The LKP as Dark Matter?

G Servant & T Tait
(U. of Chicago + Argonne)

- Universal Extra Dimensions
- Kaluza-Klein photon as the LKP
- Kaluza-Klein neutrino as the L.K.P
- Coannihilation Effects
- 6 D Cases
- Detection issues

Universal Extra Dimensions

- **ALL** Standard Model fields propagate in δ extra dim
  APPELQUIST-CHENG-DOBRESCU PRD '01.

- To be contrasted with:
  - Brane World Scenario — S.M localized in 3D, only gravity in extra dim.
    ARKANI HAMED - DIMOPOULOS - DVALI
    RANDALL - SUNDRUM.
  - "Intermediate Models": Bulk gauge bosons & Higgs, localized fermions.
    ANTONIADIS - MUÑOZ - QUIROS '93
    ANTONIADIS - BENAKLI - QUIROS '94
    ANTONIADIS - DIMOPOULOS - POMAROL - QUIROS '99
    ...

  ↳ Bounds on virtual exchanges of the KK modes of the W, Z, γ:

$\rightarrow R^{-1} > 6.8$ TeV at the 95%

from LEP 2, TEVATRON, HERA

CHEUNG - LANDSBERG '01

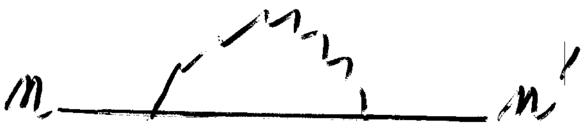
U.E.D SCENARIO

- MOMENTUM IS CONSERVED AT TREE LEVEL LEADING TO CONSERVATION OF KK NUMBER IN THE INTERACTIONS OF THE 4D THEORY. N K.K MODES $n_1, n_2, \dots n_N$ CAN ONLY COUPLE ONE ANOTHER IF $|n_1 \pm n_2 \pm \dots \pm n_{N-1}| = n_N$

  ↳ NO TREE LEVEL EFFECT ON EW OBSERVABLES

  ↳ NO SINGLE KK MODE PRODUCTION AT COLLIDERS

- STATEMENT BROKEN AT LOOP LEVEL



KK modes in the loop ↳ CONSTRAINTS FROM EW D

$$R^{-} \gtrsim 300\ \text{GeV} \quad \text{for } \delta = 1$$

$$R^{-1} \gtrsim 500\ \text{GeV} \quad \text{for } \delta = 2$$

MOTIVATIONS FOR UNIVERSAL EXTRA DIMENSIONS

- DYNAMICAL EW SYMMETRY BREAKING

  ARKANI-HAMED CHENG DOBRESCU HALL '00

- NUMBER OF FERMION GENERATIONS

  DOBRESCU- POPPITZ 01

- PROTON STABILITY

  APPELQUIST - DOBRESCU PONTON YEE 01

DARK MATTER CANDIDATE ?

KK NUMBER IS BROKEN TO KK PARITY $(-1)^{KK}$

KK PARITY : PRESERVED BY ORBIFOLD.

Under A translation by πR :

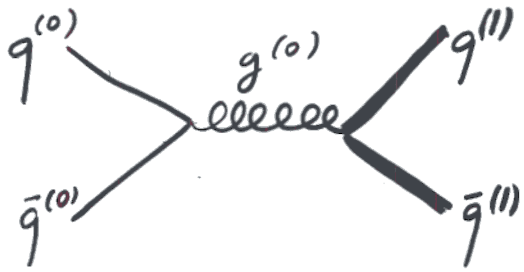
EVEN MODES OF THE KK DECOMPOSITION are INVARIANT under this transla

ODD MODES CHANGE SIGN → $(-1)^{KK}$ is a symmetry.

THE THEORY HAS INTERACTIONS ONLY BETWEEN **EVEN** NUMBER OF THE ODD-NUMBER KK MODES

↳ KK MODES MUST BE PAIR-PRODUCED

CHALLENGING COLLIDER SEARCHES



COLLIDER PHENOMENOLOGY DEPENDS CRUCIALLY ON SPLITTINGS OF KK SPECTRUM DUE TO RADIATIVE CORRECTIONS.

CHENG_MATCHEV_SCHMALTZ '02

AT TREE LEVEL, KK PARTICLES OF A GIVEN LEVEL ARE DEGENERATE WITH MASS $\frac{n}{R}$.

BUT AT LOOP LEVEL : DEGENERACY IS LIFTED BY BOTH CALCULABLE & UNCALCULABLE CORRECTIONS.

CHENG - MATCHEV - SCHMALTZ hep-ph/0204342

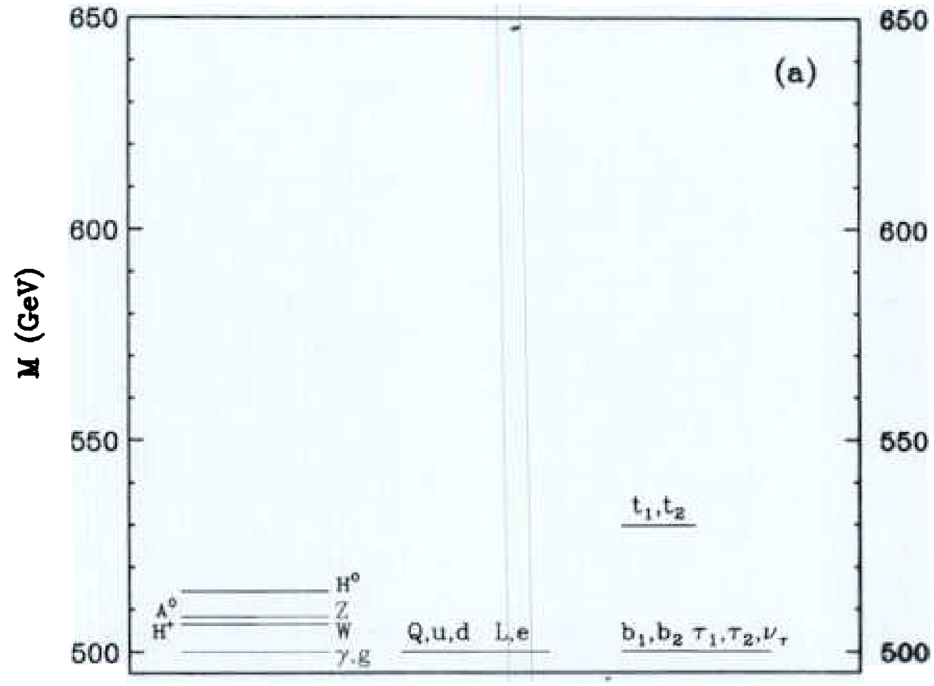


Figure 1: Spectrum of the first KK level at tree level for R^{-1} = 500 GeV, ΛR = 20, m_h = 120 GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut–off scale.

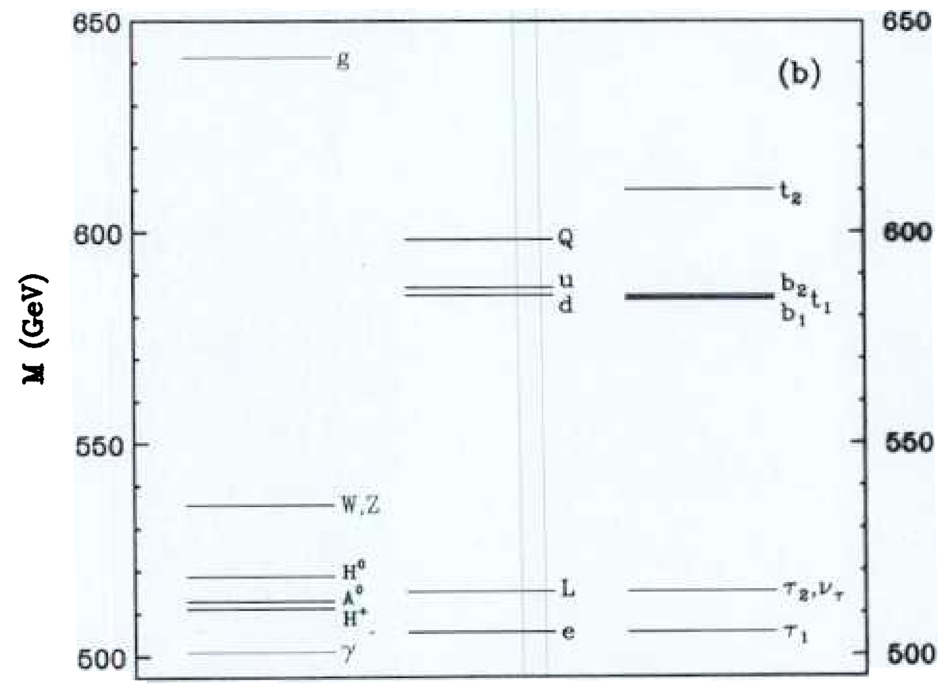


Figure 2: Spectrum of the first KK level at one loop for R^{-1} = 500 GeV, ΛR = 20, m_h = 120 GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut–off scale.

