Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground

arXiv:1901.03588, Phys. Rev. D 99, 082003 (2019)

Bradley J. Kavanagh
GRAPPA, University of Amsterdam
working with the EDELWEISS Collaboration

LHC Results Forum - 29th May 2019

GRAPPA
GRavitation AstroParticle Physics Amsterdam

b.j.kavanagh@uva.nl
@BradleyKavanagh

Looking for tiny and tough WIMPs with EDELWEISS-surf

arXiv:1901.03588, Phys. Rev. D 99, 082003 (2019)

Bradley J. Kavanagh
GRAPPA, University of Amsterdam
working with the EDELWEISS Collaboration

LHC Results Forum - 29th May 2019

GRAPPA
GRavitation AstroParticle Physics Amsterdam

b.j.kavanagh@uva.nl
@BradleyKavanagh

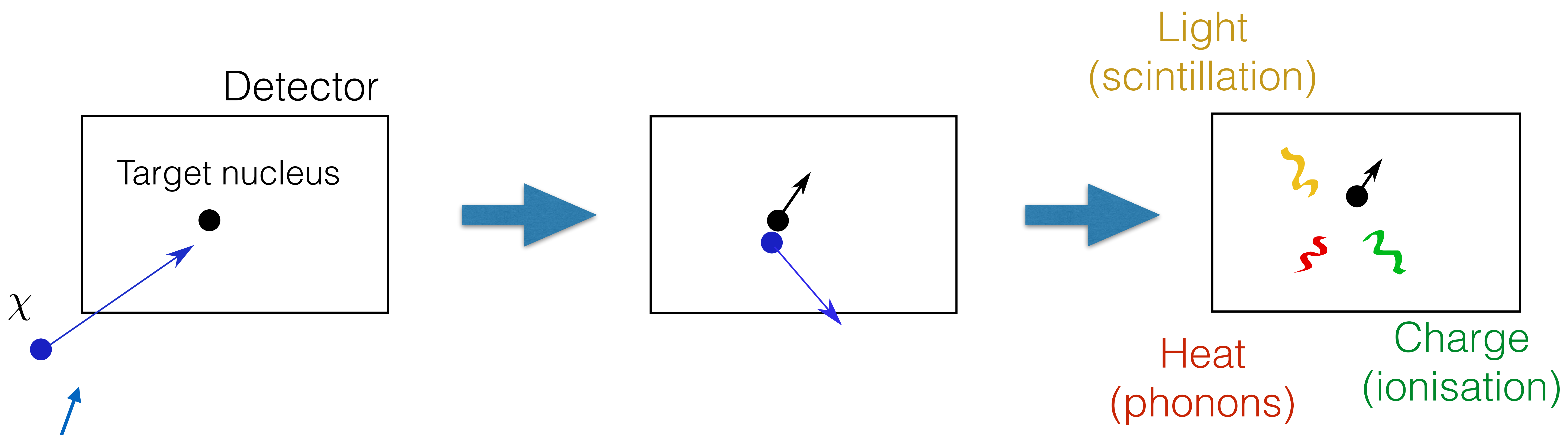
EDELWEISS (EDW) Collaboration

+ Me…

[April 2016]

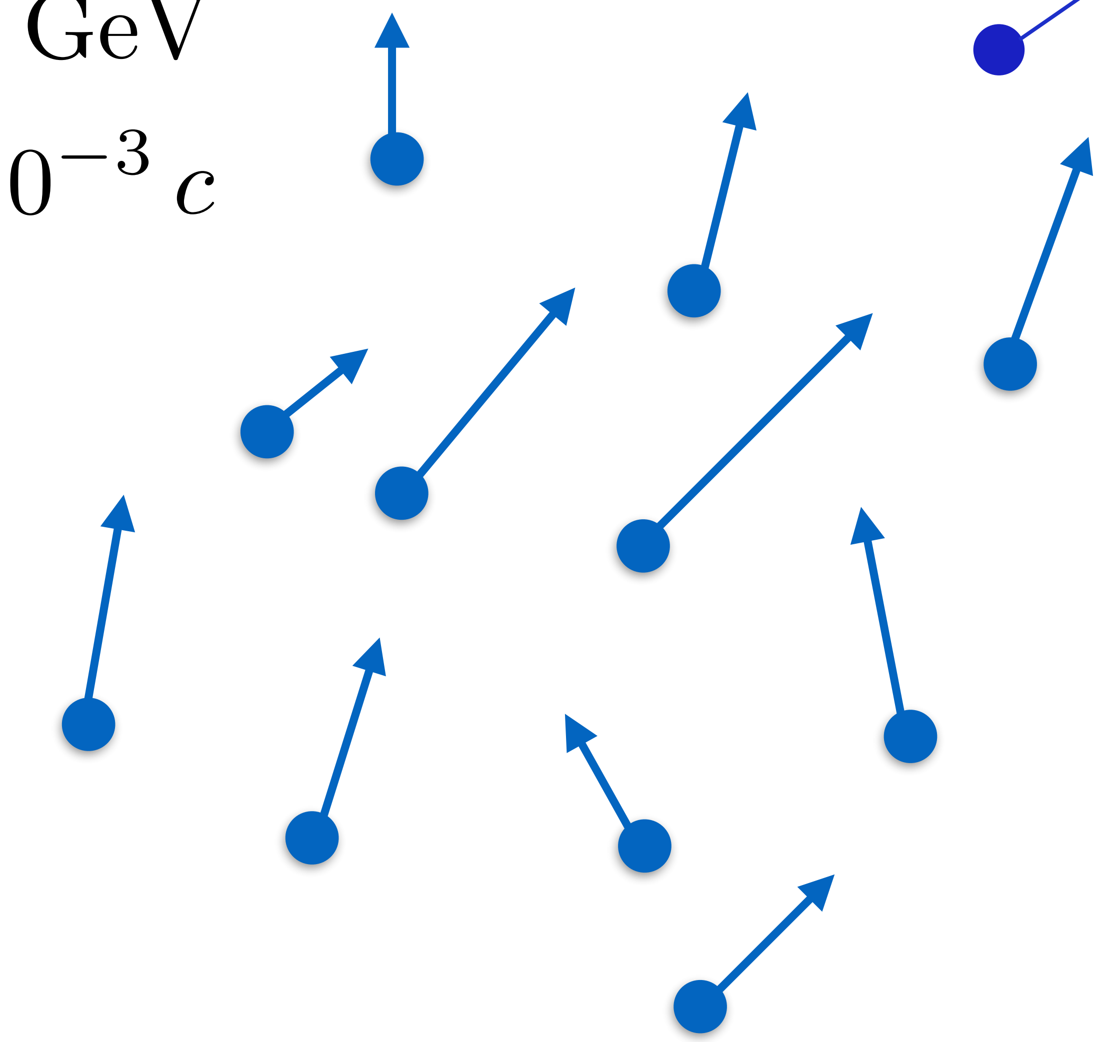
Searching for Dark Matter

Look for Dark Matter in the form of new **W**eakly **I**nteracting **M**assive **P**articles (**WIMPs**)



$m_\chi \gtrsim 1\,\mathrm{GeV}$

$v_\chi \sim 10^{-3}\,c$

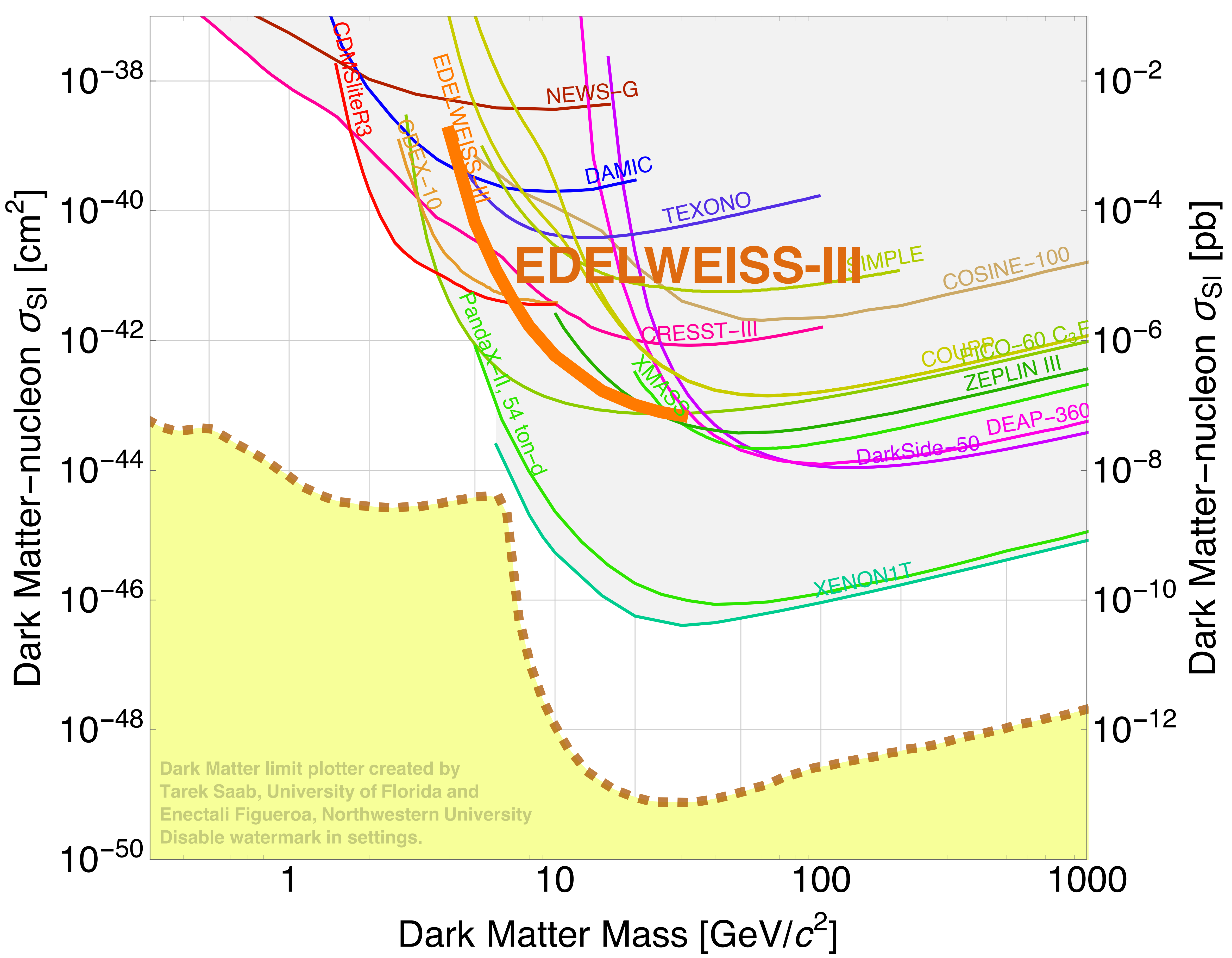


Galactic ‘wind’ of DM particles

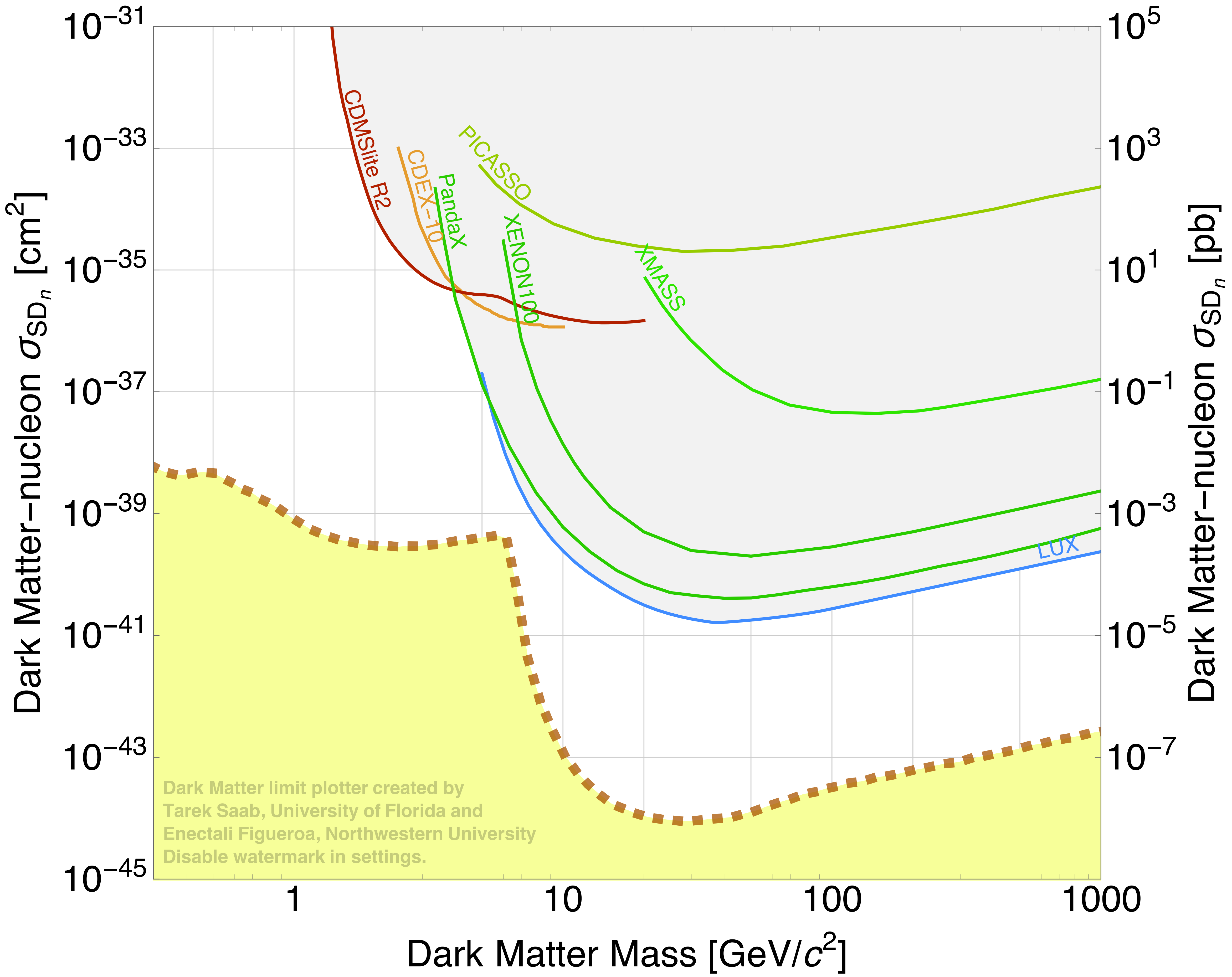
- Low energy nuclear recoils —> need **low energy threshold** O(keV)
- Rare event search —> need **large target mass**
- Large backgrounds —> need **shielding and underground labs**

Direct Detection Landscape

Spin-independent DM-nucleon interactions



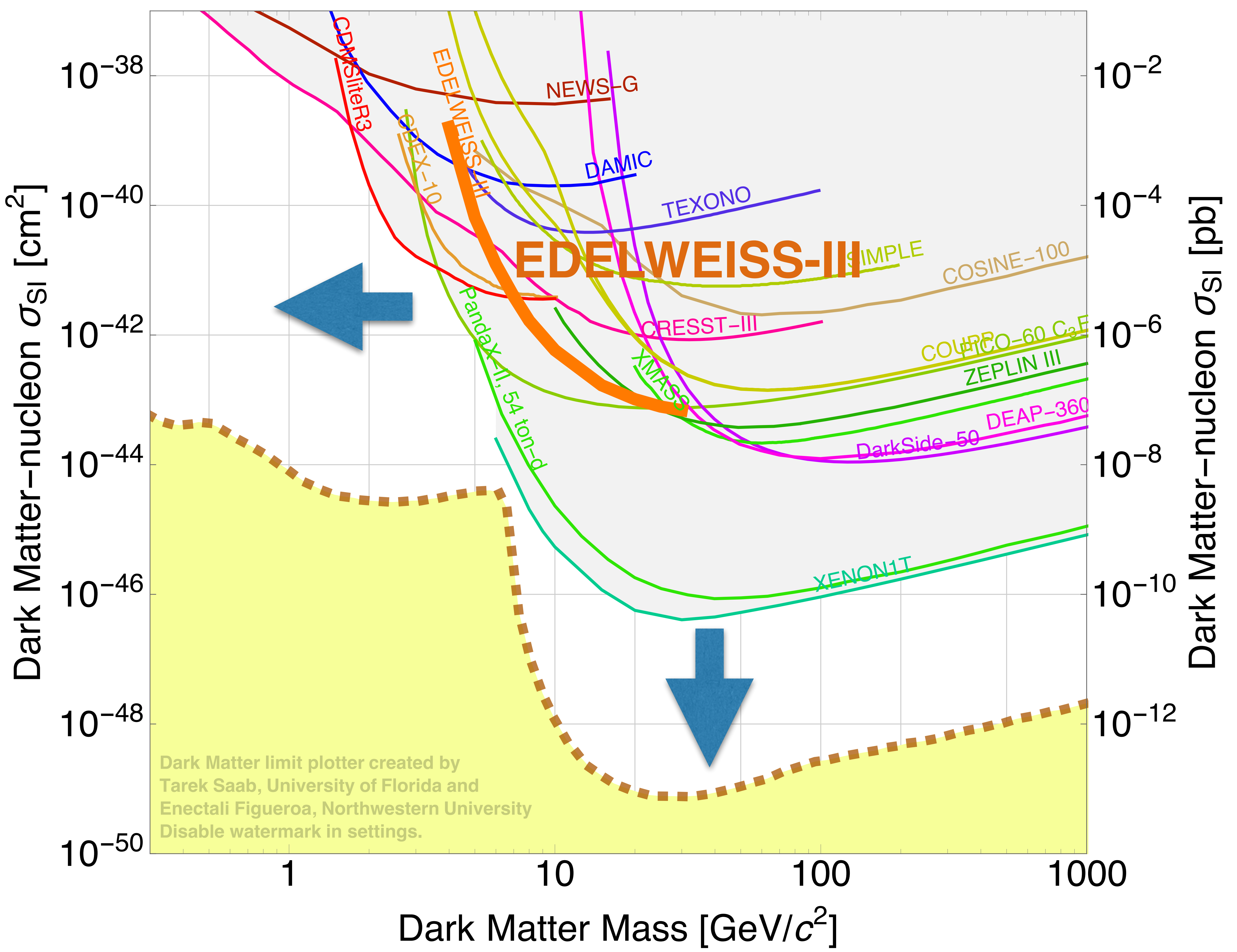
Spin-dependent DM-*neutron* interactions



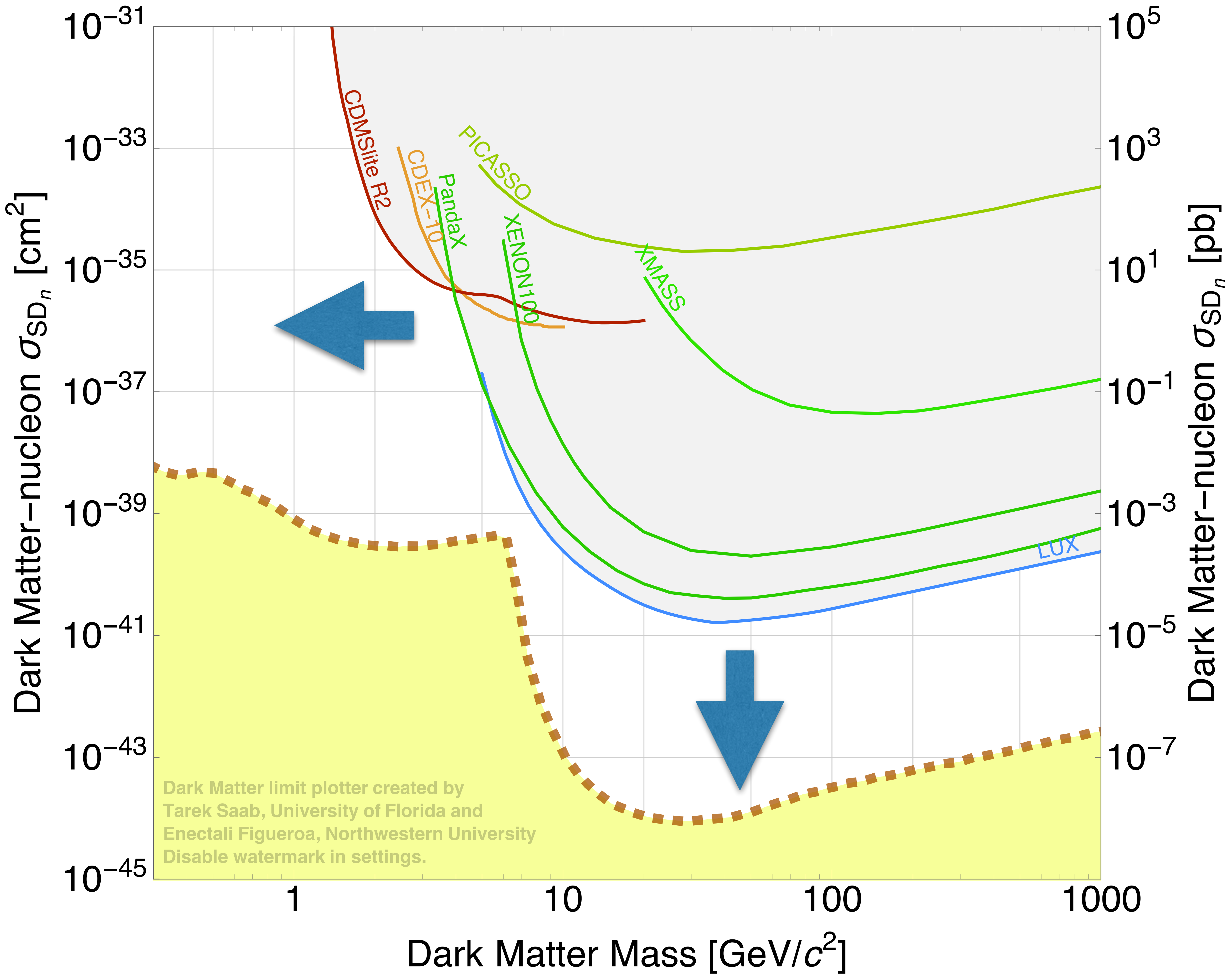
Direct Detection Landscape

"Leave no stone unturned!" [Bertone & Tait - 1810.01668]

Spin-independent DM-nucleon interactions



Spin-dependent DM-*neutron* interactions



EDELWEISS-III

~**20 kg Cryogenic Germanium** mass
(24 x ~800g FID800 modules)

Operated in **underground lab** in Modane, France (1700 m rock —> 5 μ/m^2/day)
(continuous operation since Summer 2014)

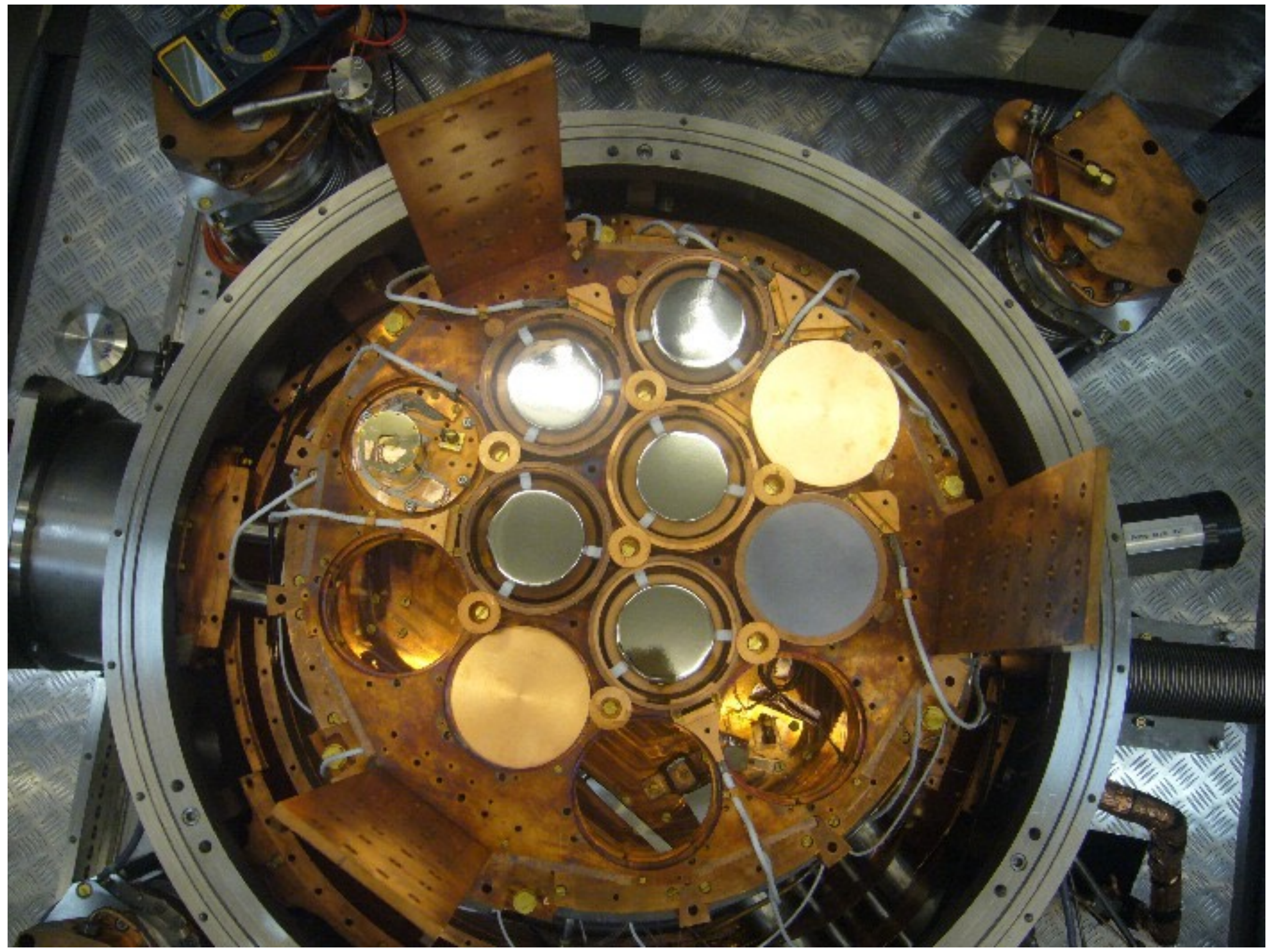
50 cm Polyethylene + 20cm Lead shielding

Measure heat and ionisation to
discriminate electron and nuclear recoils

Energy threshold of 2.5 keV —> sensitivity down to WIMP masses of 4 GeV

496 kg-day exposure reported so far

[**EDW:** 1603.05120, 1607.03367, 1706.01070]



EDELWEISS-surf

Technological development for DM searches and coherent neutrino-nucleus scattering

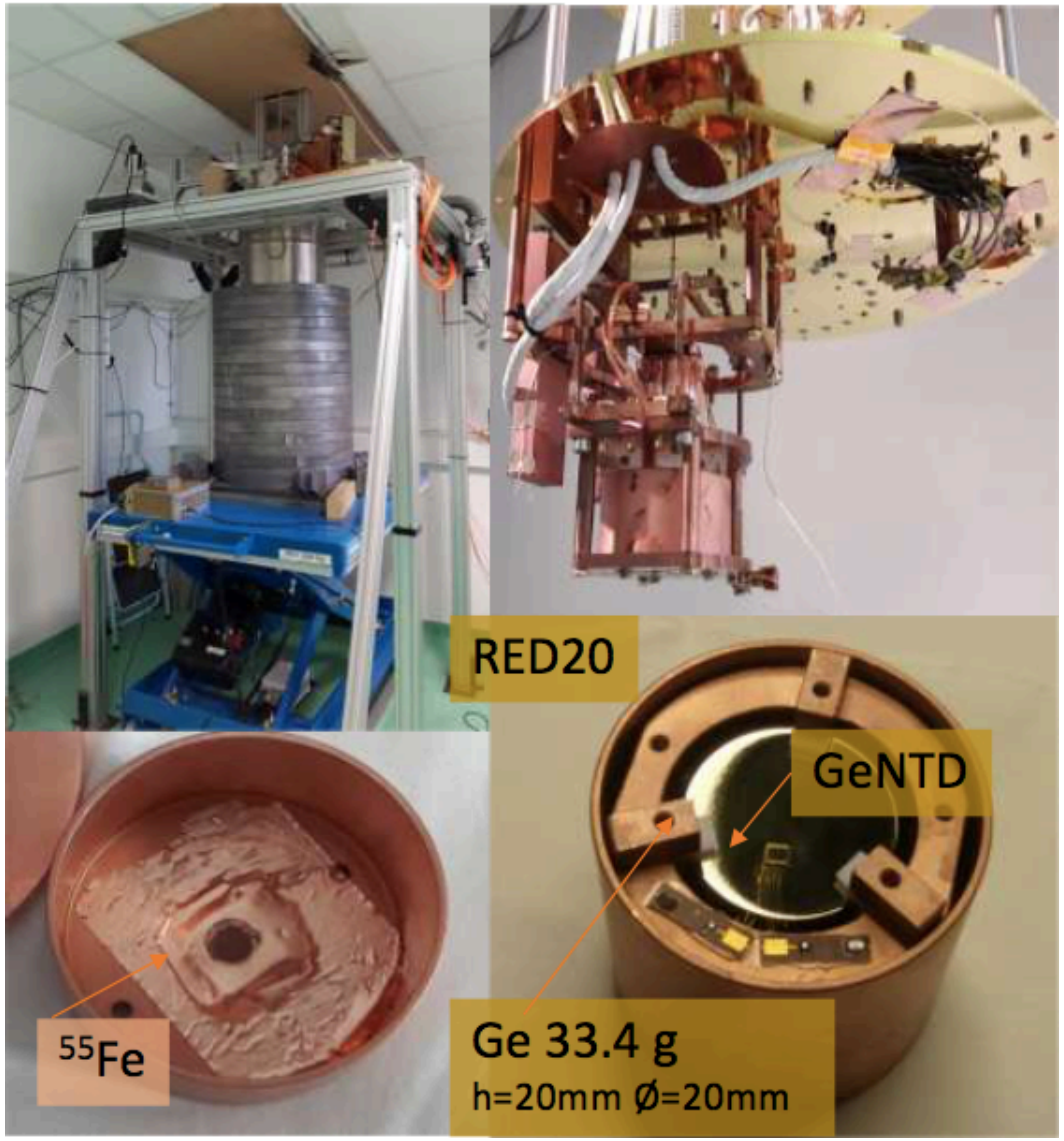
RED20: **Single 33.4g Ge** detector with neutron-transmutation-doped Ge (Ge-NTD) *phonon sensor*

Direct measurement of total deposited energy - *no quenching, but also **no event discrimination***

Data taking in a **surface lab** in Lyon (IPNL) for 6 days with minimal shielding

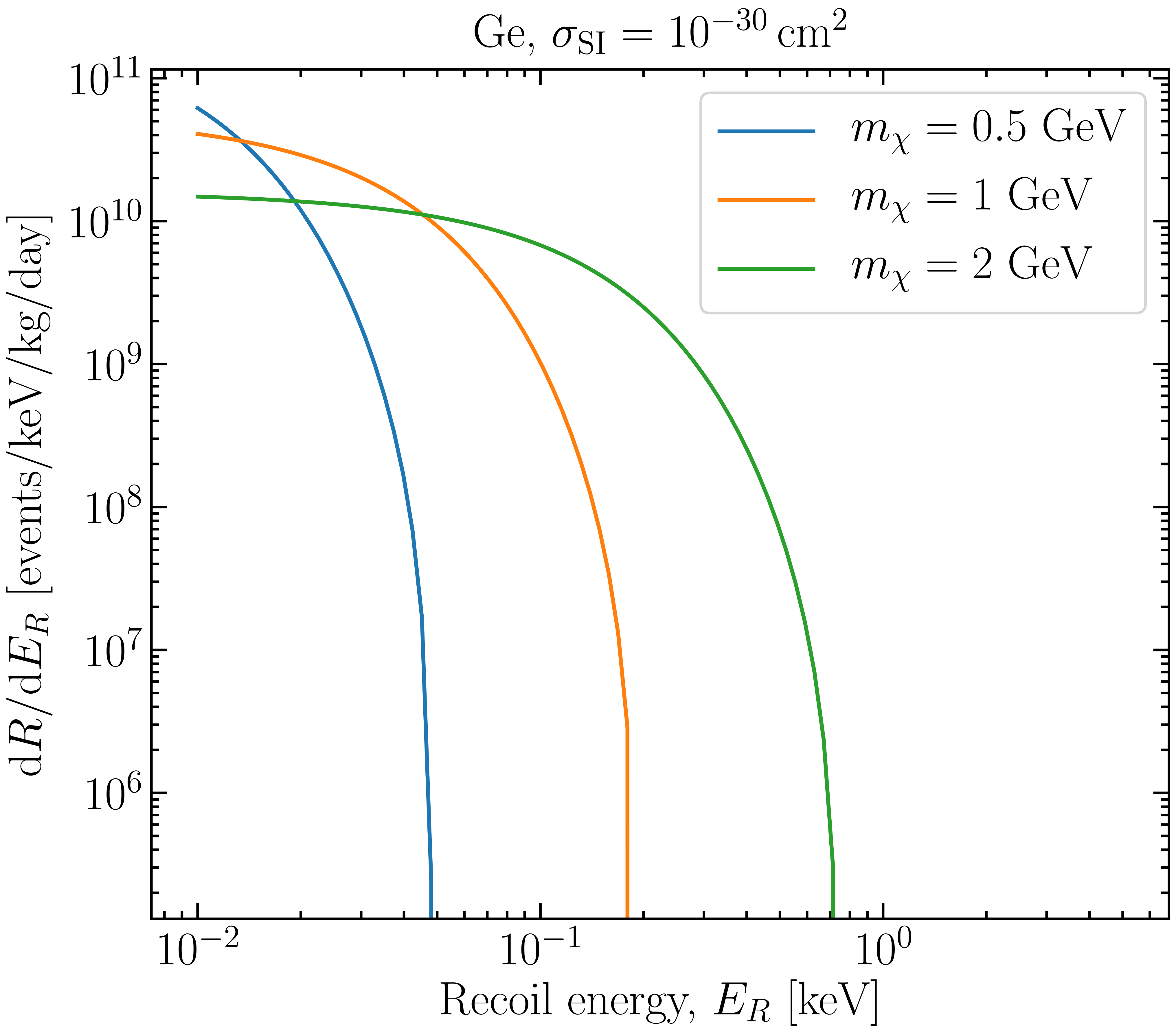
Small ~0.03 kg-day exposure

[**EDW:** 1703.08957,1803.03463]



