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

Sebastian Arrenberg
University of Zürich

IDM 2008 – Identification of Dark Matter 2008
18.08.2008
Stockholm

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

(approved to appear in PRD)

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: $m_n^2 = m^2 + \frac{n^2}{R^2}$

  - n: quantum number labelling the n^{th} KK mode
  - m: mass of the associated SM particle
  - R: 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

- WIMP candidates:

5D: ~~G_1~~ ~~ν_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

$$\sigma_{eff}(x) = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{eff}^2} (1+\Delta_i)^{\frac{3}{2}} (1+\Delta_j)^{\frac{3}{2}} e^{-x(\Delta_i + \Delta_j)} \qquad x = \frac{m_1}{T}$$

$$g_{eff}(x) = \sum_{i}^{N} g_i (1+\Delta_i)^{\frac{3}{2}} e^{-x \Delta_i} \qquad \Delta_i = \frac{m_i - m_1}{m_1}$$

mass degeneracy parameter → Δ_i

What about the masses?

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

→ radiative corrections to the masses can be computed (hep-ph/0204342)

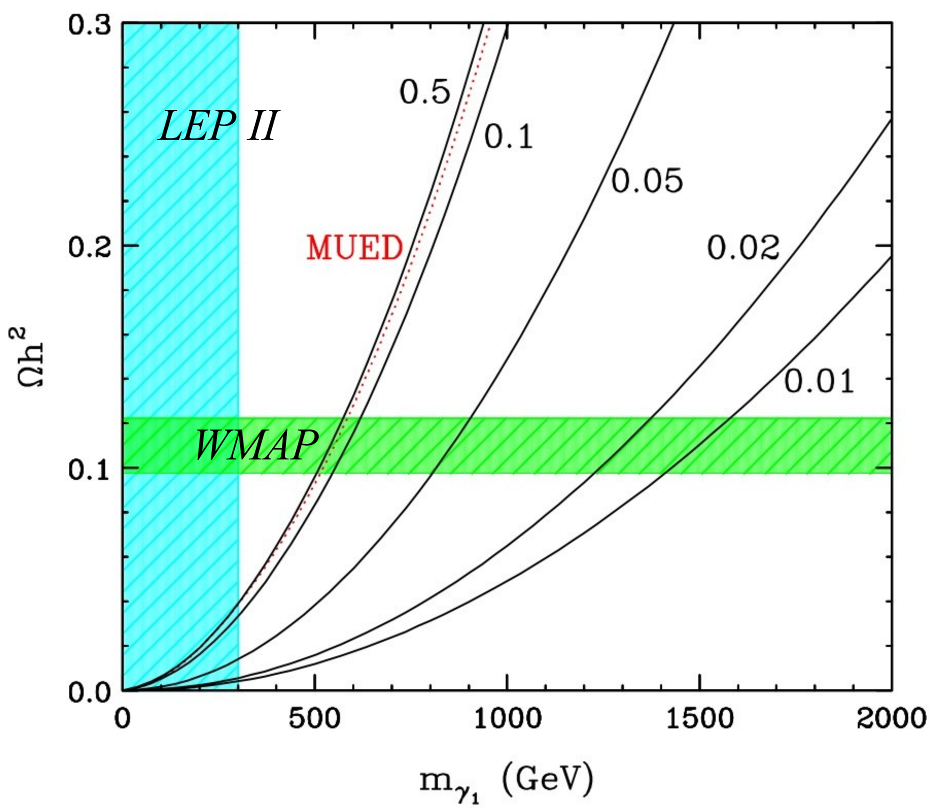
LKP using MUED framework → 5D γ_1 ; → 6D γ_H

But consider other possibilities as well...

