

Searching for low-mass dark matter *with cryogenic detectors*

J. Billard

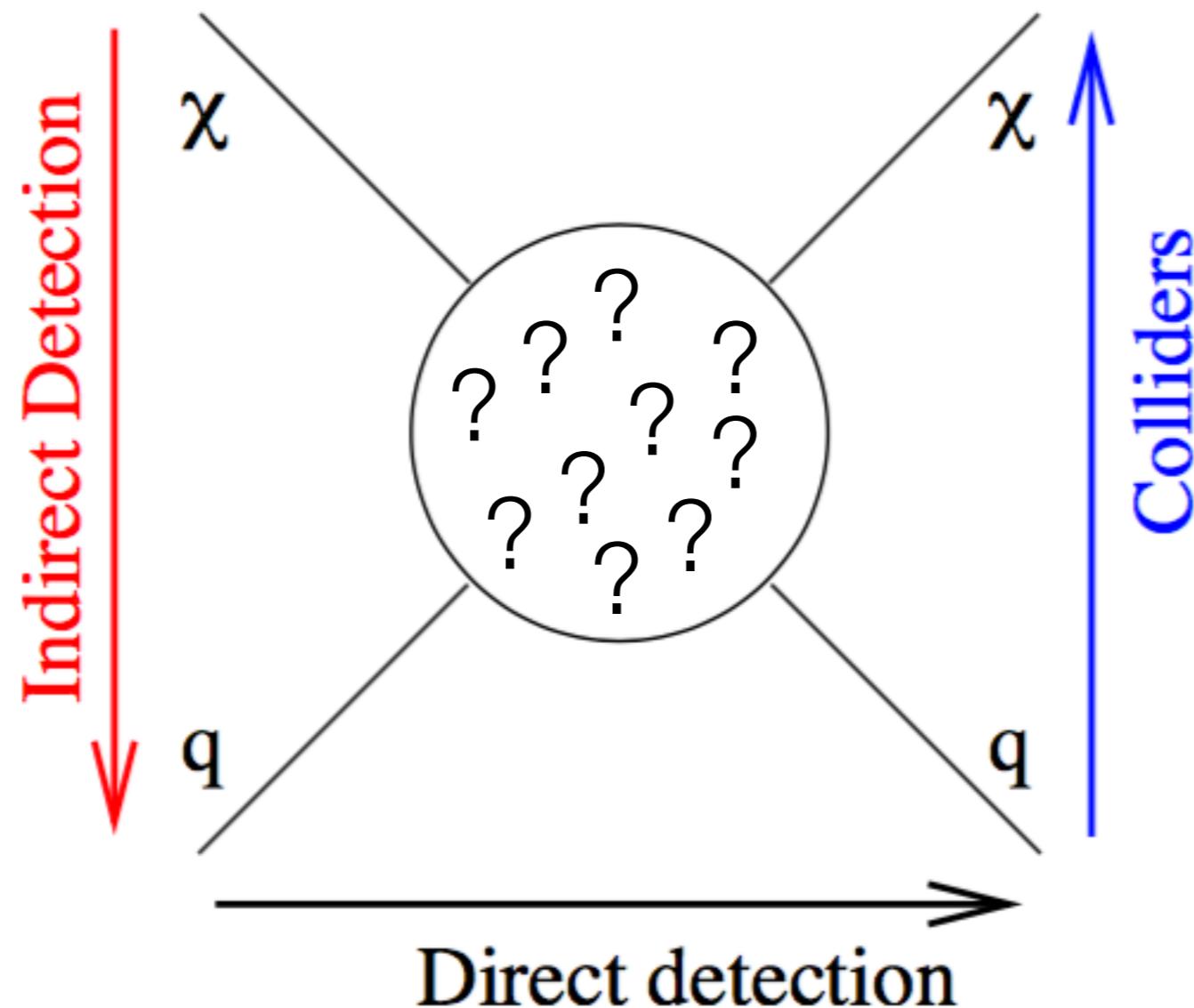
Institut de Physique Nucléaire de Lyon / CNRS / Université Lyon 1

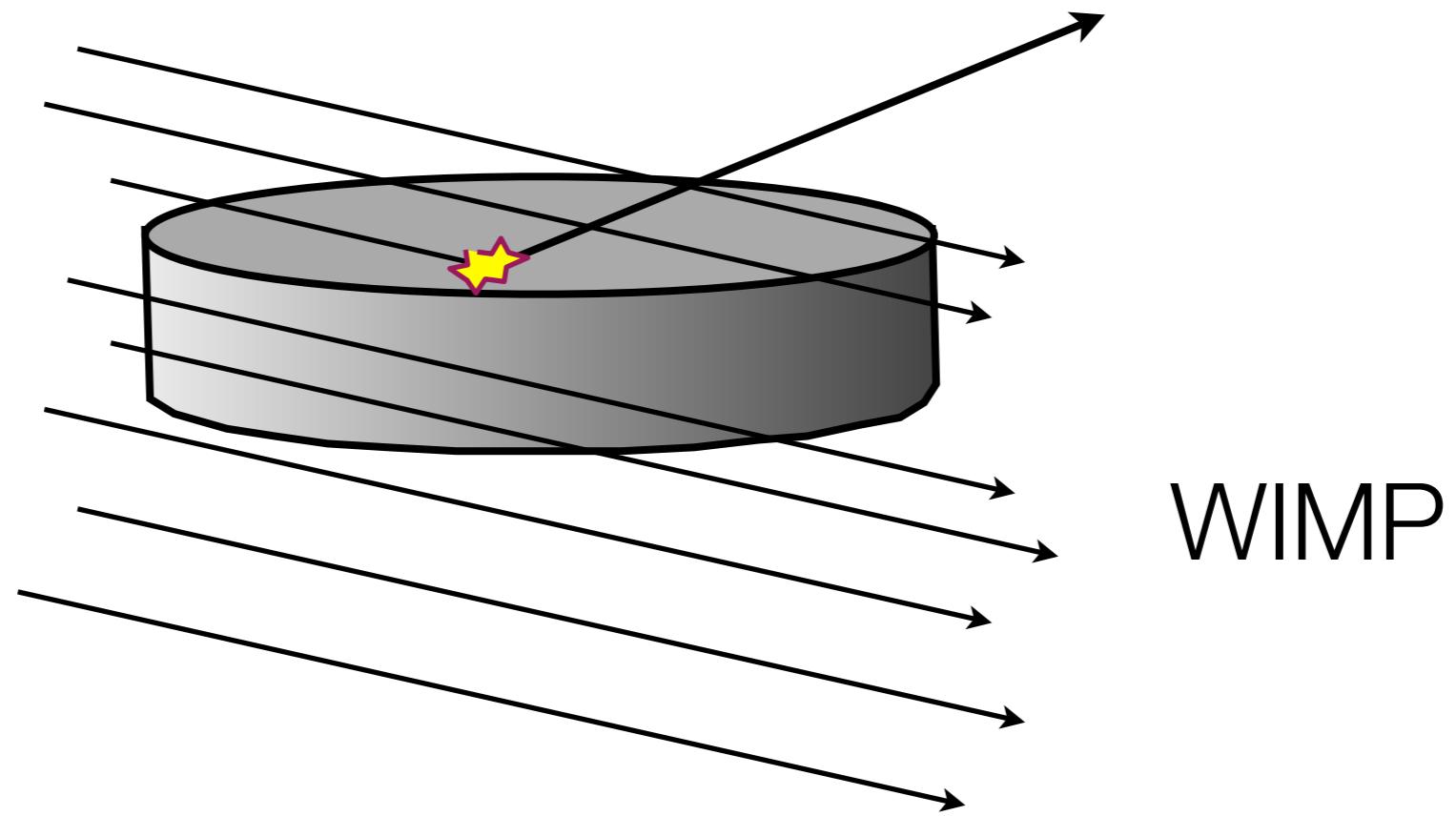
Dark Side of the Universe
Annecy, June 25, 2018



Introduction to direct detection

The hunt for Dark Matter:





A brief introduction to Direct Detection

Introduction to direct detection

Goodman & Witten (PRD 1985)

Differential event rate:

- Astrophysics
- Nuclear physics
- Particle physics

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2} \frac{\sigma_0}{m_\chi} F^2(E_r) \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$

Standard assumptions:

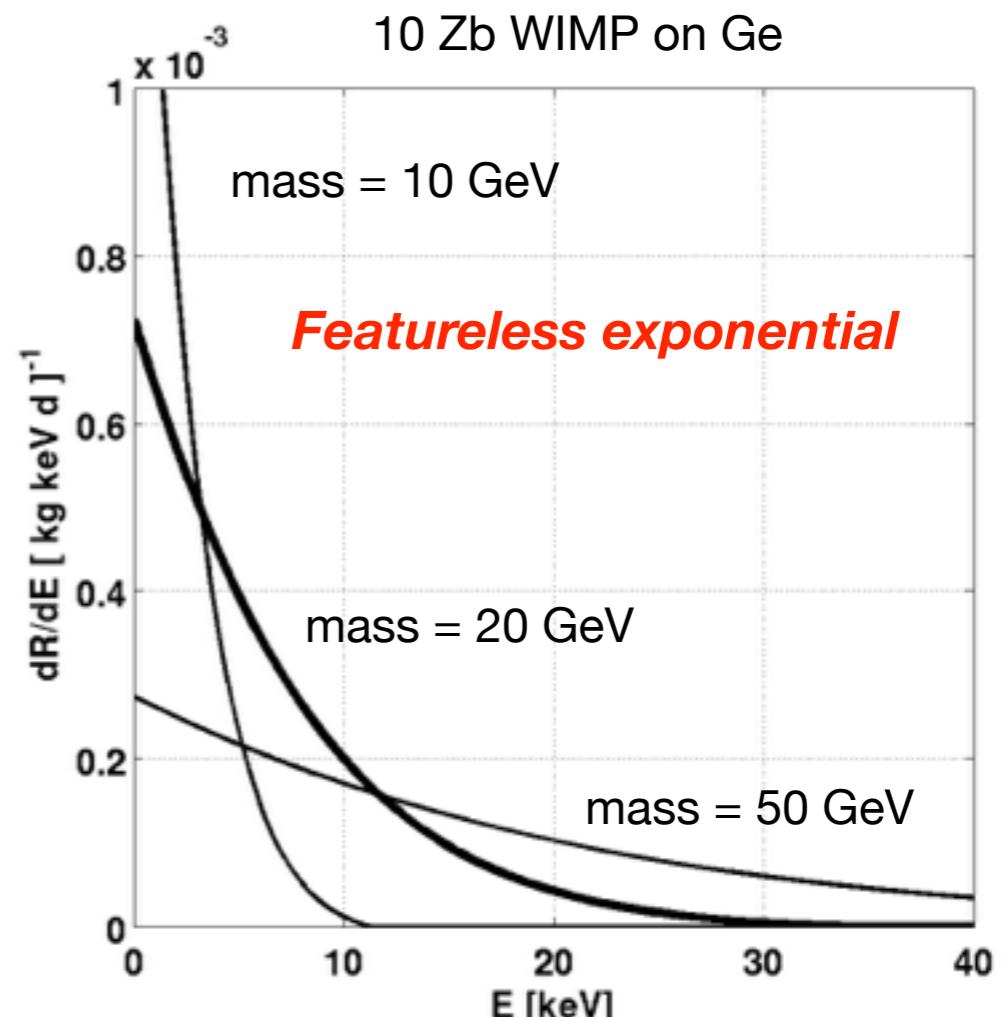
See N. Bozorgnia and T. Lacroix talks

- Maxwell Boltzmann « OK » (N. Bozorgnia et al. arXiv:1601.04707)
- Elastic WIMP-nucleus scattering
- Spin dependent and independent interactions
- *But could be much more complex* *See B. Kavanagh talk*



Direct detection challenges:

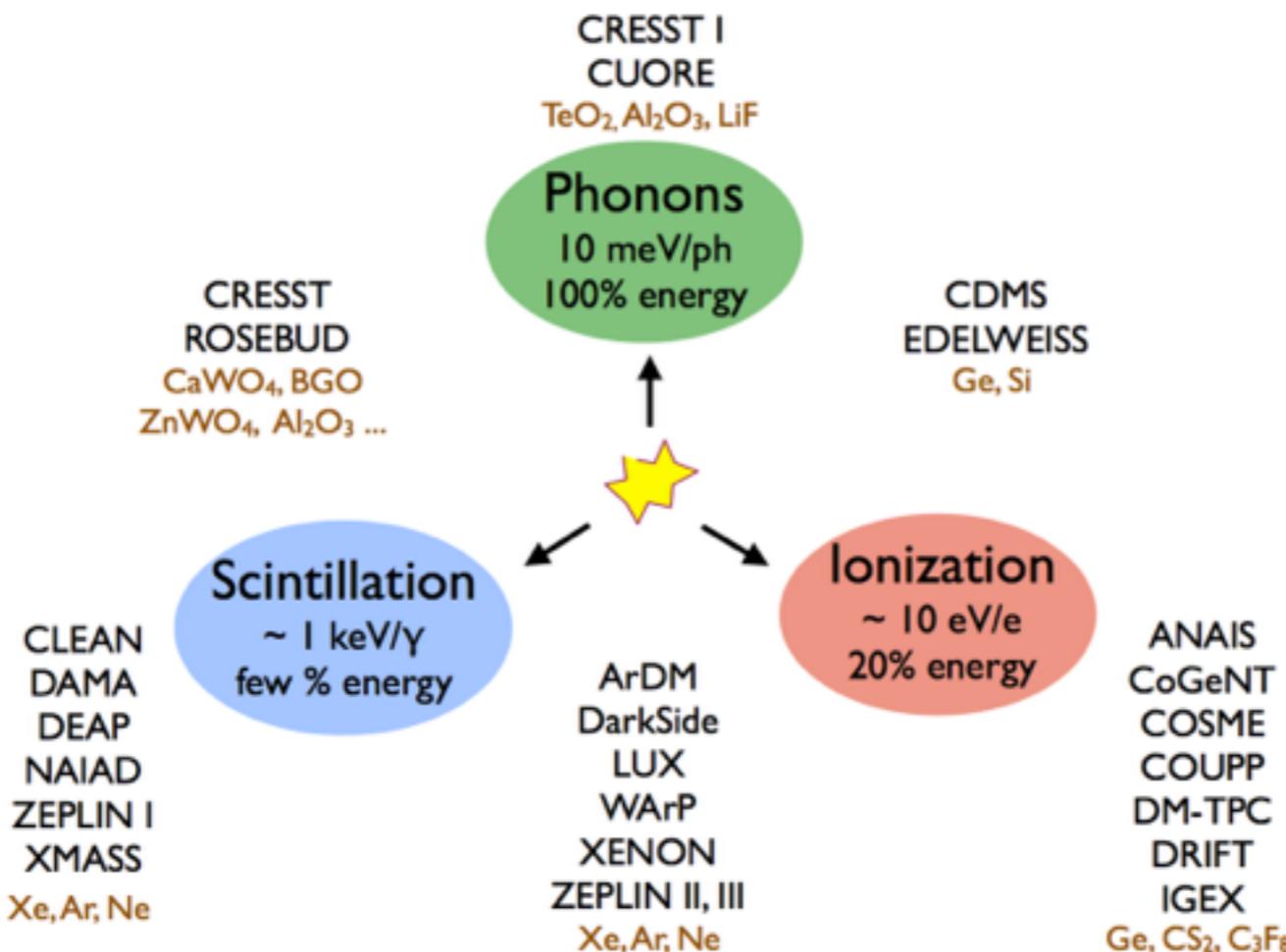
- **Low event rate:** $R < O(10)$ evts/ton/year
- **Background reduction:** *active + passive*
- **Mean recoil energy:** $\sim O(10)$ keV



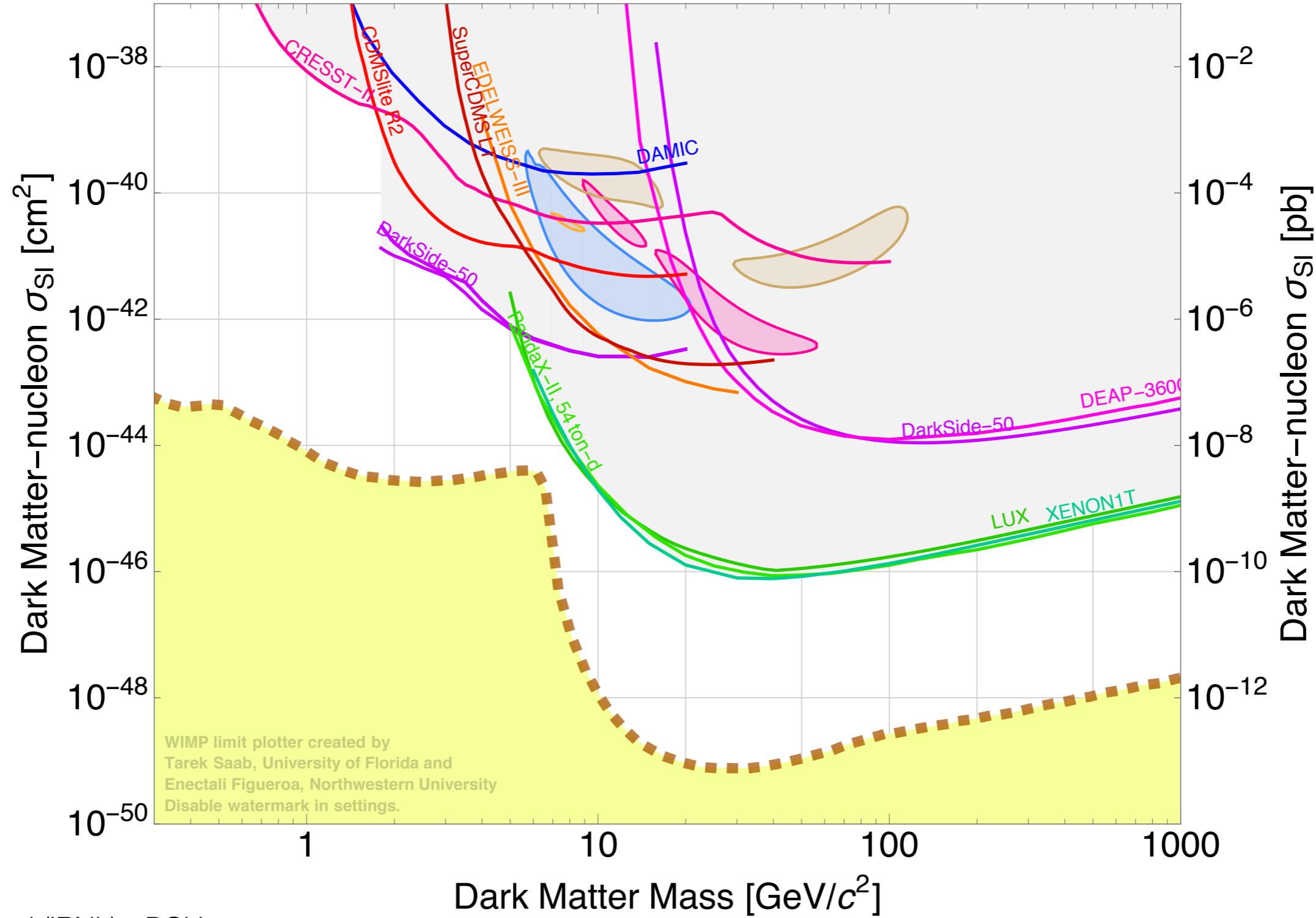
Designing a direct detection experiment

The « wish list » for a standard direct detection experiment:

