Directional Experiments: Special Signatures in Dark Matter Searches

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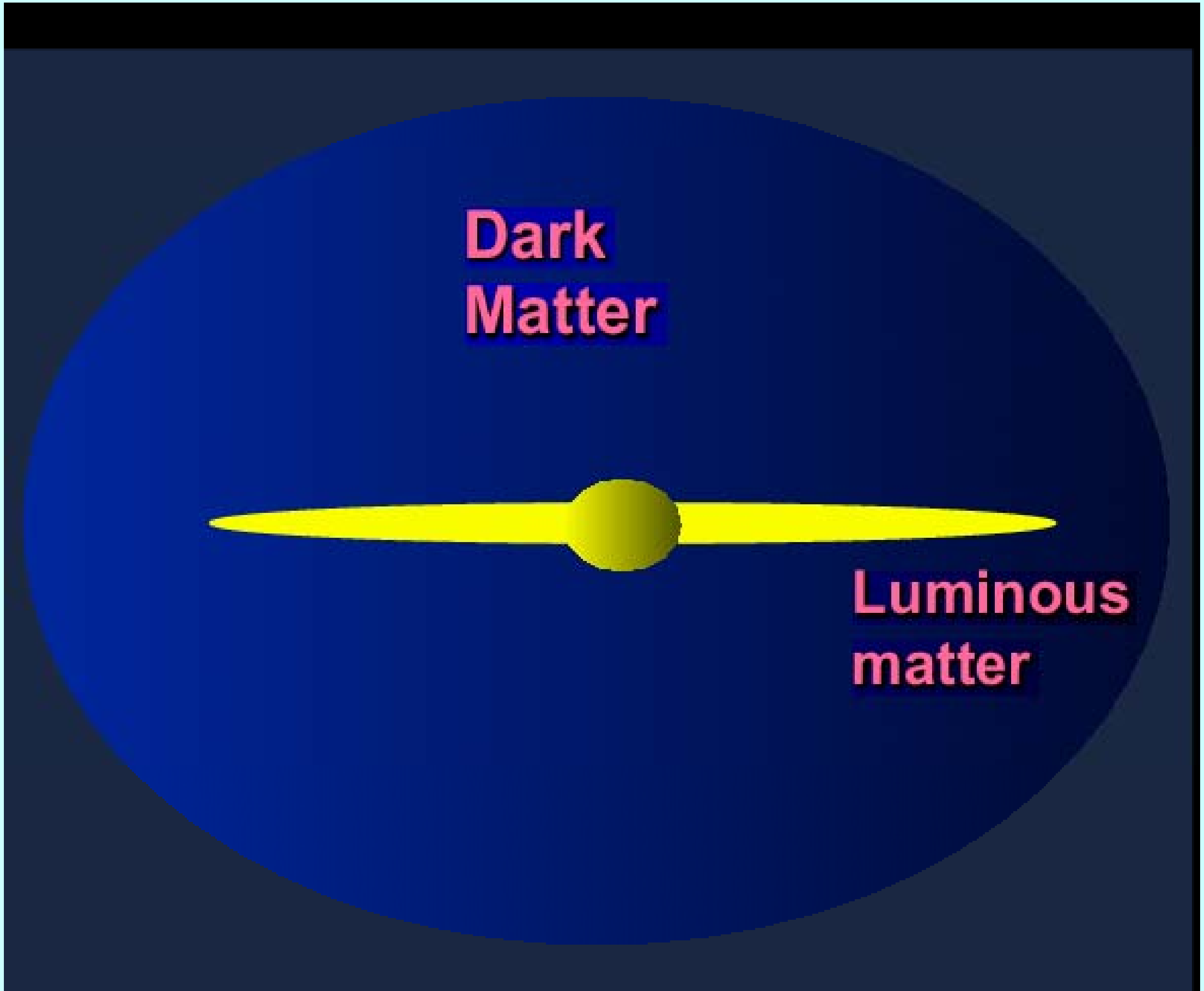
EVIDENCE FOR THE EXISTENCE OF DARK MATTER

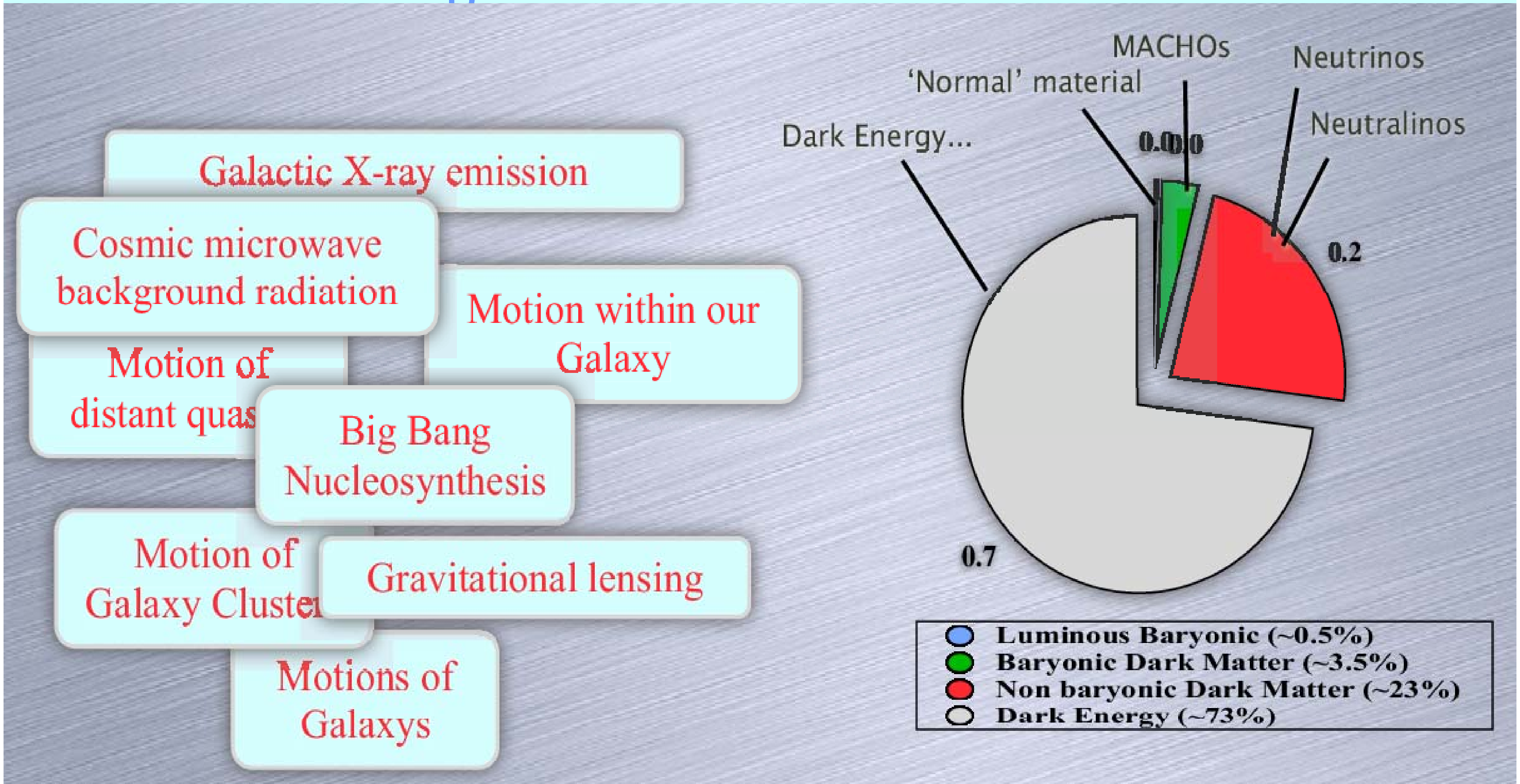
- Gravitational effects around galaxies
- The recent observation of the collision of two galaxy clusters (to-day 3.5×10^9 ly away from us, 2×10^6 ly apart)
- Cosmological Observations (confirmed by the recent WMAP3 ; together with dark energy)

If we could see Dark Matter



Slicing the Pie of the Cosmos WMAP3:

Ω_{CDM} =0.24±0.02, Ω_{Λ} =0.72±0.04, Ω_b =0.042±0.003



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.

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-νετρίνο: Excluded on the basis of results of underground experiments and accelerator experiments (LEP)

ii) Gravitino: Not directly detectable

iii) Axino: 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)

Rate in a given direction of recoil/ Standard non directional rate

- The WIMP Mass (the only particle parameter needed). Free parameter
- The WIMP velocity distribution
- The nuclear form factor

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, $\upsilon_{MB} = \upsilon_0 = 220$ km/s,

  and escape velocity $\upsilon_{esc} = 2.84\upsilon_0$ put in by hand.
- (2) Modification of M-B characteristic velocity υ_{MB} following the interaction of dark matter with dark energy:

  $\upsilon_{MB} = n\upsilon_0$, $\upsilon_{esc} = n2.84\,\upsilon_0$, $n>1$

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

  $\rho(\mathbf{r}) \Leftrightarrow \Phi(\mathbf{r}) \Leftrightarrow f(\mathbf{r},\mathbf{v})$ (JDV-Owen)
- Realistic axially symmetric velocity distributions obtained via simulations ⇒ Tsallis type functions (Hansen and JDV)
- Other non-thermal models:

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

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

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

$$\left(1-\frac{(1-q)v^2}{(3-q)\sigma^2}\right)^{\frac{q}{1-q}} \longrightarrow Exp(-v^2/2\sigma^2) \text{ as } q \longrightarrow 1$$

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

Tsallis type functions (for radial and Tangential components) $\rightarrow$ MB as $q \rightarrow 1$

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

- Adopt: q=3/4

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

- Adopt: q=5/3

MB and Tsallis functions. Asymmetry β (Hansen and JDV)

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

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

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

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

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

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.

