Ion-Channeling in Direct DM Detectors

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Based on work done with Nassim Bozorgnia and Paolo Gondolo

GGI Florence, May 19, 2010

Channeling and Blocking Effects in Crystals

refer to the orientation dependence of ion penetration in crystals.

Channeling:

Ions **incident** upon the 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)*

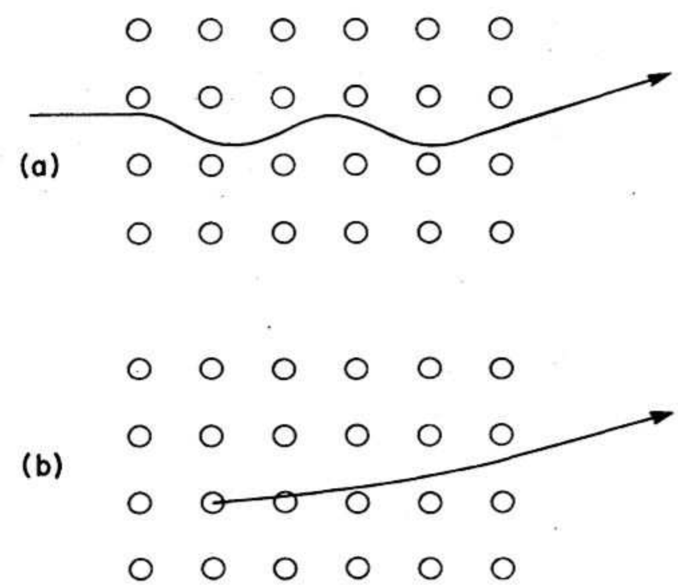


FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

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

Blocking:

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

Channeling and blocking in crystals is used in

- studies of lattice disorder

- ion implantation

- to locate dopant and impurity atoms

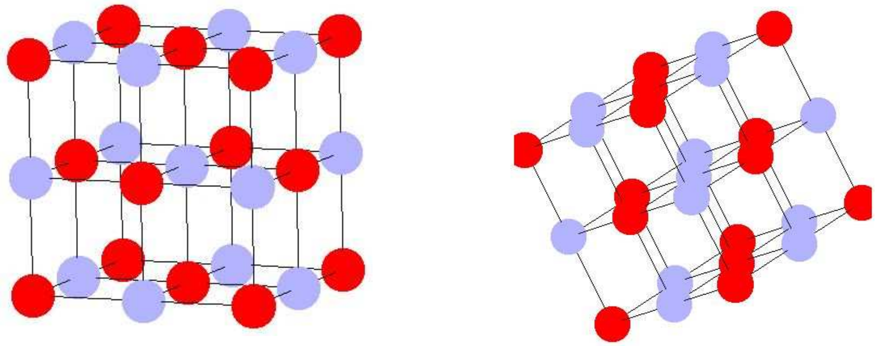
- studies of surfaces and interfaces

- measurement of nuclear lifetimes

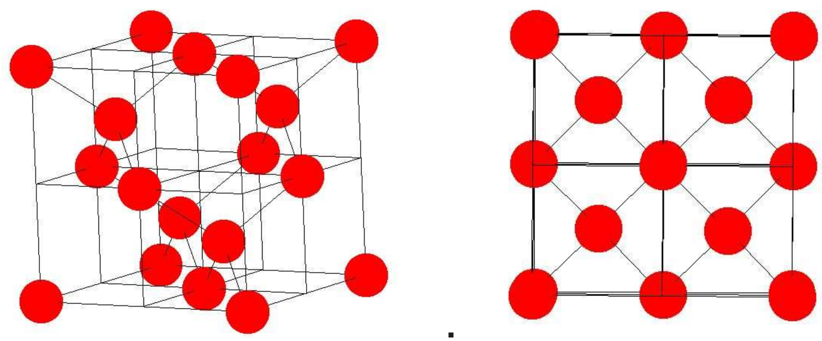
- production of polarized beams... etc

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

NaI crystal



.Si or Ge crystal



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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*

M. R. Altman, H. B. Dietrich,† and R. B. Murray
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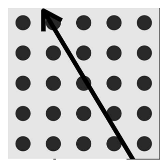
T. J. Rock
Ballistic Research Laboratory Radiation Division, Aberdeen Proving Ground, Maryland 21010
(Received 29 September 1972)

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.

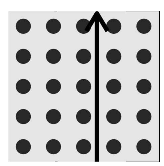
Channeling effect observed in NaI (TI) Altman et.al 1973

Sintillation output of a monochromatic 10 MeV ^{16}O beam through NaI(TI) scintillator

