Optimizing WIMP Directional Detectors

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1: The Smoking Gun

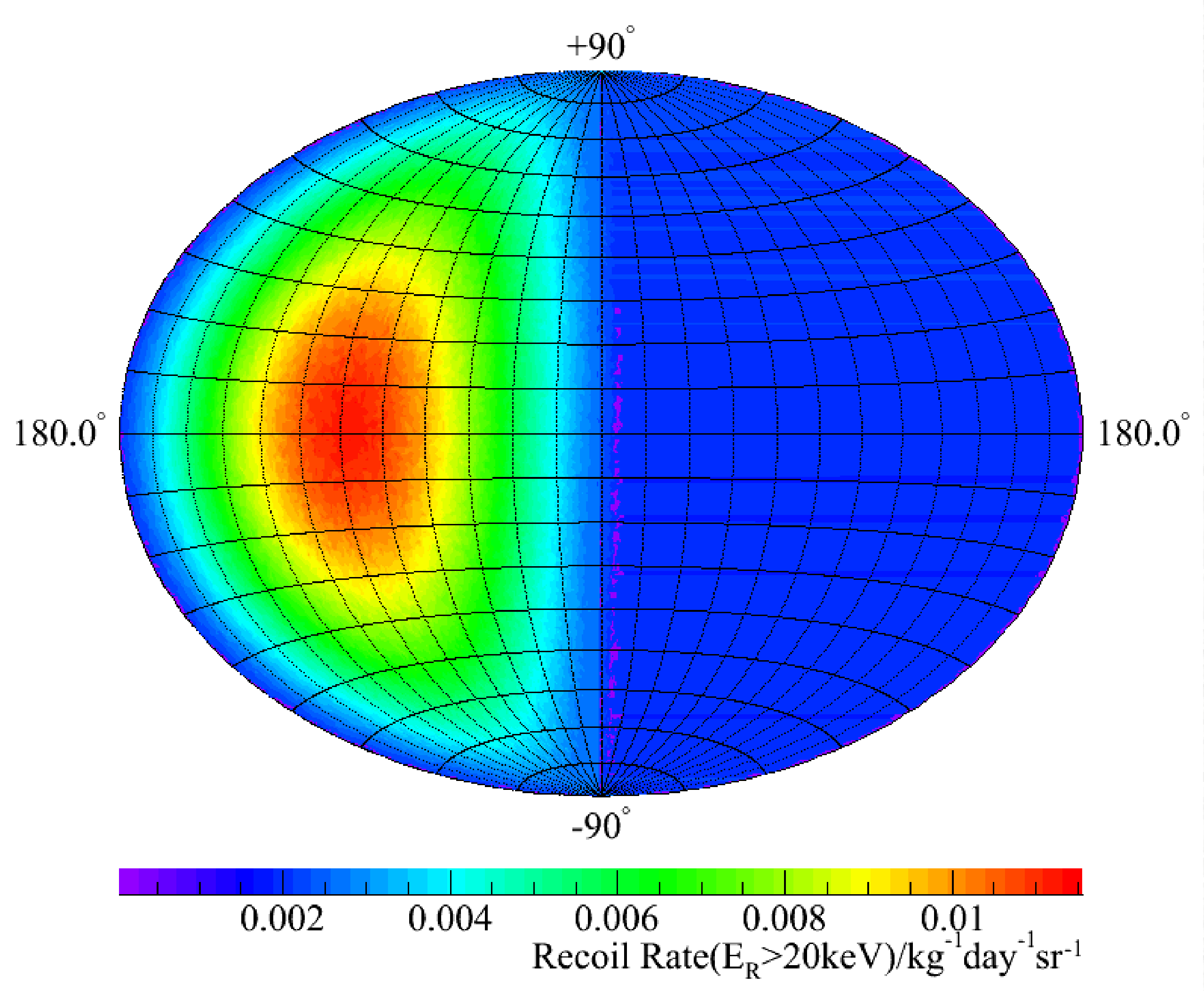
- Directional dependence of the recoil rate is a potentially powerful way to identify a WIMP signal.

Example:
Recoil arrival directions in a Maxwell-Boltzmann halo:

100GeV WIMPs

^{32}S target

O(5) ratio forward to backward event rate. Backgrounds would be isotropic…



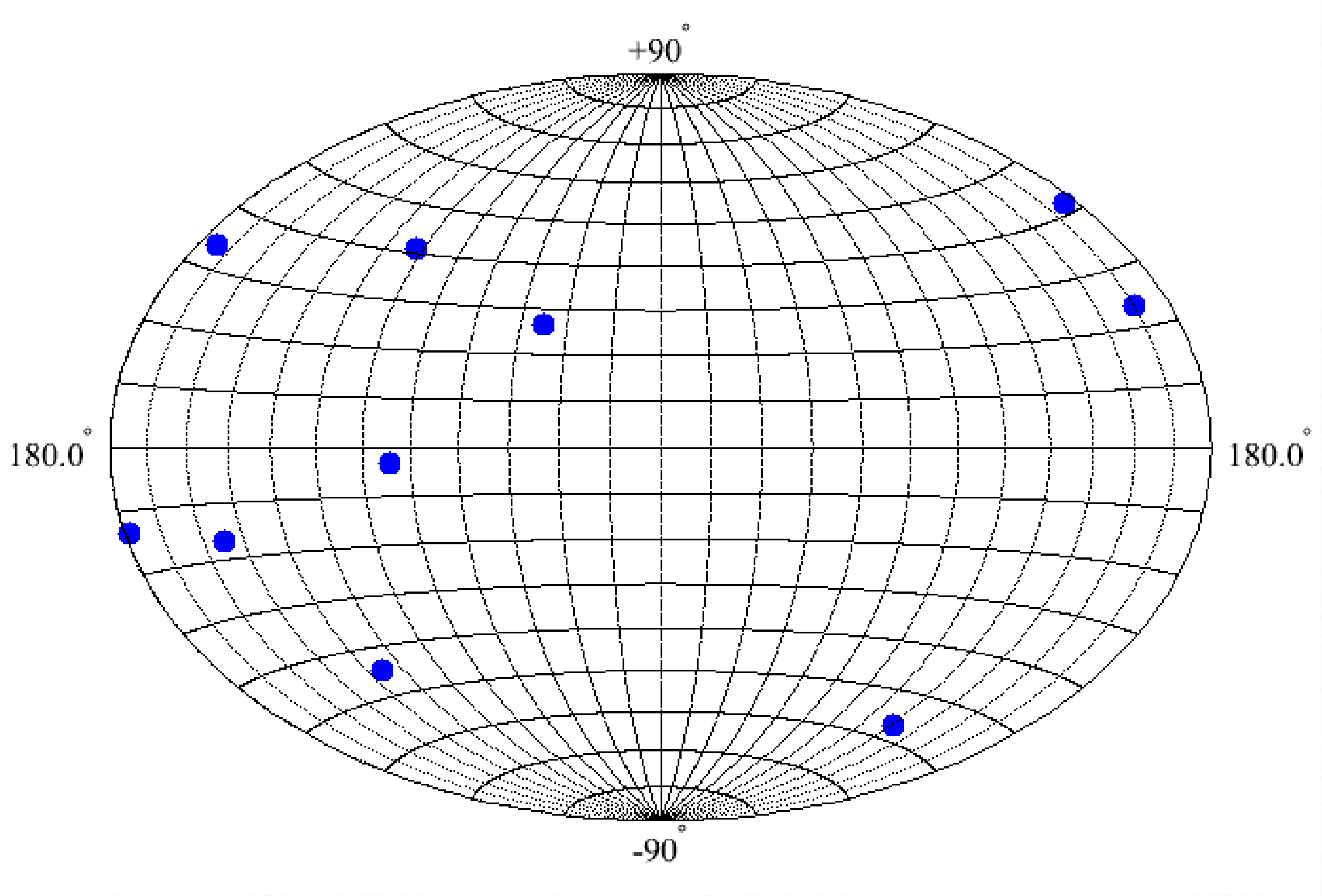
2: Posing the Question

- We expect any background to be isotropic in galactic coordinates*.

