Direct detection of low-mass dark matter with strong matter interactions

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

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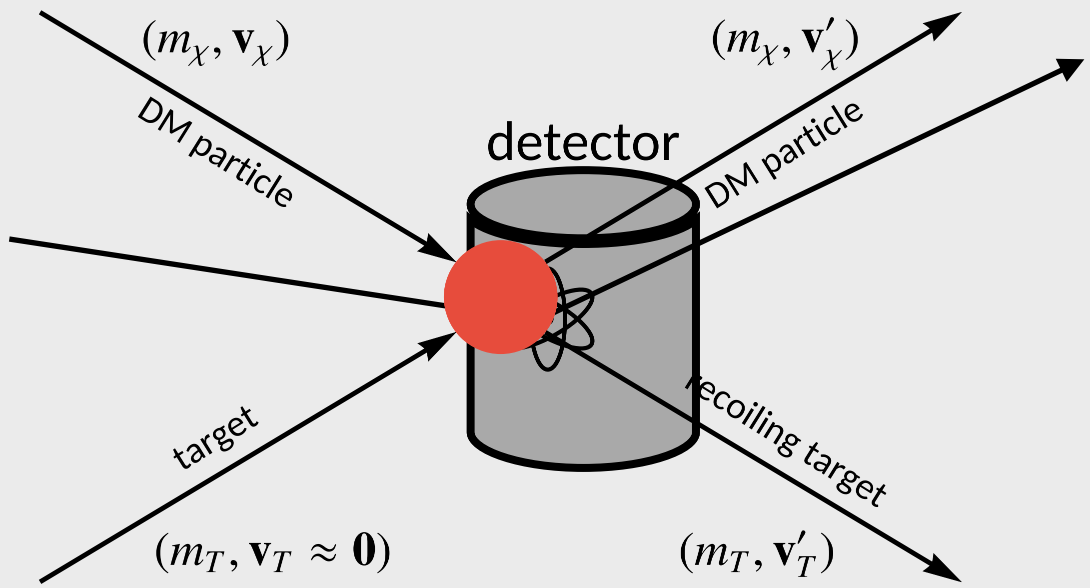
Direct Detection of Dark Matter

Basic idea: Look for the aftermath of a DM-atom collision in a detector.



Nuclear recoils as observable for GeV-scale DM searches.

M.W. Goodman and E. Witten, Phys.Rev. D31 (1985) 3059
I. Wasserman, Phys. Rev. D33 (1986) 2071
A.K. Drukier et al., Phys. Rev. D33 (1986) 3495

Event spectrum:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \frac{\rho_\chi}{m_\chi} \iiint \mathrm{d}^3\mathbf{v}\; v f_\chi(\mathbf{v}) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R} \Theta(v - v_{\min}(E_R))\,.$$

