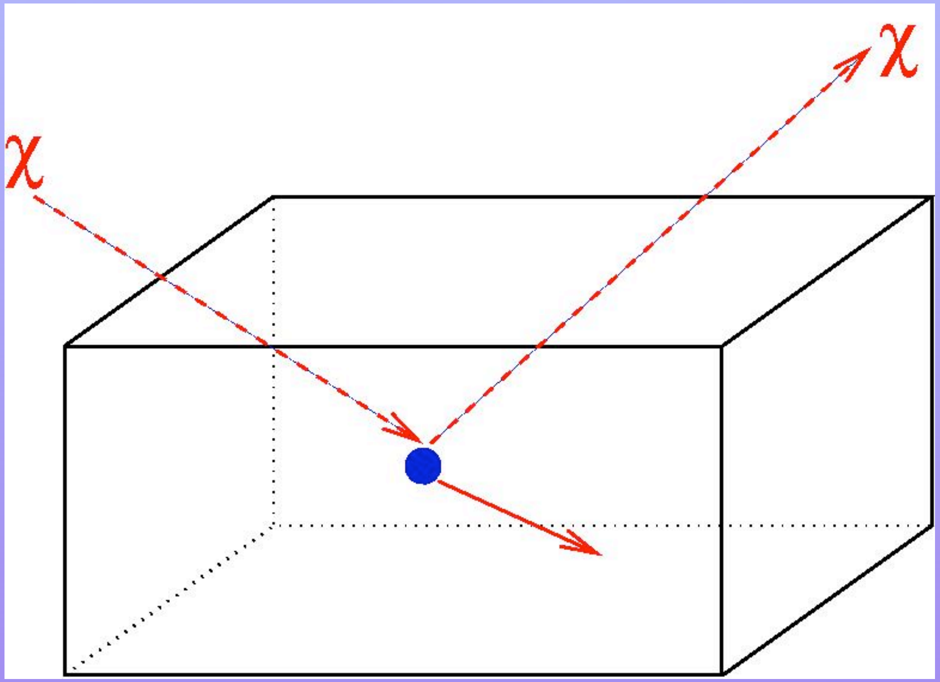
Dark matter halos and directionality

Anne Green
University of Sheffield

- Brief review of WIMP direct detection
- Halo structure and consequences for experiments
- (very) small scale structure

WIMP direct detection

Via elastic scattering in the lab:



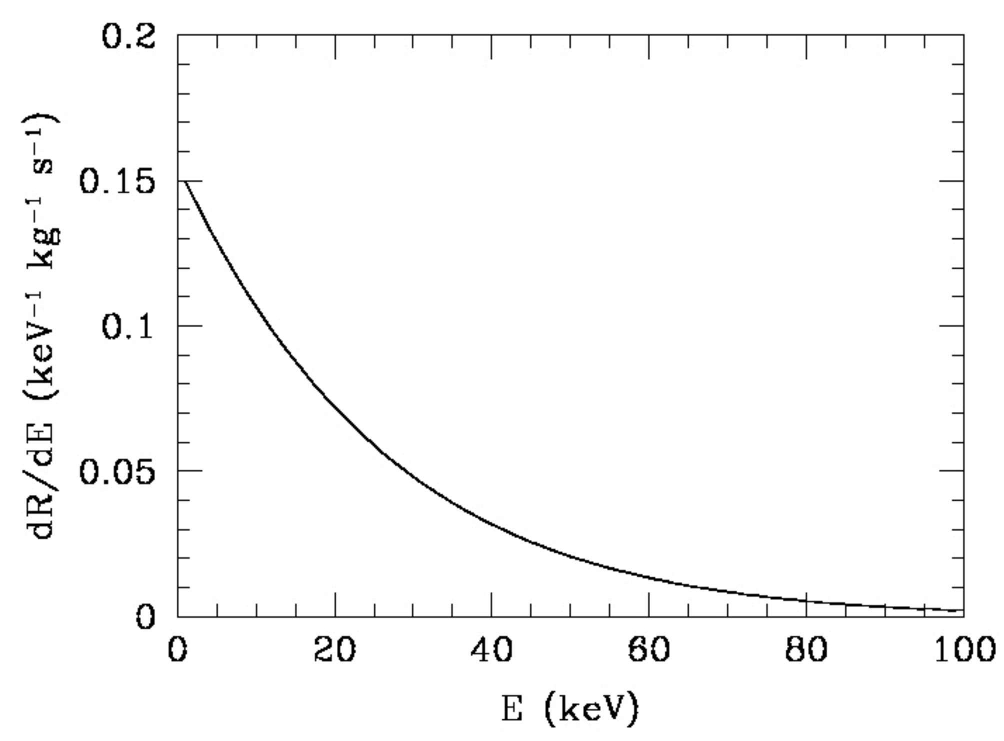
$$\chi + N \Rightarrow \chi + N$$

Detect recoil energy via ionisation, scintillation and/or heat.

Event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma\,\rho \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v}\mathrm{d}v$$

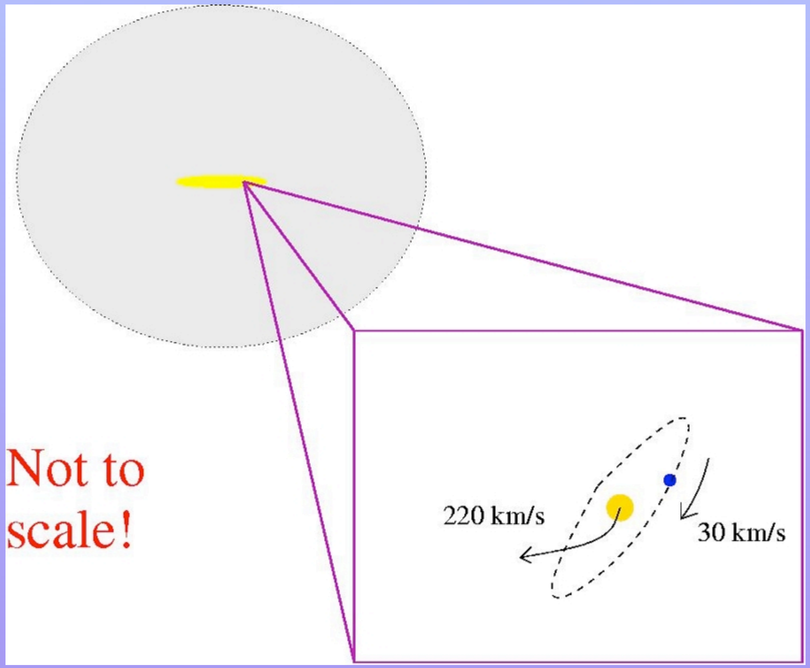
$$v_{\rm min} = \left[\frac{(m_\chi + m_{\rm N})^2}{2 m_\chi^2 m_{\rm N}} E\right]^{1/2}$$