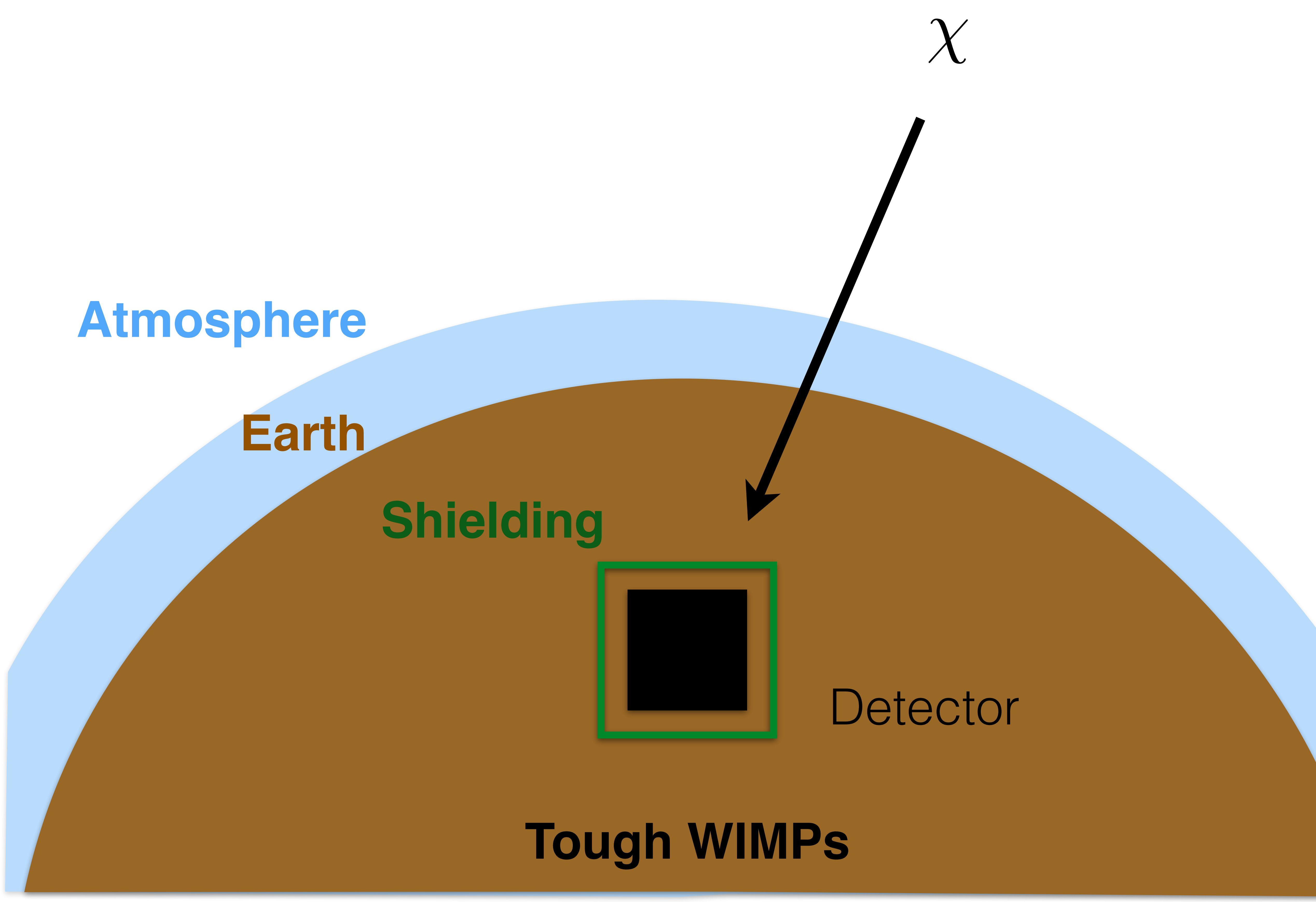
Why I love EDELWEISS-surf

Very low energy threshold: 60 eV



Tiny WIMPs

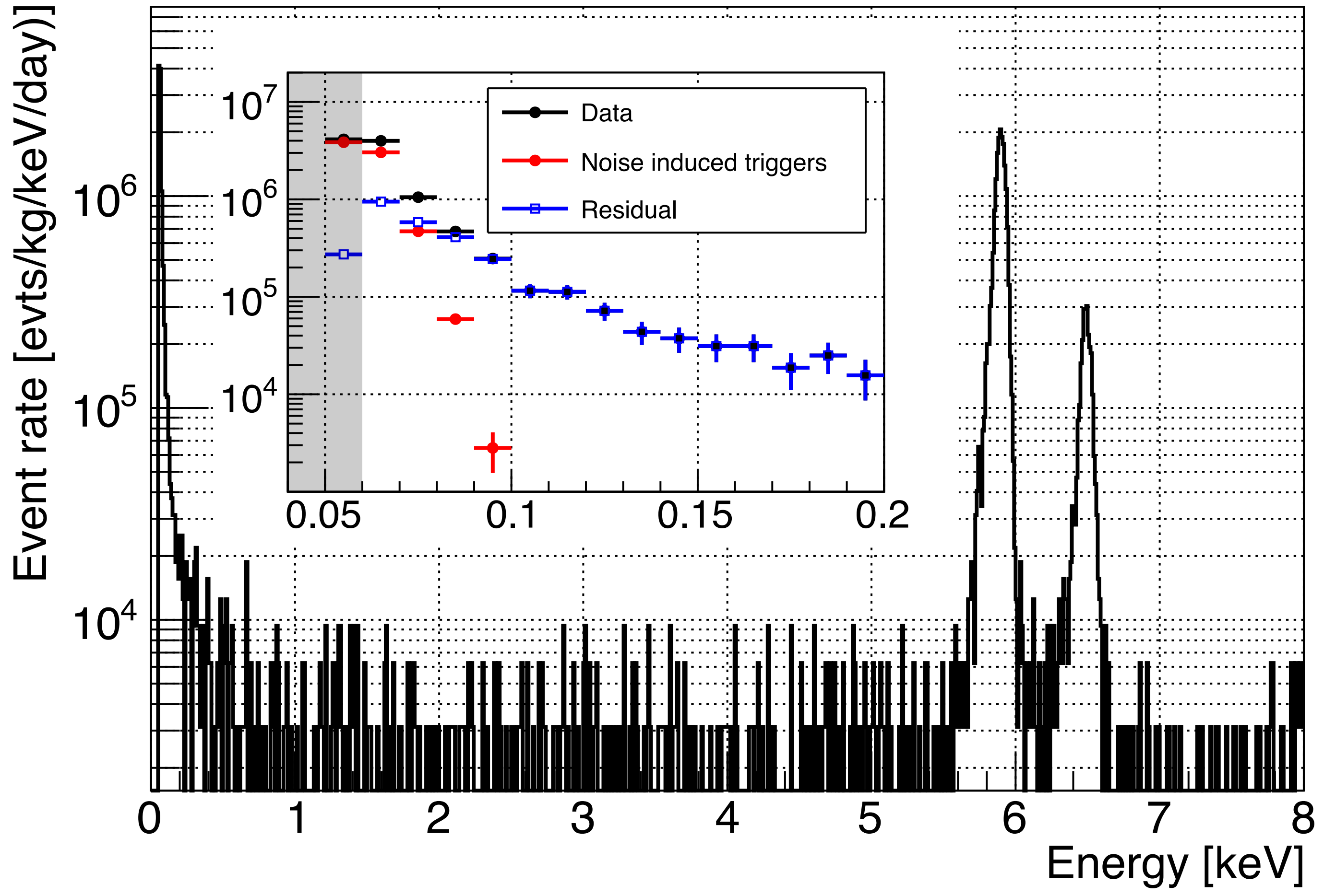
Minimal shielding



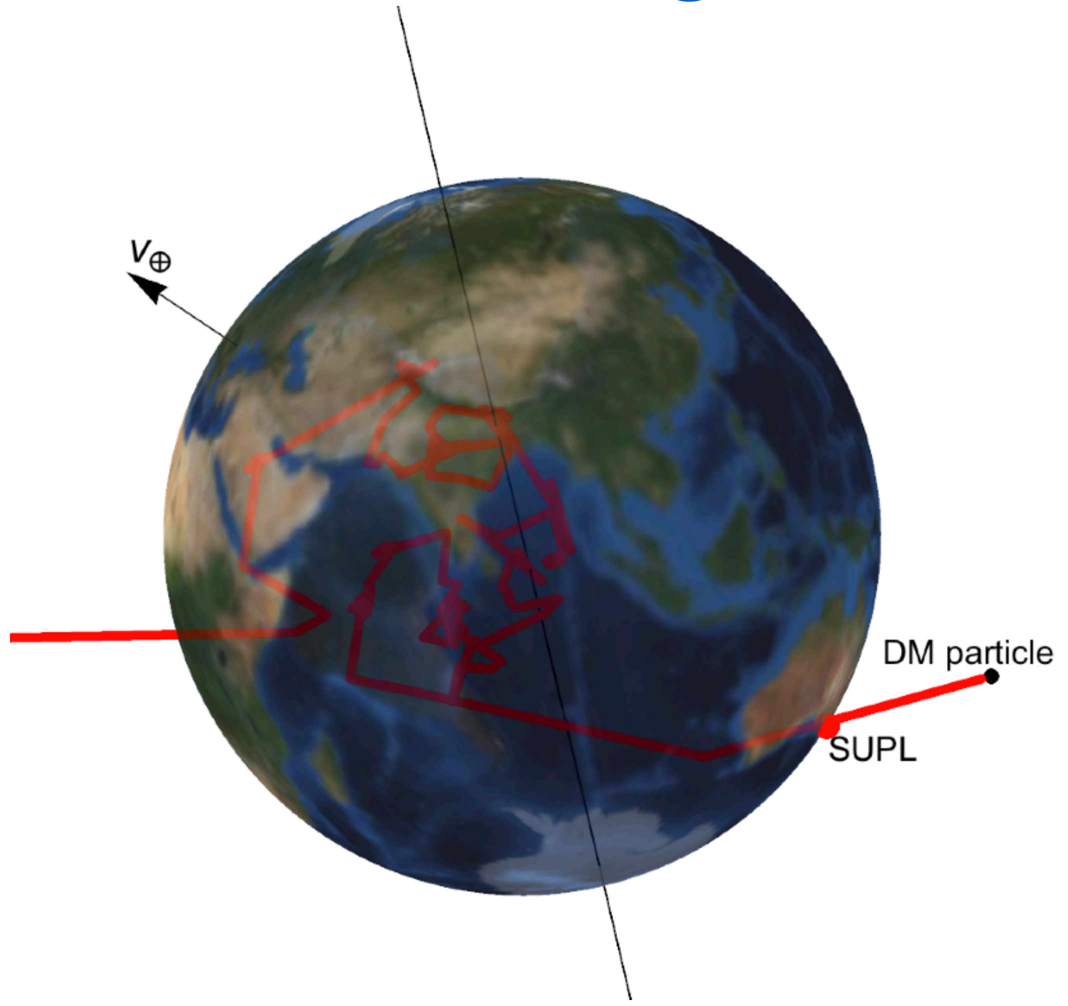
Tough WIMPs

Overview

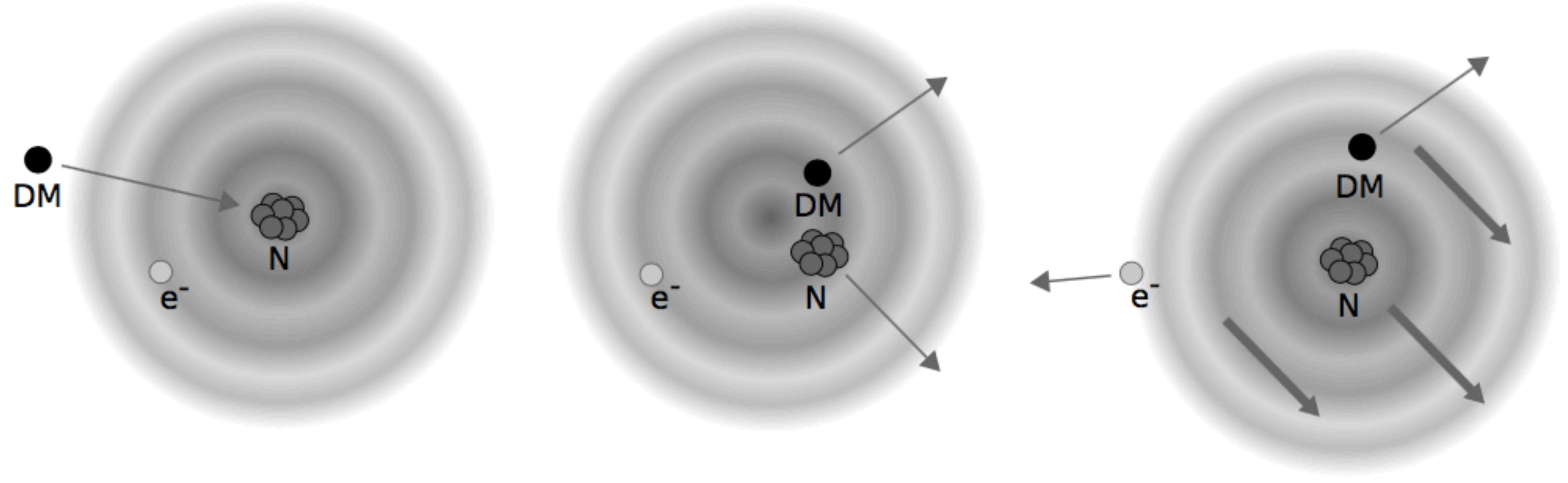
EDELWEISS-surf



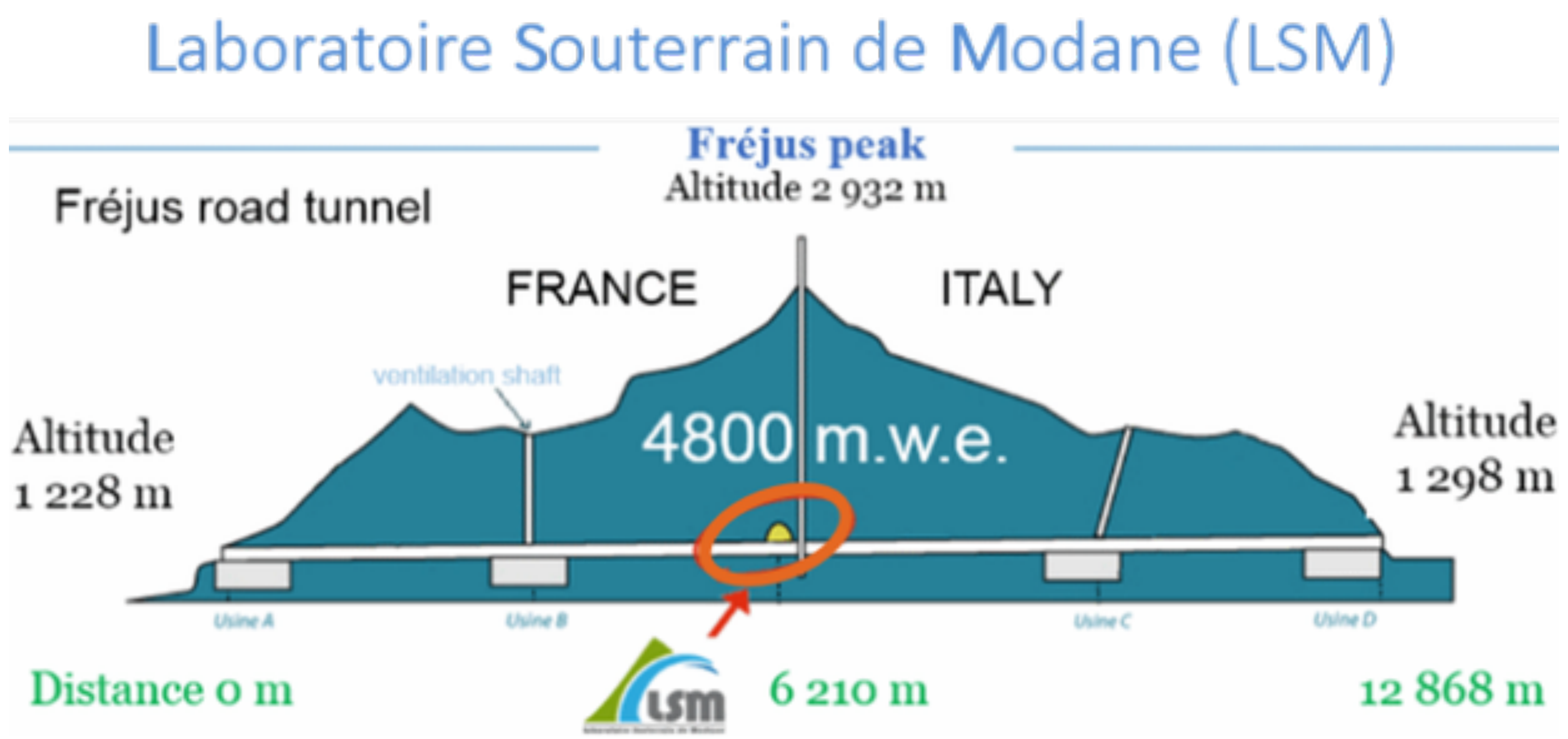
Earth-shielding effects



Sub-sub-GeV Dark Matter searches

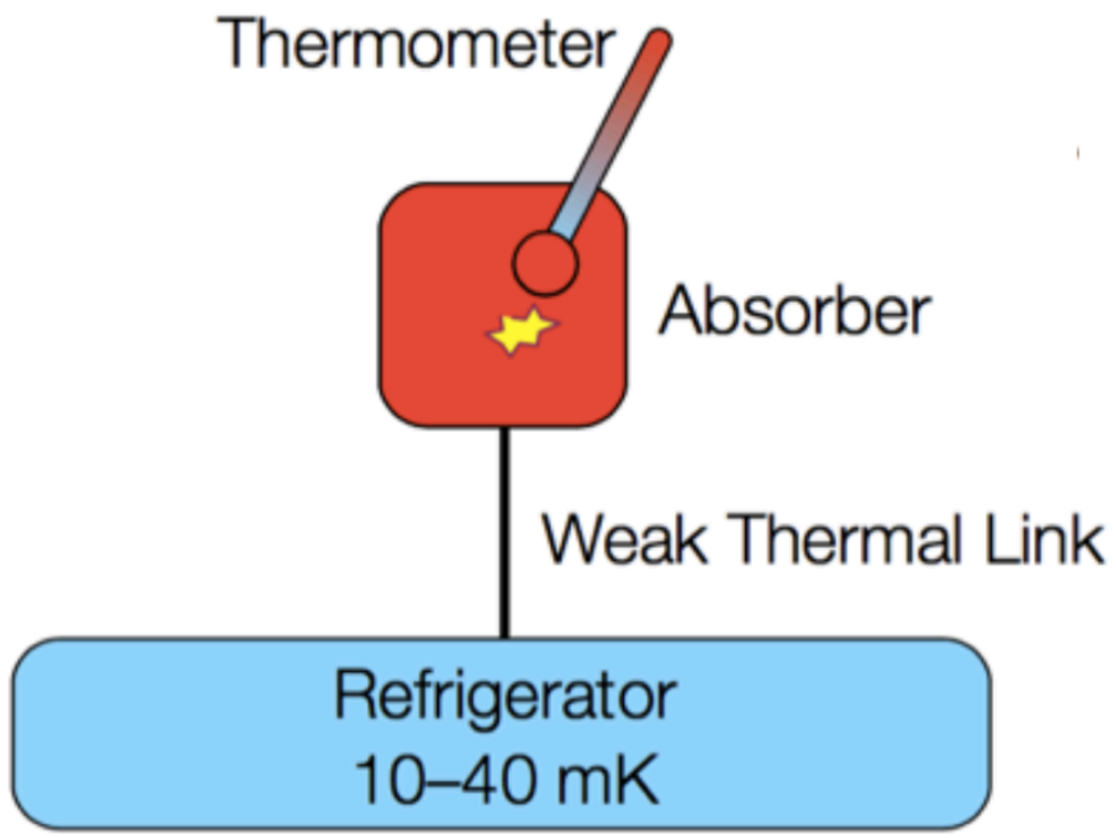


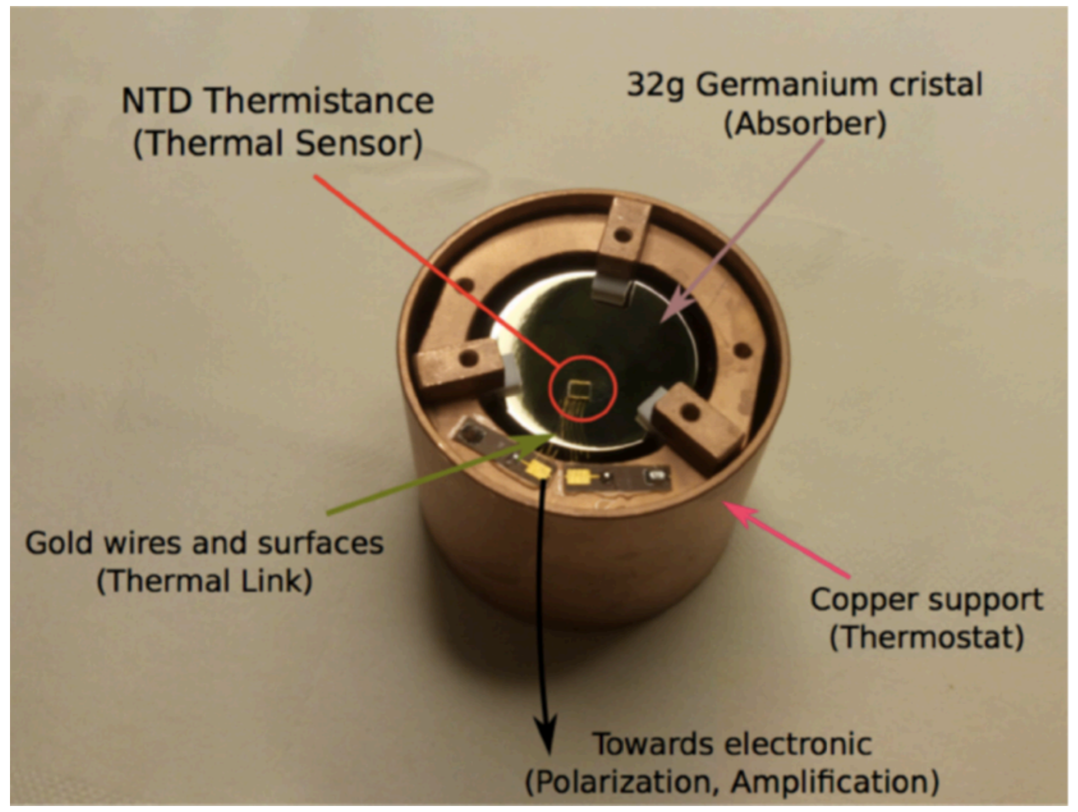
The future

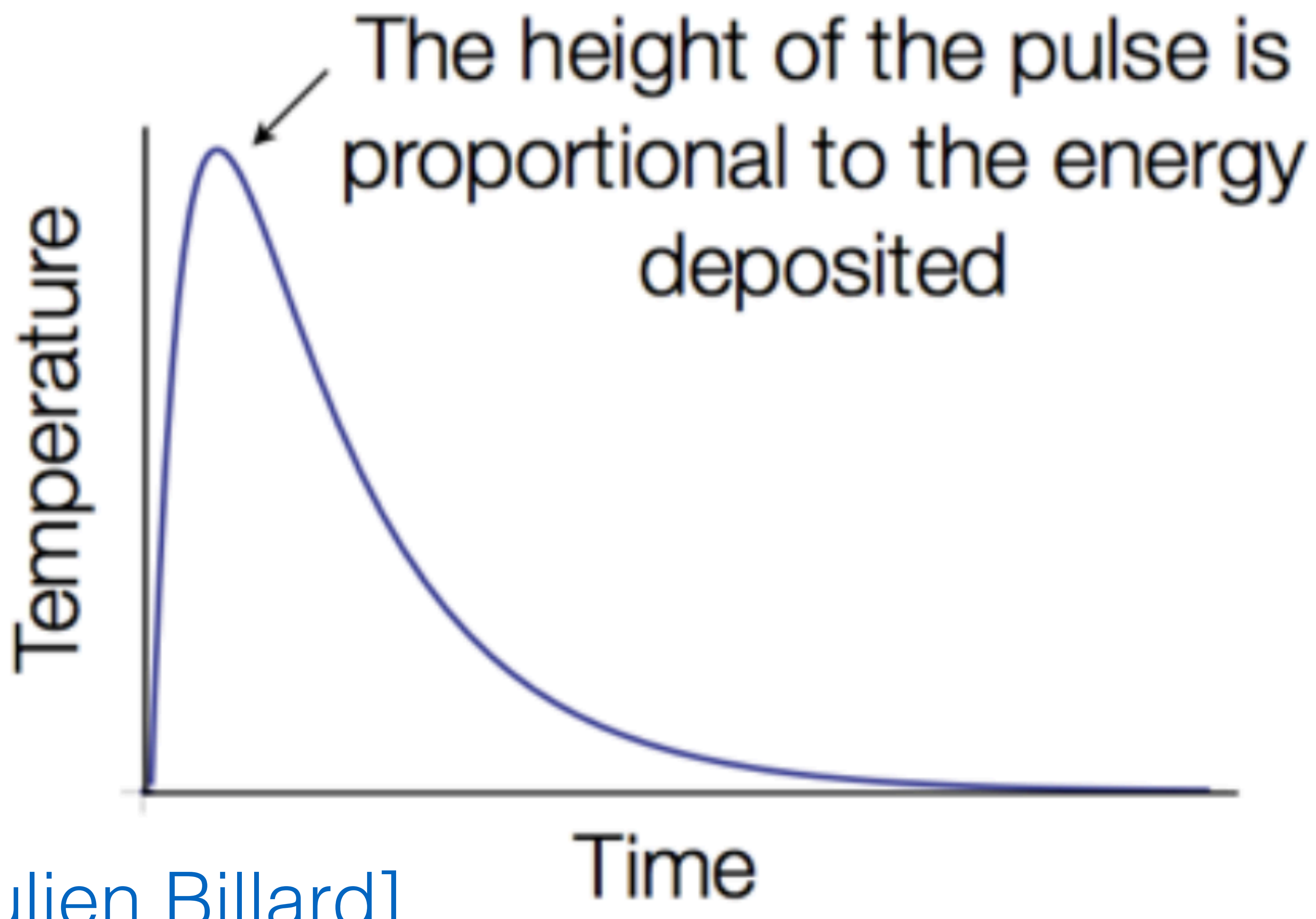


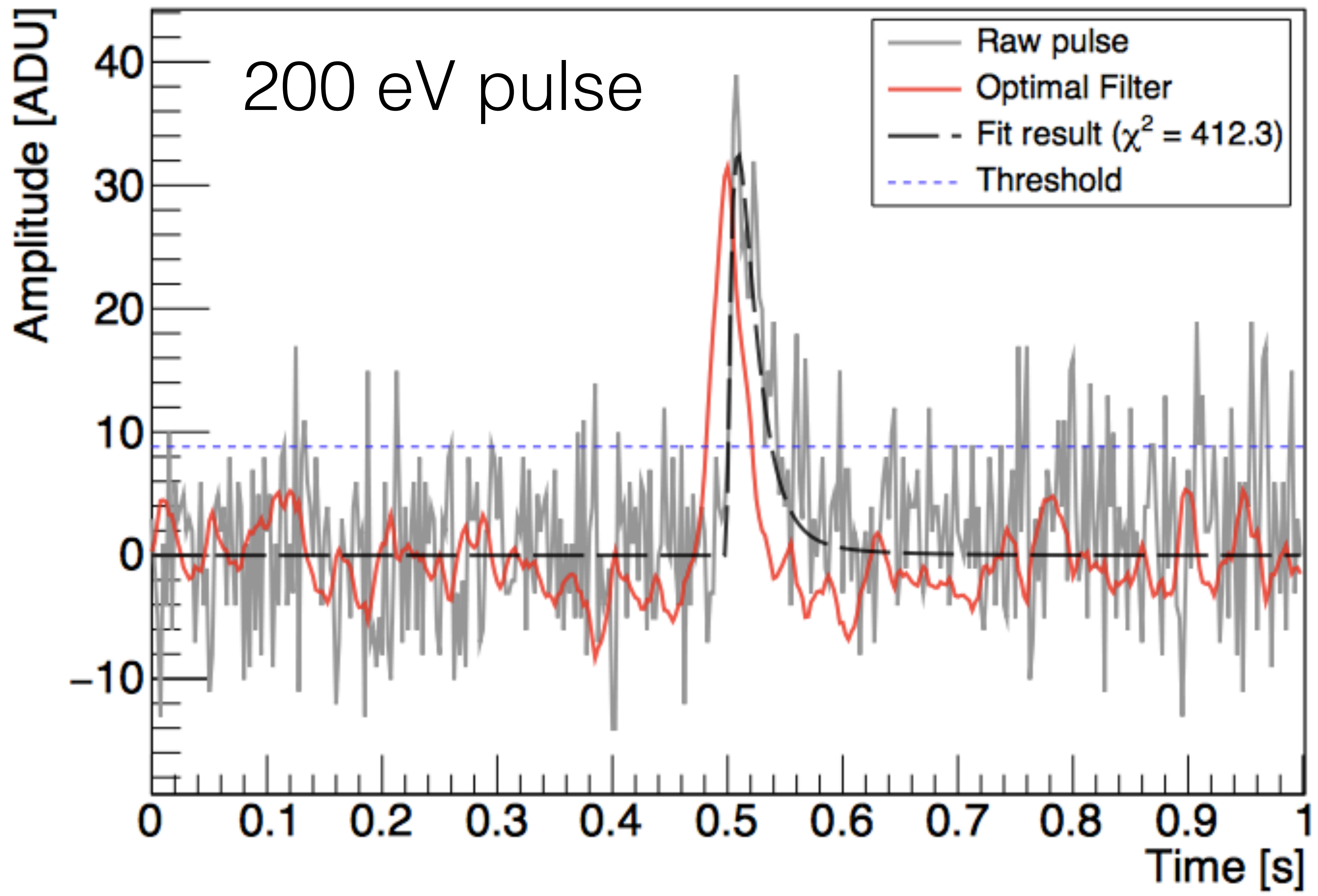
RED20

Single 33.4g Ge detector (20mm x 20mm) with neutron-transmutation-doped Ge (Ge-NTD) *phonon sensor*