- So, the question posed by a directional detector observing an anomalous recoil signal is:
  - ***"Is the distribution of observed recoil directions consistent with an isotropic distribution"***

- But event rate is very low, so sampling is poor…
- ***How many events are needed to reject isotropy?***

2: Posing the Question



- But event rate is very low, so sampling is poor…
- ***How many events are needed to reject isotropy?***

3: Challenges for Anisotropy Detection

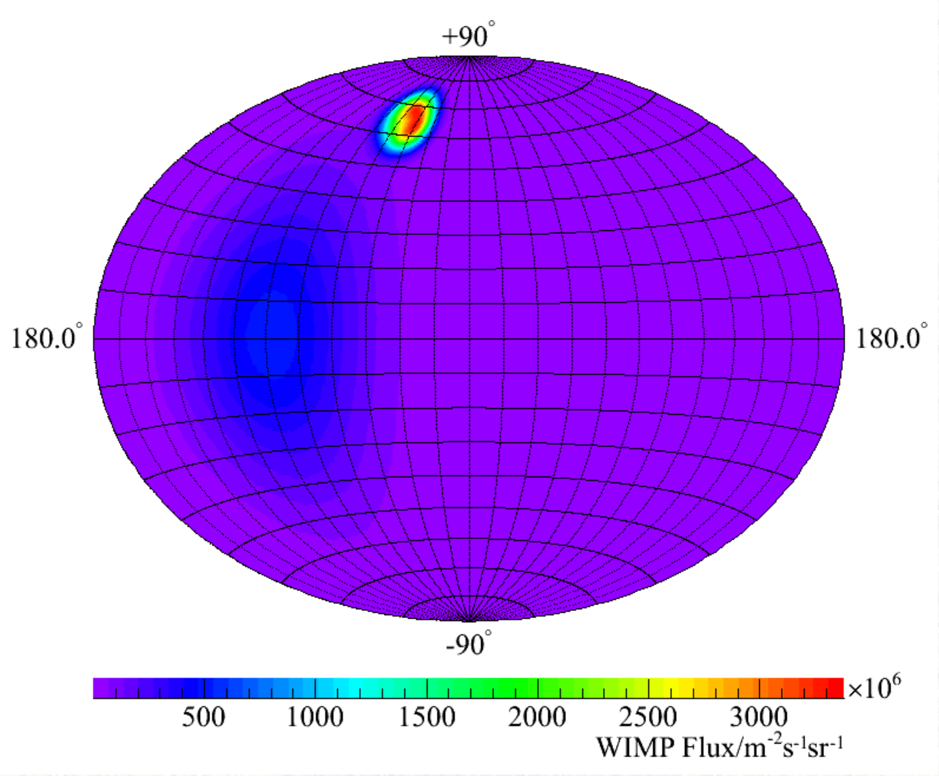
- Several factors may influence the number of events required to detect anisotropy in recoil signal:
- Detector:
  - ***Angular resolution (smearing of anisotropy)?***
  - ***Measure 2 or 3 components of recoil momentum?***
  - ***Can sense of momentum (+p or -p) be measured?***
  - ***Is there expected background?***
- ***How do these effects influence the number of events needed?***

4: Astrophysics Inputs

- Assume the simplest isothermal sphere model for the local WIMP velocity distribution.
- Number of events only varies by ~10% for observationally motivated ***smooth*** halo models.

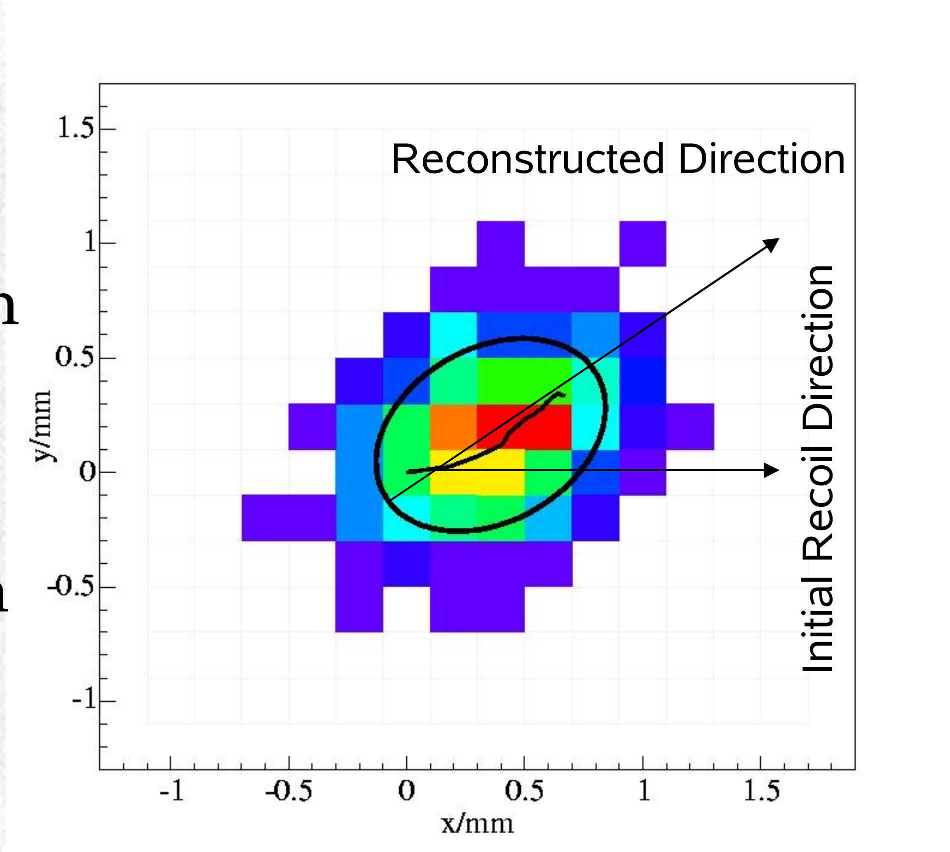
Morgan, Green, Spooner
Phys. Rev. D71/103507

- Open question whether there are dark matter streams.



