Kaluza-Klein Dark Matter
-
Direct Detection vis-a-vis LHC

Sebastian Arrenberg
University of Zürich

Doktorandenseminar 2008
11.09.2008

Based on hep-ph/0805.4210 by
Sebastian Arrenberg
Laura Baudis
Kyoungchul Kong
Konstantin T. Matchev
Jonghee Yoo

(approved to appear in PRD)

Outline

Short overview of Universal Extra Dimensions (UEDs)

The relic density of Kaluza-Klein particles

Elastic scattering cross sections – predictions and limits

Limits on the degeneracy parameter Δ, the Higgs mass m_h and spin-dependent WIMP-nucleon couplings

- all Standard Model particles are promoted to one or more compactified flat extra dimensions

- infinite number of new particles (Kaluza-Klein tower)

- tree level masses: $$m_n^2 = m^2 + \frac{n^2}{R^2}$$

quantum number labelling the nth KK mode

mass of the associated SM particle

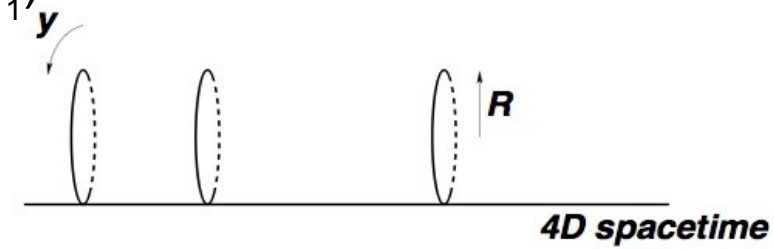
compactification scale

- high degree of mass degeneracy
  → radiative corrections are of crucial importance

- including radiative corrections yields KK parity $(-1)^n$ conservation
  → stable level 1 particles
  → possible dark matter candidates

Why do UEDs lead to new particles and thus to possible dark matter candidates?

Example: Complex Klein-Gordon field $\phi = \phi(x^\mu, y)$ with one extra dimension y compactified on a sphere with radius R (S_1).



Boundary condition: $y \to y + 2\pi R$

↓

Expansion in y: $\phi(x^\mu, y) = \frac{1}{\sqrt{(2\pi R)}} \sum_{n=-\infty}^{\infty} \phi_n(x^\mu) e^{\frac{i n y}{R}}$ with $p_5 = \frac{n}{R}$

↓

5-dimensional action: $S_5 = \int dx^4 \int_0^{2\pi R} dy\, L = \int dx^4 \int_0^{2\pi R} dy \left[\frac{1}{2}(\partial_M \phi^*)(\partial^M \phi) - \frac{1}{2} m^2 \phi^* \phi\right]$

↓

4-dimensional action: $S_4 = \int dx^4 \left[\sum_{n=-\infty}^{\infty} \frac{1}{2}(\partial_\mu \phi_n^*)(\partial^\mu \phi_n) - \frac{1}{2}\left(m^2 + \frac{n^2}{R^2}\right)\phi_n^* \phi_n\right]$

↓

Result: Infinite Tower of Klein-Gordon fields $\phi_n(x^\mu)$ with masses $m_n^2 = m^2 + \frac{n^2}{R^2}$.

- extra dimensional translation invariance

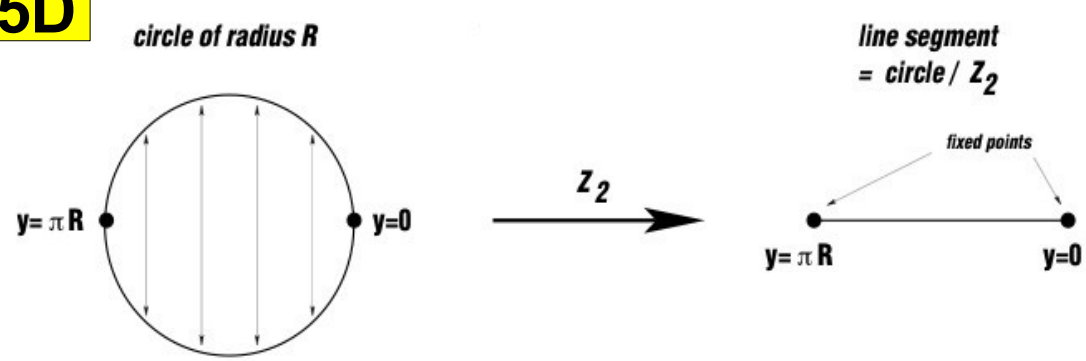
→ conservation of momentum p_5 → KK number n conservation

Additional breaking of 5D Lorentz-invariance is needed to obtain chiral gauge theory in effective 4D theory.

- use boundary condition $y \to -y$ (S_1/Z_2 orbifold)

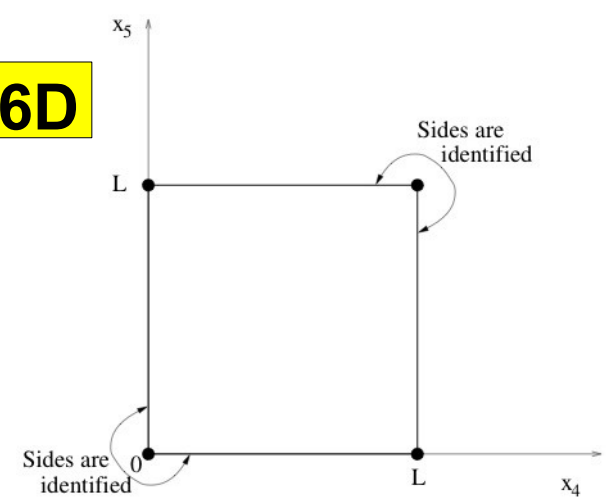
→ KK number conservation is broken down to KK parity $(-1)^n$ conservation

5D



$\cancel{G_1}$ $\cancel{\nu_1}$ γ_1 Z_1 H_1

6D



γ_H Z_H

high degree of mass degeneracy

→ coannihilations with all n=1 KK particles were taken into account

lightest particle obeys the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle (n^2 - n_{eq}^2)$$

with

$$\sigma_{eff}(x) = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{eff}^2} (1+\Delta_i)^{\frac{3}{2}} (1+\Delta_j)^{\frac{3}{2}} e^{-x(\Delta_i+\Delta_j)}$$

$$x = \frac{m_1}{T}$$

$$g_{eff}(x) = \sum_{i}^{N} g_i (1+\Delta_i)^{\frac{3}{2}} e^{-x\Delta_i}$$

$$\Delta_i = \frac{m_i - m_1}{m_1}$$

mass degeneracy parameter

What about the masses?

assume vanishing boundary interactions at the cut-off scale (minimal UED)

→ radiative corrections to the masses can be computed

Phys. Rev. D**66**, 036005 (2002)

