Issues and Prospects in DIRECT DARK MATTER DETECTION*

J.D. Vergados

University of Ioannina,

Ioannina, Greece.

* Work supported in part by:

MRTN-CT-2006-035863 (UniverseNet)

PLENTY OF EVIDENCE FOR THE EXISTENCE OF DARK MATTER

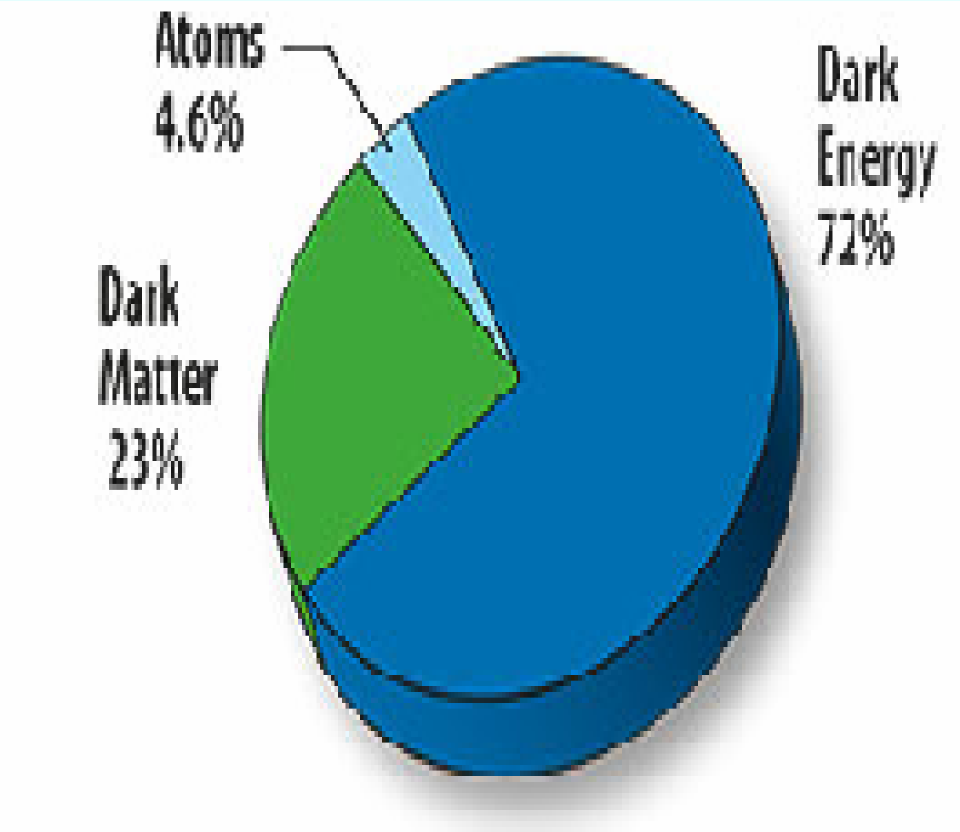
- Gravitational effects around galaxies
- The observation of the collision of two galaxy clusters (to-day 3.5�10^9 ly away from us, 2�10^6 ly apart)
- Cosmological Observations, confirmed by WMAP, of the dominance of dark matter in the universe (together with dark energy)

Slicing the Pie of the Cosmos (WMAP5):

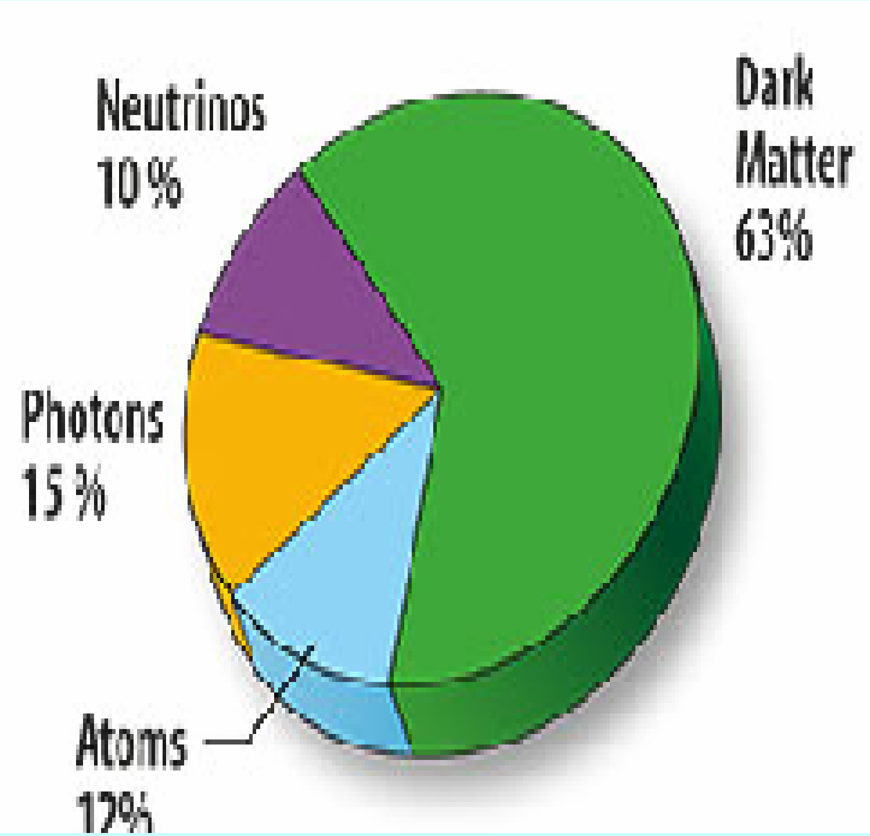
$\Omega_{CDM} = 0.24 \pm 0.02$, $\Omega_{\Lambda} = 0.72 \pm 0.04$,

$\Omega_b = 0.042 \pm 0.003$

The pie To-day



The pie at age t=400000 y



Dark Matter exists!

What is the nature of dark matter?

It is not known. However:

- It possesses gravitational interactions (from the rotation curves)
- No other long range interaction is allowed. Otherwise it would have formed "atoms" and , hence, stars etc. So

  It is electrically neutral
- It does not interact strongly (if it did, it should have already been detected)
- It may (hopefully!) posses some very weak interaction ☺

  WIMPs (Weakly Interacting Massive Particles)

  This will depend on the assumed theory
- Such an interaction may be exploited for its direct detection
- The smallness of the strength of such an interaction and its low energy makes its direct detection extremely difficult. So we have to seek for its special signatures, if any.

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 very difficult since the recoiling nucleus signature cannot be distinguished from that of the background
- The backgrounds are formidable, since the sought counting rates are extremely low
- So ingenious experimental approaches are needed exploiting any characteristic signatures of the reaction

DARK MATTER (WIMP) CANDIDATES

- The axion: 10^{-6} eV$<m_a<10^{-3}$ eV
- The neutrino: It is not dominant. It is not cold, not CDM.
- Supersymmetric particles. Many possibilities:

i) s-νετρίνο: More or less Excluded on the basis of results of underground experiments and accelerator experiments (LEP)

ii) Gravitino: Interesting possibility, but not directly detectable

iii) Axino: Interesting, but not directly detectable

iv) A Majorana fermion, the neutralino or LSP (Lightest Supersymmetric Particle): A linear combination of the 2 neutral gauginos and the 2 neutral Higgsinos. MOST FAVORITE CANDIDATE!

- Particles from Universal Extra Dimension Theories (e.g. Kaluza-Klein WIMPs)
- The Lightest Technibaryon, LTB (Gudnason-Kouvaris-Sannino)
- Secluded Dark matter Mediated by a very light gauge boson (introduced to explain the e^+,e- excess in cosmic rays)

I: Essential Physics Ingredients

- A particle model for WIMPs. It must yield the amplitude at the quark level. The most crucial element of any theory.

- Many theoretical models

- The most favored scenario is provided by R parity conserving Supersymmetry (LSP)

- Ib : A model for the nucleon (going from the quark to the nucleon level is NOT TRIVIAL)

- Ic : Some nuclear physics input.

II:The WIMP Velocity Distribution and density

- 1) Conventional: Isothermal models. Such as Maxwell-Boltzmann (symmetric or axially symmetric) with characteristic velocity equal to the sun's velocity around the center of the galaxy, $u_{MB} = u_0 = 220$ km/s, and escape velocity $u_{esc} = 2.84 u_0$, put in by hand.
- 2) From halo models employing Eddington's approach:
  Start with density $\rho=\rho(\mathbf{r})$. Solve Poisson's eq. to get

  $$\Phi = \Phi(\mathbf{r}) \Downarrow \rho = \rho(\Phi)$$

  $\Downarrow$ bounded distribution $f(\mathbf{r},\mathbf{v})$ (JDV-Owen)

  ⇒It leads approximate axially symmetric M-B
- 3) Axially symmetric velocity distributions extracted from realistic halo densities via simulations Tsallis type functions (Hansen, Host and JDV)

A. The standard not directional Total event rate for the coherent mode

- The number of events during time t is given by:

$$R \simeq 1.60\ 10^{-3} \frac{t}{1y} \frac{\rho(0)}{0.3 GeV cm^{-3}} \frac{m}{1\mathrm{Kg}} \frac{\sqrt{\langle v^2 \rangle}}{280\mathrm{km} s^{-1}} \frac{\sigma^S_{p,\chi^0}}{10^{-6}\ \mathrm{pb}} \frac{f_{coh}(A, \mu_r(A))}{A}$$

with

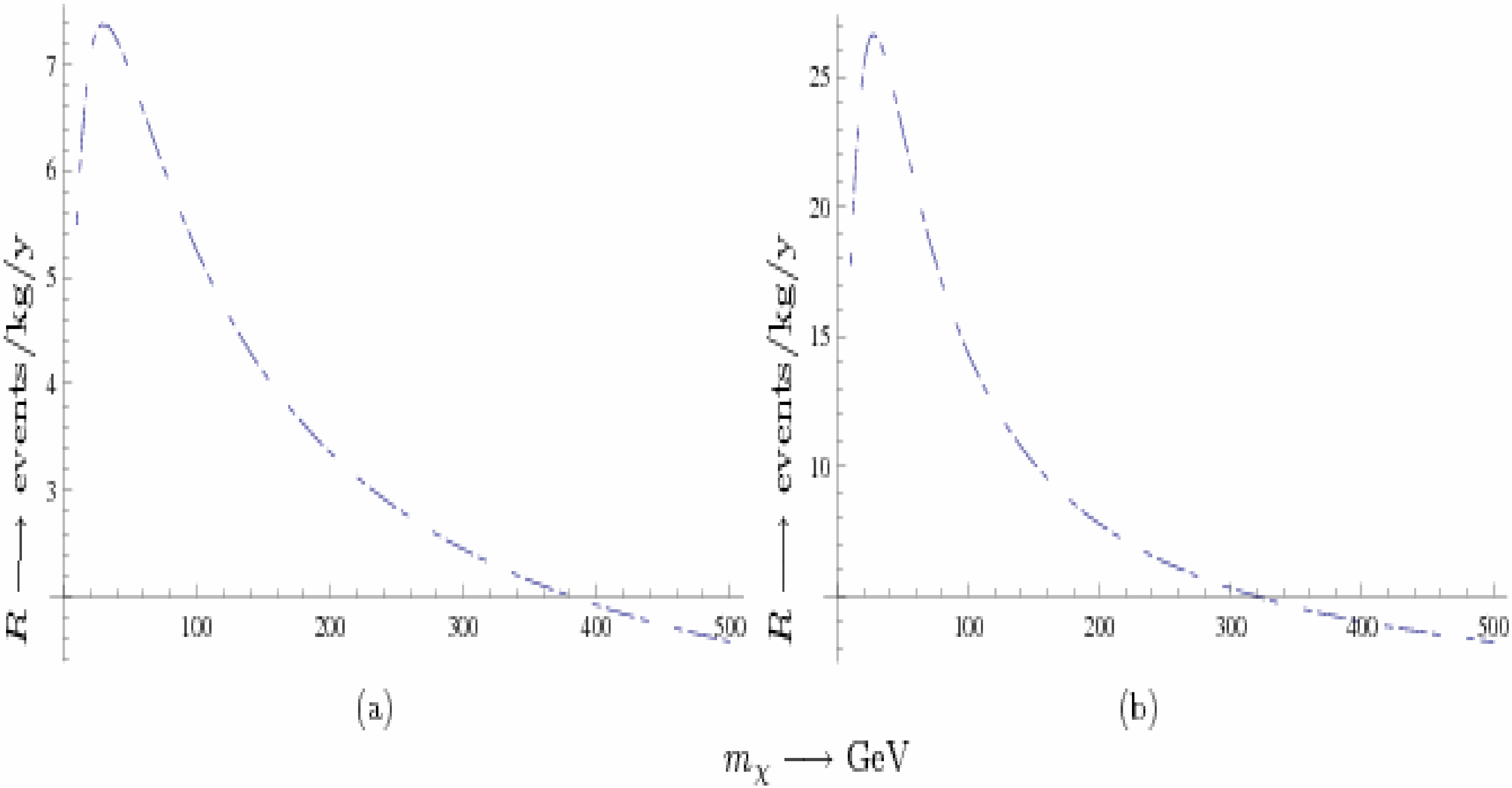
$$f_{coh}(A, \mu_r(A)) = \frac{100\mathrm{GeV}}{m_{\chi^0}} \left[\frac{\mu_r(A)}{\mu_r(p)} \right]^2 A^2\ t_{coh}\left(1 + h_{coh} cos\alpha\right)$$

Where:

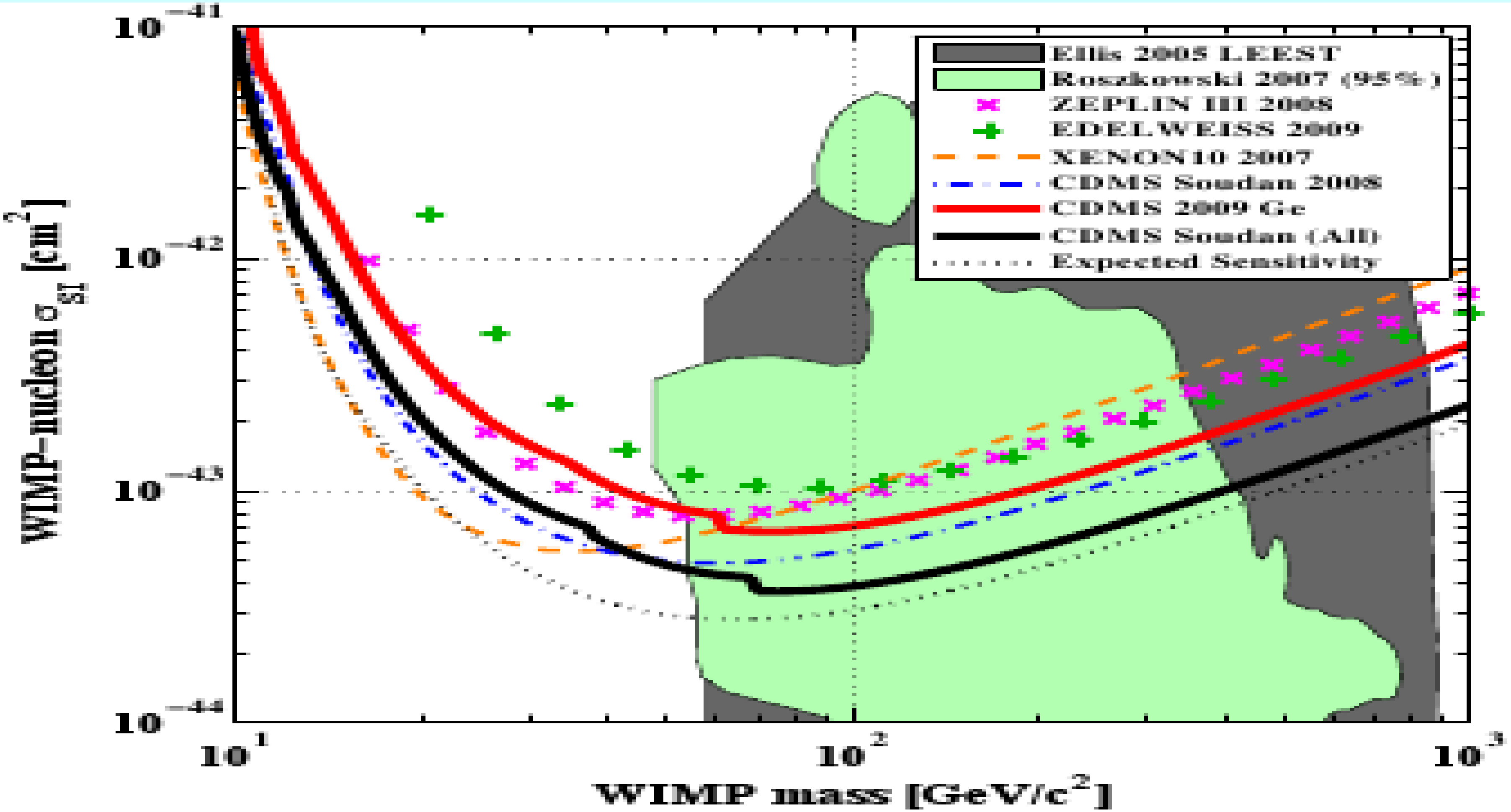
- μ_r is the reduced mass of the nucleus-WIMP system
- t_{coh} , h_{coh} depend on nuclear physics, μ_r and the velocity distribution
- $\rho(0)$: the local WIMP density≈0.3 GeV/cm^3.

$\sigma^S_{p,\chi}$: the WIMP-nucleon cross section. It is computed in a particle model. It can also be extracted from the data once $f_{coh}(A,m_\chi)$ is known

The coherent event rate as a function of the WIMP mass for a light target, A=32, (a) and a heavy target, A=131, (b) for $\sigma^{S}_{p,\chi} = 10^{-7}$pb



Extraction of the coherent nucleon cross section from the data (CDMS II, arXiv 0912.3592 [astro-ph])



Extraction of the coherent nucleon cross section from the data (Xenon100, arXiv 1005.0380 [astro-ph])

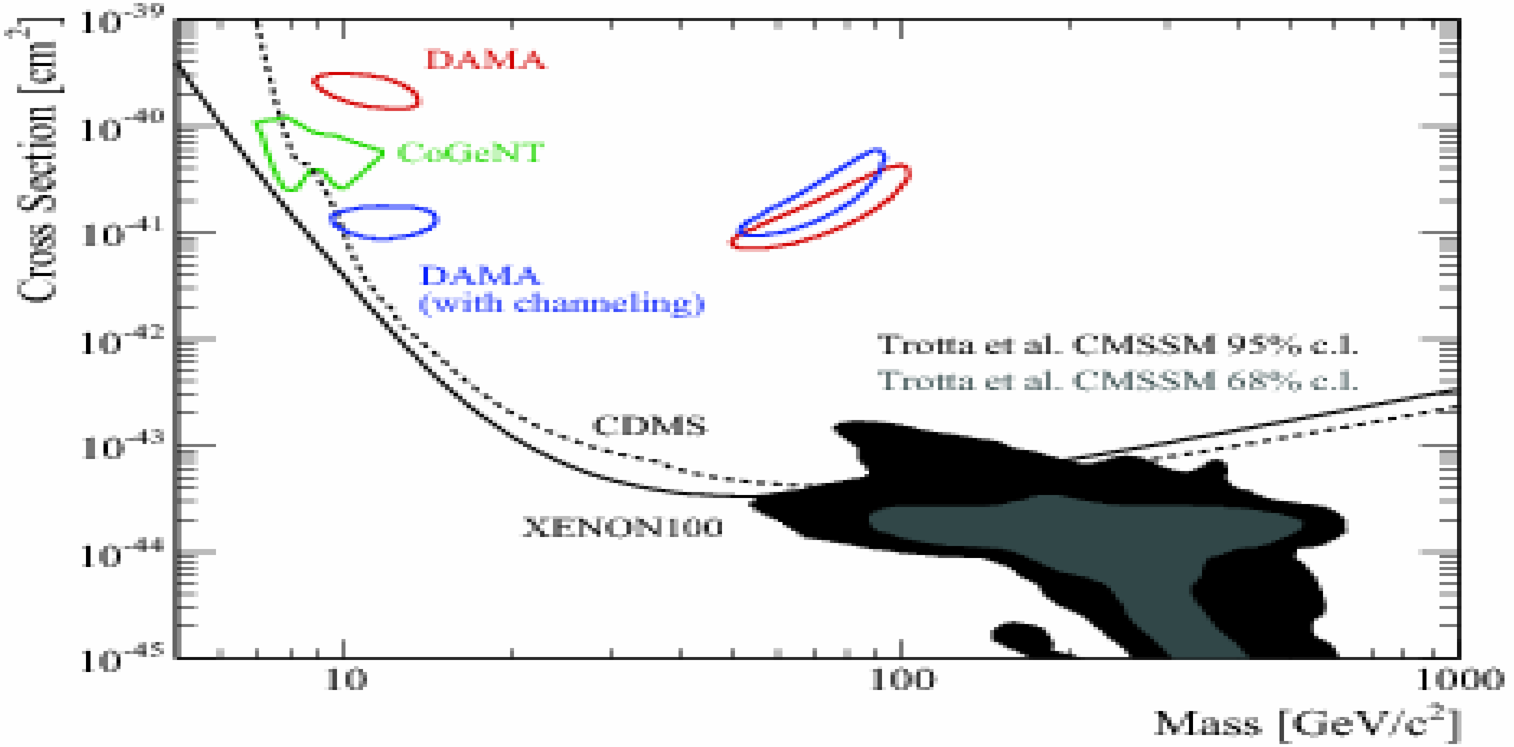


FIG. 5: 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section (solid line), together with the best limit to date from CDMS (dashed) [13], expectations from a theoretical model [14], and the areas (90% CL) favored by CoGeNT (green) [15] and DAMA (blue/red) [16].

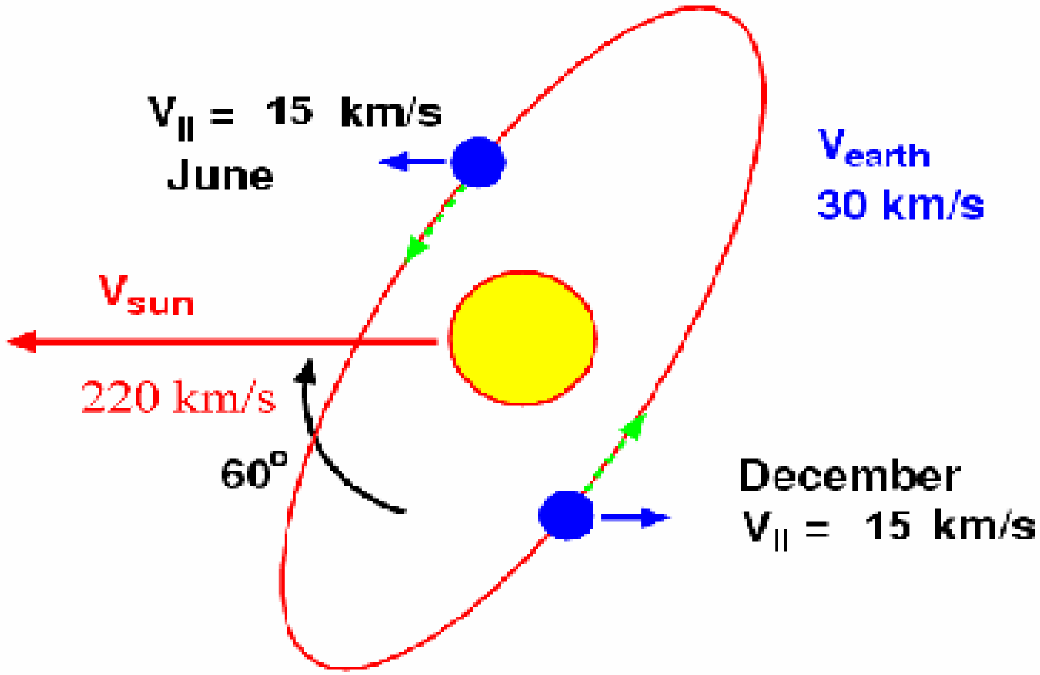
Novel approaches: Exploitation of other signatures of the reaction

- The modulation effect: The seasonal, due to the motion of the Earth, dependence of the rate.
- Asymmetry measurements in directional experiments (the direction of the recoiling nucleus must also be measured).
- Detection of other particles (electrons, X-rays), produced during the LSP-nucleus collision
- The excitation of the nucleus (in some cases , e.g. heavy WIMP etc, that this is realistic) and detection of the subsequently emitted de-excitation γ rays.
- Transitions to excited WIMP states

Seasonal Dependence of the Rate (The modulation effect)

$$\boldsymbol{v}_E = \boldsymbol{v}_0 \hat{z} + \boldsymbol{v}_1 (\, sin\alpha \, \hat{\mathbf{x}} - cos\alpha \, cos\gamma \, \hat{\mathbf{y}} + cos\alpha \, sin\gamma \, \hat{\mathbf{z}} \,) \qquad (80)$$

where α is phase of the earth's orbital motion. The LSP velocity distribution



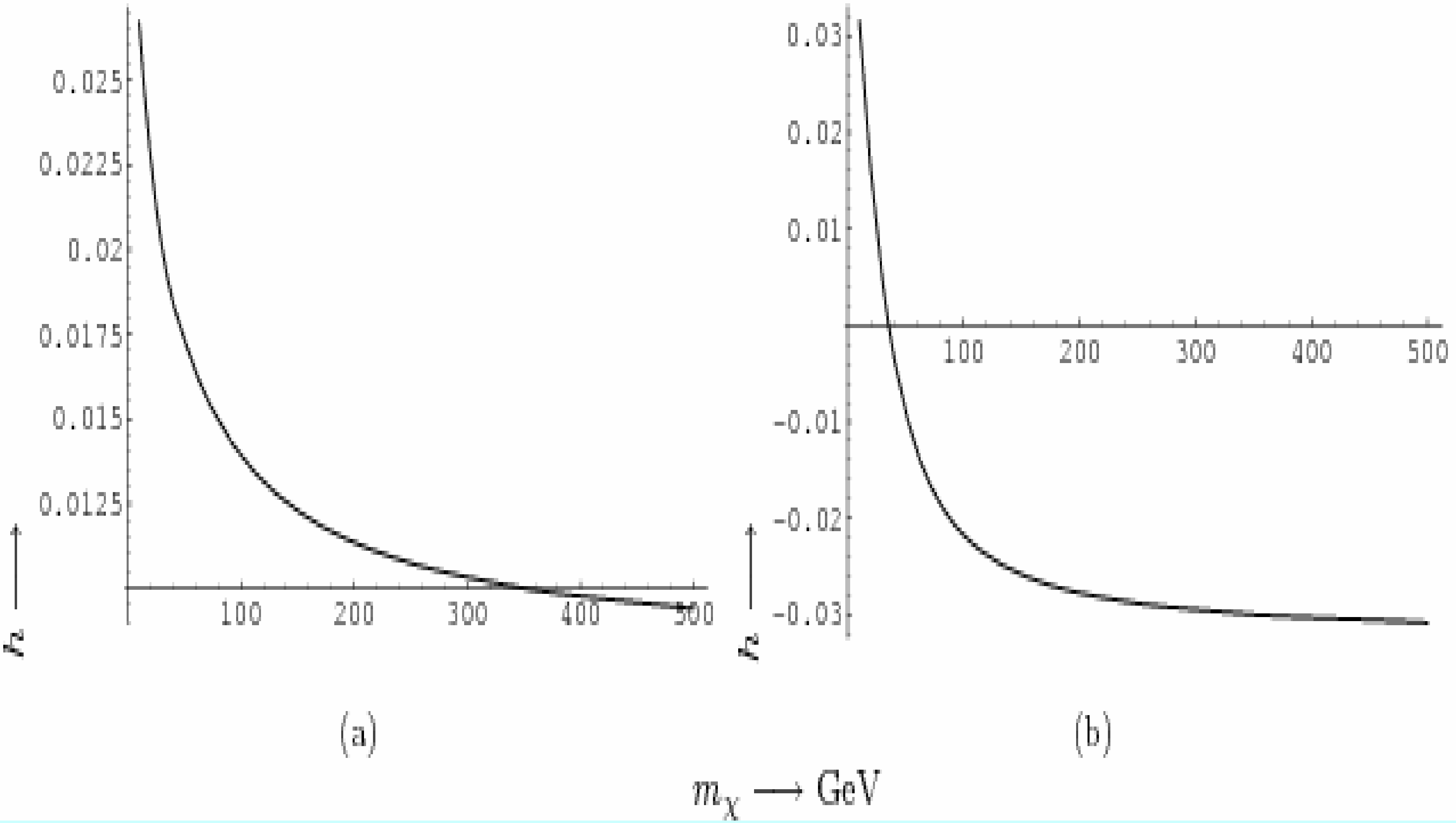
THE MODULATION EFFECT (continued)

- $R = R_0\,(1 + h\cos\alpha)$

  α is the phase of the Earth ($\alpha=0$ around June 3nd)

- h=modulation amplitude.
- R_0 =time averaged rate.

The modulation amplitude as a function of the WIMP mass for a light target, A=32, (a) and a heavy target, A=131, (b). Note the change in sign in (b).



Extraction of all the elementary cross sections from the data, i.e. the rates R

$$R = \frac{\rho(0)}{100\ \text{GeV}} \frac{m}{m_p} \sqrt{\langle v^2 \rangle}$$
$$\left\{ c_{coh}(A, \mu_r(A), m_{\chi^0}) \sigma^{SI} + c_{spin}(A, \mu_r(A), m_{\chi^0}) \sigma^{spin}_{nuc} \right\}$$

$$c_{coh}(A, \mu_r(A), m_{\chi^0})) = \frac{100\ \text{GeV}}{m_{\chi^0}} \left[\frac{\mu_r(A)}{\mu_r(p)} \right]^2 A\ t_{coh}(A)$$

$$c_{spin}(A, \mu_r(A), m_{\chi^0})) = \frac{100 GeV}{m_{\chi^0}} \left[\frac{\mu_r(A)}{\mu_r(p)} \right]^2 \frac{t_{spin}(A)}{A}$$

$$\sigma^{spin}_{nuc} = \frac{1}{3} \left(\left(\Omega^{A_i}_p\right)^2 \sigma^{SD}_p + \left(\Omega^{A_i}_n\right)^2 \sigma^{SD}_n + 2\cos\delta\ \Omega^{A_i}_p \Omega^{A_i}_n \sqrt{\sigma^{SD}_p} \sqrt{\sigma^{SD}_n} \right)$$

The previous equation for a number of targets A_i becomes

The above equation in the case of many targets the constraint on the nucleon cross sections can be cast in the form:

$$\sigma^{SI} + \mathcal{R}_{A_i}\left(\left(\Omega_p^{A_i}\right)^2\sigma_p^{SD} + \left(\Omega_n^{A_i}\right)^2\sigma_n^{SD} + 2\cos\delta\,\Omega_p^{A_i}\Omega_n^{A_i}\sqrt{\sigma_p^{SD}}\sqrt{\sigma_n^{SD}}\right) = S_{A_i}, \quad i = 1,\cdots \qquad (5)$$

where $\Omega_p^{A_i}$ and $\Omega_n^{A_i}$ are the proton and neutron components of the nuclear spin ME associted with the target A_i. The quantities $\mathcal{R}_{A_i}$ are calculable kinematical functions which depend on the target and the WIMP mass, while S_{A_i} depends on the target, the WIMP mass and the observed event rate, if and when it becomes available. The σ^{SI}, σ_p^{SD} and σ_n^{SD} are the the unknown elementary nucleon cross sections, while δ represents the phase netween the corresponding nucleon amplitudes. The last four quantities can be calculated in a given paricle model or given enough targets they can be extrcted from the data.

It is adequate to consider one target with dominant proton component, e.g. $A_2={}^{19}F$, one with a dominant neutron component, e.g. $A_3={}^{73}Ge$, and one with both, e.g. $A_1={}^{127}I$.

Then the solutions attain simple analytic form.

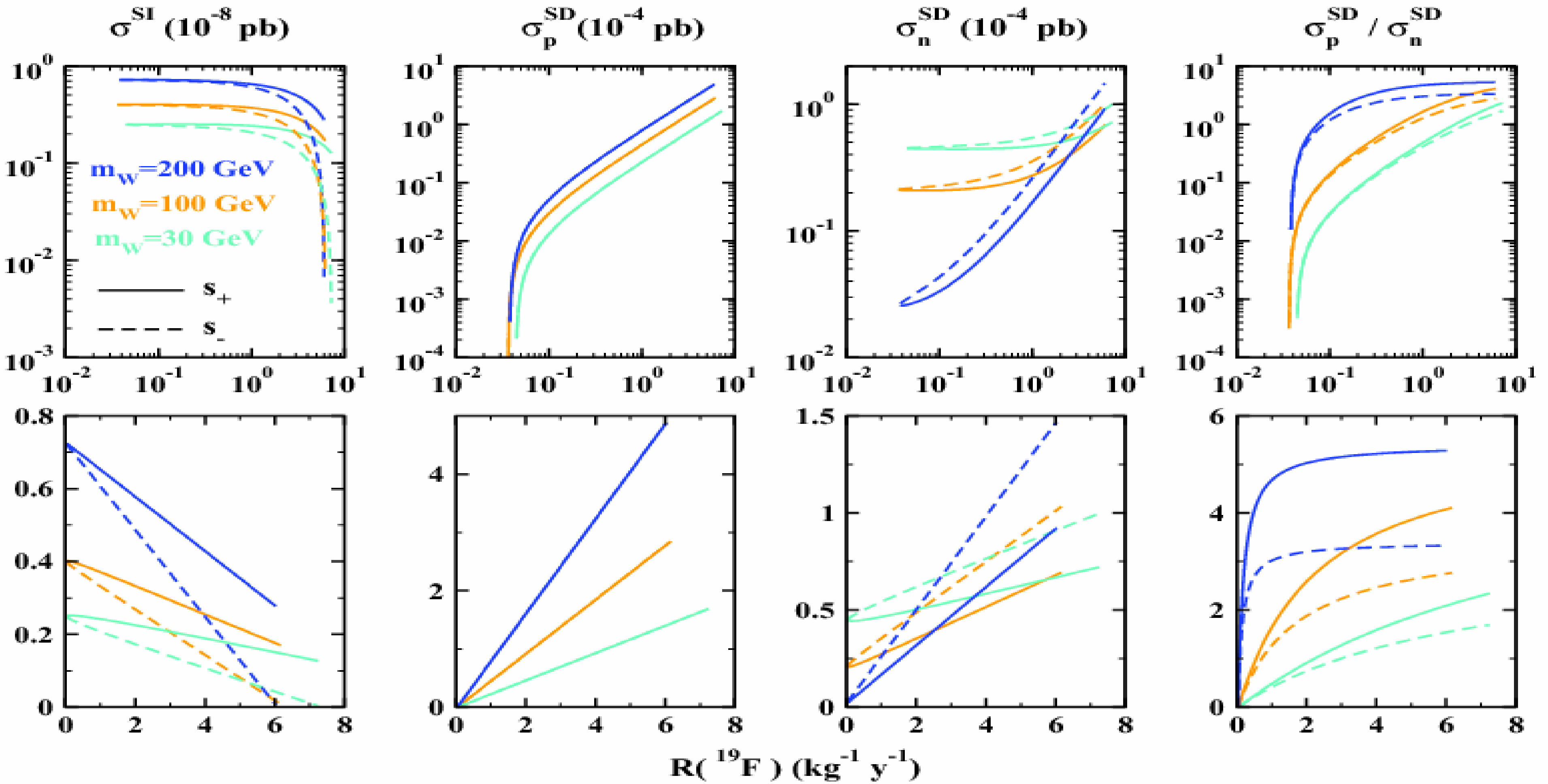
$$\sigma^{SI} + \mathcal{R}_{A_2}\left(\left(\Omega_p^{A_2}\right)^2 \sigma_p^{SD}\right) = S_{A_2}$$

$$\sigma^{SI} + \mathcal{R}_{A_3}\left(\left(\Omega_n^{A_3}\right)^2 \sigma_n^{SD}\right) = S_{A_3}$$

$$\sigma^{SI} + \mathcal{R}_{A_1}\left(\left(\Omega_p^{A_1}\right)^2 \sigma_p^{SD} + \left(\Omega_n^{A_1}\right)^2 \sigma_n^{SD} + 2\cos\delta\, \Omega_p^{A_1}\Omega_n^{A_1}\sqrt{\sigma_p^{SD}}\sqrt{\sigma_n^{SD}}\right) = S_{A_1}$$

Preliminary Results (Canoni, JDV, Gomez):

Using the current Exp. limits: R(^{73}Ge)= R(^{127}I)=1 kg^{-1} y^{-1}



Theoretical Results (Canoni, JDV,Gomez): Constrained minimal SUSY Standard model

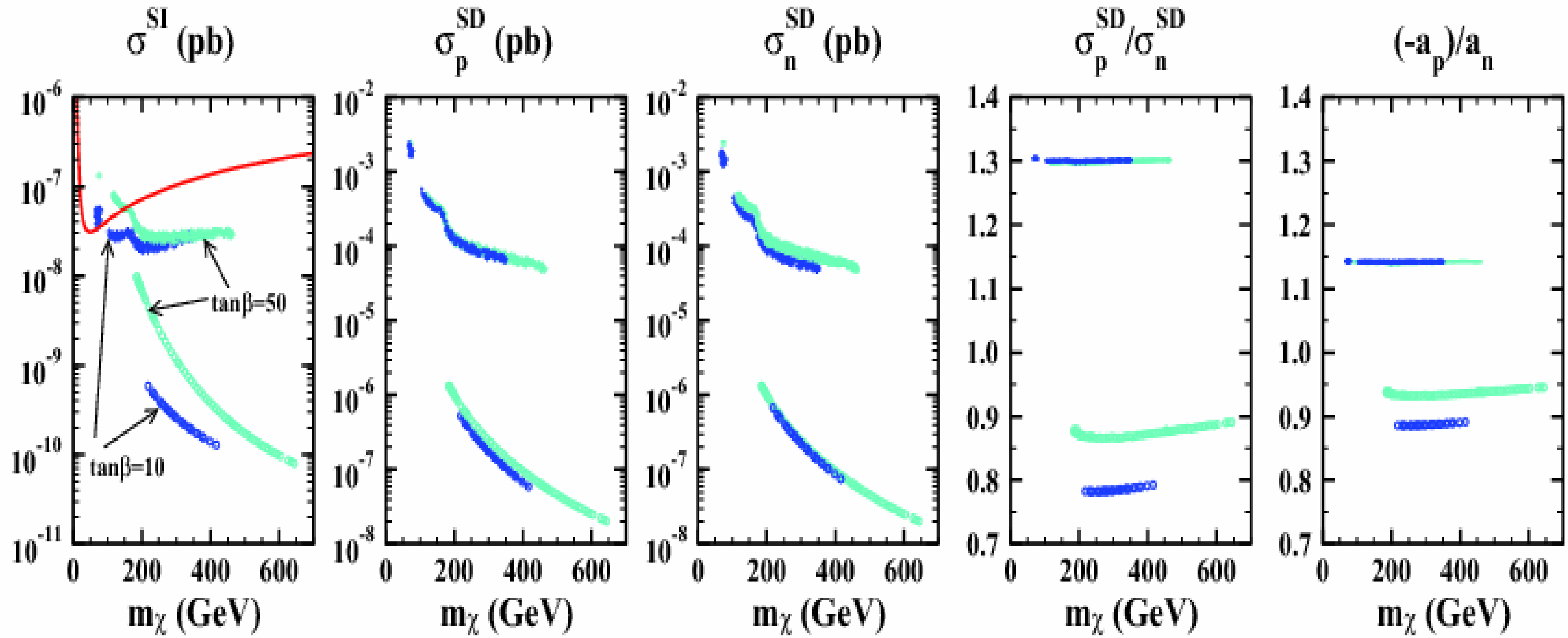


Figure 4. Neutralino-nucleon cross sections as a function of the neutralino mass in the constrained minimal supersymmetric standard model with $A_0 = 0$, $\mu > 0$, $m_0 < 4000$ GeV, $m_{1/2} < 1500$ GeV, $\tan\beta = 10$ and $\tan\beta = 50$. The column on right is the ratio of the SD amplitudes. The points satisfy the WMAP 3σ bound $0.094 < \Omega h^2 < 0.128$ [18] on the relic density. The blue points are for $\tan\beta = 10$, the turquoise ones for $\tan\beta = 50$. The red curve is the XENON100 upper limit on the SI cross

B. The directional event rate
(The direction of recoil is also observed)

- The calculation will proceed in two steps:
- A) In a direction fixed in galactic coordinates:

-The directional event rate will show an asymmetry due to the sun's motion around the galaxy.

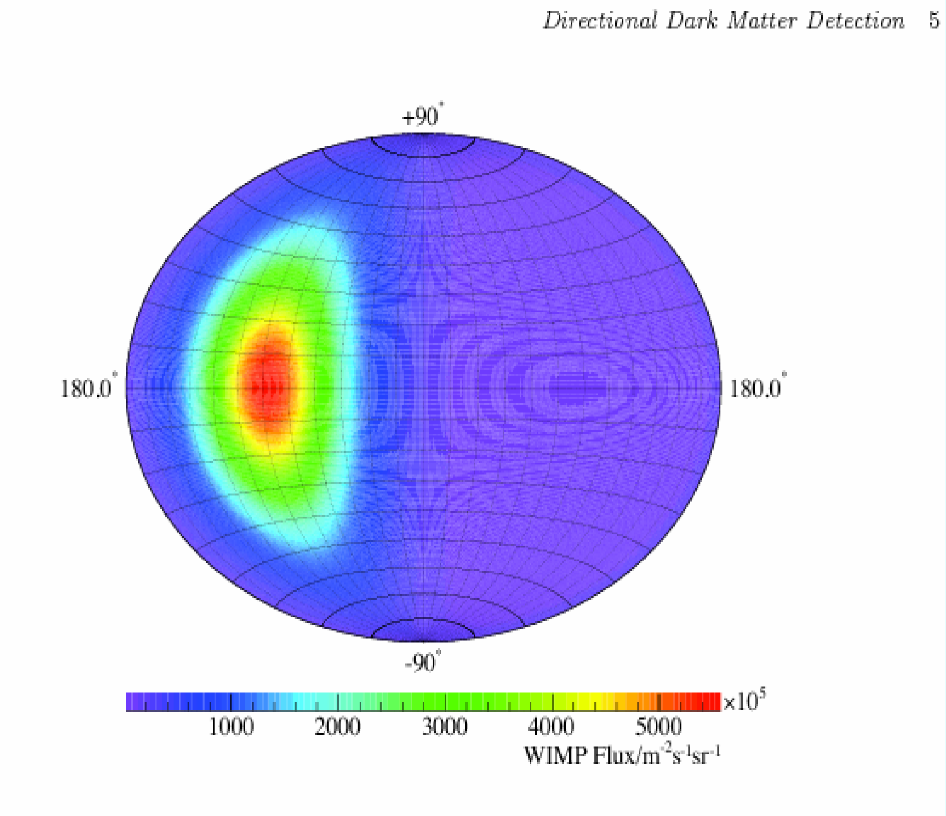
-Due to the Earth's annual motion it will show a modulation with very characteristic signature

- B) The direction of observation fixed in the lab.

