3-D WIMP Velocity Distribution Observed at the CJPL Laboratory

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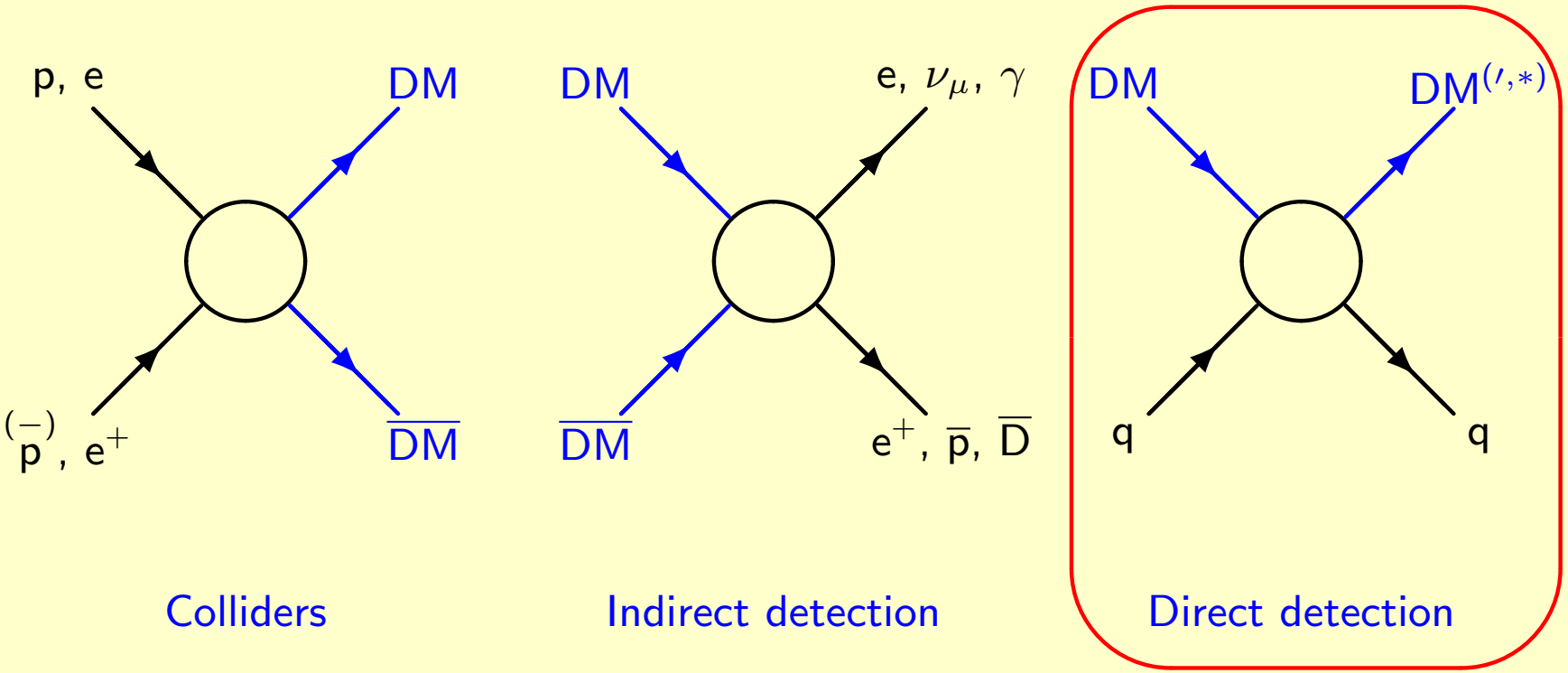
3rd Beijing Normal University Workshop on Dark Matter
December 9, 2019

Based on arXiv:1905.11279

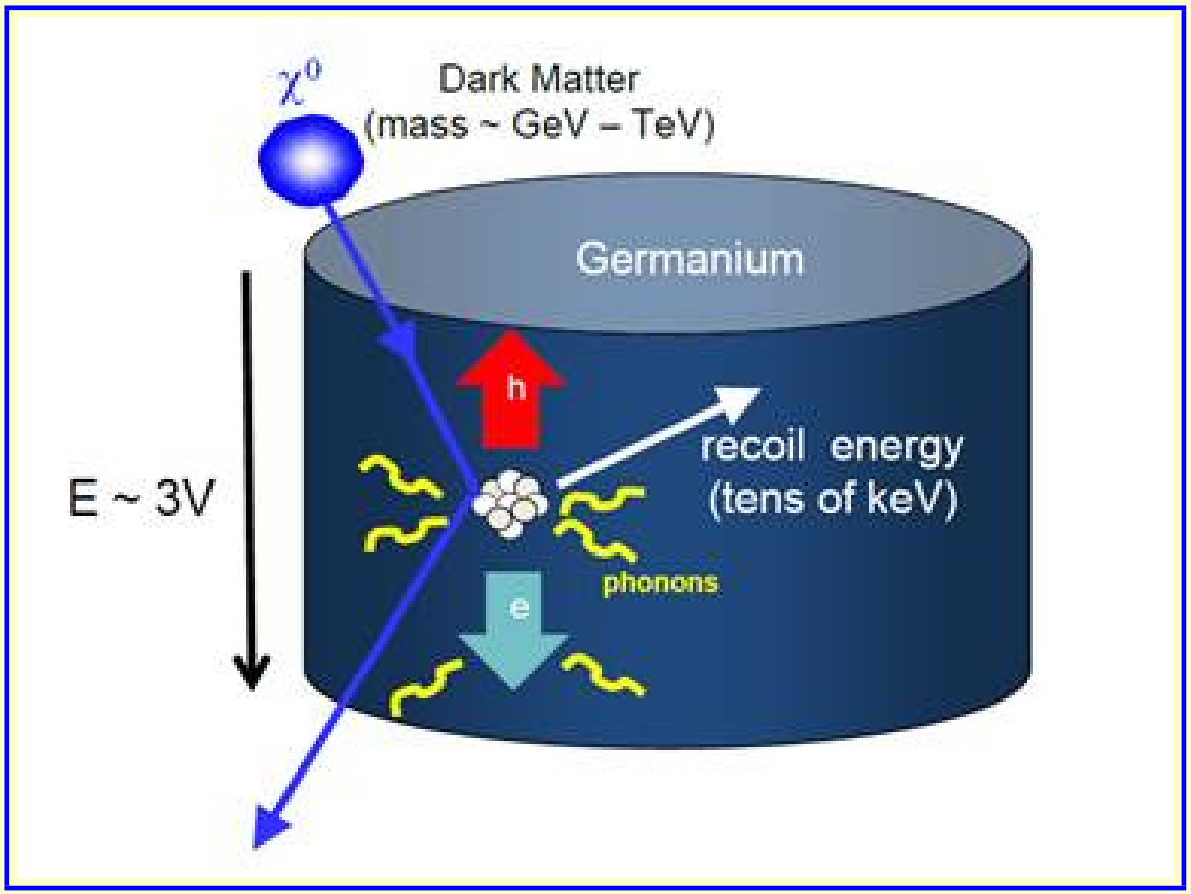
Dark Matter searches

- Three ways to search for WIMP Dark Matter particles



Dark Matter searches

- Three detector types for detecting WIMP Dark Matter directly
  - Semiconductor/scintillator detectors



ANAIS

CDEX

CDMS → SuperCDMS

CoGeNT → C-4

CRESST → EURECA

DAMA/NaI → DAMA/LIBRA

DM-Ice → COSINE

EDELWEISS → EURECA

KIMS → COSINE

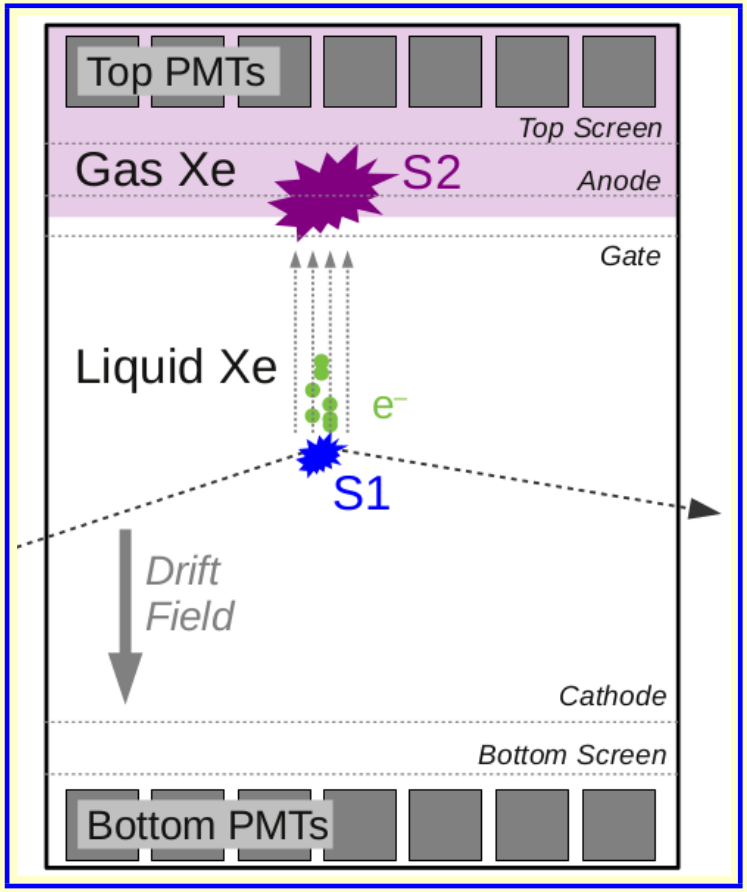
NaIAD

SABRE

[CDMS, https://www.slac.stanford.edu/exp/cdms/]

Dark Matter searches

- Three detector types for detecting WIMP Dark Matter directly
  - Liquid noble gas detectors



ArDM → ARGO

DarkSide → ARGO

DARWIN

DEAP/CLEAN → ARGO

LUX → LZ

NEWS-G

PandaX-II → PandaX-4

WARP

XENON

XMASS

ZEPLIN → LZ

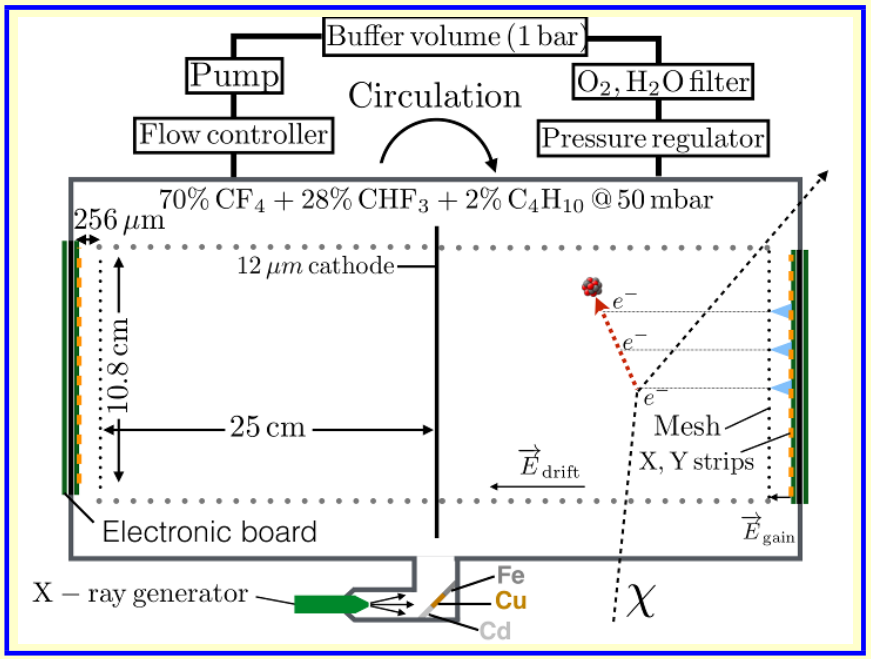
[XENON1T Collab., E. Aprile et al., Eur. Phys. J. C77, 881 (2017)]

Dark Matter searches

- Three detector types for detecting WIMP Dark Matter directly
  - Superheated droplet/gas detectors (w/o directional sensitivity)

COUPP + PICASSO → PICO
SIMPLE, TREX-DM

D3 + DRIFT + NEWAGE → CYGNUS
DMTPC, MIMAC, NEWSdm



[MIMAC, Q. Riffard et al., J. Inst. 12, P06021 (2017)]

Dark Matter searches

- Three detector types for detecting WIMP Dark Matter directly
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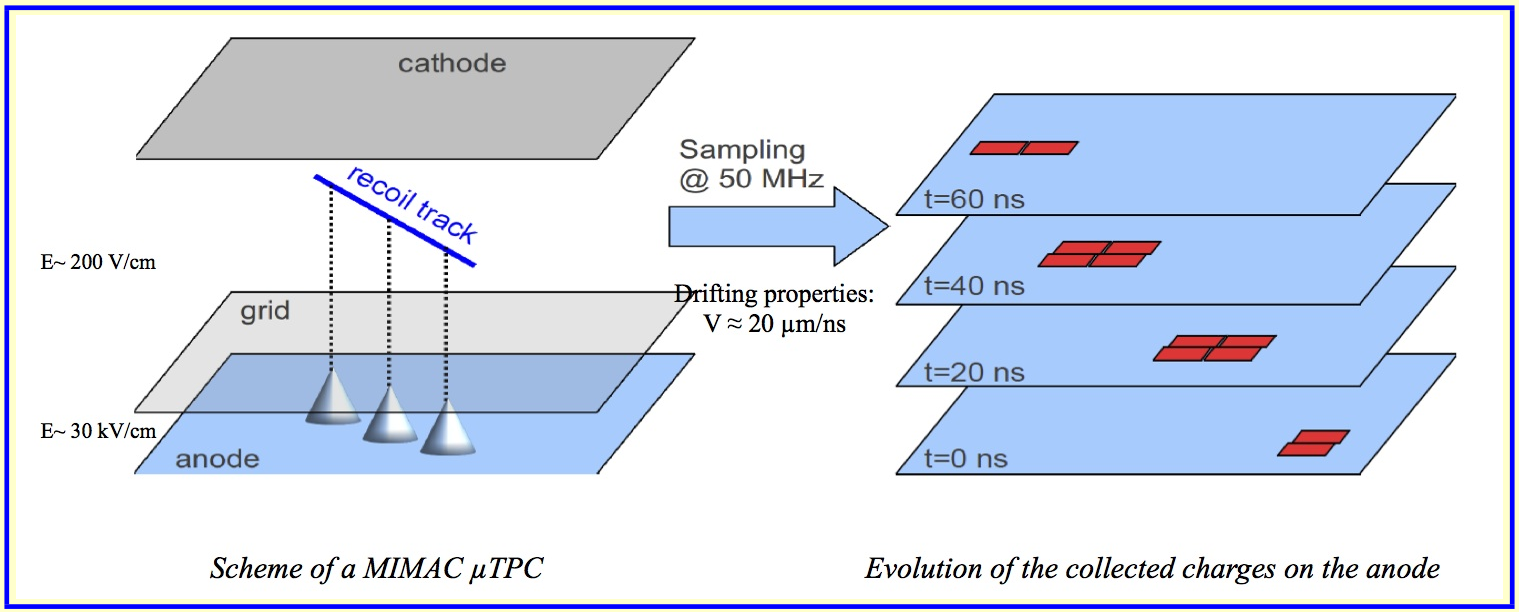


Scheme of a MIMAC µTPC *Evolution of the collected charges on the anode*

[MIMAC, Q. Riffard et al., J. Inst. 11, P08011 (2016)]

Dark Matter searches

- Directional (direct) Dark Matter detection experiments
  - Recoil track (3D) reconstruction
  - Sense (head-tail) recognition
- Techniques
  - (Low pressure) gaseous time-projection chamber (TPC)
  - Micromegas
  - Gas electron multiplier (GEM)
  - Nuclear emulsion
- Materials
  - CF_4, C_3F_8, C_4F_{10}
  - CF_3I, CHF_3, C_2ClF_5
  - CS_2, CH_4
  - SF_6

Basic concept → misunderstanding?

Basic concept

- Basic concept of the directional (direct) Dark Matter detection
  - Based on the rotation of the Earth
  - Directionality: diurnal modulation of the (main) direction of WIMP events
  - Flux shielding: diurnal modulation of the number (rate) of WIMP events
  - Can not accumulate a few (tens of) WIMP events in a few days/nights!

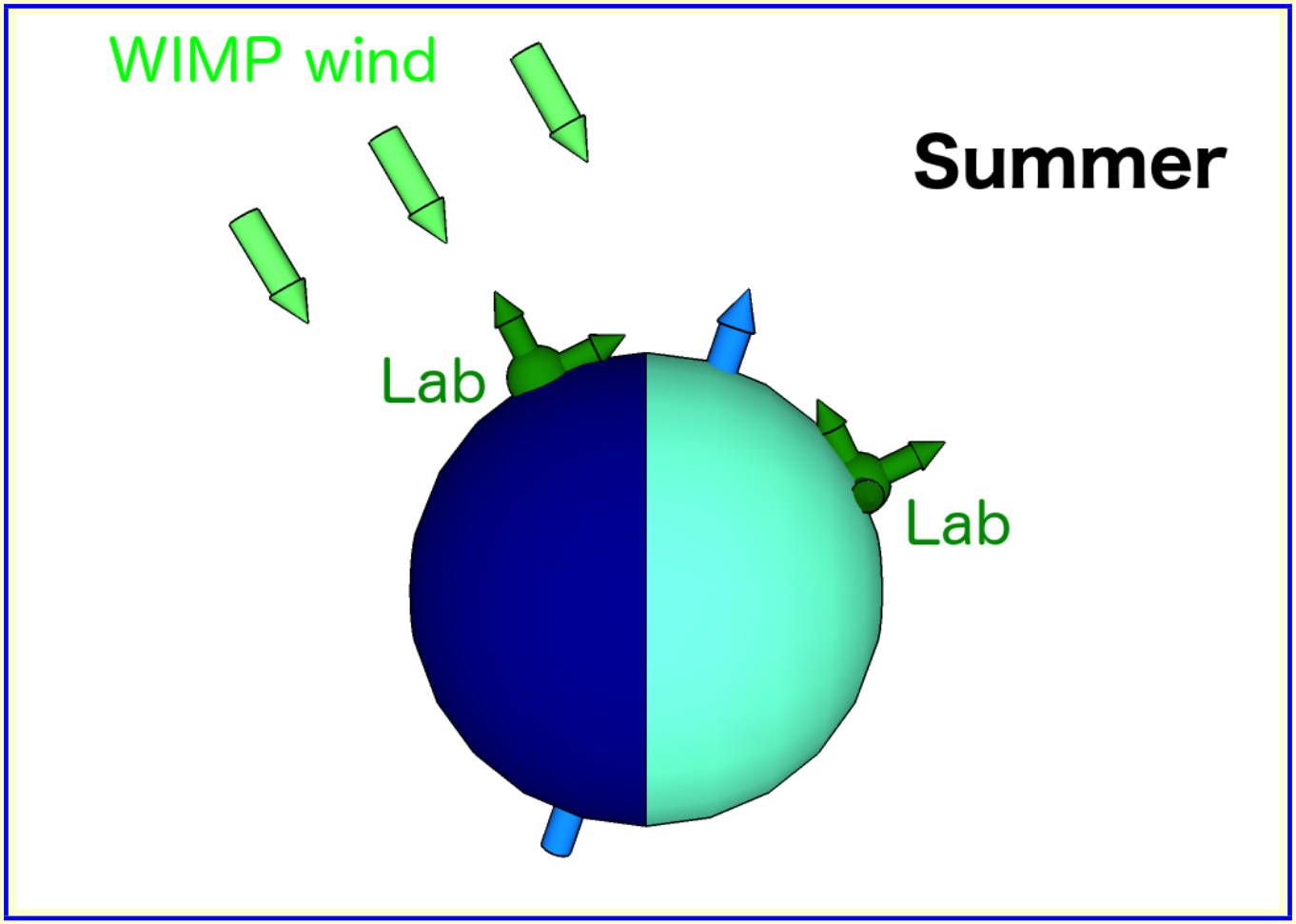
    ⇒ Run experiments for long time periods

    ⇒ The Earth's orbital motion around the Sun has to be taken into account!

    ⇒ The effects of the diurnal modulations could be reduced or even cancelled!
  - What (else) can we do with directional DM detection data???

