Searching for Dark Matter:
Alternative Detection Concepts

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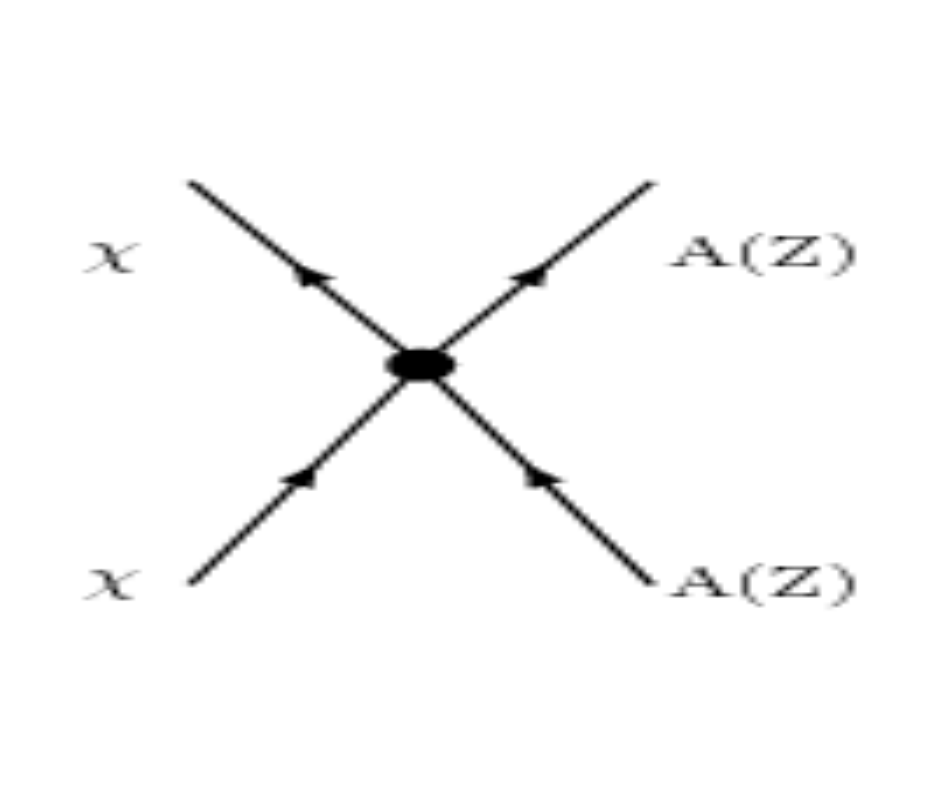
Some Examples

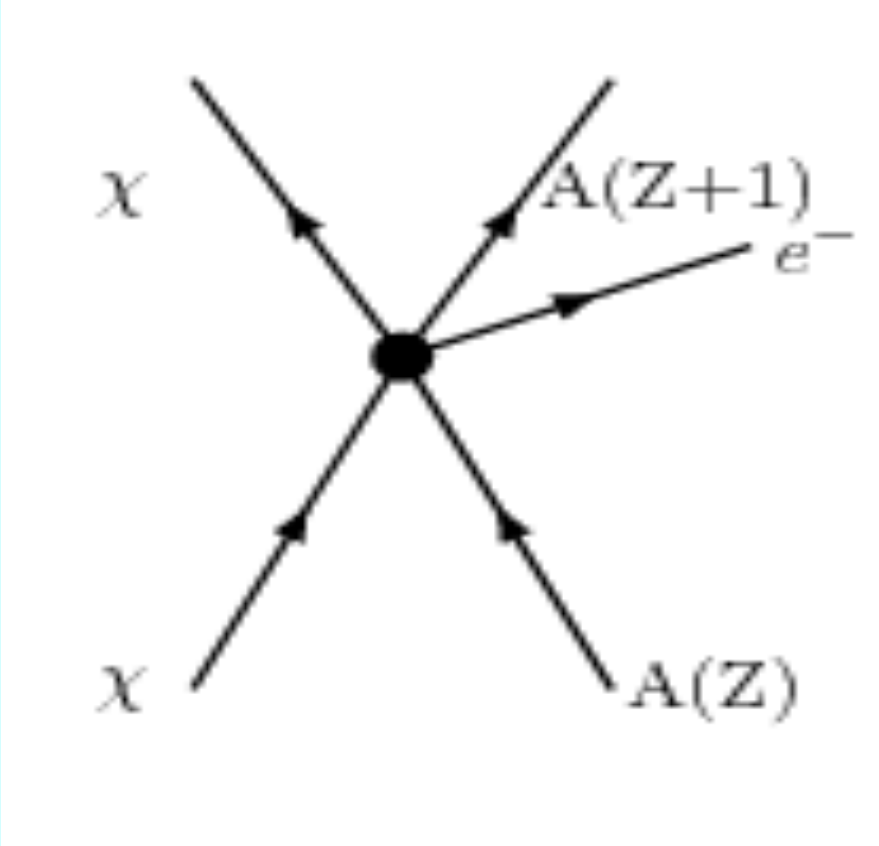
- A: Detection of electrons produced during the WIMP-nucleus collisions
- B: Detection of X-rays resulting after the electron ejection in WIMP-nucleus collision
- C: Detection of leptophilic dark matter
- D: Detection of γ-rays following the de-excitation of the nucleus
- S: Directional Experiments for Dark Matter Detection

A:Detection of electrons produced during the WIMP-nucleus collisions

Standard nuclear recoil



Nuclear recoil +electron



Electrons +nuclear recoil

Phase space considerations

$$d\sigma(\mathbf{k}) = \frac{1}{v}\frac{m_e}{E_e}|M|^2 \frac{d^3\mathbf{q}}{(2\pi)^3}\frac{d^3\mathbf{k}}{(2\pi)^3}(2\pi)^3 \frac{1}{2(2\ell+1)} \tag{1}$$

$$\sum_{n\ell m} p_{n\ell} \quad [\tilde{\phi}_{n\ell m}(\mathbf{k})]^2 2\pi\delta\left(T_\chi + \epsilon_{n\ell} - T - \frac{q^2}{2m_A} - \frac{(\mathbf{p}_\chi - \mathbf{k} - \mathbf{q})^2}{2m_\chi}\right),$$

Differential Cross section

Relative to total recoil rate

$$\frac{d\sigma(T)}{\sigma_{nrec}} = \frac{1}{2}\sum_{n\ell} p_{n\ell}|\tilde{\phi}_{n\ell}(\sqrt{2m_e T})|^2 [1 - (\frac{m_\chi}{\mu_r}\frac{(T-\epsilon_{n\ell})}{T_\chi}) + \sqrt{1 - (\frac{m_\chi}{\mu_r}\frac{(T-\epsilon_{n\ell})}{T_\chi})}] m_e\sqrt{2m_e T}\, dT.$$

^{20}Ne: Differential electron production rate/ total recoil rate. (Full, dotted dashed) <-> (1s, 2s, 2p) electron (JDV & Ejiri NPB (2005))

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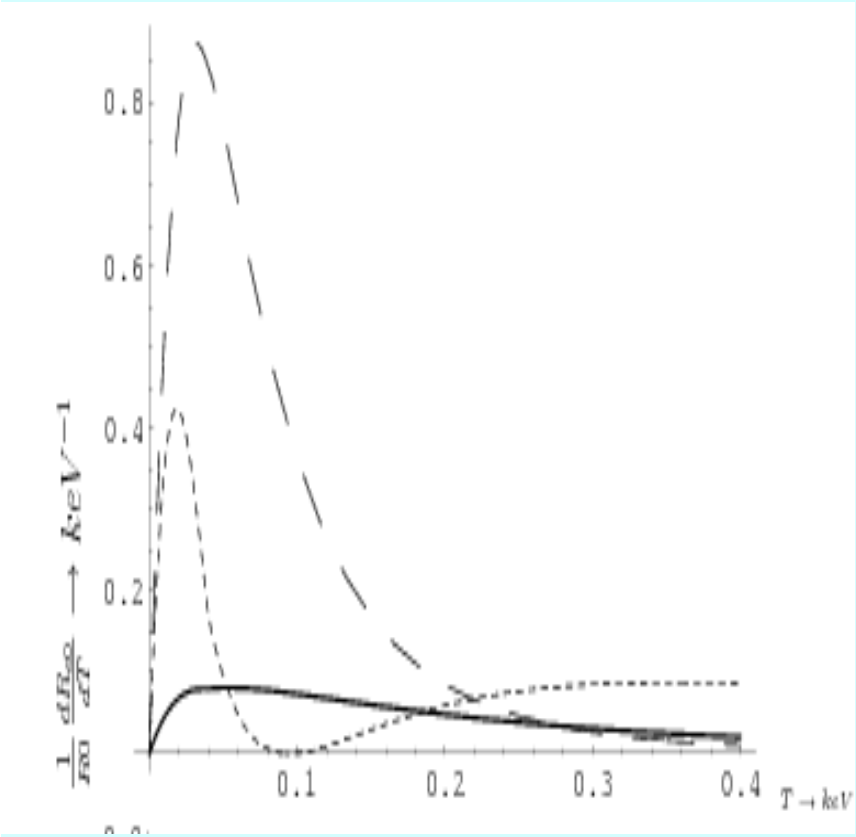
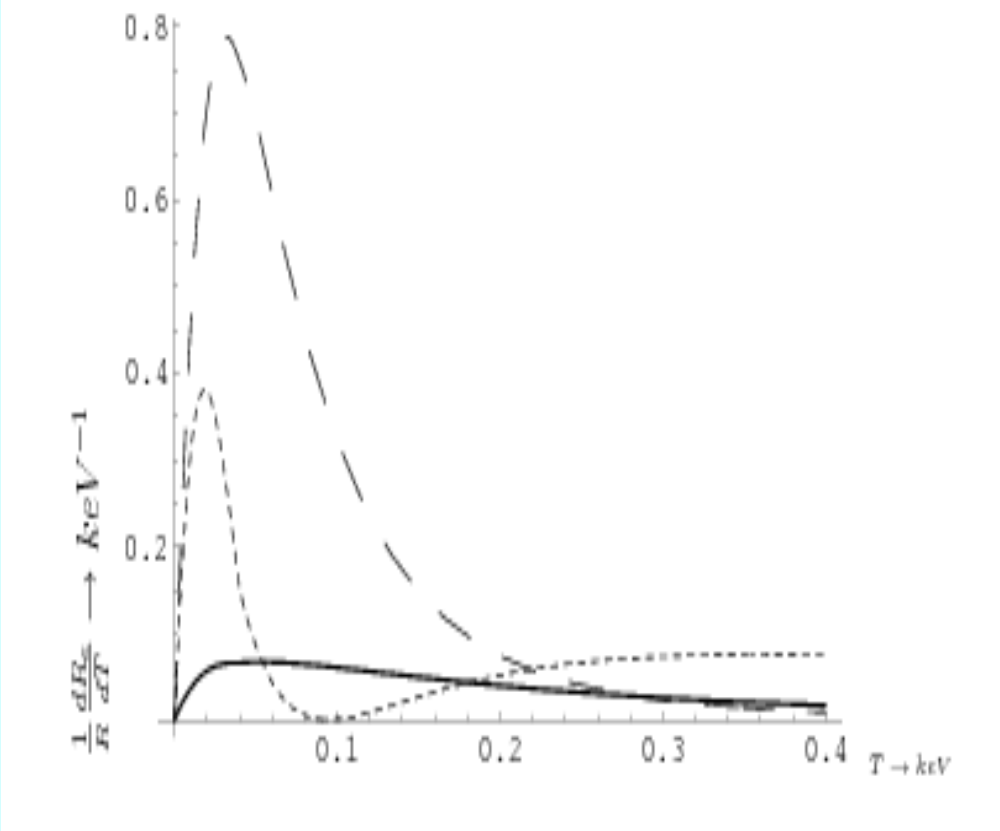


With Form factor



^{20}Ne: Differential electron production rate/total recoil rate. All (1s, 2s, 2p) electron orbits are included

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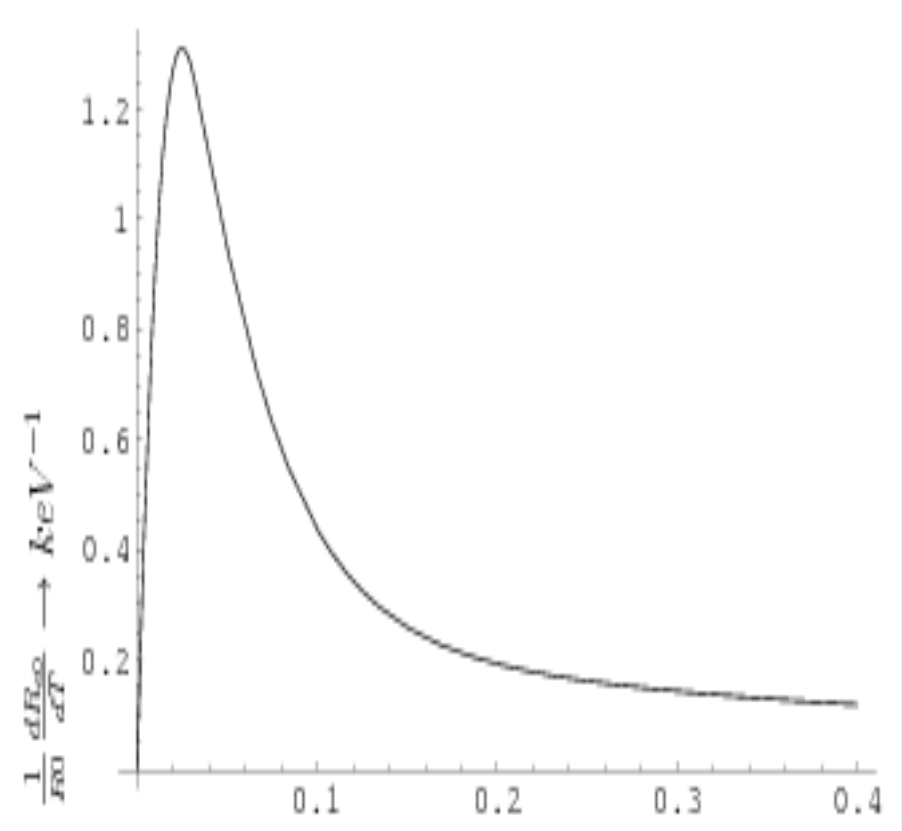

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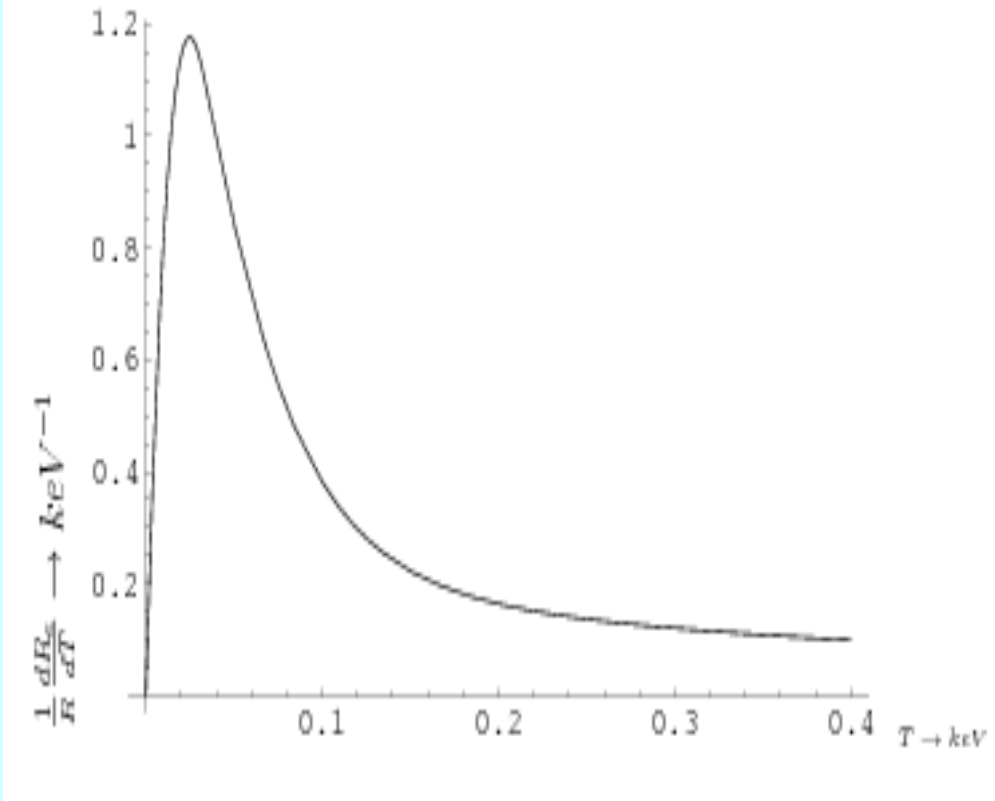

^{20}Ne: Electron production rate/total recoil rate. (As a function of threshold)

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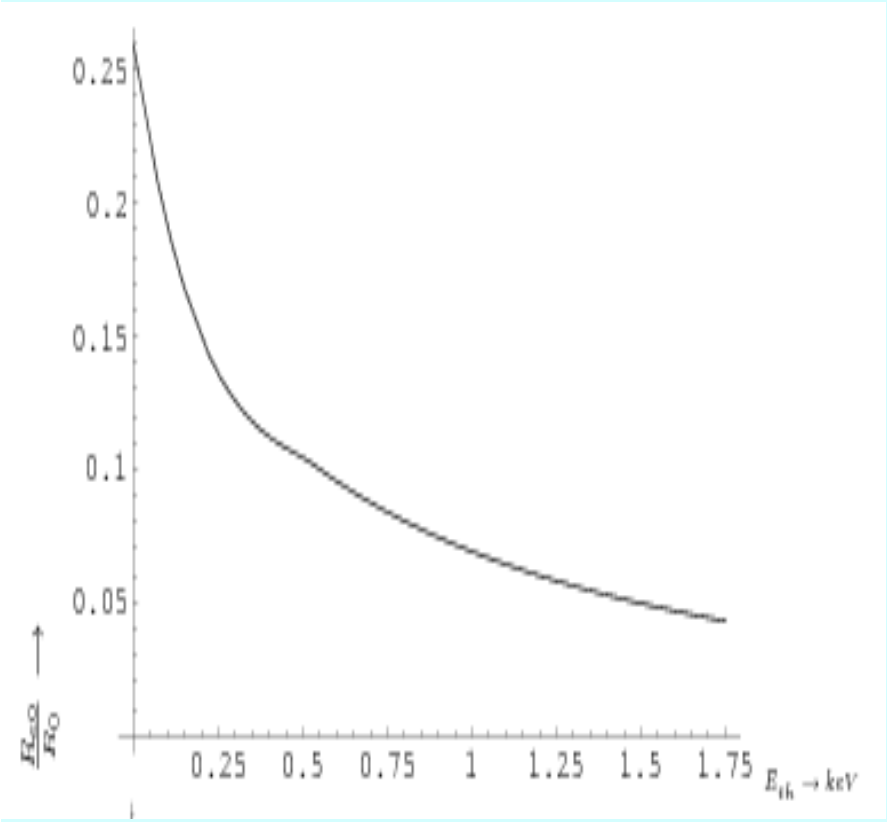

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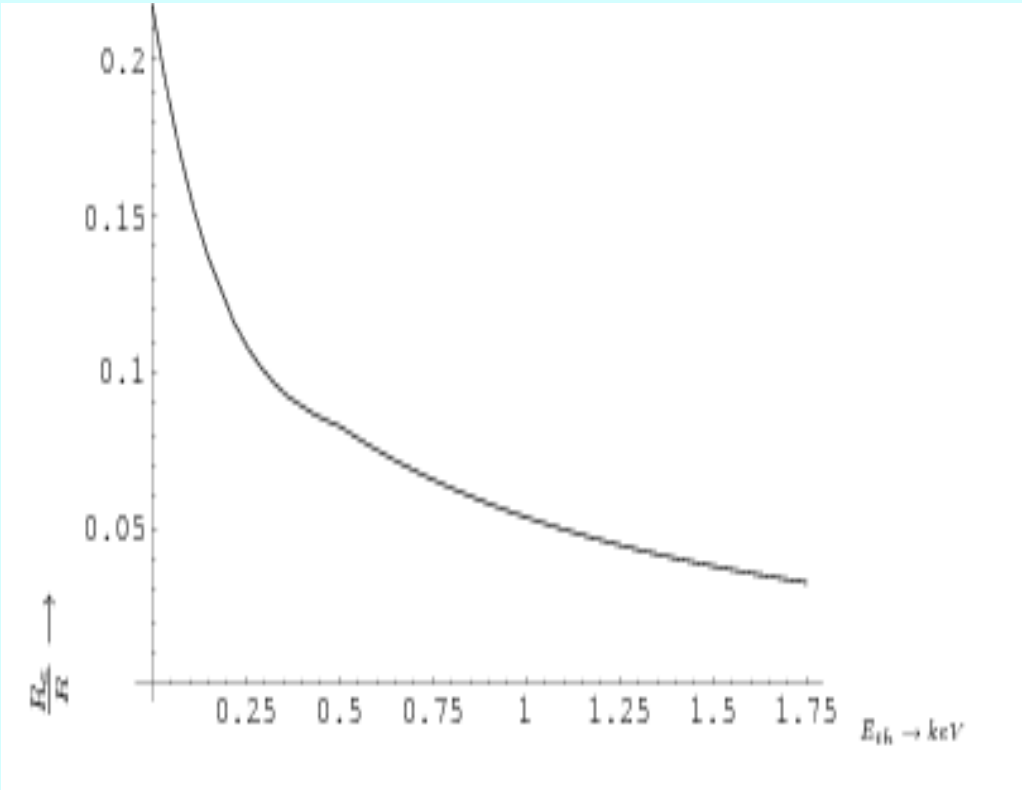
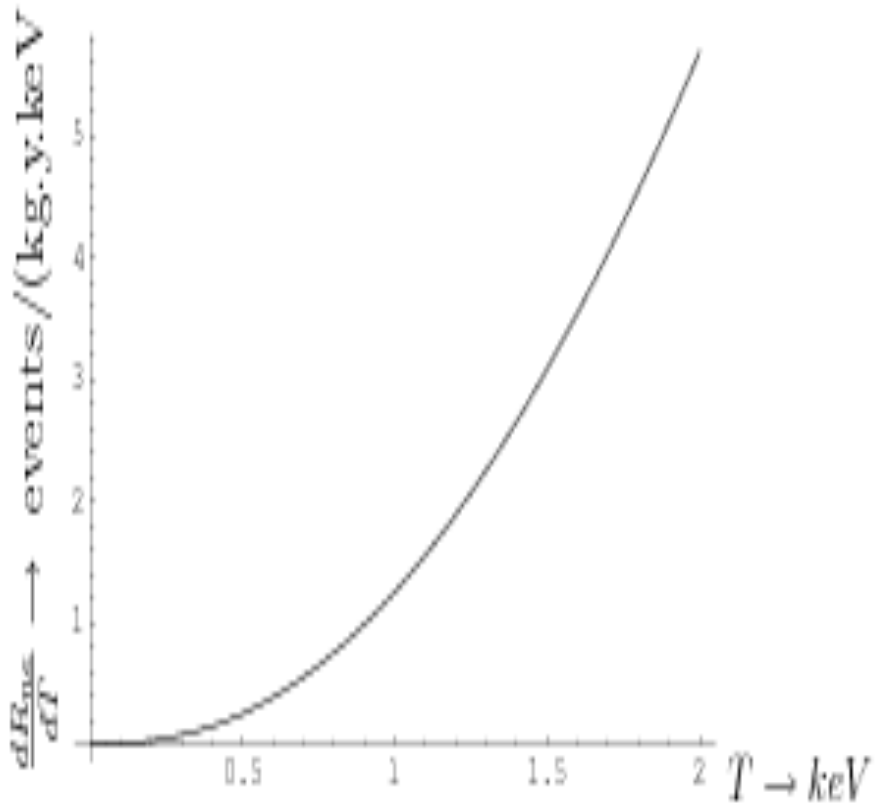
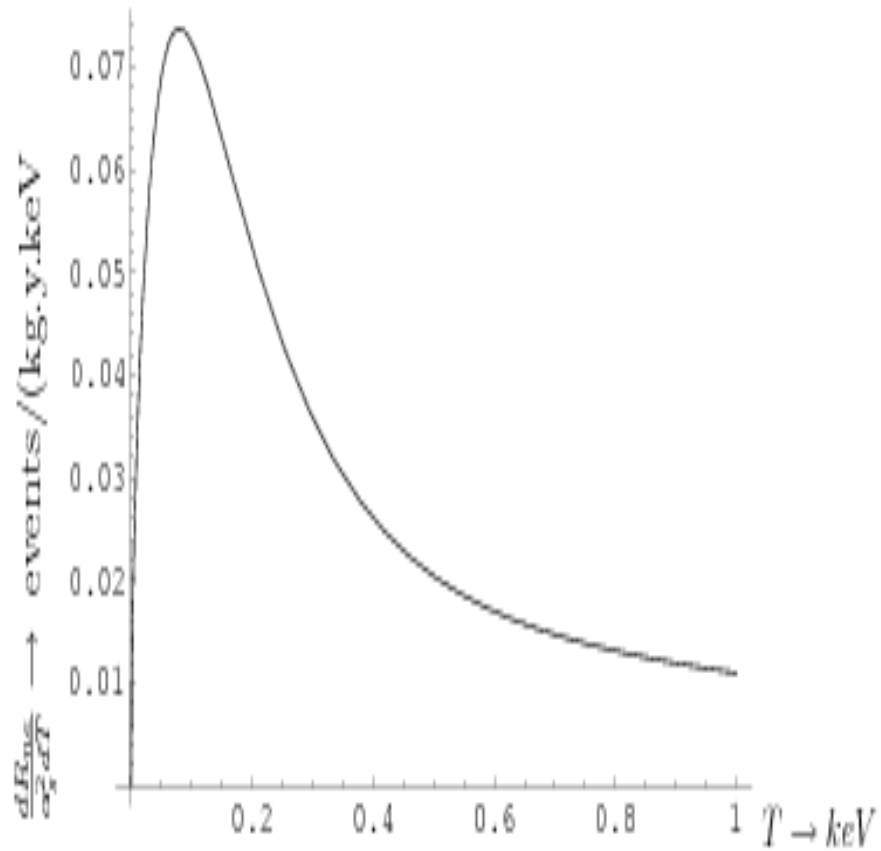


^{20}Ne: Electron production due to Neutron Background (Gaitskell Dist):<0.05 $kg^{-1}y^{-1}$ for all e

Neutron magnetic moment **Strong n-Nucleus interaction**

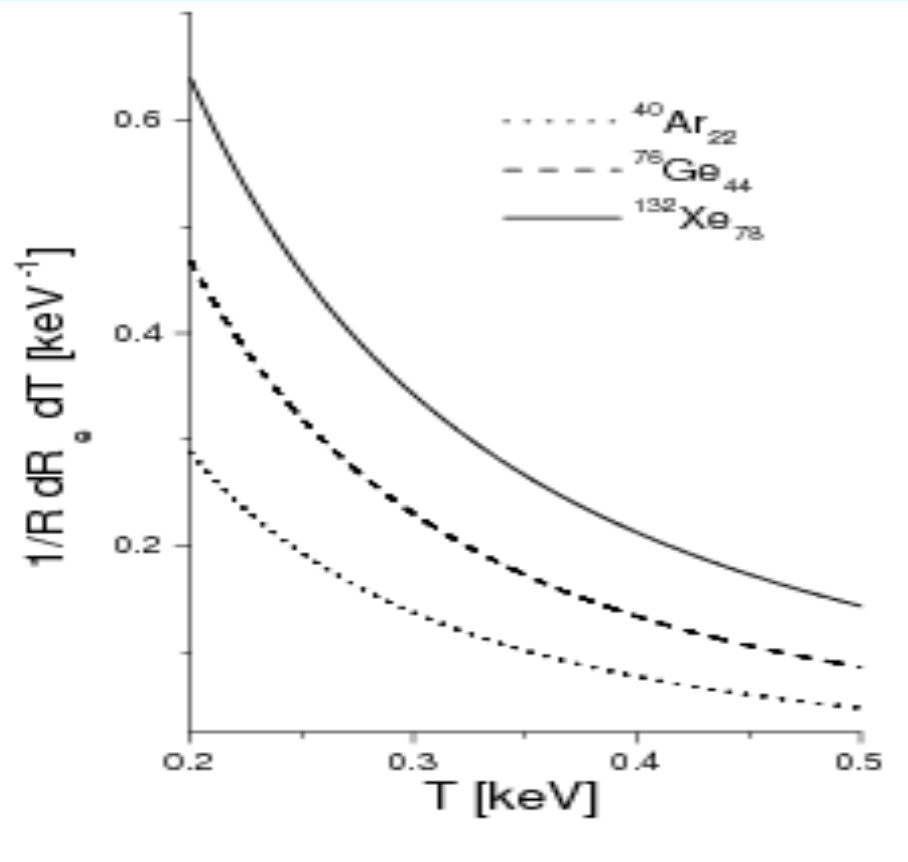




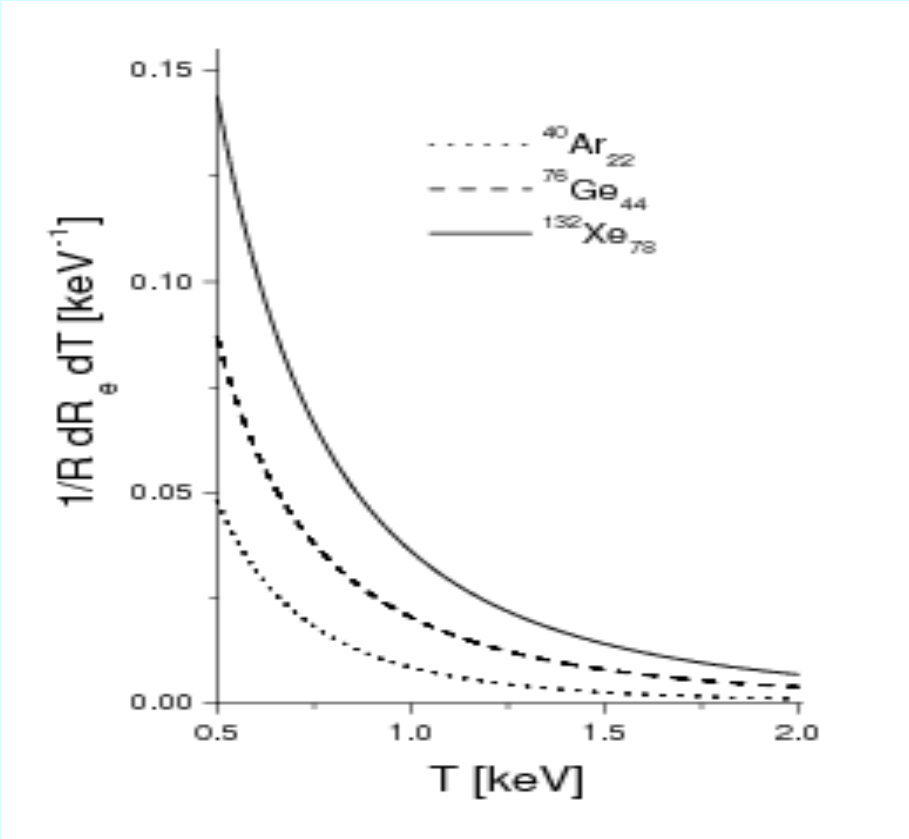
Differential electron production rate/total recoil rate for m_χ =100GeV. Realistic electron orbits

(Moustakidis, Ejiri, &JDV, Nucl.Phys. B727 (2005) 406)

Near Threshold

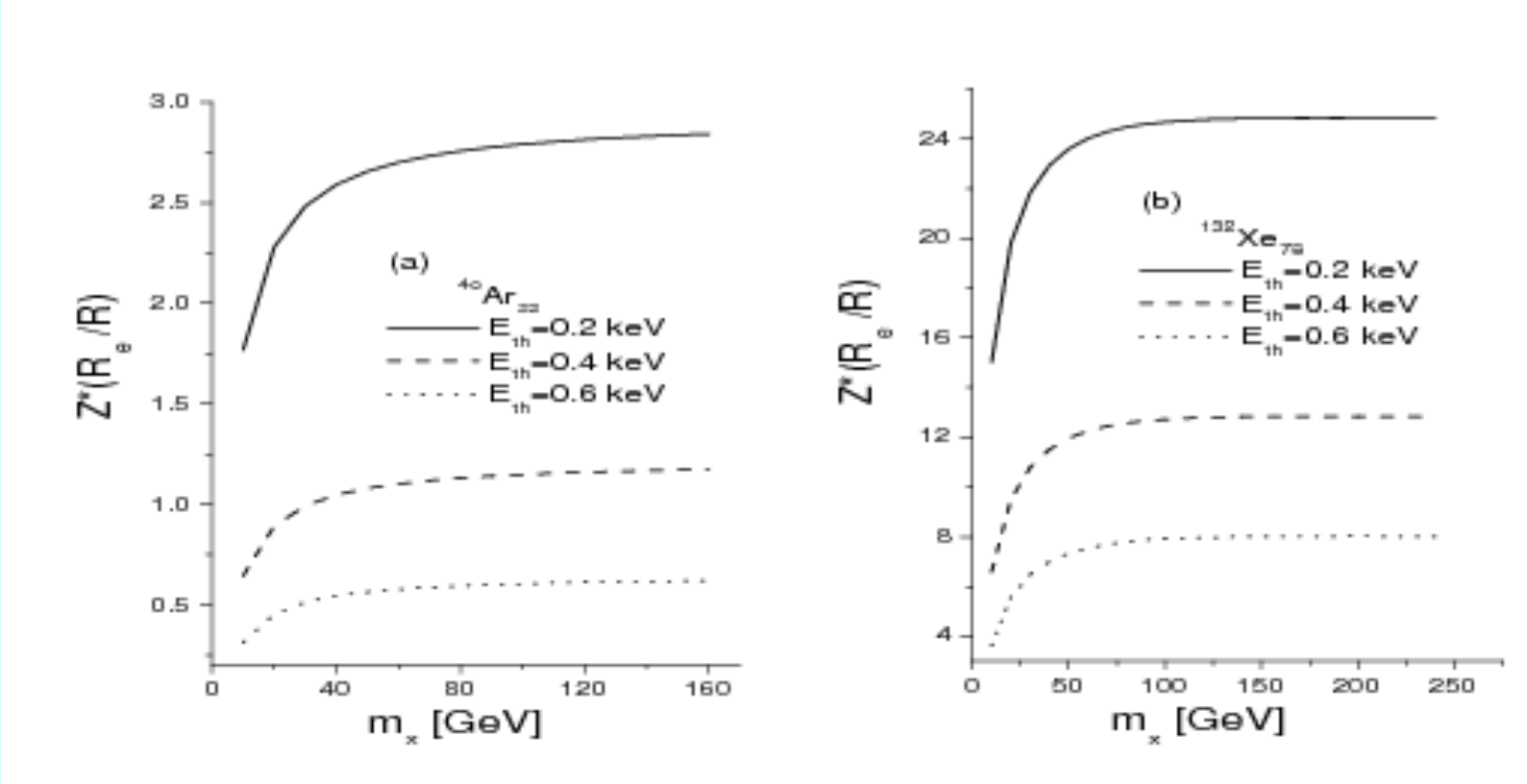


Much above Threshold



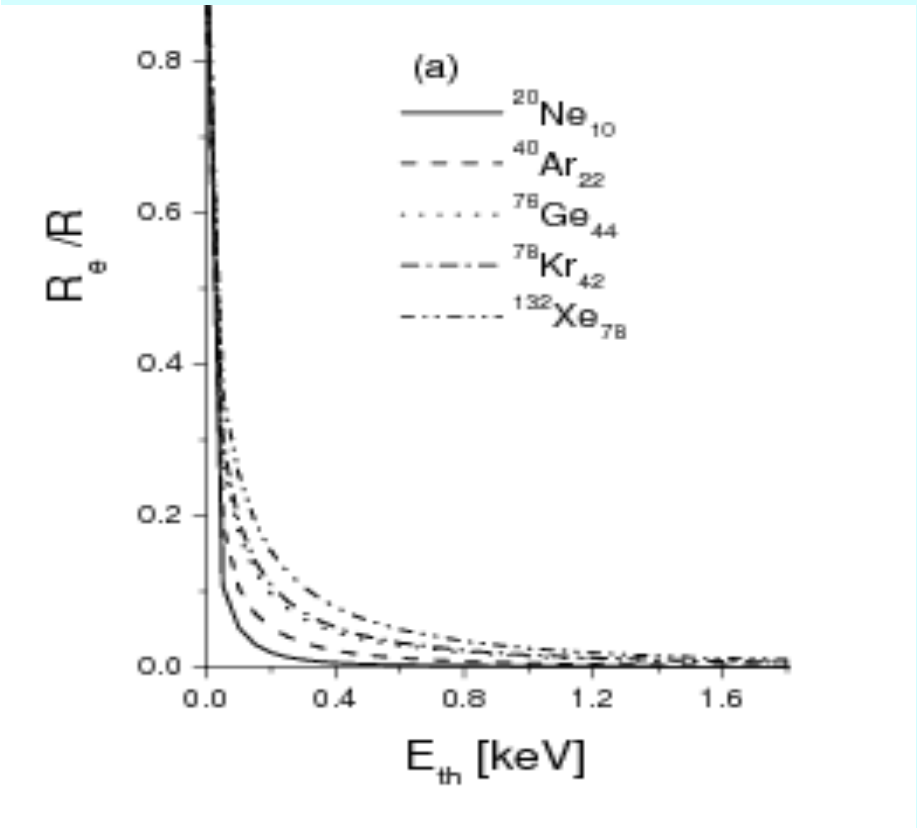
Total electron production rate/total recoil rate (all electrons) vs WIMP mass. Nuclear Recoil quenched. Realistic electron orbits

(Moustakidis, Ejiri, &JDV, Nucl.Phys. B727 (2005) 406)

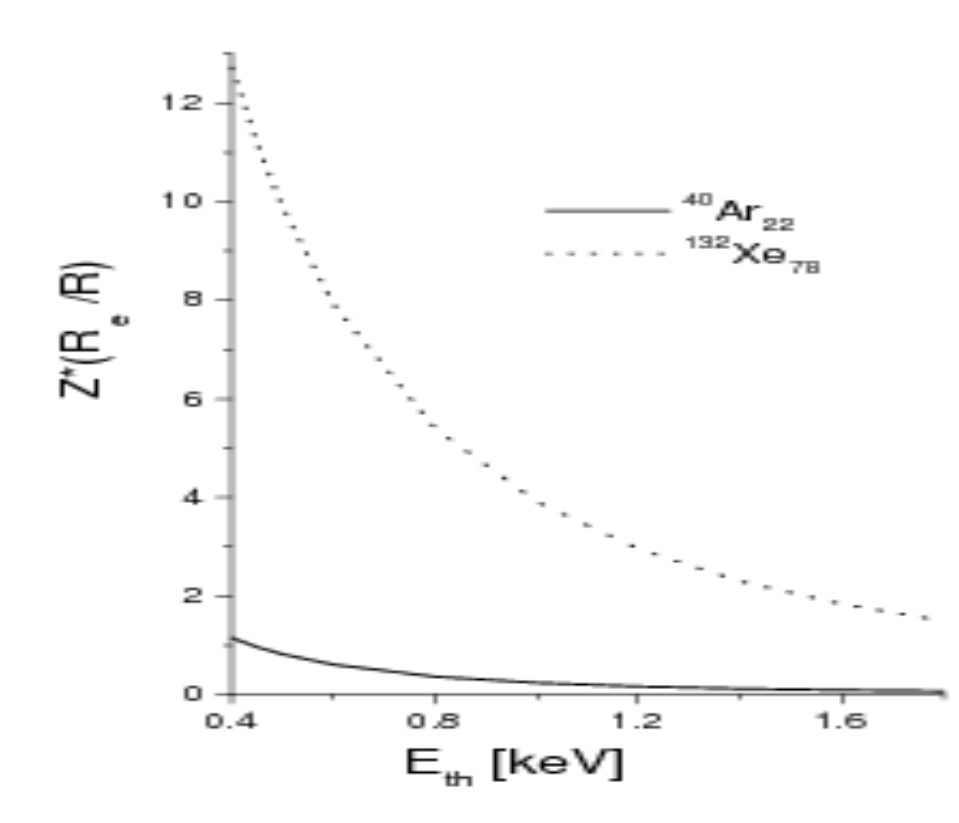


Total electron production rate/total recoil rate for m_χ =100 GeV. Realistic electron orbits

Per electron



All electrons



B: 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_{ij} X-ray ratio is evaluated as

  $\sigma_K(K_{ij})/\sigma_r = (\sigma_{1s}/\sigma_r)b_{1s}B_K(K_{ij})$, $B_K(K_{ij})$=the K_{ij} branch

The K X-ray BR in WIMP interactions in ^{131}Xe

(Ejiri, Moustakidis & JDV, Phys. Lett. B639 (2006) 218-222)

K X-ray cross sections relative to the nuclear recoil, rates and energies in WIMPs nuclear interactions with ^{131}Xe. $[Z\sigma_K/\sigma_r]_L$, $[Z\sigma_K/\sigma_r]_M$ and $[Z\sigma_K/\sigma_r]_H$ are the ratios for light (30 GeV), medium (100 GeV) and heavy (300 GeV) WIMPs.

K X-ray	$E_K(K_{ij})$ keV	$B_K(K_{ij})$	$[\frac{Z\sigma_K(K_{ij})}{\sigma_r}]_L$	$[\frac{Z\sigma_K(K_{ij})}{\sigma_r}]_M$	$[\frac{Z\sigma_K(K_{ij})}{\sigma_r}]_H$
$K_{\alpha 2}$	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

Detector Requirements: Such K X-rays in NaI have a range of 200 μm

Exclusive studies of the X-rays are very powerful for high sensitivity experiments. K X-rays from Xe fly through Xe detectors for about 100 mg/cm^2, while L X-rays for about 4 mg/cm^2, before depositing their energies via photoelectric effects. Thus separation of the X-rays signals from those of the nuclear recoil and the ionization electrons can be made by using good position-resolution detectors of the order of 1 mg/cm^2 (i.e. 1.5 mm in 1 atm Xe gas) One option of detectors for exclusive studies of the X-rays following WIMPs scattering off nuclei is a TPC with Xe gas. The trajectory analysis makes it possible to identify the WIMP nuclear interaction point with the recoil and ionization electrons and the X-ray interaction point with the photo-electron track. A super-module of Xe gas ionization chambers for nuclear recoils and plastic scintillation-fibers for K X-rays is an alternative way for exclusive studies of X-rays and nuclear recoils.

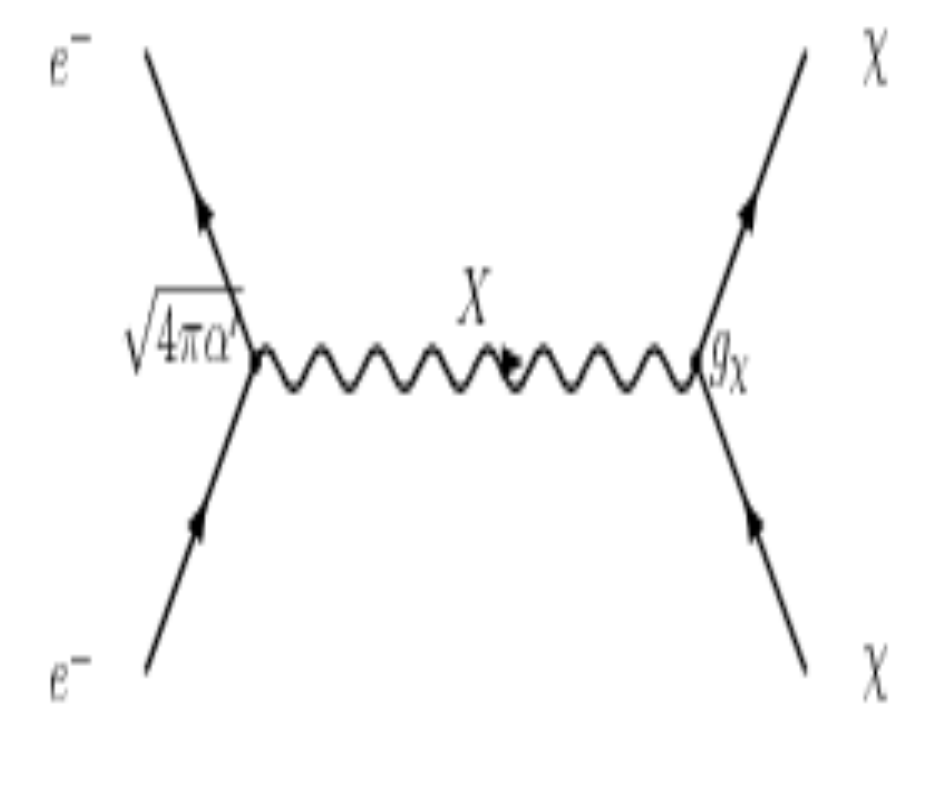
Backgrounds for X-rays: a) Compton and photoelectric scattering- not very serious b) Cosmogenic neutrons <0.01 $kg^{-1}y^{-1}$

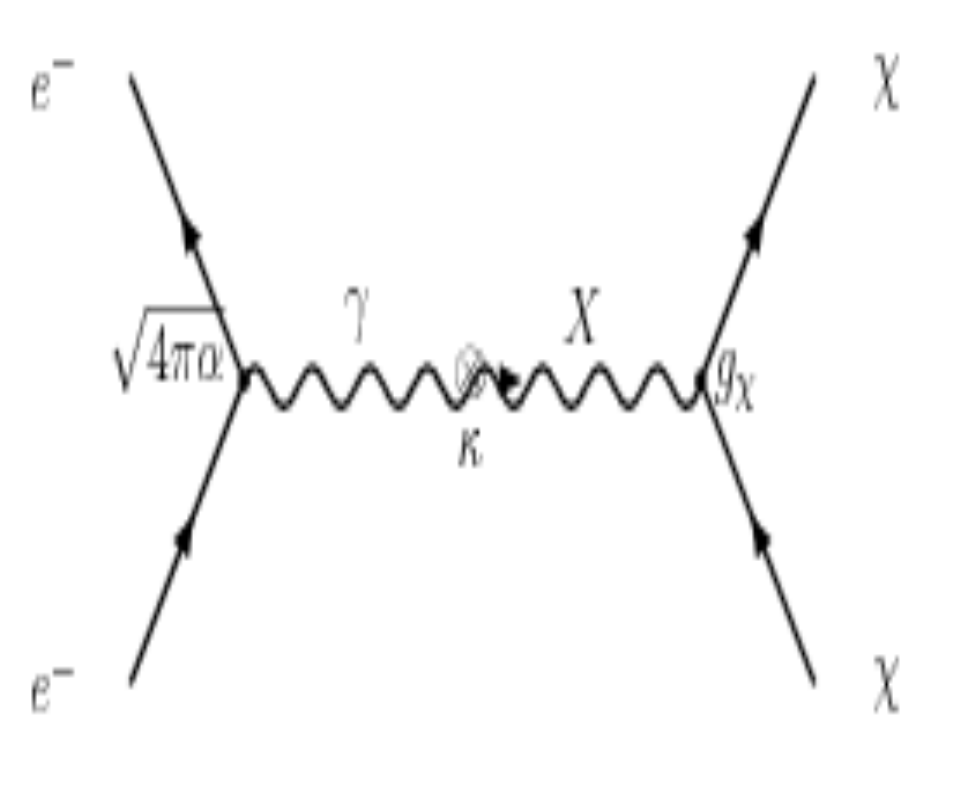
The exclusive experiments are free of most backgrounds from natural and cosmogenic radioactive impurities in detector components, detector shields and experimental walls. Cosmogenic muons are well rejected by veto counters against charged particles. Then remaining backgrounds in the exclusive experiments are due to cosmogenic neutrons scattered off target nuclei, resulting in inner-shell electron excitations and X-ray emissions.

