Directional Modulation in Crystalline Detectors

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Based on work in progress with Graciela Gelmini and Nassim Bozorgnia

Summary

- Channeling in crystalline detectors can lead to a daily modulation in the recoil spectrum
  (Avignone, Creswell, Nussinov 2008)

- We set out to do a careful calculation, and in the process understand channeling and blocking for dark matter detection

- We find much smaller modulation amplitudes (<1% vs their ~25%)

- Our results are preliminary and our work is in progress

Channeling (and blocking) in crystals

Channeling

Blocking

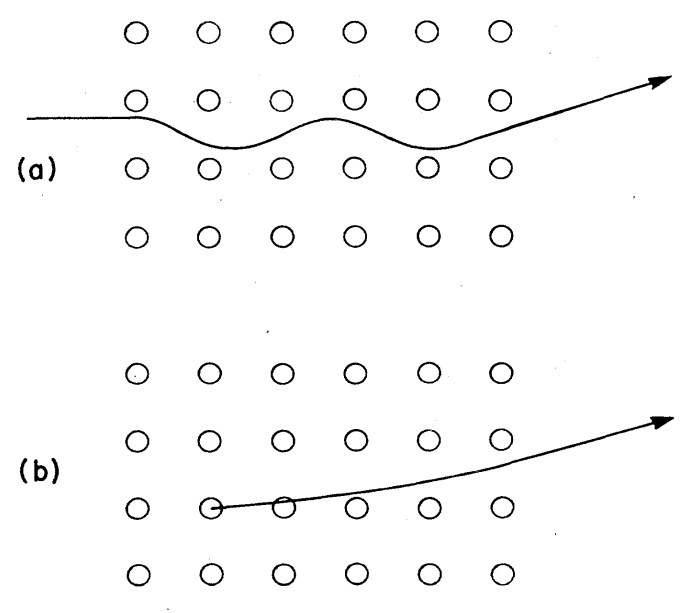

FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

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

Channeling (and blocking) in crystals

- Channeling and blocking in crystals is used in
  - studies of lattice disorder
  - ion implantation
  - to locate dopant and impurity atoms
  - studies of surfaces and epitaxial layers
  - crystallography
  - measurement of nuclear lifetimes
  - production of polarized beams
  - etc.

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)

Observation of channeling in NaI(Tl)

