Channeling in Dark Matter Detection

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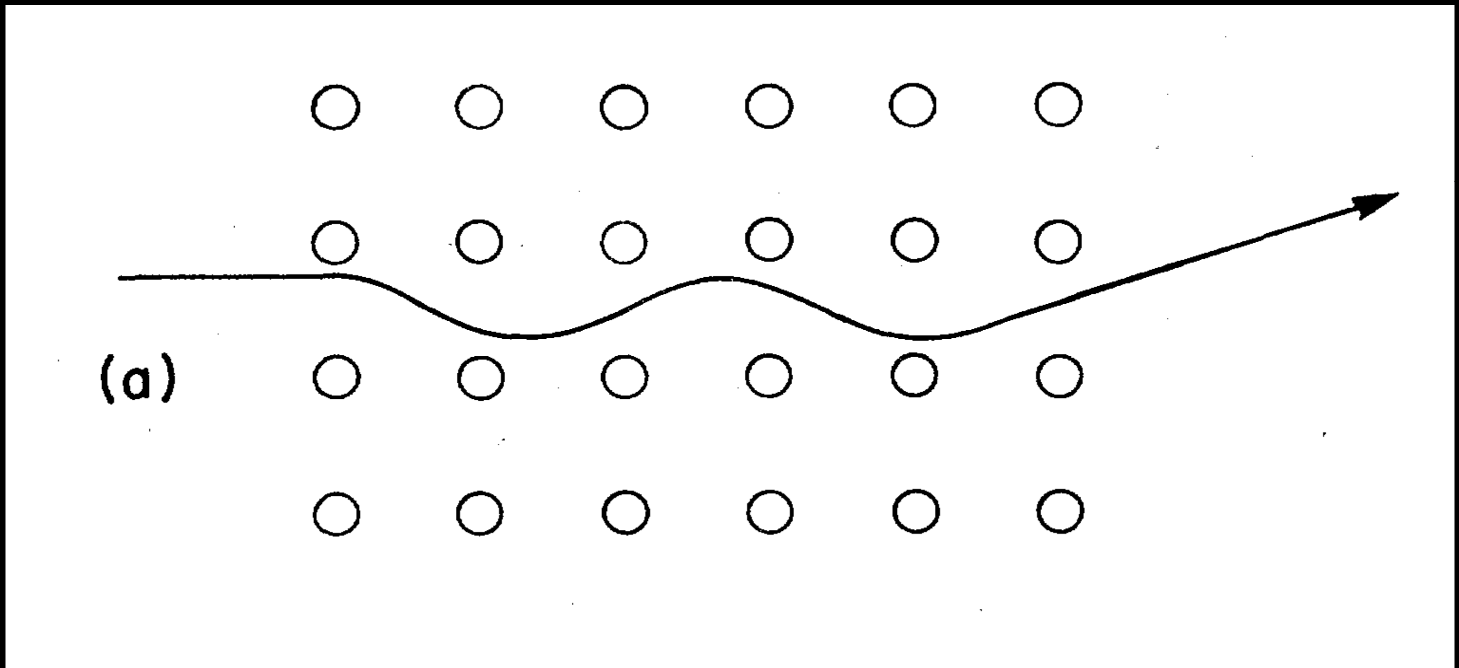
Based on work in progress with Graciela Gelmini and Nassim Bozorgnia

Outline

- Channeling and blocking in crystals
- Channeling in direct dark matter detection
- Basic idea for daily modulation
- Channeling fractions for
  - incoming particles
  - recoiling nuclei
- Conclusions and work in progress

Channeling and blocking in crystals

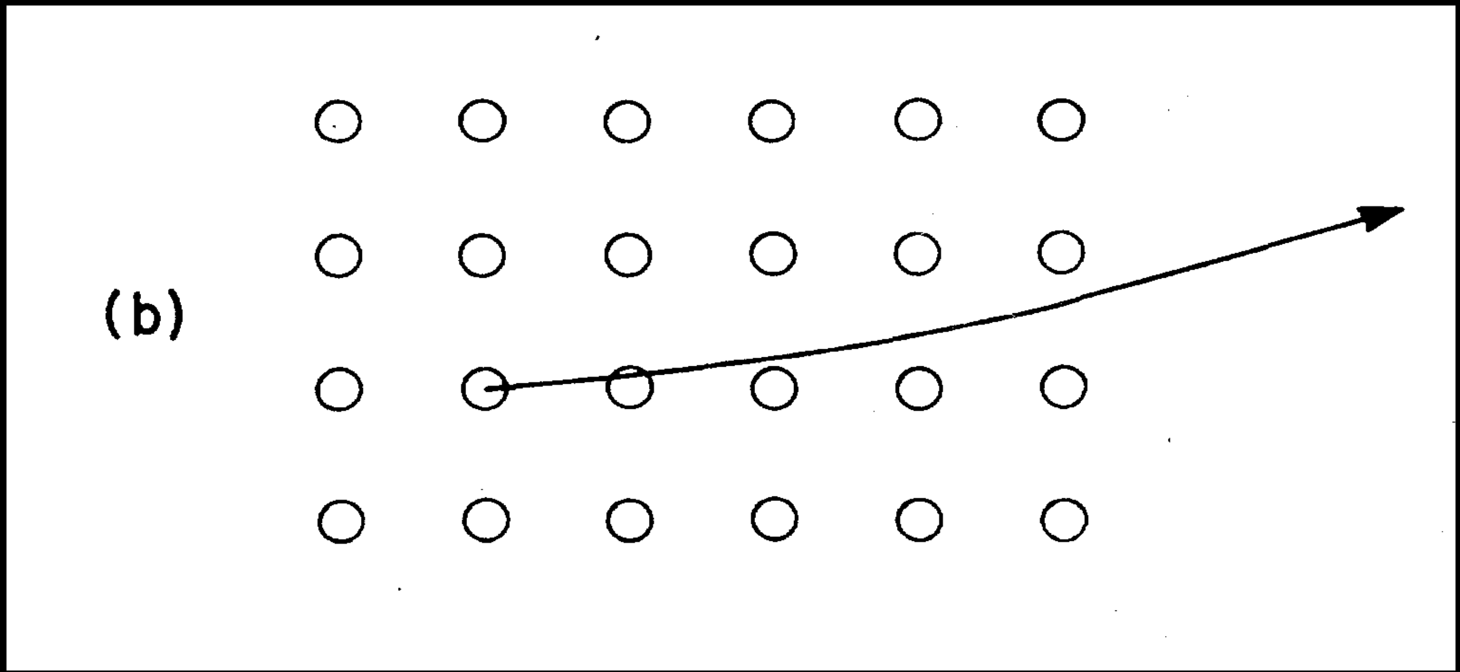
Channeling. If an ion incident onto the crystal moves in the direction of a symmetry axis or plane of the crystal, it has a series of small-angle scatterings which maintains it in the open channel. The ion penetrates much further into the crystal than in other directions.



From Gemmel 1974, Rev. Mod. Phys. 46, 129

Channeling and blocking in crystals

Blocking. If an ion originating at a crystal lattice site moves in the direction of a symmetry axis or plane of the crystal, there is a reduction in the flux of the ion when it exit the crystal, creating a "blocking dip".



From Gemmel 1974, Rev. Mod. Phys. 46, 129

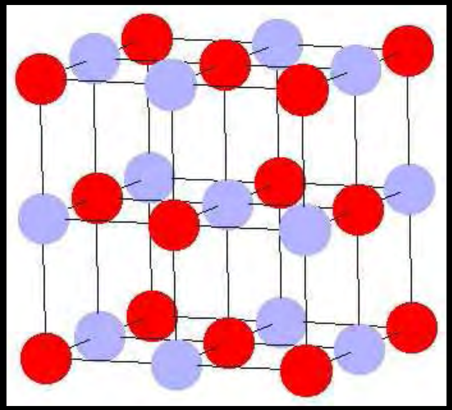
Channeling and blocking in crystals

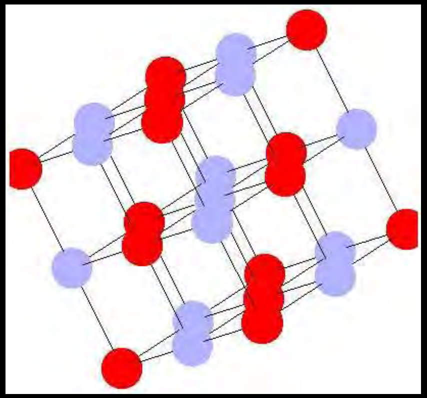
- Channeling and blocking in crystals is used in
  - crystallography
  - studies of lattice disorder
  - ion implantation
  - finding the location of dopant and impurity atoms
  - studies of surfaces and interfaces
  - measurement of short nuclear lifetimes
  - production of polarized beams
  - etc.

To make electronic circuits in Si through B, P, As ion implantation, channeling must be avoided (good data at ~100 keV and analytic models by Gerhard Hobler of Vienna University of Techonology, 1995)

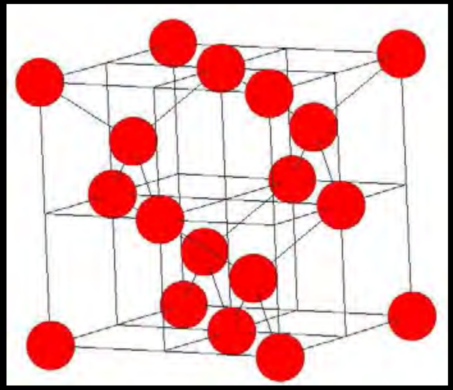
Channeling and blocking in crystals

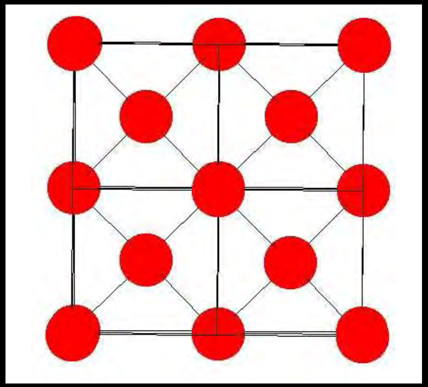
- NaI or CsI crystals (fcc)





- 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

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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)

Observation of channeling in NaI(Tl)

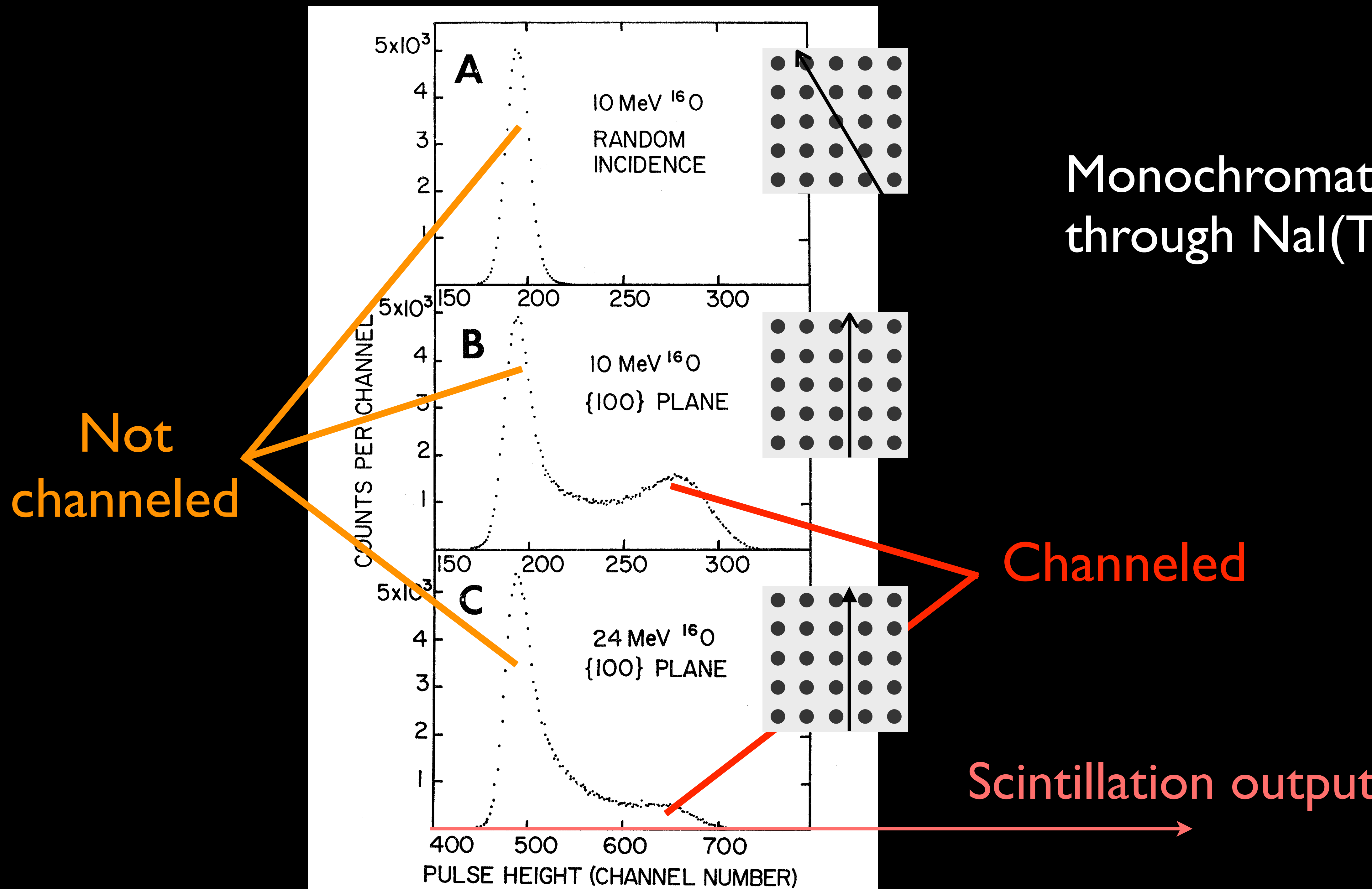


FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

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

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

Observation of channeling in NaI(Tl)

- Channeled ions produce more scintillation light

  (because they loose most of their energy via electronic stopping rather than nuclear stopping)

