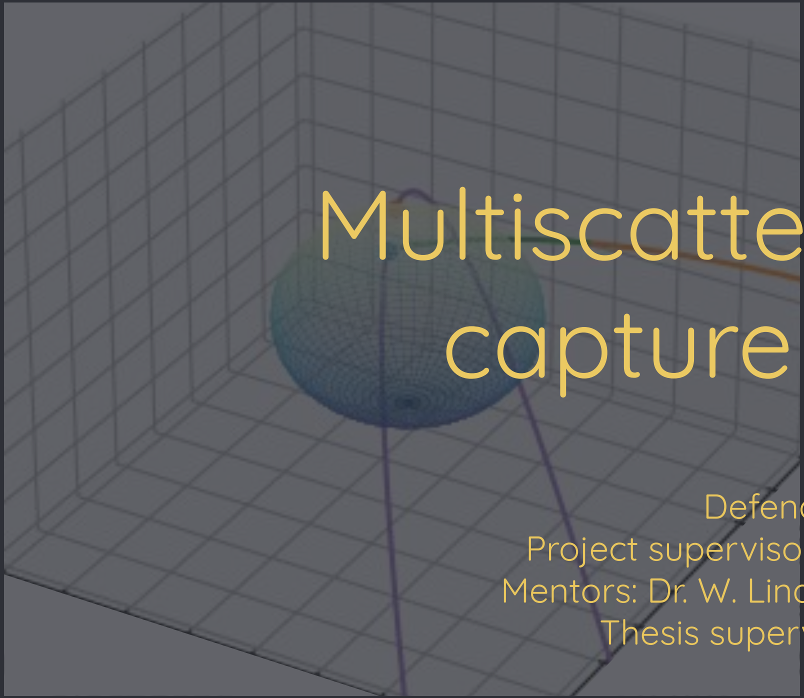
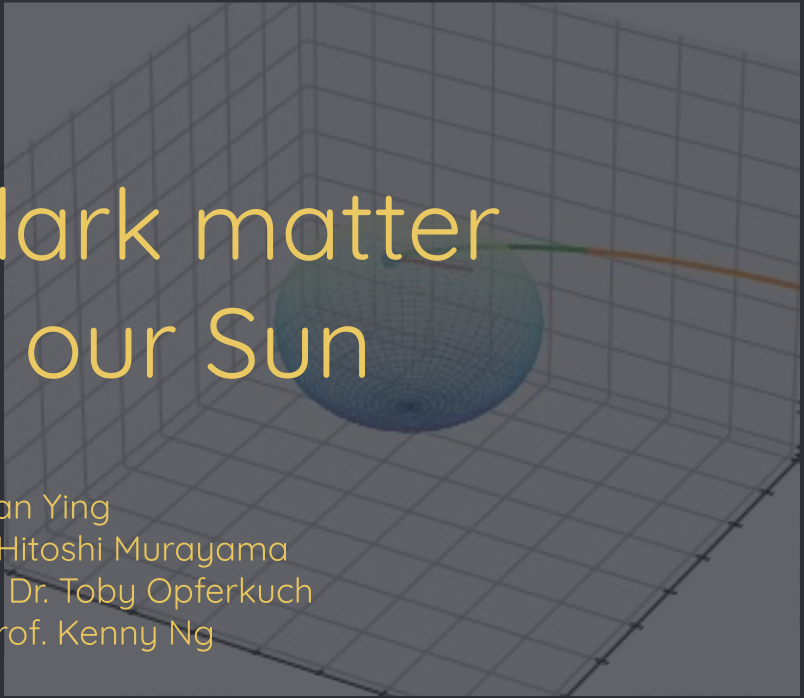
Senior Project I: Oral examination slides

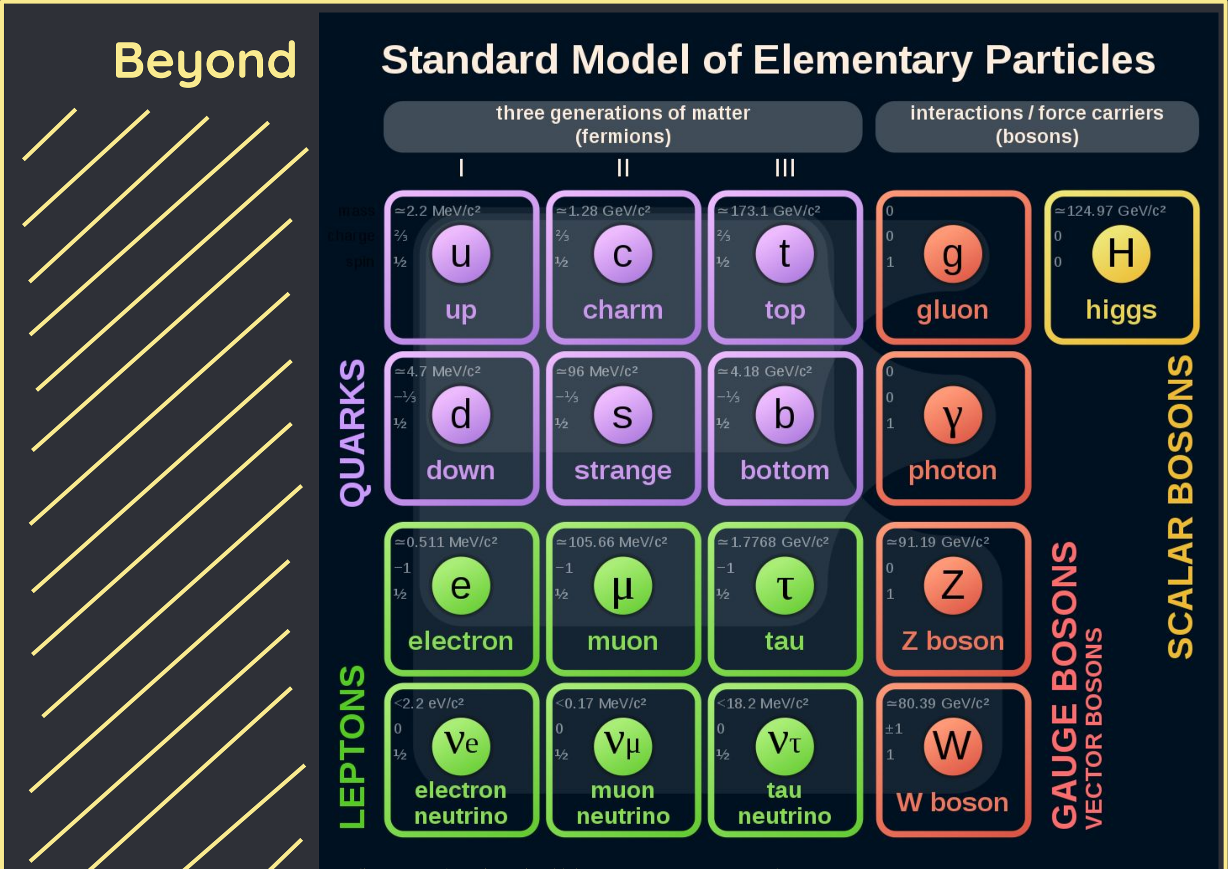




Multiscatter dark matter capture of our Sun

Defender: Chan Ying
Project supervisor: Prof. Hitoshi Murayama
Mentors: Dr. W. Linda Xu & Dr. Toby Opferkuch
Thesis supervisor: Prof. Kenny Ng