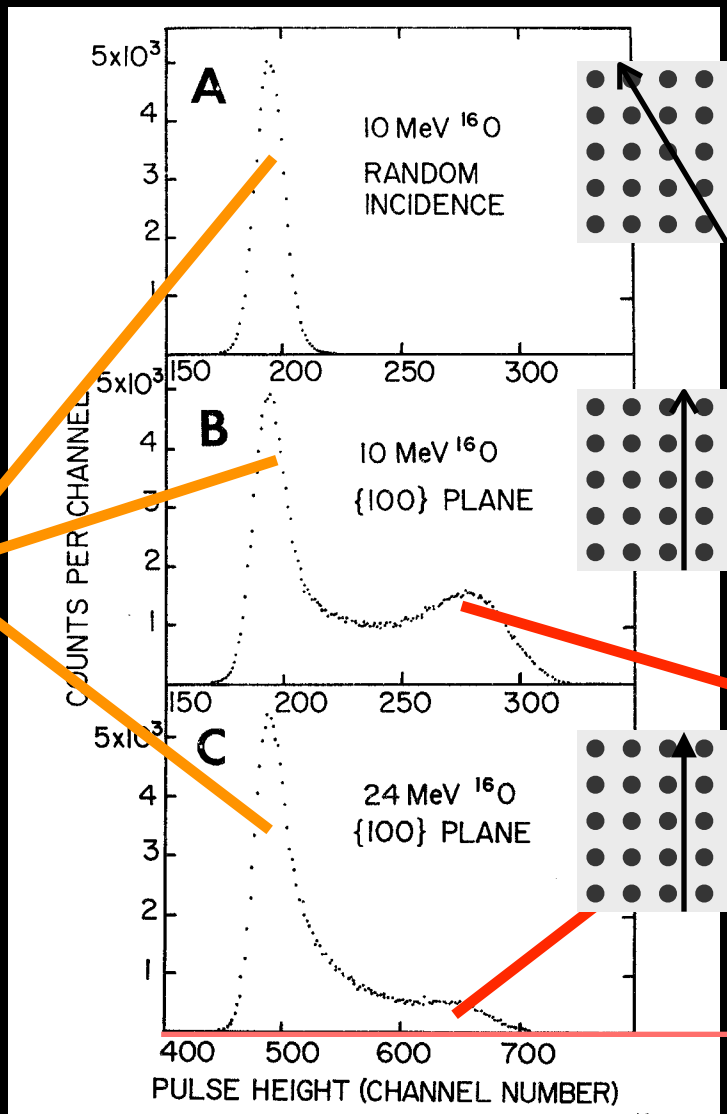

FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

Not channeled

Channeled

Scintillation output

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

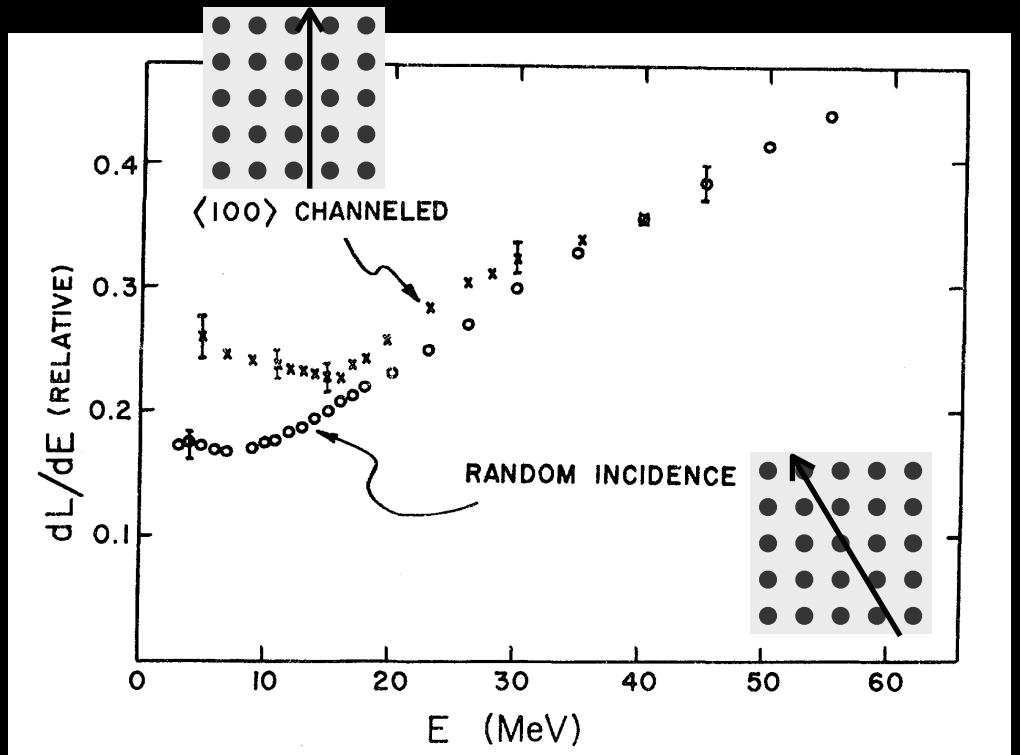

FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

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

Basic idea for directional modulation

Avignone, Creswick, Nussinov 2008 (arxiv:0807.3758)

- The WIMP wind comes preferentially from one direction
- When that direction is aligned with a channel, the scintillation output is larger (Q=1 instead of <1)
- The rotation of the Earth 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)*
- Thus a modulation in the "measured" recoil spectrum

Our work

- Avignone et al claim a modulation amplitude of ~25%, but it is 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 are preliminary and our work is in progress

What we need

(1) Angular distribution of recoil directions due to WIMPs

(2) Fraction of recoils that are channeled as a function of recoil energy and recoil direction

(3) Combine (1) and (2) and compute directional modulation

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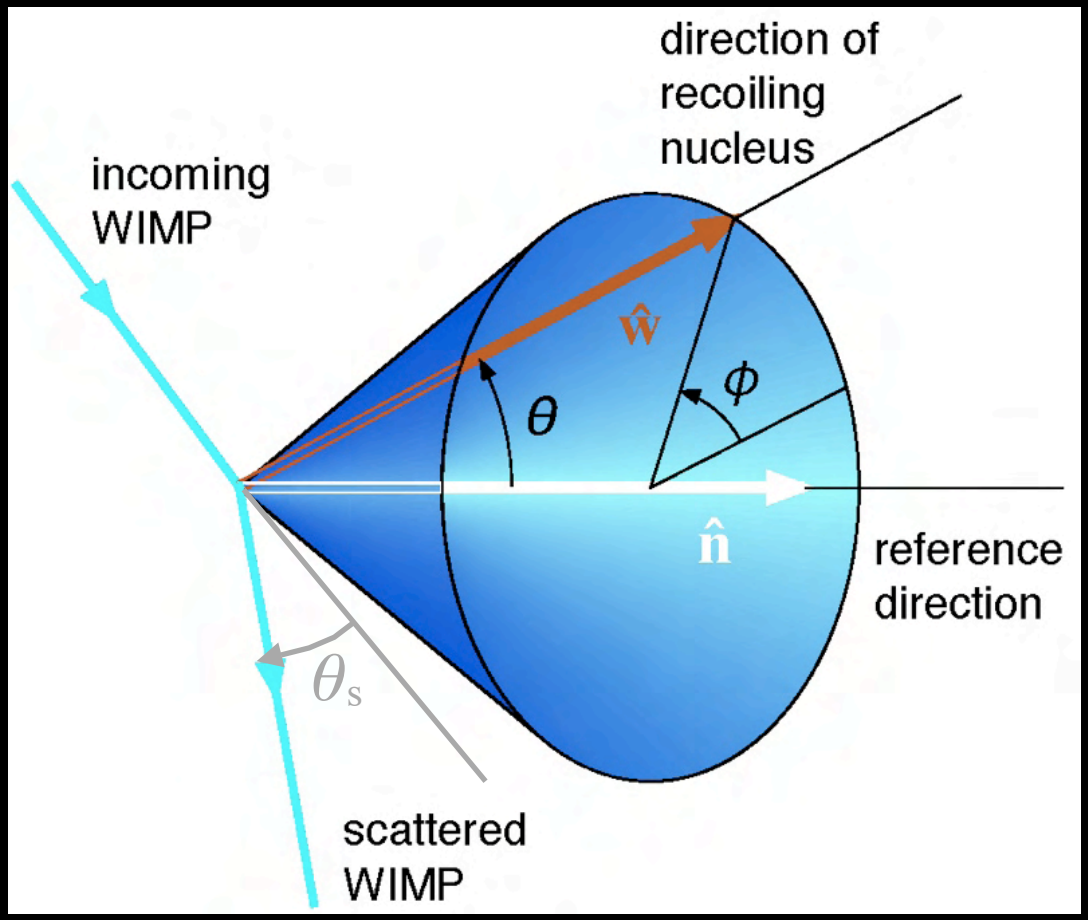
Angular distribution of recoil directions