DARK MATTER

MOST OF THE MATTER IN THE UNIVERSE IS DARK & COSMOLOGICAL EVIDENCE HAS ACCUMULATED TO PROVIDE **INDEPENDANT** CONFIRMATIONS THAT A LARGE PART OF DARK MATTER IS **NON BARYONIC**.

CMB ANISOTROPY + MEASUREMENT OF HUBBLE PARAMETER SUGGEST A FLAT UNIVERSE IN WHICH 30% OF THE ENERGY DENSITY IS DUE TO NON RELATIVISTIC MATTER & ONLY 4% IS DUE TO BARYONS.
(Consistent with measurements from Clusters & BIG BANG Nucleosynthesis)

TURNER
ASTRO-PH/0106035

COMBINES ALL THE CURRENT DATA TO DERIVE

$$\Omega_M = 0.33 \pm 0.035$$

$$h = 0.69 \pm 0.04$$

$$\left(\rightarrow \Omega h^2 = 0.16 \pm 0.04\right)$$

NO SOLID CLUE AS TO THE IDENTITY OF D.M

HOWEVER THEORY OF STRUCTURE FORMATION

→ should be weakly interacting (WIMP) & NON RELATIVISTIC at late times (C.DM)

The issue when searching for a DM candidate

FIND A STABLE PARTICLE

2 OPTIONS

↓

The D.M particle does not interact with the S.M, has very small decay rate

→ STABLE on COSMOLOGICAL SCALES

↓

The D.M particle is coupled to the S.M → THERE MUST BE A SYMMETRY TO GUARANTEE ITS STABILITY

↓

LSP in SUSY with R-parity

and

LKP in UED with KK-parity

For the L.K.P to be a D.M candidate = has to be
ELECTRICALLY NEUTRAL & NON BARYONIC

Most Promising Candidates → FIRST LEVEL KK MODES OF THE NEUTRAL GAUGE BOSONS AND THE KK NEUTRINO

The mass eigenstates & eigenvalues of the KK "photons" and "Z" are obtained by diagonalizing their mass squared matrix:
In the B_n, $W_n^{(3)}$ basis it is

$$\begin{pmatrix} \frac{n^2}{R^2} + \frac{1}{4} g_1^2 v^2 + \delta M_1^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{n^2}{R^2} + \frac{1}{4} g_2^2 v^2 + \delta M_2^2 \end{pmatrix}$$

ONE LOOP CORRECTIONS
$\delta M_2^2 > \delta M_1^2$

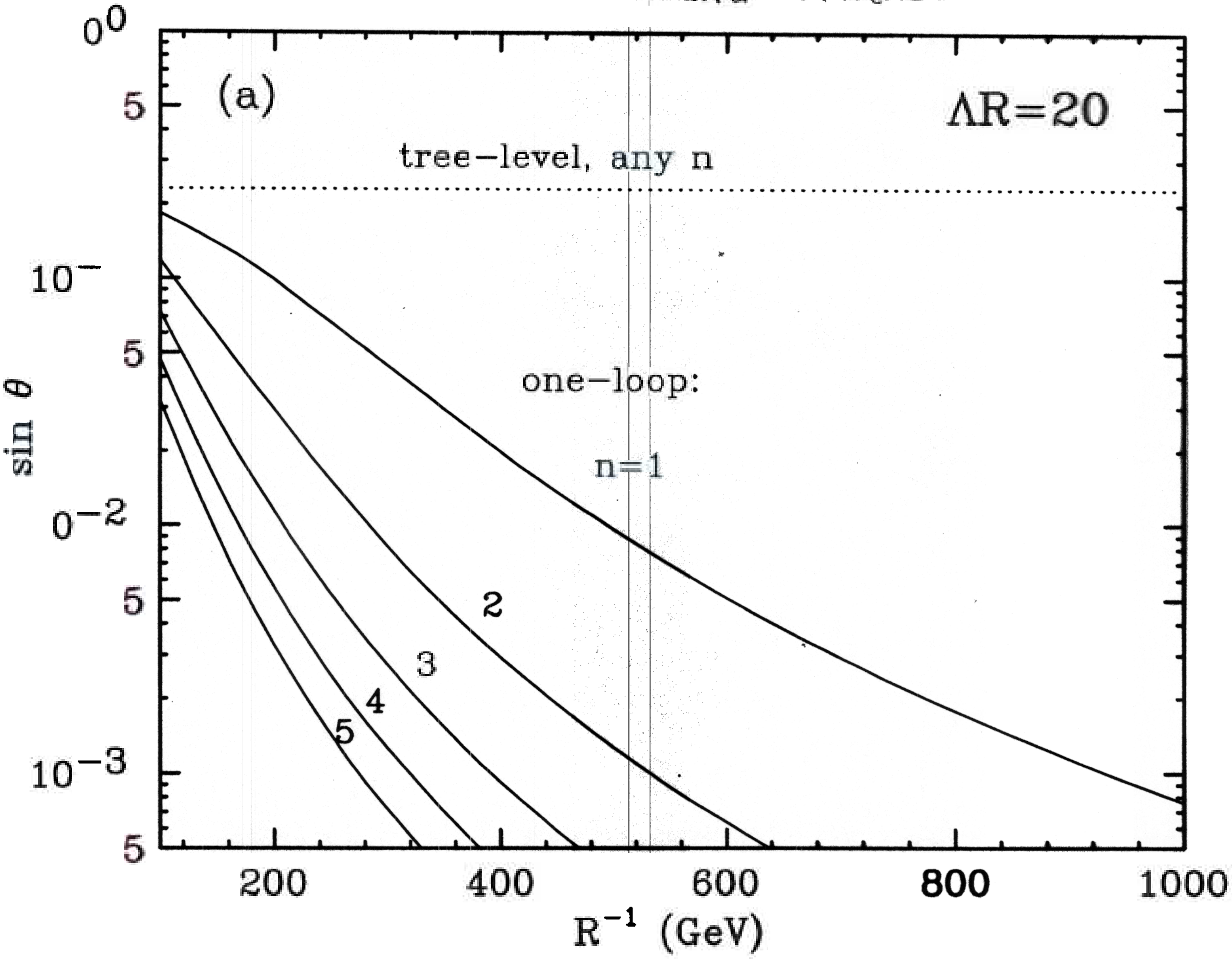
IN THE LIMIT $\delta M_2^2 - \delta M_1^2 \gg g_1 g_2 v^2 \Rightarrow$ MIXING ANGLE DRIVEN TO ZERO.

→ LKP is APPROXIMATELY ENTIRELY $B^{(1)}$

NLKP $e_R^{(1)}$

DEPENDANCE OF THE WEINBERG ANGLE θ_n for FIRST KK LEVELS (n 2, 5) ON R^{-1}

CHENG MATCHEV-SCHWALTZ

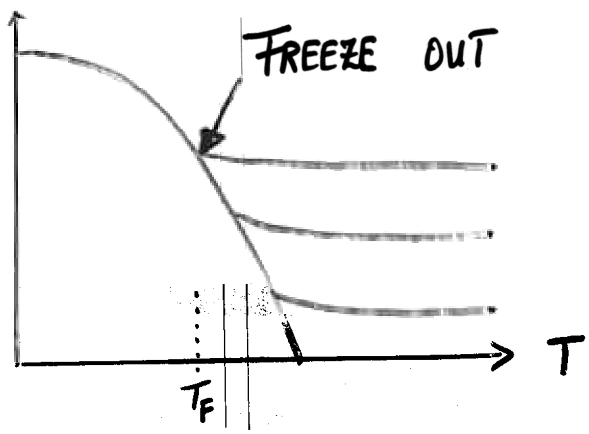


Density of a Cold relic particle

Solve Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n^{eq\,2}\right)$$

$$n^{eq} \propto \;^{-m/T}$$



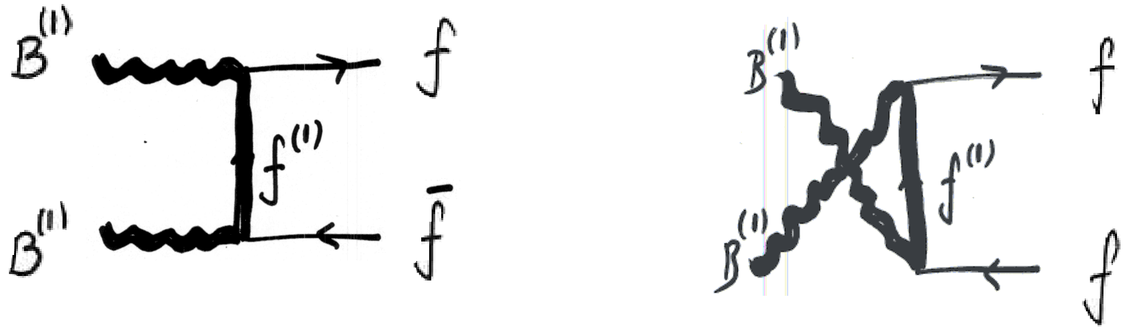
$$x_F = \frac{m}{T_F}$$

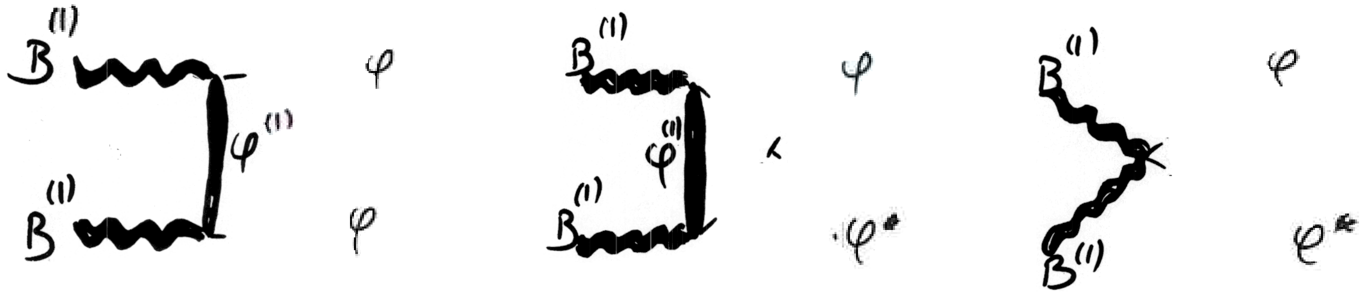
$$\Omega h^2 \approx \frac{10^9 x_F}{M_{pl} \sqrt{g_*}} \; \frac{1}{a + 3b/x_F}$$