The event rate for the coherent mode

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

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

with

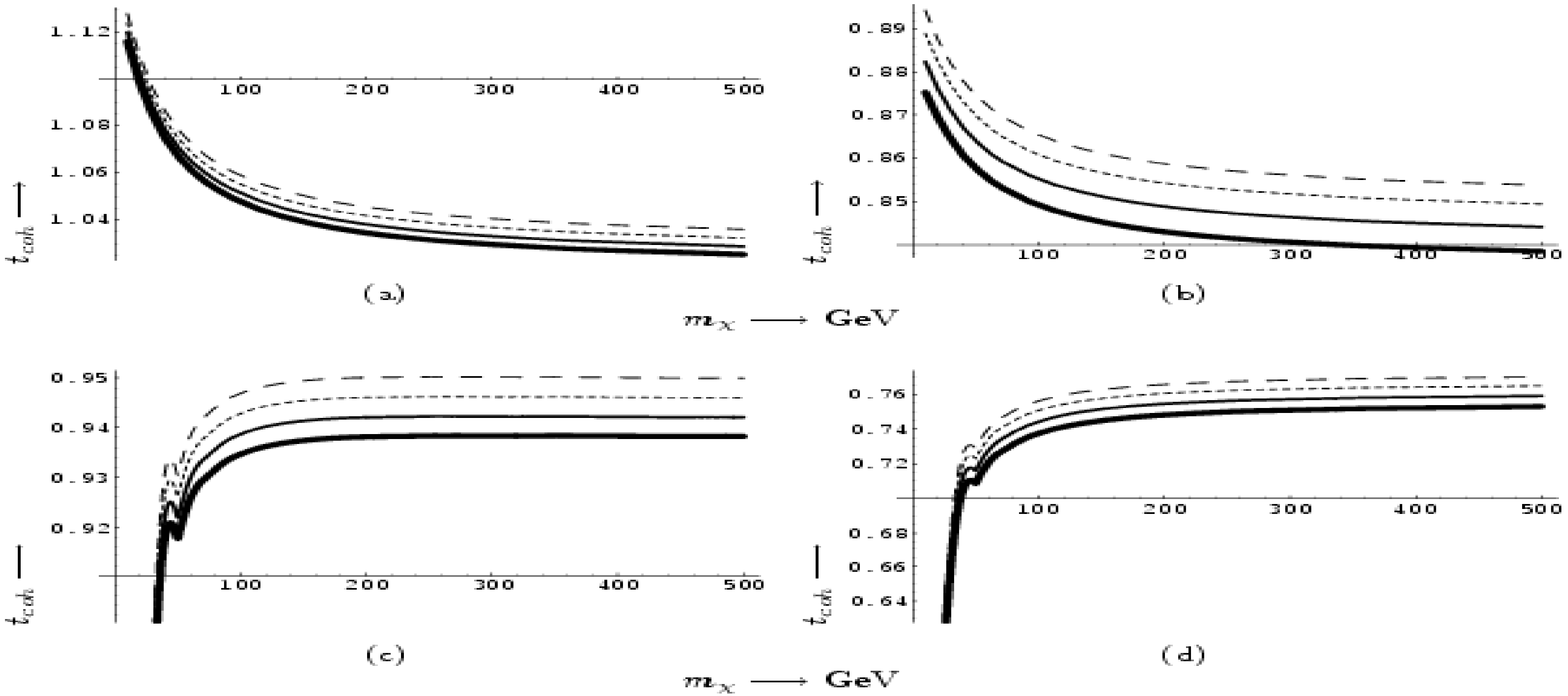
$$f_{coh}(A, \mu_r(A)) = \frac{100\mathrm{GeV}}{m_{\chi^0}} \left[\frac{\mu_r(A)}{\mu_r(p)}\right]^2 A^2\ t_{coh}\,(1 + h_{coh} cos\alpha)$$

Where:

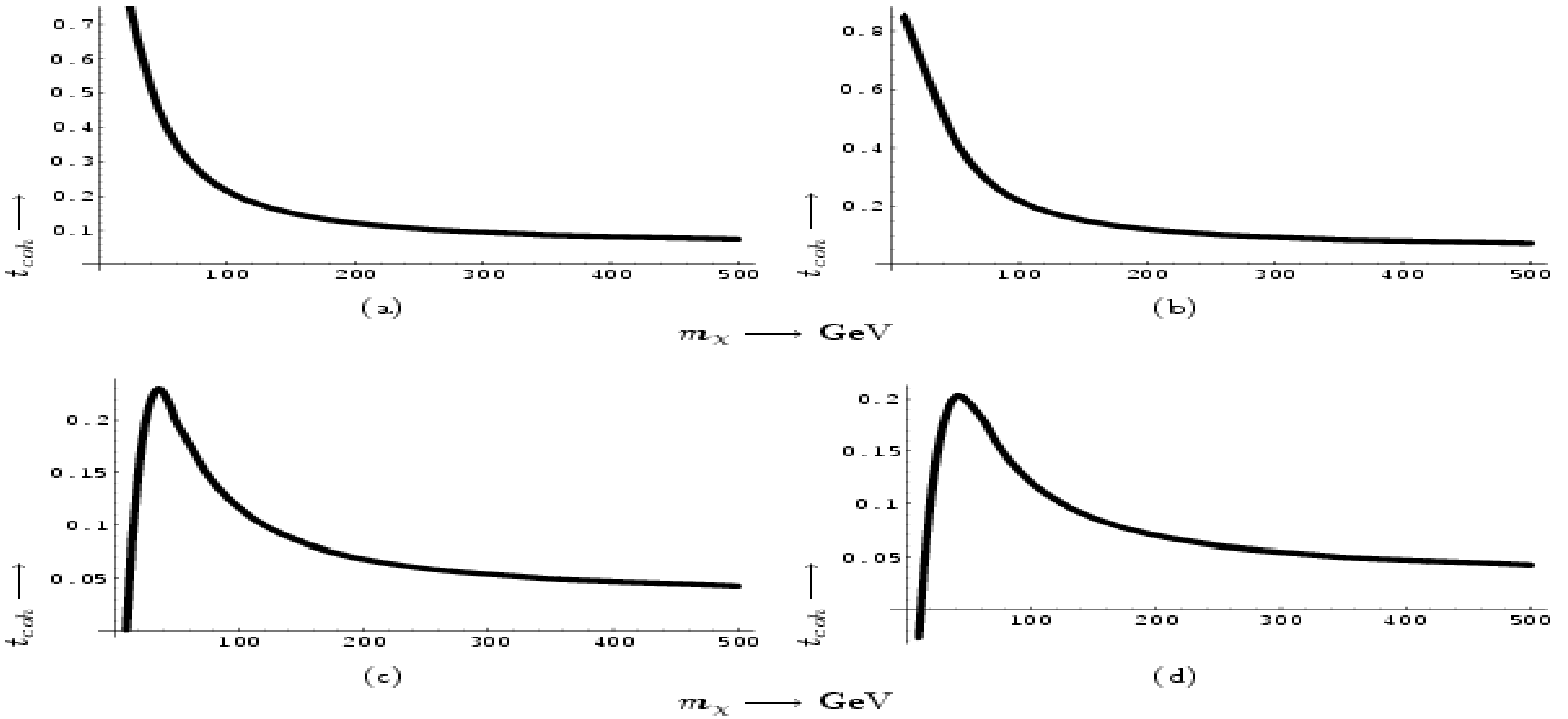
- t depends on nuclear physics, the WIMP mass and the velocity distribution
- ρ(0): the local WIMP density≈0.3 GeV/cm^3.

