Title: Channeling and Directional Features in Direct Dark Matter Detection

Date: Dec 06, 2011 10:00 AM

URL: http://pirsa.org/11120058

Abstract: The channeling of the ion recoiling after a collision with a WIMP produces a larger ionization/scintillation signal in direct dark matter detection experiments than otherwise expected. I will present estimates of the channeling fractions and their impact on data fits. I will also discuss the possibility of having a daily modulation of the signal due to channeling. Since this modulation depends on the recoil directions and thus on the orientation of the detector with respect to the galaxy, it would be a background free signature. Finally, I will discuss other novel signatures which depend on the direction of recoils and are relevant for directional detectors: a ring of maximum recoil rate around the average arrival direction of WIMPs, aberration features and directional annual modulation amplitudes, in particular the North and South Galactic hemisphere annual modulation.

Direct dark matter detection

- Direct dark matter (DM) experiments look for energy deposited in low-background detectors by the scattering of Weakly Interacting Massive Particles (WIMPs) in the dark halo of our galaxy.
  - Many experiments: **DAMA, XENON, CDMS, CoGeNT, CRESST, Edelweiss, ZEPLIN, LUX...**

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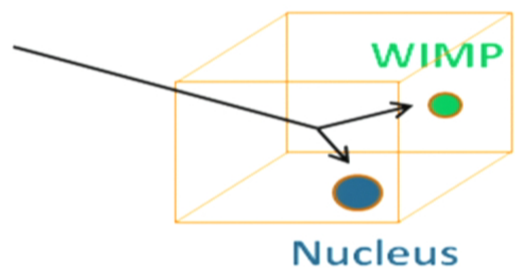

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- WIMPs interact with nuclei and produce:
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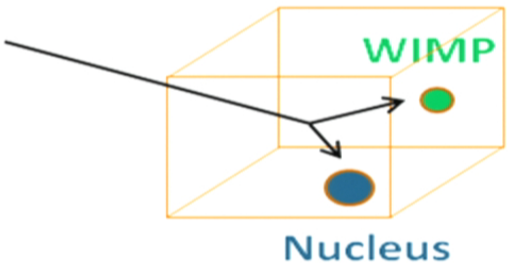
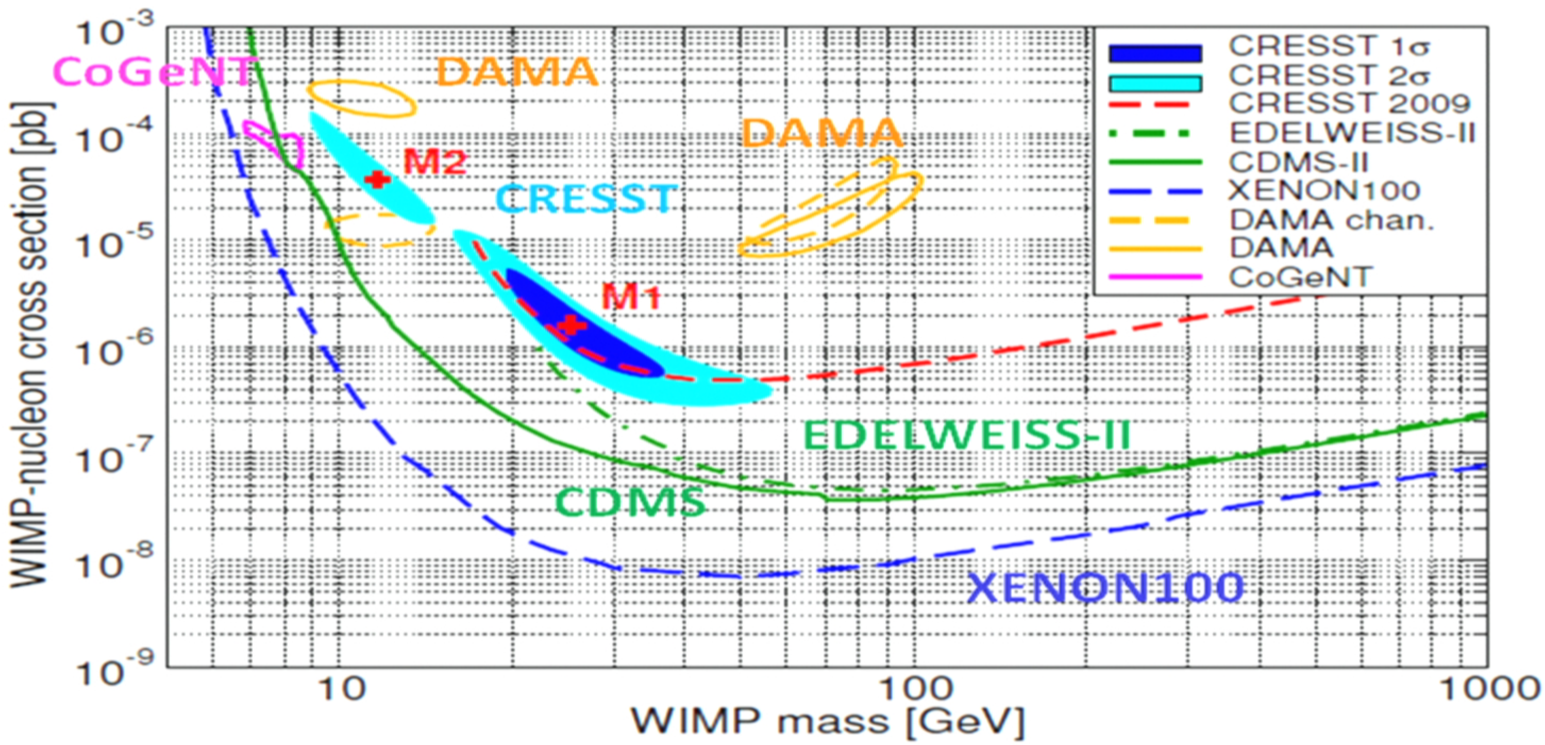
- Data from three experiments pointing to light WIMPs:
  - DAMA: scintillation (NaI)
  - CoGeNT: ionization (Ge)
  - CRESST: scintillation + phonons ($CaWO_4$)

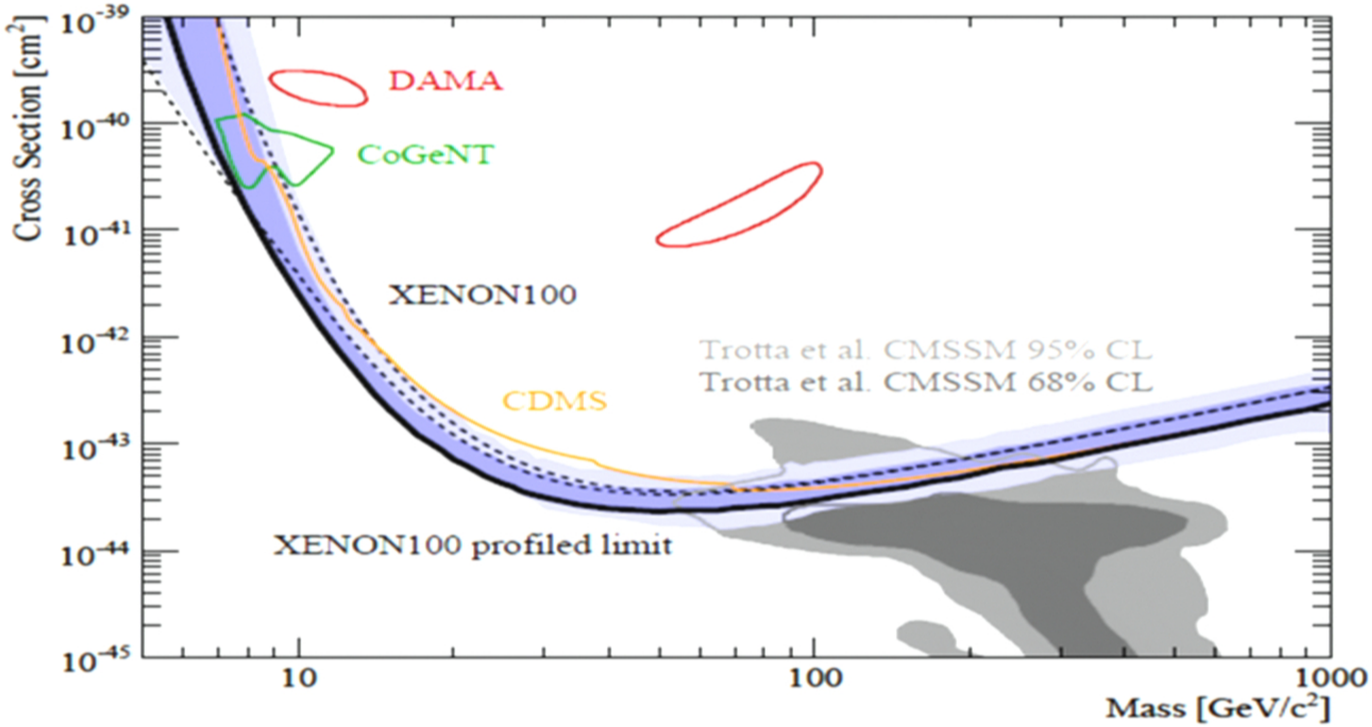


Direct dark matter detection



CRESST Collaboration, arXiv:1109.0702

Direct dark matter detection



XENON100 Collaboration, arXiv:1103.0303

Channeling effect in direct DM detection

- Ions that move parallel to the crystal's axes or planes feel the **"channeling effect"**, which will enhance the energy deposited to electrons. Thus the scintillation/ionization signal is larger.

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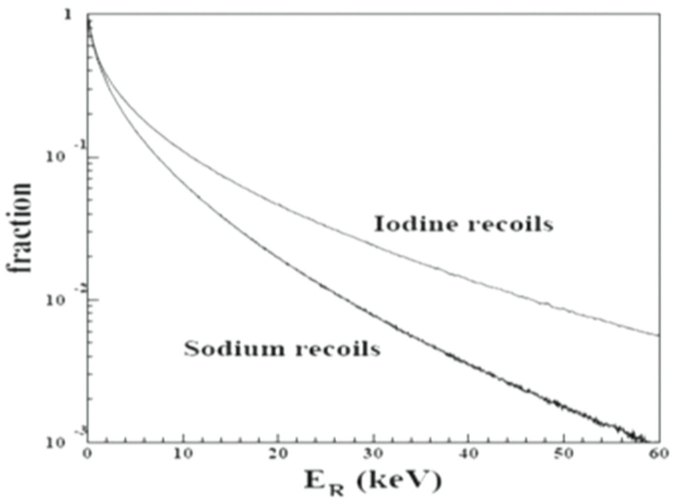
- The potential importance of the channeling effect for direct DM detection was first pointed out for NaI (Tl) by Drobyshevski (2007) and by the DAMA collaboration (2008).

$$E_{\mathrm{measured}} = Q E_{\mathrm{recoil}}$$

- Quenching factor Q : not all of the recoil energy is detected.
- When Na or I recoils move along a channel, their quenching factor is $Q = 1$ instead of $Q_{Na} = 0.3$ and $Q_I = 0.09$, since they give their energy to electrons.

Channeling effect in direct DM detection

- The DAMA collaboration found that the fraction of channeled recoils would be large for low recoil energies.



DAMA- Eur. Phys. J. C 53, 205, 2008

Daily modulation due to channeling

(Creswick, Nussinov, Avignone, Astropart. Phys. 35, 62, 2011 [arXiv:0807.3758])

- The WIMP wind comes preferentially from one direction, due to the motion of the Earth with respect to the galaxy.

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- Earth's daily rotation makes the WIMP wind change direction with respect to the crystal.
- This would produce a daily modulation in the "measured" recoil energy (as if the quenching factor were modulated).

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- Earth's daily rotation makes the WIMP wind change direction with respect to the crystal.
- This would produce a daily modulation in the "measured" recoil energy (as if the quenching factor were modulated).
- **If a daily modulation is measured it would have no background!**
  ⇒ Ideal for DM search.

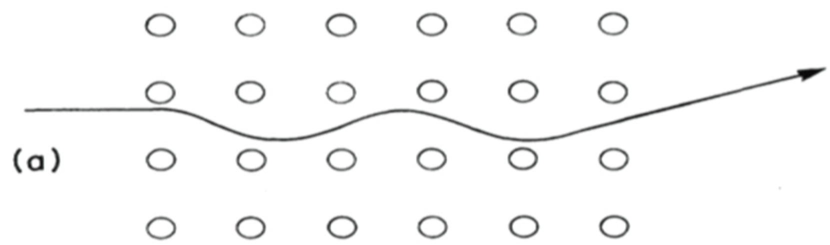
Our work

- Graciela Gelmini, Paolo Gondolo and I set out more three years ago to do an analytic calculation initially to estimate amplitudes of daily modulation due to channeling, but we soon understood that the channeling fraction estimates of DAMA did not include blocking, an effect which makes channeling fractions of recoiling ions much smaller at low energies than evaluated by DAMA....
  - NaI: JCAP **11**, 019 (2010)
  - Si and Ge: JCAP **11**, 028 (2010)
  - CsI: JCAP **11**, 029 (2010)
  - Solid Xe, Ar and Ne: NIM A **654**, 162 (2011)
  - Daily modulation: Phys. Rev. D **84**, 023516 (2011)

Channeling and blocking in crystals

Channeling:

If an ***incident*** ion is along the symmetry axis or planes of the crystal, it will have a series of small-angle scatterings which will maintain it in the open channels. The ion will penetrate much further into the crystal than in other directions.