Basic concept

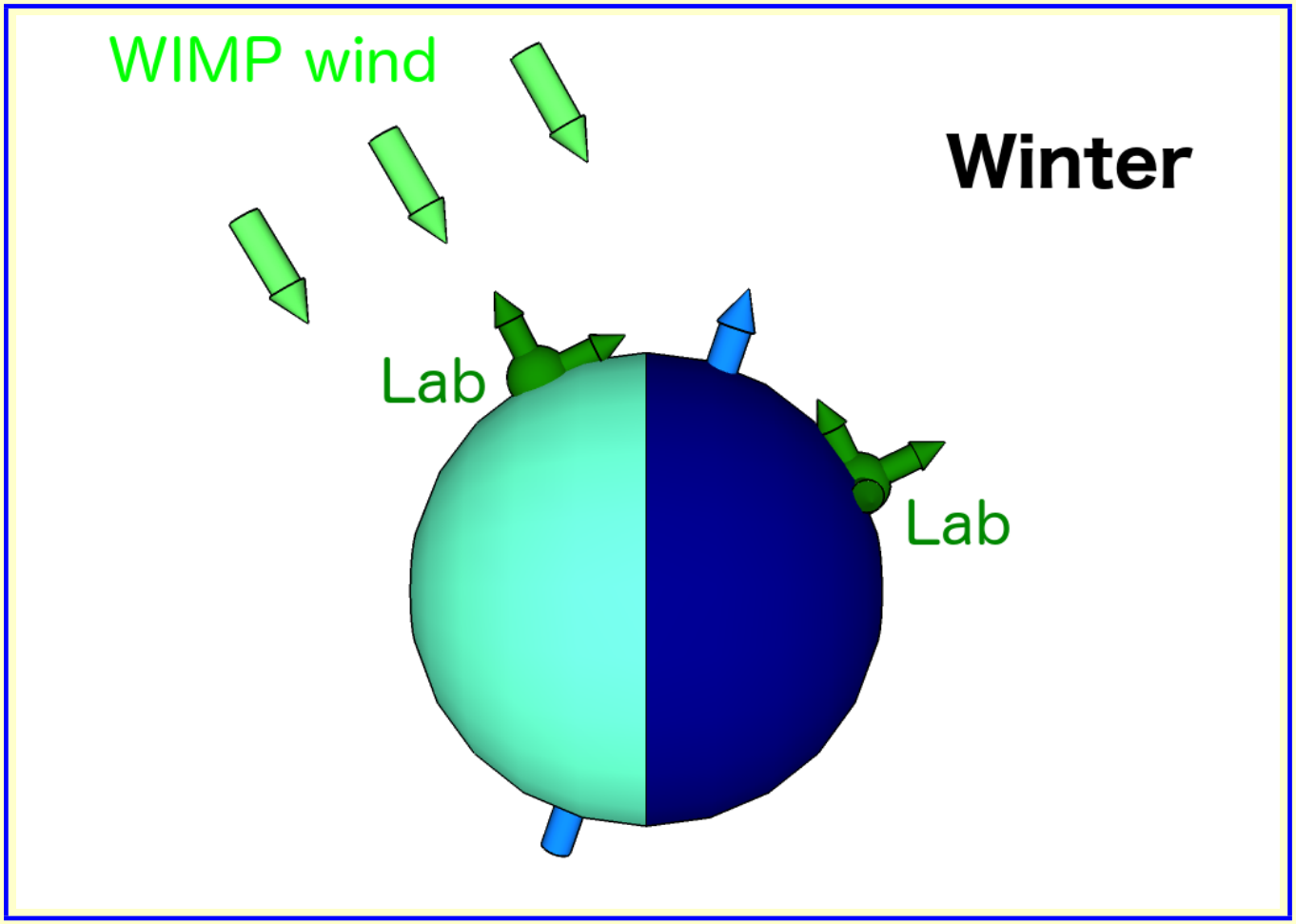
- Directionality: diurnal modulation of the (main) direction of WIMP events



[CLS, Google SketchUp]

Basic concept

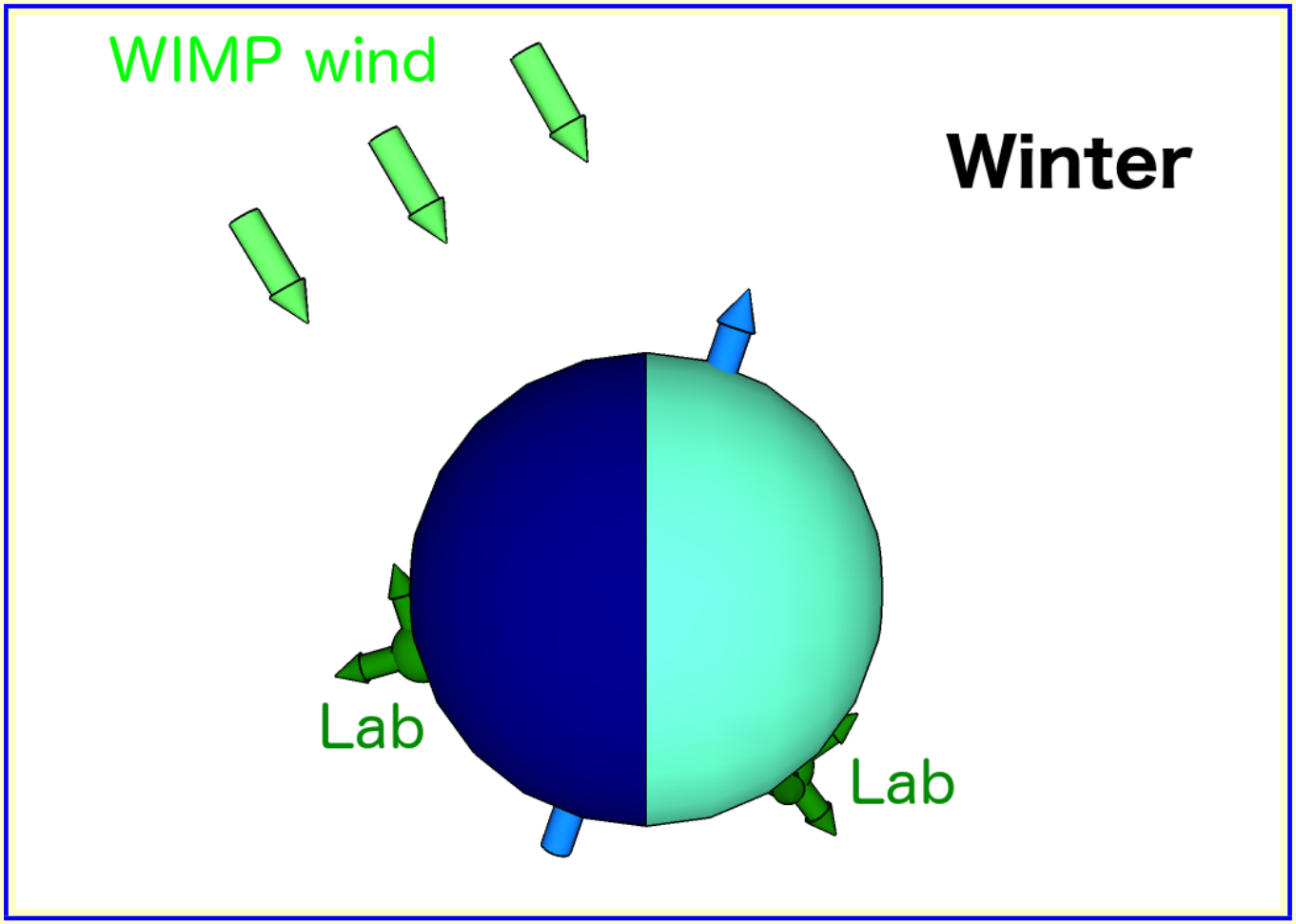
- Directionality: diurnal modulation of the (main) direction of WIMP events



[CLS, Google SketchUp]

Basic concept

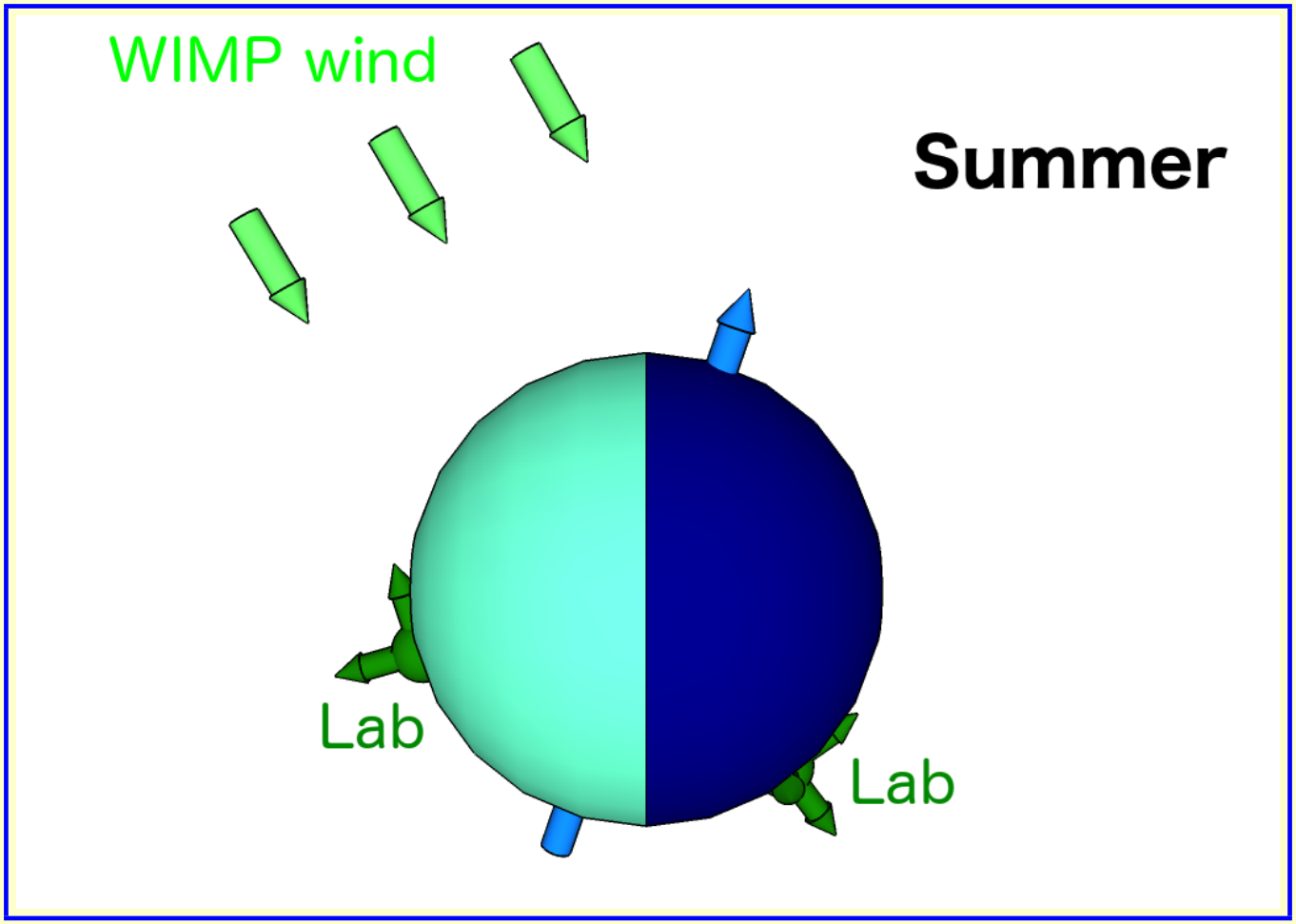
- Flux shielding: diurnal modulation of the number (rate) of WIMP events



[CLS, Google SketchUp]

Basic concept

- Flux shielding: diurnal modulation of the number (rate) of WIMP events



[CLS, Google SketchUp]

Motivation

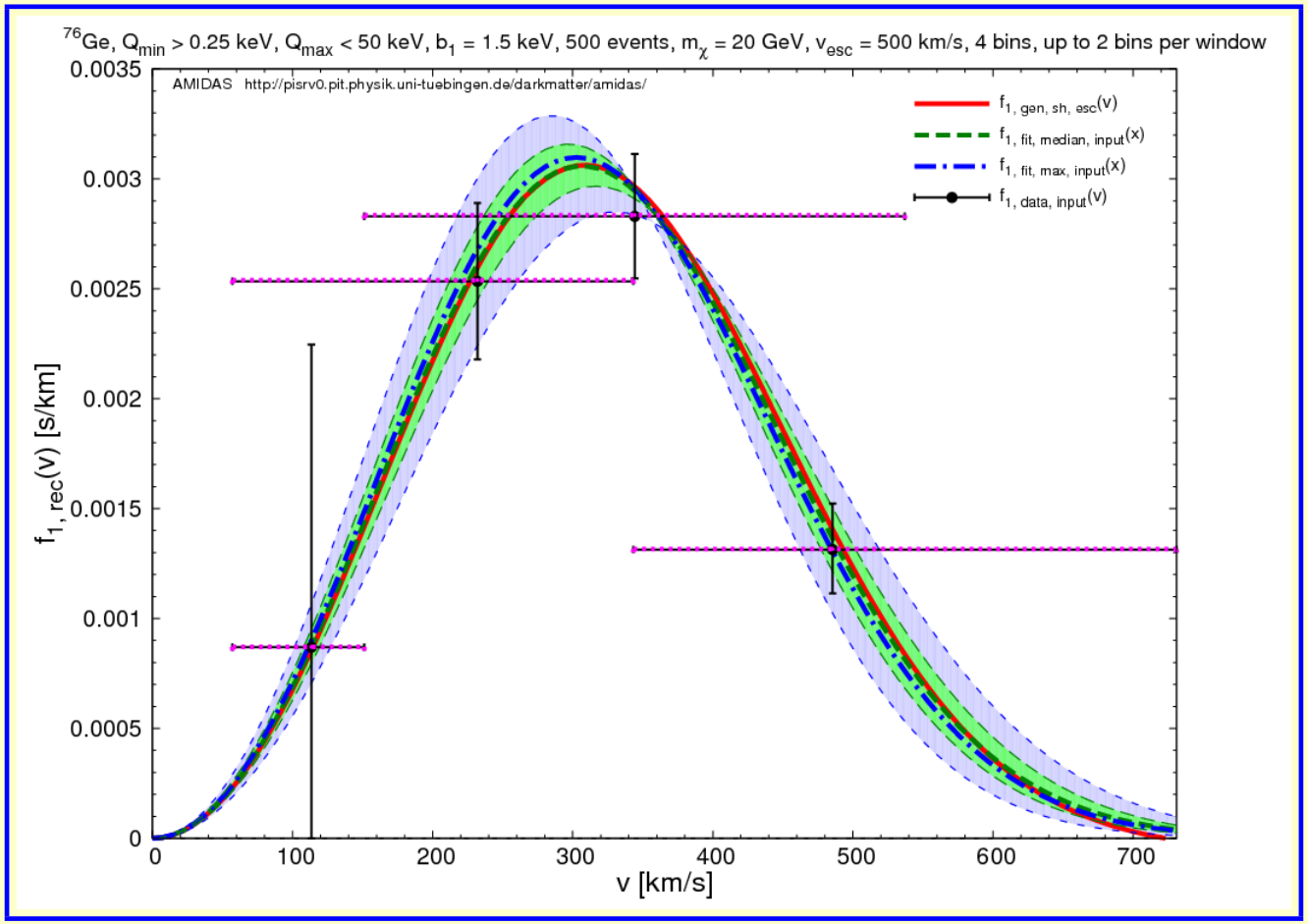
Motivation

- Preparation for our future works
  - ➢ We developed model-independent methods for using direct DM detection data (measured recoil energies)
  - ➢ To (Bayesian) reconstruct the 1-D WIMP velocity distribution, the WIMP mass, and (the ratios between) different WIMP-nucleon cross sections
  - **?** Can we develop methods for using/combining 3-D information from directional detection experiments?
- As the first step, we need to generate 3-D WIMP events (velocities and measuring times) and check our generated events

!? Then we have found something, which is not as what we expected (n)or can be explained (straightforwardly)...

Motivation

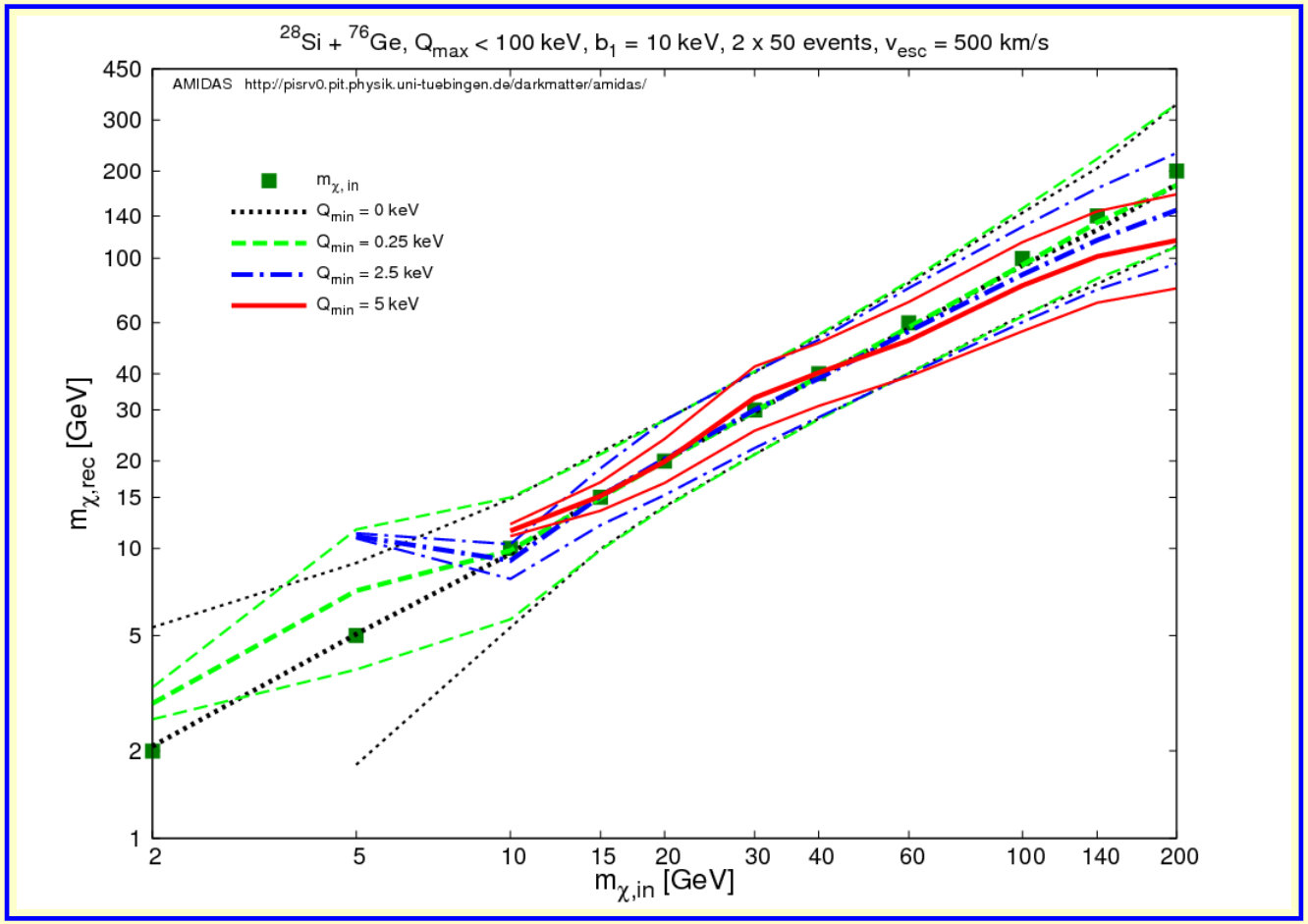
- Reconstructed $f_{1,\mathrm{Bayesian}}(v)$ with the input WIMP mass
  (^{76}Ge, 0.25 - 50 keV, $b_1 = 1.5$ keV, 500 events, $m_\chi = 20$ GeV, $f_{1,\mathrm{sh},v_0}(v; v_0)$)



[CLS, IJMPD 24, 1550090 (2015); http://pisrv0.pit.physik.uni-tuebingen.de/darkmatter/amidas/]

