitivity for dark matter particles between
  0.7* and 1.7 GeV/c²

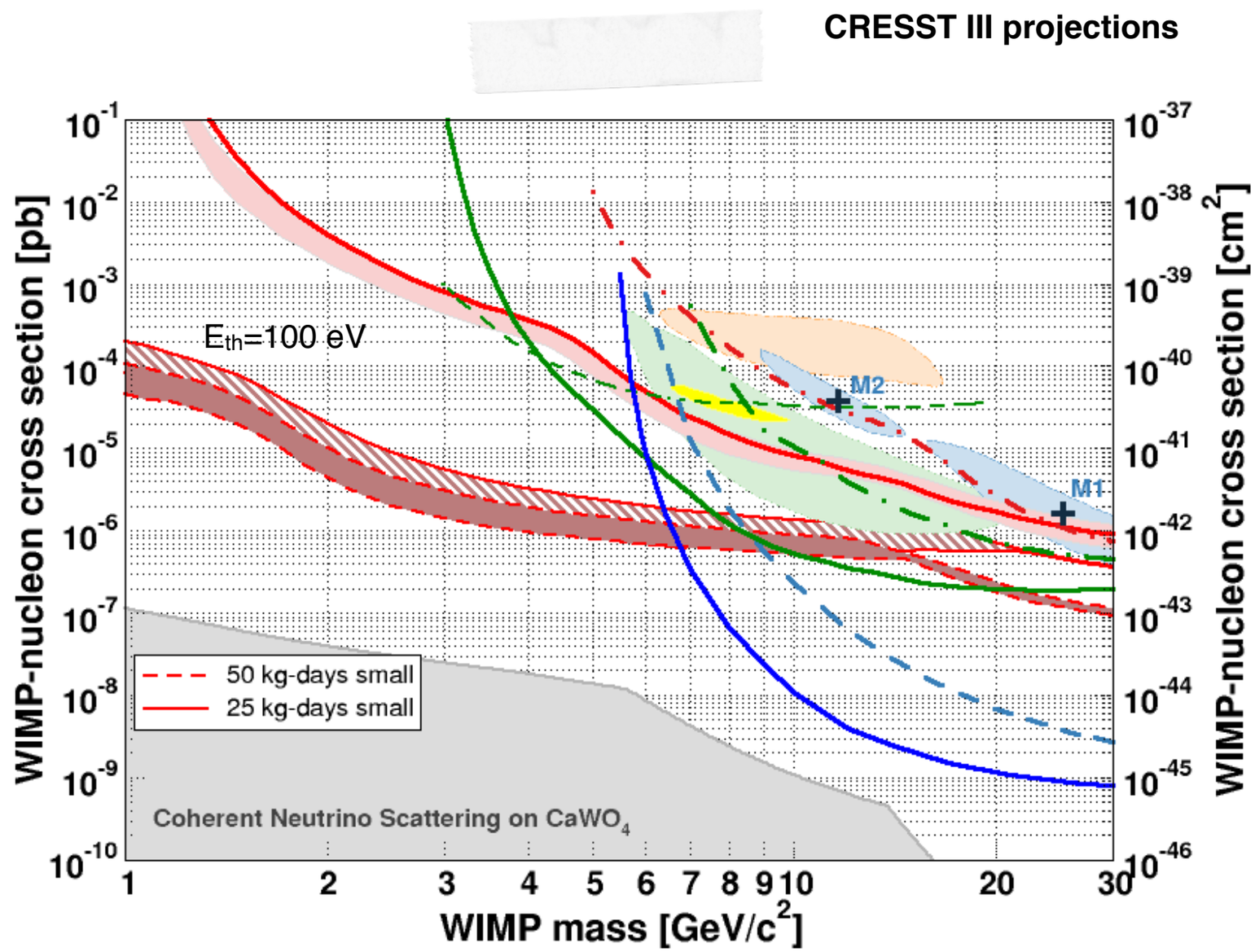
*July 2017: NEWS-G arxiv:1706.04934

CRESST III

CRESST III - expected sensitivity

- expect to reach $\sigma_{\chi\text{-}n} \sim 10^{-40}$ cm^2 for 1 GeV/c^2 dark matter particles
- detector R&D program for improved radio purity ongoing
- to increase exposure upgrade of read out system planned

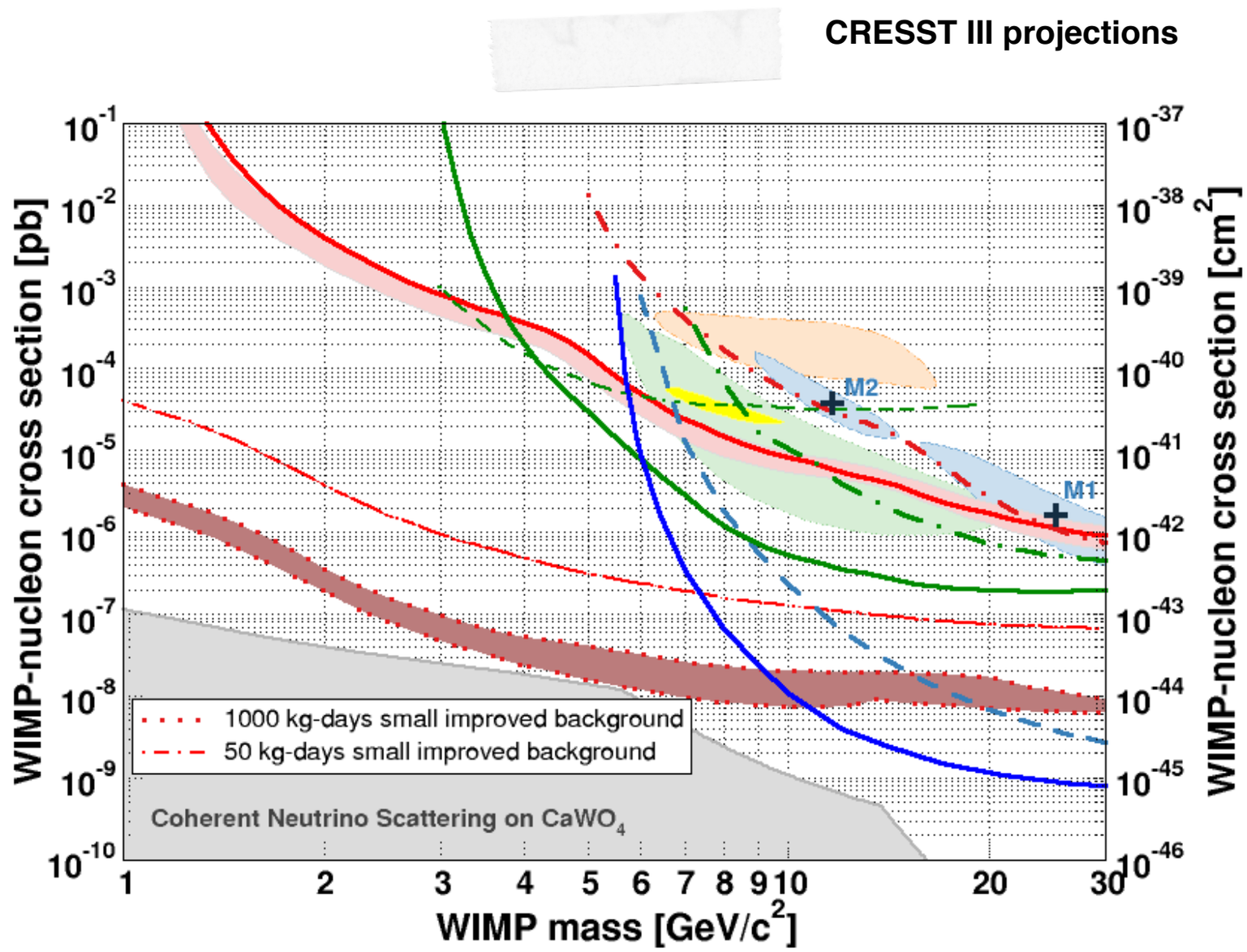
arXiv 1503.08065



CRESST III - expected sensitivity

- expect to reach $\sigma_{\chi\text{-}n} \sim 10^{-40}$ cm^2 for 1 GeV/c^2 dark matter particles
- detector R&D program for improved radio purity ongoing
- to increase exposure upgrade of read out system planned

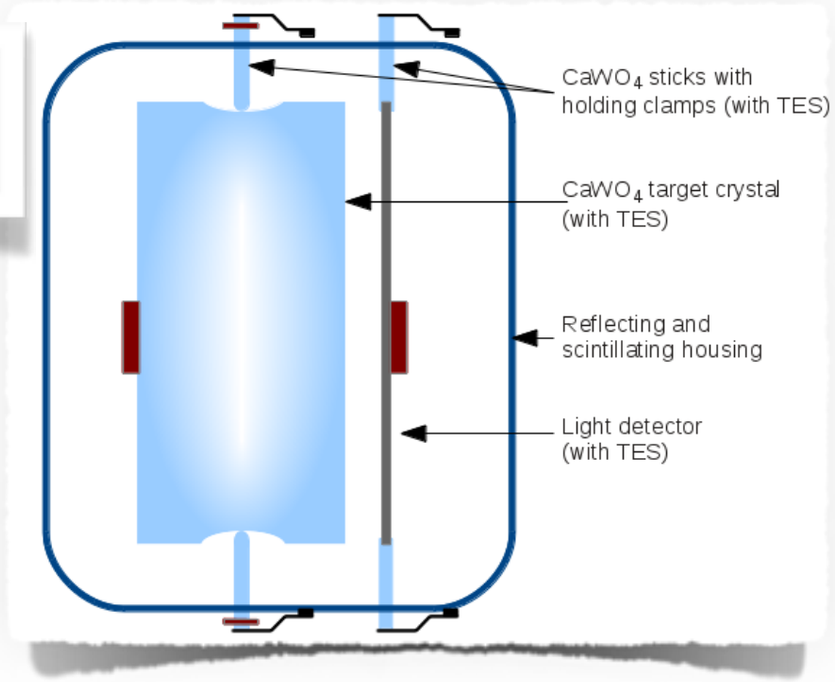
arXiv 1503.08065

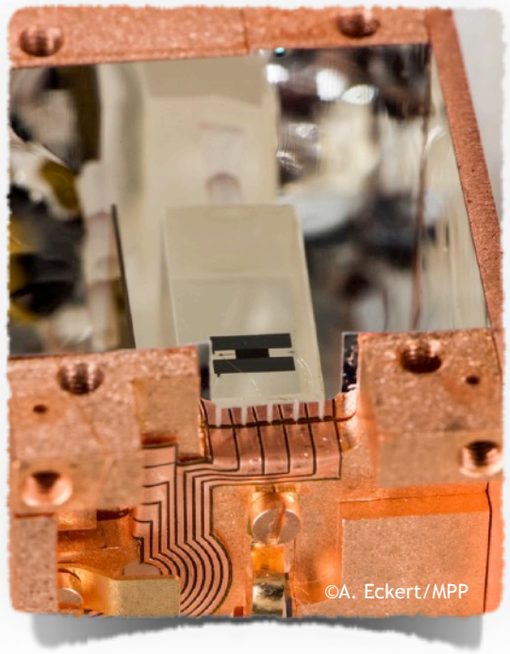


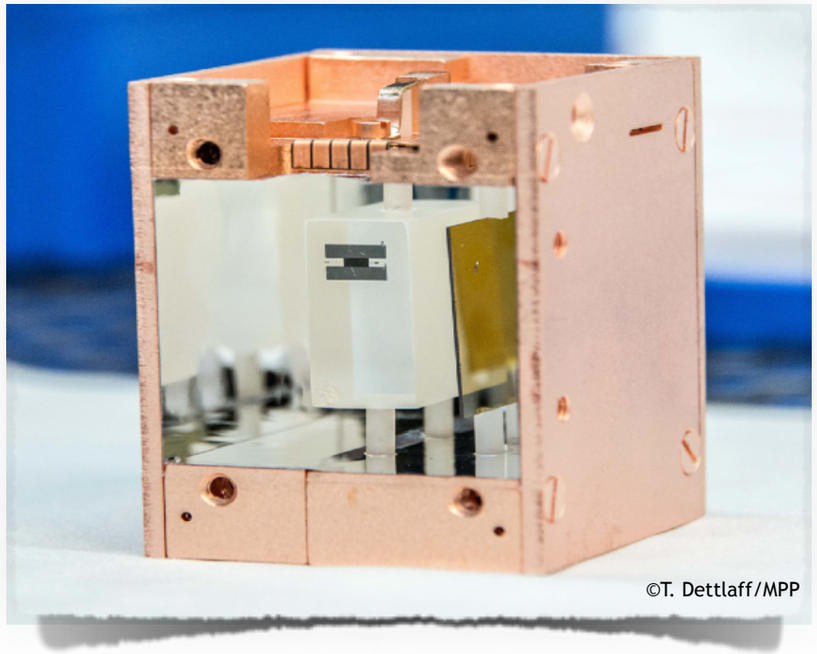
CRESST-III - low threshold detectors

- **layout optimised for low-mass dark matter**
  - cuboid crystal (20 · 20 · 10) mm^3 ~ 24g
  - self-grown crystal with ~ 3 counts /(keV · kg · d)
  - full scintillating housing and instrumented sticks

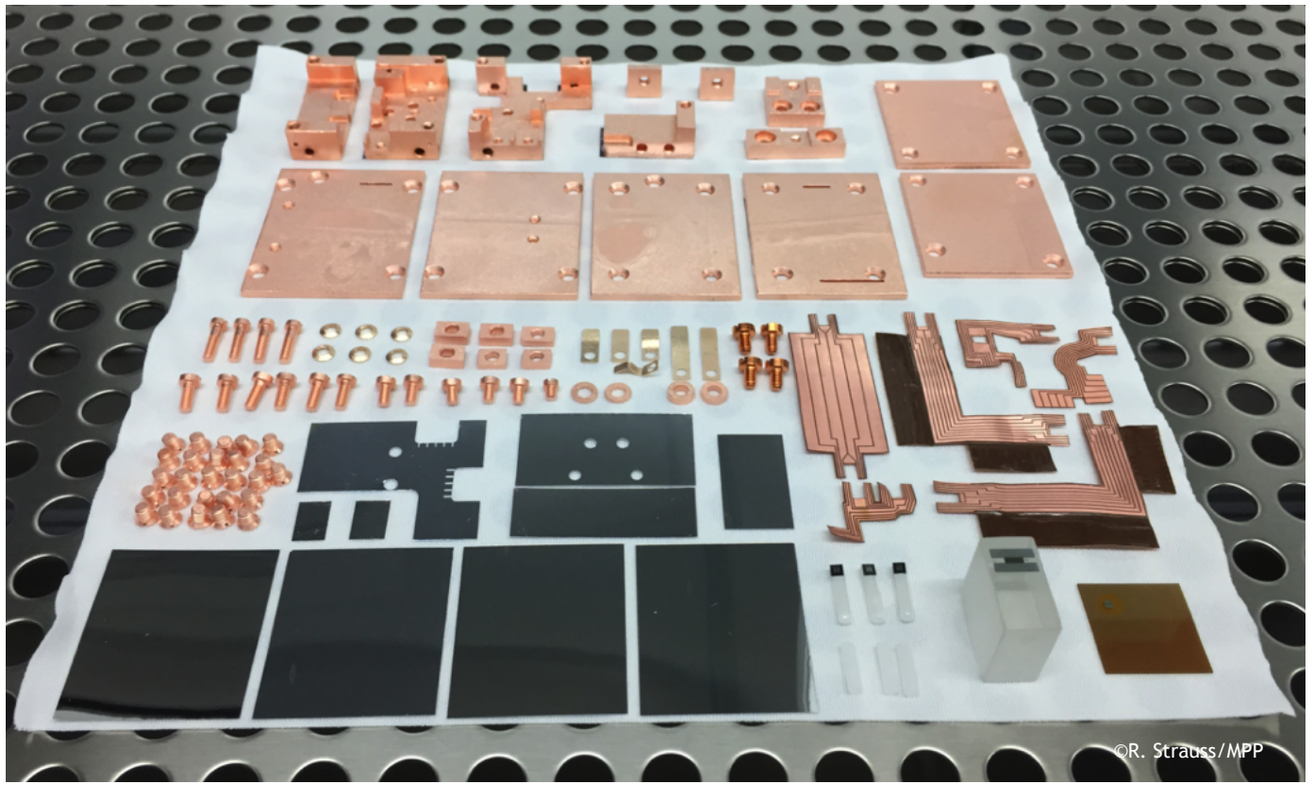
$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

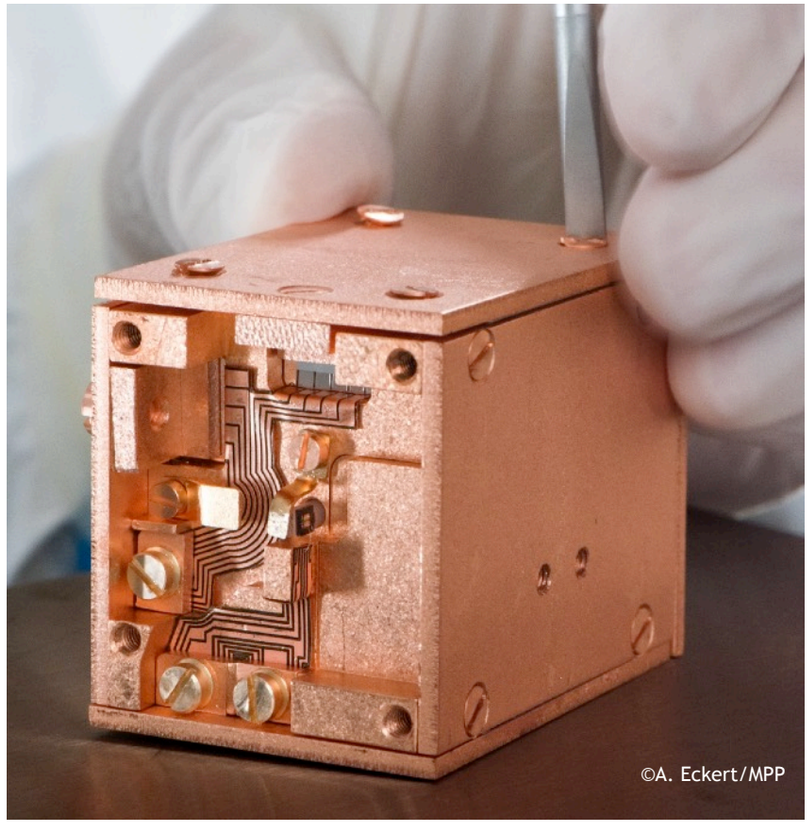




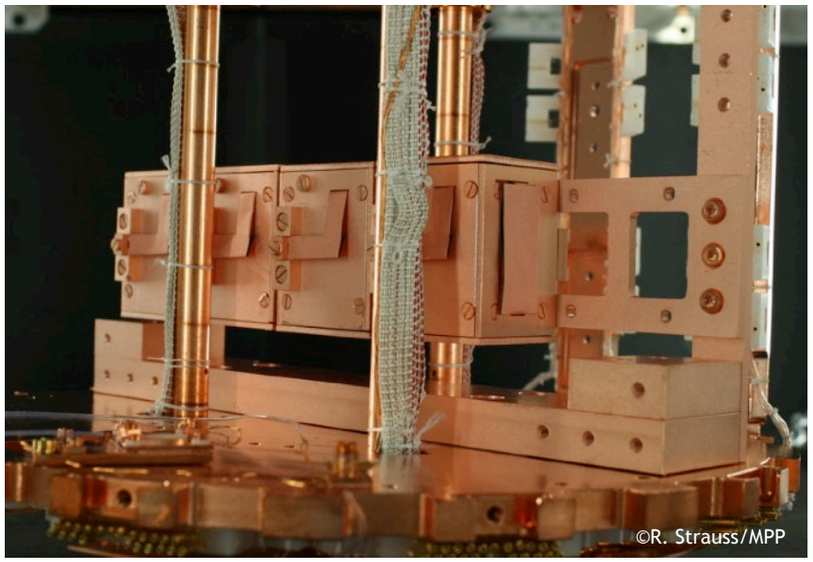


CRESST-III low threshold detectors





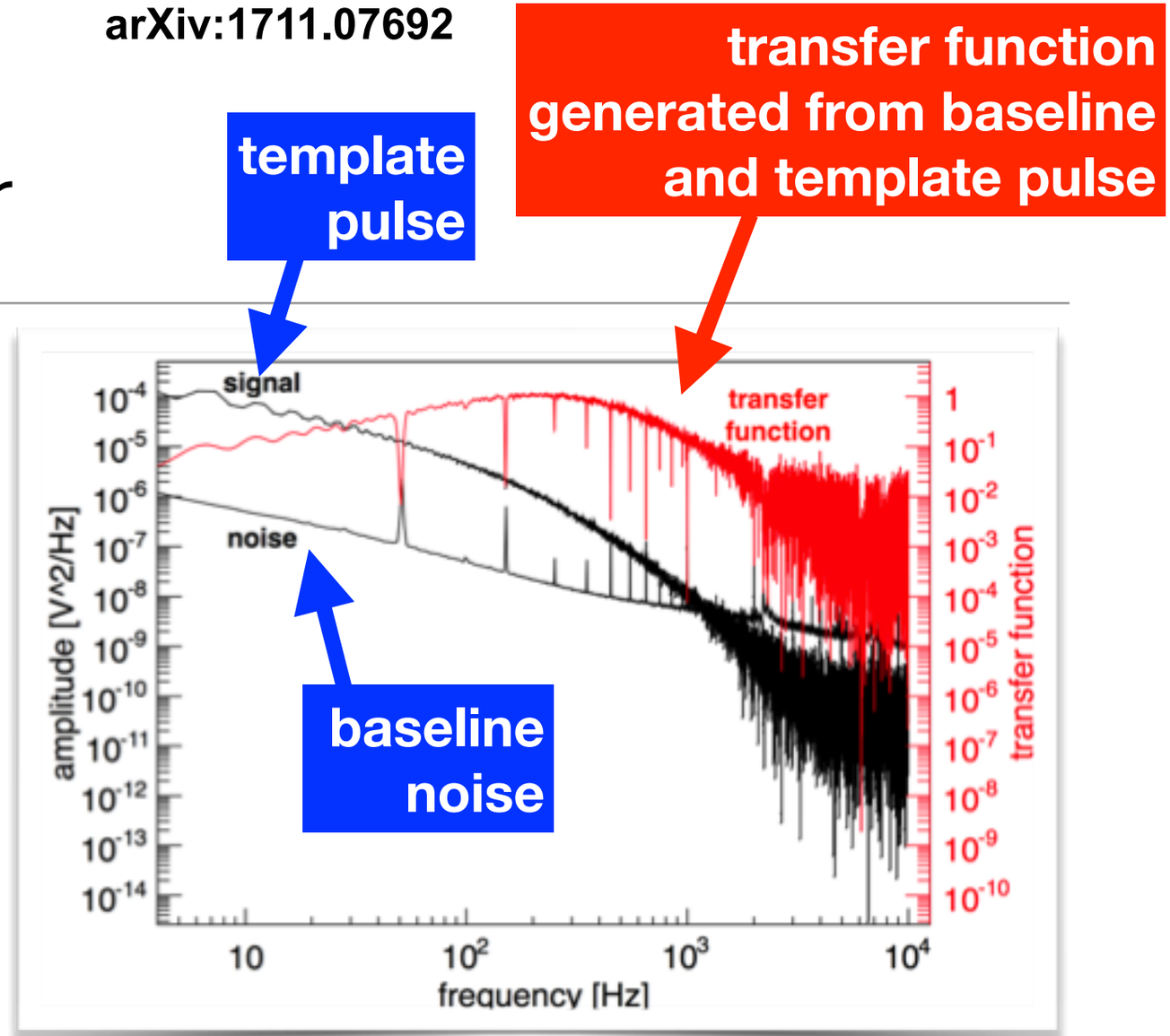
- operation started in July 2016
  - high statistics γ- and neutron calibration
  - 20% of data used as training set