Detector size — Particle physics

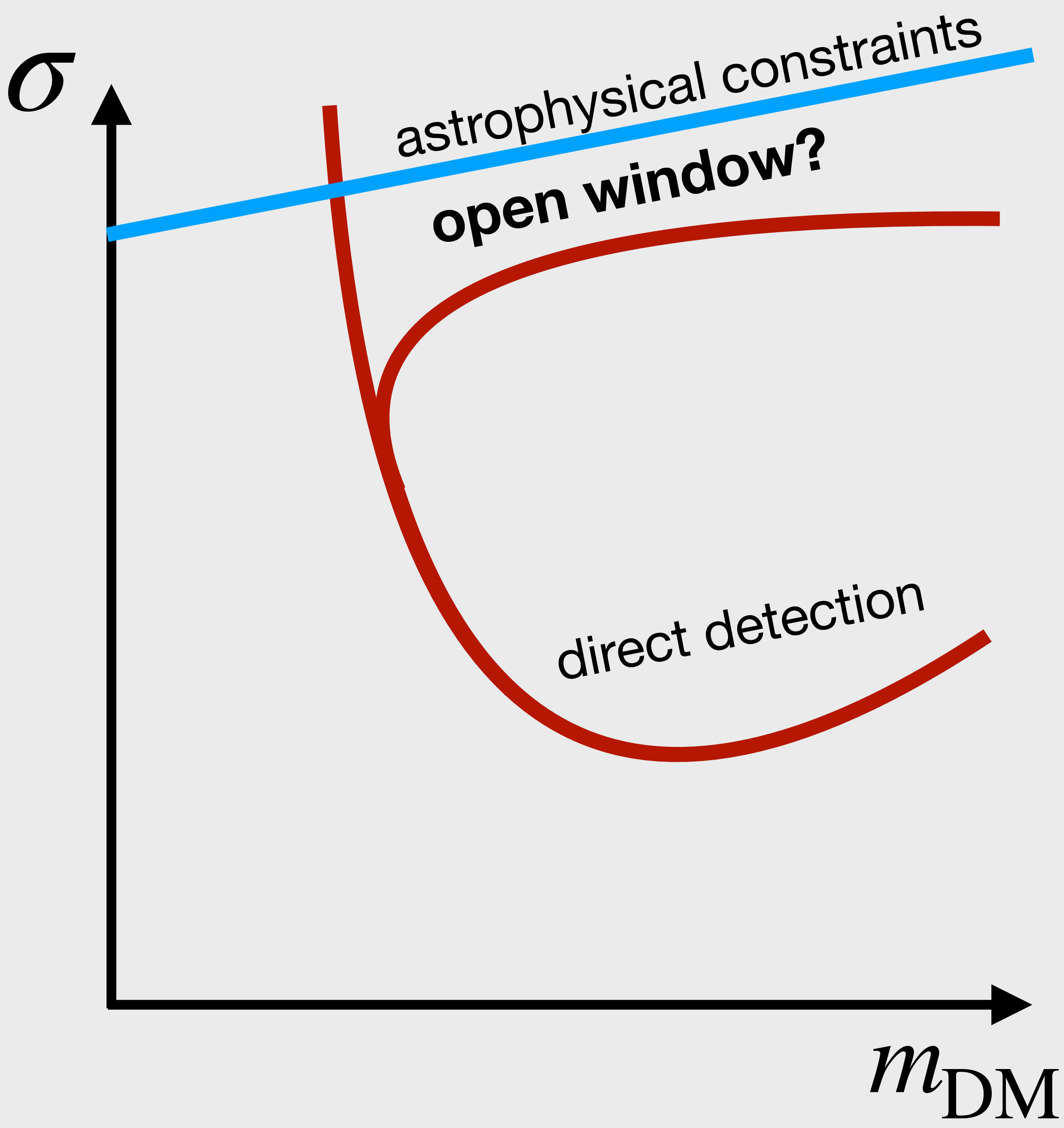
Astrophysics — Kinematics

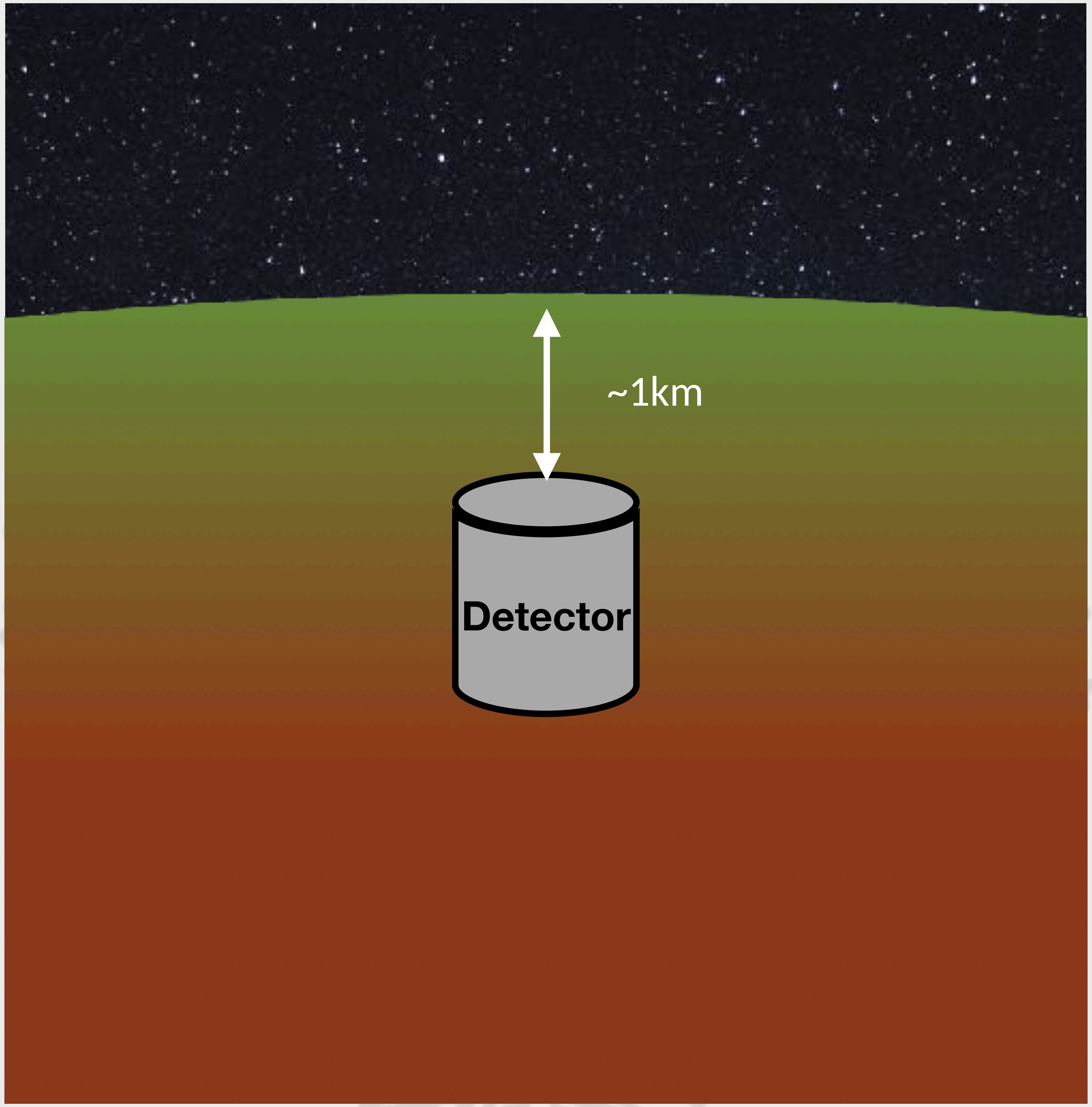
For sub-GeV DM, one can also look for DM-electron interactions.