LKP using MUED framework

→ 5D γ_1

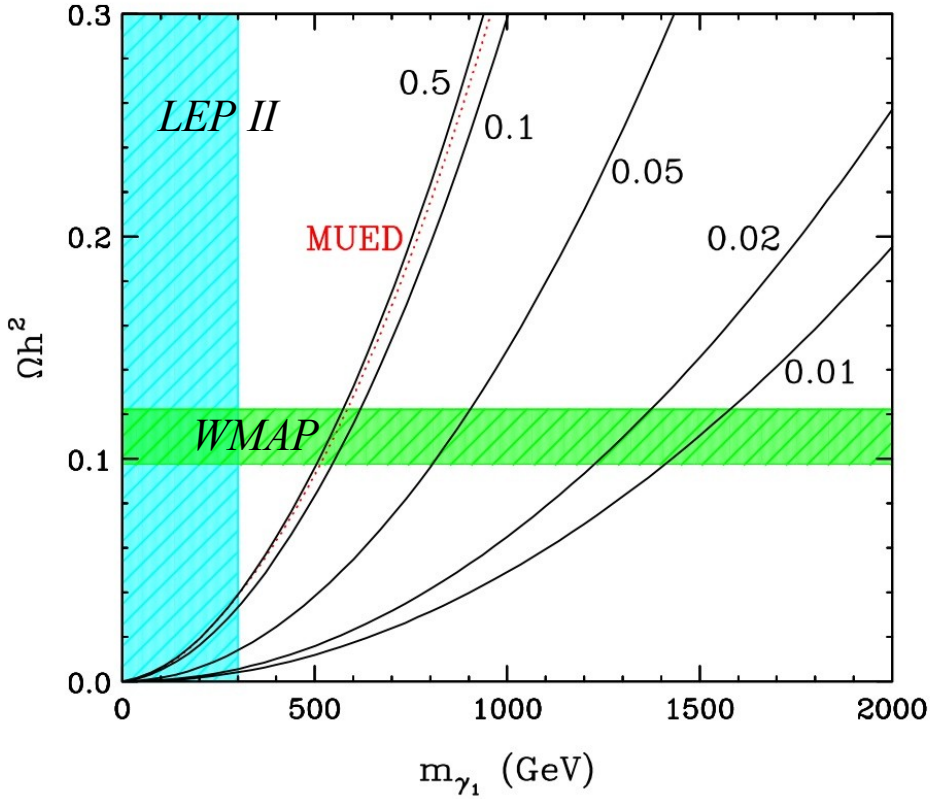
→ 6D γ_H

But consider other possibilities as well...

γ_1

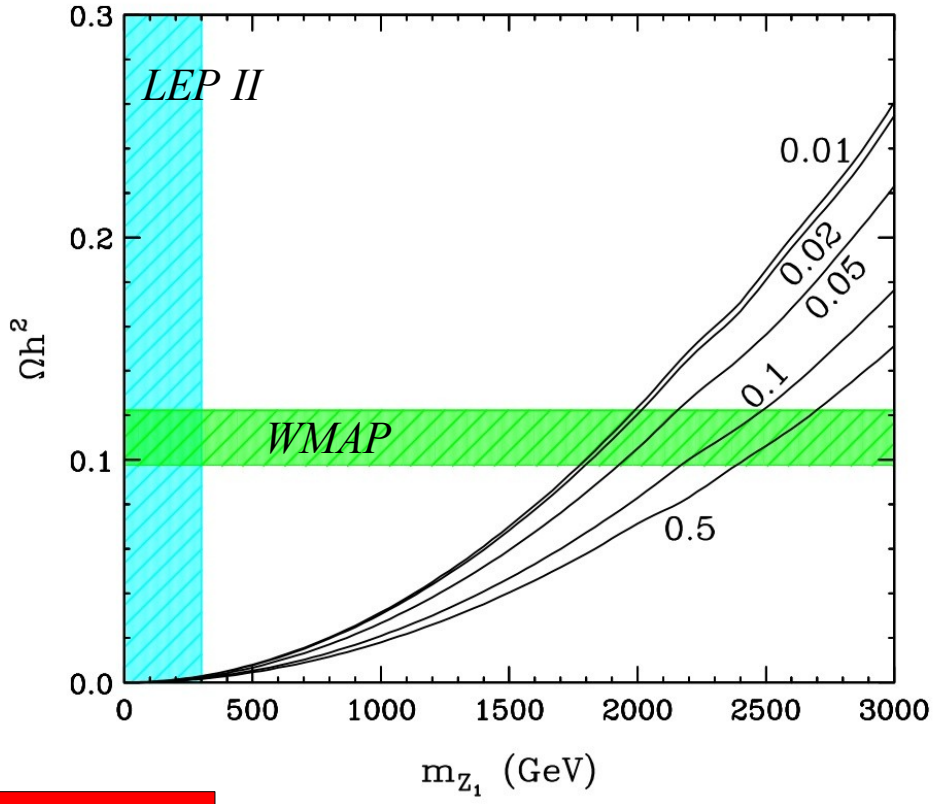
1) MUED framework

2) - assume certain mass splitting Δ between LKP and KK quarks
- fix rest of the spectrum using MUED



Z_1

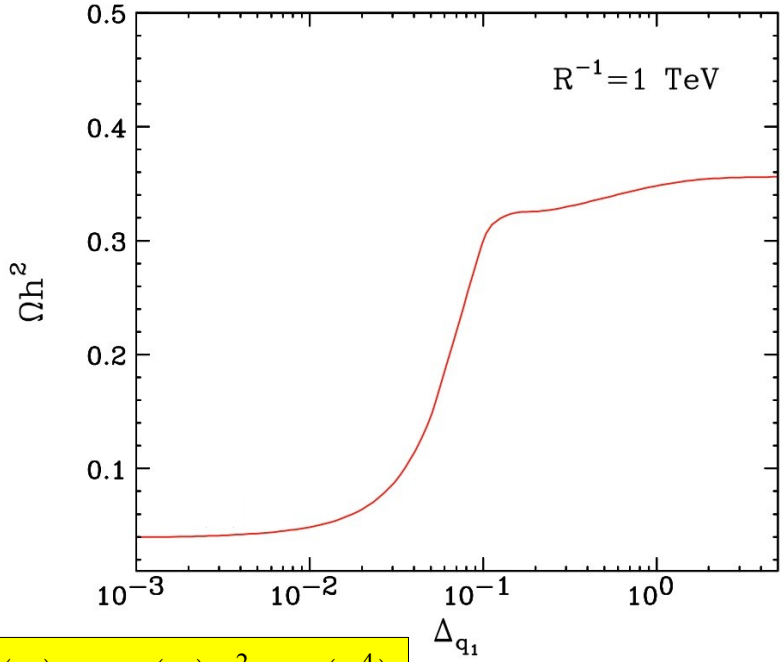
- Z_1 and $W_1^{\pm}$ are degenerate
- gluon is heavier than Z_1 by 20%
- all other particles are heavier than Z_1 by 10%



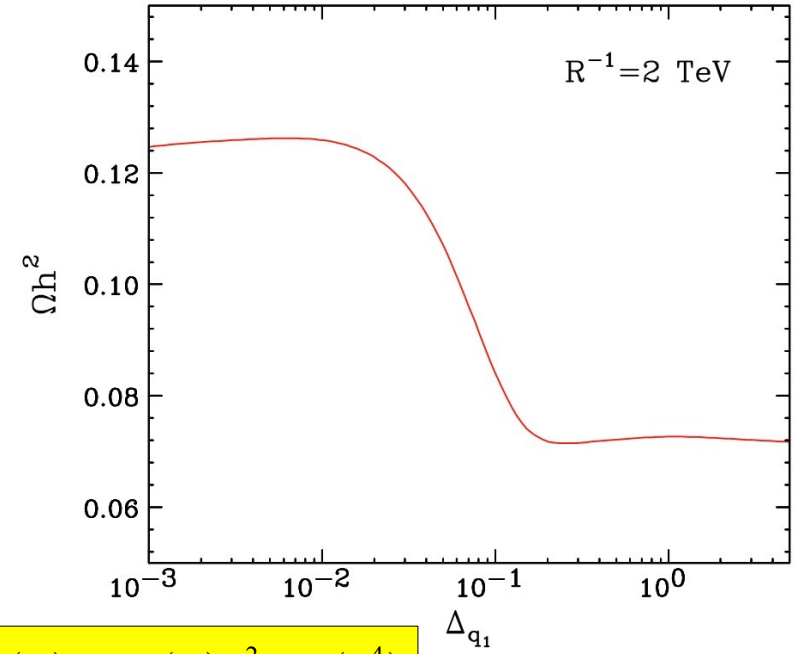
- coannihilations are indeed important
- the sign of the effect cannot easily be predicted

Computations of the relic density for 6D including coannihilations do not exist yet.

