Learning from WIMPs

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Contents

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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**

Need for non–baryonic DM

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$\Longrightarrow$ Need exotic particles as DM!

Possible loophole: primordial black holes; not easy to make in sufficient quantity sufficiently early.

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- and has (strongly) suppressed coupling to elm radiation

Weakly Interacting Massive Particles (WIMPs)

- Exist in well–motivated extensions of the SM: SUSY, (Little Higgs with $T-$Parity), ((Universal Extra Dimension))

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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:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\rm ann} v\rangle \left(n_\chi^2 - n_{\chi,\,{\rm eq}}^2\right) + \sum_{X,Y} n_X \Gamma(X \to \chi + Y)$$

$H = \dot{R}/R$: Hubble parameter
$\langle \ldots \rangle$: Thermal averaging
$\sigma_{\rm ann} = \sigma(\chi\chi \to {\rm SM\ particles})$
v : relative velocity between χ's in their cms
$n_{\chi,\,{\rm eq}}$: 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 $T_R \lesssim T_F, \; n_\chi(T_R) = 0$

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$$Y_\chi \equiv \frac{n_\chi}{s}, \quad x \equiv \frac{m_\chi}{T}$$

(s: entropy density).

Use non–relativistic expansion of cross section:

$$\sigma_{\rm ann} = a + bv^2 + \mathcal{O}(v^4) \Longrightarrow \langle \sigma_{\rm ann} v \rangle = a + 6b/x$$

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

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

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

Low temperature scenario (cont.'d)

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

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

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

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$$Y_1 = Y_0 + \delta \, .$$

$\delta < 0$ 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: $\delta \propto \sigma_{\rm ann}^3$

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

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

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

Numerical comparison: $b = 0$

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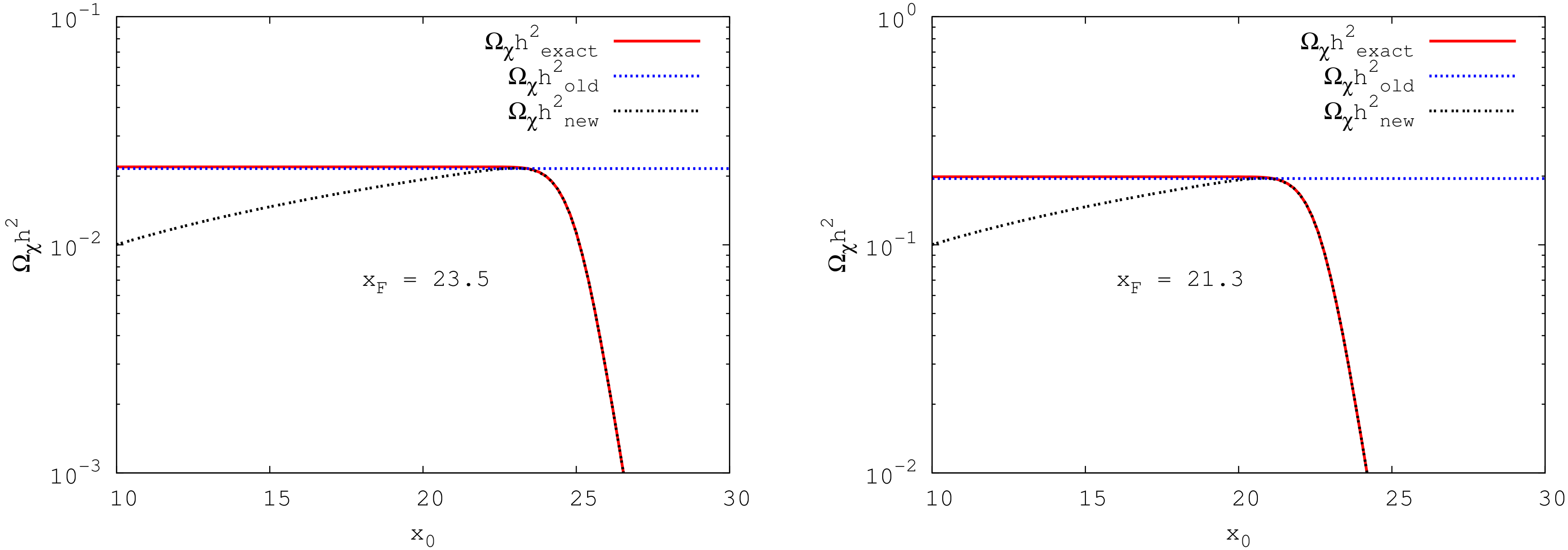

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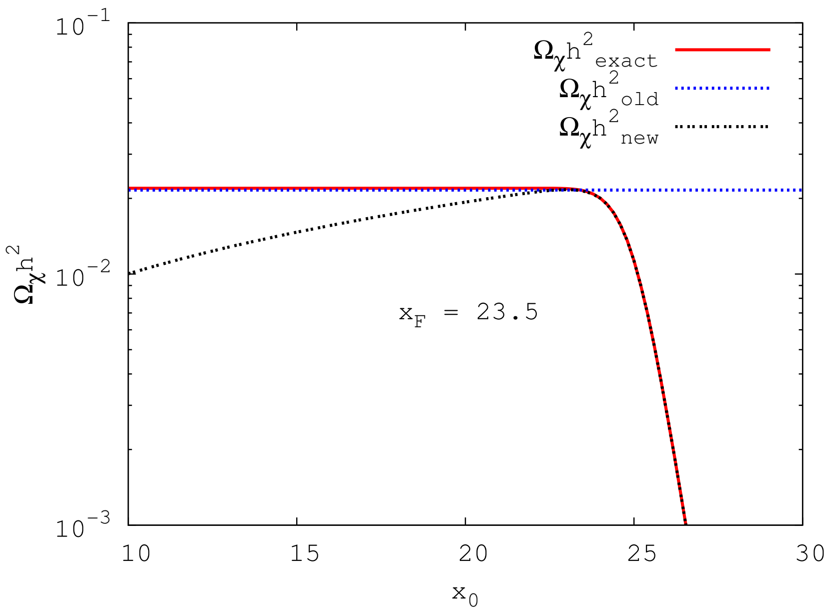

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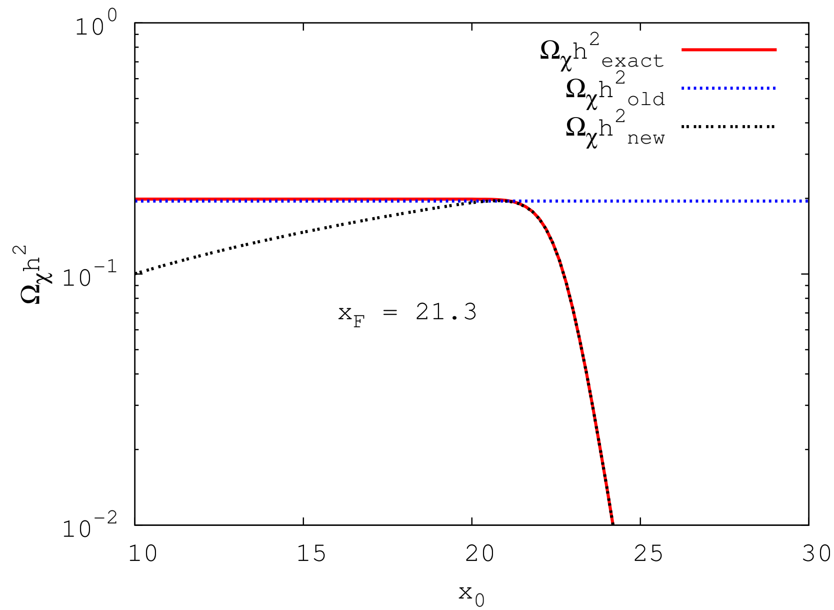

