Search for light Dark Matter with CRESST and DANAE

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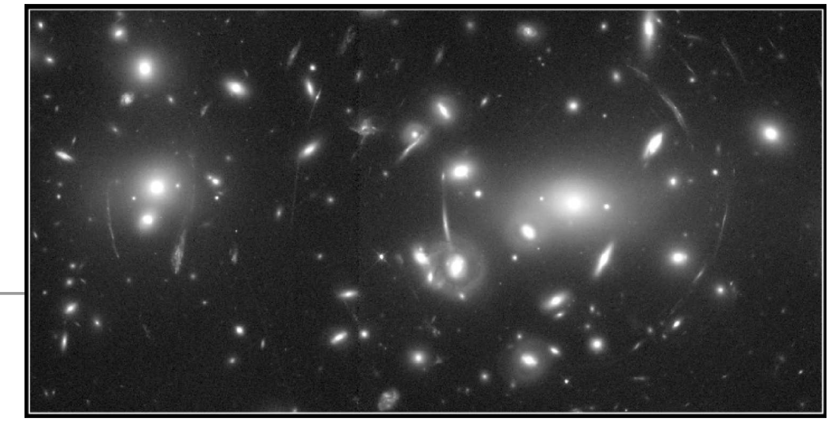
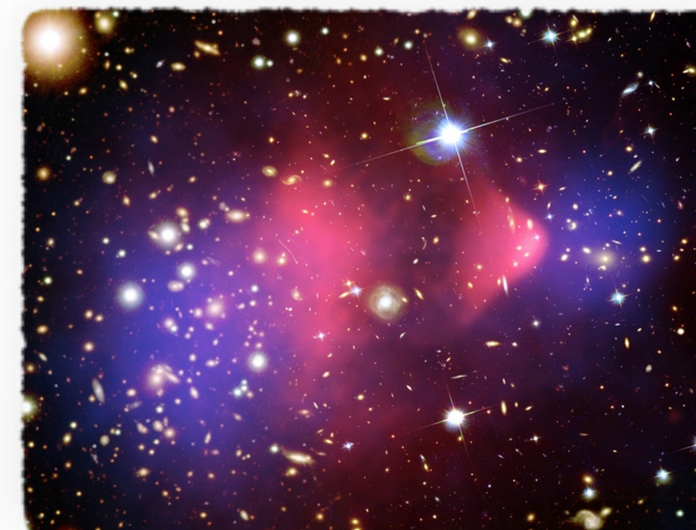
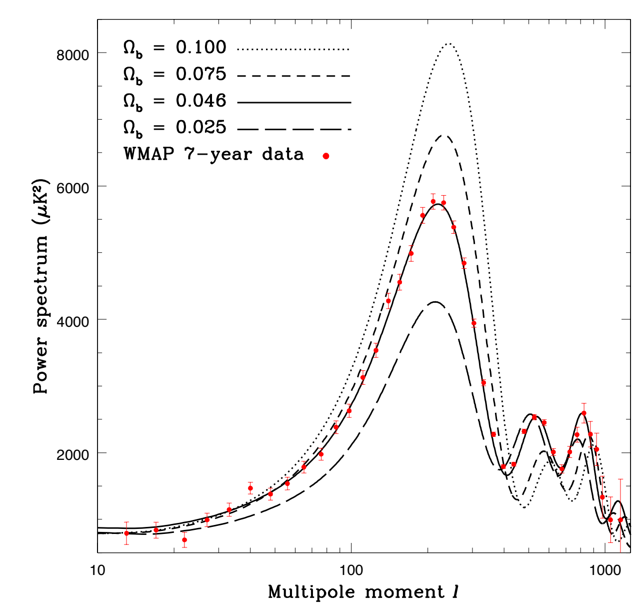
More evidence for Dark Matter



- **rotation curves of galaxies**
  - arms of spiral galaxies rotate faster than anticipated
- **gravitational lensing**
  - light of distant galaxies is bended by gravitational potential
- **temperature fluctuations of microwave background**
  - acoustic oscillations depend on baryonic density
- **bullet cluster**
  - collision-less penetration of two massive galaxies
- **structure formation**
  - observed present-day structure requires Dark Matter

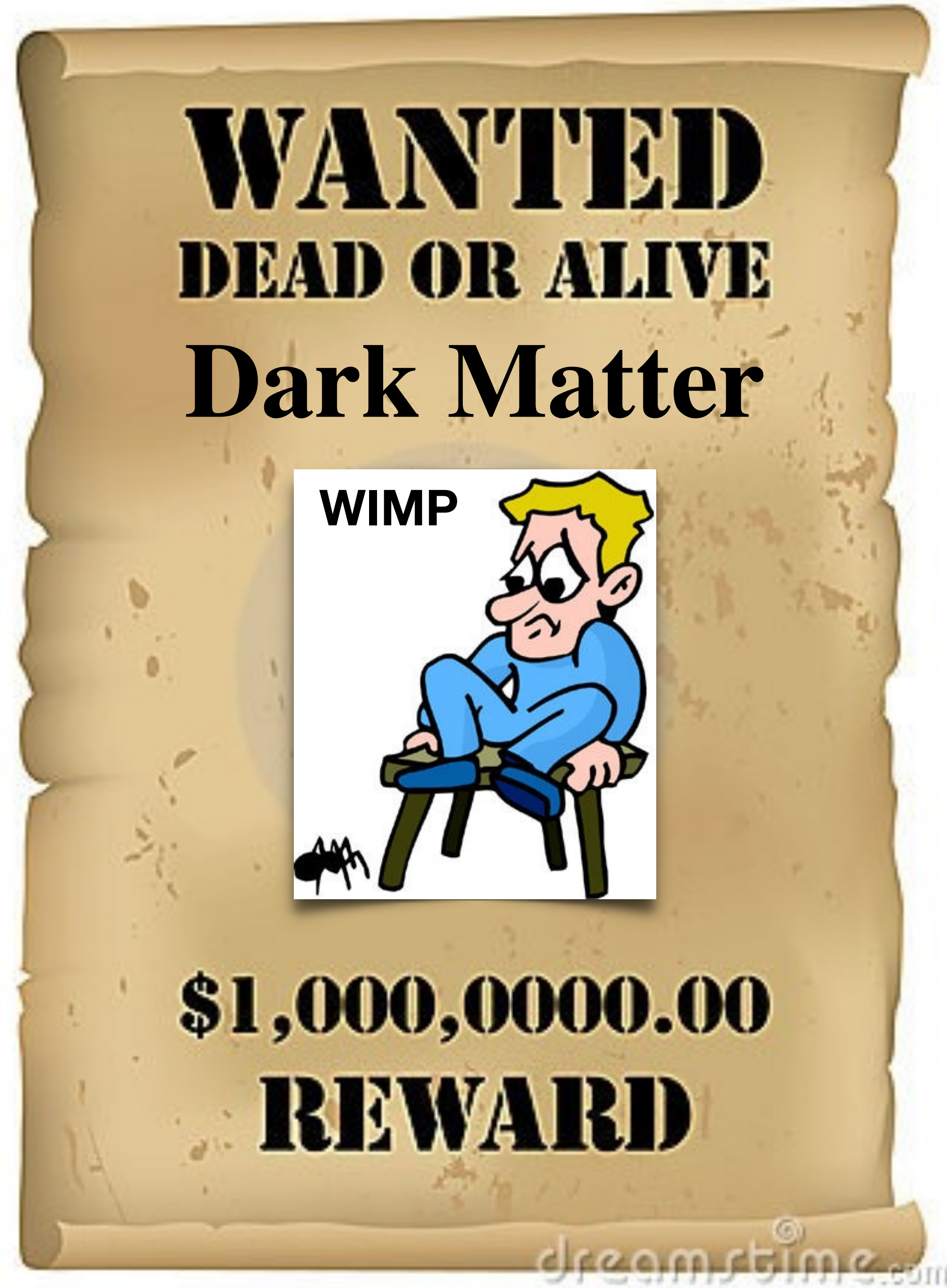




all observations are based on gravitational pull of Dark Matter on visible matter

Profile of a Dark Matter Candidate

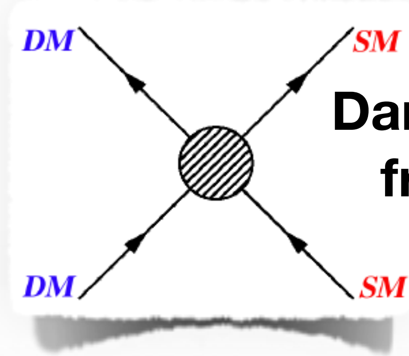
- massive particle
- non-luminous, i.e. electrically neutral
- non-baryonic
- cold, i.e. non-relativistic
- stable with respect to the lifetime of the universe
- only weakly (or less) interacting with ordinary matter



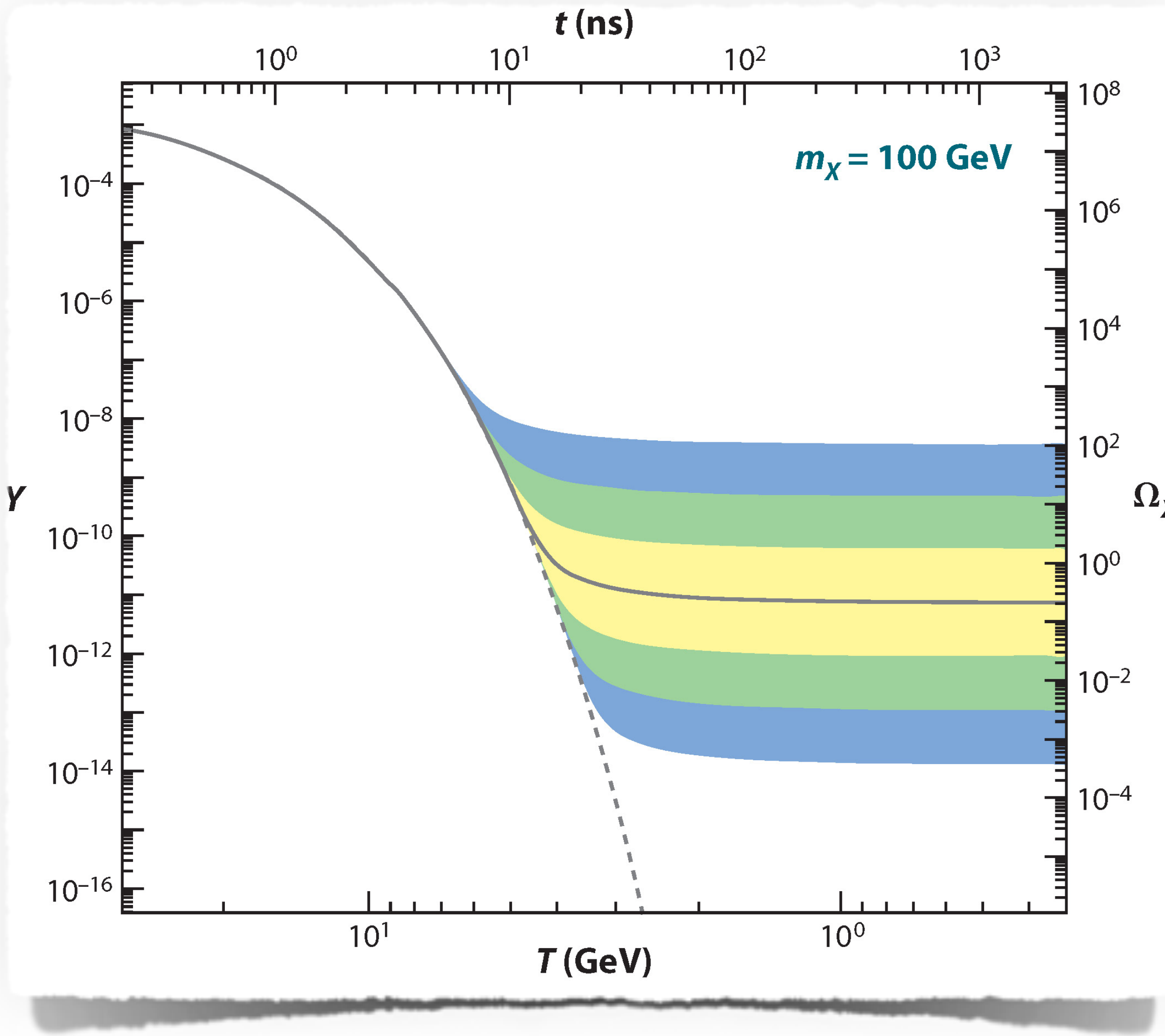
WIMP: weakly interacting massive particle

The best Candidate? The WIMP miracle!

- WIMPs are produced in the early hot phase of the universe
- in thermal equilibrium until universe cools down
- survivors are known as “thermic relics”
- “weak” cross-section and mass scale returns relic density consistent with Dark Matter content
- mass range **~ 2 GeV to 120 TeV**
- **⇒“WIMP miracle”**



Dark Matter freeze out



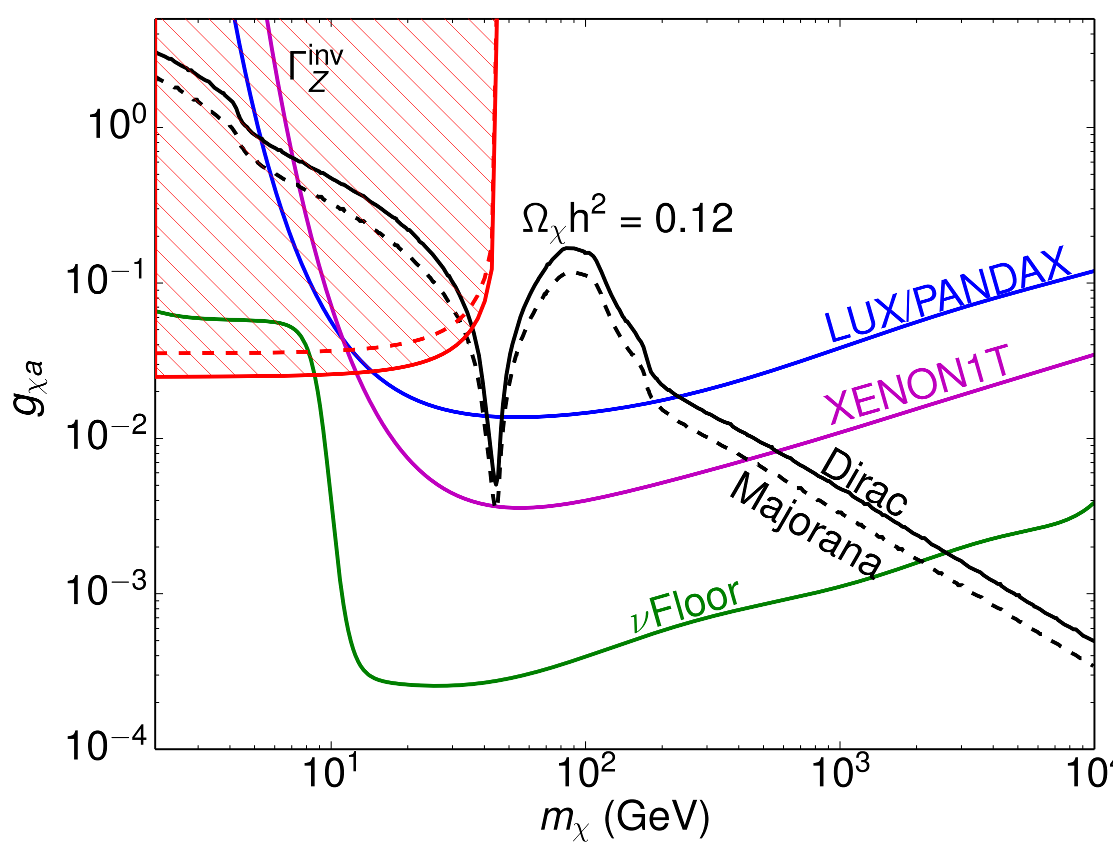
~WIMP density

temperature

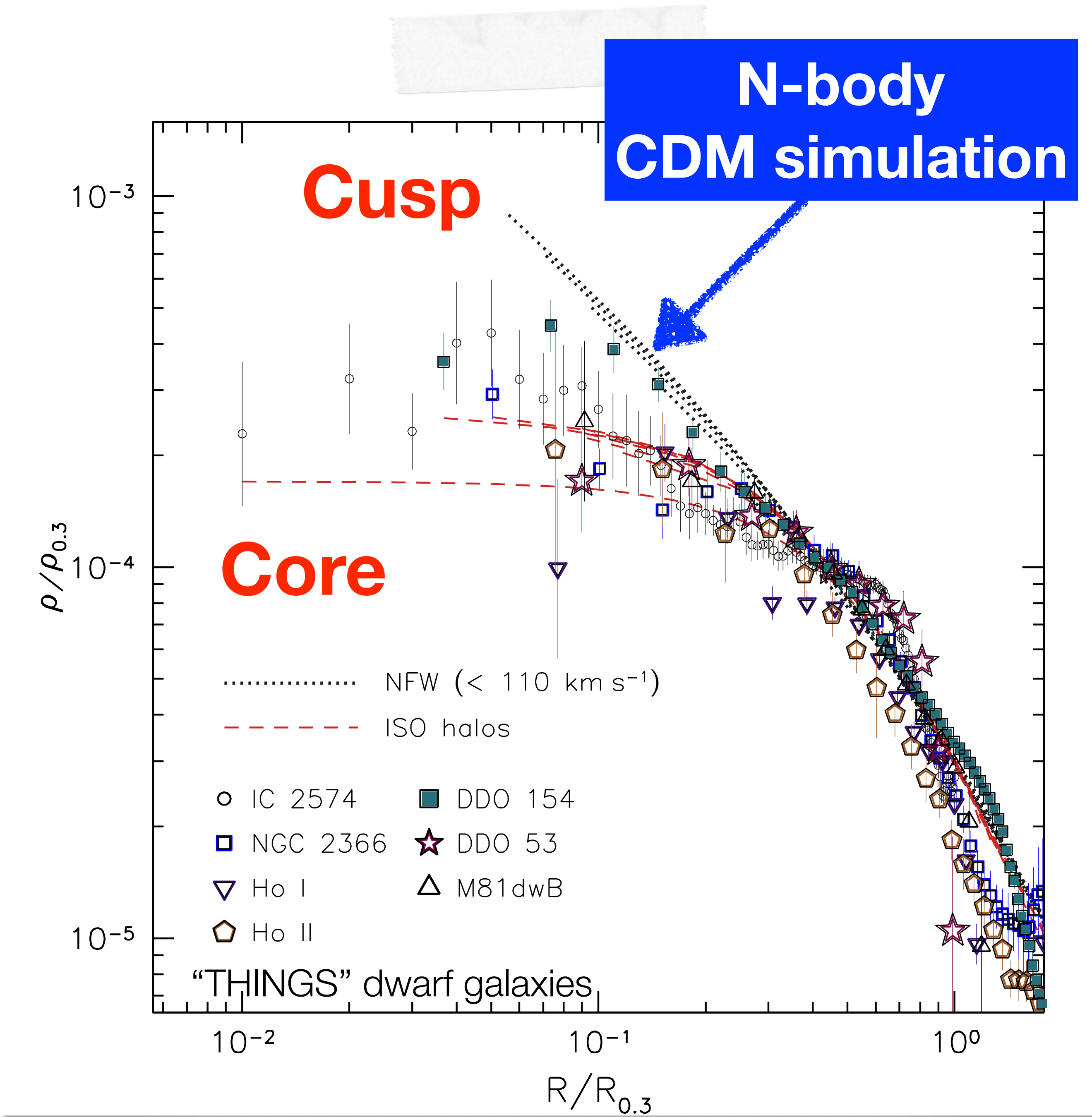
Dark Matter versus Dark Sector

- so-called "WIMP" miracle predicts dark matter WIMP mass between 2 GeV and 120 TeV
    - dark matter particle weakly interacting with matter
      $<\sigma_{WIMP} \cdot v> \sim \mathbf{G_F^2} \cdot m_X^2 \sim 1/\Omega_X$
      → **lower bound** on m_X from prohibiting over-closure of the universe
- coupling to Z and H almost ruled out
- new force coupling matter to dark matter
  → **Dark Sector**

arXiv:1609.09079



Dark Matter - Small Structure Problems

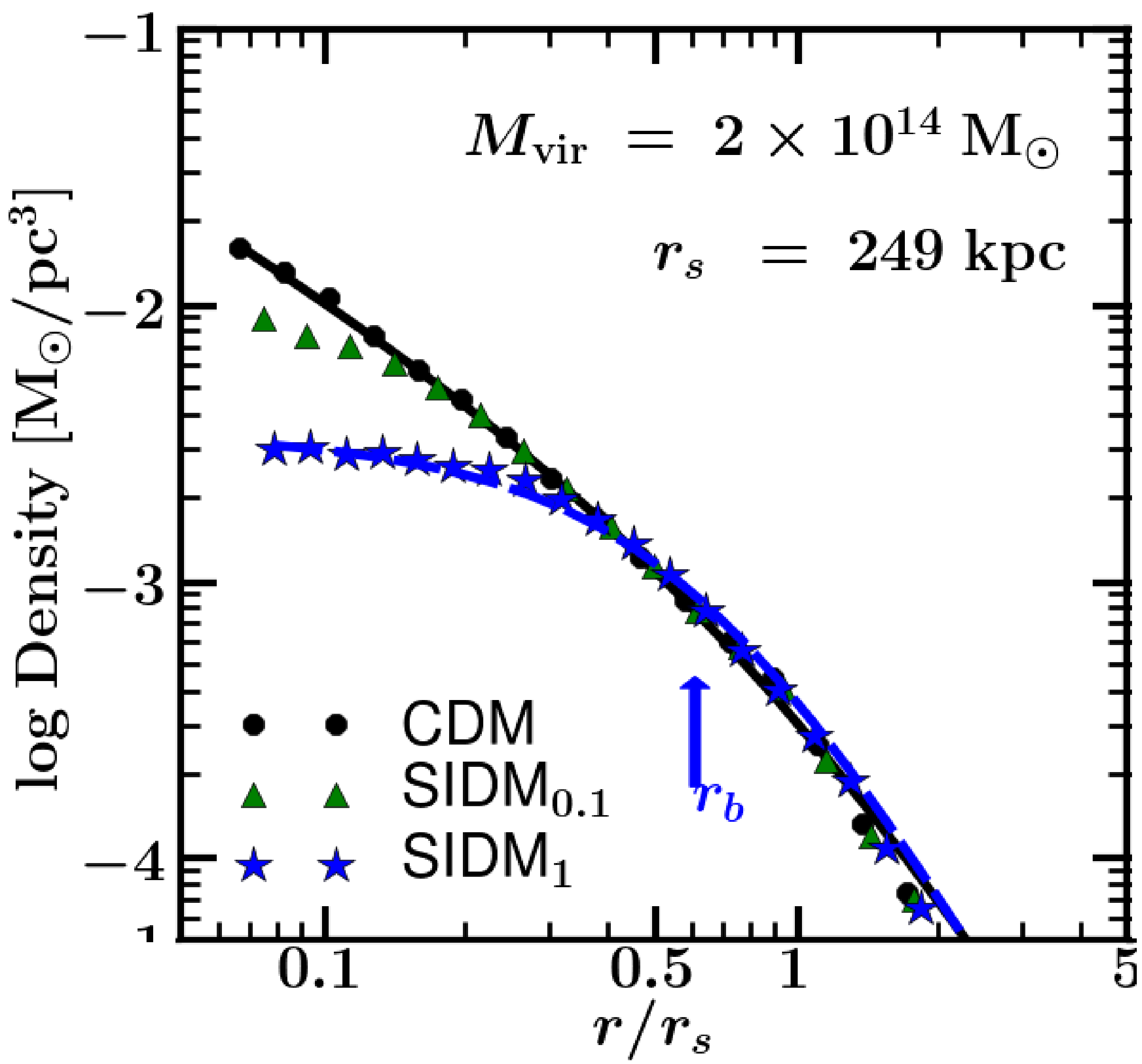


arXiv:1011.0899

- simulations based on Cold Dark Matter assumption can not reproduce all observations
- long-standing **core-versus-cusp problem**
- reduced Dark Matter density at center of halo