m_χ = 100 GeV, ρ = 0.3 GeV/cm^3, σ =10^{-5} pb

and assuming 'standard' halo model.

WIMP smoking guns



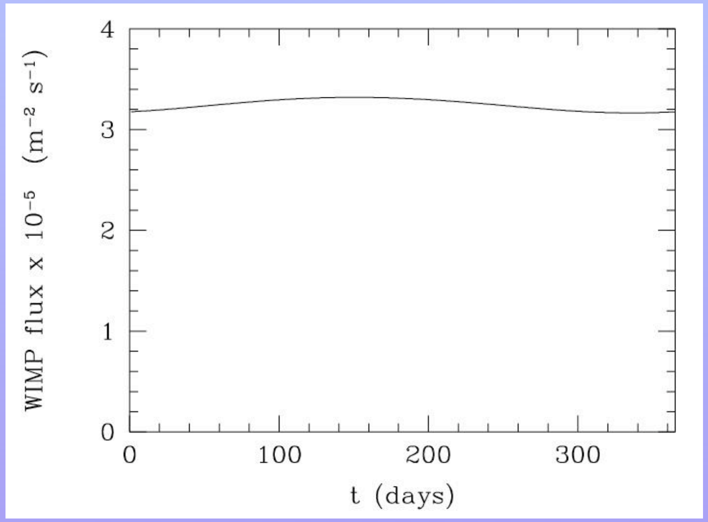
Earth's orbit

annual modulation and direction dependence

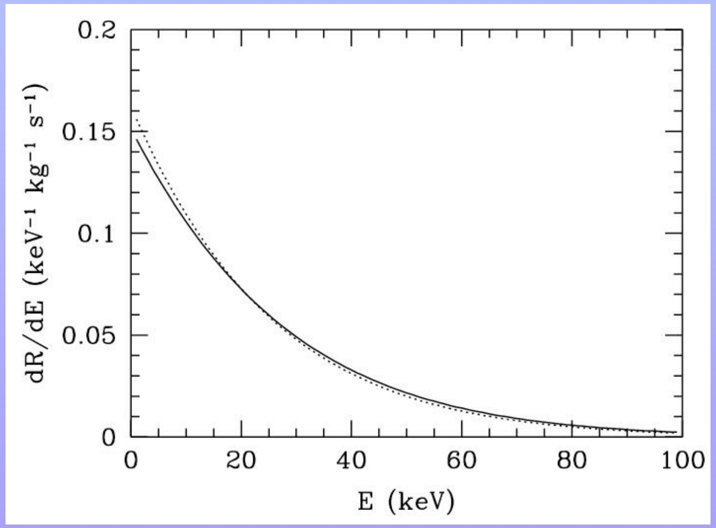
[Drukier, Freese & Spergel] [Spergel]

Annual modulation

m_χ = 100 GeV, ρ = 0.3 GeV/cm^3, σ =10^{-5} pb ('standard' halo model)