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Can extend validity of new solution to all T, including $T \gg T_R$, by using $\Omega_\chi(T_{\rm max})$ if $T_R > T_{\rm max} \simeq T_F$

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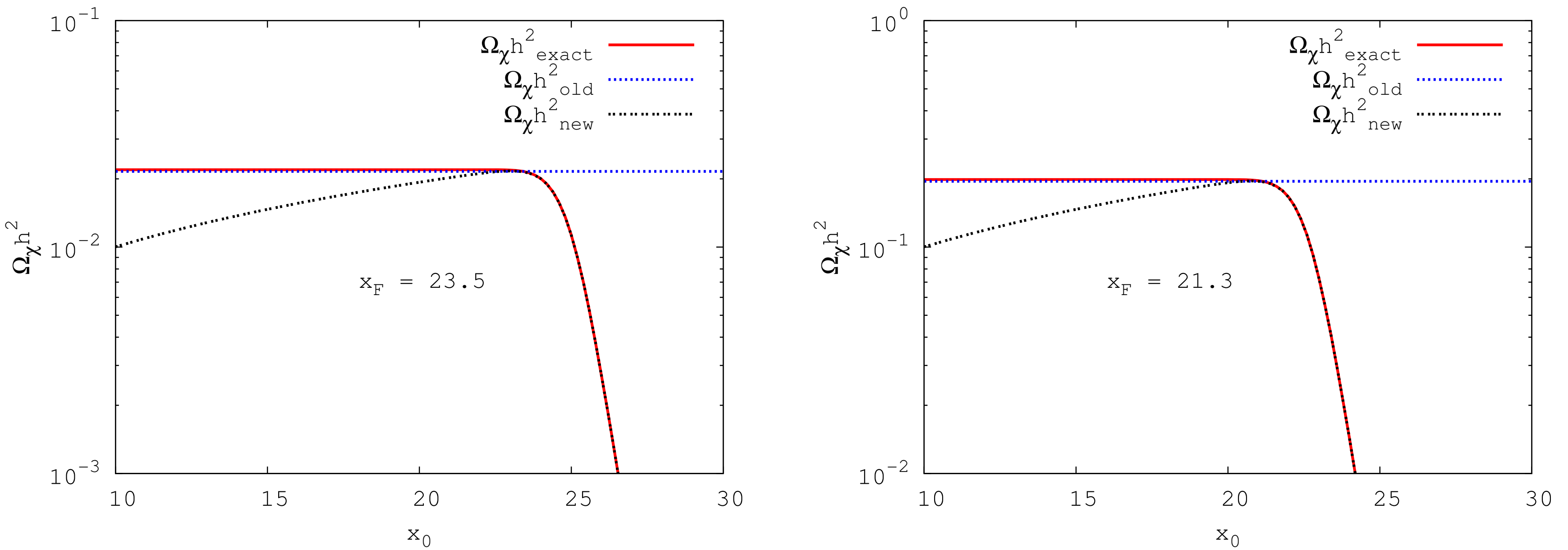

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Note: $\Omega_\chi(T_R) \leq \Omega_\chi(T_R \gg T_F)$

Application: lower bound on T_R for thermal WIMP

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

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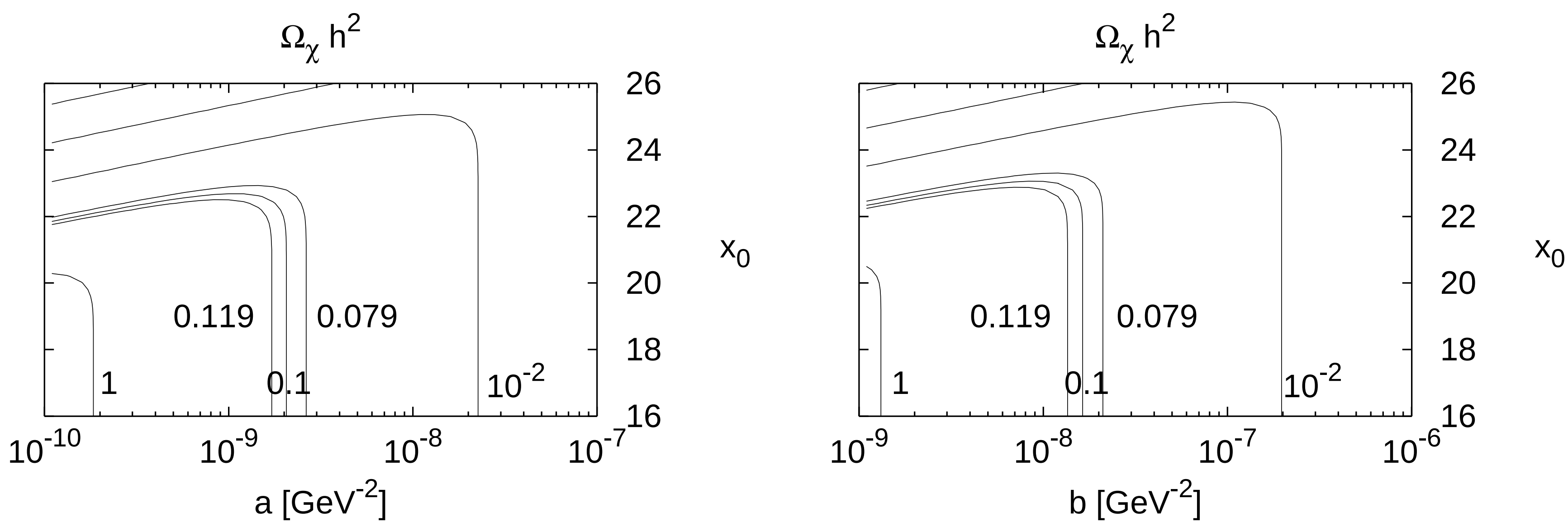