γ_1

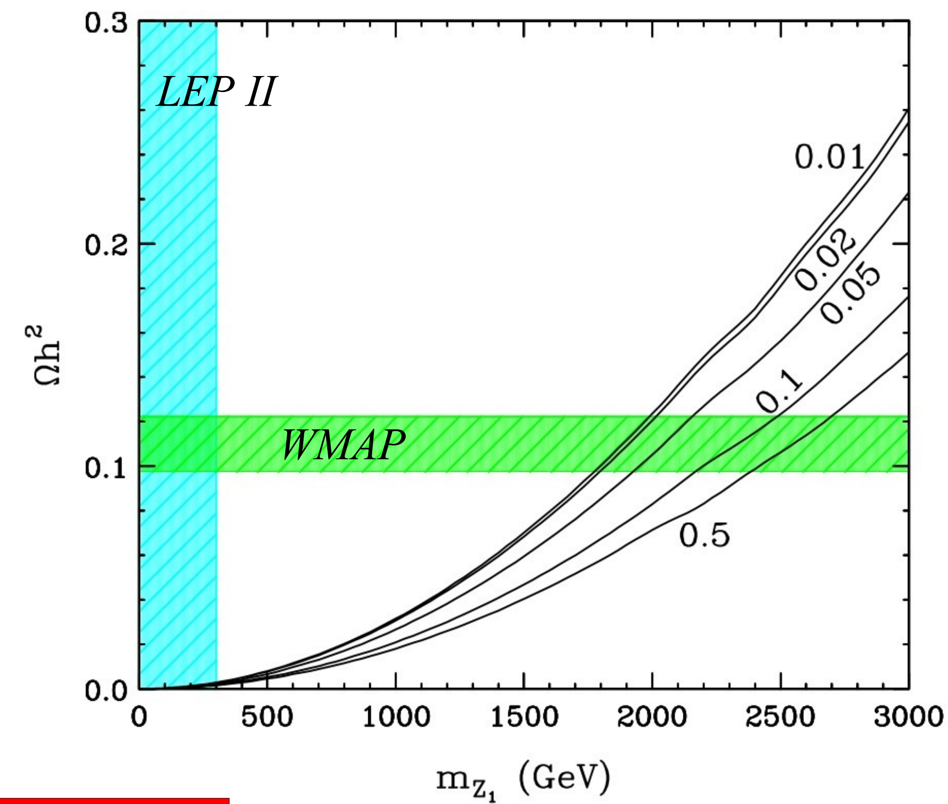
1) MUED framework

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%

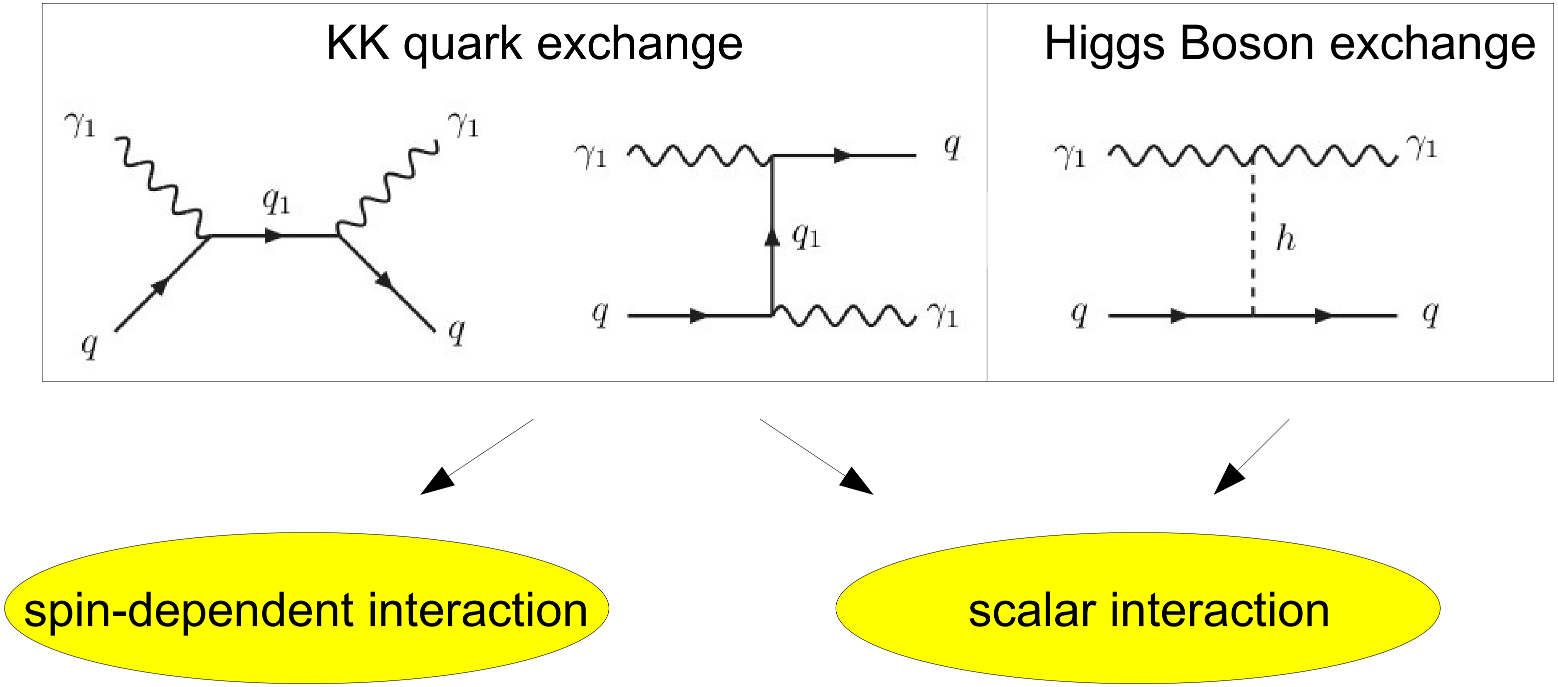


- coannihilations are indeed important
- the sign of the effect cannot easily be predicted

