Ion-Channeling in Direct DM Crystalline Detectors

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Based on work done with Nassim Bozorgnia and Paolo Gondolo

IDM2010, July 26, 2010

Channeling and Blocking Effects in Crystals

refer to the orientation dependence of ion penetration in crystals.

Channeling:

Ions **incident** upon a crystal along symmetry axis and planes suffer a series of small-angle scattering that maintain them in the open "channels" and penetrate much further *(ions do not get close to lattice sites)*

Blocking:

Reduction of the flux of ions **originating in lattice sites** along symmetry axis and planes *("blocking dip")*

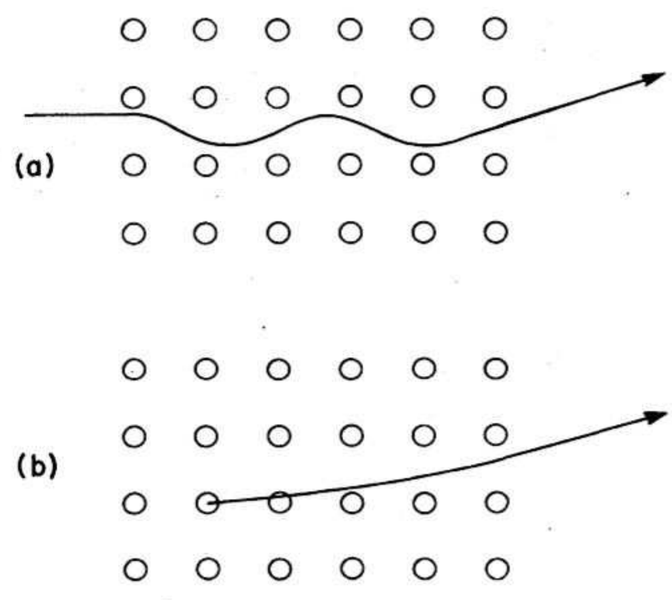


FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

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

Channeling and blocking in crystals is used in

- studies of lattice disorder

- ion implantation

- to locate dopant and impurity atoms

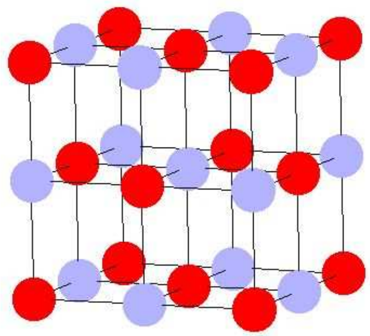
- studies of surfaces and interfaces

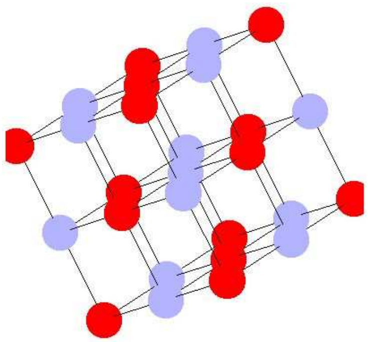
- measurement of nuclear lifetimes

- production of polarized beams... etc

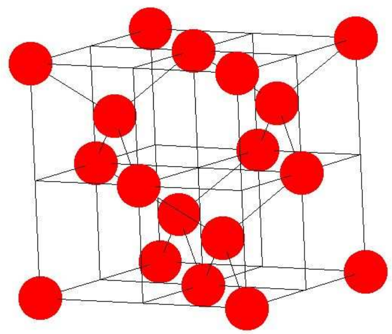
- channeling is to be avoided in ion implantation (Boron, Phosphorus, Arsenic) in Si to make circuits: good data at ~ 100's keV (and analytic models by Gerhard Hobler from Vienna University of Technology, 1995)

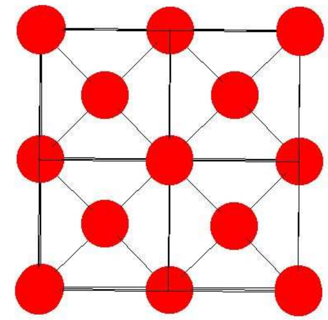
NaI or CsI crystal: "mixed" and "pure" rows and planes





Si or Ge crystal





Channeling effect observed in NaI (Tl) Altman et.al 1973

PHYSICAL REVIEW B VOLUME 7, NUMBER 5 1 MARCH 1973

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

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(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.

Channeling effect observed in NaI(Tl) Altman et.al 1973

Measured the scintillation output of a monochromatic 10 MeV ^{16}O beam through NaI(Tl) scintillator

Channeled ions produce more scintillation light

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

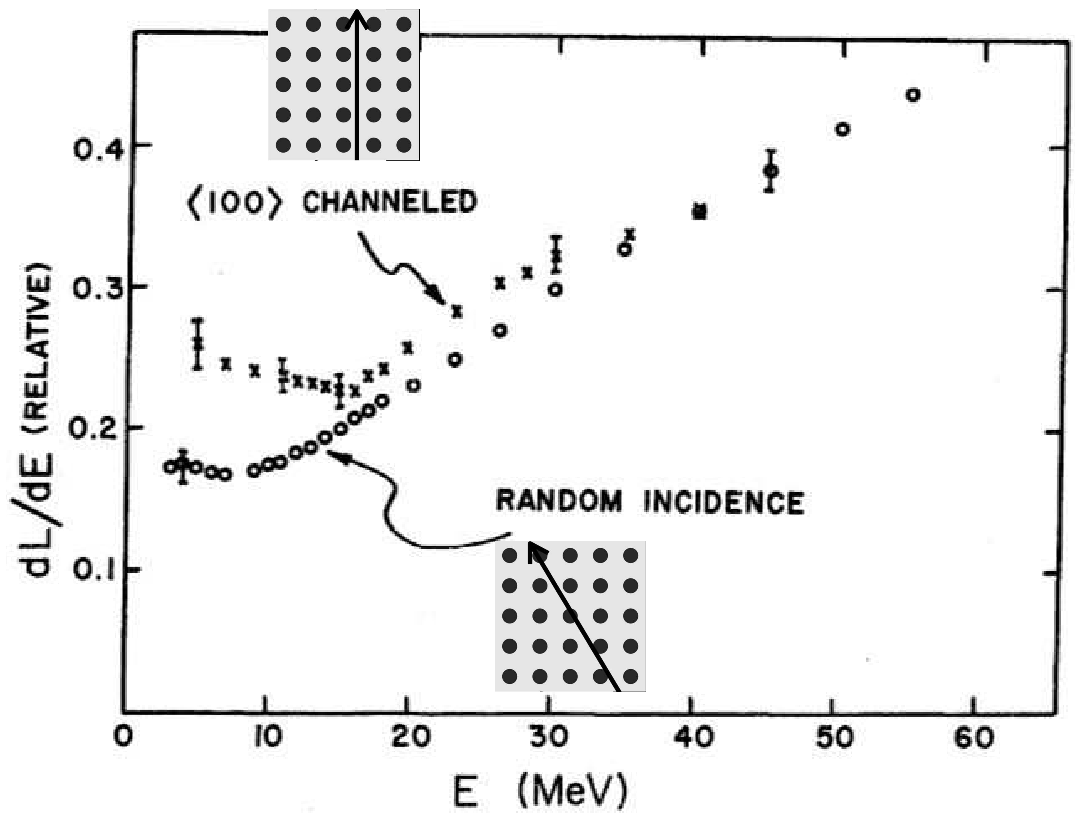
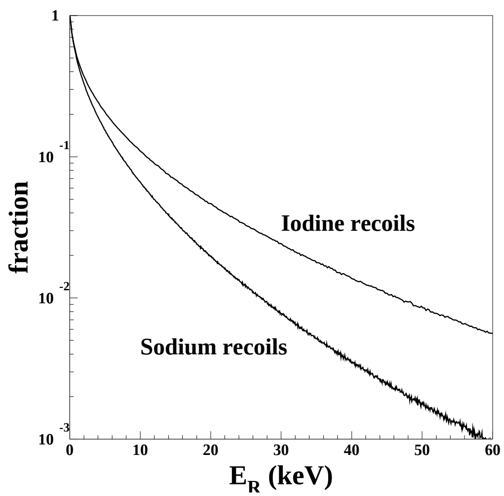


FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

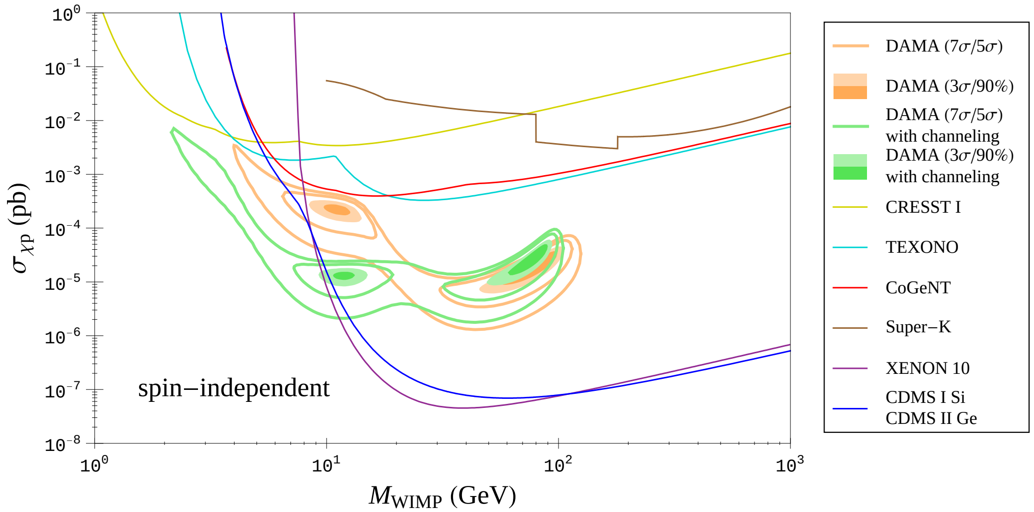
Channeling effect in DM detection:

The potential importance of the channeling effect for direct DM detection was first pointed out in stilbene crystals by H. Sekiya et al. (2003) and subsequently for NaI (Tl) by Drobyshevski (2007) and by the DAMA collaboration (2008).

When ions recoiling after a collision with a WIMP move along crystal axes and planes, they give their energy to electrons, so $Q = 1$ instead of $Q_I = 0.09$ and $Q_{Na} = 0.3$



(DAMA coll. 2008)



(For example: Savage,Gelmini, Gondolo, Freese JCAP 0904:010,2009)

Daily-Modulation due to Channeling:

H. Sekiya et al. (2003); Avignone, Creswick, Nussinov (2008 and 1007.0214)

- The WIMP wind comes preferentially from one direction (towards which the Sun moves)
- When that direction is aligned with a channel, the scintillation or ionization output is larger
- Earth's daily rotation makes the WIMP wind change direction with respect to the crystal, which produces a daily modulation in the measured recoil energy (equivalent to a modulation of the quenching factor) which depends on the orientation of the crystal

This daily modulation would be a background free DM signature!

Nassim Bosognia, Paolo Gondolo and I set out more than a year ago to do an analytic calculation to understand channeling and blocking for DM detection, and estimate daily modulation amplitudes...

Our calculation of the fraction of recoils that are channeled as function of recoil energy and direction:

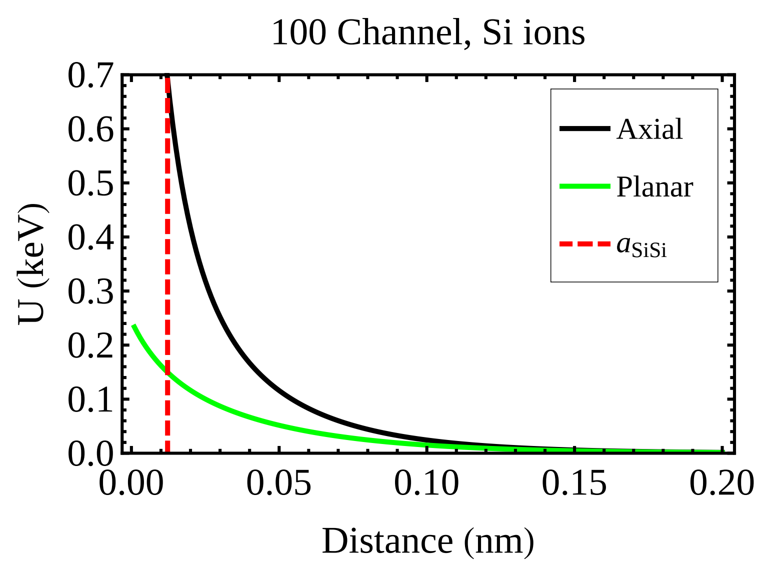
- Use classical analytic models of the 60's and 70's, in particular Lindhard's model(Lindhard 1965, Morgan & Van Vliet 1971, Dearnaley 1973, Gemmell 1974, Appleton & Foti 1977, Hobler 1995)

- Continuum string and plane model, in which the screened Thomas-Fermi potential is averaged over a direction parallel to a row/plane (took just one)

- In the direction perpendicular the row or plane, the "transverse energy" is conserved

$$E_{\rm perp} = E\phi_i^2 + U_i$$

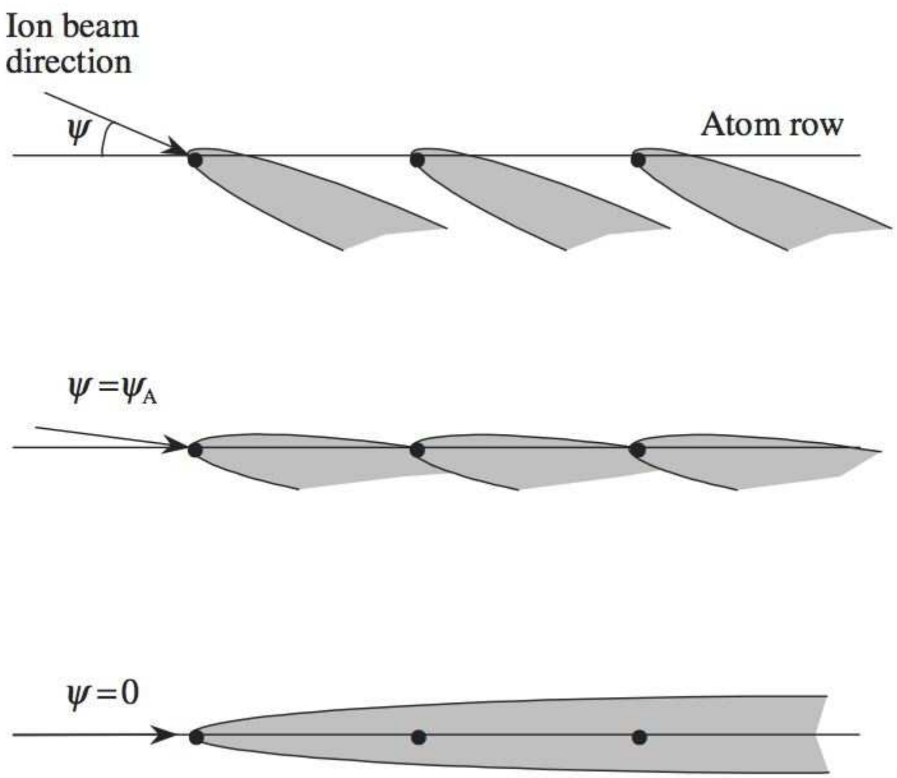
$v_{\rm perp} = v \sin\phi \simeq v\phi$ transverse velocity component and $E_{\rm perp} = M v_{\rm perp}^2/2$



