Learning from WIMPs

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- Models of structure formation, X ray temperature of clusters of galaxies, ...
- Cosmic Microwave Background anisotropies (WMAP) imply $\Omega_{\rm DM} h^2 = 0.105^{+0.007}_{-0.013}$ **Spergel et al., astro–ph/0603449**

Weakly Interacting Massive Particles (WIMPs)

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- In standard cosmology, roughly weak cross section automatically gives roughly right relic density for thermal WIMPs! (On logarithmic scale)
- Roughly weak interactions may allow both *direct* and *indirect* detection of WIMPs

WIMP production

Let χ be a generic DM particle, n_χ its number density (unit: GeV^3). Assume $\chi = \bar{\chi}$, i.e. $\chi\chi \leftrightarrow$SM particles is possible, but single production of χ is forbidden by some symmetry.

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Evolution of n_χ determined by Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\text{ann}} v \rangle \left(n_\chi^2 - n_{\chi,\,\text{eq}}^2 \right)$$

$H = \dot{R}/R$: Hubble parameter
$\langle \ldots \rangle$: Thermal averaging
$\sigma_{\text{ann}} = \sigma(\chi\chi \to \text{SM particles})$
v : relative velocity between χ's in their cms
$n_{\chi,\,\text{eq}}$: χ density in full equilibrium

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Gives

$$\Omega_\chi h^2 \propto \frac{1}{\langle v \sigma_{\rm ann} \rangle} \sim 0.1 \text{ for } \sigma_{\rm ann} \sim \text{pb}$$

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Can we test these assumptions, if Ω_χ and "all" particle physics properties of χ are known?

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Assume $T_0 \lesssim T_F,\ n_\chi(T_0) = 0$ (T_0: Initial temperature)

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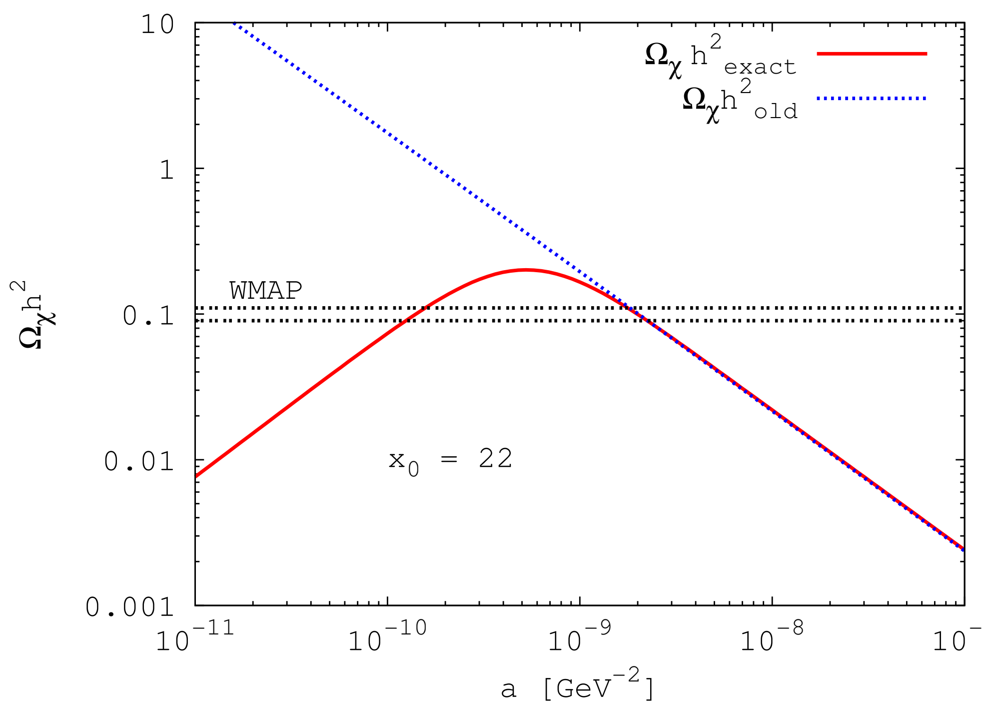

Low temperature scenario (cont.'d)

Using explicit form of H, $Y_{\chi,\mathrm{eq}}$, Boltzmann eq. becomes

$$\frac{dY_\chi}{dx} = -f\left(a + \frac{6b}{x}\right)x^{-2}\left(Y_\chi^2 - cx^3\mathrm{e}^{-2x}\right) .$$

$f = 1.32\, m_\chi M_{\mathrm{Pl}}\sqrt{g_*},\ c = 0.0210\, g_\chi^2/g_*^2$

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For $T_0 \ll T_F$: Annihilation term $\propto Y_\chi^2$ negligible: defines $0-$th order solution $Y_0(x)$, with

$$Y_0(x \to \infty) = f c \left[\frac{a}{2} x_R \mathrm{e}^{-2x_R} + \left(\frac{a}{4} + 3b\right) \mathrm{e}^{-2x_R}\right]\ .$$

Note: $\Omega_\chi h^2 \propto \sigma_{\text{ann}}$ in this case!

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For intermediate temperatures, $T_0 \lesssim T_F$: Define 1st–order solution

$$Y_1 = Y_0 + \delta .$$

$\delta < 0$ describes pure annihilation:

$$\frac{d\delta}{dx} = -f\left(a + \frac{6b}{x}\right) \frac{Y_0(x)^2}{x^2} .$$

$\delta(x)$ can be calculated analytically: $\delta \propto \sigma_{\mathrm{ann}}^3$

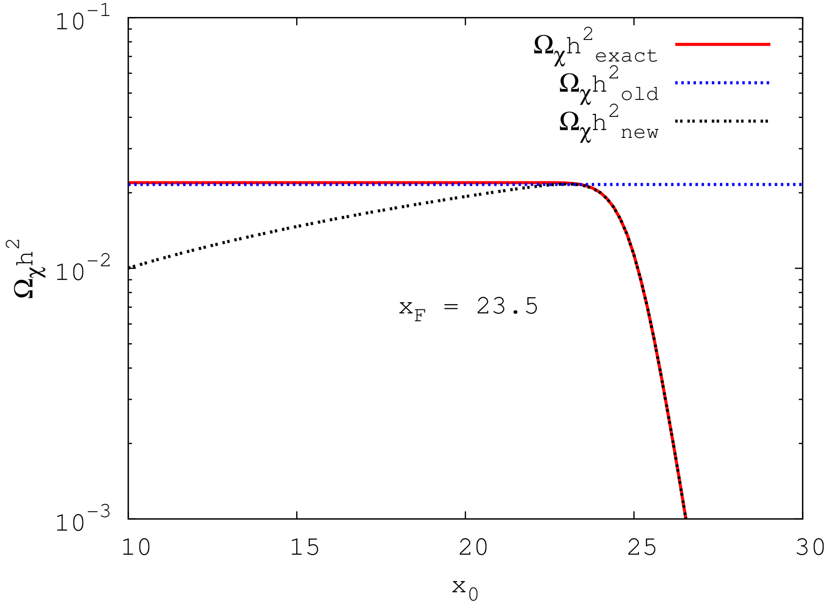
Low temperature scenario (cont.'d)

Get good results for $\Omega_\chi h^2$ for all $T_0 \leq T_F$ through "resummation":

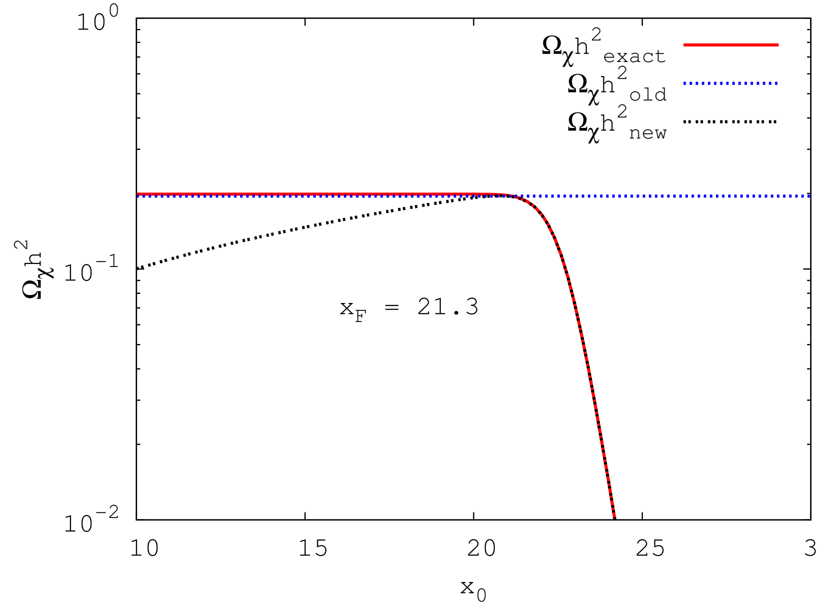
$$Y_1 = Y_0 \left(1 + \frac{\delta}{Y_0} \right) \simeq \frac{Y_0}{1 - \delta / Y_0} \equiv Y_{1,r}$$

$Y_{1,r} \propto 1/\sigma_{\text{ann}}$ for $|\delta| \gg Y_0$ MD, Imminniyaz, Kakizaki, hep-ph/0603165

Numerical comparison: $b = 0$



$a = 10^{-8}$ GeV^{-2}



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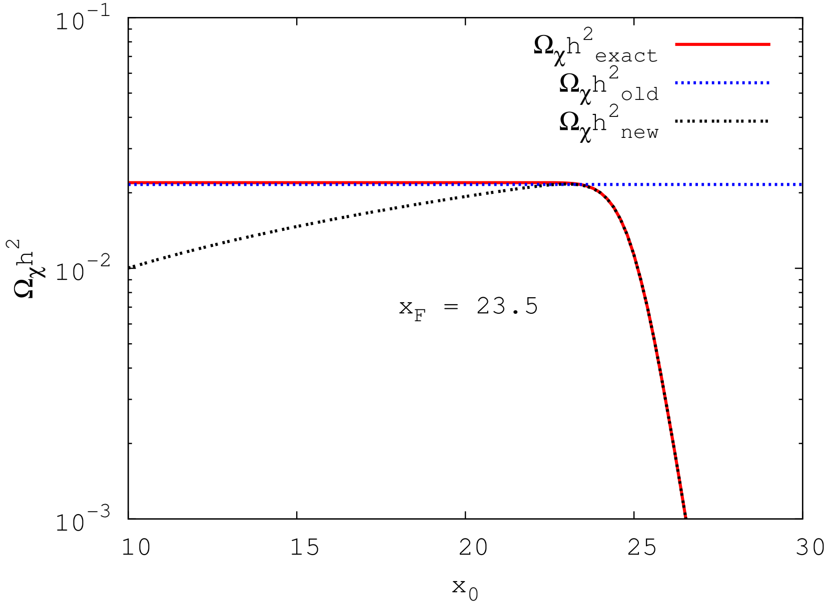

