How do detector capabilities affect the number of events required to detect a WIMP directional signal?

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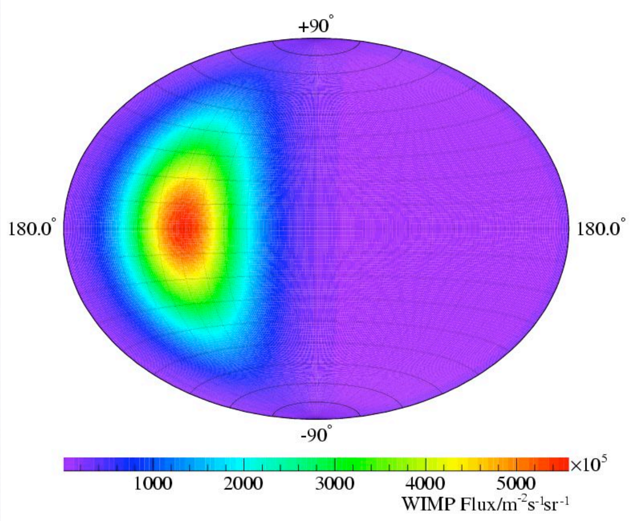
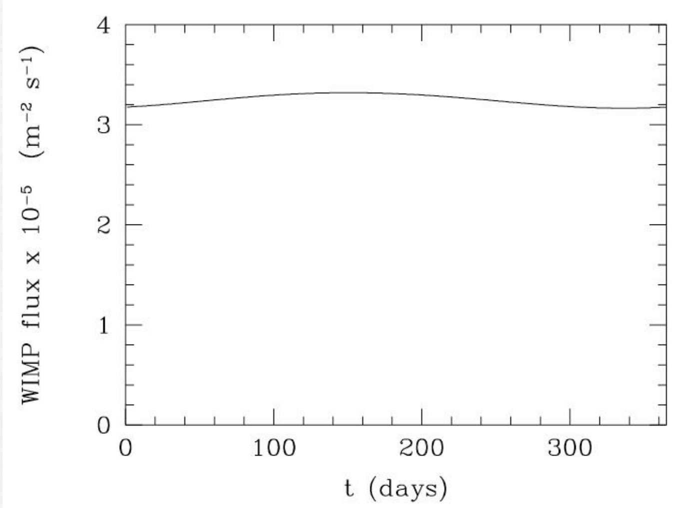
Based on: Green & Morgan, astro-ph/0609115
See also: Morgan & Green, astro-ph/0508134
Morgan, Green & Spooner astro-ph/0408047

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 costs (financial and time) of improvements).

WIMP distribution

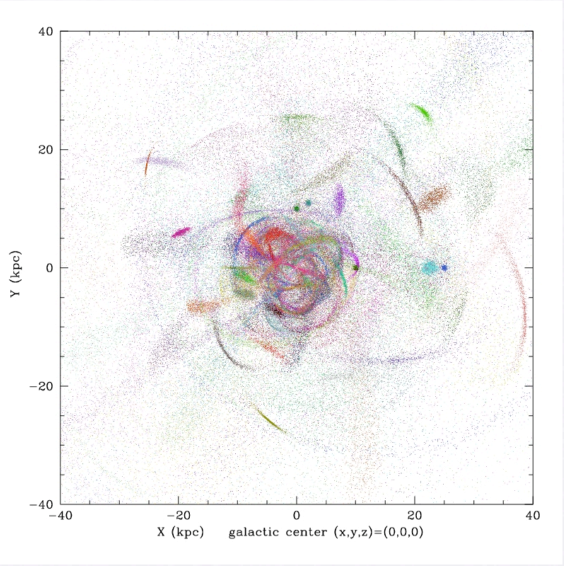
Assume the simplest possible model for the Milky Way halo: isothermal sphere with Maxwellian velocity distribution.

Number of events required only varies by ~10% for other observationally and theoretically motivated predominantly **smooth** halo models.
[Morgan, Green & Spooner]

Caveat:

Whether or not the dark matter distribution (on the sub-milli-pc scales probed by direct detection experiments) is smooth is an open question [Moore et al., Helmi et al., Stiff & Widrow]

Depends on fate of first (~earth mass) halos to form.