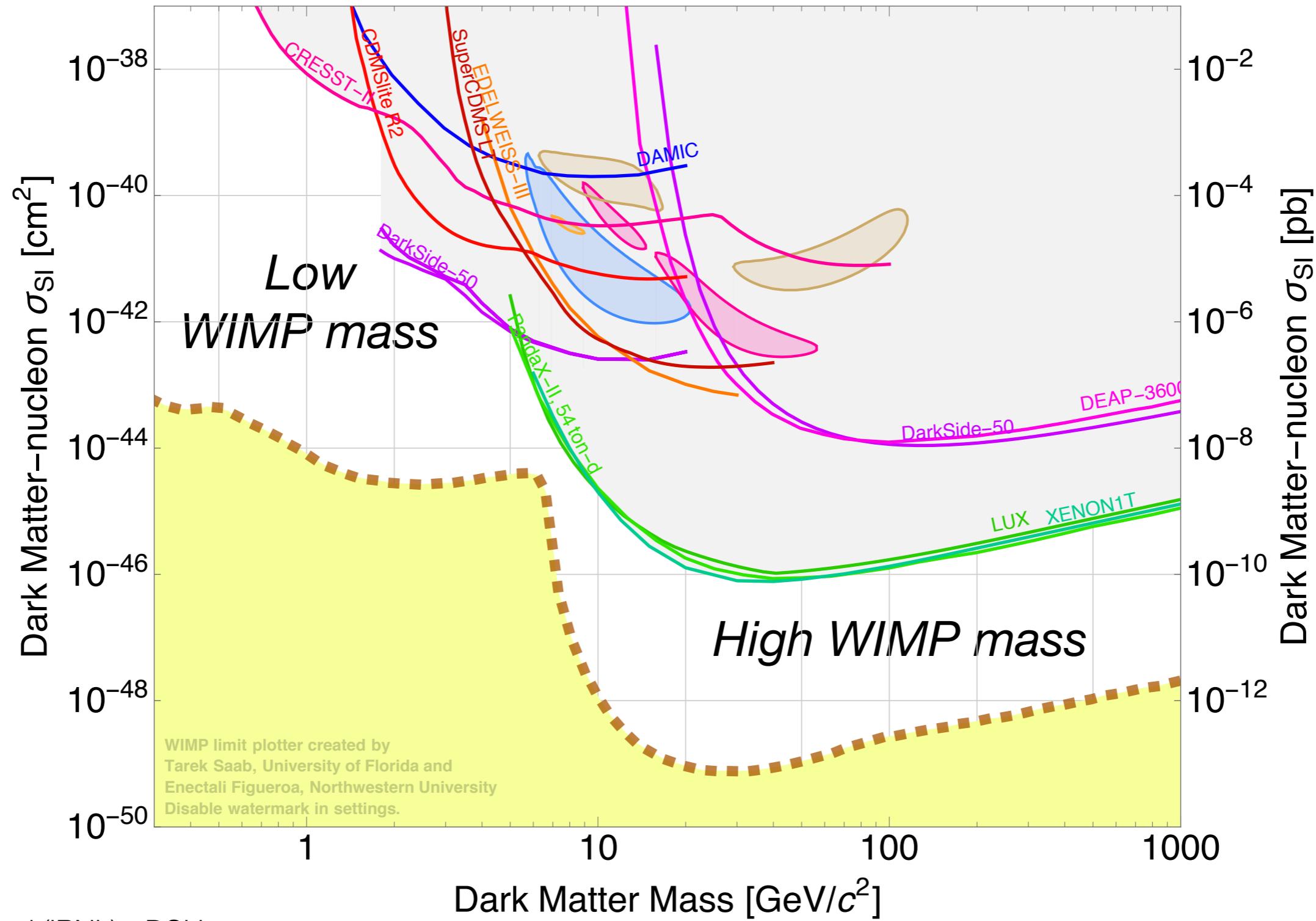
- **Large exposure** (few events per ton-year)
- **Low and controlled backgrounds**
- **Low energy threshold**
- **Discrimination** between signal and background



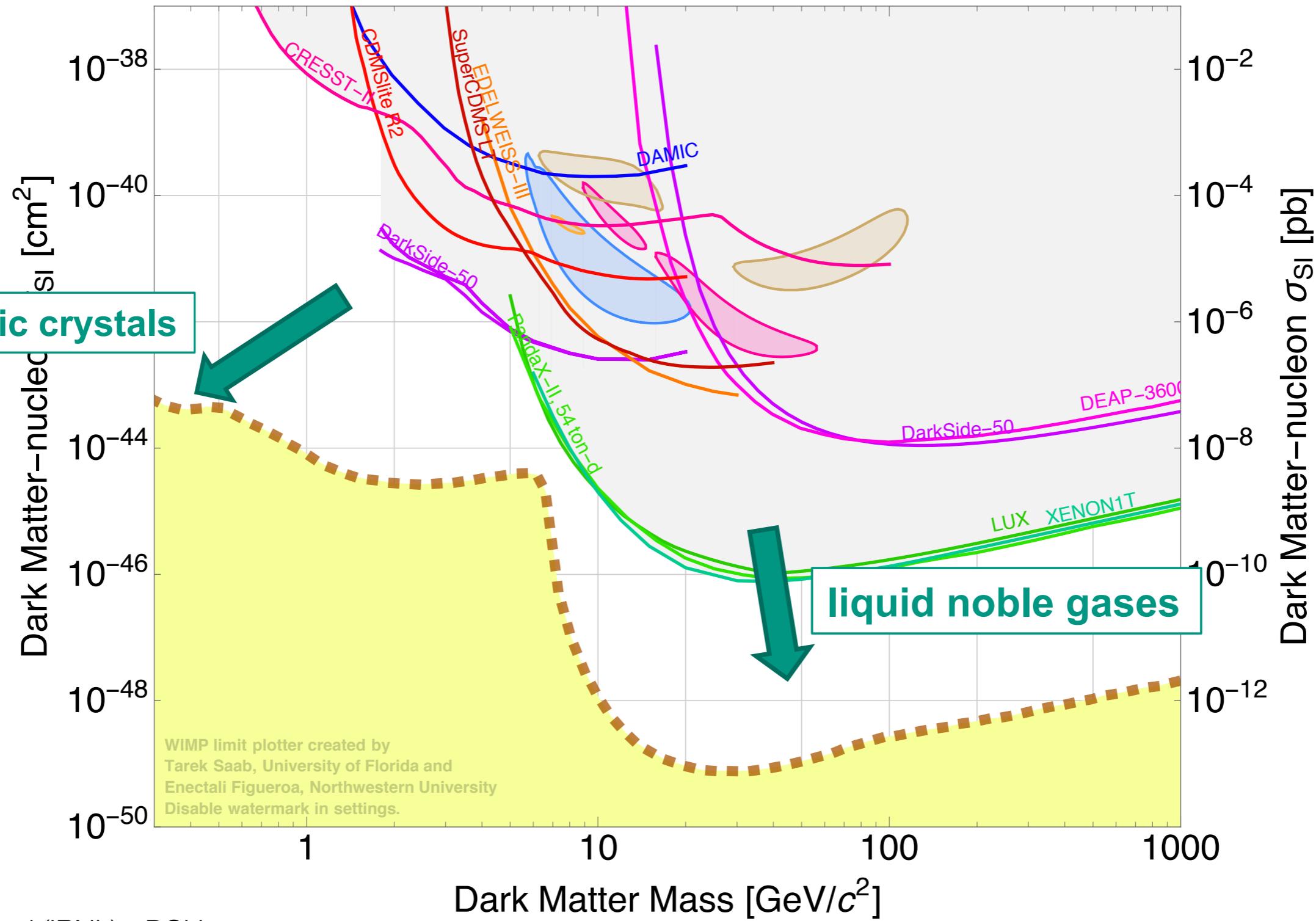
Introduction to direct detection

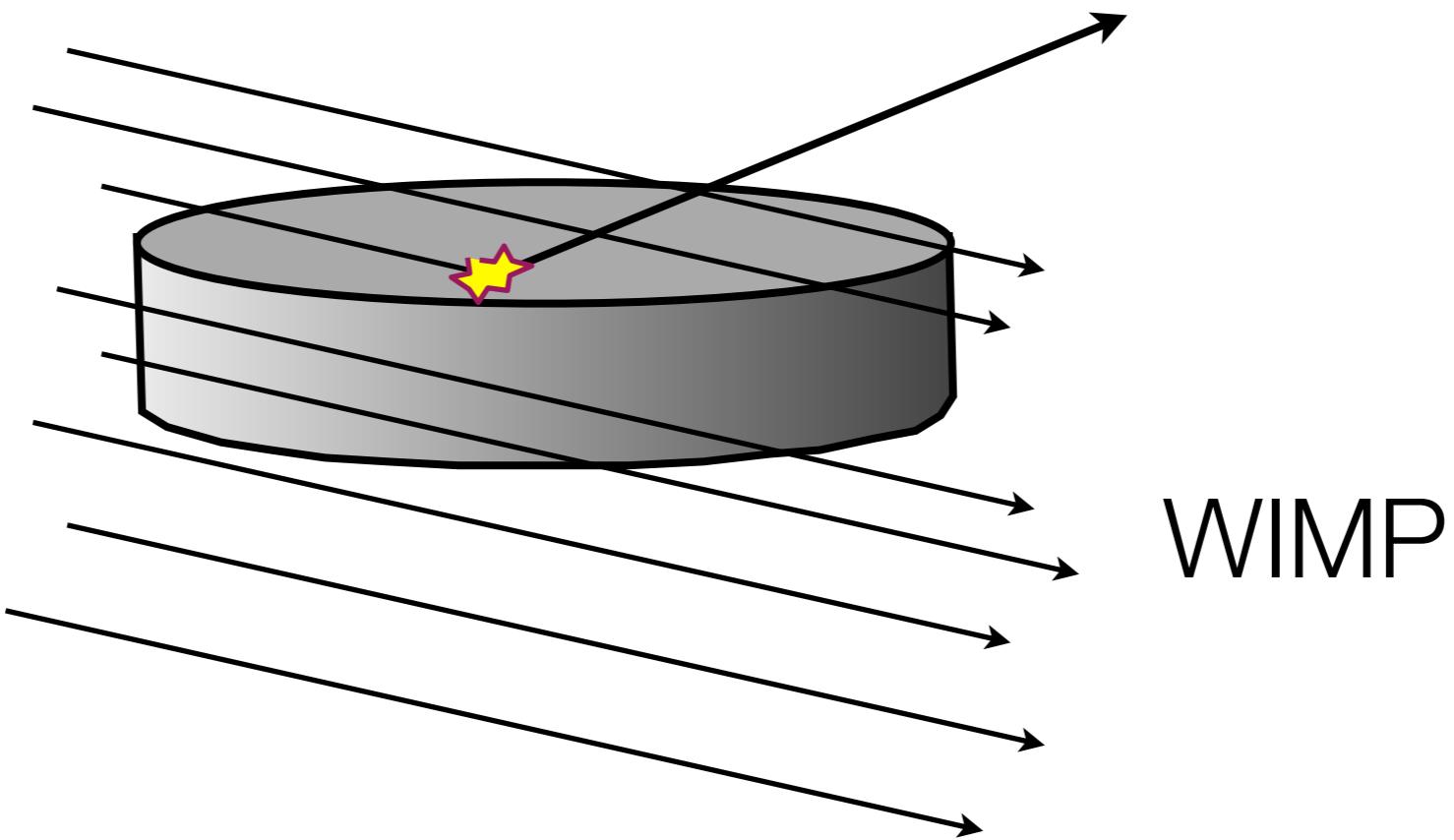


Introduction to direct detection



Introduction to direct detection

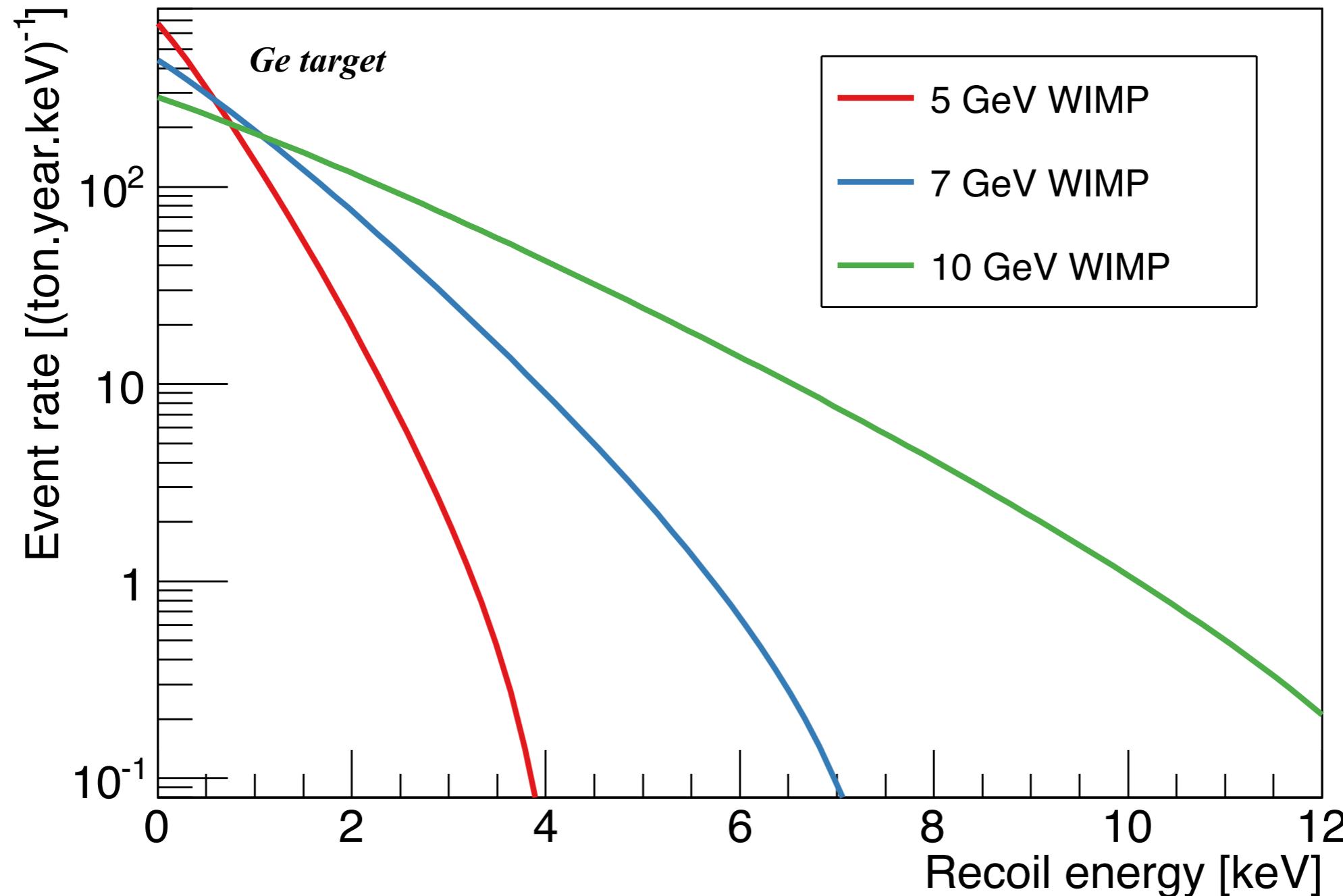




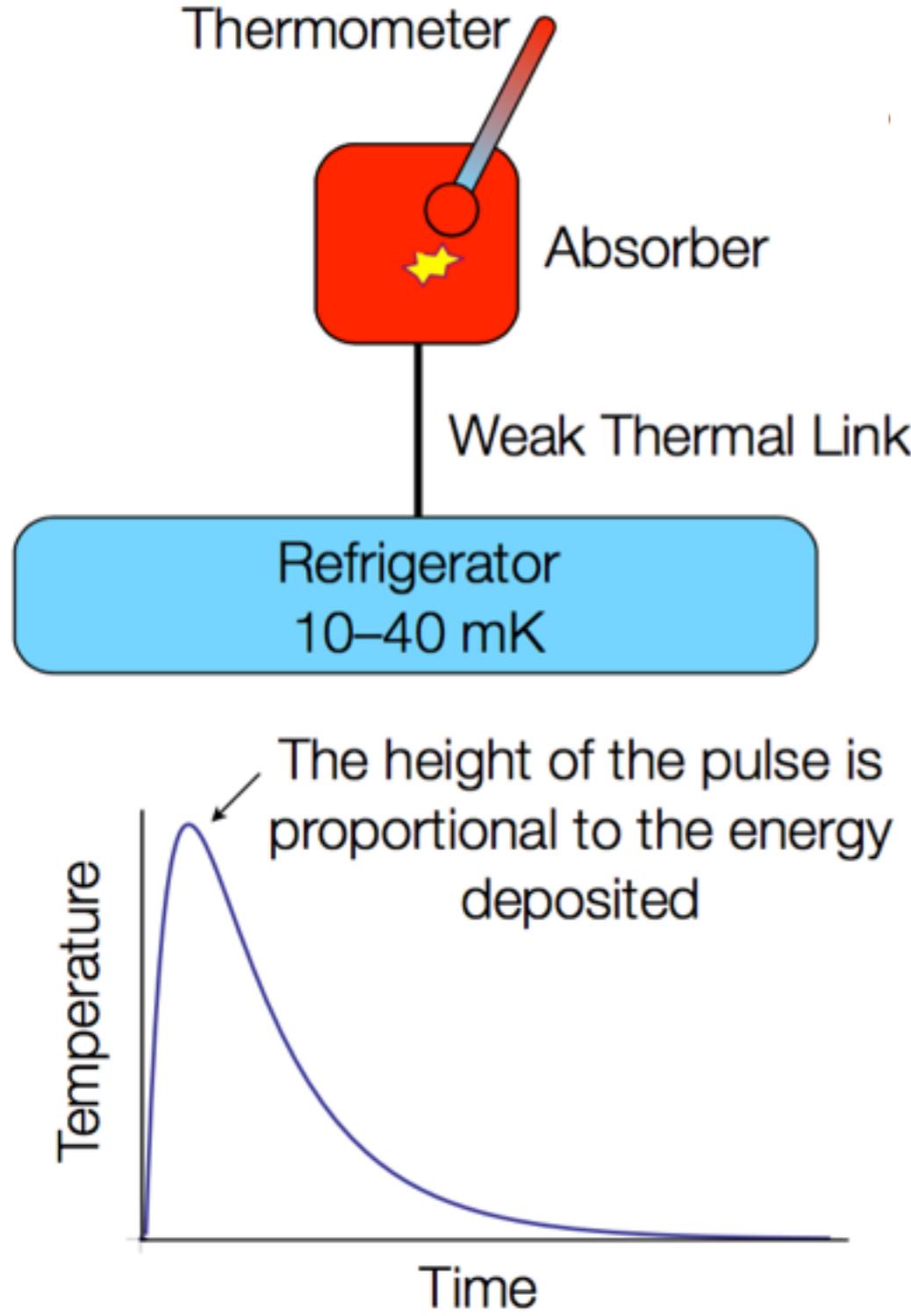
Searching for low-mass dark matter
with cryogenic detectors (GeV - scale)

Searching for low-mass Dark Matter (GeV-scale)

Lowering the energy threshold is the key for low-mass WIMP searches



Searching for low-mass Dark Matter (GeV-scale)



