Determining the WIMP mass from direct detection experiments

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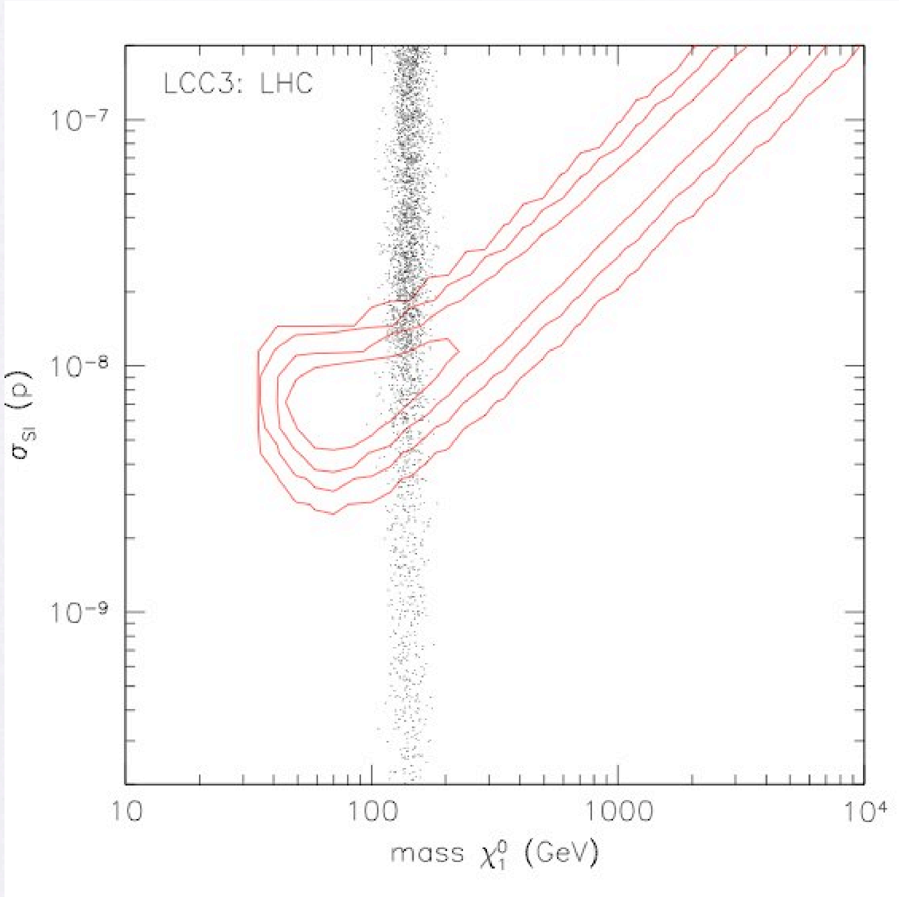
- ✯ Why?
- ✯ How?
- ✯ Results
- ✯ Caveats/validity of assumptions.......

based on: hep-ph/0703217

Why?

Would:

- help us work out what WIMPs are
- probe parameter space of particle physics models (supersymmetry, universal extra dimensions....)
- provide complementary information to collider experiments