5: TPC Detector Inputs

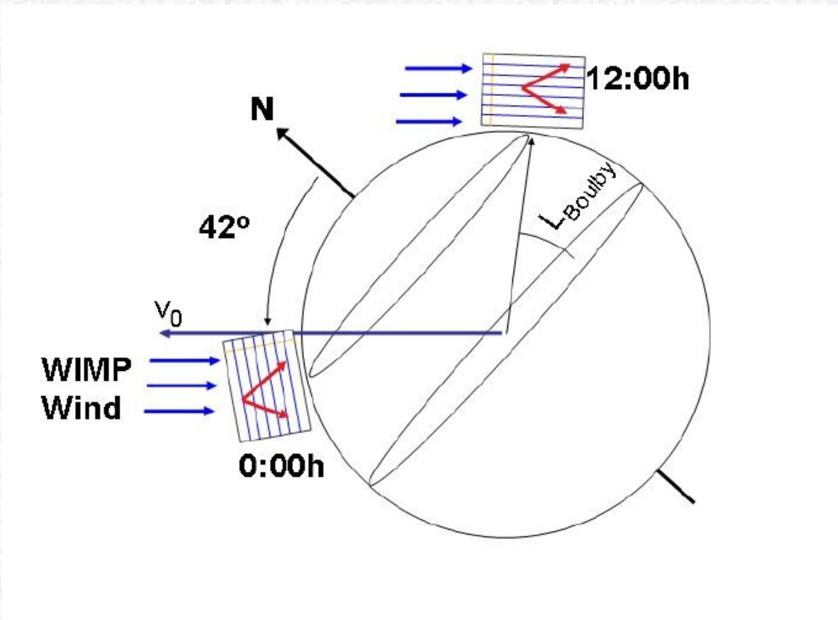
- Model a 0.05bar CS2 TPC, 10cm drift, 1kV/cm drift field, 200μm 3d pixel readout, 5-200keV SRIM recoils
- Direction/sense reconstructed from PCA of pixel signals.
- 10-20° RMS angular resolution (multiple scattering and diffusion limited).
- Smooth ionization distribution so no +**p**/-**p** measurement.
- More experiments needed!

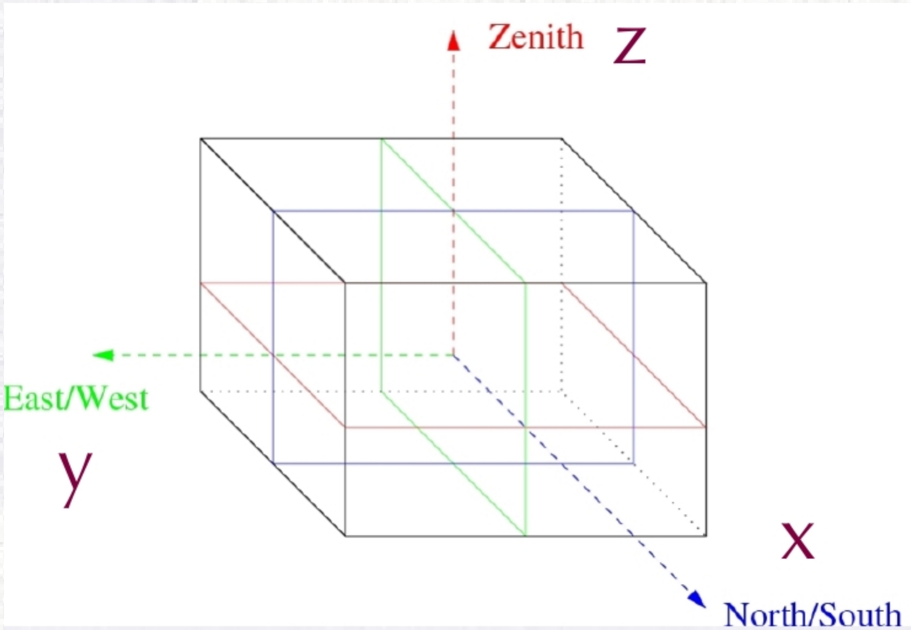


- Below 20keV tracks are too short (<3-4pixels) to be reconstructed.

6: Detectors with 2d Readout

- If **p** is measured in 2d, output is **angles** (rel. to arbitray dirn.) of **p** projected into readout plane.
- Anisotropy of angle distribution depends of orientation of readout plane.