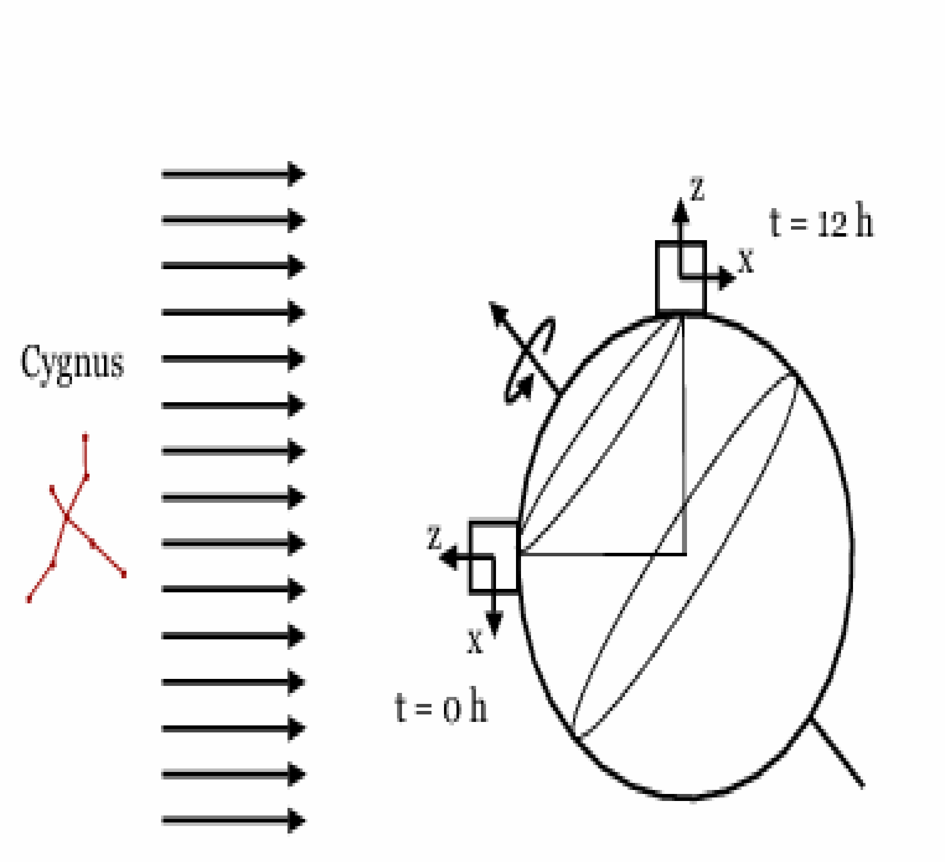
-Then Diurnal variation due to the rotation of the Earth

For Directional Experiments. A peak in the direction opposite to the Sun's velocity (Courtesy of Anne Green)

The apparent WIMP flux



Time variation of event rate



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

$$\left\langle \frac{dR_{dir}}{du} \right\rangle = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} \sqrt{\langle v^2 \rangle}$$

$$\int \frac{\upsilon.\hat{e}\ \Theta(\upsilon.\hat{e})}{\sqrt{\langle v^2 \rangle}} f(\upsilon, \upsilon_E) \frac{d\sigma(u, \upsilon)}{du} \frac{1}{2\pi} \delta\left(\frac{\sqrt{u}}{\mu_r b \upsilon} - \hat{\upsilon}.\hat{e}\right) d^3\upsilon$$

u is the energy in dimensionless units.

$$u = \frac{1}{2}(qb)^2 = Am_p Q b^2 \Rightarrow u = \frac{Q}{Q_0} \quad , \quad Q_0 = \frac{1}{Am_p b^2} \simeq 4.1 \times 10^4 \ A^{-4/3} \ KeV$$

The factor of $1/2\pi$ appears, since we are using the same cross section as in the non directional

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

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

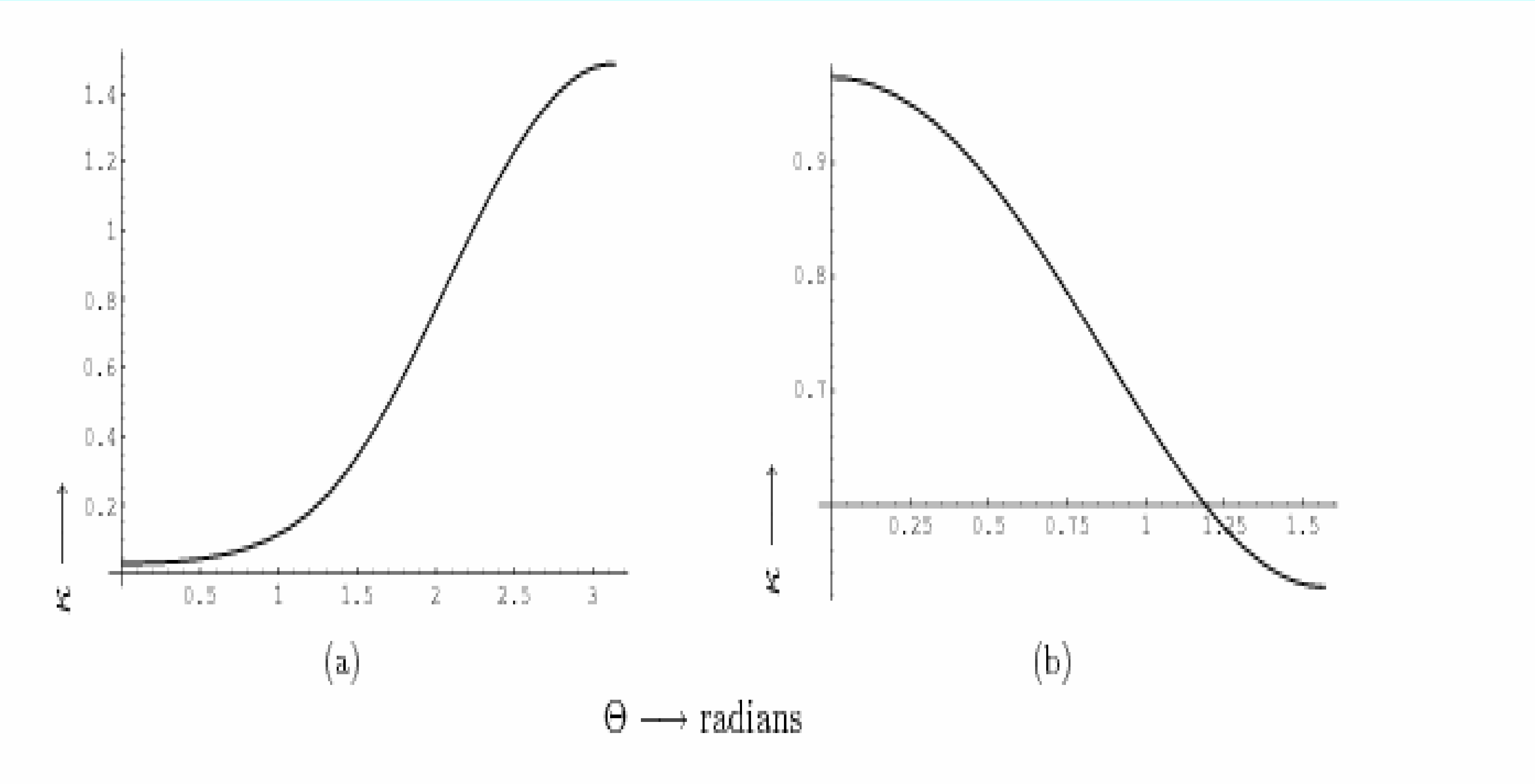
- The event rate in a direction fixed in the galactic frame is:

$$R_{dir} = (\kappa/2\pi) R_0 [1 + h_m \cos(\alpha - \alpha_m)]$$

- R_0 is the average usual (**non-dir**) rate
- α the phase of the Earth (as usual)
- h_m is the modulation amplitude (it strongly depends on the direction of observation)
- α_m is the shift in the phase of the Earth (it strongly depends on the direction of observation)
- $\kappa/2\pi$ 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.
- κ, h_m and α_m depend only slightly on SUSY parameters and μ_r

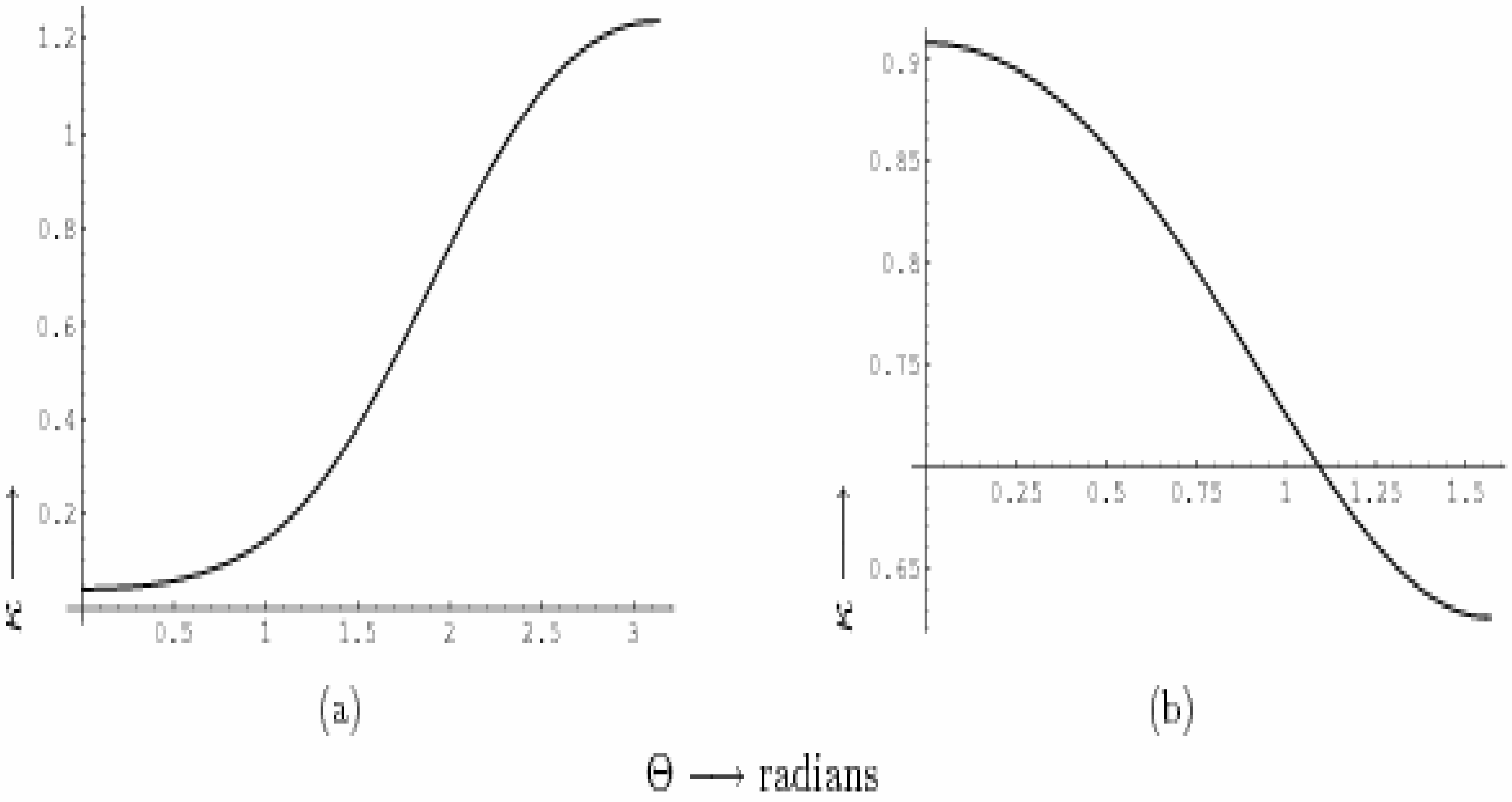
The parameter κ vs the polar angle Θ in the case of A=32; m_χ=10 GeV; Symmetric M-B

Definite Sense **Sense not distinguished**



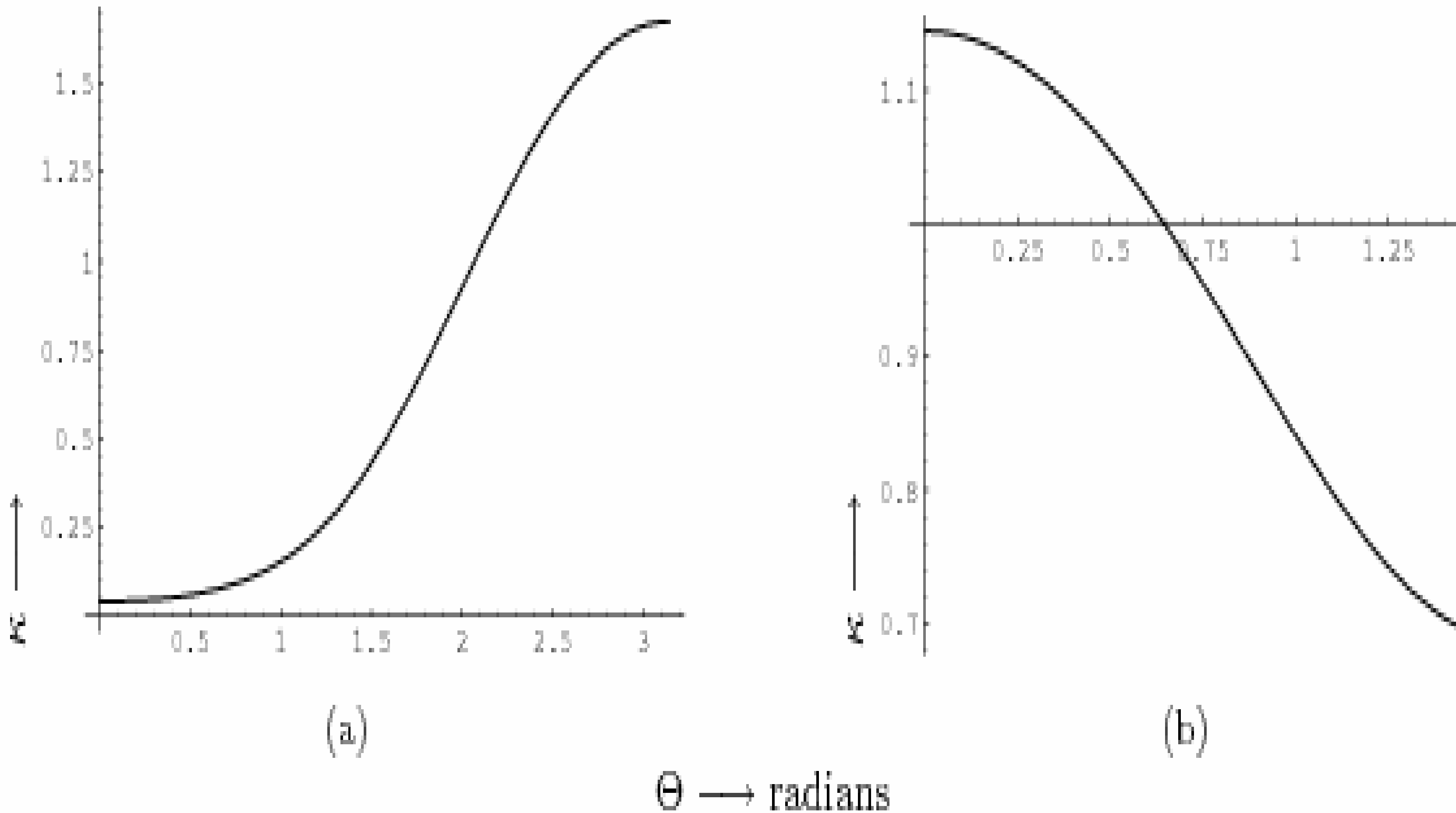
The parameter κ vs the polar angle Θ in the case of A=32;m_χ=100 GeV;Symmetric M-B

Definite Sense **Sense not distinguished**



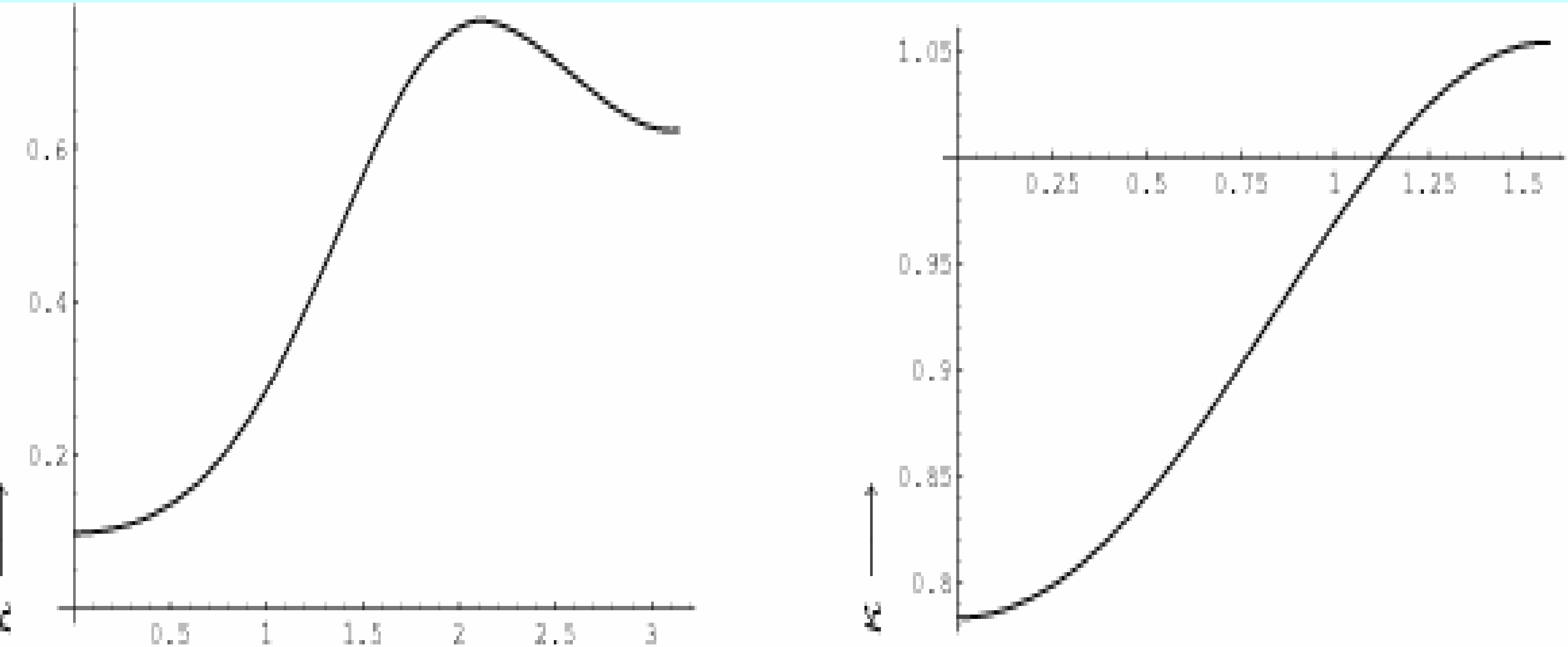
The parameter κ vs the polar angle Θ in the case of A=131;m_χ=10 GeV;Symmetric M-B

Definite Sense **Sense not distinguished**



The parameter κ vs the polar angle Θ in the case of A=131;m_χ=100GeV;Symmetric M-B

Definite Sense | **Sense not distinguished**



(a) (b)

Θ ⟶ radians

From the celestial to galactic coordinates

z in the direction of sun, x in the radial direction (outwards), y perpendicular to the galactic plane.

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

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

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 rate becomes time dependent. It will show a periodic dependence.

The rate depends on Θ. Θ depends on time due to the earth's rotation

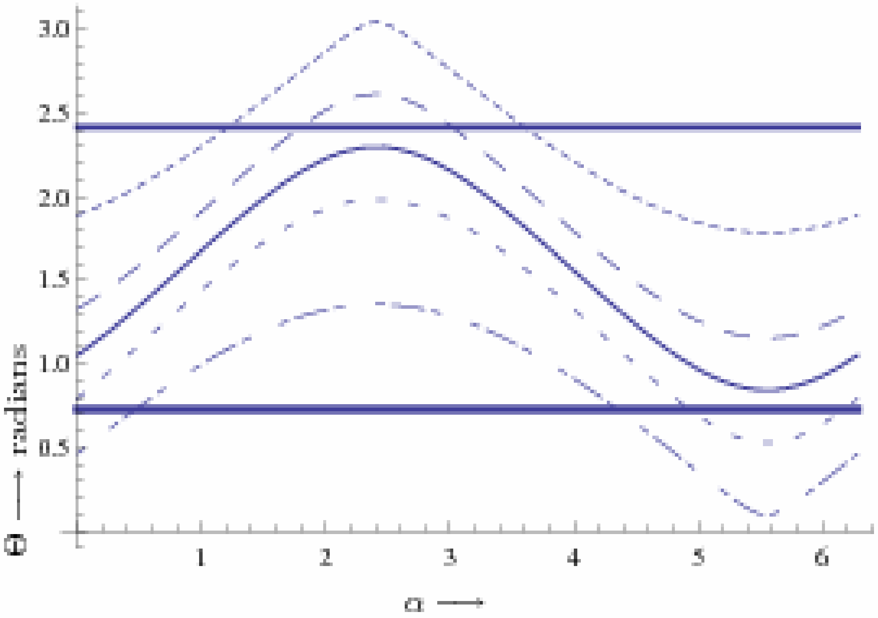
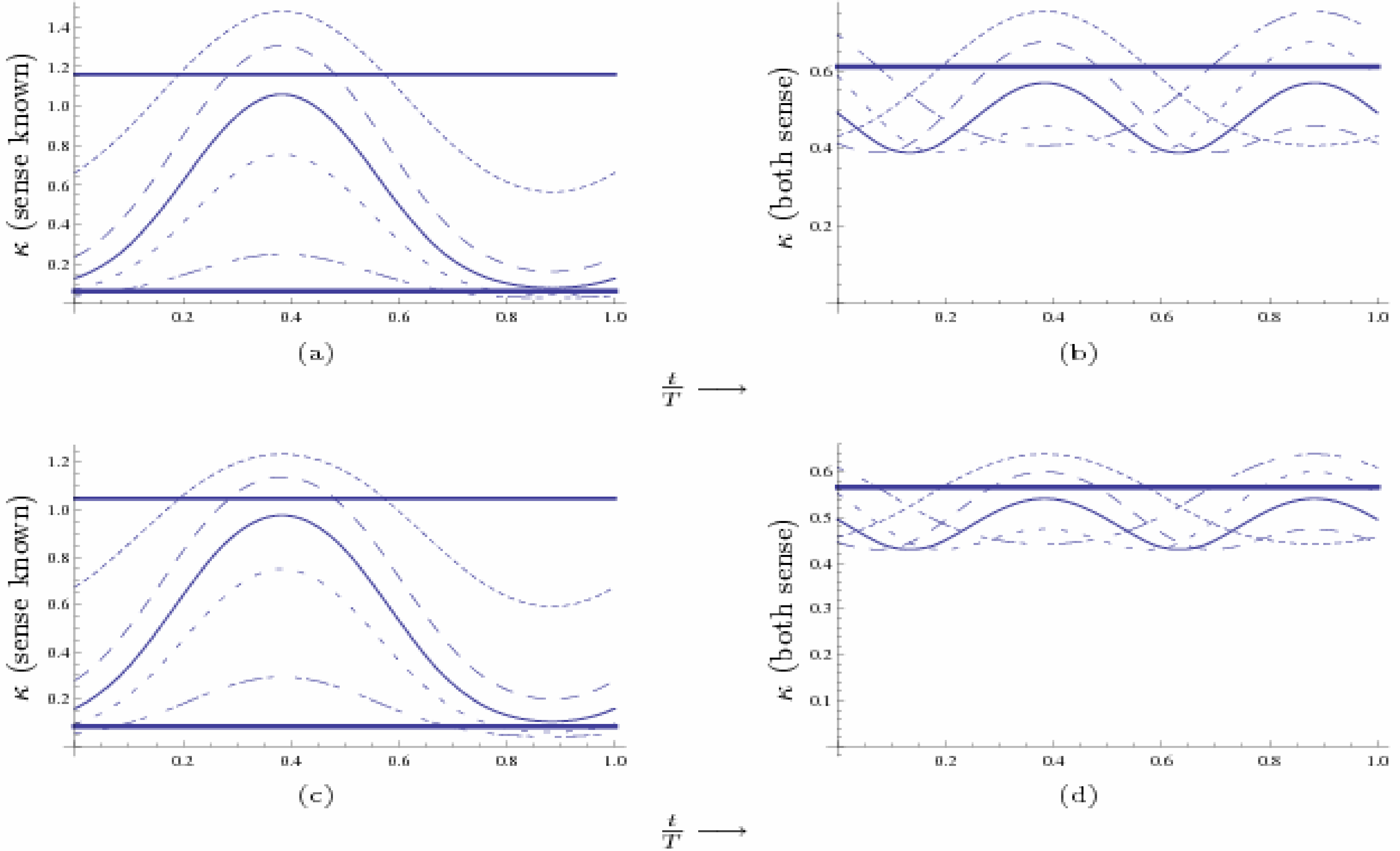


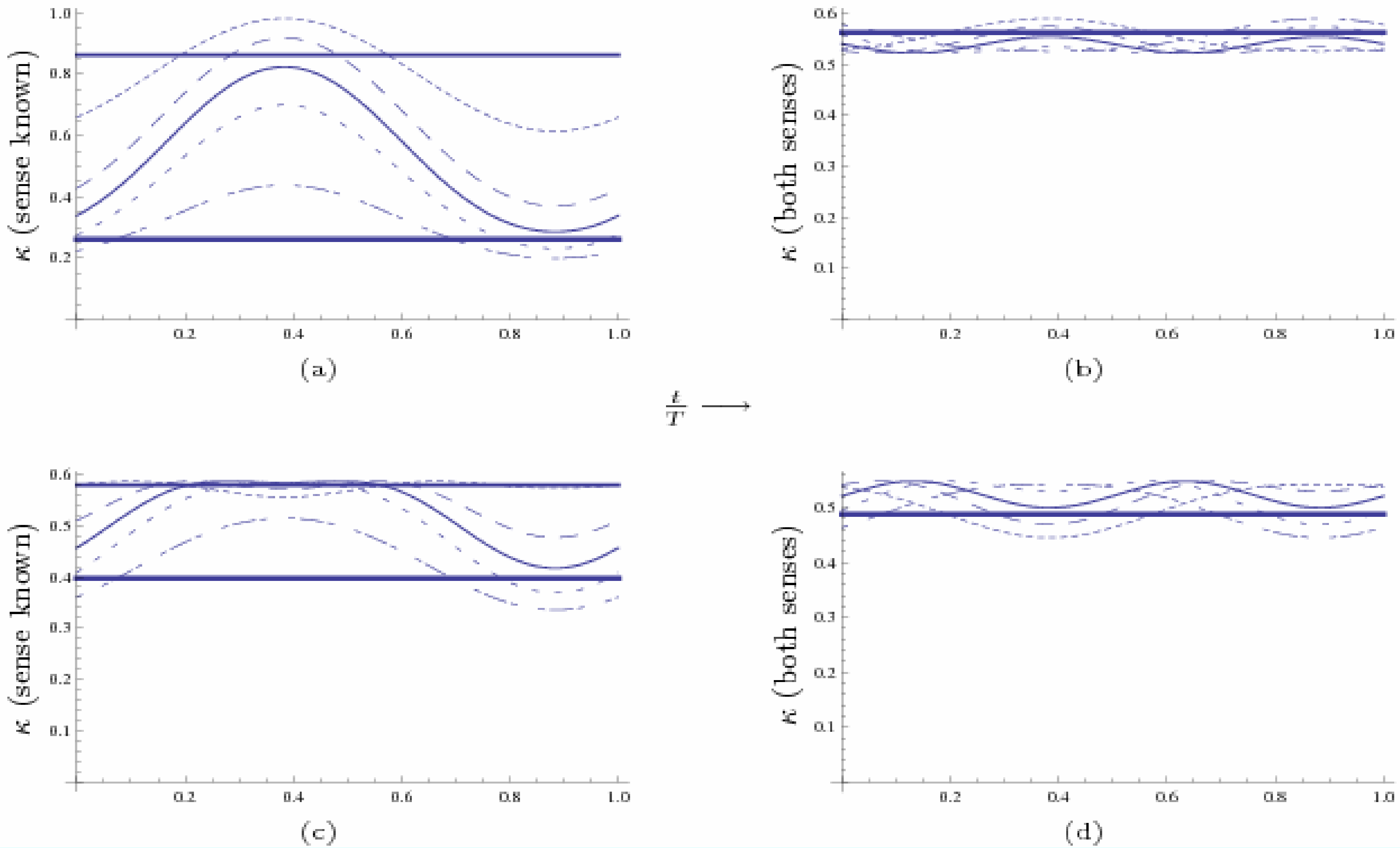
FIG. 18: Due to the diurnal motion of the Earth different angles Θ in galactic coordinates are sampled as the earth rotates. The angle Θ scanned by the direction of observation is shown for various inclinations δ. The intermediate thickness, the short dash, the long dash, the fine line, the long-short dash, the short-long-short dash and the thick line correspond to inclination $\delta = -\pi/2, -3\pi/10, -\pi/10, 0, \pi/10, 3\pi/10$ and $\pi/2$ respectively. We see that, for negative inclinations, the angle Θ can take values near π, i.e. opposite to the direction of the sun's velocity, where the rate attains its maximum.

Diurnal variation of the Event Rate for a light target. WIMP mass 10 GeV (top) and 100 GeV (bottom)



Diurnal variation of the Event Rate for a heavy target.

WIMP mass 10 GeV (top) and 100 GeV (bottom)



CONCLUSIONS: Non-directional recoil Exps

- The direct WIMP detection experiments have made impressive progress. They have reached sensitivities of 10^{-7} pb
- Given experimental results on a least three odd mass targets, all three nucleon cross sections (coherent, proton spin and neutron spin) can be extracted from the data.

CONCLUSIONS: Non-directional recoil Exps

IIa. The Modulation Amplitude h.

A good signature but:

- It depends on two unknown parameters, the LSP mass and the velocity distribution
- It is small, less than 2%.
- Its sign is also uncertain. It is positive for light targets. For heavy targets it is positive for light WIMPs and negative for heavy WIMPs

CONCLUSIONS: Non directional Exps.

IIb. Electron production during LSP-nucleus collisions

- During the neutralino-nucleus collisions, electrons may be kicked off the atom
- Electrons can be identified easier than nuclear recoils (Needed: low threshold (~0.25keV) TPC detectors)
- The branching ratio for this process depends on the atomic number, the threshold energies and the LSP mass.
- For a threshold energy of 0.25 keV the ionization event rate in the case of a heavy target can exceed the rate for recoils by an order of magnitude.
- Detection of hard X-rays (30 keV) seams feasible (branching about 4%)

CONCLUSIONS: III. directional Exps

- 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)
- The modulation in a plane perpendicular to the sun's velocity can be quite large (up to 40%). The time of the maximum depends on the direction of observation.

CONCLUSIONS: III. directional Exps (continued)

- As the Earth rotates the angle between the direction of observation and the sun's velocity is changing. Thus:
- 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 for negative inclinations.
- The variation persists even if the sense of direction is not known, but the effect is smaller
- The experiments are hard, but the rewards are high …

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!

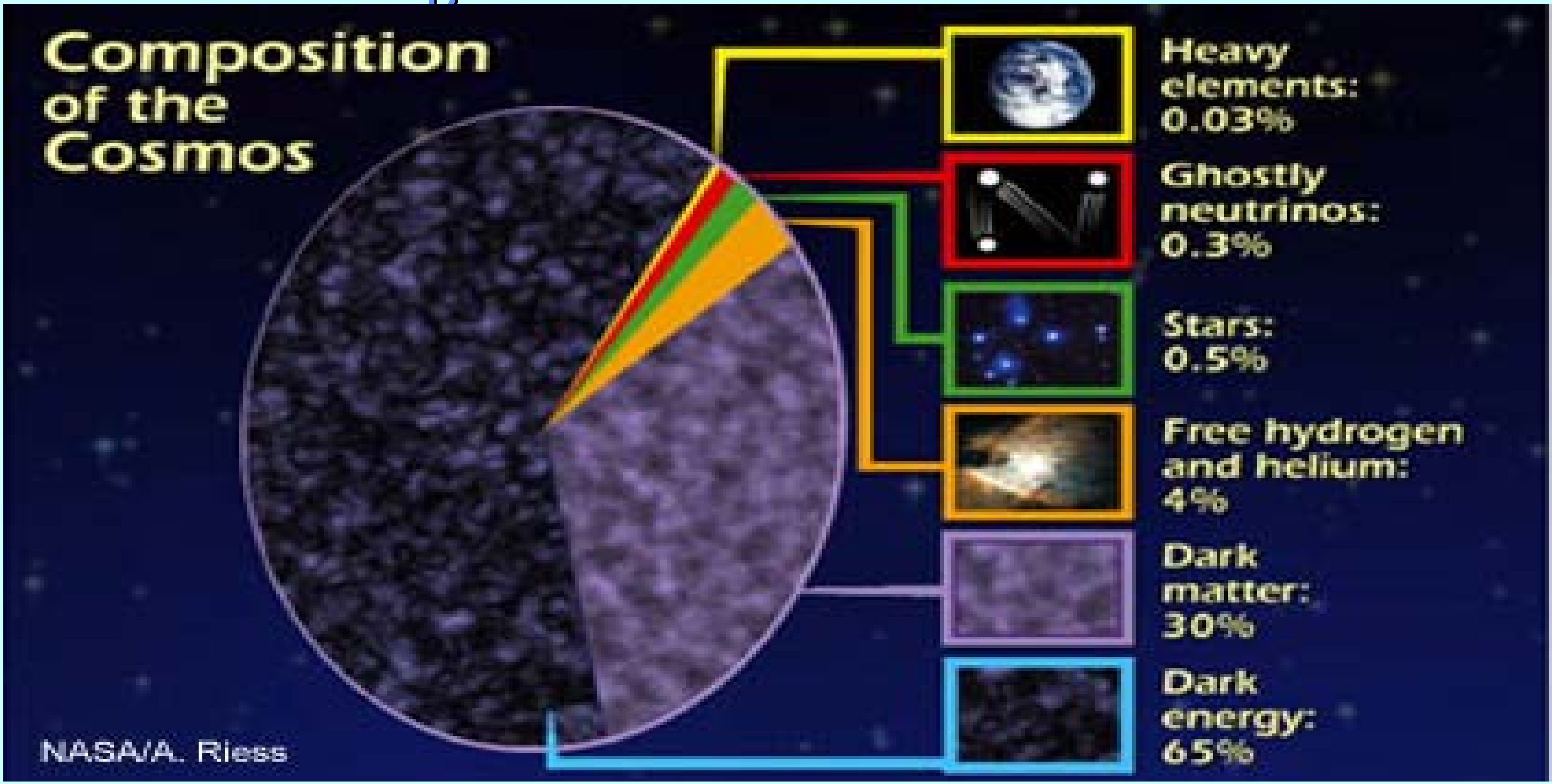
(Such a reward!)

- THE END

Slicing the Pie of the Cosmos WMAP5:

Ω_{CDM} =0.24±0.02, Ω_{Λ} =0.72±0.04,

Ω_{b} =0.042±0.003



II:LSP Velocity Distributions and density

- Conventional: Isothermal models
- (1) Maxwell-Boltzmann (symmetric or axially symmetric)
  with characteristic velocity equal to the sun's velocity around the center of the galaxy, $u_{MB} = u_0 = 220$ km/s,
  and escape velocity $u_{esc} = 2.84 u_0$ put in by hand.
- (2) Modification of M-B characteristic velocity u_{MB} following the interaction of dark matter with dark energy:
  $u_{MB} = n u_0$, $u_{esc} = n 2.84\ u_0$, $n>1$
  (Tetradis, Feassler and JDV)
- Halow models employing Eddington's approach: **Start with density $\rho=\rho(\mathbf{r})$. Solve Poisson's equation to get** $\Phi = \Phi(\mathbf{r})$ ⇓
  $\rho=\rho(\Phi)$ ⇓ distribution $f(\mathbf{r},\mathbf{v})$ (JDV-Owen)
  ⑩Also yield approximate axially symmrtric M-B
- **Axially symmetric velocity distributions extracted from realistic halo densities via simulations Tsallis type functions (Hansen, Host and JDV)**
- Other non-thermal models:
  -Caustic rings (Sikivie , JDV), WIMP's in bound orbits etc
  -Sgr Dwarf galaxy⑩anisotropic flux, (Green & Spooner)

The Eddington approach

As we have seen in the introduction the matter distribution can be given(Vergados & Owen 2007) as follows

$$dM = 2\pi \; f(\Phi(\mathbf{r}), \upsilon_r, \upsilon_t) \; dx \; dy \; dz \; \upsilon_t \; d\upsilon_t \; d\upsilon_r \tag{1}$$

where the function f the distribution function, which depends on $\mathbf{r}$ through the potential $\Phi(\mathbf{r})$ and the tangential and radial velocities υ_t and υ_r. We will limit ourselves in spherically symmetric systems. Then the density of matter $\rho(|r|)$ satisfies the equation:

$$d\rho = 2\pi \; f(\Phi(|\mathbf{r}|), \upsilon_r, \upsilon_t) \;\; \upsilon_t \; d\upsilon_t \; d\upsilon_r \tag{2}$$

The distribution is a function of the total energy:

- The energy E is $\Phi(r) + \frac{\upsilon^2}{2}$. Then

$$\rho(r) = 4\pi \int f(\Phi(r) + \frac{\upsilon^2}{2})\upsilon^2 d\upsilon = 4\pi \int_{\Phi}^{0} f(E)\sqrt{2(E-\Phi)}dE \tag{3}$$

This is an integral equation of the Abel type. It can be inverted to yield:

$$f(E) = \frac{\sqrt{2}}{4\pi^2}\frac{d}{dE}\int_{E}^{0}\frac{d\Phi}{\sqrt{\Phi - E}}\frac{d\rho}{d\Phi} \tag{4}$$

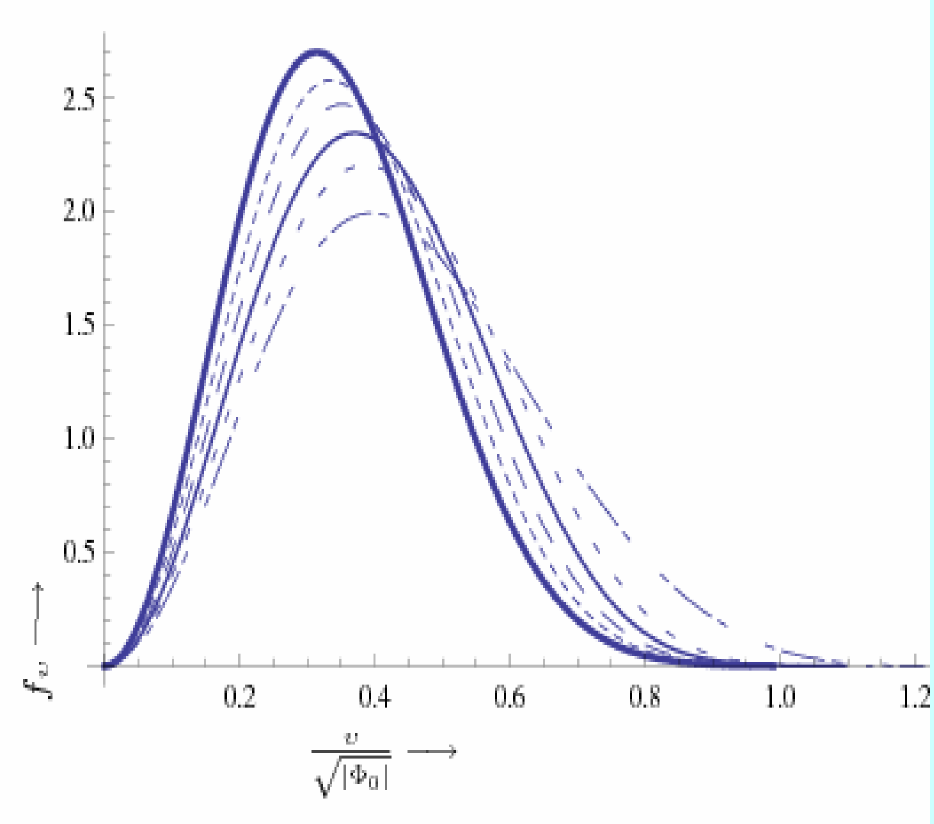
The above equation can be rewritten as:

$$f(E) = \frac{1}{2\sqrt{2}\pi^2}\left[\int_{E}^{0}\frac{d\Phi}{\sqrt{\Phi - E}}\frac{d^2\rho}{d\Phi^2} - \frac{1}{\sqrt{-E}}\frac{d\rho}{d\Phi}|_{\Phi=0}\right] \tag{5}$$

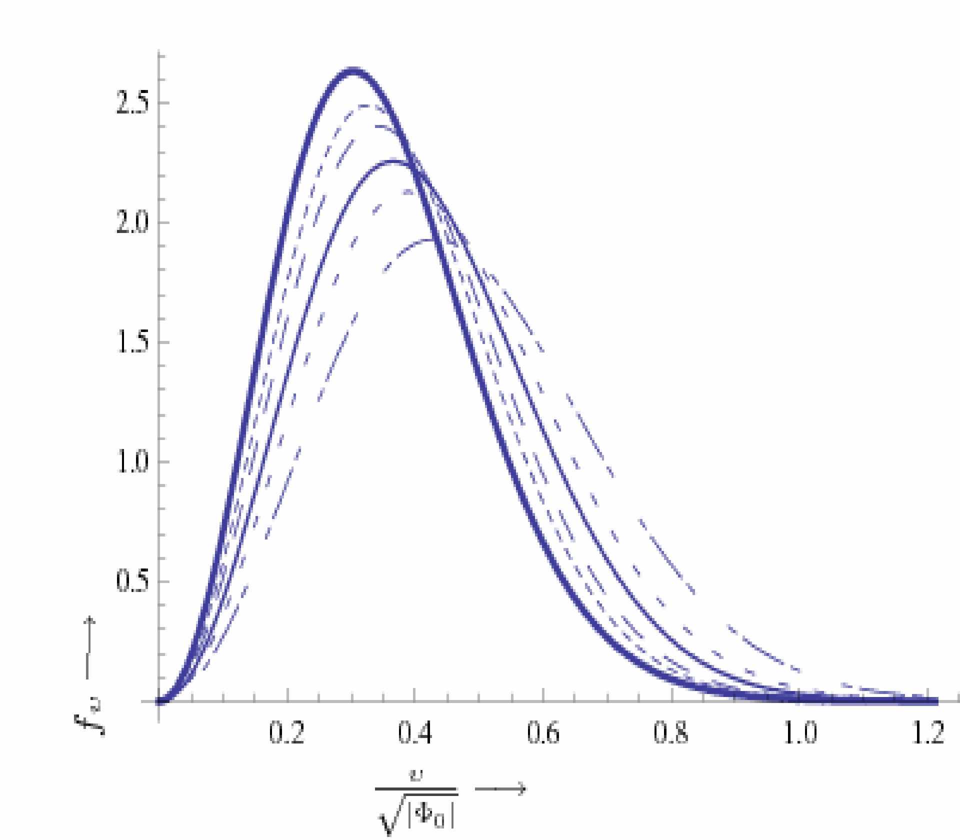
In order to proceed it is necessary to know the density as a function of the potential. In practice only in few cases this can be done analytically. This, however, is not a problem, since this function can be given parametrically by the set $(\rho(r), \Phi(r))$ with the position r as a parameter. The potential $\Phi(r)$ for a given density $\rho(r)$ is obtained by solving Poisson's equation.

