(KALUZA-KLEIN) DARK MATTER

Geraldine Servant - University of Chicago + Argonne Lab.
(with Tim Tait @ fermilab)

4 PUZZLES in COSMOLOGY

$\Omega_i = \frac{\rho_i}{\rho_c}$ ← critical energy density for a flat universe $\rho_c = 3 m_{pl}^2 H_0^2$

- $\Omega_{TOTAL} \simeq 1$: FLAT UNIVERSE ⇝ INFLATION!
- $\Omega_{baryons} \simeq 0.04$ ⇝ BARYOGENESIS
  if matter-antimatter symmetric universe ⇝ $\Omega_{baryons} \simeq 10^{-12}$
- $\Omega_{MATTER} \simeq 0.3$ ⇝ DARK MATTER
- $\Omega_{\Lambda} \simeq 0.7$ ⇝ DARK ENERGY

S.M neutrinos cannot account for D.M.

$$\Omega_\nu h^2 = \sum_i \frac{m_{\nu_i}}{93\,eV}$$

$(H = h \times 100\, km\, s^{-1} Mpc^{-1})$
$h \sim 0.7$

1) Neutrinos : Hot Dark Matter (HDM)
↳ BAD for structure formation

Large Scale Structures Surveys → $\sum_i m_{\nu_i} < 0.7\, eV$
↳ $\Omega_\nu h^2 < 0.0076$

2) Experimental data from ν oscillations.

- $\Delta m^2_{atm} \sim 3 \times 10^{-3}\, eV^2$ $\quad \sum_i m_{\nu_i} \sim (\Delta m^2_{atm})^{1/2} \gtrsim 0.05\, eV$
- neutrinoless double β decay $\quad \sqrt{\left|\sum_i |U_{ei}|^2 m_i\right|} < 2.2\, eV$

▼

$$5 \times 10^{-4} \lesssim \Omega_\nu h^2 \lesssim 0.07$$

The issue when searching for a D.M. 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

- $\Omega \propto \sigma^{-1}_{annihilation}$

$\sigma_{ann.} \sim \frac{\alpha^2}{m^2}$

$\alpha \sim \alpha_{weak}$ and $m \sim m_{weak} \sim 200\, GeV$

↳ $\sigma_{ann.} \sim 10^{-9}\, GeV^{-2}$

↳ $\Omega \sim \mathcal{O}(1)$

- NEUTRINOS ACTIFS (du Modèle Standard) — HDM
- NEUTRINOS STÉRILES ($m \sim$ KeV) — WDM

Weakly Interacting Massive Particles (produites à l'éq. thermique):

- Lightest Supersymmetric Particle:
  - GRAVITINO
  - NEUTRALINO
  - SNEUTRINO
  - AXINO
- Lightest Kaluza-Klein Particle

CDM

Mécanisme de Production non thermique:

- Axions: $\Omega h^2 \sim \frac{10^{-5}\,\mathrm{eV}}{m_a}$

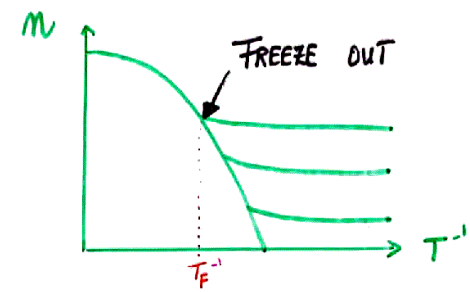
  $\rightarrow m_a \sim \frac{\Lambda_{QCD}^2}{f_{PQ}} \sim 10^{-5} - 10^{-4}\,\mathrm{eV} \rightarrow f_{PQ} \sim 10^{11} - 10^{12}\,\mathrm{GeV}$
- Particules super lourdes (WIMPZILLAS)
- Strongly Interacting Massive Particles
  ex: techni-baryons
- Q-balls

Density of a Cold relic particle

Solve Boltzmann equation

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

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



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

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

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

Kaluza-Klein Dark Matter:

- has to be WEAKLY INTERACTING
- requires KK excitations @ a TEV.
- stability?
  e.g.: in models with "Universal extra dimensions"

Why extra Dimensions @ a TeV?

- WE EXPECT NEW PHYSICS @ a TeV
- EXPLORATION OF NON SUSY NEW TEV PHYSICS
  (→ "little higgs" models
  → TEV KK excitations)...

