

# How Scatterings affect the Dark Matter Velocity Distribution in the Laboratory

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September 18, 2019, INFN - LNF, Frascati

## Autumn Institute 2019

### Collaborators

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Niklas G. Nielsen

Mukul Sholapurkar

### Based on

[arXiv:1905.06348]

[arXiv:1802.04764]

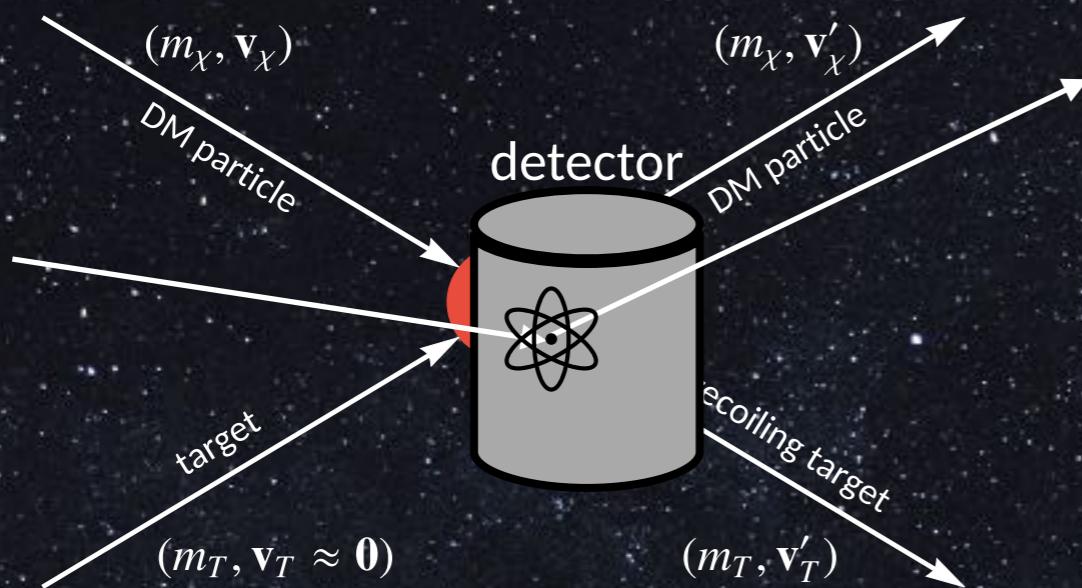
[arXiv:1709.06573]

[arXiv:1706.02249]



# 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:

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \iiint d^3v v f_\chi(v) \frac{d\sigma_N}{dE_R} \Theta(v - v_{\min}(E_R)).$$

Detector size

Astrophysics

Particle physics

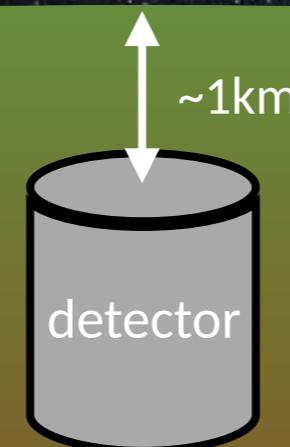
Kinematics

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

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



*Cosmic ray*



# How Scatterings affect the Dark Matter Velocity Distribution in the Laboratory

- I. Describing DM Scatterings in MC simulations
- II. Terrestrial Effects on Direct Detection Experiments
  - (a) Diurnal Signal Modulations
  - (b) Constraints on strongly interacting DM
- III. Solar Reflection of sub-GeV Dark Matter
- IV. Cosmic ray up-scattered DM

I.

# Describing DM Scatterings in MC simulations

# Underground Scatterings of DM Particles

- If DM can scatter in a detector, they scatter anywhere.
- Underground DM scatterings have two consequences:
  1. spatial re-distribution of DM particles,
  2. Change of the DM velocities.
- For stronger DM-nucleus interactions inside the Earth, these two effects could affect DM detection experiments severely.
  1. daily/diurnal modulation of the signal rate,
  2. loss of sensitivity to strongly interacting DM.
- Scattering on energetic targets (in the Sun, or cosmic rays) could also **accelerate** DM.

# How to include the effect of ‘pre-detection’ scatterings into signal rates?

$$\frac{dR}{dE_R} = \frac{1}{m_N m_\chi} \int_{v > v_{\min}(E_R)} dv v f_\chi(v) \frac{d\sigma_N}{dE_R}$$

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

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

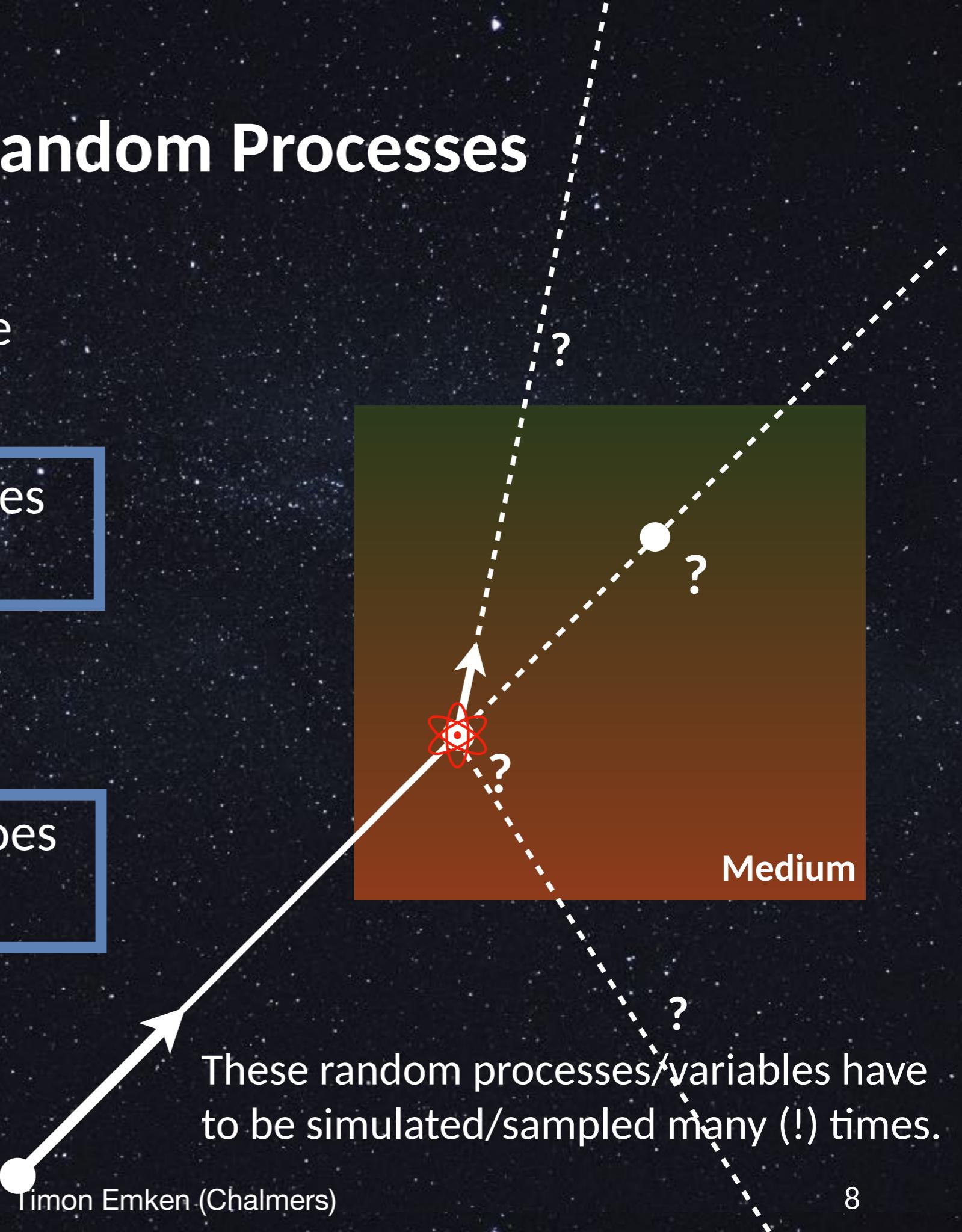
$$\frac{dR_{\text{crystal}}}{dE_e} = \frac{\rho_\chi}{m_\chi M_{\text{cell}}} \frac{1}{\mu_{\chi e}^2} \frac{\sigma_e \alpha m_e^2}{\mu_{\chi e}^2} \int dq \frac{1}{q^2} \int_{v > v_{\min}(E_e, q)} dv \frac{f_\chi(v)}{v} \left| F_{\text{DM}}(q) \right|^2 \left| f_{\text{crystal}}(E_e, q) \right|^2$$

DM scatterings modify the underground DM **density** and **velocity distribution**.

# 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.**



# Free distance

- The CDF of the free distance is given by

$$P(L) = 1 - \exp\left(-\int_0^L \frac{dx}{\lambda(x, v)}\right), \quad \text{integrate along the path}$$

where we used the *mean free path*,

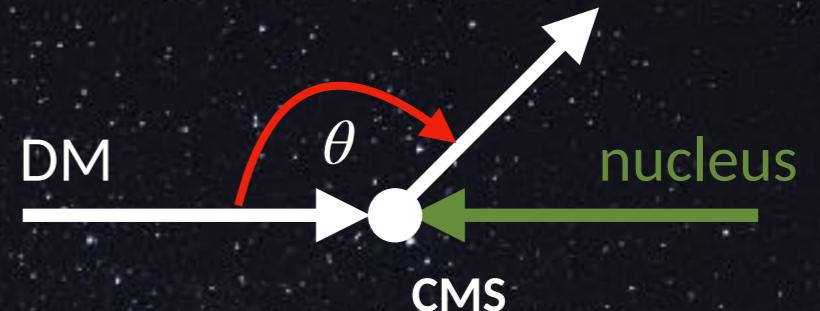
$$\lambda(\mathbf{x}, v)^{-1} = \sum_i \lambda_i(\mathbf{x}, v)^{-1} \equiv \sum_i n_i(\mathbf{x}) \sigma_{\chi i}.$$

- To sample a specific free distance, we need a uniform random number  $\xi$  and solve

$$\begin{aligned} P(L) = \xi \in \mathcal{U}_{[0,1]} \cdot \\ \rightarrow L = P^{-1}(\xi). \end{aligned} \quad \text{inverse transform sampling}$$

- Can be complicated for (dis-)continuous changes of the medium.

# Scattering angle



- The PDF of the scattering angle  $\cos \theta$  is given by

$$f_\theta(\cos \theta) = \frac{1}{\sigma_N} \frac{d\sigma_N}{d \cos \theta} = \frac{E_R^{\max}}{2\sigma_N} \frac{d\sigma_N}{d E_R}. \quad \text{particle physics input}$$

For isotropic contact interactions, this is simply

$$f_\theta(\cos \theta) = \frac{1}{2}.$$

inverse transform sampling  
or  
rejection sampling

For other interaction types, it can be more complicated.

- This angle fixes the new DM velocity after a scattering:

$$\mathbf{v}'_\chi \approx \frac{m_T \mathbf{v}_\chi \mathbf{n} + m_\chi \mathbf{v}_\chi}{m_T + m_\chi} \quad (\mathbf{v}_T \approx \mathbf{0})$$

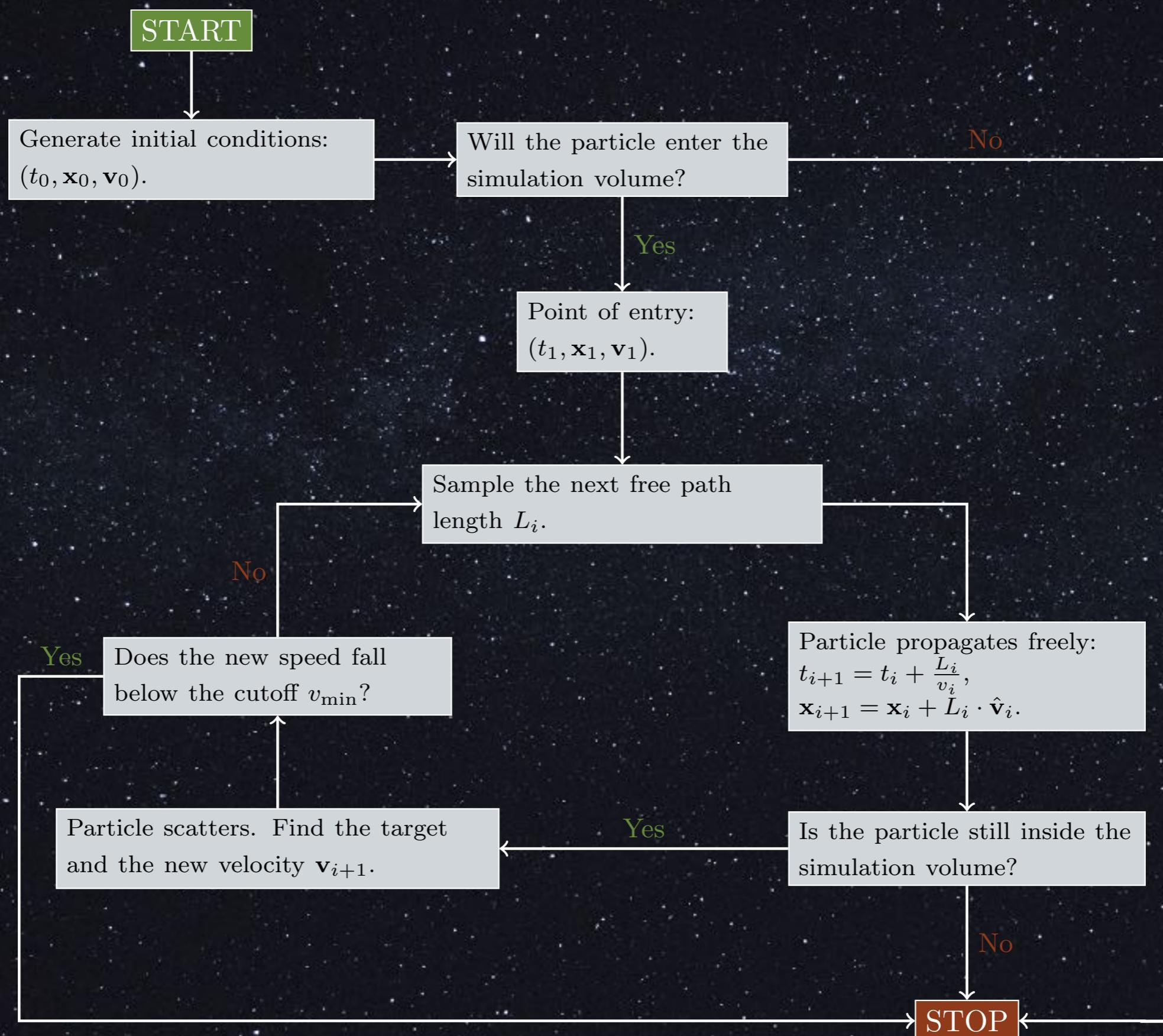
kinematics

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# Terrestrial Effects on Direct Detection of Dark Matter

## Diurnal Signal Modulations

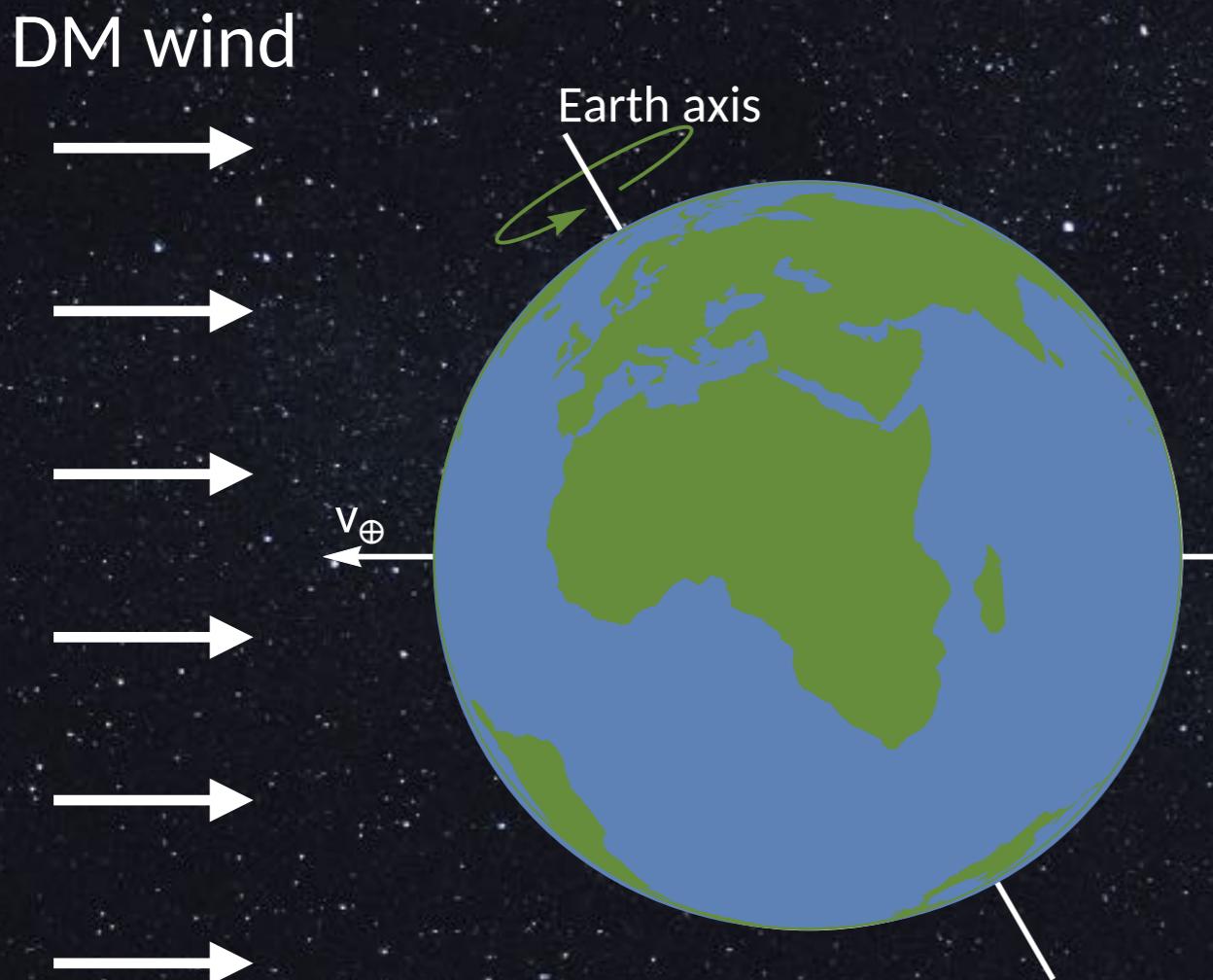
# Monte Carlo Simulation Algorithm



$t=0$  s



# Isodetection angle



How deep is a laboratory in  
Earth's 'shadow'?

$$\Theta(t) = \arccos \left[ \frac{\mathbf{v}_{\oplus}(t) \cdot \mathbf{x}_{\text{lab}}^{(\text{gal})}(t)}{v_{\oplus}(t)(r_{\oplus} - d)} \right]$$

