Probing the Smallest Dark Matter Halos with Direct Detection Experiments

Jonathan Cornell

Based on J.M. Cornell and S. Profumo
JCAP06(2012)011

Chemical vs. Kinetic Decoupling of WIMPs

- *Chemical decoupling*, or “freeze out”, occurs at approximately $T_f \approx \frac{m_\chi}{20}$.
- After freeze out, WIMPs can still scatter at a sufficient rate to stay in thermal equilibrium with the SM particle heat bath.
- After more time, WIMPs can no longer find enough SM scattering particles within H^{-1}, so we have *kinetic decoupling.*

In a nutshell…

- Kinetic decoupling of WIMPs in the early universe leads to a exponential cutoff in the WIMP power spectrum, along with a cutoff in the possible masses of protohalos that can form.
- The smallest of these protohalos have masses of around $10^{-6}\ M_{\odot}$, making them extremely difficult to find through conventional methods.
- WIMP/SM particle scattering processes set this cutoff, and since they also are the same processes relevant to direct detection, we expect direct detection results should be an indirect probe of this cutoff mass.

Temperature of WIMP Kinetic Decoupling

- Use Boltzmann equation for a precise calculation of T_{kd}:

$$E\left(\partial_t - H\,\boldsymbol{p}\cdot\boldsymbol{\nabla}_{\boldsymbol{p}}\right)f = C[f]$$

$$C[f] = c(T)m_\chi^2\left[m_\chi T\,\boldsymbol{\nabla}_{\boldsymbol{p}}^2 + \boldsymbol{p}\cdot\boldsymbol{\nabla}_{\boldsymbol{p}} + 3\right]f(\boldsymbol{p})$$

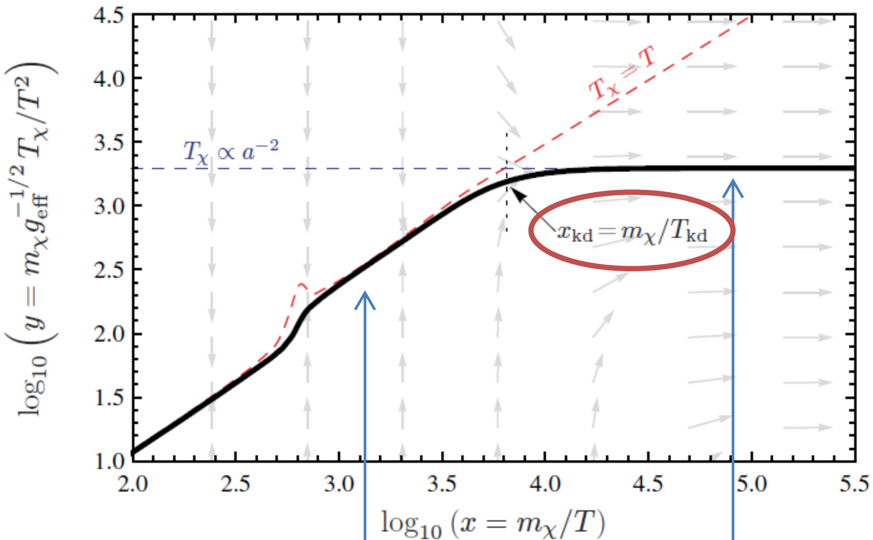
- By manipulating Boltzmann equation, we find an equation for the evolution of temperature parameter T_χ:

$$\boxed{(\partial_t + 5H)\,T_\chi = 2\,m_\chi\,c(T)\left(T - T_\chi\right)}$$

$$T_\chi \equiv \frac{2}{3}\left\langle\frac{\boldsymbol{p}^2}{2M_\chi}\right\rangle$$