ASKING "WHY EXTRA DIM.s @ a TEV" is the analog of ASKING "WHY SHOULD SUSY BE BROKEN @ a TeV"
(no satisfying answer)

- VERY RICH PHENOMENOLOGY, NEW INGREDIENTS FOR MODEL BUILDING
- STILL MUCH TO BE EXPLORED.

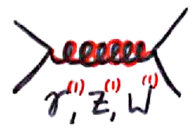
Why extra Dimensions @ a TeV?

Antoniadis '90
Antoniadis - Muñoz - Quiros '93

- ↳ Susy à la Scherk-Schwarz → $R^{-1} \sim$ TeV
- ↳ Embed the Higgs into higher dimensional gauge multiplet → $R^{-1} \sim$ TeV
- ↳ EW through strong dynamics of bulk Gauge bosons (TOP SEESAW) → $R^{-1} \sim$ TeV

Constraints on R^{-1} (colliders)

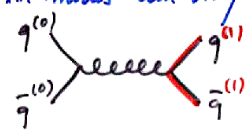
- "BRANE UNIVERSE" $R^{-1} \gtrsim (100\,\mu m)^{-1} \approx 10^{-3}$ eV (gravity experiment)
- "HYBRID" models
  (fermions are localized
  bosons are in the bulk)



→ $R^{-1} > 6.8$ TeV Cheung & Landsberg '01

- "Universal" models $R^{-1} > 250$ GeV Appelquist & Yee '02

because of tree level conservation of p_5
KK modes can only be produced by pairs.



Cosmology?

not yet explored except for KK dark Matter in "universal" models.

Servant - Tait '02
Cheng - Feng - Matchev '02

The L.K.P as Dark Matter?

- Universal Extra Dimensions
- Kaluza-Klein photon as the L.K.P
- Kaluza-Klein neutrino as the L.K.P *
- Coannihilation Effects (absence of)
- 6 D Case.
- Detection issues.

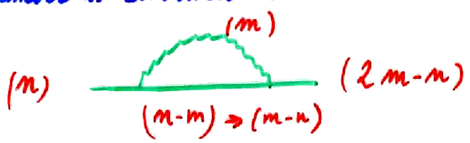
*also: KK graviton as the L.K.P

Motivations for Universal Extra Dimensions

- Dynamical EW Symmetry Breaking. Natural setting for top-see saw models.
  Arkani-Hamed – Cheng – Dobrescu – Hall '00
  Cheng – Dobrescu – Hill
  He – Hill – Tait
- Number of Fermion Generations
  Dobrescu – Poppitz '01
- Proton Stability
  Appelquist – Dobrescu – Ponton – Yee '01
- Dark Matter Candidate ?

Kaluza-Klein Parity

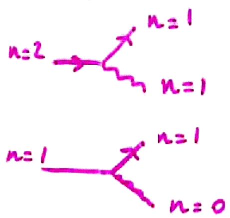
K.K number is Conserved at tree level but broken at loop level

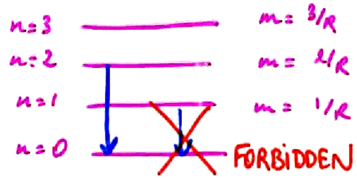


n can change by an EVEN number only

↳ KK PARITY : $(-1)^n$: preserved at all orders.

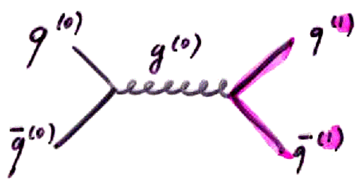
⇝ Only interactions between an EVEN number of ODD KK modes.





⇨ the Lightest KK particle (LKP) is stable

⇨ Production of 1st KK modes only by Pairs



↳ weak bound on $\frac{1}{R}$: $R^{-1} \gtrsim 300$ GeV for $\delta=1$

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

CHENG - MATCHEV - SCHMALTZ hep-ph/0204342

Spectrum of FIRST KK MODES at tree level ($R^{-1}=500$ GeV)

