Ring-like and aberration patterns in directional dark matter detection

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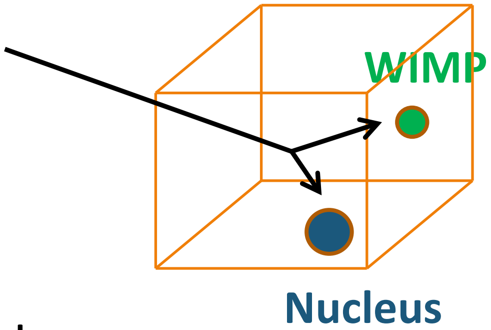
Based on work done with Graciela Gelmini and Paolo Gondolo

Direct dark matter detection

- Direct dark matter (DM) experiments look for energy deposited within detectors by the scattering of Weakly Interacting Massive Particles (WIMPs) in the dark halo of our galaxy.
  - Many experiments: **DAMA, XENON, CDMS, CoGeNT, CRESST, Edelweiss, ZEPLIN, LUX...**
- WIMPs interact with nuclei and produce:
  - **phonons, scintillation, or ionization**



- Dark matter signatures in non-directional detectors:
  - **Annual modulation** of the signal due to the motion of the Earth around the Sun.
  - **Daily modulation** due to the spinning of the Earth around its axis.

DM signatures in directional detection

- **Directional DM detectors**: measure the recoil direction
  - **DRIFT, DMTPC, NEWAGE, MIMAC** (using **CS_2**, **CF_4**, or **^{3}He**)
- The detector is moving with velocity $\mathbf{V}_{\rm lab}$ with respect to the Galaxy.
- If the particles in the dark halo of our galaxy are on average at rest with respect to the Galaxy, the average velocity of the dark matter particles with respect to the detector is $-\mathbf{V}_{\rm lab}$.
- Two DM signatures easiest to detect in directional detectors:
  - **Departure from isotropy** of the recoil directions with respect to the Galaxy: **~10 events** ***(Morgan, Green, Spooner, 2005)***.
  - **An average recoil direction**, expected to be in the direction of $-\mathbf{V}_{\rm lab}$: **~30 events** ***(Green, 2010)***.

Studying the WIMP properties

$180\ \mathrm{km/s} < V_{\mathrm{lab}} < 340\ \mathrm{km/s}$? , $170\ \mathrm{km/s} < \sigma_v < 300\ \mathrm{km/s}$?

- WIMP velocity distribution determination:
  - V_{lab} : 100 events with 100 km/s error ***(Lee & Peter, 2012)***
  - σ_v : 100 events with 100 km/s error ***(Lee & Peter, 2012)***, ~700 events with error ~20 km/s ***(Billard, Mayet, Santos, 2011)***
- Two novel features in directional detection:
  - **A ring of maximum recoil rate around the average arrival direction of WIMPs:** can be used as a secondary indication of DM (100s of events); additional indication of mass (1000 events); testing the shape of the velocity distribution.
  - **Aberration:** can be used to determine V_{lab} and σ_v (1000 events).

Novel directional detection features:

- Ring-like features [arXiv:1111.6361]
- Aberration features [arXiv:1205.2333]

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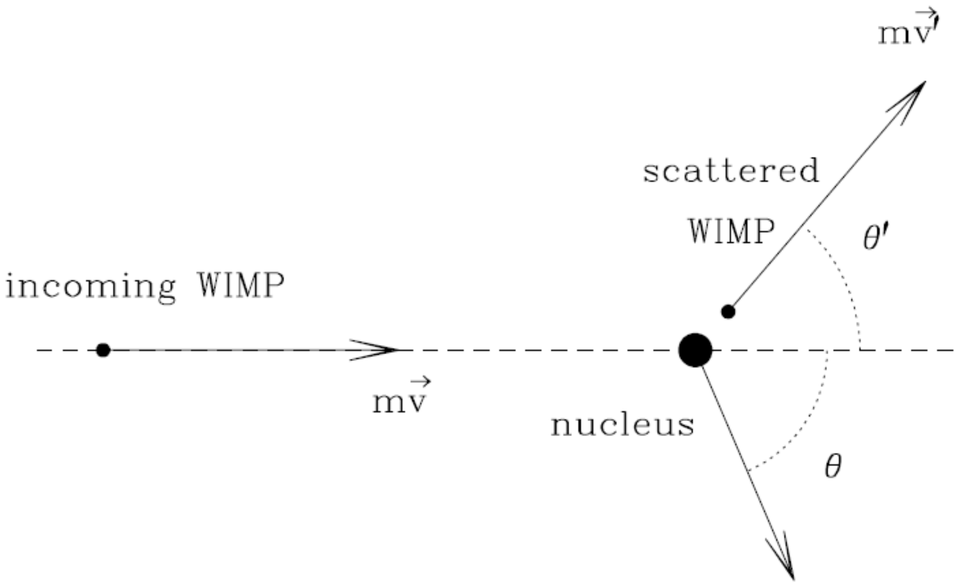
What we need

- Consider the WIMP-nucleus elastic collision for a WIMP of mass m and a nucleus of mass M.



recoil direction $\vec{q}$

From Gondolo 2002, Phys. Rev. D 66, 103513

Angular distribution of recoil directions

- The differential recoil spectrum is written in terms of the “Radon transform” of the WIMP velocity distribution ***(Gondolo 2002, Phys. Rev. D 66, 103513)***:

$$\frac{dR}{dE_R\, d\Omega_q} = \frac{\rho\sigma_0 S(q)}{4\pi m\mu^2}\hat{f}_{\rm lab}\left(\frac{q}{2\mu}, \hat{\mathbf{q}}\right)$$

- For a Maxwellian distribution:

$$\hat{f}_{\rm lab}\left(\frac{q}{2\mu}, \hat{\mathbf{q}}\right) = \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left\{-\frac{\left[(q/2\mu)+\hat{\mathbf{q}}.\mathbf{V}_{\rm lab}\right]^2}{2\sigma_v^2}\right\}$$

- We need to orient the nuclear recoil direction $\hat{\mathbf{q}}$ with respect to $\mathbf{V}_{\rm lab}$ ⇒ write the transformations from the lab frame to the Galactic reference frame with the rotation of the Earth included.

Ring of maximum recoil rate

- For **heavy enough WIMPs** and **low enough recoil energies**, the maximum of the recoil rate is not in the direction of the average WIMP arrival direction but in a ring around it.