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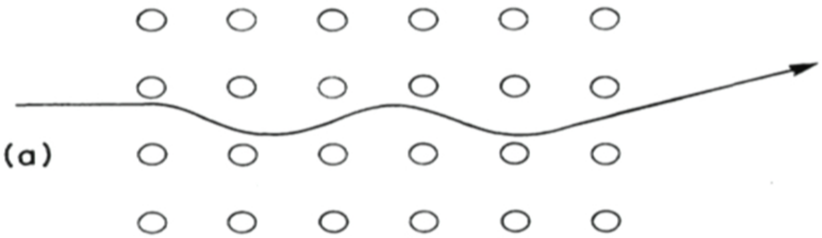
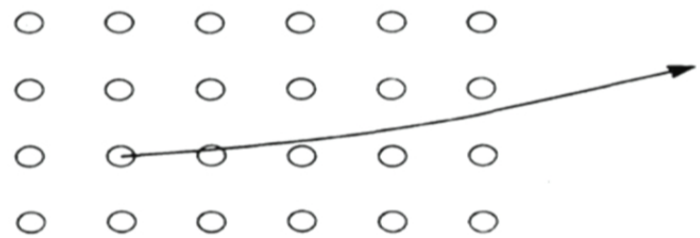


Blocking:

If an ion ***originating*** in the lattice sites is along the symmetry axis or planes, there is a ***reduction*** in the flux of the ion when it exits the crystal creating a "blocking dip".

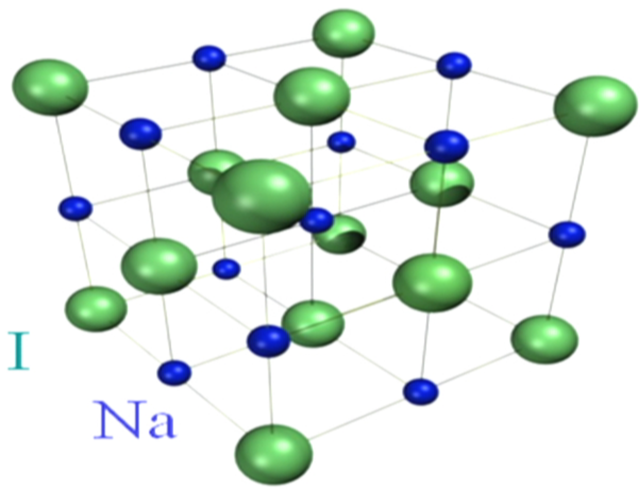
(b)



From D. Gemmell 1974, Rev. Mod. Phys. 46, 129

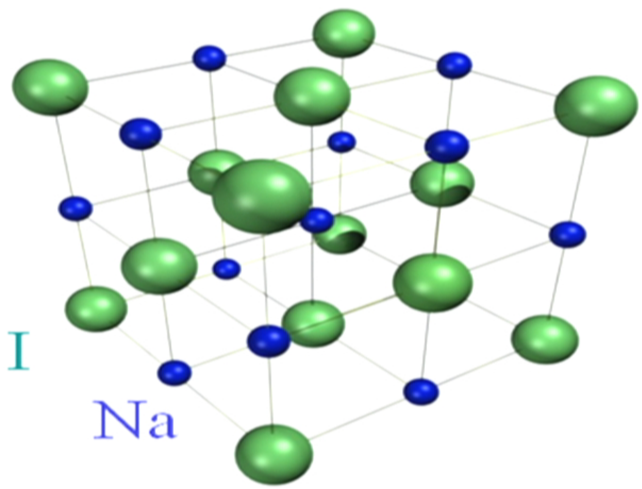
Channeling and blocking in crystals

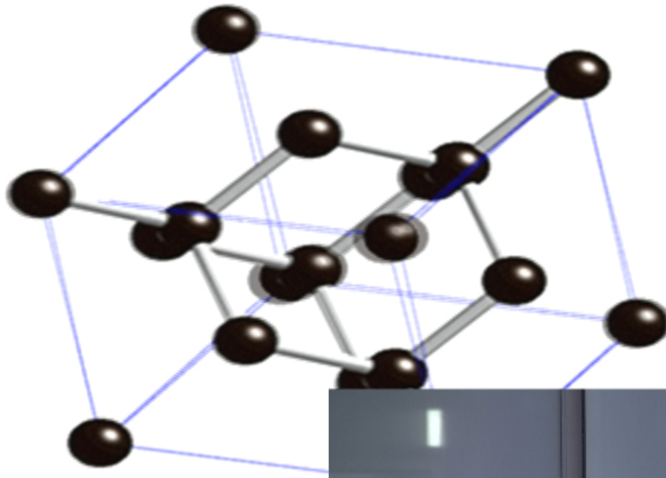
- NaI or CsI crystals (fcc)



Channeling and blocking in crystals

- **NaI** or **CsI** crystals (fcc)
- **Si** or **Ge** crystals (fcc diamond)





Observation of channeling in NaI (Tl)

PHYSICAL REVIEW B VOLUME 7, NUMBER 5 1 MARCH 1973

Scintillation Response of NaI(Tl) and KI(Tl) to Channeled Ions*

M. R. Altman, H. B. Dietrich,† and R. B. Murray
Physics Department, University of Delaware, Newark, Delaware 19711

T. J. Rock
Ballistic Research Laboratory Radiation Division, Aberdeen Proving Ground, Maryland 21010
(Received 29 September 1972)

The scintillation pulse-height response of NaI(Tl) and KI(Tl) to ^{4}He and ^{16}O ions in the 2–60-MeV range has been studied with the ion beam aligned along low-index planes and axes and also aligned along a random direction. The scintillation efficiency increases by as much as 50% when the ion beam is channeled along a major symmetry direction. The effect of channeling has been observed by recording the pulse-height spectra for monoenergetic ions oriented along {100}, {110}, and {111} planes, and along ⟨100⟩, ⟨110⟩, and ⟨111⟩ axes. The increase in pulse-height response is in semiquantitative agreement with recent model calculations. Observation of this effect permits study of channeling phenomena in thick crystals that are scintillators. In particular, this paper reports a measurement of the critical angle for channeling of 15-MeV ^{16}O along a {100} plane.

Altman et al. 1973 (Phys. Rev. B7, 1743)

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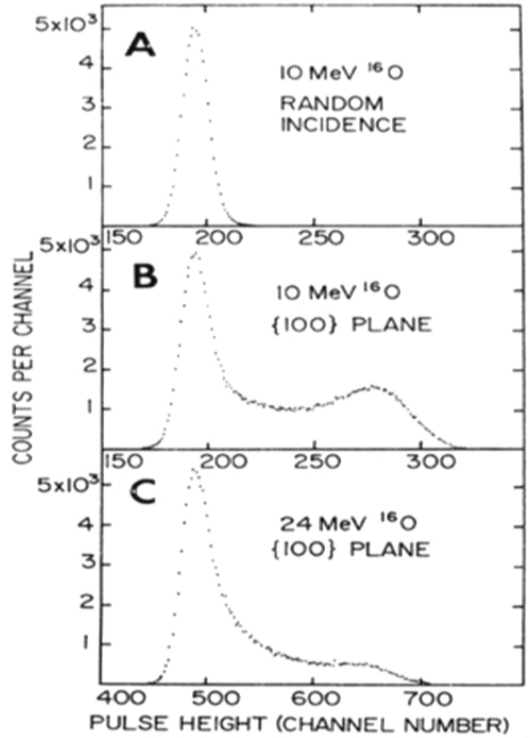

FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

Monochromatic ^{16}O beam through NaI (Tl) scintillator

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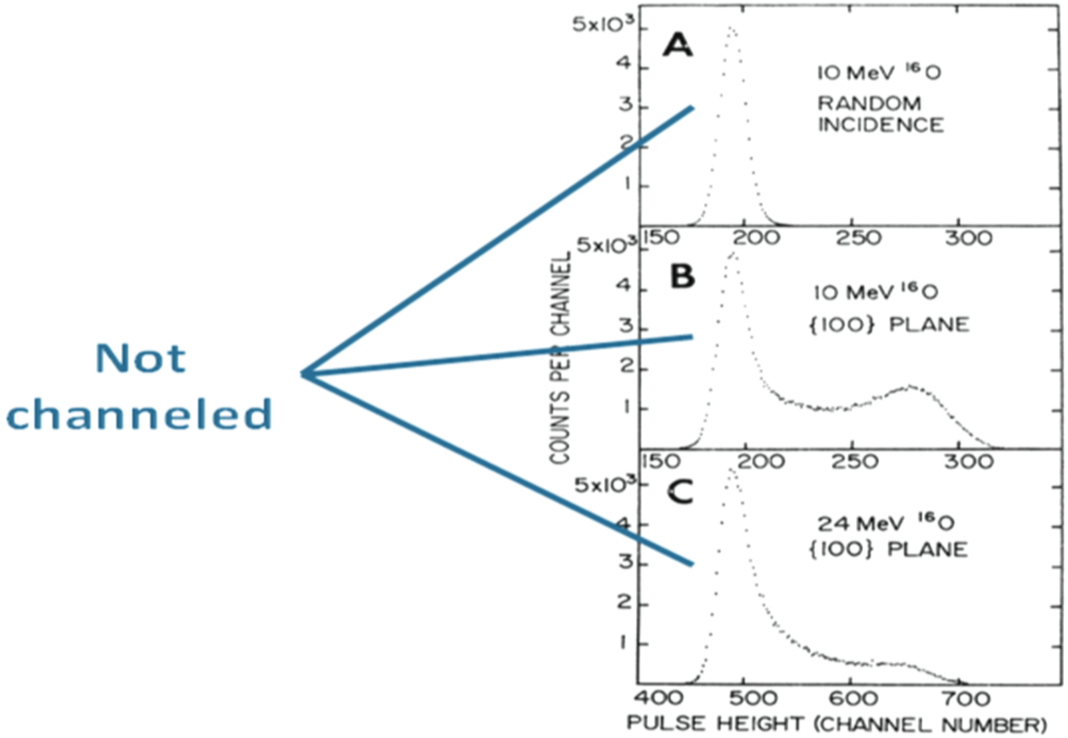

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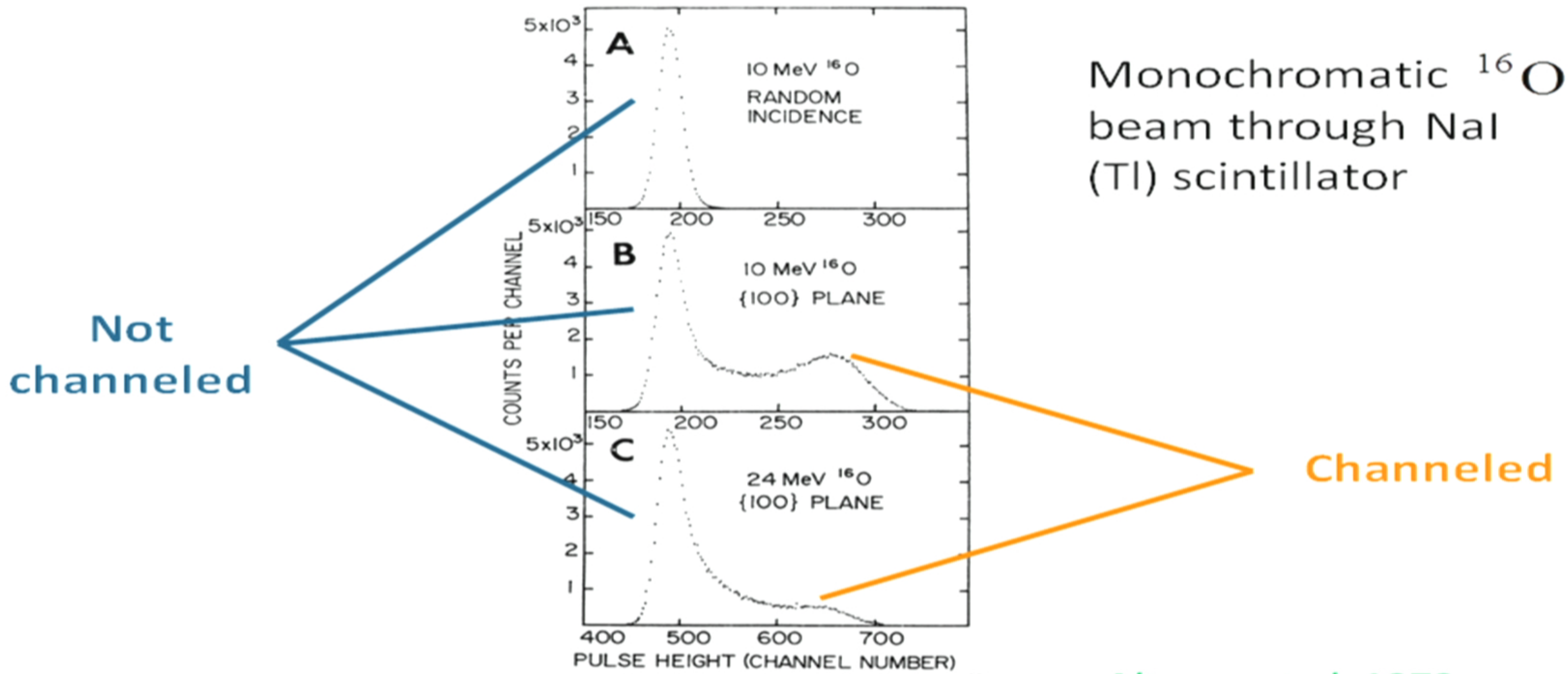

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Channeling and blocking in crystals

- Channeling and blocking in crystals is used in:
  - crystallography
  - studies of lattice disorder
  - ion implantation
  - finding the location of dopant and impurity atoms
  - studies of surfaces and interfaces
  - measurement of short nuclear lifetimes
  - production of polarized beams

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- Channeling is to be ***avoided*** in ion implantation in **Si** to make circuits: good data at ~100's keV and analytic models by Gerhard Hobler ***(Vienna Univ. of Technology, 1995)***.

Models of channeling

- Our calculations are based on classical analytic models developed in the 1960's and 70's, in particular Lindhard's model ***(Lindhard 1965, Morgan & Van Vliet 1971, Dearnaley 1973, Gemmell 1974, Appleton & Foti 1977)***.
- We use the continuum string or plane model, in which the screened Thomas-Fermi potential is averaged over a direction parallel to the row or plane.