C1: Leptophilic WIMPS and exotic light gauge bosons X(motivated by PAMELA positron excess)

Via the X Boson directly: $\alpha = \alpha'$, m_X=1 GeV, m_{WIMP}=100 GeV,

Via the (X, γ) kinetic coupling: $|g_X \kappa| \leq 2\ 10^{-10}$





Massless mediator, i.e. (X, γ) coupling

Dedes, Giomataris, Suxho & JDV, Nucl Phys B826:148-173 2010

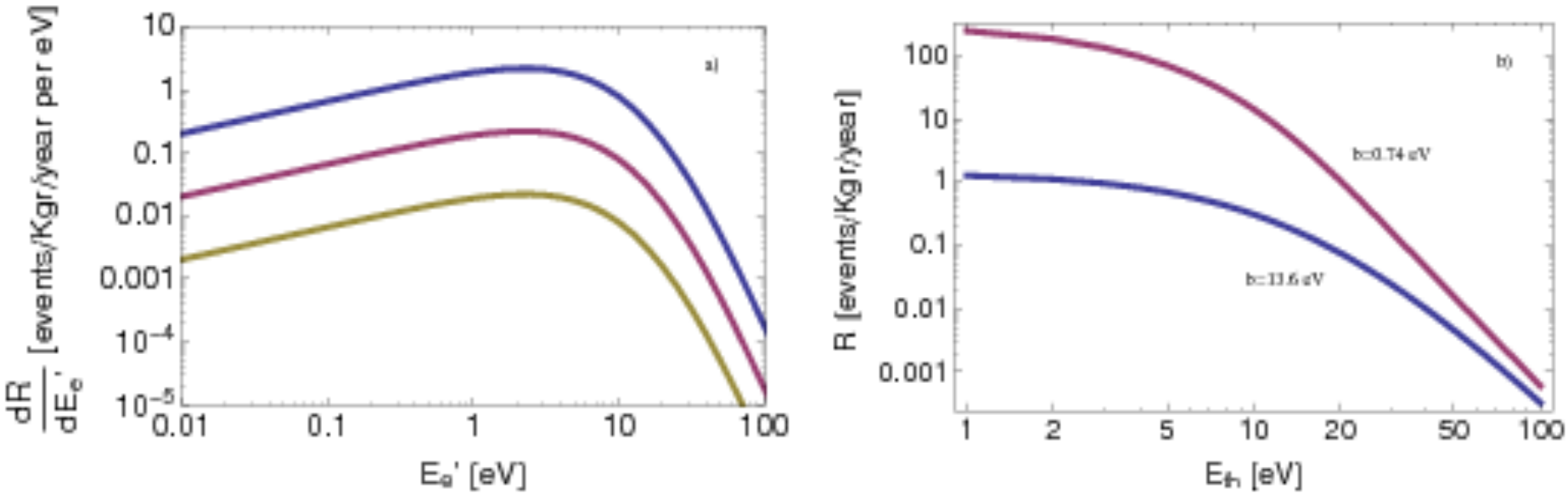


Figure 8: *a) Differential event rate of Dirac WIMP scattered off hydrogen (Z=1, A=1) target electrons per year per Kgr as a function of ejected electron energy E_e' in eV. Three different WIMP masses have been assumed : $m_\chi = 10, 100, 1000$ GeV, from top to bottom, respectively. b) The total event rate as a function of the experimental threshold energy for $m_\chi = 100$ GeV for two different binding energies. Other input parameters are taken from eq. (4.67) for the massive mediator.*

Massive mediator X (Dedes, Giomataris, Suxho & JDV, Nucl.Phys.B826:148-173,2010)

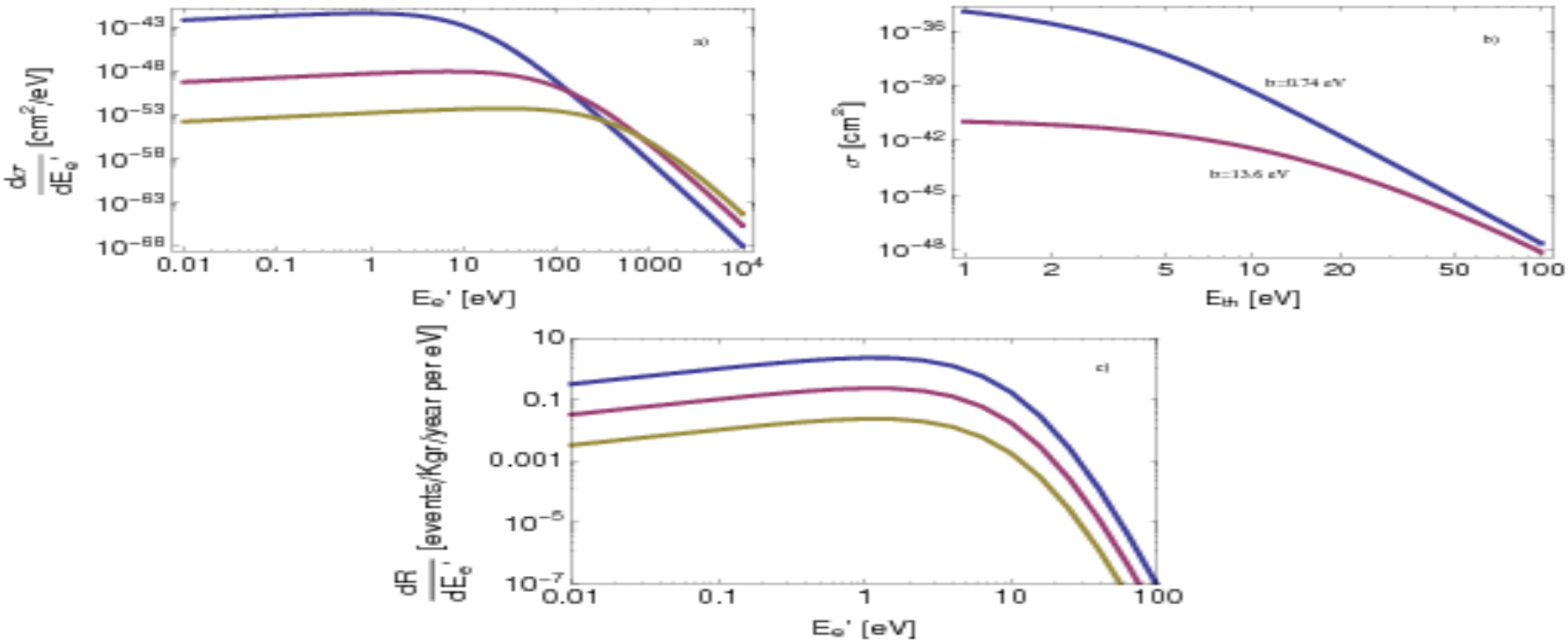
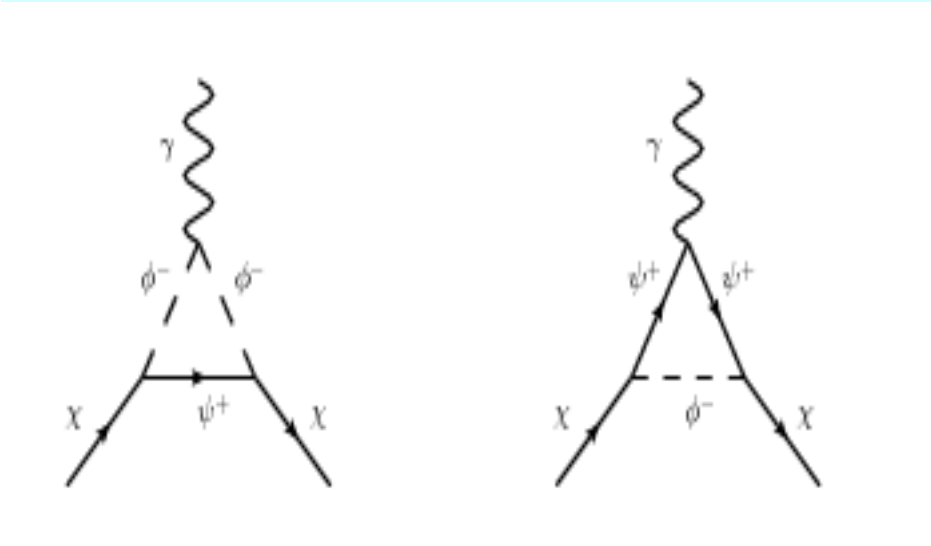


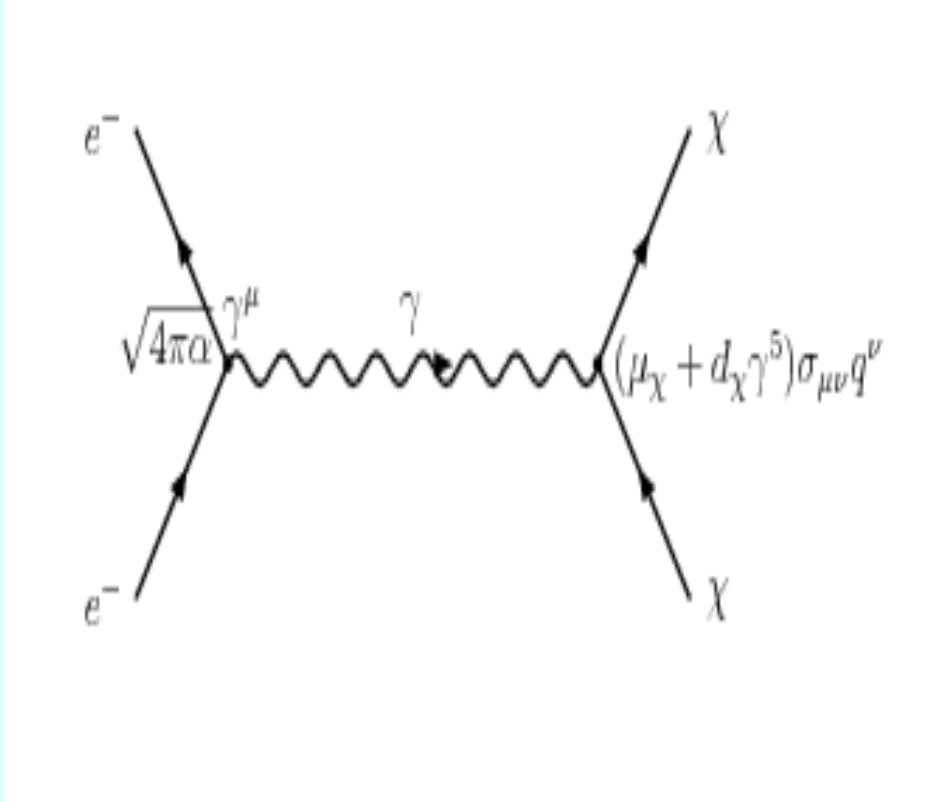
Figure 6: *a) Predictions for $d\sigma/dE_e'$ as a function of the ejected electron energy E_e'. The target is assumed to be a hydrogenic atom in the ground state with Z=1,3,6 (from top to bottom). b) The total cross section for process (4.43) as a function of the experimental threshold energy for two binding energies. c) The differential event rate as a function of the electron energy and various WIMP masses (10,100,1000) GeV from (top to bottom). Other parameters not shown, are taken from eq. (4.65).*

C2: Coupling of WIMPS to leptons via their magnetic moment (Graham et al arXiv:1203.2531)

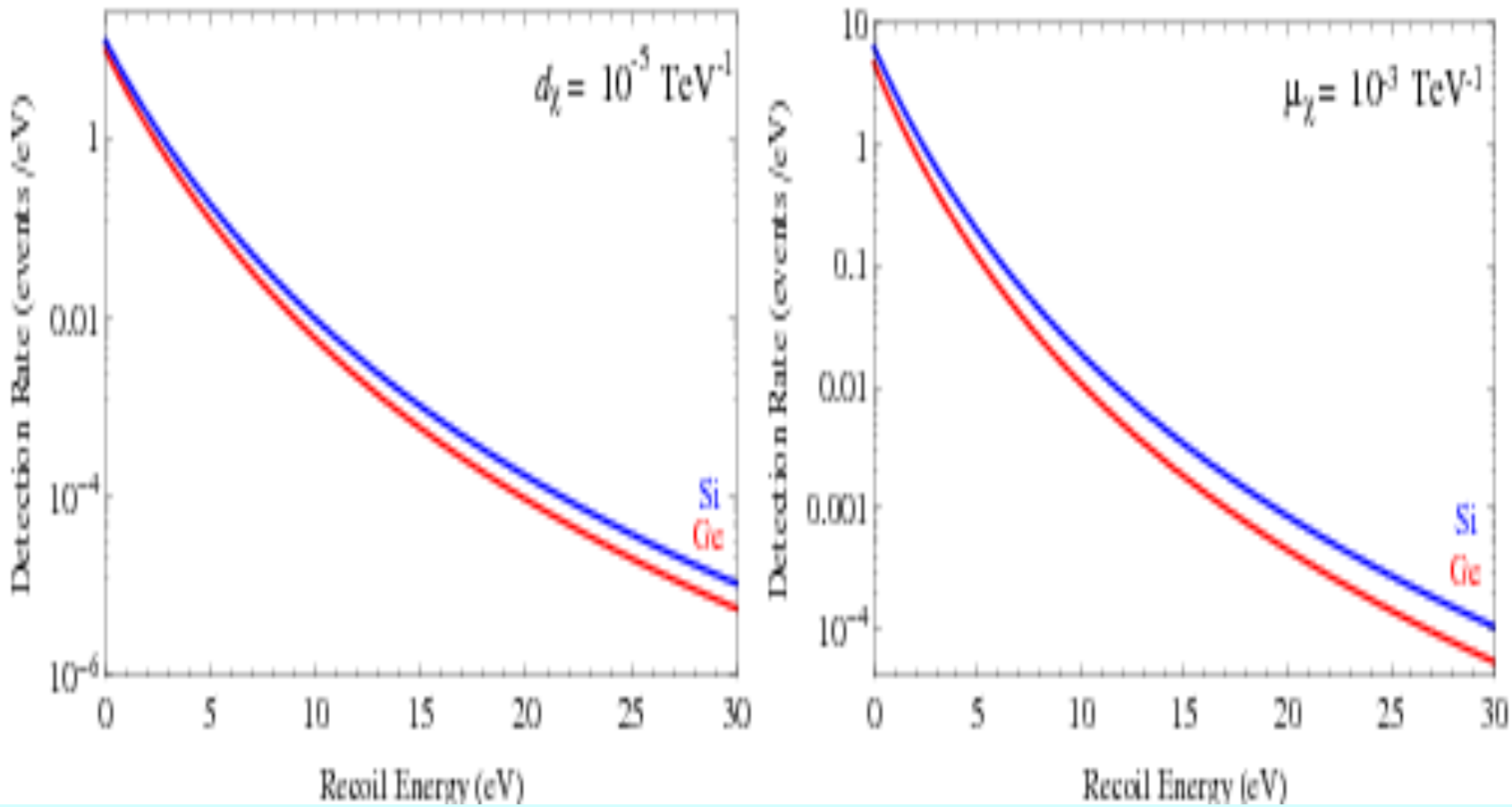
WIMP dipole moment at 1 loop level; Φ is a scalar, ψ is a fermion of mass 1 TeV.

μ_χ =magnetic, d_χ =electric dipole moment





Rates for 4.4 kg-y of Ge (red), 1.1 kg-y of Si (blue) and a WIMP mass 100GeV $\mu_\chi = 10^{-3}\text{TeV}^{-1} = 10^{-6}\mu_B$, $d_\chi = 10^{-5}\text{TeV}^{-1}$. (Graham et al arXiv:1203.2531)



Electron Detector Requirements

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

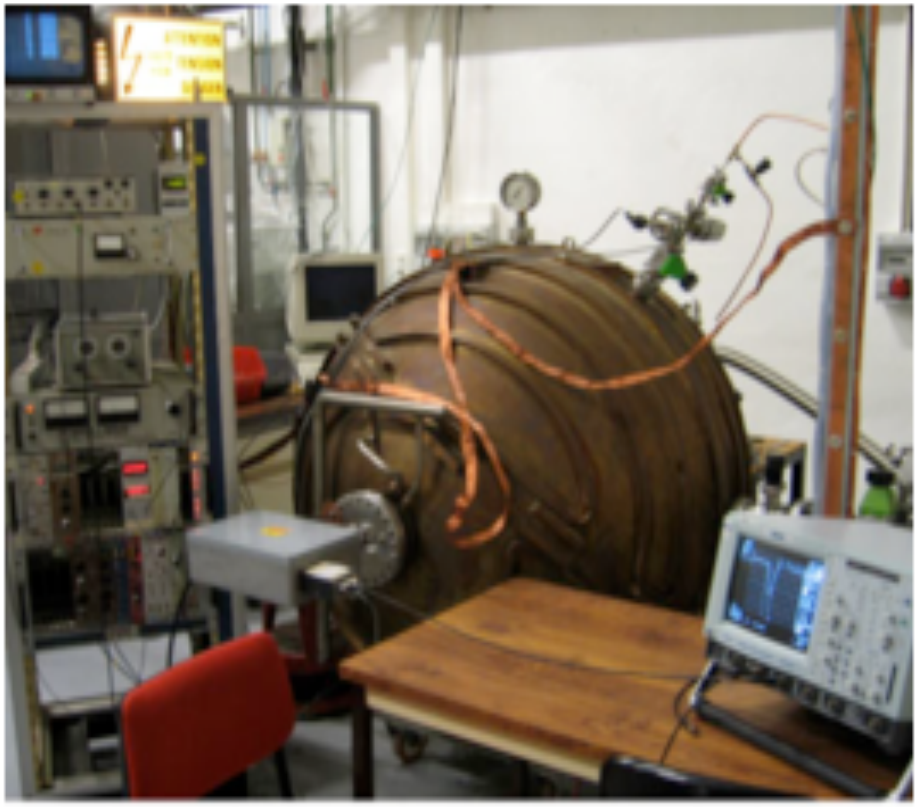
- Single electron efficiency.
  this is achieved with gaseous detectors reaching very-high gains
  (in order to cope with electronic noise).
- Large drift volumes and operation at high pressure (like the HELLAZ prototypes).
- Versatility of target material: various gases from the lightest (H_2) to heaviest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

a) Cryogenic detectors b) Semi- conductor detectors c)The SACLAY Sphere (0.1 keV)

(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



D: Excitation of the nucleus:

The average WIMP energy is:

- $\langle T_\chi \rangle \approx 40$ keV $(m_\chi/100\text{GeV})$
- $T_{\chi,max} \approx 215$ keV $(m_\chi/100\text{GeV})$. Thus
- $m_\chi = 500$GeV
  $\langle T_\chi \rangle \approx 0.2$ MeV, $T_{\chi,max} \approx 1$ 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 (q momentum, Q

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

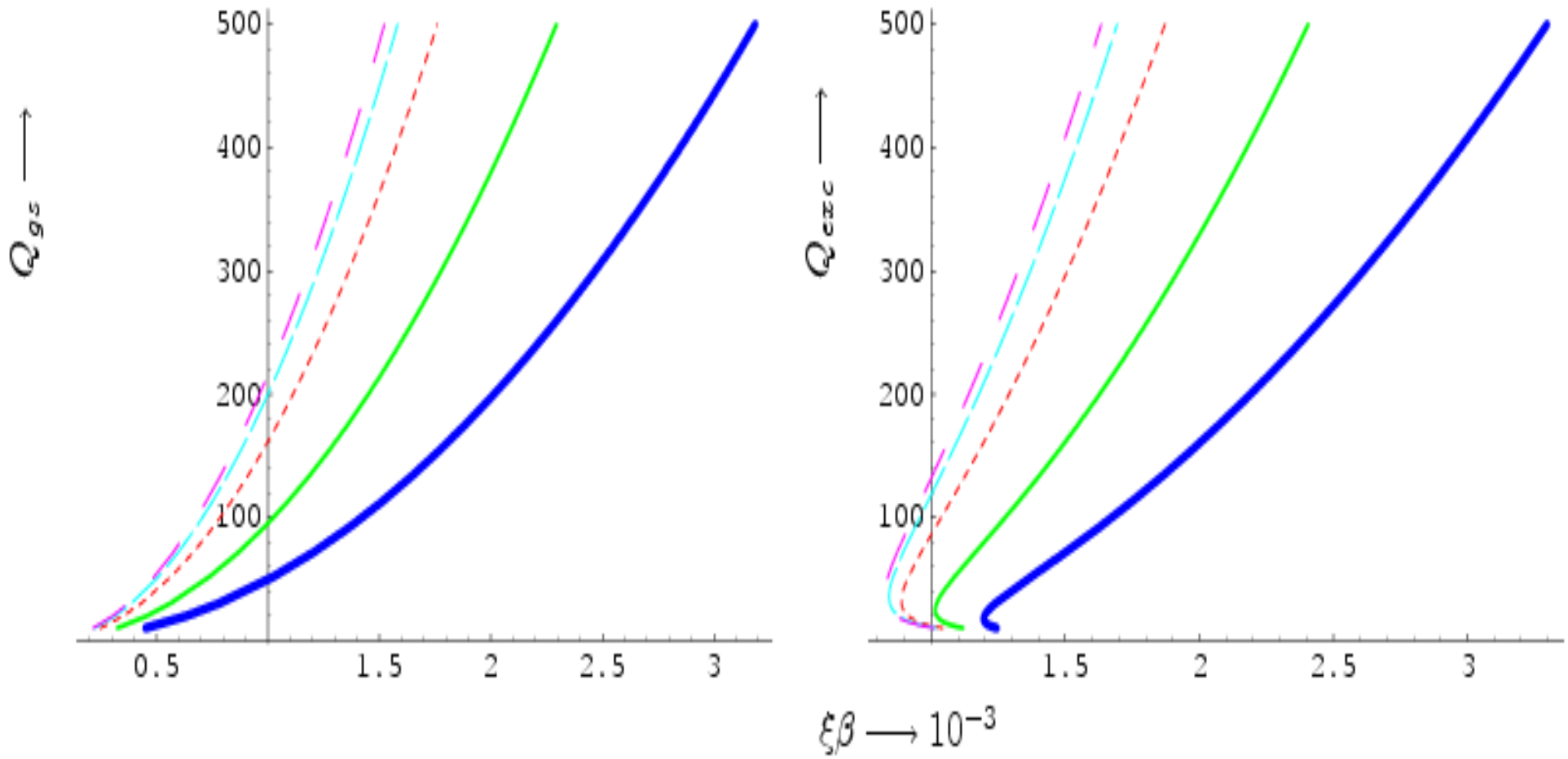
- For Transitions to excited states

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

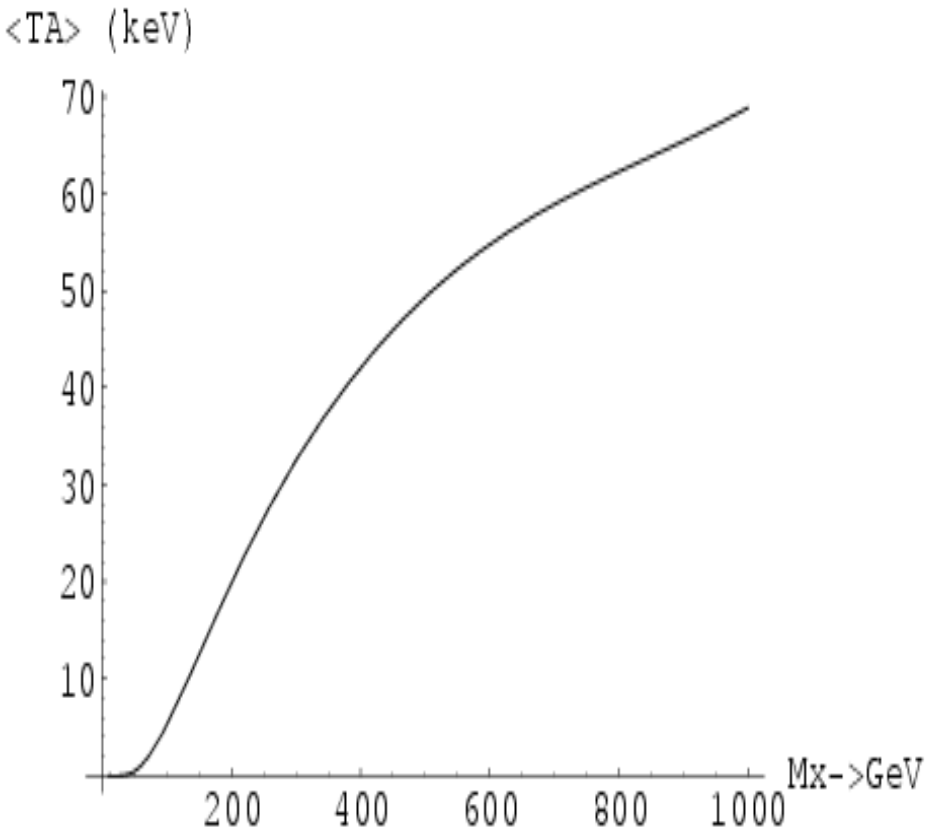
where $\beta = v/c$ with v the wimp velocity, ξ the cosine of the angle between the oncoming WIMP and the outgoing nucleus and Δ the excitation energy of the nuclear state.

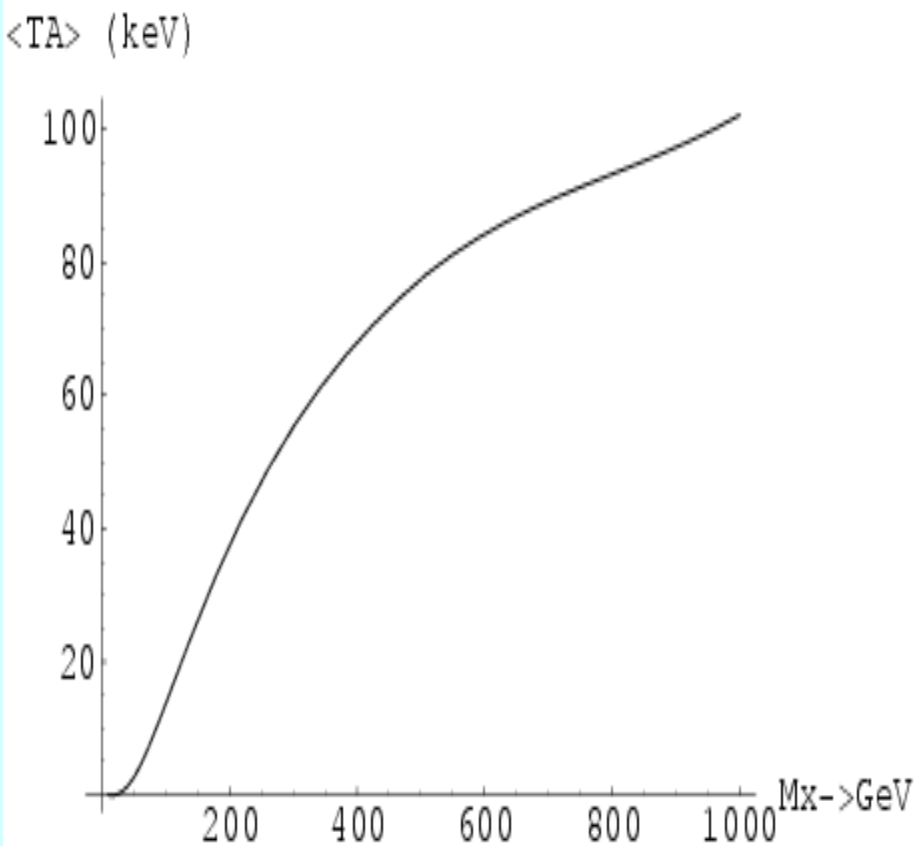
- Both are peaked around $\xi = 1$ (forward scattering)

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. $<\beta>=1.5 \times 10^{-3}$



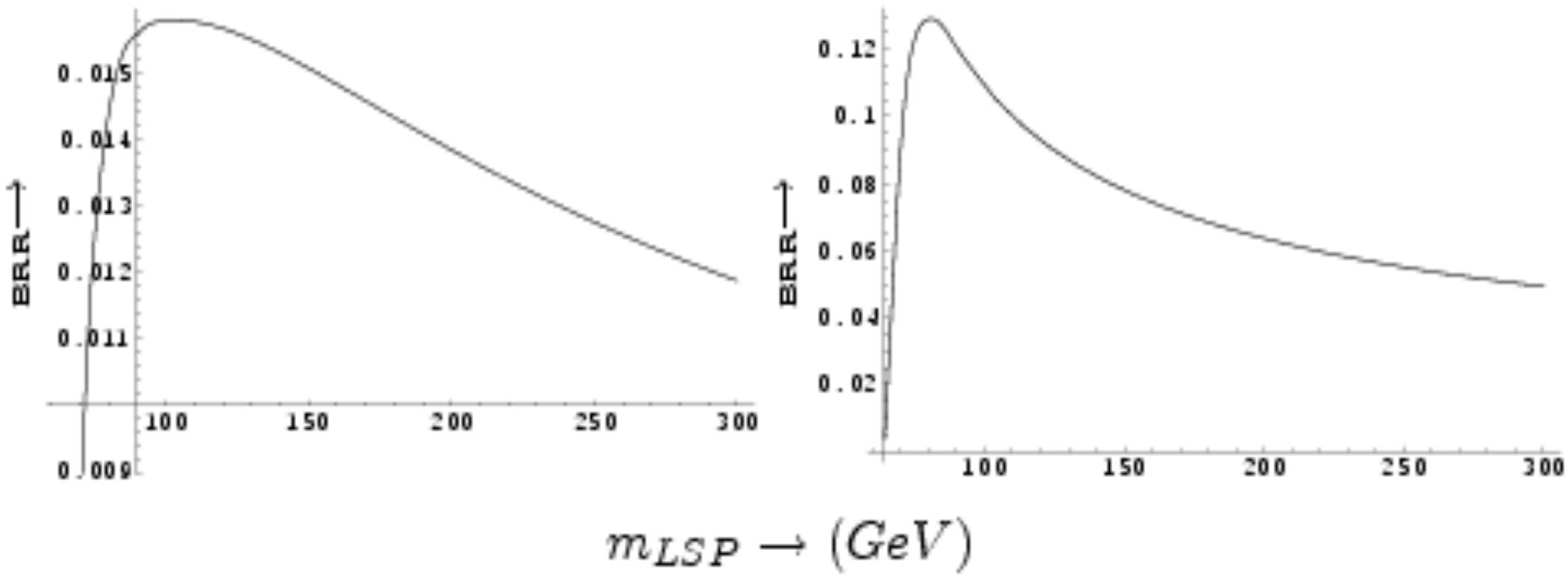
The average nuclear recoil energy:
A=127; Δ =50 keV (left), Δ =30 keV (right)





BR for transitions to the first excited state at 50 keV of I vs LSP mass (Ejiri, Quentin, Strottman and JDV,IJMPE (2005)) Relative to nucleon recoil. Quenching not included in the recoil

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



E: Directional Experiments* (Measuring both the energy and direction of the recoiling nucleus)

We will show that the observed events:

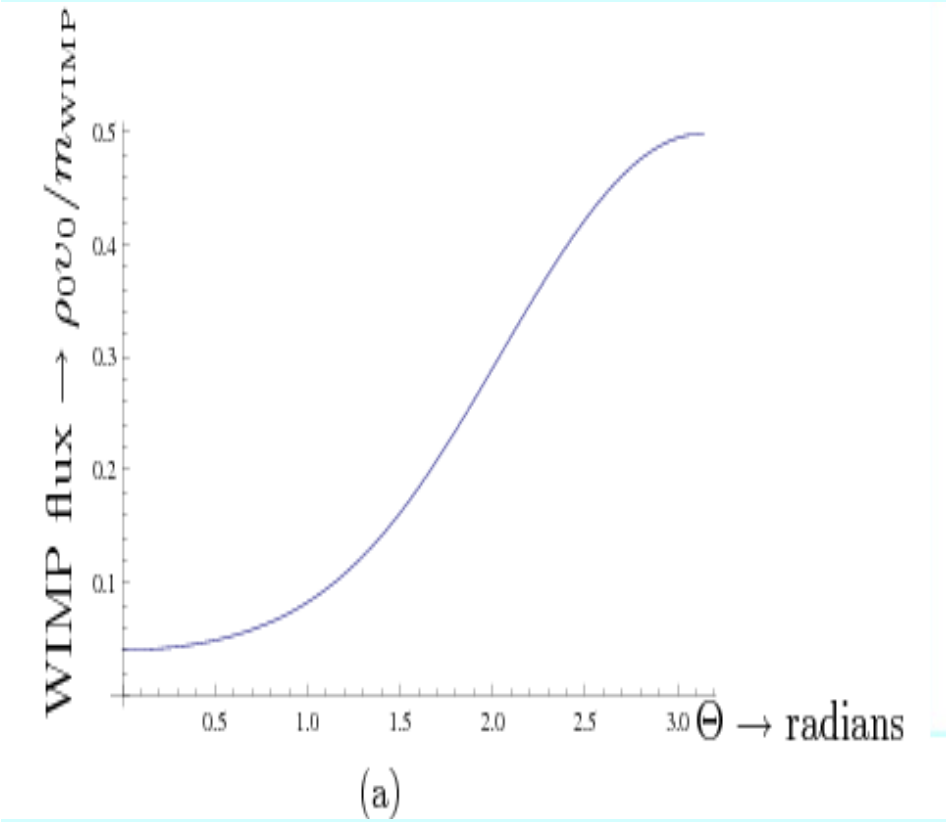
- will exhibit asymmetry due to the motion of the Sun
- On top of this they will exhibit characteristic annual modulation due to the annual motion of the Earth
- Both of these will exhibit periodic diurnal variation due to the rotation of the Earth.
- * DM-TPC, NEWAGE, DRIFT, MIMAC (Review: S. Ahlen et al, arXiv:0911.0323)
- *Also gaseous TPC detectors (3-D reconstruction arXiv:1001.2983 (atro-ph.CO)

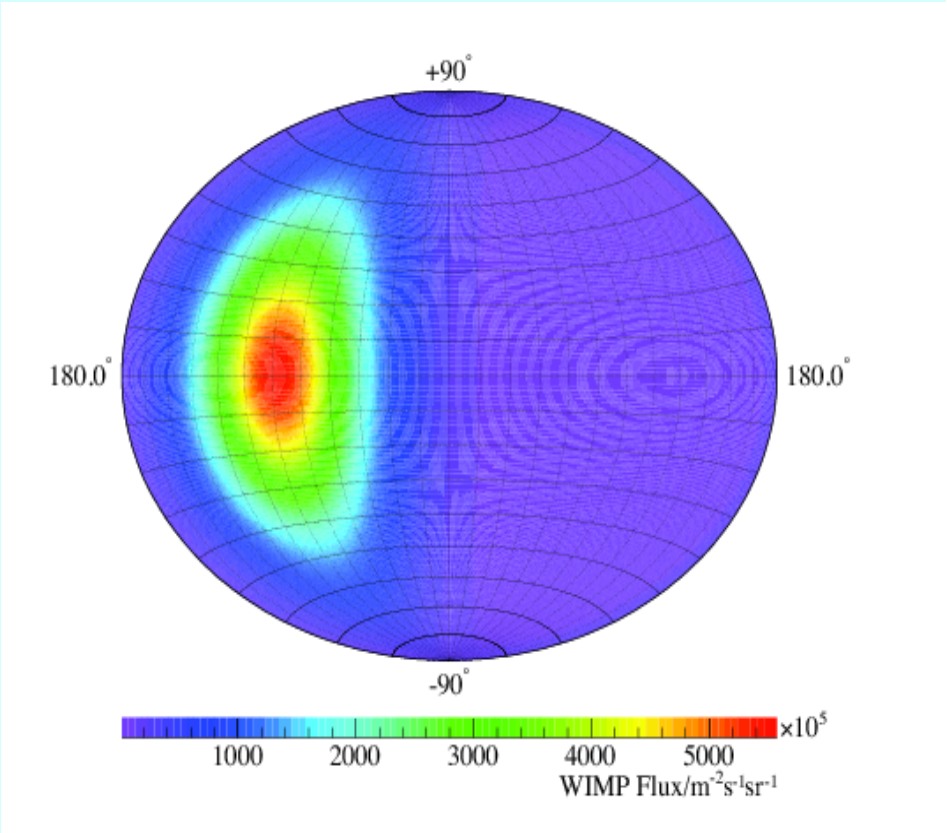
WIMP flux,"The solar wind" (towards the Cygnus constellation), Spergel (88), vergados (02), Morgan-Green-Spooner (04), Battat et al (IJMP A, 2009)

Bozorgnia, Gelmini, Gondolo (2012).

Flux variation

Morgan-Green-Spooner (04).





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

- The calculation will proceed in two steps:
- A) Evaluation of the event rate as a function of (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 (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 time average 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) The 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) total rates

$$R = \frac{\rho_\chi}{m_{\chi^0}} \frac{m}{A m_p} \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \sqrt{\langle v^2 \rangle} \left[\sigma^S_{p,\chi^0} A^2\, t_{\rm coh} \left(1 + h_{\rm coh} \cos\alpha\right) + \sigma_{\rm spin} t_{\rm spin} \left(1 + h_{spin} cos\alpha\right)\right]$$

$$\frac{dR}{d\Omega} = \frac{\rho_\chi}{m_{\chi^0}} \frac{m}{A m_p} \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \sqrt{\langle v^2 \rangle} \frac{1}{2\pi} \quad \left\{\sigma^S_{p,\chi^0}\, A^2 t^{\rm dir} \left(1 + h_c^{\rm dir} \cos\alpha + h_s^{\rm dir} \sin\alpha\right)\right.$$

$$\left. + \sigma_{\rm spin} t^{\rm dir}(spin) \left(1 + h_c^{\rm dir}(spin) \cos\alpha + h_s^{\rm dir}(spin) \sin\alpha\right)\right\}. \quad (10$$

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

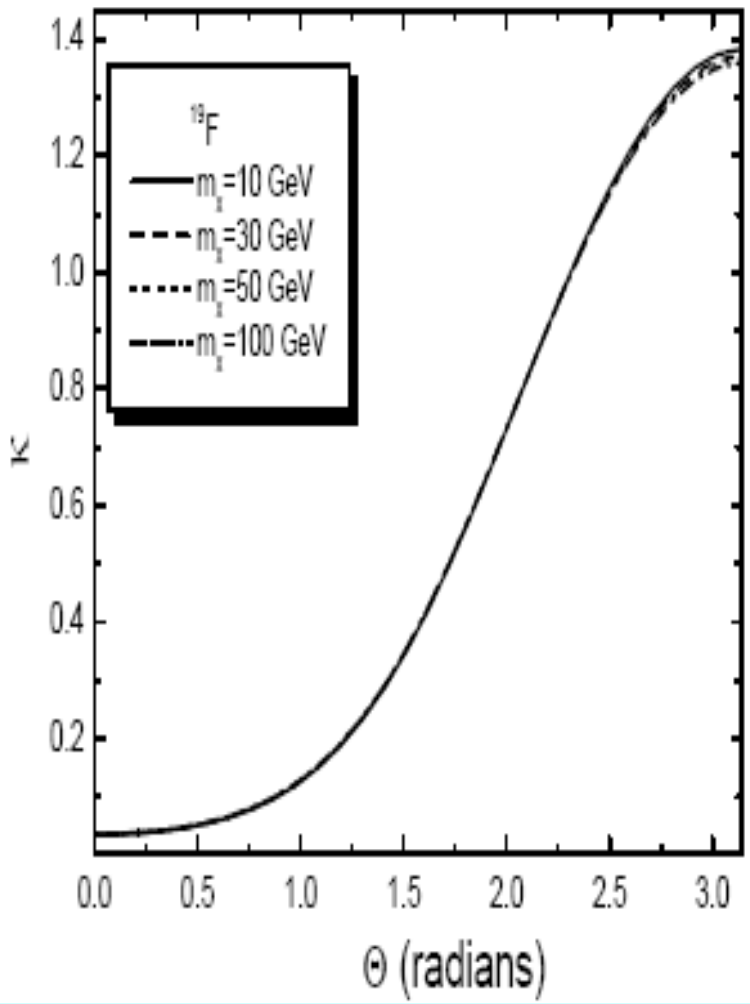
- The event rate as a function of the direction angles (Θ, Φ) is:

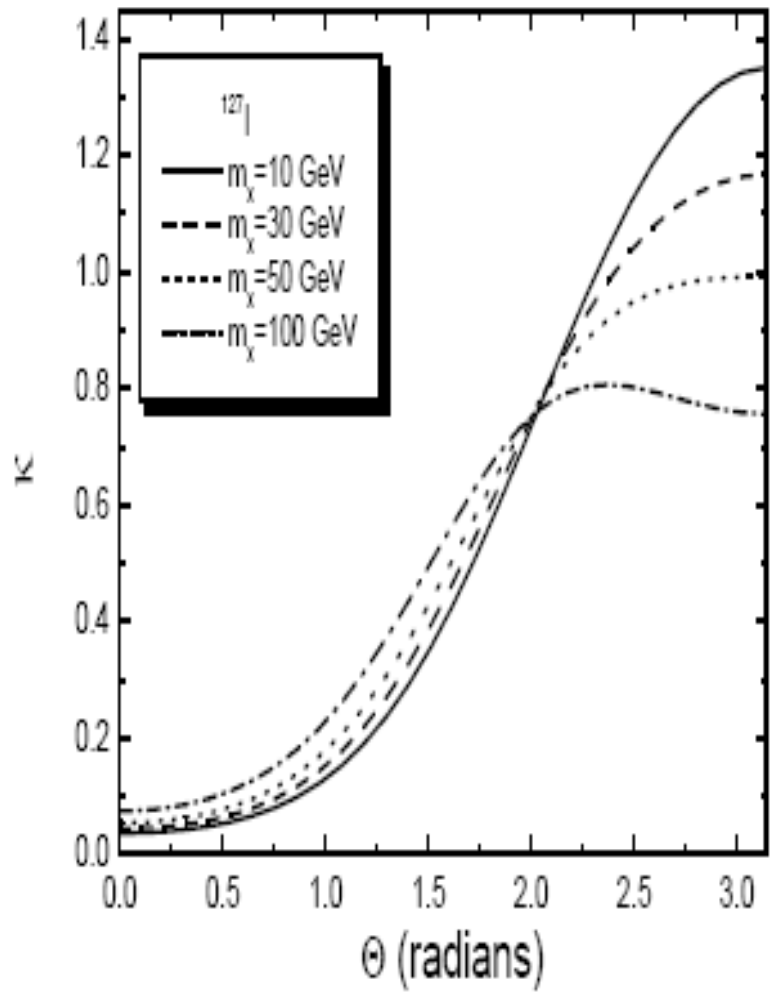
$$dR/d\Omega = (\kappa/2\pi)R_0[1+h_c\cos\alpha + h_c\cos\alpha],$$

$$\kappa = t/t_{dir}$$

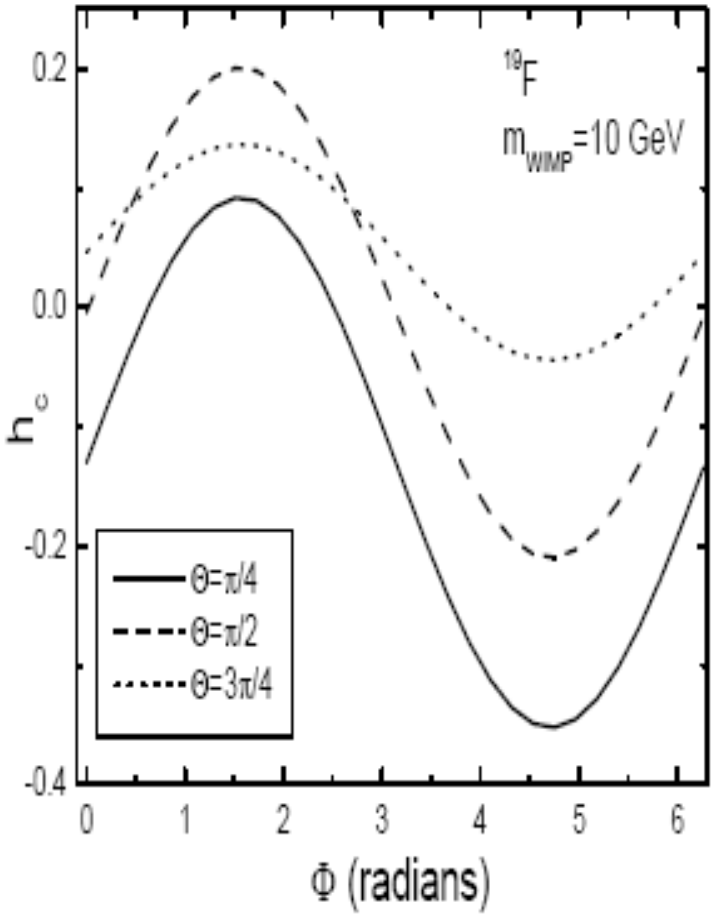
- R_0 is the average usual (**non-dir**) rate
- α the phase of the Earth (as usual)
- h_m: $h_m\cos(\alpha+\alpha_0)=h_c\cos\alpha + h_s\sin\alpha$ is the total modulation amplitude (it strongly depends on the direction of observation): α_0 is the shift in the phase of the Earth (it strongly depends on the direction of observation)
- $\kappa/2\pi$ 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. $dR/d\Omega \to dR/d(\cos\Theta)$
- κ, h_m and α_m depend only slightly on the particle (e.g. SUSY) parameters and the reduced mass μ_r

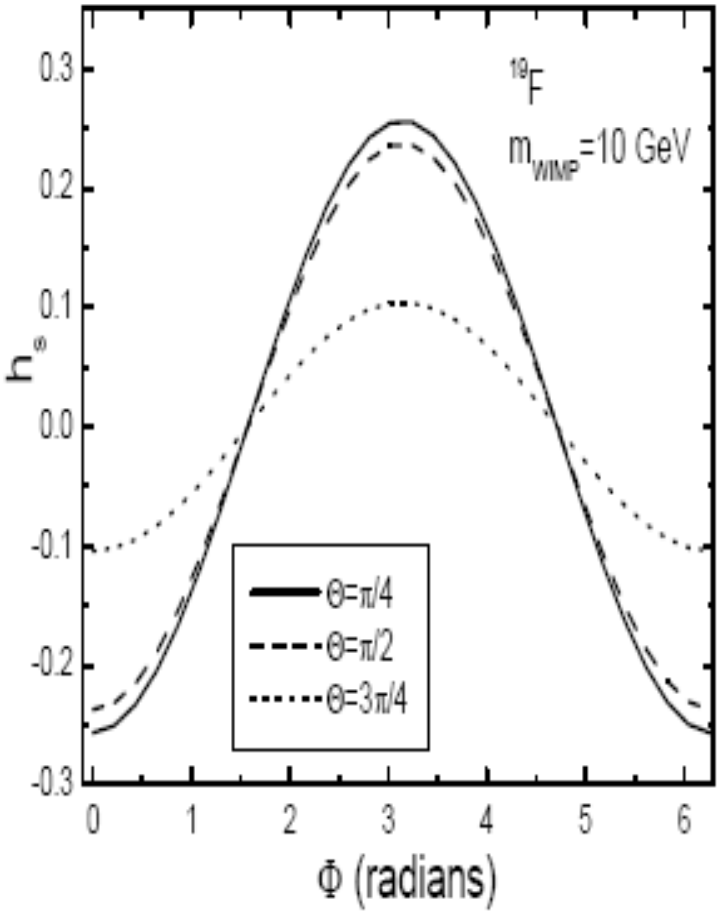
The parameter κ vs Θ for light target (S or F) & heavy targe (JDV & Moustakidis)



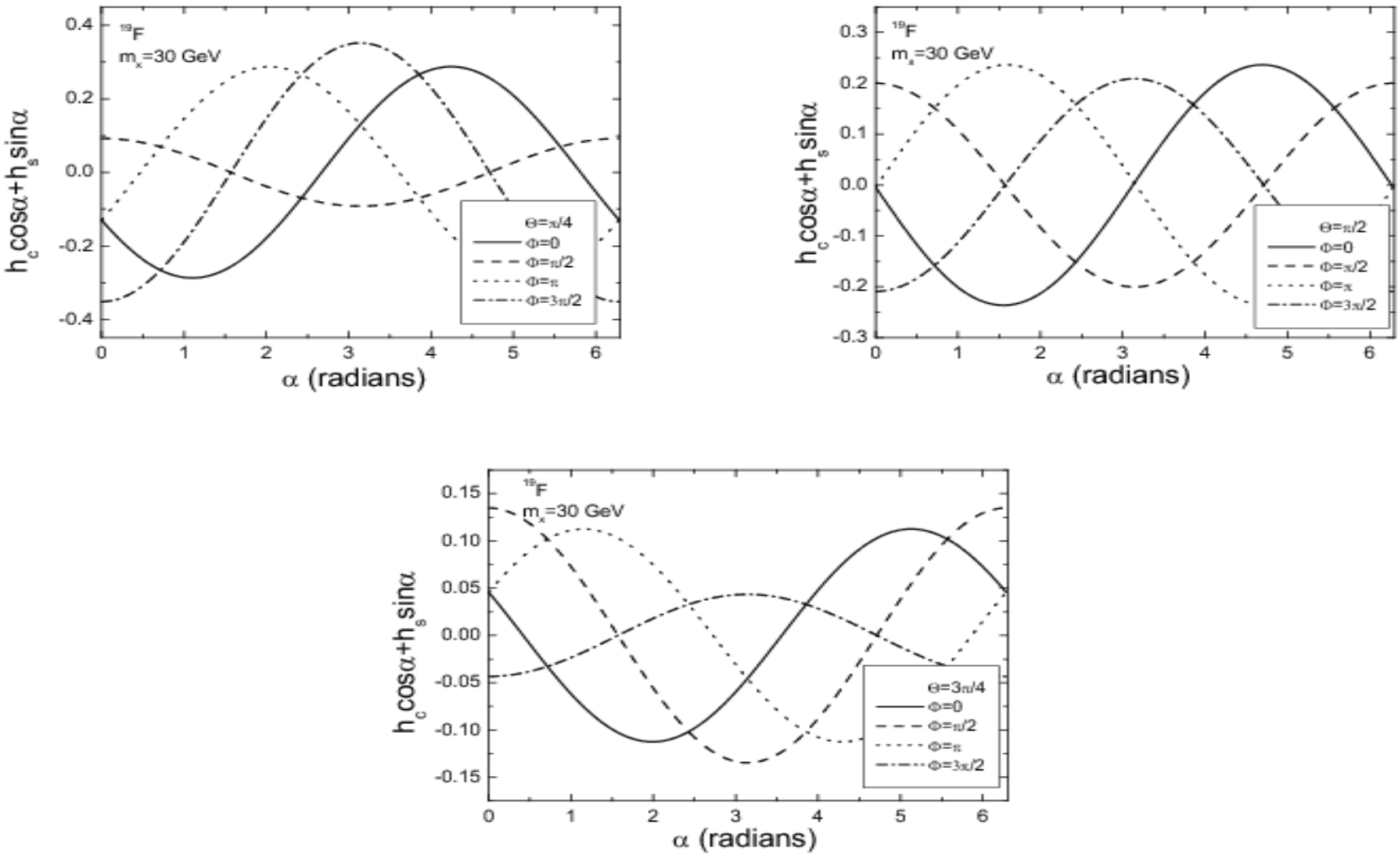


The modulation amplitudes vs Φ for m_χ =10 GeV for a light target





Modulation vs the phase of the earth.



CII: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 thus show a periodic behavior.

From the celestial

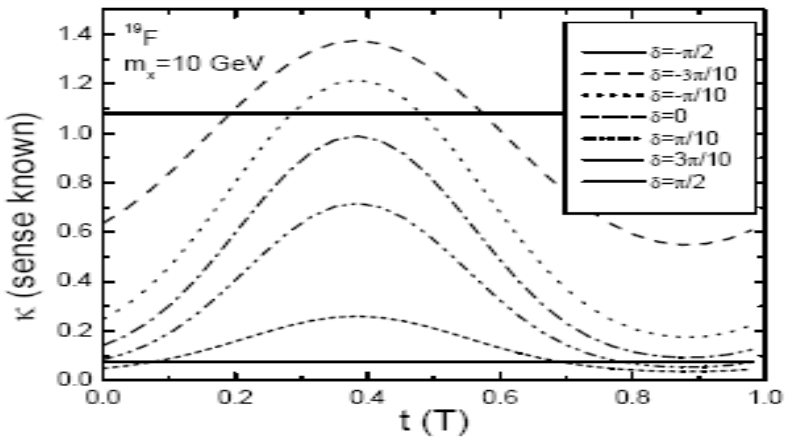
(α =ascention, δ =inclination)

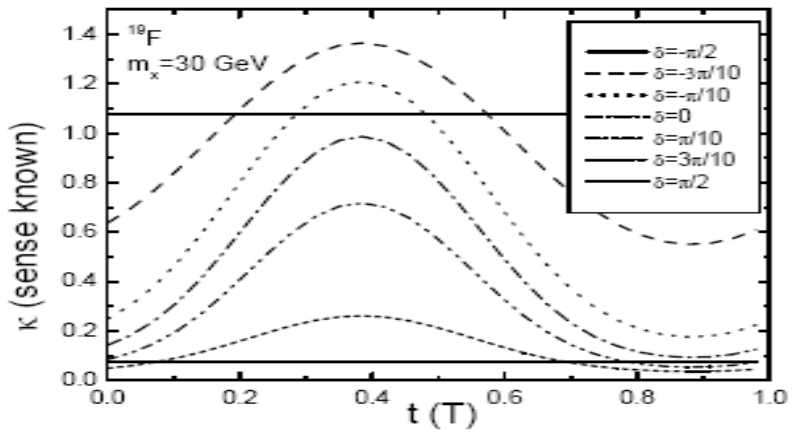
to galactic coordinates

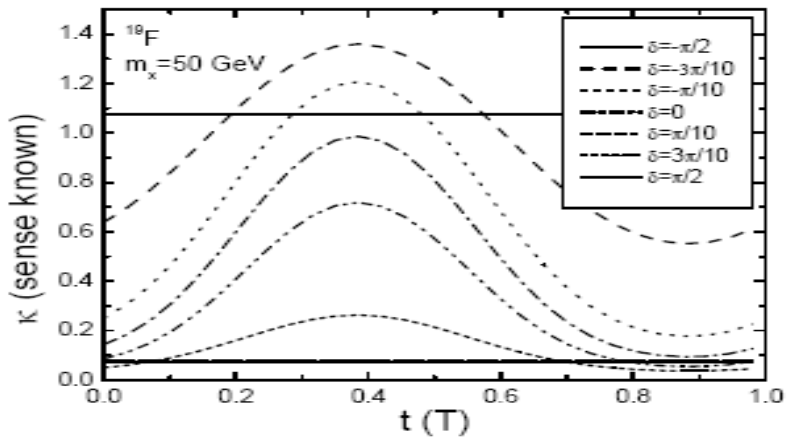
A vector oriented by (α, δ) in the laboratory is given in the galactic frame by a unit vector with components:

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

Diurnal Variation of the rate (κ) ^{19}F Target & Fully Directional







CONCLUSIONS I: Non-directional

The relative modulation amplitude h :

- is small, less than 2%, and depends strongly on the LSP mass.
- It depends on the velocity distribution
- Its sign is also uncertain. it is positive for light systems, but it may become negative for intermediate and heavy nuclei and heavy WIMPs (for both M-B and Realistic velocity distributions). Can this be exploited to extract the WIMP mass?
- The time behavior of the differential event rates at low energy transfers exhibits characteristic dependence on the WIMP mass.
- The spin modulation exhibits a similar behavior
-

CONCLUSIONS II: Asymmetry of the rates in directional Experiments

- 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)
- $\kappa \approx 1$ in the most favored direction ($\Theta \approx \pi$ in M B)
- As the Earth rotates the detector samples a different angle Θ ->
- The event rate (κ) exhibits a diurnal variation (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 III : The modulation in directional Experiments (preliminary)

- The modulation amplitude in the most favored direction ($\kappa \approx 1$) is $0.05 < h_m < 0.15$ (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% relative 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 weak but spectacular signal (it 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!