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

Elastic scattering cross sections

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



Important parameters

SI WIMP-nucleon couplings f_n, f_p

SD WIMP-nucleon couplings a_n, a_p

Higgs mass m_h

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

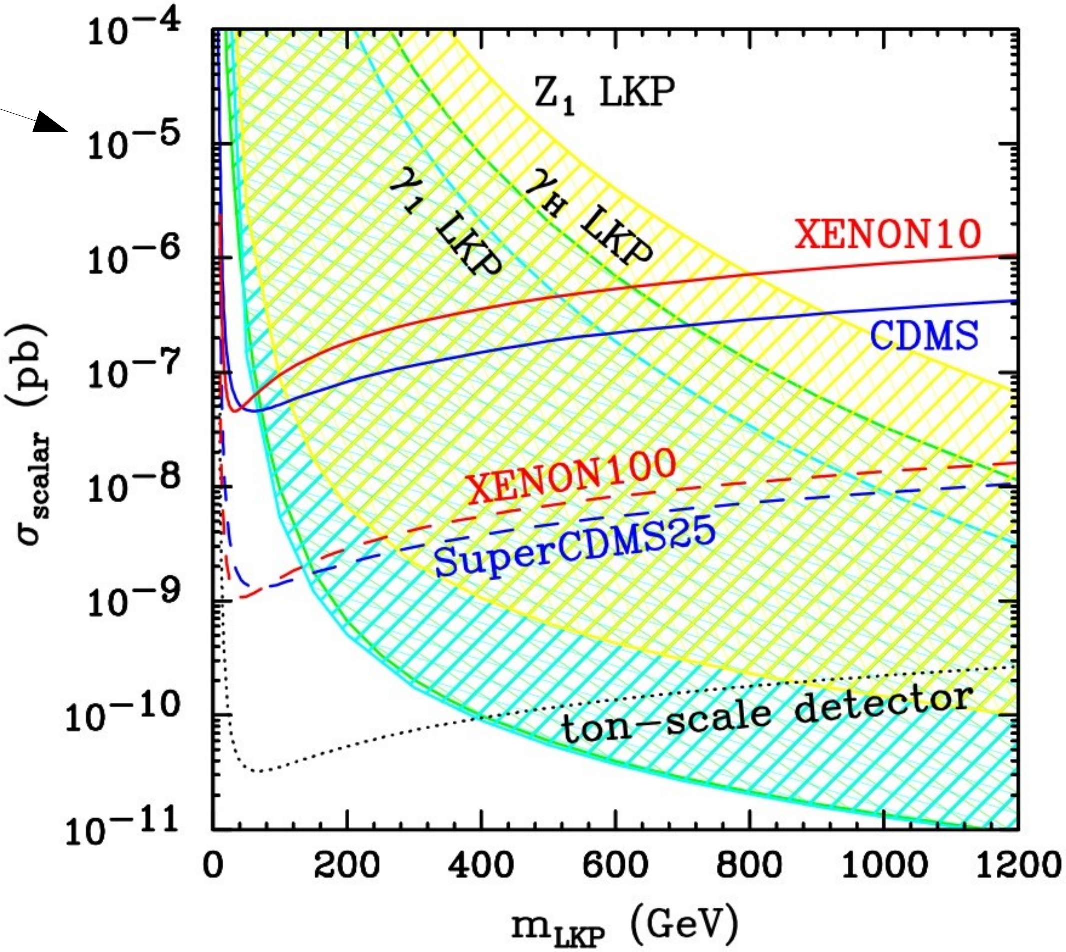
Spin-independent scattering

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

γ_1

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

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



- 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

Spin-dependent scattering

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

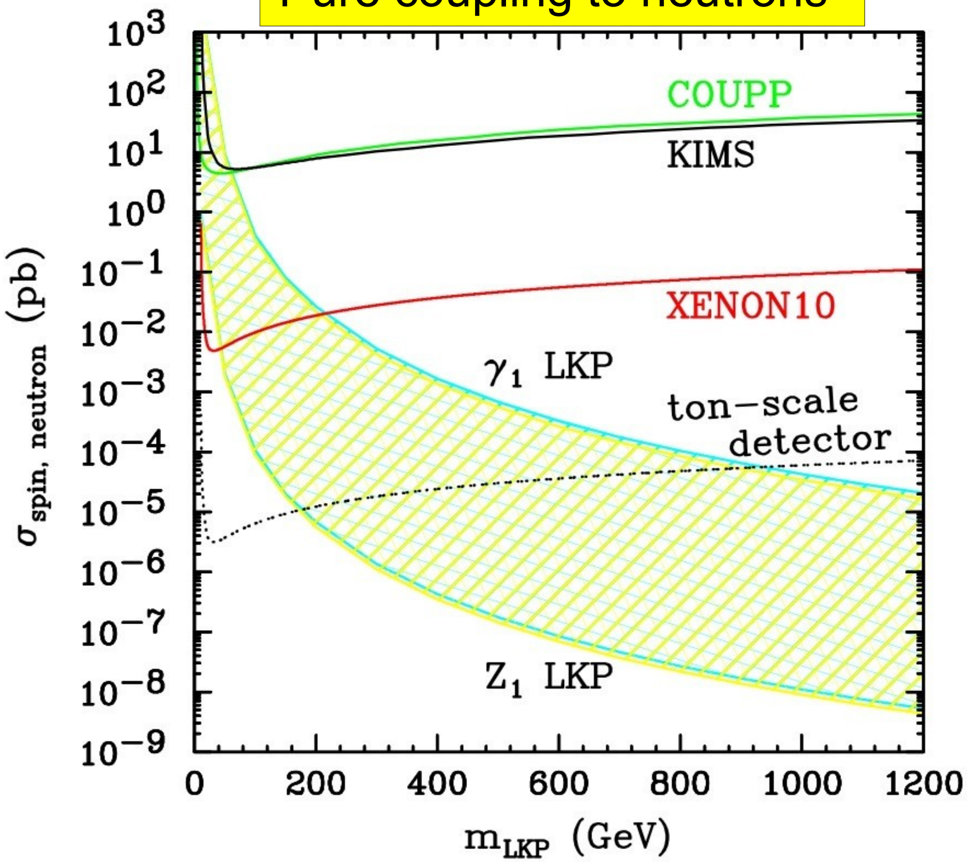
$a_{p,n}$ contain the whole theoretical model-dependence