Bringmann, 2009

Numerical Calculation of T_{kd}

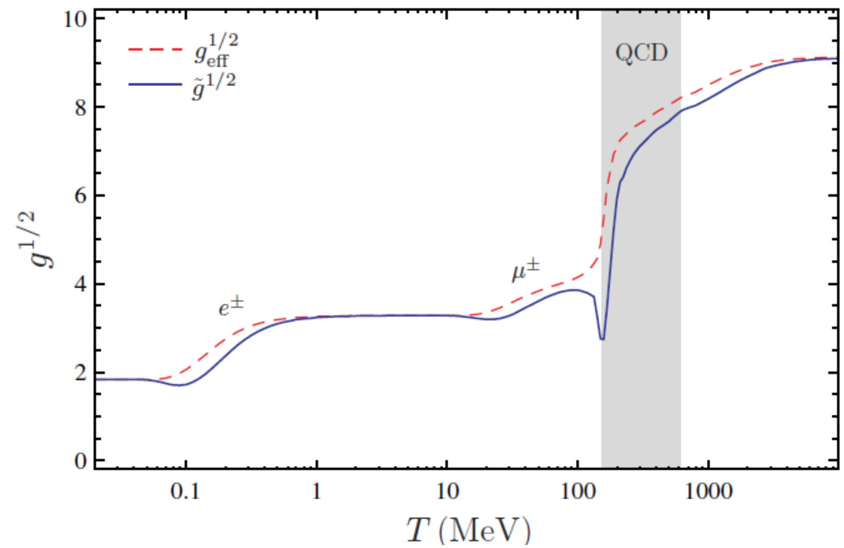


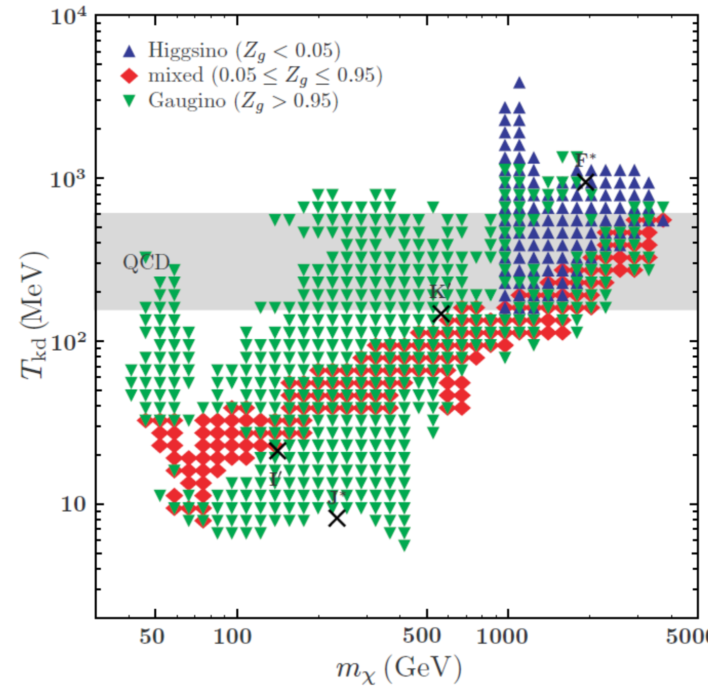
Thermal equilibrium

Collision term is effectively zero, $T_\chi \propto a^{-2} \propto T^2$ from Hubble expansion

$$x = M_\chi / T \qquad y = \frac{M_\chi T_\chi}{s^{2/3}}$$

Bringmann, 2009





From T_{kd} to the DM Halo Cutoff Mass

- *Viscosity:* Viscosity between the WIMP and SM particle fluids around T_{kd} leads to damping of perturbations.
- *Free streaming:* After kinetic decoupling, DM propagates from areas of high density to low density, leading to further damping.
- *WIMP acoustic oscillations:* Before T_{kd}, perturbation modes in the WIMP fluid smaller than the horizon size couple to acoustic oscillations in the SM particle heat bath. As decoupling occurs, these modes are damped out.

