Optimising directional detectors

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How important are:

- 3-d v. 2d read-out?
- recoil sense measurement?
- energy threshold?
- background rate?

Based on: Green & Morgan *'Consequences of statistical sense determination for WIMP directional detection'*, PRD '08, arXiv:0711.2234

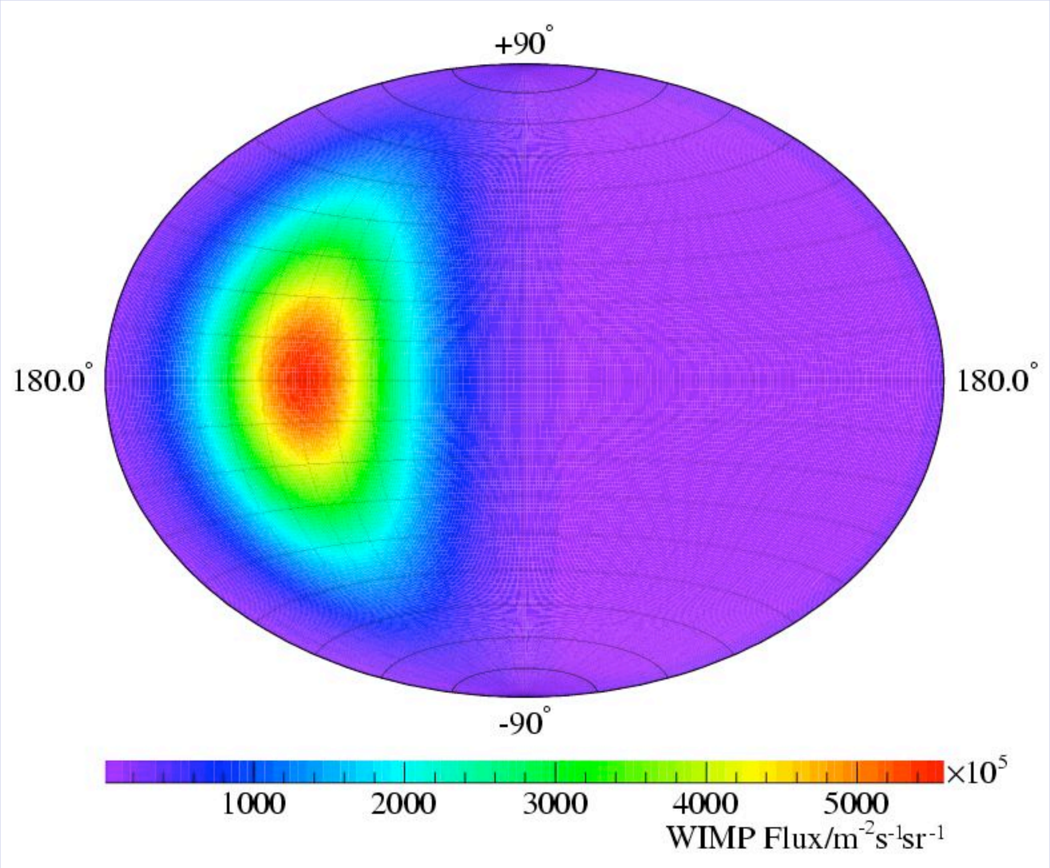
Green & Morgan, *'Optimizing WIMP directional detectors'*, Astropart. Phys '07, astro-ph/0609115

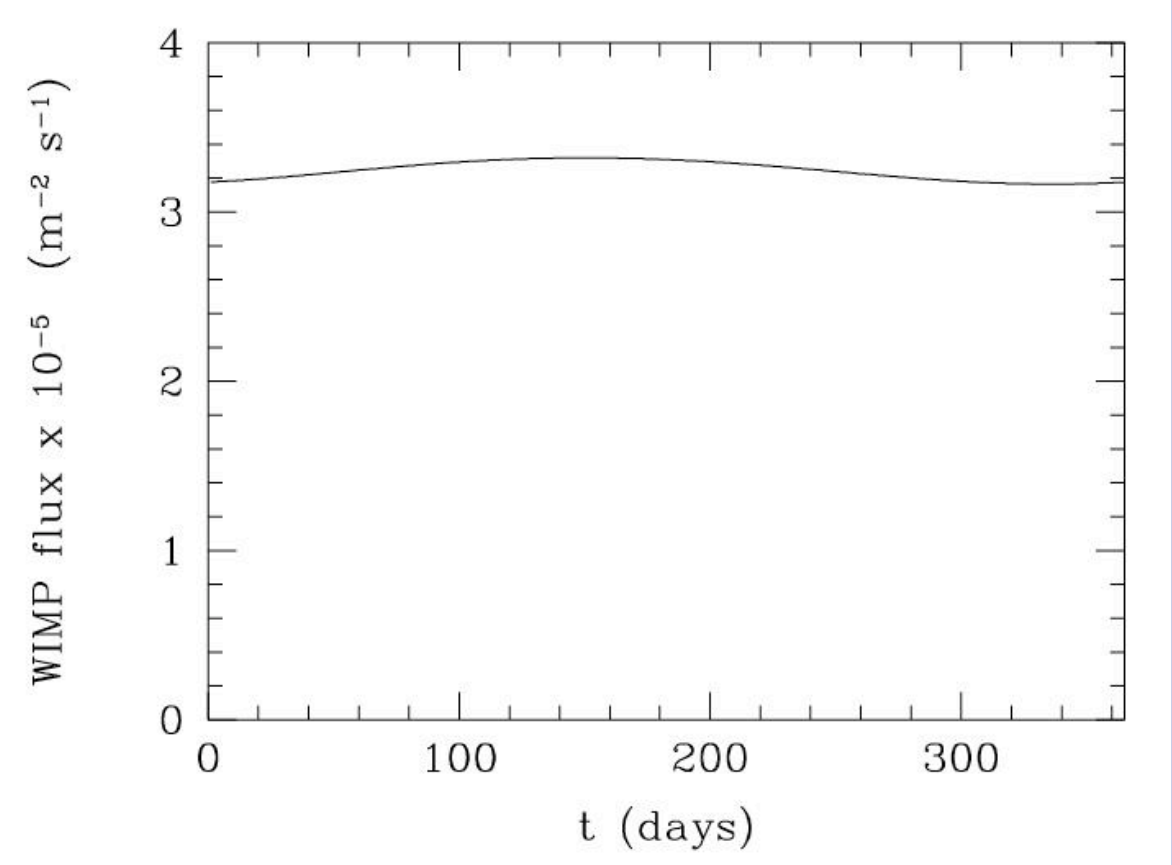
See also: Morgan & Green, *'Directional statistics for WIMP direct detection II: 2-d read out'*, PRD '06 ,astro-ph/0508134

Morgan, Green & Spooner, *'Directional statistics for realistic WIMP direct detection experiments'*, PRD '05, astro-ph/0408047

Direction dependence v. annual modulation

Directional signal far larger than annual modulation.





Hard for a background to mimic the directional signal.
(anisotropic backgrounds in lab are isotropic in Galactic rest-frame)

A WIMP directional signal could ***(in principle)*** be detected with of order 10 events [Copi, Heo & Krauss; Copi & Krauss; Lehner et al.].

How many events are likely to be required in practice?

(and how does this depend on the detector capabilities?)

[Morgan, Green & Spooner; Morgan & Green; Copi, Krauss, Simmons-Duffin & Stroiney; Green & Morgan]

Detector capabilities:

- 2d or 3d read-out
- Can the sense (+**x** or -**x**) of the nuclear recoils be measured?
- Energy threshold
- Angular resolution
- Background rate

Which of these properties has the biggest effect on the exposure required to detect a WIMP signal?

Where should experiments focus their efforts to maximise their discovery potential?