$\sigma^S_{p,\chi}$: 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

t_{coh} for a light target. Q_{thr} =0 (top), 5keV (bottom); MB ⑩Left, Tsallis form⑩Right (asymmetry shown in both)



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



Novel approaches: Exploitation of other signatures of the reaction

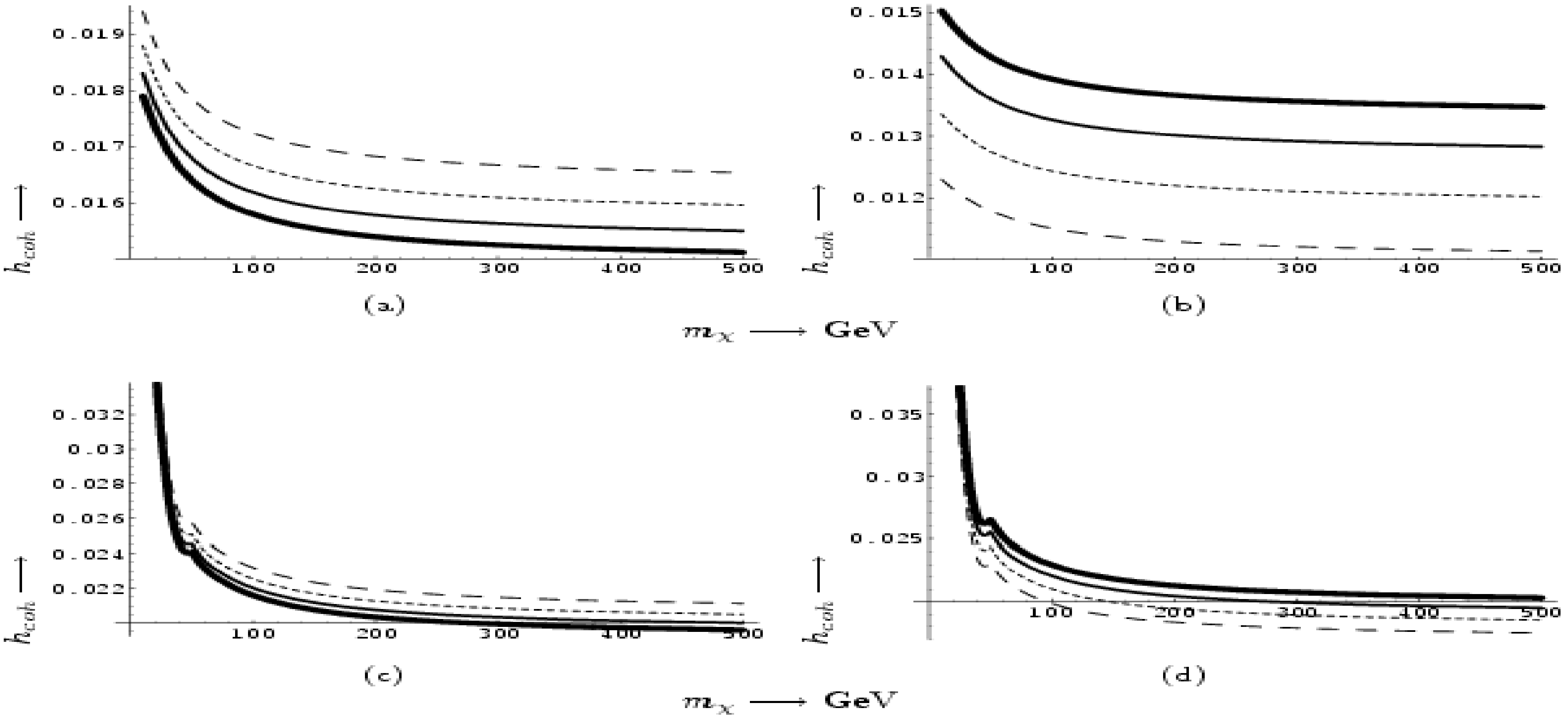
- The modulation effect: The seasonal, due to the motion of the Earth, dependence of the rate.
- The excitation of the nucleus (in some cases , heavy WIMP etc, that this is realistic) and detection of the subsequently emitted de-excitation γ rays.
- Asymmetry measurements in directional experiments (the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

THE MODULATION EFFECT* (continued)

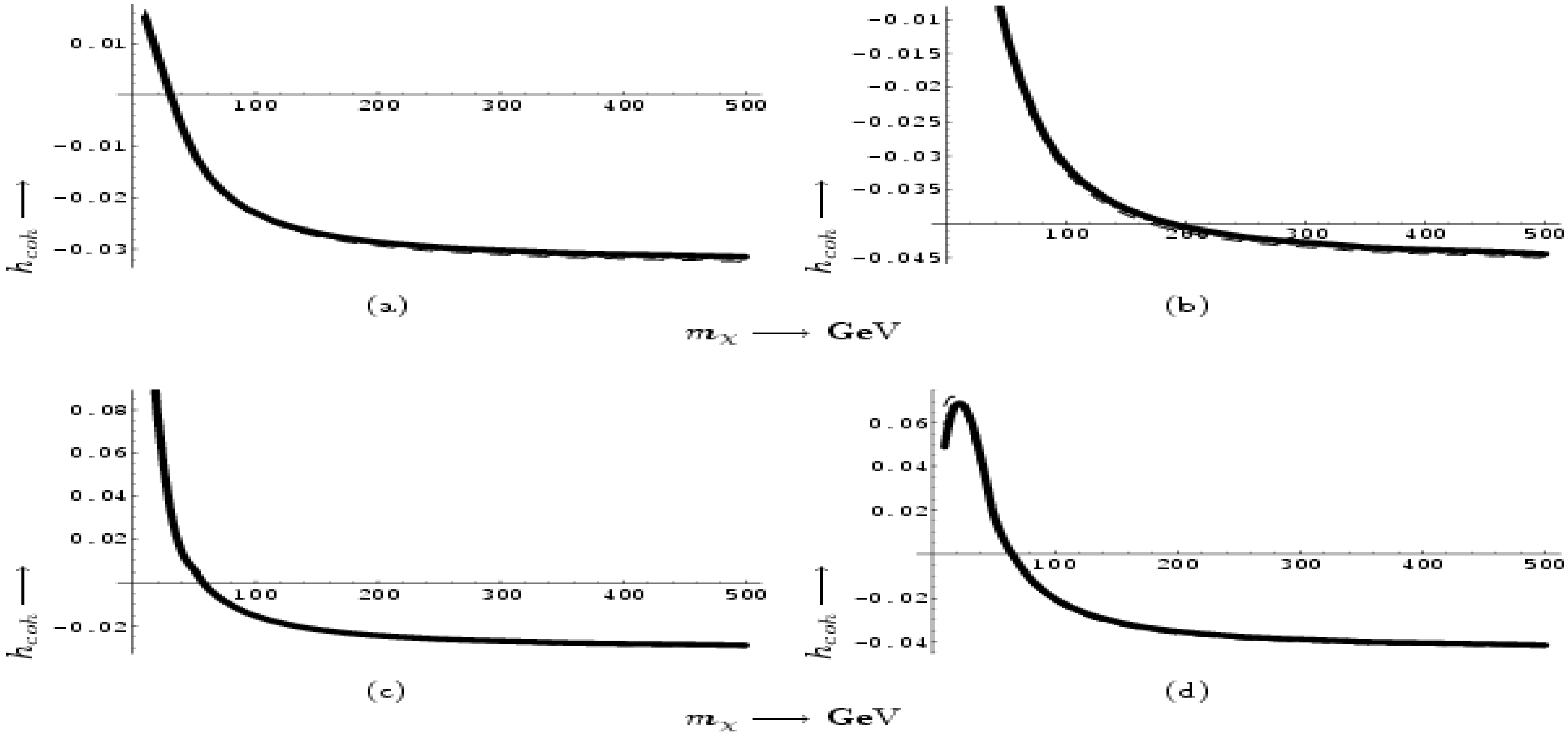
- $R=R_0\,(1+h\cos\alpha)$

 ($\alpha=0$ around June 3nd)
- h=modulation amplitude.
- R_0 =average rate.
- *n=2 corresponds to calculations with non standard M-B (Tetradis, Faeesler and JDV)

h_{coh} for a light target. Q_{thr} =0 (top), 5keV (bottom); MB ⑩Left, Tsallis form⑩Right (asymmetry shown in both)



