Direct Detection of sub-GeV Dark Matter with strong interactions through a light mediator

Timon Emken
Chalmers University of Technology, Göteborg

Light Dark World 2019
ESI, Vienna, 12.08.2019

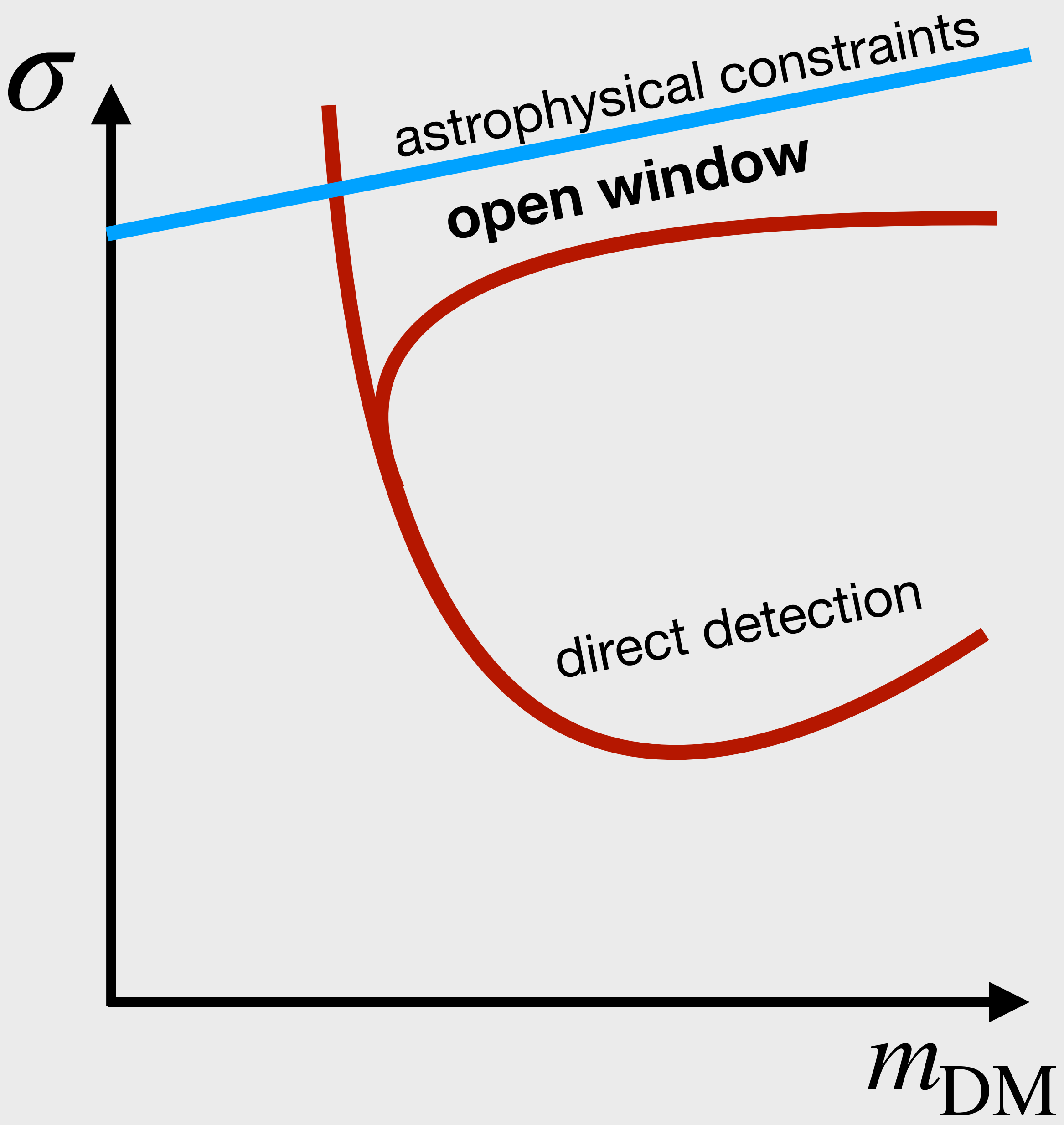
In collaboration with
- Rouven Essig
- Chris Kouvaris
- Mukul Sholapurkar

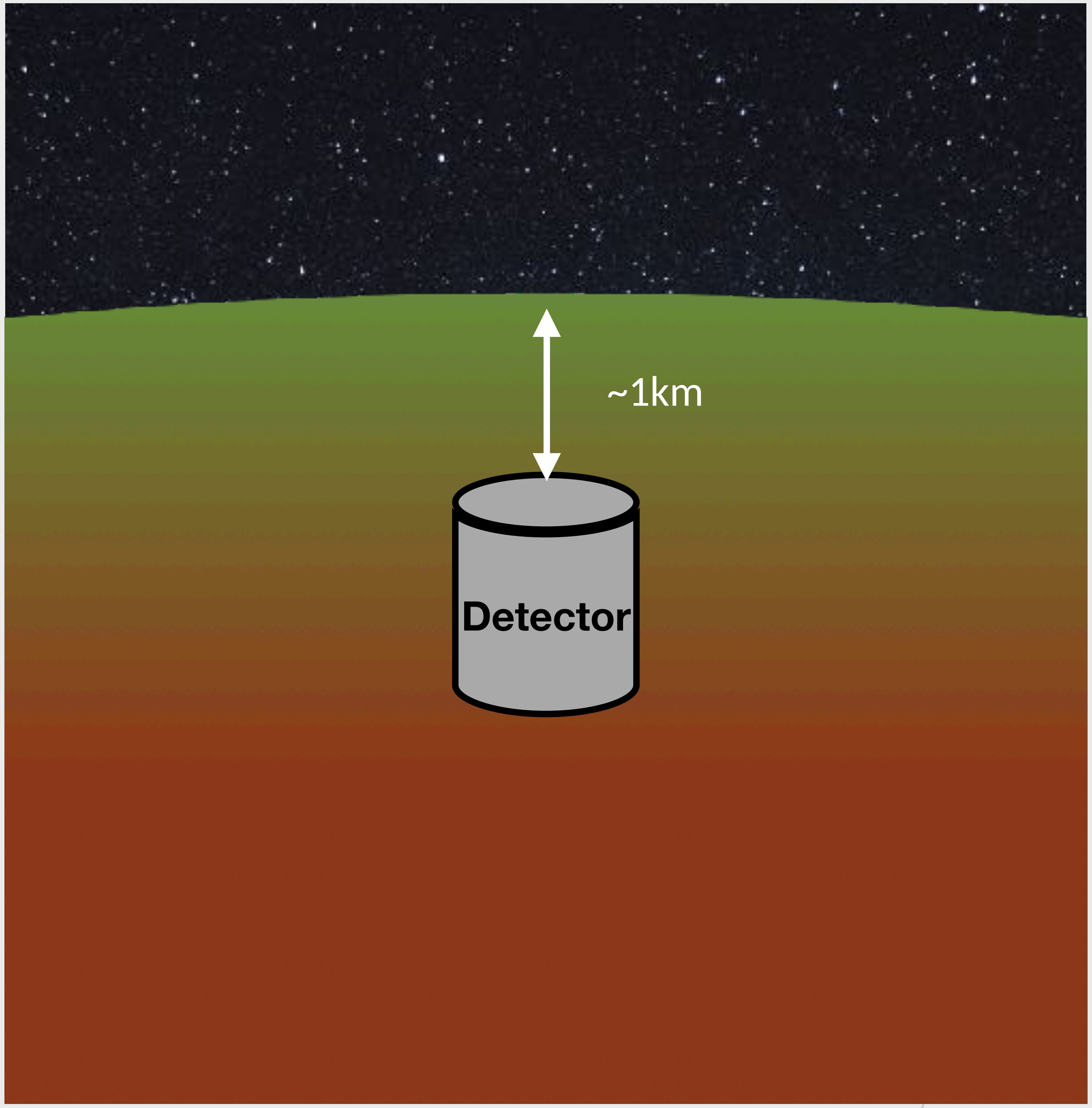
Based on
- [arXiv:**1905.06348**]
- [arXiv:**1802.04764**]