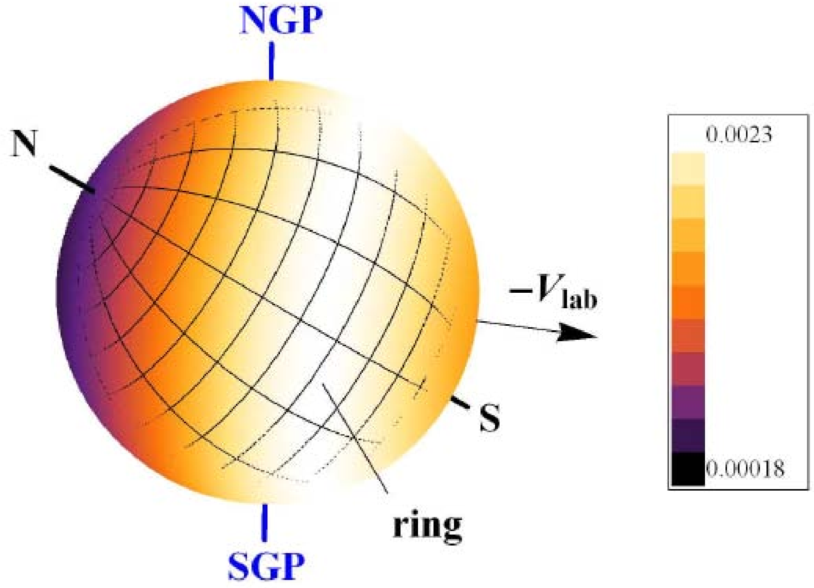
$$\hat{f}_{\rm lab}\left(\frac{q}{2\mu},\hat{\mathbf{q}}\right) = \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left\{-\frac{\left[(q/2\mu)+\hat{\mathbf{q}}.\mathbf{V}_{\rm lab}\right]^2}{2\sigma_v^2}\right\}$$

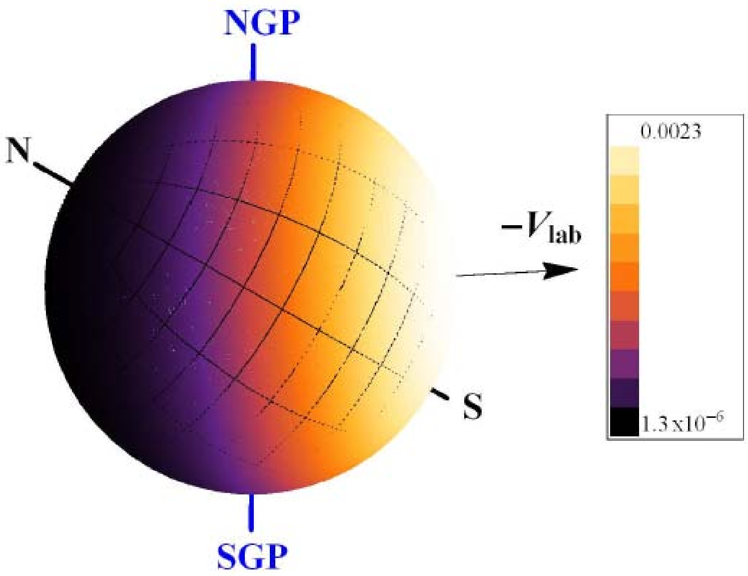
v_q : min WIMP speed required to impart a recoil momentum q

- If $v_q < V_{\rm lab}$, the maximum of $\hat{f}_{\rm lab}$ happens at: $-\hat{\mathbf{q}}.\mathbf{V}_{\rm lab} = v_q$
- Max of $\hat{f}_{\rm lab}$ is on a ring around $-\mathbf{V}_{\rm lab}$.
- The ring is visible when $\hat{f}_{\rm lab}$ is plotted on a sphere of recoil directions.