γ_1

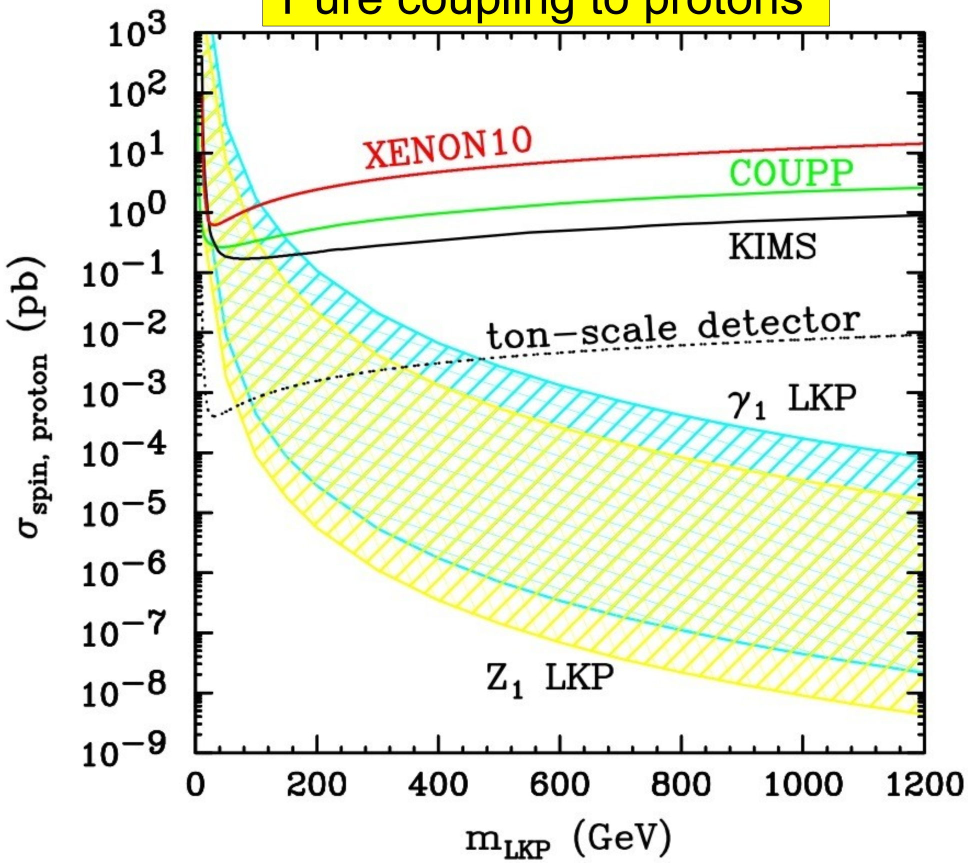
$$a_{p,n} = \frac{e^2}{4\sqrt{3}\, G_F \cos^2\theta_W} \sum_{u,d,s} \left[\frac{Y_{qL}^2}{m_{q_L^1}^2 - m_{\gamma_1}^2} + (L \to R) \right] \Delta_q^{p,n}$$