Caveats: Real detectors are more complicated than our simulated detector.....
Pure theoretical analysis (no consideration of practicalities or costs (financial and time)....).

WIMP distribution

Assume the simplest possible model for the Milky Way halo:

standard halo model, isothermal sphere with Maxwellian (gaussian) velocity distribution

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standard halo model, isothermal sphere with Maxwellian (gaussian) velocity distribution

Simulations now have the resolution to probe the dark matter velocity distribution on kpc^3 scales at the solar radius.

Find deviations from gaussian distribution:
[Vogelsberger et al. using Aquarius simulations]

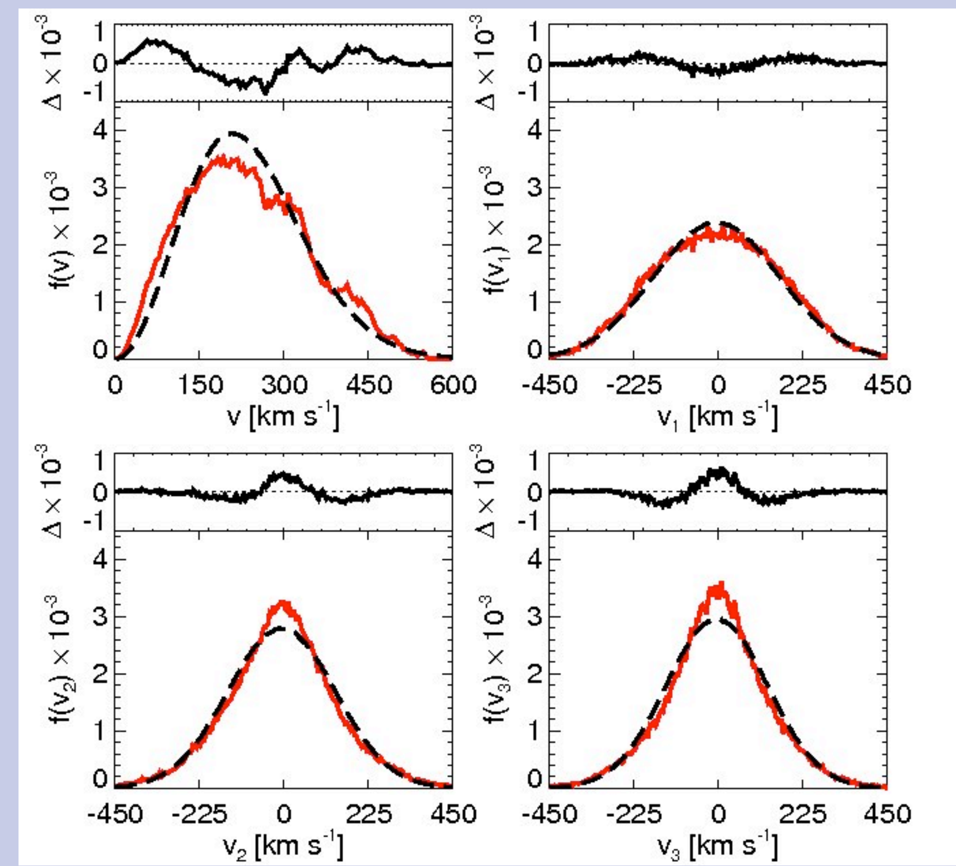
All halos have similar form for f(v):

compared with multi-variate Gaussian
more low v particles, peak suppressed

features (bumps and dips) at high v

High v features reflect merger history of halo:

appear in different places for different halos, but are similar for different regions within a given halo. [n.b. not streams, too broad]



Speed distribution (top left) + distribution of principle components
[red lines: simulation data,
black lines: best fit multi-variate Gaussian]

Hansen et al. & Fairbairn et al. have found similar results.

Deviations from multi-variate gaussian distribution relatively small, therefore standard halo model probably not an unreasonable assumption for sensitivity estimates.

BUT:

i) What about baryons?

These simulations are dark matter only (baryonic physics hard to simulate, but baryons dominate in the inner regions of the Milky Way).

[Read et al. dark matter disc?]

ii) Is the dark matter distribution on the ultra-local (milli-pc) scales probed by direct detection experiments the same as on the kpc scales probed by simulations?

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Bottom line: Provided the ultra-local WIMP distribution has a smooth component the number of events required to detect directionality probably only varies by of order ~10%.

With a large number of events could probe the ultra-local WIMP velocity distribution and do 'WIMP astronomy'. [Copi & Krauss; Morgan, Green & Spooner; Host & Hansen talk by Afshordi later today]

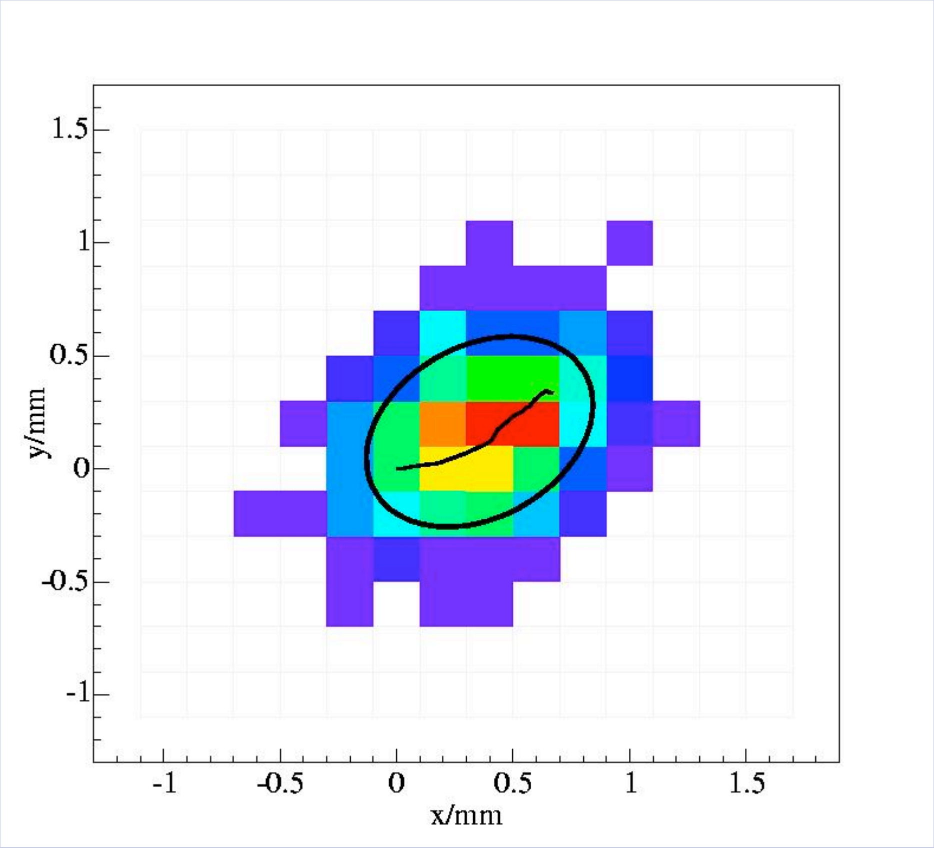
Detector simulations

[see Morgan, Green & Spooner for further details]

Use SRIM2003 to simulate nuclear recoils in a Time Projection Chamber based detector filled with Carbon Sulfide, with a 10cm drift length over which a uniform drift field of 1 kV/cm is applied with 200 μm 3-d pixel read-out. [c.f. DRIFT I/II design]

Recoil direction reconstruction limited by:
- multiple scattering of recoiling nucleus
- (small) diffusion of drifted ionisation

Use moment analysis to reconstruct recoil direction from pixel charge distribution.
(dist. of difference between primary recoil dir & reconstructed dir peaks at 15°, decreasing weakly with increasing E).