R. Essig et al., Phys. Rev. D85 (2012) 076007

Direct detection of strongly interacting DM

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



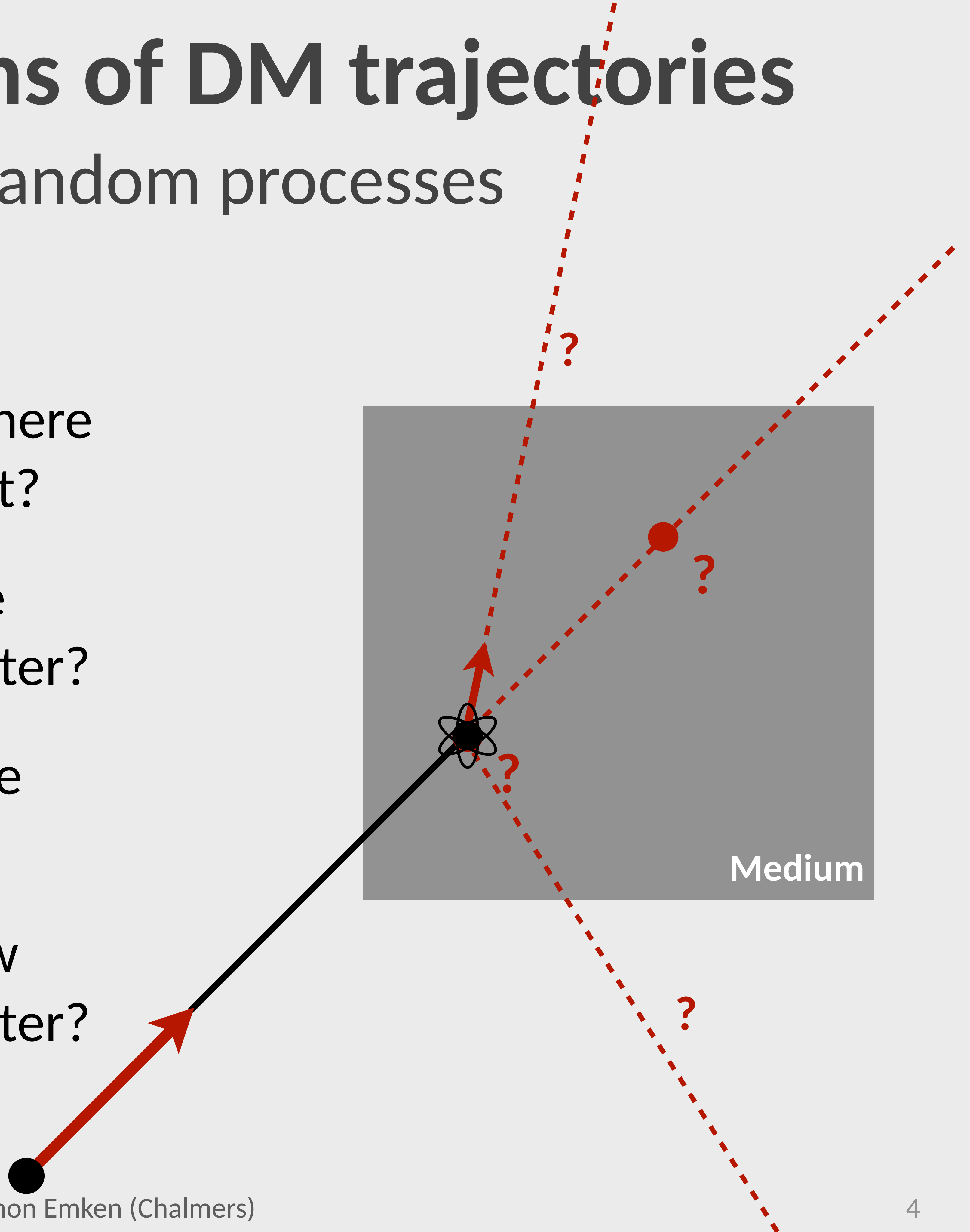


MC simulations of DM trajectories

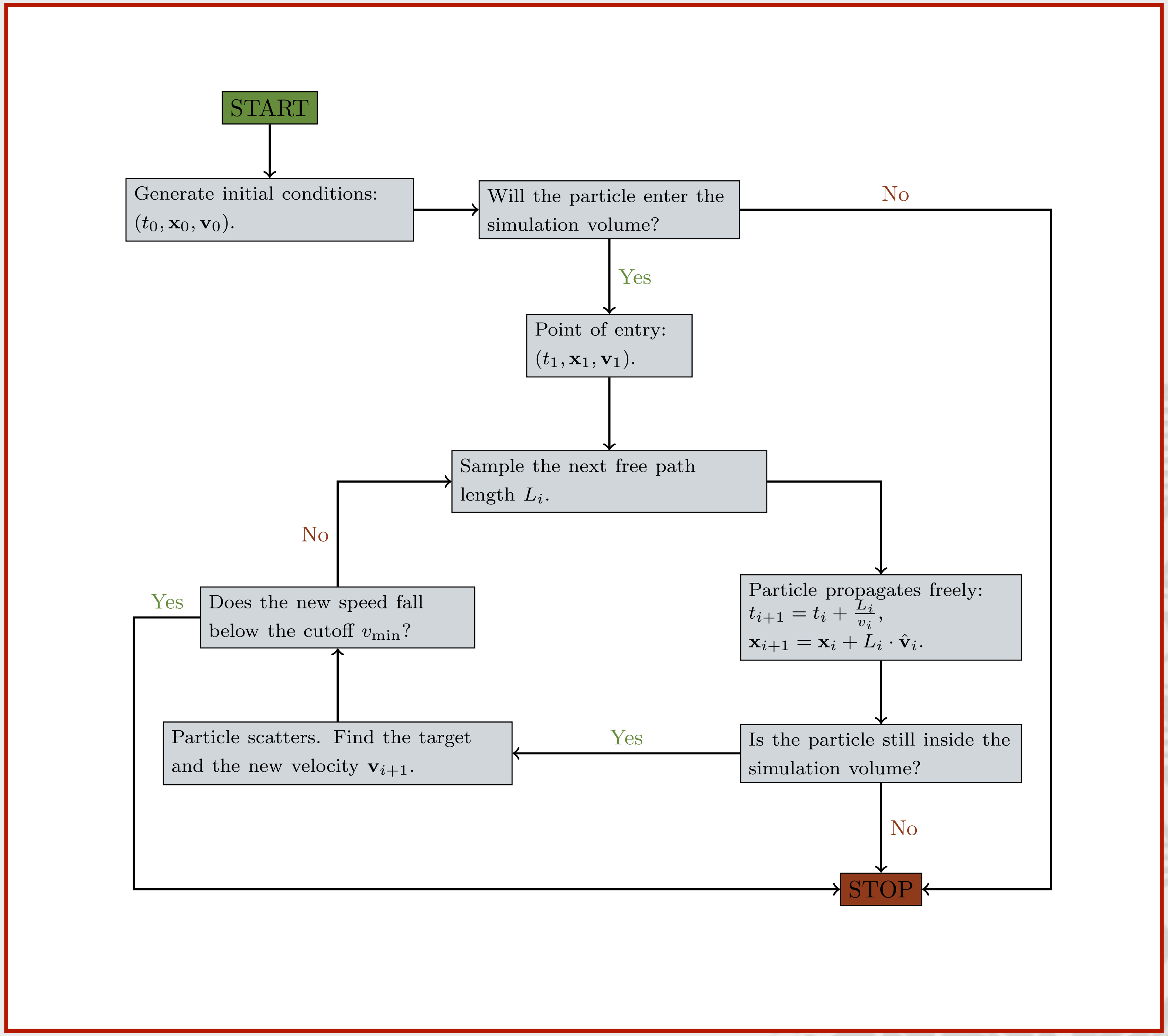
The fundamental random processes

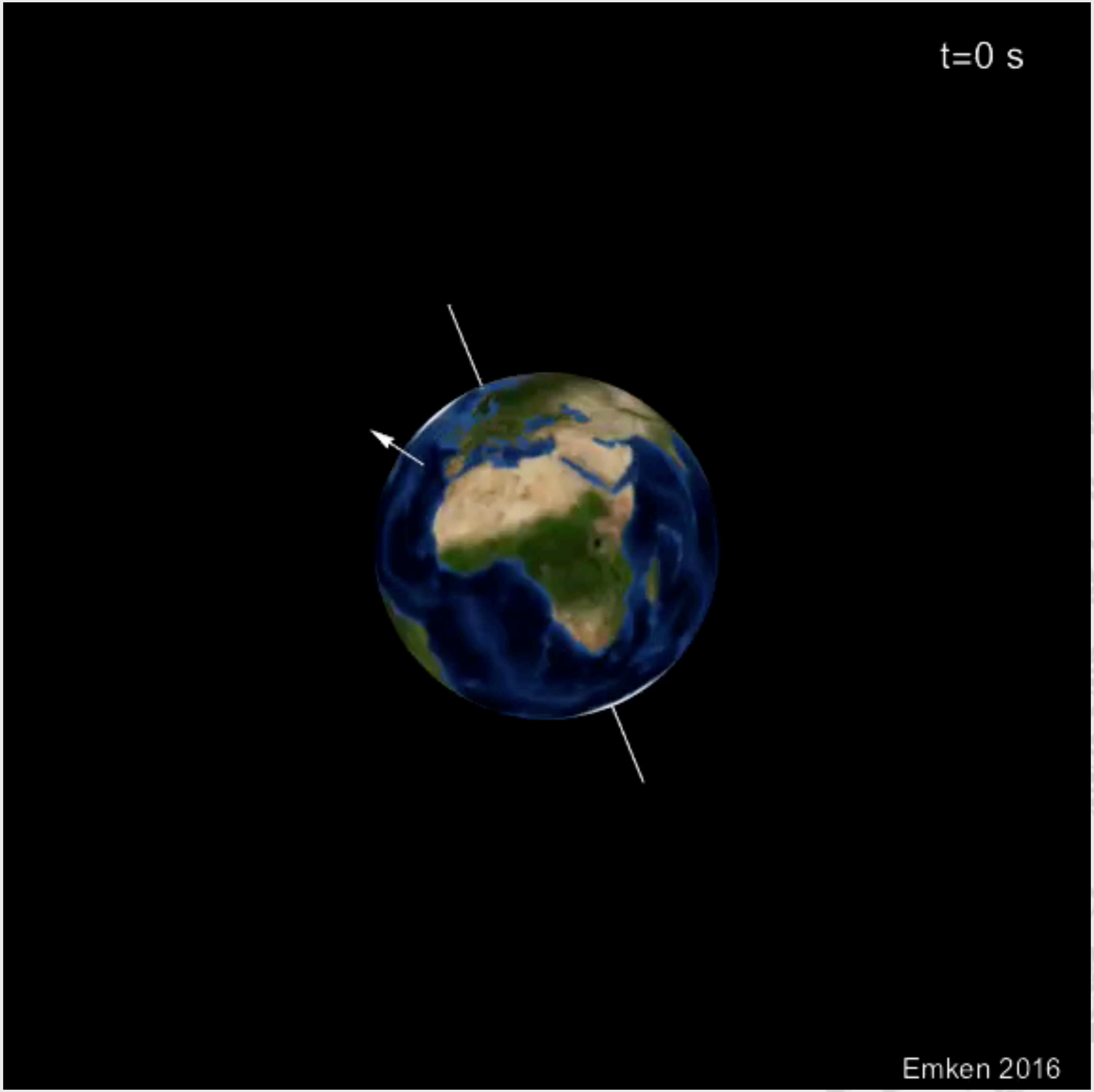
1. **Initial Conditions**: Where does the particle start?
2. **Free distance**: Where does the particle scatter?
3. **Target**: What does the particle scatter on?
4. **Scattering angle**: How does the particle scatter?

Repeat steps 2.-4.