$$\langle \sigma v \rangle \approx a + b v^2 = a + 6b/x$$

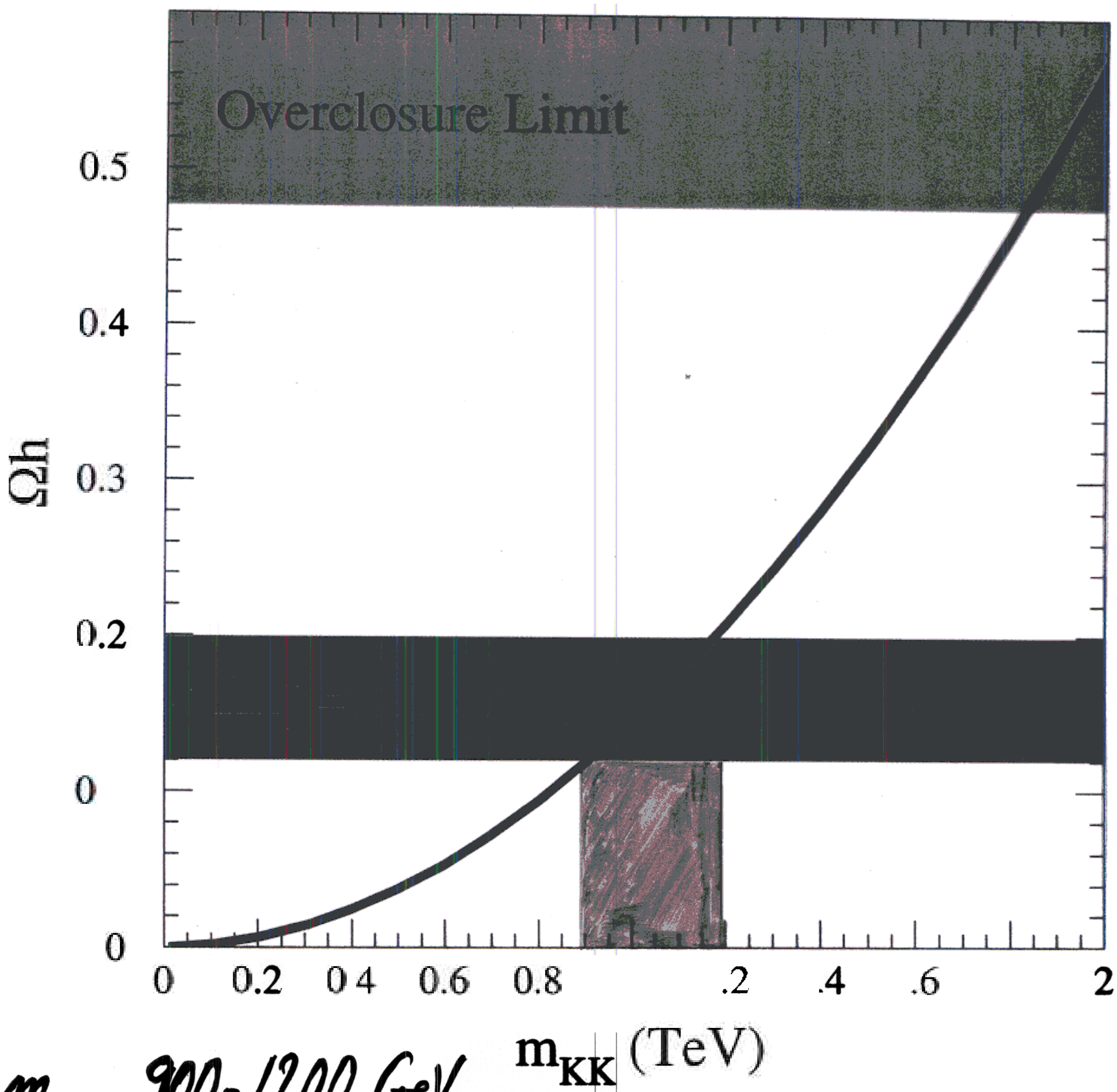
① LKP is $B^{(1)}$

Annihilation cross sections





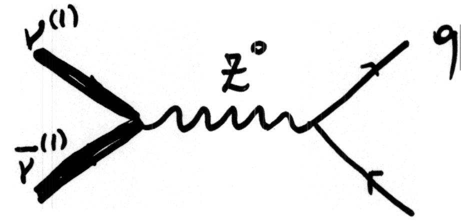
PREDICTION FOR $B^{(1)}$ ENERGY DENSITY
A FUNCTION OF THE K.K MASS



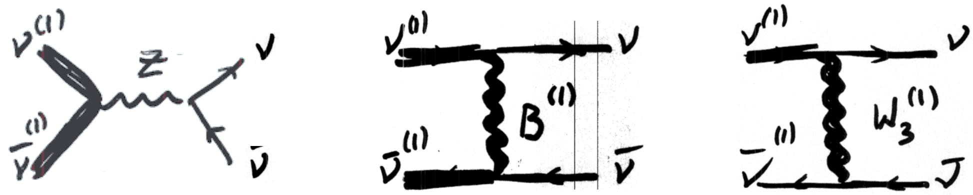
$m_{KK} \sim 900\text{-}1200$ GeV

② P is ν''