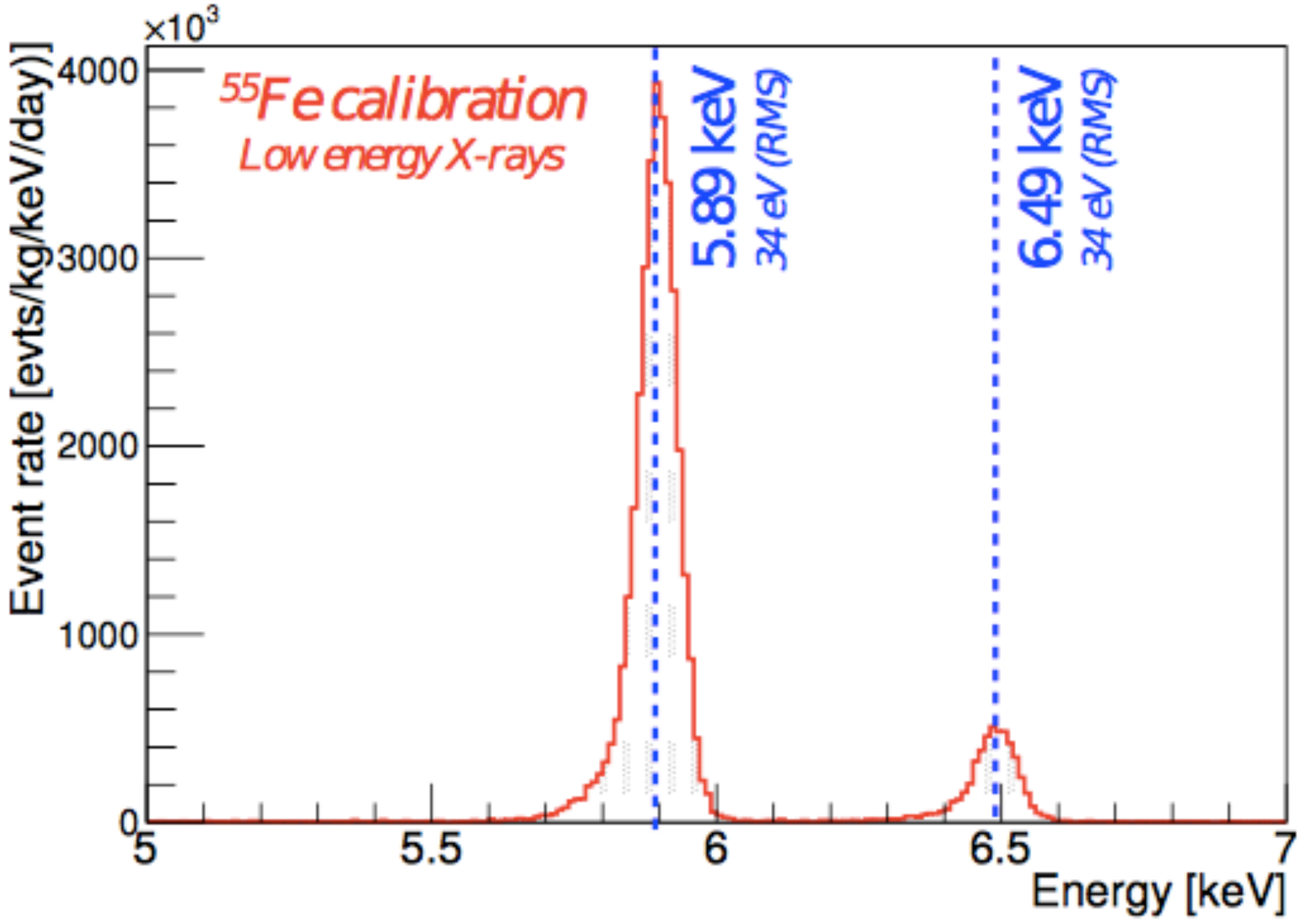






[Credit: Julien Billard]

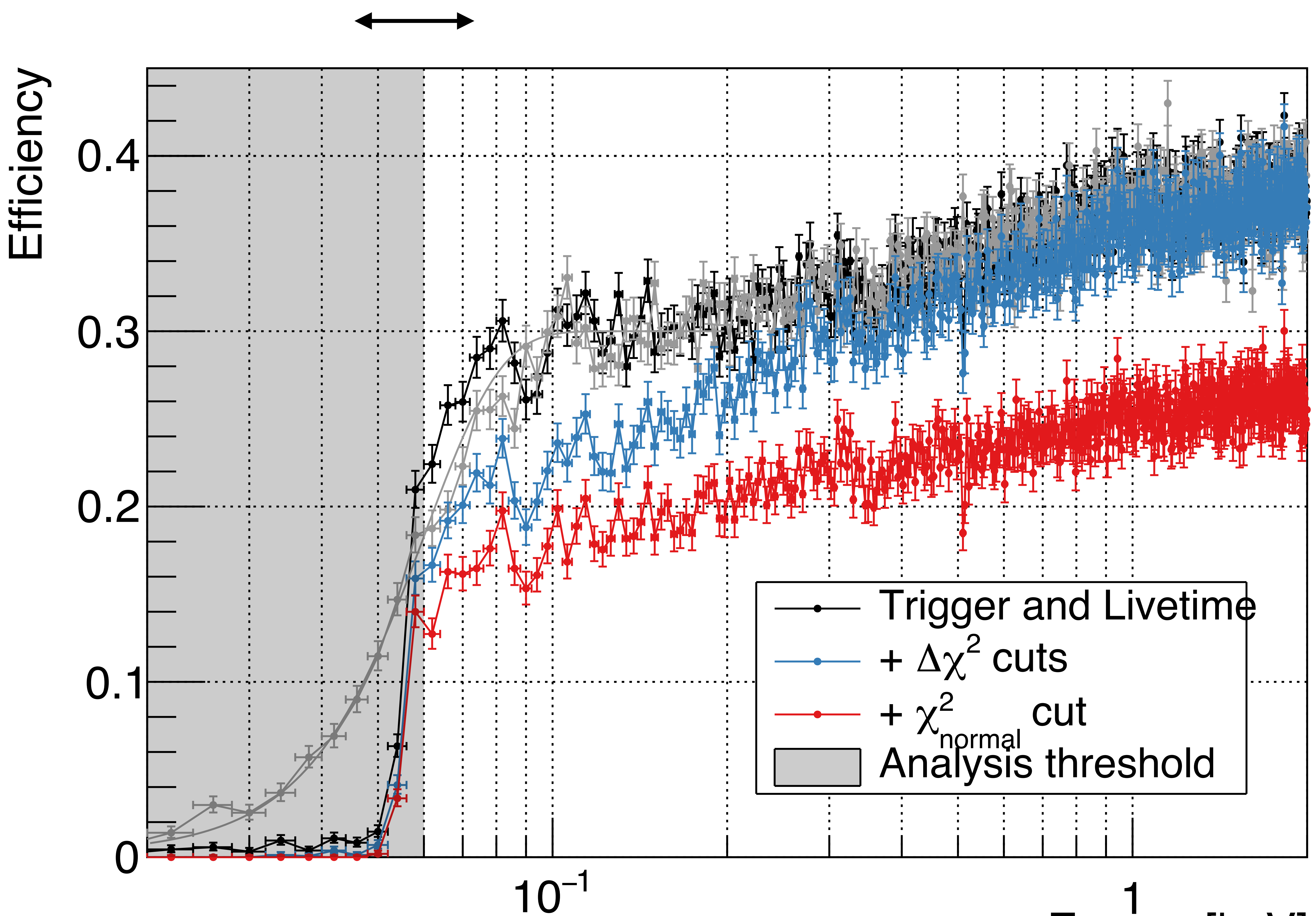
Calibration and Resolution



Calibrated with low energy X-rays from ^{55}Fe

No ionisation read-out (only phonons) - total deposited energy is collected, allowing for a low threshold

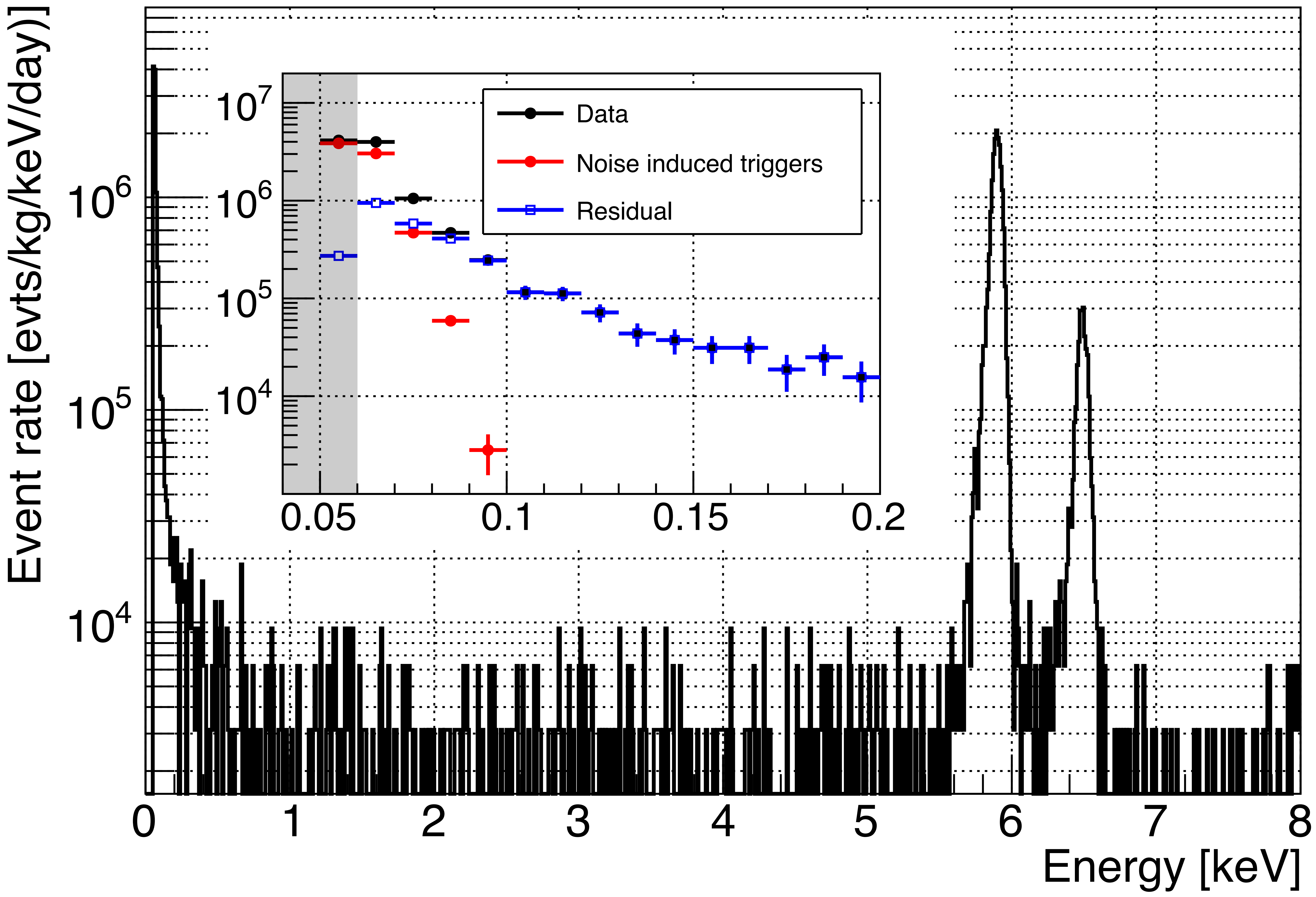
18 eV RMS energy resolution



60 eV energy threshold

Data

Energy spectrum recorded in the blinded day (26th May 2018) of the **DM search data**, after all cuts.



What would a Dark Matter signal look like?

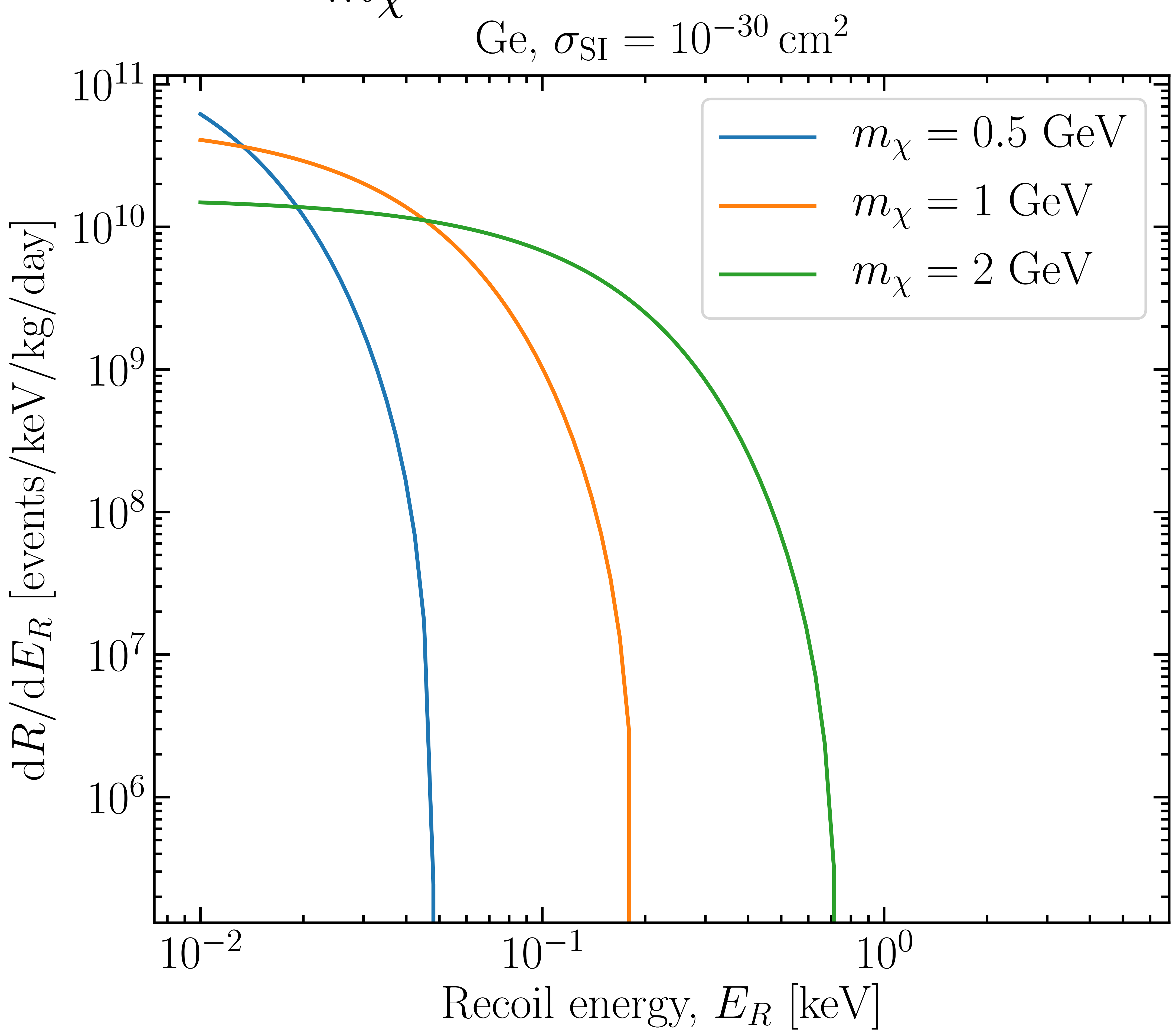
Dark Matter scattering rate

Detector

$\chi \longrightarrow$ ■

DM flux:

$$\Phi_\chi = \frac{\rho_\chi}{m_\chi} v f(\mathbf{v})$$



Convolve with DM-nucleus cross section to obtain nuclear recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \frac{\rho_\chi}{m_\chi} \int_{v_{\mathrm{min}}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \mathrm{d}v$$

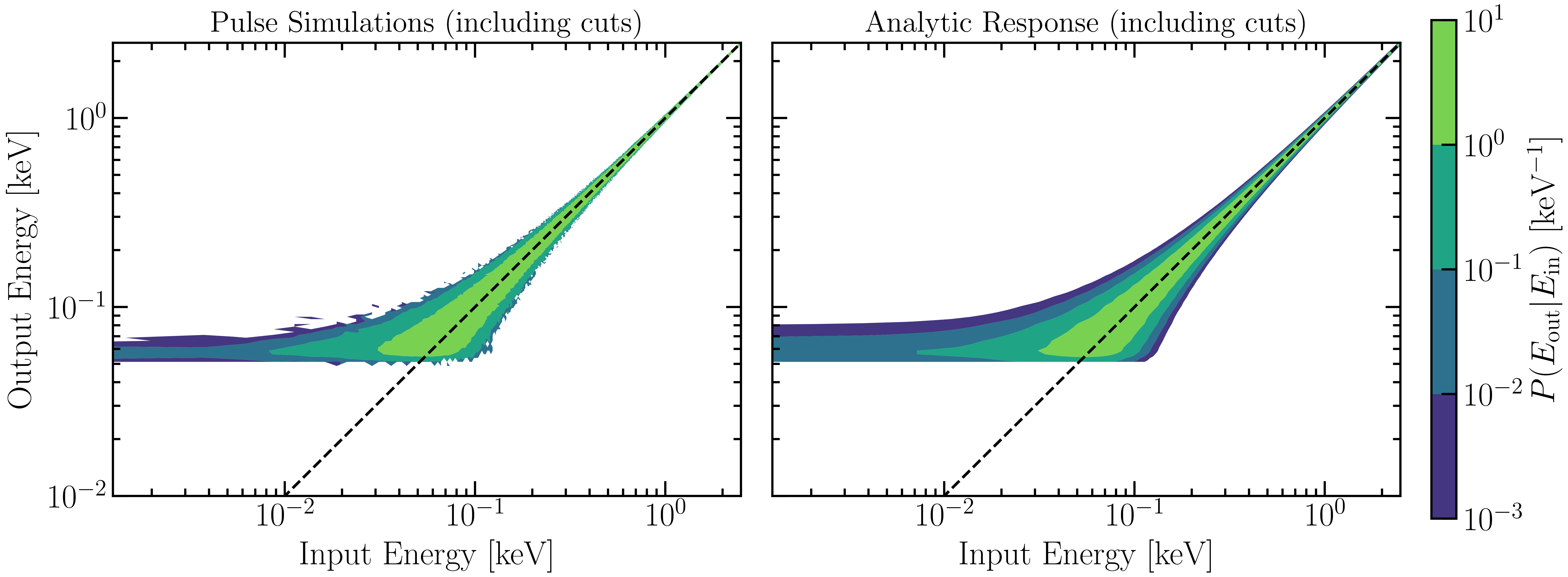
Spin-independent (SI): $\sigma_{\mathrm{SI}}^A \propto \sigma_{\mathrm{SI}}^p A^2$

Spin-dependent (SD): $\sigma_{\mathrm{SD}}^A \propto \sigma_{\mathrm{SD}}^{p,n} \langle S_{p,n} \rangle^2$

(Spin-content dominated by single unpaired neutron in ^{73}Ge)

Detector Response

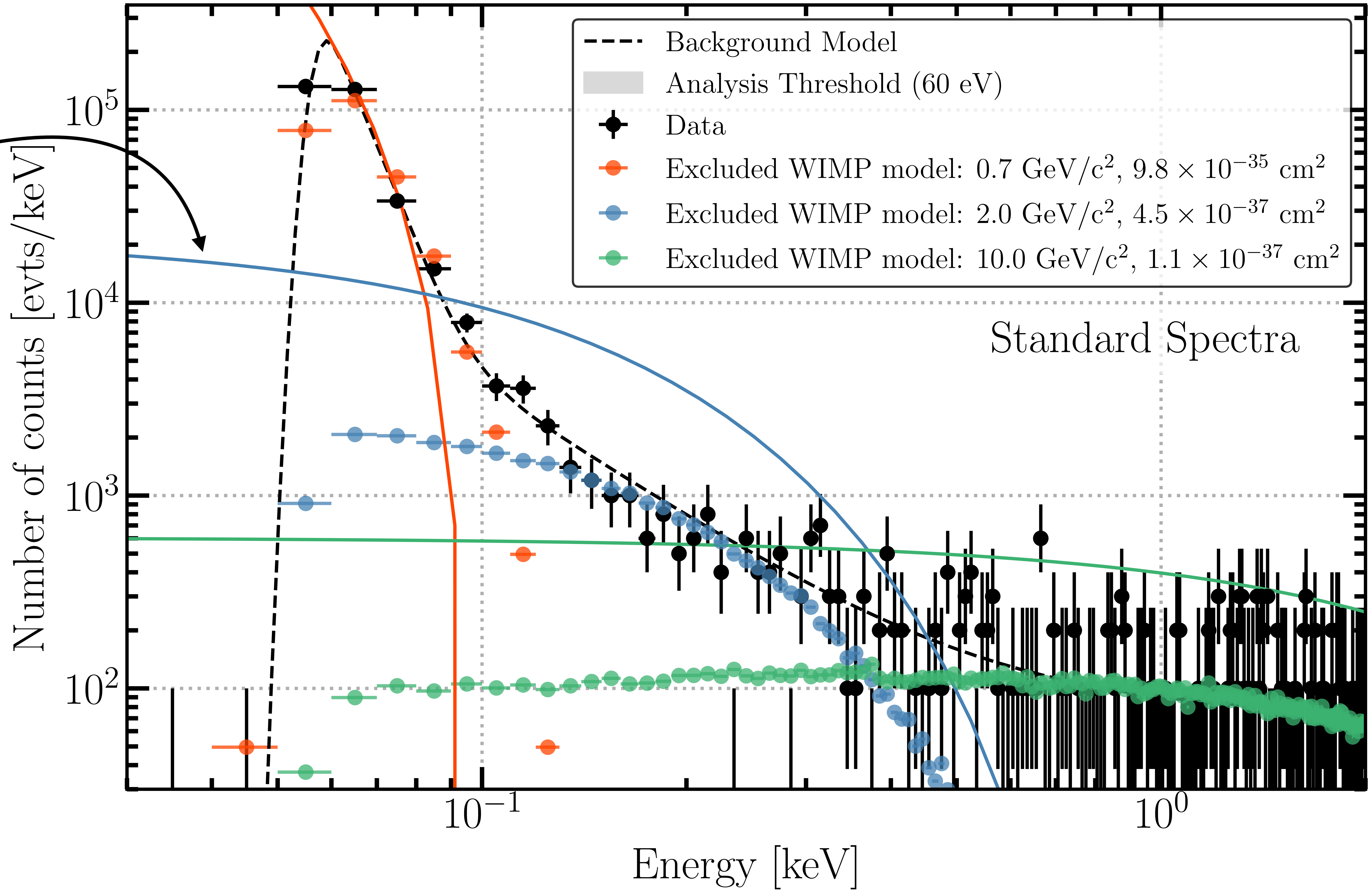
Simulate 10^7 simulated DM signal pulses and determine reconstructed energy - also developed more efficient analytic model for the detector response:



Convolve recoil spectrum with detector response to obtain expected distribution of events

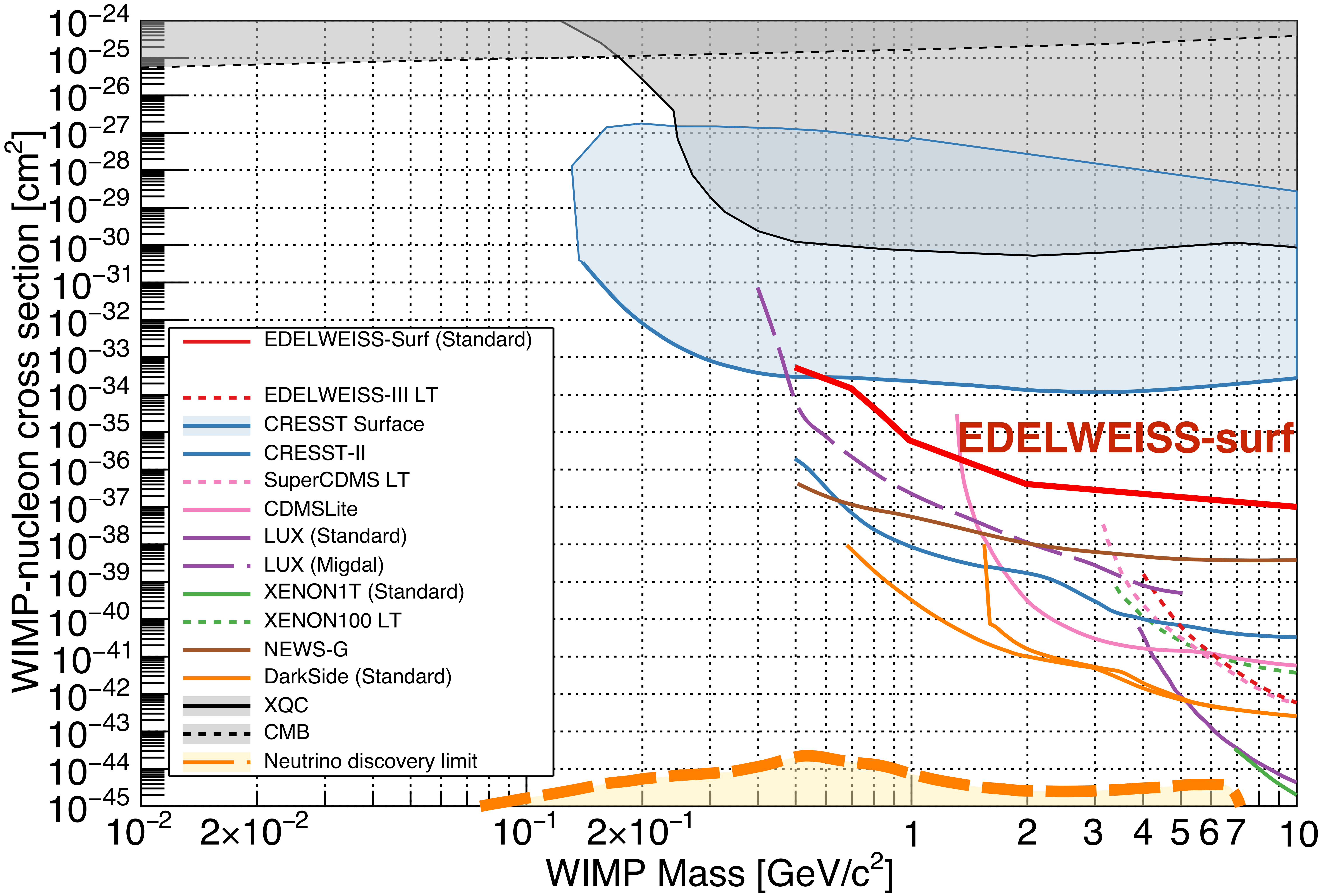
Signal and Data

'Unsmeared' spectra



Set upper limit based on optimal poisson interval
(given empirical background model from 5 days unblinded data)

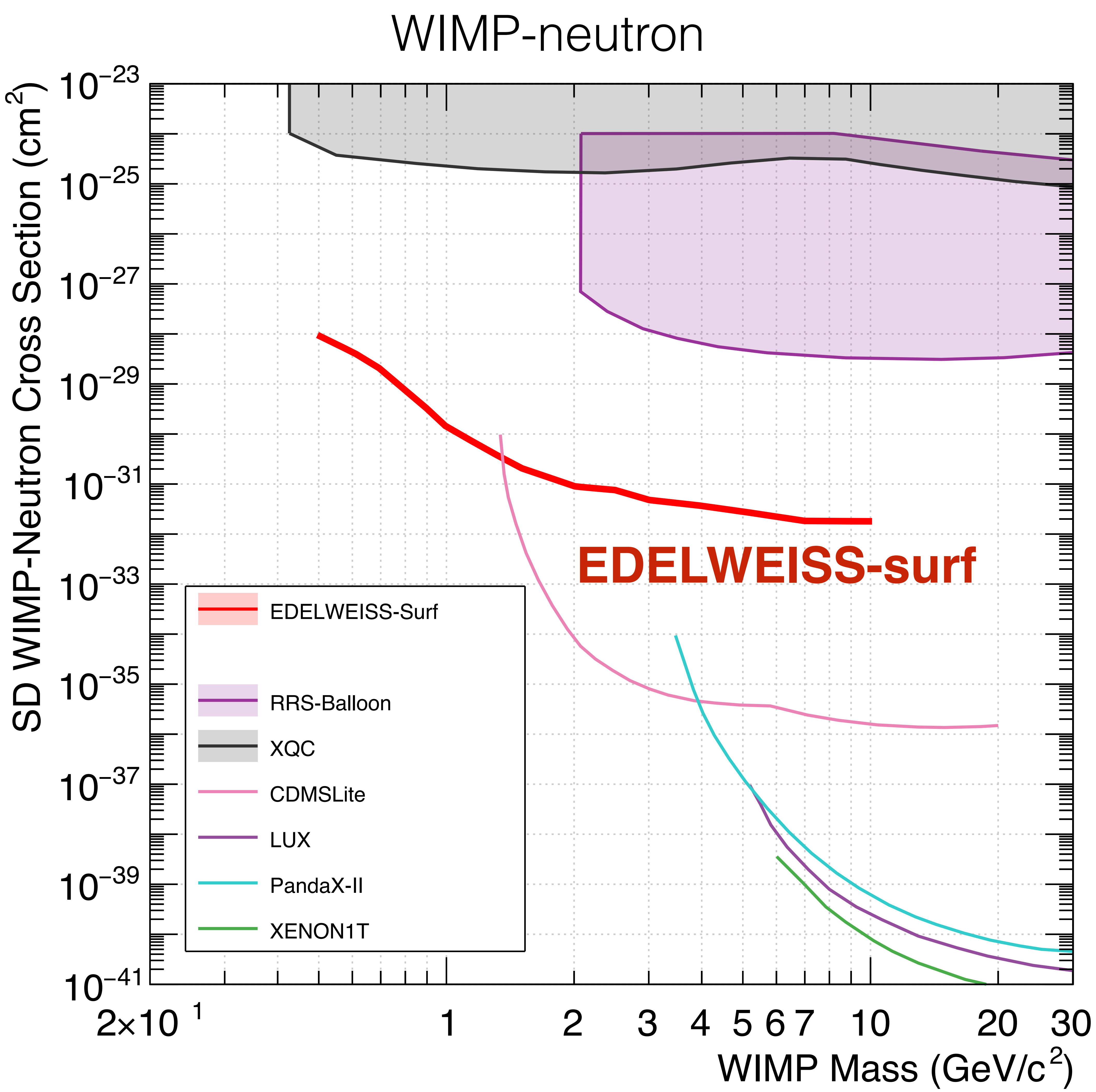
EDELWEISS-surf Limits: Spin-independent

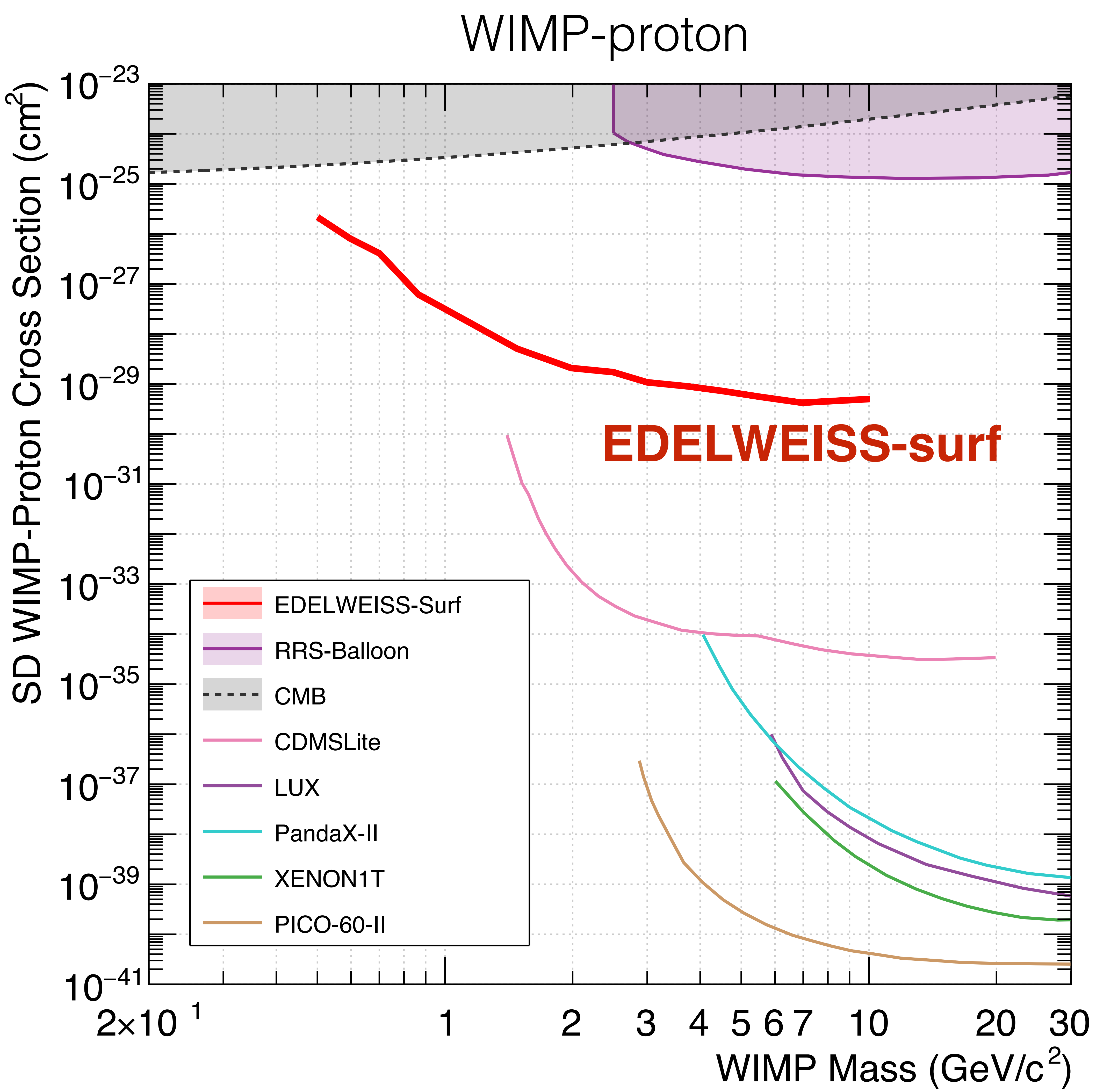


Strongest above-ground limit, down to 600 MeV

First sub-GeV limit with Ge, down to 500 MeV

EDELWEISS-surf Limits: Spin-dependent





World-leading limits on SD-neutron interactions below 1.5 GeV!