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



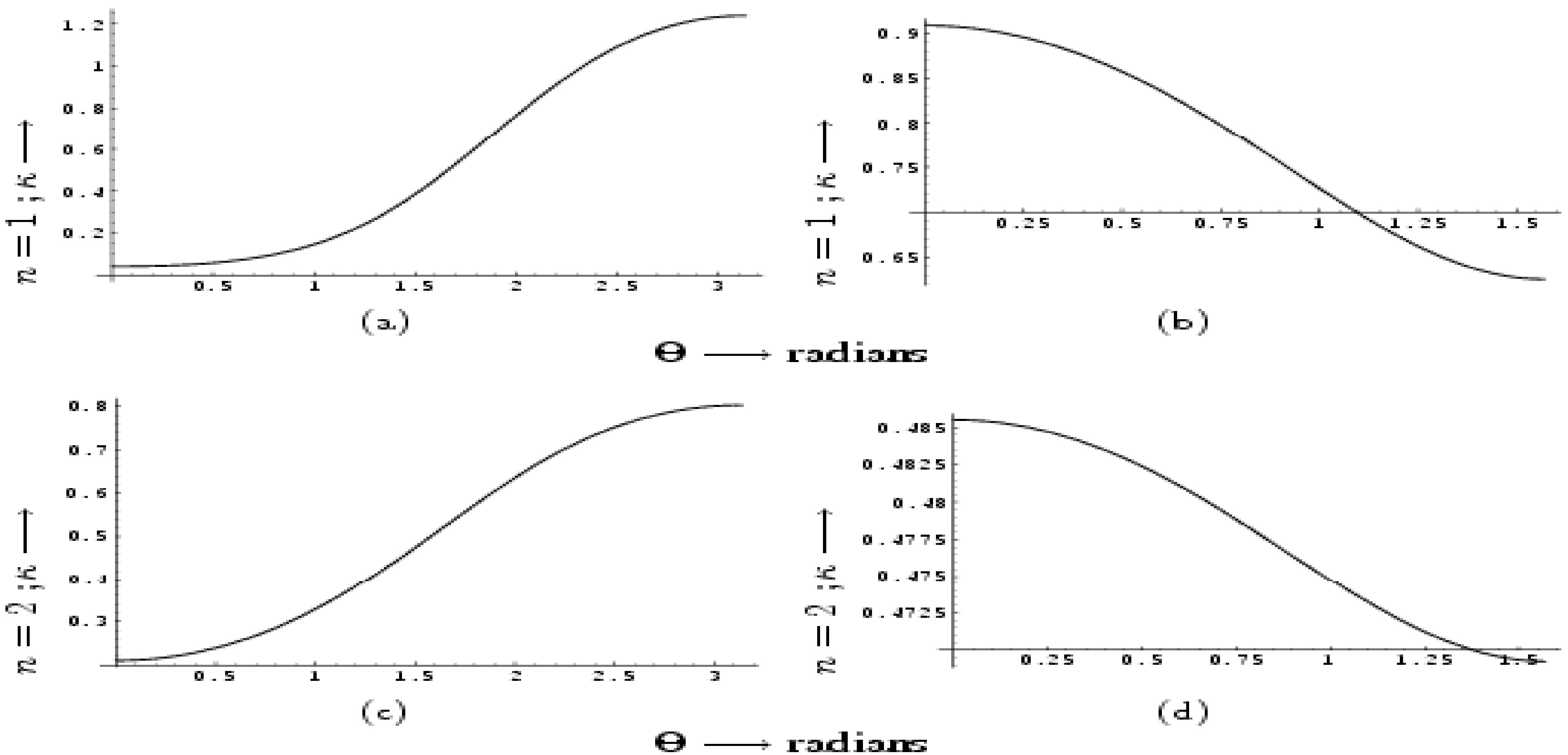
The directional event rate*
(The direction of recoil is observed)

- The event rate in directional experiments is:

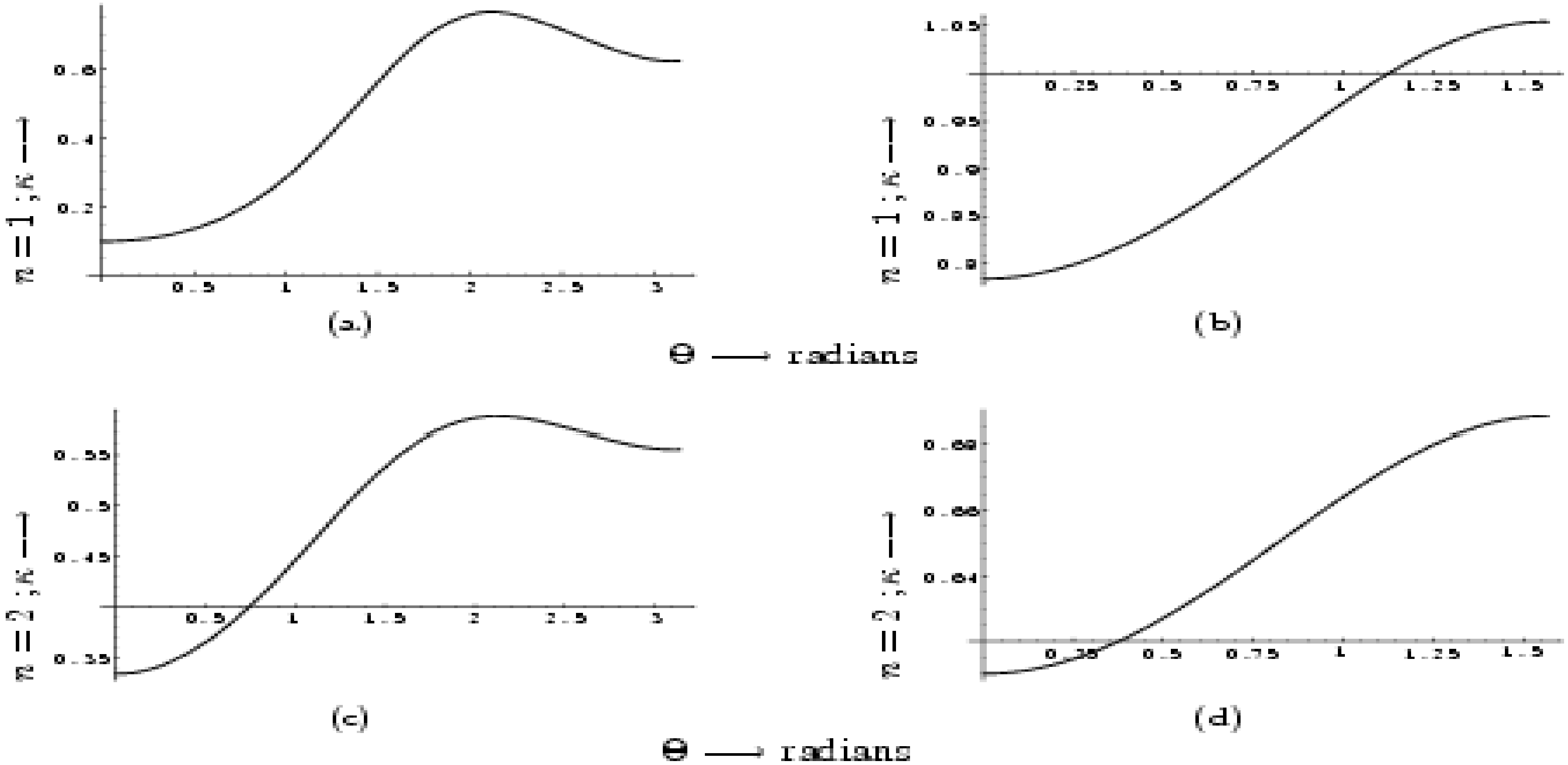
  $$R_{dir}=(\kappa/2\pi)R_0[1+h_m\cos(\alpha-\alpha_m\pi)]$$

- 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)
- K, 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 in the case of A=32; m_χ=100 GeV definite sense (Left), Both senses (Right)



The parameter κ vs the polar angle in the case of A=127; m_χ=100 GeV definite sense (Left), Both senses (Right)



What about if the recoil is not exactly in the direction of observation?

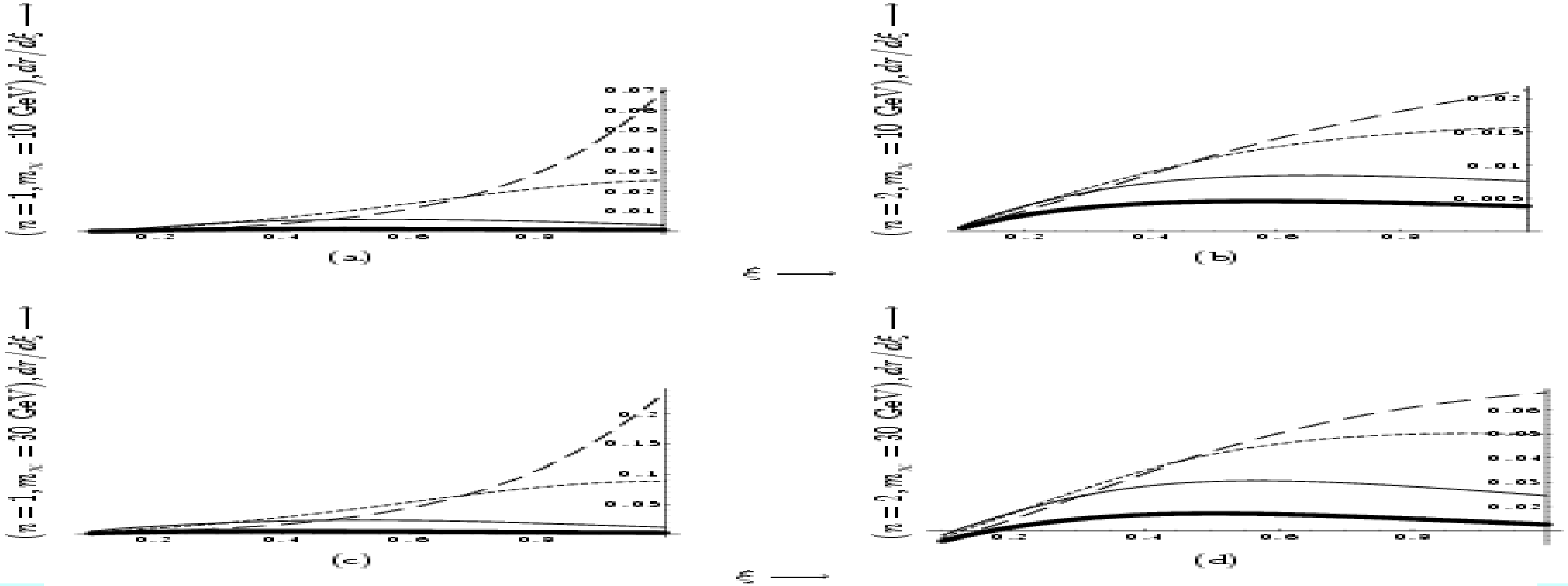


FIG. 3. The differential rate $dr/d\xi$ for ^{32}S in as function of ξ, the cosine of the angle between the line of observation and the line of recoil. The thick solid, fine solid, short, and long dash correspond to $\Theta = \pi/4$, $\pi/2$, $3\pi/4$, and π respectively.