Simulation of stellar halo by Morrison

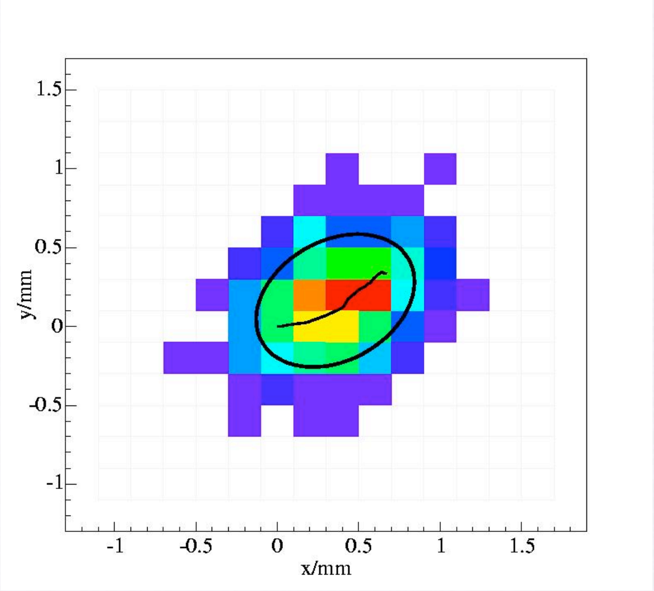
Detector simulations

[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 keV/cm is applied with 200 μm 3-d pixel read-out [c.f. DRIFT I/II design]

Multiple scattering of recoiling nucleus and (small) diffusion of drifted ionisation limit accuracy with which recoil direction can be reconstructed. Use moment analysis to reconstruct recoil direction from pixel charge distribution.

With SRIM2003 generated recoils ionisation distribution along track is uniform so sense (+**x** or -**x**) can not be determined. Whether or not this is the case in reality needs to be determined experimentally.



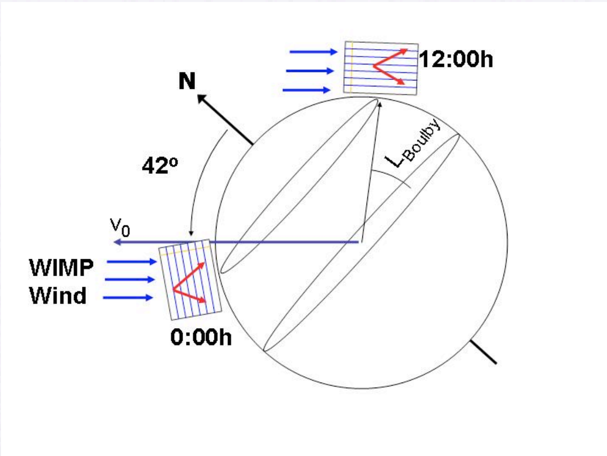
Below 20 keV tracks are so short (<3-4 pixels) that direction can not be reconstructed. (n.b. this is higher than the threshold for detecting recoils and may be lower than the threshold for discriminating nuclear recoils from electron backgrounds.)

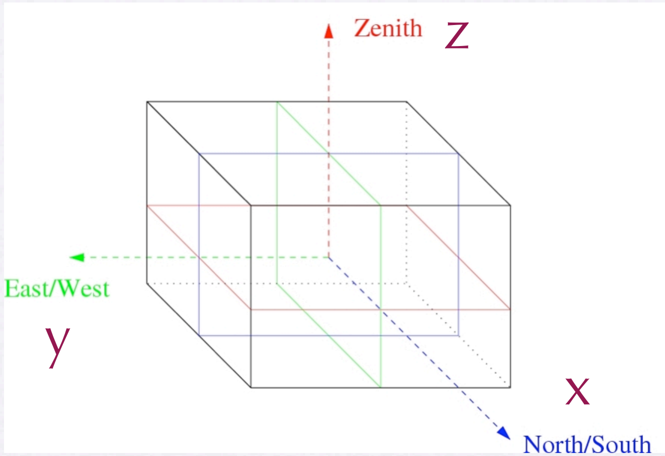
2-d read-out

[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.

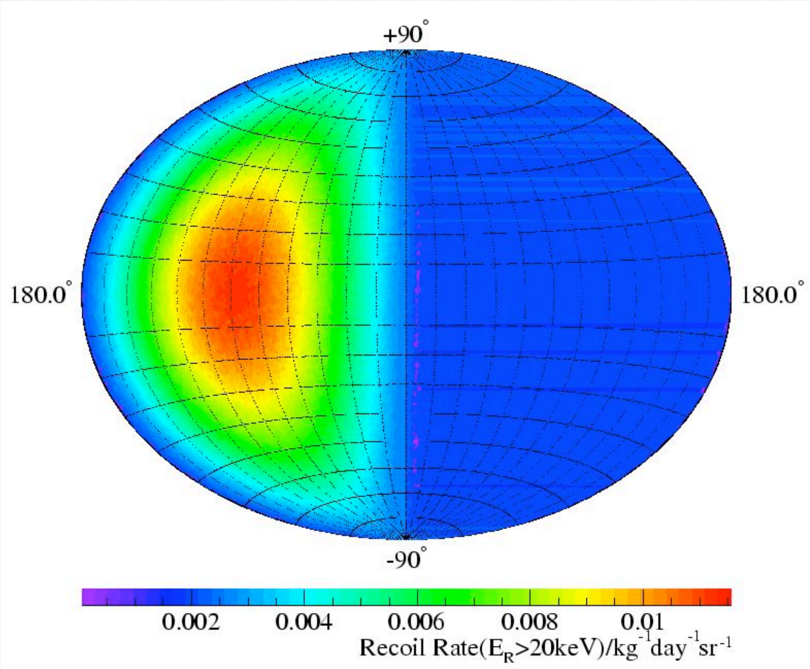
For other (non-optimal) read-out planes anisotropy depends on detector location.