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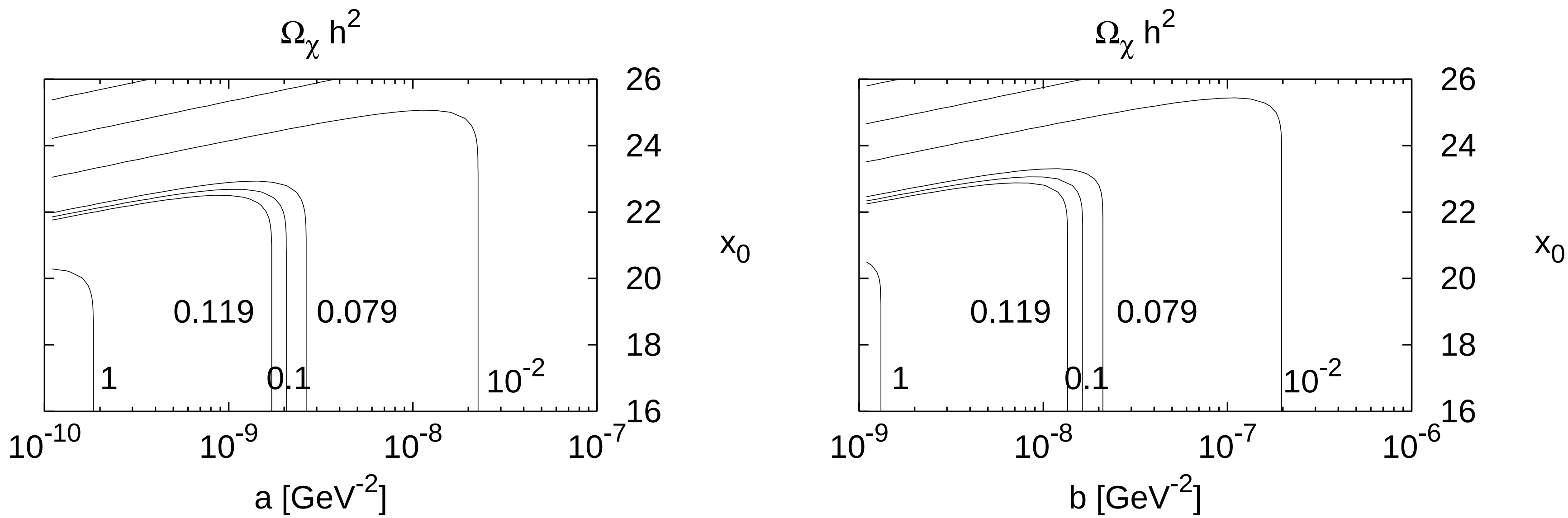

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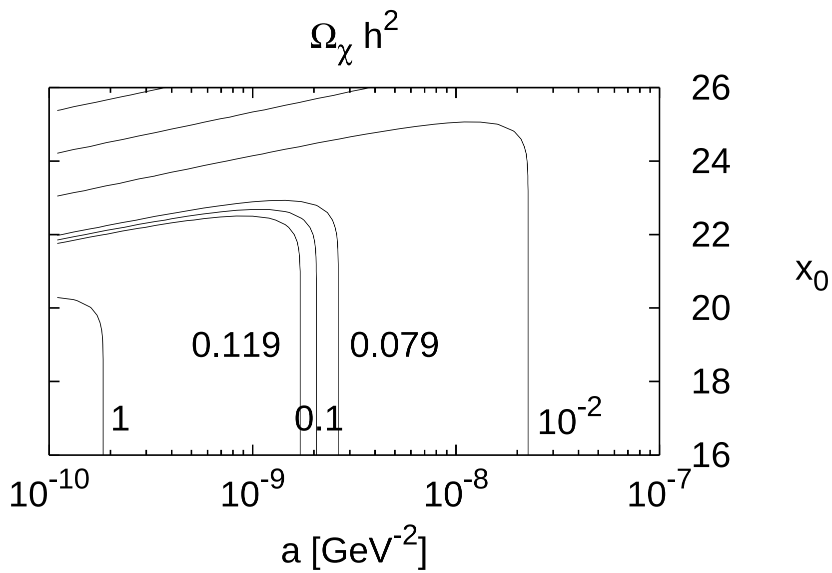

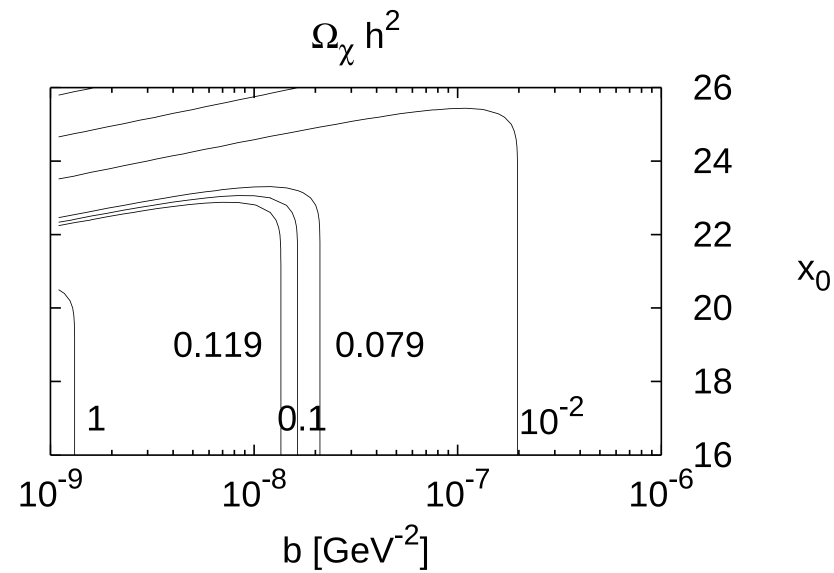

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If $T_R \simeq m_\chi/22$: Get right $\Omega_\chi h^2$ for wide range of cross sections!

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

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

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

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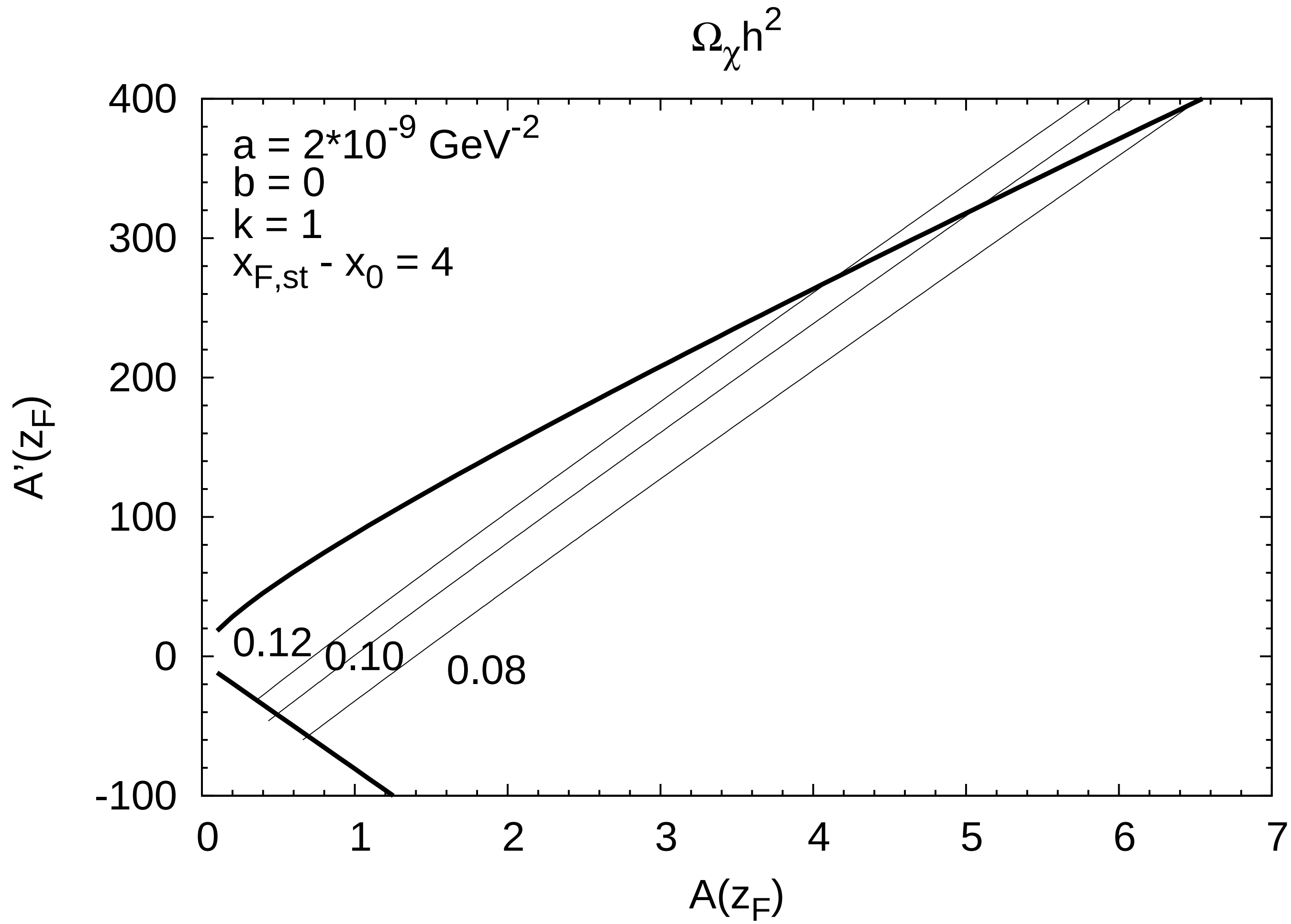