Ring of maximum recoil rate **(Sulfur recoils)**

$m = 100$ GeV

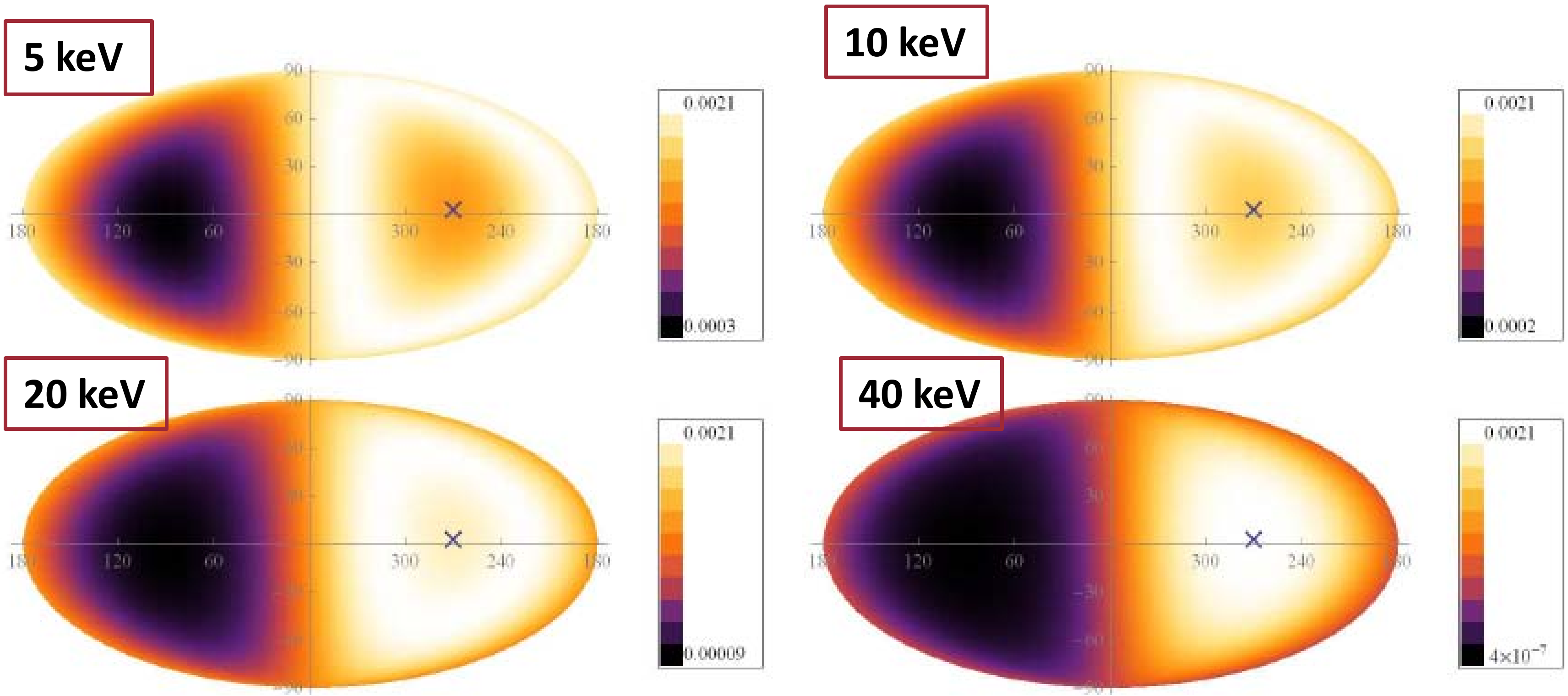




- $\hat{f}_{\text{lab}}$ in December
- $E_R = 5$ keV

- $\hat{f}_{\text{lab}}$ in June
- $E_R = 40$ keV

Ring-like features



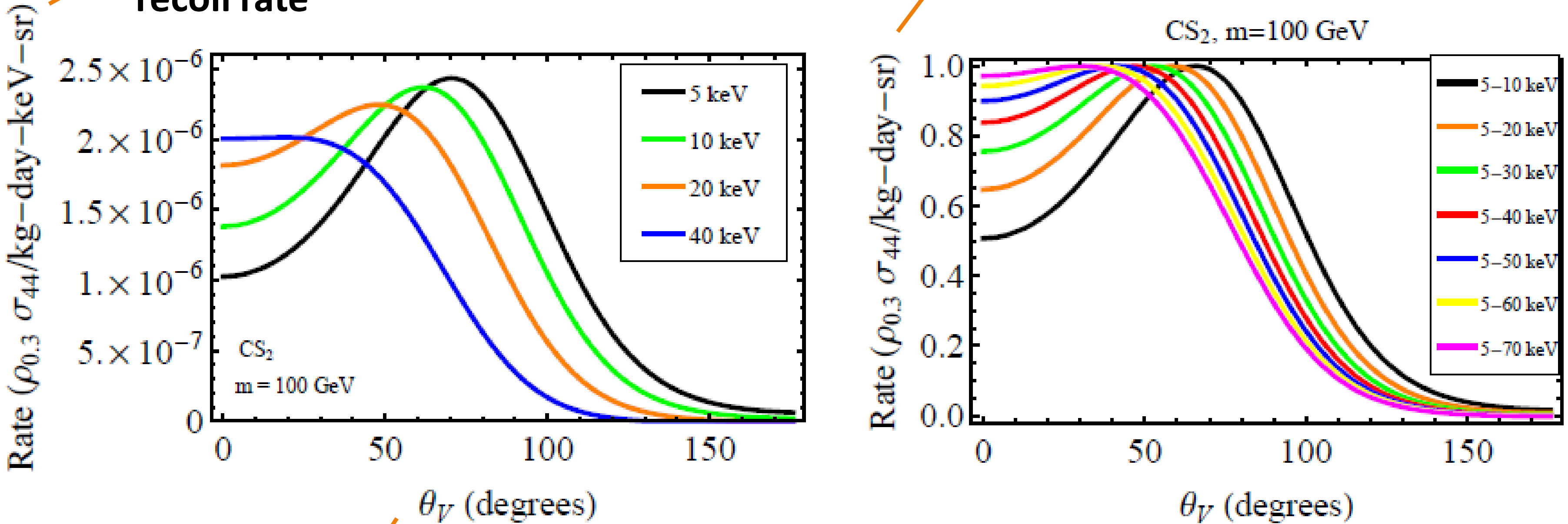
- $\hat{f}_{\rm lab}$ for sulfur recoils in June
- $m = 100$ GeV

Mollweide equal-area projection maps of the celestial sphere in Galactic coordinates

Ring-like features

Directional differential recoil rate

Energy-integrated directional recoil rate

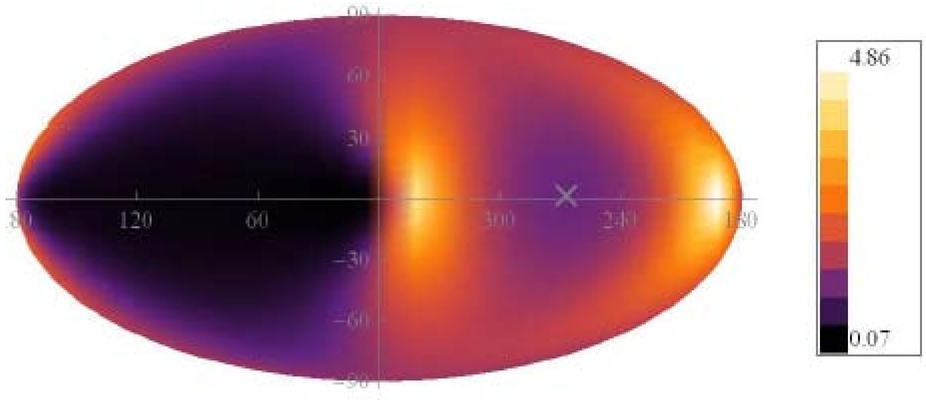


Polar angle measured from $-\mathbf{V}_{\rm lab}$

- With 100's of events we could detect the ring, which would be a secondary indicator of dark matter.

Ring-like features in anisotropic models

- The ring-like feature persists with different characteristics in an anisotropic logarithmic-ellipsoidal halo model.



- The ring is still circular with constant radius at any azimuthal angle around $-\mathbf{V}_{\mathrm{lab}}$, but the value of the rate at the maximum depends on the azimuthal angle.
- Thus the ring-like feature can give information on the WIMP velocity distribution.

Novel directional detection features:

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Aberration features

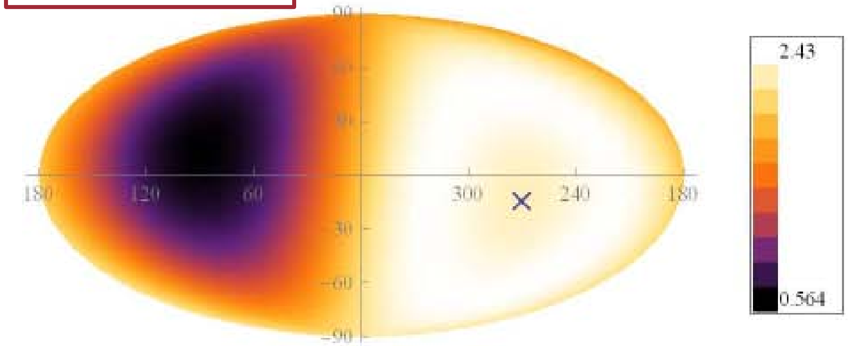
- The motion of the Earth around the Sun causes an annual change in the ***magnitude*** and ***direction*** of the arrival velocity of dark matter particles on Earth.
- Change in **magnitude** → annual modulation in non-directional direct DM detection.
- Change in **magnitude** ***and*** **direction** → aberration.
- Aberration features depend on the **orbital velocity of Earth** and the **WIMP velocity distribution**. Knowing the former, WIMP aberration can give information on the latter.
- Observing the full aberration pattern may require very large detectors.
- Annual modulation of the rate over some solid angles may be detectable with moderately large exposures.