Axial and planar channeling

can be understood as overlap of Coulomb shadow cones, $\rho_{\min} > \rho_c$ and $\psi < \psi_c$

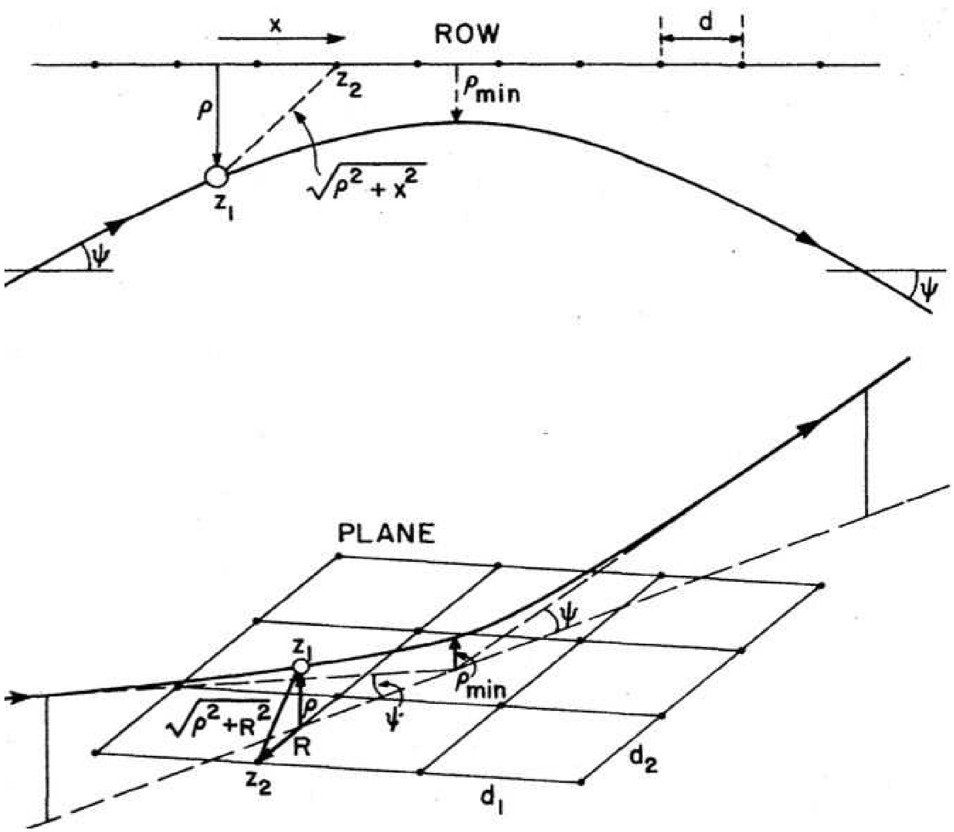
(Fig. from Hiroshi Kudo, 2001)



Axial and planar channeling

$\rho_{\rm min}$: min. distance of approach - ψ: angle far away from row or plane

(Fig. from D. Gemmell 1974, Rev. Mod. Phys. 46, 129)



$$E_{\rm perp} = E\phi_i^2 + U_i$$
$$= U(\rho_{\rm min})$$
$$= E\psi^2 + U_{\rm middle}$$

$U_{\rm middle}$: at middle of channel, far from row/plane, where angle is

$$\psi = \sqrt{\frac{[U(\rho_{\rm min}) - U_{\rm middle})]}{E}}$$

Channeling requires

$\rho_{\rm min} > \rho_c$

which amounts to

$\psi \leq \psi_c$

All the difficulty of this approach resides in calculating ρ_c

Channeling requires (Lindhard 1965, Morgan & Van Vliet 1971, Hobler 1995)

- Min. distance of approach to row or plane larger than a critical value:

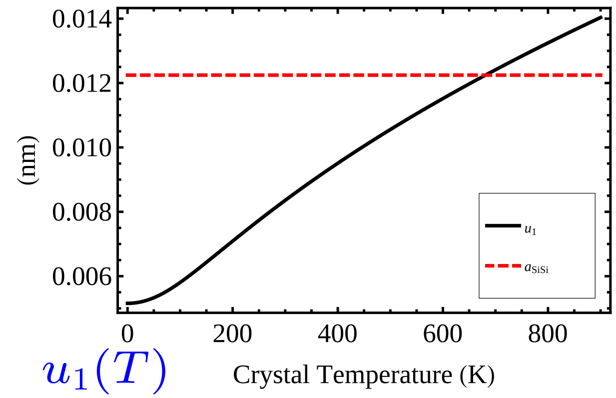
$$\rho_{\min} > \rho_c(E,T) = \sqrt{\rho_c^2(E) + [c\, u_1(T)]^2}$$