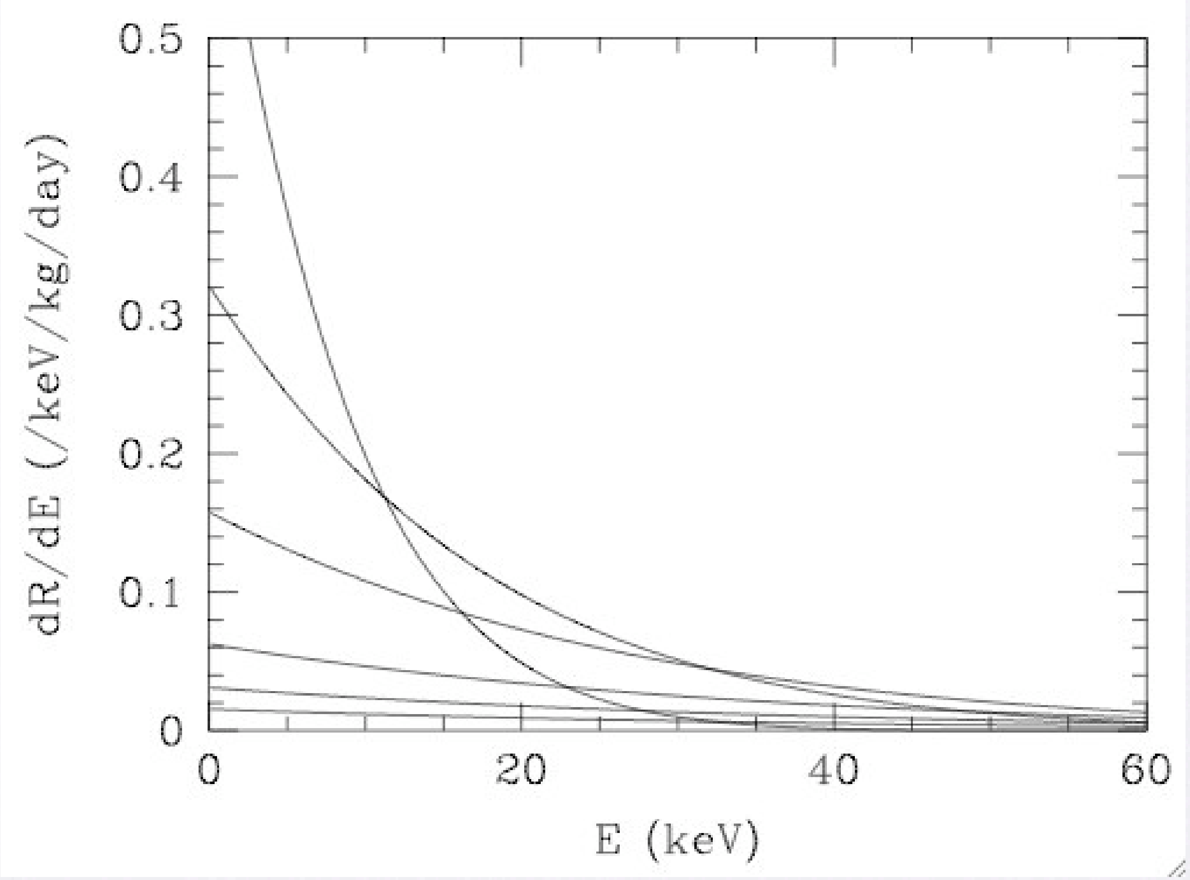
Baltz, Battaglia, Peskin & Wiszansky benchmark point in stau coannihilation region, LHC v. SuperCDMS
c.f. also Hooper and Taylor.

How?

General principle:

Differential event rate depends on the WIMP mass:

$$\frac{dR}{dE}(E) = \frac{\sigma_p \rho_\chi}{2\mu_{p\chi} m_\chi} A^2 F^2(E) \langle \int_{v_{min}}^{\infty} \frac{f_v(t)}{v} dv \rangle \qquad v_{min} = \left(\frac{E m_A}{2\mu_{A\chi}} \right)^{1/2}$$



WIMP mass
(top to bottom)
25, 50, 100, 250,
500 & 1000 GeV

[c.f. Lewin & Smith]

Neglecting the Earth's orbit and the Galactic escape speed:

$$\frac{dR}{dE}(E) = \left(\frac{dR}{dE}\right)_0 F^2(E) \exp\left(-\frac{E}{E_R}\right)$$

$$\left(\frac{dR}{dE}\right)_0 = \frac{\sigma_p \rho_\chi}{\sqrt{\pi}\mu_{p\chi}^2 m_\chi v_c} A^2$$