Self Interacting Dark Matter I

arXiv:1208.3025



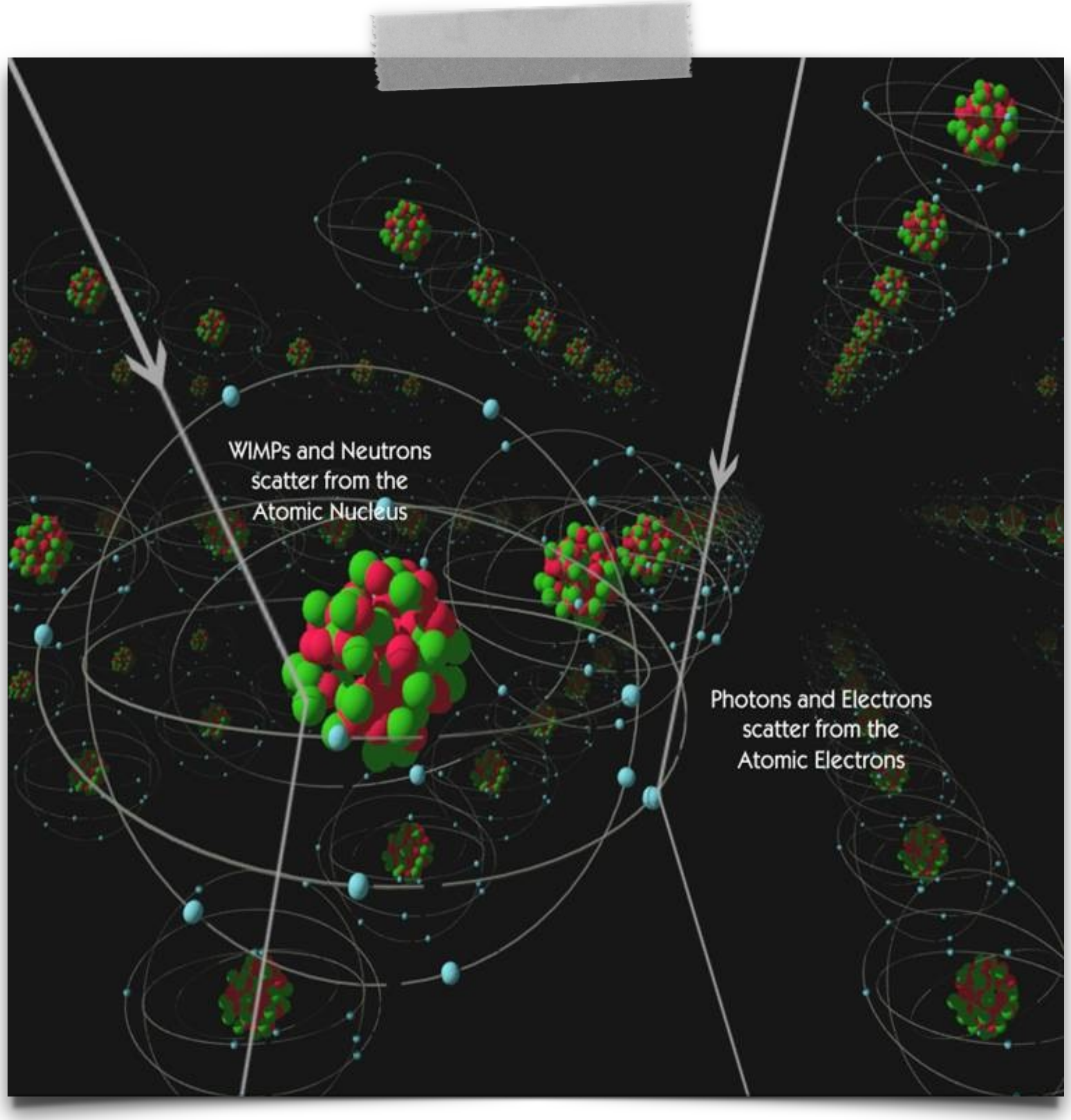
SIDM: self interacting Dark Matter

- N-body simulation assumes collision-less Dark Matter particles
  - gravitational interaction only
- **strong self-interaction** between Dark Matter particles reduces density at the centre of the galaxy

How to search for Dark Matter?

Recipe for a Direct Dark Matter Search Experiment

- experimental challenges for measuring elastic Dark Matter-nucleus scattering:
  - **low energy threshold:** very small energy transfers (O(100 eV)); differential event rate decreases exponentially
  - **low background:** small interaction rate (O(events/kg year))
- **sensitivity to small energy deposition in a low background environment**

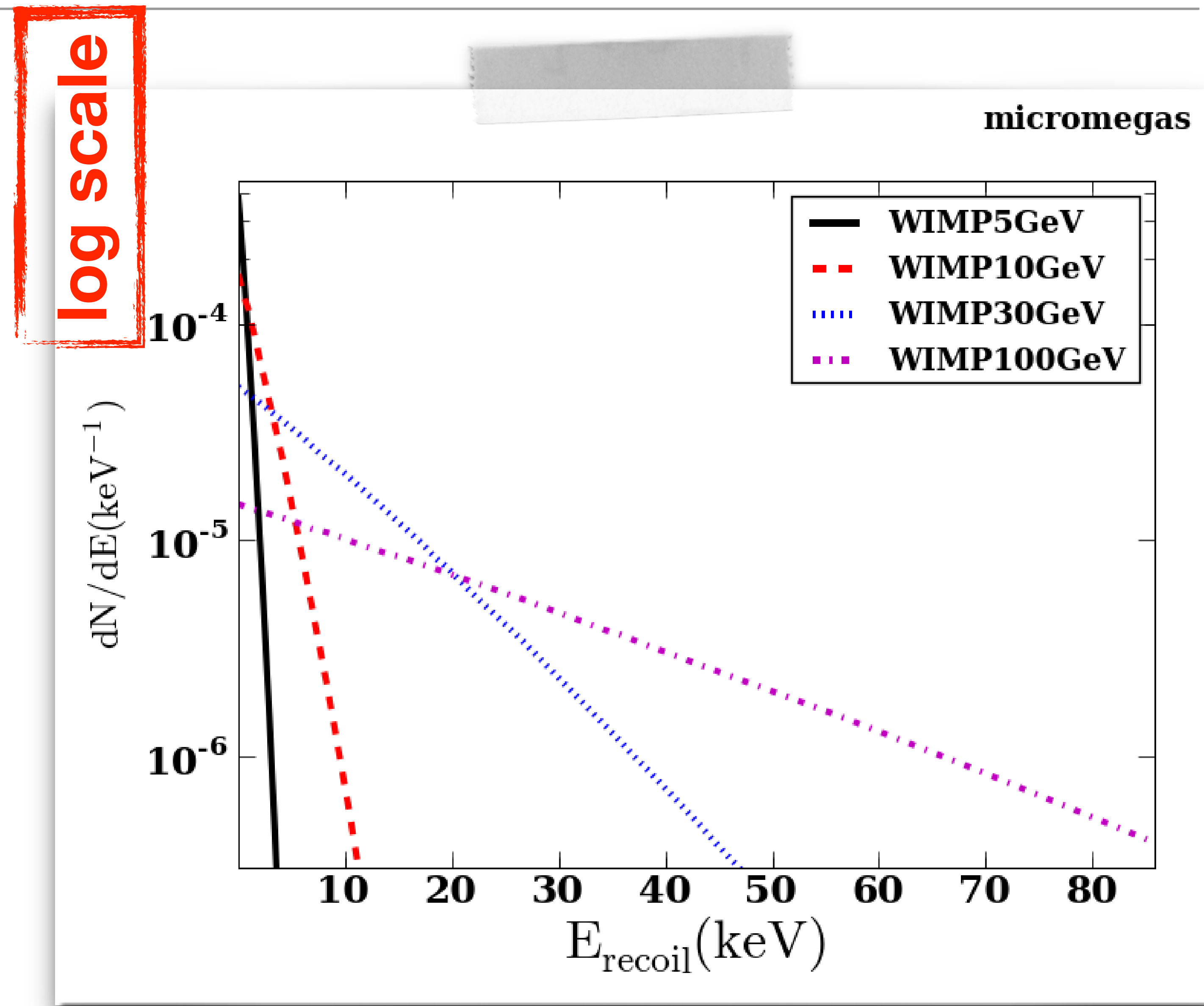


Direct Detection - Event Rate

- differential event rate decreases exponentially with recoil energy

$$\frac{dR}{dE_R} = \left(\frac{dR_0}{dE_R}\right)_0 F^2(E_R)\,\exp(-E_R/E_c)$$

- low detection threshold for WIMP-nucleon scattering crucial

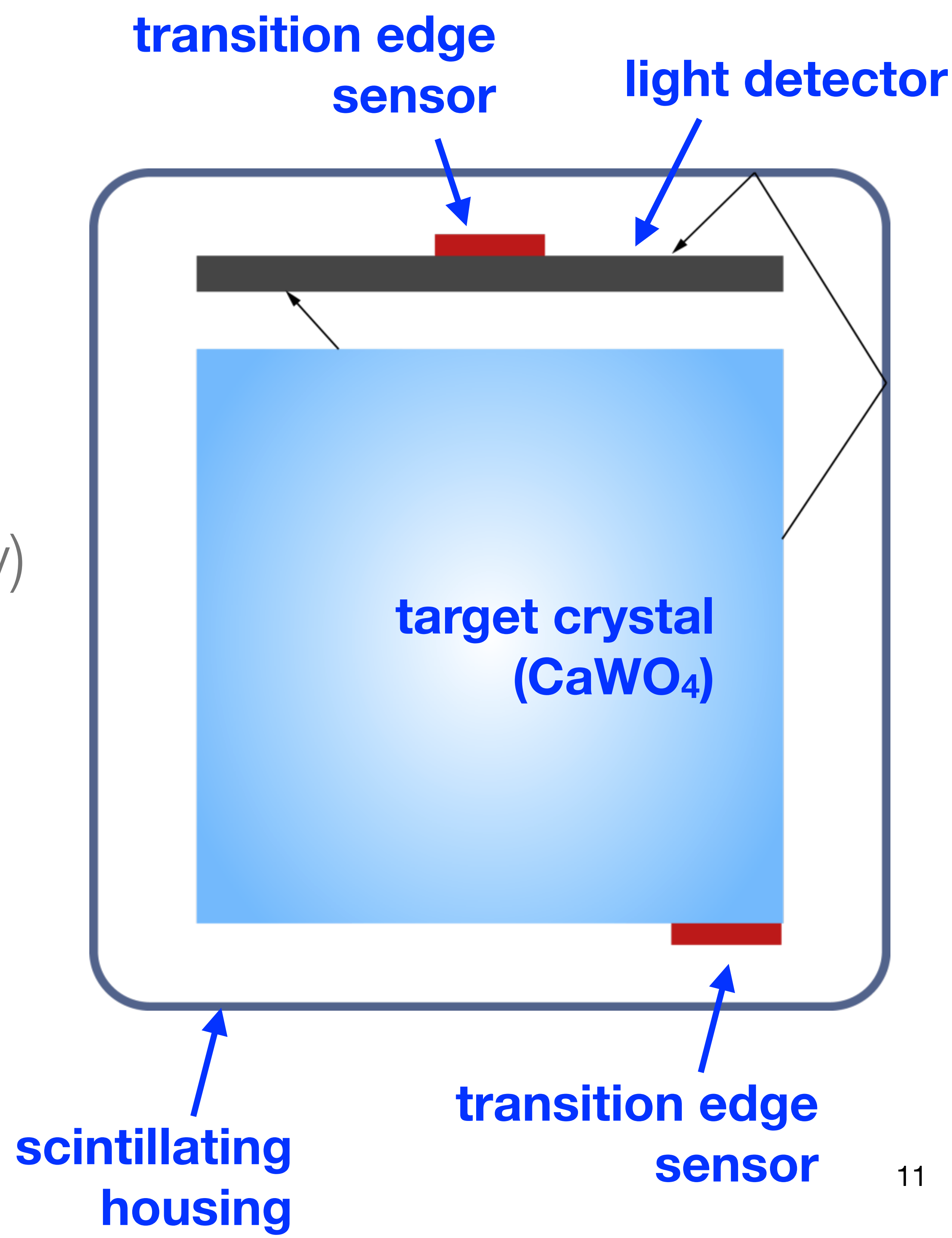


WIMP - ^{78}Ge nucleon scattering

CRESST - Detection Principle I

simultaneous read-out of two signals

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



CRESST - Detection Principle II

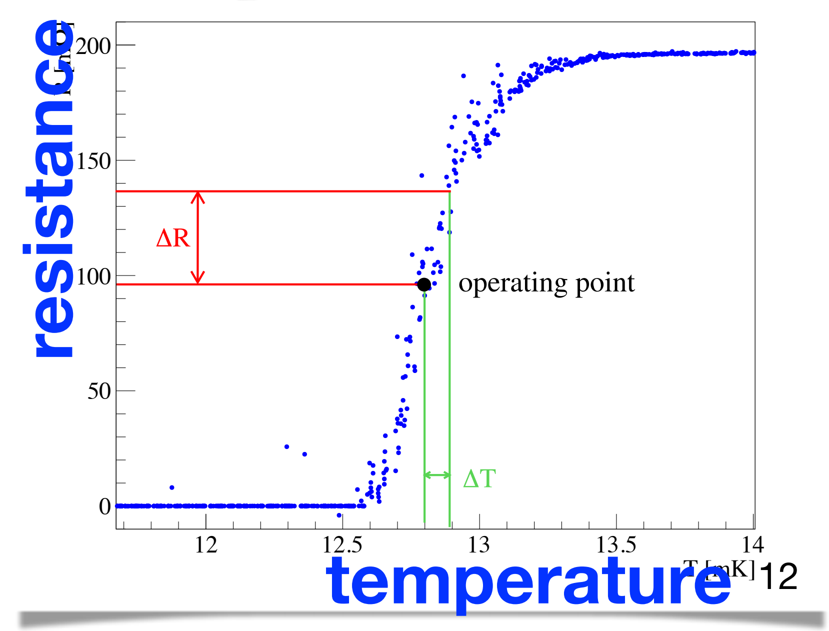
- experiment operated at cryogenic temperature (~15 mK)
- nuclear recoil will deposit energy in the crystal leading to a temperature rise proportional to energy

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

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

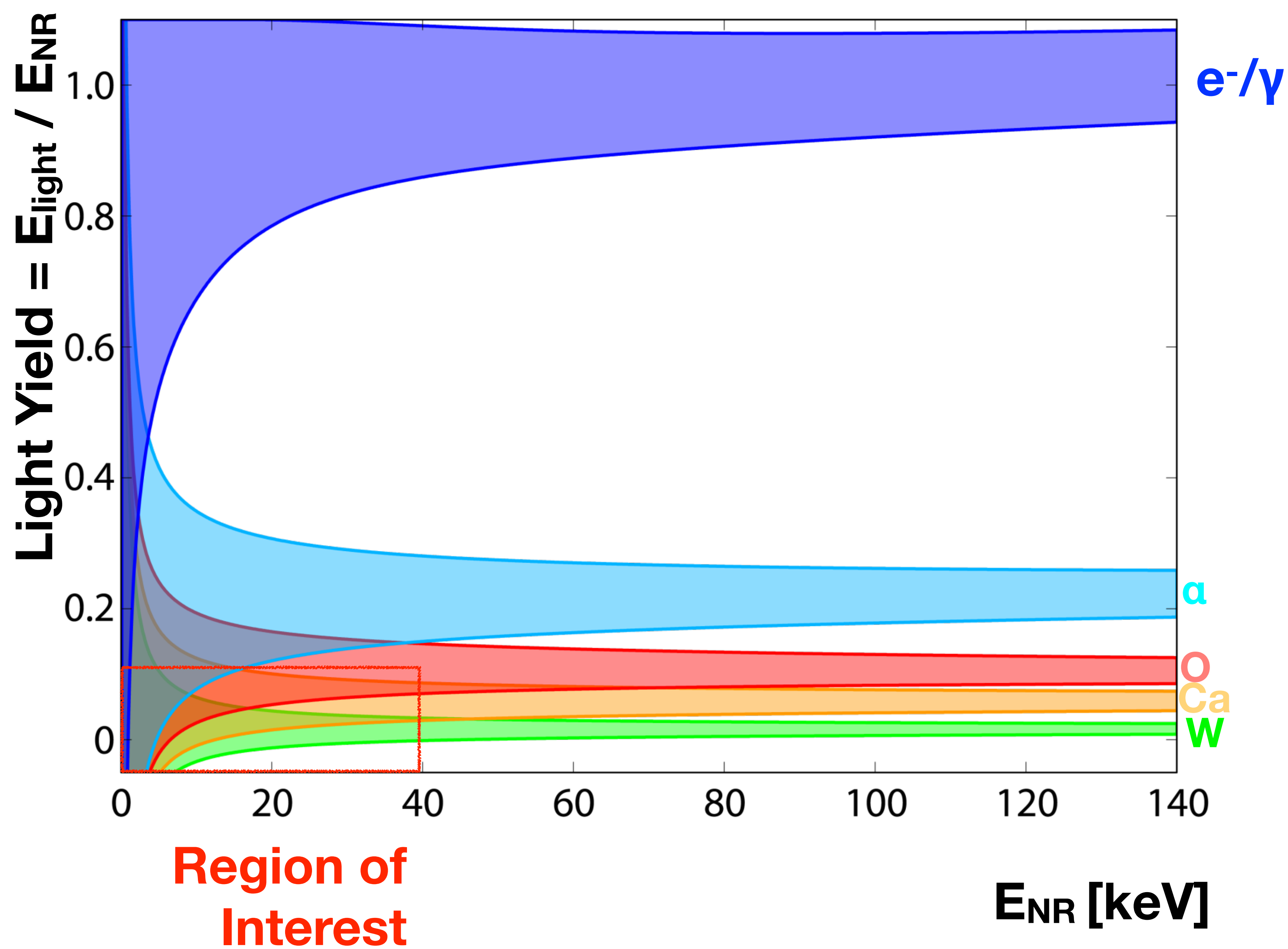
Θ_D:Debye temperature

- 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



Signal-Background Separation

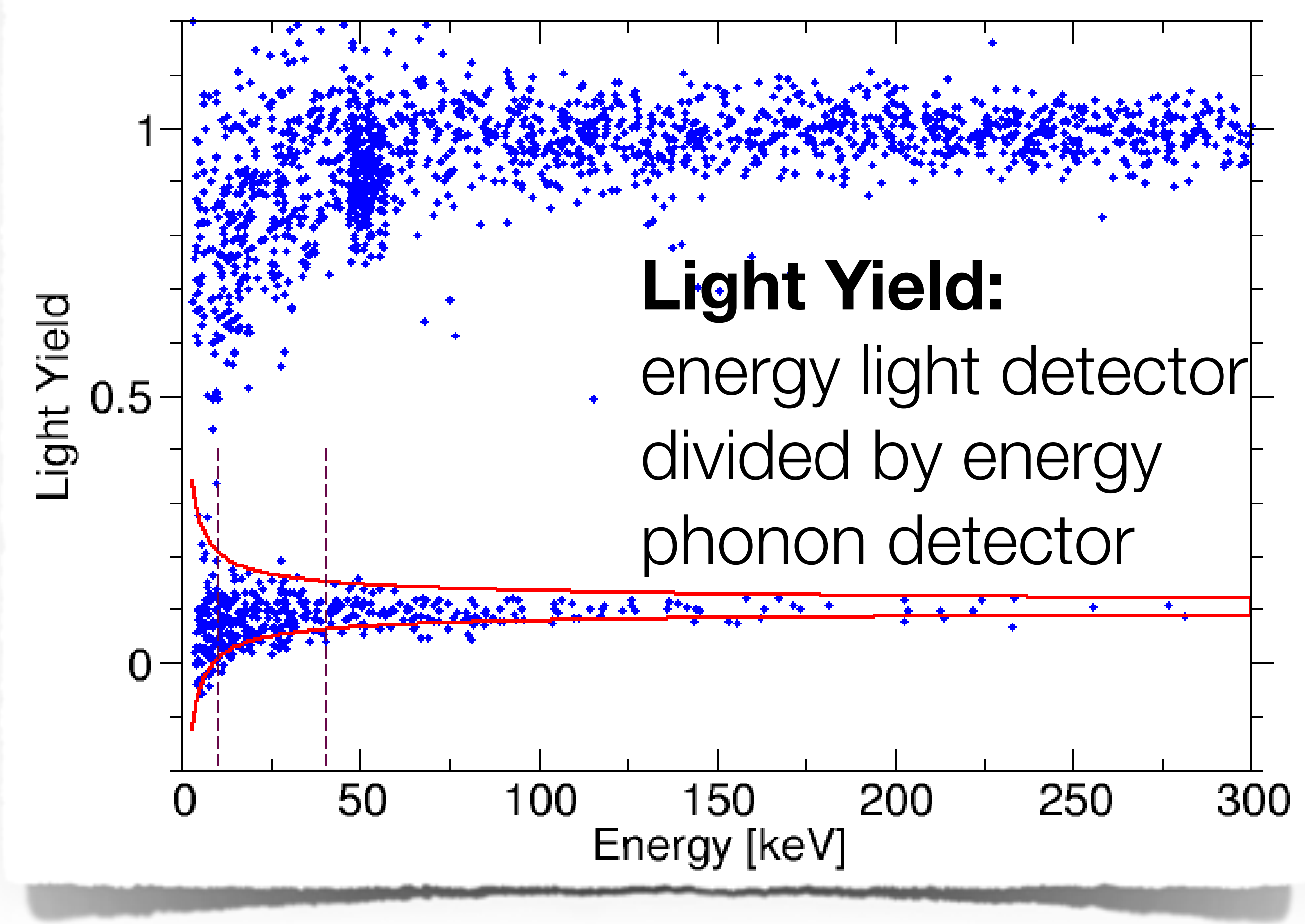
- simultaneous readout of light and phonon channel allows background reduction
- less scintillation light from dark matter-nucleus scattering ("Quenching")
    - clear separation between signal and background at large E_{NR}
    - **significant overlap of bands at low energies (= low mass dark matter)**