Motivation

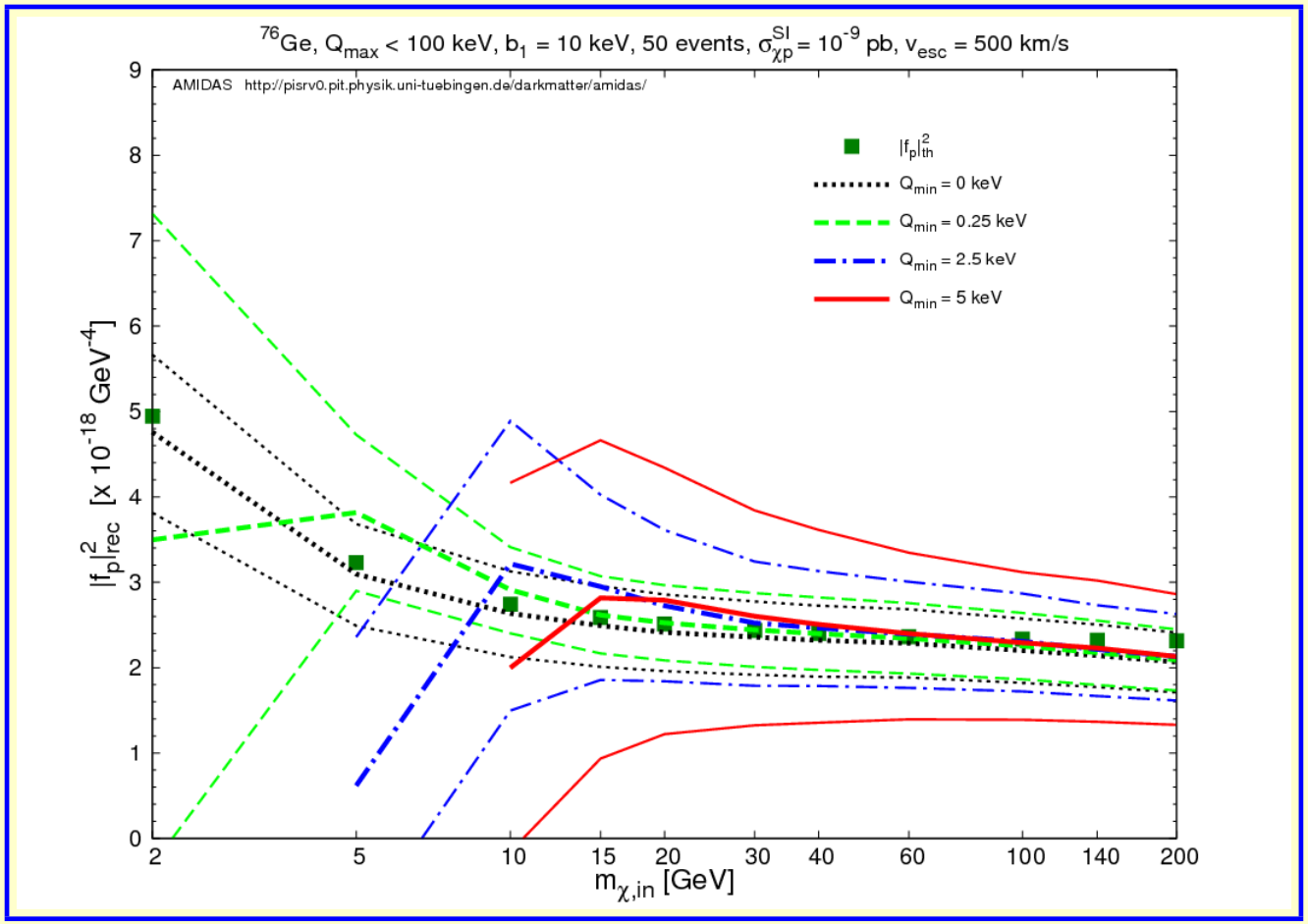
- Reconstructed $m_{\chi,\mathrm{rec}}$
  ($^{28}\mathrm{Si} + {}^{76}\mathrm{Ge}$, $Q_{\max} < 100$ keV, $b_1 = 10$ keV, 2×50 events)



[Y. Bai, W. Sun and CLS, IJMPA 33, 1850120 (2018)]

Motivation

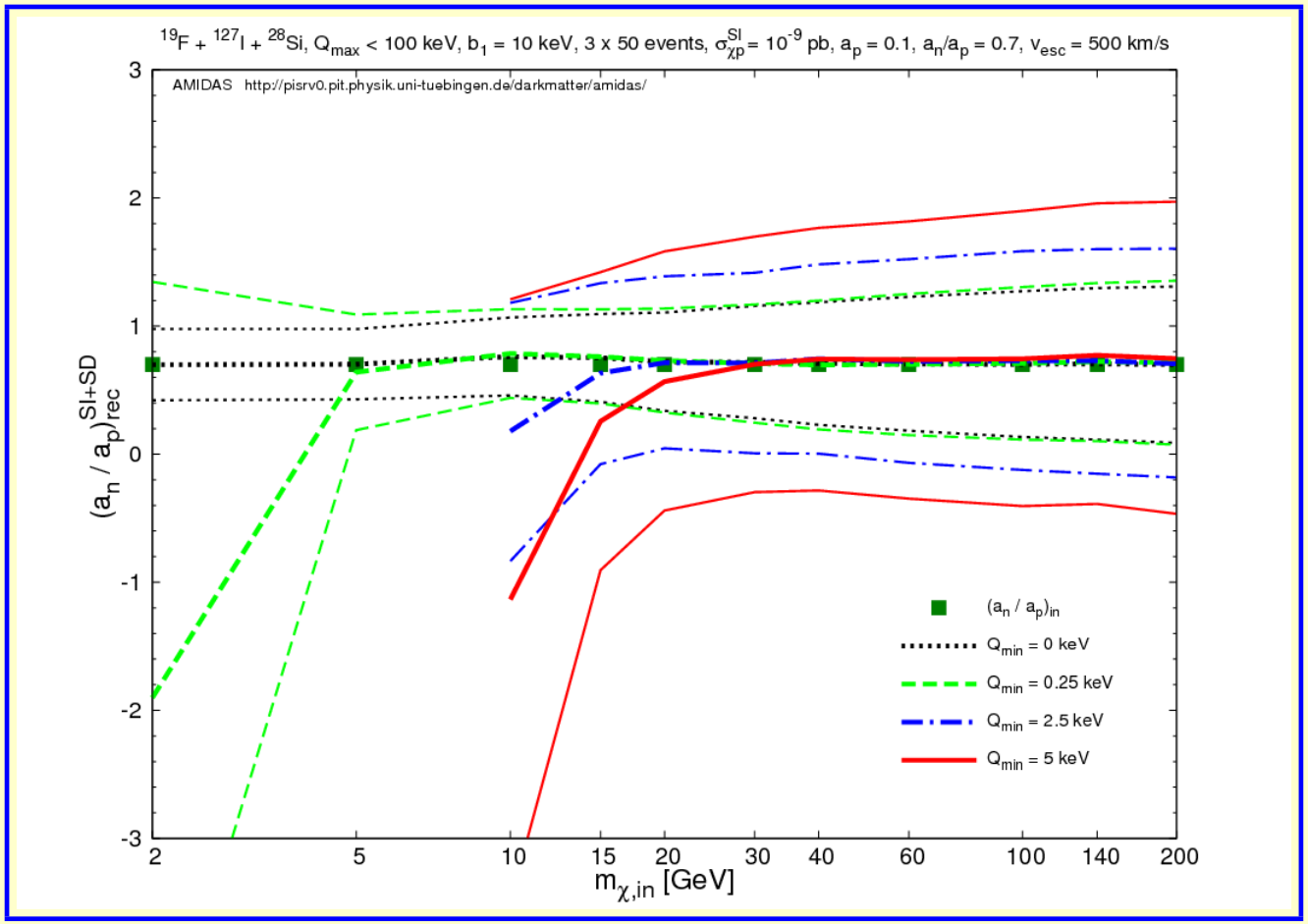
- Reconstructed $|f_p|^2_{rec}$
  (^{76}Ge, $Q_{max} < 100$ keV, $b_1 = 10$ keV, 50 events, $\sigma^{SI}_{\chi p} = 10^{-9}$ pb)



[Y. Bai, W. Sun and CLS, IJMPA 33, 1850120 (2018)]

Motivation

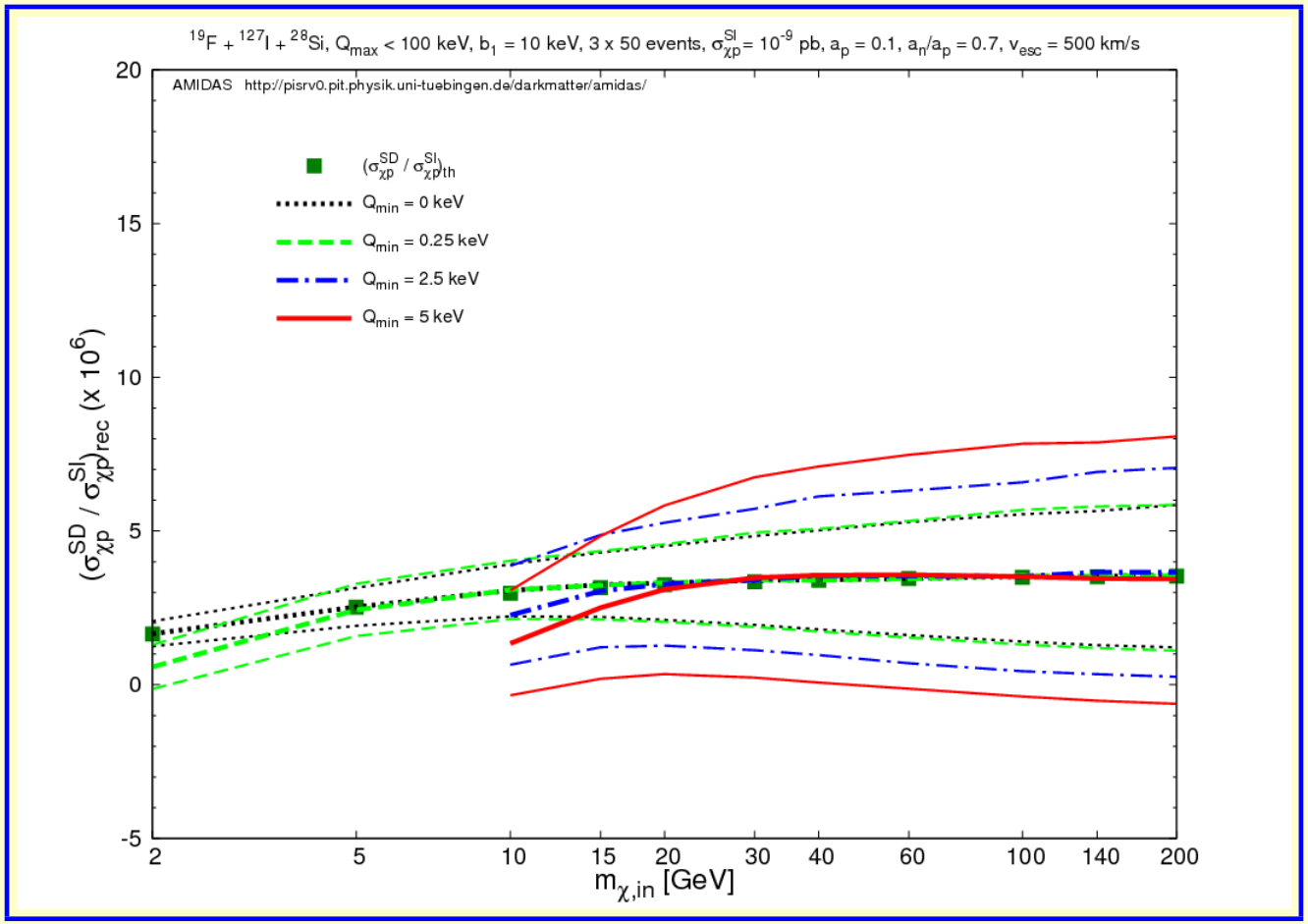
- Reconstructed $(a_n/a_p)^{\mathrm{SI+SD}}_{\mathrm{rec}}$
  ($^{19}\mathrm{F} + {}^{127}\mathrm{I} + {}^{28}\mathrm{Si}$, $Q_{\max} < 100$ keV, $b_1 = 10$ keV, 3×50 events, $\sigma^{\mathrm{SI}}_{\chi\mathrm{p}} = 1$ zb, $a_n/a_p = 0.7$)



[Y. Bai, W. Sun and CLS, IJMPA 33, 1850120 (2018)]

Motivation

- Reconstructed $\left(\sigma^{\mathrm{SD}}_{\chi\mathrm{p}}/\sigma^{\mathrm{SI}}_{\chi\mathrm{p}}\right)_{\mathrm{rec}}$
  ($^{19}\mathrm{F} + {}^{127}\mathrm{I} + {}^{28}\mathrm{Si}$, $Q_{\max} < 100$ keV, $b_1 = 10$ keV, 3×50 events, $\sigma^{\mathrm{SI}}_{\chi\mathrm{p}} = 1$ zb, $a_{\mathrm{p}} = 0.1$)

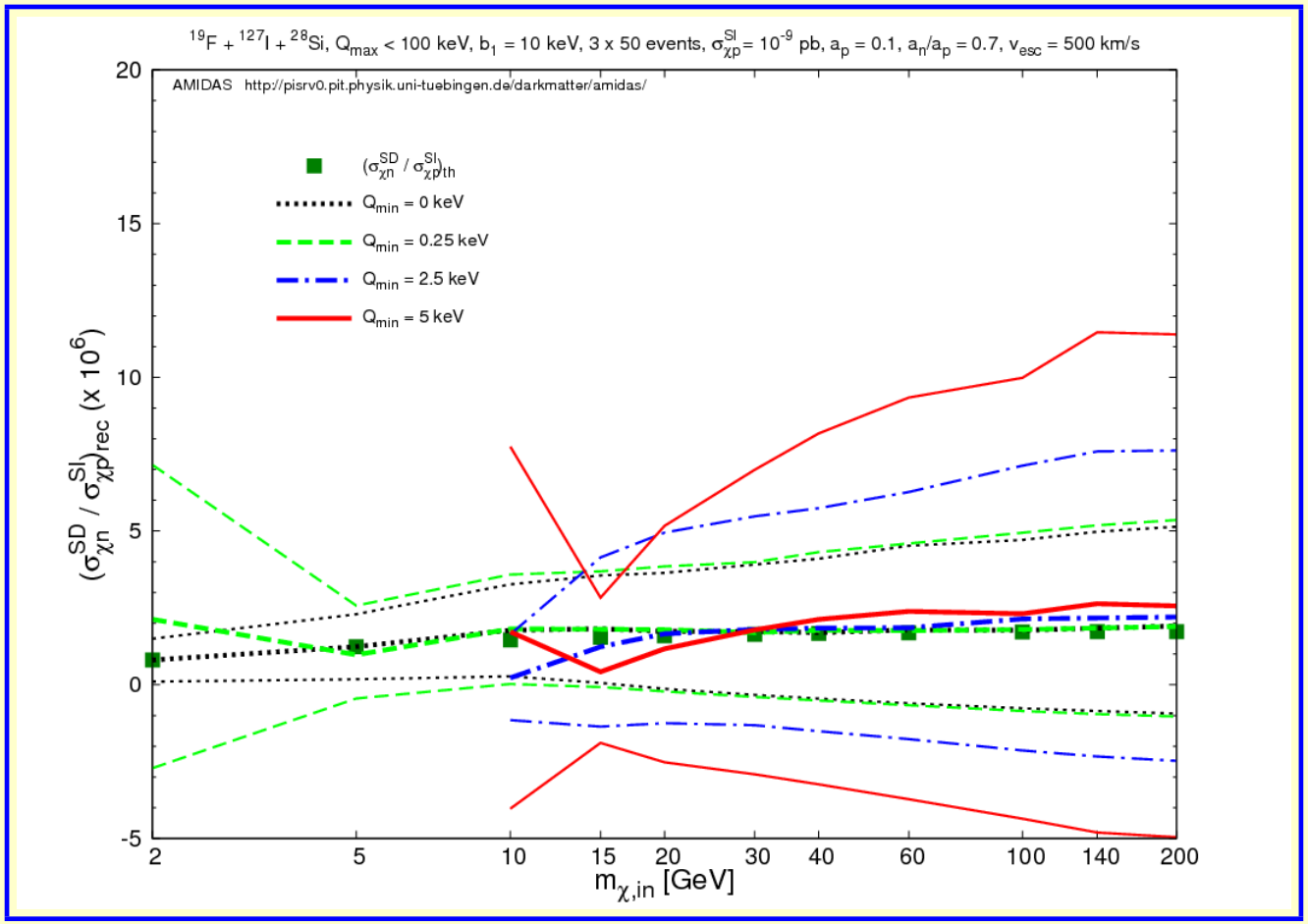


[Y. Bai, W. Sun and CLS, IJMPA 33, 1850120 (2018)]

Motivation

- Reconstructed $\left(\sigma^{\mathrm{SD}}_{\chi\mathrm{n}}/\sigma^{\mathrm{SI}}_{\chi\mathrm{p}}\right)_{\mathrm{rec}}$

  ($^{19}\mathrm{F} + {}^{127}\mathrm{I} + {}^{28}\mathrm{Si}$, $Q_{\max} < 100$ keV, $b_1 = 10$ keV, 3×50 events, $\sigma^{\mathrm{SI}}_{\chi\mathrm{p}} = 1$ zb, $a_\mathrm{n}/a_\mathrm{p} = 0.7$)

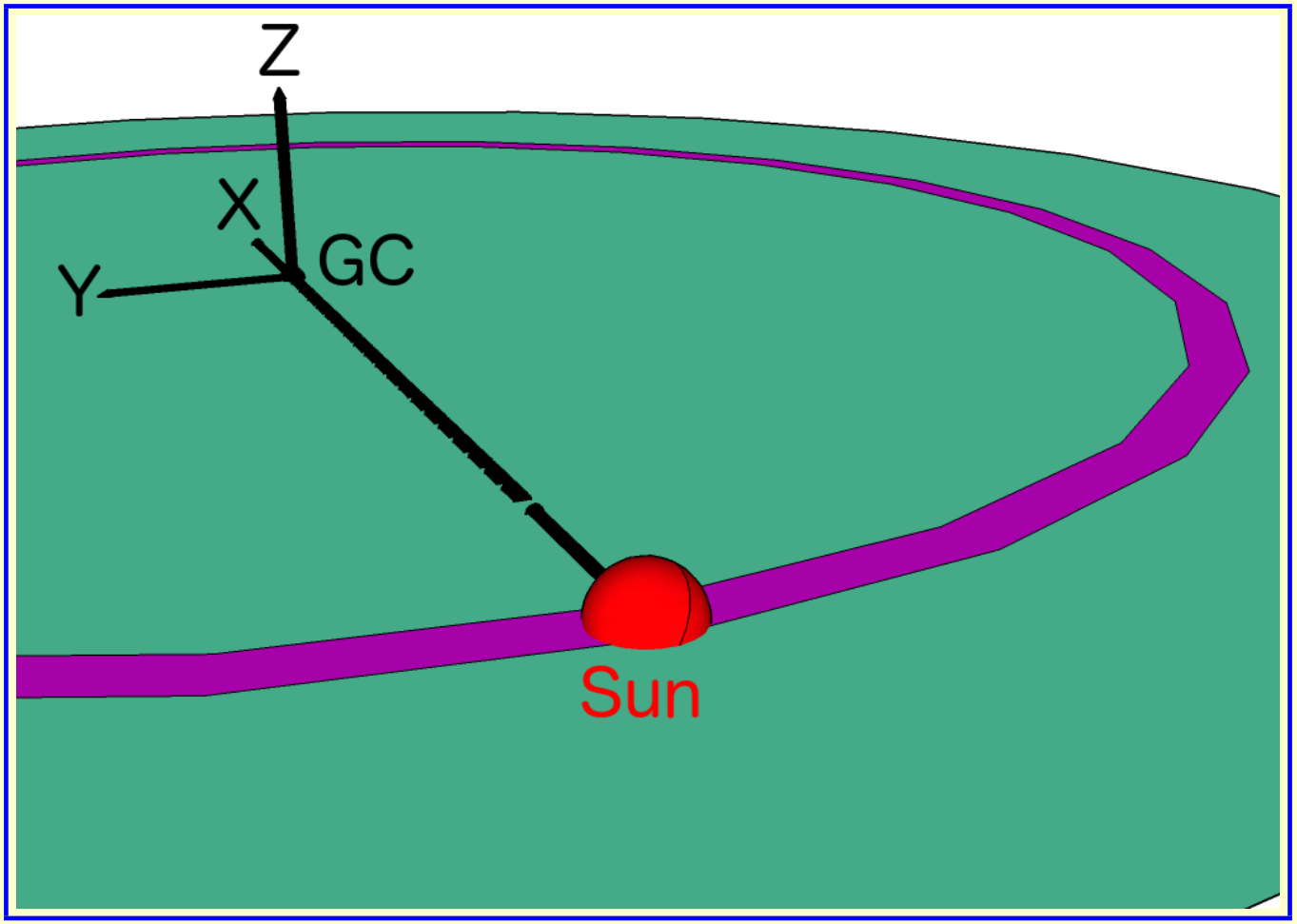


[Y. Bai, W. Sun and CLS, IJMPA 33, 1850120 (2018)]