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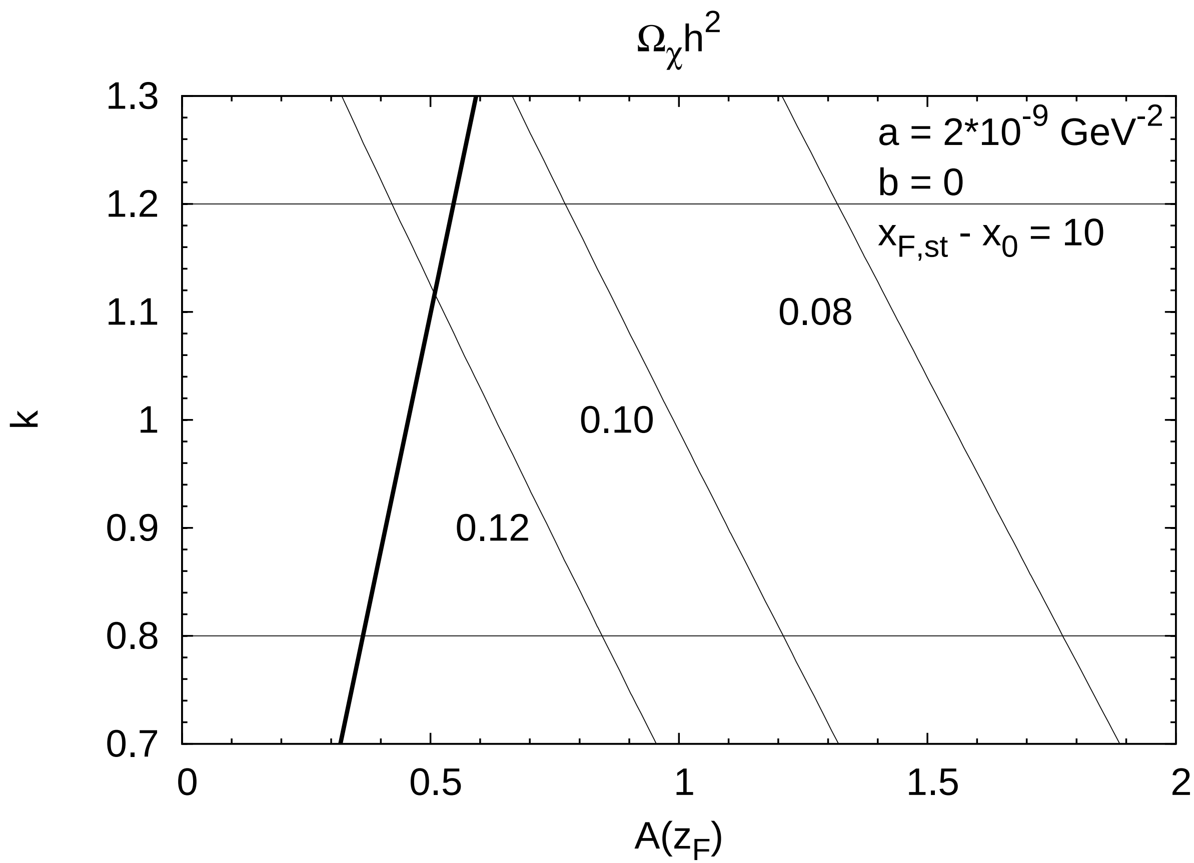

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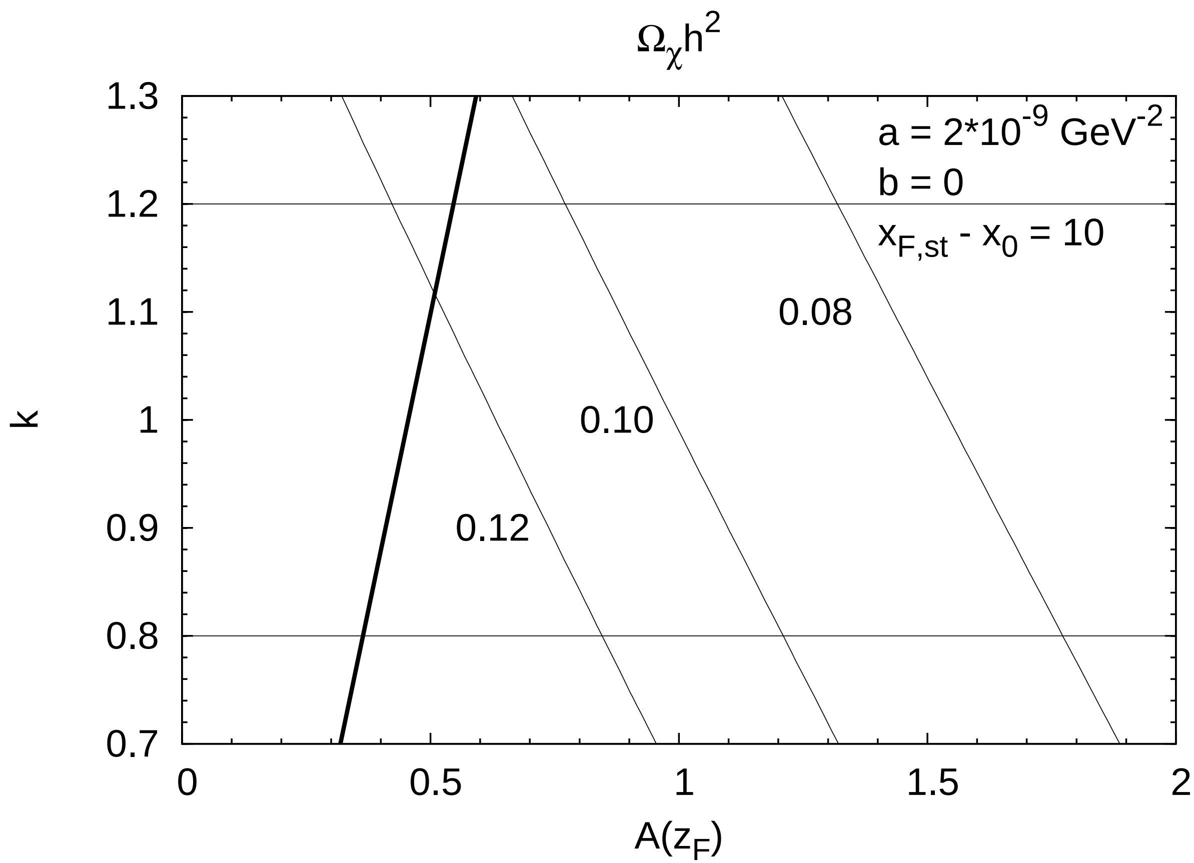