Left peak: Not channeled ions



Right peak: higher energy channeled ions



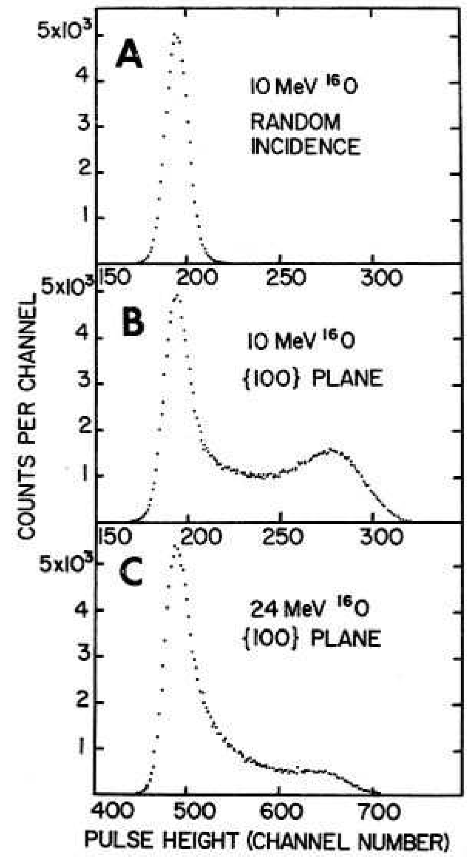


FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

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

Channeled ions produce more scintillation light

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

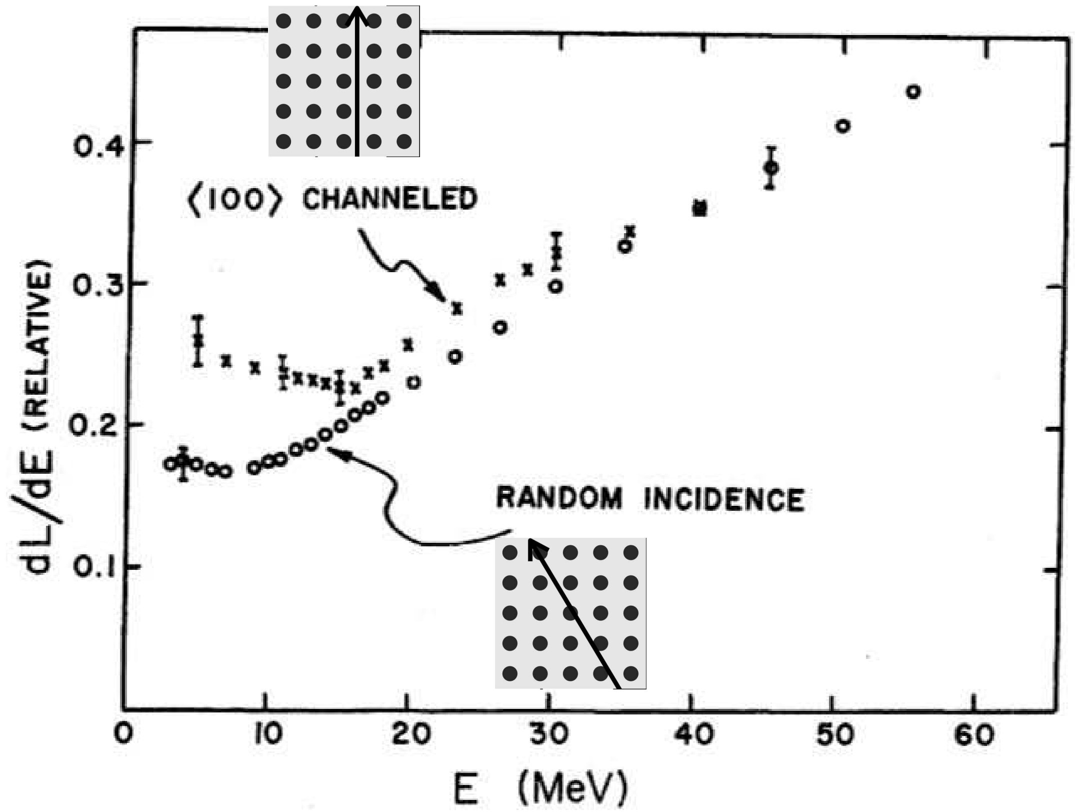
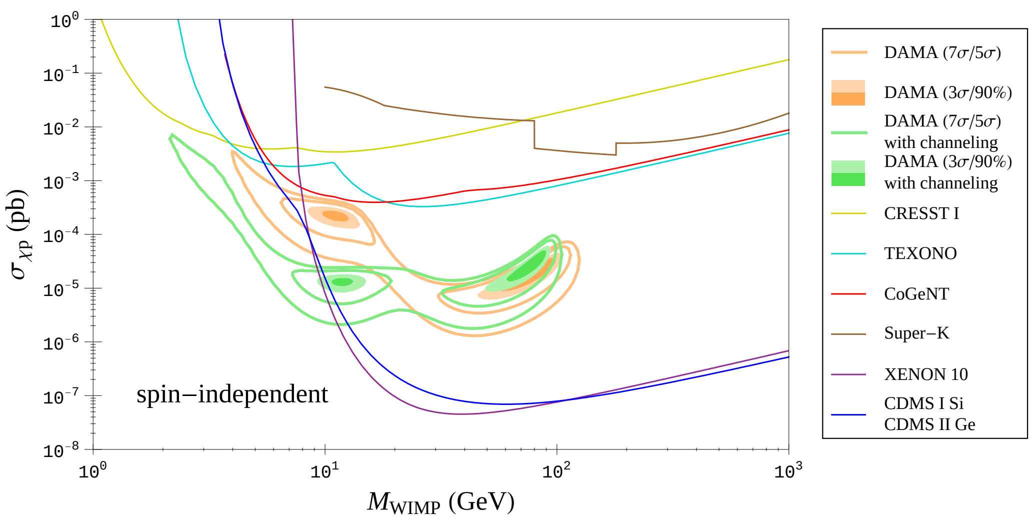


FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

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 $Q_{Na} = 0.3$



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

Daily-Modulation due to Channeling:

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

- The WIMP wind comes preferentially from one direction
- When that direction is aligned with a channel, the scintillation or ionization output is larger
- Earth's 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)

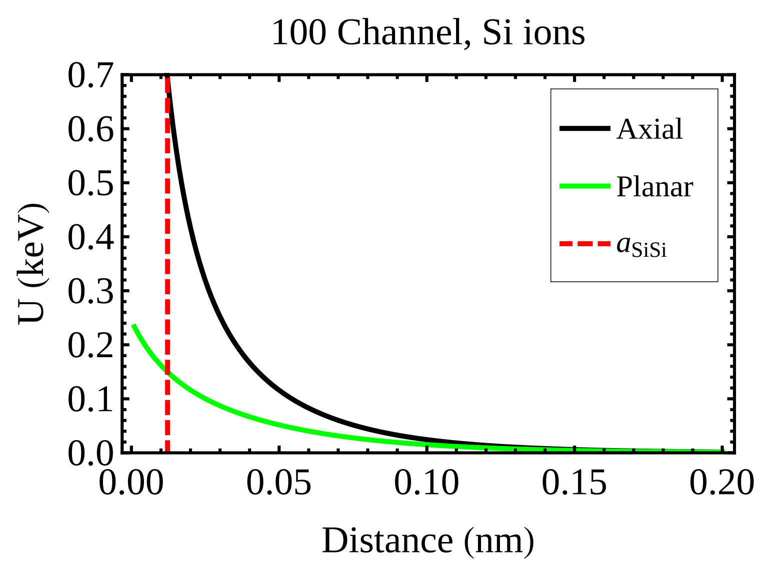
This daily modulation would be a background free DM signature!

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 daiy 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