Preparations
(for the preparation for our future works)

Definitions of celestial different coordinate systems

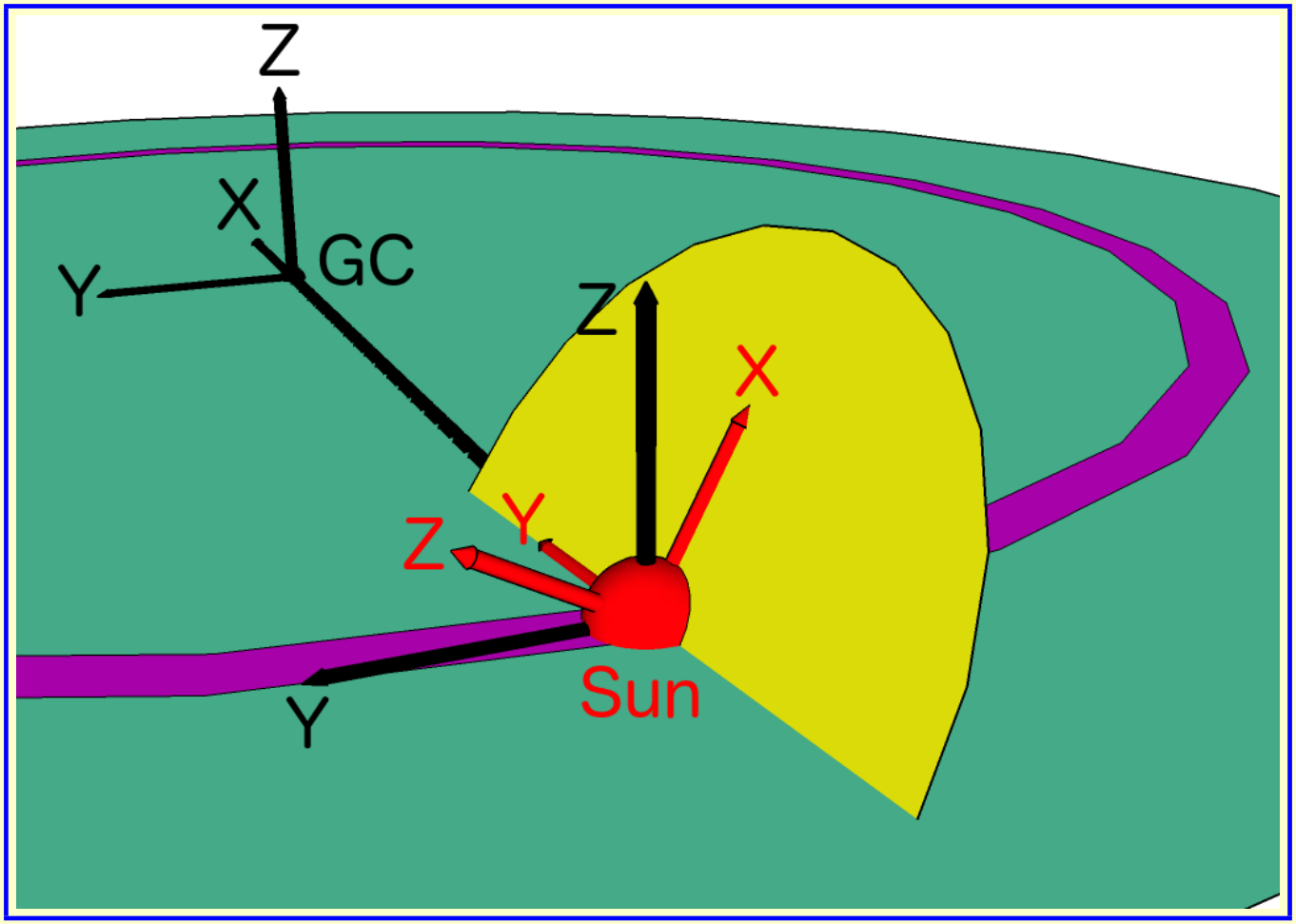
- Galactic (G) coordinate system



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

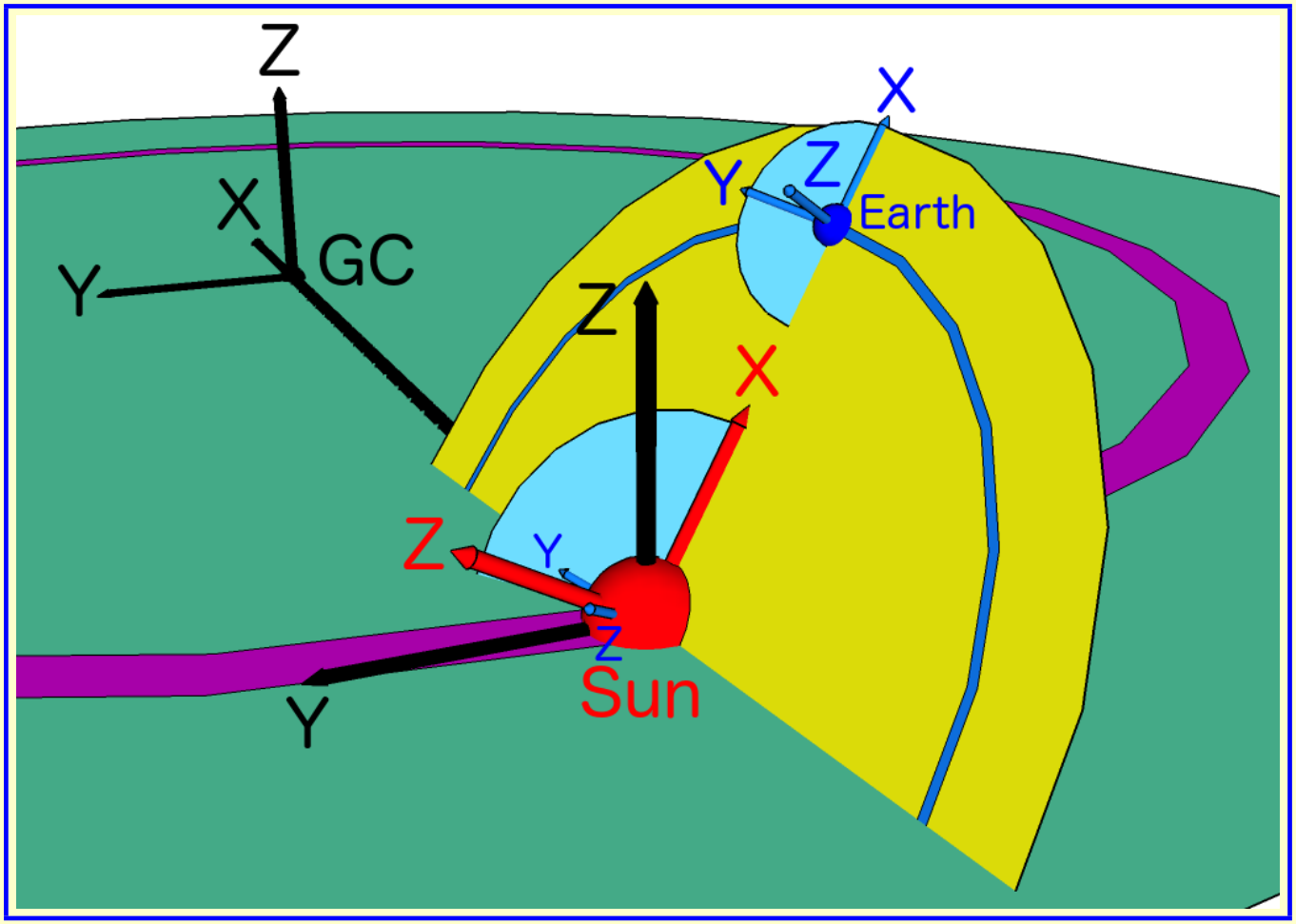
- Ecliptic (S) coordinate system



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

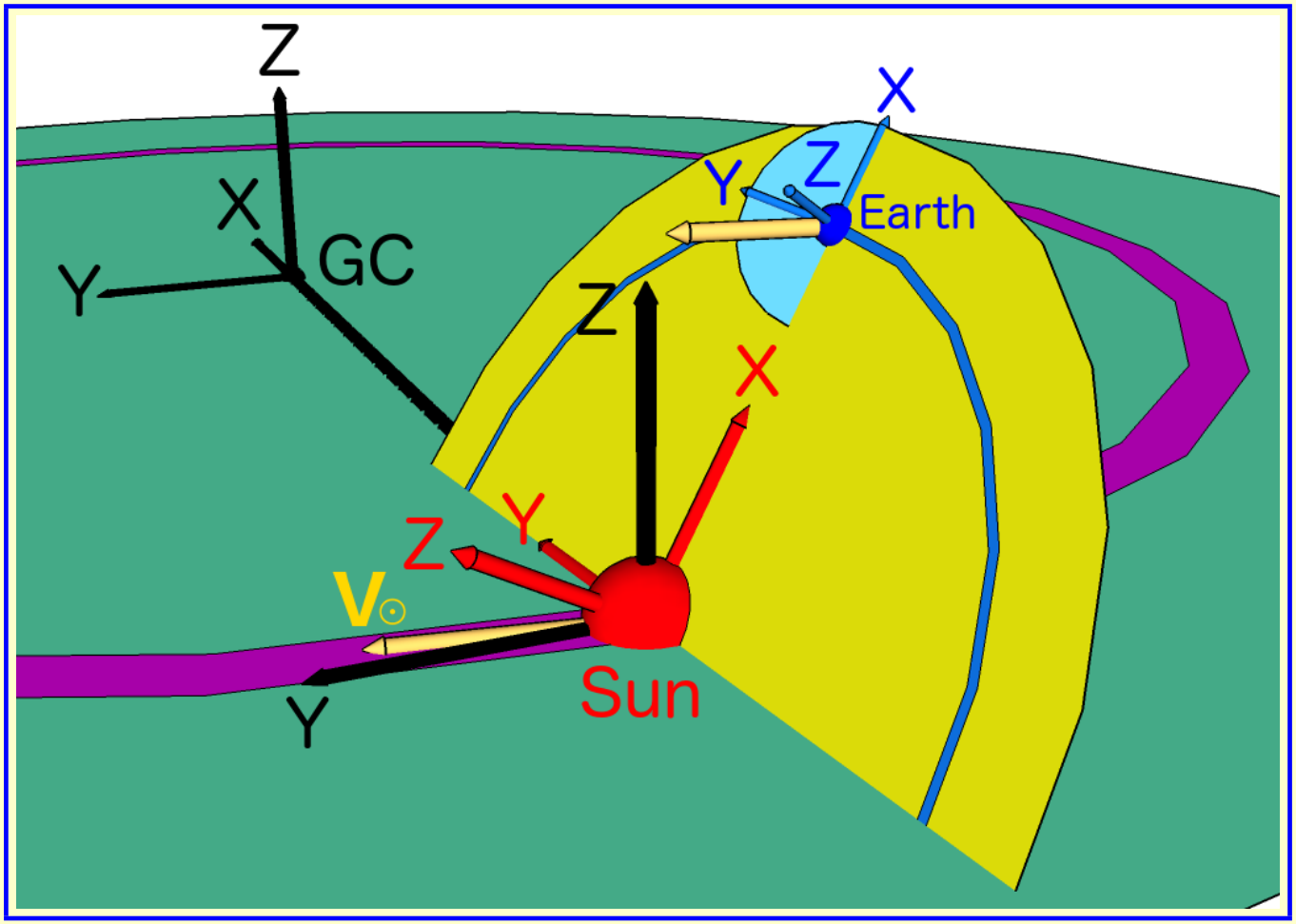
- Equatorial (Eq) coordinate system



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

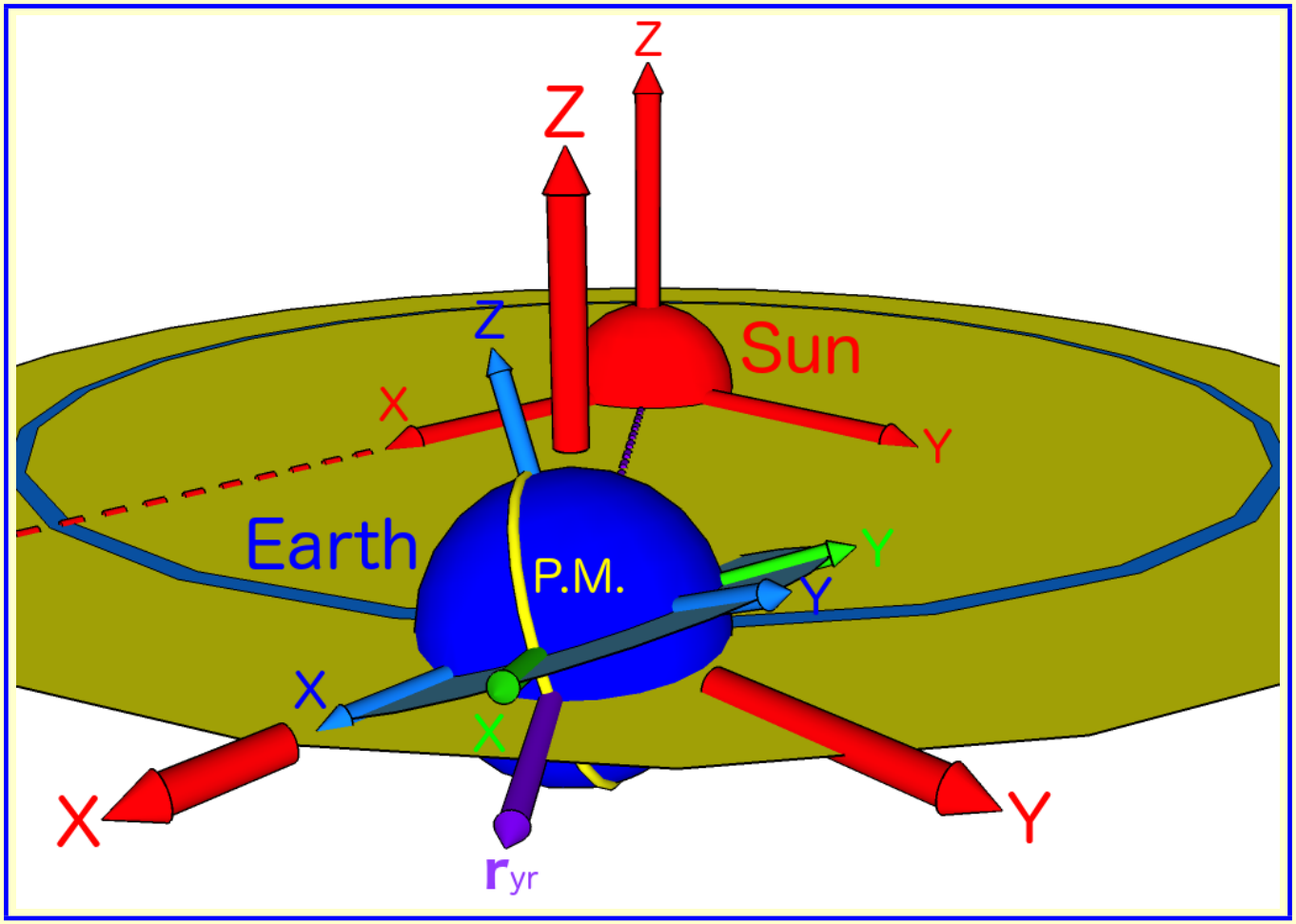
- Solar movement in the Dark Matter halo



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

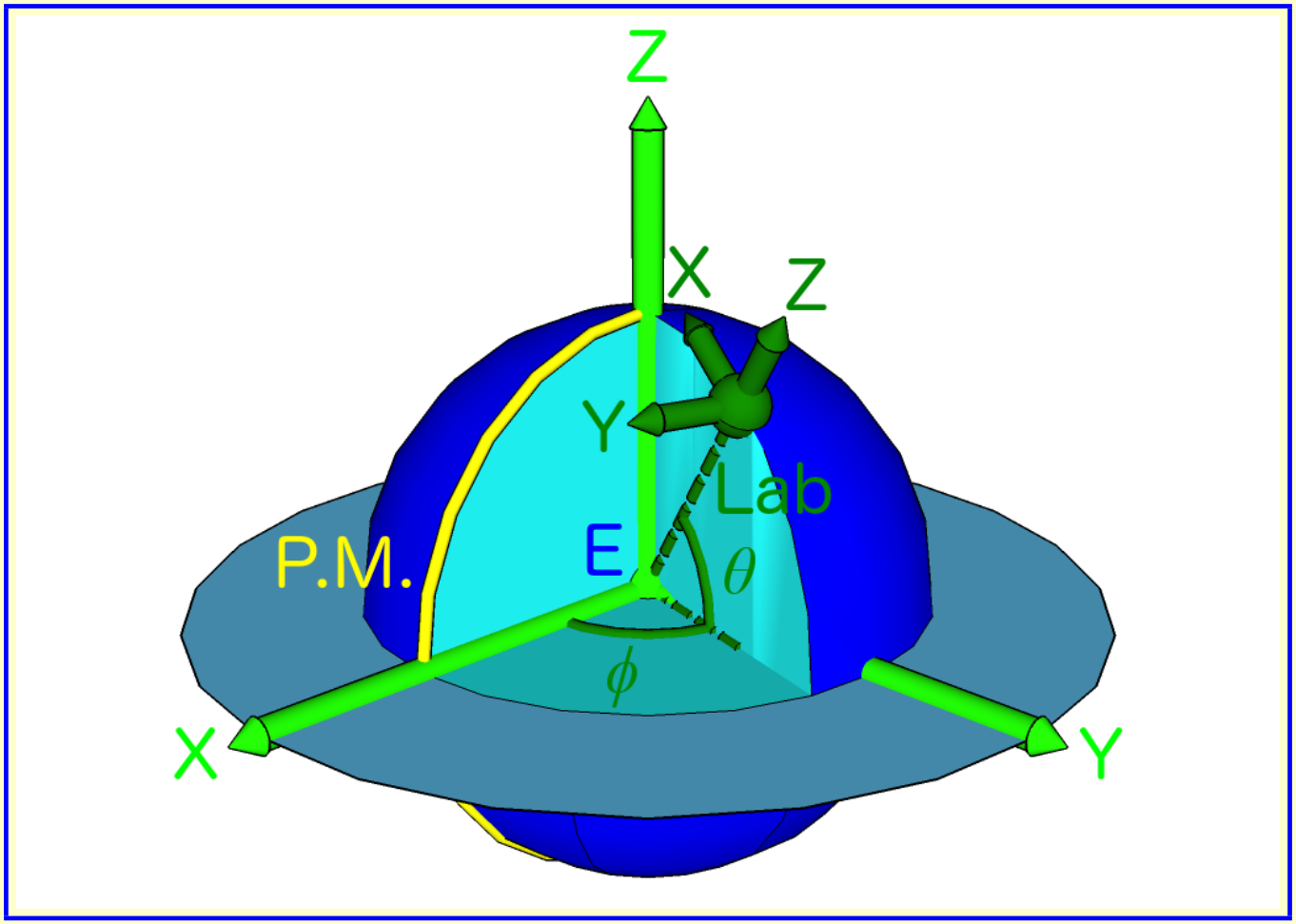
- Earth (E) coordinate system



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

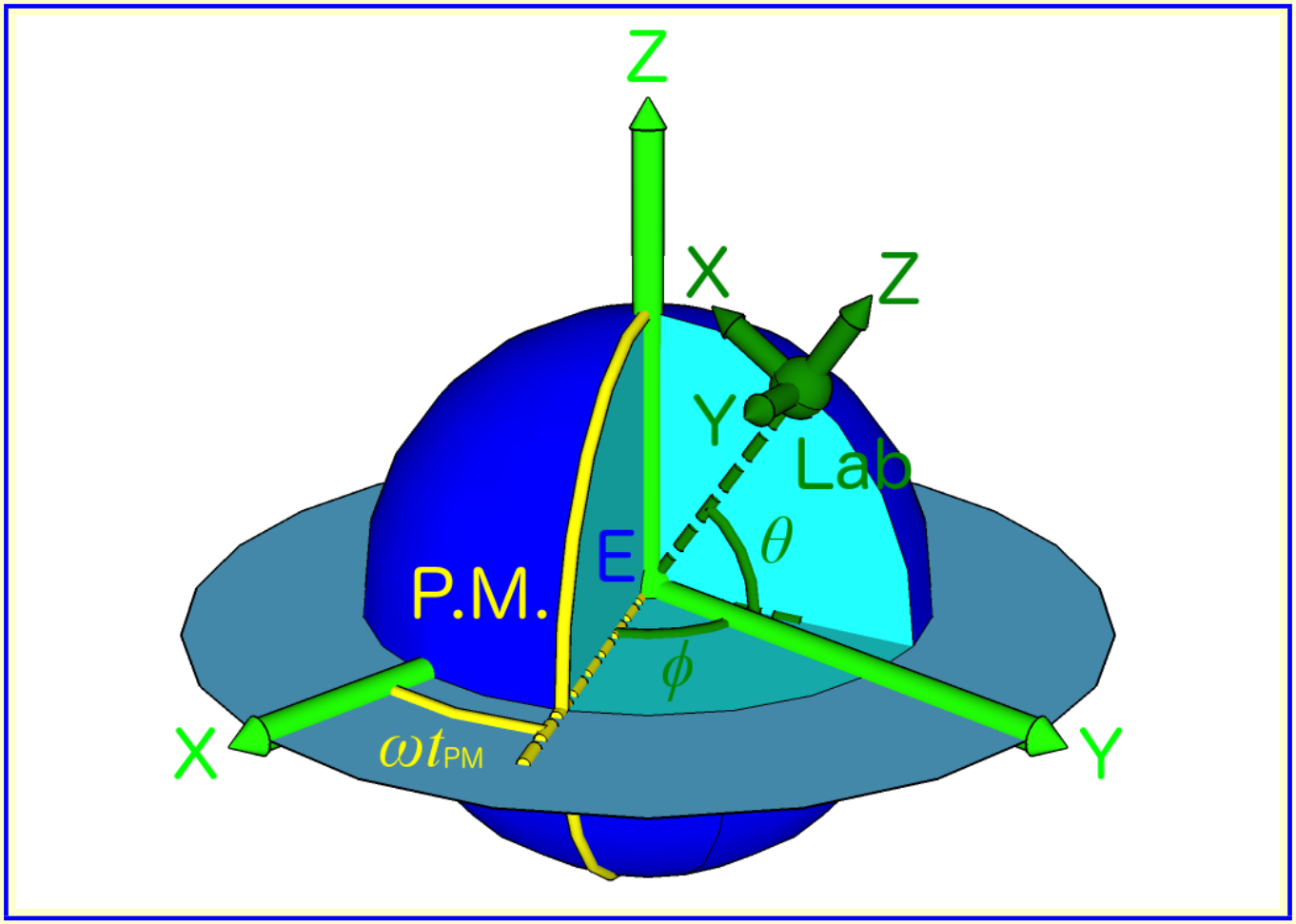
- Horizontal (H) coordinate system



[CLS, arXiv:1905.11279 (2019)]

