3-Dimensional WIMP Effective Velocity Distribution

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Based on arXiv:2103.06485, 2103.06883

Questions
- Arguments

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

Numerical results
- Radial component (magnitude)
- Angular component (direction)
- Angular distribution of the 3-D average kinetic energy
- Forward-backward asymmetry

Summary

Three simple questions

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- Q1: Does the subgroup of WIMPs scattering off target nuclei have the same 3-D velocity distribution as the main group of the entire halo WIMPs (impinging on a (directional) direct Dark Matter detector but not necessarily scattering off target nuclei)?

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  A1: Yes?

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  A1: Yes?

- Q2: Does the WIMPs scattering off Ar or Xe nuclei have the same 3-D velocity distribution as the WIMPs scattering off Si or Ge nuclei?

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- Q1: Does the subgroup of WIMPs scattering off target nuclei have the same 3-D velocity distribution as the main group of the entire halo WIMPs (impinging on a (directional) direct Dark Matter detector but not necessarily scattering off target nuclei)?

  A1: Yes?

- Q2: Does the WIMPs scattering off Ar or Xe nuclei have the same 3-D velocity distribution as the WIMPs scattering off Si or Ge nuclei?

  A2: Yes?

Three simple questions

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  A1: Yes?

- Q2: Does the WIMPs scattering off Ar or Xe nuclei have the same 3-D velocity distribution as the WIMPs scattering off Si or Ge nuclei?

  A2: Yes?

- Q3: Once one can reconstruct the (3-D) velocity distribution of WIMPs by using (directional) direct detection data, is the reconstructed (3-D) velocity distribution indeed that of the entire halo WIMPs?

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  A2: Yes?

- Q3: Once one can reconstruct the (3-D) velocity distribution of WIMPs by using (directional) direct detection data, is the reconstructed (3-D) velocity distribution indeed that of the entire halo WIMPs?

  A3: Yes?

Three simple questions

- Q1: Does the subgroup of WIMPs scattering off target nuclei have the same 3-D velocity distribution as the main group of the entire halo WIMPs (impinging on a (directional) direct Dark Matter detector but not necessarily scattering off target nuclei)?

  A1: No...

- Q2: Does the WIMPs scattering off Ar or Xe nuclei have the same 3-D velocity distribution as the WIMPs scattering off Si or Ge nuclei?

  A2: No...

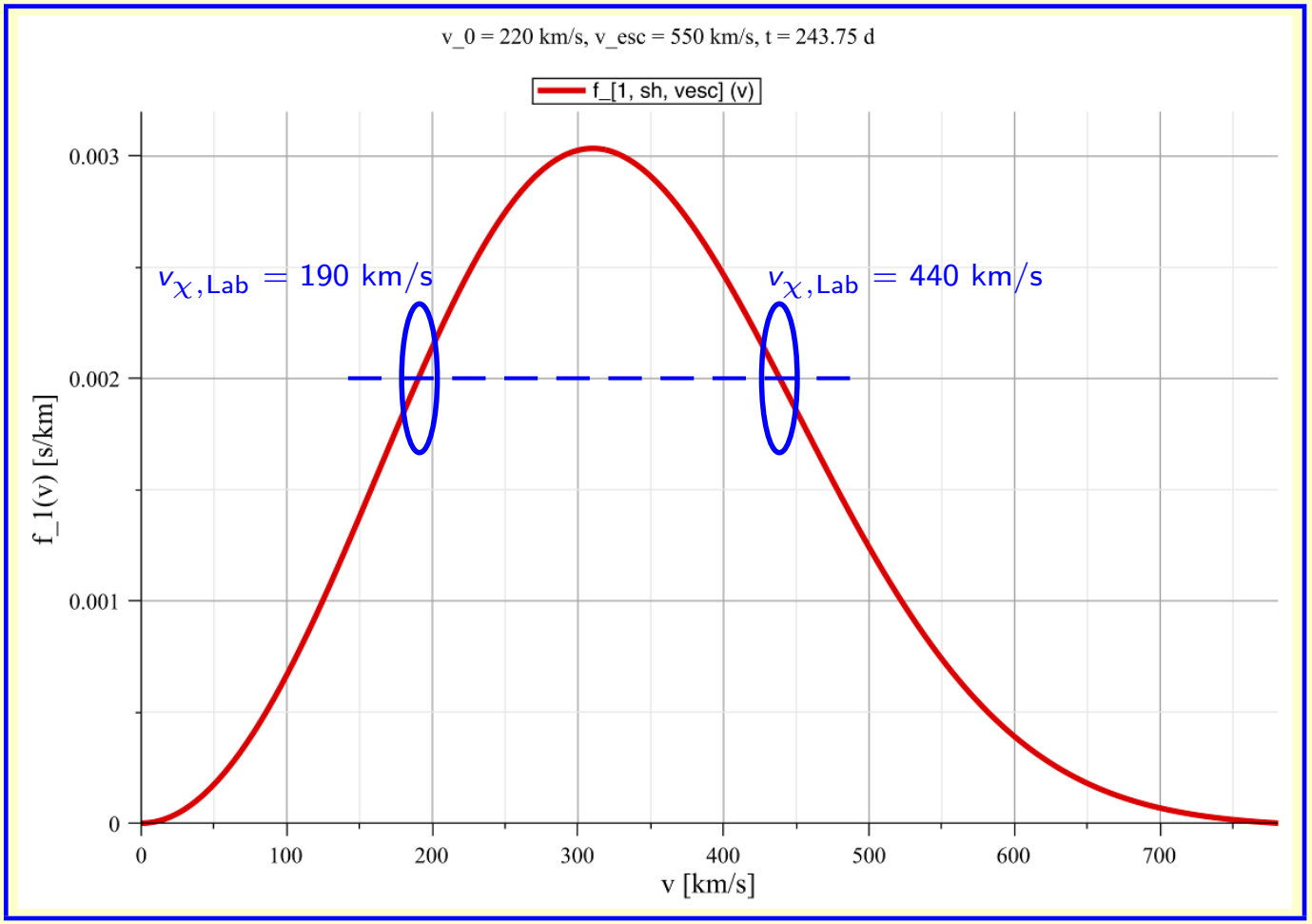
- Q3: Once one can reconstruct the (3-D) velocity distribution of WIMPs by using (directional) direct detection data, is the reconstructed (3-D) velocity distribution indeed that of the entire halo WIMPs?

  A3: Not directly?? $\Longrightarrow$ Yes??

Arguments

Arguments

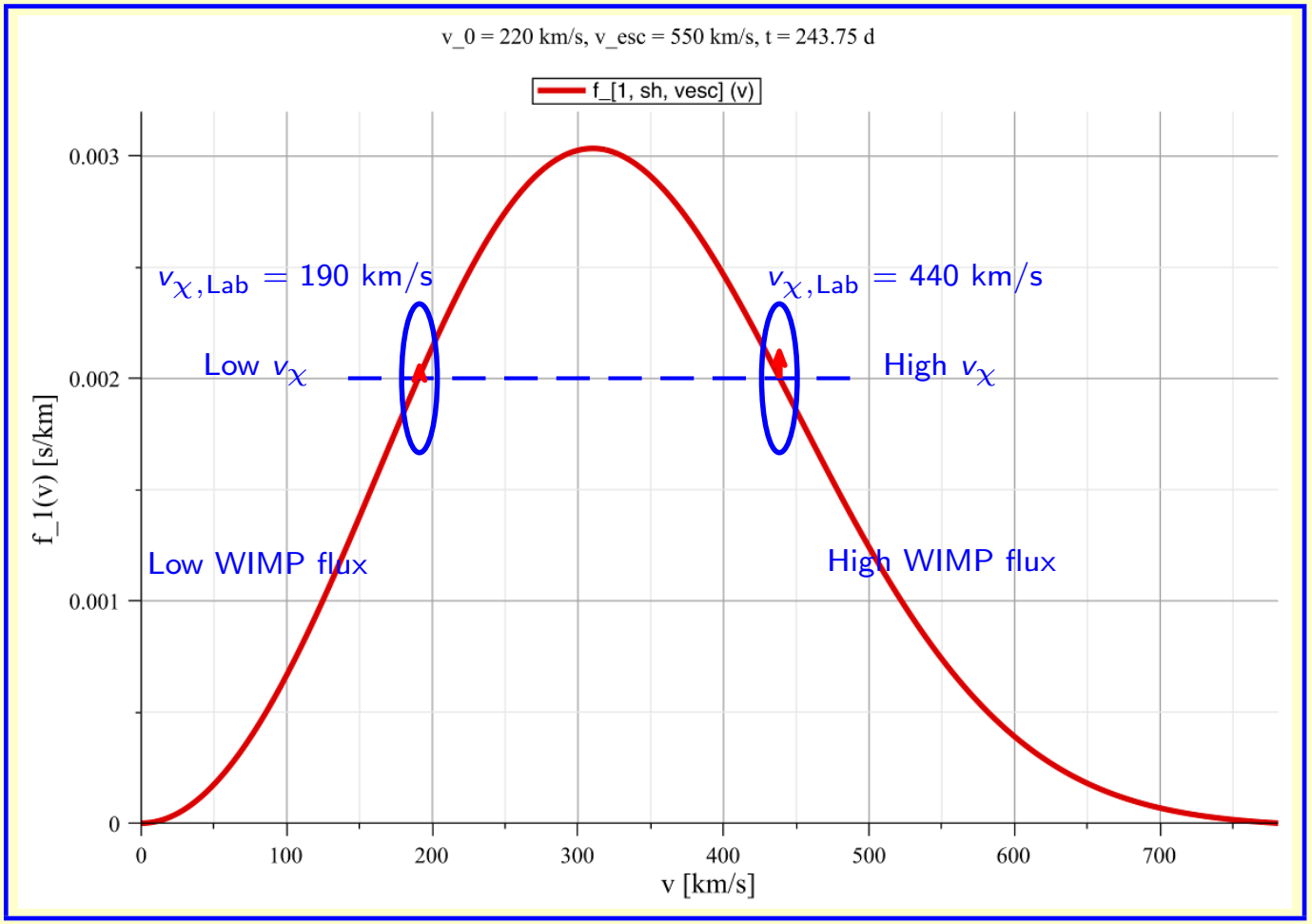
- Shifted Maxwellian velocity distribution



[CLS, arXiv:2103.06883 (2021)]

Arguments

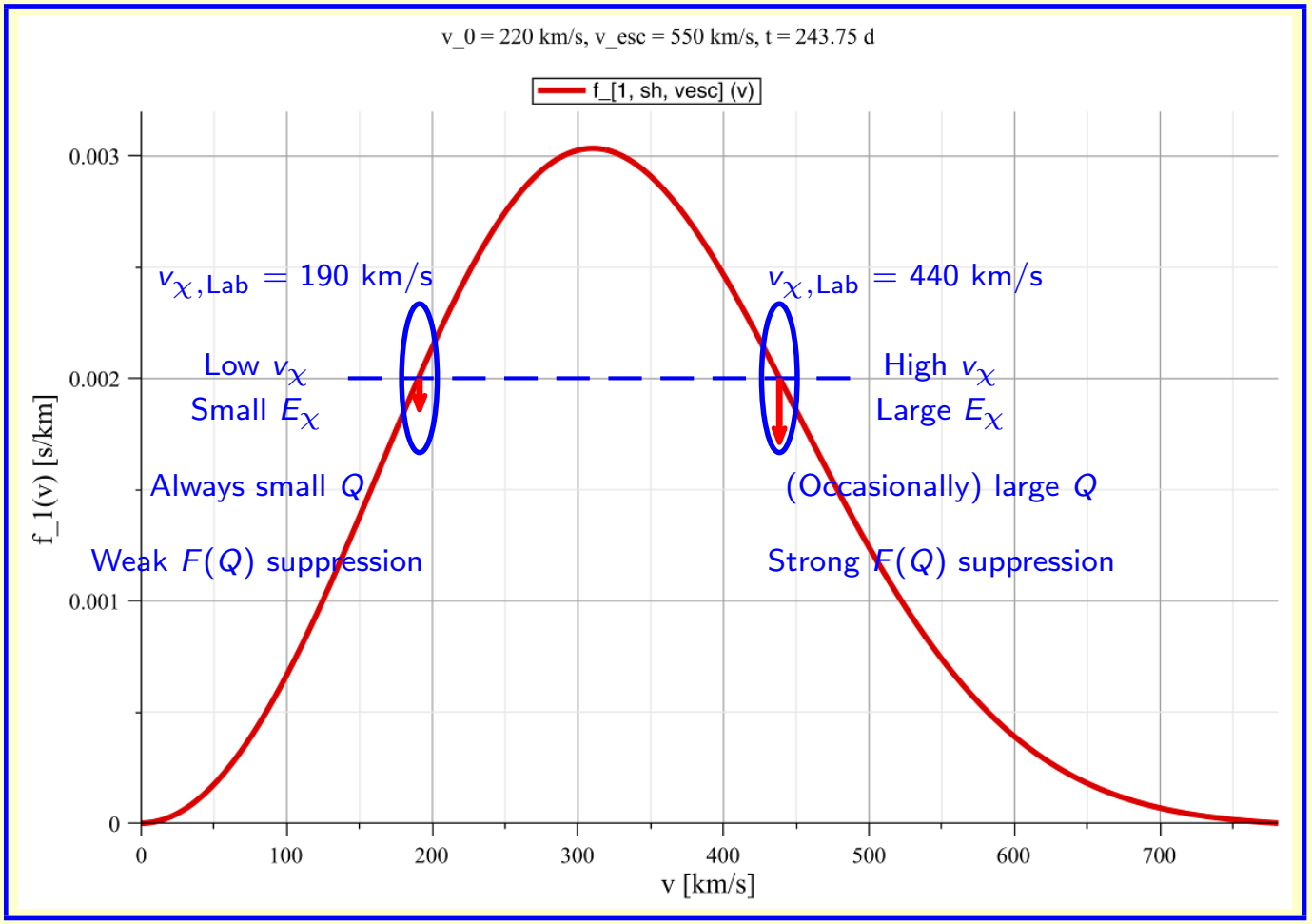
- Proportionality of the WIMP flux to the incident velocity



[CLS, arXiv:2103.06883 (2021)]

Arguments

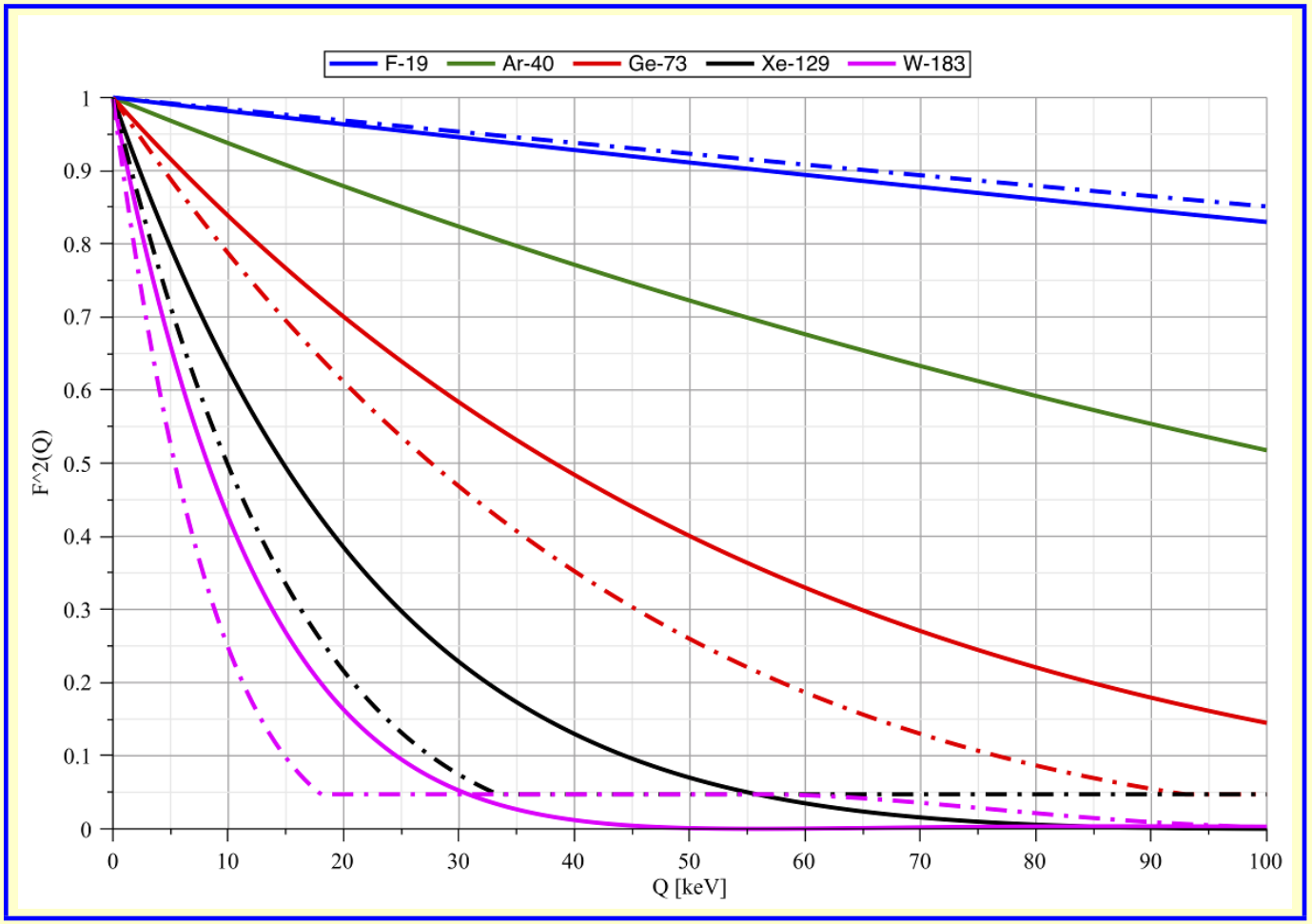
- Cross section (nuclear form factor) suppression



[CLS, arXiv:2103.06883 (2021)]

Arguments

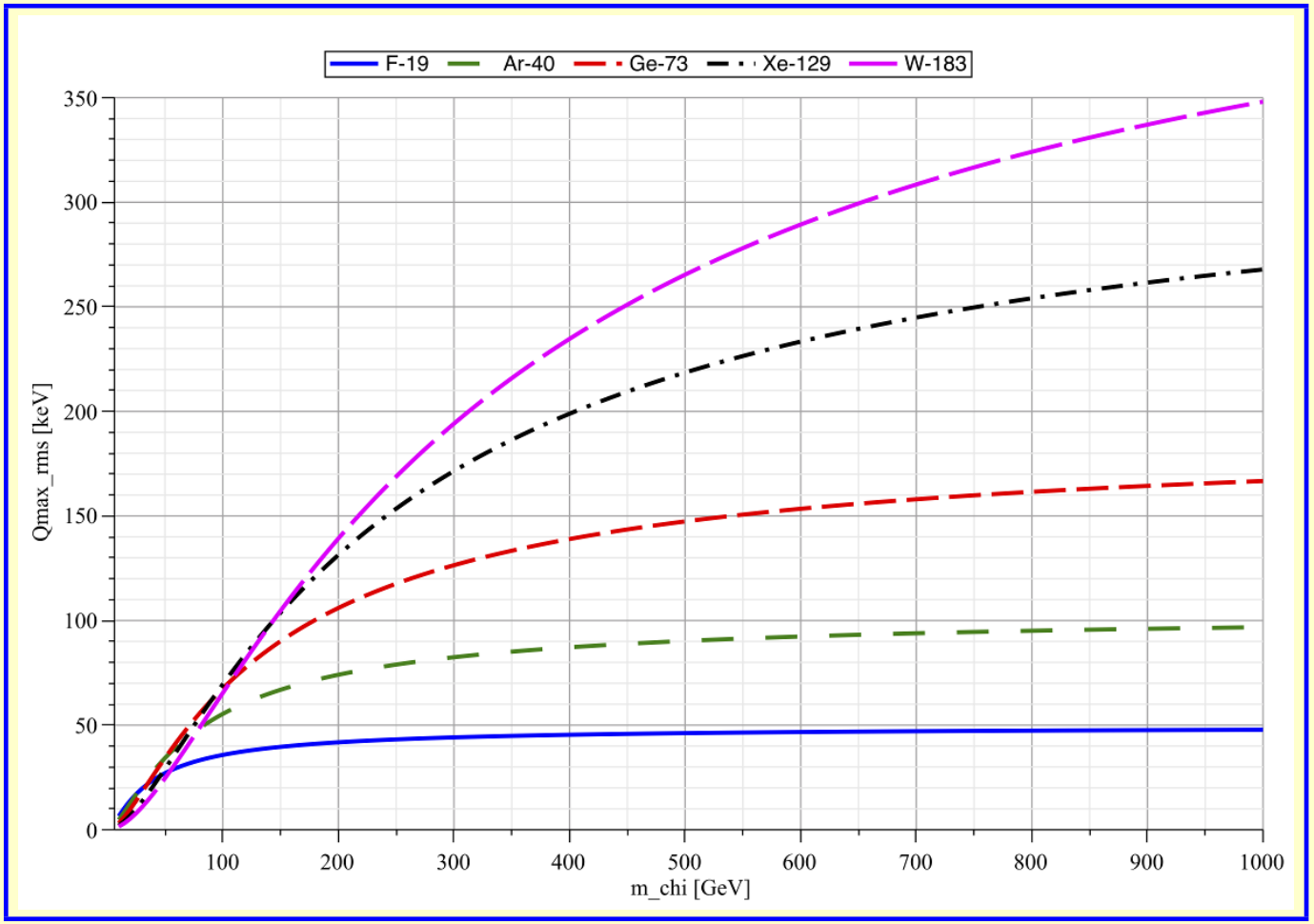
- Recoil-energy dependence of the nuclear form factor



[CLS, arXiv:2103.06883 (2021)]

Arguments

- WIMP-mass dependence of the maximal transferable recoil energy $Q_{\mathrm{max,rms}}$

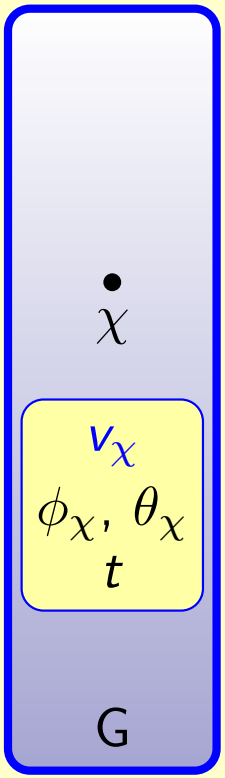


[CLS, arXiv:2103.06883 (2021)]

3-D Monte Carlo "scattering–by–scattering" elastic WIMP–nucleus scattering simulation

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

- 3-D velocity distribution of Galactic WIMPs
  - Simple Maxwellian velocity distribution

$$f_{\chi,\mathrm{G},\mathrm{r}}(v_{\chi,\mathrm{G}}) = \left[\left(\frac{\sqrt{\pi}}{4}\right)\mathrm{erf}\left(\frac{v_{\mathrm{esc}}}{v_0}\right) - \left(\frac{v_{\mathrm{esc}}}{2v_0}\right)e^{-v_{\mathrm{esc}}^2/v_0^2}\right]^{-1}\left(\frac{v_{\chi,\mathrm{G}}^2}{v_0^3}\right)e^{-v_{\chi,\mathrm{G}}^2/v_0^2} \qquad \text{for } v_{\chi,\mathrm{G}} \leq v_{\mathrm{esc}}$$