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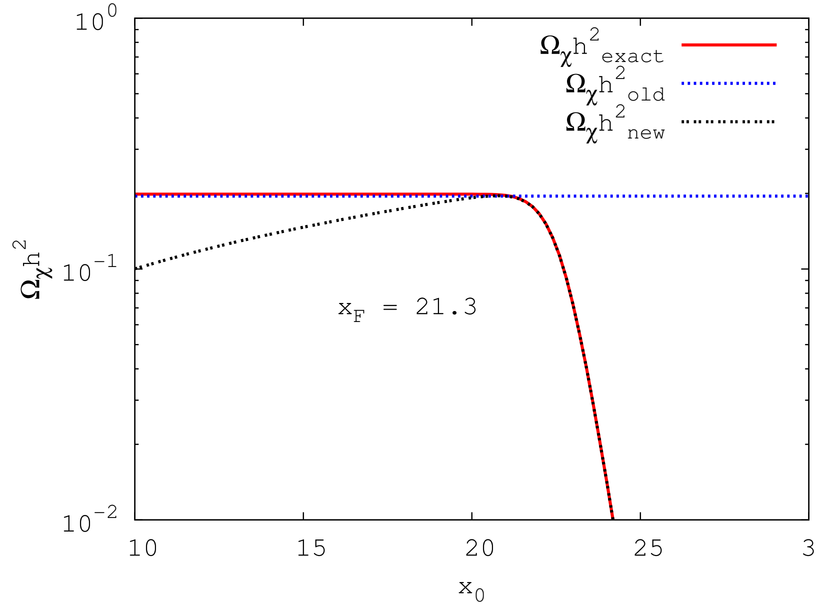

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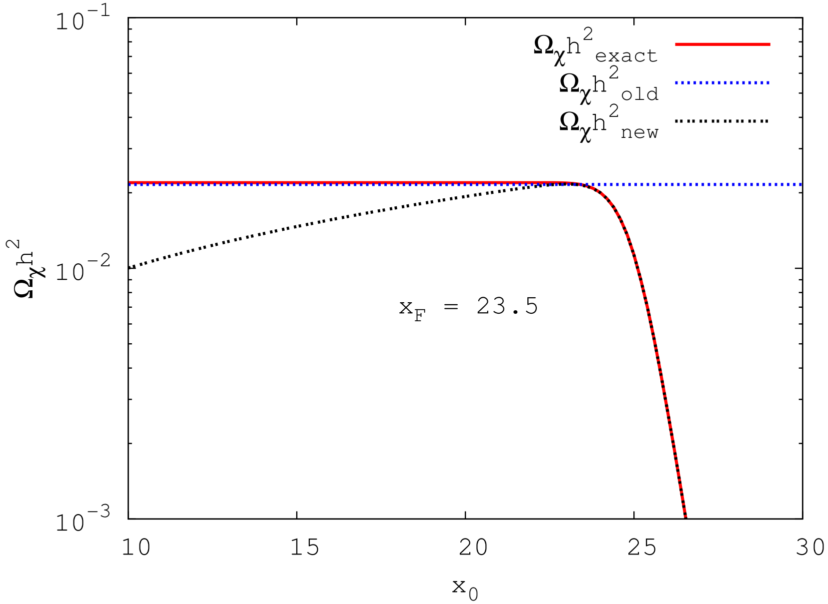

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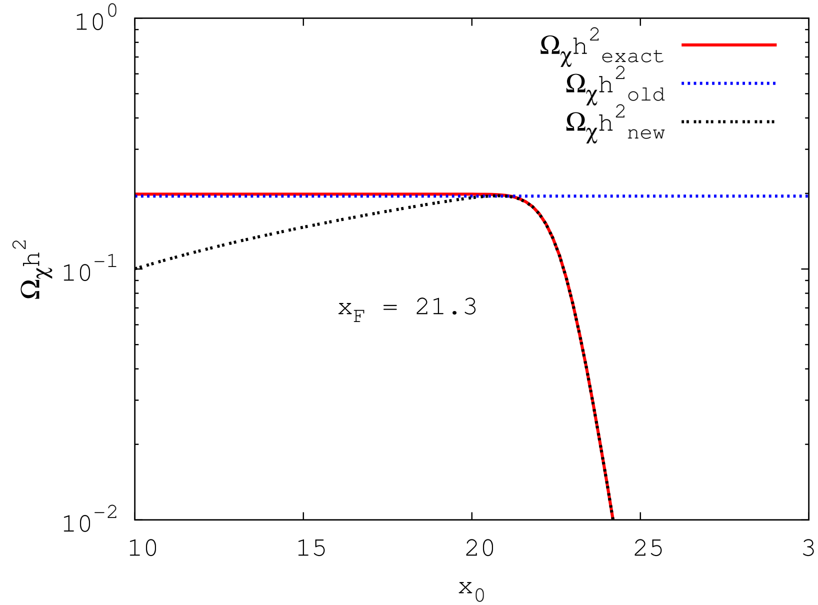

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Note: $\Omega_\chi(T_0) \leq \Omega_\chi(T_0 \gg T_F)$

Application: lower bound on T_0 for thermal WIMP

MD, Imminniyaz, Kakizaki, arXiv:0704.1590 [hep-ph]

If $n_\chi(T_0) = 0$, demanding $\Omega_\chi h^2 \simeq 0.1$ imposes lower bound on T_0:

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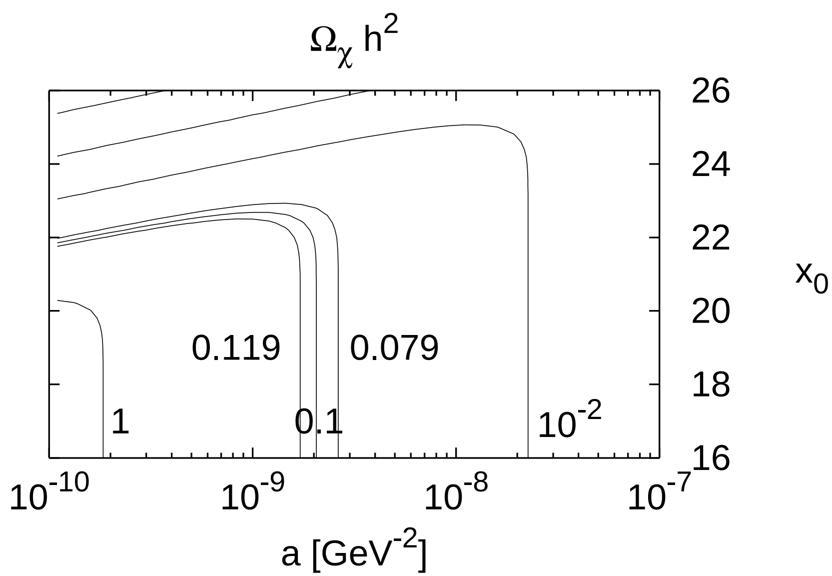

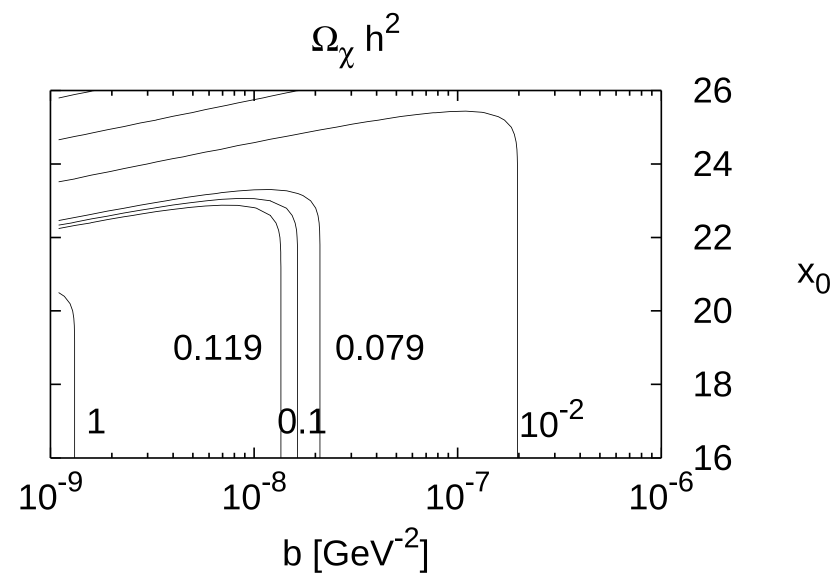

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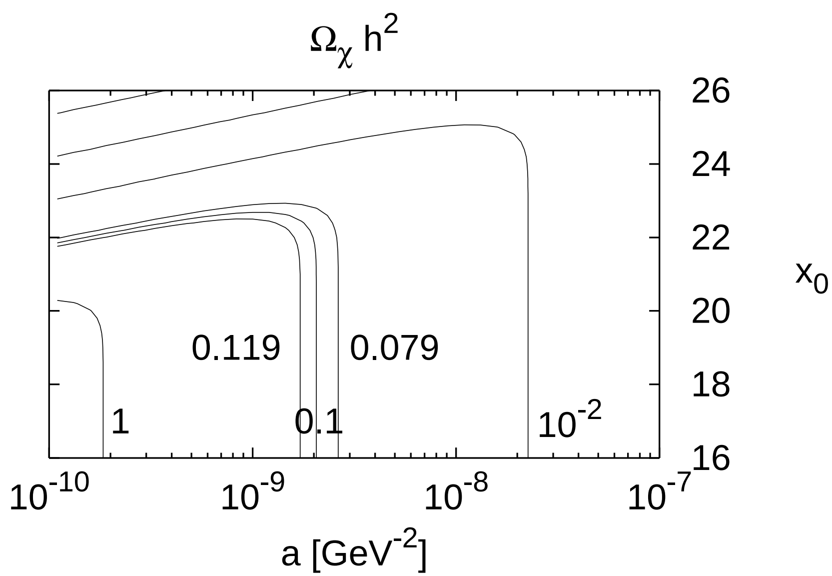