$\nu\bar{\nu}^{(1)} \to qq$

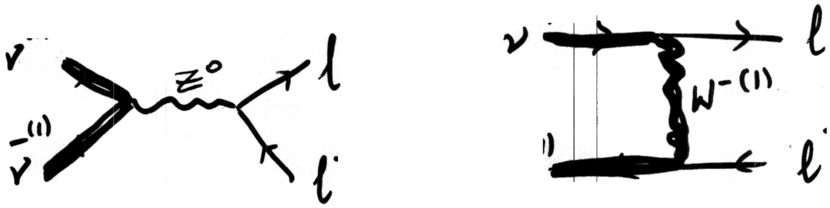


$^{(1)}\nu \to \nu\nu$



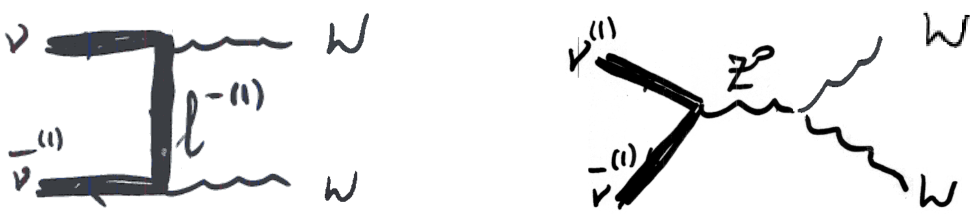
+ u-diagrams

$\nu \to l^+ l$

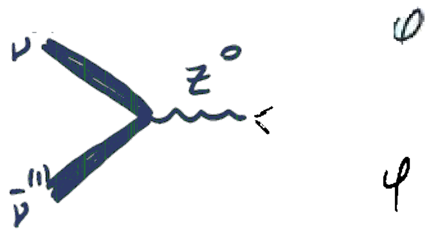


$\nu'' \to Z^0 Z^0$

$\bar{\nu}^{(1)} \to W\,W$



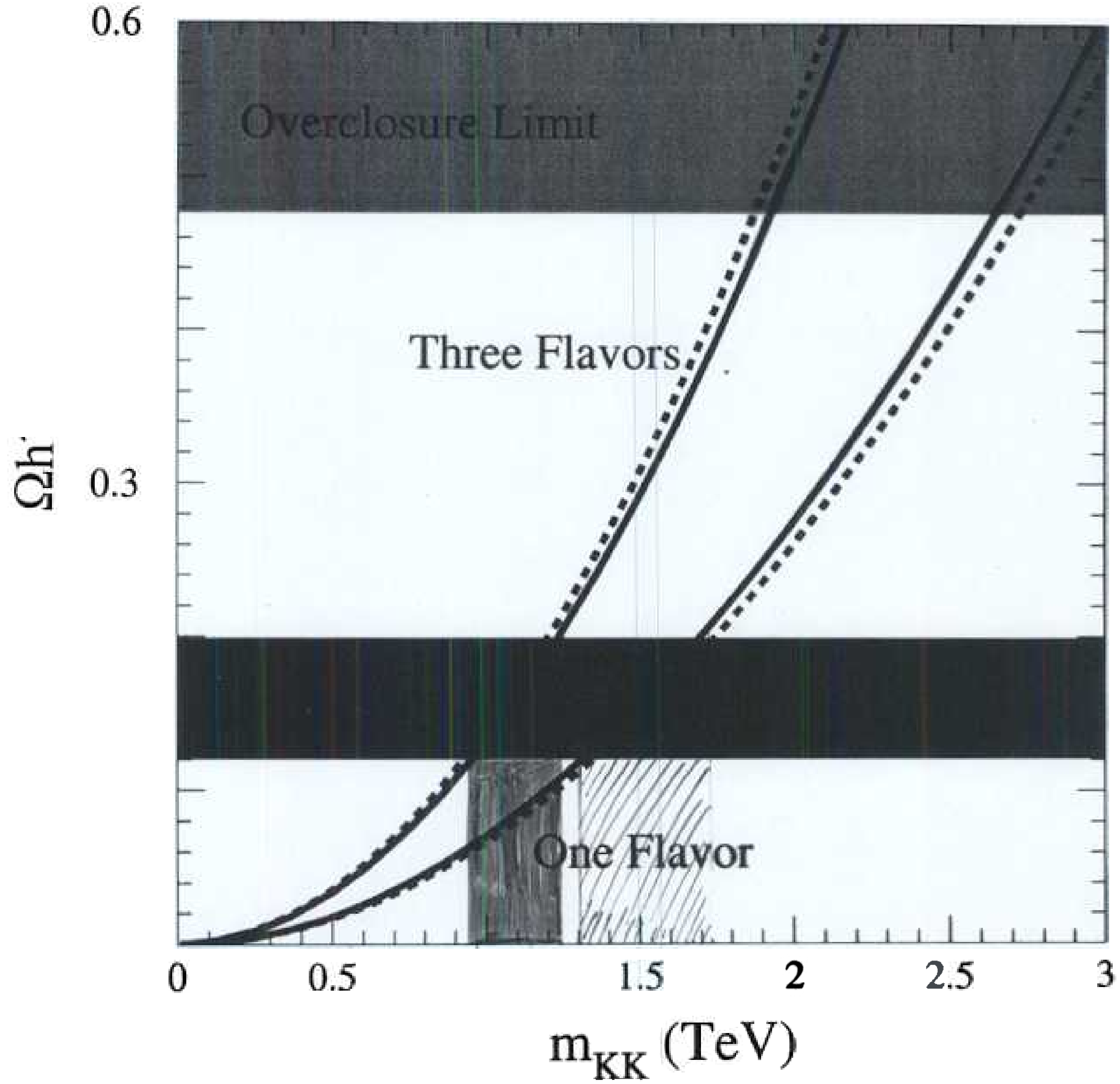
$\to \varphi\varphi^*$



$\nu \quad \nu\nu$

+ u-diagrams

PREDICTION FOR $\nu^{(1)}$ ENERGY DENSITY AS A FUNCTION OF THE KK MASS



1 flavor m_{KK} 1.3 8 TeV

3 flavors m_{KK} 950 1250 GeV

Coannihilation

- NEARLY degenerate particles are nearly as abundant as the LKP and are thermally accessible

Then annihilat° will play a role in determining the relic abundance of the LKP

$Z_i Z_i \quad XX$ self annih

$Z_i Z_j \to XX$

$Z_i Z_j \to XX$ coannih

$$\frac{dn}{dt} + 3Hn \quad \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right.$$

$$\sigma_{eff} \quad \sum_{i,j} \sigma_{ij} \frac{g_i g_j}{g_{eff}} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \times e^{x(\Delta_i + \Delta_j)}$$

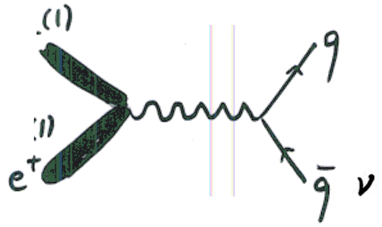
$$g_{eff} = \sum_i g_i \left(+\Delta_i \right.^{3/2} e^{x\Delta_i}$$

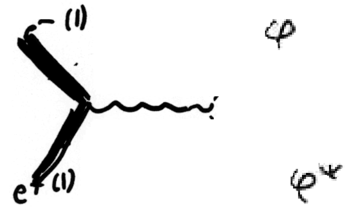
③ $B^{(1)}$ and $e_R^{(1)}$ ARE NEARLY DEGENERATE

↳ COANNIHILATION EFFECTS

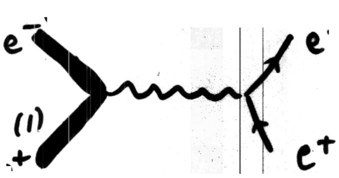
ADD

$e^+ e_R \quad qq \quad \nu\nu \quad \varphi\varphi$





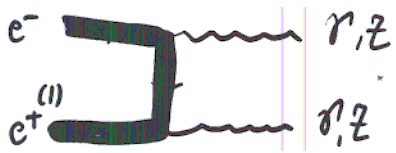
$e^+ e_R^{(1)} \rightarrow e\ e$



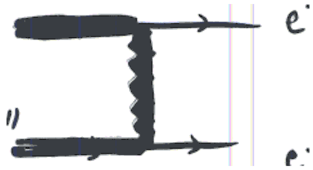
$e_R^+ e^{(1)} \rightarrow \gamma\gamma$

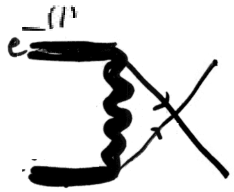
$e^+ e_R^{(1)} \rightarrow ZZ$

$e^+ e^{(1)R} \rightarrow Z\gamma$



$e_R\, e_R \rightarrow e\ e$

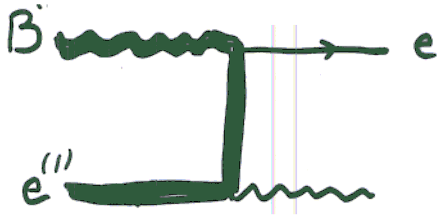


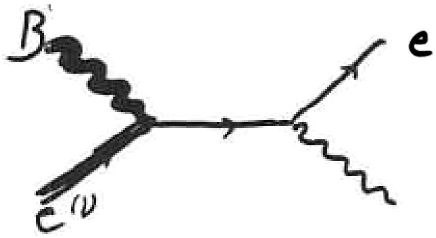


COANNIHILATION CHANNELS

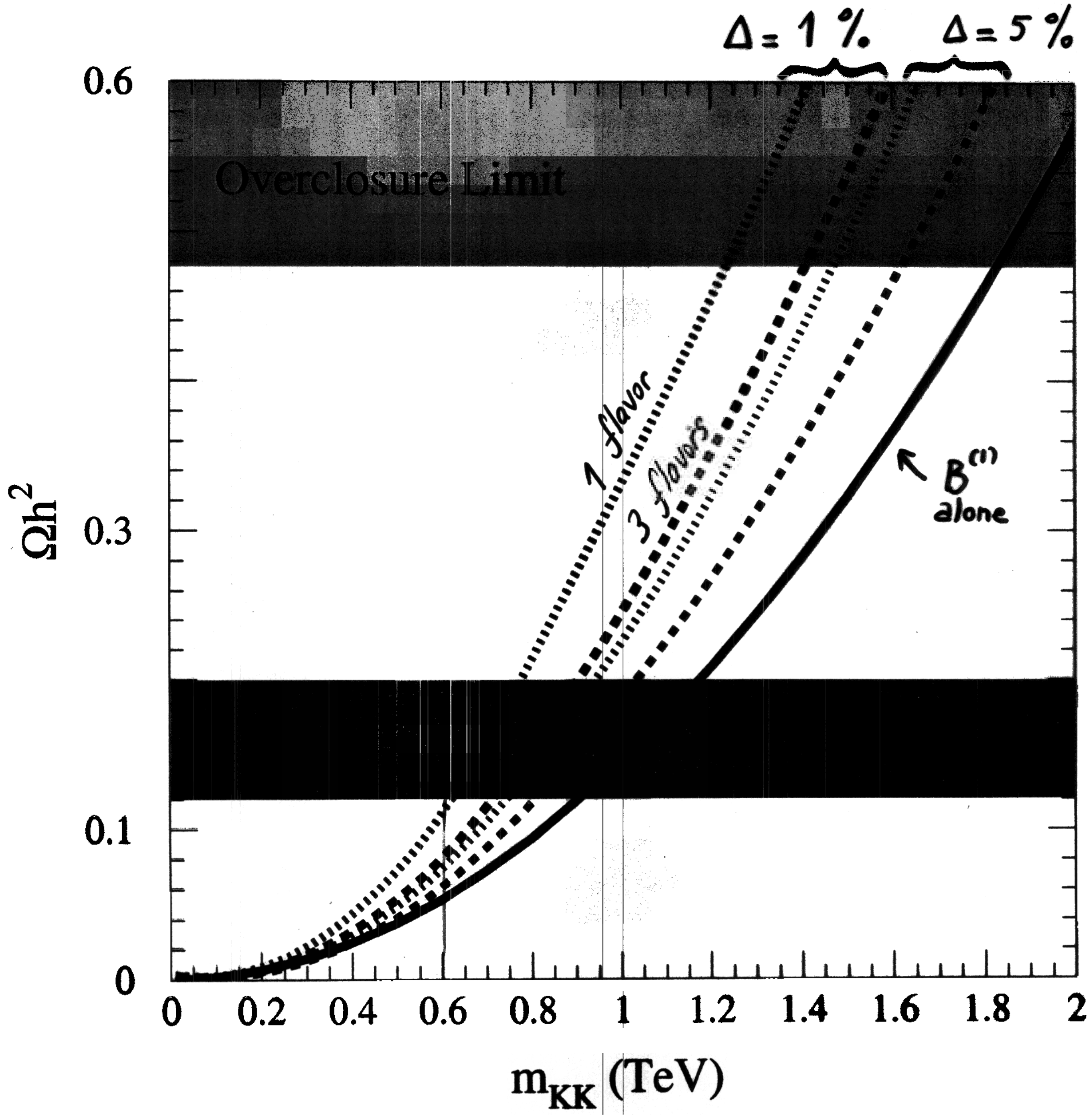
$B^{(1)} e^{(1)} \rightarrow \gamma\, e$