We assume
- i) senses of recoils (+**x** or -**x**) can be measured on an event by event basis (vectorial data).
- ii) no sense measurement (axial data).
- iii) senses measured statistically

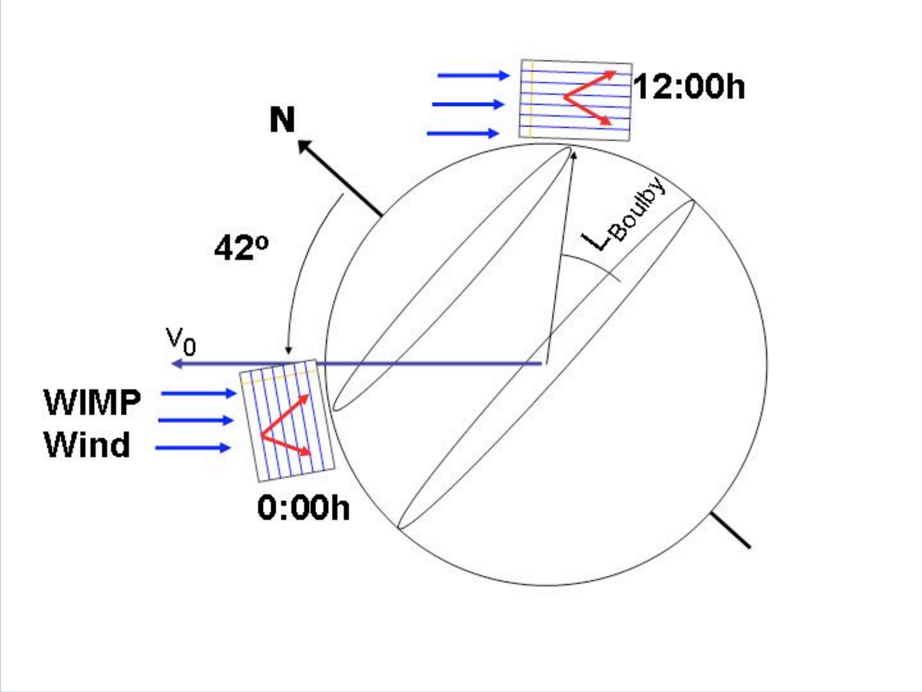
Below 20 keV tracks too short (<3-4 pixels) to reconstruct direction. (n.b. direction reconstruction threshold > recoil detection threshold and ≠ background discrimination threshold).

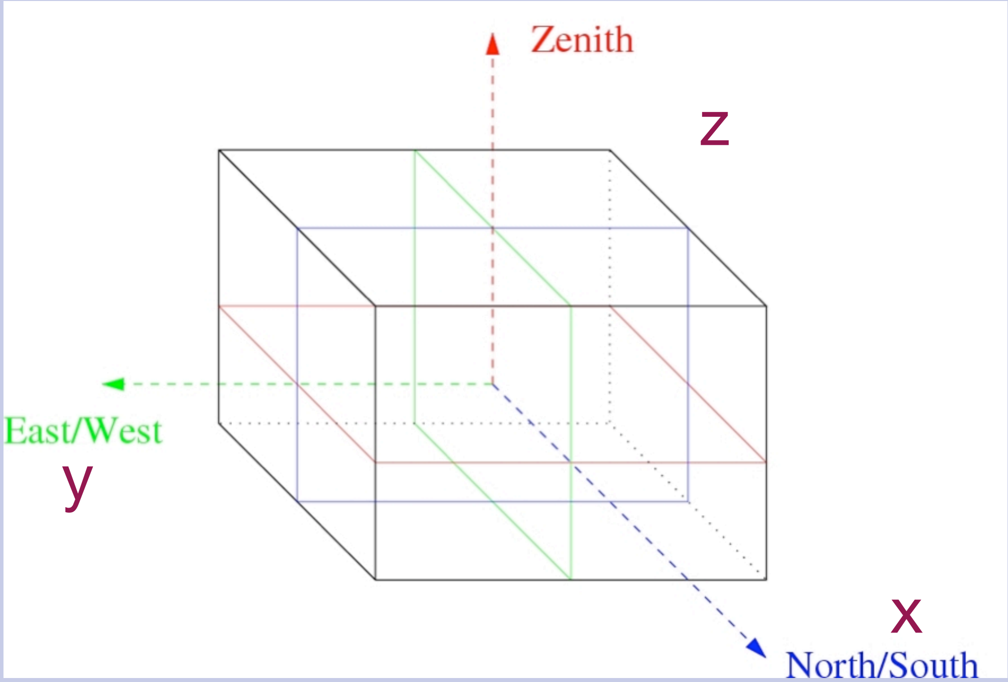
2-d read-out

[Morgan & Green; Copi, Krauss, Simmons-Duffin & Stroiney]

If only 2-d read-out is possible, output is angles (relative to some arbitrary direction) of recoil vectors projected into read-out plane.

The anisotropy of the 2-d angle distribution (and hence the detectability of a WIMP signal) depends on the orientation of the read-out plane.





Anisotropy is maximised if normal to read-out plane is perpendicular to spin axis of Earth. This is the case for the x-z plane.

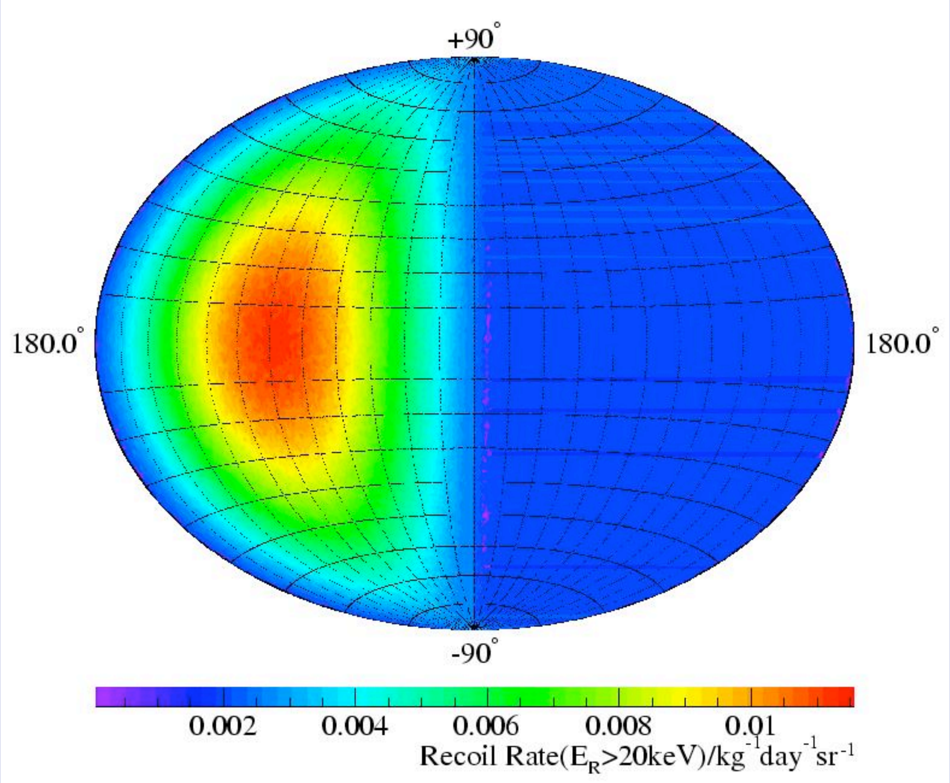
For other (non-optimal) read-out planes anisotropy depends on detector location.

n.b. In this case we assume perfect recoil reconstruction. Angular resolution of 2-d detector is non-trivial; because of projection it will be a function of energy and direction.