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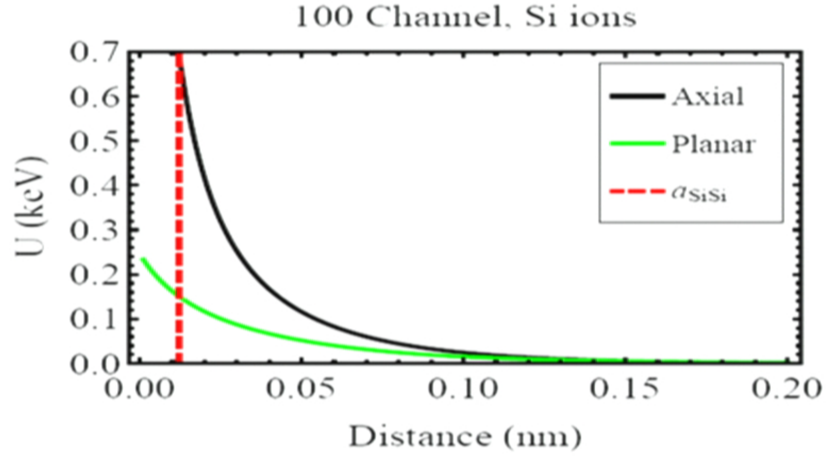

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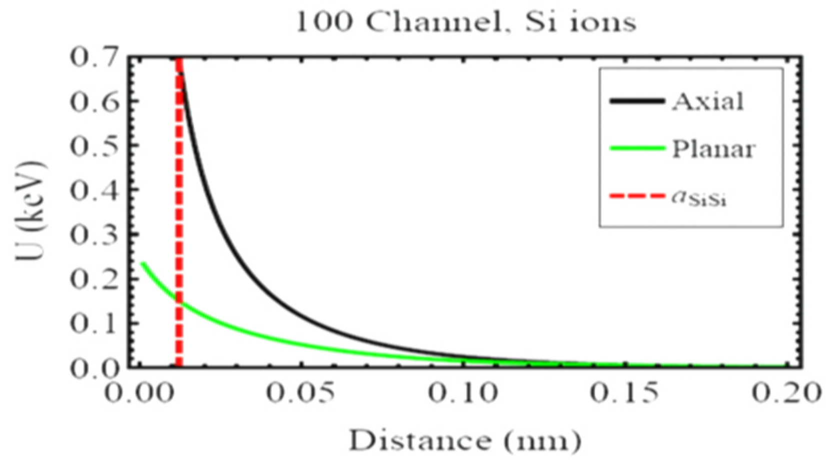
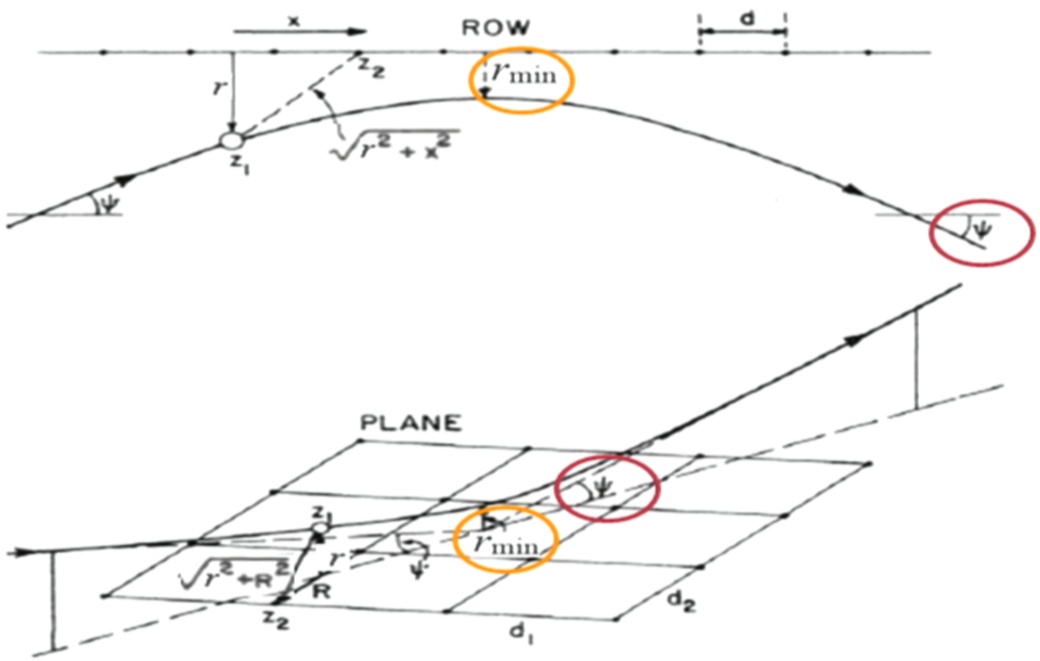
- We use the continuum string or plane model, in which the screened Thomas-Fermi potential is averaged over a direction parallel to the row or plane.
- Only one row or one plane is considered.
- In the direction perpendicular to the row or plane, the "transverse energy," $E_\perp = E\sin^2\psi + U$ is conserved.



Axial and planar channels



- $r_{\min}$: min. distance of approach
- ψ : angle far away from row or plane
- **Channeling requires:**

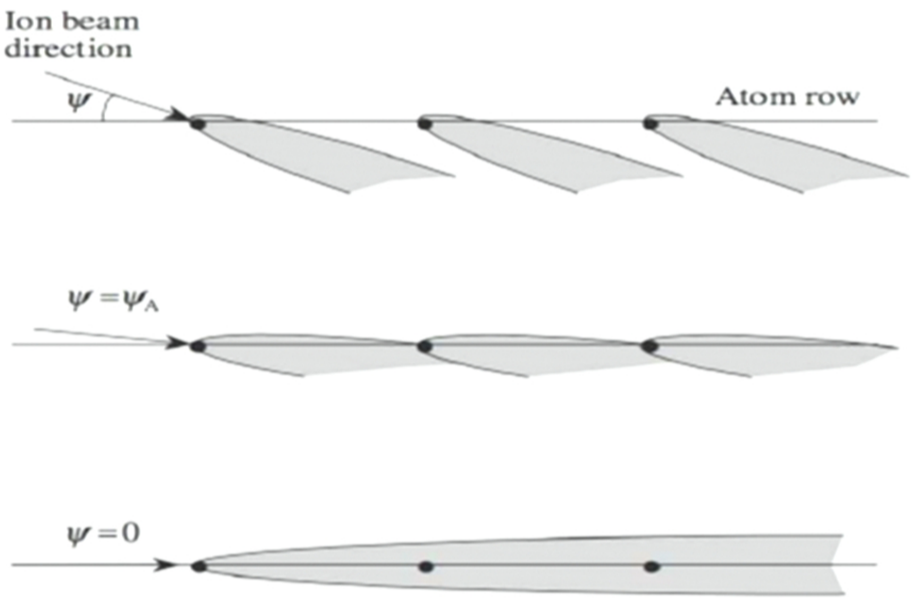
$$r_{\min} > r_c$$

which amounts to

$$\psi \leq \psi_c$$

Axial and planar channels

- Axial and planar channels can be understood as superposition of Coulomb shadow cones:



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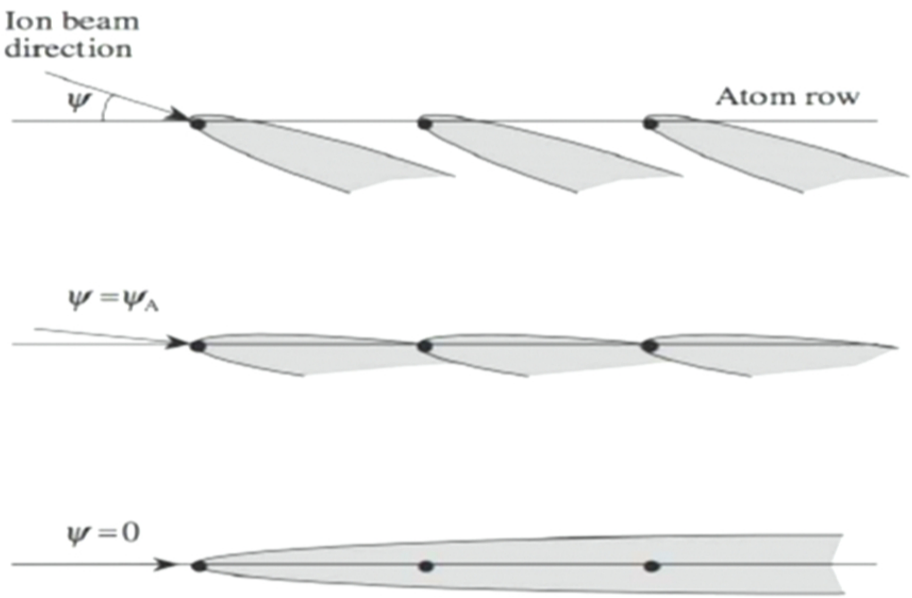

Channeling requires:

- Min. distance of approach to row/plane larger than a critical value ***(Lindhard 1965, Morgan & Van Vliet 1971, Hobler 1995)***:

$$r_{\min} > r_c(E,T) = \sqrt{r_c^2(E) + [c\ u_1(T)]^2}$$

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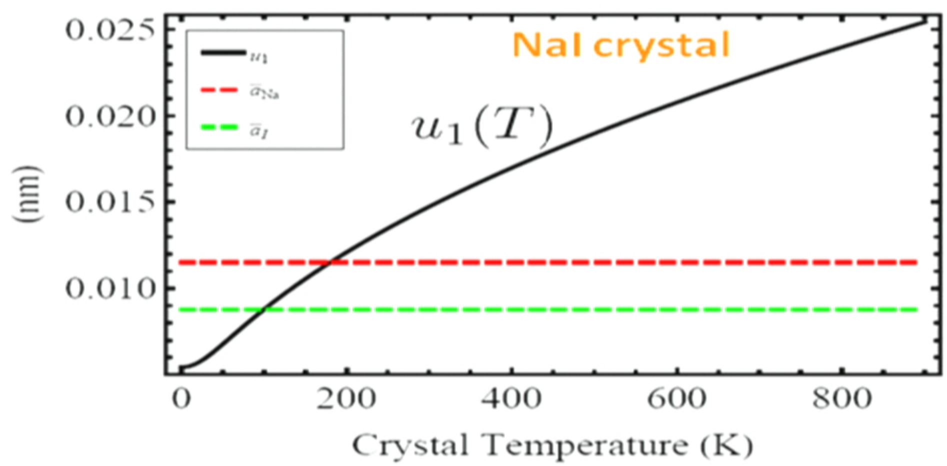
c : found through data/simulations, $1 < c < 2$

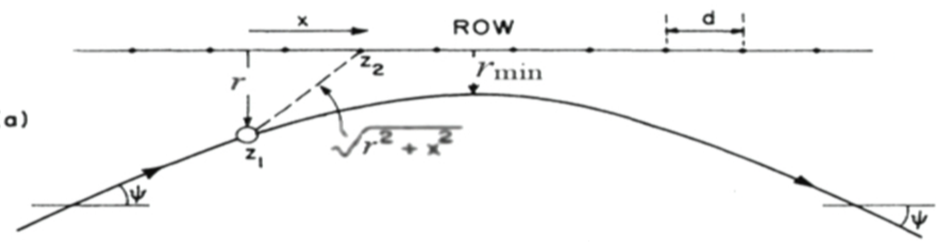


Channeling requires:

- Conservation of transverse energy:

$$E_{\perp} = E\psi^2 + U(r_{\rm ch}) = U(r_{\rm min})$$

angle far from row/plane — radius of channel



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$$\psi \leq \psi_c = \sqrt{\frac{[U(r_c) - U(r_{\text{ch}})]}{E}}$$

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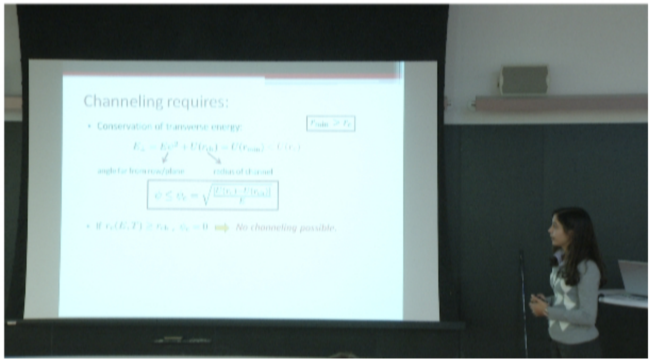
$$\psi \le \psi_c = \sqrt{\frac{[U(r_c) - U(r_{\text{ch}})]}{E}}$$