$B^{(1)} e_R^{(1)} \rightarrow Z\, e$





Adding nearly degenerate $e_R^{(1)}$



$$\Delta = \frac{m_{NLKP} - m_{LKP}}{m_{LKP}}$$

HIGHER DIMENSIONAL CASE ?

STANDARD MODEL IN 4+2 D

Depends on type of orbifold

- **T^2/Z_2** 4 STABLE PARTICLES $B^{(1,0)}$ $B^{0,}$

  $B^{1,1)}$ $B^{(\ \ 1)}$

  ↳ 40% heavier

  DO NOT CONTRIBUTE TO RELIC DENSITY

  BECAUSE OF KK # CONSERVATION MOD 2

  $B^{(0,1}$ and $B^{(}$ DO NOT TALK TO EACH OTHER AND ANNIHILATE INDEPENDENTLY AT TREE LEVEL

  TWICE AS MANY LKP
  SAME # of ZERO MODES } ⟹ Relic density multiplied by

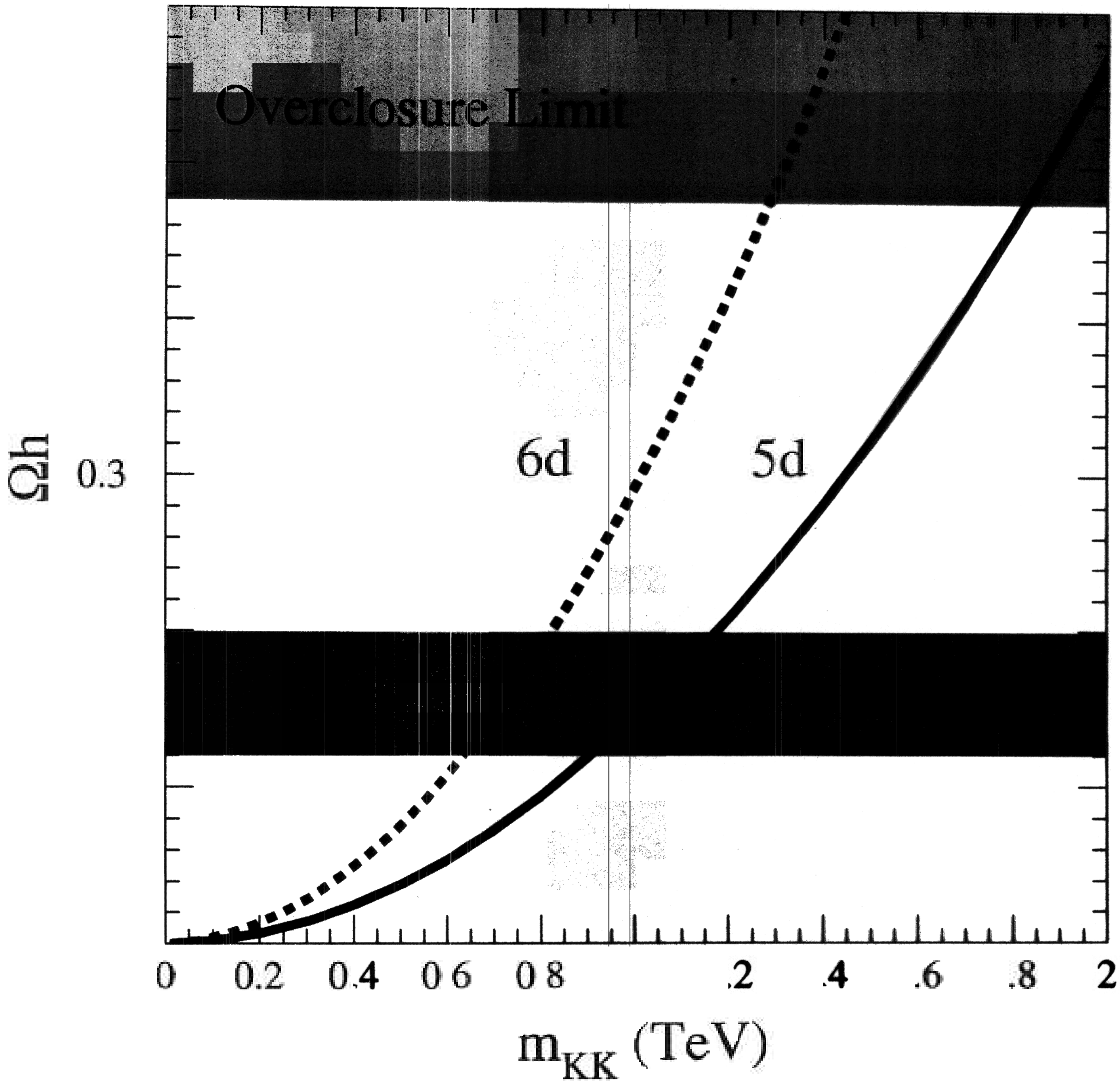
  $$\Omega h^2 \sim \frac{10\ x_F}{M_{pl}\sqrt{g_*}\ \langle \sigma v \rangle} \propto m^2$$

  ↳ KK mass window smaller by factor $\sqrt{2}$

- **T^2/Z_4** 2 STABLE PARTICLES $B^{(0,1)}$ & $B^{(1,1)}$

  same 5D case

Compare 5D and 6D cases



5D $m_{KK} \sim 900$ 1200 GeV

6D $m_{KK} \sim 650$ 850 GeV

Next step Detection issues?

Similar to usual Wimps

→ Direct searches : Deposition of ~ keV recoil energy when the L.K.P scatters from a nucleus in a detector

→ Indirect searches : - Detection of Cosmic rays resulting from LKP annihilation in center of Milky Way.

- Neutrino Spectrum from annihilation in the Sun.

⤳ Within sensitivity of future km^3 neutrino telescopes (Hooper & Kribs)

Direct Detection: Elastic scattering of the L.K.P with a nucleus

FOR $m \sim 1$ TeV & $v \sim 270$ km.s^{-1}

↳ Recoil energy $E_r \sim 50$ keV for $A \sim 100$

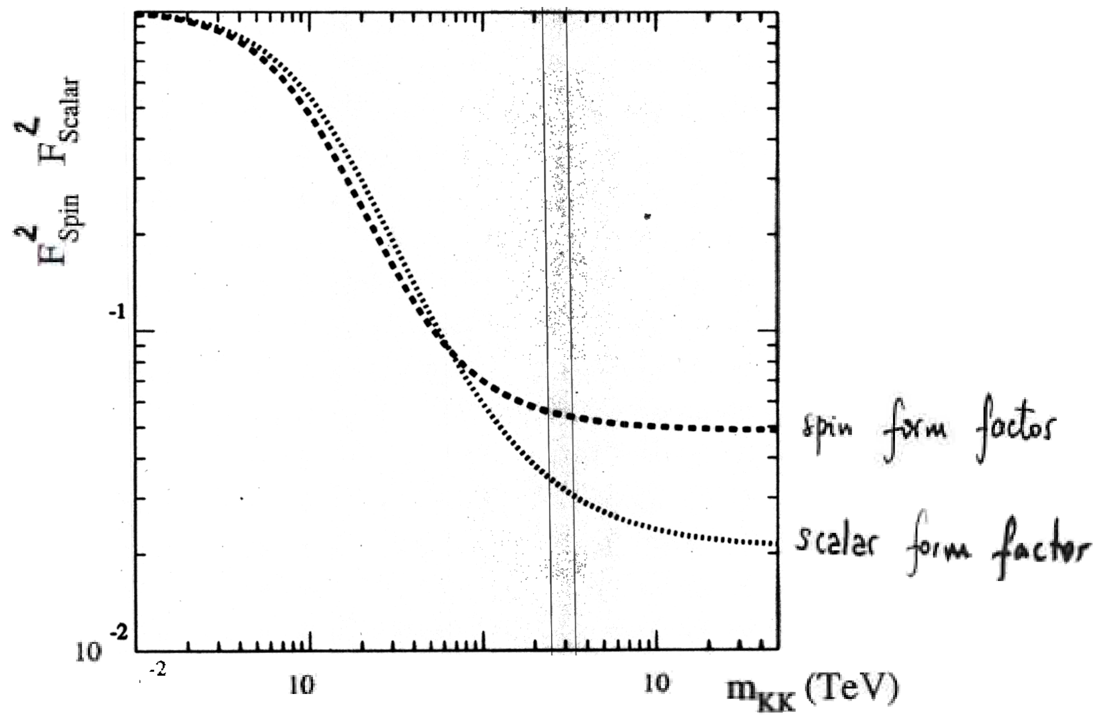
E_r is typically 3 to 4 times larger (depending on A) than for a 100 GeV WIMP