Velocity distribution obtained in the Eddington approach

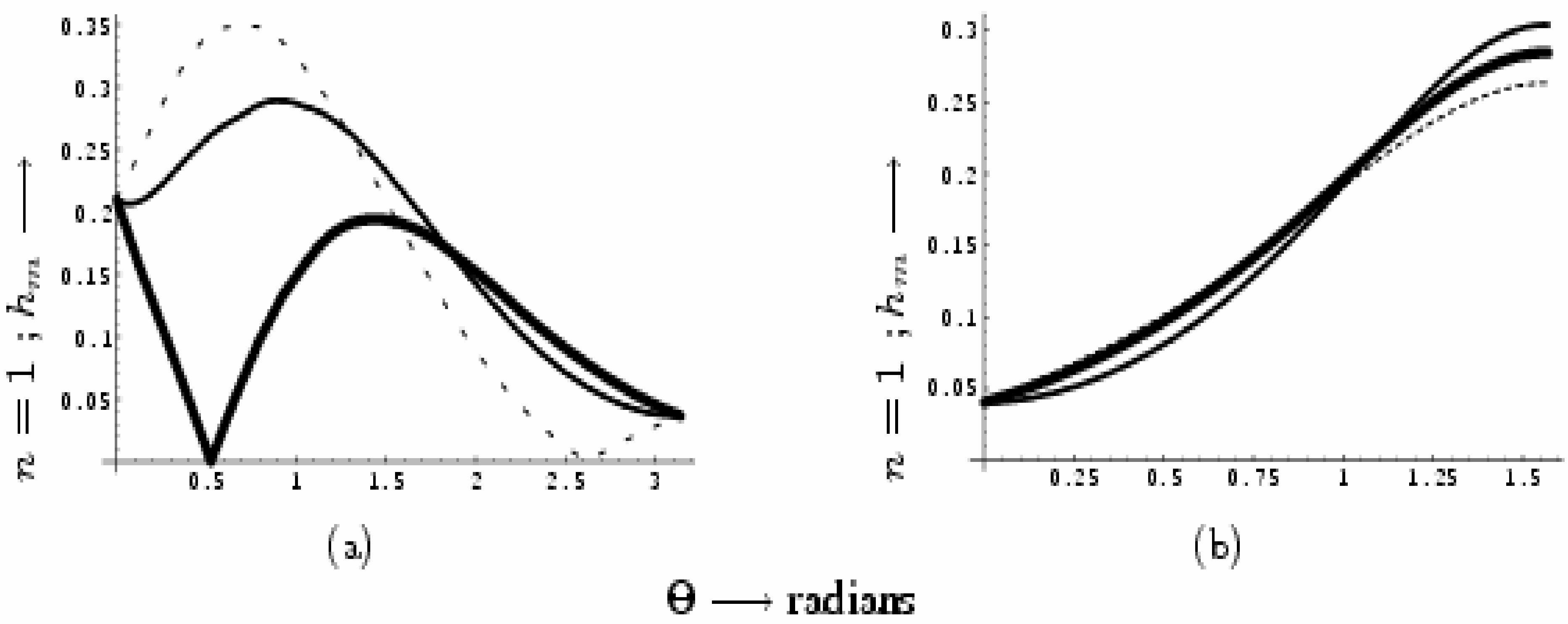
NFW Halo Density profile



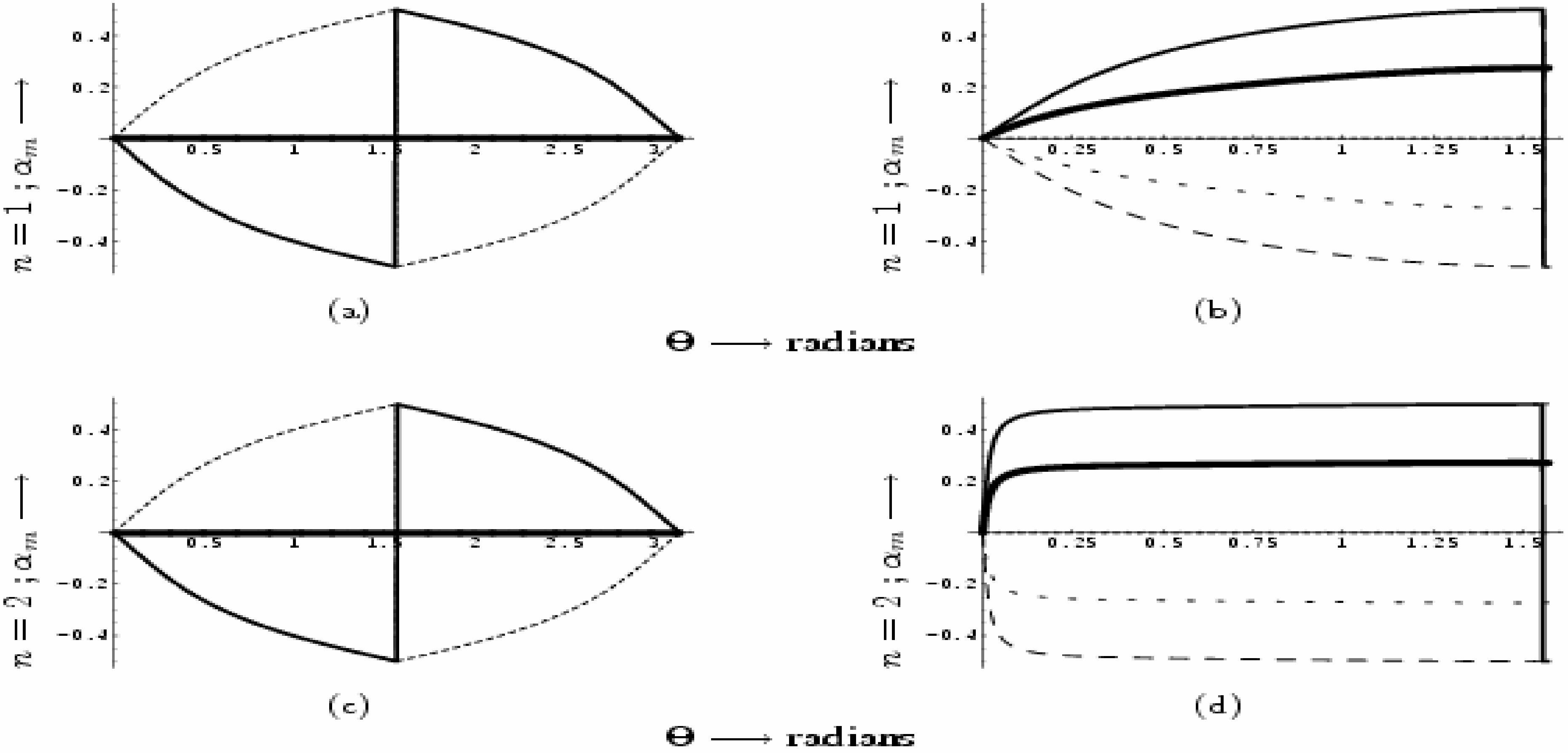
Axially symmetric M-B



The parameter h_m vs the polar angle Θ in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right) fine, thick, dashed <->Φ=(0, π/2, π)



The phase α_m vs the polar angle in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right)



From the celestial to galactic coordinates

The galactic frame is defined by:

- the galactic pole with ascention $\alpha = 12^h\ 51^m\ 26.282^s$ and inclination $\delta = +27^0\ 7'\ 42.01''$
- the galactic center at $\alpha = 17^h\ 45^m\ 37.224^s$, $\delta = -(28^0\ 56'\ 10.23'')$.

Thus the galactic unit vectors can be expressed in terms of the celestial ones:

$$\hat{y} = -0.868\hat{i} - 0.198\hat{j} + 0.456\hat{k}$$

(galactic axis)

$$\hat{x} = -\hat{s} = 0.055\hat{i} + 0.873\hat{j} + 0.483\hat{k}$$

(radially out towards the sun)

$$\hat{z} = \hat{x} \times \hat{y} = 0.494\hat{i} - 0.445\hat{j} + 0.747\hat{k}$$

direction of the sun's motion

Note in our system the x-axis is opposite to the s-axis used by the astronomers.

The circular path in the galactic system

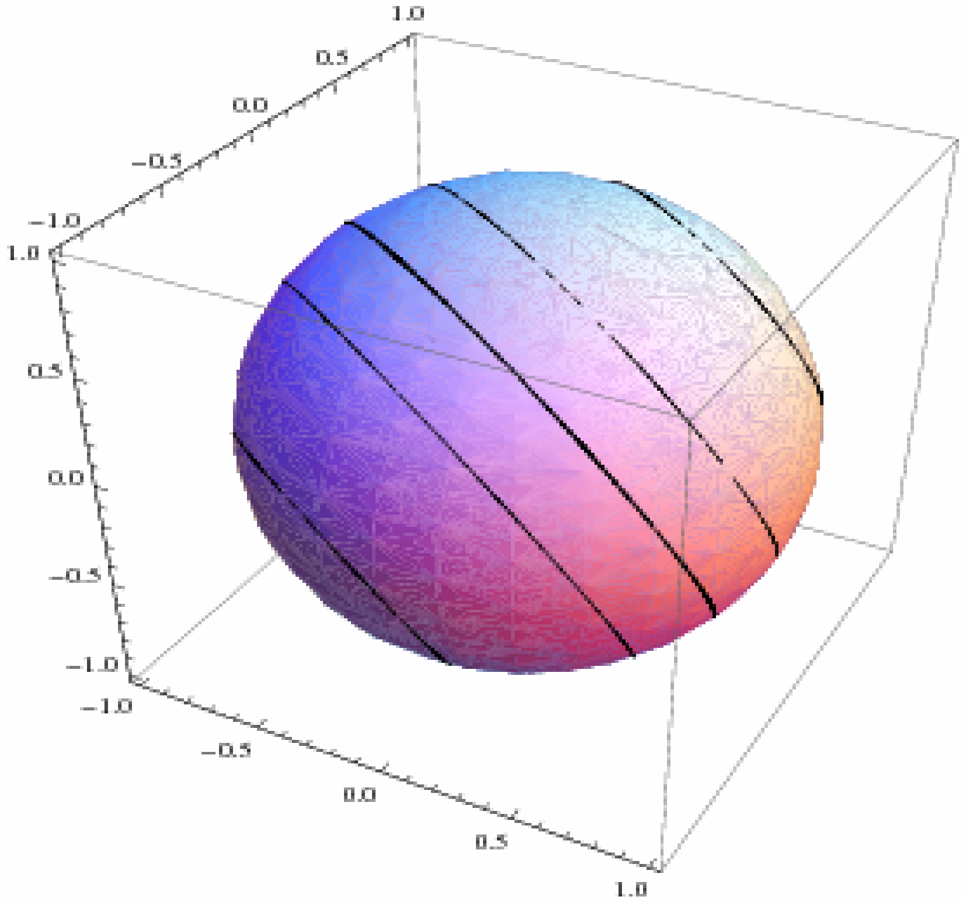
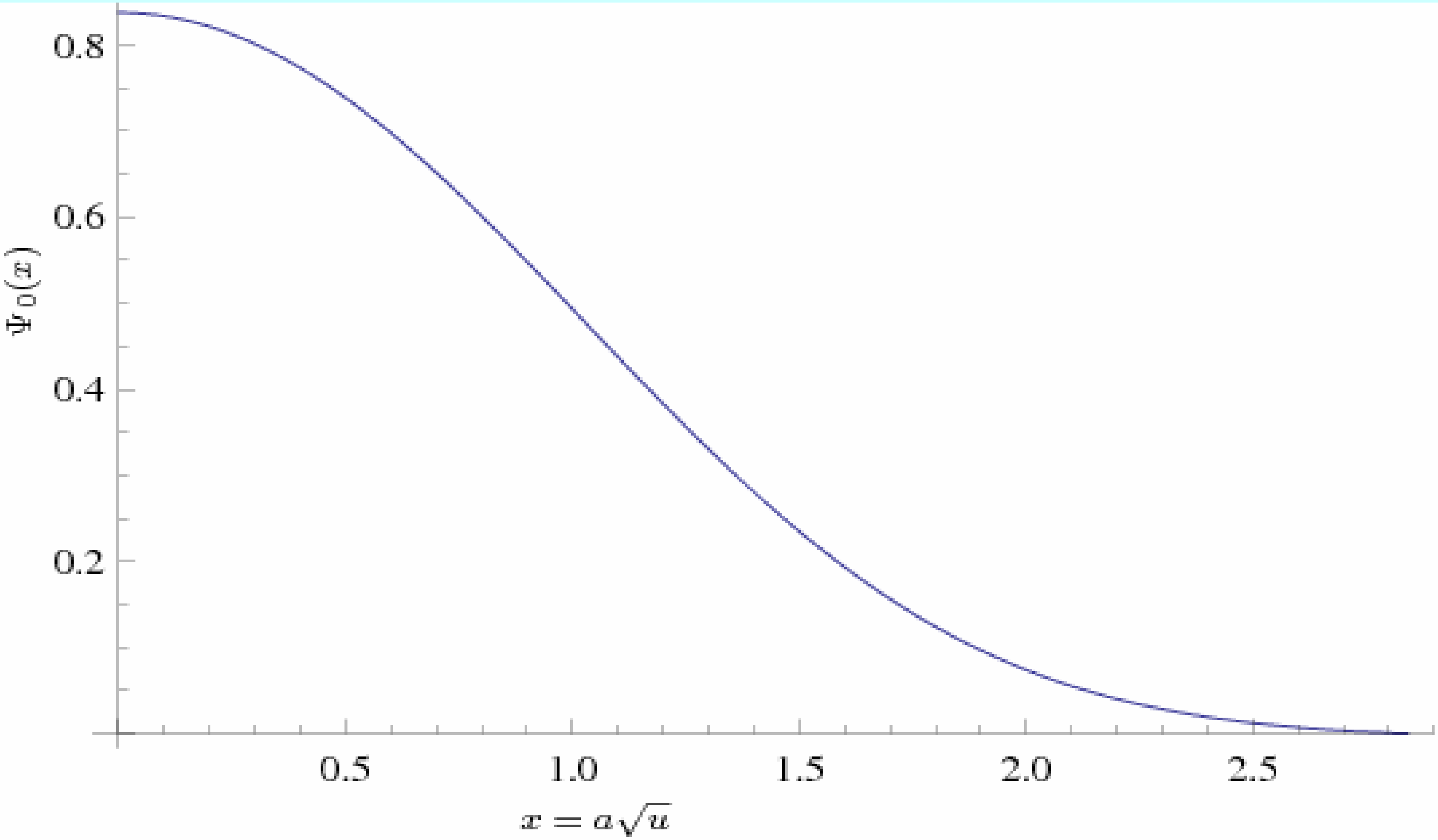


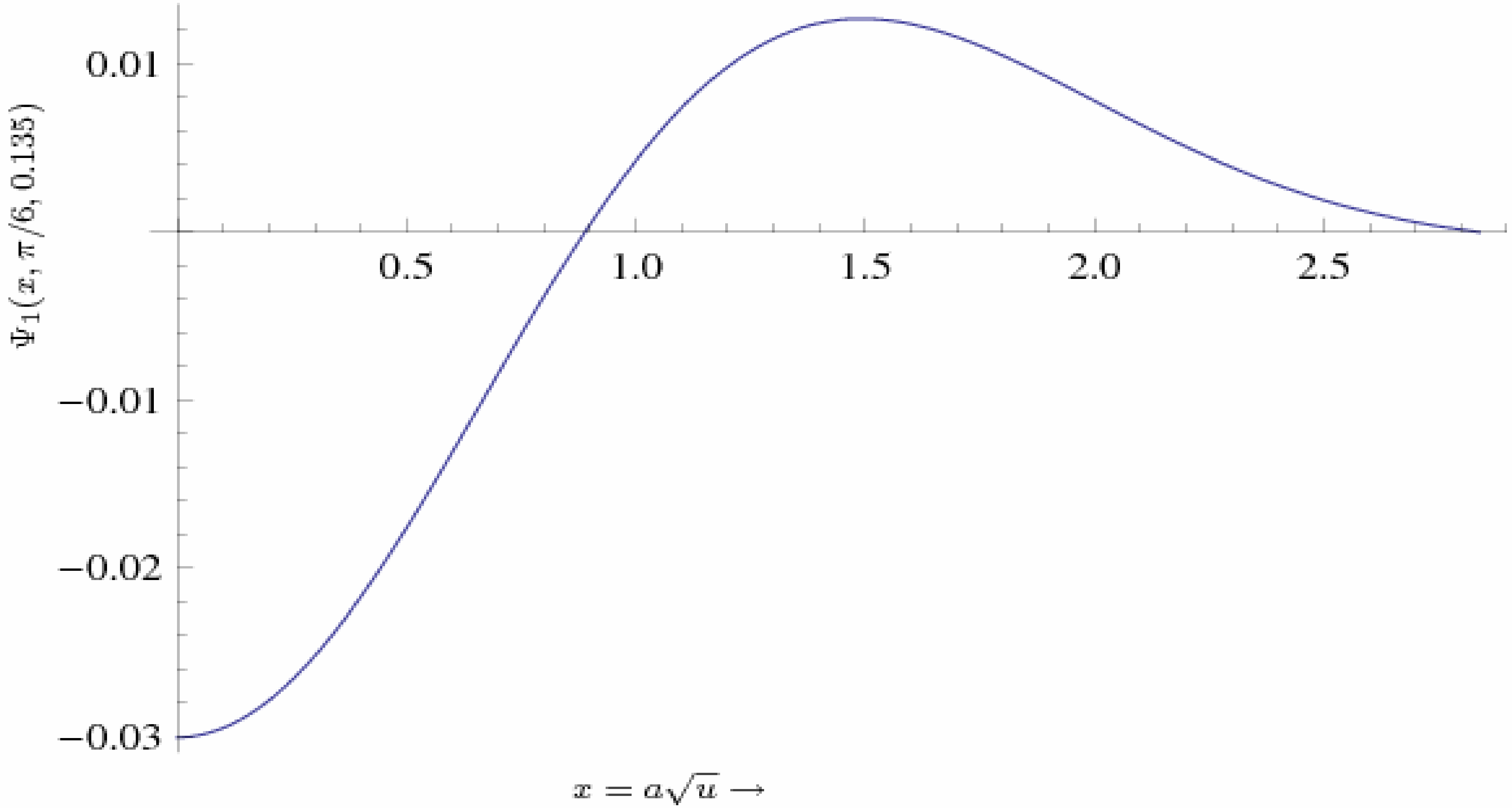
FIG. 19: The circular path followed by the point of the direction of observation as seen in the galactic system due to the Earth's rotation for various inclinations δ. The galactic axis is indicated upward. For the path notation see Fig. 18.

Differential Event rate

(time averaged) Form factor not included



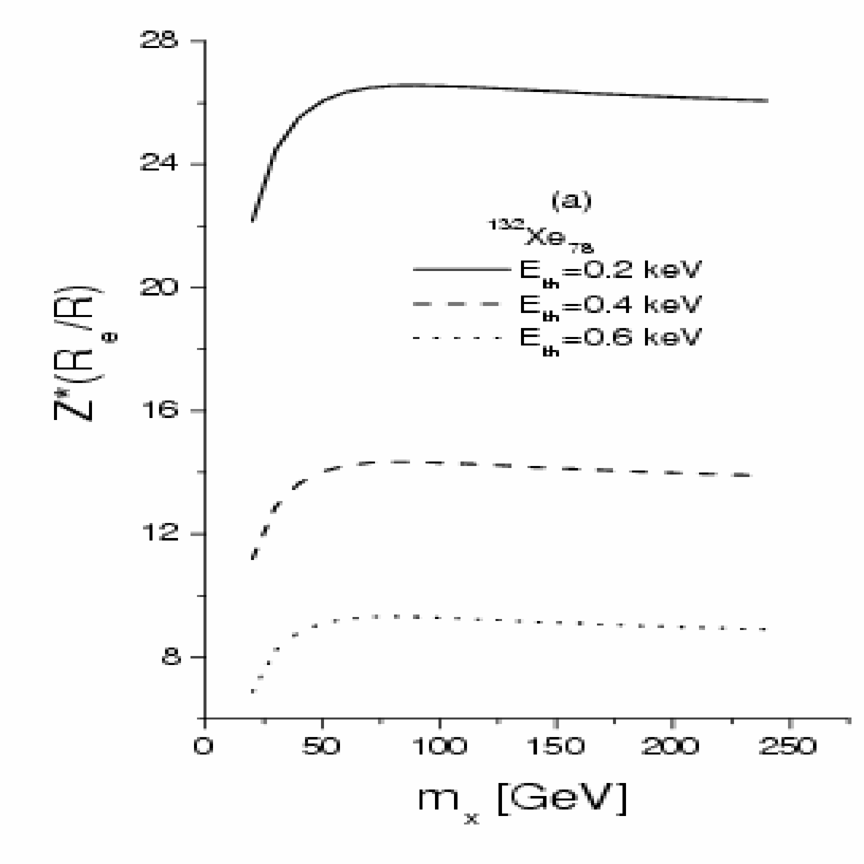
Modulated differential event Rate (Form factor not included)

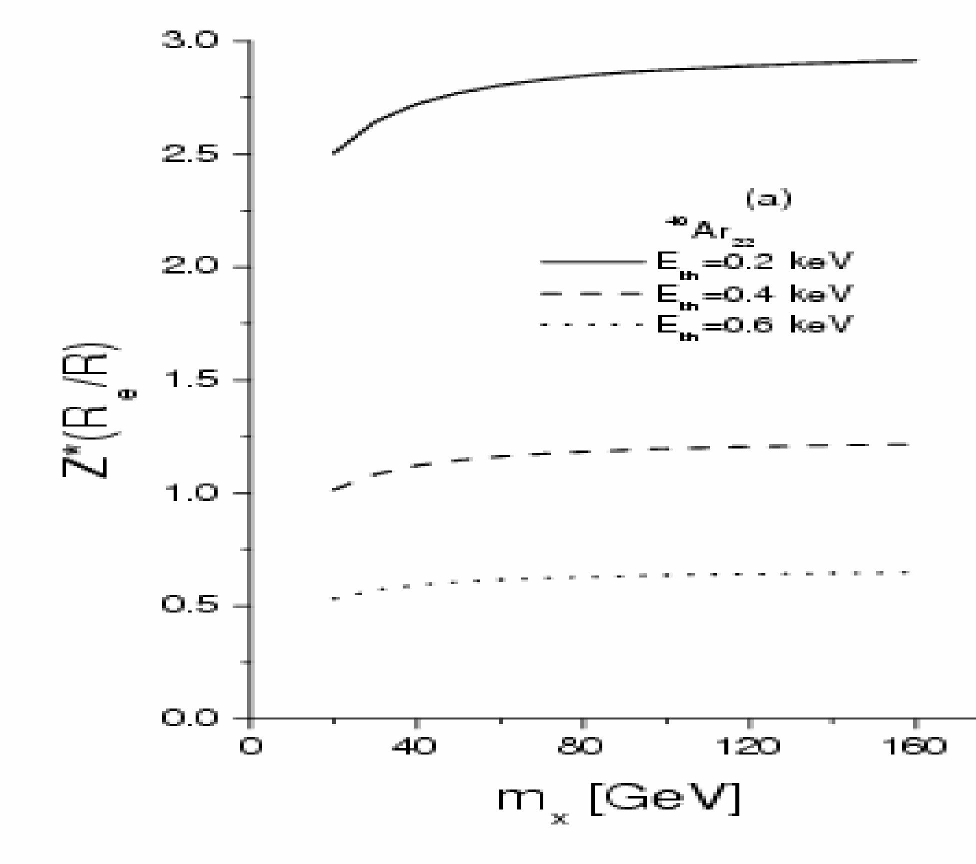


NON RECOIL MEASUREMENTS

- (a) Measurement of ionization electrons produced directly during the WIMP-nucleus collisions
- (b) Measurement of hard X-rays following the de-excitation of the atom in (a)
- (c) Excitation of the Nucleus and observation of the de-excitation γ rays

Relative rate for electron ionization (there are Z electrons in an atom!)





Detection of hard X-rays

- After the ionization there is a probability for a K or L hole
- This hole de-excites via emitting X-rays or Auger electrons.
- the fraction of X-rays per recoil is:

  $\sigma_{X(n\ell)}/\sigma_r = b_{nl}(\sigma_{n\ell}/\sigma_r)$ with $\sigma_{n\ell}/\sigma_r$ the relative ionization rate per orbit and $b_{n\ell}$ the fluorescence ratio (determined experimentally)

The K X-ray BR in WIMP interactions in ^{132}Xe for masses: L⑩30GeV, M⑩100GeV, H⑩300GeV

K X-ray	$E_K(K_{ij})$ keV	$B_K(K_{ij})$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_L$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_M$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_H$
$K_{\alpha 2}$	29.5	0.284	0.0086	0.0560	0.0645
$K_{\alpha 1}$	29.8	0.527	0.0160	0.1036	0.1196
$K_{\beta 1}$	33.6	0.154	0.0047	0.0303	0.0350
$K_{\beta 2}$	34.4	0.034	0.0010	0.0067	0.0077

Excitation of the nucleus:

The average WIMP energy is:

- $<T_{\chi}> \approx 40$ keV n^2 $(m_{\chi}/100\text{GeV})$
- $T_{\chi,max} \approx$ 215 keV n^2 $(m_{\chi}/100\text{GeV})$. Thus
- m_{χ} =500GeV, n=2 $\Downarrow$
  $<T_{\chi}> \approx 0.8$ MeV, $T_{\chi,max} \approx$ 4 MeV
- So excitation of the nucleus appears possible in exotic models with very heavy WIMPs

Unfortunately, Not all available energy is exploitable!

- For ground to ground transitions (q⑩momentum, Q ⑩ energy)

$$q = 2\frac{A m_p M_\chi}{A m_p + M_\chi}\beta\xi \quad , \quad Q = A m_p\left(1 + \frac{A m_p}{M_\chi}\right)^{-2}\beta^2\xi^2 \quad , \quad \beta = \upsilon/c$$

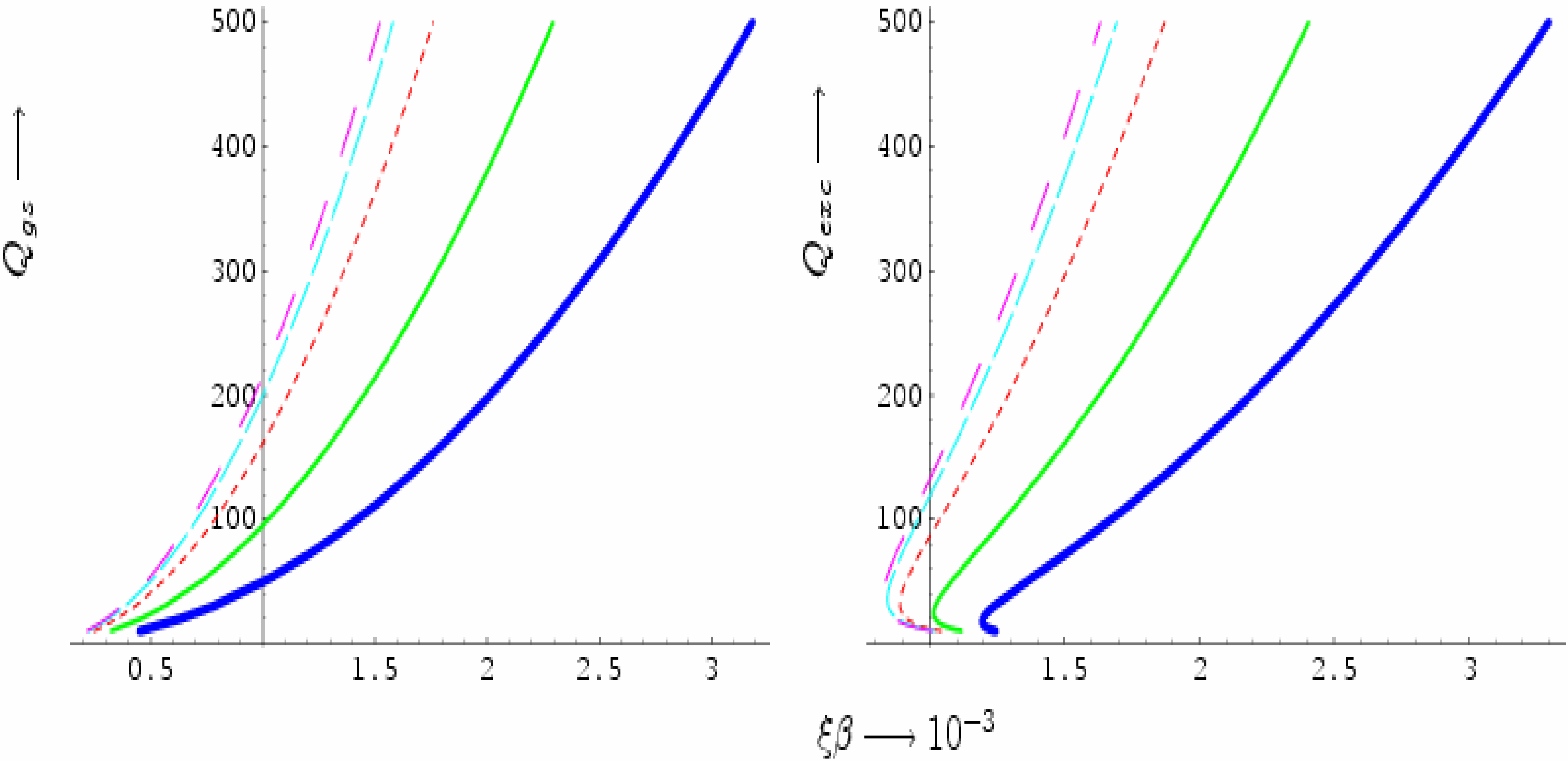
- For Transitions to excited states

$$\frac{(A m_p + M_\chi)Q}{M_\chi} + \Delta - \sqrt{2 A m_p Q}\,\beta\xi = 0 \ , \ \beta = \upsilon/c \qquad (1)$$

where $\beta = \upsilon/c$ with υ the wimp velocity, ξ the cosine of the angle between the oncoming WIMP and the outgoing nucleus and Δ the excitation energy of the nuclear state.

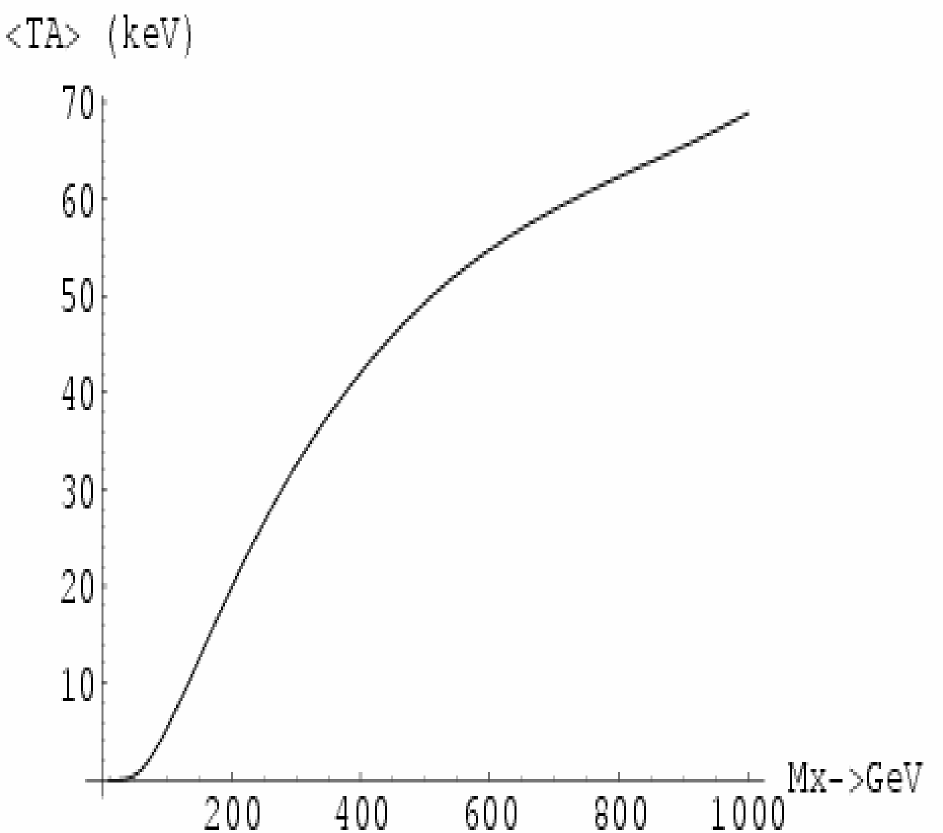
- Both are peaked around ξ=1

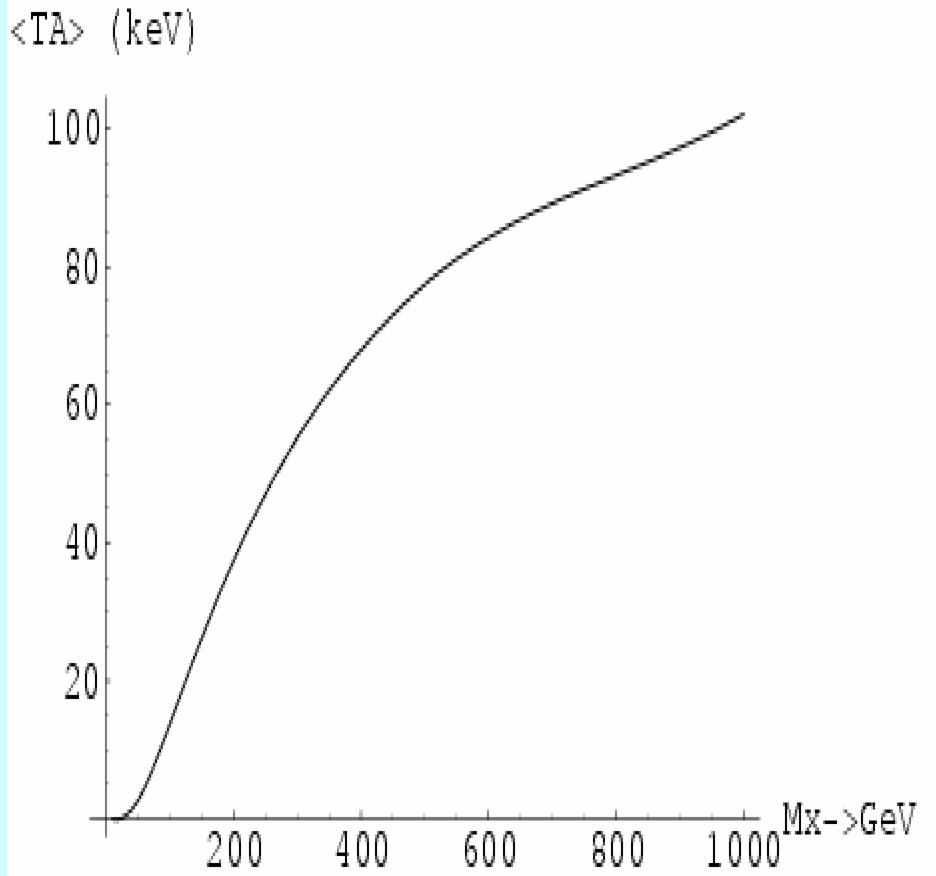
The recoil energy in keV as a function of the WIMP velocity, in the case of A=127. Elastic scattering on the left and transitions to the Δ=50 keV excited state on the right. Shown for WIMP masses in the 100, 200, 500, 1000 and 1500 GeV. $<\xi\beta>=10^{-3}$



The average nuclear recoil energy:

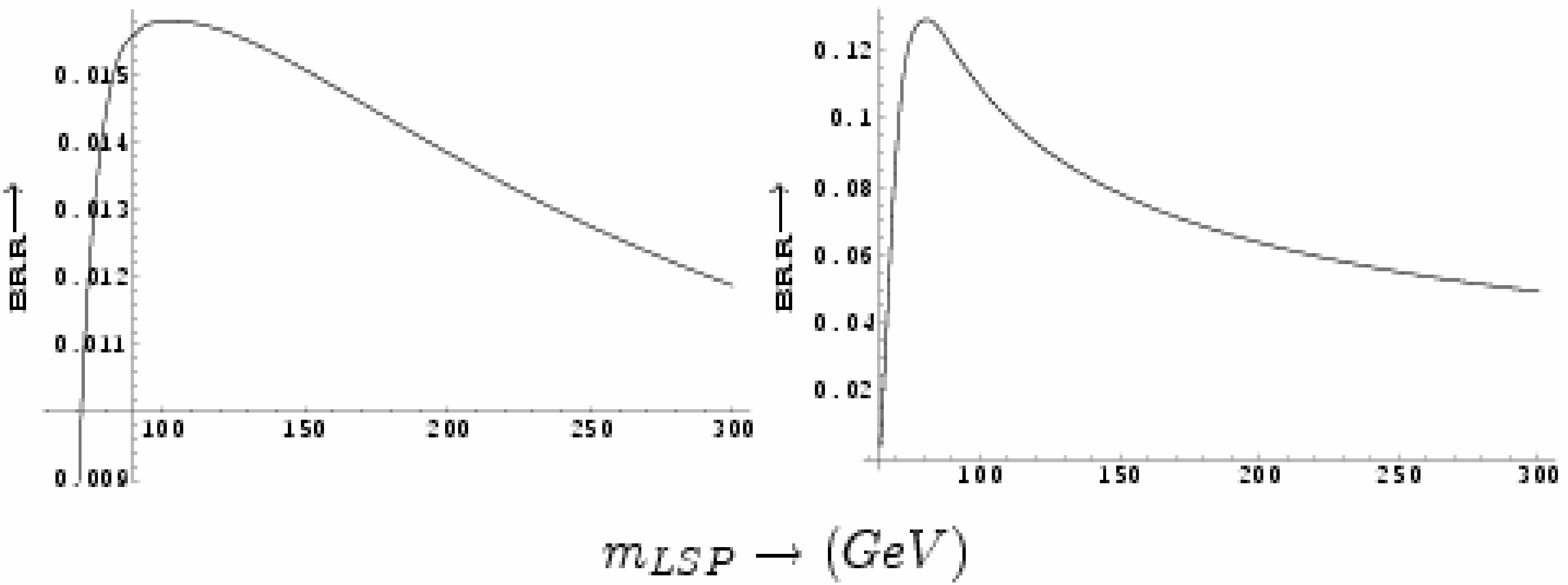
A=127; Δ=50 keV (left), Δ=30 keV (right)





BR for transitions to the first excited state at 50 keV of I vs LSP mass (Ejiri; Quentin, Strottman and JDV) Relative to nucleon recoil. Quenching not included in the recoil

i) Left ➓ E_{th} =0 keV ii) Right ➓ E_{th} =10 keV



CONCLUSIONS: Electron production during LSP-nucleus collisions

- During the neutralino-nucleus collisions, electrons may be kicked off the atom
- Electrons can be identified easier than nuclear recoils (Needed: low threshold (~0.25keV) TPC detectors)
- The branching ratio for this process depends on the atomic number, the threshold energies and the LSP mass.
- For a threshold energy of 0.25 keV the ionization event rate in the case of a heavy target can exceed the rate for recoils by an order of magnitude.
- Detection of hard X-rays seams more feasible

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!