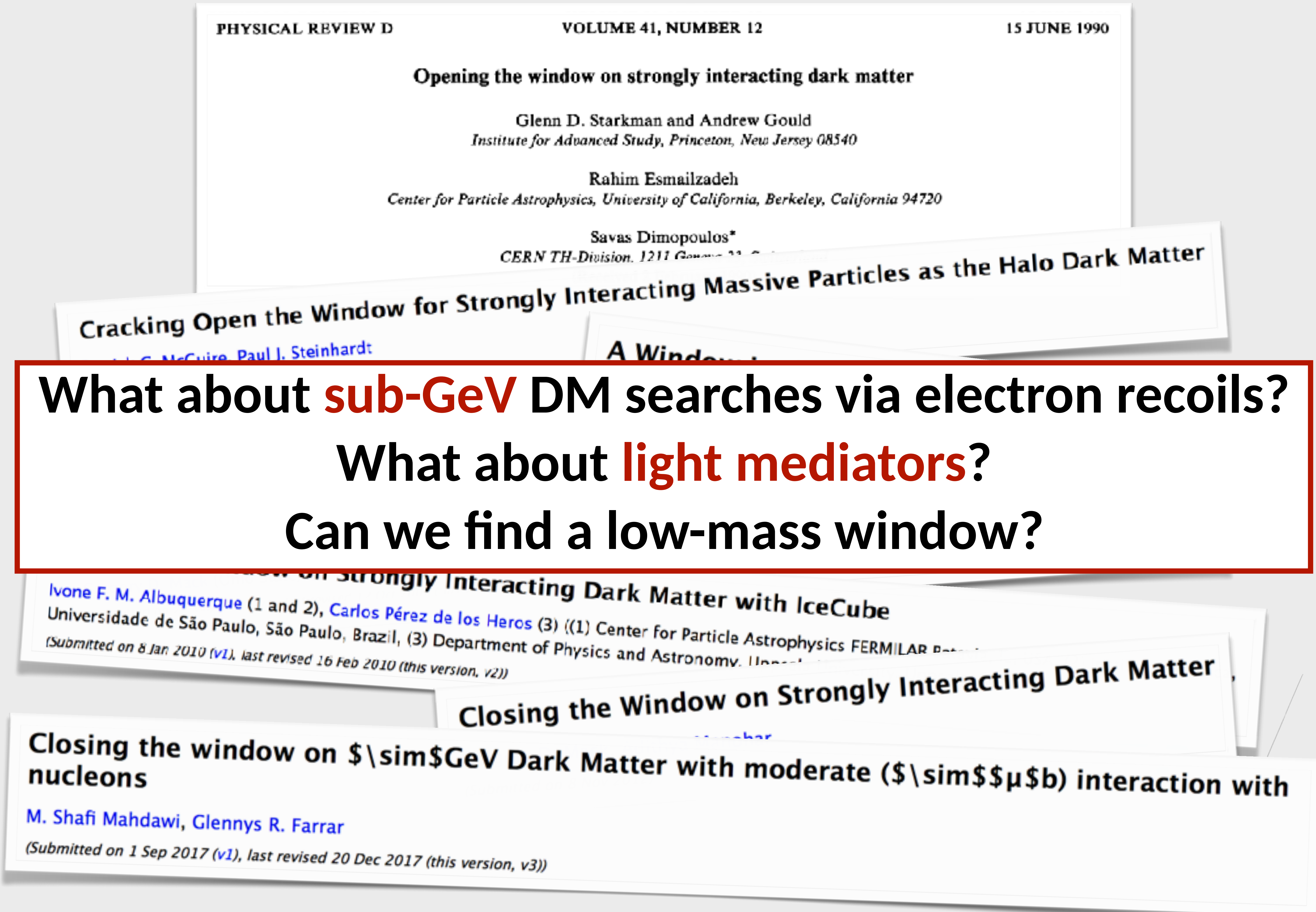
CHALMERS
UNIVERSITY OF TECHNOLOGY

Direct detection of strongly interacting DM

Goodman and Witten, Phys.Rev. D31 (1985) 3059
Starkman et al, Phys.Rev. D41 (1990) 3594







What about sub-GeV DM searches via electron recoils?

What about light mediators?

Can we find a low-mass window?

Outline

I. Simulating terrestrial effects on direct detection experiments

II. Nuclear recoil experiments

III. Sub-GeV DM and light mediators

Part I

Simulating terrestrial effects on direct detection experiments

How to include the effect of Earth scatterings?

J. Kopp et al., Phys. Rev. D80 (2009) 083502
R. Essig et al., Phys. Rev. D85 (2012) 076007
R. Essig et al., Phys. Rev. Lett. 109 (2012) 021301
R. Essig et al., JHEP 1605 (2016) 046

- Nuclear recoil spectrum:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}(E_R)} \mathrm{d}v\, v f_\chi(v) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R}$$

- Energy spectrum for DM induced atomic ionizations:

$$\frac{\mathrm{d}R_{\text{ion}}}{\mathrm{d}E_e} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\sum_{nl}\frac{\sigma_e}{8\mu_{\chi e}^2 E_e}\int \mathrm{d}q\, q \int_{v>v_{\min}(\Delta E_e,q)} \mathrm{d}v \frac{f_\chi(v)}{v}\left|F_{\text{DM}}(q)\right|^2 \left|f_{\text{ion}}^{nl}(k',q)\right|^2$$

- Energy spectrum for DM induced excitations in semiconductors:

$$\frac{\mathrm{d}R_{\text{crystal}}}{\mathrm{d}E_e} = \frac{\rho_\chi}{m_\chi}\frac{1}{M_{\text{cell}}}\frac{\sigma_e \alpha m_e^2}{\mu_{\chi e}^2}\int \mathrm{d}q \frac{1}{q^2}\int_{v>v_{\min}(E_e,q)} \mathrm{d}v \frac{f_\chi(v)}{v}\left|F_{\text{DM}}(q)\right|^2 \left|f_{\text{crystal}}(E_e,q)\right|^2$$

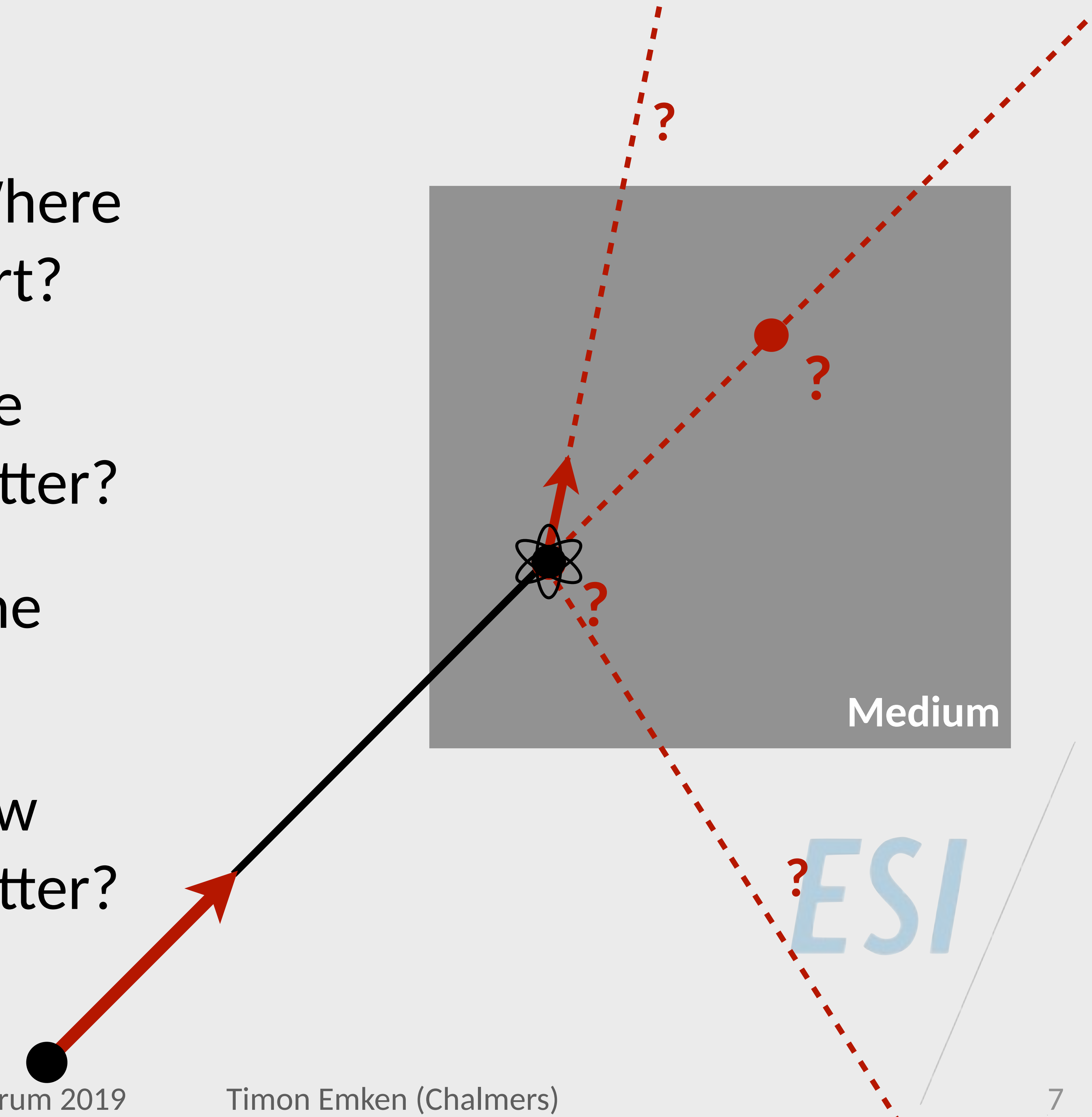
Earth scatterings modify the underground DM density and velocity distribution.