Differential event rate $\frac{dR}{dE_r} \propto \sigma(q^2=0) \times F^2(q)$

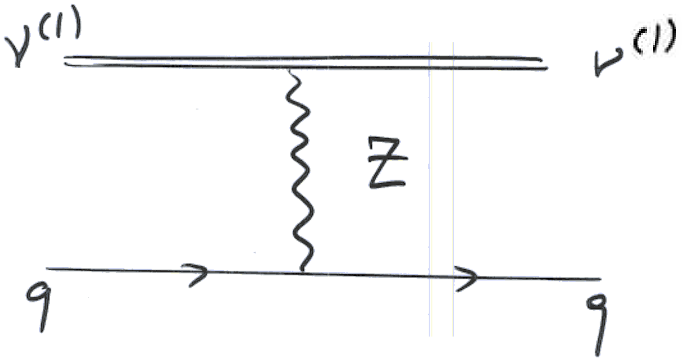
$F^2(q)$ → nuclear form factor

NUCLEAR FORM FACTOR EFFECTS

Example Iodine (A 127)



1) Neutrino Case

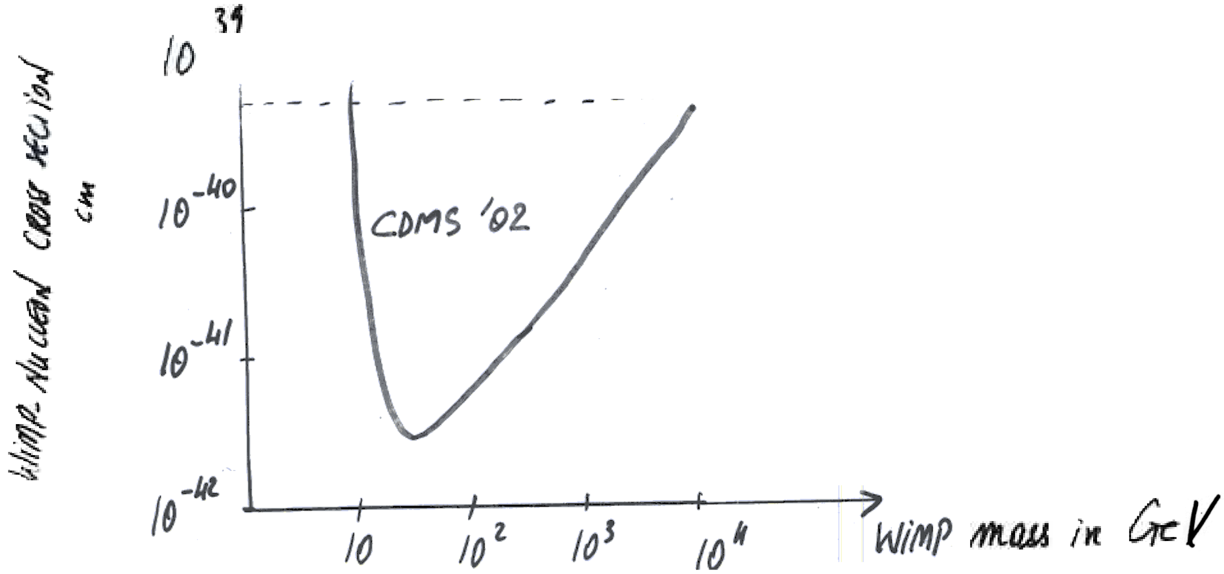


$$\mathcal{L}_{eff} \sim u_{\nu^{(1)}} \gamma^{\mu} u_{\nu^{(1)}} \quad N \gamma N$$

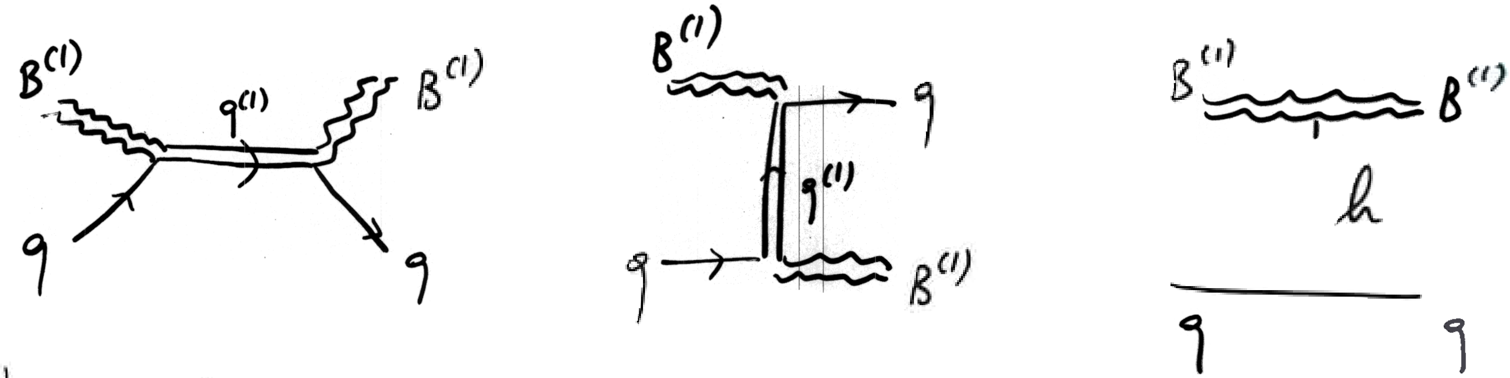
↳ $\sigma_0^{vector} \quad \dfrac{\mu^2 G_F^2 A^2}{8\pi}$

↳ WIMP. NUCLEON CROSS SECTION $\quad \sigma_n \sim 5 \times 10^{40}\ cm^2$

$\Rightarrow m_{\nu^{(1)}} > 20\ TeV$



2) $B^{(1)}$ CASE

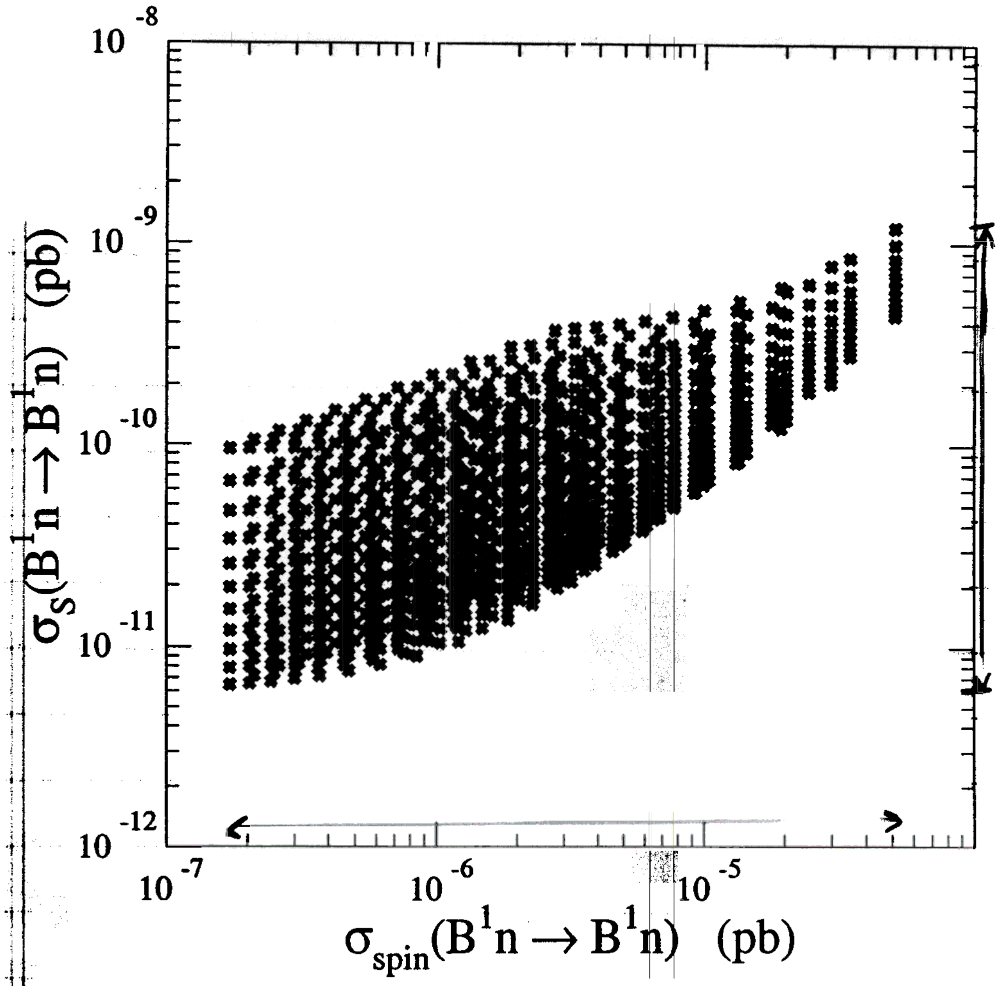


↳ SPIN & SCALAR CROSS SECTIONS

$$\mathcal{M}^{scalar} \propto \varepsilon^*_\mu \varepsilon^\mu \, u \, u \rightsquigarrow \sigma_p^{scalar} \; 10^{10} \, pb$$