[See also recent results from CRESST-III, 1904.00498]

Tough WIMPs

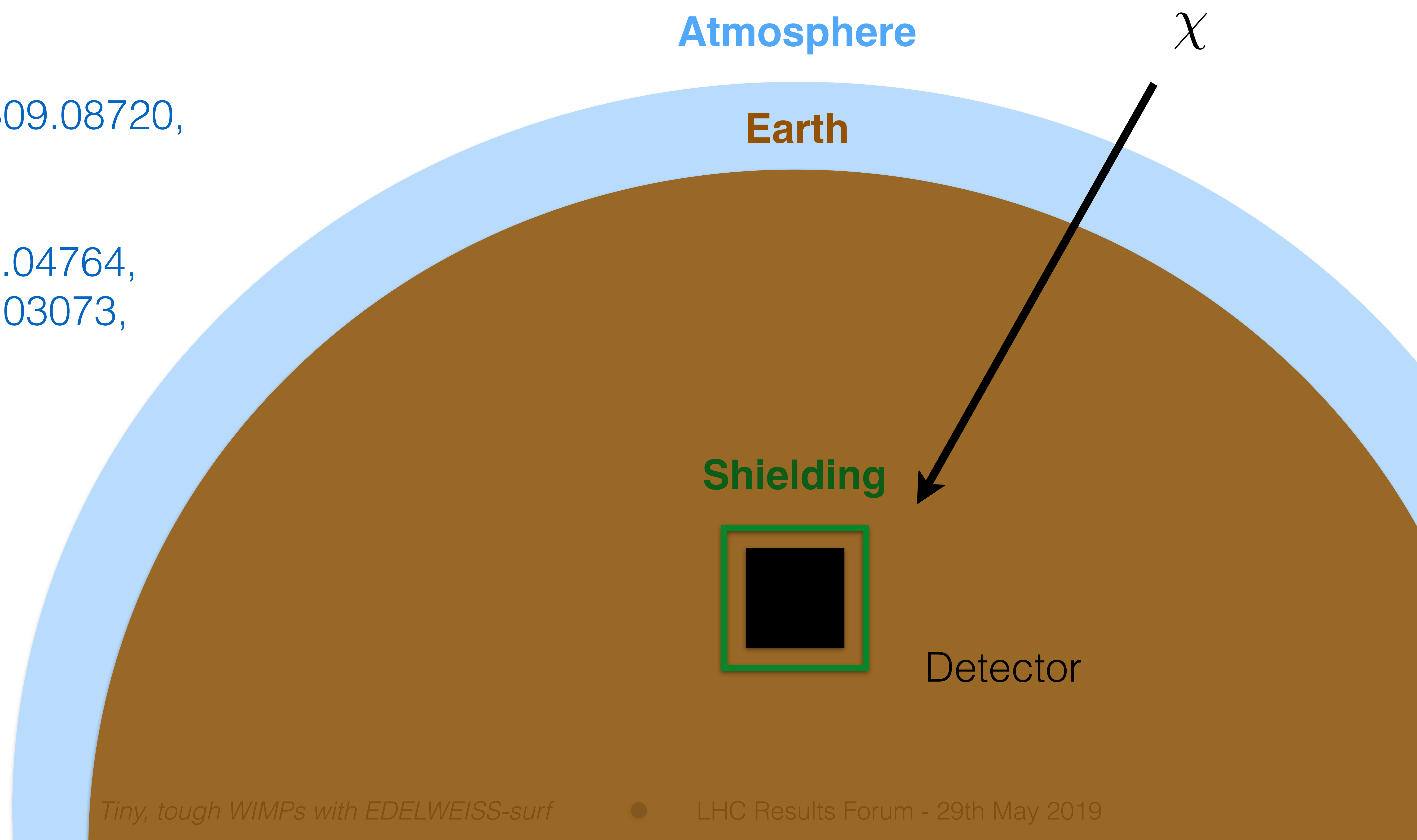
or “Earth-scattering effects in (sub)-surface direct detection experiments”

Journey to the centre of the Earth

Strongly **I**nteracting **M**assive **P**articles (**SIMPs**) may scatter *before* reaching the detector!

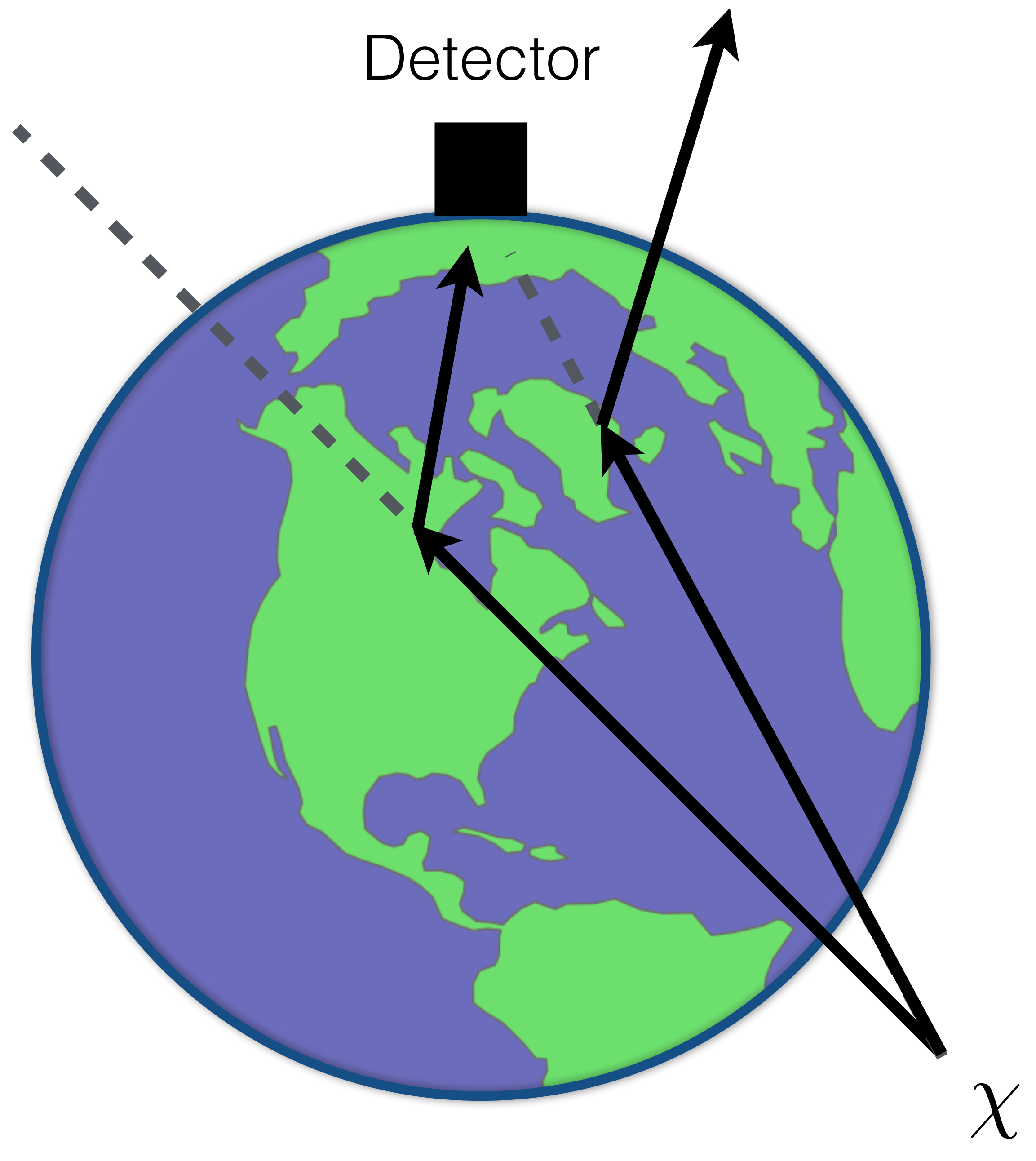
Collar & Avignone - PLB 275, 1992 and others

Kouvaris & Shoemaker - 1405.1729,1509.08720,
DAMA - 1505.05336,
BJK, Catena, Kouvaris - 1611.05453,
Emken & Kouvaris - 1706.02249, 1802.04764,
Mahdawi & Farrar - 1709.00430, 1804.03073,
Davis - 1708.01484,
BJK - 1712.04901,
Hooper & McDermott - 1802.03025,
and many others…



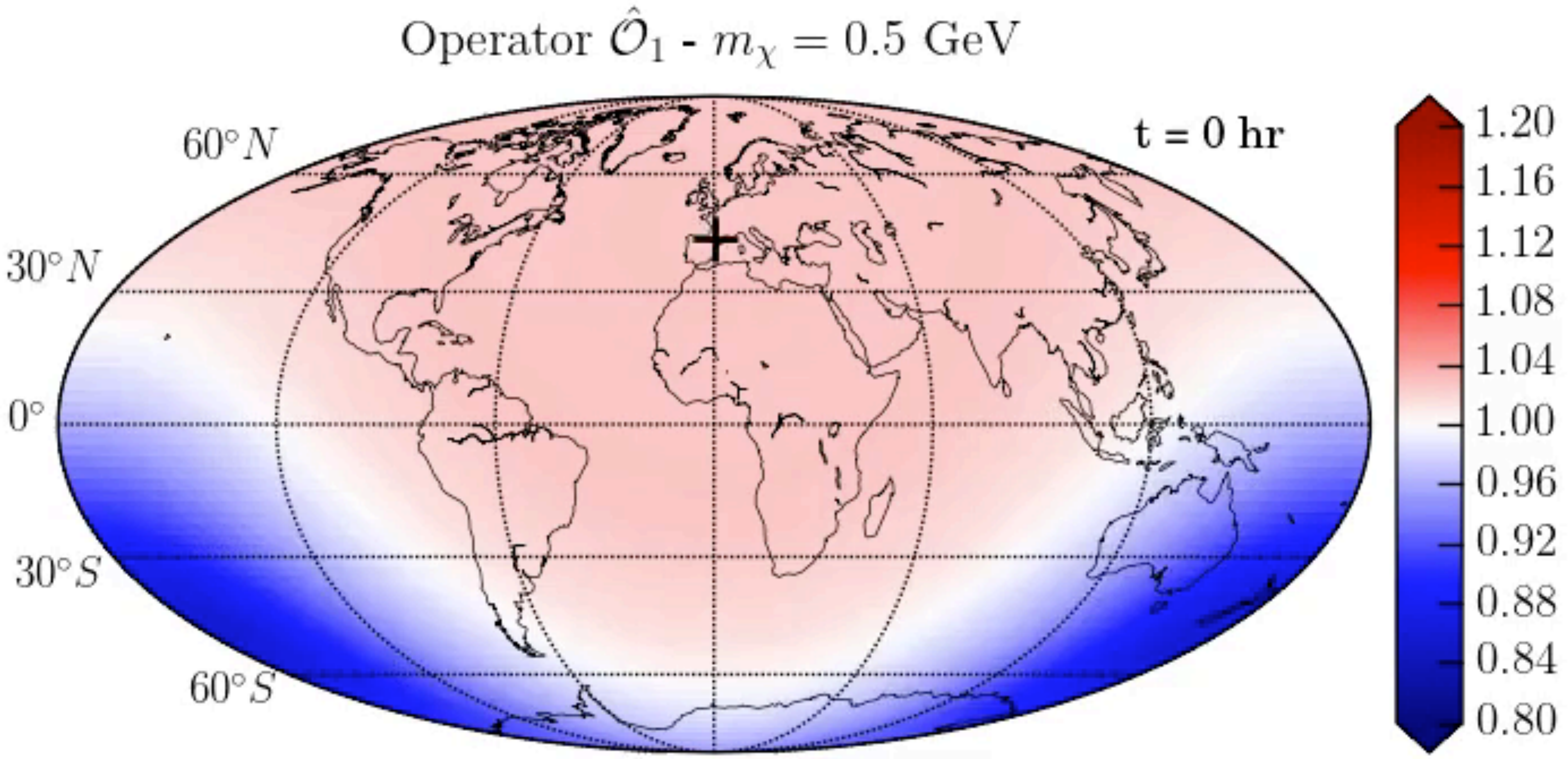
Earth-scattering Effects

Moderate DM interactions before reaching the detector may lead to **strong anisotropy (and daily modulation)** due to Earth's motion and rotation:



Semi-analytic calculation for O(1) scatter before reaching the detector

[**BJK,** Catena, Kouvaris - 1611.05453]



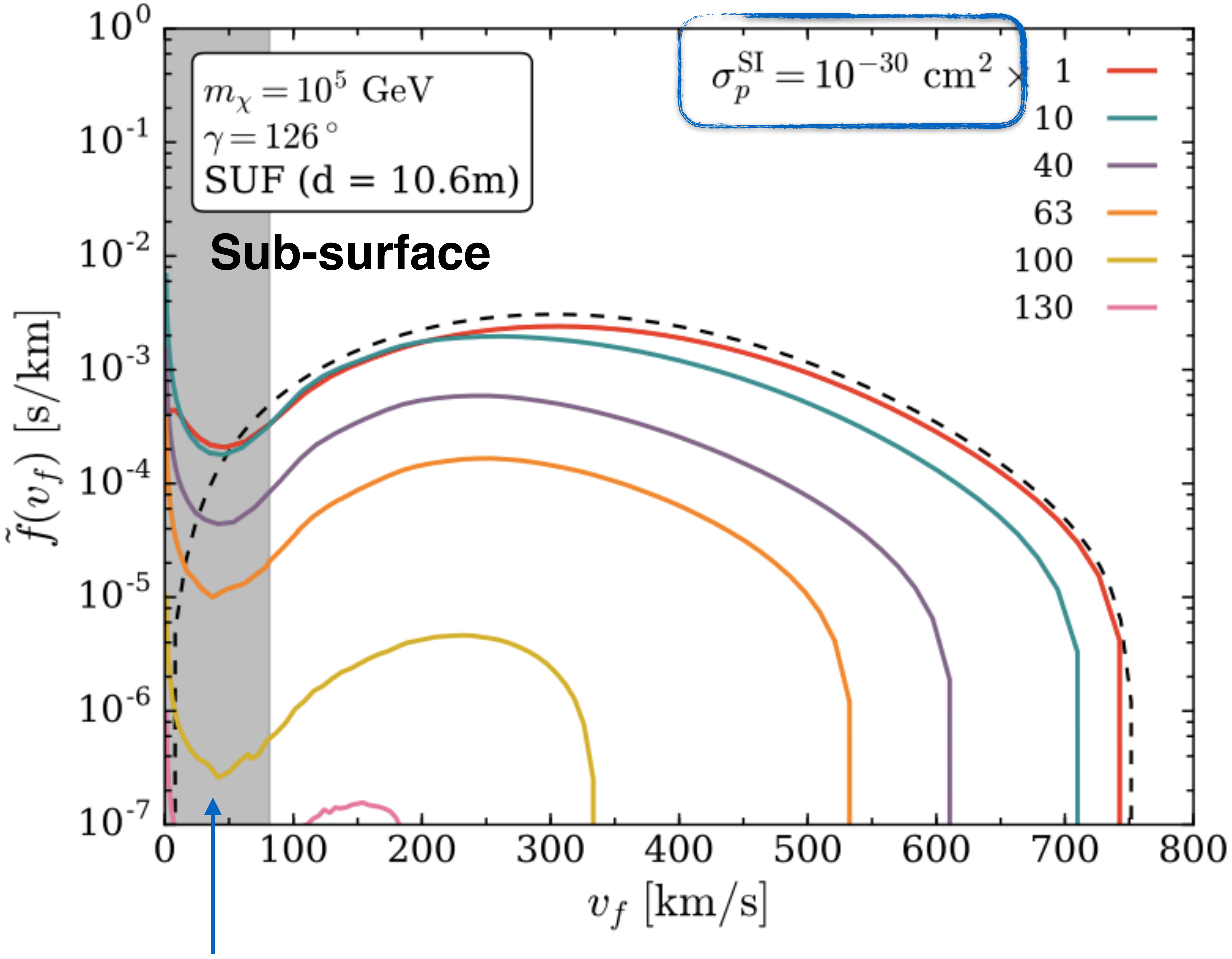
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

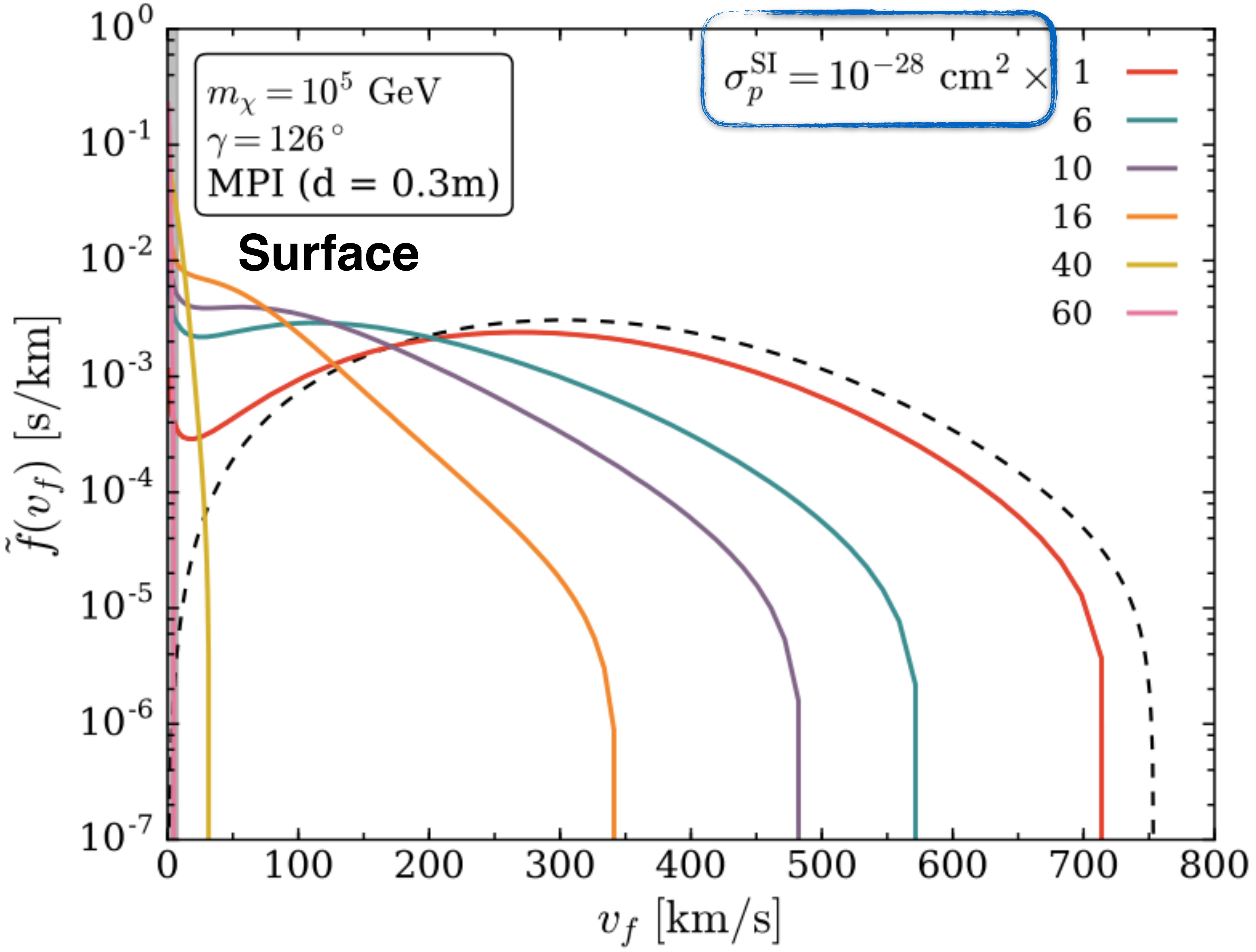
But for very large cross sections, the biggest effect is **attenuation**…

Attenuation

Follow 'straight-line' trajectories of DM particles as they scatter and continuously lose energy:

$$\frac{\mathrm{d}\langle E_\chi \rangle}{\mathrm{d}x} = -\sum_i n_i(\mathbf{r}) \langle E_R \rangle_i \, \sigma_i(v)$$





At large enough cross sections, particles drop below threshold…

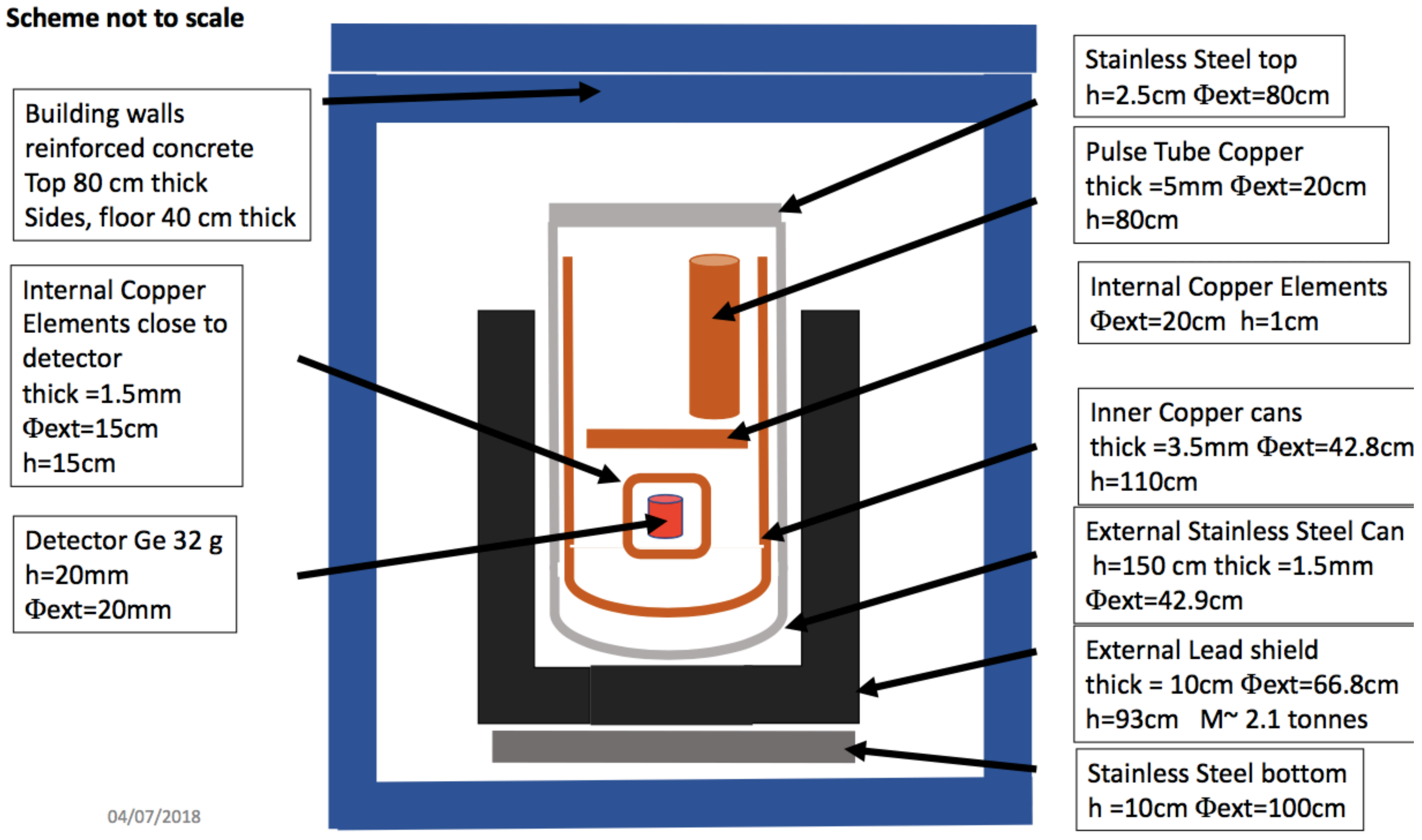
[**BJK,** 1712.04901]

Setting SIMP limits

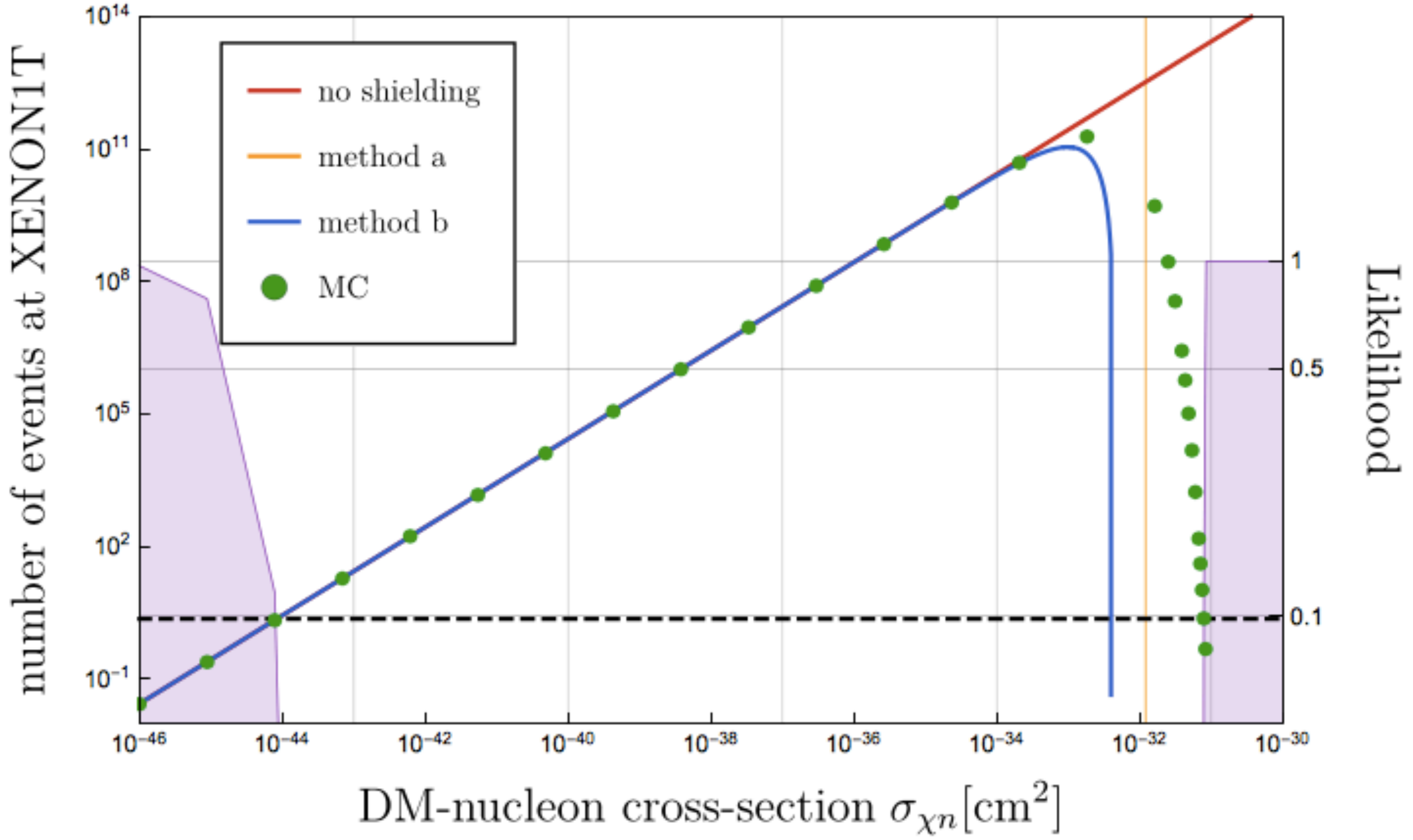
Use semi-analytic code **verne** (https://github.com/bradkav/verne) to calculate speed distribution of SIMP DM at the detector, including scattering in the atmosphere, Earth, buildings and shielding

Incorporate full 3-D incoming DM velocity distribution, but assume **straight-line trajectories**

Stop tracking DM particles below v = 20 km/s - here the calculations are no longer reliable



[Credit: Maryvonne De Jesus]



[1802.04764]

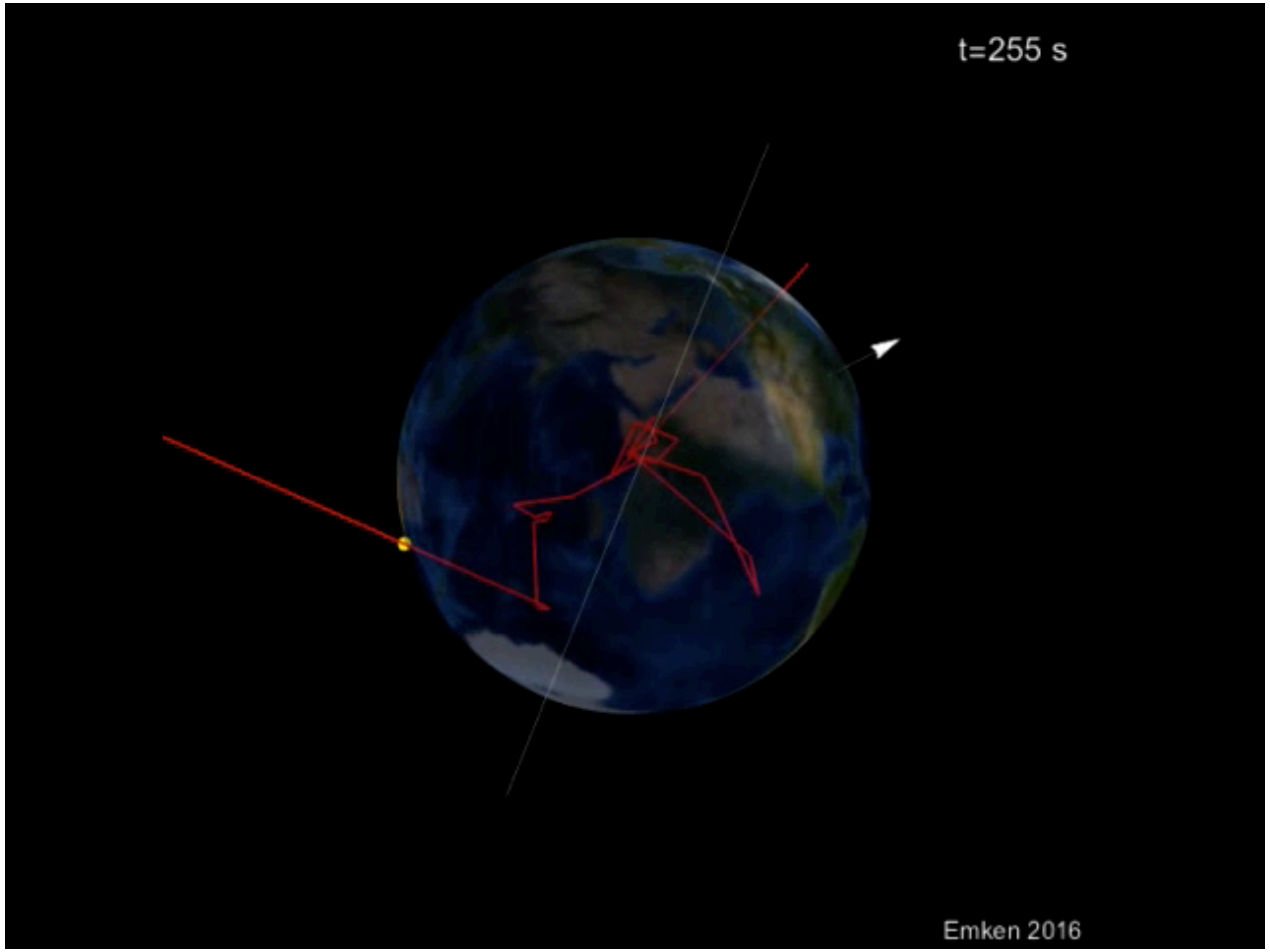
Comparison with detailed Monte Carlo

We use this semi-analytic 'straight-line' trajectory approach, because its computationally cheap.