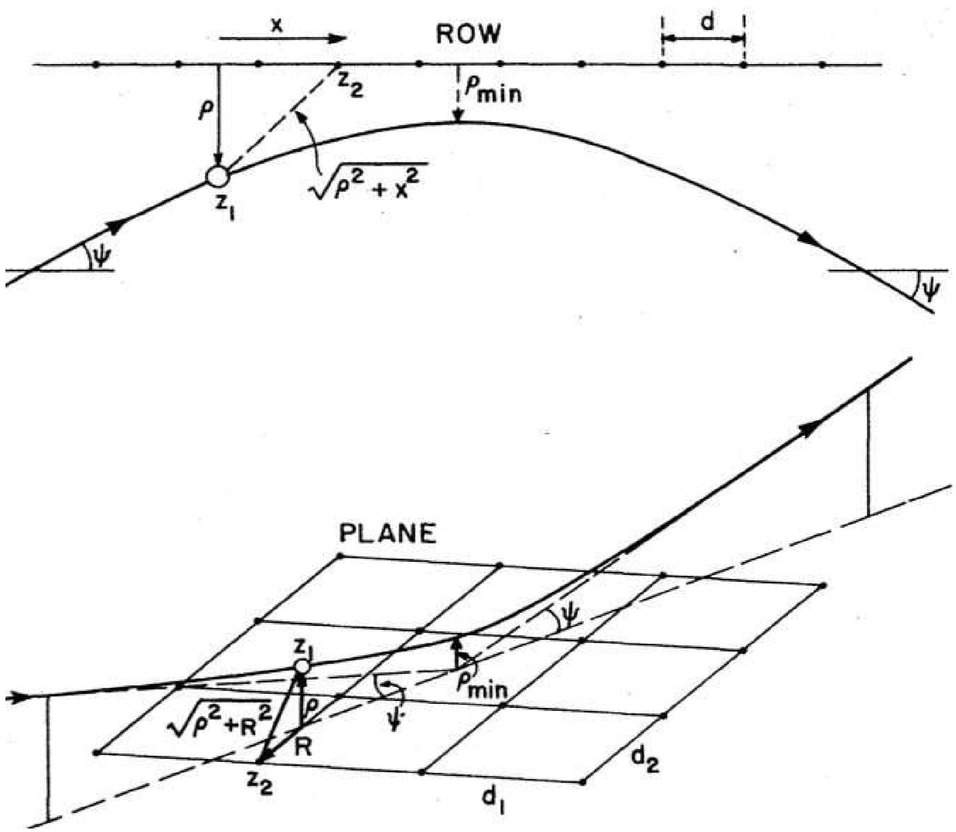
$$E_{\rm perp} = E\phi_i^2 + U_i$$

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

Axial and planar channels

$\rho_{\rm min}$: 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,

angle there is

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

Channeling requires

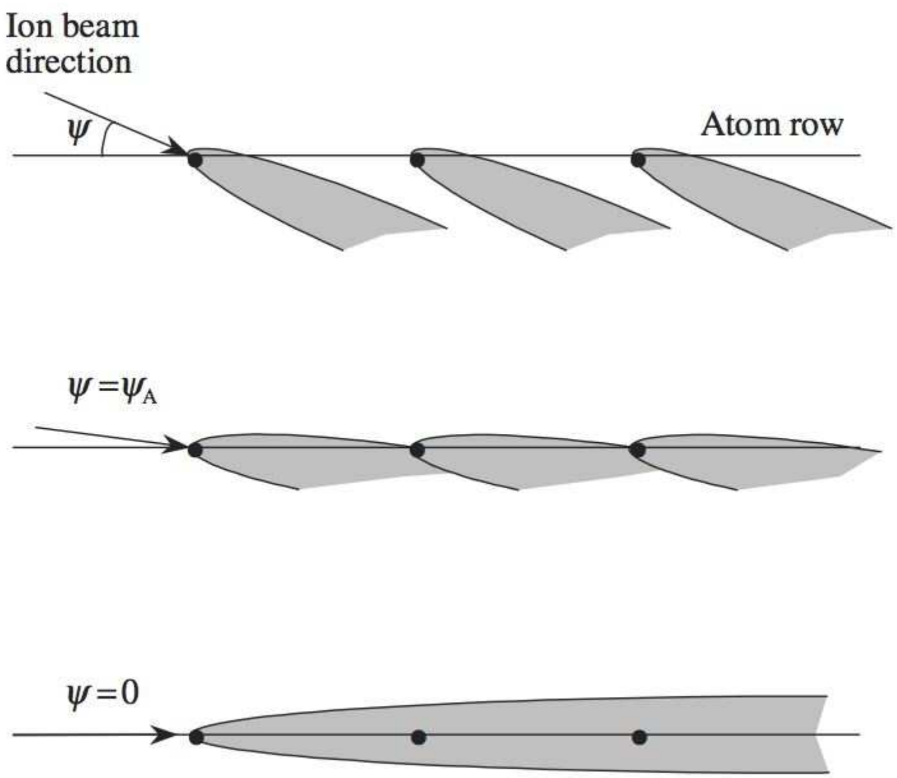
$\rho_{\rm min} > \rho_c$

which amounts to

$\psi \leq \psi_c$

Axial and planar channels can be understood as interference of Coulomb shadow cones, $\rho_{\rm min} > \rho_c$ and $\psi < \psi_c$

(Fig. from Hiroshi Kudo, 2001)



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

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

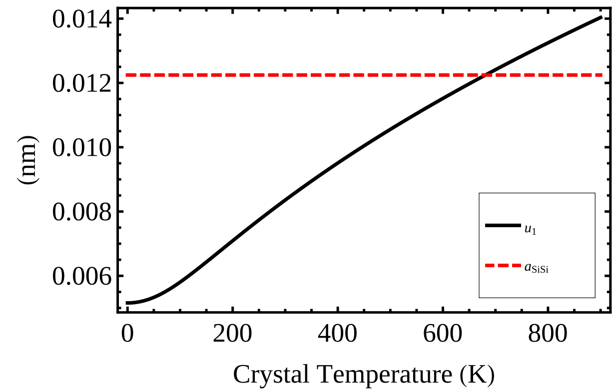
$$\rho_{\min} > \rho_c(E,T) = \sqrt{\rho_c^2(E) + [c\; u_1(T)]^2}$$

$\rho_c(E)$: 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

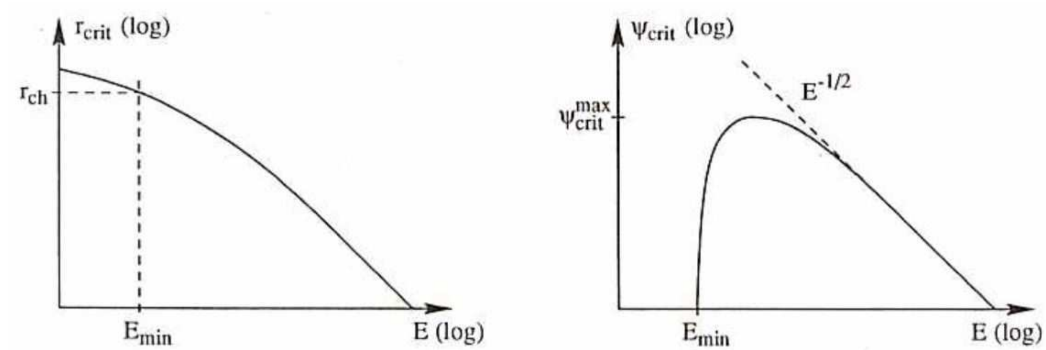
c: found through data/simulations, $1 < c < 2$



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

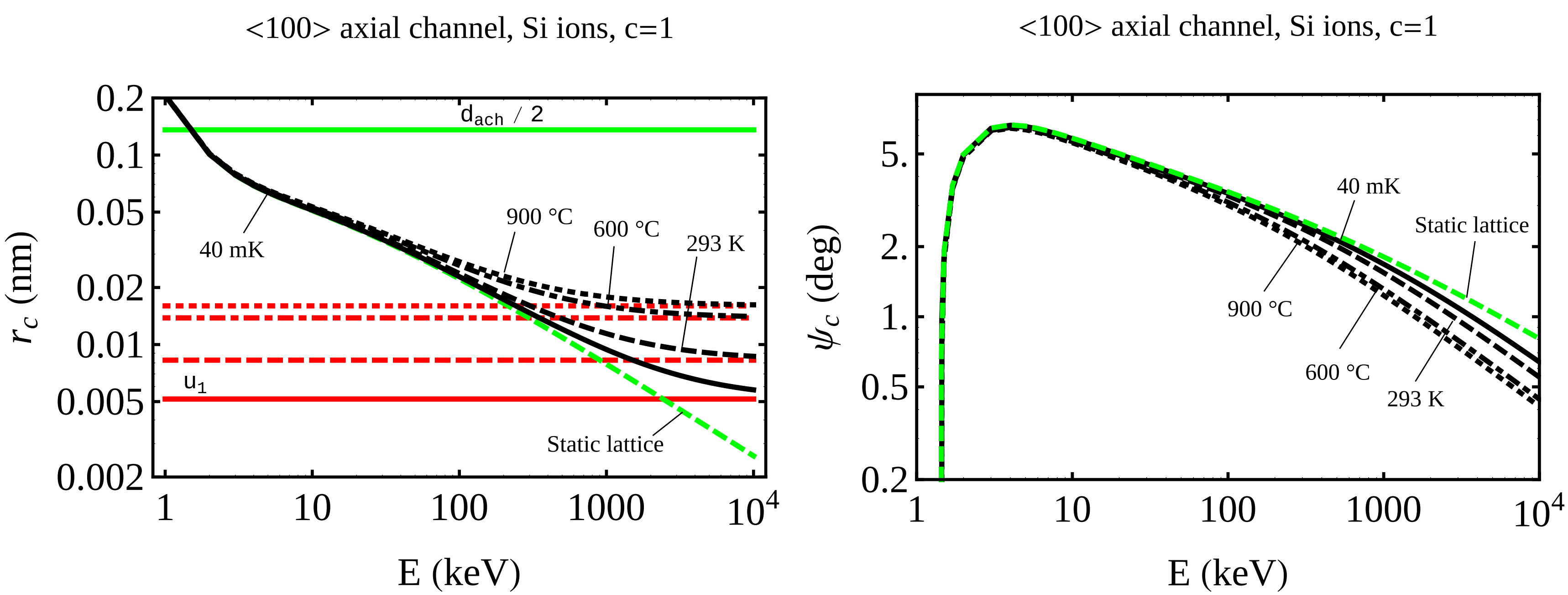
$$\psi \leq \psi_c = \sqrt{\frac{[U(\rho_c) - U(r_{ch})]}{E}}$$

If $\rho_c(E,T) \geq$ the radius of the channel $r_{ch} = d_{ch}/2$, $\psi_c = 0$:
NO CHANNELING POSSIBLE