event rate in $E \rightarrow 0\, keV$ limit

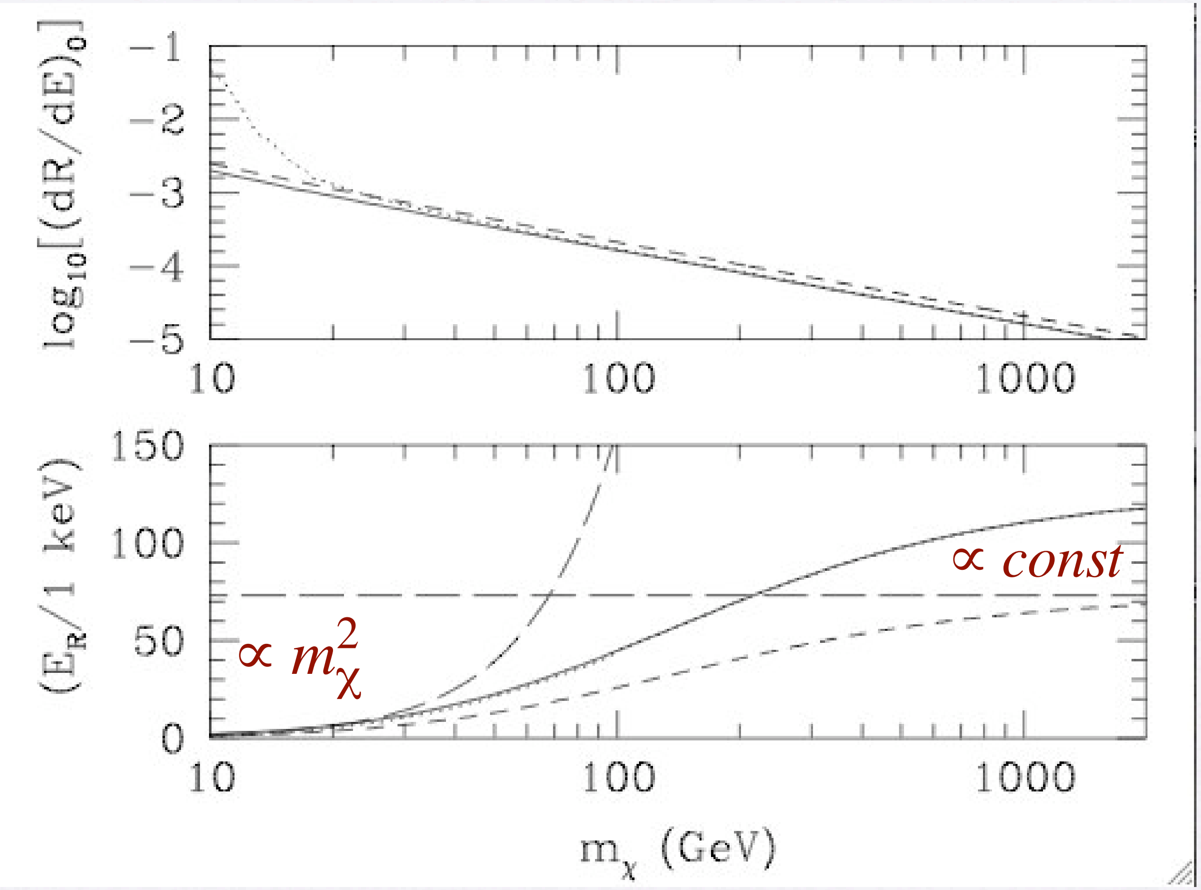
$$E_R = \frac{2\mu_{A\chi}^2 v_c^2}{m_A}$$

characteristic energy scale

Including (and averaging over) the Earth's orbit and the Galactic escape speed:

$$\frac{dR}{dE}(E) \approx c_1 \left(\frac{dR}{dE}\right)_0 F^2(E) \exp\left(-\frac{E}{c_2 E_R}\right)$$

c_1 and c_2 fitting parameters of order unity (exact values depend on target mass, energy threshold, escape velocity)



- - - - simple analytic calculation neglecting Earth's motion

——— with fitting constant to take into account Earth's motion, for E_{th}=0 keV

.... as ———, for E_{th}=10 keV

– – – asymptotic large and small mass expressions

Main upshot:

Dependence of spectrum on WIMP mass strong (weak) for light (heavy) WIMP [compared with target mass].

Footnote: Could in principle measure mass from energy at which annual modulation changes phase [c.f. Lewis & Freese], but this would require lots of data.

Application to MC `data':

Consider range of input WIMP masses: 25, 50, 100, 250 & 500 GeV.