3D directional rate

(in events/kg-day-keV-sr)

$$\frac{\mathrm{d}R}{\mathrm{d}E\mathrm{d}\Omega}$$



θ is not the scattering angle θ_s

$$\mathrm{d}\Omega = \sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

Angular distribution of recoil directions

- Non-directional recoil rate (in events/kg-day)

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \int \frac{\mathrm{d}R}{\mathrm{d}E\mathrm{d}\Omega}\,\mathrm{d}\Omega = \frac{\sigma(q)}{2m\mu^2}\,\rho\,\eta(q,t)$$

Astrophysical factor

$$\rho\,\eta(q,t) = \rho \int_{v>\frac{q}{2\mu}} \frac{f(\vec{v},t)}{v}\,\mathrm{d}^3v$$

Scattering cross section

$$\sigma(q) = \sigma_{\mathrm{SI}}(q) + \sigma_{\mathrm{SD}}(q)$$

Angular distribution of recoil directions

- Directional recoil rate (in events/kg-day)

$$\frac{\mathrm{d}R}{\mathrm{d}\cos\theta} = \int \frac{\mathrm{d}R}{\mathrm{d}E\mathrm{d}\Omega}\,\mathrm{d}\phi\,\mathrm{d}E$$

Angular distribution of recoil directions

- 3D directional recoil rate (in events/kg-day-keV-sr)

$$\frac{\mathrm{d}R}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\rho\sigma(E)}{4\pi m\mu^2}\,\hat{f}\left(\tfrac{q}{2\mu}, \hat{\mathbf{q}}\right)$$

$\hat{f}(w, \hat{\mathbf{w}})$ is the Radon transform of the velocity distribution function $f(\mathbf{v})$

$$\hat{f}\left(\frac{q}{2\mu}, \hat{\mathbf{q}}\right) = \int f(\mathbf{v})\;\delta\left(\frac{q}{2\mu} - \hat{\mathbf{q}}\cdot\mathbf{v}\right)\,d^3v$$

Gondolo 2002 (Phys.Rev. D66, 103513)

Radon transform

Energy-momentum conservation imposes $q = 2\mu v \cos\theta$

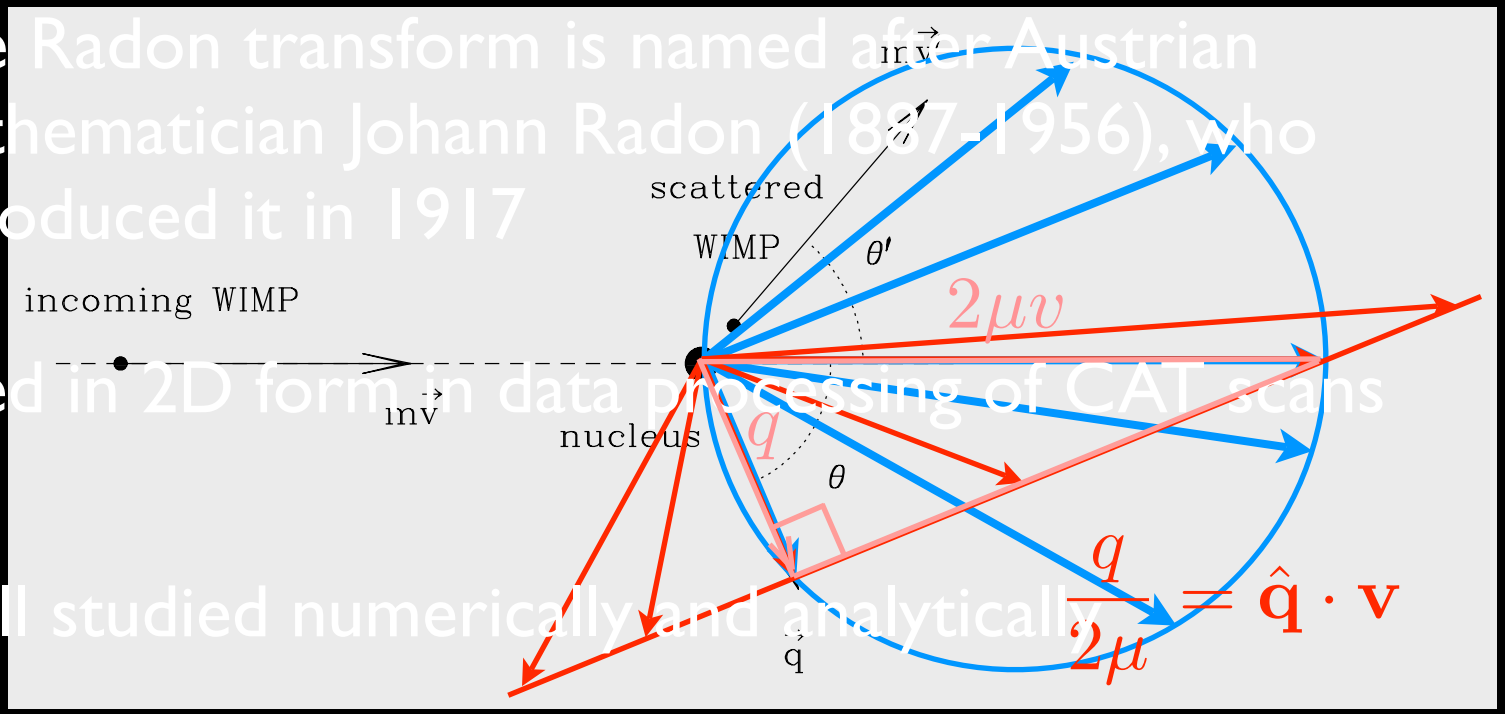
Events with the same q lies on the same plane