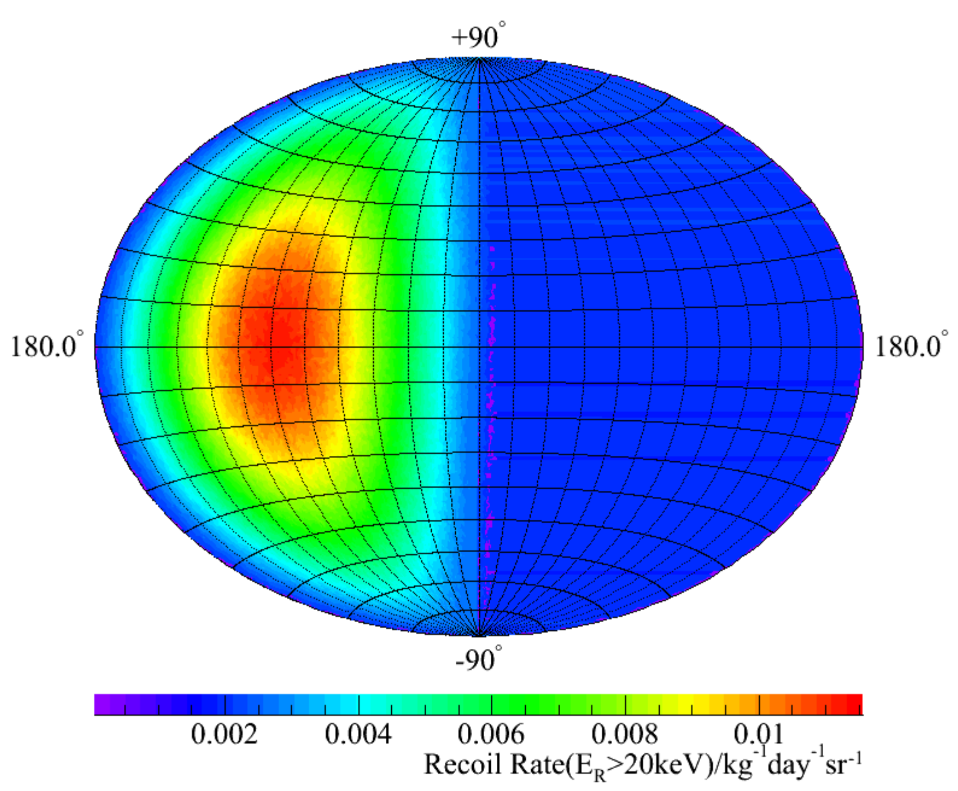




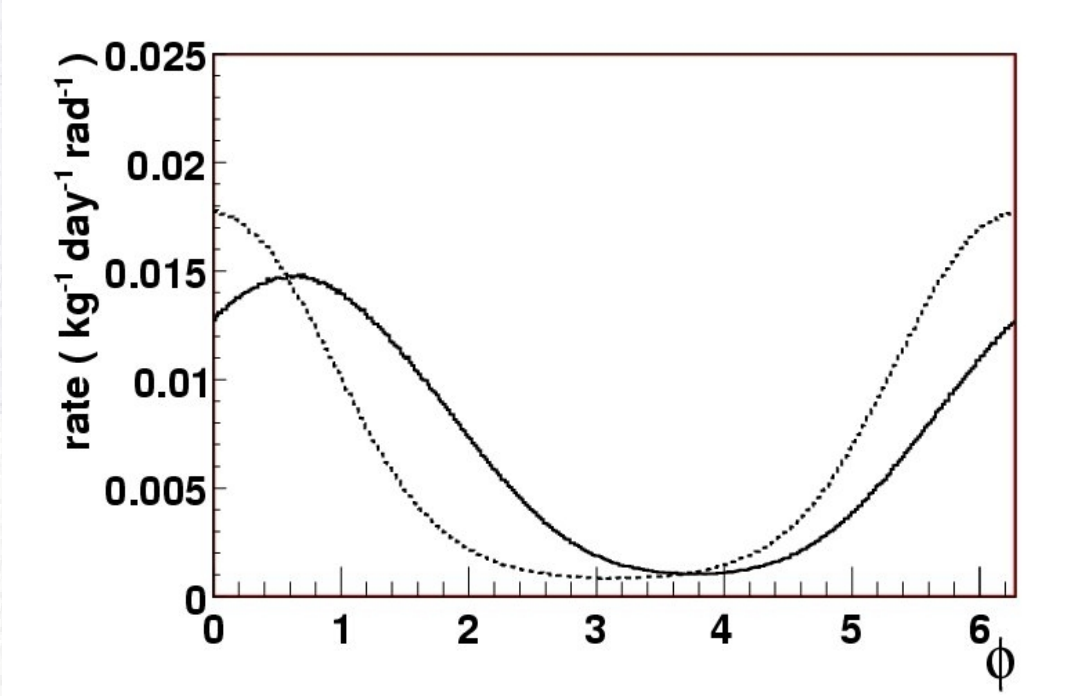
- Readout plane perpendicular to spin axis is optimal.
- No detector effects – energy AND direction dependent!

7: Recoil Angle Distributions

- Baseline configuration: ***3d vector readout, 20keV threshold, detector effects, no background.***
  - Assume ρ_0=0.3GeVcm^{-3}, m_χ=100GeV.



3d



2d (optimal readout plane)

raw angles

reduced angles (relative to solar motion)

8.1: Statistical Analysis Strategy

- Use non-parametric spherical (3d) and circular (2d) tests of isotropy (used in geology, biology).
  - No assumptions about (unknown) WIMP distribution
- For 3d readout, most powerful statistic is mean dot product of recoils and direction of solar motion:

$$\langle \cos\theta \rangle = \frac{1}{N}\sum_i \hat{\vec{r}}_i . \hat{\vec{v}}_{sun}$$

vector data

$$\langle |\cos\theta| \rangle = \frac{1}{N}\sum_i |\hat{\vec{r}}_i . \hat{\vec{v}}_{sun}|$$

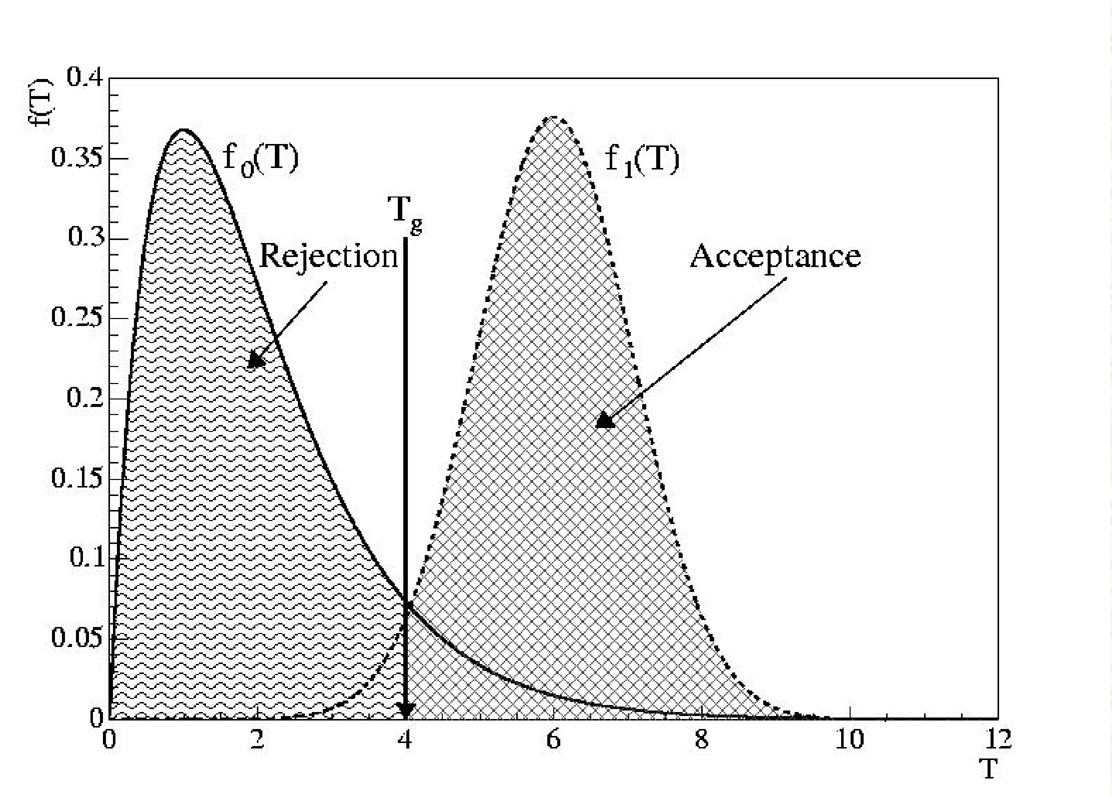
axial data

- For 2d readout, it's the Rayleigh statistic, which measures deviation of mean resultant from zero.

8.2: Statistical Analysis Strategy

- For given number of events, N, generate distribution of statistic for isotropic and WIMP halo hypotheses.

- Calculate Acceptance and Rejection factors:



- Find N such that A=R=0.9(0.95)

- ***Gives N for 90%(95%) confidence detection of anisotropy in 90%(95%) of experiments.***

9: Baseline Results

- Baseline numbers of events for 90/95% confidence detection of anisotropy in 90/95% of experiments:

difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_{\rm T} = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_{\rm T} = 50$ keV	5	7
$E_{\rm T} = 100$ 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