Aberration features

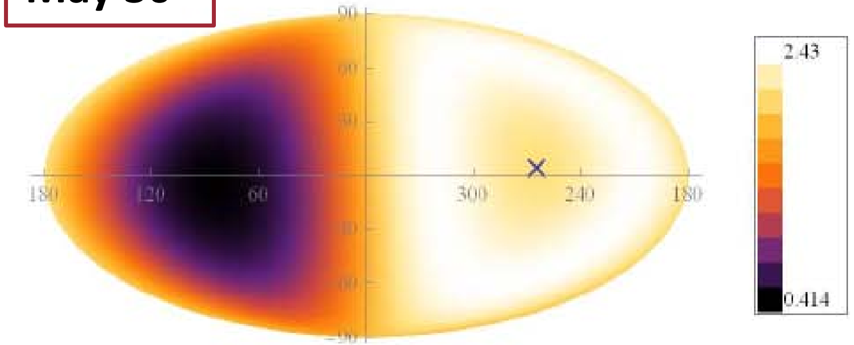
- Directional differential recoil rate in CS_2

$$m = 100 \text{ GeV}$$
$$E_R = 5 \text{ keV}$$

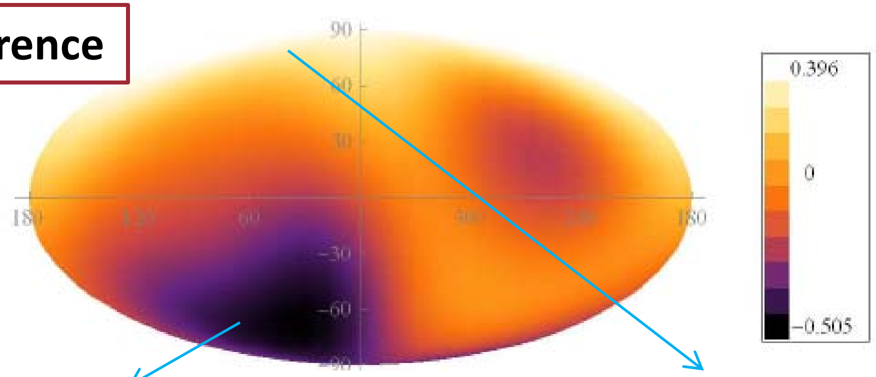
December 1



May 30



May-Dec difference



Negative, SGH

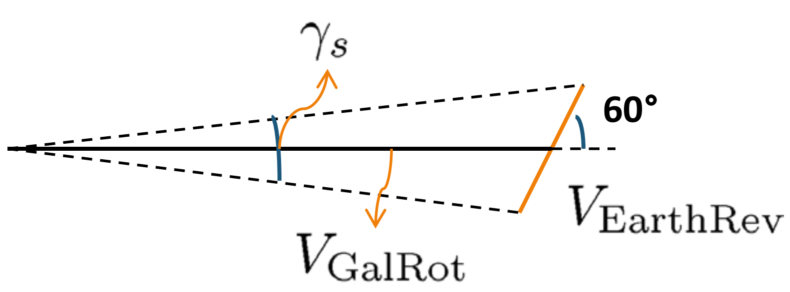
Positive, NGH

Maximal angular variation in direction $-\mathbf{V}_{\text{lab}}$

- After having obtained a dark matter signature, the next goal will be to study the WIMP properties (e.g. its local velocity distribution).
- The largest uncertainty in $\mathbf{V}_{\text{lab}}$ is due to our uncertain knowledge of the velocity of the Galactic rotation, $\mathbf{V}_{\text{GalRot}}$.

How to measure V_{GalRot} ?

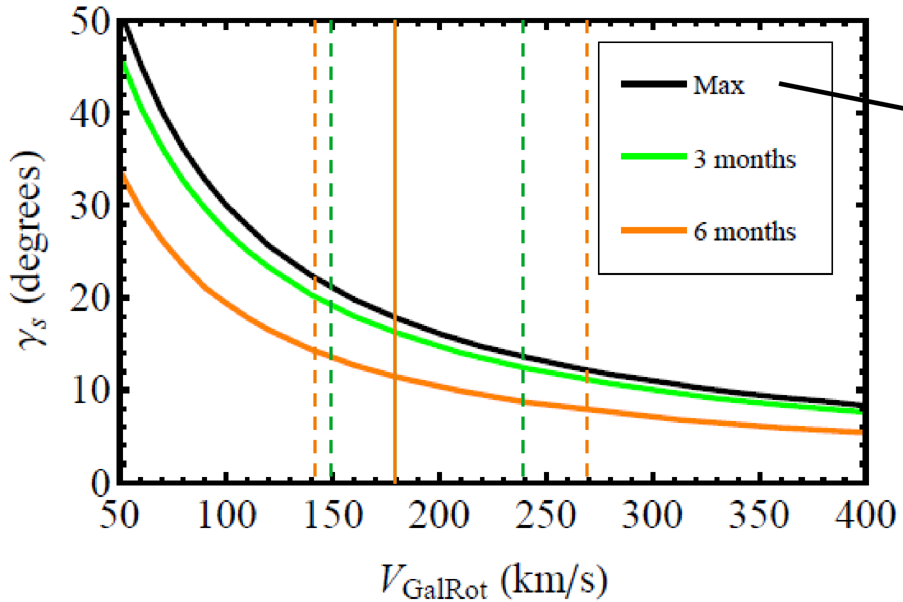
- We can use the change in the mean recoil directions in a year to measure V_{GalRot} .



$$\gamma_s \sim \frac{V_{\text{EarthRev}}}{V_{\text{GalRot}}}$$

Maximal angular variation in direction $-\mathbf{V}_{\rm lab}$

Maximal angular separation between the mean recoil directions in a year



Difference between the directions in March and September

- An order of 1000 events needed to measure the mean recoil direction with an error of a few degrees.
- Assuming an error of $\Delta\gamma_s = 3.5°$, $V_{\rm GalRot}$ would be 180^{+60}_{-30} km/s using the 3 month average and 180^{+90}_{-40} km/s using the 6 months average.

