Signatures in Directional Dark Matter Searches
Asymmetries and the Diurnal Variation

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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο
ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ
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ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

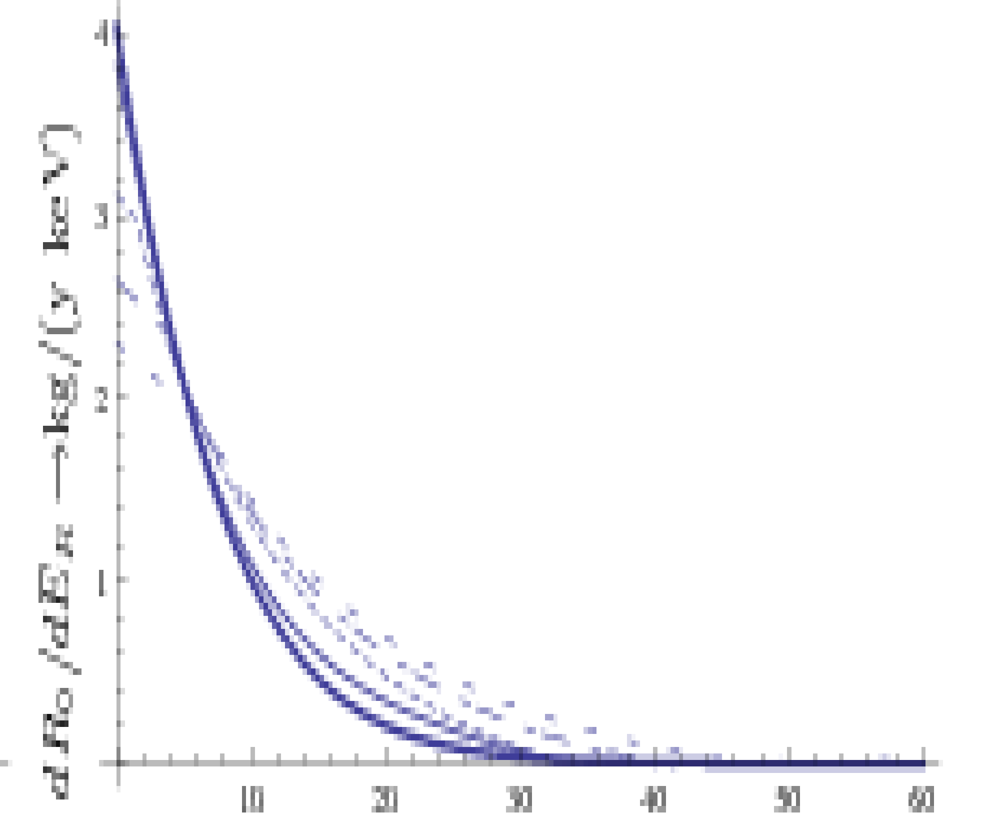
Windows on the Universe
Quy Nhon, Aug. 14, 2013

The Direct Detection of Dark Matter

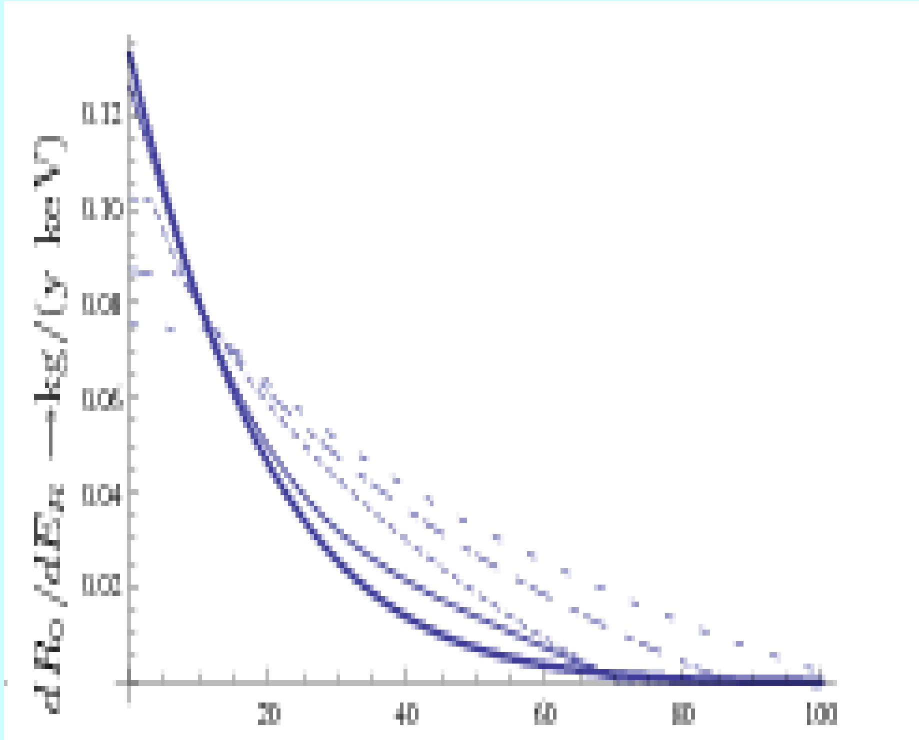
- Is crucial to both particle physics and cosmology
- The standard experiments attempt to measure the energy of the recoiling nucleus
- These experiments are hard to analyze since the sought signature cannot be distinguished from the background
- The backgrounds are formidable for the expected low counting rates
- So ingenious experimental approaches are needed

Differential (time averaged) event rates cannot be distinguished from background, e.g. for WIMP mass of 30 GeV, as functions of the recoil energy in keV, and $\sigma_{p,\chi}=10^{-7}$ pb we get:

Heavy Nucleus, e.g. ^{127}I



Light Nucleus, e.g. ^{19}F



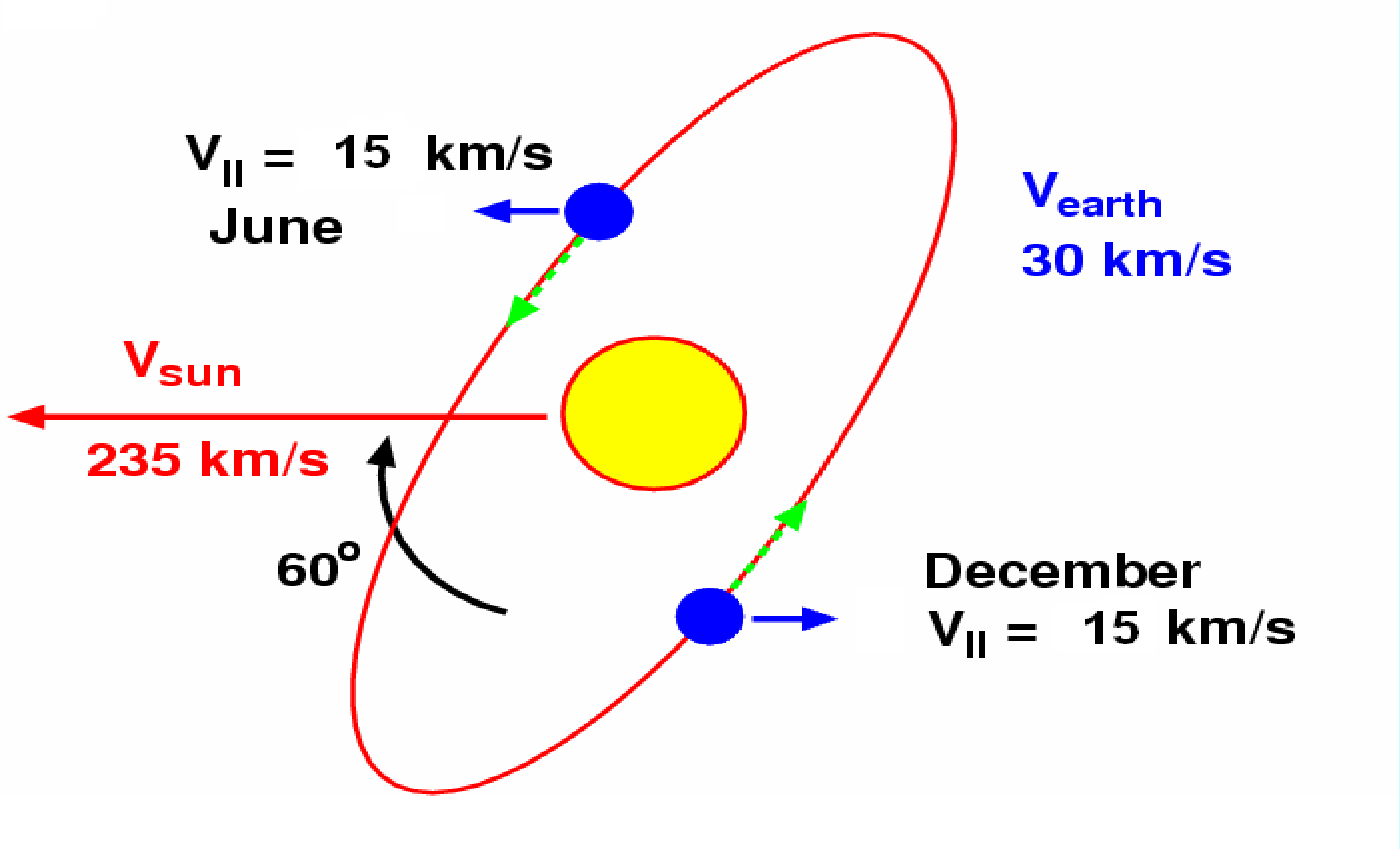
Novel approaches: Exploitation of other signatures of the reaction