Baseline Detector

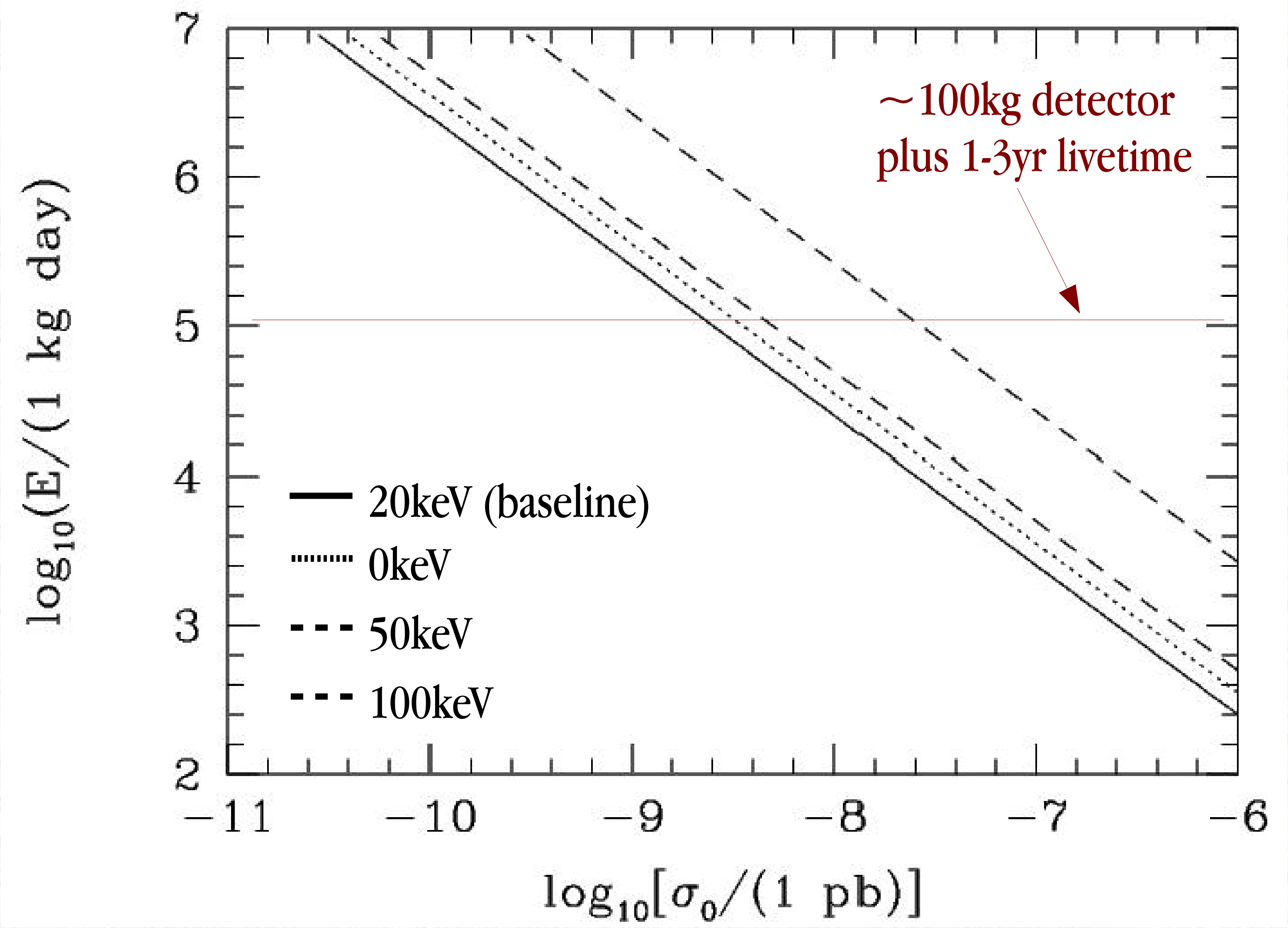
Upgraded, and unrealistic, detector

Note that all 2d numbers assume perfect angular resolution

See Green & Morgan, Astropart. Phys., 27, 142-149

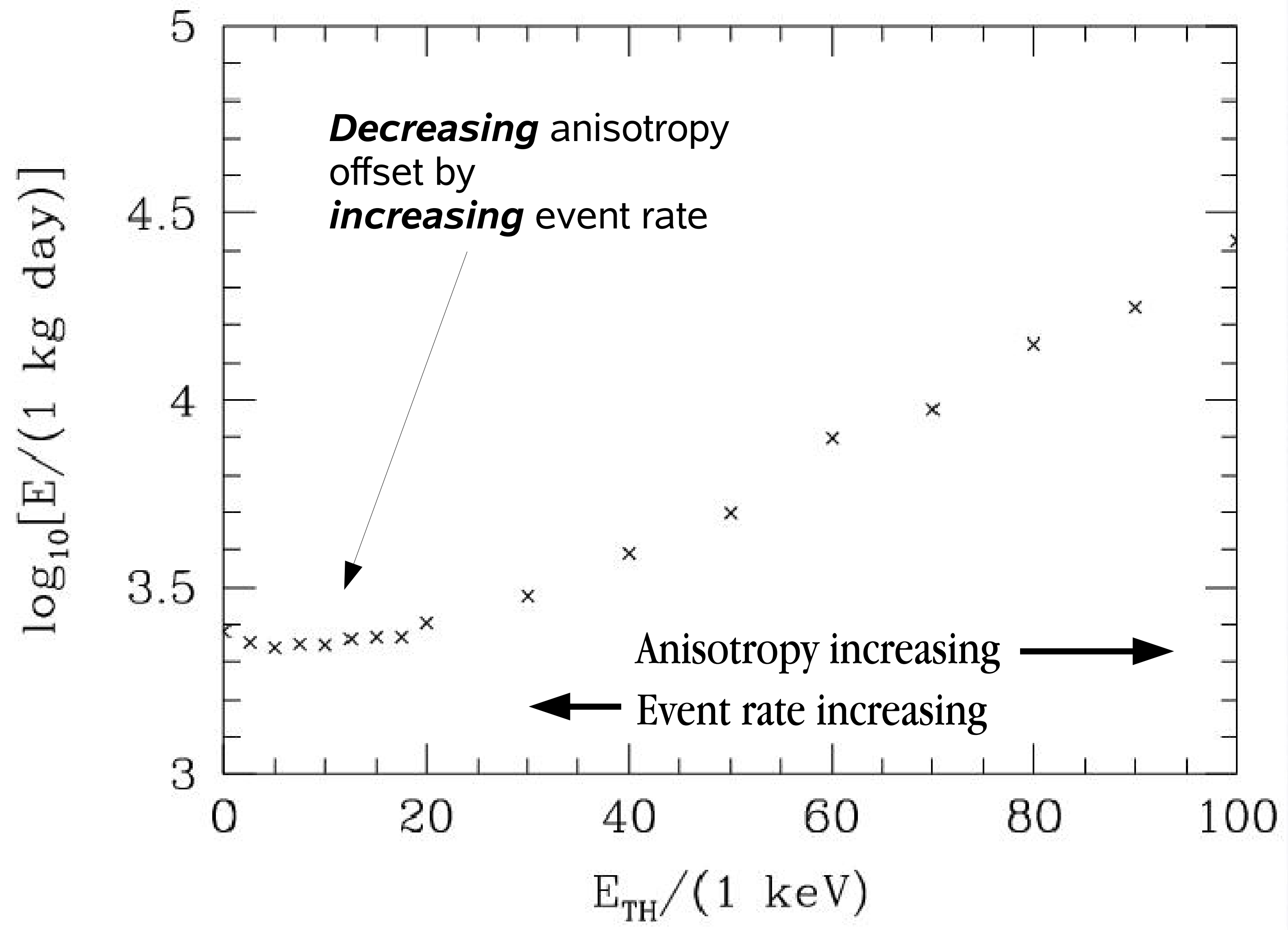
10: Directional Energy Threshold

- There is an optimum energy threshold for directionality!