where $\mu = m M/(m+M)$ is the reduced mass

The Radon transform is named after Austrian mathematician Johann Radon (1887-1956), who introduced it in 1917

Used in 2D form in data processing of CAT scans

Well studied numerically and analytically



Gondolo 2002 (Phys.Rev. D66, 103513)

Radon transform: Maxwellian distribution

$$f(\mathbf{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{|\mathbf{v}-\mathbf{V}|^2}{2\sigma_v^2}\right)$$

$$\hat{f}(w, \hat{\mathbf{q}}) = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp\left(-\frac{(w-\hat{\mathbf{q}}\cdot\mathbf{V})^2}{2\sigma_v^2}\right)$$

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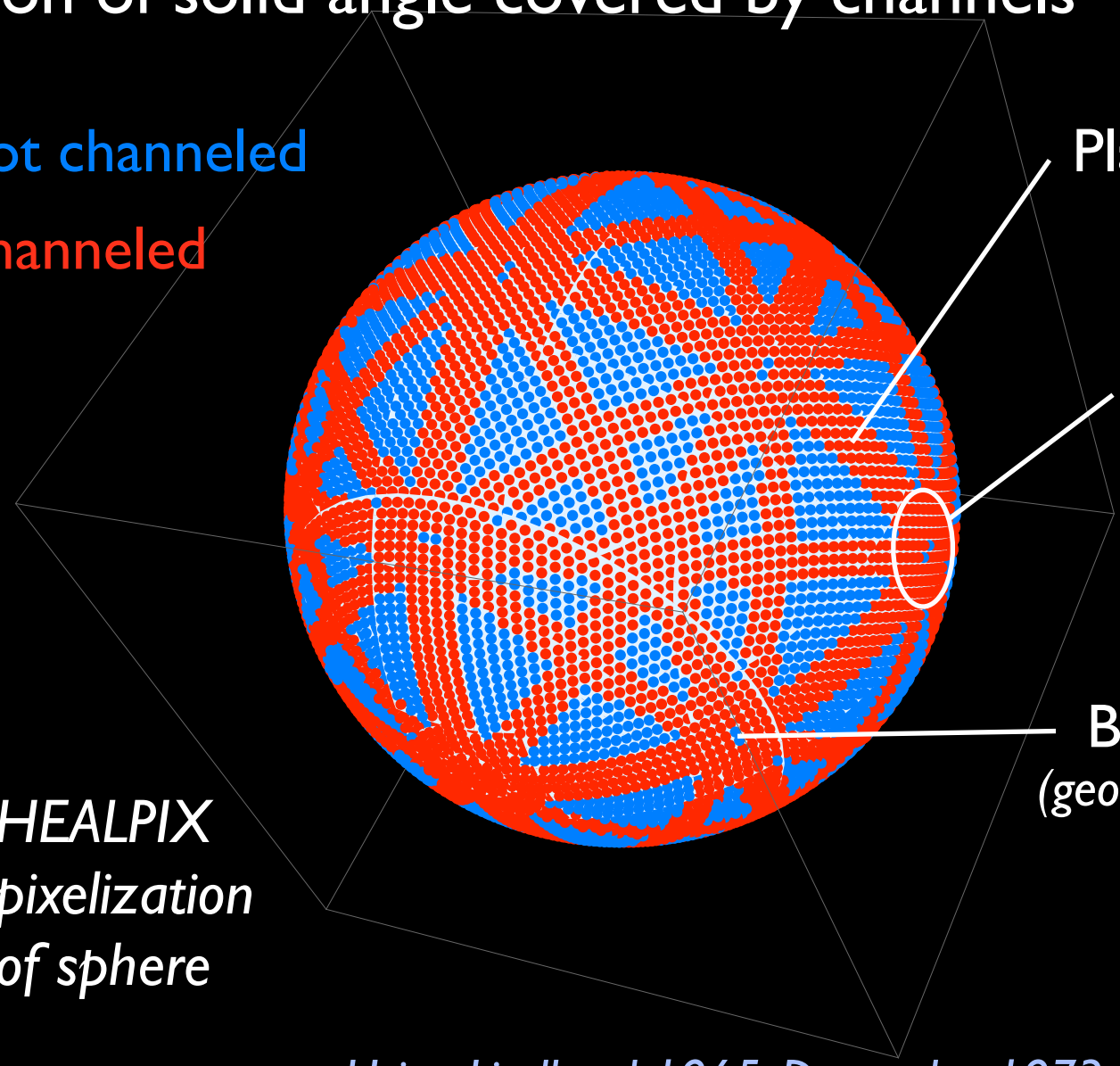
Fraction of channeled recoils