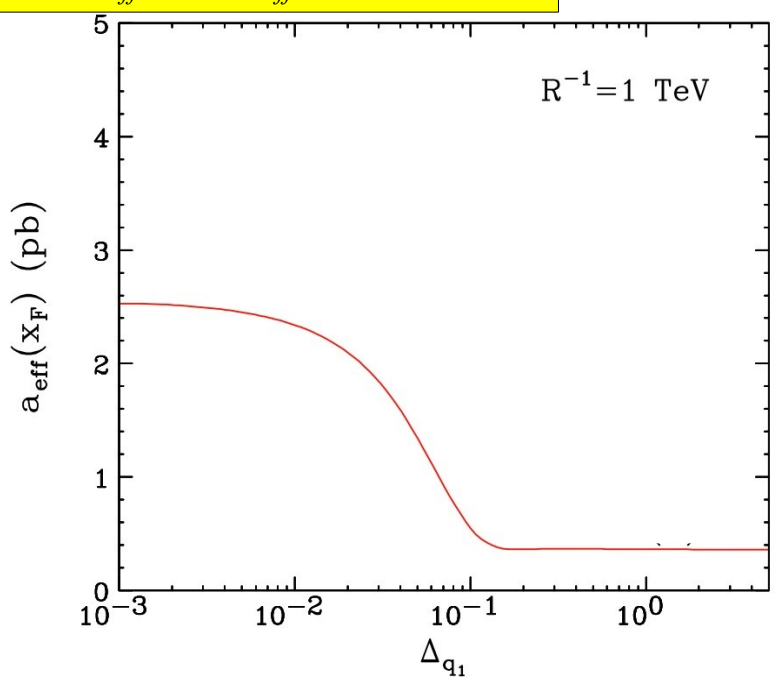
γ_1



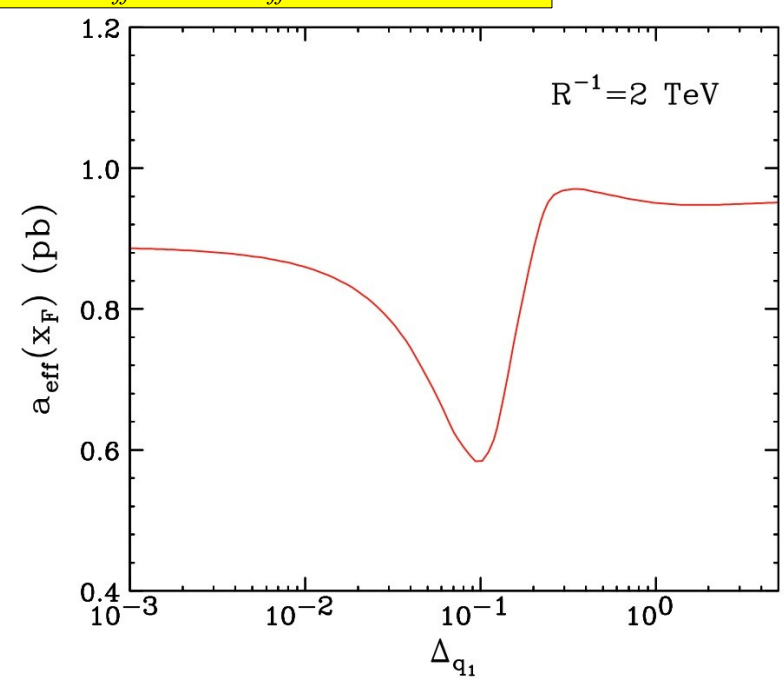
Z_1



$$\sigma_{eff}(x)v = a_{eff}(x) + b_{eff}(x)v^2 + O(v^4)$$

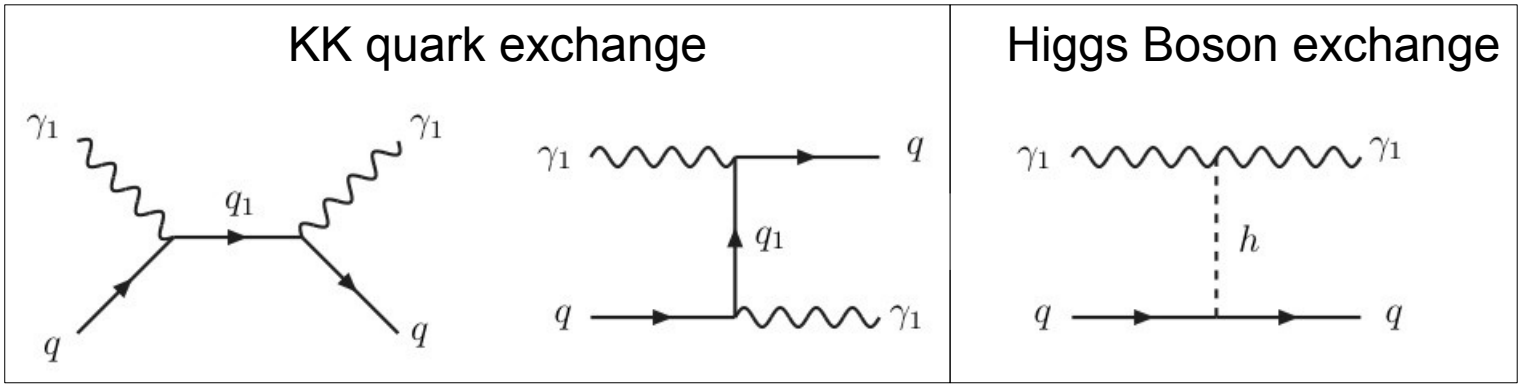


$$\sigma_{eff}(x)v = a_{eff}(x) + b_{eff}(x)v^2 + O(v^4)$$



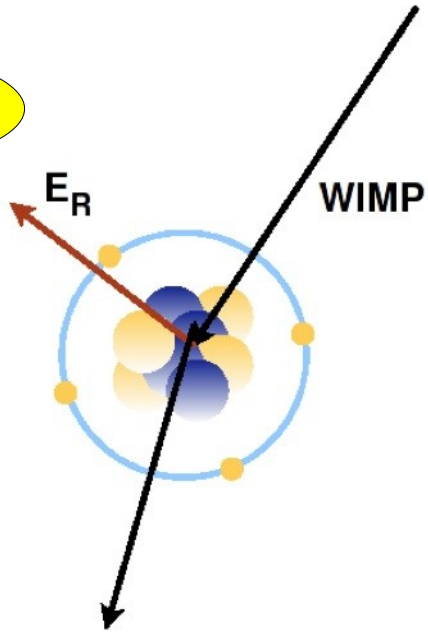
Final results depend on the detailed balance of several numerical factors.