MC simulation algorithm

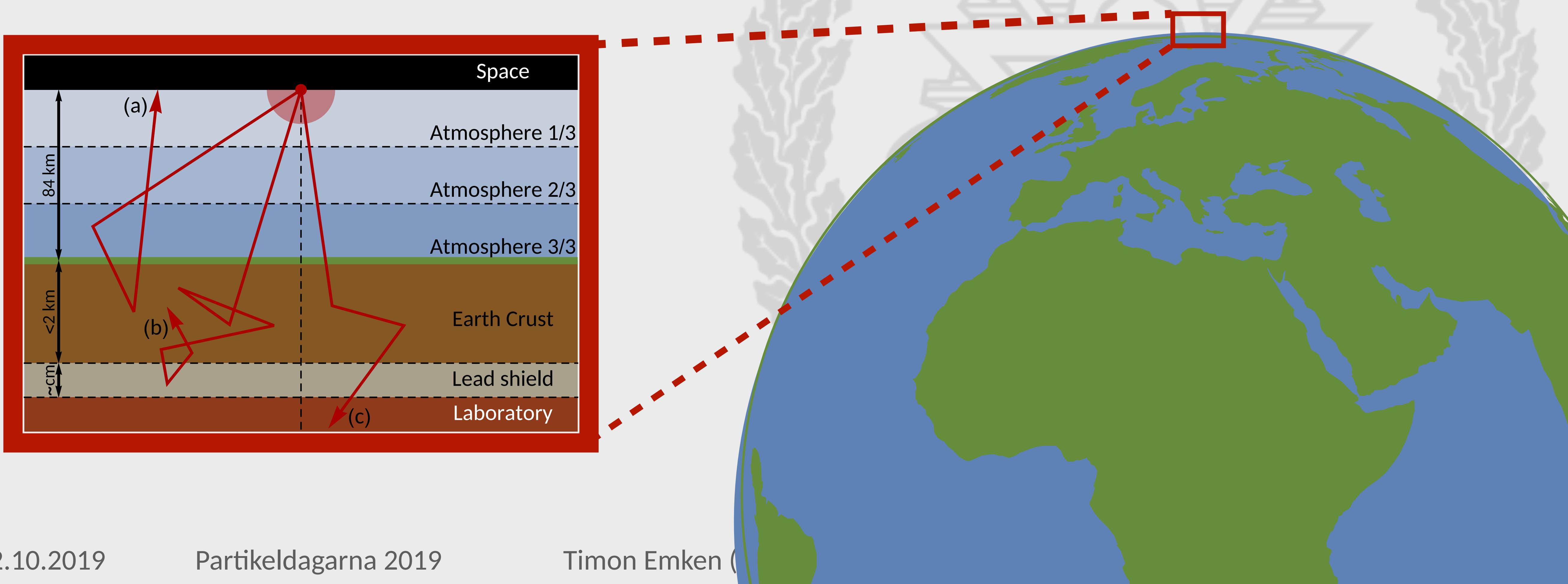



t=0 s
Emken 2016

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.



Shielding vs. Detection

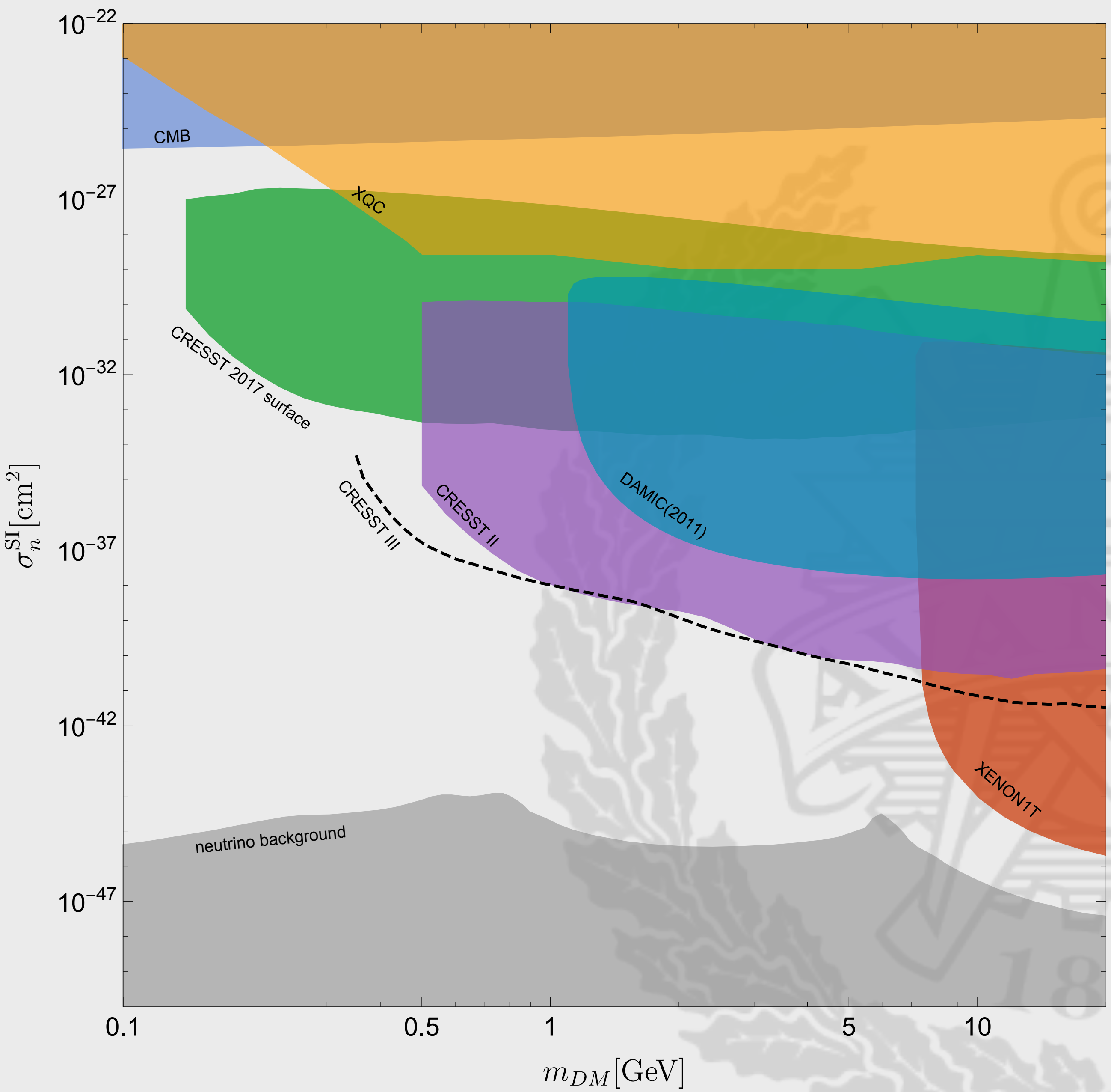
increase cross-section

increases shielding

decreases event rate

increases event rate

Constraints on the DM-nucleon scattering cross-section



Including DM-electron scatterings

The incoming DM flux gets attenuated by

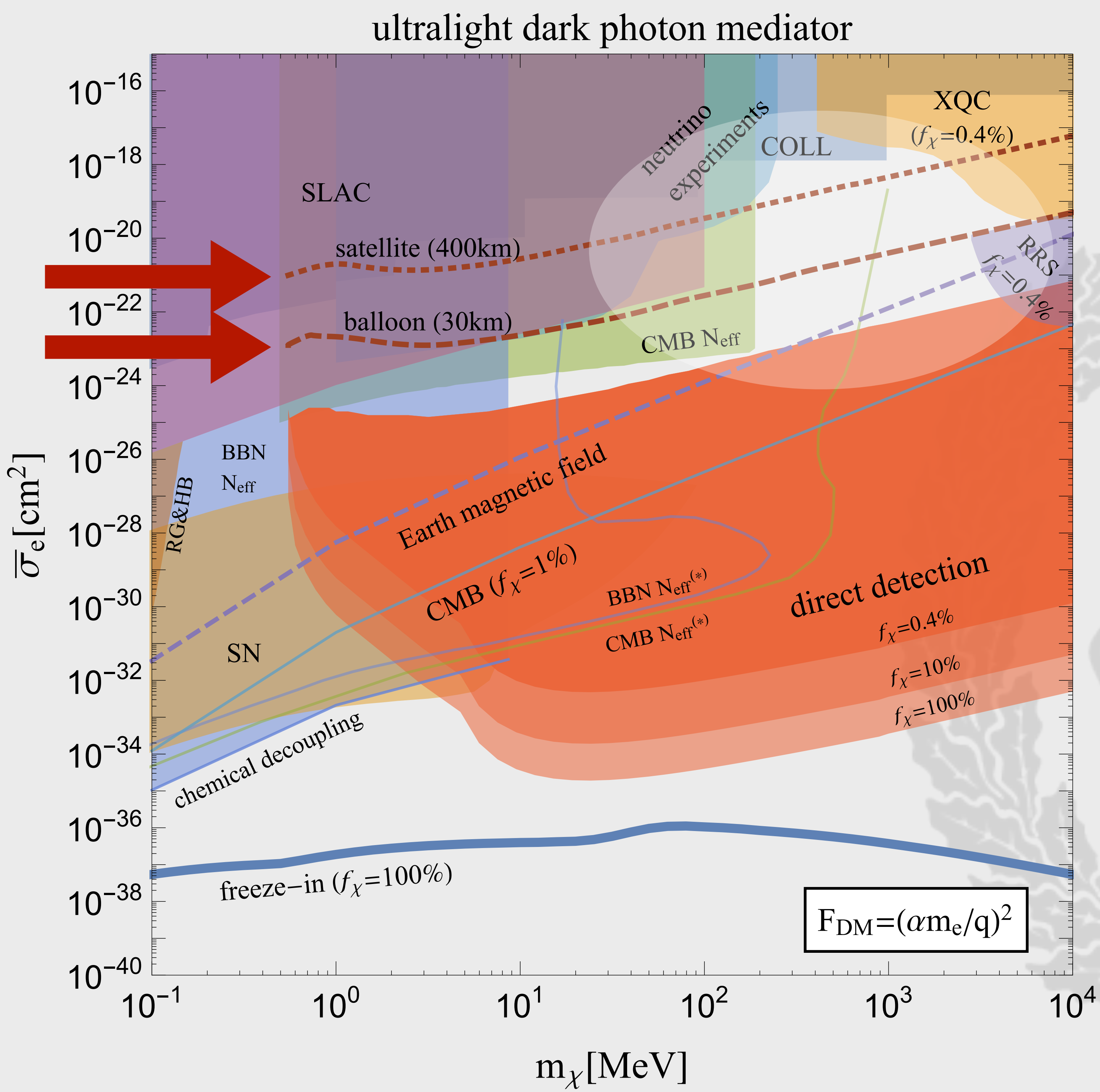
1. Elastic nuclear scatterings.
2. Elastic DM-electron scatterings.
3. Inelastic DM-electron scatterings (ionizations/excitations).