$0.01 < \Delta < 0.5$

Pure coupling to neutrons



Pure coupling to protons

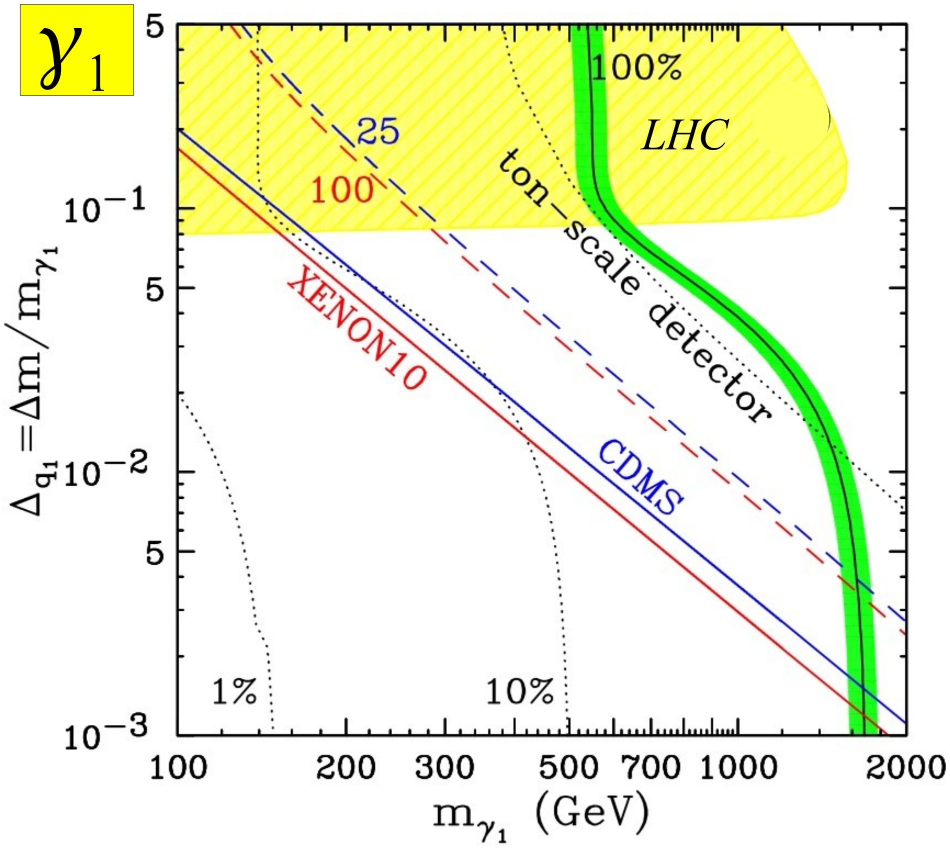


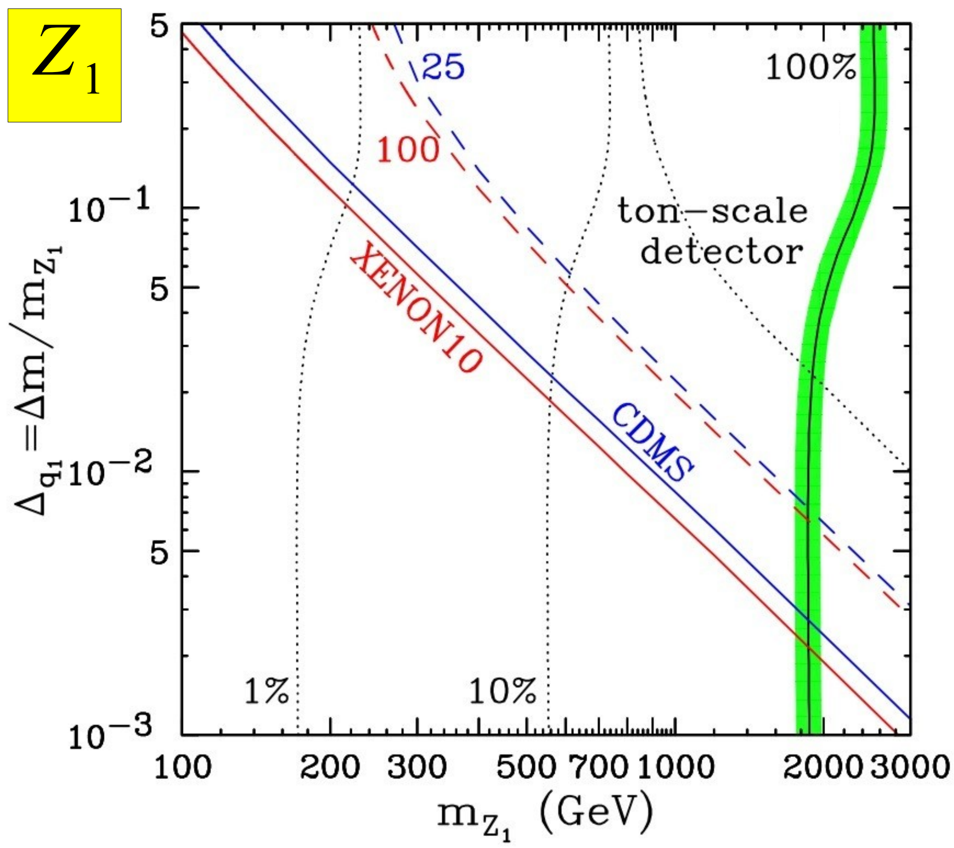
Proton and neutron SD cross sections are exactly equal in the case of Z_1.

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

- 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.

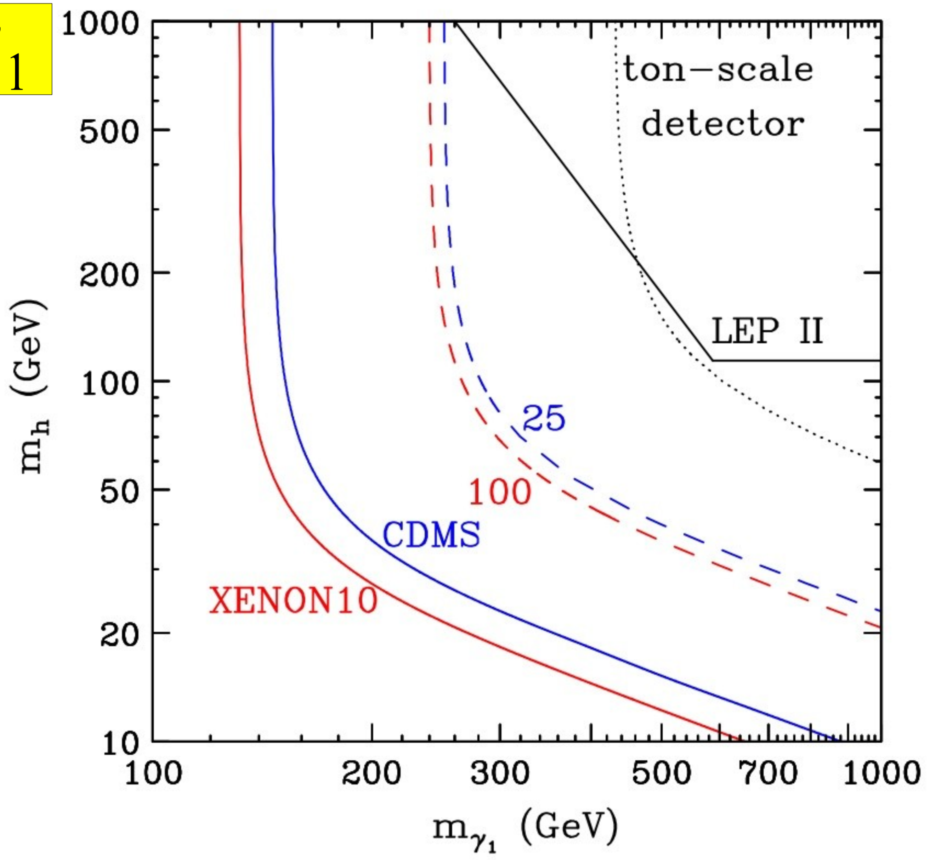
Cosmology provides **upper limit on LKP masses**.
Colliders are sensitive to **large** Δ.
Direct detection experiments are sensitive to **small** Δ.