And (efficiency weighted) detector exposures 3×10^2, 3×10^3, 3×10^4 and 3×10^5 kg day. (last 3 exposures correspond, roughly to 3 proposed phases of SuperCDMS [25kg, 150kg and 1 ton] taking data for a year with detection efficiency ~0.5)

Assumptions:

- Ge detector, with E_{th}=10 keV, zero background and perfect energy resolution
- detection efficiency is independent of energy
- form factor has Helm form (with parameters values as advocated by Lewin and Smith)
- $\sigma = 10^{-7}$ pb (just below current CDMS exclusion limits)
- local WIMP speed distribution is known (Maxwellian with v_c=220 km/s)
- local WIMP density is 0.3 GeV/cm^3

These are, generally, optimistic assumptions

→ results are for best case scenario

For each WIMP mass-exposure combination, simulate 10^4 experiments.

For each experiment:

i) draw number of events observed from Poisson distribution

ii) draw this number of events from input spectrum

iii) find best fit mass and cross-section by maximising extended likelihood function:

$$L = \frac{\lambda^{N_{expt}} \exp(-\lambda)}{N_{expt}} \Pi_{i=1}^{N_{expt}} f(E_i)$$

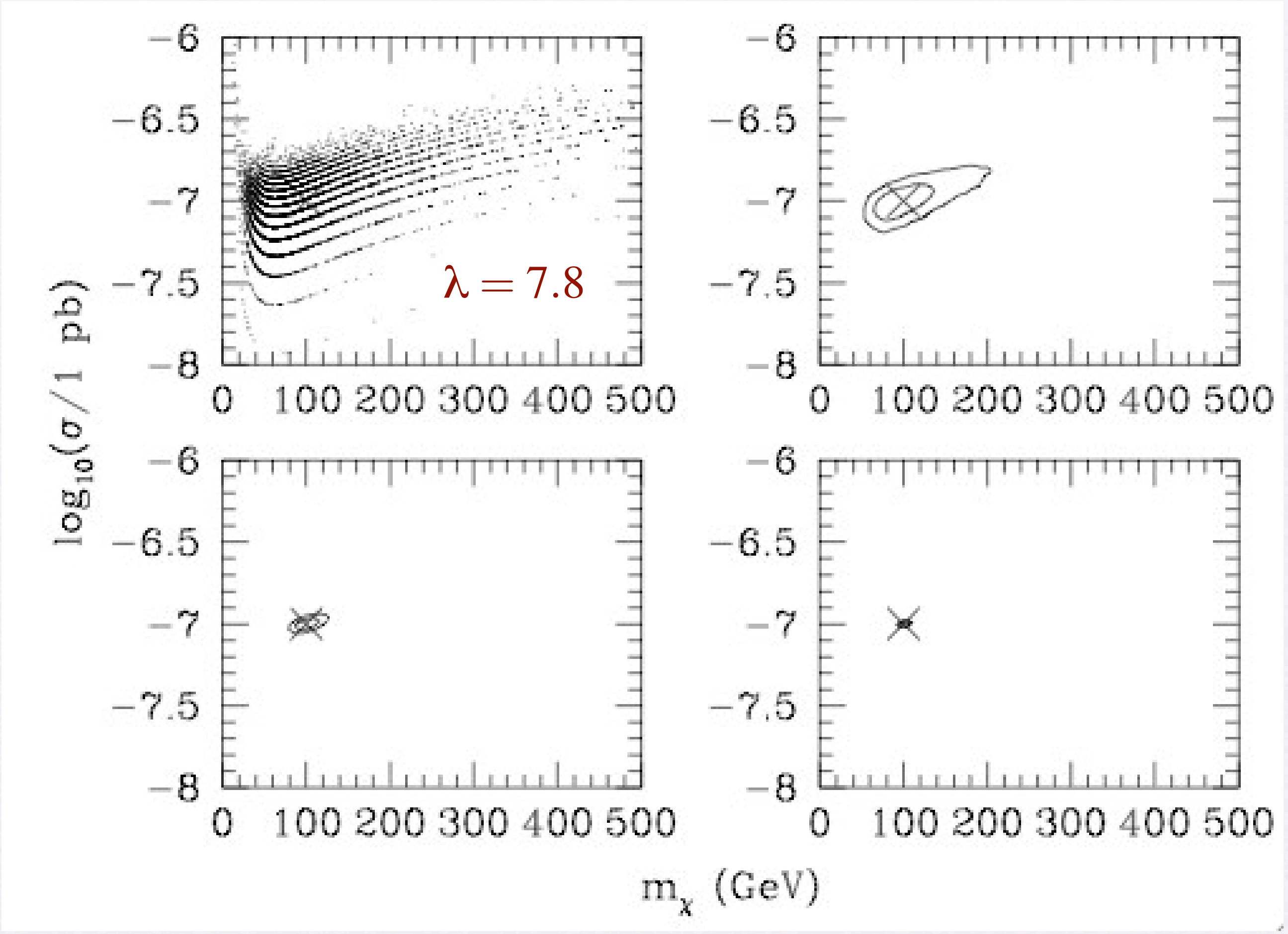
λ	Expected number of events	N_{expt}	Observed number of events
$f(E)$	Normalised event rate	E_i	Energy of i-th event