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

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➢ Angular distribution

$$f_{\chi,\mathrm{G},\phi}(\phi_{\chi,\mathrm{G}}) = 1 \qquad \phi_{\chi,\mathrm{G}} \in (-\pi,\ \pi]$$

$$f_{\chi,\mathrm{G},\theta}(\theta_{\chi,\mathrm{G}}) = 1 \qquad \theta_{\chi,\mathrm{G}} \in [-\pi/2,\ \pi/2]$$

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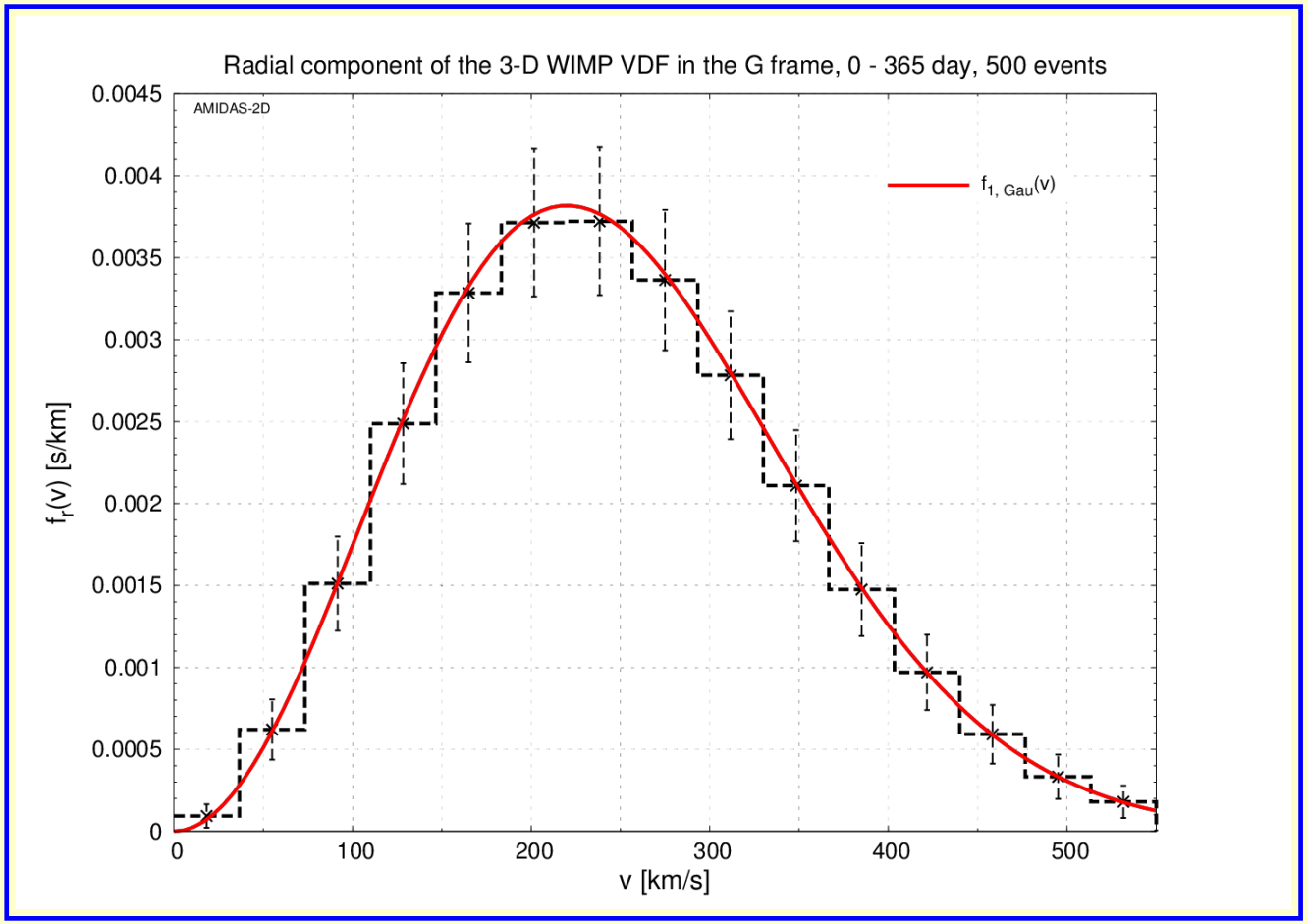
➢ Time dependence

$$f_t(t) = 1 \qquad t \in [t_\mathrm{start},\ t_\mathrm{end}]$$

[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

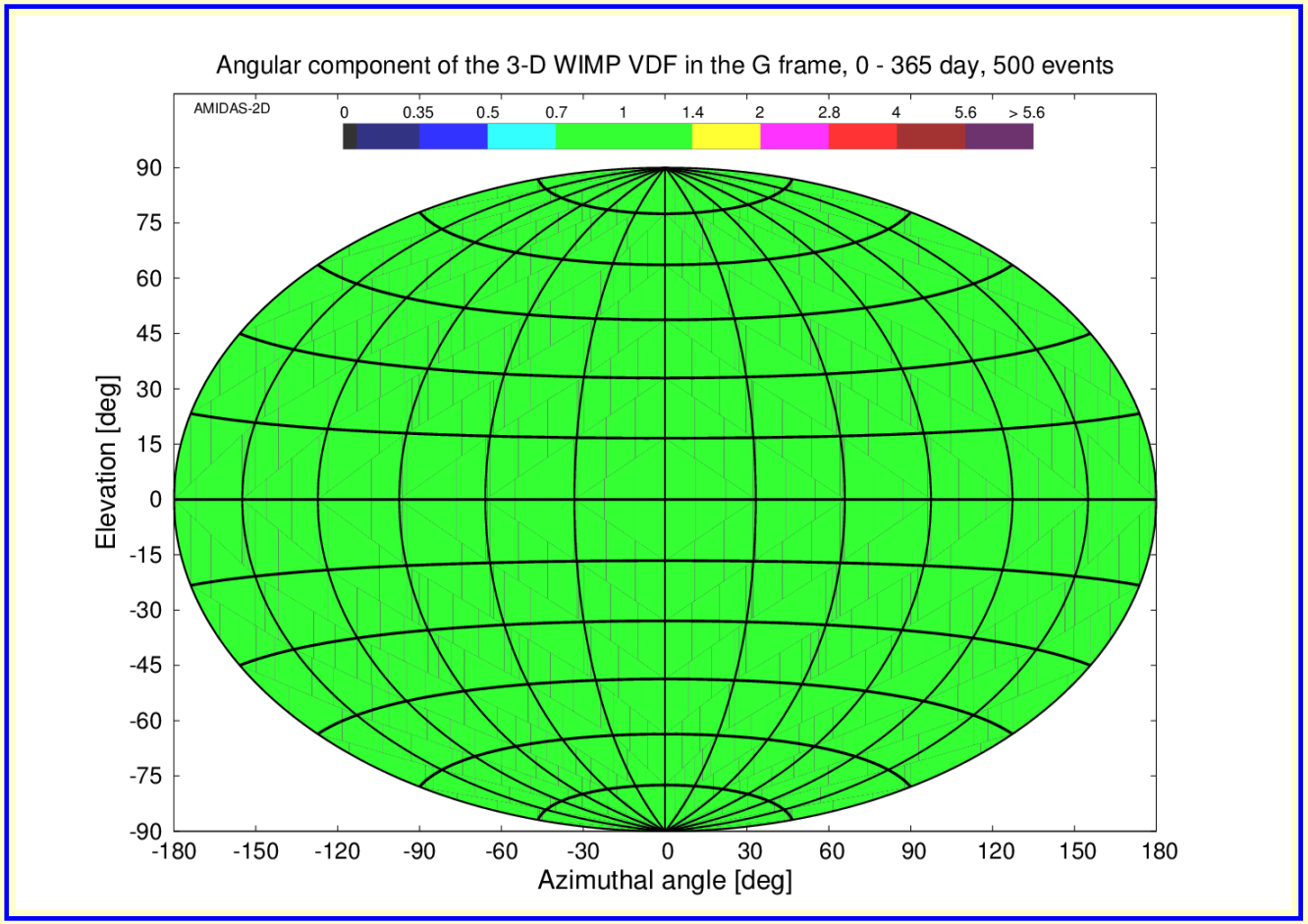
- Radial component (magnitude) of the 3-D WIMP velocity distribution (Galactic frame, 0 - 365 day, 500 events)



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

- Angular component (direction) of the 3-D WIMP velocity distribution (Galactic frame, 0 - 365 day, 500 events)



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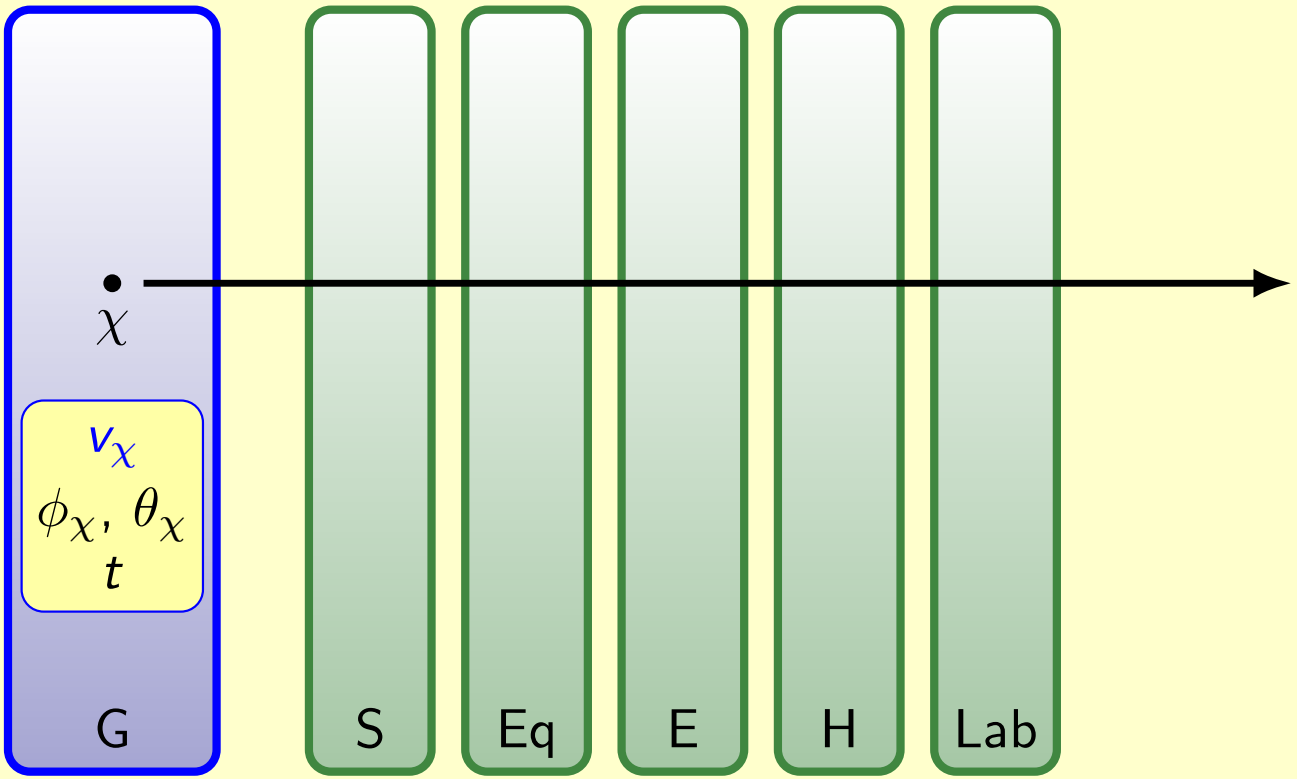
3-D Monte Carlo elastic WIMP–nucleus scattering simulation

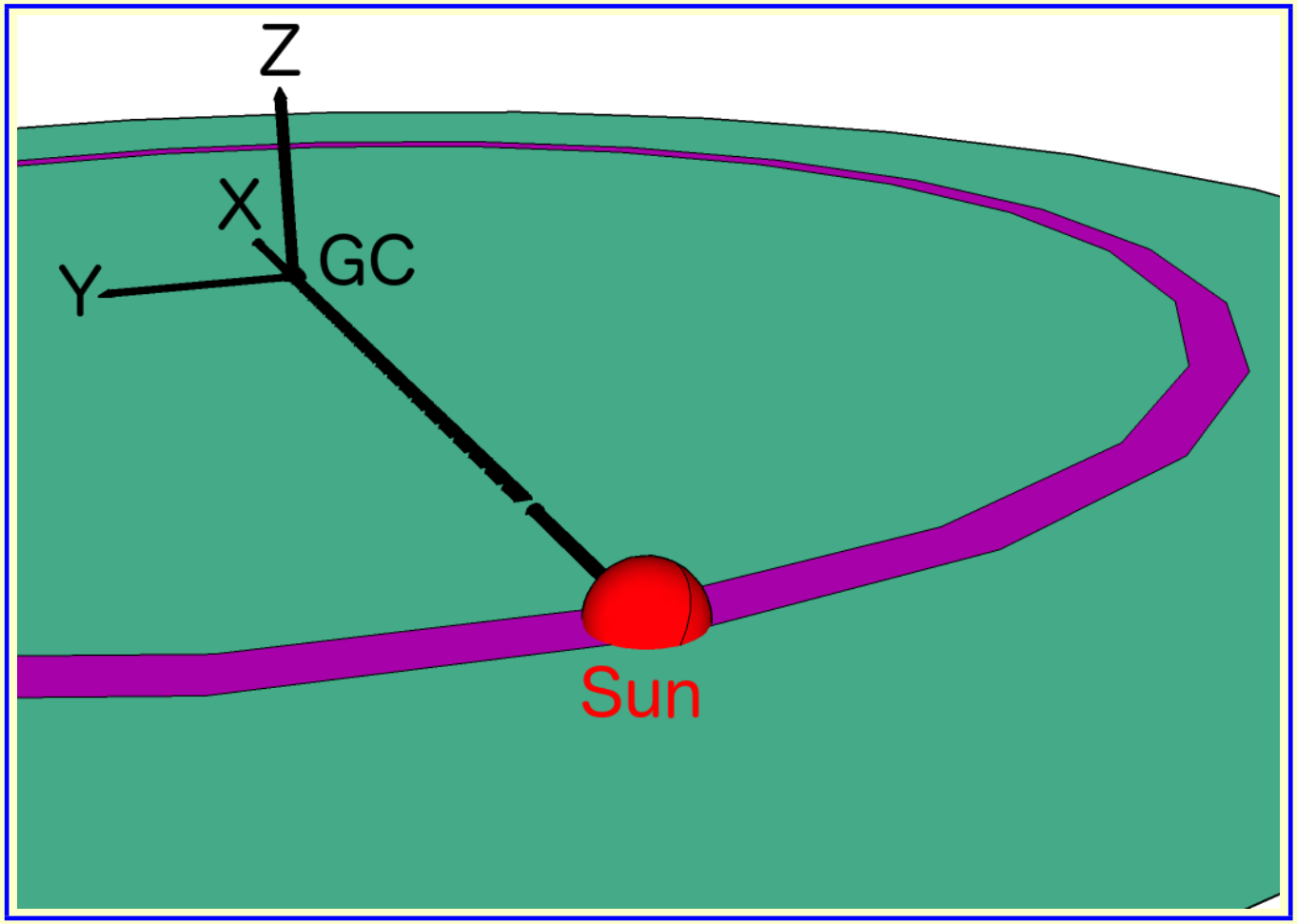
❑ Simulation workflow



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

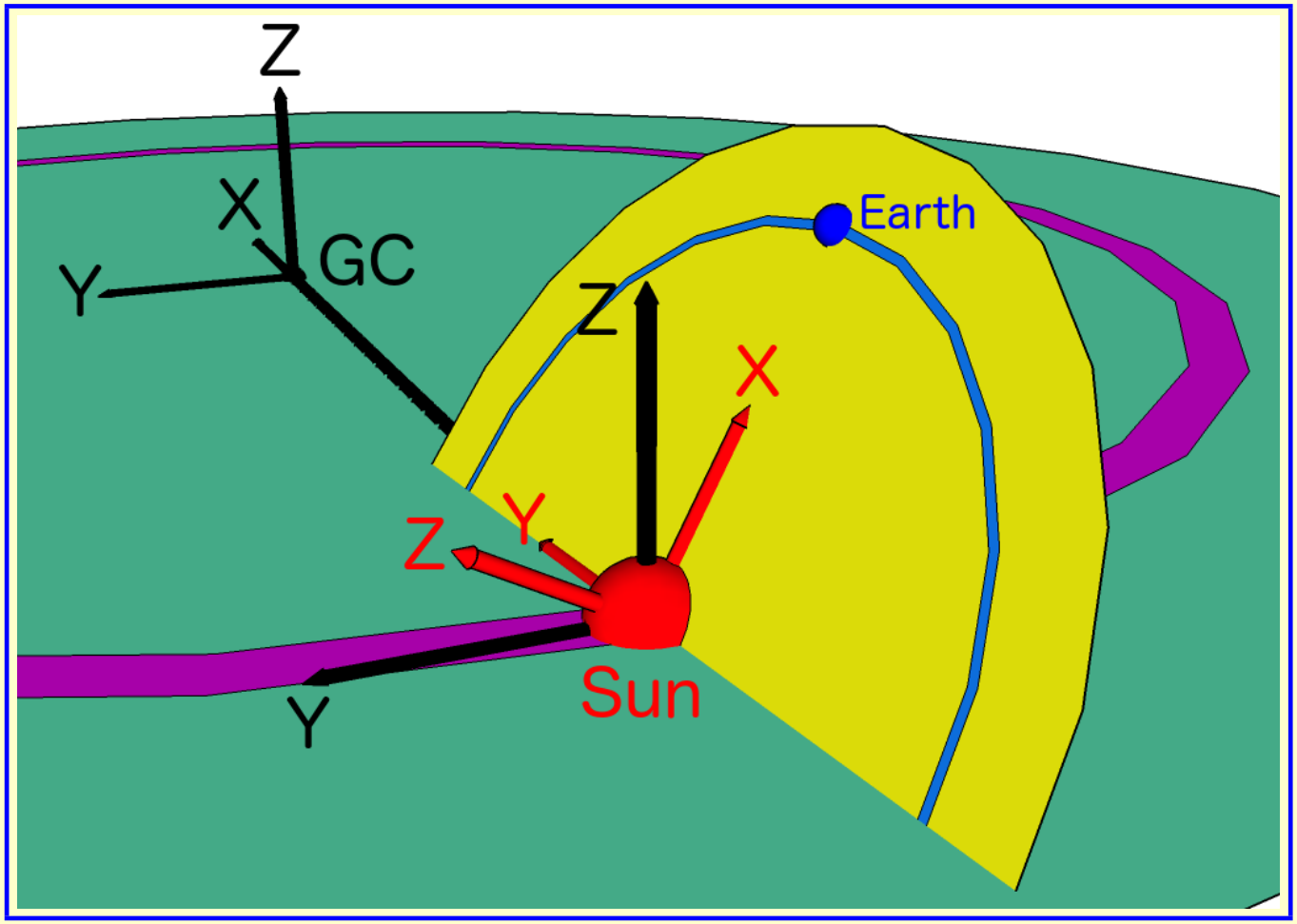
- Galactic (G) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

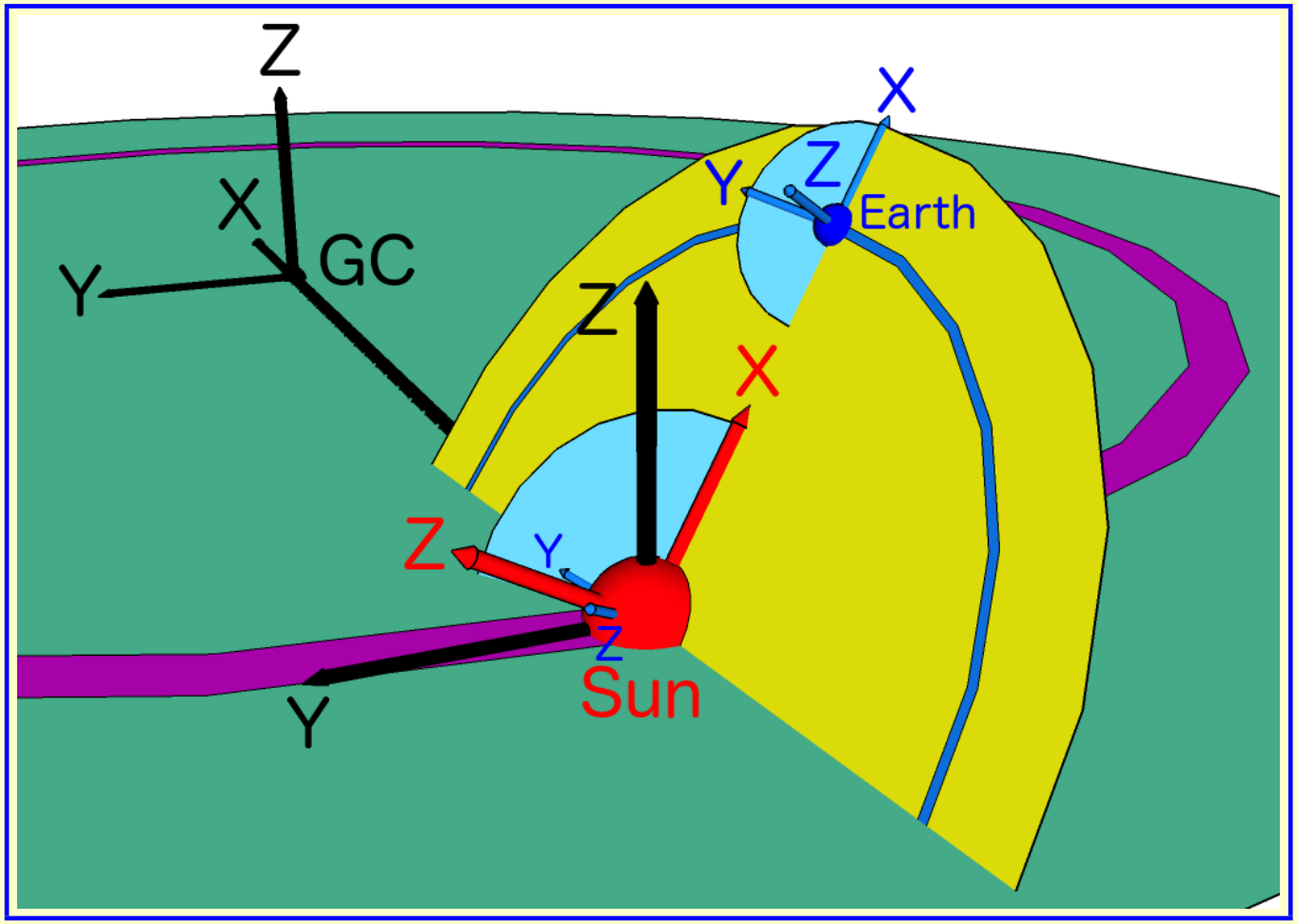
- Ecliptic (S) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