Spin-independent limits on m_h from 5D UED

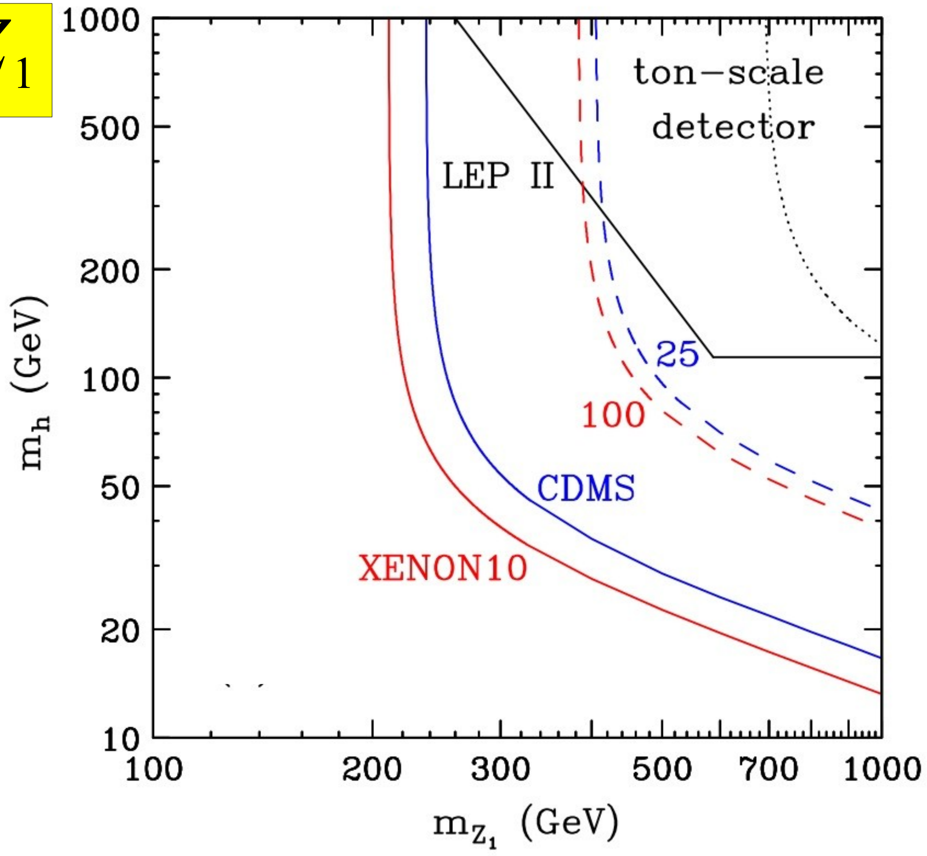
- free parameters: LKP mass and m_h
- Fix Δ at 0.1

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

γ_1



Z_1



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

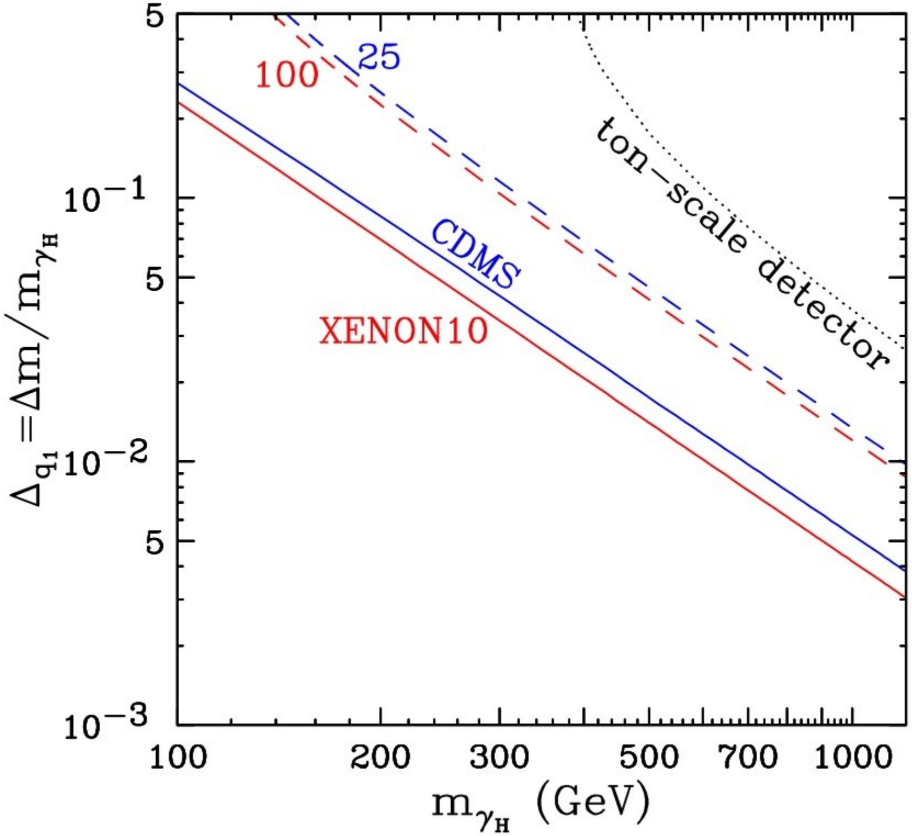
Future direct detection experiments only probe a small part of the parameter space.

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

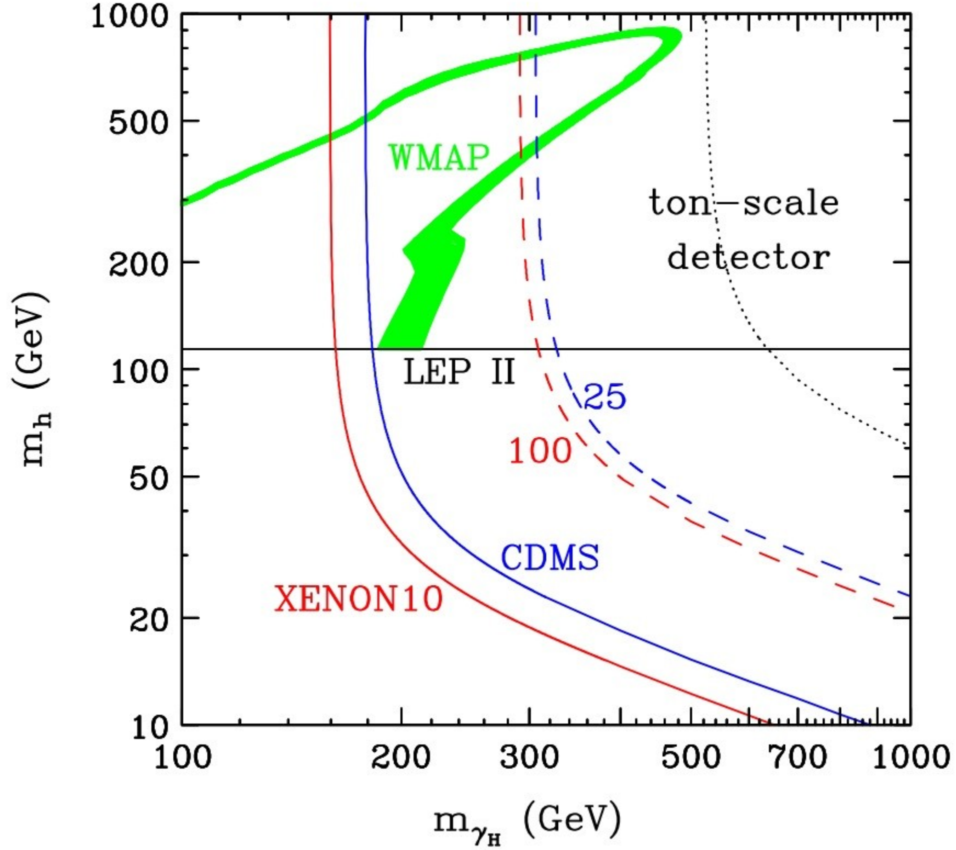
Spin-independent limits on Δ and m_h from 6D UED