- Advantages of a phonon readout:
 - Direct measurement of the recoil energy, *no quenching involved*
 - ~100 % of the recoil energy is sensed, *allowing for low-thresholds*
 - *No intrinsic threshold (meV)*
 - From thermodynamics, ultimate energy resolution is: **~eV (RMS) for ~ 10 g detectors**
- Phonon readout can be done in two ways:
 - Thermal measurement (EDELWEISS)
 - Athermal measurement (CRESST/SCDMS)

$$E_T \propto M_{\text{detector}}^n$$

Scaling law ($n \sim 1$) depends on phonon readout

Searching for low-mass Dark Matter (GeV-scale)

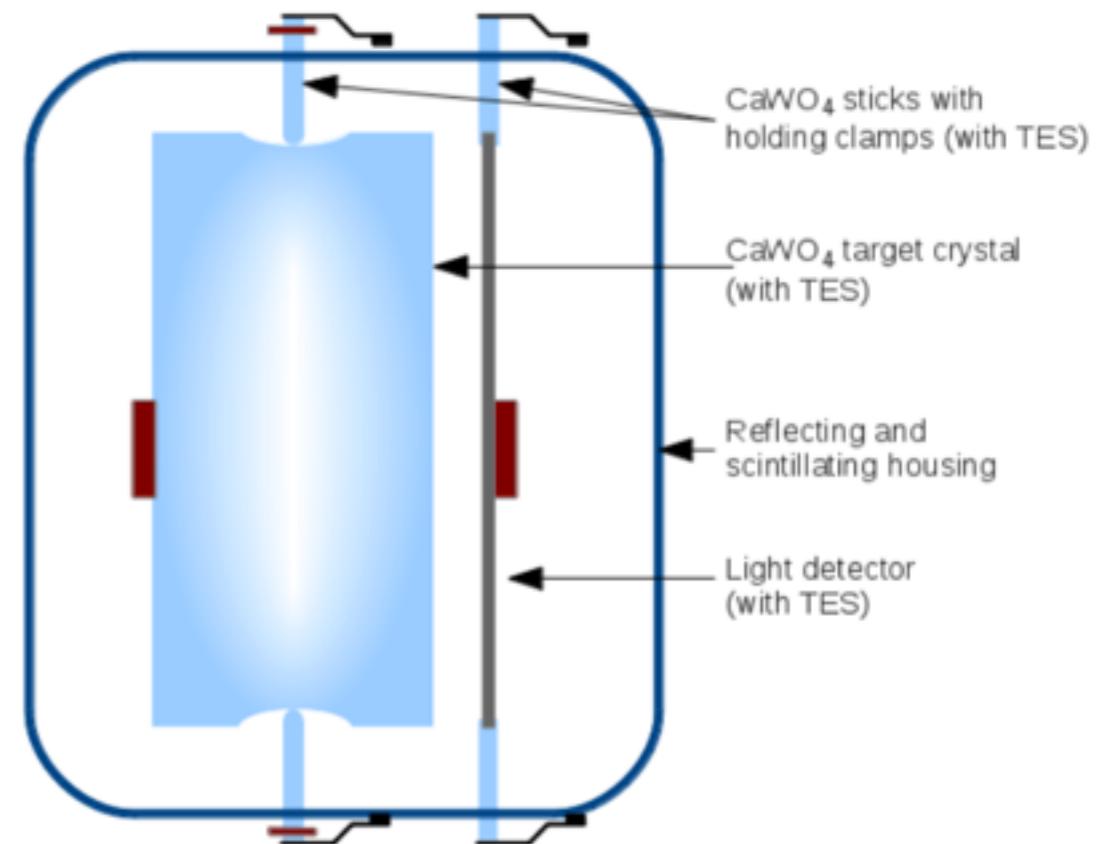
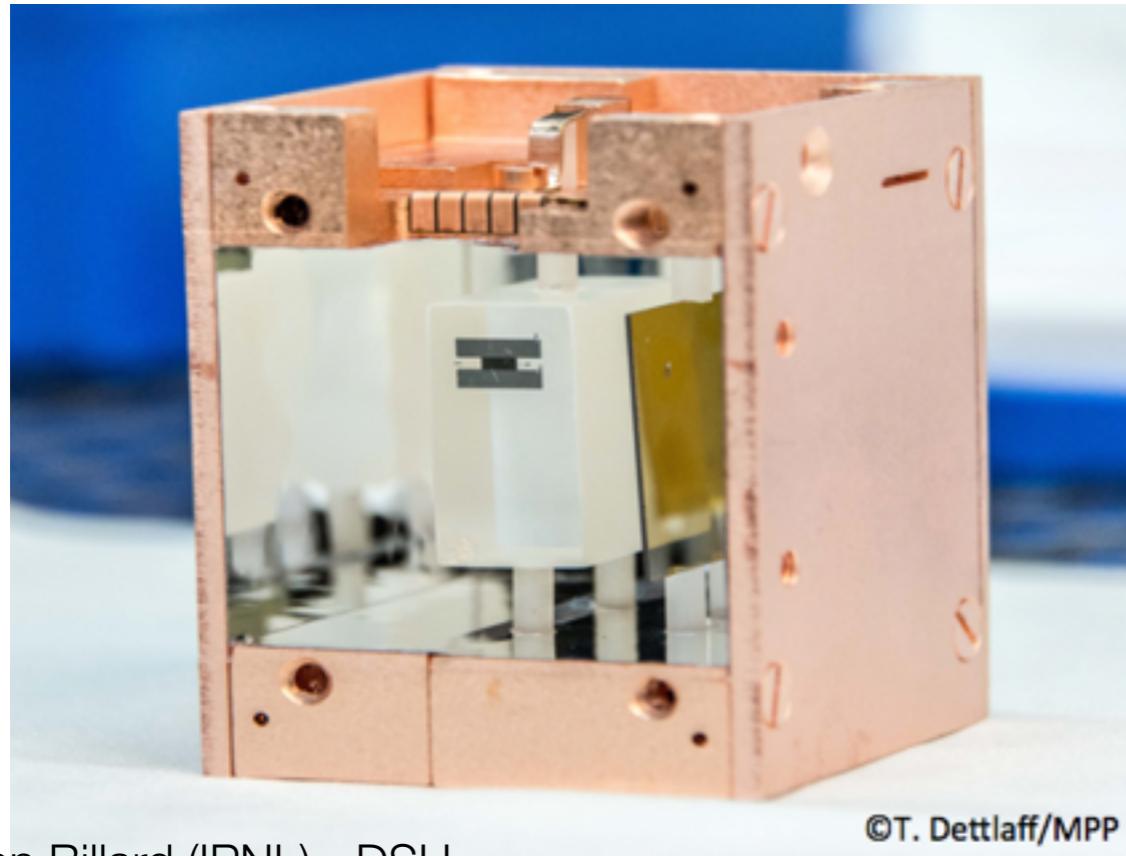
CRESST strategy: heat + scintillation

Detector layout optimized for low-mass dark matter, radical reduction of dimensions:

- Cuboid CaWO₄ crystals (20 x 20 x 10) mm³ ~ **24 g** with its light detector (**scintillation**)
- Self grown crystals ~ **3 counts/(keV kg day)**
- Designed to reach **100 eV energy threshold** (*achieved 20 eV on detector A, 60 eV on average !*)
- Fully scintillating housing
- Instrumented sticks

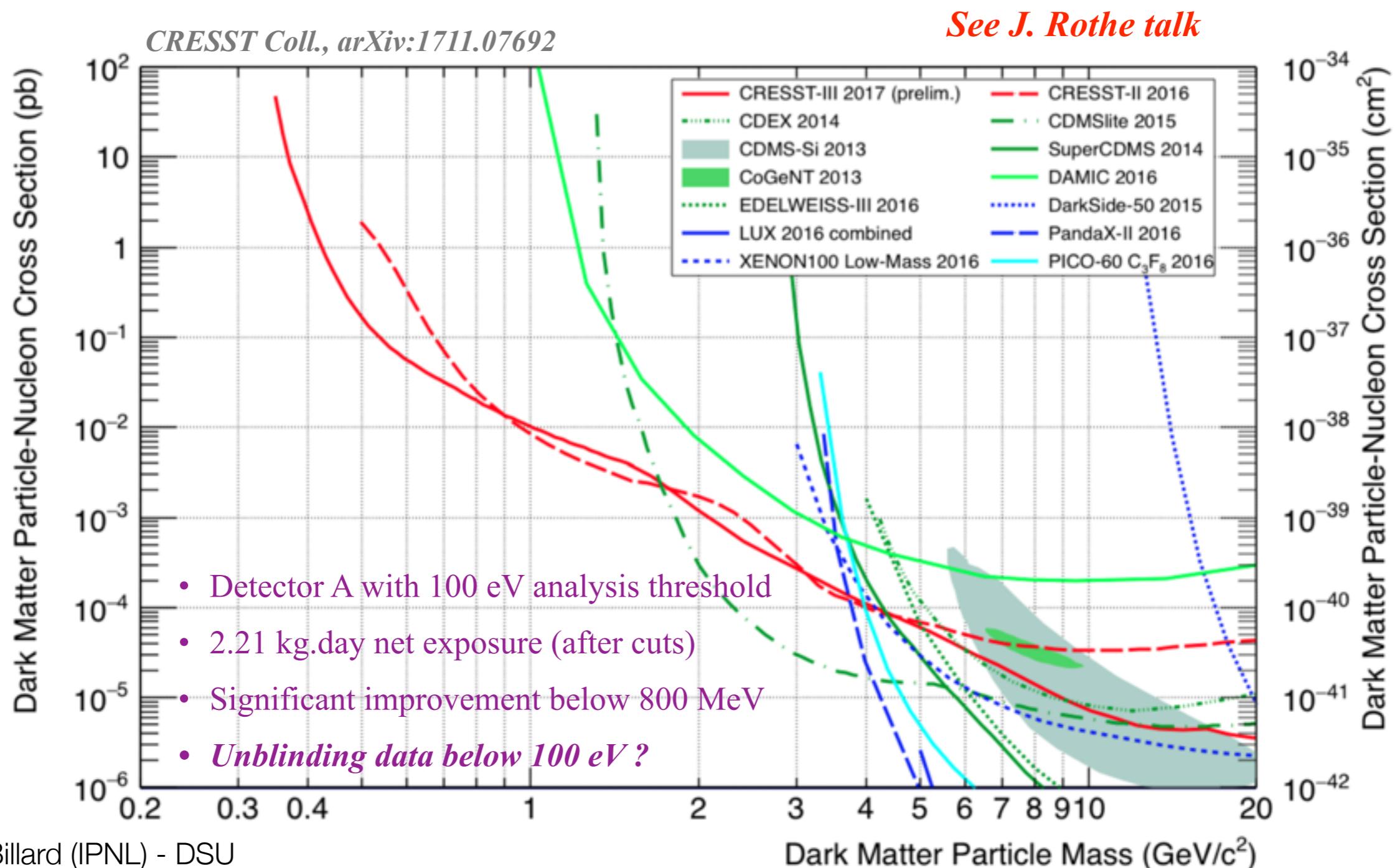


Veto surface related backgrounds



Searching for low-mass Dark Matter (GeV-scale)

CRESST strategy: heat + scintillation

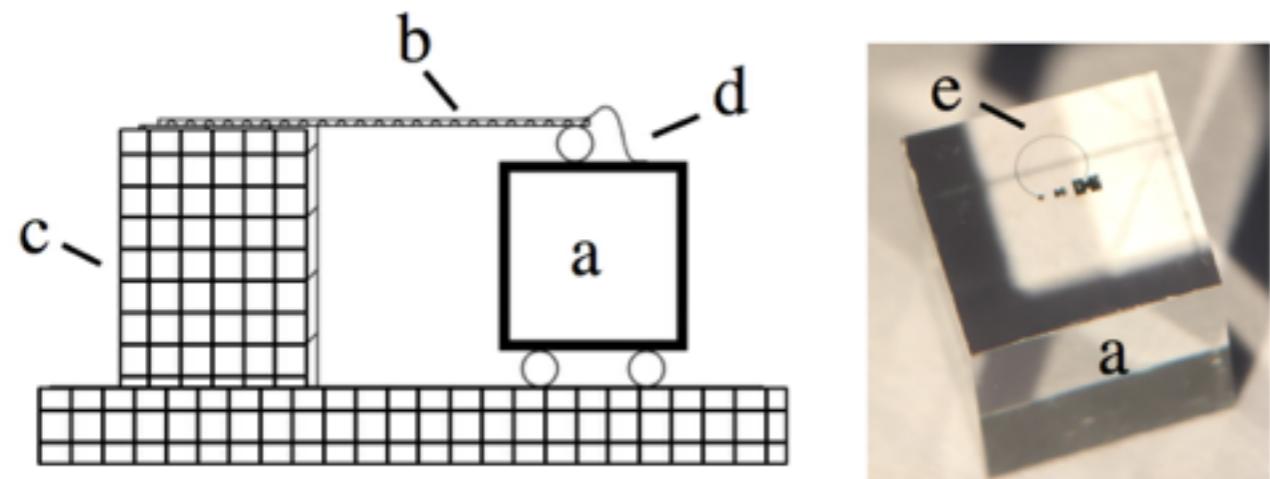


Searching for low-mass Dark Matter (GeV-scale)

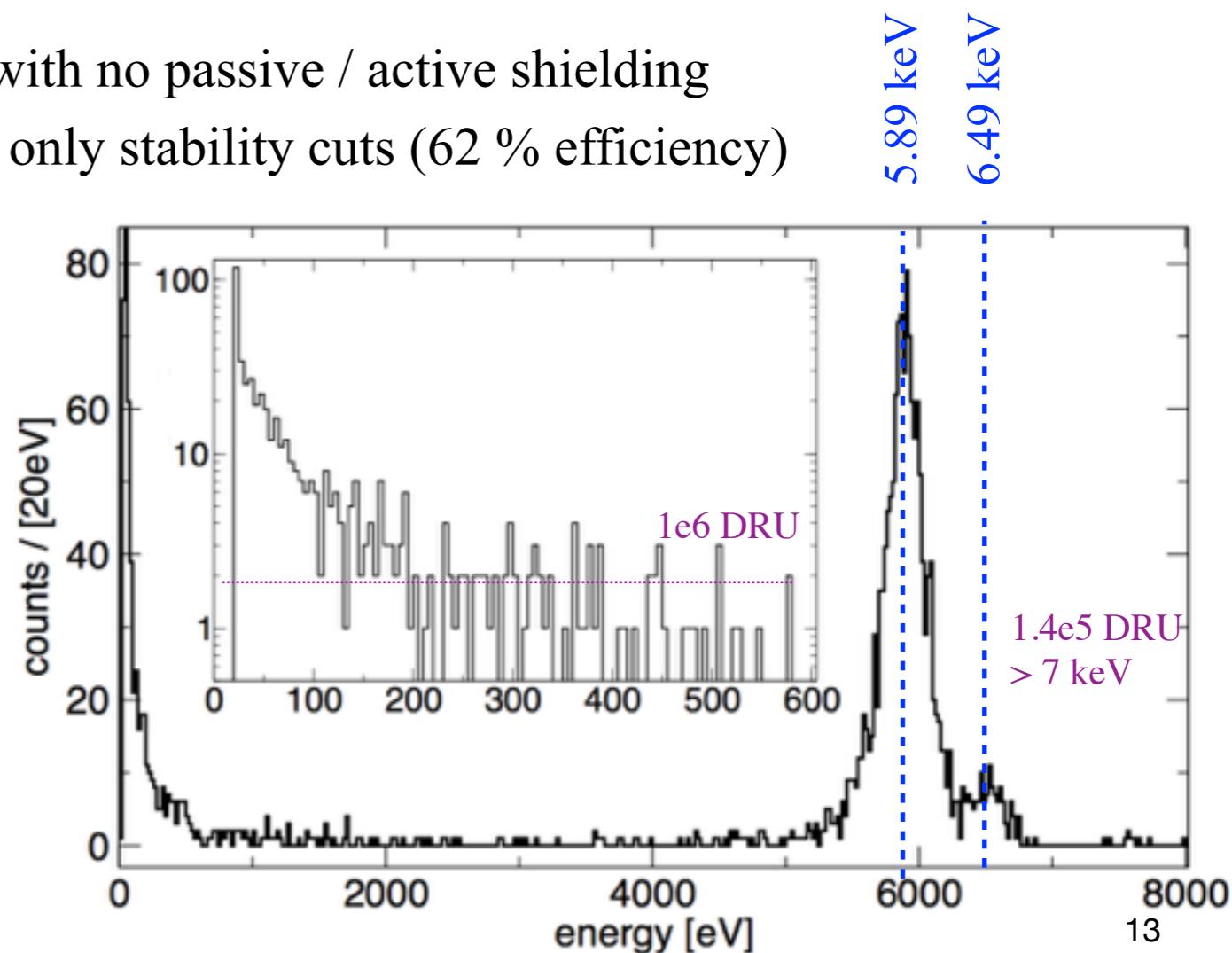
CRESST strategy: heat + scintillation

Detector layout optimized for VERY low threshold, further reduction of dimensions:

- Cuboid Al_2O_3 crystals ($5 \times 5 \times 5$) mm 3 ~ 0.49 g with no light detector (**no particle identification**)
- Dedicated to CENNS science at nuclear reactors: NuCleus (*R. Strauss et al., EPJC 2017*)
- Achieved a **19.6 eV energy threshold**
- Above ground operation from MPI in Munich with no passive / active shielding
- Non-blind analysis with no event selection cut, only stability cuts (62 % efficiency)

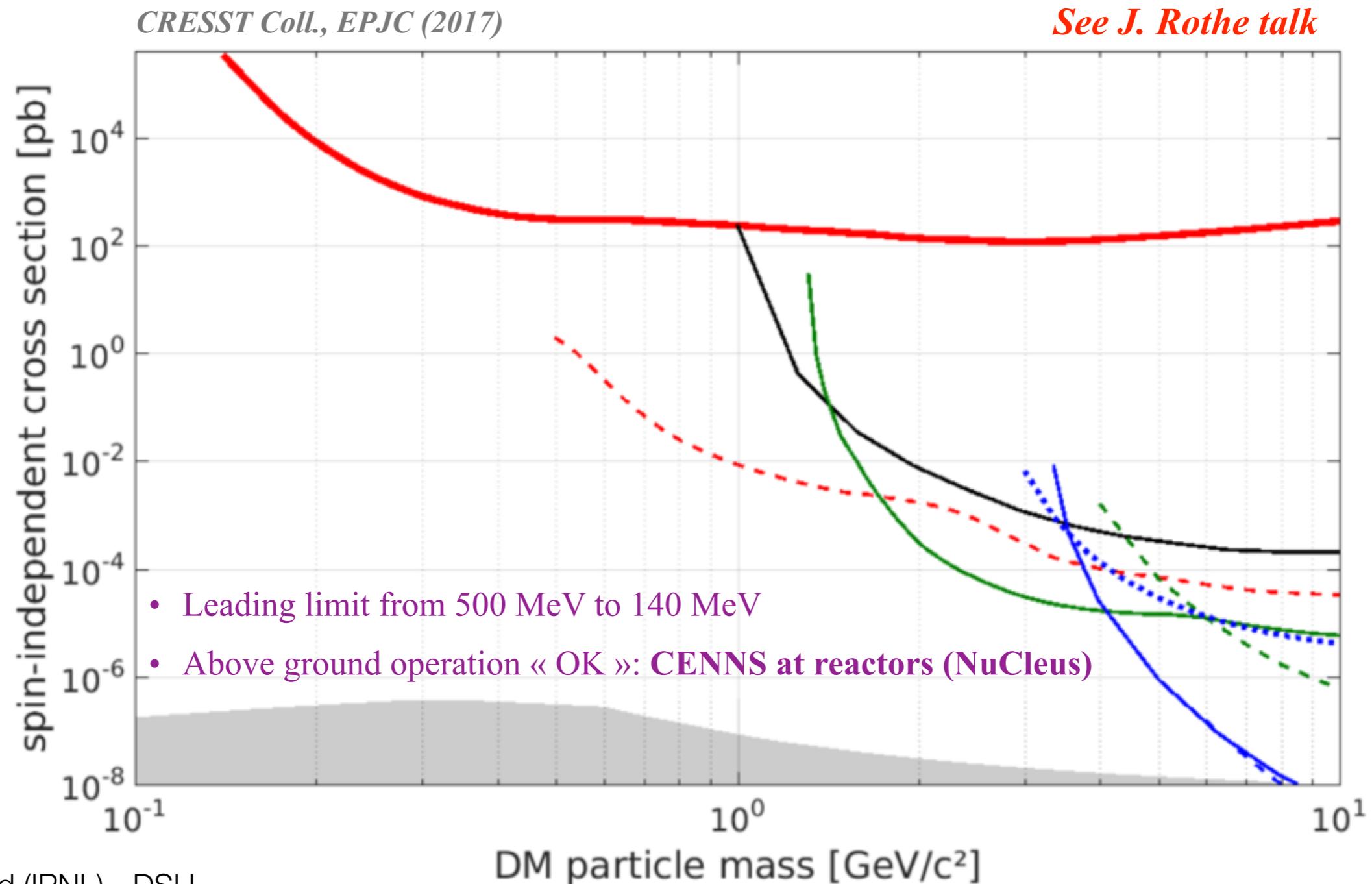


R. Strauss et al., Phys. Rev. D 96 (2017)



Searching for low-mass Dark Matter (GeV-scale)