- Equatorial (Eq) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

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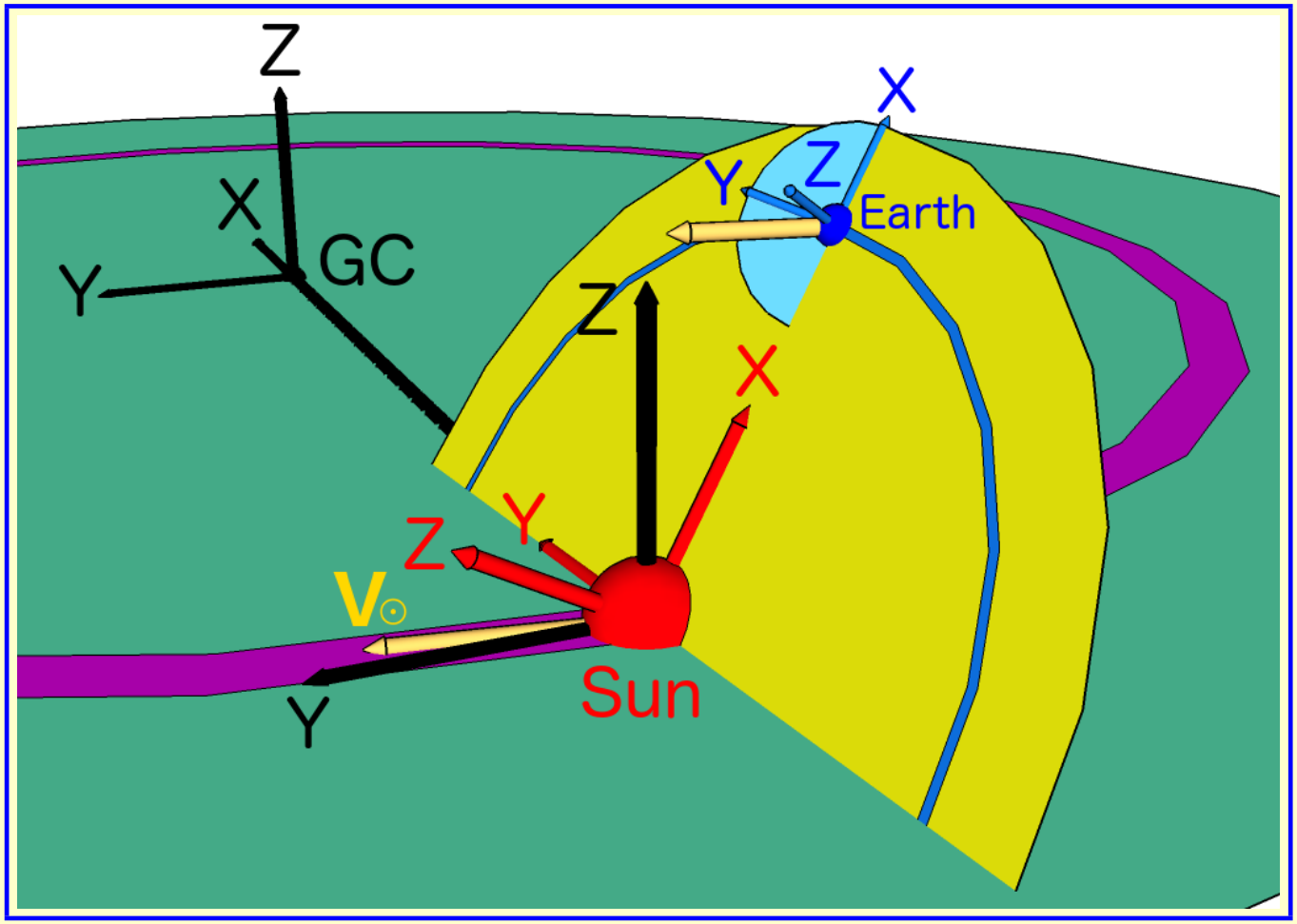
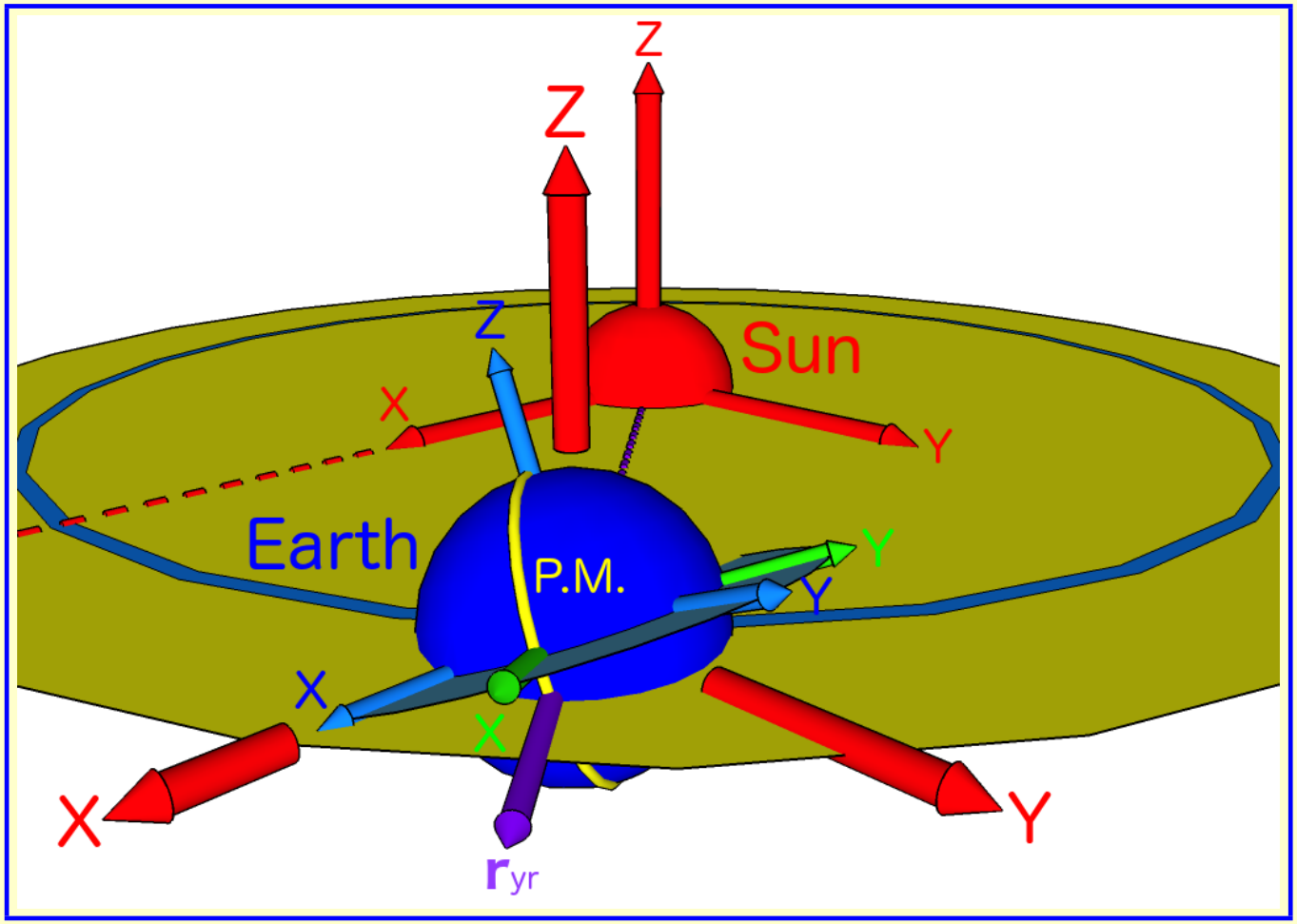


[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

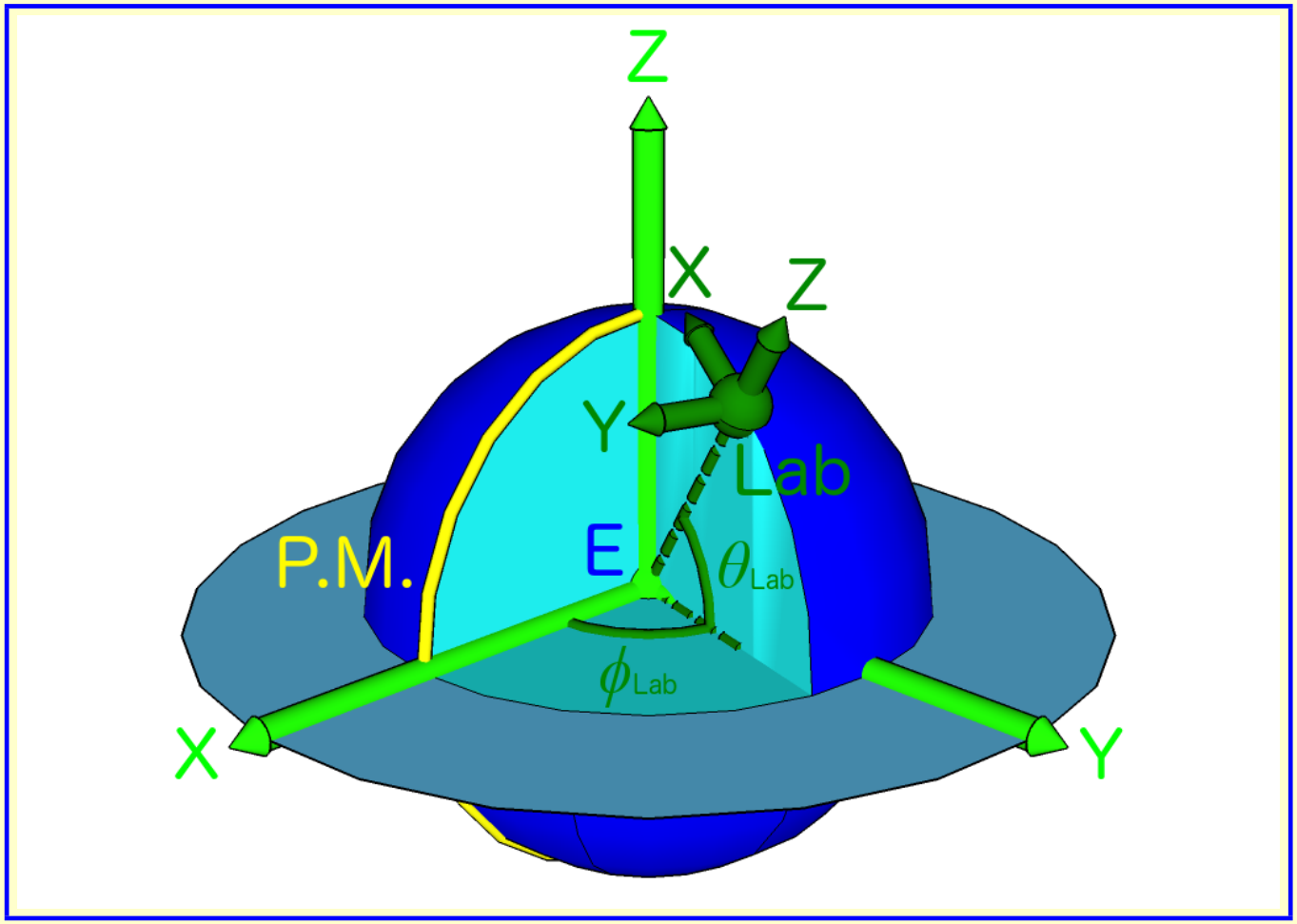
- Earth (E) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

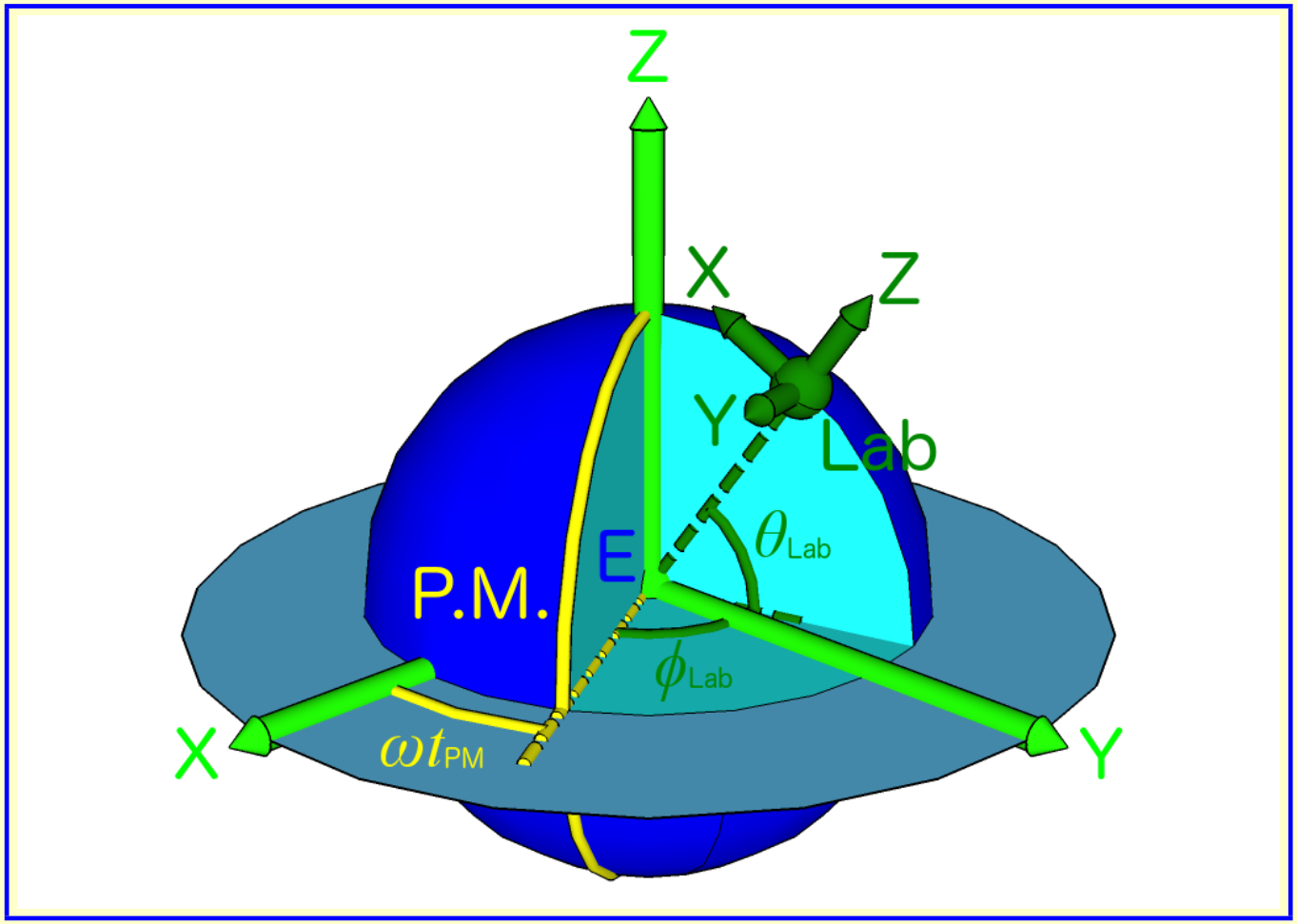
- Horizontal (H) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

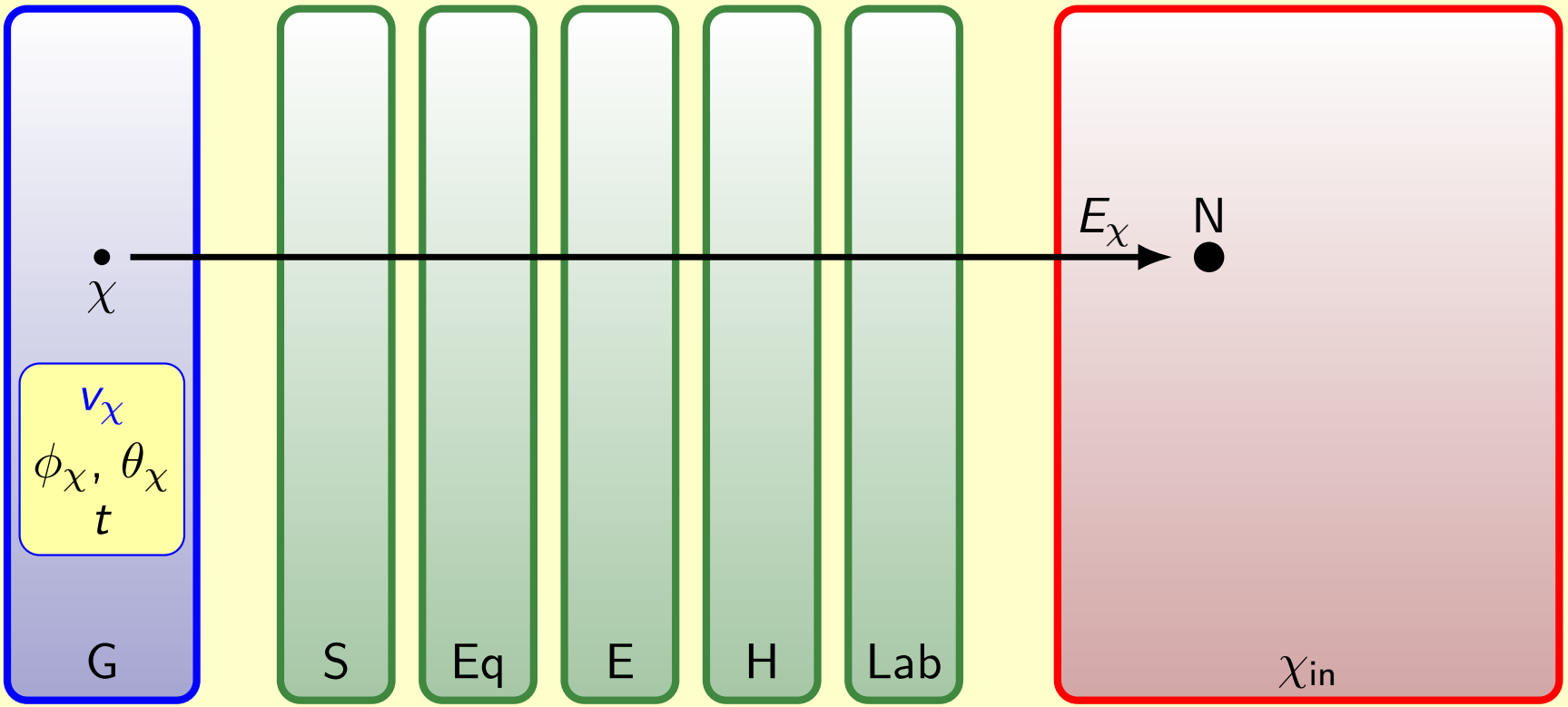
- Laboratory (Lab) coordinate system



[CLS, arXiv:1905.11279 (2019)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



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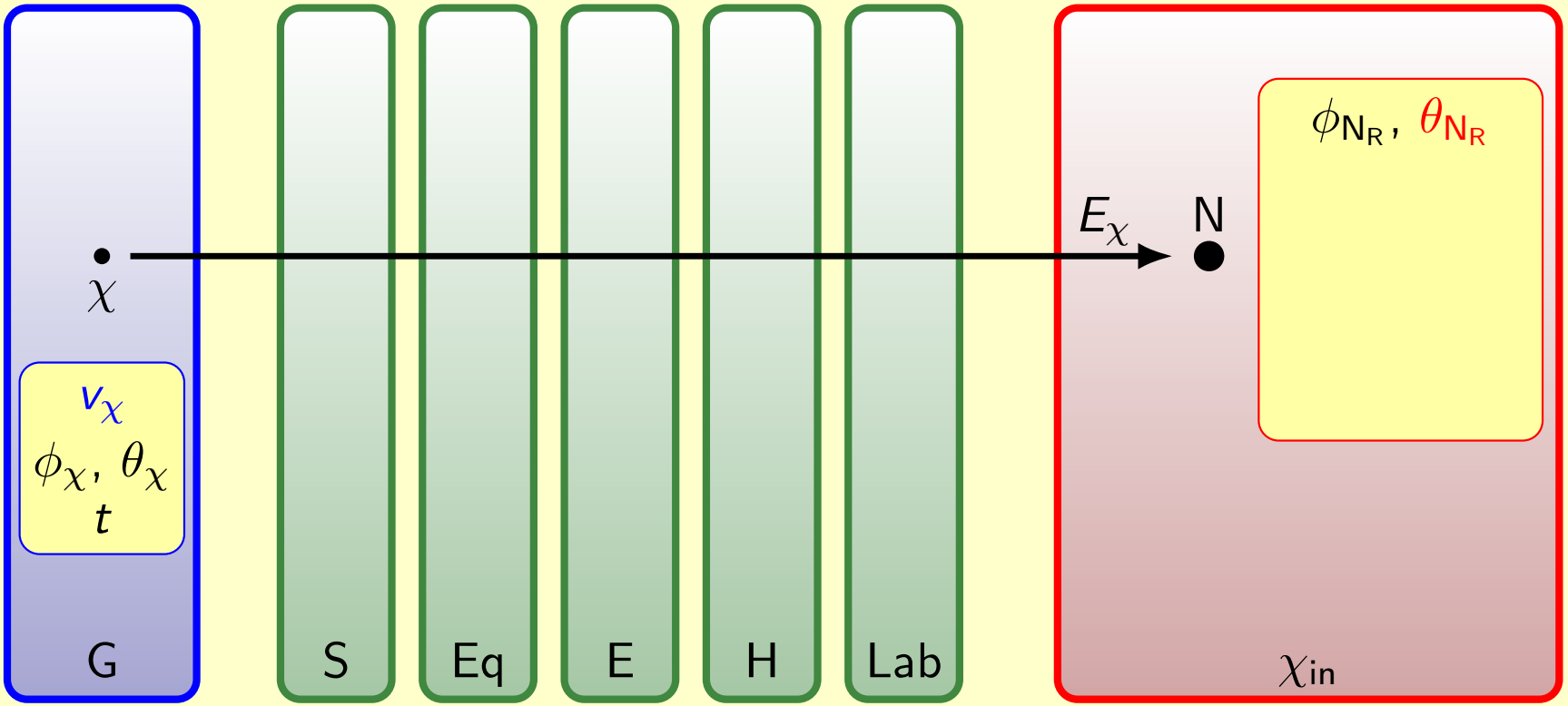
3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