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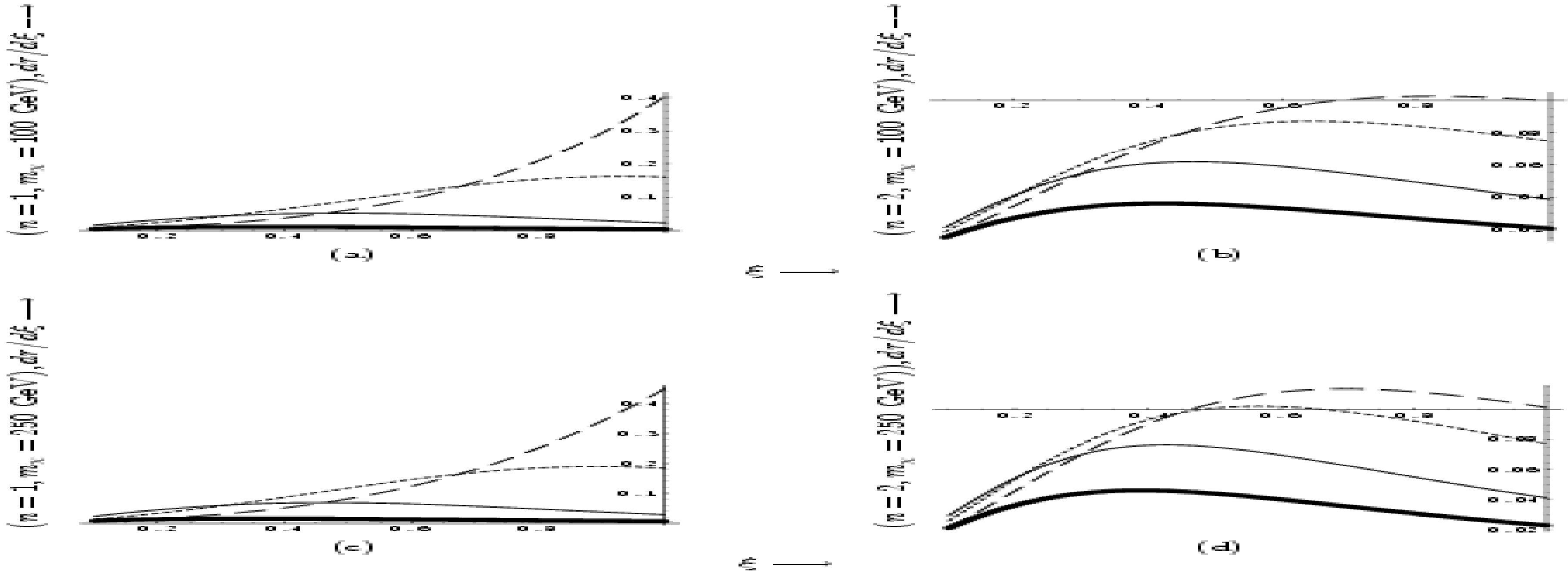

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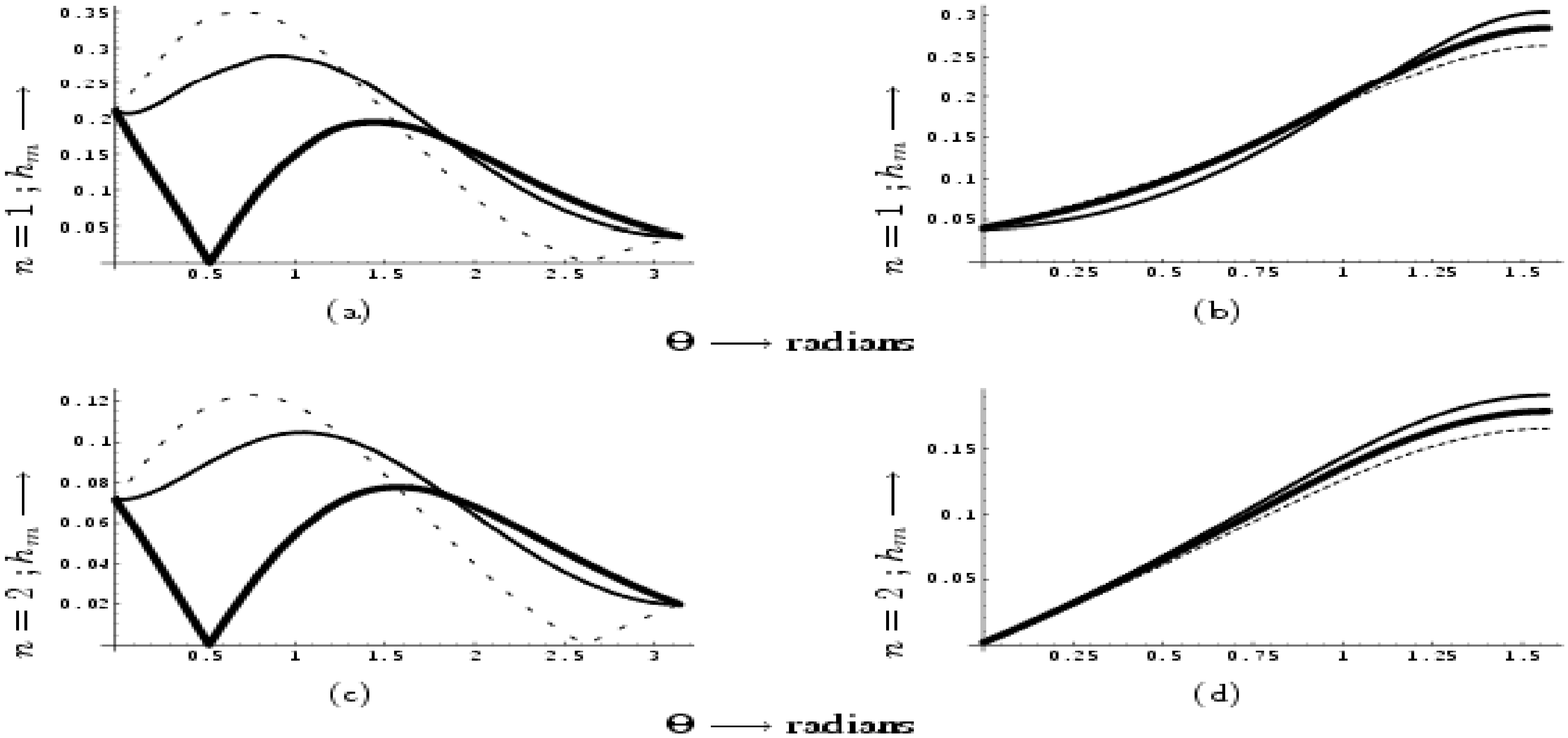
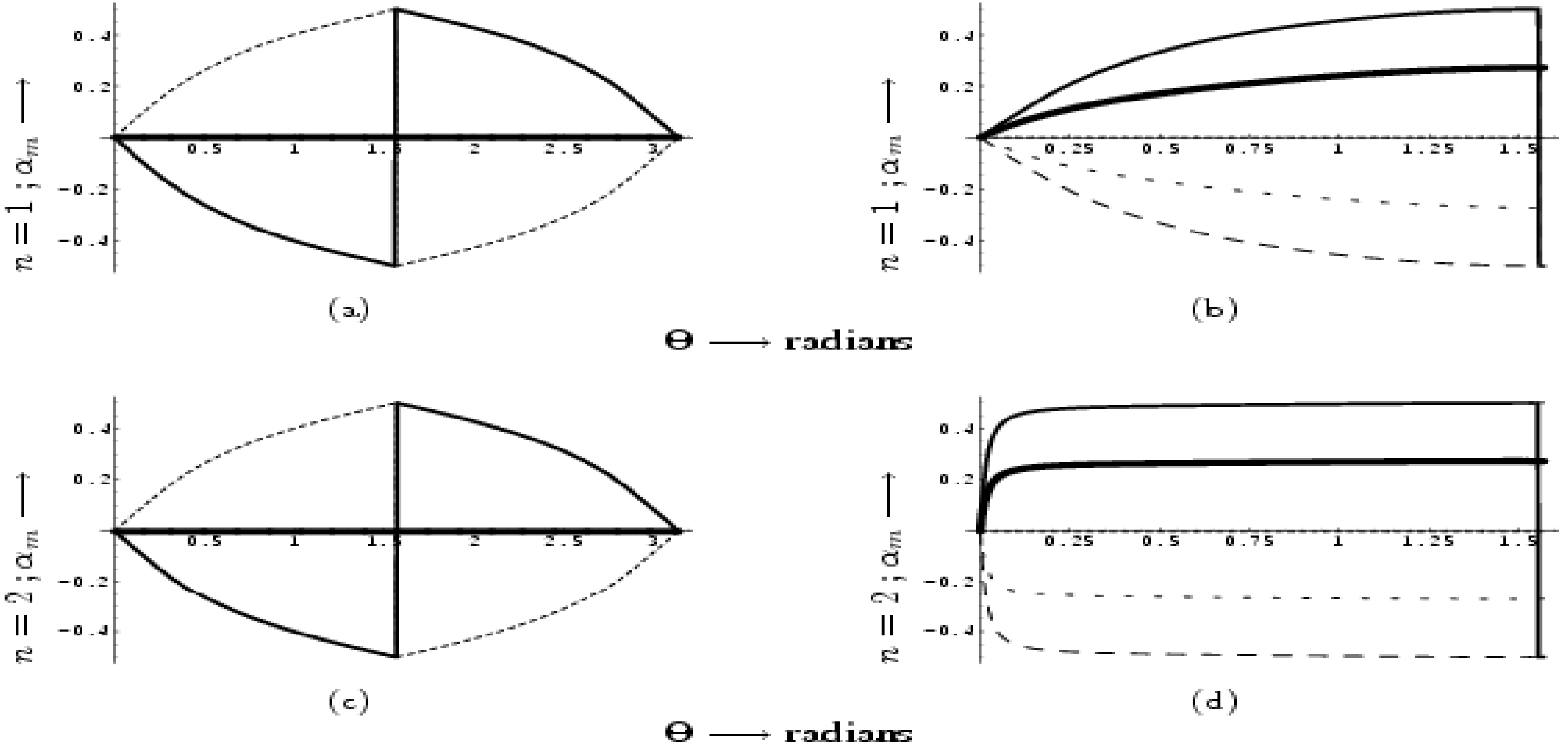
The parameter h_m vs the polar angle in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right)