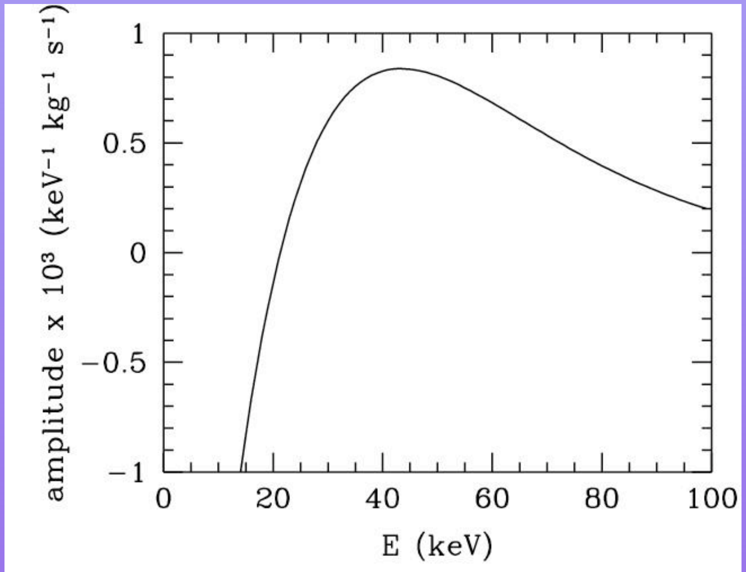


WIMP flux

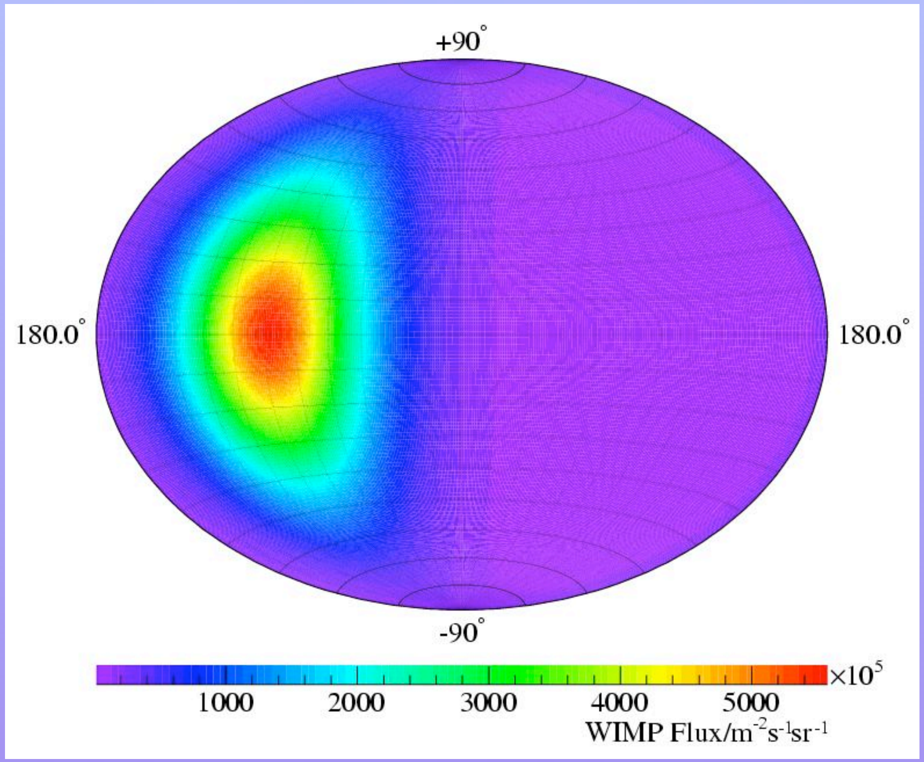


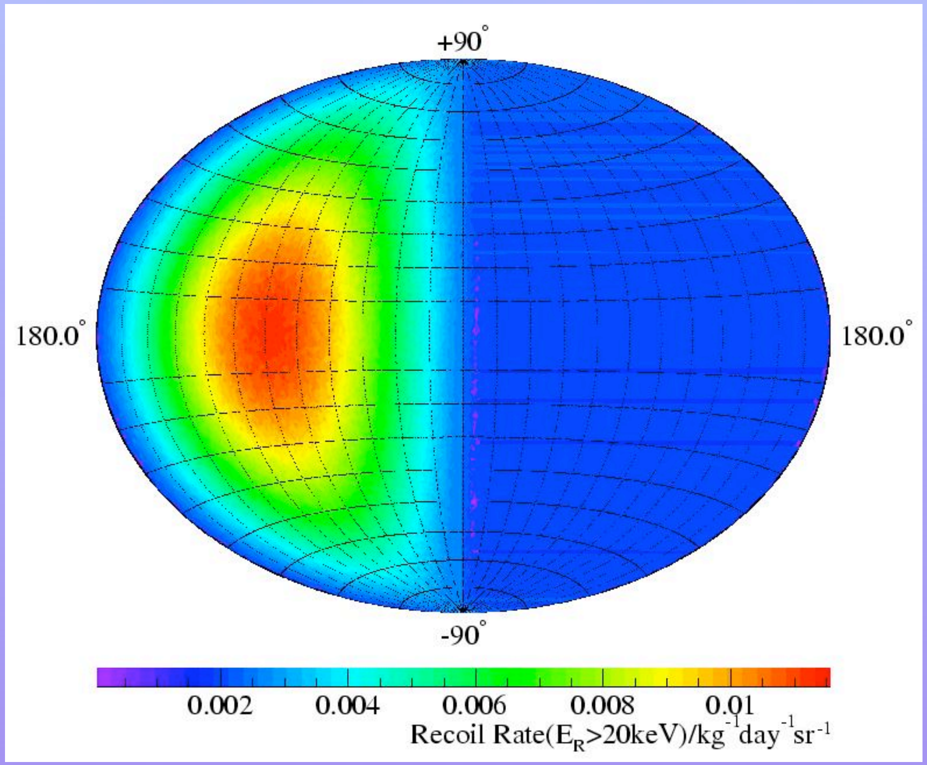
Differential event rate (June and December)

Annual modulation amplitude (event rate in June minus mean event rate)



Direction dependence





WIMP flux

Recoil rate

[Morgan, Green & Spooner]

Experimental considerations

(as seen by a theorist....)

General

Need low energy threshold and low backgrounds.

Annual modulation

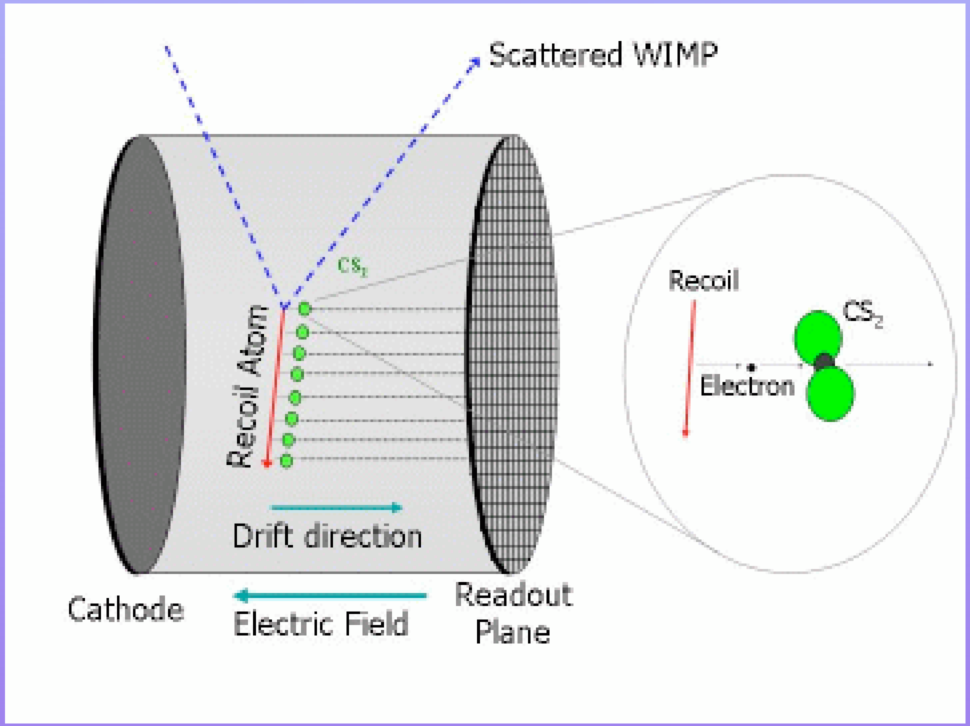
Signal is very small (a few per-cent) => need stable operation of a large mass detector (and eliminate other possible causes of a time dependence of the event rate).