Definitions of celestial different coordinate systems

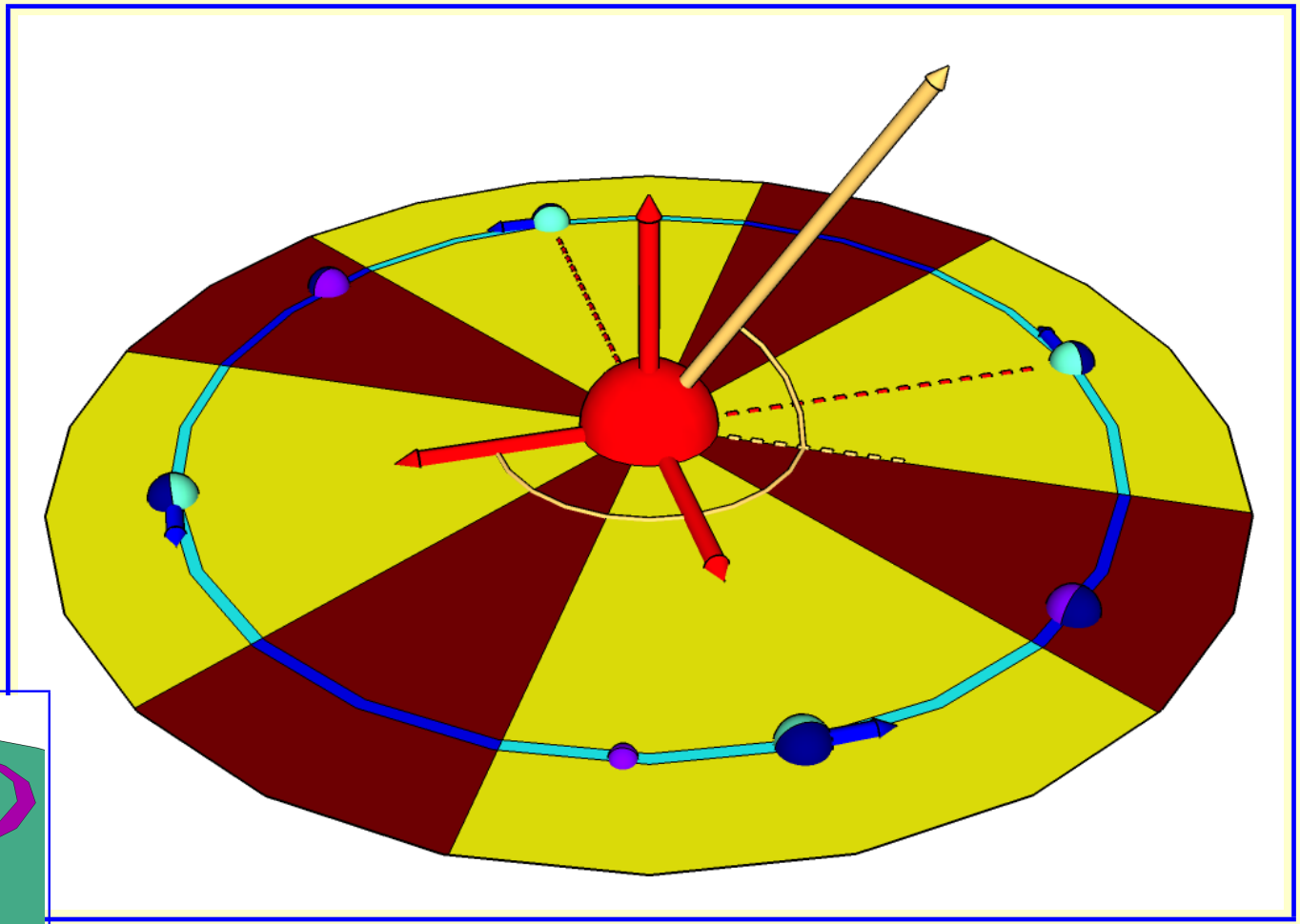
- Laboratory (Lab) coordinate system

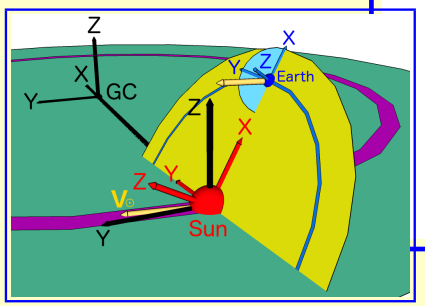


[CLS, arXiv:1905.11279 (2019)]

Earth's velocity relative to the Dark Matter halo

- Four normal seasons

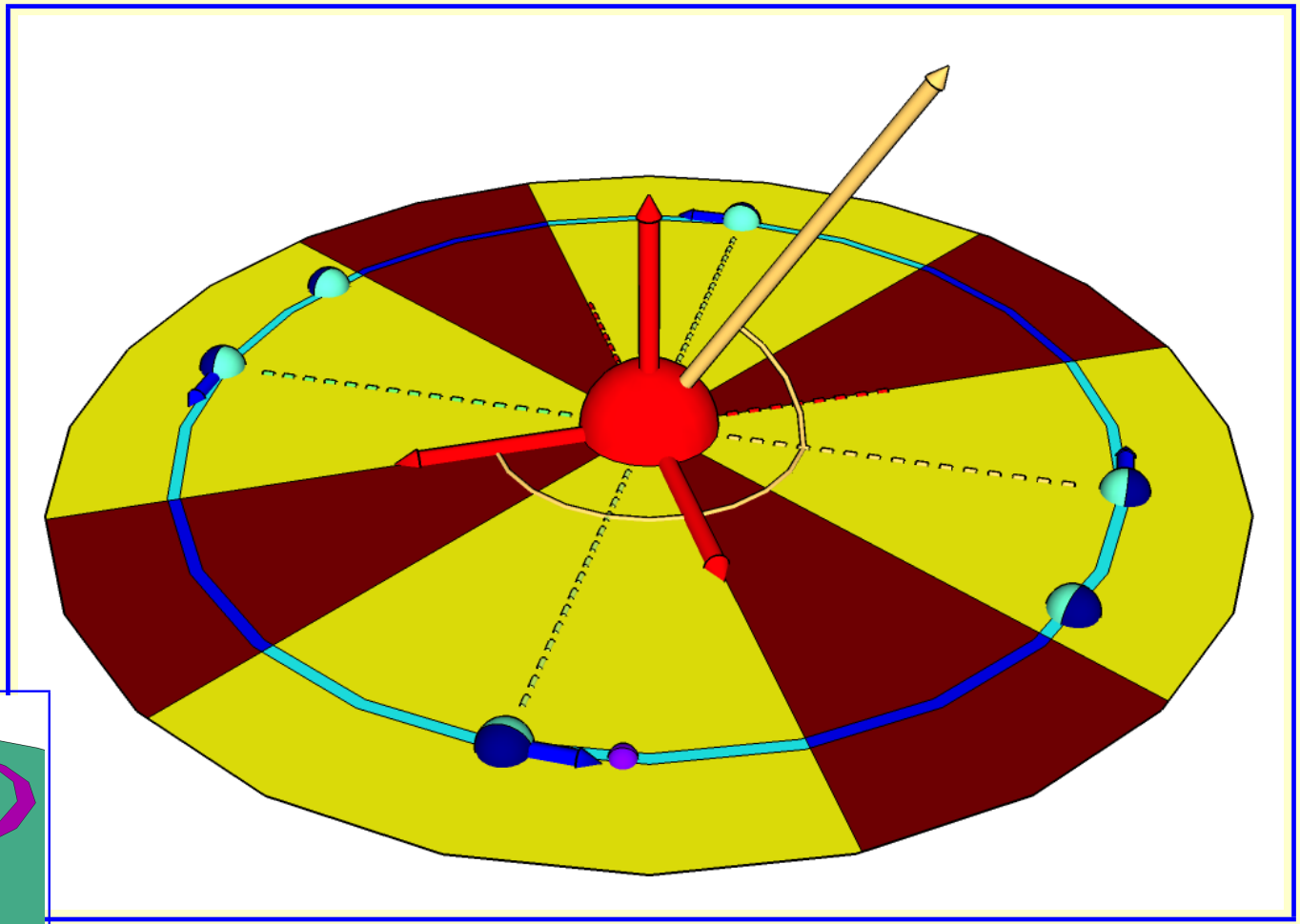


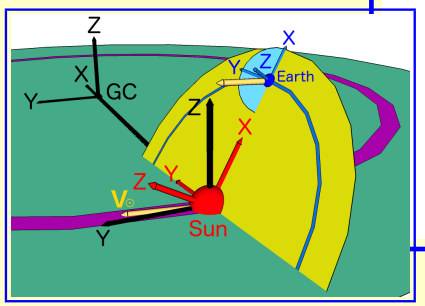


[CLS, arXiv:1905.11279 (2019)]

Earth's velocity relative to the Dark Matter halo

- Four advanced seasons

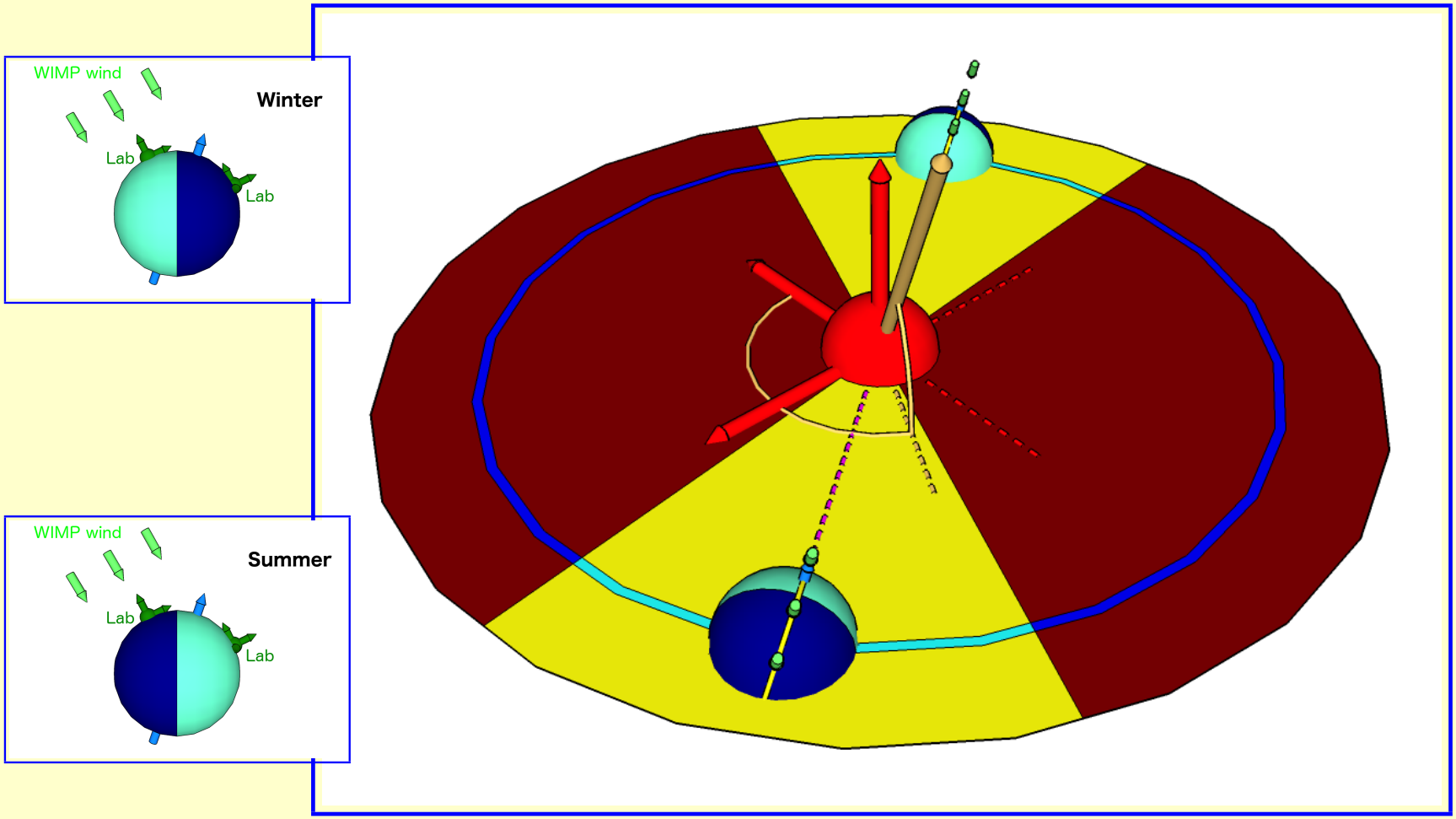




[CLS, arXiv:1905.11279 (2019)]

Earth's velocity relative to the Dark Matter halo

- Two periods for demonstrating the diurnal modulation



[CLS, arXiv:1905.11279 (2019)]

Angular distributions of the 3-D WIMP velocity

Simulation setup

Simulation setup

3-D Velocity distribution of Galactic WIMPs

- Simple Maxwellian velocity distribution

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

- Angular distribution

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

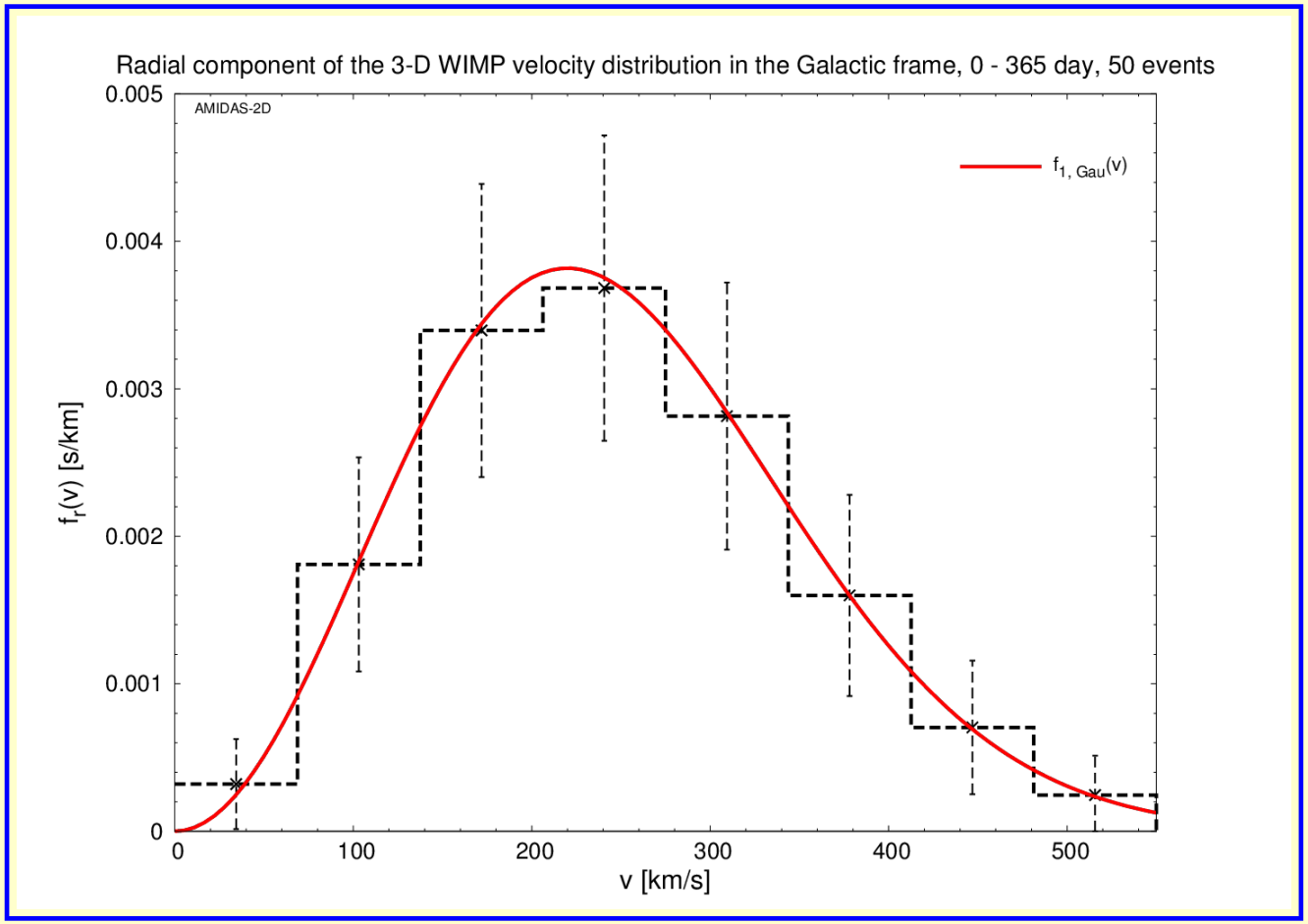
$$f_{\theta,\,\mathrm{G}}(\theta) = 1 \qquad \theta \in [-\pi/2,\ \pi/2]$$