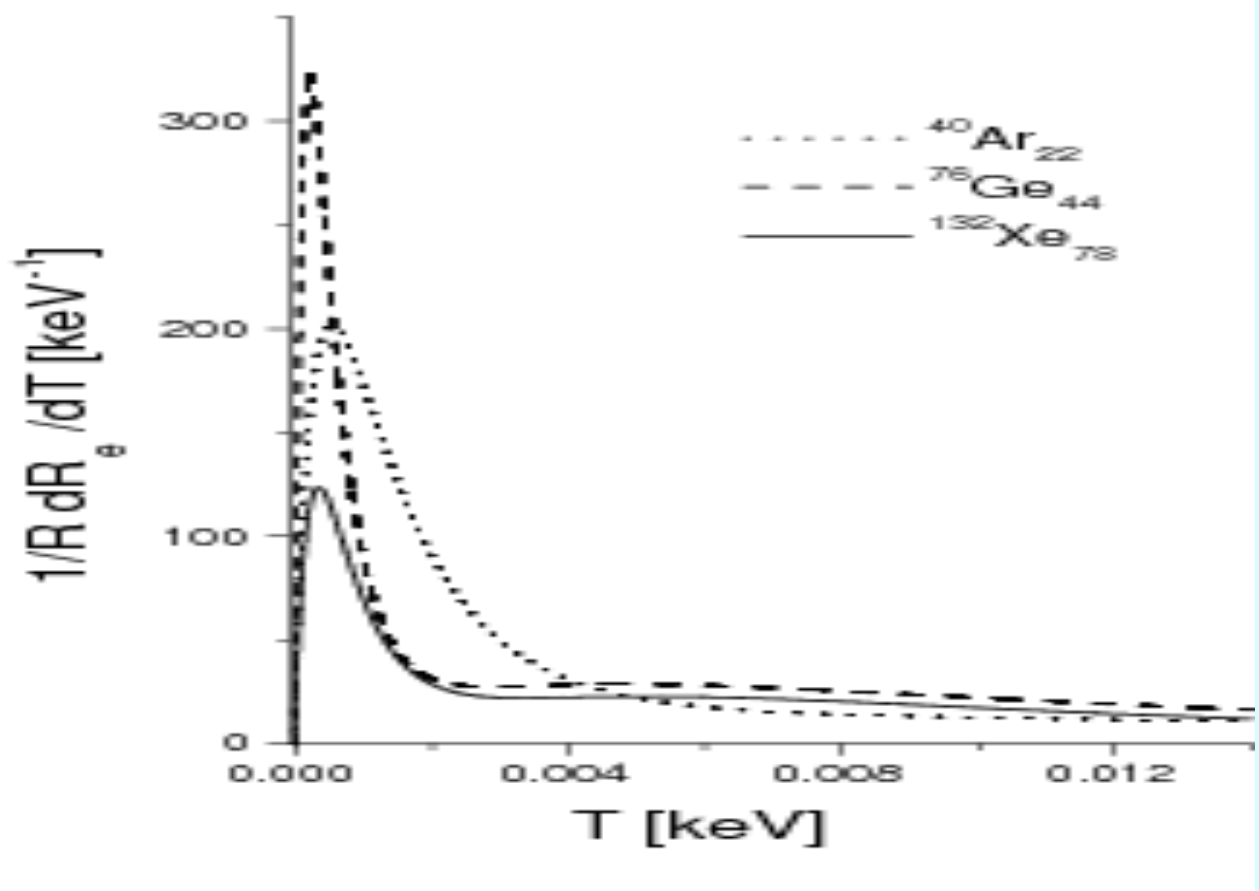
- Mullah Nasrudin did not know how to sum up infinite series. However theorists do:

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

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

- THE END

Differential electron production rate/ total recoil rate for m_χ =100GeV. Realistic electron orbits (Moustakidis, Ejiri, &JDV, Nucl.Phys. B727 (2005) 406)



Massless mediator

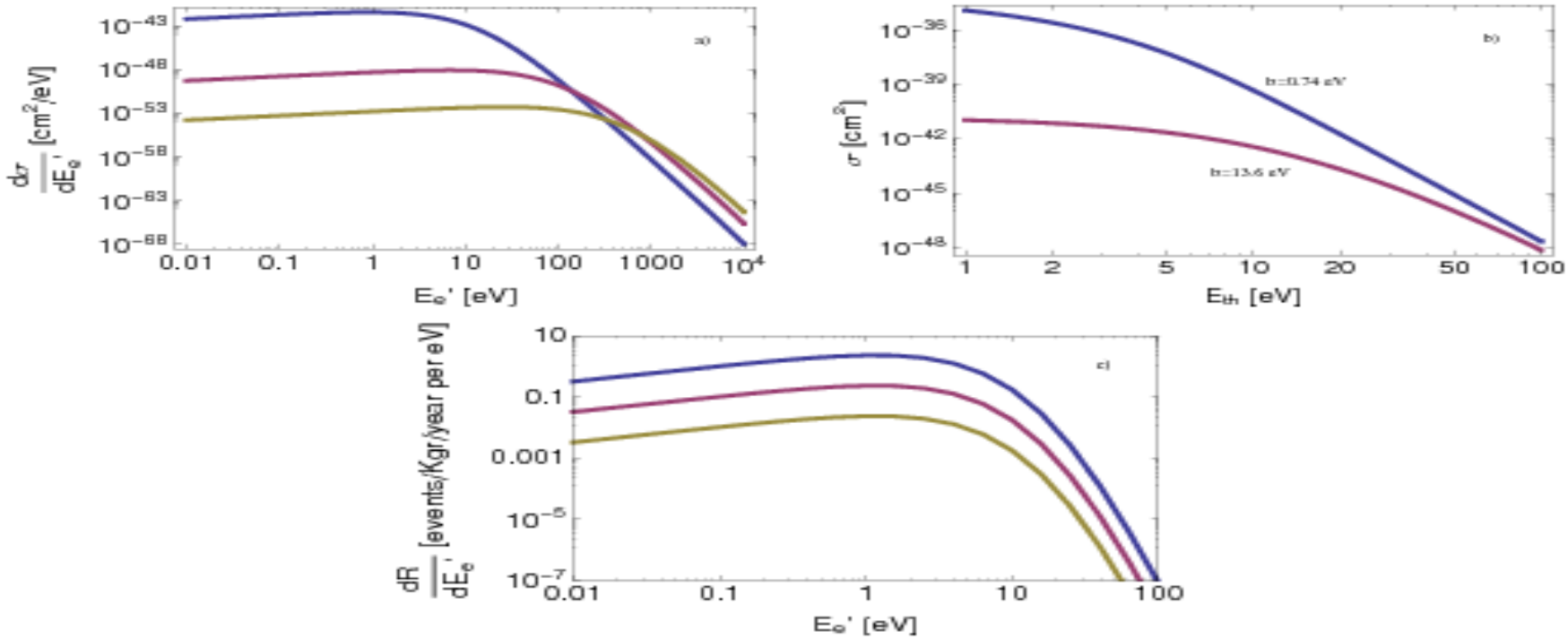


Figure 6: *a) Predictions for $d\sigma/dE_e'$ as a function of the ejected electron energy E_e'. The target is assumed to be a hydrogenic atom in the ground state with Z=1,3,6 (from top to bottom). b) The total cross section for process (4.43) as a function of the experimental threshold energy for two binding energies. c) The differential event rate as a function of the electron energy and various WIMP masses (10,100,1000) GeV from (top to bottom). Other parameters not shown, are taken from eq. (4.65).*

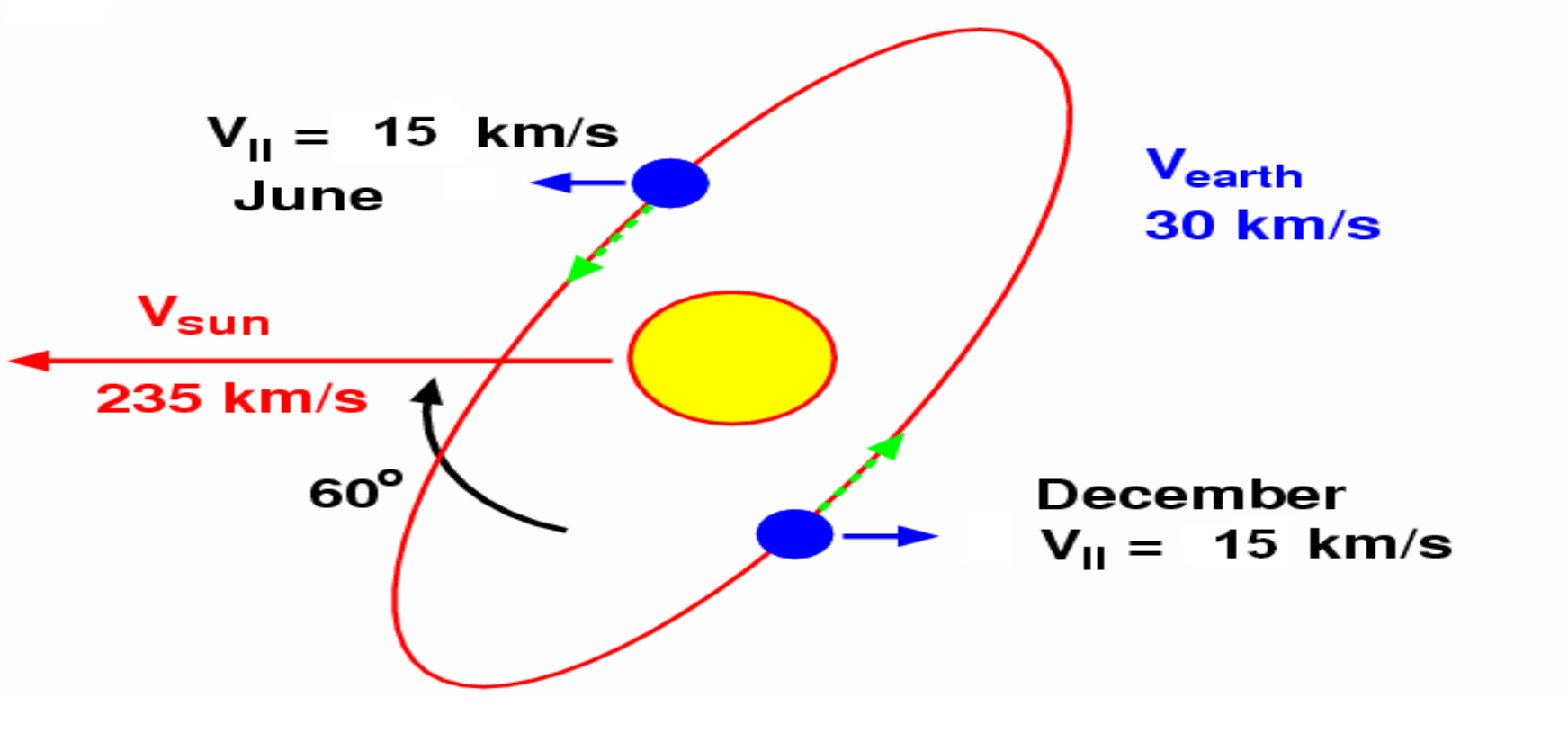
B: Novel approaches: Exploitation of other signatures of the reaction

- 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 (it will not be discussed to-day).
- The excitation of the nucleus (in some cases : heavy WIMP, low excitation energy etc.) and detection of the subsequently emitted de-excitation γ rays. (it will not be discussed to-day).
- Asymmetry measurements in directional experiments (the direction of the recoiling nucleus must also be measured)-->
- DIURNAL VARIATION.

The cross section depends on the relative velocity of the WIMP with the target

v_{June}=235+15=250km/s

v_{Dec}=235-15=220km/s



BI: THE MODULATION EFFECT (in standard recoil experiments)

Goodman & Witten (1985)

- Total Rates:

$$R = R_0 + \tilde{H}\cos\alpha, \quad R = R_0\,(1 + h\cos\alpha)$$

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

R_0 =average rate,The 2nd term is the modulated rate.
h=relative modulation amplitude.

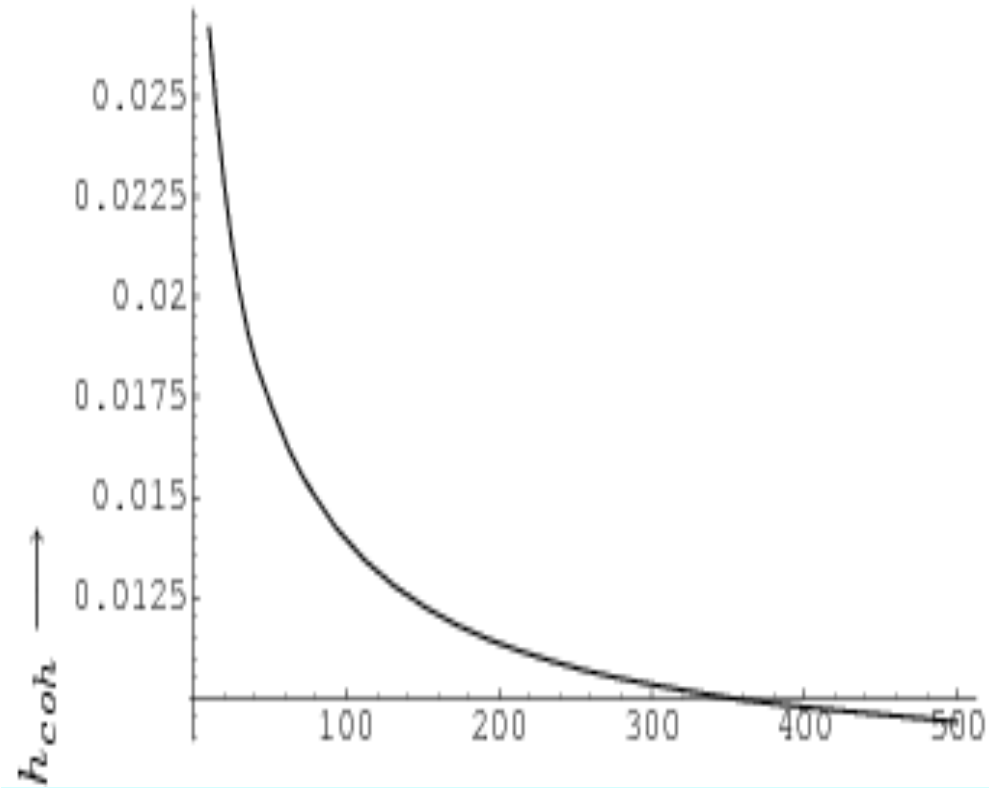
- The percentage difference between the minimum and the maximum is 2h
- The location of the maximum depends on the sign of h

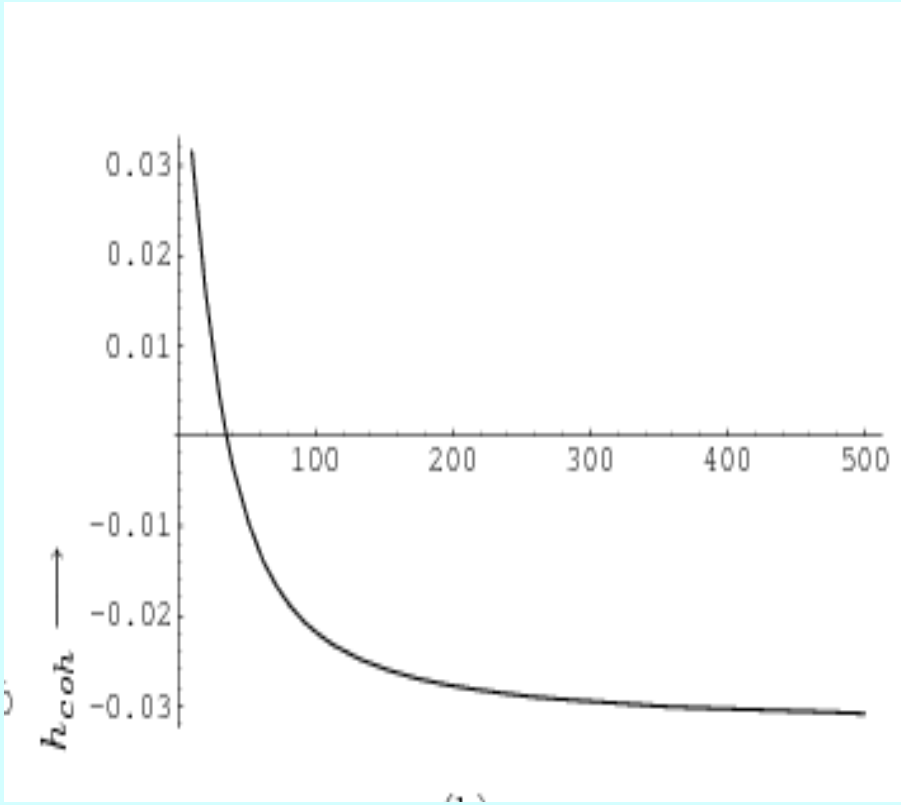
BIc: The total Relative modulation amplitude (As a function of WIMP mass in GeV)

Heavy system (e.g. A=127)

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

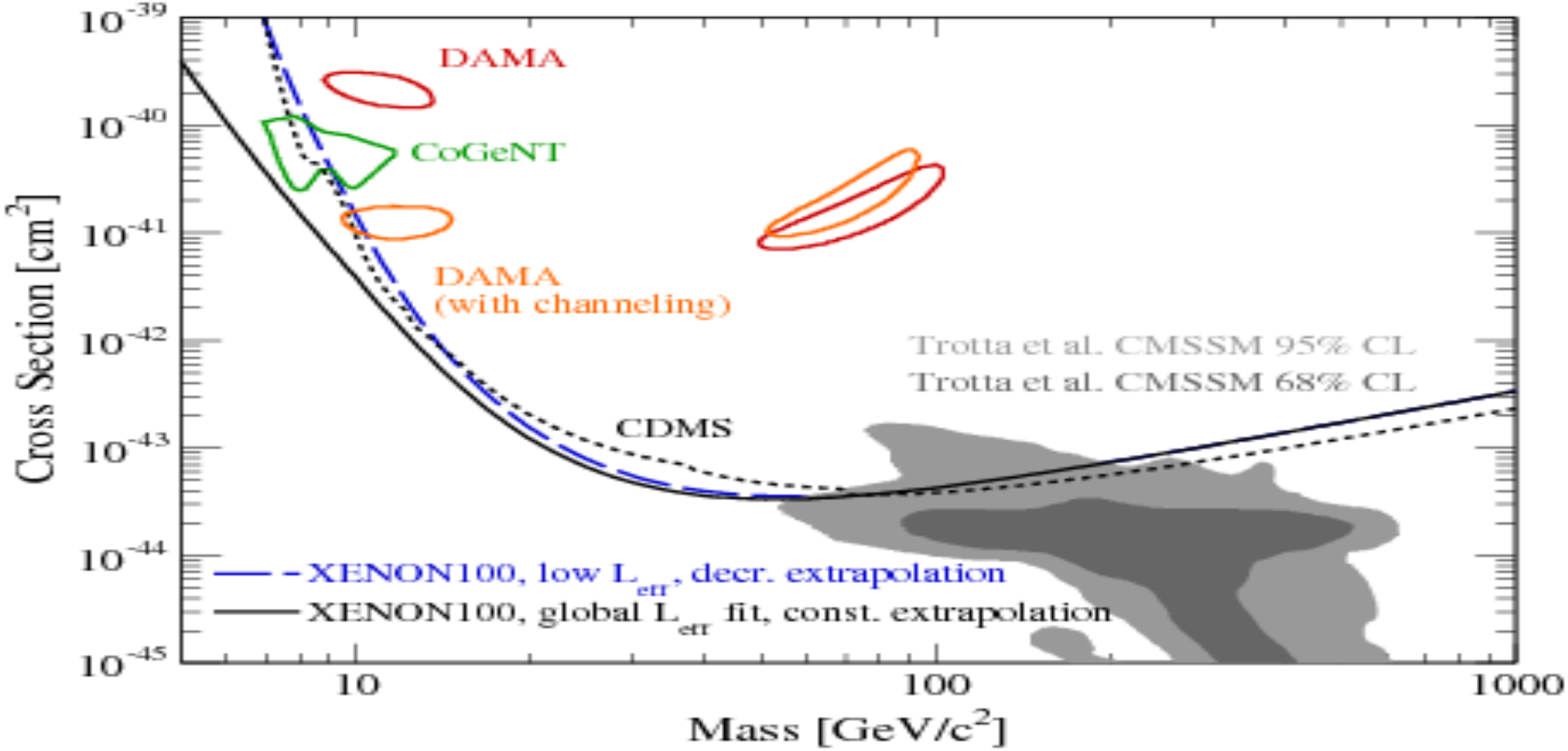
Note sign change





Light WIMPs: Motivated by exclusion plots.

Possible in some models: Cerdeno (this workshop), Cao-Hikasa-Wang-Yang

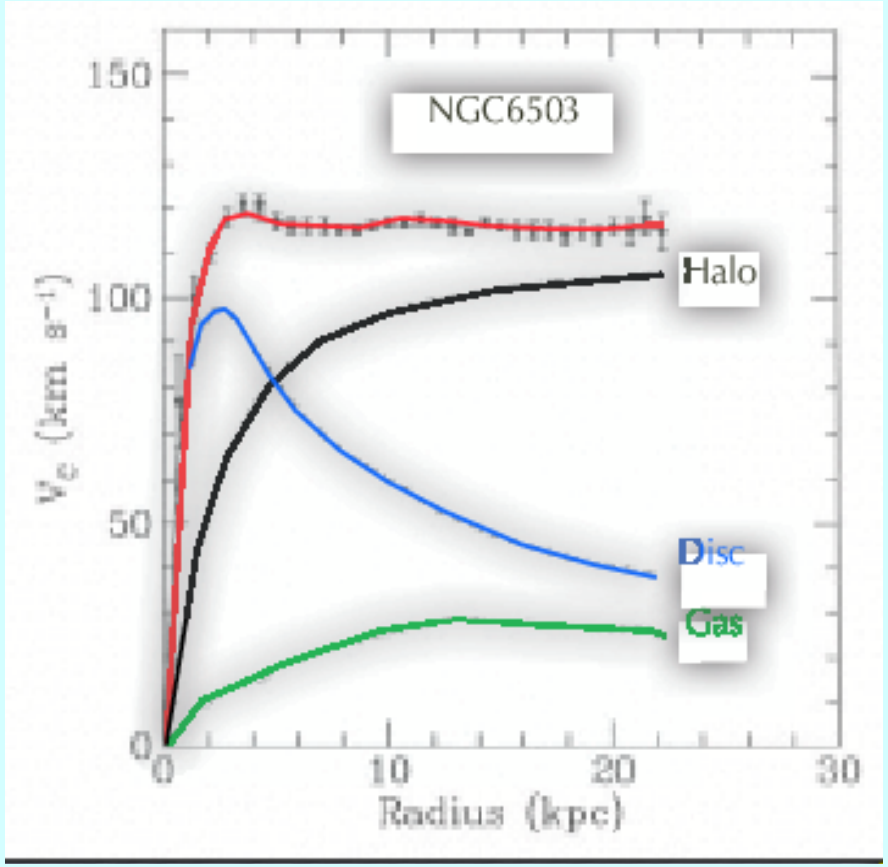


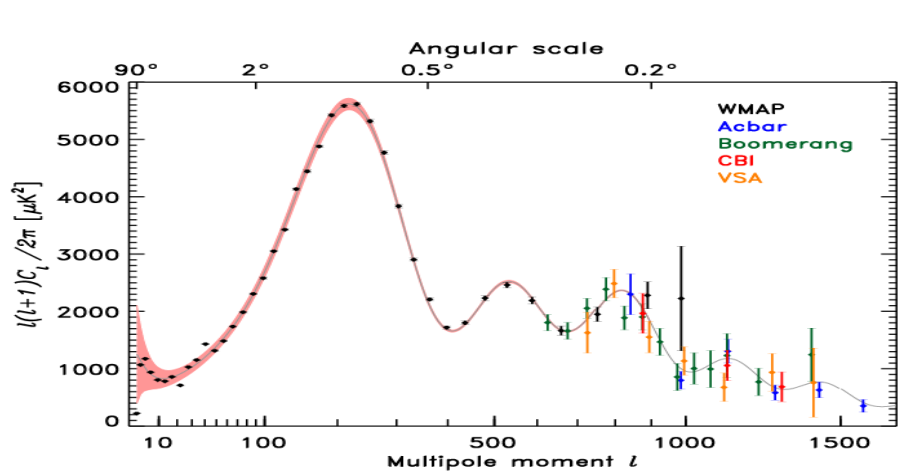
BII: Relatively light WIMPS: Focus on the differential event rate

- $\frac{dR}{dQ}|_A = \frac{dR_0}{dQ}|_A$ (1+H cos α), relative mod. Amp.

$$\frac{dR}{dQ}|_A = \frac{dR_0}{dQ}|_A + \frac{d\tilde{H}}{dQ}|_A \cos\alpha$$

Dark Matter Exists! Galaxies (rotational velocities); gravitational Lensing (cluster 1E0657-56, DM in blue); WMAP5





The nature of DM can be unraveled in direct experiments←→Elastic scattering of dark matter particles with nuclei←→recoil

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

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

with

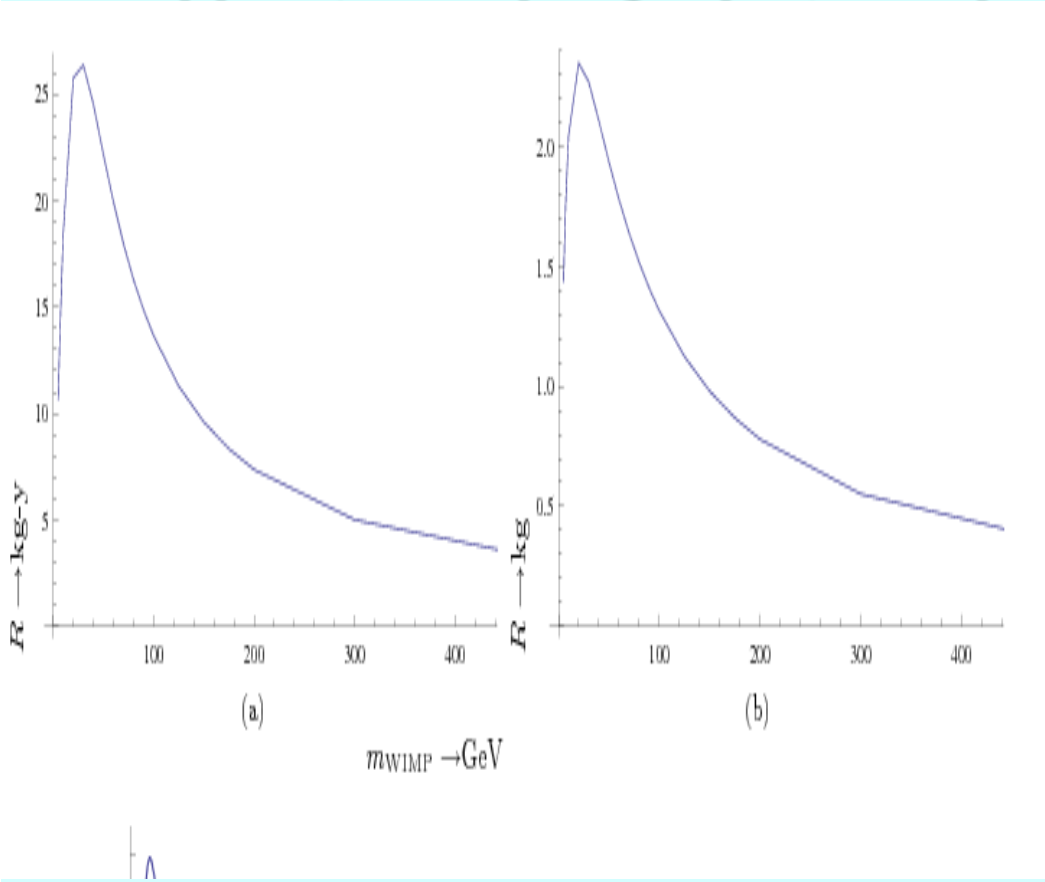
$$f_{coh}(A, \mu_r(A)) = \frac{100\mathrm{GeV}}{m_{\chi^o}} \left[\frac{\mu_r(A)}{\mu_r(p)}\right]^2 A^2\ t_{coh}\,(1 + h_{coh} cos\alpha)$$

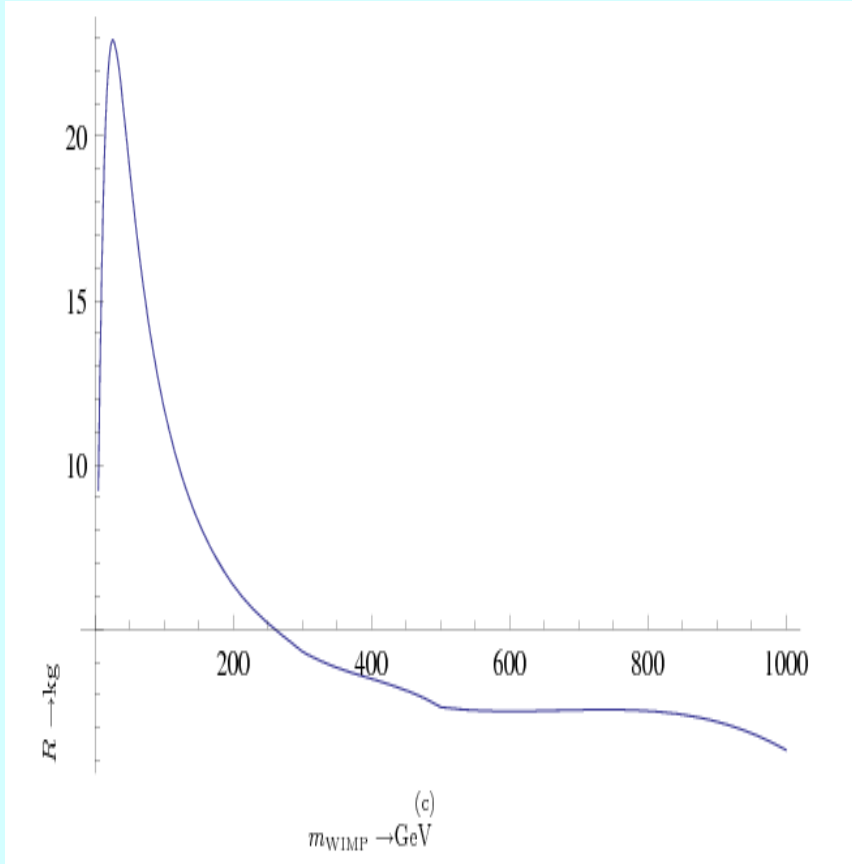
Where:

- t_{coh} , h_{coh} depend on nuclear physics, the WIMP mass and the velocity distribution. We assume here the standard M-B velocity distribution. α the phase of the Earth
- ρ (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$_\chi$) is known

A: The coherent event rates for zero threshold energy ($\sigma_{p,\chi}=10^{-7}$ pb)

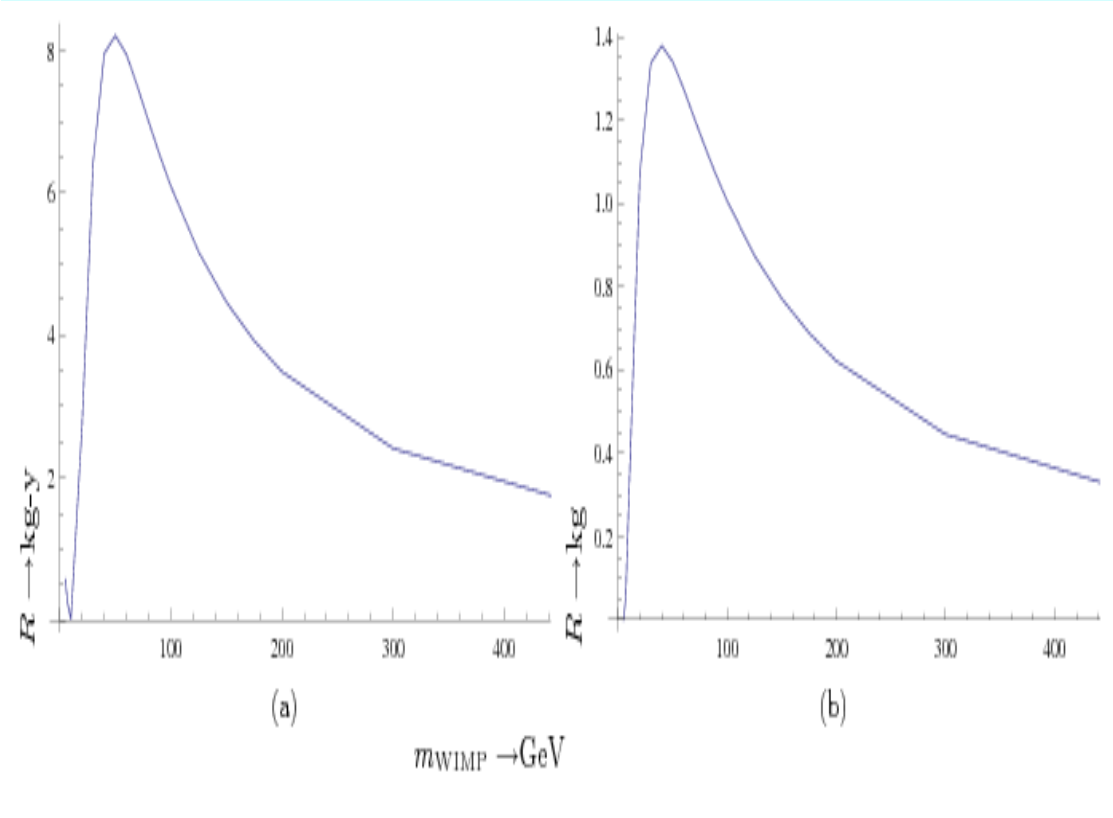
Heavy(^{127}I , ^{131}Xe) Light(^{19}F, ^{23}Na) NaI

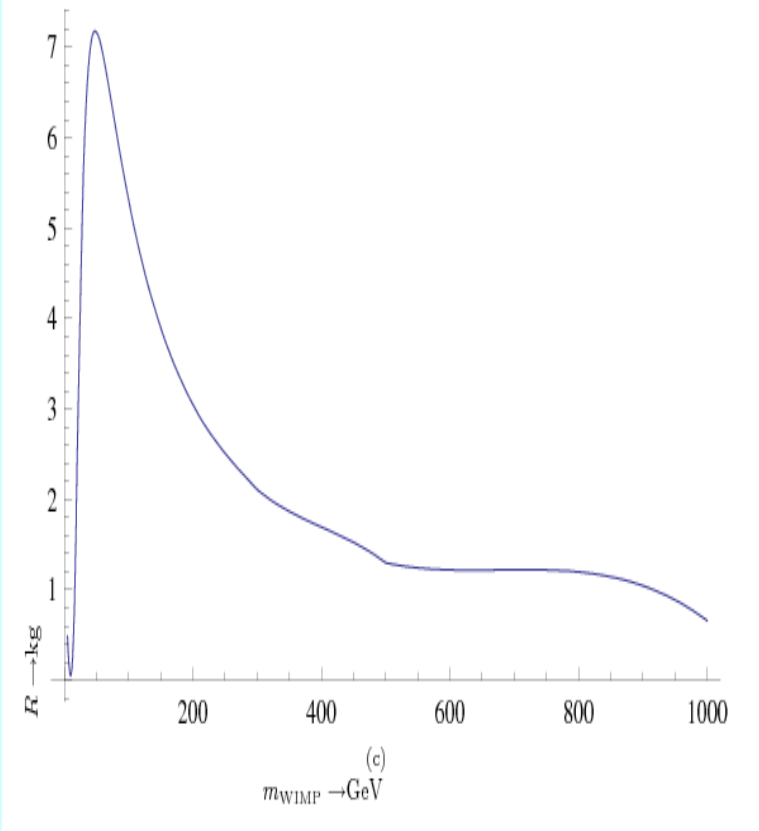




Threshold effect on coherent event rates for threshold energy of 5 keVee ($\sigma_{p,\chi} = 10^{-7}$ pb)

Heavy(^{127}I , ^{131}Xe) Light(^{19}F, ^{23}Na) **NaI**





BII: Relatively light WIMPS: Focus on

- The total Rate: $R = R_0 + R_m \cos\alpha = R_0(1 + h \cos\alpha)$

  R_0 is the time averaged differential Event Rate

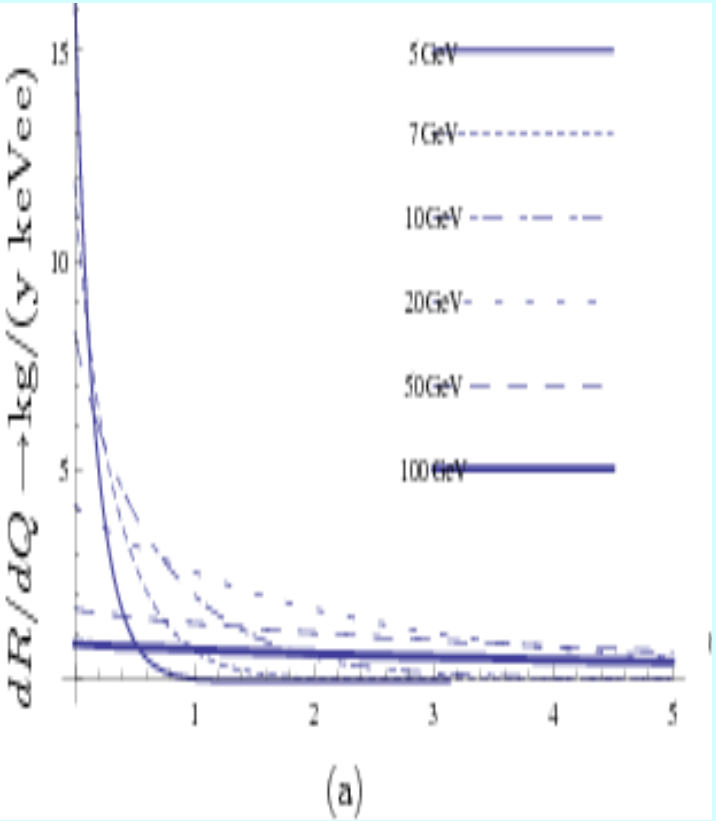
  R_m: the amplitude for the modulated differential Rate
- The relative differential event rate

$$\frac{dR}{dQ}\Big|_A = \frac{dR_0}{dQ}\Big|_A + \frac{d\tilde{H}}{dQ}\Big|_A \cos\alpha$$

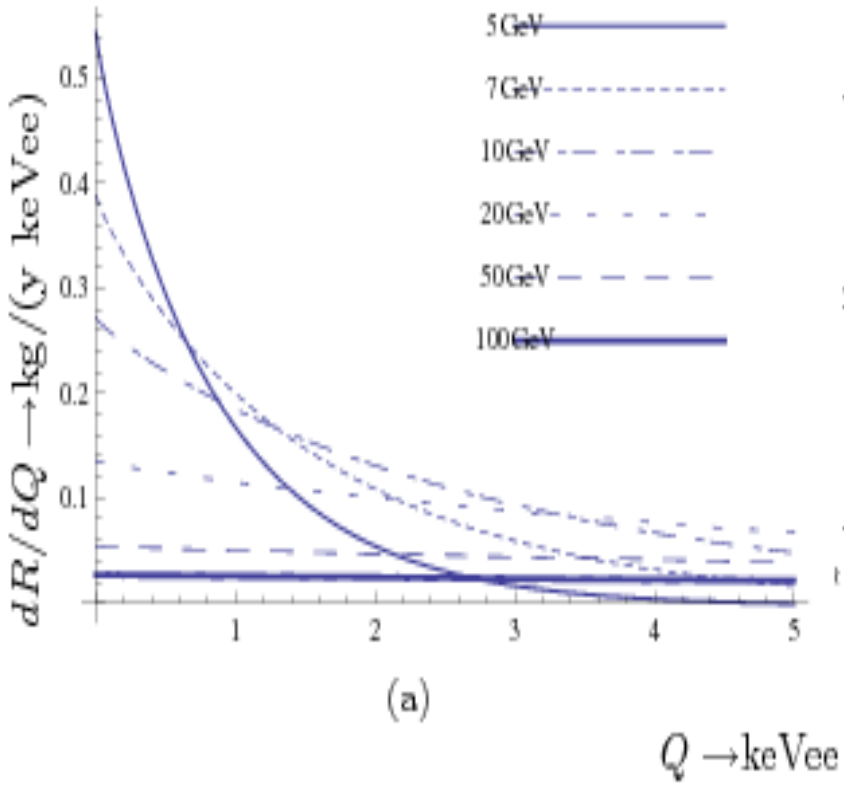
- $$\frac{dR}{dQ}\Big|_A = \frac{dR_0}{dQ}\Big|_A (1 + H \cos\alpha)$$

BTLD: The coherent differential rate for $\sigma_N = 10^{-7}$pb (constant) Q in keVee

Heavy (e.g. ^{127}I, ^{131}Xe)

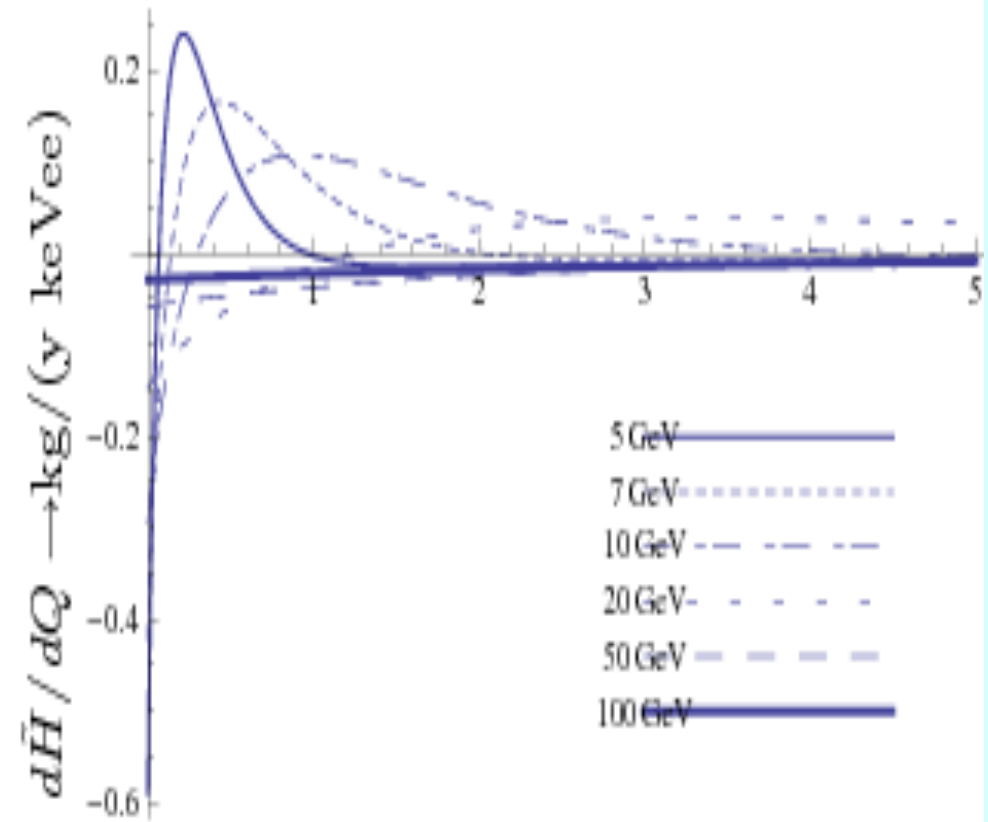


Light (e.g. ^{19}F, ^{23}Na)

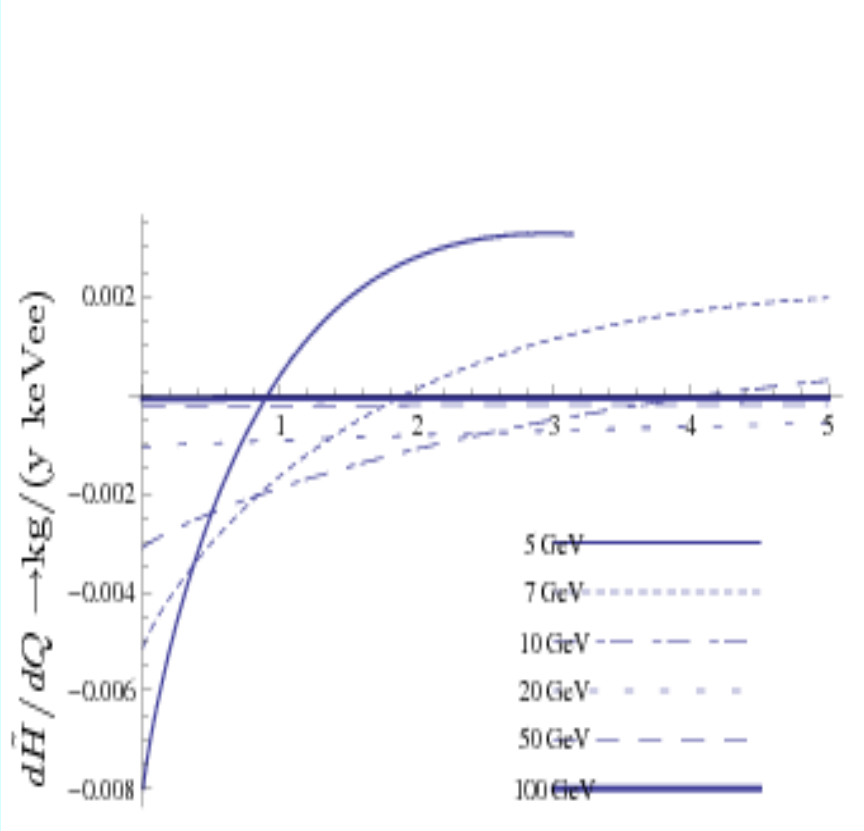


BIIc: The coherent differential mod. rate for $\sigma_N = 10^{-7}$pb (constant) Q in keVee

Heavy (e.g. ^{127}I, ^{131}Xe)



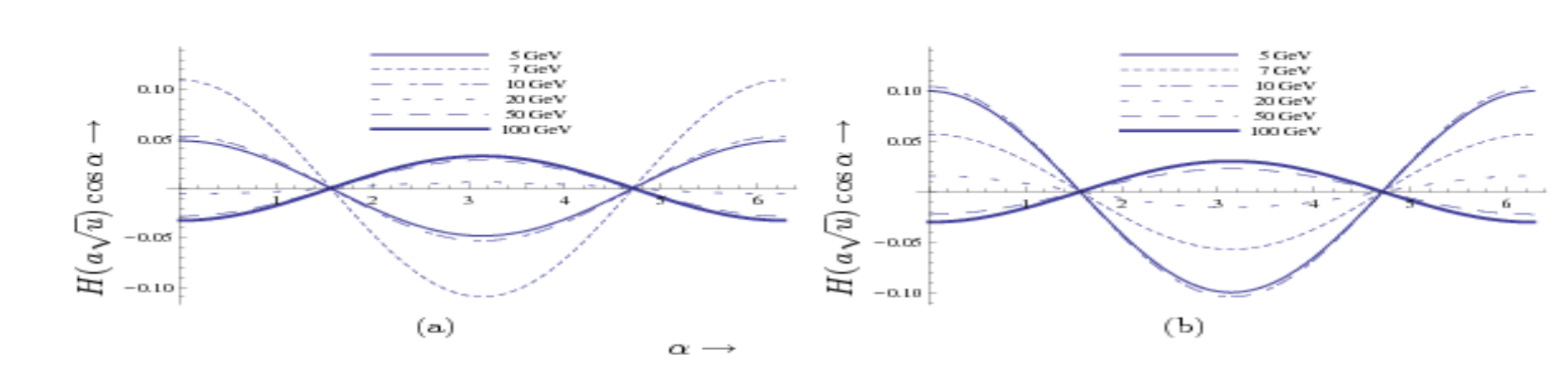
Light (e.g. ^{19}F, ^{23}Na)

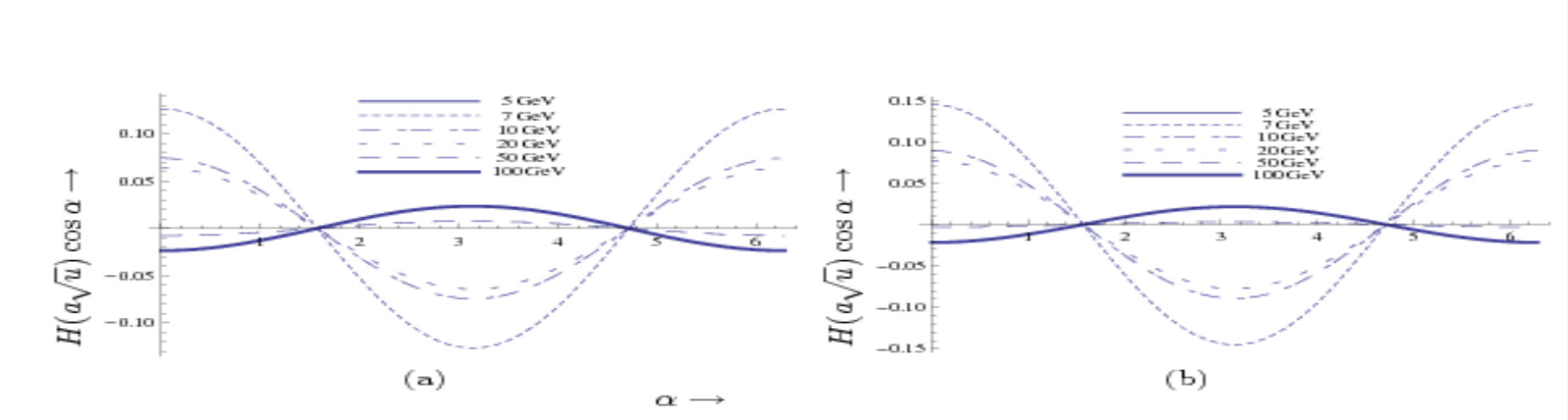


BIIIb: The relative (differential) Modulation amplitude

It is independent of the nucleon cross section. Example NaI

From left to right top to bottom : Q=1,2,5,6 keVee

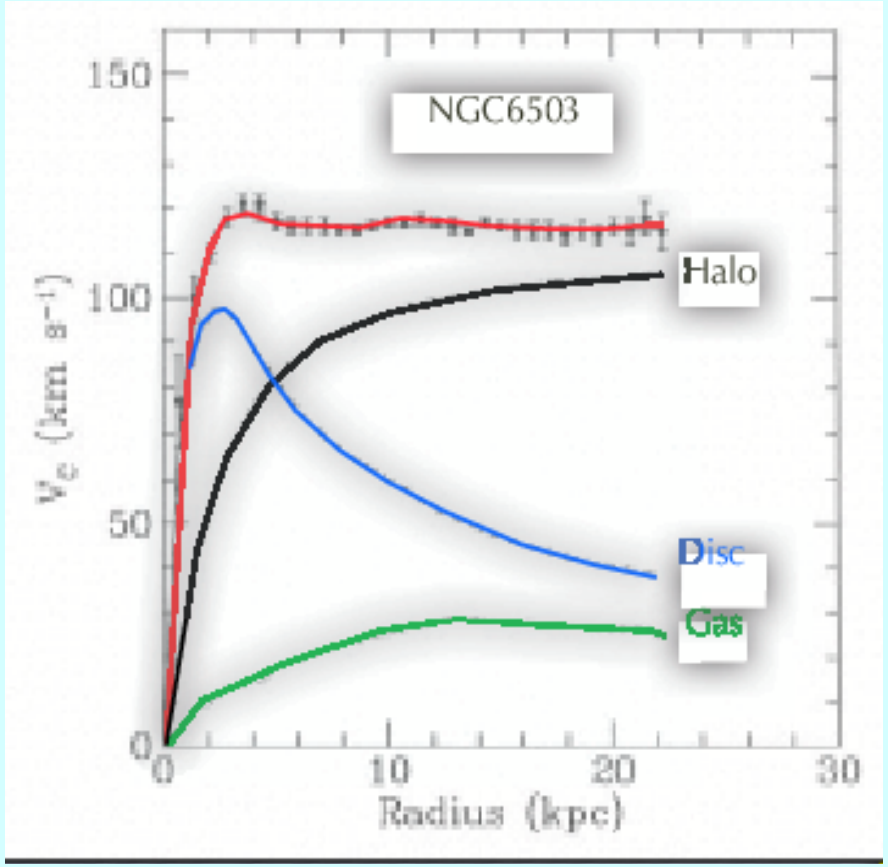


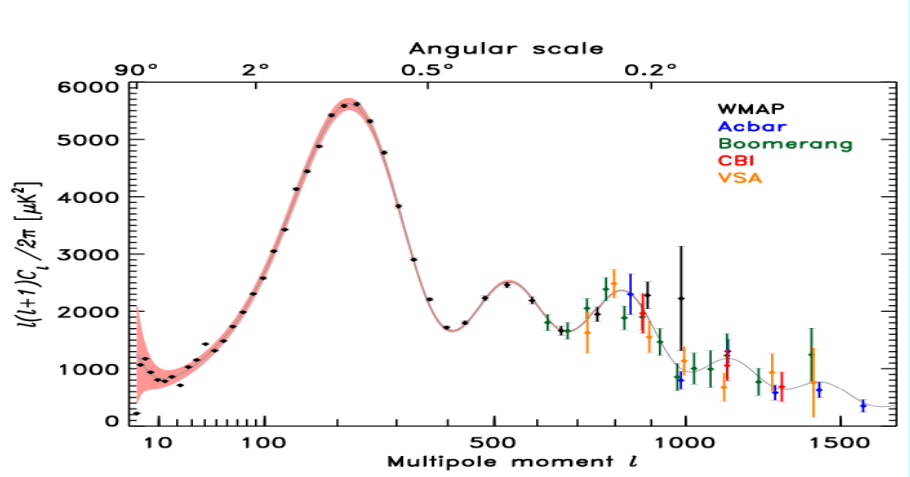


EVIDENCE FOR THE EXISTENCE OF DARK MATTER

- Gravitational effects around galaxies
- Gravitational Lensing.
  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 the recent WMAP5 ; together with dark energy)

Galaxies (rotational velocities); gravitational Lensing (cluster 1E0657-56, DM in blue); WMAP5



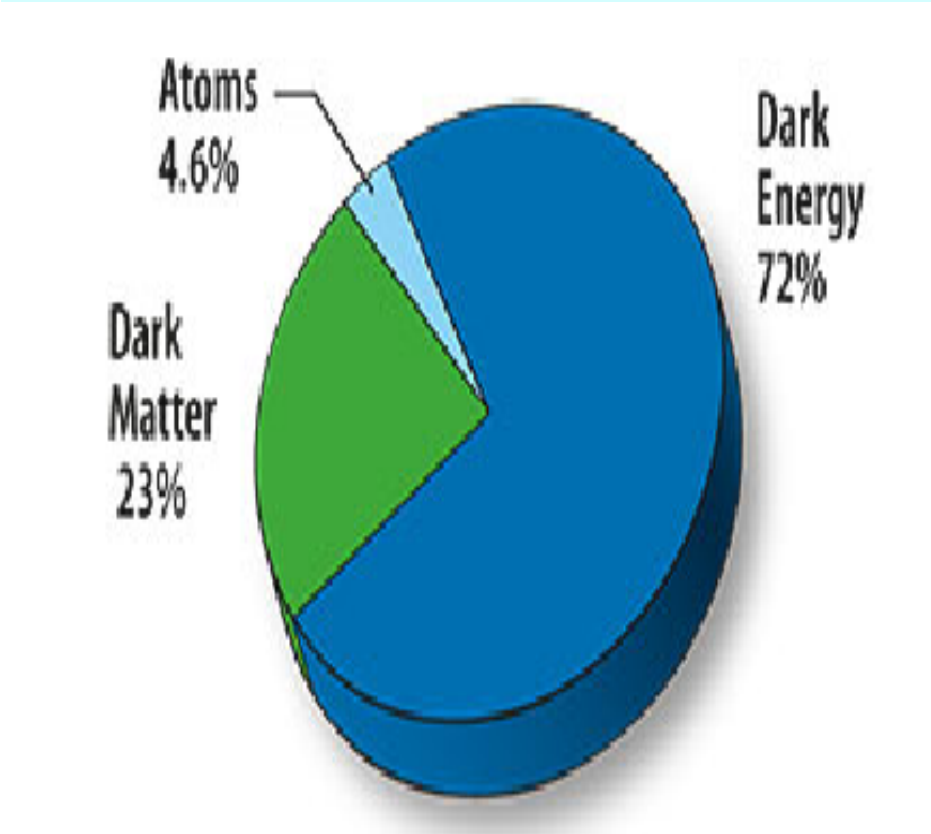


Slicing the Pie of the Cosmos WMAP3:

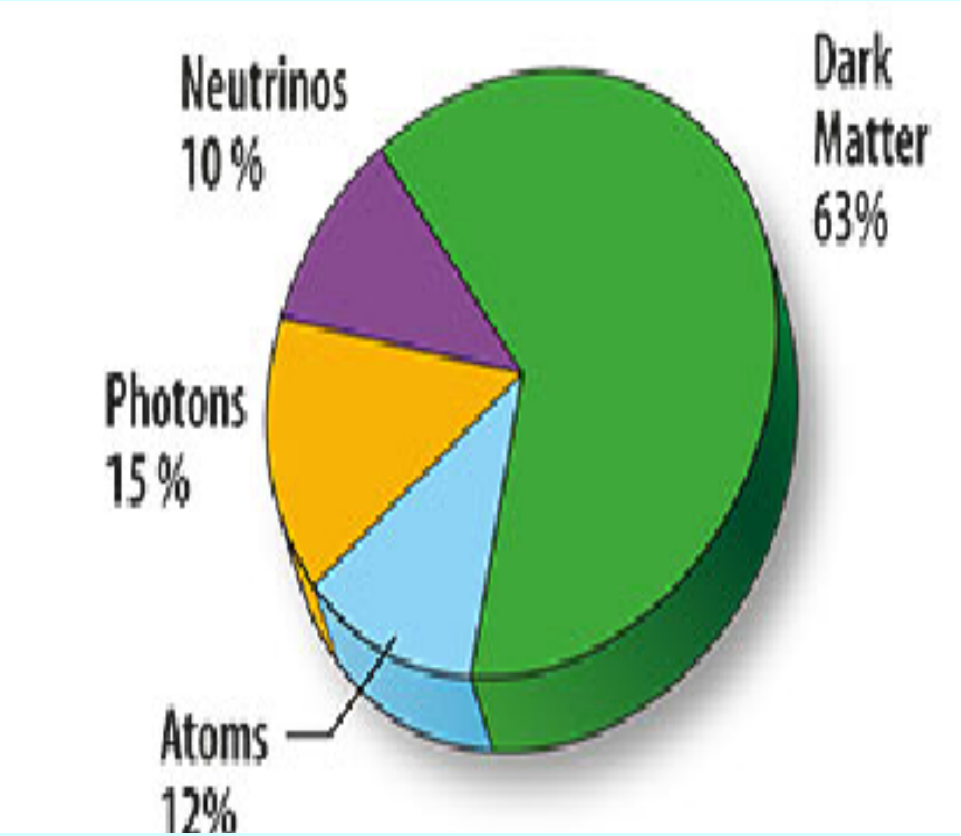
$\Omega_{CDM} = 0.24 \pm 0.02$, $\Omega_{\Lambda} = 0.72 \pm 0.04$,