Direction dependence

Much cleaner signal: only of order 10 events required for a positive detection, hard for backgrounds to mimic.

Need a detector which can measure the direction as well as the energy of nuclear recoil.

Directional Recoil Identification From Tracks



[UKDMC]

Modelling the Milky Way halo

Standard halo model

isothermal sphere: spherical, isotropic, smooth $\rho \sim r^{-2}$

$$f(v) = \frac{1}{\sqrt{\pi} v_c} \exp\left(-\frac{v^2}{v_c^2}\right)$$

Observations and simulations indicate that dark matter halos are (to some extent) triaxial, anisotropic and contain substructure.

Is the standard halo model a good approximation?

For the mean signal (averaged over time and direction): Perhaps

For the annual modulation and direction dependence: No

Observations:

Of other galaxies: b/a > 0.8 0.2 < c/a < 1.0

[e.g. Sackett & Merrifield reviews]

Milky Way: c/a ~ 0.7-0.9 [Olling & Merrifield]

Upper limit from kinematics of Sgr stream?

Contains >10 satellite galaxies

Simulations:

Triaxiality and anisotropy vary significantly between halos and also as a function of radius (closer to spherical and isotropic in the inner regions). [e.g. Moore et al.]

Simulations with gas cooling produce more spherical halos. [Dubinski, Kazantzidis et al.]

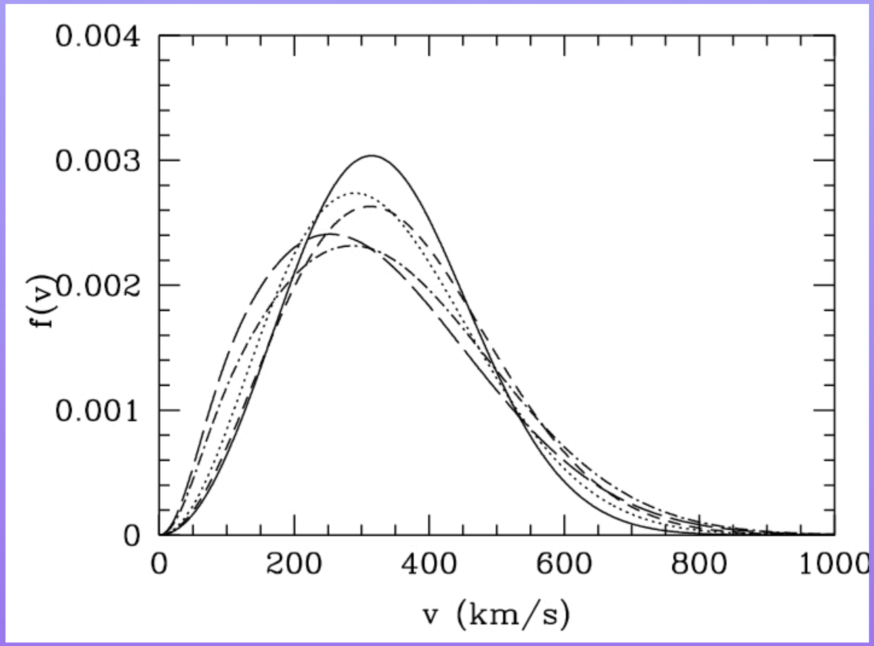
Contain large amounts of substructure. [Klypin et al., Moore et al.]

Halo modelling

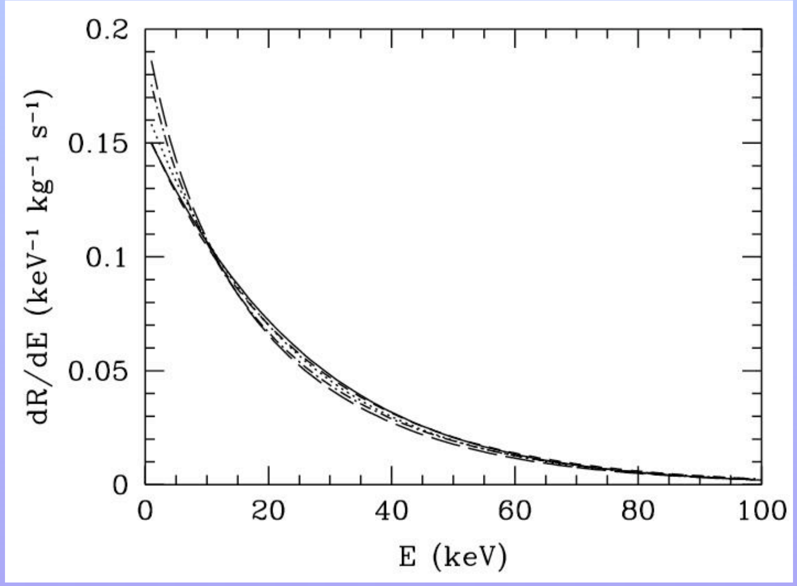
Standard approach: use analytic models which are solutions of the collisionless Boltzmann equation (i.e. assume the phase space distribution function has reached a steady state).