Feynman diagrams for γ_1 - quark scattering (others are similar):



spin-dependent interaction

scalar interaction



Important parameters

SI WIMP-nucleon couplings f_n, f_p

SD WIMP-nucleon couplings a_n, a_p

Higgs mass m_h

degeneracy parameter $\Delta = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$

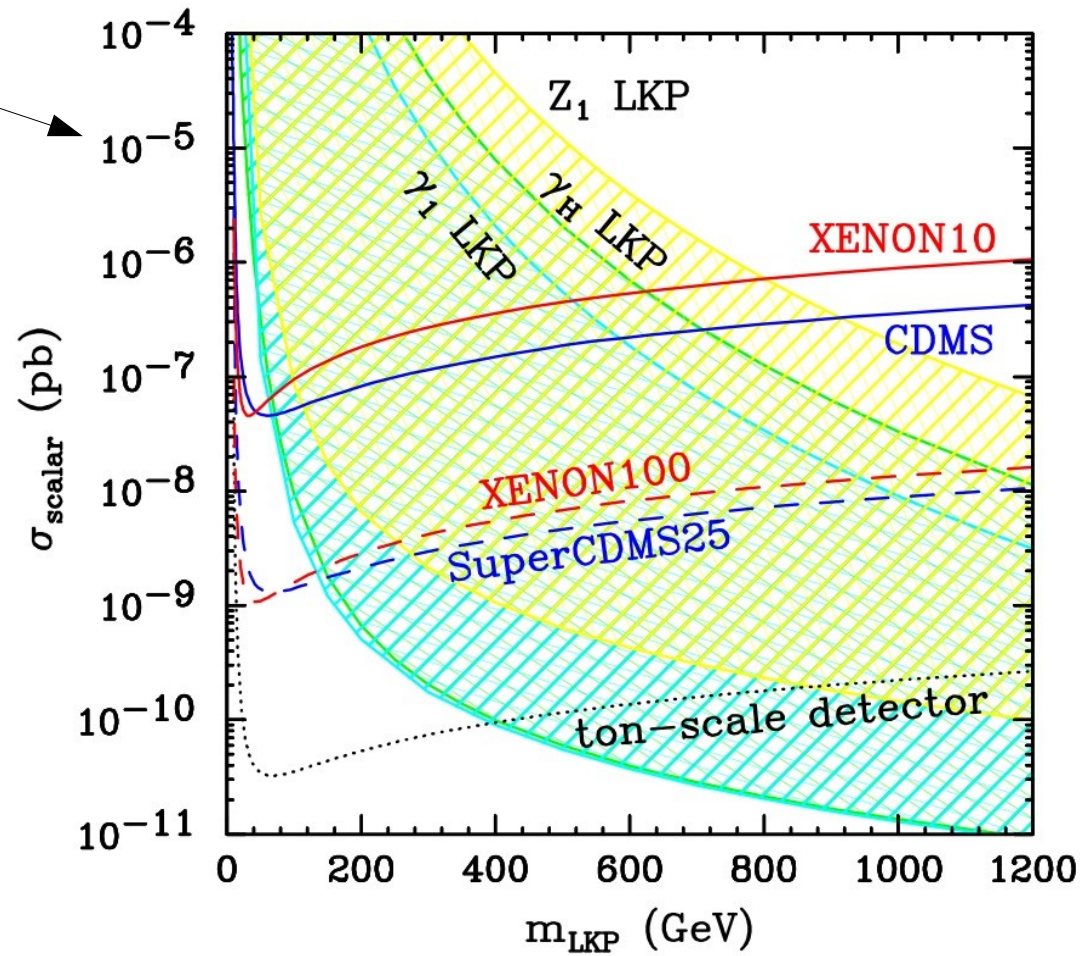
Spin-independent scattering

$$\sigma_{scalar} = \frac{m_T^2}{4\pi(m_{\gamma_1}+m_T)^2}[Zf_p+(A-Z)f_n]^2 \qquad f_{p,n} = \sum_{u,d,s}(\beta_q+\gamma_q)\frac{m_{p,n}}{m_q}f_{T_q}^{p,n}$$

γ_1

$$\beta_q = m_q \frac{e^2}{\cos^2\theta_W}\left[Y_{qL}^2 \frac{m_{\gamma_1}^2+m_{q_L^1}^2}{(m_{q_L^1}^2-m_{\gamma_1}^2)^2}+(L\to R)\right] \qquad \gamma_q = m_q \frac{e^2}{2\cos^2\theta_W}\frac{1}{m_h^2}$$

$m_h = 120\,GeV \qquad 0.01<\Delta<0.5$



- significant enhancement of cross sections for small Δ
- CDMS and XENON10 already exclude small mass splittings
- future ton-scale experiments should cover most of the interesting parameter space

$$\sigma_{spin} = \frac{32}{\pi} G_F^2 \mu^2 \frac{J_N+1}{J_N} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

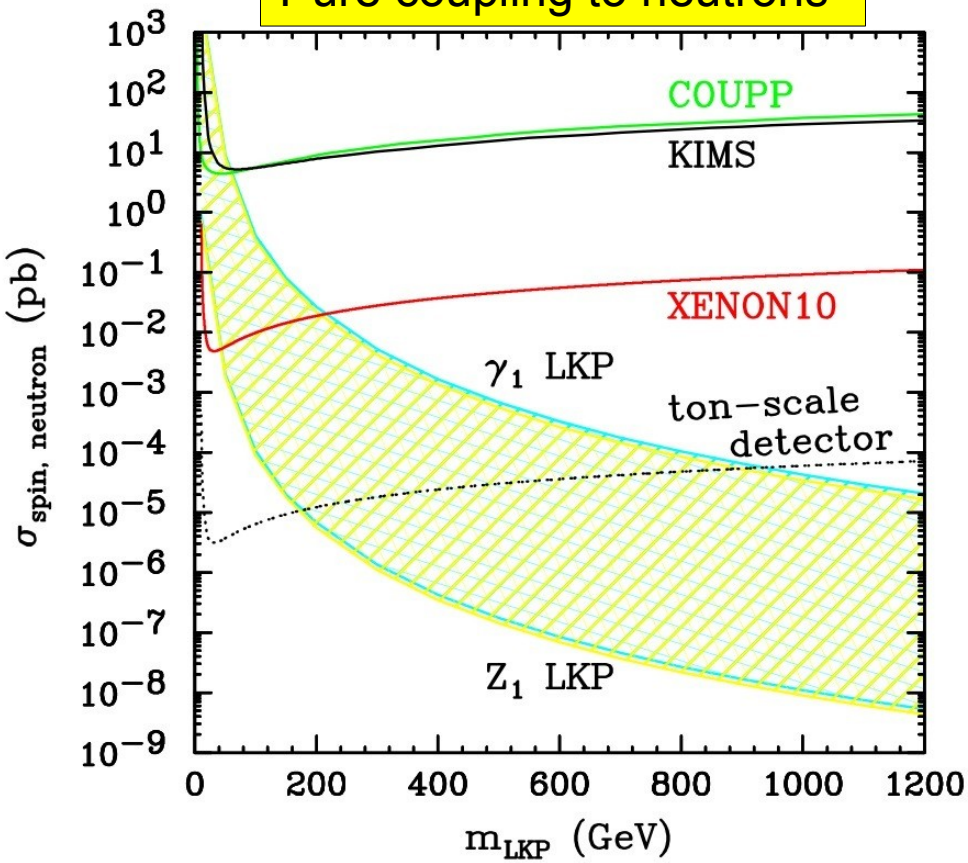
$a_{p,n}$ contain the whole theoretical model-dependence