Galactic Hemisphere Annual Modulation

- We can integrate the directional differential rate over the recoil directions pointing to ***half of the sky*** and define the **G**alactic **H**emisphere **A**nnual **M**odulation (**GHAM**).
- Choosing well the hemisphere, the GHAM amplitude is larger than the usual annual modulation amplitude, thus easier to detect.
- Integrate over direction:

$$\Delta\left(\frac{dR}{dE_R}\right) = \frac{dR_{\max}}{dE_R} - \frac{dR_{\min}}{dE_R} = \int \left(\frac{dR_{\max}}{dE_R\, d\Omega_q} - \frac{dR_{\min}}{dE_R\, d\Omega_q}\right) d\Omega_q$$

- Integrate over energy:

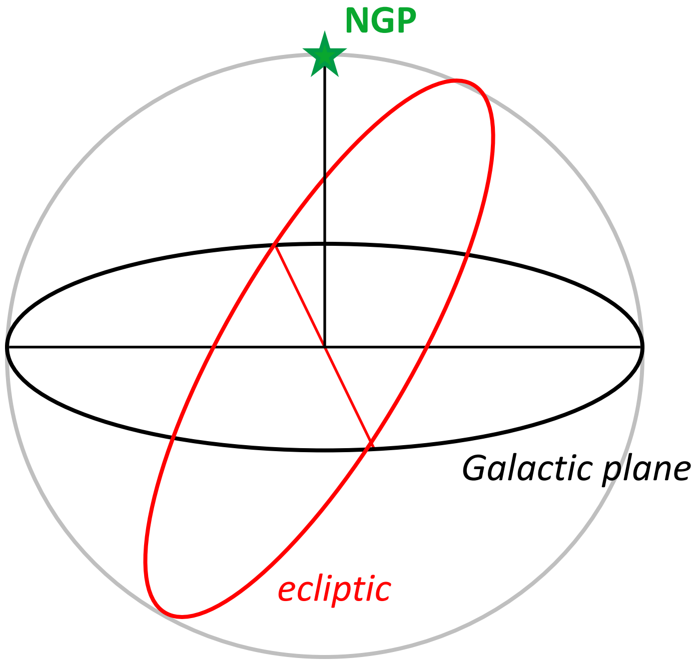
$$\Delta R = R_{\max} - R_{\min} = \int_{E_1}^{E_2} \Delta\left(\frac{dR}{dE_R}\right) dE_R$$

Maximum GHAM amplitudes

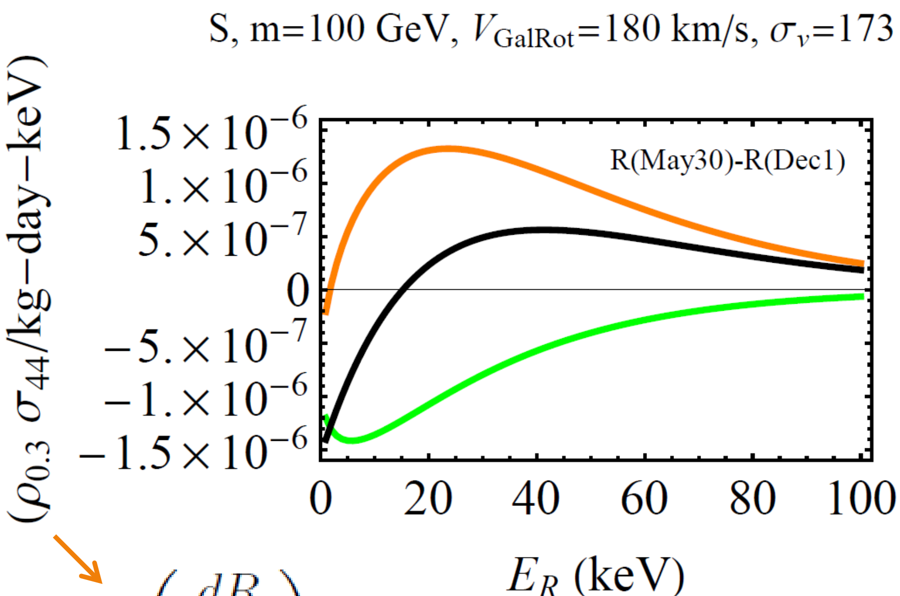
- Galactic hemispheres with the largest GHAM are divided by planes that are perpendicular to the Earth's orbit around the Sun (in particular when $V_{\rm lab}$ is max and min).

- The orbital velocity $\mathbf{V}_{\rm EarthRev}$ points to one hemisphere at some time and away from it half a year later.

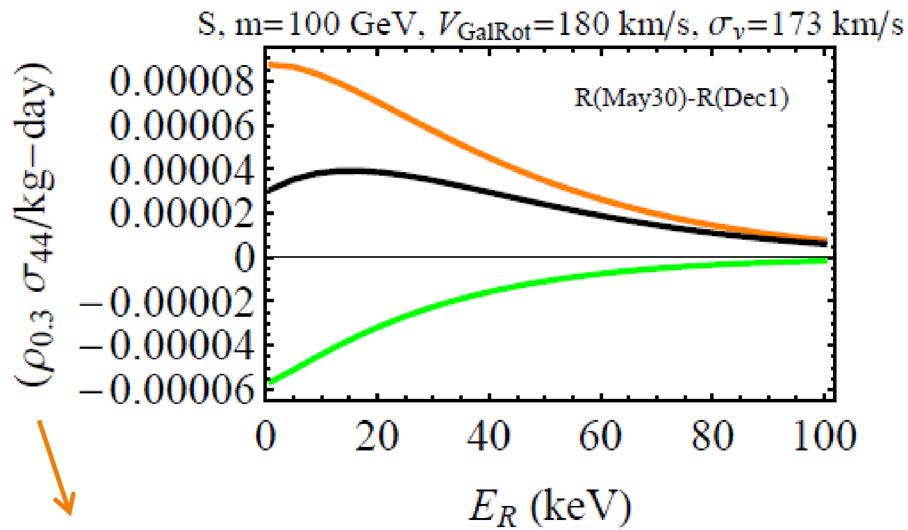
- **Two complimentary hemispheres with max GHAM:** in one the rate is max when $V_{\rm lab}$ is max, and min when $V_{\rm lab}$ is min, and in the other the opposite is true.