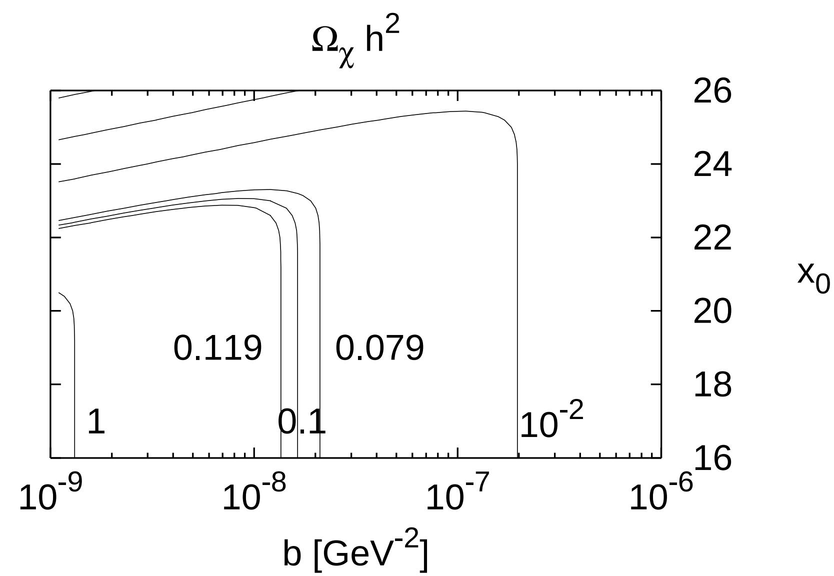

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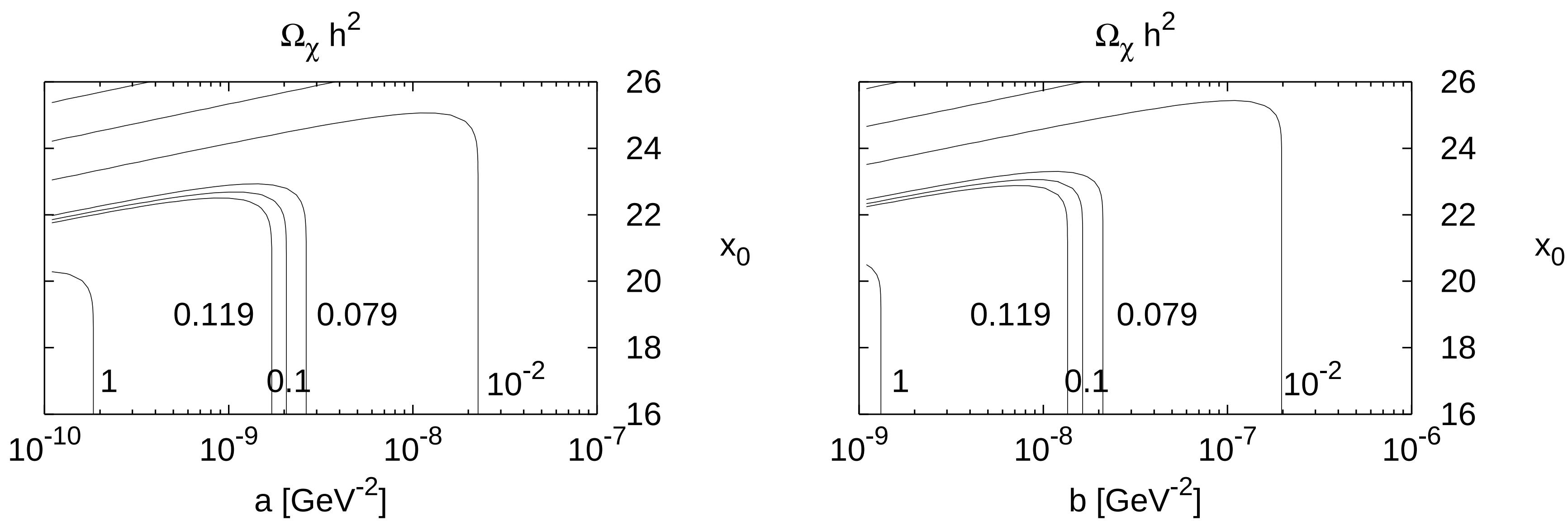

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If $T_0 \simeq m_\chi/22$: Get right $\Omega_\chi h^2$ for wide range of cross sections!

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- Successful BBN $\Longrightarrow k \equiv A(z \to 0) = 1.0 \pm 0.2$

Constraining $H(T)$ (cont.d)

Assume $T_0 \gg T_F \Longrightarrow \Omega_\chi h^2 \propto \frac{1}{\int_0^{z_F} A(z)(a+6bz)\,dz}$

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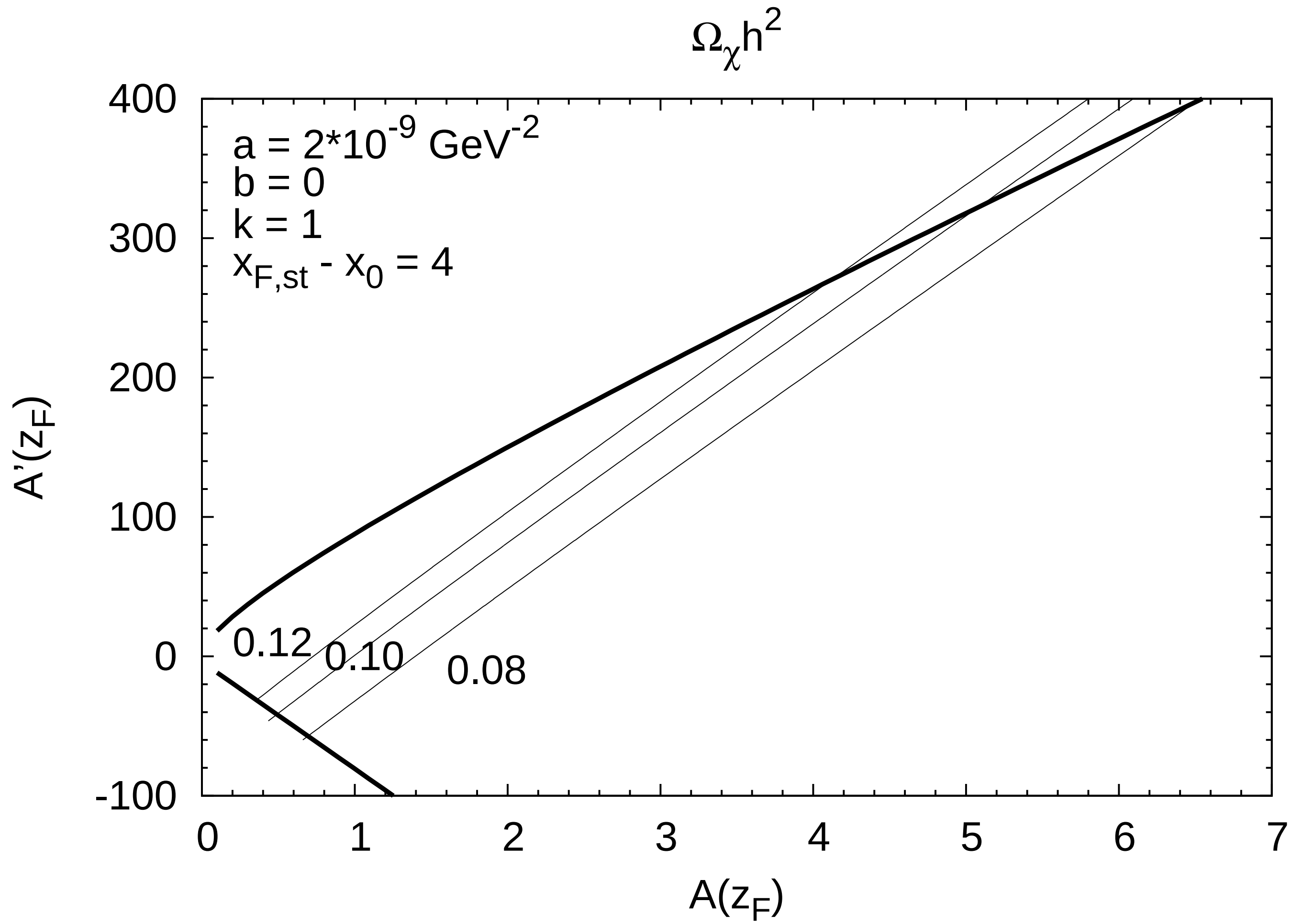
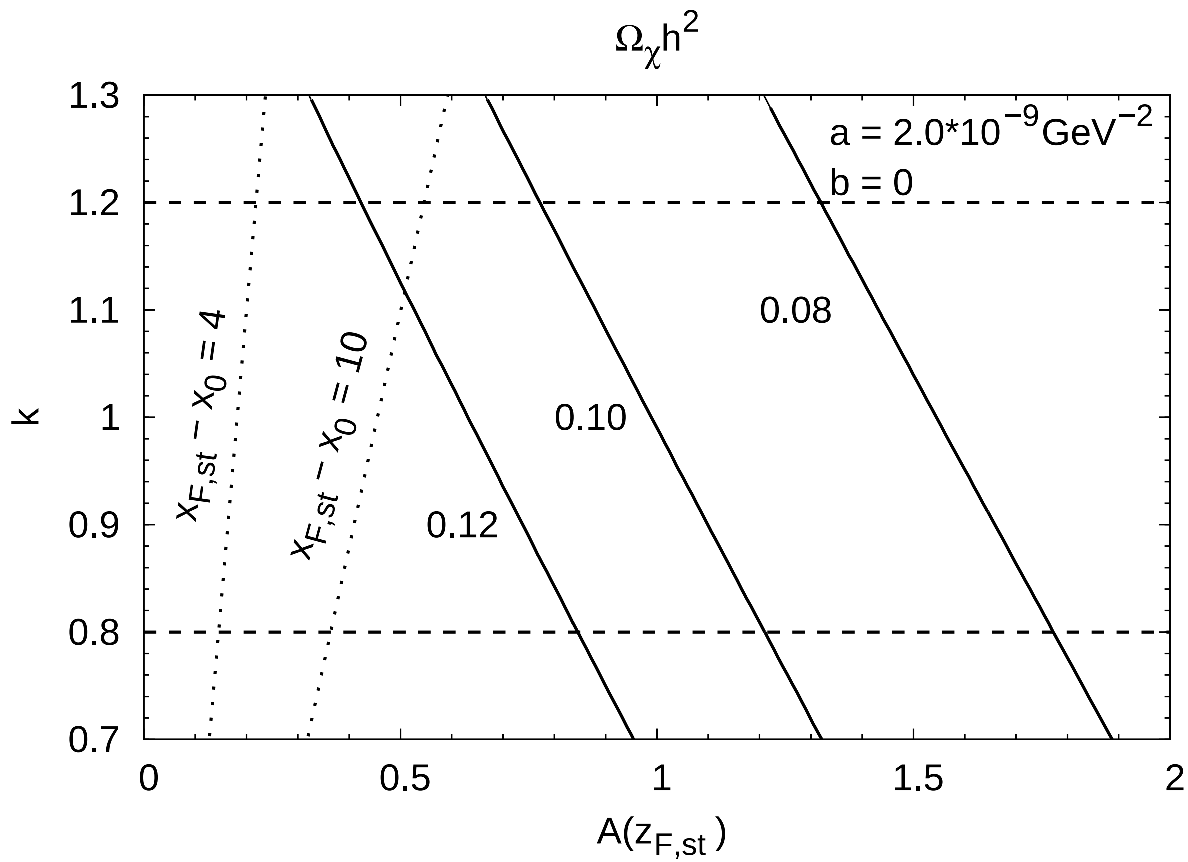