MC simulations of DM trajectories

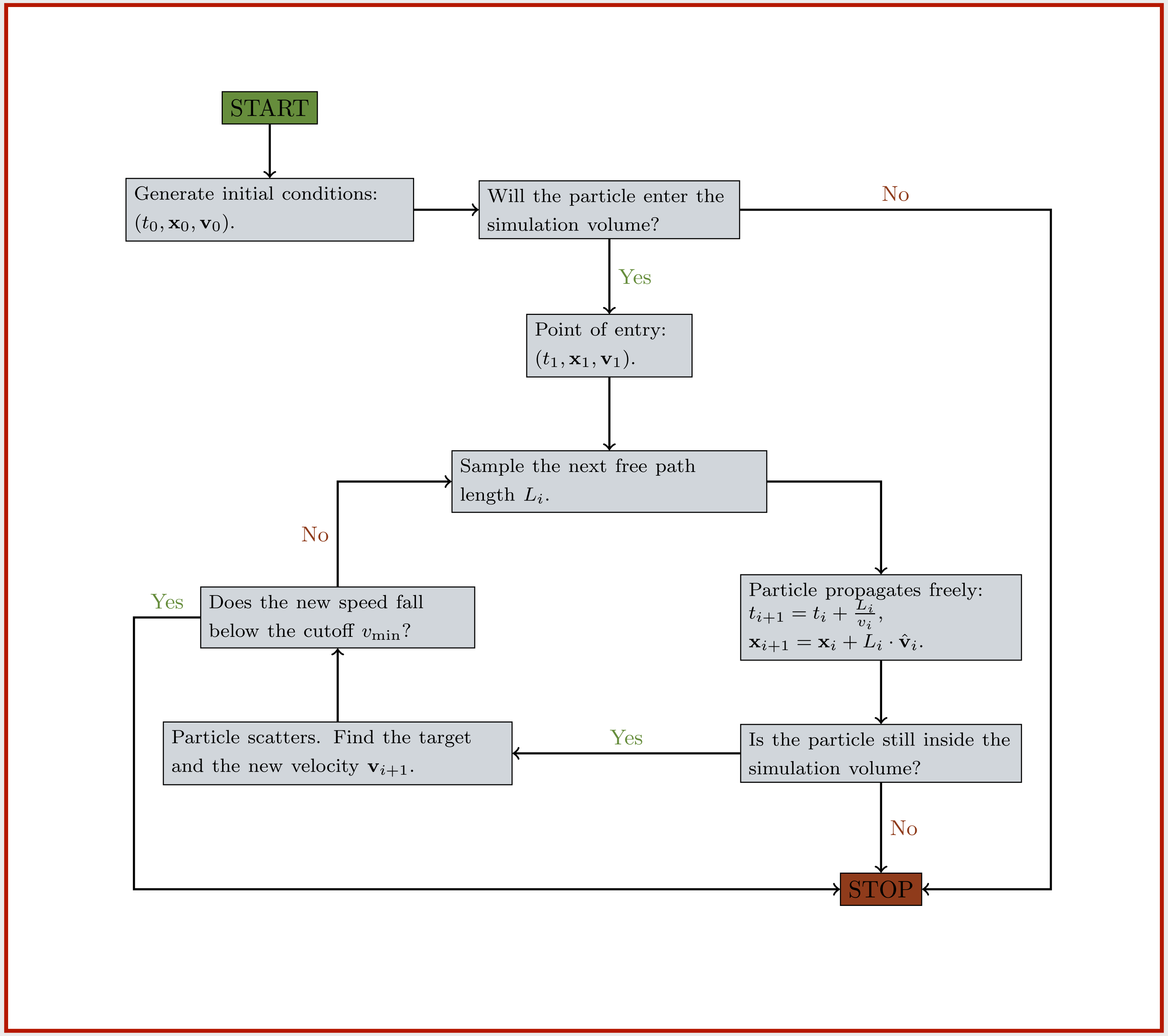
The fundamental random processes

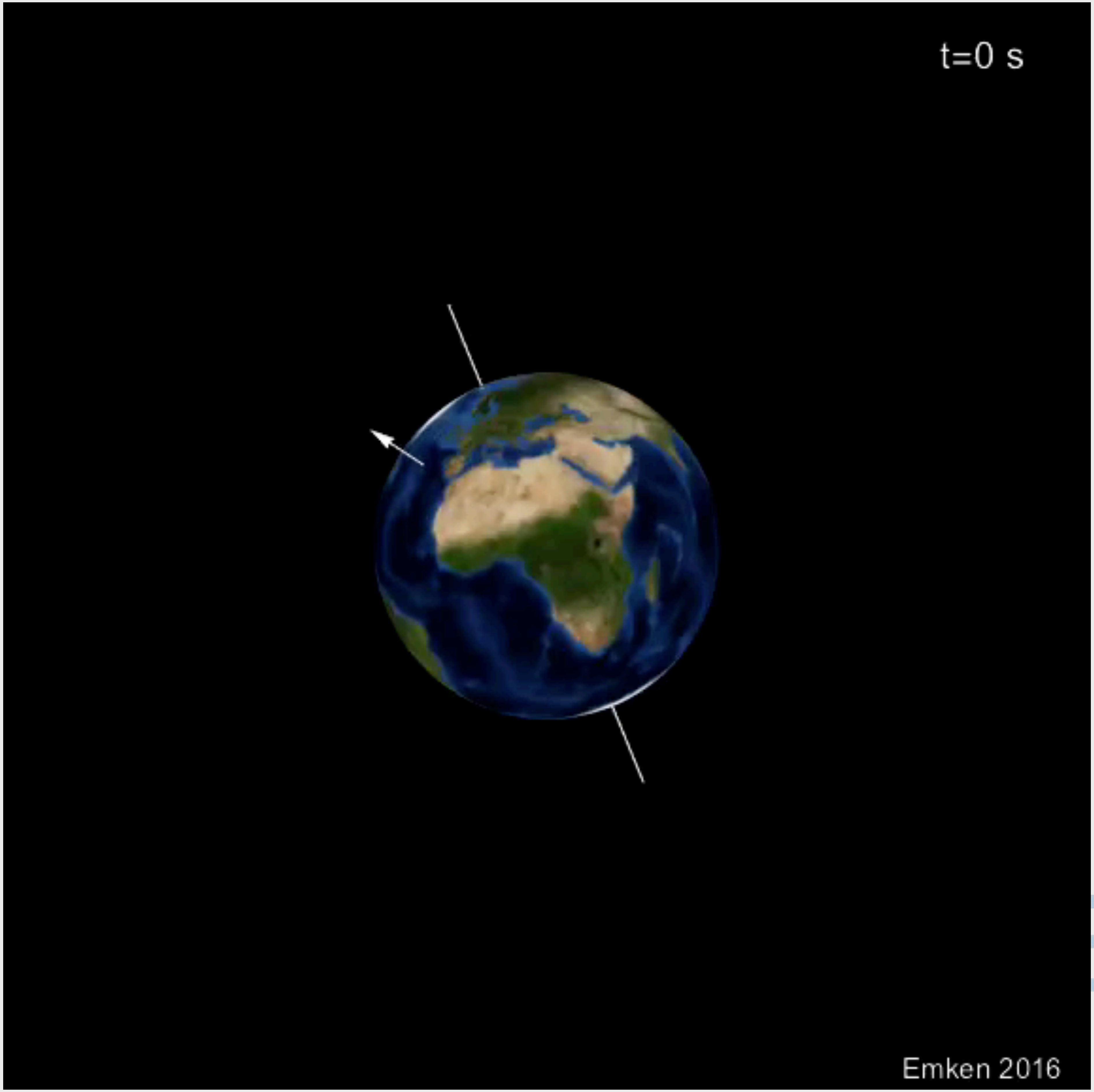
1. **Initial Conditions**: Where does the particle start?
2. **Free distance**: Where does the particle scatter?
3. **Target**: What does the particle scatter on?
4. **Scattering angle**: How does the particle scatter?

Repeat steps 2.-4.



MC simulation algorithm

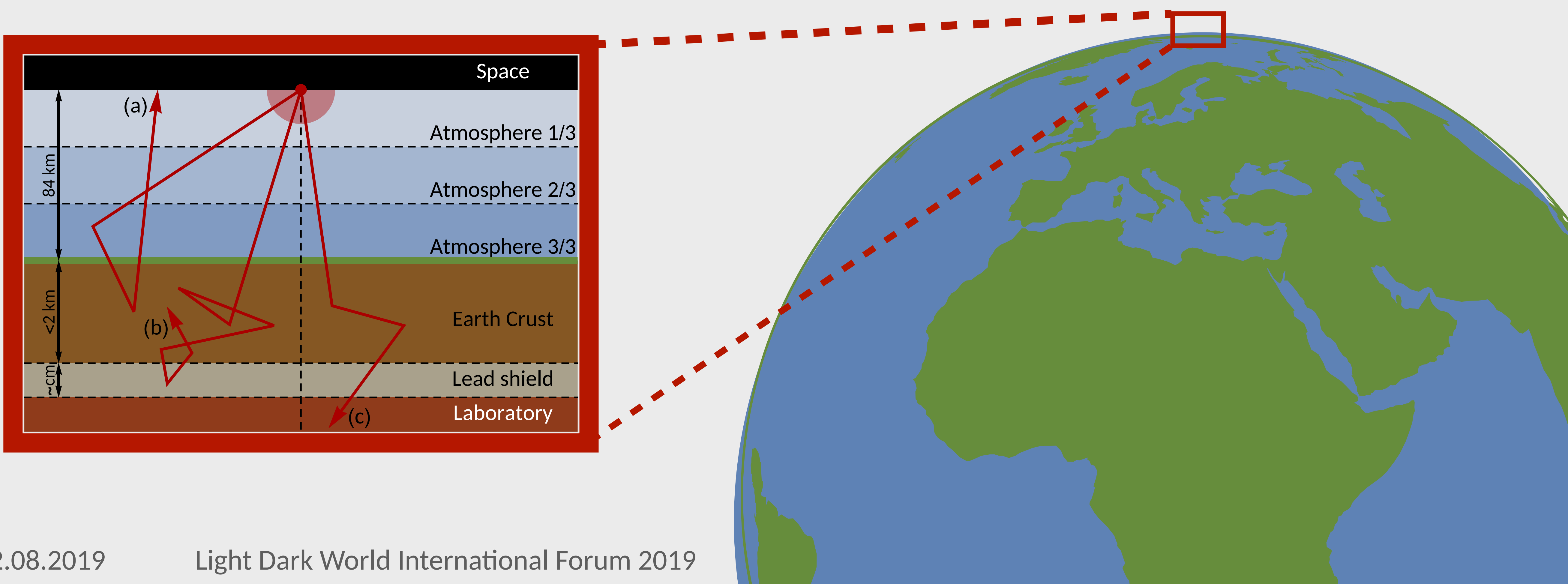



t=0 s
Emken 2016

MC simulation of the overburden of detectors

TE, C. Kouvaris, I.M. Shoemaker, Phys.Rev. D96 (2017) no.1, 015018
M.S. Mahdawi, G.R. Farrar, JCAP 1712 (2017) 004
TE, C. Kouvaris, Phys.Rev. D97 (2018) no.11, 115047
M.S. Mahdawi, G.R. Farrar, JCAP 1810 (2018) no.10, 007

To find the critical cross-section, where a given experiment loses sensitivity to strongly interacting DM, we only simulate the overburden, not the entire Earth.