$$\Theta = 0^\circ$$

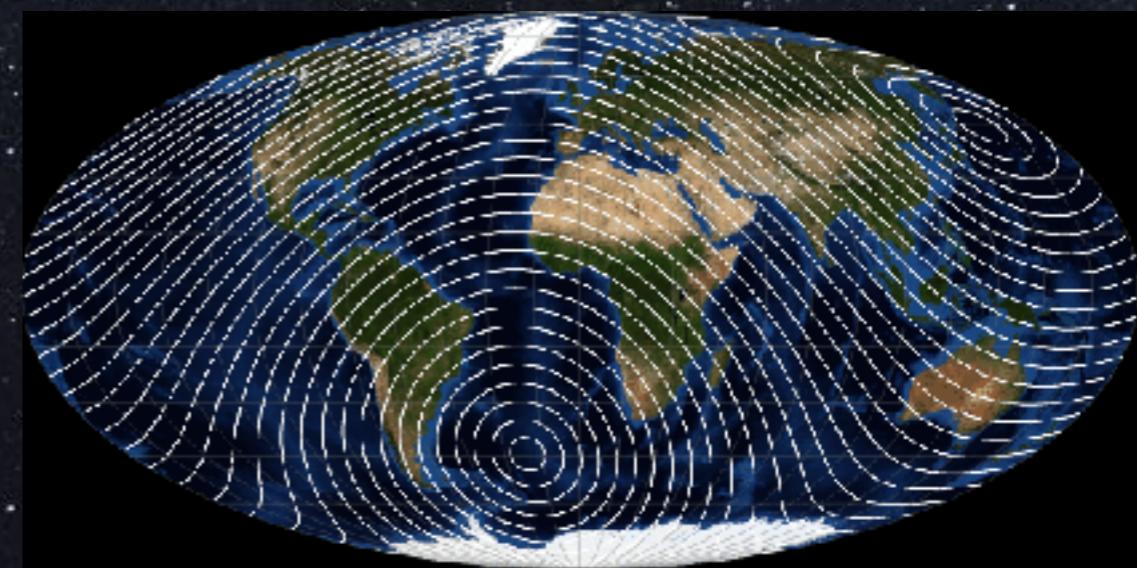
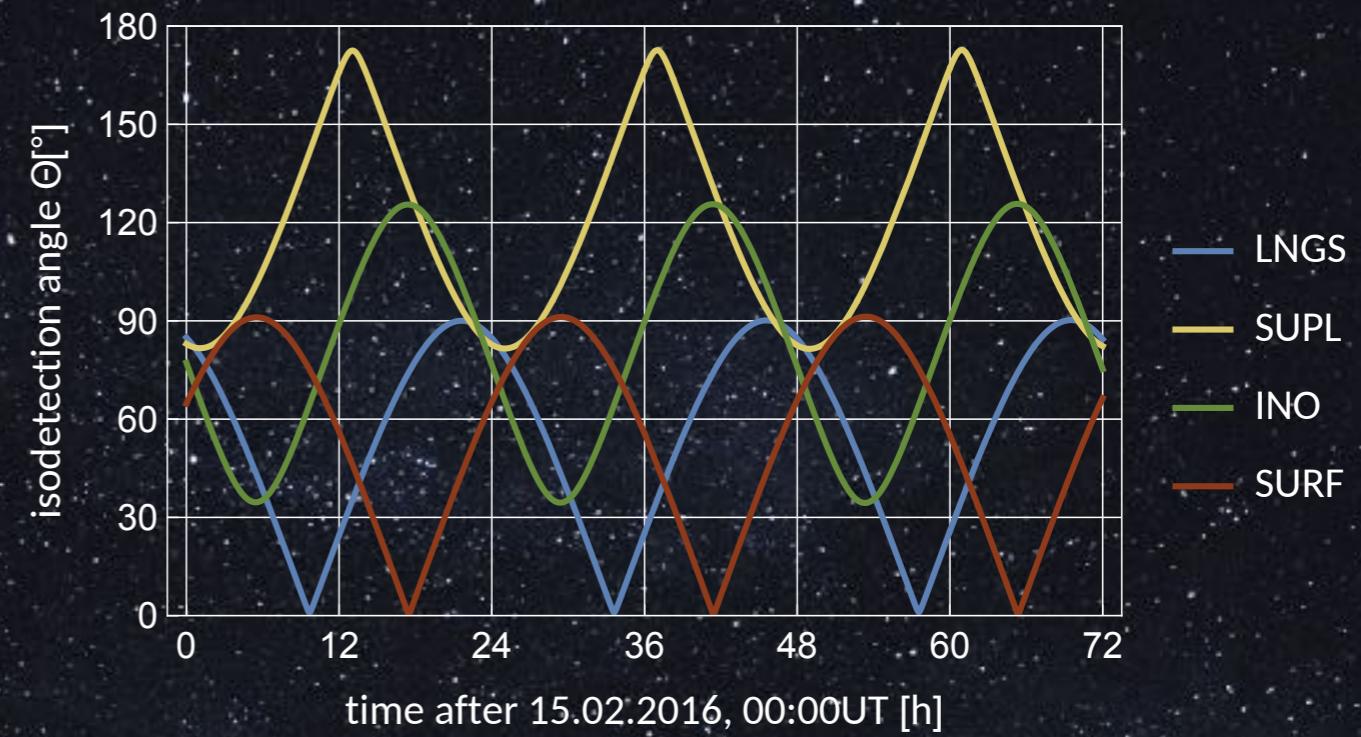
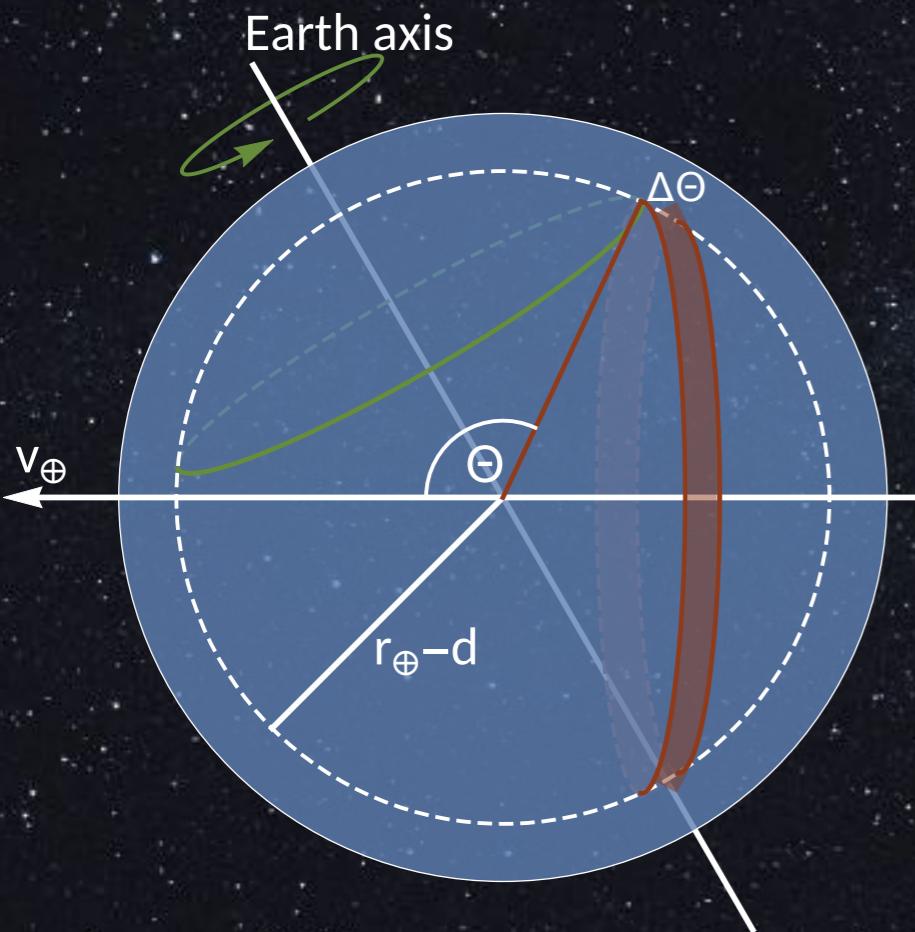
→ DM wind from above

$$\Theta = 180^\circ$$

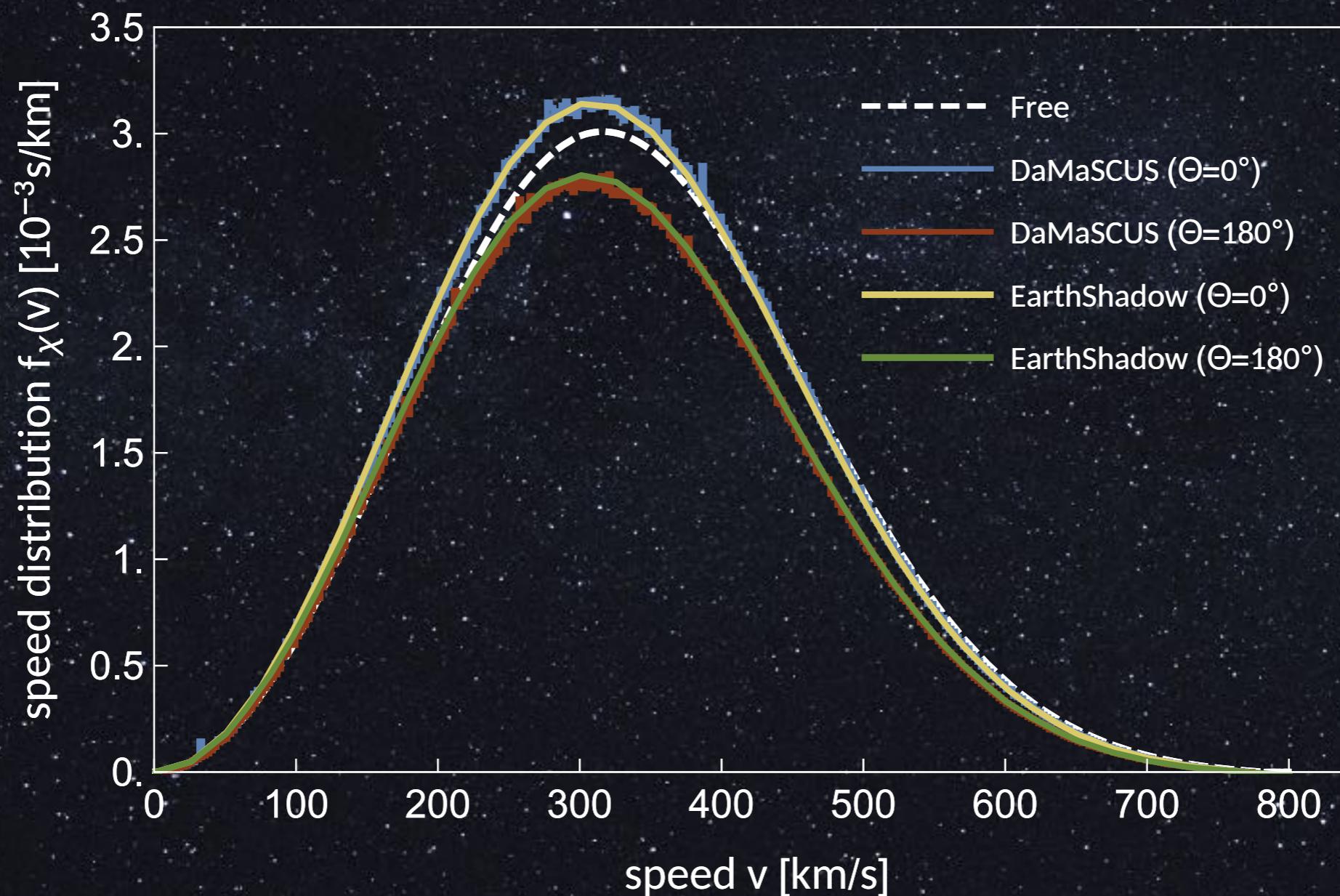
→ Shadow

J.I. Collar, F.T. Avignone, Phys. Lett. B275 (1992), 181-185  
J.I. Collar, F.T. Avignone, PRD 47 (1993), 5238-5246  
Hasenbalg et al., PRD 55 (1997), 7350-7355

# Isodetection angle

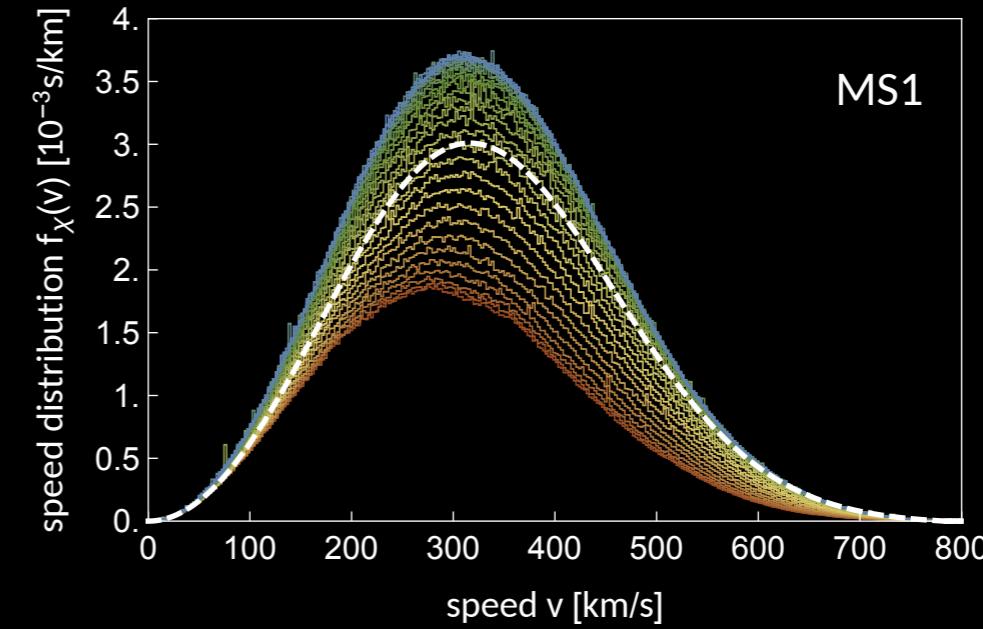
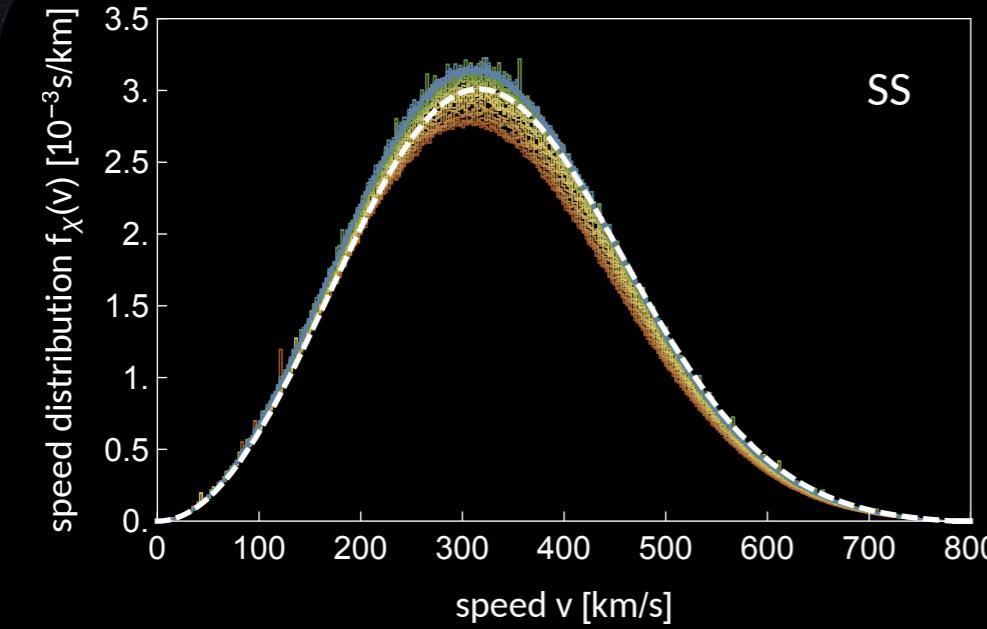


# DM distribution inside the Earth



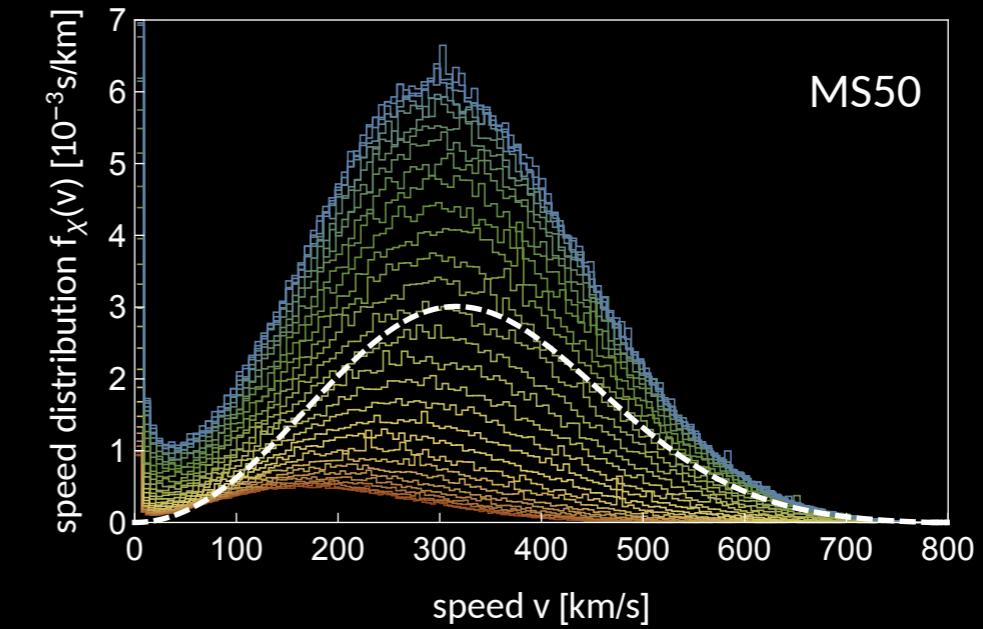
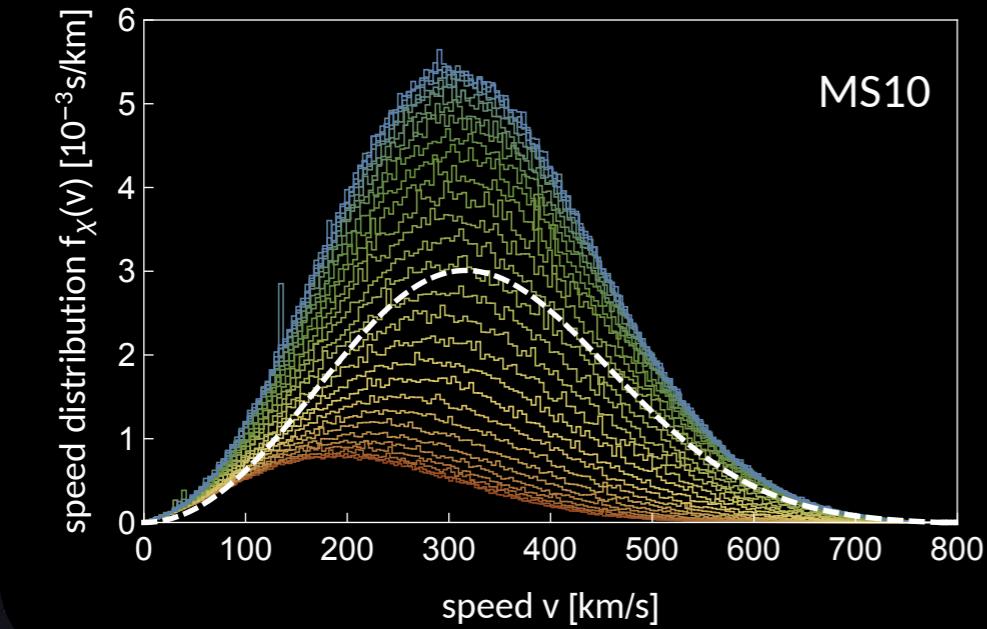
B.J. Kavanagh, R. Catena, C. Kouvaris, JCAP 1701 (2017) no 01, 012

# DM distribution inside the Earth



$\Theta$  [ $^\circ$ ]

180
150
120
90
60
30
0



$m_\chi = 500\text{MeV}$

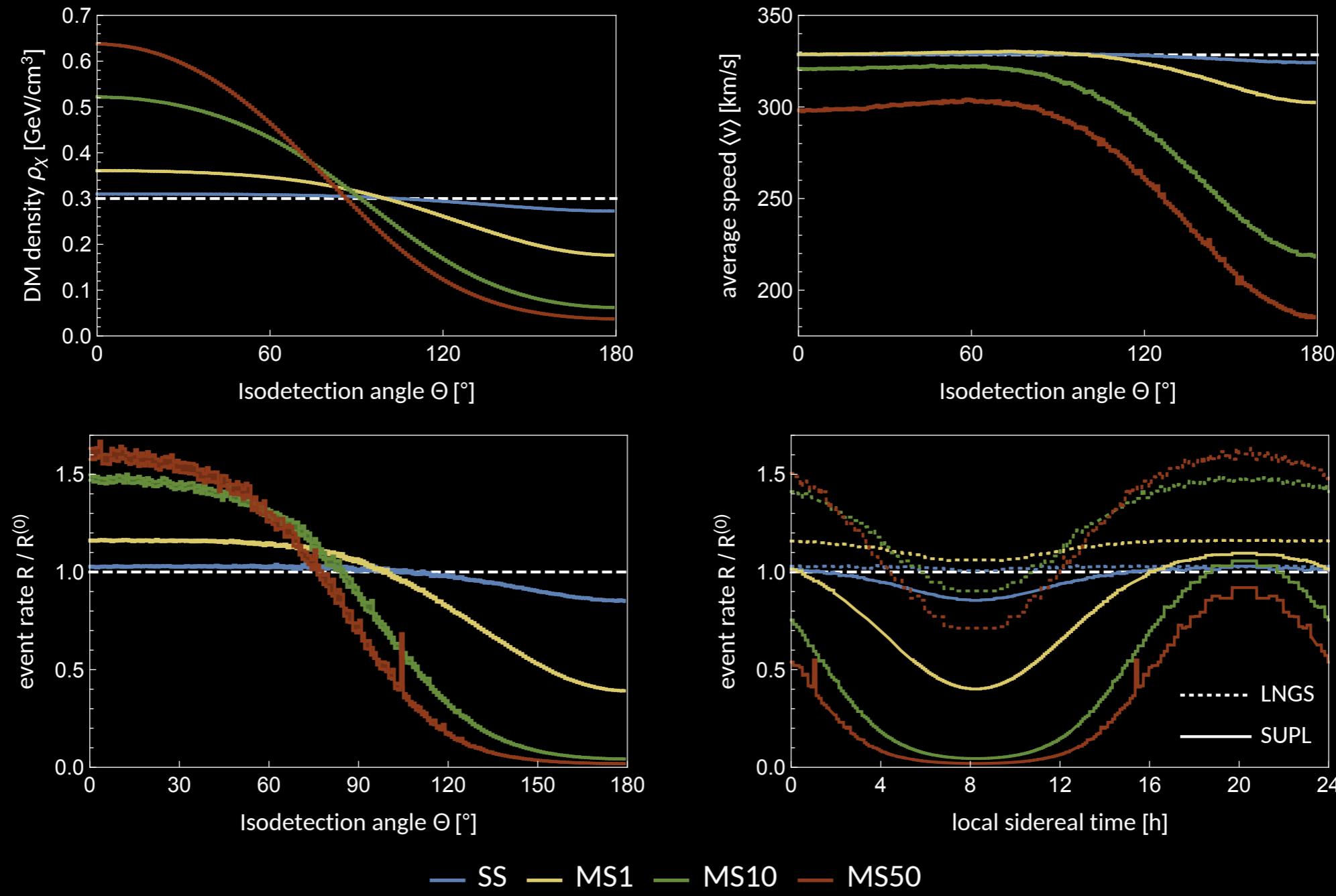
SS:  
 $\sigma_p \approx 0.5\text{pb}$

MS1:  
 $\sigma_p \approx 4.3\text{pb}$

MS10:  
 $\sigma_p \approx 42.5\text{pb}$

MS50:  
 $\sigma_p \approx 300\text{pb}$

# Diurnal Modulation Results



$$m_\chi = 500\text{MeV}$$

$$\begin{aligned} \text{SS: } & \sigma_p \approx 0.5\text{pb} \\ \text{MS1: } & \sigma_p \approx 4.3\text{pb} \end{aligned}$$

$$\begin{aligned} \text{MS10: } & \sigma_p \approx 42.5\text{pb} \\ \text{MS50: } & \sigma_p \approx 300\text{pb} \end{aligned}$$

# Constraints on strongly interacting DM

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# Terrestrial Effects on Direct Detection of Dark Matter