$$\mathcal{M}^{spin} \propto \varepsilon^*_\mu \varepsilon_\nu \; \varepsilon^{oijk} \, \bar{u} \gamma_k \gamma_s u \rightsquigarrow \sigma_p^{spin} \; 10^{7} \, pb$$

SCALAR & SPIN-DEPENDENT $B^{(1)}$- nucleon CROSS SECTIONS.

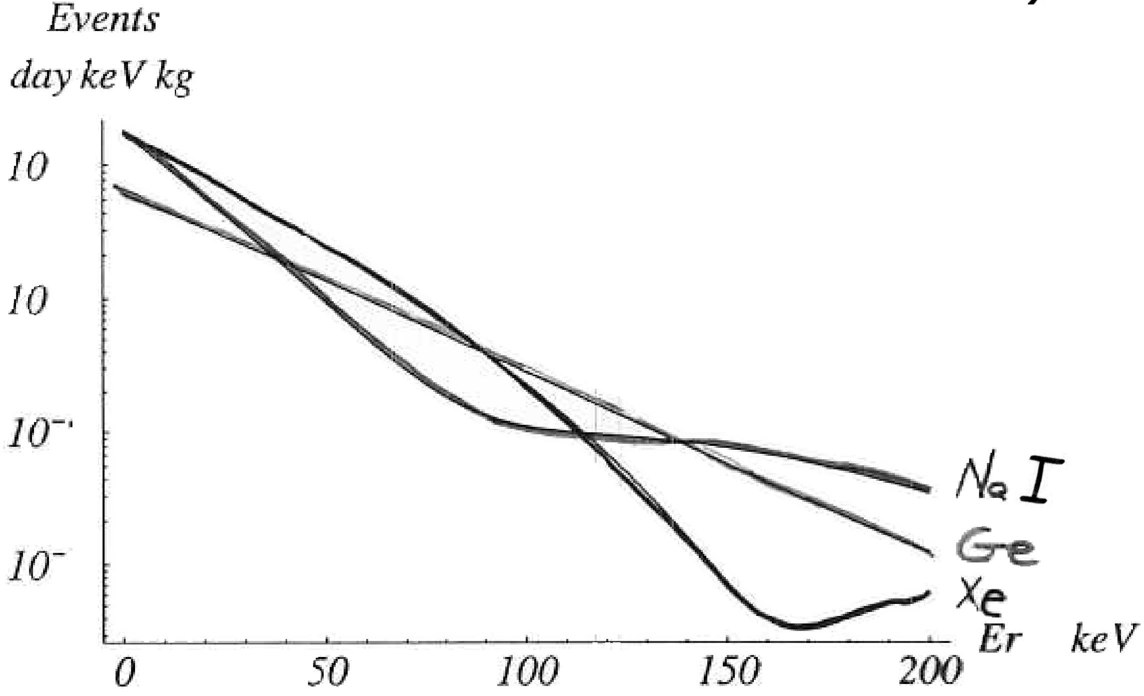


Compare with typical neutralino:

$\sigma_S \sim 10^{-12} \quad 10^{-6}$ pb

$\sigma_{spin} \sim 10^{-9} \quad 10^{-4}$ pb.

Differential Rate $\frac{dR}{dE_r} \propto \frac{\sigma_0}{m\mu^2} \times F^2(|q|)$



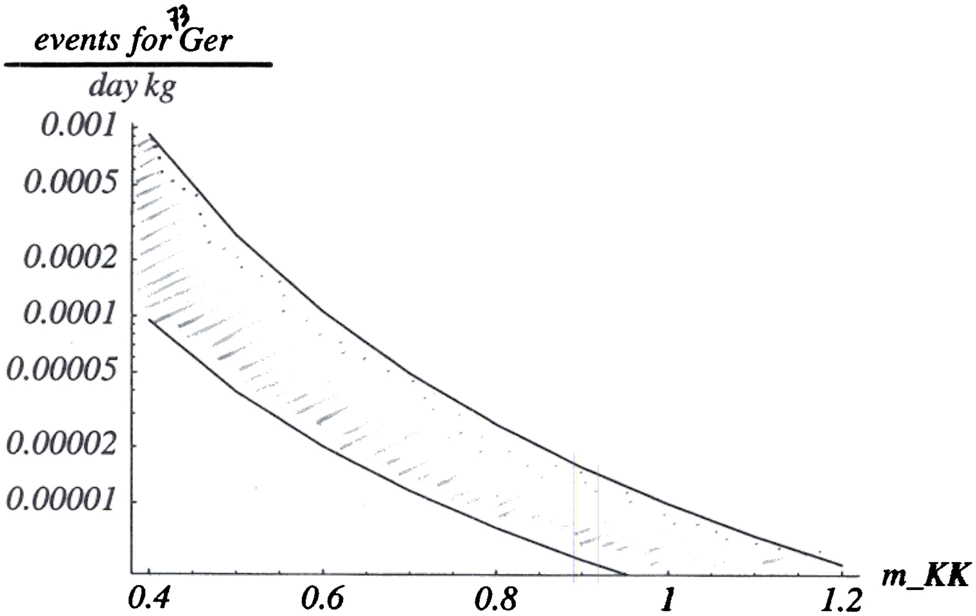


Figure 9: Integrated rate for ^{73}Ge in the two limiting cases m_h=110 GeV, $\Delta = 5\%$ and m_h=120 GeV, $\Delta = 15\%$.