The case $A''(z_{F,\mathrm{st}}) = 0$



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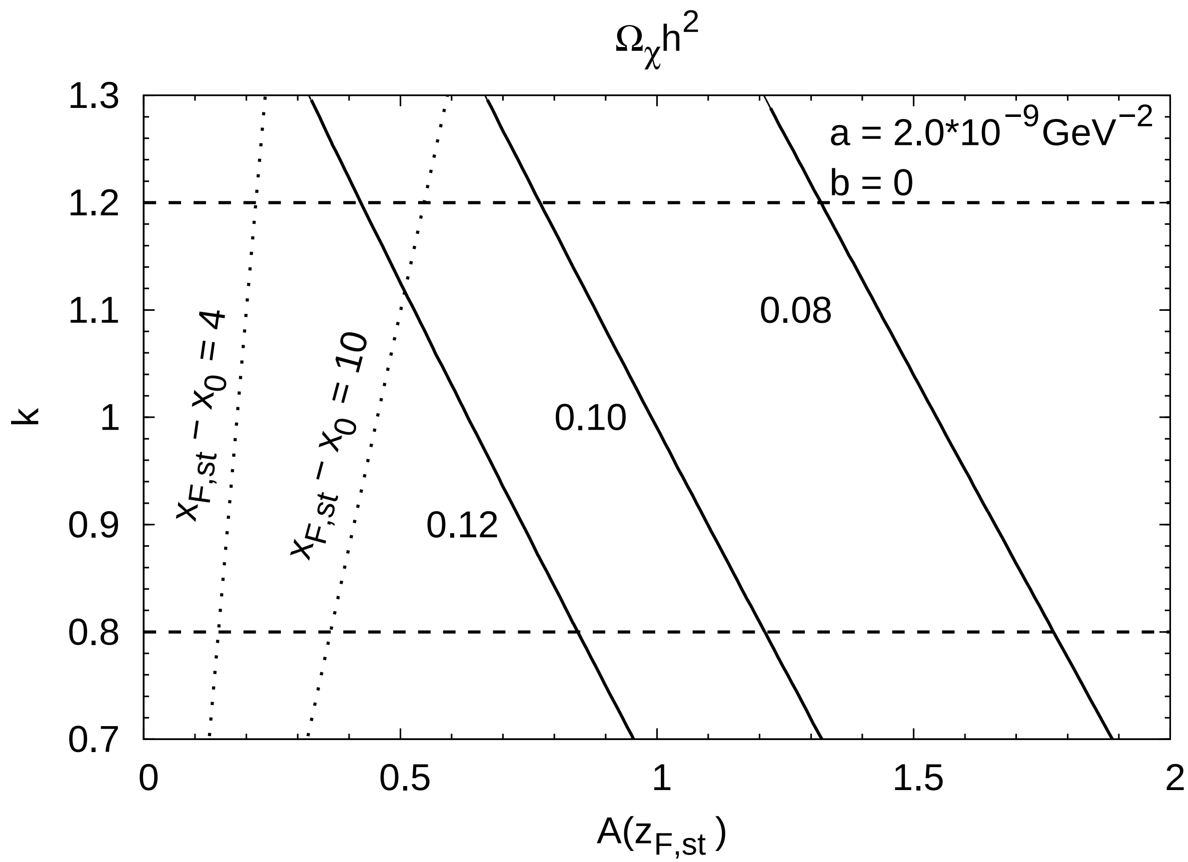

Relative constraint on $A(z_{F,\mathrm{st}})$ weaker than that on $\Omega_\chi h^2$.

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- Is being pursued vigorously around the world!

Direct WIMP detection: theory

Counting rate given by

$$\frac{dR}{dQ} = AF^2(Q) \int_{v_{\min}}^{v_{\rm esc}} \frac{f_1(v)}{v} dv$$

Q: recoil energy

$A = \rho\sigma_0/(2m_\chi m_r) =$ const.: encodes particle physics

$F(Q)$: nuclear form factor

v: WIMP velocity in lab frame

$v_{\min}^2 = m_N Q/(2m_r^2)$

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In principle, can invert this relation to measure $f_1(v)$!

Direct reconstruction of f_1

MD & C.L. Shan, astro-ph/0703651

$$f_1(v) = \mathcal{N} \left\{ -2Q \frac{d}{dQ} \left[\frac{1}{F^2(Q)} \frac{dR}{dQ} \right] \right\}_{Q=2m_r^2 v^2 / m_N}$$

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dR/dQ is approximately exponential: better work with logarithmic slope

Determining the logarithmic slope of dR/dQ

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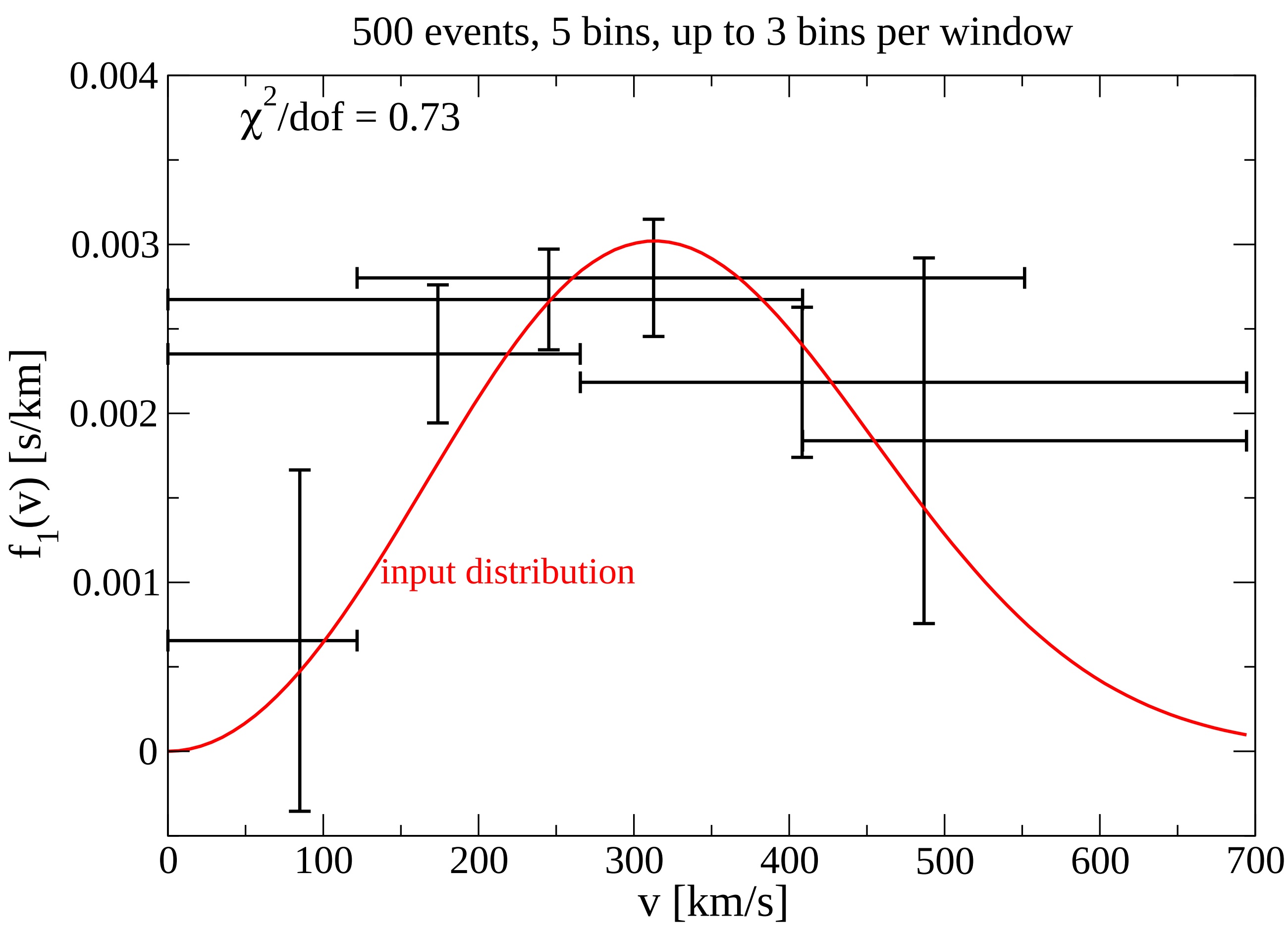
- To maximize information: use overlapping bins ("windows")