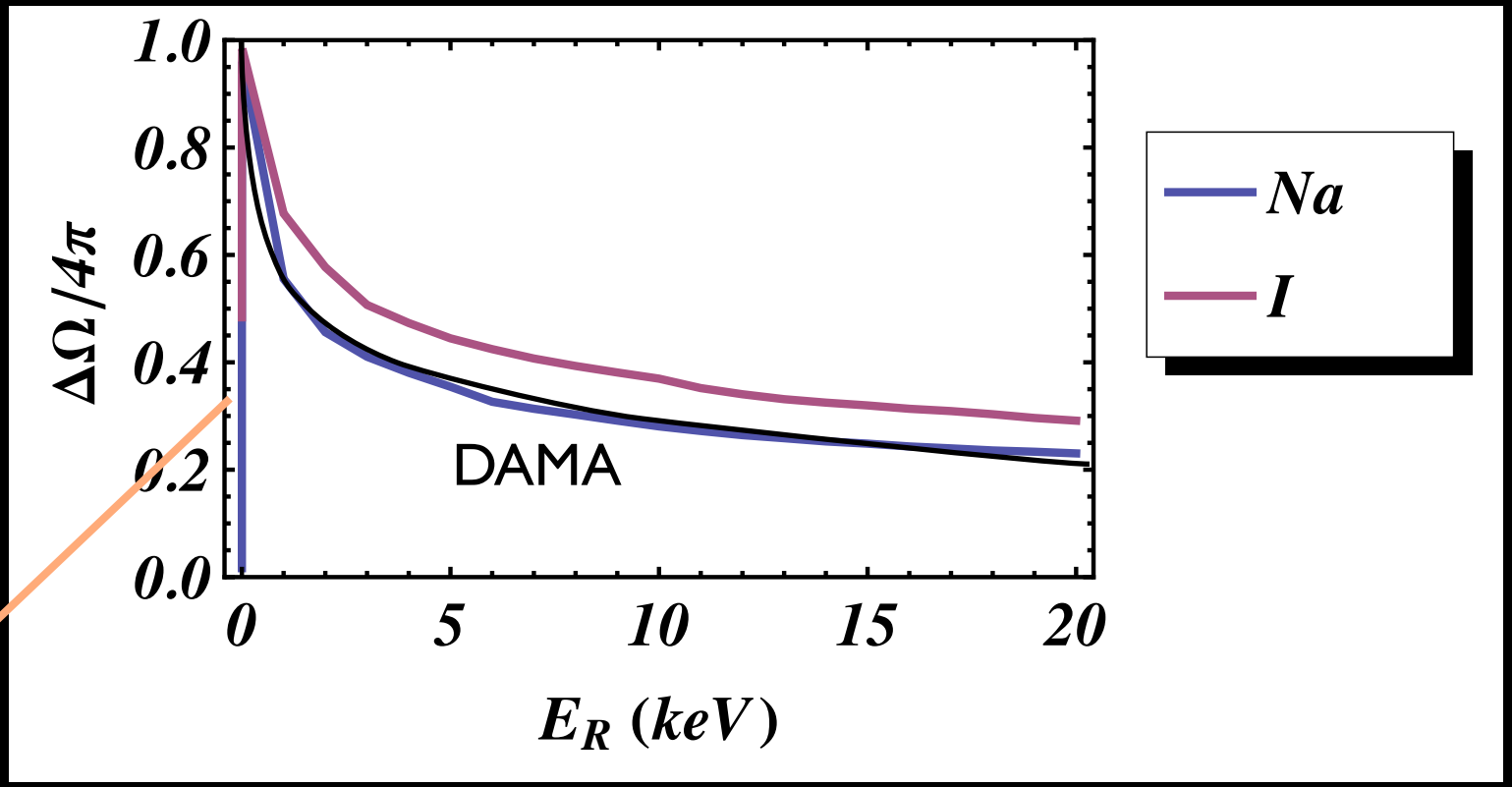
Fraction of solid angle covered by channels



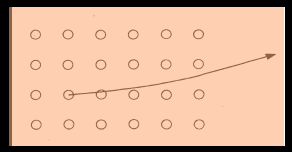
Using Lindhard 1965, Dearnaley 1973, Appleton & Foti 1977