γ_H

Limits on Δ for $m_h = 120\,GeV$

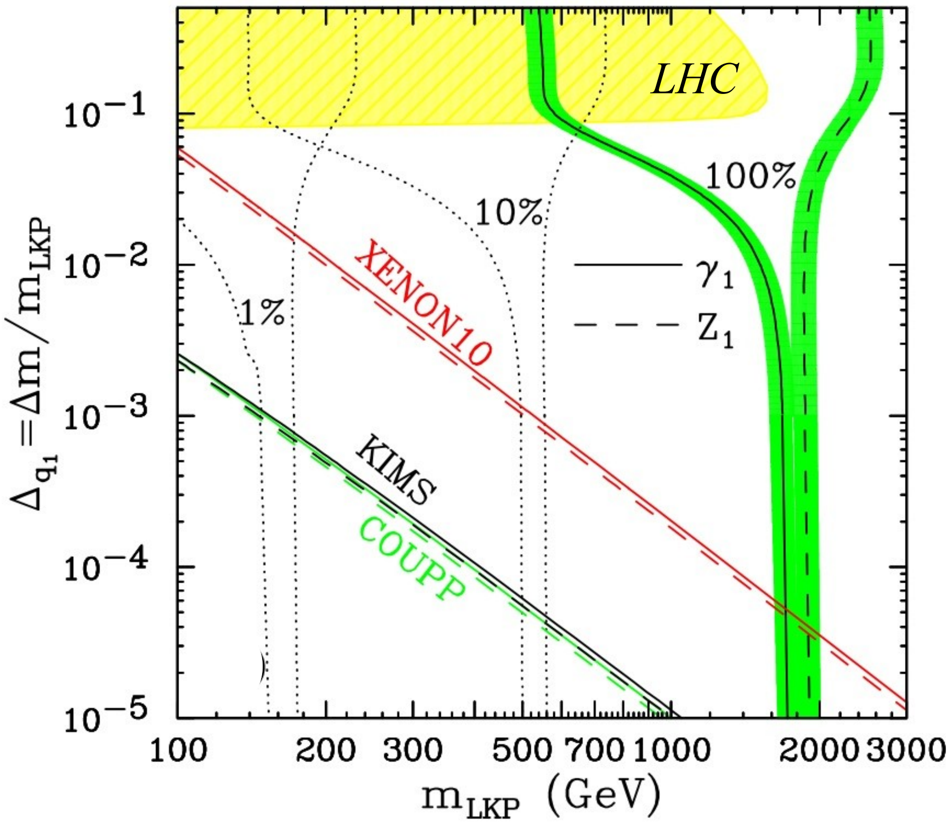


Limits on m_h for $\Delta = 0.1$

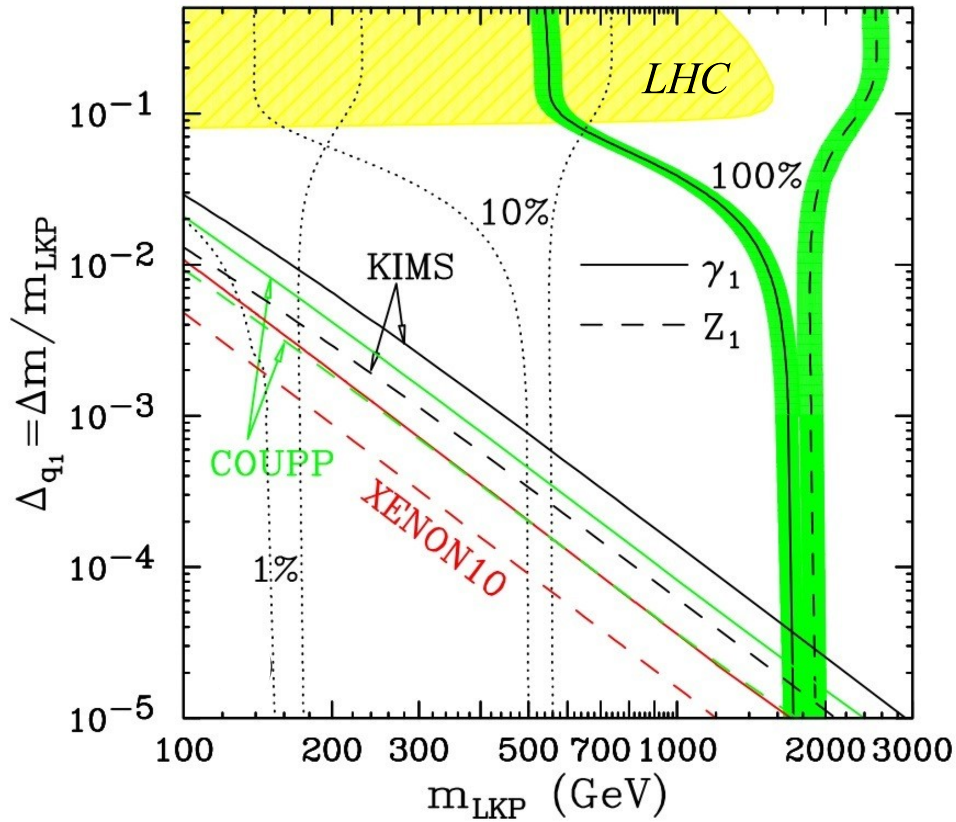


Limits on Δ can also be computed considering spin-dependent interactions.