- Channeled recoils have a quenching factor close to 1

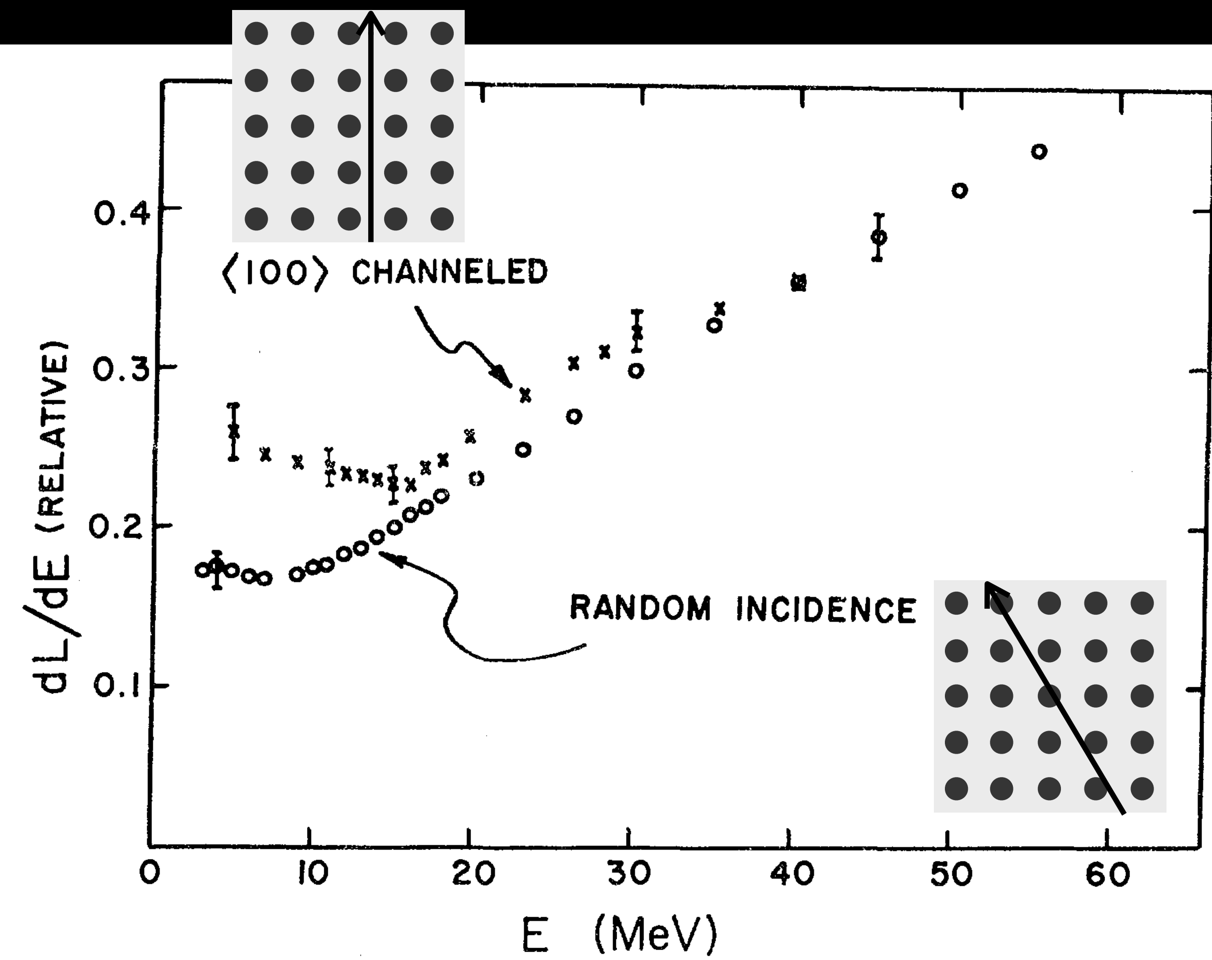
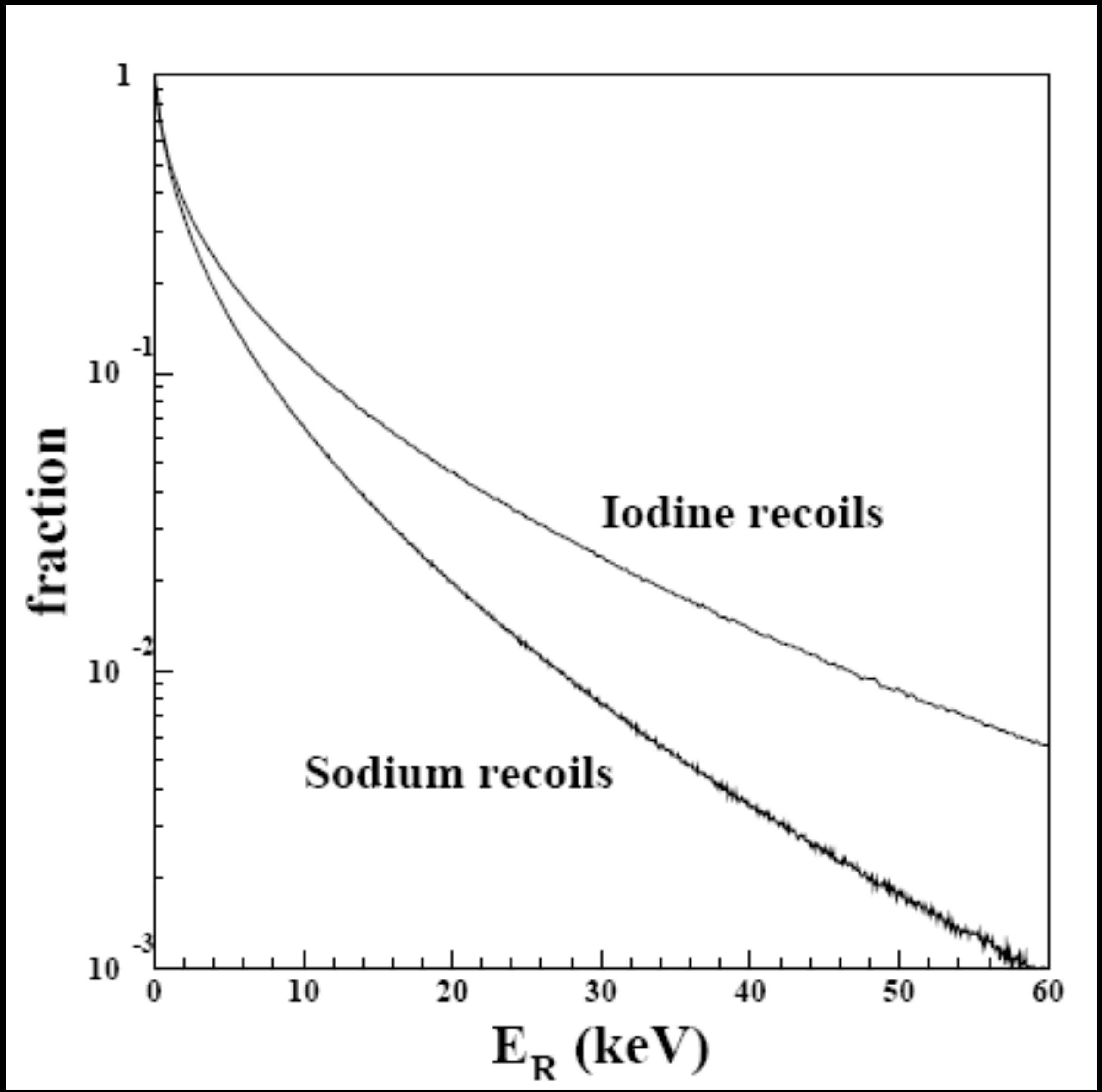


FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

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

Channeling in direct dark matter detection

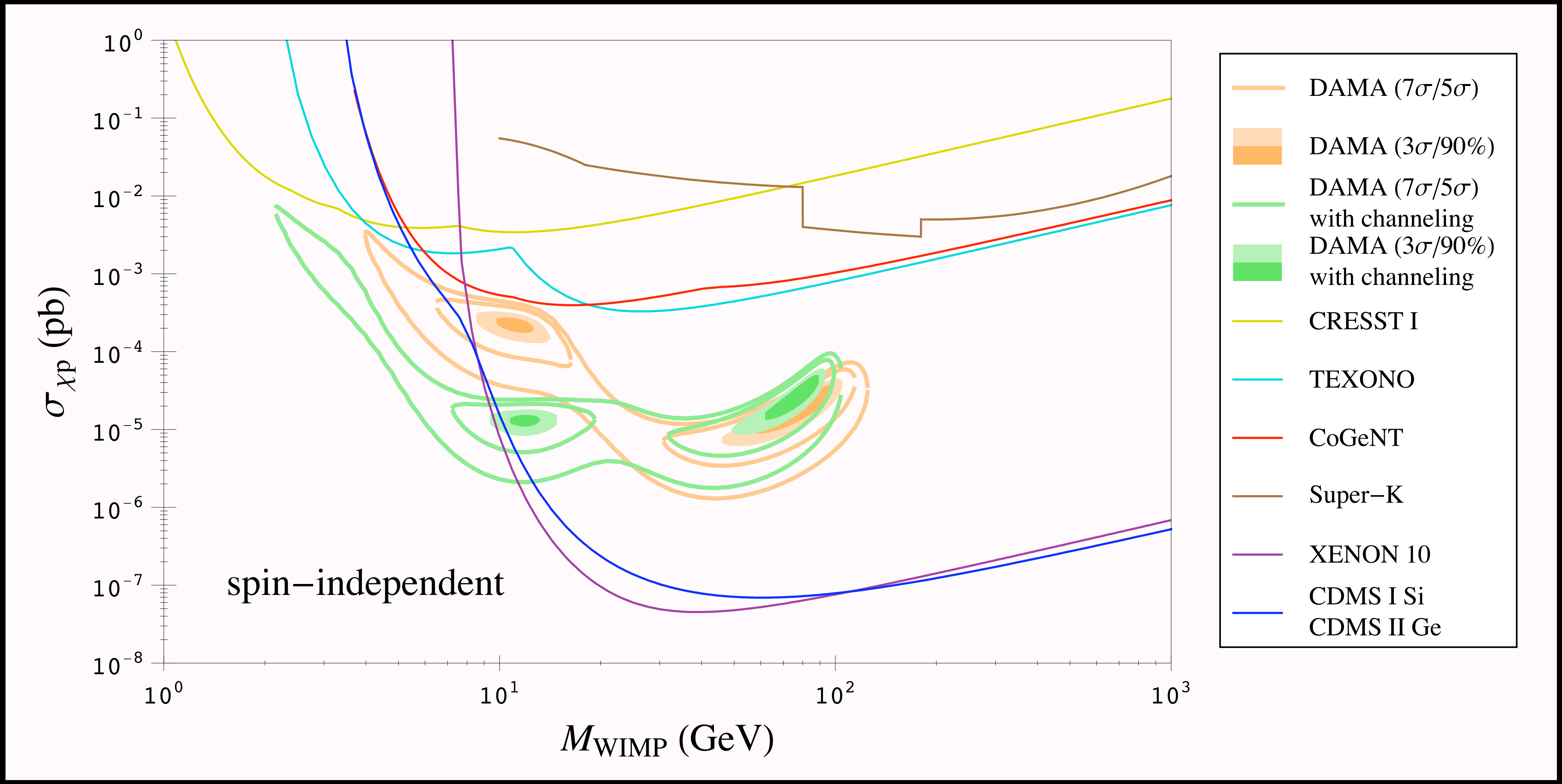
- The DAMA collaboration found that the fraction of channeled recoils is large at low recoil energies



Bernabei et al. 2008, Eur. Phys. J. C53, 205

Channeling in direct dark matter detection

- Channeling changes the position of the interesting regions in the dark matter mass-cross section plane



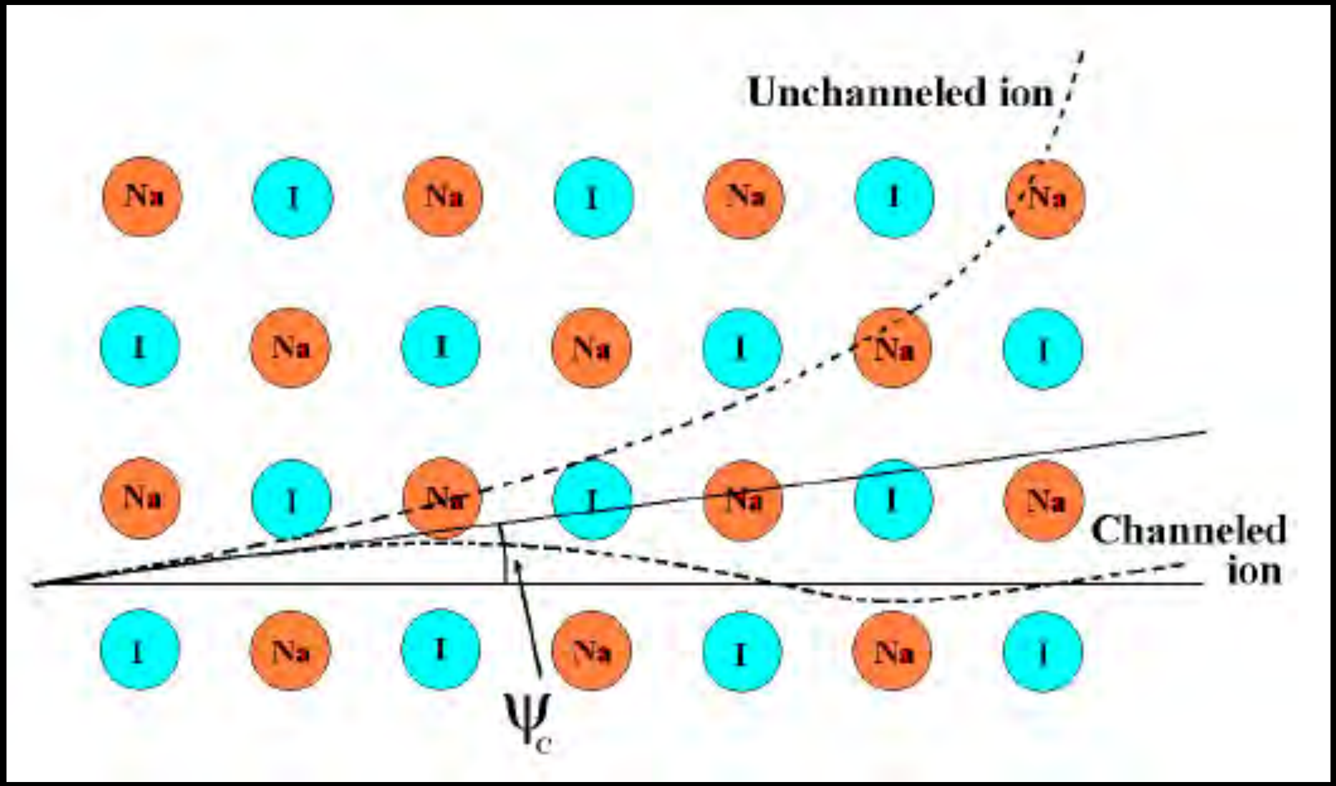
Savage. Gelmini, Gondolo, Freese 2008

Channeling in direct dark matter detection

- Quenching factor *Q*: not all of the recoil energy is detected

$$E_{\rm measured} = Q\, E_{\rm recoil}$$

- When Na or I recoils move along a channel, their quenching factor is Q=1 instead of $Q_{\rm Na}$=0.3 and $Q_{\rm I}$=0.09, since they give their energy to electrons.