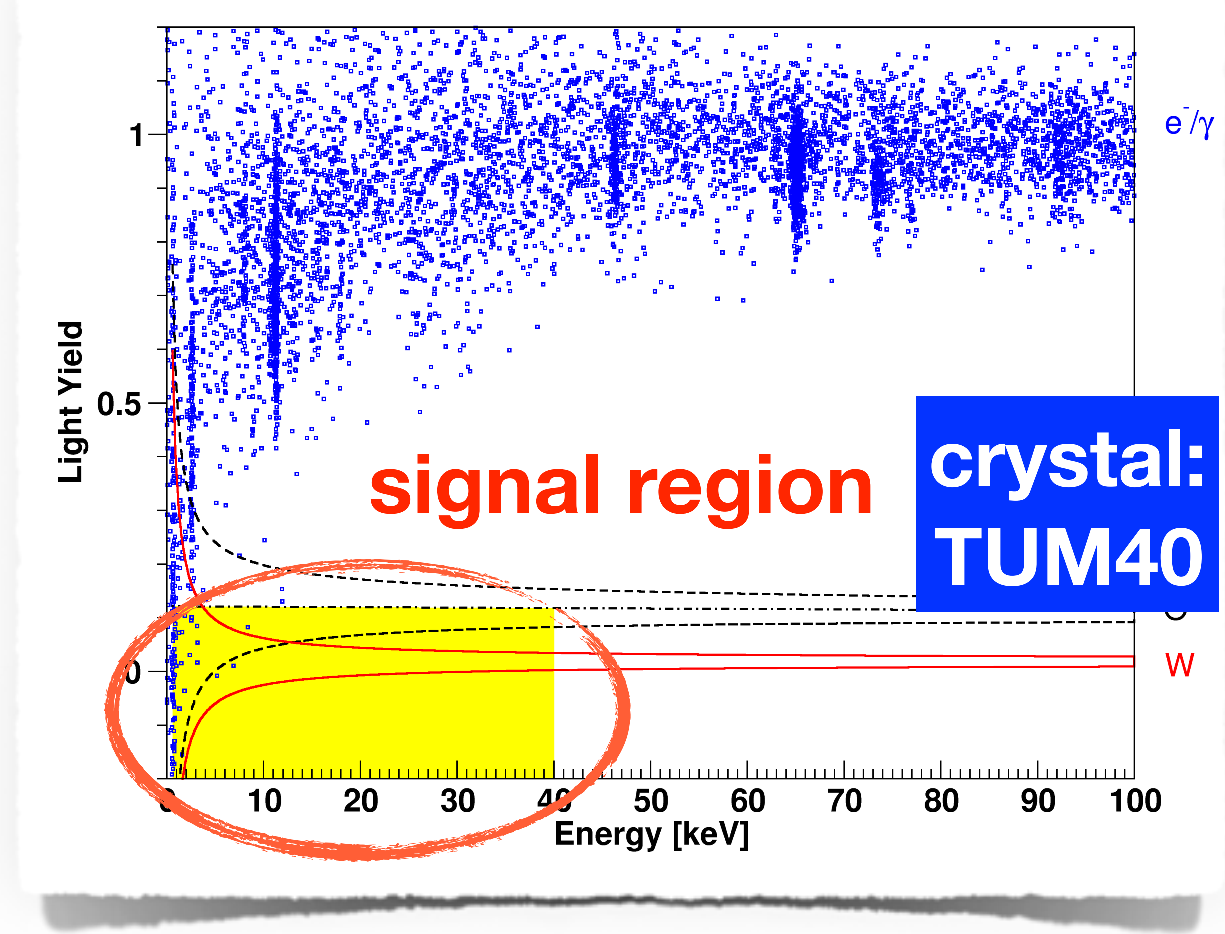
Signal-Background Separation - Data

Eur.Phys.J. C74 (2014) 12, 3184
arxiv 1407.3146

neutron calibration



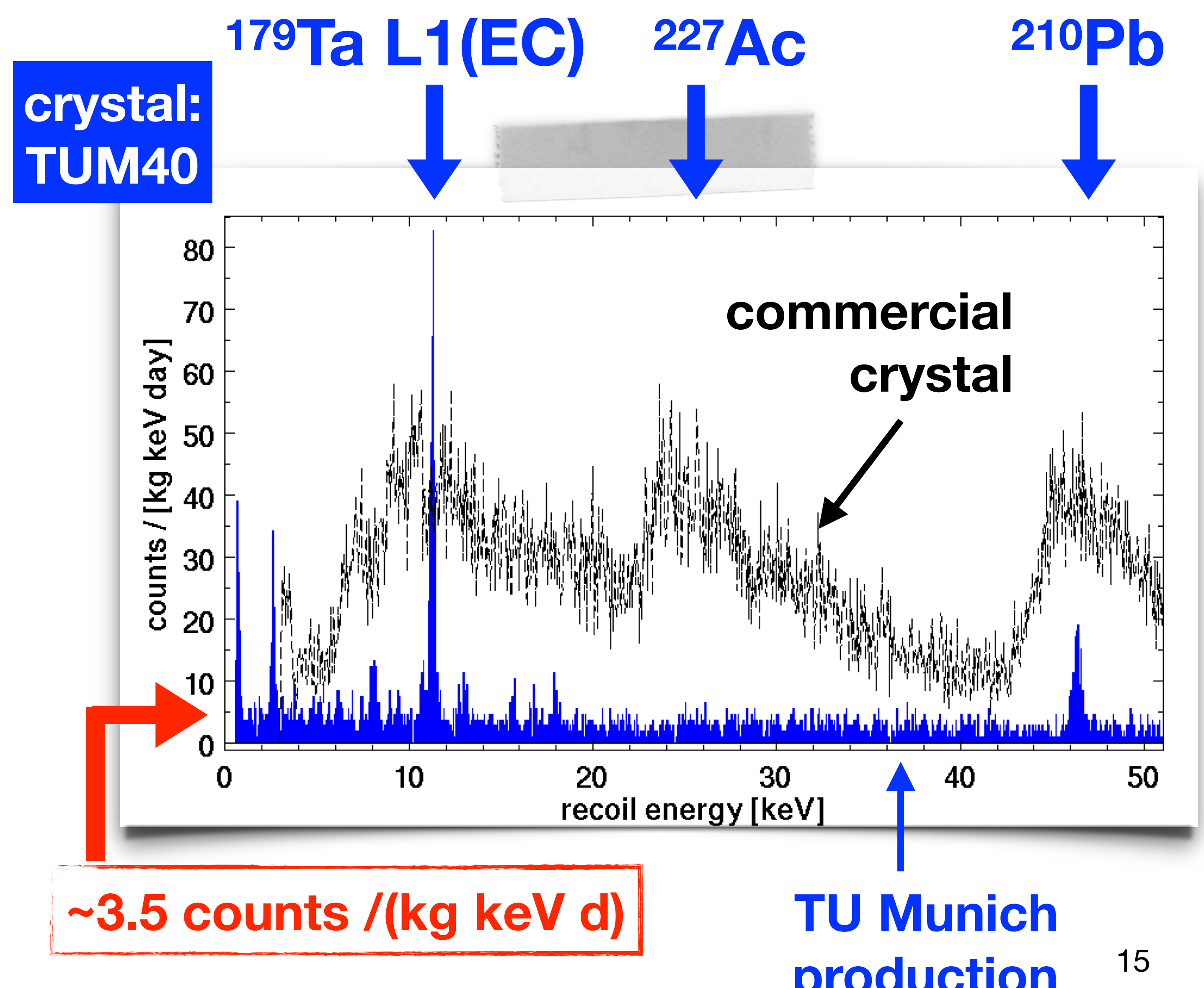
measurement



- signal region identified in light yield / energy space
- **reduction and understanding of intrinsic background crucial for low mass Dark Matter searches**

Crystal Intrinsic Background

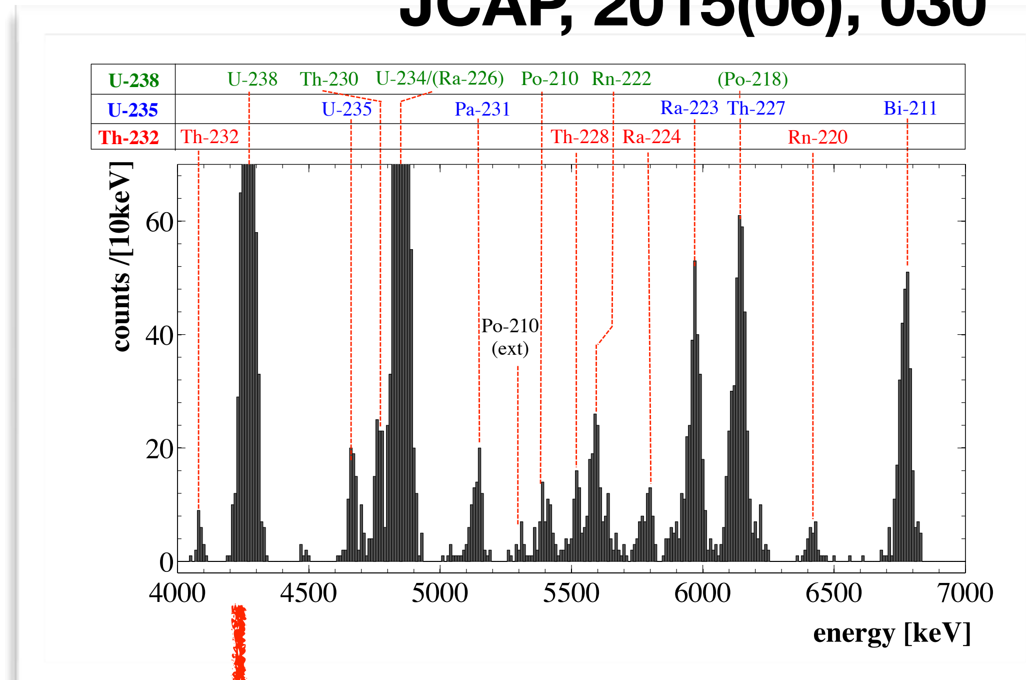
- experimental sensitivity limited by background
  - CRESST dominated by crystal-intrinsic radioactive contaminations
- **improve radio purity**
- in-house production of $CaWO_4$ crystals improves radio purity significantly

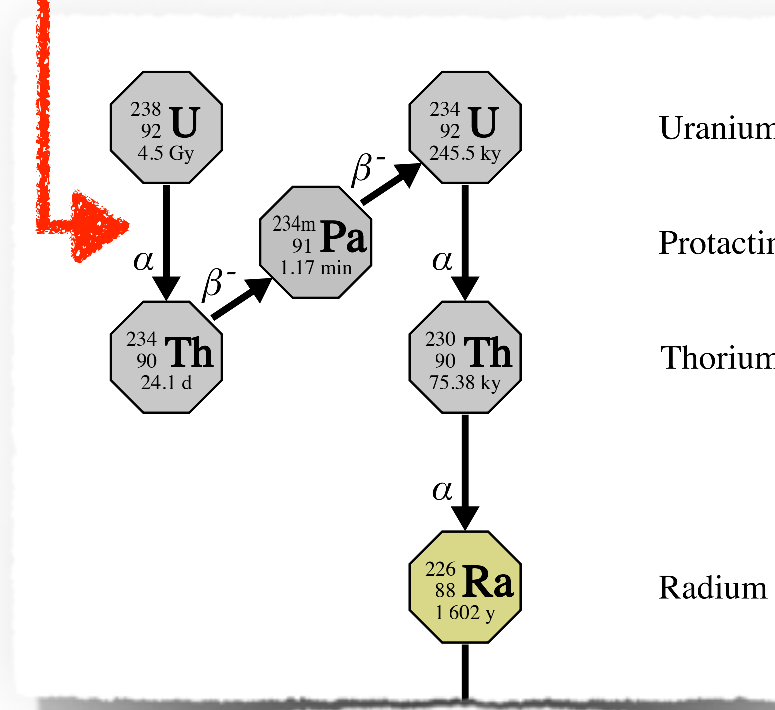


Background Simulation of CRESST - Method I

- Geant4 based simulation to estimate intrinsic background
- use α-activity as input:
  - identification of decay / isotope
  - measured activity reflects size of contamination
- determine energy spectrum of isotope decay and scale it accordingly to the measured activity