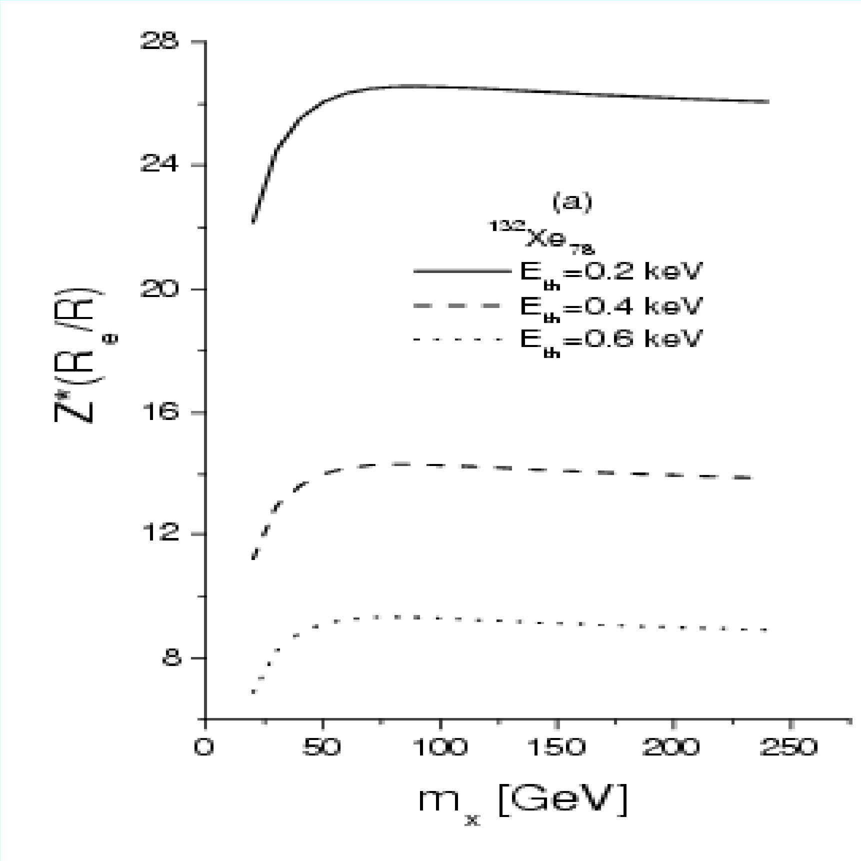
The phase α_m vs the polar angle in the case of A=32; m_χ=100 GeV One sense (Left), Both senses (Right)

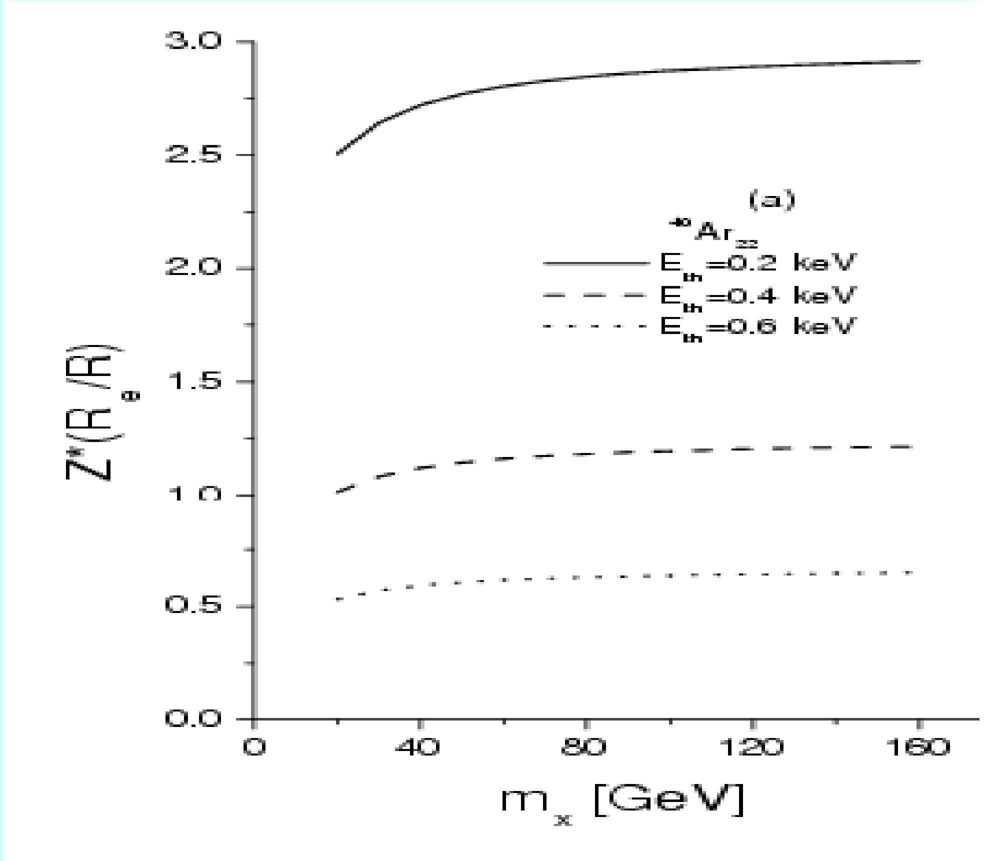


NON RECOIL MEASUREMENTS

- (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:

Appears possible in the exotic models

- $\langle T_\chi \rangle \approx 40$ keV $n^2\,(m_\chi/100\text{GeV})$
- $T_{\chi,max} \approx 215$ keV $n^2\,(m_\chi/100\text{GeV})$.

  Thus
- $m_\chi = 500$GeV, $n=2$ $\Downarrow$

  $\langle T_\chi \rangle \approx 0.8$ MeV, $T_{\chi,max} \approx 4$ MeV

Unfortunately,
Not all available energy is exploitable!