Recoil spectrum: prediction and simulated measurement



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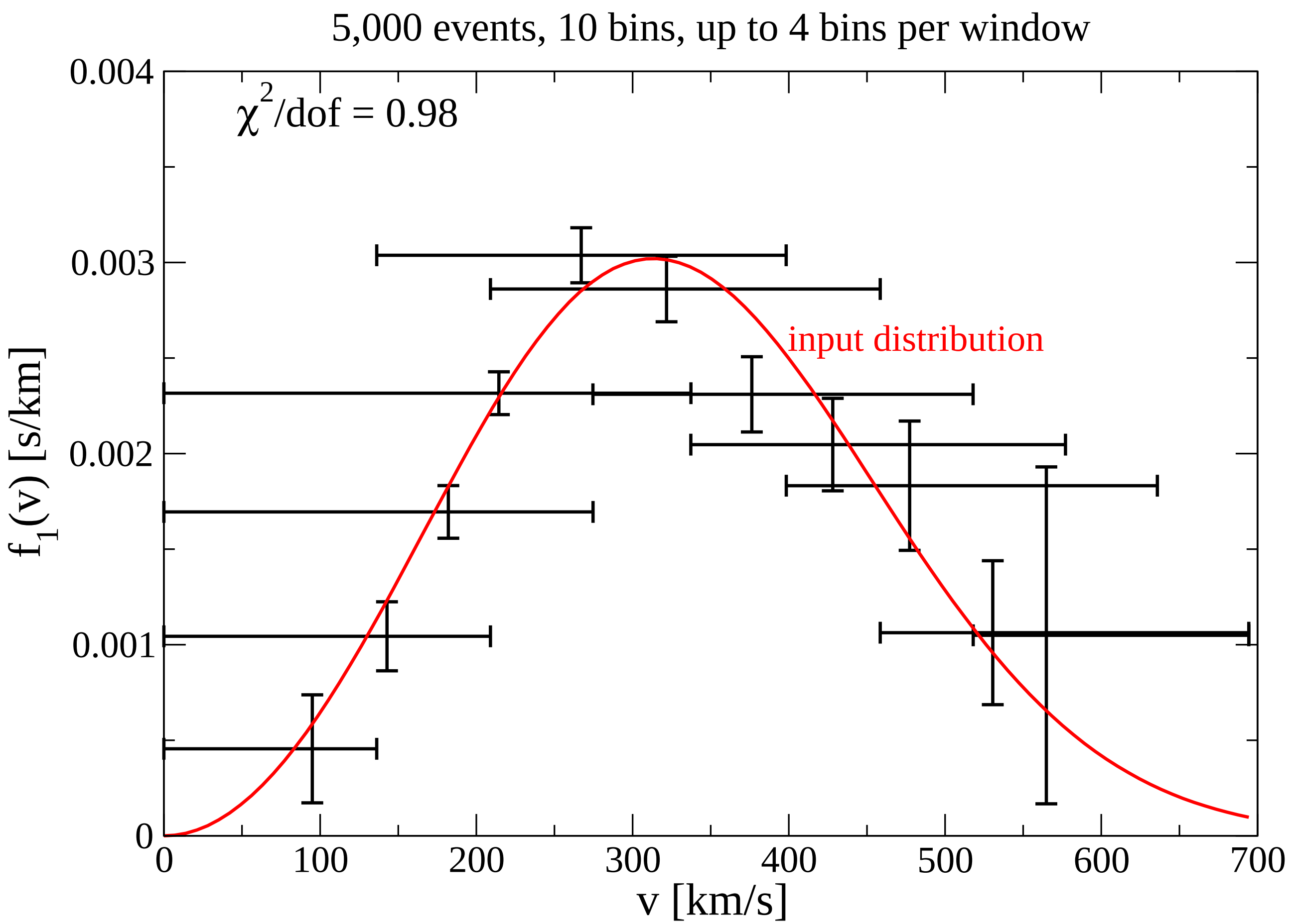
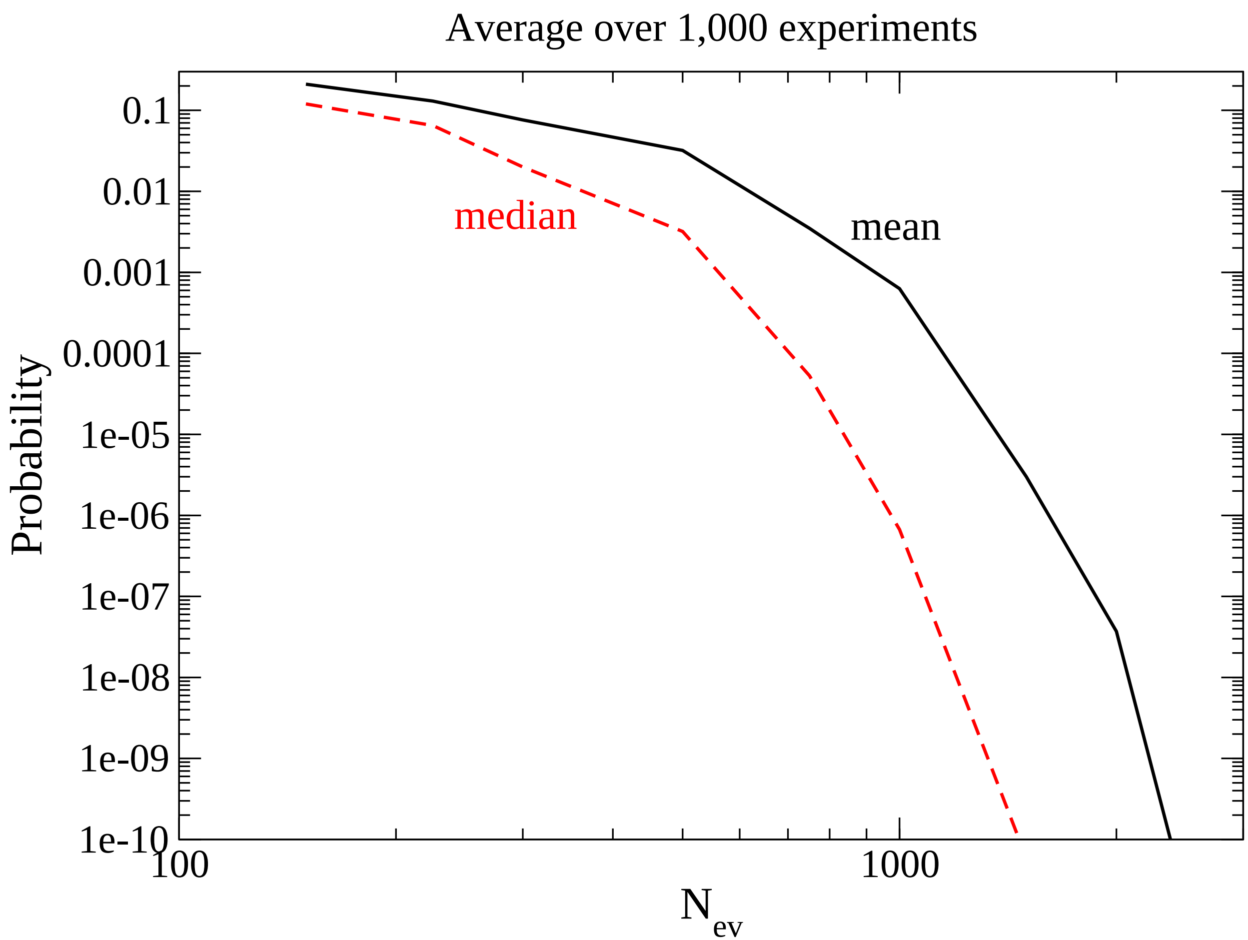


Statistical exclusion of constant f_1



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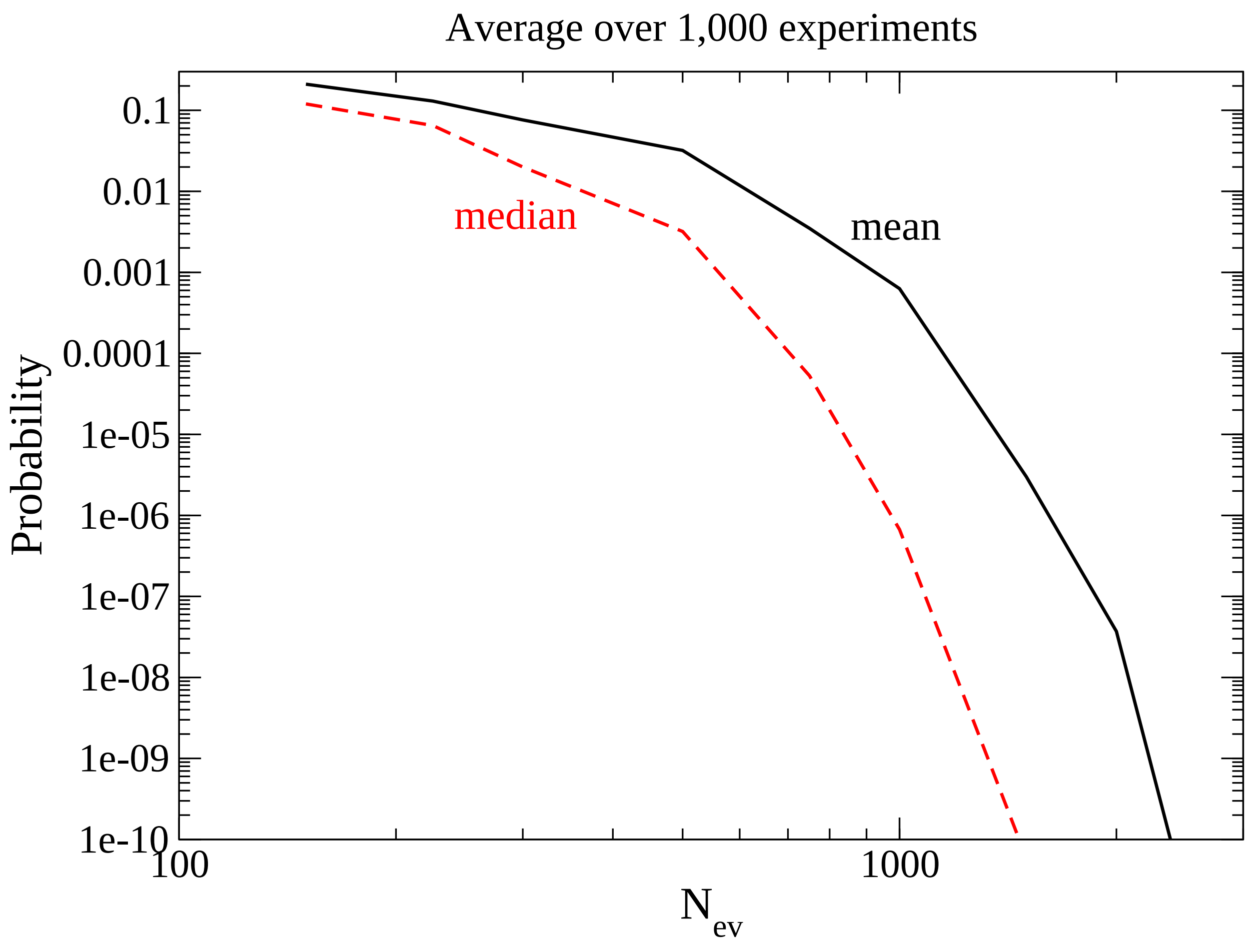

Need several hundred events to begin direct reconstruction!