detection process $\neq$ attenuation/stopping process

↓

We need a model.

Constraints on a sub-dominant component of strongly interacting DM

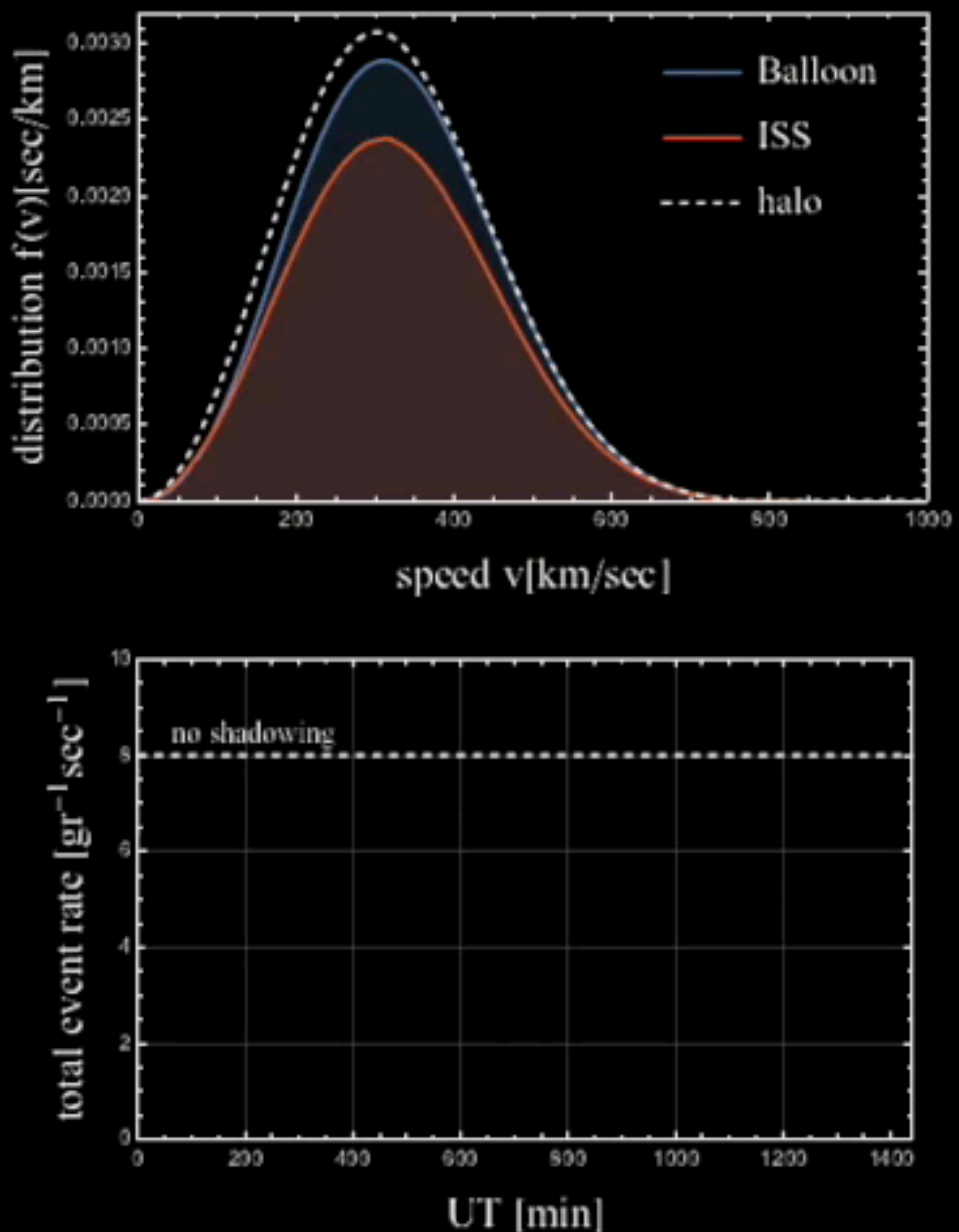


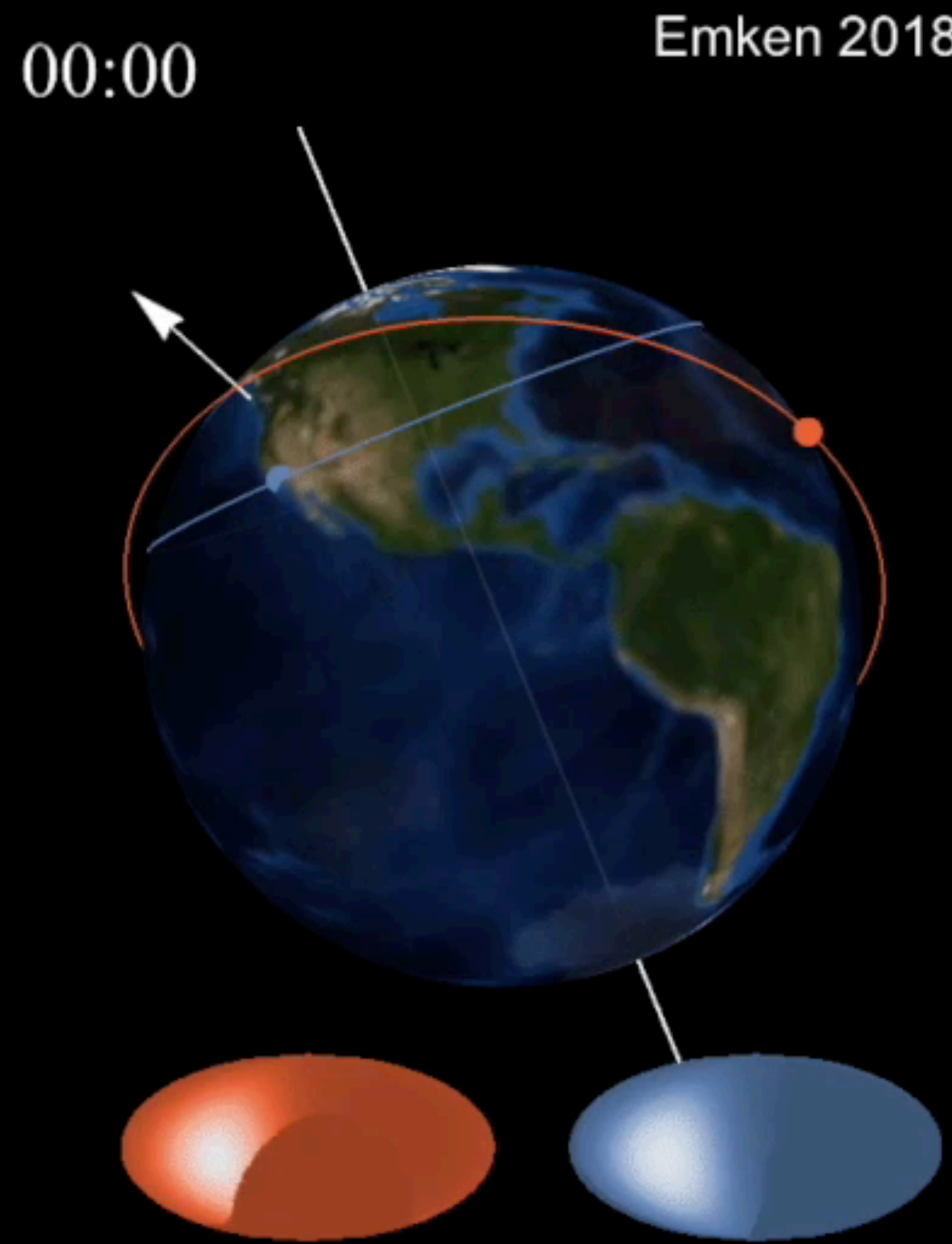
- So is there an open window in parameters space?
- Probably not for milli-charged DM.
- Definitely not for