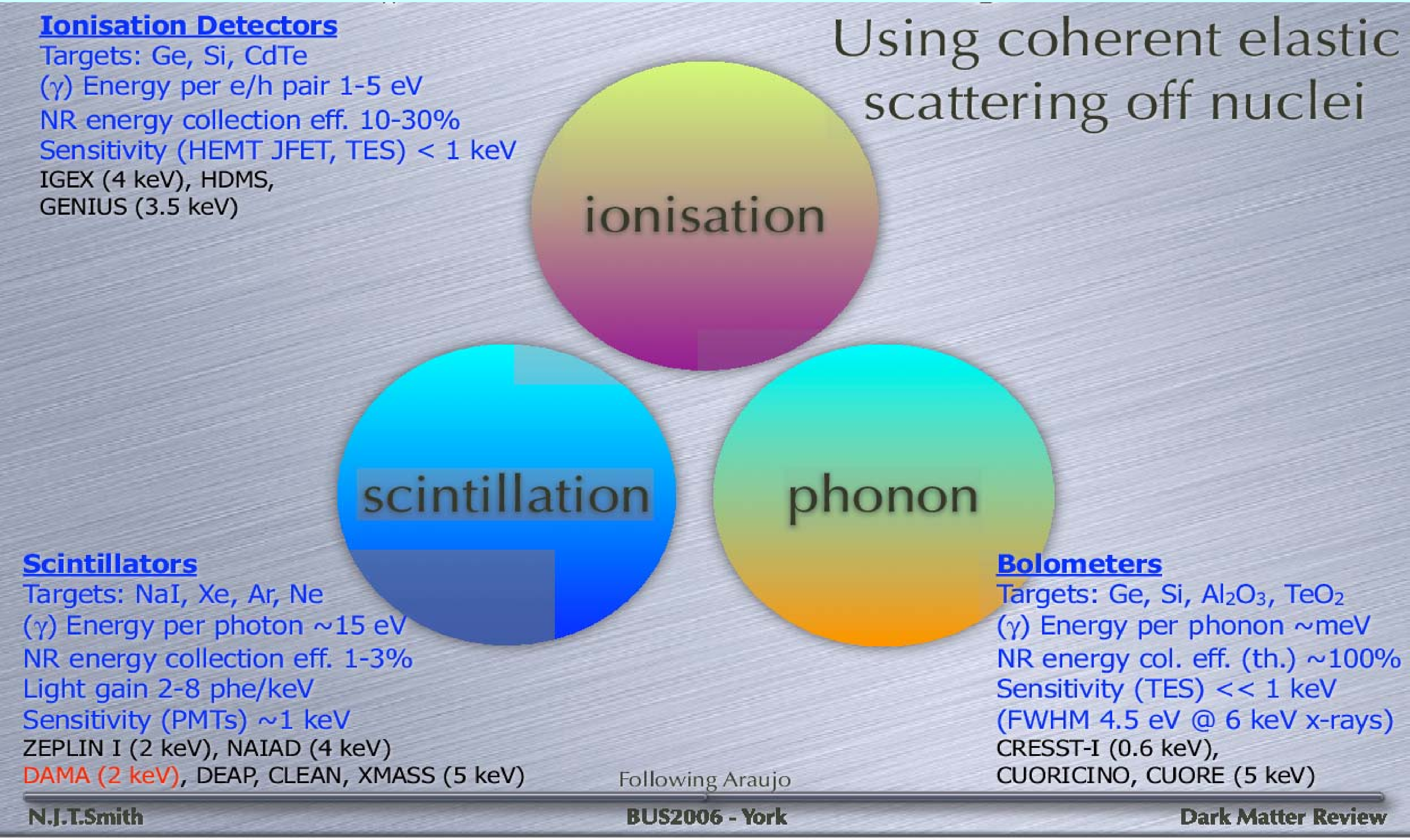
He sternly replied:

-Imagine, though, that it works!

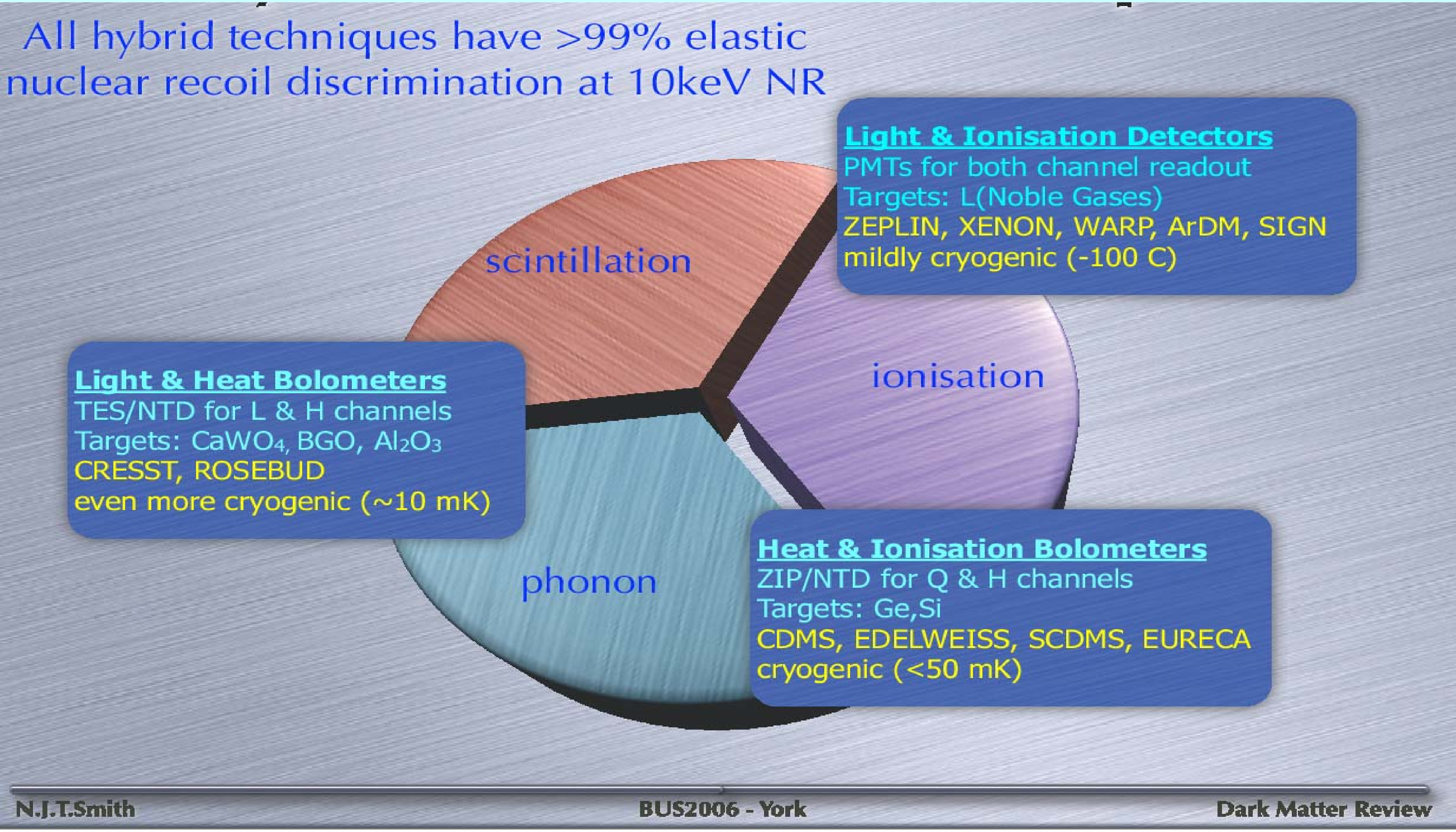
(Such a reward!)

- THE END

Techniques for direct WIMP detection

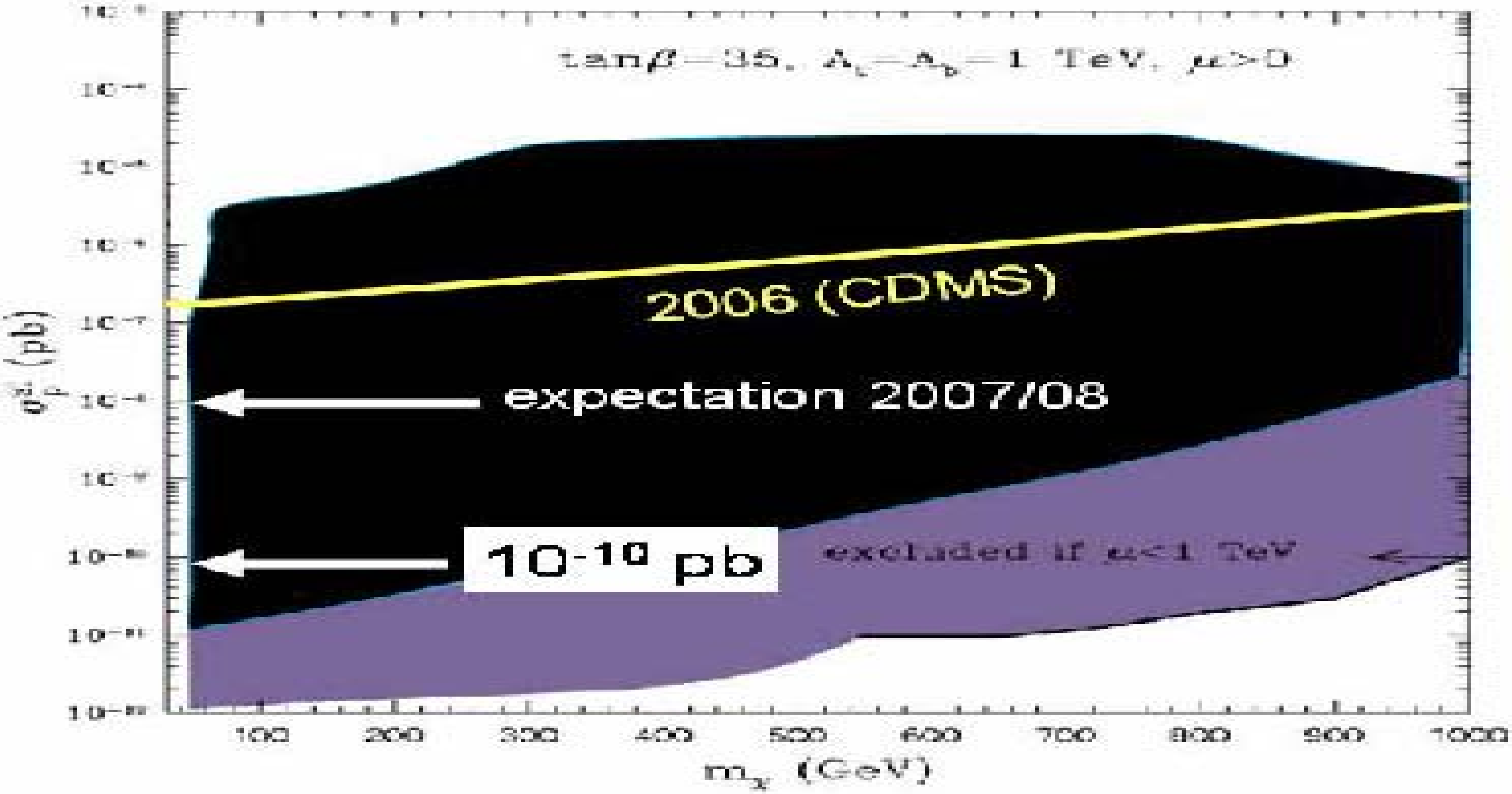


Techniques for direct WIMP detection



Another view (ApPEC 19/10/06)

Blue SUSY calculations (parameters on top)



A: Conversion of the energy of the recoiling nucleus into detectable form (light, heat, ionization etc.)

- The WIMP is non relativistic,< β>≈10^{-3}.

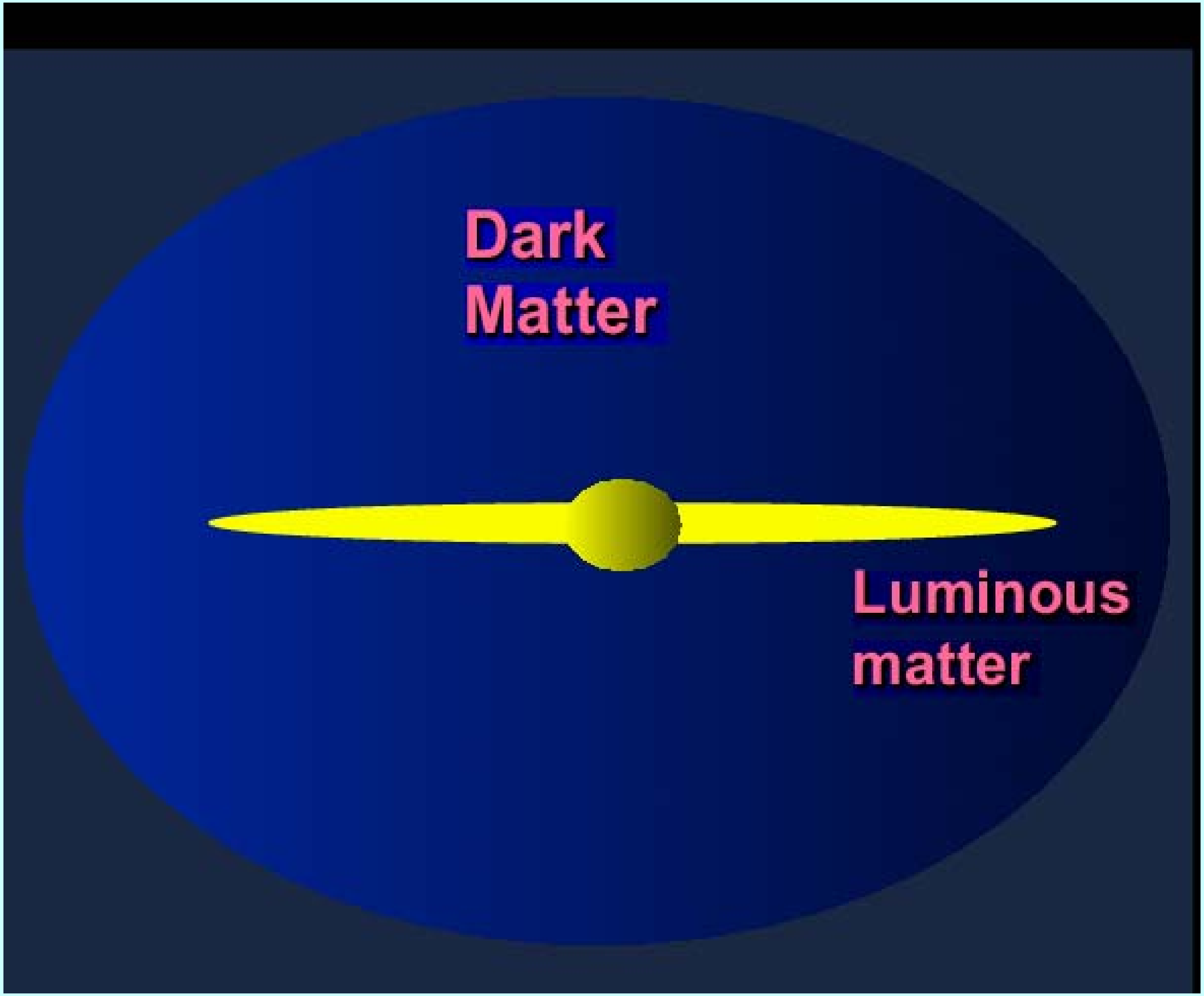
$$\langle T^{0}_{\tilde{\chi}} \rangle = 50keV \frac{m^{0}_{\tilde{\chi}}}{100GeV}$$

- With few exceptions, it cannot excite the nucleus. It only scatters off elastically:

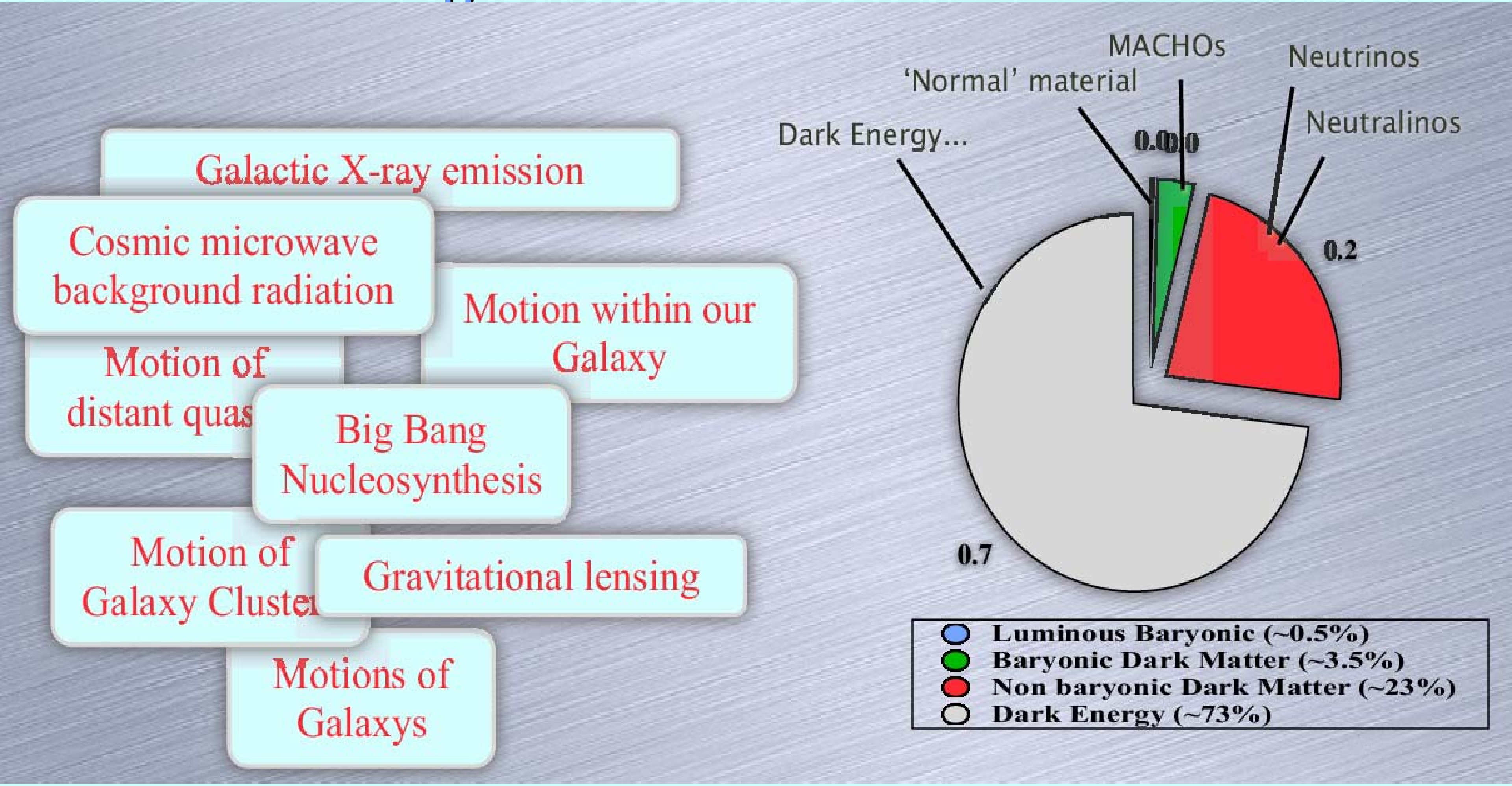
$$\tilde{\chi}^0(\mathbf{p}_0) + (A,Z)(0) \longrightarrow \tilde{\chi}^0(\mathbf{p}_0 - \mathbf{q}) + (A,Z)(\mathbf{q})$$

- Measuring the energy of the recoiling nucleus is extremely hard:
  -Low event rate (much less than 10 per Kg of target per year are expected).
  -Bothersome backgrounds (the signal is not very characteristic).
  -Threshold effects.
  -Quenching factors.

If we could see Dark Matter

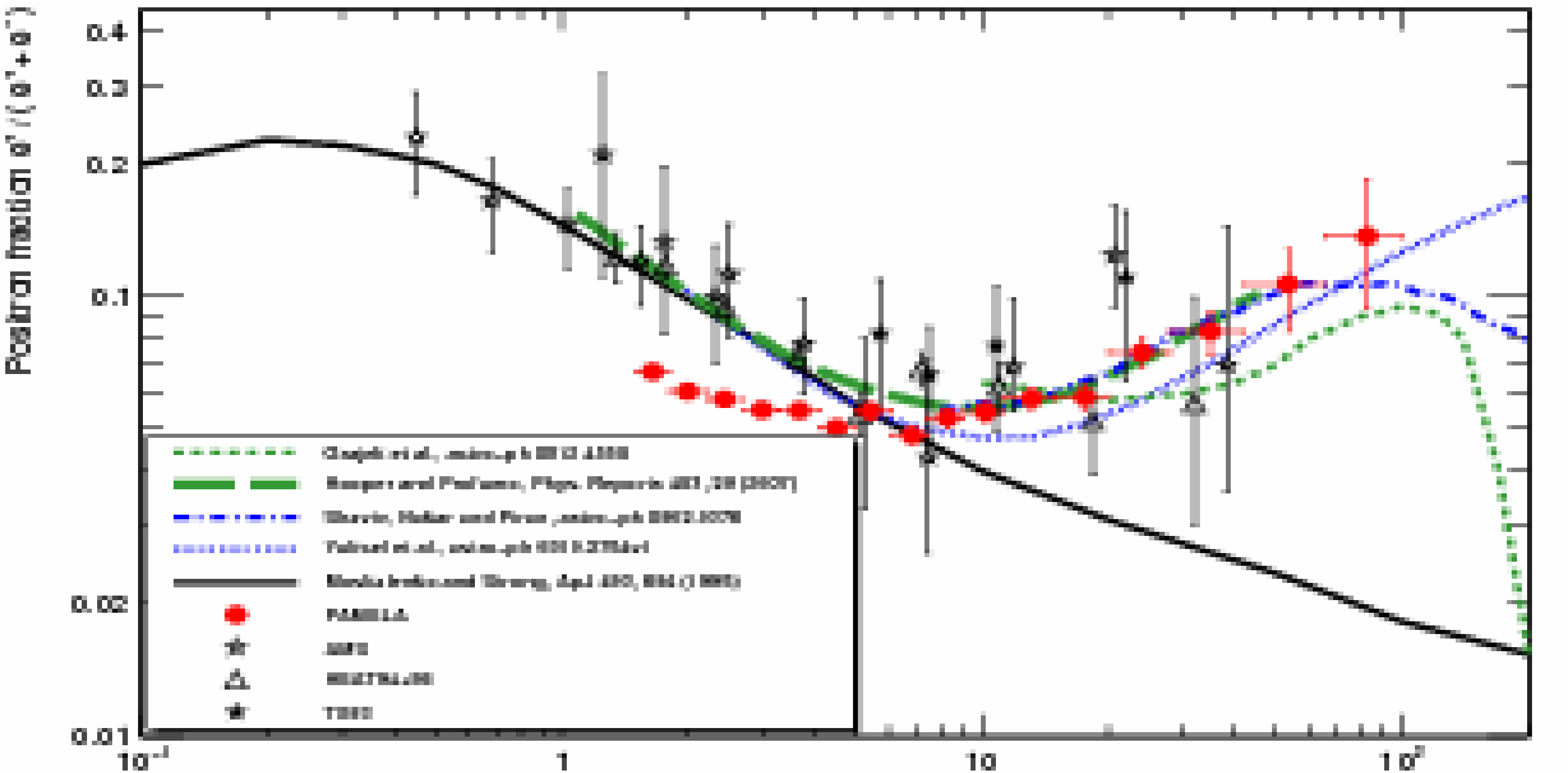


Slicing the Pie of the Cosmos WMAP3: $\Omega_{CDM} = 0.24 \pm 0.02$, $\Omega_\Lambda = 0.72 \pm 0.04$, $\Omega_b = 0.042 \pm 0.003$



The positron excess in the high energy region of the PAMELA Experiment (red dots) with predictions of secondary positron production

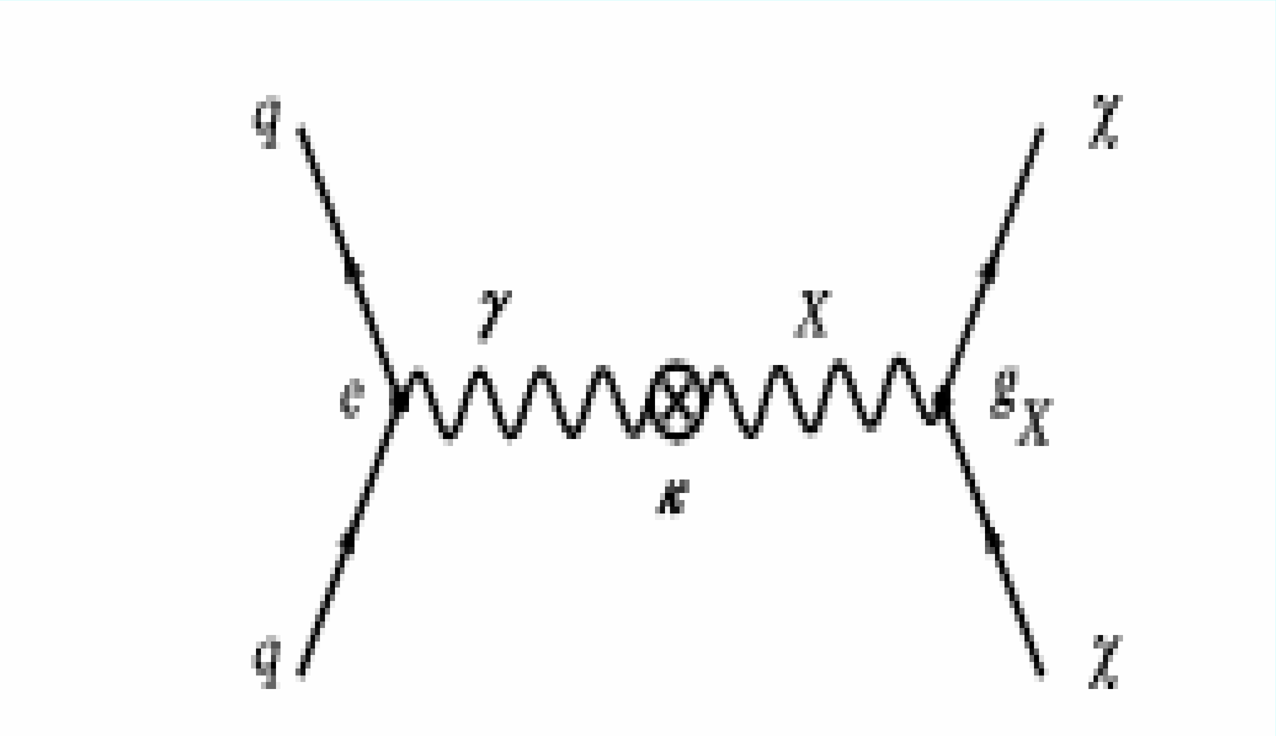
Nature 458:607-609,2009 ; arXiv:0810.4995 (astro-ph)



A Theoretical Scenario

- To explain these data the following a scenario is proposed involving a new gauge boson X with mass around 1 GeV, which:
- Does not directly couple to hadrons
- Couples to leptons
- Couples to the photon

Implications
on Direct Dark Matter Searches
Crucial: The mixing parameter κ



A:Model II: Non-standard mass mixing M^2 (the order is (A_μ, X_μ, Z_μ)

Stueckelberg model (1938); Cors & Nath (2004)

- Massless Mediator: $\kappa=\cos(\theta_W)(m_Y/m_X)$
- Massive Mediator: $\kappa=-\cos(\theta_W)(m_Y/m_X)$

$$K = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad M^2 = \begin{pmatrix} \frac{1}{4}g_Y^2 v^2 + m_Y^2 & m_Y m_X & -\frac{1}{4}g_Y g v^2 \\ m_Y m_X & m_X^2 & 0 \\ -\frac{1}{4}g_Y g v^2 & 0 & \frac{1}{4}g^2 v^2 \end{pmatrix}$$

B:Model I: Non-standard kinetic mixing K (the order is (A_μ, X_μ, Z_μ)

- Massive mediator only: $\kappa=\varepsilon\cos(\theta_W)$

$$K = \begin{pmatrix} 1 & -\epsilon\cos\theta_W & 0 \\ -\epsilon\cos\theta_W & 1 & \epsilon\sin\theta_W \\ 0 & \epsilon\sin\theta_W & 1 \end{pmatrix} \quad , \quad M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_X^2 & 0 \\ 0 & 0 & m_Z^2 \end{pmatrix}$$

The proton-WIMP cross section for a massless mediator

$$d\sigma=\frac{1}{\beta}s(\beta)\frac{4\pi\alpha}{q^4}(g_\chi\kappa)^2$$

$$\frac{d^3\mathbf{p}^{'}}{(2\pi)^3}\frac{d^3\mathbf{q}}{(2\pi)^3}(2\pi)^3\delta(\mathbf{p}-\mathbf{p}^{'}-\mathbf{q})2\pi\delta(\mathbf{T}-\mathbf{T}^{'}-\mathbf{T_q})$$

where β is the WIMP velocity and
$s(\beta)=1$ for a WIMP which is a Dirac Fermion, while
$s(\beta)=\beta^2$ in case it is Majorana particle.
(The Majorana fermion does not possess electromagnetic properties. Hence only the $\gamma_\mu\gamma_5$ of the WIMP-X interaction contributes).
In the above equation $\mathbf{p}'$, $\mathbf{p}$ are the momenta of the initial WIMP and the final WIMP and and $\mathbf{q}$ the momentum transfer to the nucleon. $T=p^2/2m_\chi$, $T'=(p')^2/2m_\chi$ and $T_q=q^2/2m_p$

$$q=2\mu_r\upsilon\xi\approx 2m_p\upsilon\xi \quad , \quad T_q\approx 2m_p\upsilon^2\xi^2$$

where μ_r is the WIMP-nucleon reduced mass and $0\leq\xi\leq 1$ is the angle between the oncoming WIMP and the outgoing nucleon.

The proton-WIMP cross section for a massless mediator

After the integrations we finally get:

$$d\sigma = \frac{s(\beta)}{\beta^2}\frac{\alpha}{2}\left(g_{\chi}\kappa\right)^2\frac{1}{m_p}\frac{dT_q}{(T_q)^2}$$

The above expression exhibits, of course, the infra red divergence. For a Majorana neutrino is independent of the velocity.

We will impose a low energy cut off given by the energy threshold E_{th}/A, where A is the mass number of the target.

$$\sigma_p \approx \frac{s(\beta)}{\beta^2}\frac{\alpha}{2}\frac{1}{(m_p)^2}\left(g_{\chi}\kappa\right)^2\frac{Am_p}{E_{th}}$$

Incorporating the Limits from WIMP searches (CDMSII &XENON10): σ<10^{-7} pb

$$\sigma_p \approx \frac{\alpha}{2} \frac{1}{(m_p)^2} (g_\chi \kappa)^2 \frac{A m_p}{E_{th}} \text{ (Majorana)}$$

or

$$\sigma_p \approx 1.6 \times 10^6 \text{ pb} \, (g_\chi \kappa)^2 \frac{A m_p}{E_{th}}$$

(independent of the WIMP velocity)

Now notice

- The event rate scales with Z^2 rather than A^2
- A threshold value must be selected

In our calculations we will use

$$\sigma^S_{N,\chi^0} = \sigma_0 \frac{A}{131} \frac{5keV}{E_{th}} \; , \; \sigma_0 = 3 \times 10^{-7}$$

Constrains on model II parameters

- Feldman-Liu-Nath from cosmic ray experiments

  $m_y / m_X = (1\text{-}0.5) \times 10^{-2}$
- Direct Experiments (Majorana WIMPs):

For E_{th} =5 keV and a Ge target we obtain

$$|g_X \kappa| \leq 1.6 \times 10^{-10} \text{ (Majorana)}$$

This leads to the bound:

$$\frac{m_Y}{m_X} \leq 5.7 \times 10^{-10}$$

Incorporating the Limits from WIMP searches (CDMSII &XENON10): σ<10^{-7} pb

The case of a Dirac WIMP.

Now

$$\sigma_p \approx \frac{1}{\beta^2}\frac{\alpha}{2}\frac{1}{(m_p)^2}(g_\chi \kappa)^2 \frac{A m_p}{E_{th}}$$

To constrain it from the experimental data

$$\sigma_p \rightarrow \prec \sigma_p \succ \approx \prec \frac{1}{\beta^2} \succ \frac{\alpha}{2}\frac{1}{(m_p)^2}(g_\chi \kappa)^2 \frac{A m_p}{E_{th}}$$

But for a Maxwell- Boltzmann distribution

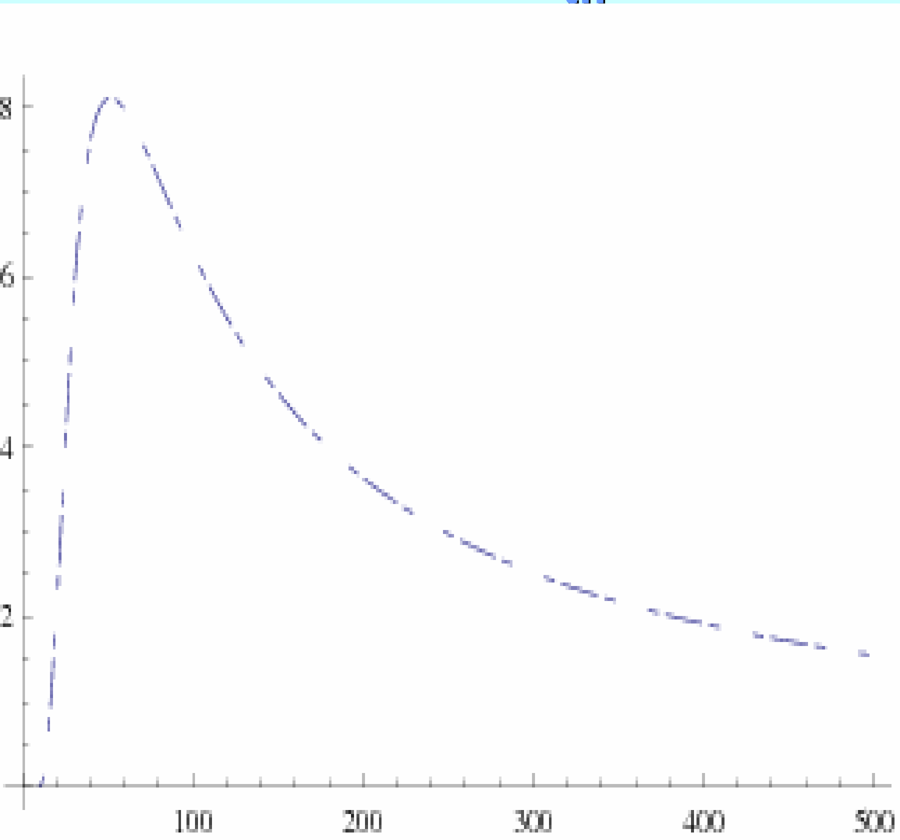
$$\prec \frac{1}{\beta^2} \succ = \frac{3}{\prec \beta^2 \succ}$$

$$\prec \sigma_p \succ \approx 3 \times 10^6 \frac{\alpha}{2}\frac{1}{(m_p)^2}(g_\chi \kappa)^2 \frac{A m_p}{E_{th}}$$

The cross section $\prec \sigma_p \succ$ is determined as before.

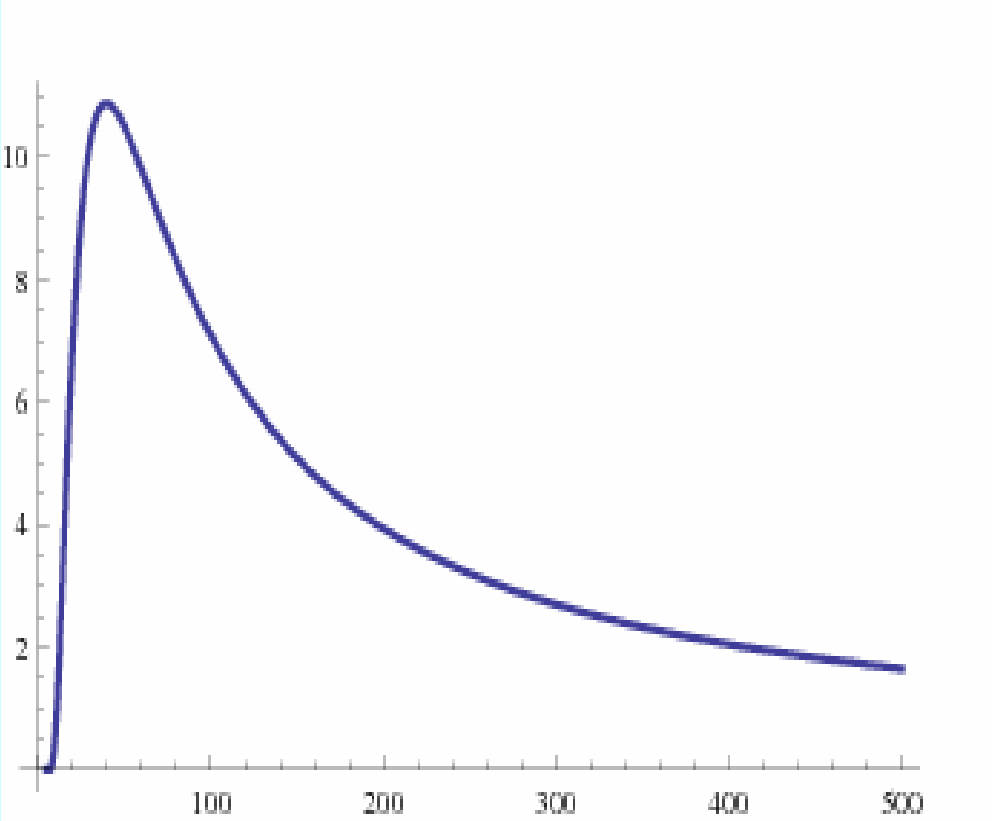
Event rates for the Iodine target

Standard CDM; $E_{th} = 5.0$



Secluded, massless mediator

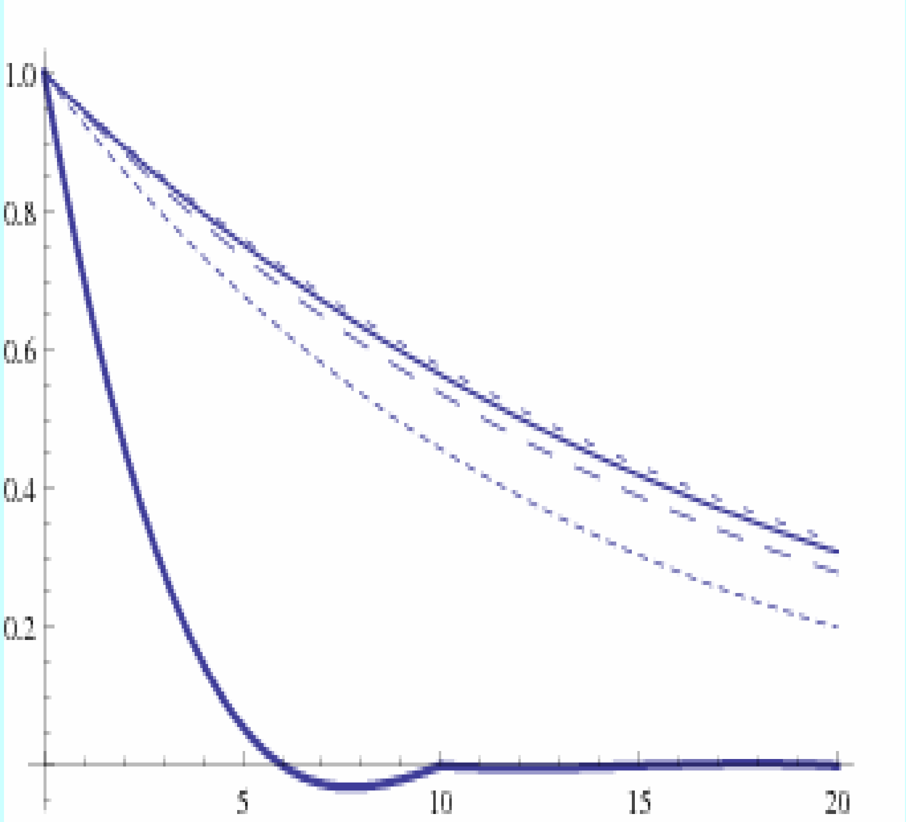
$E_{th} = 5.0$ keV



The Ratio Rate(E_{th})/Rate(E_{min})

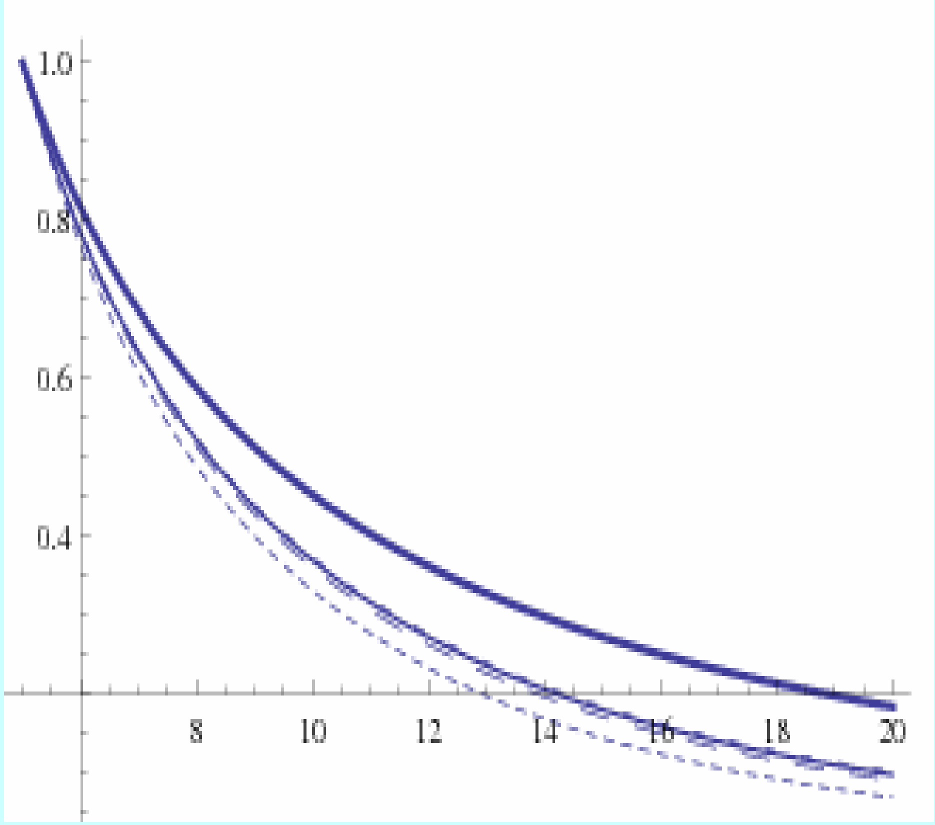
WIMP masses 10, 50, 100, 200, 500 GeV (from bottom to top as on left panel)

Standard WIMP E_{min} = 0



Secluded WIMP

E_{min} = 5keV E_{cutoff} = 0.038 keV



Limits from WIMP Searches for Massive Mediator

In the case of massive mediator no cut off is needed. Now

$$\sigma = s(\beta)\,\frac{16\pi\alpha_{EM}\kappa^2\alpha_{DM}m_p^2}{m_X^4} \Rightarrow$$

$$\sigma = 1.2\times 10^6\ \text{pb}\ s(\beta)\kappa^2\left(\frac{m_p}{m_X}\right)^4$$

Taking

$$\beta^2 \longrightarrow \prec \beta^2 \succ \approx 10^{-3}\ ,\ m_X = m_p$$

for Dirac (Majorana) WIMP from the experimental limits we get:

$$\kappa \leq 3\times 10^{-7}\ (3\times 10^{-4})$$

Constraining the models I and II

From the limit on κ we obtain for Dirac (Majorana) WIMP the bounds:

$$\epsilon \leq 3.0 \times 10^{-7} \, (3. \times 10^{-3}) \, , \qquad \text{Model I}$$

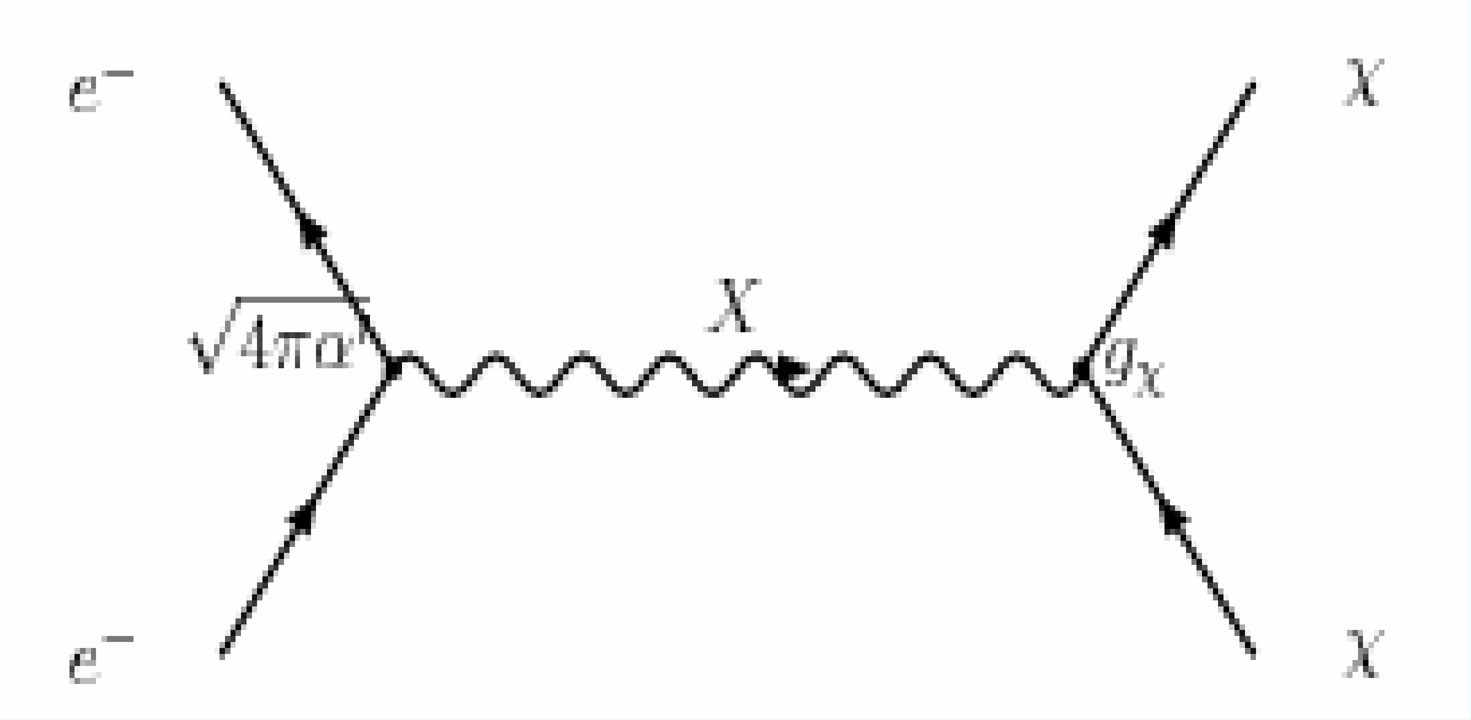
Very Stringent indeed.
(the limit from muon $g_s - 2$ yields $\epsilon \leq 3 \times 10^{-2}$) .

$$\frac{m_Y}{m_X} \leq 1.6 \times 10^{-6} \, (1.6 \times 10^{-3}) \, , \qquad \text{Model II}$$

This is quite stringent, but less so than the massive mediator case.