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

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

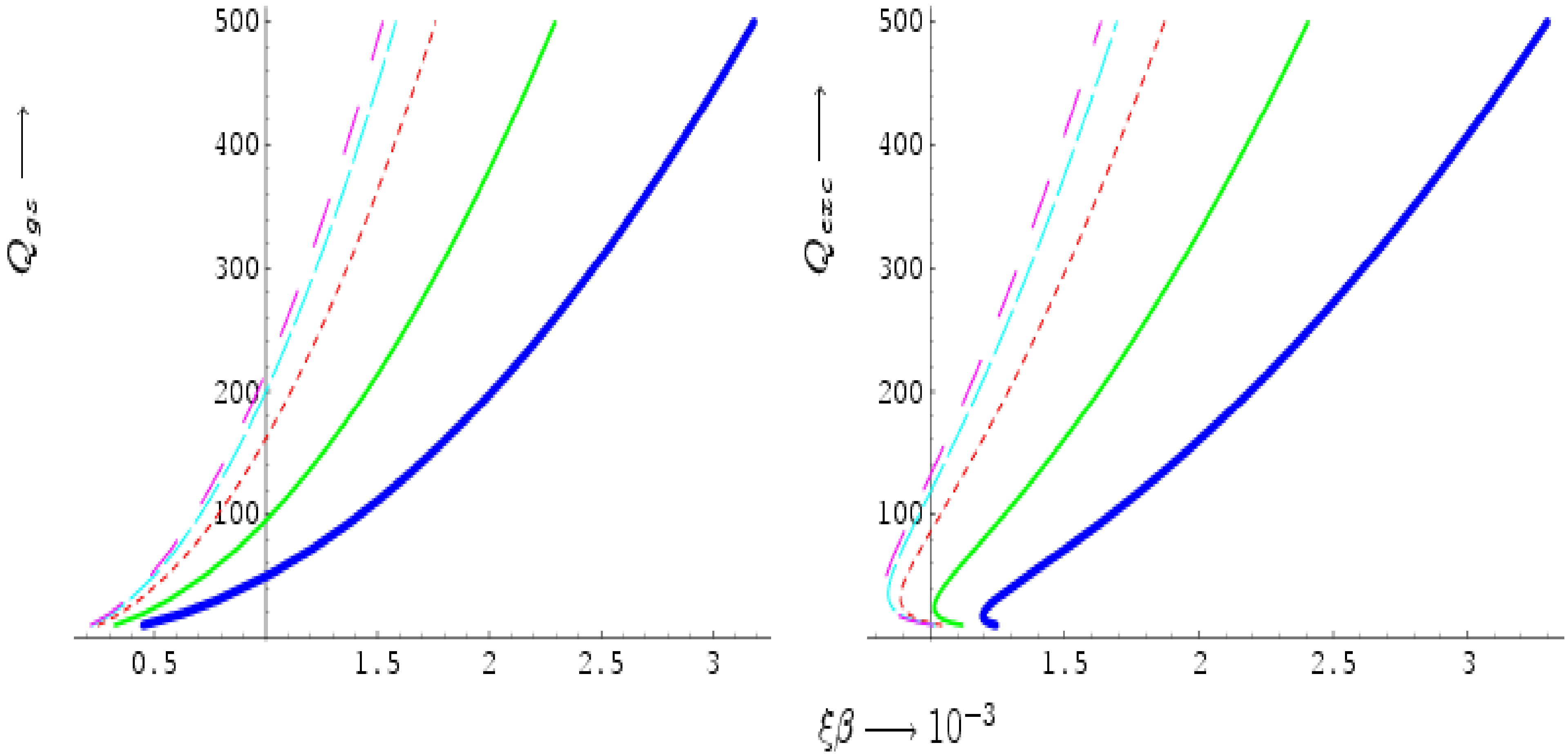
- For Transitions to excited states

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

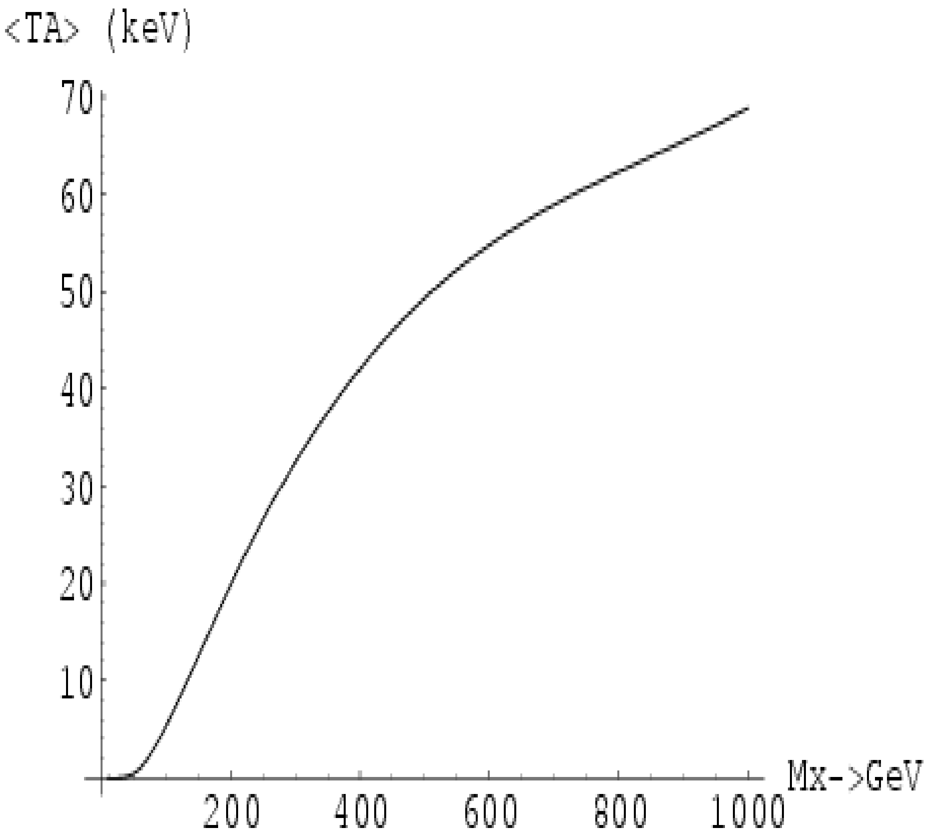
where $\beta = \upsilon/c$ with υ the wimp velocity, ξ the cosine of the angle between the oncoming WIMP and the outgoing nucleus and Δ the excitation energy of the nuclear state.

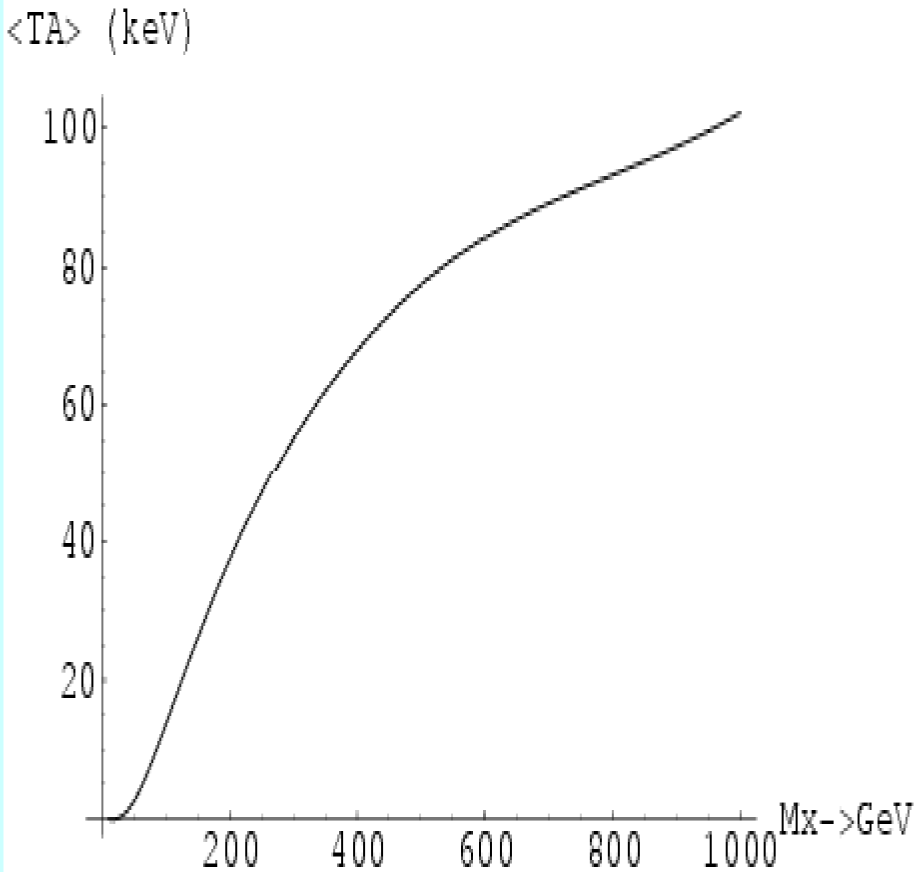
- Both peaked around ξ=1

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. <ξβ>=10^{-3}



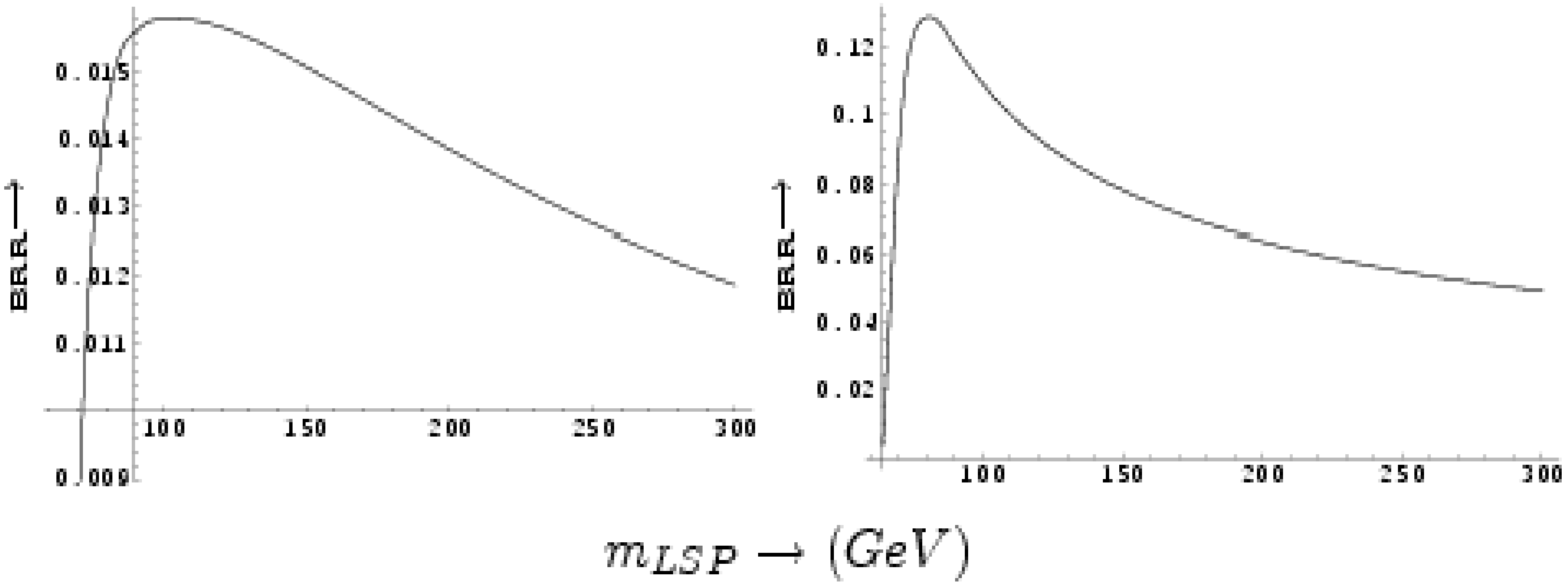
The average nuclear recoil energy:
A=127; Δ=50 keV (left), Δ=30 keV (right)