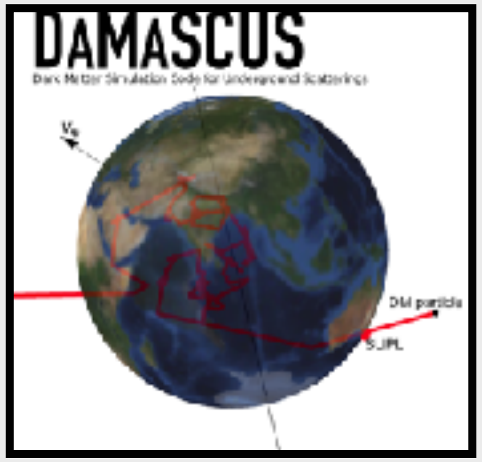
$$f_\chi = 100\,\%$$

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

Balloon/satellite experiments



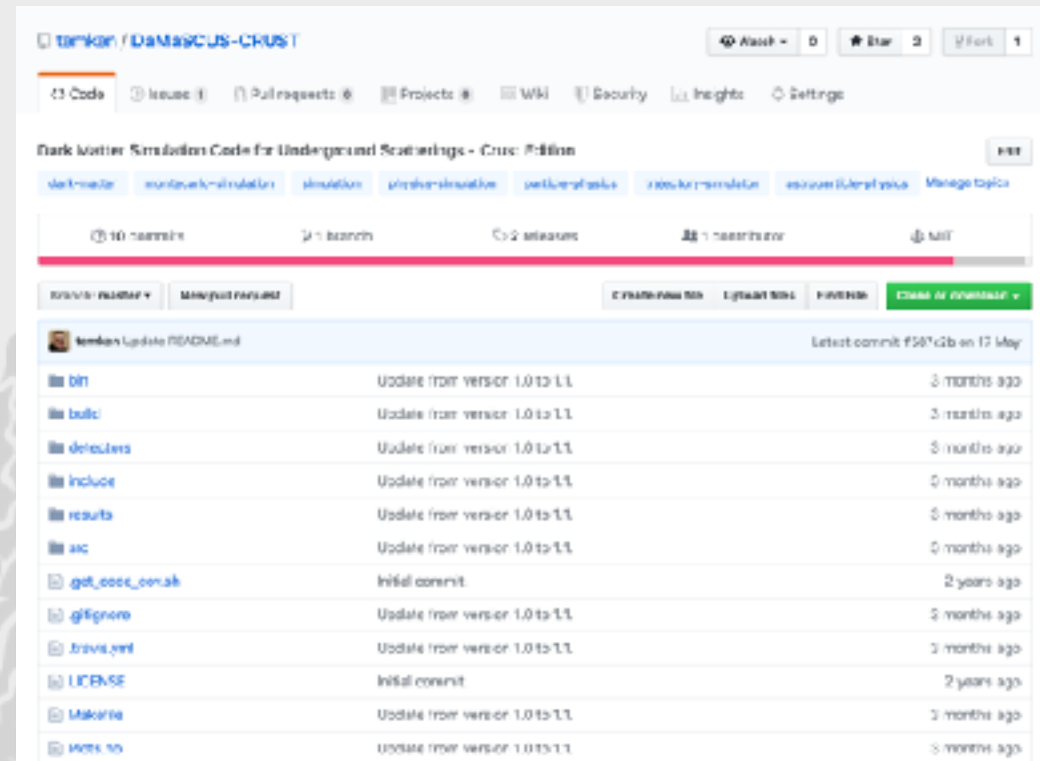




The DaMaSCUS code

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

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

Rare event simulation II

Geometric Importance Splitting

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

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

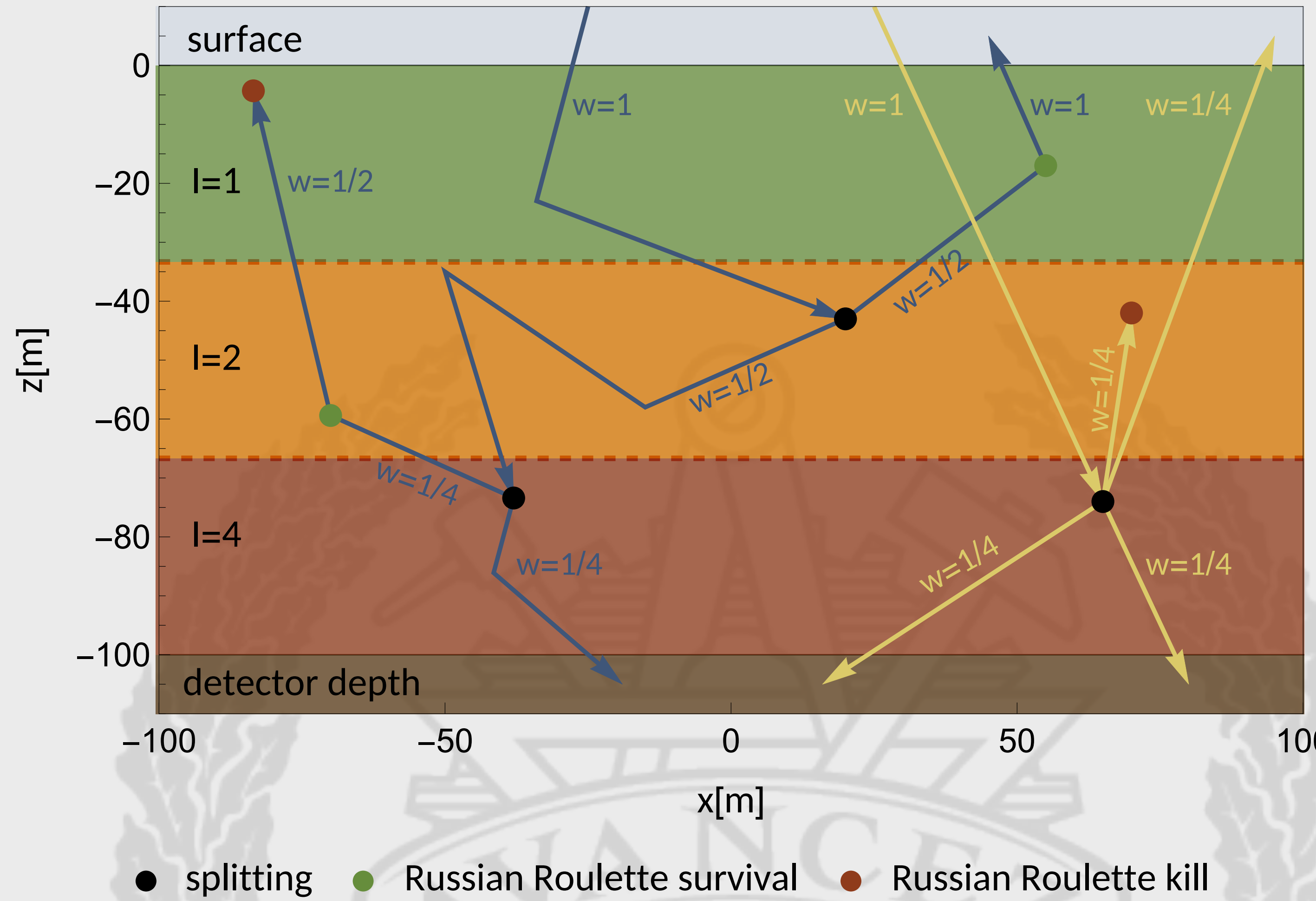
- If the importance increases,

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

- the particle gets split into