- Time dependence

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

Simulation setup

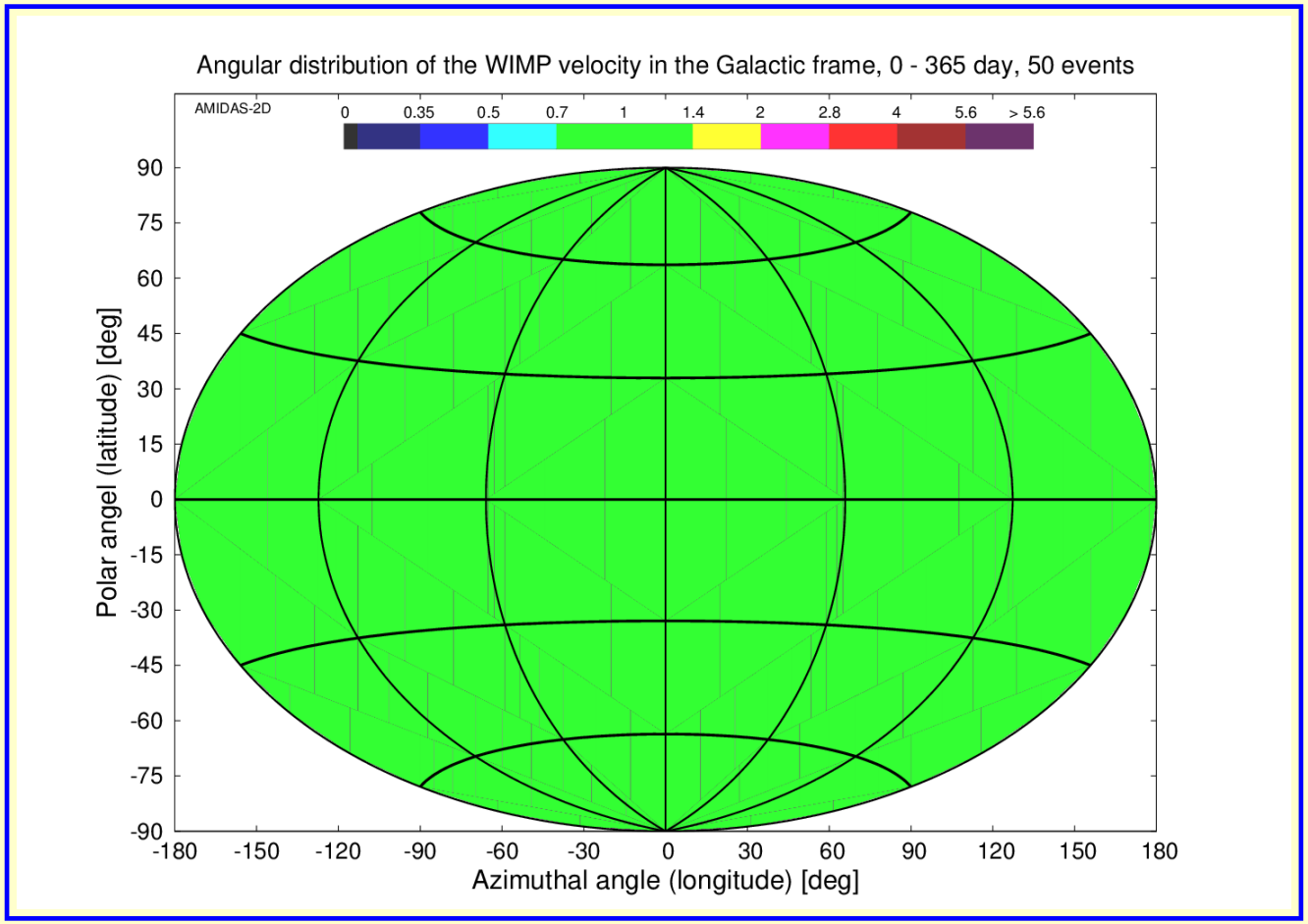
- Radial component of the 3-D WIMP velocity distribution
  (Galactic frame, 0 - 365 day, 50 events)



[CLS, arXiv:1905.11279 (2019)]

Simulation setup

- Angular distribution of the 3-D WIMP velocity
  (Galactic frame, 0 - 365 day, 50 events)

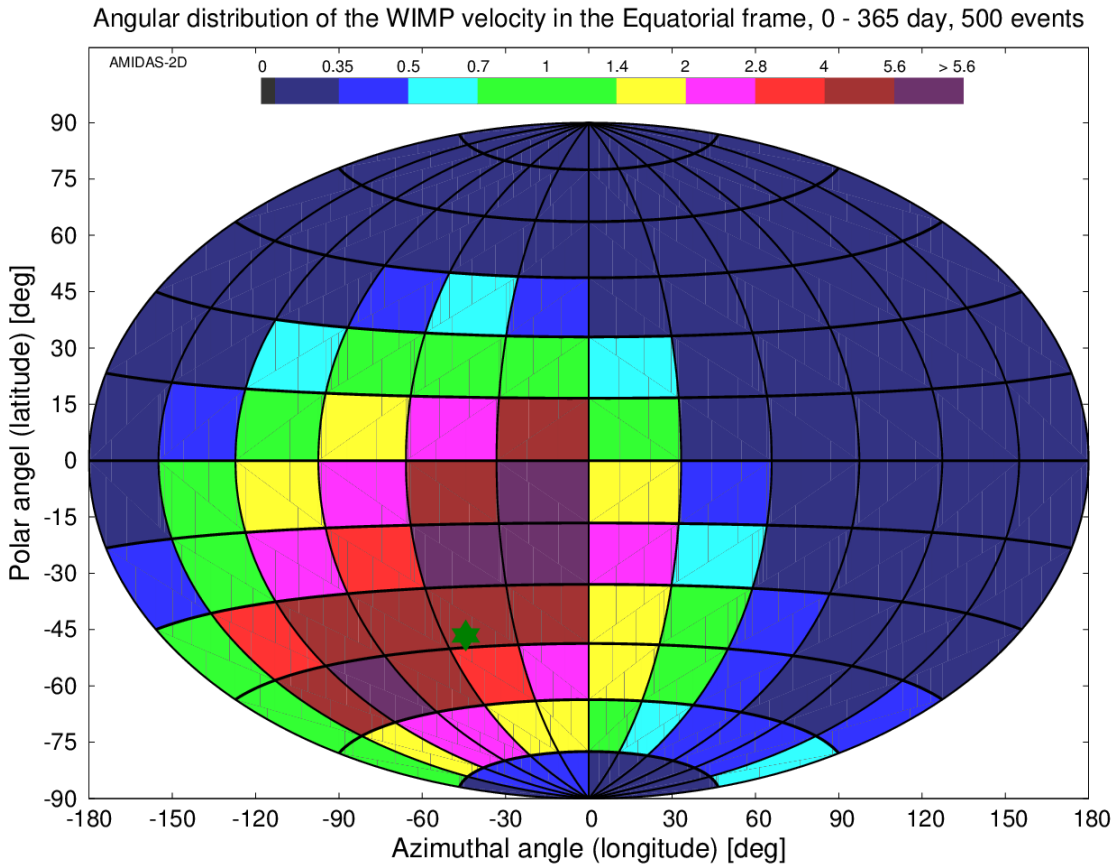


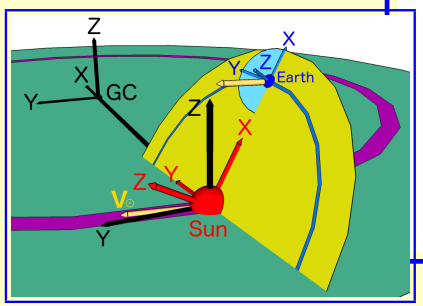
[CLS, arXiv:1905.11279 (2019)]

In the Equatorial coordinate system

Angular distributions of the 3-D WIMP velocity

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

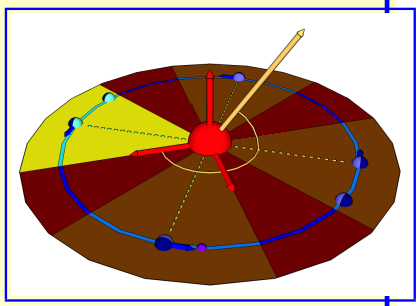


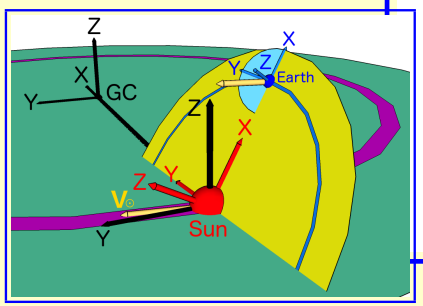


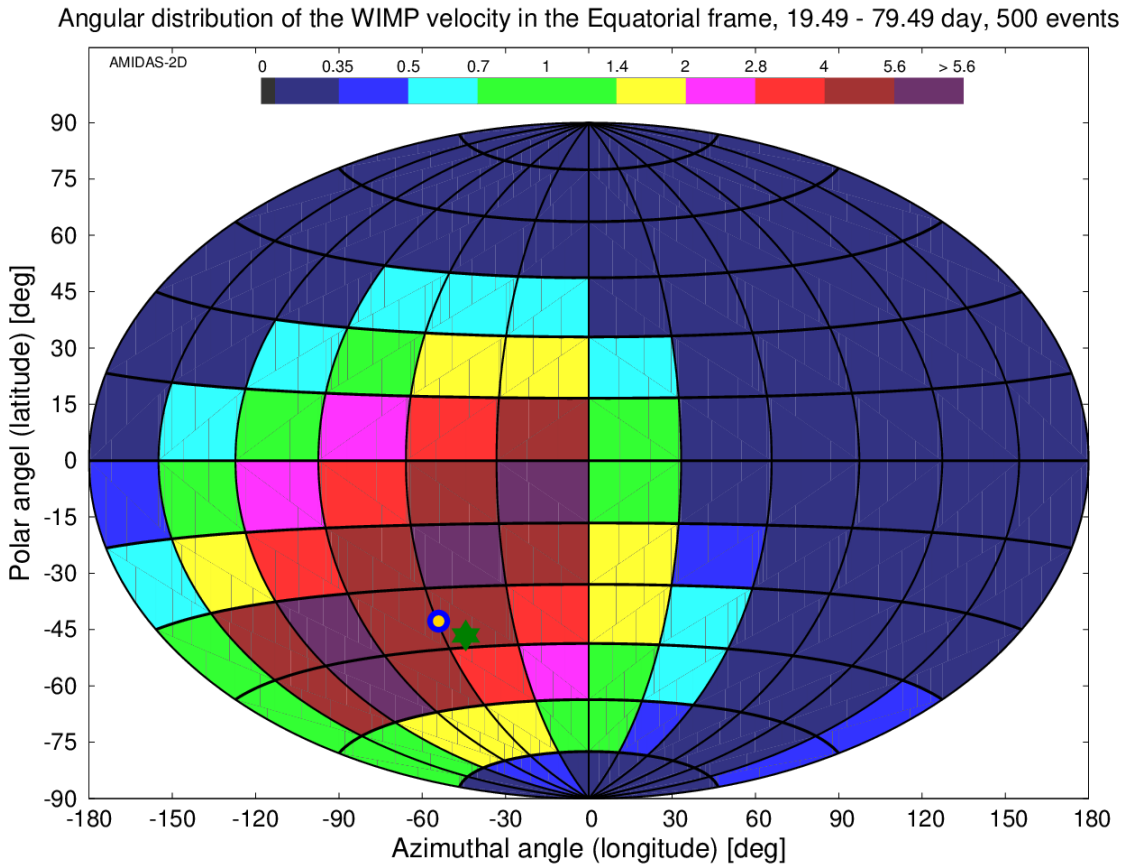
[CLS, arXiv:1905.11279 (2019)]

Angular distributions of the 3-D WIMP velocity

- Angular distribution of the 3-D WIMP velocity
  (Equatorial frame, 19.49 - 79.49 day, 500 events)



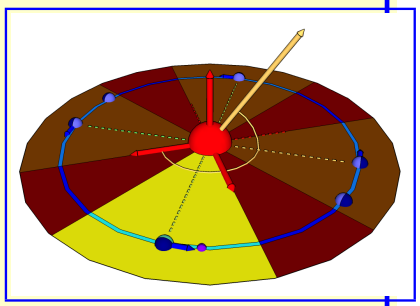


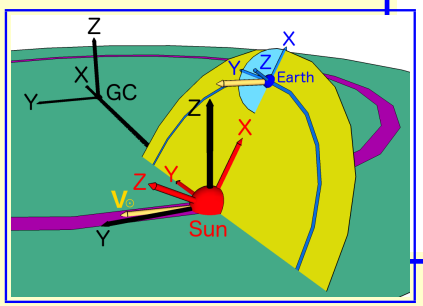


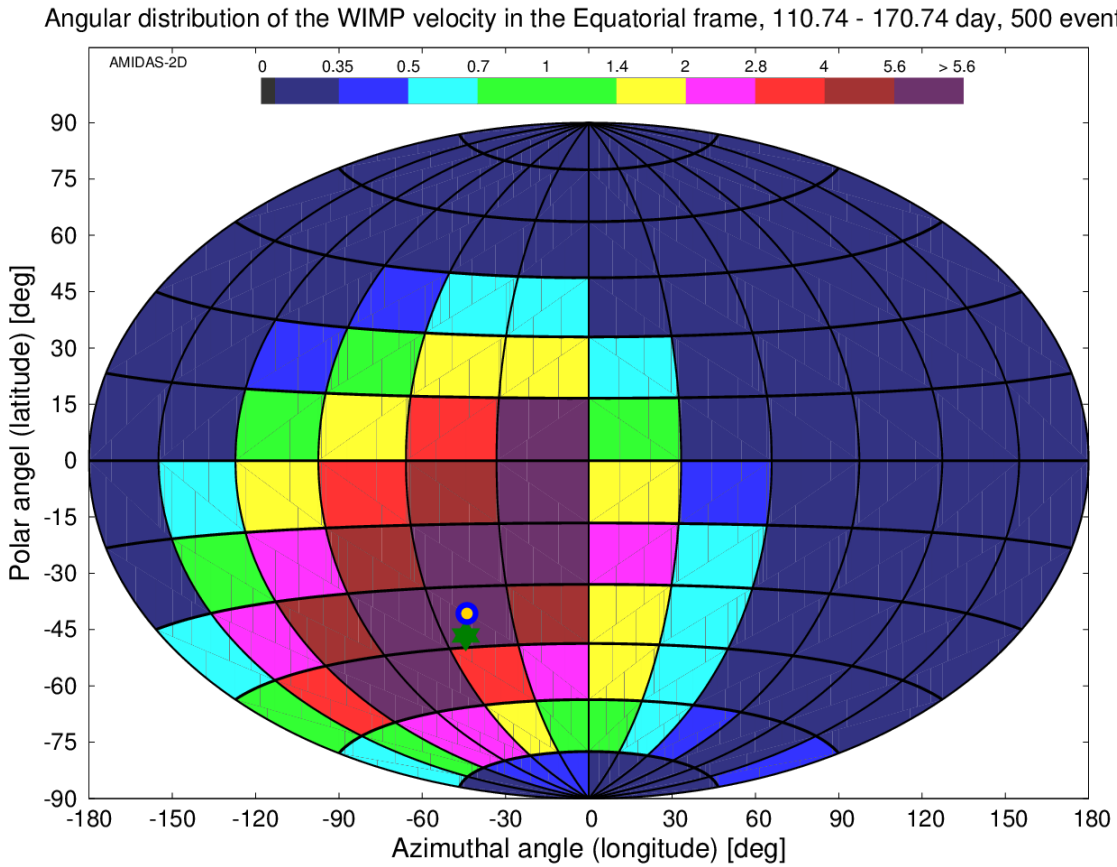
[CLS, arXiv:1905.11279 (2019)]

Angular distributions of the 3-D WIMP velocity

- Angular distribution of the 3-D WIMP velocity
  (Equatorial frame, 110.74 - 170.74 day, 500 events)



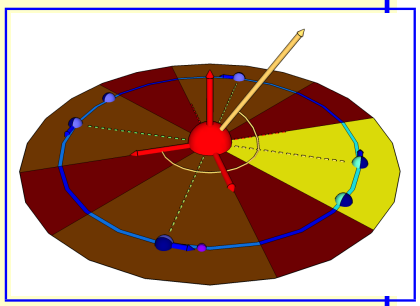


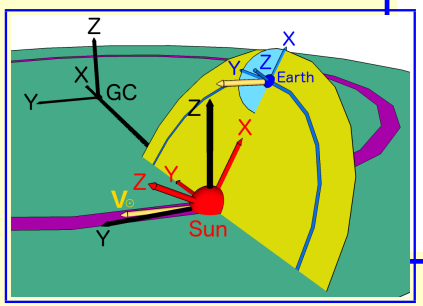


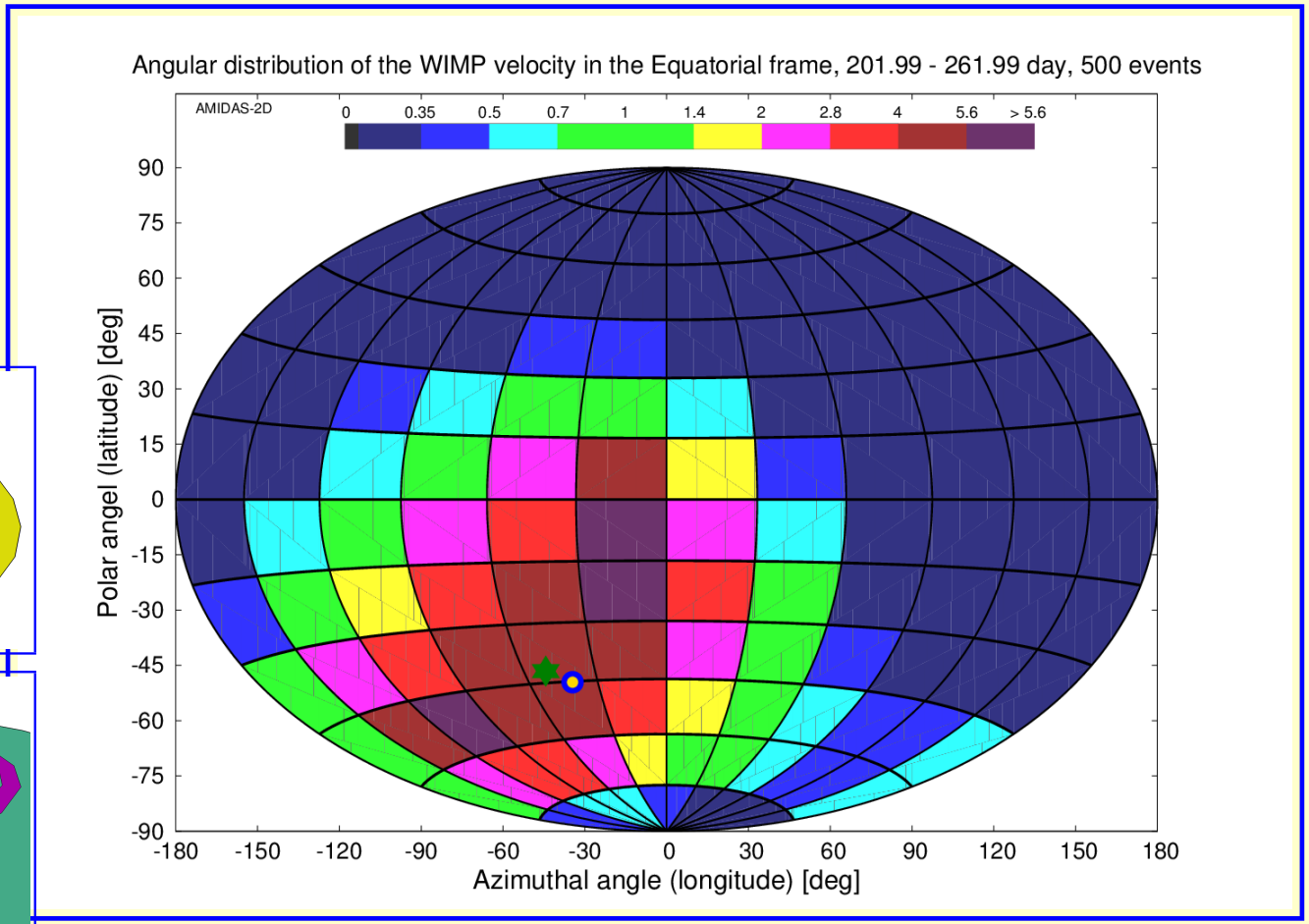
[CLS, arXiv:1905.11279 (2019)]

Angular distributions of the 3-D WIMP velocity

- Angular distribution of the 3-D WIMP velocity
  (Equatorial frame, 201.99 - 261.99 day, 500 events)