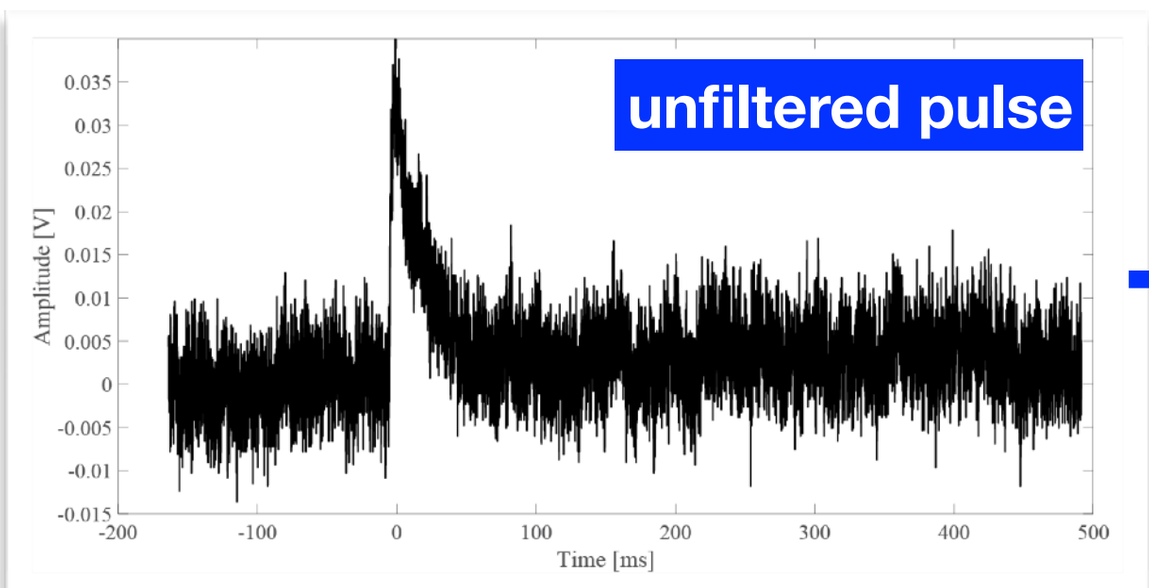


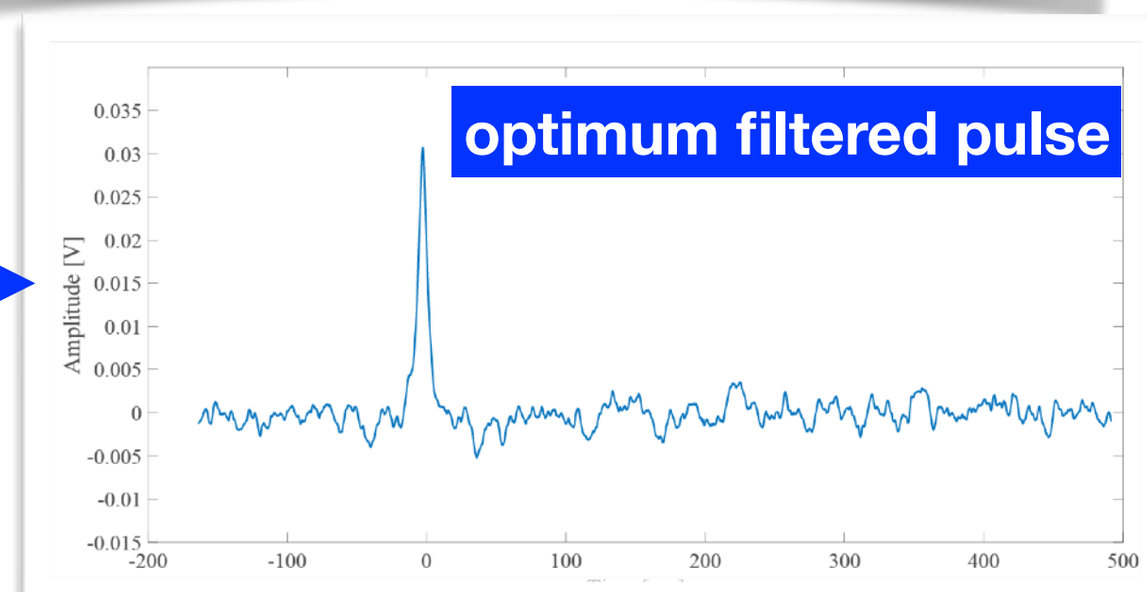
arXiv:1711.07692

CRESST-III Optimum filter

- implementation of the Gatti-Manfredi filter
- optimum filter maximizes signal-to-noise ratio
- typical improvement about factor 2-3
- new DAQ for CRESST-III with continuous data sampling. threshold set after optimum filter

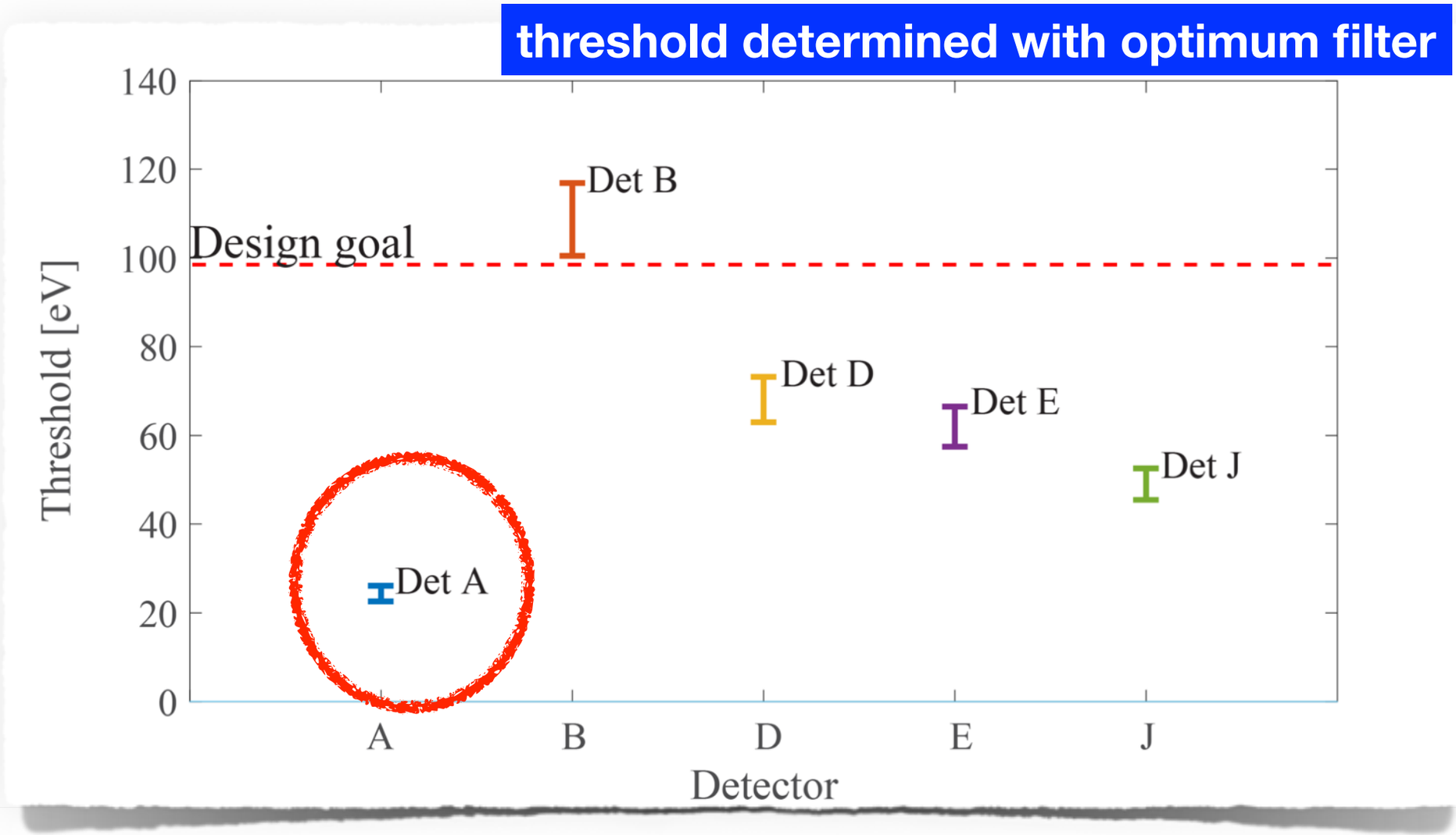






CRESST-III Energy threshold

- ten detectors installed
- six of ten detectors can be operated
- four detectors have technical problems (no transition or noise)

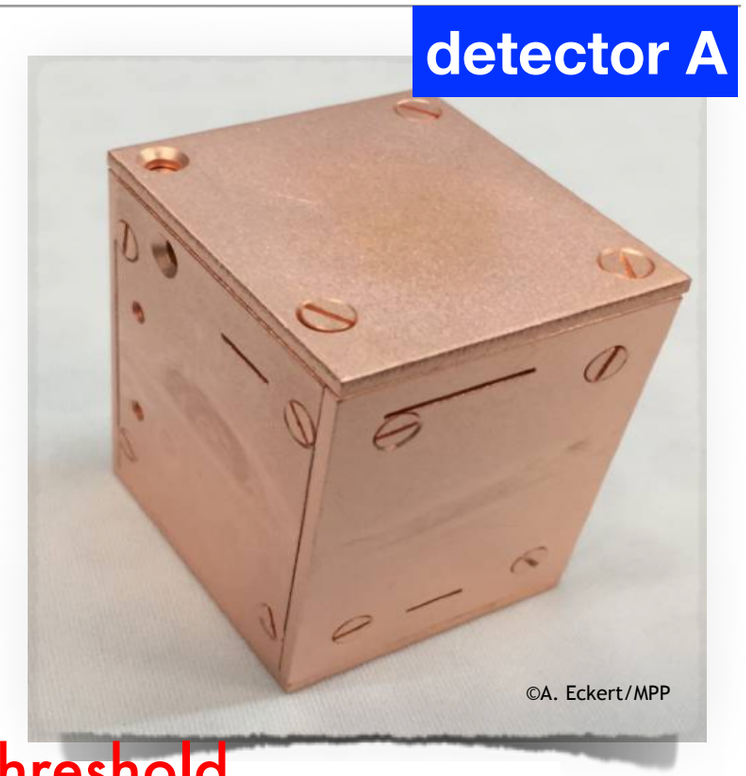


J Low Temp Phys (2018). https://doi.org/10.1007/s10909-018-1948-6

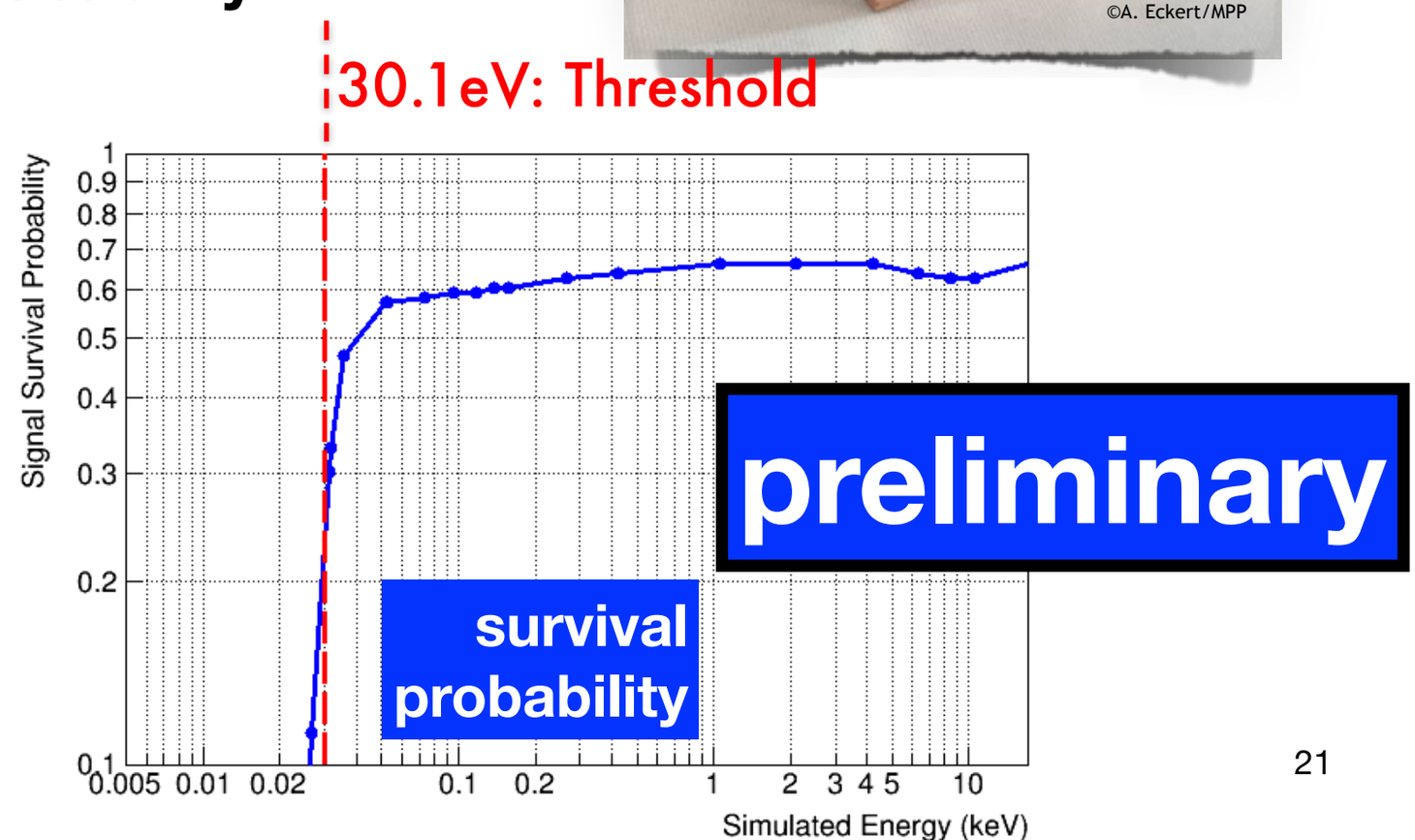
- **4 out of 5 detectors exceed design goal of 100 eV threshold**

Analysis of Detector A

- **analysed data: 10/2016-01/2018**
- **non-blind data: 20% randomly selected**
- **detector mass: 24 g**
- **exposure: 5.7 kg·d**
- **exposure after cuts: ~3.7 kg·d**
- **threshold: 30.1 eV; ≳ 60% survival probability**

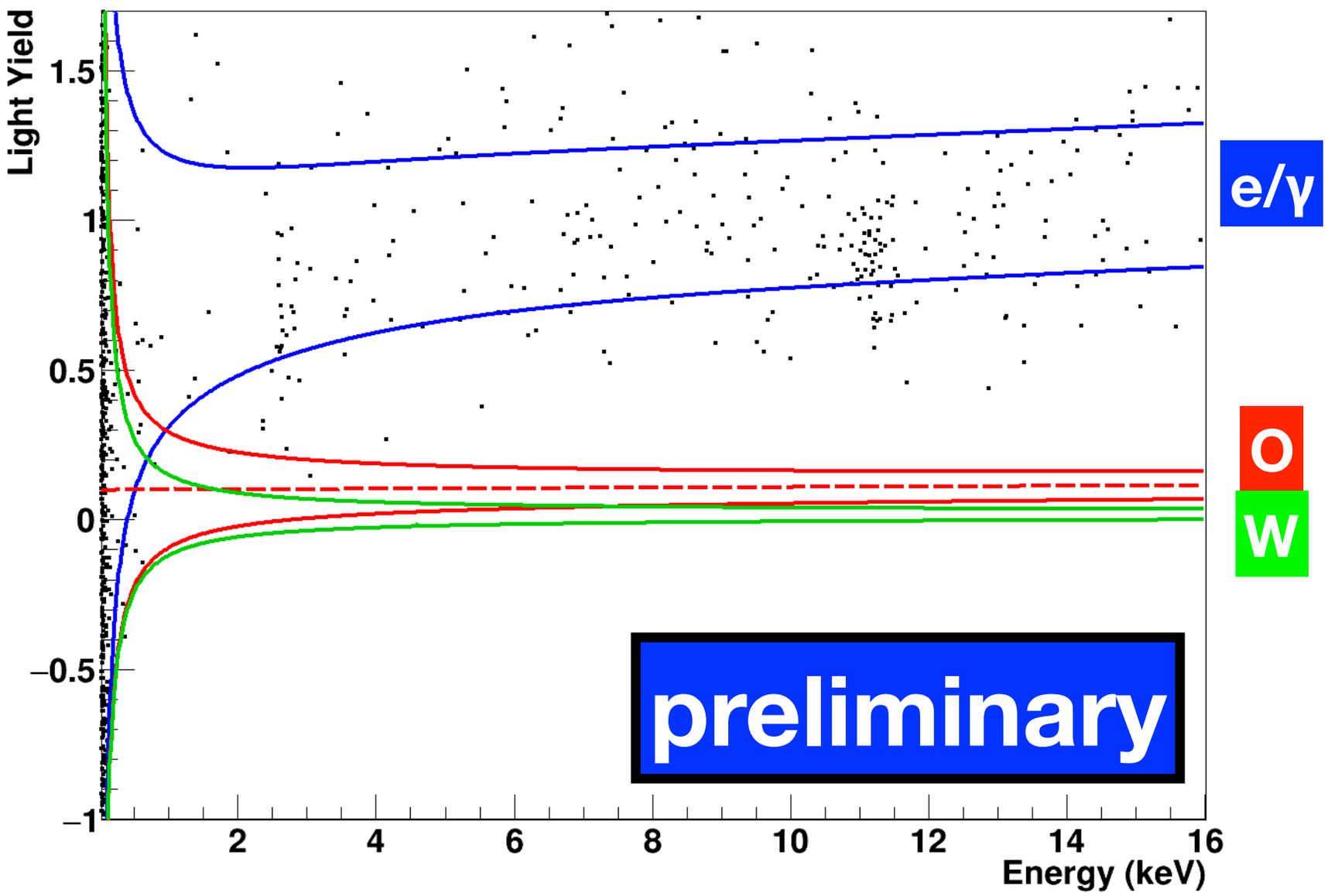


- data selection design on non-blinded data set
- cuts to guaranty correct reconstruction of amplitude



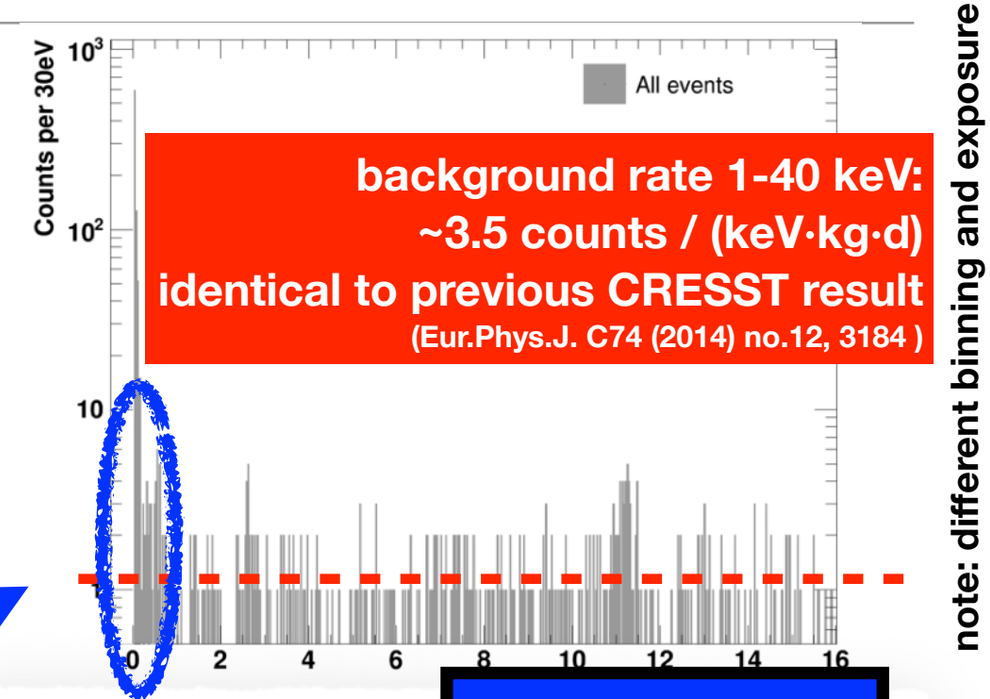
Detector A - Unblinding and Analysis optimised for 30 eV Threshold