γ_1

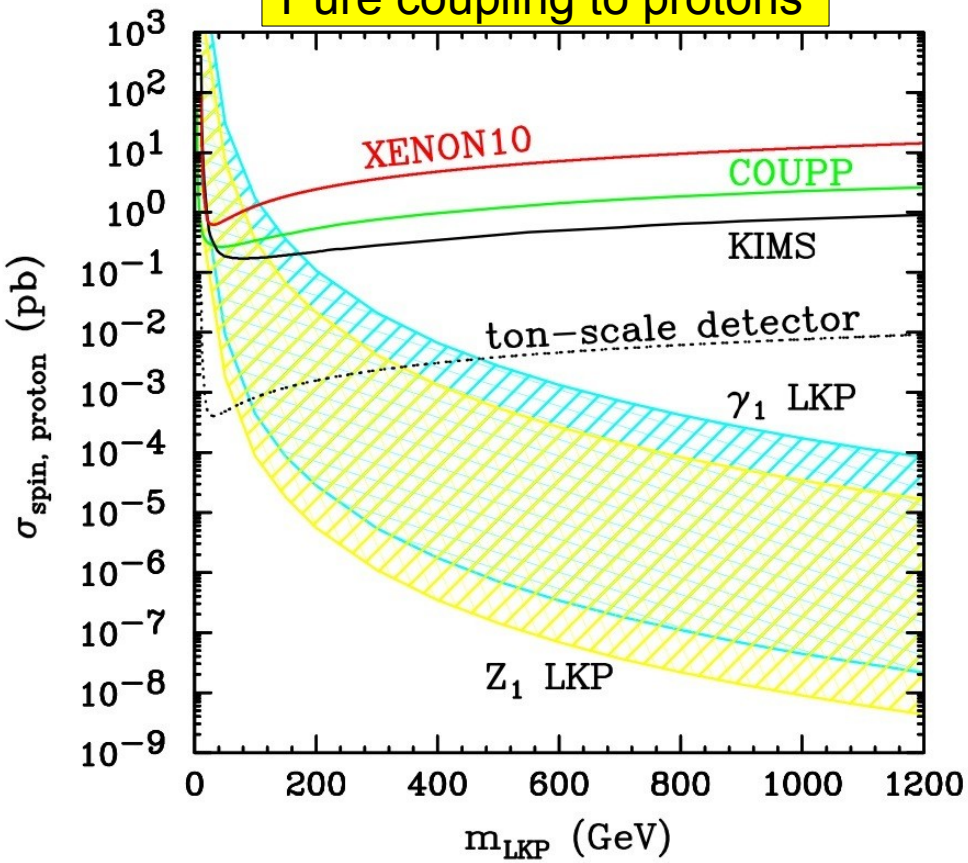
$$a_{p,n} = \frac{e^2}{4\sqrt{3}\, G_F \cos^2\theta_W} \sum_{u,d,s} \left[\frac{Y_{qL}^2}{m_{q_L^1}^2 - m_{\gamma_1}^2} + (L \to R) \right] \Delta_q^{p,n}$$

$0.01 < \Delta < 0.5$

Pure coupling to neutrons



Pure coupling to protons



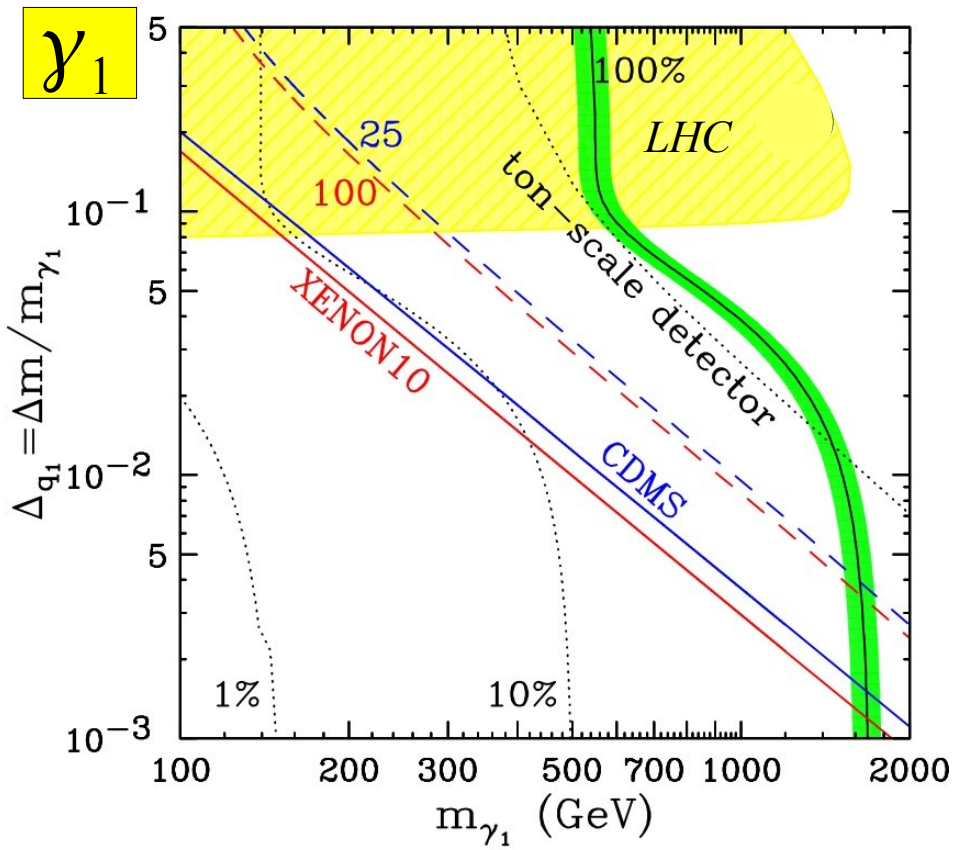
Proton and neutron SD cross sections are exactly equal in the case of Z_1.

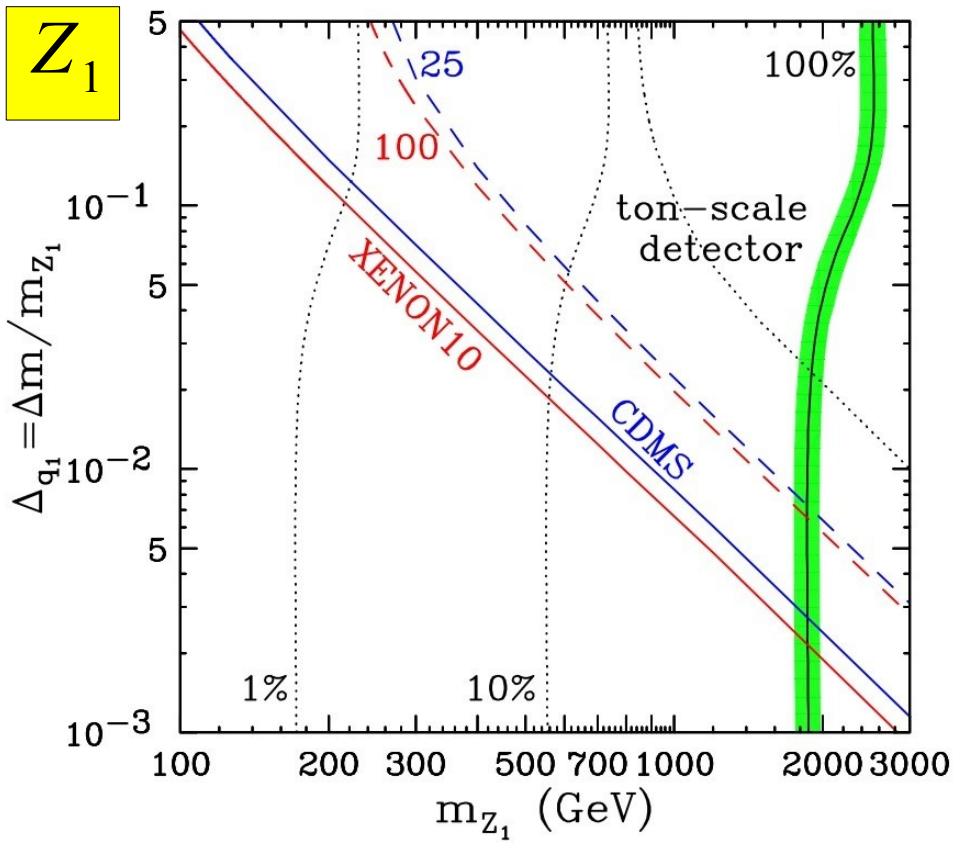
Neutron SD cross sections are approximately equal for γ_1 and Z_1.