Maximum GHAM amplitudes



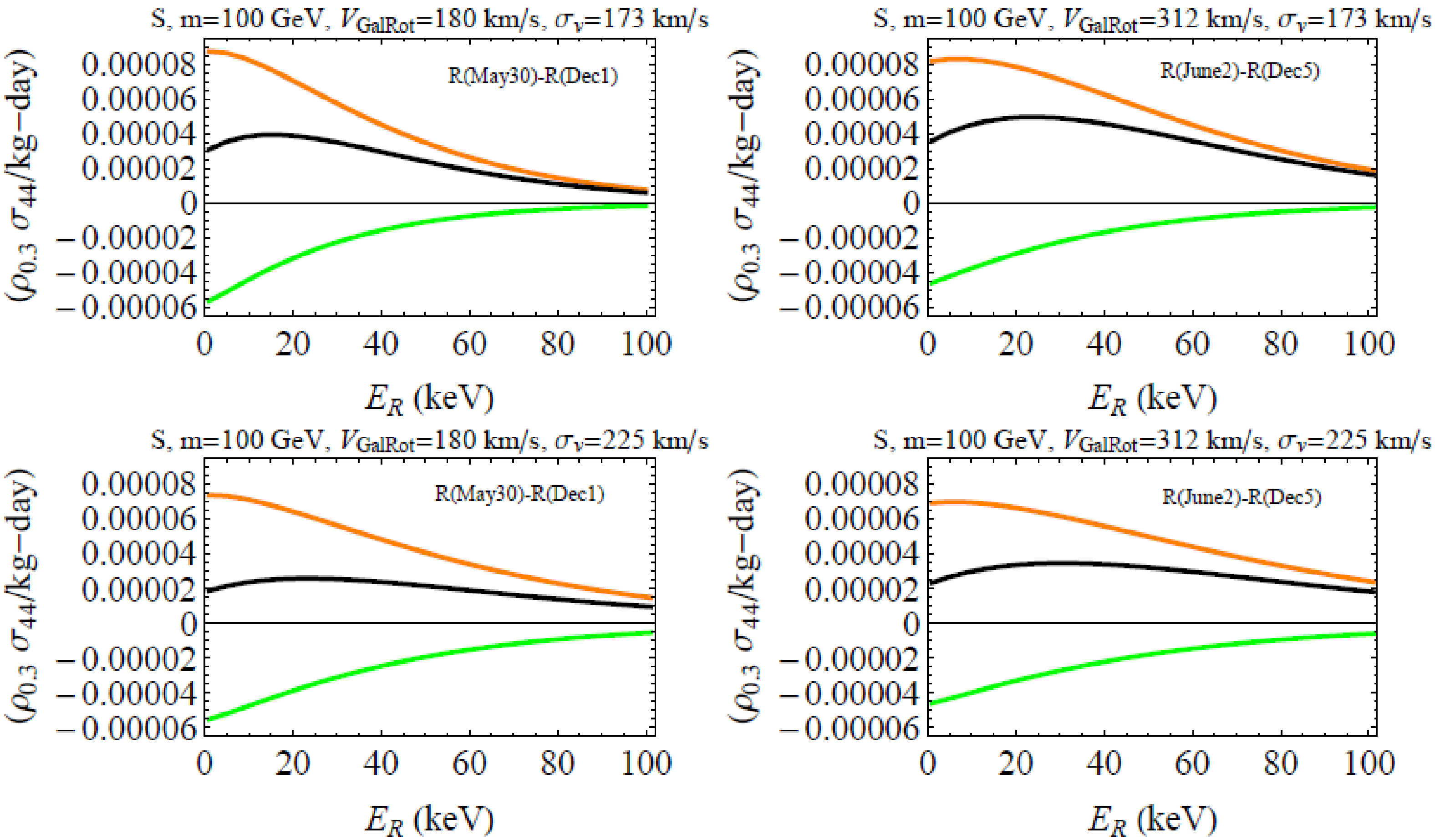
$$\Delta\left(\frac{dR}{dE_R}\right)$$



Annual modulation amplitude ΔR of the rate integrated above E_R

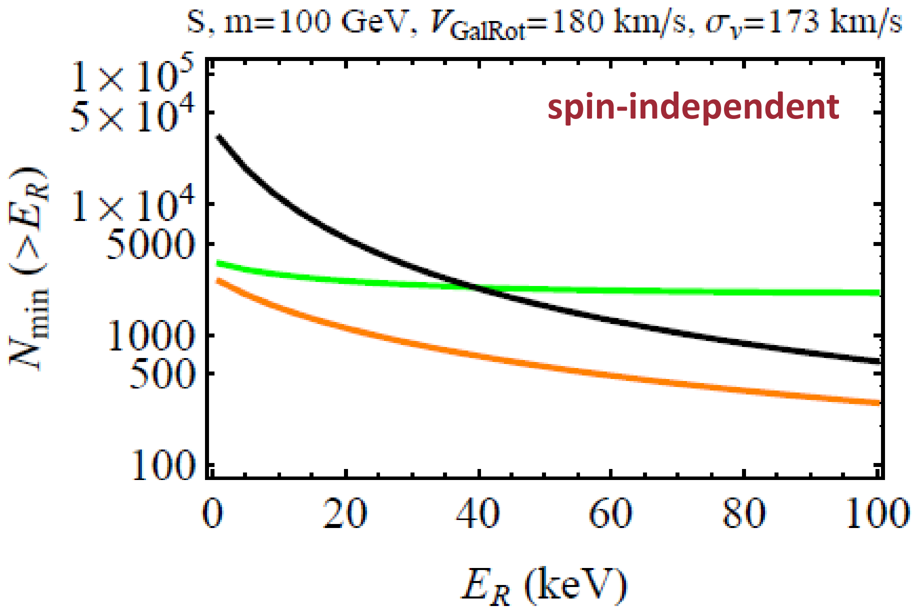
- We find that both GHAM amplitudes are larger than the usual non-directional annual modulation which is the sum of the two.