Unconventional WIMP searches

Detection of Electrons directly produced from the exotic Boson:



Unconventional WIMP searches

Detection of very low energy Electrons directly produced from the exotic Boson:

- The initial electron is bound
- The momentum transfer is small $q=2m_e\beta\xi$ (2000 times smaller than for a nucleon). There maybe a compensation coming from the fact that it is bound)
- Detecting low energy electrons may be advantageous compared to nuclear recoils
- Theoretically it relies on fewer model assumptions
-

The differential Cross Section

$$d\sigma = s(\beta)\frac{1}{\beta}\frac{4\pi\alpha'}{m_\chi^4}(g_\chi)^2\,\frac{d^3\mathbf{p}'}{(2\pi)^3}\frac{d^3\mathbf{p}'_e}{(2\pi)^3}$$

$$(2\pi)^3 2\pi\delta(T - T' - T'_e - b)\phi^2_{n,\ell}(Z,\mathbf{p}' + \mathbf{p}'_\mathbf{e} - \mathbf{p})$$

where $\mathbf{p_e}$, b are the momentum and binding energy of the initial electron and $\phi_{n,\ell}(Z,\mathbf{p_e})$ the bound electron wf in momentum space. By defining

$$\mathbf{q} = \frac{\mathbf{p}' - \mathbf{p}}{m_e}, p'_e = \frac{\mathbf{x}}{m_e}, \tilde{b} = \frac{b}{m_e}, \lambda = \frac{m_e}{m_\chi}, \xi = \hat{\mathbf{p}}_\chi.\hat{\mathbf{q}}, \eta = \hat{\mathbf{p}}_e.\hat{\mathbf{q}}$$

we get

$$d\sigma = \frac{s(\beta)}{\beta}\frac{4\pi\alpha'}{m_\chi^4}(g_\chi)^2\, m_e^2 x^2 dx d\xi q^2 dq d\eta$$

$$\delta(\beta q\xi + (\lambda/2)q^2 + \tilde{b} + x^2/2)\phi^2_{n,\ell}(Z,(\sqrt{q^2 + 2qx\eta + x^2}))$$

The integration over ξ can trivially be done using the energy conserving δ function. The integrations over q and η can also be done analytically for hydrogenic w.f. yielding a function $\Psi(x)$.

The differential cross section can be cast in the form:

$$\frac{d\sigma}{dy} = \frac{s(\beta)}{\beta^2}4\pi\alpha'\left(\frac{m_e}{m_\chi}\right)^4\left(\frac{g_\chi}{m_e}\right)^2\frac{4(\alpha Z)^5}{3\pi^2}\Psi(\sqrt{2y}), y = \frac{E'_e}{m_e}$$

Cross Sections for:
ἀ=α, m_χ =1GeV, m_χ=100GeV, Z=1

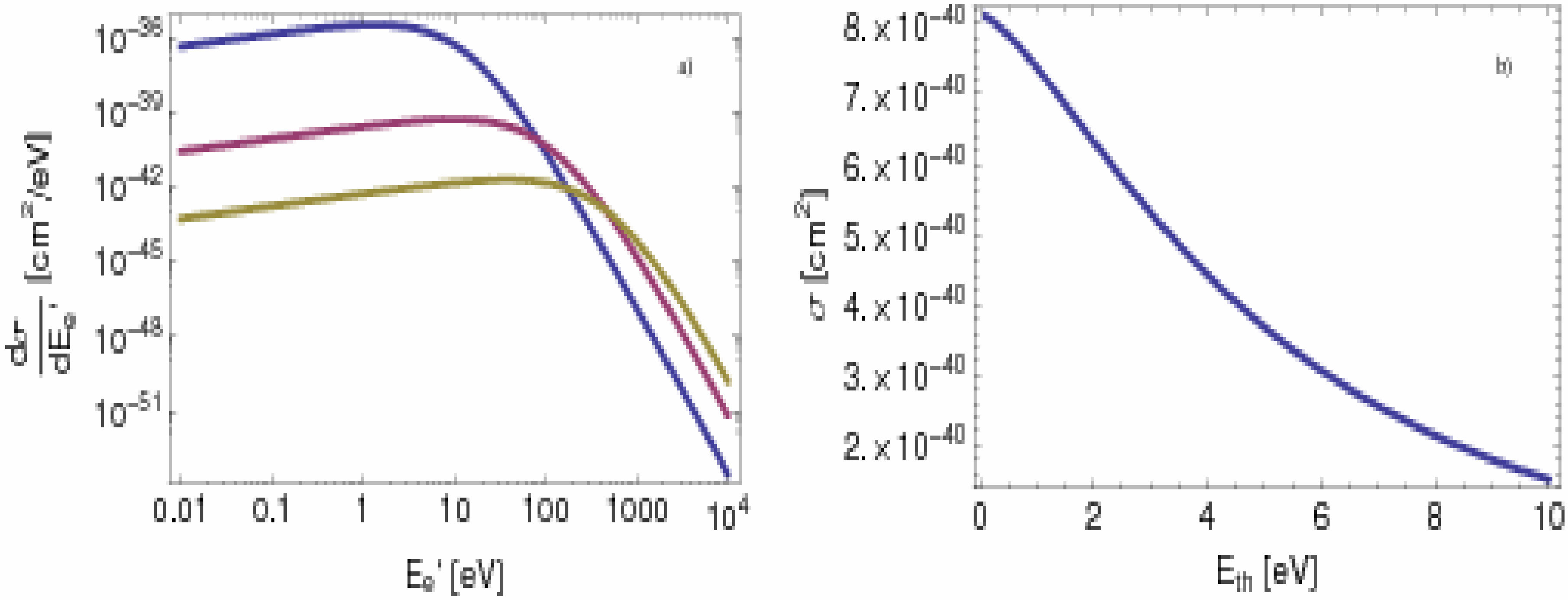


FIG. 2: a) *Predictions for $d\sigma/dE'_e$ as a function of the ejected electron energy E'_e. The target is assumed hydrogenic atom with Z=1,3,6 (from top to bottom) in the ground state. b) The total cross section as a function of threshold energy. We assume a Dirac WIMP and various parameters taken from Eq. 23.*

Event Rates for:
ἀ=α, m_χ =1GeV, m_χ=100GeV, Z=1

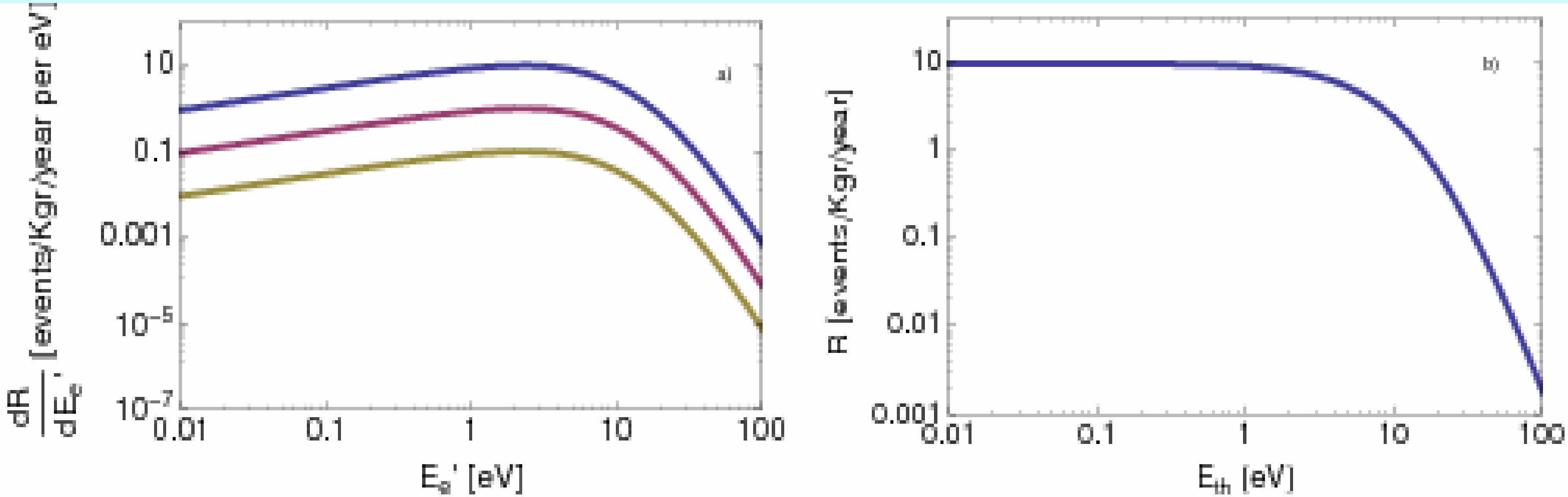


FIG. 3: *a) Differential event rate of Dirac WIMP scattered off hydrogen (Z=1, A=1) target electrons per year per Kgr as a function of ejected electron energy E_e' in eV. Three different WIMP masses have been assumed : $m_\chi = 10, 100, 1000$ GeV, from top to bottom, respectively. b) The total event rate as a function of the experimental threshold energy for $m_\chi = 100$ GeV. Other input parameters are taken from Eq. 23.*

Differential Event Rates for electron detection from secluded WIMPS

E_e' [eV]	$\left\langle \frac{dR}{dE_e'} \right\rangle$ [events/kgr target/year/eV]		
	unmod.	mod.	H
0.1	0.30	0.02	0.07
1	0.85	0.07	0.08
10	0.35	0.03	0.09
100	8.29×10^{-5}	8.01×10^{-6}	0.10

Detector Requirements

Detector Requirements resolution and low threshold. To achieve this one needs

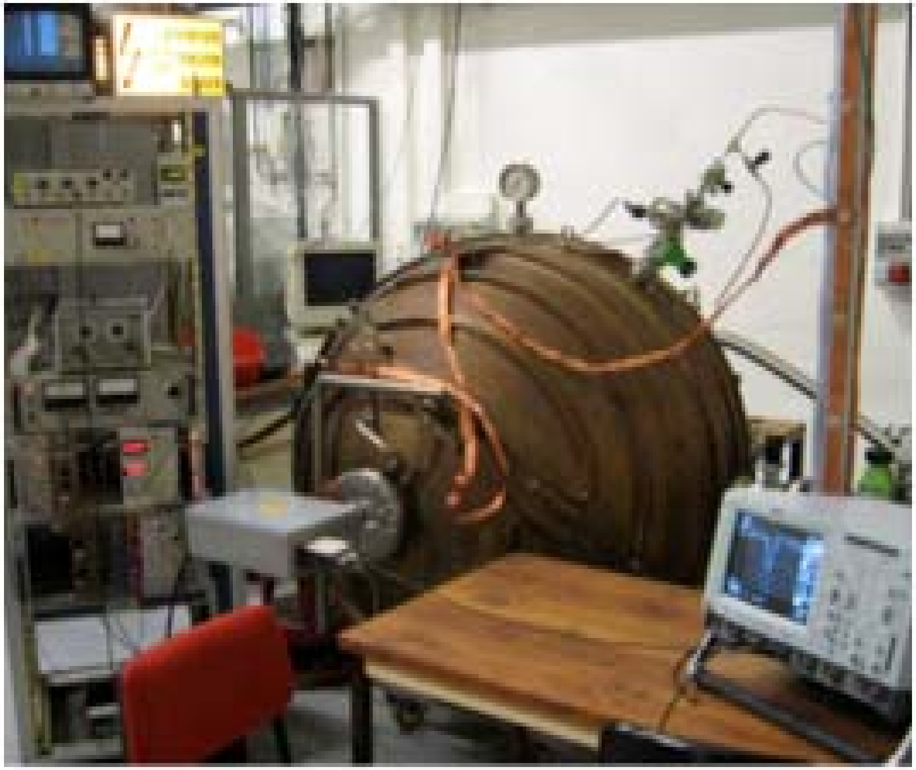
- Single electron efficiency.
  this is achieved with gaseous detectors reaching very-high gains
  (in order to cope with electronic noise).
- Large drift volumes and operation at high pressure (like the HELLAZ prototypes).
- Versatility of target material: various gases from the lightest (H_2) to heaviest (Xe).

The SACLAY Sphere

(I. giomataris et al, JINST 3 (2008) P09007; arXiv:0807.2802.)

It looks realistic to soon have

- A spherical TPC of 5 meter radius.
- Under a pressure of 5 bars.
- Filled with 80% Ar and 20% Isobutane $(C_4H_{10}) \Rightarrow$
- 212 Kg of Hydrogen



An optimist's view

With

- a threshold of 10 eV
- $\dot{\alpha}=\alpha$, (EM X boson - electron coupling often employed in the analysis of the PAMELA data) and $m_X = 1 GeV$
- one gets 9 events per Kg of target per year
- The SCALAY sphere

One expects 500 events per year

Point of Caution

- The limit on g_s -2 impses the constraint
- $\dot{\alpha}/(m_X)^2 < 6\times10^{-3}\,\alpha/(m_X)^2$
- which means only 1.5×10^{-4} events per year

Let us fall back to the photon

- Like the standard WIMP searches. Only Replace the proton by an electron
- The massless mediator is the most important.
- Since the electron is bound there is no infra red divergence, but the momentum tranfer can be quite low yielding some enhancement

Massless mediator scattering electrons

$$d\sigma = \frac{1}{\beta} s(\beta) \frac{4\pi\alpha}{(\mathbf{p}' - \mathbf{p})^4} (g_\chi \kappa)^2 \frac{d^3\mathbf{p}'}{(2\pi)^3} \frac{d^3\mathbf{p}'_e}{(2\pi)^3}$$

$$(2\pi)^3 2\pi \delta(T - T' - T'_e - b) \phi^2_{n,\ell}(Z, \mathbf{p}' + \mathbf{p}'_\mathbf{e} - \mathbf{p})$$

where $\mathbf{p_e}, b$ are the momentum and binding energy of the initial electron and $\phi_{n,\ell}(Z, \mathbf{p_e})$ the bound electron wf in momentum space. By defining

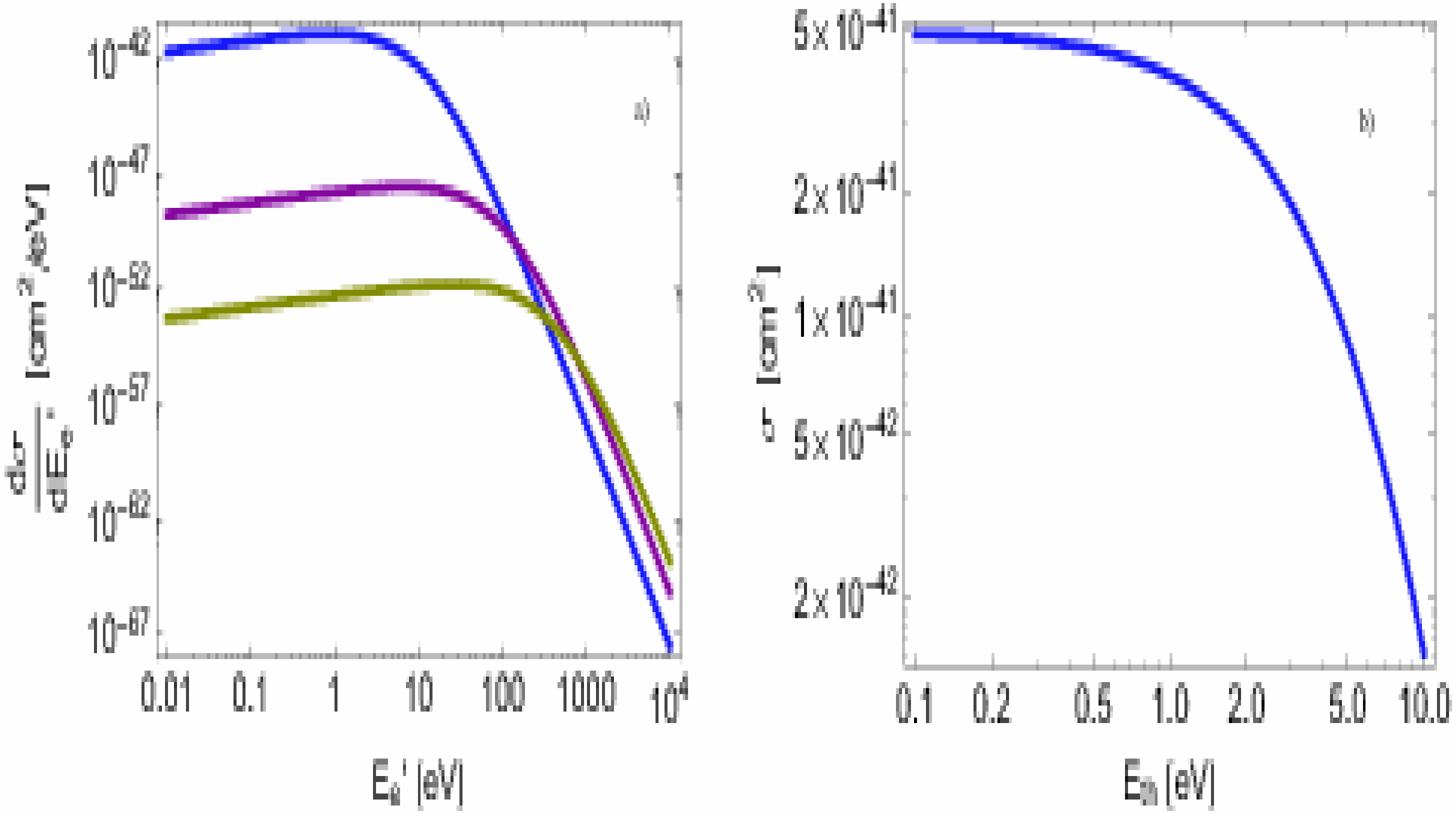
$$\mathbf{q} = \frac{\mathbf{p}' - \mathbf{p}}{m_e}, \mathbf{p}'_e = \frac{\mathbf{x}}{m_e}, \tilde{b} = \frac{b}{m_e}, \lambda = \frac{m_e}{m_\chi}, \xi = \hat{\mathbf{p}}_\chi . \hat{\mathbf{q}}, \eta = \hat{\mathbf{p}}_e . \hat{\mathbf{q}}$$

we get

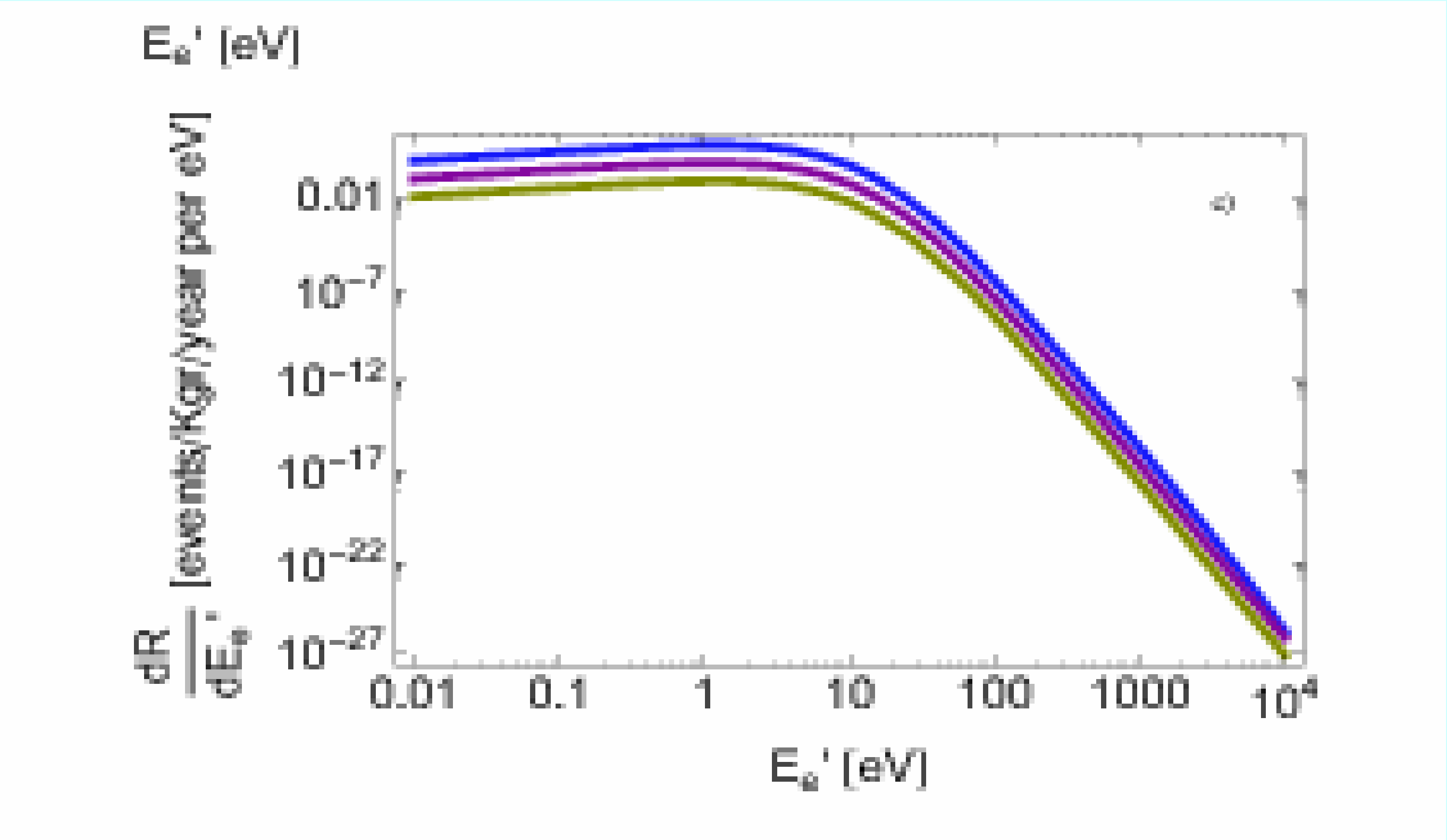
$$d\sigma = \frac{1}{\beta} s(\beta) \frac{4\pi\alpha}{q^4} (g_\chi \kappa)^2 \frac{1}{m_e^2} x^2 dx d\xi q^2 dq d\eta$$

$$\delta(\beta q \xi + (\lambda/2) q^2 + \tilde{b} + x^2/2) \phi^2_{n,\ell}(Z, (\sqrt{q^2 + 2qx\eta + x^2}))$$

Cross Sections for: m_χ=100GeV, Z=1, $\kappa=10^{-10}$



Differential Event Rates
m_χ=100GeV, Z=1, $\kappa=10^{-10}$



For a massless mediator

With

- a threshold of 10 eV
- $\kappa=10^{-10}$
- one gets 5 events per Kg of target per year
- The SCALAY sphere

One expects 250 events per year

Unconventional WIMP searches: Detection of elec

- THE END

The positron excess in the high energy region of the PAMELA Experiment

Nature 458:607-609,2009 ; arXiv:0810.4995 (astro-ph)

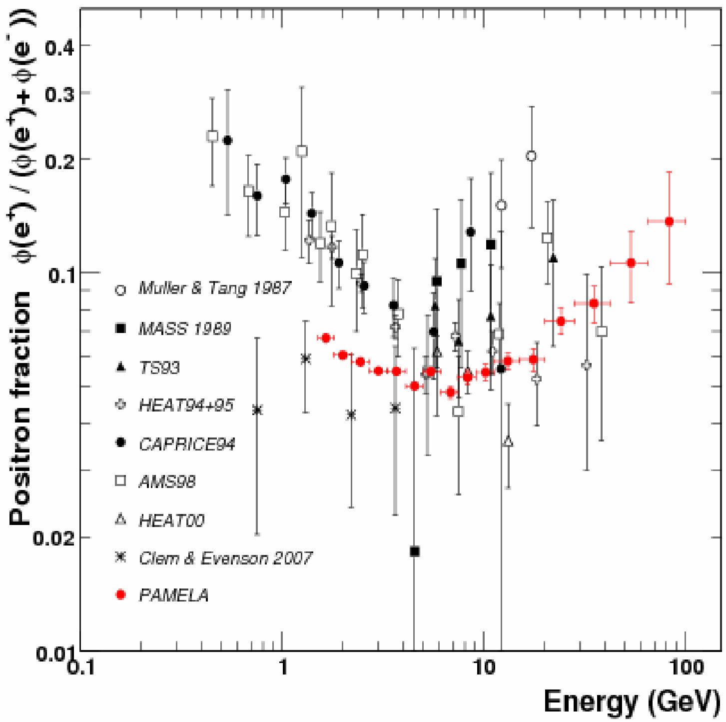


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the data points.

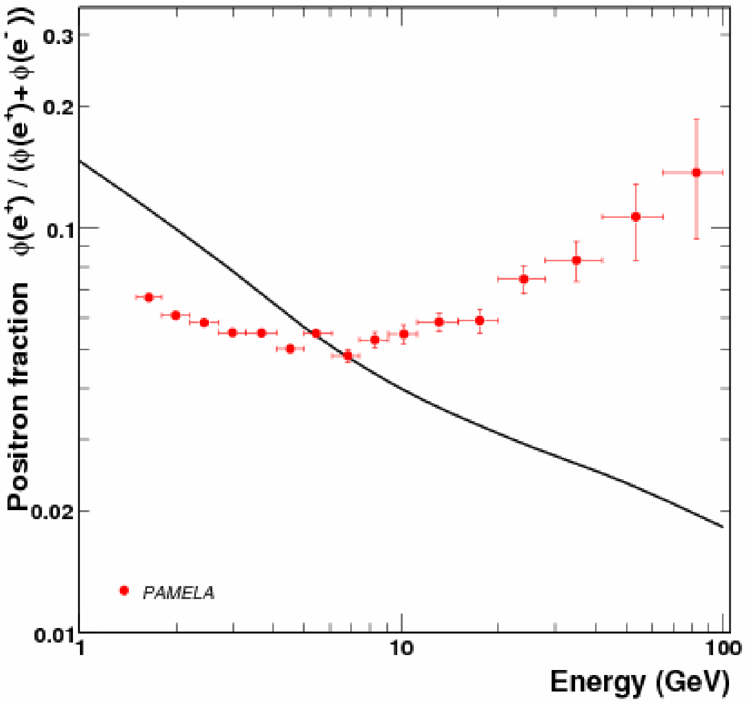


FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.

LSP Velocity Distributions

- Conventional: Isothermal models
- (1) Maxwell-Boltzmann (symmetric or axially symmetric)

  with characteristic velocity equal to the sun's velocity around the center of the galaxy, $u_{MB} = u_0 = 220$ km/s,

  and escape velocity $u_{esc} = 2.84 u_0$ put in by hand.
- (2) Modification of M-B characteristic velocity u_{MB} following the interaction of dark matter with dark energy:

  $u_{MB} = n u_0$, $u_{esc} = n 2.84\, u_0$, $n > 1$

  (Tetradis, Feassler and JDV)
- Adiabatic models employing Eddington's approach:

  $\rho(\mathbf{r}) \Rightarrow \Phi(\mathbf{r}) \Rightarrow f(\mathbf{r},\mathbf{v})$ (JDV-Owen)
- Axially symmetric velocity distributions extracted from realistic halo densities via simulations ⇒ Tsallis type functions (Hansen, Host and JDV)
- Other non-thermal models:

  -Caustic rings (Sikivie , JDV), WIMP's in bound orbits etc

  -Sgr Dwarf galaxy ⇒ anisotropic flux, (Green & Spooner)

Tsallis type functions (for radial and Tangential components) ⇒MB as q→1

$$f_r(q,\sigma,v] = N(q,\sigma)\left(1 - \frac{(1-q)v^2}{(3-q)\sigma^2}\right)^{\frac{q}{1-q}}$$

- Adopt: q=3/4 (Normalized in one dimension)

$$f_t = \frac{1}{2\pi\sigma_t^2(2-q)}\left(1 - \frac{q-1}{2(q-2)}\left(\frac{v}{\sigma_t}\right)^2\right)^{\frac{q}{1-q}}$$

- Adopt: q=5/3 (Normalized in two dimensions)

I: MB and Tsallis functions.

Asymmetry β (Hansen, Host and JDV)

$$\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

$$f_{MB}(\sigma, v) = \frac{e^{-\frac{v^2}{2\sigma^2}(1-(2/3)\beta)}}{\sqrt{2\pi}\sigma}\sqrt{1-\frac{2}{3}\beta}$$

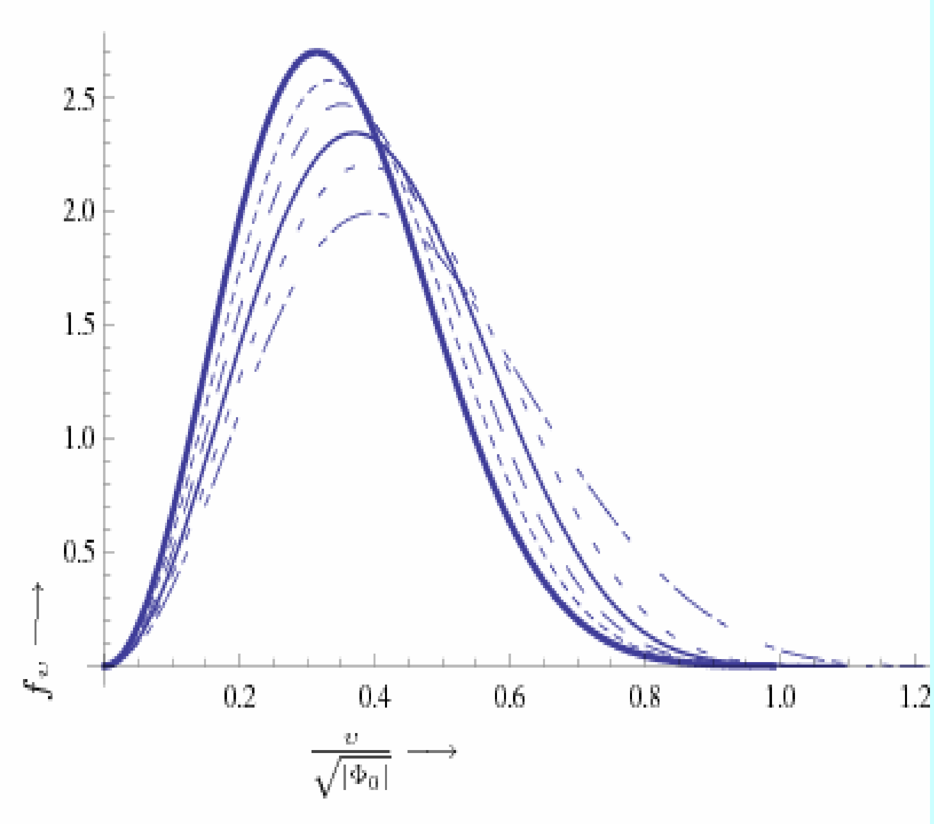
$$fmb(v,\beta,\sigma) = (1-\frac{2}{3}\beta)\frac{e^{-\frac{v^2}{2(1-\beta)\sigma^2}(1-\frac{2}{3})\beta)}}{2\pi(1-\beta)\sigma^2}$$

$$f_r(\sigma,v) = \frac{35}{96\sigma}\left(1-\frac{v^2}{9\sigma^2}(1-\frac{2}{3}\beta)\right)^3\sqrt{1-\frac{2}{3}\beta}\ , \quad -3\sigma/\sqrt{1-\frac{2}{3}\beta} \le v \le 3\sigma/\sqrt{1-\frac{2}{3}\beta}$$

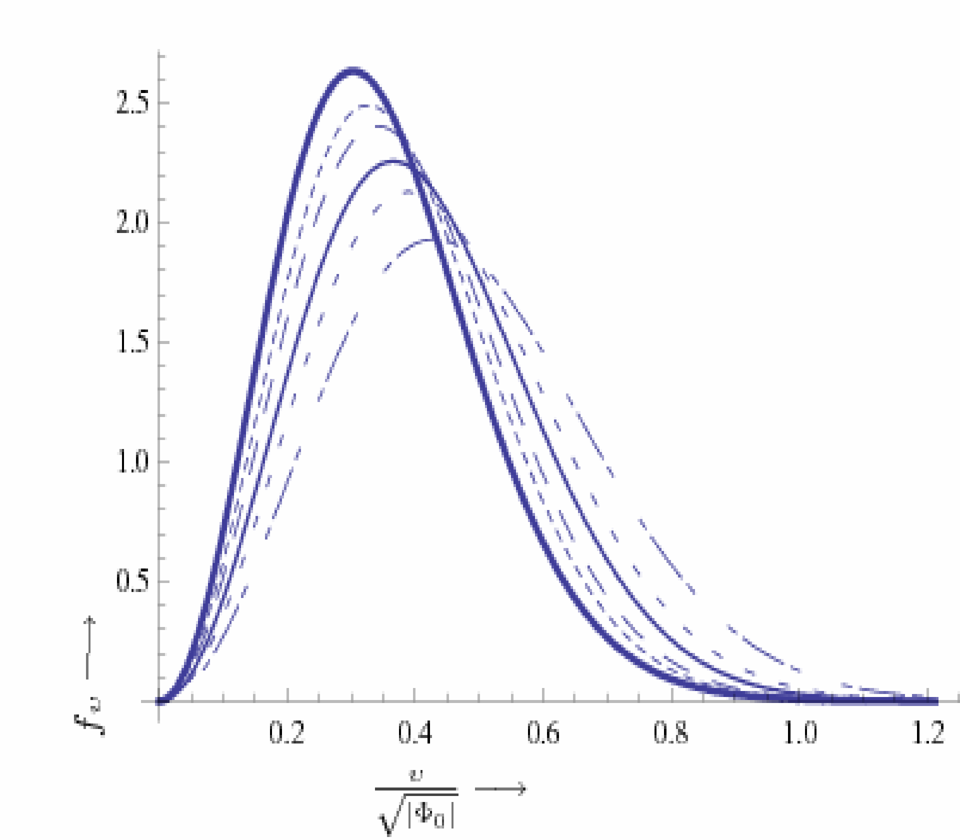
$$f_t = \frac{1}{2\pi\sigma^2(2-q)}\frac{1-(2/3)\beta}{1-\beta}\left(1-\frac{(q-1)}{2(q-2)}\frac{1-(2/3)\beta}{1-\beta}\left(\frac{v}{\sigma}\right)^2\right)^{\frac{q}{1-q}} \ , \quad 1<q<2$$

II: Velocity distribution obtained in the Eddington approach

NFW Halo Density profile



Axially symmetric M-B



II Asymmetric Velocity Distribution From Realistic Density Profiles In the Eddington Approach

- It can be fitted to an Axially Symmetric M-B Velocity Distribution
- The asymmetry parameter β is linked to the angular momentum of DM fluid

The event rate for the coherent mode

- The number of events during time t is given by:

$$R \simeq 1.60\ 10^{-3} \frac{t}{1\text{y}} \frac{\rho(0)}{0.3 GeV cm^{-3}} \frac{m}{1\text{Kg}} \frac{\sqrt{\langle v^2 \rangle}}{280\text{km}s^{-1}} \frac{\sigma^S_{p,\chi^0}}{10^{-6}\ \text{pb}} \frac{f_{coh}(A,\mu_r(A))}{A}$$

with

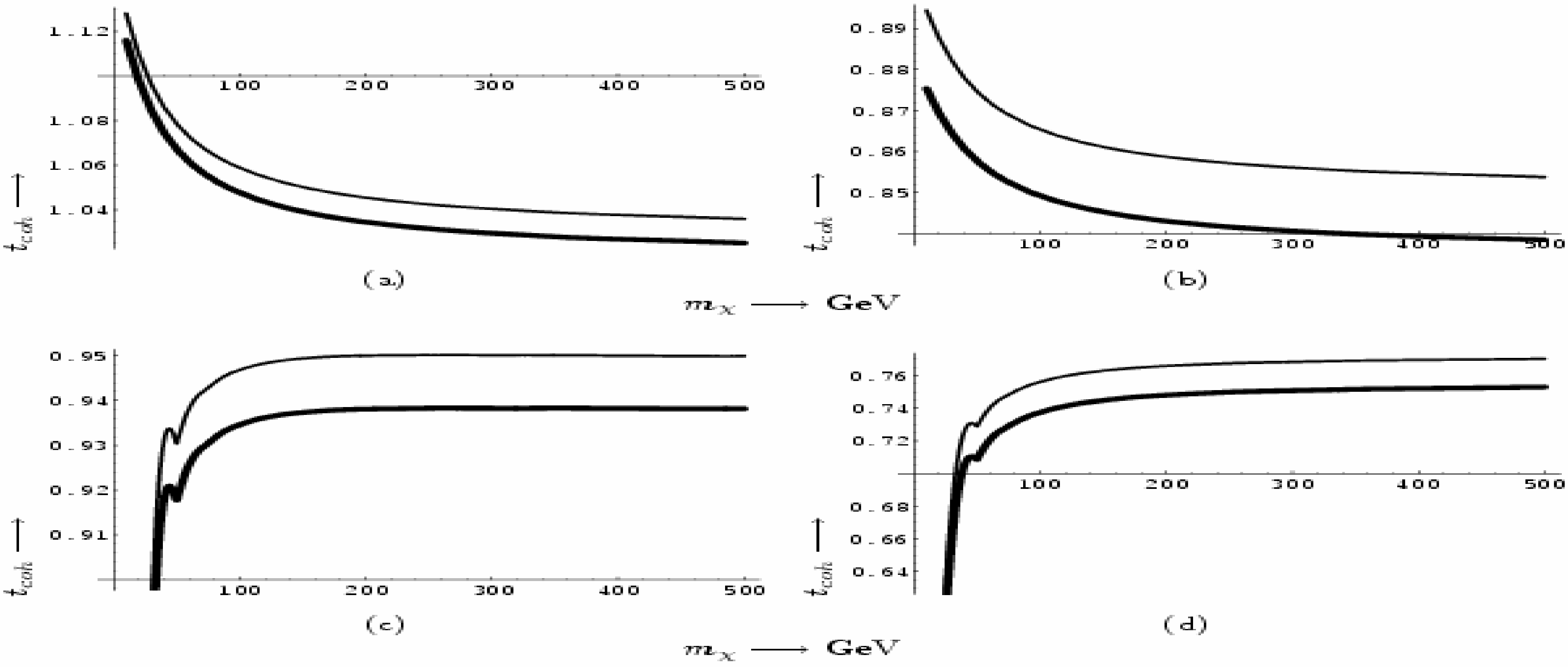
$$f_{coh}(A,\mu_r(A)) = \frac{100\text{GeV}}{m_{\chi^0}} \left[\frac{\mu_r(A)}{\mu_r(p)}\right]^2 A^2\ t_{coh}\,(1 + h_{coh} cos\alpha)$$

Where:

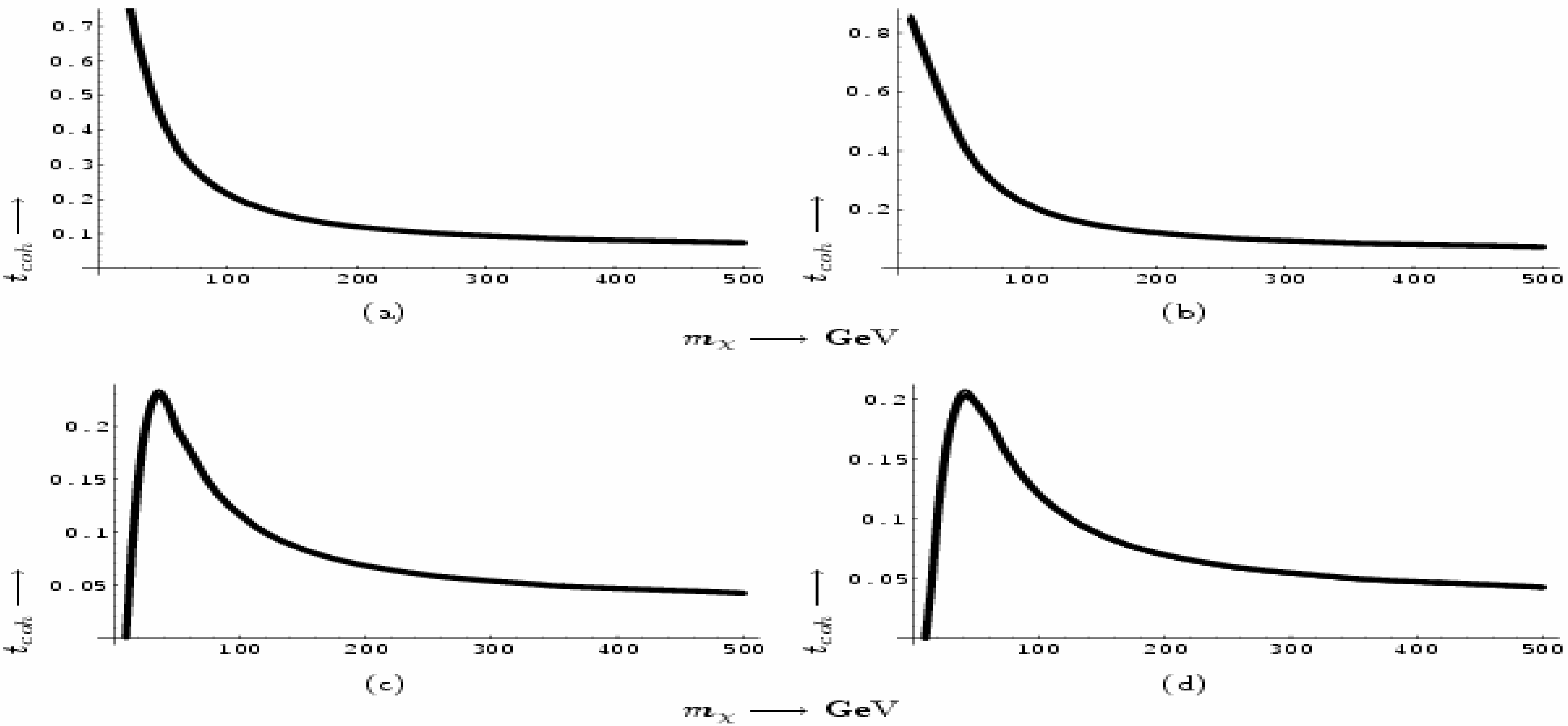
- t_{coh} depends on nuclear physics, the WIMP mass and the velocity distribution
- $\rho(0)$: the local WIMP density≈0.3 GeV/cm^3.