Spin-independent limits on Δ from 5D UED

- free parameters: LKP mass and Δ
- Higgs mass is fixed at 120 GeV

Include....
- direct detection limits
- relic density constrains
- collider studies (hep-ph/0205314)





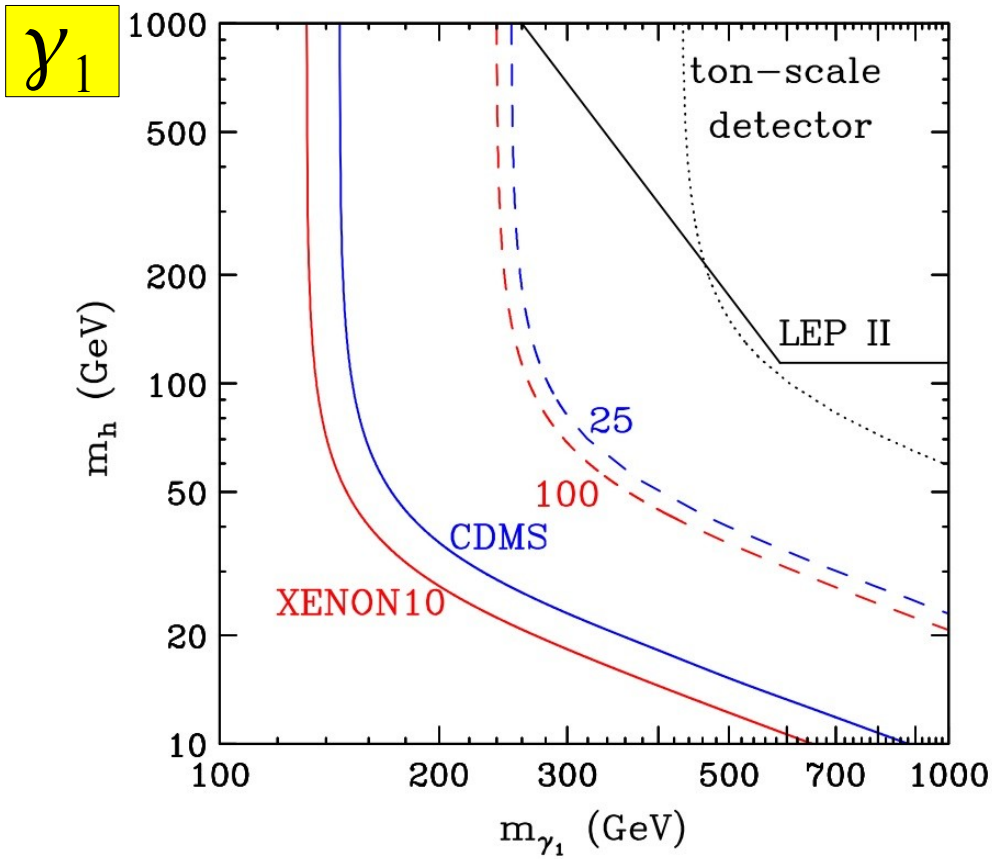
The three probes are highly complementary.

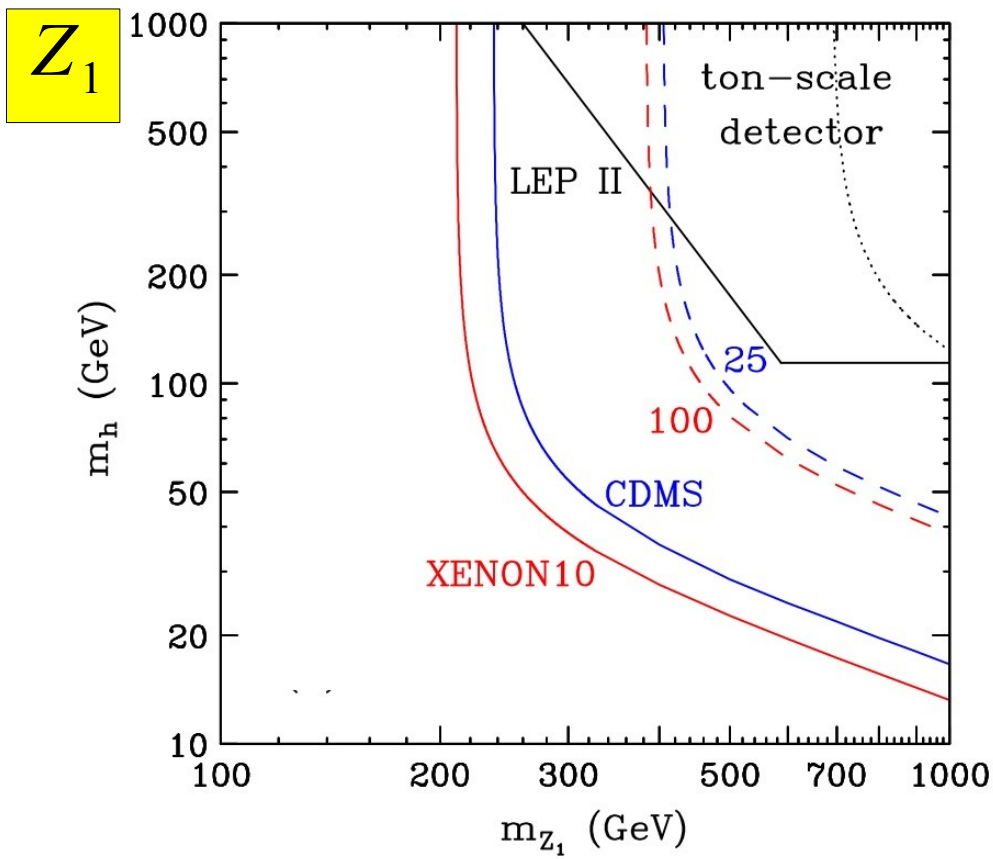
Cosmology provides **upper limit on LKP masses**.
Colliders are sensitive to **large** Δ.
Direct detection experiments are sensitive to **small** Δ.

Spin-independent limits on m_h from 5D UED

- free parameters: LKP mass and m_h
- Fix Δ at 0.1

Include....
- direct detection limits
- collider studies (hep-ph/0605207)





LKP mass and Δ are primary parameters. m_h plays only a secondary role.

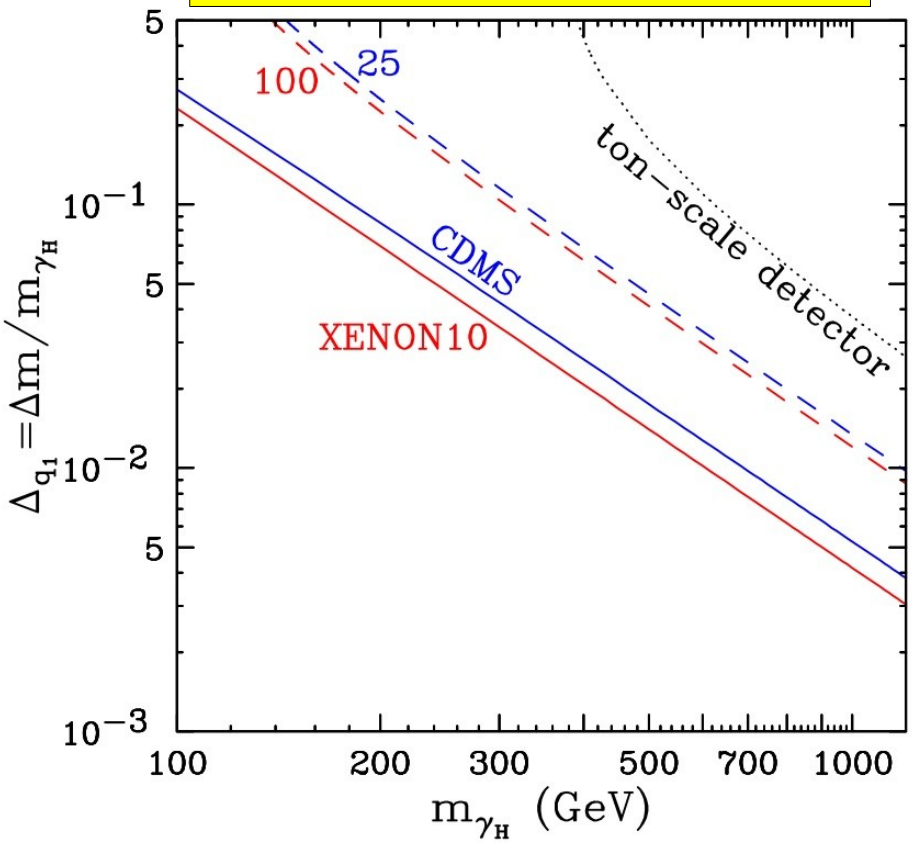
Future direct detection experiments only probe a small part of the parameter space.