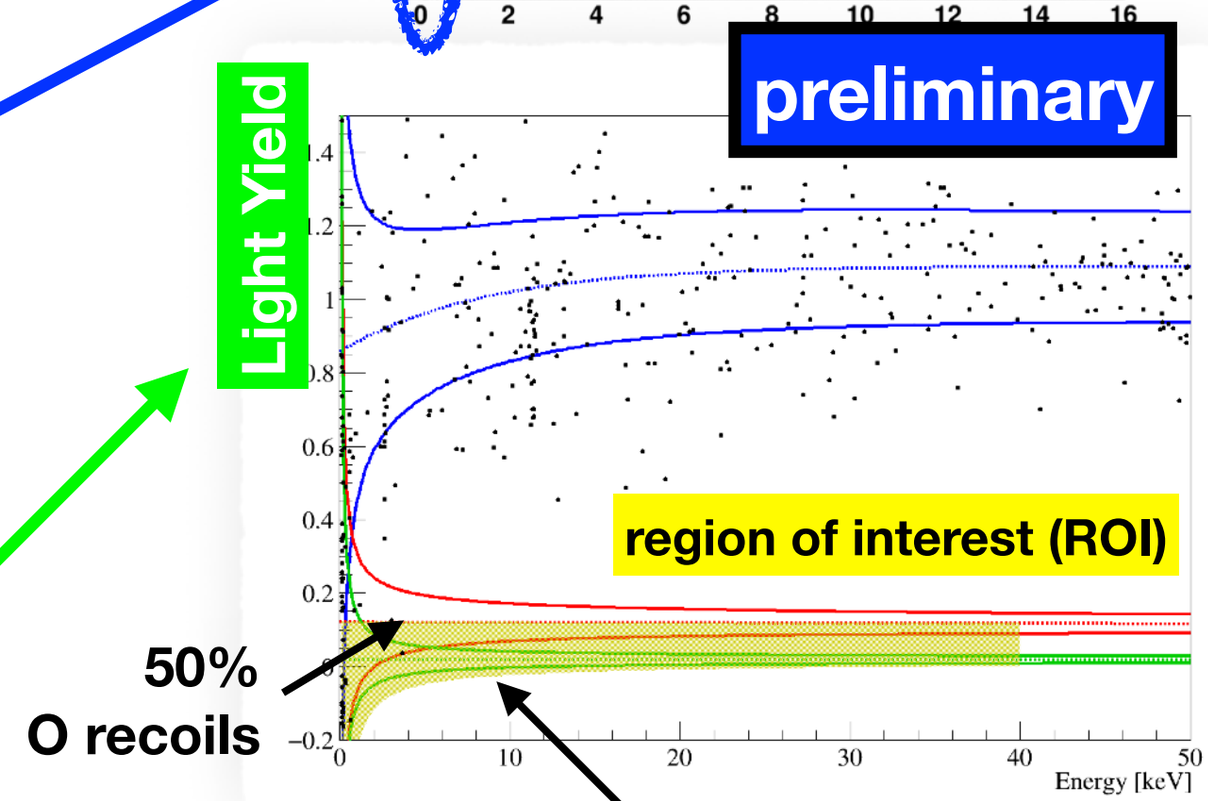
- extensive studies on training set (~20%)



Detector A - Background and Acceptance Region

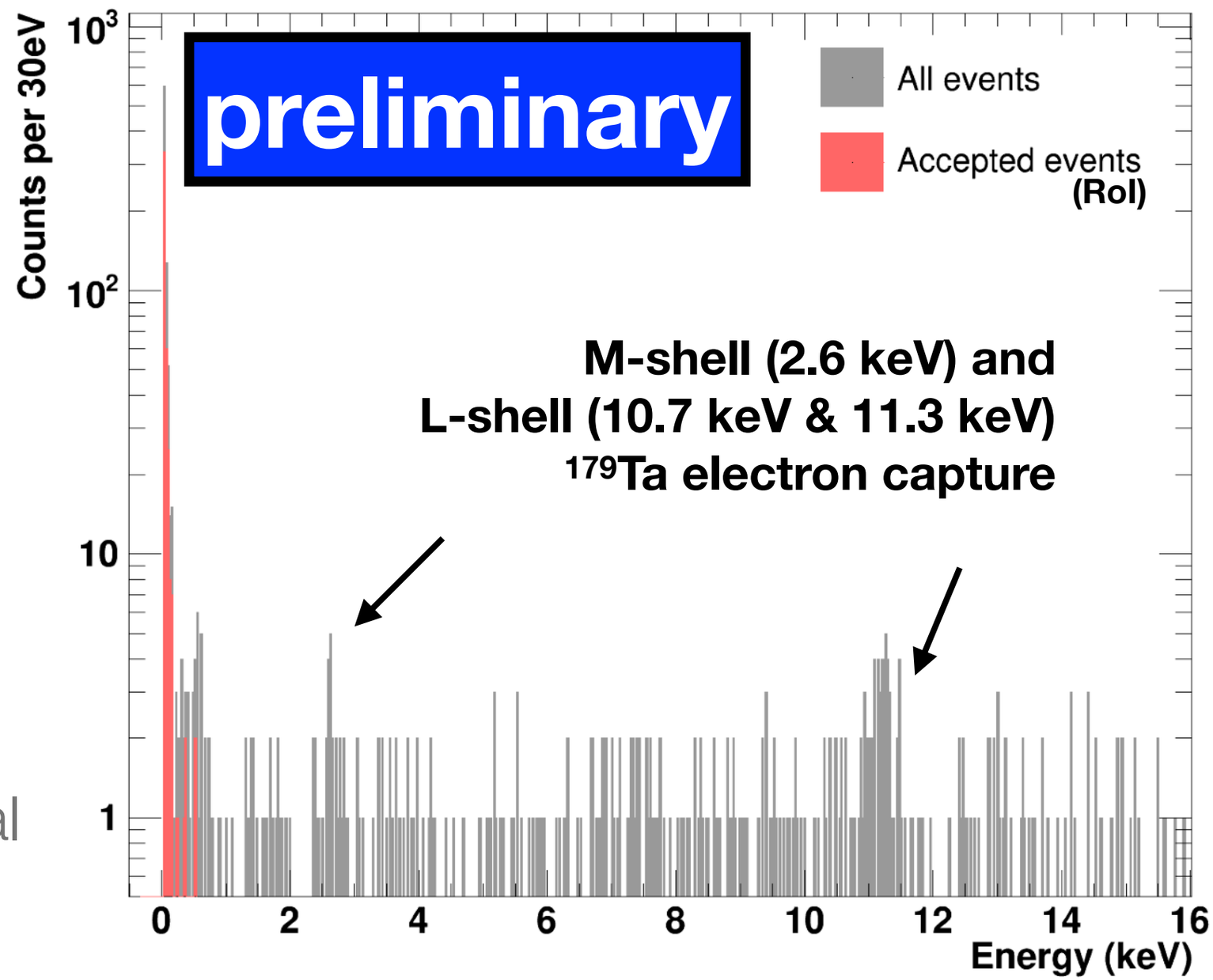
- background in the energy range above 1 keV identical to previous CRESST results
- increased sensitivity towards lower recoil energies opens unexplored background regions
  - strong raise of counts below 0.2 keV
  - further studies needed
- separation of signal and background using light yield





Detector A - Energy Spectrum

- region of interest between 30 eV and 16 keV
- 445 events between 30 eV and 16 keV in RoI
- set limit with Yellin's optimal interval method; using standard astrophysical assumptions

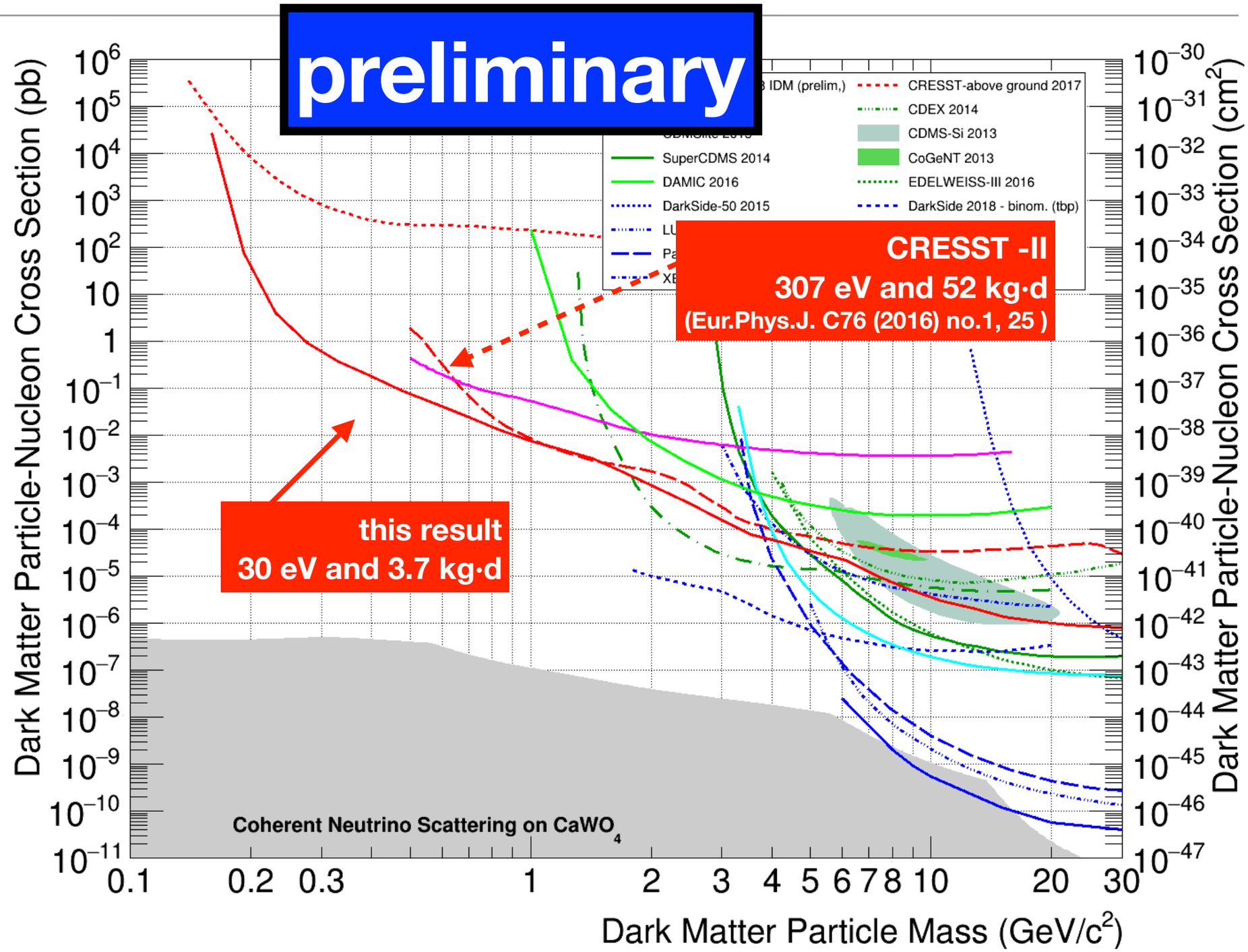


Detector A - Dark Matter Exclusion Limit

reach extended down to 160 MeV/c²

sensitivity at 500 MeV/c² improved by factor 10

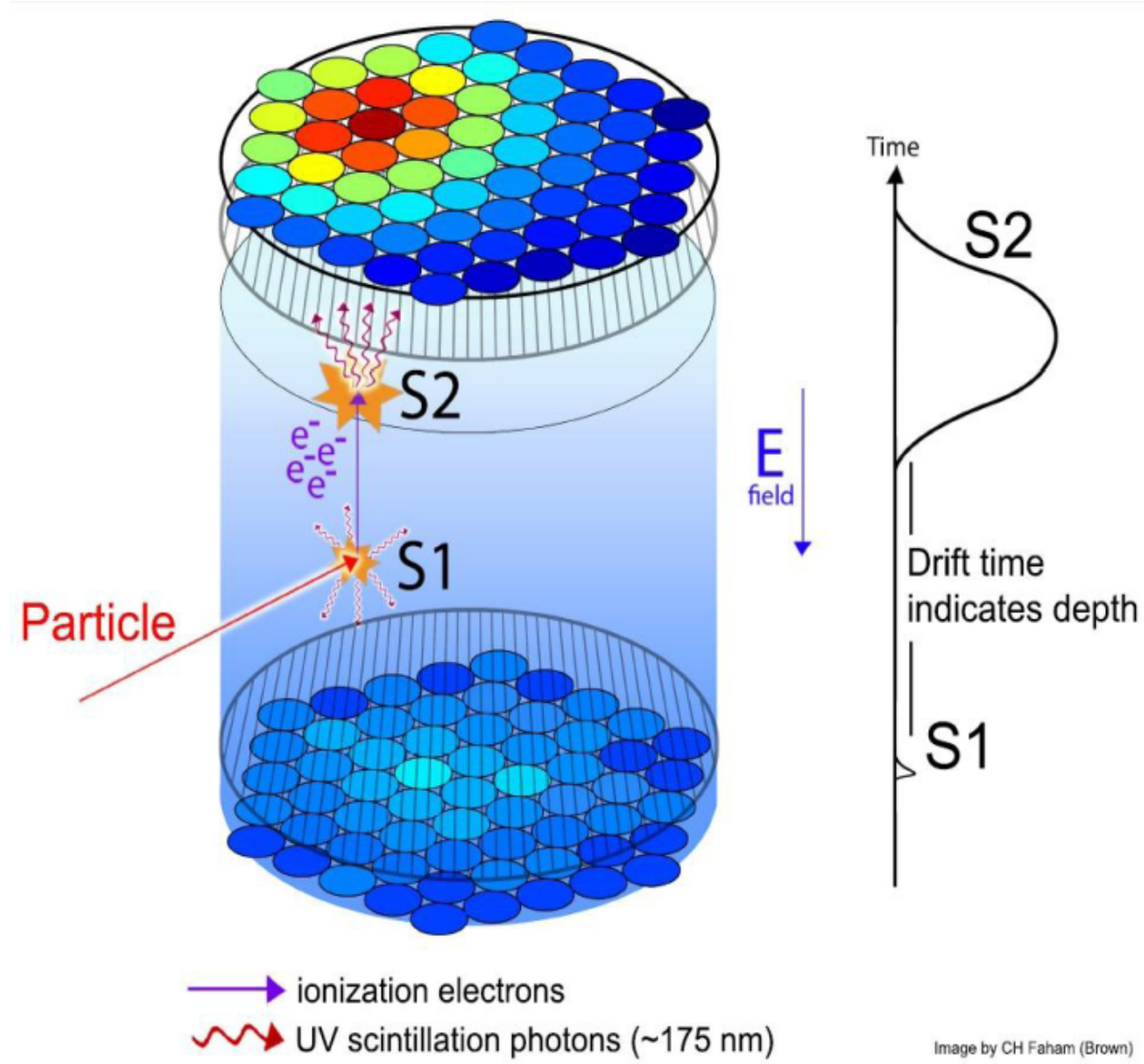
deeper understanding of background required



Search for Dark Matter with masses at serval GeV/c^2

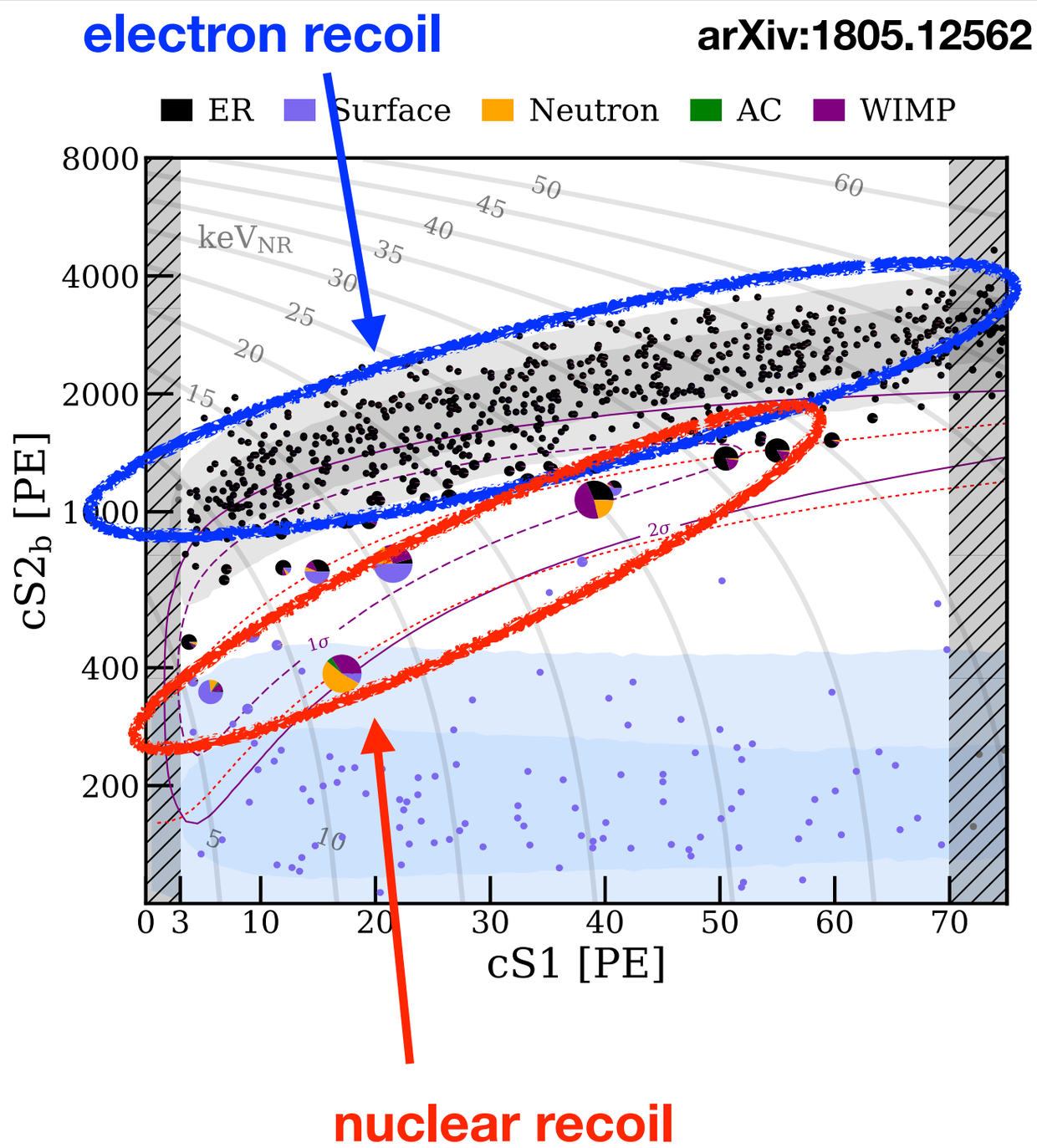
Dark Matter Searches with Liquid Nobel Gases

- Dark Matter experiments based on Xenon lead the limit in the high mass ($m_X \gtrsim 5$ GeV)
- Simultaneous read out of
  - (a) Scintillation (S1)
  - (b) Ionisation (S2)



Latest result from Xenon1T

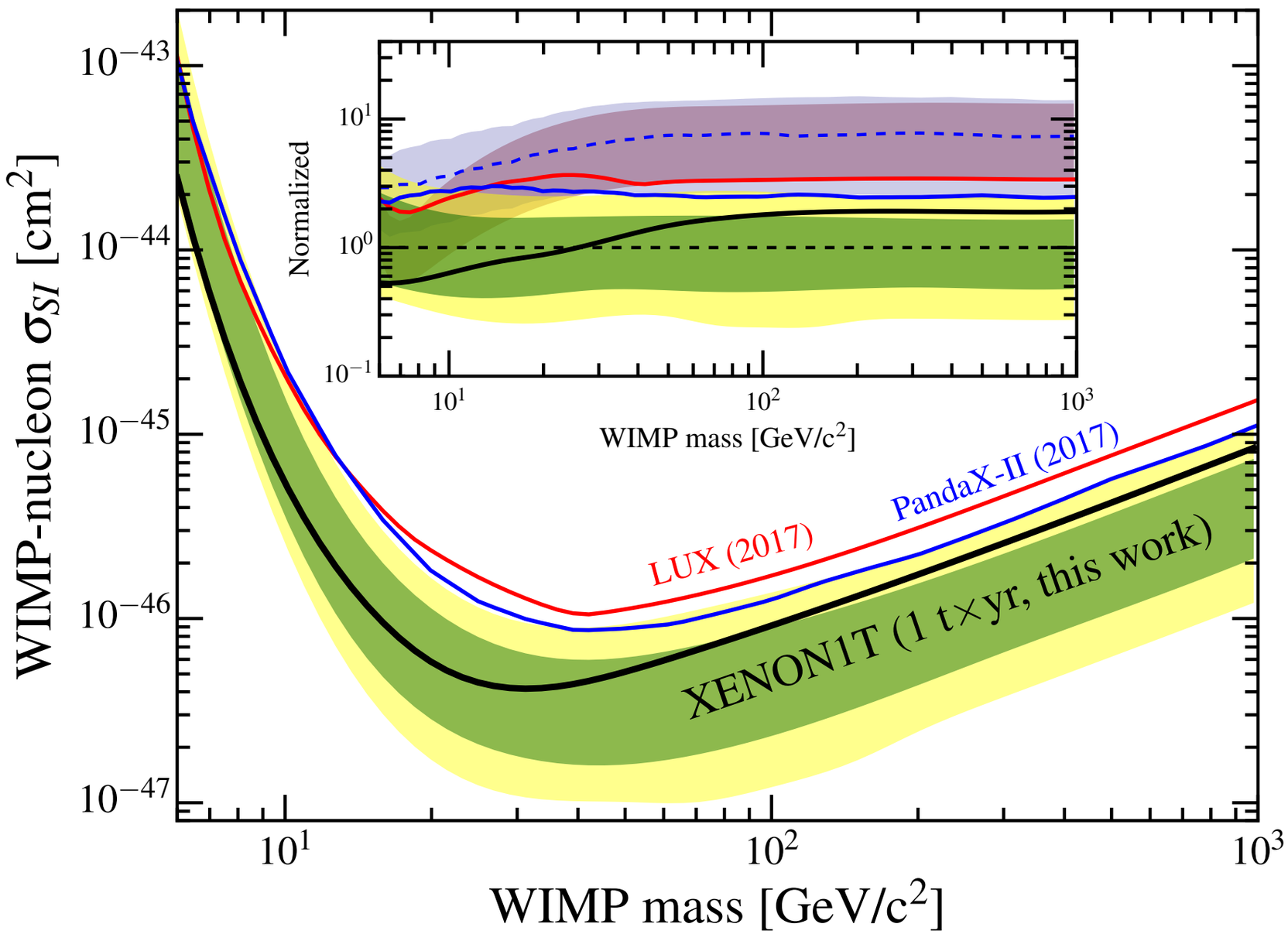
- separation of electron and nuclear recoil events in the S1 / S2 plane
- total exposure of 1 t x yr
- profile likelihood analysis returns no excess of events above the expected background