Motivation to searching for Dark Matter (DM)



https://upload.wikimedia.org/wikipedia/commons/thumb/2/2b/Standard_Model_of_Elementary_Particles_dark.svg/1070px-Standard_Model_of_Elementary_Particles_dark.svg.png

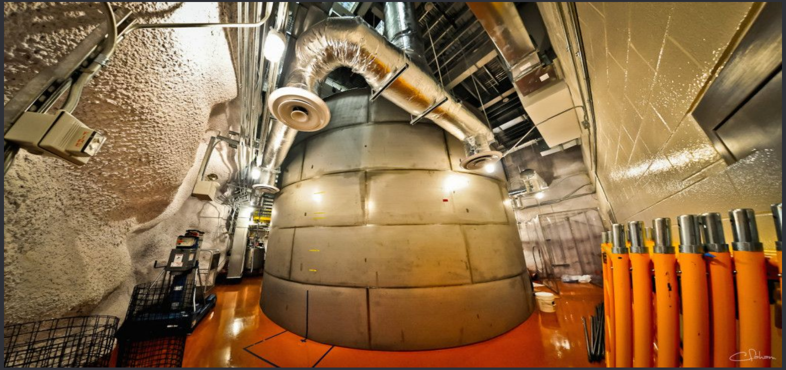
? ψ_{DM}

1. DM particle nature?

2. DM interactions?

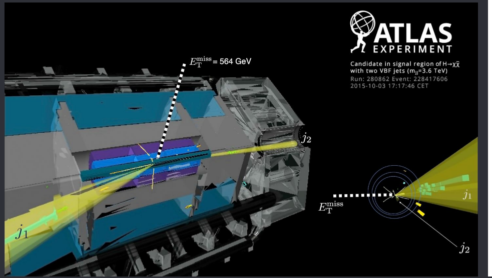
Direct detection etc.

1. LUX-ZEPLIN (LZ)

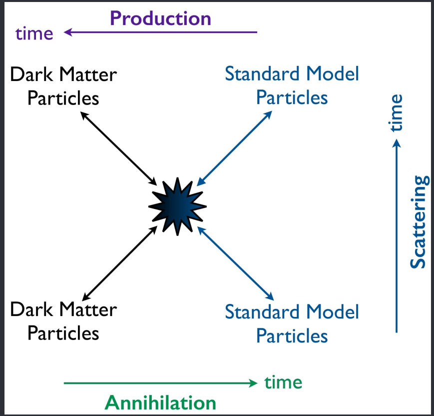


https://lz.lbl.gov/wp-content/uploads/sites/6/2014/07/LUX_watertank-1024x587.jpg

2. Collider Production



https://cds.cern.ch/images/CERN-HOMEWEB-PHO-2015-002-1/file?size=large



https://particleastro.brown.edu/files/2019/10/Screenshot-from-2019-10-22-17-11-47.png

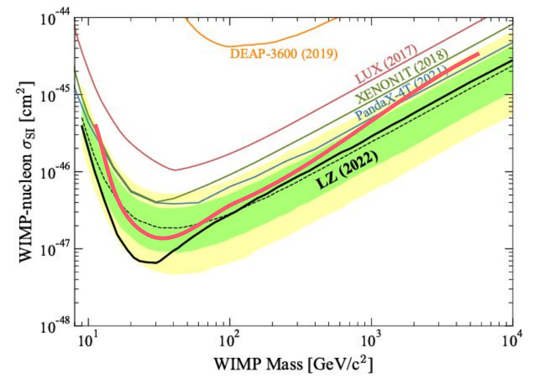
Theoretical prediction

Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + h.c.$$
$$+i\psi_i y_{ij}\psi_j\phi + h.c.$$
$$+|D_\mu\phi|^2 - V(\phi) + ?$$

J. Aalbers, 2022 Fig 5

Predicted



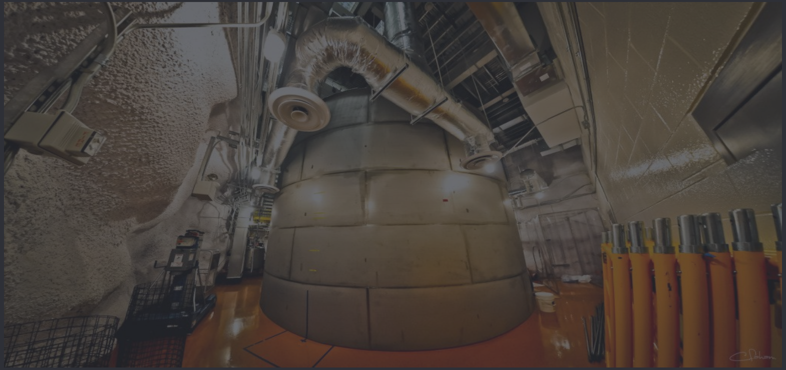
Monte Carlo simulation

⇒ Covers a range of models

Direct detection

etc.