$\rho_c(E)$: for perfect-rigid-lattice decreases with E

$u_1(T)$: 1-dim. amplitude of thermal fluctuations

. (used Debye model) increases with T, e.g. in Si

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

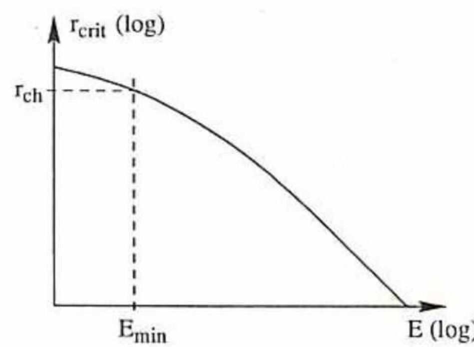


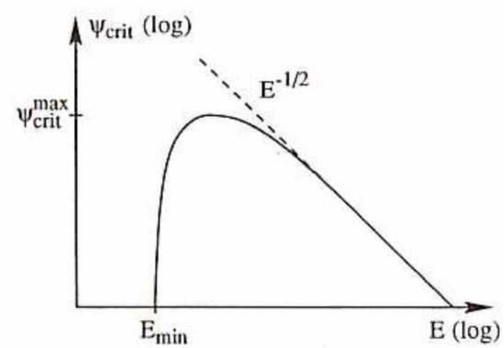
$u_1(T)$

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

$$\psi \le \psi_c = \sqrt{\frac{[U(\rho_c) - U(\rho_{ch})]}{E}}$$

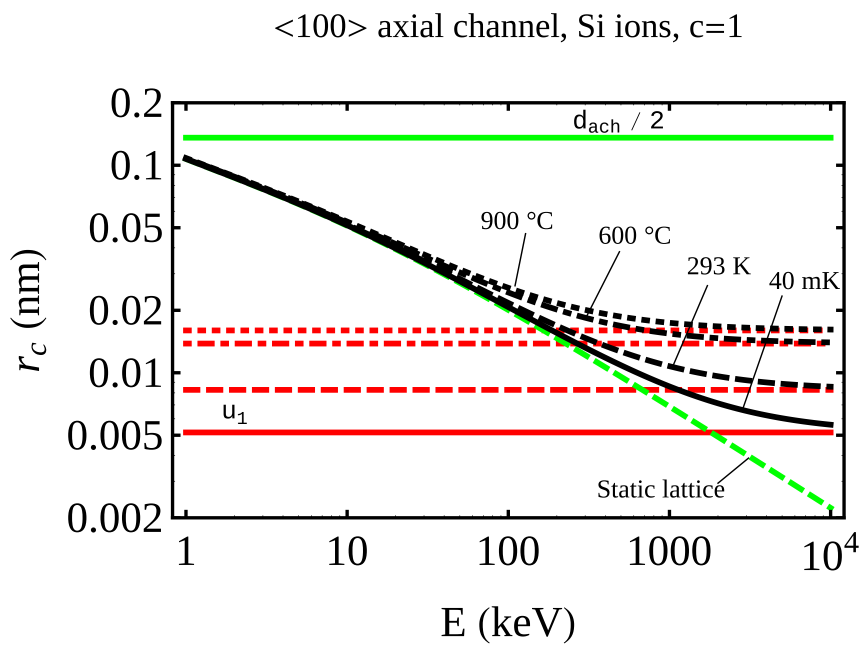
If $\rho_c(E,T) \geq$ the radius of the channel ρ_{ch}, $\psi_c = 0$:
NO CHANNELING POSSIBLE

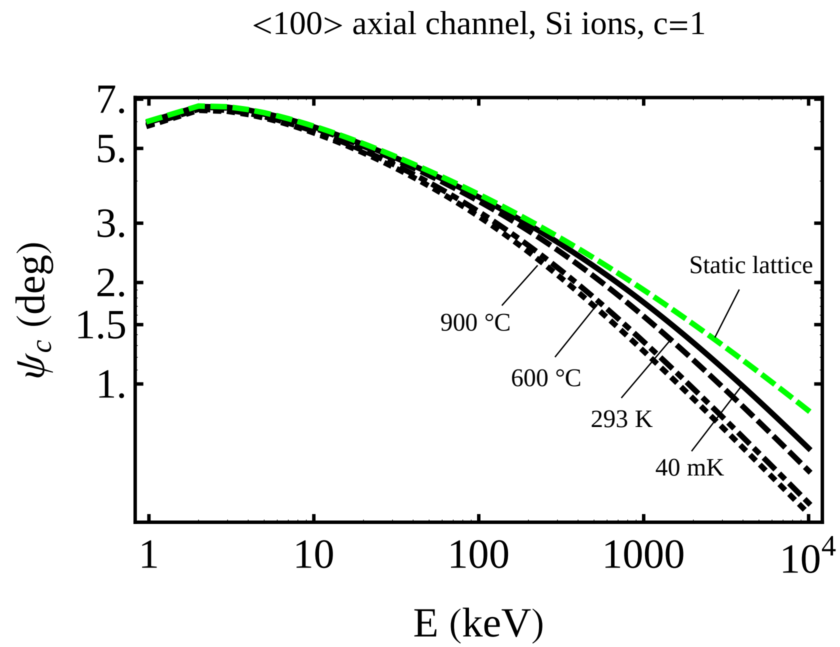




Si ion in Si crystal, $c = 1$ (i.e. $r_c \to u_1(T)$ at high E)

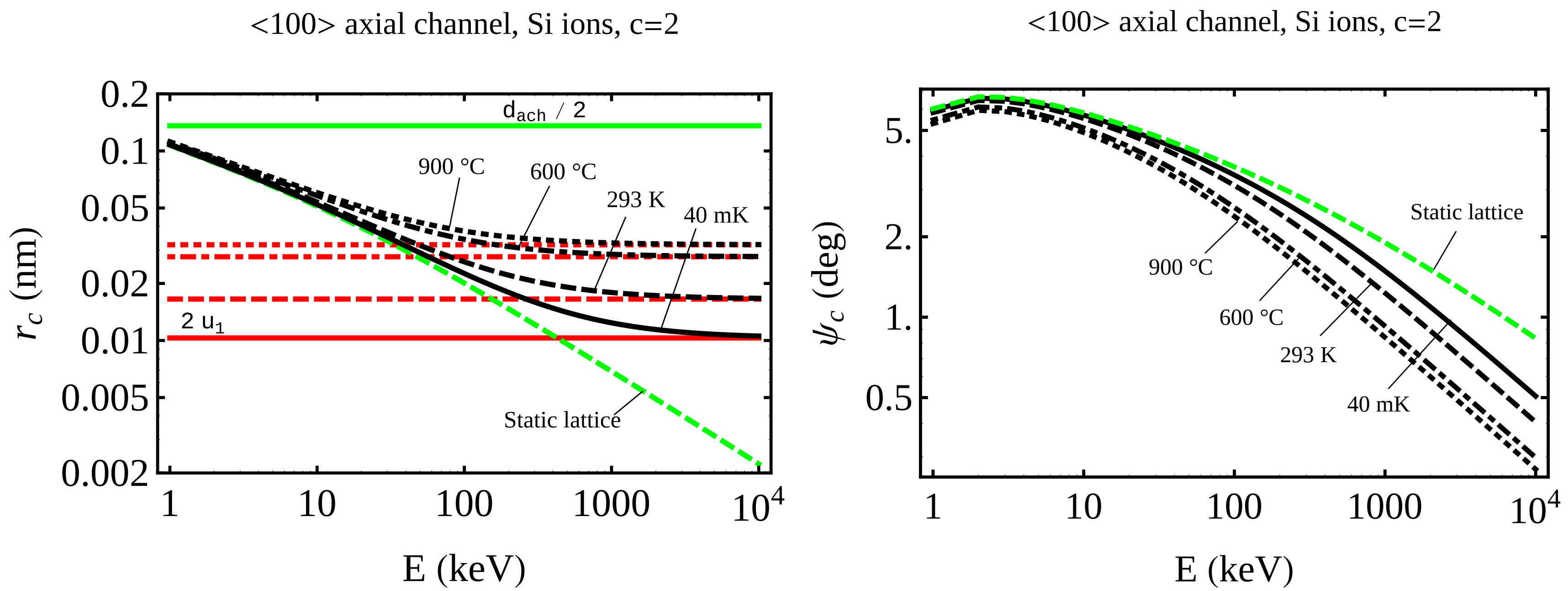
(Bozorgnia, Gelmini, Gondolo 2010)