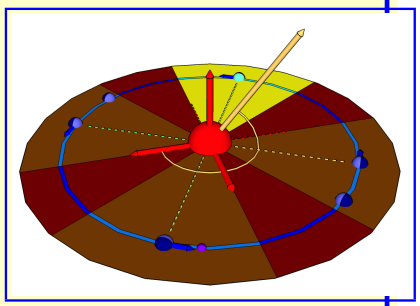


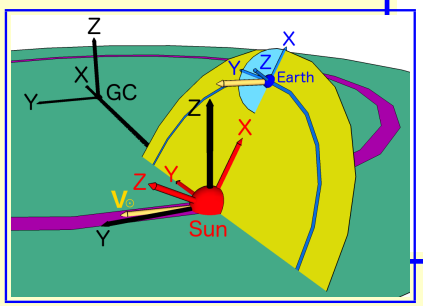


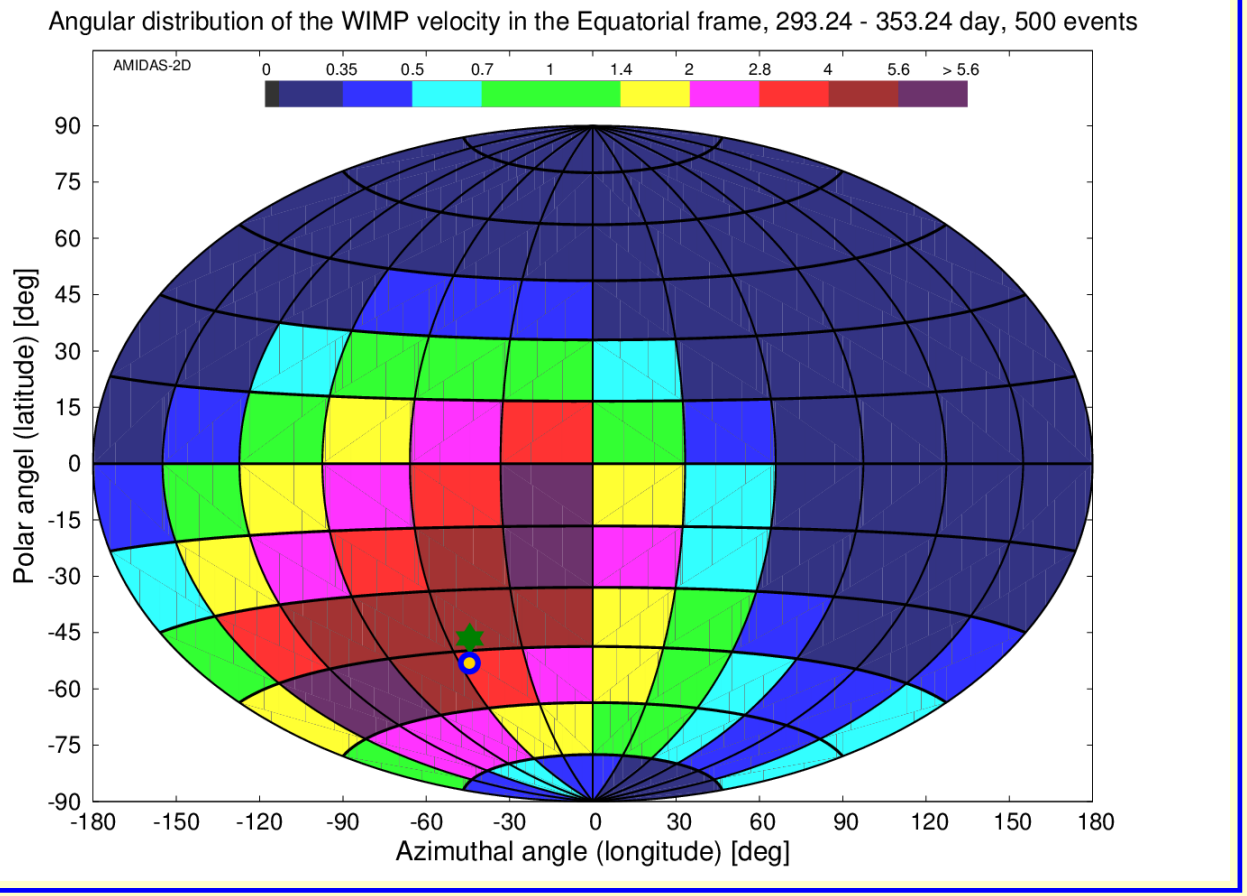
[CLS, arXiv:1905.11279 (2019)]

Angular distributions of the 3-D WIMP velocity

- Angular distribution of the 3-D WIMP velocity
  (Equatorial frame, 293.24 - 353.24 day, 500 events)



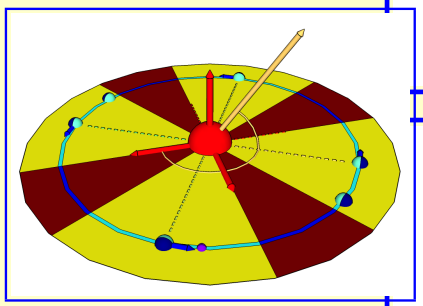


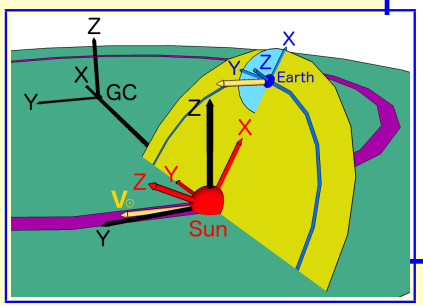


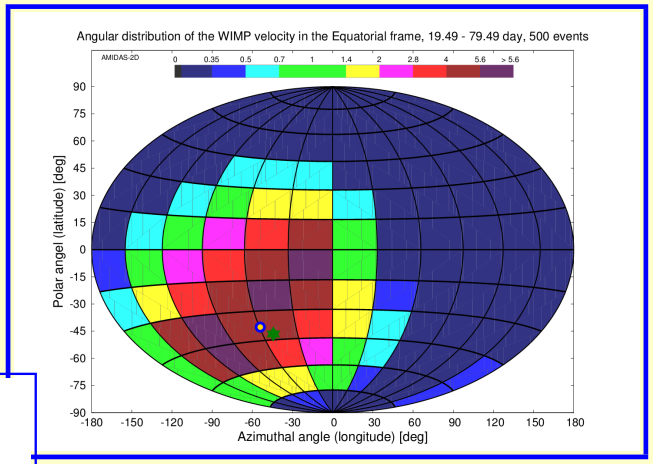
[CLS, arXiv:1905.11279 (2019)]

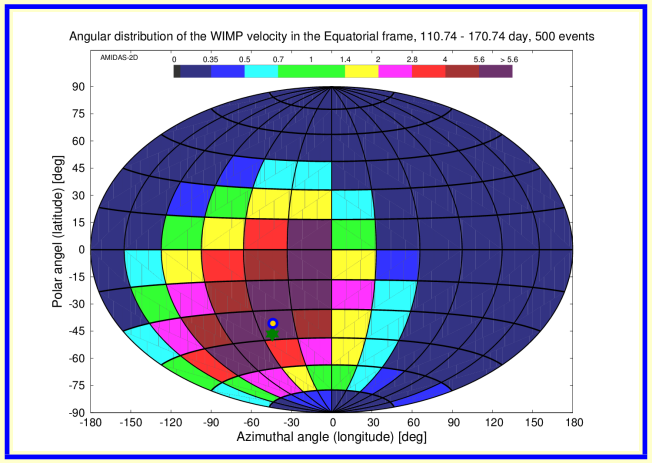
Angular distributions of the 3-D WIMP velocity

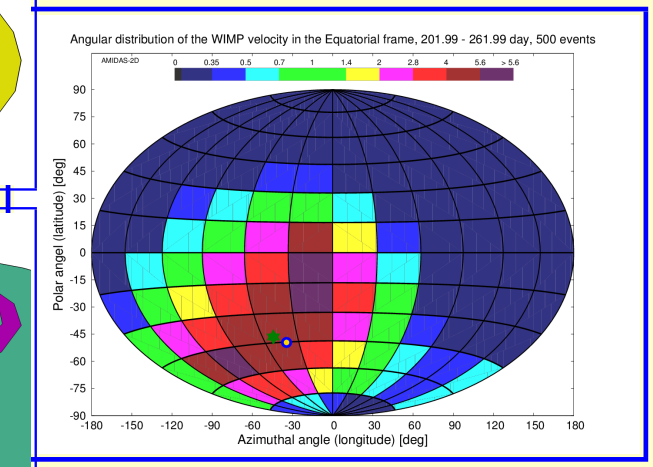
- Annual modulation of the angular distribution of the 3-D WIMP velocity
  (Equatorial frame, four advanced seasons, 500 events)

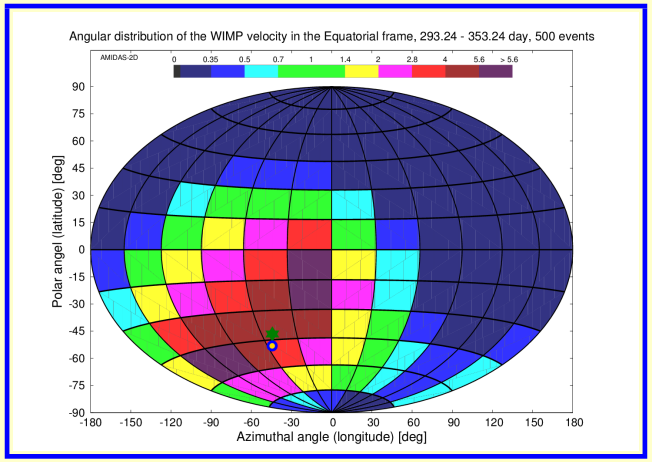










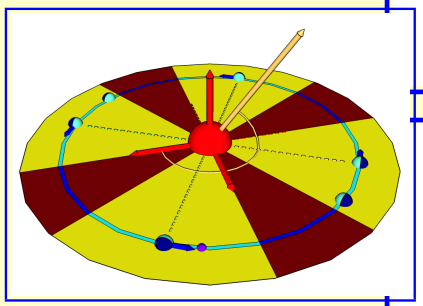


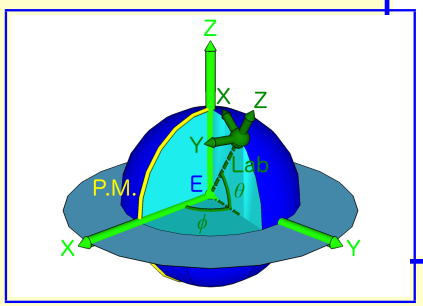
[CLS, arXiv:1905.11279 (2019)]

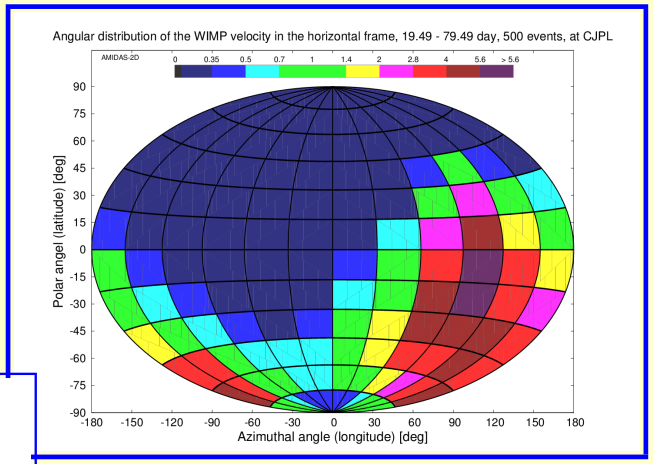
In the horizontal/laboratory coordinate systems

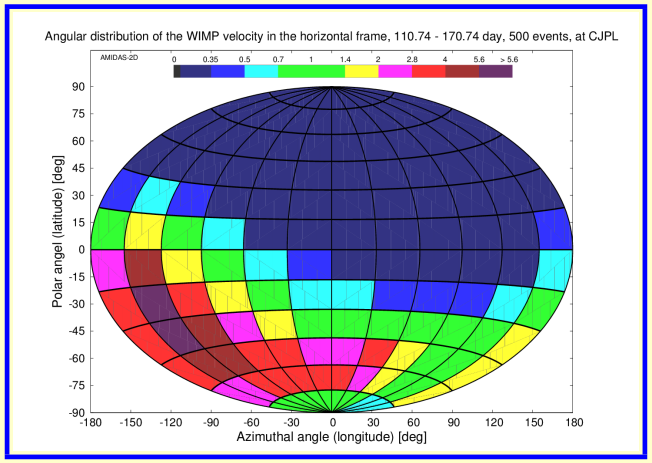
Angular distributions of the 3-D WIMP velocity

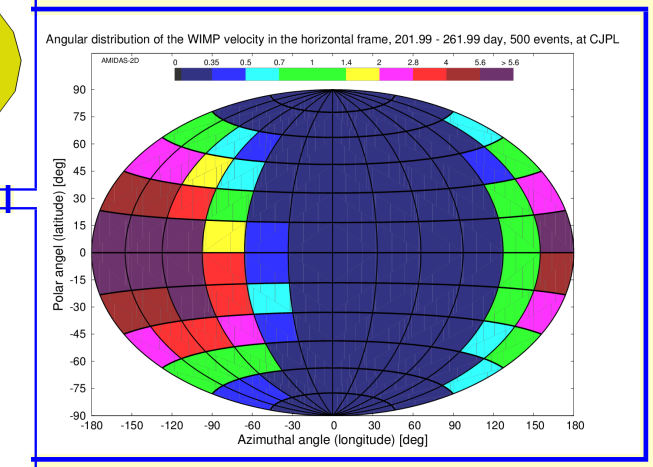
- Annual modulation of the angular distribution of the 3-D WIMP velocity (Horizontal frame, four advanced seasons, 500 events, at CJPL Lab)

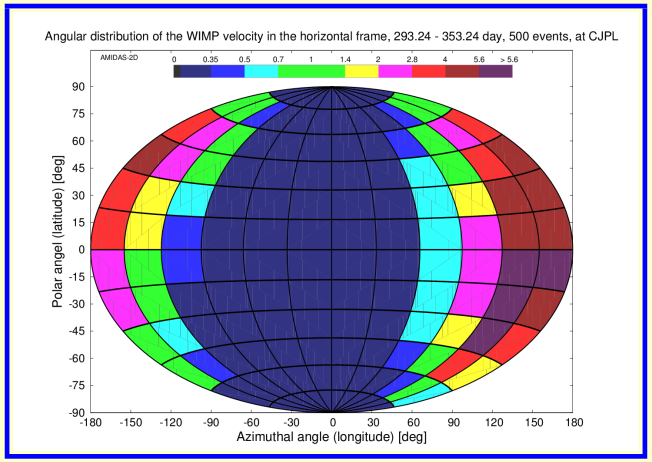








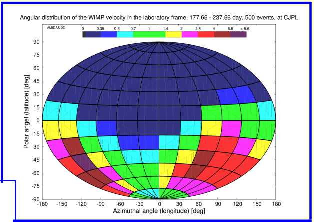


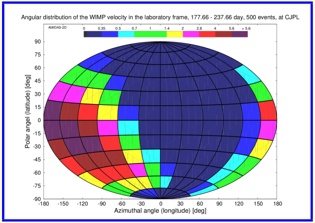


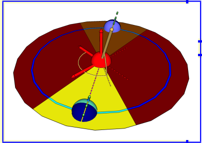
[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

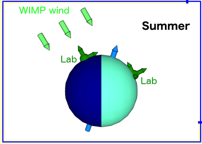
Angular distributions of the 3-D WIMP velocity

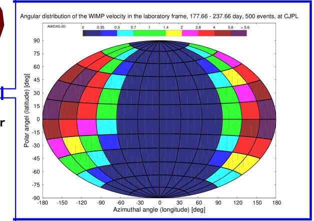
- Diurnal modulation of the angular distribution of the 3-D WIMP velocity (Laboratory frame, 177.66 - 237.66 day, 500 events, at CJPL Lab)

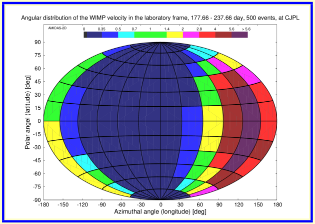








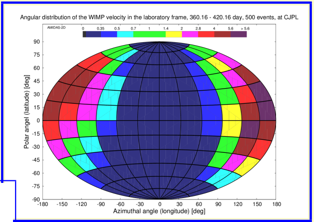


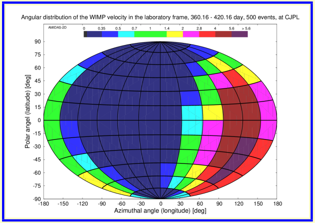


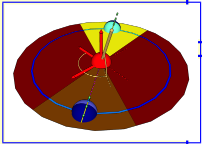
[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

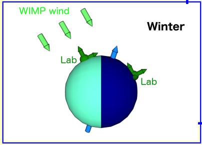
Angular distributions of the 3-D WIMP velocity

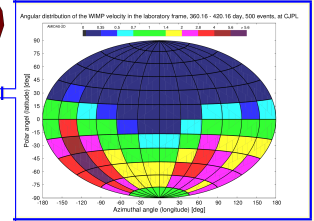
- Diurnal modulation of the angular distribution of the 3-D WIMP velocity
  (Laboratory frame, 360.16 - 420.16 day, 500 events, at CJPL Lab)

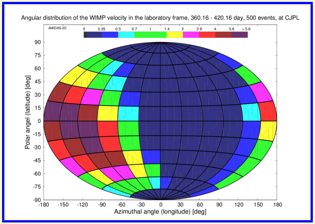








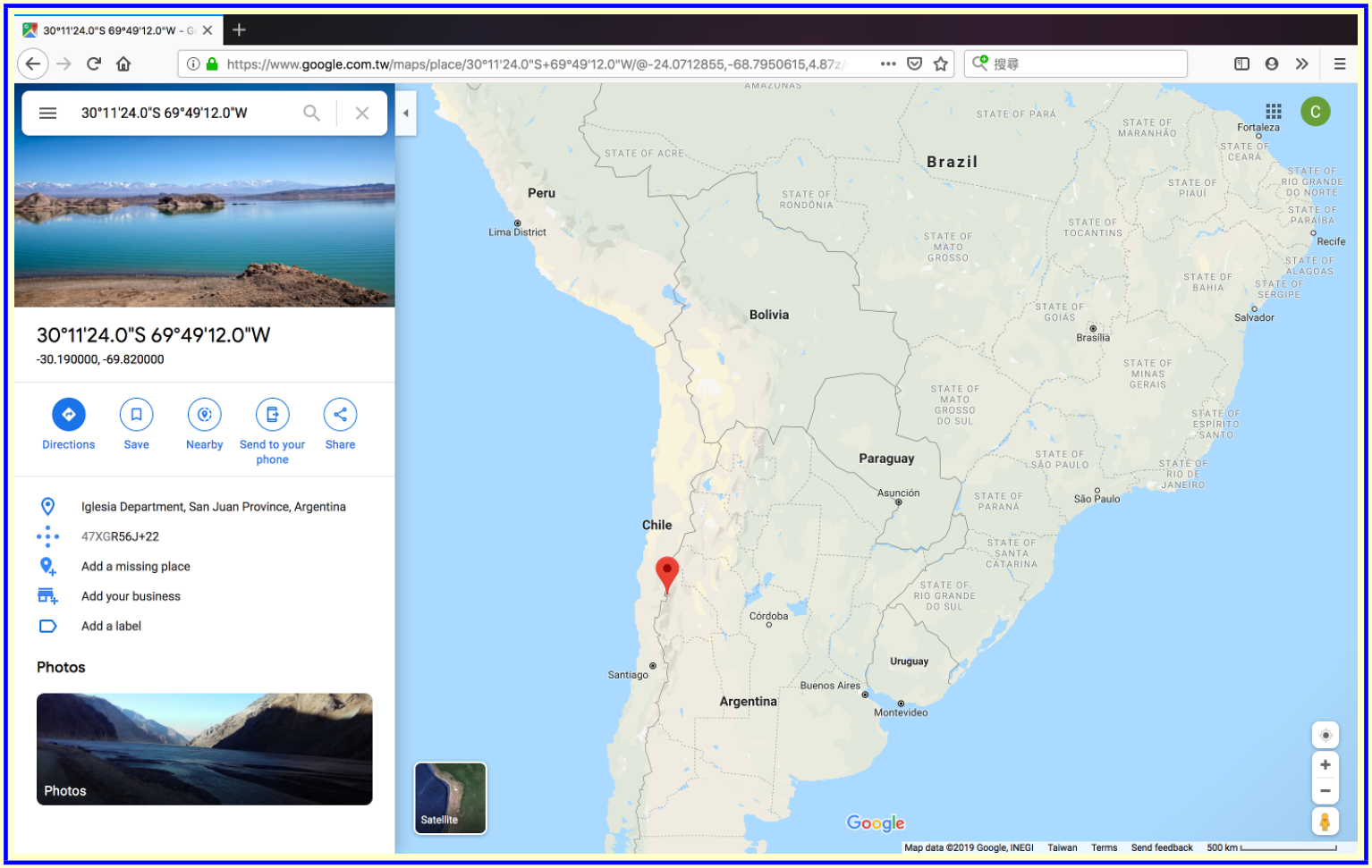




[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

Angular distributions of the 3-D WIMP velocity

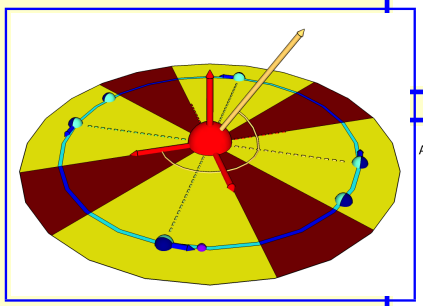
- Agua Negra Deep Experiment Site (ANDES, 30.19°S, 69.82°W)