1. LUX-ZEPLIN (LZ)



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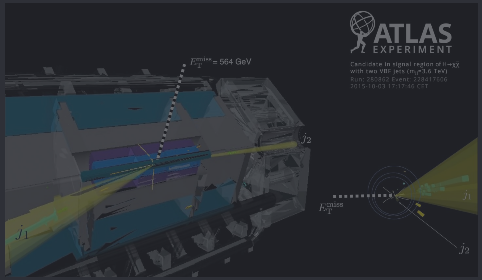

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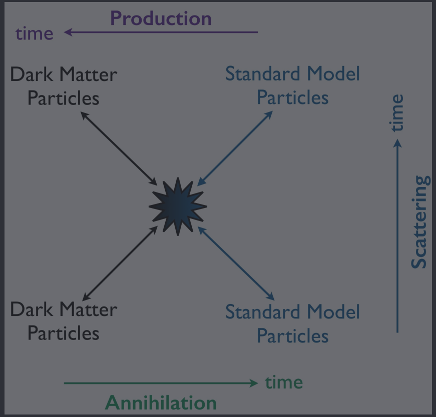

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J. Aalbers, 2022 Fig 5

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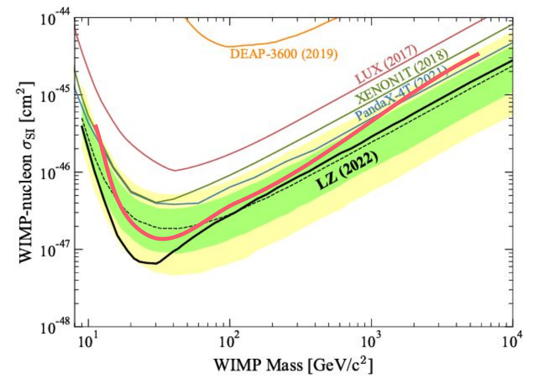
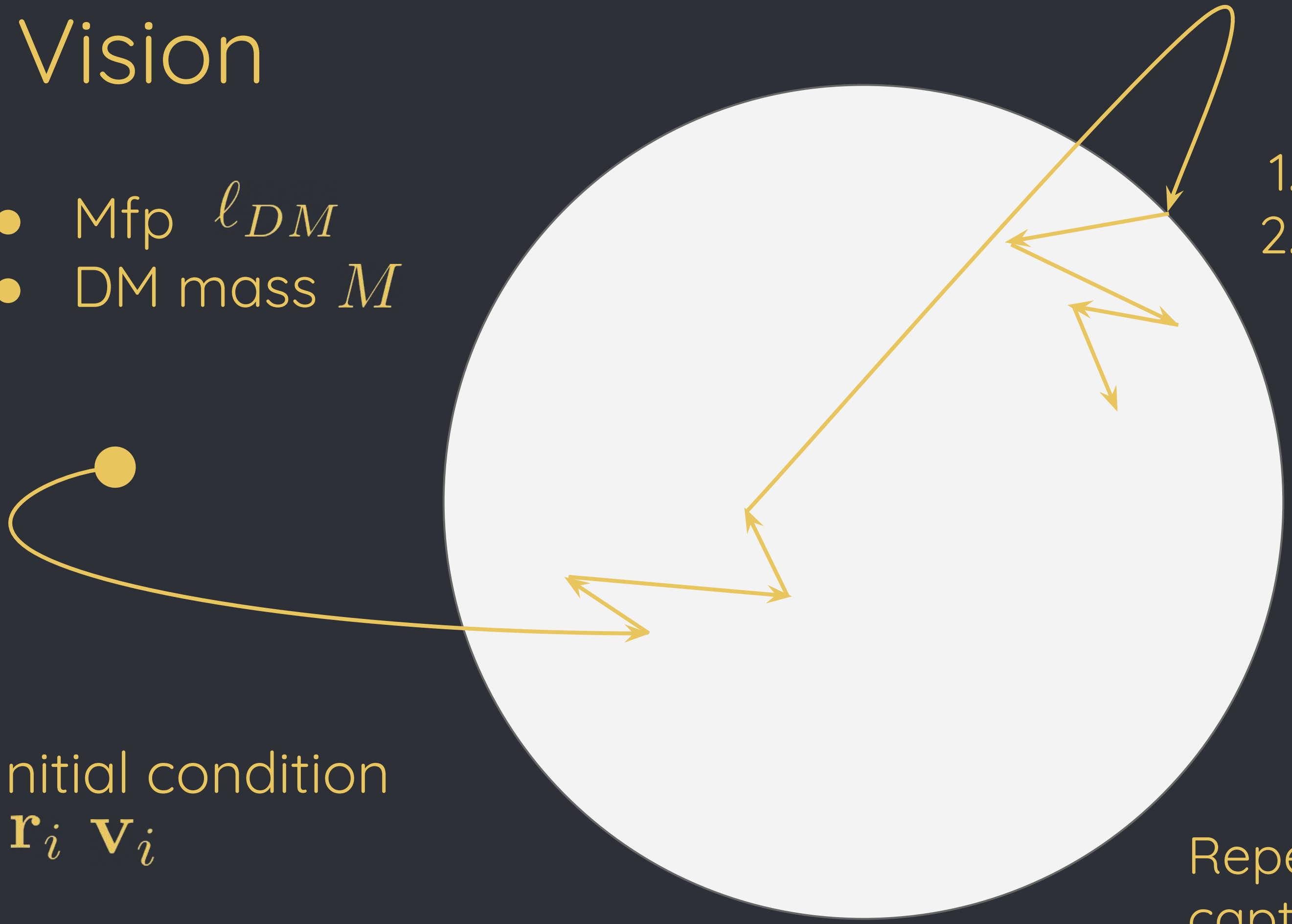


Vision

- Mfp ℓ_{DM}
- DM mass M



1. Orbit around Sun
2. Enter Sun

3. Scattering after entrance

4. Leaves if energy < escape energy

Initial condition

$\mathbf{r}_i \ \mathbf{v}_i$

Repeat 1, 2, 3 until DM is captured

- <u>Simulate successful DM capture event</u>

Content

1. Motivation and recent efforts to DM detection

2. Theoretical overview of DM multiscattering

3. Monte Carlo simulation of DM capture

Content

Classical scattering

1. Mean free path: ℓ_{DM}
2. Kinematic parameters: $\vec{p}\,,\, E$

Consider a series of continuous scattering, $\Delta E_{tot} = \sum_{i}^{n} (\Delta E)_i$

For $i = 1$,

$$\Delta E_1 \approx \frac{\mu^2}{mM}\left(-Mv_i^2 + mV_i^2\right) \qquad \Delta E_1 = \frac{1}{2}M\left(v_1^2 - v_i^2\right)$$

Defining a new variable, $\beta_+ \equiv \dfrac{4Mm}{(M+m)^2}$

$$v_1^2 = \left(1 - \frac{\beta_+}{2}\right)v_i^2 + \frac{2m^2}{(m+M)^2}V_i^2$$

$$\Delta E_{tot} \approx \frac{1}{2} M v_i^2 \left[\left(1 - \frac{\beta_+}{2} \right)^n - 1 \right]$$

$$\|$$

$$\Delta E_{\rm tot} = \frac{1}{2} m_{\rm DM} v_0^2 \left[\left(1 - \frac{\beta_+}{2} \right)^{n_{\rm coll}} - 1 \right] .$$