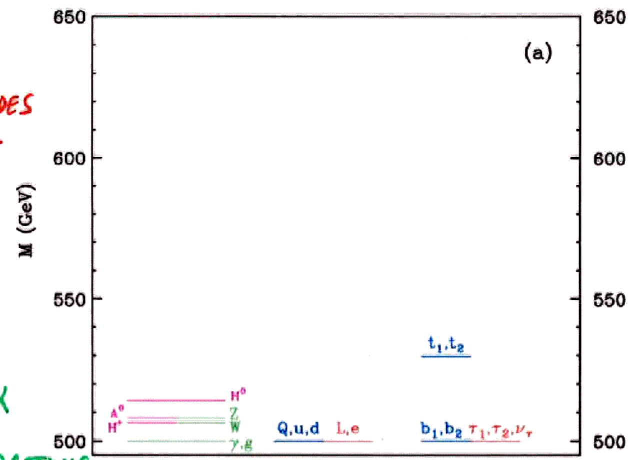


Figure 1: Spectrum of the first KK level at tree level for $R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut–off scale.

DISTORSION OF KK TOWER BY RADIATIVE CORRECTIONS

KK Spectrum @ 1-loop

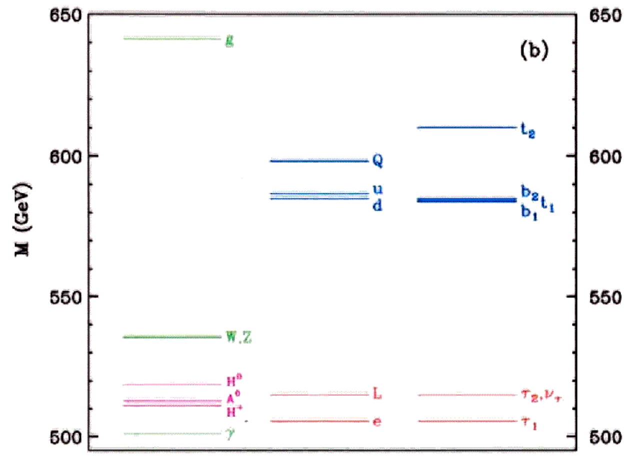


Figure 2: Spectrum of the first KK level at one loop for $R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut–off scale.

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 $\delta M_2^2 > \delta M_1^2$

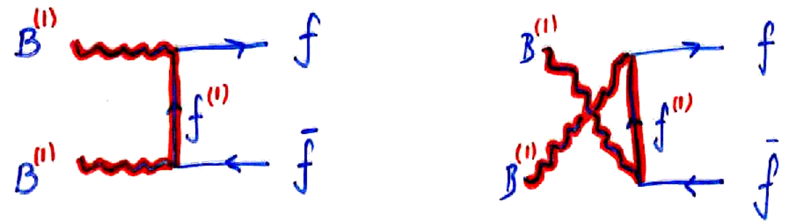
IN THE LIMIT $\delta M_2^2 - \delta M_1^2 \gg g_1 g_2 v^2 \Rightarrow$ MIXING ANGLE DRIVEN TO ZERO.

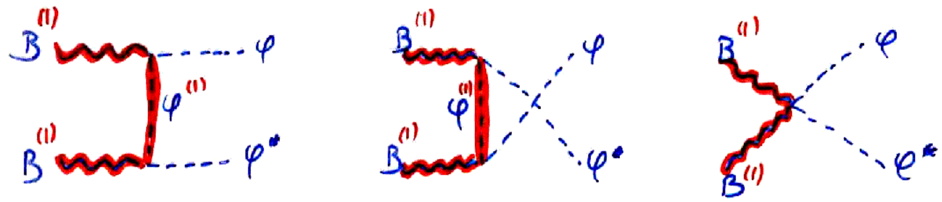
→ LKP is APPROXIMATELY ENTIRELY $B^{(1)}$.