Result from Xenon1T

arXiv:1805.12562

- set limit in the cross-section vs mass plane
- observed sensitivity consistent within the 2σ expectation
- best limit in the above 6 GeV/c²

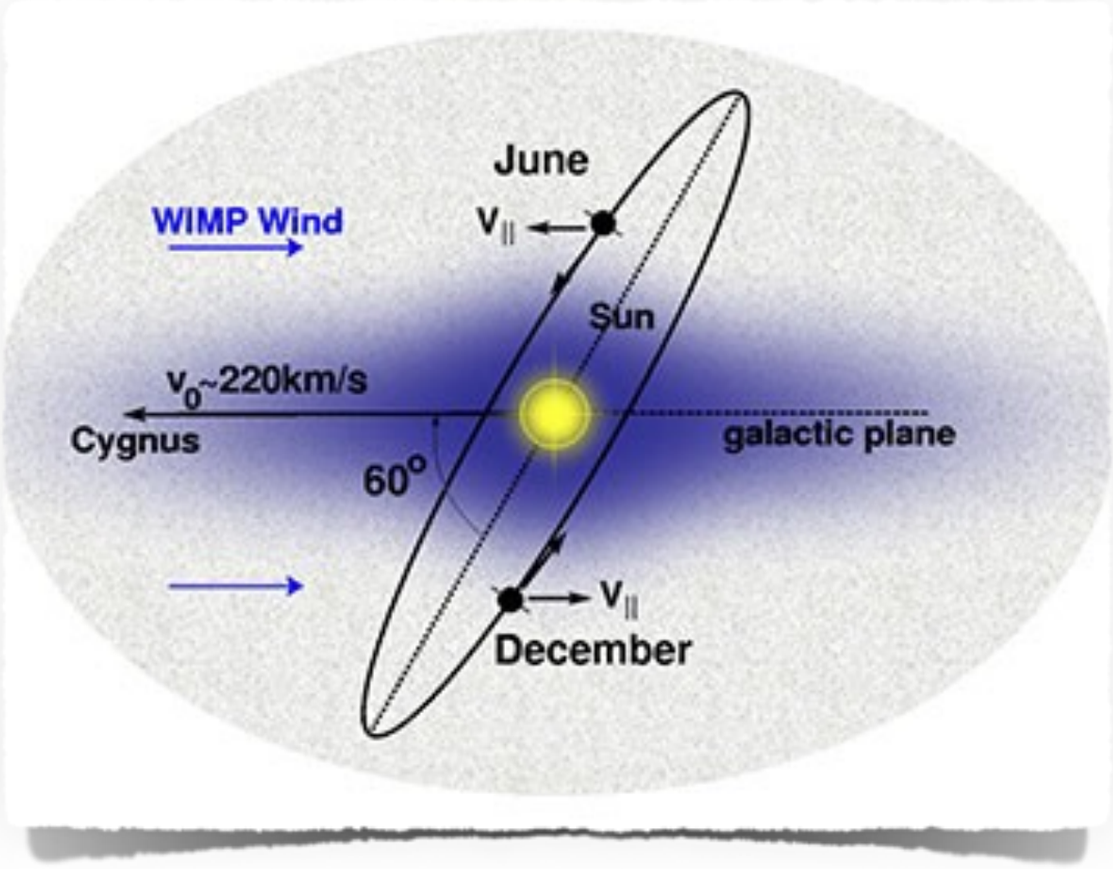


4.1x10^{-47} cm² @30 GeV

Annual modulation of Signal

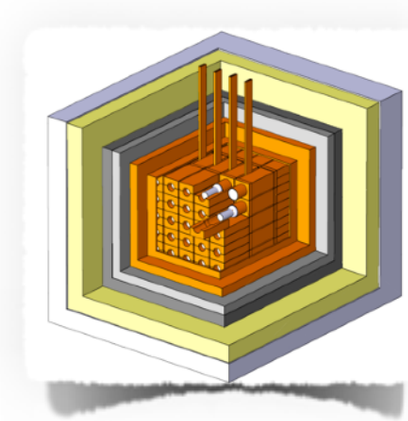
Dark Matter searches by Annual Modulation

- small interaction rate of dark matter expected
- excellent knowledge of background required to identify dark matter signal
- movement of earth in dark matter wind leads to **annual modulation of dark matter signal**
  - size of **modulation amplitude** can reach **up to 7%**



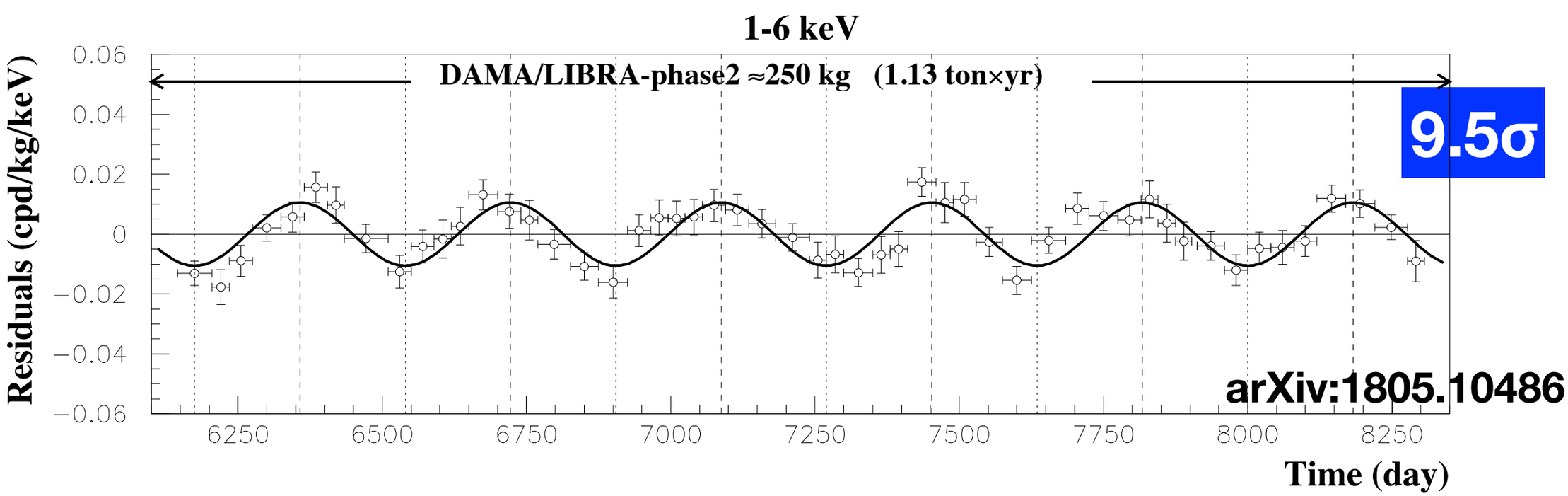
Annual Modulation of Dark Matter Interaction Rate

- DAMA/LIBRA experiment searches for dark matter via annual modulation of signal rate



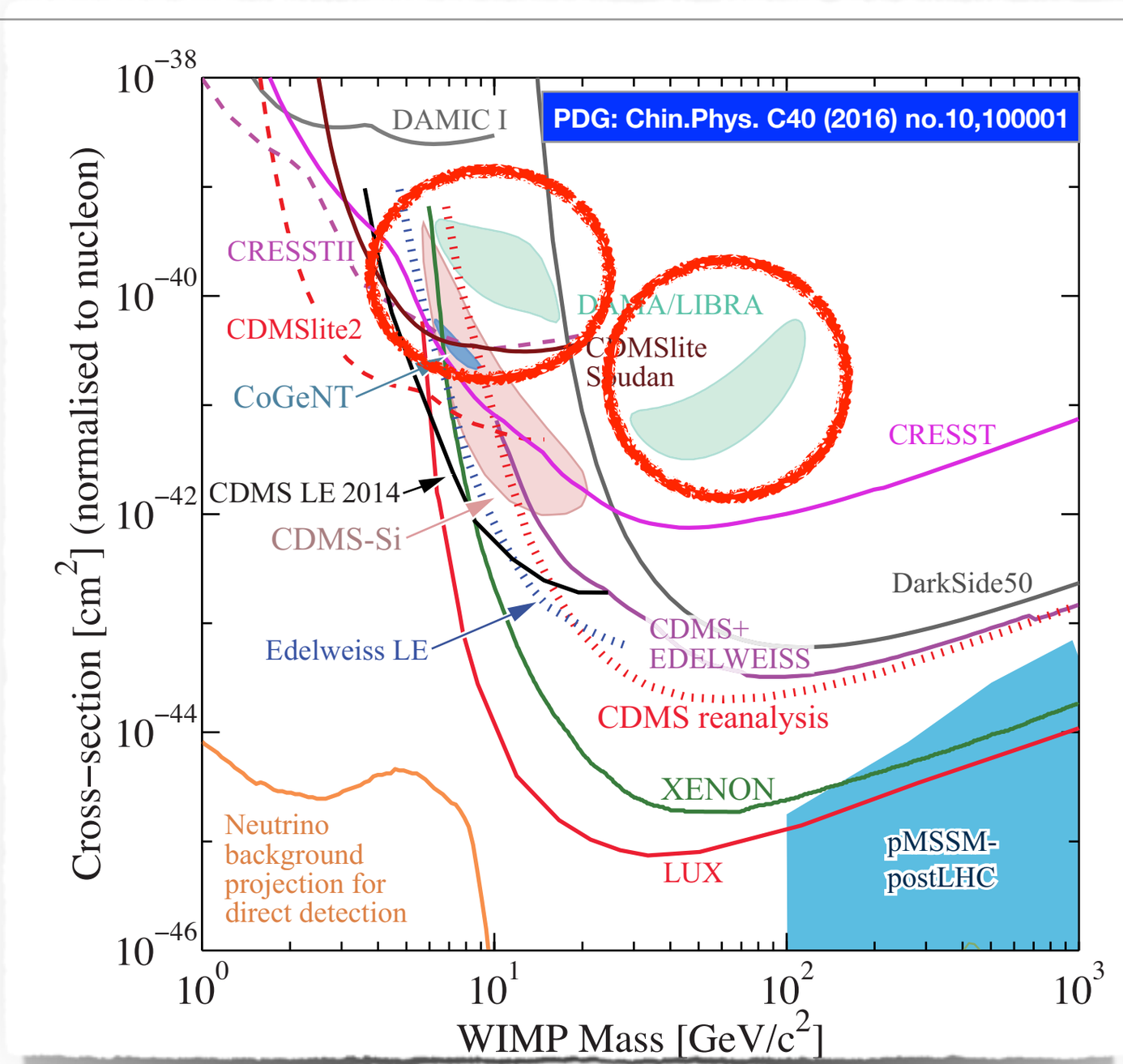
- operation of radiopure NaI(Tl)-crystals and **detection of scintillation light from dark matter - nucleus scattering**

- **residual signal** shows clear sign for an **annual modulation** of interaction rate in the energy region of **1-6 keVee (new - previously 2-6 keVee)**



Interpretation of Annual Modulation as Dark Matter

valid for standard assumptions only



$m_X \approx 50$ GeV ; $\sigma_{Xn} \approx 7 \cdot 10^{-6}$ pb

$m_X \approx 6$-10 GeV ; $\sigma_{Xn} \approx 10^{-3}$ pb

- **interpretation** of annual modulation as **dark matter** scattering (previous 2-6 keVee results)
- **preferred mass and cross-section area excluded by other dark matter experiments**
- **latest results 1-6 keVee cannot be explained with WIMP spin-independent interaction**

Annual Modulation - what do we know?

- statistically significant observation of annual modulated rate of events observed through NaI(Tl) scintillation light
  - **origin of underlying process is unknown**
- observation is **consistent** with expectation from **dark matter** scattering modulated by annual changes of dark matter flux
- detailed systematic studies cannot explain annual fluctuation by background processes
- **assumptions:** quenched scintillation light, together with standard astrophysical assumption could explain signal modulation via dark matter-nucleus scattering

Independent NaI(Tl) experiments

- gain deeper understanding of DAMA/LIBRA results

  i. repeat experiment with identical conditions

  ii. detailed study origin of annual modulation
  (locate experiment at southern hemisphere)

  iii. understanding underlying scattering process

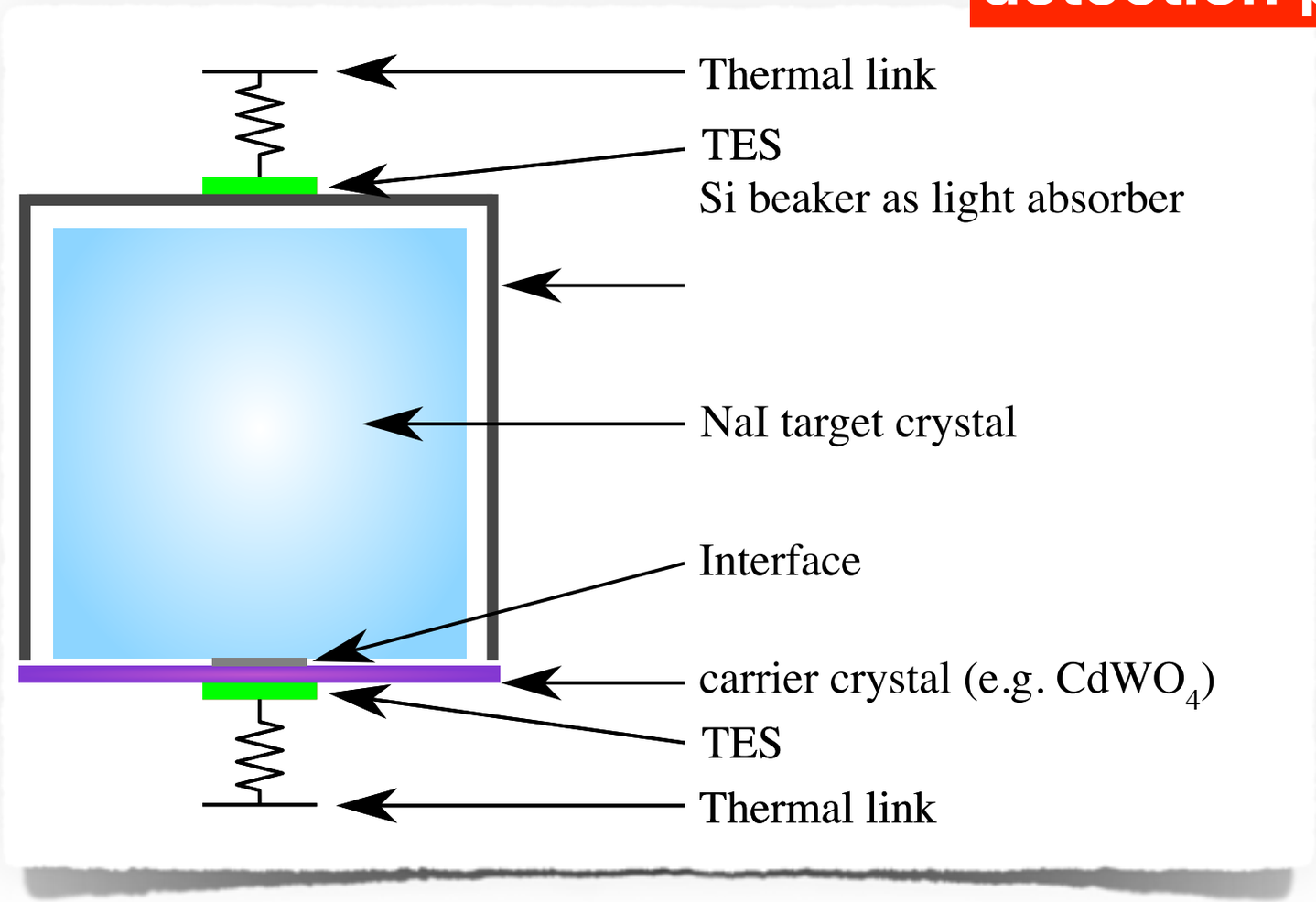
- several experiments started or ongoing to understand origin of observed annual modulation

Global NaI(Tl) efforts

H.S.Lee at ICHEP 2018

The COSINUS Experiment - Detection Principle

detection principle similar to CRESST



- **cryogenic operation of NaI-crystal**
- simultaneous read-out of
  - **phonon channel:** particle independent measurement of deposited energy (= nuclear recoil energy)
  - **(scintillation) light:** different response for signal and background events for background rejection ("quenching")

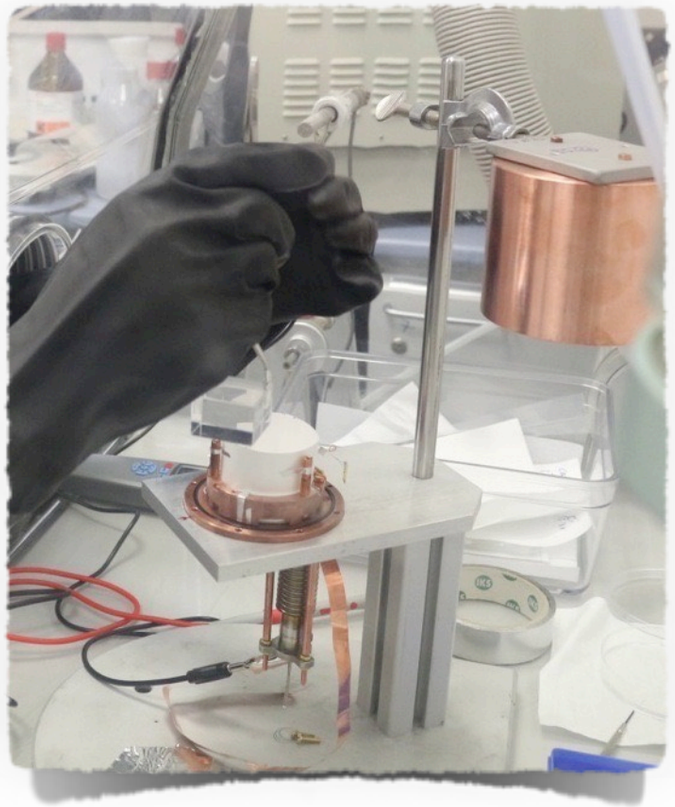
→separation between nuclear scattering and β/γ background events

The COSINUS Experiment - Challenges

- NaI is hygroscopic
  → requires careful handling in glove box

- high contamination with ^{40}K
  emission of ~3 keV Auger electron possible

- small signal amplitude



$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

c: specific heat capacity of the crystal

$$c \propto (T/\Theta_D)^3$$

Θ_D:Debye temperature

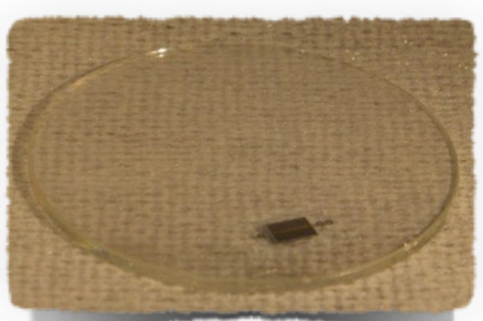
Properties	NaI(pure)	CsI(pure)	$CdWO_4$	$CaWO_4$
Density [g/cm^3]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 ±1.0	58.9±5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

Florian Reindl

1st NaI-Prototype and Mounting in Cryostat

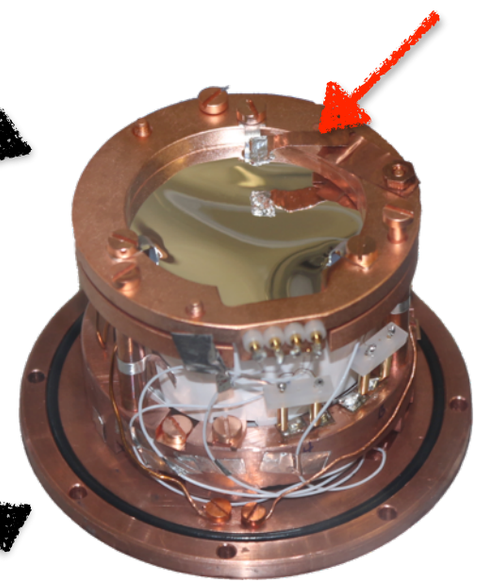
30x30x20 mm³ (66g)

NaI phonon detector
(undoped)