n.b. In this case we assume perfect recoil reconstruction. Angular resolution of 2-d detector has not yet been calculated-because of projection it will be a function of energy and direction.

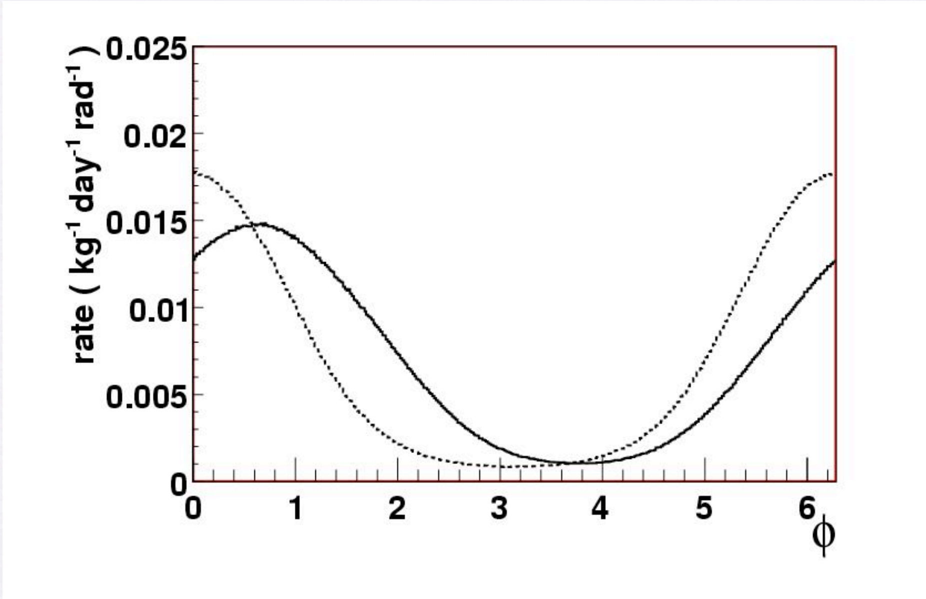
Recoil angle distributions

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 (a priori unkown) WIMP distribution

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

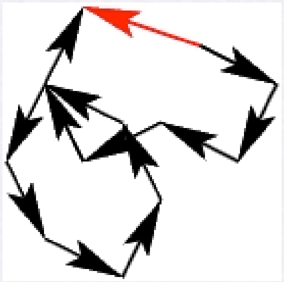
$$\langle \cos\theta \rangle = \frac{\Sigma_{i=1}^{N} \cos\theta_{\rm i}}{N}$$