JCAP, 2015(06), 030

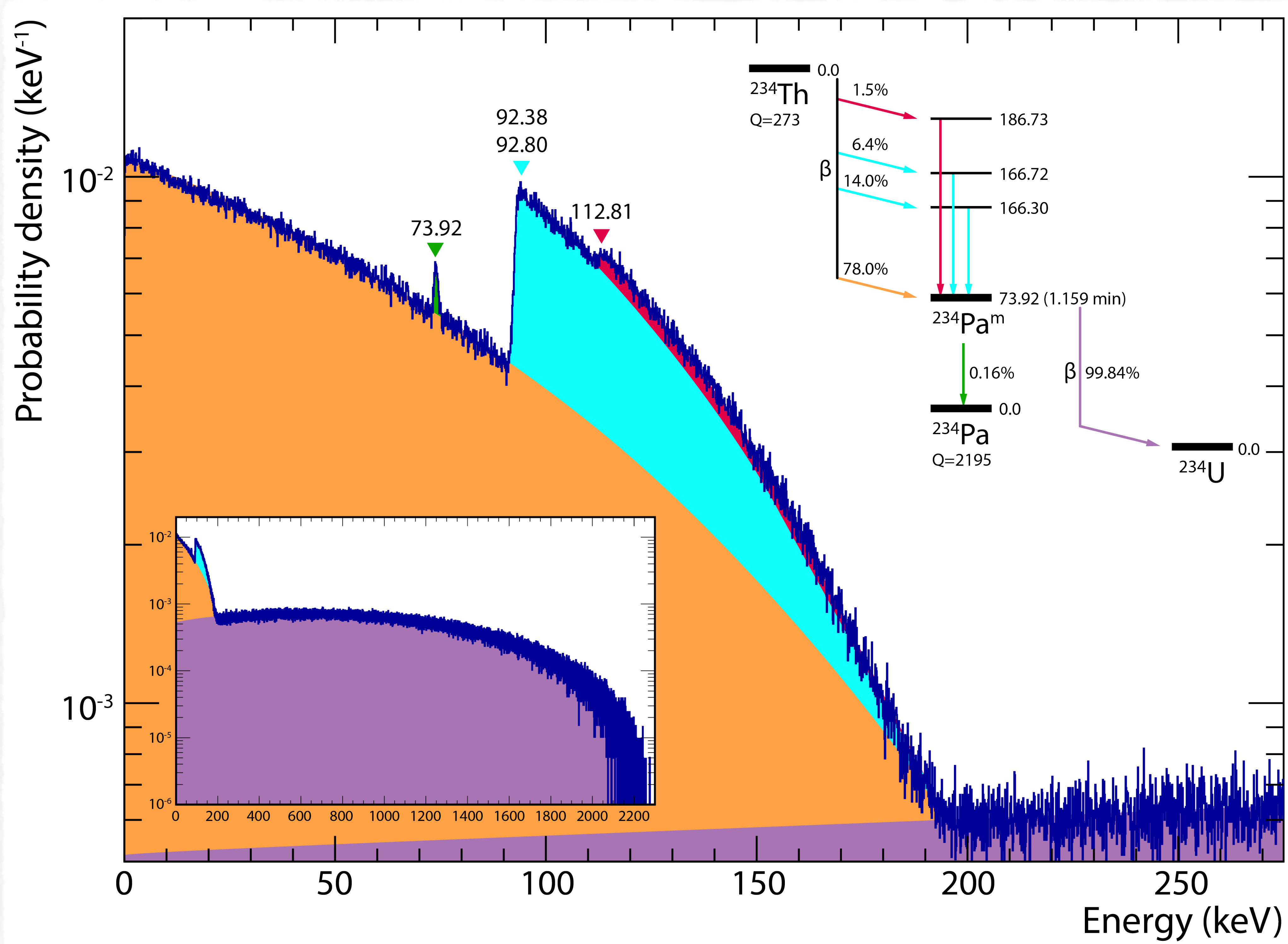




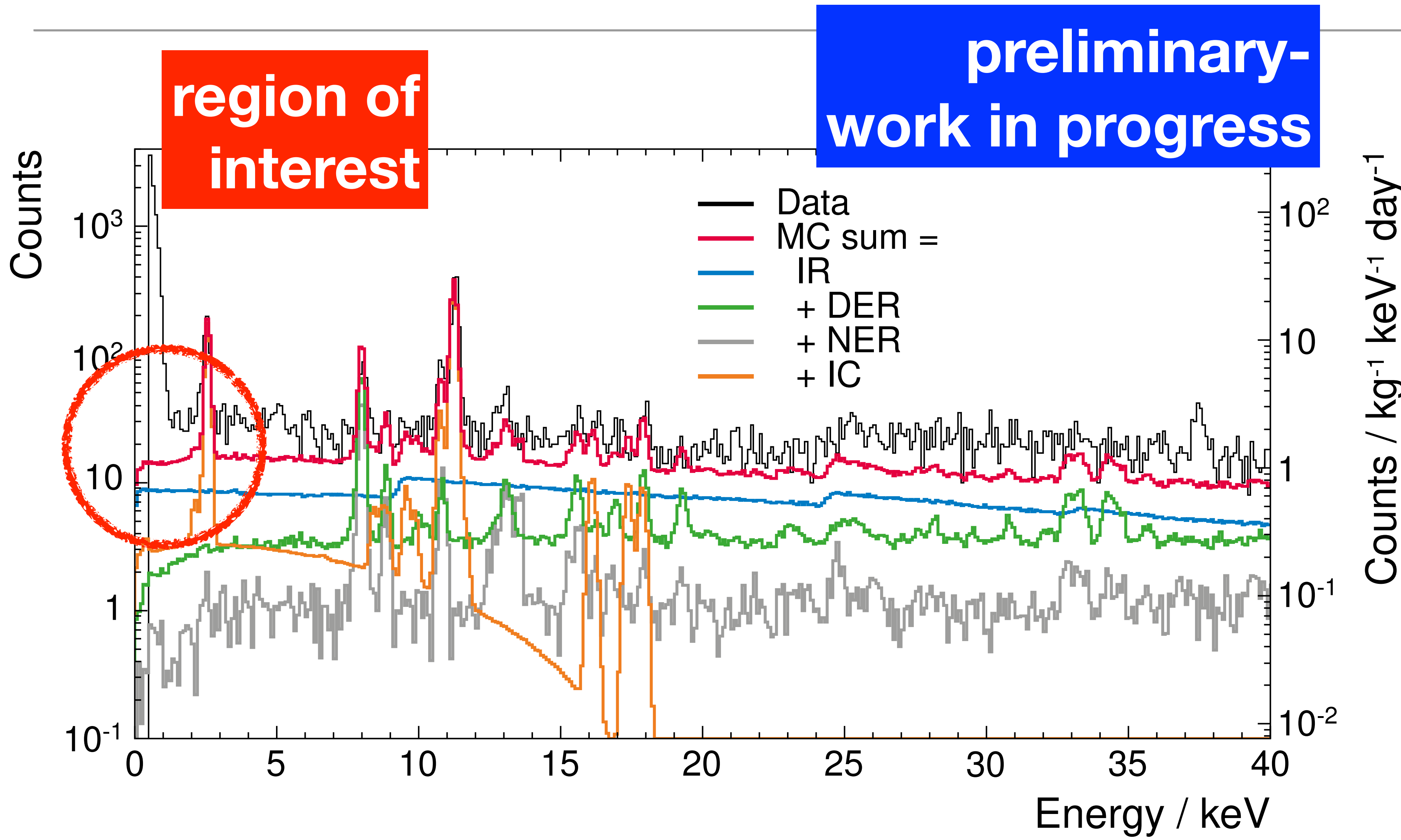
Wikipedia

Background Simulation of CRESST - Method II

energy spectrum of simulated ^{234}Th decay with Giant



Background Simulation of CRESST - Status

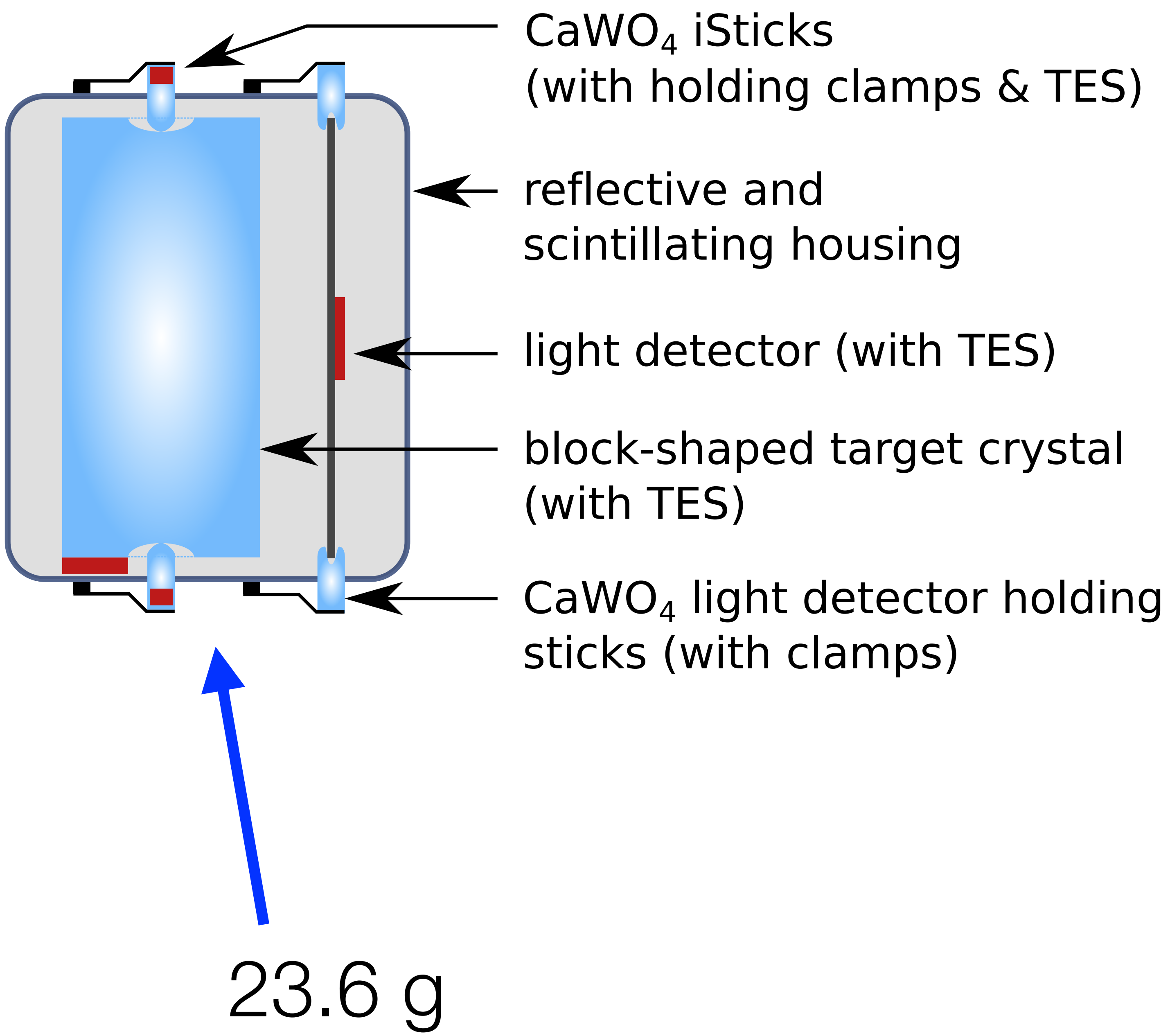


- internal background of 45 isotopes
- include simulation of detector module

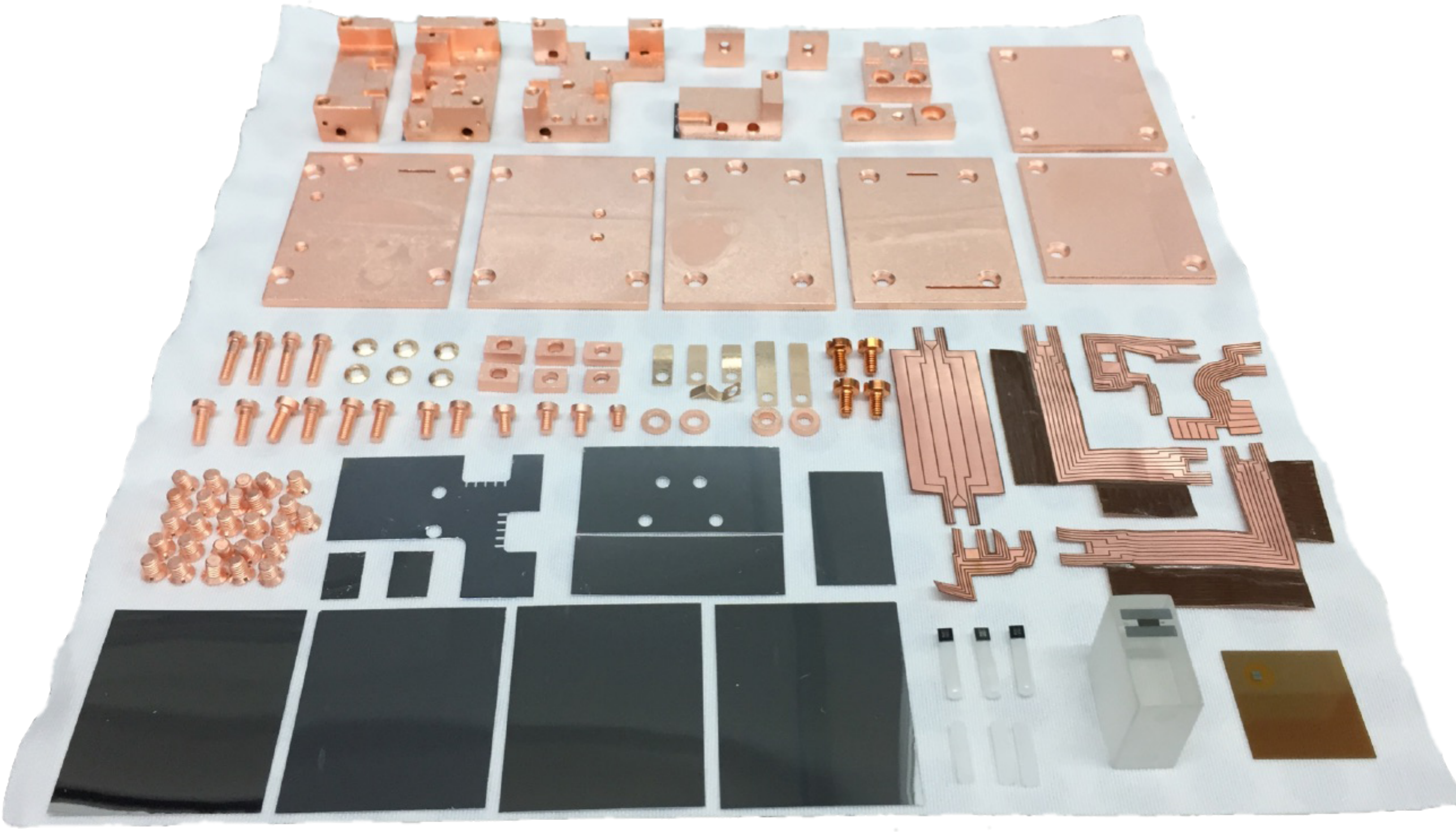
- working towards better understanding of background for $CaWO_4$-based low background measurements

Results with CRESST III

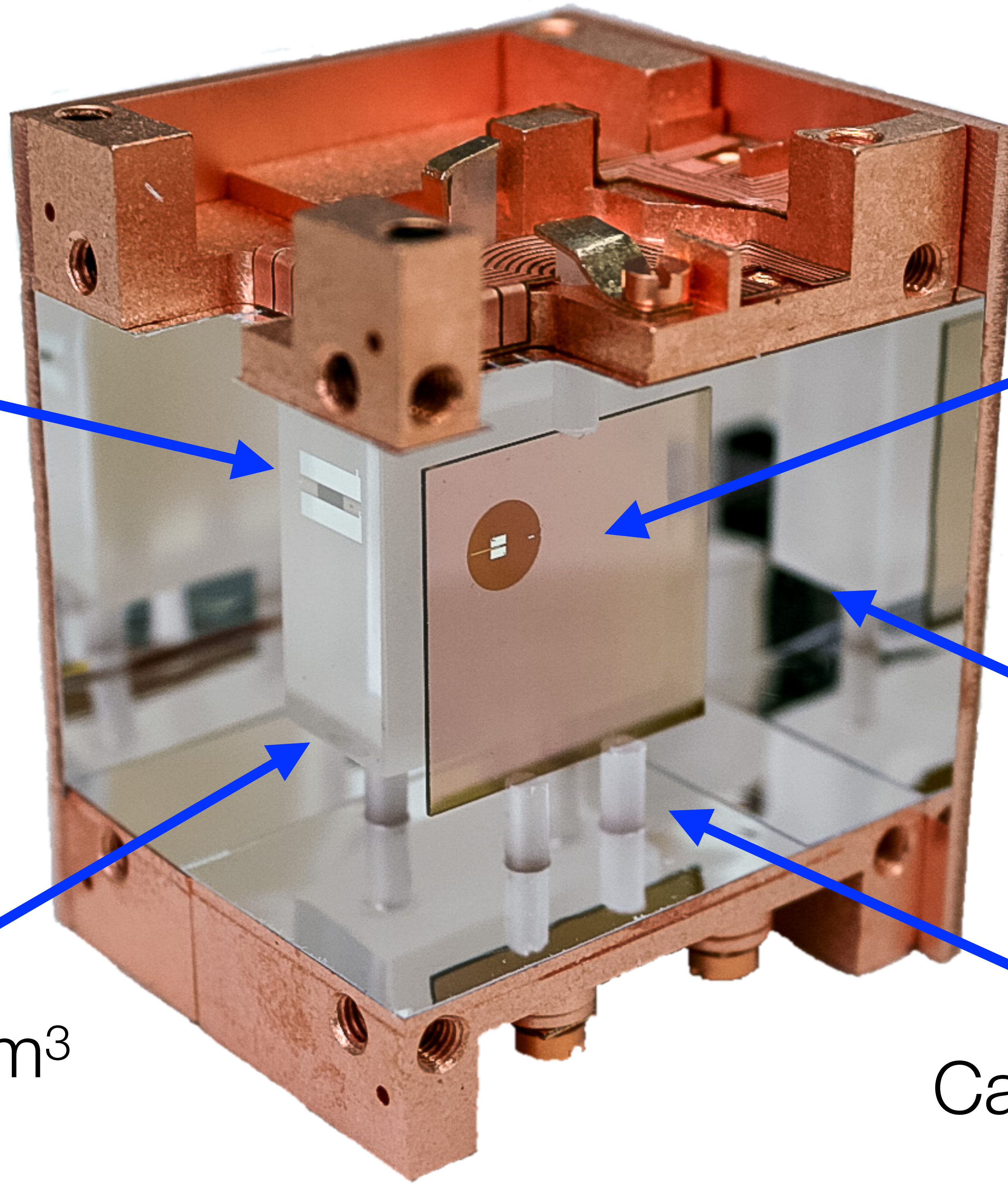
- focus on low-mass dark matter nuclear recoil
- instrumented detector holder (iSticks)
- small crystal to increase phonon density and energy threshold
- self-grown crystal with ~3 counts/(keV · kg · d)
- data taking from 5/2016-2/2018