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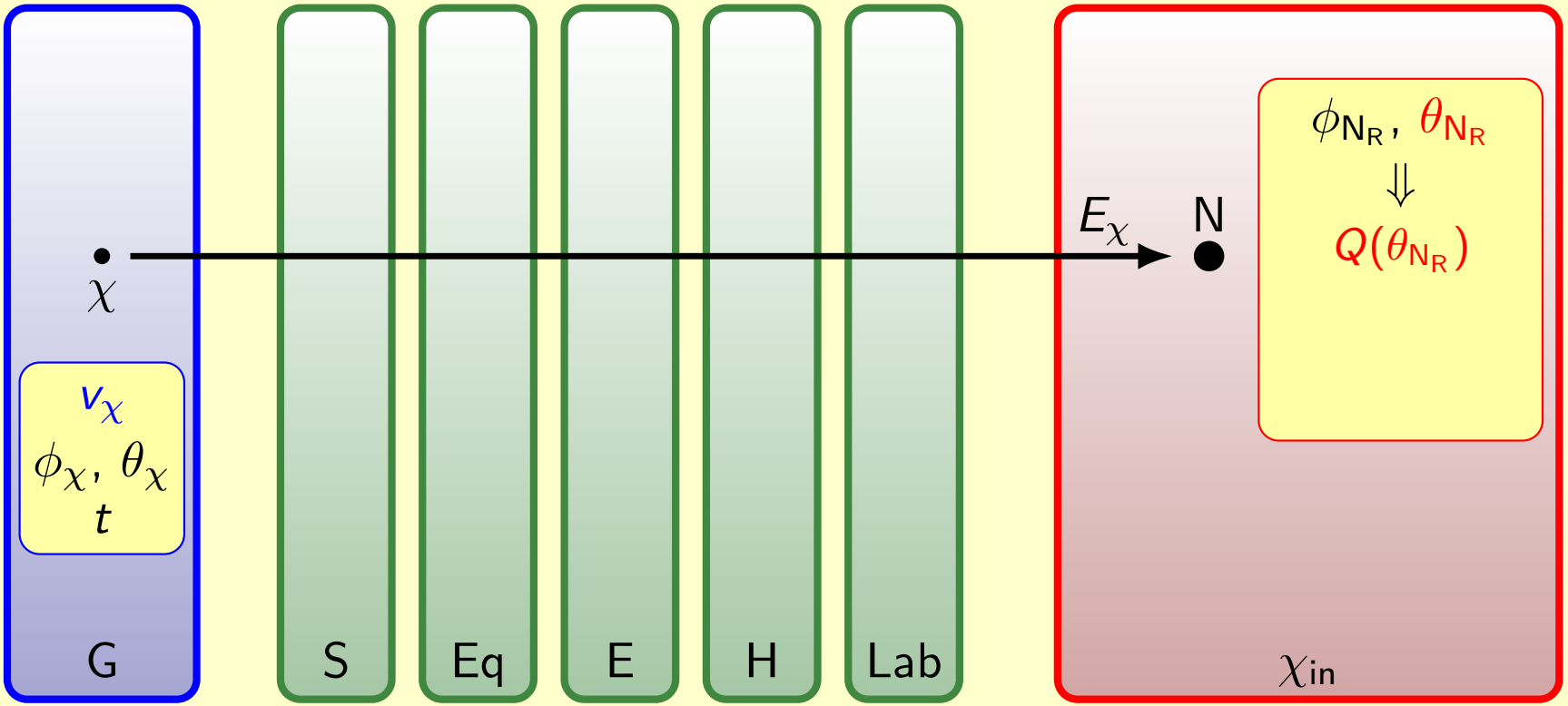
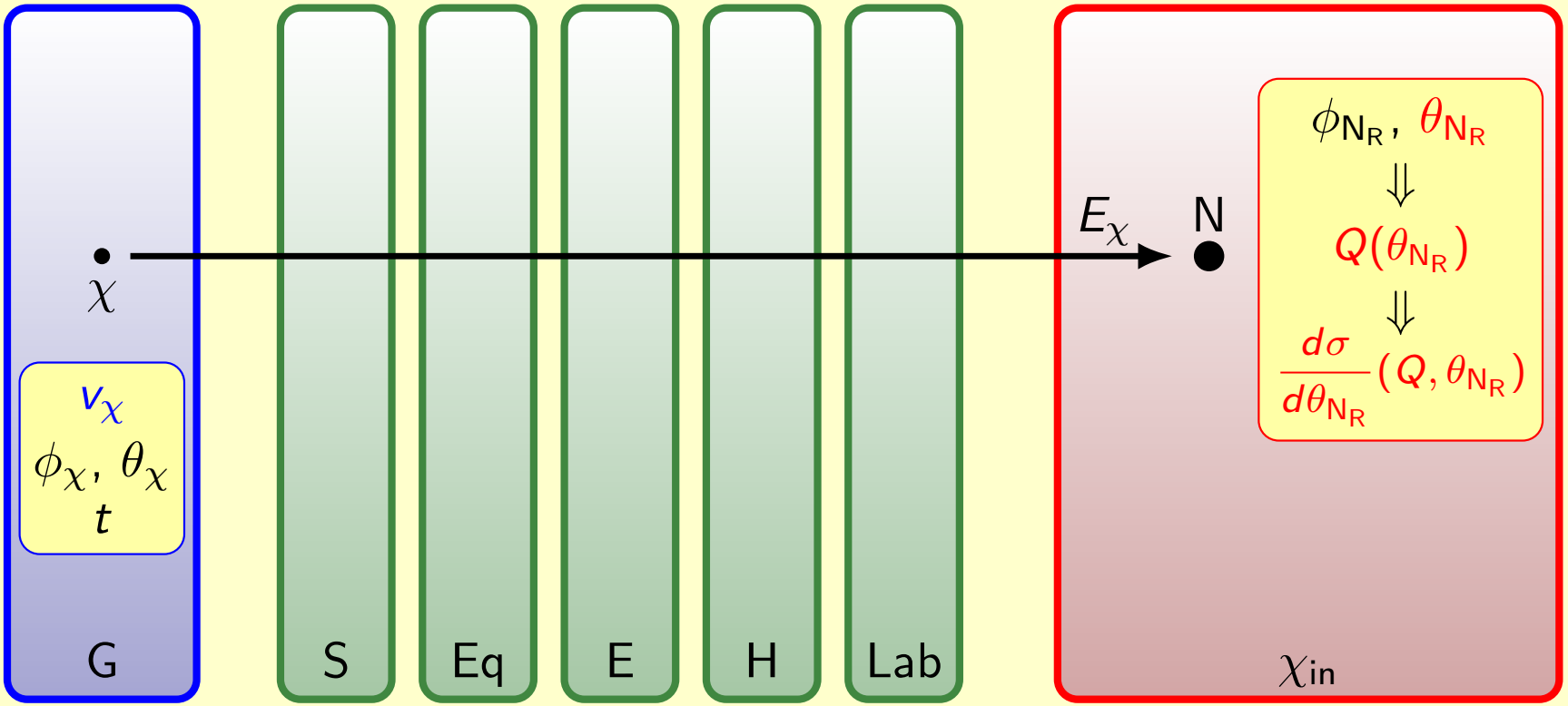


[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

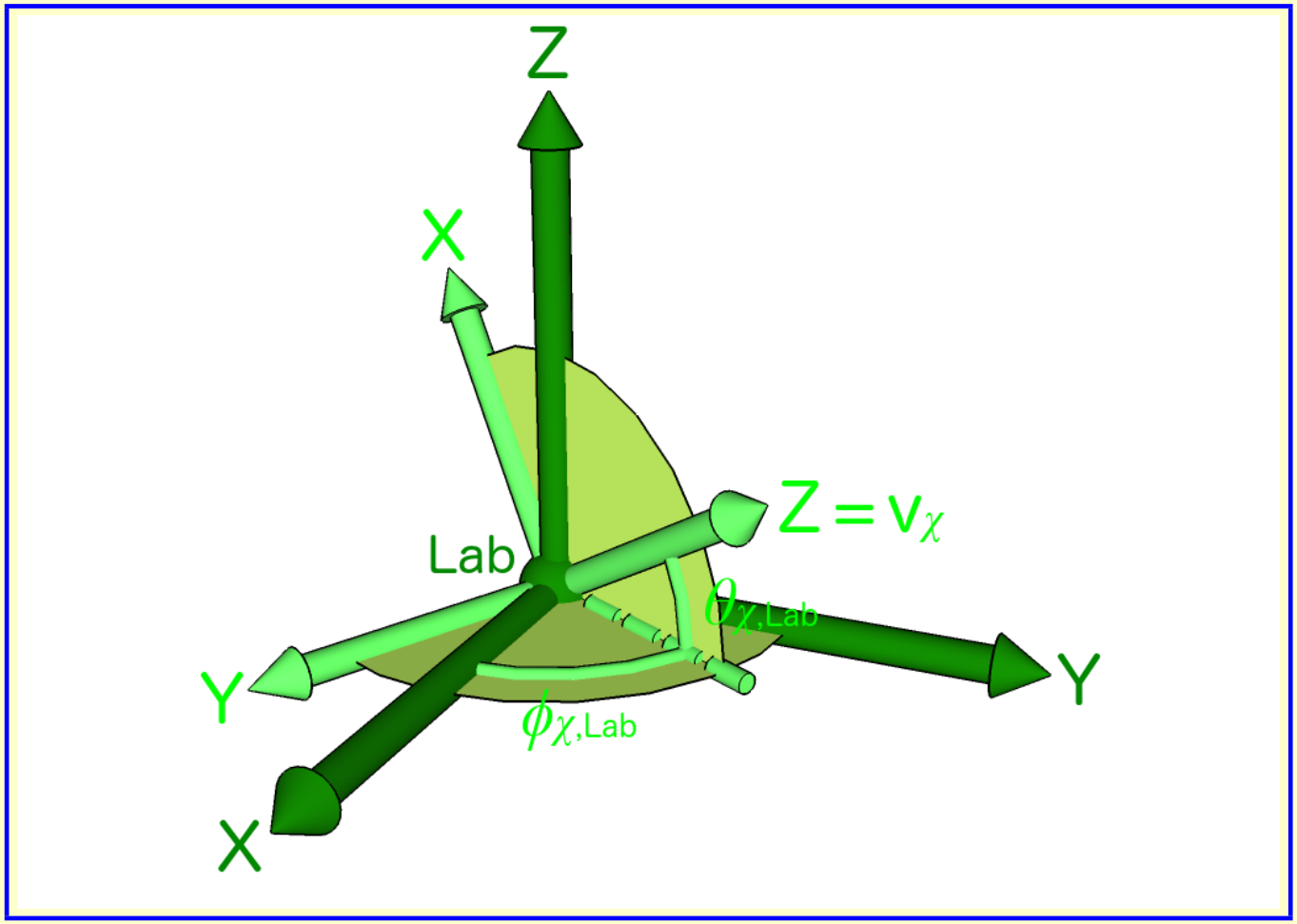
❑ Simulation workflow



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

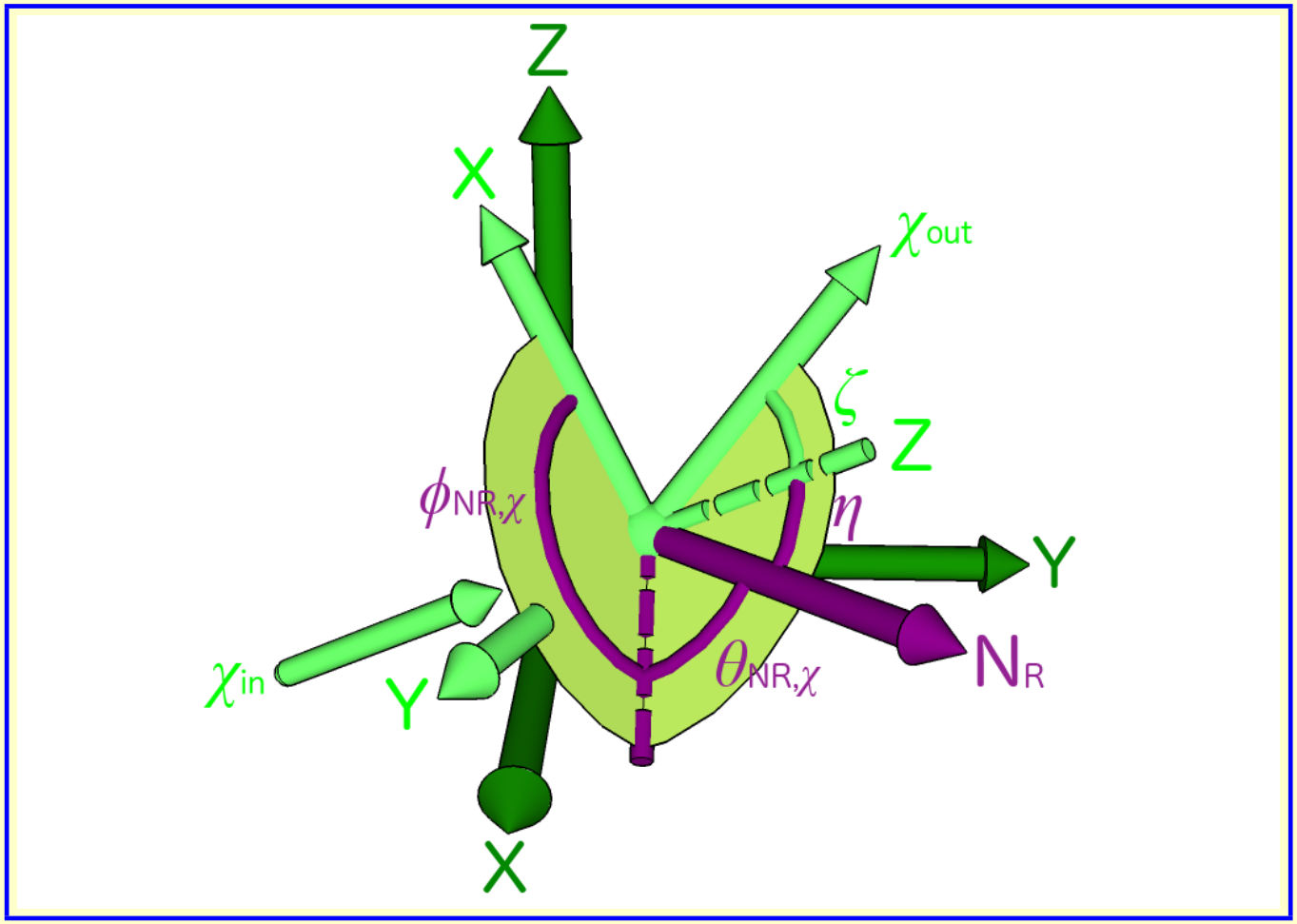
- Incoming-WIMP (χ_{in}) coordinate system



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

- Orientation of the scattering plane and the (equivalent) recoil angle



[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Scattering simulation

➢ Azimuthal distribution

$$f_{\mathrm{NR},\chi_{\mathrm{in}},\phi}(\phi_{\mathrm{N_R},\chi_{\mathrm{in}}}) = 1 \qquad \phi_{\mathrm{N_R},\chi_{\mathrm{in}}} \in (-\pi,\ \pi]$$

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Scattering simulation

➢ Azimuthal distribution

$$f_{\mathrm{NR},\chi_{\mathrm{in}},\phi}(\phi_{\mathrm{N_R},\chi_{\mathrm{in}}}) = 1 \qquad \phi_{\mathrm{N_R},\chi_{\mathrm{in}}} \in (-\pi,\ \pi]$$

➢ Recoil energy of the scattered target nucleus

$$Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}) = \left[\frac{4 m_\chi m_{\mathrm{N}}}{(m_\chi + m_{\mathrm{N}})^2} E_\chi\right] \sin^2(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}) \qquad E_\chi = \frac{1}{2} m_\chi v_{\chi,\mathrm{Lab}}^2 \qquad \theta_{\mathrm{N_R},\chi_{\mathrm{in}}} \in [0,\ \pi/2]$$

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

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➢ Cross section (nuclear form factor) suppression on the equivalent recoil angle

$$d\sigma = \frac{1}{v_{\chi,\mathrm{Lab}}^2}\left(\frac{\sigma_0}{4 m_{\mathrm{r,N}}^2}\right) F^2(q)\, dq^2 = \frac{1}{v_{\chi,\mathrm{Lab}}^2}\left(\frac{m_{\mathrm{N}}}{2 m_{\mathrm{r,N}}^2}\right) \sigma_0 F^2(Q)\, dQ \qquad q = \sqrt{2 m_{\mathrm{N}} Q}$$

$$\frac{d\sigma}{d\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}} = \left[\sigma_0^{\mathrm{SI}} F_{\mathrm{SI}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})) + \sigma_0^{\mathrm{SD}} F_{\mathrm{SD}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}))\right] \sin(2\,\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})$$

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Scattering simulation

➢ Azimuthal distribution

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$$\frac{d\sigma}{d\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}} = \left[\sigma_0^{\mathrm{SI}} F_{\mathrm{SI}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})) + \sigma_0^{\mathrm{SD}} F_{\mathrm{SD}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}))\right] \sin(2\,\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})$$

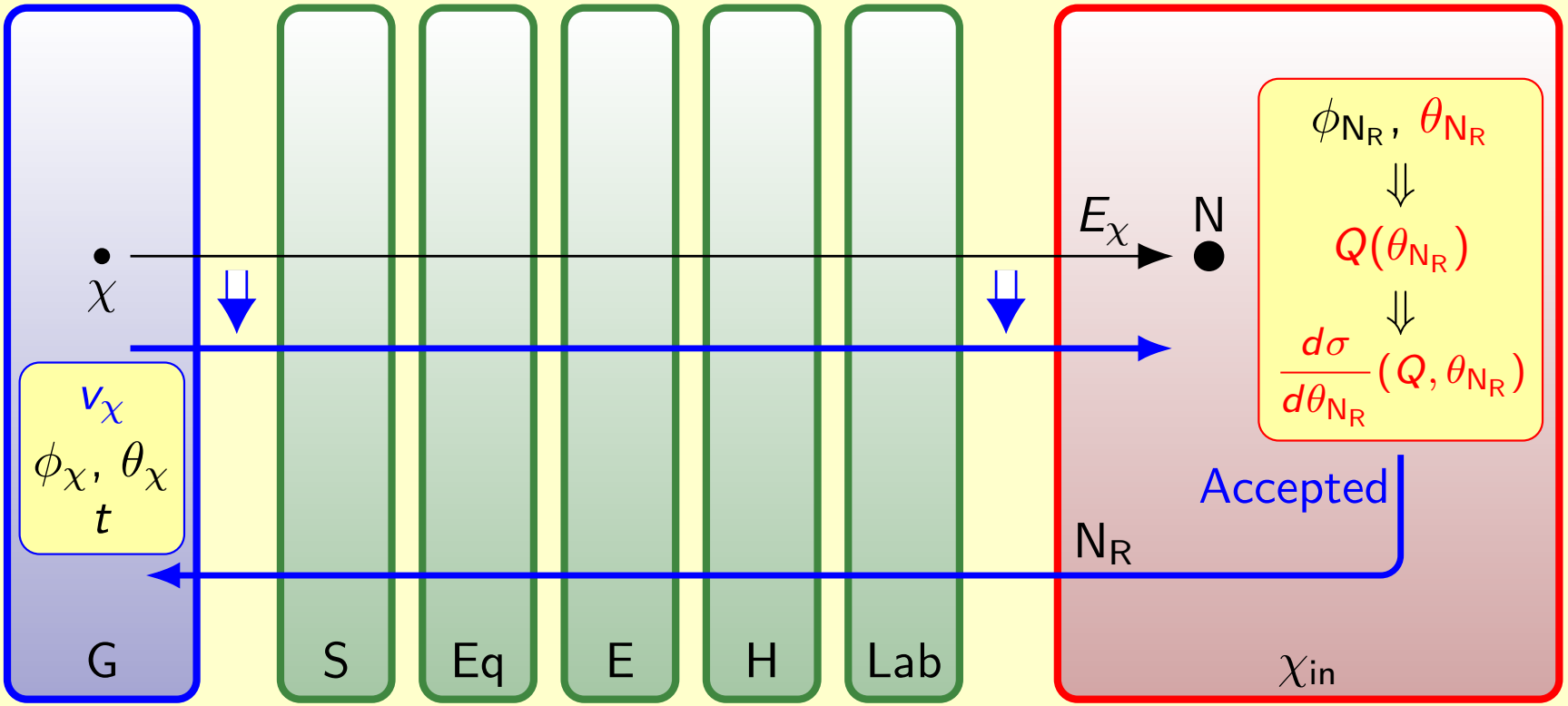
➢ Generating probability distribution of the equivalent recoil angle

$$f_{\mathrm{N_R},\chi_{\mathrm{in}},\theta}(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}) = \left(\frac{v_{\chi,\mathrm{Lab}}}{v_{\chi,\mathrm{cutoff}}}\right)\left[\sigma_0^{\mathrm{SI}} F_{\mathrm{SI}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})) + \sigma_0^{\mathrm{SD}} F_{\mathrm{SD}}^2(Q(\theta_{\mathrm{N_R},\chi_{\mathrm{in}}}))\right] \sin(2\,\theta_{\mathrm{N_R},\chi_{\mathrm{in}}})$$

[CLS, arXiv:2103.06485 (2021)]

3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



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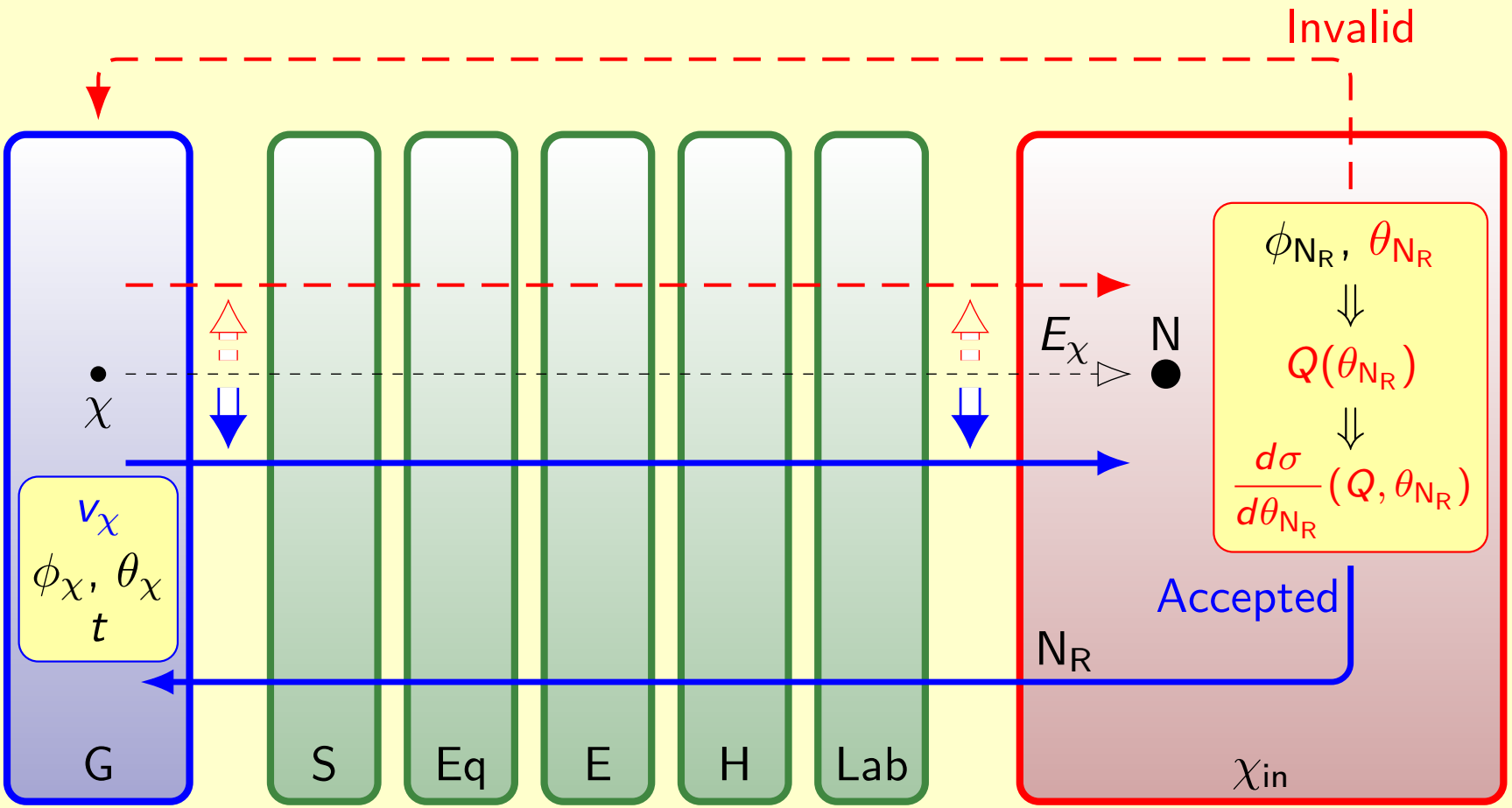
3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