CRESST strategy: heat + scintillation

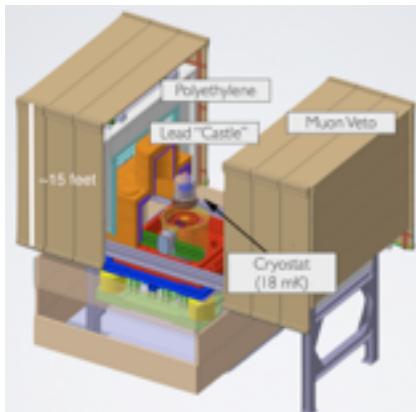


Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

EDELWEISS

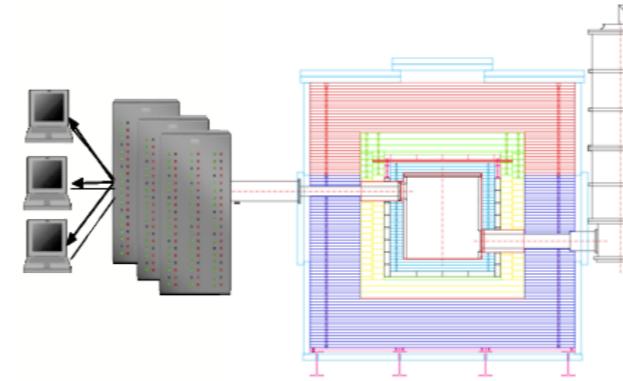
- In Modane Underground Laboratory
- Upgrade from EDELWEISS II, in continuous operation since summer 2014
- 850g Germanium detectors measure ionization and **thermal phonons**
- 36 detectors = 20 kg target mass (largest array)



Julien Billard (IPNL) - DSU

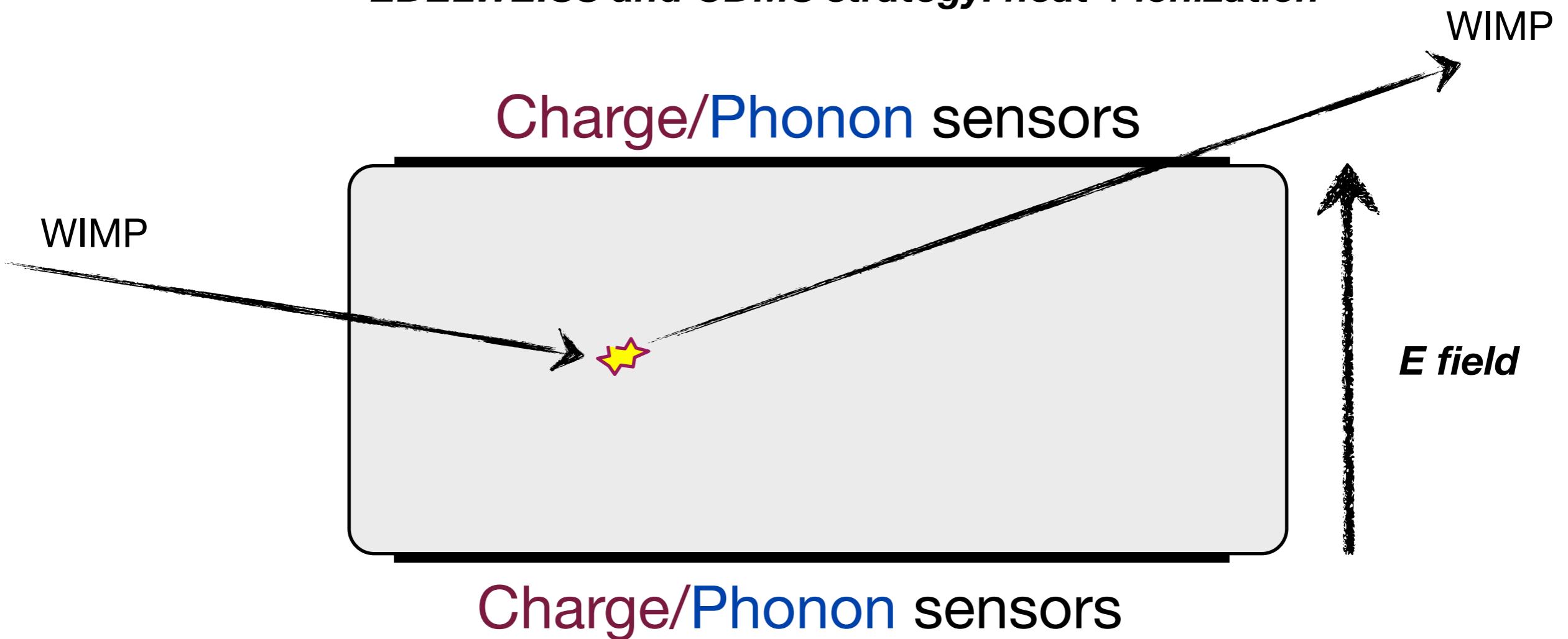
SuperCDMS

- In Soudan mine, but now being un-installed to be installed in SNOLAB
- Upgrade from CDMS II, in continuous operation since spring 2012, stopped in 2016
- 600g Germanium detectors measure ionization and **non-equilibrium phonons**
- 15 detectors = 9 kg target mass



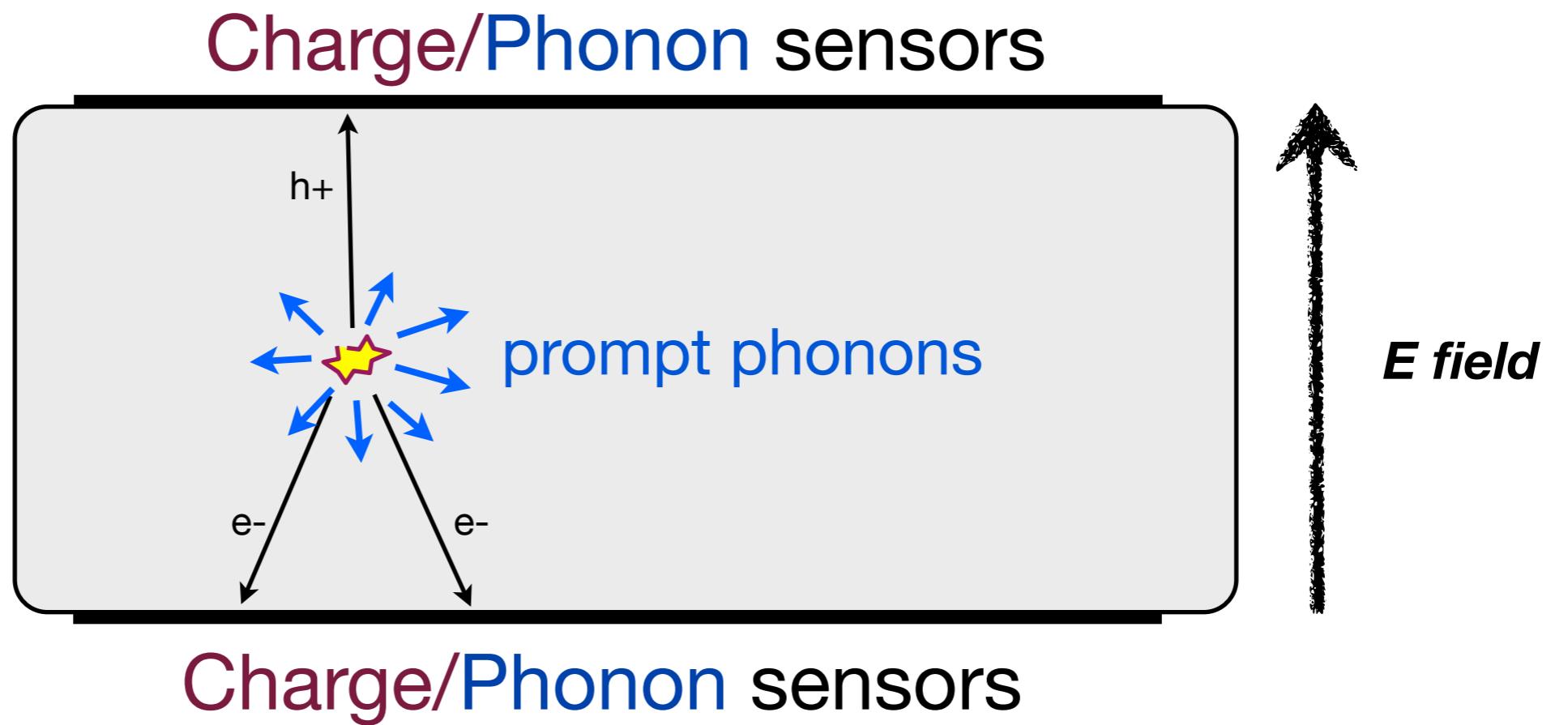
Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization



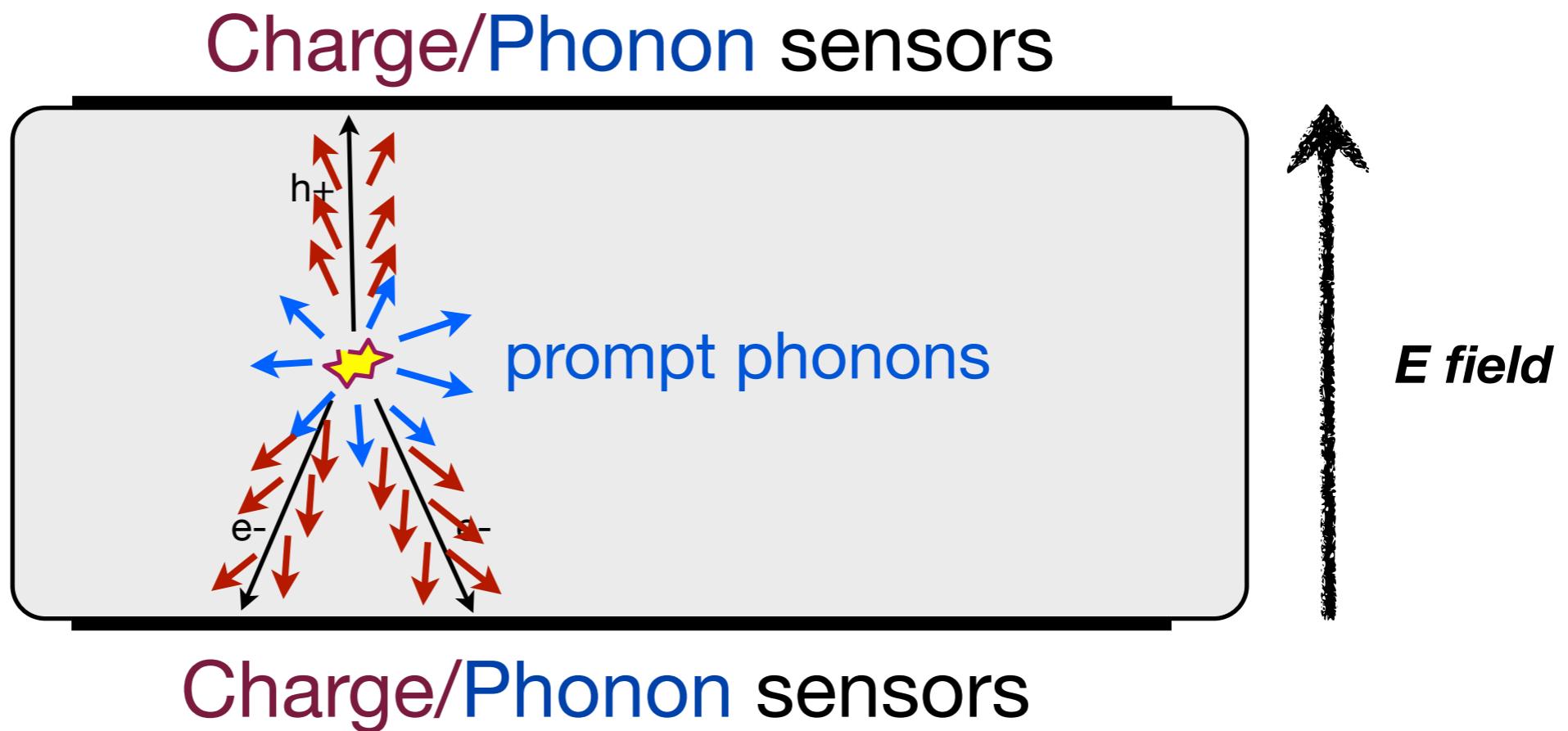
Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization



Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization



Charge/Phonon sensors

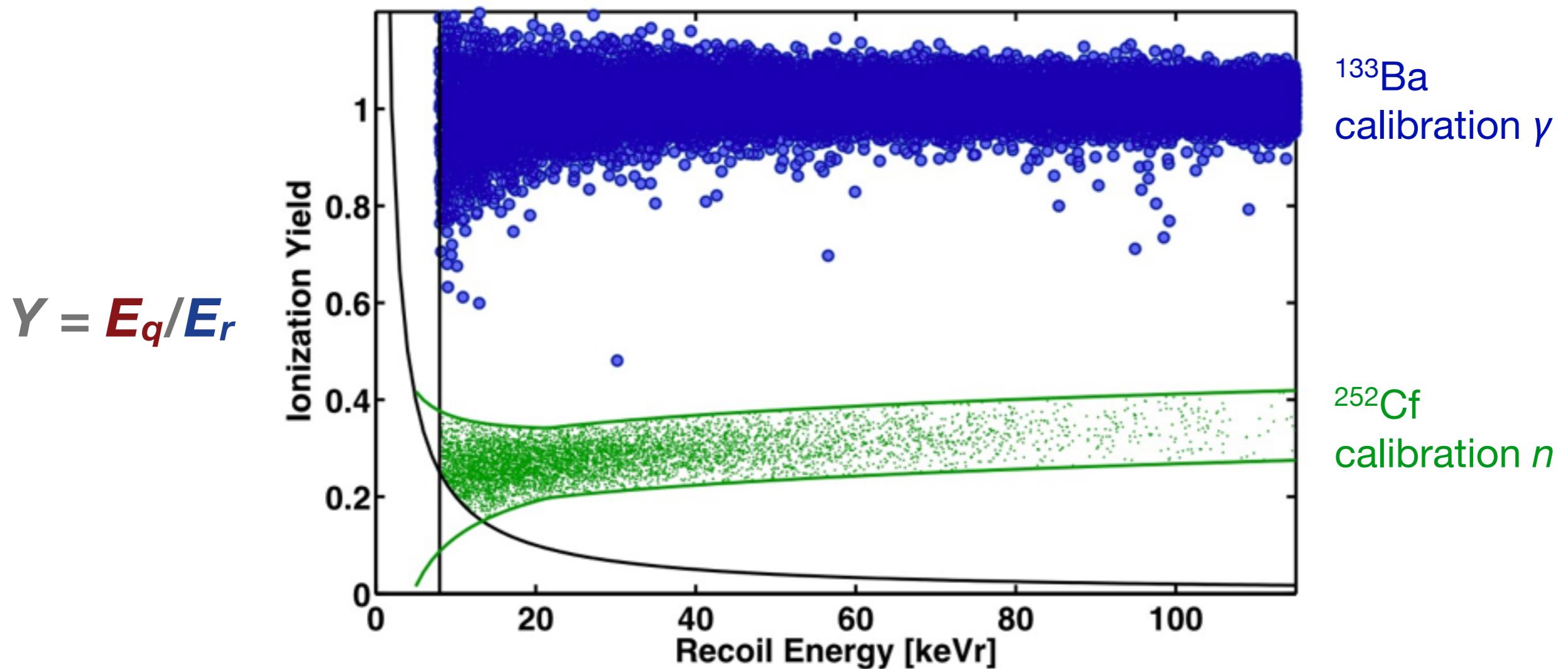
$$E_{total} = E_{recoil} + E_{luke}$$

$$= E_{recoil} + \frac{1}{3\text{ eV}} E_{ion} \Delta V$$

Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

Electron recoils have a **higher ionization yield** than nuclear recoils



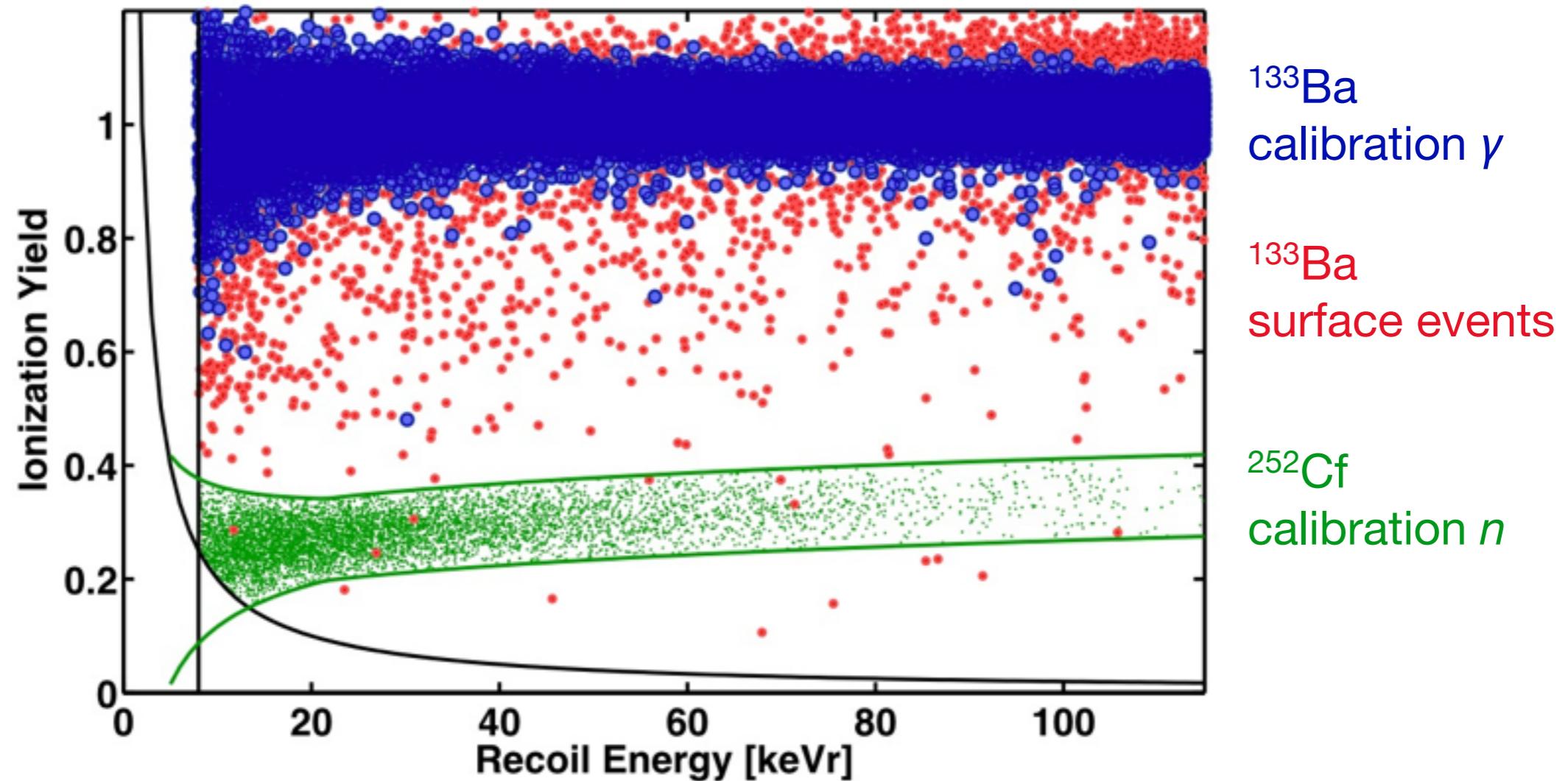
Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