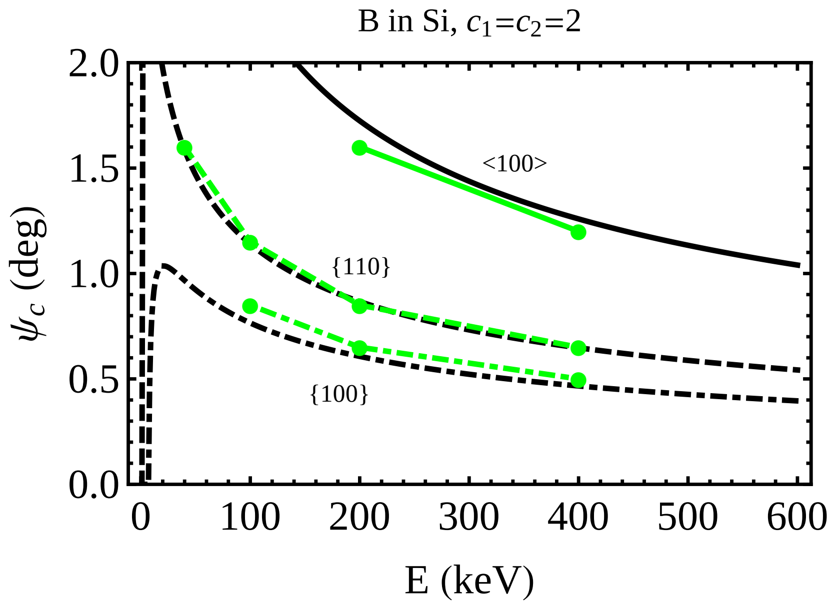
Si ion in Si crystal, $c = 2$ (i.e. $r_c \to 2\ u_1(T)$ at high E)

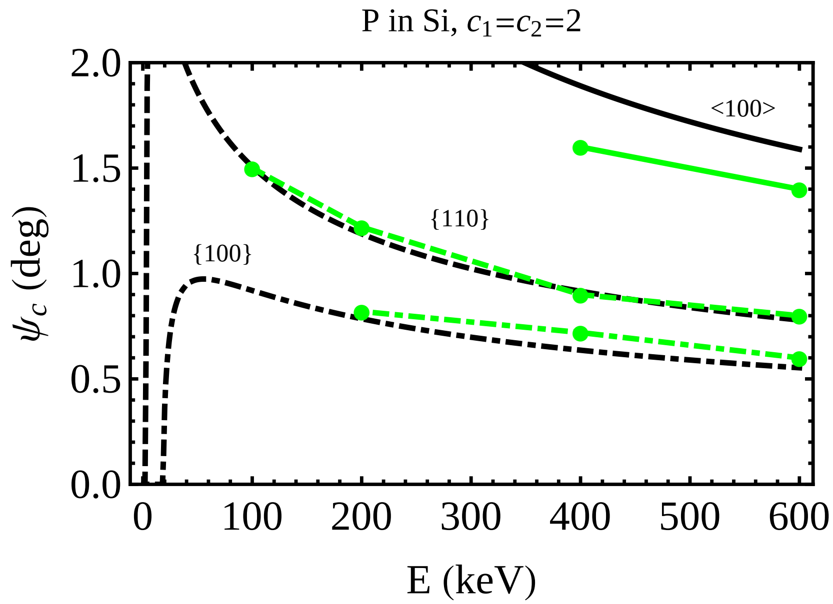
(Bozorgnia, Gelmini, Gondolo 2010)



Data B and P ion in Si crystal fitted with $c = 2$ (data from Hobler-1995)

(Bozorgnia, Gelmini, Gondolo 2010)

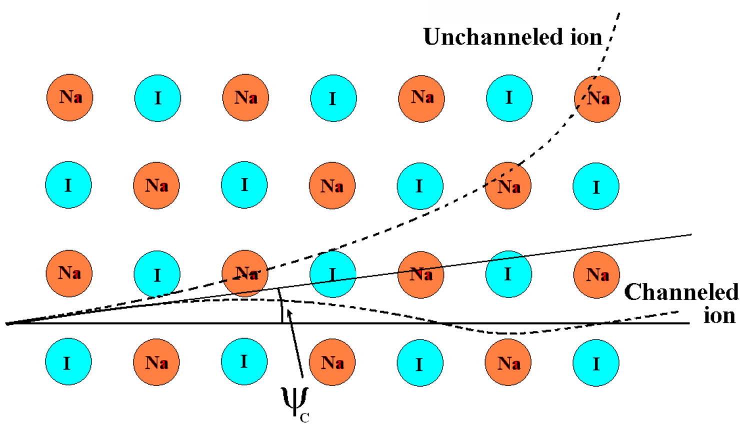


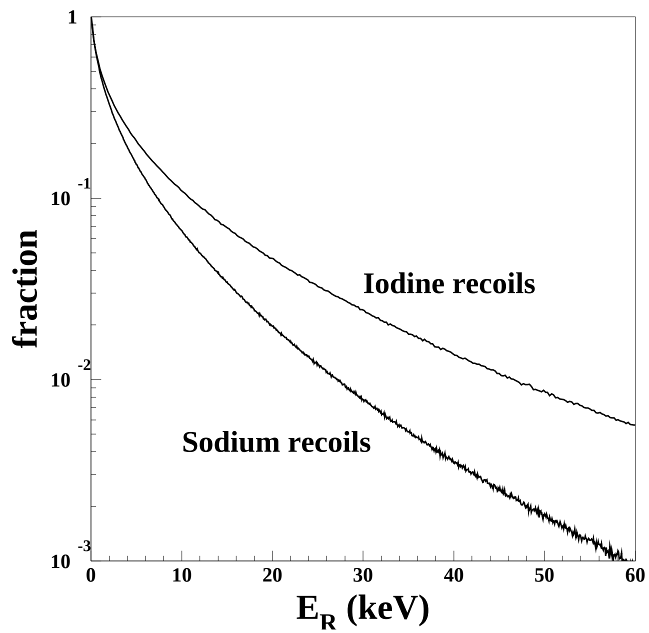


In NaI, no data or modeling available at low energies

DAMA channeling fraction:(DAMA- Eur. Phys. J. C 53, 205-2313, 2008)

Calculated as if ions start from the middle of the channel. Good for incident ions but not for recoiling ions!

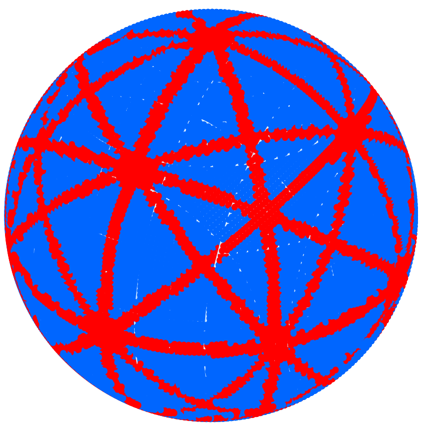


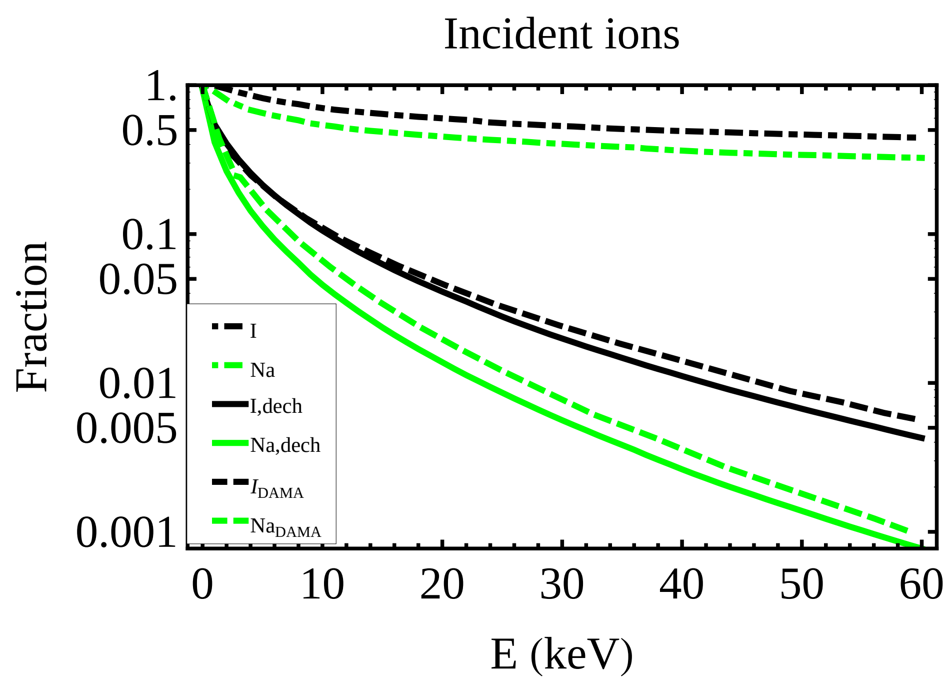


Reproduced DAMA calculations of channeled fraction

We used HEALPix (Hierarchical Equal Area iso Latitude Pixelisation) method to compute the integral over all directions. Dechanneling due to Tl doping (only first interaction and no rechanneling)