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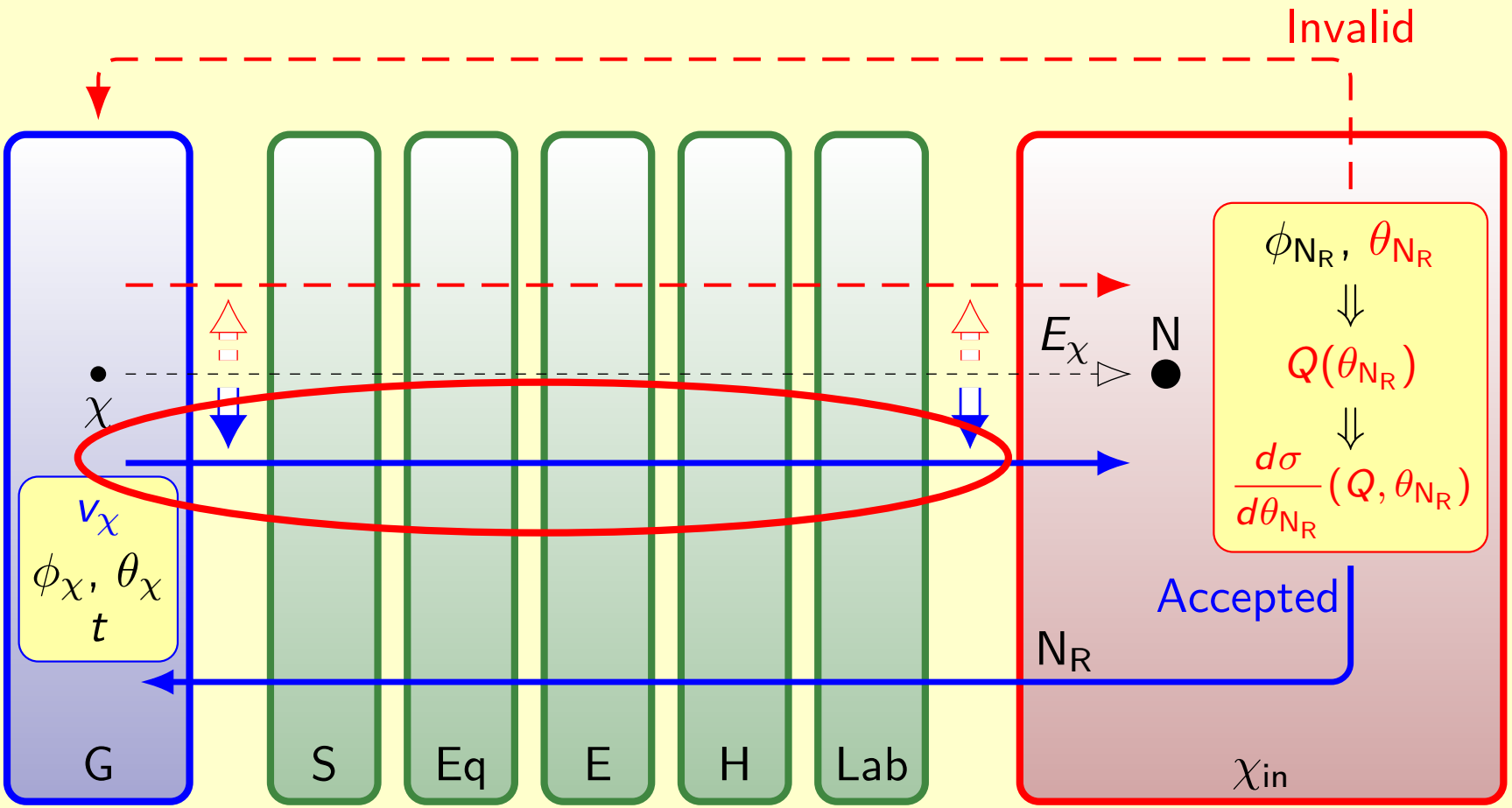
3-D Monte Carlo elastic WIMP–nucleus scattering simulation

❑ Simulation workflow



[CLS, arXiv:2103.06485 (2021)]

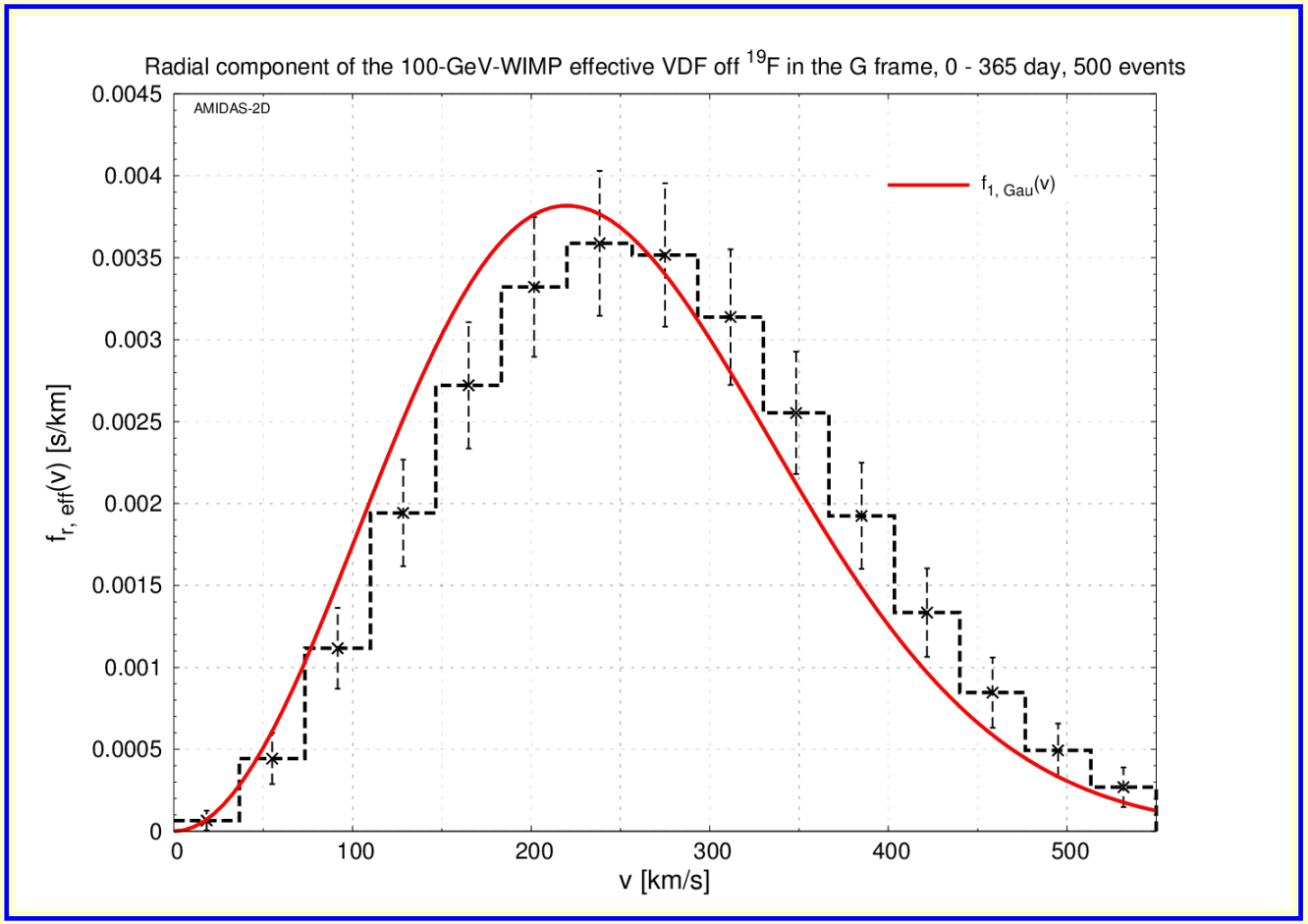
Numerical results

Radial component (magnitude) in the Galactic coordinate system

3-D WIMP effective velocity distribution in the Galactic frame

- Radial component

  (100 GeV, off ^{19}F, Galactic frame, 0 - 365 day, 500 events)

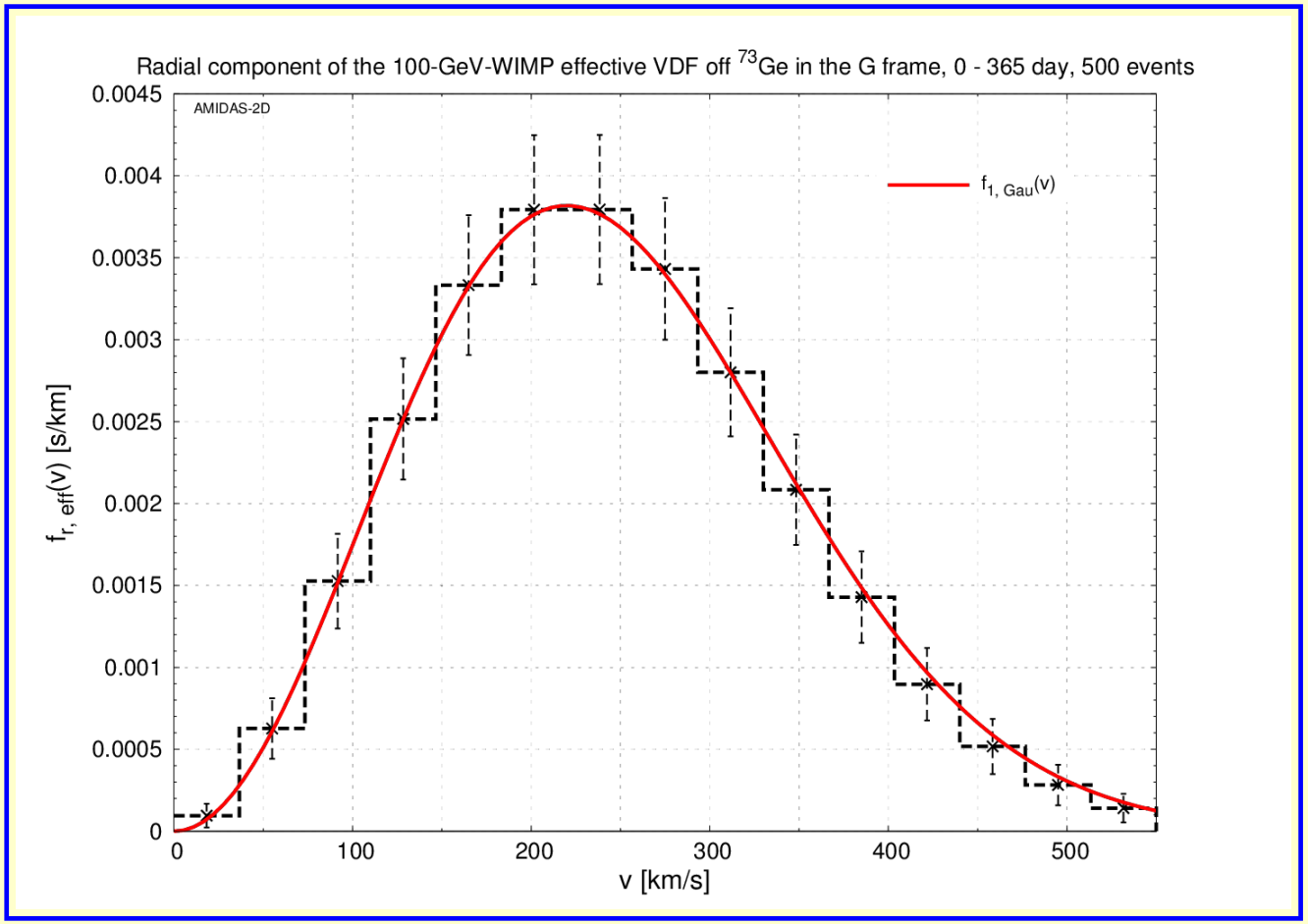


[CLS, arXiv:2103.06883 (2021)]

3-D WIMP effective velocity distribution in the Galactic frame

- Radial component

  (100 GeV, off ^{73}Ge, Galactic frame, 0 - 365 day, 500 events)

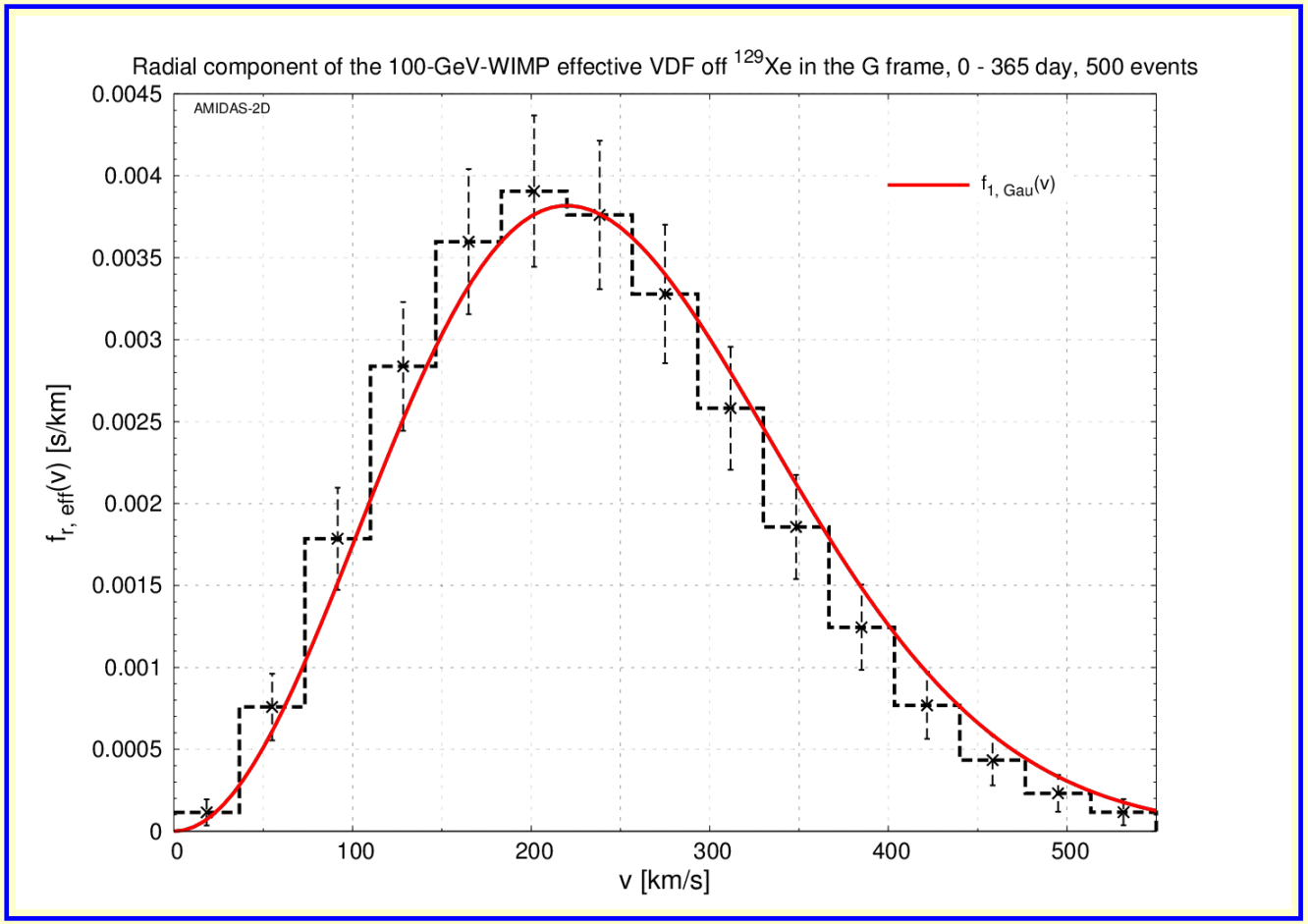


[CLS, arXiv:2103.06883 (2021)]

3-D WIMP effective velocity distribution in the Galactic frame

- Radial component

  (100 GeV, off ^{129}Xe, Galactic frame, 0 - 365 day, 500 events)



[CLS, arXiv:2103.06883 (2021)]

3-D WIMP effective velocity distribution in the Galactic frame

- Radial component

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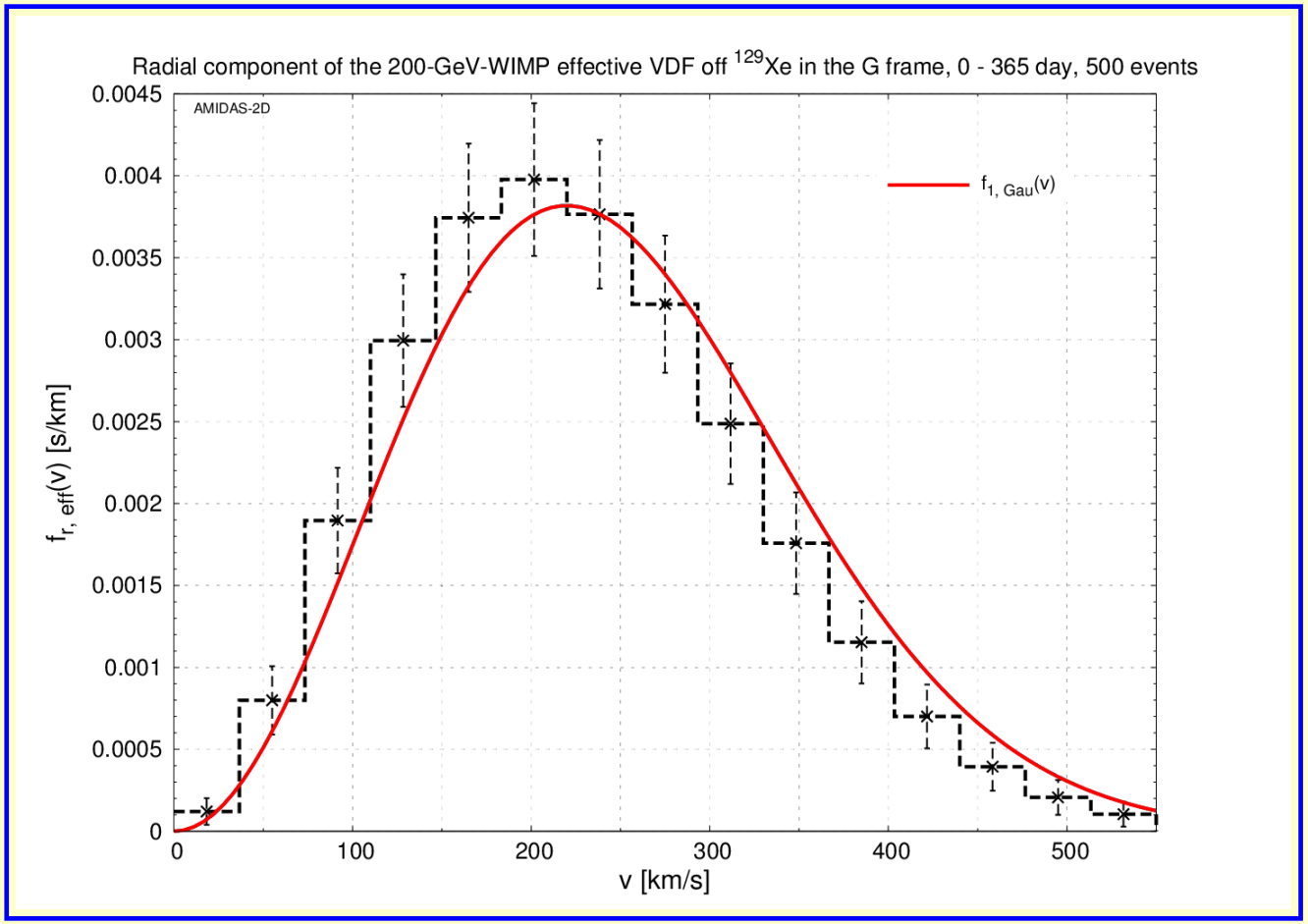
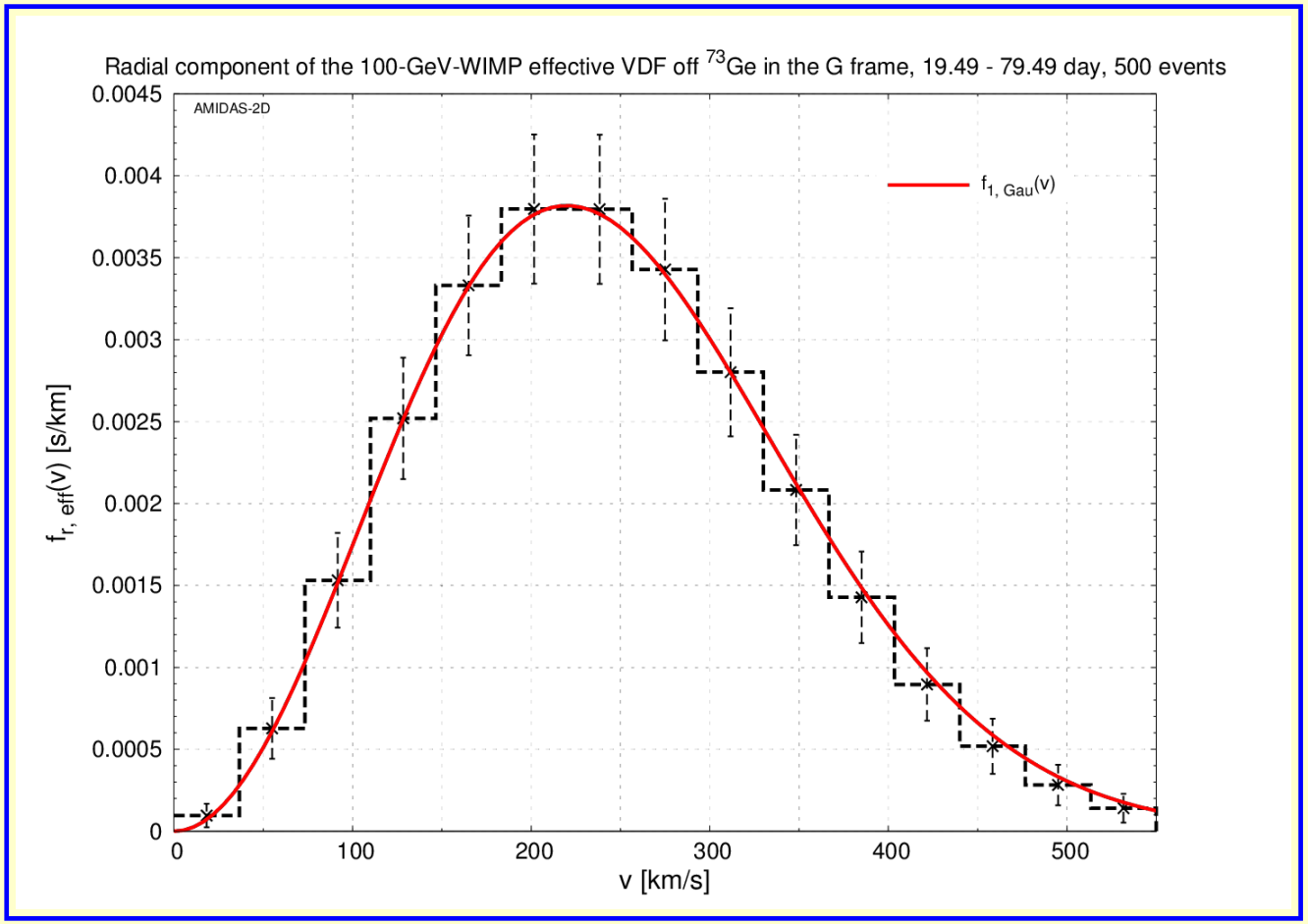