$CdWO_4$ carrier crystal

Light detector
(Silicon on Saphire + TES)



surrounded by
reflecting foil

5 cm of Pb to shield radioactivity
from the dilution unit of the cryostat

Decoupling system
to reduce microphonic nois

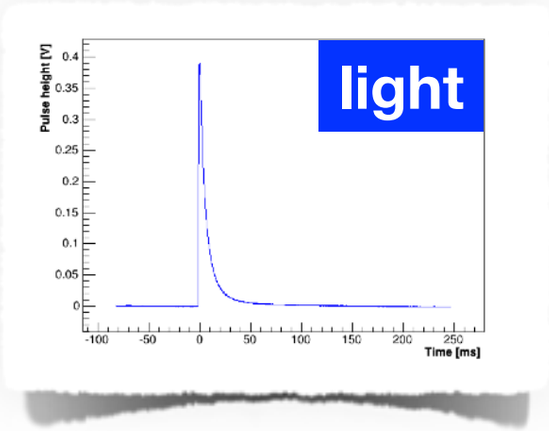
Copper
housing

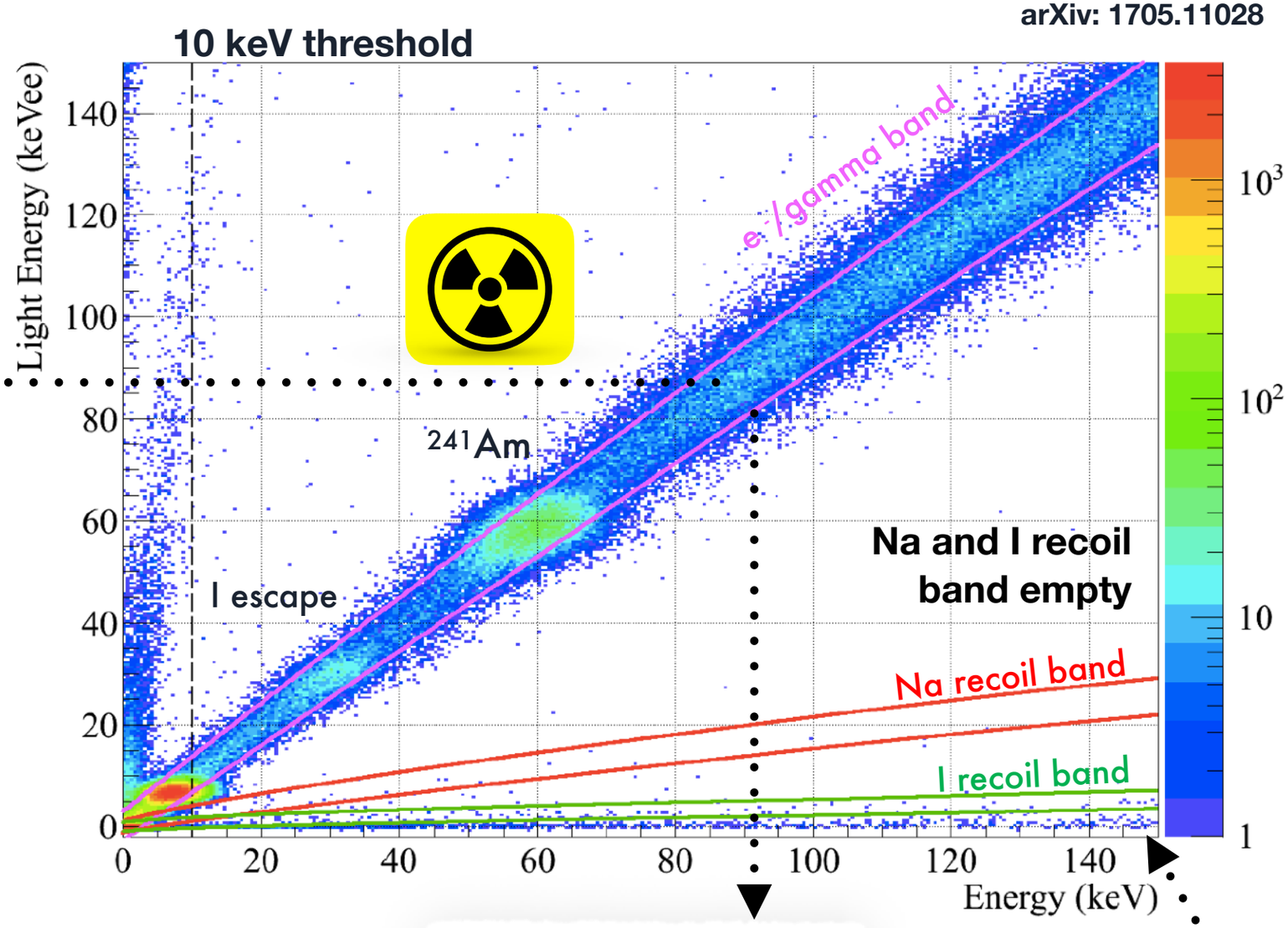
Construction and operation of first detector module for cryogenic operation

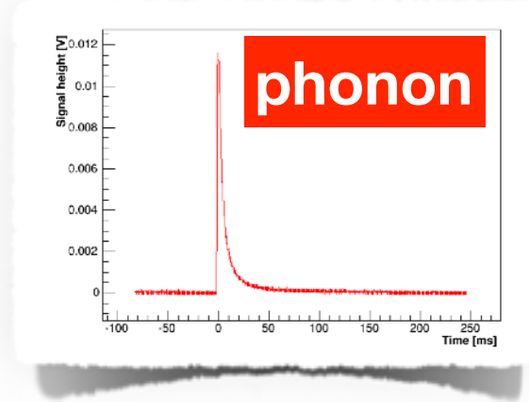
arXiv:1705:11028

NaI-crystal - Prototype Performance

arXiv: 1705.11028





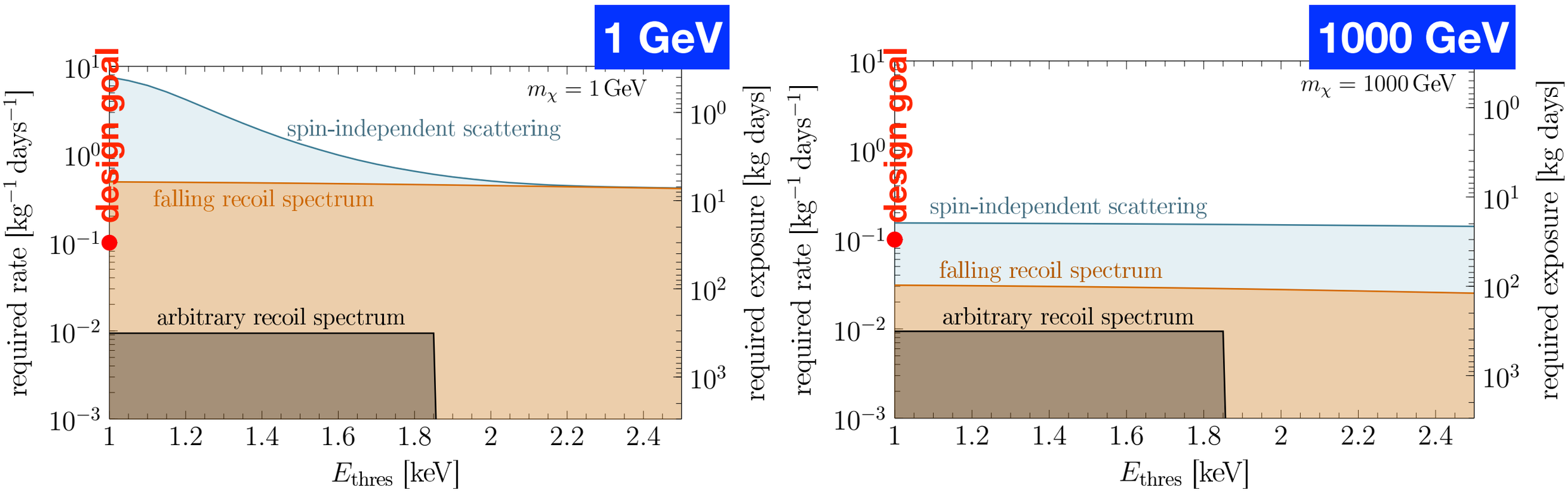


→first successful measurement of NaI crystal as cryogenic detector

hits of the $CdWO_4$ carrier

arxiv 1802.10175

Required Sensitivity for COSINUS



- relate rate from annual modulation with total rate for dark matter-nucleus scattering → **requirement on exposure**

- need to be sensitive to a rate of **0.01 / (kg day)** in order to exclude dark matter interpretation of DAMA / LIBRA

Towards even lighter Dark Matter mass scales

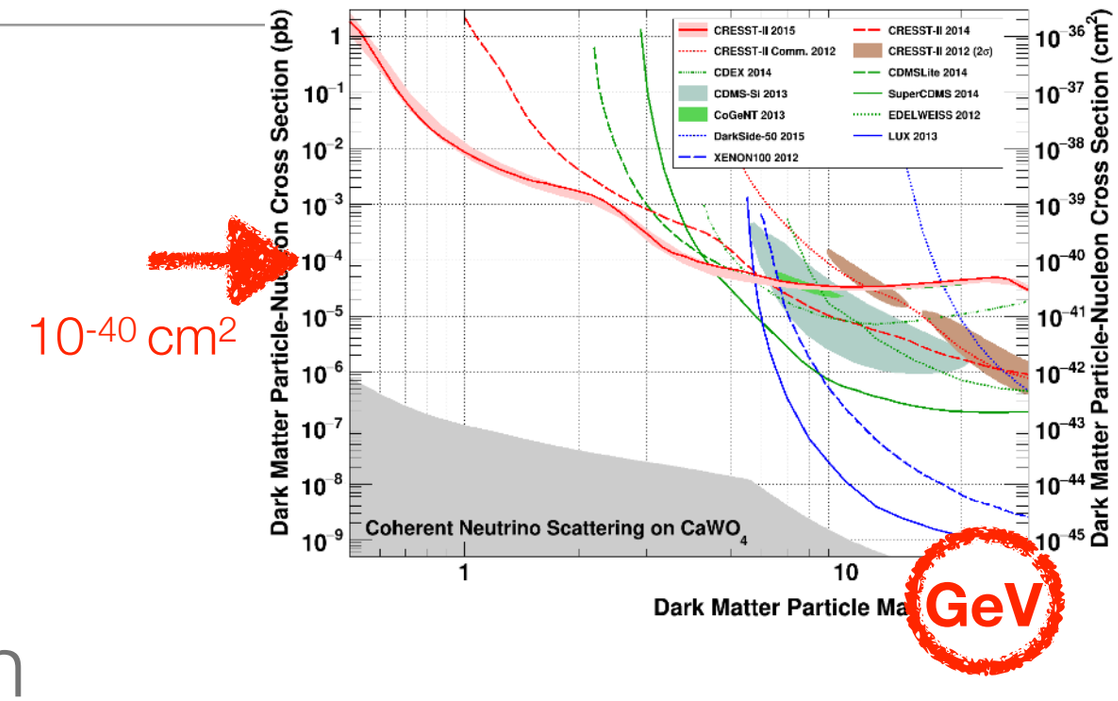
Physics of the Dark Sector

- new forces / new mediators relax the theoretical lower bound on dark matter masses
  → **sub-GeV dark matter**

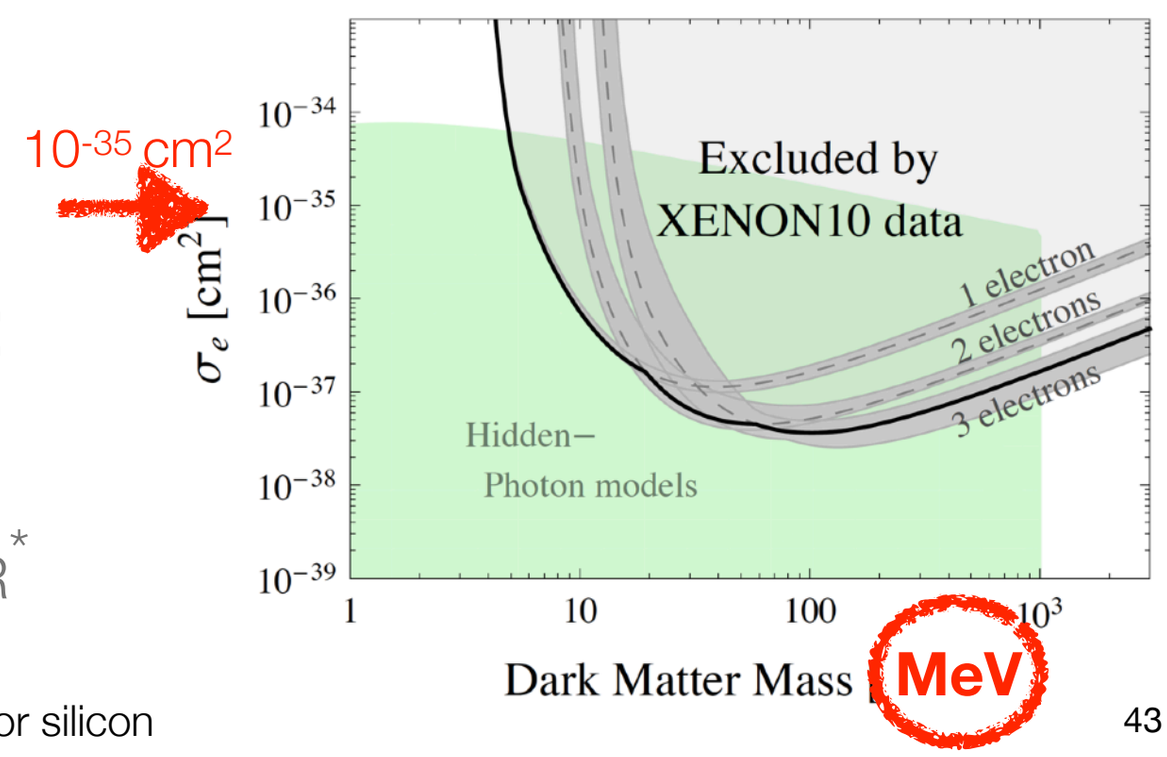
- dark matter searches based on dark matter nucleon **elastic scattering**

- energy deposition from recoil:
  $E_{NR} \simeq 2\mu_{X,N}^2 \cdot v_X^2/m_N$
  → for 100 MeV $m_X \sim 1$ eV E_{NR}*

arXiv:1509.01515



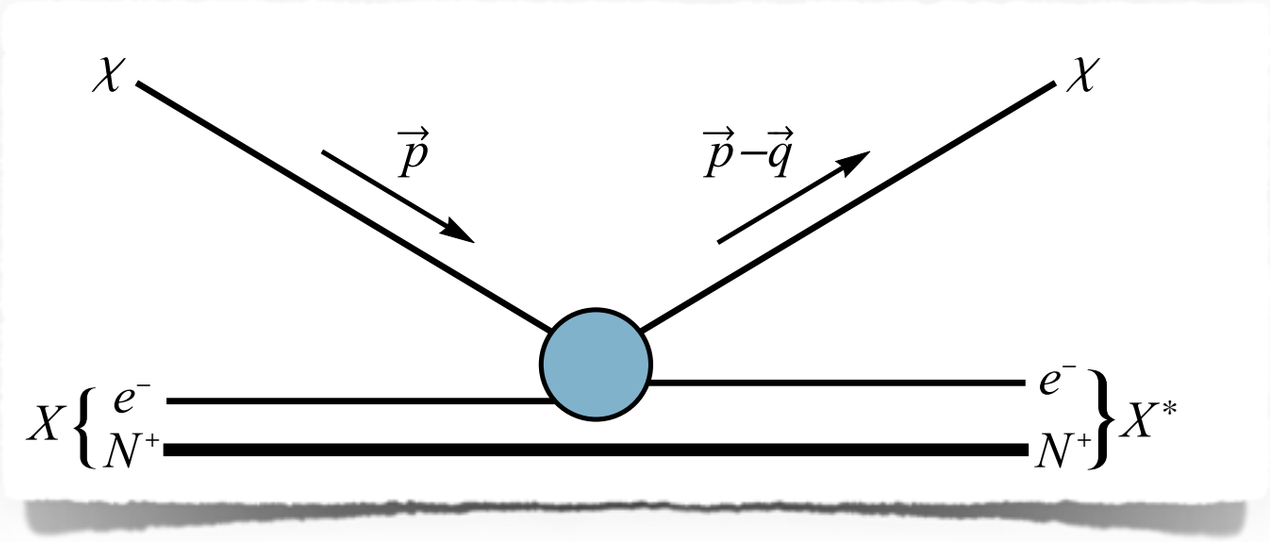
arXiv:1206.2644



* for silicon

Detection techniques for light Dark Matter

- dark matter detection using ionisation signal from **Dark Matter-electron** scattering

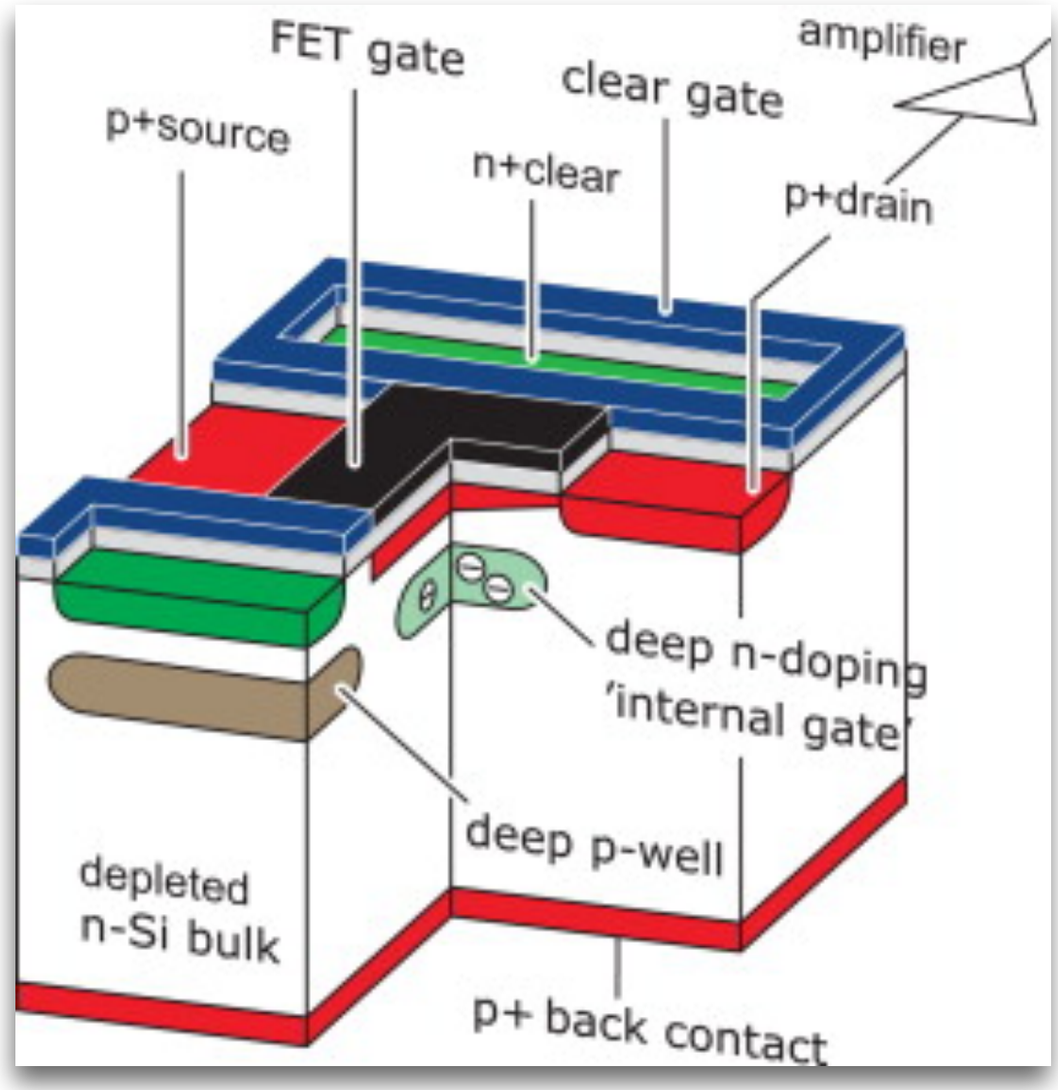


- inelastic nature of scattering and increased energy transfer possible due to lightness of electron

- detection of small ionisation signals allow to probe Dark Matter particles down to ~ 1 MeV

DEPFET detector as sub-GeV Dark Matter detector

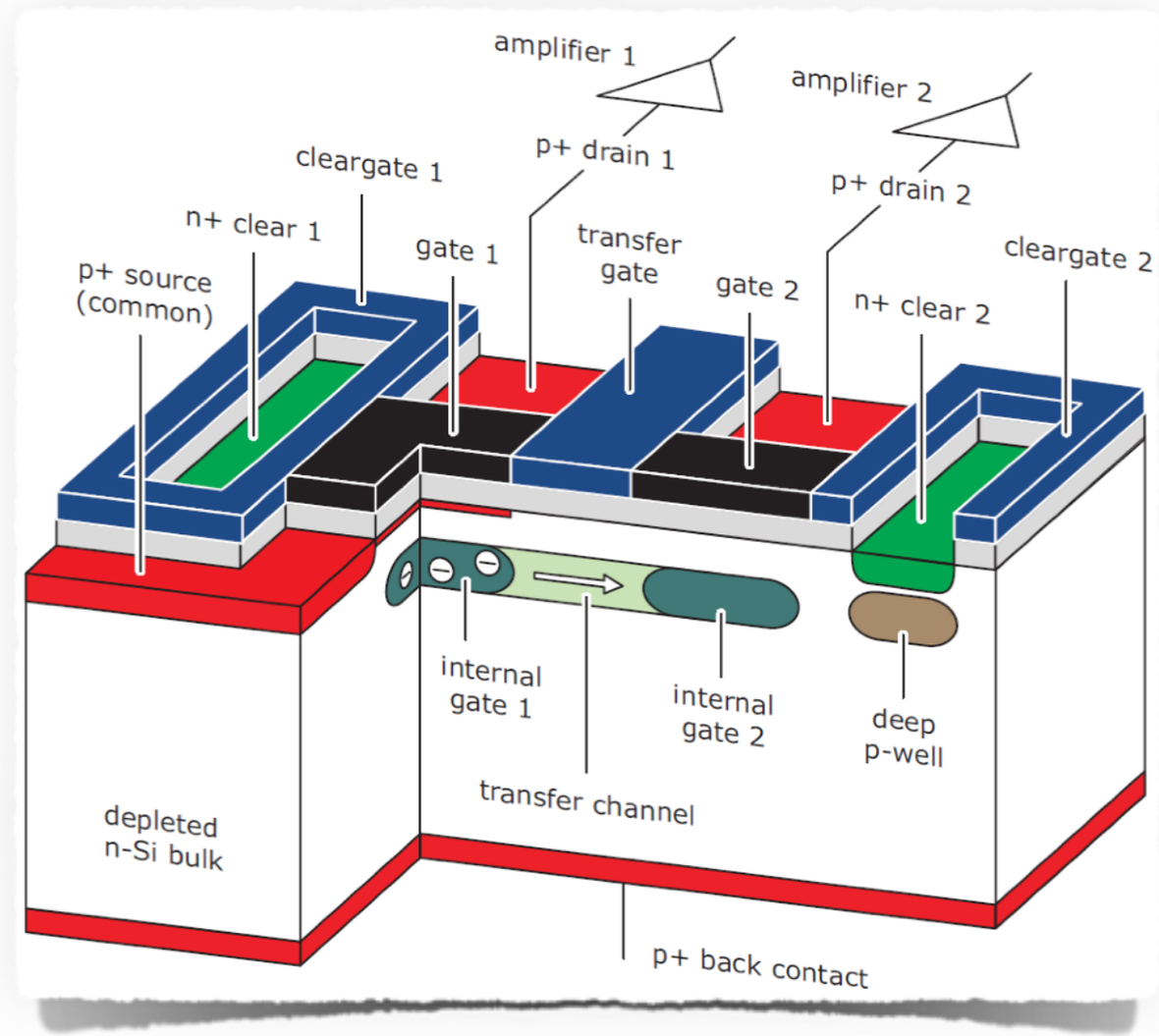
- DEPFET: depleted field effect detector
  - charge collection in an internal gate
  - collected charge modulates current in FET
- known and applied detector concept, e.g. for Belle II
  - focus previously on energy measurement and spatial resolution
- **noise performance limited by 1/f noise**