(Bozorgnia, Gelmini, Gondolo 1006.3110)





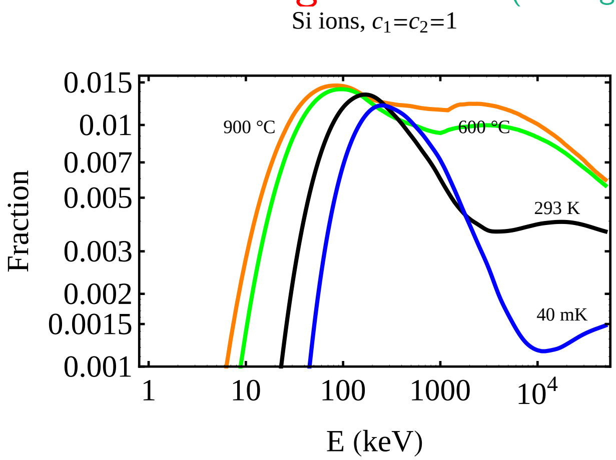
Channeling probability of ions ejected from lattice sites

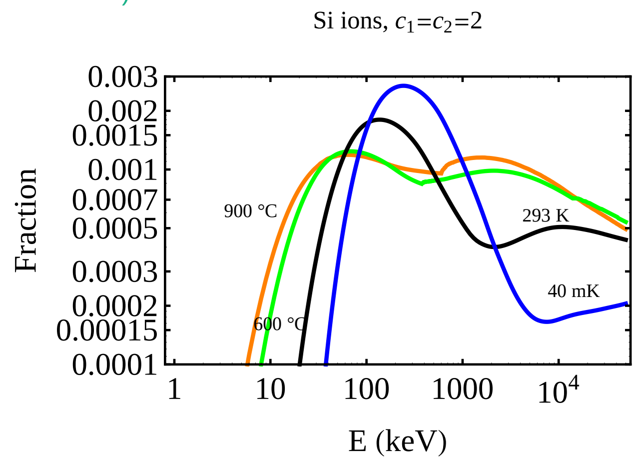
- Recoiling nuclei start at or close to lattice sites
- Blocking effects are important
- In a perfect lattice no recoil would be channeled *("rule of reversibility")*.
- However, there are channeled recoils due to lattice vibrations! Collision may happen when nucleus is somewhat within the channel, with prob. $g(\rho) = \frac{\rho}{u_1^2} e^{(-\rho^2/2u_1^2)}$ thus $P_{Ch} = \int_{\rho_{i,\min}}^{\infty} dr g(\rho) = e^{(-\rho_{i,\min}^2/2u_1^2)}$ and $\rho_{i,\min}$ is given by ρ_c (uncertainty in ρ_c is exponentiated in P_{Ch})
- Recoiling nucleus leaves an empty lattice site.

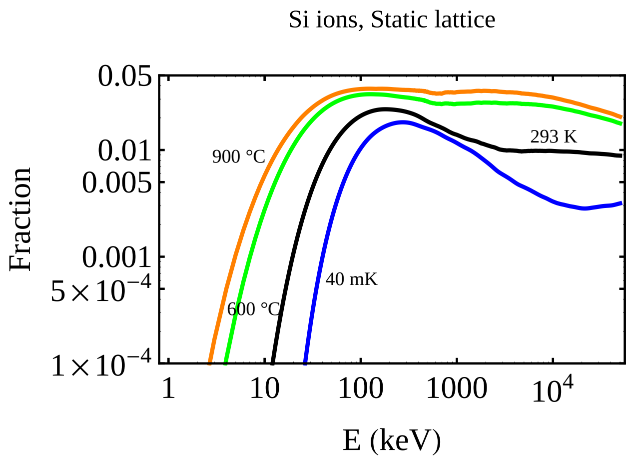
Two main T effects: amplitude $u_1(T)$ increases with T which increases channneling prob.- but ρ_c also increases with T what decreases the prob.

Channeling probability of ions ejected from lattice sites: Si

No dechanneling included (Bozorgnia, Gelmini, Gondolo 2010)





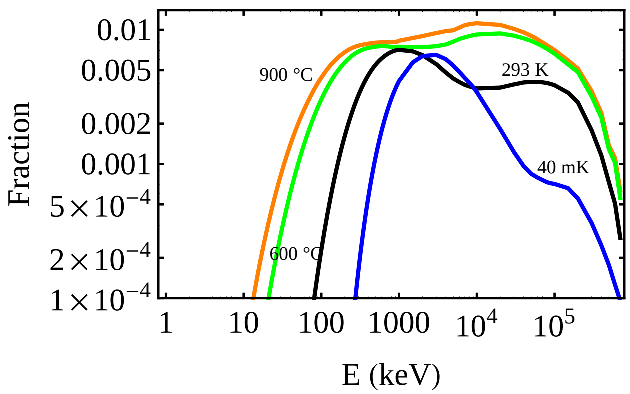


Upper bound (static lattice, $c = 0$)

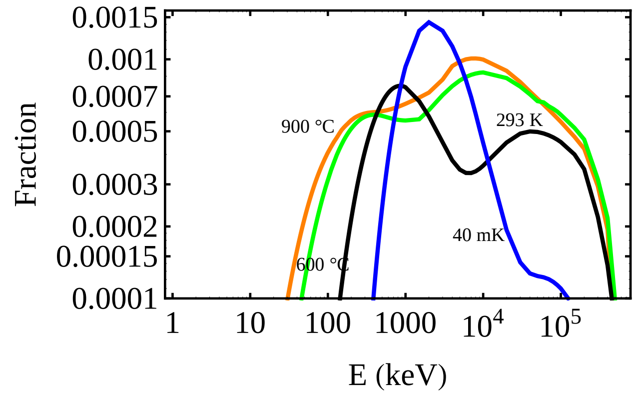
Channeling probability of ions ejected from lattice sites: Ge

No dechanneling included (Bozorgnia, Gelmini, Gondolo 2010)