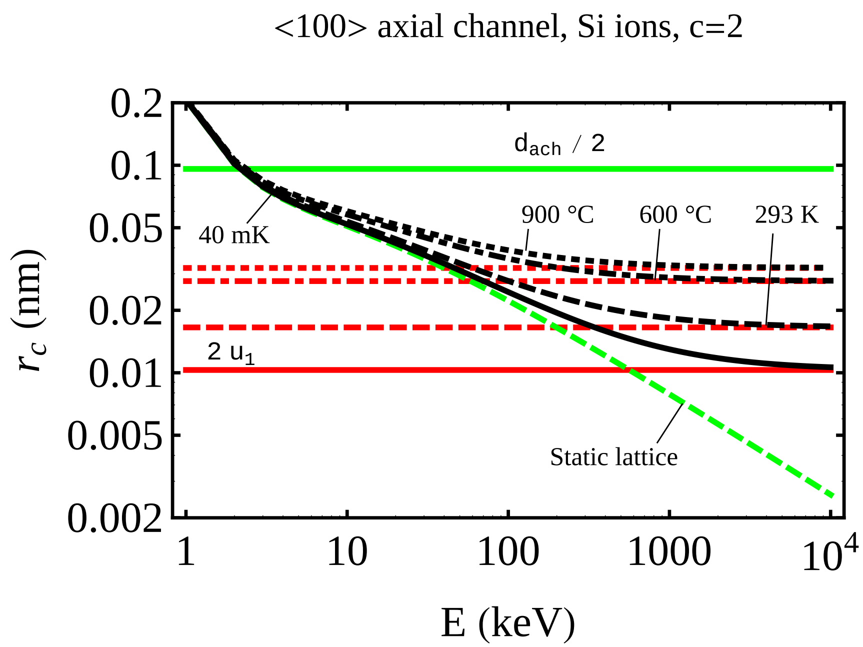
Si ion in Si crystal, $c = 1$ (i.e. $r_c \to u_1(T)$ at high E)

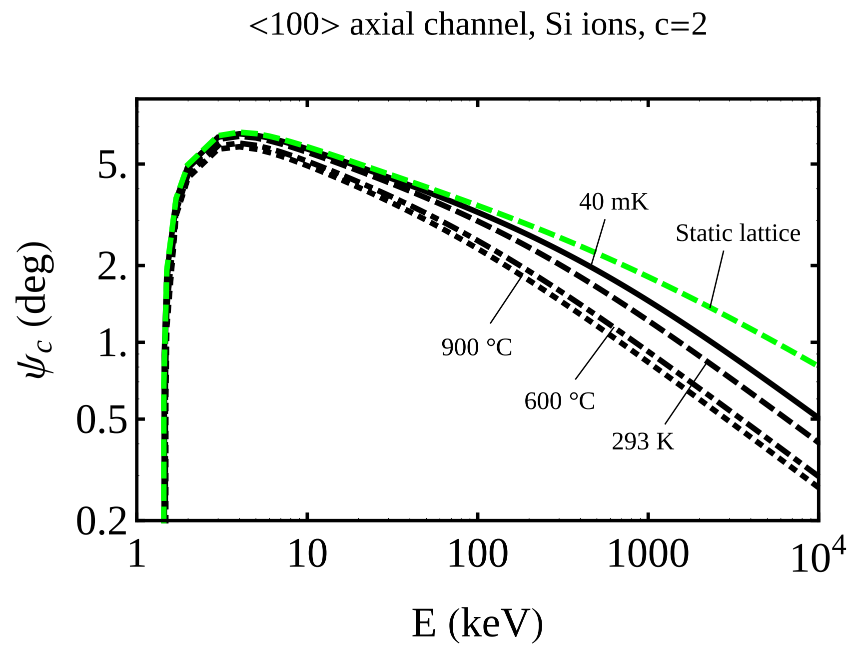
(Bozorgnia, Gelmiin, Gondolo 2010)



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

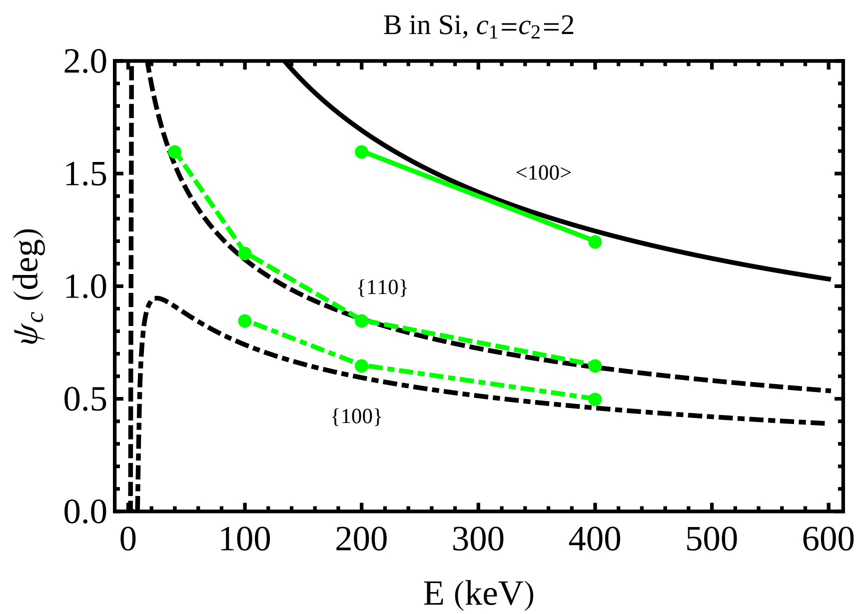
(Bozorgnia, Gelmiin, Gondolo 2010)

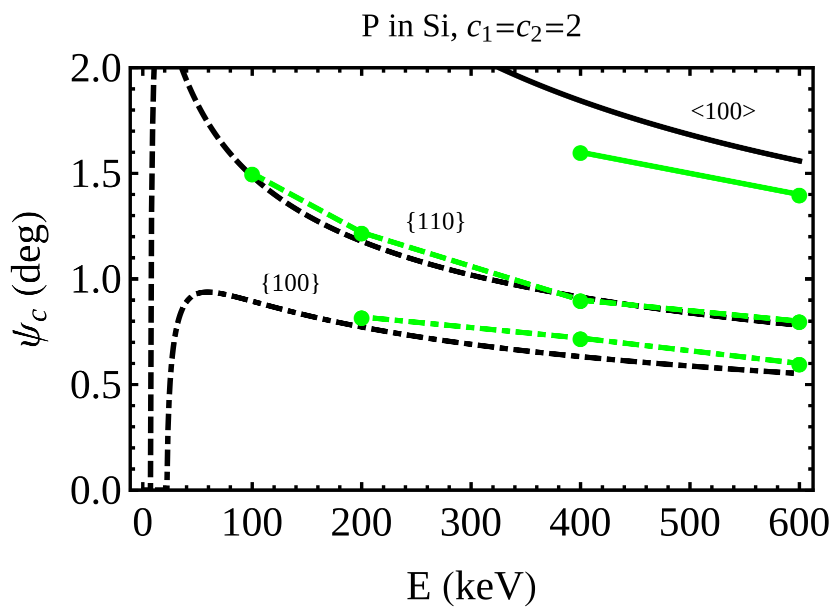




Data B and P ion in Si crystal fitted with $c = 2$ (data from Hobler-1995)

(Bozorgnia, Gelmiin, Gondolo 2010)