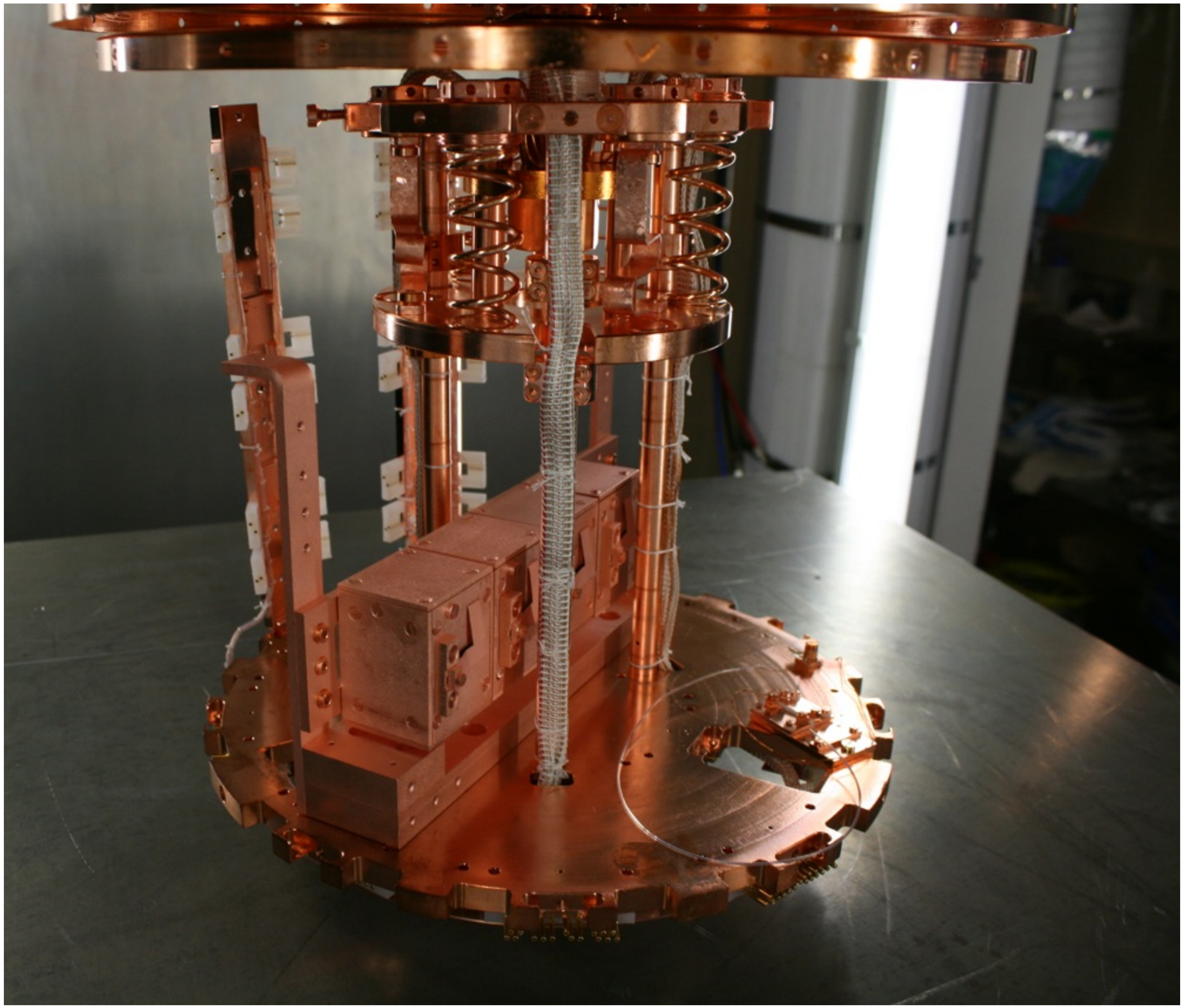
CRESST III Module Construction Kit

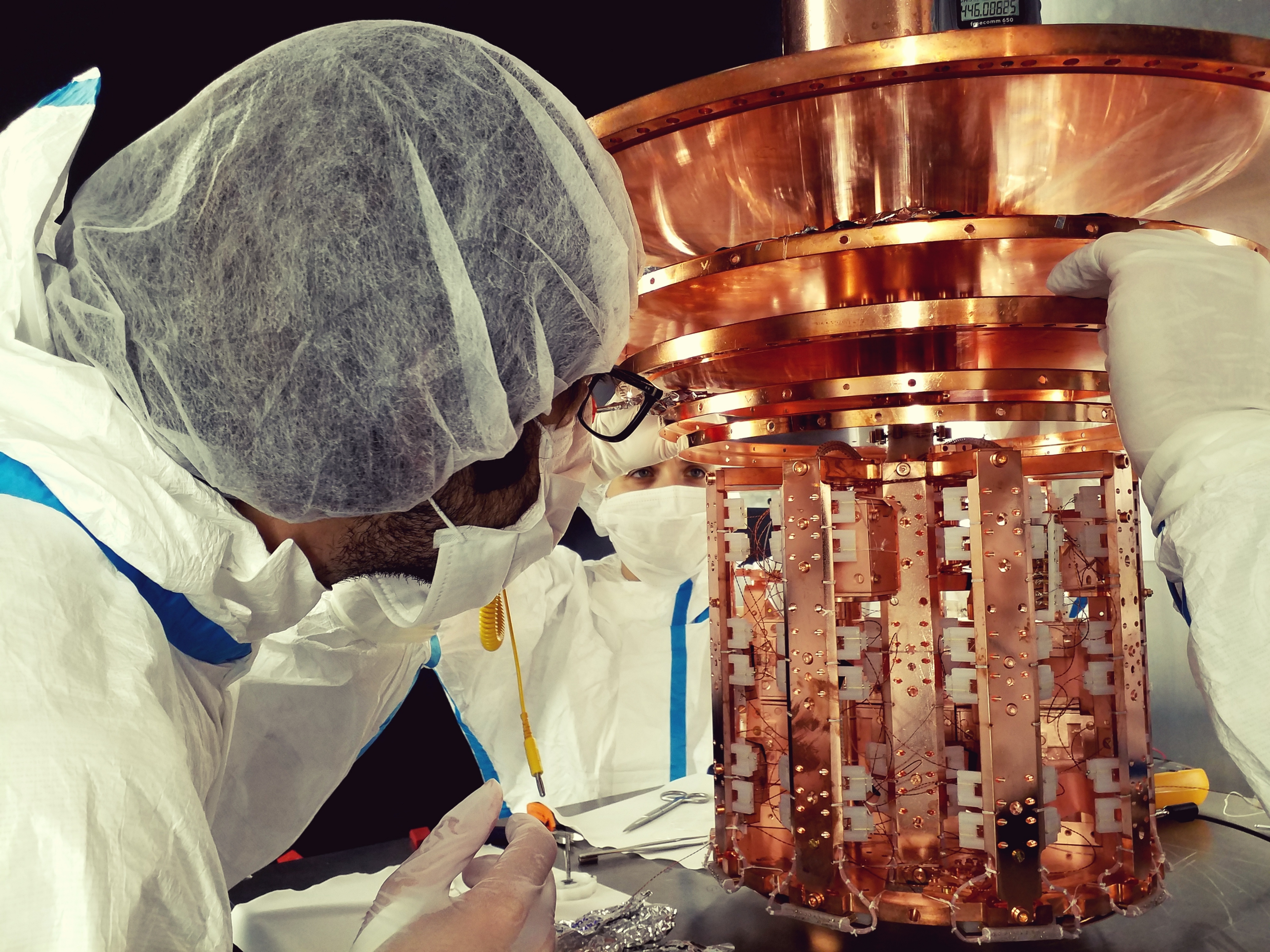


CRESST III - Detector Module



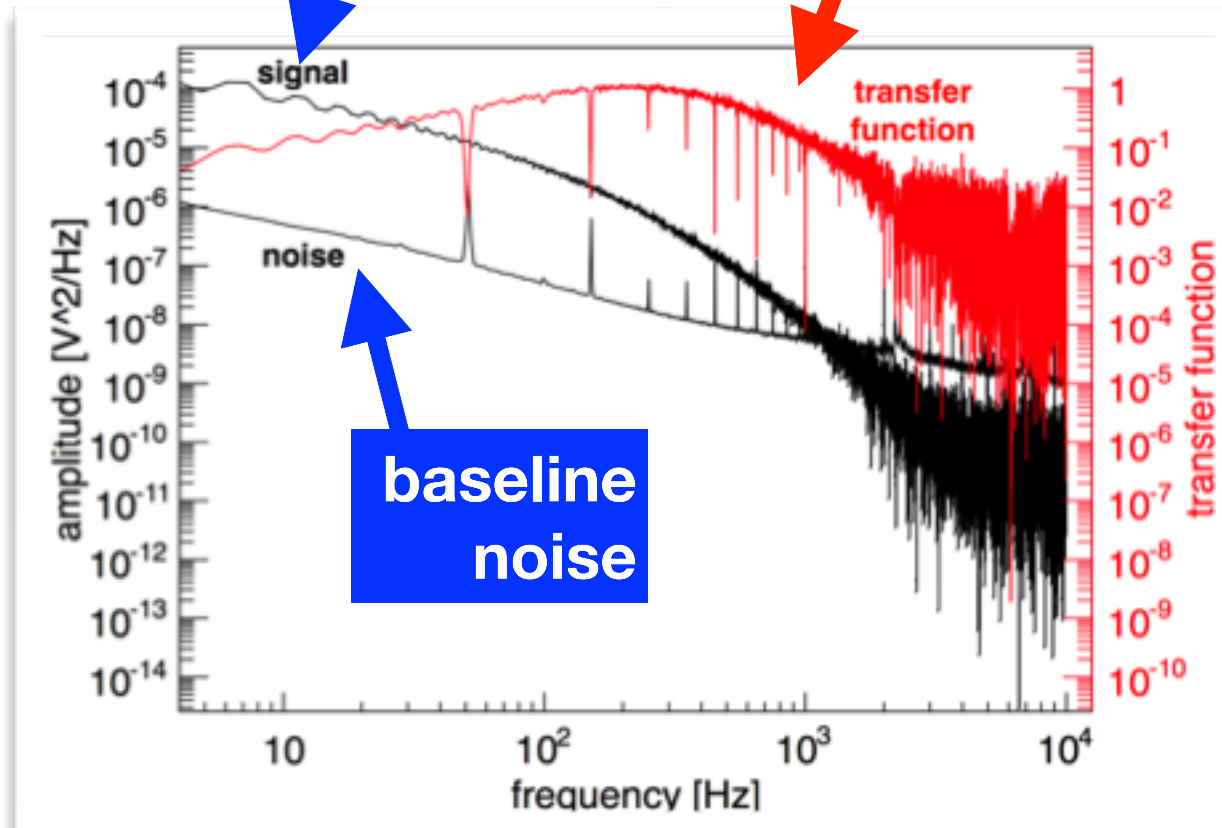
Module in the Cryostat

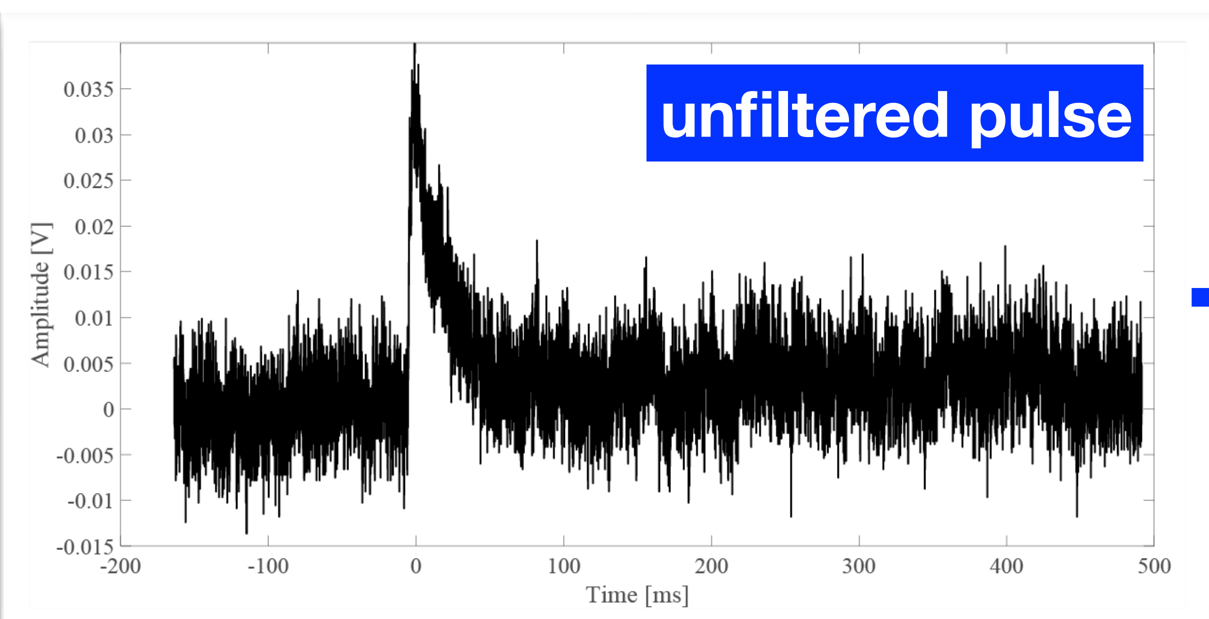


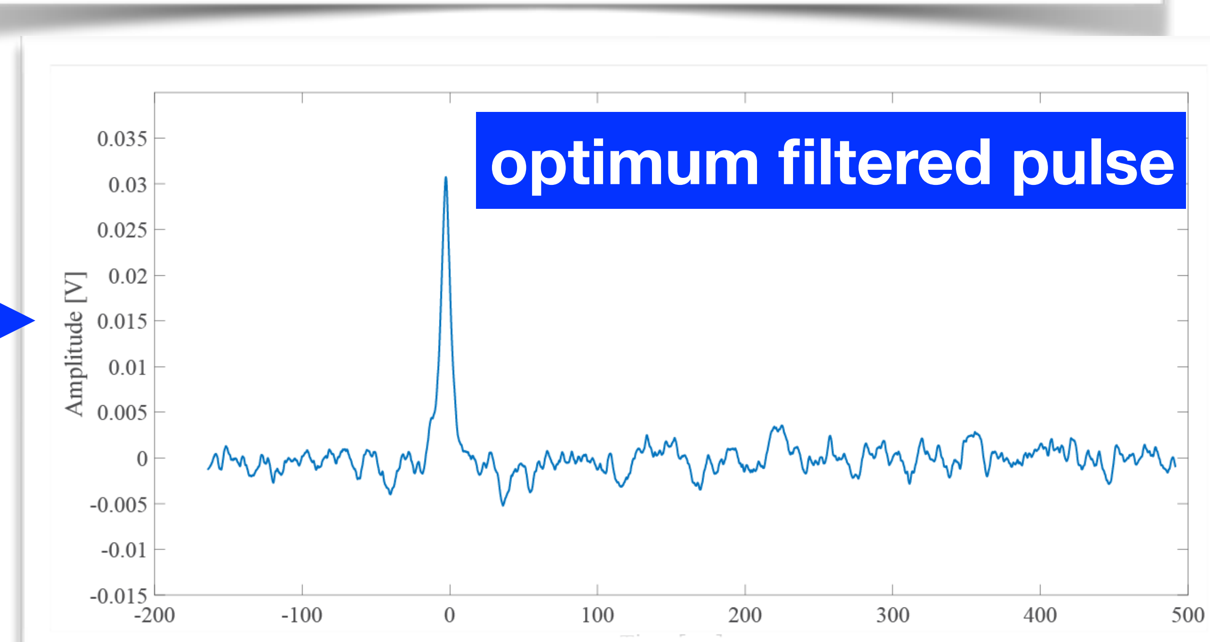

freecomm 650

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



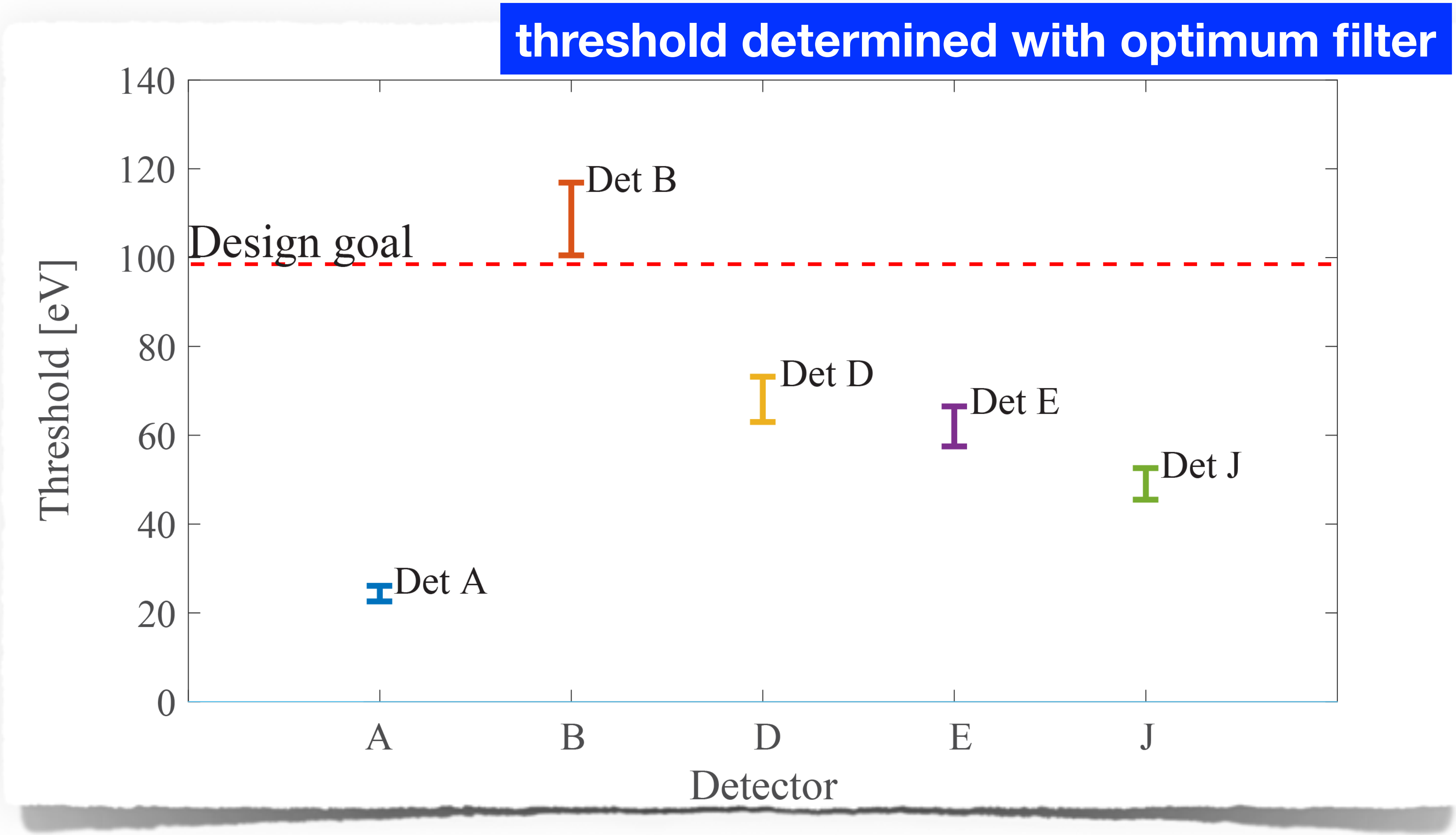




CRESST-III Energy threshold

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

threshold determined with optimum filter

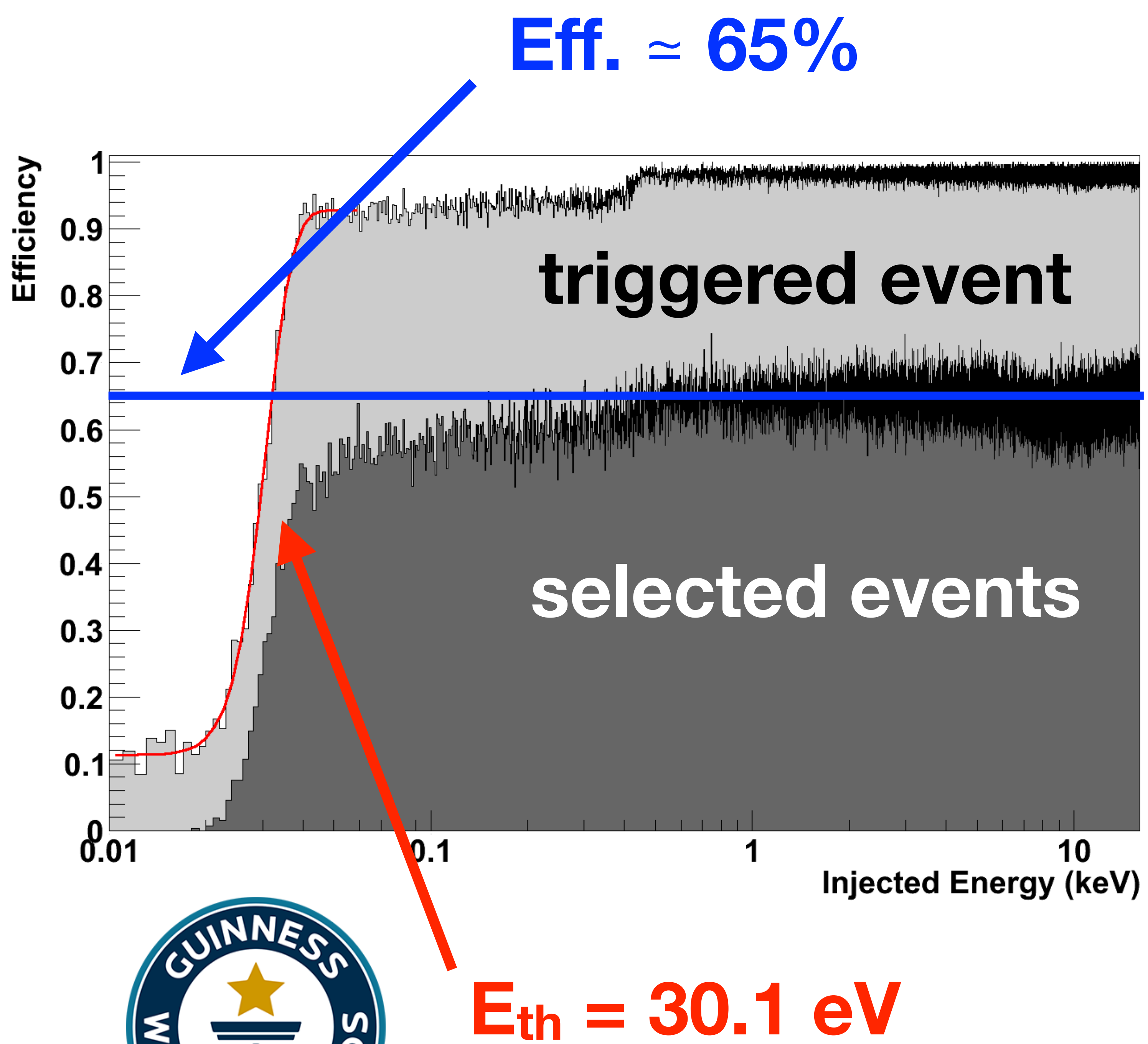


- **4 out of 5 detectors exceed design goal of 100 eV threshold**

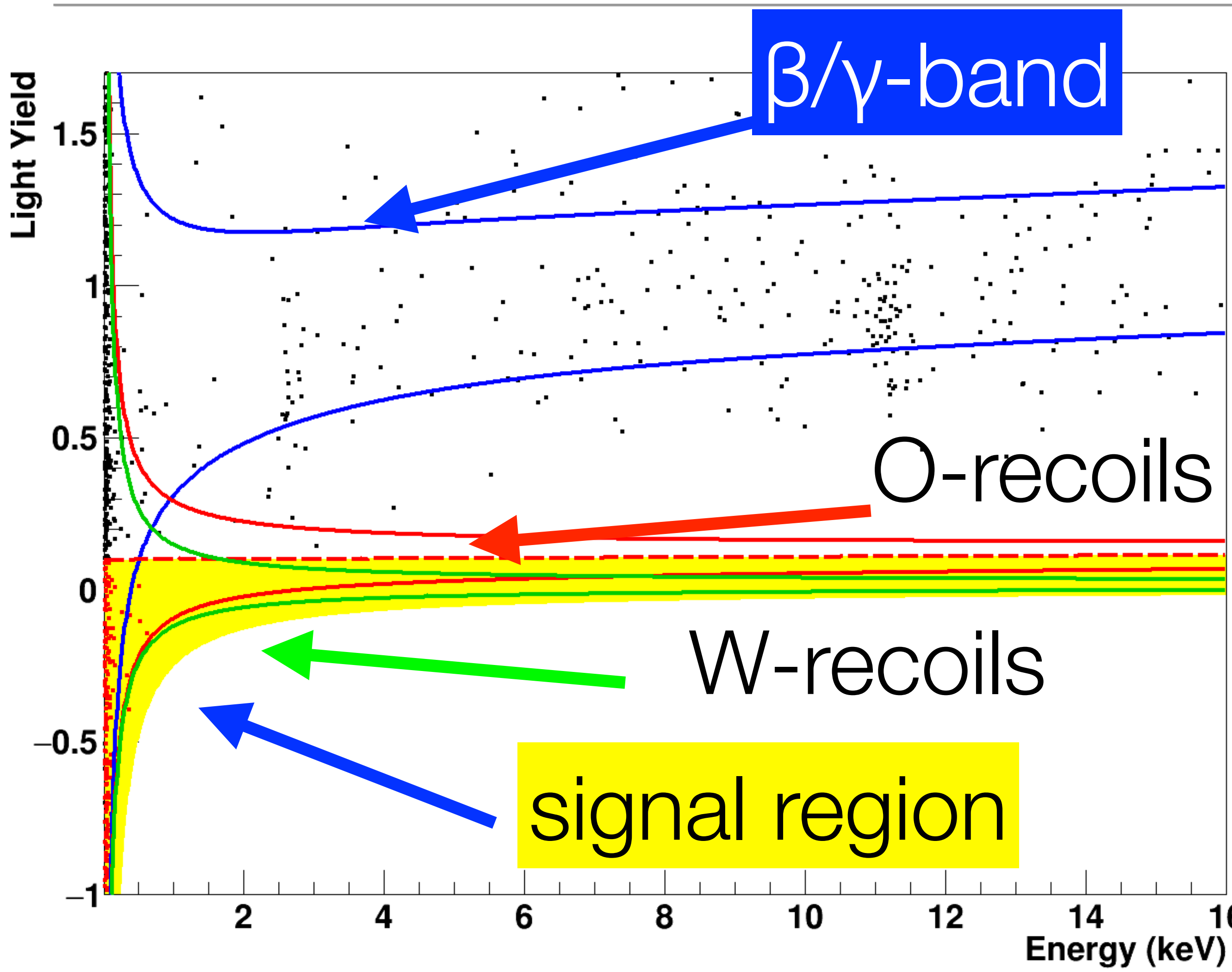
Selection Efficiency

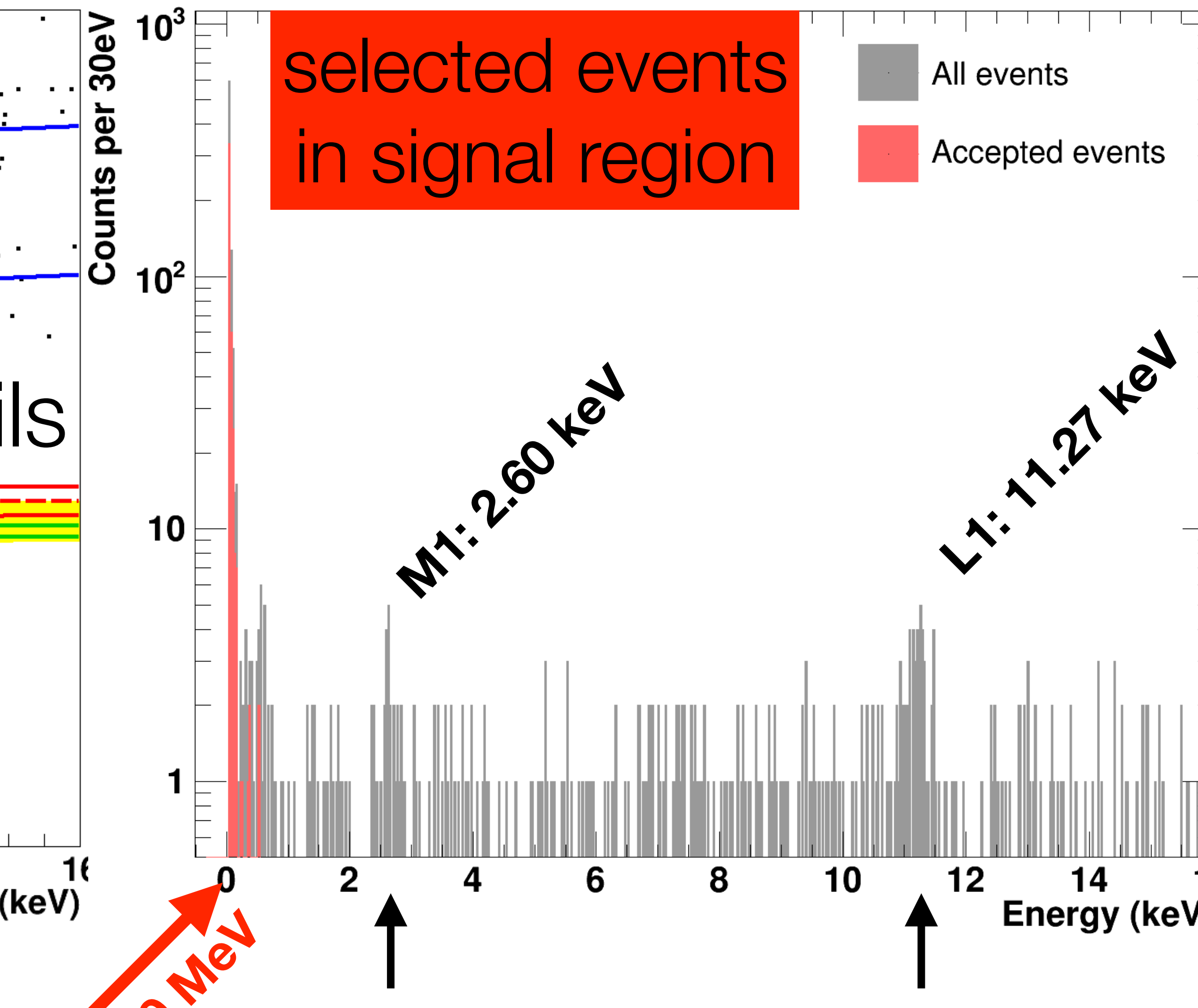
- size of selected data set (after cuts): 3.64 kg·d

- efficiency (energy dependence not taken into account) ~65%



CRESST III - Data



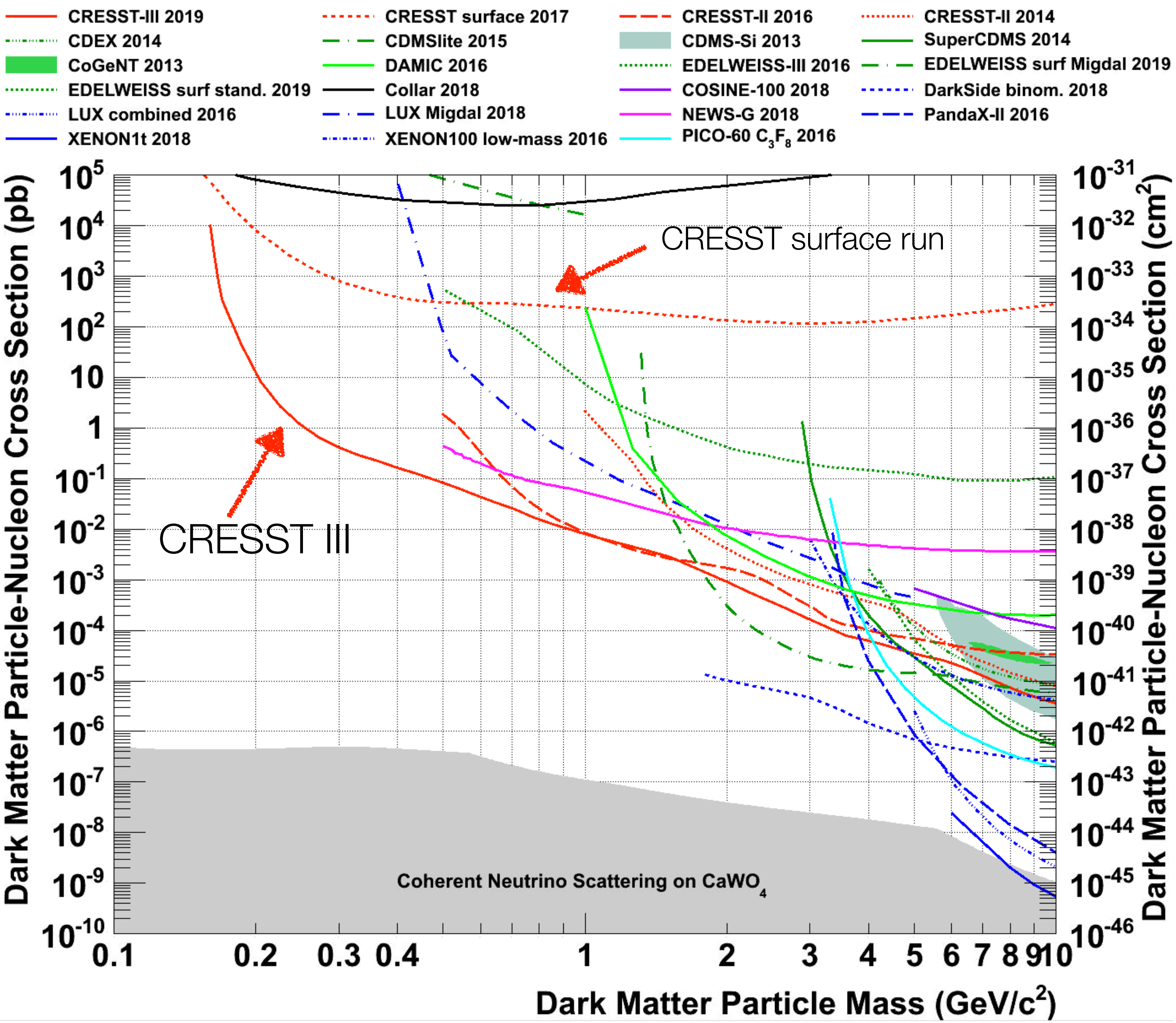


- number of events exponentially increasing for low energies

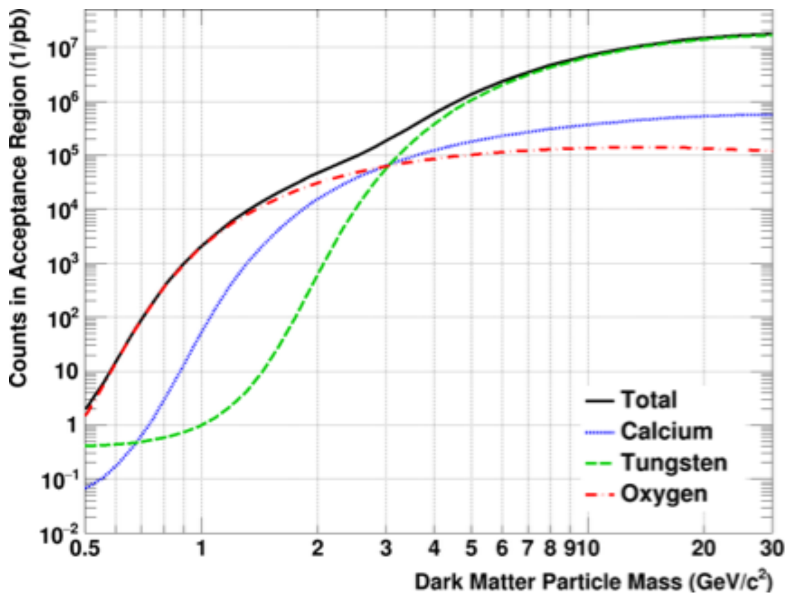
cosmogenic activation:

$$^{182}\mathrm{W} + \mathrm{p} \rightarrow {}^{179}\mathrm{Ta} + \alpha, \quad {}^{179}\mathrm{Ta} \xrightarrow{\mathrm{EC}} {}^{179}\mathrm{Hf} + \gamma.$$