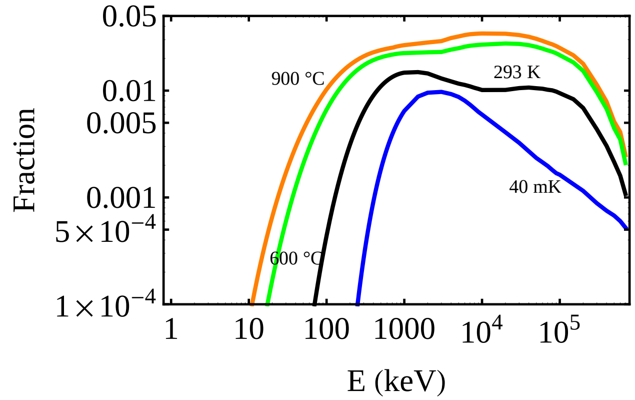
Ge ions, c_1=c_2=1



Ge ions, c_1=c_2=2



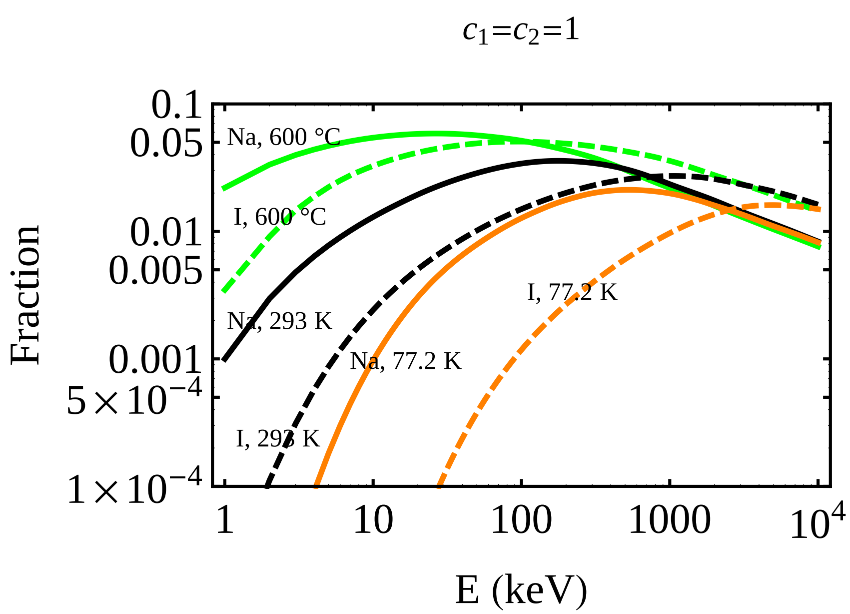
Ge ions, Static lattice



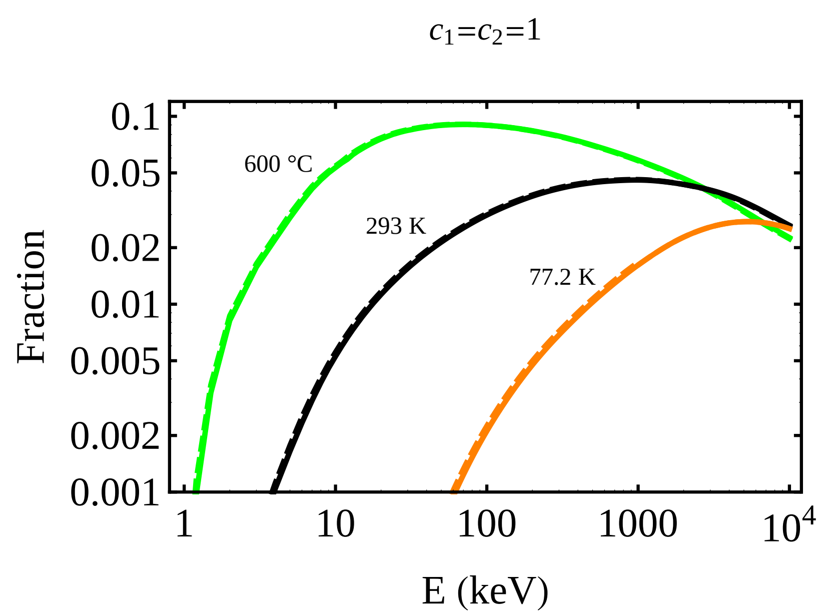
Upper bound (static lattice, $c = 0$)

Channeling probability of ions ejected from lattice sites: NaI and CsI

T-dependent upper bounds with lattice oscillations included ($c = 1$)
(no dechanneling included)



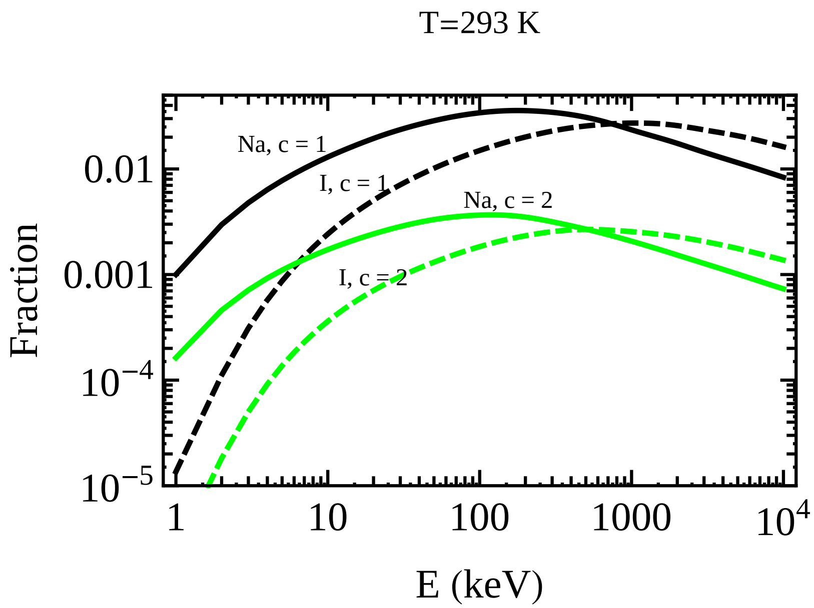
NaI (Bozorgnia, Gelmini, Gondolo 1006.3110)



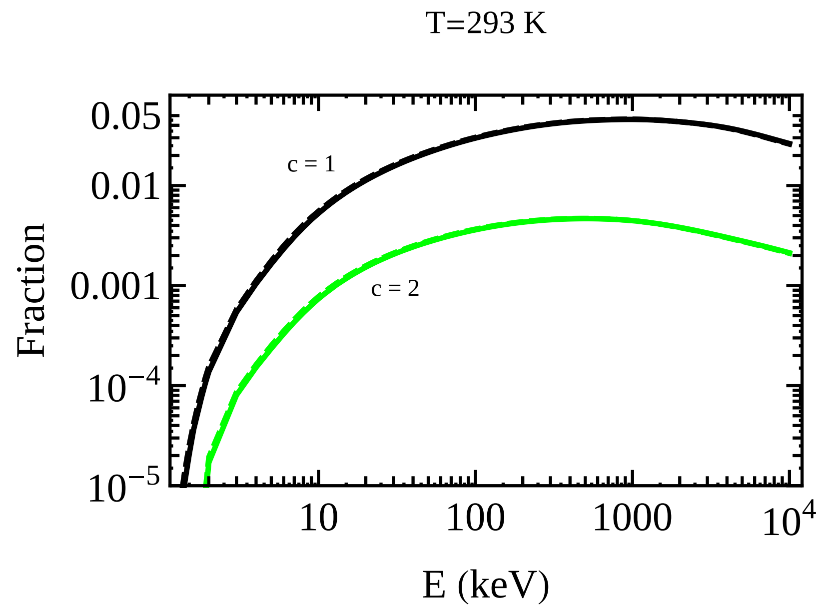
CsI (Bozorgnia, Gelmini, Gondolo 2010)