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

copies.



New statistical weight

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

- Otherwise: Russian Roulette

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.

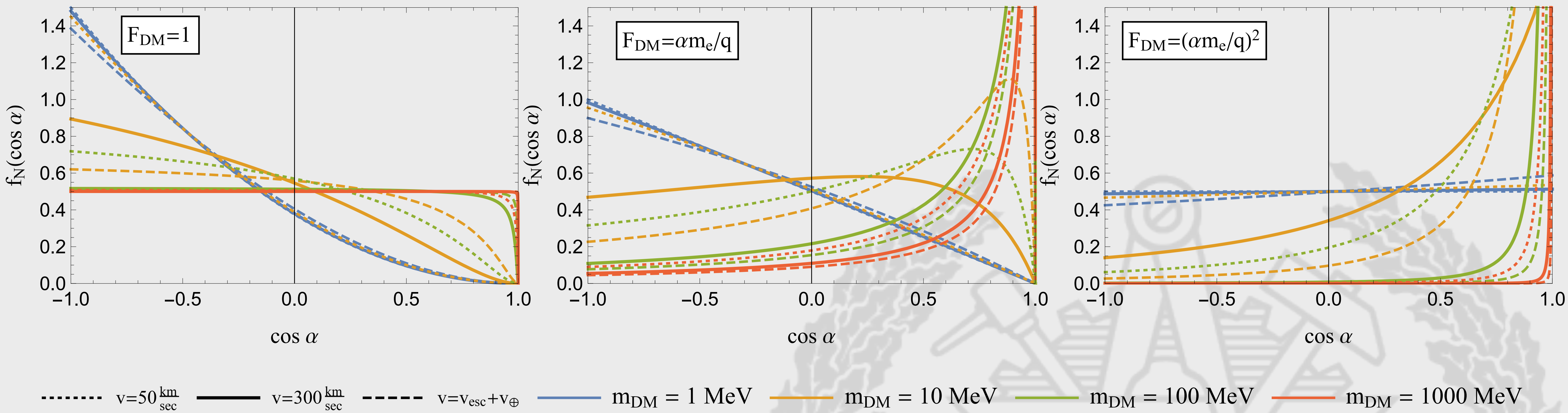
$$\frac{\mathrm{d}\sigma_N}{\mathrm{d}q^2} = \frac{\sigma_p}{4\mu^2_{\chi p}v^2_\chi}F_{\mathrm{DM}}(q)^2\, F_N(q)^2\, Z^2$$

- 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

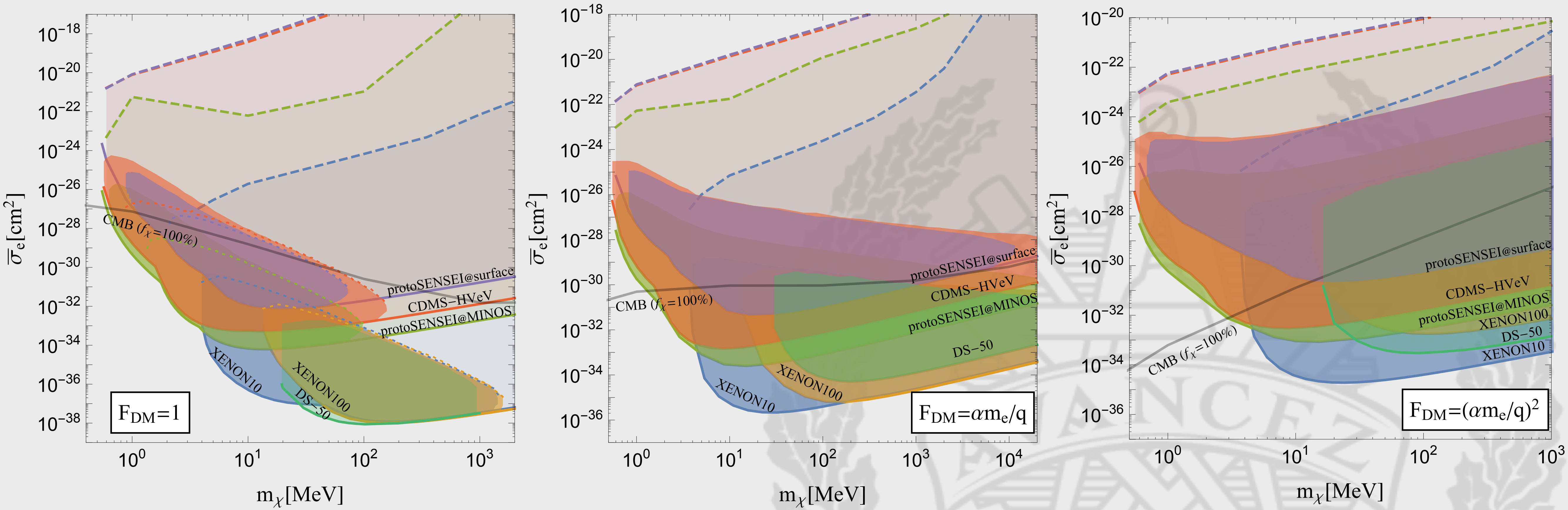


DM form factor **vs** Charge screening

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

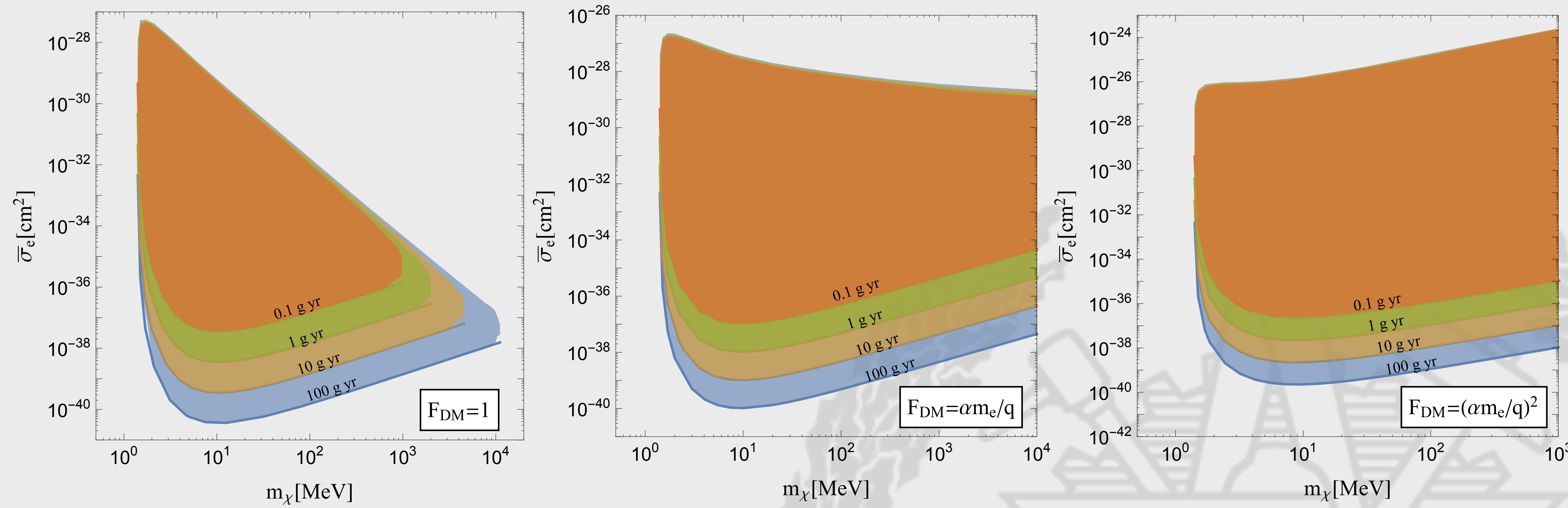
$$F_A(q) = \frac{a^2 q^2}{1 + a^2 q^2}$$