Relative constraint on $A(z_{F,\mathrm{st}})$ weaker than that on $\Omega_\chi h^2$.

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- Is being pursued vigorously around the world!

Direct WIMP detection: theory

Counting rate given by

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

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

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

$v_{\rm esc}$: Escape velocity from galaxy

$f_1(v)$: normalized one–dimensional WIMP velocity distribution

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

Direct reconstruction of f_1

MD & C.L. Shan, in progress

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

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

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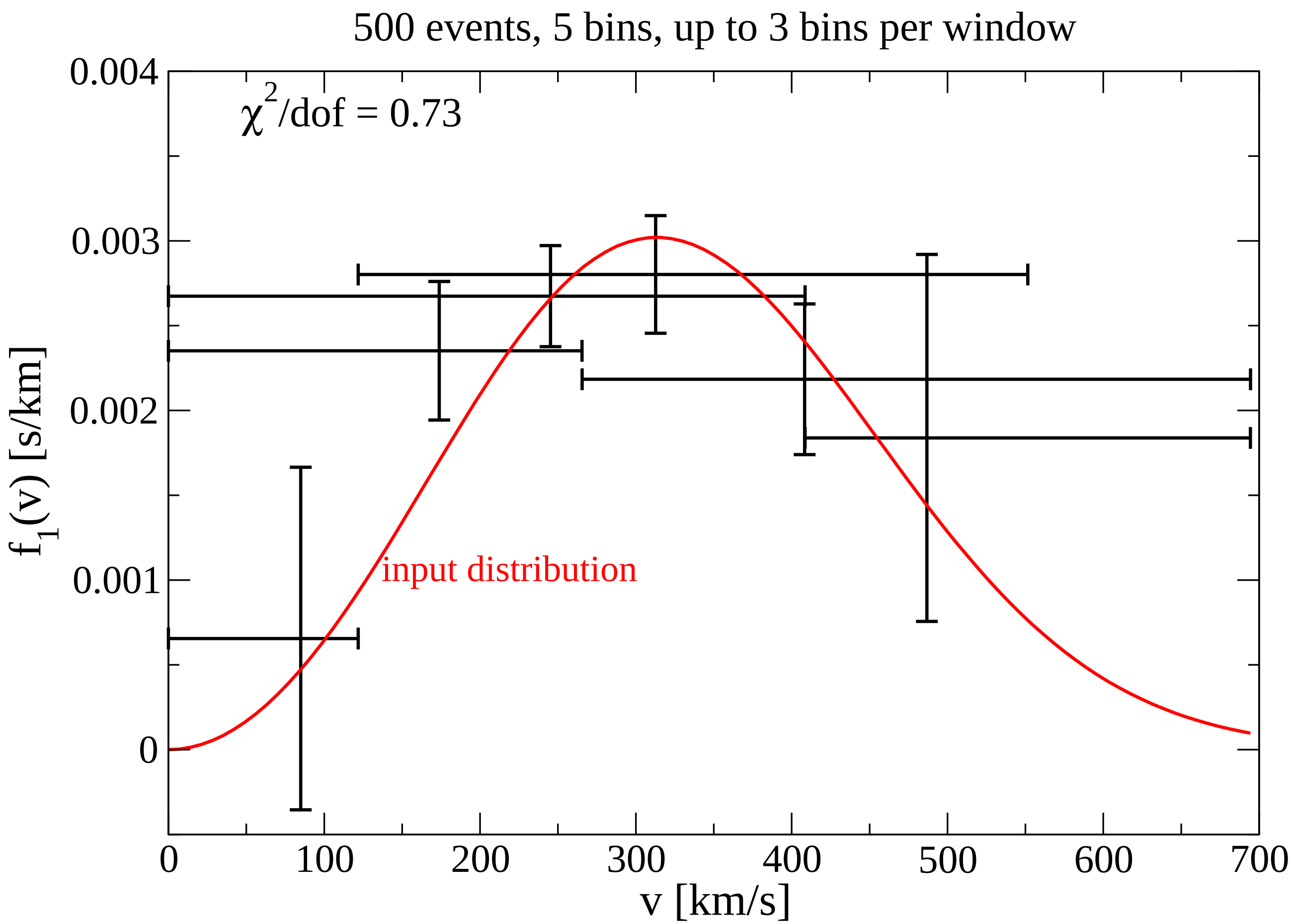
- To maximize information: use overlapping bins ("windows")