Pure coupling to neutrons



Pure coupling to protons



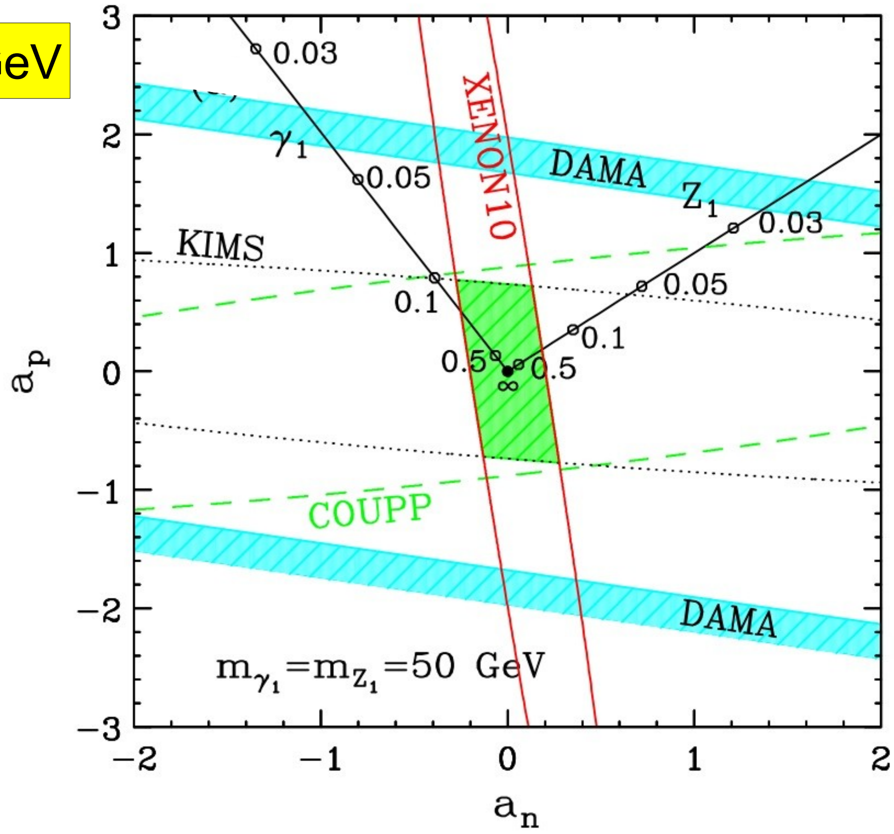
SD constrains are about an order of magnitude smaller than the SI limits.

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

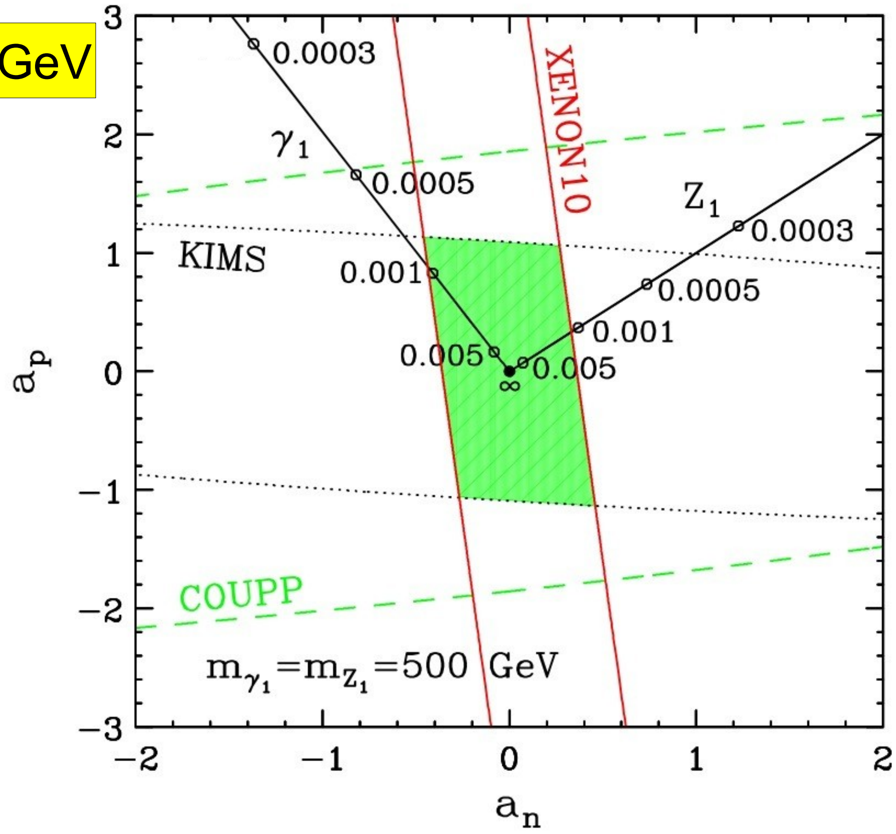
- free parameters a_p and a_n

- limits from Xenon10: Introduce polar coordinates in $a_p - a_n$ plane.
  → Scan over θ .

50 GeV



500 GeV



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