Fraction of channeled recoils

Fraction of solid angle covered by channels



Effect of blocking



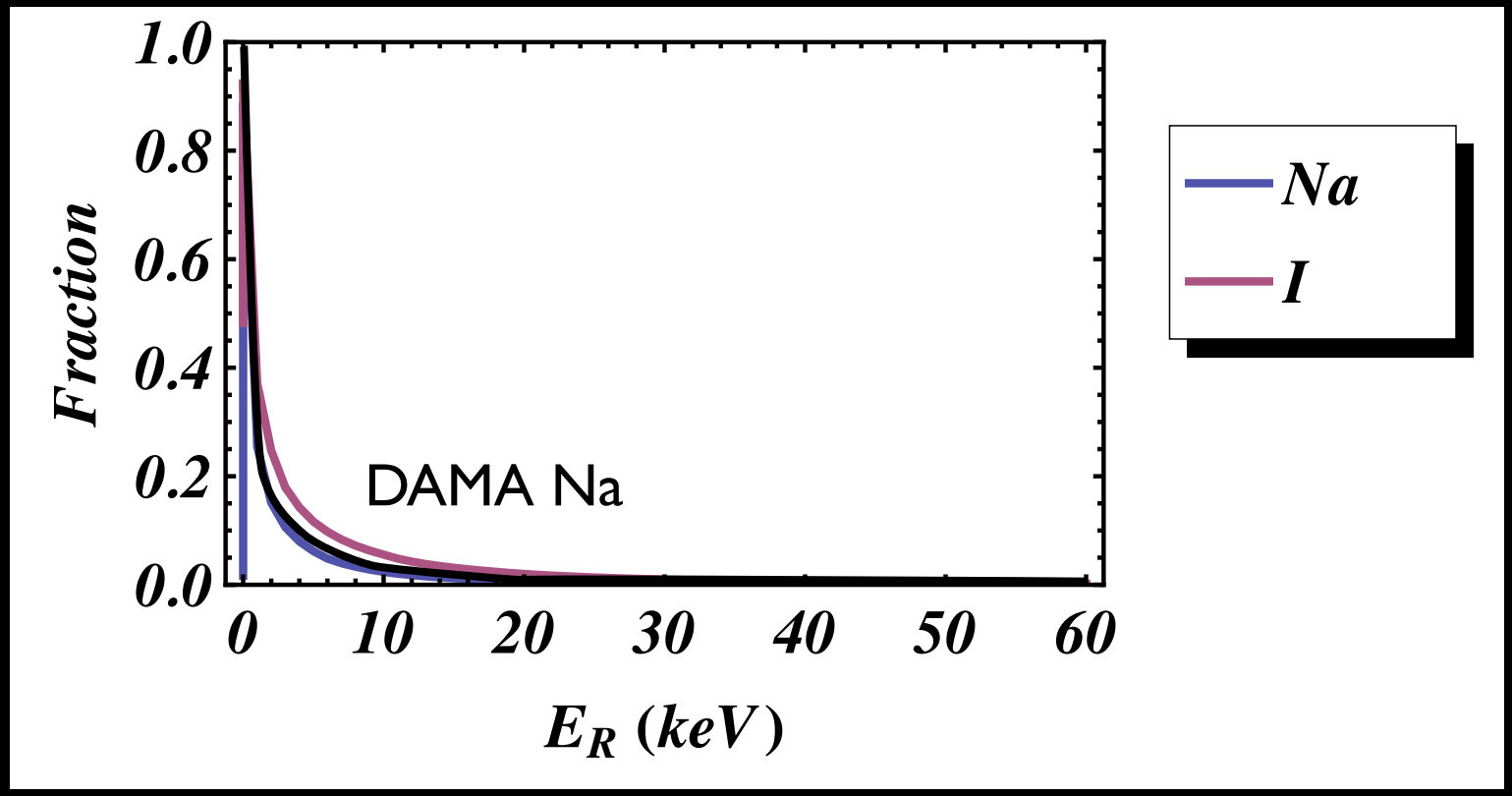
(using a geometrical cross section)

Bernabei et al. (DAMA) arxiv:0710.0288

Fraction of channeled recoils

Effect of dechanneling

Scattering off thallium can remove recoiling nuclei from channels



(using first scattering only)