$\Omega_{b} = 0.042 \pm 0.003$

To-day (T=13.6 billion y old)



T=380000 y old



DARK MATTER EXISTS; WIMPCANDIDATES

- The axion: 10^{-6} eV<m_a <10^{-3} eV (not a subject of this talk)
- The neutrino: It is not dominant. It is not cold, not CDM. Sterile neutrino?
- Supersymmetric particles. Four possibilities:

  i) s-ν ε τ ρ ί ν ο : Not favored on the basis of results of underground experiments and accelerator experiments (LEP)

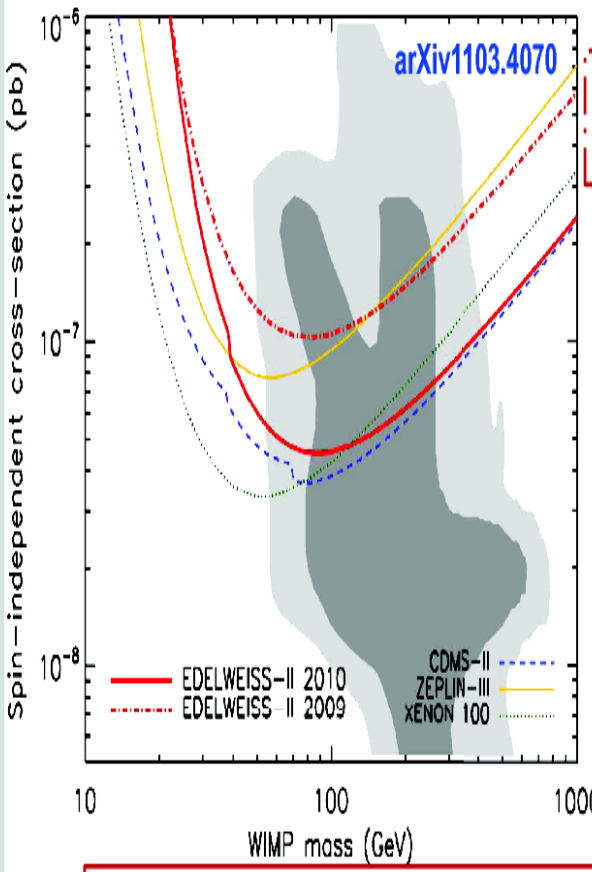
  ii) Gravitino: Interesting possibility, but not directly detectable

  iii) Axino: Interesting, but not directly detectable

  iv) A Majorana fermion, the neutralino or LSP (The 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. Very massive Kaluza-Klein WIMPs)
- The Lightest Technibaryon, LTB (Gudnason-Kouvaris-Sannino)
- Secluded Dark matter (to explain excess e^+,e^- in cosmic rays), Ioannina group (2009), T. Schwetz (2009))

EDELEEISS (Dr Eitel) XENON100 (prl/2010

WIMP search : final result (2008+2009+2010)

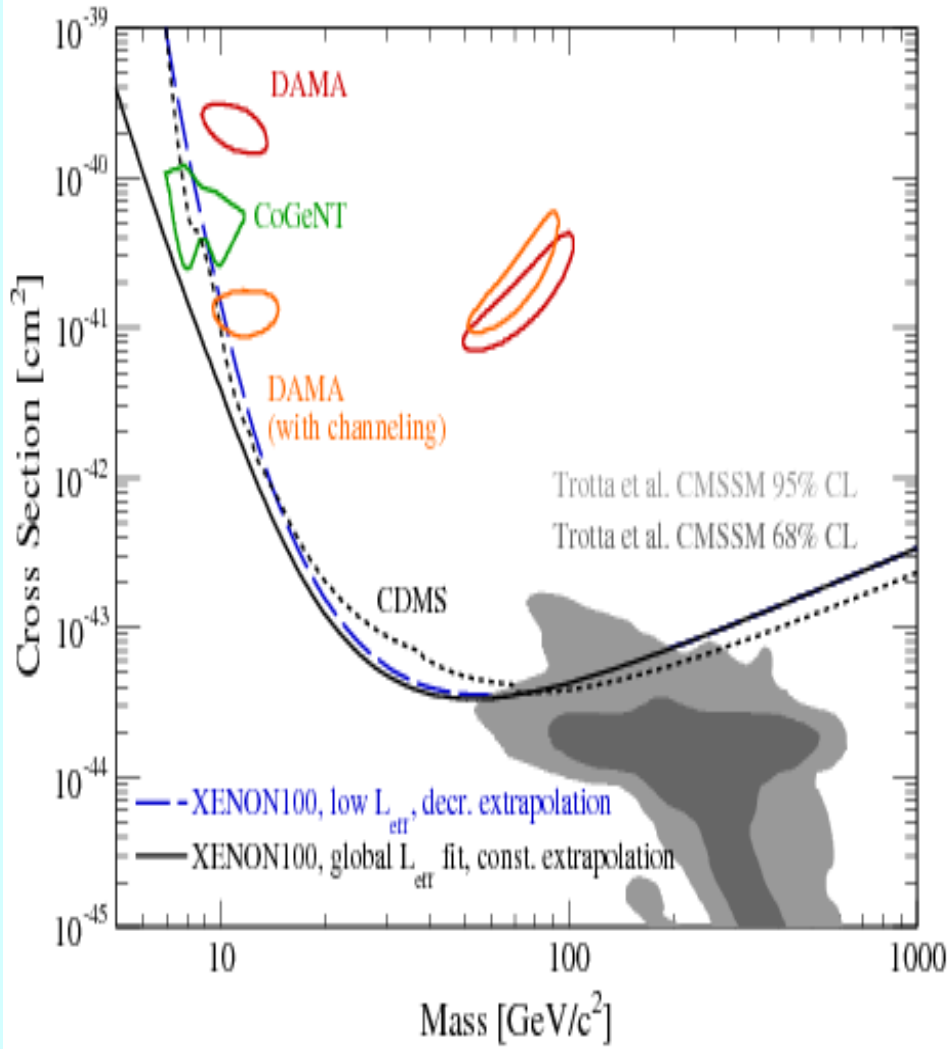


~50% of total data set:
PLB 2010;687(4-5):294-298.
arXiv:1011.2319v1 [astro-ph.CO]

keeping 5 candidate events as possible signal, use Optimal Interval Method + prescriptions:
[S. Yellin, PRD 66 (2002) 032005]

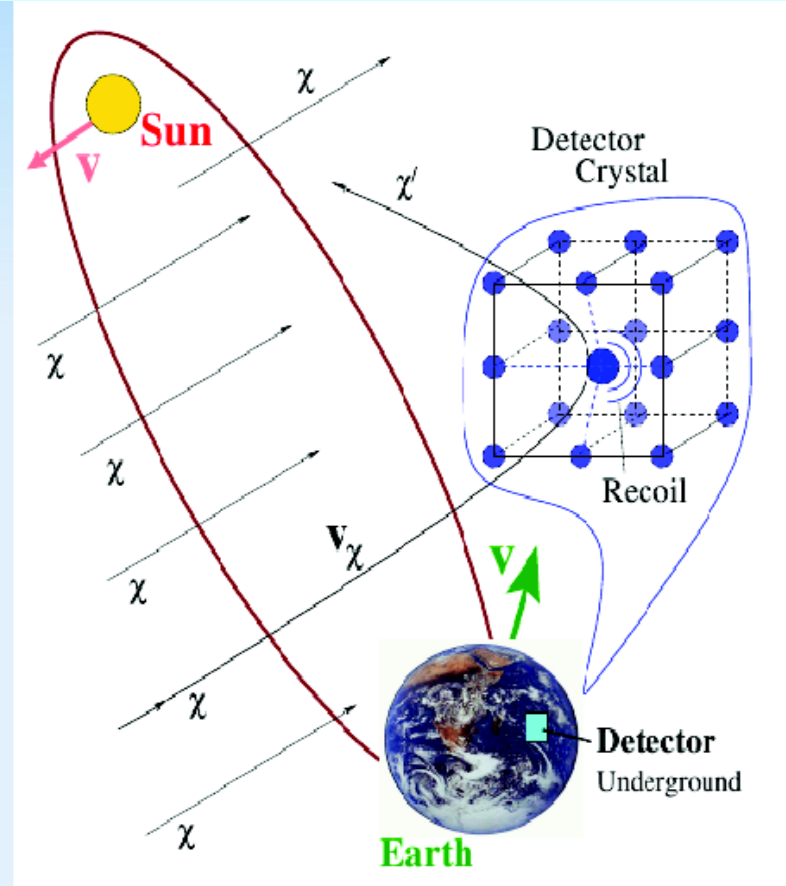
WIMP Halo
local density ρ=0.3 GeV/c^2
Maxwellian velocity distribution
v_{rms} = 270 km/s
v_{Earth} = 235 km/s
v_{escape} = 544 km/s

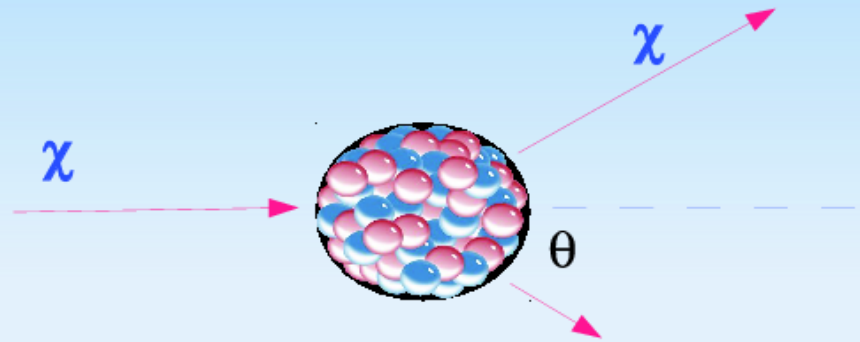
$\sigma_{SI} < 4.4 \times 10^{-8}$ pb at 90% CL for $M\chi$ = 85 GeV/c^2



WIMP-Nucleus Elastic scattering

(measure the energy of the recoiling nucleus)





$$q = |\vec{q}| = 2\mu_A v_\chi \cos\theta$$

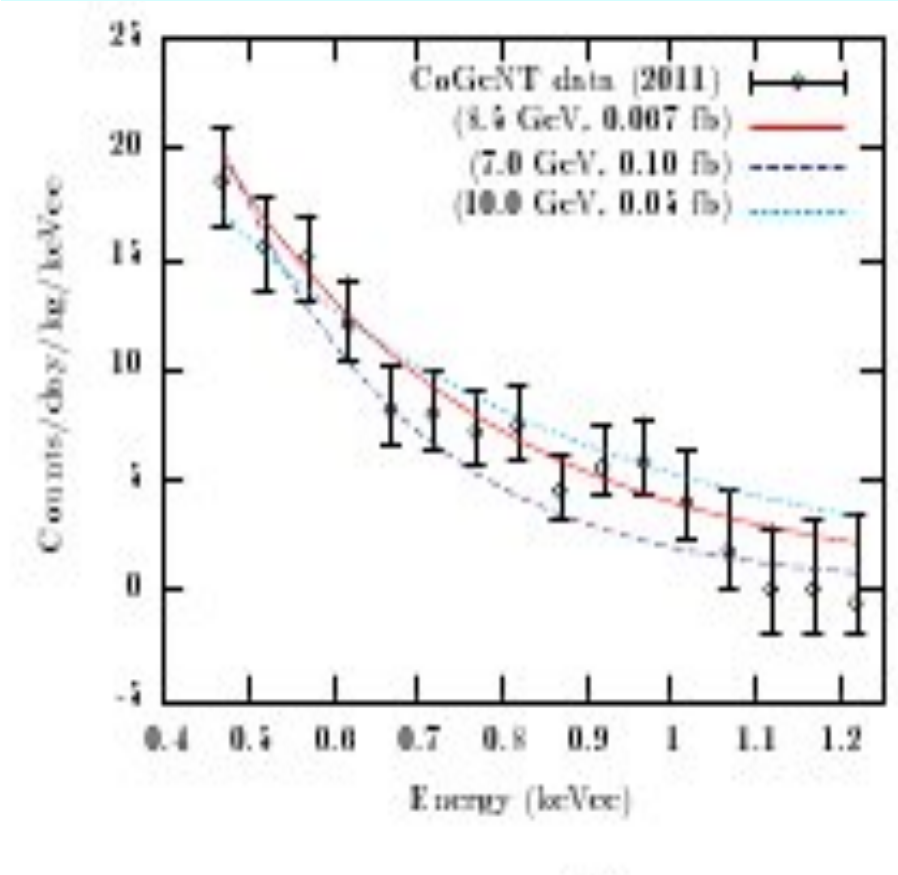
$$E_R = \frac{q^2}{2m_A}$$

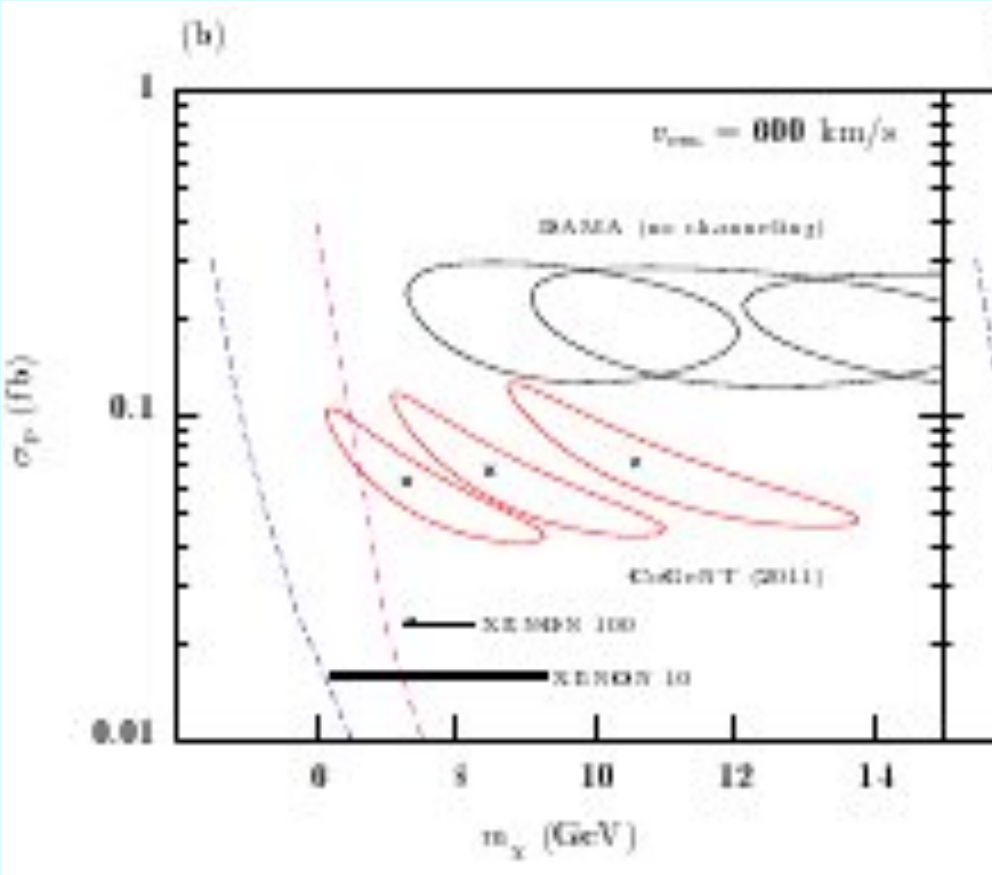
Non relativistic WIMP scatters elastically with nuclei. The recoil of the nucleus deposits a tiny amount of energy in the detector: recoil energies are from few to 100 keV

The CoGeNT data (a) and 3 σ contours by varying υ_0 for CoGeNTand DAMA (b) (From Savage –Freese-Nataraj arXiv:1109.0014)

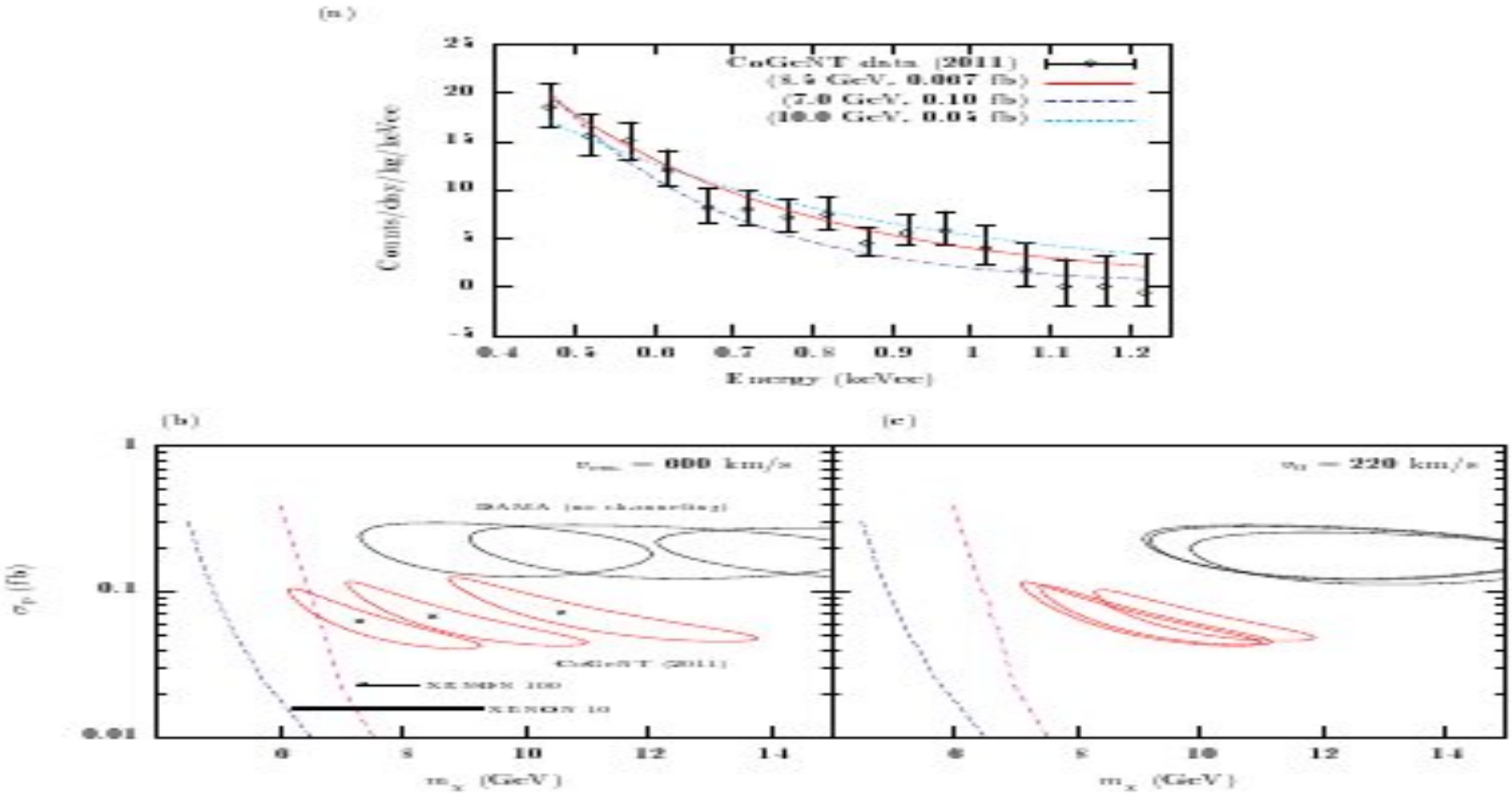
CoGeNT data

3 σ: contours in (m_χ, σ_p) plane

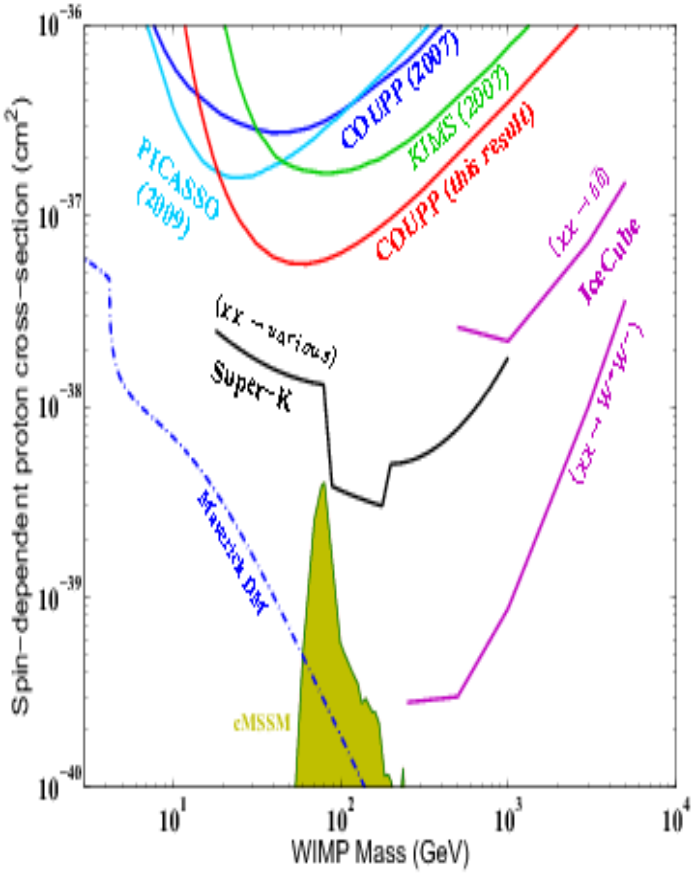


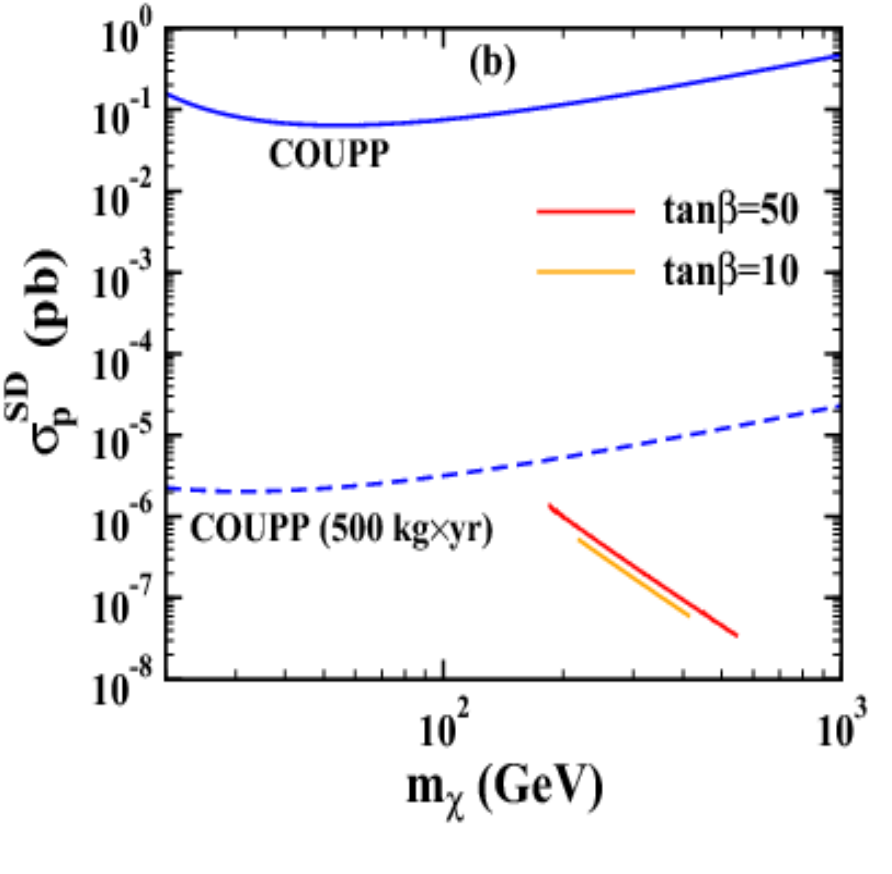


The CoGeNT data (a)



Spin Exclusion Plots σ_p for actual data (a) and rescaled (b)





AII:The spin Event Rate

As before with the replacement:

$A^2\ \sigma_{coh}\ t_{coh}$ ⊠ $\sigma_{spin}\ t_{spin}$ With

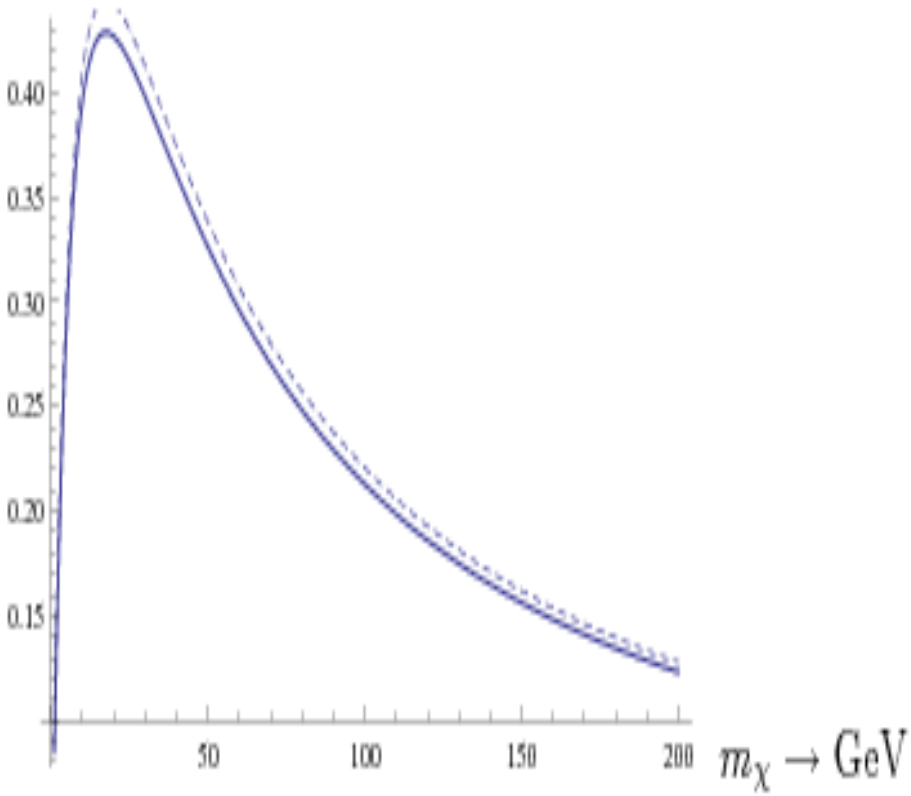
$$\sigma_{nuc}^{spin} = \frac{1}{3}|\Omega_p\sqrt{\sigma_p} + \Omega_n\sqrt{\sigma_n}e^{i\delta}|^2$$

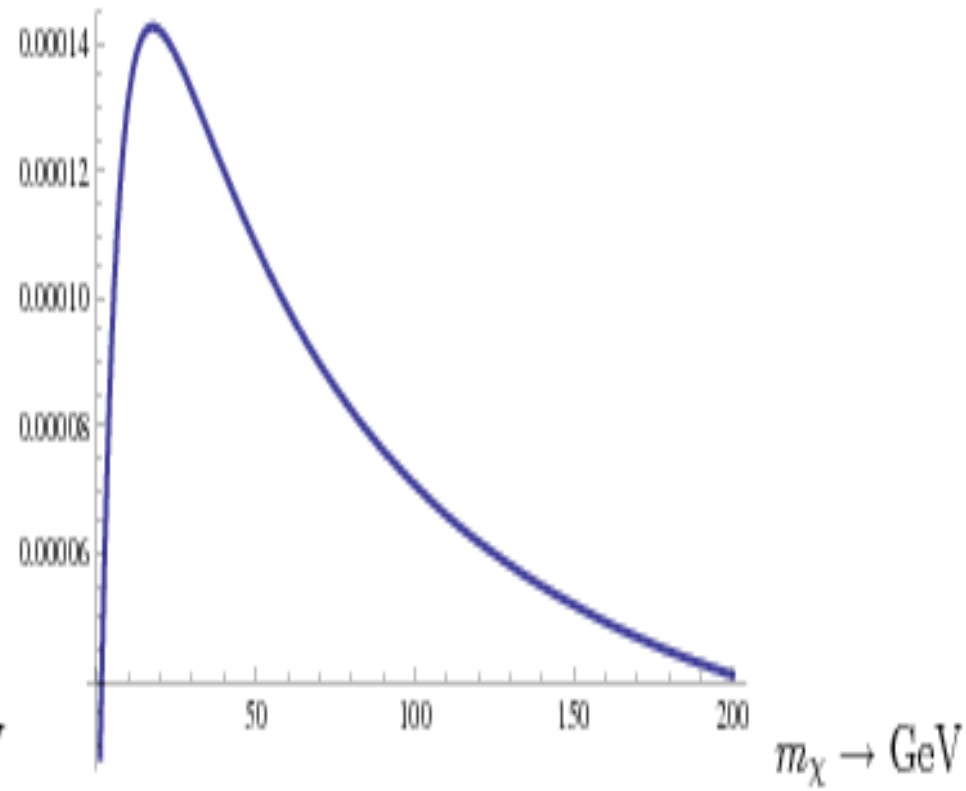
Ω_p and Ω_n are the spin nuclear matrix elements

δ is the phase difference between the elementary amplitudes a_p and a_n .

The spin induced event rate (kg-y) for ^{19}F

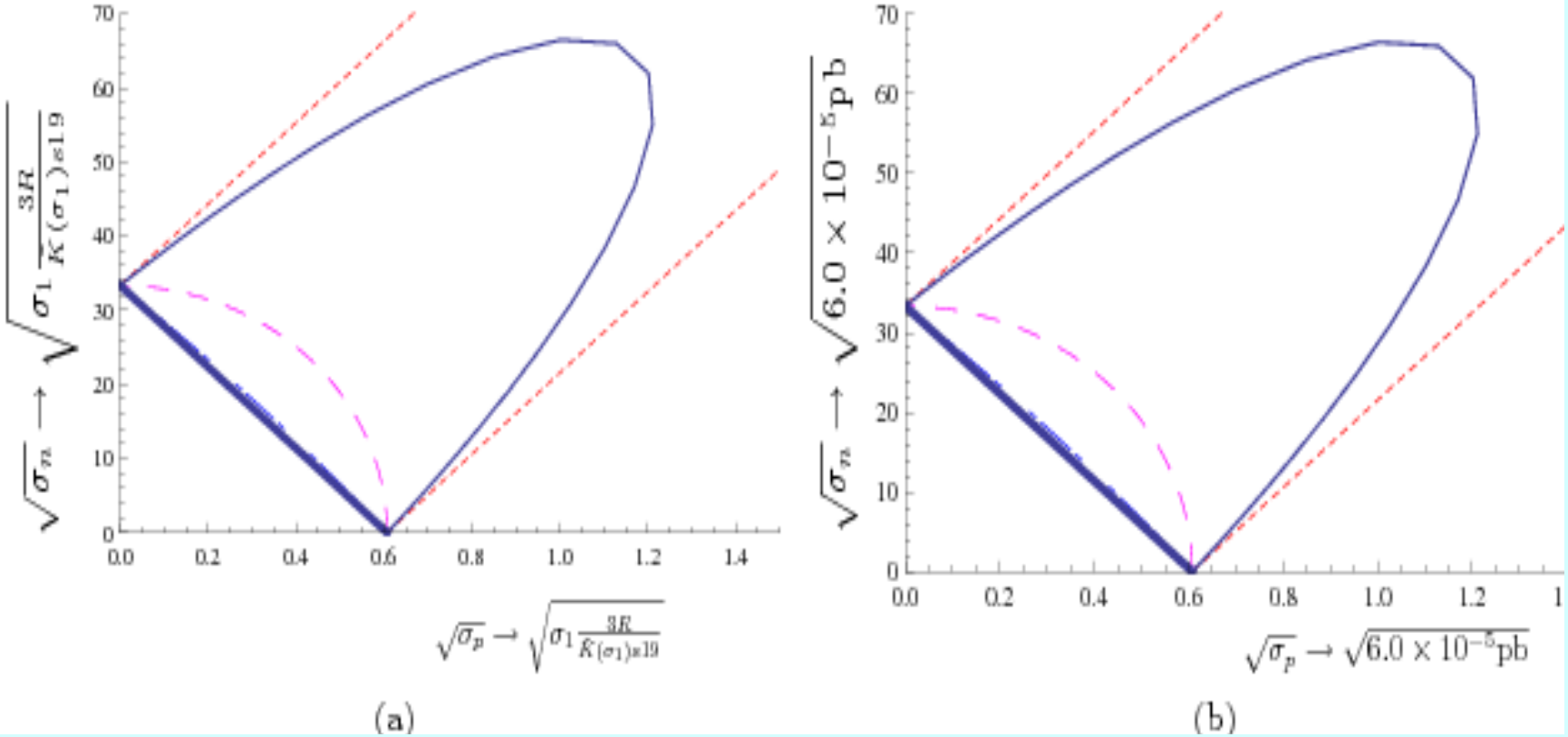
$\sigma_p = 10^{-5}$ pb , $\sigma_p = 0$ $\sigma_p = 0$, $\sigma_n = 10^{-5}$ pb





2-d exclusion plots for ^{19}F: $\sigma_1=10^{-5}$ in (b)

dot: $\delta=0$, fine solid : $\delta=\pi/6$, dash: $\delta=\pi/2$, dot-dash: $\delta=5\pi/6$, thick: $\delta=\pi$ ($\Omega_p=1.646$, $\Omega_n=-0.030$), see JDV:NPB289(2010)283



AIII.WIMP-Nucleus scattering (both SI and SD); Modulation ignored

$$R = \frac{\rho_l}{m_\chi} \frac{1}{A m_p} \sqrt{\langle v^2 \rangle} \left(\sigma^{SI}_{(A)}(0)\ t^{SI} + \sigma^{SD}_{(A)}(0)\ t^{SD} \right)$$

$$\sigma^{SI}_{(A)}(0) = \left(\frac{\mu_A}{\mu_p} \right)^2 A^2 \sigma^{SI}$$

$$\sigma^{SD}_{(A)}(0) = \left(\frac{\mu_A}{\mu_p} \right)^2 \frac{1}{3} \left(\Omega^A_p \sqrt{\sigma^{SD}_p} + \varrho \Omega^A_n \sqrt{\sigma^{SD}_n} \right)^2$$

$$\varrho = \mathrm{sgn}(a_p/a_n) = \pm 1$$

The equation for the total rate can be rewritten as:

$$\mathcal{S}_A = \sigma^{SI} + \mathcal{R}_A \left(\Omega^A_p \sqrt{\sigma^{SD}_p} + \varrho \Omega^A_n \sqrt{\sigma^{SD}_n} \right)^2$$

All the terms have the dimensions of a cross section

Choice of nuclei

A_1 both $\Omega_p^{A_1}$ and $\Omega_n^{A_1}$ **DAMA, KIMS COUPP, ANAIS** $^{127}\mathrm{I} \Longleftrightarrow A_1$: $\Omega_p^{127} = 0.731$ $\Omega_n^{127} = 0.177$

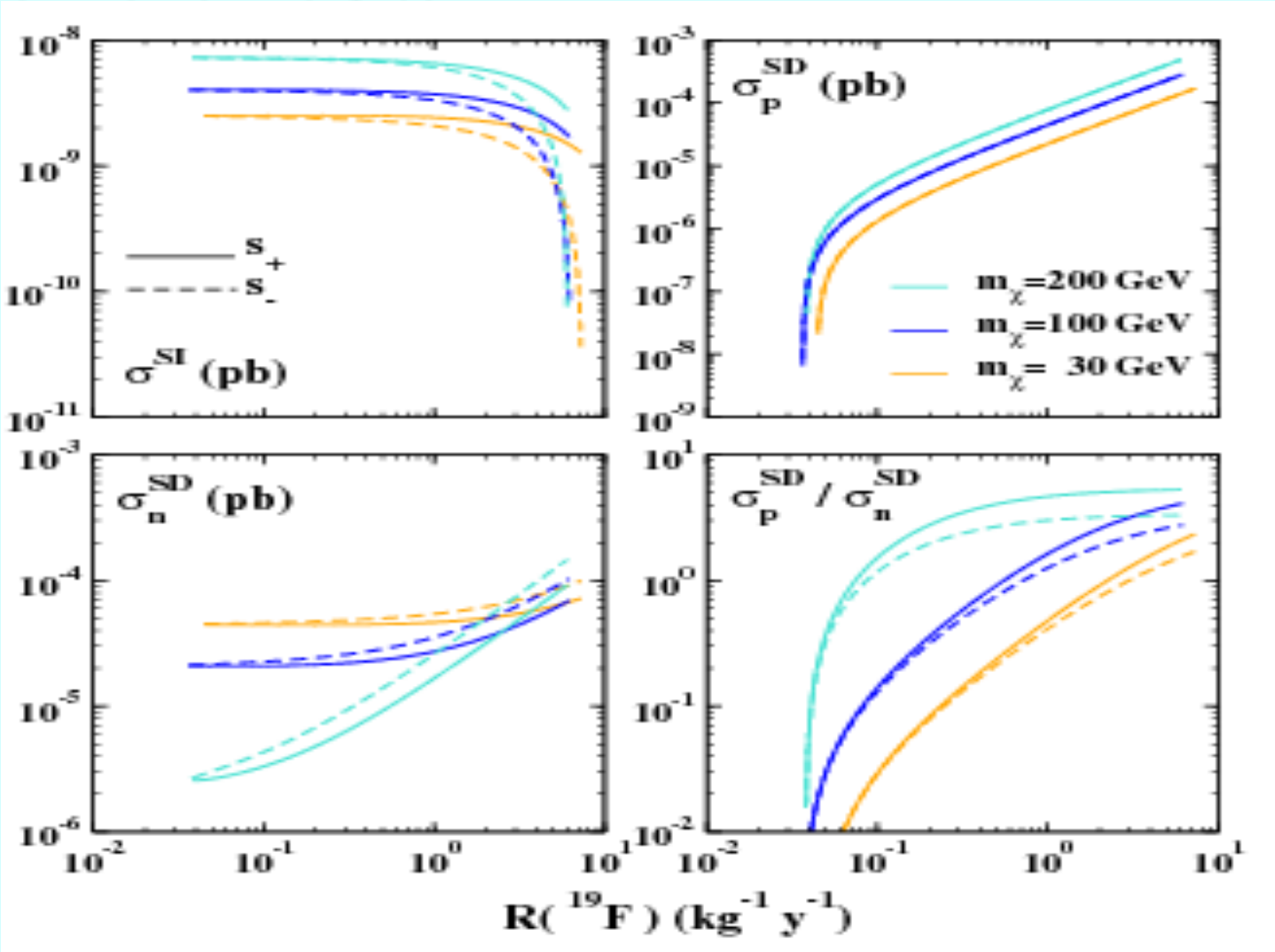
A_2 with $\Omega_p^{A_2} \gg \Omega_n^{A_2}$ **COUPP PICASSO SIMPLE** $^{19}\mathrm{F} \Longleftrightarrow A_2$: $\Omega_p^{19} = 1.646$ $\Omega_n^{19} = -0.030$

A_3 with $\Omega_n^{A_3} \gg \Omega_p^{A_3}$ **CDMS, COGENT EDELWEISS** $^{73}\mathrm{Ge} \longleftrightarrow A_3$: $\Omega_p^{73} = 0.066$ $\Omega_n^{73} = 0.836$

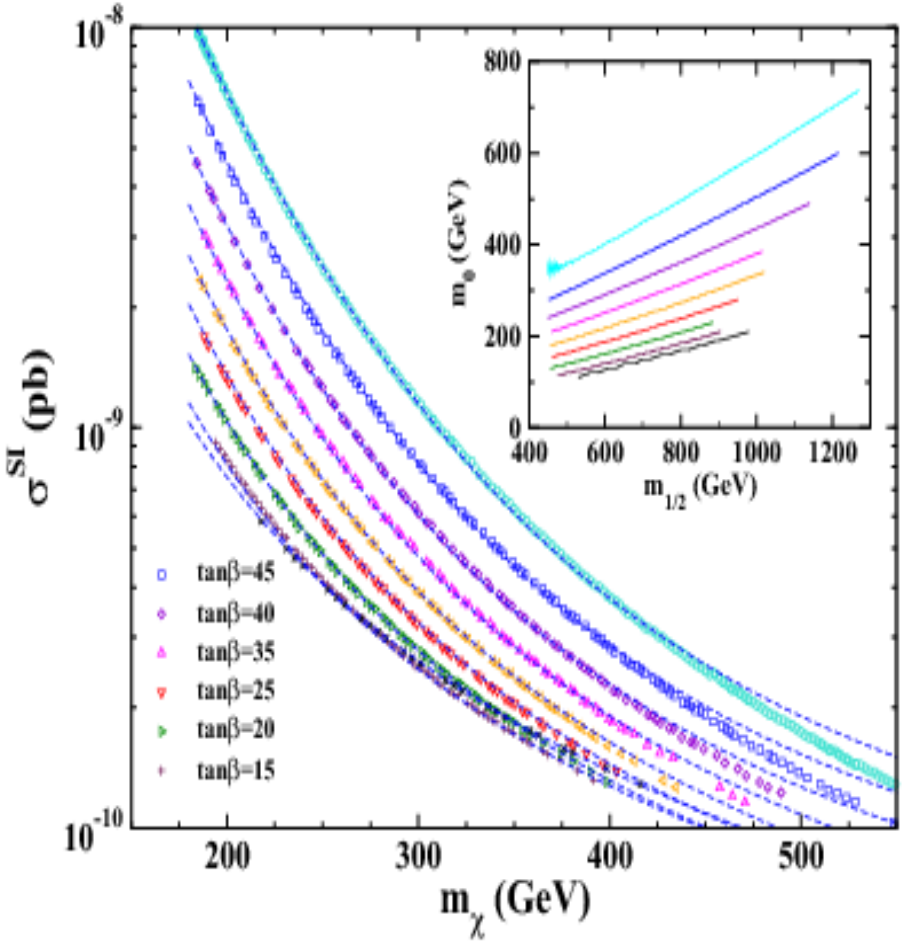
$$\begin{cases} \sigma^{SI} + \mathcal{R}_{A_1}\left(\Omega_p^{A_1}\sqrt{\sigma_p^{SD}} + \varrho\Omega_n^{A_1}\sqrt{\sigma_n^{SD}}\right)^2 - \mathcal{S}_{A_1} = 0 \\ \sigma^{SI} + \mathcal{R}_{A_2}(\Omega_p^{A_2})^2\sigma_p^{SD} - \mathcal{S}_{A_2} = 0 \\ \sigma^{SI} + \mathcal{R}_{A_3}(\Omega_n^{A_3})^2\sigma_n^{SD} - \mathcal{S}_{A_3} = 0 \end{cases}$$

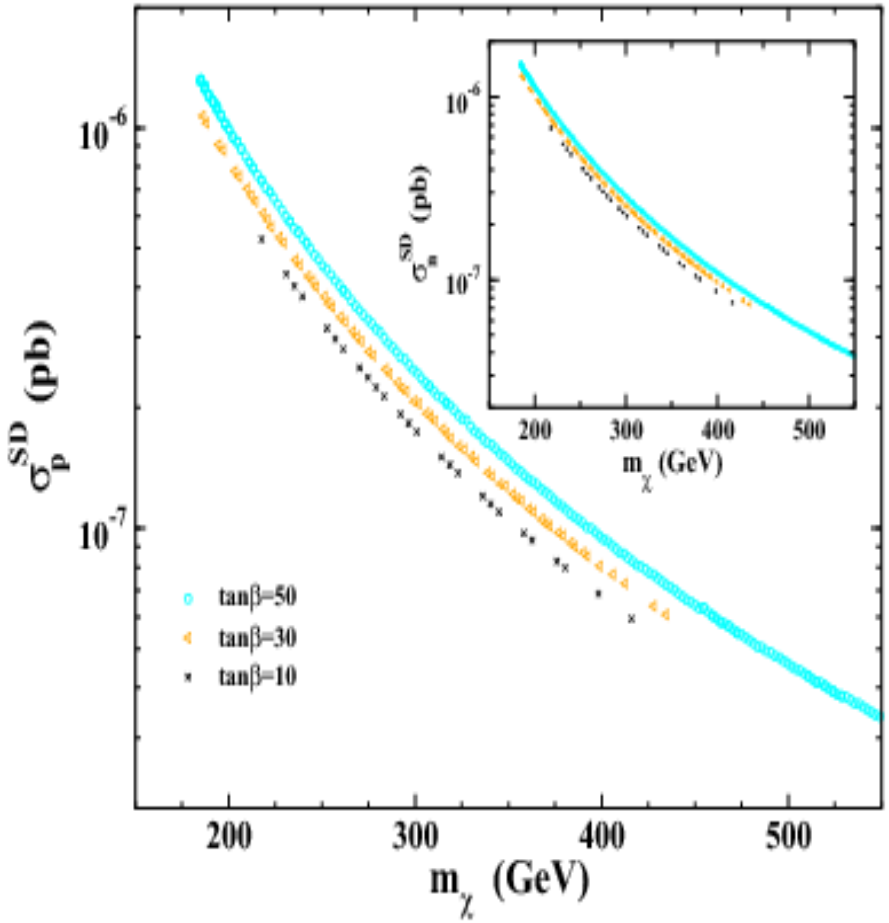
Cross sections extracted from the rates

R(127)=R(73)=1(kg-y)$^{-1}$ Cannoni, Gomez and JDV, PRD 83(2011)075010

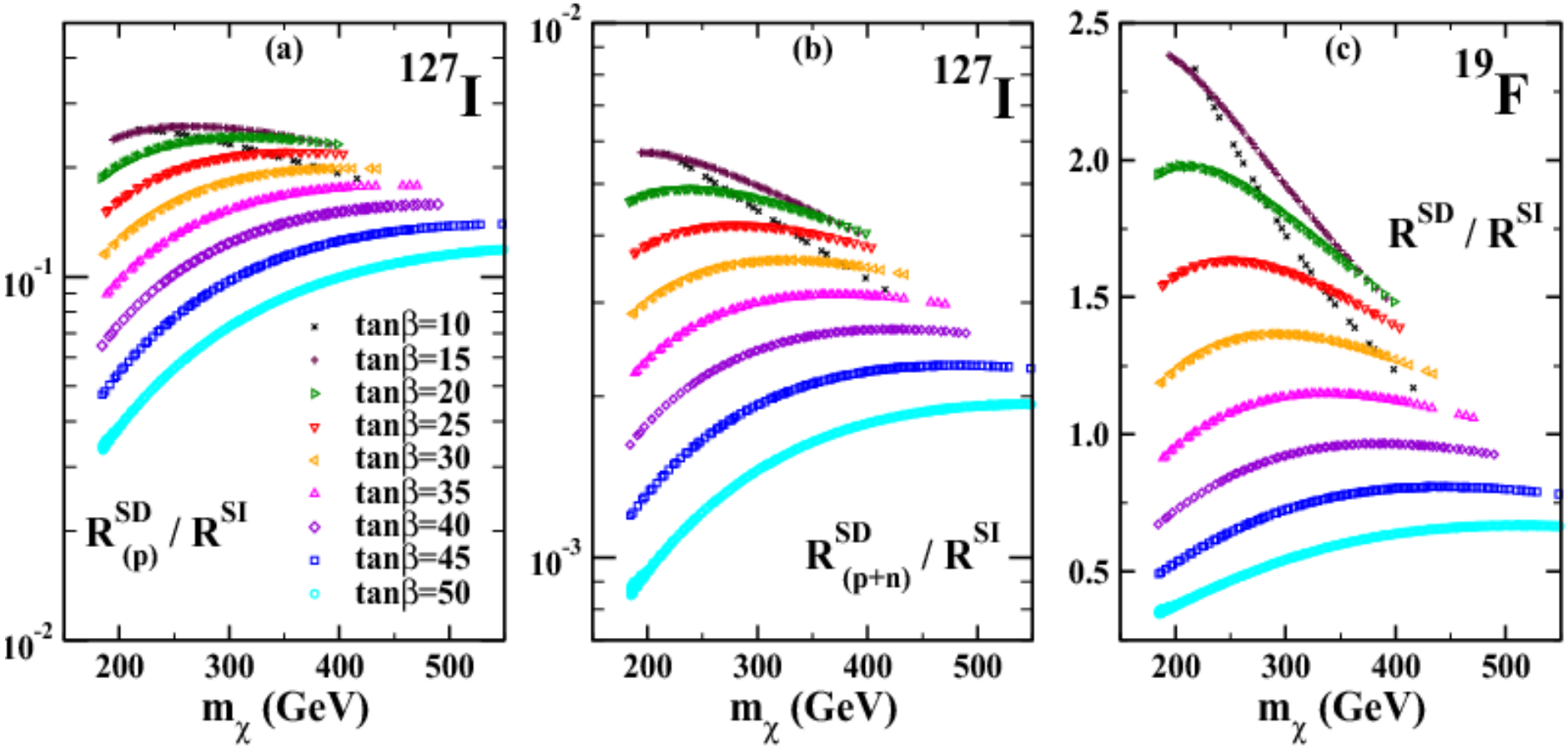


Theory: SUSY SI and SD cross sections in the co-annihilation region (A_0=0, μ >0) for large WIMP masses (Cannoni, Gomez, JDV).





Theory: The spin rate can compete with the coherent: SUSY in the co-annihilation region (A_0=0, μ >0) for large WIMP masses (Cannoni, GOMEZ, JDV).