- If $r_c(E,T) \ge r_{\text{ch}}$, $\psi_c = 0$ ➡ ***No channeling possible.***



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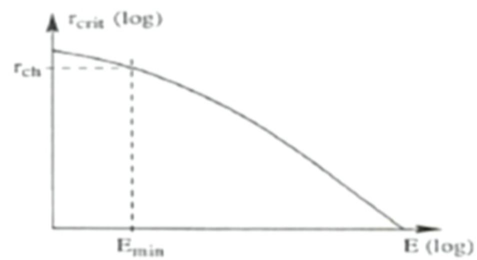
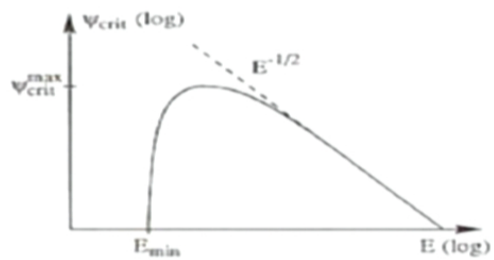
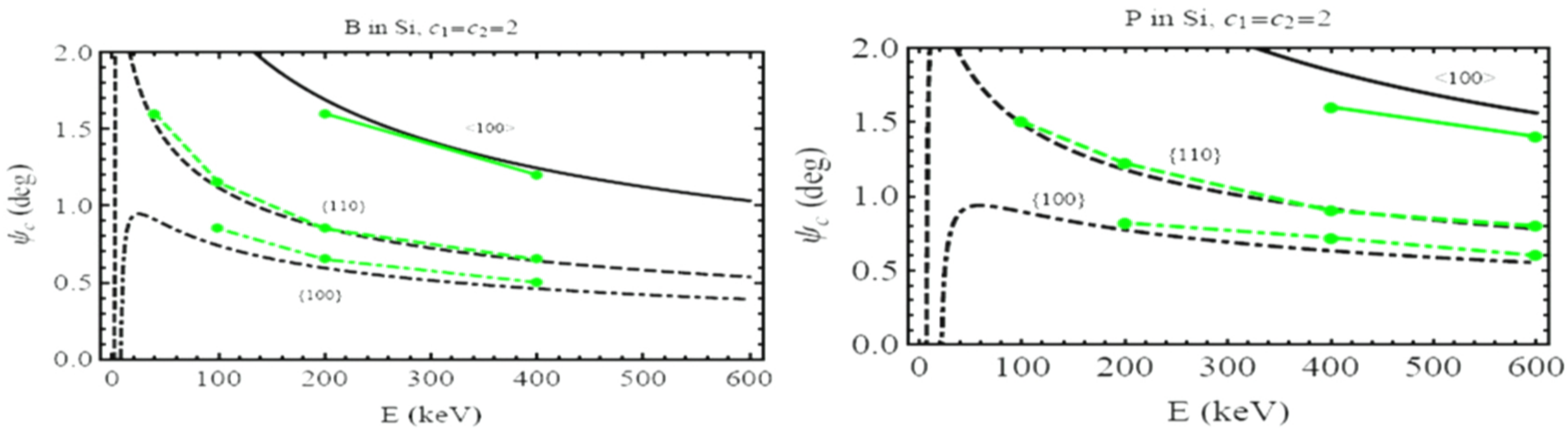




From Hobler 1995

Data: B and P ions in Si crystal

- Data from thermal wave measurements for B and P ions in Si crystal fitted with $c = 2$ *(data extracted from Hobler 1995).*



N. B., Gelmini, Gondolo, JCAP 11, 028 (2010)

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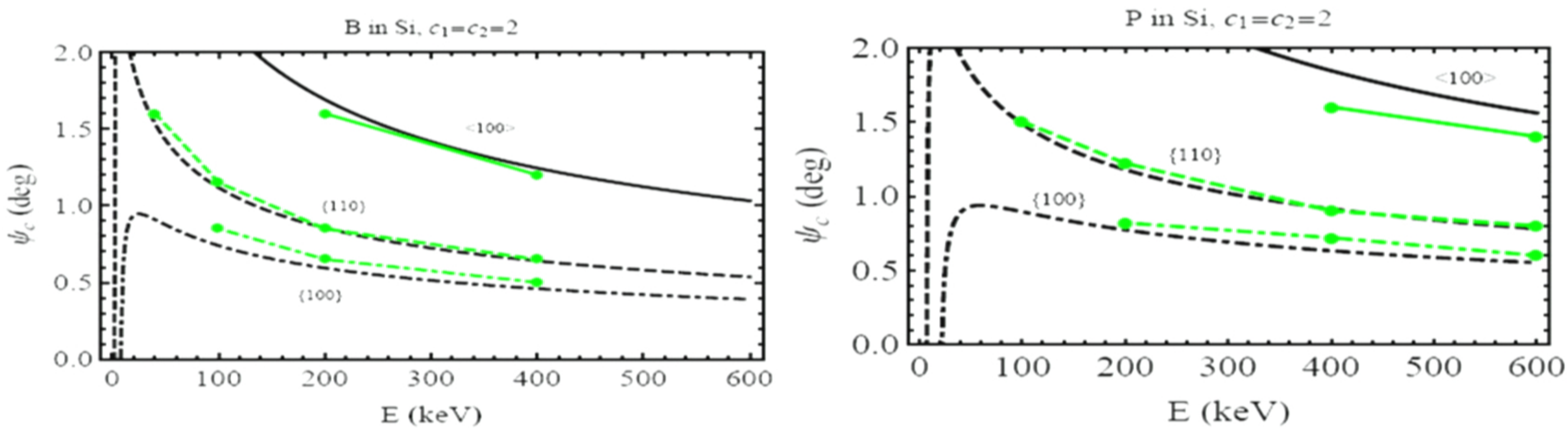
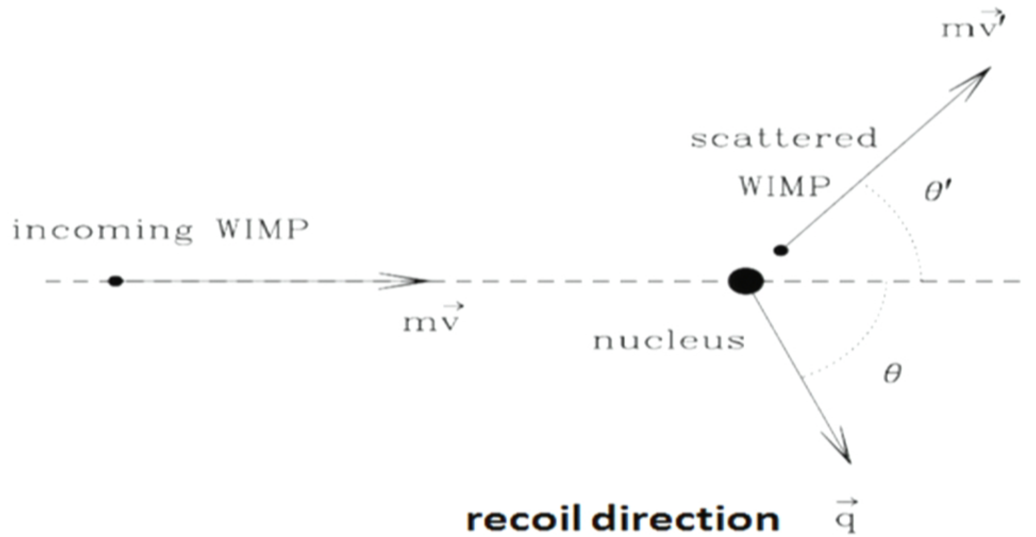


N. B., Gelmini, Gondolo, JCAP 11, 028 (2010)

What we need

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



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

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- The recoiling nucleus can either be channeled or not channeled:

$$p(E, E_R, \hat{\mathbf{q}}) = \chi(E_R, \hat{\mathbf{q}})\delta(E - E_R) + [1 - \chi(E_R, \hat{\mathbf{q}})]\delta(E - QE_R)$$

where $\chi(E_R, \hat{\mathbf{q}})$ is the fraction of channeled nuclei with recoil energy E_R in direction $\hat{\mathbf{q}}$.

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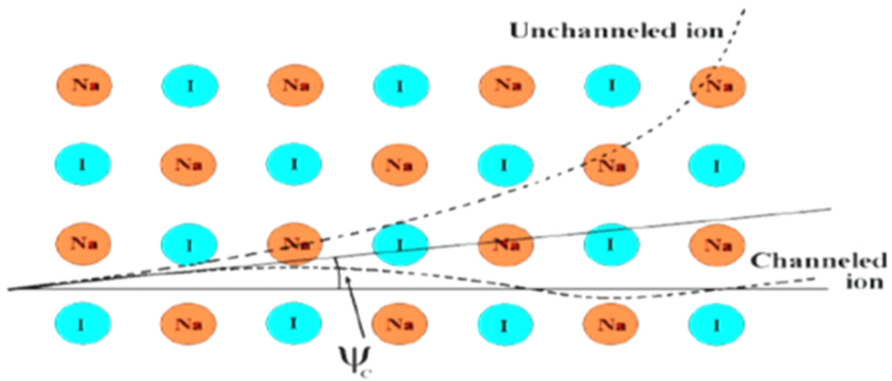
where $\chi(E_R, \hat{\mathbf{q}})$ is the fraction of channeled nuclei with recoil energy E_R in direction $\hat{\mathbf{q}}$.

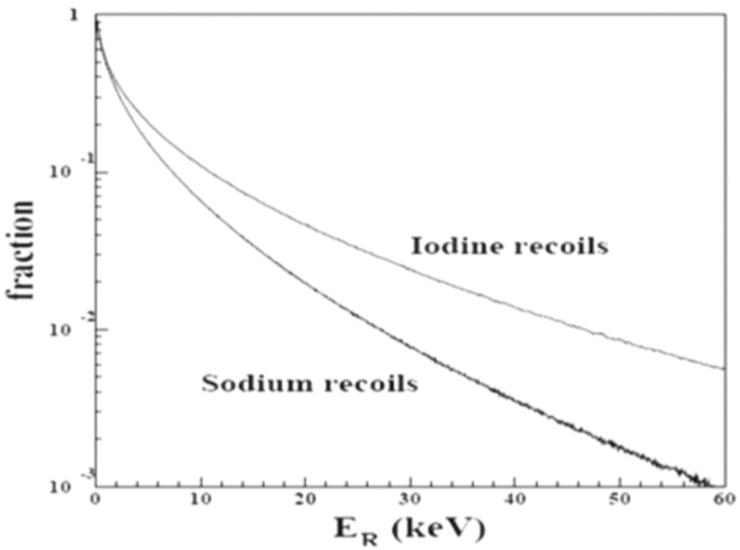
Our Calculations

- Compute the channeling fraction for:
  - Incident particles
  - Recoiling nuclei
- Daily modulation amplitudes
- Directional features

DAMA channeling fraction

- DAMA channeling fraction calculated as if ions start from the middle of the channel.

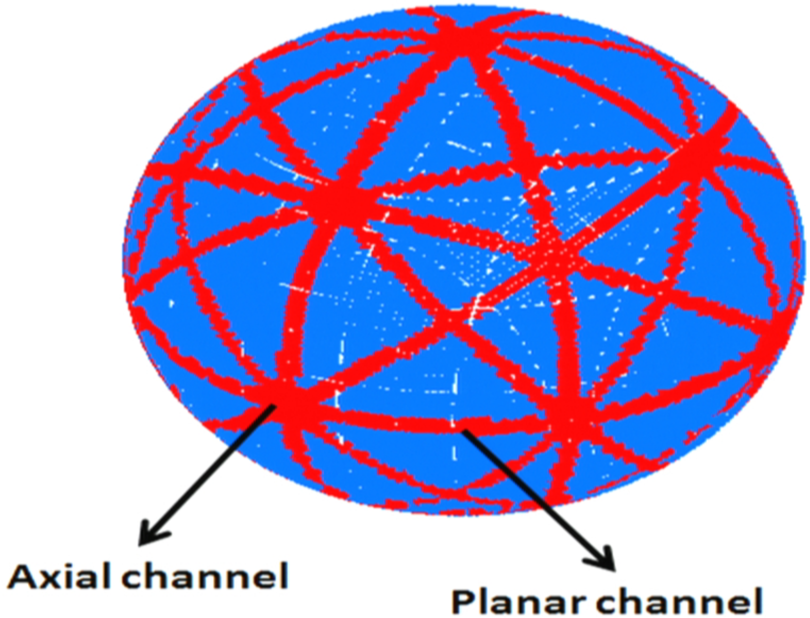




DAMA- Eur. Phys. J. C 53, 205, 2008

Channeling of incident particles

Using the HEALPix pixalization of the sphere for incident energy of 50 keV



For each axial channel:

$$\chi_{\rm axial}(E,\psi) = 1 \quad \text{if} \quad \psi < \psi_c^{\rm axial}$$

For each planar channel:

$$\chi_{\rm planar}(E,\psi) = 1 \quad \text{if} \quad \psi < \psi_c^{\rm planar}$$

NB, G. Gelmini and P. Gondolo, JCAP 11,

Channeling of incident particles

- We integrate the channeling probability over direction to find the total fraction of channeled nuclei using the HEALPix method.