Bernabei et al. (DAMA) arxiv:0710.0288

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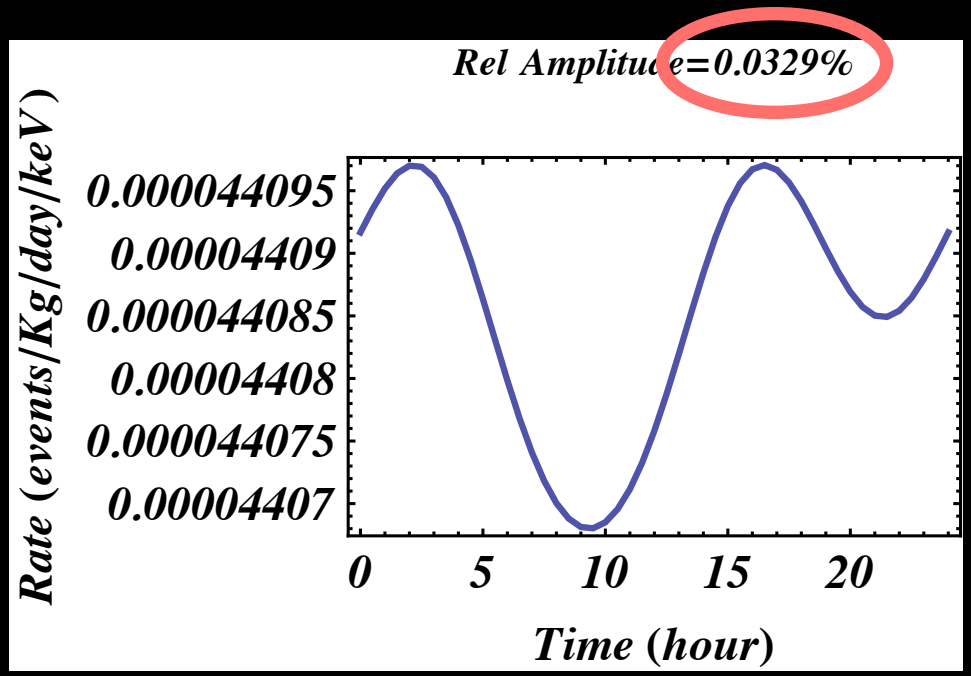
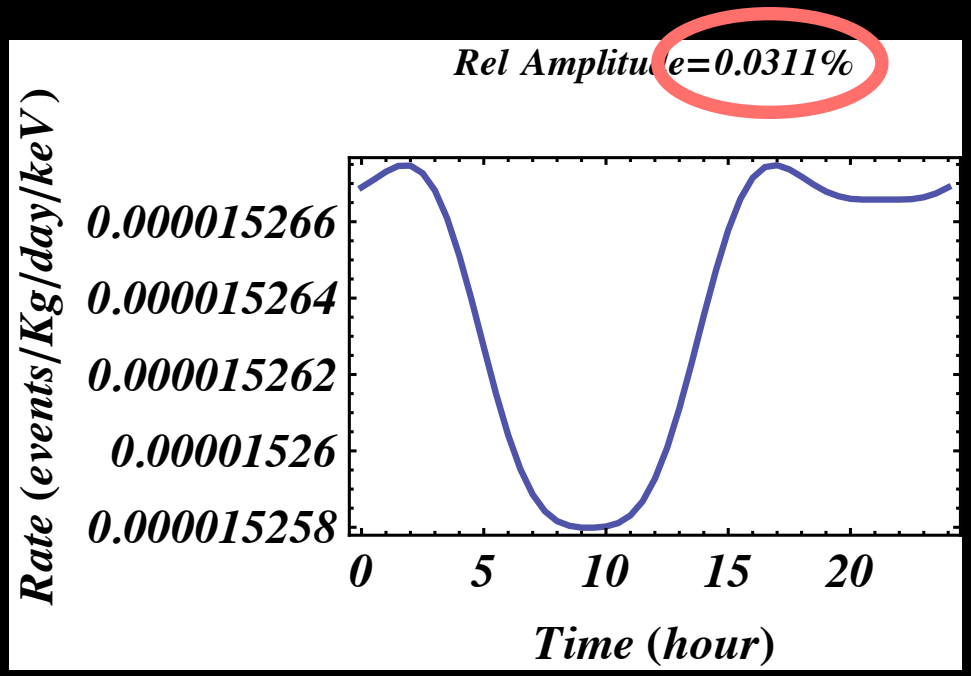
Directional modulation