$\sigma^S_{p,\chi}$: the WIMP-nucleon cross section. It is computed in a particle model. It can be extracted from the data once f_{coh} (A,m_χ) is known

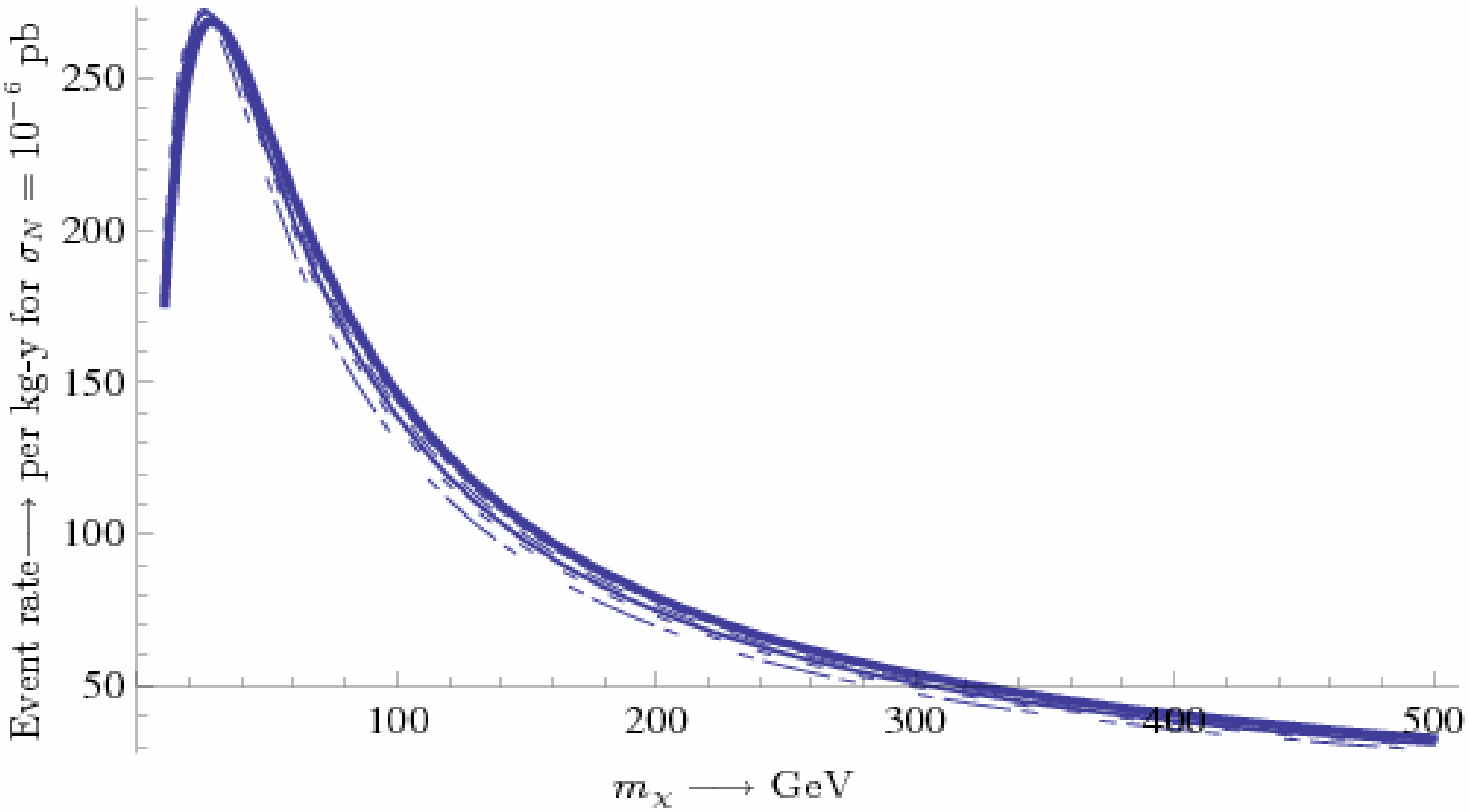
Ia: t_{coh} for a light target. Q_{thr} =0 (top), 5keV (bottom); MB ⑩Left, Tsallis form ⑩ Right (asymmetry shown in both)



Ib: t_{coh} for medium target. Q_{thr} =0 (top), 10keV (bottom); MB ⑩Left, Tsallis form ⑩ Right (asymmetry shown in both)

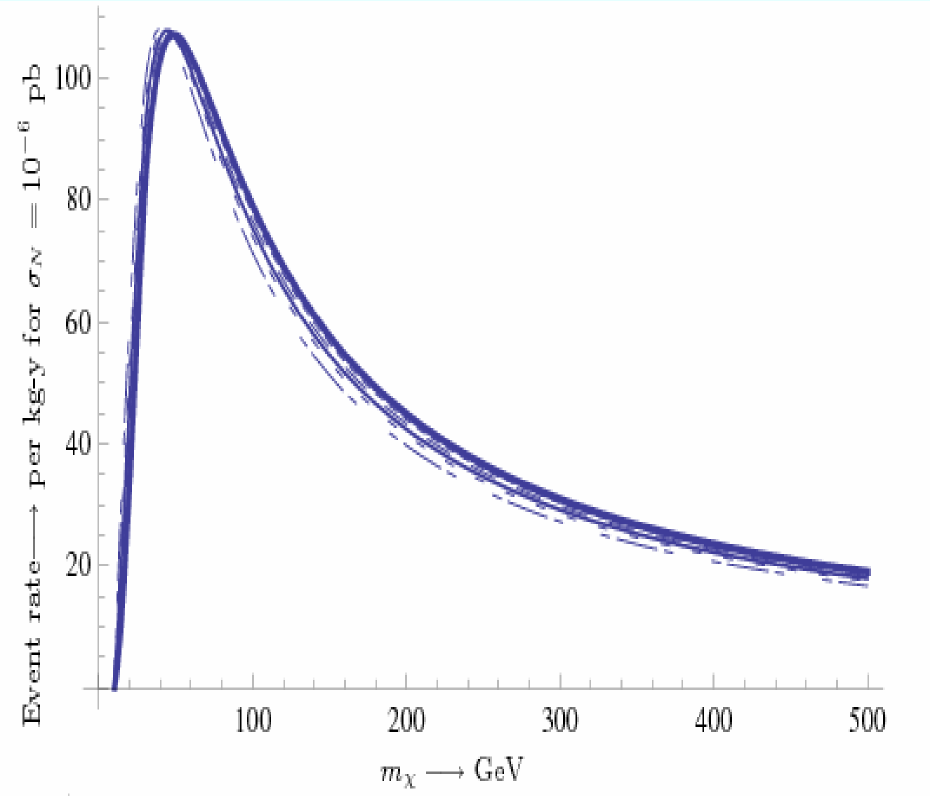


IIc:The time averaged event rate for a medium-heavy target vs WIMP mass (zero threshold)

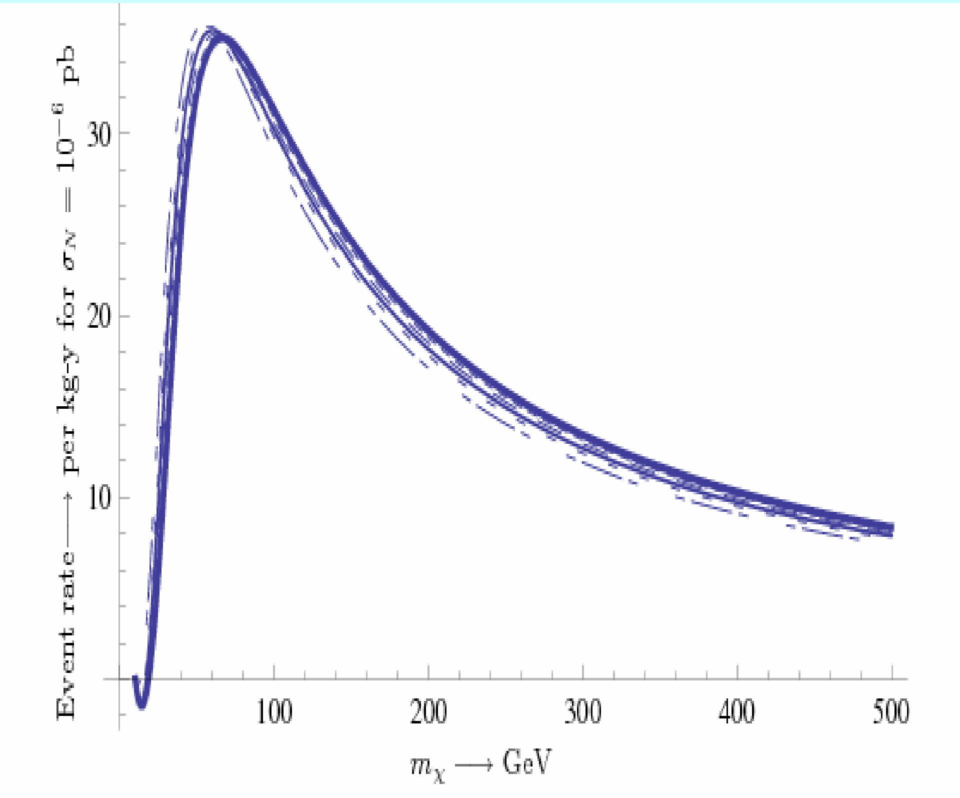


IId:The time averaged event rate for a medium-heavy target vs WIMP mass

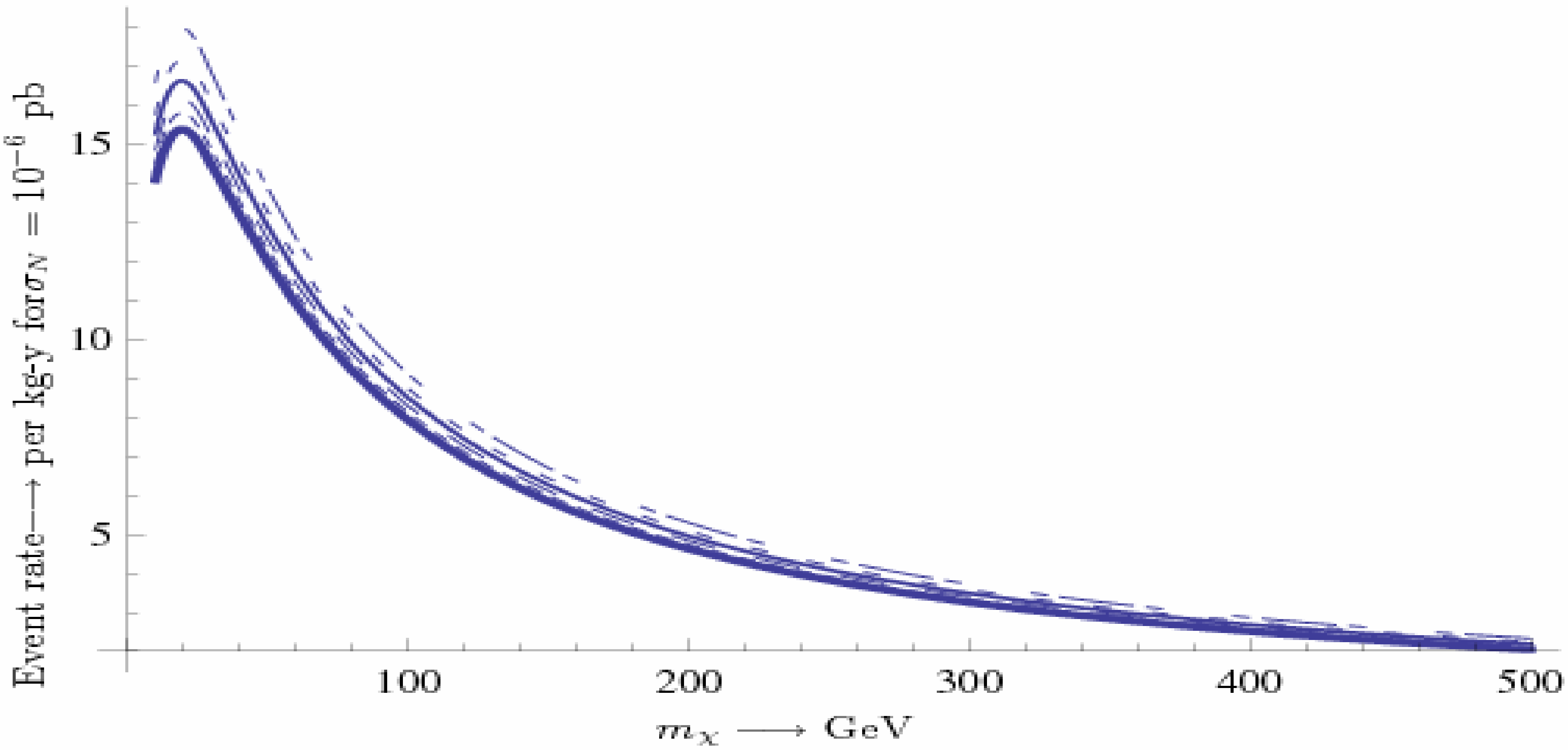
E_{th}=10 keV (no quenching)



E_{th}=10 keV (quenching)

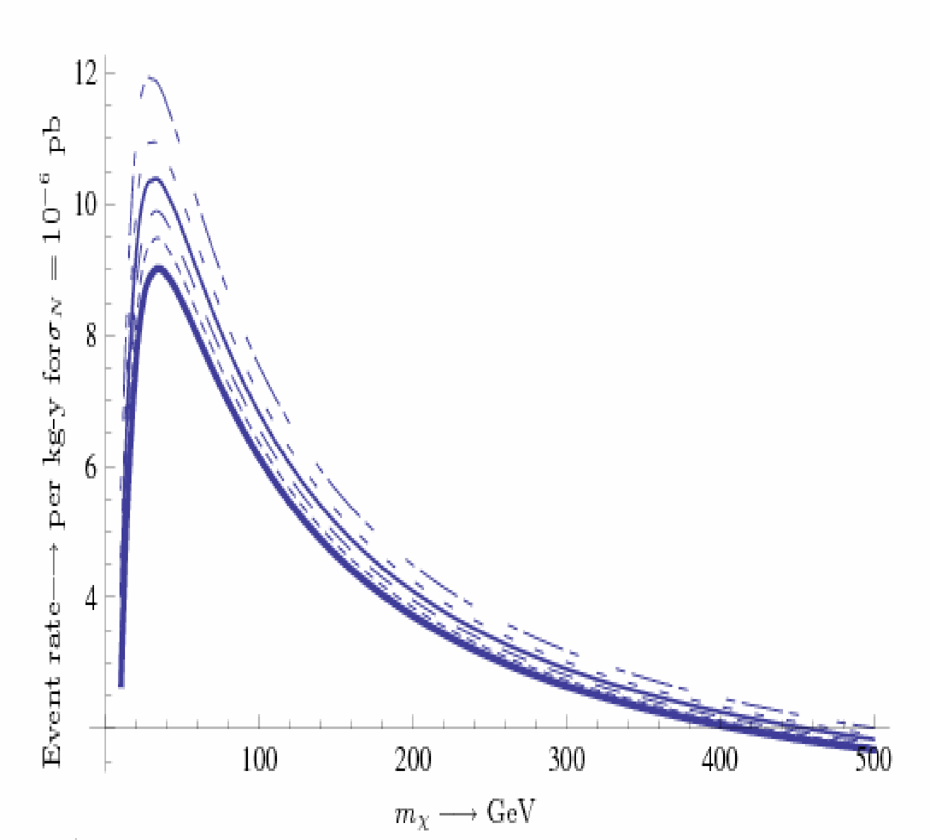


IIe:The time averaged event rate for a light target vs WIMP mass (zero threshold)

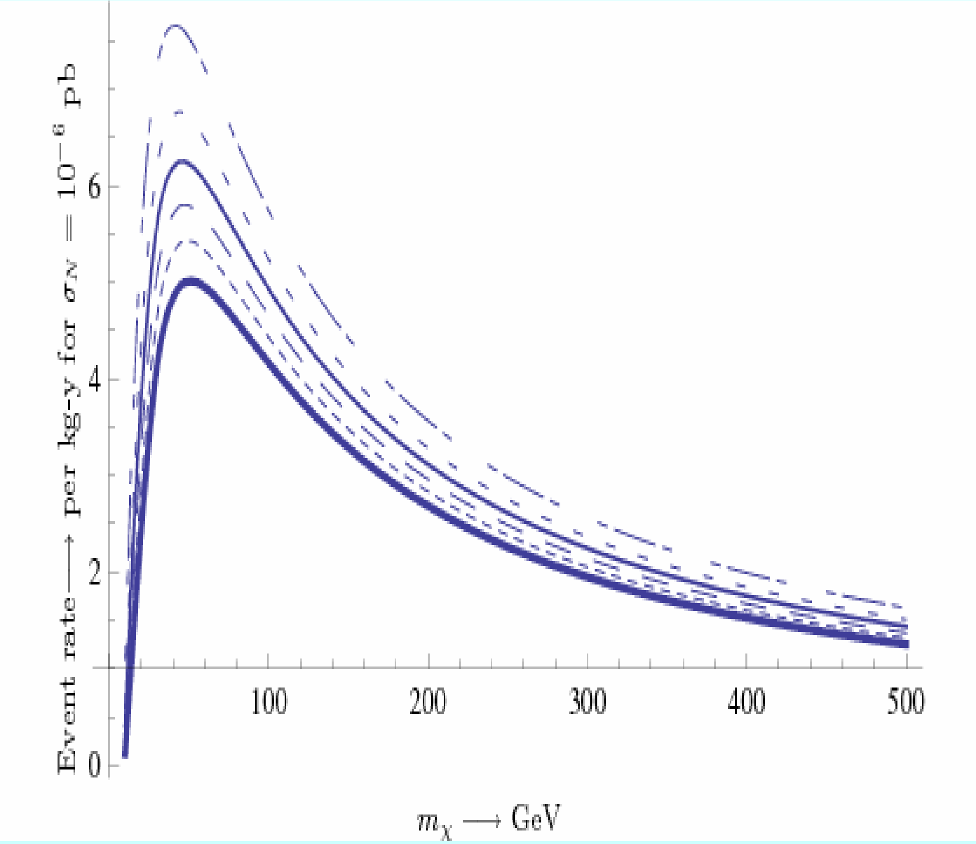


IIf:The time averaged event rate for a light target vs WIMP mass

E_{th}=10 keV (no quenching)



E_{th}=10 keV (quenching)



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.
- Asymmetry measurements in directional experiments (the direction of the recoiling nucleus must also be measured).
- Detection of other particles (electrons, X-rays), produced during the LSP-nucleus collision
- The excitation of the nucleus (in some cases , heavy WIMP etc, that this is realistic) and detection of the subsequently emitted de-excitation γ rays.

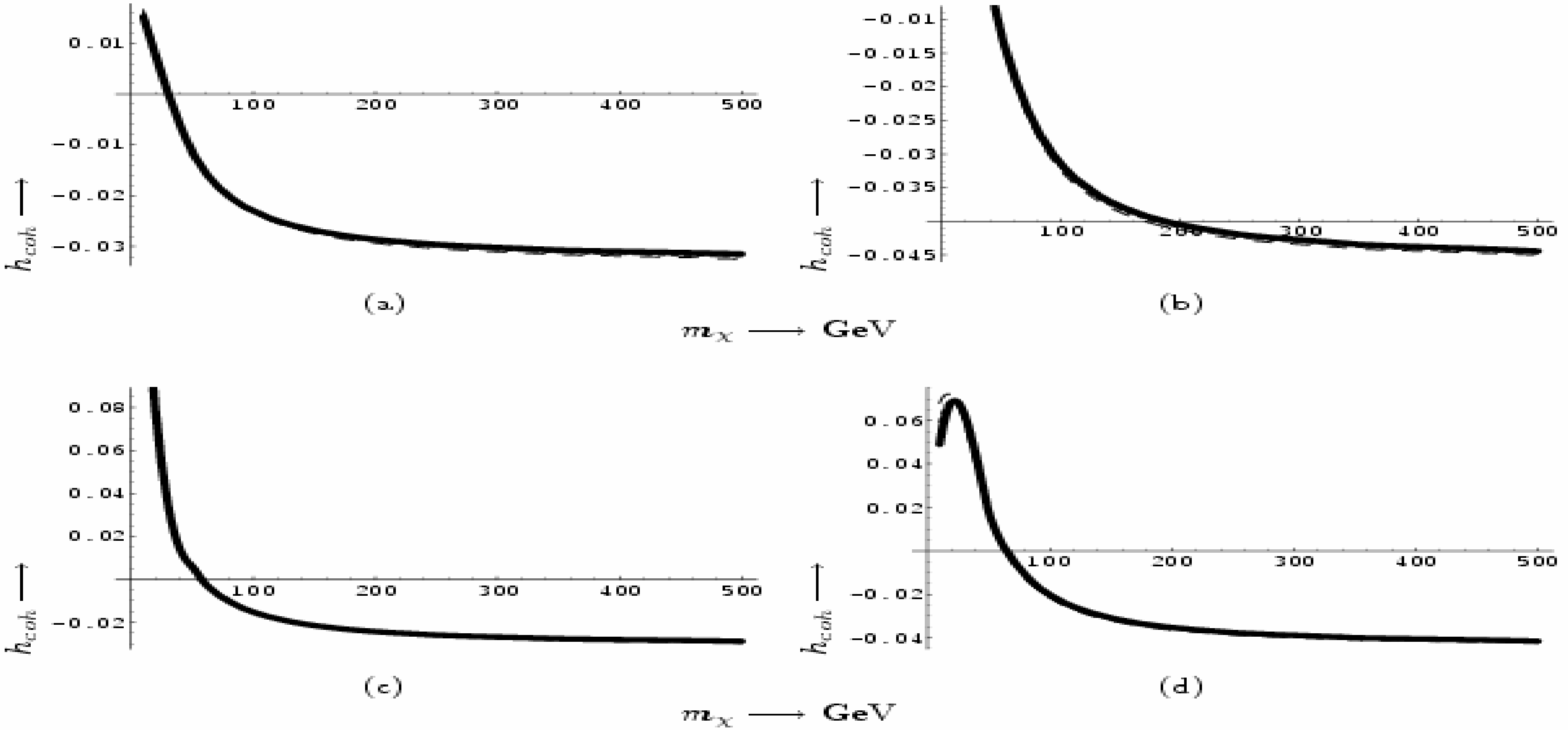
THE MODULATION EFFECT* (continued)

- $R = R_0\,(1 + h\cos\alpha)$

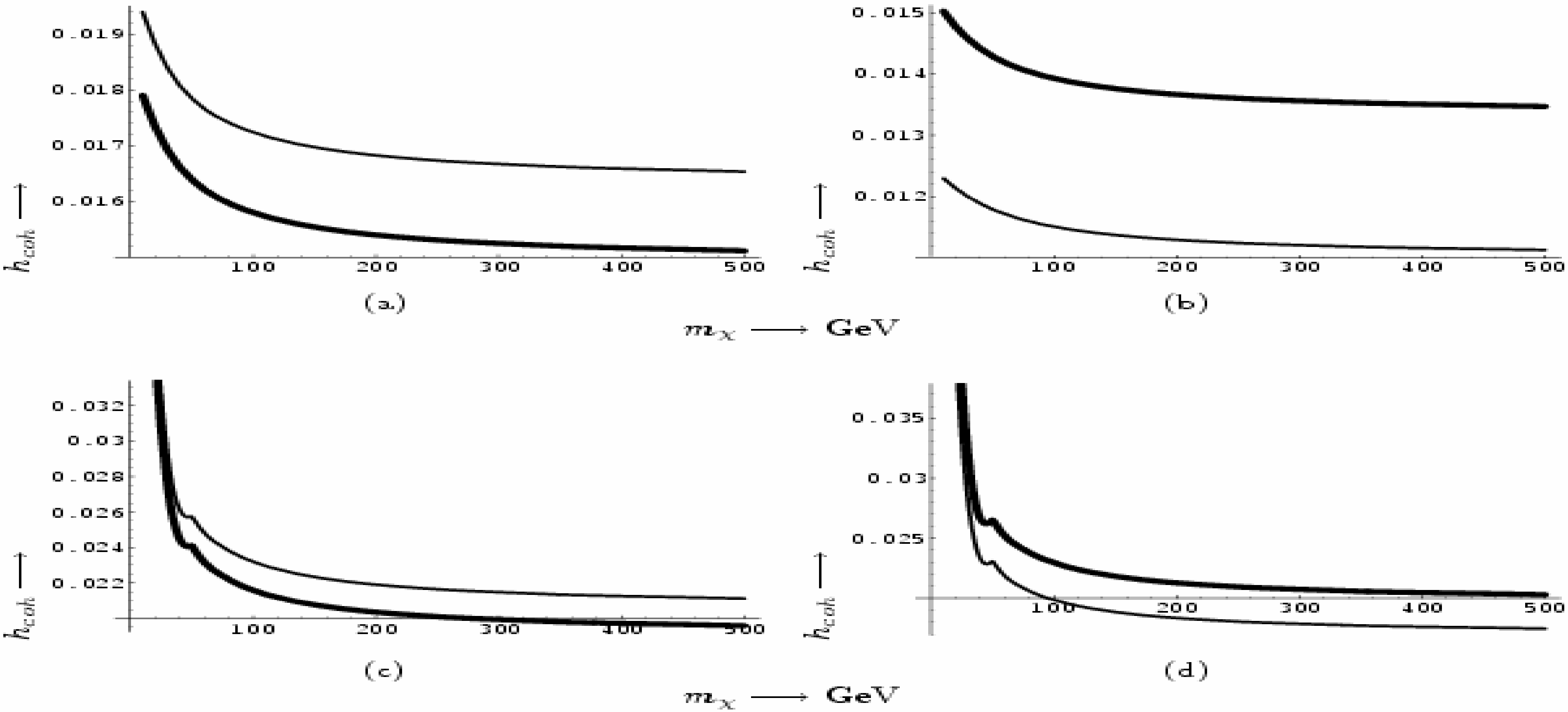
 ($\alpha = 0$ around June 3nd)

- h=modulation amplitude.
- R_0 =average rate.
- *n=2 corresponds to calculations with non standard M-B (Tetradis, Faeesler and JDV)

Ia: h_{coh} for medium target. Q_{thr} =0 (top), 10 keV (bottom); MB ⑩Left, Tsallis form⑩Right (asymmetry shown in both)



Ib:h_{coh} for a light target. Q_{thr} =0 (top), 5keV (bottom); MB ➉Left, Tsallis form➉Right (asymmetry shown in both)



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

- The calculation will proceed in two steps:
- A) In a direction fixed in galactic coordinates:

-Due to the motion of the sun the directional event rate will show an asymmetry due to the sun's motion around the galaxy.

-Due to the Earth's annual motion it will show a modulation with very characteristic signature

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

-Then Diurnal variation due to the rotation of the Earth

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

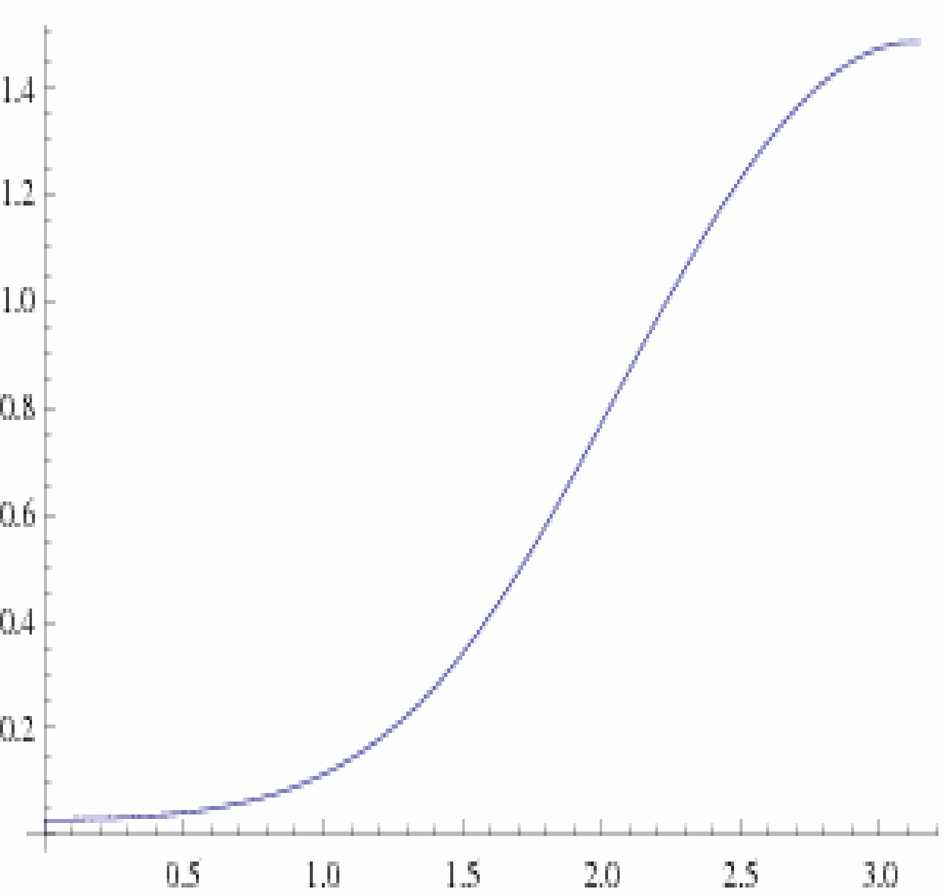
- The event rate in a direction fixed in the galactic frame is:

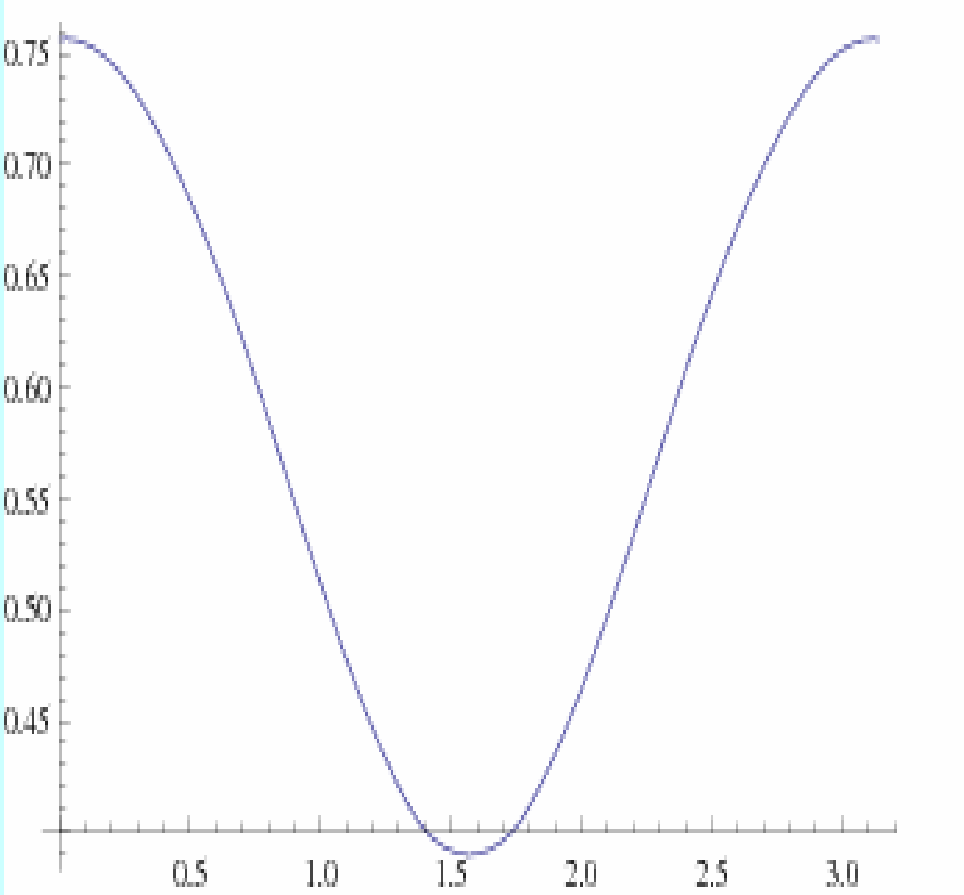
$$R_{dir}=(\kappa/2\pi)R_0[1+h_m\cos(\alpha-\alpha_m\pi)]$$

- R_0 is the average usual (**non-dir**) rate
- α the phase of the Earth (as usual)
- h_m is the modulation amplitude (it strongly depends on the direction of observation)
- α_m is the shift in the phase of the Earth (it strongly depends on the direction of observation)
- $\kappa/2\pi$ is the reduction factor (it depends on the direction of observation). This factor becomes κ, after integrating over Φ, since κ is independent of the angle Φ.
- κ, h_m and α_m depend only slightly on SUSY parameters and μ_r
- * Calculations by Faessler and JDV