Plot distribution of best fit masses and cross-sections.

Results

3x10² kg day

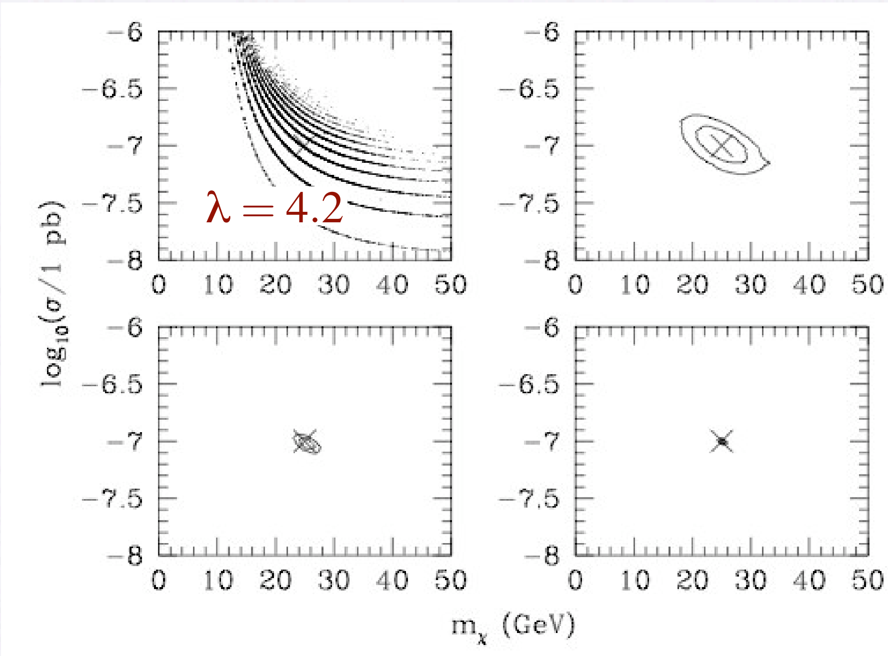
3x10³ kg day



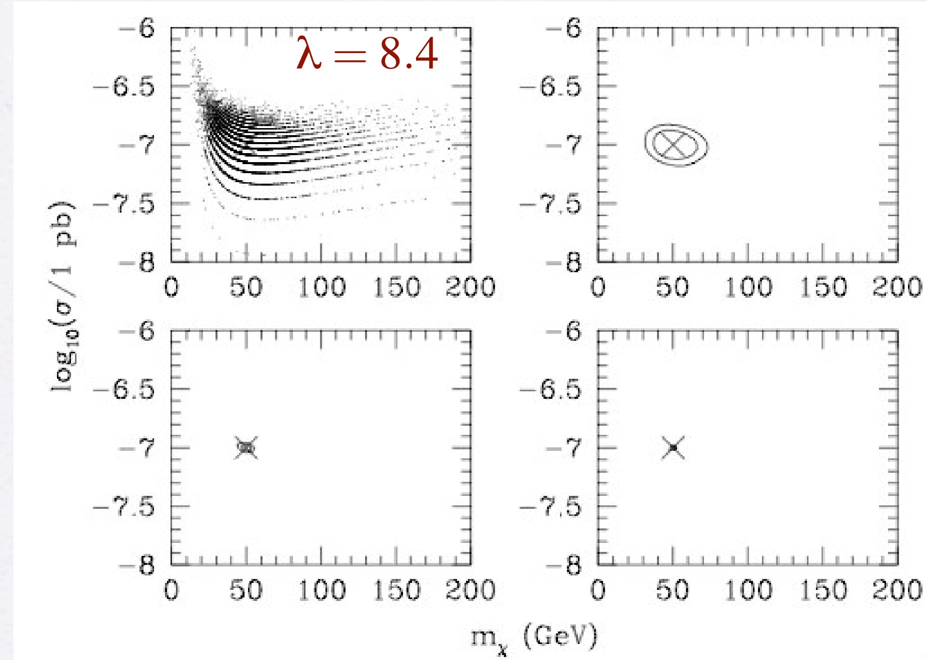