Bernabei et al. 2008, Eur. Phys. J. C53, 205

Basic idea for daily modulation

Sekiya et al 2003, Avignone, Creswick, Nussinov 2008, 1007.0214

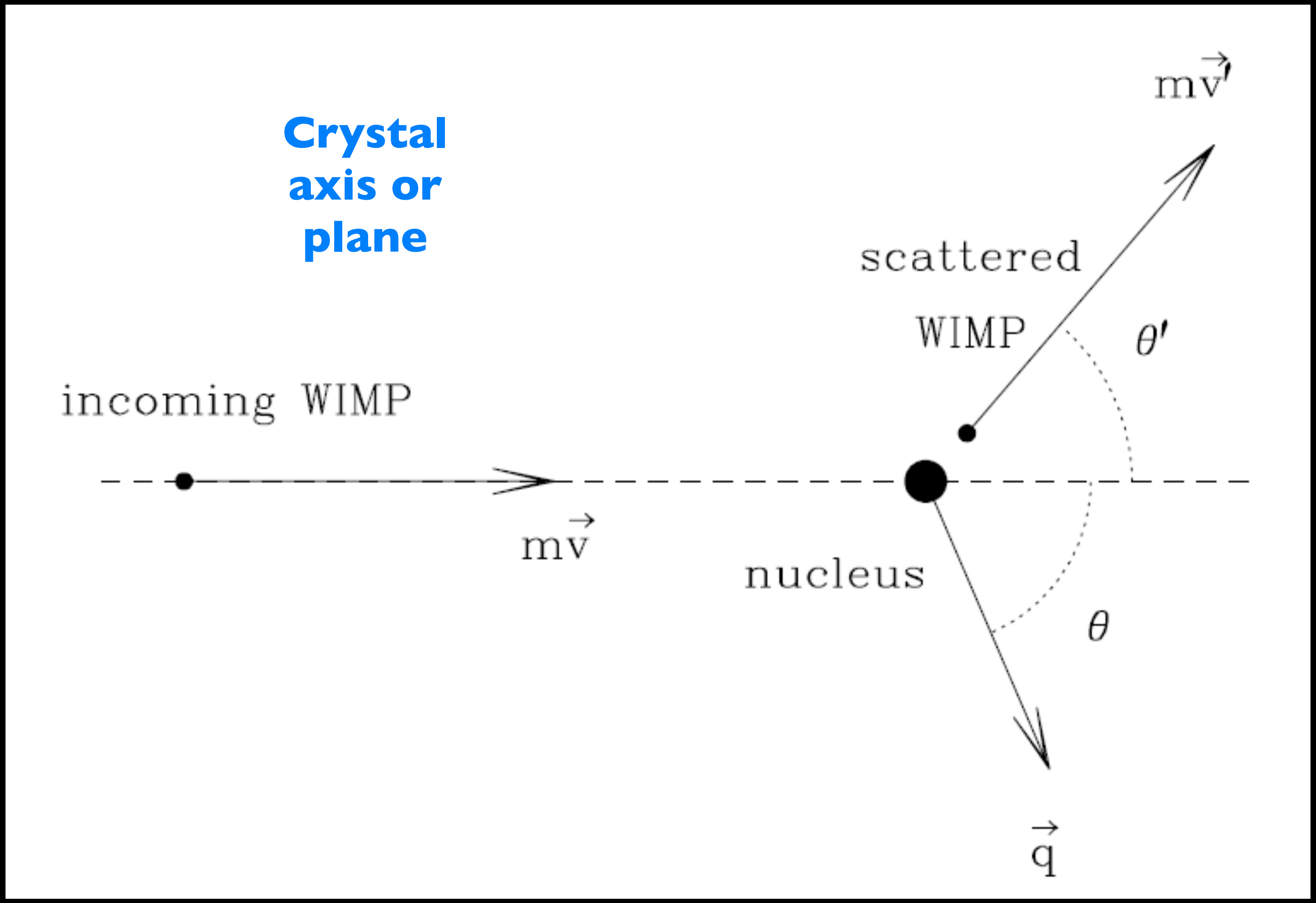
- The WIMP wind comes preferentially from one direction, due to the motion of the Earth with respect to the Galaxy.
- When that direction is aligned with a channel, the scintillation or ionization output is larger ($Q=1$ instead of $Q<1$).
- Earth's daily rotation makes the WIMP wind direction change with respect to the crystal.
- This produces a daily modulation in the "measured" recoil energy (as if the quenching factor were modulated).

Basic idea for daily modulation

- If this daily modulation is measured, it would have no background, thus it would be ideal for dark matter searches
- Avignone et al mention a modulation amplitude of ~25% as a somewhat simplistic estimate
- We set out to do a better calculation, and in the process understand channeling and blocking for dark matter detection
- Our results on channeling and blocking are available on the arxiv: 1006.3110 for NaI, 1008.3676 for Ge and Si, and in preparation for CsI and daily modulation

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. D66, 103513

What we need

- We need to determine the probability $p(E, E_R, \hat{\mathbf{q}})$ that an energy E is measured when the recoil is in direction $\hat{\mathbf{q}}$ with energy E_R.

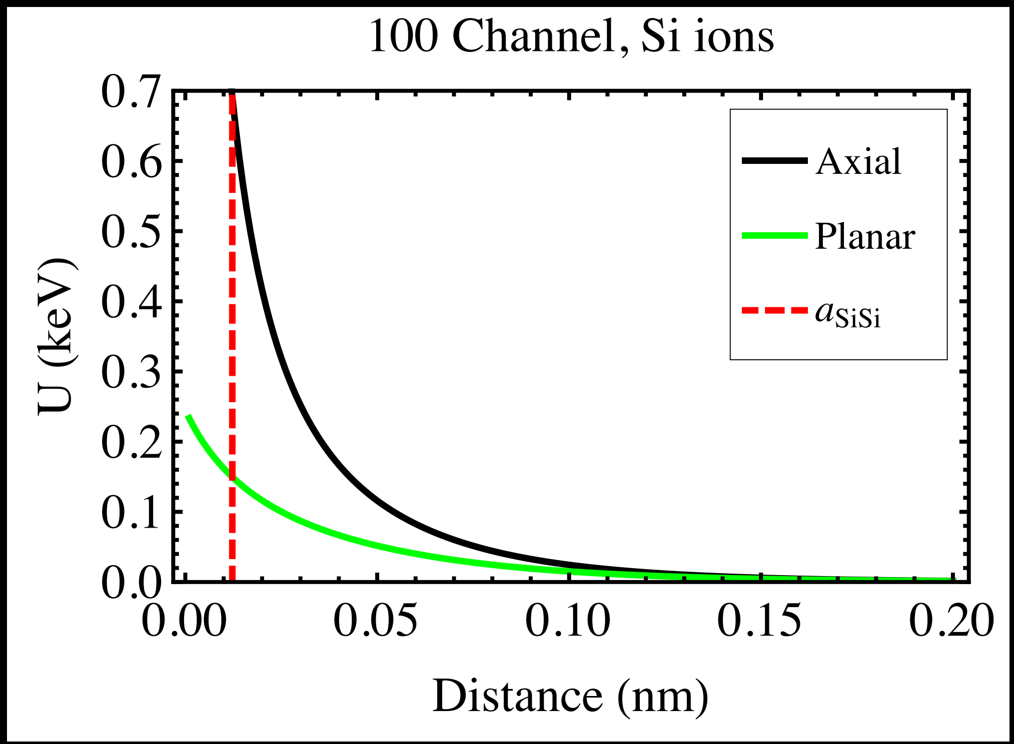
- The recoil nucleus can either be channeled or not channeled:

$$p(E, E_R, \hat{\mathbf{q}}) = \chi(E_R, \hat{\mathbf{q}})\delta(E - E_R) \quad \textit{Channeled}$$
$$+[1 - \chi(E_R, \hat{\mathbf{q}})]\delta(E - QE_R) \quad \textit{Not channeled}$$

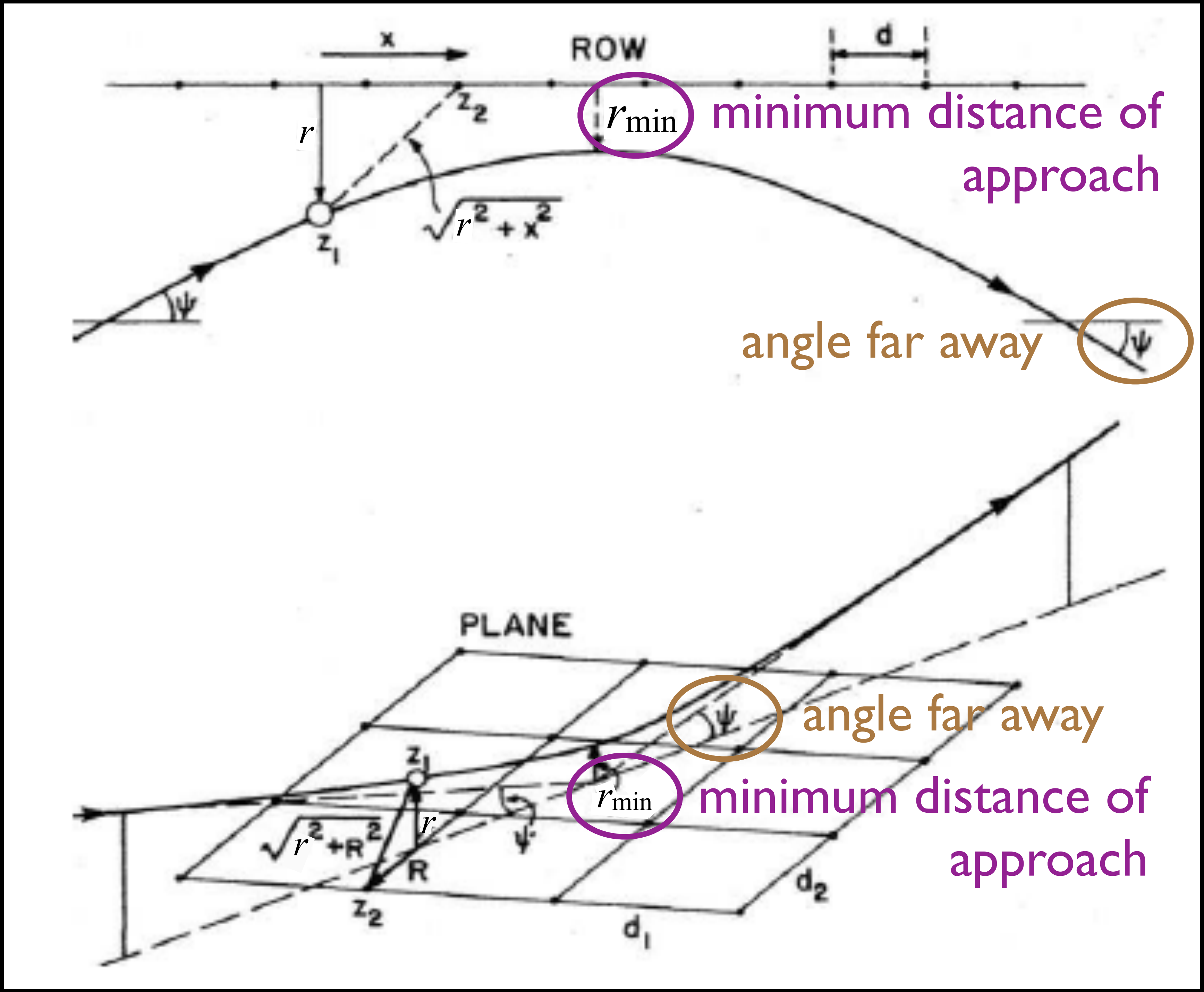
where $\chi(E_R, \hat{\mathbf{q}})$ is the fraction of channeled nuclei with recoil energy E_R in direction $\hat{\mathbf{q}}$

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, Komaki & Fujimoto 1970, 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.
- 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



From Gemmel 1974, Rev. Mod. Phys. 46, 129

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

$U(r_{ch})$ at middle of channel, far away from row/plane

Channeling requires $r_{min} > r_c$ or $\psi < \psi_c$

The difficulty lies in calculating r_c.

Channeling requires:

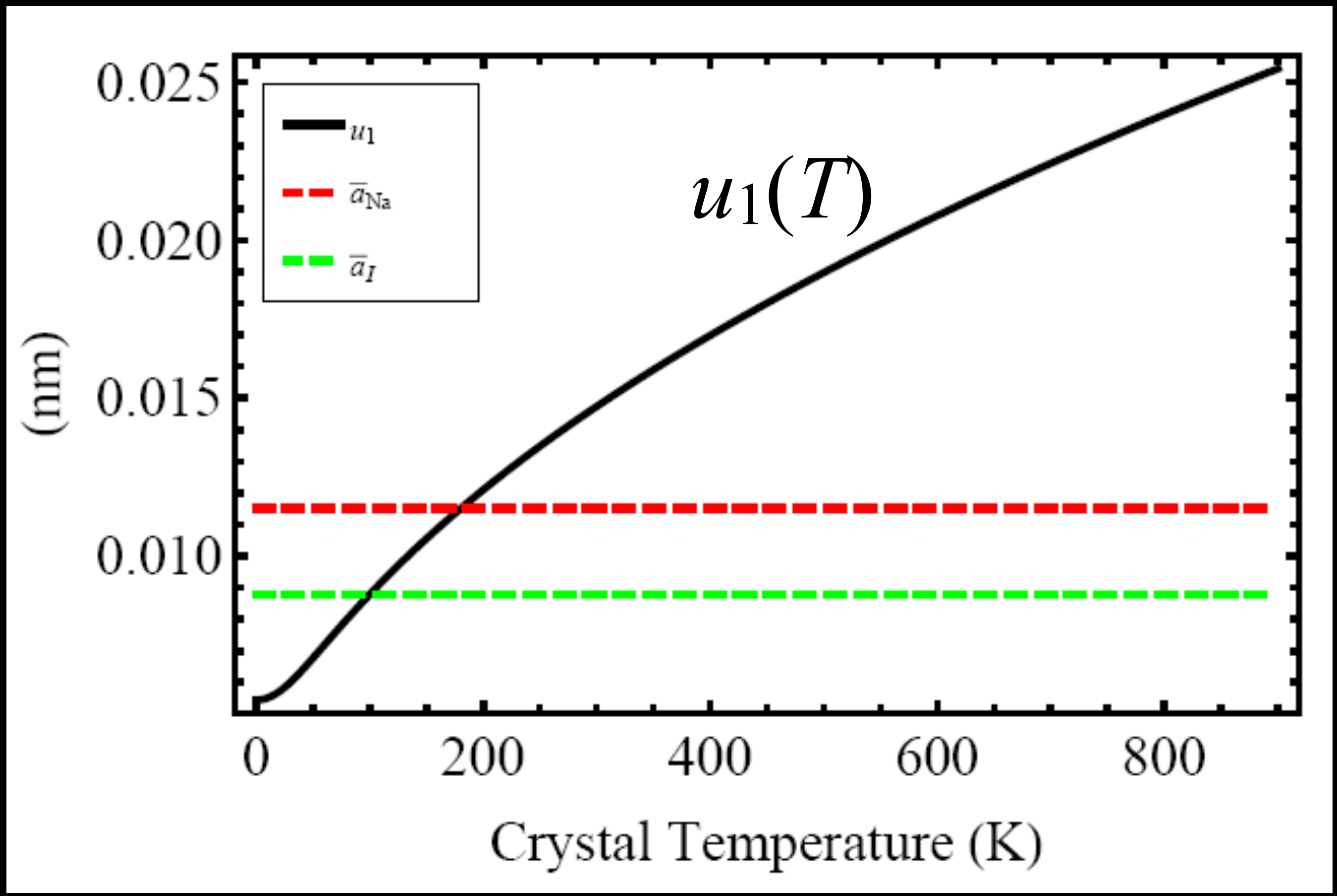
- Minimum distance of approach to row/plane larger than a critical value *(Lindhard 1965, Morgan & van Vliet 1971, Hobler 1995)*

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

$r_{\rm c}(E)$: for perfect static lattice; decreases with E

$u_1(T)$: 1-dim vibration amplitude (used Debye model); increases with T

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

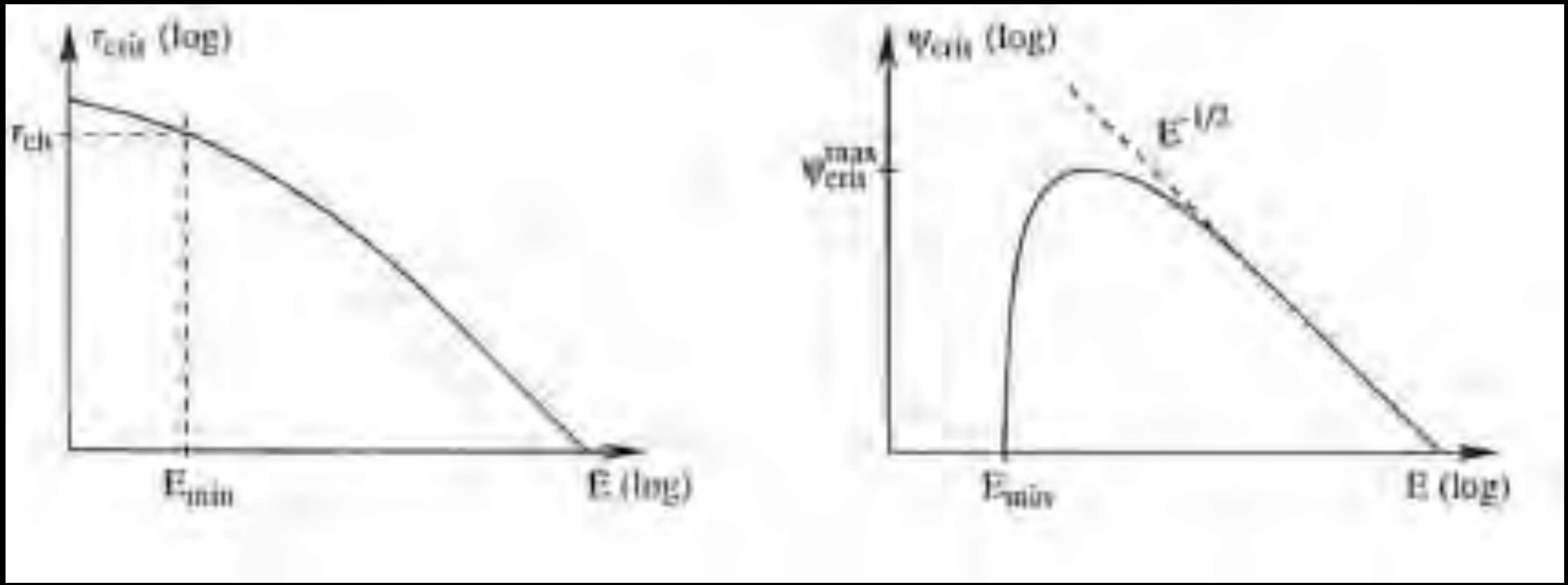


Channeling requires:

- Angle far from the row/plane smaller than a critical angle

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

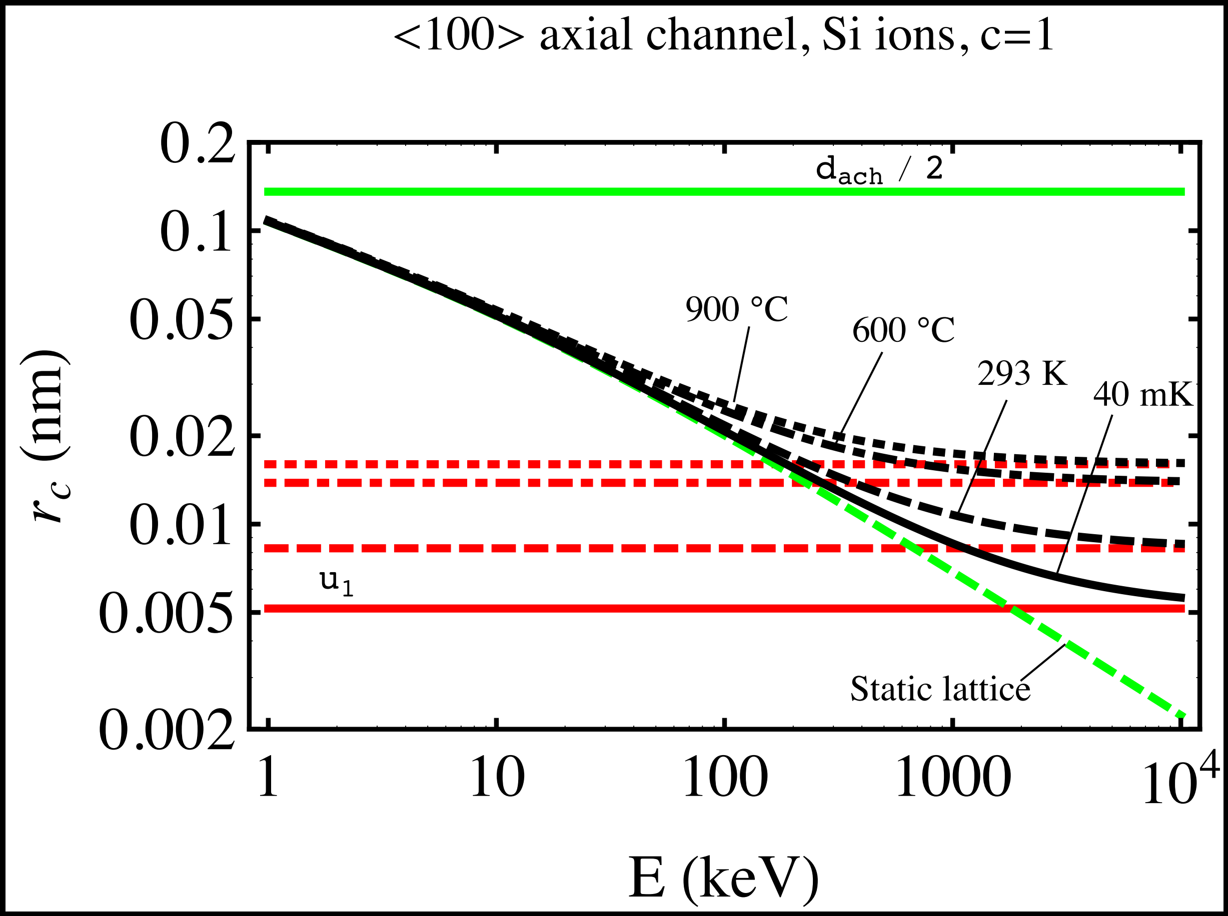
If $r_c(E,T)$ > channel radius r_c, $\psi_c=0$; no channeling is possible

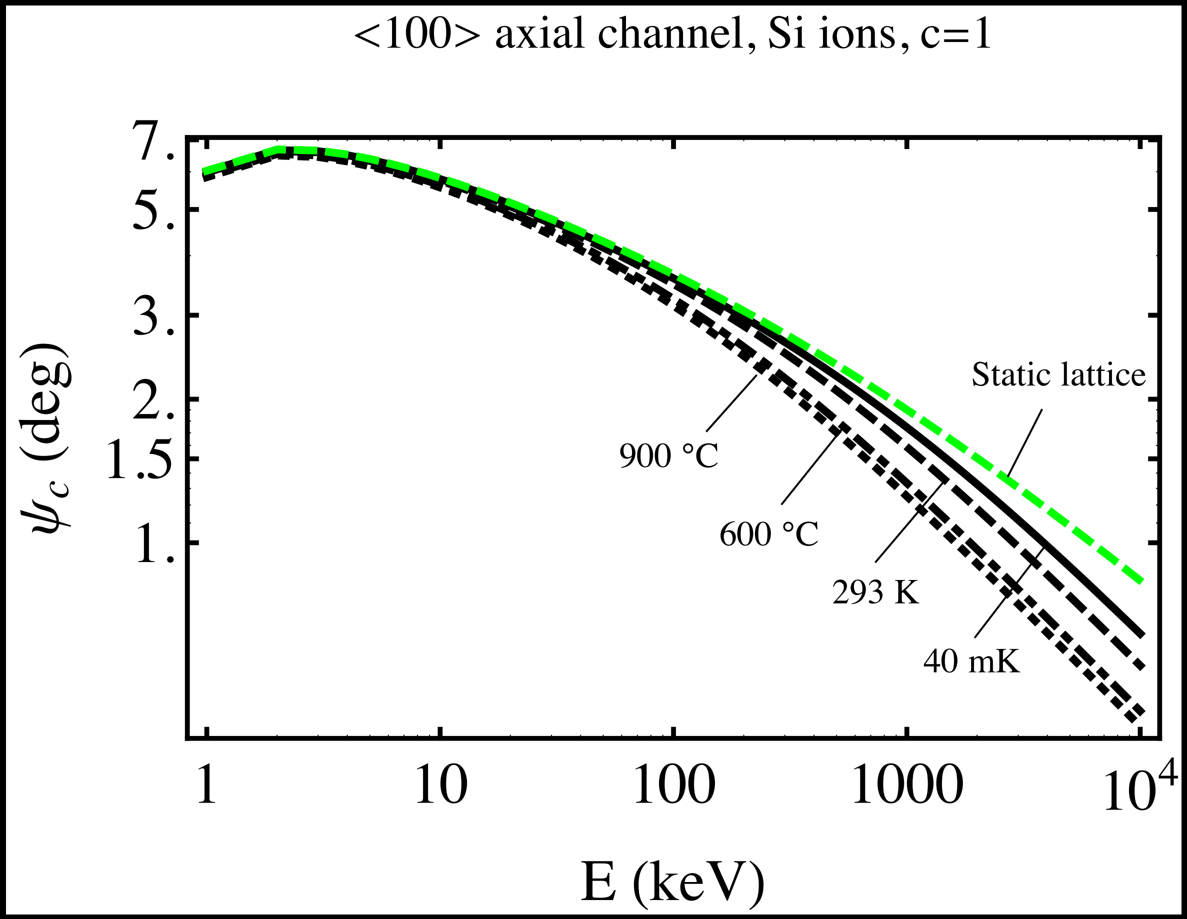


From Hobler 1995

- Si ion in Si crystal

c=1 (i.e. $r_c \rightarrow u_1(T)$ at high E)

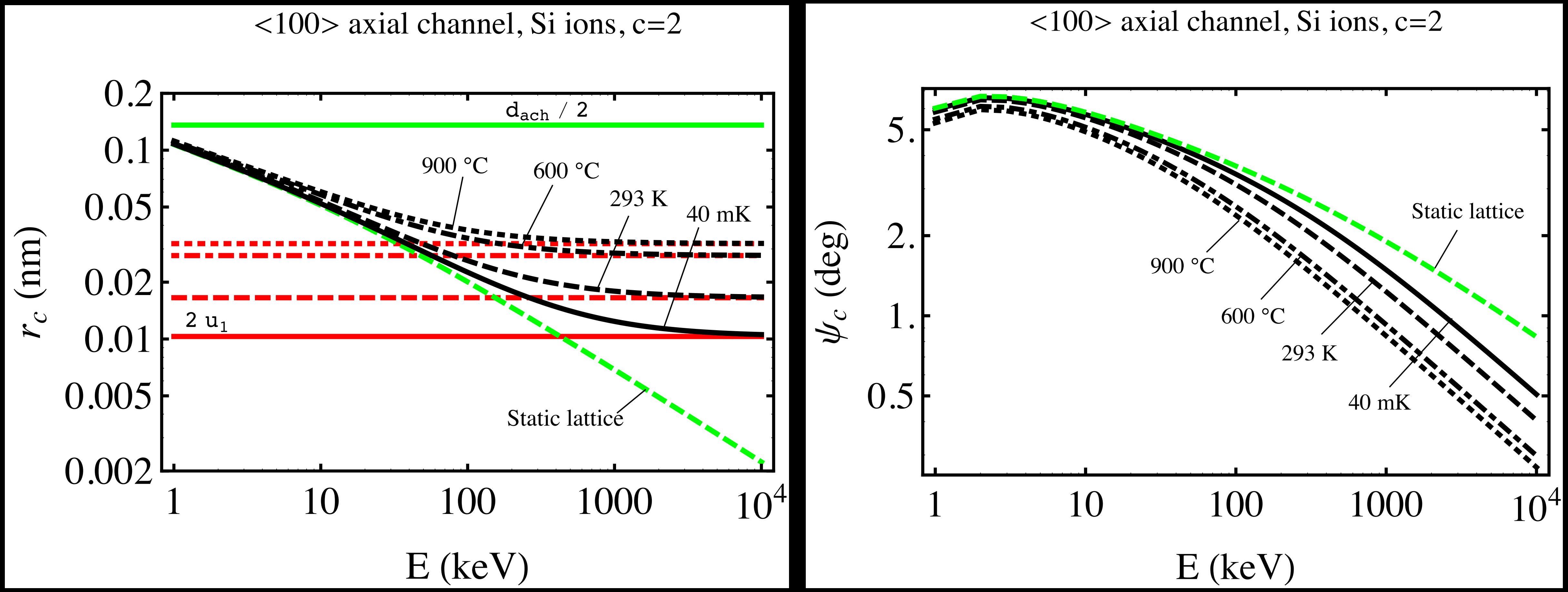




Bozorgnia, Gelmini, Gondolo 2010

- Si ion in Si crystal

c=2 (i.e. $r_c \rightarrow 2\, u_1(T)$ at high E)



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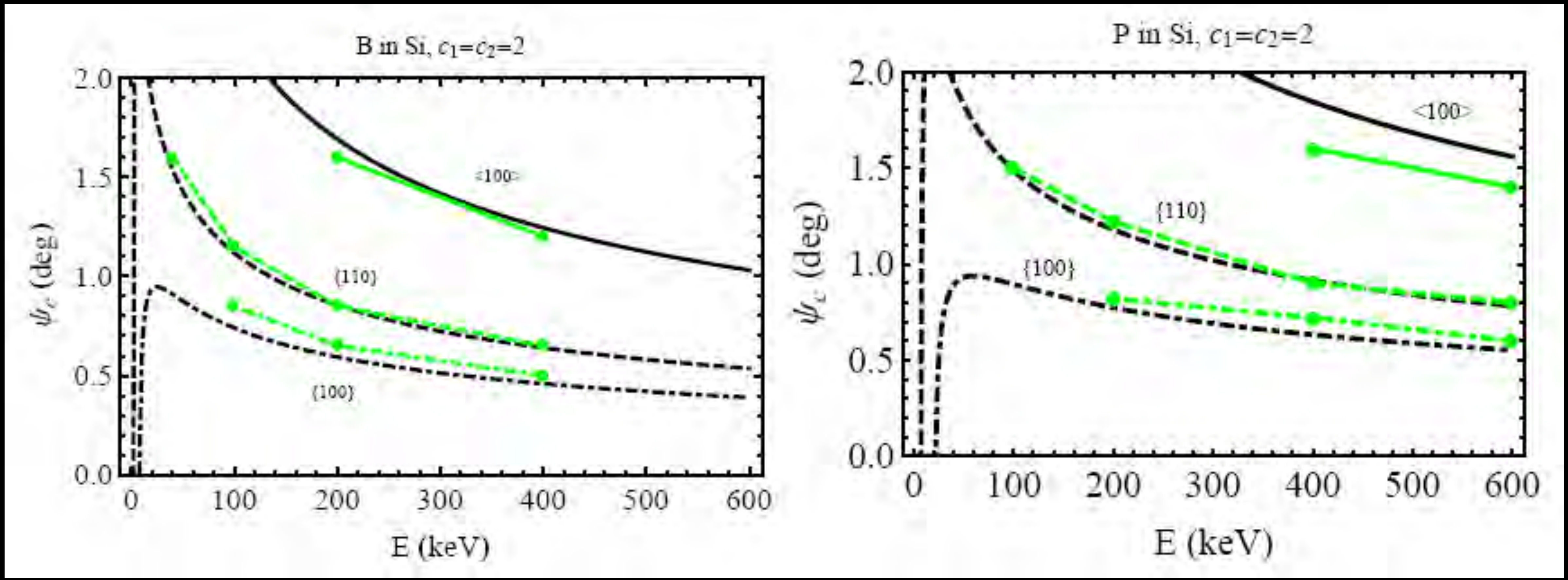
- ***DATA:*** B and P ions in Si crystal

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



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Our calculations of channeling fractions

- Compute the channeling fraction for:
  - Incoming particles
  - Recoiling nuclei