Channeling probability of ions ejected from lattice sites: NaI and CsI

Upper bounds at room temperature with lattice oscillations included
(no dechanneling included)



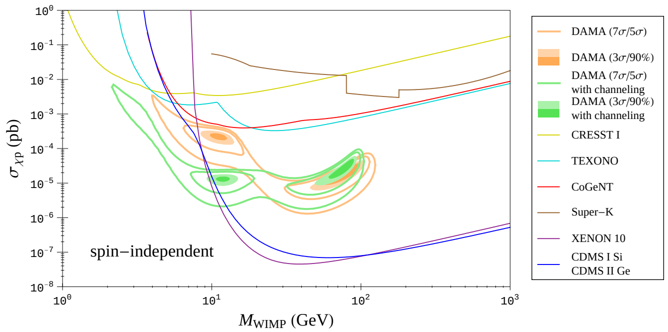
NaI (Bozorgnia, Gelmini, Gondolo 1006.3110)



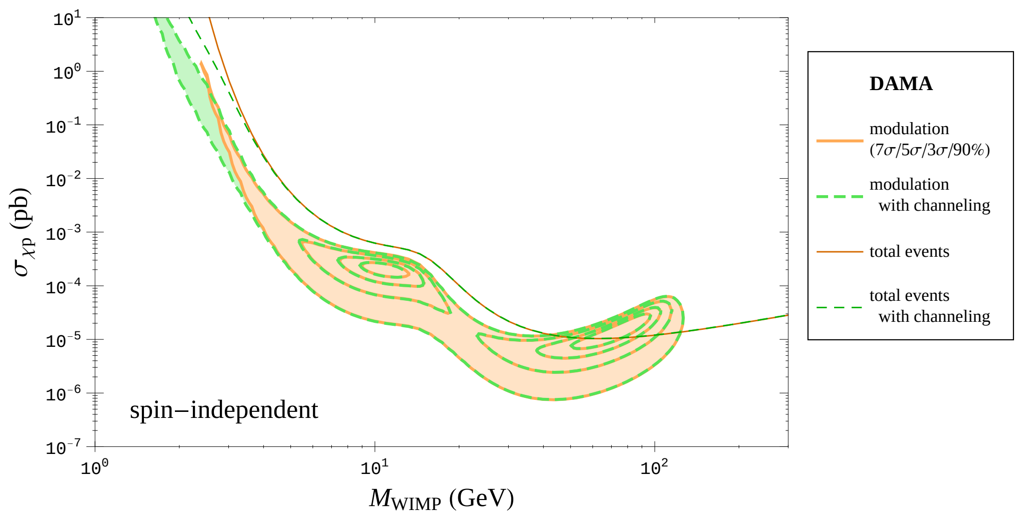
CsI (Bozorgnia, Gelmini, Gondolo 2010)

Compatibility of DAMA/LIBRA with other experiments

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

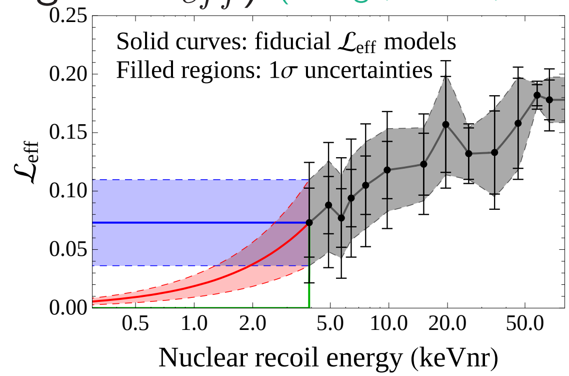


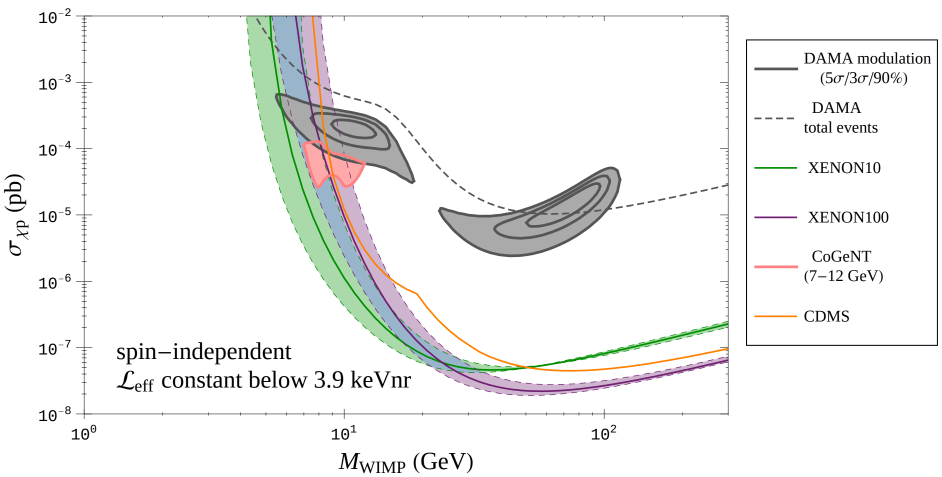
and now (diff. at 7σ)(Savage et al. 1006.3110)

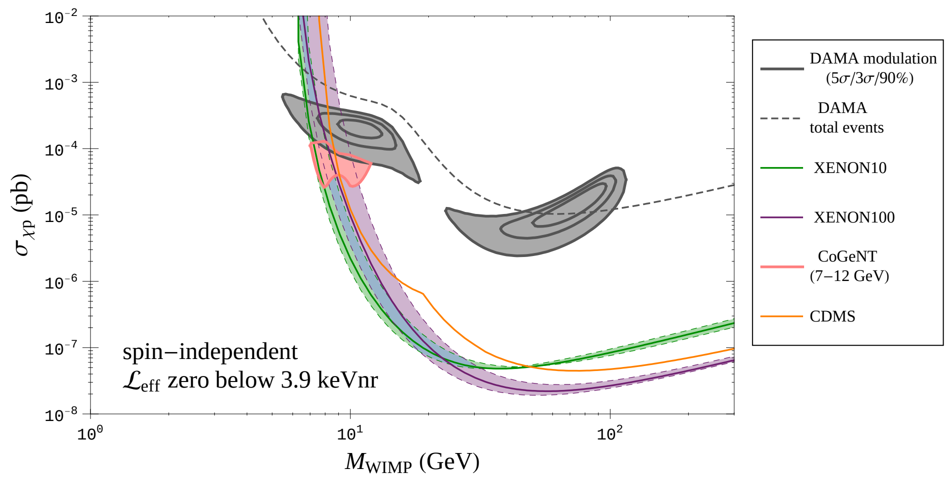


Compatibility of DAMA/LIBRA with other experiments

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) (see talk of C. Savage)







Conclusions:

- The effect of blocking is important to understand the channeling of recoiling nuclei: the channeled fraction of recoils is smaller and it is strongly temperature dependent. DAMA region is not affected by channeling up to the 5σ level.

- Channeling in crystaline detectors can lead to a daily modulation of a WIMP signal, a DM signature without any background (with small amplitudes- but larger for halo components with small velocity dispersion)

  As initially proposed by H. Sekiya et al. (2003); Avignone, Creswick, Nussinov (2008 and 1007.0214)

- Analytic models give good qualitative results but need data/simulations to get good quantitative results (not available or NaI).
  Montecarlo simulations may be needed to settle these issues (many are used in other applications of channeling).