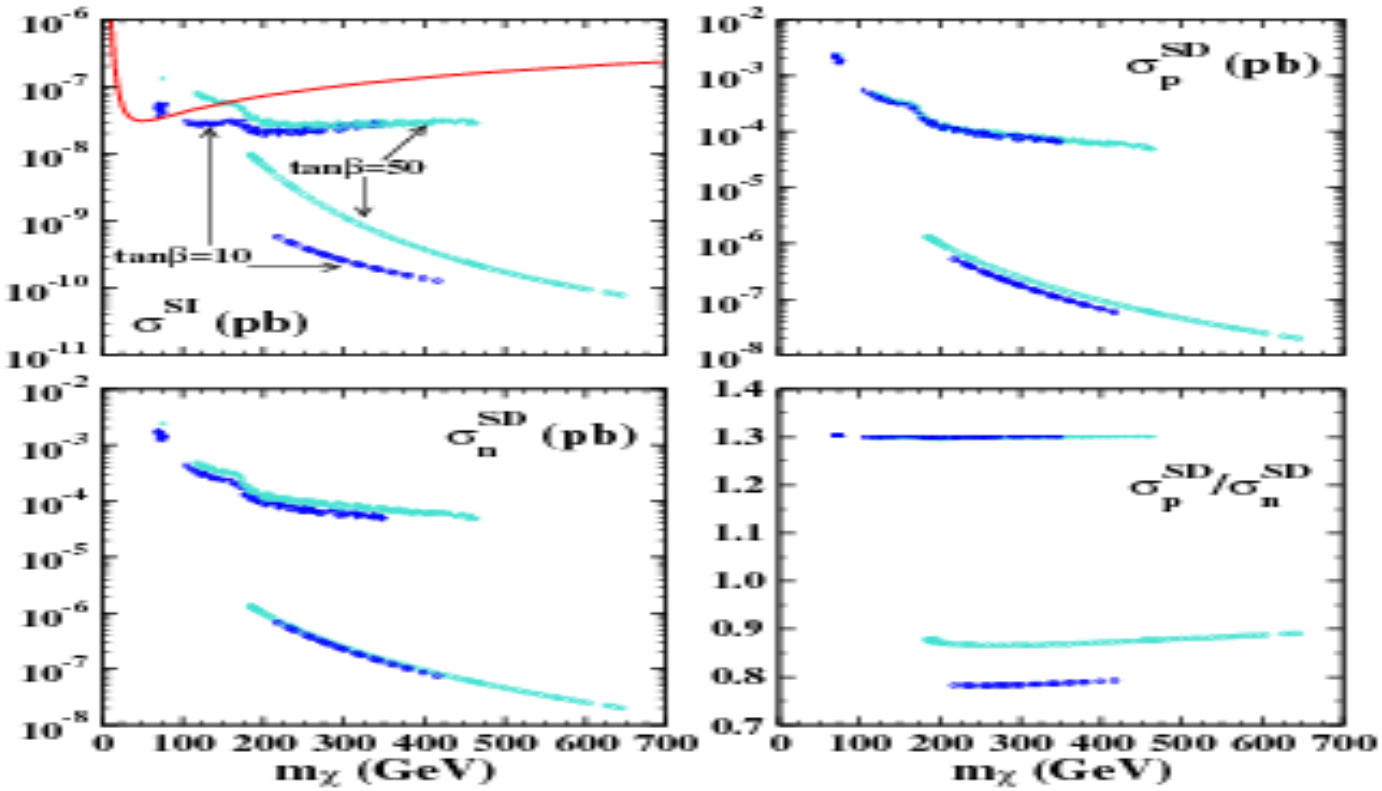
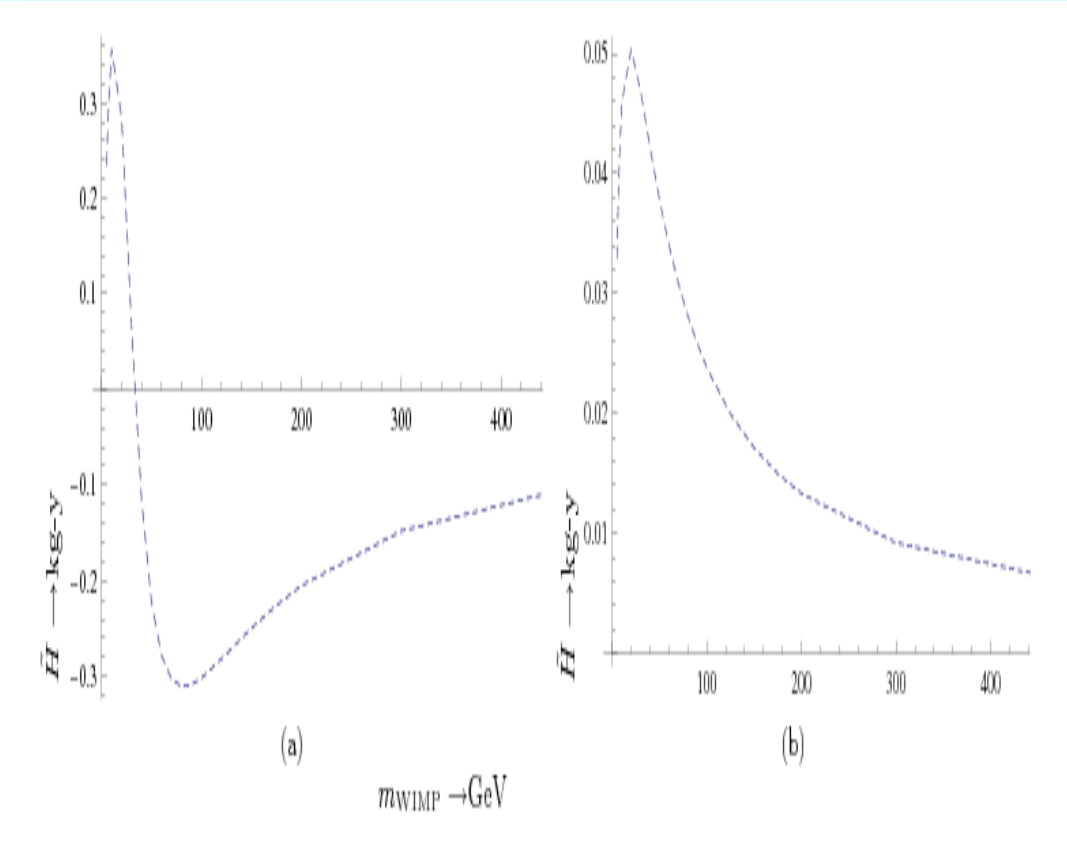
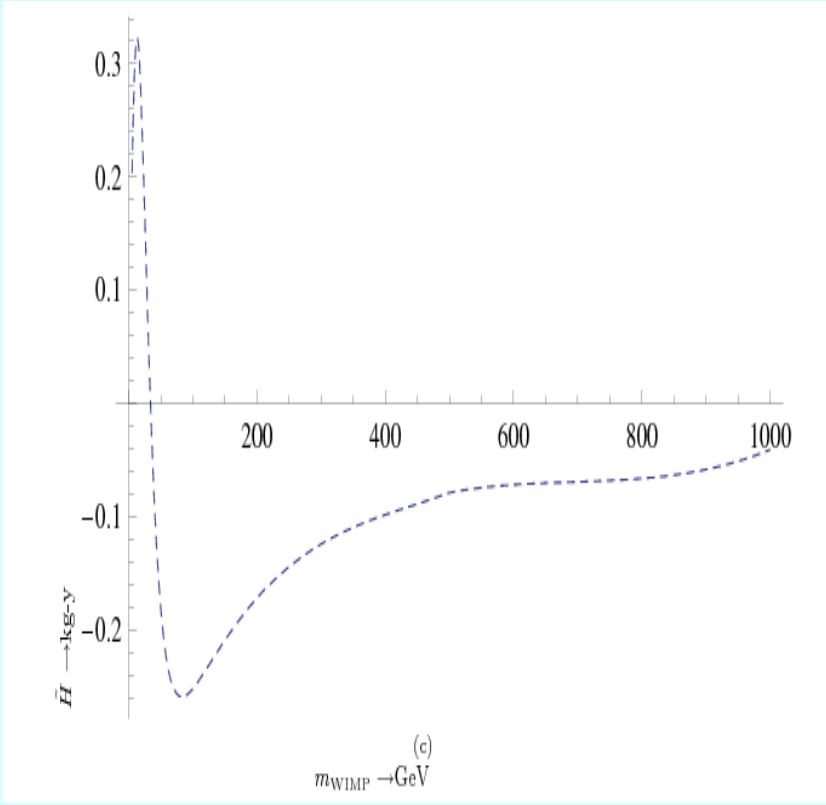


Figure 3. Neutralino-nucleon cross sections as a function of the neutralino mass in the constrained minimal supersymmetric standard model with $A_0 = 0$, $\mu > 0$, $m_0 < 4000$ GeV, $m_{1/2} < 1500$ GeV, $\tan\beta = 10$ and $\tan\beta = 50$. The points satisfy the WMAP 3σ bound $0.094 < \Omega h^2 < 0.128$ [26] 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 section.

Bia: The modulated total event rates for 0 threshold energy ($\sigma_{p,\chi}=10^{-7}$ pb) vs the WIMP mass.

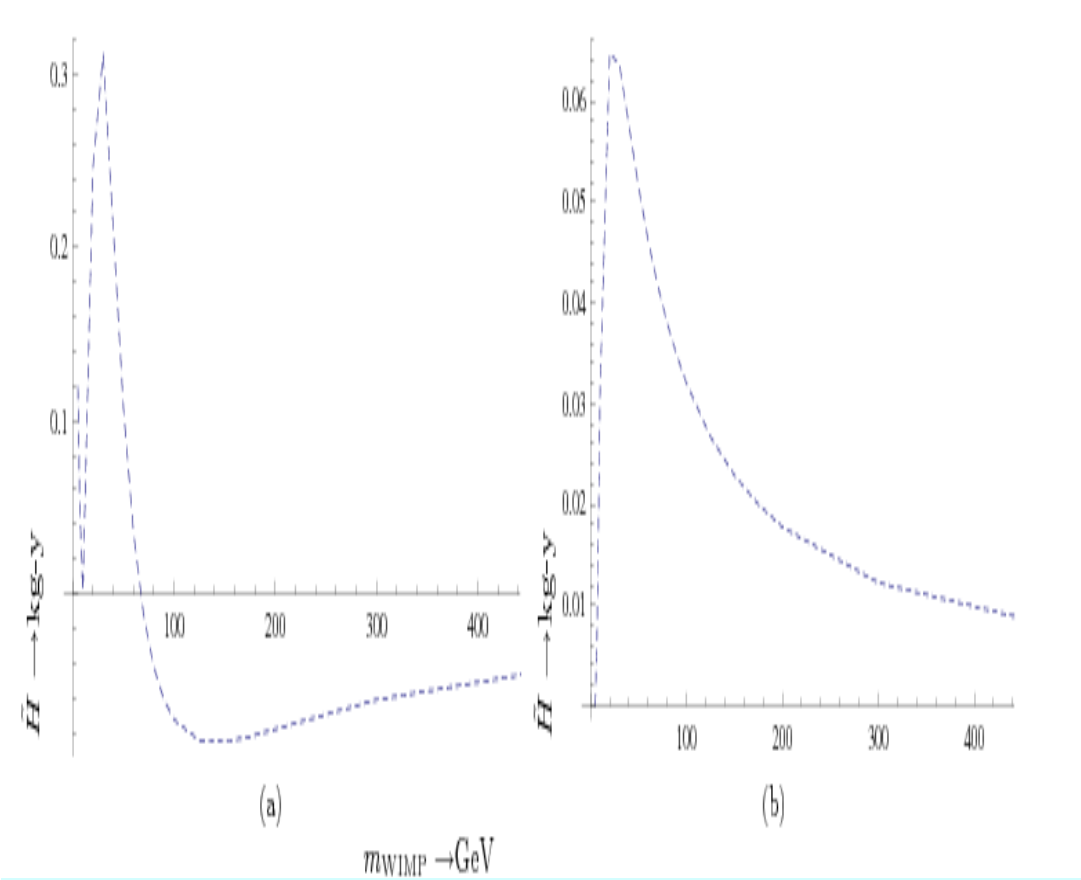
Heavy(^{127}I , ^{131}Xe) **Light(^{19}F, ^{23}Na)** **NaI**

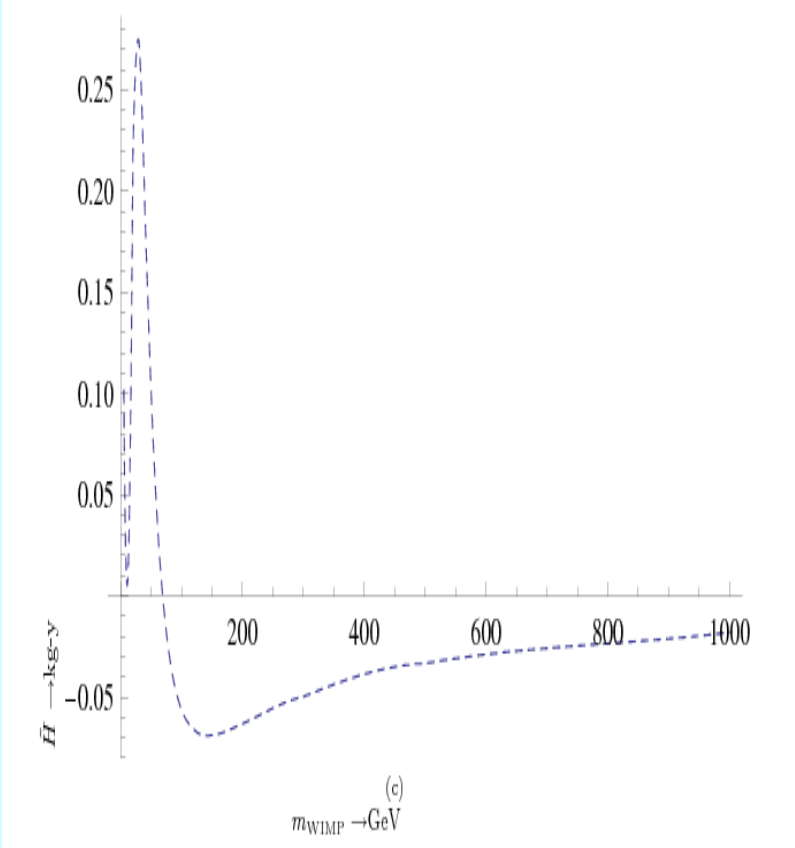




BIb: The total modulated event rates for threshold energy of 5 keVee ($\sigma_{p,\chi} = 10^{-7}$ pb)

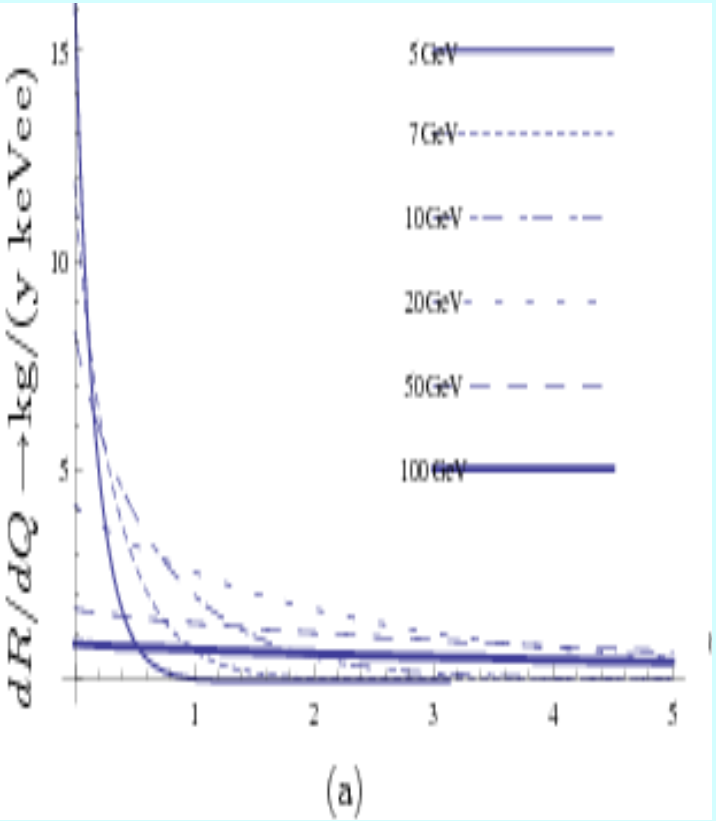
Heavy(^{127}I , ^{131}Xe) Light(^{19}F, ^{23}Na) **NaI**



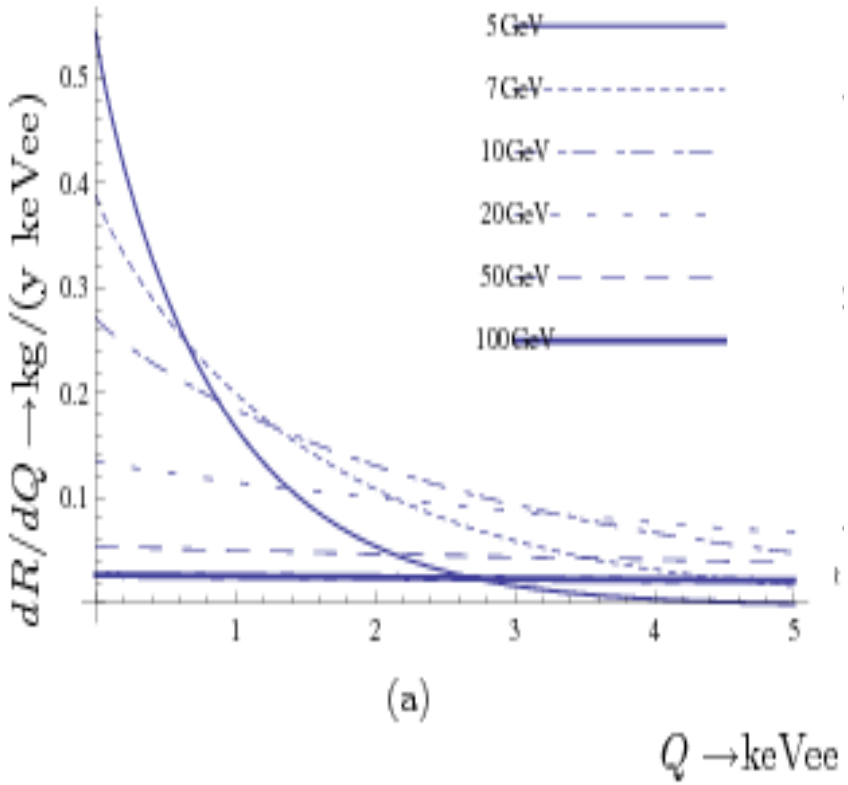


BIIb: The coherent differential rate for $\sigma_N = 10^{-7}$ pb Q in keVee

Heavy (e.g. ^{127}I, ^{131}Xe)



Light (e.g. ^{19}F, ^{23}Na)

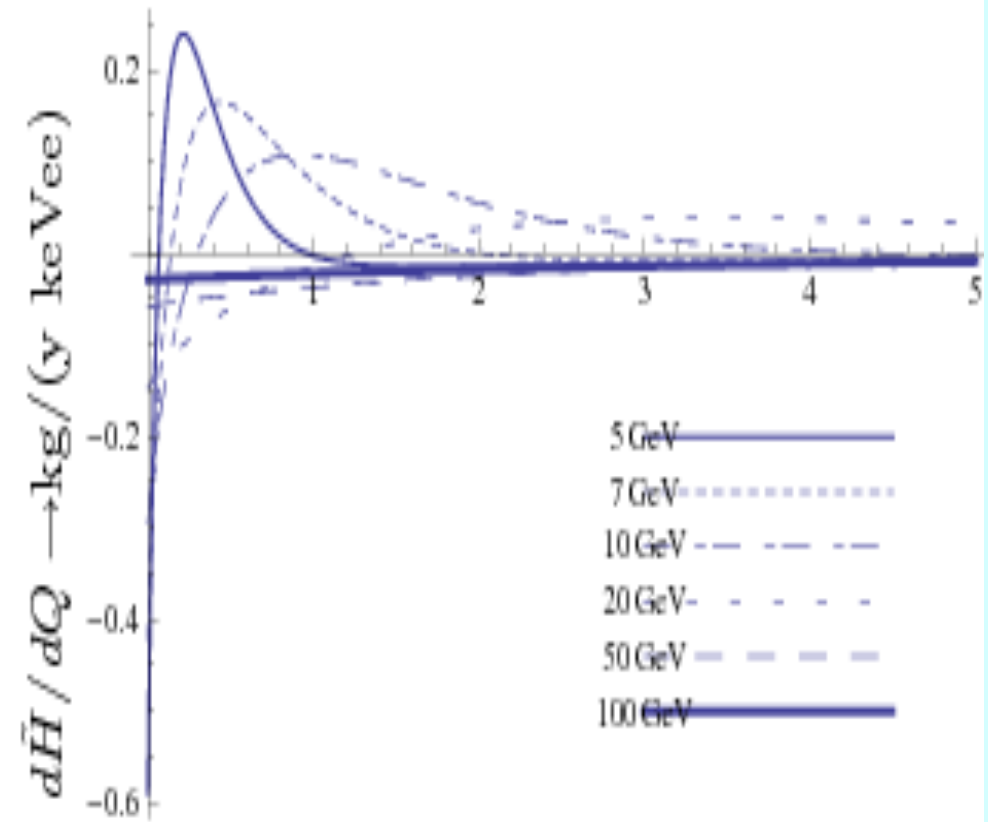


BIIa: Low WIMP mass: Total Event Rates: ($\sigma_{p,\chi} = 10^{-7}$ pb)

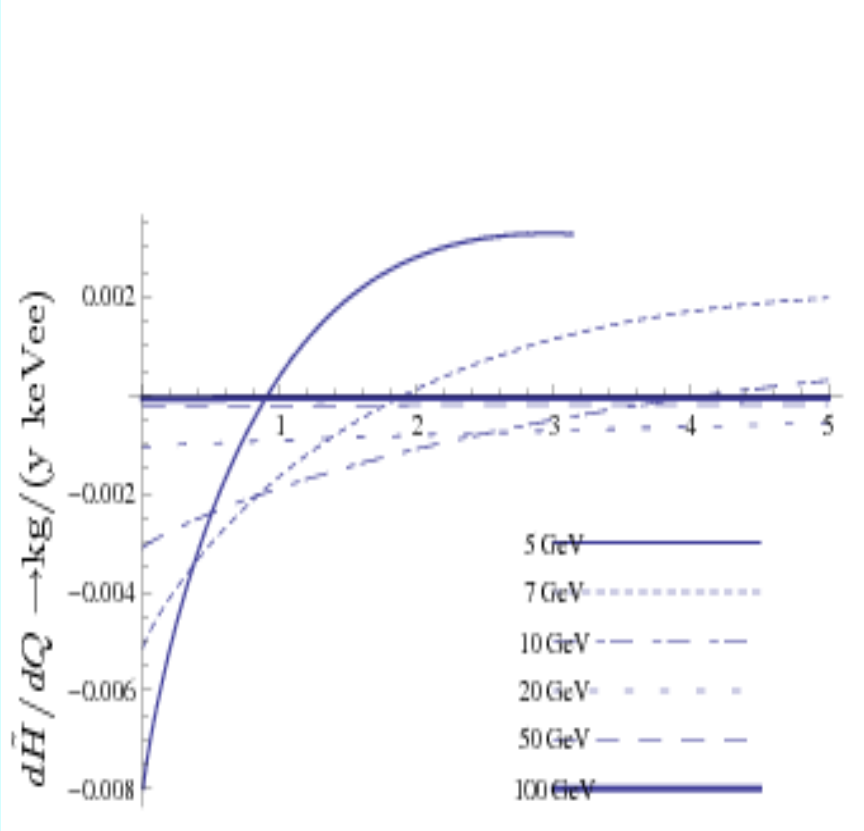
E_{th} (keVee)	m_{WIMP} GeV	R_0(I) kg-y	$\tilde{H}$(I) kg-y	h(I)	R_0(Na) kg-y	$\tilde{H}$(Na) kg-y	h(Na)	R_0(NaI) kg-y	$\tilde{H}$(NaI) kg-y	h(NaI)
0	80	16.3	-0.311	-0.019	1.518	0.028	0.019	14.0	-0.259	-0.018
0	20	25.8	0.285	0.011	2.35	0.050	0.021	22.2	0.249	0.019
0	10	18.4	0.356	0.019	2.045	0.046	0.022	15.9	0.309	0.019
5	80	7.00	-0.042	-0.006	1.133	0.038	0.034	6.11	-0.030	-0.005
5	20	2.72	0.247	0.091	1.07	0.065	0.060	2.47	0.219	0.089
5	10	0.008	0.001	0.187	0.303	0.031	0.103	0.053	0.006	0.114

BIIc: The coherent differential mod. rate for $\sigma_N = 10^{-7}$ pb Q in keVee

Heavy (e.g. ^{127}I, ^{131}Xe)



Light (e.g. ^{19}F, ^{23}Na)



BIIIa: The relative (differential) Modulation amplitude H

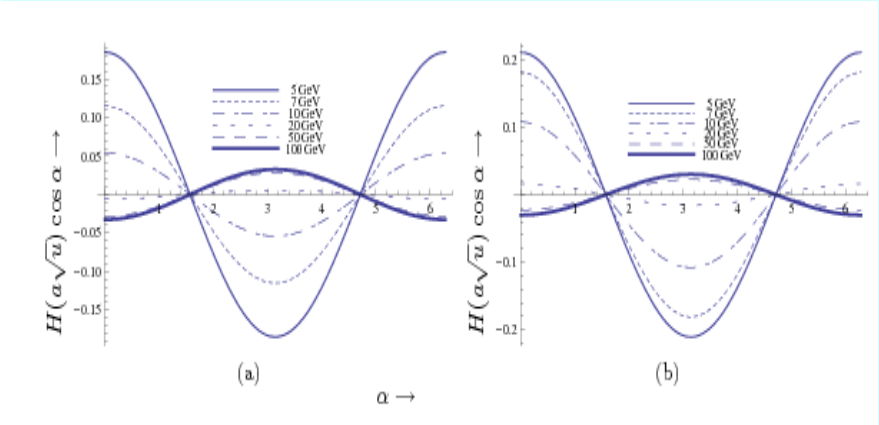
(As a function of α for various WIMP mass in GeV)

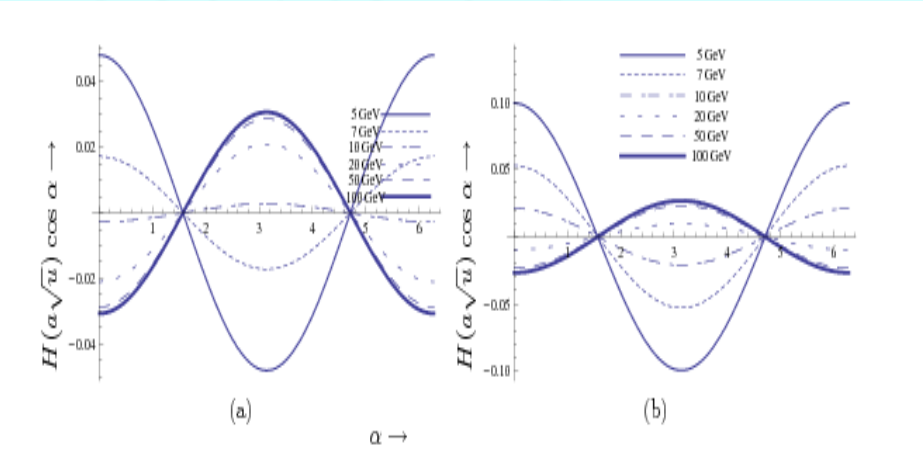
From left to right top to bottom: Q=1,2,5,6keVee

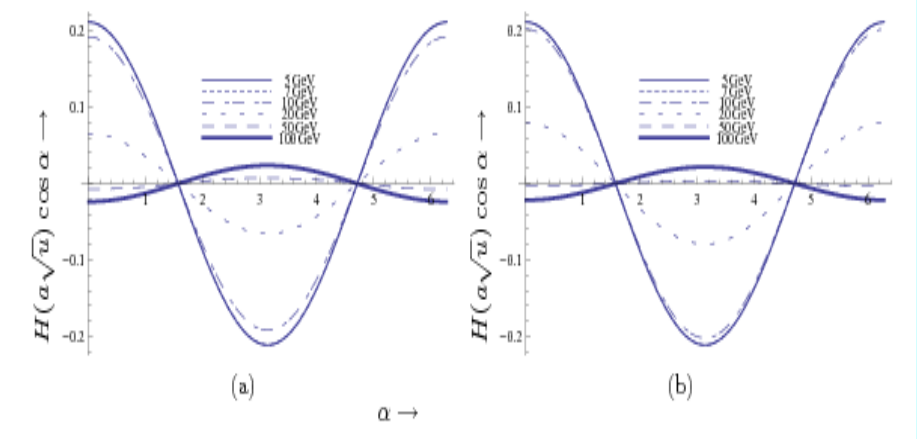
Heavy System (e.g. A=127, 131)

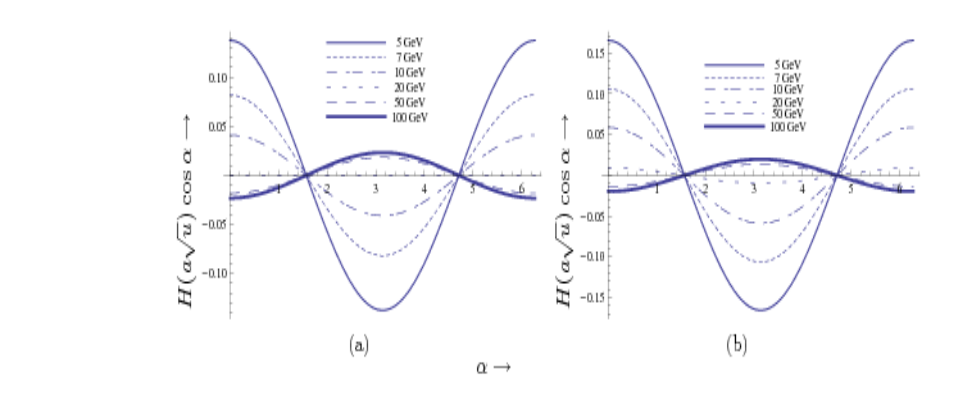
Light system (e.g. A=F, Na)

It is a bit smaller

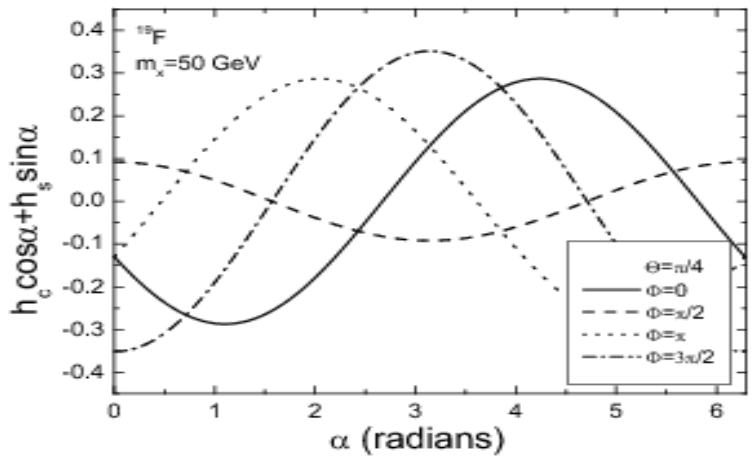


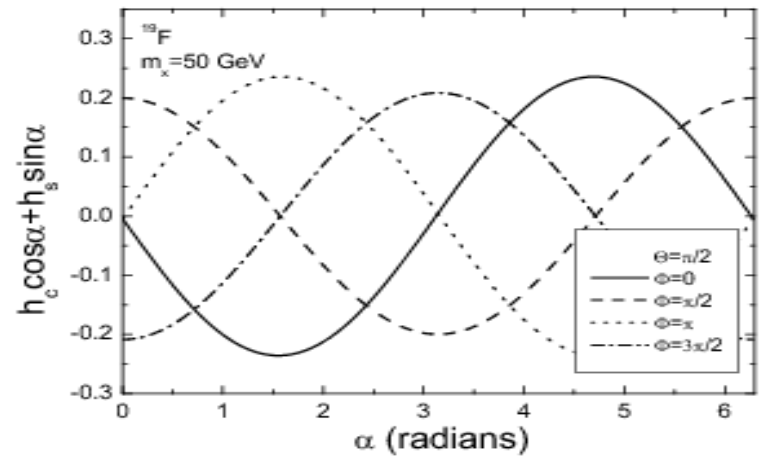


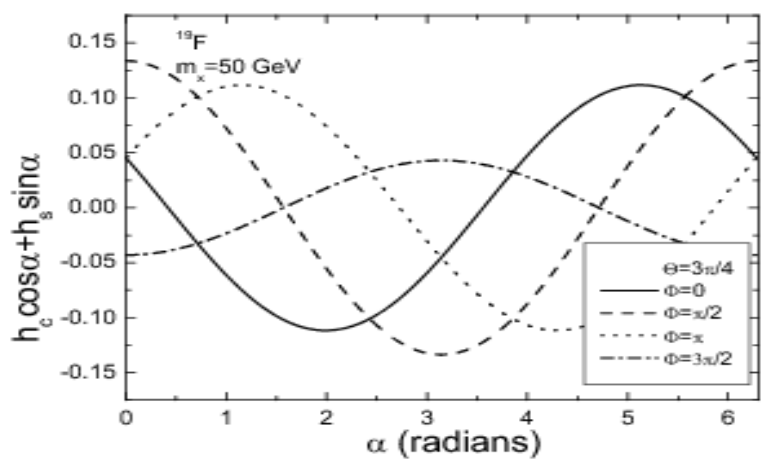




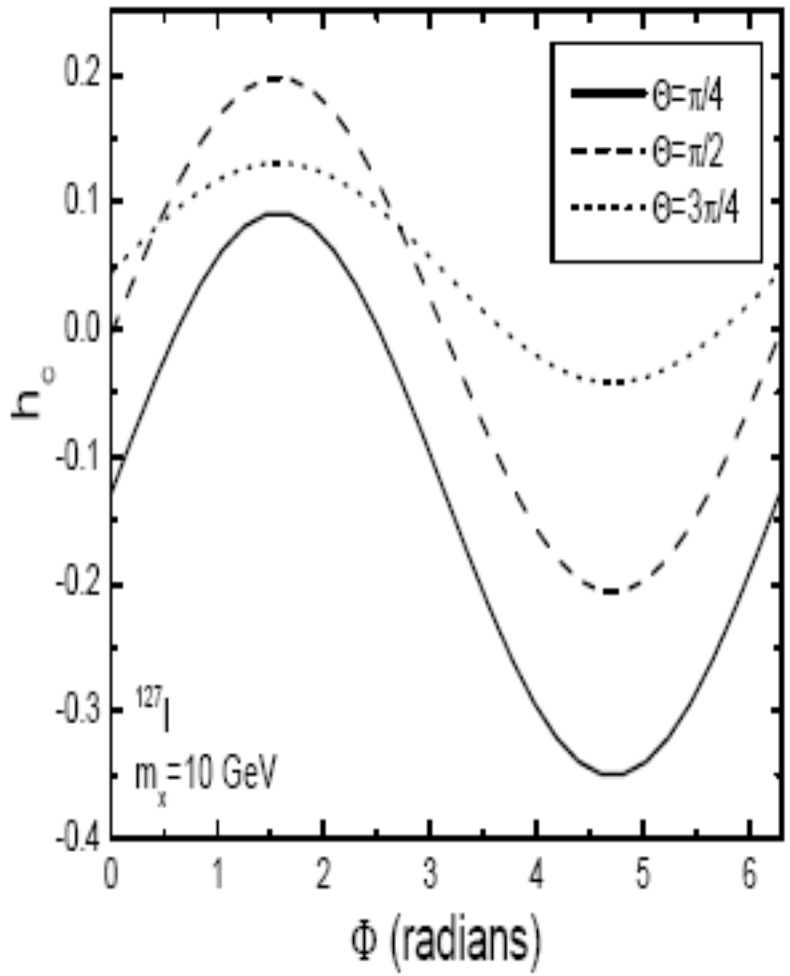
Modulation vs the phase of the earth.

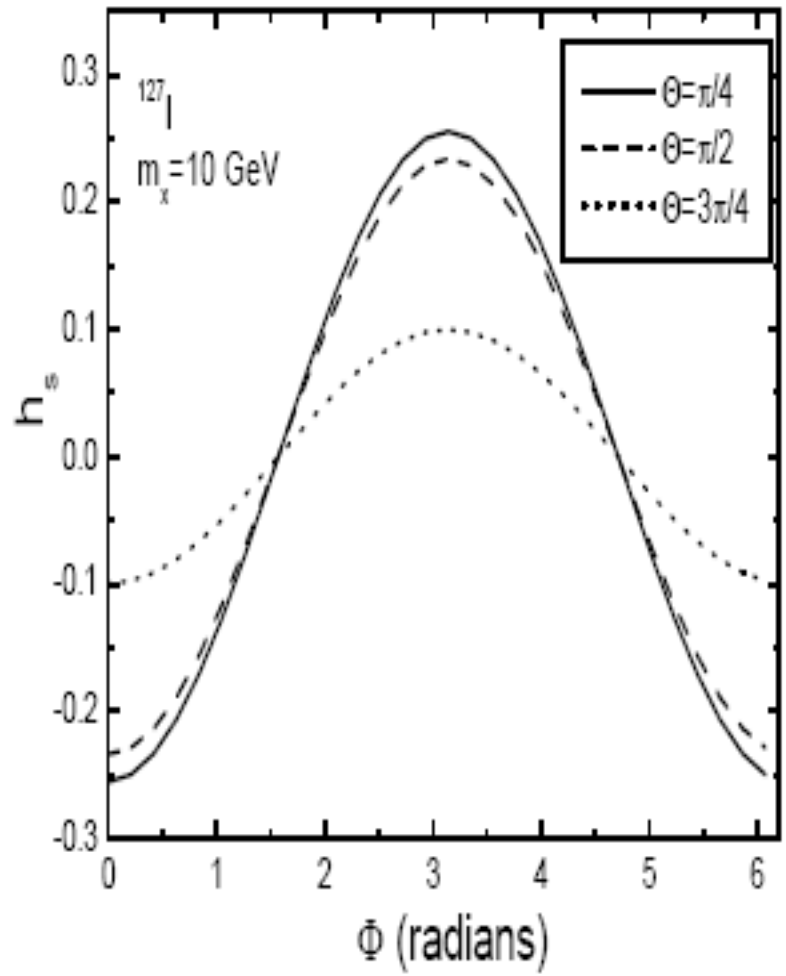




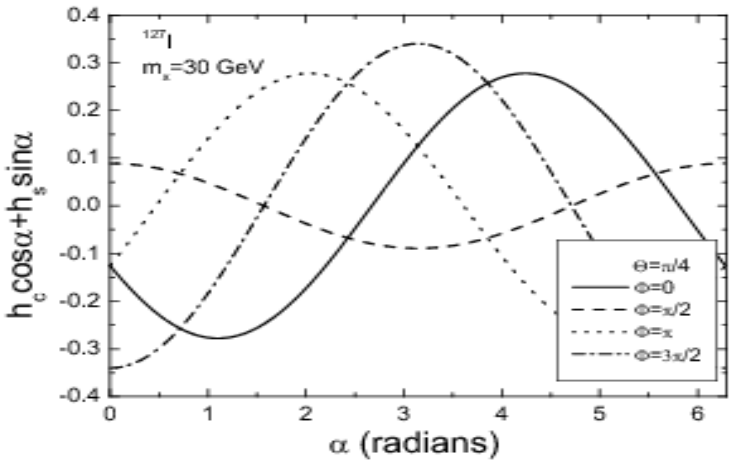


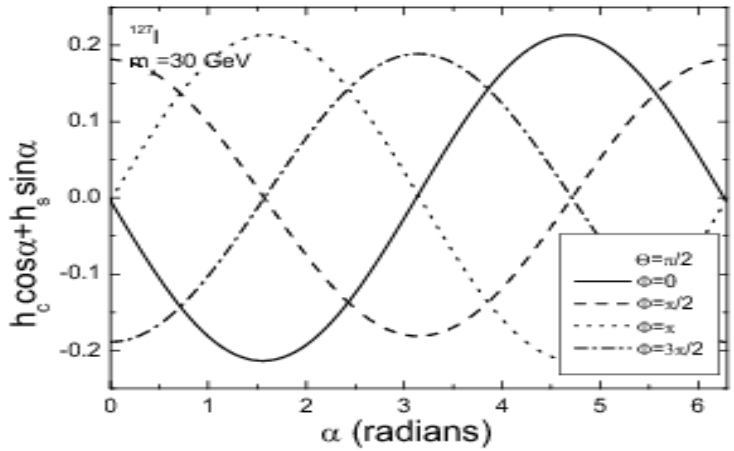
The modulation amplitudes vs Φ for m_χ =10 GeV for a heavy target

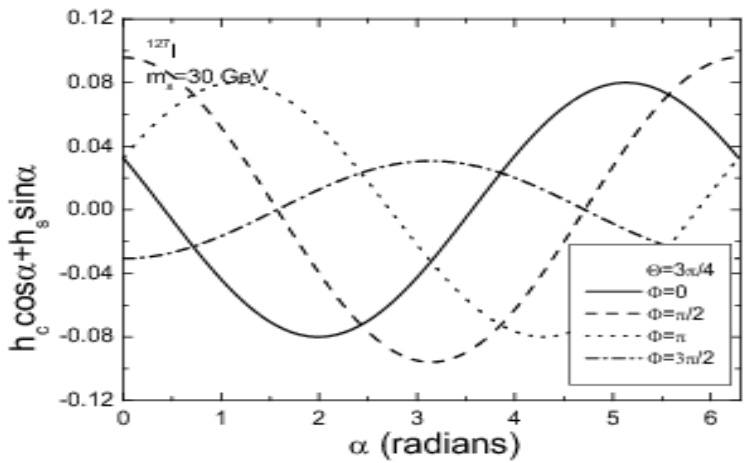




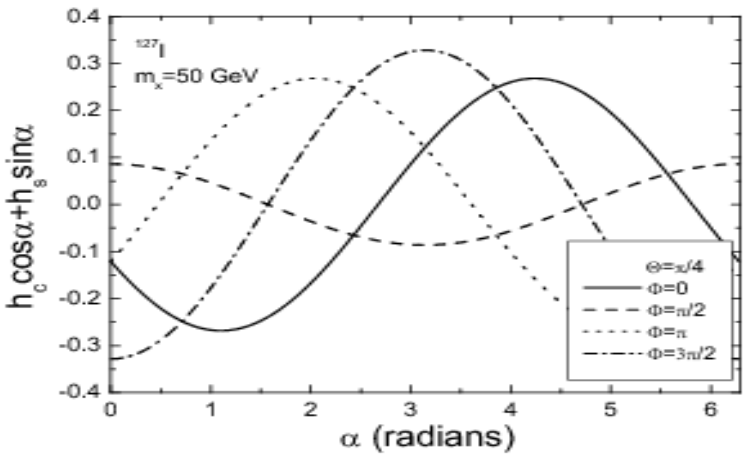
Modulation vs the phase of the earth.

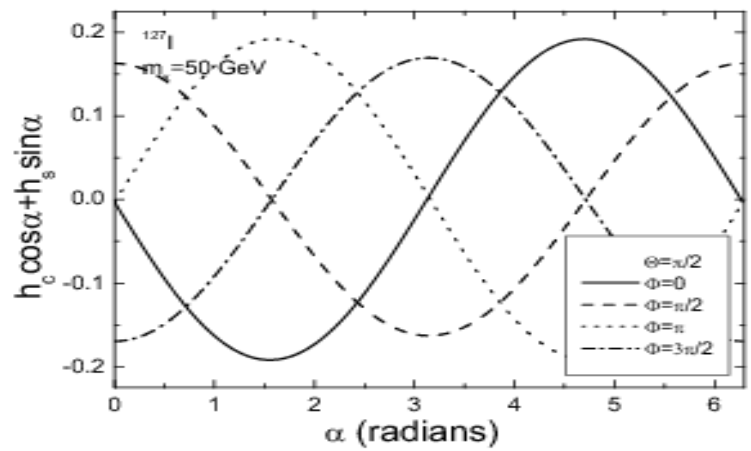


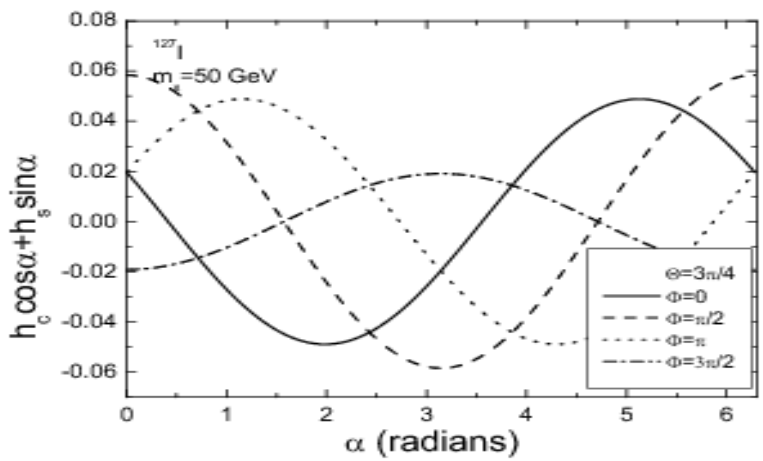




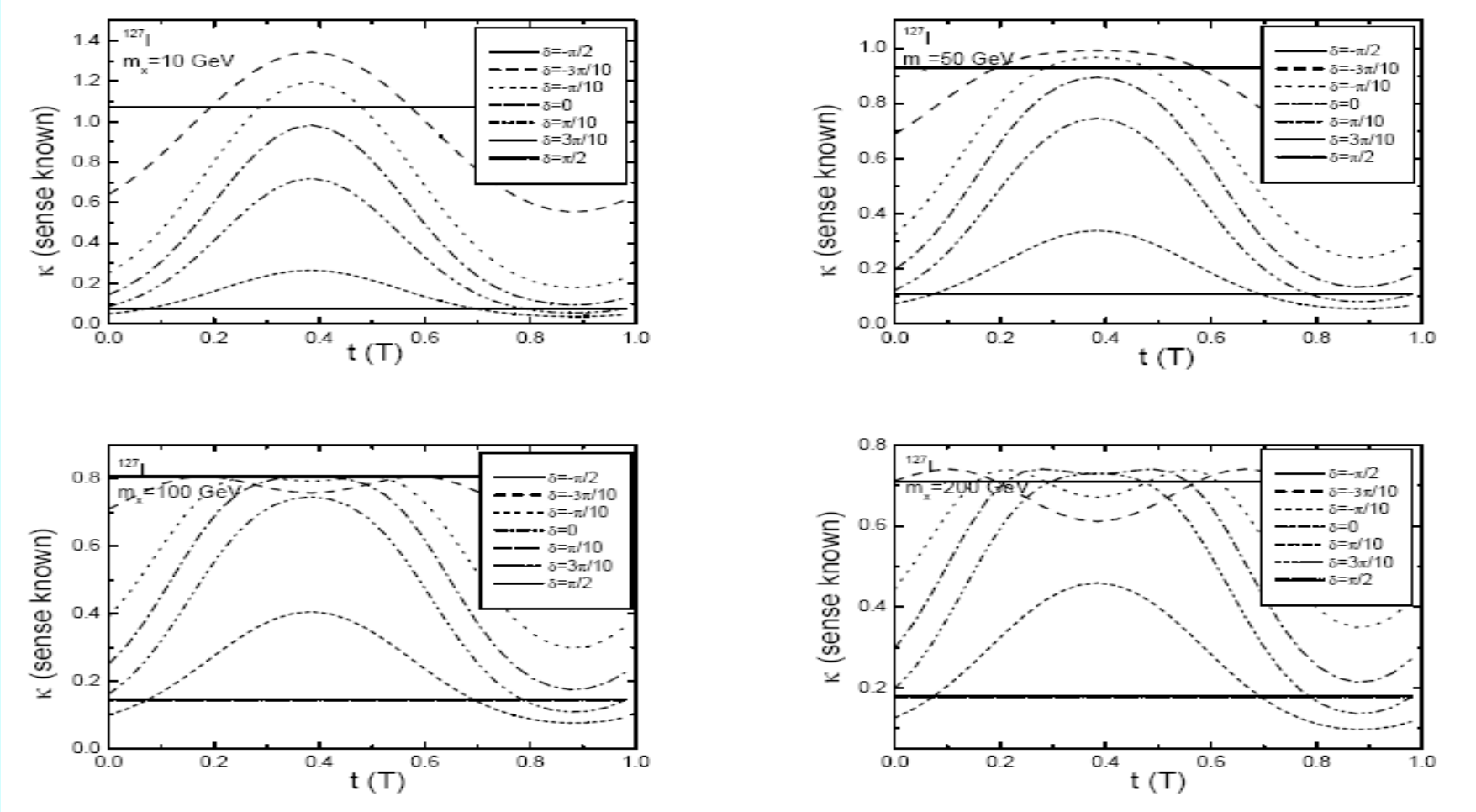
Modulation vs the phase of the earth.







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



COMMON WISDOM!

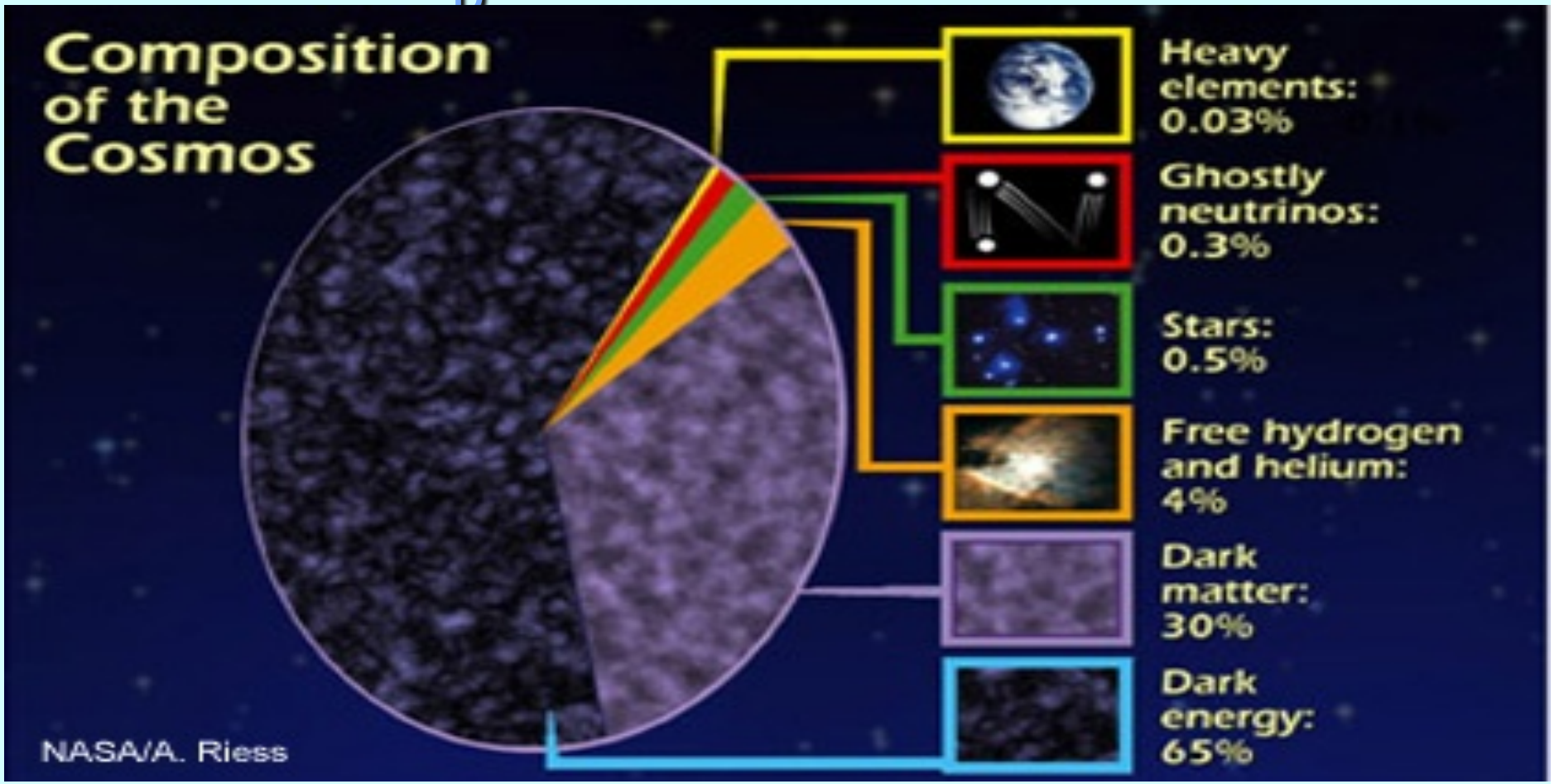
Are Physicists optimists or Don Quixotes?

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!)

Slicing the Pie of the Cosmos WMAP3:

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

$\Omega_{b} = 0.042 \pm 0.003$



What I will say applies to:

ALL 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. Four possibilities:

  i) s-ν ε τ ρίν ο : Excluded on the basis of results of underground experiments and accelerator experiments (LEP)

  ii) Gravitino: Interesting possibility, but not directly detectable

  iii) Axino: Intersting, but not directly detectable

  iv) A Majorana fermion, the neutralino or LSP (The 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 (to explain excess e^+,e- in cosmic rays)

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

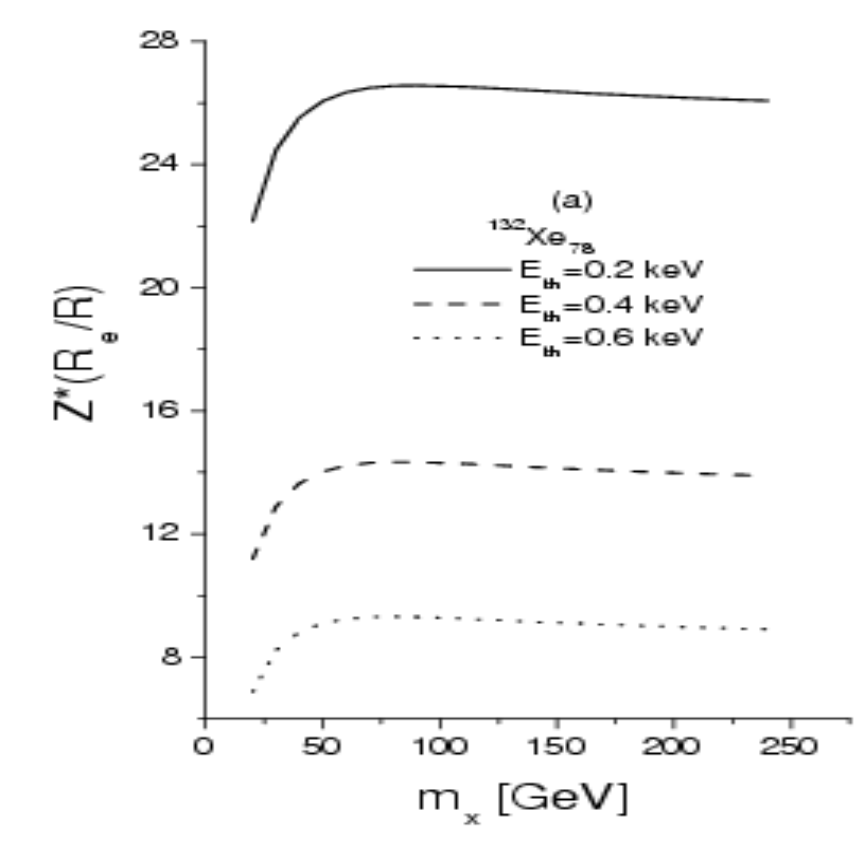
  This will depend on the assumed theory

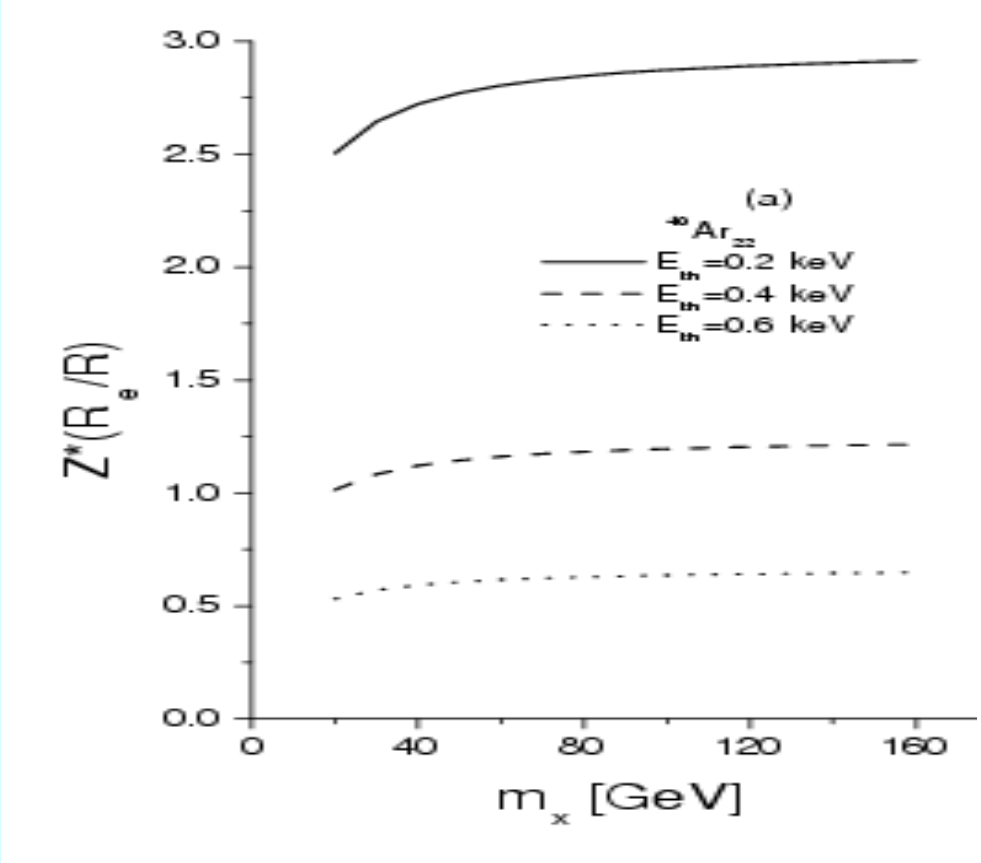
  WIMPs (Weakly Interacting Massive Particles)
- Such an interaction may be exploited for its direct detection
- The smallness of the strength of such an interaction and its low energy makes its direct detection extremely difficult. So we have to seek for its special signatures, if any.