- The modulation effect: The seasonal, due to the motion of the Earth, dependence of the rate.
- Detection of other particles (electrons, X-rays), produced during the LSP-nucleus collision
- The excitation of the nucleus (in some cases : heavy WIMP, low excitation energy etc.) and detection of the subsequently emitted de-excitation γ rays.
- Asymmetry measurements in directional experiments (the direction of the recoiling nucleus must also be measured)->DIURNAL VARIATION.

Fortunately the rate depends on the relative velocity:

V_{June}= 235+15=250km/s; V_{Dec}= 235-15=220km/s;

-> Modulation Effect (time dependence)



II: THE MODULATION EFFECT (standard recoil experiments)

- The total Rate is parametrized as:
- $R=R_0\,(1+h\cos\alpha)$

(α is the phase of the Earth; α=0 around June 3nd)

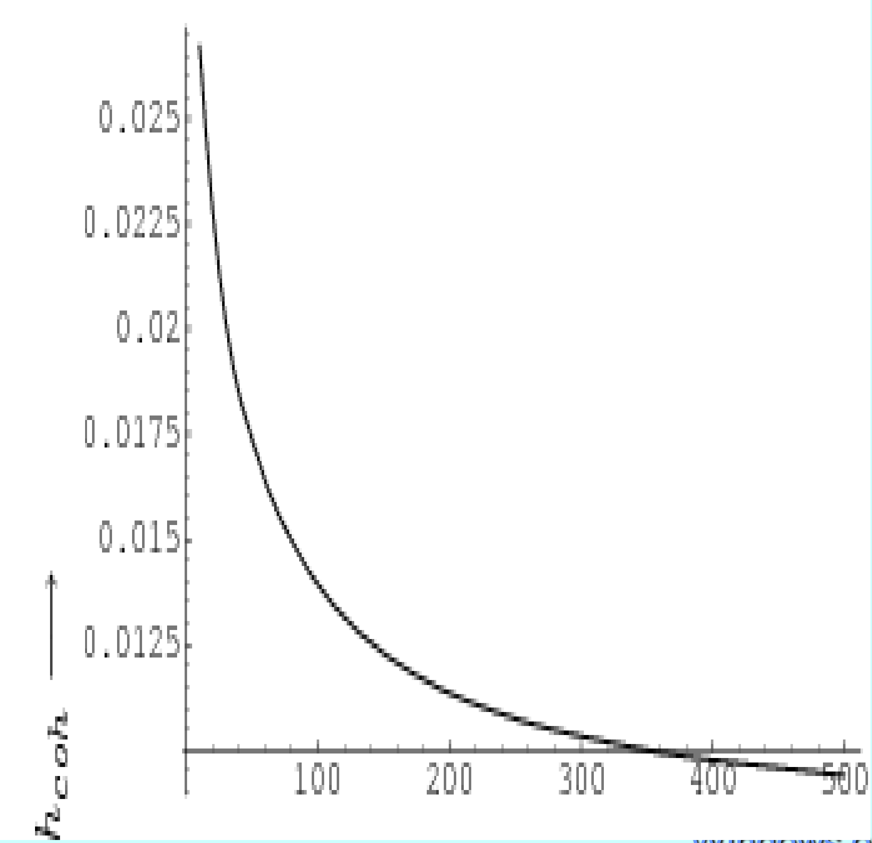
- h=modulation amplitude.
- R_0 =time averaged rate.
- The relative difference between the minimum and the maximum is 2h
- The location of the maximum depends on the sign of h

Iia: The Modulation amplitude

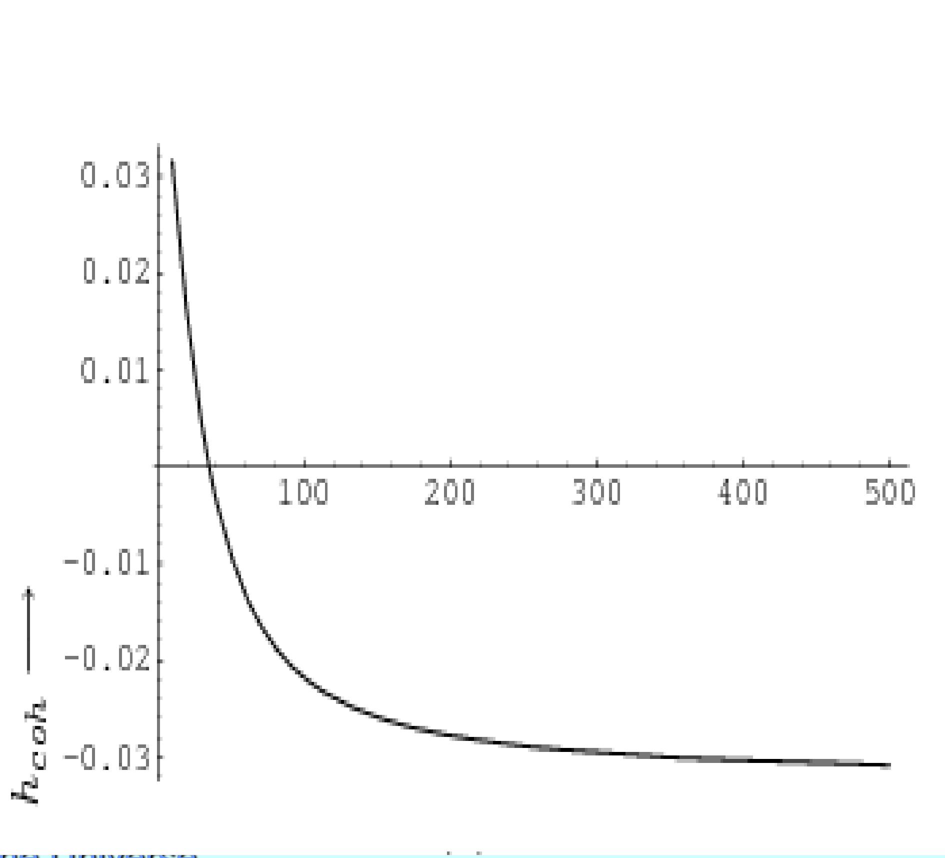
(As a function of WIMP mass in GeV). It is small.

Note its sign for large reduced mass

Light System (e.g. A=32, A=19)



Heavy system (e.g. A=127)



B:Directional Experiments (Review: S. Ahlen et al, arXiv:0911.0323, F Mayet et al arXiv:1001.2983) D. Santos, LTPC Conference, Paris Dec. 17, 2012

- Measure the energy and direction of the recoiling nucleus
- They require track reconstruction of recoiling nuclei down to a few keV (preferably 3D reconstruction)
- Candidates:

- DM-TPC, NEWAGE, DRIFT :low pressure gaseous detectors CF_4 , CS_2 , C_4H_{10}+^{3}He <->dE/dx <->head-tail problem
- μTPC detectors (MIMAC): Low threshold, good 3D reconstruction of 3 mm tracks with gas ^{3}He +CF_4
- Most recently DNA detectors (A. Drukier & K. Freese): Easy 3-D reconstruction. Can use heavy target, e.g. Au.