LHC will be able to test the whole parameter space shown here.

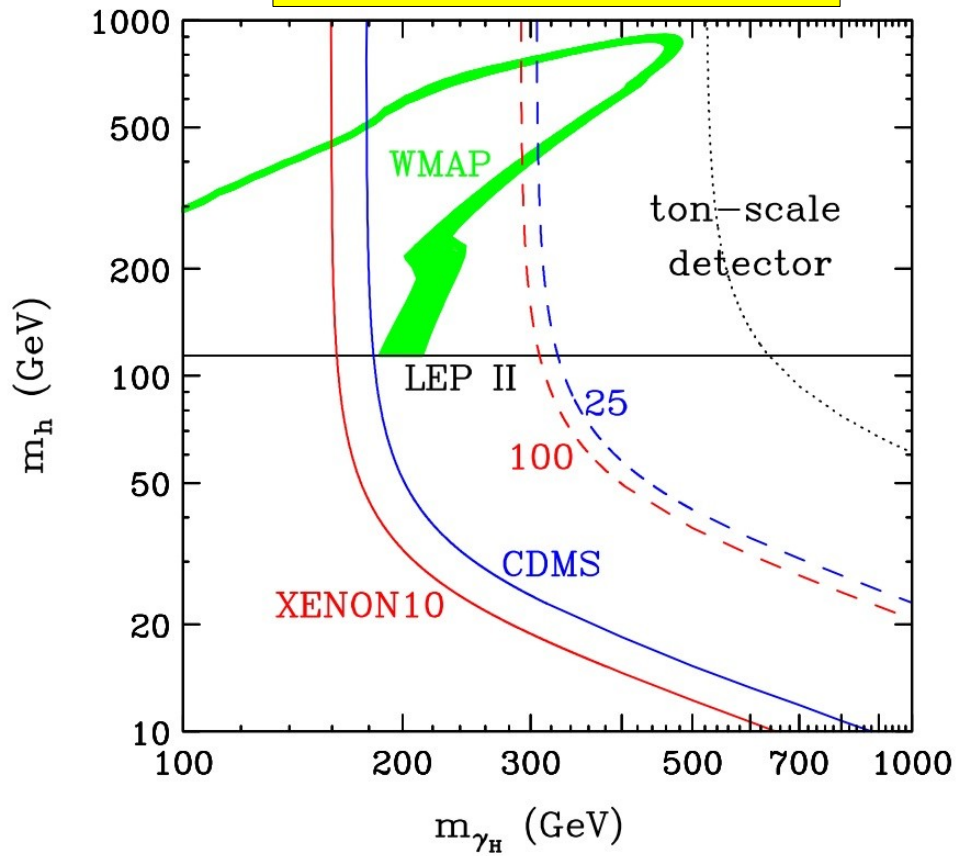
Spin-independent limits on Δ and m_h from 6D UED

γ_H

Limits on Δ for $m_h = 120\,GeV$



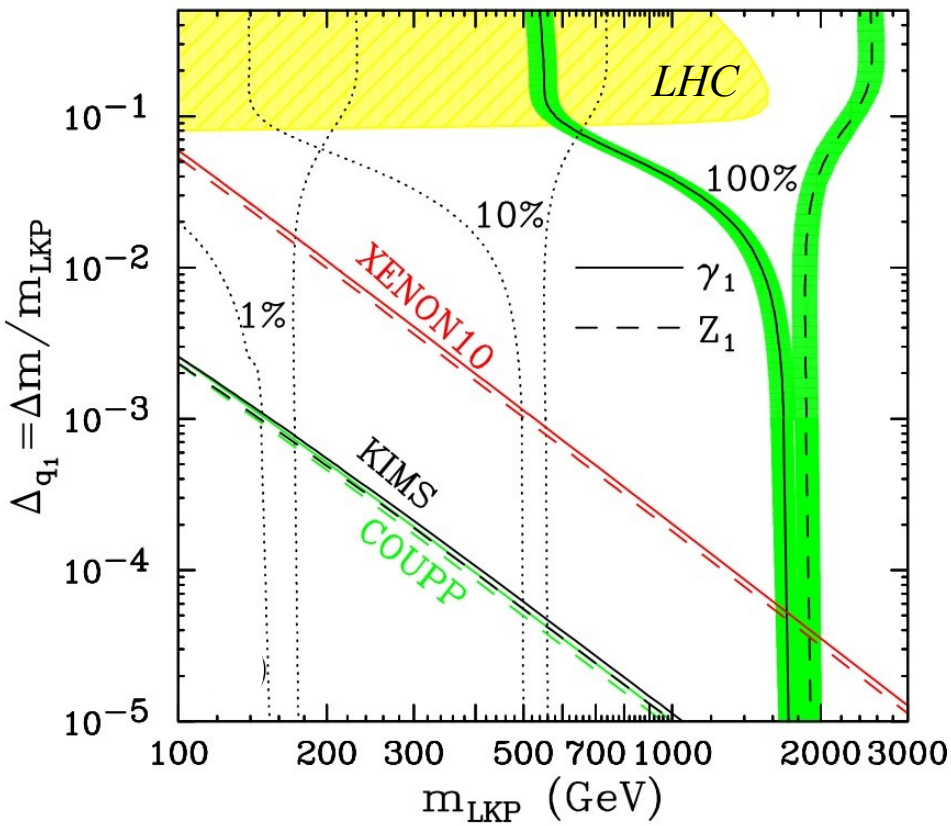
Limits on m_h for $\Delta = 0.1$



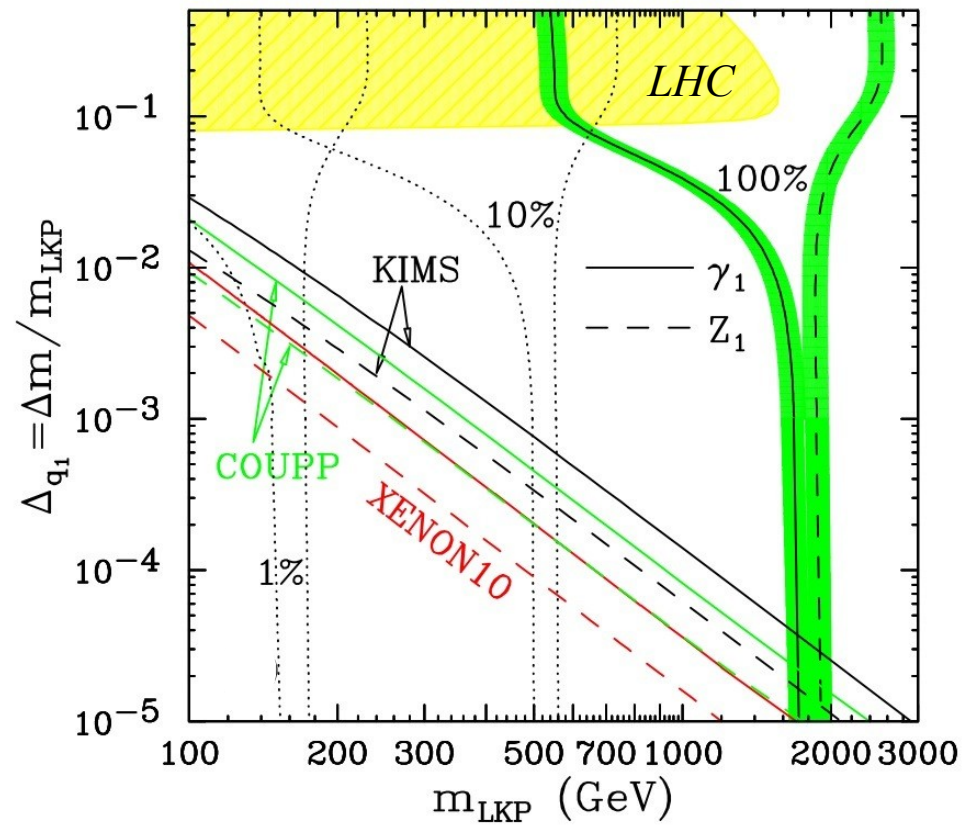
Spin-dependent limits on Δ from 5D UED

Limits on Δ can also be computed considering spin-dependent interactions.