Premature Black Hole Death of Population III Stars by Dark Matter

Sebastian A. R. Ellis

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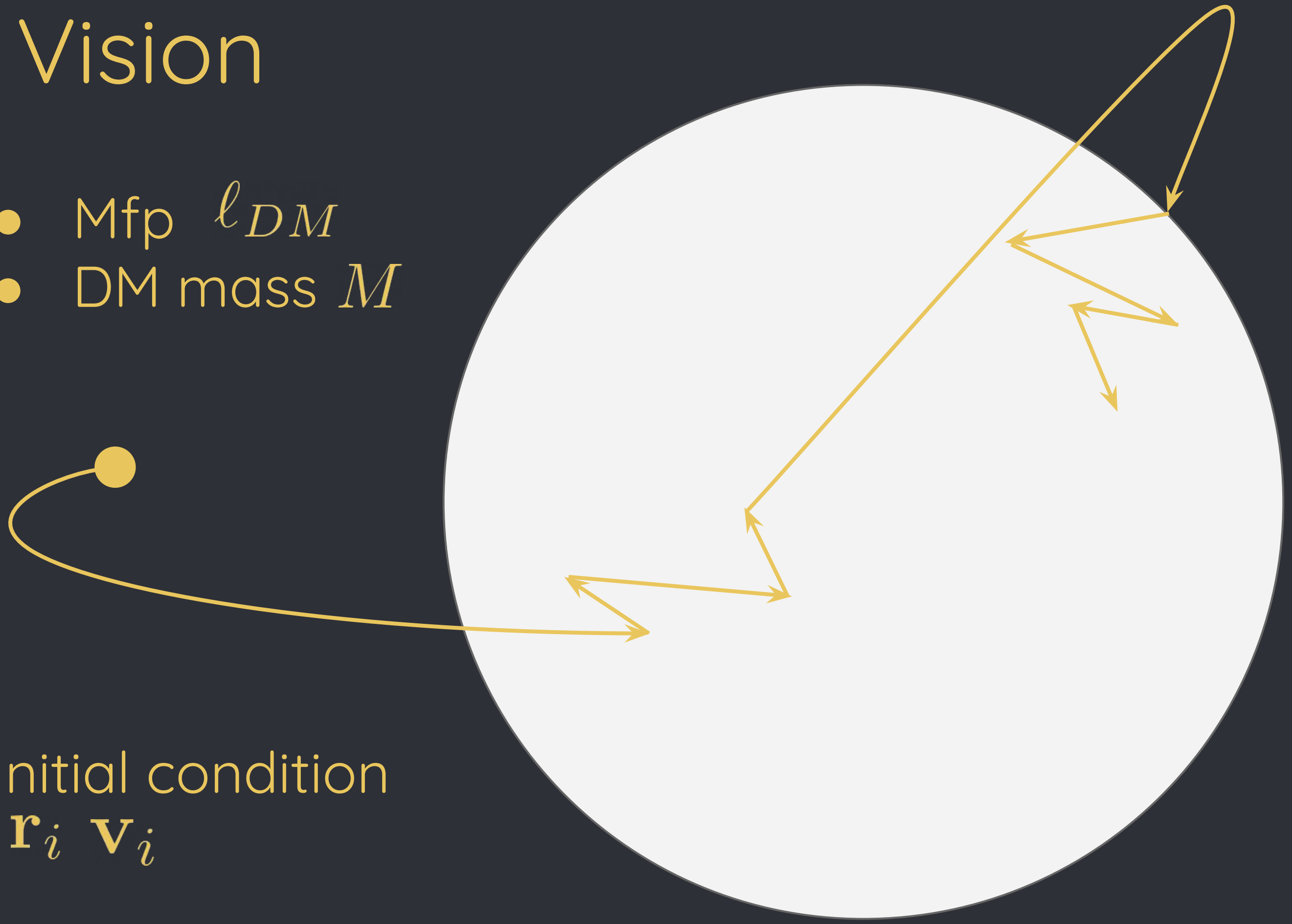
where we remind the reader that m is the mass of the stellar constituent with which the DM scatters. A kinematic analysis shows that, in the star's rest frame, the fraction of DM energy lost in a single scatter is evenly distributed over the interval $0 < \Delta E / E_0 < \beta_+$. For single scatter capture, the required fraction of DM kinetic energy loss is u^2/w^2, which is the ratio of DM's kinetic