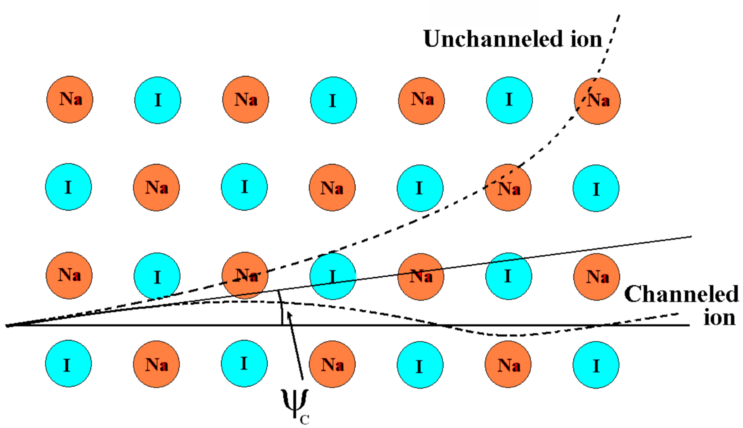


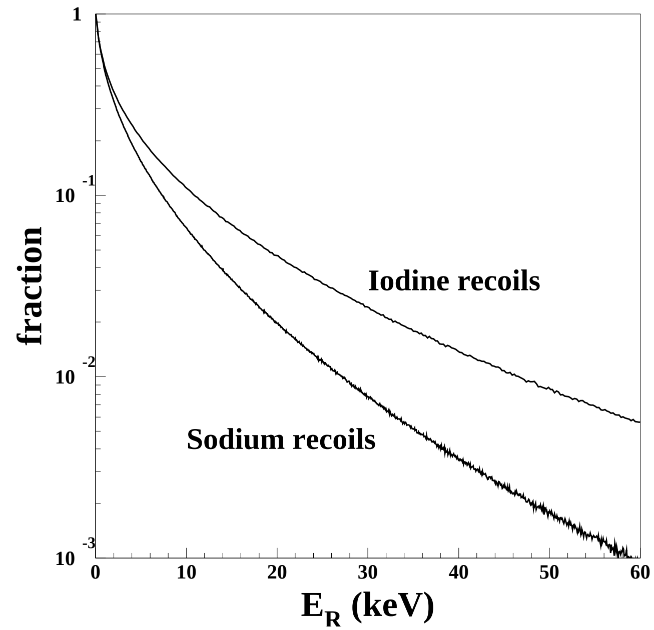
In NaI, no data or modeling available at low energies

DAMA channeling fraction:

Calculated as if ions start from the middle of the channel

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

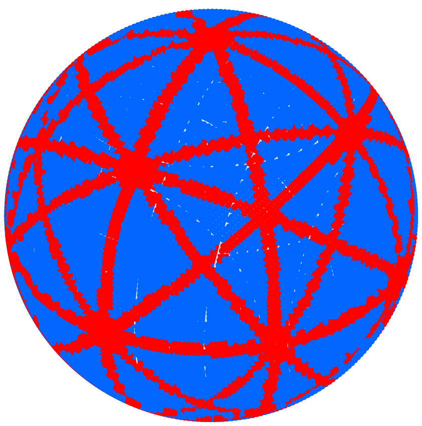


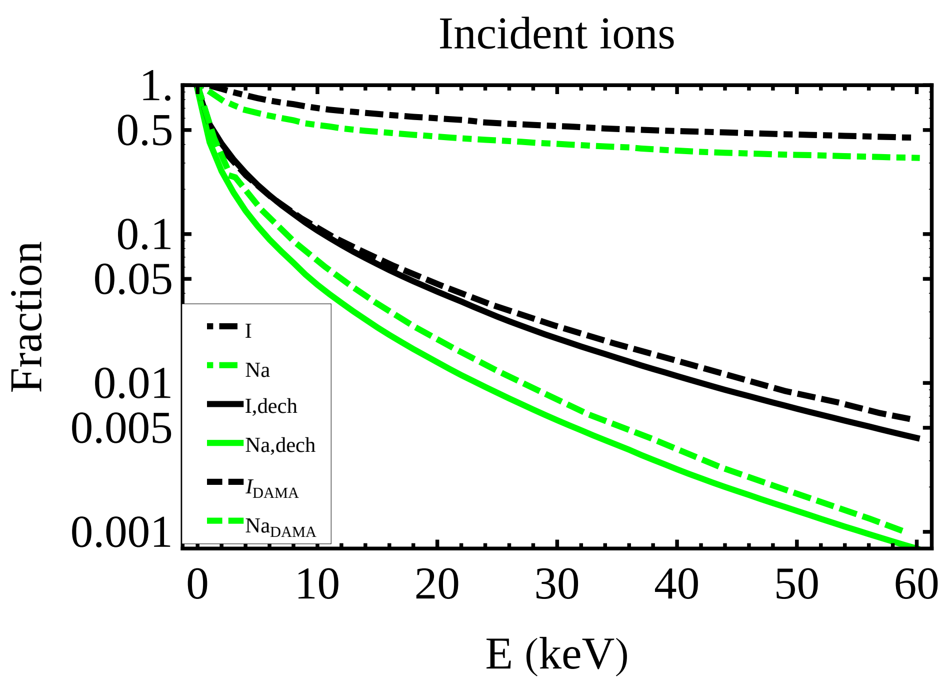


Reproduced DAMA calculations of channeled fraction

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, Gelmiin, Gondolo 2010)





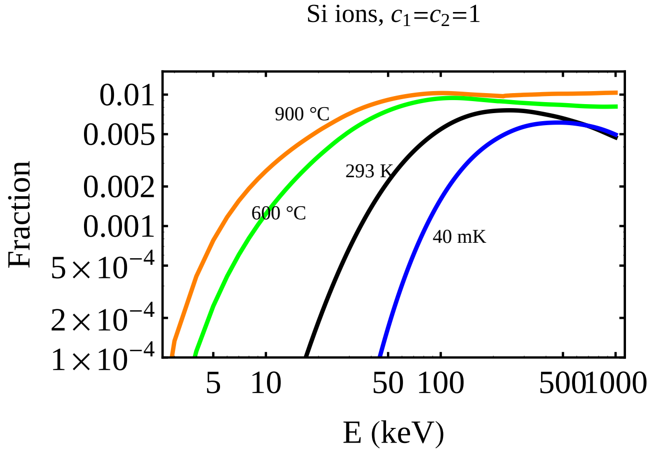
Channeling probability of ions ejected from lattice sites

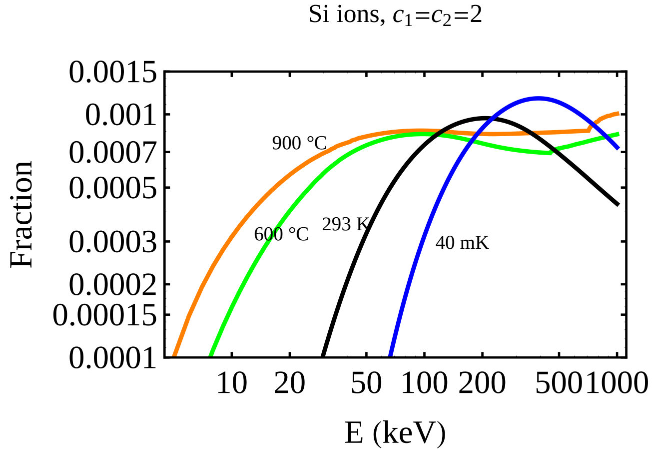
- Recoiling nuclei start at or close to lattice sites
- Blocking effects are important
- In a perfect lattice no recoil would be channeled *("rule of reversibility")*.
- However, there are channeled recoils due to lattice vibrations! Collision may happen when nucleus is somewhat within the channel, with 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.

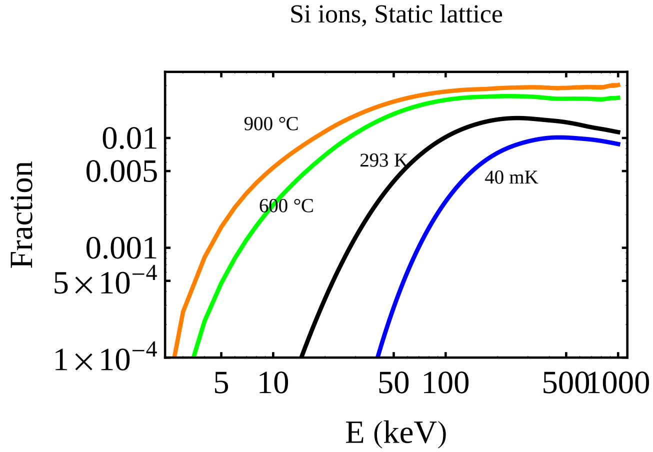
Two main T effects: amplitude $u_1(T)$ increases with T which increases channneling prob.- but r_c also increases with T what decreases the prob.