Eur.Phys.J. C77 (2017) no.12, 905

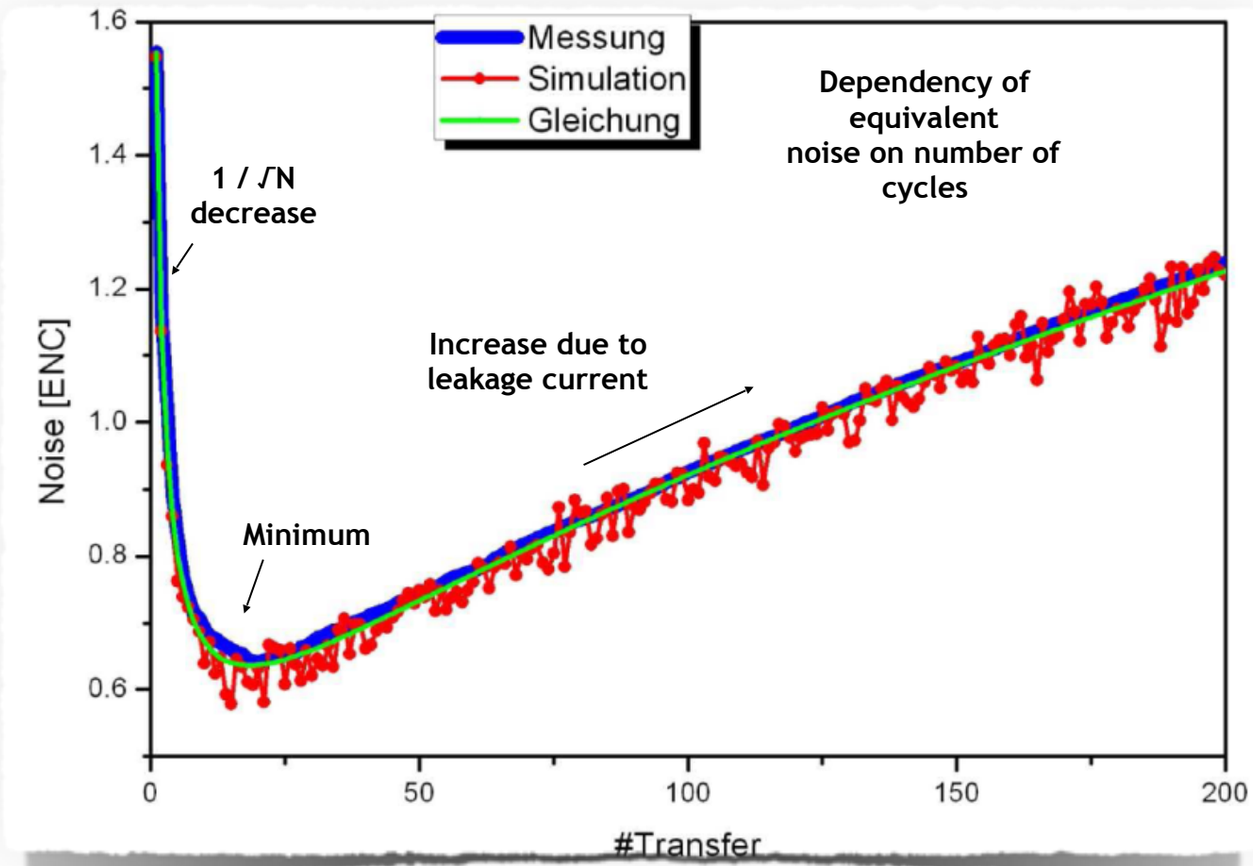
DEPFET detector as sub-GeV Dark Matter detector

- 1/f noise limit can be further reduced by using repetitive non-destructive readout (RNDR)
- charge transfer between sub-pixels in a “super-pixel” allow statistically independent measurements
- **effective noise can be reduced to $\sigma_{eff} \approx \sigma/\sqrt{N}$**

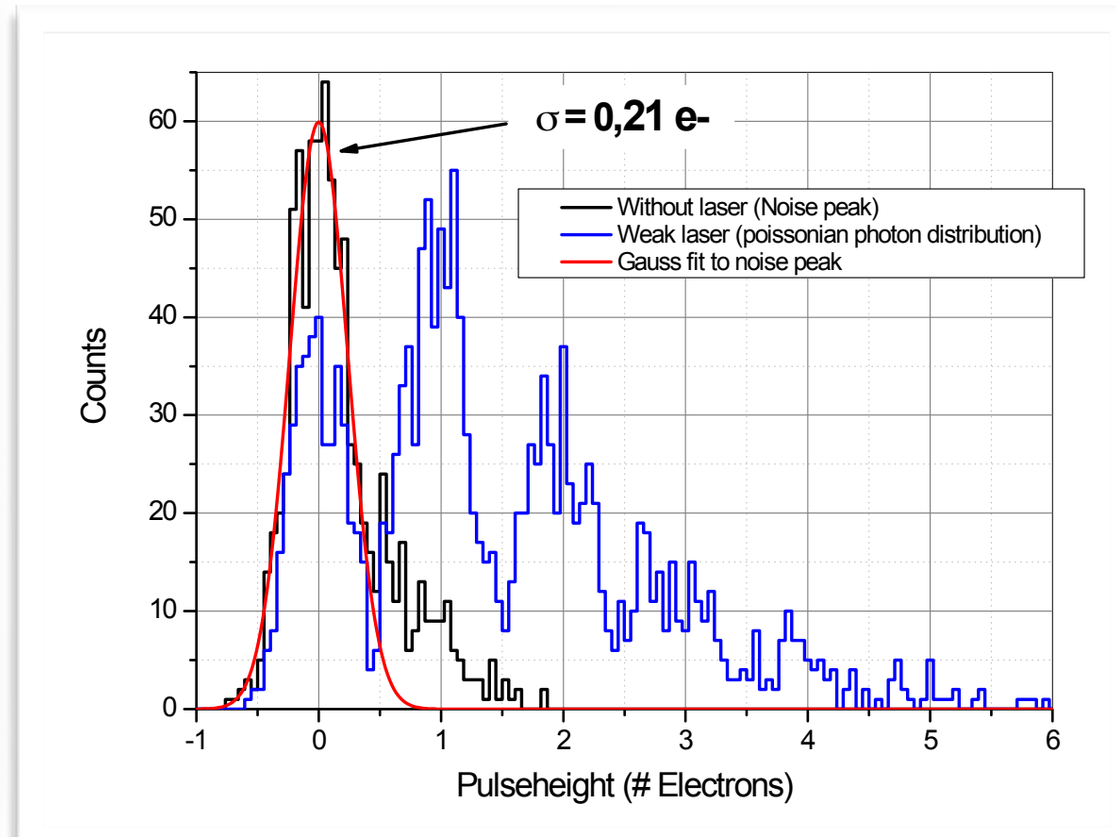


Measured Performance of DEPFET-RNDR

J. Treis, HLL



J. Treis, HLL

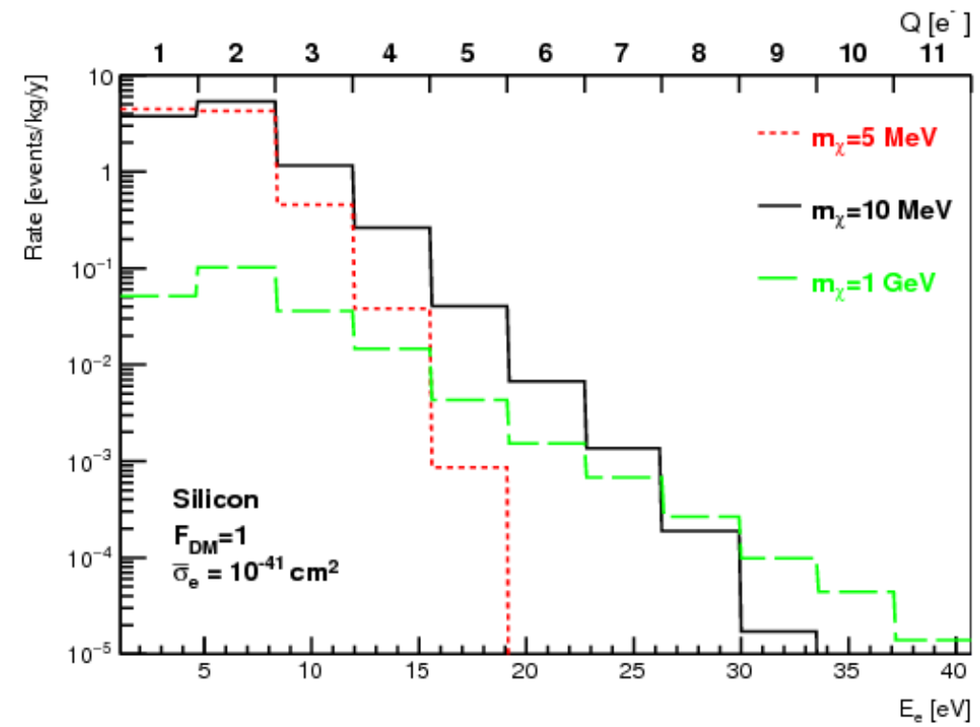


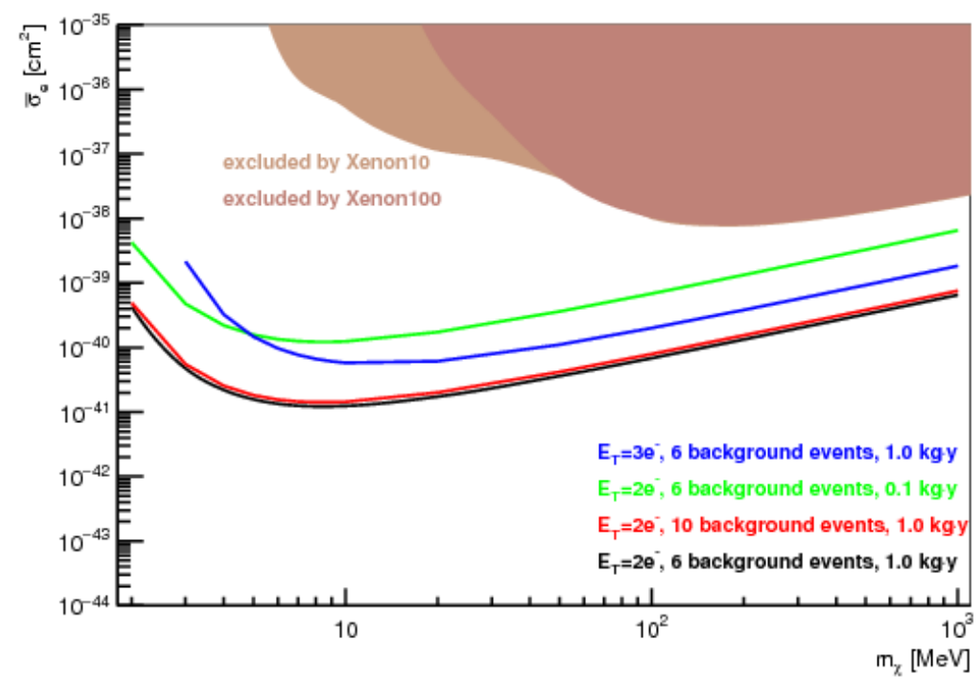
- noise performance as a function of readout cycles measured and reproduced by simulation

- **noise performance of σ=0,21 e^- achieved**

Dark Matter studies using RNDR DEPFET

- common R&D project between semiconductor laboratory of Max Planck Society and HEPHY
- ongoing study with a 64x64 pixel test device
- understanding and reduction of dark current essential
- first measurements expected by early 2019





Eur.Phys.J. C77 (2017) no.12, 905

Summary and Outlook

- CRESST operates $CaWO_4$ crystals at cryogenic temperatures to search for low mass dark matter particles - threshold of 30 eV reached
- excellent sensitivity to low energy nuclear recoils provide the best sensitivity for dark matter particles < 1.7 GeV/c^2
- Xenon1T provides best limit for dark matter > 6 GeV/c^2
- (region between 1.7 and 6 GeV/c^2 covered by DarkSide (formerly CDMS))
- several projects underway to perform independent measurement of DAMA/LIBRA observation → COSINUS
- new detector developments to move towards MeV/c^2 dark matter

additional information

Results from a gram-scale cryogenic calorimeter

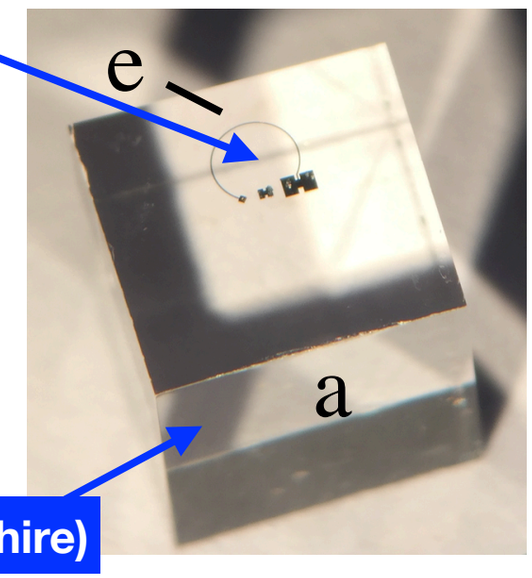
Results from gram-scale cryogenic calorimeter

- energy detection threshold $E_{th} \propto M^{2/3}$
- O(1g) detector is expected to reach 10 eV threshold
- cryogenic operation of detector above ground without significant shielding
- initially planed as a proof-of-principle measurement
- run-time of 0.11 g · days

arXiv 1707.06749 (accepted by EPJC)
and Phys. Rev. D 96 (2017) 022009

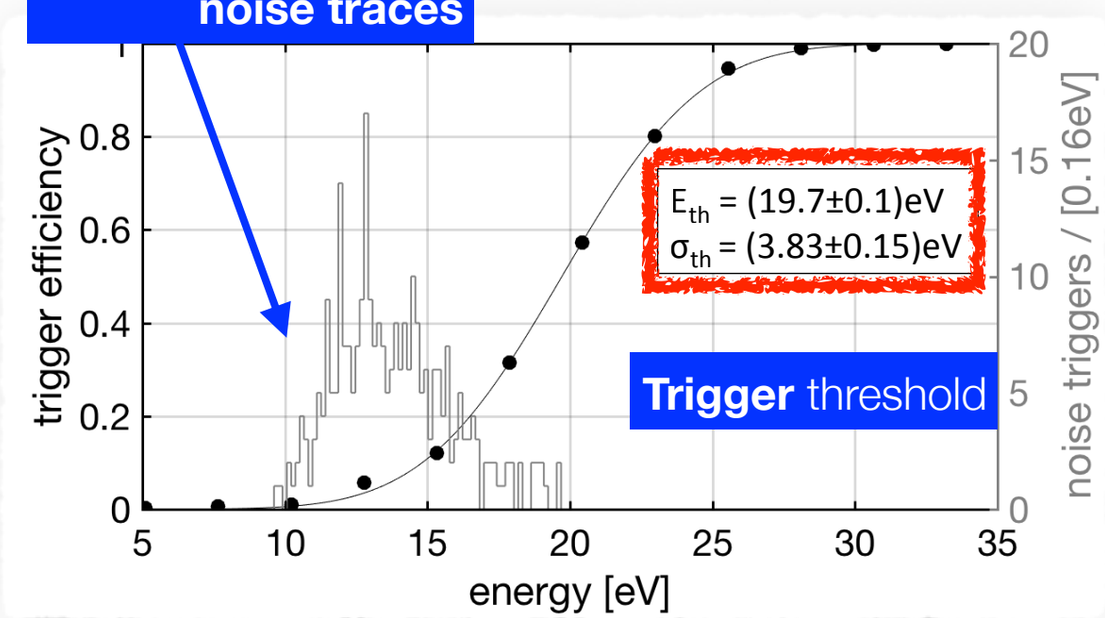
Transition Edge Sensor (TES)

size: 5x5x5 mm³
weight: 0.49 g
TES for phonon readout



Al_2O_3 (Sapphire)