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 ⑩ E_{th} =0 keV ii) Right ⑩ E_{th} =10 keV



CONCLUSIONS: Non-directional

- The modulation amplitude h is small less than 2% and depends on the LSP mass.
- It crucially depends on the velocity distribution
- Its sign is also uncertain for intermediate and heavy nuclei.
- 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.
- The modulation is reduced in velocity distributions resulting from the coupling of dark matter to dark energy

CONCLUSIONS: directional Exps

- κ (the reduction factor) small. $\kappa \approx 1/(2\pi)$ 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 h_m is much bigger:

  $|h_m| \approx 0.3$ (60% difference between maximum and minimum). Both the magnitude and its sign depend on the azymouthal angle Φ

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 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!

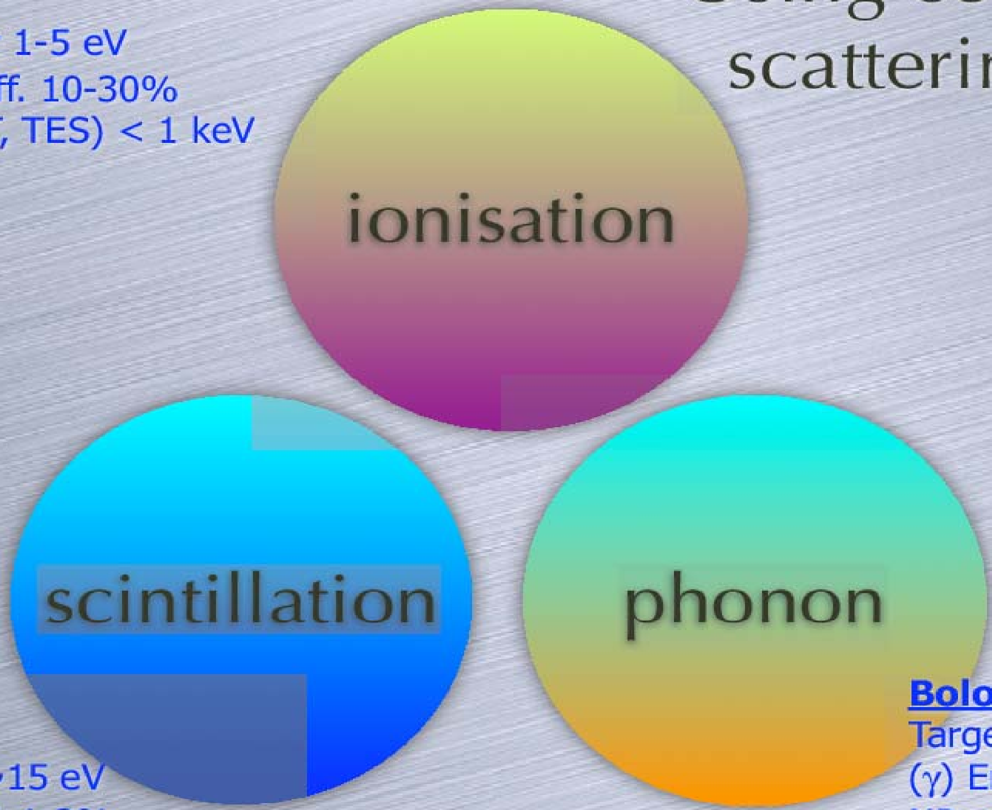
(Such a reward!)

- 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

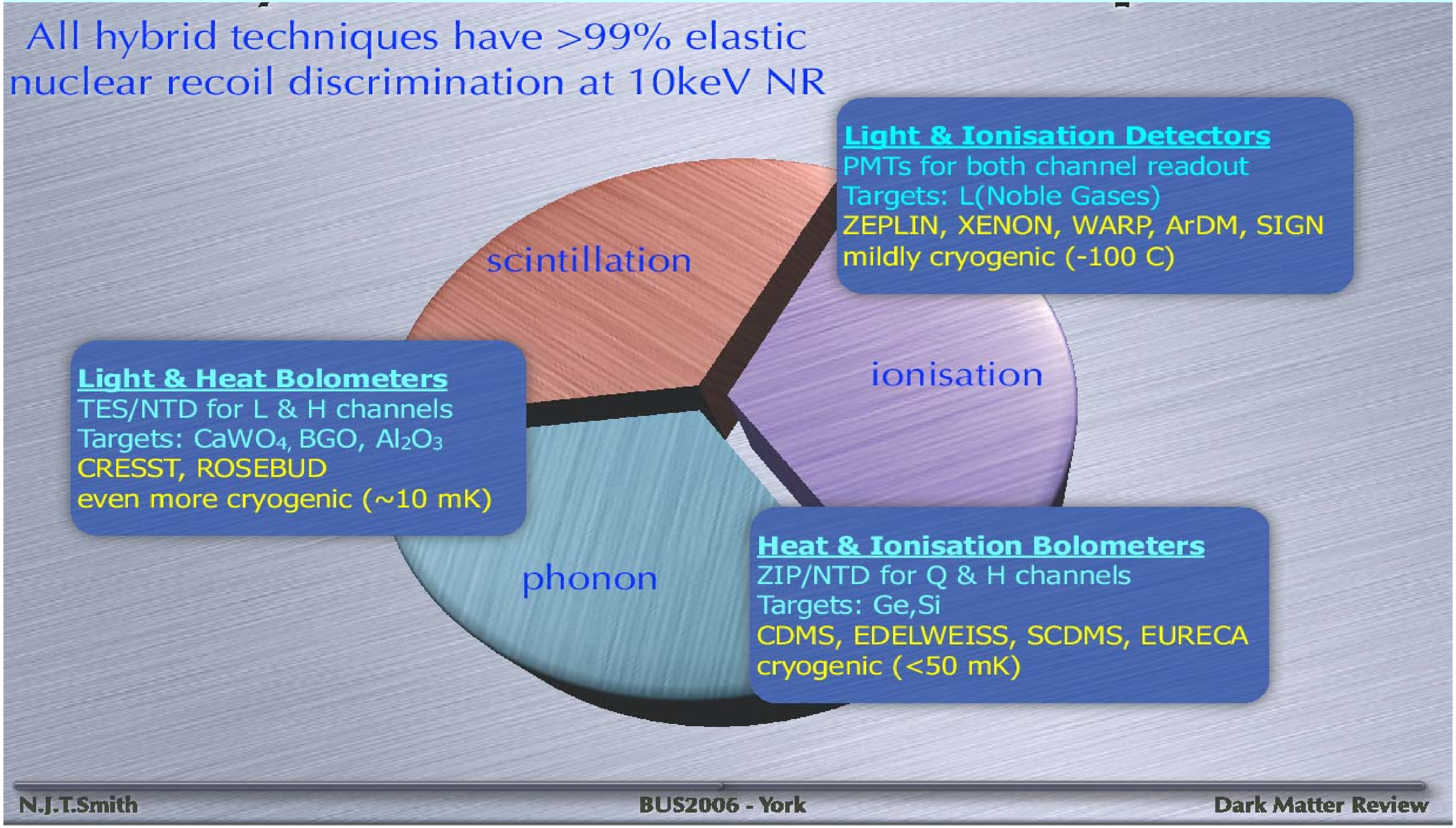


Scintillators
Targets: NaI, Xe, Ar, Ne
(γ) Energy per photon ~15 eV
NR energy collection eff. 1-3%
Light gain 2-8 phe/keV
Sensitivity (PMTs) ~1 keV
ZEPLIN I (2 keV), NAIAD (4 keV)
DAMA (2 keV), DEAP, CLEAN, XMASS (5 keV)

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

Techniques for direct WIMP detection



Another view (ApPEC 19/10/06)

Blue SUSY calculations (parameters on top)