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

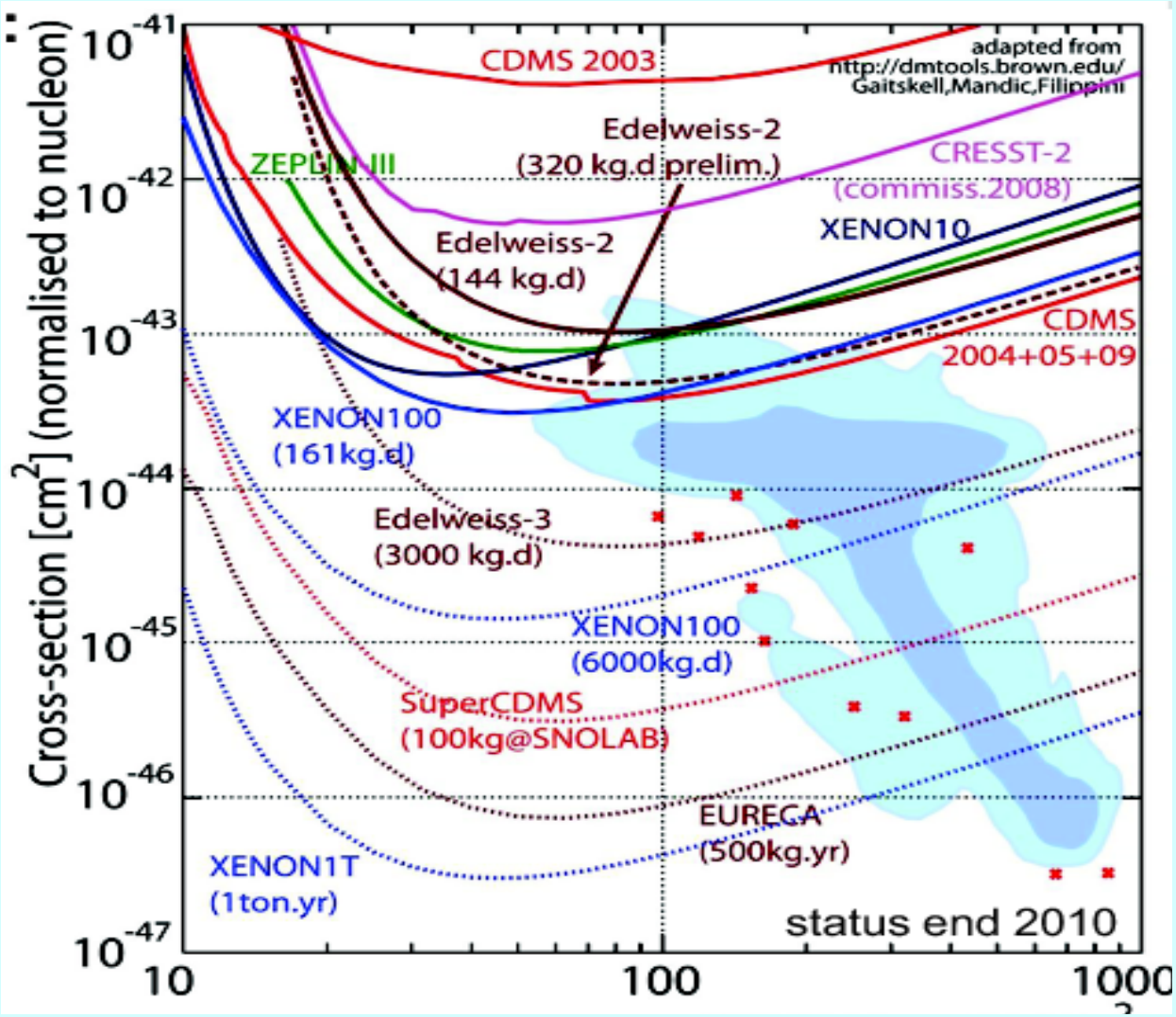
Relative rate for electron ionization (there are Z electrons in an atom!)





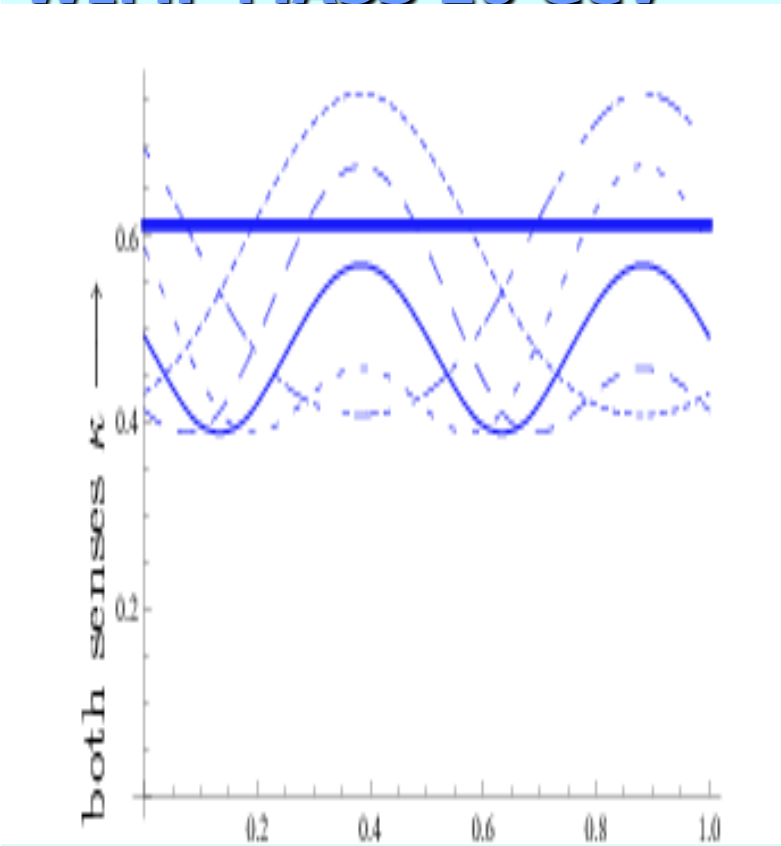
Prospects for (coherent) exclusion plots

(WIMP mass in GeV)

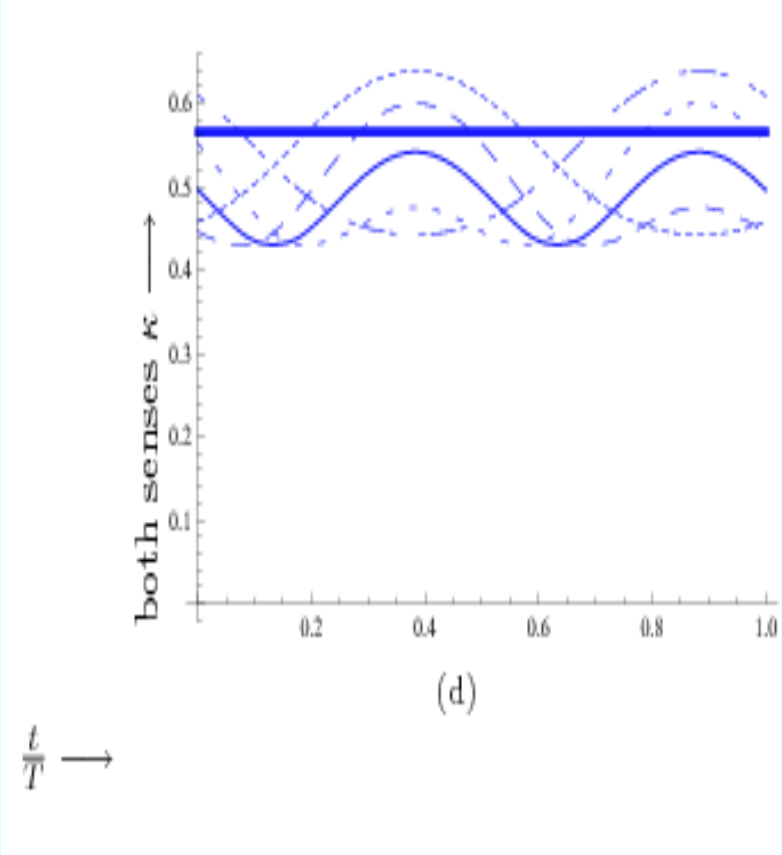


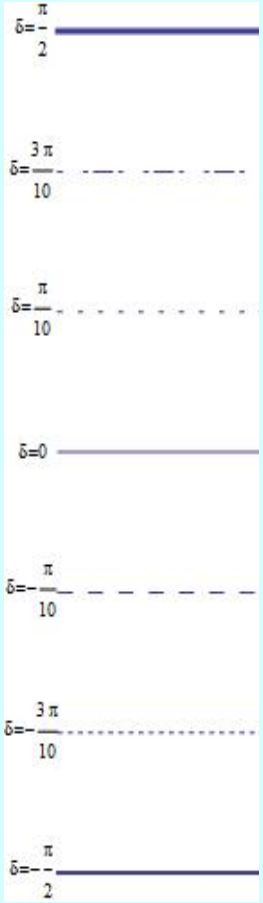
Diurnal Variation of the rate (κ) CS_2 Target& partly Directional

WIMP MASS 10 GeV



WIMP MASS 100 GeV

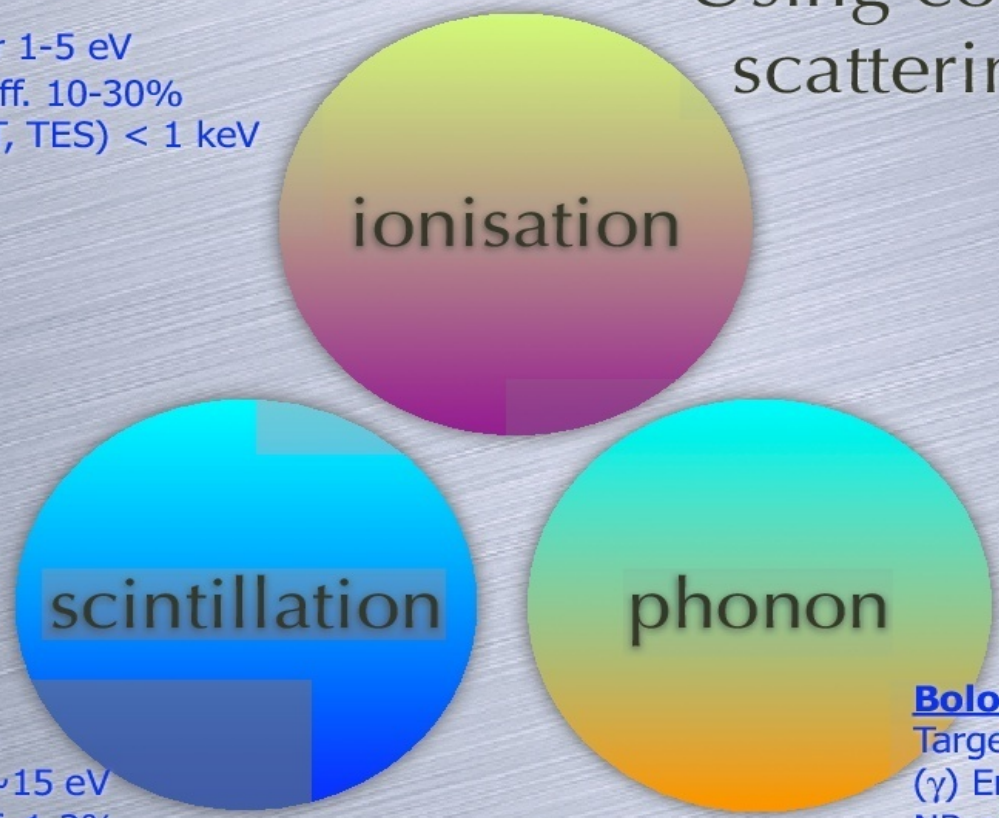




Techniques for direct WIMP detection

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)

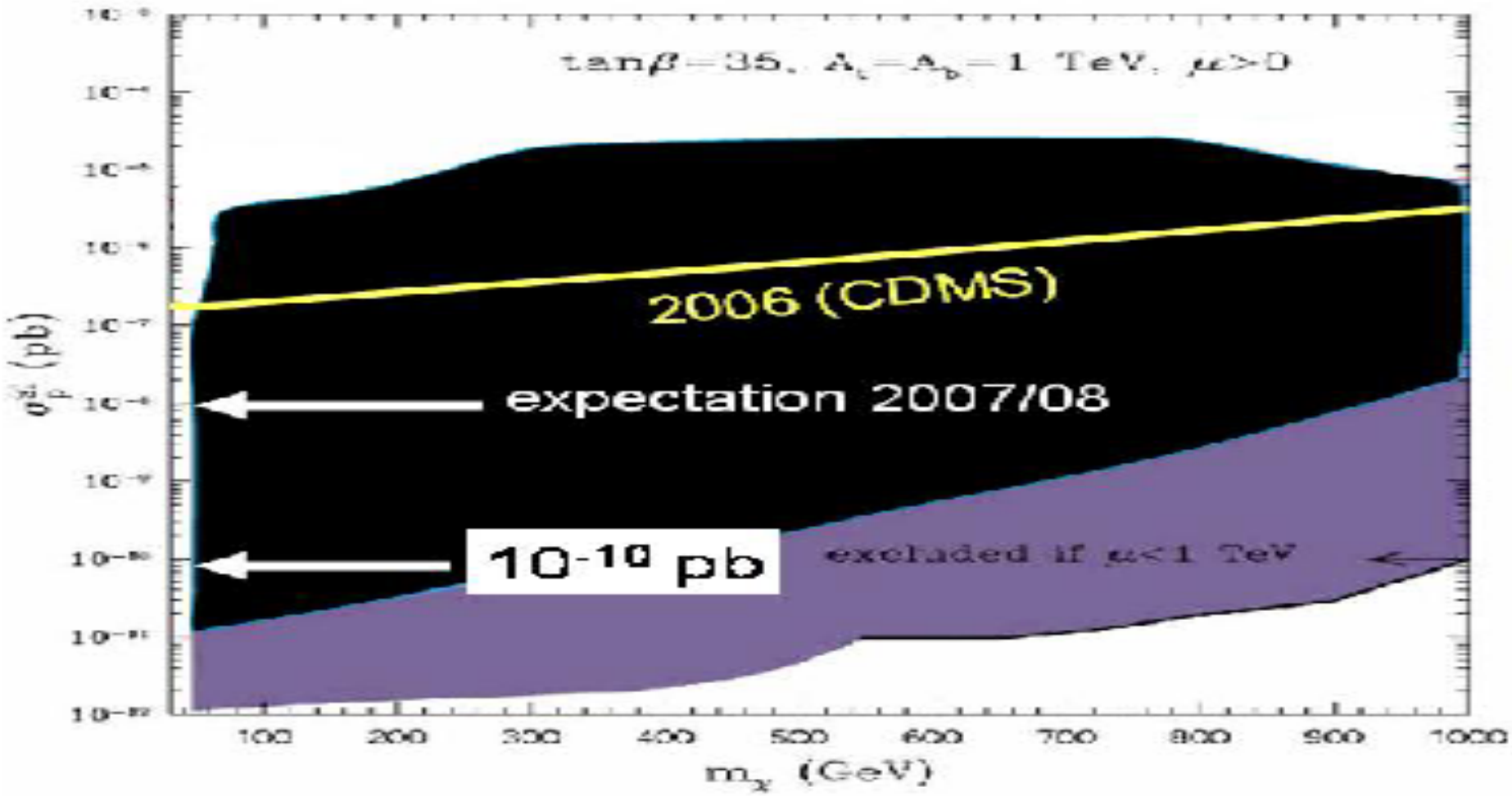
Following Araujo

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

Techniques for direct WIMP detection

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, $< \beta > \approx 10^{-3}$.

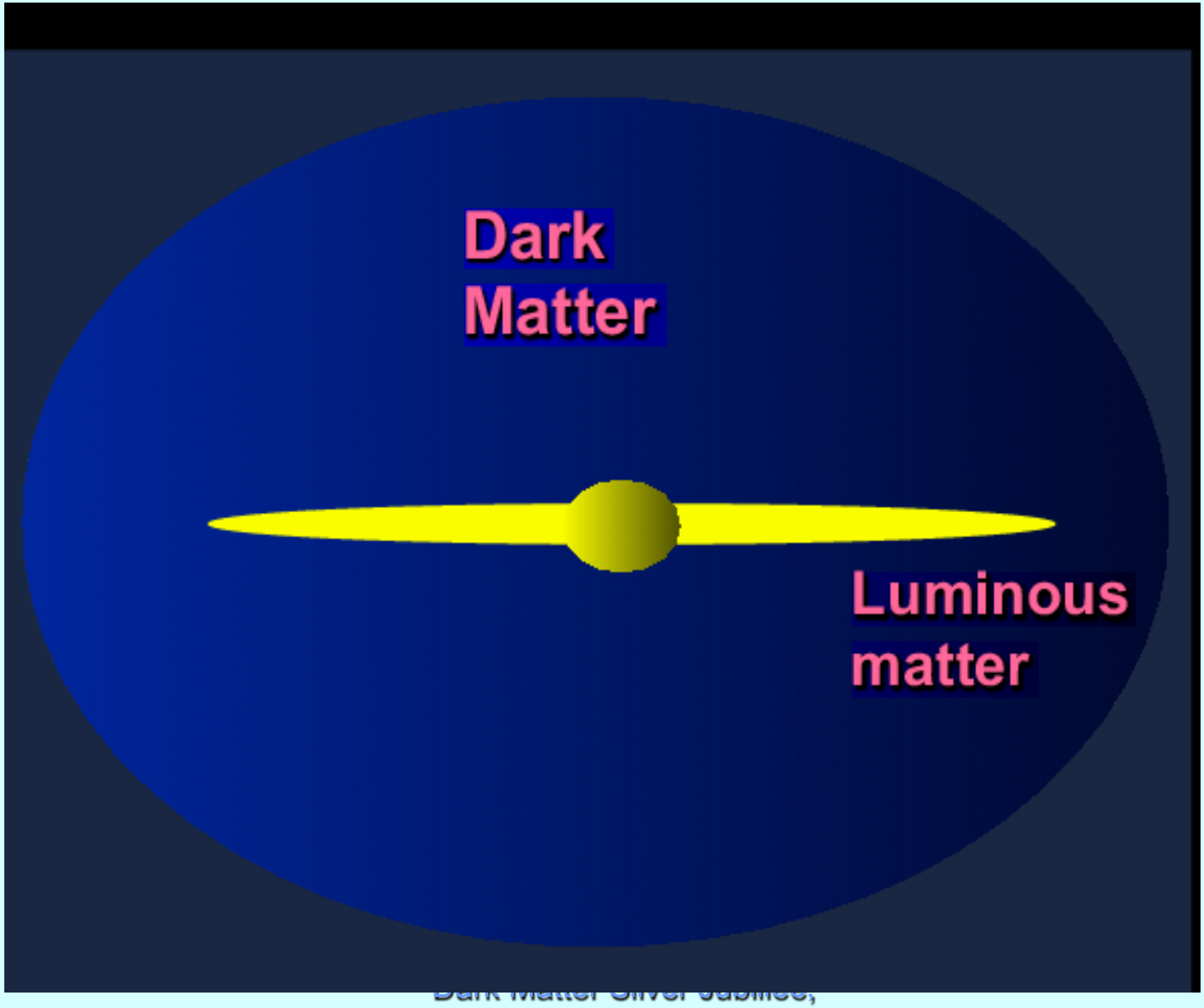
$$\langle T^0_{\tilde{\chi}} \rangle = 50 keV \frac{m^0_{\tilde{\chi}}}{100 GeV}$$

- 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:

$\Omega_{CDM} = 0.24 \pm 0.02$, $\Omega_{\Lambda} = 0.72 \pm 0.04$, $\Omega_{b} = 0.042 \pm 0.003$

Galactic X-ray emission

Cosmic microwave background radiation

Motion within our Galaxy

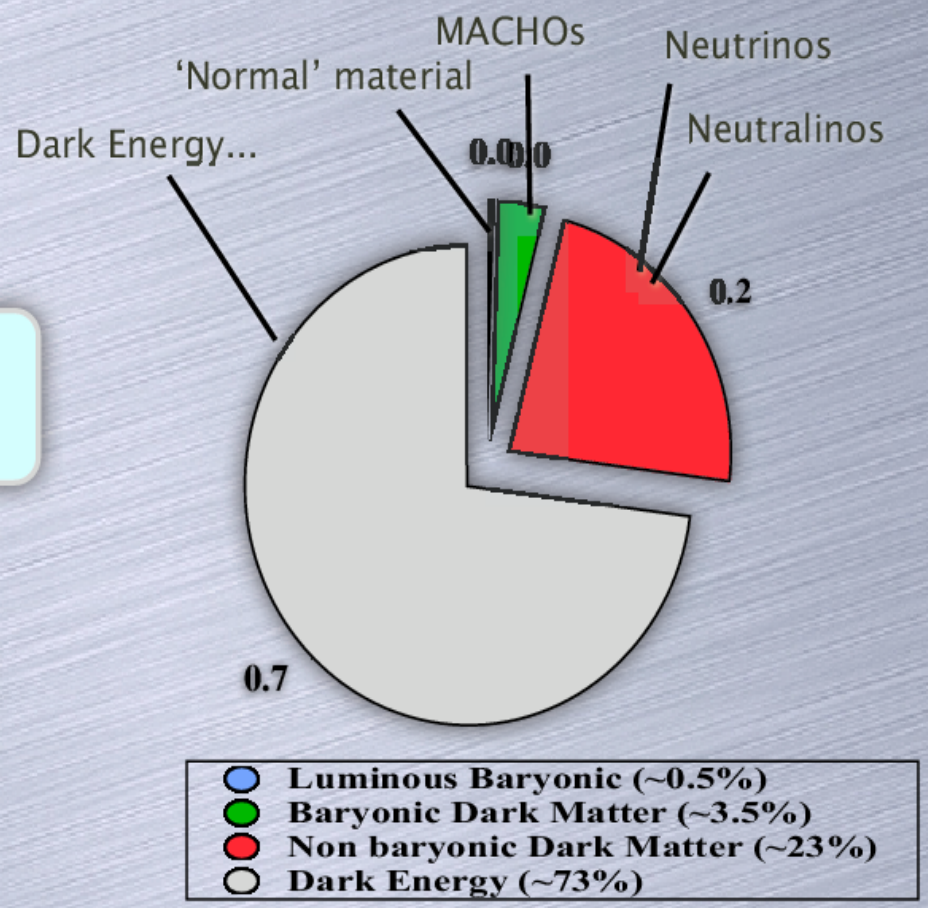
Motion of distant quas

Big Bang Nucleosynthesis

Motion of Galaxy Cluste

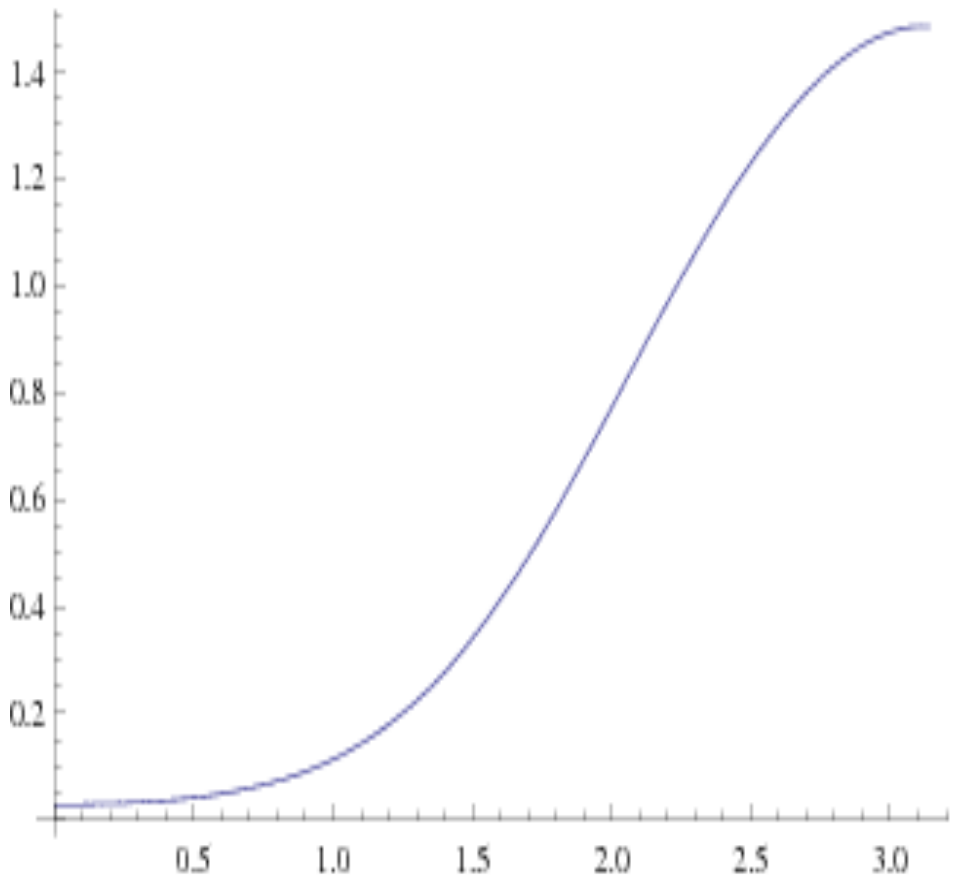
Gravitational lensing

Motions of Galaxys

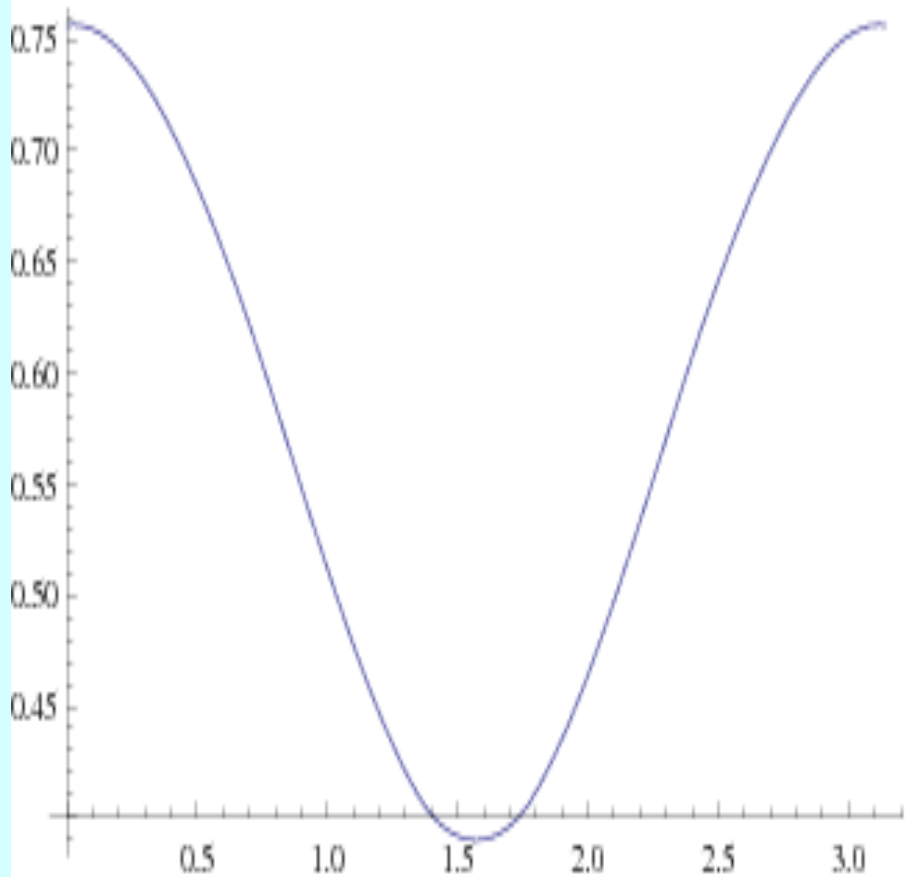


The parameter κ vs the polar angle Θ in the case of A=32; m_χ =10 GeV; Symmetric M-B

definite sense

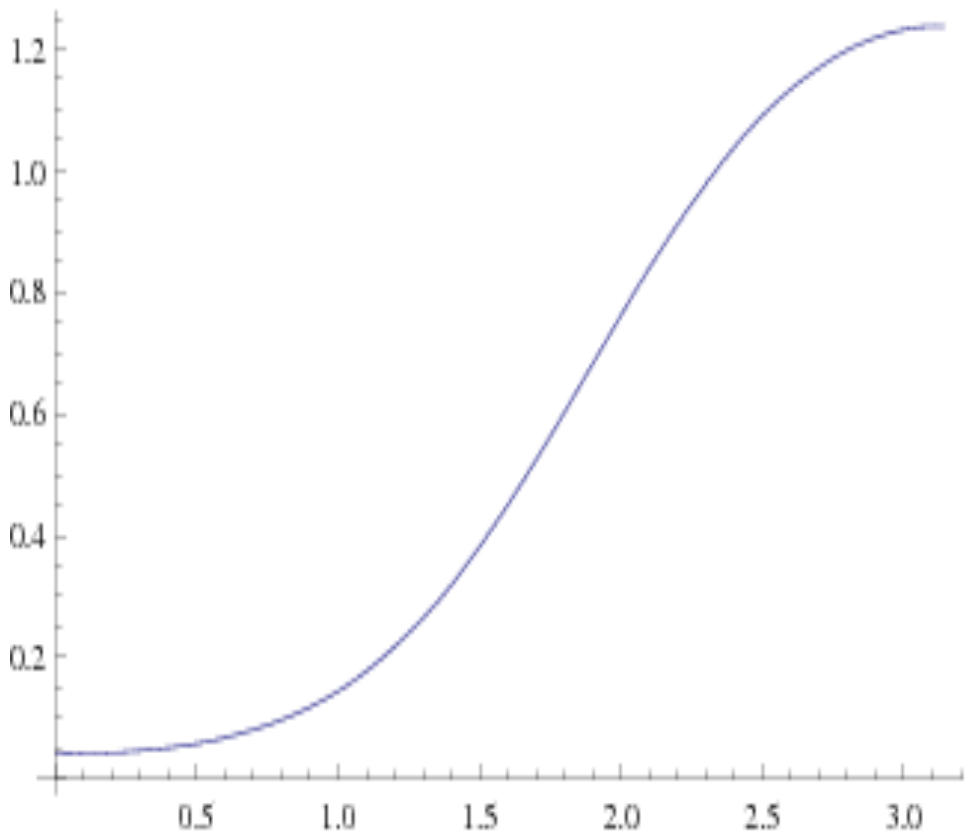


Both senses

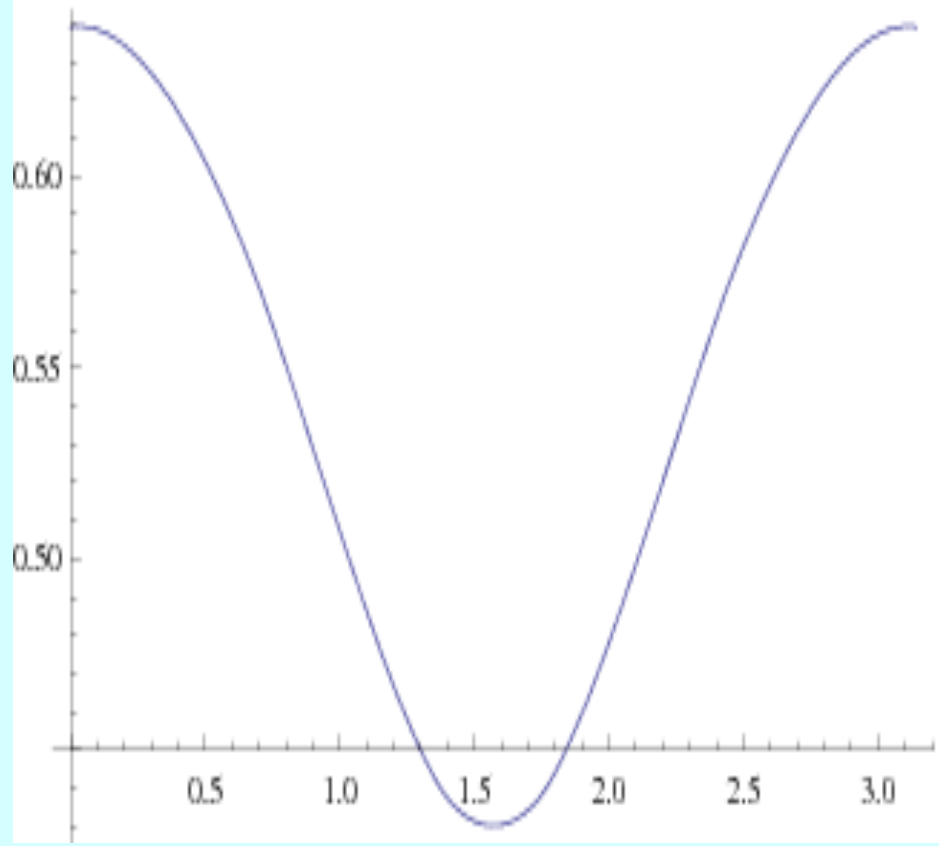


The parameter κ vs the polar angle Θ in the case of A=32; m_χ=100 GeV

definite sense

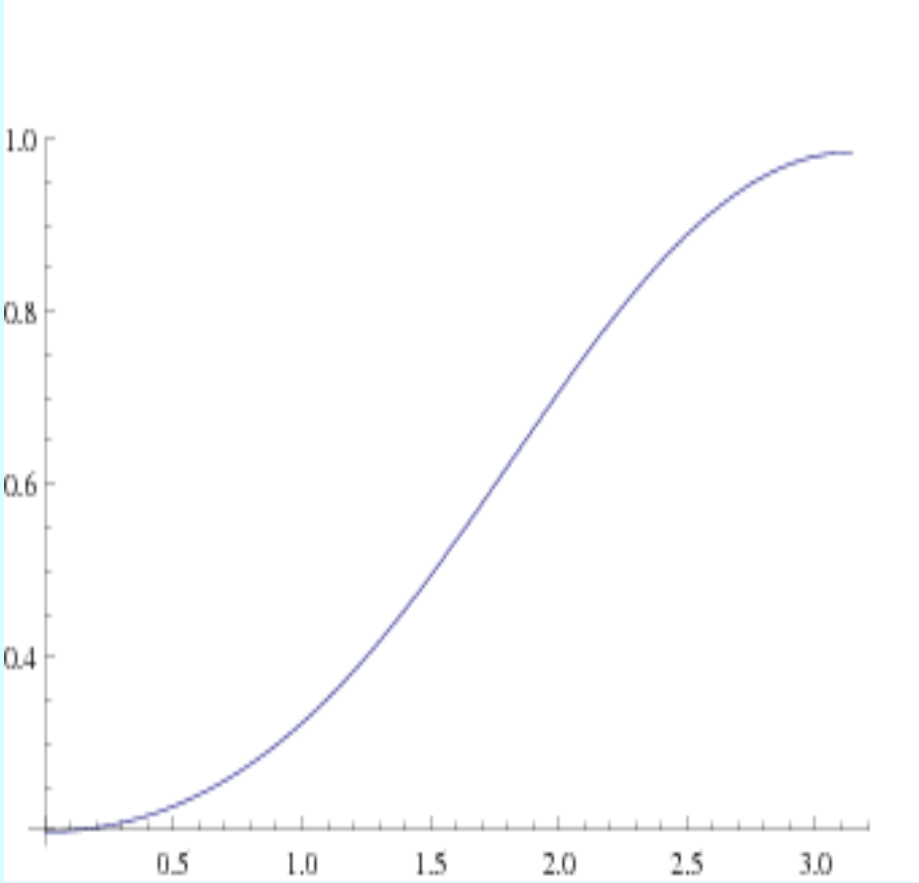


Both senses

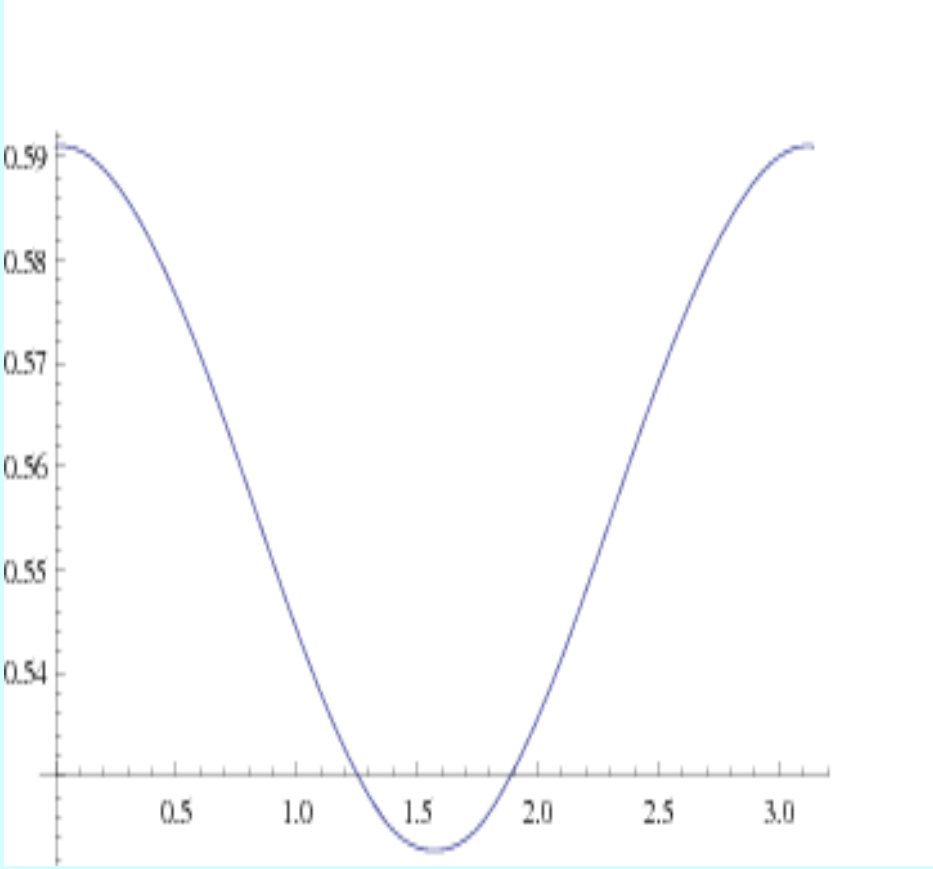


The parameter κ vs the polar angle Θ in the case of A=127; m_χ=10 GeV

definite sense

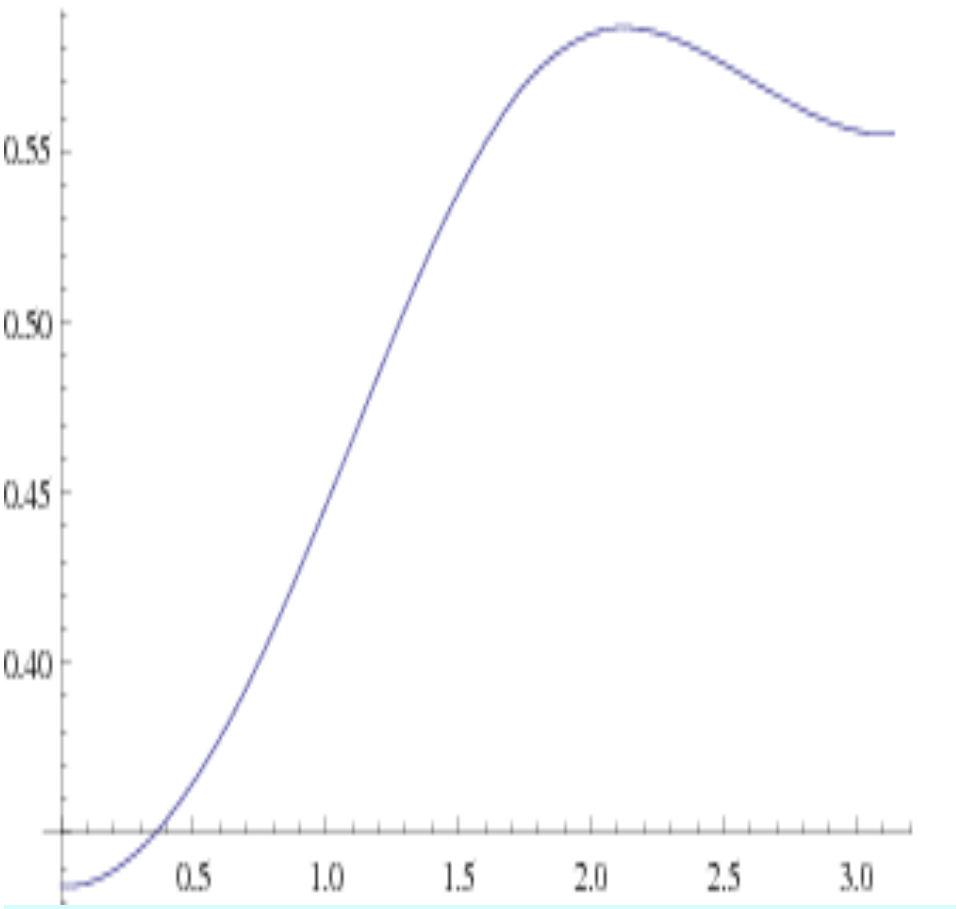


Both senses

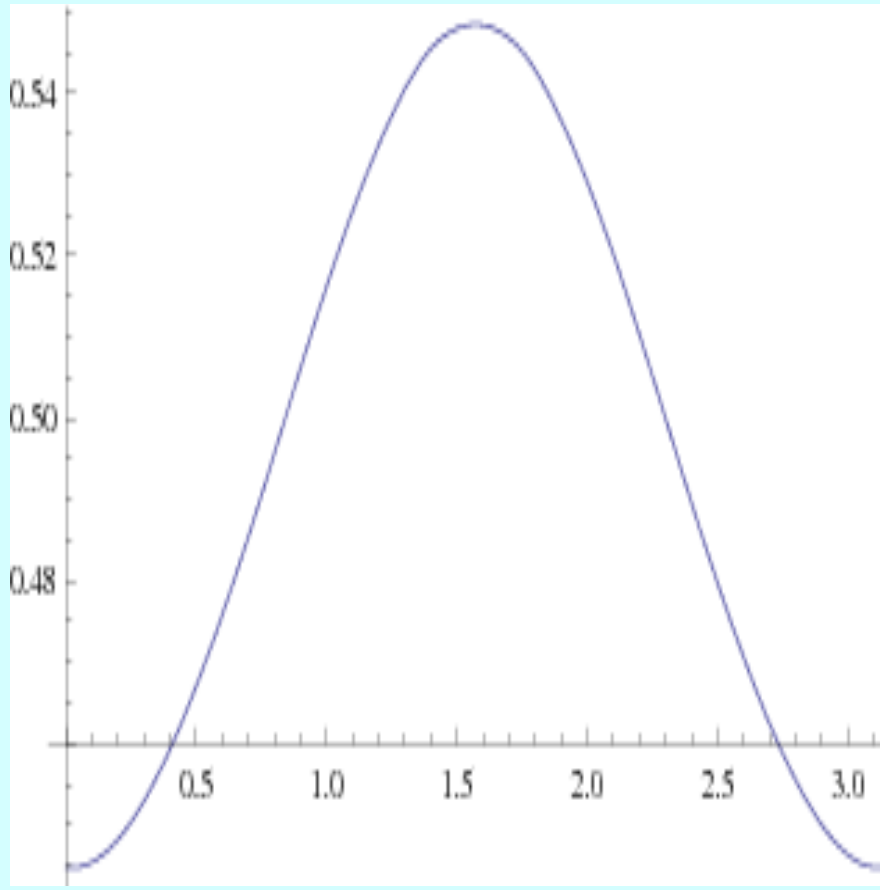


The parameter κ vs the polar angle Θ in the case of A=127; m_χ=100 GeV

definite sense



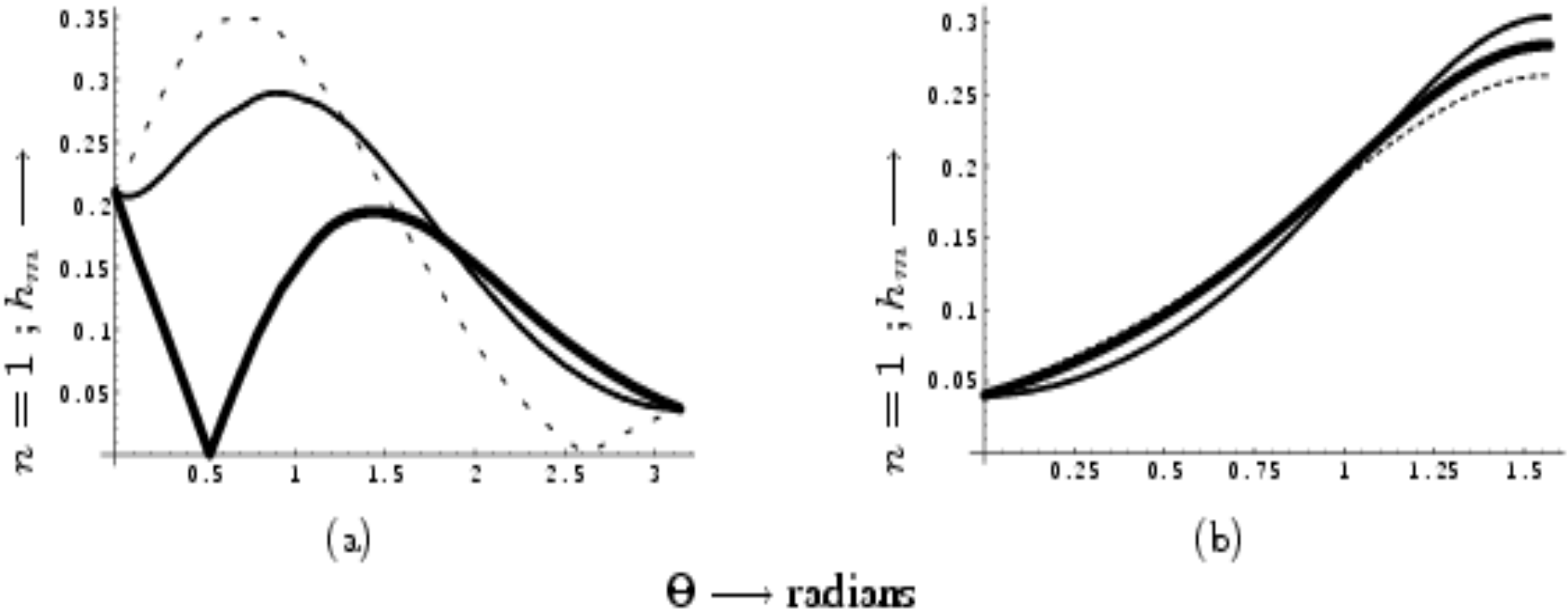
Both senses



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

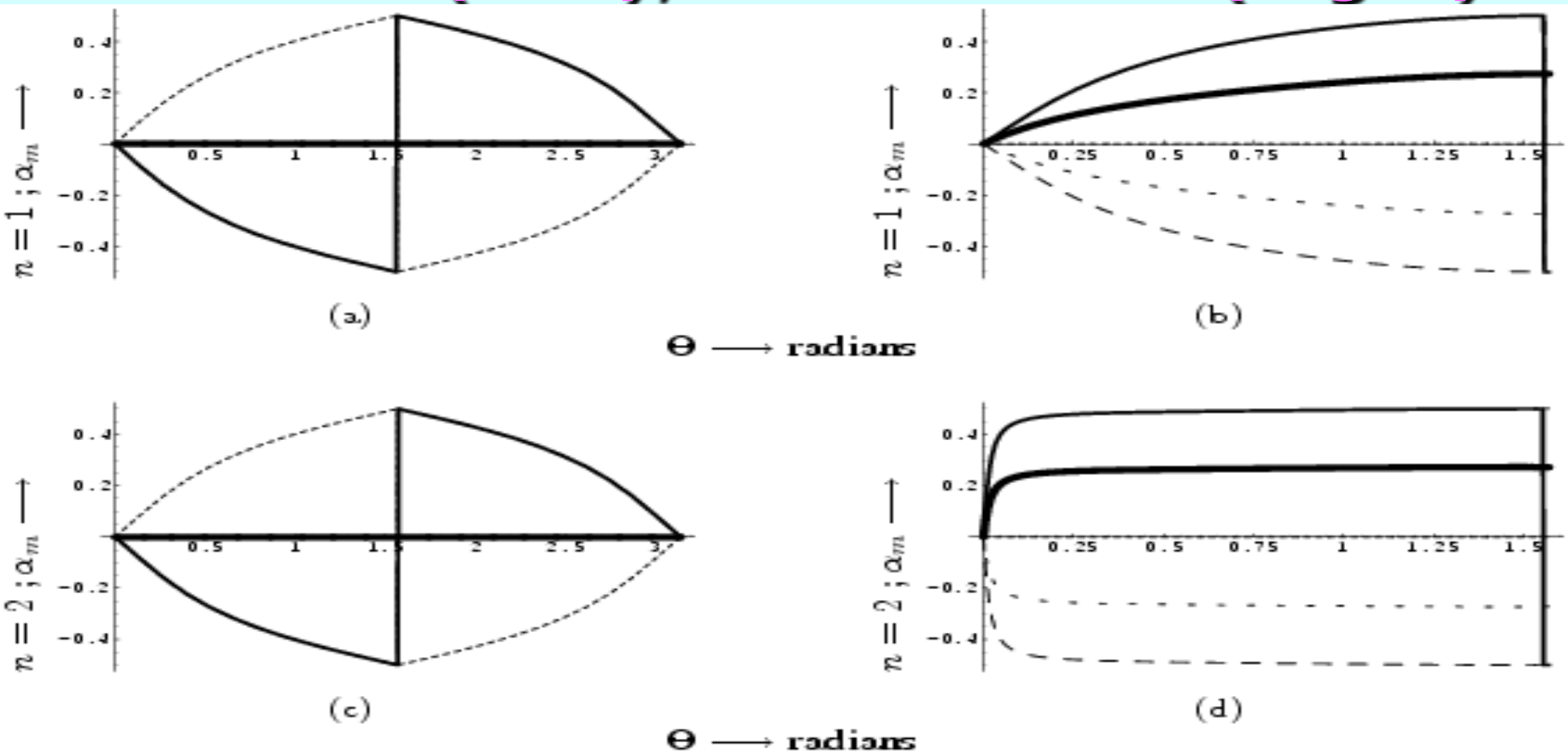
One sense (Left), Both senses (Right)

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)



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

Prelude : I. The standard (non directional) event rate for the coherent mode

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

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

with

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

Where:

- t_{coh} , h_{coh} (modulation) depend on nuclear physics, the WIMP mass and the velocity distribution
- ρ (0): the local WIMP density≈0.3 GeV/cm^3.

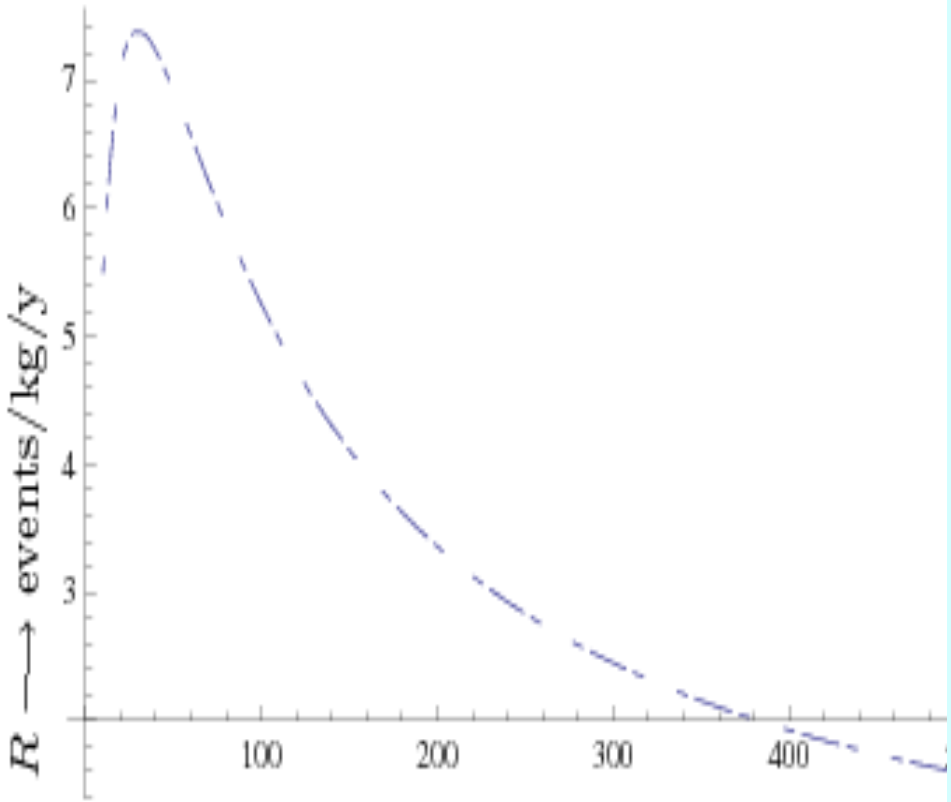
  $\sigma^S_{p,\chi}$: the WIMP-nucleon cross section. It is computed in a particle model.