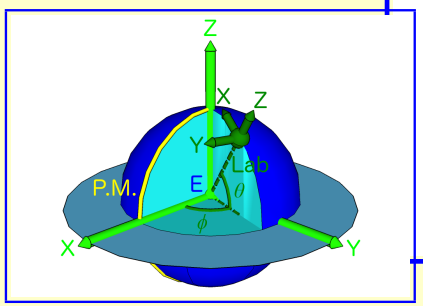


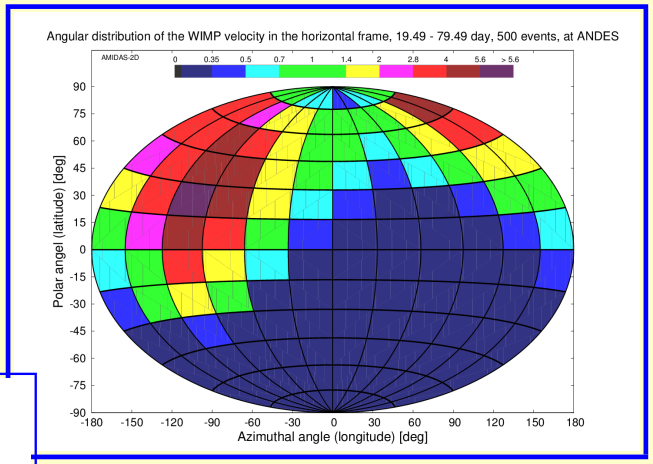
[Google Map]

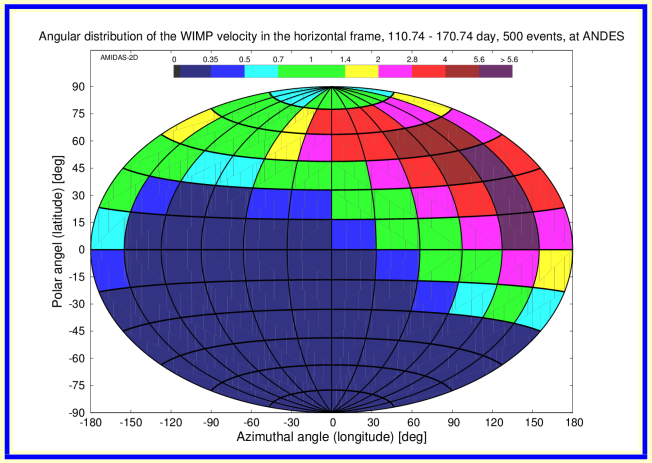
Angular distributions of the 3-D WIMP velocity

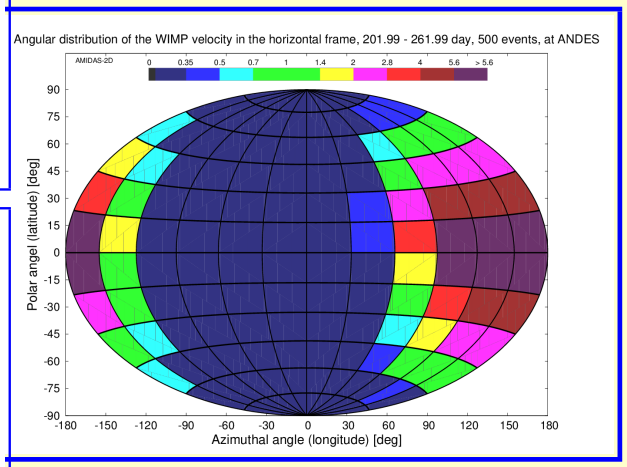
- Annual modulation of the angular distribution of the 3-D WIMP velocity
  (Horizontal frame, four advanced seasons, 500 events, at ANDES Lab)

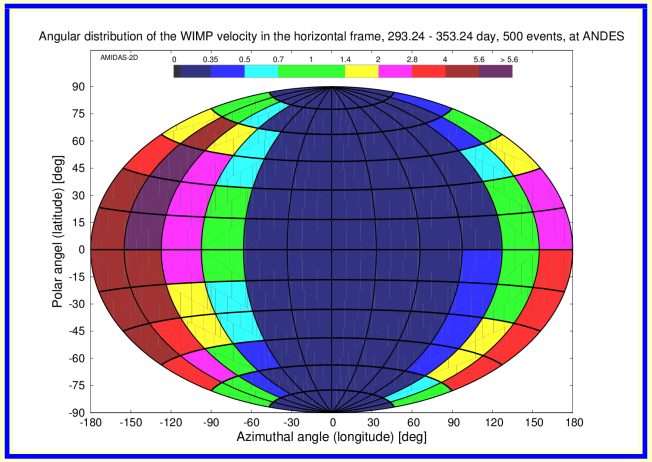








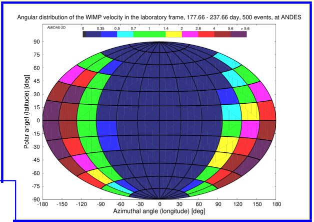


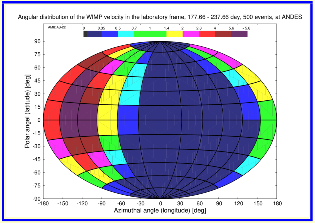


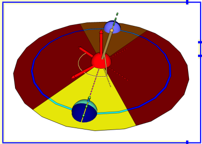
[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

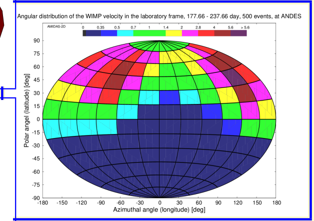
Angular distributions of the 3-D WIMP velocity

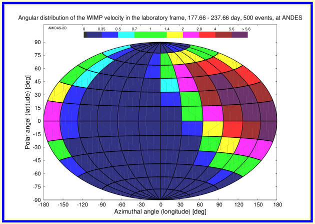
❑ Diurnal modulation of the angular distribution of the 3-D WIMP velocity
(Laboratory frame, 177.66 - 237.66 day, 500 events, at ANDES Lab)

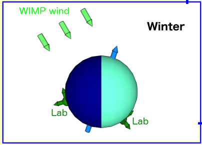








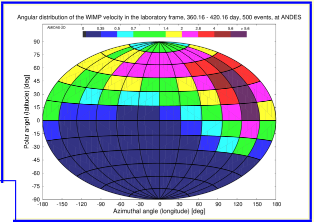


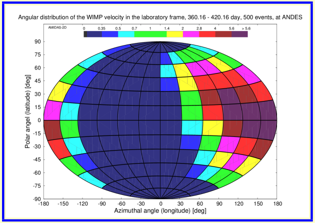


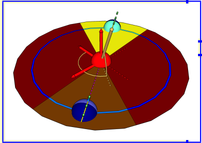
[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

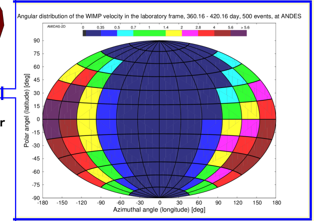
Angular distributions of the 3-D WIMP velocity

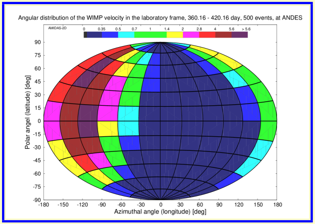
- Diurnal modulation of the angular distribution of the 3-D WIMP velocity (Laboratory frame, 360.16 - 420.16 day, 500 events, at ANDES Lab)

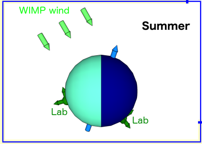










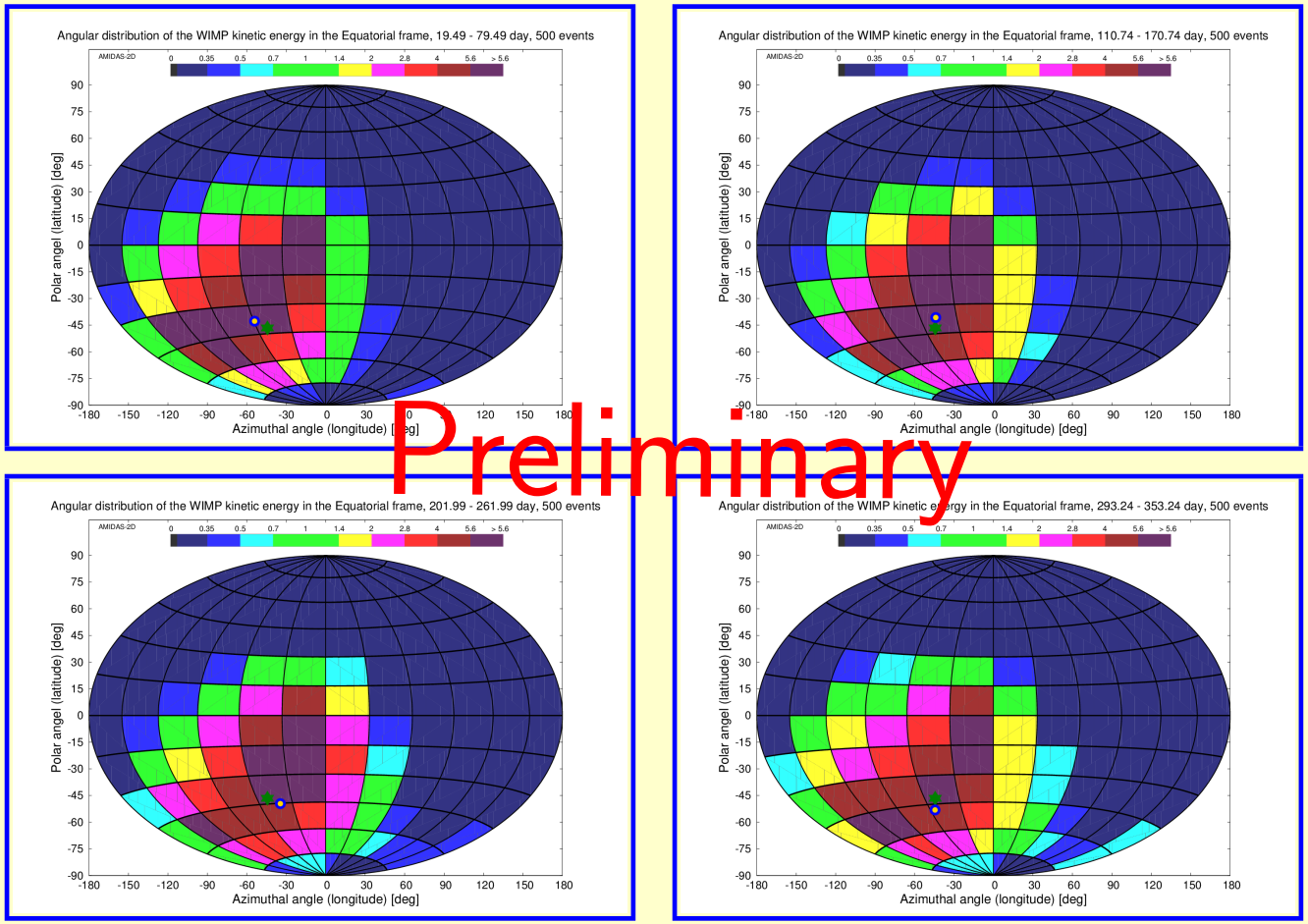


[CLS, arXiv:1905.11279 (2019), arXiv:1910.11763 (2019)]

Angular distributions of the 3-D WIMP kinetic energy

Angular distributions of the 3-D WIMP kinetic energy

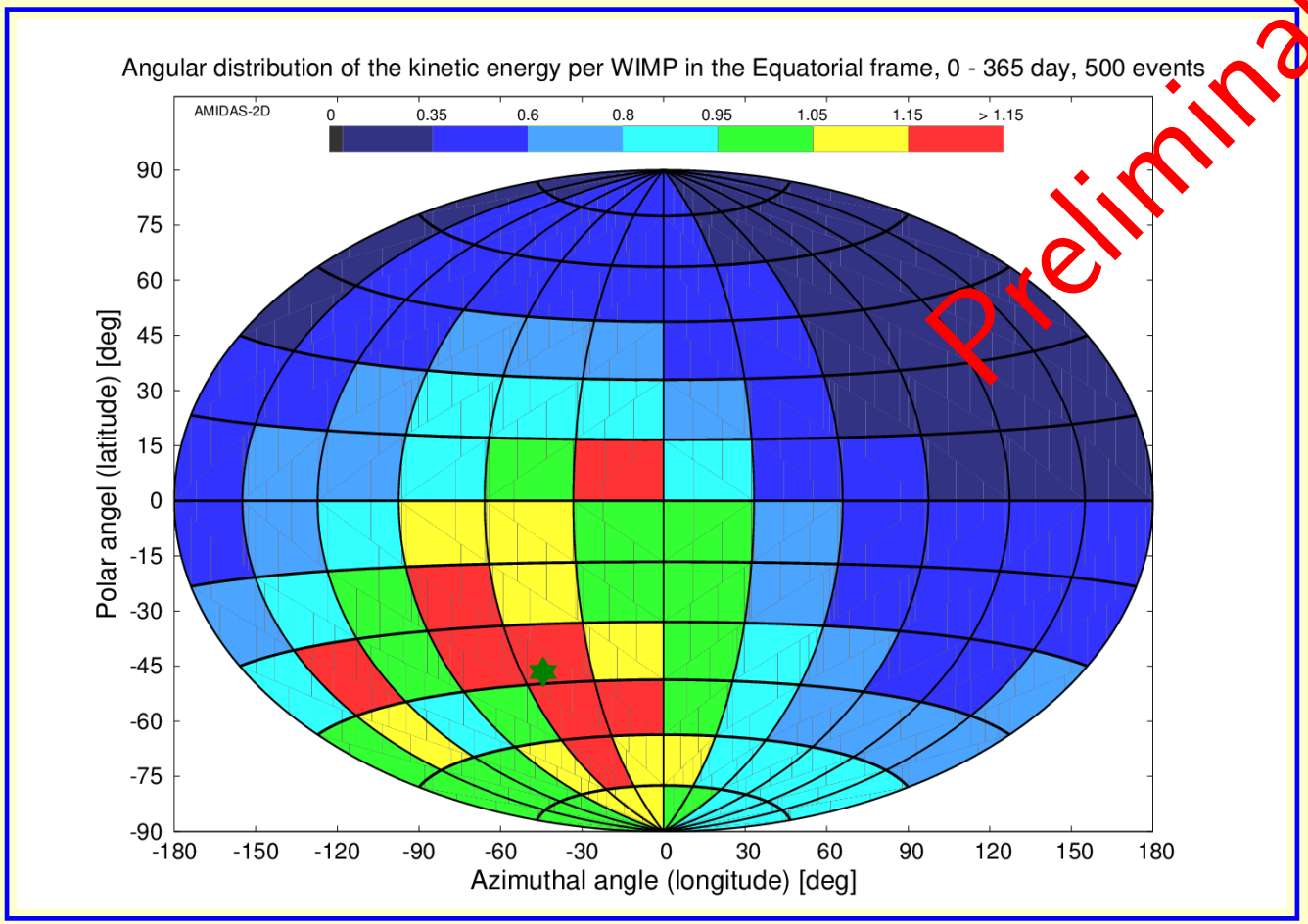
- Annual modulation of the angular distribution of the WIMP kinetic energy
  (Equatorial frame, four advanced seasons, 500 events)



[CLS, in finalization]

Angular distributions of the 3-D kinetic energy "per WIMP"

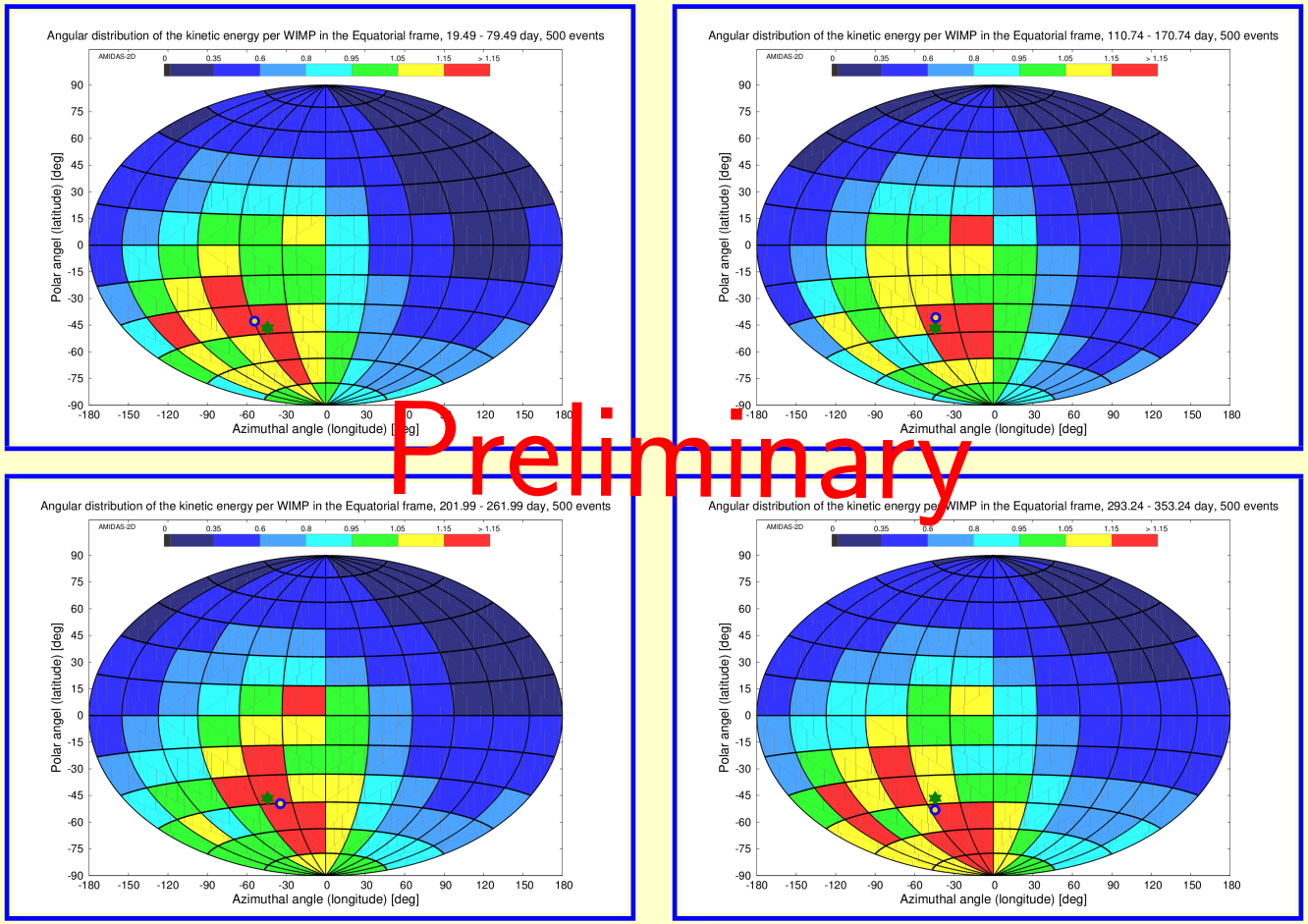
- Angular distribution of the kinetic energy per WIMP
  (Equatorial frame, 0 - 365 day, 500 events)



[CLS, in finalization]

Angular distributions of the 3-D kinetic energy "per WIMP"

- Annual modulation of the angular dist. of the kinetic energy per WIMP
  (Equatorial frame, four advanced seasons, 500 events)



[CLS, in finalization]

Summary

Summary

- Angular distribution of the 3-D WIMP velocity
  - ➢ The angular distribution patterns of the 3-D WIMP velocity would show a clear anisotropy (directionality)
  - **!?** The main direction of the WIMP velocity could somehow deviate from the theoretical prediction
  - ➢ The laboratory-(in)dependent annual modulations of the (main) direction of the WIMP velocity could be observed with a few tens of events in each season of a few tens of days (a few hundreds of total events per year)
  - ➢ The laboratory-dependent diurnal modulation of the (main) direction of the WIMP velocity could also be observed, with however much more ($\sim 3-6$ times) events

Summary

- Angular distribution of the 3-D WIMP velocity
  - The clockwise rotated annual modulation of the angular WIMP velocity distribution could be a second (important) characteristic for discriminating directional WIMP signals from any (unexpected) backgrounds with some specified incoming directions
  - The location-dependence of the annual/diurnal modulation of the angular WIMP velocity distribution could be seen clearly:
    - The 3/6-month difference (with the 180°-rotation around the center) for several pairs of underground laboratories [CLS, arXiv:1910.11763 (2019)]
    - The 12-hour shift in two observation periods with a half-year difference for each underground laboratory

Summary

- Moreover ...
  - The recorded 3-D velocity information of WIMP signals offered by different laboratories could be combined in all laboratory-independent (Galactic, Ecliptic, Equatorial, and Earth) coordinate systems

Thank you very much for your attention!