Our calculations of channeling fractions

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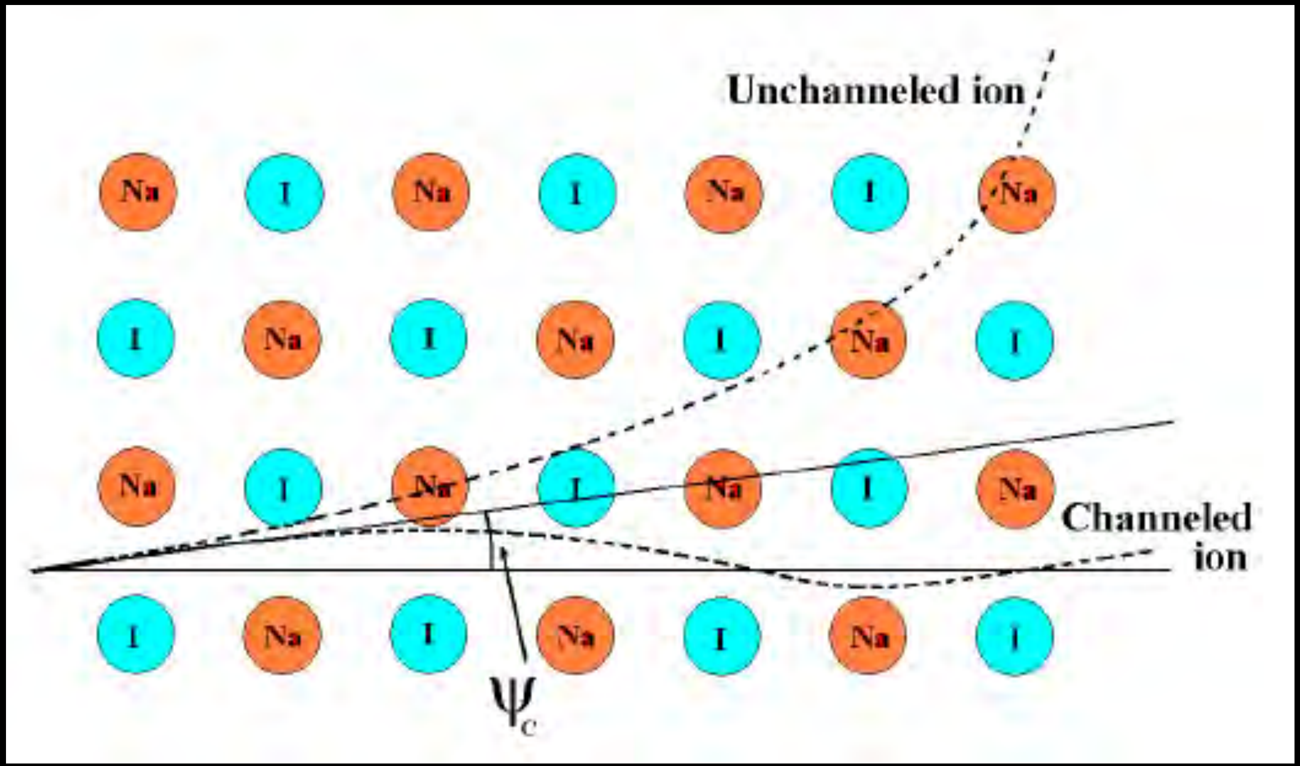
Channeling of incoming particles

- Low energy incident ions are channeled if they are incident upon a string or plane of atoms at an angle ψ smaller than a critical angle ψ_c *(Lindhard 1965)*



Bernabei et al. 2008, Eur. Phys. J. C53, 205

Channeling fraction of incoming particles

- We integrate the channeling probability over direction to find the total fraction of channeled nuclei

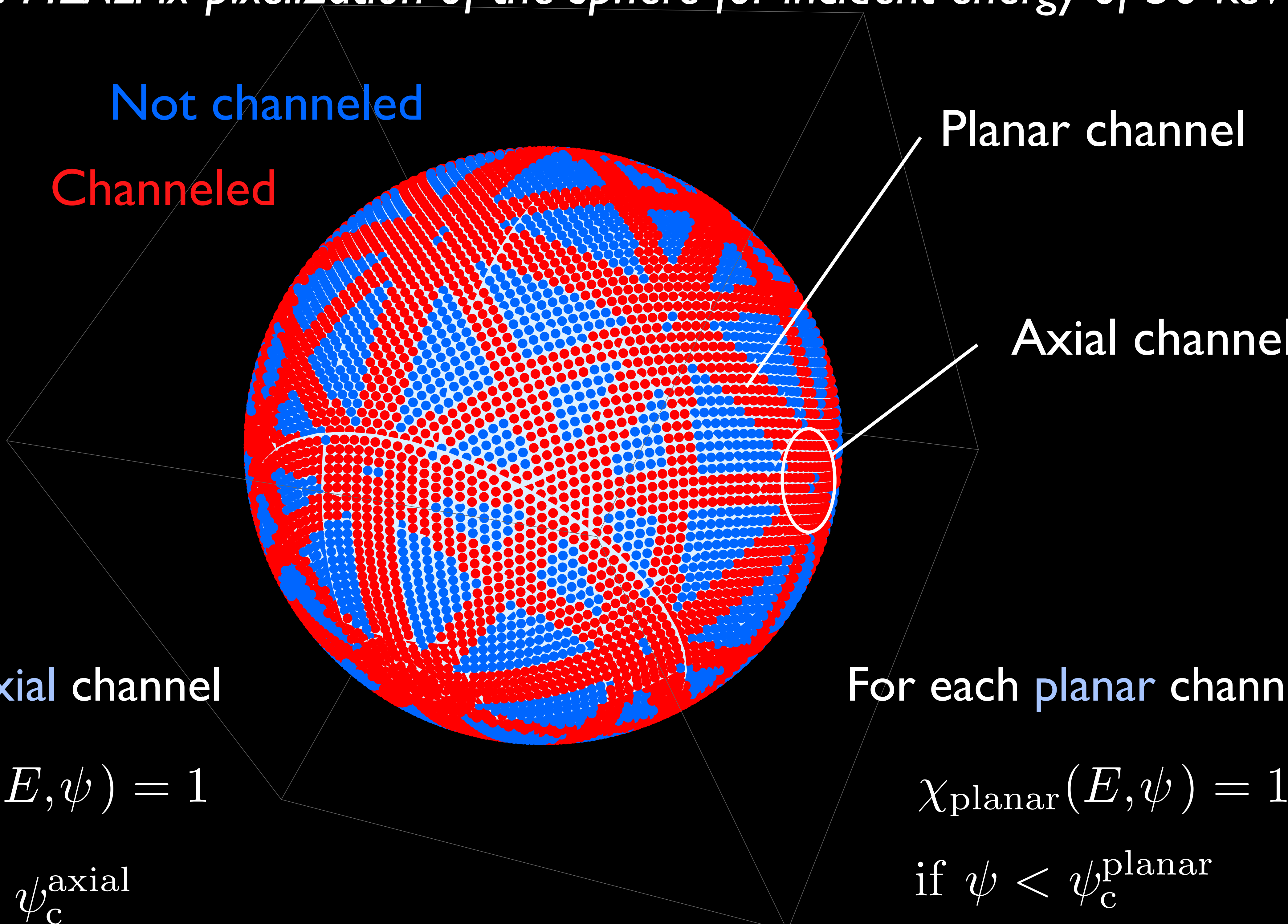
$$P(E) = \frac{1}{4\pi} \int \chi(E, \hat{\mathbf{q}}) \, d\Omega_q$$

where $d\Omega_{\mathrm{q}}$ is a infinitesimal solid angle around $\hat{\mathrm{q}}$

- We use the Hierarchical Equal Area isoLatitude Pixelization (HEALPix) method to compute the integral

Fraction of channeled Na recoils

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



For each axial channel

$$\chi_{\rm axial}(E,\psi) = 1$$

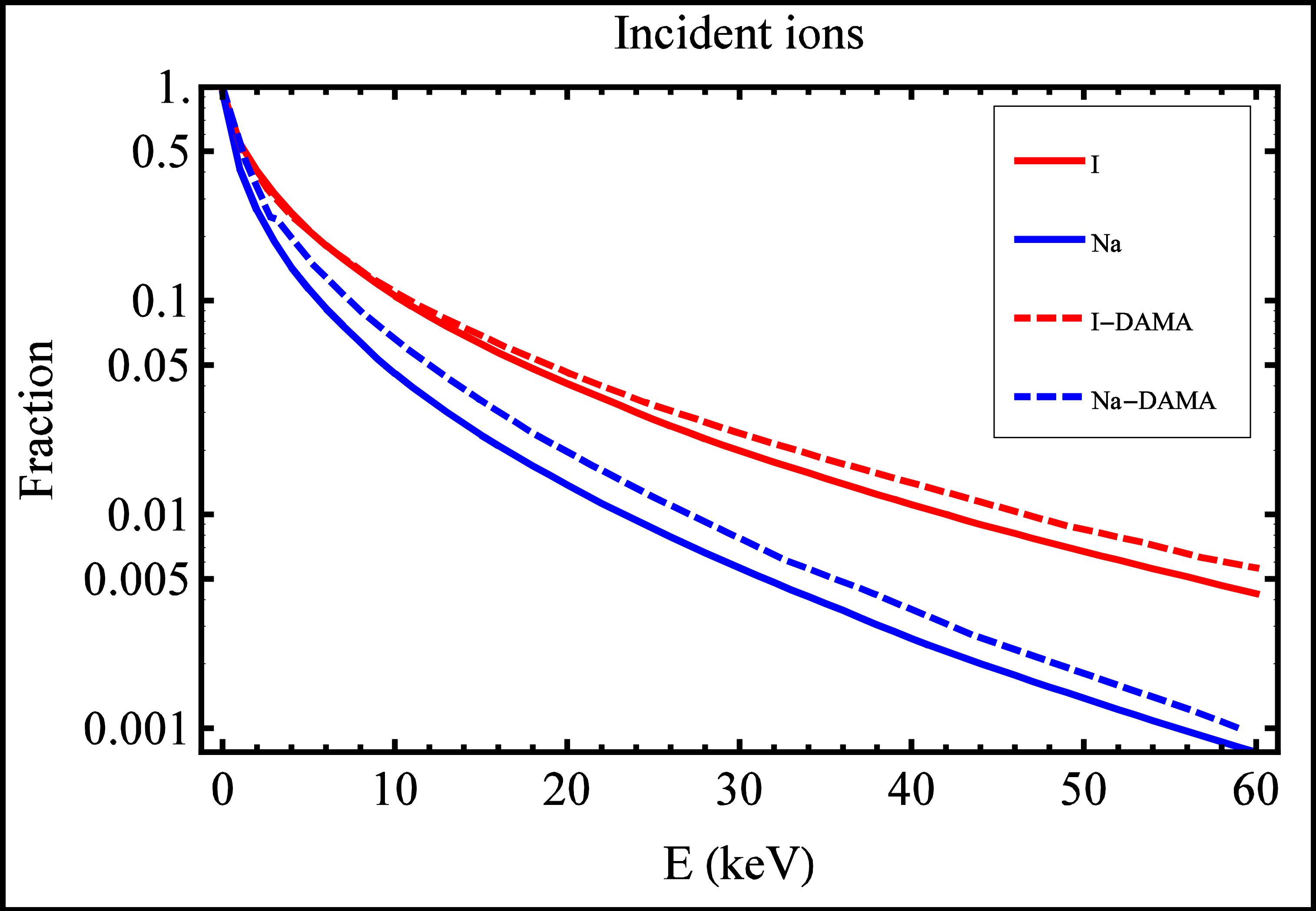
$$\text{if } \psi < \psi_c^{\rm axial}$$

For each planar channel

$$\chi_{\rm planar}(E,\psi) = 1$$

$$\text{if } \psi < \psi_c^{\rm planar}$$

Channeling fraction for incoming particles



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

Our calculations of channeling fractions

- Compute the channeling fraction for:
  - Incoming particles
  - Recoiling nuclei

Our calculations of channeling fractions

- Compute the channeling fraction for:
  - Incoming particles
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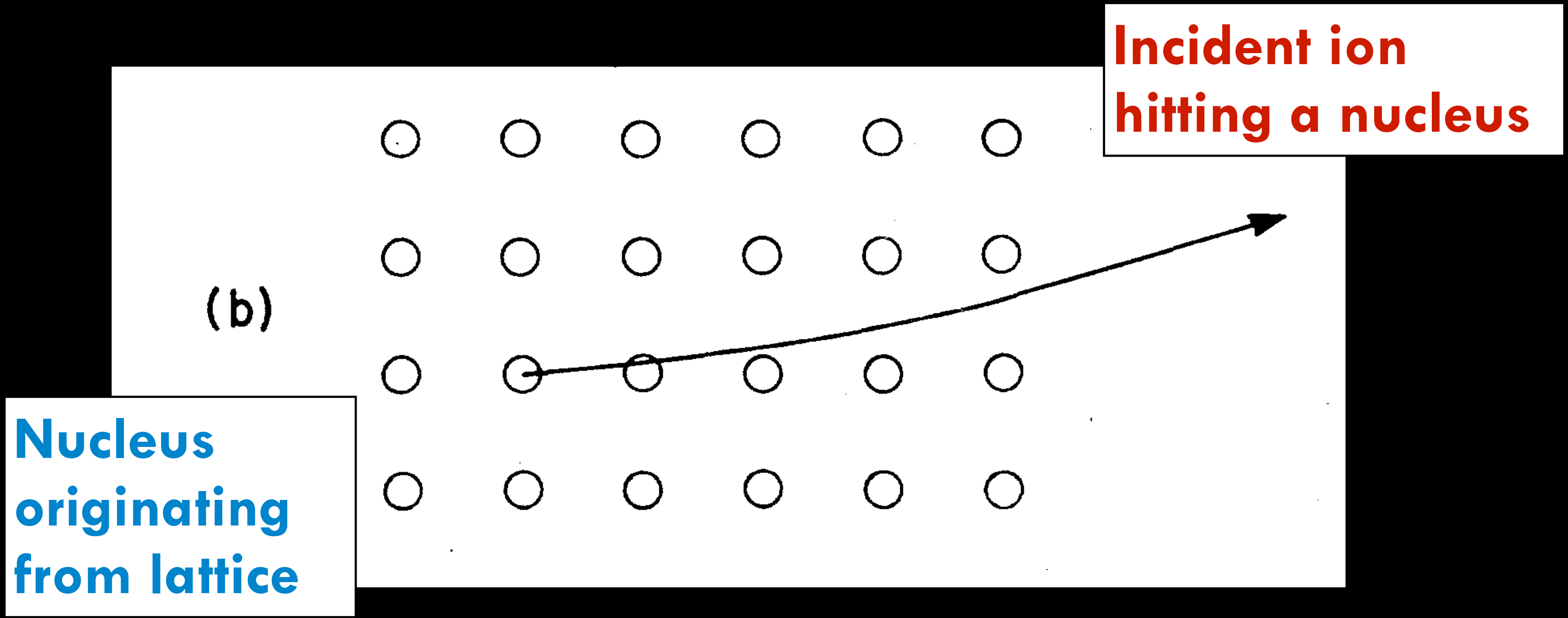
Channeling of recoiling nuclei

- Recoiling nuclei start at or close to the lattice sites
- In a perfect lattice no recoil would be channeled (“rule of reversibility”)