Recoil spectrum: prediction and simulated measurement



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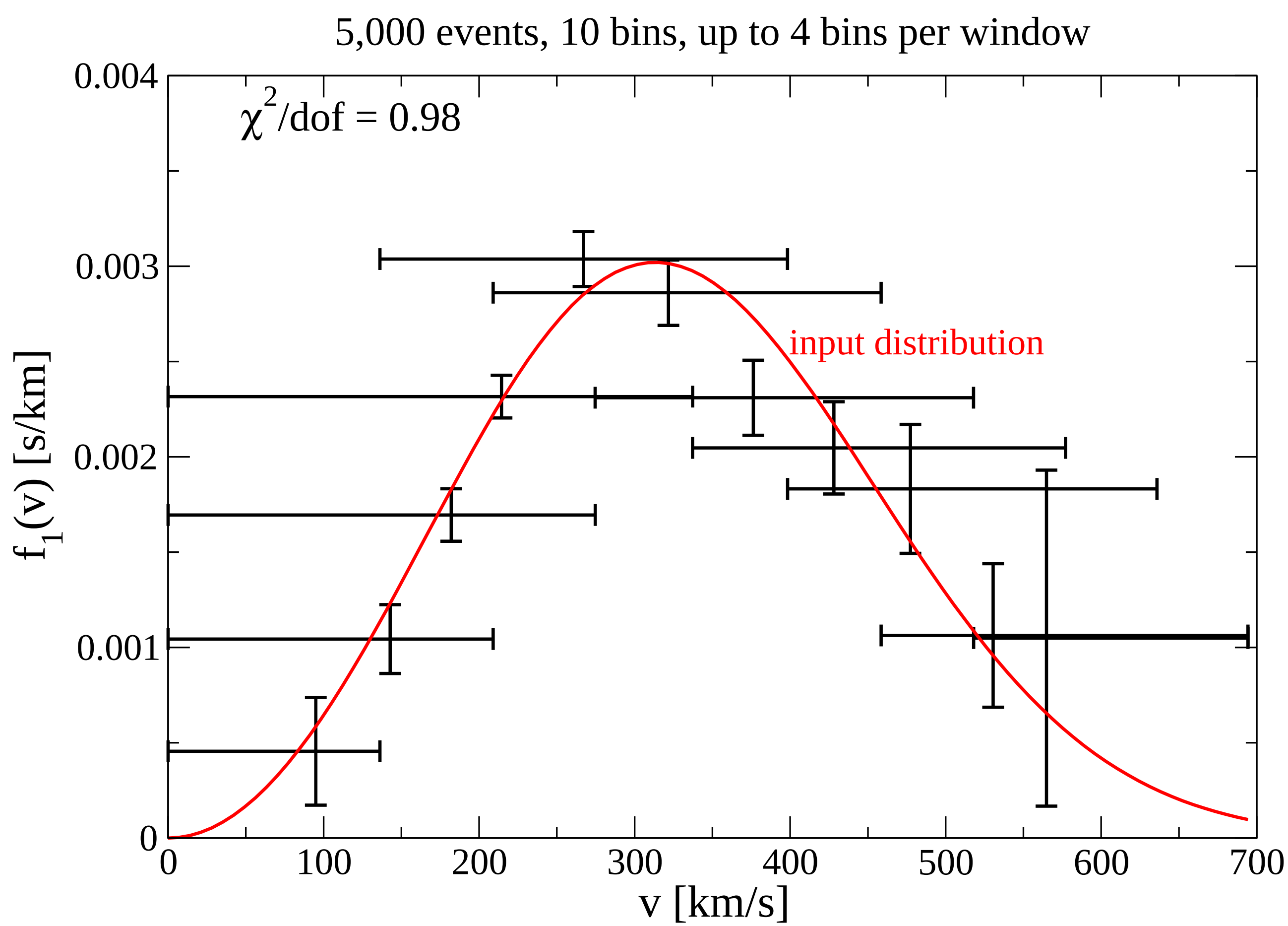
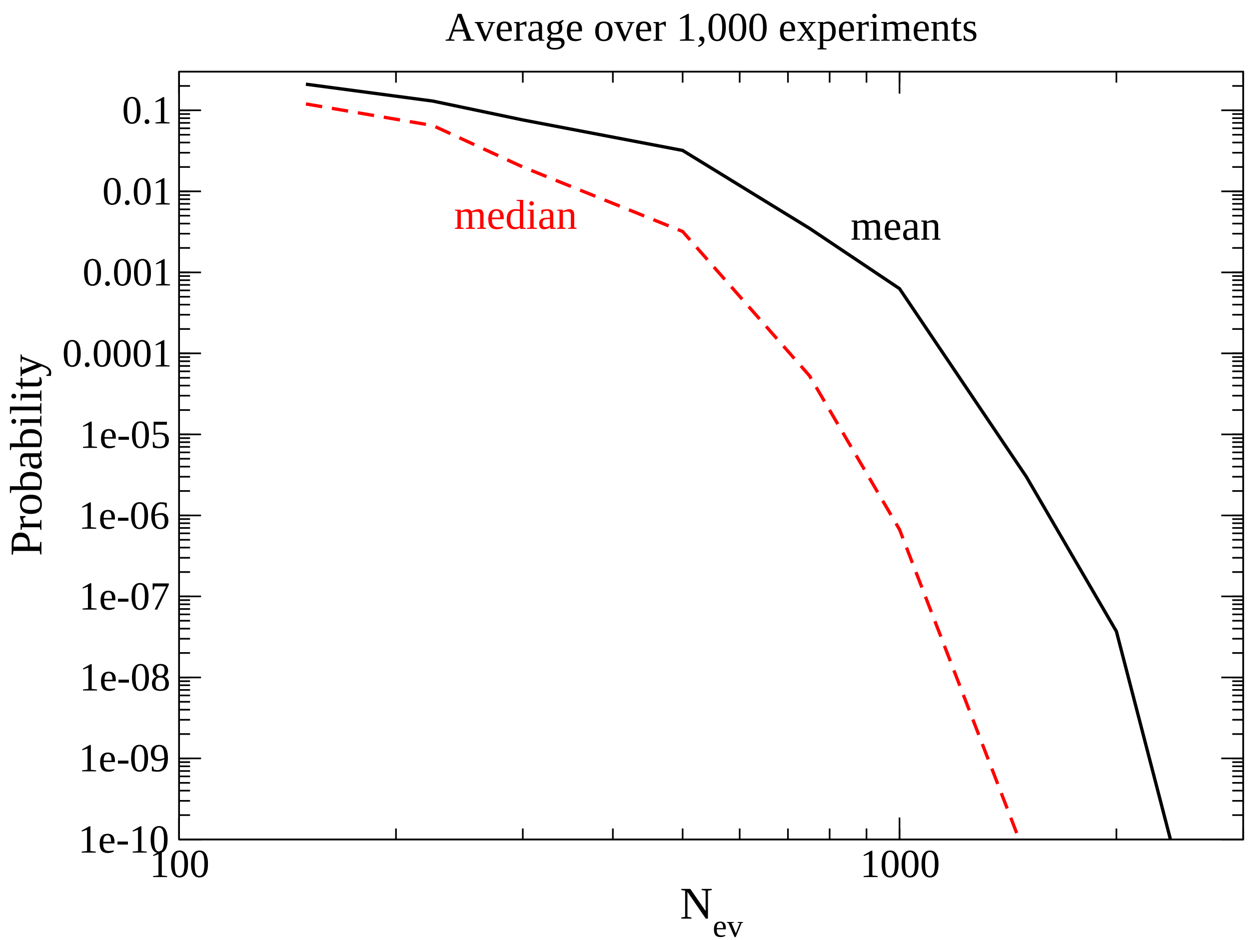