Comparison with careful, 3D Monte Carlo (including particle deflections) yields similar results:

DaMaSCUS:
https://github.com/temken/DaMaSCUS

DaMaSCUS-CRUST:
https://github.com/temken/damascus-crust



[Emken & Kouvaris - 1706.02249, 1802.04764]

Comparison with detailed Monte Carlo

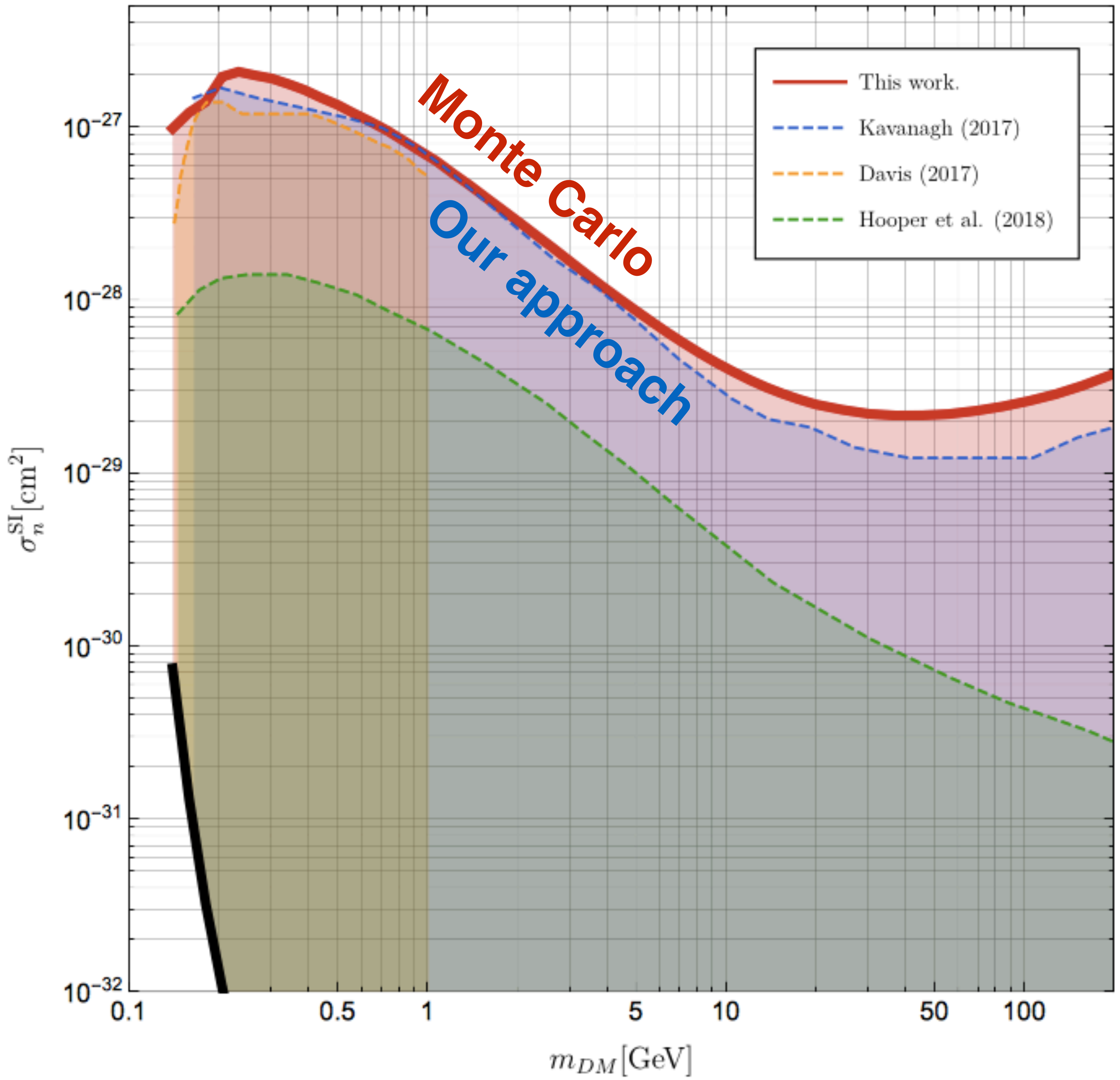
We use this semi-analytic 'straight-line' trajectory approach, because its computationally cheap.

Comparison with careful, 3D Monte Carlo (including particle deflections) yields similar results:

DaMaSCUS:
https://github.com/temken/DaMaSCUS

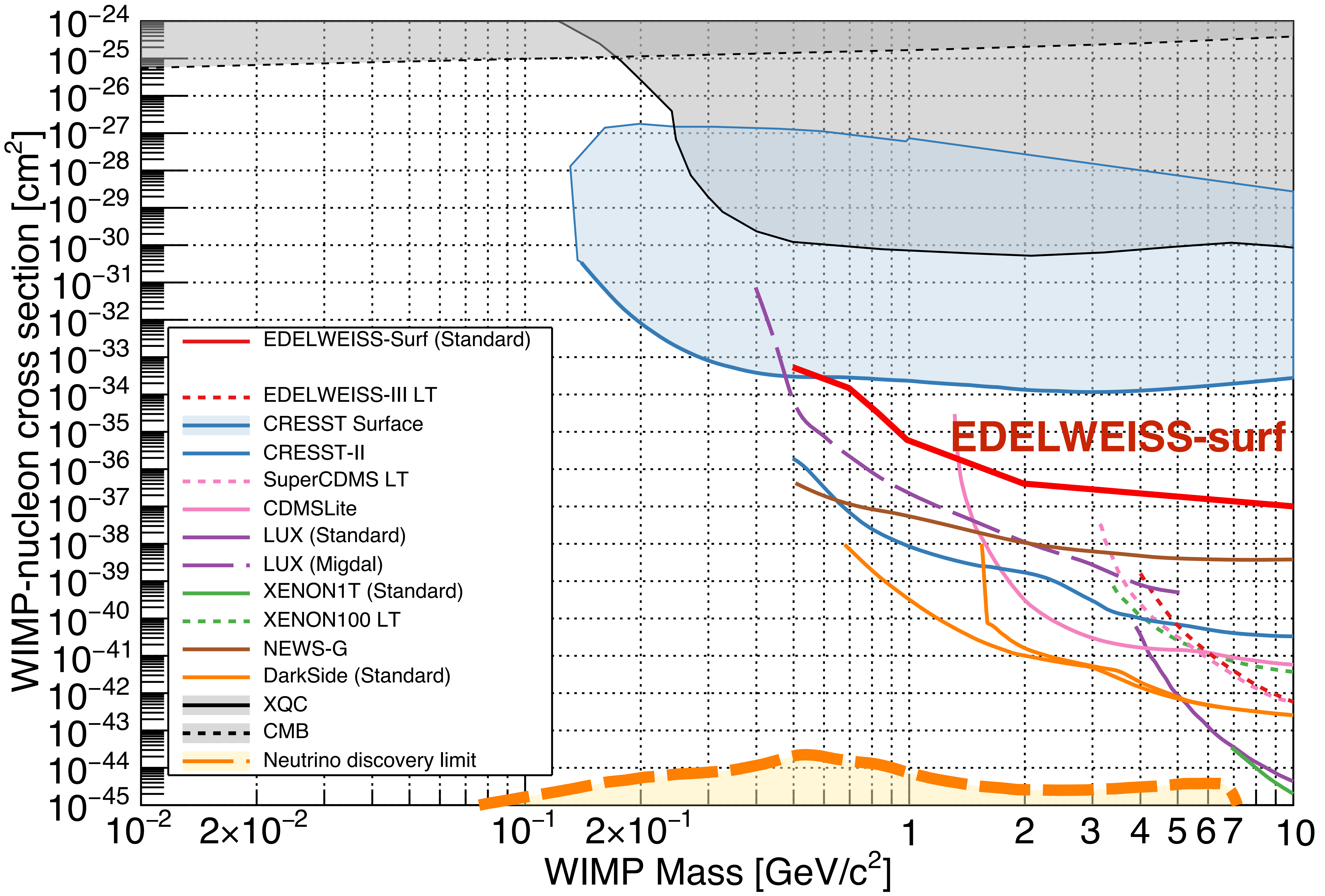
DaMaSCUS-CRUST:
https://github.com/temken/damascus-crust

Excluded region from CRESST-surface (2017) using different calculations

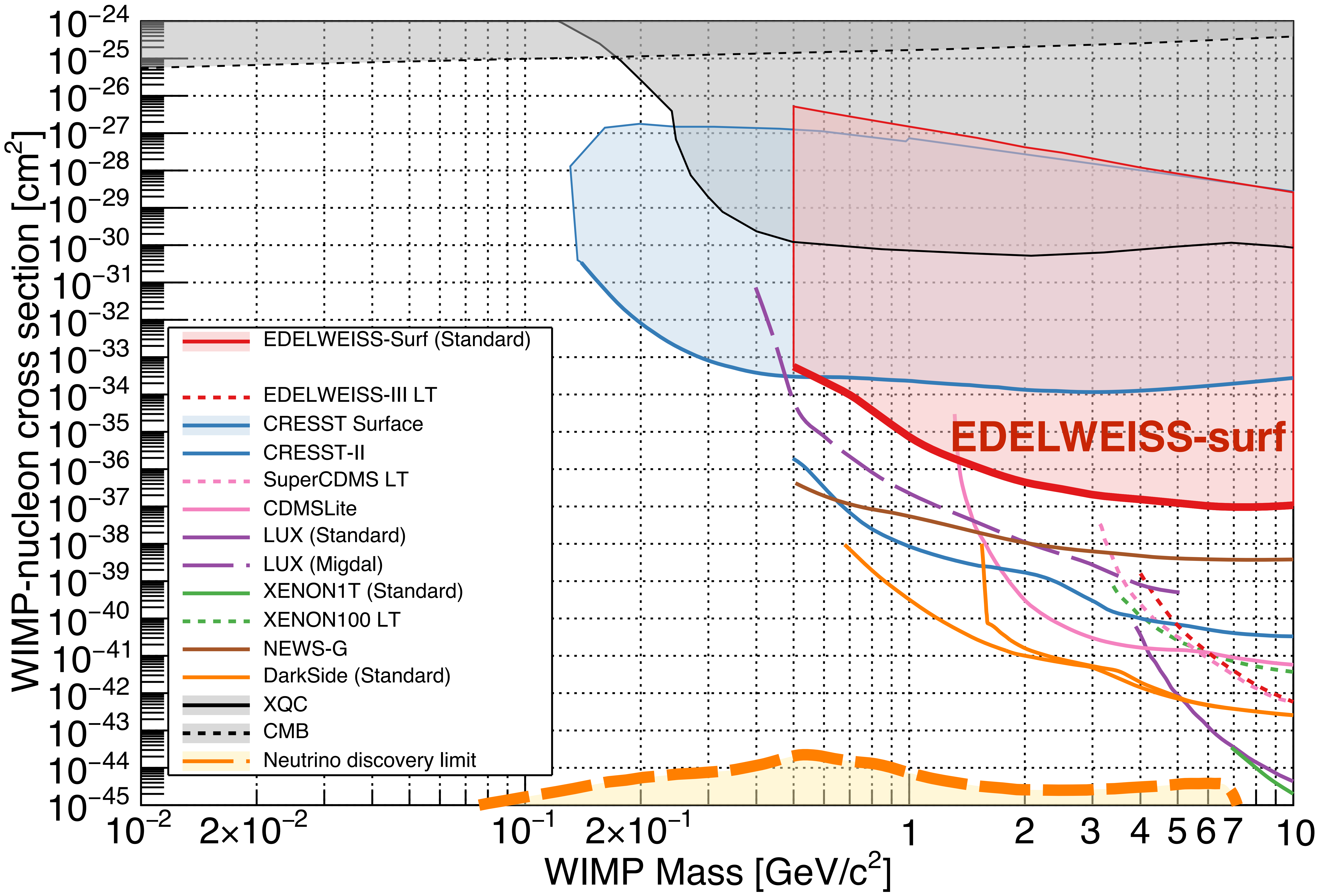


[Emken & Kouvaris - 1706.02249, 1802.04764]

EDELWEISS-surf Limits: Spin-independent

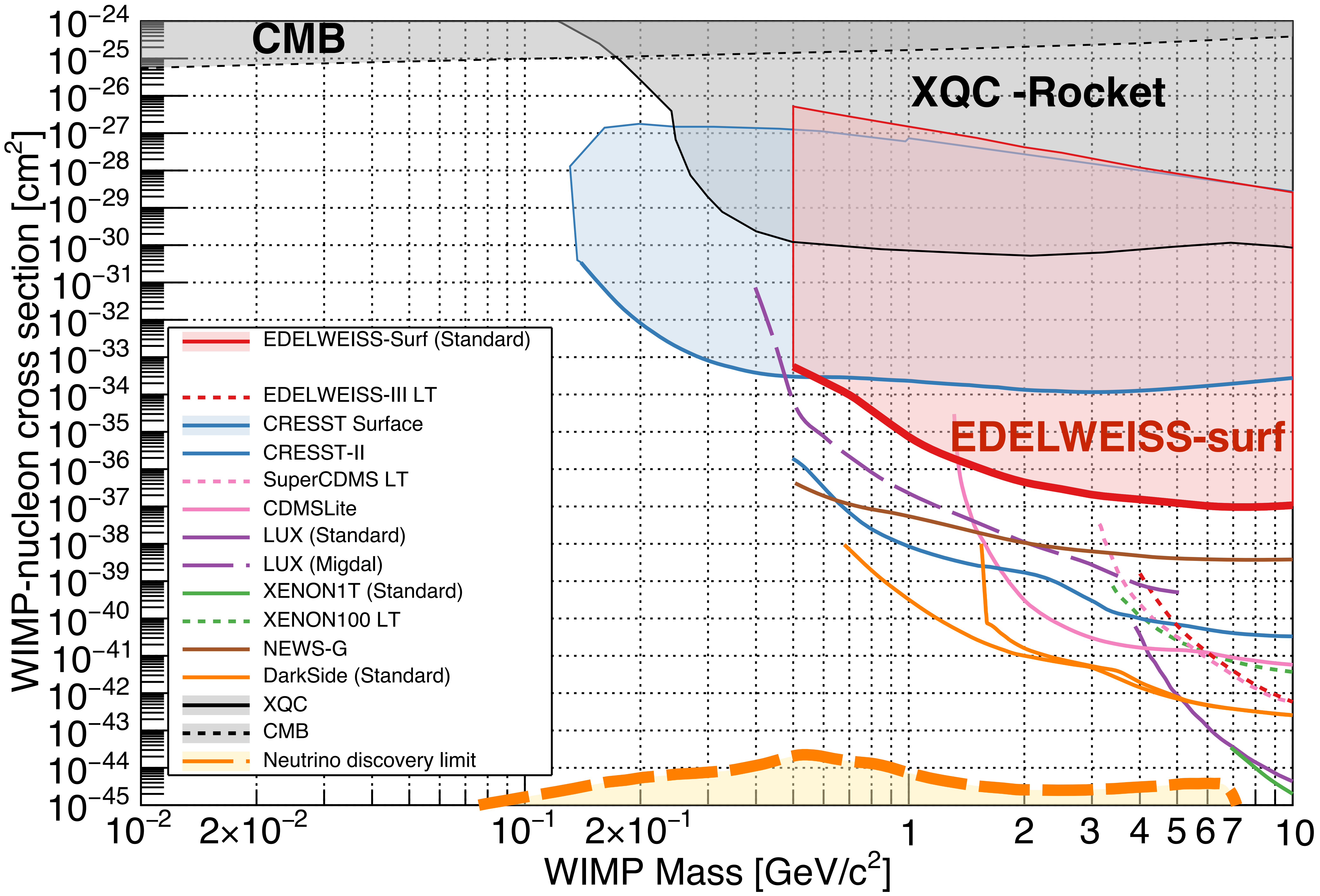


EDELWEISS-surf Limits: Spin-independent



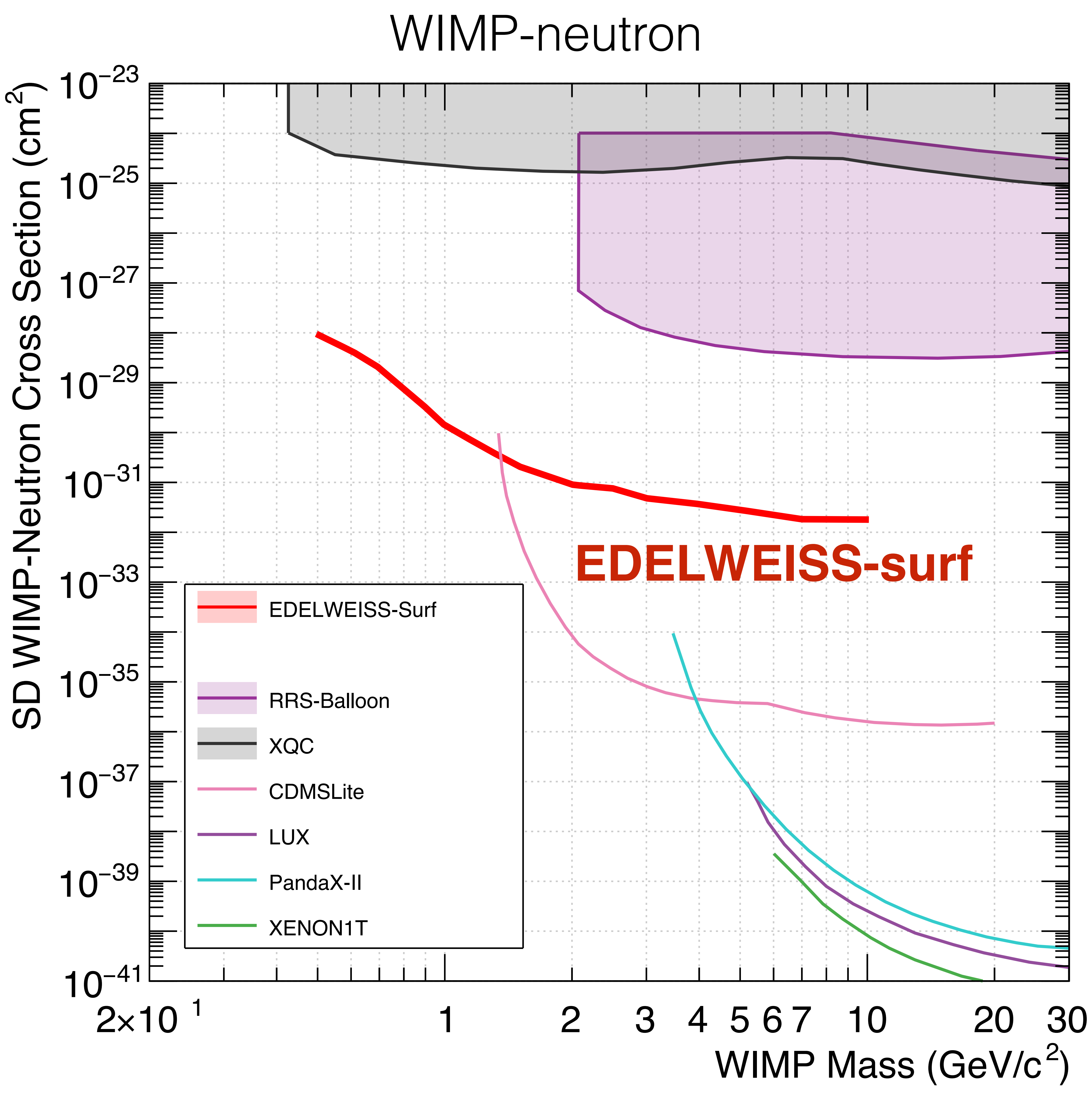
One of the first ‘official’ SIMP limits from a direct detection experiment - exclude up to 10^{-27} cm^2

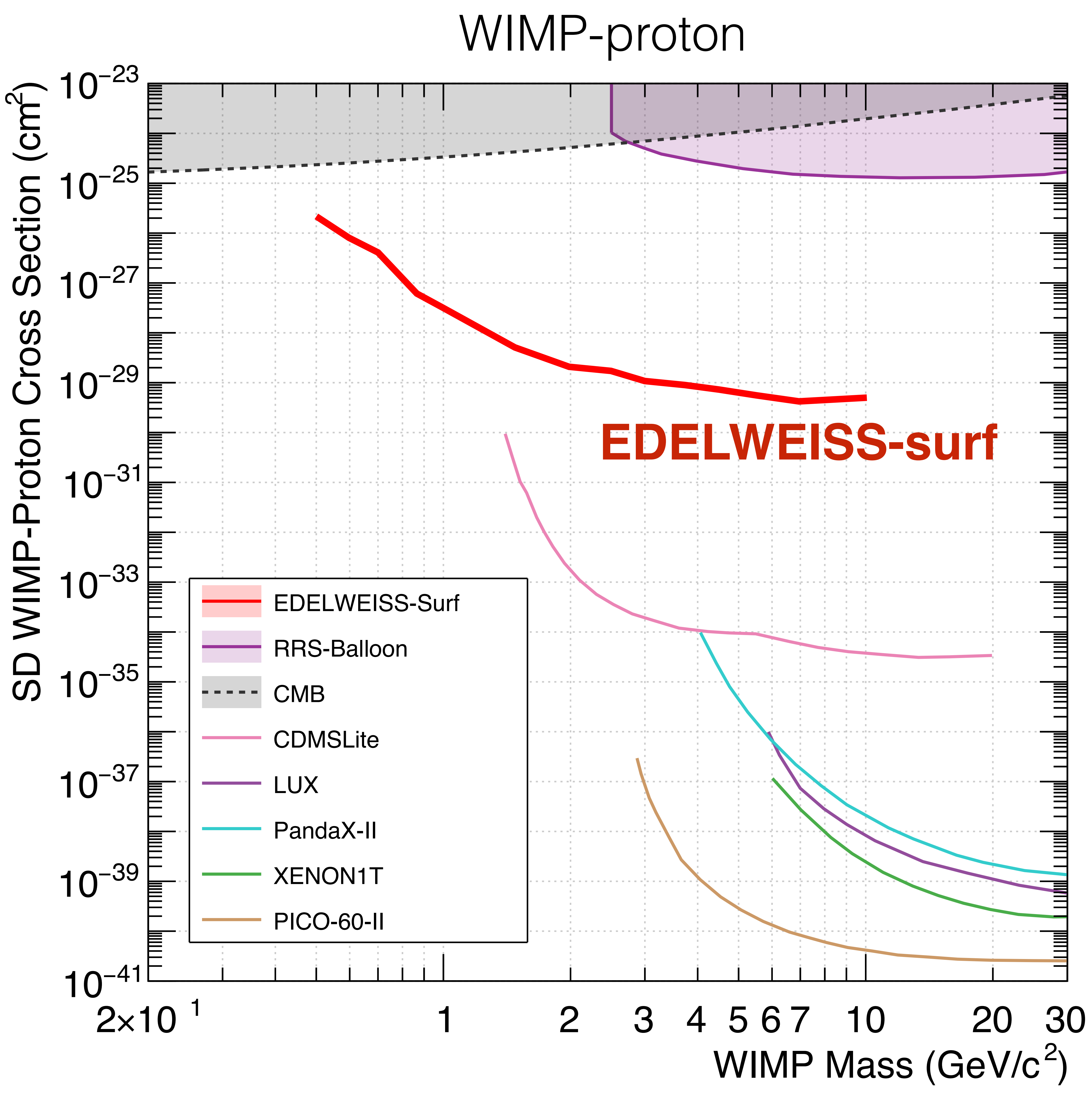
EDELWEISS-surf Limits: Spin-independent



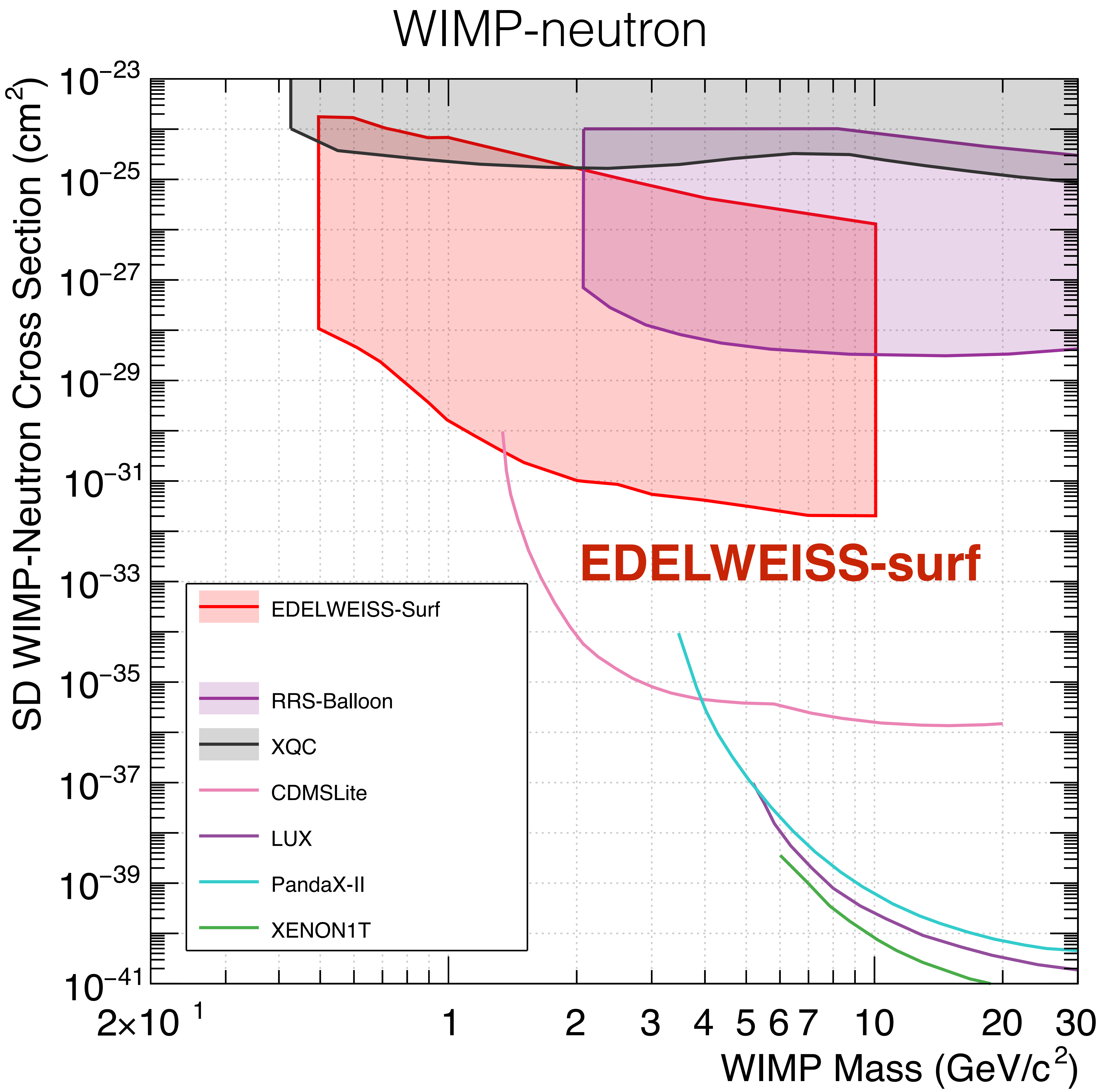
One of the first 'official' SIMP limits from a direct detection experiment - exclude up to 10^{-27} cm^2

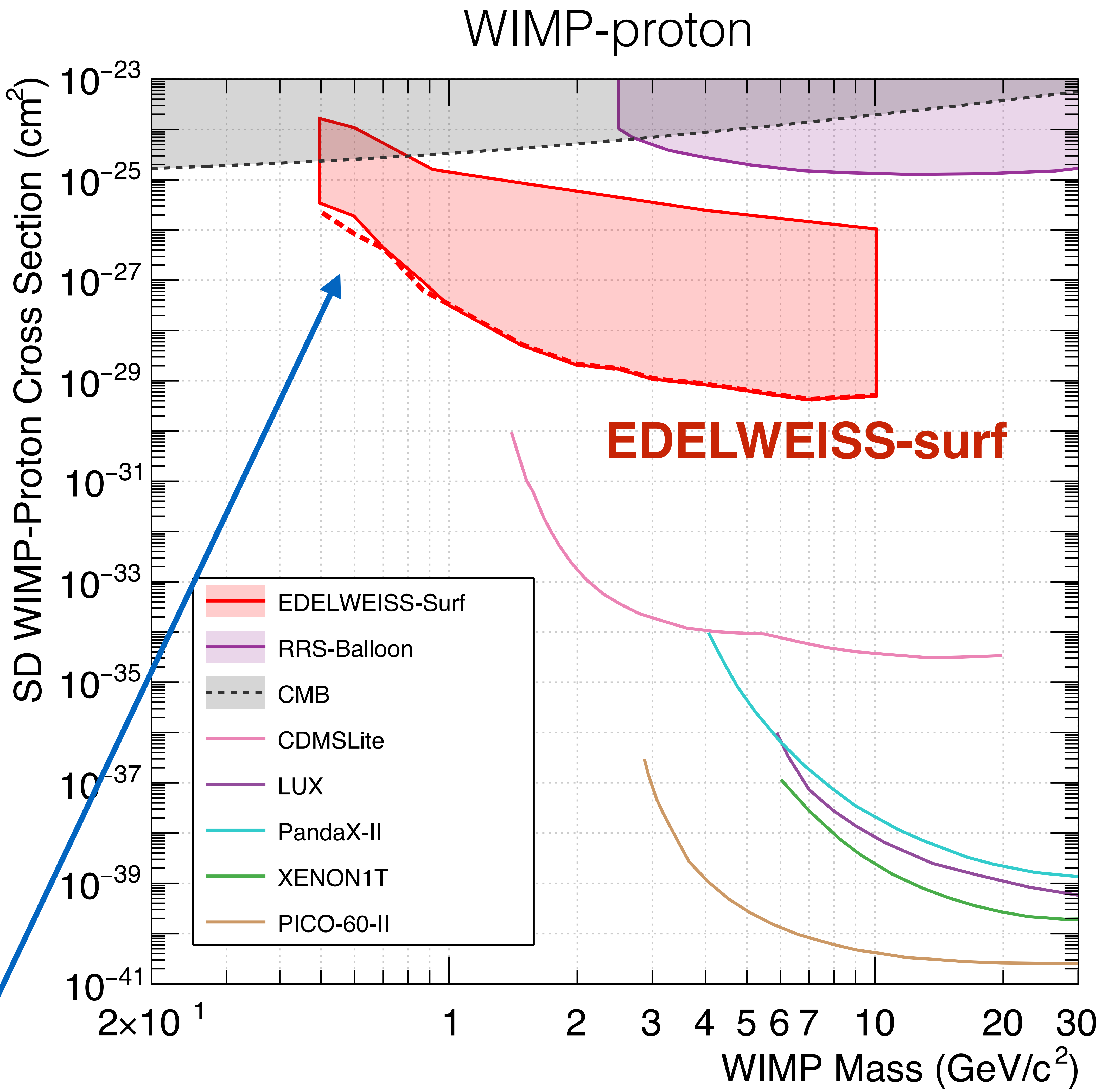
EDELWEISS-surf Limits: Spin-dependent





EDELWEISS-surf Limits: Spin-dependent





Most SD stopping comes from Nitrogen in the atmosphere

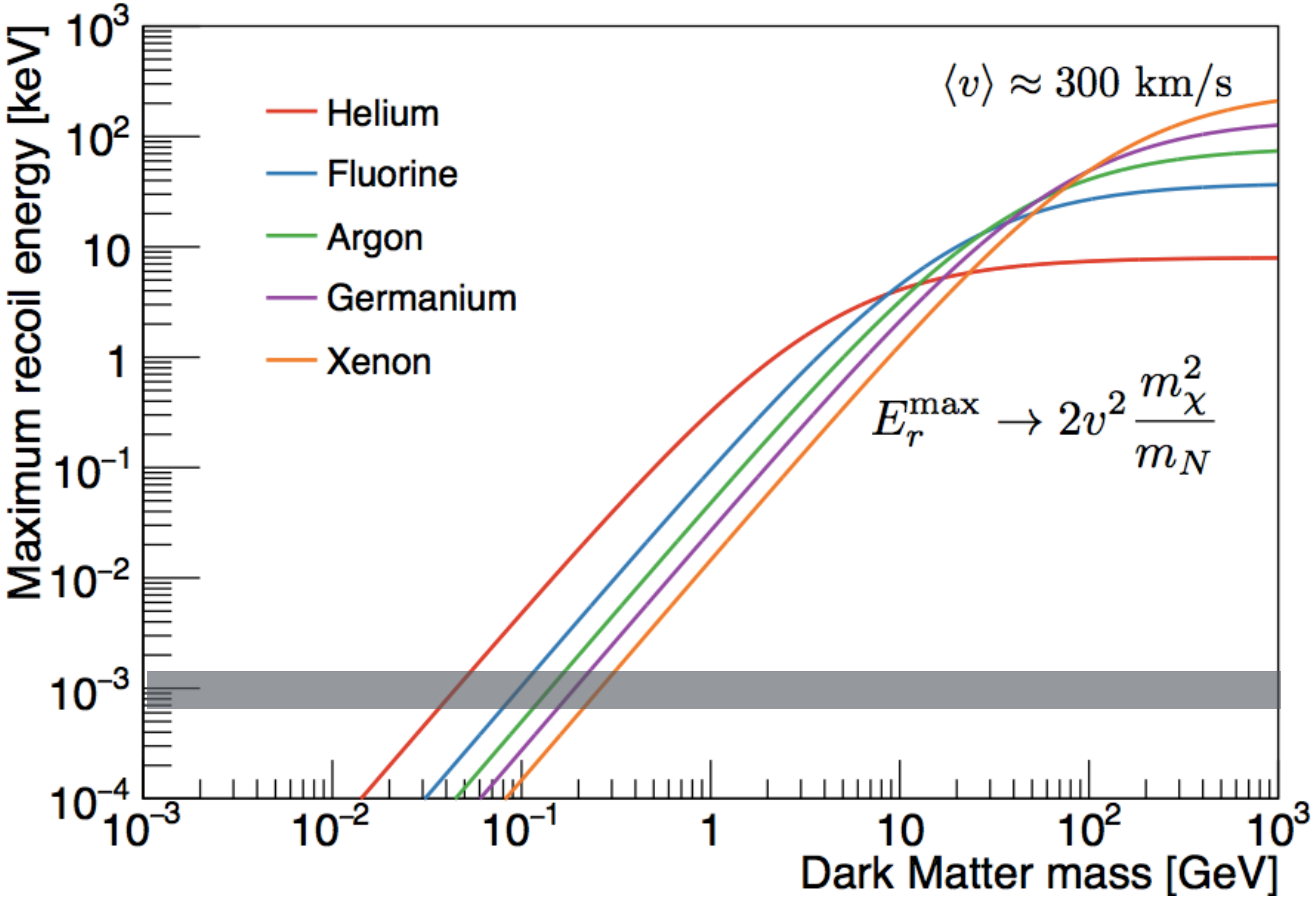
Earth-scattering effects relevant at low mass!