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

Channeling of recoiling nuclei

- For a given E_R and ψ_i, the condition for channeling is given by

$$E_R\,\psi_{\rm i}^2 + U(r_{\rm i}) < U(r_{\rm c})$$

- Thermal vibrations in the initial position of the recoiling nucleus can be represented by a Gaussian

$$g(r_{\rm i}) = \frac{r}{u_1^2}\, e^{-r_{\rm i}^2/2u_1^2}$$

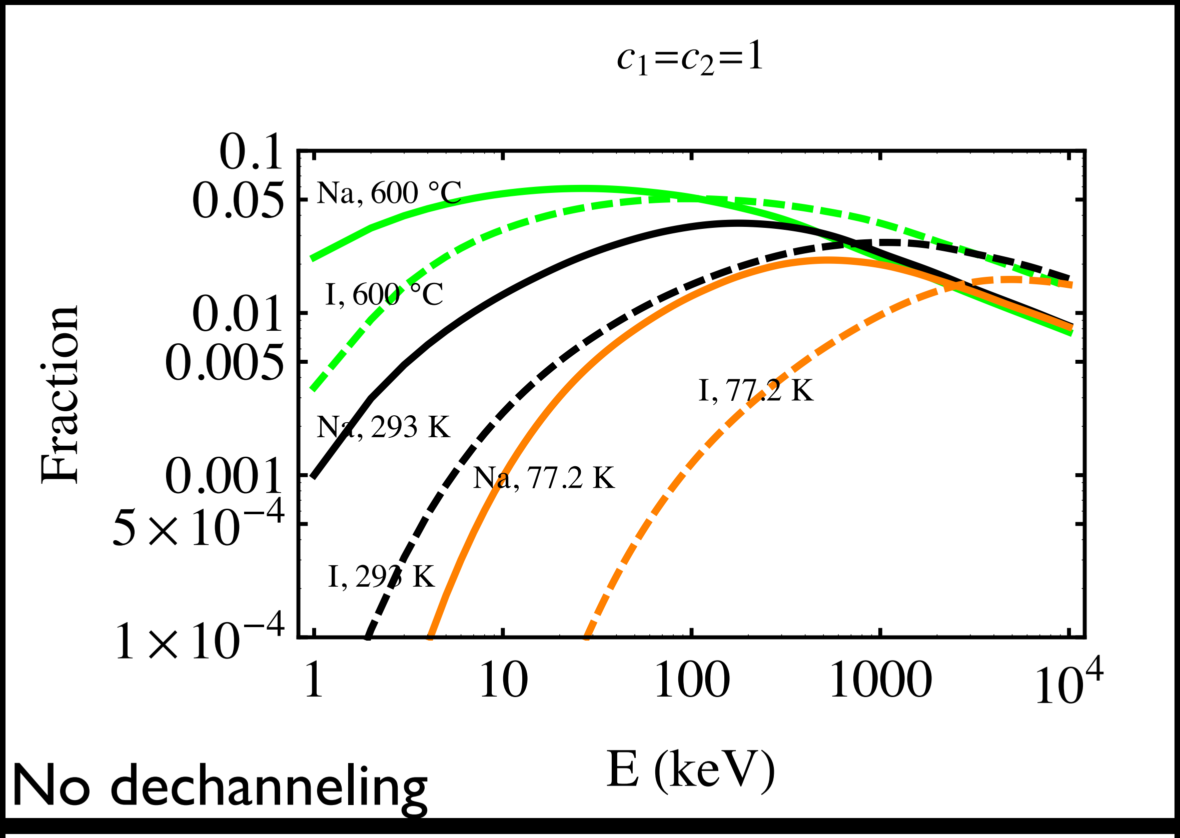
- The fraction of channeled nuclei recoiling at angle $\psi_{\rm i}$ with the axis is equal to

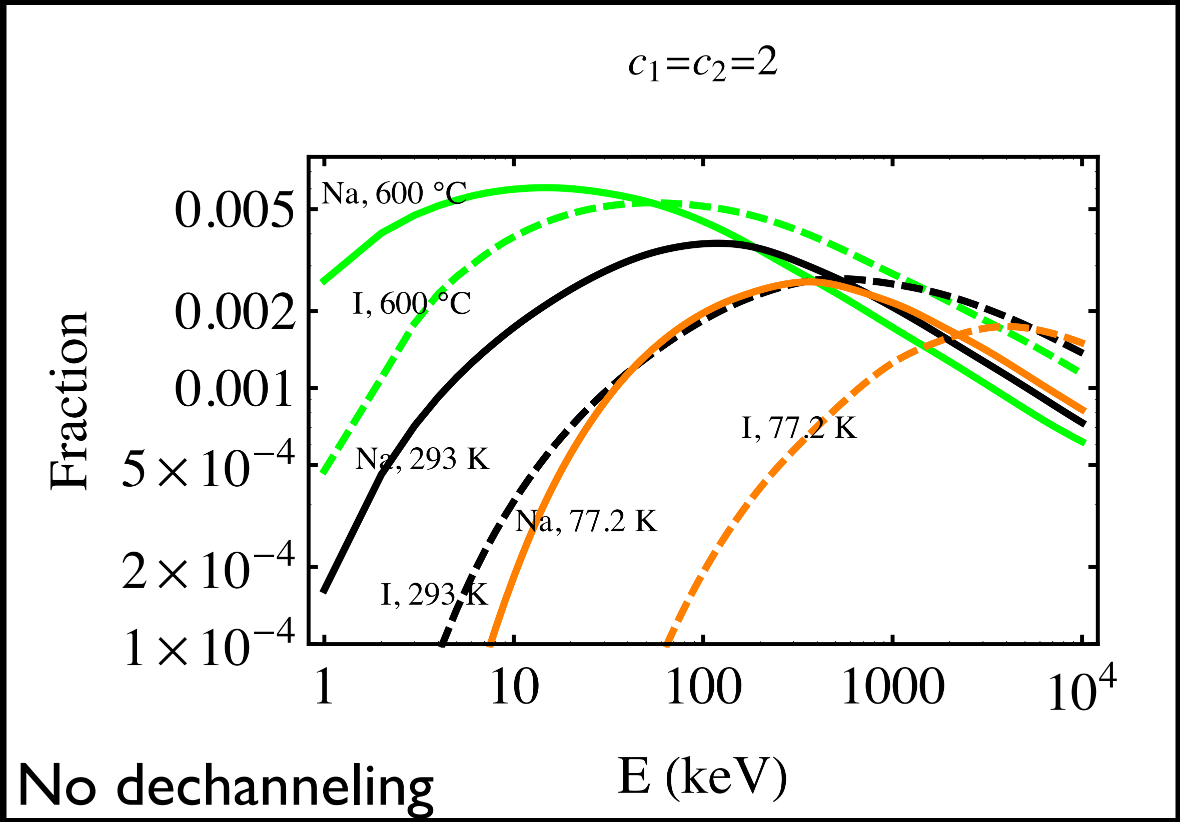
$$\chi_{\rm axial}(E_R,\psi_{\rm i}) = \int_{r_{\rm i,min}}^{\infty} g(r_{\rm i})\,dr_{\rm i} = e^{-r_{\rm i,min}^2/2u_1^2}$$

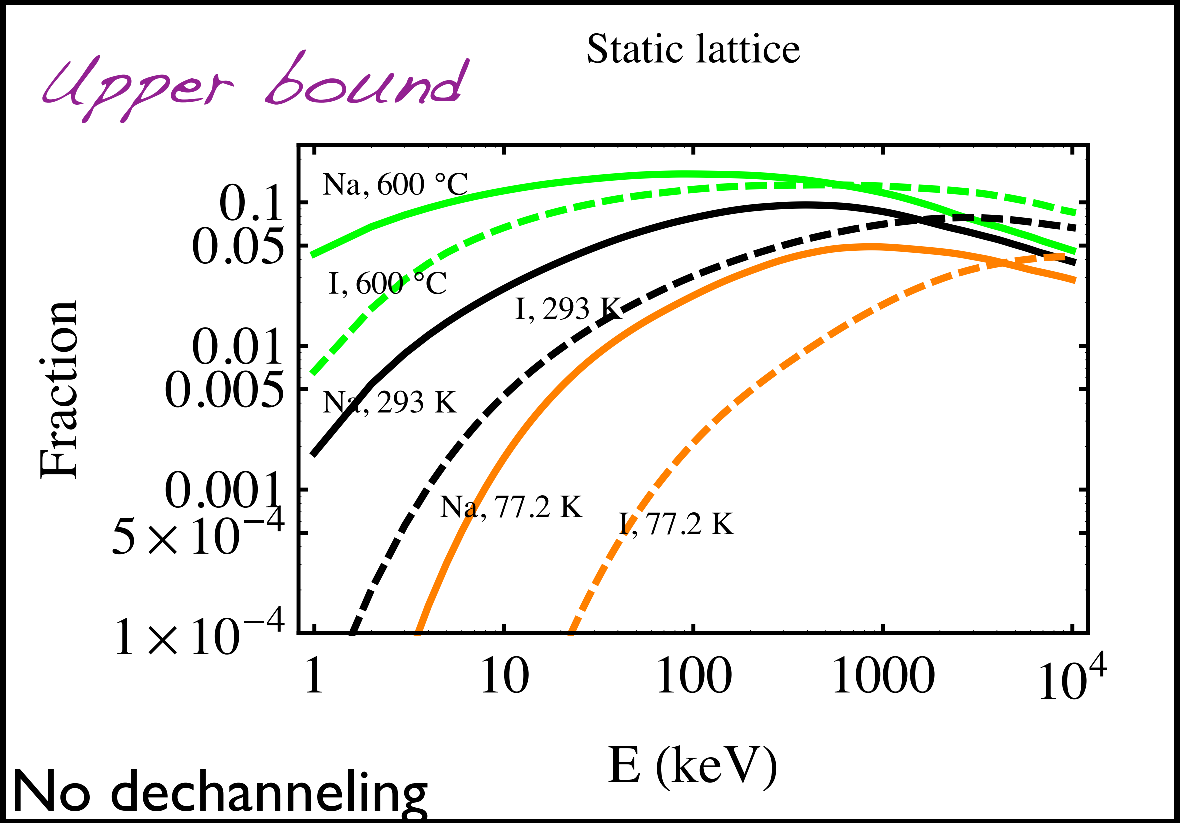
Uncertainty in r_c enters $r_{i,min}$ and is exponentiated!

- There are two main temperature effects:
  $u_1(T)$ increases with T ⇨ χ increases
  r_c increases with T ⇨ χ decreases

Fraction of channeled recoils: NaI



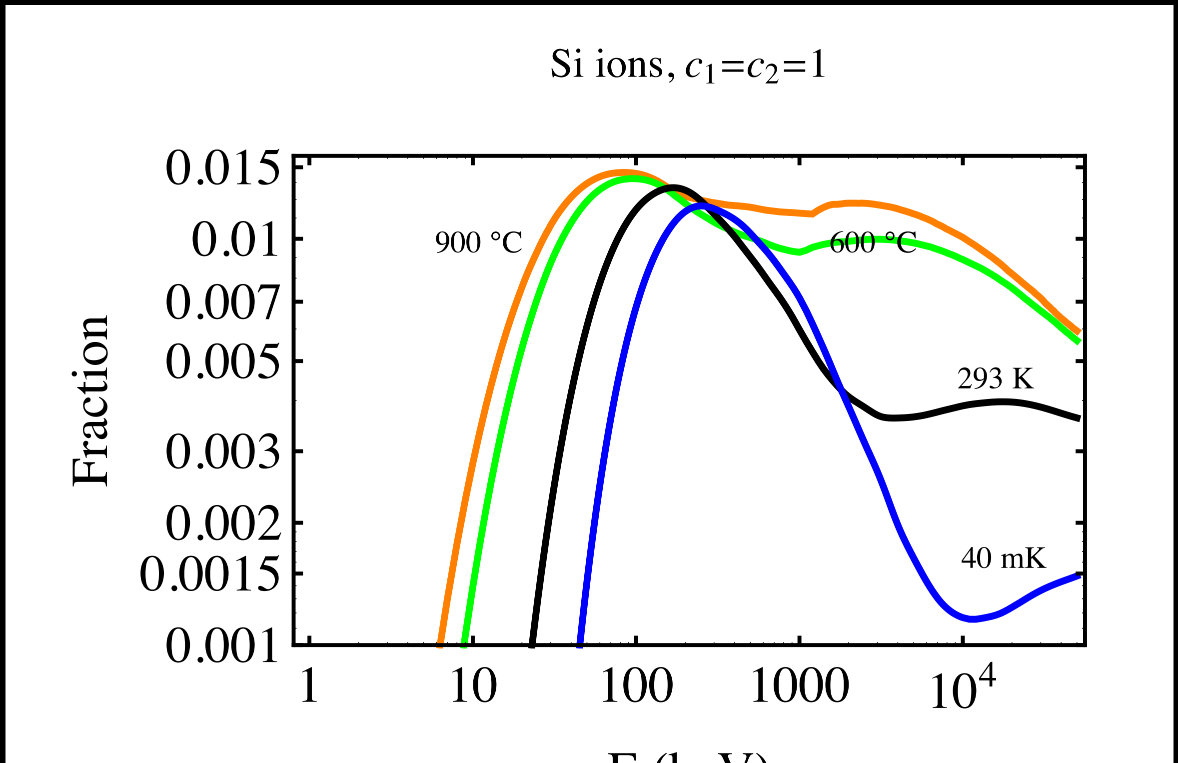




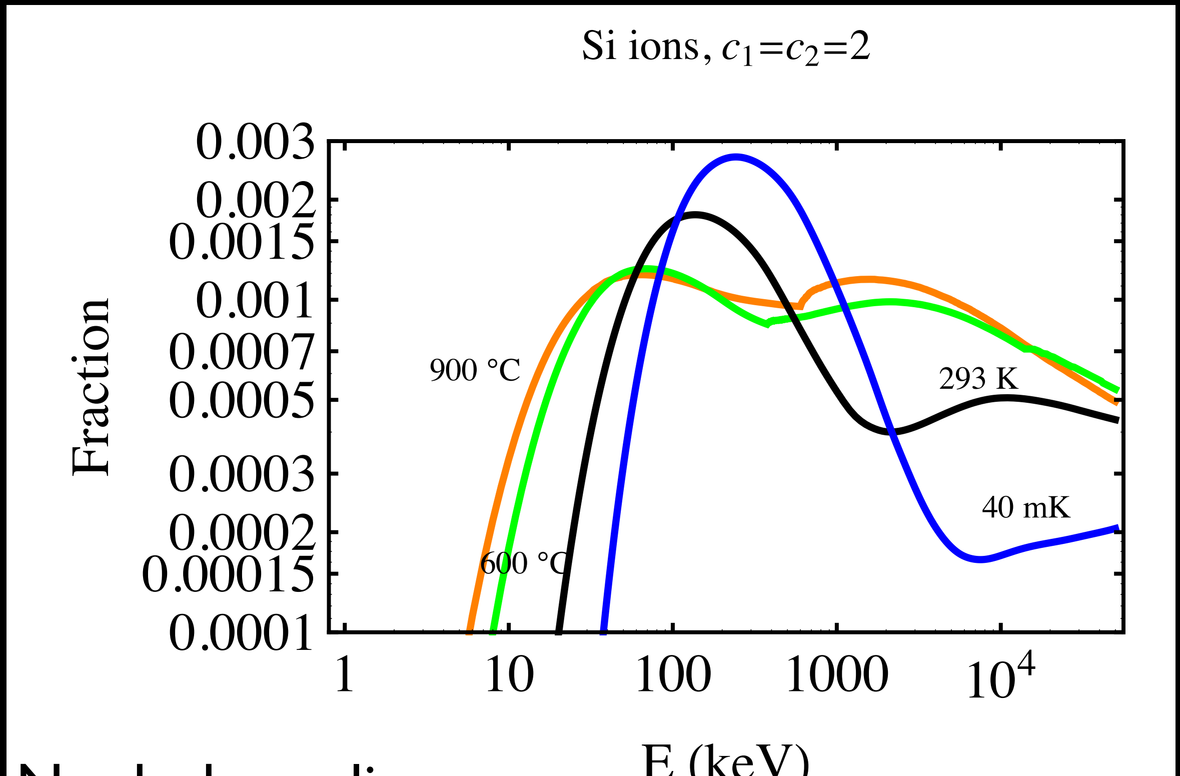
These results now differ from DAMA's.
The channeling fraction is much smaller.