E: Directional Experiments*

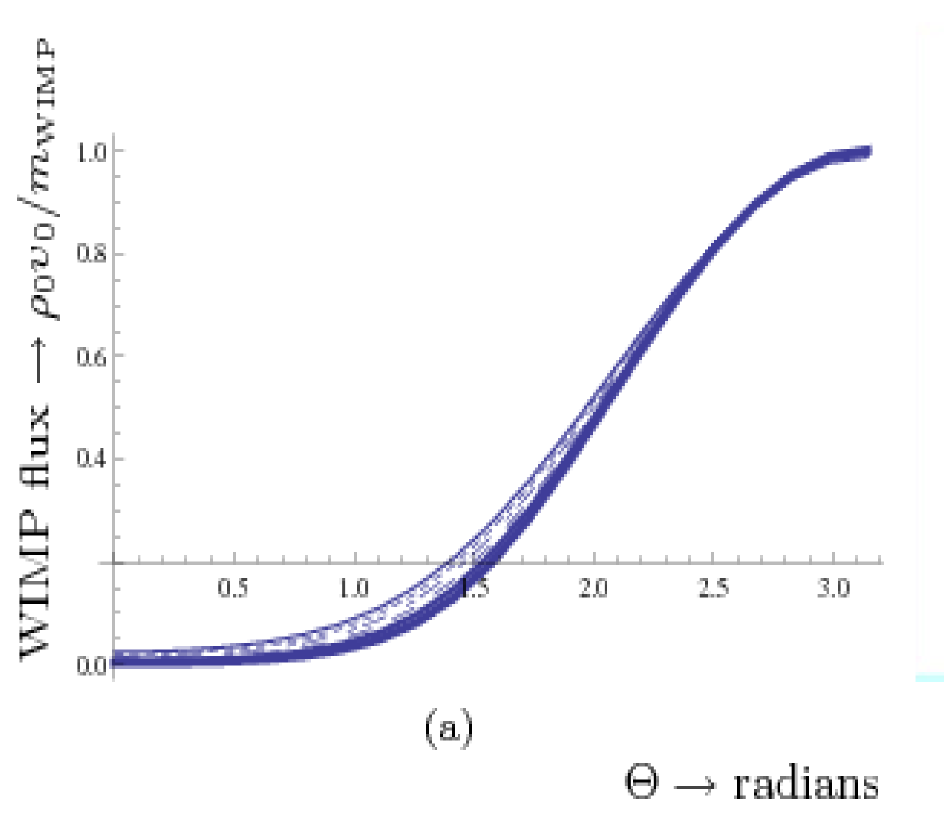
Assuming that such experiments become feasible we will show that the observed events:

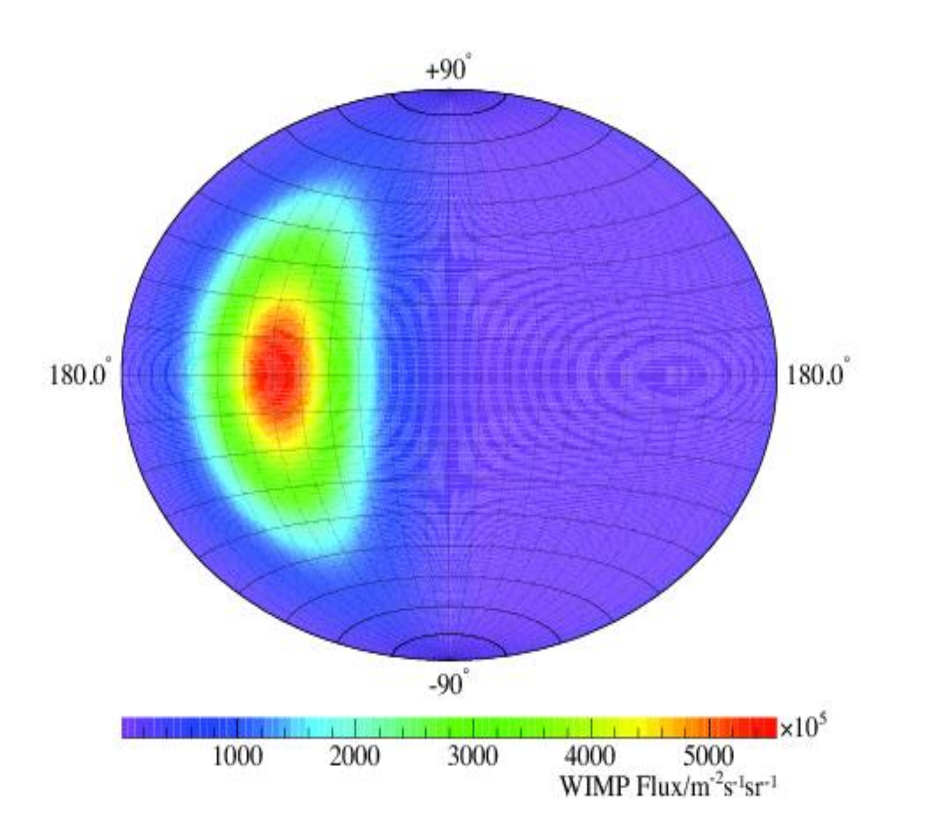
- Will exhibit asymmetry due to the motion of the Sun
- On top of this they will exhibit characteristic large annual modulation due to the annual motion of the Earth
- Both of these will exhibit periodic diurnal variation due to the rotation of the Earth.
- * DM-TPC, NEWAGE, DRIFT, MIMAC (Review: S. Ahlen et al, arXiv:0911.0323)
- *Also gaseous μTPC detectors (arXiv:1001.2983 (atro-ph.CO)

WIMP flux,"The solar wind" (signal towards the Cygnus constellation), Spergel (88), vergados (02), Morgan-Green-Spooner (04), Battat et al (IJMP A, 2009) Bozorgnia, Gelmini, Gondolo (2012).

Flux variatio*n (MB distr.)*

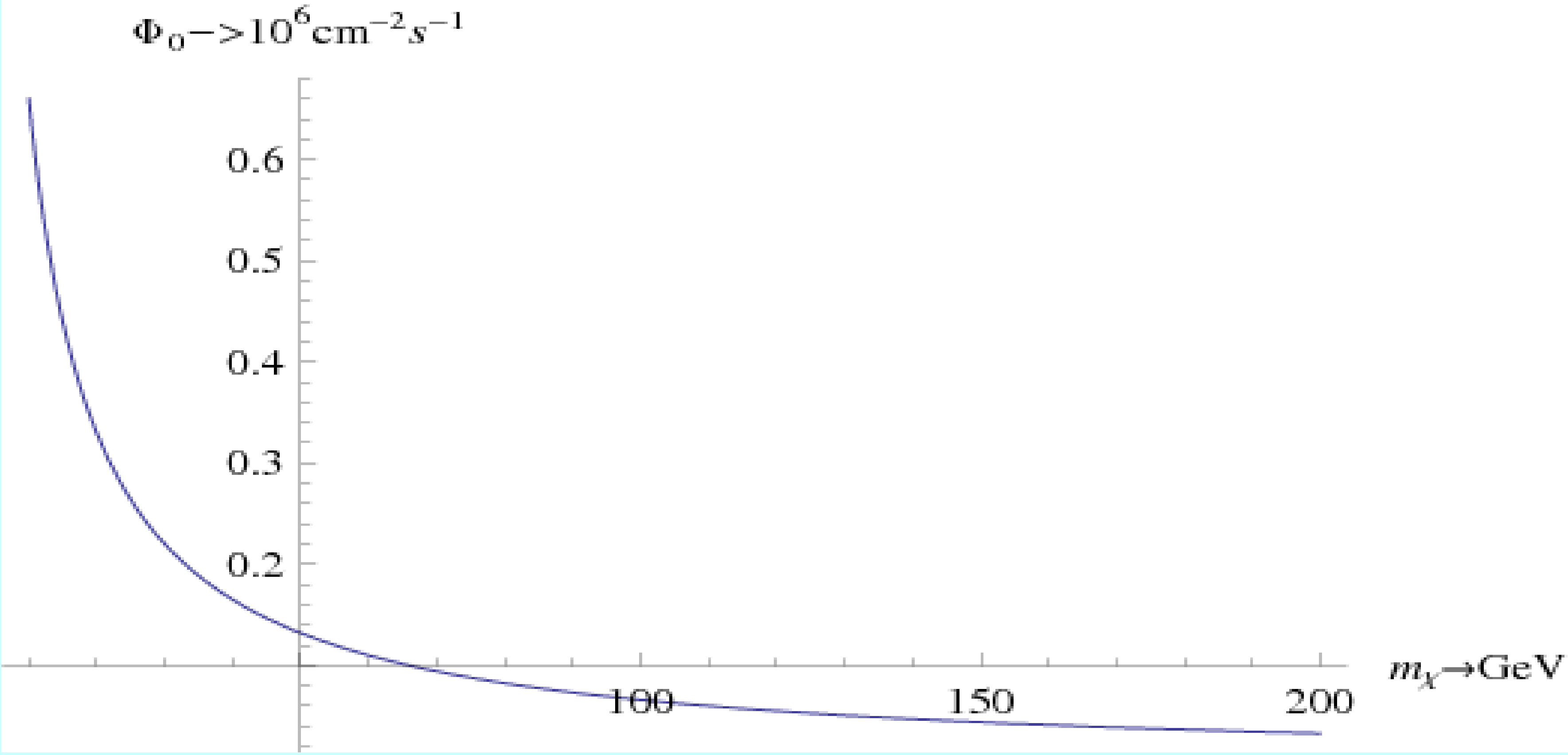
Morgan-Green-Spooner (04).