Content

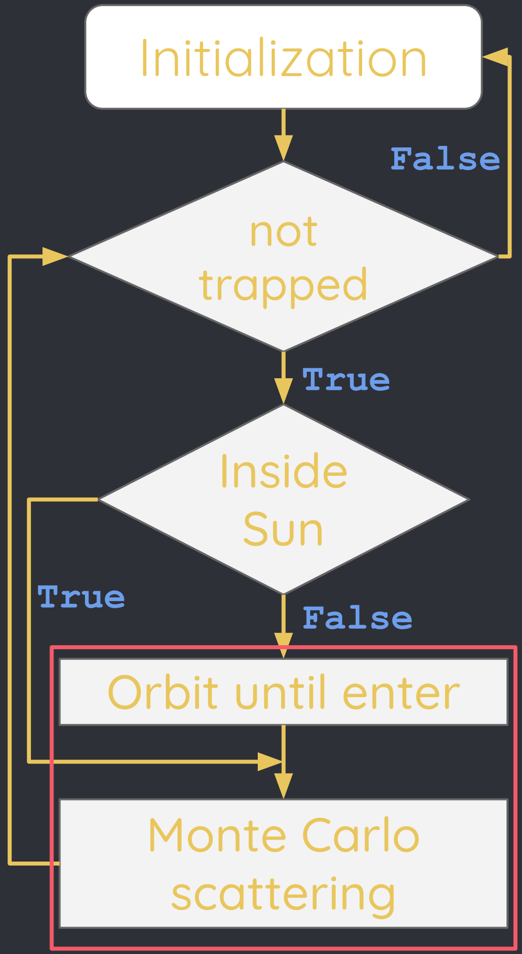
Vision

- Mfp ℓ_{DM}
- DM mass M



Initial condition
$\mathbf{r}_i$ $\mathbf{v}_i$

- <u>Simulate successful DM capture event</u>



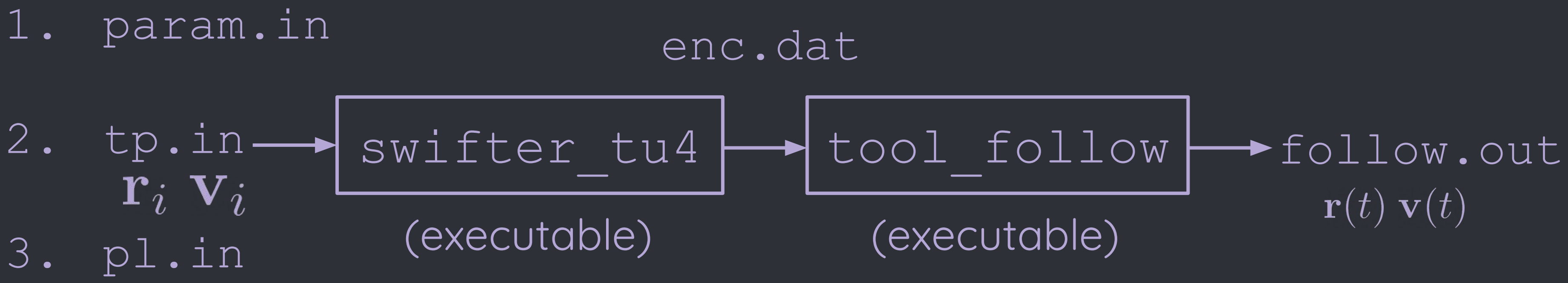
Tasks to simulate DM capture

1. Orbiting: `swifter` (Fortran + Python)
2. Scattering algorithm (Python)

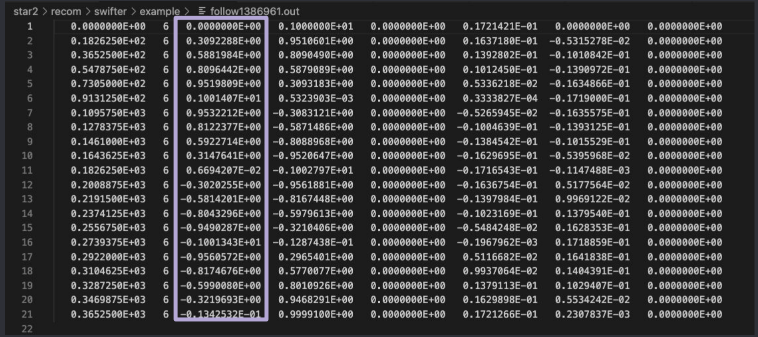
Tasks to simulate DM capture

1. Orbiting: `swifter` (Fortran + Python)
    - Inputs and outputs by `swifter`
2. Scattering algorithm (Python)
    - Fortran: reduces computation time
    - Symplectic fourth order T+U integrator