Determining moments of f_1

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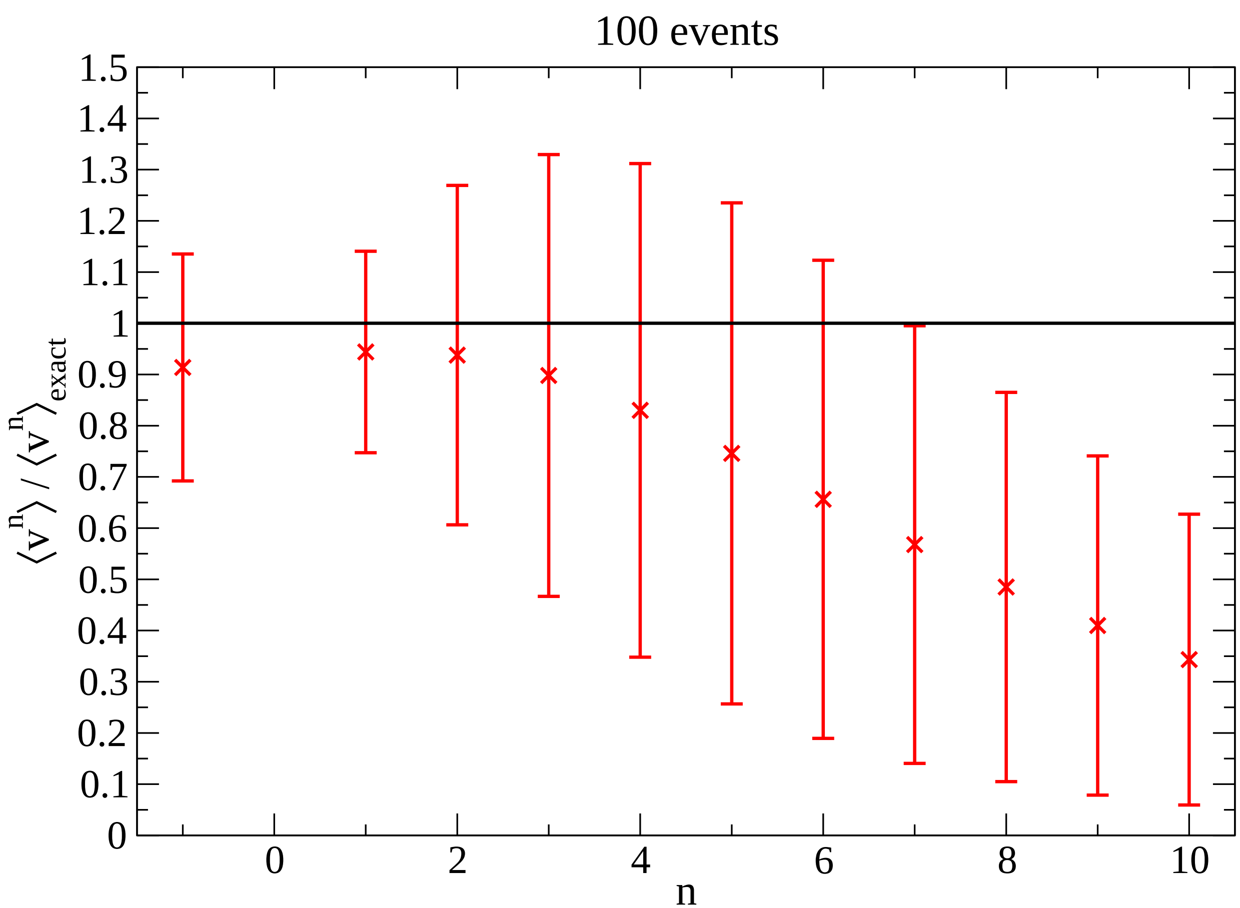
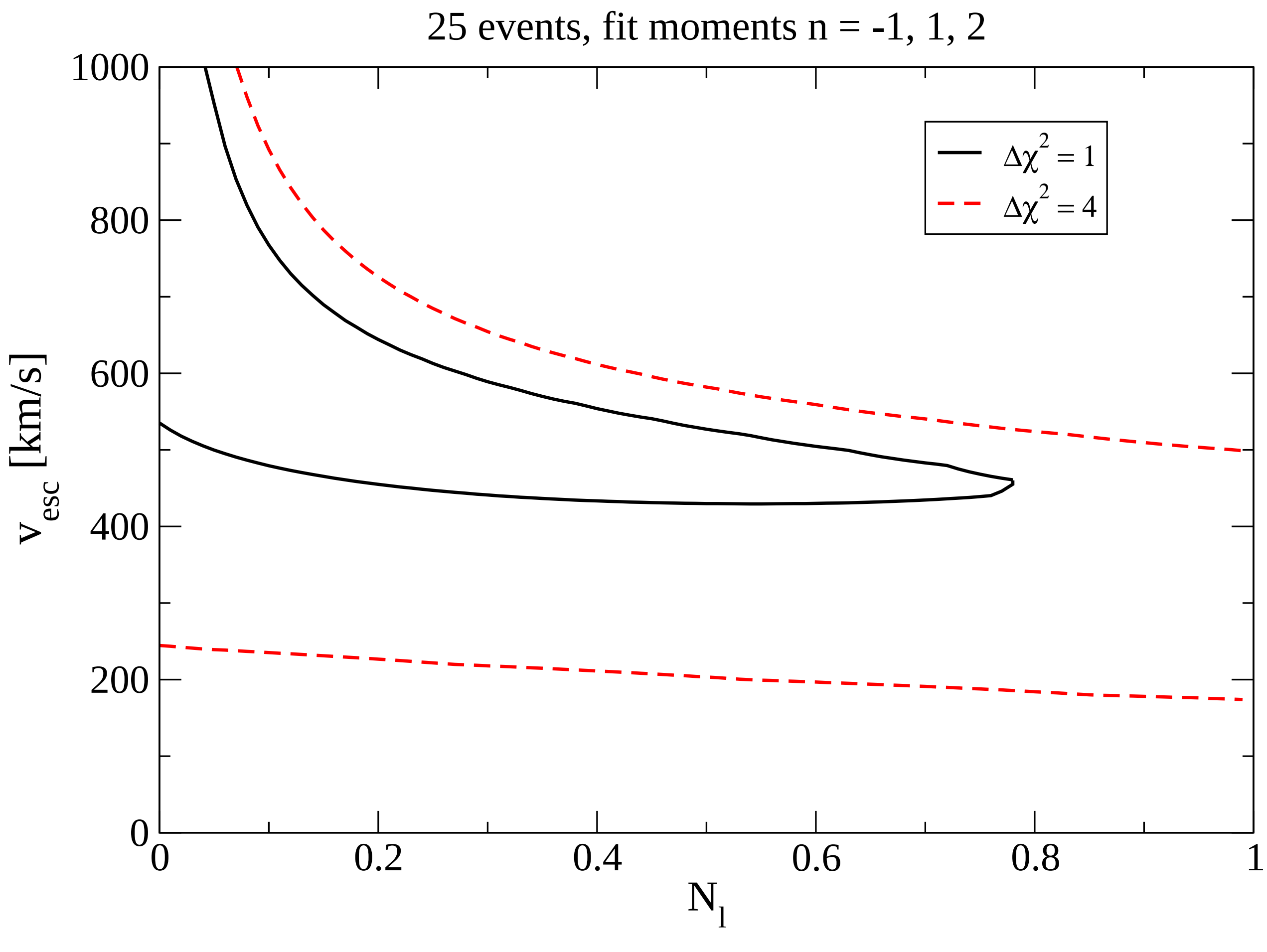
High moments, and their errors, are underestimated in "typical" experiment: get large contribution from large Q