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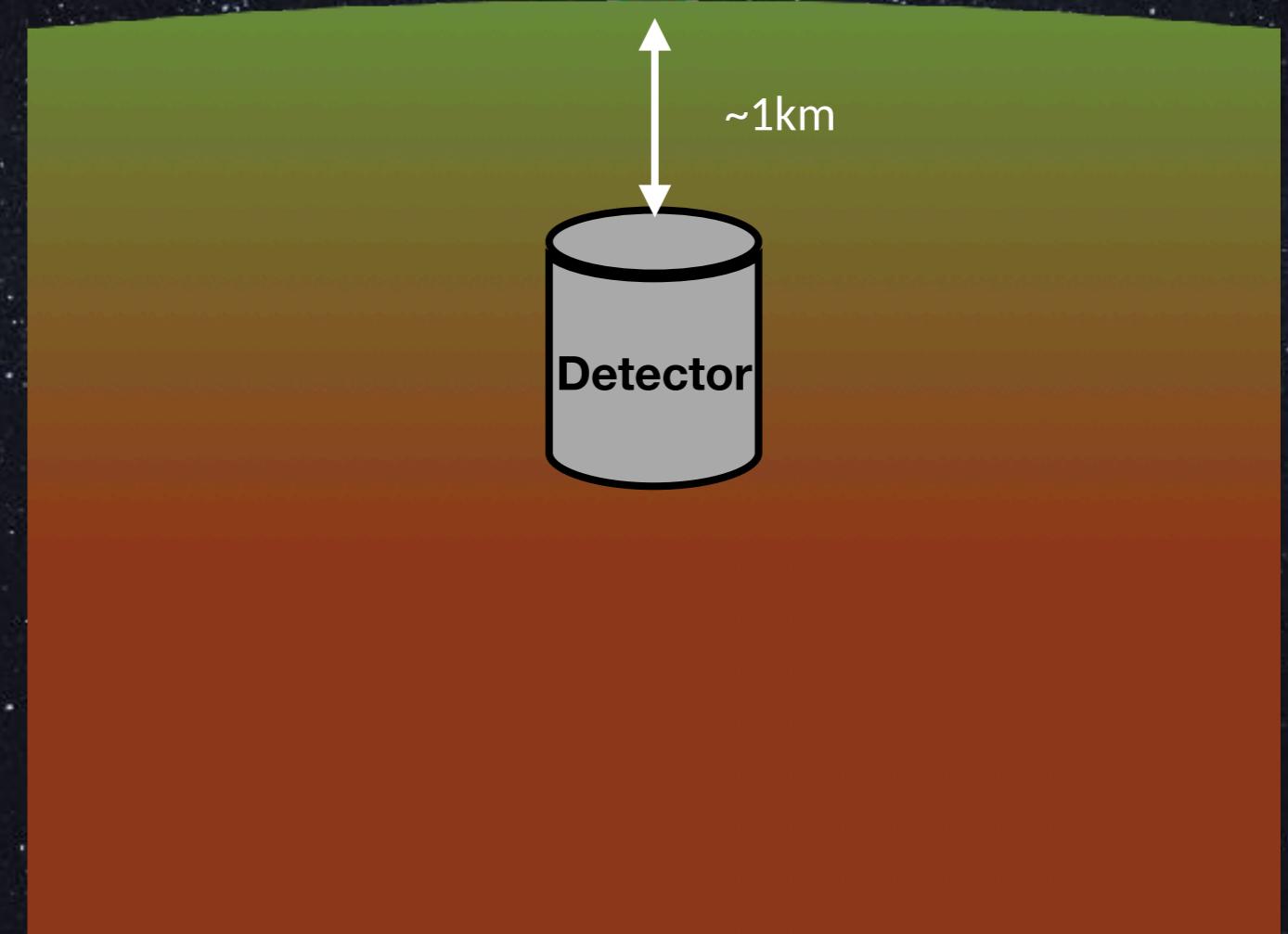
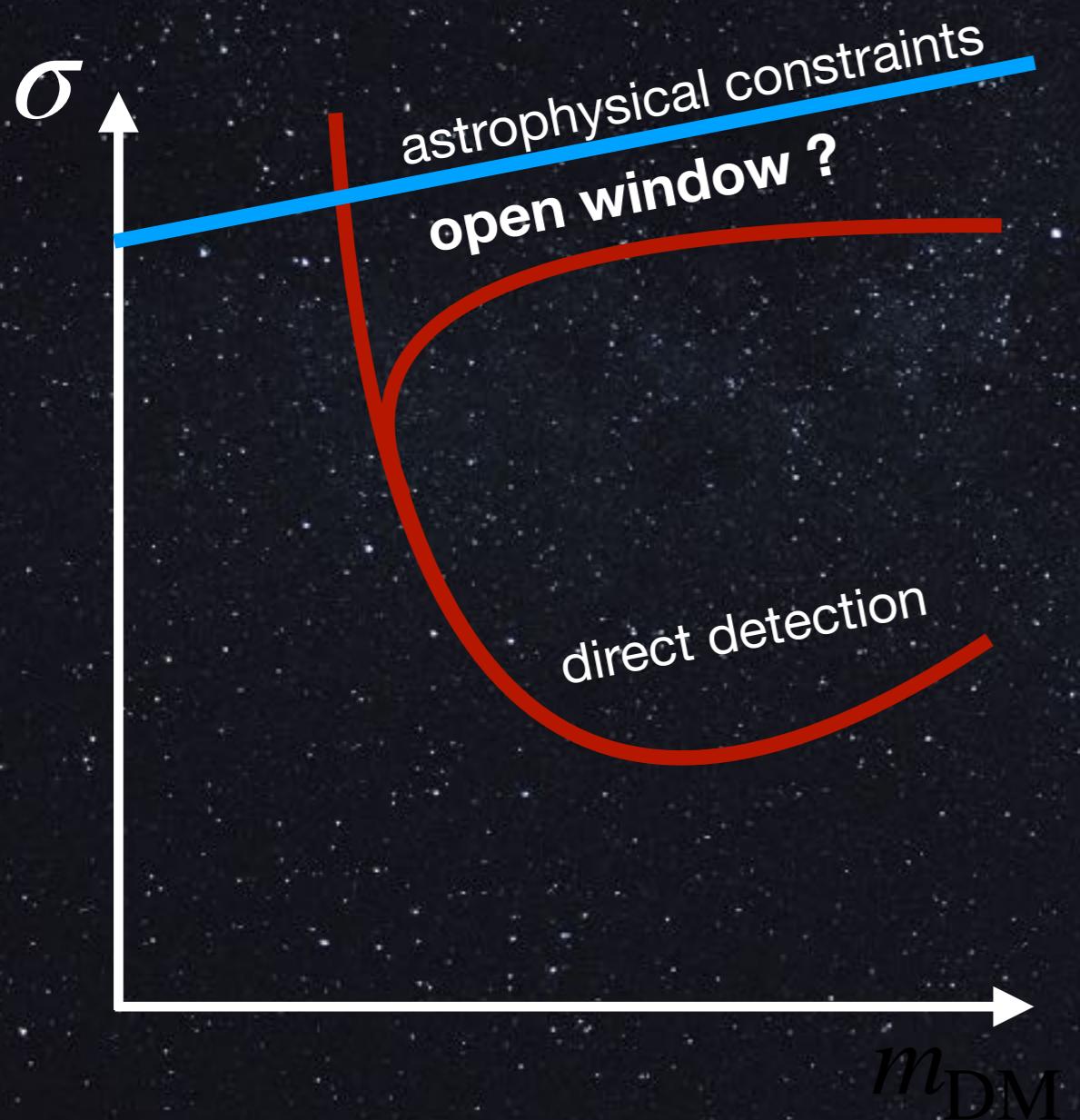
```
_pass(
```

`kde =`

`double  
ints=1;`

# Direct detection of strongly interacting DM

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



**Opening the window on strongly interacting dark matter**

Glenn D. Starkman and Andrew Gould

*Institute for Advanced Study, Princeton, New Jersey 08540*

Rahim Esmailzadeh

*Center for Particle Astrophysics, University of California, Berkeley, California 94720*

Savas Dimopoulos\*

*CERN TH-Division, 1211 Geneva 23, Switzerland***Cracking Open the Window for Strongly Interacting Dark Matter**

Patrick C. McGuire, Paul J. Steinhardt

(Submitted on 31 May 2001)

**A Window in the Dark Matter Exclusion Limit**

Gabrijela Zaharijas, Glennys R. Farrar

(Submitted on 24 Jun 2004)

**Towards Closing the Window on Strongly Interacting Dark Matter****Closing the Window on Strongly Interacting Dark Matter with IceCube**

Ivone F. M. Albuquerque (1 and 2), Carlos Pérez de los Heros (3) ((1) Center for Particle Astrophysics FERMILAB, Batavia, IL, USA, (2) Universidade de São Paulo, São Paulo, Brazil, (3) Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA, USA)

(Submitted on 8 Jan 2010 (v1), last revised 16 Feb 2010 (this version, v2))

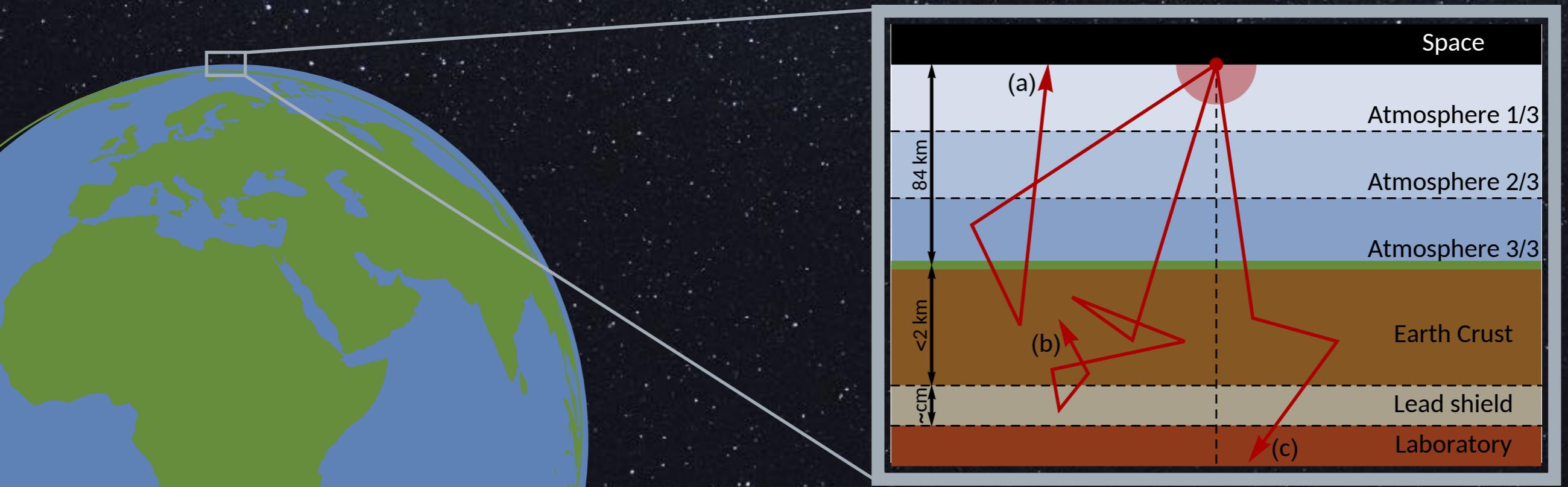
**Closing the Window on Strongly Interacting Dark Matter****Closing the window on  $\sim$ GeV Dark Matter with moderate ( $\sim$ \$ $\mu$ b) interaction with nucleons**

M. Shafi Mahdawi, Glennys R. Farrar

(Submitted on 1 Sep 2017 (v1), last revised 20 Dec 2017 (this version, v3))

# Direct Detection Constraints on Strongly Interacting DM

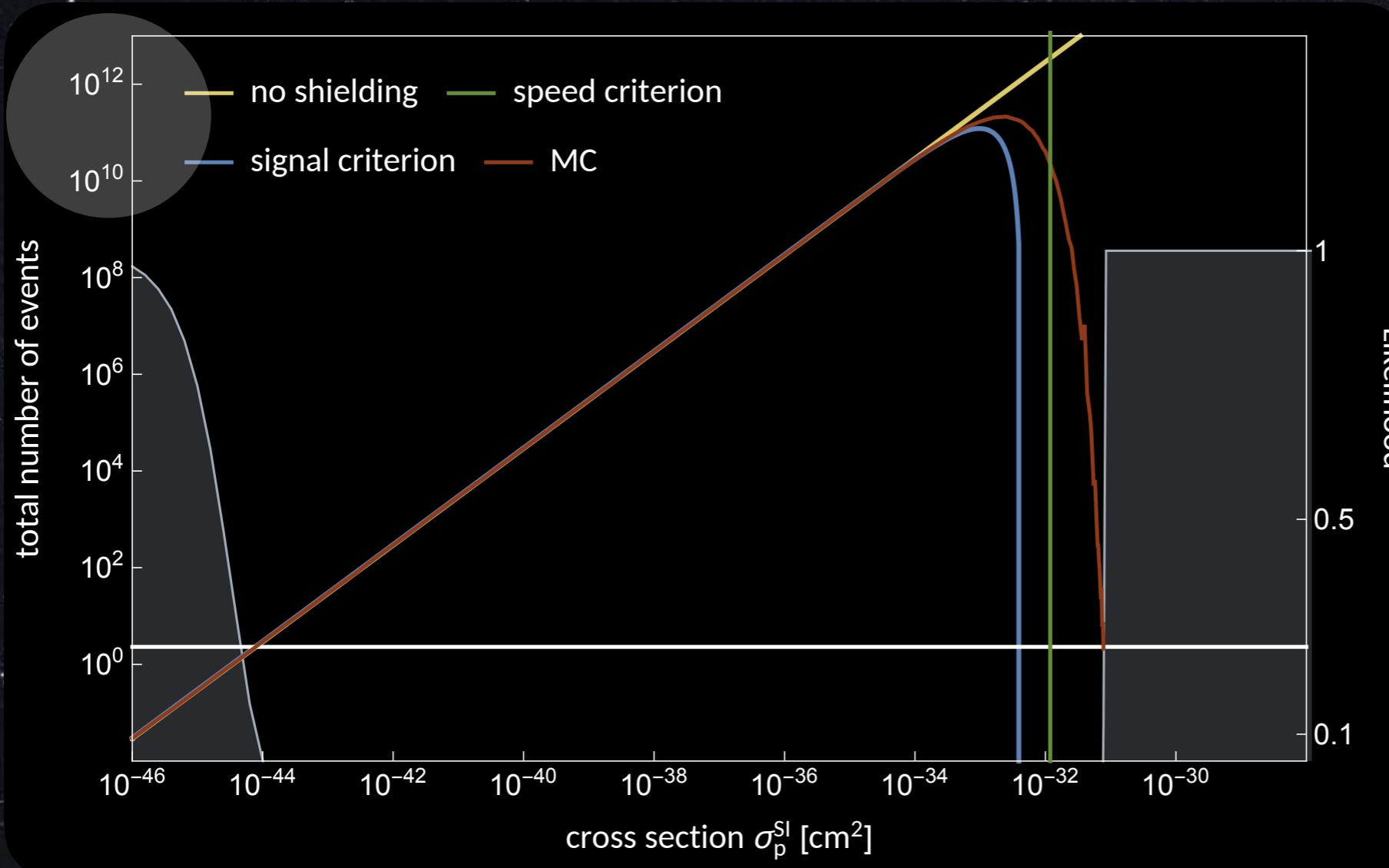
- DM detectors are typically underground to *shield off* background sources from the detector.
  - Above some high critical cross section, the overburden (Earth crust/atmosphere) shields off DM particles itself. Goodman and Witten, Phys.Rev. D31 (1985) 3059  
Starkman et al, Phys.Rev. D41 (1990) 3594
- Terrestrial experiments lose sensitivity to DM above this critical value.



# Overburden Shielding vs. Detection I



# Overburden Shielding vs. Detection II



Rare-event techniques  
are absolutely crucial!

- Importance Sampling
- Importance Splitting

# Importance Sampling (IS)

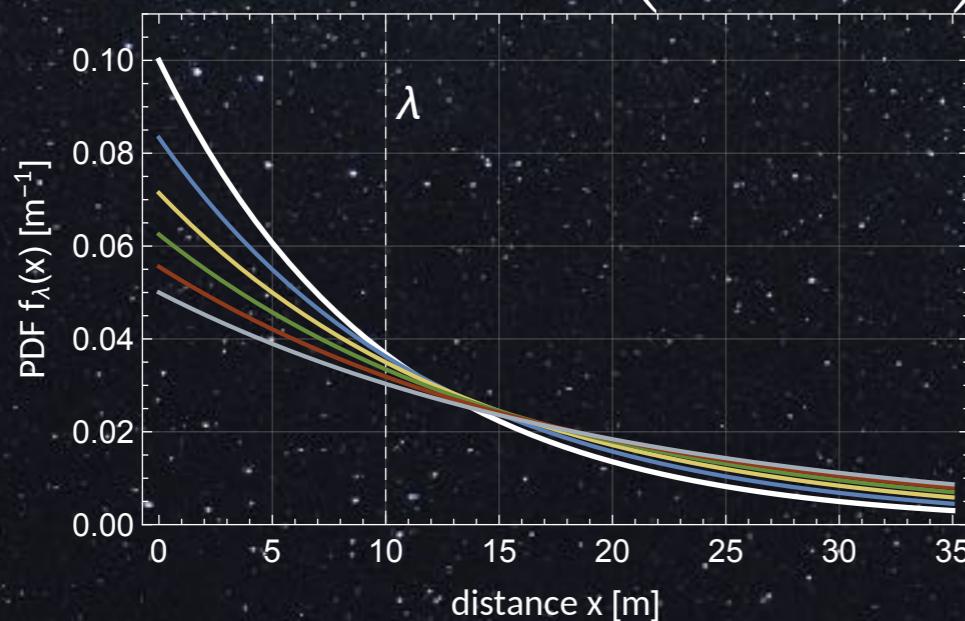
- Rare event technique, which modifies the PDFs of the simulation.

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

- Try to “mimic” the successful runs by introducing a bias into the simulations.

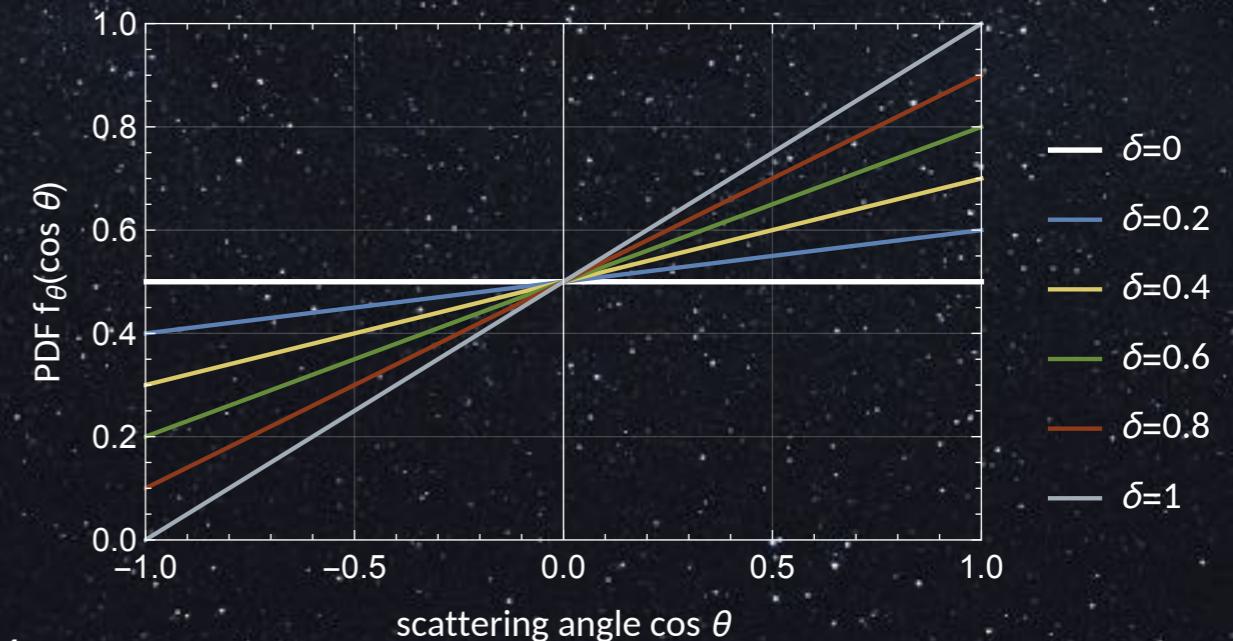
$$f_\lambda(x) = \frac{1}{\lambda} \exp\left(-\frac{x}{\lambda}\right)$$

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



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

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

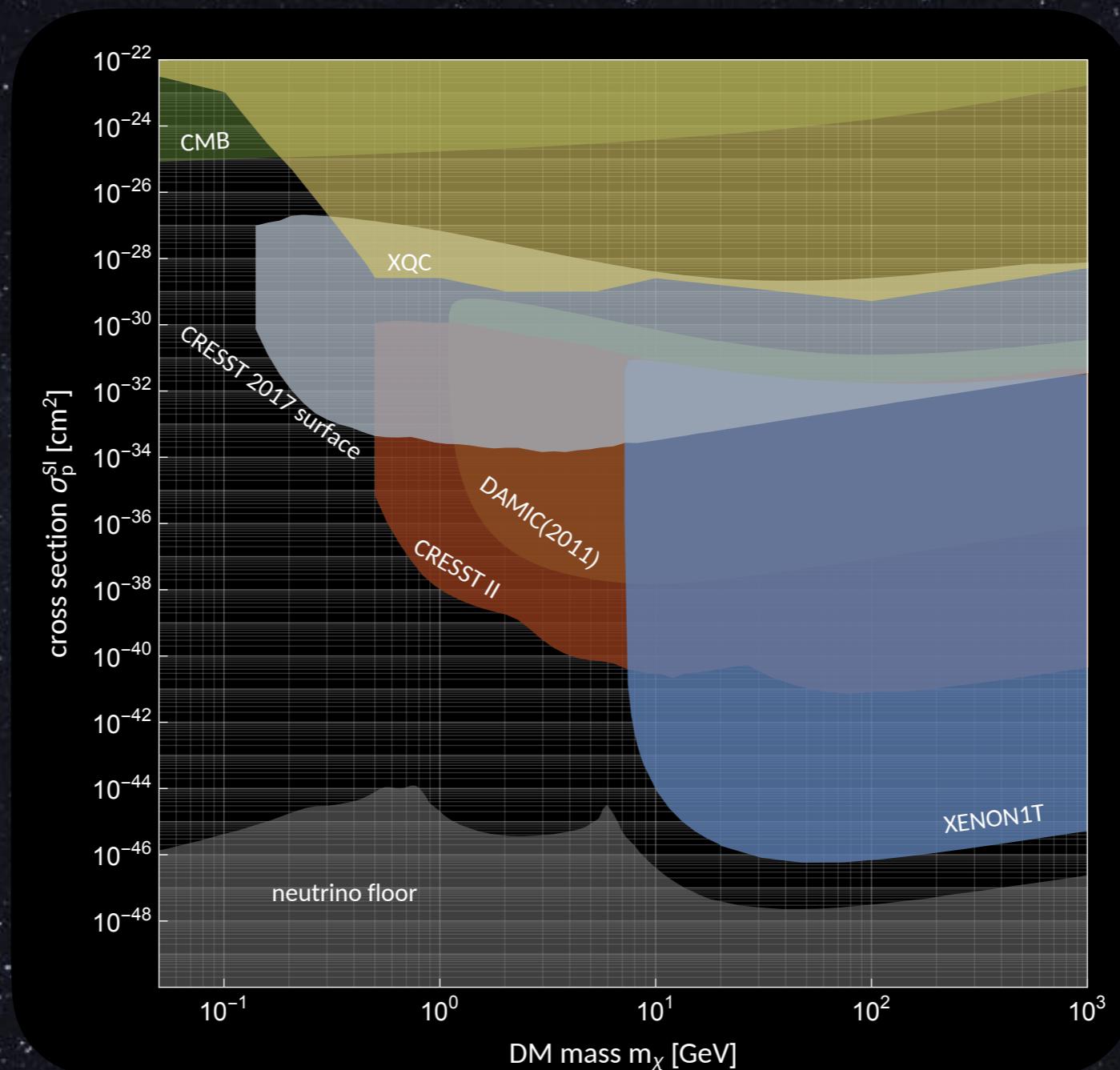


- Compensate by a statistical weight factor.