3x10⁴ kg day

3x10⁵ kg day

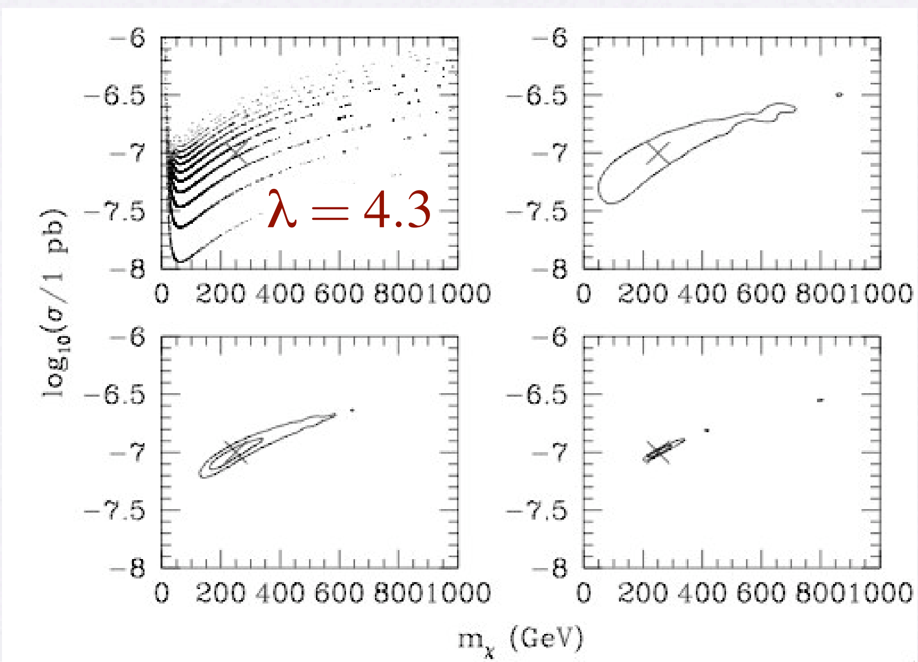
m_χ = 100 GeV



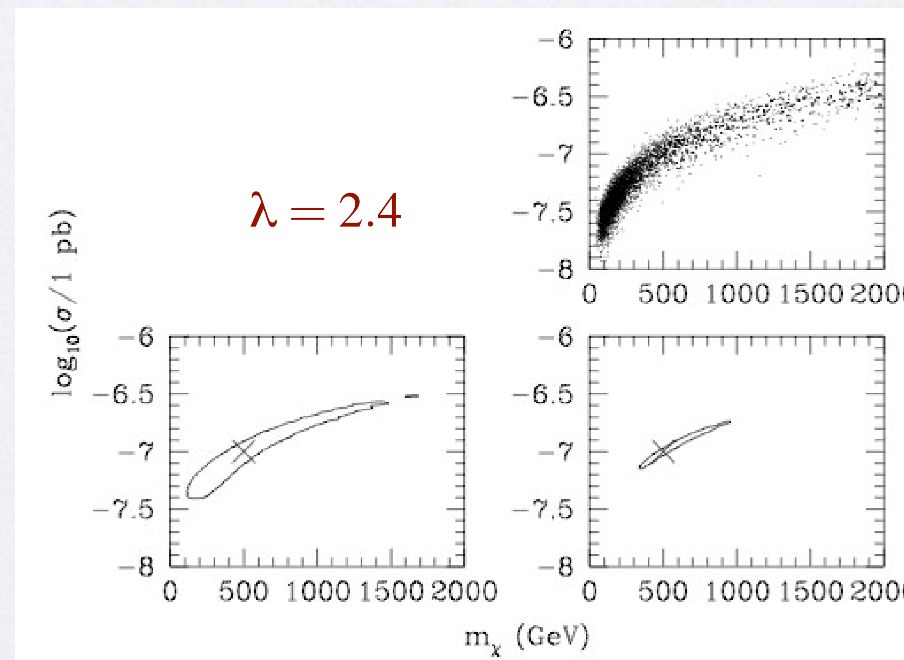
$m_\chi = 25$ GeV



$m_\chi = 50$ GeV



$m_\chi = 250$ GeV