Determination of first 10 moments



Constraining a “late infall” component



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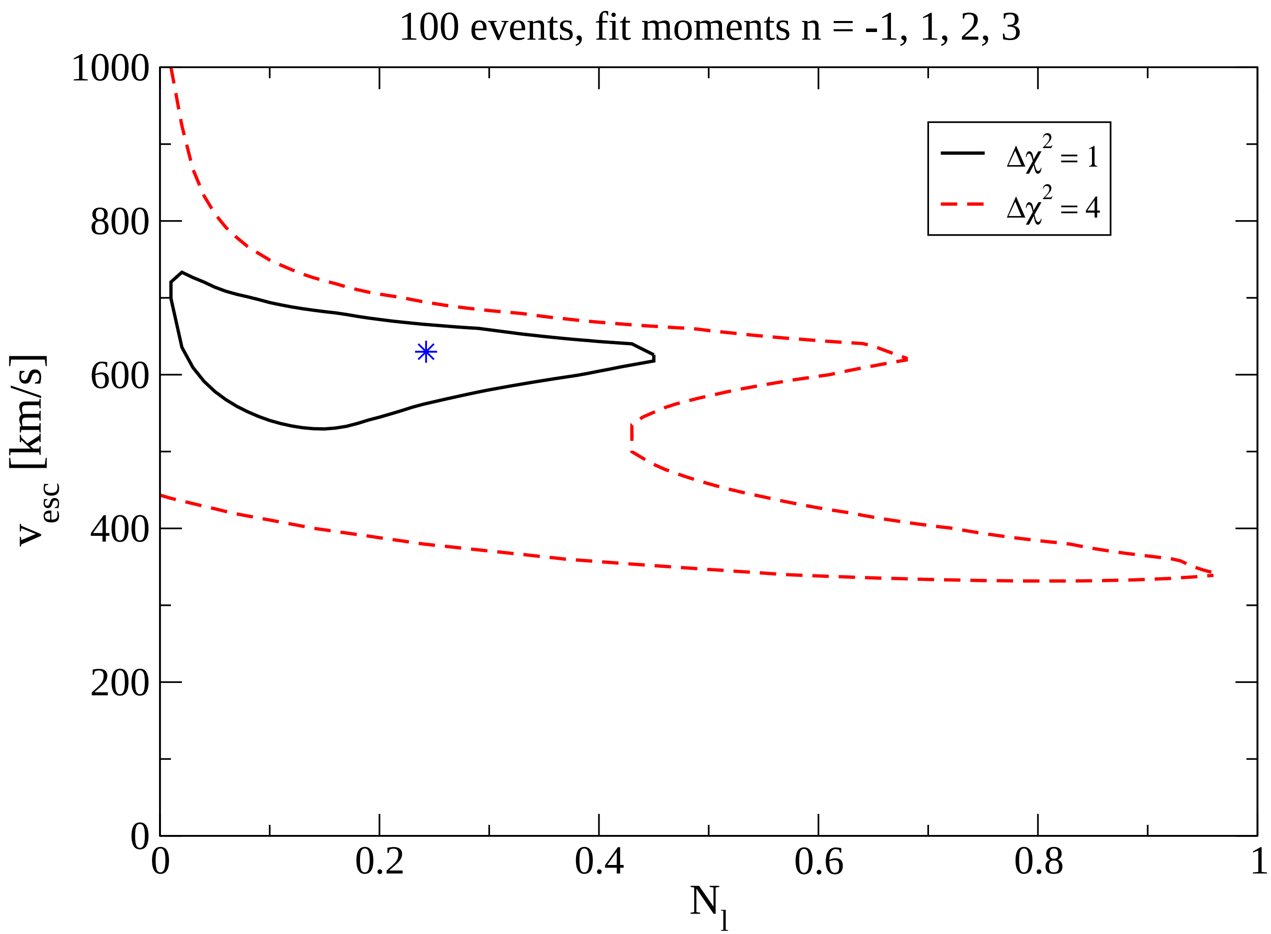
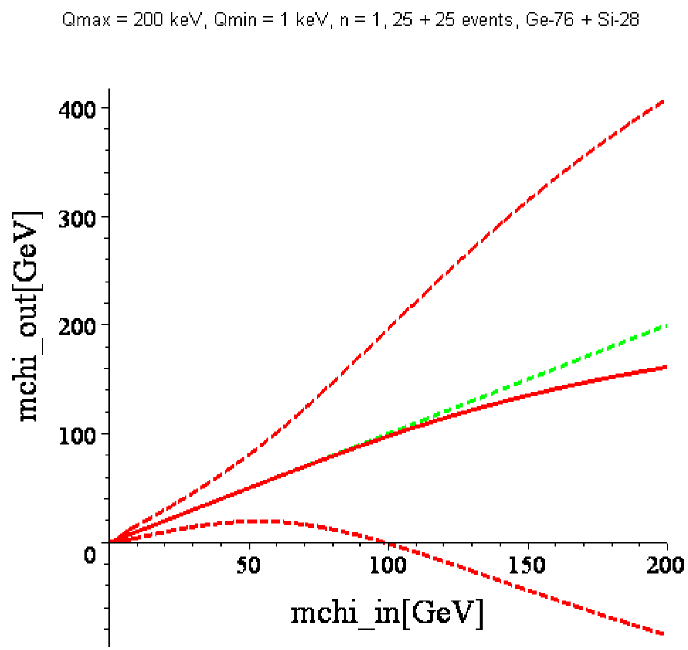
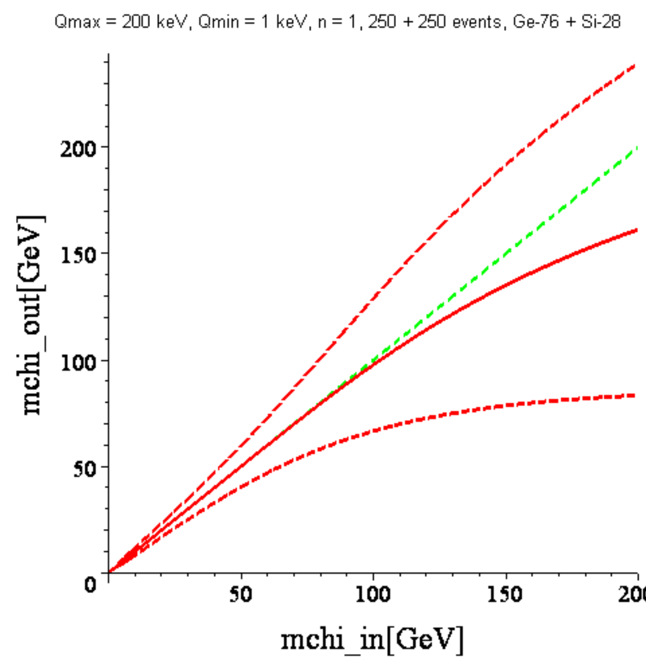


Determining the WIMP mass

MD & C.L. Shan, in progress

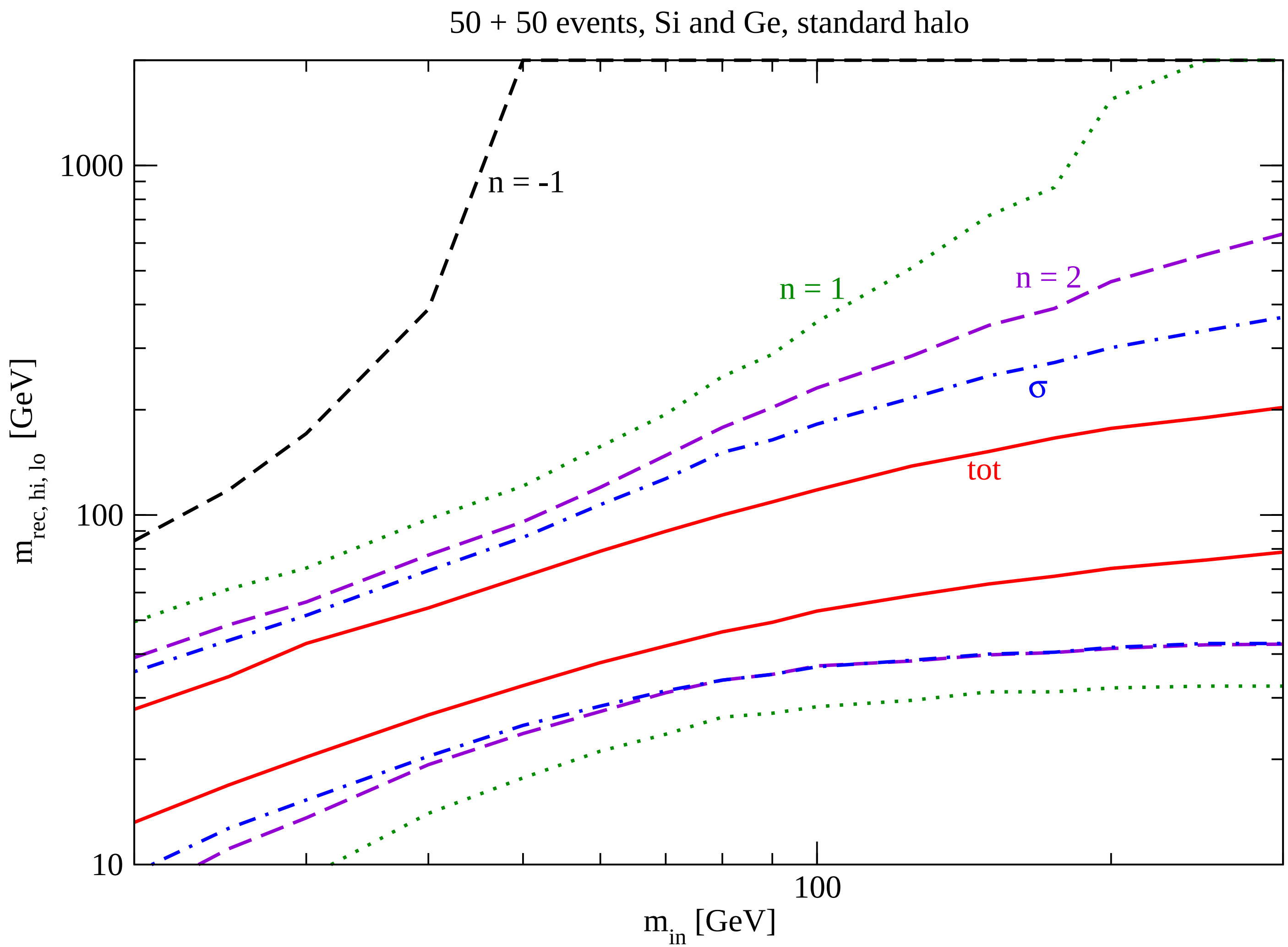
Can determine m_χ from requirement that different targets yield *same* moments of f_1





Range of WIMP mass from simulation

Preliminary!