- Automation inside Python using `subprocess`

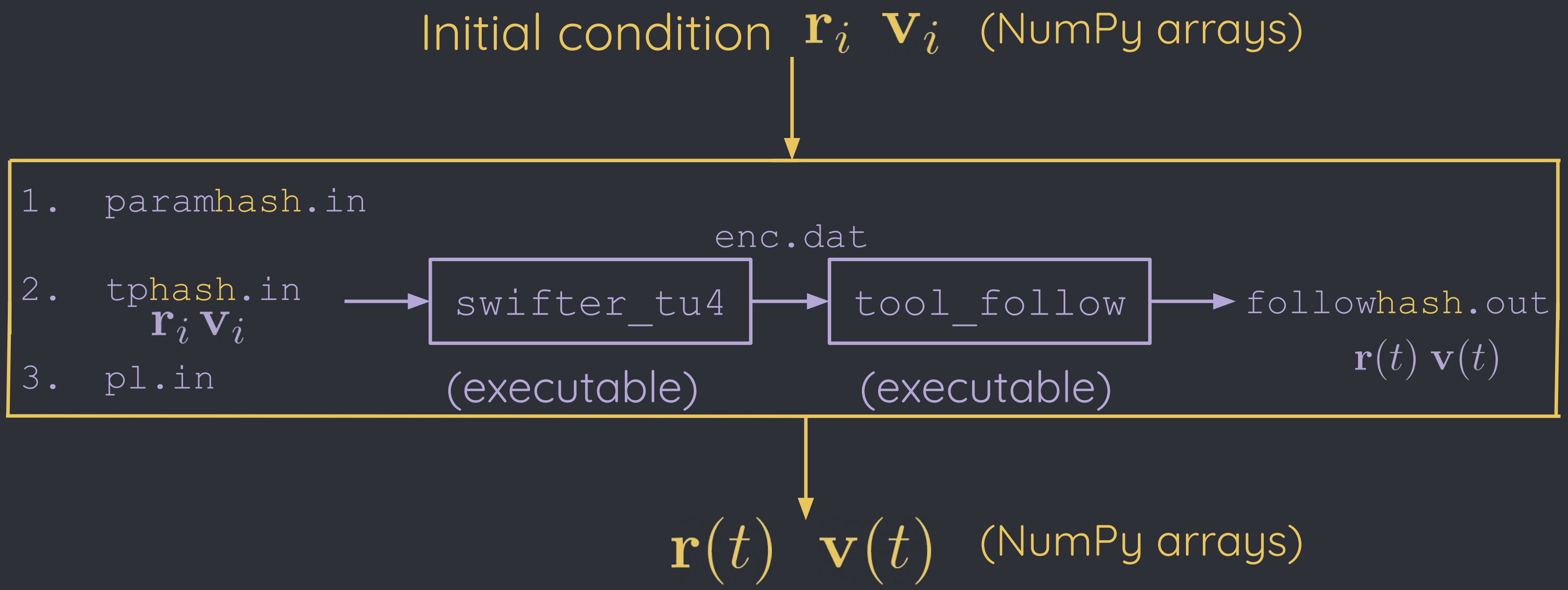


- Recompilation for `tool_follow` solving display numerical data display problem

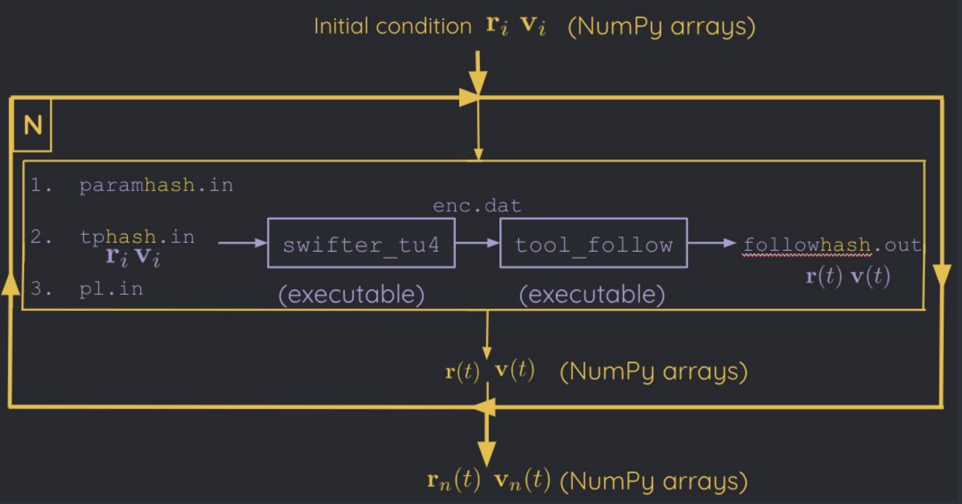


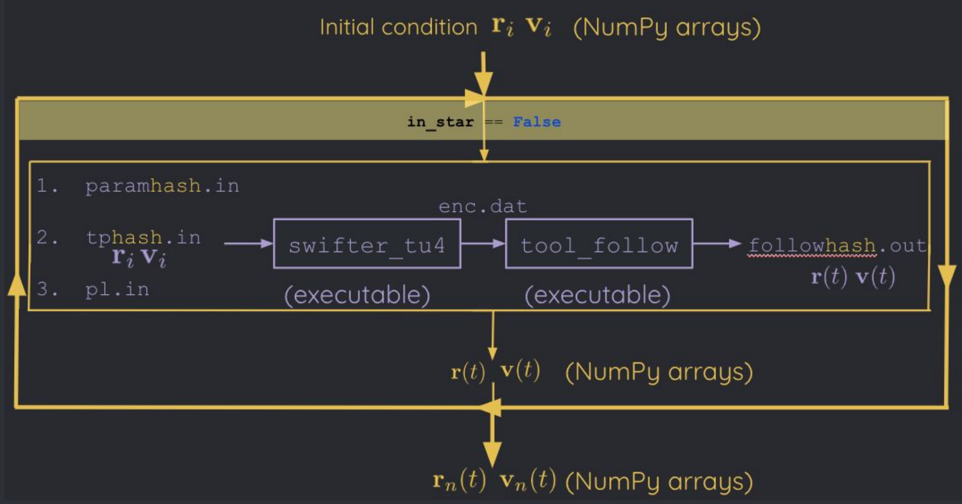
star2 > recom > swifter > example > follow1386961.out

0.0000000E+00	6	0.0000000E+00	0.1000000E+01	0.0000000E+00	0.1721421E-01	0.0000000E+00	0.0000000E+00
0.1826250E+02	6	0.3092288E+00	0.9510601E+00	0.0000000E+00	0.1637180E-01	-0.5315278E-02	0.0000000E+00
0.3652500E+02	6	0.5881984E+00	0.8090490E+00	0.0000000E+00	0.1392802E-01	-0.1010842E-01	0.0000000E+00
0.5478750E+02	6	0.8096442E+00	0.5879089E+00	0.0000000E+00	0.1012450E-01	-0.1390972E-01	0.0000000E+00
0.7305000E+02	6	0.9519809E+00	0.3093183E+00	0.0000000E+00	0.5336218E-02	-0.1634866E-01	0.0000000E+00
0.9131250E+02	6	0.1001407E+01	0.5323903E-03	0.0000000E+00	0.3333827E-04	-0.1719000E-01	0.0000000E+00
0.1095750E+03	6	0.9532212E+00	-0.3083121E+00	0.0000000E+00	-0.5265945E-02	-0.1635575E-01	0.0000000E+00
0.1278375E+03	6	0.8122377E+00	-0.5871486E+00	0.0000000E+00	-0.1004639E-01	-0.1393125E-01	0.0000000E+00
0.1461000E+03	6	0.5922714E+00	-0.8088968E+00	0.0000000E+00	-0.1384542E-01	-0.1015529E-01	0.0000000E+00
0.1643625E+03	6	0.3147641E+00	-0.9520647E+00	0.0000000E+00	-0.1629695E-01	-0.5395968E-02	0.0000000E+00
0.1826250E+03	6	0.6694207E-02	-0.1002797E+01	0.0000000E+00	-0.1716543E-01	-0.1147488E-03	0.0000000E+00
0.2008875E+03	6	-0.3020255E+00	-0.9561881E+00	0.0000000E+00	-0.1636754E-01	0.5177564E-02	0.0000000E+00
0.2191500E+03	6	-0.5814201E+00	-0.8167448E+00	0.0000000E+00	-0.1397984E-01	0.9969122E-02	0.0000000E+00
0.2374125E+03	6	-0.8043296E+00	-0.5979613E+00	0.0000000E+00	-0.1023169E-01	0.1379540E-01	0.0000000E+00
0.2556750E+03	6	-0.9490287E+00	-0.3210406E+00	0.0000000E+00	-0.5484248E-02	0.1628353E-01	0.0000000E+00
0.2739375E+03	6	-0.1001343E+01	-0.1287438E-01	0.0000000E+00	-0.1967962E-03	0.1718859E-01	0.0000000E+00
0.2922000E+03	6	-0.9560572E+00	0.2965401E+00	0.0000000E+00	0.5116682E-02	0.1641838E-01	0.0000000E+00
0.3104625E+03	6	-0.8174676E+00	0.5770077E+00	0.0000000E+00	0.9937064E-02	0.1404391E-01	0.0000000E+00
0.3287250E+03	6	-0.5990080E+00	0.8010926E+00	0.0000000E+00	0.1379113E-01	0.1029407E-01	0.0000000E+00
0.3469875E+03	6	-0.3219693E+00	0.9468291E+00	0.0000000E+00	0.1629898E-01	0.5534242E-02	0.0000000E+00
0.3652500E+03	6	-0.1342532E-01	0.9999100E+00	0.0000000E+00	0.1721266E-01	0.2307837E-03	0.0000000E+00