The parameter κ vs the polar angle Θ in the case of A=32; m_χ=10 GeV

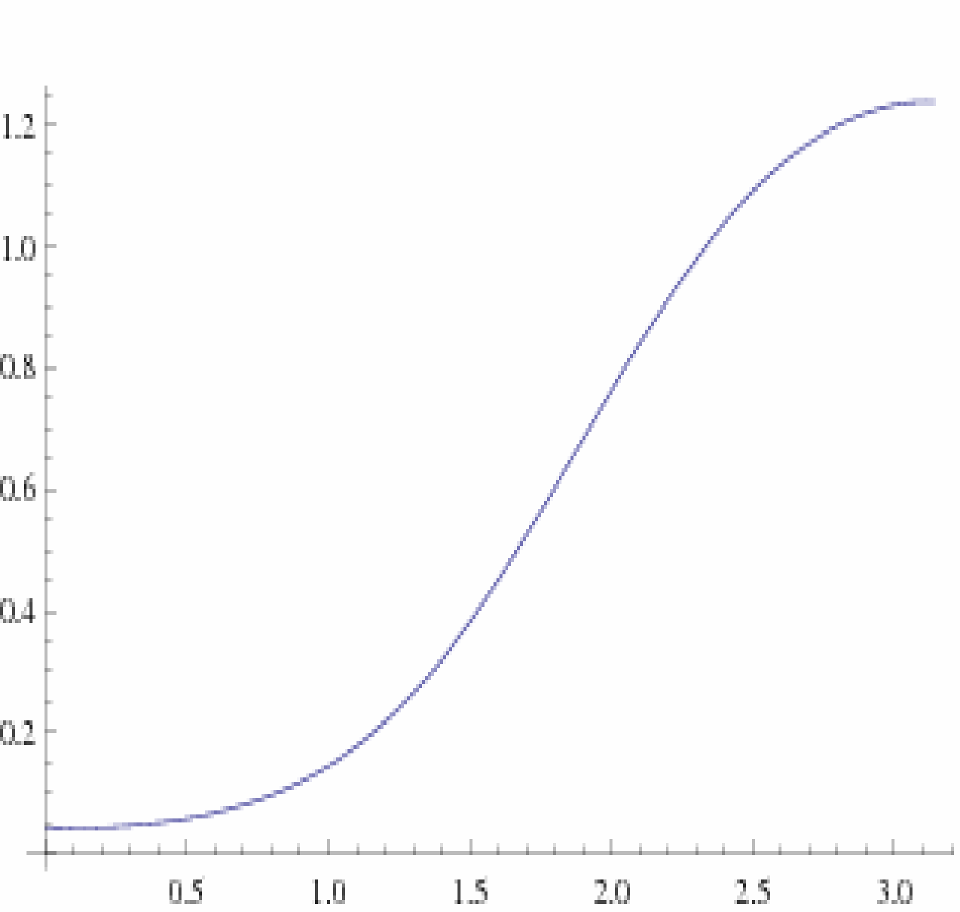
definite sense **Both senses**



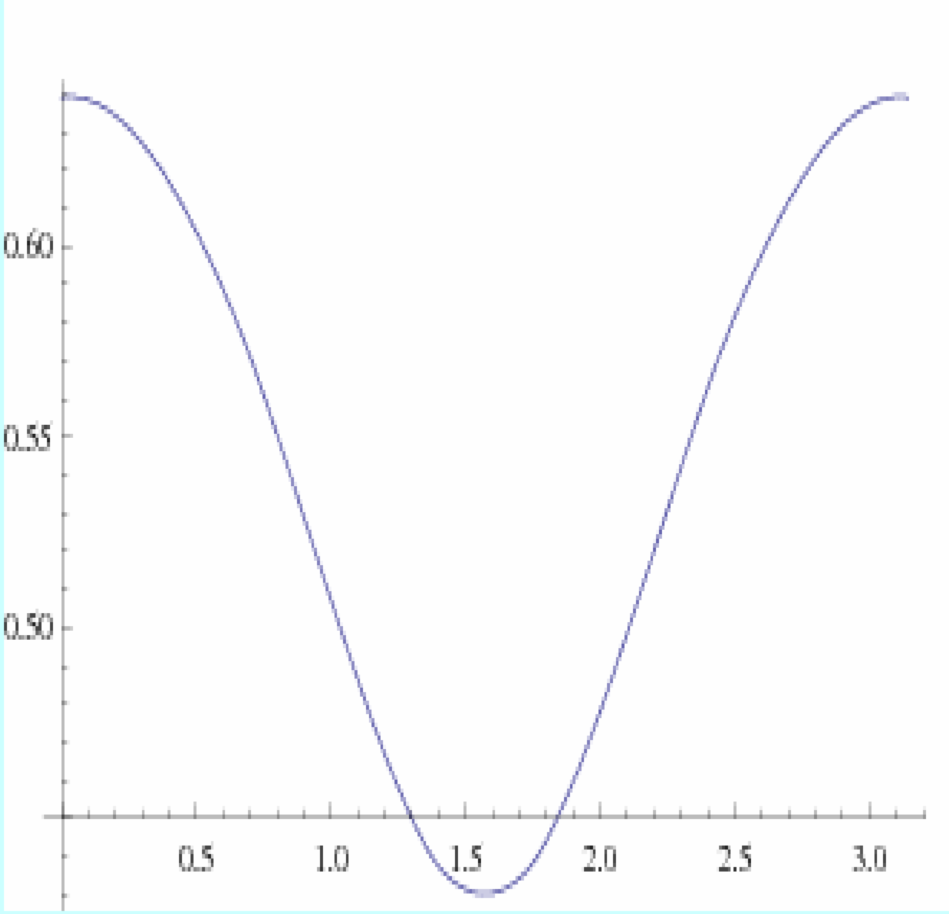


The parameter κ vs the polar angle Θ in the case of A=32; m_χ=100 GeV

definite sense

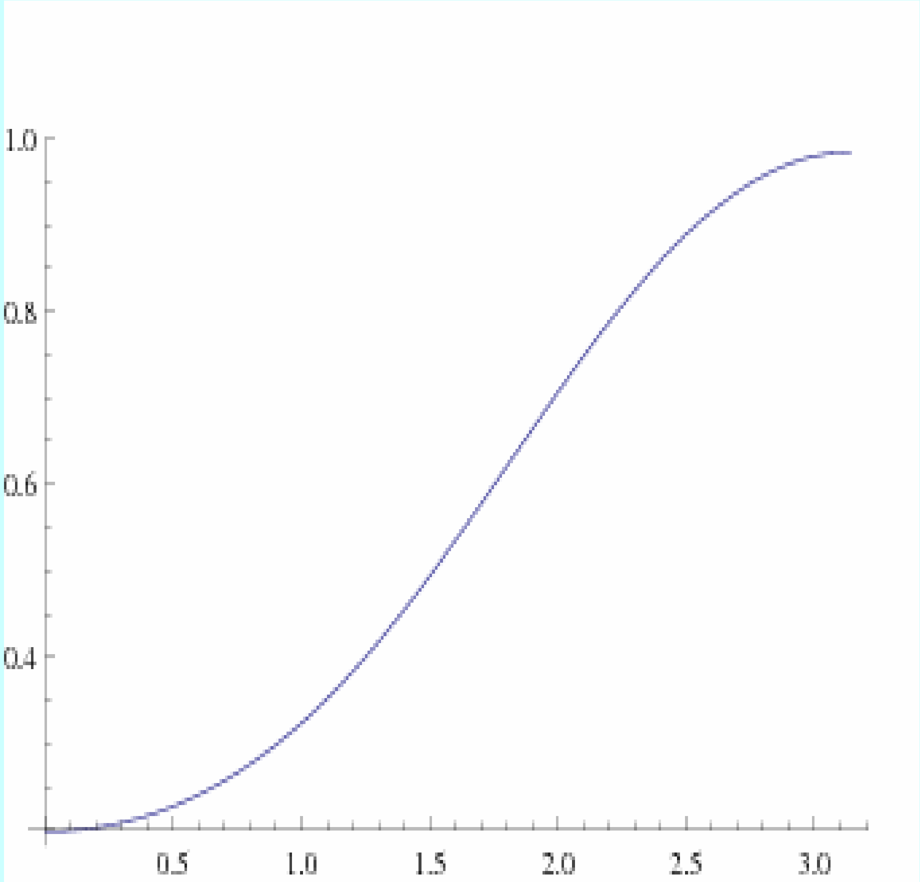


Both senses

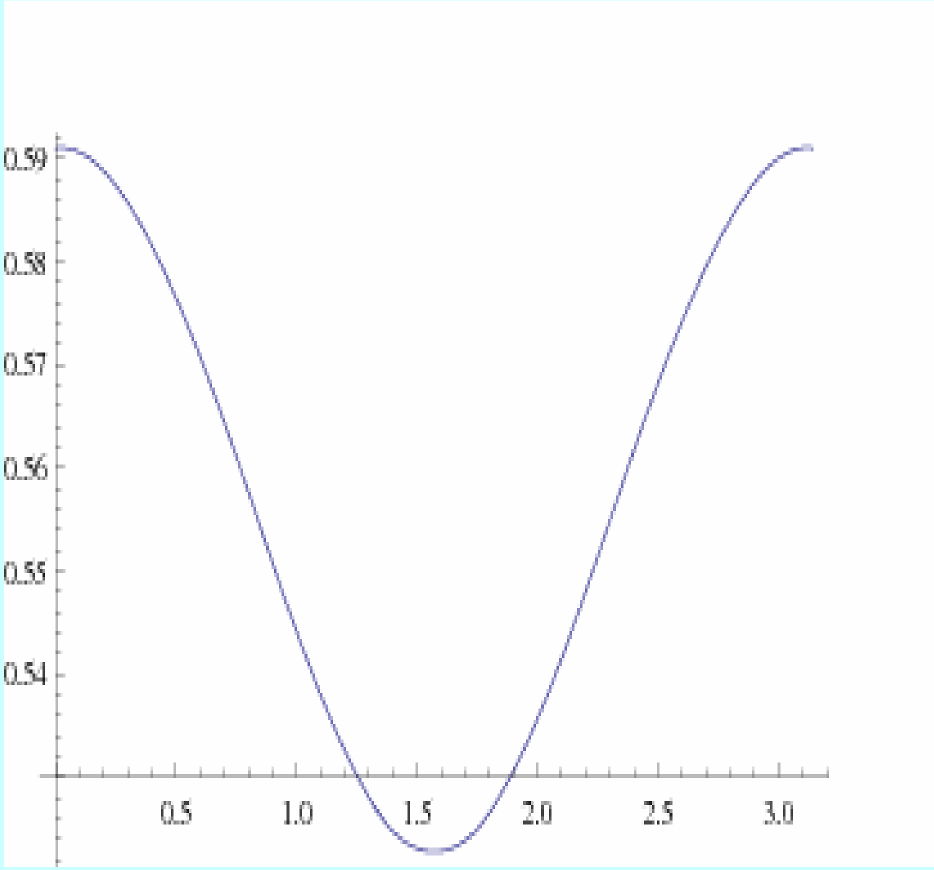


The parameter κ vs the polar angle Θ in the case of A=127; m_χ=10 GeV

definite sense

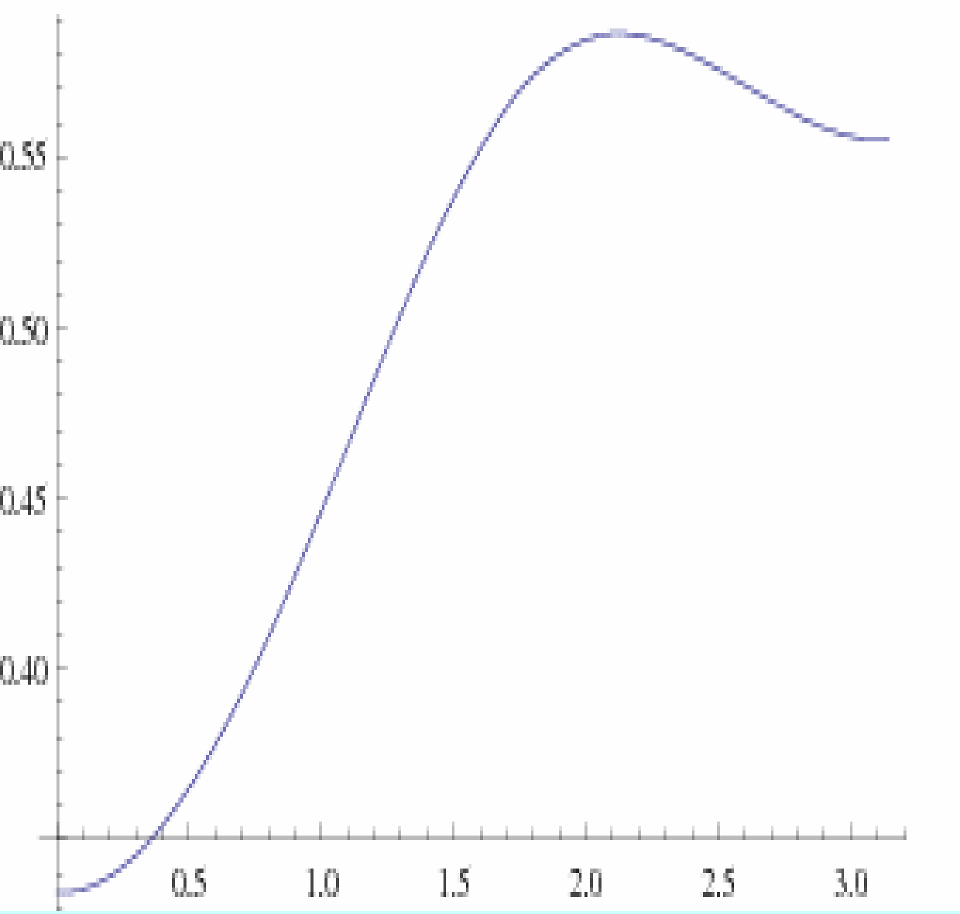


Both senses

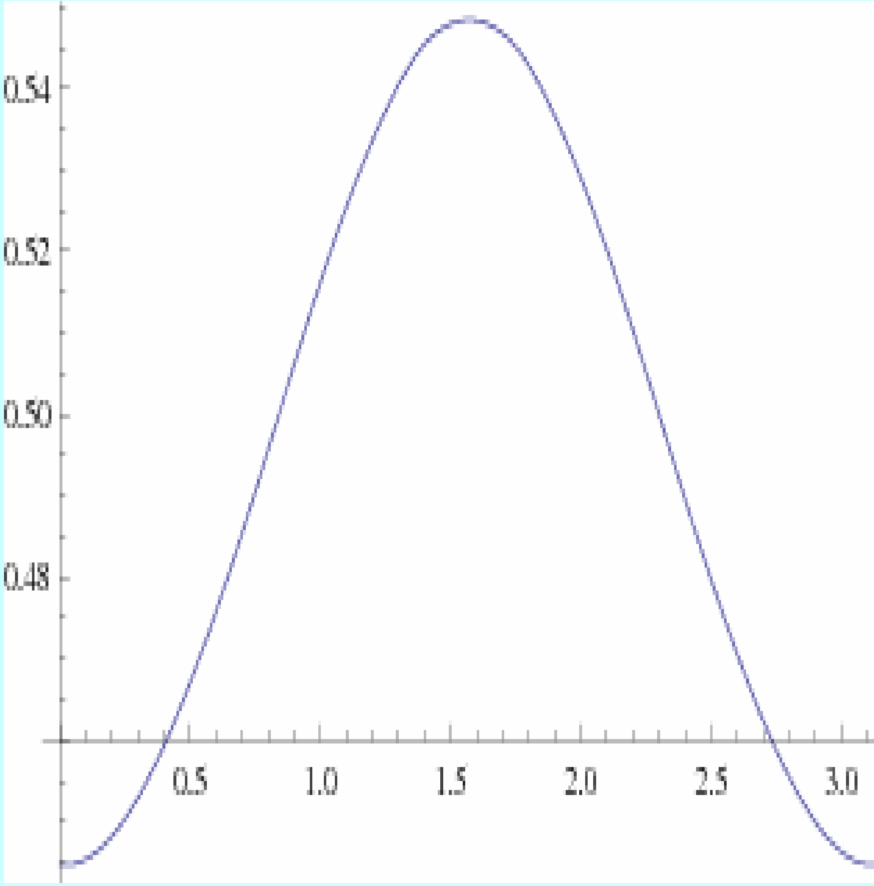


The parameter κ vs the polar angle Θ in the case of A=127; m_χ=100 GeV

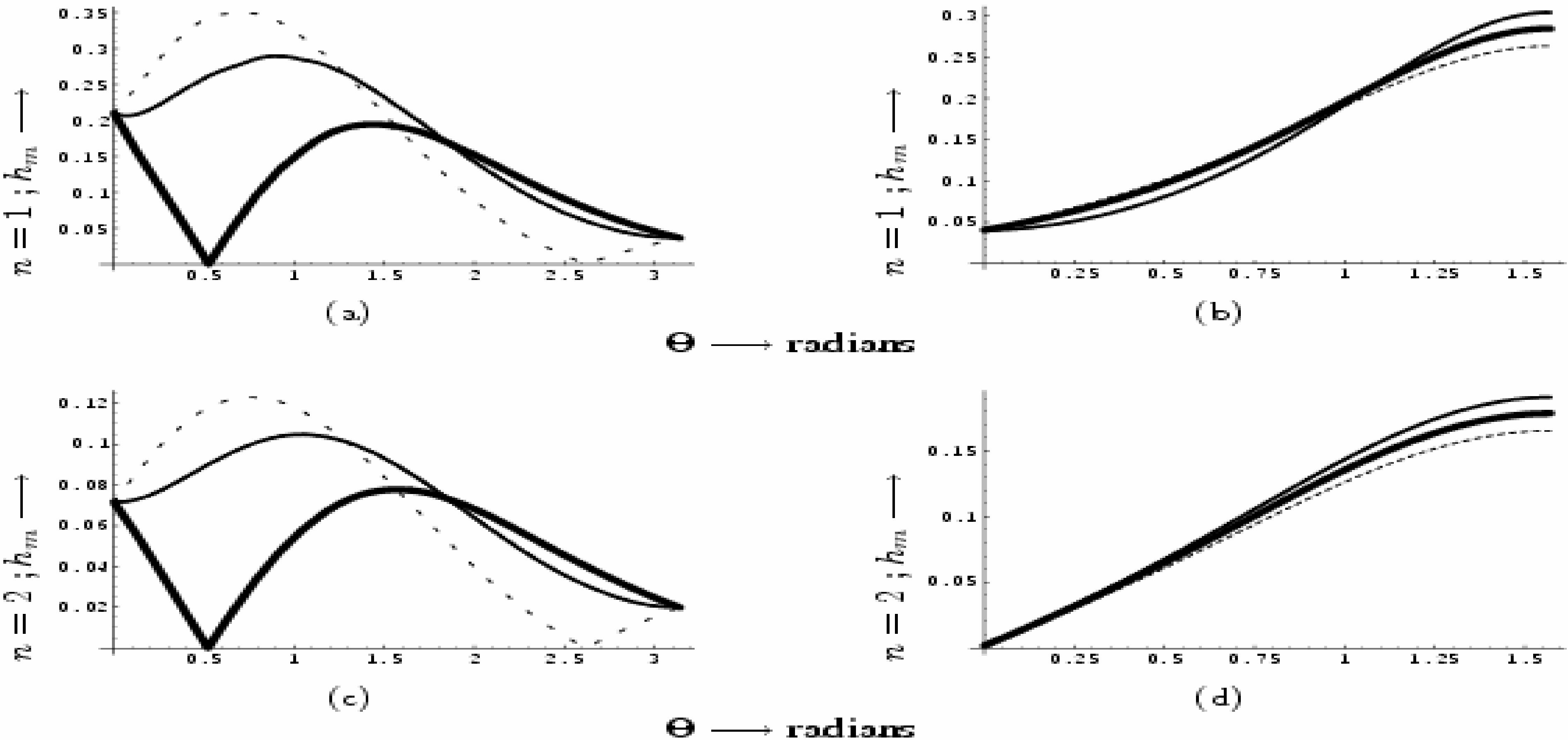
definite sense



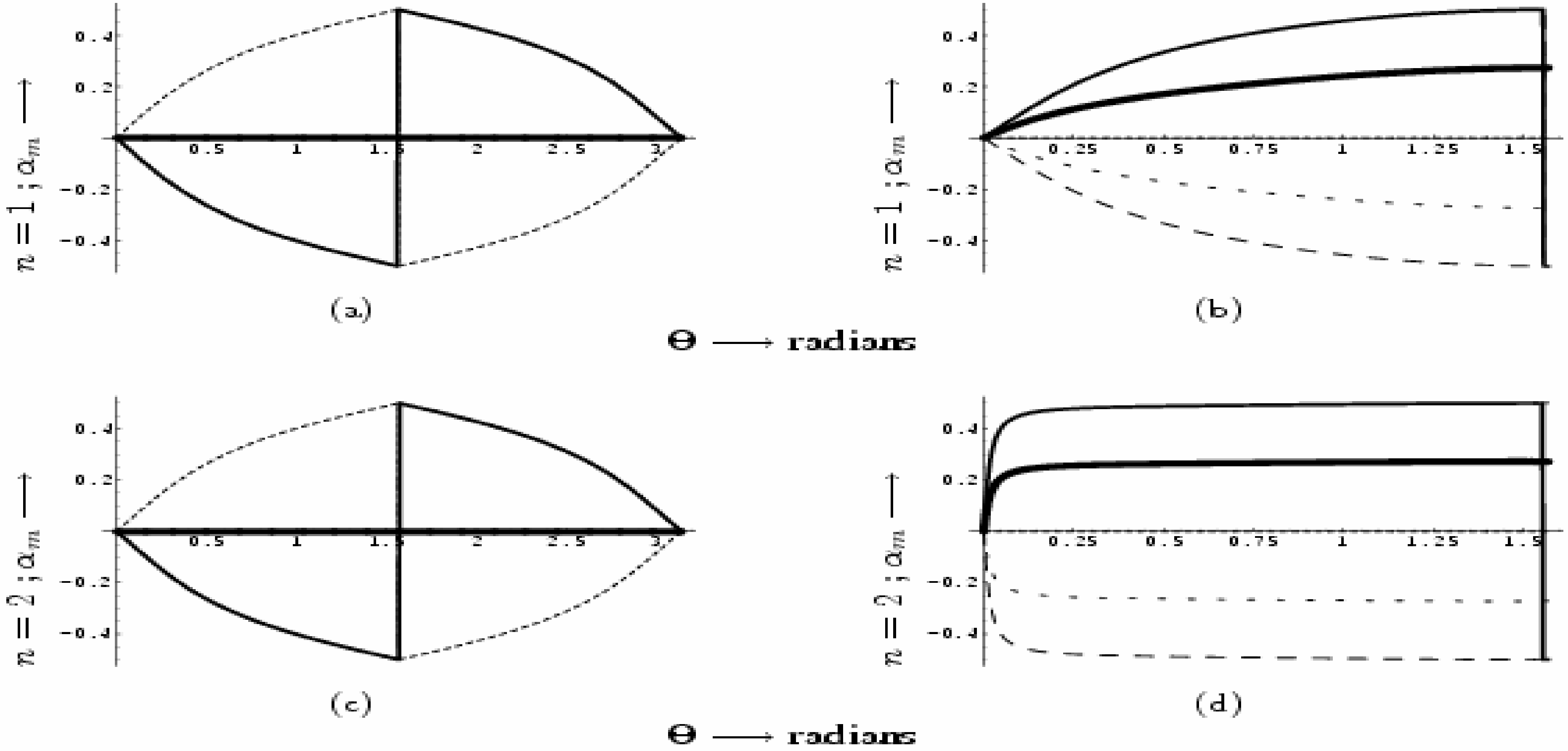
Both senses



The parameter h_m vs the polar angle in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right)



The phase α_m vs the polar angle in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right)



From the celestial to galactic coordinates

The galactic frame is defined by the galactic pole with ascention $\alpha = 12^h\ 51^m\ 26.282^s$ and inclination $\delta = +27^0\ 7'\ 42.01''$ and the galactic center at $\alpha = 17^h\ 45^m\ 37.224^s$, $\delta = -(28^0\ 56'\ 10.23'')$. Thus the galactic unit vectors can be expressed in terms of the celestial ones:

$$\hat{y} = -0.868\hat{i} - 0.198\hat{j} + 0.456\hat{k} \text{ (galactic axis)}$$

$$\hat{x} = \hat{s} = 0.055\hat{i} + 0.873\hat{j} + 0.483\hat{k}$$

$$\text{(radially out towards the sun)}$$

$$\hat{z} = \hat{x} \times \hat{y} = 0.494\hat{i} - 0.445\hat{j} + 0.747\hat{k}$$

$$\text{(the sun's direction of motion)} \quad (0.1)$$

Note in our system the x-axis is opposite to the s-axis used by the astronomers.

From the celestial to galactic coordinates

Note in our system the x-axis is opposite to the s-axis used by the astronomers. Thus a vector oriented by (α, δ) in the laboratory is given in the galactic frame by a unit vector with components:

$$\begin{pmatrix} y \\ x \\ z \end{pmatrix} = \begin{pmatrix} -0.868\cos\alpha\cos\delta - 0.198\sin\alpha\cos\delta + 0.456\sin\delta \\ 0.055\cos\alpha\cos\delta + 0.873\sin\alpha\cos\delta + 0.4831\sin\delta \\ 0.494\cos\alpha\cos\delta - 0.445\sin\alpha\cos\delta + 0.747\sin\delta \end{pmatrix} \tag{0.2}$$

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 rate becomes time dependent. It will show a periodic dependence.

The circular path in the galactic system

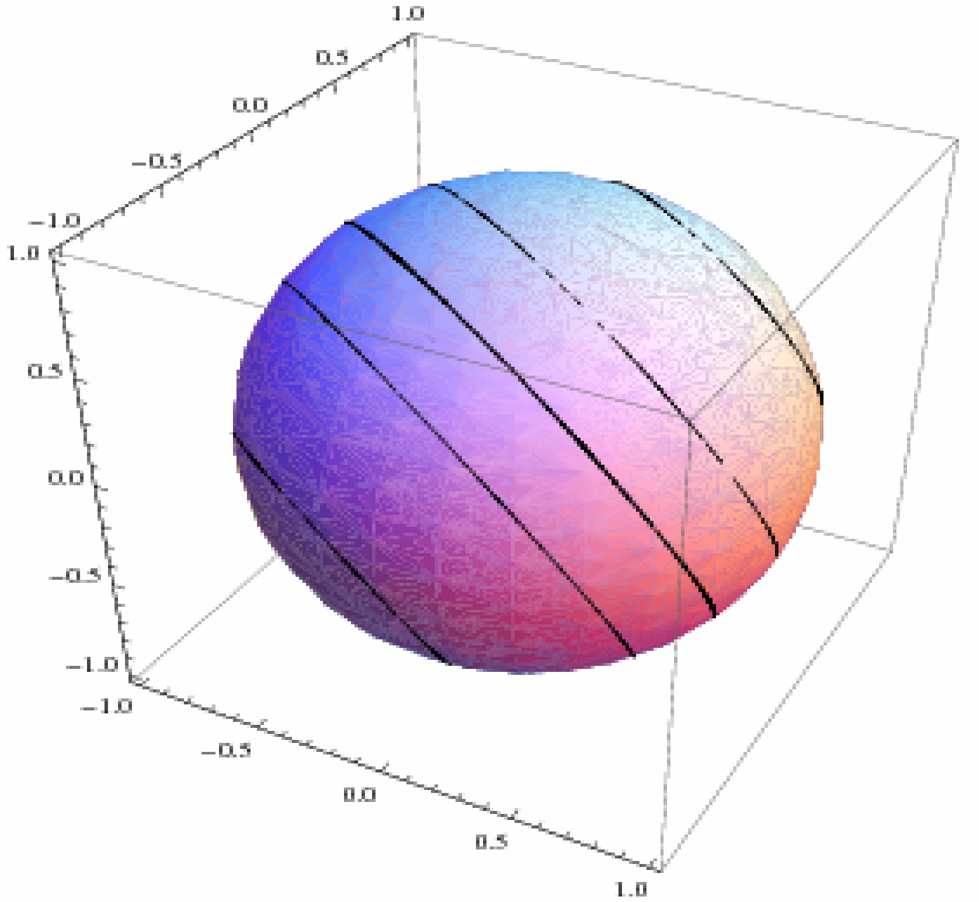


FIG. 19: The circular path followed by the point of the direction of observation as seen in the galactic system due to the Earth's rotation for various inclinations δ. The galactic axis is indicated upward. For the path notation see Fig. 18.

The rate depends on Θ. Θ depends on time due to the earth's rotation

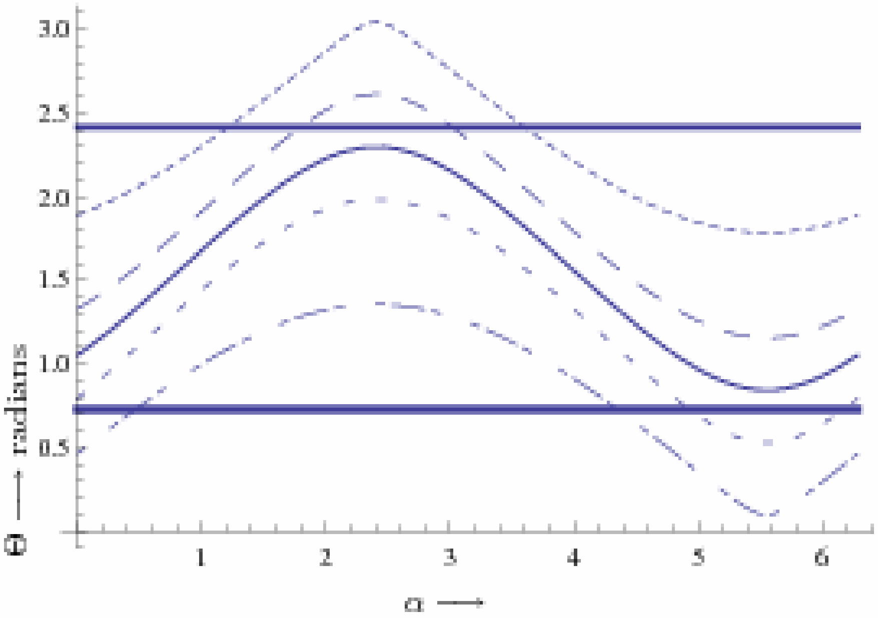
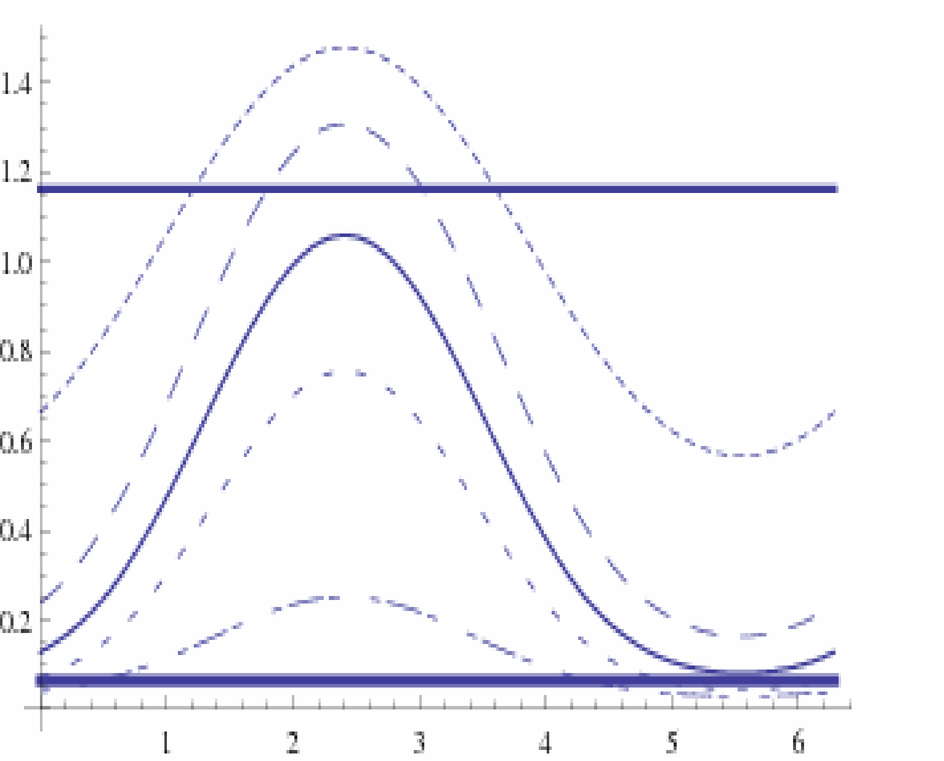


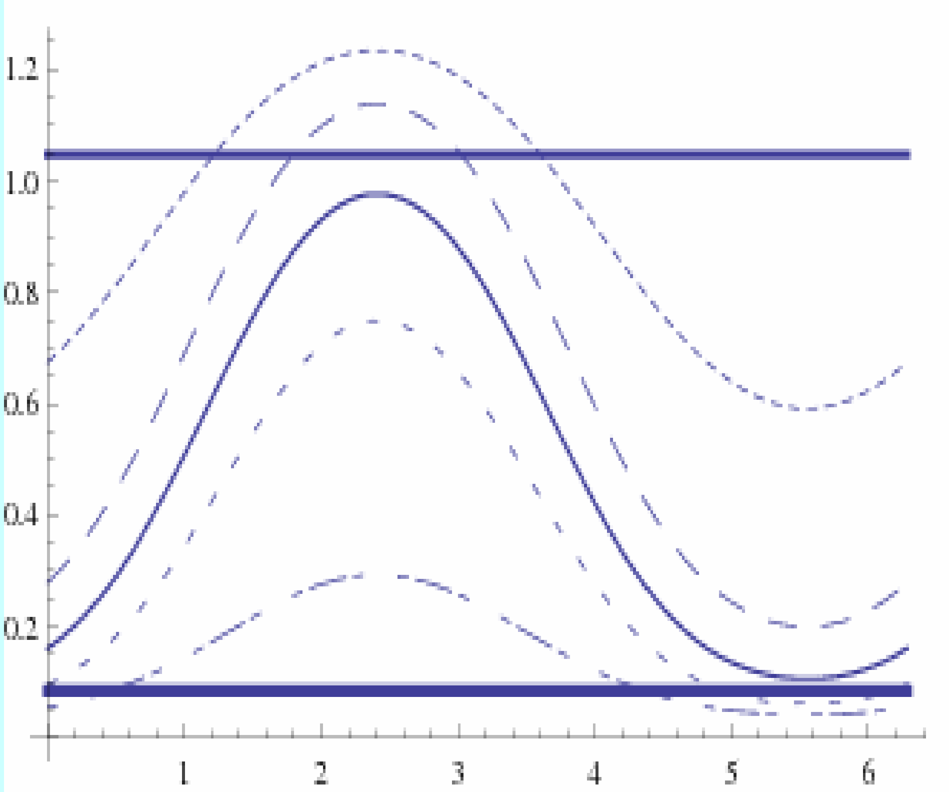
FIG. 18: Due to the diurnal motion of the Earth different angles Θ in galactic coordinates are sampled as the earth rotates. The angle Θ scanned by the direction of observation is shown for various inclinations δ. The intermediate thickness, the short dash, the long dash, the fine line, the long-short dash, the short-long-short dash and the thick line correspond to inclination $\delta = -\pi/2, -3\pi/10, -\pi/10, 0, \pi/10, 3\pi/10$ and $\pi/2$ respectively. We see that, for negative inclinations, the angle Θ can take values near π, i.e. opposite to the direction of the sun's velocity, where the rate attains its maximum.