Electron recoils have a **higher ionization yield** than nuclear recoils

Surface events have a **reduced ionization yield** and can mimic nuclear recoils

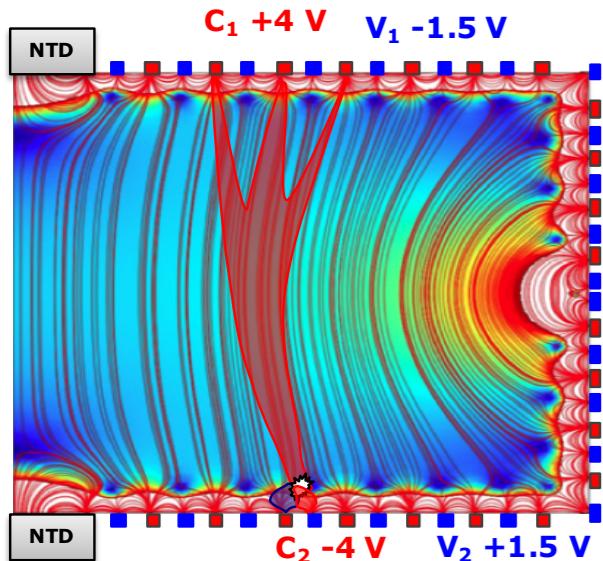
$$Y = E_q/E_r$$



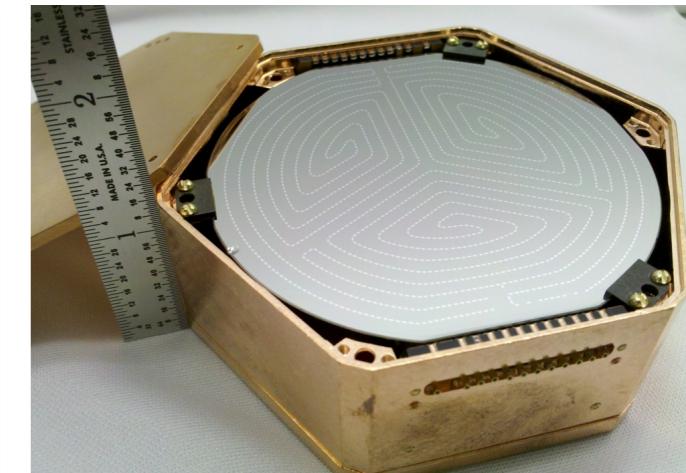
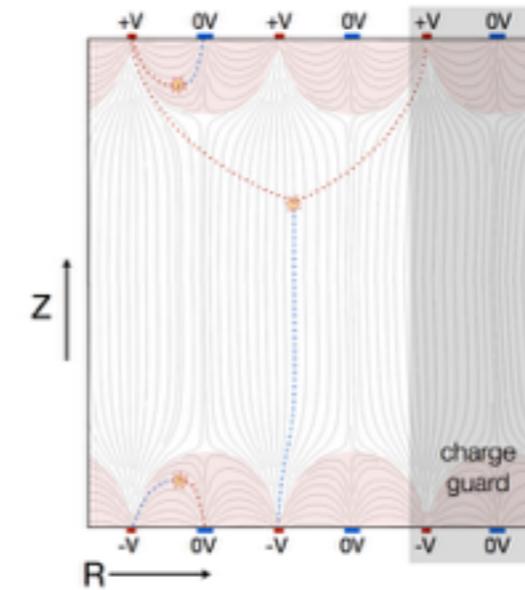
Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

EDELWEISS FID800



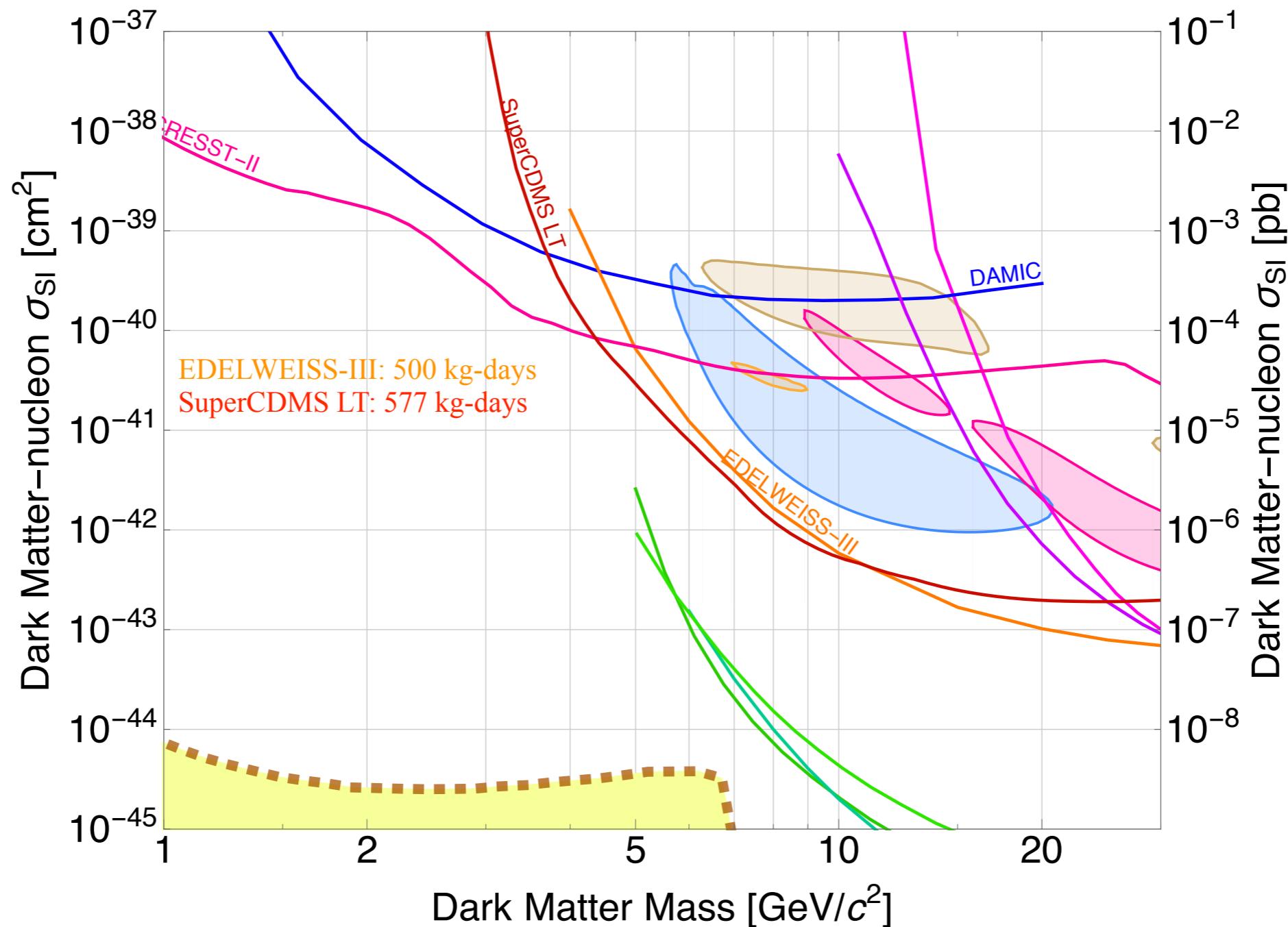
SuperCDMS iZIP



- The two detector technologies have interleaved bias lines to reject surface events
- **Rejection power is over 10^5 while keeping a high NR acceptance down to a few keV**
- EDELWEISS has a full coverage and readouts all electrodes (**best rejection and charge collection**)
- BUT, SuperCDMS iZIP detectors can perform event fiducialization using phonon information

Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

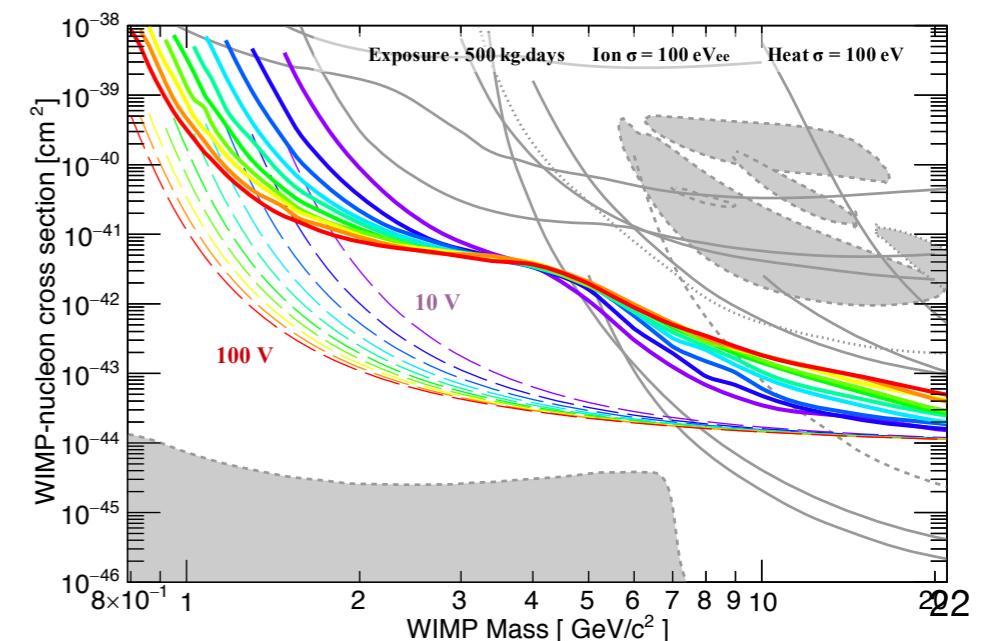
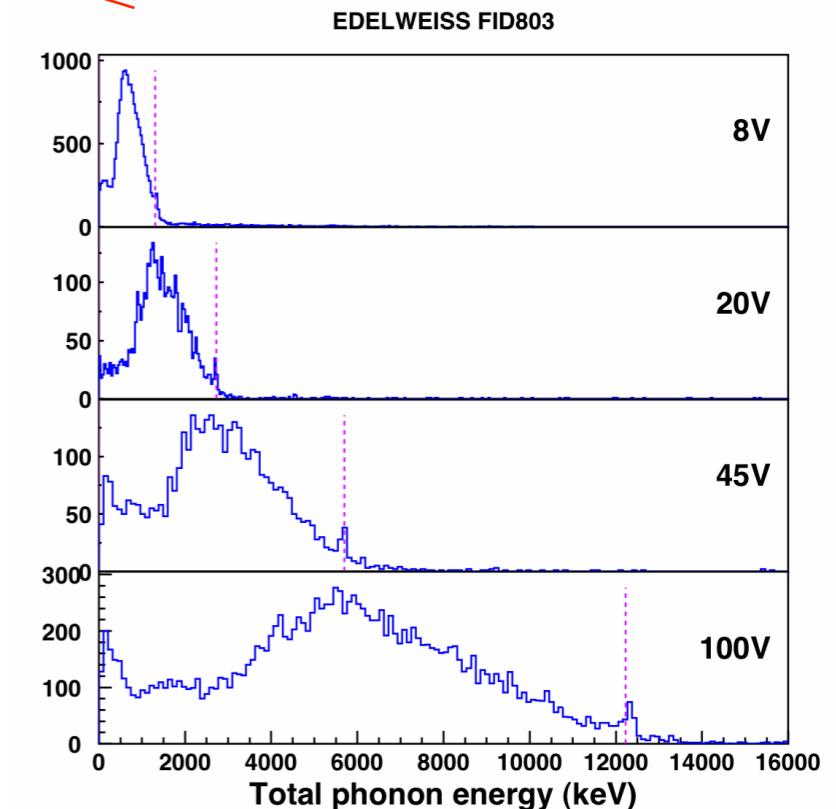
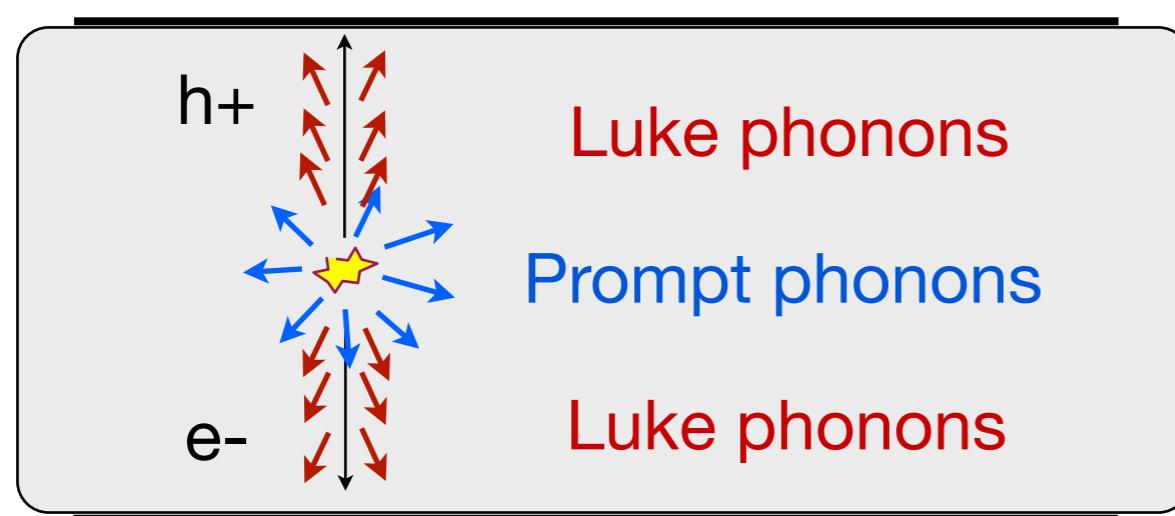


Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

$$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + \frac{1}{3\text{ eV}} E_Q \Delta V \end{aligned}$$

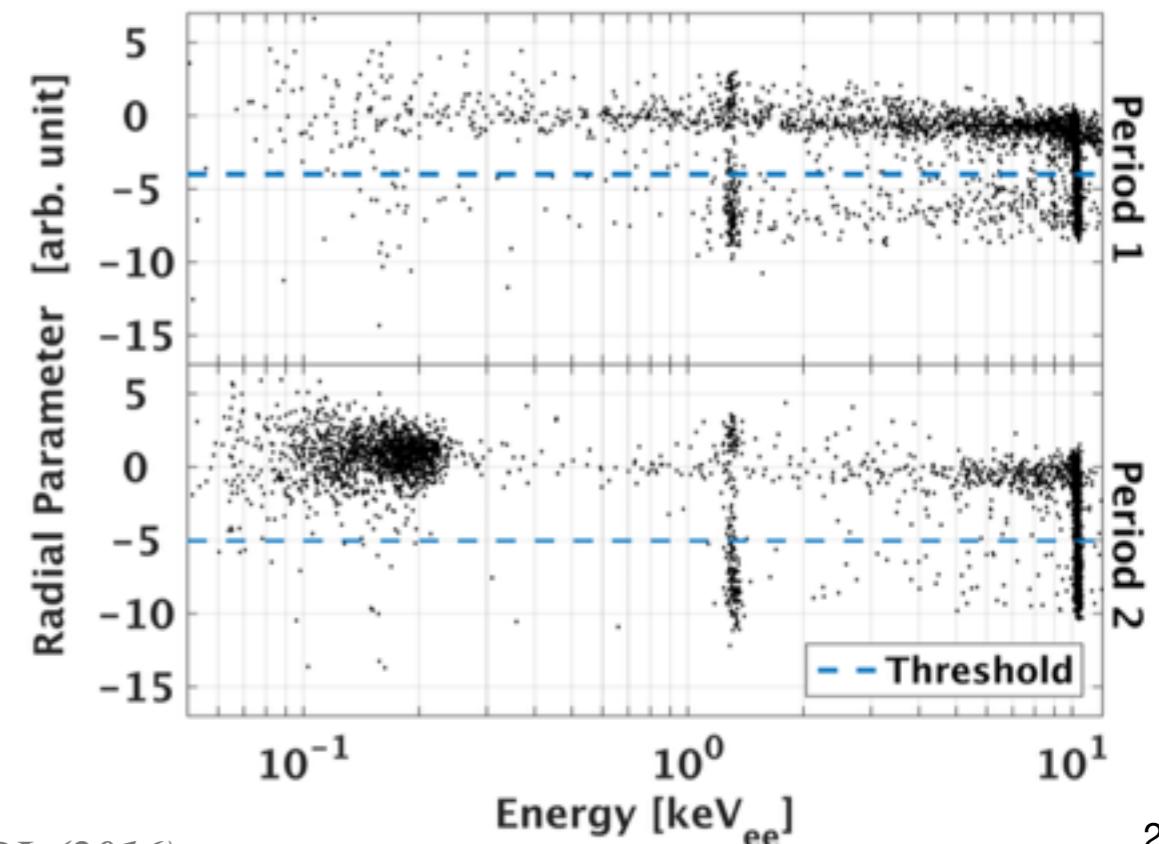
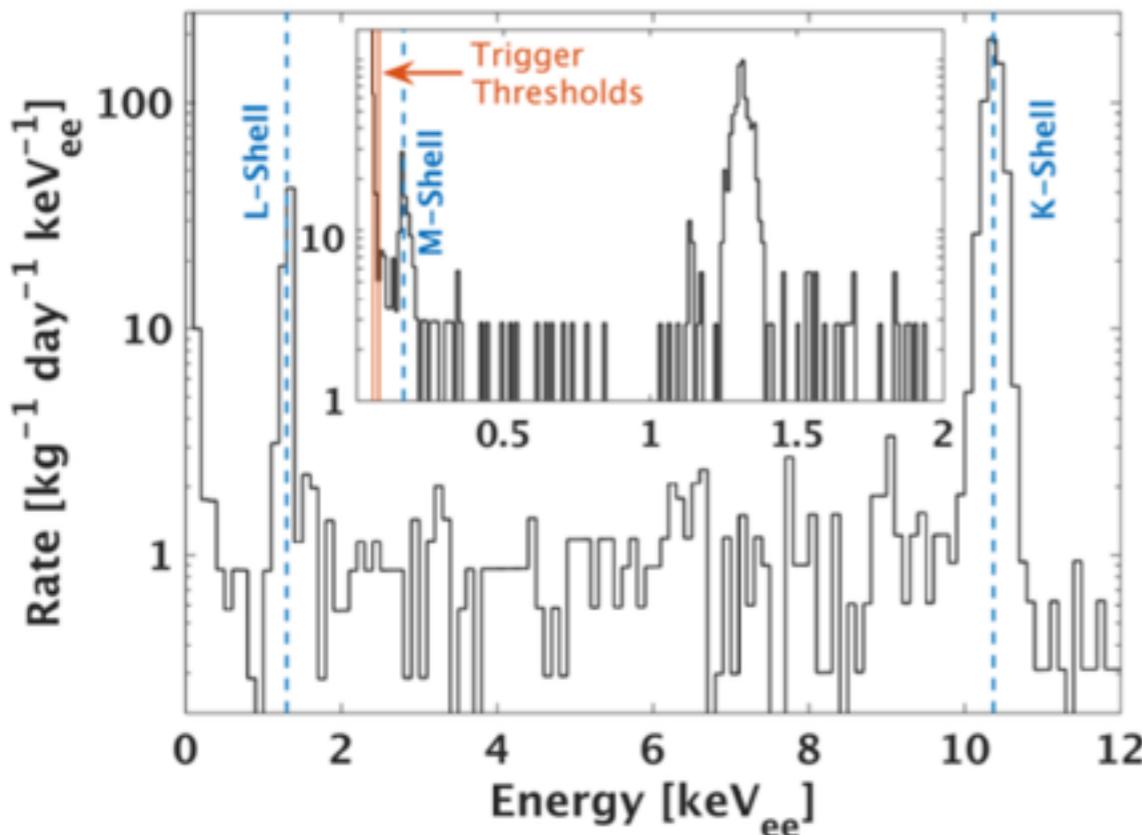
- Measure charge with phonons, and increase voltage to amplify signal
- Lose background discrimination, but achieve lower ionization energy threshold
- SuperCDMS and EDELWEISS both reached ~ 100 V and ~ 60 eVee energy thresholds