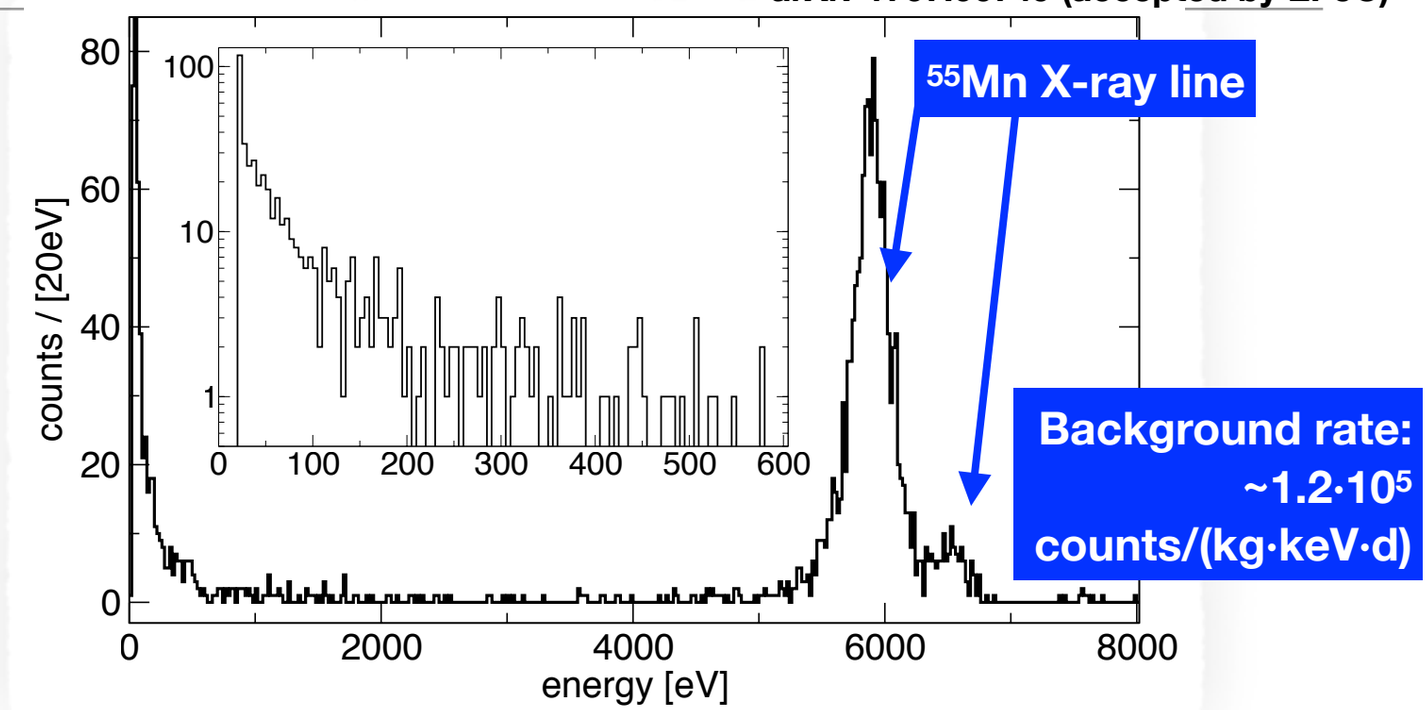
randomly triggered noise traces

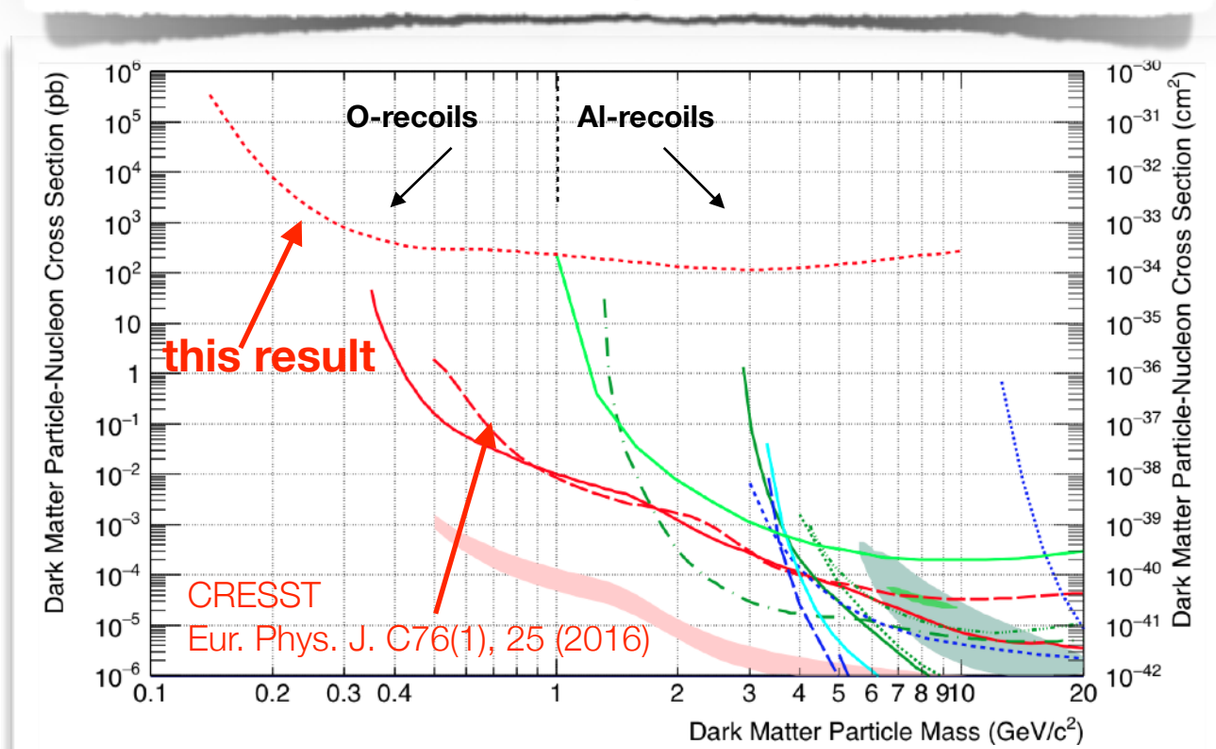


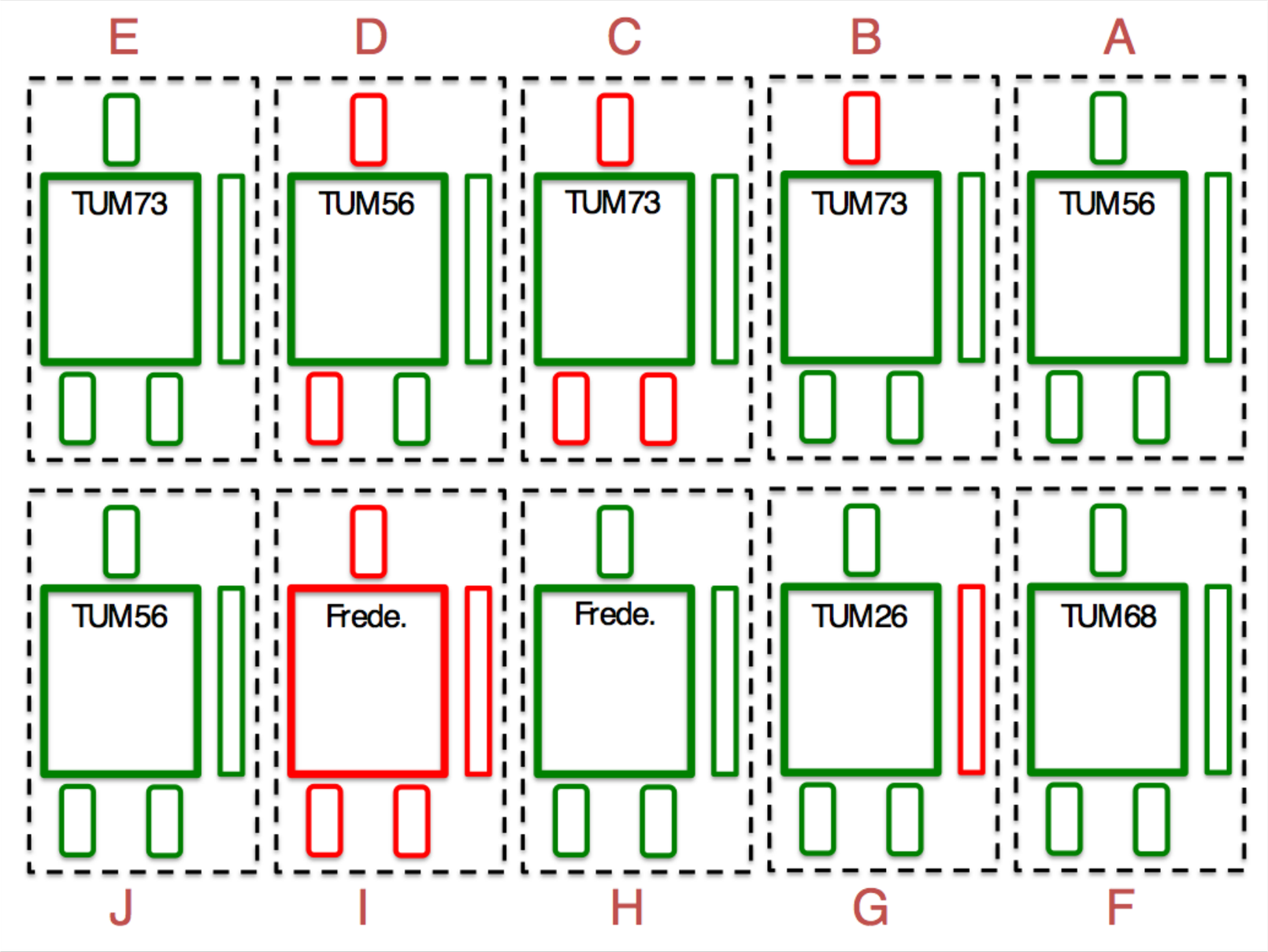
Results from gram-scale cryogenic calorimeter

- improve signal to noise performance by applying optimum filter
- no-data blinding
  → no data quality cuts applied (only stability cuts)
  → most conservative approach
- dark matter limit using standard astrophysical assumptions and Yellin optimal interval method
- **probe elastic dark matter scattering down to 140 MeV/c²**
- see also ν-cleus proposal (Eur.Phys.J. C77 (2017) 506) for application as detector for coherent ν-nucleus scattering

arXiv 1707.06749 (accepted by EPJC)





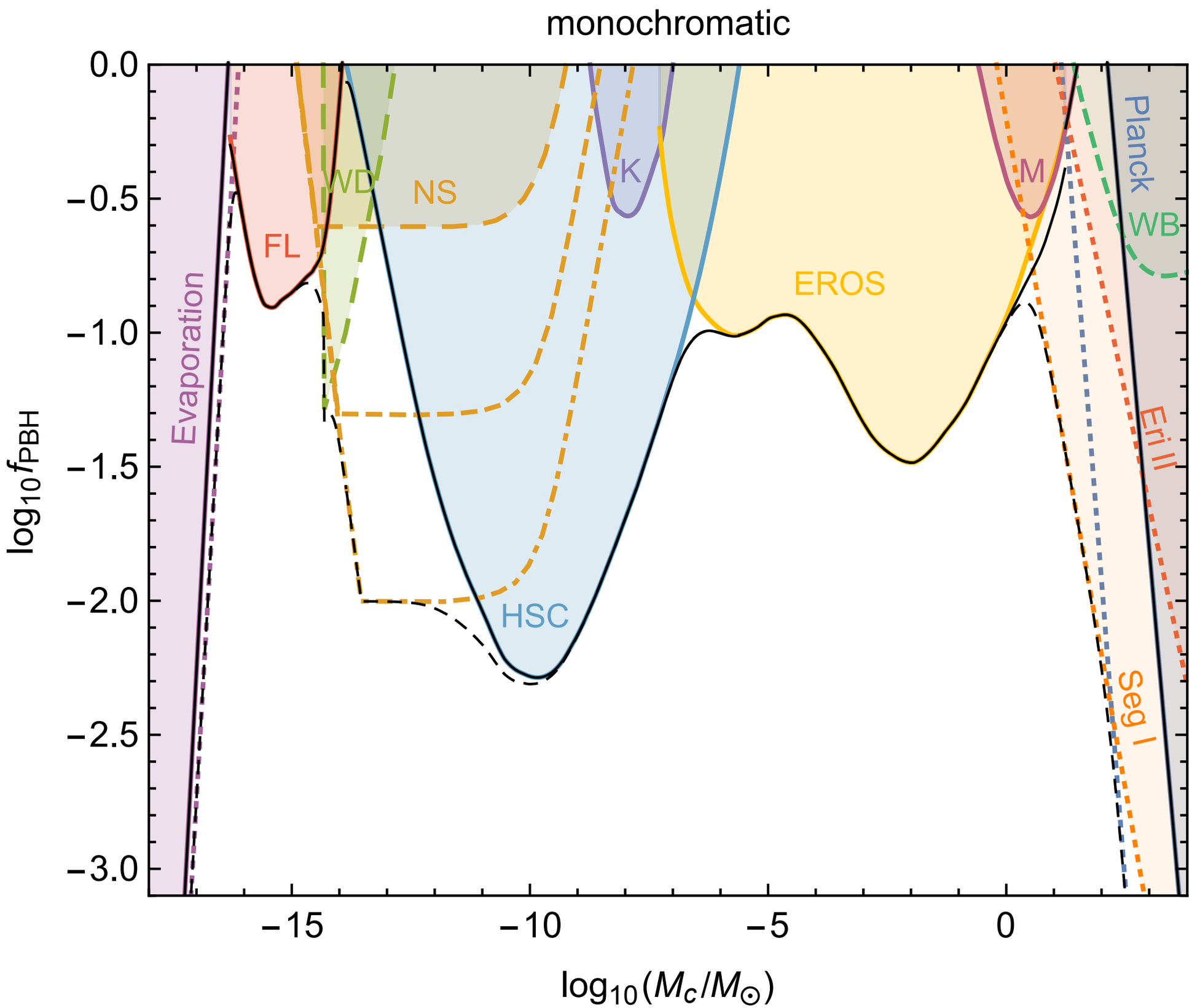


- G-LD: no transition
- I-all: no transitions
- B- one iStick : heater broken cannot be operated
- C and D - iStick system: working, but introduces strong noise on phonon channel

6/50 TES not working (including the 5 of detector I)

- The wiring is >10 years old
- A TES is a sensitive but challenging device

arxiv:1705.05567



Search for Dark Photons

Dark Photons as Dark Matter Candidates

- Dark Matter candidate through U'(1) Standard Model allowed extension → **Dark Photon**
- coupling to the Standard Model U(1) symmetry via kinetic mixing term κ
  - $\mathscr{L}=\mathscr{L}_{SM}-\frac{1}{4}V_{\mu\nu}^2-\kappa/2\, F_{\mu\nu}V^{\mu\nu}+m_V^2/2\, V_\mu V^\mu$
- relic abundance of dark photons from inflationary perturbations can account for Dark Matter relic density
  - $\Omega_V \approx 0.3 \sqrt{(m_V/1\ \text{keV})}\ (H_{inf}/10^{12}\ \text{GeV})^2$

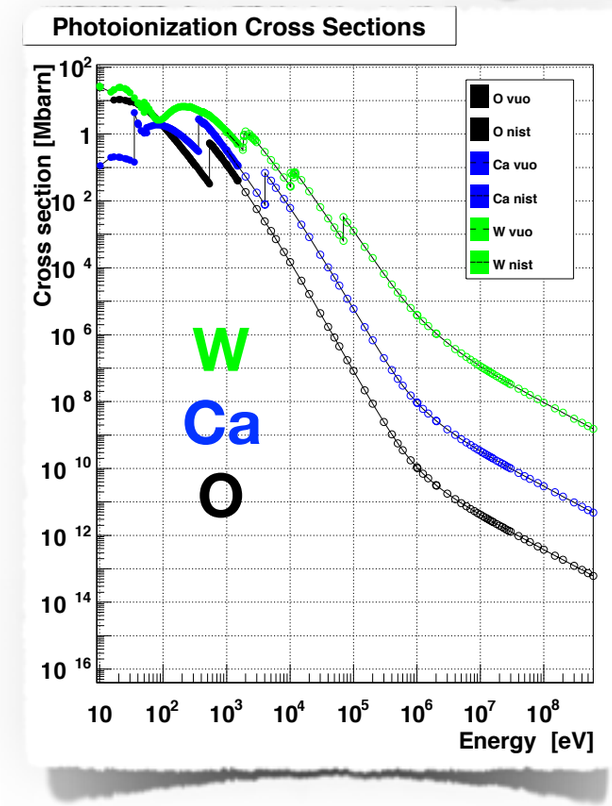
arXiv:1504.02102

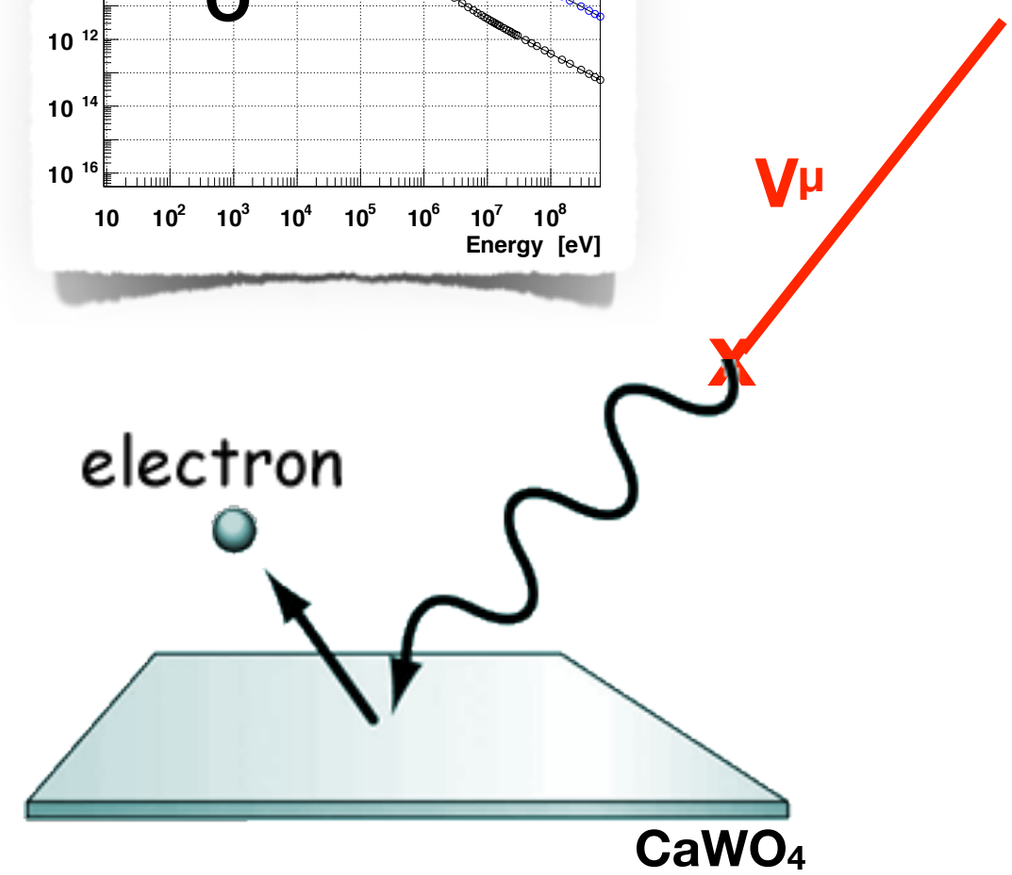
H_{inf}: Hubble scale at inflation

- possible parameter space for kinematic mixing term κ experimentally not excluded

Detection Principle of Dark Photons

- dark photons couple with $\epsilon\kappa$ to charged particles
  - ‘photoelectric effect’ leads to deposition of total energy in the crystal
    - **total absorption - no elastic scattering!**
- expected cross-section for Dark Photons: $\sigma_V(E_V=m_V)v_V \simeq \kappa^2\sigma_\gamma(\omega=m_V)c$
- expected rate per $\simeq$ $\rho_{DM}/m_V c^2 \cdot \kappa^2\sigma_\gamma(\omega=m_V)c$

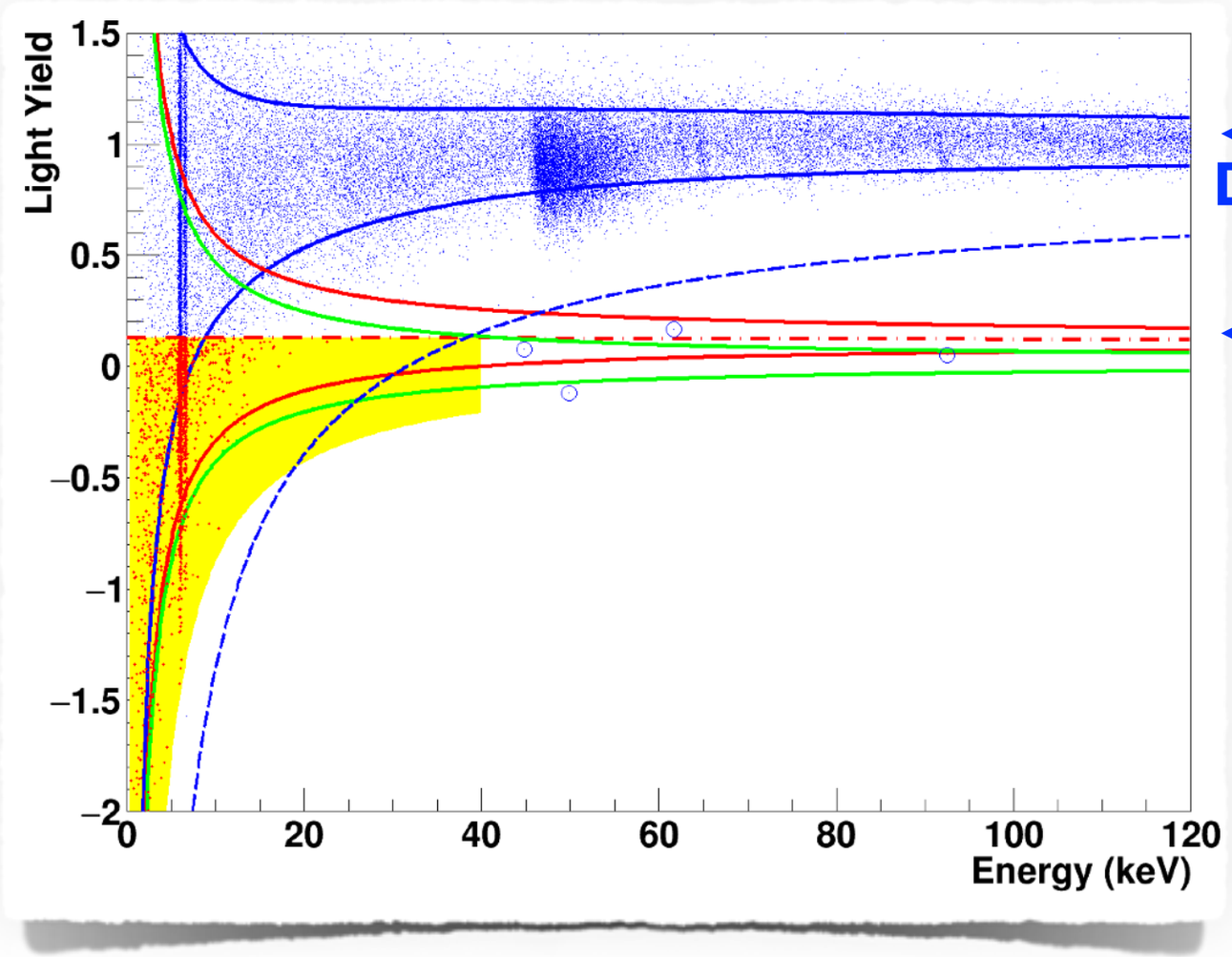




Detection of Dark Photons with CRESST

NEW

- data collected with the Lise detector
  - $E_{thr} \approx 300$ eV
- signal expected in the electron band
- search for mono-energetic peak at dark photon mass

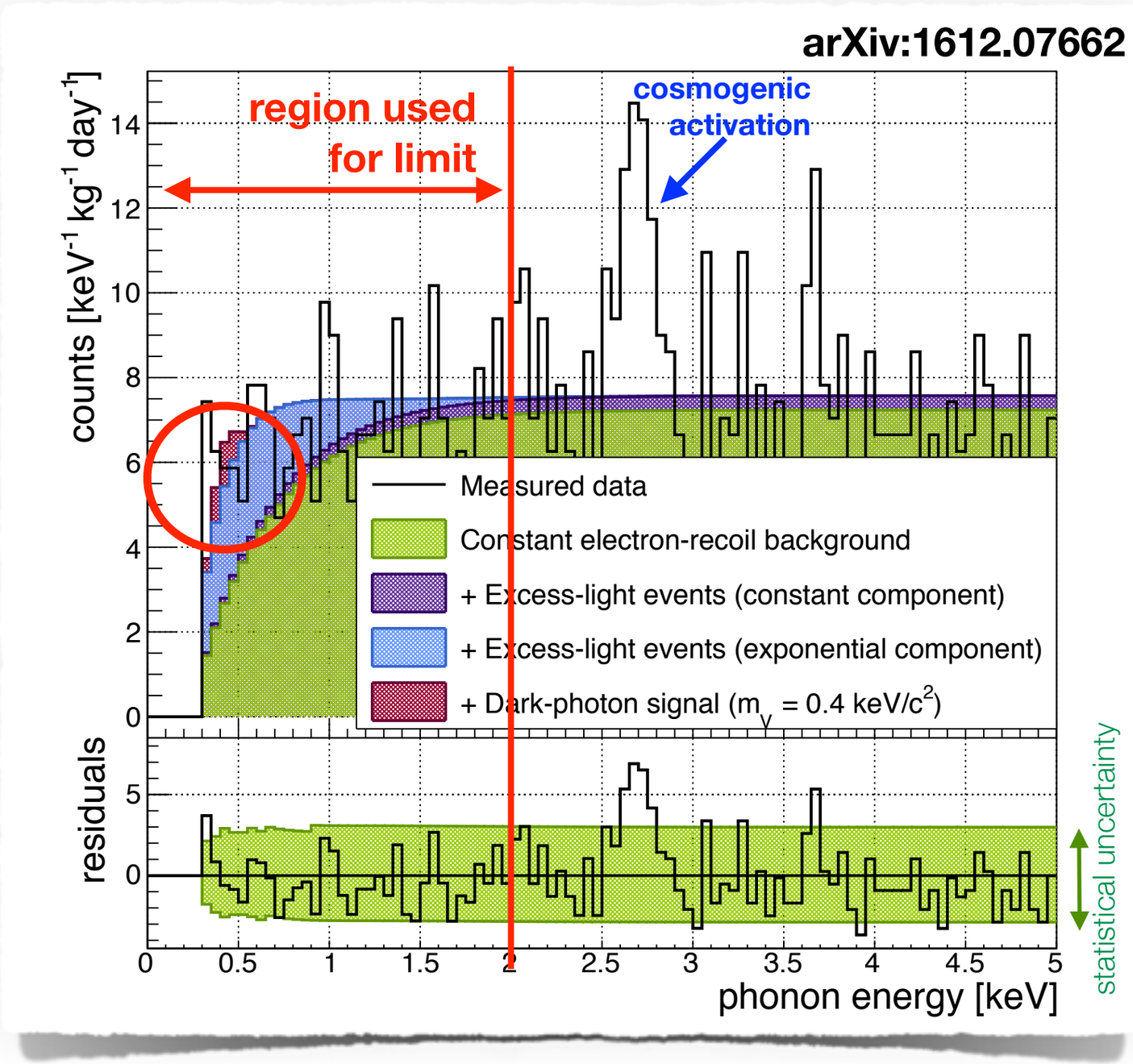


Dark Photons
(photoelectric effect)