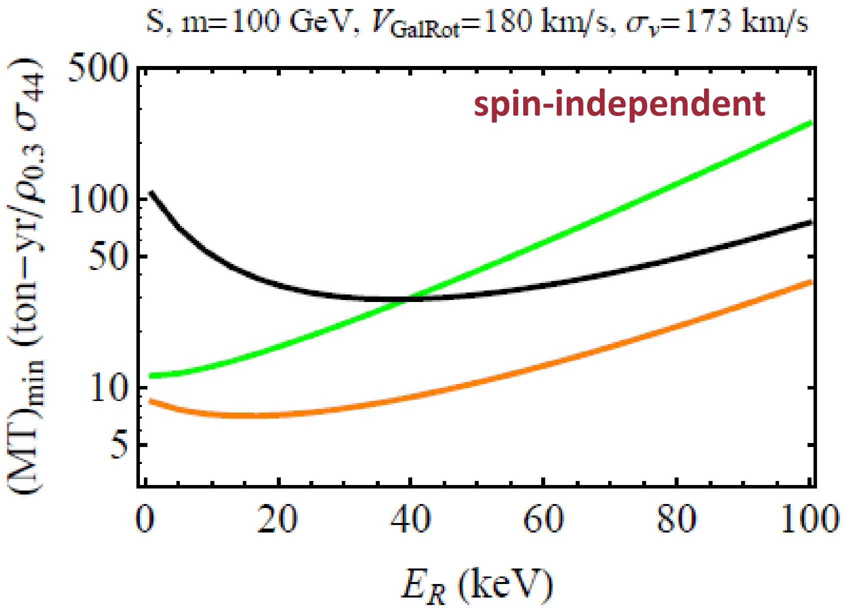
Maximum GHAM amplitudes



- GHAM amplitudes depend strongly on the average velocity and velocity dispersion.

Test of detectability of the GHAM

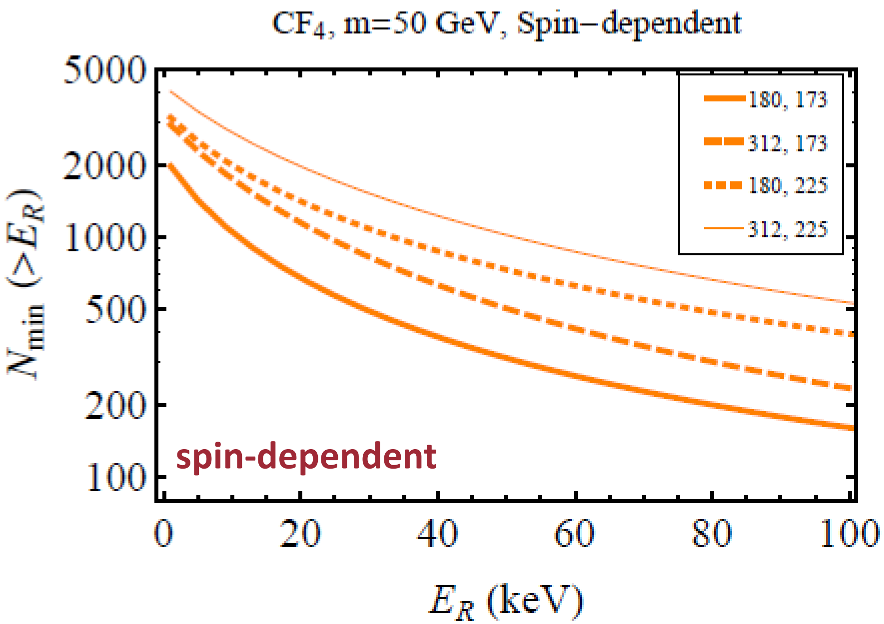


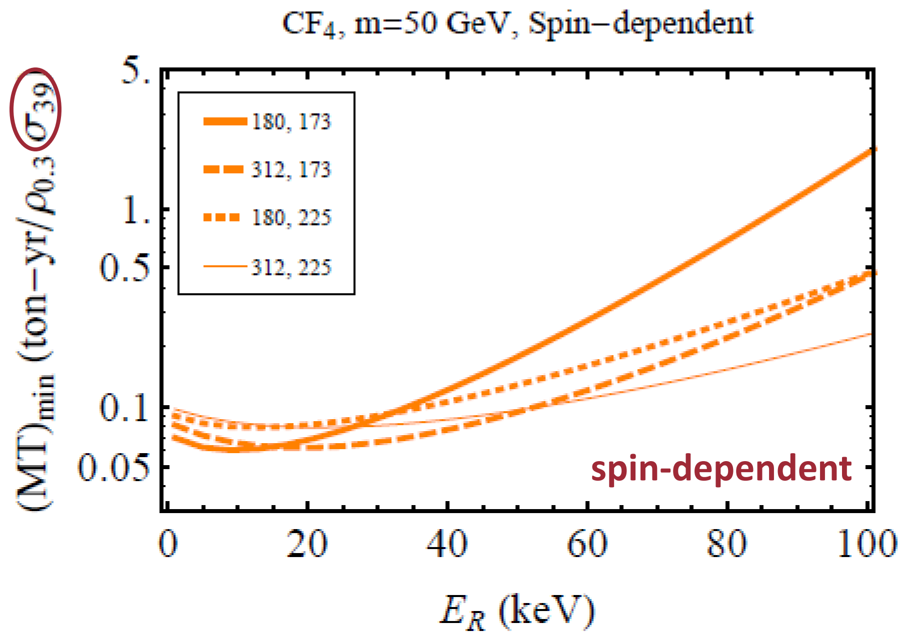


- Combination of low V_{GalRot} and σ_v gives the smallest min number of events.
- One needs a minimum of a few 1000 events to observe the largest GHAM amplitude and at least 10 times more to observe the usual annual modulation in **Sulfur**.

Test of detectability of the GHAM

$\sigma_p^{SD} = 10^{-39}\ \mathrm{cm}^2$





- One needs between a few 100 and a few 1000 events to observe the largest GHAM amplitude in the spin-dependent rate in **CF_4**. The min exposure needed is between 0.06 ton-yr and a few ton-yr.

Summary

- **Ring**: at low recoil energies and for heavy enough WIMPs, the maximum of the recoil rate is not in the direction of $-\mathbf{V}_{\rm lab}$, but on a ring around it.
  - **Secondary signature of dark matter (at least x5 events than others).**
  - **Could be used to test the WIMP velocity distribution.**
- **Aberration**: features in recoil directions due to the Earth's rotation around the Sun. With more than 1000 of events one can determine:
  - **The annual change of direction of $\mathbf{V}_{\rm lab}$:** to determine $V_{\rm GalRot}$.
  - **The Galactic Hemisphere Annual Modulation (GHAM):** to determine σ_v and $V_{\rm GalRot}$. Max GHAM amplitudes larger than the usual annual modulation amplitude by factors 2-3 at low energies.