Pure coupling to neutrons



Pure coupling to protons



SD constrains are about an order of magnitude smaller than the SI limits.

The experiments' sensitivities to both interactions crucially depend on the used target material.

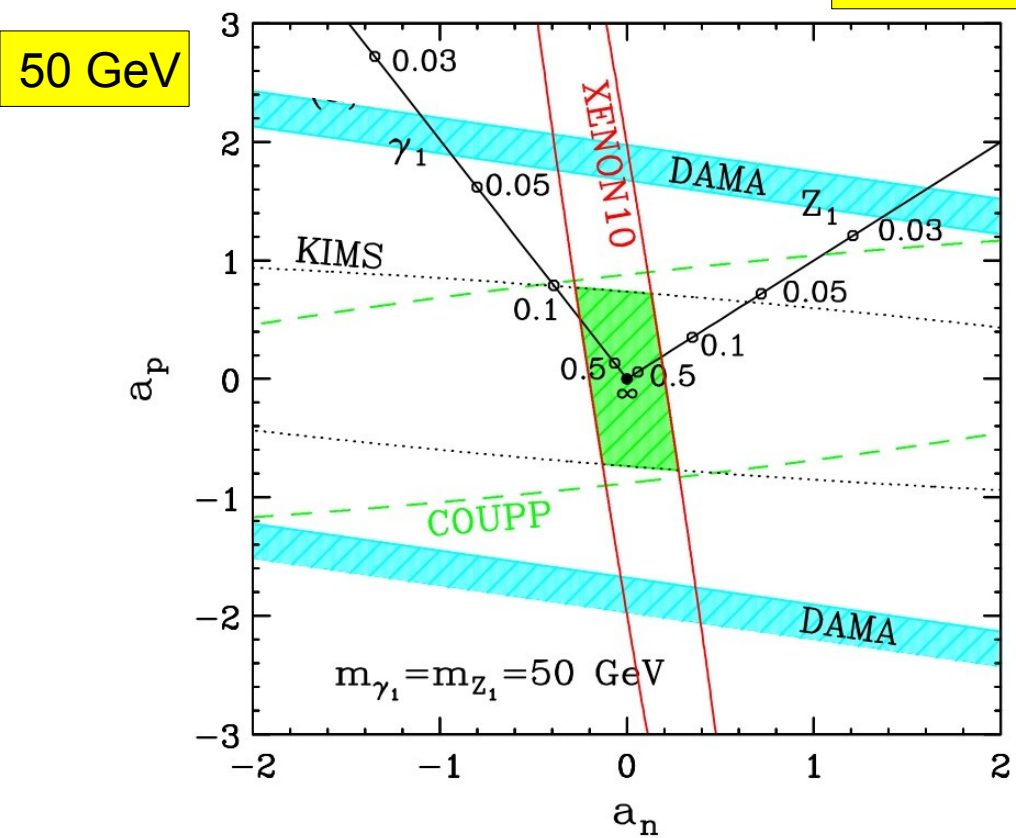
Limits on spin-dependent WIMP-nucleon couplings from 5D UED

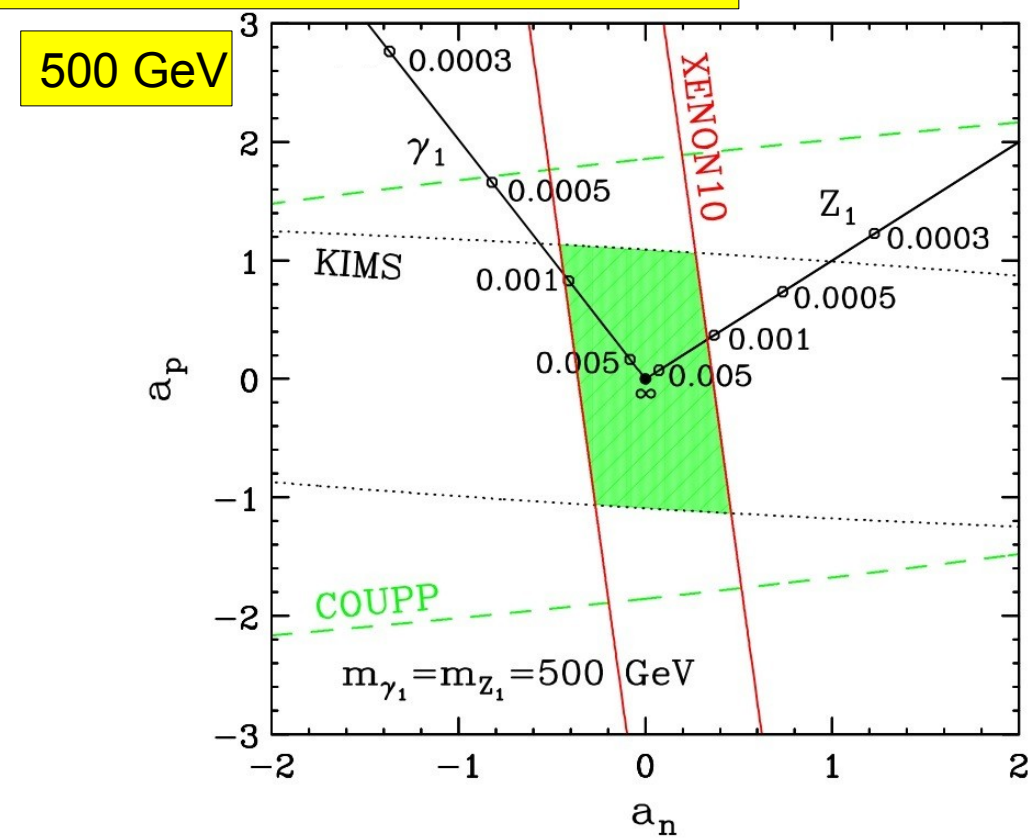
- free parameters a_p and a_n

- limits from DAMA & XENON10: Introduce polar coordinates in $a_p - a_n$ plane.
  → Scan over θ.

- limits from KIMS & COUPP:

$$\sum_A \left(\frac{a_p}{\sqrt{\sigma_p^{\lim(A)}}} \pm \frac{a_n}{\sqrt{\sigma_n^{\lim(A)}}} \right)^2 \leq \frac{\pi}{24\, G_F^2 \mu_p^2}$$





Combining limits from odd-neutron and odd-proton experiments substantially diminishes the allowed parameter space.

What has been done?

Comprehensive analysis of 5D and 6D Kaluza-Klein dark matter including constrains from...

- direct detection experiments
- collider studies
- cosmology

Results

- All three approaches are complementary and have the potential to cover a huge part of the relevant parameter space.

  Direct detection experiments restrict small values of Δ.

  Colliders are sensitive to large Δs.

  Cosmology rules out large LKP masses.
- Reasonable parameters to explore the KK phenomenology are Δ and m_{LKP}.
- Coannihilation processes are of crucial importance for relic density calculations.

What is missing?

- detailed LHC studies for small Δ
- further relic density computations for e.g. the γ_H including coannihilations