Dark Matter
(nuclear recoil)

- focus on dark photons with $m_V < 2$ keV

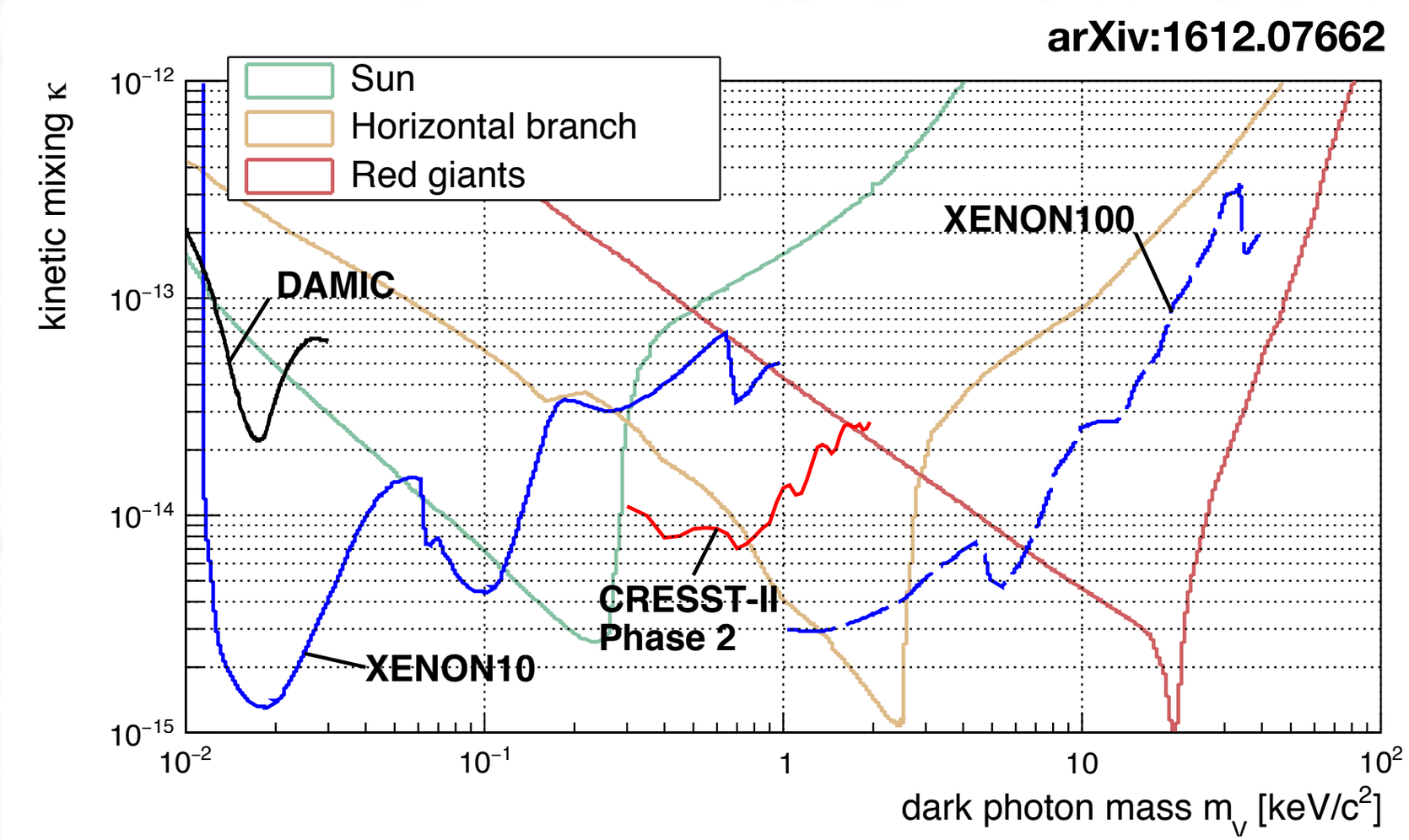
Detection of Dark Photons with CRESST



- empirical background model with several components
  - constant electron recoil background
  - excess-light events (electrons originating from outside detector module
    → light from scintillating foil)
- Dark Photon signal with assuming detector resolution (~60 eV to ~100 eV)

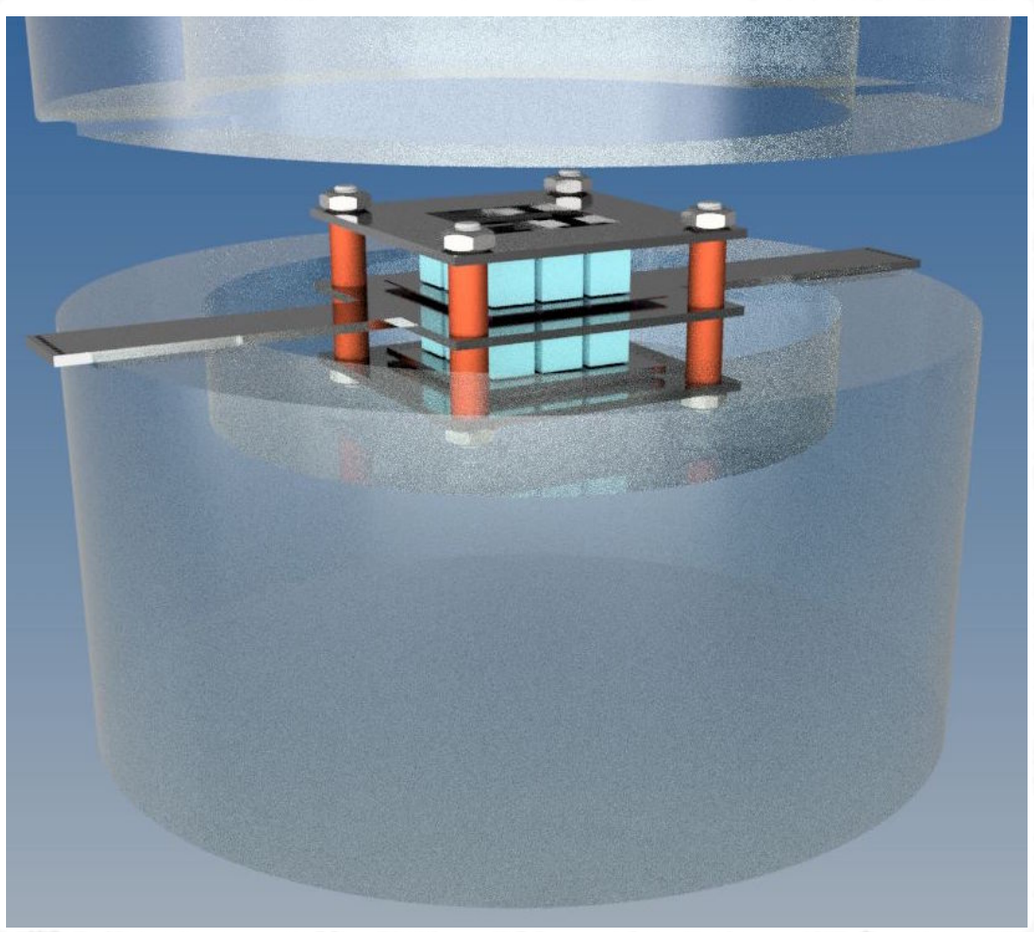
Detection of Dark Photons with CRESST

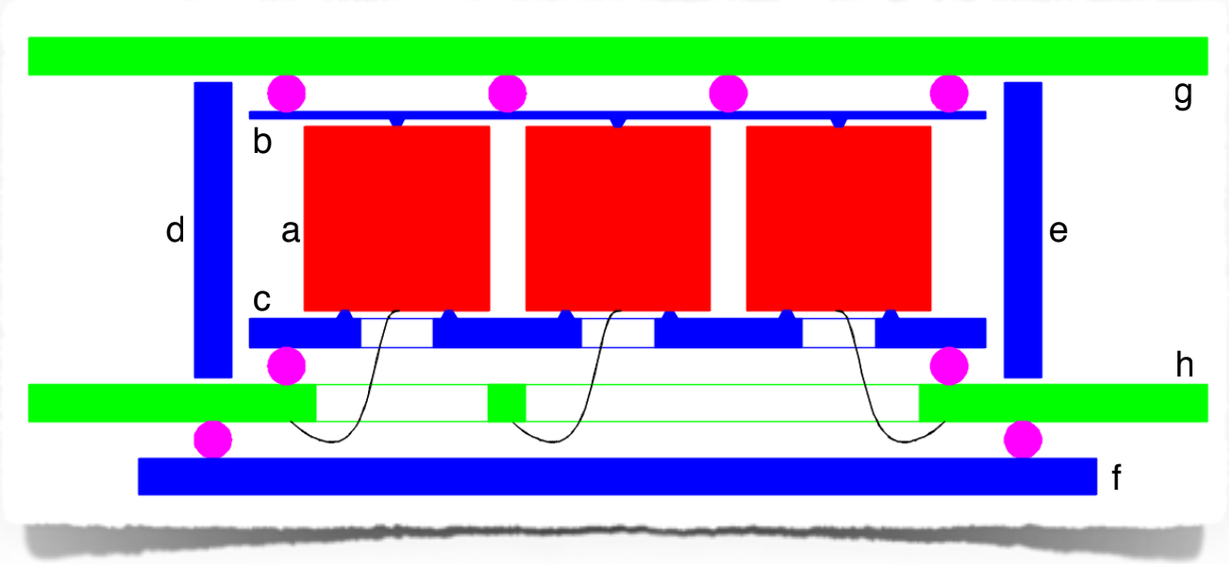
- deposited energy corresponds directly to the Dark Photon mass
- performance determined by background and detector resolution



best limit for Dark Photons between 300 and 800 eV

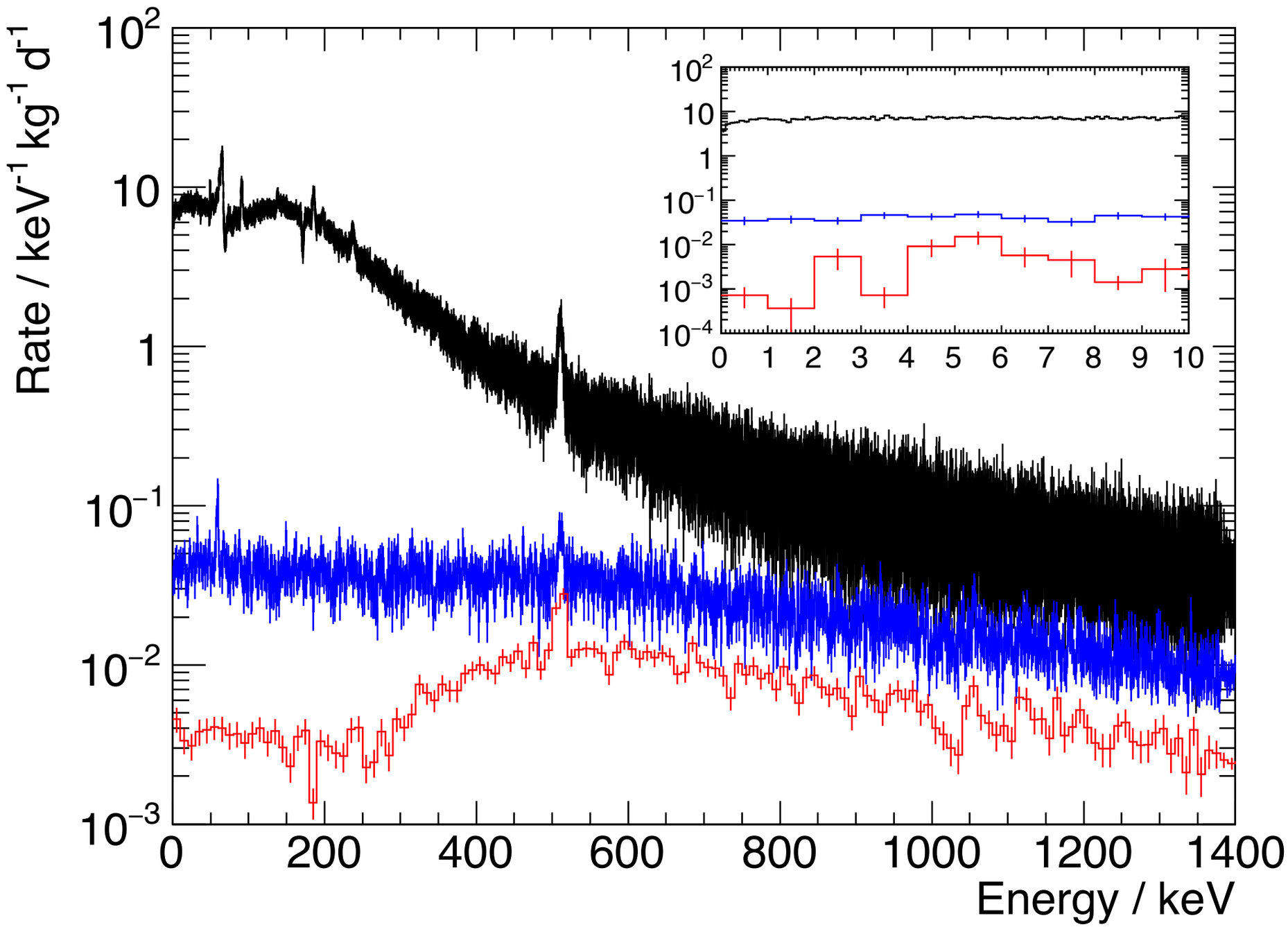
v-cleus





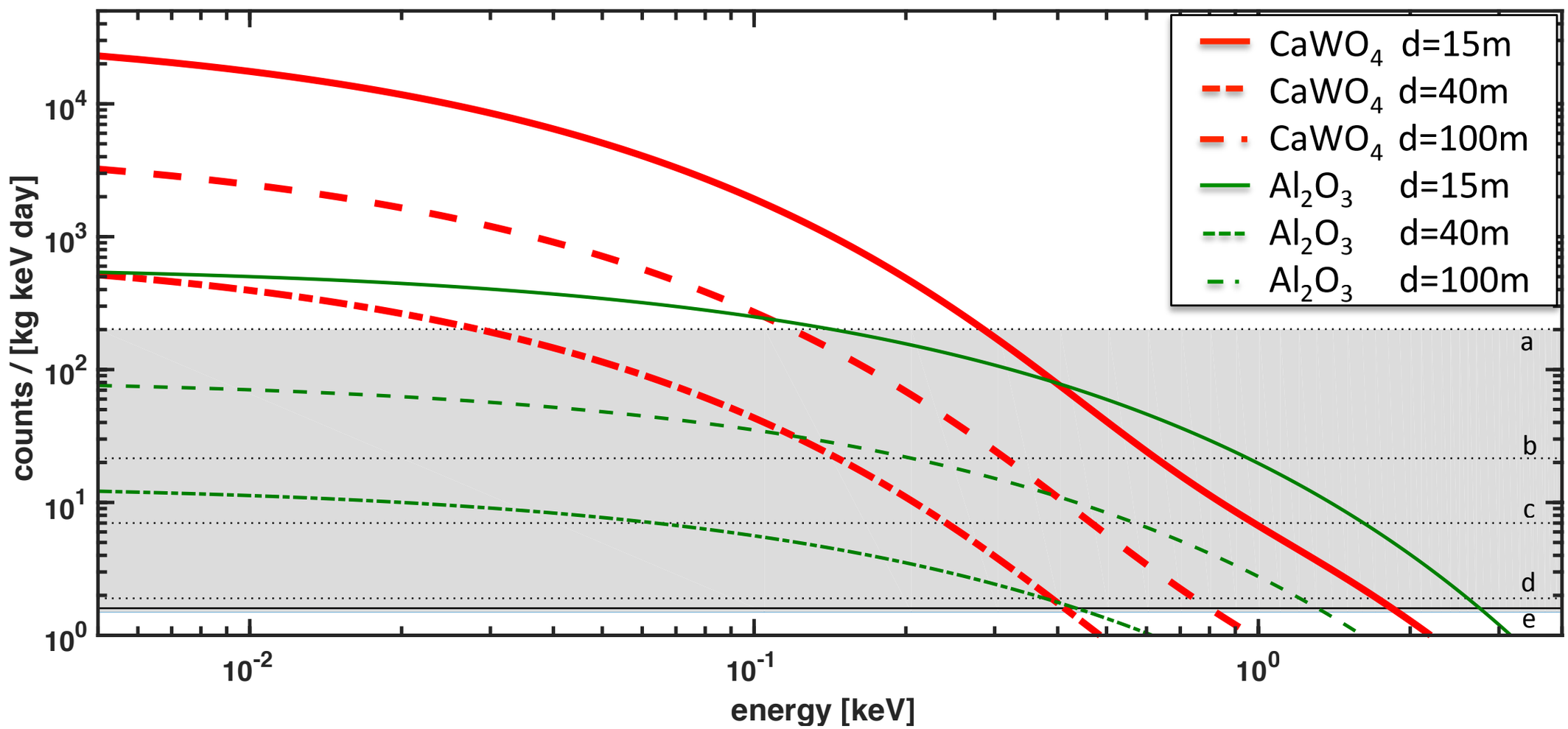
arXiv:1704.04320

ν-cleus



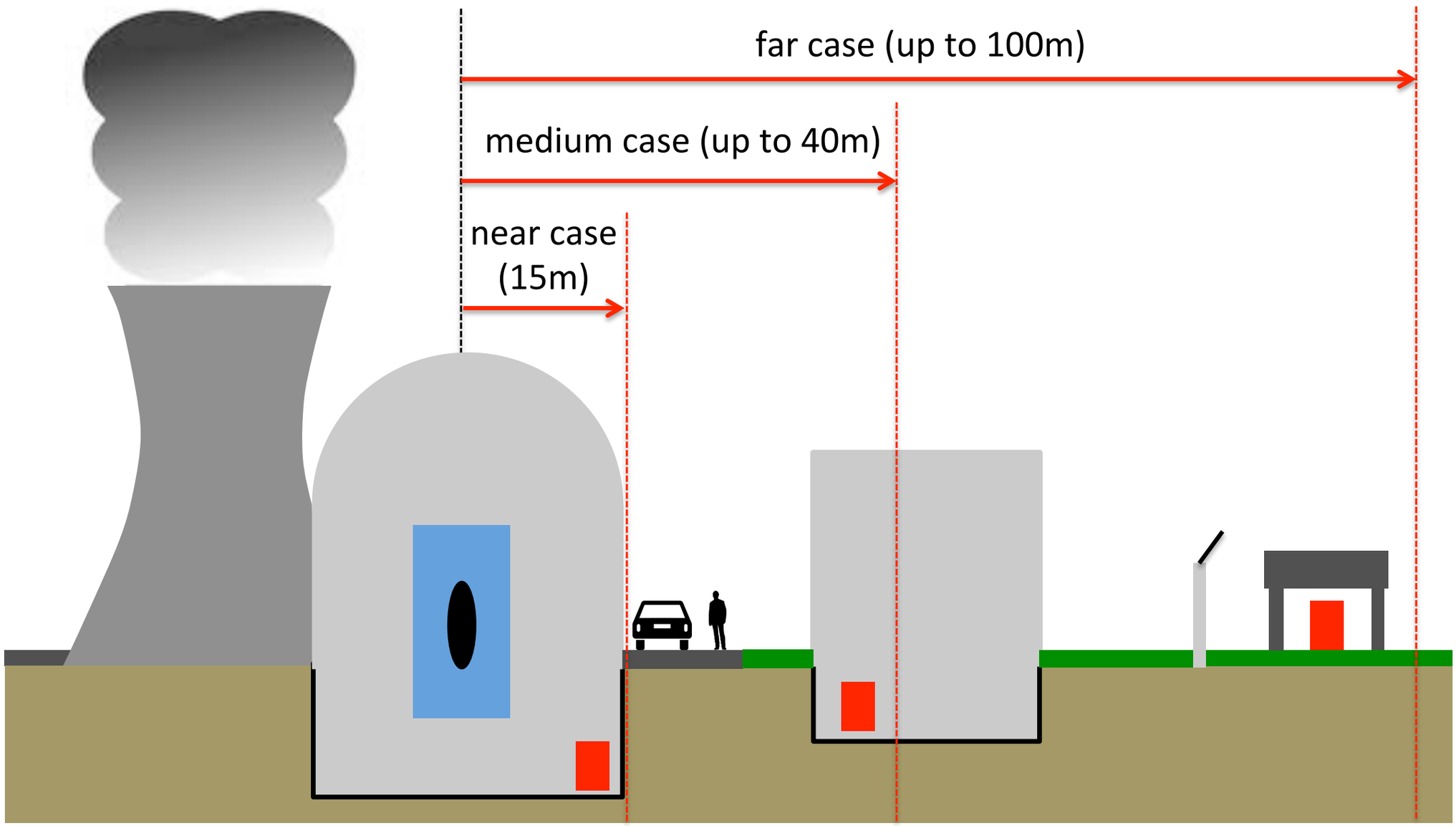
arXiv:1704.04320

ν-cleus



arXiv:1704.04320

v-cleus



arXiv:1704.04320