[CLS, arXiv:2103.06883 (2021)]

3-D WIMP effective velocity distribution in the Galactic frame

- Annual modulation of the radial component

  (100 GeV, off ^{73}Ge, Galactic frame, 19.49 – 79.49 day, 500 events)



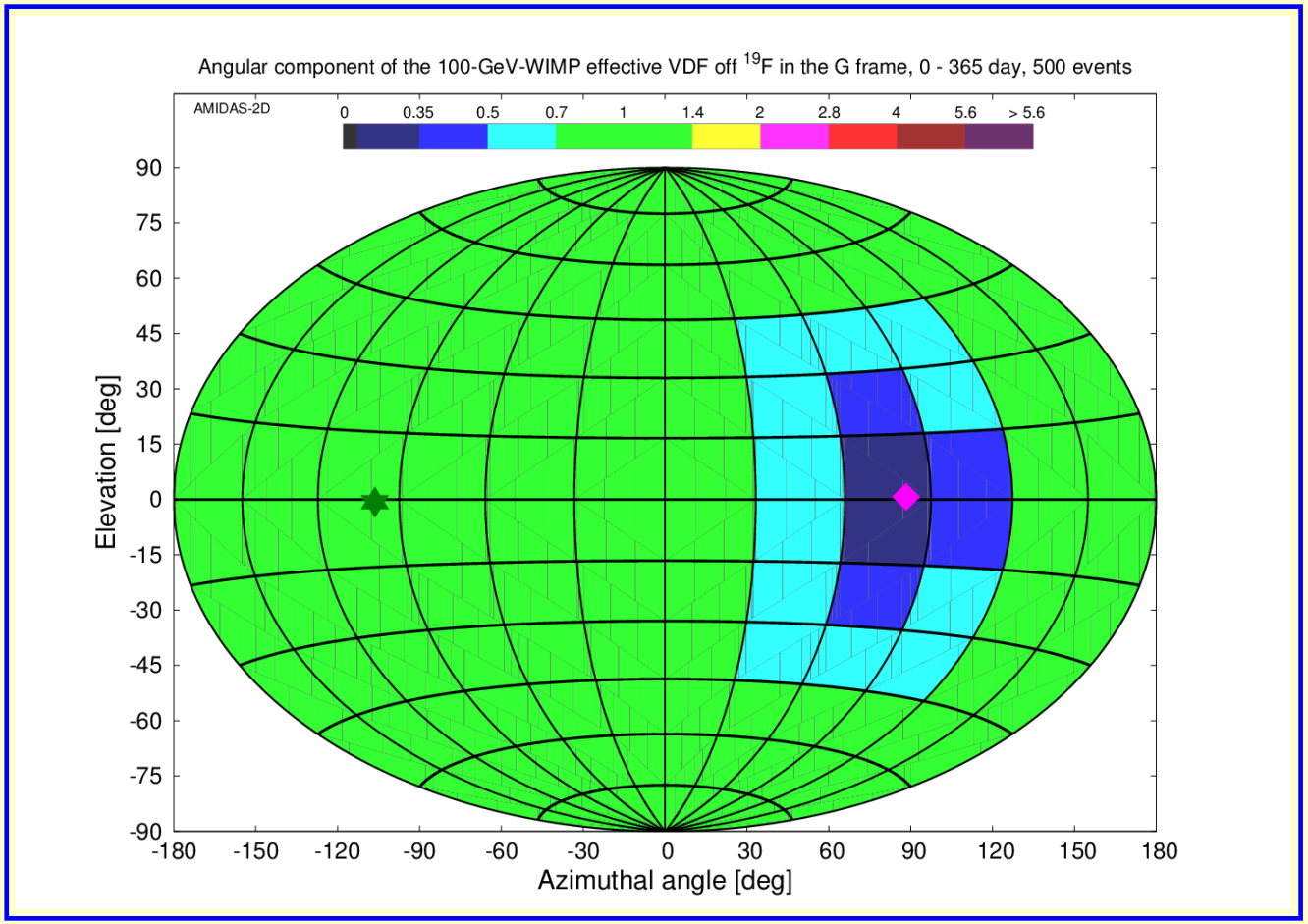
[CLS, arXiv:2103.06883 (2021)]

Angular component (direction) in the Galactic coordinate system

3-D WIMP effective velocity distribution in the Galactic frame

- Angular component

  (100 GeV, off ^{19}F, Galactic frame, 0 - 365 day, 500 events)



[CLS, arXiv:2103.06883 (2021)]

3-D WIMP effective velocity distribution in the Galactic frame

- Angular component

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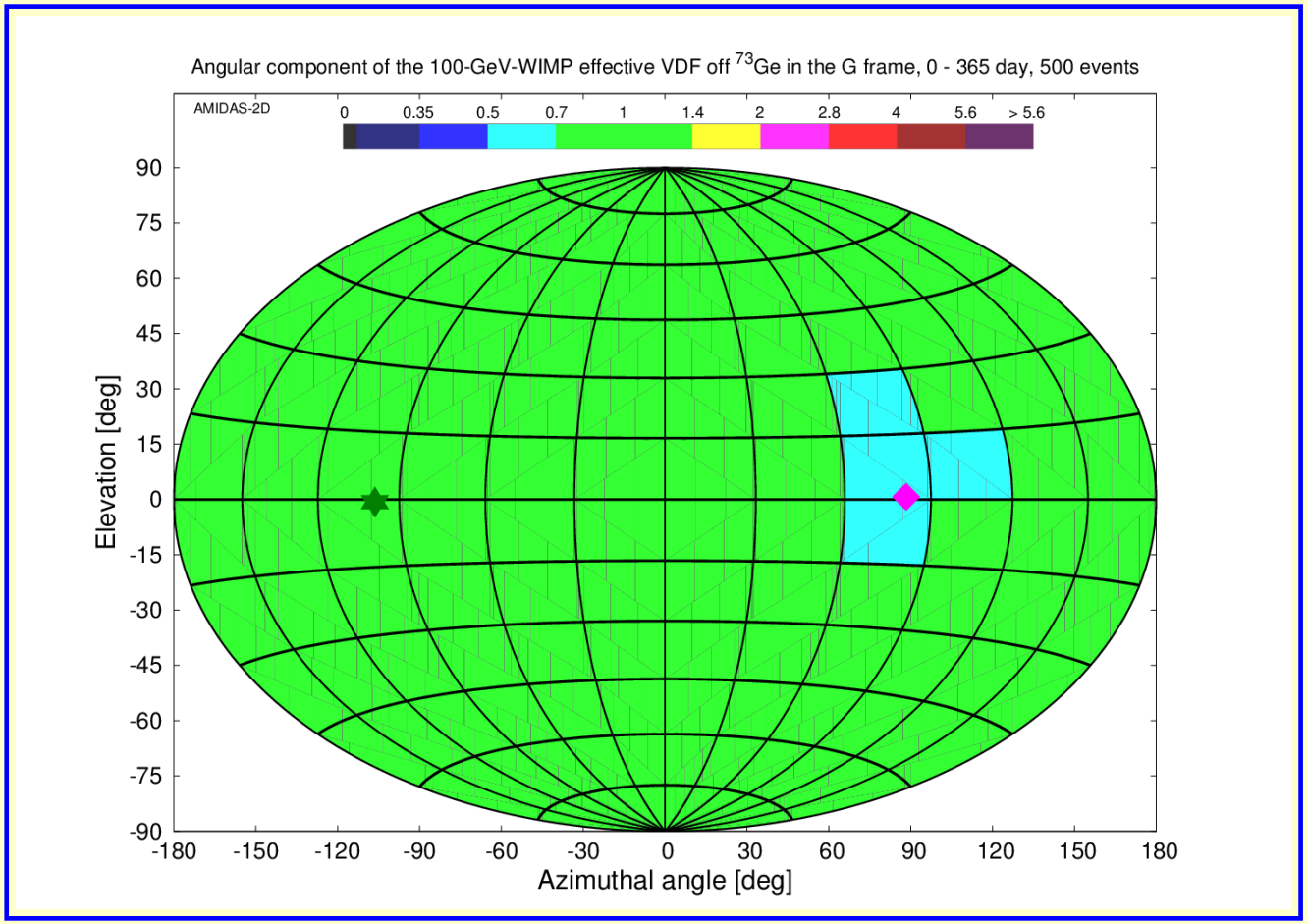

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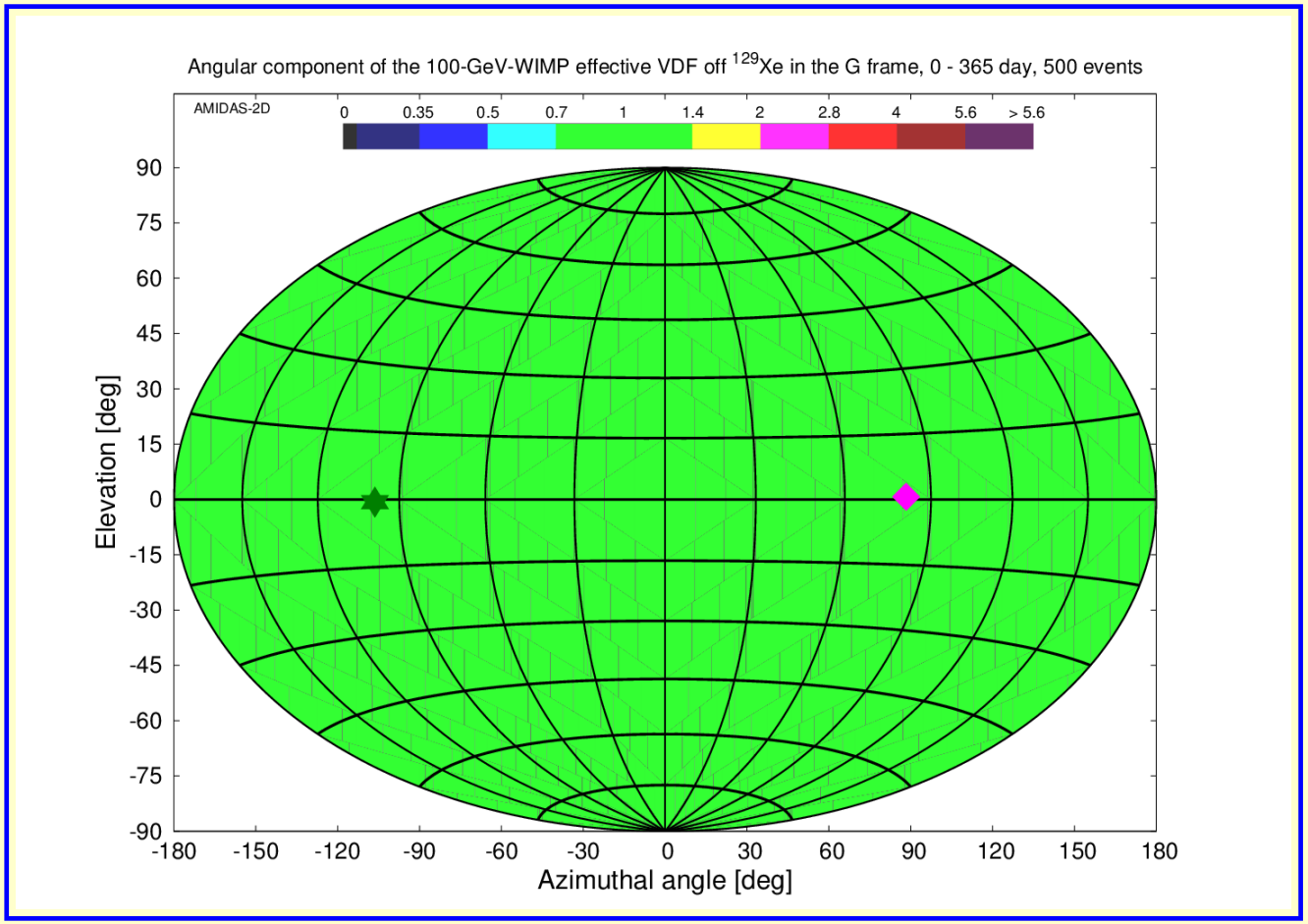

[CLS, arXiv:2103.06883 (2021)]

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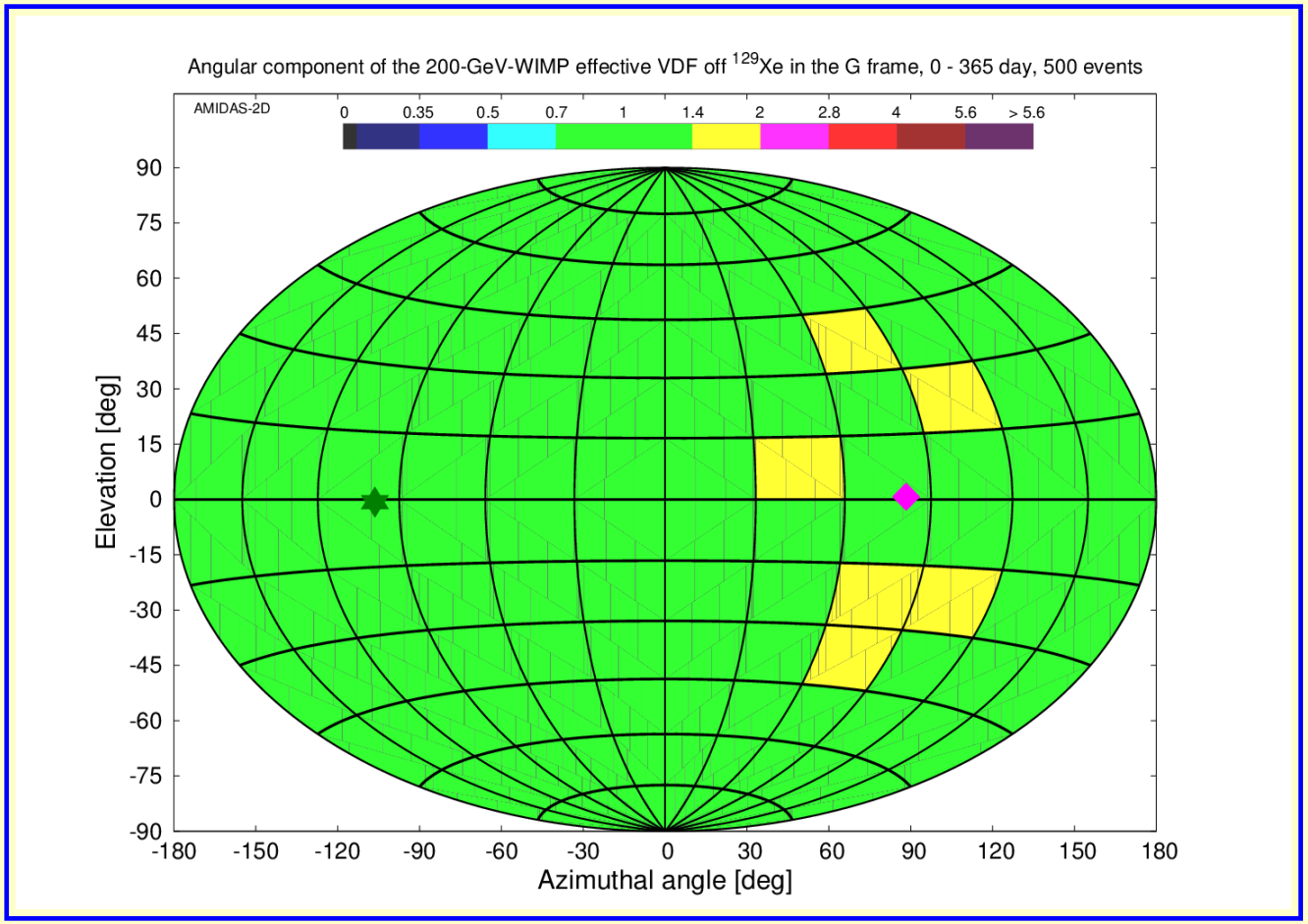
- Angular component

  (200 GeV, off ^{129}Xe, Galactic frame, 0 - 365 day, 500 events)



[CLS, arXiv:2103.06883 (2021)]

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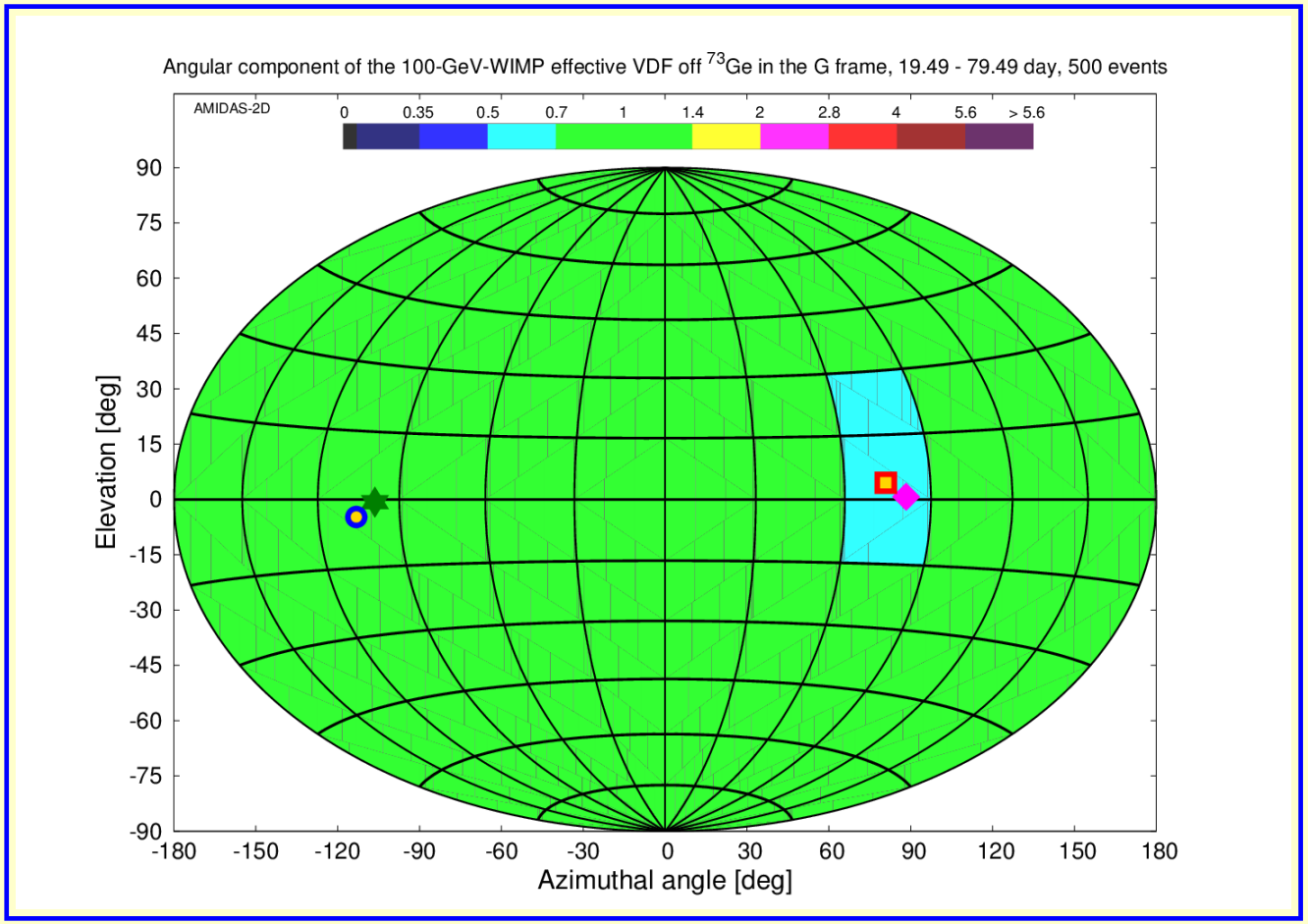

[CLS, arXiv:2103.06883 (2021)]

Angular distribution of the 3-D average kinetic energy in the Galactic coordinate system

3-D WIMP effective velocity distribution in the Galactic frame

- Angular distribution of the 3-D average kinetic energy
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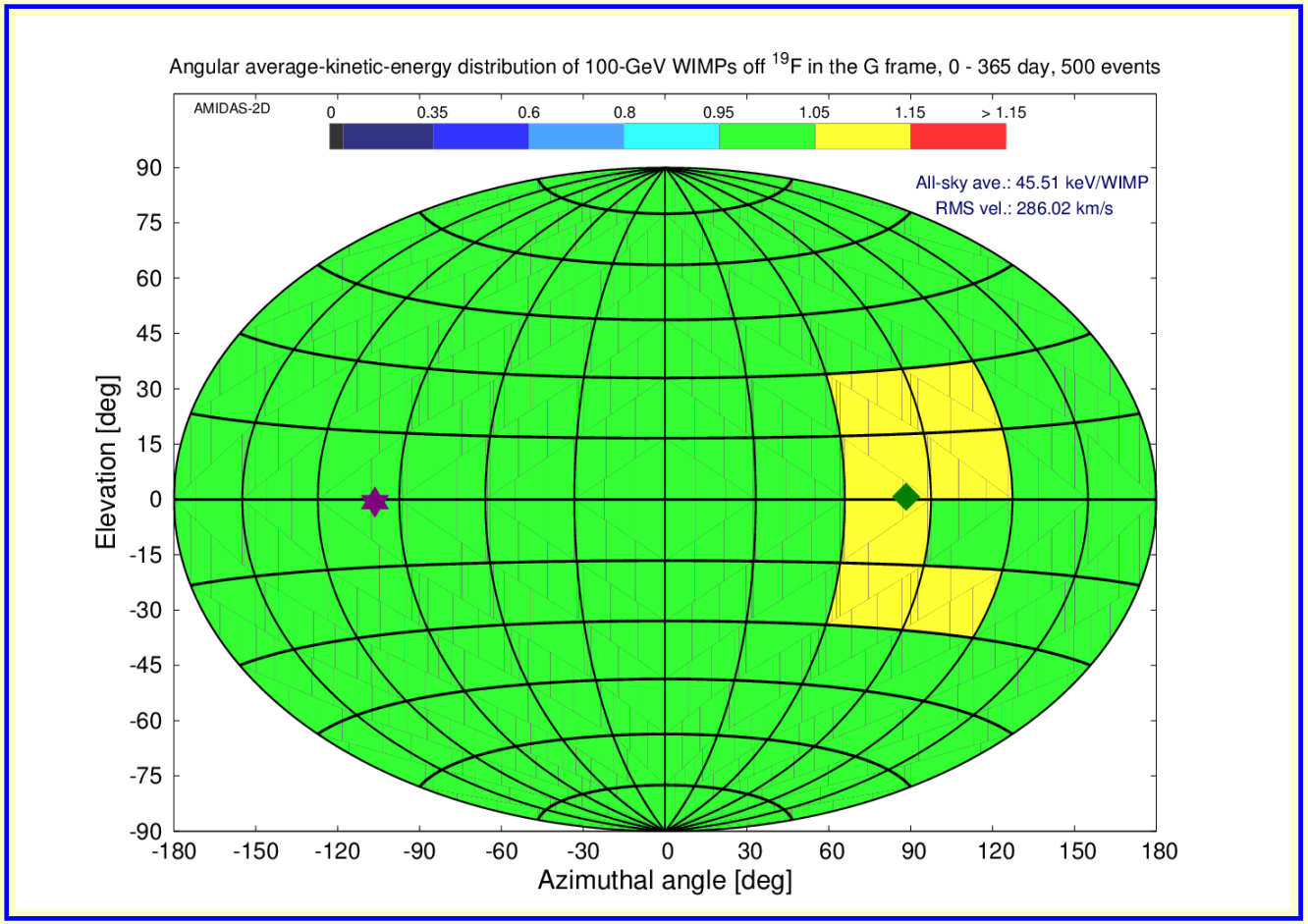