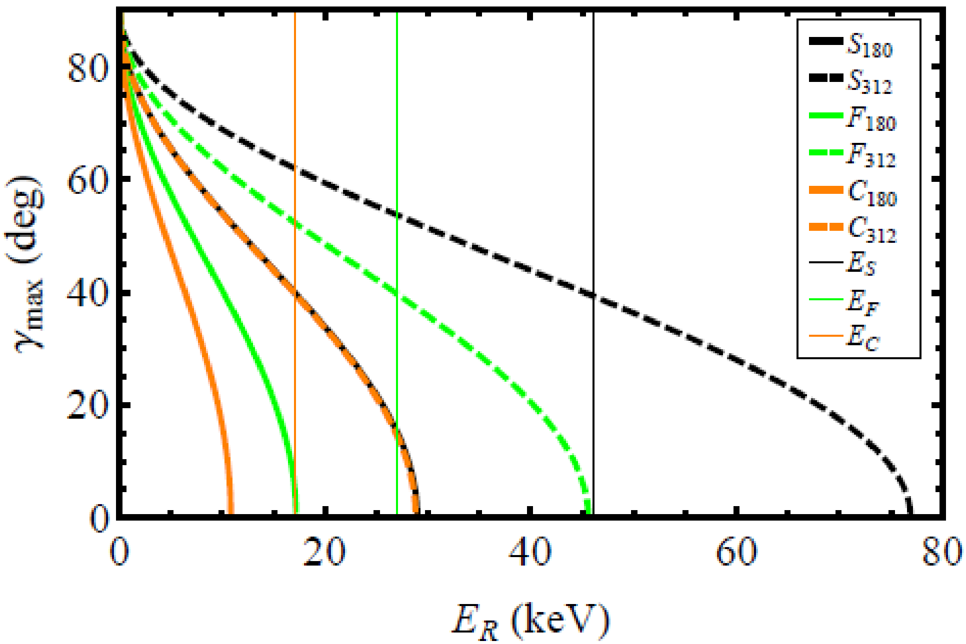
➢ More work is necessary to determine how best the aberration features could be used to extract the characteristics of the WIMP velocity distribution.

Additional

Maximum ring radius

- The maximum possible ring radius is obtained when

$\mu = M$ as $m \gg M$



$$\cos\gamma_{\max} = \sqrt{\frac{E_R}{2MV_{\rm lab}^2}}$$

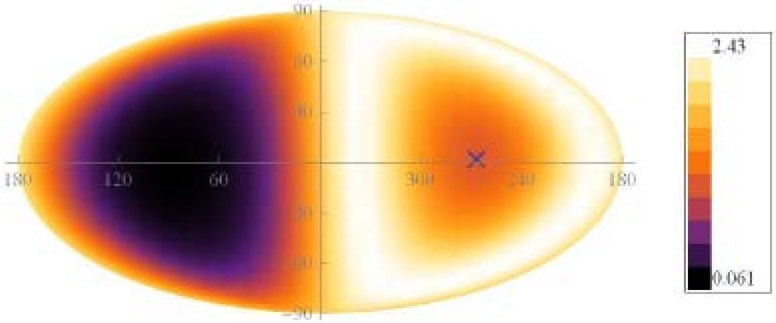
There can be no ring if:

$$E_R > 2MV_{\rm lab}^2$$

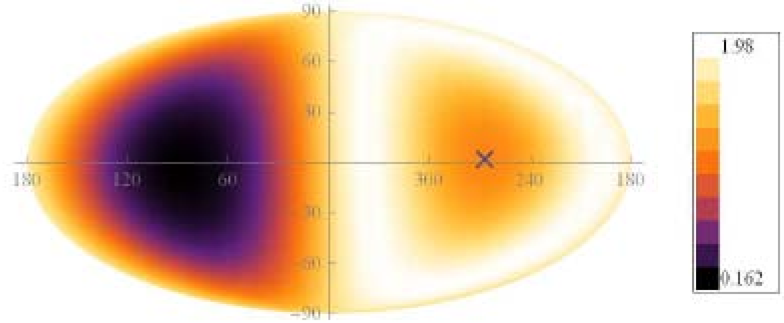
NB, G. Gelmini and P. Gondolo, arXiv:1111.6361

Ring-like features

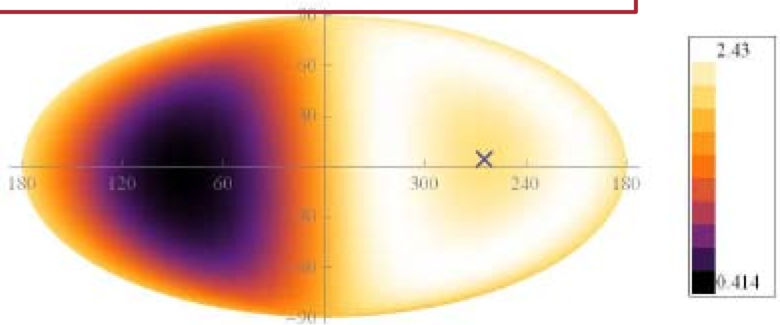
$V_{\mathrm{GalRot}} = 312\ \mathrm{km/s}$, $\sigma_v = 173\ \mathrm{km/s}$



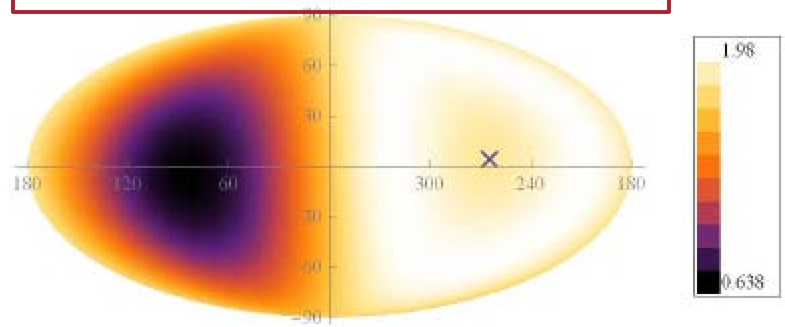
$V_{\mathrm{GalRot}} = 312\ \mathrm{km/s}$, $\sigma_v = 225\ \mathrm{km/s}$



$V_{\mathrm{GalRot}} = 180\ \mathrm{km/s}$, $\sigma_v = 173\ \mathrm{km/s}$



$V_{\mathrm{GalRot}} = 180\ \mathrm{km/s}$, $\sigma_v = 225\ \mathrm{km/s}$



- Directional recoil rate for sulfur.
- $m = 100$ GeV

Mollweide equal-area projection maps of the celestial sphere in Galactic coordinates