Tiny, tiny WIMPs

or “Searching for *very* sub-GeV Dark Matter with low-threshold detectors”

Kinematic Limit for Elastic Scattering

Maximum DM speed set by galactic escape speed (~544 km/s)
plus Solar orbital speed (~220 km/s)



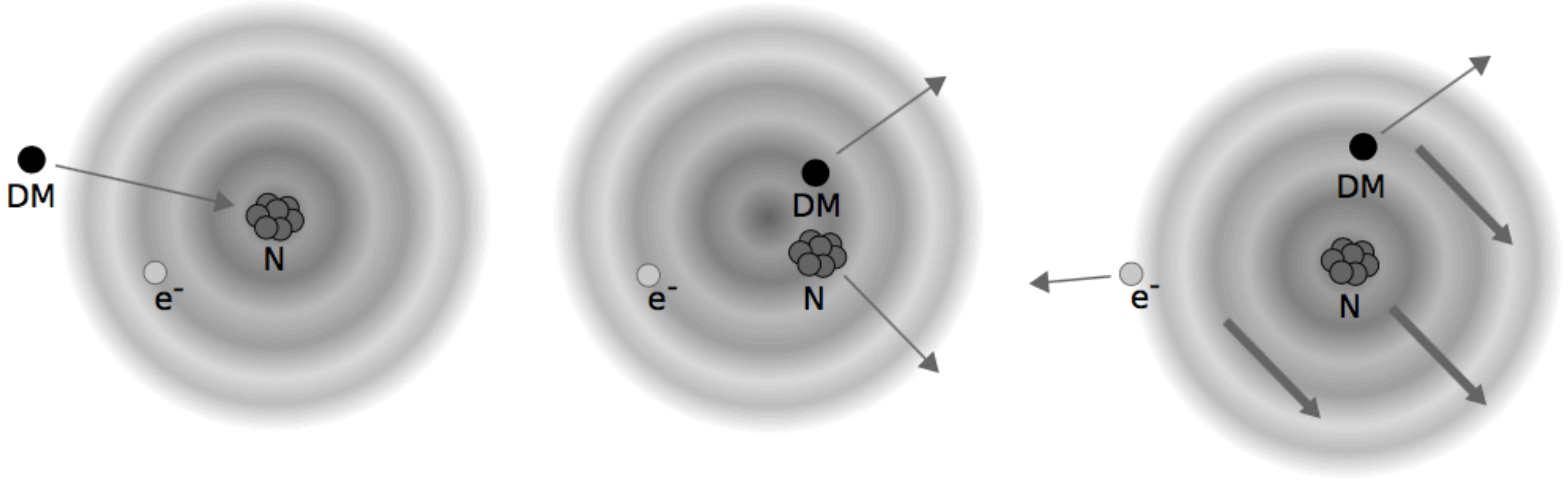
Intrinsic thermodynamic limit for ~10g detectors

[Credit: Julien Billard]

Migdal Effect

Consider instead **inelastic scattering**. In particular, look for the possible ionisation of an electron after a DM-nucleus interaction - "**Migdal Effect**"

[1711.09906]



Energy deposited in nuclear recoil and electromagnetic energy from ionisation:

$$E_{\mathrm{R,max}} = \frac{2\mu_N^2 v_{\mathrm{max}}^2}{m_N}, \quad E_{\mathrm{EM,max}} = \frac{\mu_N v_{\mathrm{max}}^2}{2}$$

Could also look for the emission of a photon along with the nuclear recoil, but this turns out to be subdominant

[1607.01789]

Migdal Rate

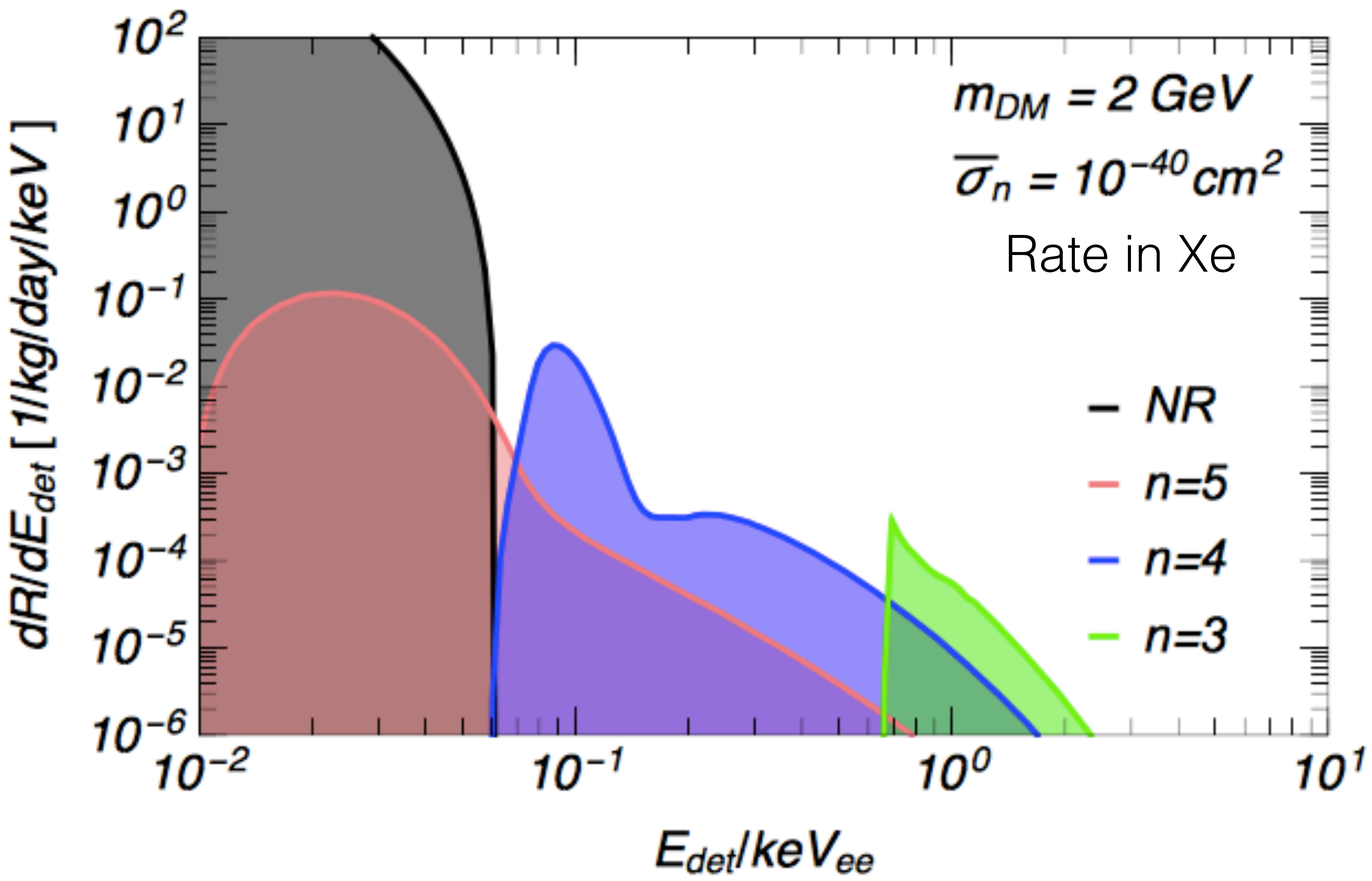
Migdal effect has not been measured experimentally, but can be calculated

$$\frac{\mathrm{d}R}{\mathrm{d}E_R\,\mathrm{d}E_{\mathrm{EM}}} \sim \frac{\mathrm{d}R}{\mathrm{d}E_R}\frac{\mathrm{d}}{\mathrm{d}E_e}p_{\mathrm{ion.}}(E_e)$$

Ionise electrons from outer shells with probability:

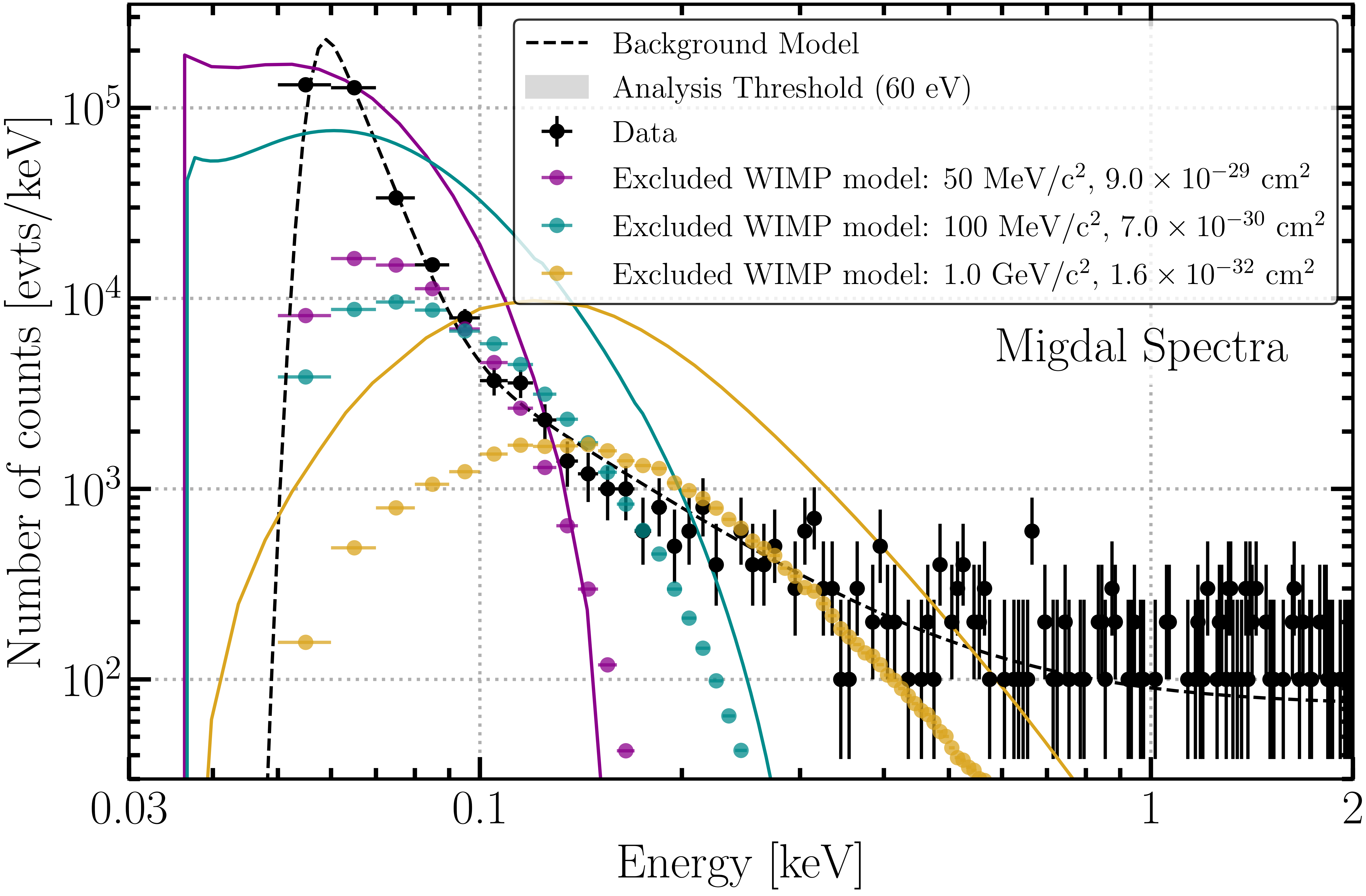
$$p_{\mathrm{ion.}} \sim 10^{-4} - 10^{-2}$$

[1707.07258]

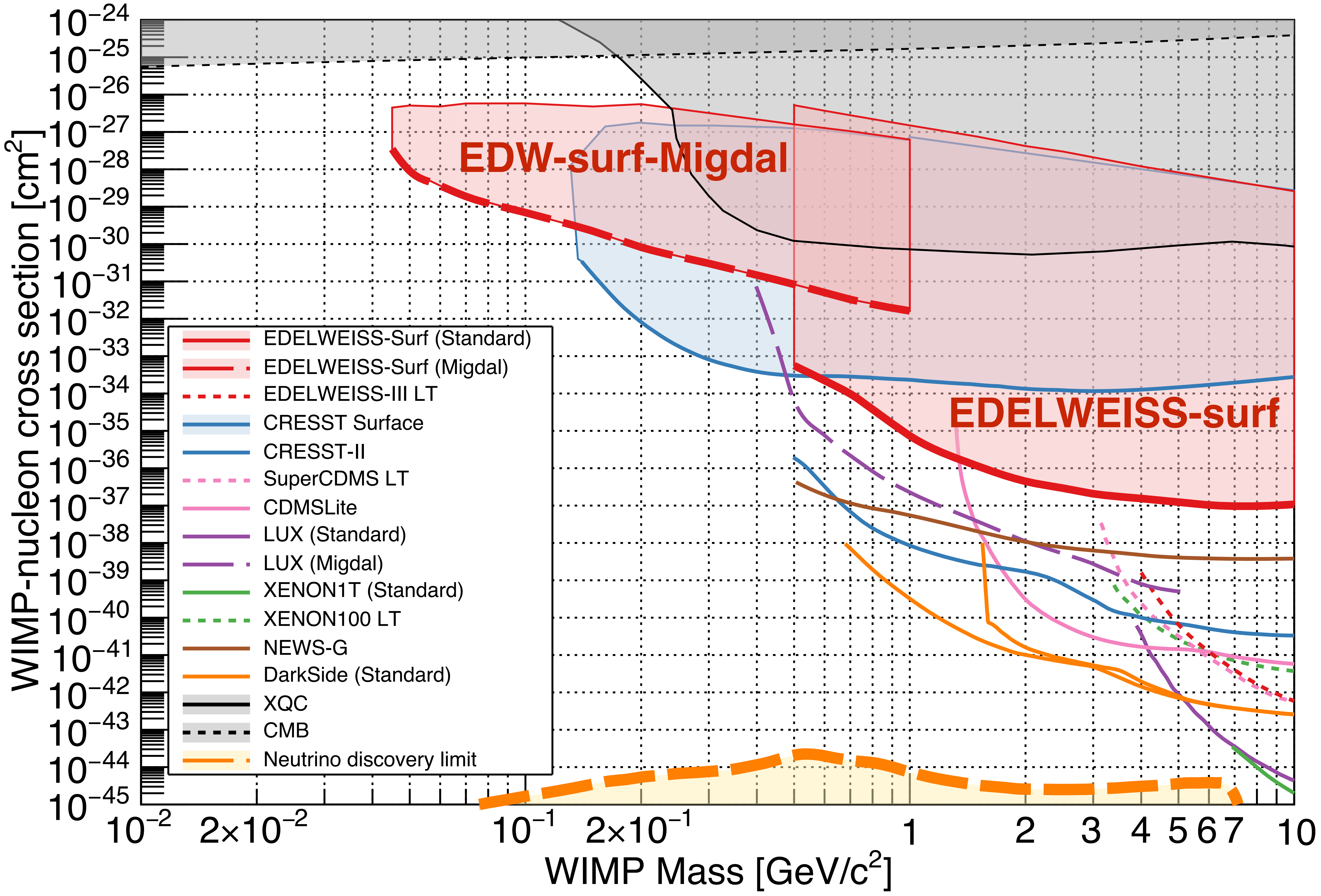


RED20 module used for EDELWEISS-surf is a **true calorimeter** - it collects all deposited energy (phonons + EM) - so it can be used to search for these inelastic interactions

Migdal Spectra

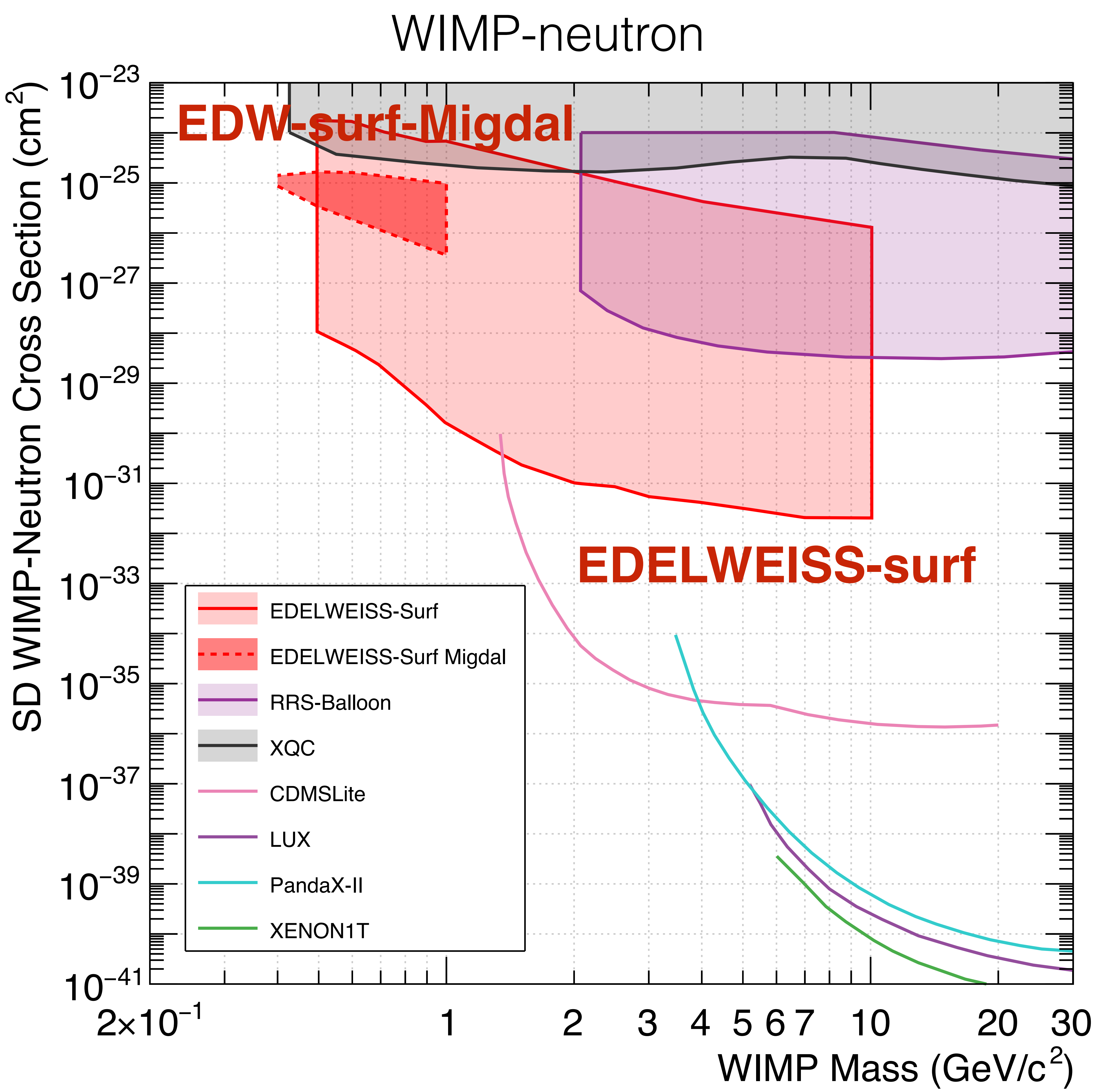


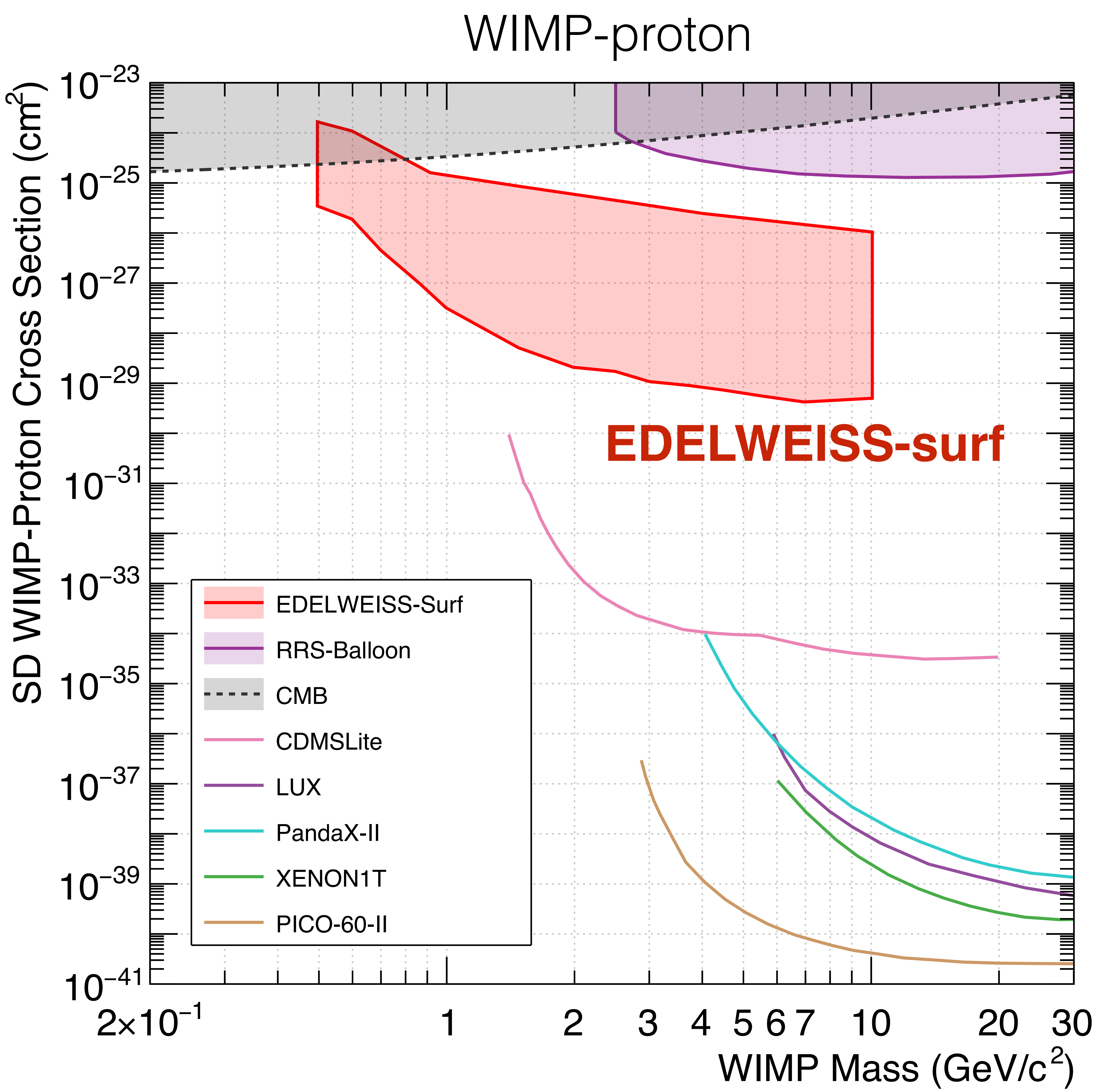
Migdal Limit - Spin-independent



Sensitive down to DM masses of 45 MeV!

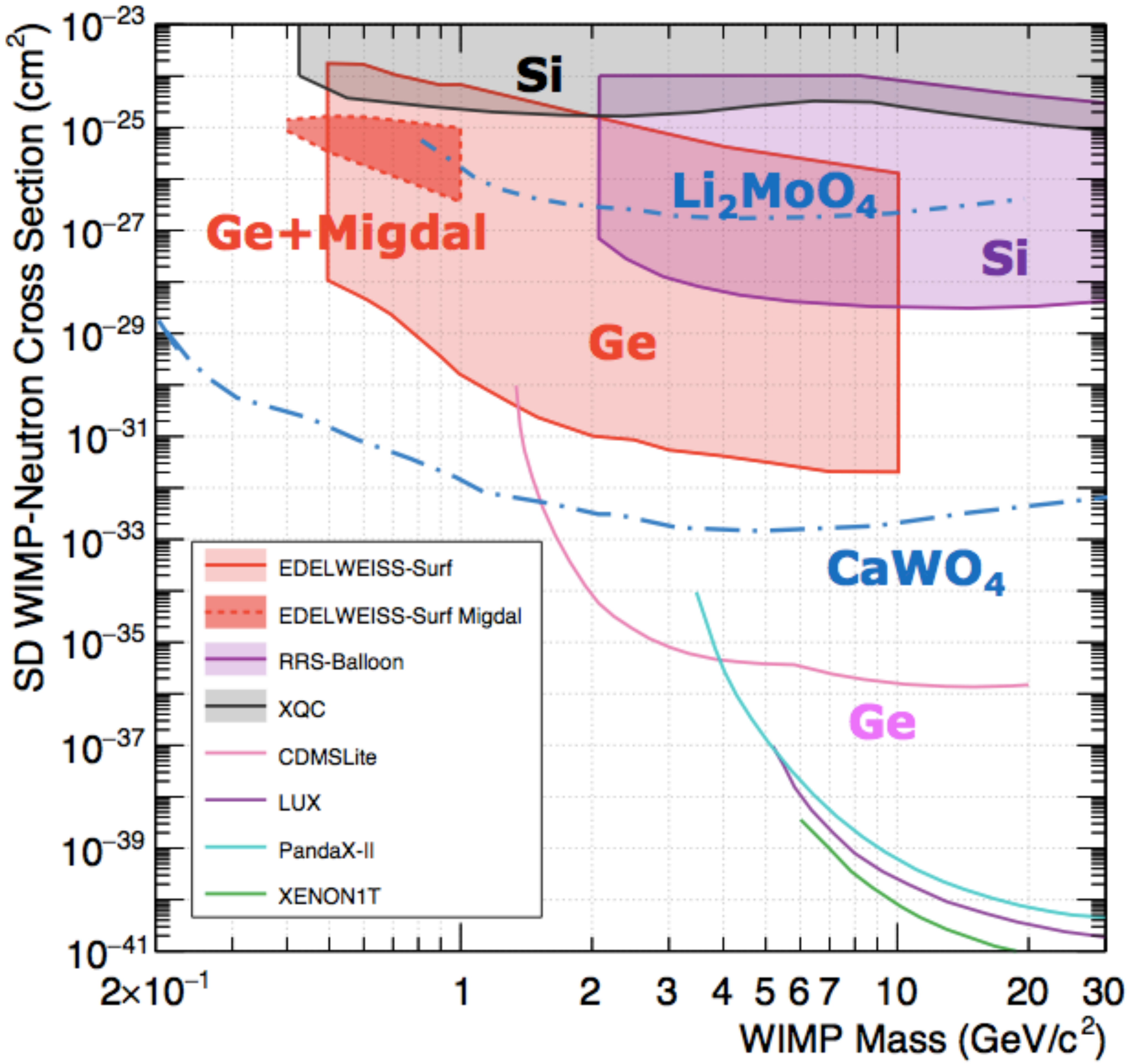
Migdal Limit - Spin-dependent



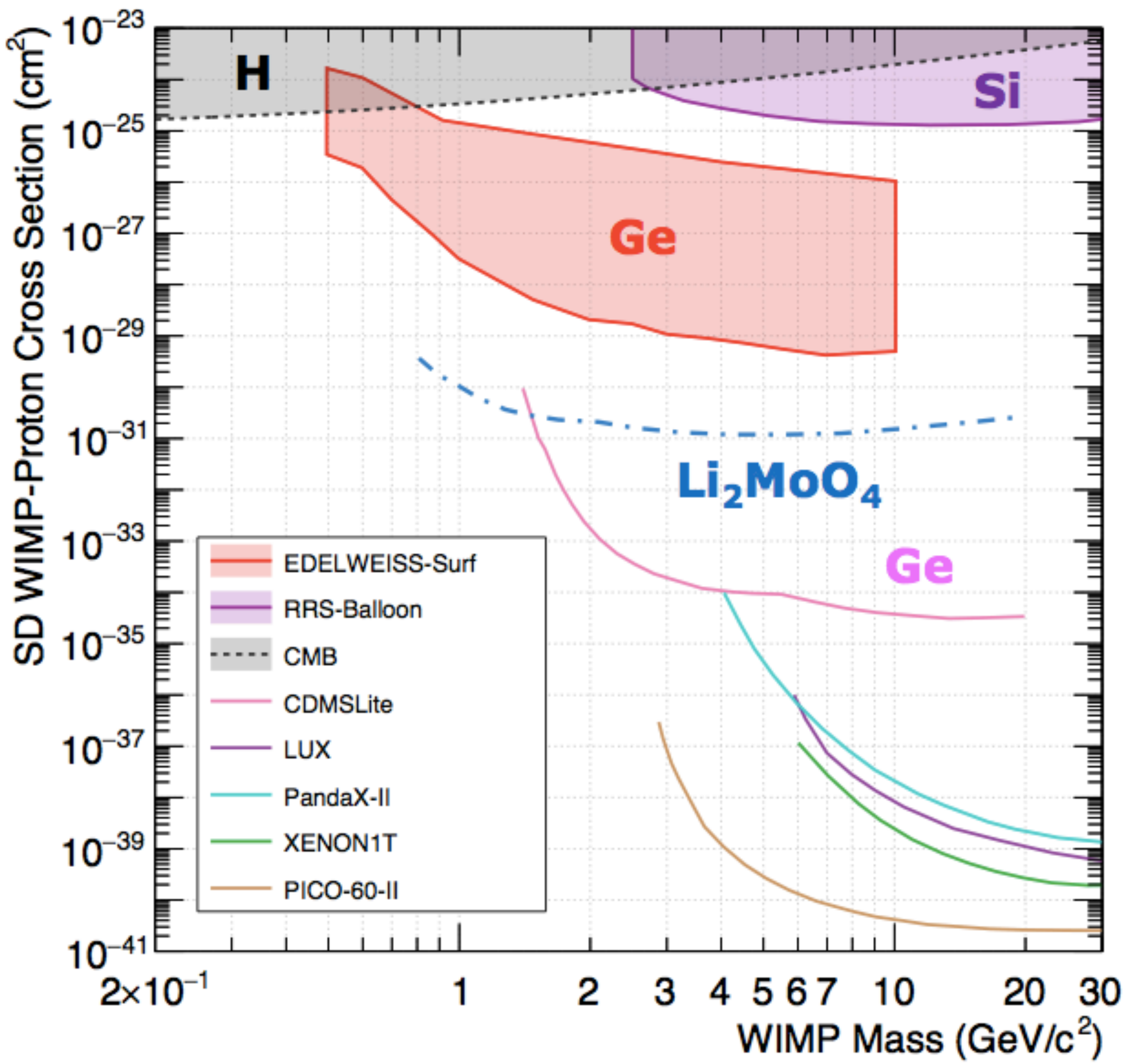


Migdal Limit - Spin-dependent

WIMP-neutron



WIMP-proton

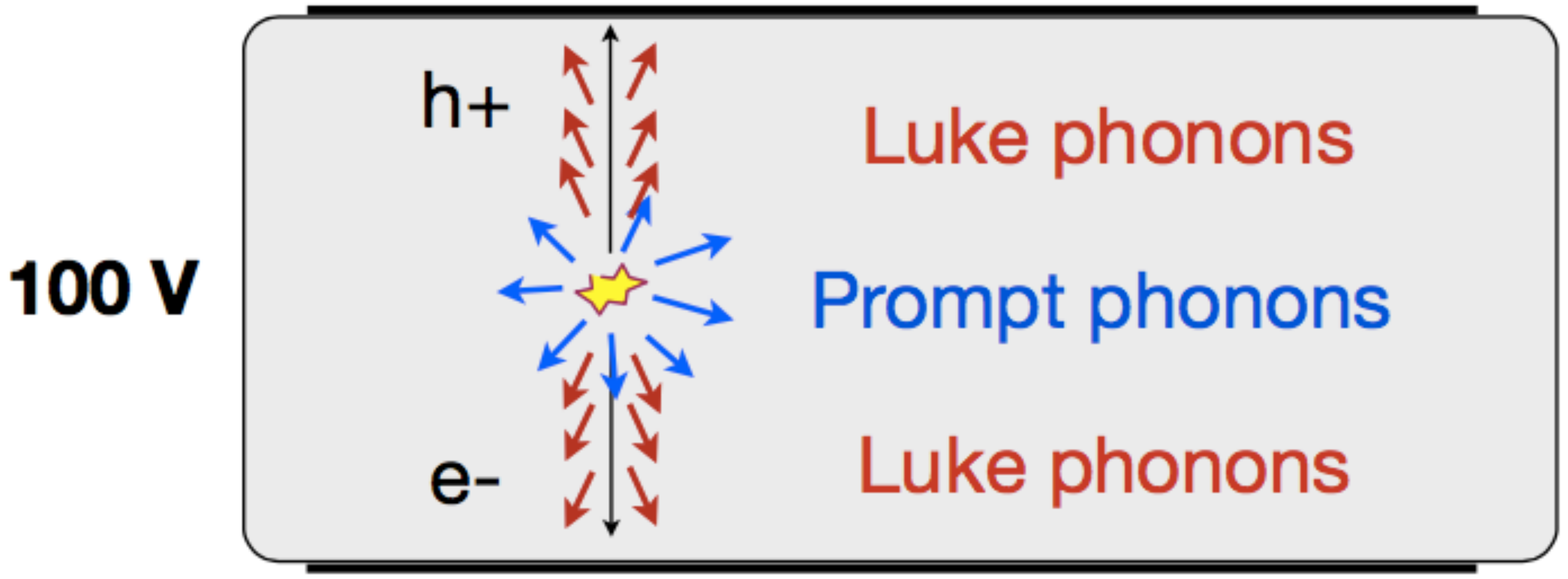


New results from CRESST surface Li_2MoO_4 [1902.07587] and underground $CaWO_4$ [1904.00498]
Earth-scattering not yet incorporated - SIMP contour calculations underway…