Two examples

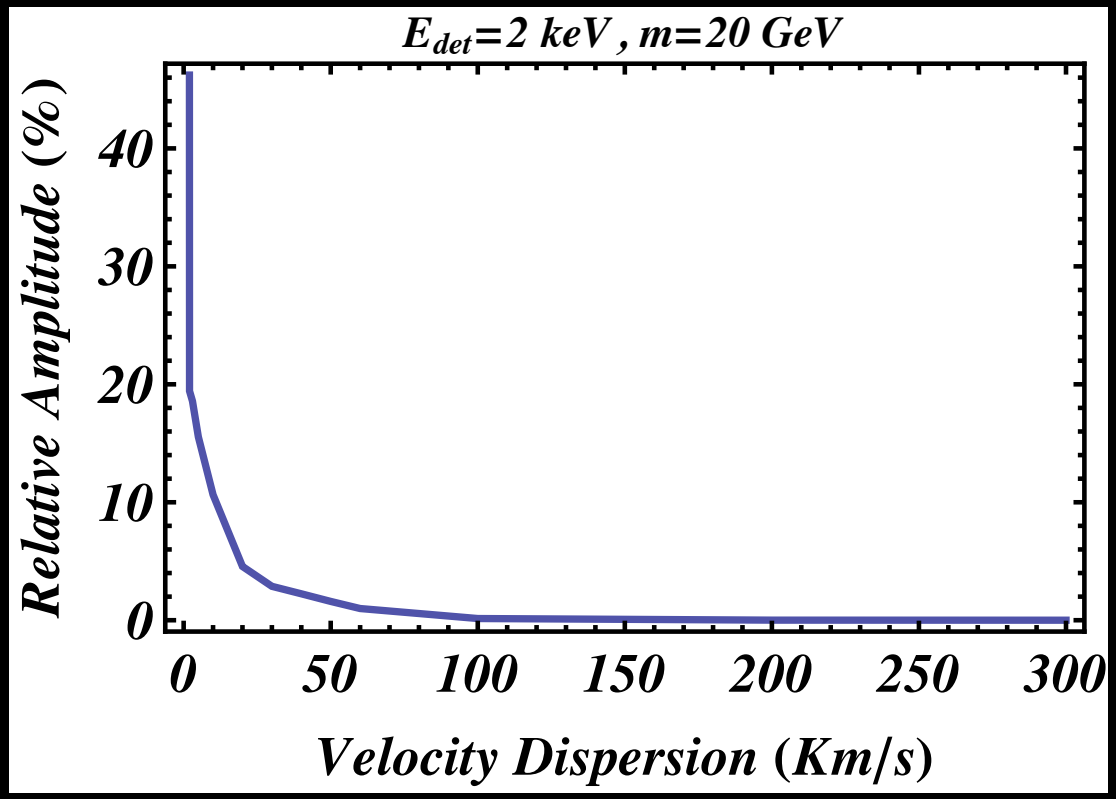




Our modulation amplitudes are much smaller than the ~25% in Avignone et al

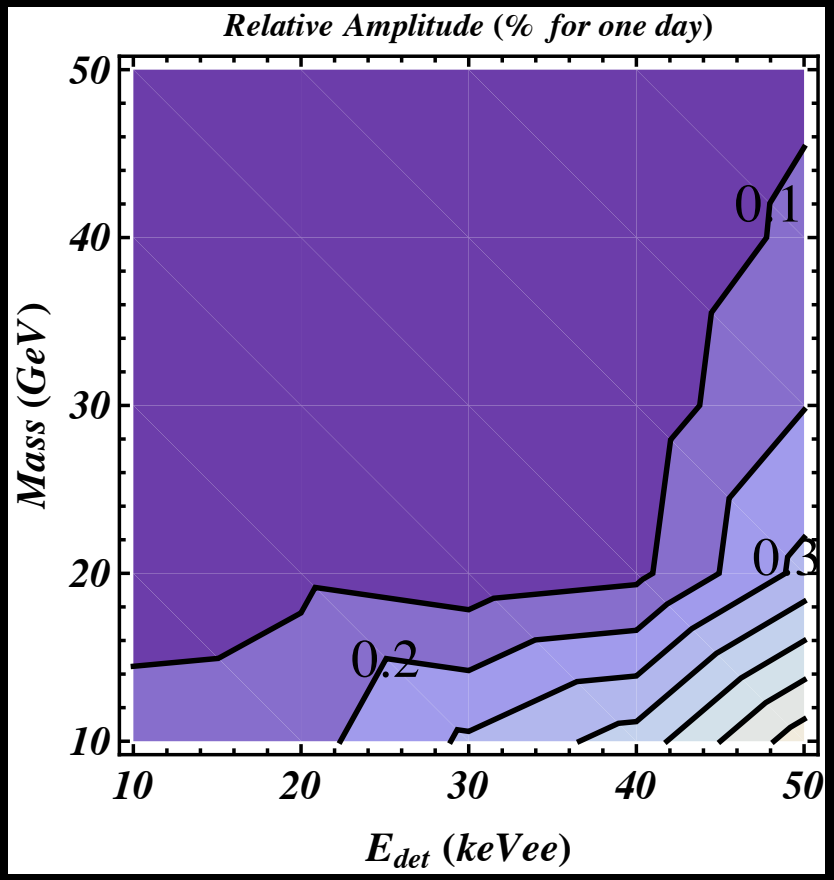
Directional modulation

The much smaller amplitudes seem to derive from the velocity dispersion

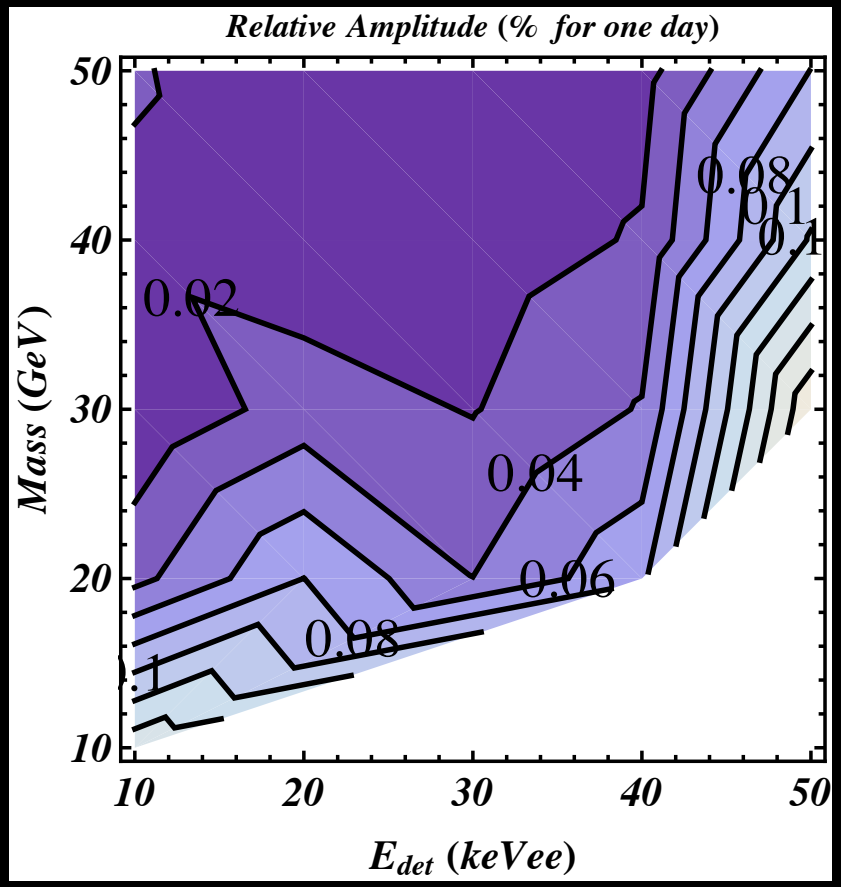


Directional modulation

Modulation is tiny, less than one percent



Maxwellian



Maxwellian truncated at v_{esc}

Conclusions

Preliminary

- Channeling in crystalline detectors can lead to a daily modulation in the recoil spectrum
  (Avignone, Creswell, Nussinov 2008)
- Bozorgnia, Gelmini, and I have been improving their simple estimates, with the secondary intent of understanding channeling and blocking in dark matter detectors
- We find much smaller modulation amplitudes (<1% vs their ~25%)
- We are still incorporating dechanneling and a better treatment of blocking