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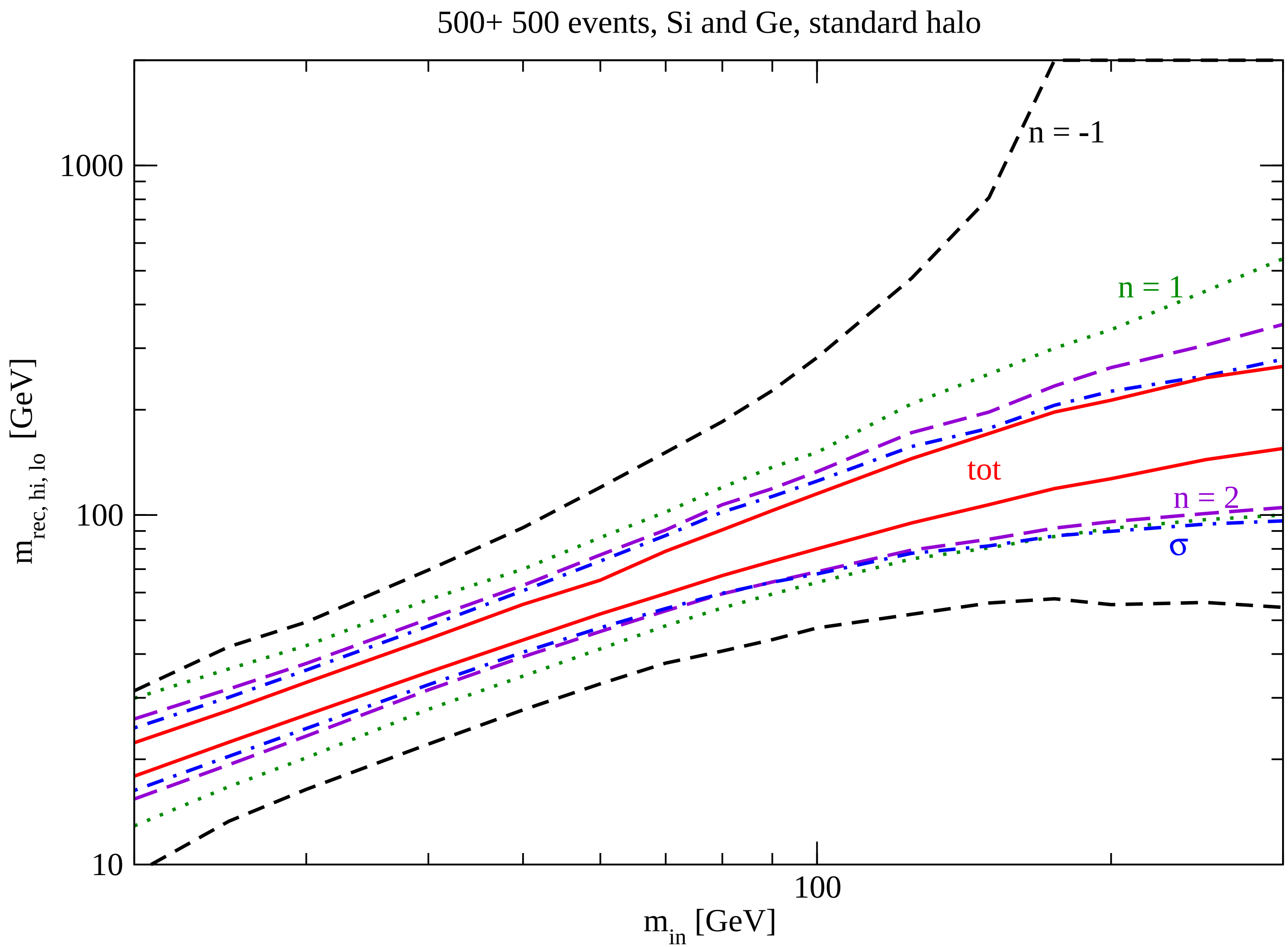

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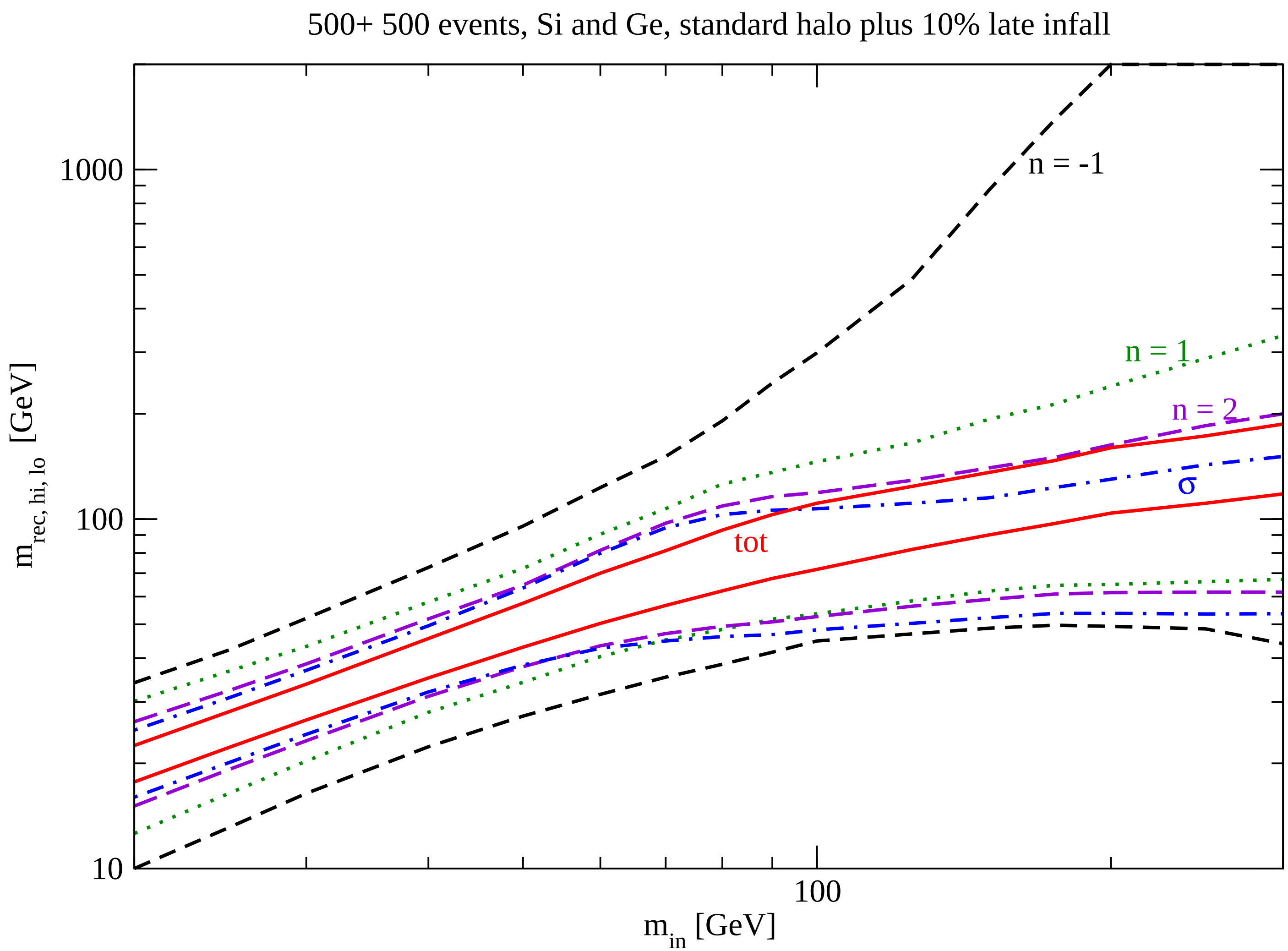

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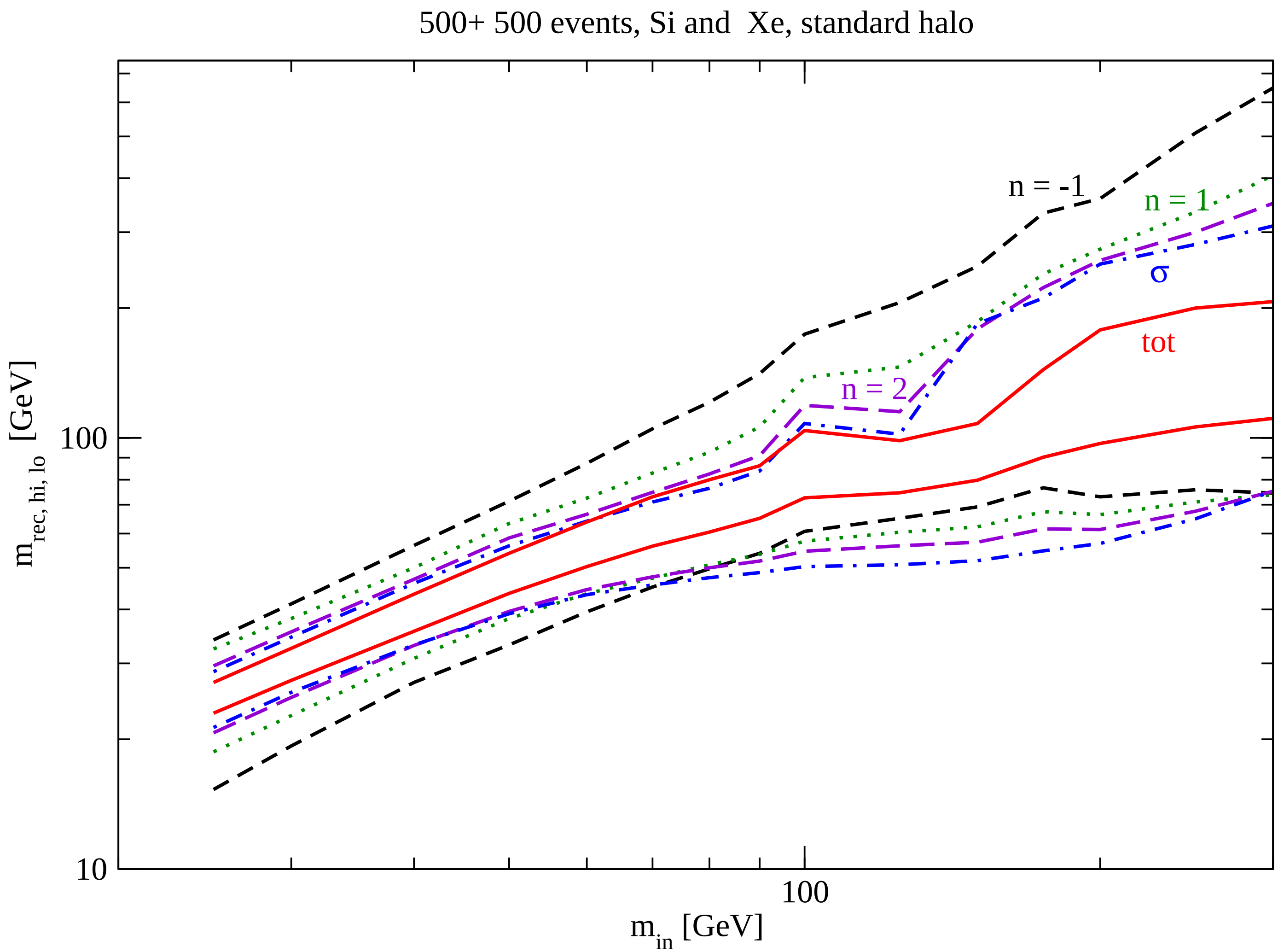

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- Learning about WIMPs: Can determine m_χ from moments of f_1 measured with two different targets.