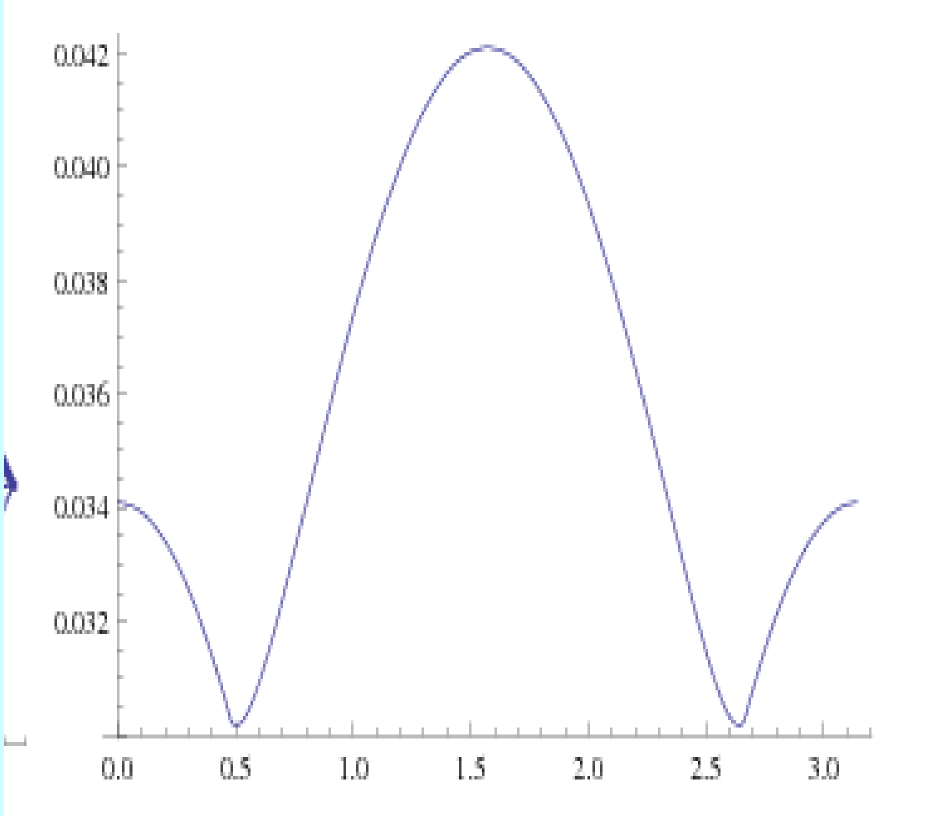
WIMP mass dependence of the flux

$\Phi_0 = (\rho_0 / m_\chi) u_0$



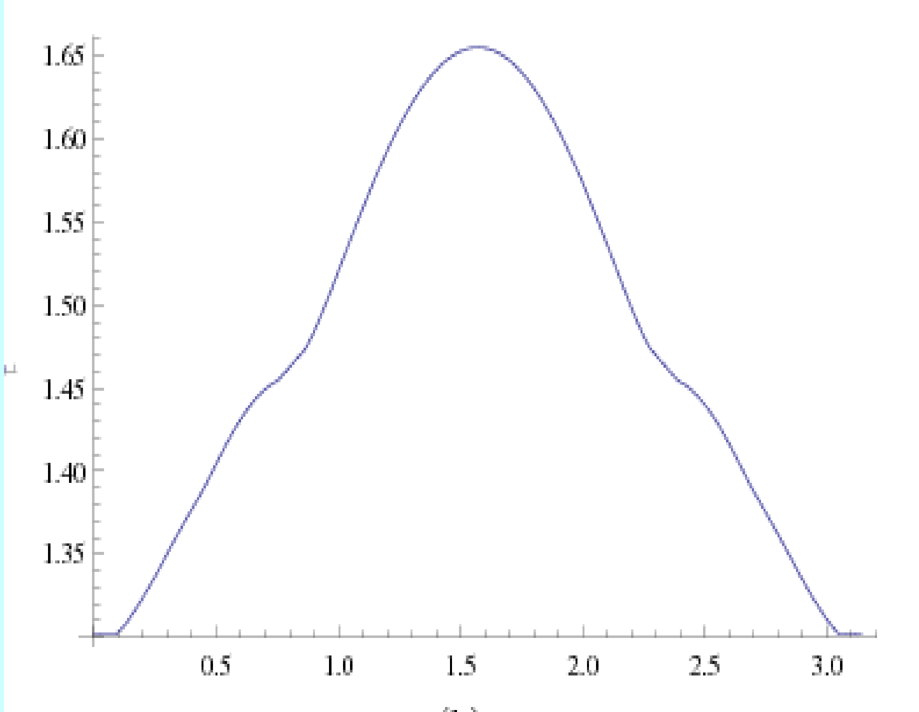
WIMP Flux: unconventional velocity distributions (maximum at Θ=π/2 !)

Saggitarius stream



(b)

Sukivies's Caustic Rings



(b)

III: The directional event rate (The direction of recoil is observed)

- The calculation will proceed in two steps:
- A) Evaluation of the event rate in a direction (Θ,Φ), taking the sun's direction of motion as polar axis (polar angle Θ);

Φ is measured on a plane perpendicular to the sun's velocity from x (x is radially out of the galaxy). The direction of recoil is

$$\hat{e} = (e_x, e_y, e_z) = (\sin\Theta\cos\Phi, \sin\Theta\sin\Phi, \cos\Theta).$$

- due to the Sun's motion the rate depends only on   Θ --> Asymmetry.

-due to the Earth's annual motion it will show a modulation, dependent on (Θ,Φ) with very characteristic signature.

- B) For a given direction of observation fixed in the lab.

-Then Diurnal variation due to the rotation of the Earth

Comparison of the usual (R) and directional (dR/dΩ) or (dR/dΞ) coherent rates (Ξ=cosΘ)
α is the phase of the Earth

$$R_{coh} = \frac{\rho_\chi}{m_\chi} \frac{m_t}{A m_p} \left(\frac{\mu_r}{\mu_p}\right)^2 \upsilon_0 \, A^2 \, \sigma_N^{coh} \, t_{coh} \, \left(1 + h_{coh} \cos\alpha\right),$$

$$\frac{dR}{d\Omega} = \frac{\rho(0)}{m_{\chi^0}} \frac{m}{A m_p} \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \upsilon_0 \frac{1}{2\pi} \left[\sigma^S_{p,\chi^0} \; A^2 t_{coh,dir} \left(1 + h^c_{coh,dir} \cos\alpha + h^s_{coh,dir} \sin\alpha\right)\right] \qquad (40)$$

The factor $\frac{1}{2\pi}$ enters, since, in order to better compare with the standard experiments, we used in the previous expression the total nucleon cross section. Note, however, that:

$$\frac{dR}{d\Xi} = \frac{\rho(0)}{m_{\chi^0}} \frac{m}{A m_p} \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \upsilon_0 \left[\sigma^S_{p,\chi^0} \; A^2 t_{coh,dir} \left(1 + h^c_{coh,dir} \cos\alpha + h^s_{coh,dir} \sin\alpha\right)\right] \qquad (41)$$

The directional event rate (The direction of recoil is observed)