  It can be extracted from the data once f_{coh} (A,m_χ) is known

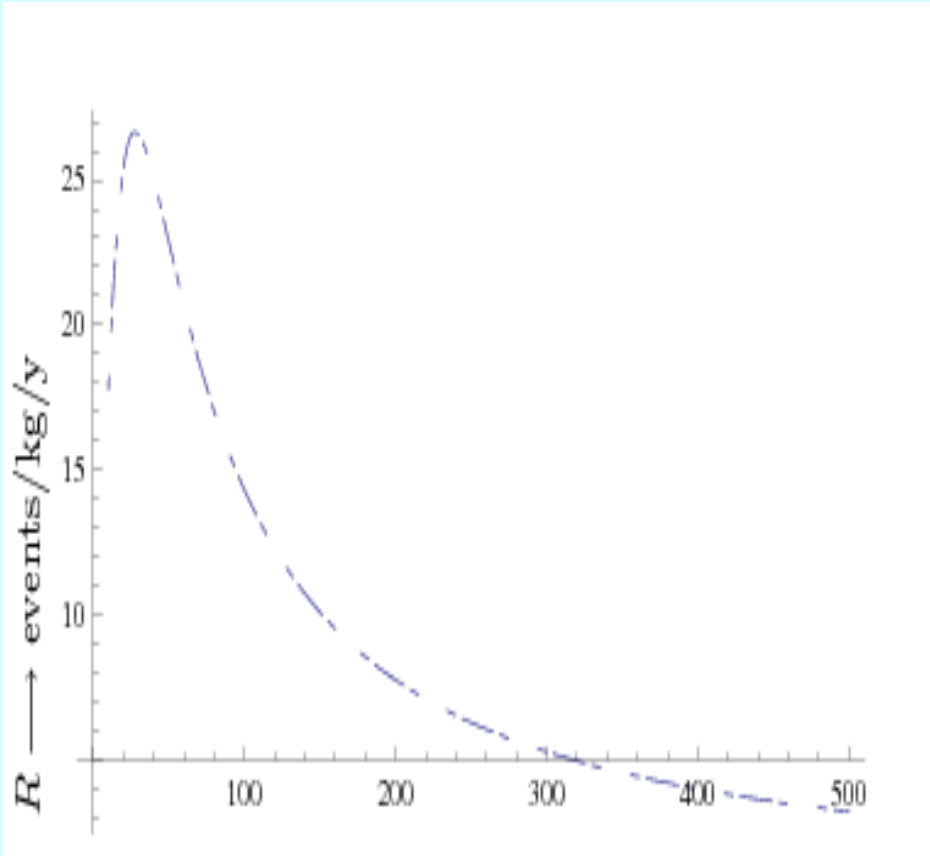
Ia:The Coherent Event Rate ($\sigma_{p,\chi}=10^{-7}$ pb)

(As a function of WIMP mass in GeV)

Light System (e.g. A=32)

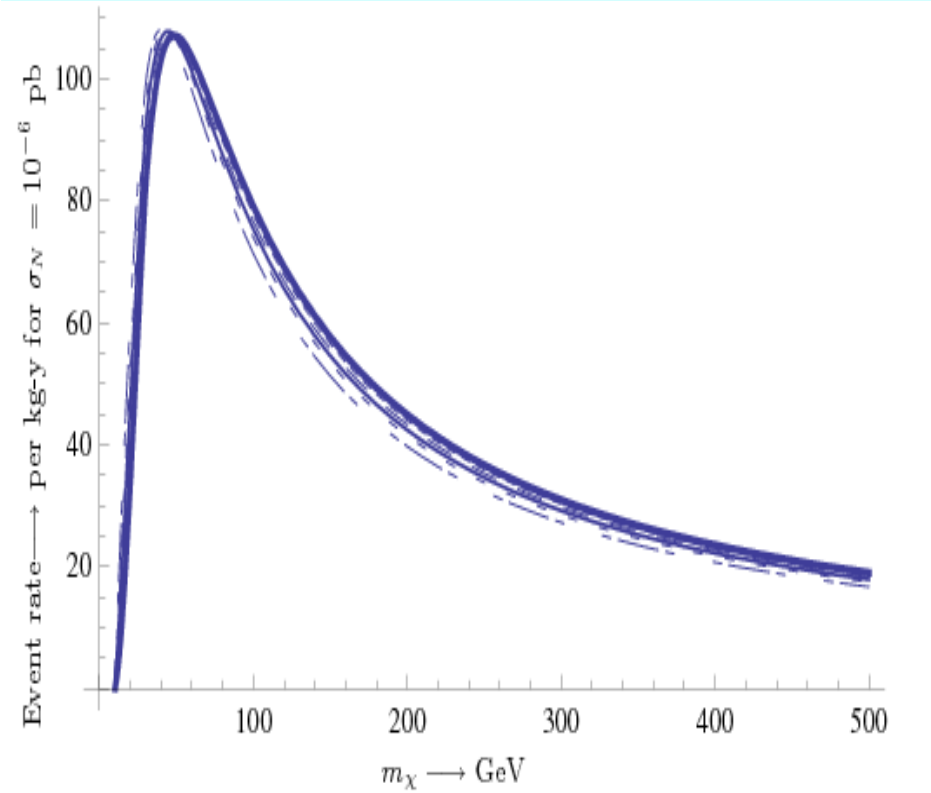


Heavy System (e.g. A=131)

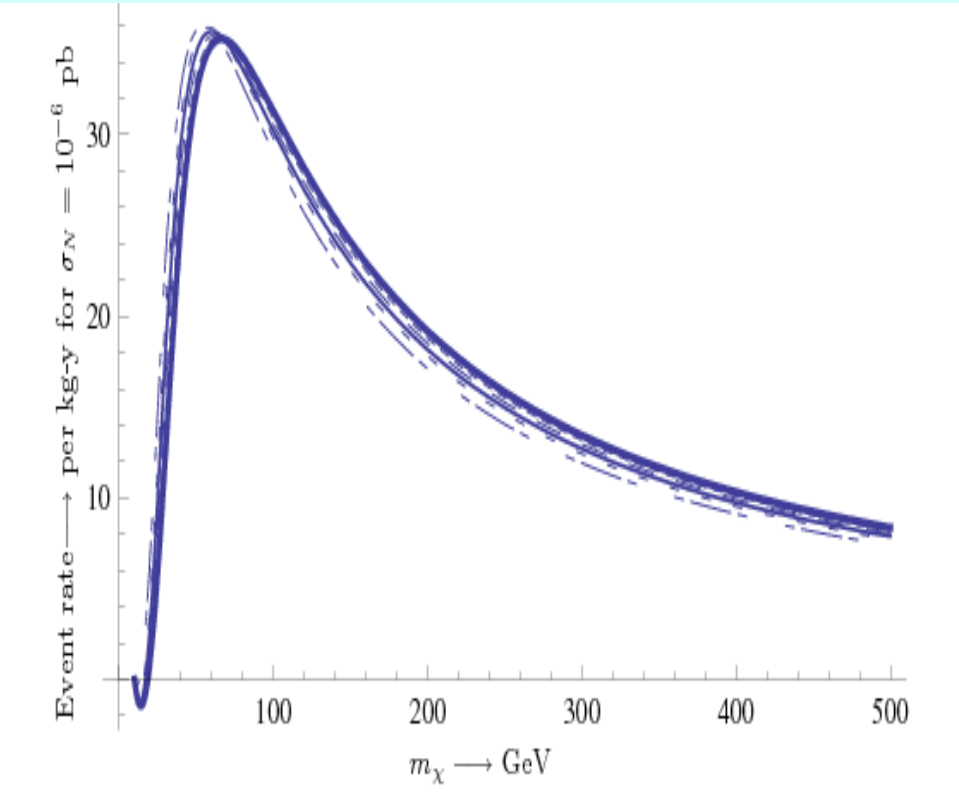


Ib:The time averaged event rate for a medium-heavy target vs WIMP mass

E_{th}=10 keV (no quenching)

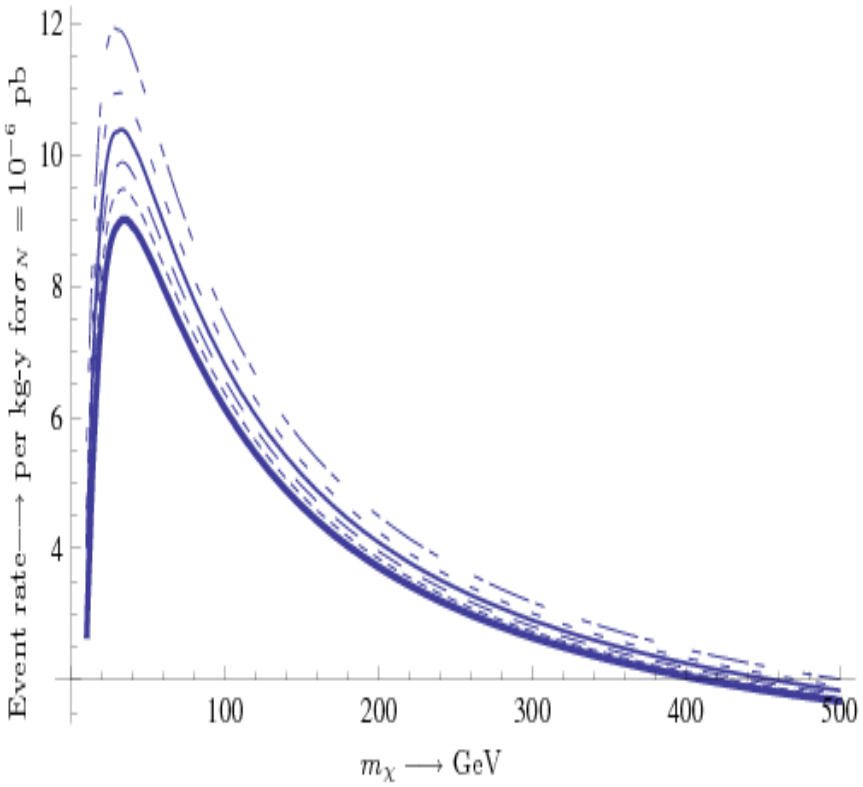


E_{th}=10 keV (quenching)

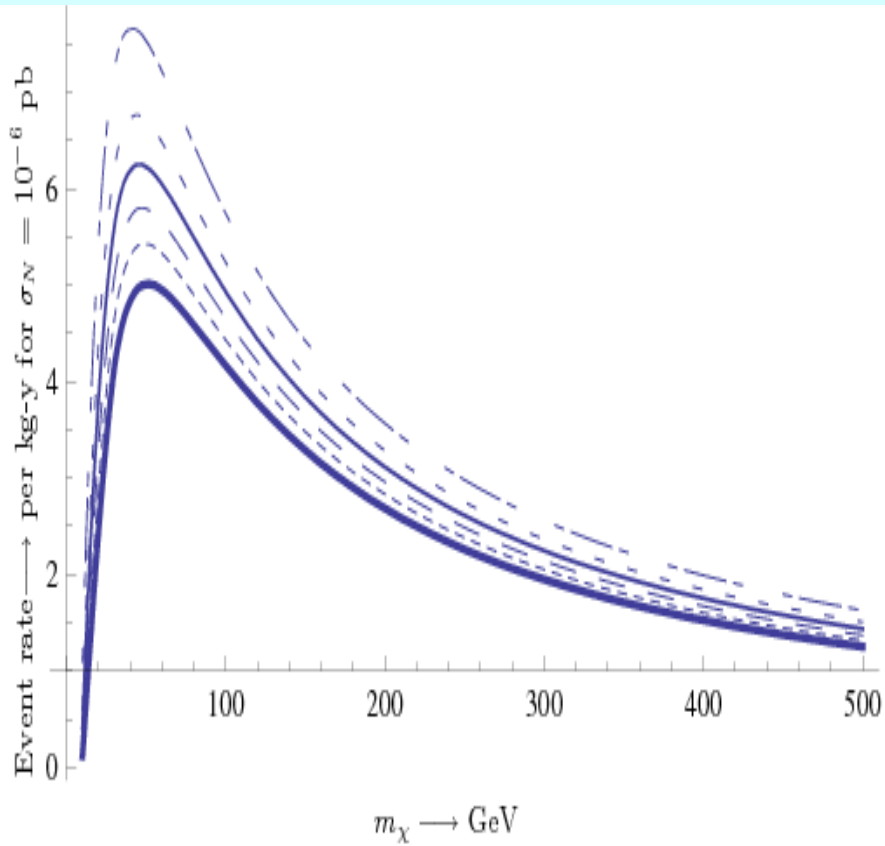


Ic:The time averaged event rate for a light target vs WIMP mass

E_{th}=10 keV (no quenching)



E_{th}=10 keV (quenching)



Directional Experiments

- To simplify our discussion we will consider the rate in a given direction divided by the Standard rate

- This will depend on

- The WIMP Mass (the only particle parameter needed). This will be treated as a free parameter
- The velocity distribution of WIMP's in our galaxy. We will employ the MB distribution.
- The nuclear form factor

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)

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

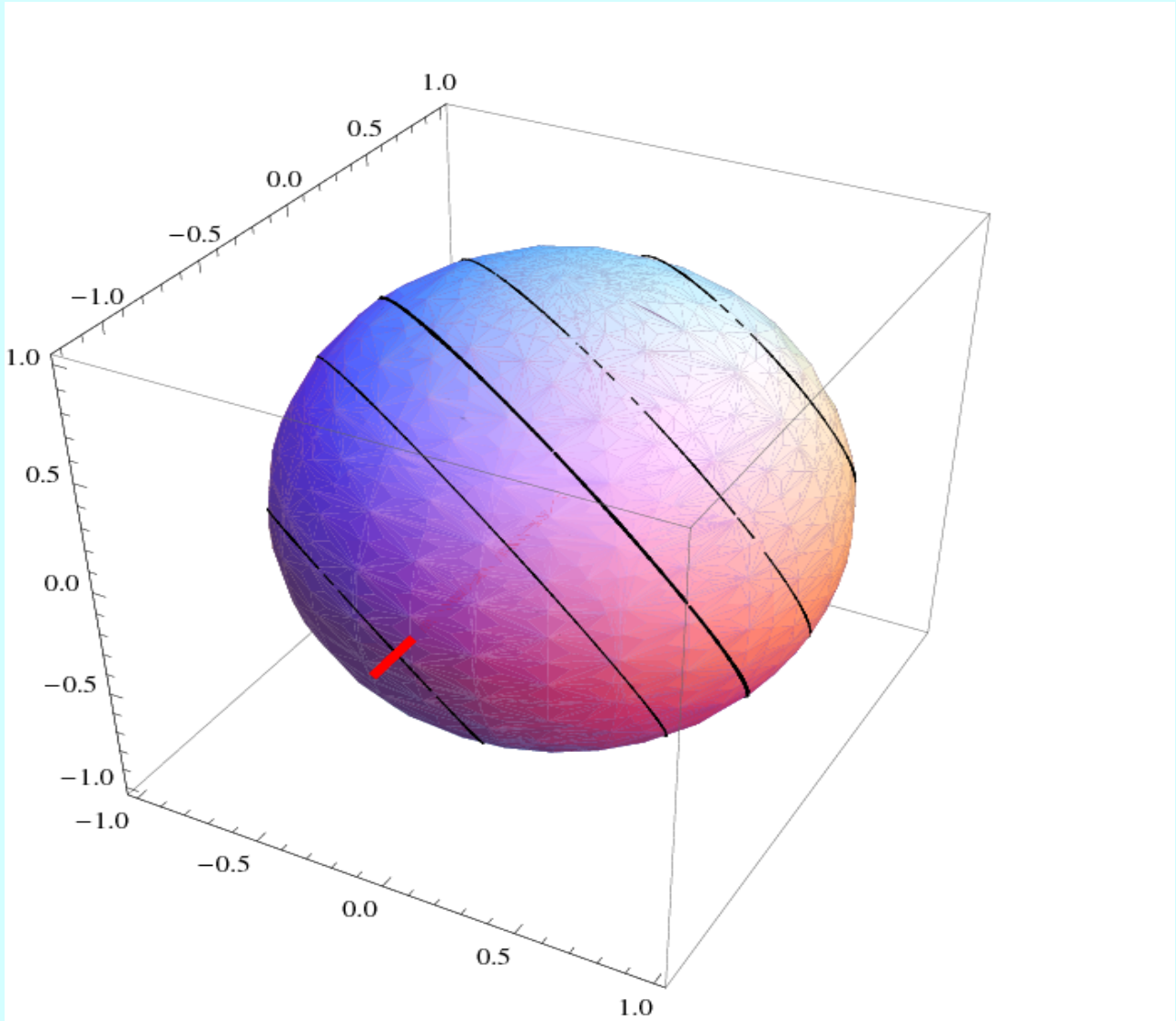
(radially out towards the sun)

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

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



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

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

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

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

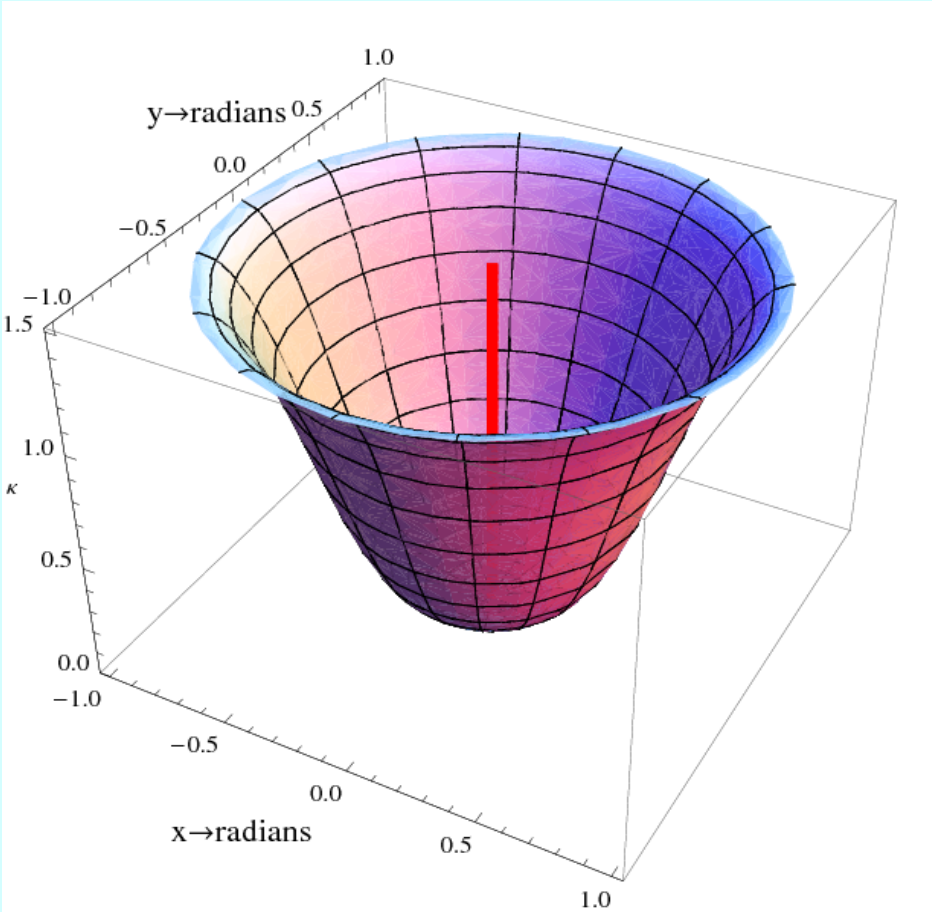
-due to the Earth's annual motion it will show a modulation dependent on (Θ,Φ) with very characteristic signature. Φ is measured on a plane perpendicular to the sun's velocity from x (radially out of the galaxy)

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

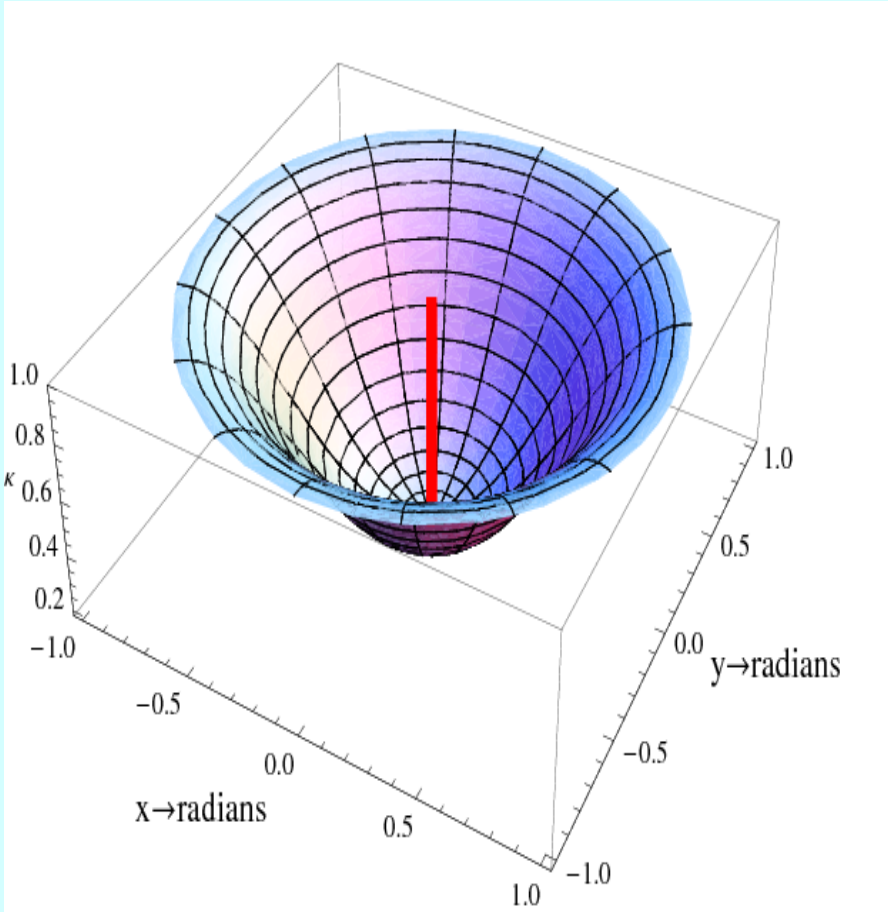
-Then Diurnal variation due to the rotation of the Earth

The parameter κ vs the polar angle Θ (axial symmetry) in the case m_χ =10 GeV; Red line: sun's velocity

A =32

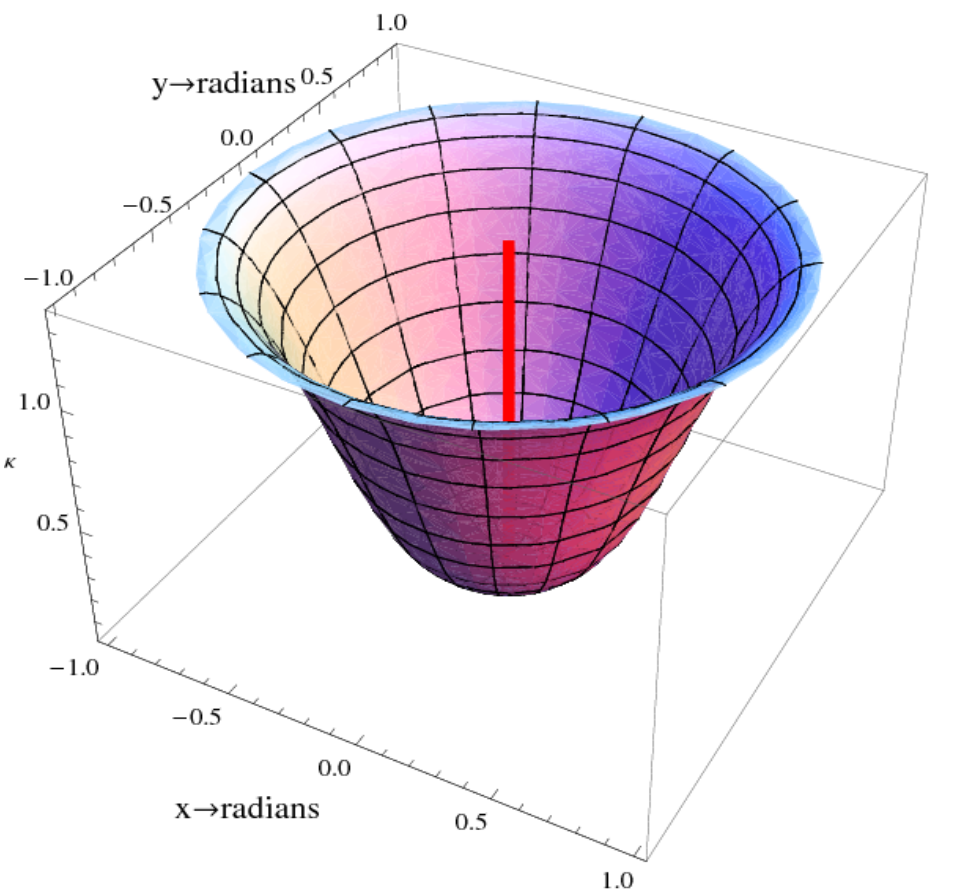


A =131

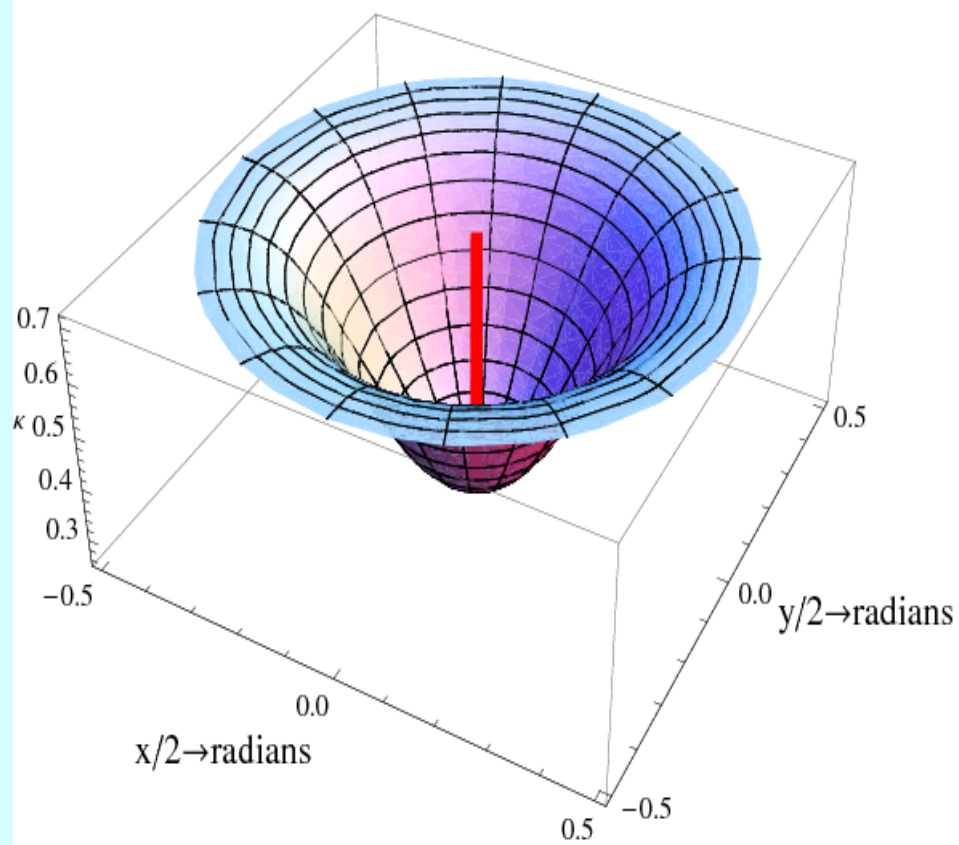


The parameter κ vs the polar angle Θ (axial symmetry) in the case m_χ =30 GeV; Red line: sun's velocity

A =32

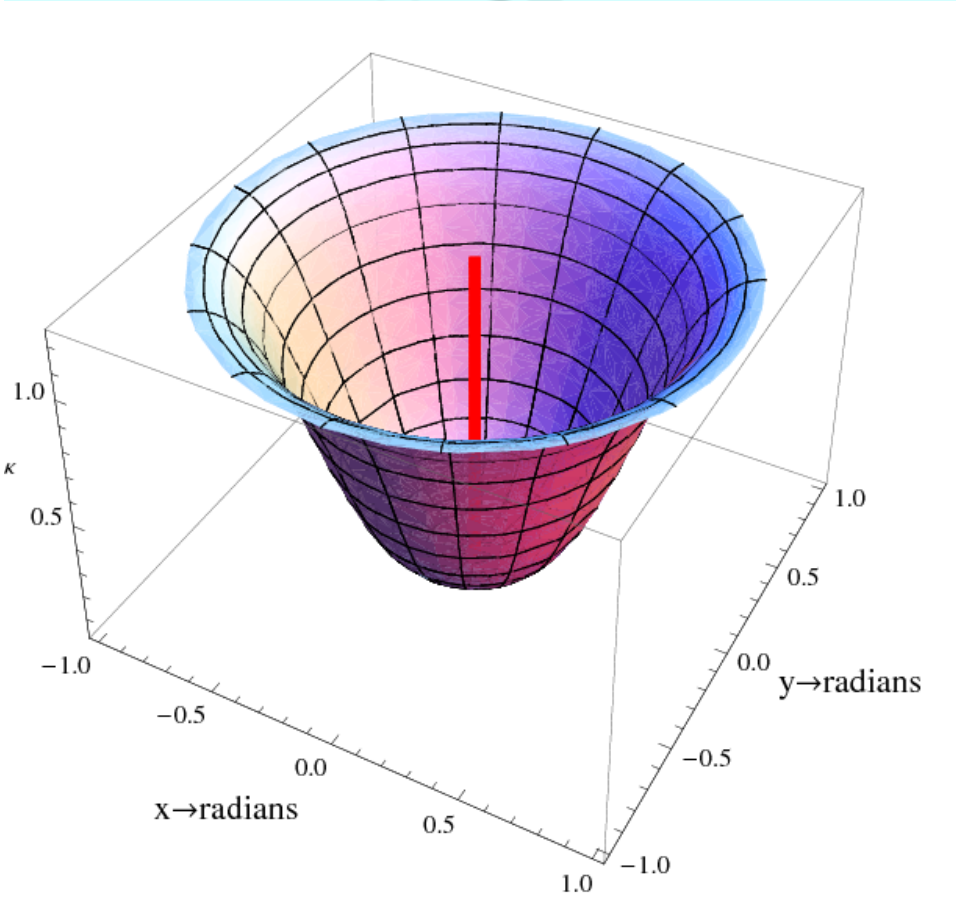


A =131

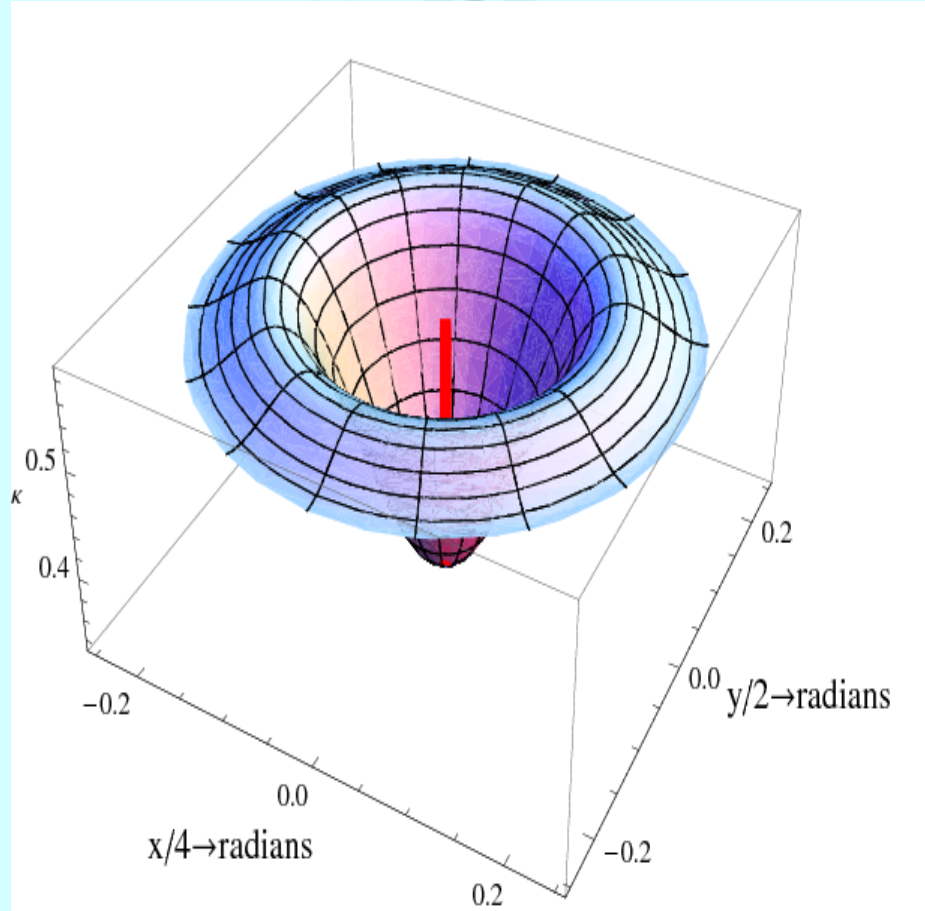


The parameter κ vs the polar angle Θ (axial symmetry) in the case m_χ =100 GeV; Red line: sun's velocity

A =32

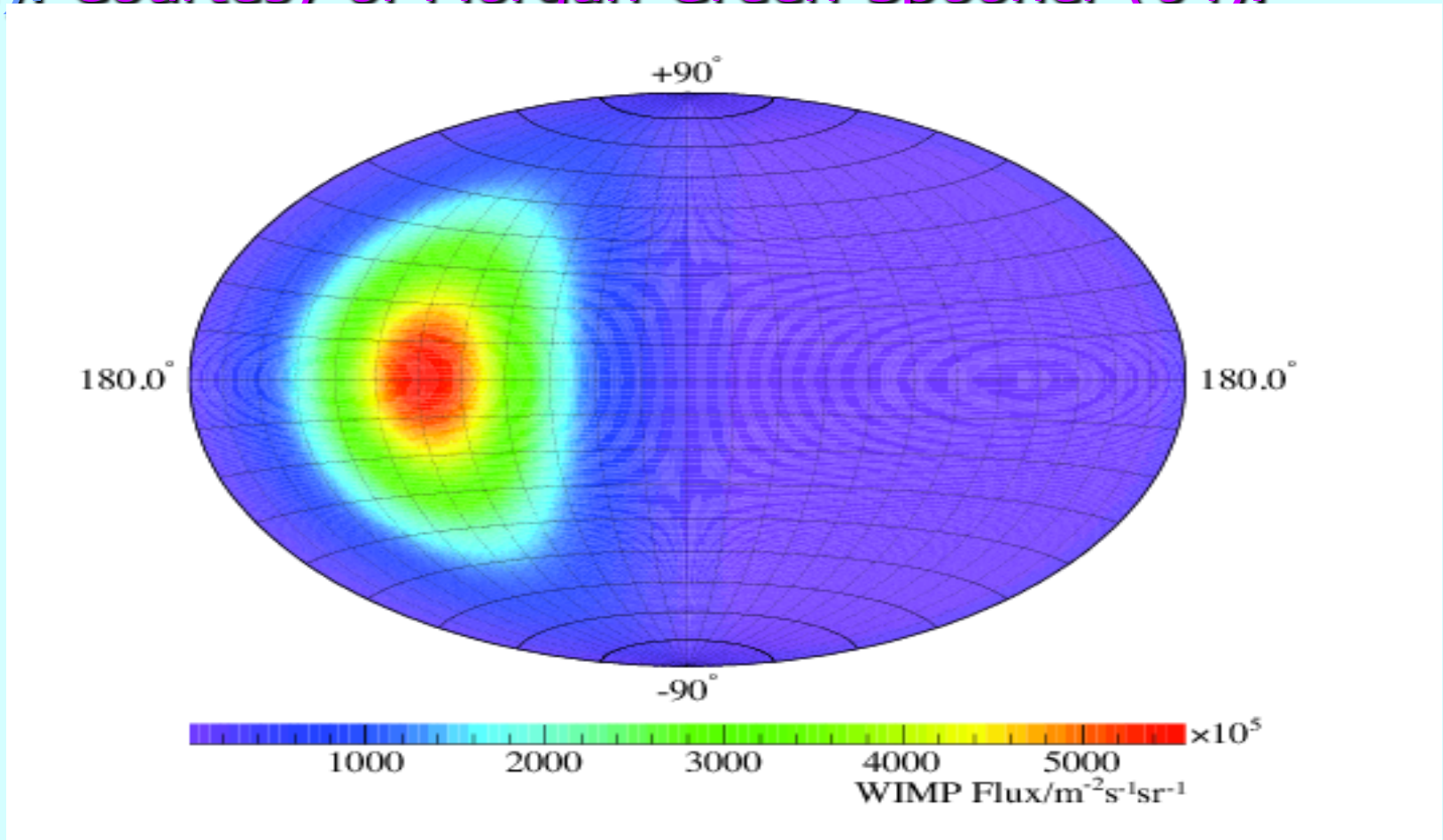


A =131



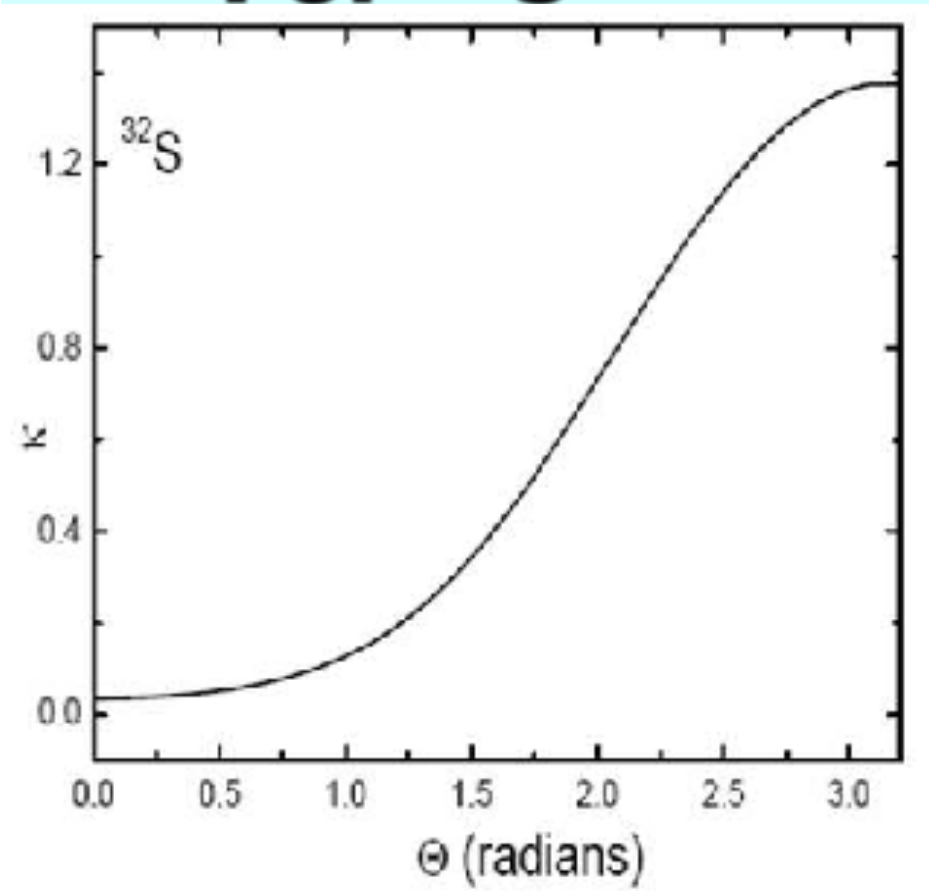
"The solar wind" (towards the Cygnus constallation)

Spergel (88), vergados (02), Morgan-Green-Spooner (04). Courtesy of Morgan-Green-Spooner (04).

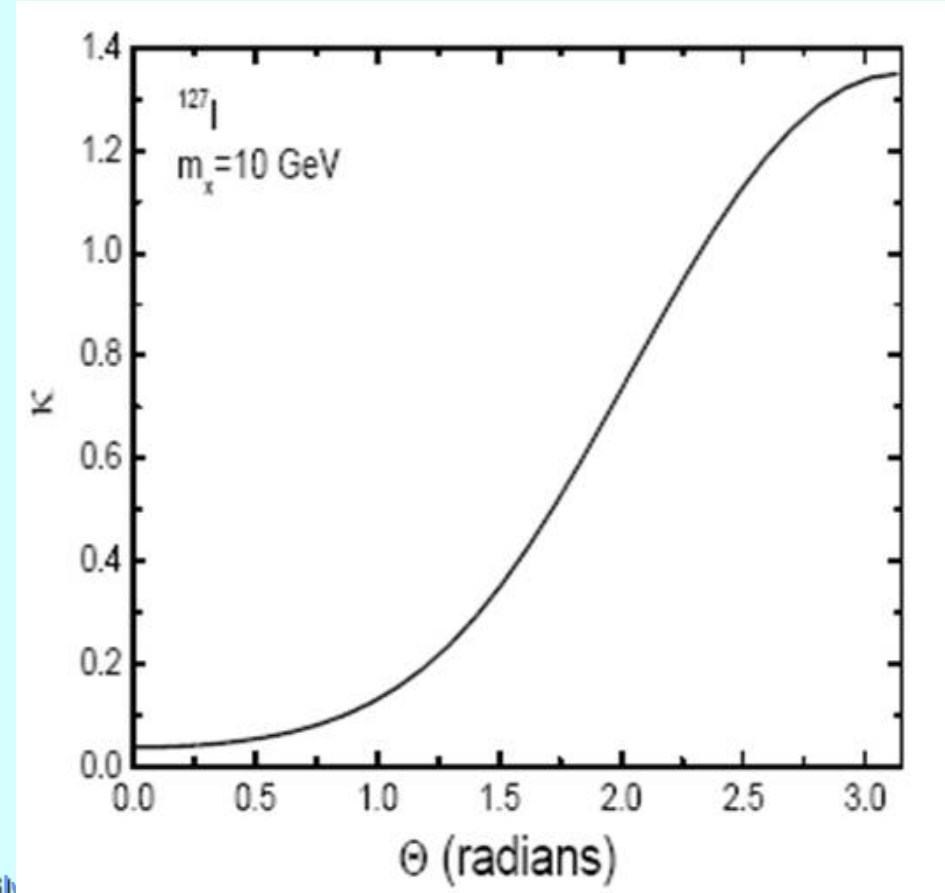


The parameter κ vs Θ for m_χ=10 GeV(Directional rates with Ch. Moustakidis)