An example

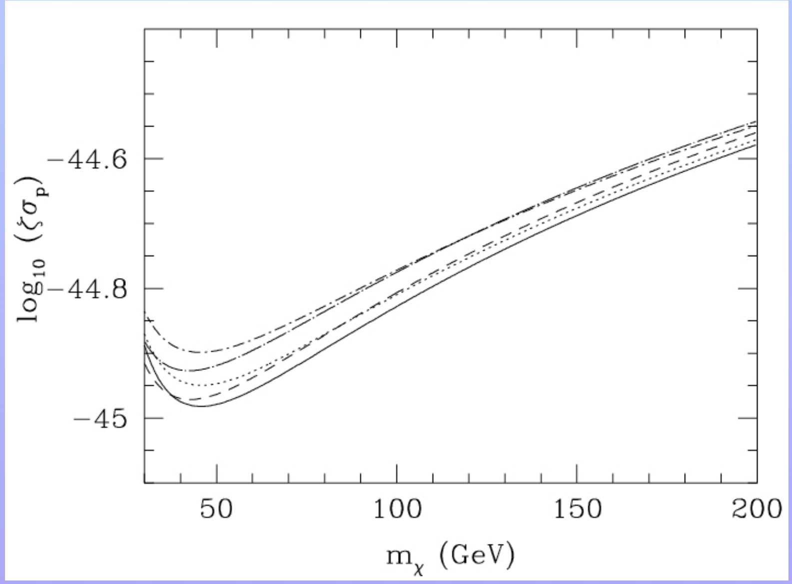
Logarithmic Ellipsoidal model [Evans, Carollo & de Zeeuw]



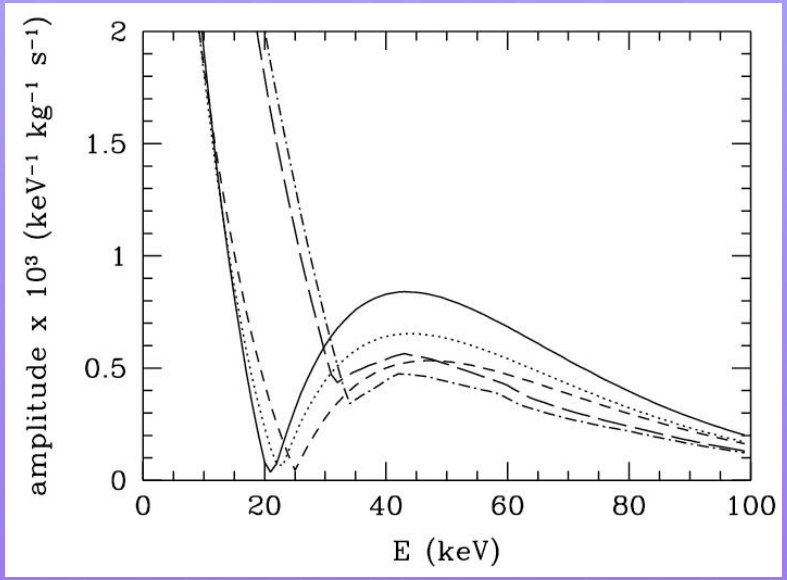
Simplest, triaxial generalisation of the isothermal sphere, f(v) is a multi-variate gaussian in conical co-ordinates. Triaxiality and anisotropy independent of radius.