Part II
Nuclear recoil experiments

Shielding vs. Detection

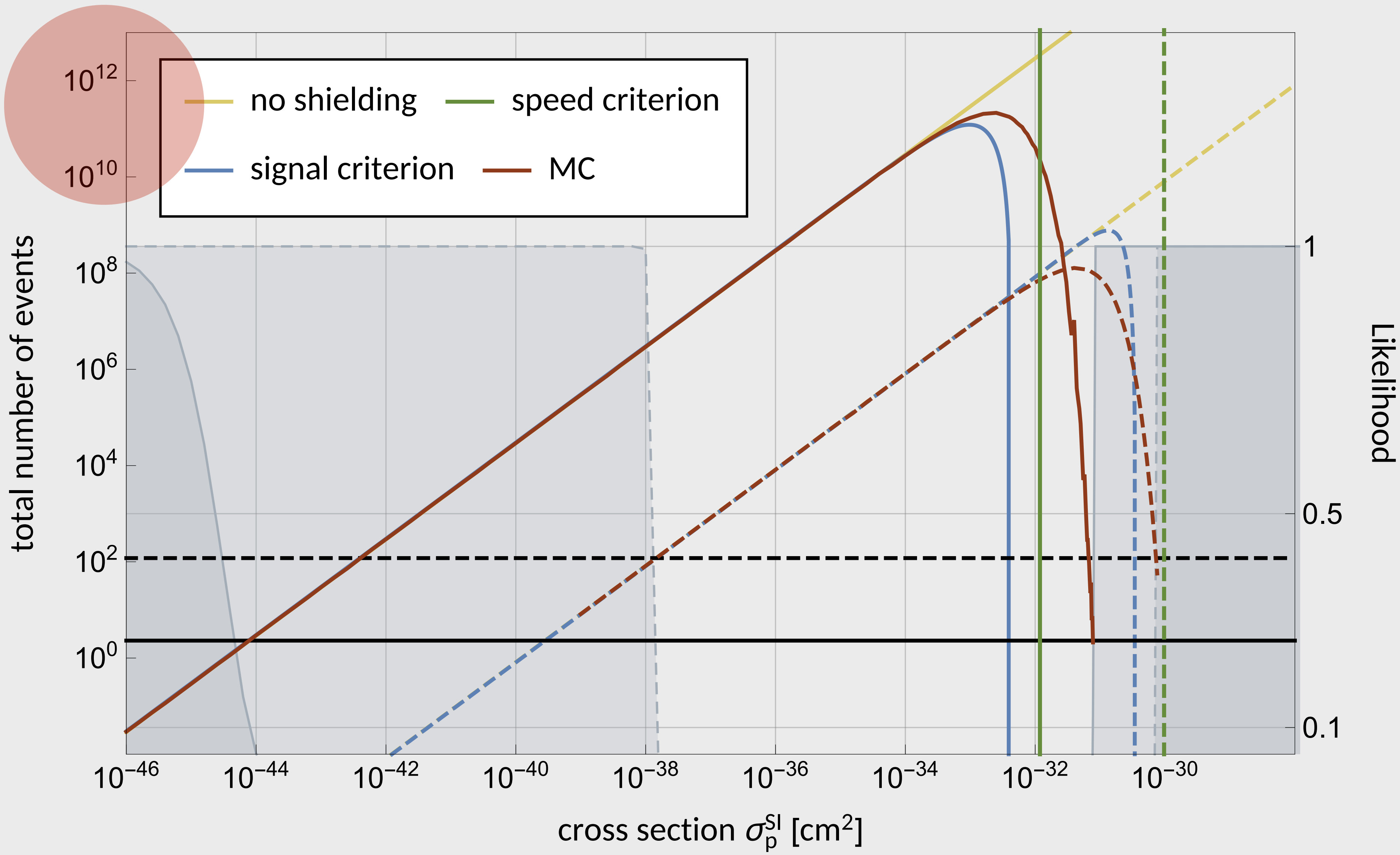
increase cross-section

increases shielding

decreases event rate

increases event rate

Shielding vs. Detection



Rare-event techniques are absolutely crucial!

- Importance Sampling
- Importance Splitting

Rare event simulation I

Importance Sampling

M.S. Mahdawi, G.R. Farrar, JCAP 1712 (2017) 004

- Rare event technique, which modifies the PDFs of the simulation.

$$\langle Y \rangle_I = \int_I \mathrm{d}x\ Y(x) f(x) = \int_I \mathrm{d}x\ Y(x) \frac{f(x)}{\hat{g}(x)} \hat{g}(x)$$

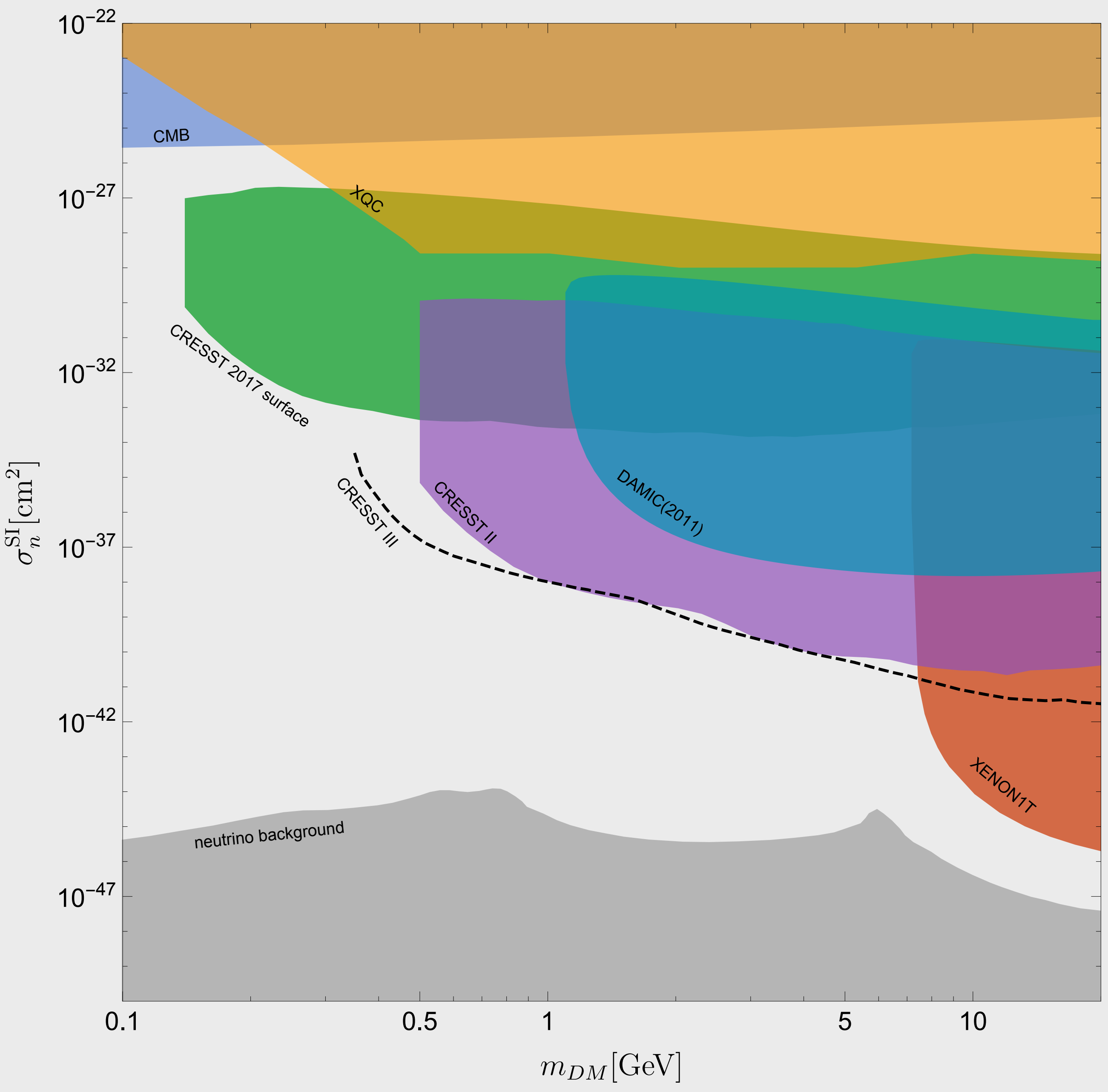
- Try to "mimic" the successful runs by introducing a bias into the simulations.
- Compensate by a weight factor.

$$f_\lambda(x) = \frac{1}{\lambda} \exp\left(-\frac{x}{\lambda}\right)$$
$$g_\lambda(x) = \frac{1}{(1+\delta_\lambda)\lambda} \exp\left(-\frac{x}{(1+\delta_\lambda)\lambda}\right)$$

$$f_\theta(\cos\theta) = \frac{1}{2}$$
$$g_\theta(\cos\theta) = \frac{1+\delta_\theta \cos\theta}{2}$$

Statistical weight: $w_{\lambda,i} = \dfrac{f_\lambda(l_i)}{g_\lambda(l_i)}$

Constraints on the DM-nucleon scattering cross-section



Part III

Sub-GeV DM and light mediators

Including DM-electron scatterings

The incoming DM flux gets attenuated by

1. Elastic nuclear scatterings.
2. Elastic DM-electron scatterings.
3. Inelastic DM-electron scatterings (ionizations/excitations).

detection process $\neq$ attenuation/stopping process

We need a model.

Including DM-electron scatterings

The Dark Photon Model

- Extend the SM by a DM particle and a U(1) gauge group with kinetic mixing.

$$\mathscr{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_\mu A'^\mu + \varepsilon F_{\mu\nu}F'^{\mu\nu}$$

- For kinetic mixing with the photon, the DM couples to electric charge.