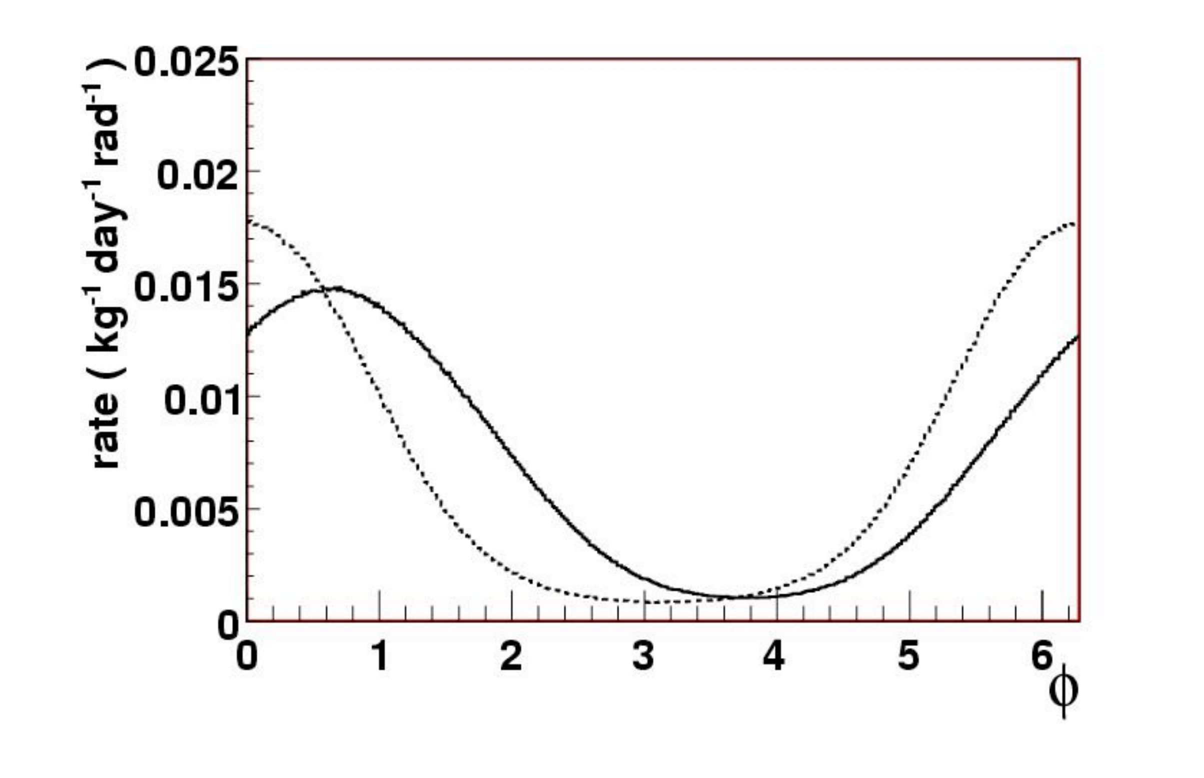
Recoil angle distributions

baseline configuration: 3-d vector read-out,
20 keV threshold,
zero background,
recoil reconstruction uncertainty taken into account

Assuming: $\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}},\ m_\chi = 100\,\mathrm{GeV}$



3-d



2-d (optimal read-out plane)

________ raw angles

.... reduced angles (projected direction of solar motion subtracted)

Statistical analysis

[see Morgan, Green & Spooner and Morgan & Green for further details]

Use non-parametric spherical (3-d) and circular (2-d) statistics commonly used in geology and biology.
No assumptions needed about WIMP distribution.

For 3-d read-out most powerful statistic is mean cosine of the angle between the recoil and direction of solar motion.

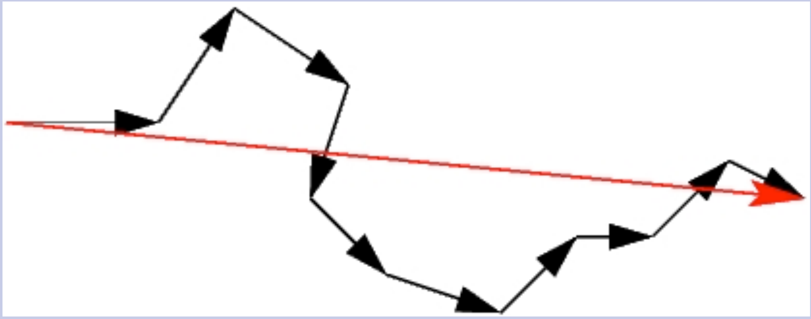
$$\langle \cos\theta \rangle = \frac{\Sigma_{i=1}^{N} \cos\theta_{\rm i}}{N}$$

vectorial data

$$\langle |\cos\theta| \rangle = \frac{\Sigma_{i=1}^{N} |\cos\theta_{\rm i}|}{N}$$

axial data

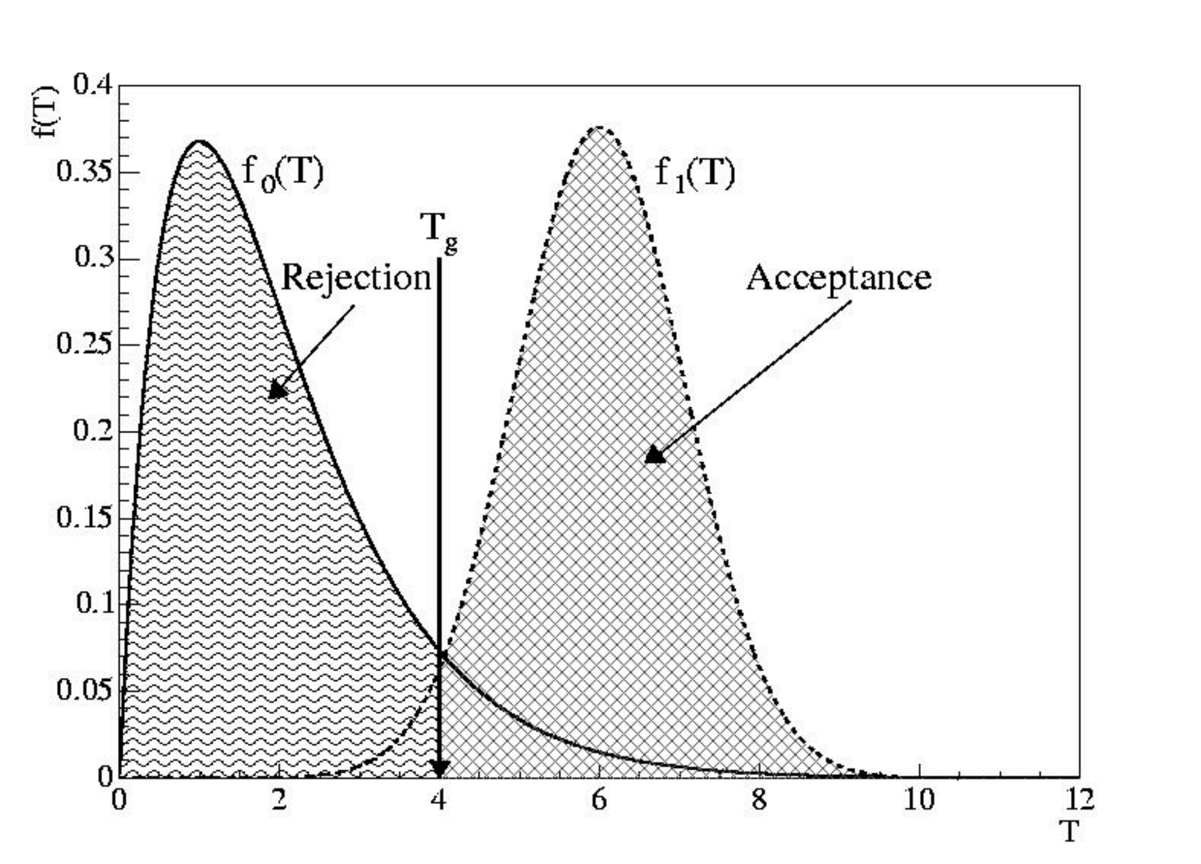
For 2-d read-out it's the Rayleigh statistic which parameterizes the deviation of mean resultant direction from zero.