Searching for low-mass Dark Matter (GeV-scale)

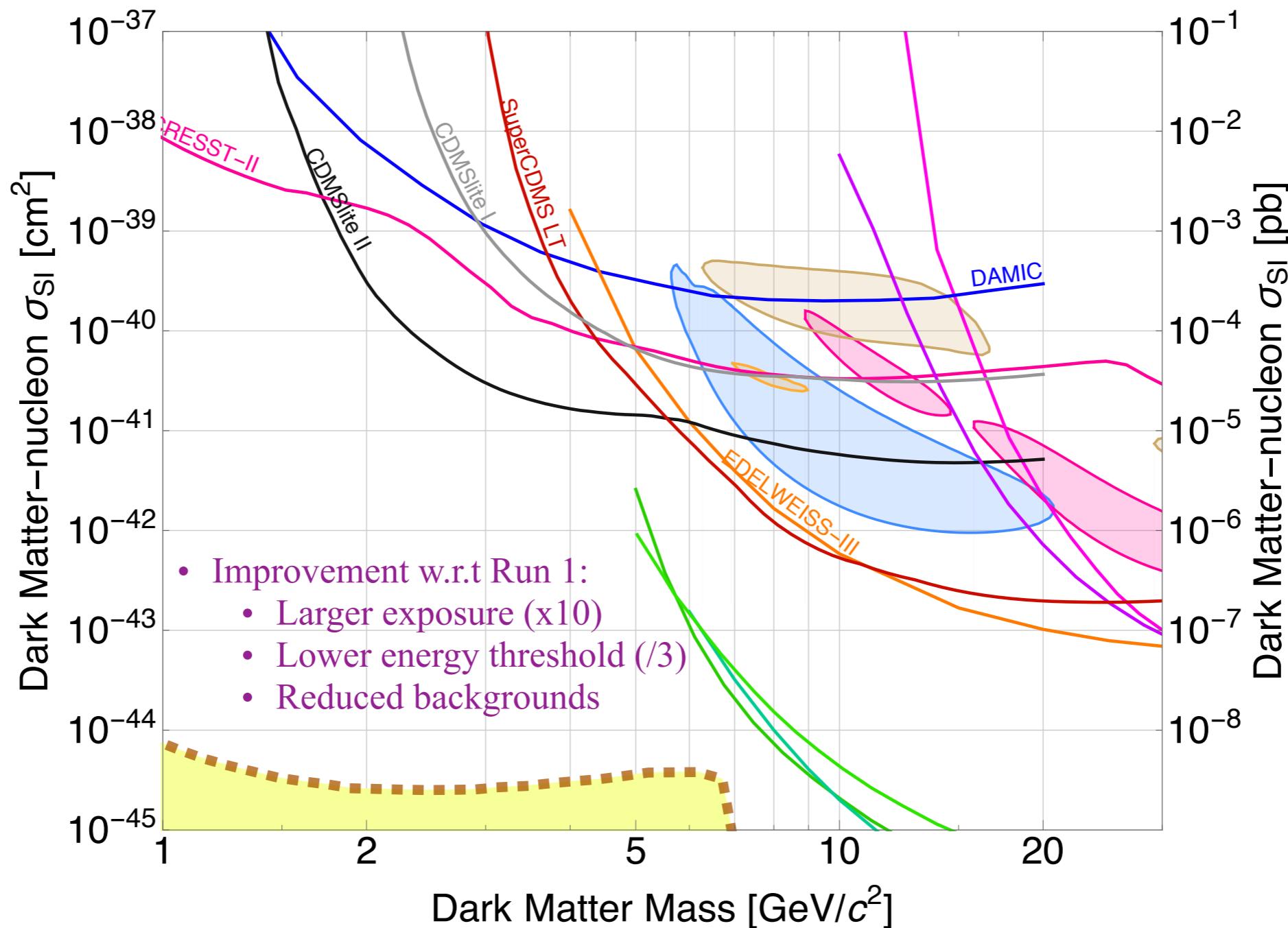
EDELWEISS and CDMS strategy: ~~heat + ionization~~

- CDMSLite run II operated stably at 70 V or **x24** amplification (*only 12x due to electronics limitations*)
- Data acquired from February to November 2014: *70 kg-days total exposure*
- Ionization energy calibration with EC lines at 1.3 keVee and 10.4 keVee
- Reduced energy threshold: from 160 eVee (run 1) to 56 eVee ($\sim 300 \text{ eVnr}$) in Run 2
- First implementation of a phonon-radial fiducialization cut (reduced background w.r.t run 1)



Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS and CDMS strategy: heat + ionization

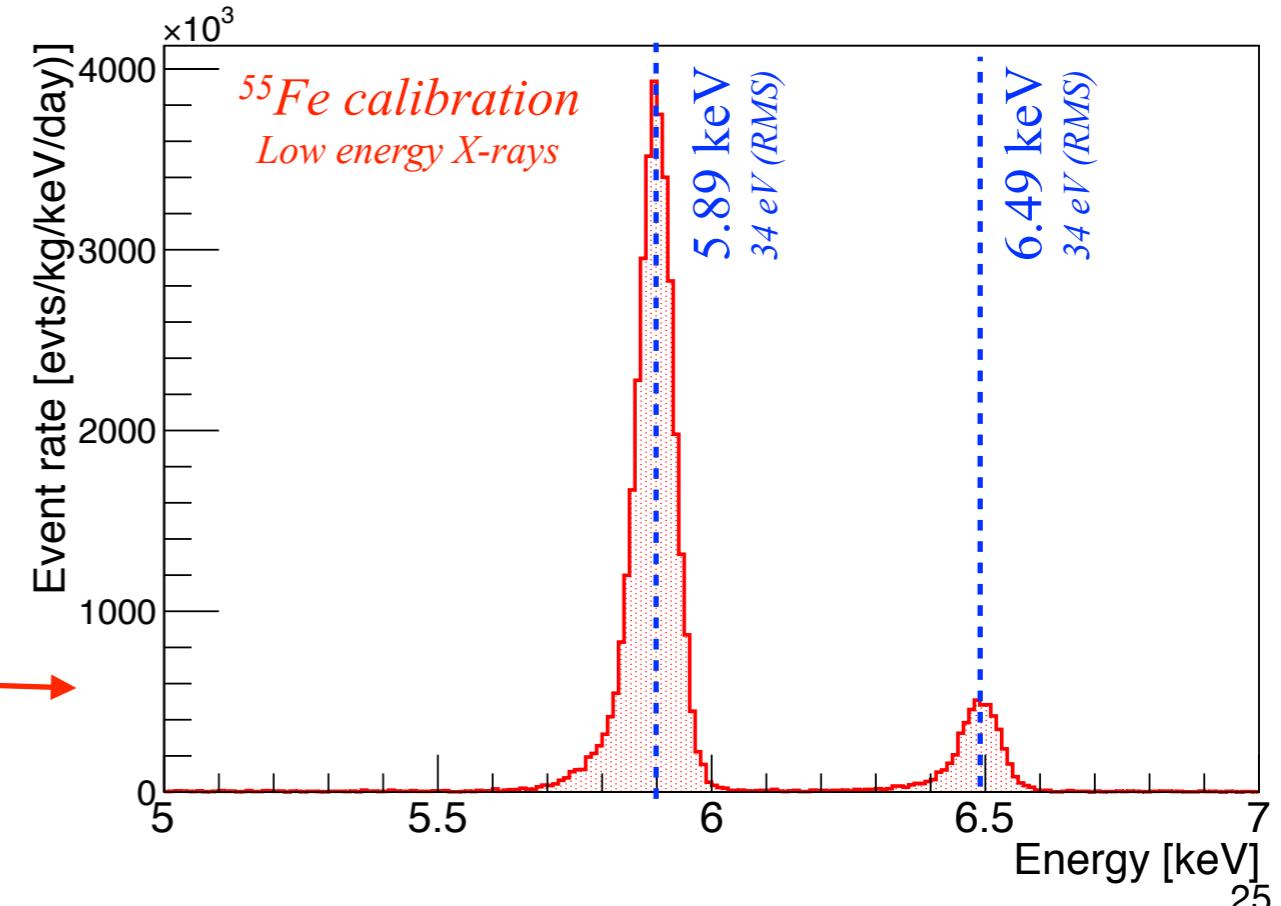
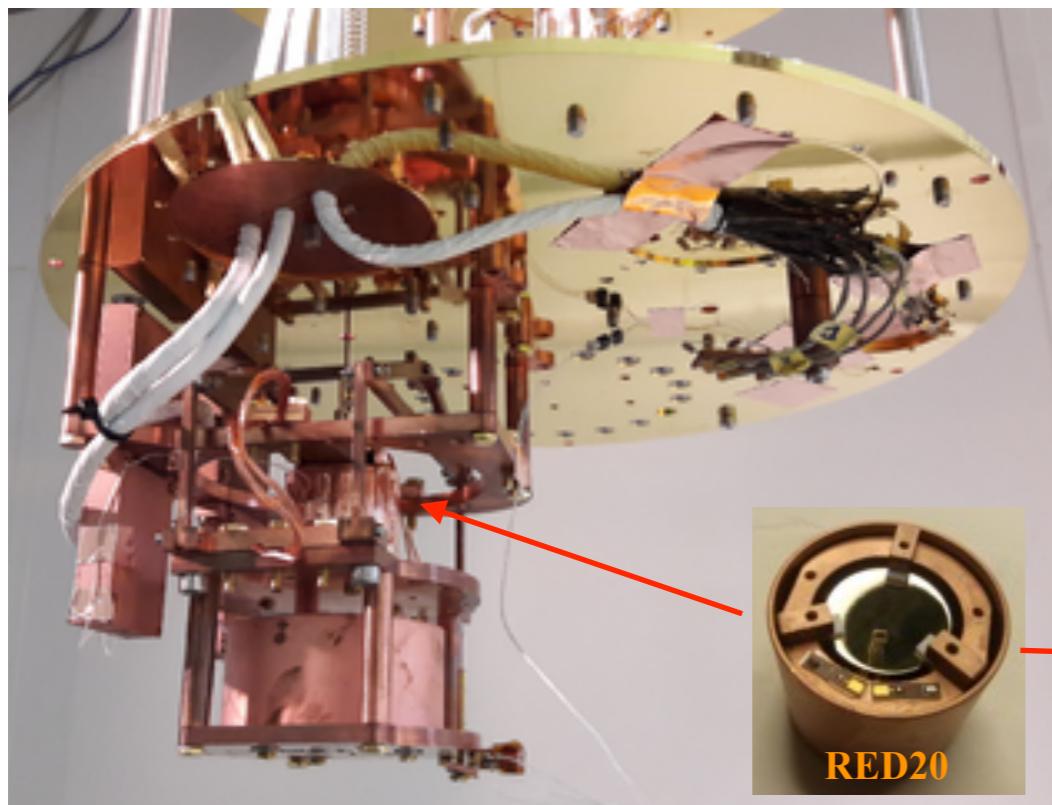


Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS-Surf strategy: heat + ~~ionization~~

NEW !!

- ***EDELWEISS-Surf***: A Surface Dark Matter search from IPNL cryogenic facility
- RED20 - **32g Ge detector with 55 eV energy threshold** but no ionization
- Continuous data stream mode with **offline trigger** and event processing based on optimal filtering
- We took data for six days (22nd to 27th of May) with **one day blinded (26th of May)**
- **Data were blinded below 4 keV, WIMP search window (ROI) between 0 keV and 2 keV**

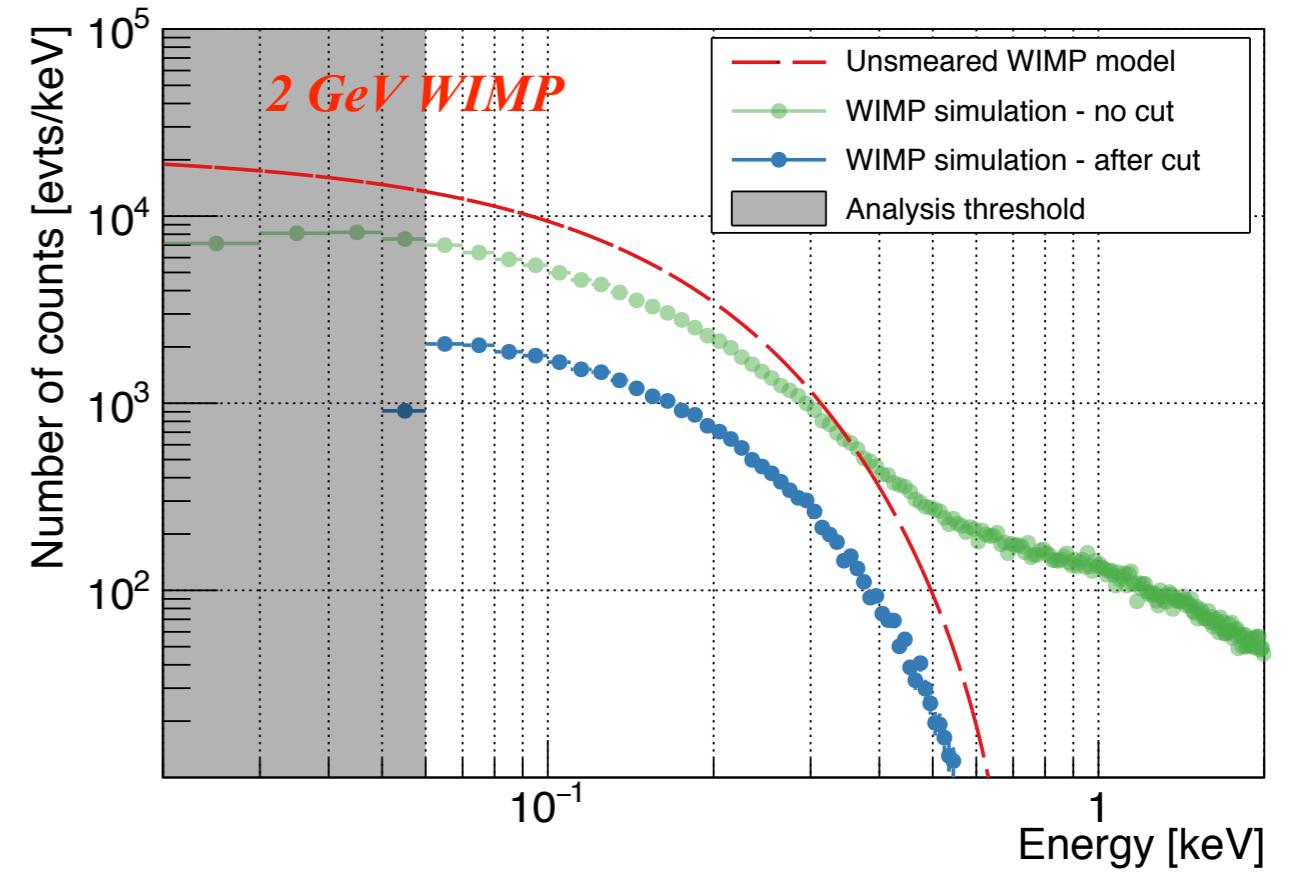
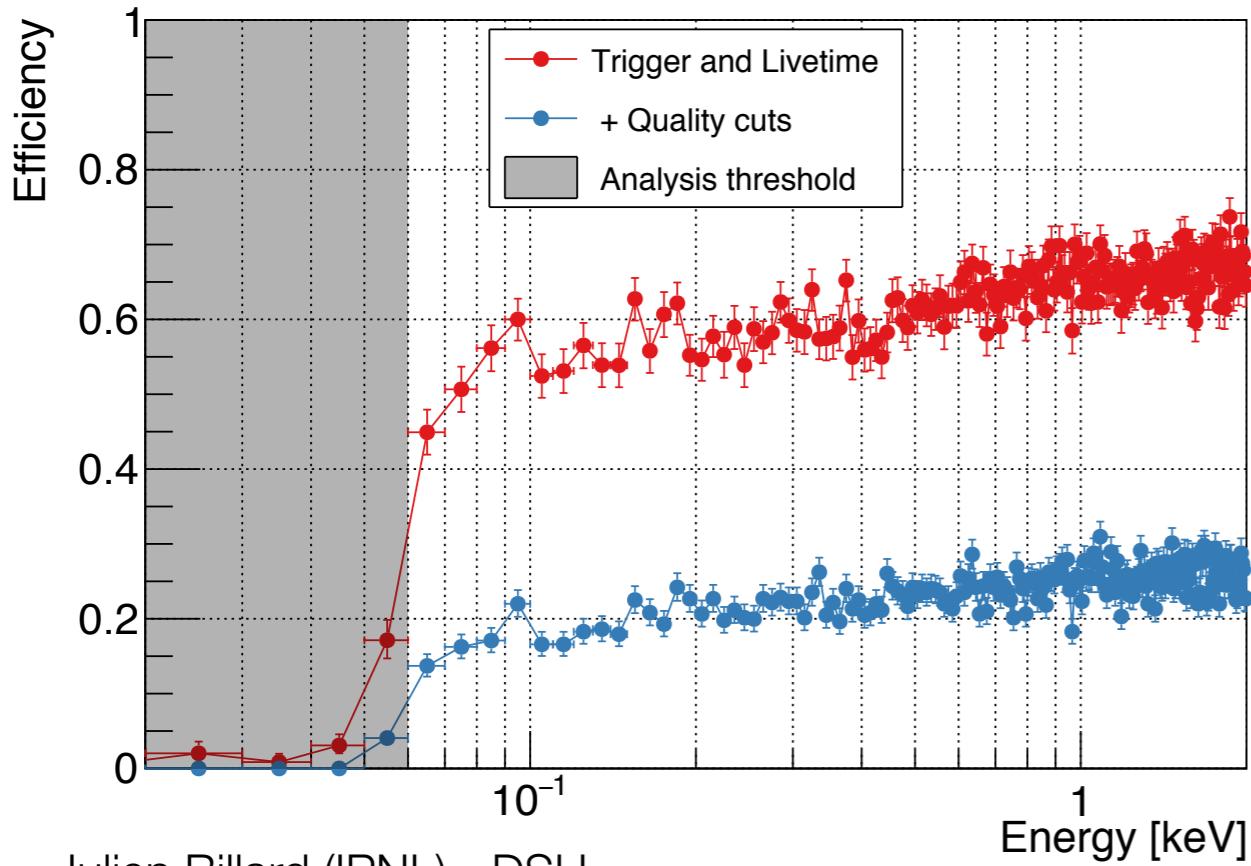


Searching for low-mass Dark Matter (GeV-scale)

EDELWEISS-Surf strategy: heat + ~~ionization~~

NEW !!