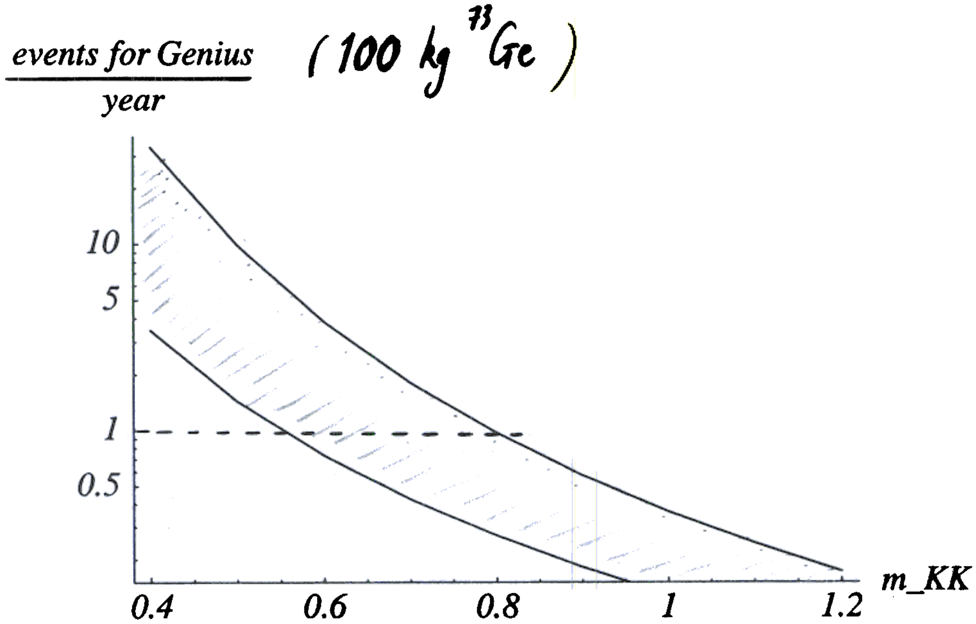
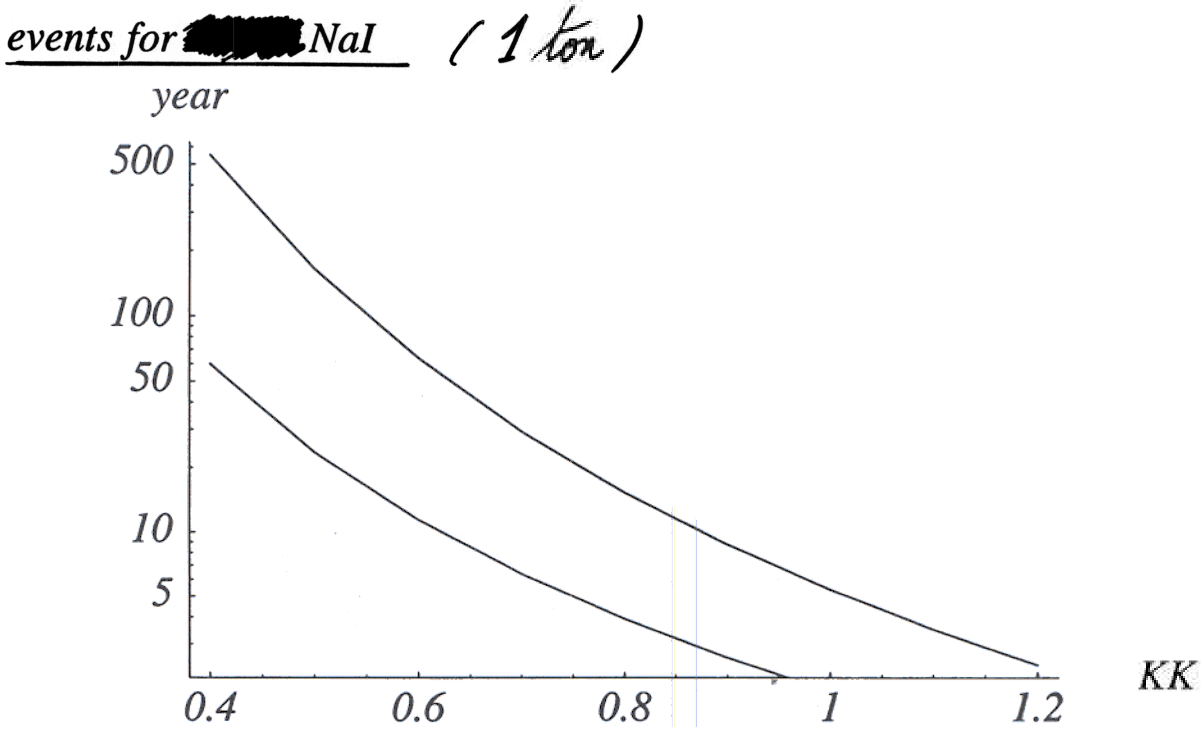
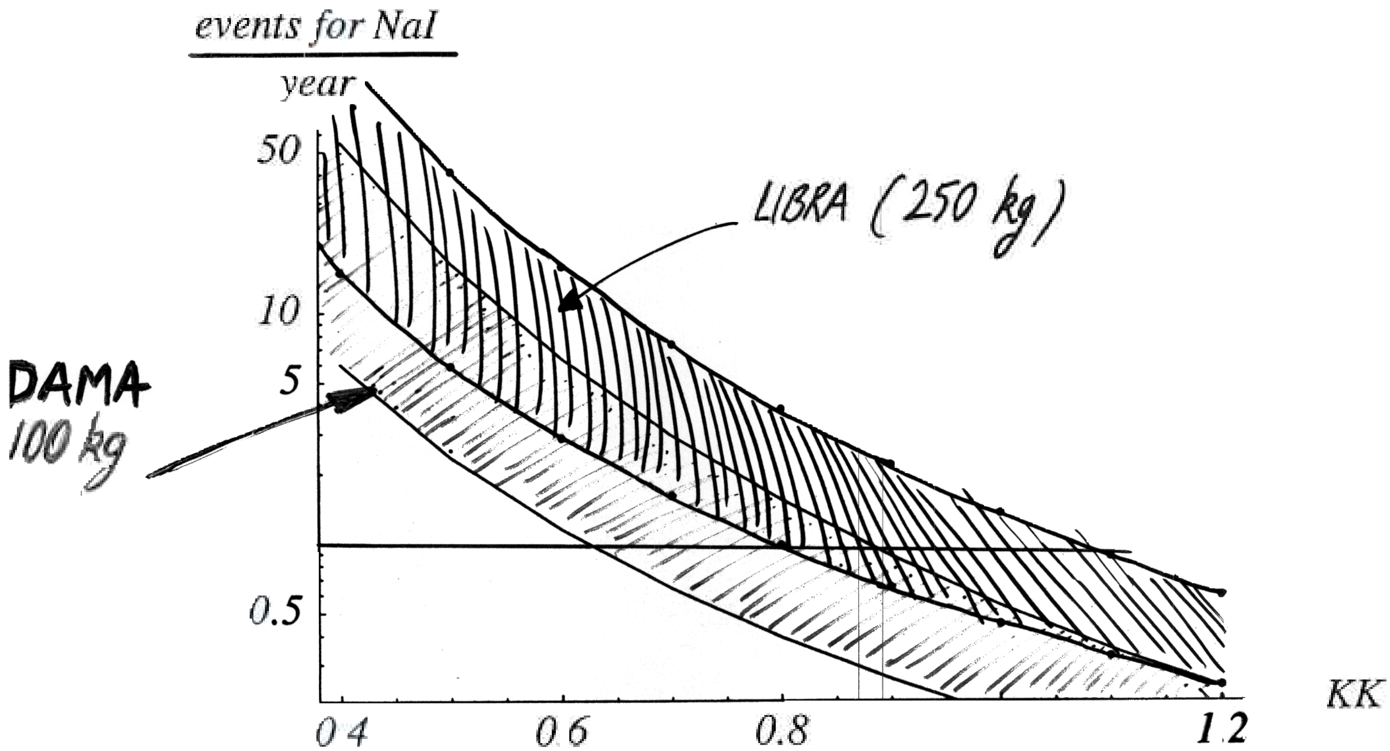
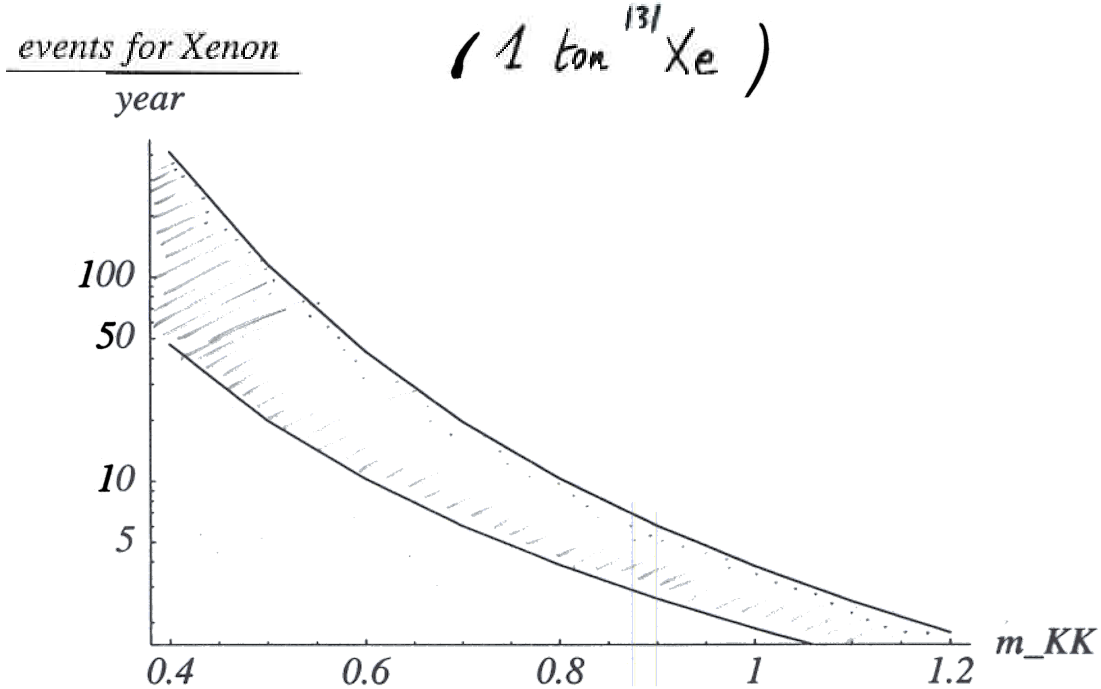


Figure 10: Number of events per year for the 100 kg ^{73}Ge Genius experiment.


events for [redacted] NaI
year
(1 ton)
500
100
50
10
5
KK
0.4
0.6
0.8
1
1.2


events for NaI
year
50
10
5
0.5
KK
0.4
0.6
0.8
1.2
LIBRA (250 kg)
DAMA
100 kg



events for Xenon
year
(1 ton 131Xe)
100
50
10
5
0.4
0.6
0.8
1
1.2
m_KK

Conclusion

- Universal Extra Dimensions WITH CONSERVED KK PARITY PREDICT the existence of a stable K.K particle.
- We checked that the L.K.P does not lead to the overclosure of the universe. Even better, it accounts for the D.M energy density for KK masses $\sim$ TeV
- Detection issues are worth pursuing
- Advantage over LSP very predictive, only one parameter R