Procedure for calculating number of events required to detect a WIMP signal:

For given number of events generate the statistic distributions for the null (isotropic recoils) and alternative (WIMP recoils) hypotheses.

Calculate the acceptance, A (prob of measuring larger value if the alternative hypothesis is true), and rejection, R (prob of measuring a smaller value if the null hypothesis is true), factors.



Find the number of events for which A=R=0.9 (0.95).
i.e. 90% (95%) confidence detection in 90% (95%) of experiments

Results

Dependence of number of events required to reject isotropy (*and detect a WIMP signal*) at 90 (95)% confidence in 90 (95)% of experiments, N_{90} (N_{95}), on detector capabilities.

difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_T = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_T = 50$ keV	5	7
$E_T = 100$ keV	3	5
$S/N = 10$	8	14
$S/N = 1$	17	27
$S/N = 0.1$	99	170
3-d axial read-out	81	130
2-d vector read-out in optimal plane, raw angles	18	26
2-d axial read-out in optimal plane, raw angles	1100	1600
2-d vector read-out in optimal plane, reduced angles	12	18
2-d axial read-out in optimal plane, reduced angles	190	270

upgraded and unrealistic

assuming perfect angular resolution

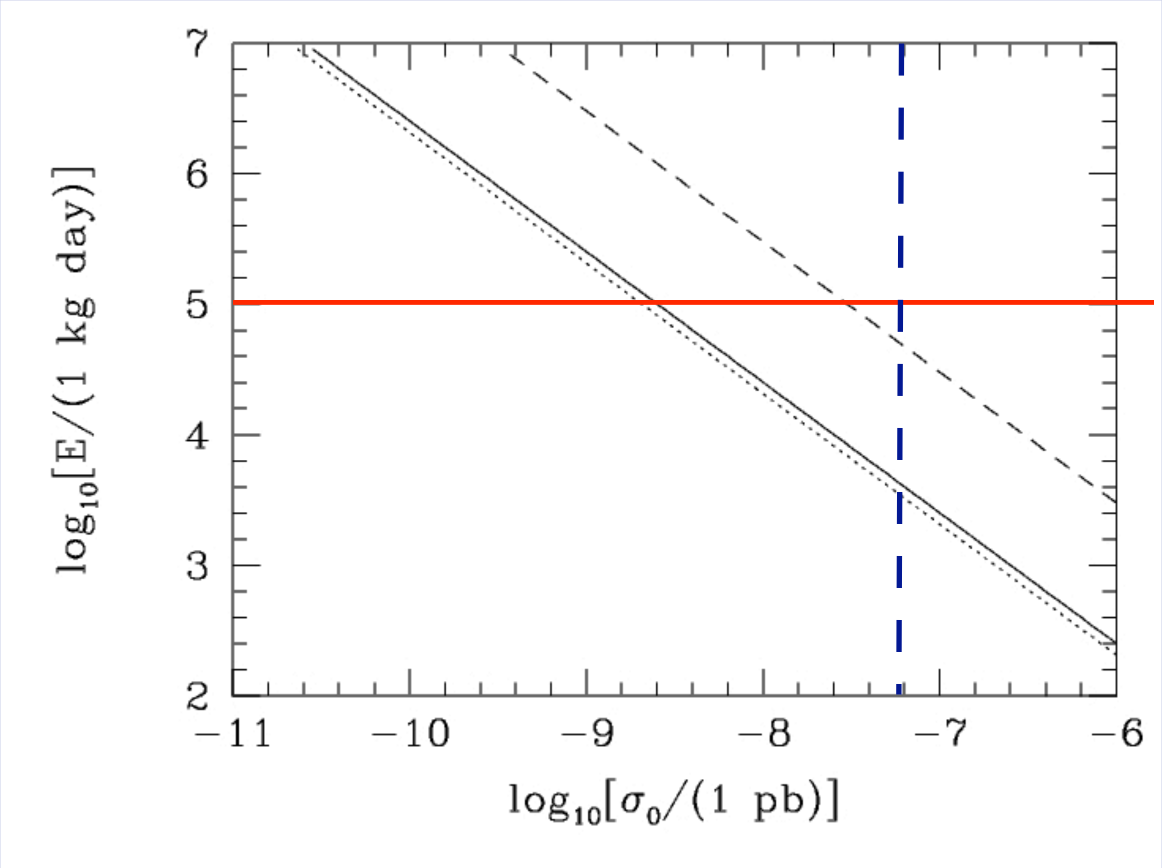
baseline configuration: 3-d vector read-out,
20 keV threshold,
zero background,
recoil reconstruction uncertainty taken into account

Measurability of senses

Exposure required to detect a WIMP signal at 95% confidence in 95% of experiments as a function of WIMP-nucleon scattering cross-section.

Assuming throughout: $\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}},\ m_\chi = 100\,\mathrm{GeV}$