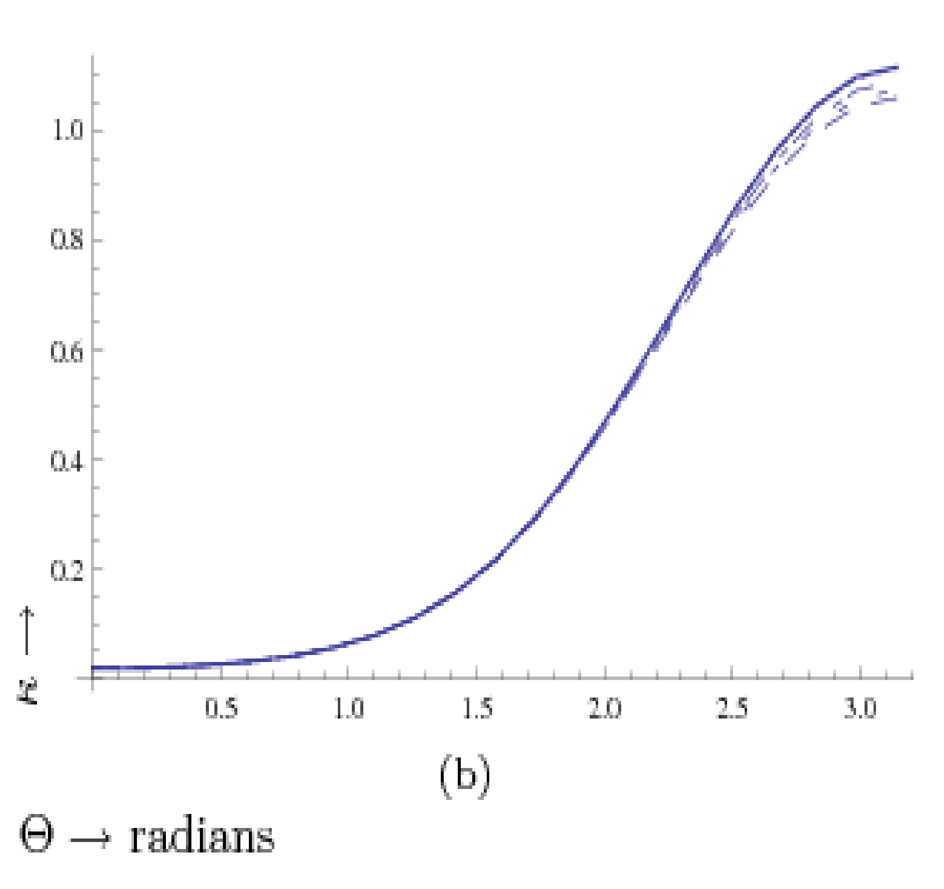
- The event rate as a function of the direction angles (Θ,Φ) is:

$$dR/d\Omega=(\kappa/2\pi)R_0[1+h_c\cos\alpha+h_s\sin\alpha)], \quad \kappa=t/t_{dir}$$

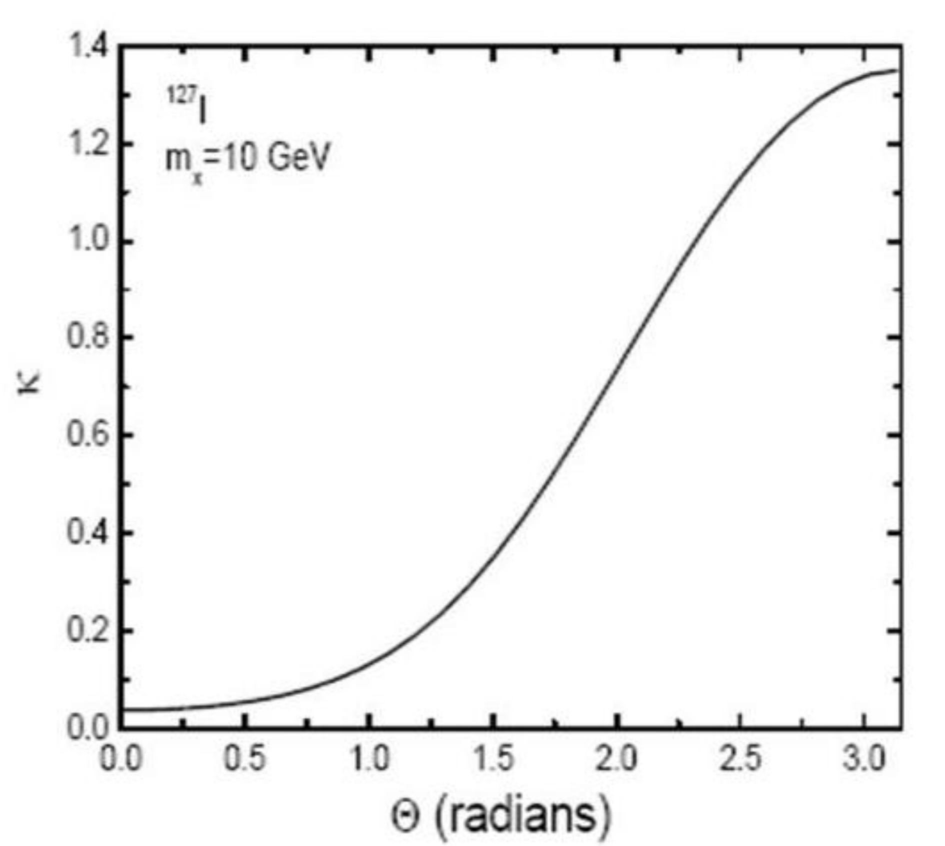
- R_0 is the average usual (**non-dir**) rate, α the phase of the Earth
- $\kappa/2\pi$ is the reduction factor (it depends on the direction of observation , but it is independent of the angle Φ). This factor becomes κ, after integrating over Φ. $dR/d\Omega \to dR/d(\cos\Theta)$
- It can also be written as: $dR/d\Omega=(\kappa/2\pi)R_0[1+h_m\cos(\alpha+\alpha_0)], \kappa=t/t_{dir}$
- h_m is the modulation amplitude (it strongly depends on the direction of observation)
- α_0 is the shift in the phase of the Earth (it strongly depends on the direction of observation)
- κ, h_c, h_s, or h_m and α_0, depend only slightly on the particle model (e.g. SUSY) parameters and μ_r

κ vs Θ for MB Distr. For a light system slight dependence on the WIMP mass

Light target (e.g. A=32)

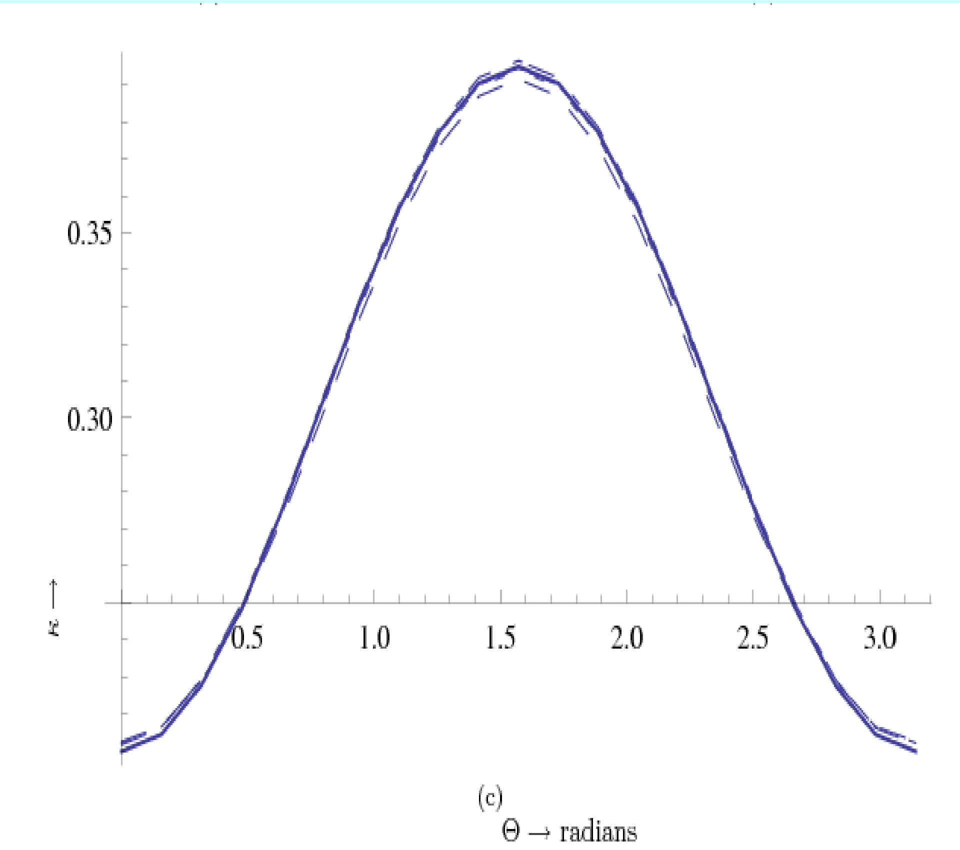


Heavy target (e.g. A=127)