Green, Hofmann, and Schwarz, 2005

Loeb and Zaldarriaga, 2005

Correlations between M_{cut} and Direct Detection rates in the MSSM

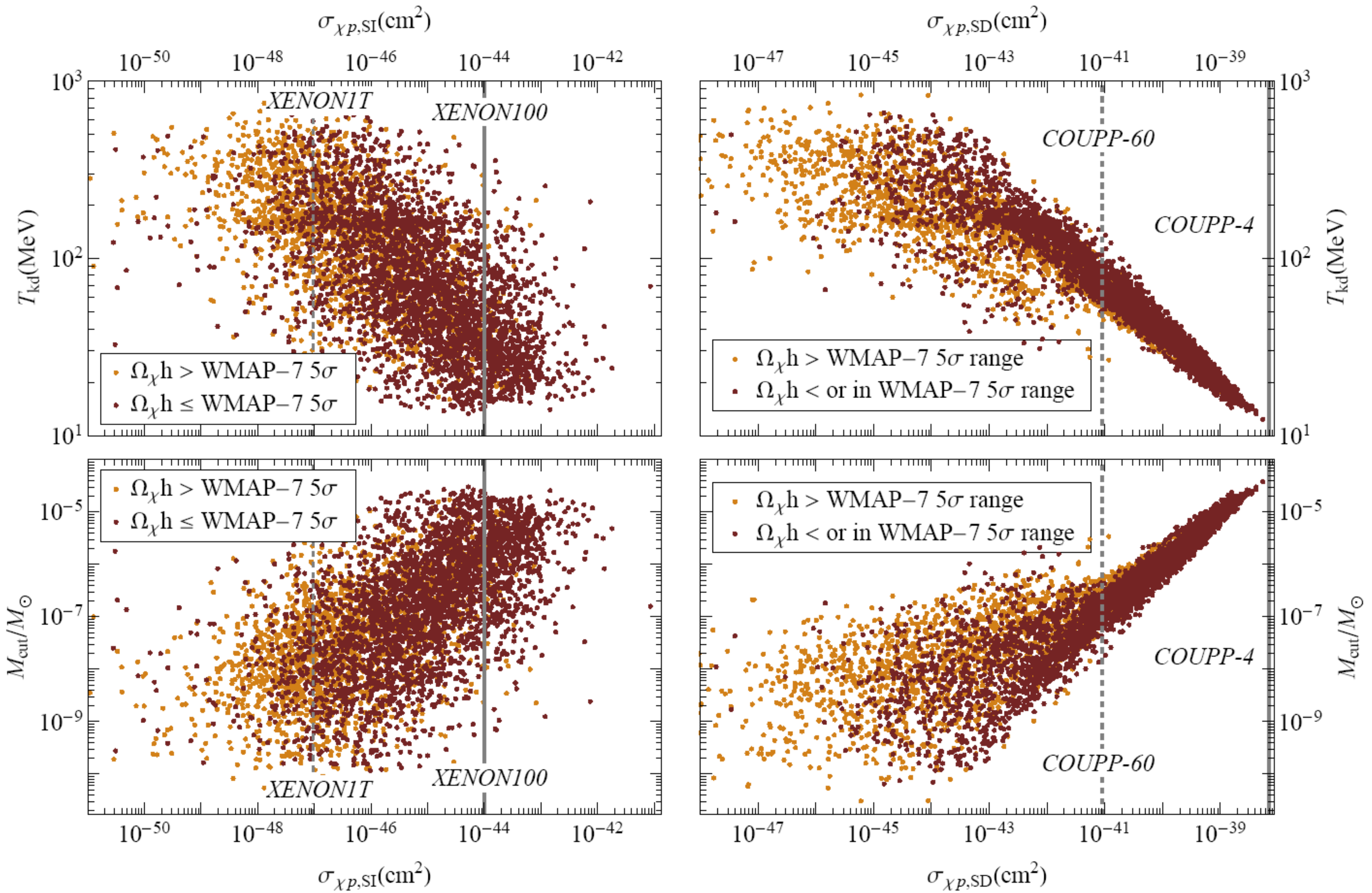
- T_{kd} is calculated using Bringmann's numerical routine, which is interfaced with the DarkSUSY code. DarkSUSY is also used to calculate direct detection cross sections