Bozorgnia, Gelmini, Gondolo 2010

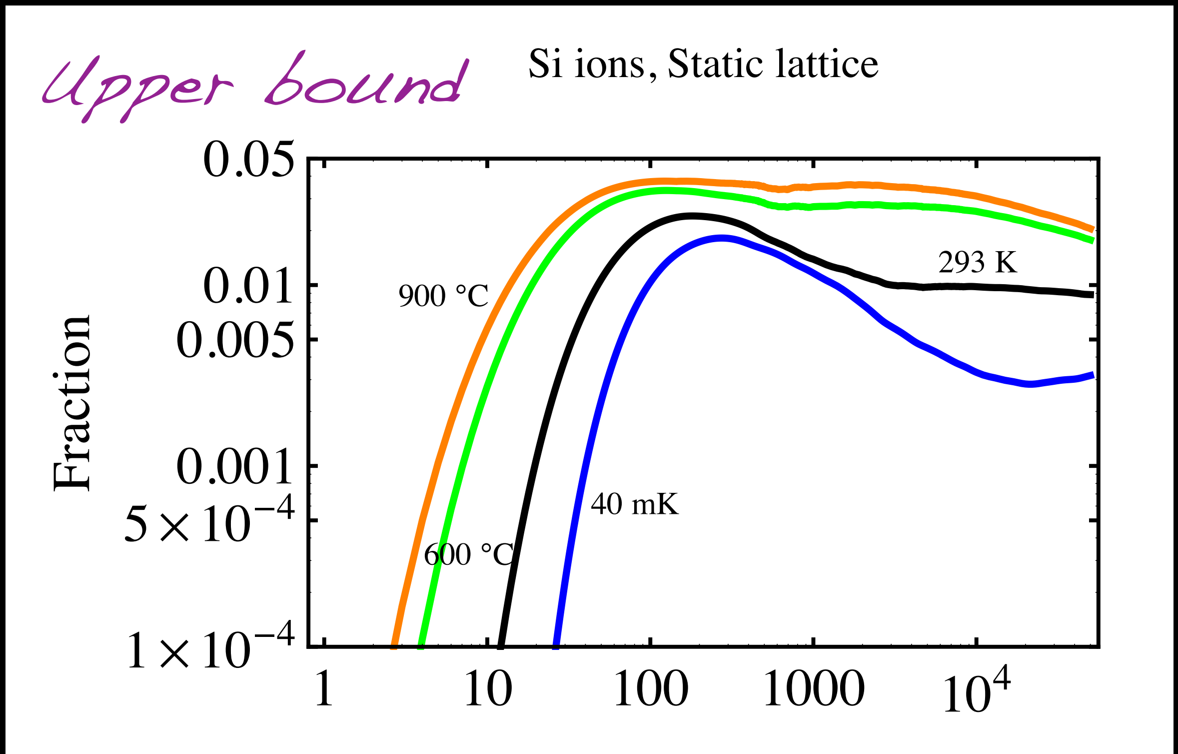
Fraction of channeled recoils: Si



No dechanneling



No dechanneling



No dechanneling

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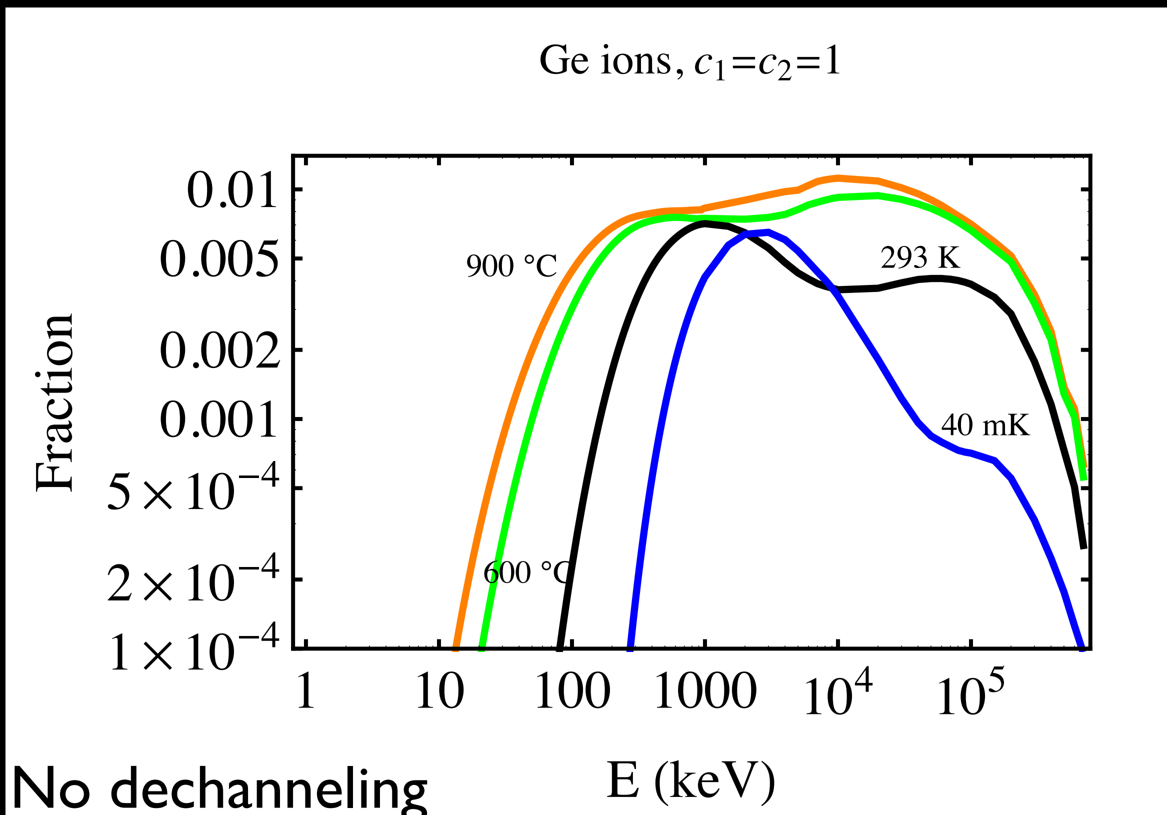
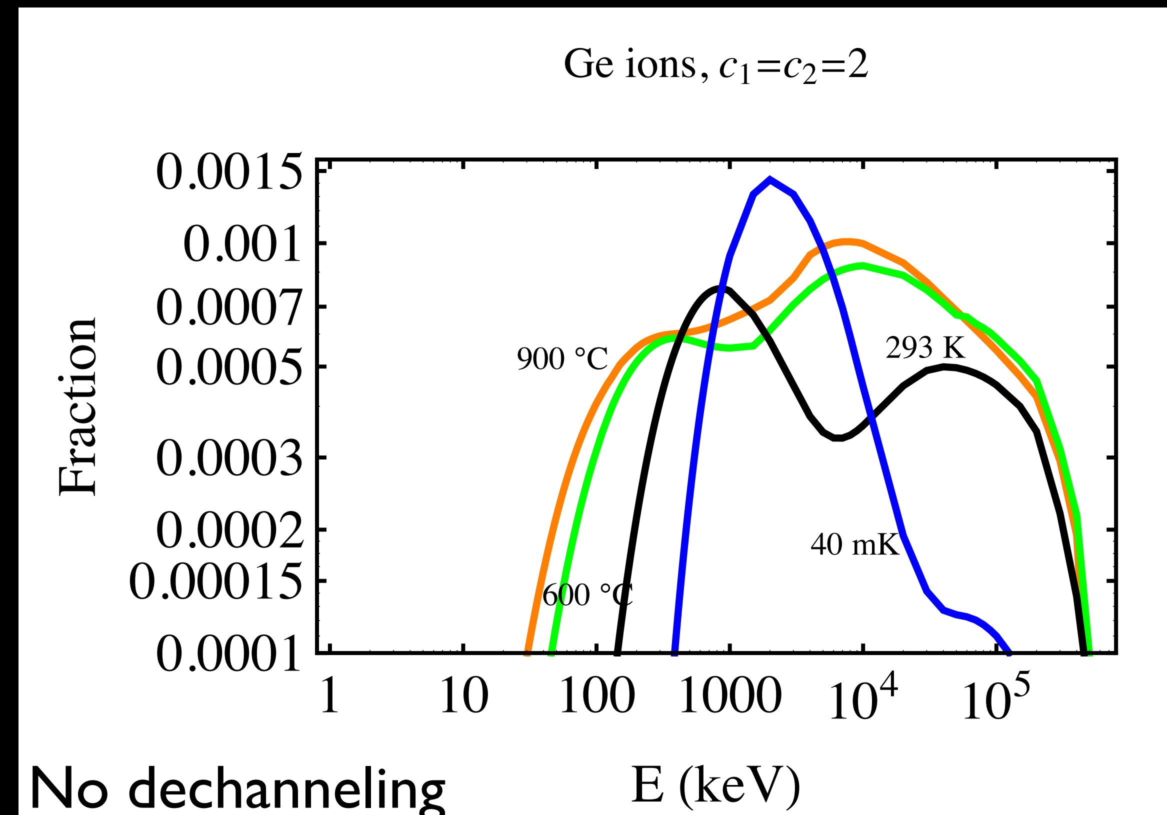
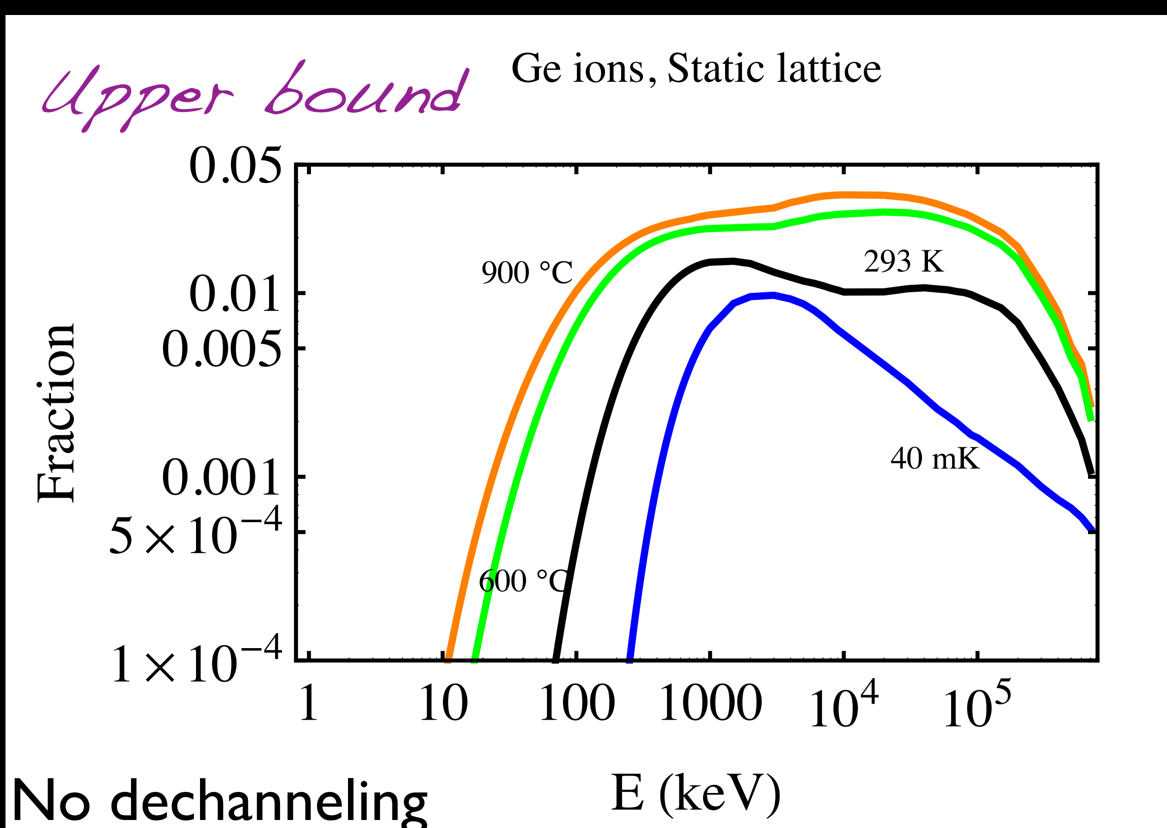
Fraction of channeled recoils: Ge