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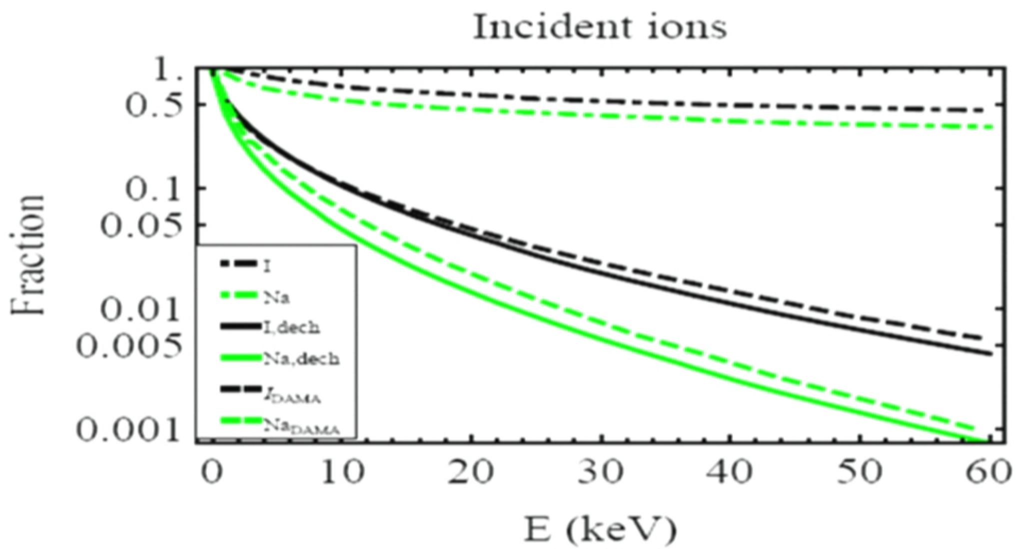

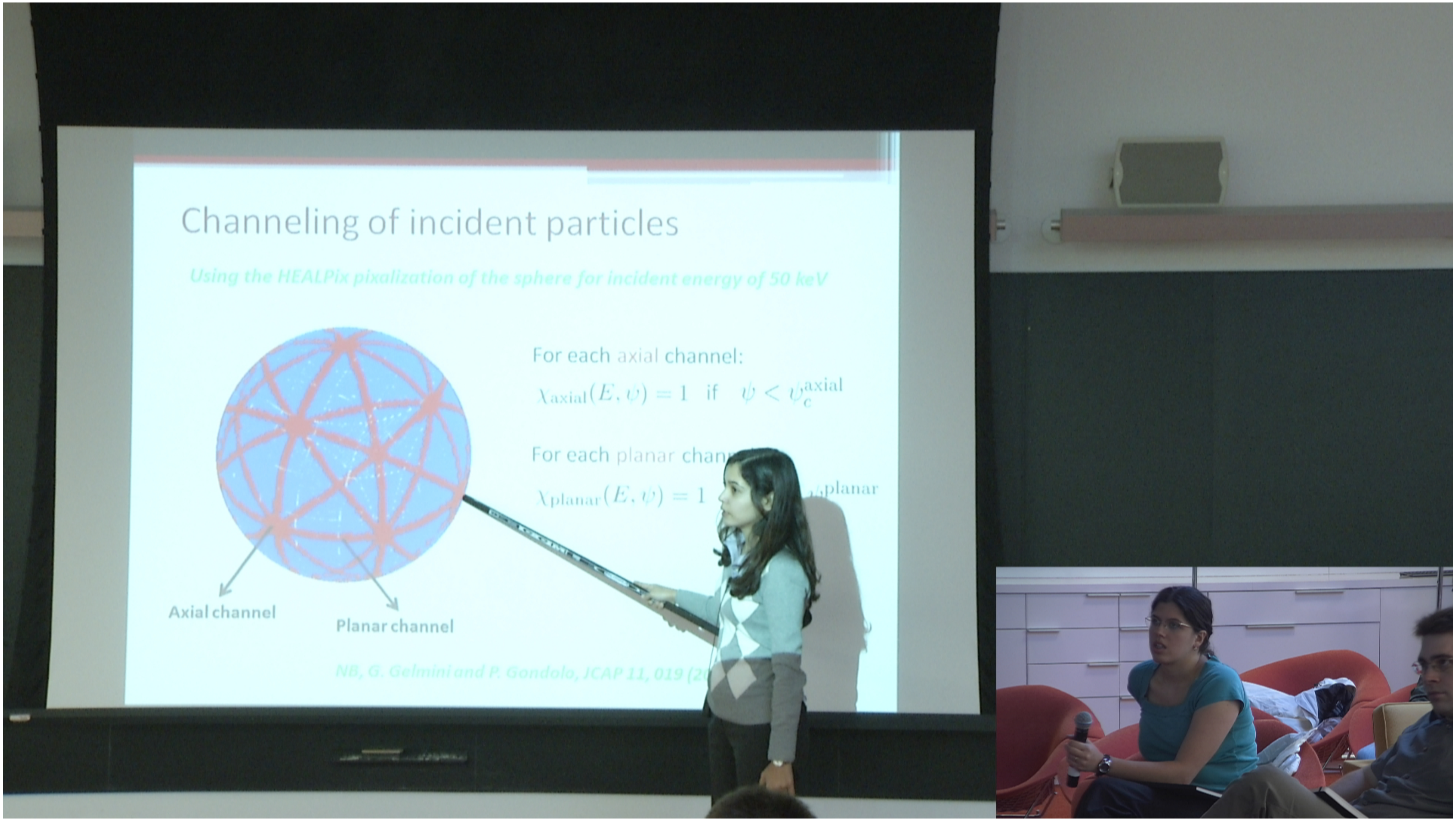

Channeling of incident particles
Using the HEALPix pixalization of the sphere for incident energy of 50 keV
For each axial channel:
$\chi_{\rm axial}(E,\psi) = 1$ if $\psi < \psi_c^{\rm axial}$
For each planar chan
$\chi_{\rm planar}(E,\psi) = 1$
Axial channel
Planar channel
NB, G. Gelmini and P. Gondolo, JCAP 11, 019 (20

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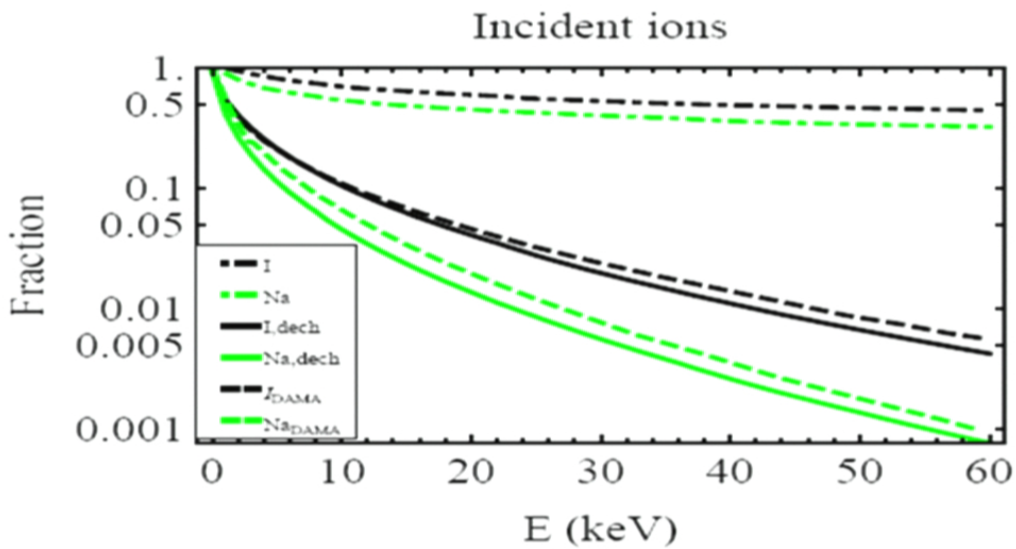

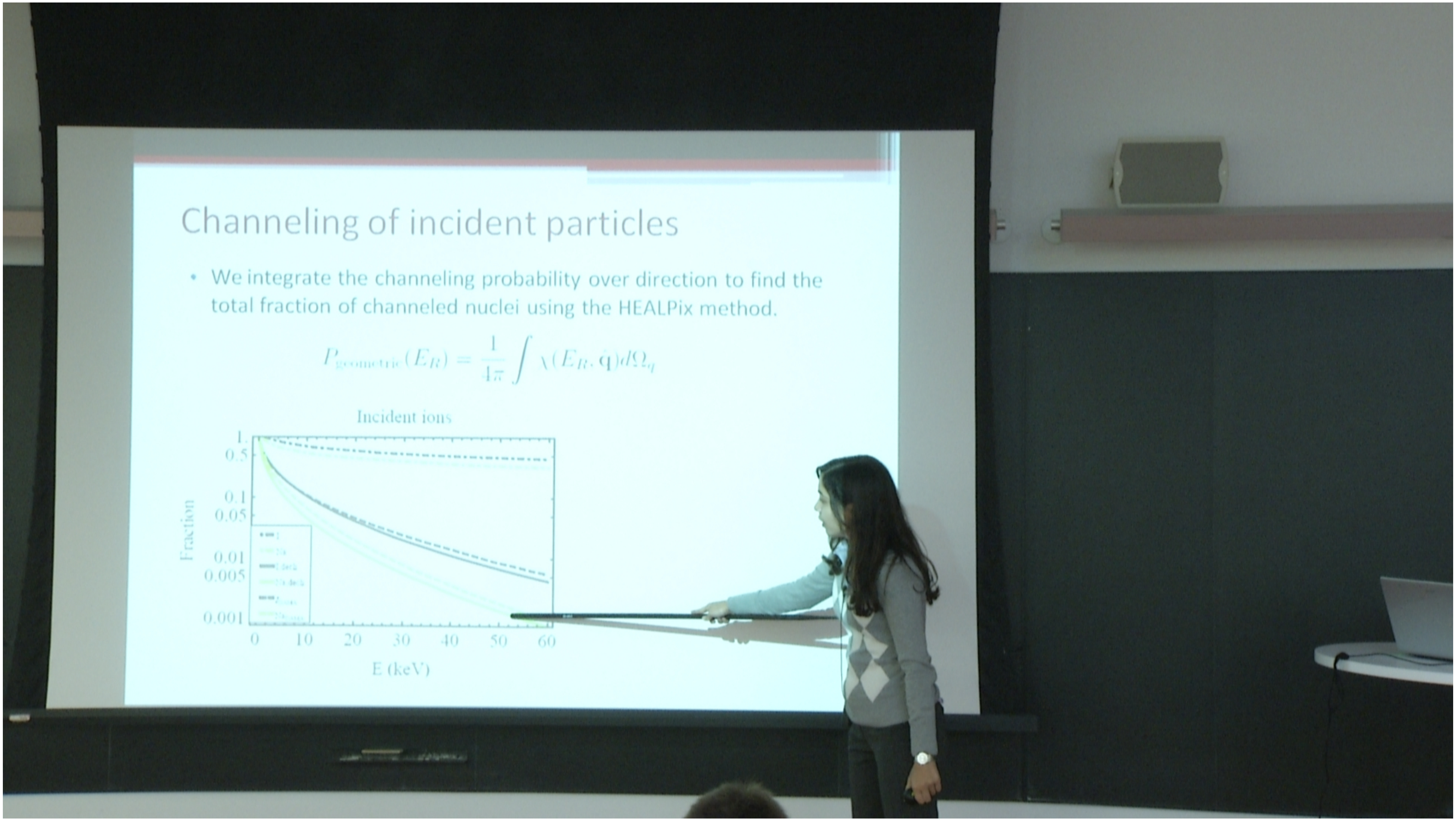
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$P_{\mathrm{geometric}}(E_R) = \frac{1}{4\pi}\int \chi(E_R,\hat{q})d\Omega_q$
Incident ions
Fraction
1.
0.5
0.1
0.05
0.01
0.005
0.001
0
10
20
30
40
50
60
E (keV)

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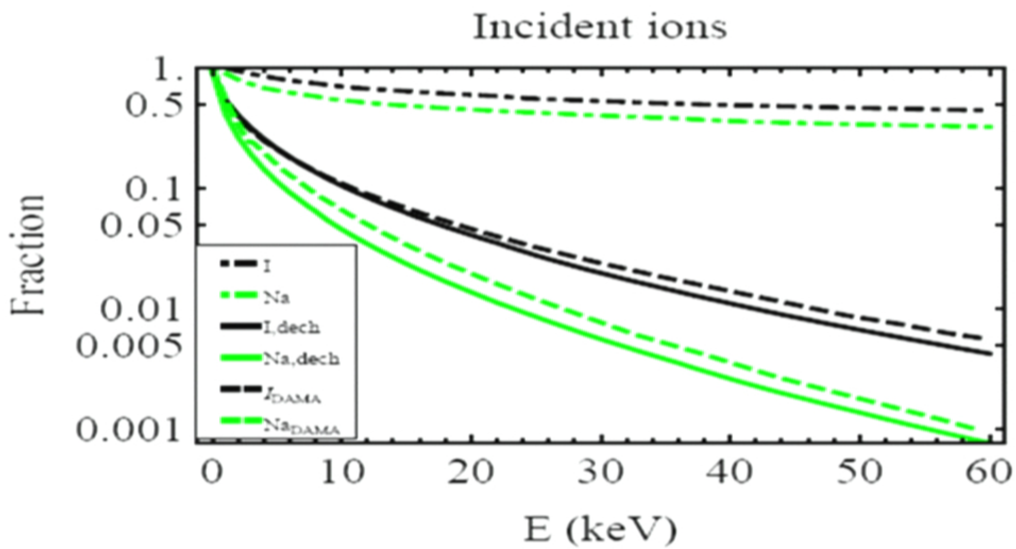

- We agree with DAMA results to a good approximation. Our result is based on analytic calculations with basic assumptions, whereas DAMA is using Monte Carlo.