- The **analysis threshold** was set to 60 eV
- Analysis based on pulse simulation where *fake events* were inserted in the data streams
- Event selection based on: data quality and pulse shape discrimination
- Background model constructed from the 4.7 days of unblinded data
- Limit based on a *Poisson optimal interval method*

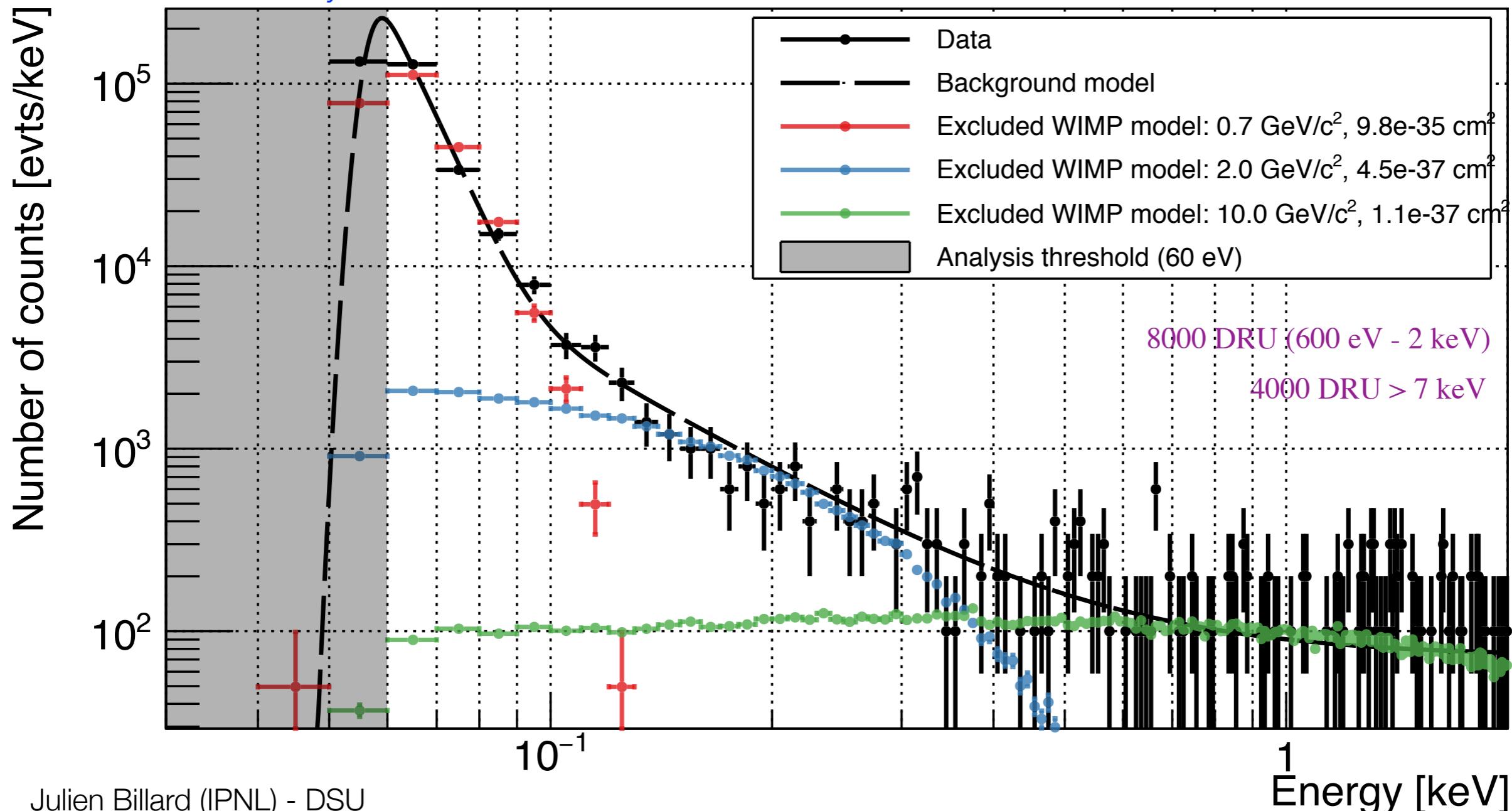


Searching for low-mass Dark Matter (GeV-scale)

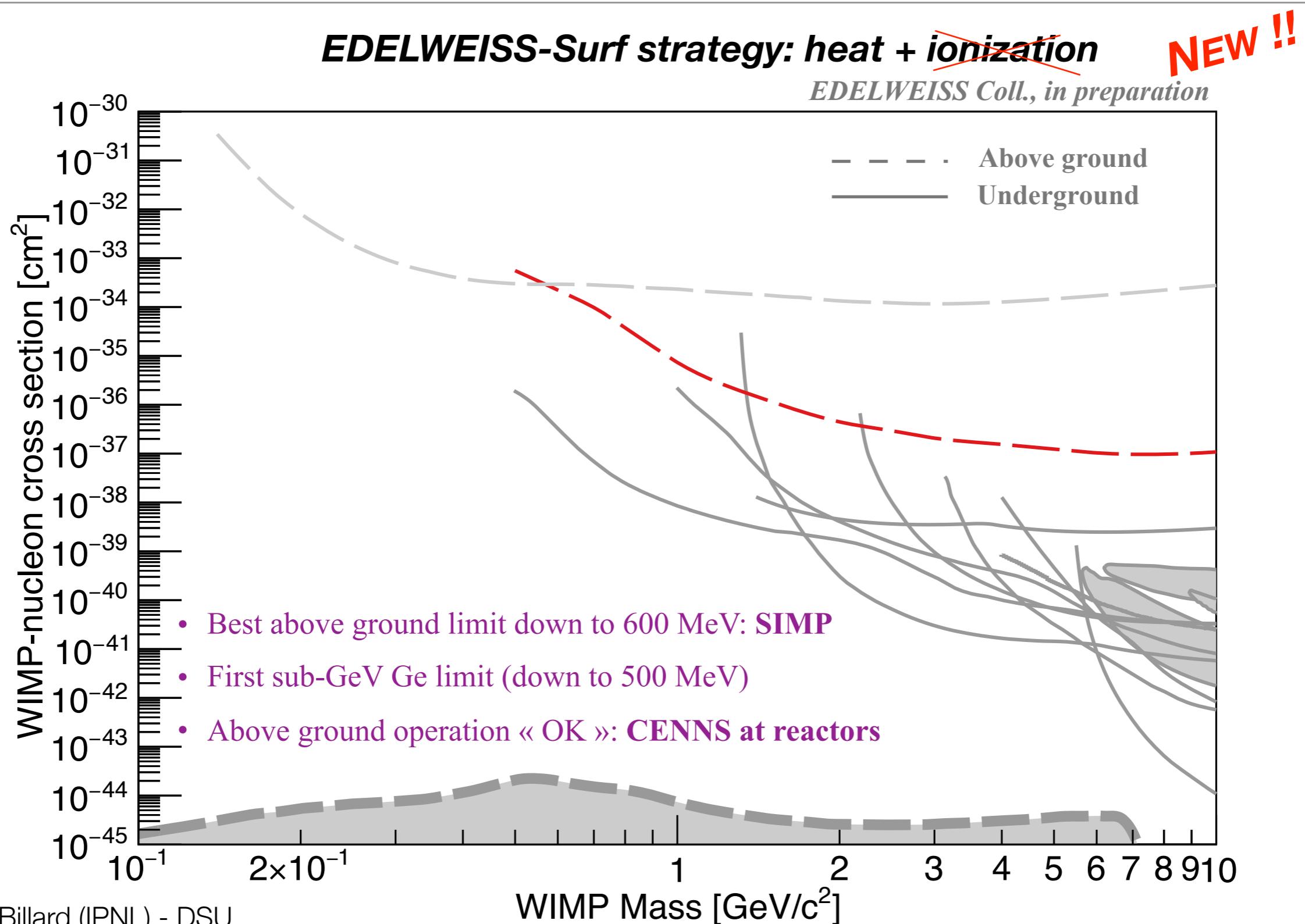
EDELWEISS-Surf strategy: heat + ~~ionization~~ **NEW !!**

Once the cut tuning based on the unblinded data sets is done, we can unblind the data (23.4 h)...

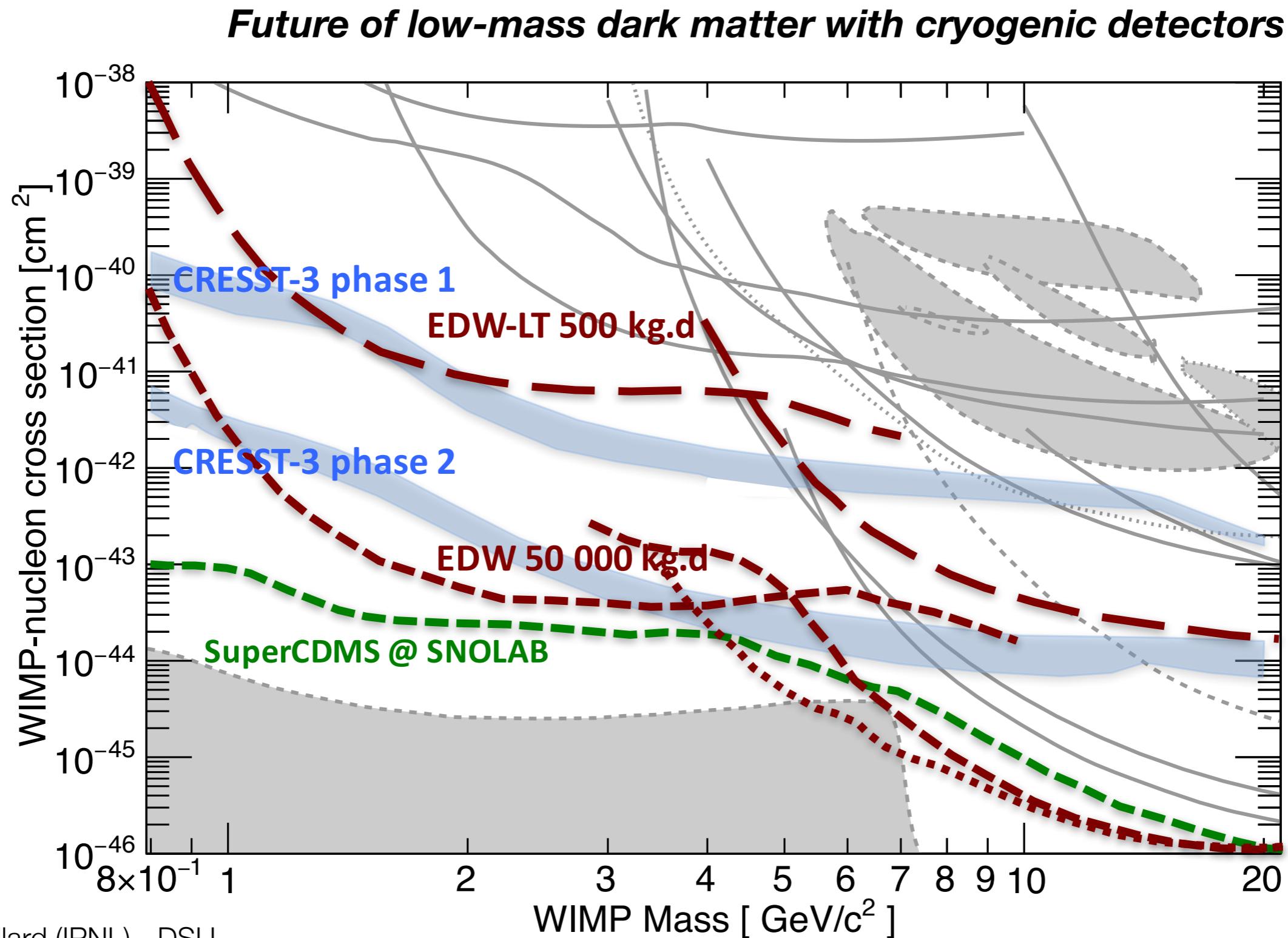
Not efficiency corrected

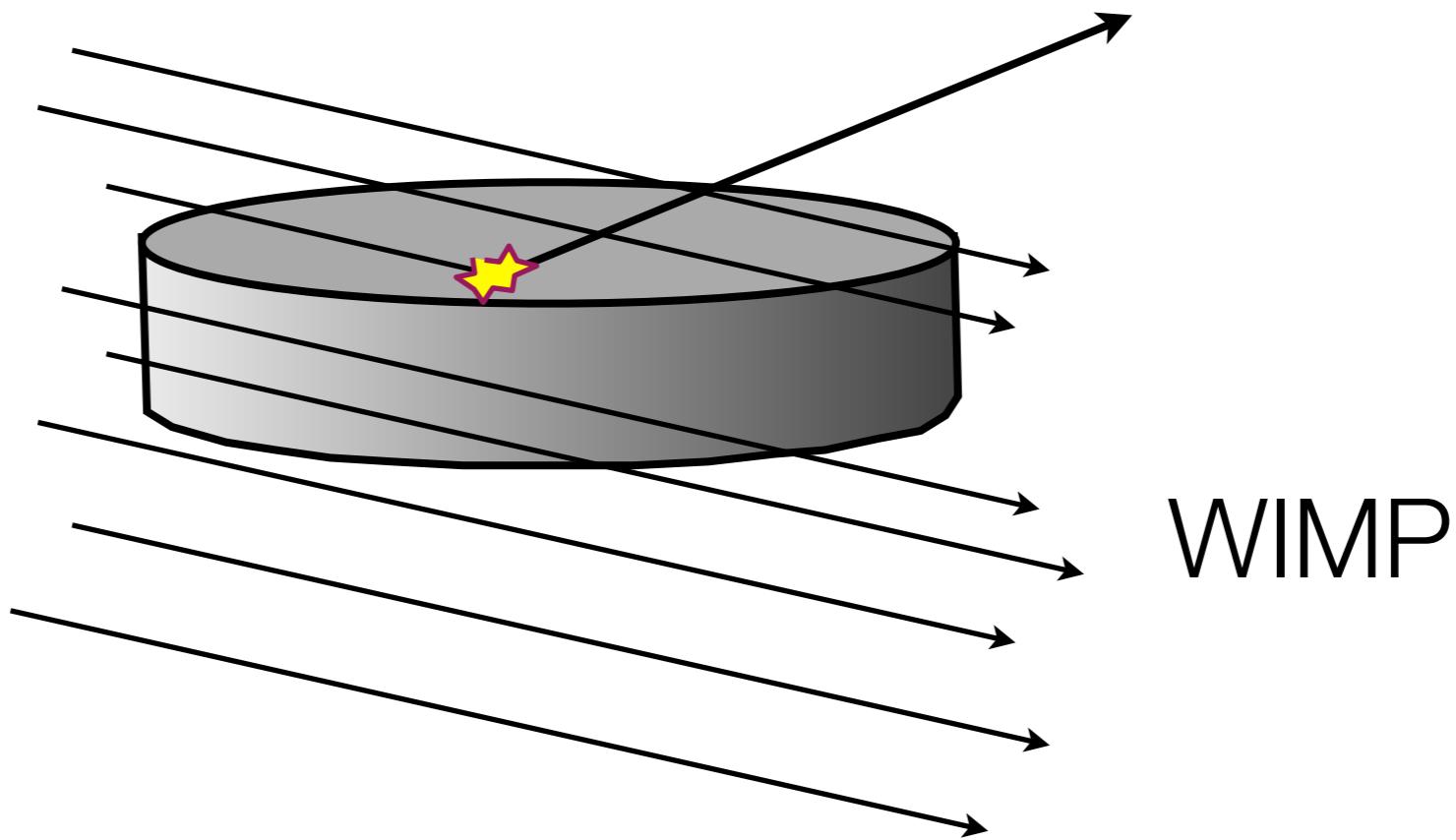


Searching for low-mass Dark Matter (GeV-scale)