Resultat



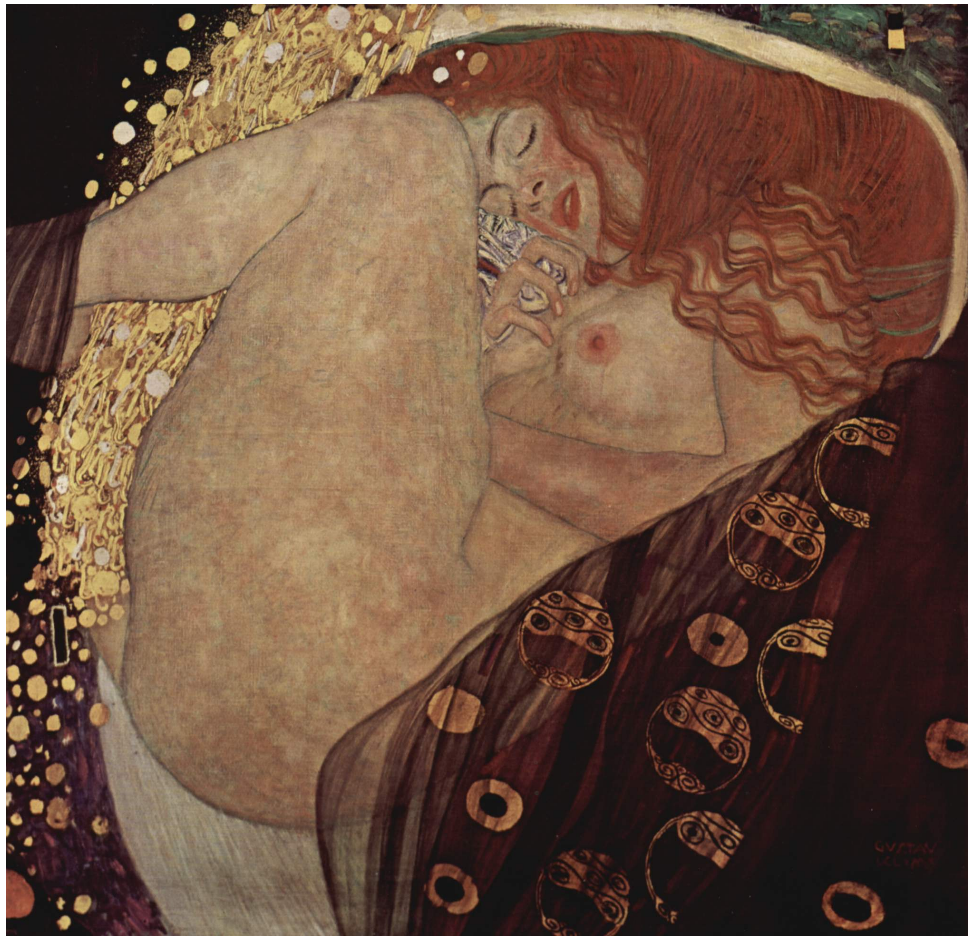
- sensitivity for dark matter particles down to 160 MeV
- limited by unknown background contribution



Towards even lighter Dark Matter mass scales -

DANAE -

Direct d**A**rk matter search using DEPFET with repetitive-**N**on-destructive-readout **A**pplication **E**xperiment)

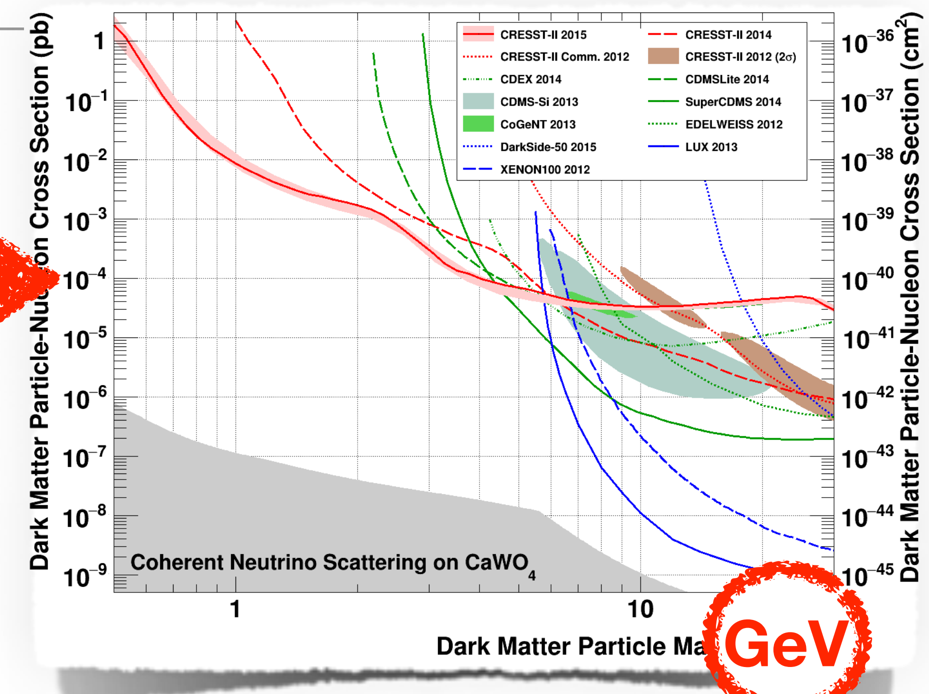


Physics of the Dark Sector

arXiv:1509.01515

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

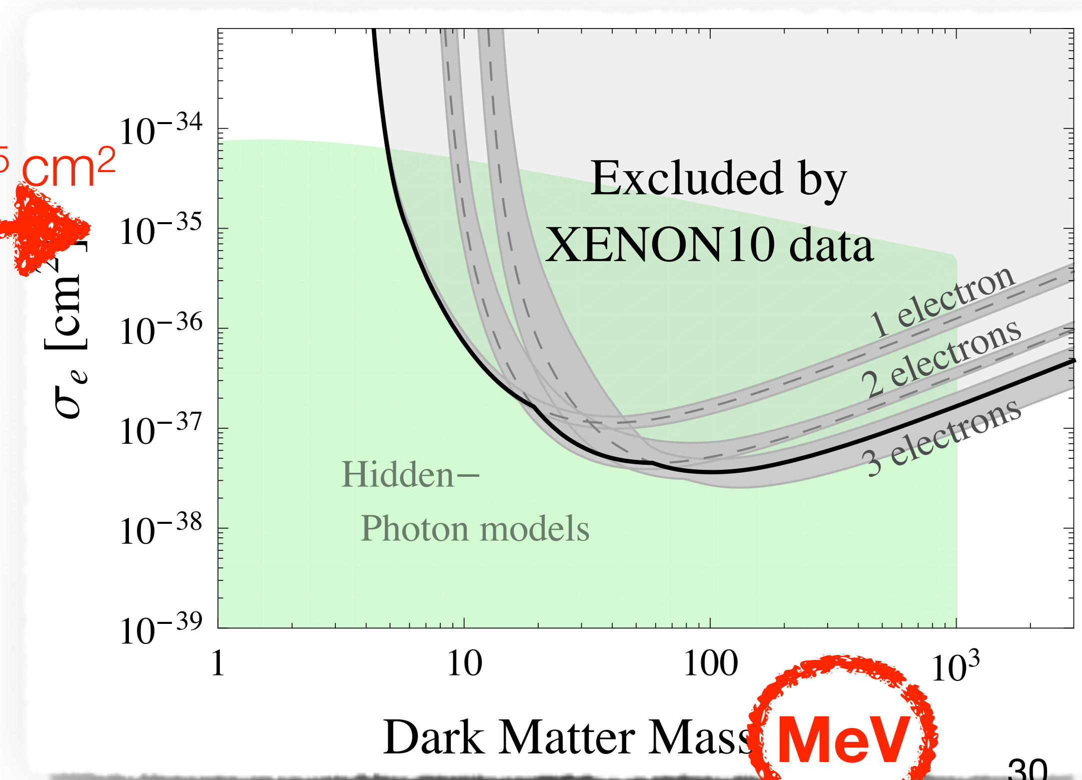
10^{-40} cm^2



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

arXiv:1206.2644

10^{-35} cm^2

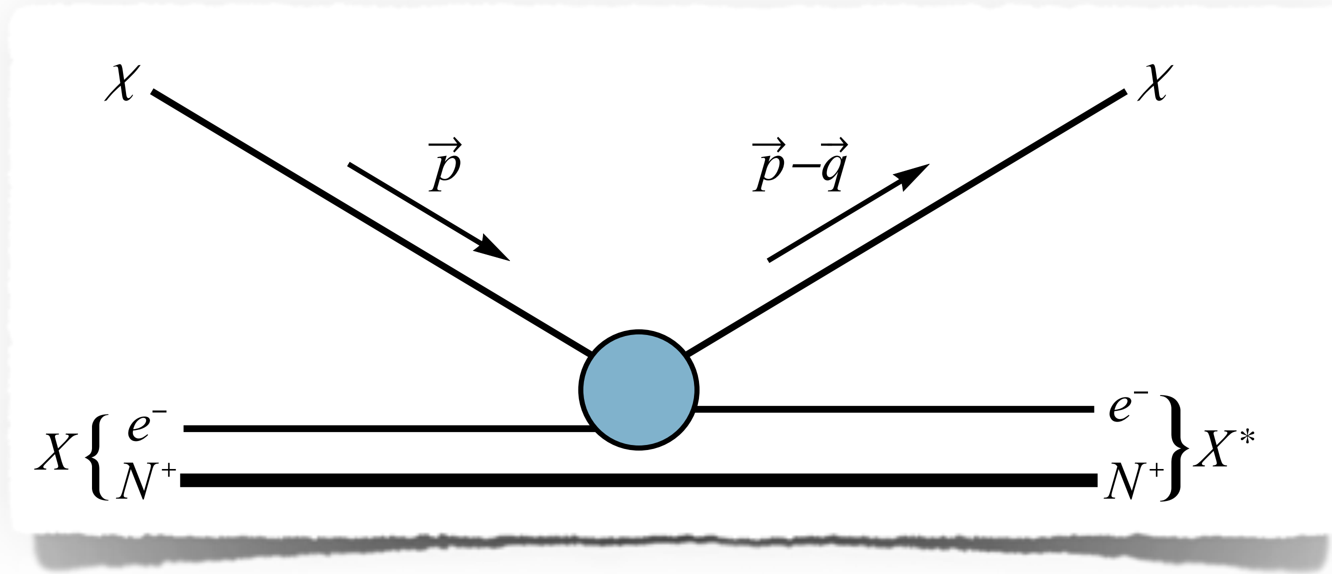


- energy deposition from recoil:
  $E_{NR} \simeq 2\mu_{X,N}^2 \cdot v_X^2/m_N$
  → for 100 MeV m_X ~ 1 eV E_{NR}*

* for silicon

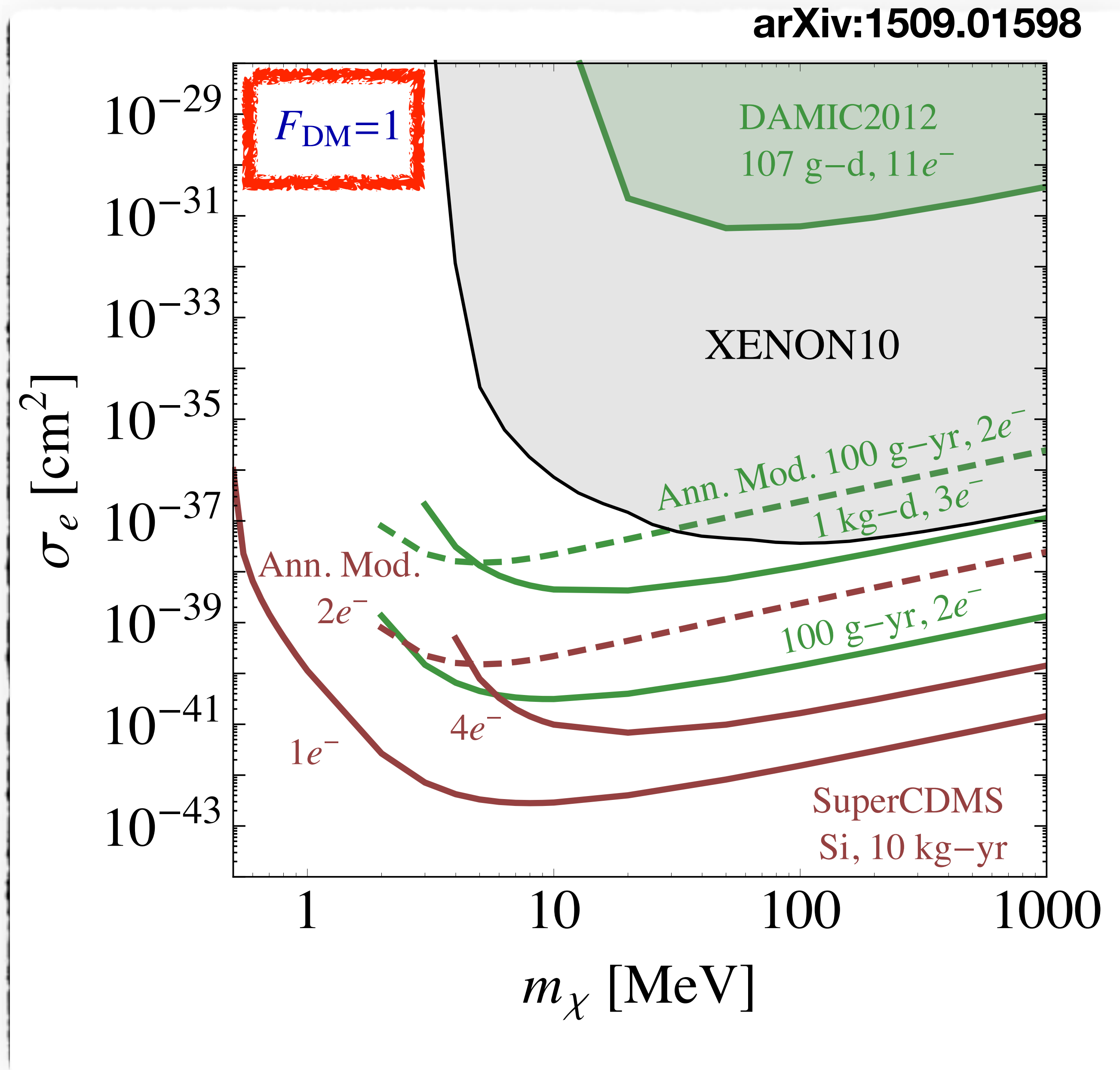
Detection techniques for light Dark Matter

- 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
- expected reach for Dark Matter $m_X \gtrsim 250$ keV · $(\Delta E_B/1\text{eV})$

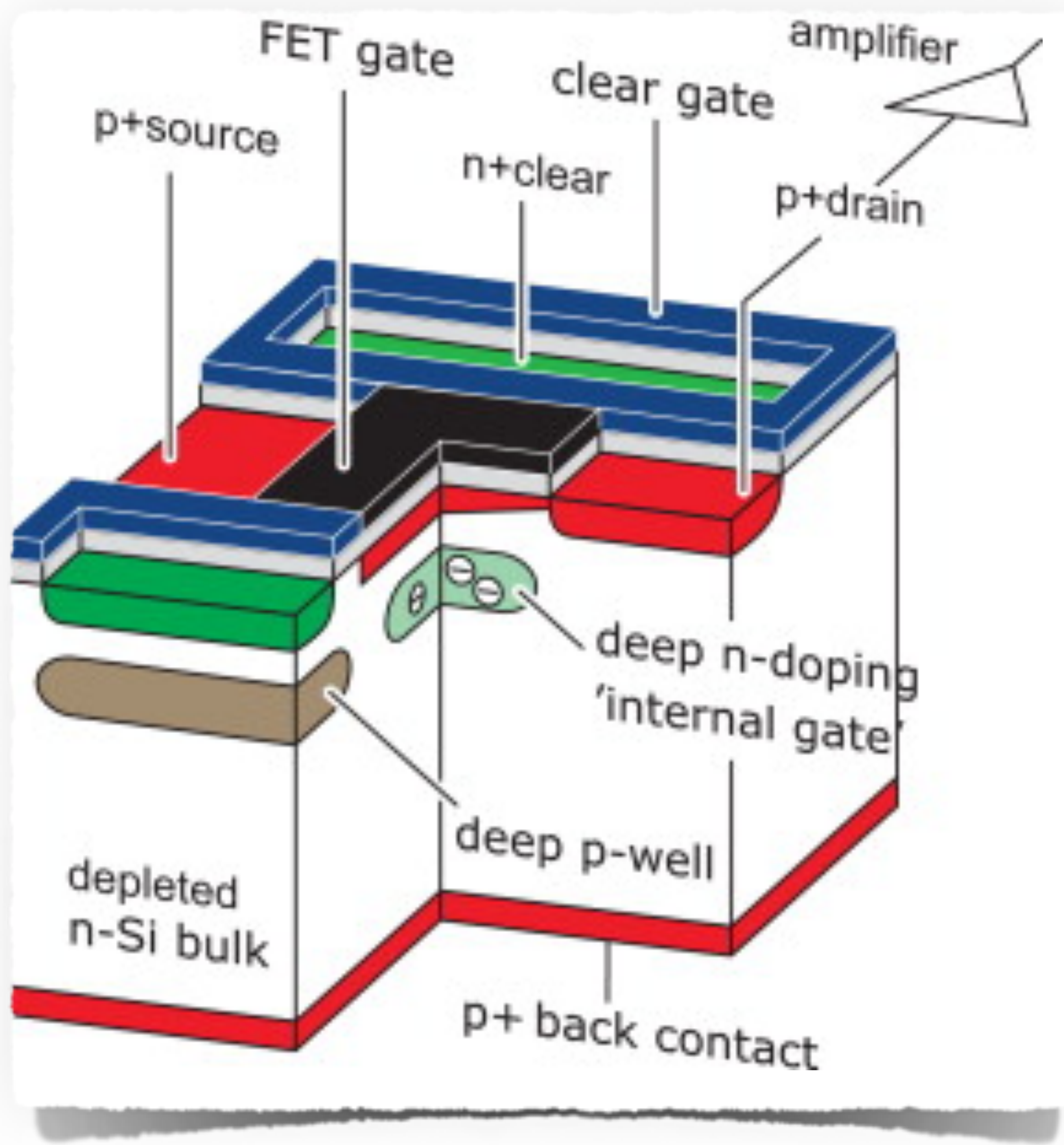
Detection techniques for light Dark Matter



- Dark Matter scatters on bound electrons in dense media
  - relation between energy deposition and momentum transfer differs to nuclear scattering
  - parametrised with a momentum dependent form factor F_{DM}
- **detection of single electrons with low noise**