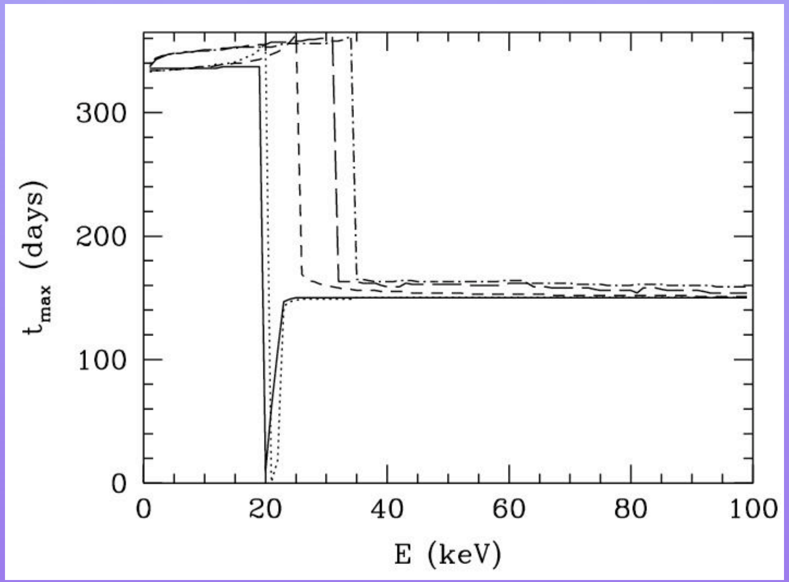
Differential event rate



Exclusion limits from IGEX experiment



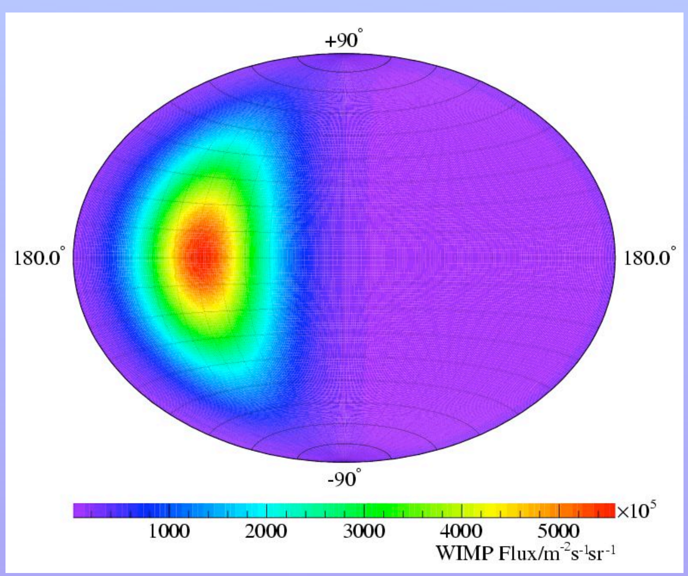
Annual modulation amplitude

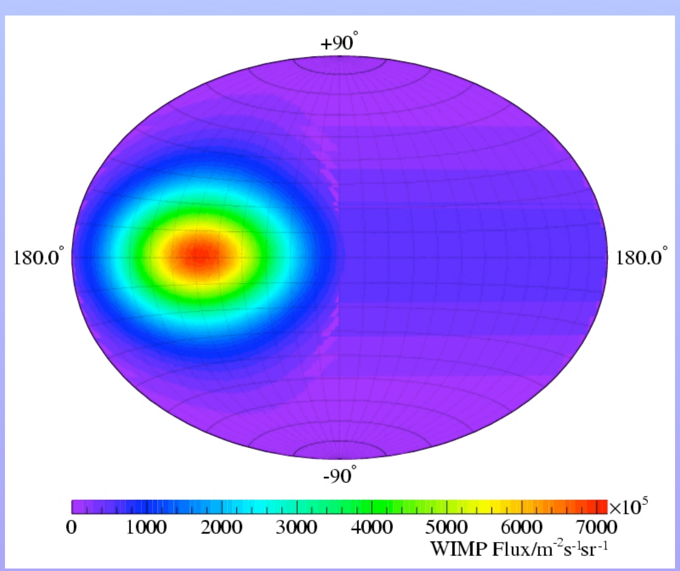


Annual modulation phase

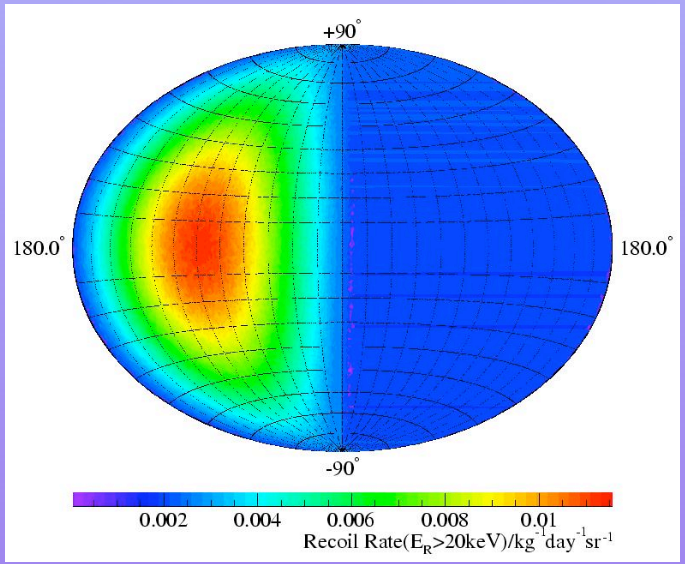
Standard halo | LGE model

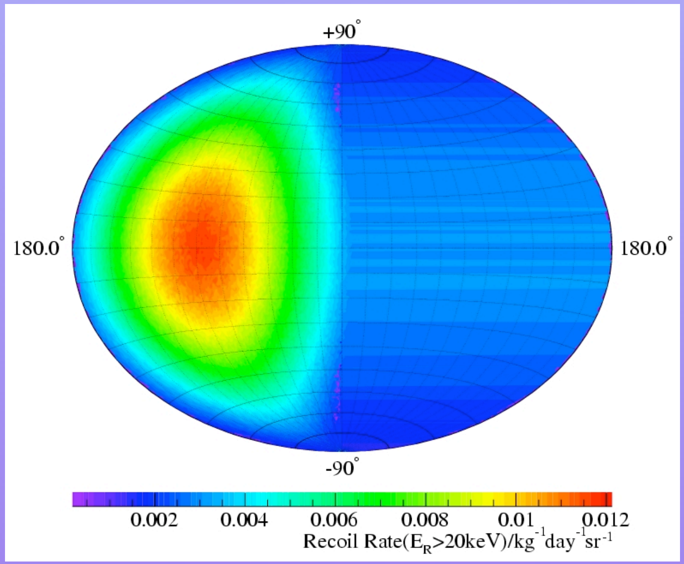
WIMP flux





Recoil rate



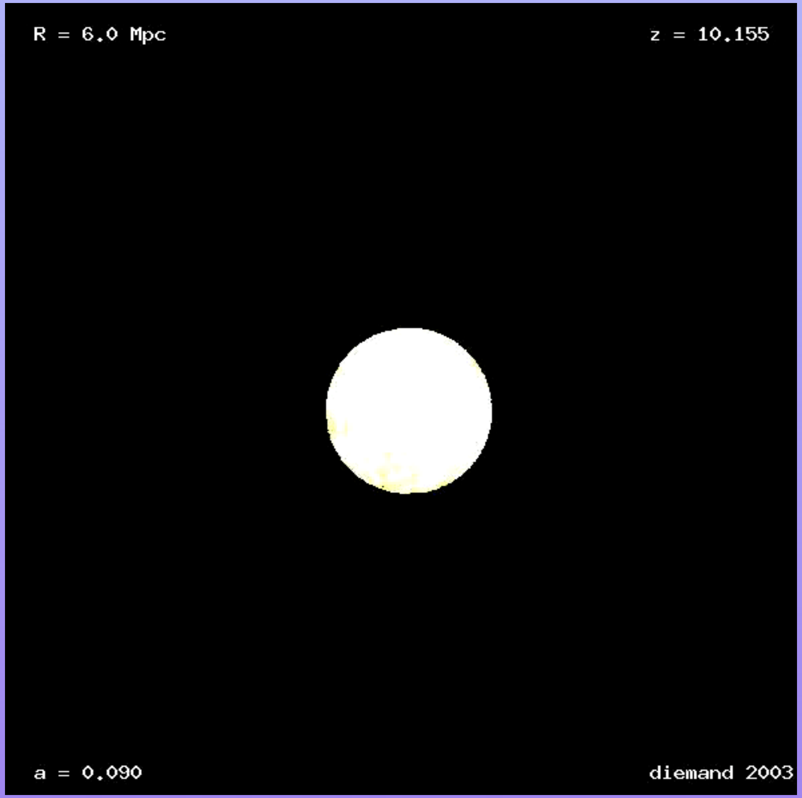


~1000s of events would be required to differentiate between recoil rate in ‘next/current’ generation detectors.