9 Parameter MSSM

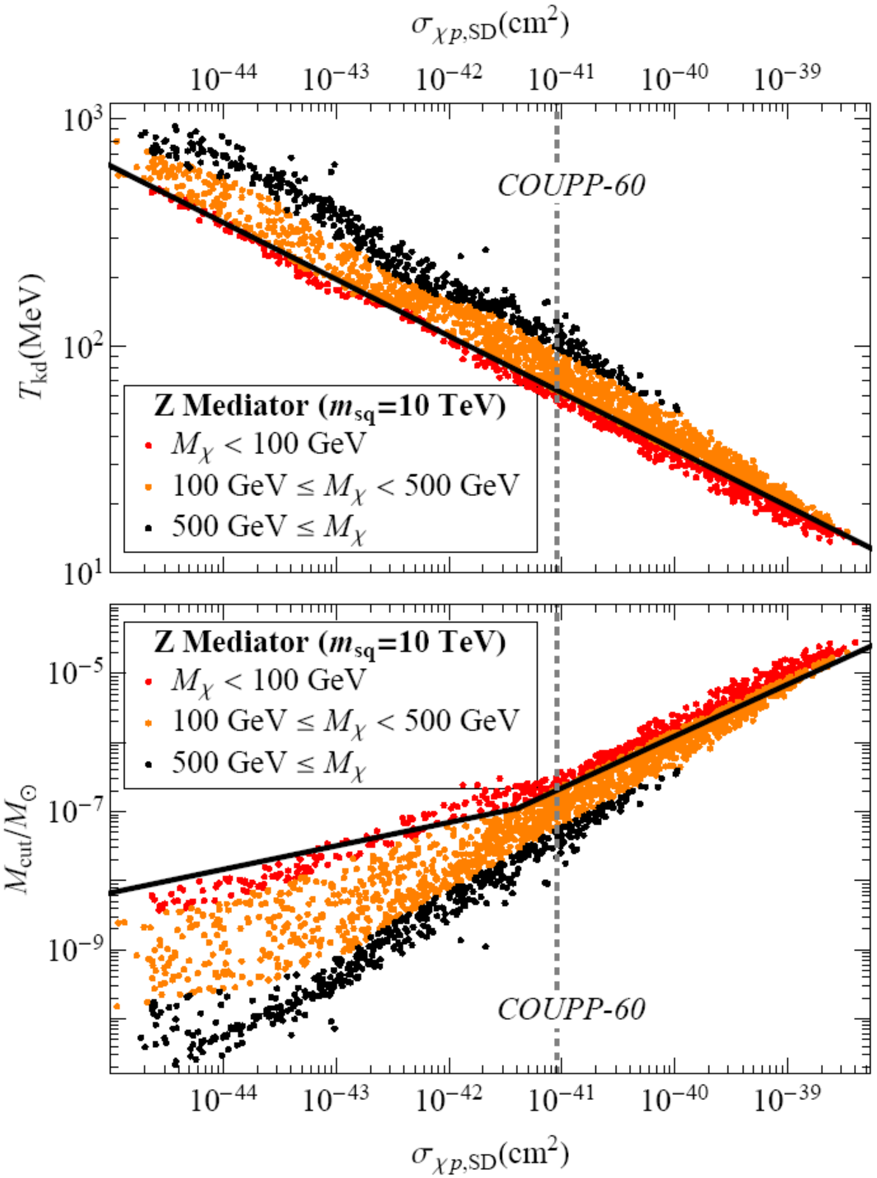
Parameter	Range
M_2, μ	±(50 GeV, 5 TeV)
M_1, M_3, m_{sq}, m_A	(50 GeV, 5 TeV)
A_t, A_b	(-5 TeV, 5 TeV)
$\tan\beta$	(2, 50)

Spin Independent

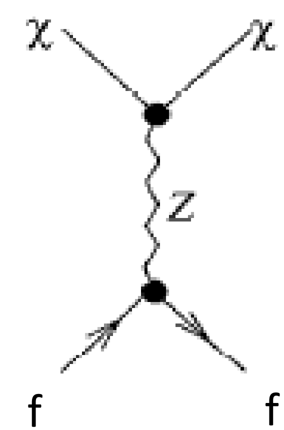
Spin Dependent



Heavy Squark Limit



- Is correlation between σ_{SD} and T_{kd} because of Z exchange processes? Set $m_{sq} = 10\ \mathrm{TeV}$ and scan to find out.



Prospects for More Direct Observations of Protohalos

- Direct gravitational lensing is difficult, but lensing of a time variable source that is multiply imaged might allow small variations in gravitational potential to be detectable.
- Anisotropy in gamma ray signal might allow detection of substructure at the necessary distance scales.
- Substructure should effect cosmic ray population.
- Could be seen by a bump in direct detection rate.