current limits from CDMS, Zenon10, ZEPLIN III



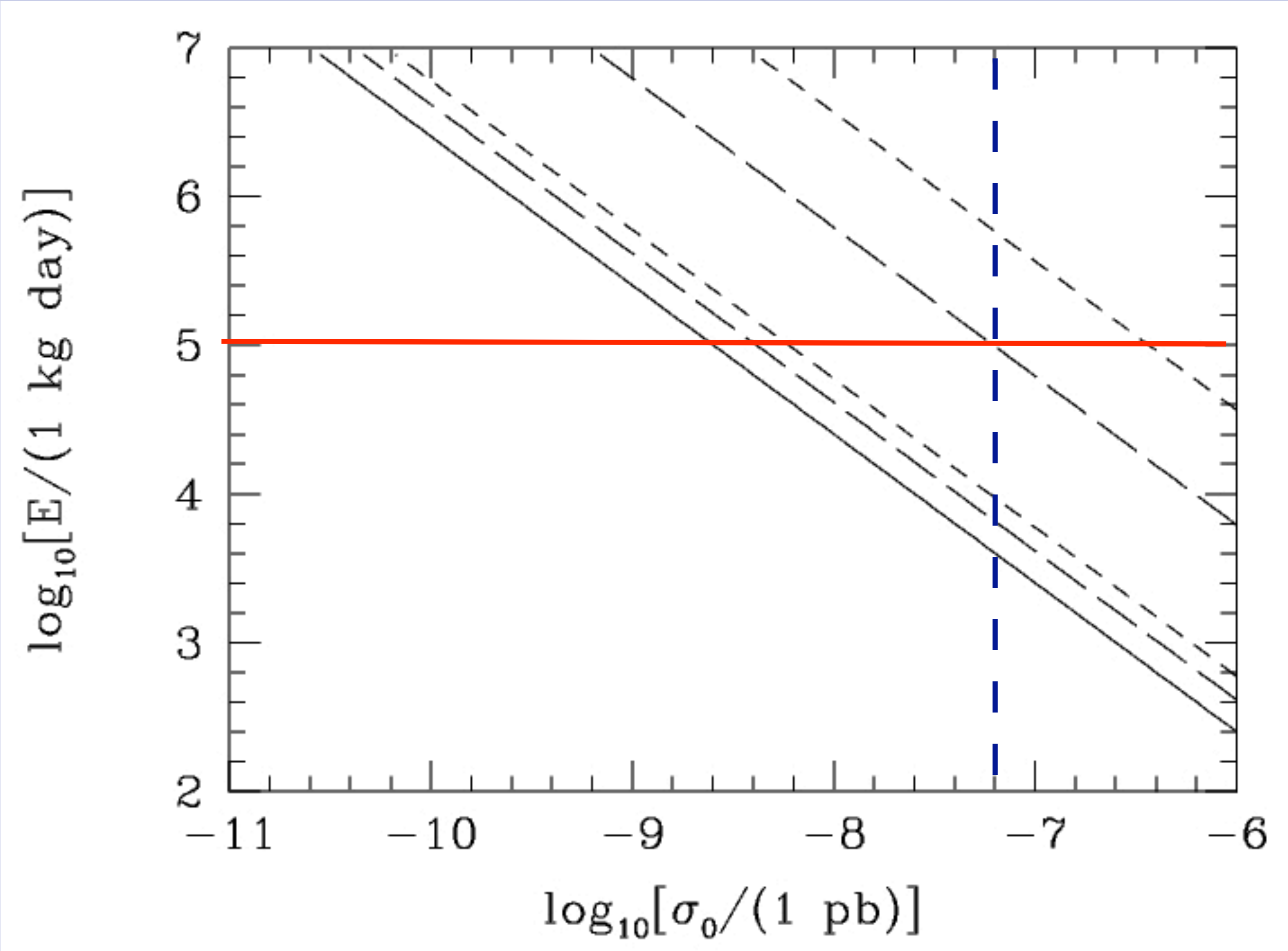
100 kg detector
several years of data

——— vector read-out, recoil reconstruction uncertainty taken into account

--------- axial read-out, " " " " " "