Our Calculations

- Compute the channeling fraction for:
  - Incident particles
  - Recoiling nuclei
- Daily modulation amplitudes
- Directional features

Channeling of recoiling nuclei

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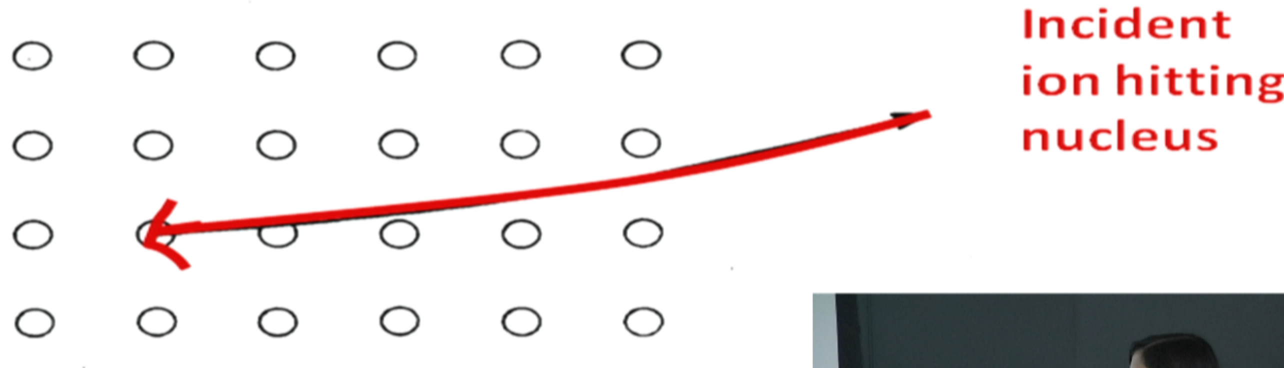
(b)



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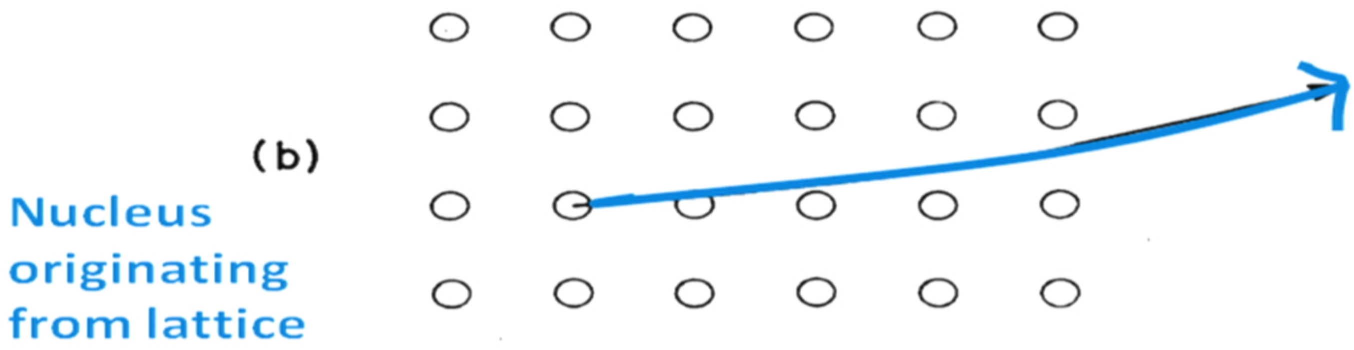

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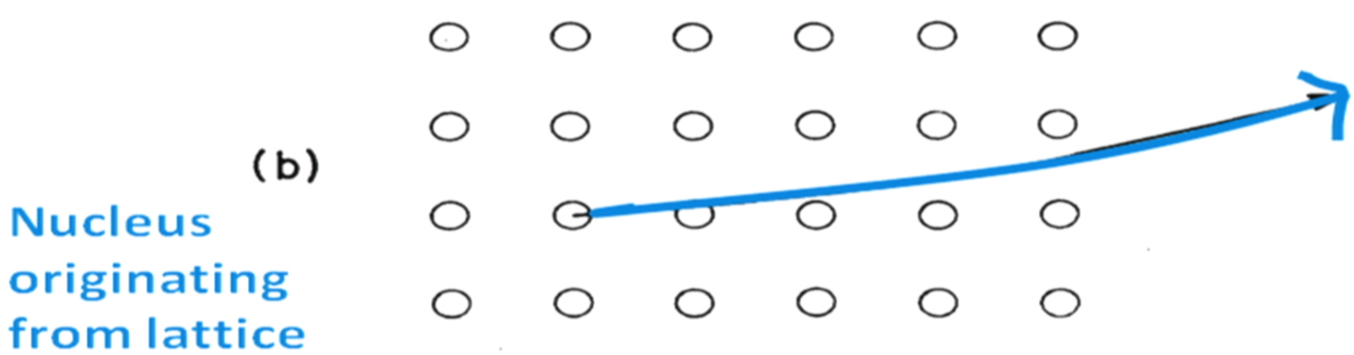

- However, there are channeled recoils due to *lattice vibrations* as already understood in the 70's.

Channeling of recoiling nuclei

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$$E_R \sin^2 \psi_i + U(r_i) < U(r_c)$$

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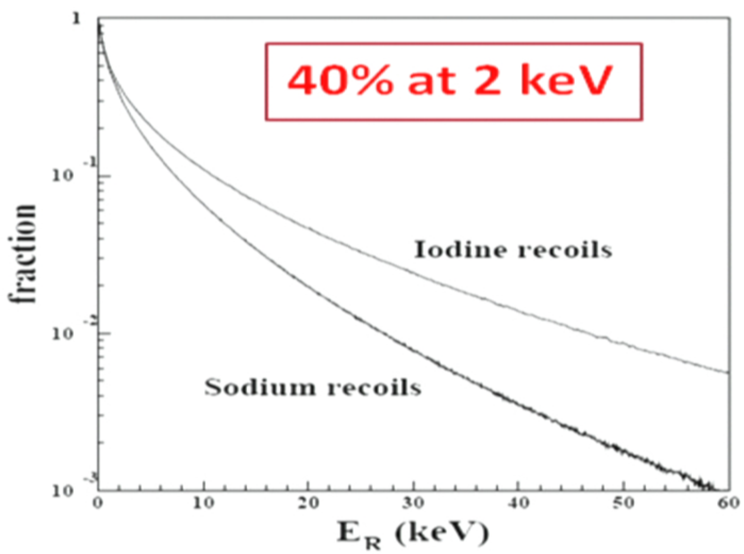
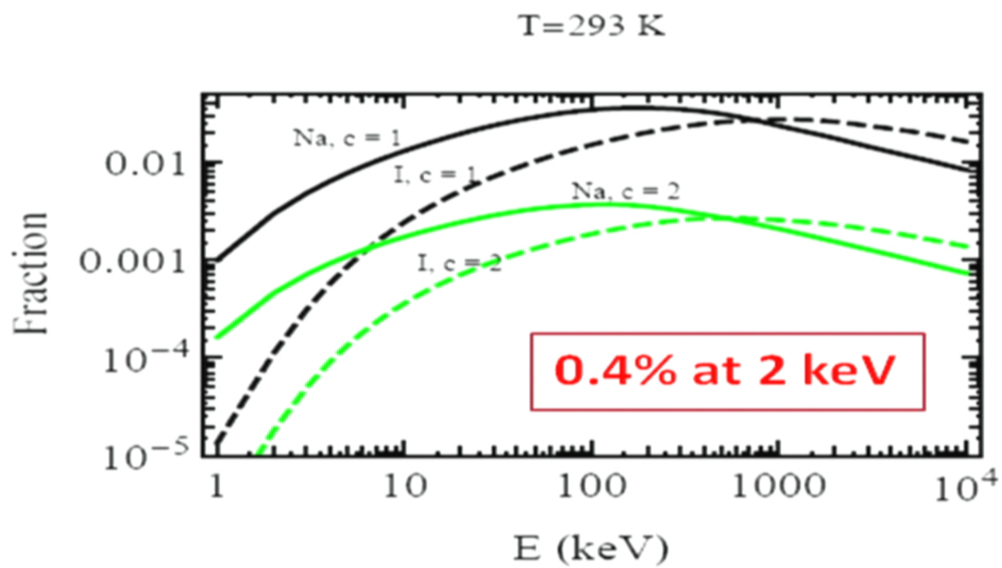
- Two main T effects: $u_1(T)$ ***increases*** with T ➡ χ ***increases***

Channeling fraction for NaI

- Channeling in DAMA's NaI(Tl) is much less than previously published:



DAMA- Eur. Phys. J. C53, 205-2313, 2008

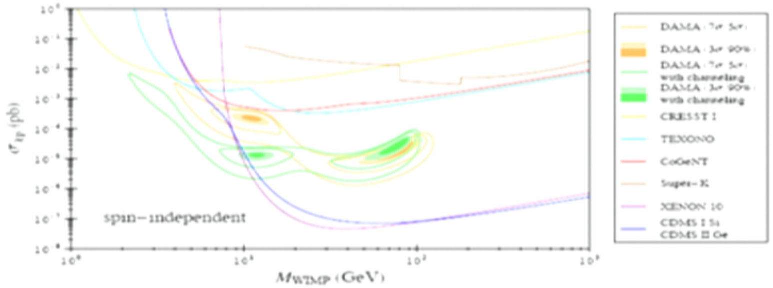


NB, G. Gelmini and P. Gondolo, JCAP 11, 019 (2010)

Consequences

Compatibility of DAMA/LIBRA with other experiments:

Then:



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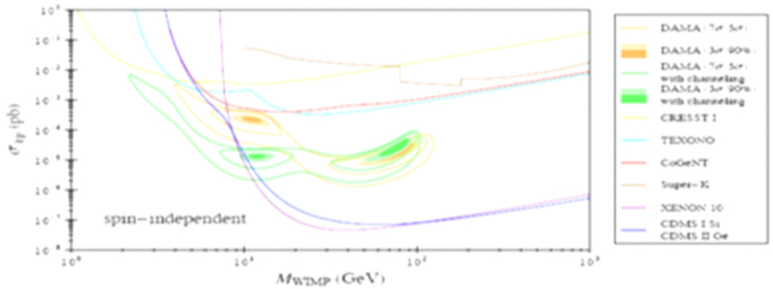
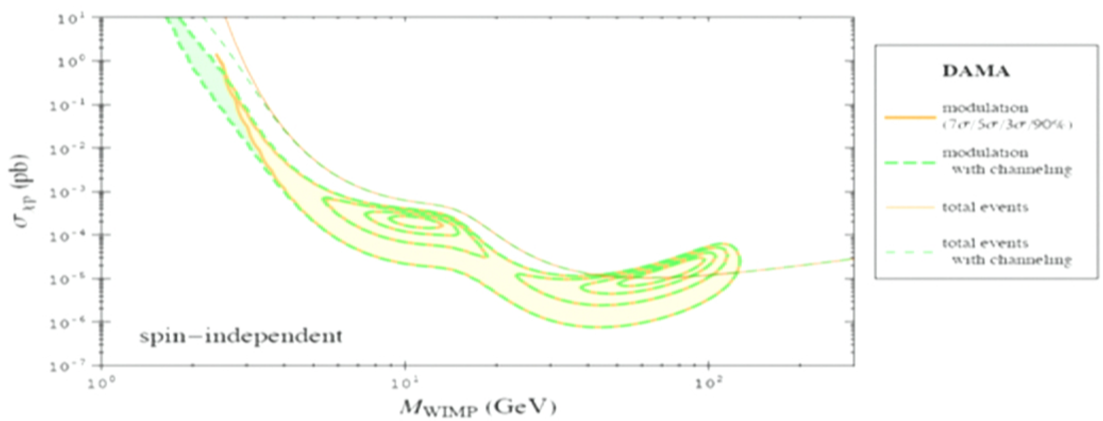
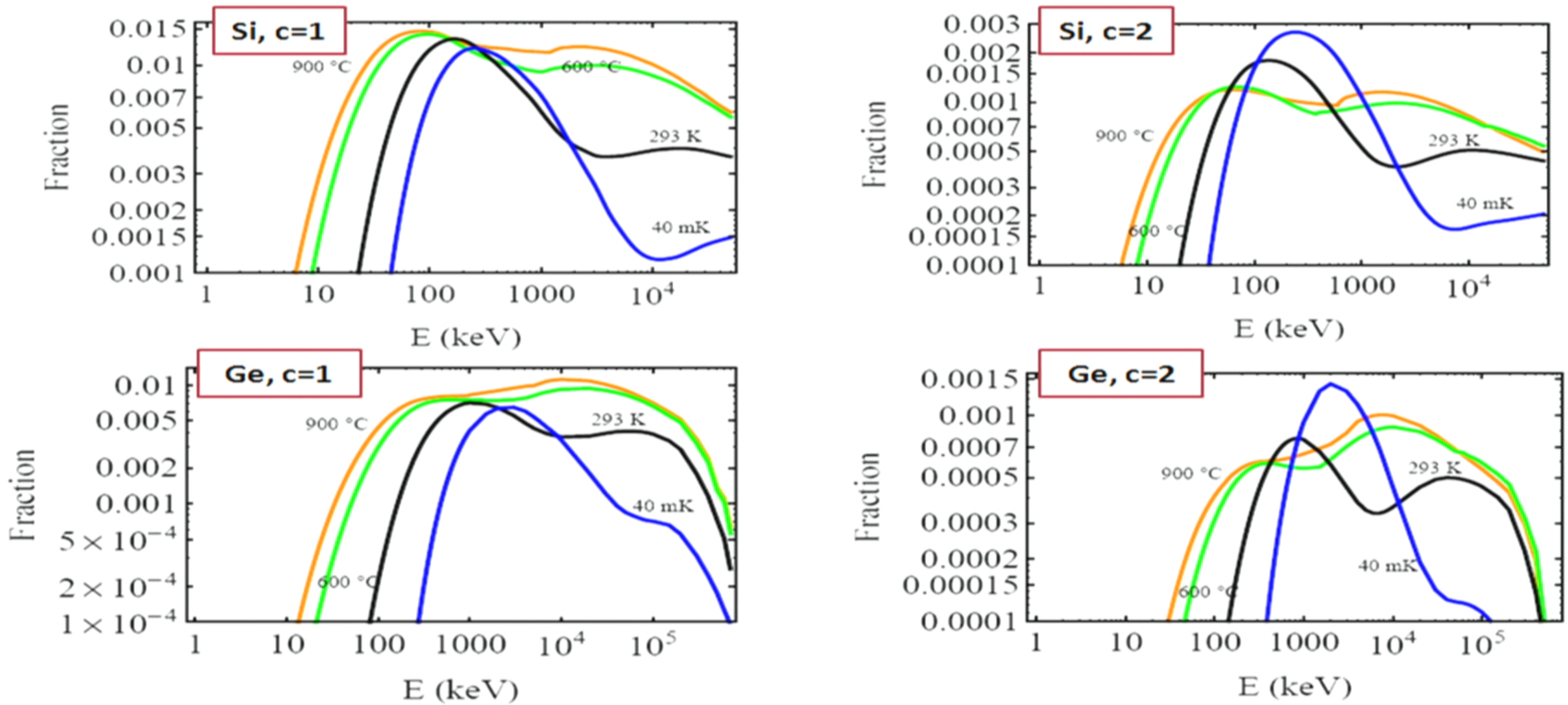


and now (diff. at 7σ):



Savage et al. arXiv:1006.0972

Channeling fraction for Si and Ge



N. Bozorgnia, UCLA

NB, G. Gelmini and P. Gondolo, JCAP 11, 028 (2010)

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$$\frac{dR}{dE} = \int \frac{dR}{dE_R d\Omega_q} p(E, E_R, \hat{\mathbf{q}})d\Omega_q dE_R$$