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

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

# Constraints from Nuclear Recoil Experiments



# 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.

# The Dark Photon Model

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

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

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

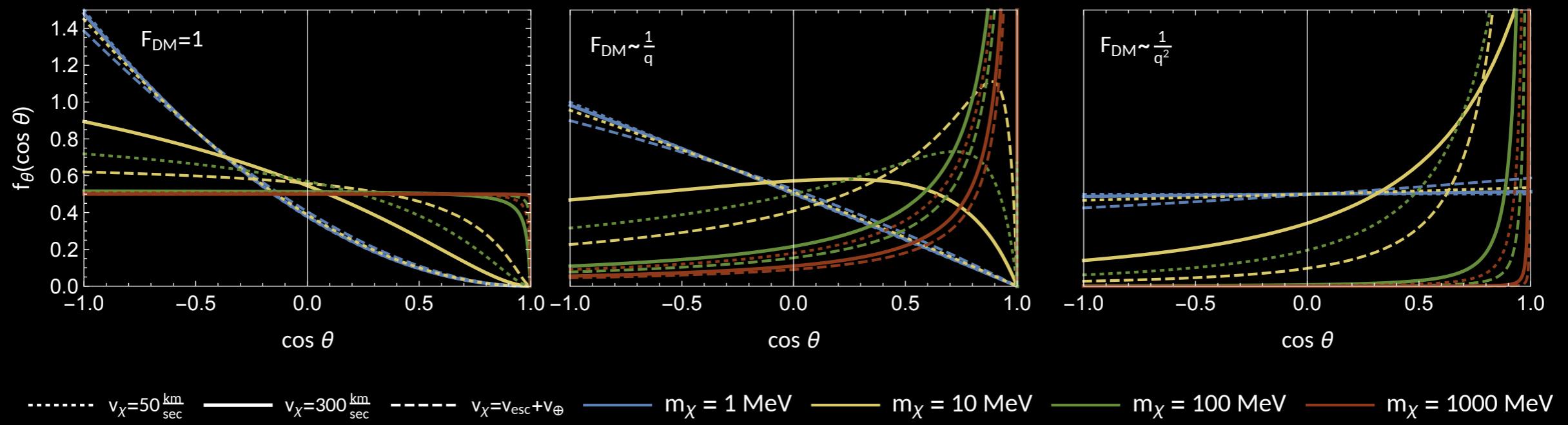
$$\frac{d\sigma_N}{dq^2} = \frac{\sigma_p}{4\mu_{\chi p}^2 v_\chi^2} F_{\text{DM}}(q)^2 F_N(q)^2 Z^2$$

- 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

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

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

# Geometric Importance Splitting (GIS)

- Rare event method.
- “More interesting” particles get split into copies.
- Requires the definition of an importance function,

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

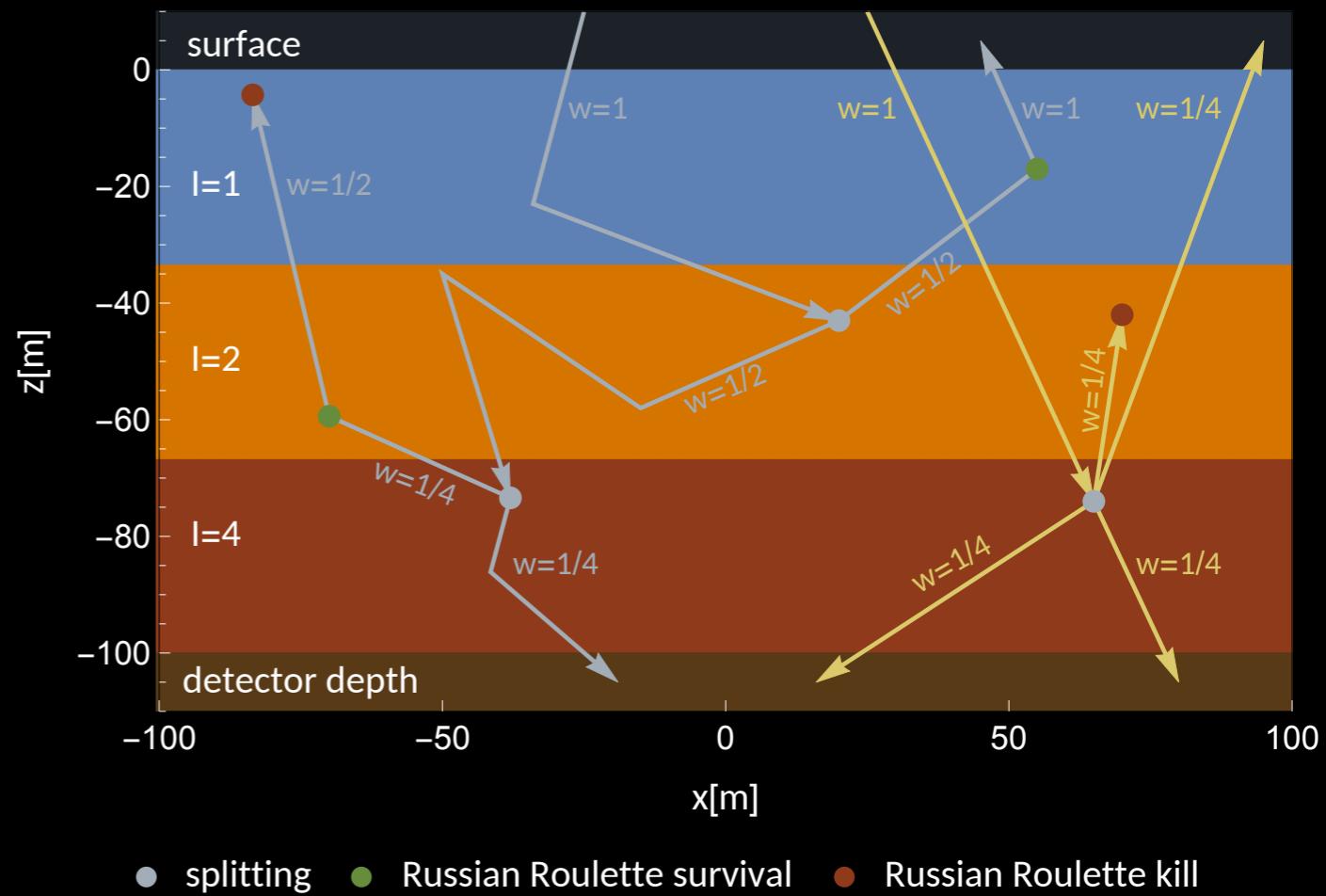
- If the importance increases,

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

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.

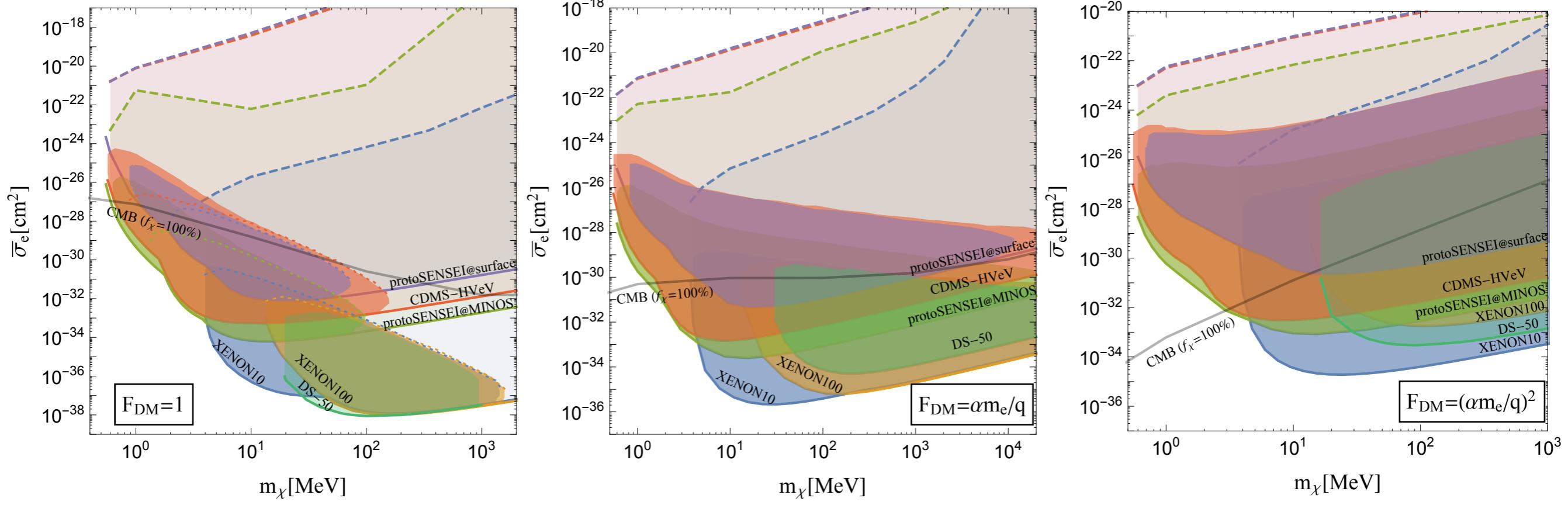


New statistical weight

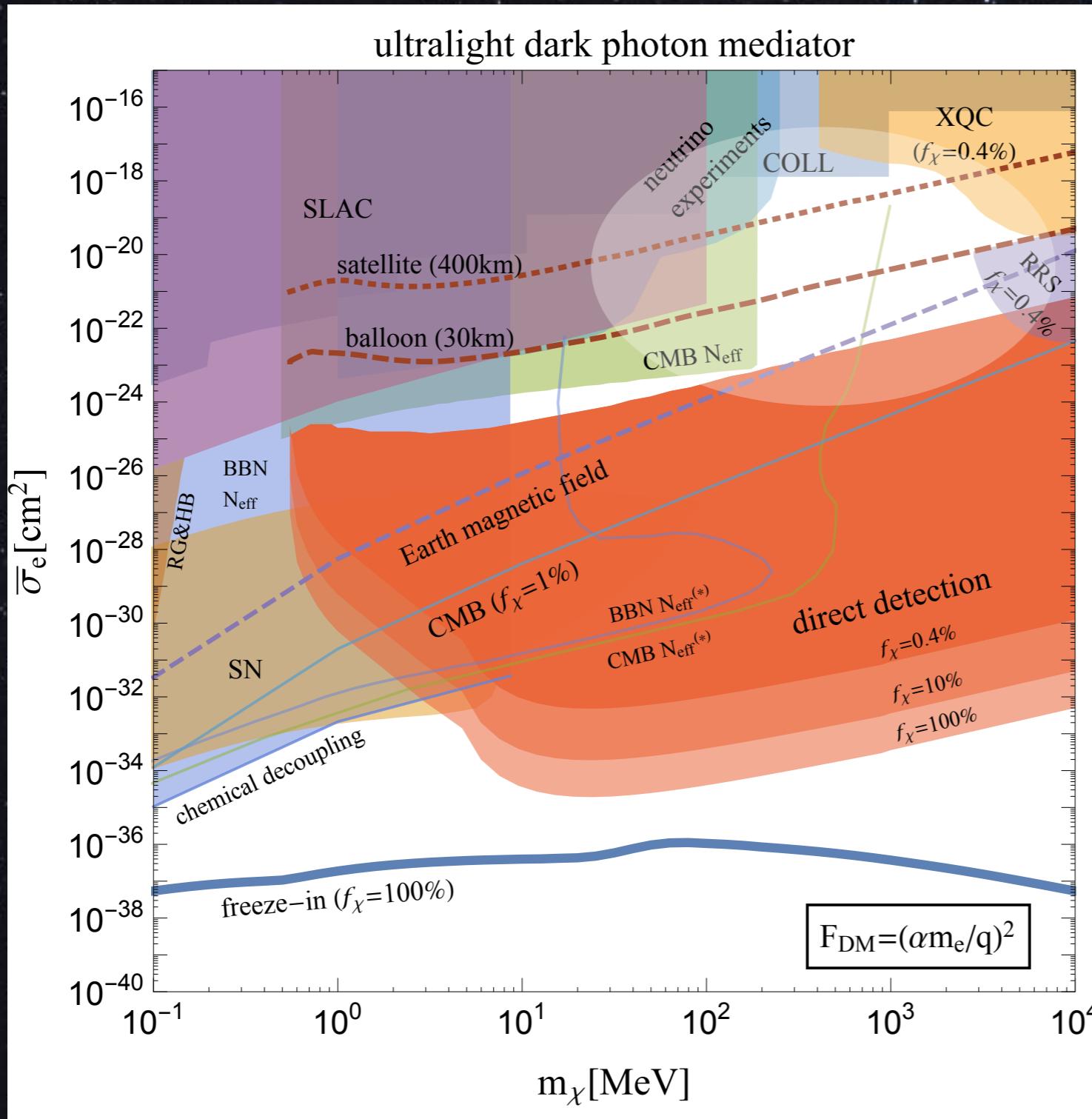
$$w_{i+1} \equiv \frac{w_i}{n}$$

- Otherwise: **Russian Roulette**

# Constraints on DM-Electron Scatterings

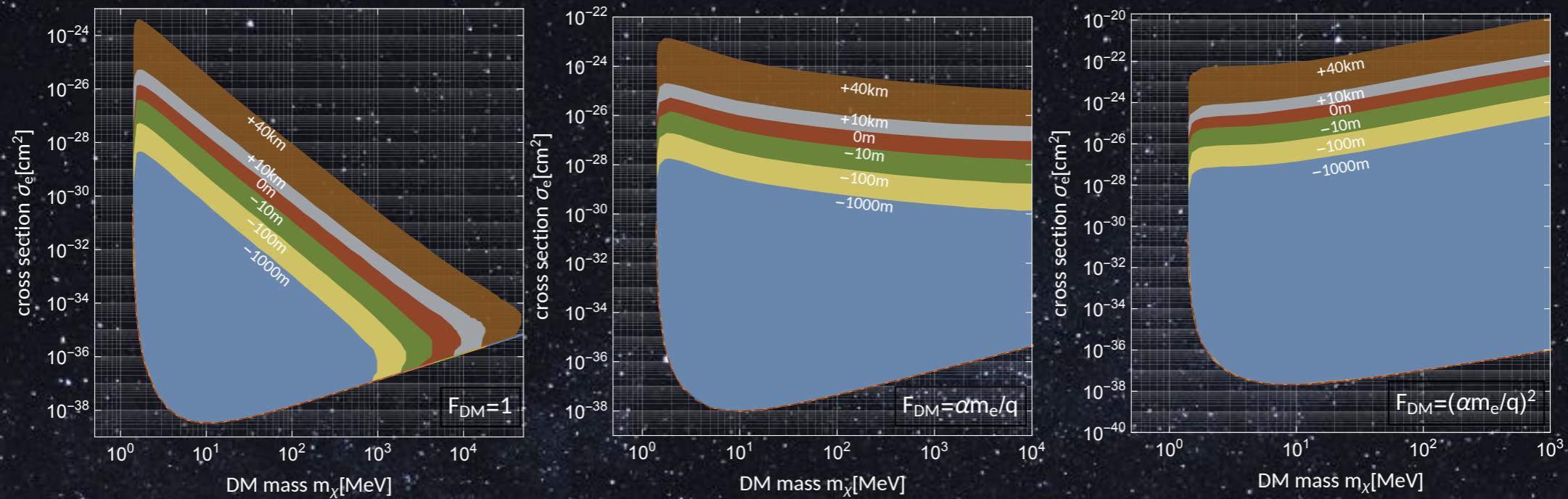


# Constraints on a sub-dominant component of strongly interacting DM

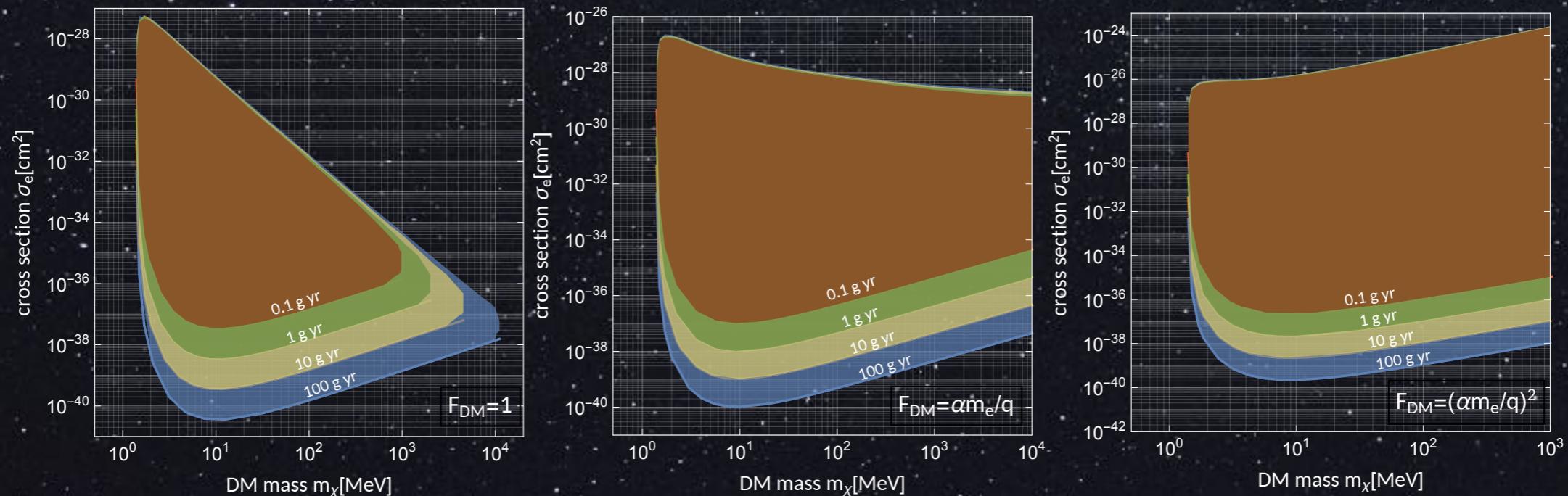


- So is there an open window in parameters space?
- Probably not for milli-charged DM.
- Definitely not for  $f_\chi = 100\%$
- Yes, under certain conditions:
  - Sub-dominant component.  $f_\chi < 0.4\%$
  - Ultralight, but not massless mediator.
  - Small dark gauge coupling.