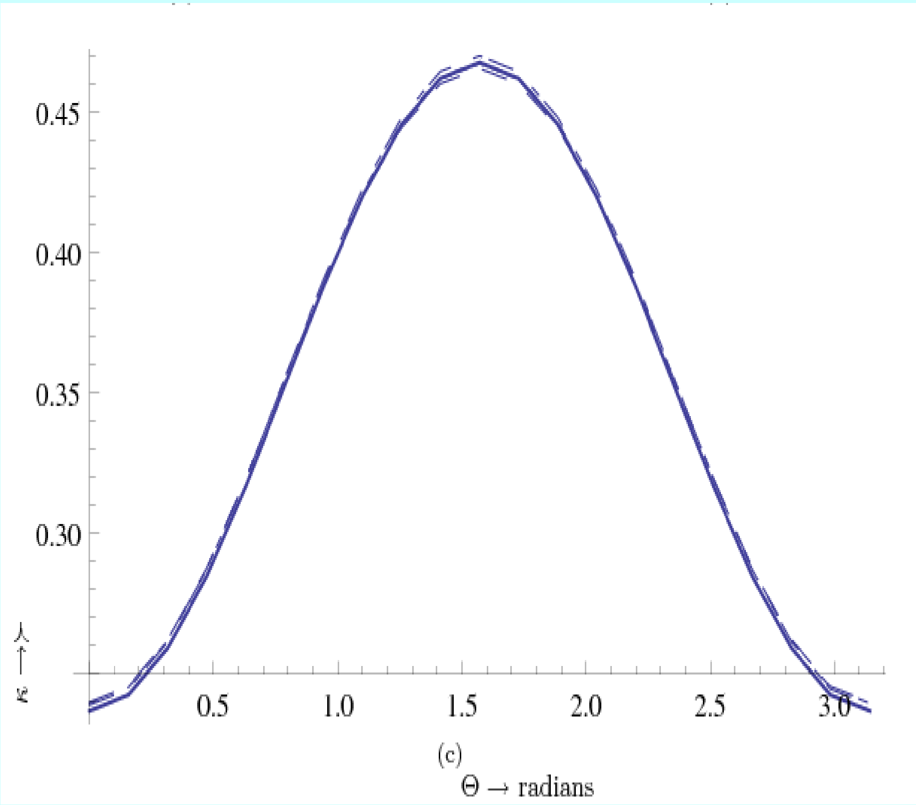


κ vs Θ for a light system.

Sagittarius Stream



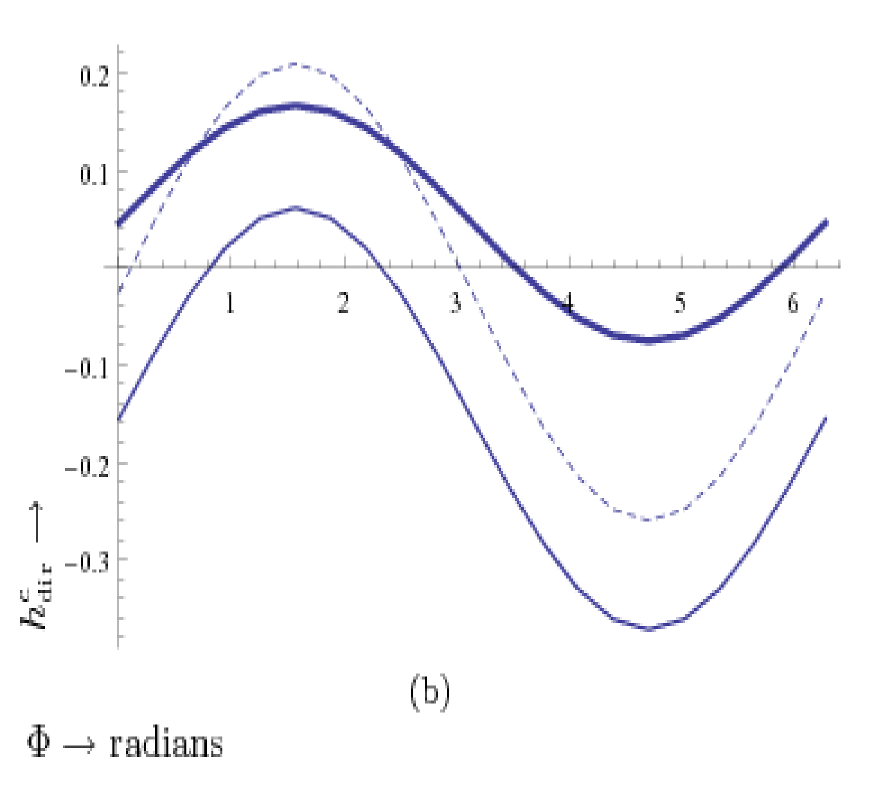
Sikivie's Caustic Rings



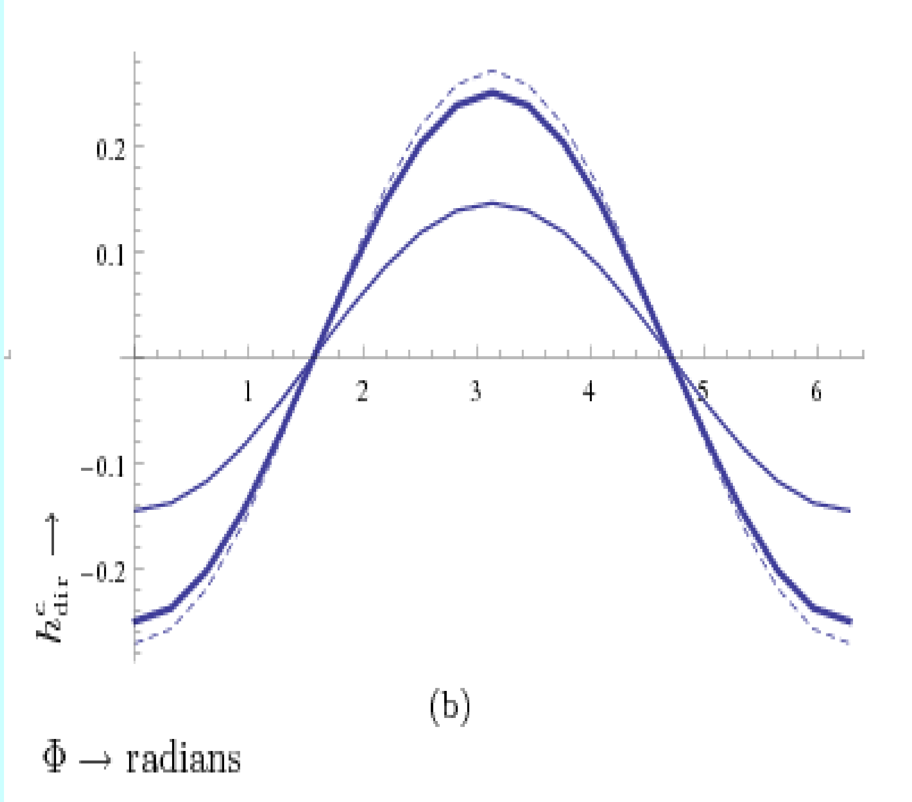
The modulation amplitudes (directional) for M-B distr., e.g. for m_χ=50 GeV.