Channeling probability of ions ejected from lattice sites: Si

No dechanneling included (Bozorgnia, Gelmiin, Gondolo 2010)



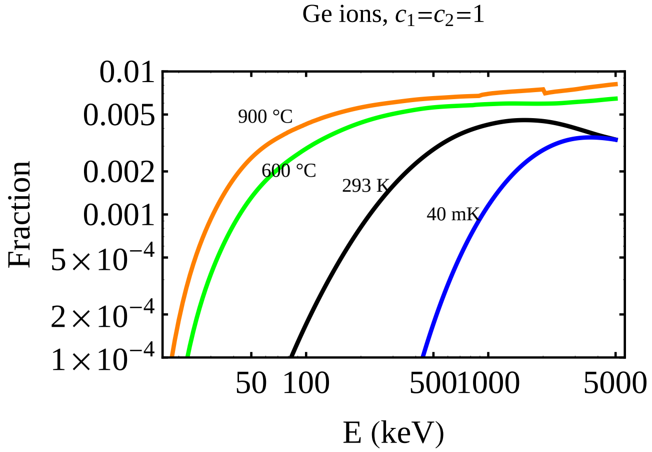


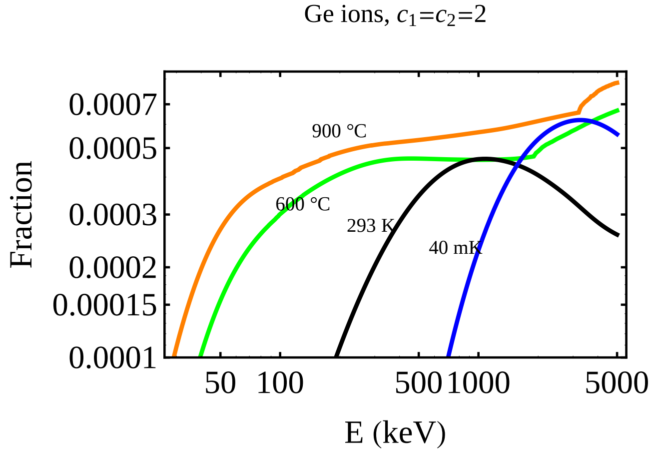


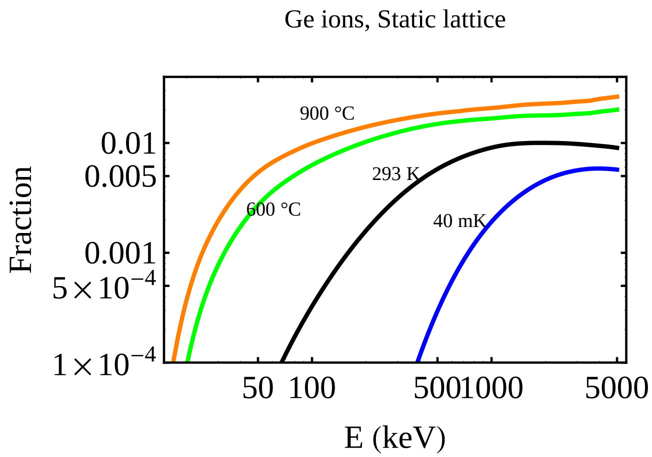
Upper bound (static lattice)

Channeling probability of ions ejected from lattice sites: Ge

No dechanneling included (Bozorgnia, Gelmiin, Gondolo 2010)







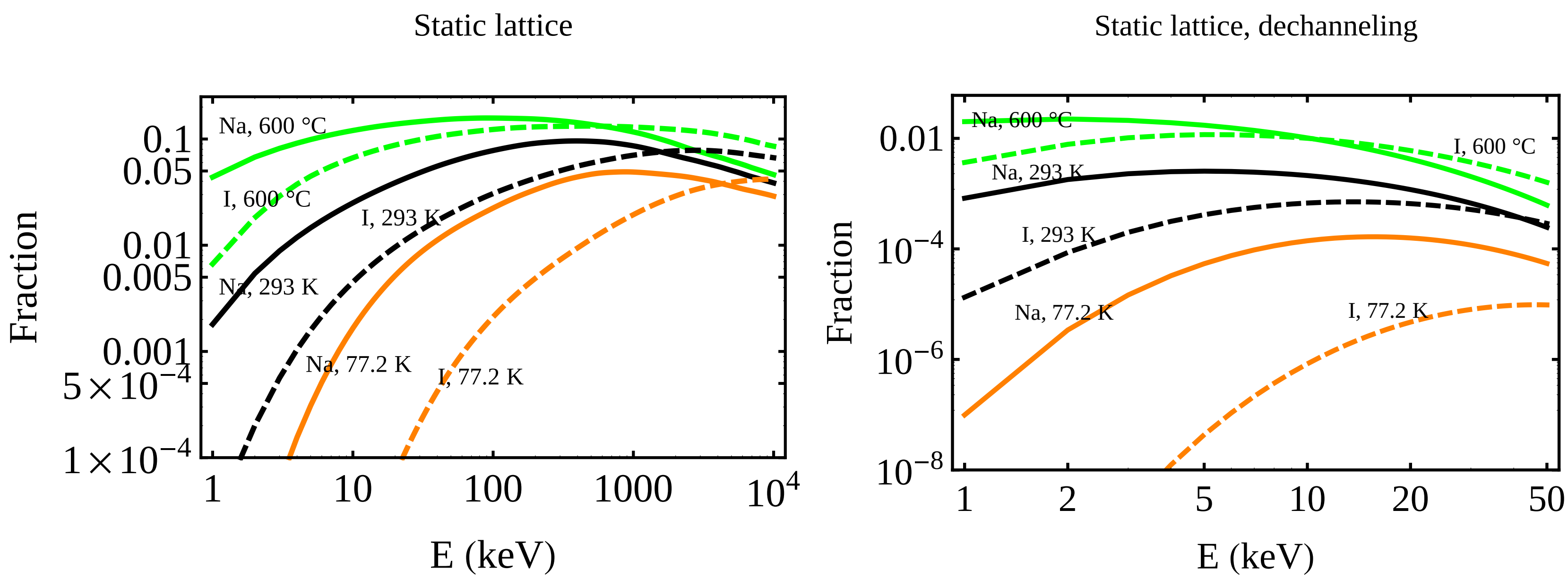
Upper bound (static lattice)

Channeling probability of ions ejected from lattice sites: NaI(Tl)

Upper bound: T-dep. static lattice.

Righ: extreme dechanneling due to Tl, with no re-channeling considered.

(Bozorgnia, Gelmiin, Gondolo 2010)