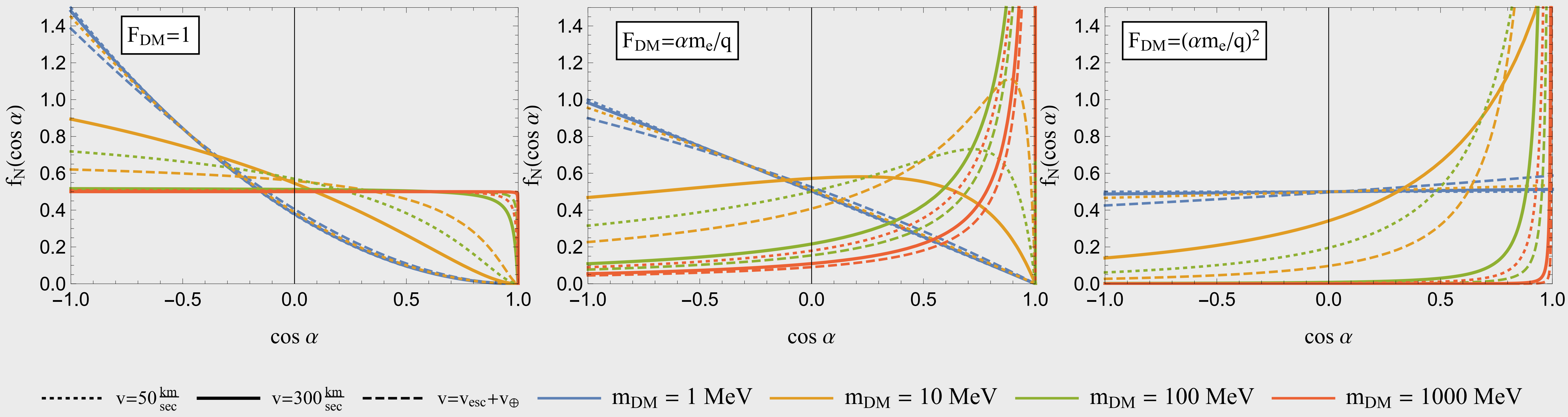
$$\frac{\mathrm{d}\sigma_N}{\mathrm{d}q^2} = \frac{\sigma_p}{4\mu^2_{\chi p}v^2_\chi}F_{\mathrm{DM}}(q)^2\, F_N(q)^2\, Z^2$$

- Hierarchy between the DM-proton and DM-electron cross section:

$$\frac{\sigma_p}{\sigma_e} = \left(\frac{\mu_{\chi p}}{\mu_{\chi e}}\right)^2$$

S.K. Lee et al, PRD92 (2015) 083517

New scattering kinematics



DM form factor **VS** Charge screening

$$F_{DM}(q) = \begin{cases} 1\,, & \textbf{for heavy mediator}\,, \\ \frac{q_{ref}}{q}\,, & \textbf{for ED interactions}\,, \\ \left(\frac{q_{ref}}{q}\right)^2\,, & \textbf{for light mediator}\,. \end{cases}$$

$$F_A(q) = \frac{a^2q^2}{1+a^2q^2}$$

Rare event simulation II

Geometric Importance Splitting

- "More interesting" particles get split into copies.
- Requires the definition of an importance function,

$$I : \mathbb{R}^3 \rightarrow \mathbb{R}$$

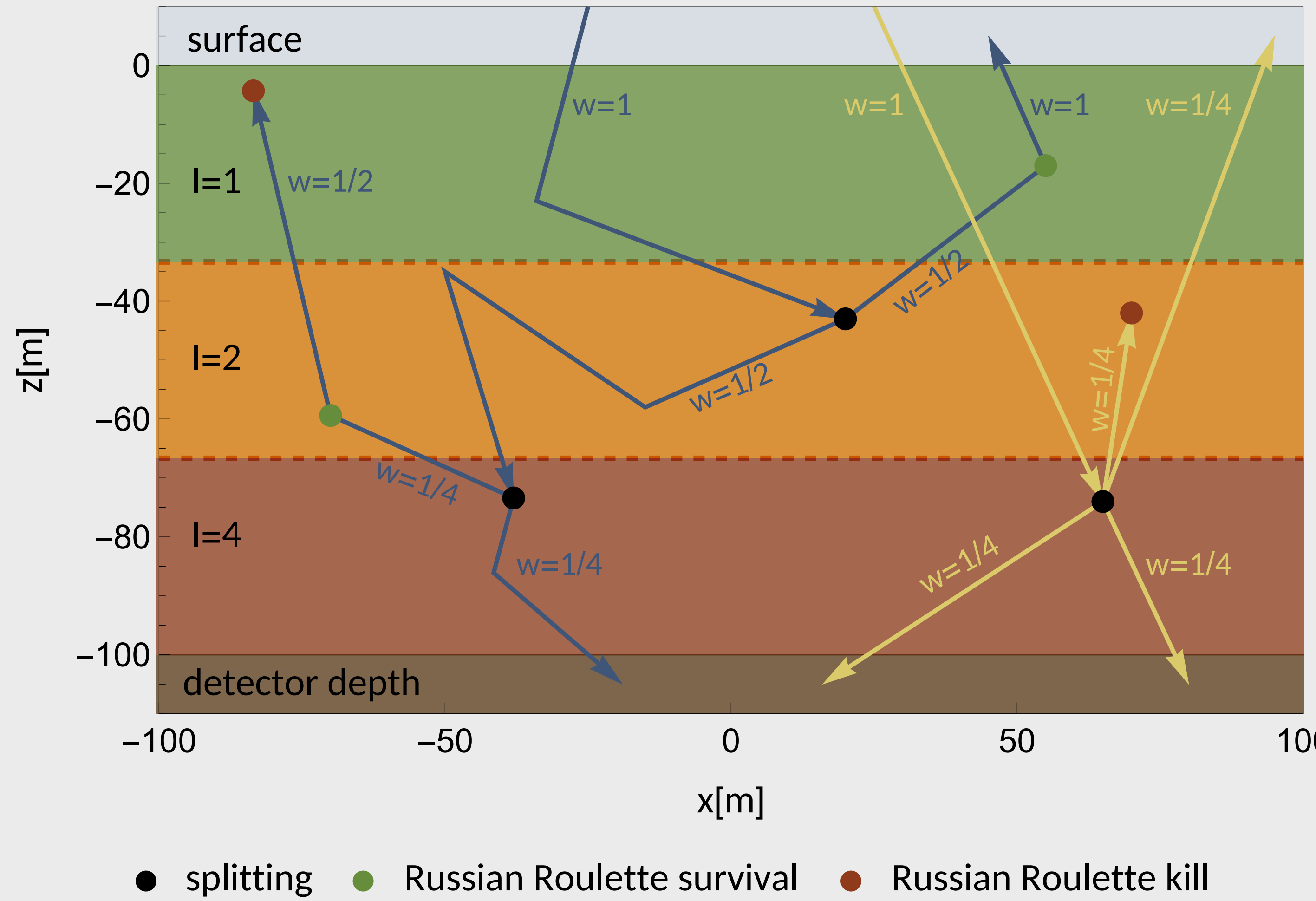
- If the importance increases,

$$\nu \equiv \frac{I_{i+1}}{I_i} > 1$$

- the particle gets split into

$$n = \begin{cases} \nu\,, & \text{if } \nu \in \mathbb{N}\,, \\ \lfloor \nu \rfloor\,, & \text{if } \nu \notin \mathbb{N} \wedge \xi \geq \Delta\,, \\ \lfloor \nu \rfloor + 1\,, & \text{if } \nu \notin \mathbb{N} \wedge \xi < \Delta\,, \end{cases}$$

copies.