[Morgan, Green & Spooner]

Formation of dark matter halos

Structure forms hierarchically: halos form from the merger and accretion of smaller sub-halos.

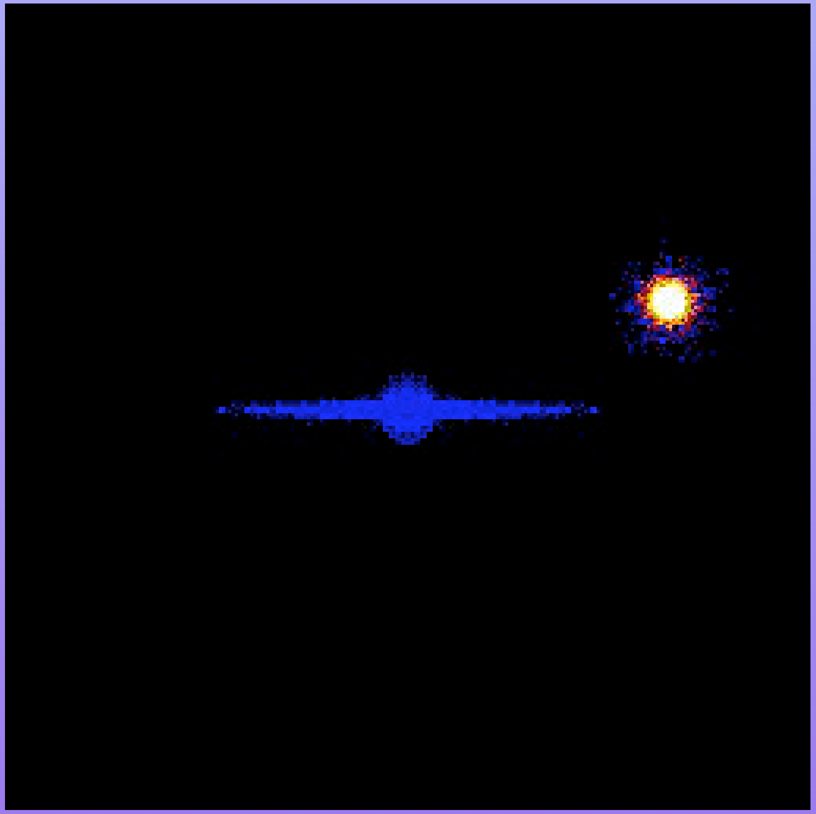


Simulation of the formation of a Galaxy Cluster by Juerg Diemand, Joakim Stadel, Ben Moore (University of Zurich) on the zBox Supercomputer at the University of Zurich.

Tidal debris

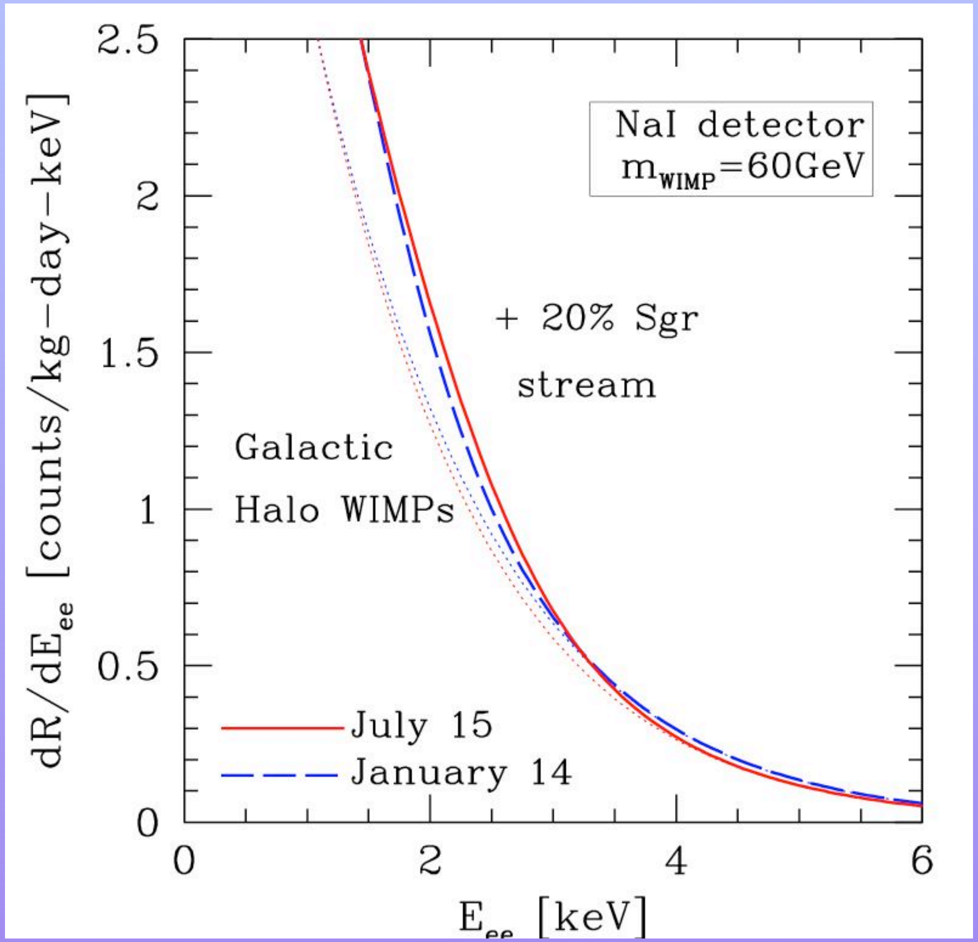
~5% of the halo stars in the solar neighbourhood are moving in a coherent stream.