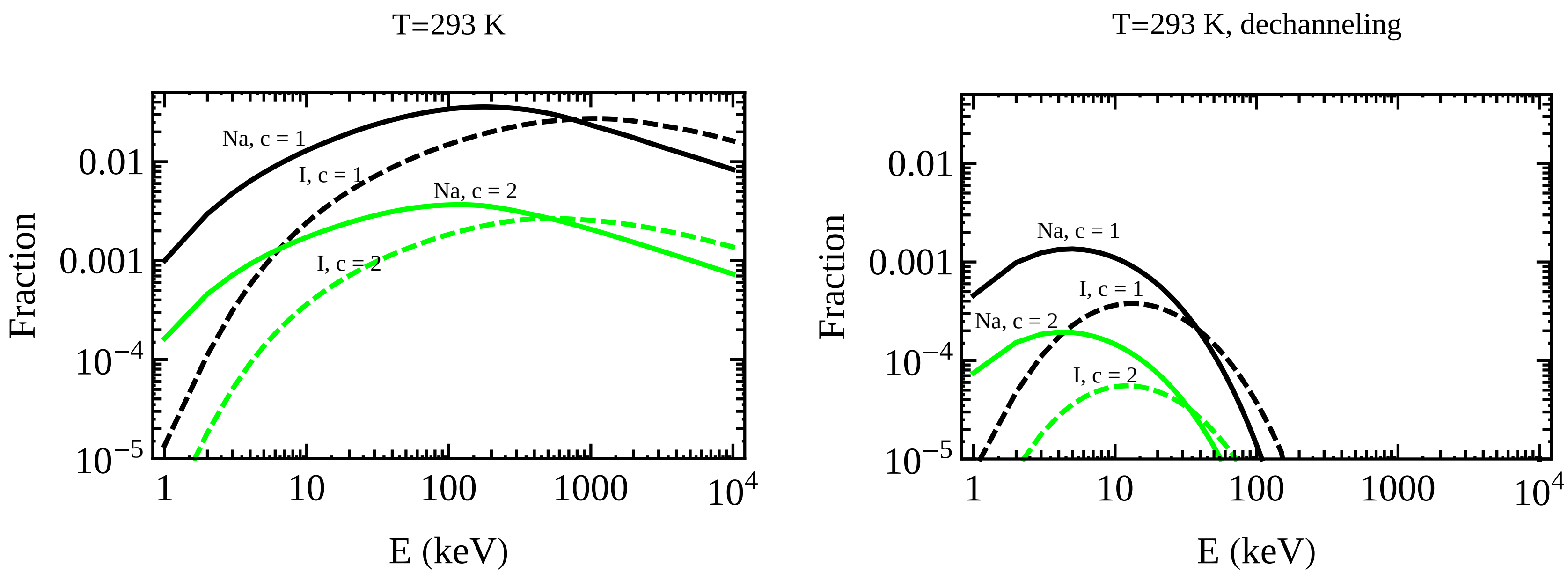


Channeling probability of ions ejected from lattice sites: NaI (Tl)

More reasonable upper bounds at 20 K with lattice oscillations included

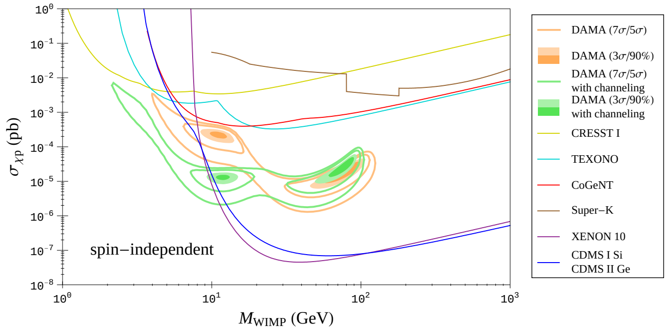
- Right: extreme dechanneling due to Tl with no re-channeling considered.

(Bozorgnia, Gelmiin, Gondolo 2010)

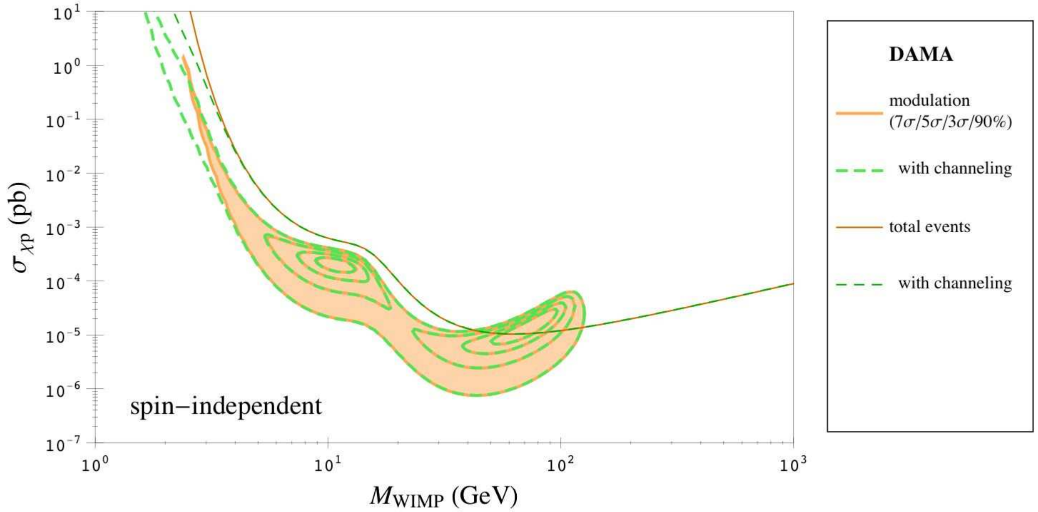


Compatibility of DAMA/LIBRA with other experiments

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



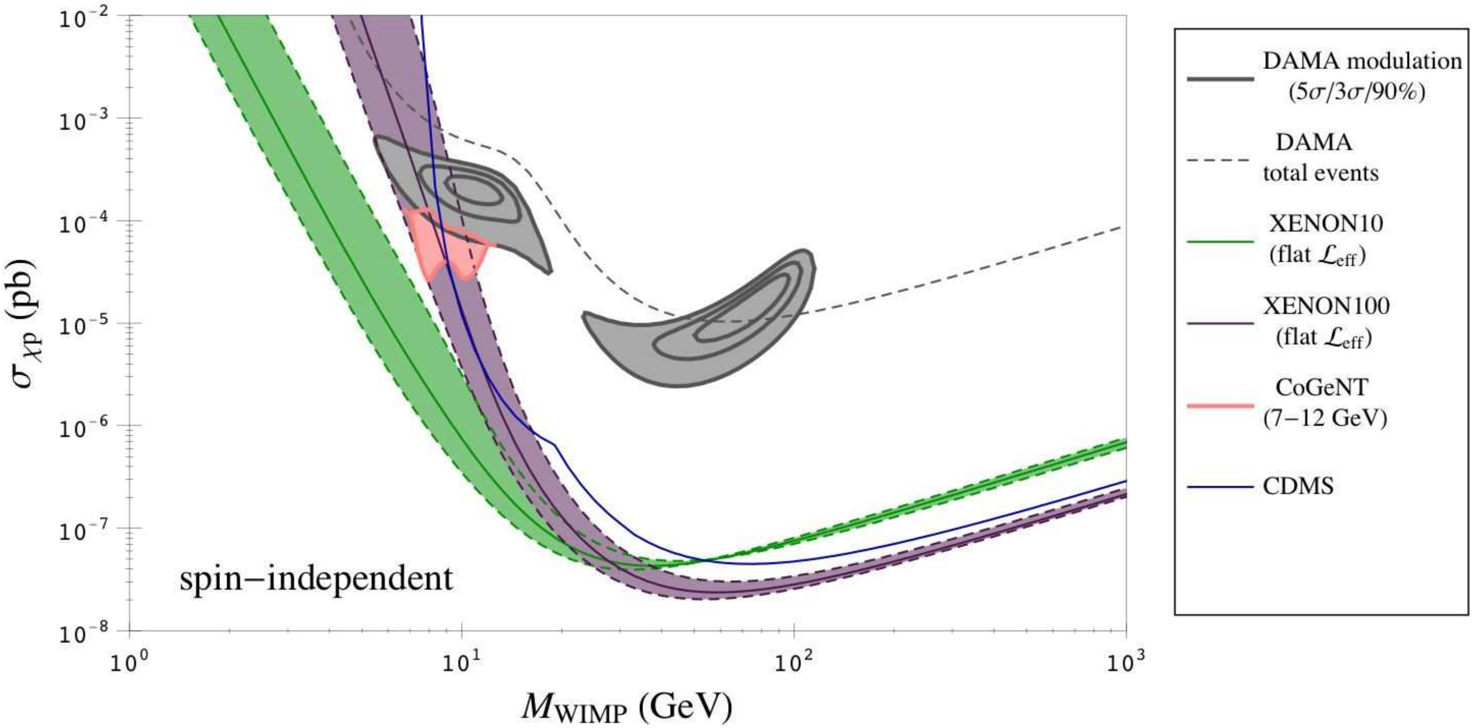
and now (diff. at 7σ)(Savage,Gelmini, Gondolo 2010)