Diurnal Variation of the rate (κ) CS_2 Target & Fully Directional

WIMP MASS 10 GeV

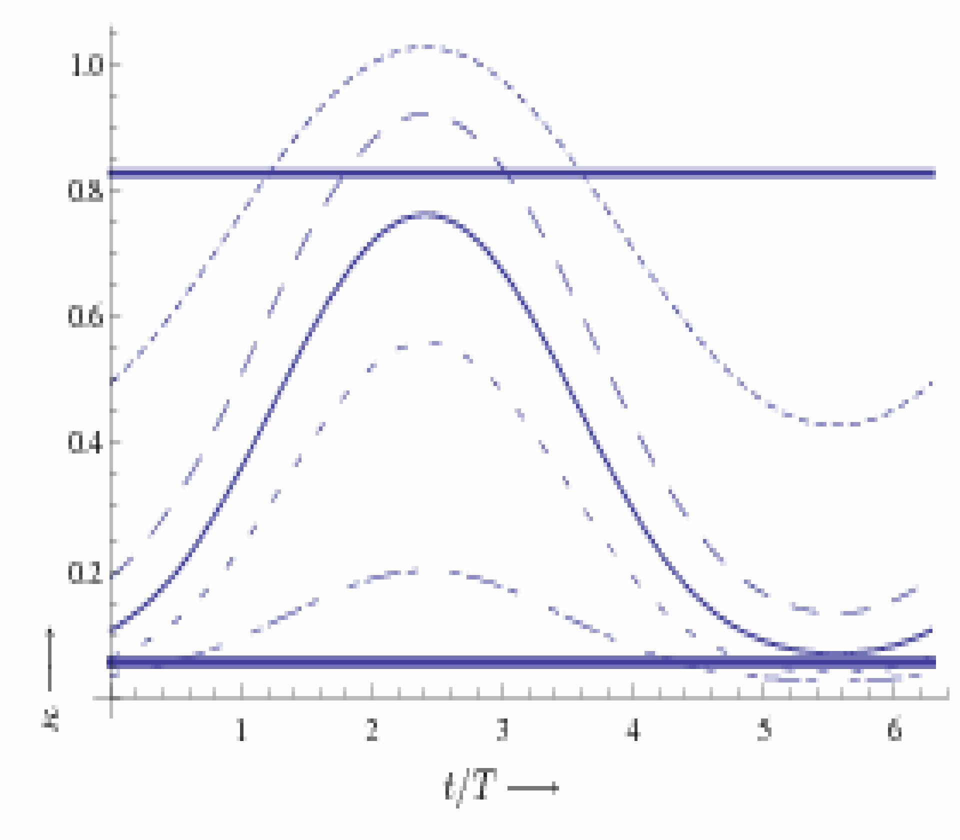


WIMP MASS 100 GeV

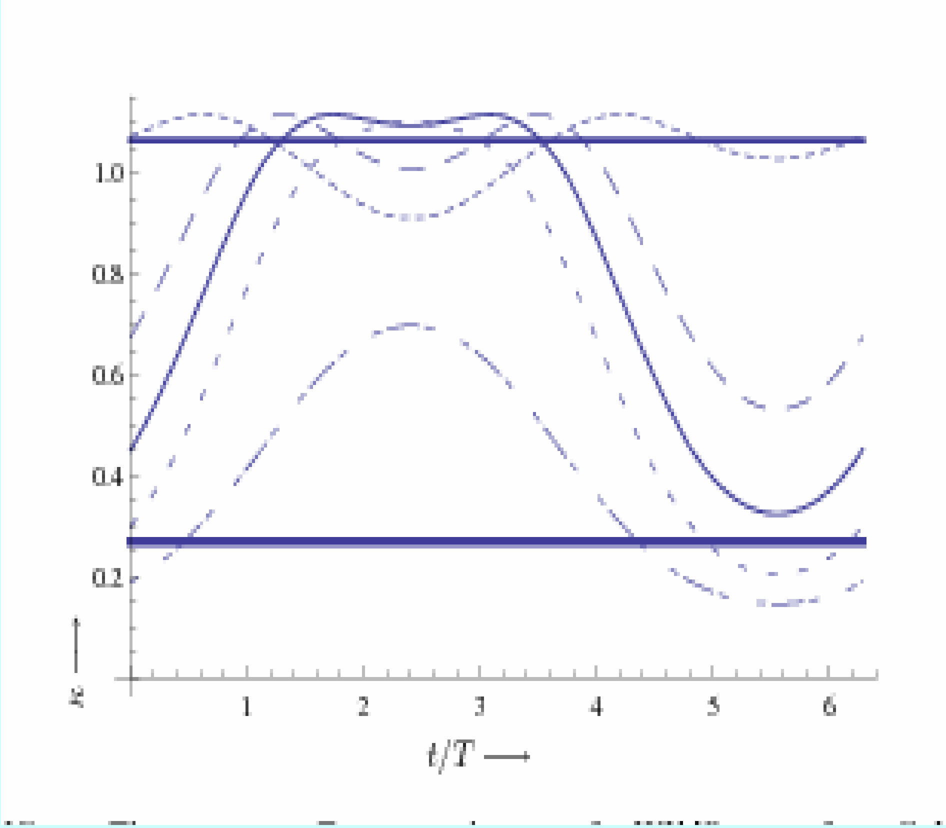


Diurnal Variation of the rate (κ) Iodine Target & Fully Directional

WIMP MASS 10 GeV

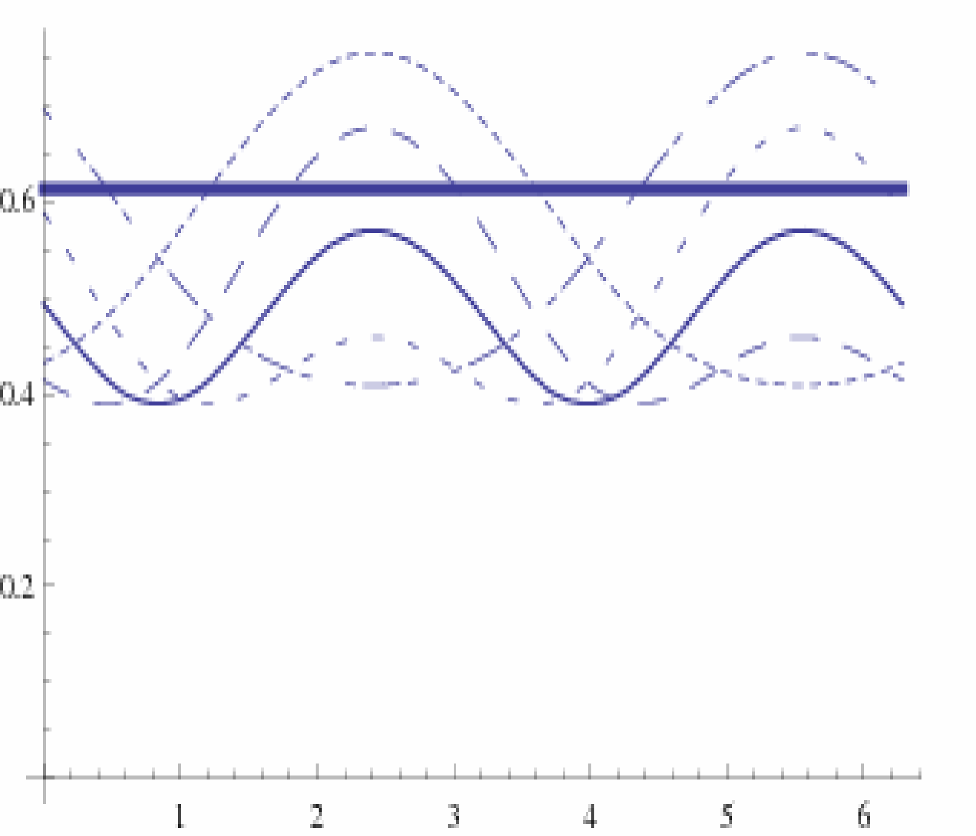


WIMP MASS 100 GeV

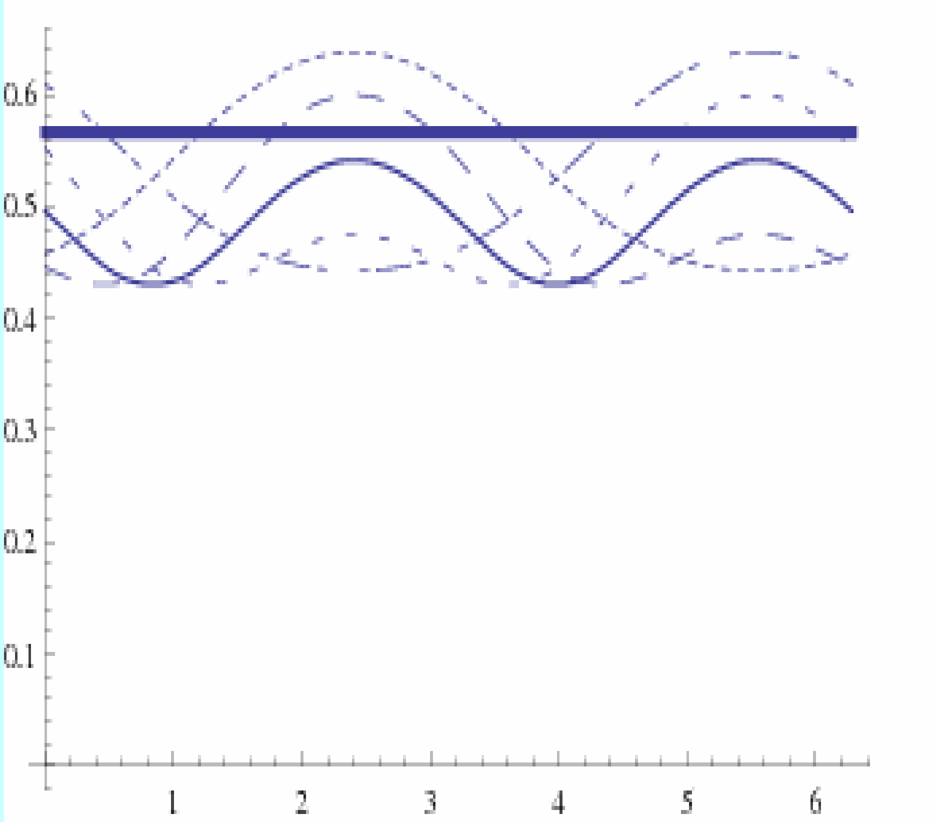


Diurnal Variation of the rate (κ) CS_2 Target& partly Directional

WIMP MASS 10 GeV

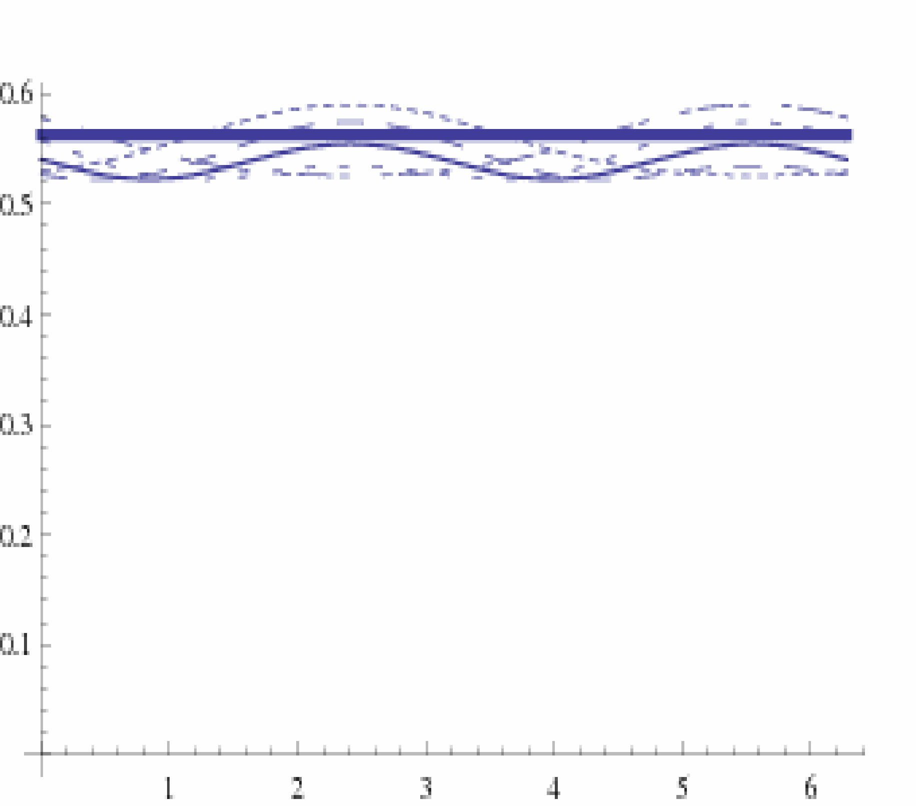


WIMP MASS 100 GeV

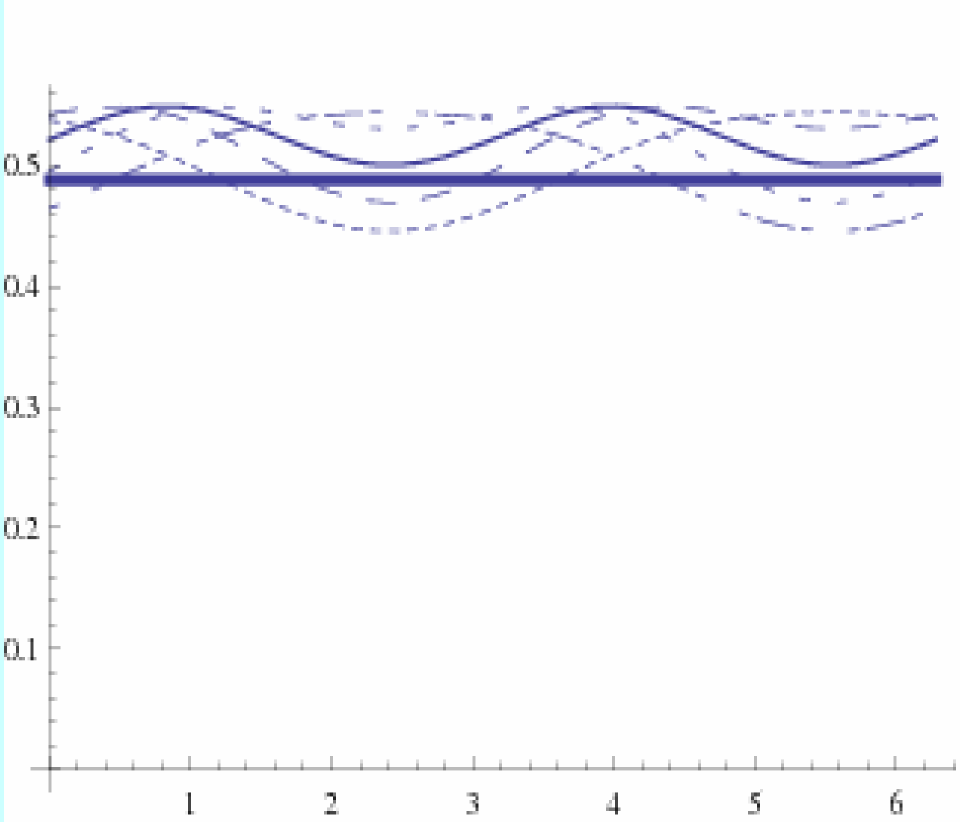


Diurnal Variation of the rate (κ) Iodine Target& partly Directional

WIMP MASS 10 GeV



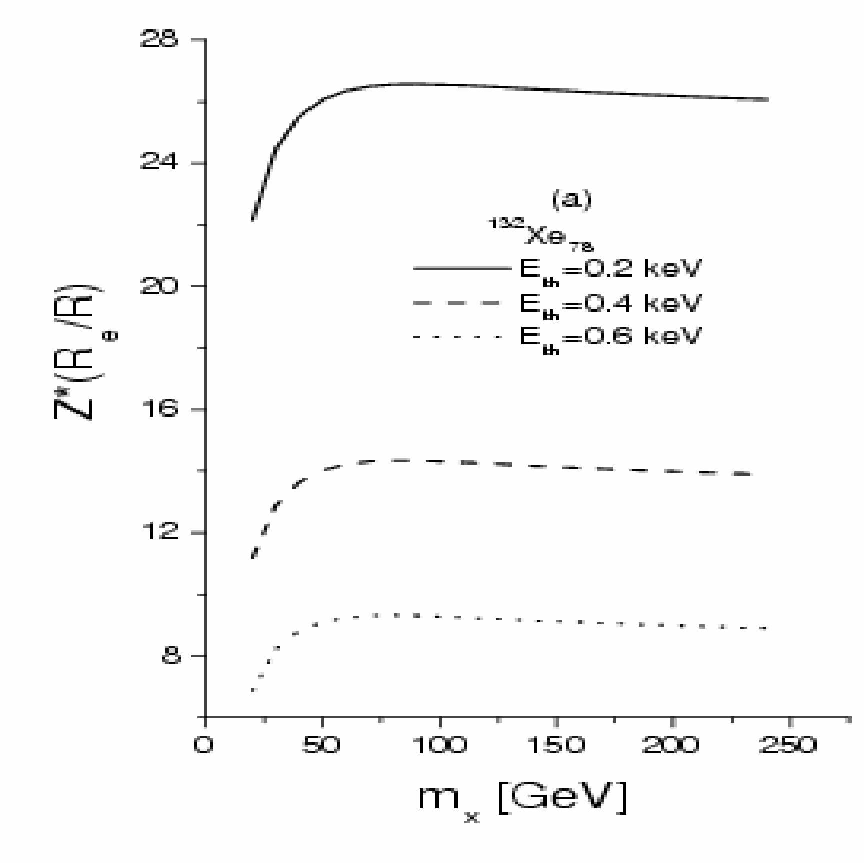
WIMP MASS 100 GeV

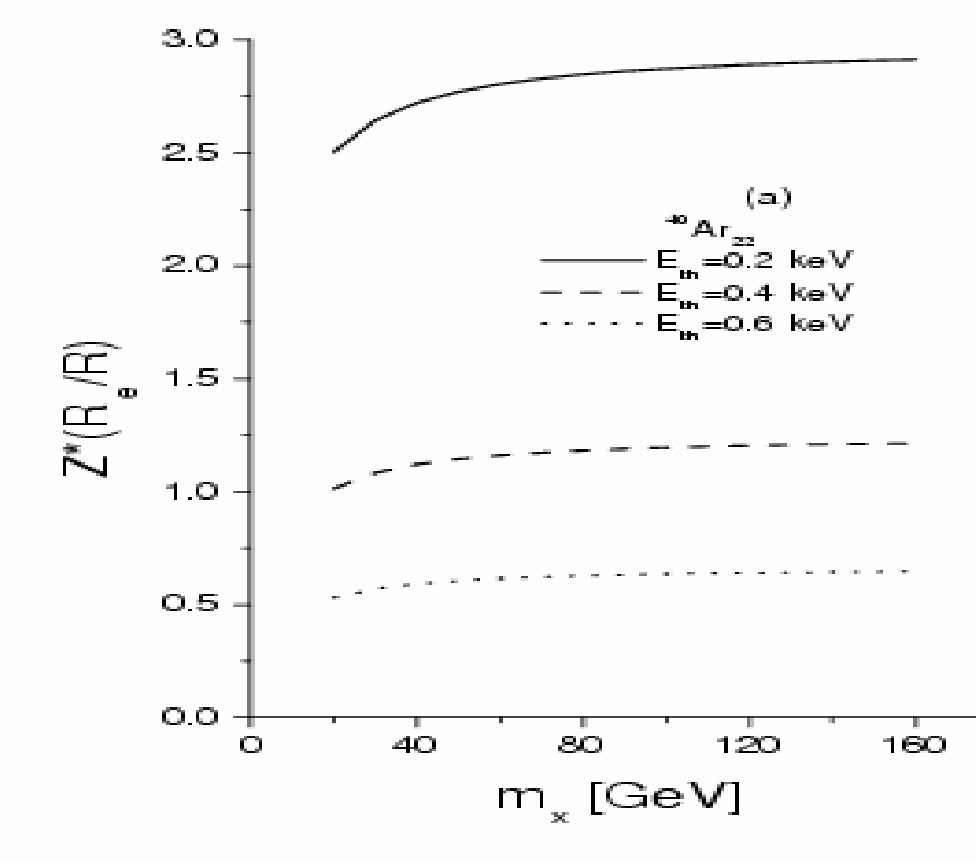


NON RECOIL MEASUREMENTS

- (a) Measurement of ionization electrons produced directly during the WIMP-nucleus collisions
- (b) Measurement of hard X-rays following the de-excitation of the atom in (a)
- (c) Excitation of the Nucleus and observation of the de-excitation γ rays

Relative rate for electron ionization (there are Z electrons in an atom!)





Detection of hard X-rays

- After the ionization there is a probability for a K or L hole
- This hole de-excites via emitting X-rays or Auger electrons.
- the fraction of X-rays per recoil is:

  $\sigma_{X(n\ell)}/\sigma_r = b_{nl}(\sigma_{n\ell}/\sigma_r)$ with $\sigma_{n\ell}/\sigma_r$ the relative ionization rate per orbit and $b_{n\ell}$ the fluorescence ratio (determined experimentally)

The K X-ray BR in WIMP interactions in ^{132}Xe for masses: L⑩30GeV, M⑩100GeV, H⑩300GeV

K X-ray	$E_K(K_{ij})$ keV	$B_K(K_{ij})$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_L$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_M$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_H$
$K_{\alpha 2}$	29.5	0.284	0.0086	0.0560	0.0645
$K_{\alpha 1}$	29.8	0.527	0.0160	0.1036	0.1196
$K_{\beta 1}$	33.6	0.154	0.0047	0.0303	0.0350
$K_{\beta 2}$	34.4	0.034	0.0010	0.0067	0.0077

Excitation of the nucleus:

The average WIMP energy is:

- $<T_\chi> \approx 40$ keV n^2 $(m_\chi/100\text{GeV})$
- $T_{\chi,max} \approx 215$ keV n^2 $(m_\chi/100\text{GeV})$. Thus
- m_χ =500GeV, n=2 $\Downarrow$

  $<T_\chi> \approx 0.8$ MeV, $T_{\chi,max} \approx 4$ MeV
- So excitation of the nucleus appears possible in exotic models with very heavy WIMPs

Unfortunately,
Not all available energy is exploitable!

- For ground to ground transitions (q⑩momentum, Q ⑩ energy)

$$q = 2\frac{Am_pM_\chi}{Am_p + M_\chi}\beta\xi \quad , \quad Q = Am_p\left(1+\frac{Am_p}{M_\chi}\right)^{-2}\beta^2\xi^2 \quad , \quad \beta = \upsilon/c$$

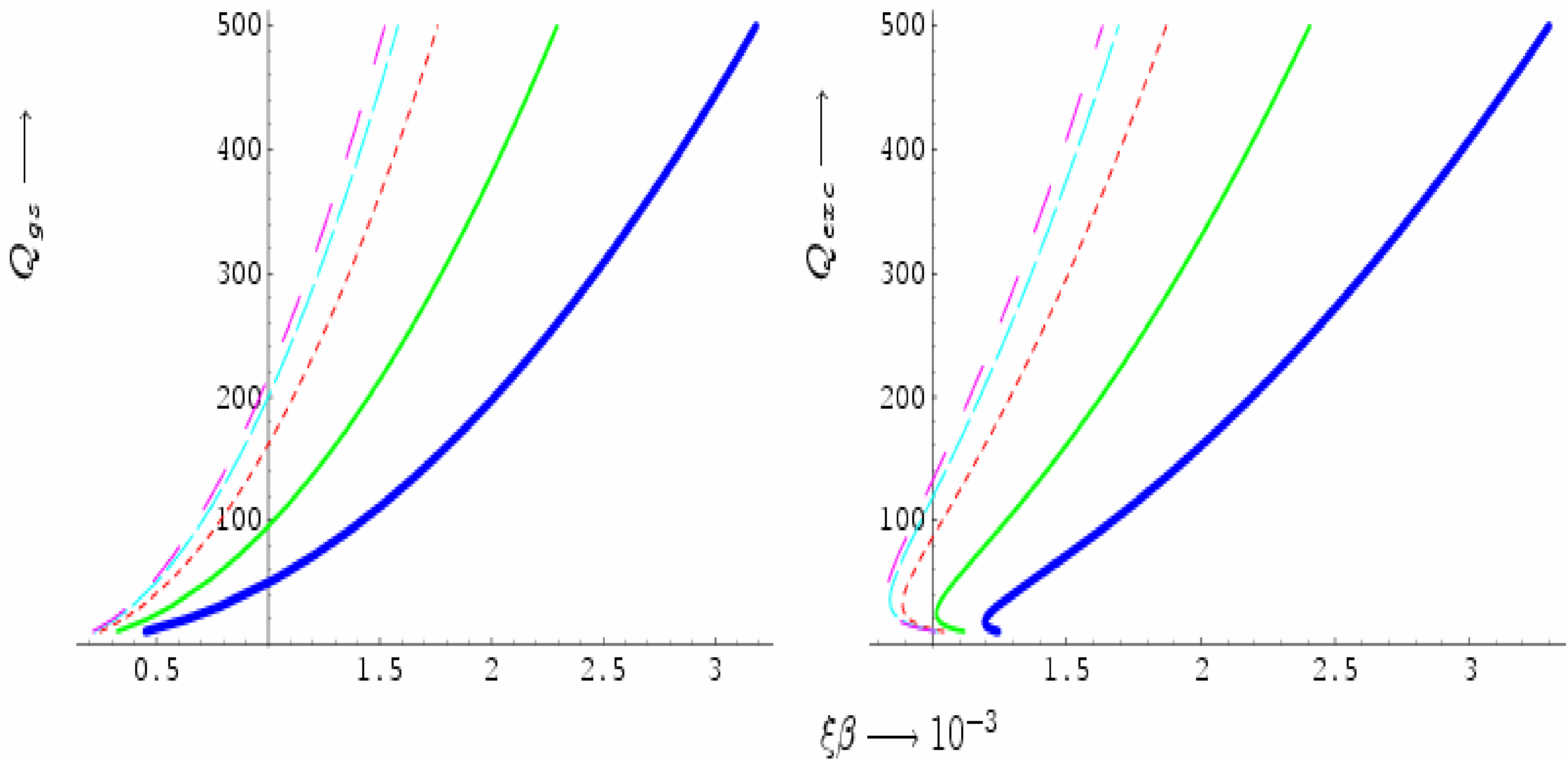
- For Transitions to excited states

$$\frac{(Am_p + M_\chi)Q}{M_\chi} + \Delta - \sqrt{2Am_pQ}\beta\xi = 0 \ , \ \beta = \upsilon/c \tag{1}$$

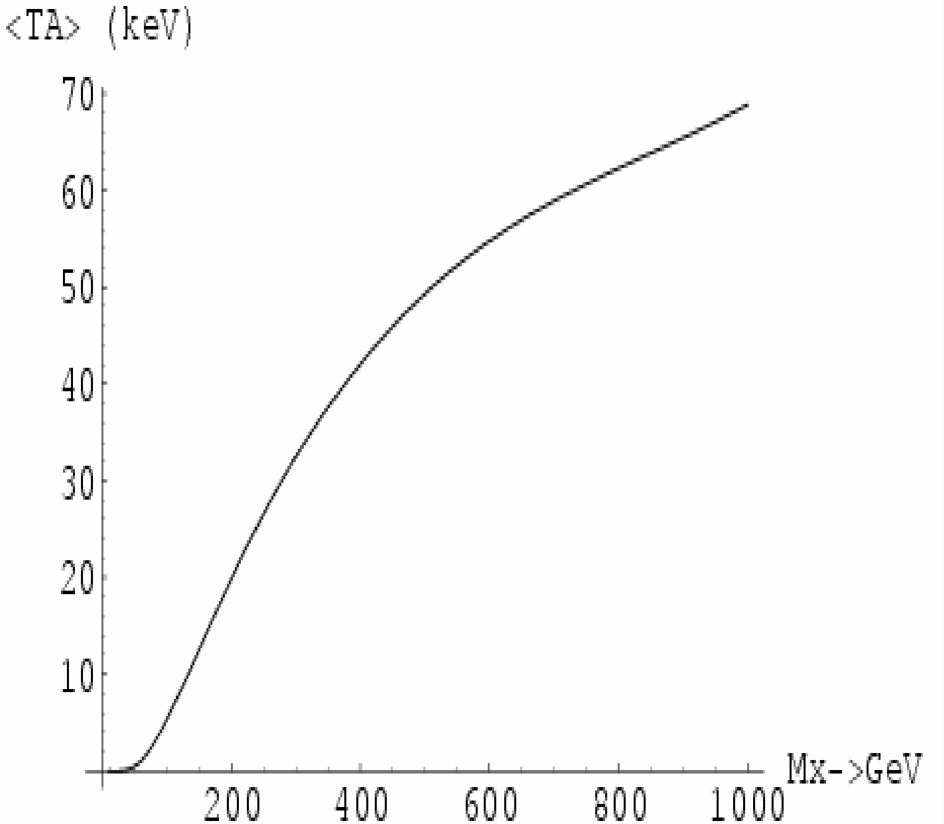
where $\beta = \upsilon/c$ with υ the wimp velocity, ξ the cosine of the angle between the oncoming WIMP and the outgoing nucleus and Δ the excitation energy of the nuclear state.

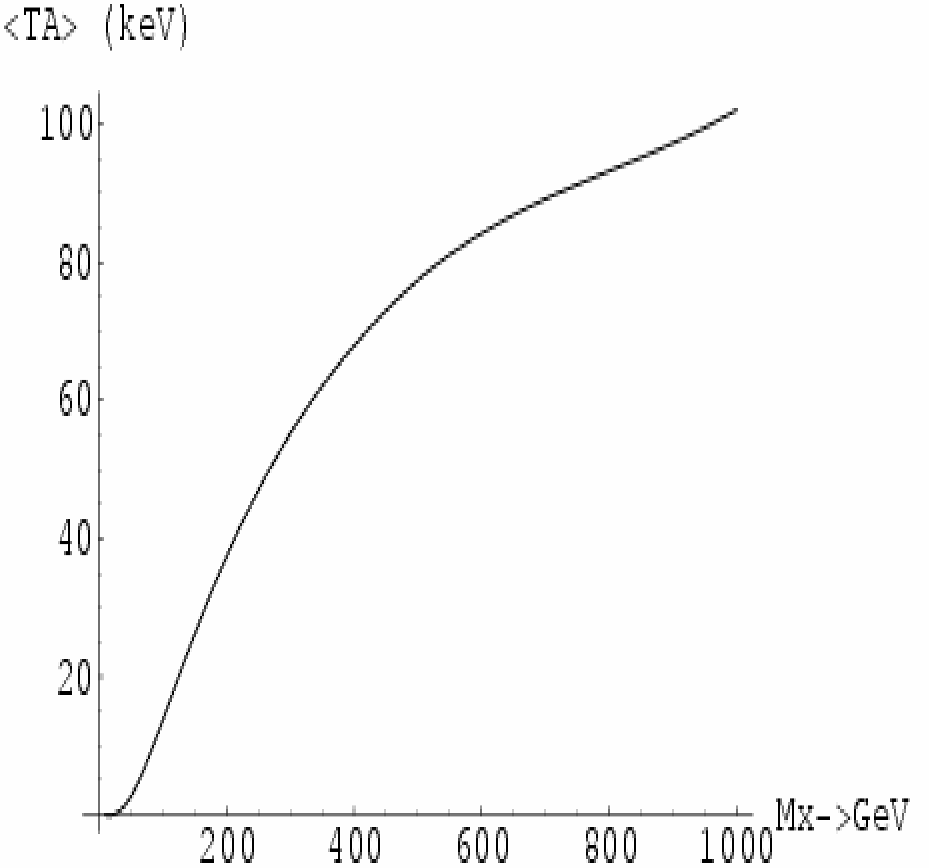
- Both are peaked around ξ=1

The recoil energy in keV as a function of the WIMP velocity, in the case of A=127. Elastic scattering on the left and transitions to the Δ=50 keV excited state on the right. Shown for WIMP masses in the 100, 200, 500, 1000 and 1500 GeV. $<\xi\beta>=10^{-3}$



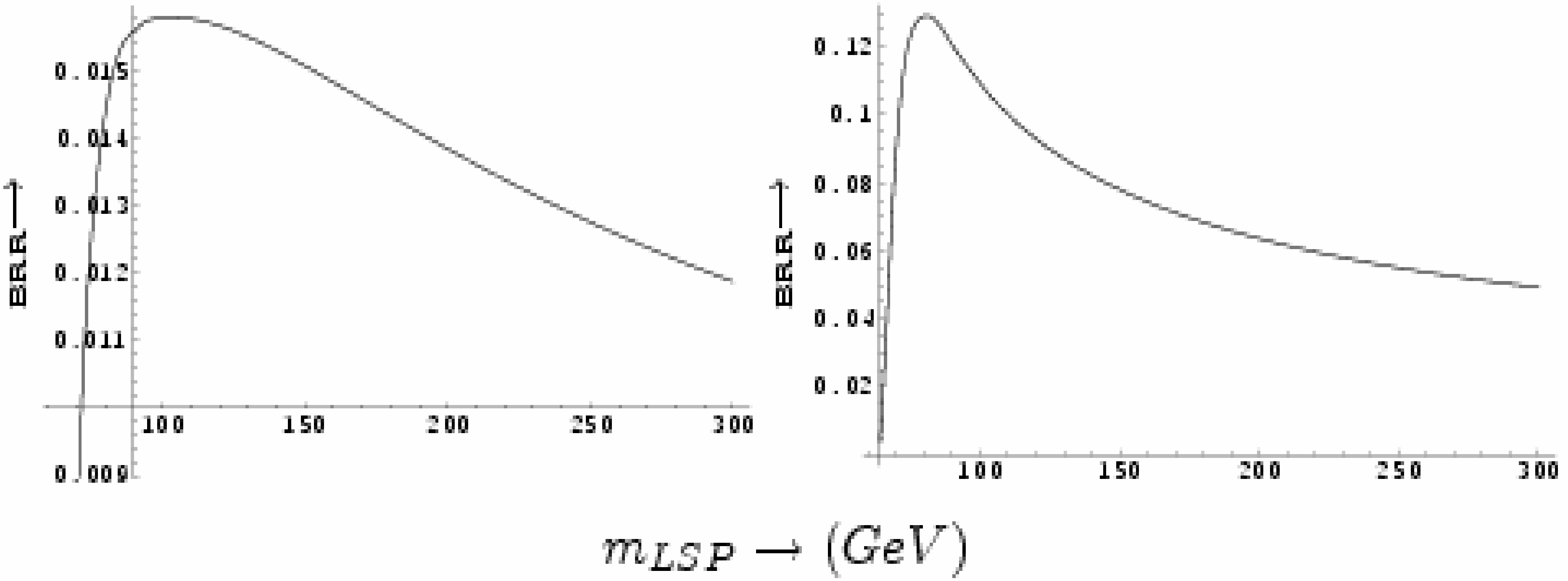
The average nuclear recoil energy:
A=127; Δ=50 keV (left), Δ=30 keV (right)





BR for transitions to the first excited state at 50 keV of I vs LSP mass (Ejiri; Quentin, Strottman and JDV) Relative to nucleon recoil. Quenching not included in the recoil

i) Left ➉ E_{th} =0 keV ii) Right ➉ E_{th} =10 keV



CONCLUSIONS: Non-directional

- The modulation amplitude h is small less than 2% and depends on the LSP mass.
- It depends on the velocity distribution
- Its sign is also uncertain. For both M-B and Realistic distributions in the case of heavy WIMPS it is positive for light systems and negative for intermediate and heavy nuclei. A good signature.
- It may increase as the energy cut off remains big (as in the DAMA experiment), but at the expense of the number of counts. The DAMA experiment maybe consistent with the other experiments, if the spin interaction dominates. Then their contour plot should move elsewhere (with the spin proton cross section).
- The modulation is reduced in fancy, but perhaps unrealistic, velocity distributions resulting from the coupling of dark matter to dark energy or in adiabatic models

CONCLUSIONS: directional Exps

- κ (the reduction factor) is small. $\kappa \approx 1$ in the most favored direction ($\Theta = \pi$ in MB)
- The modulation amplitude in the most favored direction is $0.02 < h_m < 0.1$ (bigger than in non-directional case) depending on the WIMP mass.
- In the perpendicular plane ($\kappa \approx 0.3$) h_m is much bigger:

  $|h_m| \approx 0.3$ (60% difference between maximum and minimum). Both its magnitude and its sign depend on the azymouthal angle Φ. A spectacular signal. Cannot be mimicked by other seasonal effects.

CONCLUSIONS: Electron production during LSP-nucleus collisions

- During the neutralino-nucleus collisions, electrons may be kicked off the atom
- Electrons can be identified easier than nuclear recoils (Needed: low threshold (~0.25keV) TPC detectors)
- The branching ratio for this process depends on the atomic number, the threshold energies and the LSP mass.
- For a threshold energy of 0.25 keV the ionization event rate in the case of a heavy target can exceed the rate for recoils by an order of magnitude.
- Detection of hard X-rays seams more feasible

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!

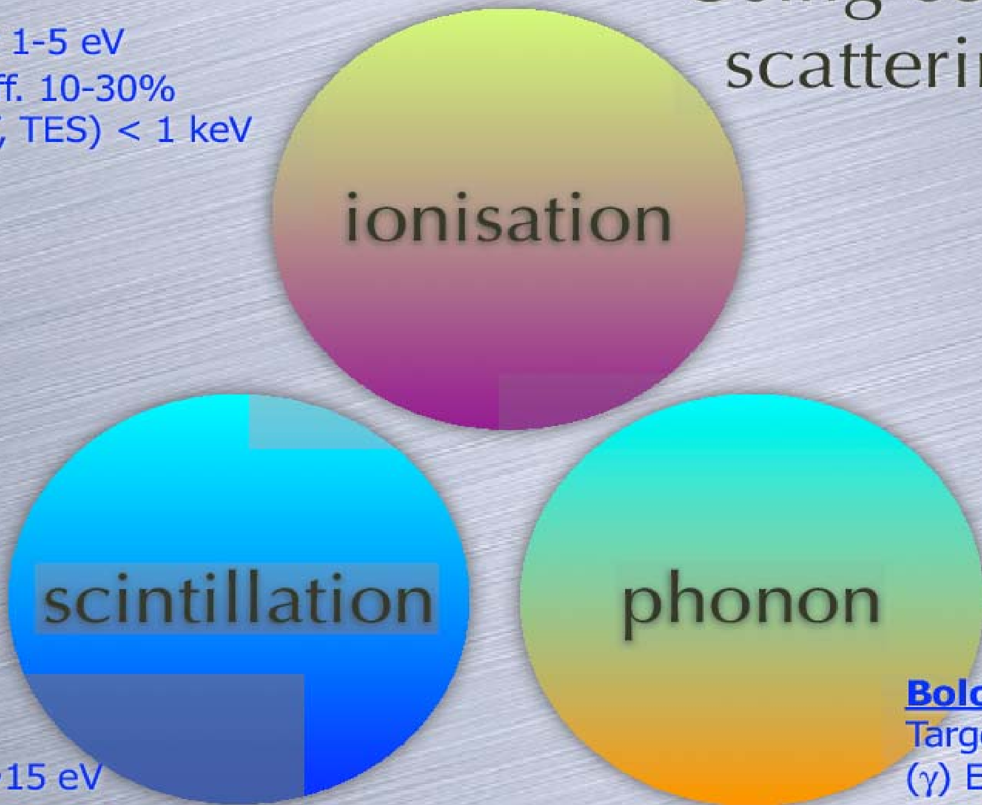
(Such a reward!)

- THE END

Techniques for direct WIMP detection

Ionisation Detectors
Targets: Ge, Si, CdTe
(γ) Energy per e/h pair 1-5 eV
NR energy collection eff. 10-30%
Sensitivity (HEMT JFET, TES) < 1 keV
IGEX (4 keV), HDMS,
GENIUS (3.5 keV)

Using coherent elastic scattering off nuclei



Scintillators
Targets: NaI, Xe, Ar, Ne
(γ) Energy per photon ~15 eV
NR energy collection eff. 1-3%
Light gain 2-8 phe/keV
Sensitivity (PMTs) ~1 keV
ZEPLIN I (2 keV), NAIAD (4 keV)
DAMA (2 keV), DEAP, CLEAN, XMASS (5 keV)

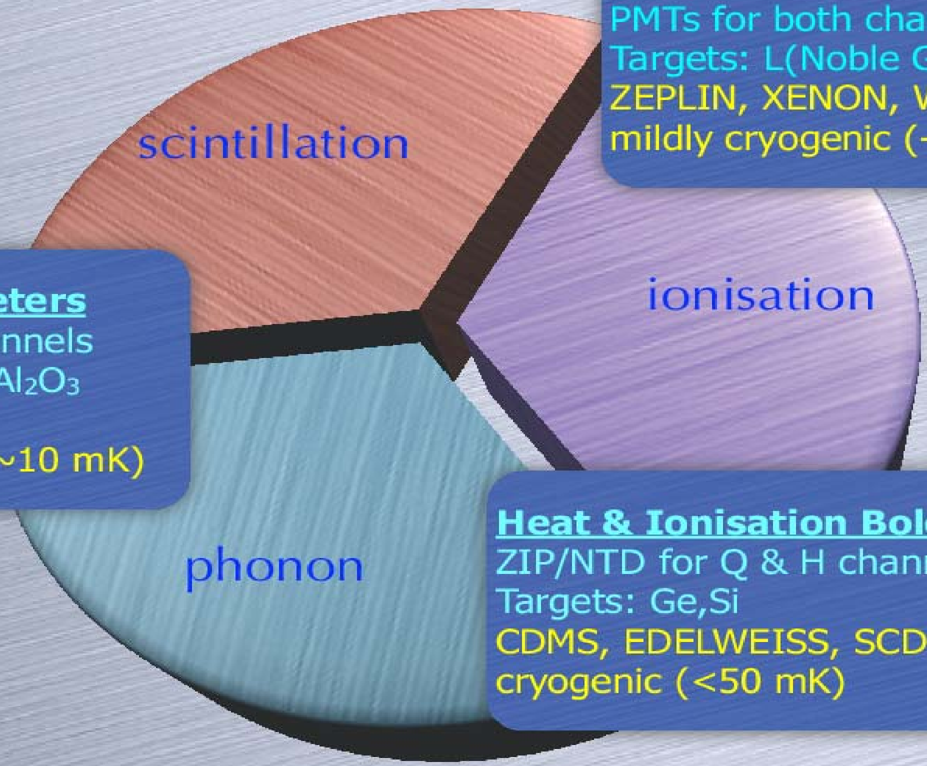
Bolometers
Targets: Ge, Si, Al_2O_3, TeO_2
(γ) Energy per phonon ~meV
NR energy col. eff. (th.) ~100%
Sensitivity (TES) << 1 keV
(FWHM 4.5 eV @ 6 keV x-rays)
CRESST-I (0.6 keV),
CUORICINO, CUORE (5 keV)

Following Araujo

N.J.T.Smith BUS2006 - York Dark Matter Review

Techniques for direct WIMP detection

All hybrid techniques have >99% elastic nuclear recoil discrimination at 10keV NR



Light & Ionisation Detectors
PMTs for both channel readout
Targets: L(Noble Gases)
ZEPLIN, XENON, WARP, ArDM, SIGN
mildly cryogenic (-100 C)

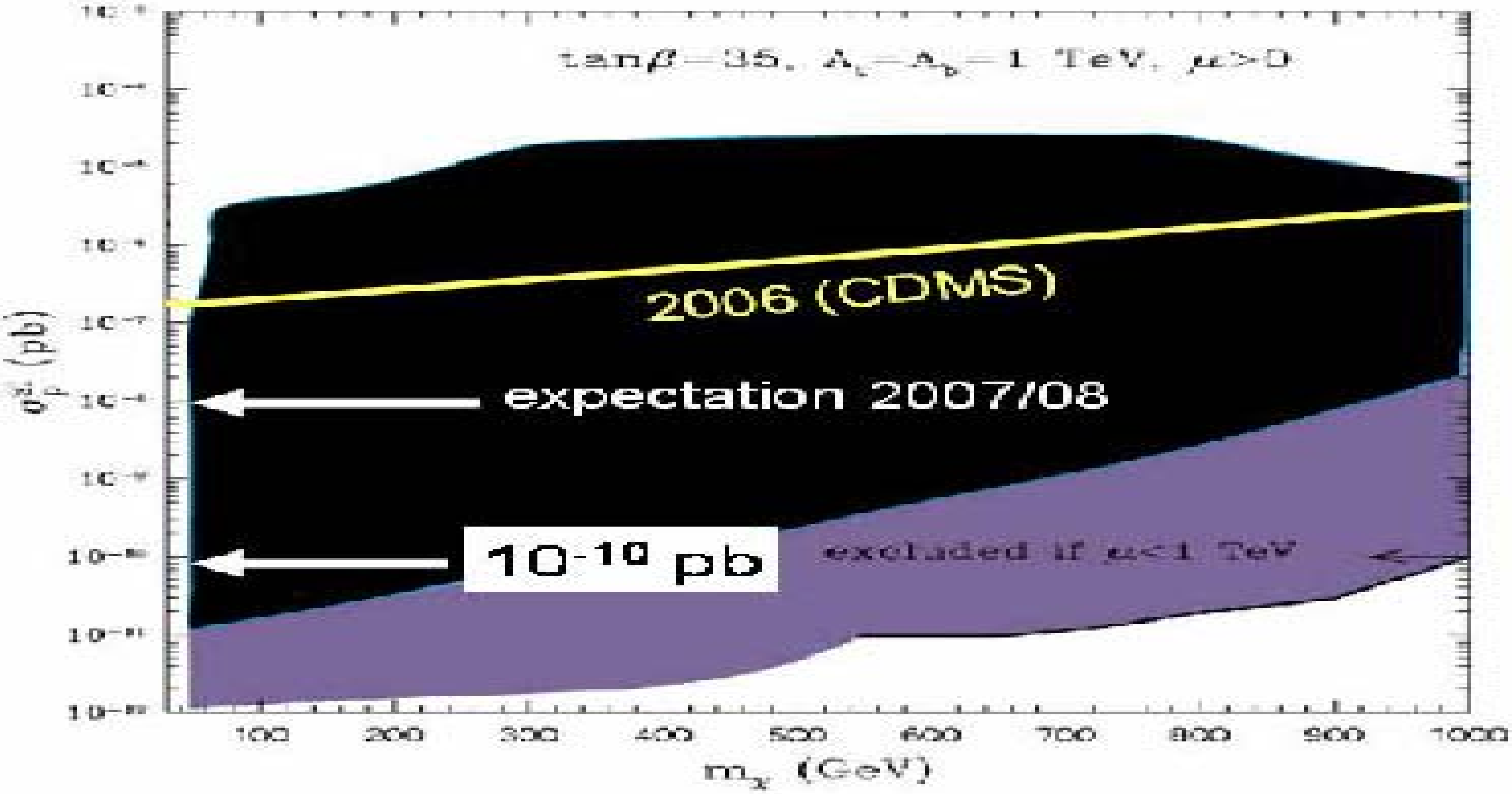
Light & Heat Bolometers
TES/NTD for L & H channels
Targets: $CaWO_4$, BGO, Al_2O_3
CRESST, ROSEBUD
even more cryogenic (~10 mK)

Heat & Ionisation Bolometers
ZIP/NTD for Q & H channels
Targets: Ge,Si
CDMS, EDELWEISS, SCDMS, EURECA
cryogenic (<50 mK)

N.J.T.Smith BUS2006 - York Dark Matter Review

Another view (ApPEC 19/10/06)

Blue SUSY calculations (parameters on top)



A: Conversion of the energy of the recoiling nucleus into detectable form (light, heat, ionization etc.)

- The WIMP is non relativistic,< β>≈10^{-3}.

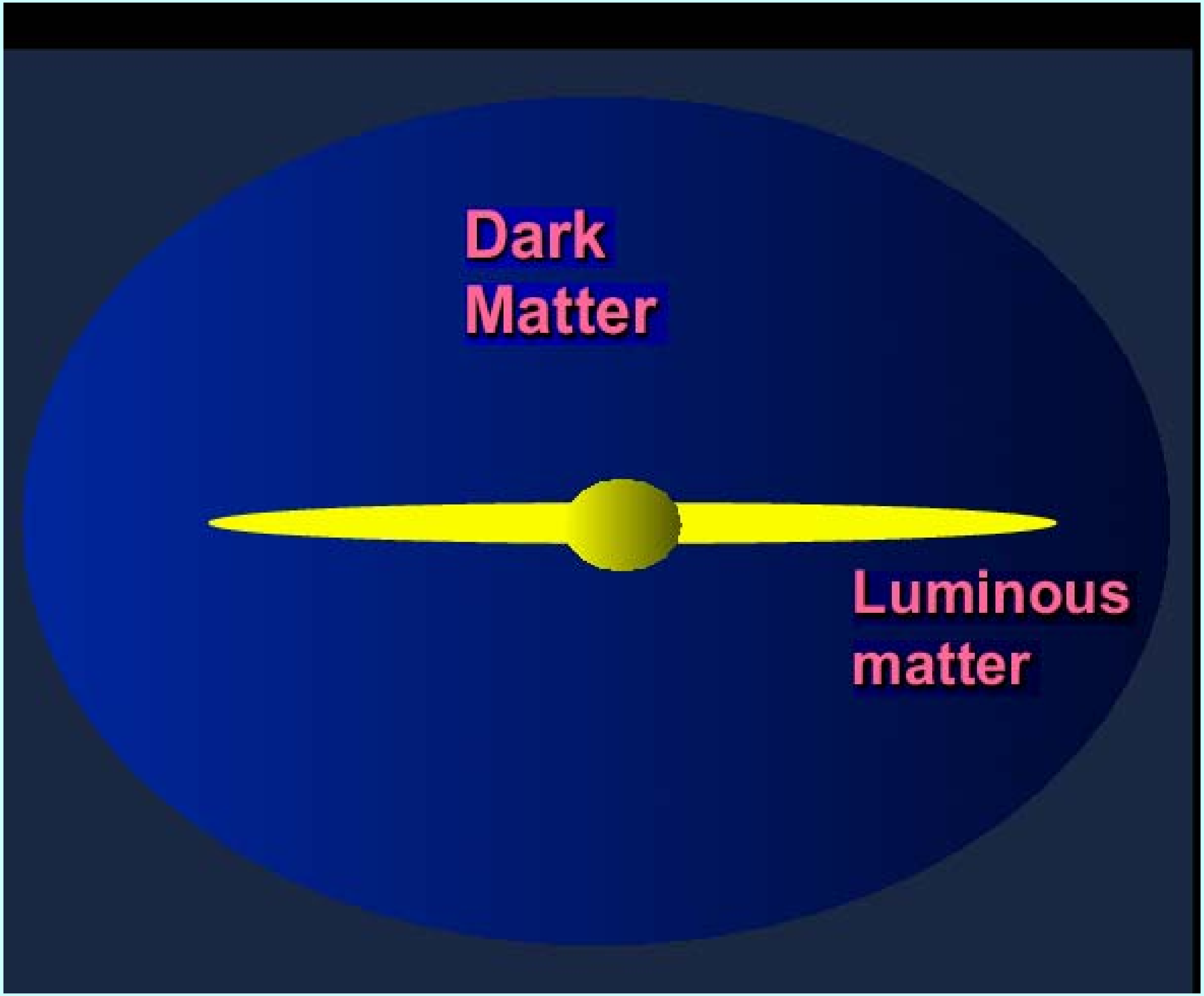
$$\langle T^0_{\tilde{\chi}} \rangle = 50keV \frac{m^0_{\tilde{\chi}}}{100GeV}$$

- With few exceptions, it cannot excite the nucleus. It only scatters off elastically:

$$\tilde{\chi}^0(\mathbf{p}_0) + (A,Z)(0) \longrightarrow \tilde{\chi}^0(\mathbf{p}_0 - \mathbf{q}) + (A,Z)(\mathbf{q})$$

- Measuring the energy of the recoiling nucleus is extremely hard:
  -Low event rate (much less than 10 per Kg of target per year are expected).
  -Bothersome backgrounds (the signal is not very characteristic).
  -Threshold effects.
  -Quenching factors.

If we could see Dark Matter



Slicing the Pie of the Cosmos WMAP3:

$\Omega_{CDM} = 0.24 \pm 0.02$, $\Omega_{\Lambda} = 0.72 \pm 0.04$,

$\Omega_b = 0.042 \pm 0.003$