[CLS, arXiv:2103.06883 (2021)]

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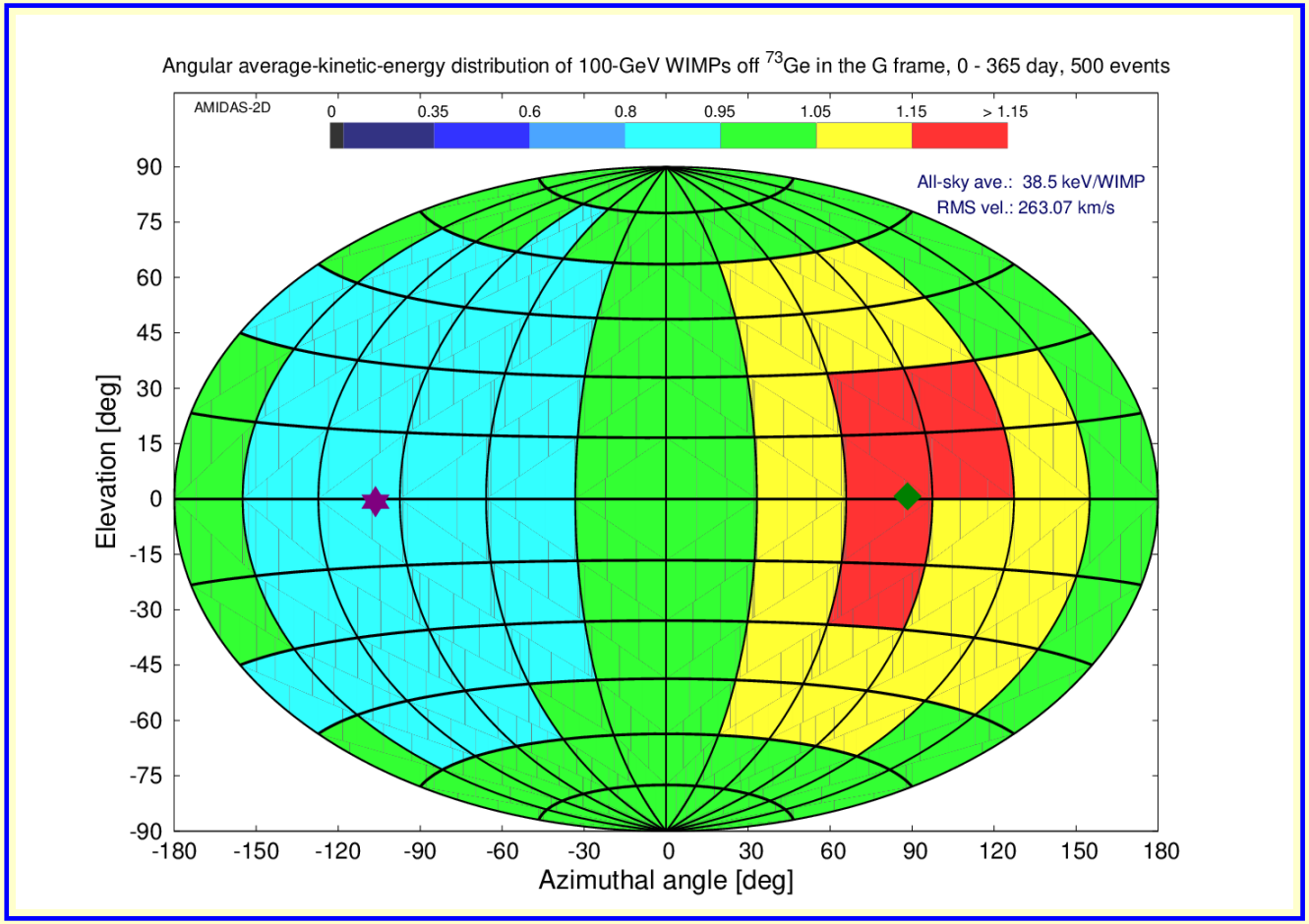

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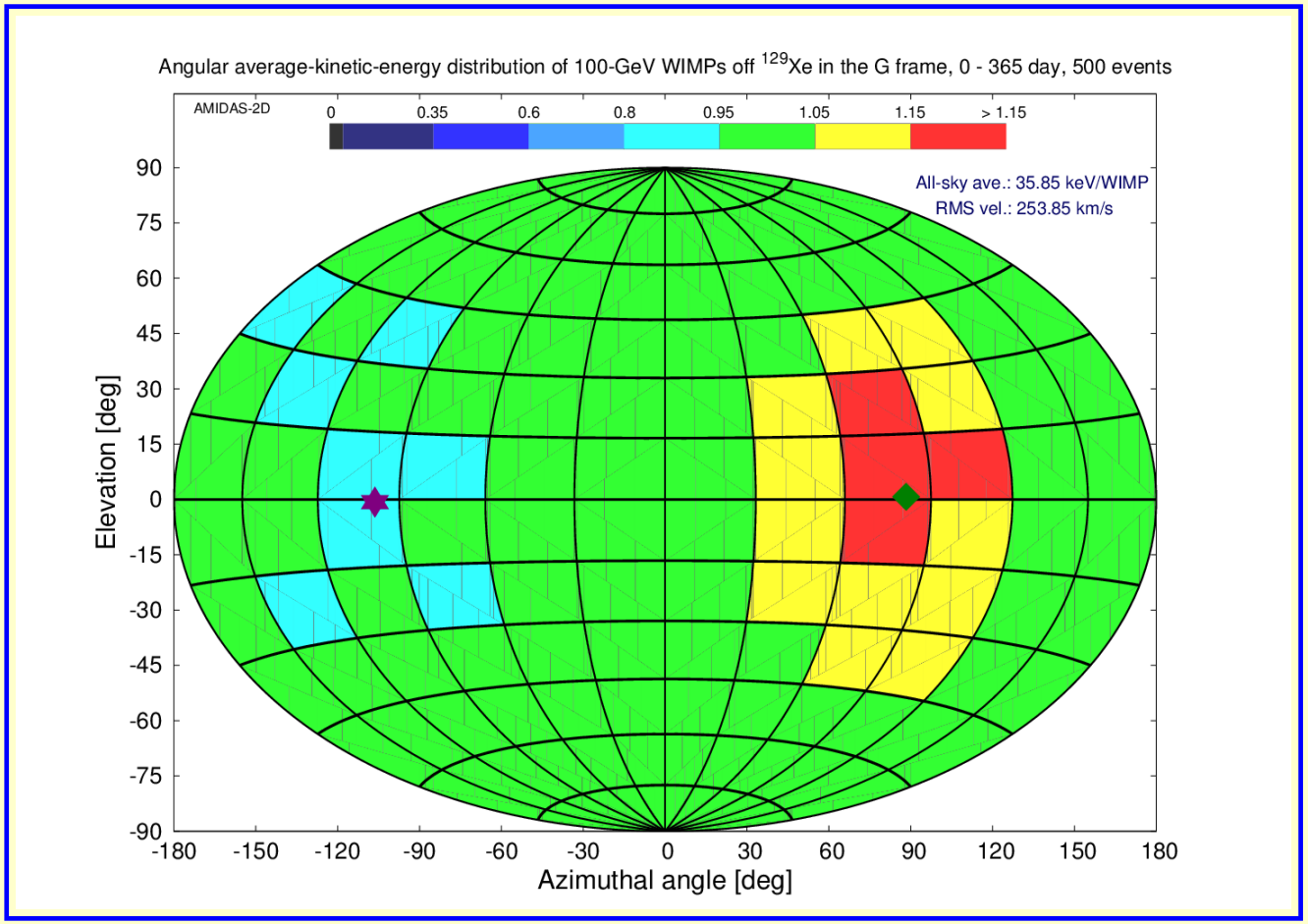

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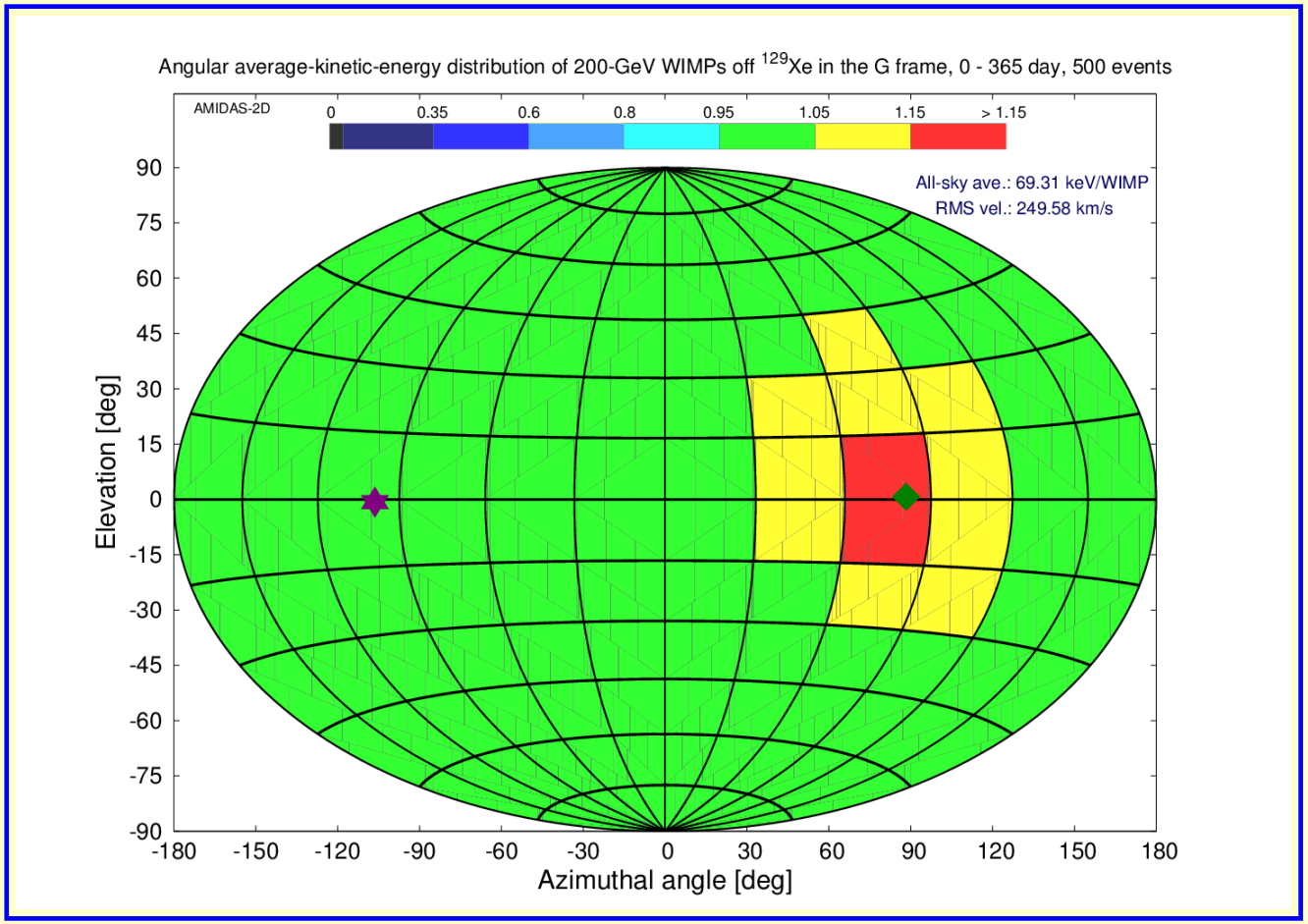

[CLS, arXiv:2103.06883 (2021)]

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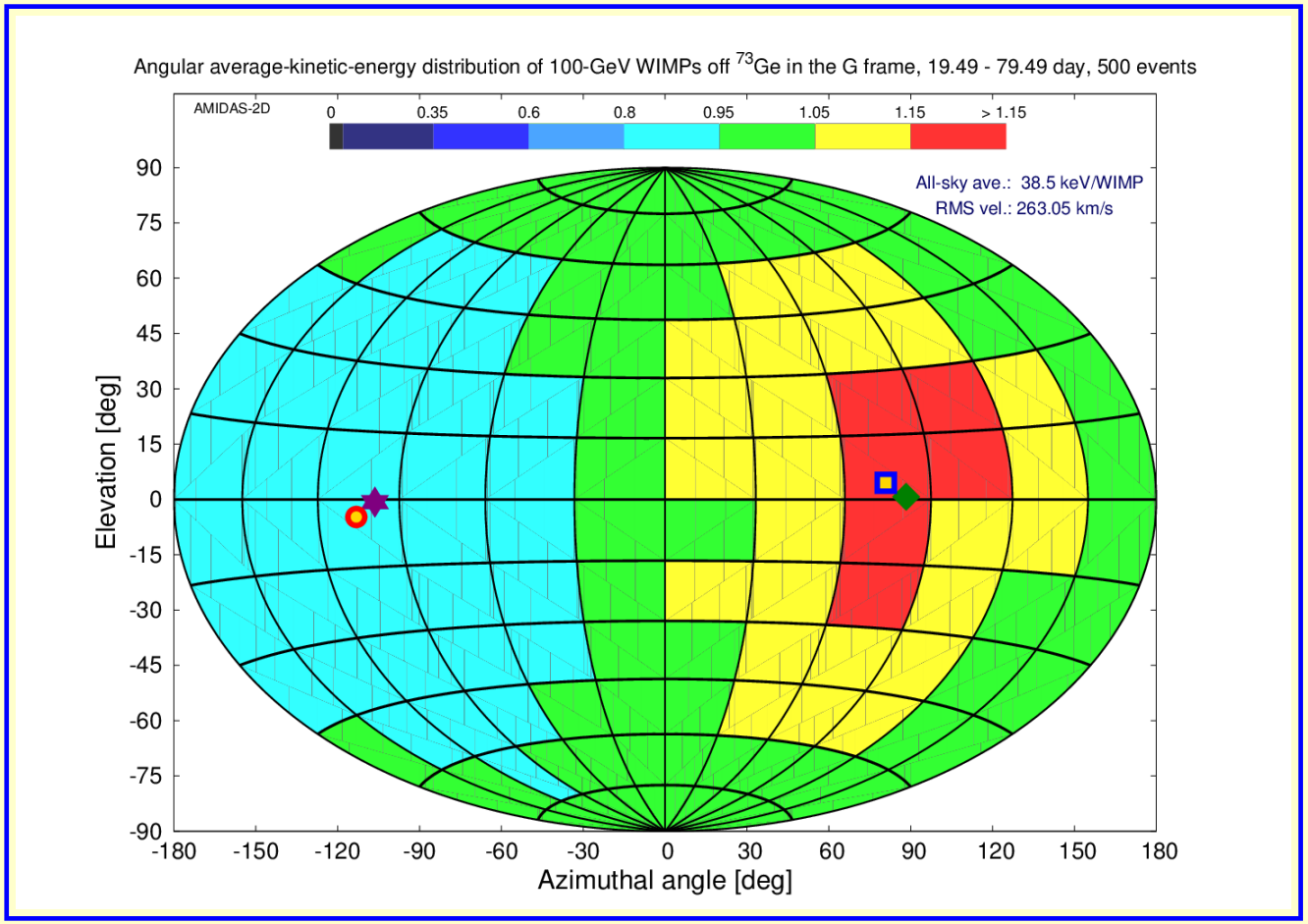
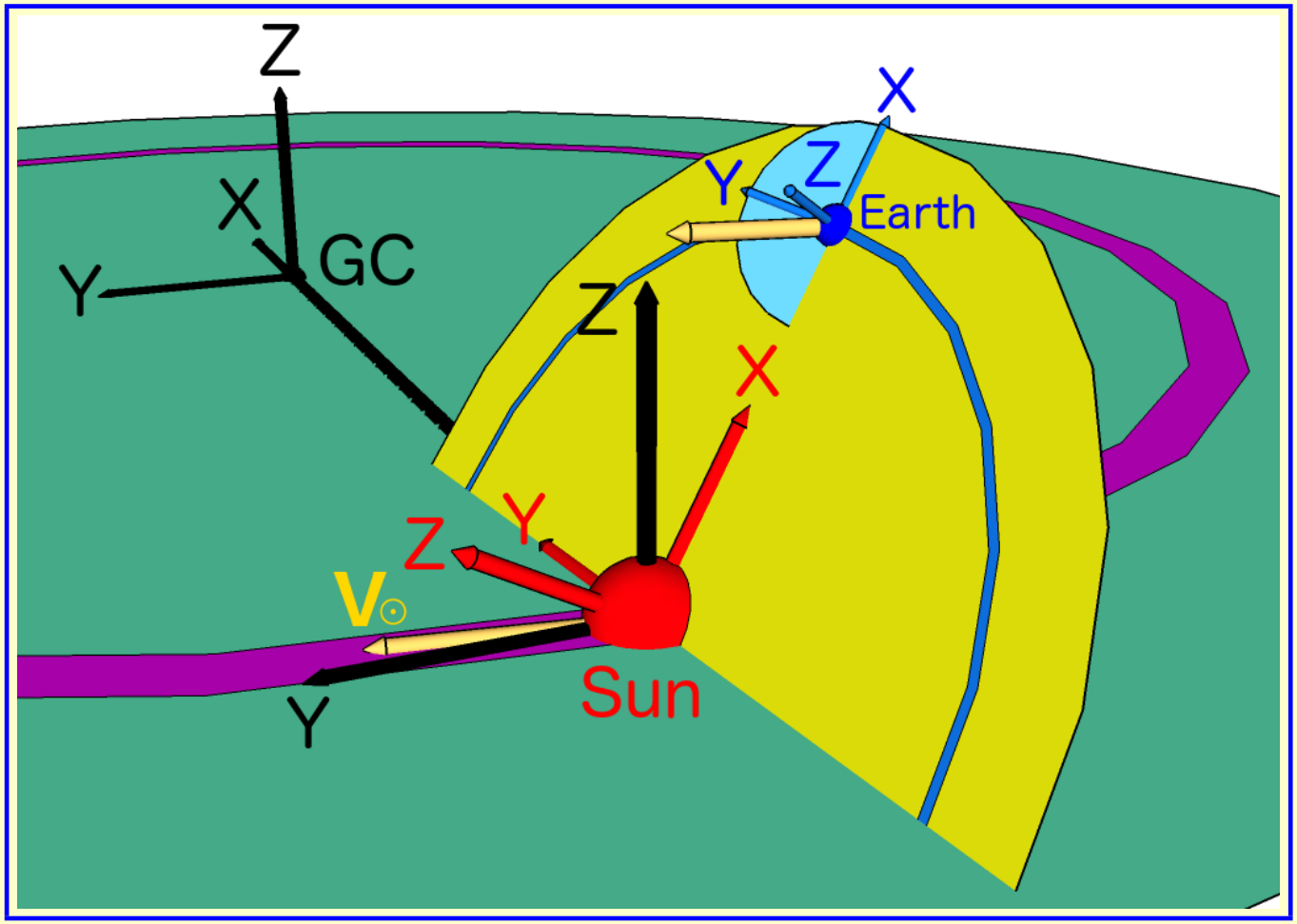


[CLS, arXiv:2103.06883 (2021)]

Forward-backward asymmetry of the 3-D WIMP Galactic effective velocity distribution

Forward-backward asymmetry of the 3-D WIMP G. eff. vel. dist.

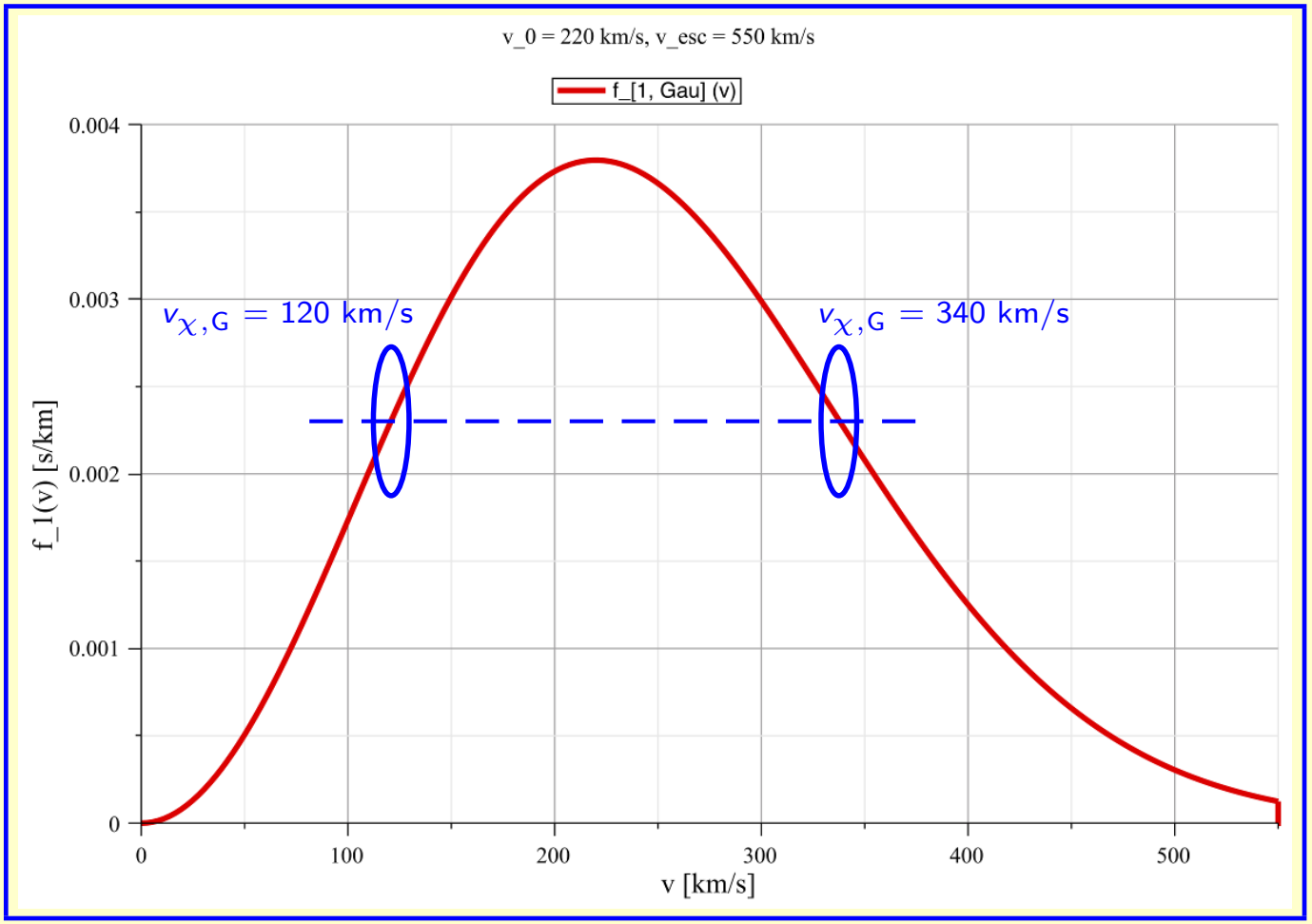
- Solar movement in the Dark Matter halo



[CLS, arXiv:1905.11279 (2019)]

Forward-backward asymmetry of the 3-D WIMP G. eff. vel. dist.