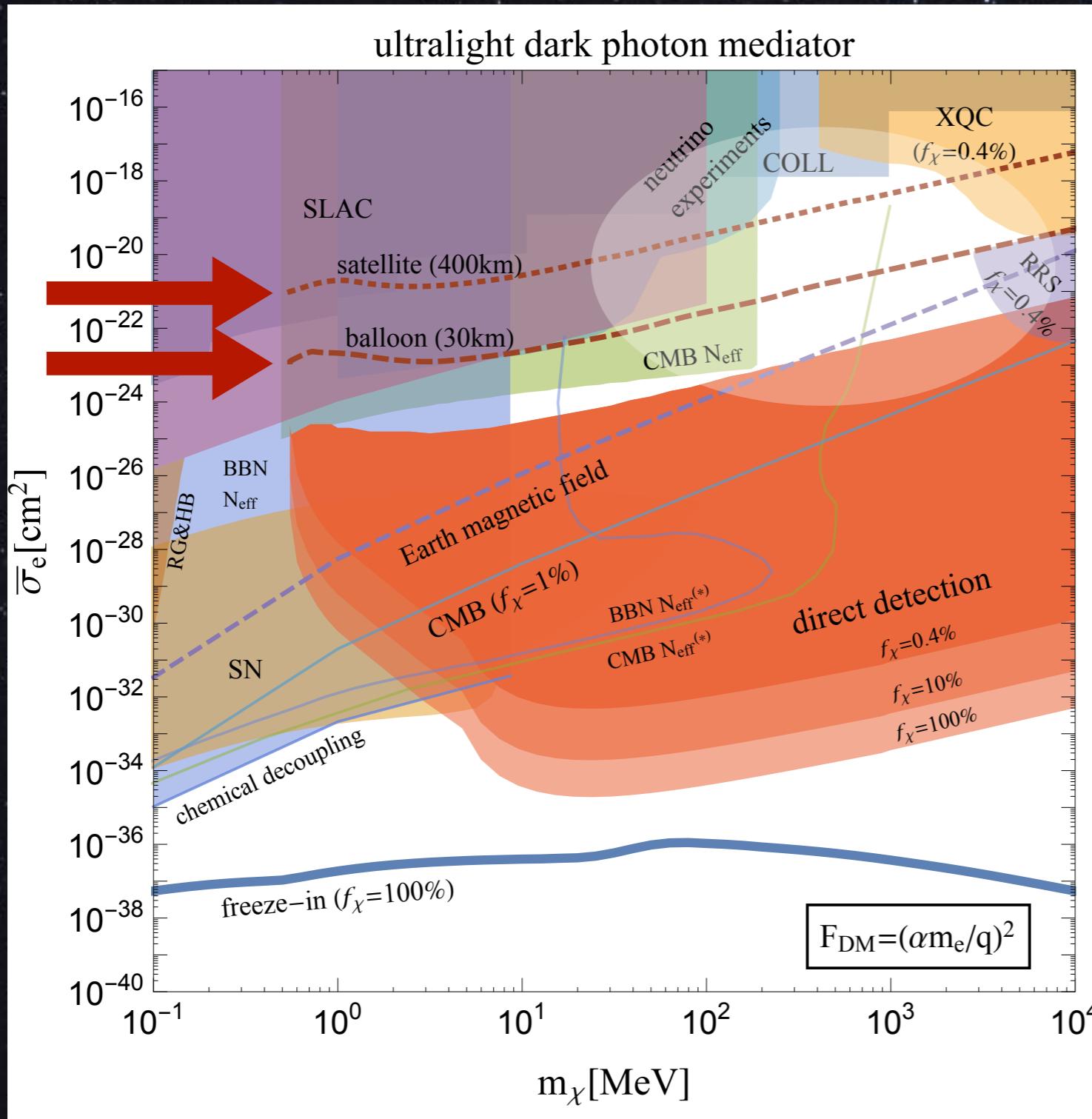
# Constraint scaling with depth



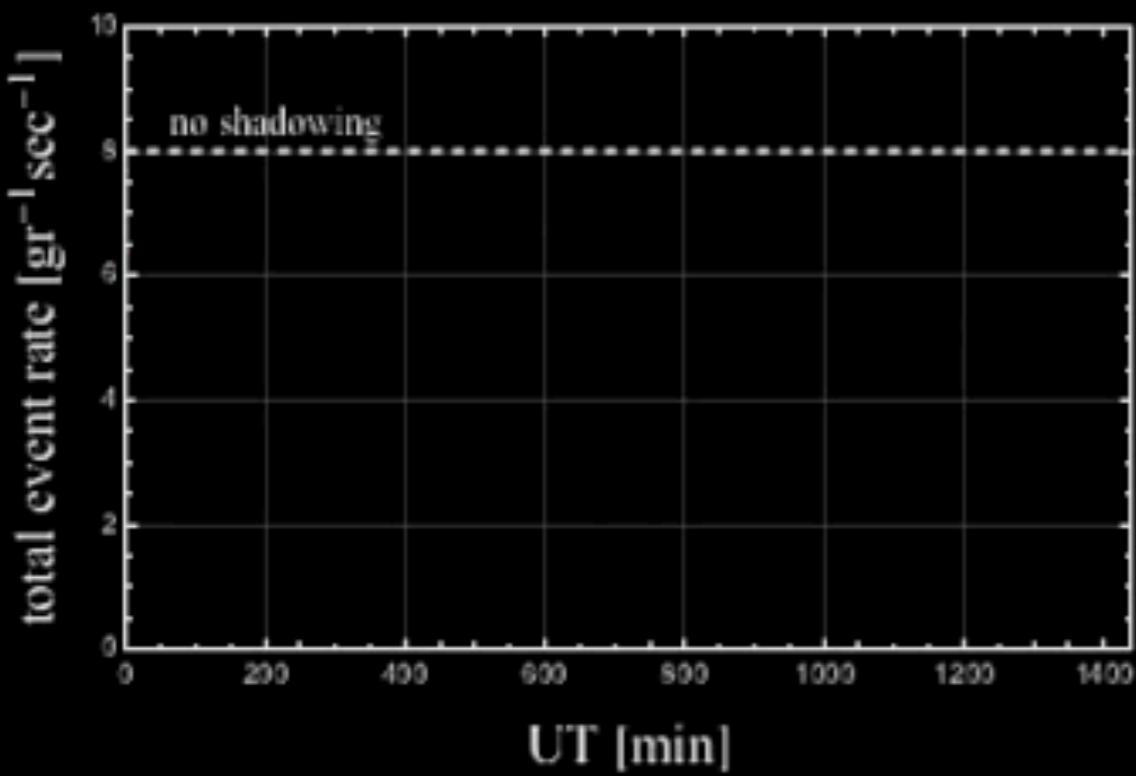
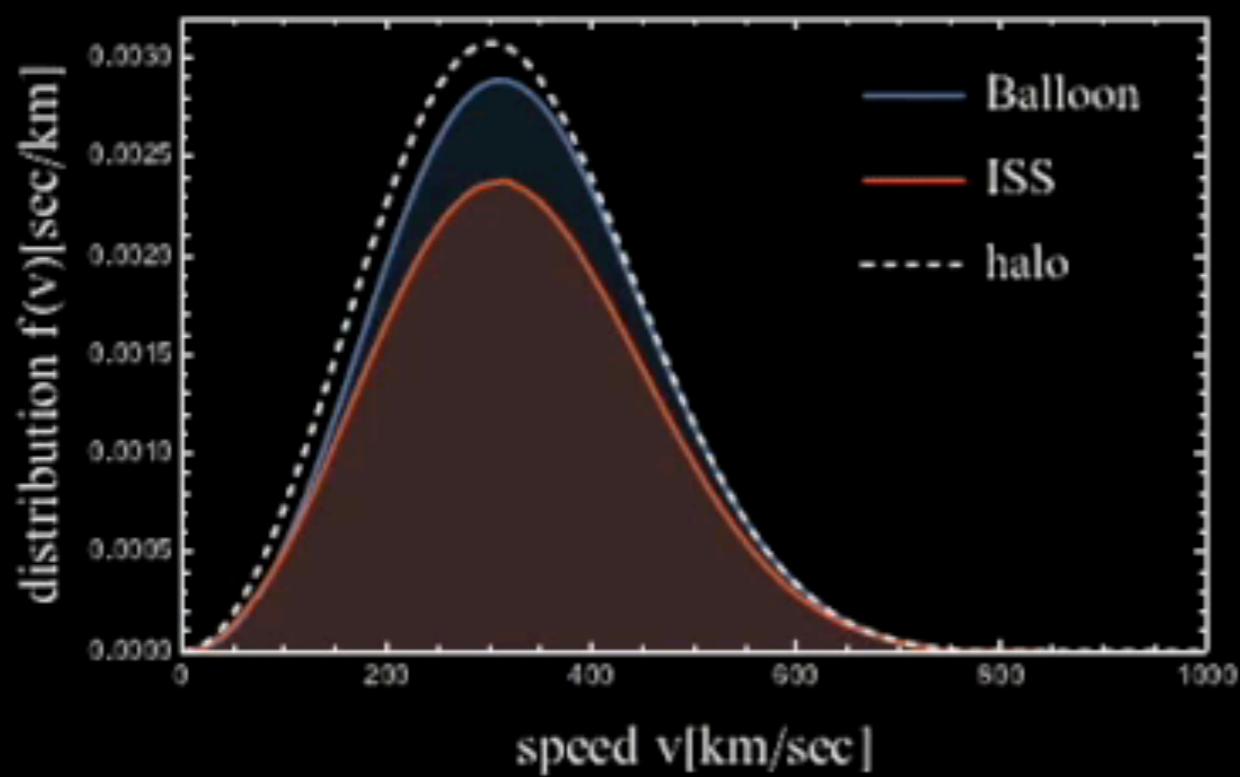
# Constraint scaling with exposure



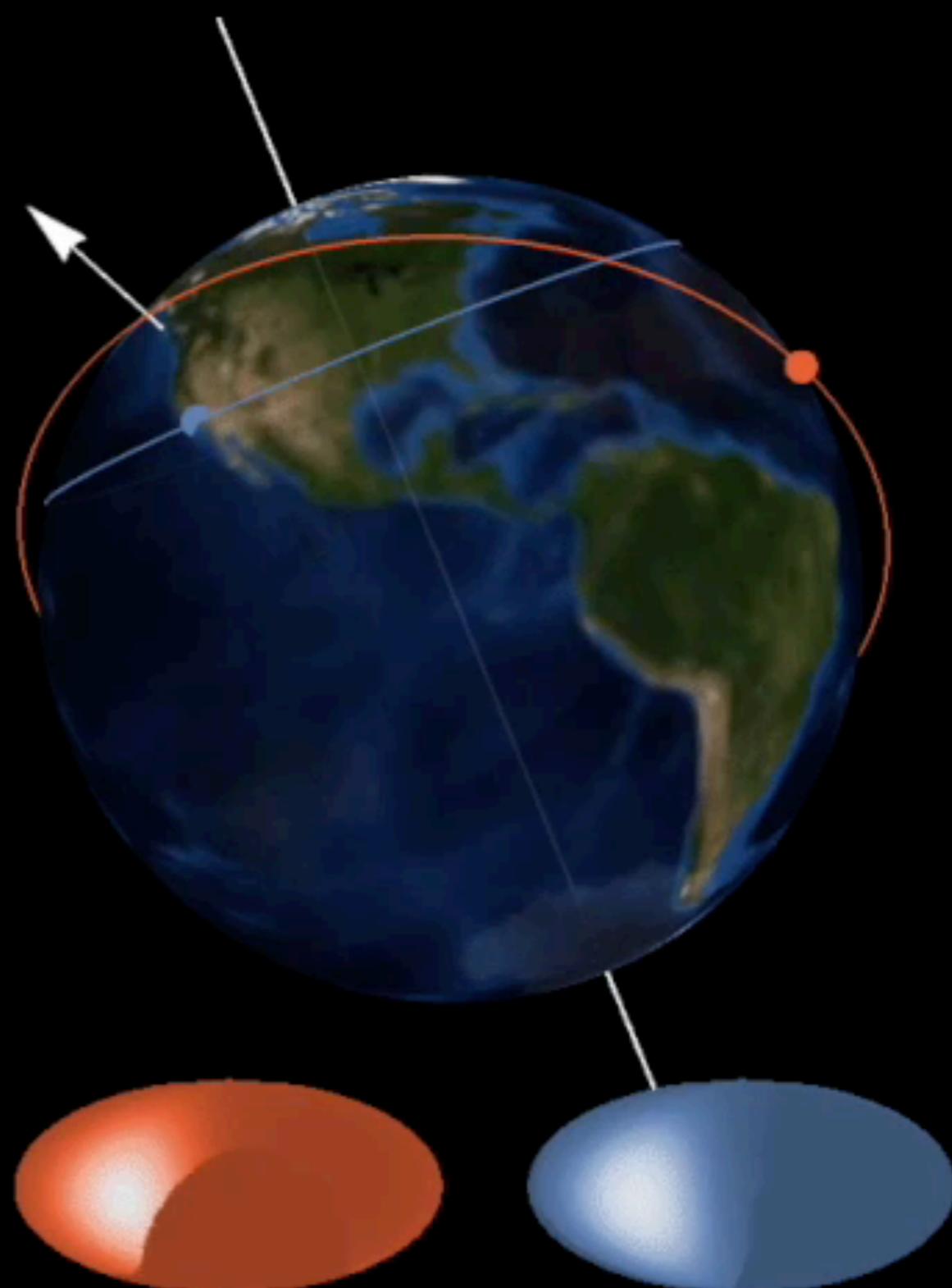
# Constraints on a sub-dominant component of strongly interacting DM



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00:00



# Solar Reflection of sub-GeV Dark Matter

III.

```

-6Newton*mSun/u2; //3. p parameter double p = JxJ/GNewton/mSun; //4. Eccentricity double e = sqrt(
y()).normalized(); Eigen::Vector3d ax_x = cos(theta1)*x1.Position().normalized() + sin(theta1)*x1.*;
ta2)*ax_y; //5. New velocity Eigen::Vector3d v2 = sqrt(GNewton*mSun/p)*(e*sin(theta2)*x2.normalized();
// double F2 = acosh((e+cos(theta2))/(1.0+e*cos(theta2))); // double M2 = e*sinh(F2)-F2; // double t2 = aq
instance at which we sample from the halo distribution double R=100.0*AU; if(R<100.0*AU) { cerr <<"Warning in
placeholders!_1,vEarth); double u = Rejection_Sampling(ndt,0.0,(vesc+vEarth),ymax,PRNG); //Velocity Directio
random Point on a flat disk at distance R Eigen::Vector3d ez=-vIni.normalized(); Eigen::Vector3d ex(0,ez*2,
*(cos(phi)*ex+sin(phi)*ey); // cout <<"Norm = "<<xini.norm()/AU<<endl; // cout <<"Norm = "<<(R*ez).norm()/A
()&[0]/rSun<<"\t"<<IC.Position()[1]/rSun<<"\t"<<IC.Position()[2]/rSun<<"\t"<<IC.Radius()/rSun<<"\t"<<IC.Velocity(
ler_Shift(IC,rMax,model); } //2. orbit simulation //Right hand sides of the 1st order equations of motion. double
ch Euler_Cromer // void EC_Step(double &t,double &r,double &v,double &phi,double J,double dt,Sun::Model &model) {
{ // //RK coefficients: // double k_r[4]; // double k_v[4]; // double k_p[4]; // k_r[0]=dt*drdt(v); // k_v[0]=
k_r[2]=dt*dvdt(r+k_r[1]/2.0,J,model); // k_p[2]=dt*dphidt(r+k_r[1]/2.0,J); // k_r[3]=dt*drdt(v+k_v[2]);
k_v[2]=dt*dvdt(r,J,model); k_p[0]=dt*dphidt(r,J); k_r[1]=dt*drdt(v+k_v[0]/4.0); k_v[1]=dt*dvdt(r+k_r[0]);
k_v[0]=dt*dvdt(r,J,model); k_r[2]=dt*drdt(v+1932.0/2197.8*k_v[0]-7200.0/2197.8*k_v[1]+7296.0/2197.8*k_v[2]); k_v[3]=dt*drdt(v+1932.0/2197.8*k_v[1]+7296.0/2197.8*k_v[2]); k_v[3]=dt*drdt(v+1932.0/2197.8*k_v[1]+7296.0/2197.8*k_v[2]); k_v[4]=dt*dvdt(r+439.0/216.0*k_r[0]-a.0*k_r[1]
[J]-3544.0/2565.0*k_v[2]+1859.0/4184.0*k_v[3]-11.0/48.0*k_v[4]); k_v[5]=dt*dvdt(r-8.0/27.0*k_r[0]+2.0*k_r[1]-354
double r4= r+25.0/216.0*k_r[0]+1488.0/2565.0*k_r[2]+2197.0/4181.0*k_r[3]-1.0/5.0*k_r[4]; double v4= v+25.0/216.0
*0*k_r[2]+28561.0/56430.0*k_r[3]-9.0/50.0*k_r[4]+2.0/55.0*k_r[5]; double v5= v+16.0/135.0*k_v[0]+6656.0/12825.0*k_v
[J]-r4),abs(v5-v4),abs(phi5-phi4)); std::vector<double> tolerance = {1.0*km,1e-3*km/sec,1e-6}; //New stepsize
(deltas),std::end(deltas)); //Next steps if(err[0]<tolerance[0]&&err[1]<tolerance[1]&&err[2]<tolerance[2]) { if(r<
logxi -= speed*dt/mfp; } t+= dt; r= r4; v= v4; phi= phi4; dt= std::max(dtMin, std::min(delta*dt,dtMax)); } else { dt
d:vector<Eigen::Vector3d>& axes) { double v_phi = J/pow(r,2); Eigen::Vector3d xNew = r*(cos(phi)*axes[0]+sin(phi)*ax
scattering or (b) leaving the sun. bool Propagate(Event& x0,DM_Particle& DM,Sun::Model &model, std::m
ty()).normalized(); Eigen::Vector3d ax_y = ax_x.cross(ax_x); std::vector<Eigen::Vector3d> axes = {ax_x,ax_y
45_Step(t,r,v_r,phi,J,dt,logXi,DM,model); if(Nx10==0) { Event xNew=PlaneTo3D(t,r,phi,v_r,J,axes); f <<xNew.Position
Speed()-model.vEsc2(xNew.Radius())); <<"\t" <<InUnits(xNew.Speed(),km/sec) <<endl; } // double dd = (xOld.Position
xOld<rMax&&r>rMax&&(v_r+v_r+J*J/r/r)>model.vEsc2(r)) { propagate=false; x0=PlaneTo3D(t,r,phi,v_r,J,axes); } // else
er(Event& x0,DM_Particle& DM,Sun::Model &model, std::mt19937& PRNG) { // double speed0=x0.Speed(); // cout <<"Scatt
ordinates(1.0,ThetaSample(PRNG),PhiSample(PRNG)); double vRel = (vTarget-x0.Mass*velocity()).norm(); Eigen
speed0<<endl; // if(speed0>sqrt(model.vEsc2(r))&&vnew.norm()<sqrt(model.vEsc2(r))) cout <<"\tcapture"<<endl; // a
del & model, unsigned int &nScattering, std::mt19937 & PRNG) { // Save trajectory of stream
(x.Speed()*x.Speed()-model.vEsc2(x.Radius()))/E0<<endl; // output // Event x = IC; bool success; //Counters nScat
ng if(r<rSun) { if(nScattering>nScattering_max) { success = false; break; } // double E1=DM.mass/2.0*(x.
0*(x.Speed()*x.Speed()-model.vEsc2(x.Radius()))/E0<<endl; // if(E1>0 & E2<0) { // cout <<"capture"<<endl;
<<"\t" << r / rSun << endl; // T. close () // // if ( x . s p e e d () < s q r t ( m o d e l . v
Position()[0]/rSun<<"\t"<<xFinal.Position()[1]/rSun<<"\t"<<xFinal.Position()[2]/rSun<<"\t"<<xFinal.Radius()
ccess=false; if(x.Time()/sec<9999) return false; return success; } Result Generate_Data(Configuration& config
fig.numprocs-1)? 0 : config.rank+1; int tag =0; MPI_Status status; MPI_Request send_request; // /Datapoin
> data; data.resize(config.nRings); //Counters //Total number of simulated particles unsigned long int G_Cou
td::vector<unsigned long int> L_Counter_Data_new(config.nRings,0); //Number of passes // std::vector<unsig
umber of scatterings; std::vector<double> G_nScattering_Av(config.nRings,0.0); std::vector<double> L_nScat
I_Isend(&G_Counter_Data.front(),config.nRings,MPI_UNSIGNED_LONG,destination,tag,MPI_COMM_WORLD
ING); unsigned int nScattering=0; bool success = Simulate_Trajectory(x,DM,model,nScattering,PRNG)
+L_nScattering_Av[IsoRing]+nScattering)/L_Counter_Data[IsoRing]; double speed=x.Speed(); f[nS
.COMM_WORLD,&flag,&status]; if(flag) { //Receive the tokens MPI_Recv(&G_Counter_Data.front(),config.nRi
ter_Data[i]+=L_Counter_Data_new[i]; L_Counter_Data_new[i]=0; } // cout <<config.rank <<"\t" <<G_Count
i; else if (nMin1>=config.nData) tag = status.MPI_TAG; //Pass on the tokens, unless you are the very la
length cout <<"\r"; for(int i=0;i<2.0*BarLength;i++)cout <<" "; cout <<"\r"; for(int i=0;i<BarLength
8) { cout <<"\r"; for(int j=0;j<10*BarLength;j++) cout <<" "; cout <<"\r"; } // for(int i=P
4_G_Counter_Free,1,MPI_UNSIGNED_LONG_LONG,MPI_SUM,MPI_COMM_WORLD); MPI_Allreduce(&L_nScat
t> Global_Data; for(int i = 0;i<config.nRings;i++) { unsigned long int Global_sampleSize; MPI
recv_displs[config.numprocs]; MPI_Allgather(&L_Counter_Data[i],1,MPI_UNSIGNED_LONG,&data_loc
_L_sampleSize); // MPI_Gatherv(&data[i].front(),data.size(),mpi_datapoint,&Ring_data.front());
} MPI_Barrier(MPI_COMM_WORLD); // for(int i=0;i<config.nRings;i++) // { // if(config.r
on,1,MPI_DOUBLE,MPI_MAX,MPI_COMM_WORLD); return Result(Global_Data,DM,G_Counter_Simulati
n, std::vector<double>& nscav,double dt) { data=dat; particle = p; // sample_size
} } nScatterings_mean=nscav; nScatterings_mean_tot=0.0; for(unsigned int i=0;i<
on & config) { if(config.rank==0) { std::cout <<"Simulation summary
<<Round(1.0*nSimulations/duration)"/sec)<<std::endl; if(config.nRings==1) st
)<<" ", <<Round(100.0*nFails/nSimulations)<<")<<std::endl <<"\tDuration[s]:"
_size[i] <<"\t\t\t" <<Round(nScatterings_mean[i])<<std::endl; } } } #inc
s_r'unctions.h>; using namespace libconfig; //1. Struct with input param
ing nbar=nb; //Parallelisation rank = myrank; numprocs= np; } Configuration
`const FileIOException &fwork) { std::cerr << "I/O error while re
try { SimID = cfg.lookup("simID").c_str(); } catch(const
FileIOException& e) { std::cerr << "FileIOException: " << e.what() << endl; exit(EXIT_FAILURE); } // / Insert
"None."<<endl<<endl; } //2. Event

```

# The Idea of Solar Reflection of DM

- direct detection experiments can only probe DM masses above

$$m_\chi^{\min} = \frac{m_N}{\sqrt{\frac{2m_N}{E_R^{\text{thr}}} v_{\max} - 1}}$$

- Experimentalists have pushed this mass down by decreasing the target mass and the recoil threshold, e.g. the CRESST collaboration.
- What if some process could increase the maximum DM speed somehow?

$$v_{\max} > v_{\text{esc}}^{(\text{gal})} + v_{\oplus}$$

- Elastic scatterings on hot solar targets inside the Sun could do just that.

$t = 0.$  hr

$N_s = 0$

$v_x = 368 \frac{\text{km}}{\text{s}}$

$E_x/E_0 = 1.$



$m_\chi = 100 \text{ MeV}$

$\sigma_p = 0.2 \text{ pb}$

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# DM Scatterings in the Sun

- Scattering rate in a spherical shell of the Sun:

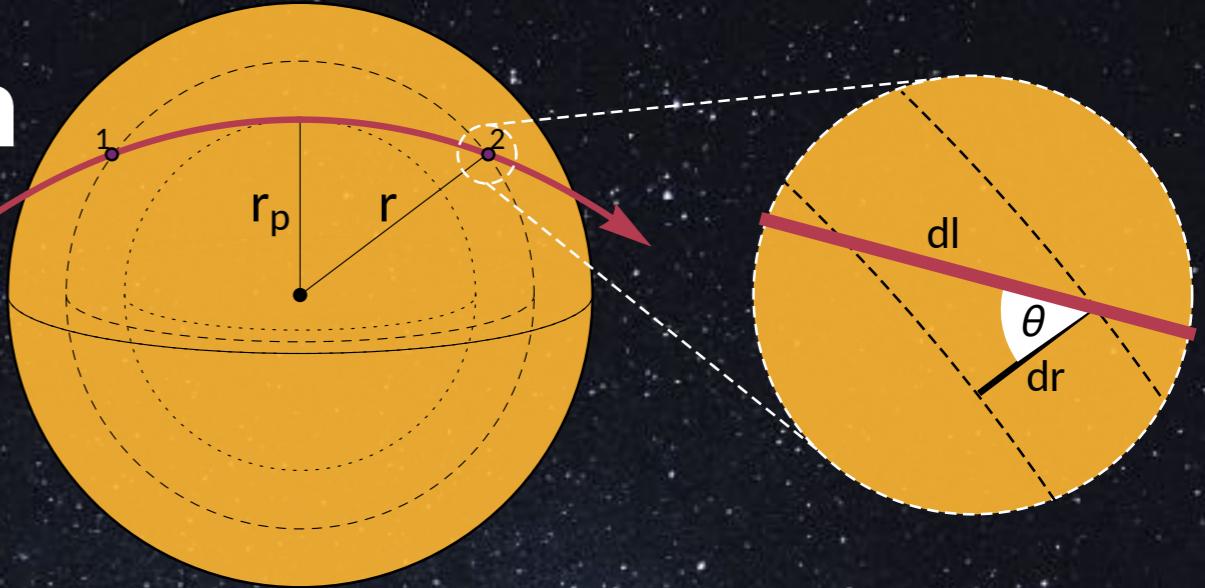
$$dS = \underbrace{d\Gamma}_{\text{passing rate}} \times \underbrace{dP_{\text{scat}}}_{\text{scattering probability}} \times \underbrace{P_{\text{shell}}}_{\text{prob. to reach shell}}$$

- The three factors are given by

$$d\Gamma = 4\pi R^2 d\Phi_\chi = \pi n_\chi f_\chi(u) \frac{du dJ^2}{u}, \quad dP_{\text{scat}} = \frac{dl}{w} \times \Omega(r, w),$$

$$P_{\text{shell}}(r) = P_{\text{surv}}(r, R_\odot) \left[ 1 + P_{\text{surv}}(r_p, r)^2 \right] \Theta \left( w(u, r_p) r_p - J \right).$$

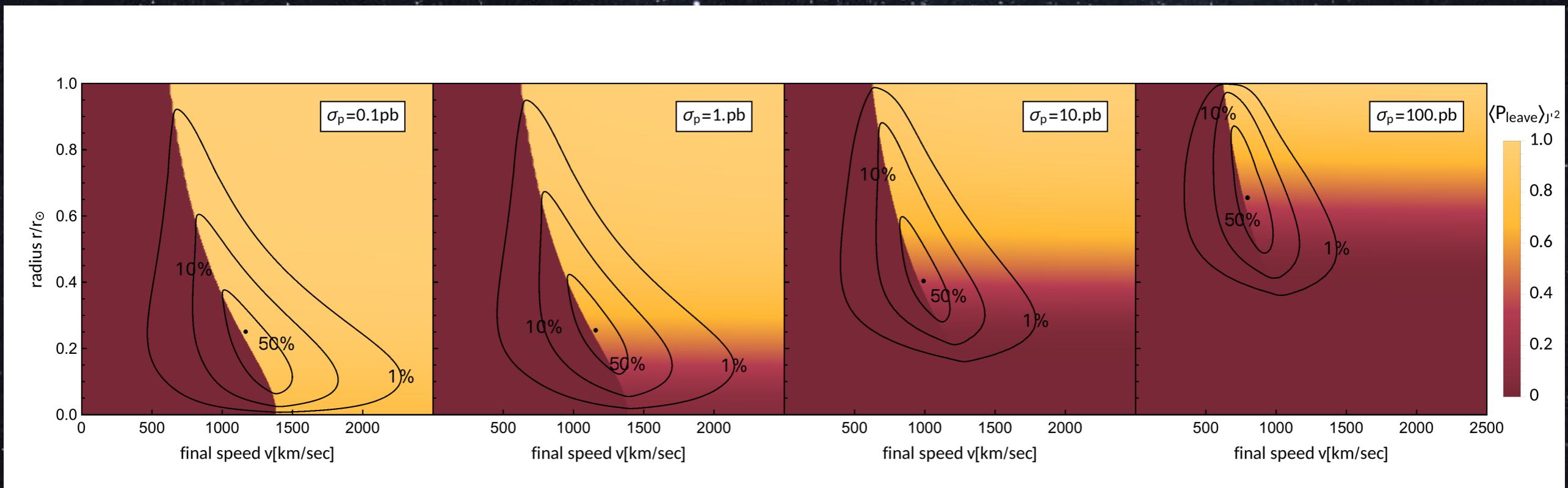
As opposed to Gould's formalism, this scattering rate applies not just to the single scattering regime.