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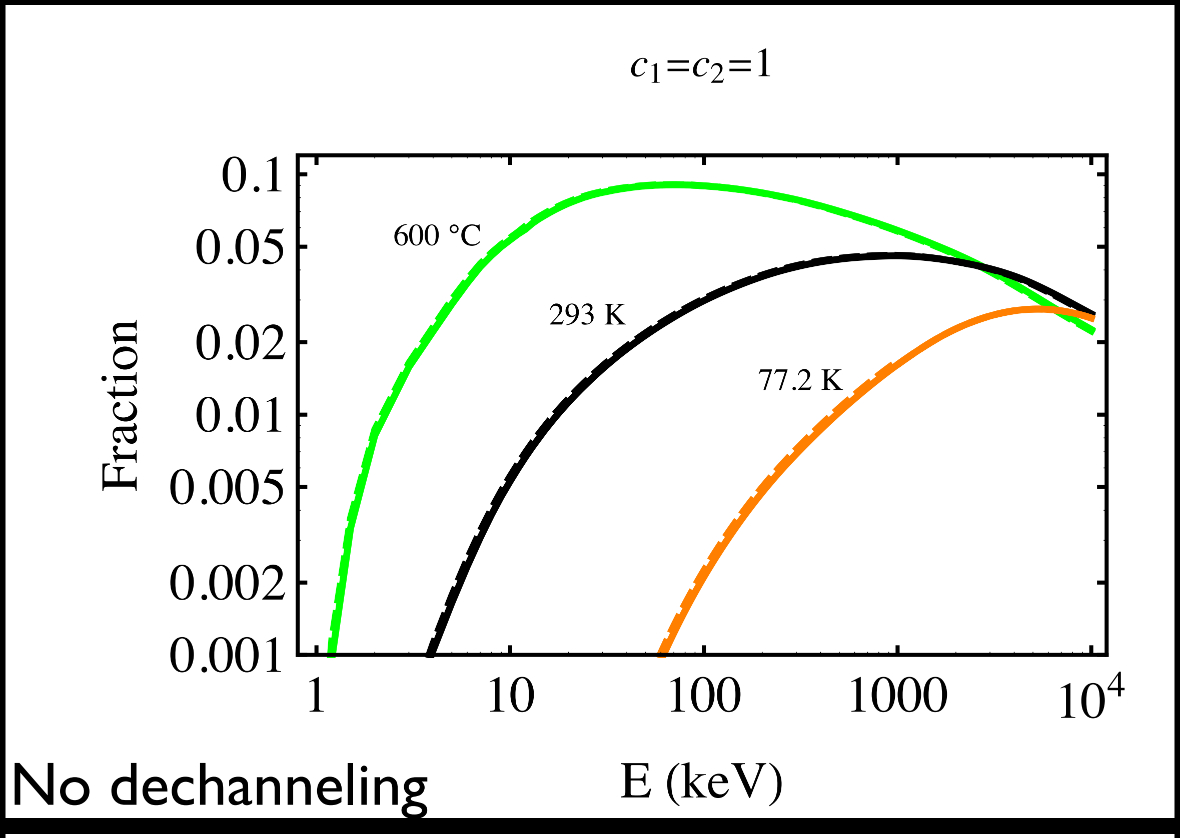
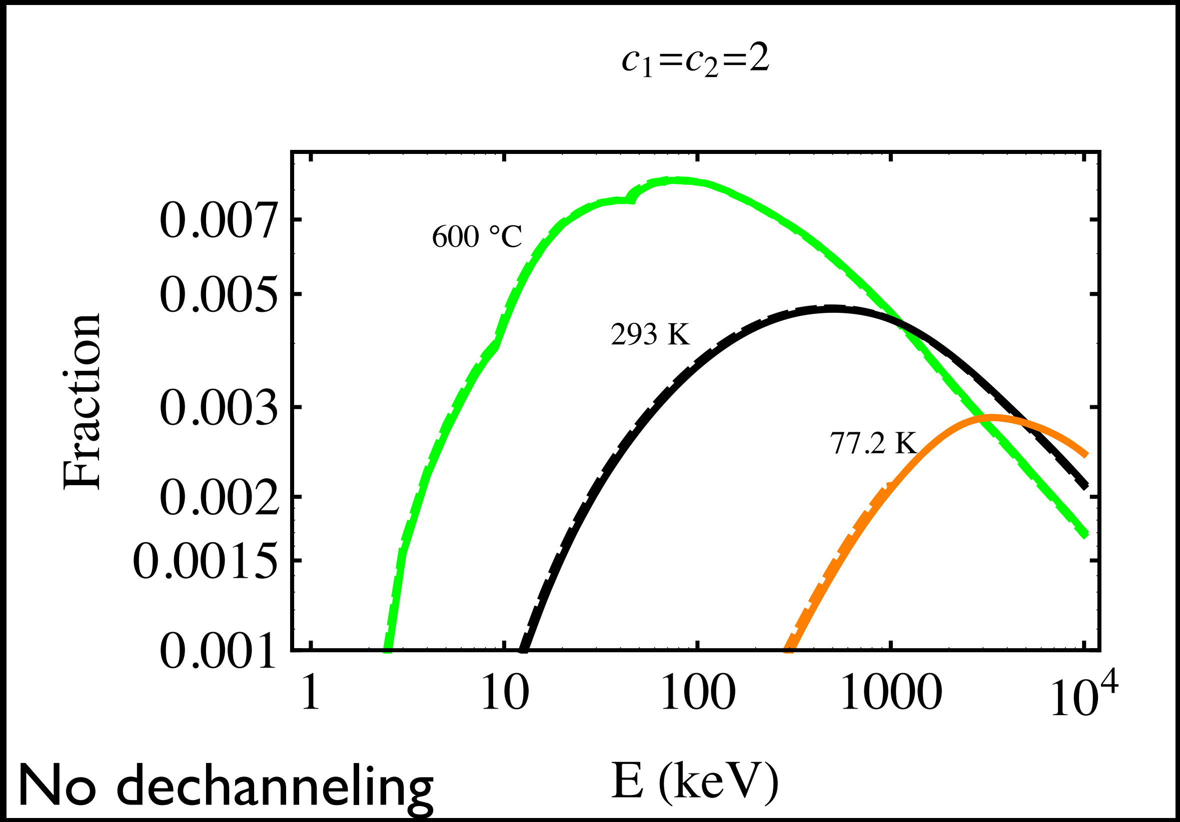
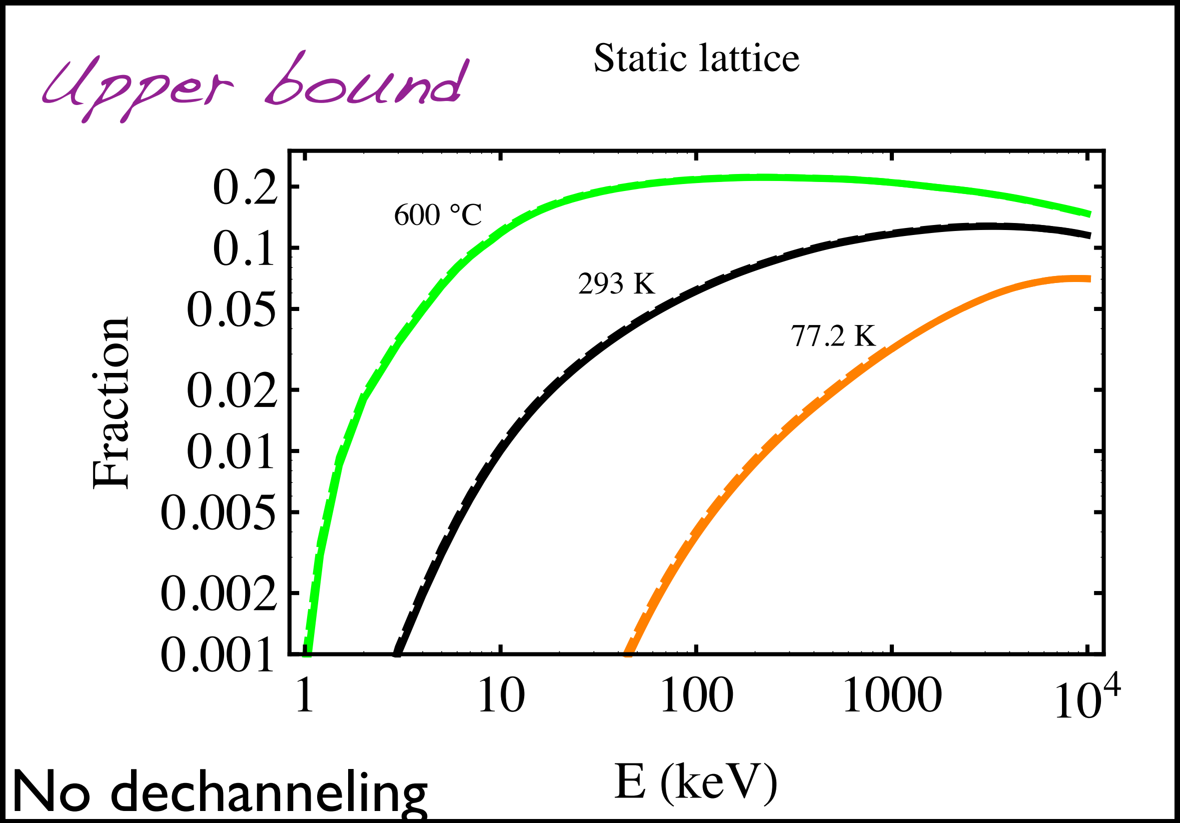
Fraction of channeled recoils: CsI





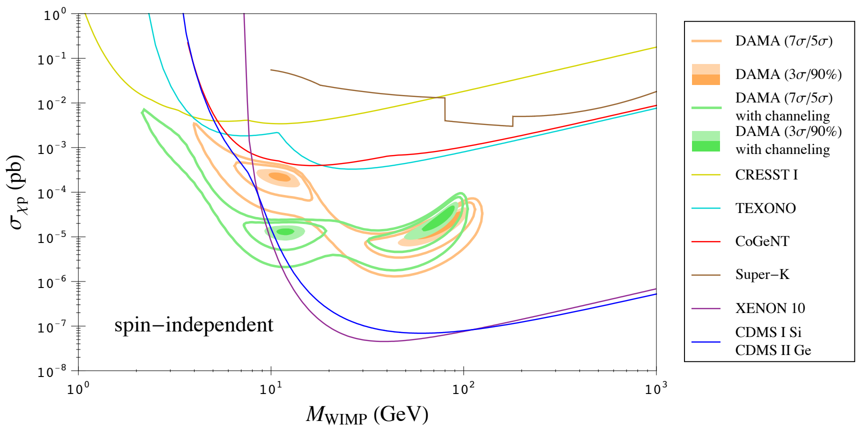


Bozorgnia, Gelmini, Gondolo 2010

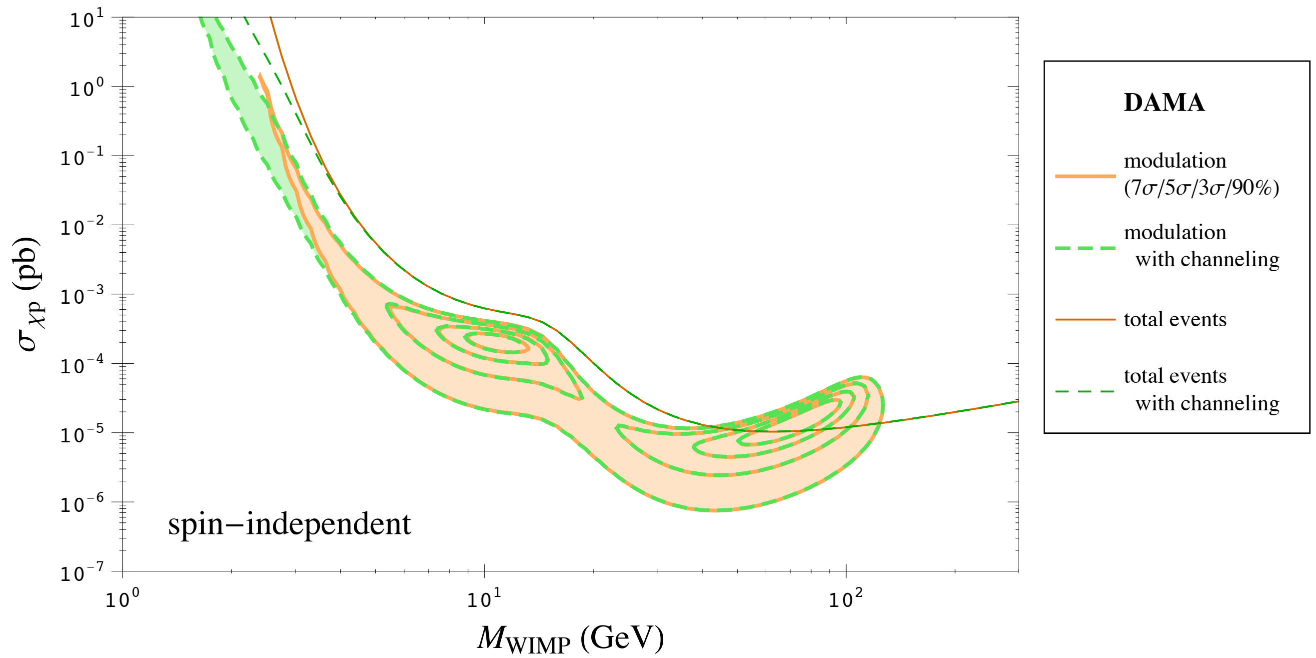
Consequences

Compatibility of DAMA/LIBRA with other experiments

Then (Savage et al JCAP 0904:010,2009)



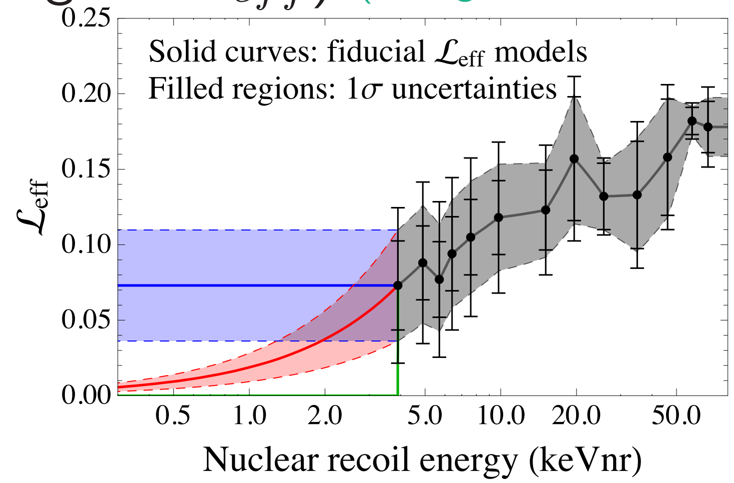
and now (diff. at 7σ)(Savage et al. 1006.3110)

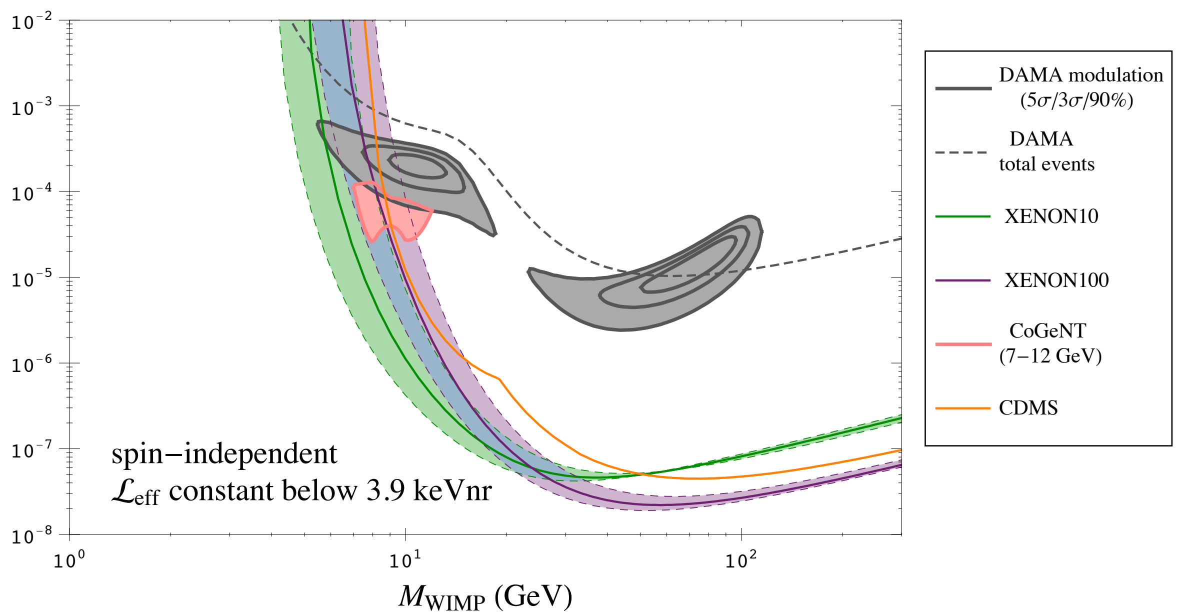


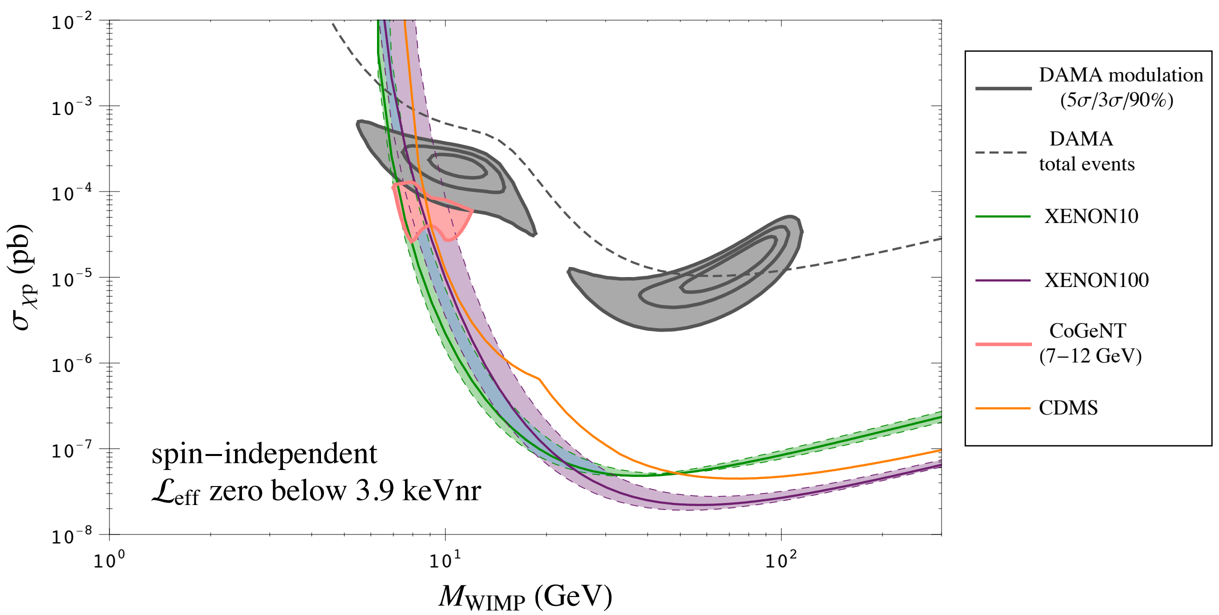
Consequences

Compatibility of DAMA/LIBRA with other experiments

If L_{eff} extrapolated as a constant or zero below 4 keVnr (band: shows how the 90%CL bound changes with 1σ change in L_{eff}) (Savage,Gelmini, Gondolo, Freese 1006.0972)







Conclusions and ....

- Channeling of recoiling nuclei and incoming 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.

- Analytic models give good qualitative results but need data/simulations to get good quantitative results (not available for NaI).

.... work in progress

- Channeling in crystalline detectors can lead to a daily modulation in a WIMP signal, a DM signature with no background (Sekiya et al 2003, Avignone et al 2008,2010). We are evaluating the daily modulations for NaI, Ge, Si, and CsI to obtain more accurate results.

- Analytic results may not be enough, and we collaborate with other groups to carry out Monte Carlo simulations to settle these issues (many such simulations are used in other applications of channeling).