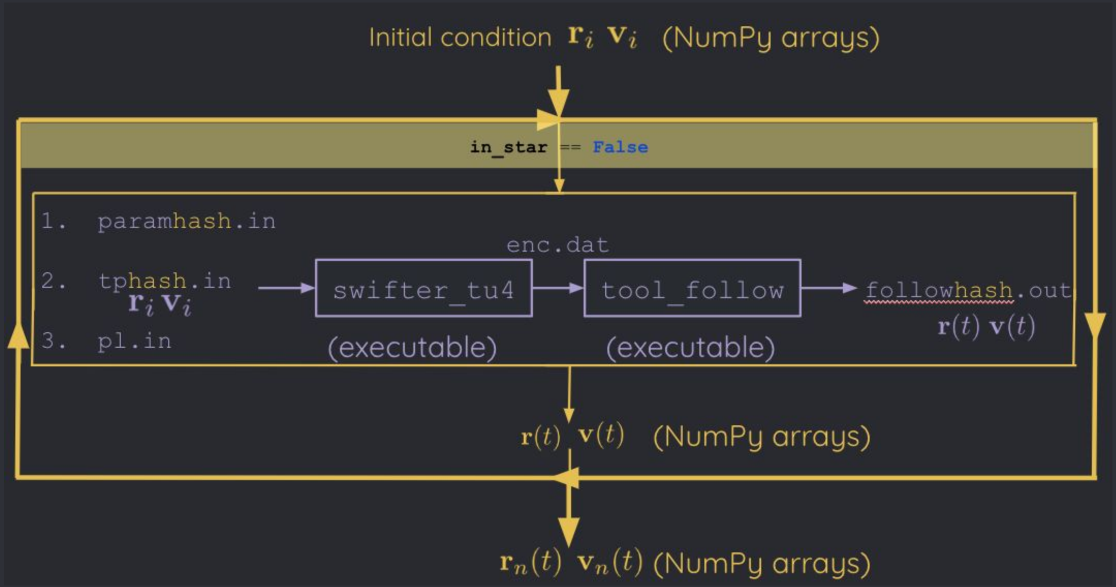

Initial condition $\mathbf{r}_i$ $\mathbf{v}_i$ (NumPy arrays)
1. paramhash.in
2. tphash.in
$\mathbf{r}_i\,\mathbf{v}_i$
3. pl.in
swifter_tu4
(executable)
enc.dat
tool_follow
(executable)
followhash.out
$\mathbf{r}(t)\ \mathbf{v}(t)$
$\mathbf{r}(t)$ $\mathbf{v}(t)$ (NumPy arrays)

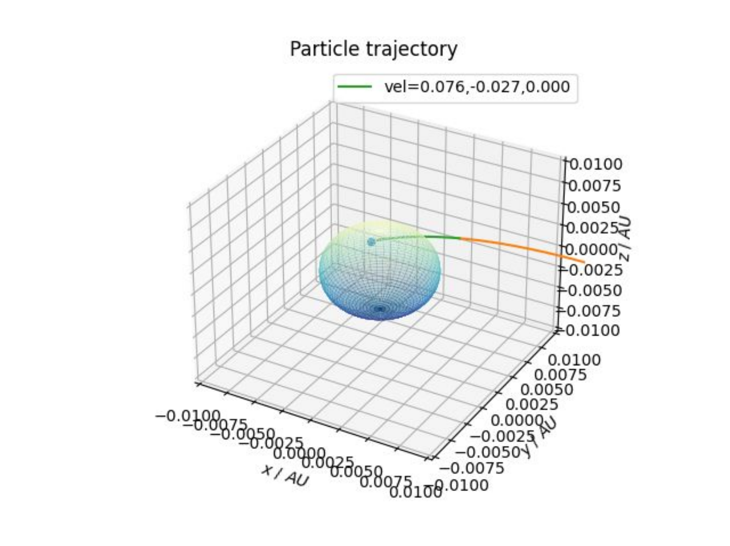
Rewrite two functions to wrap the `swifter` `subprocess` as loops





while loop `swifter` until entering the Sun





Tasks to simulate DM capture

1. Orbiting: `swifter` (Fortran + Python)
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2. Scattering algorithm (Python)
    - Restoring Maxwell-Boltzmann Statistics
    - Scattering Energy
    - Randomization of scattering processes

Initial condition $\mathbf{r}_i$ $\mathbf{V}_i$

Maxwell-Boltzmann distribution

$$f(\vec{v}) = \sqrt{\left(\frac{m}{2\pi kT}\right)^3} 4\pi v^2 e^{-\frac{mv^2}{2kT}}$$

- Box-muller transform

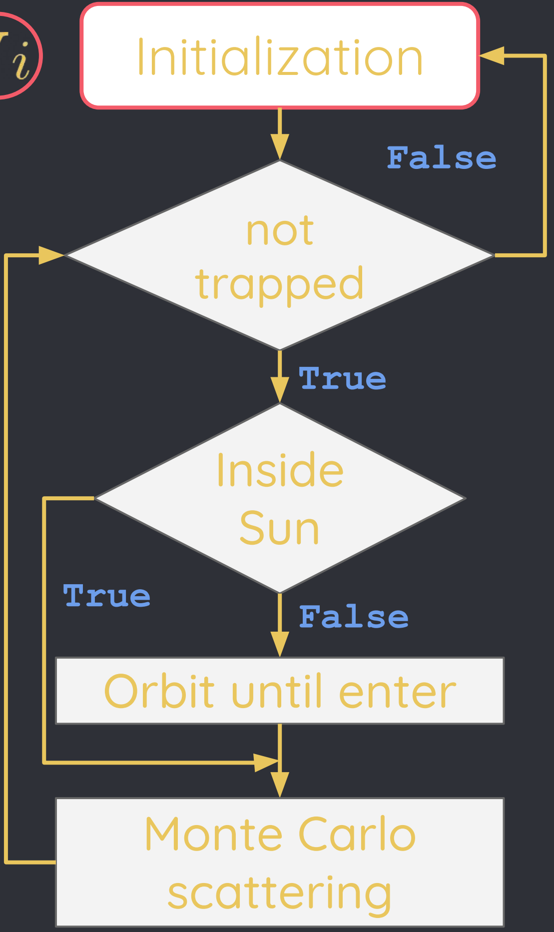
Independent uniform random variables x_1, x_2

$$y = \sqrt{-2\ln x_1}\cos(2x_2)$$

$$v_i = \sqrt{\frac{kT}{m}} \times y$$

For each dimension (x, y, z)

With the knowledge of using natural units $G = k = 1$



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Recall probabilistic energy loss

$$\Delta E_{tot} \approx \frac{1}{2} M v_i^2 \left[\left(1 - \frac{\beta_+}{2} \right)^n - 1 \right]$$

||

$$\Delta E_{\rm tot} = \frac{1}{2} m_{\rm DM} v_0^2 \left[\left(1 - \frac{\beta_+}{2} \right)^{n_{\rm coll}} - 1 \right] .$$

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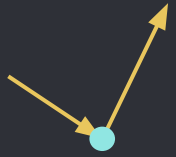
Following only 1 scattering