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

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

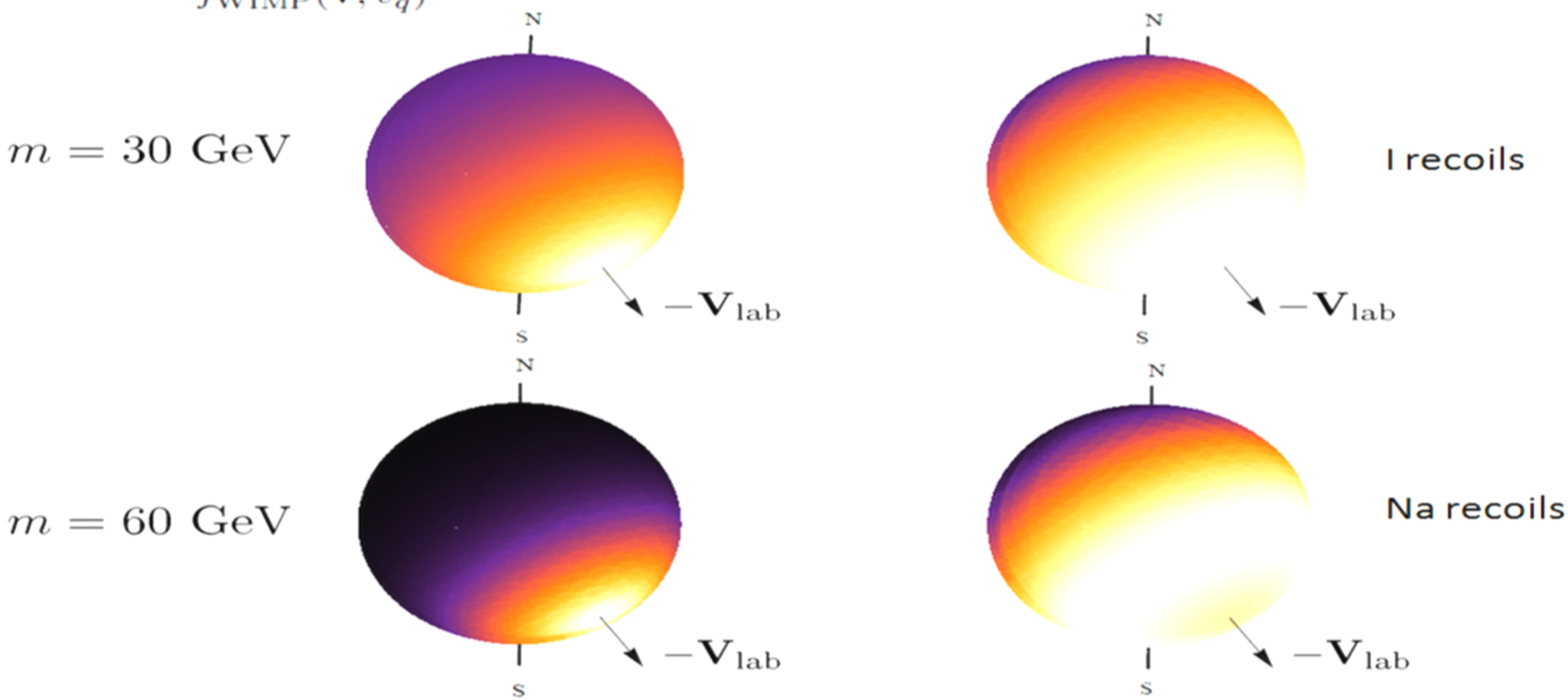
WIMPs and recoils with SHM

$E = 10 \text{ keV}$

WIMPs number density per solid angle

$f_{\text{WIMP}}(\hat{\mathbf{v}}, v_q)$

$\hat{f}_{\text{lab}}$



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- Relative signal modulation amplitude:

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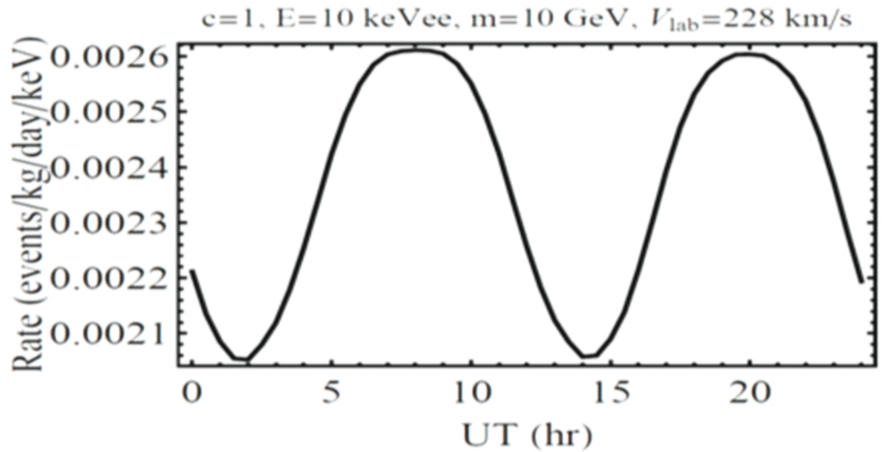
Example of daily modulation due to channeling in NaI:

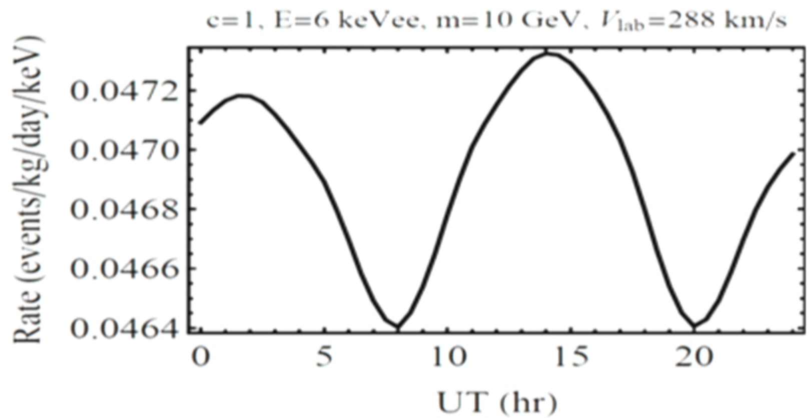
$$\boxed{A_s = 12\%}$$

$$\sigma_v = 300 \text{ km/s}$$
$$\sigma_p = 2 \times 10^{-40} \text{ cm}^2$$



Could it be observed in DAMA?

- Detectability of the daily modulation depends on the exposure of DAMA: **1.17 ton year**
- The large daily modulation amplitudes we predict are not observable at 3σ (not even at 1σ).
- **For the most favorable case to be observable:** with the current total rate of DAMA (dominated by background), we need: $40 \times MT$



Future prospects for other experiments

- **Daily modulation in the usual rate:** the change in the direction of the velocity of the Earth's rotation around its axis, would produce a daily modulation of the signal.

(assuming no background)

Material	m (GeV/c^2)	E_R (keV)	v_{esc} (km/s)	MT range $(\text{ton-yr}/\rho_{0.3}\sigma_{39}\cos^2(\lambda_{\mathrm{lab}})\Delta E_{\mathrm{keV}})$
Ge	7	10	650	1.6 - 6.5
Ne	5	6	544	2.6 - 4.8
Ne	5	6	650	2.9 - 6.9
Xe	5	3	544	0.15 - 0.51
Xe	5	3	650	0.27 - 0.92
Ar	5	8	544	1.4 - 4.4
Ar	5	8	650	2.5 - 24.7
NaI	10	9	544	0.51 - 77.8
NaI	10	9	650	0.75 - 6.2

DM signatures in directional detection

- **Directional DM detectors**: measure the recoil direction
  - **DRIFT, DMTPC, NEWAGE, MIMAC** (using CS_2, CF_4, or ^3He)

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- In an ideal detector which provides a **3-D reconstruction of the recoil directions** (including their senses), has **low energy threshold**, and excellent **background rejection capability**, few events would be enough to reject isotropy.

DM signatures in directional detection

- I will discuss other novel dark matter signature relevant for directional detection:
  - **A ring of maximum recoil rate around the average arrival direction of WIMPs**
  - **Aberration features**
  - **Directional annual modulation amplitudes: the North and South Galactic hemisphere annual modulation**

Ring of maximum recoil rate

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

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

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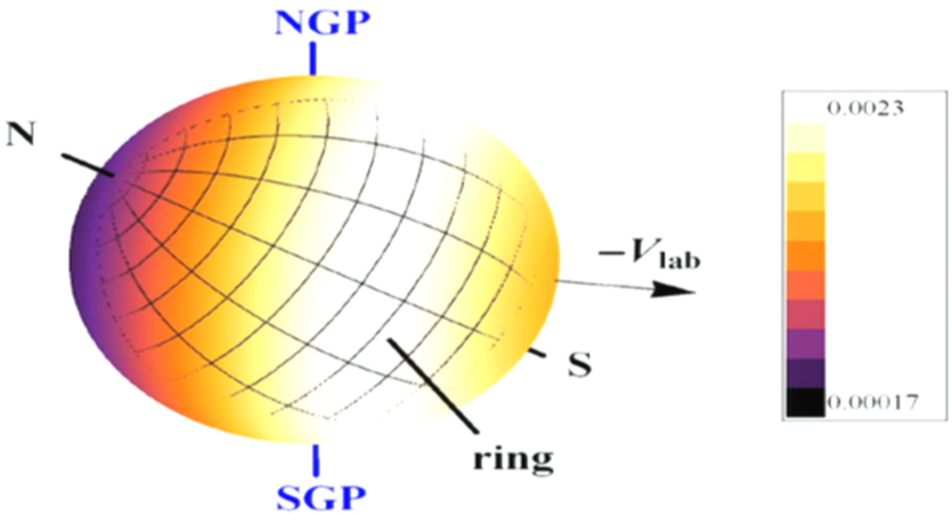
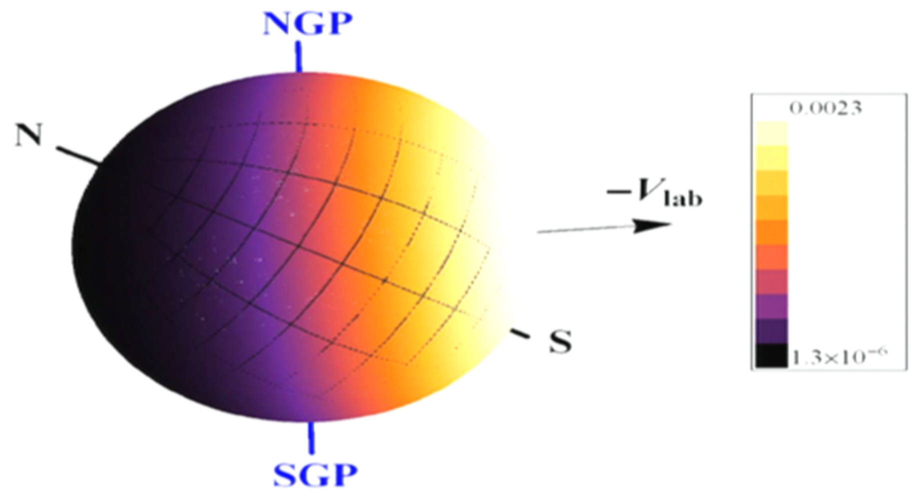
- Max of $\hat{f}_{\rm lab}$ is on a ring of angular aperture γ around $-\mathbf{V}_{\rm lab}$.

Ring of maximum recoil rate (Sulfur recoils)