A. Gould, *Astrophys. J.* 321, (1987), 571  
*Astrophys. J.* 321, (1987), 560  
*Astrophys. J.* 388, (1992), 338

# Scattering rate and leaving probability in the Sun

$$\frac{dS}{drdv} = \int d\Gamma \frac{dP_{\text{scat}}}{drdv} P_{\text{shell}}(r) = \pi n_\chi \int_0^\infty du \int_0^{w(u,r)^2 r^2} dJ^2 \frac{f_\chi(u)}{u} \frac{d\Omega}{dv} (w(u, r) \rightarrow v) \left[ w(u, r)^2 - \frac{J^2}{r^2} \right]^{-1/2} \times P_{\text{surv}}(r, R_\odot) [1 + P_{\text{surv}}(r_p, r)^2]$$



# Detection of Reflected Dark Matter

- DM flux of solar reflection

$$\frac{d\mathcal{R}}{dvdr} = \frac{dS}{dvdr} \langle P_{\text{leave}}(v, r) \rangle_{J^2}$$

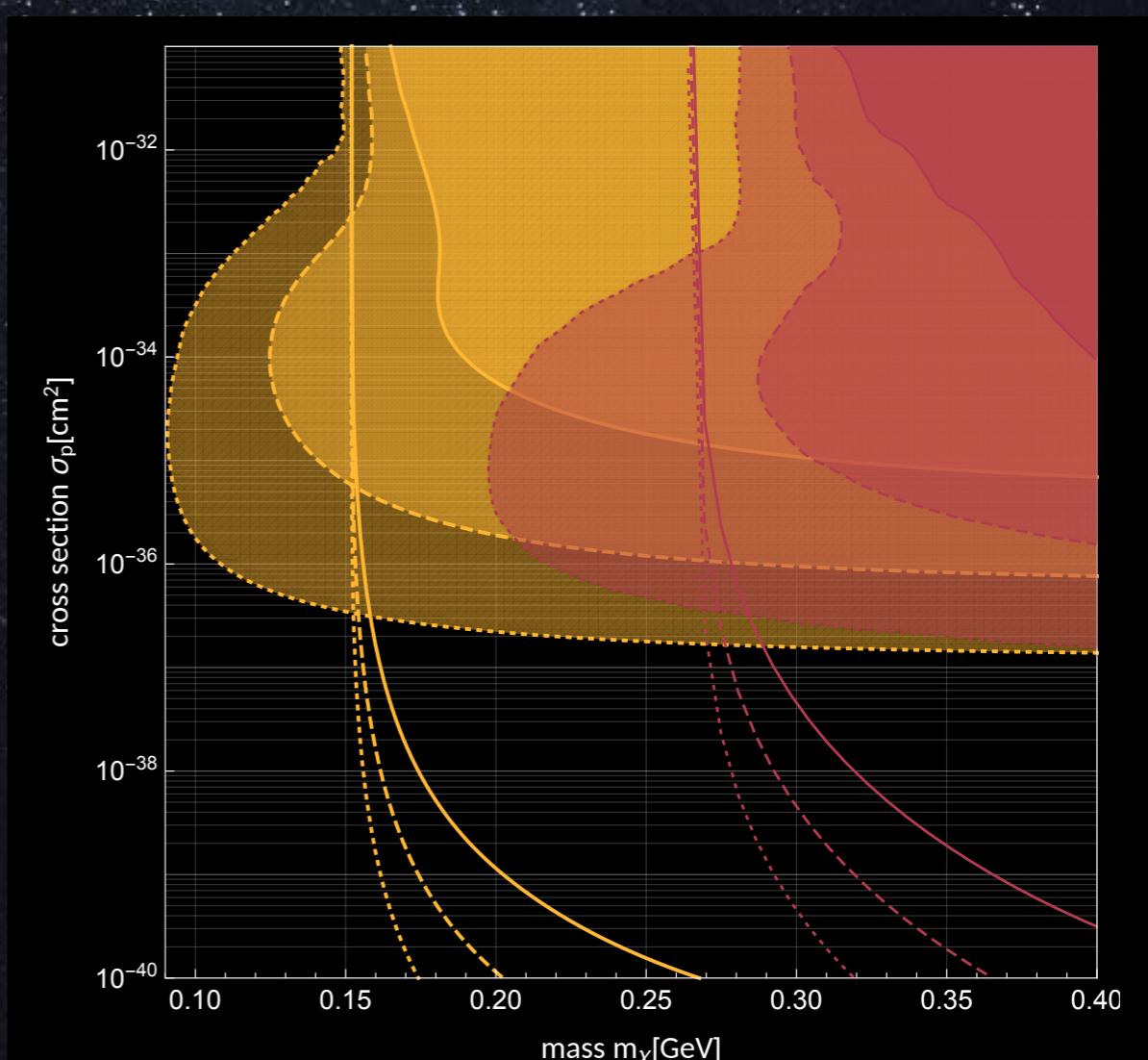
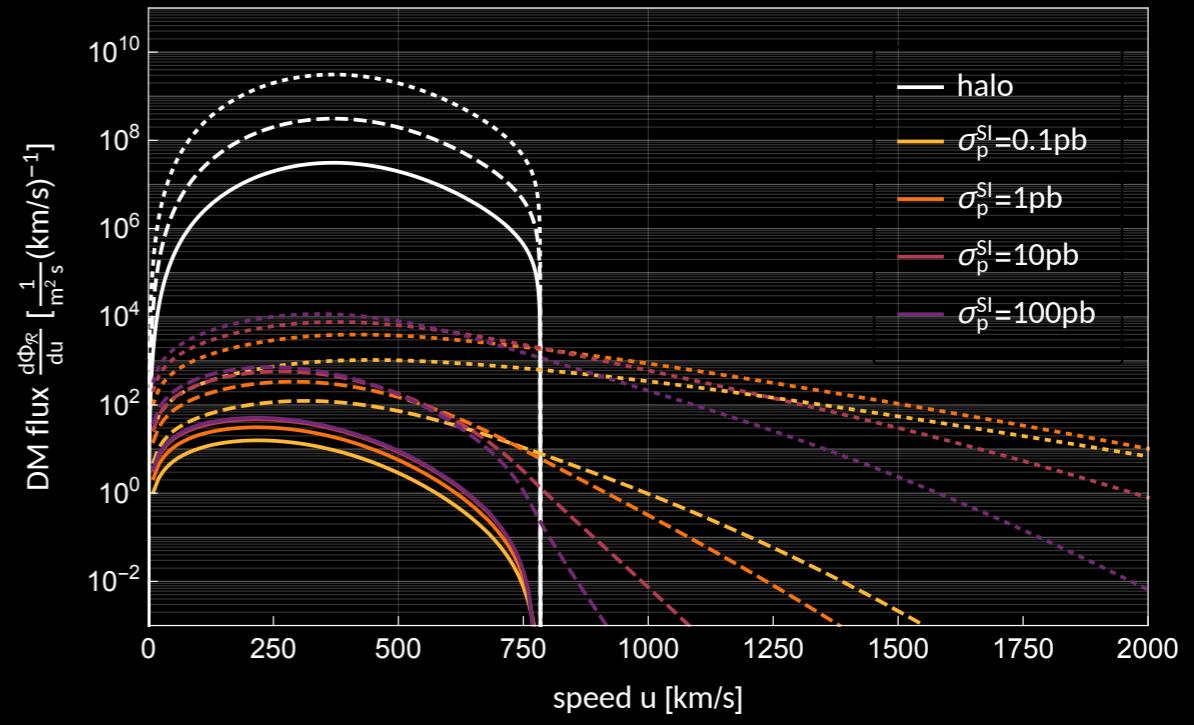
$$\frac{d\mathcal{R}}{du} = \int_0^{R_\odot} dr \frac{d\mathcal{R}}{dvdr} \frac{dv}{du} \Big|_{v=\sqrt{u^2 + v_{\text{esc}}(r)^2}}$$

'red-shift' to the Earth's location

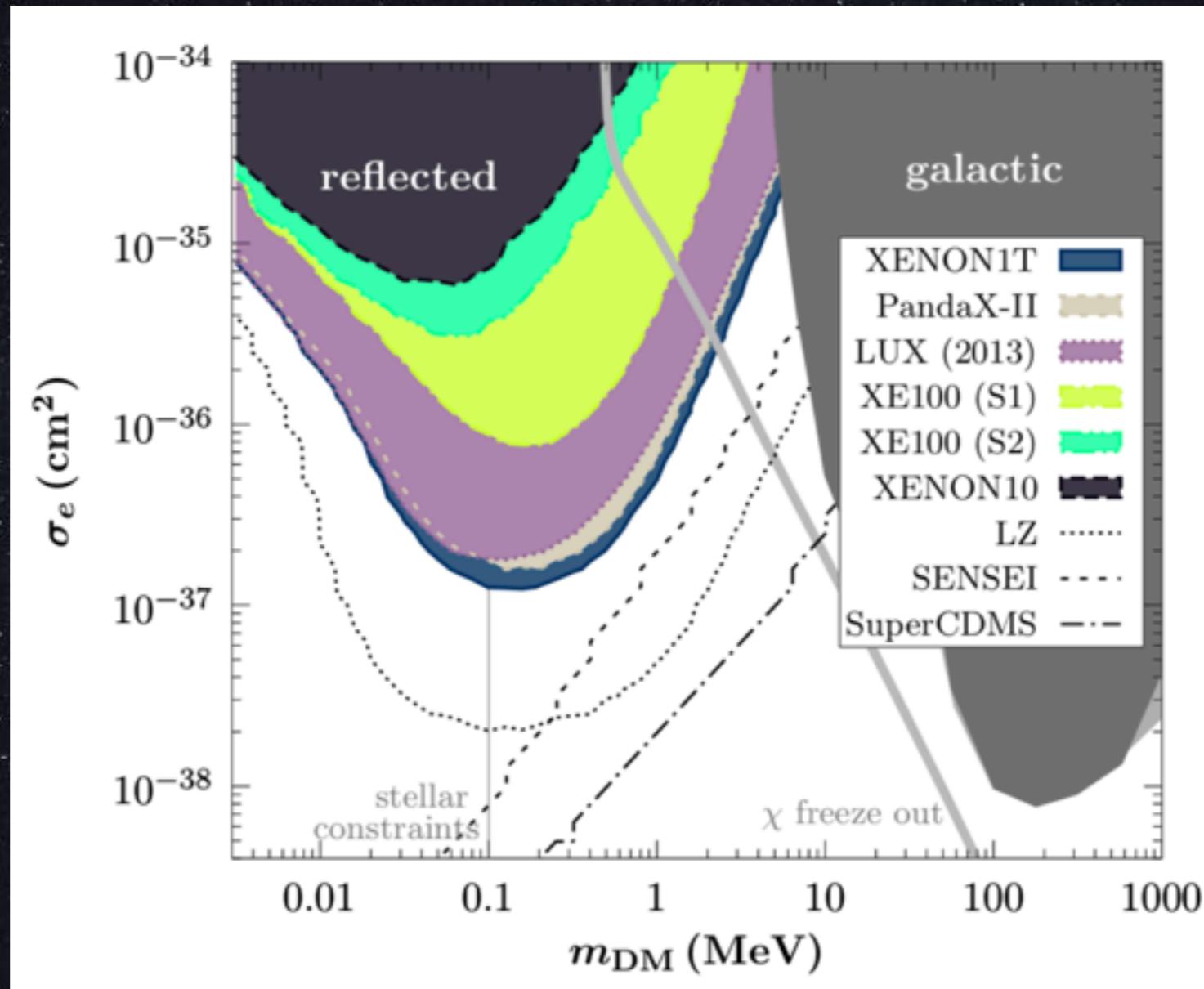
- Include into recoil spectrum

$$\frac{dR}{dE_R} = \frac{1}{m_N} \int_{u_{\min}(E_R)}^{\infty} du \left[ \frac{\rho_\chi}{m_\chi} u f_\oplus(u) + \frac{1}{4\pi\ell^2} \frac{d\mathcal{R}}{du} \right] \frac{d\sigma_N}{dE_R}$$

- Compute likelihoods and constraints as usual.



# Detection of Reflected Dark Matter with electrons



H. An, M. Pospelov, J. Pradler, A. Ritz, Phys. Rev. Lett. 120 (2018), 141801

# Features of a solar reflection signal

- DM flux from the Sun → directional detection
- **Higher exposures probe lower masses.**
- (Semi-) halo-model independent.
- A new type of annual modulation (~7% with peak in January).
- Our results so far are conservative (single scattering, only nuclear targets).  
→ MC simulations

# MC Simulations of DM Particles in the Sun

Extend the Earth simulations in **five** ways:

1. **Solar model:** density, composition, temperature.
2. **Gravity:** Solve the equations of motion numerically.
3. **Temperature:** thermal motion of the solar targets.
4. **Targets:** Include electrons.
5. **Initial conditions:** Generalize generation of ICs to account for gravitational focussing.

# The mean free path inside the Sun

- When simulating DM passing through the Earth we computed the mean free path via

$$\lambda^{-1} = \sum_i n_i \times \sigma_i .$$

- However, this is only valid for the resting-targets assumption.
- Inside the Sun, the important quantity is the **scattering rate**.

$$\Omega = \sum_i n_i \times \sigma_i \times \langle |w - v_i| \rangle .$$

- If we still want to define a mean free path, we can do so.

$$\lambda^{-1} = \frac{\Omega}{w} = \sum_i n_i \times \sigma_i \times \frac{\langle |w - v_i| \rangle}{w}$$

$t = 0.$  hr

$N_s = 0$

$v_x = 456 \frac{\text{km}}{\text{s}}$

$E_x/E_0 = 1.$

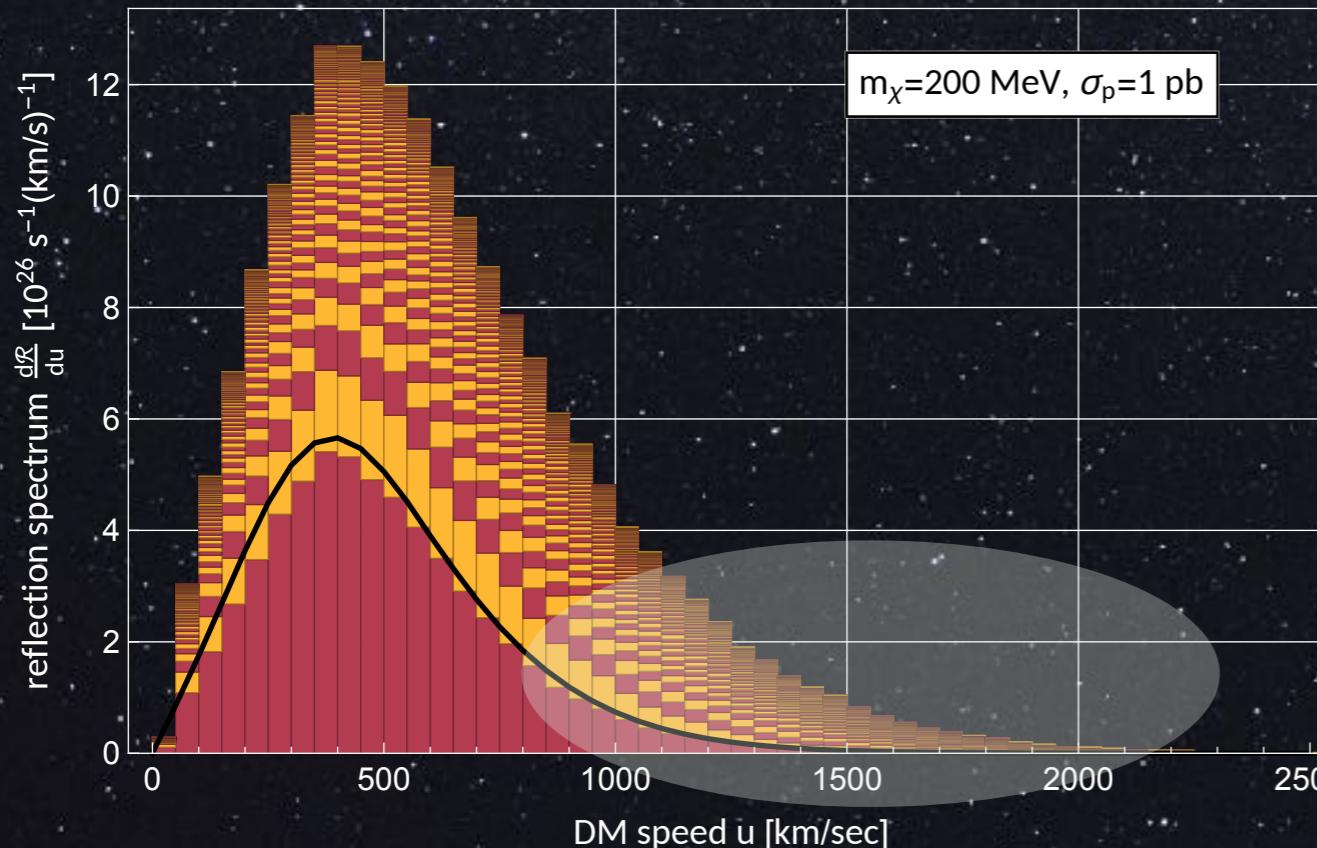
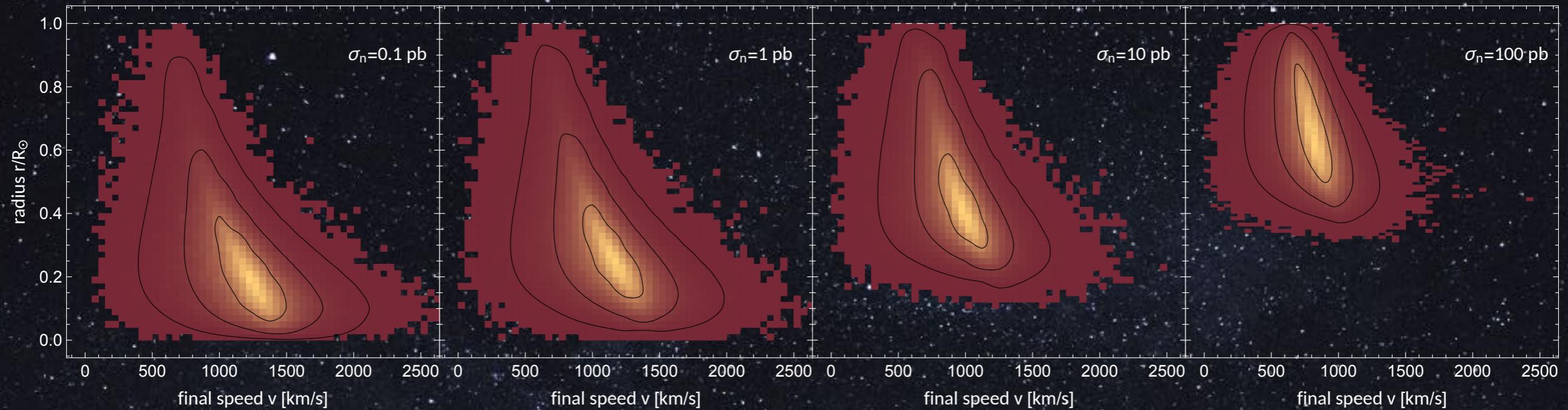