- Simple Maxwellian velocity distribution



[CLS, arXiv:2103.06883 (2021)]

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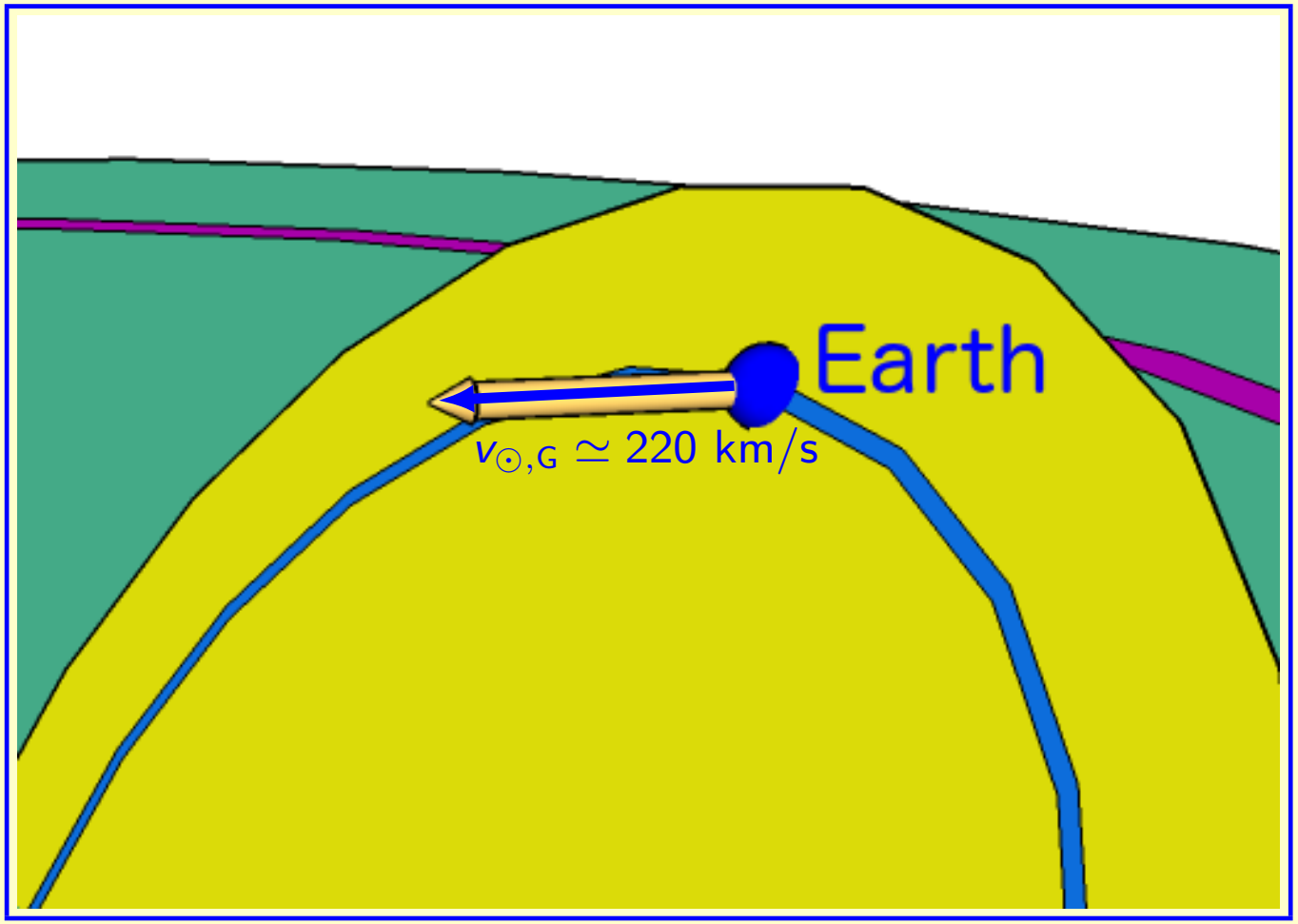

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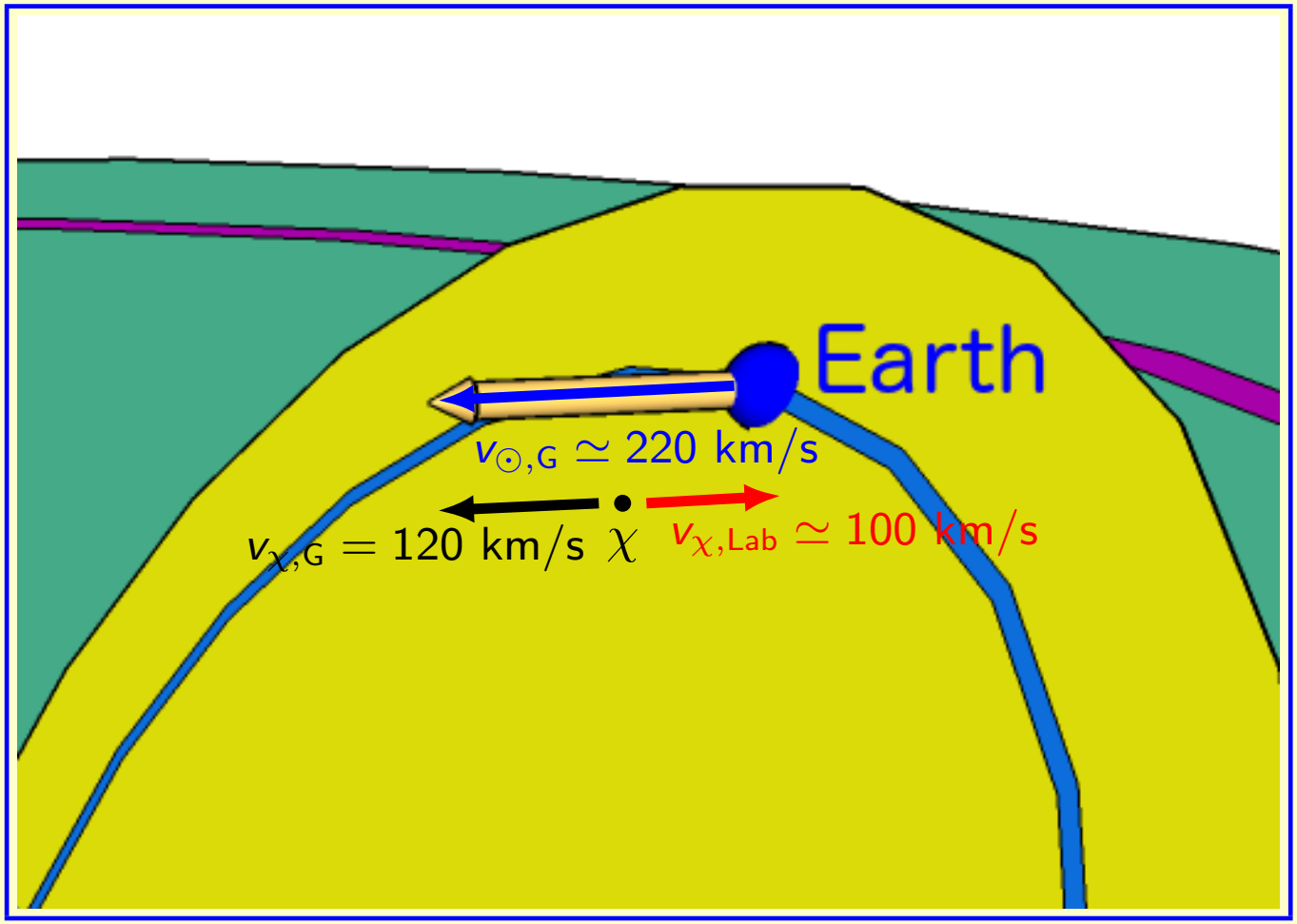

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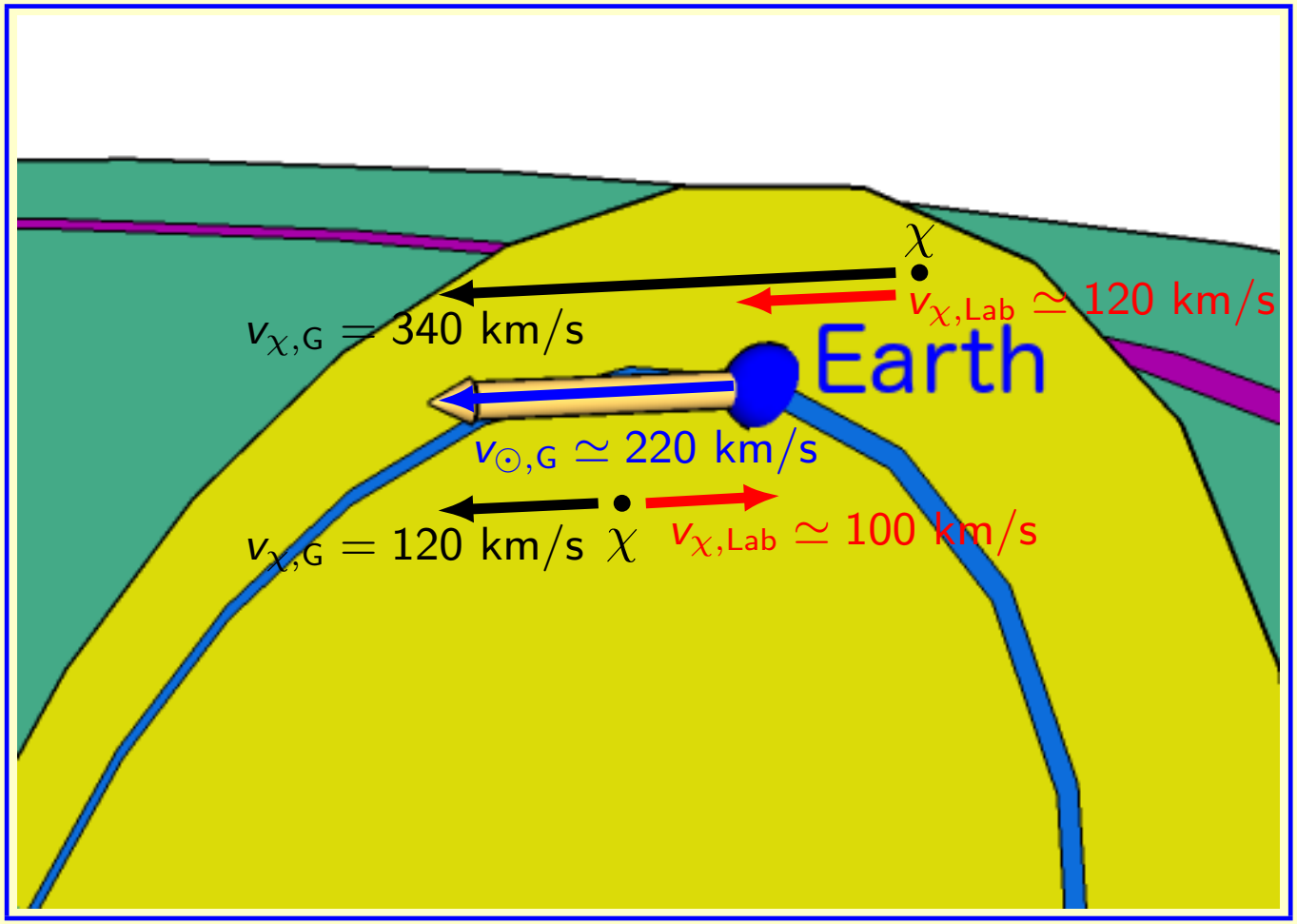

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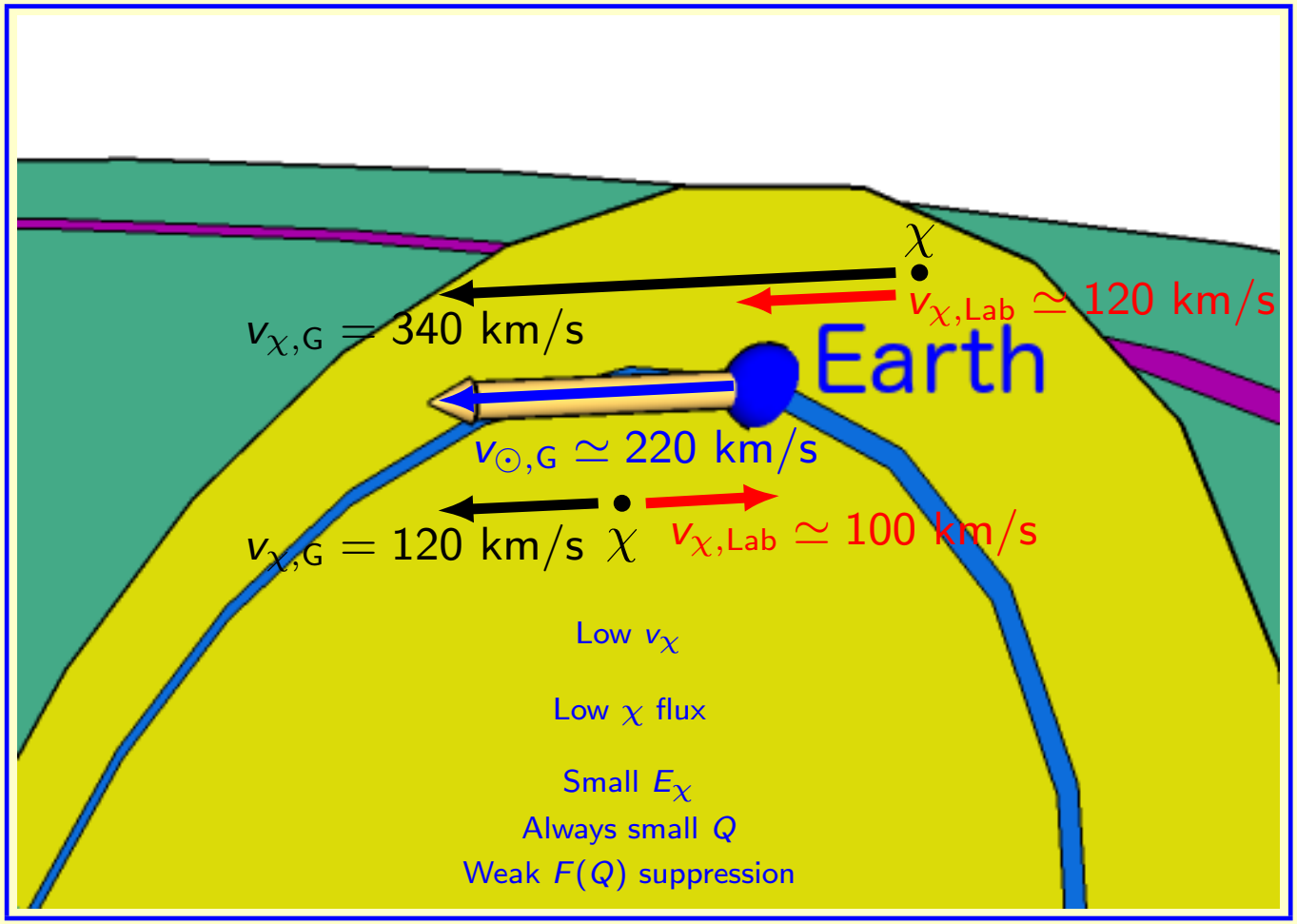

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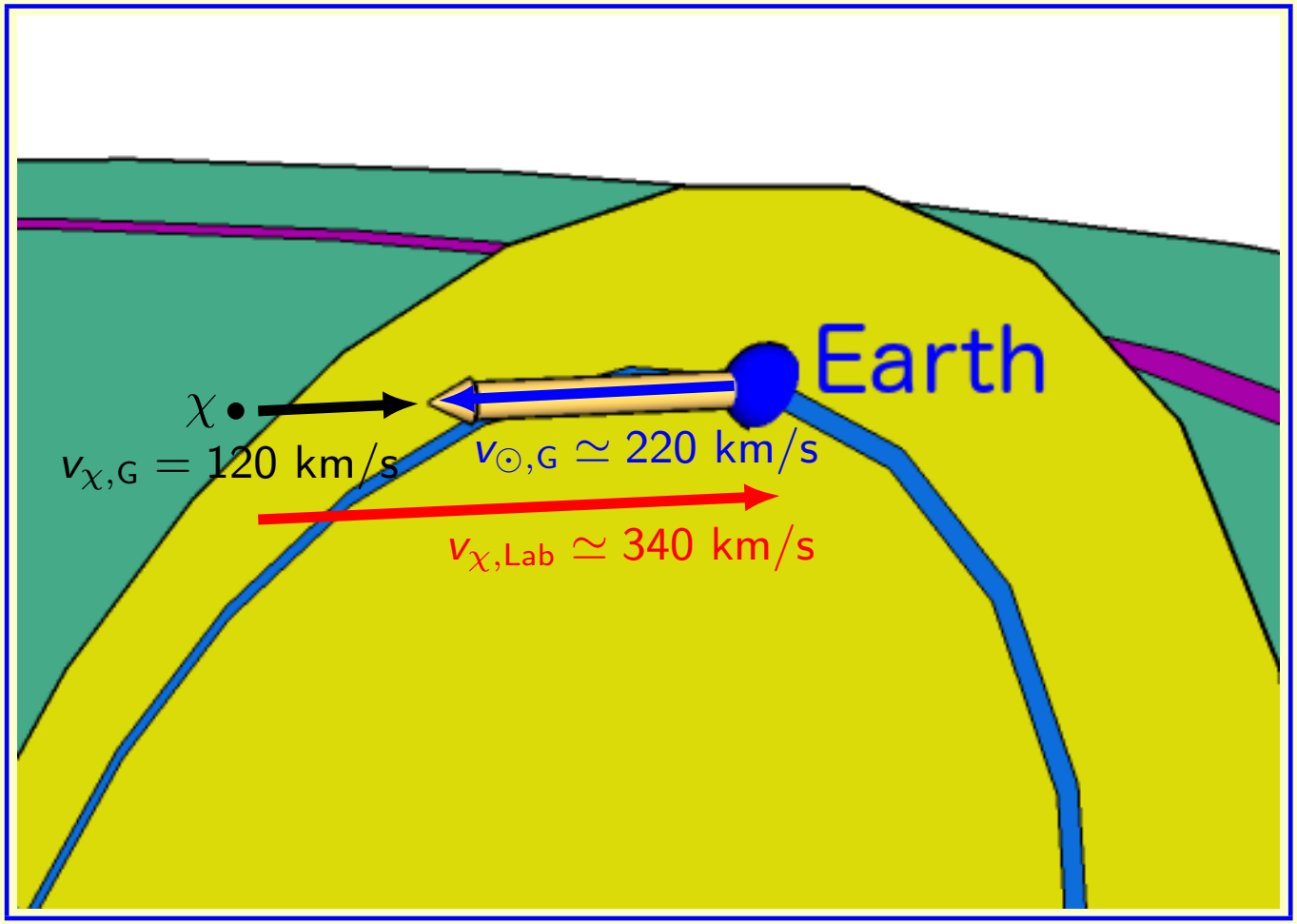

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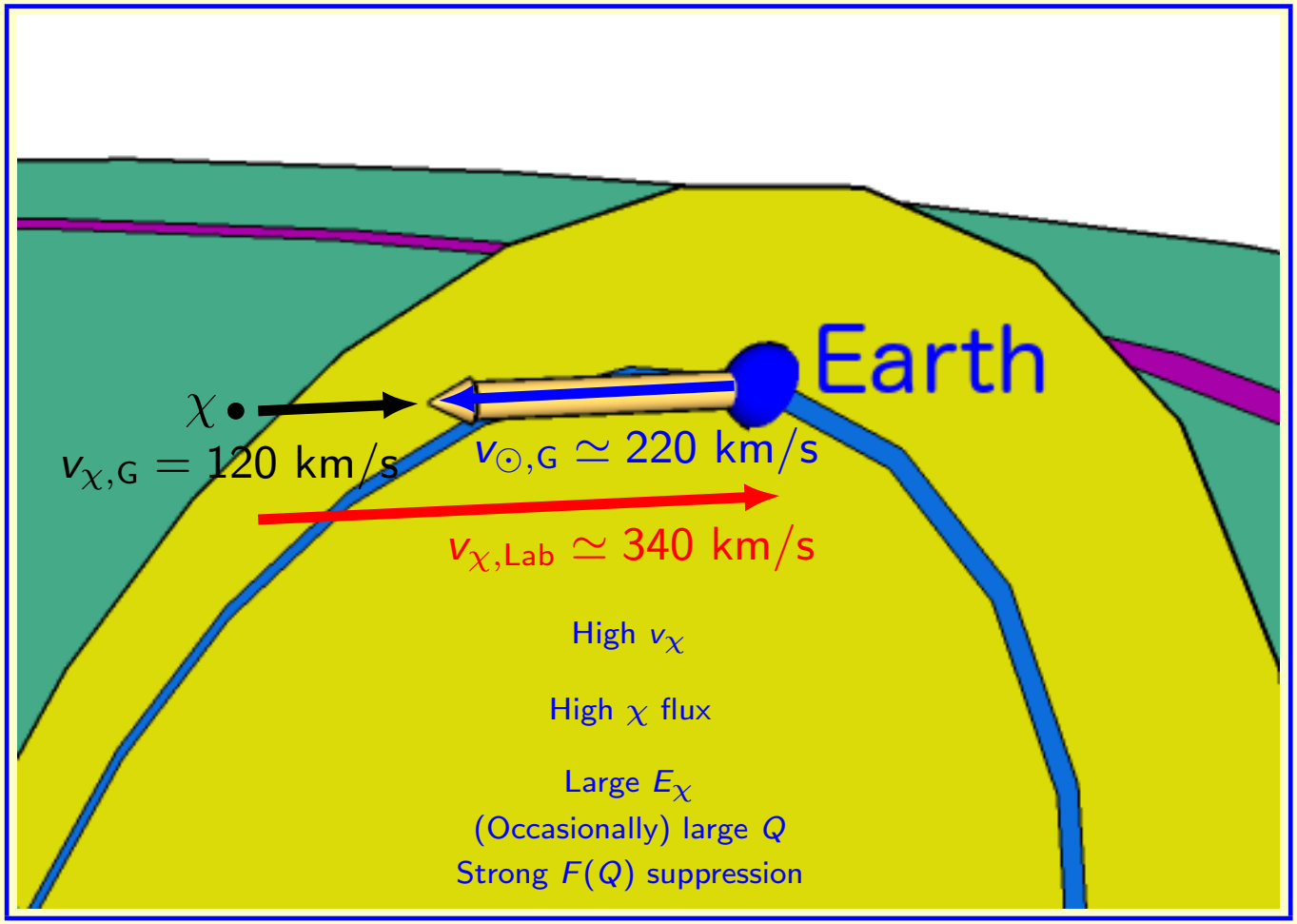

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