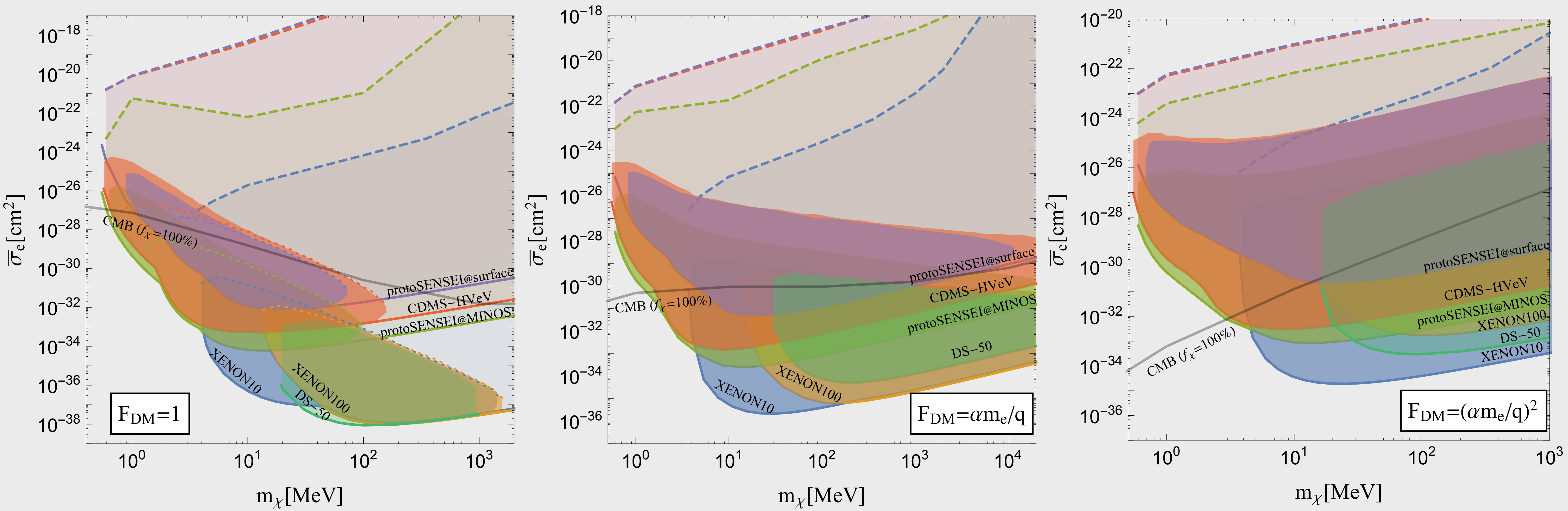


New statistical weight

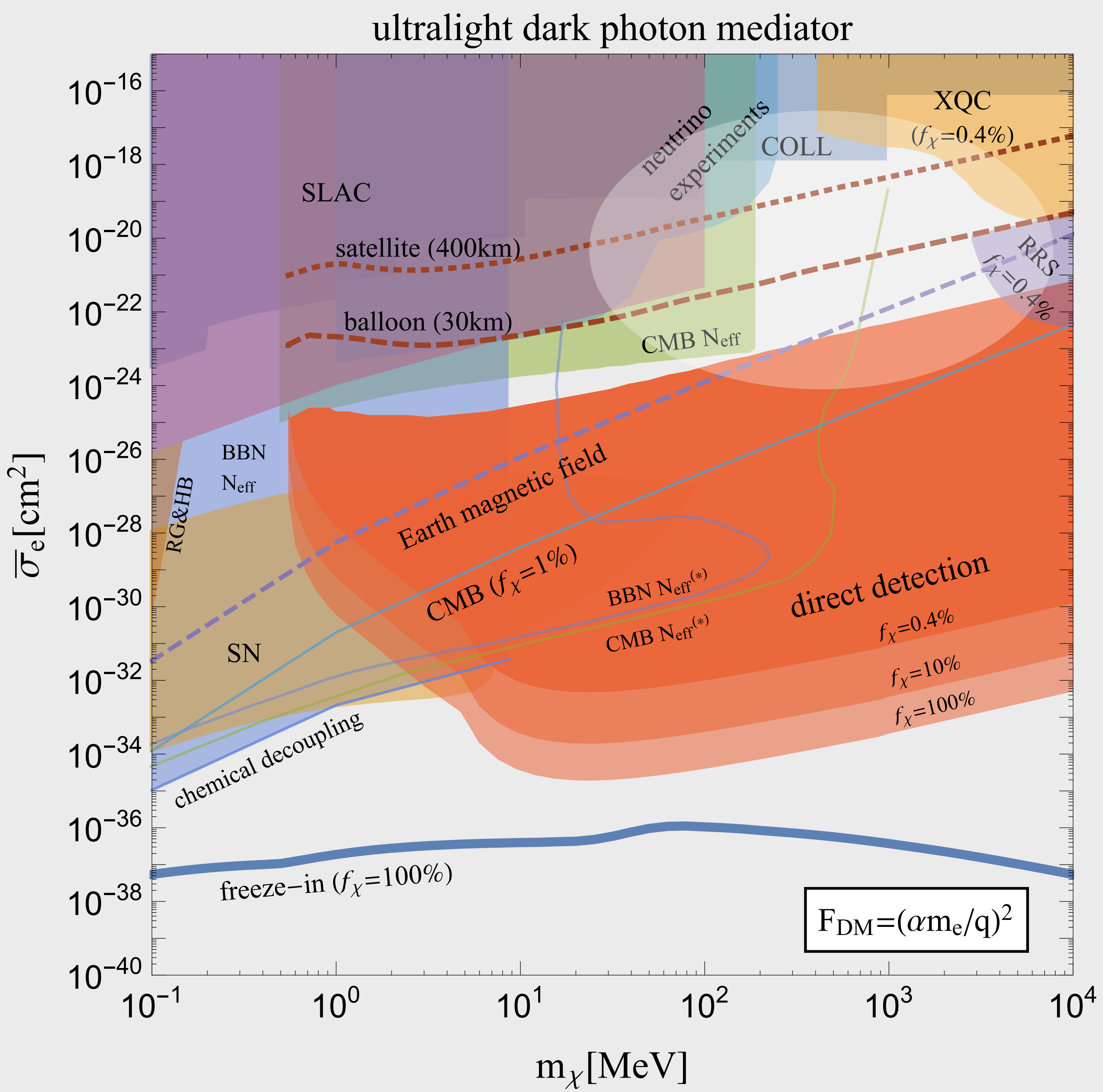
$$w_{i+1} \equiv \frac{w_i}{n}$$

- Otherwise: Russian Roulette

DM-Electron Scattering constraints



Constraints on a sub-dominant component of strongly interacting DM



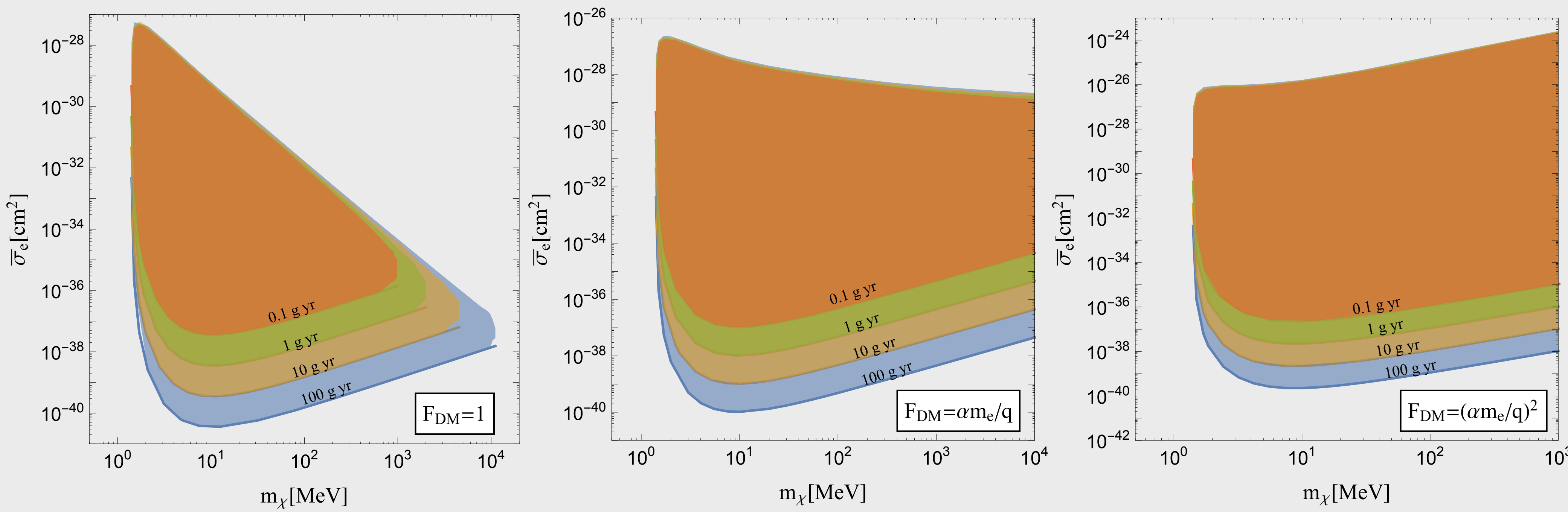
- So is there an open window in parameters space?
- Probably not for milli-charged DM.
- Definitely not for

$$f_\chi = 100\,\%$$

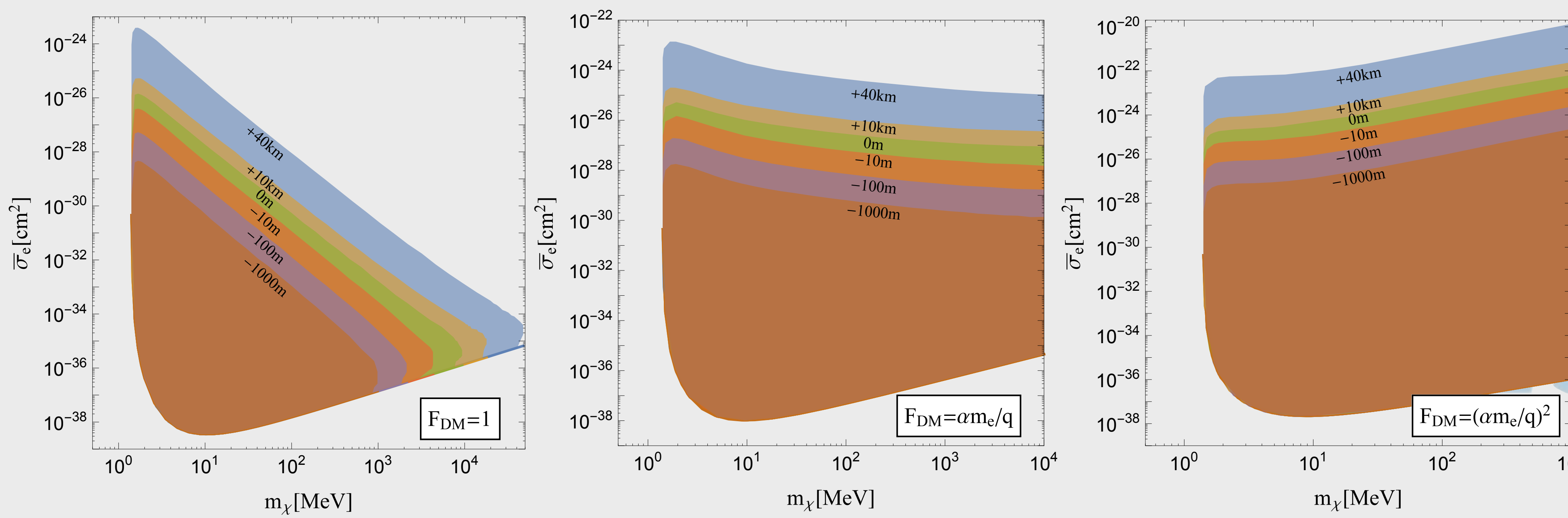
- Yes, under certain conditions:
  - Sub-dominant component.
    $$f_\chi < 0.4\,\%$$
  - Ultralight, but not massless mediator.
  - Small dark gauge coupling.