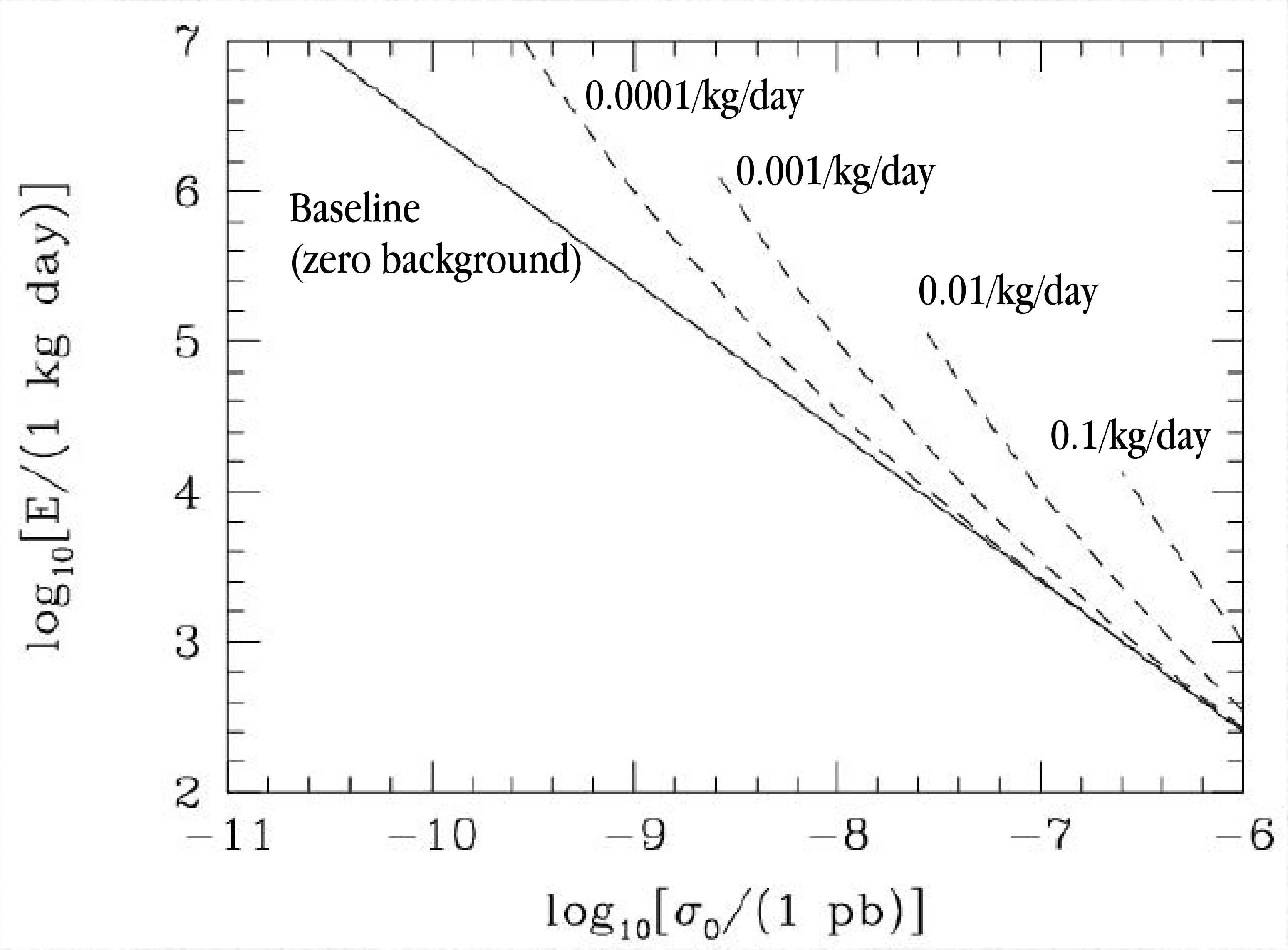
10.1: Why an Optimum Threshold?

- Plot exposure as function of threshold at $\sigma=10^{-7}$pb:



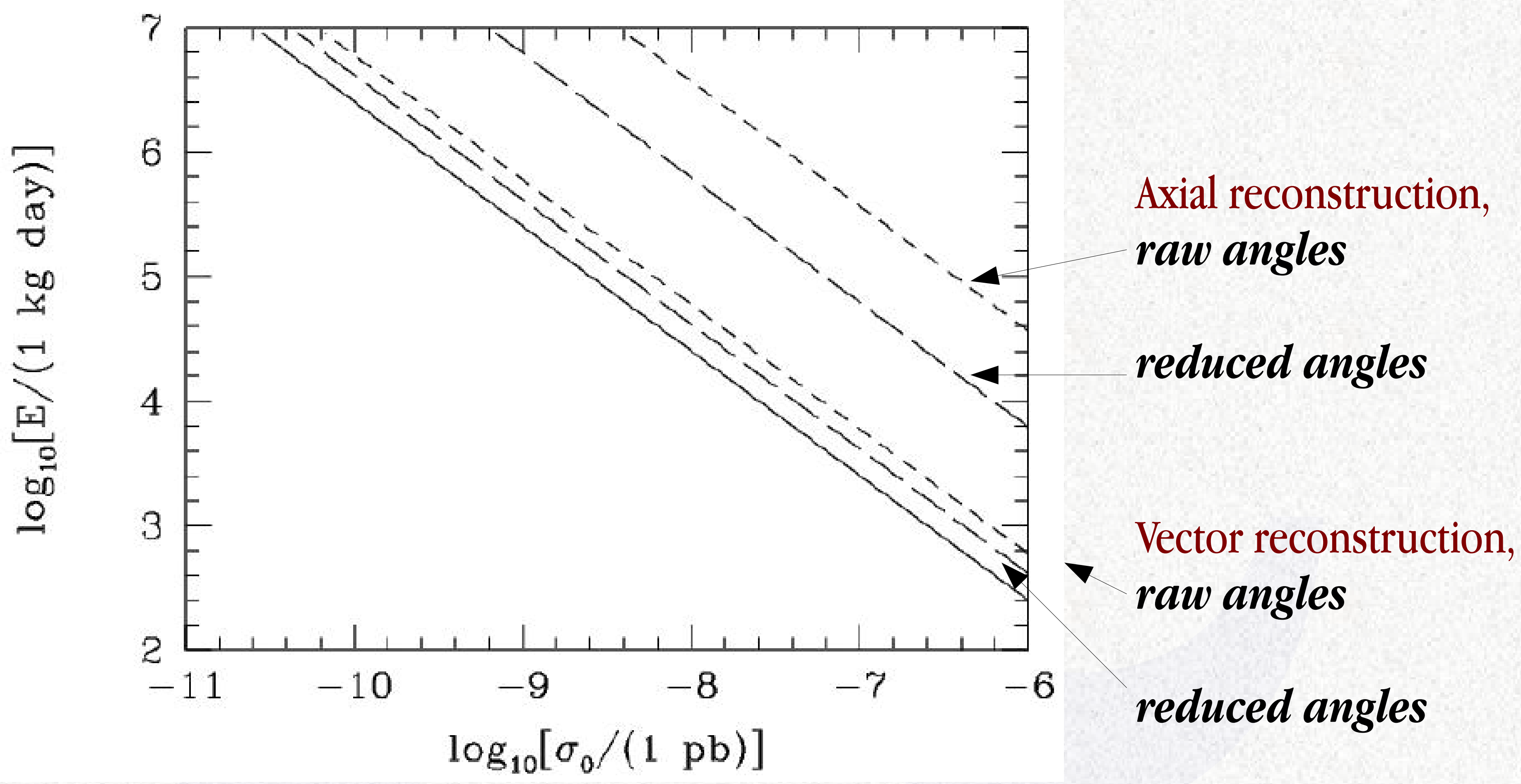
11: Background rate

- If there is an isotropic background, anisotropy decreases



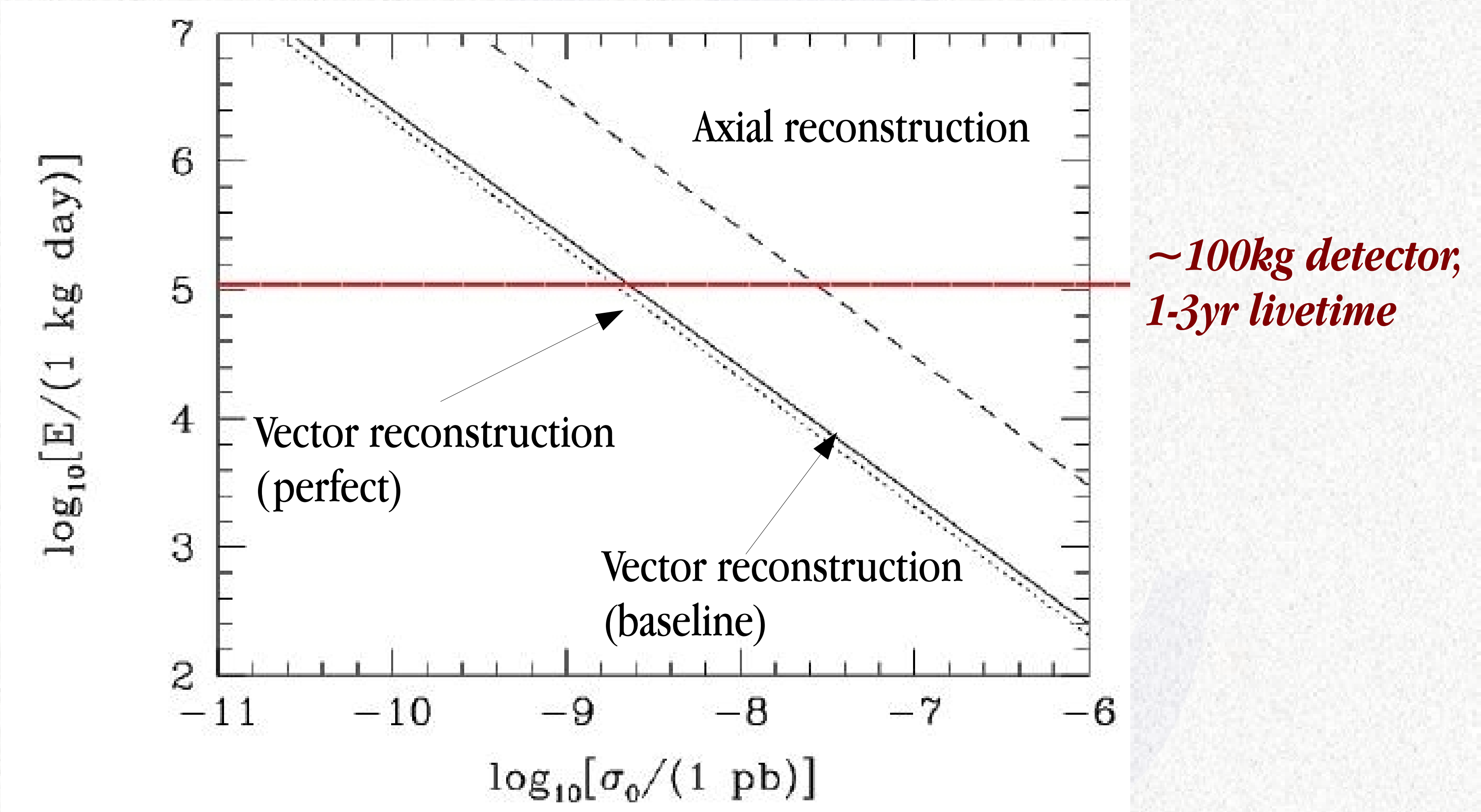
12: 3d vs 2d Readout

- 2d readout requires 2-100 times more events than 3d.
- Does not include detector resolution effects – so real numbers will be (potentially much) higher.



13: Sense or No Sense?

- If we cannot measure +**p**/-**p**, then for 3d readout, number of events increased by 1 order or magnitude.



14: Partial Sense Reconstruction

- Experiments now indicate that **+p/-p** ***may*** be measurable at energies <100keV.

- What happens if the sense is only reconstructed correctly with a recoil energy dependent probability?
  - *Indicated for E>100keV in Dujmic et. al., arxiv:0708.2370*

- We consider two cases:
  - *P(correct sense | E)=k, k=0.55-1.0*
  - *P(c.s. |E)=mE+c, P(20keV)=0.55,0.75, P(100keV)=0.55,1.0*
  - **See Green & Morgan, arxiv:0711.2234**