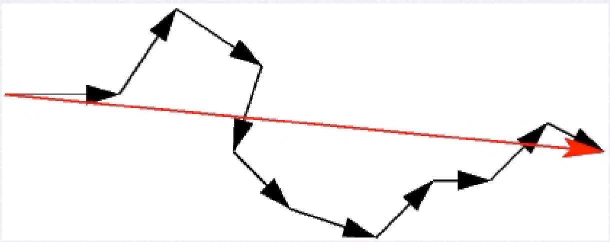
vectorial data

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

axial data

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

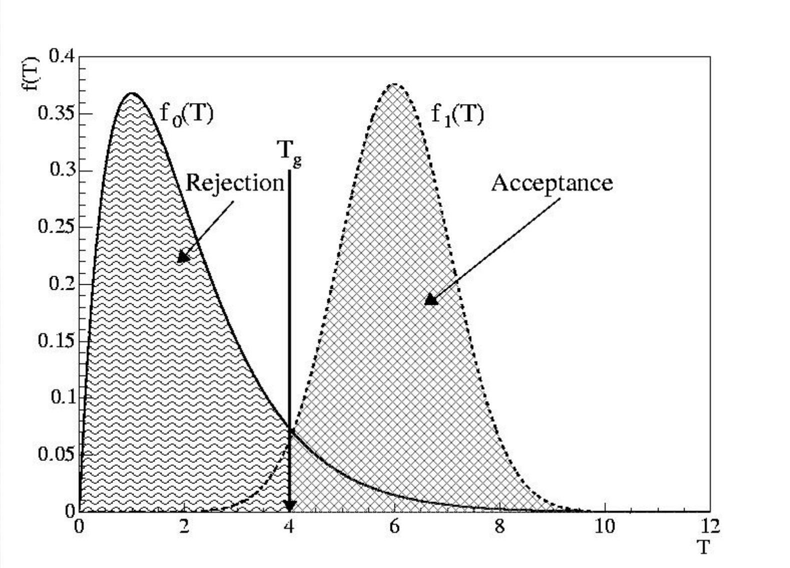




Procedure for calculating number of events required to detect a WIMP signal:

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 readout in optimal plane, raw angles	18	26
2-d axial readout in optimal plane, raw angles	1100	1600
2-d vector readout in optimal plane, reduced angles	12	18
2-d axial readout in optimal plane, reduced angles	190	270

} upgraded and unrealistic

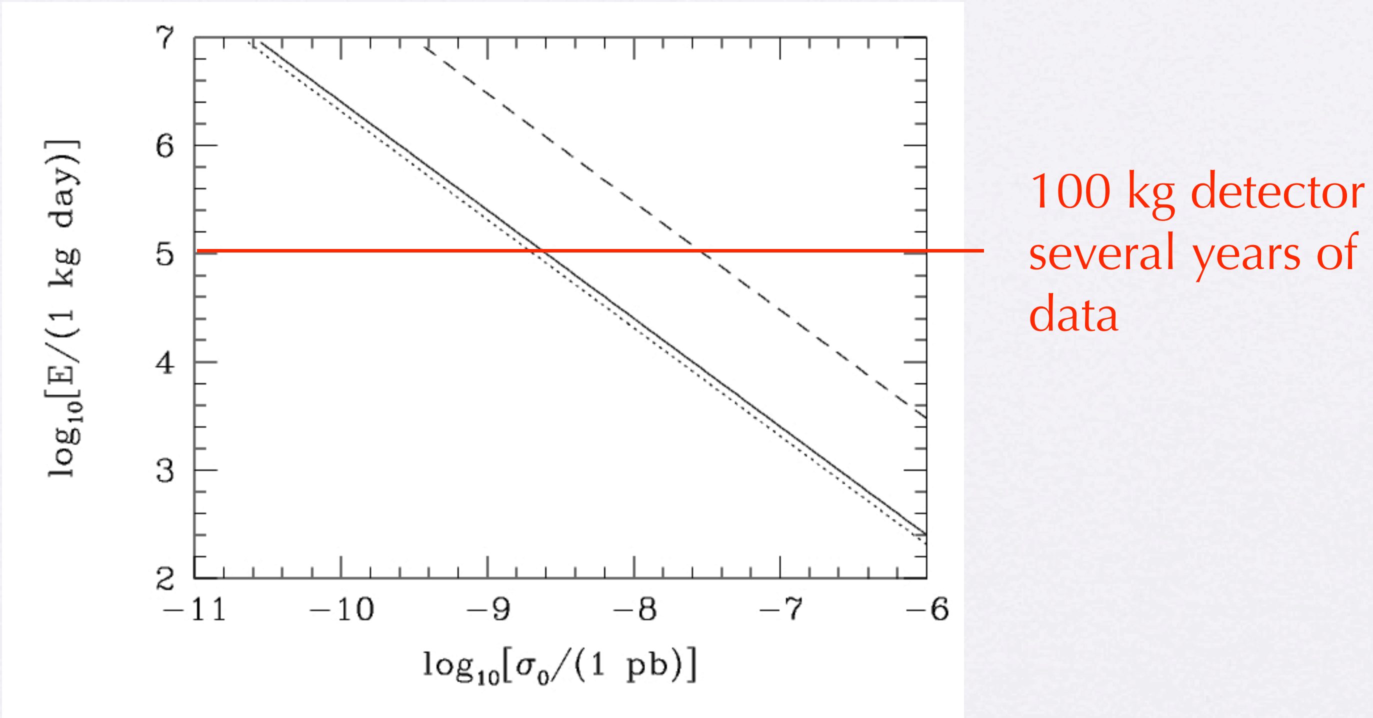
} n.b. assuming perfect angular resolution