$m_\chi = 100 \text{ MeV}$

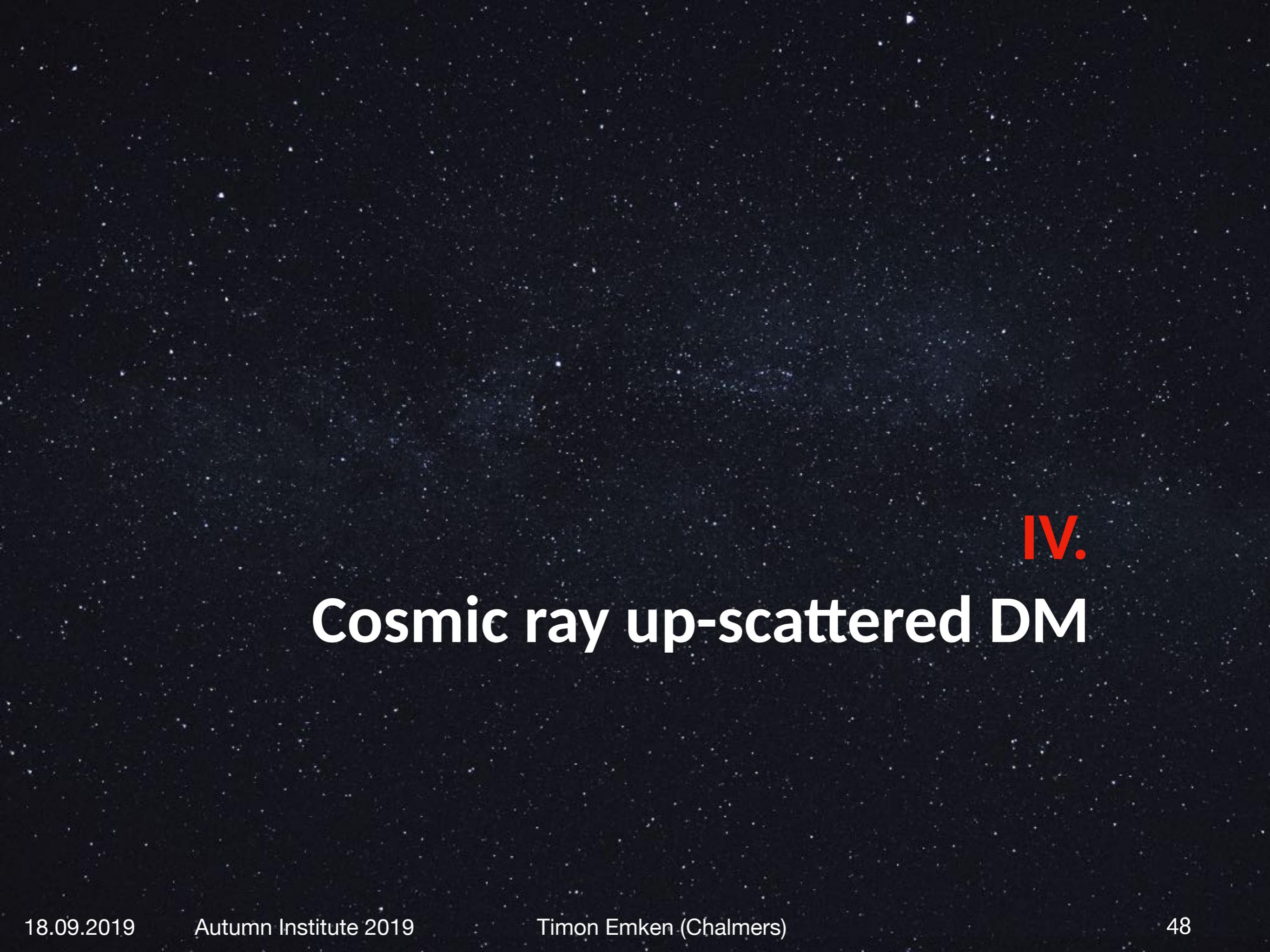
$\sigma_p = 0.2 \text{ pb}$

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# First MC Results for Solar Reflection of Dark Matter

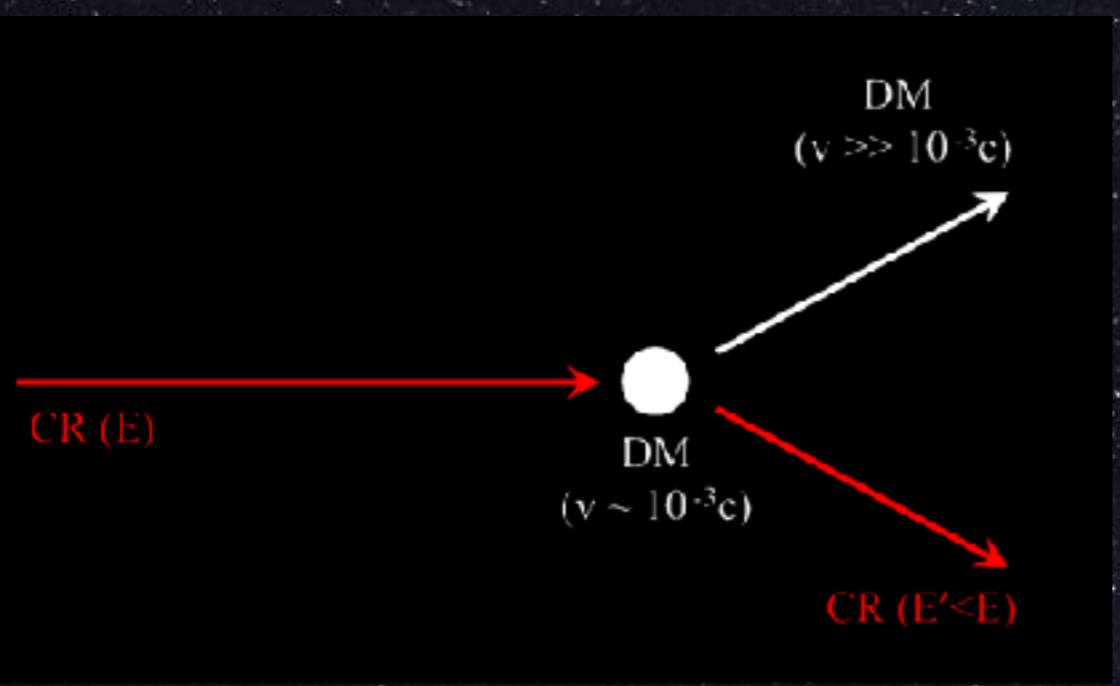


- Comparing the first scattering to our analytic results shows great agreements.
- The inclusion of multiple scatterings greatly enhances the high energy tail of the reflection spectrum.



# IV. Cosmic ray up-scattered DM

# A relativistic DM flux from Cosmic Ray Scatterings

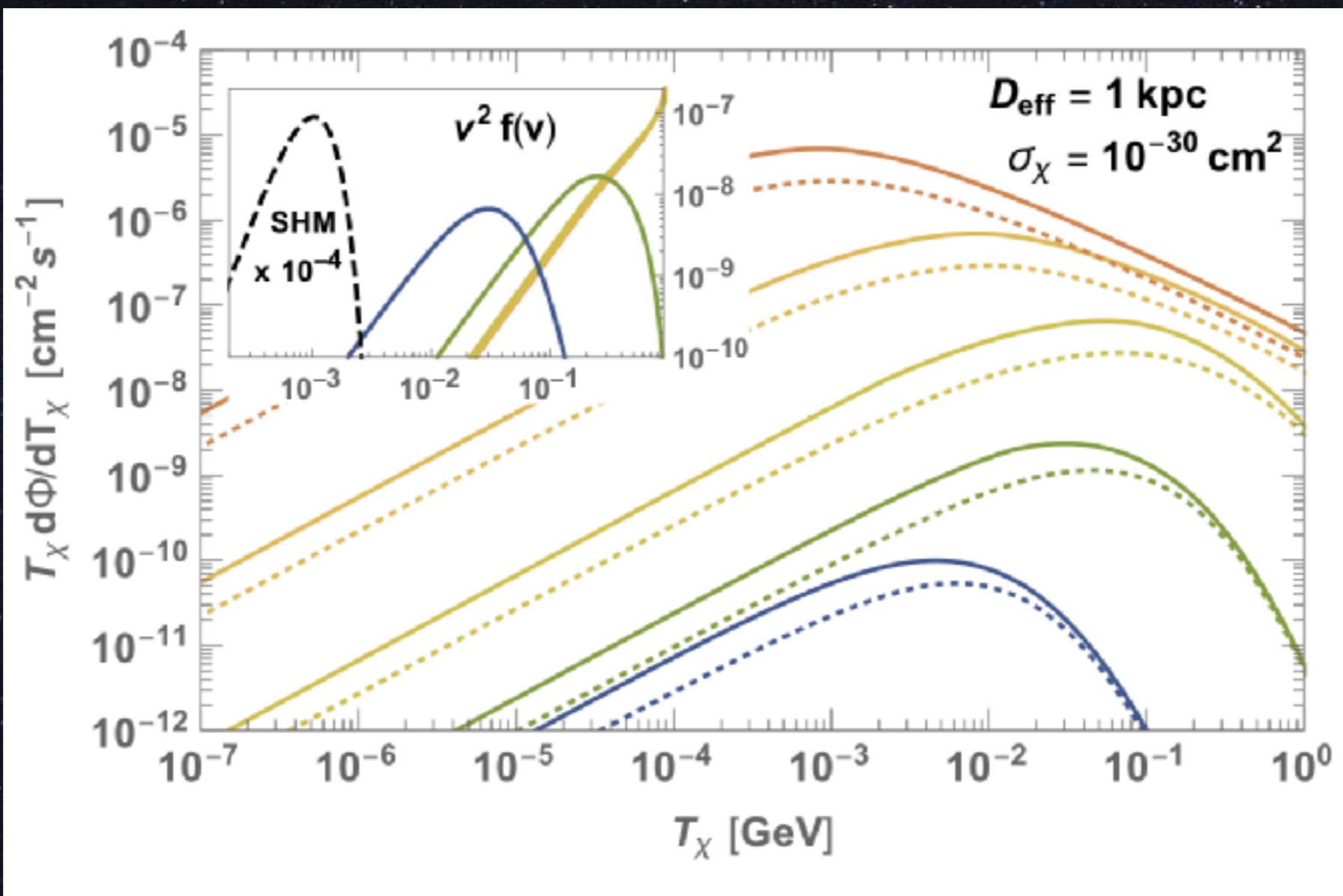


- Similar effect to solar reflection.
- DM particles get accelerated to **relativistic** speeds.

Cappiello, Beacom (2019)

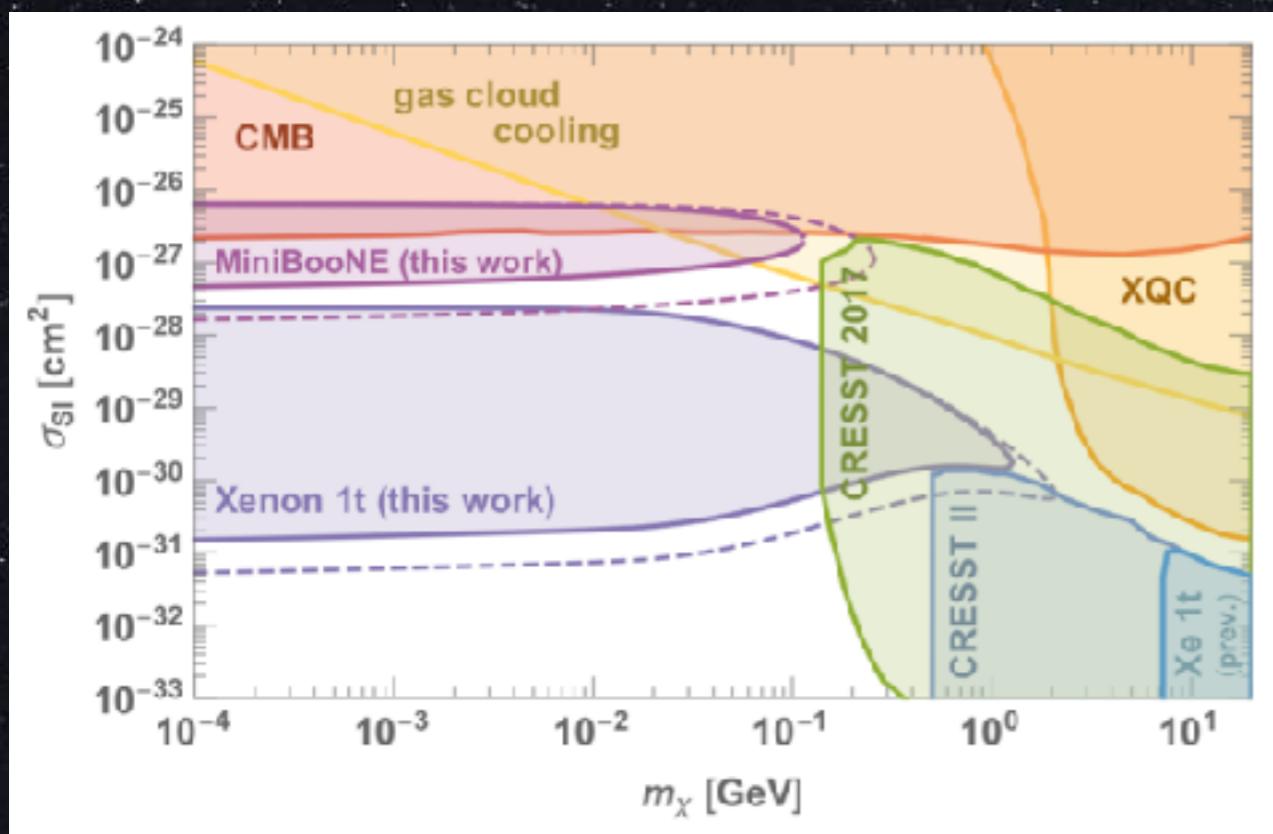
- T. Bringmann, M. Pospelov, Phys.Rev.Lett. 122 (2019) no.17, 171801, [arXiv:1810.10543]  
Y. Ema, F. Sala, R. Sato, Phys.Rev.Lett. 122 (2019) no.18, 181802, [arXiv:1811.00520]  
C. Cappiello, J.F. Beacom, [arXiv:1906.11283]  
J.B. Dent, B. Dutta, J.L. Newstead, I.M. Shoemaker, [arXiv:1907.03782]  
G. Krnjaic, S.D. McDermott, [arXiv:1908.00007]

# Spectrum of CR up-scattered DM

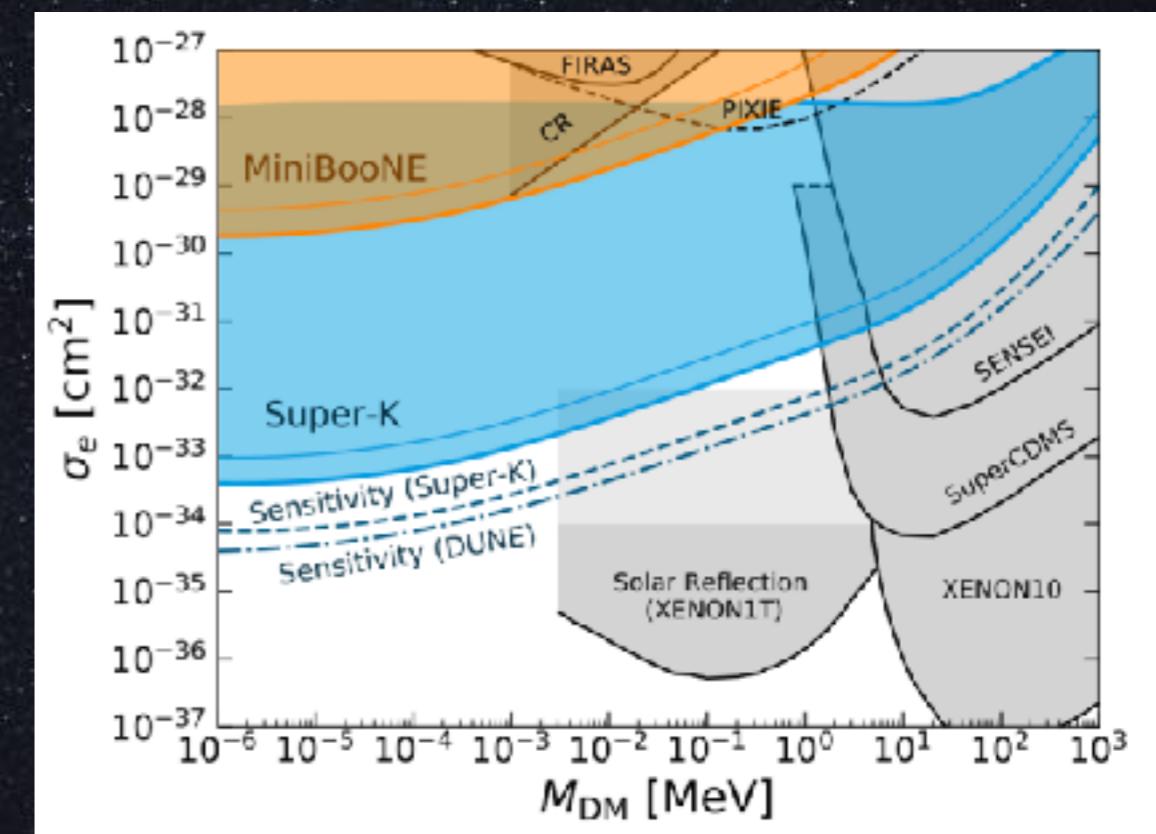


Bringmann, Pospelov (2018)

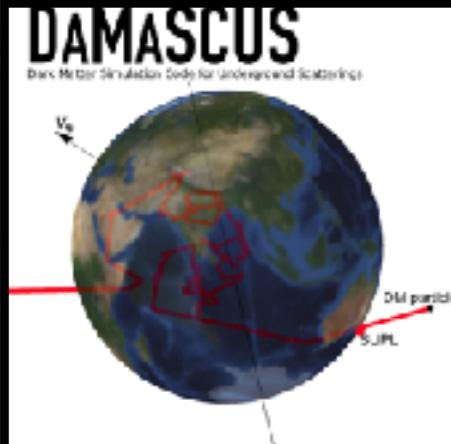
# Constraints from CR up-scattered DM



Bringmann, Pospelov (2018)



Ema, Sala, Sato, (2018)



# DaMaSCUS

## 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.
- Two versions available:
  1. DaMaSCUS
  2. DaMaSCUS-CRUST

File	Description	Last Commit
README.md	Initial commit.	May 17, 2019
bin	Update from version 1.0 to 1.1.	3 months ago
build	Update from version 1.0 to 1.1.	3 months ago
defectors	Update from version 1.0 to 1.1.	3 months ago
include	Update from version 1.0 to 1.1.	3 months ago
results	Update from version 1.0 to 1.1.	3 months ago
src	Update from version 1.0 to 1.1.	3 months ago
got_code_onak	Initial commit.	2 years ago
.gitignore	Update from version 1.0 to 1.1.	3 months ago
.travis.yml	Update from version 1.0 to 1.1.	3 months ago
LICENSE	Initial commit.	2 years ago
Makemake	Update from version 1.0 to 1.1.	3 months ago
Notes.txt	UPDATE FROM VERSION 1.0 TO 1.1.	3 months ago

<http://github.com/temken/>

## VI.

# Summary

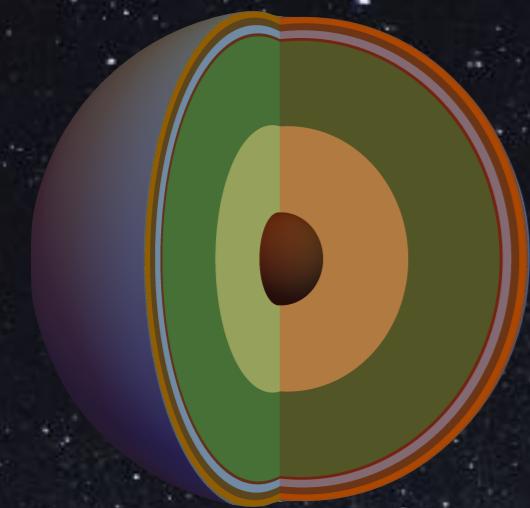
- Pre-detection scatterings change the DM properties inside a laboratory. This can have important implications for DM searches:
  1. Diurnal modulations.
  2. Loss of sensitivity due to overburden scatterings.
  3. Extended sensitivity to lower masses via solar reflection or cosmic ray up-scatterings.
- Multiple scatterings in a medium are best described by MC simulations and