$m_\chi = 500$ GeV

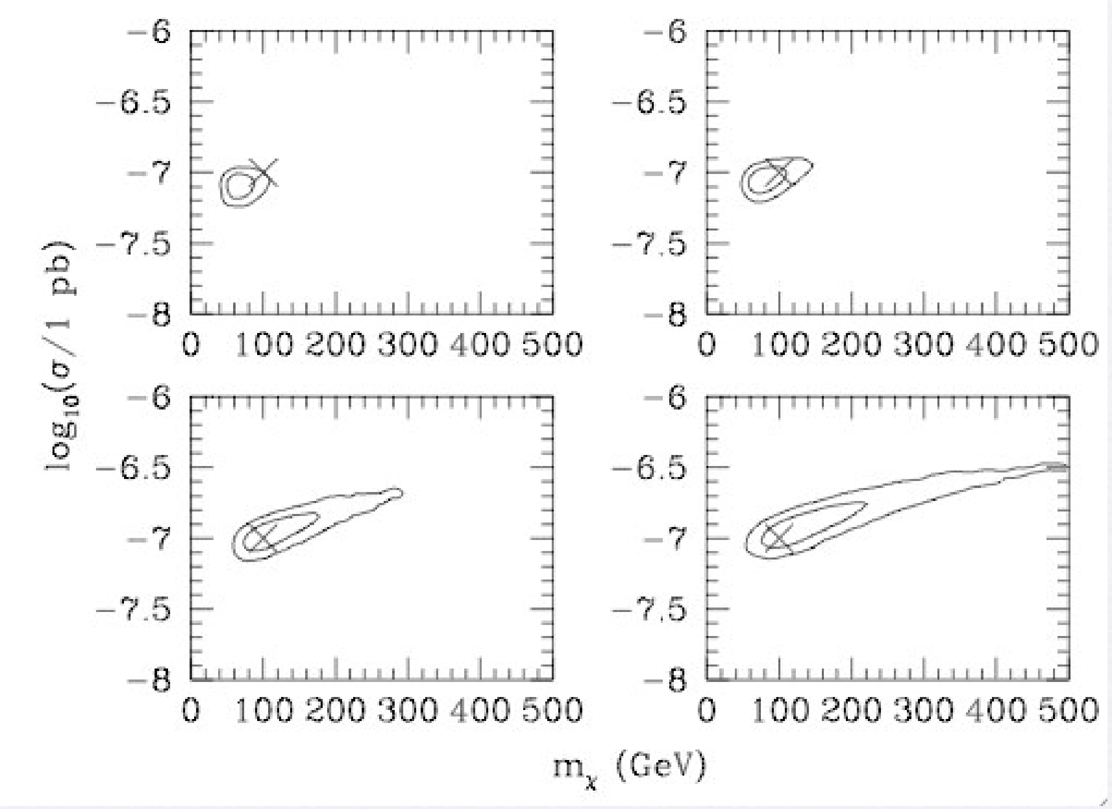
Caveats/validity of assumptions

WIMP speed distribution

Varying v_c in observationally allowed range: 220 +/- 20 km/s:

v_c=180 km/s

v_c=200 km/s



v_c=240 km/s

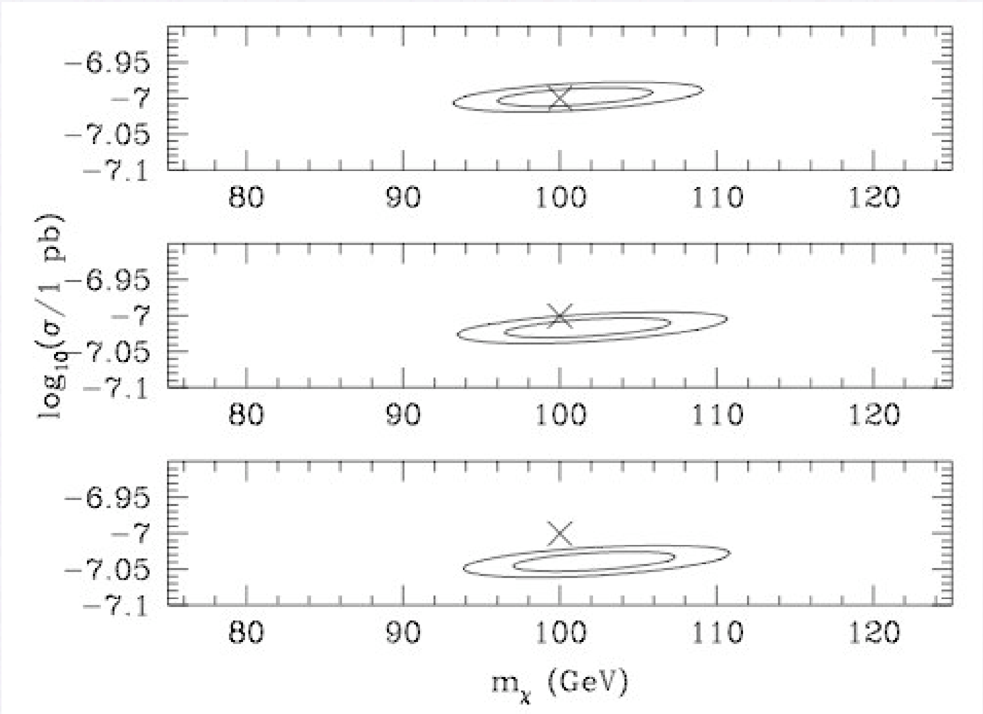
v_c=260 km/s

m_χ = 100 GeV 3x10[3] kg day

Systematic error: $$\frac{\Delta m_\chi}{m_\chi} = [1 + (m_\chi / m_A)] \frac{\Delta v_c}{v_c}$$

Non-standard (but still smooth) halo models:

Evans,Carollo & de Zeeuw logarithmic ellipsoidal model, triaxial and anisotropic



Standard halo

Plausible parameters

Extreme parameters

m_{χ} = 100 GeV 3×10^{5} kg day

IF WIMP distribution is smooth, mean differential event rate depends only weakly on WIMP speed dist, therefore systematic error (from lack of knowledge of true WIMP dist) small.

BUT WIMP distribution on sub-millipc scales probed by direct detection experiments may not be smooth. [e.g. Moore et al., Stiff & Widrow]

Local WIMP density

For smooth halo of models, factor of ~3 uncertainty [Gates, Gyuk & Turner; Bergström, Ullio & Buckley] in local WIMP density leads to similar uncertainty in cross-section.

Bigger issue if small scale WIMP dist not smooth.

Zero background

Validity??? Non-zero background could in principle be included in maximum likelihood analysis, also fit for background rate (and possibly shape of background spectrum), [c.f. Krauss et al.] measurements of WIMP mass and cross-section would be degraded.

Other

Uncertainty in form factor and finite resolution (if FWHM ~ 1 keV) likely to be sub-dominant compared to above issues.

Spin dependent interactions and/or different interactions with proton and neutron.....[c.f. Bourjaily & Kane]

Conclusions

☆ Direct detection energy spectrum depends on the WIMP mass, strongly for light (compared with target) WIMPs, weakly for heavy WIMPs.

☆ **IF** optimistic assumptions about the WIMP properties ($\sigma = 10^{-7}$ pb, *just below current CDMS exclusion limits*, smooth WIMP distribution on sub-milli-pc scales) and detector set-up (zero background) are valid, with exposures of 3×10^3, 3×10^4, 3×10^5 kg day (corresponding, roughly, to the 3 proposed phases of SuperCDMS) it will be possible to measure the mass of a light WIMP with an accuracy of ~25%, 15% and 2.5% respectively.

☆ If the WIMP is heavy even with optimistic assumptions and large exposures it will only be possible to place a lower limit on its mass.

☆ If the WIMP mass was accurately measured by other means could invert the process and reconstruct the local WIMP velocity distribution [Drees & Shan] but need ~1000s of events to do this with reasonable accuracy.