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

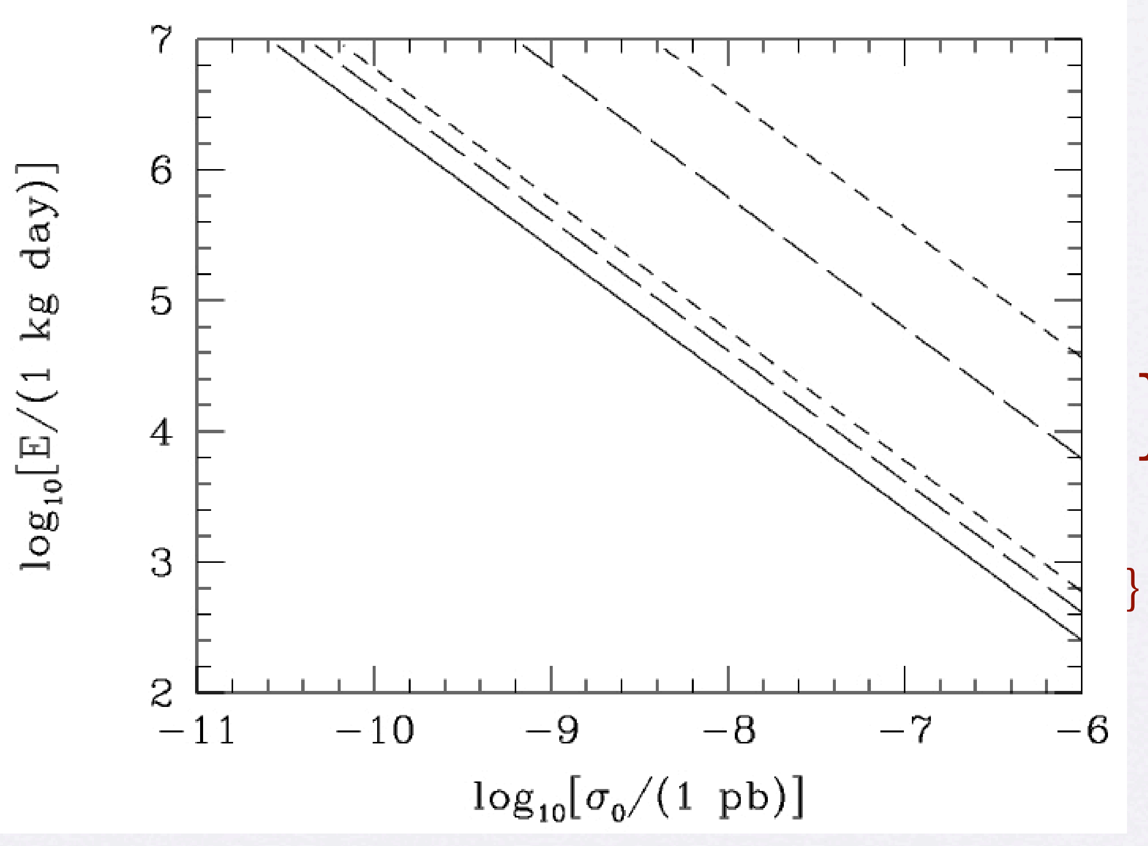


——— vector read-out, recoil reconstruction uncertainty taken into account

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

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

2-d read-out



} 2-d axial read-out