# Thank you

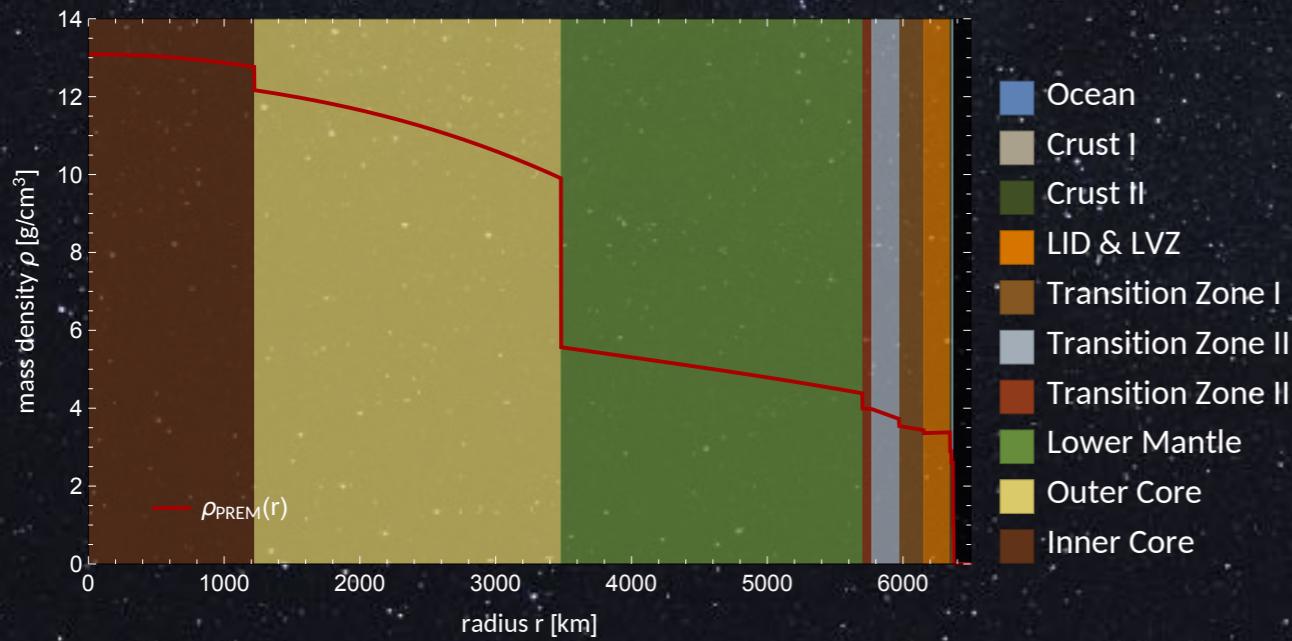
# VII. Backup Slides

# Modelling the Earth

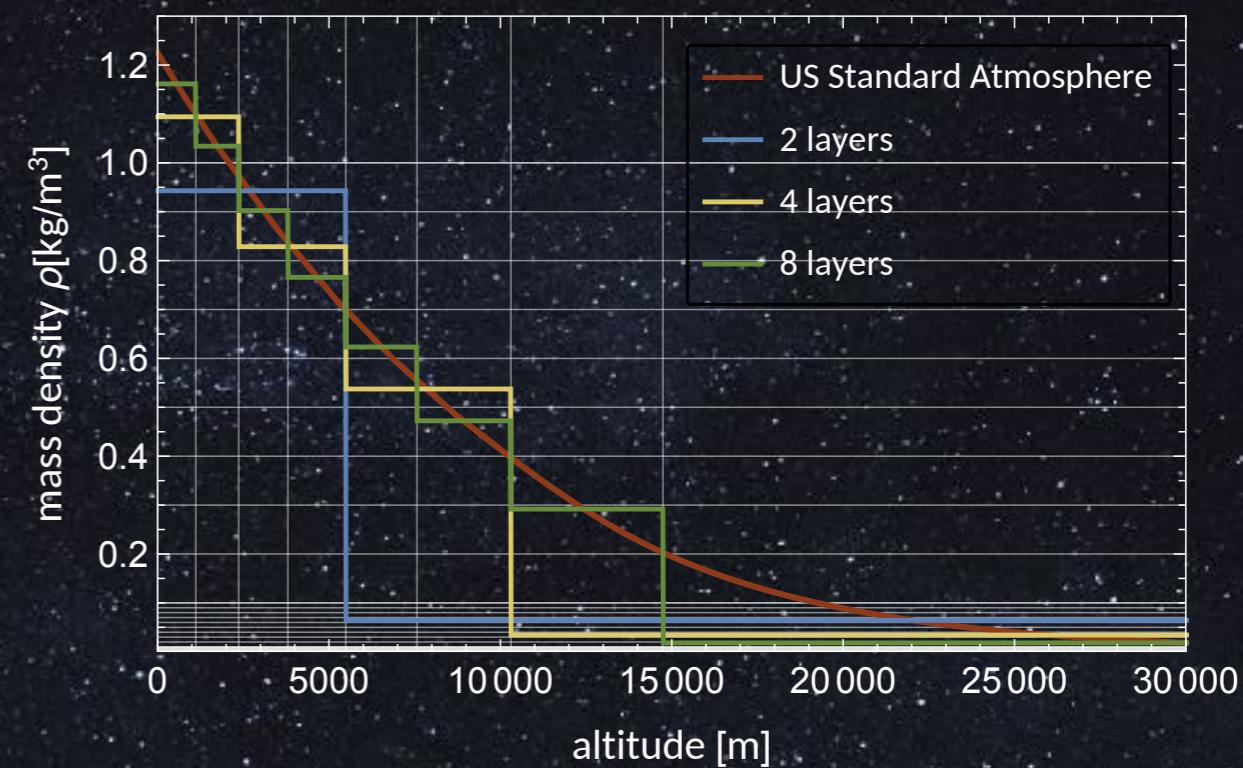
## Preliminary Reference Earth Model



- 10 mechanical layers
- 2 compositional layers



## US Standard Atmosphere



## Earth Crust

- constant mass density
- composition

W. McDonough, Treatise on Geochemistry 2 (2003) 568

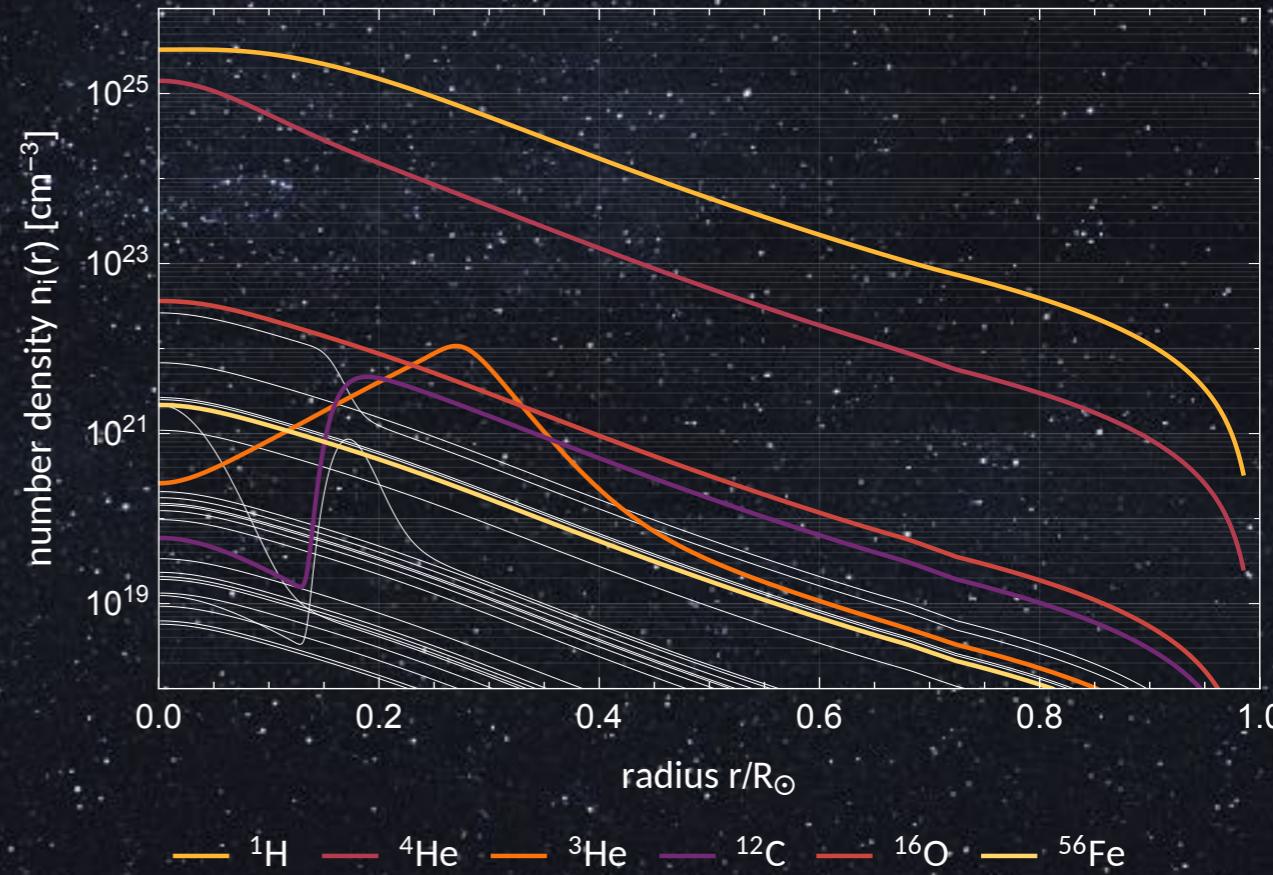
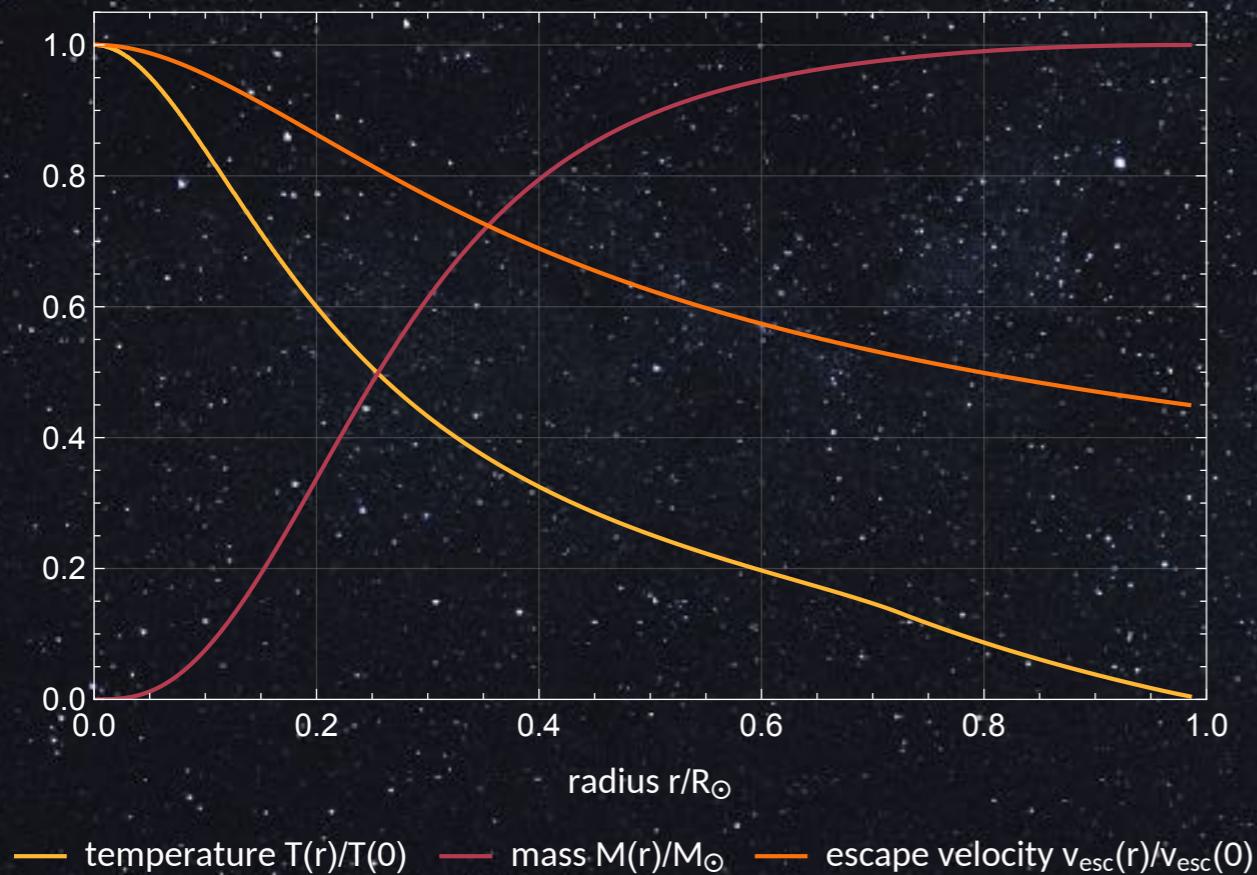
A.M. Dziewonski, D.L. Anderson, Phys. Earth Planet. Interiors 25 (1981) 297-356

R. Rudnick, S. Gao, Treatise on Geochemistry, p. 1-64, Oxford, (2003)

U.S. Government Printing Office, U.S. Standard Atmosphere, (1976)

# Modelling the Sun Standard Solar Model AGSS09

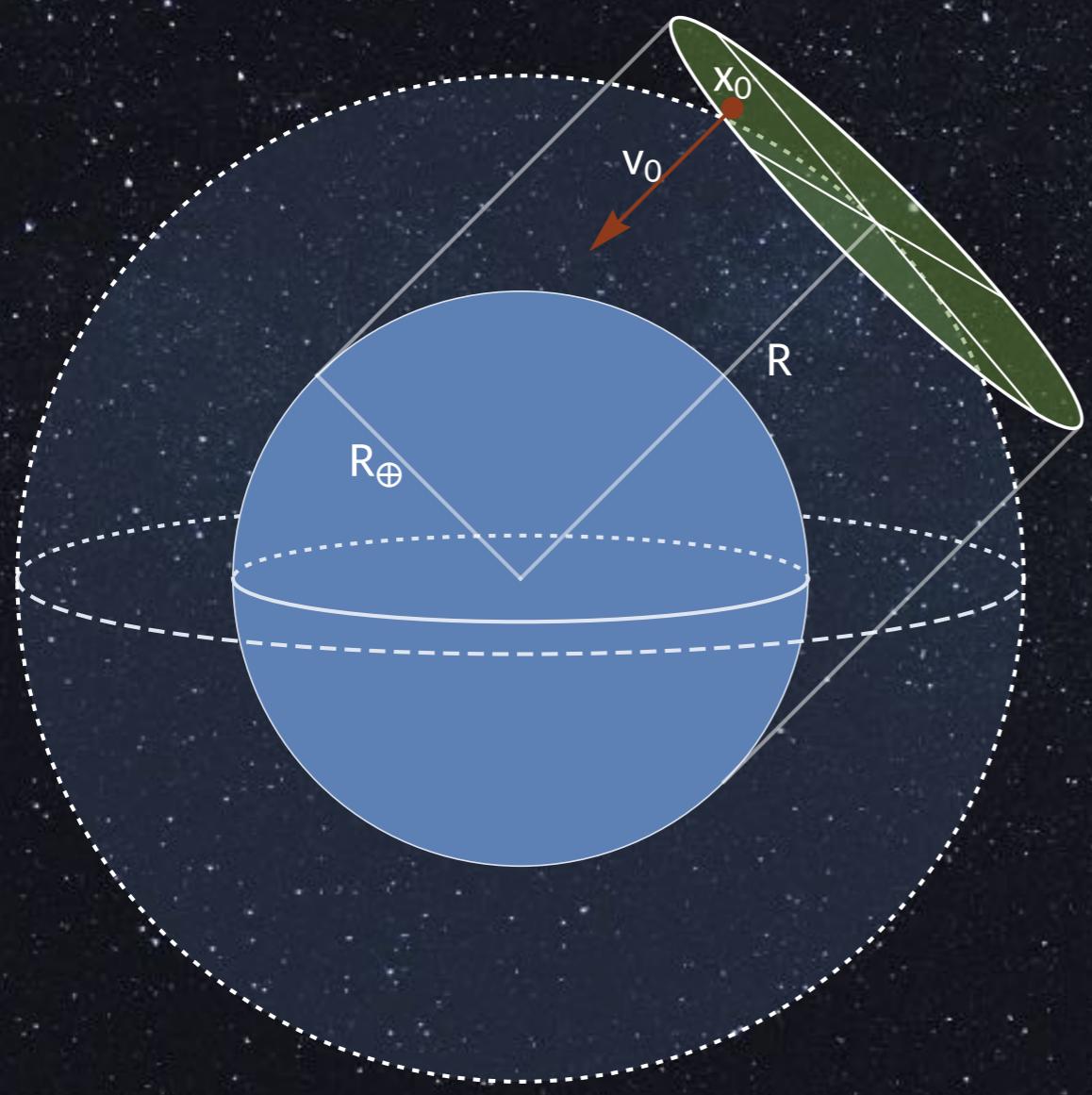
A. Serenelli et al., *Astrophys. J.* 705 (2009), L123-L127



- Mass Function  $M(r)$
- Temperature  $T(r)$

- Nuclear composition
- Number densities

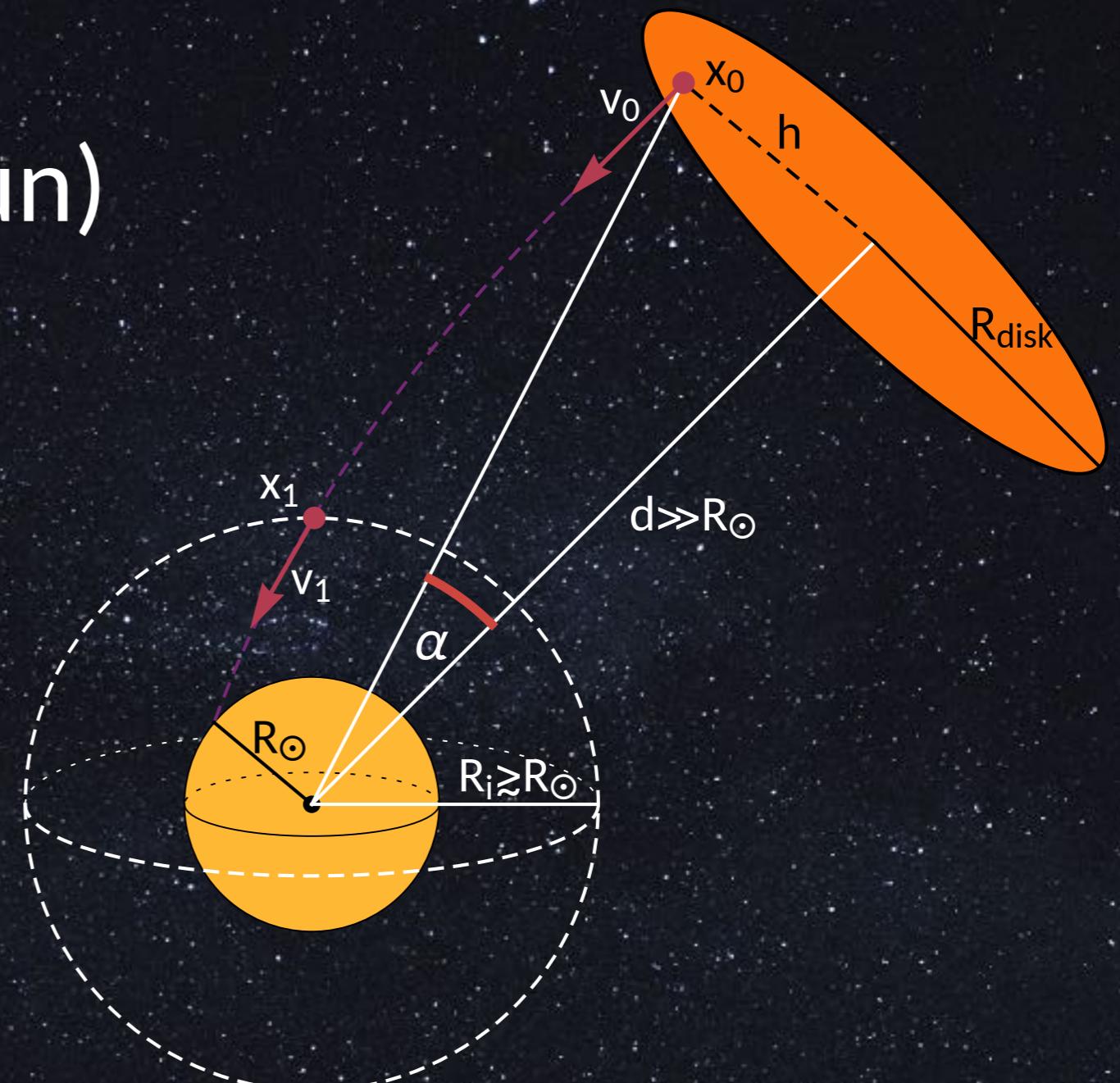
# Initial Conditions (Earth)



- 1. Initial velocity:** Sample from the isotropic halo distribution, and boost into the Earth's rest frame.
- 2. Initial position:** To ensure a homogenous distribution of initial DM positions, and an Earth "hit", all particles start from a circular disk, or from within a cylinder parallel to  $v_0$ .

# Initial Conditions (Sun)

1. Sample a velocity  $u$  far away from the Sun from the halo.
2. Sample the initial position on a disk.
3. Propagate the particle analytically on its hyperbolic Kepler orbit to a location close to the Sun.



$$R_{\text{disk}}(u) = \sqrt{1 + \frac{v_{\text{esc}}^2(R_\odot)}{u^2}} R_\odot + \mathcal{O}\left(\frac{v_{\text{esc}}^2(r_0)}{u^2}\right)$$

$R_{\text{disk}}(u) > R_\odot$

gravitational focusing

# Kernel Density Estimation (KDE)

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

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

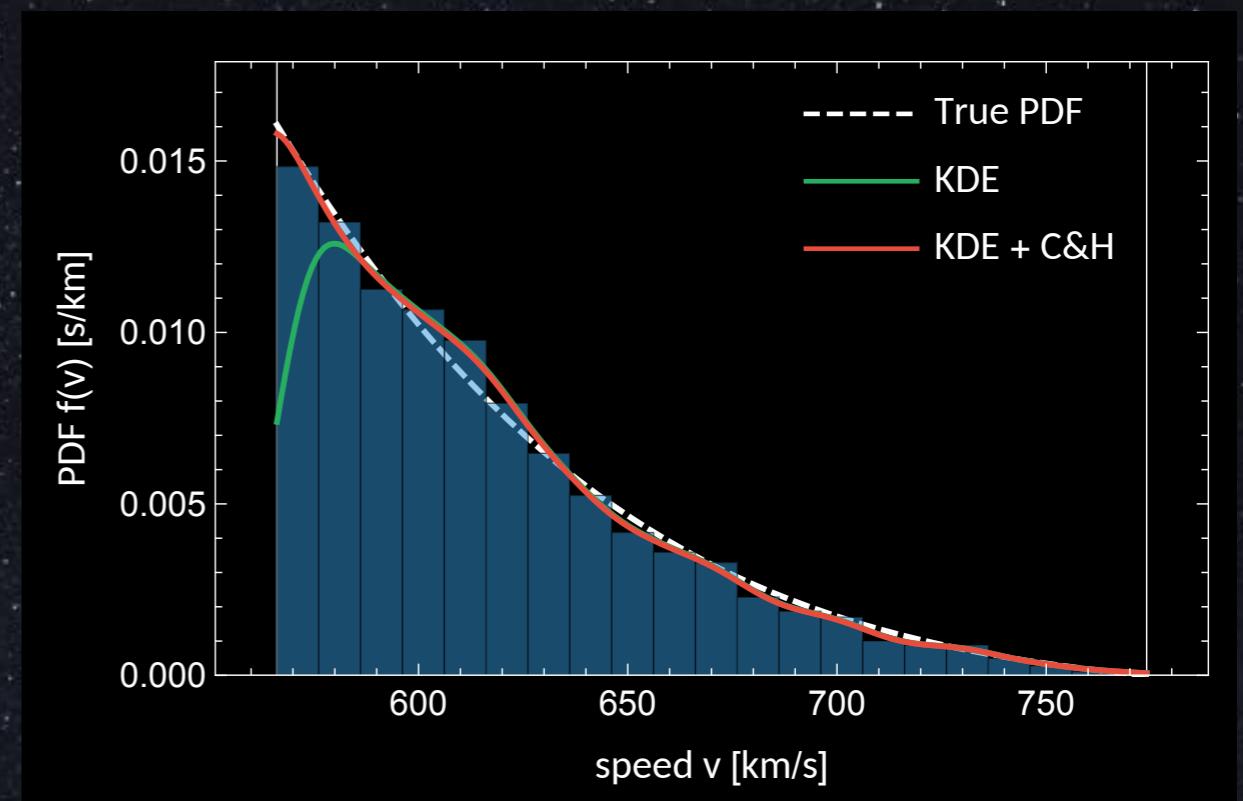
$$\hat{f}_h(x) = \frac{1}{h} \sum_{i=1}^N K\left(\frac{x - x_i}{h}\right).$$

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

# Runge-Kutta-Fehlberg (RK45)

E. Fehlberg, NASA technical report, NASA, 1969

Adaptive method for the numerical solution of 1st order ODEs.

$$\dot{y} = f(t, y), \quad y(t_0) = y_0,$$

Requires the same number of function evaluation of RK6, but is rather a combination of RK4,

$$y_{k+1} = y_k + \frac{25}{216}k_1 + \frac{1408}{2565}k_3 + \frac{2197}{4101}k_4 - \frac{1}{5}k_5,$$

and RK5,

$$\tilde{y}_{k+1} = y_k + \frac{16}{135}k_1 + \frac{6656}{12825}k_3 + \frac{28561}{56430}k_4 - \frac{9}{50}k_5 + \frac{2}{55}k_6.$$

The comparison of both yields an estimate of the error, and allows to choose the step size adaptively.

$$\Delta t_{k+1} = 0.84 \left( \frac{\epsilon}{|y_{k+1} - \tilde{y}_{k+1}|} \right)^{1/4} \Delta t_k$$