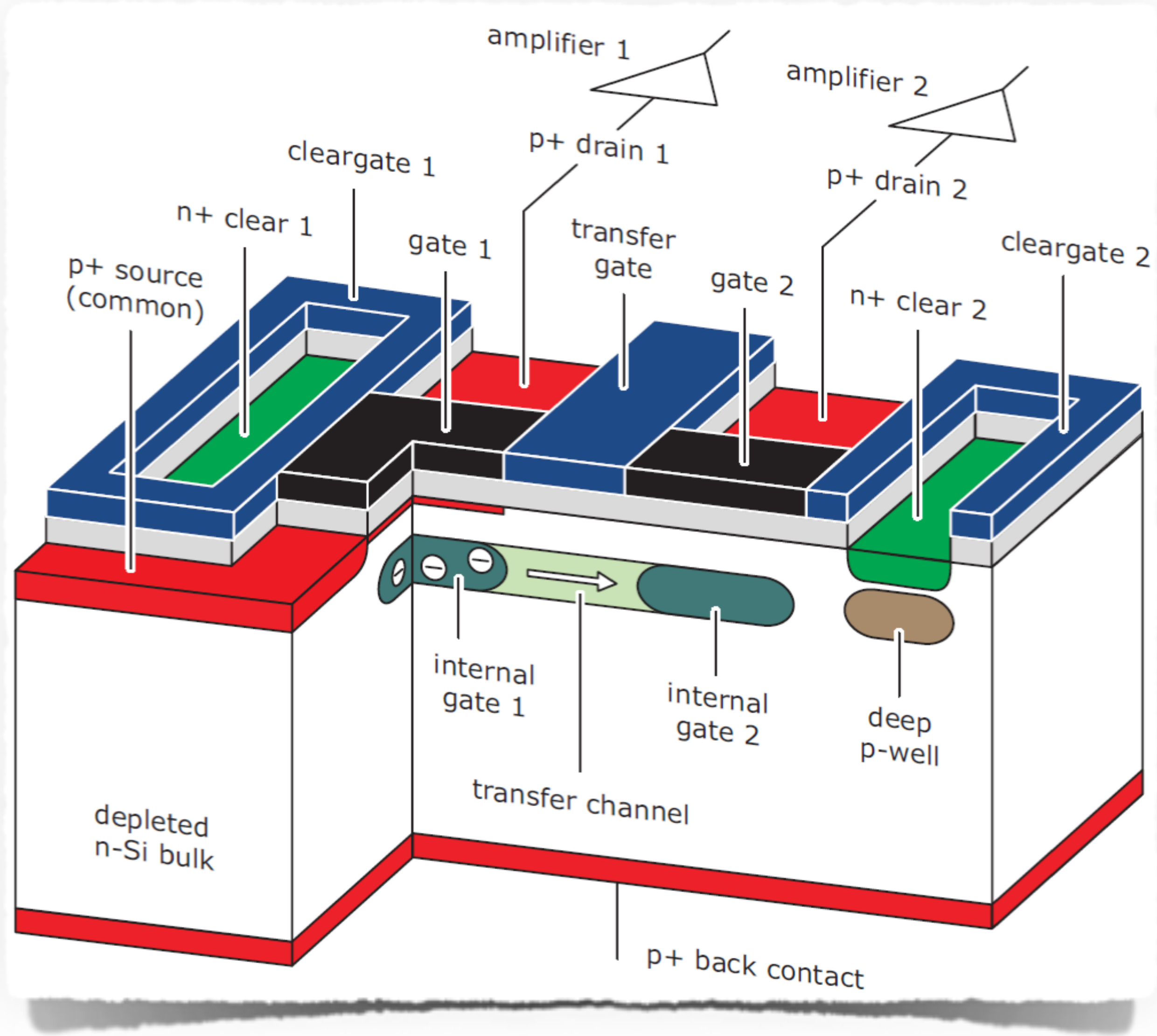
DEPFET detector as sub-GeV Dark Matter detector

- 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**



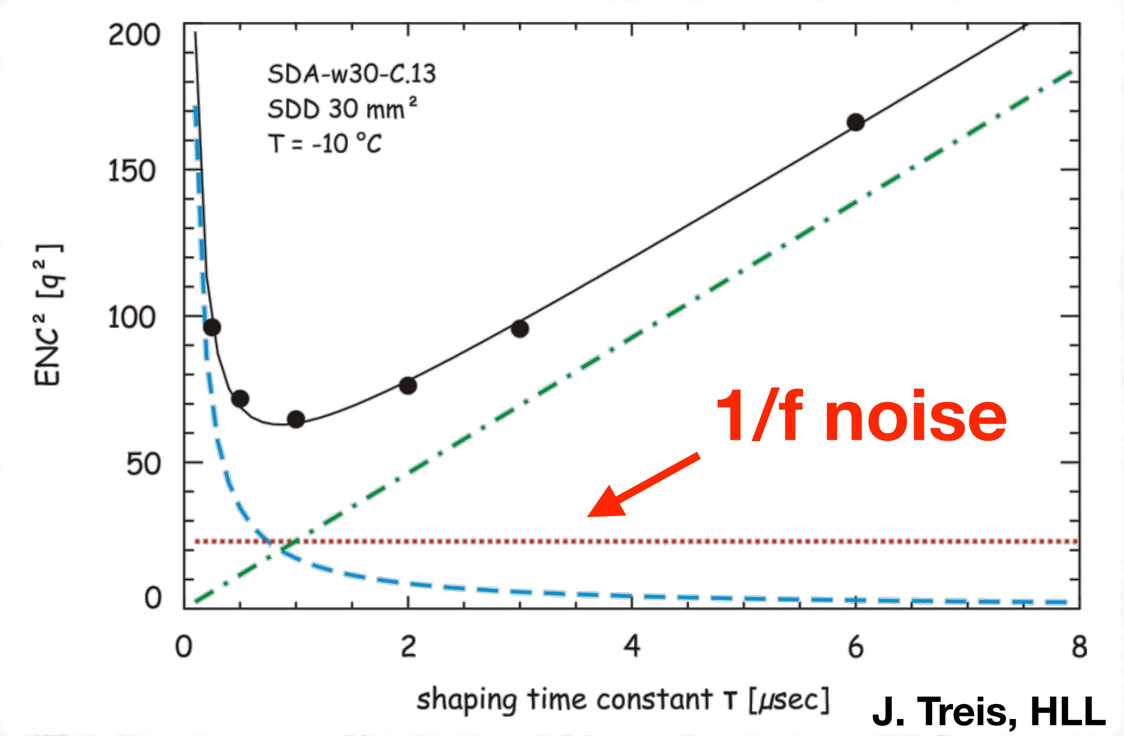
DEPFET detector as sub-GeV Dark Matter detector

- 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 $\sigma_{eff} \approx \sigma/\sqrt{N}$**

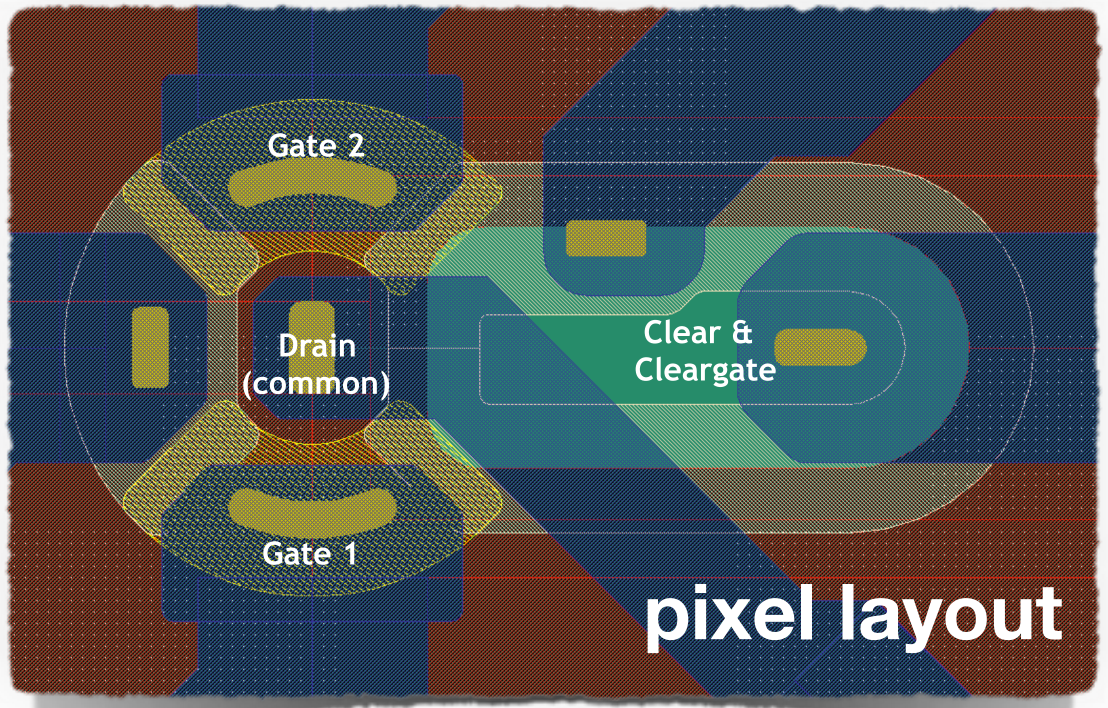


DEPFET-RNDR Prototypes

- proof-of-principle for DEPFET-RNDR demonstrated (Wölfel et al., NIMA 566 (2006) 536)
- DEPFET-RNDR prototype sensors are available
- 450 µm thickness, in principle up to 850 (1000?) µm possible
- “target mass” about 13 g / module

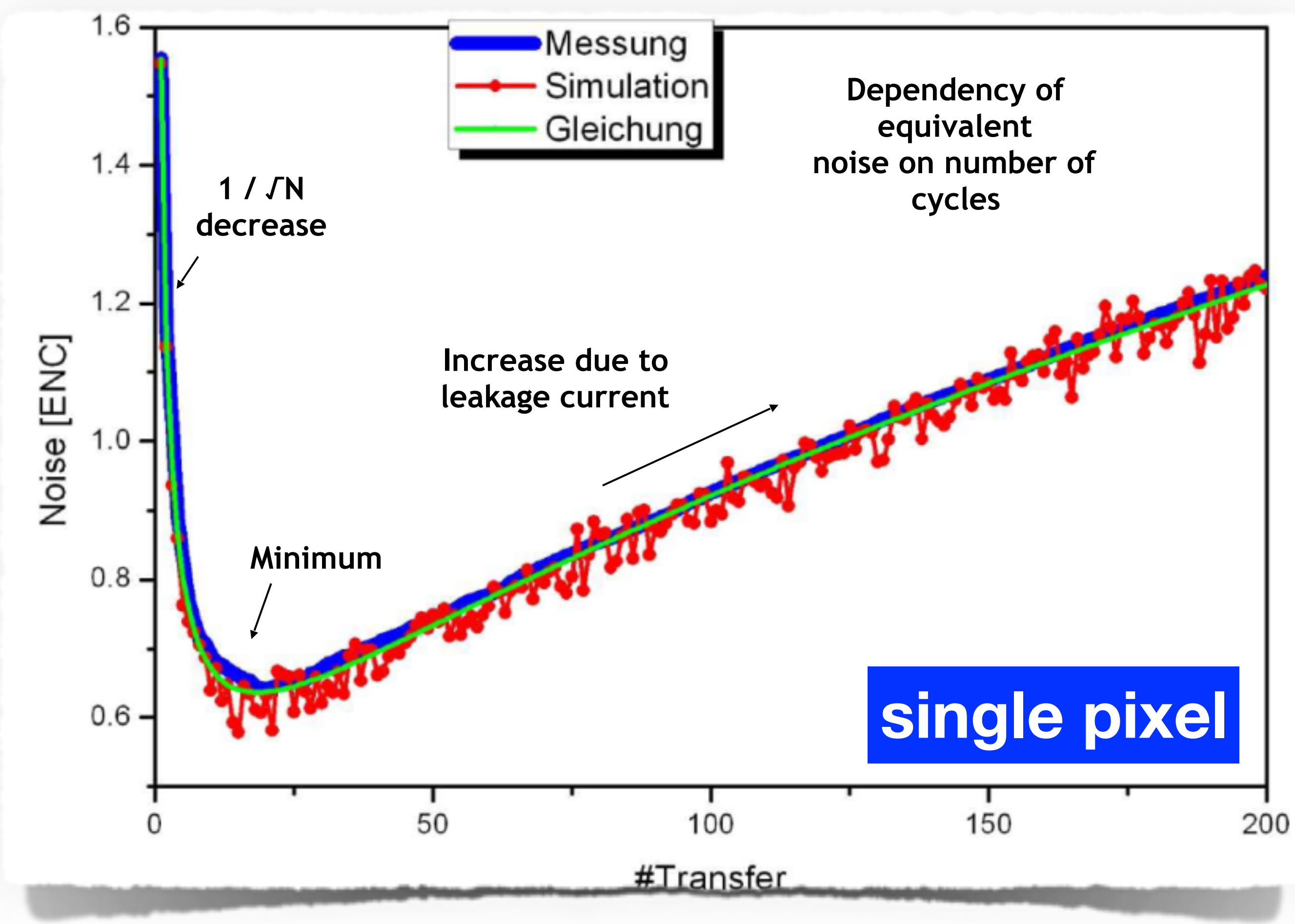


J. Treis, HLL



Measured Performance for DEPFET-RNDR

J. Treis, HLL



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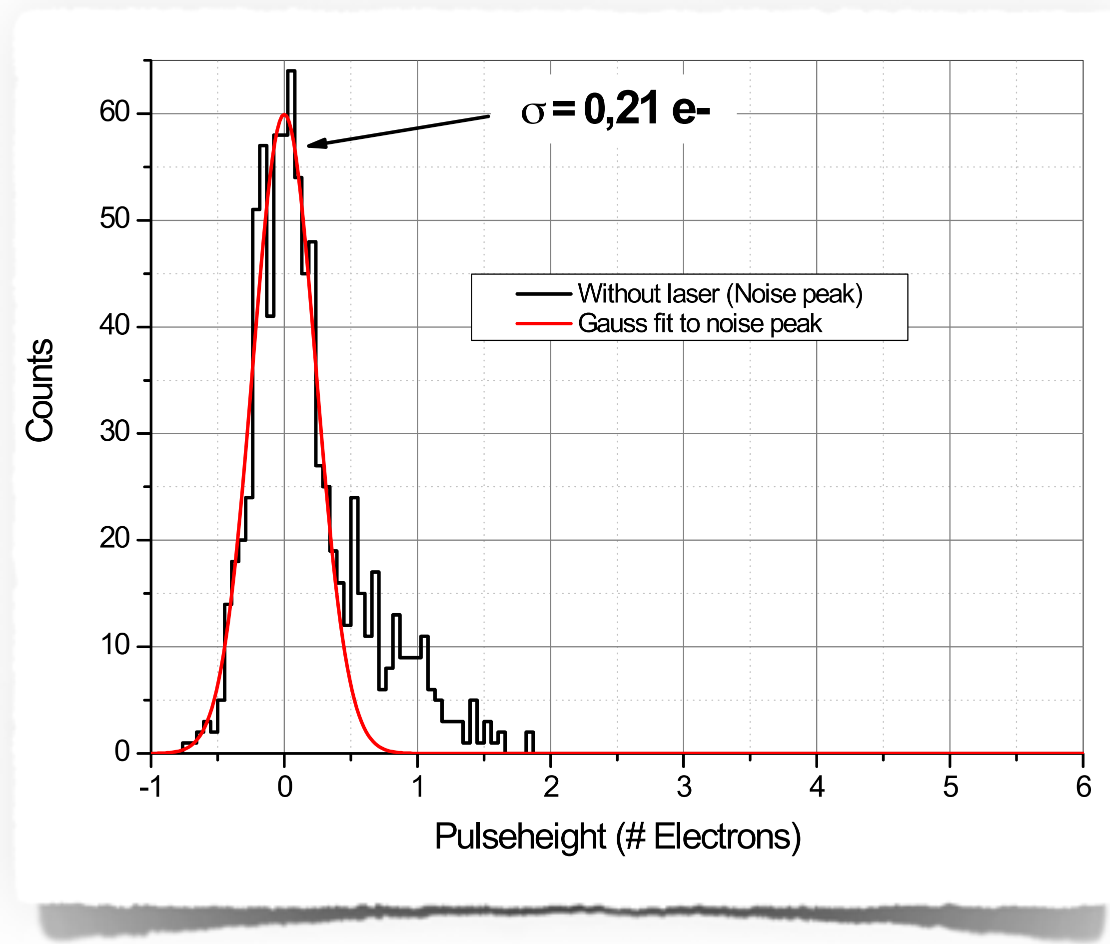
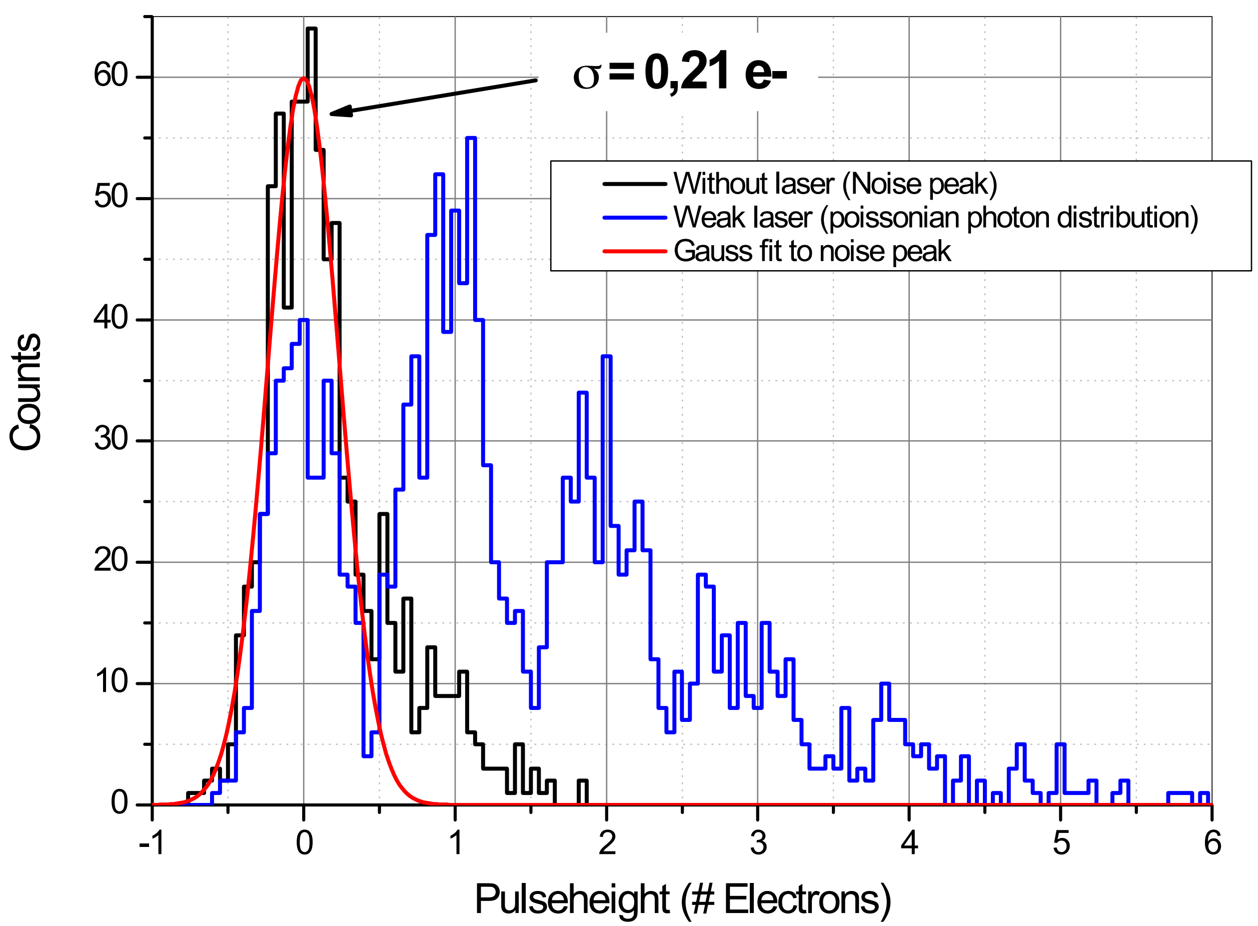


- noise performance as a function of readout cycles measured and reproduced by simulation

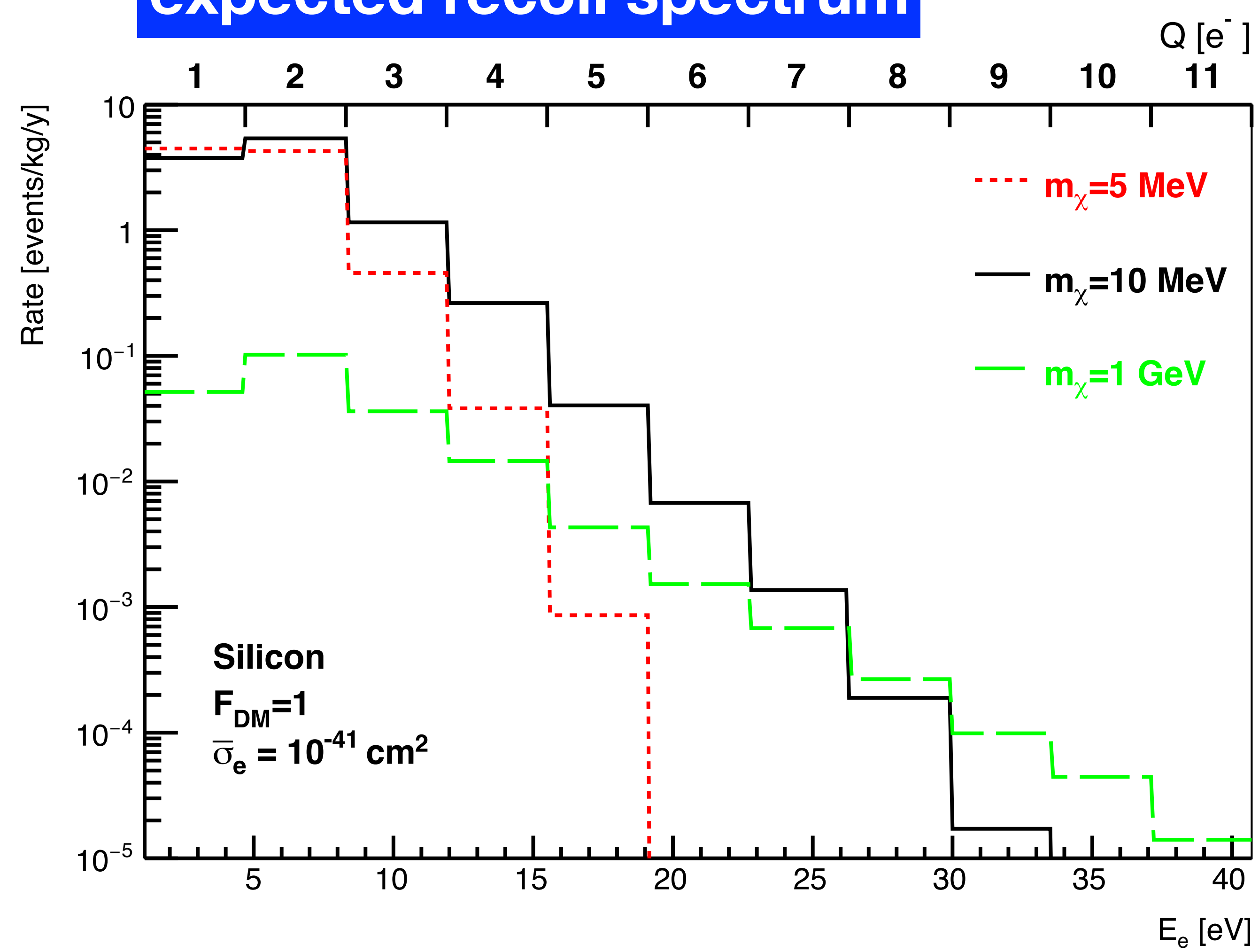
- **noise performance of σ=0,21 e$^-$ achieved**