.... vector read-out, perfect recoil reconstruction

2-d read-out



} 2-d axial read-out

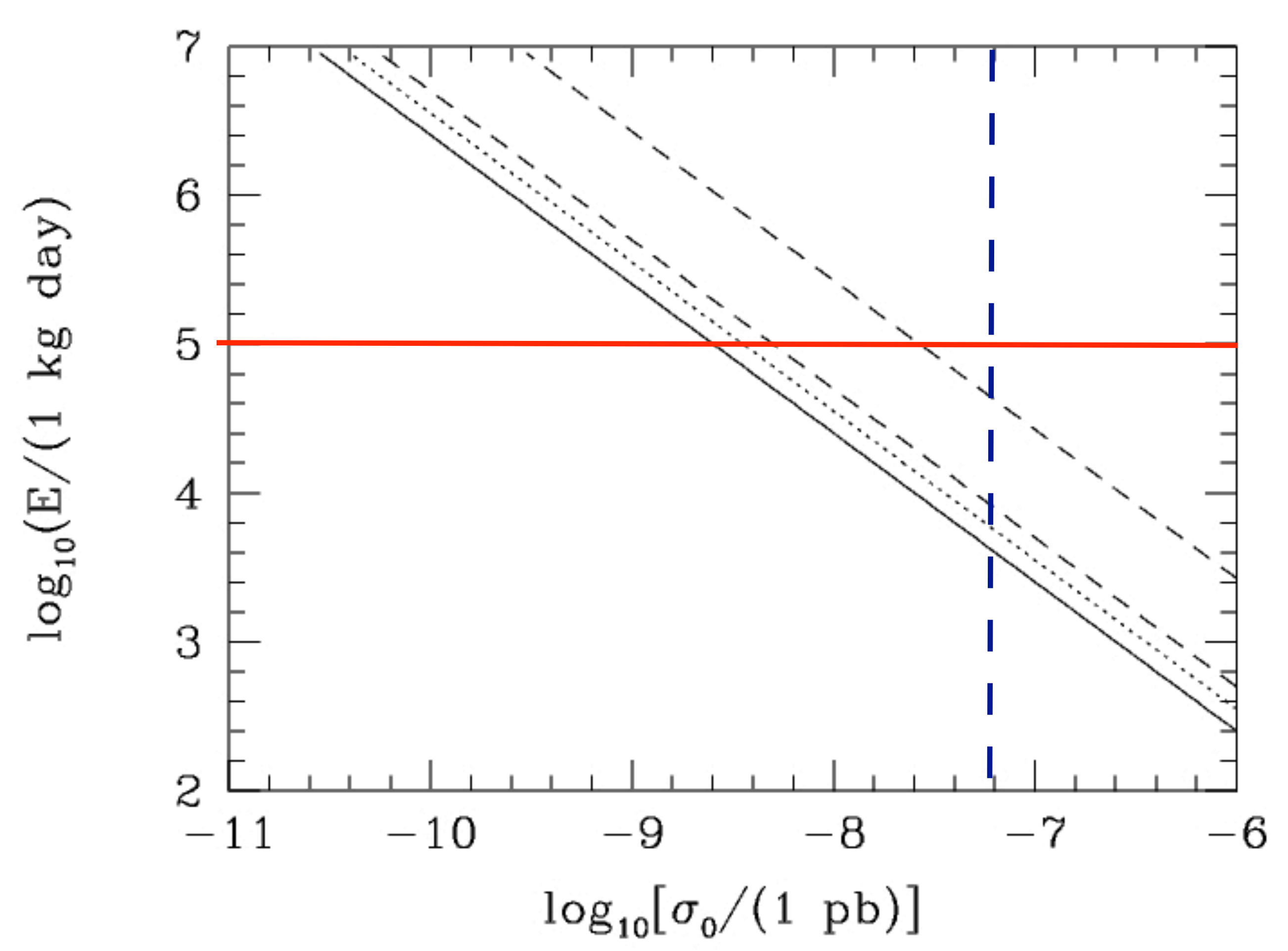
} 2-d vector read-out

3-d vector read-out

raw angles

reduced angles

Energy threshold



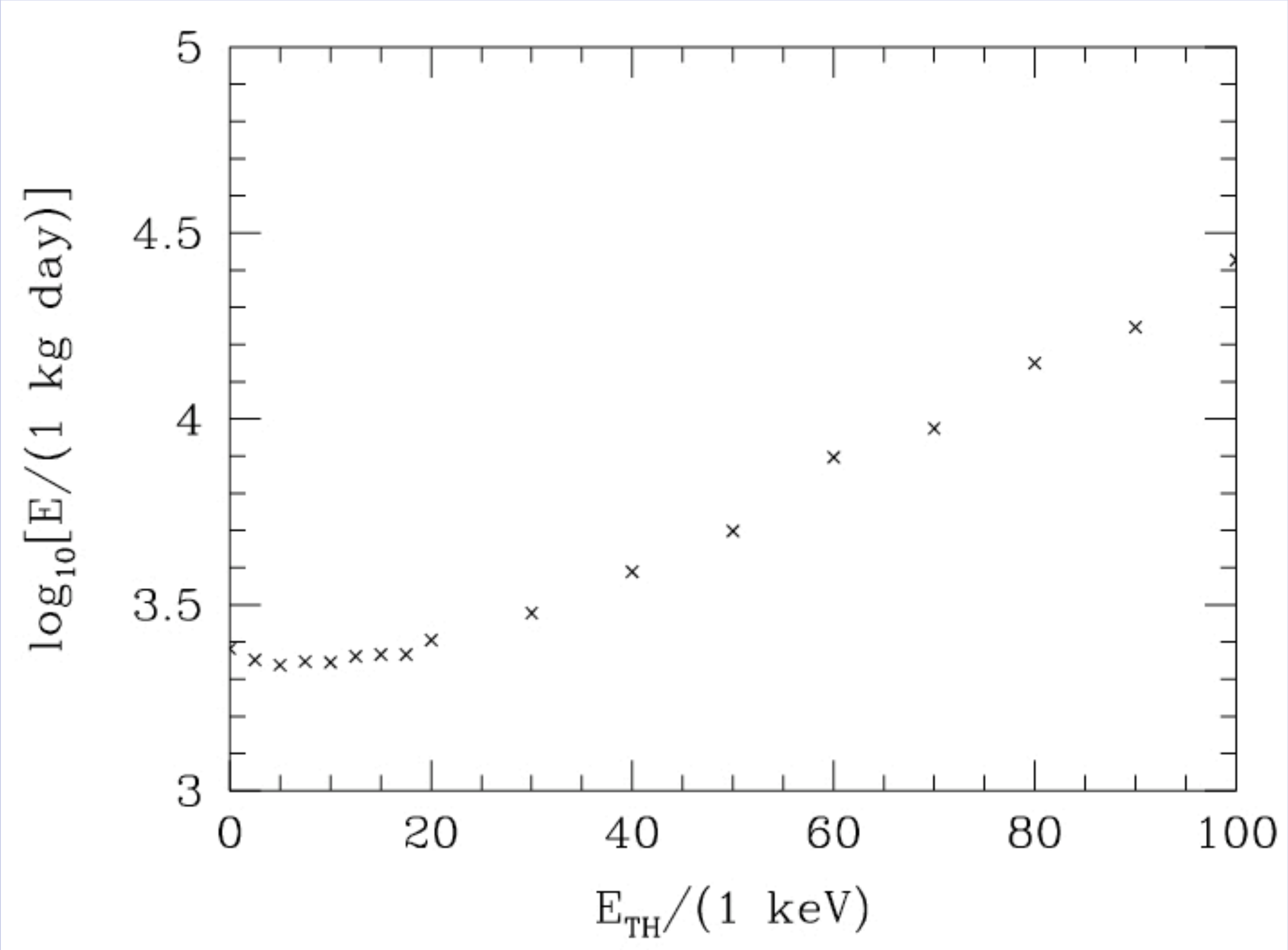
Energy threshold:

——— 20 keV

.... 0 keV

-------- 50 keV & 100 keV

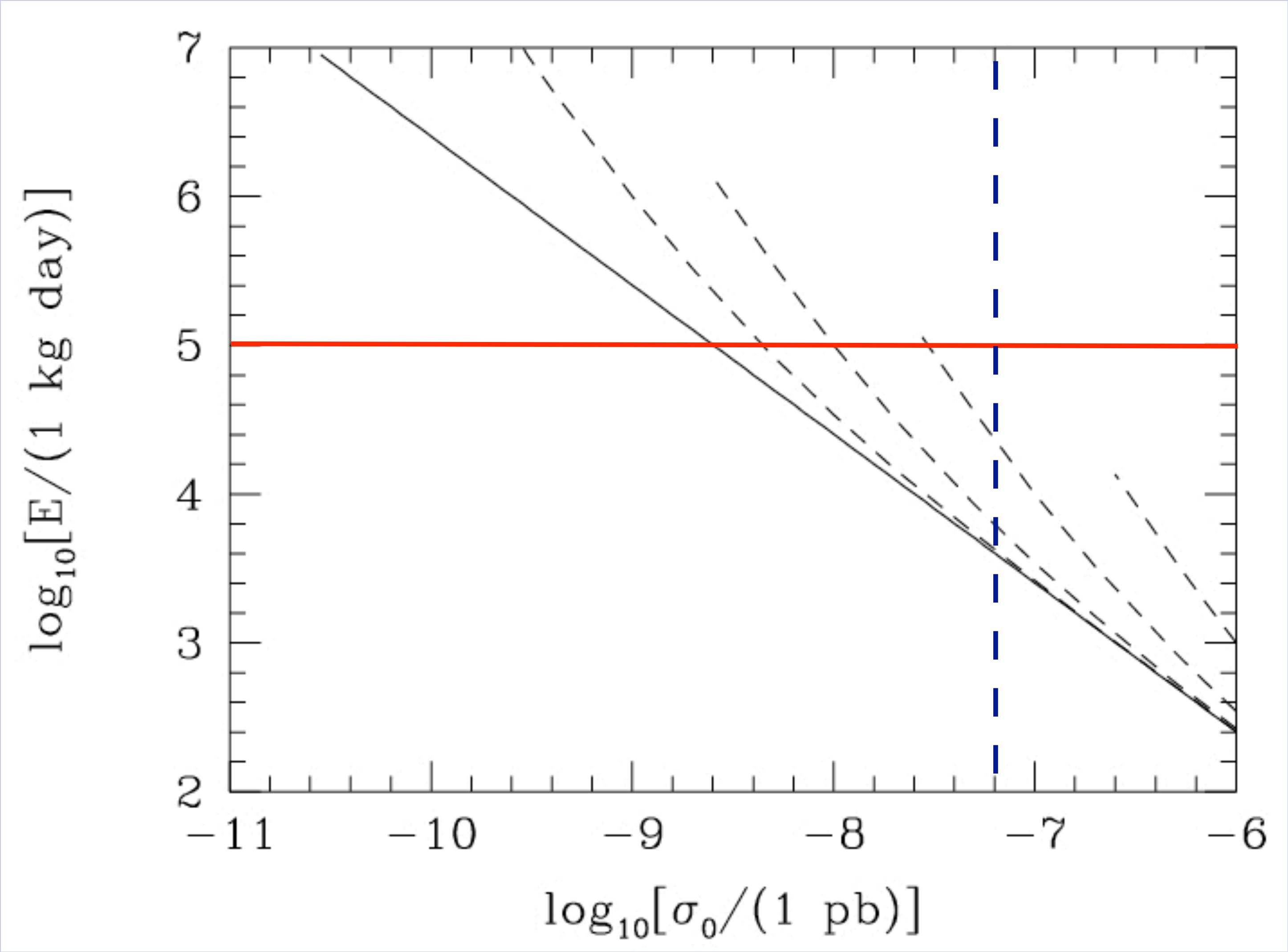
Exposure as a function of threshold energy for $\sigma = 10^{-7}\,\mathrm{pb}$



As energy threshold is increased:

anisotropy increases so number of events required decreases,
but event rate also decreases. Net effect: exposure increases.

Background



Varying background rate:

——— 0 /kg/day

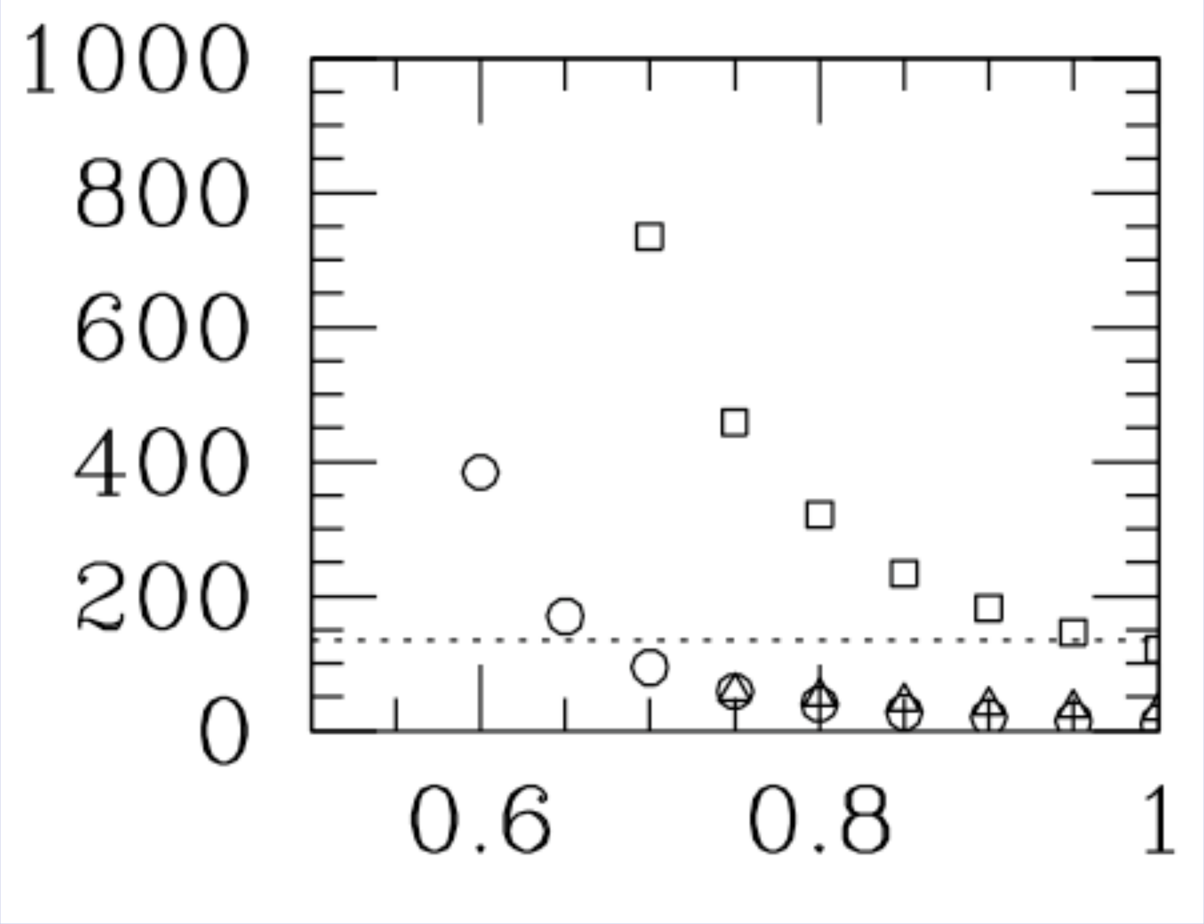
--------- from right to left: 0.1, 0.01, 0.001, 0.0001 /kg/day

Statistical sense determination

Number of events required (for a 95% confidence detection in 95% of experiments) with a constant or linearly increasing probability of correctly determining recoil sense:

N_{95}

using <|cos ϑ|> statistic (i.e. disgarding sense information)



P(100 keV)

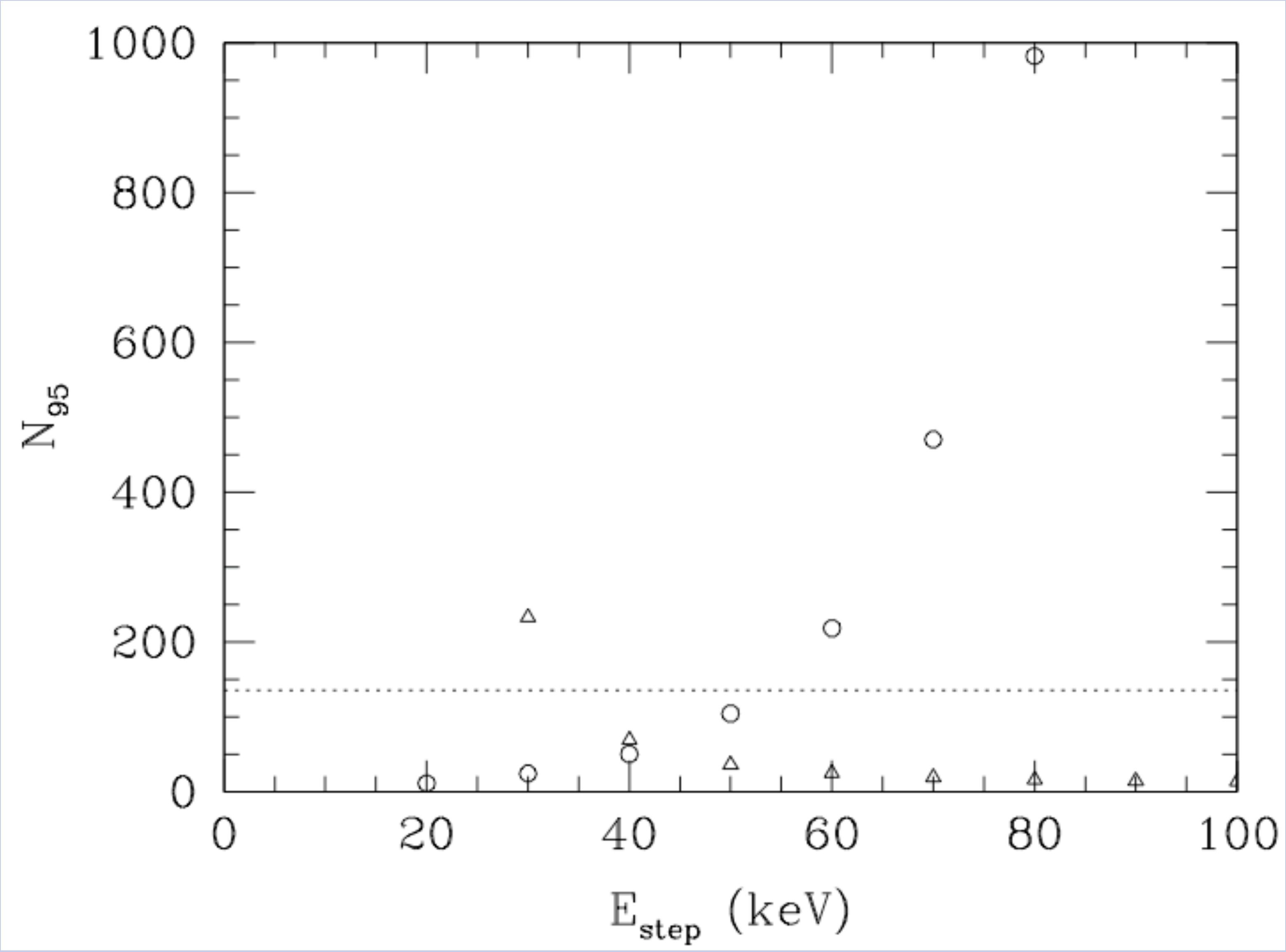
circles: P(E)=const=P(100 keV)

triangles: linearly increasing prob with P(20 keV)=0.75

squares: linearly increasing prob with P(20 keV)=0.5

If probability of correctly determining sense is ~0.75 number of events is increased by a factor of a few, if probability decreased further number of events increases significantly.

Number of events required with a step function probability of correctly determining sense:



circles: $P(E<E_{step})=0.5$ $P(E<E_{step})=1.0$

triangles: $P(E<E_{step})=1.0$ $P(E>E_{step})=0.5$

Bottom line: Determining the sense of the more abundant, but less anisotropic, low energy events is most important for minimising the number of events required.

Main conclusions

☆ Property with the biggest effect: whether the sense (+**x** or -**x**) of recoils can be measured.

If not exposure increased by ~10 (~100) for 3-d (2-d) read-out.

Can be reduced to ~30 for 2-d read-out if reduced angles (with projected direction of solar motion subtracted are use).

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Determining the sense of the more abundant, but less anisotropic, low energy events is most important for minimising the number of events required.

☆ For 2-d vector read-out in optimal plane *(and perfect resolution)* exposure increased by factor 3 (2) if raw (reduced) angles are used.

☆ For 3-d read-out finite angular resolution only increases exposure by ~10%.

2-d angular resolution (depends on energy & direction due to projection effects) has not yet been determined. Increase in exposure due to shortened track lengths alone is factor of ~2.

☆ For threshold energies greater than 20 keV exposure increases by 1.3 for every 10 keV increase in threshold.