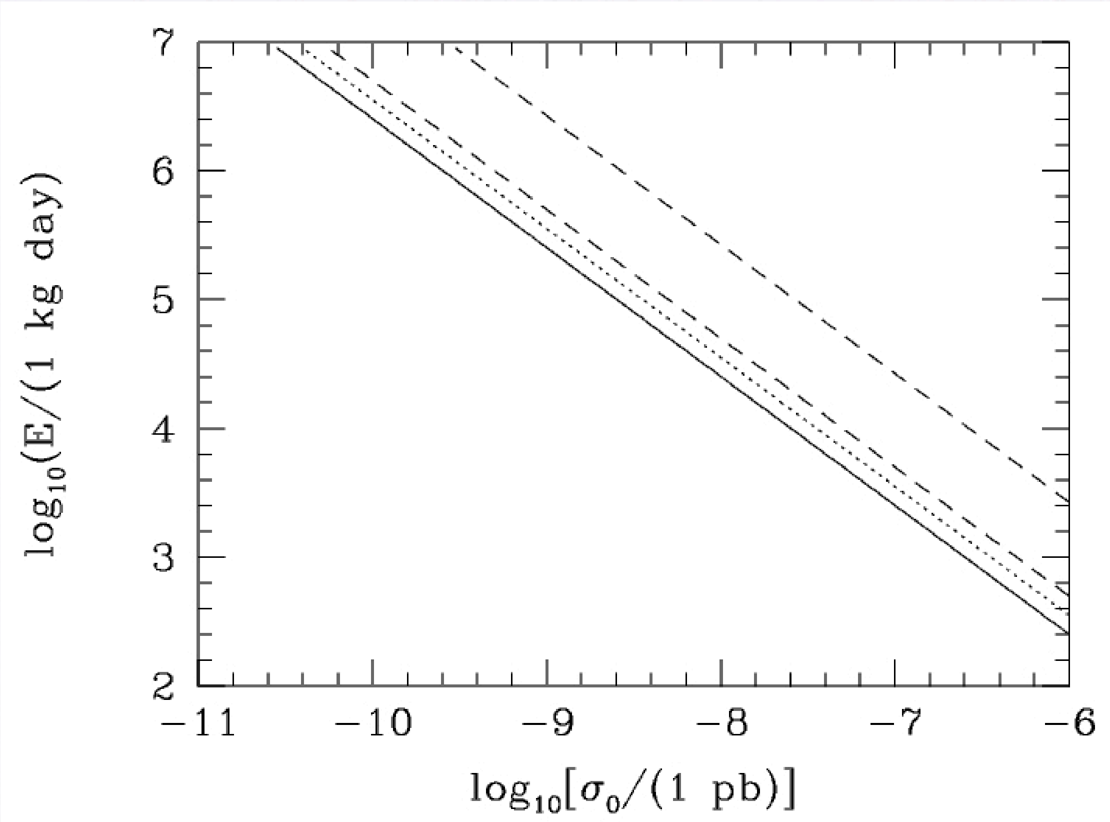
} 2-d vector read-out

——————— 3-d vector read-out

--------------- raw angles

– – – – – – – – reduced angles

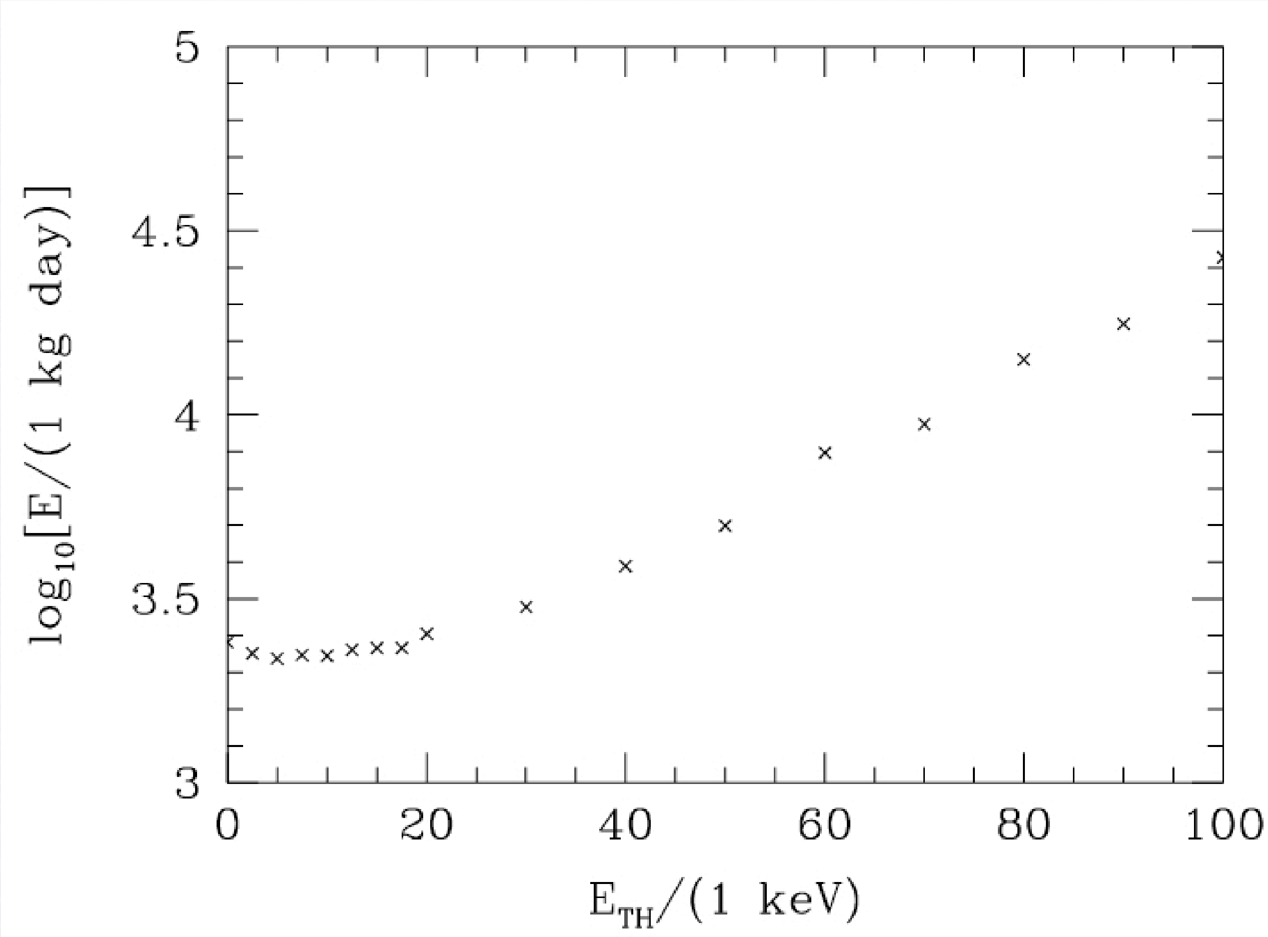
Energy threshold



Energy threshold:

- ———— 20 keV
- ·········· 0 keV
- --------- 50 keV & 100 keV

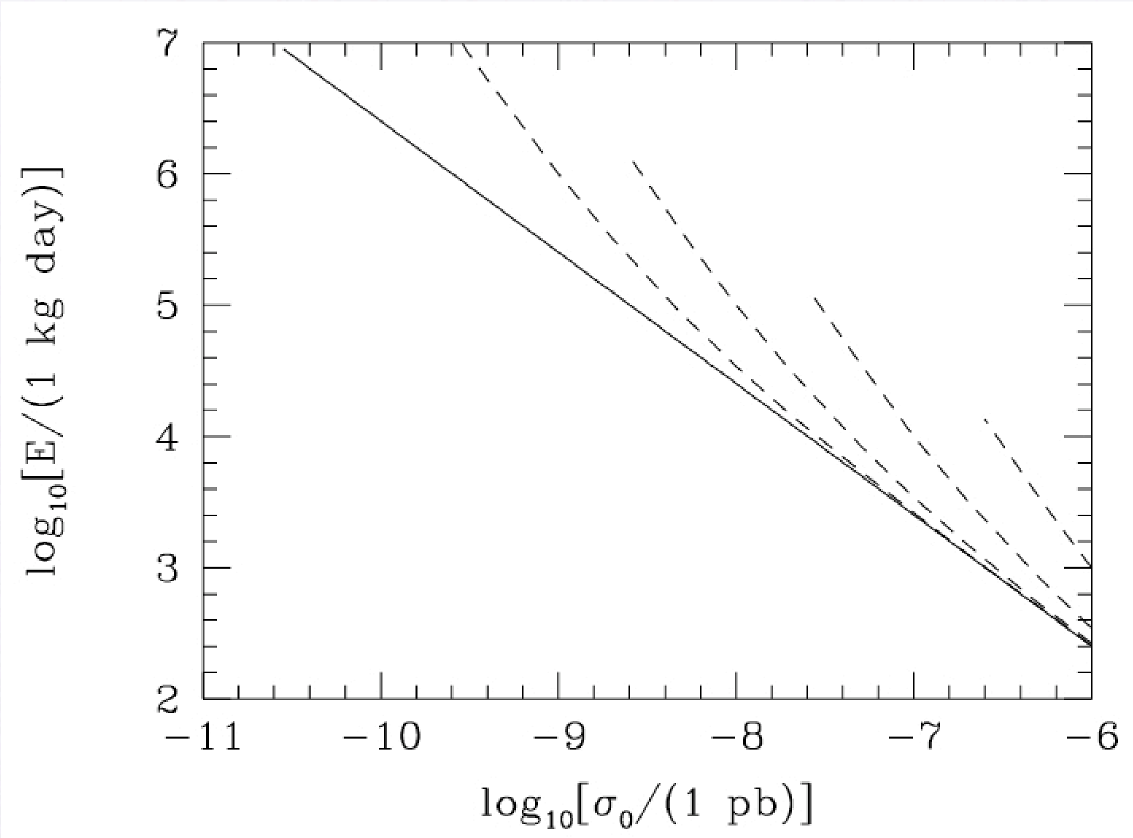
Exposure as a function of threshold energy for $\sigma = 10^{-7}\,\mathrm{pb}$



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

If we detect a directional signal: what next?

i) Cast iron demonstration of its WIMP origin:
observe the change in the mean recoil detection over a sidereal day (due to rotation of Earth).