Measurement of single electrons with DEPFET-RNDR

single pixel



expected recoil spectrum

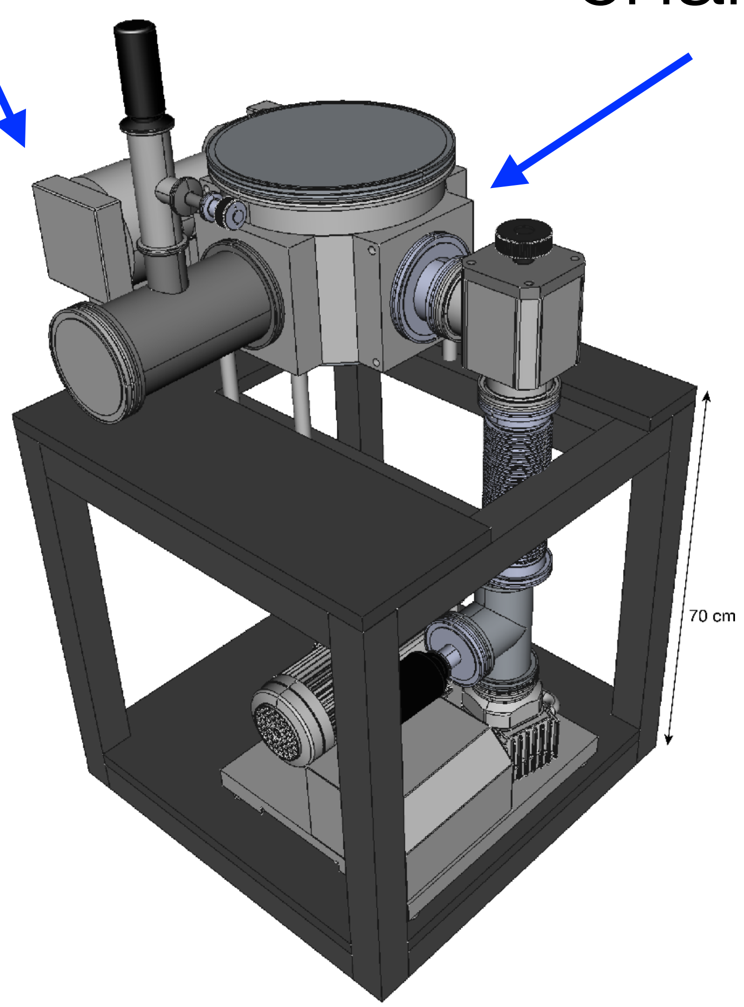


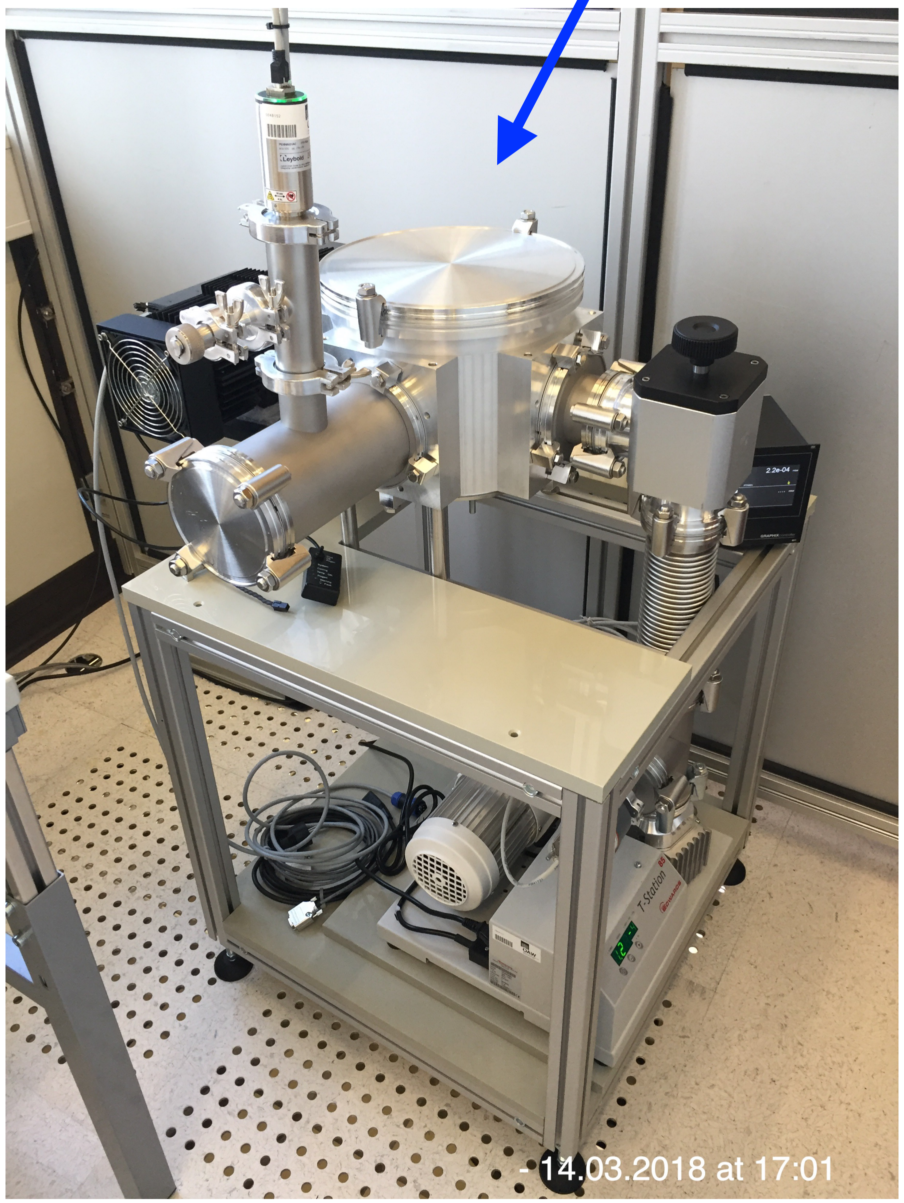
- measurement of single electrons with 5σ separation possible
- key issue: reduction of leakage current

Prototype test setup @ HLL

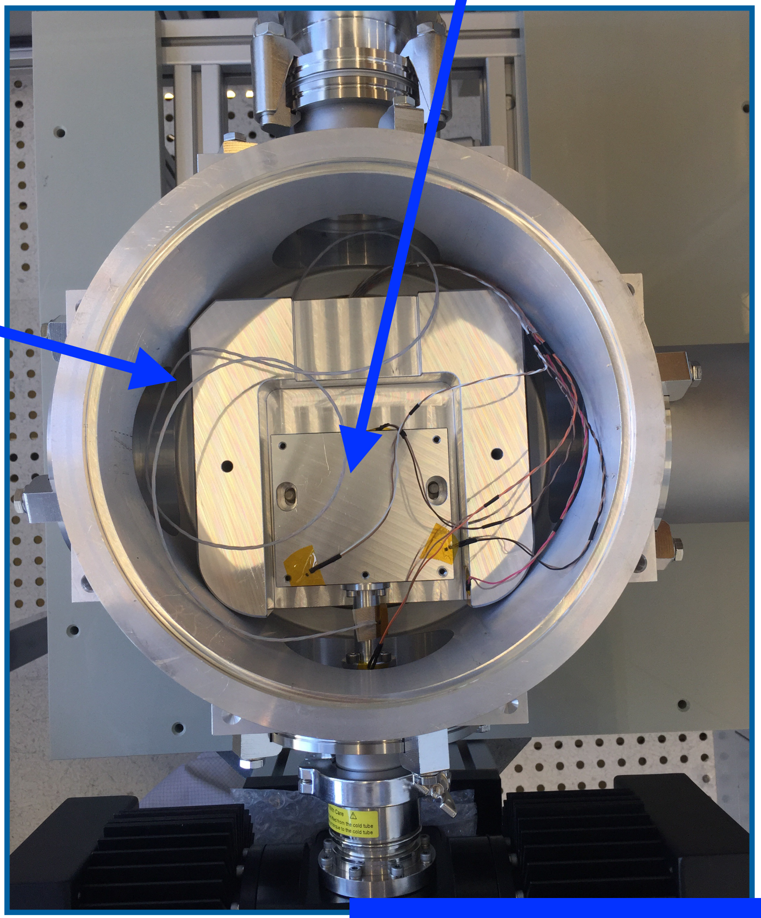
stirling cooler

vacuum chamber



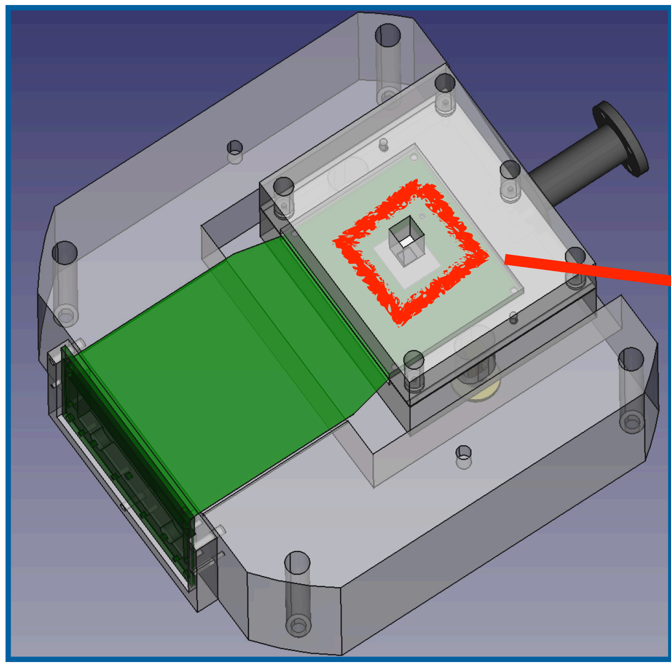


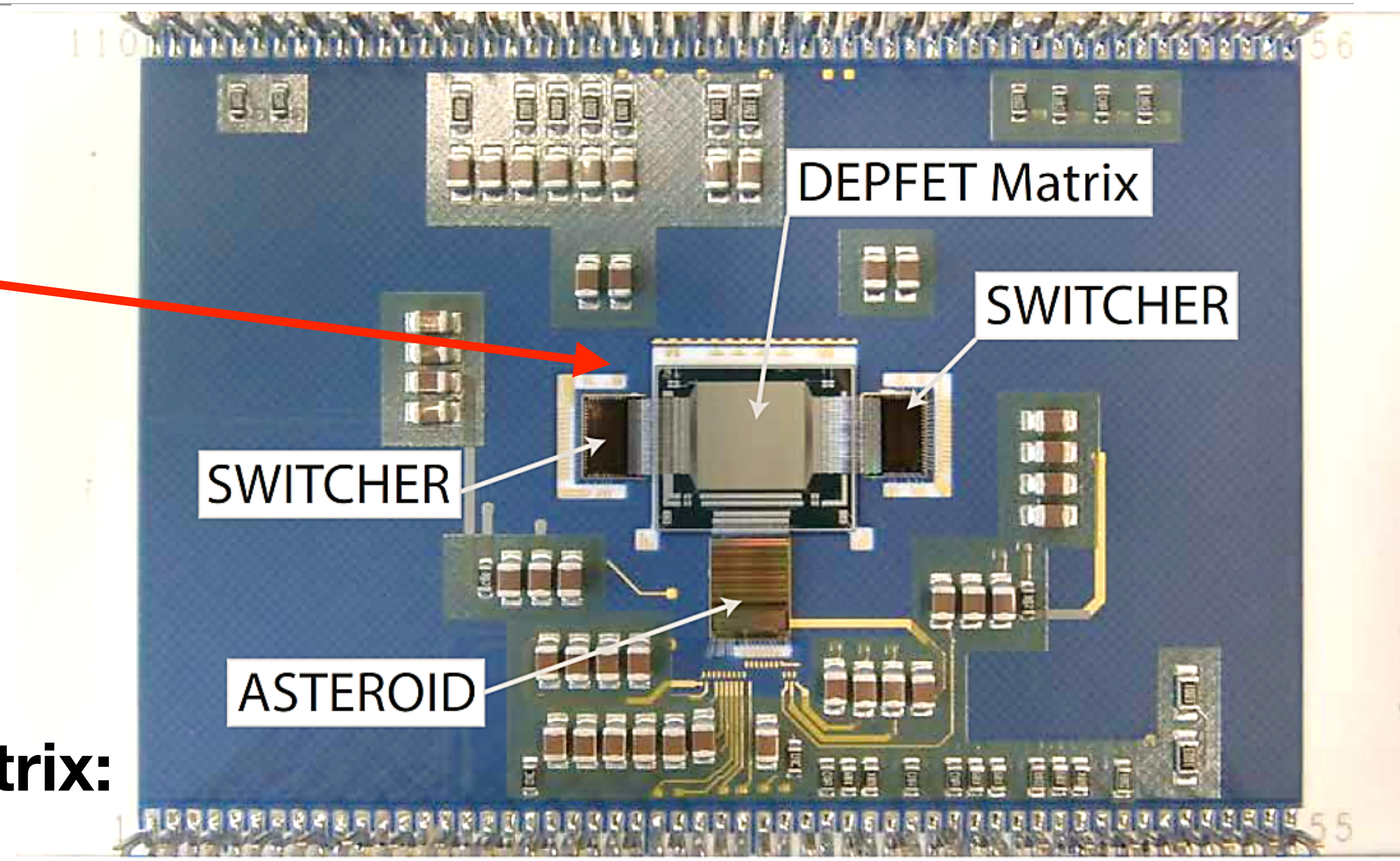
location of DEPFET sensor



150k reached at cooling pad

DEPFET-Sensor





Prototype detector matrix:

- 64pixel x 64pixel
- Single pixel: 75µm x 75µm x 450µm
- Sensitive volume: **24mg**

- software for operation of sensor readout under development
- first test to operate Sensor expected for summer

Expected Performance

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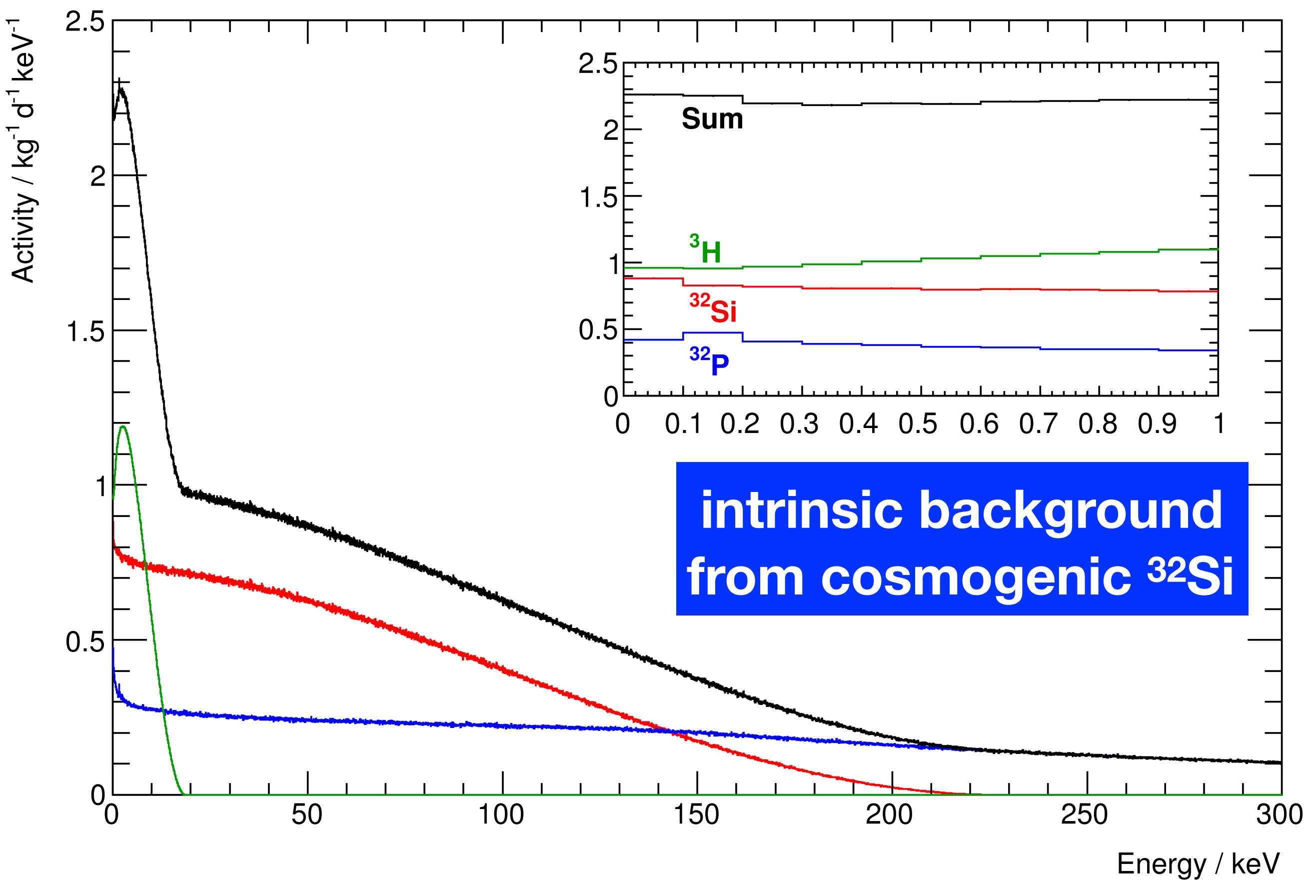

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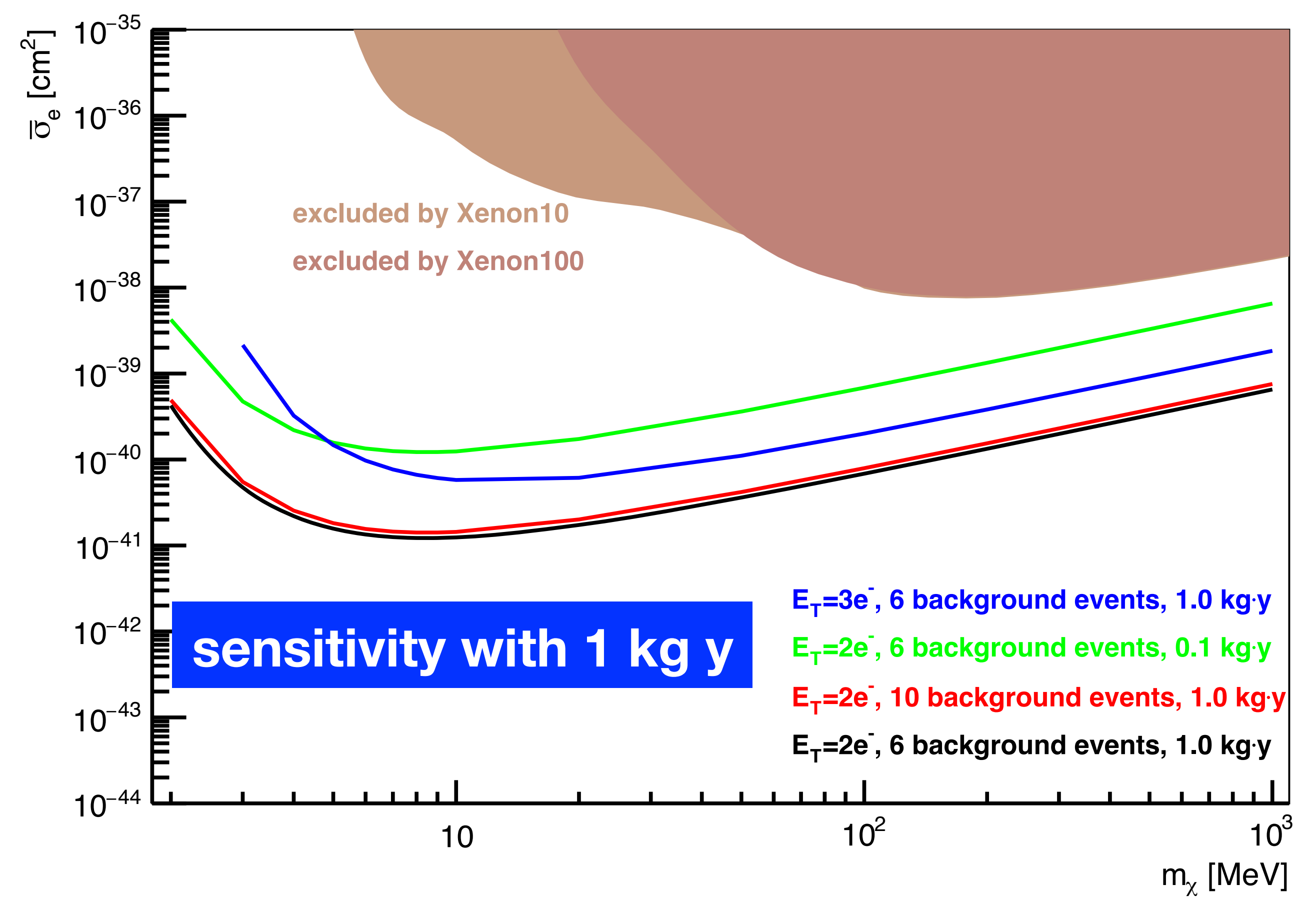

- first estimates indicate sensitivity down to few MeV
- contribution from intrinsic radiogenic background and leakage current to be experimentally studied

Summary

- the Standard Model of particle physics is an effective theory
    - some astro physical observations cannot be explained → **Dark Matter**
- new particle(s) could explain Dark Matter
    - several new theoretical models (strongly interacting Dark Matter, asymmetric Dark Matter, Dark Photons,…) predict new particles **in the sub-GeV region**
- key experimental technique: **energy detection threshold**
- **CRESST** aims for best Dark Matter limit in the ~300 MeV - 3 GeV region
- **DANAE** aims for the best Dark Matter limit in the ~1 - 100 MeV region