solid, dashed, thick<->Θ=π/4, π/2, 3π/4

h_c

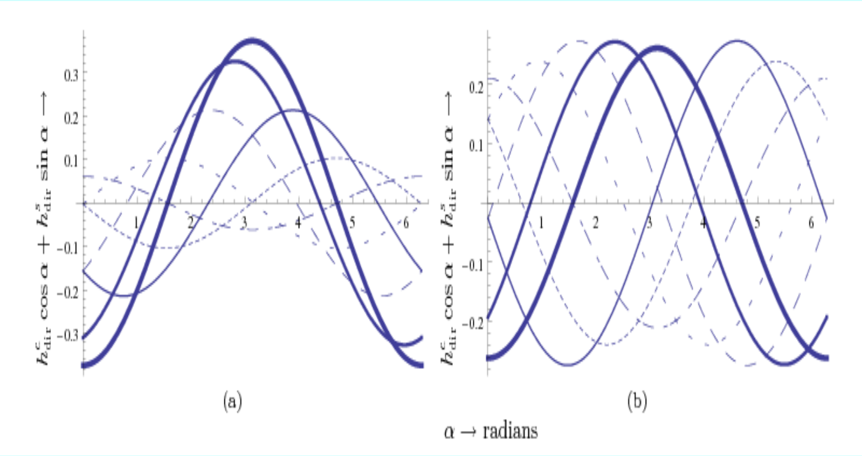


h_s

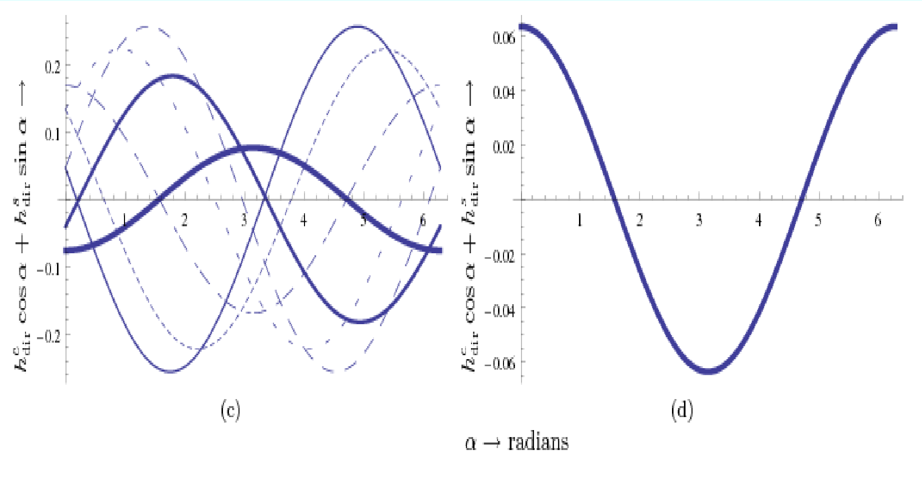


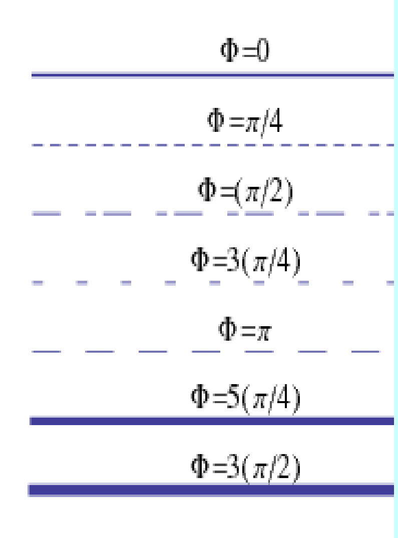
The modulation pattern (relative to the time averaged). α is the phase of the Earth

Θ=π/4 (a), Θ=π/2 (b)



Θ=3π/4 (c), Θ=π (d)



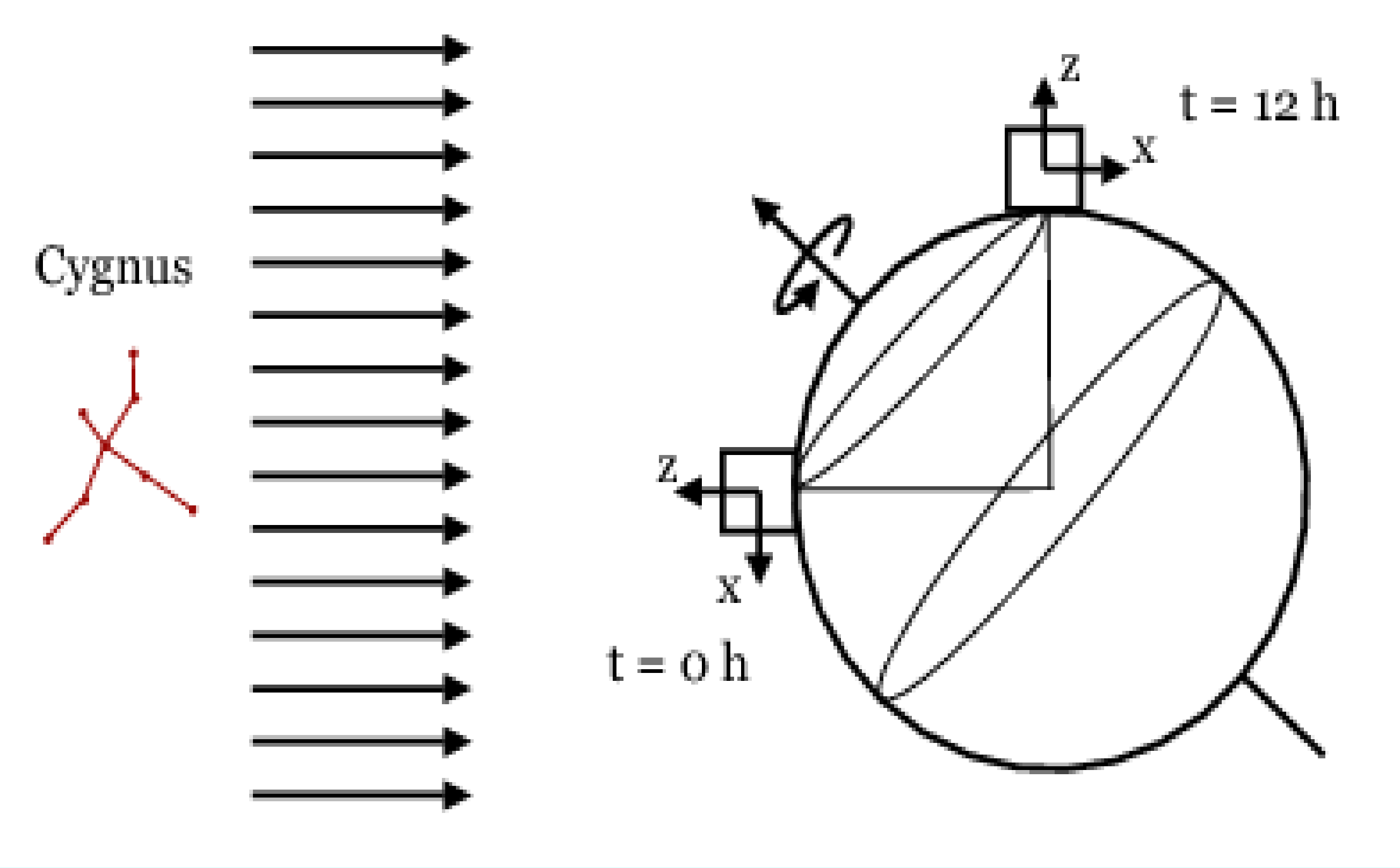


The Diurnal variation of the rate in Directional Experiments

- We have seen that:
- the parameters κ and h_m depend on the direction of observation relative to the sun's velocity
- In a directional experiment the direction of observation is fixed with respect to the earth.
- Due to the rotation of the Earth during the day this direction points in different parts of the galactic sky. So the angles (Θ,Φ) change and the rate becomes time dependent. It will show a periodic behavior.

Schematic time dependence of the rate as may be seen in a directional experiment.