Conclusions

- There is a strong correlation between spin dependent DM direct detection rates and the dark matter protohalo mass spectrum cutoff in the MSSM.
- Therefore, direct detection results allow us to probe the protohalo mass cutoff.
- A limit on the cutoff mass, combined with a DM direct detection or limit on the scattering cross section, would allow us to place constraints on allowed DM models.

Extras

Minimal Universal Extra Dimensions

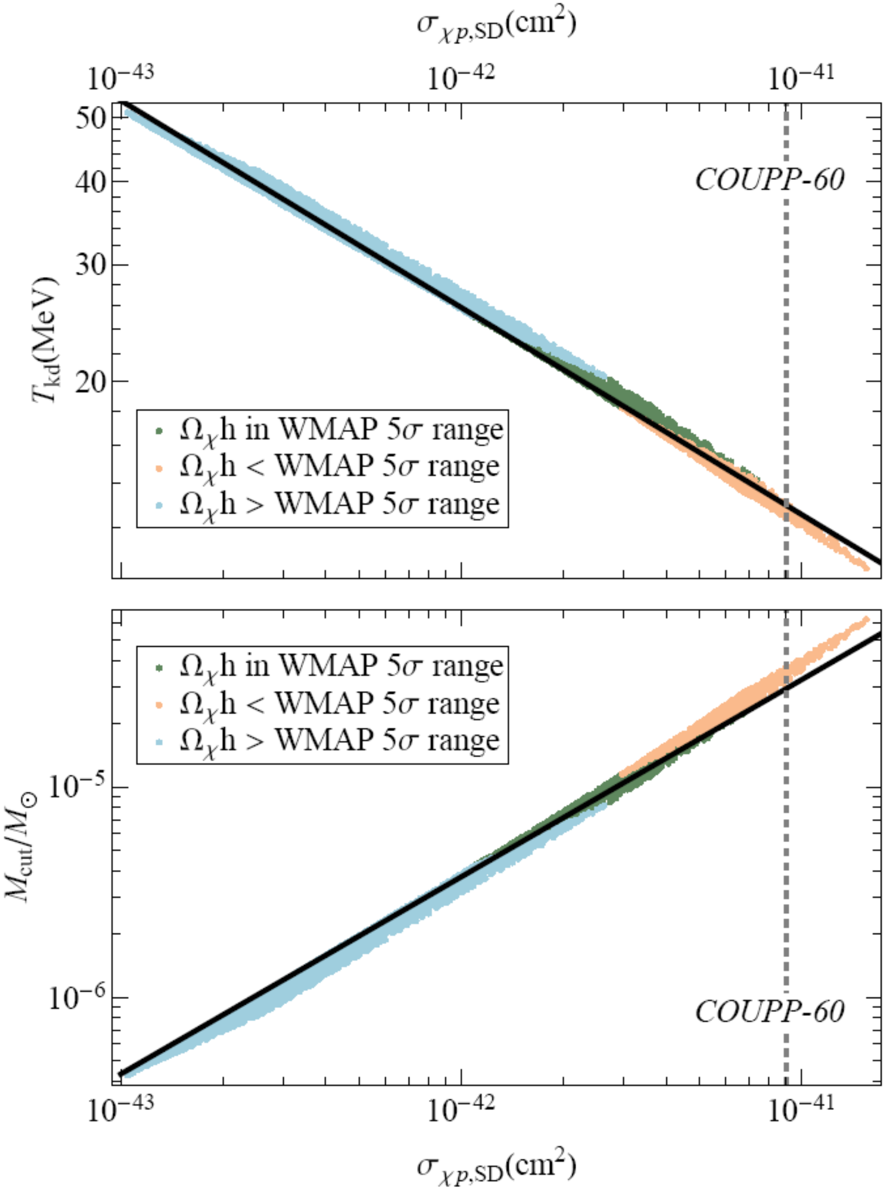
- One extra compactified dimension leads to towers of Kaluza-Klein mass states $m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}}$
- Has natural dark matter candidate: *KK photon*, which is stable, charge and colorless, and can have the correct relic density
- Our parameters: $500 \text{ GeV} \leq R^{-1} \leq 1400 \text{ GeV}$

$$10 \leq \Lambda R \leq 40$$

Hooper and Profumo (2007)

Direct detection cross sections from Servant and Tait (2002)

Spin Dependent



Spin Independent