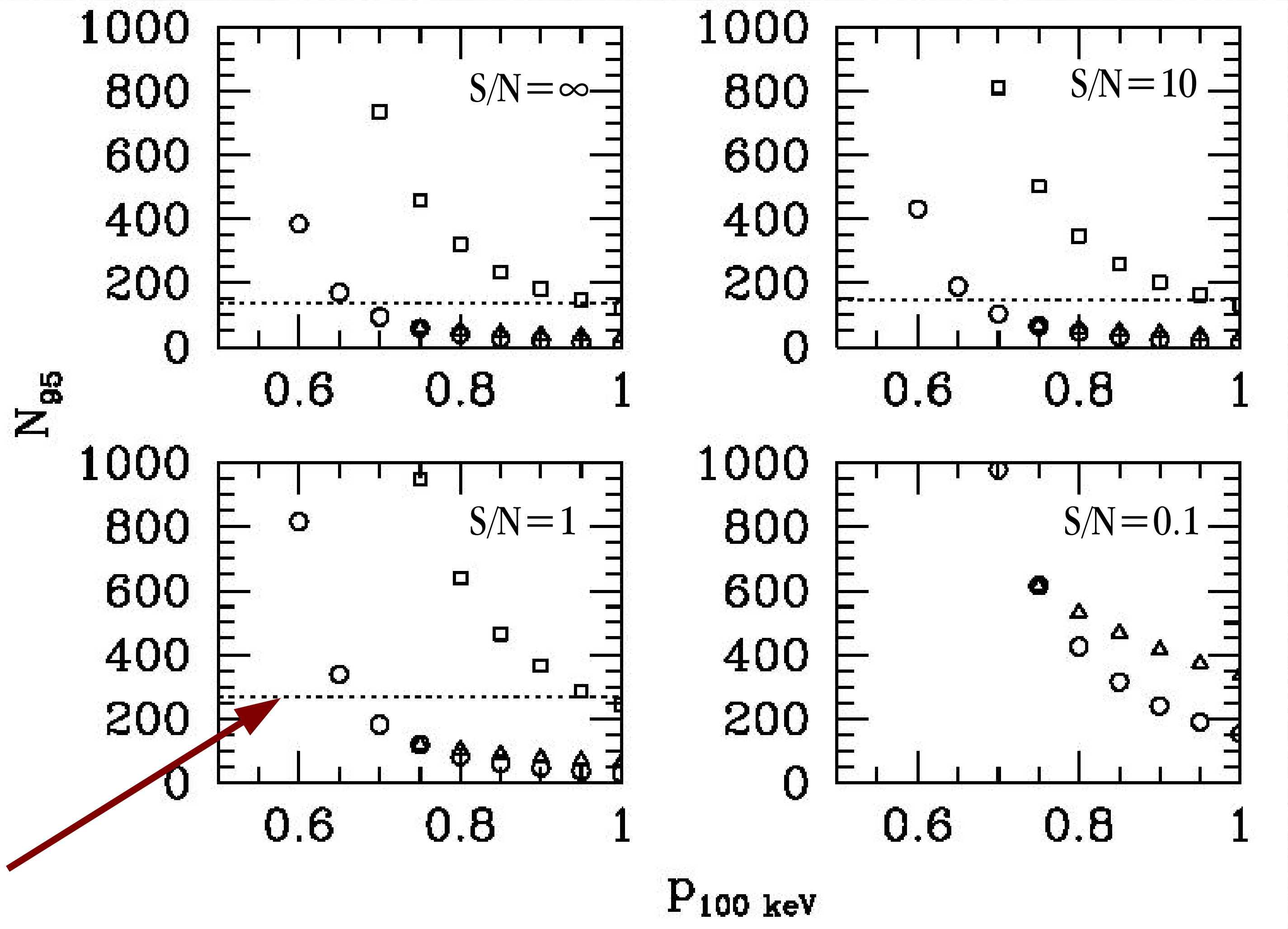
15: Partial Sense in 3d

$p_{100} = P(\text{c.s.} \mid 100\text{keV})$

circles: $P(E) = k = p_{100}$

triangles: $P(E) = mE + c$,
$P(20\text{keV}) = 0.75$
$p_{100} = 0.75\text{-}1.0$

squares: $P(E) = mE + c$,
$P(20\text{keV}) = 0.55$
$p_{100} = 0.55\text{-}1.0$



$\langle |\cos\theta| \rangle$

Gives comparison with pure axial (no sense) reconstruction

16: Vectors vs Axes

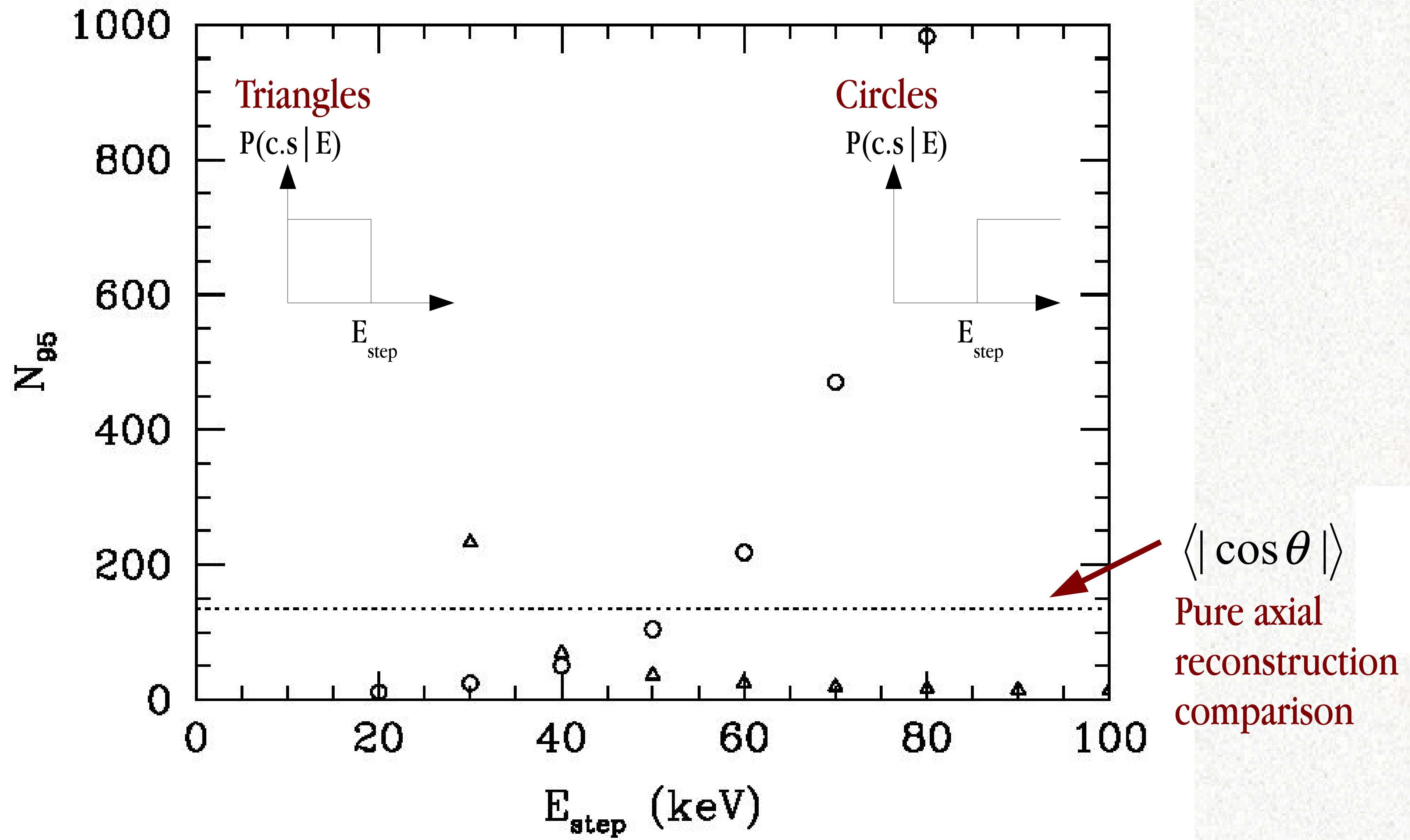
- Main conclusion of partial sense reconstruction:
  - ***If <100keV recoils have sense correctly measured <70% of the time, more efficient to throw away sense info and just use axial statistics!***

- This is due to the compromise between recoil rate and anisotropy (as with the energy threshold).

- We considered step functions for P(c.s.|E) with:
  - *P(c.s.|E<Estep)=0.5, P(c.s.|E>Estep)=1.0*
  - *P(c.s.|E<Estep)=1.0, P(c.s.|>Estep)=0.5*

16.1: What Energies for Sense Measure?

- Partial sense has the biggest effect at low recoil energy:



14: Conclusions

- 'Baseline' detector with 20keV threshold, realistic angular resolution, 3d readout with sense:
  - ***O(10) events to detect anisotropy***
- **Energy threshold** – *may not need to be that low.*
- **Background** – *minimize to optimize directional 'reach'.*
- **3d vs 2d** – *3d at least an order of magnitude better.*
- **Sense reconstruction – the** main effect...
  - *1. perfect sense reconstruction gives an order of magnitude reduction in number of events.*
  - *2.* ***BUT, sense reconstruction must work well at low (<50-100keV) energy or no better than axial readout.***