Statistical exclusion of constant f_1



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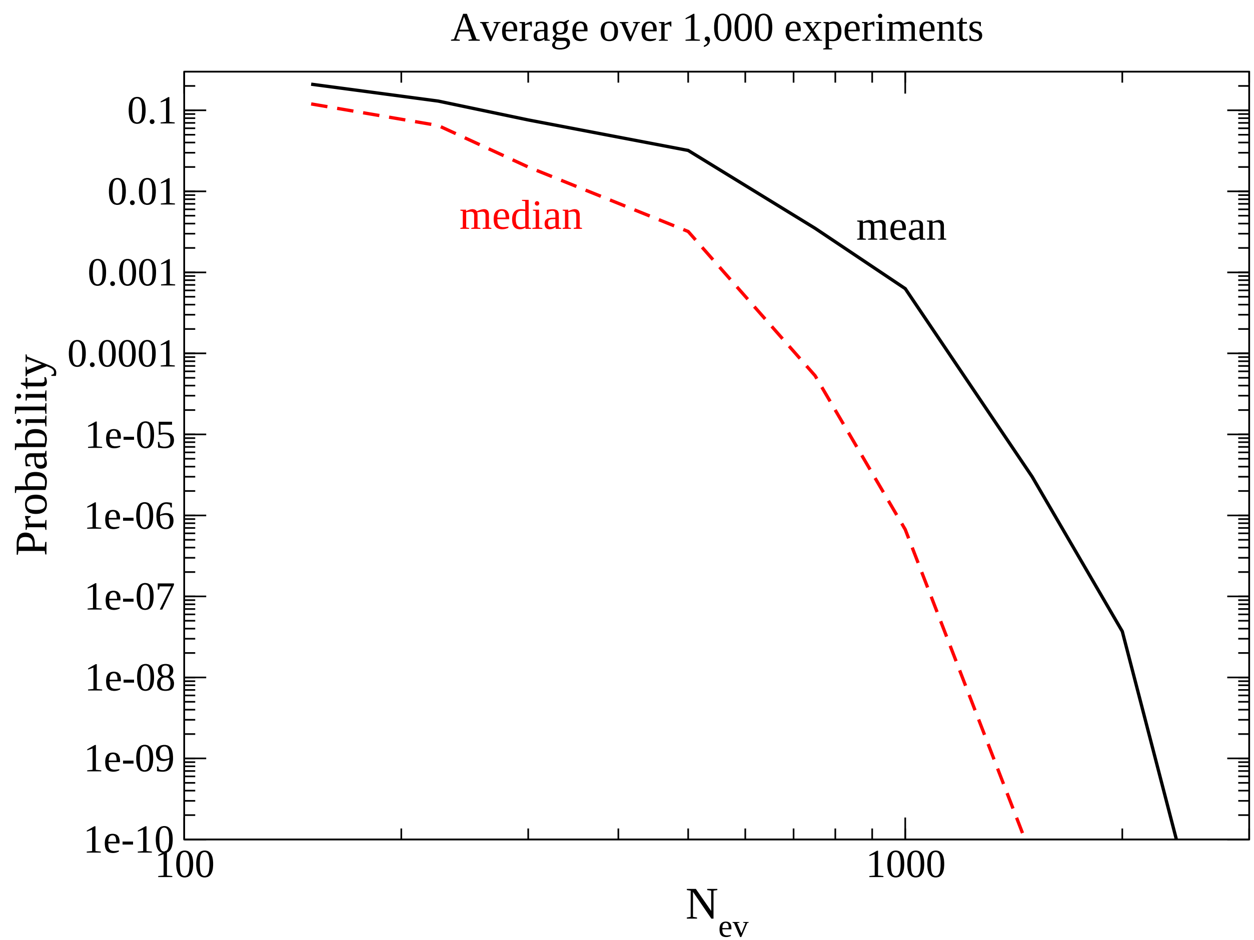

Need several hundred events to begin direct reconstruction!

Determining moments of f_1

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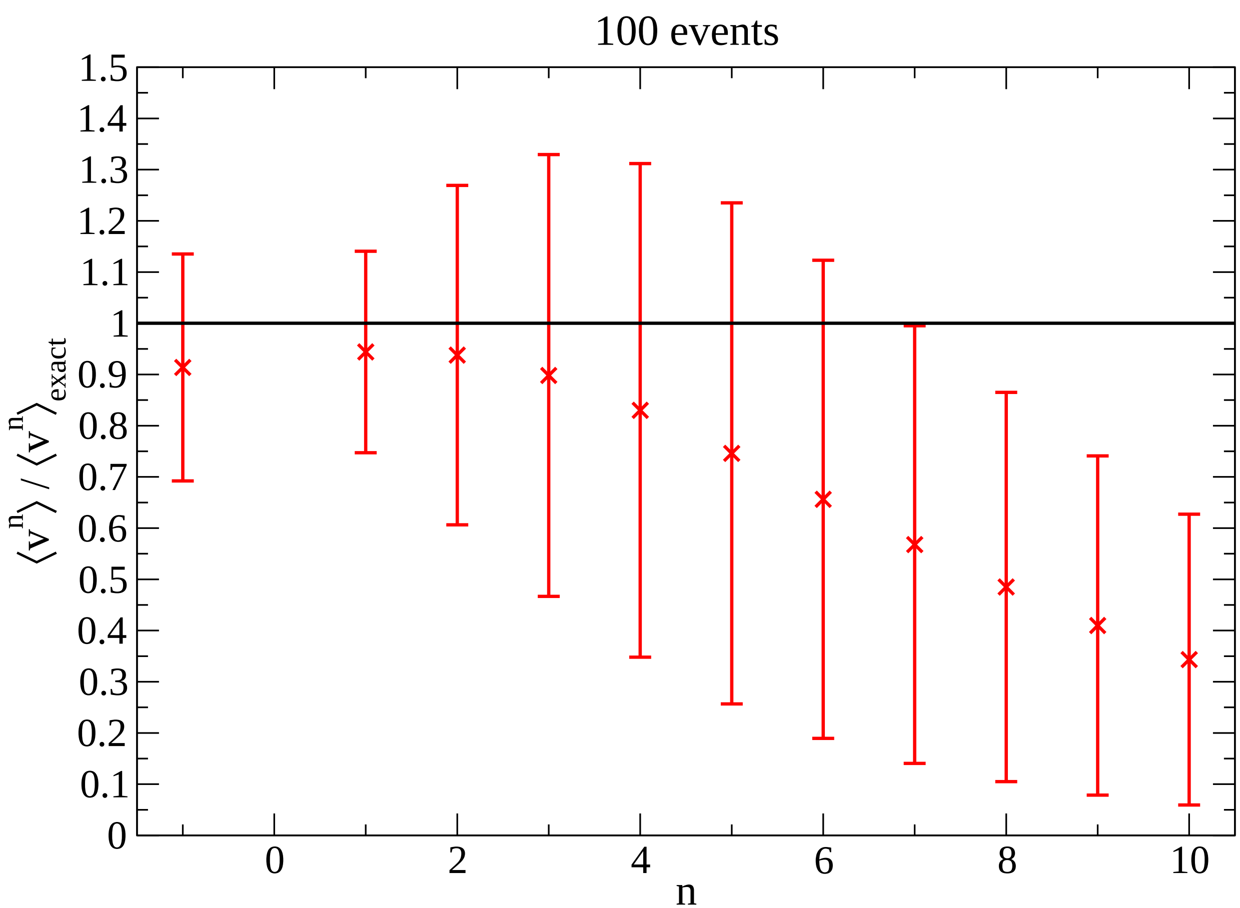
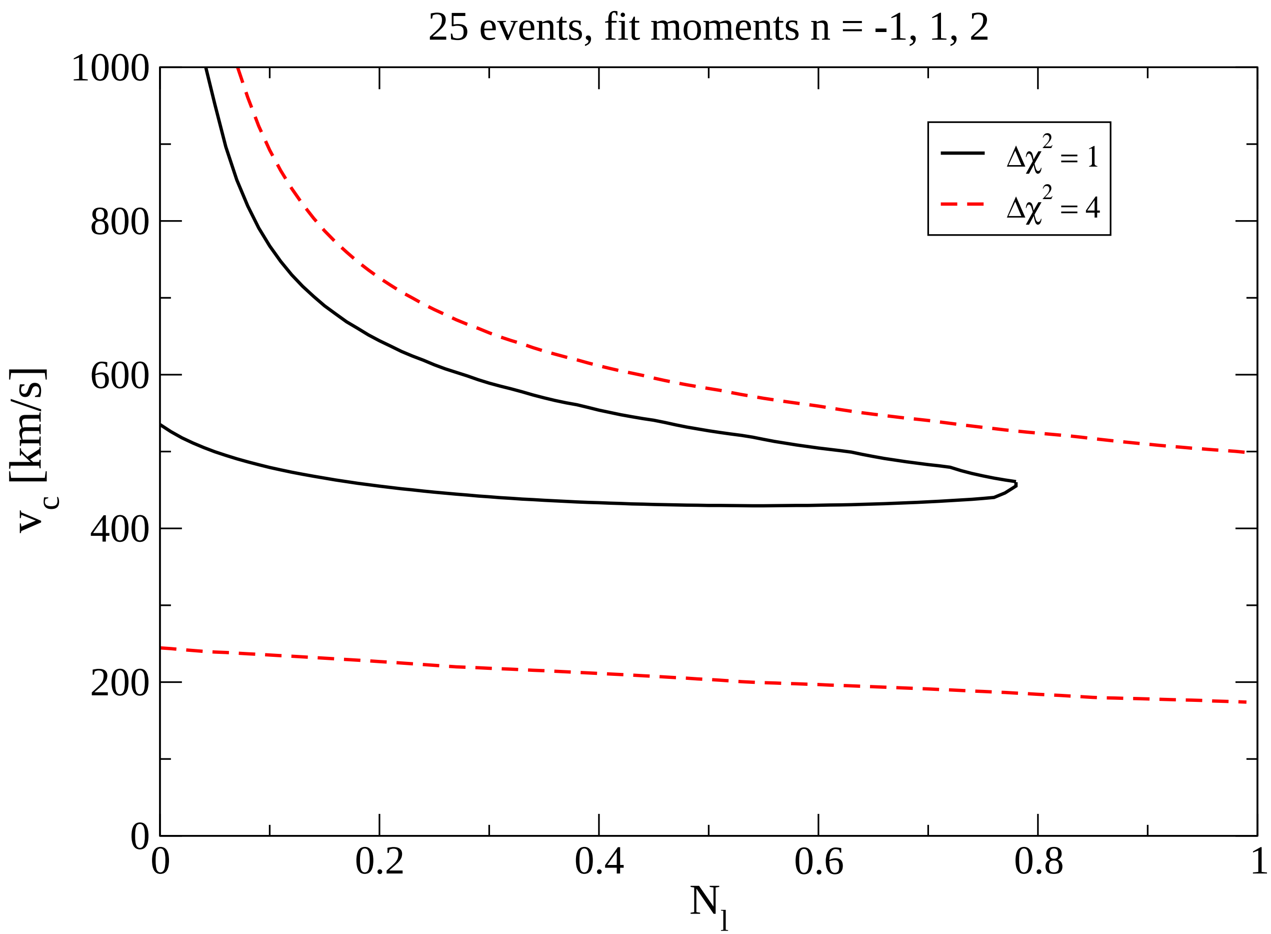
High moments, and their errors, are underestimated in "typical" experiment: get large contribution from large Q