How to push towards stronger interactions

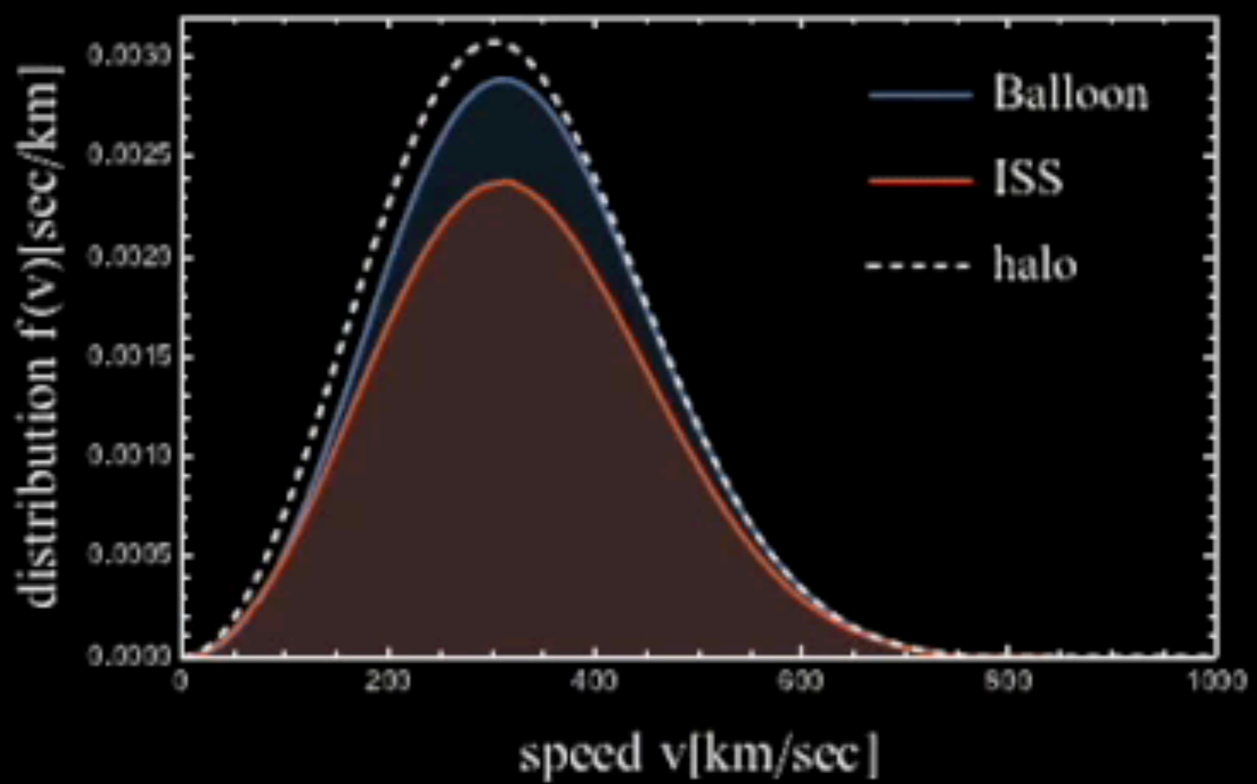
- **Higher Exposures**

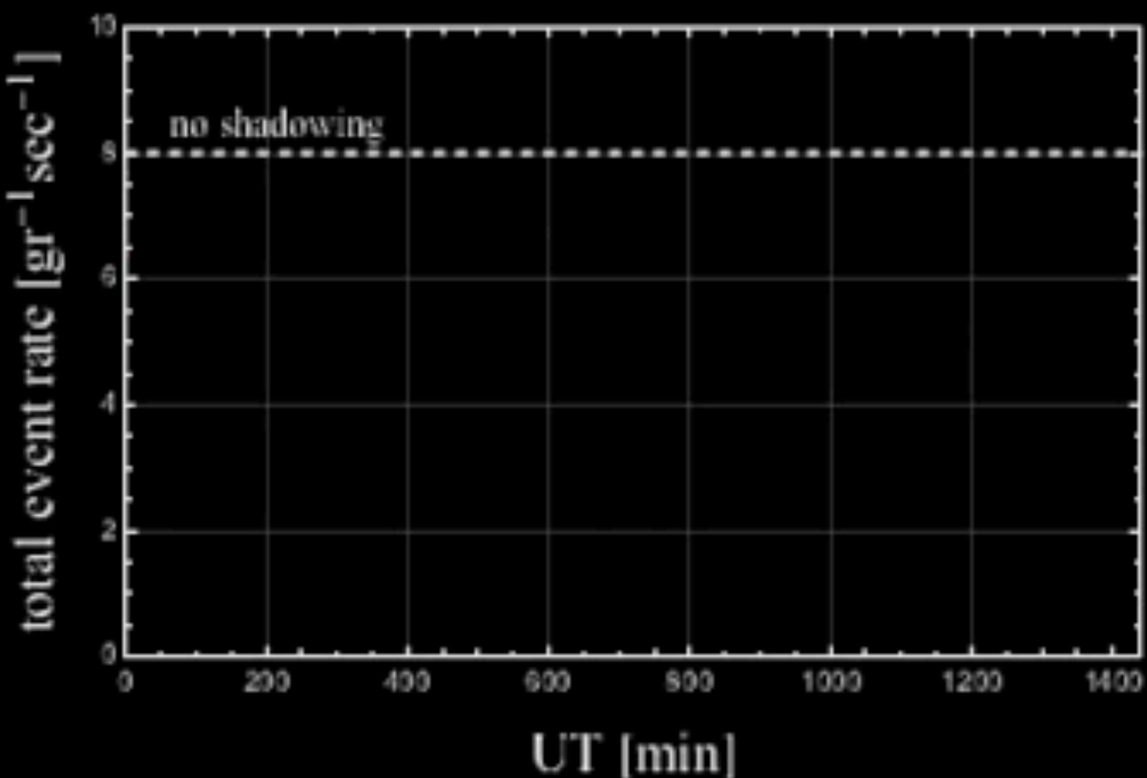


- **Shallower Laboratories**

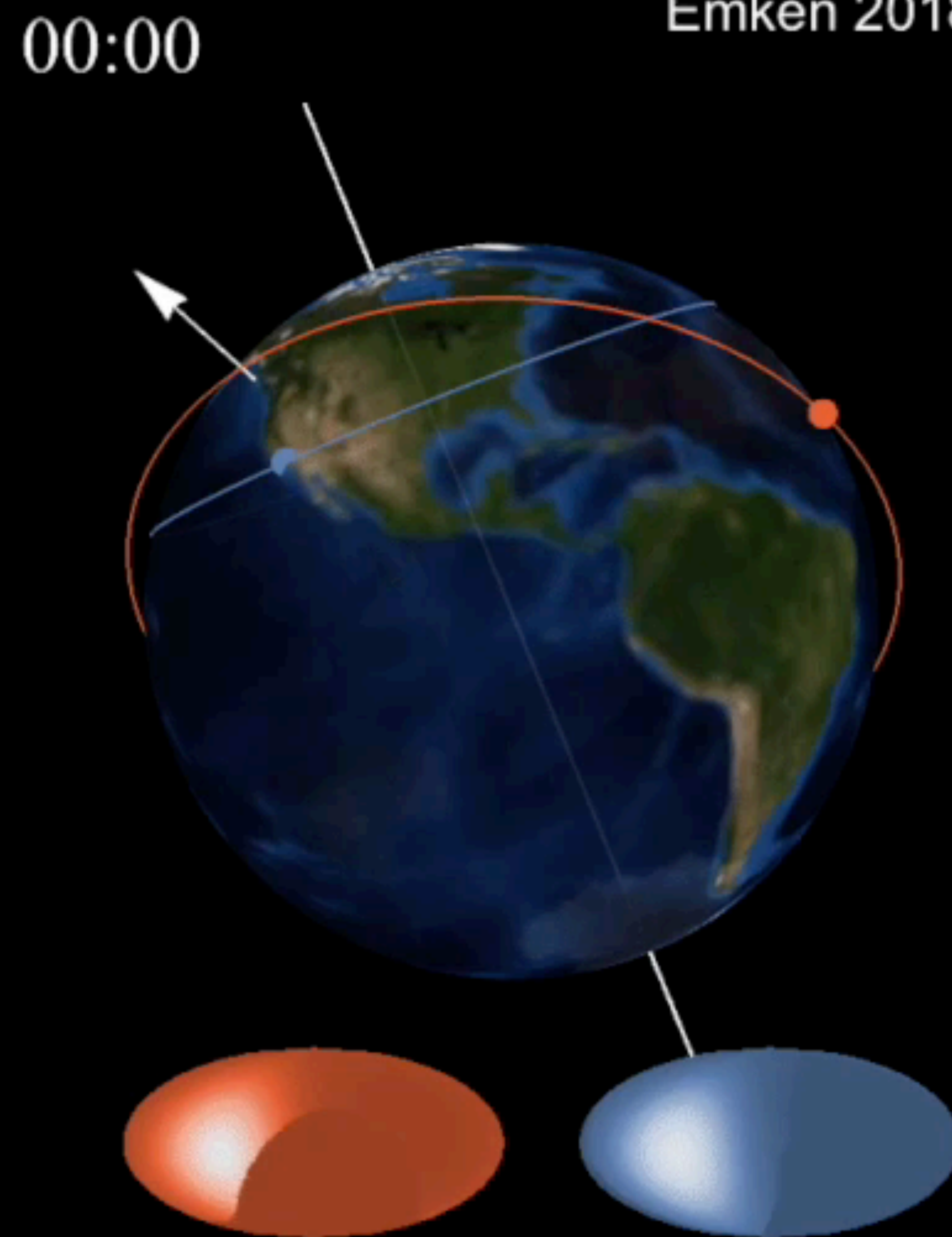


Balloon/satellite experiments

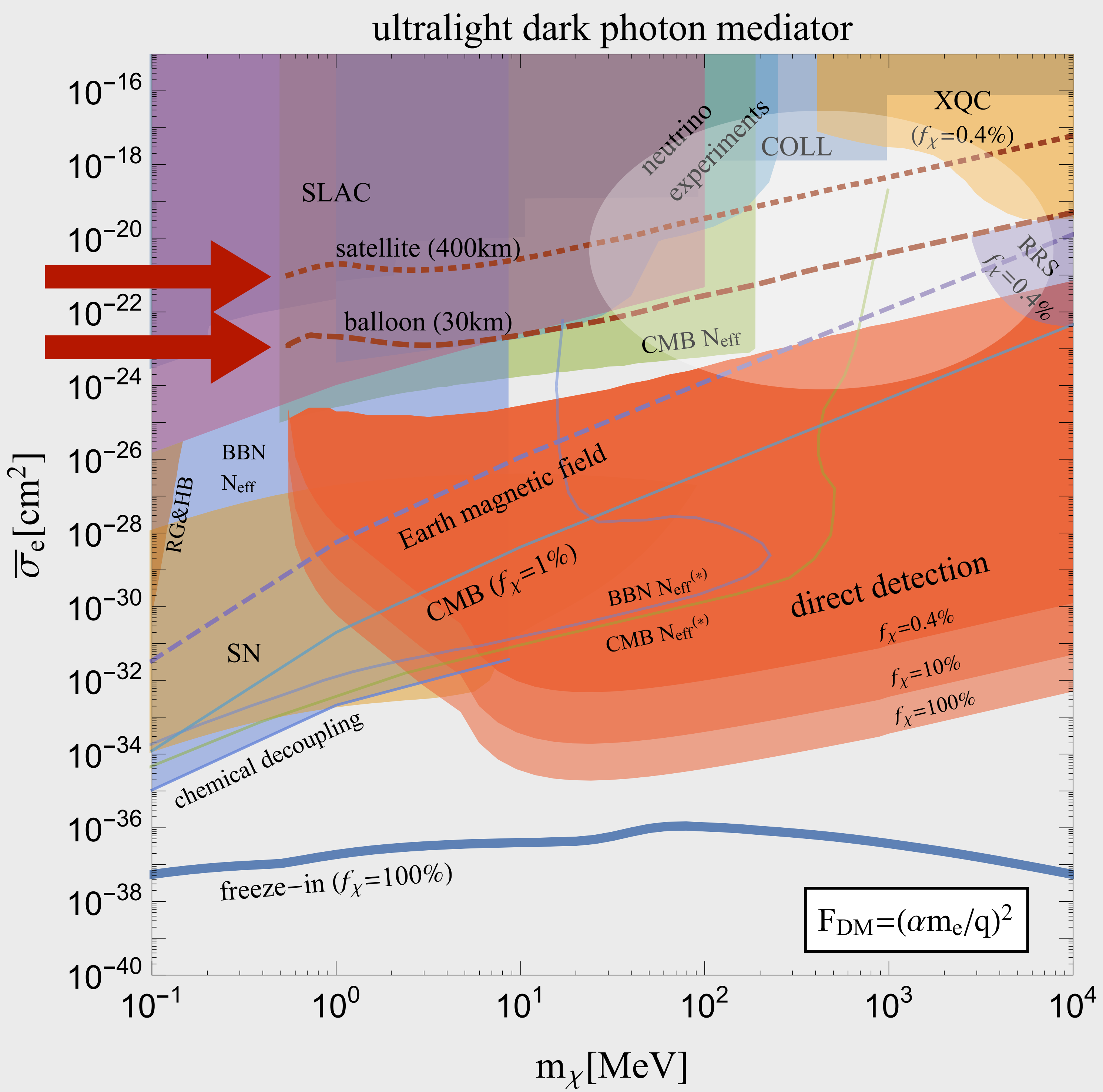




Emken 2018



Constraints on a sub-dominant component of strongly interacting DM



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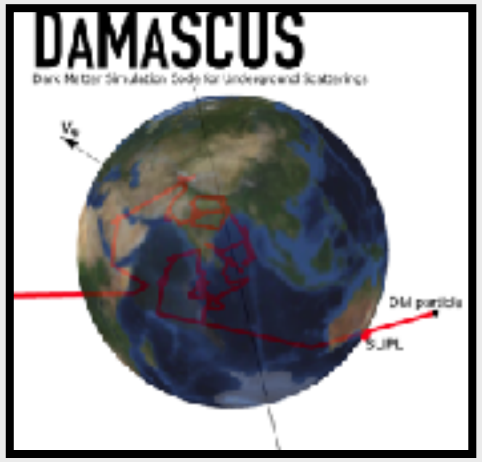
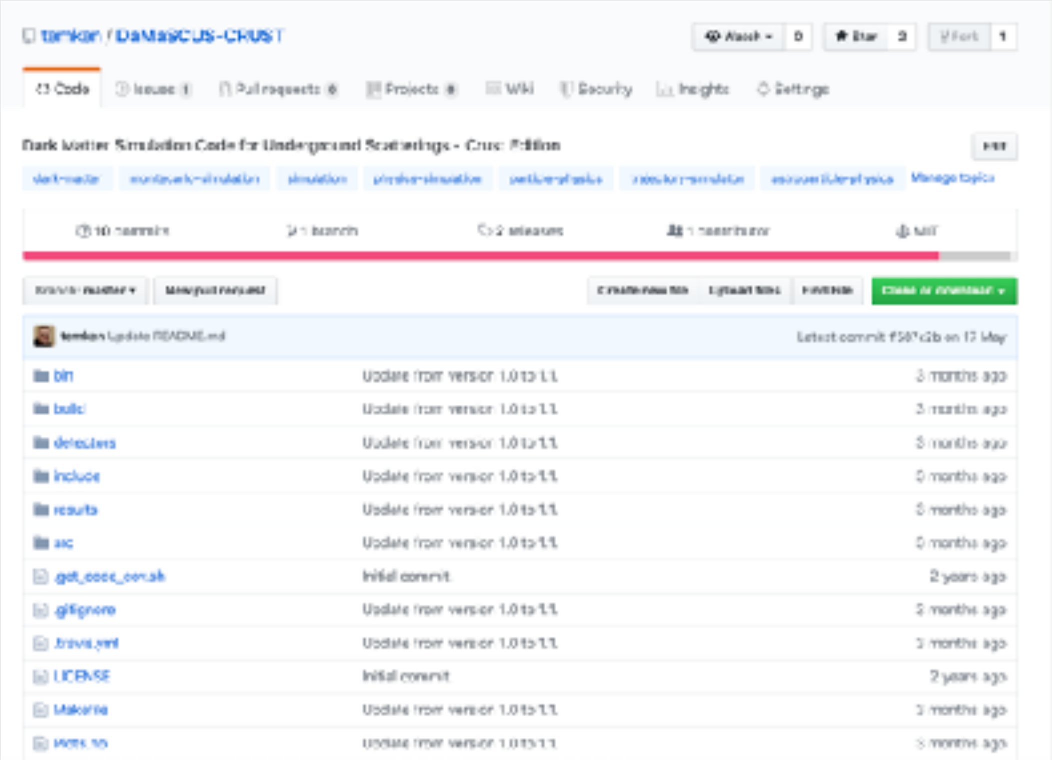


The DaMaSCUS code

Dark Matter Simulation Code for Underground Scatterings

- Written in C++.
- Fully parallelized with *MPI*.
- Results were generated on the ABACUS2.0 supercomputer.
- The code is public.



http://github.com/temken/

Thank you!