For ^{32}S

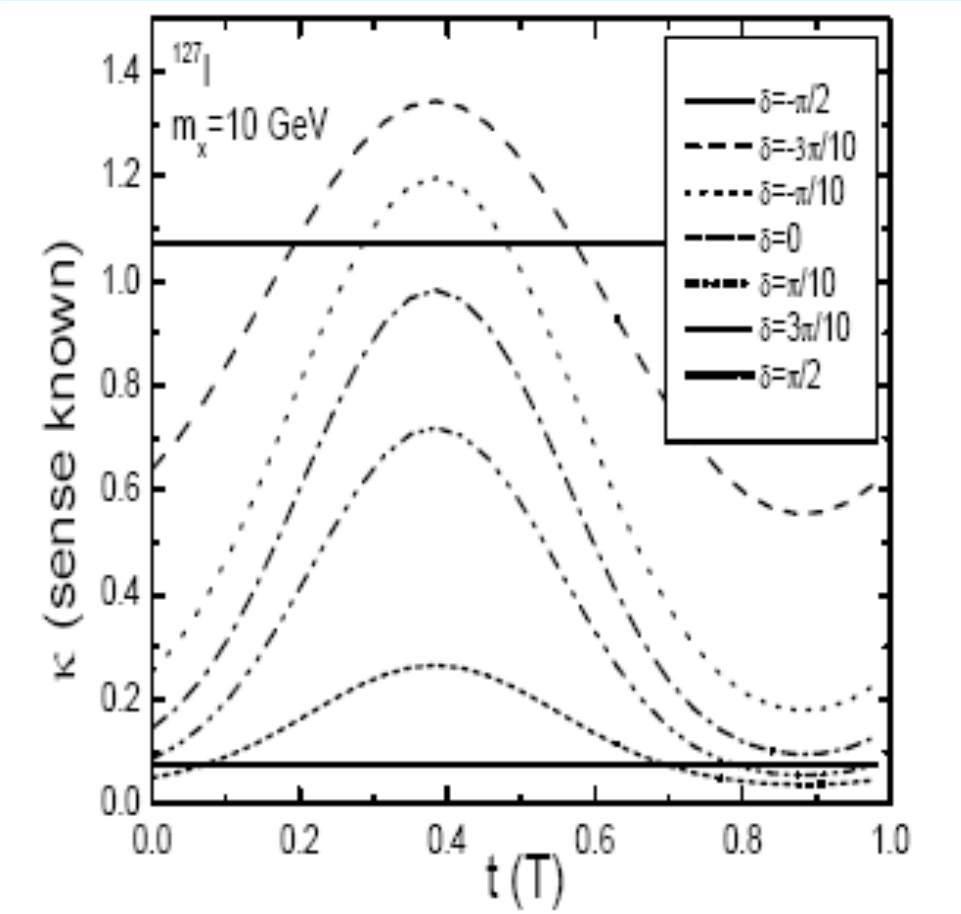


For ^{127} I

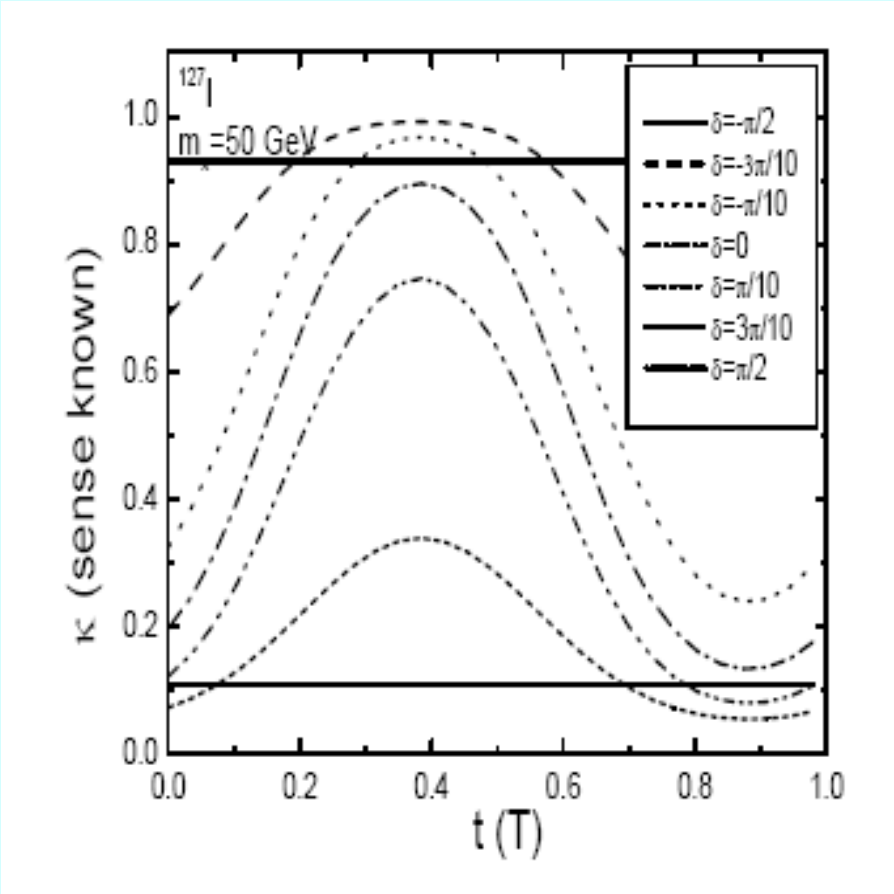


Diurnal Variation of the rate (κ) Iodine Target & Fully Directional

WIMP MASS 10 GeV

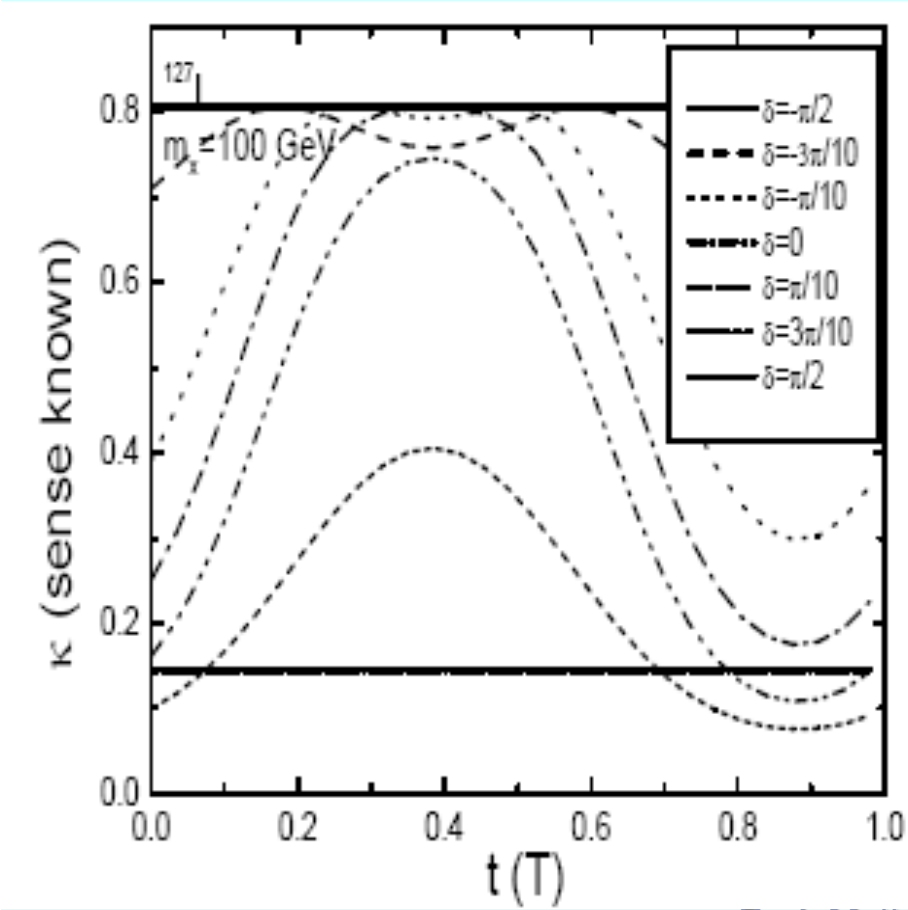


WIMP MASS 50 GeV

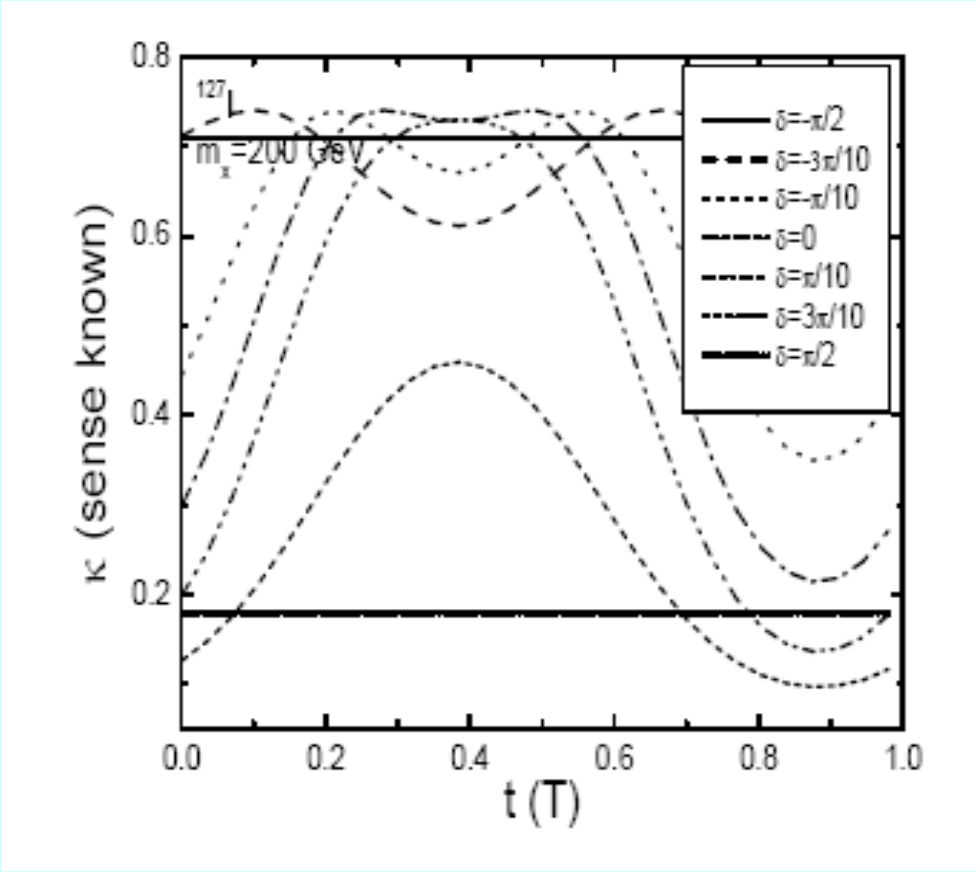


Diurnal Variation of the rate (κ) Iodine Target & Fully Directional

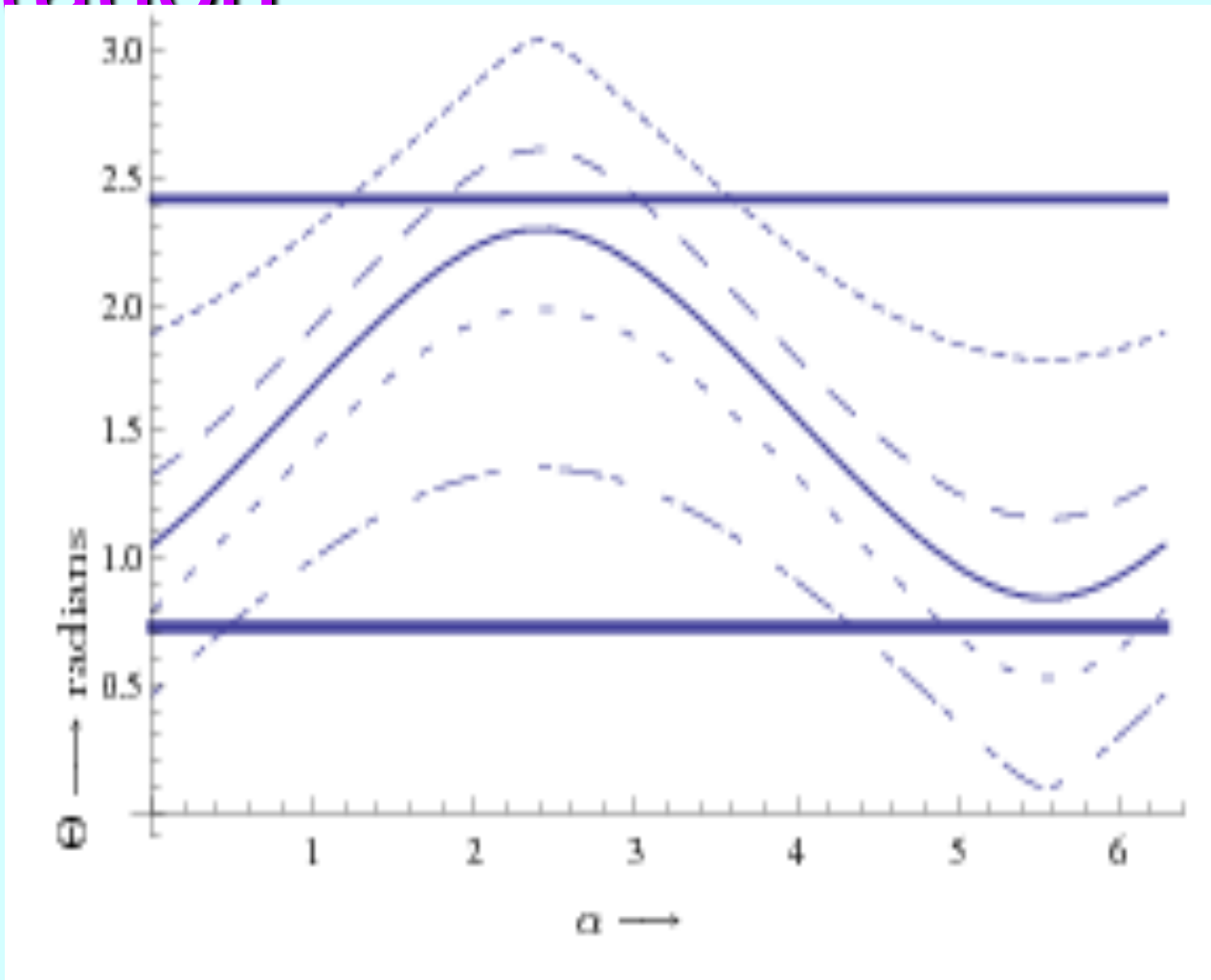
WIMP MASS 100 GeV

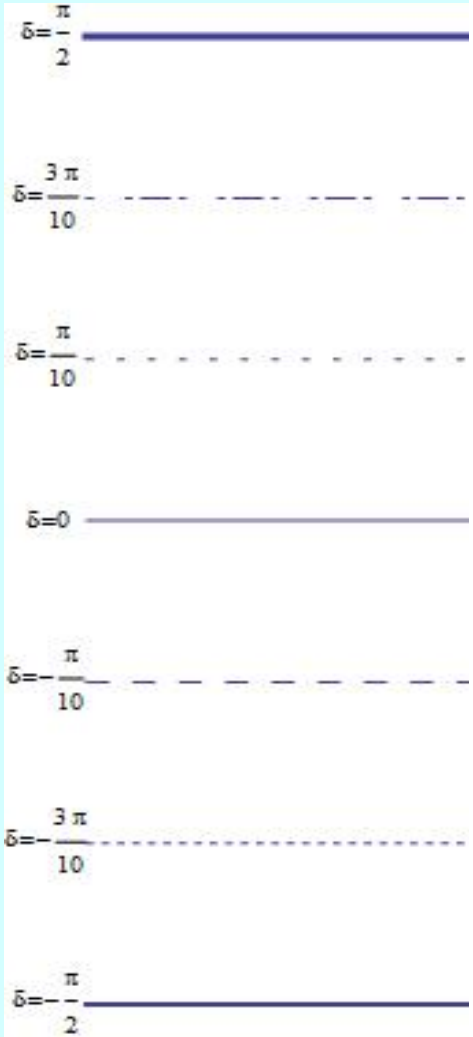


WIMP MASS 200 GeV



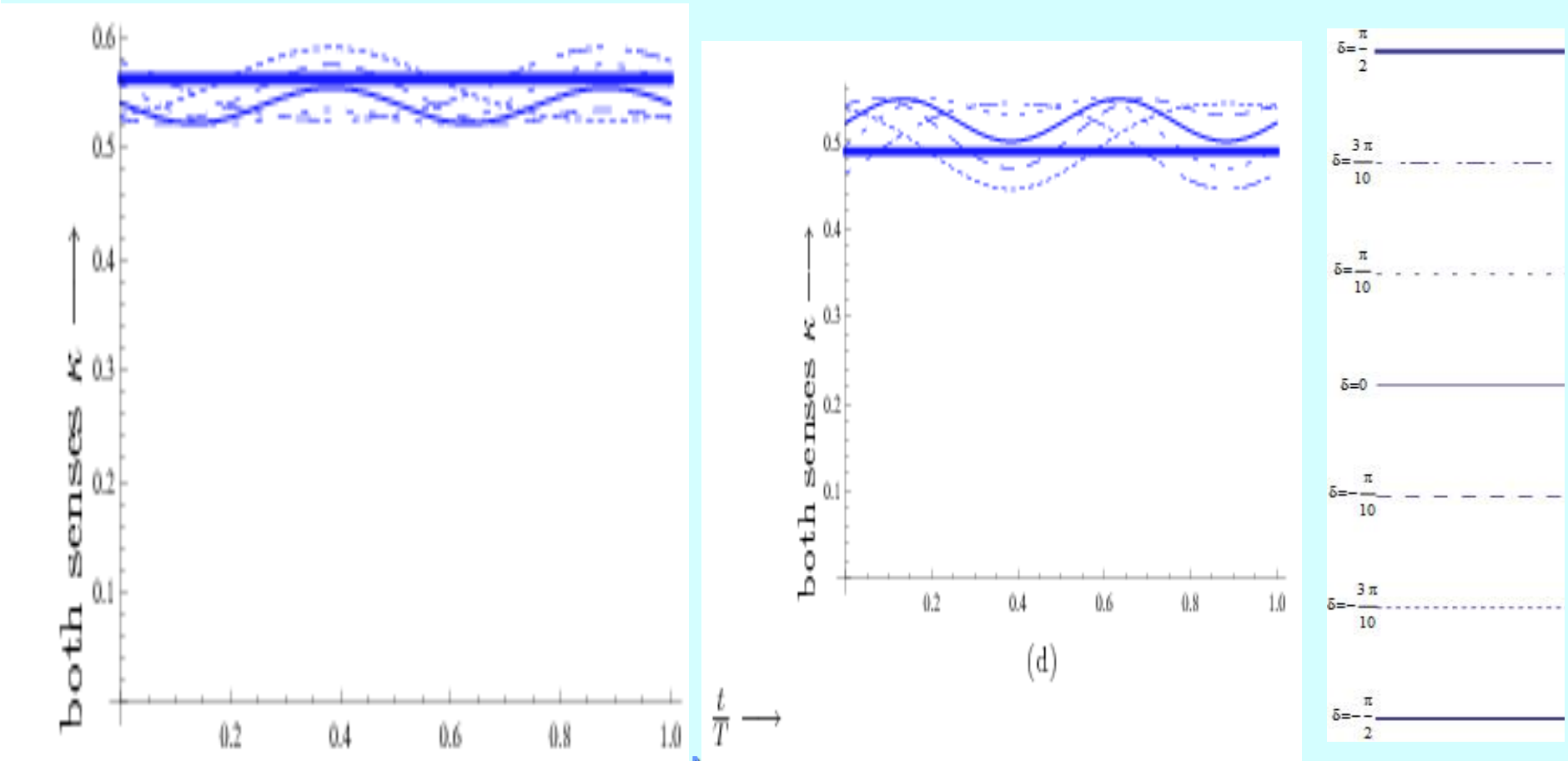
The rate depends on θ. θ depends on time due to the earth's rotation



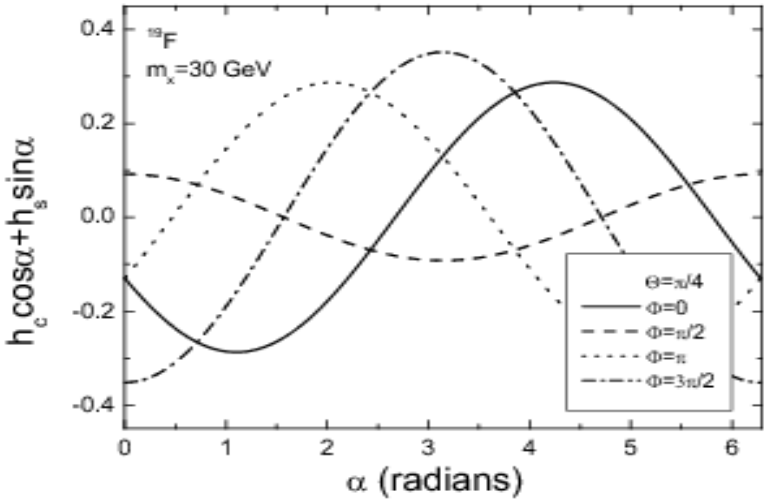


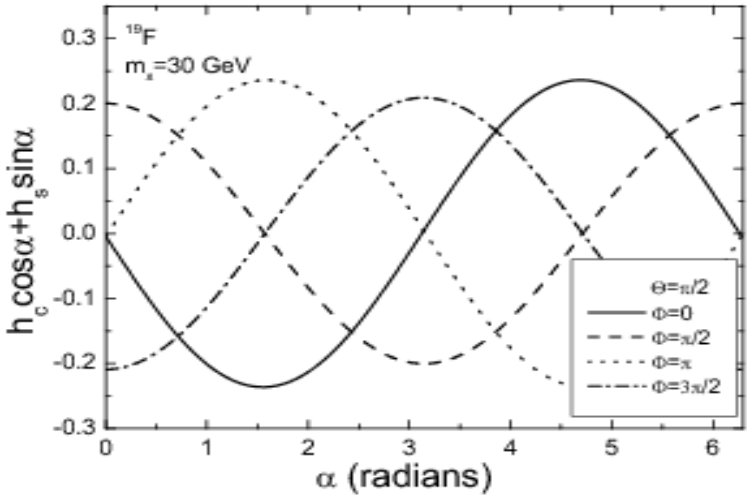
Diurnal Variation of the rate (κ) Iodine Target& partly Directional

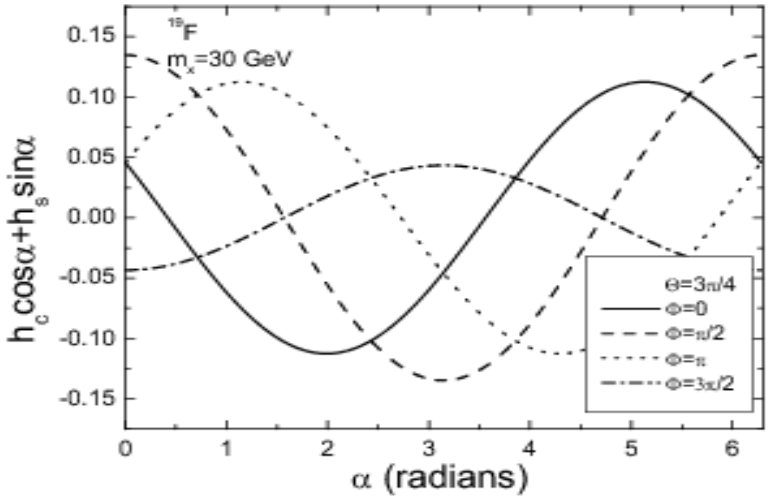
WIMP MASS 10 GeV **WIMP MASS 100 GeV**



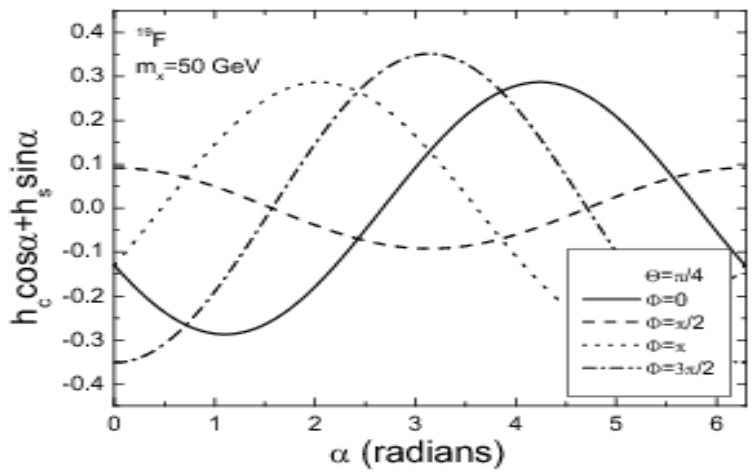
Modulation vs the phase of the earth.

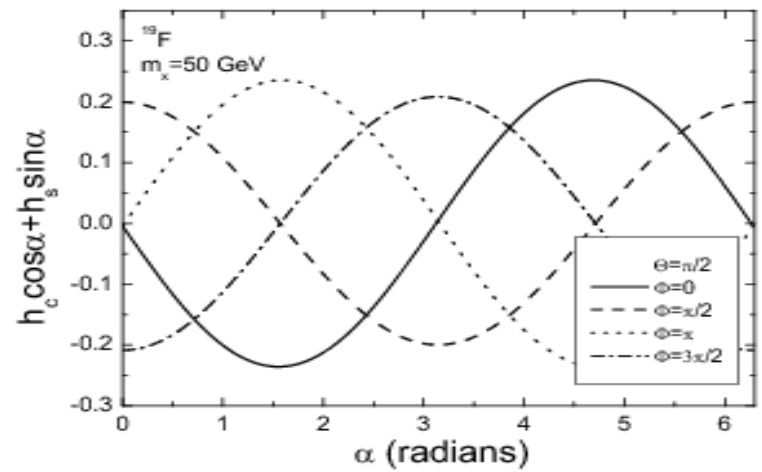


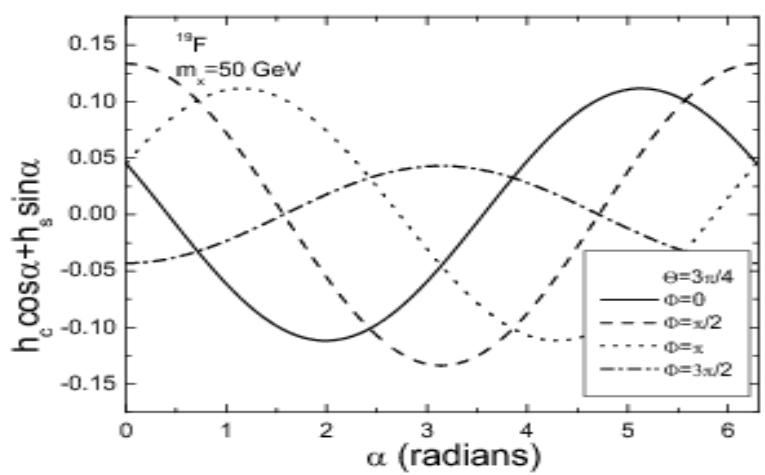




Modulation vs the phase of the earth.





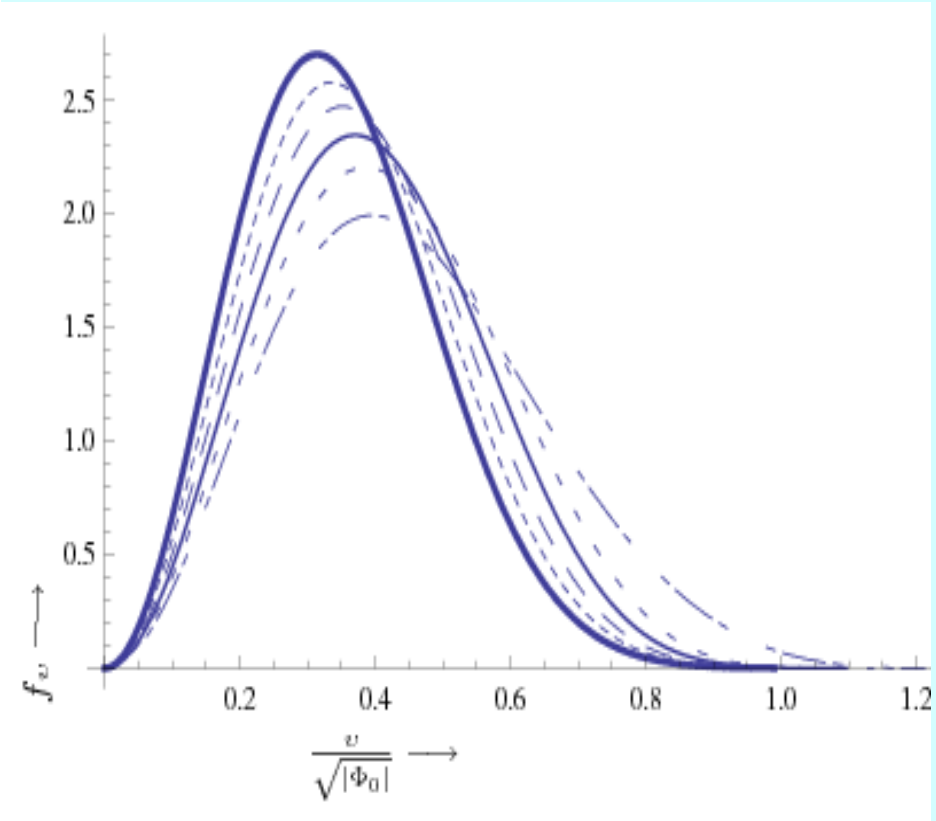


The Next step is to use realistic Asymmetric Velocity Distribution

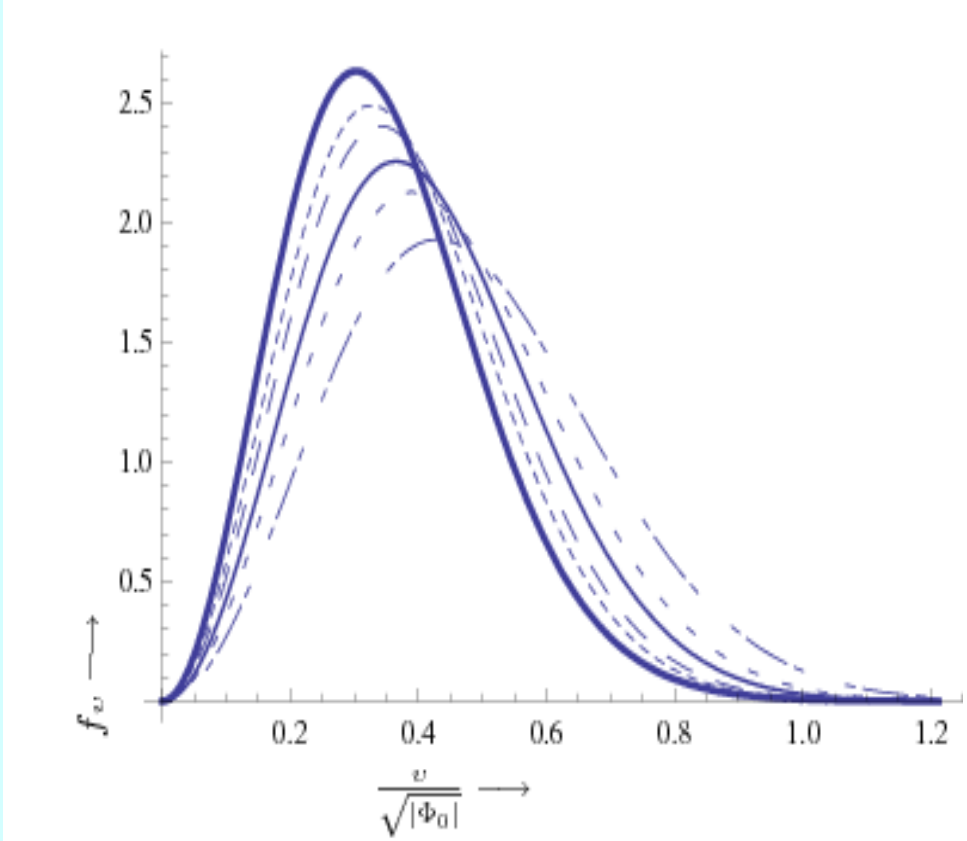
- Obtained from Realistic Density Profiles In the Eddington Approach
- The asymmetry parameter β is linked to the angular momentum of DM fluid
- It can be fitted to an Axially Symmetric M-B Velocity Distribution

Velocity distribution obtained in the Eddington approach

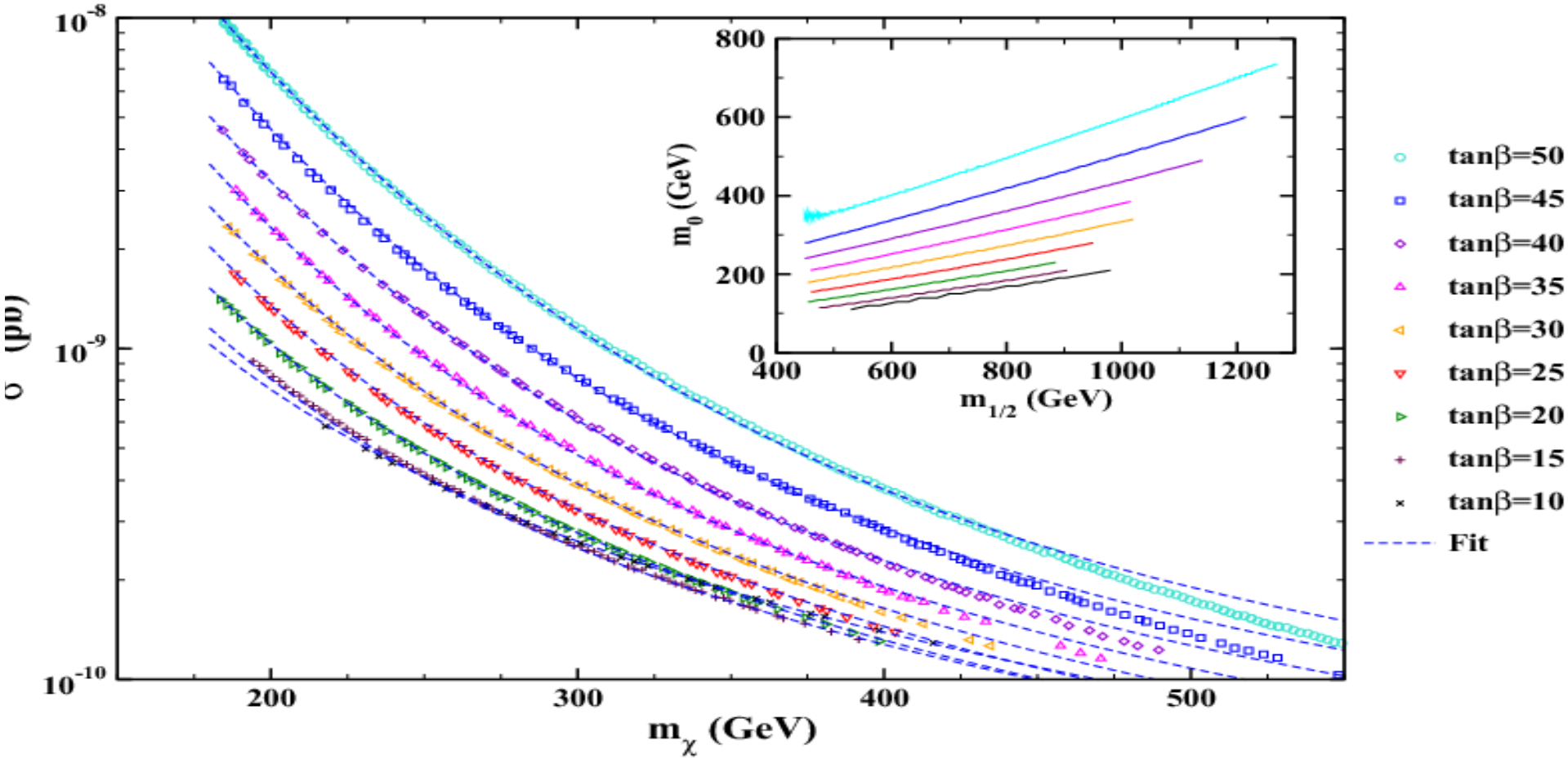
NFW Halo Density profile



Axially symmetric M-B



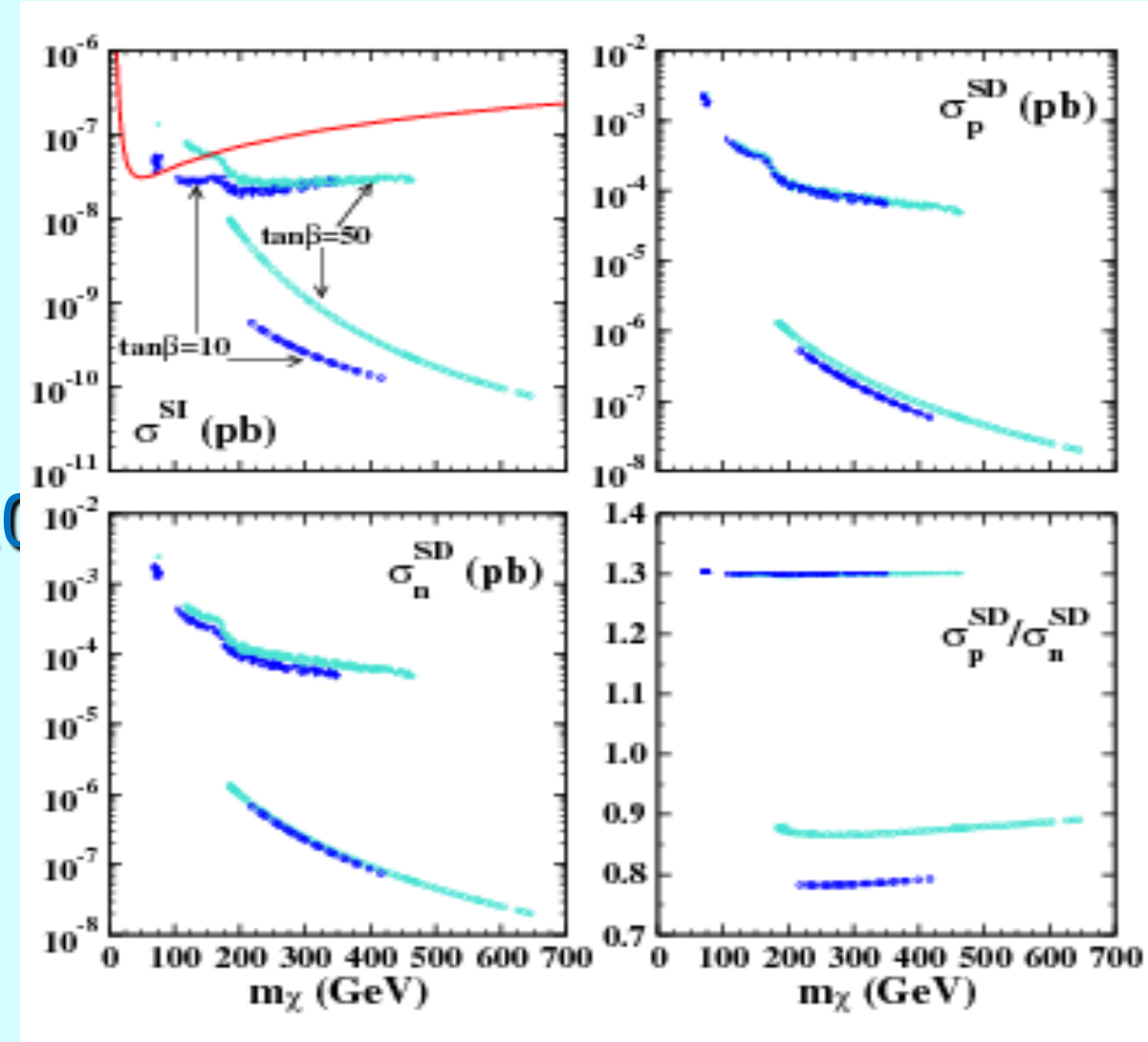
Theory: The coherent cross section vs WIMP mass: SUSY in the co-annihilation region (A_0=0, μ >0) for large WIMP masses (Cannoni, Gomez, JDV).



Cross sections in a constrained MSSM

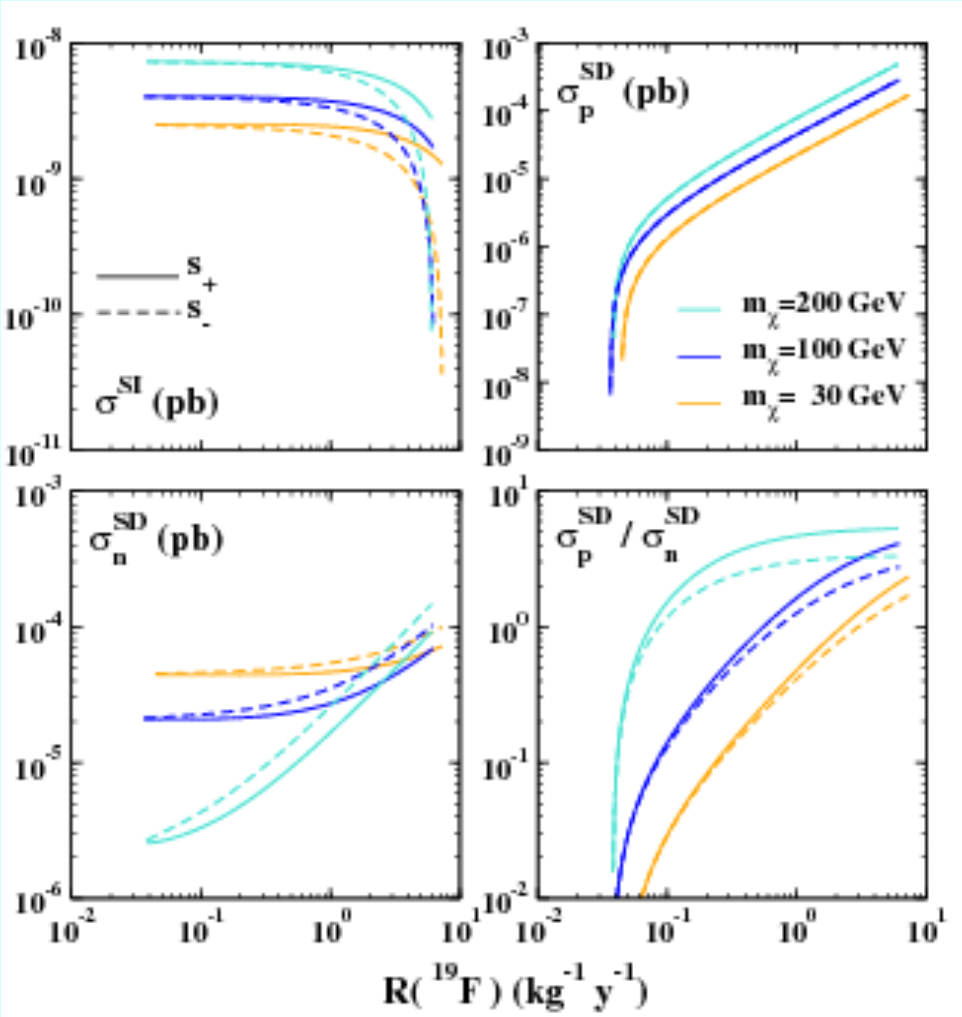
Cannoni, Gomez and JDV, PRD 83(2011)075010

- A_0=0, μ >0
- m_0 <4000 GeV
- $m_{1/2}$ <1500 GeV
- Blue<->tan β =1(
- Turquoise <->
  tan β =50
- Red: XENON100 limit

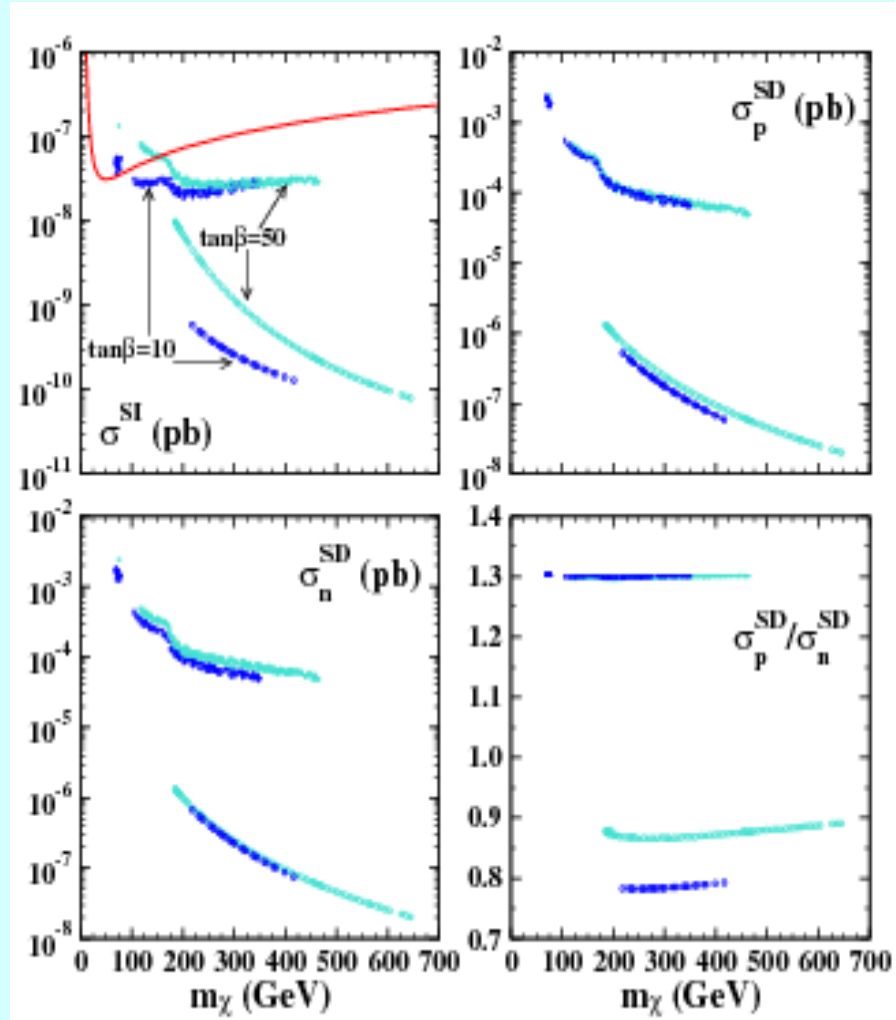


Comparison of the cross sections

Extracted



Constrained MSSM



Signatures in Directional Experiments

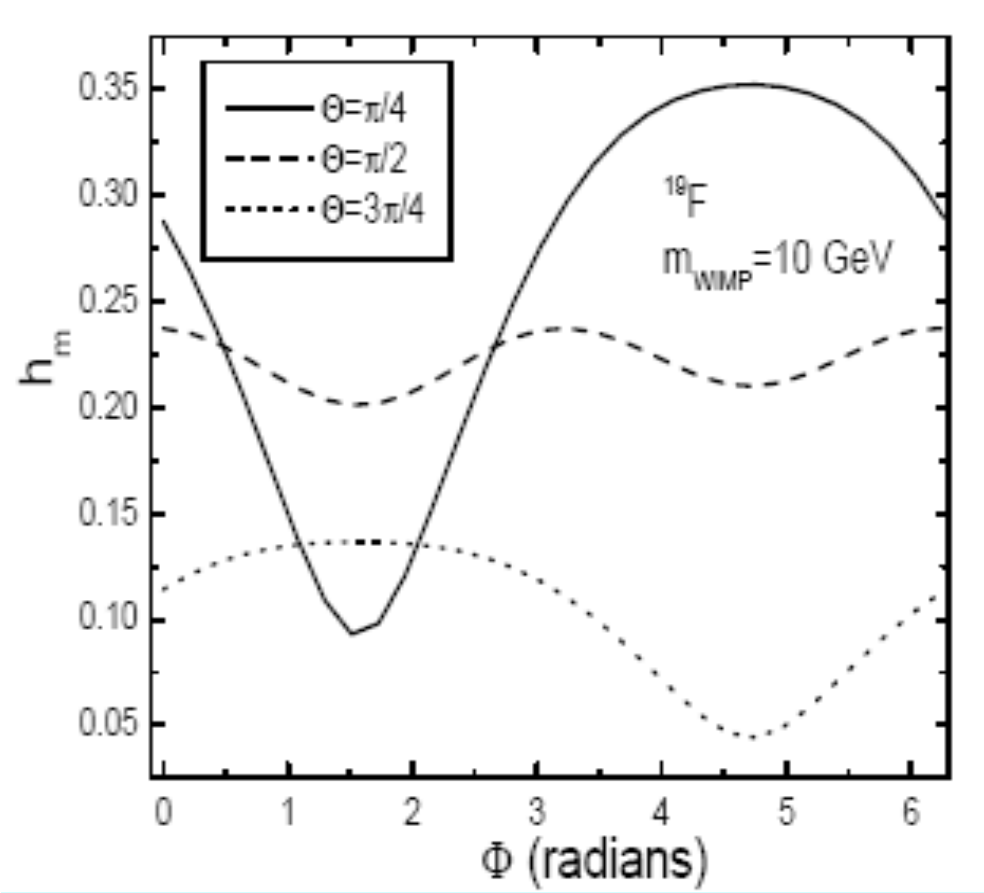
-These experiments will attempt to measure both the energy and the direction of recoiling nucleus.

- To simplify our discussion we will consider the rate in a given direction divided by the Standard rate
- This will depend on

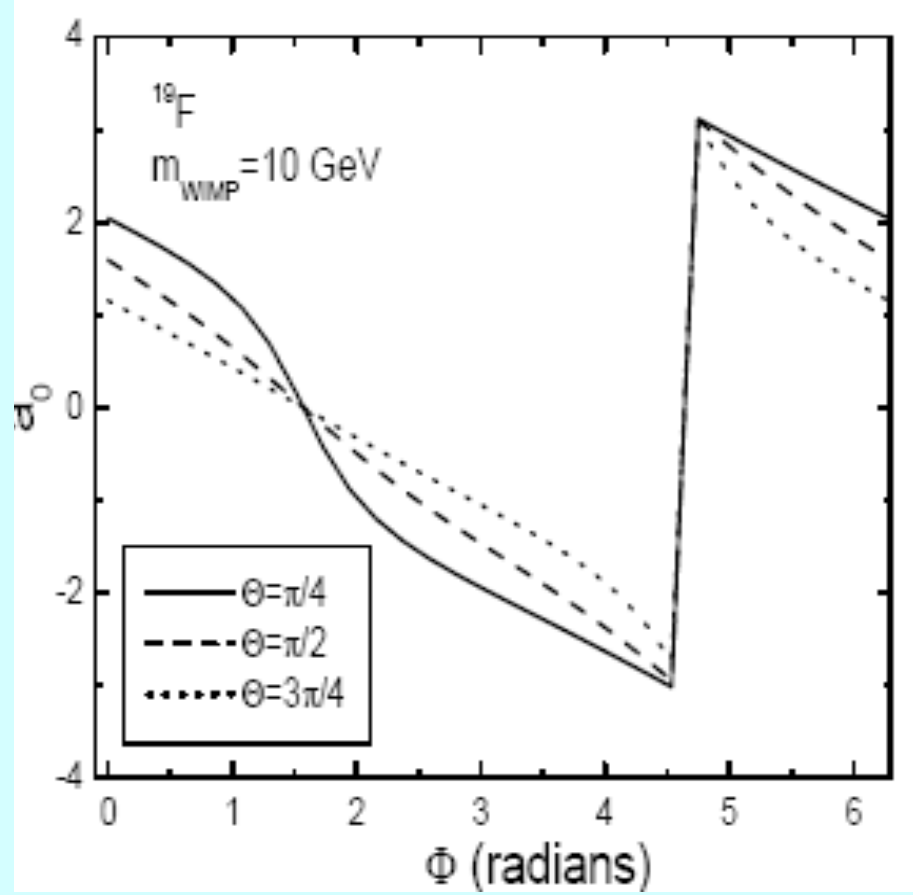
- The WIMP Mass (the only particle parameter left). This will be treated as a free parameter
- The velocity distribution of WIMP's in our galaxy
- The nuclear form factor

The total modulation amplitude vs Φ for m_χ =10 GeV for a light target

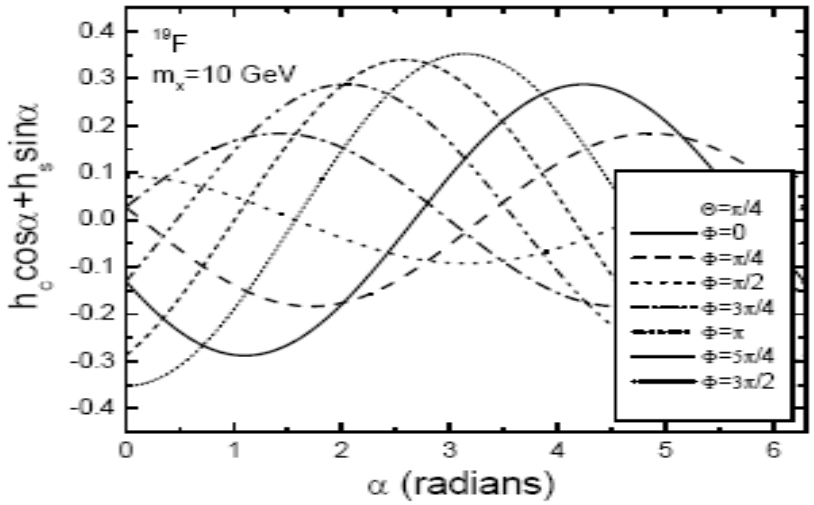
The amplitude

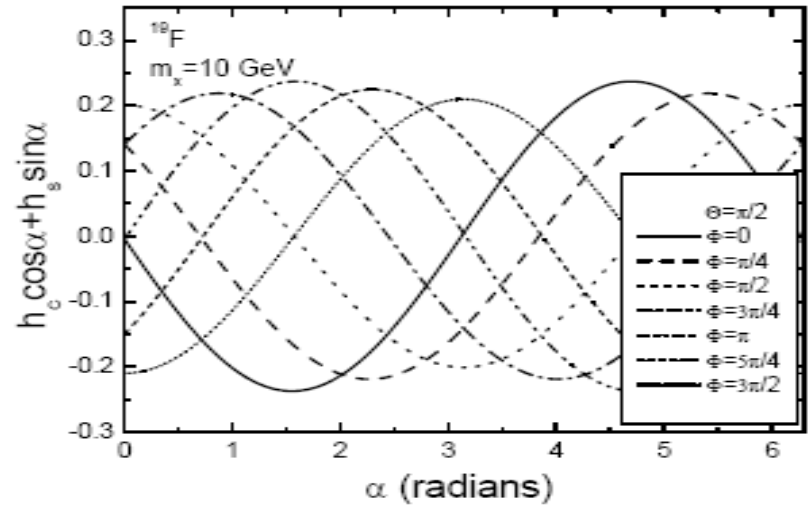


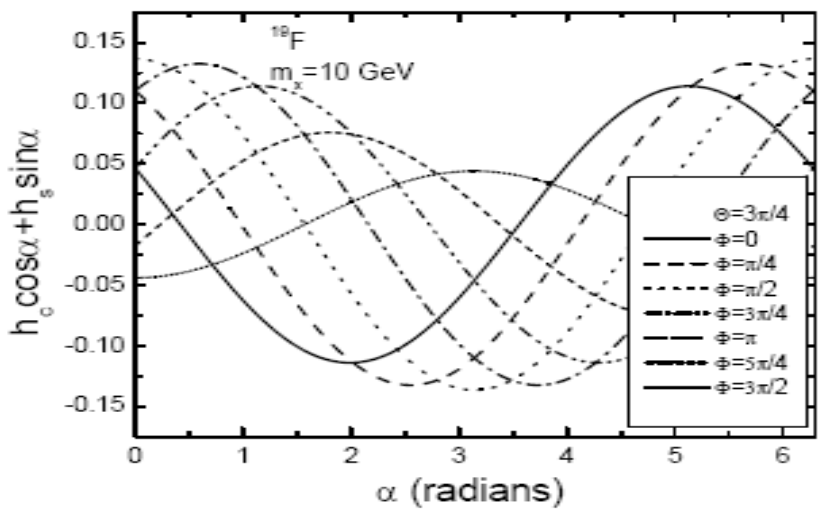
The shift in the location



Modulation vs the phase of the earth.

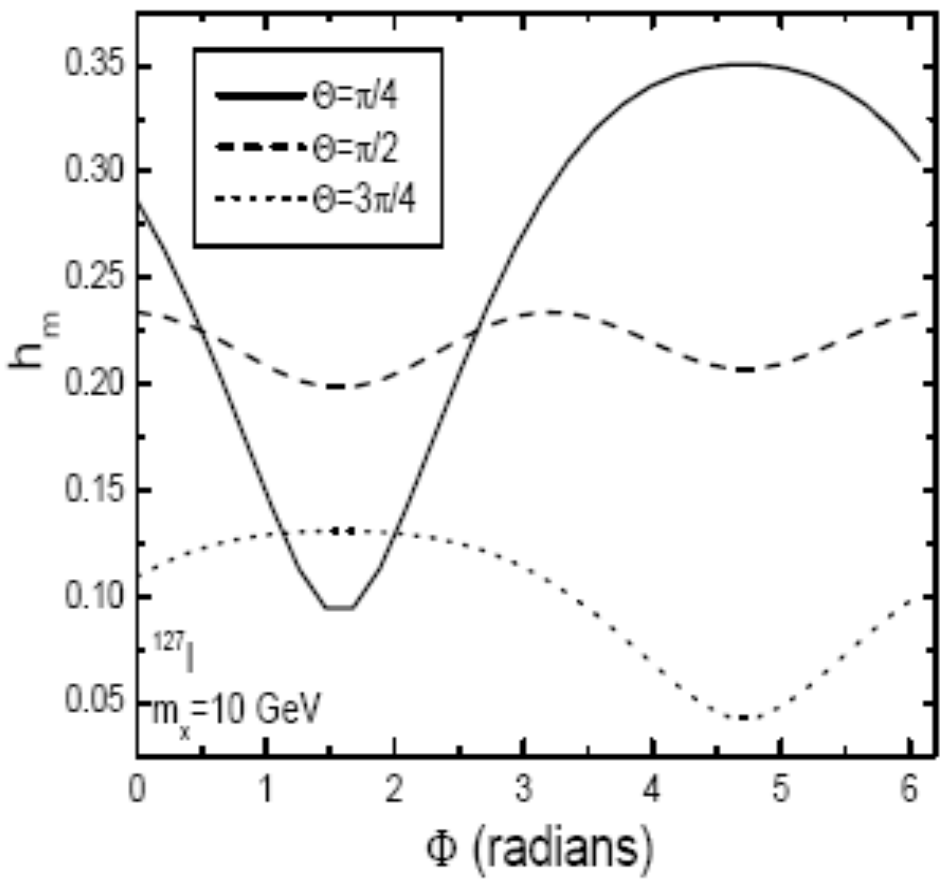




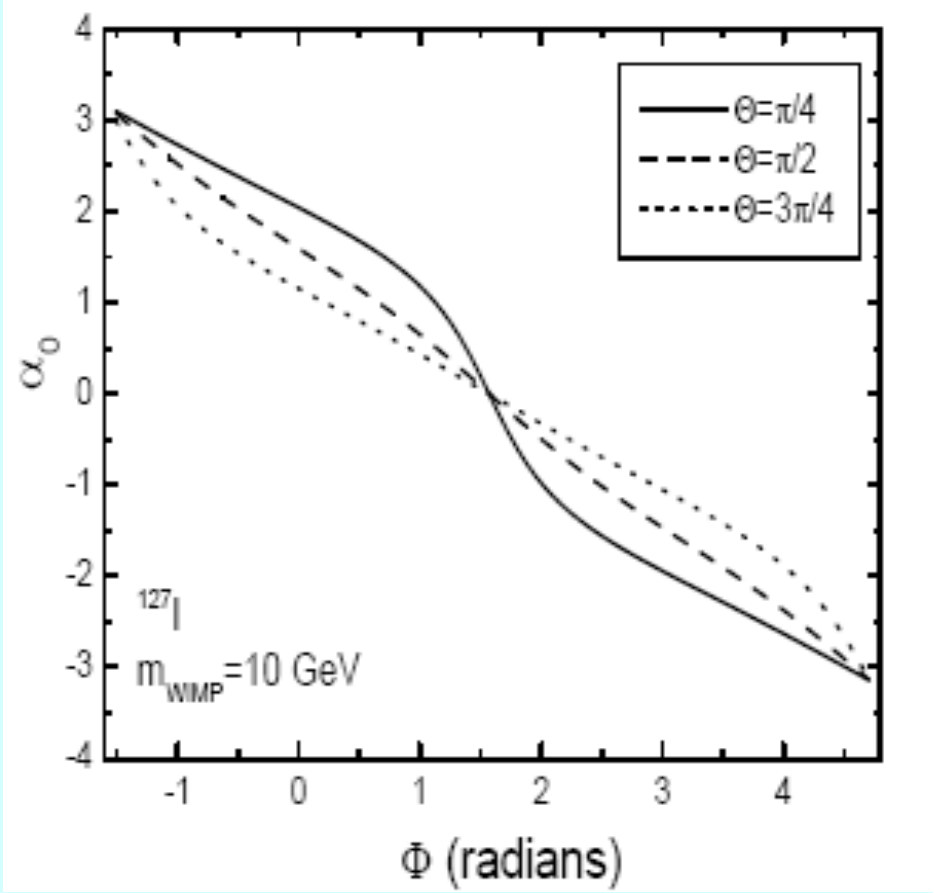
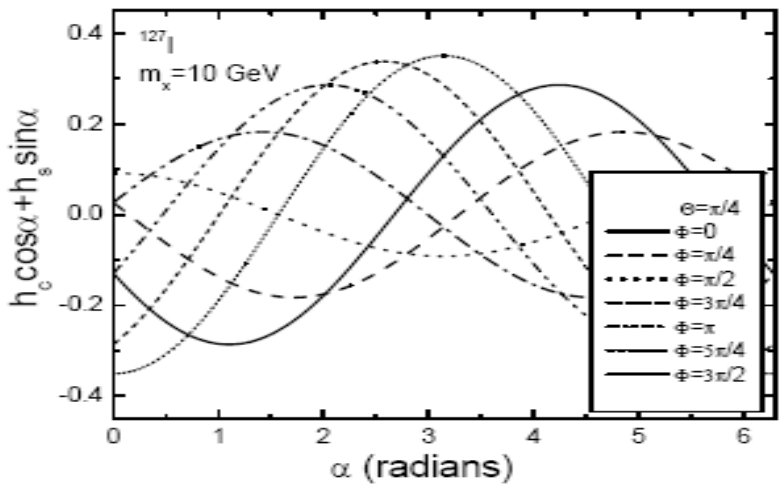
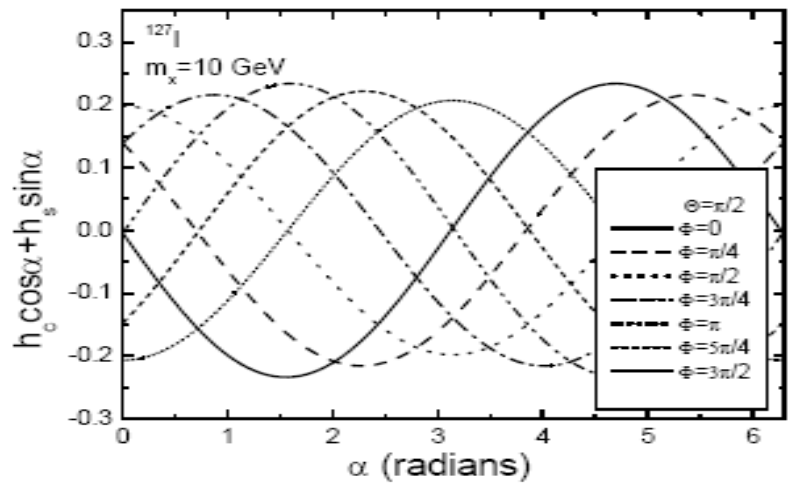
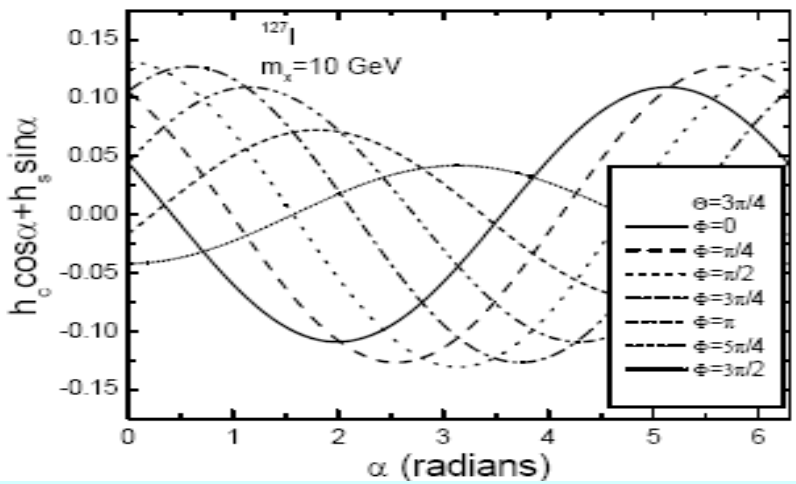


The total modulation amplitude vs Φ for m_χ =10 GeV for a heavy target

The amplitude



The shift in phase



Modulation vs the phase of the earth.