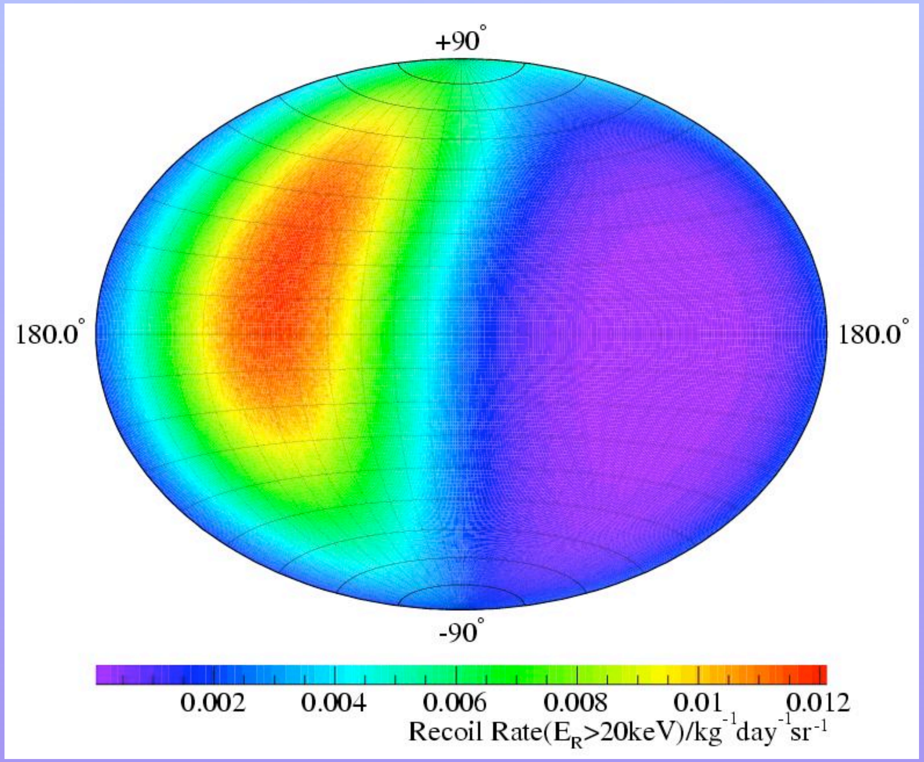
Sagittarius and 'Galactic ring' debris streams found in SDSS and 2MASS data.



Johnston

Signals from a WIMP stream





Step in the differential event rate (position and height modulated annually).

[Gondolo, Freese & Newberg]

Peak direction deviates from Sun's motion.

Detectable with ~200 events (depending on density and velocity of stream).

[Morgan, Green & Spooner]

Small scale structure

WIMP direct detection probes the dark matter distribution on sub-mpc scales (c.f. ~100pc resolution of Galaxy simulations).

How clumpy is the small scale dark matter distribution?

This depends on the structure and evolution of the first generation of DM halos to form, which in turn depends on the nature of the dark matter and its interactions

WIMP microphysics

[Hofman, Schwarz & Stocker; Berezinsky, Dokuchaev & Eroshenko; Green, Hofmann & Schwarz; Loeb & Zaldarriaga]

After freeze-out (chemical decoupling) WIMPS carry on interacting kinetically with radiation.

$$\chi + \chi \not\Leftrightarrow X + X \qquad\qquad \chi + X \Rightarrow \chi + X$$

Energy transfer erases v. small scale density perturbations (collisional damping).

After kinetic decoupling WIMPs free-stream, erasing perturbations on slightly larger scales.

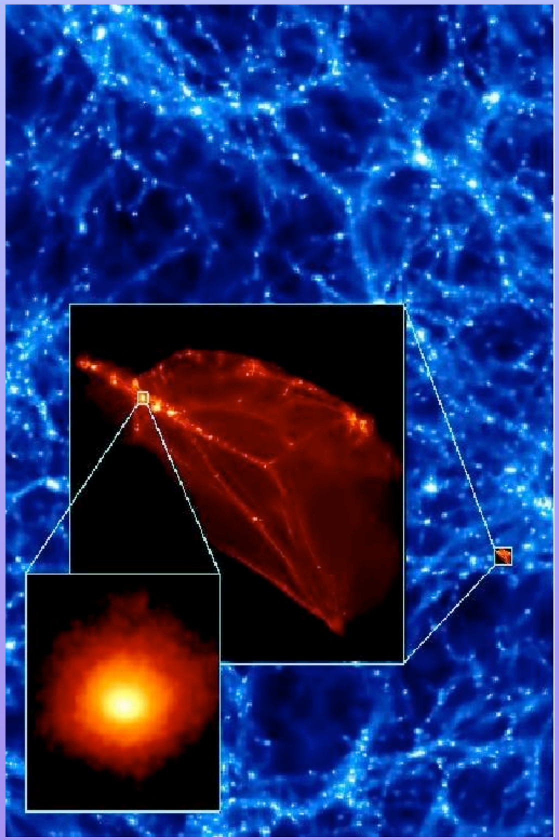
Net result: perturbations on (comoving) scales smaller than 1pc are erased.

Properties of first halos: $r \sim 0.01$ pc, mass $\sim 10^{-6} M_{sun}$,

present day overdensity (assuming they survive....) $\sim 10^6$

Numerical simulations

[Diemand, Moore & Stadel]



Re-simulate a small region starting at z=350 (when the fluctuations are still linear) up until z=26 (when the high resolution region begins to merge with surrounding low resolution regions).

Do they survive do the present day?

Possibly destroyed by interactions with stars? [Zhao, Taylor, Silk & Hooper]

Extrapolating sub-structure mass function to small masses, tens of per-cent of MW mass in bound sub-halos, ***BUT*** very sensitive to slope of the sub-halo mass function.

Summary

- Two potential WIMP smoking guns: annual modulation and direction dependence.
- Signals depend on the local WIMP distribution.
- The ‘standard’ halo model is unlikely to be a good approximation.
- Tidal streams are potentially detectable (WIMP astronomy).
- How smooth is the dark matter distribution on small scales?