Determination of first 10 moments



Constraining a “late infall” component



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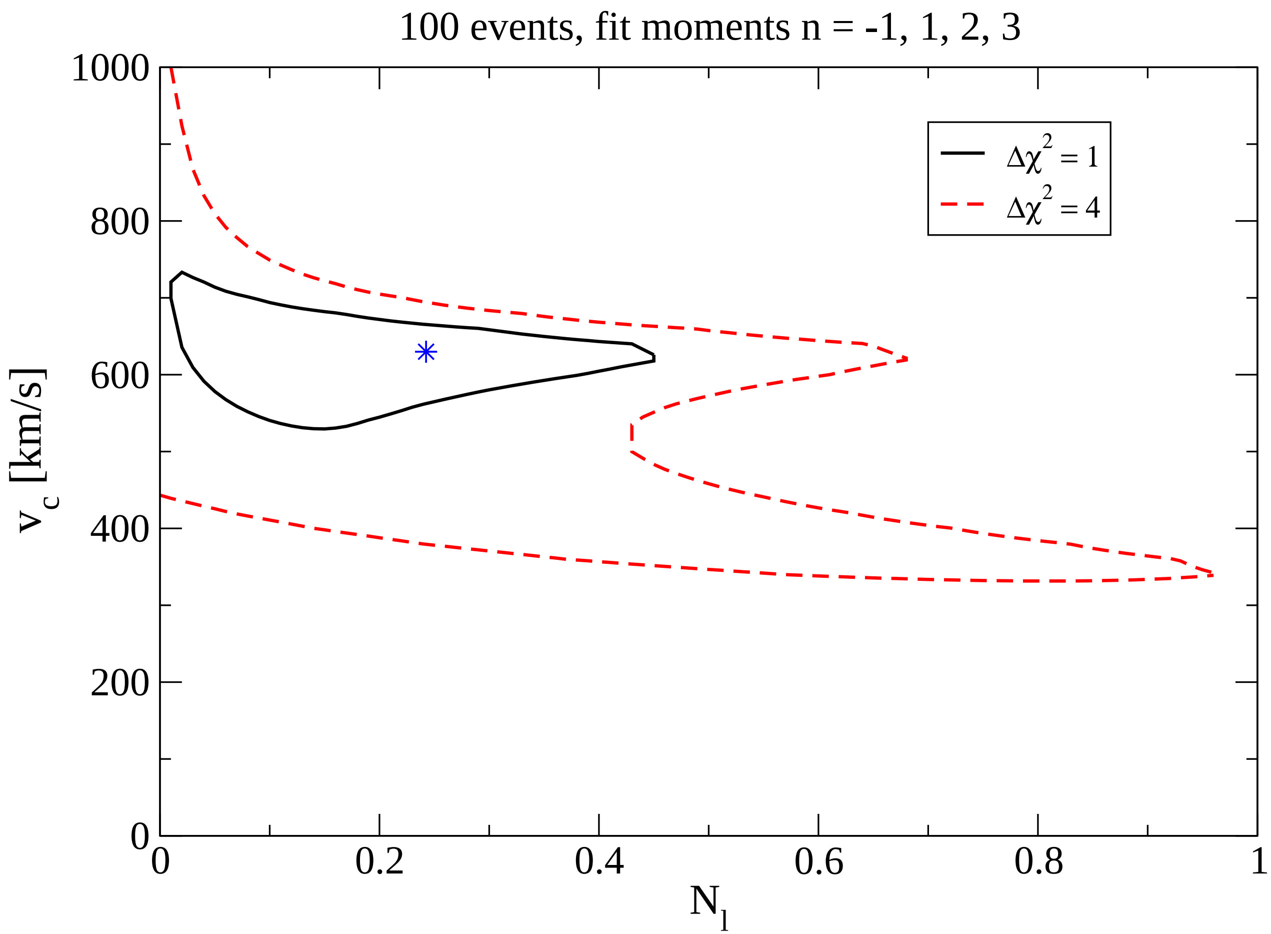

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  - Needs to be done to determine ρ_χ: required input for learning about early Universe!