Backup Slides

Kernel Density Estimation (KDE)

A non-parametric method to estimate an unknown PDF based on data.

For a data set $\{x_1, x_2, \ldots, x_N\}$ we can estimate the PDF via

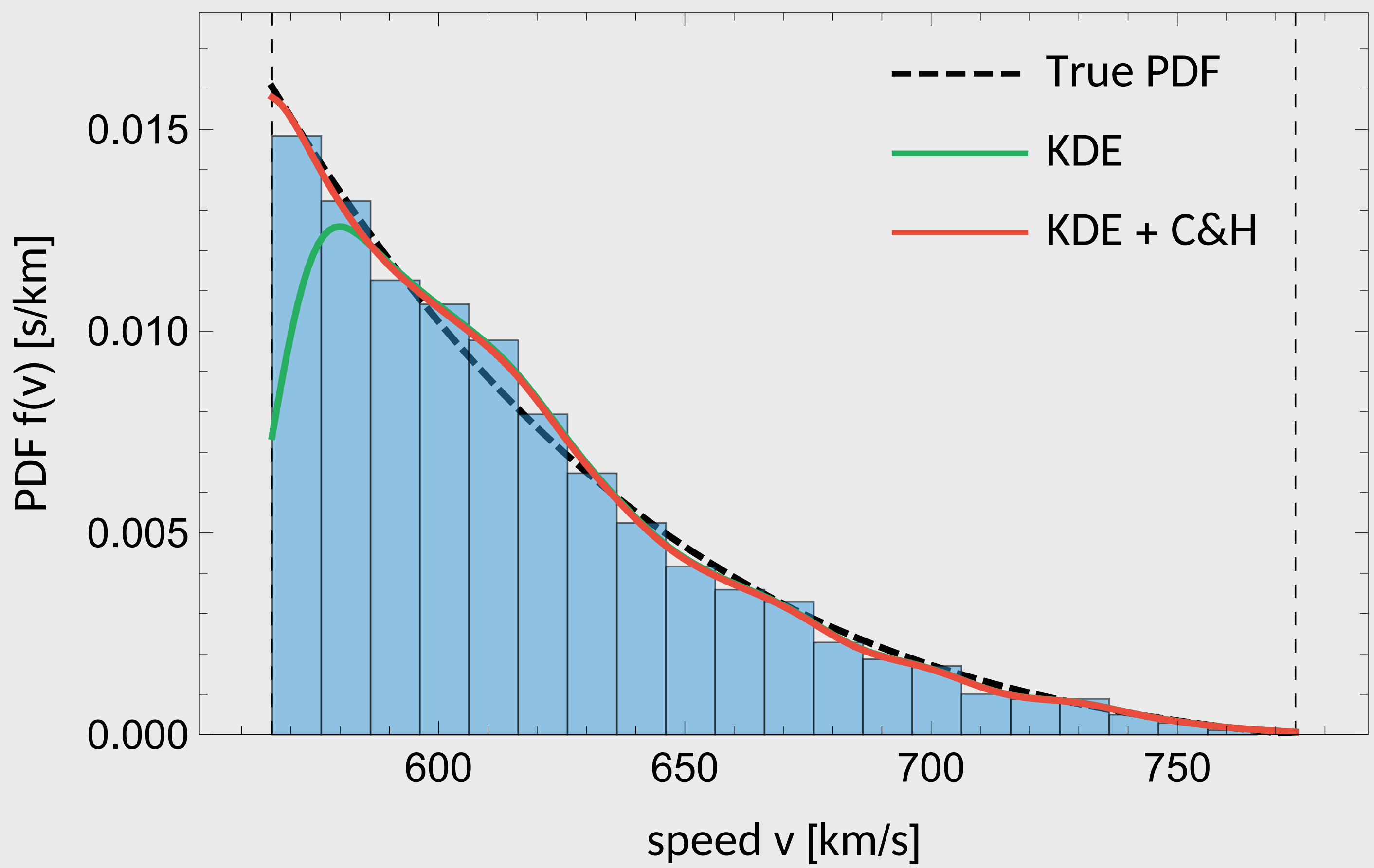
$$\hat{f}_h(x) = \frac{1}{h}\sum_{i=1}^{N} K\left(\frac{x - x_i}{h}\right) .$$

E.g. with a Gaussian Kernel,

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-x^2}{2}\right) .$$

We set the bandwidth h using Silverman's rule of thumb,

$$h = \left(\frac{4}{3N}\right)^{1/5} \hat{\sigma} .$$



The bias at the domain's boundary has to be compensated, e.g. by a pseudo-data method by Cowling and Hall

ESI

R. Karunamuni, T. Alberts, Statistical Methodology 2 (2005), 191
A. Cowling, P. Hall, Journal of the Royal Statistical Society, B58 (1996), 551