Battat et al (IJMP A, 2009)



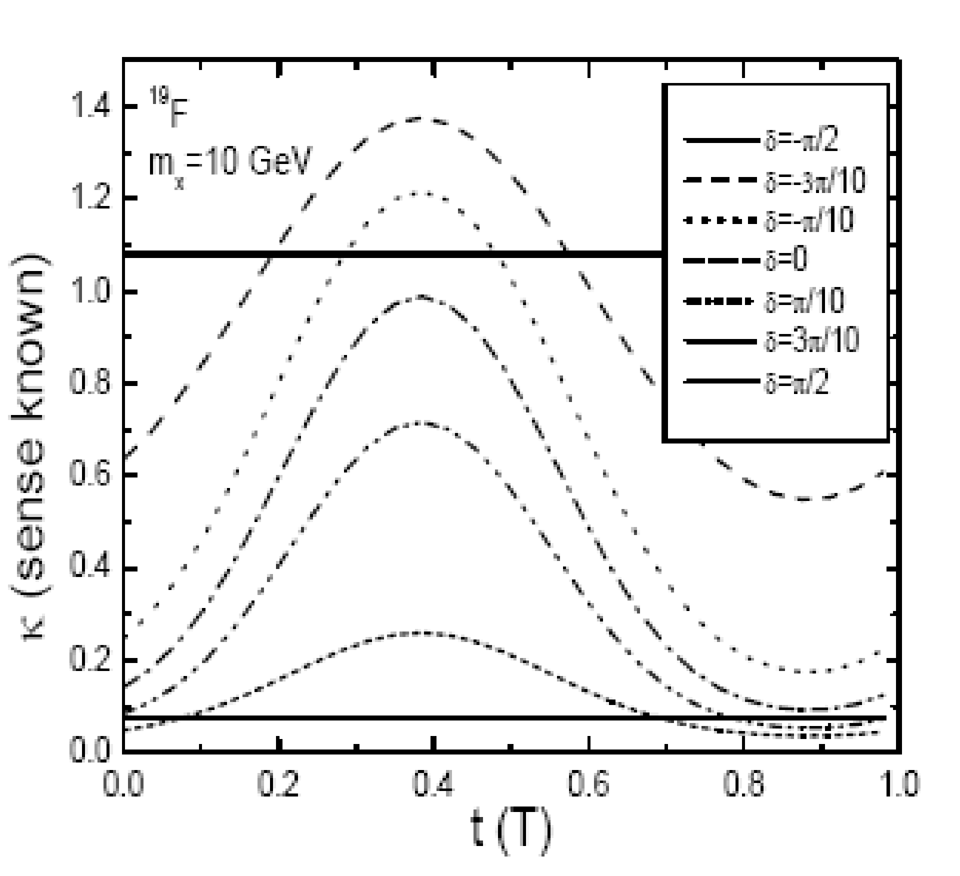
From the celestial (α=ascention,δ=inclination) to galactic coordinates

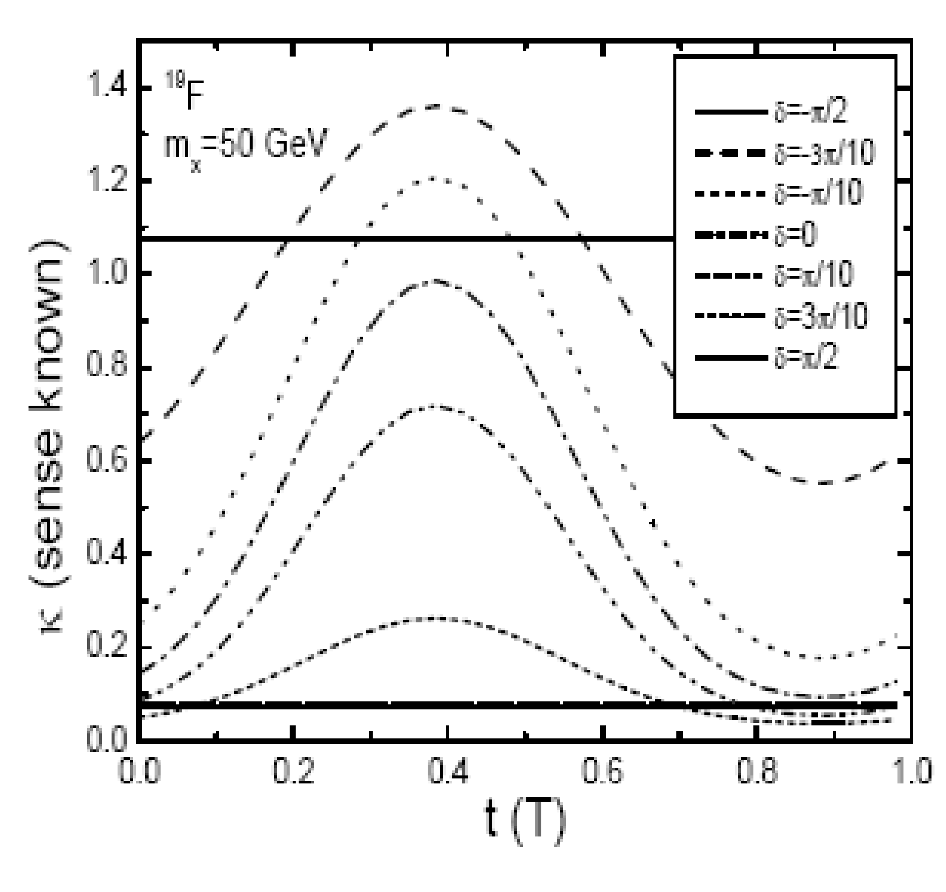
A vector oriented by (α, δ) in the laboratory is given in the galactic frame by a unit vector with components:

$$\begin{pmatrix} y \\ x \\ z \end{pmatrix} = \begin{pmatrix} -0.868\cos\alpha\cos\delta - 0.198\sin\alpha\cos\delta + 0.456\sin\delta \\ 0.055\cos\alpha\cos\delta + 0.873\sin\alpha\cos\delta + 0.4831\sin\delta \\ 0.494\cos\alpha\cos\delta - 0.445\sin\alpha\cos\delta + 0.747\sin\delta \end{pmatrix}$$

Diurnal Variation of the rate (κ) for a light target & fully directional

WIMP MASS 10 GeV **WIMP MASS 50 GeV**





CONCLUSIONS: Non modulated rate in directional Experiments (for both modes, coherent and spin)

- A useful parameter is κ the reduction factor relative to the non directional rate
- κ strongly depends on the polar angle Θ (the angle between the direction of observation and the sun's velocity)
- κ≈1 in the most favored direction (Θ≈π in MB)
- As the Earth rotates the detector samples a different angle Θ->
- The event rate (κ) exhibits a periodic variation with a period of 24 hours.
- The form of the variation depends on the WIMP mass
- The amplitude of this variation depends on the inclination of the line of observation. It can be quite large.
- The variation persists, even if the sense of direction is not known. Then, however, the effect is smaller

CONCLUSIONS : The modulation in directional Experiments (preliminary)

- The modulation amplitude in the most favored direction ($\kappa \approx 1$) is $0.02 < h_m < 0.1$ (bigger than in non-directional case) depending on the WIMP mass.
- In plane perpendicular to the sun's velocity ($\kappa \approx 0.3$) h_m is much bigger:
- $|h_m| \approx 0.25$ (50% difference between maximum and minimum).
- Both its magnitude and its sign depend on the azymouthal angle Φ
- We are currently computing its time variation. Preliminary results show a spectacular signal, which Cannot be mimicked by other seasonal effects

An alternative way to settle controversies!

Once all mighty God gave 5 golden cows, made of pure gold, to be divided among the Dark Matter Searches as follows:

- 1/3 goes to Direct the Experiments (CoGeNT/COUP, PICASSO, DAMA, EDELWEISS, CDMS, CRESST, ZEPLIN-3, XENON, KIMS etc).
- 1/3 goes to the Indirect Measurements (neutrinos,gamma-rays, astrophysics etc)
- 1/6 goes to future experiments (directional, e-detection, γ or X-ray detection etc)

Condition: No cow should be carved.

Obviously the three groups did not know how to do this.

So they went, where else?, to Mulah Nasrudin.

He thought for a while and ordered his wife to bring into the pack their own cow, which he valued more than golden.

Now there are 6 cows in the pack. It was easy for the first two groups to get 2 each and the future expeiments to get 1.

His cow was left and his wife took it back to the stable.

Was this a fair deal?

Was it a fair deal? After the fact theory pops in!

- Mullah Nasrudin did not know how to sum up infinite series. However theorists do:

$$\frac{5}{3}+\frac{1}{3}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{3}+\frac{1}{3}=2$$

$$\frac{5}{6}+\frac{1}{6}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{6}+\frac{1}{6}=1$$

COMMON WISDOM!

Are Physicists optimists or Don Quixotes?

Once the wise Mullah Nasrudin was seen beating a lake with a huge spoon.

Evidently in the hope of transforming the lake into gold.

When his fellow villagers teased him:

-Mullah! You surely are wasting your time!

He sternly replied:

-Imagine, though, that it works!

(Such a reward!)

- THE END