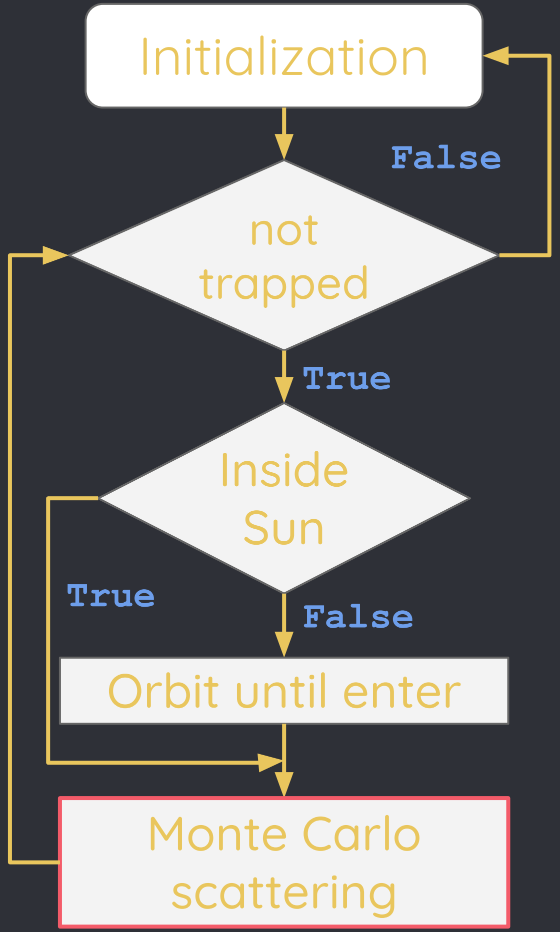


$$\frac{|\Delta E|}{E_i} \in [0, \beta_+]$$

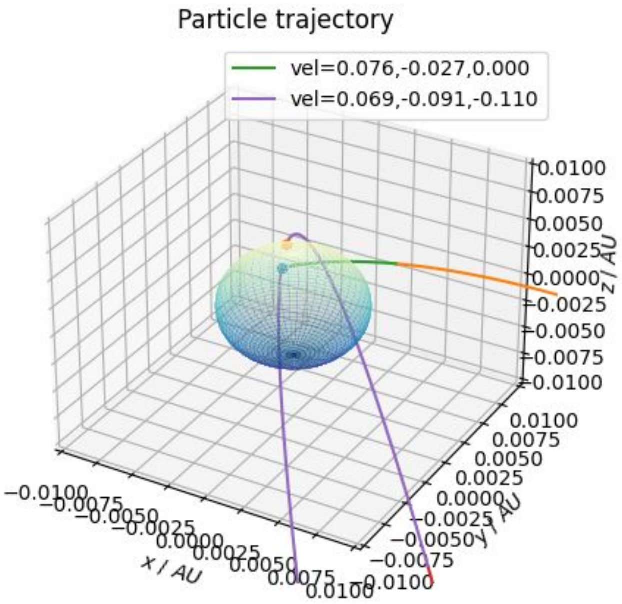
- Uniform probabilistic fractional energy change
- Make use of v_{j-1} from previous run, energy after scattering will be sampled
- $E_j\left(v_j\right) \to v_j\left(E_j\right)$ the magnitude of new velocity is obtained
- project the $v_j\left(E_j\right)$ and ℓ_{DM} to a random unit vector

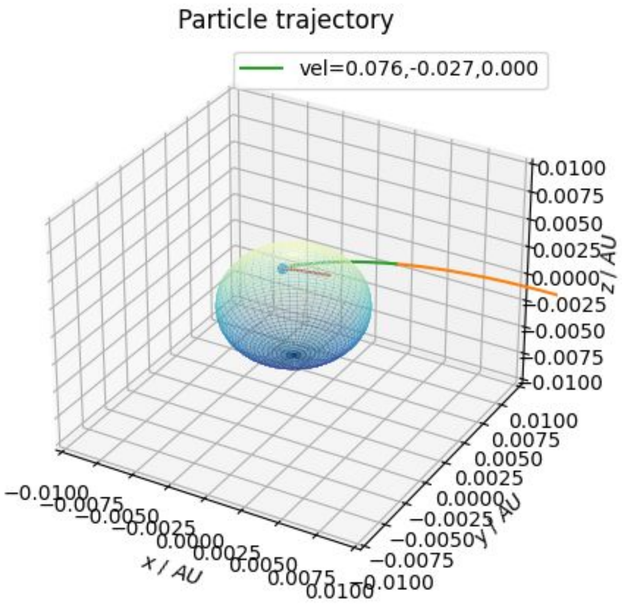
$$\mathbf{r} = |\mathbf{r}|\left(\cos u \sin v \quad, \sin u \sin v \quad, \cos v\right)$$

- where we generate 2 independent uniform random variable u, v

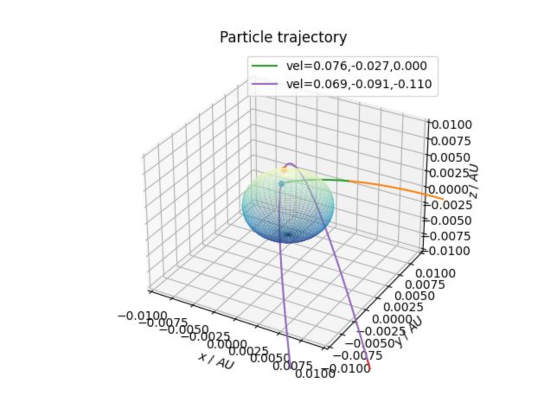


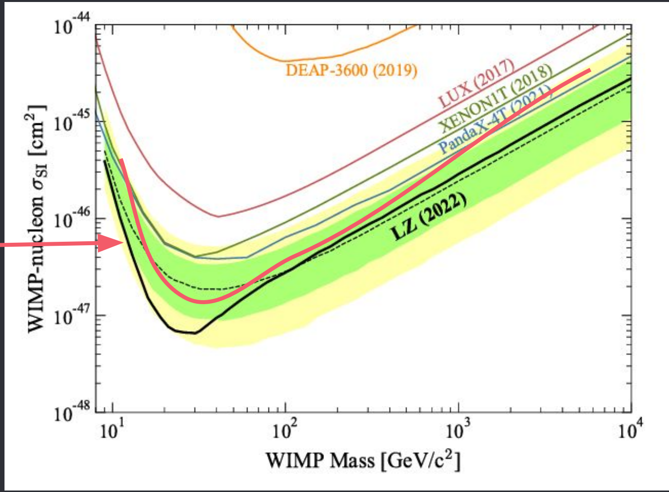
Successfully simulated DM capture events!

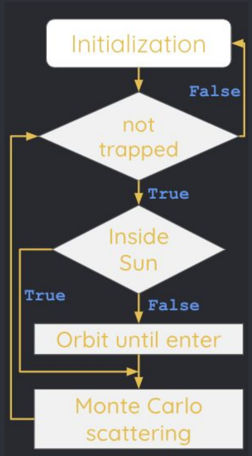




Future work

- 

$\times N$


- 

apply to other astronomical bodies and make radial profile for $\rho(\mathbf{r})$

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Q&A