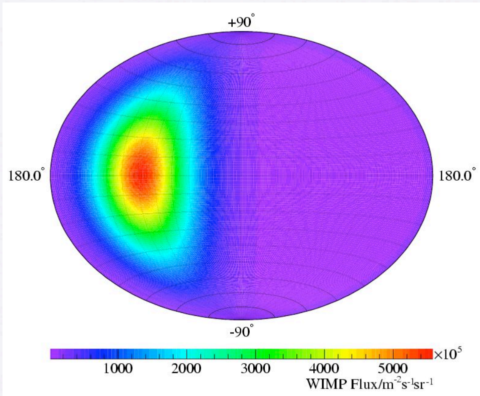
ii) WIMP astronomy
probe the local dark matter distribution

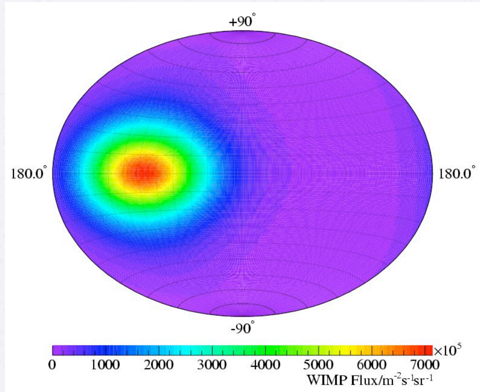
WIMP astronomy

standard halo

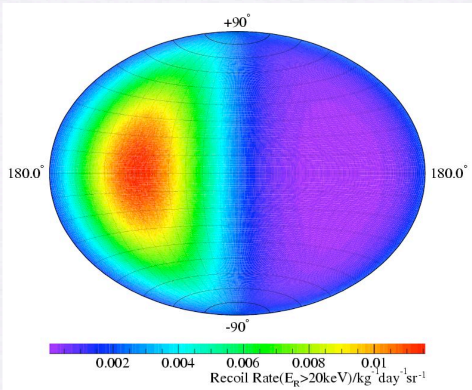
flattened halo

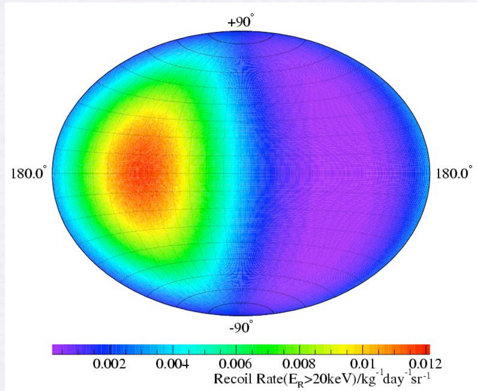
WIMP flux





recoil rate

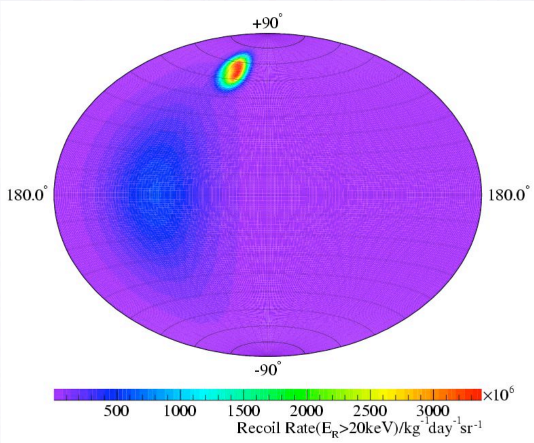




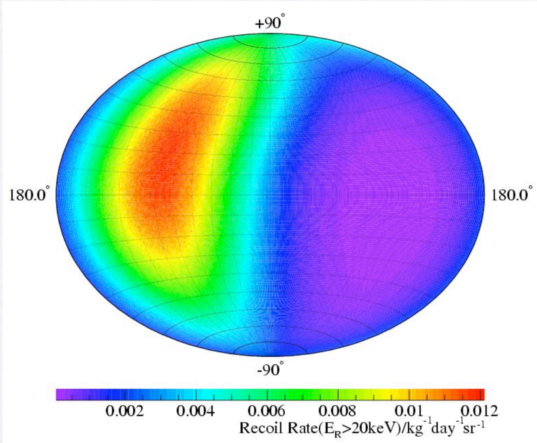
Thousands of events would be needed to detect even extreme flattening of the WIMP flux/MW halo.

Host & Hansen: similar results for measuring anisotropy of dark matter speed distribution. See also Copi & Krauss.

standard halo plus stream (25% of local density, with velocity of Sagittarius stream [which doesn't actually pass through the solar neighbourhood.....])



WIMP flux



recoil rate

With ~300 events could detect a tidal stream of WIMPs, via the deviation of the mean direction from the direction of solar motion.

(provided the stream density is sufficiently high and the stream direction is sufficiently different from the direction of solar motion).

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).

This is a (big....) question which needs to be answered experimentally.

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

[n.b. These numbers assume 2-d angular resolution is perfect]

☆ 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.

Other conclusions

☆ If Signal/Noise ~ 1 (0.1) exposure increased by factor 2.5 (15).

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

Main conclusions

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

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