- $\hat{f}_{\rm lab}$ on December 2, 2010
- $m = 100$ GeV , $E_R = 5$ keV

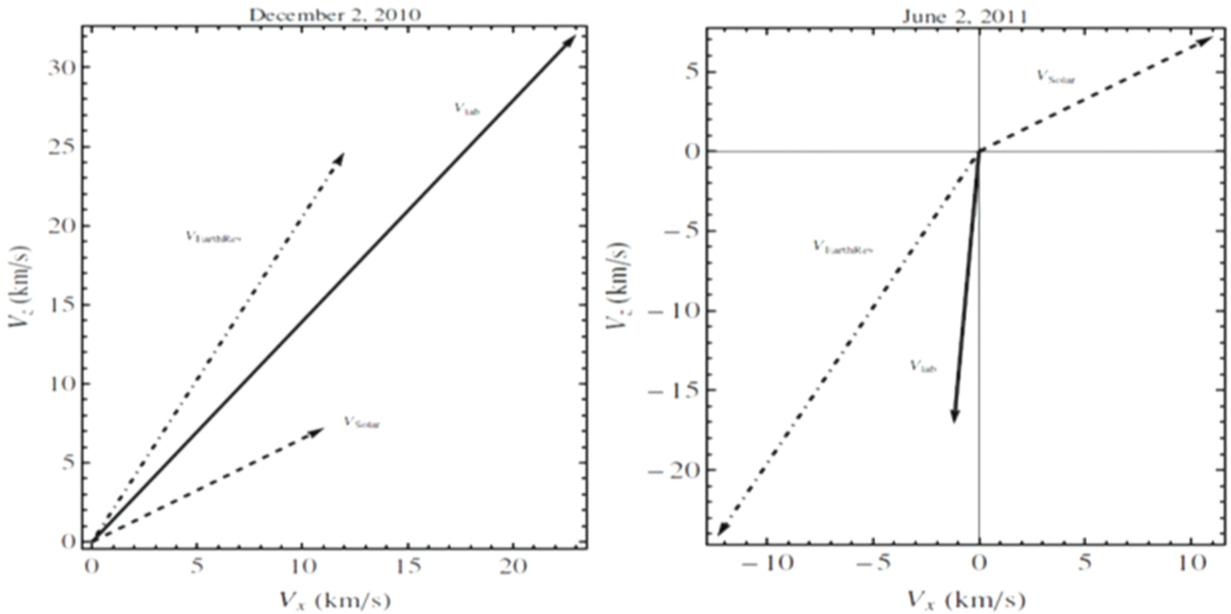
  $\gamma = 66°$

- $\hat{f}_{\rm lab}$ on June 2, 2011
- $m = 100$ GeV , $E_R = 40$ keV

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

$\mathbf{V}_{lab}$ in the x-z galactic plane

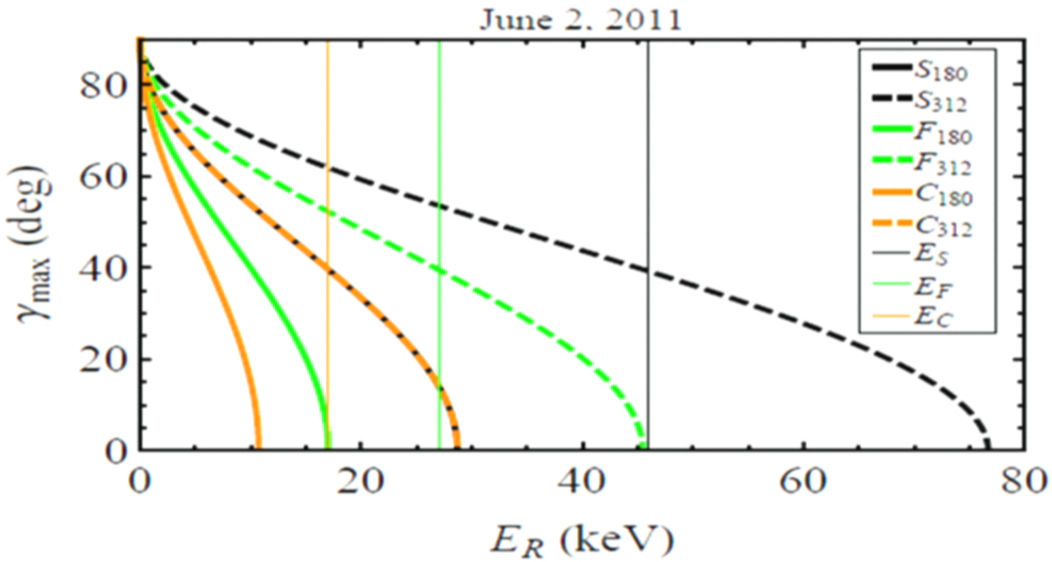
$$\mathbf{V}_{\text{lab}} = \mathbf{V}_{\text{GalRot}} + \mathbf{V}_{\text{Solar}} + \mathbf{V}_{\text{EarthRev}} + \mathbf{V}_{\text{EarthRot}}$$



- The x-axis points towards the Galactic center, and the z-axis points towards the Galactic North.

Maximum ring aperture

- The maximum possible ring radius is obtained when $\mu = M$ as $m \gg M$



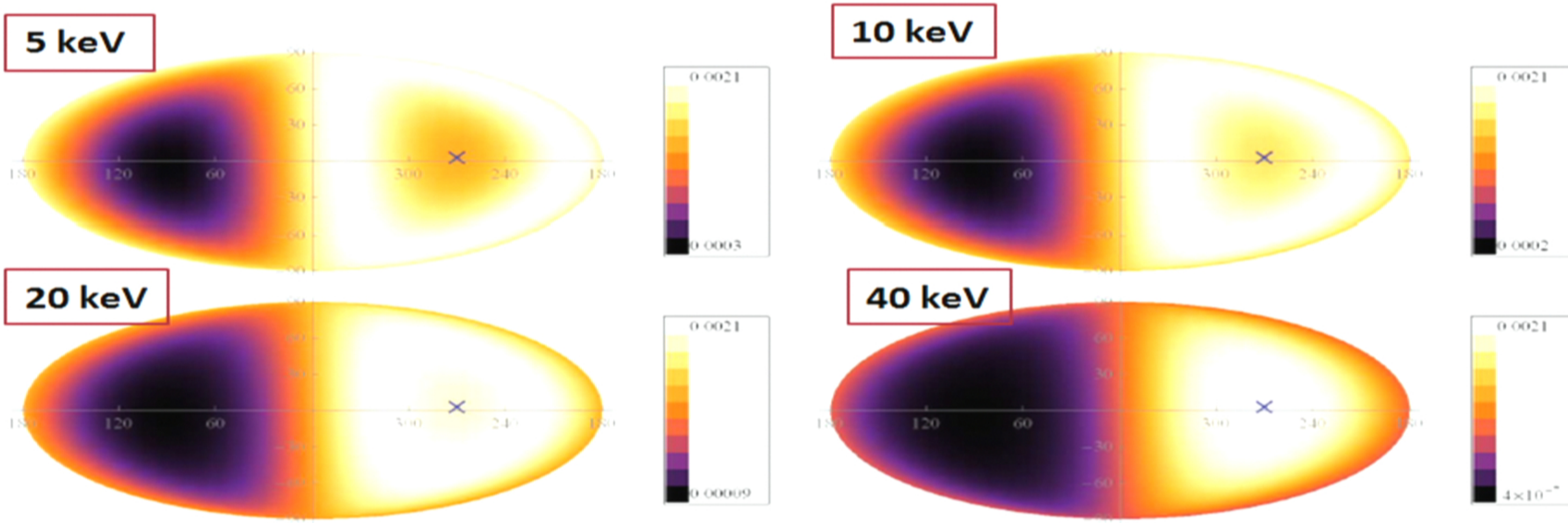
$$\cos(\gamma_{max}) = \sqrt{\frac{E_R}{2MV_{lab}^2}}$$

There can be no ring if:

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

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

Ring-like features



- $\hat{f}_{\text{lab}}$ for sulfur recoils in June.
- $m = 300$ GeV

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

Inferring the WIMP mass

- For a given recoil energy and element in a detector, the mass of the WIMP can be inferred from the measured aperture angle of the ring.

- For compounds, one or more rings can be present due to more than one type of recoiling nucleus. → A powerful way for checking consistency, since all rings must be consistent with the same WIMP mass.

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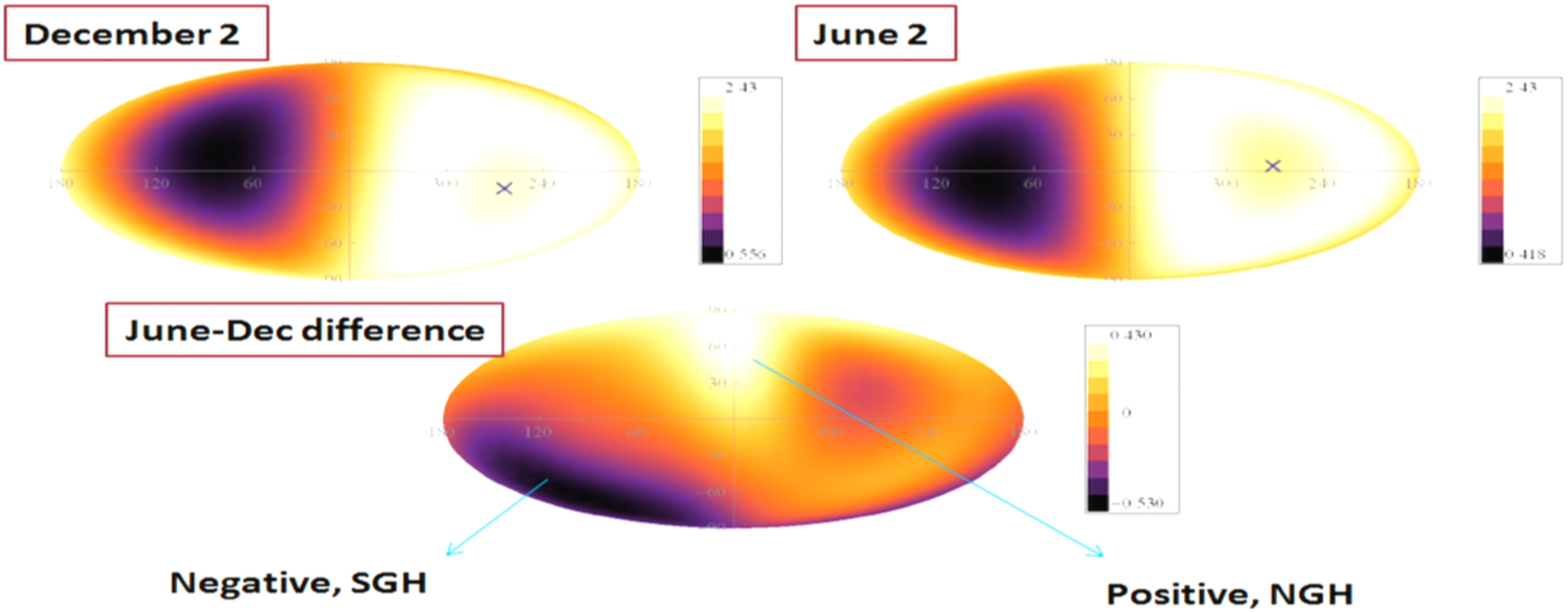
Aberration features

- Directional differential recoil rate in CS_2

$$m = 300\ \mathrm{GeV}$$
$$E_R = 5\ \mathrm{keV}$$



NGHAM and SGHAM

- Integrate the directional differential rate over direction and compute the annual modulation amplitude:

$$\Delta\left(\frac{dR}{dE_R}\right) = \int \left(\frac{dR}{dE_R\ d\Omega_q}\Big|_{\mathrm{June}} - \frac{dR}{dE_R\ d\Omega_q}\Big|_{\mathrm{Dec}}\right) d\Omega_q$$

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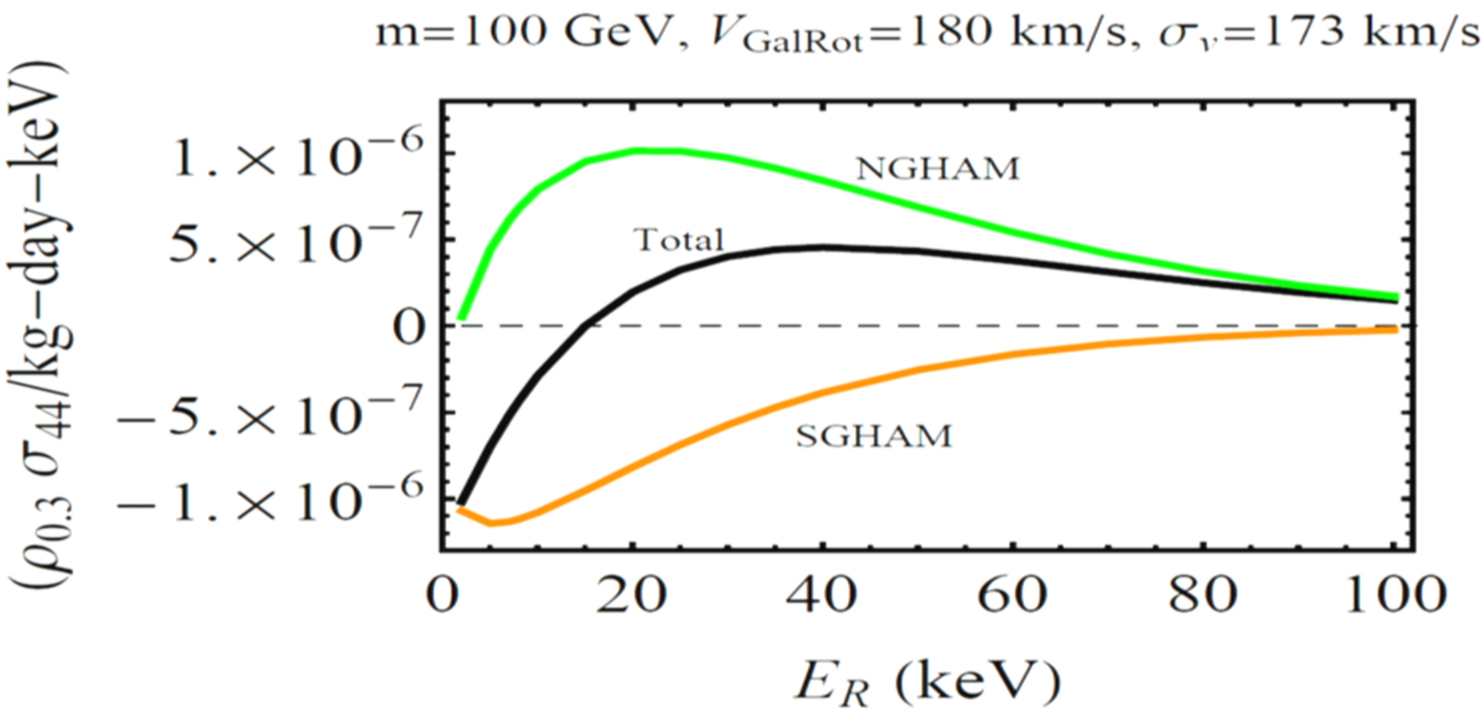
- We find that :
  - **Both the GHAM amplitudes are lager than the total, which is the sum of the two.**
  - **The GHAM amplitudes do not change sign with energy. The NGHAM amplitude is positive and the SGHAM amplitude is negative.**

NGHAM and SGHAM



NGHAM and SGHAM

- NGHAM is positive and SGHAM is negative because the average WIMP velocity, the direction at which most of the recoils happen, points slightly **North** in **June** and slightly **South** in **December**.
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- The change in sign with energy of the sum of both is due to the variation of their respective magnitudes.
- The most striking difference between the GHAM and the total annual modulation amplitudes happen at the energy at which both GHAM are equal in magnitude, so that the total modulation amplitude is zero.

Summary

- **Channeling** of recoiling nuclei and incident particles have different mechanisms. We were able to reproduce DAMA results for incident ions, but for recoiling nuclei the channeling fraction is much smaller, and strongly temperature dependent due to blocking.
- We have studied the possibility of a **daily modulation** due to channeling , which would be a background free signature of dark matter. We find large modulation amplitudes for NaI which are not observable in DAMA. The daily modulation might be detectable in other experiments with smaller background or larger exposure.

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- The GHAM are just some partitions which give large modulation amplitudes for the SHM but there maybe other partitions for others halo models.
- We intend to study the GHAM amplitudes for other halo models in the future.