DM-Electron Scattering constraints

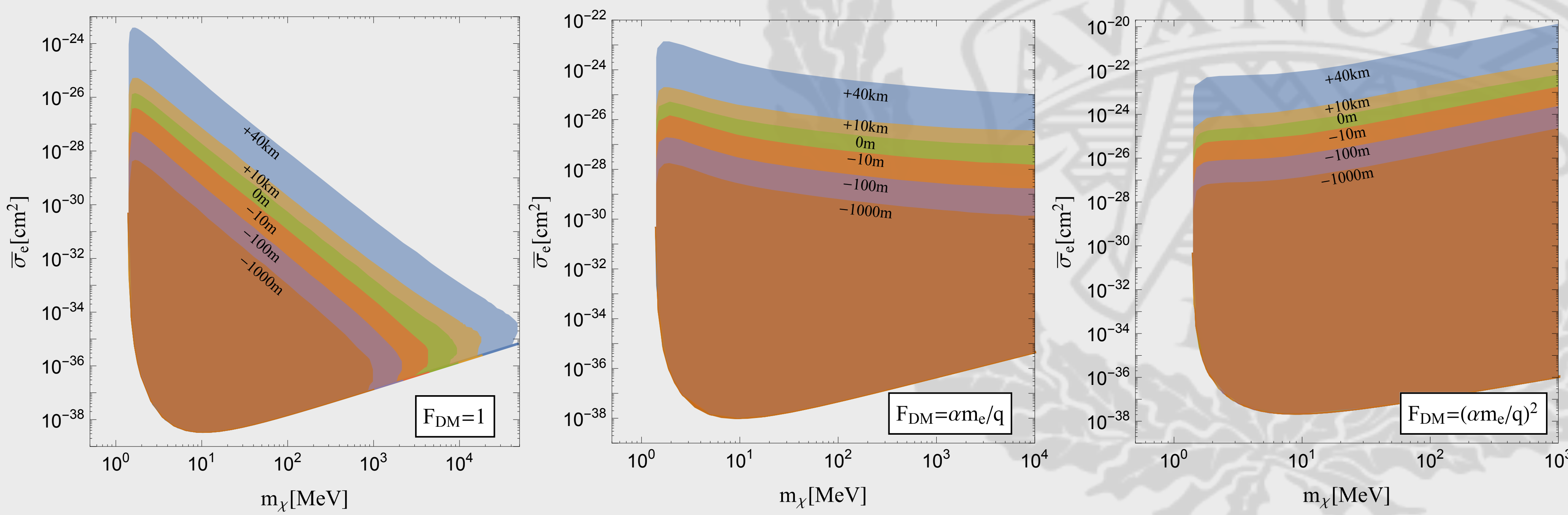


How to push towards stronger interactions

- **Higher Exposures**



- **Shallower Laboratories**



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

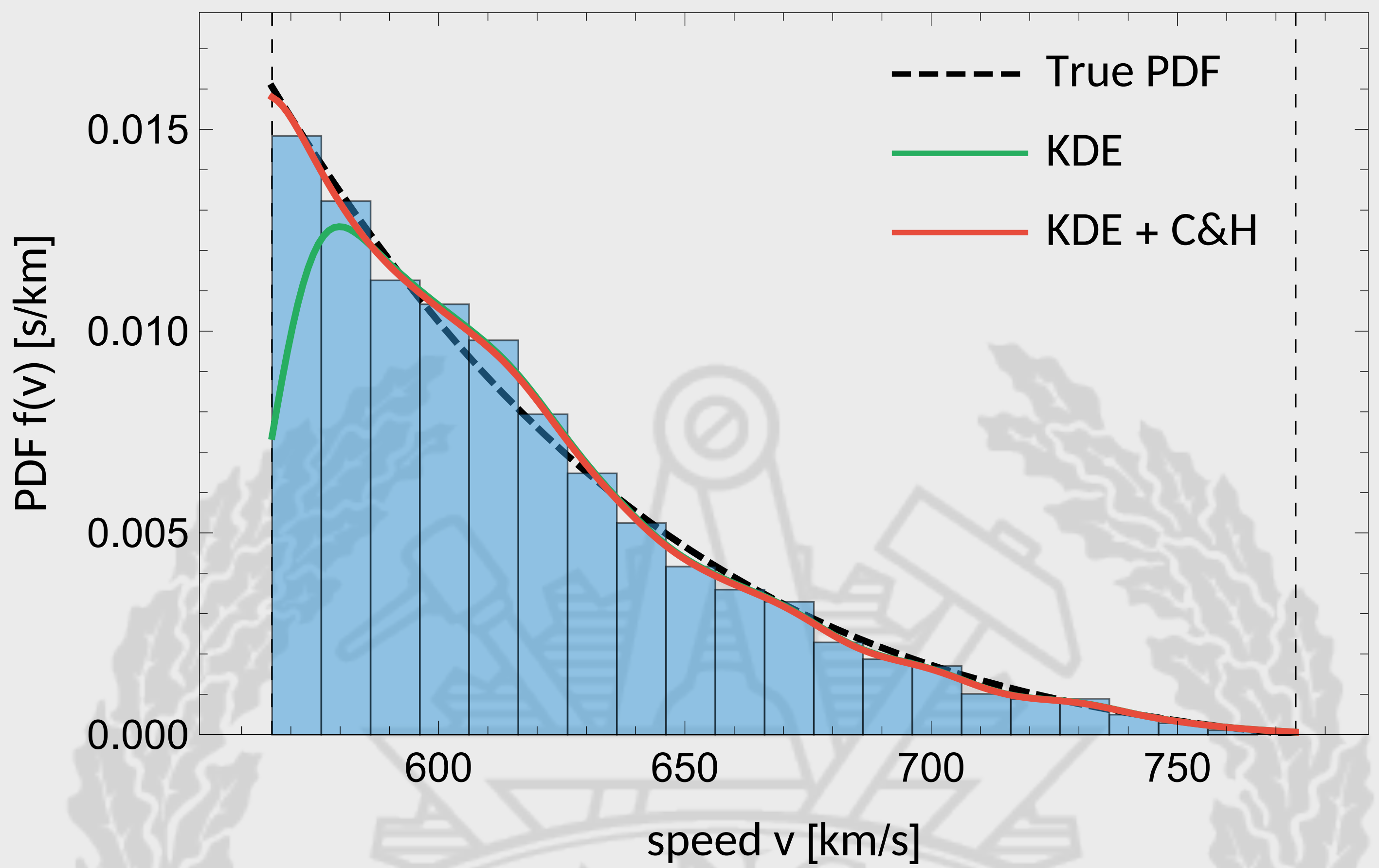
$$\hat{f}_h(x) = \frac{1}{h}\sum_{i=1}^{N} K\left(\frac{x - x_i}{h}\right) .$$

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

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