The future

Low-background exposure is underway at Laboratoire Souterrain de Modane, France (alongside continuous EDELWEISS-III exposure)

Detectors equipped with electrodes - electric field can amplify the phonon signal due to the Neganov-Trofimov-Luke effect —> **even lower threshold**



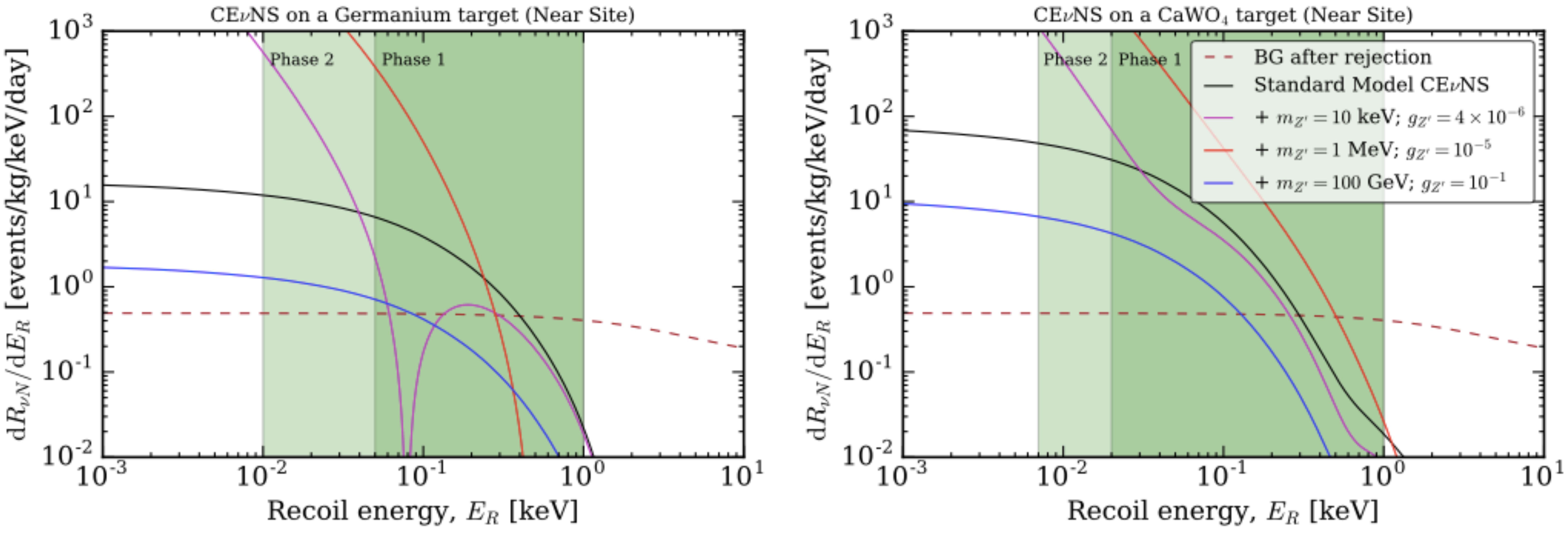
[Credit: Julien Billard]

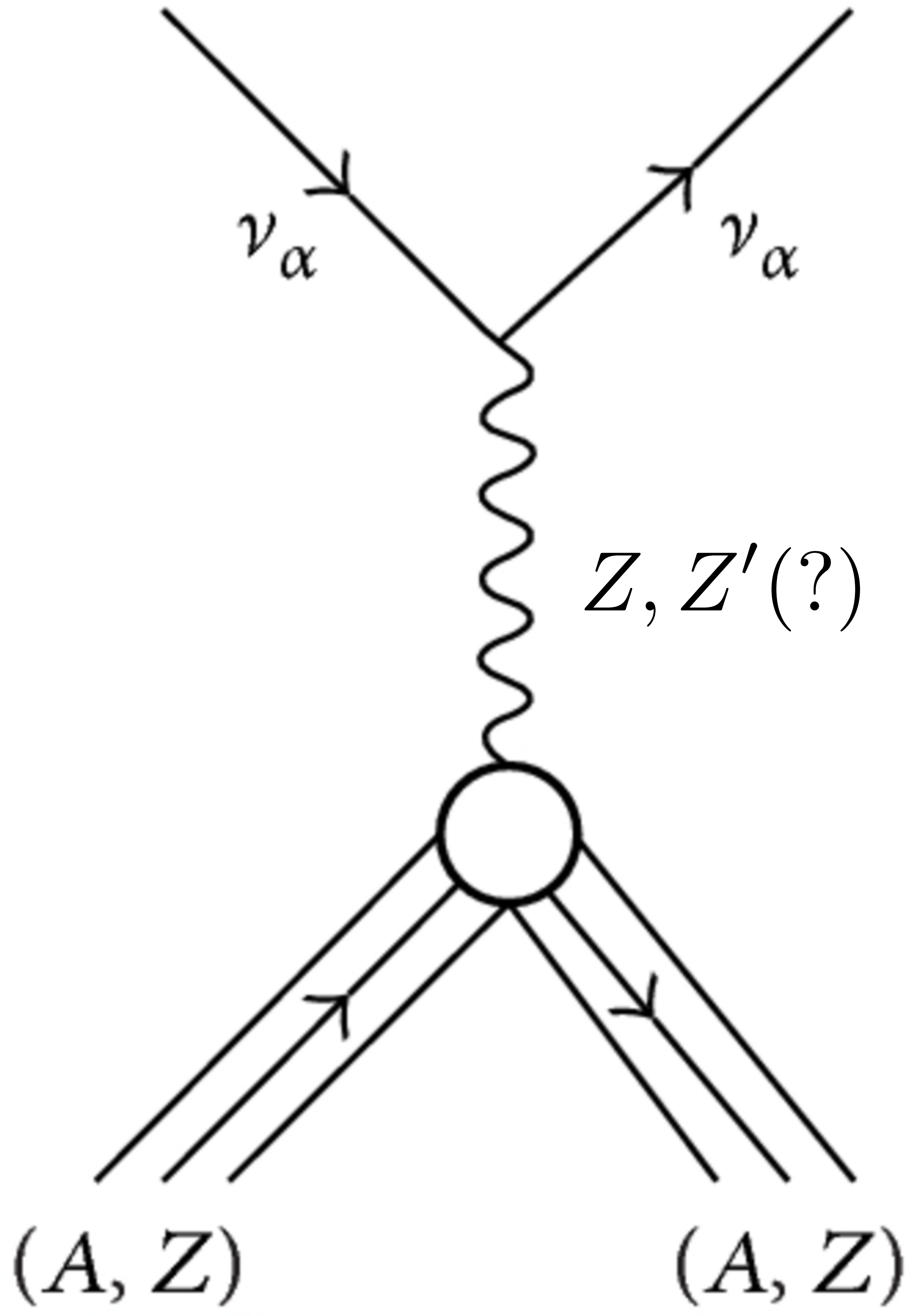
With these high performance detectors, it may also be possible to achieve first experimental measurement of the Migdal effect using a neutron calibration source

Coherent Elastic Neutrino Nucleus Scattering (CENNS)

CENNS recently observed for the first time by COHERENT collaboration [1708.01294]

Low-energy measurements open up **powerful probes of New Physics** in neutrino sector





[Billard, Johnston, **BJK** - 1805.01798]

Conclusions

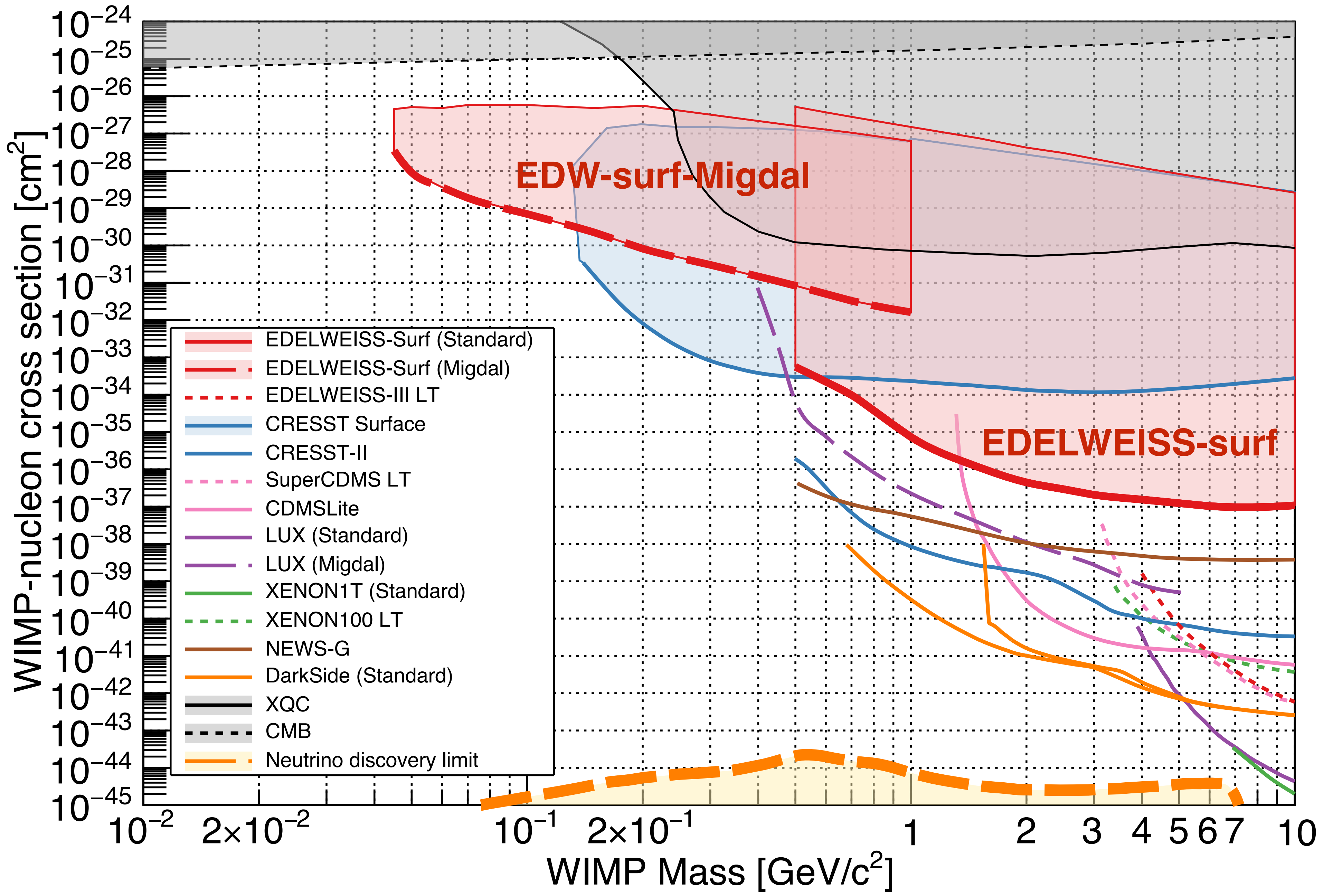
EDELWEISS-surf achieved a **threshold of just 60 eV** in a 33.4g Ge detector - low background, underground is underway

Small one-day exposure, but very sensitive down to **low mass and large cross sections**

Probing new regions of the spin-independent and spin-dependent parameter space: down to masses of **500 MeV** with conventional nuclear recoils and **45 MeV** with inelastic signatures

Incorporating **Earth-shielding effects** is essential as we go to lower DM mass and our limits weaken

Paves the way for **even lower DM masses** and for precision measurements of **coherent neutrino scattering**



Conclusions

EDELWEISS-surf achieved a **threshold of just 60 eV** in a 33.4g Ge detector - low background, underground is underway

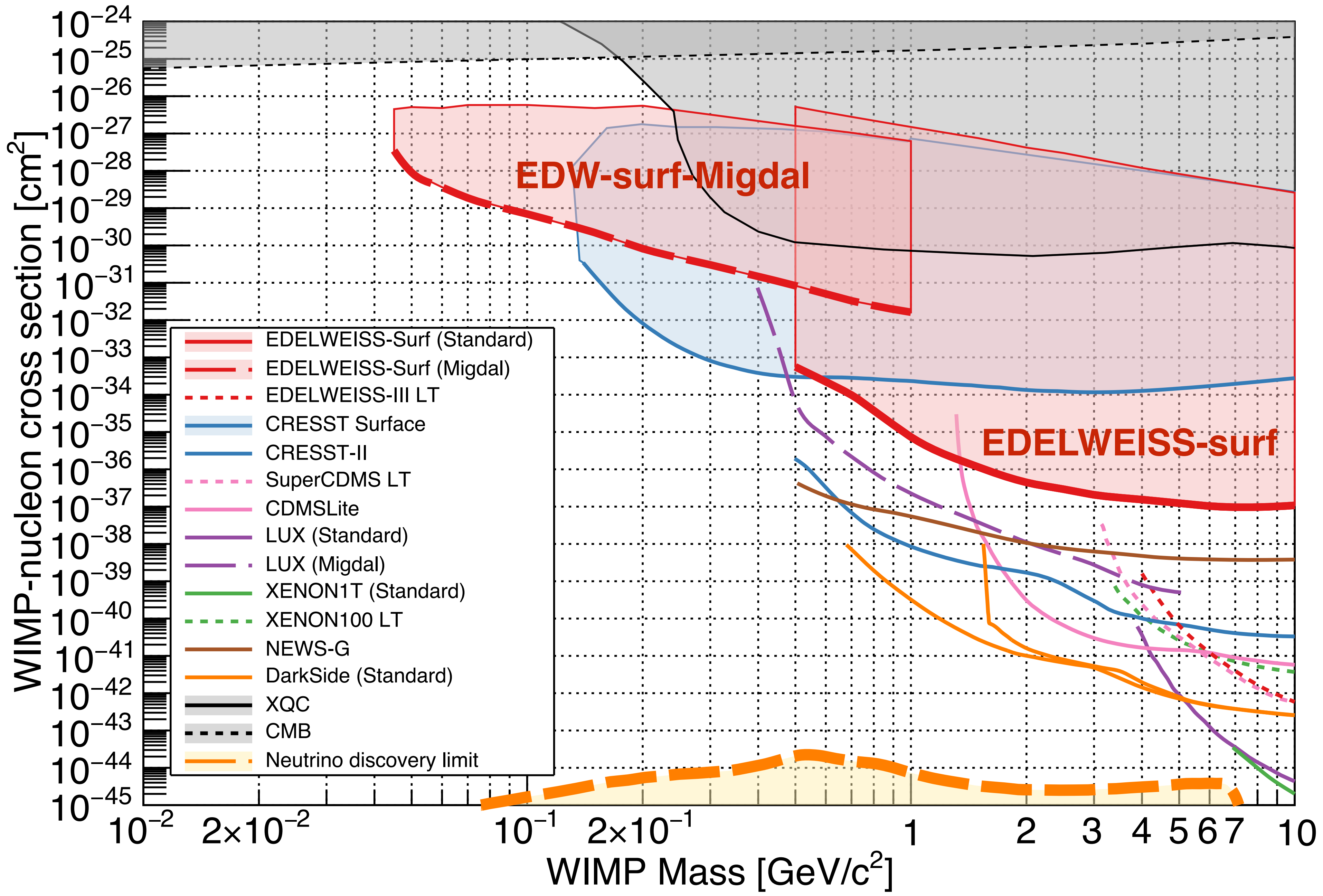
Small one-day exposure, but very sensitive down to **low mass and large cross sections**

Probing new regions of the spin-independent and spin-dependent parameter space: down to masses of **500 MeV** with conventional nuclear recoils and **45 MeV** with inelastic signatures

Incorporating **Earth-shielding effects** is essential as we go to lower DM mass and our limits weaken

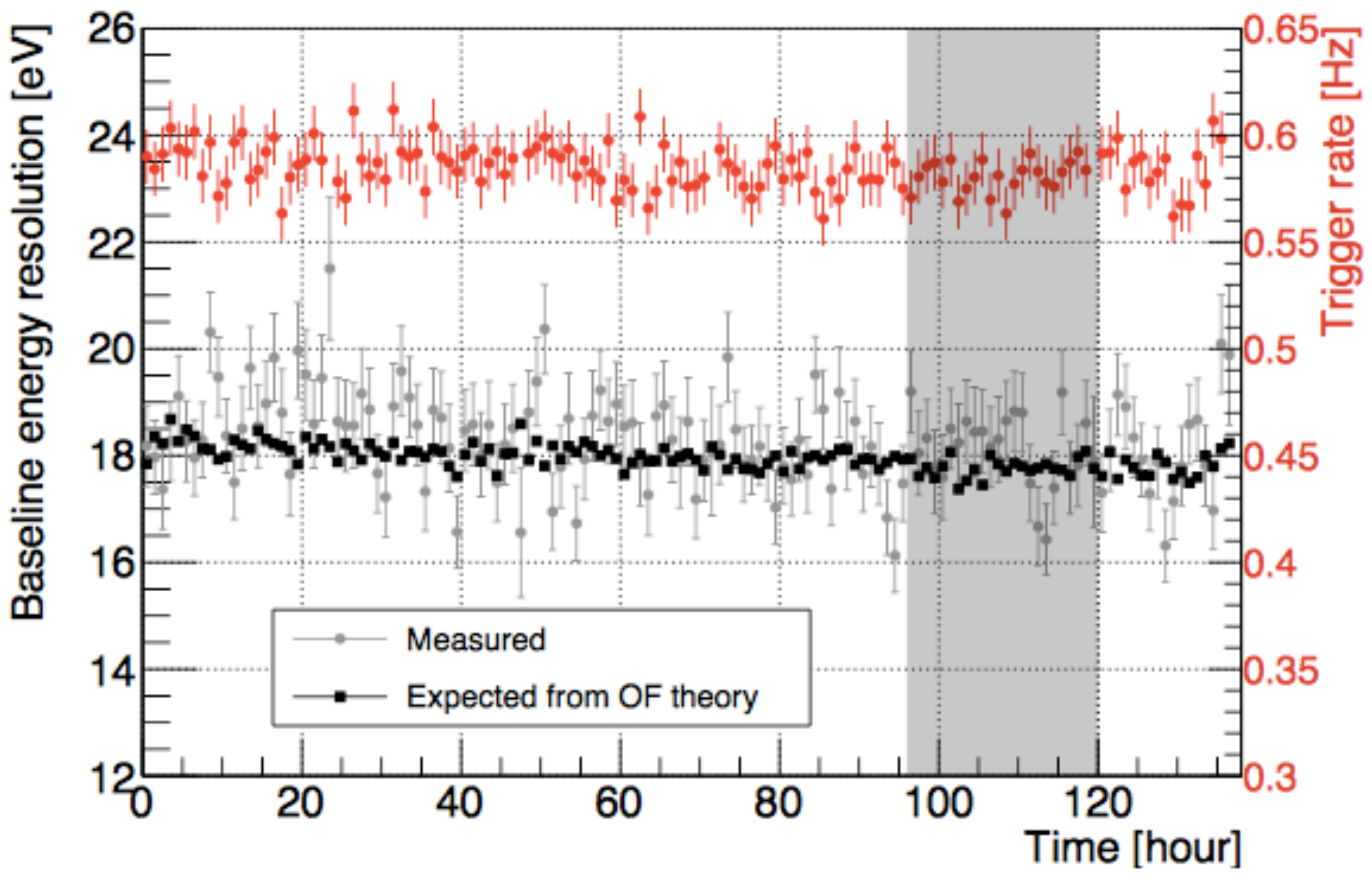
Paves the way for **even lower DM masses** and for precision measurements of **coherent neutrino scattering**

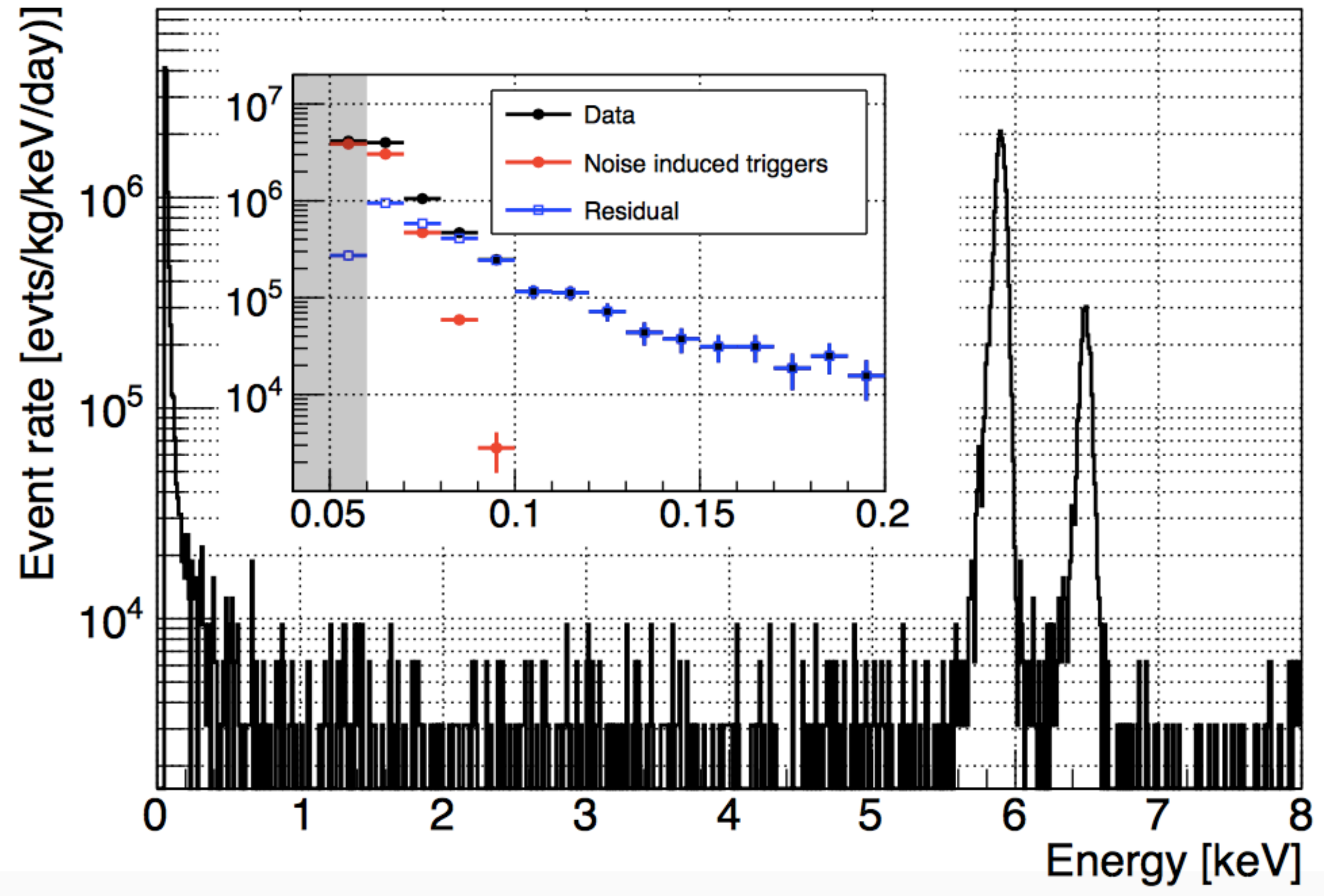
Thank you!