Compatibility of DAMA/LIBRA with other experiments

If L_{eff} extrapolated as a constant below 4 keVnr (band: how the 90%CL bound changes with 1σ change in L_{eff})

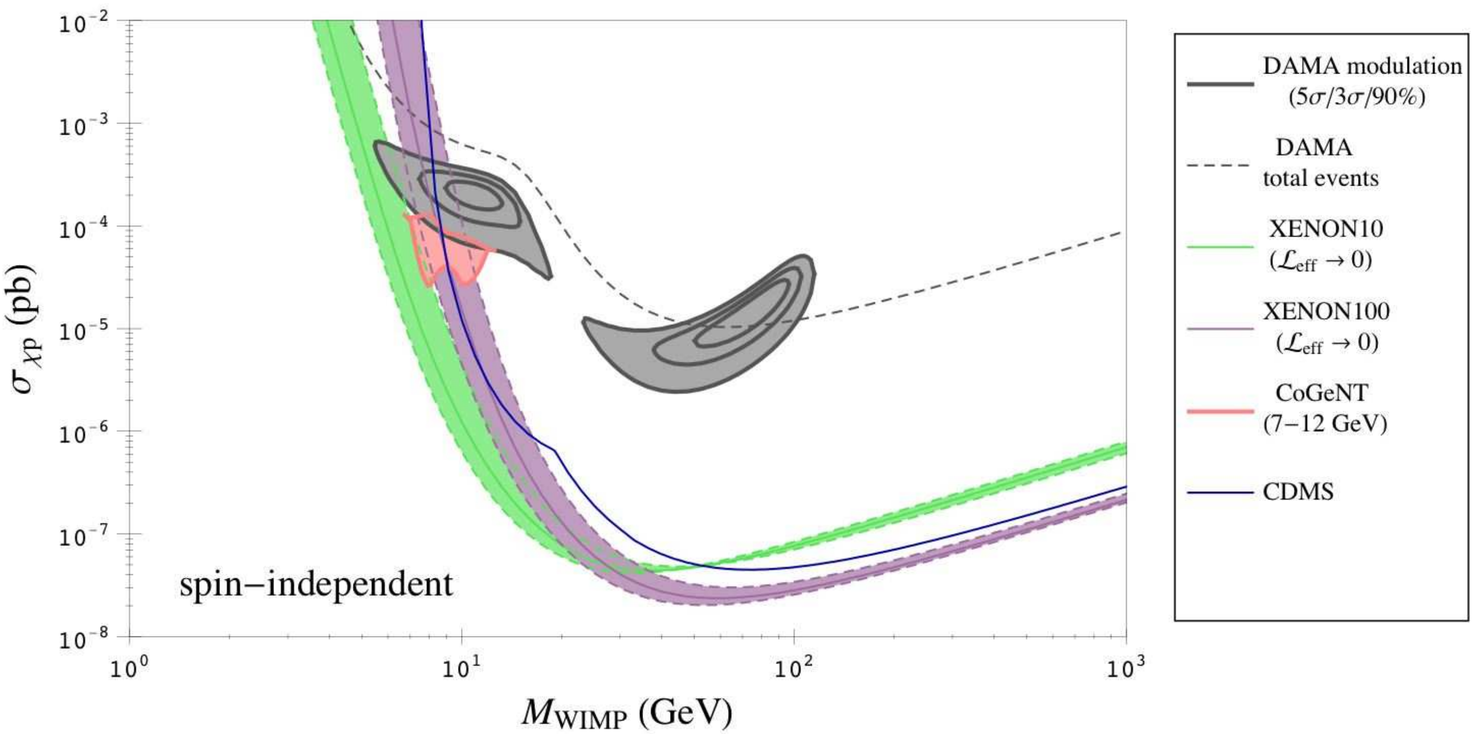
(Savage,Gelmini, Gondolo 2010)



Compatibility of DAMA/LIBRA with other experiments

If L_{eff} extrapolated linearly to zero as E decreases below 4 keVnr (band: how the 90%CL bound changes with 1σ change in L_{eff} from Manzur (2010) data set)

(Savage, Gelmini, Gondolo 2010)



Conclusions:

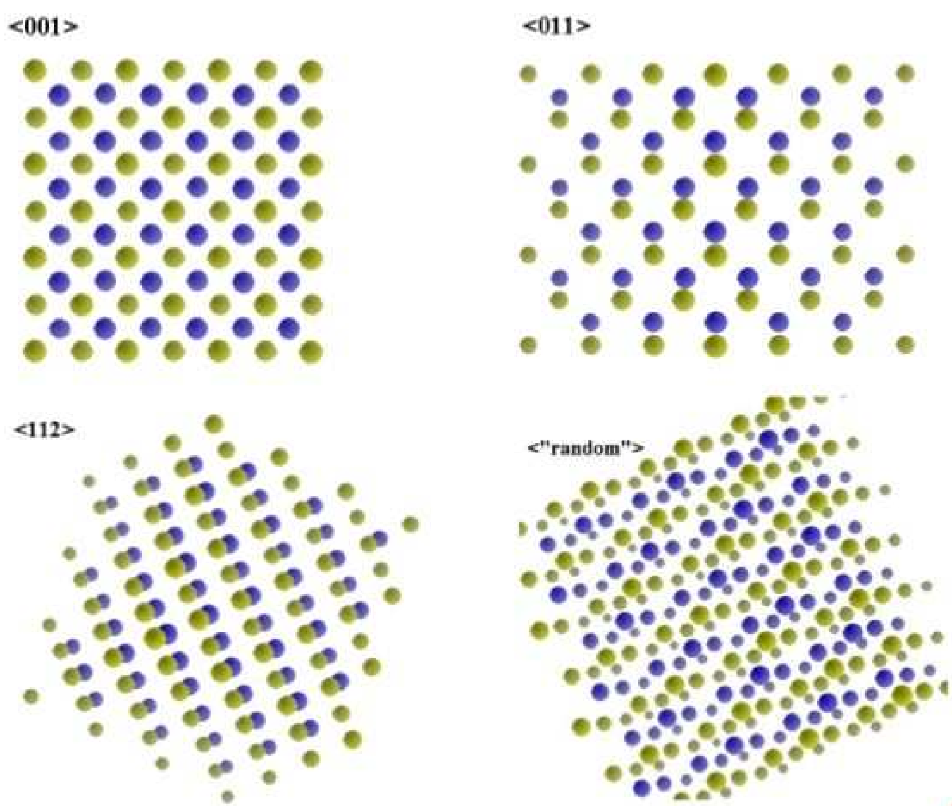
- The channeling of recoiling lattice ions and incident ions is different. The effect of blocking is important to understand the channeling of recoil nuclei: the channeled fraction of recoils is smaller and it is strongly temperature dependent (so it is negligible at mK).

- Channeling in crystaline detectors can lead to a daily modulation of a WIMP signal, a DM signature without any background (Avignone, Creswell & Nussinov 2008) (with small amplitudes- but larger for halo components with small velocity dispersion)

- 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).

Advances in Ion Implantation Modeling for Doping of Semiconductors

Different Orientation of Silicon Crystal Structure



Classification of Simulation Models

Molecular Dynamics

Classical MD: many, more recent studies by *T.Diaz de la Rubia et al.* *on defects in silicon*

Recoil approximation MD: many, for example the REED program by *Beardmore & Jensen* for ion implantation, *Hobler & Betz's*, etc.

Binary Collision Approximation

BC(Binary Collision) programs: the location of target atoms are determined by well-defined crystal structure. Stochastic methods play only an auxiliary role, supplying, for example, initial ion positions and directions, thermal vibrations, chemical disorder, etc. Typical programs are:
MARLOWE, UT-MARLOWE, CRYSTAL in Silvaco's process simulator, etc.

MC(Monte-Carlo) codes: stochastic methods are used to locate the target atoms or to determine the impact parameters, flight distances, scattering angles, etc. The best known code is the TRIM(SRIM).