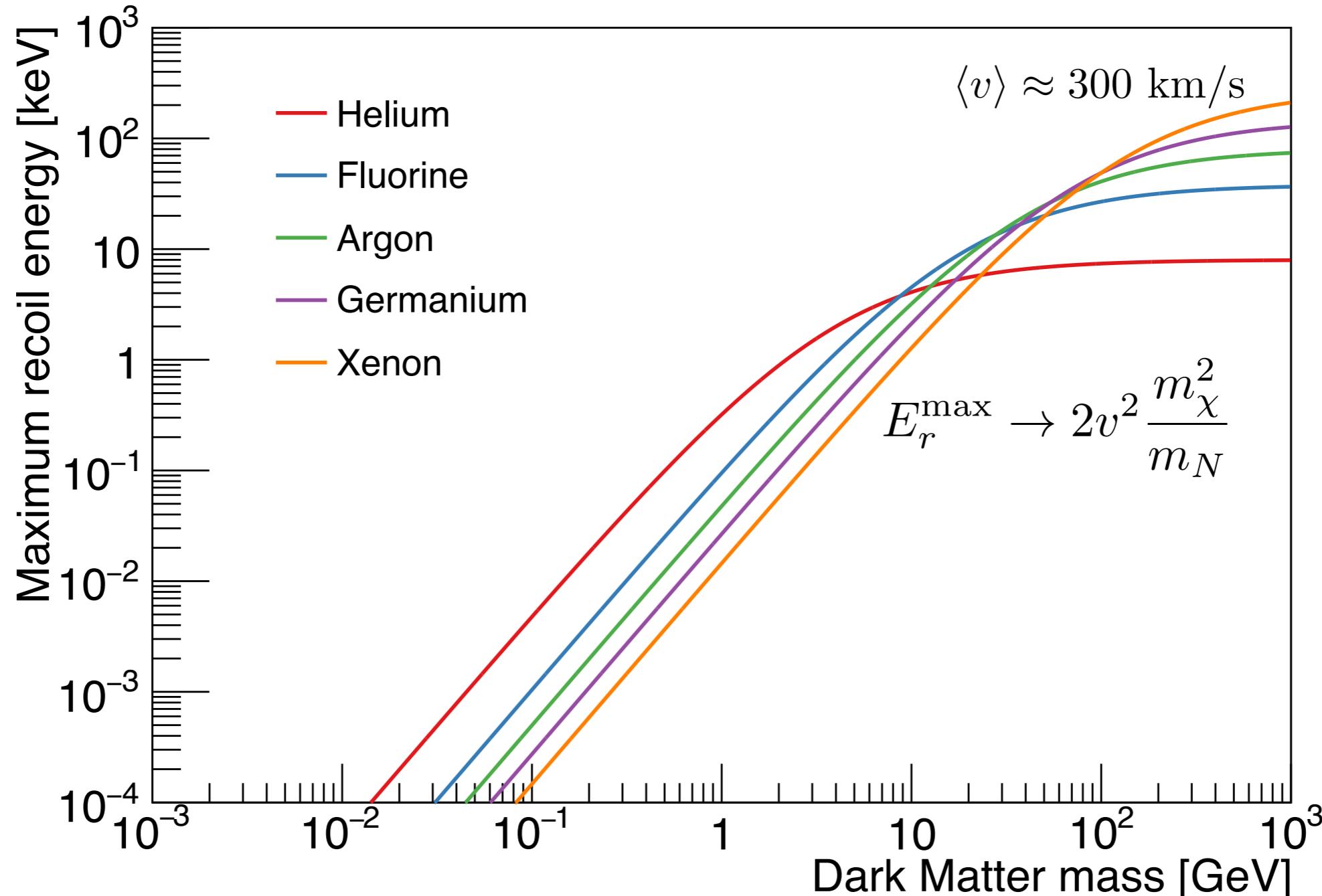
Searching for low-mass Dark Matter (GeV-scale)





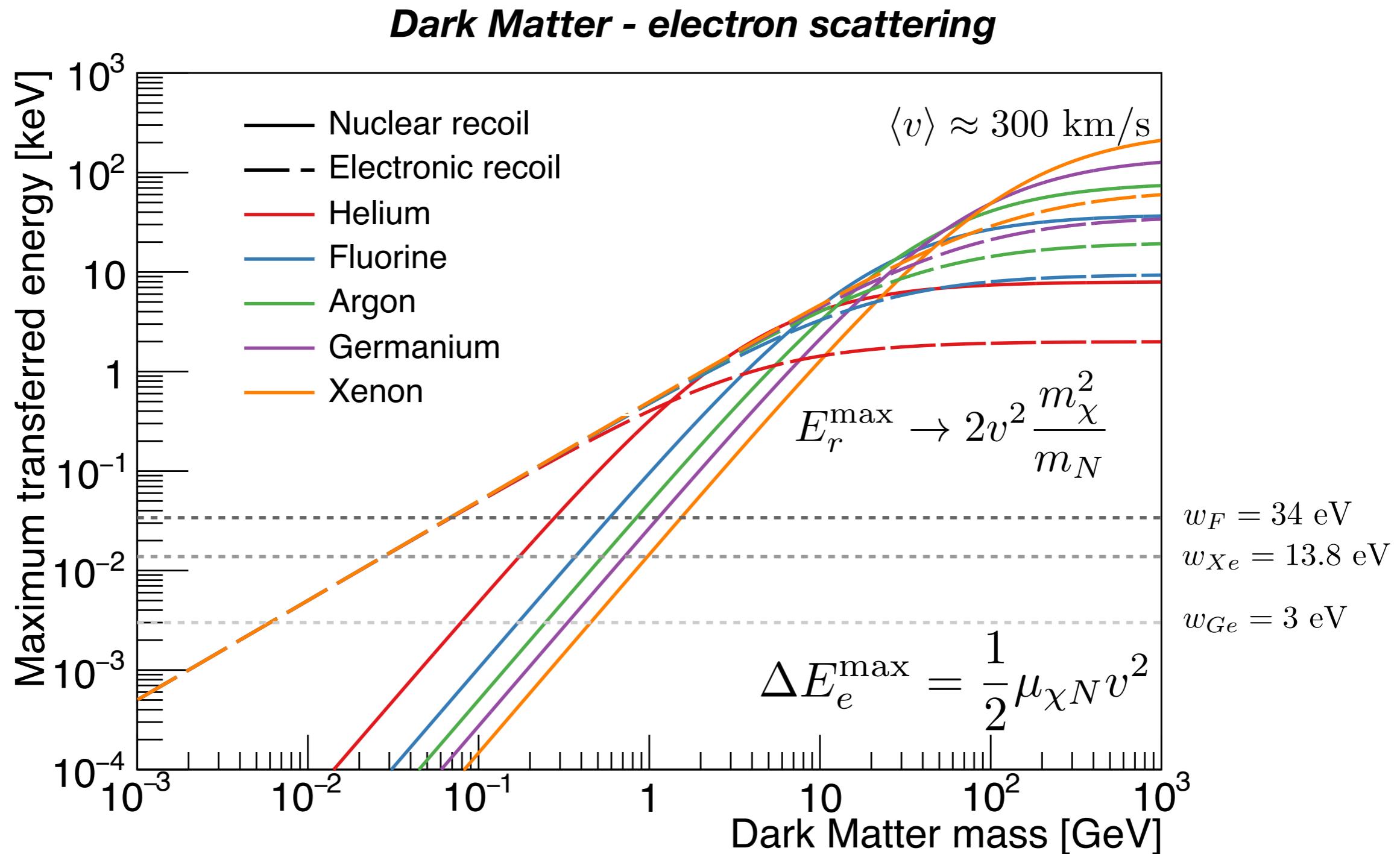
Searching for very light dark matter
with cryogenic detectors (MeV - GeV)

Searching for light Dark Matter (1 MeV - 1 GeV)



But direct detection of Sub-100 MeV dark matter via nuclear recoil is nearly impossible !

Searching for light Dark Matter (1 MeV - 1 GeV)



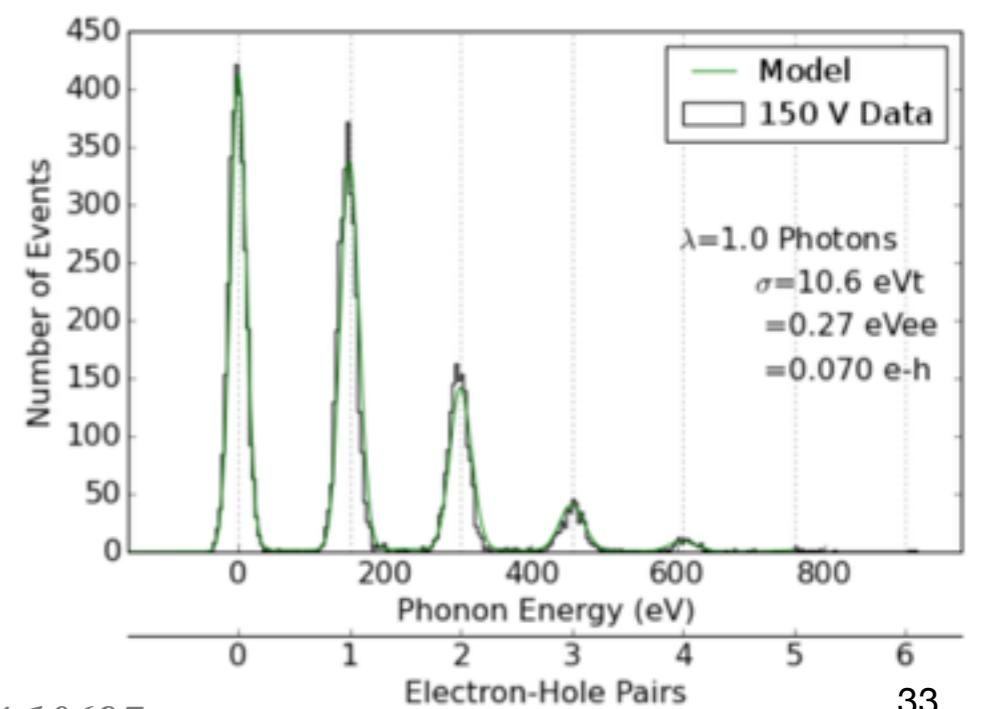
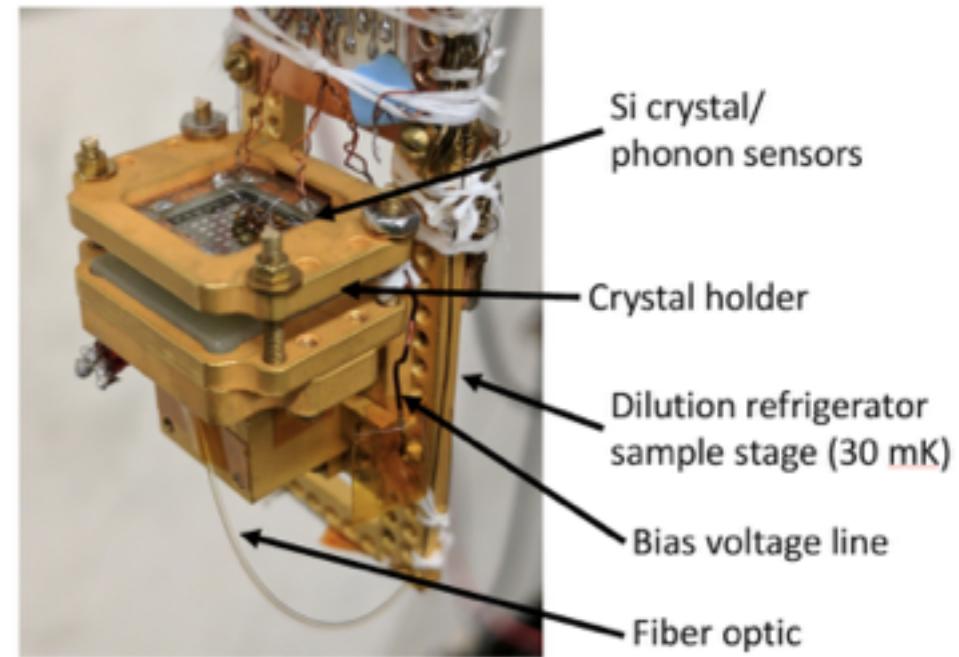
For DM masses below 100 MeV switch to DM-electron scattering searches

Searching for light Dark Matter (1 MeV - 1 GeV)

R. K. Romani et al., arXiv:1710.09335

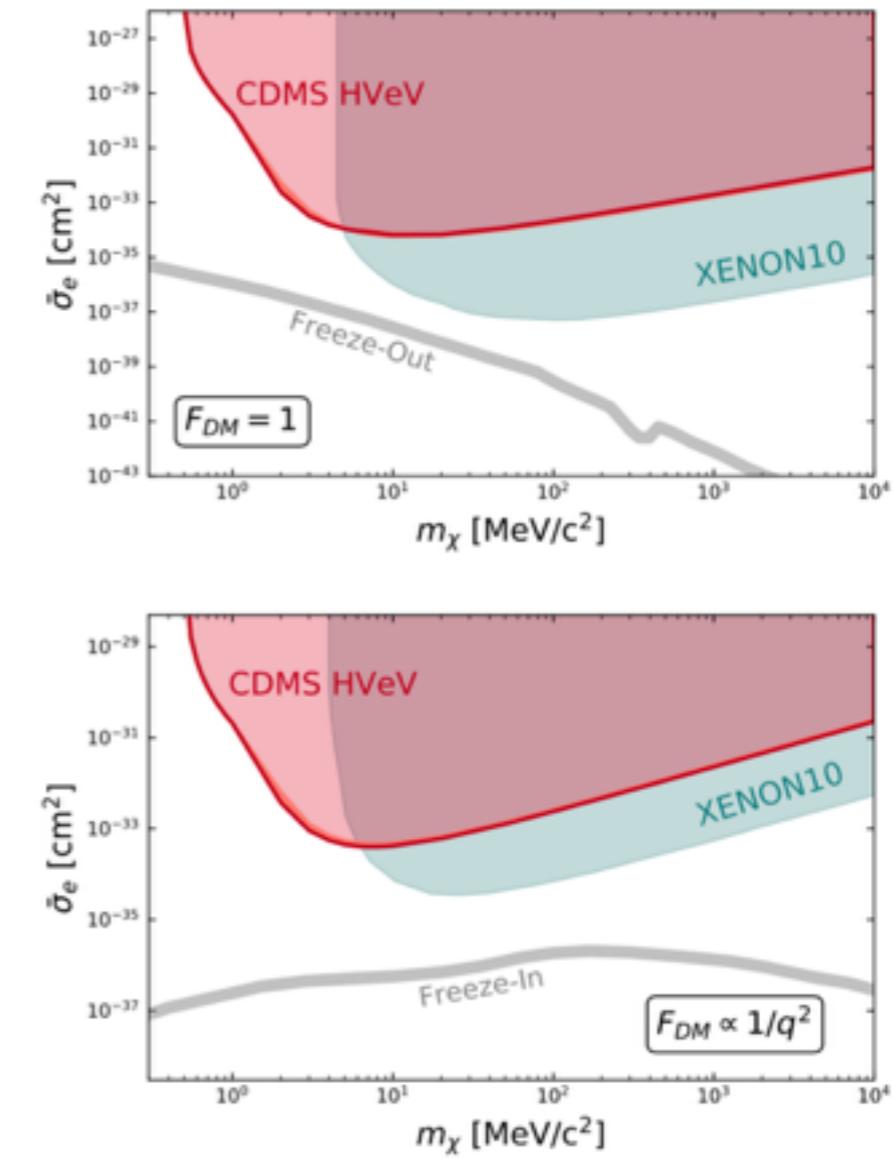
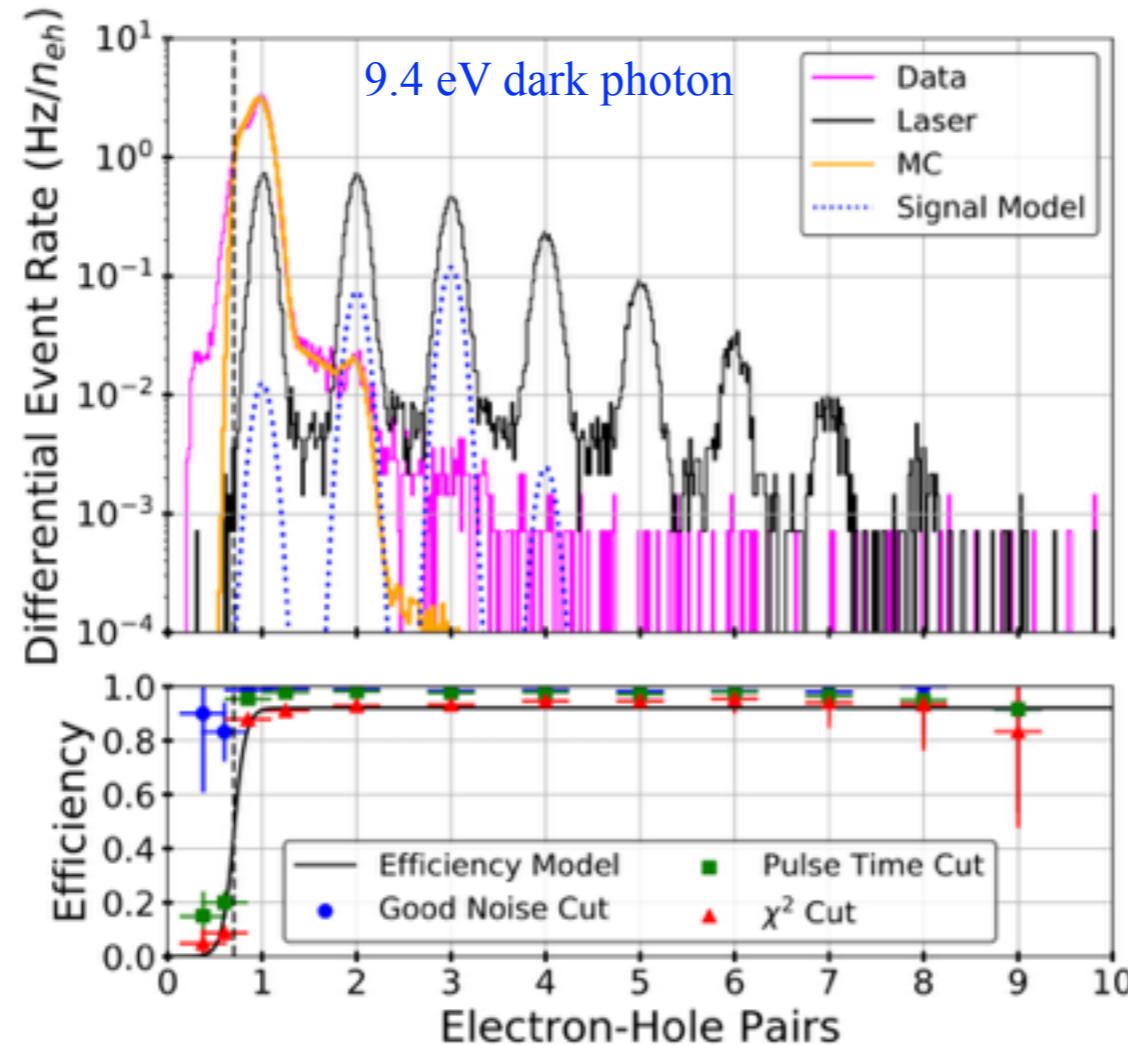
First observation of electron-hole pair quantization in a cryogenic semiconductor

- Using a 0.93 g Si detector instrumented with two W-TES phonon sensors with baseline resolution of 14 eV (RMS)
- Applied voltage up to 160 V (gain of ~ 43) - *HV mode*
- Based on a pulsed IR laser beam (650 nm) data, clear **observation of electron-hole pair quantization**
- Opens the possibility to:
 - probe Dark Matter models < 1 MeV,
 - achieve NR/ER discrimination down to the eV-scale
 - measure the NR ionization yield down to the lowest energies
- Science run at 140 V
- Leakage current **dominated by Sub-Gap IR photons ionizing overcharged states**



Searching for light Dark Matter (1 MeV - 1 GeV)

- An exposure of 12.6 hours passed the initial, trigger- and leakage-burst cuts, yielding a science exposure of 0.49 g-days for the 0.93 g Si detector.
- Leading Light Dark Matter limit from 5 MeV down to 500 keV
- With higher exposure, future and larger HV Ge/SI detectors are expected to have leading sensitivity for $n > 2$ ($\sim 7 \text{ eVee}$)



Conclusions

Take away points:

- From the last few years, an increasing interest in the low-mass dark matter region (*beyond the standard WIMP scenario*)
- Cryogenic detectors are the best suited technology to probe dark matter masses at the GeV-scale
- By the horizon of 2025 CRESST, SuperCDMS and EDELWEISS will reach the neutrino floor from 1 to 5 GeV in the standard searches (*DM-nucleus*)
- New detector technology to go even lower (keV-scale) are on their way (*DM-electron*):
 - Cryogenic semiconductors (Ge/Si) ~ 500 keV
 - Cryogenic superconducting metals (Al/Zn) \sim keV