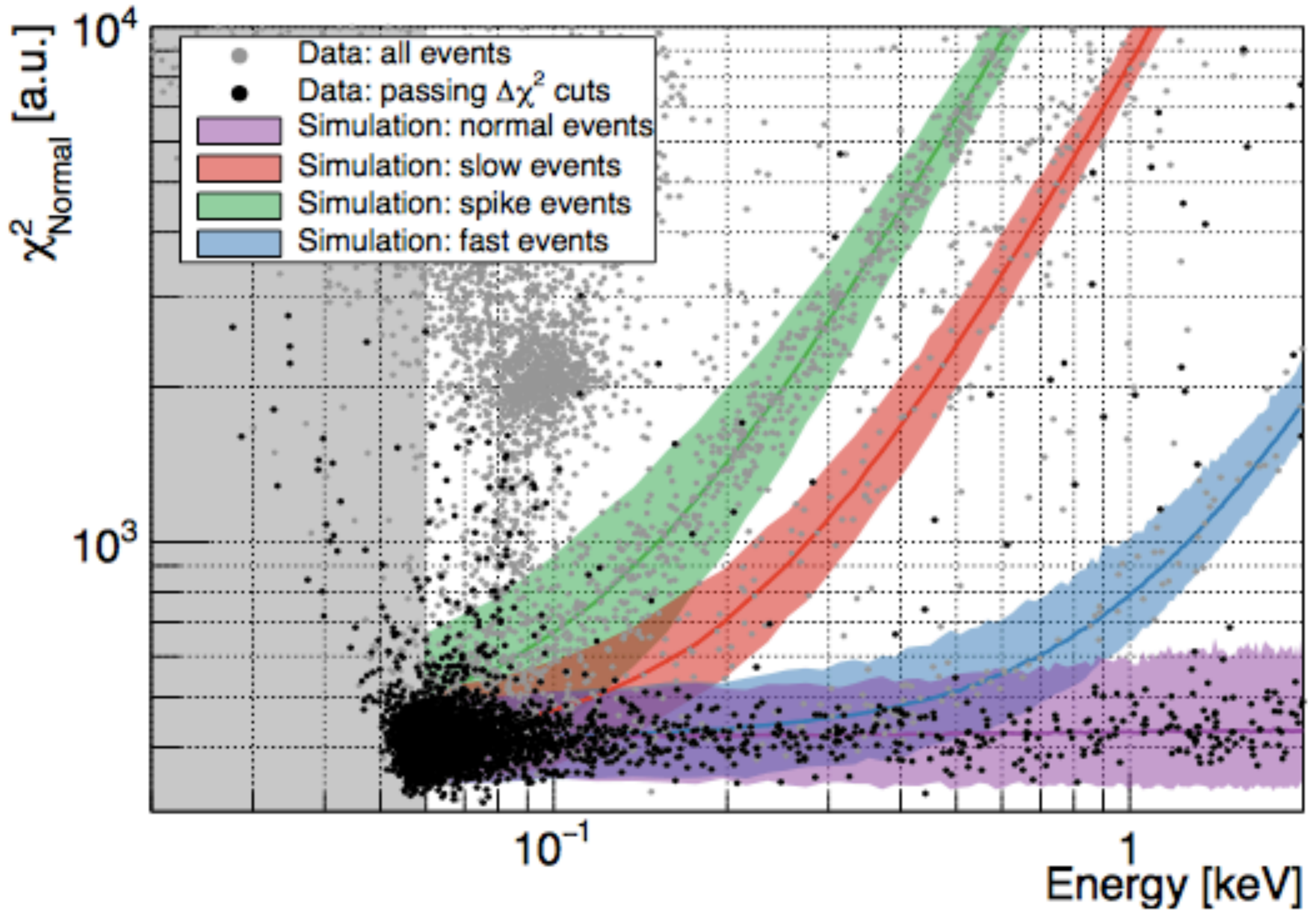


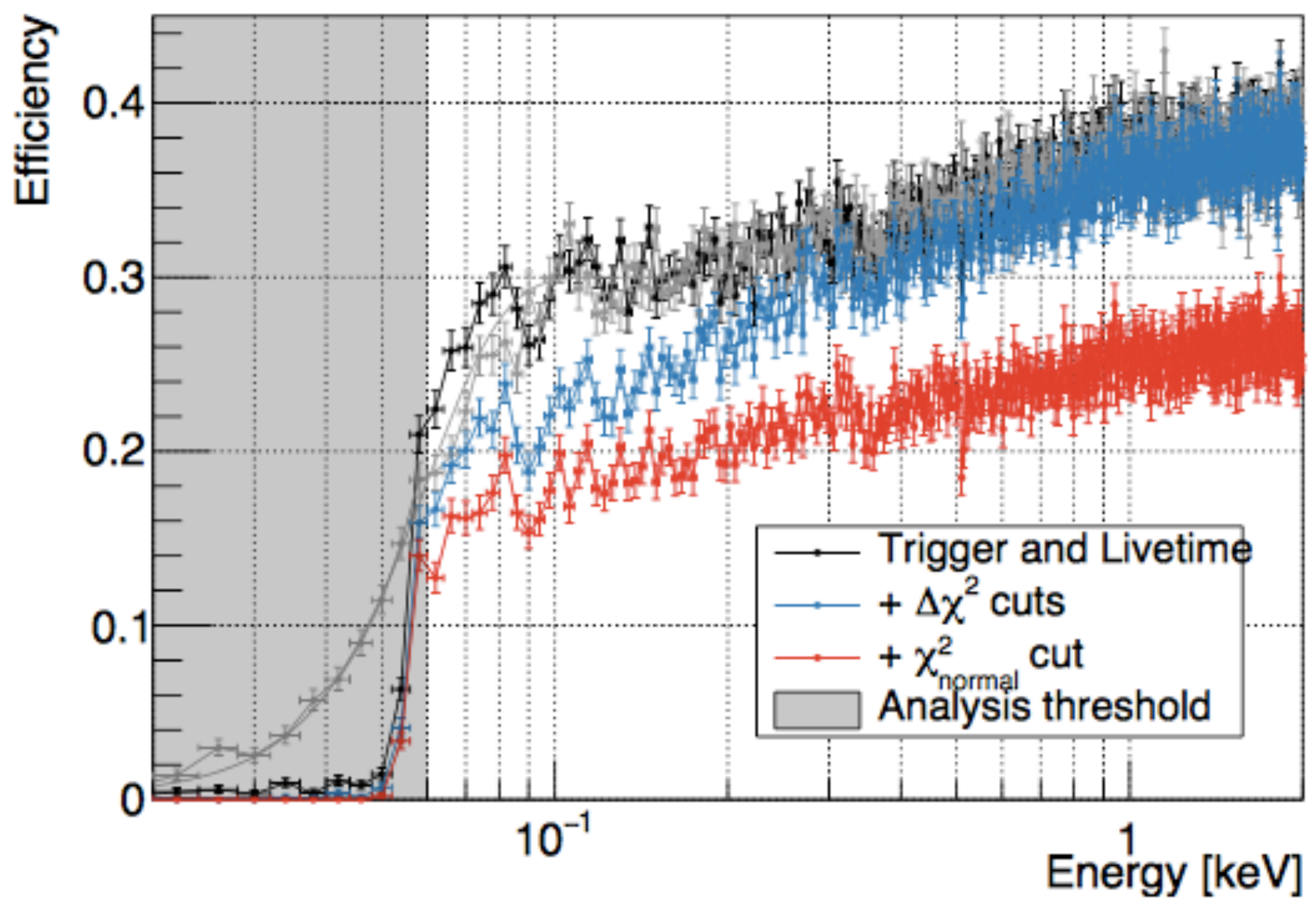
Backup Slides

Detector Performance



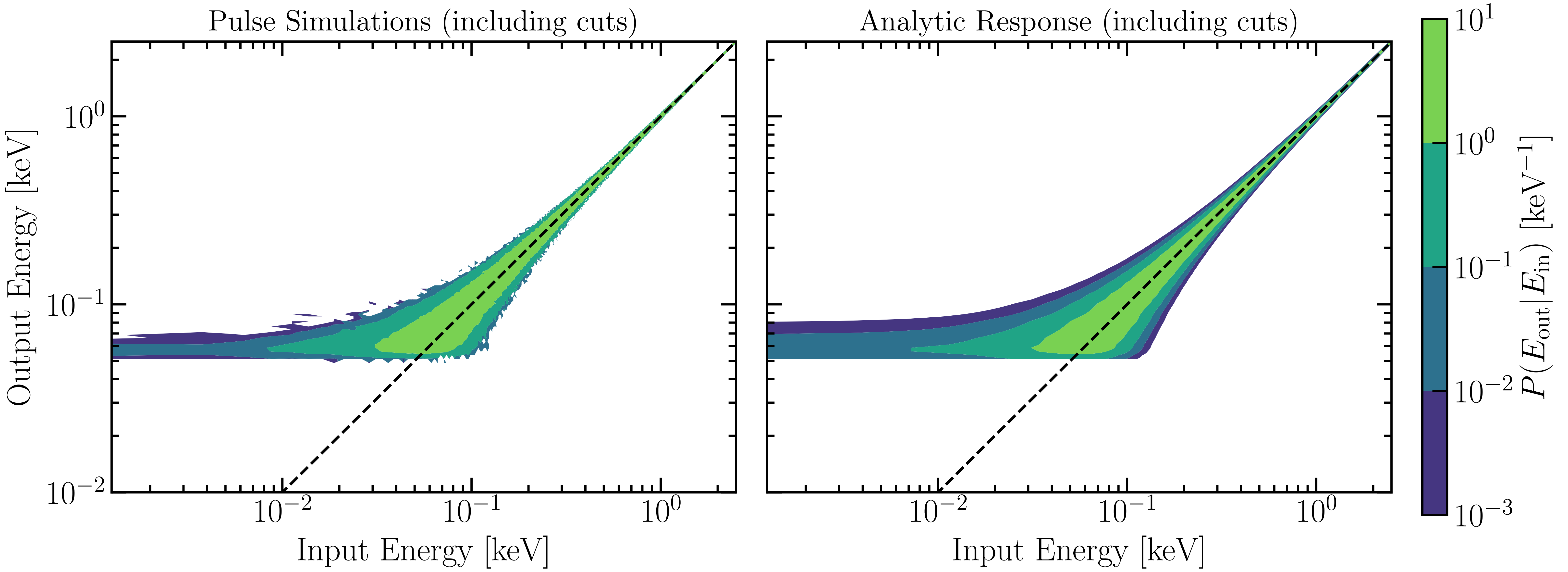






Analytic Detector Response

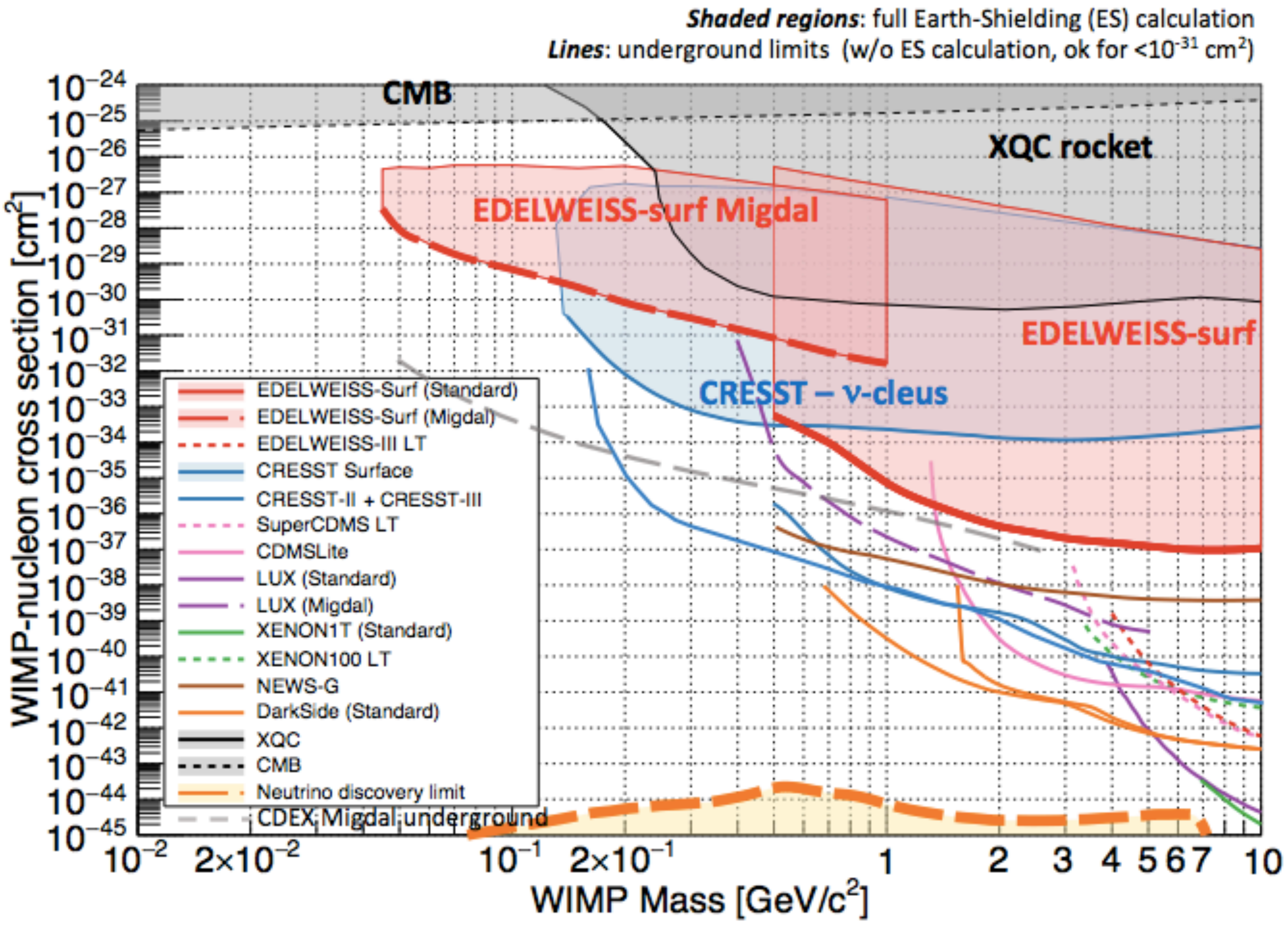
Probability of largest fluctuation within the Optimal Filter window (given ~3 independent samples)



$$P_{\rm OF}\left(X^*|E_{\rm in}\right) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(X^* - E_{\rm in})^2}{2\sigma^2}\right)\left[\mathrm{erf}\left(\frac{|X^*|}{\sqrt{2}\sigma}\right)\right]^{(N_s-1)}$$

$$+ \frac{(N_s-1)}{2\sqrt{2\pi\sigma^2}} \exp\left(-\frac{|X^*|^2}{2\sigma^2}\right)\left[\mathrm{erf}\left(\frac{|X^*|}{\sqrt{2}\sigma}\right)\right]^{(N_s-2)}\left[\mathrm{erf}\left(\frac{|X^*| - E_{\rm in}}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{-|X^*| - E_{\rm in}}{\sqrt{2}\sigma}\right)\right]$$

Spin-independent Limits Summary



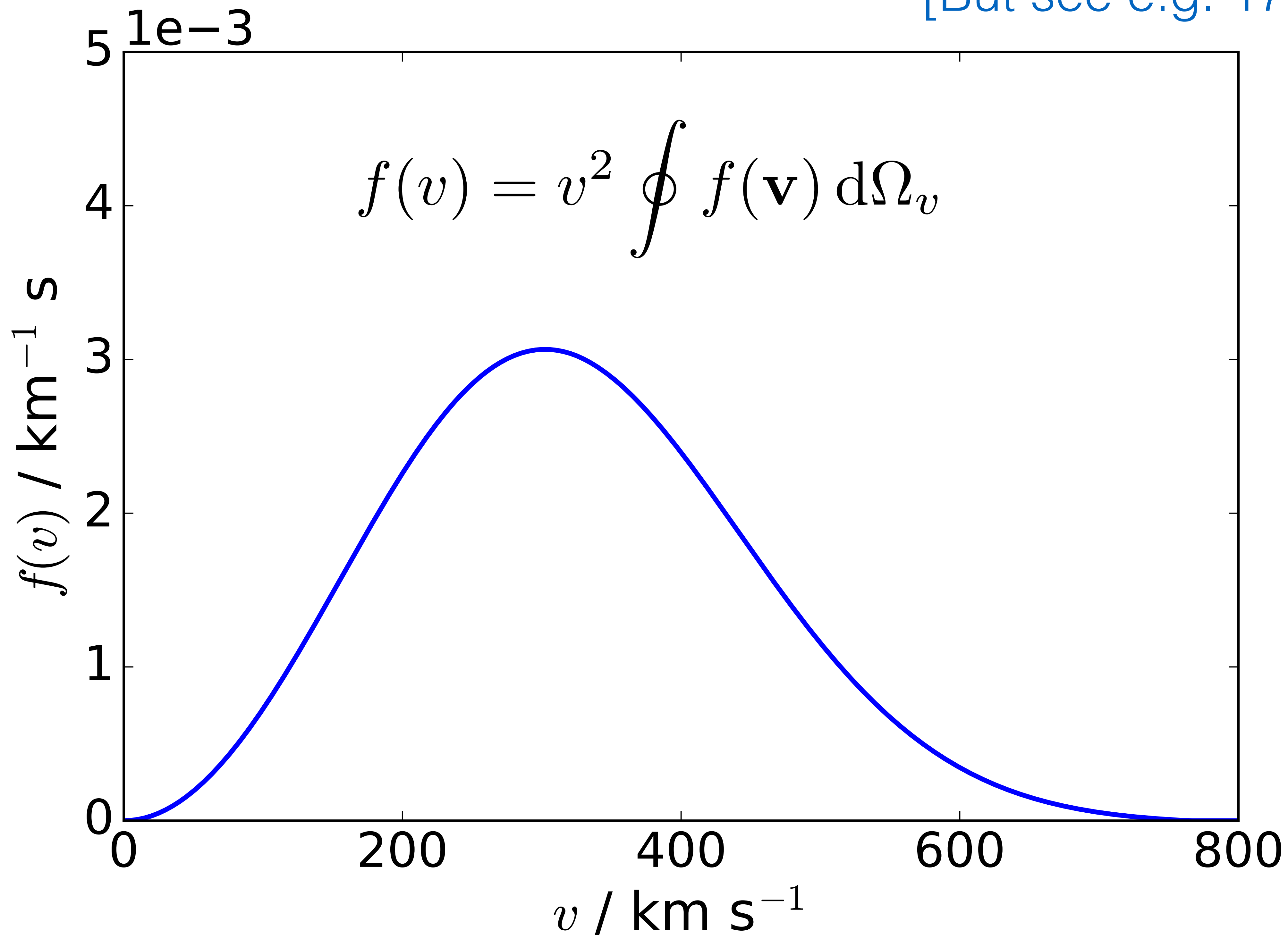
Standard Halo Model

Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution (*in the lab frame*):

$$f_{\mathrm{Lab}}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_\mathrm{e})^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v}-\mathbf{v}_\mathrm{e}| - v_\mathrm{esc})$$

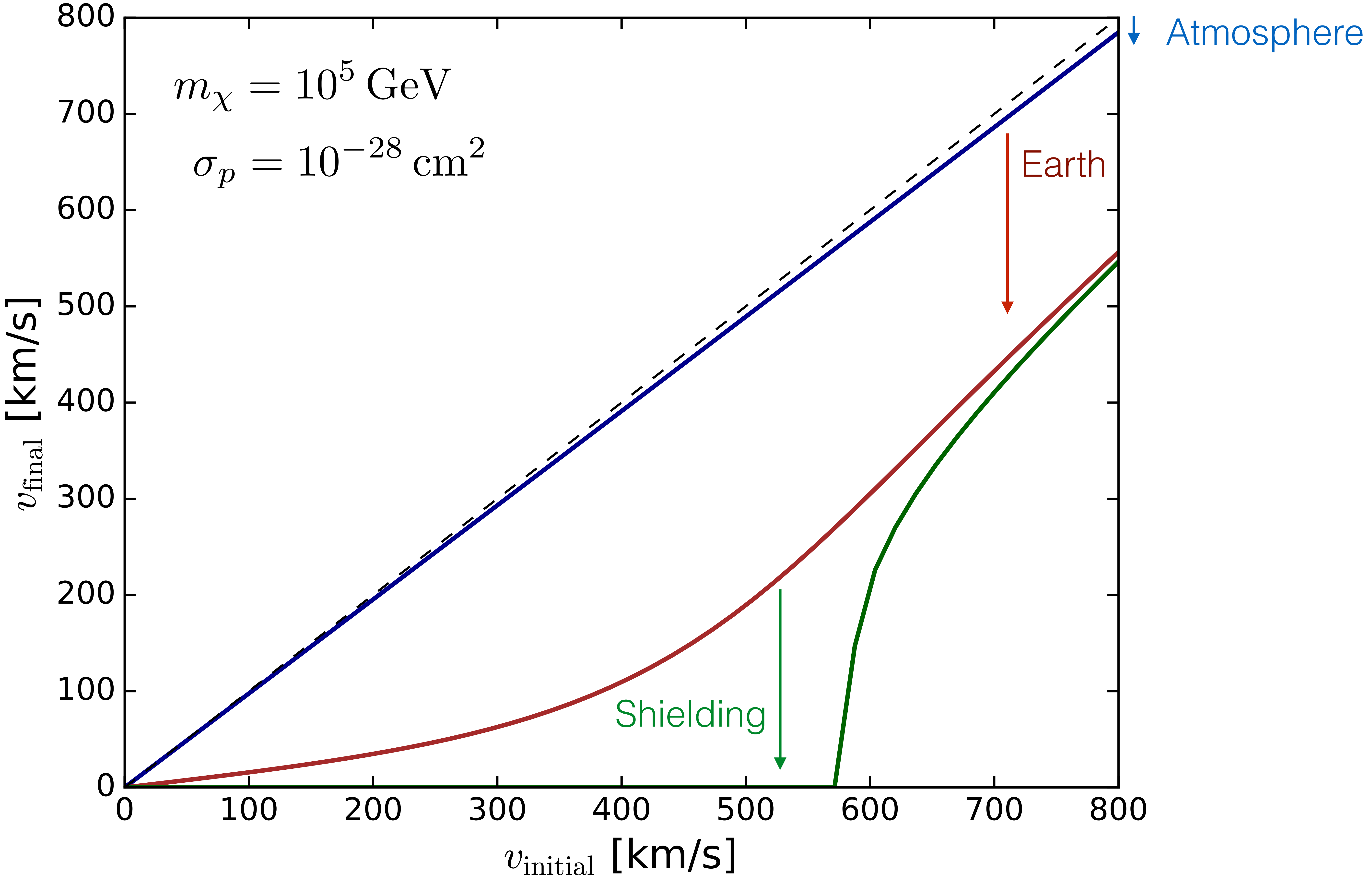
[But see e.g. 1705.05853]



Stopping power

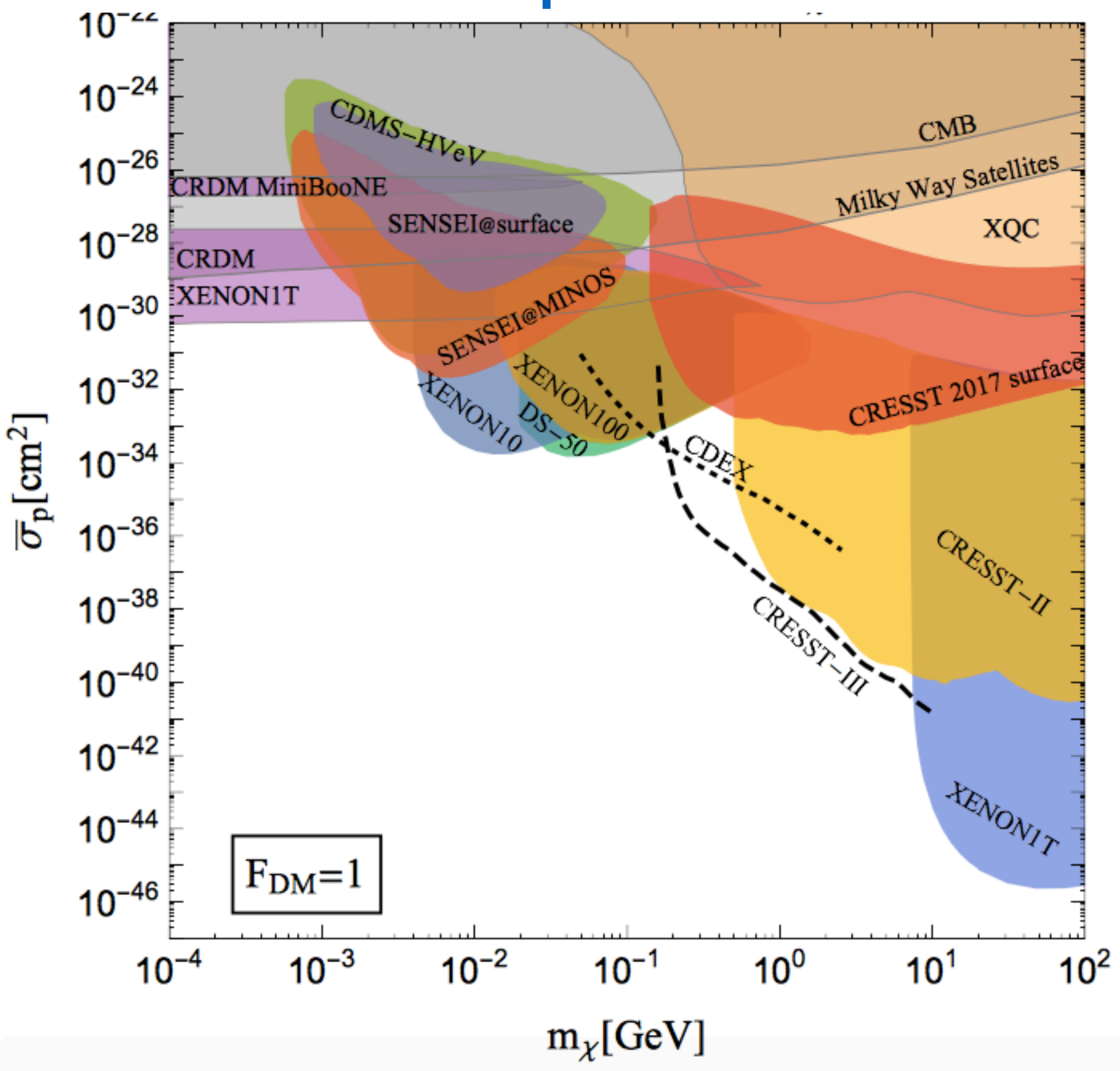
Consider a detector at a depth of 10.6m, with DM particles coming from directly overhead:

CDMS I at the Stanford Underground Facility
[astro-ph/0203500]

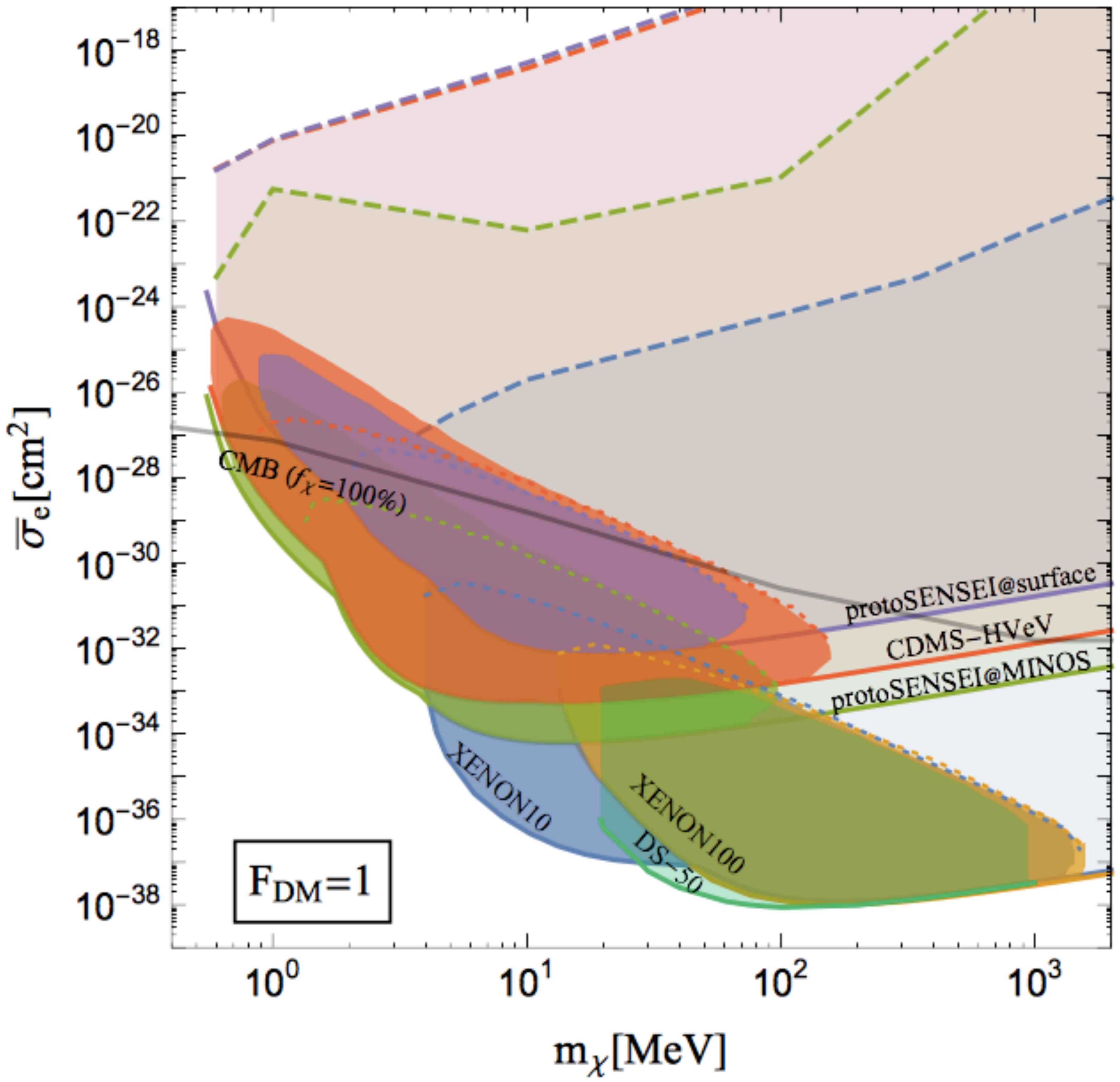


DM-Electron scattering + Monte Carlo

DM-proton



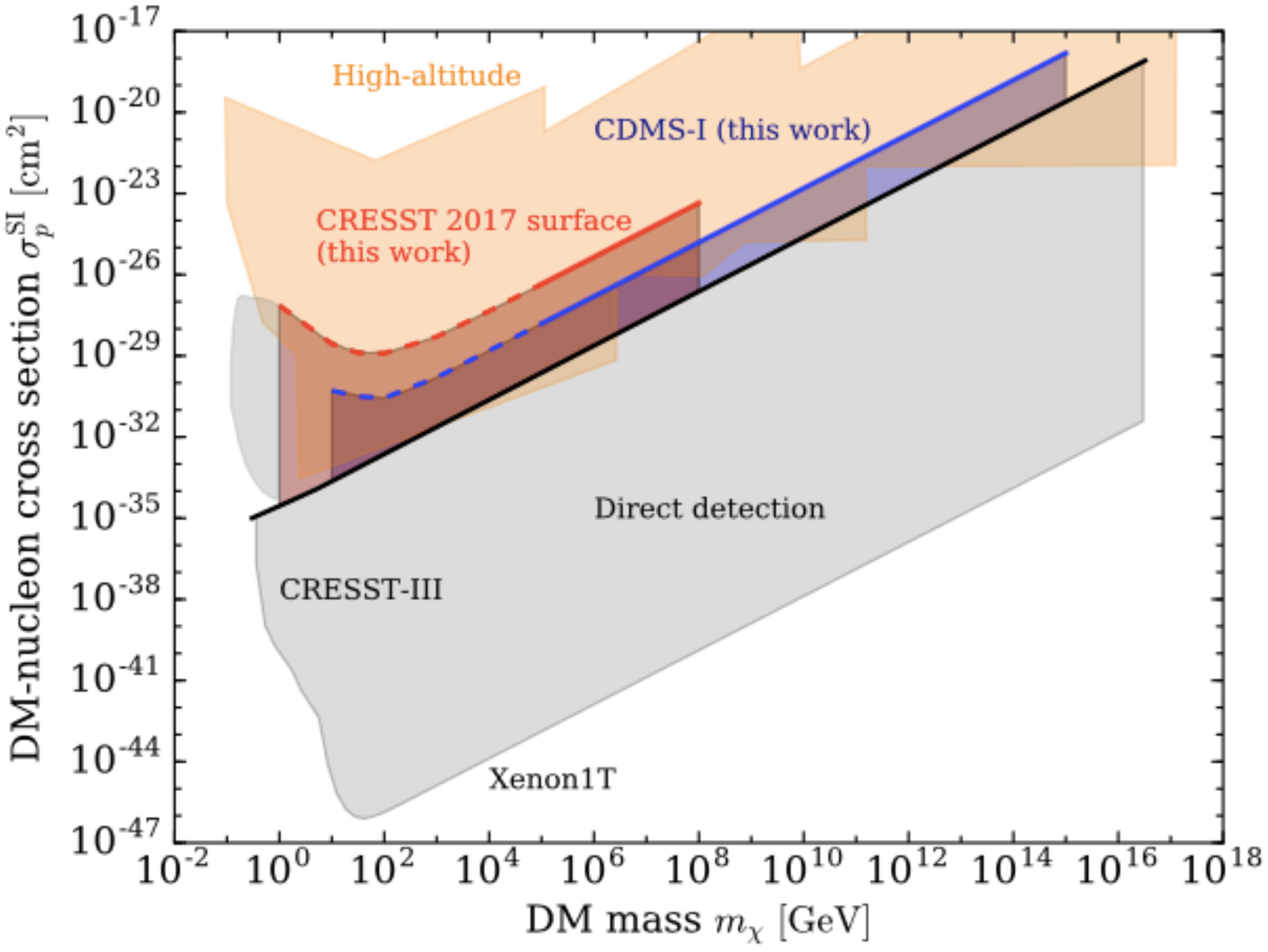
DM-electron

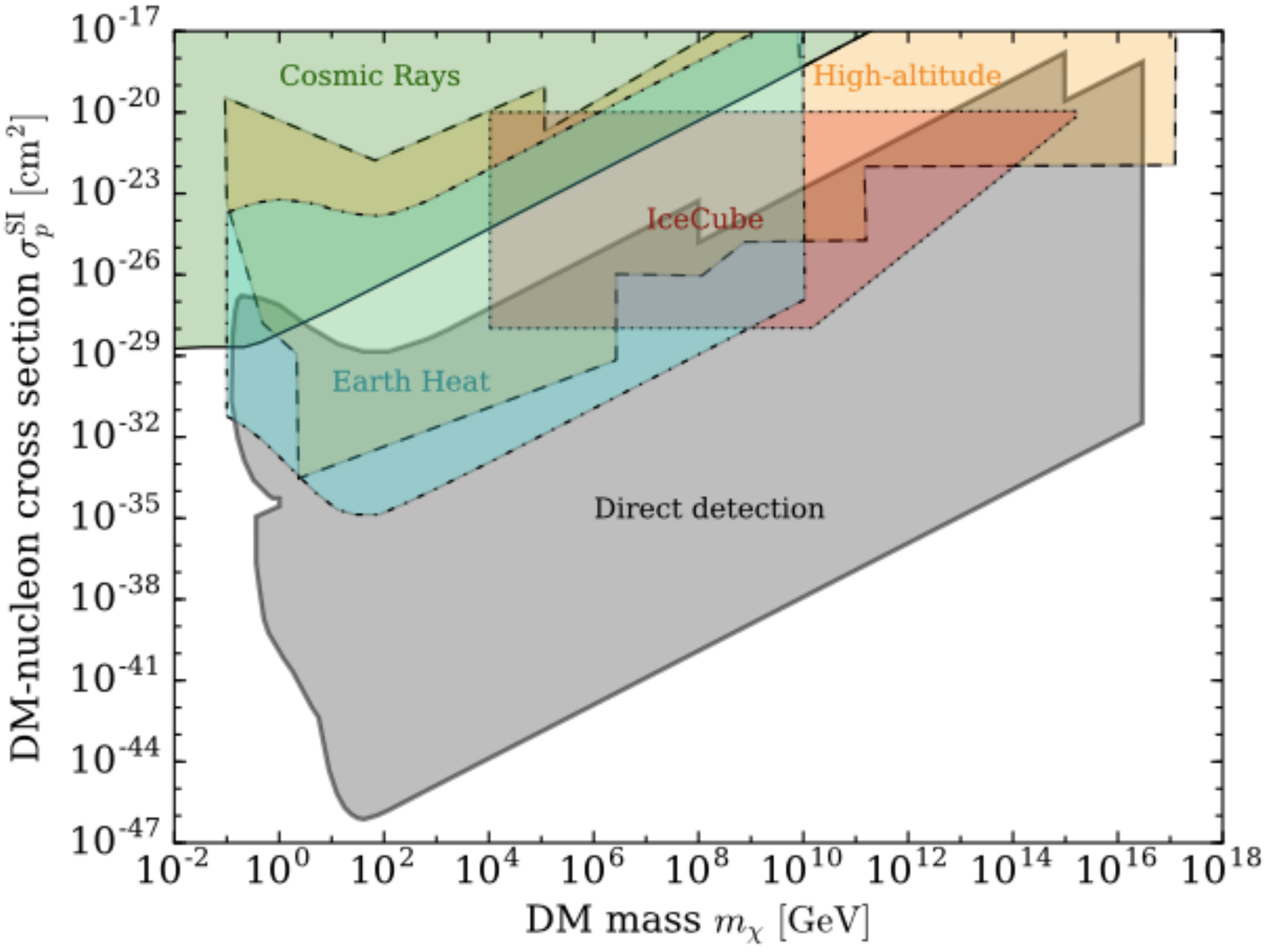


[Emken, Kouvaris & Shoemaker -1702.07750]

[Emken, Essig, Kouvaris & Sholapurkar - 1905.06348]

Direct Detection Landscape - zoomed out





[**BJK** - 1712.04901]

Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]