NLKP : $e_R^{(1)}$

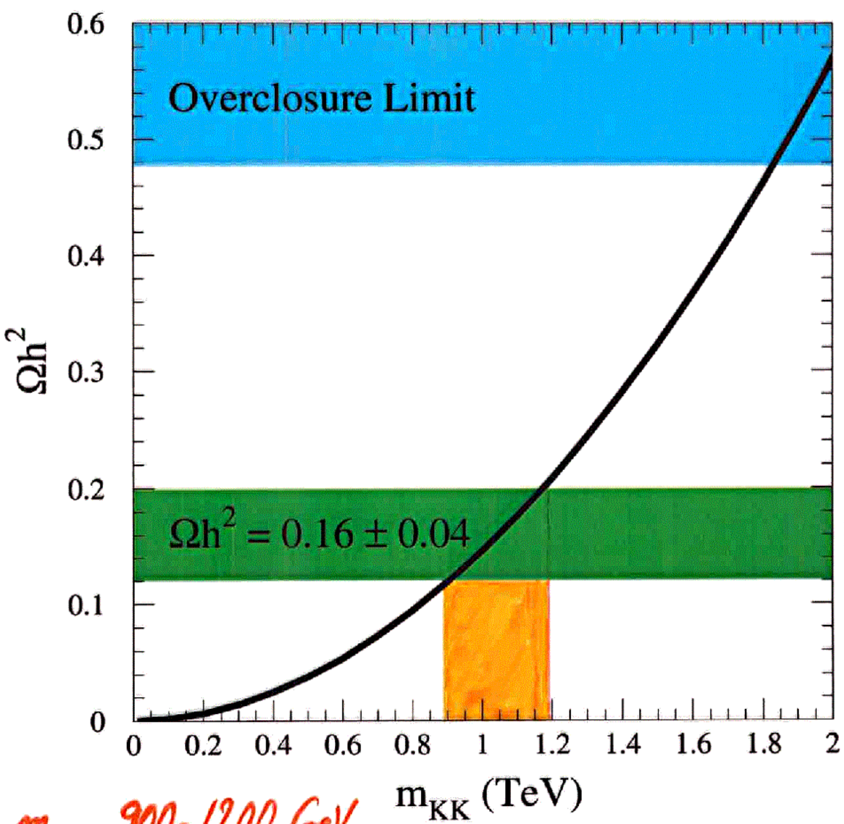
① L.K.P is $B^{(1)}$

Annihilation cross sections



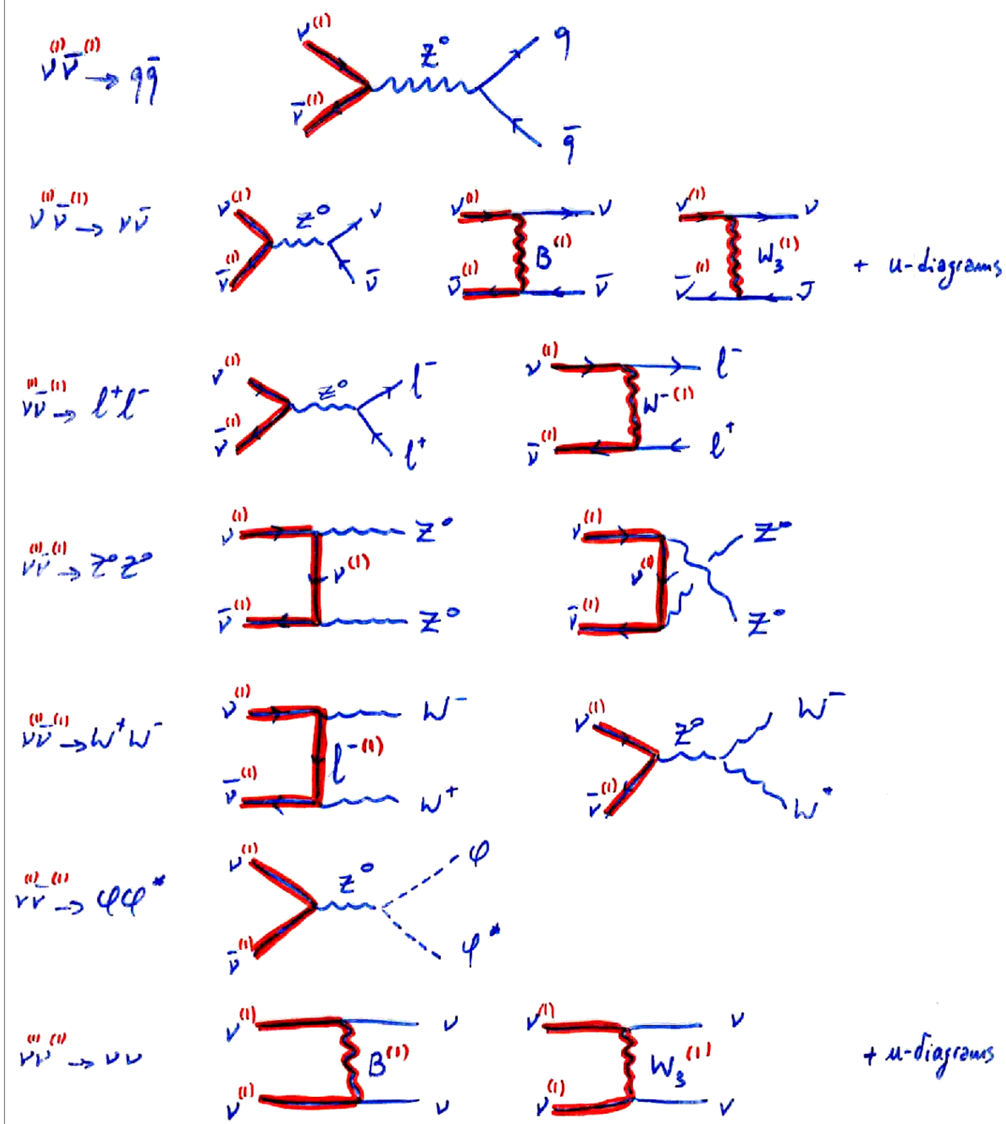


PREDICTION FOR $B^{(1)}$ ENERGY DENSITY AS A FUNCTION OF THE K.K. MASS

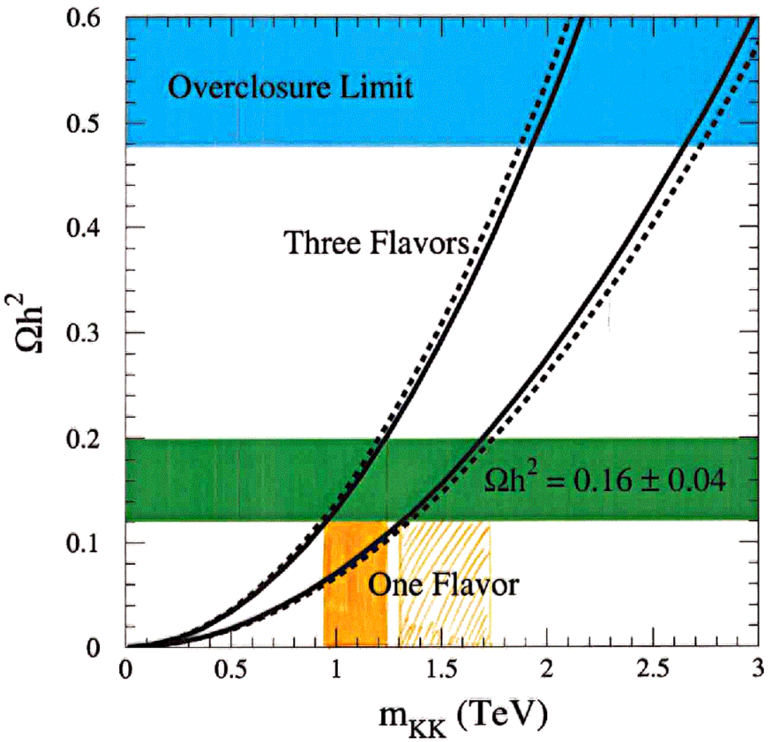


$m_{KK} \sim 900\text{-}1200$ GeV

② L.K.P is $\nu^{(1)}$



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



1 flavor $m_{KK} \sim 1.3 - 1.8$ TeV

3 flavors $m_{KK} \sim 950 - 1250$ GeV

Coannihilation :

- NEARLY degenerate particles are nearly as abundant as the LKP and are thermally accessible
- Their annihilat° will play a role in determining the relic abundance of the LKP.

$Z_i Z_i \to X X'$ } self annih°

$Z_j Z_j \to X X'$

$Z_i Z_j \to X X'$ coannihil°

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

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

$$g_{eff} = \sum_i g_i (1+\Delta_i)^{3/2} e^{-x\Delta_i}$$

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

↳ COANNIHILATION EFFECTS

ADD:

$e_R^{+(1)} e_R^{-(1)} \to q\bar{q},\ \nu\bar{\nu},\ \varphi\varphi^*$

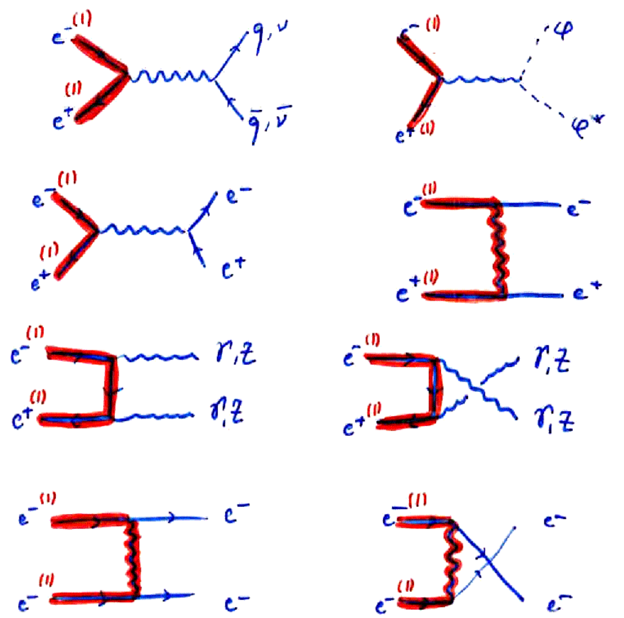
$e_R^{+(1)} e_R^{-(1)} \to e^+ e^-$

$e_R^{+(1)} e_R^{-(1)} \to \gamma\gamma$

$e_R^{+(1)} e_R^{-(1)} \to ZZ$

$e_R^{+(1)} e_R^{-(1)} \to Z\gamma$

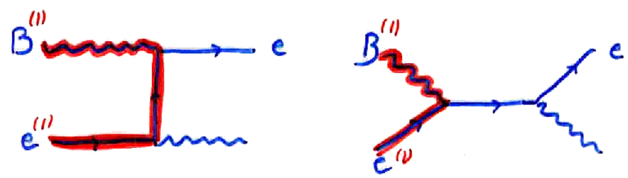
$e_R^{-(1)} e_R^{-(1)} \to e^- e^-$



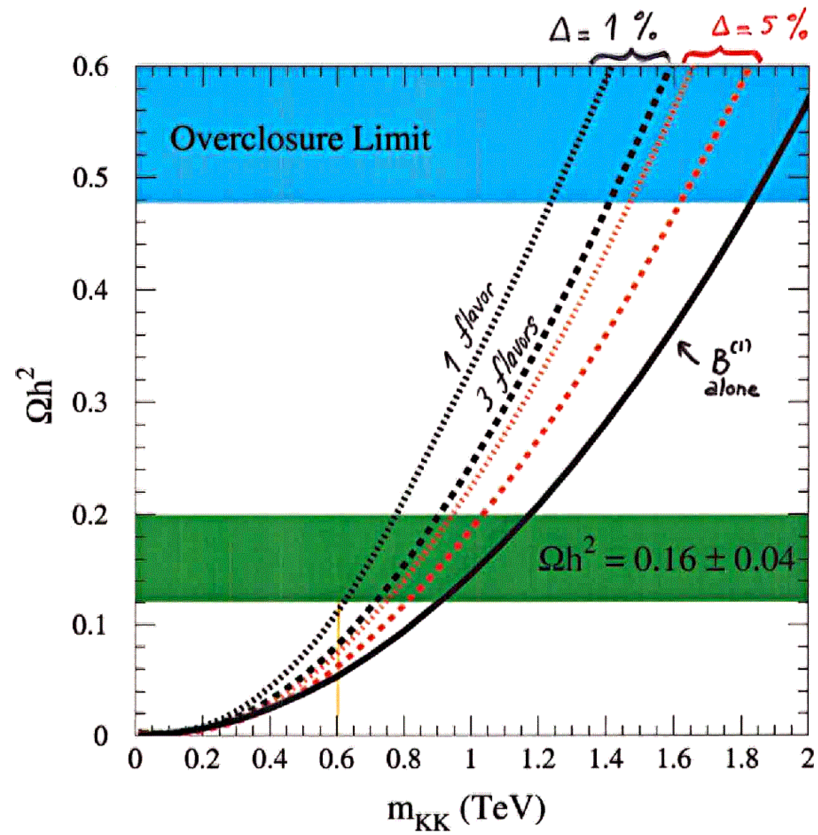
COANNIHILATION CHANNELS:

$B^{(1)} e_R^{(1)} \to \gamma e$

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



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: $B^{(1,0)}$ $B^{(0,1)}$ $B^{(1,1)}$ $B^{(1,-1)}$

$B^{(1,1)}$, $B^{(1,-1)}$ → 40% heavier : Do NOT CONTRIBUTE TO RELIC DENSITY.

BECAUSE OF K.K # CONSERVATION MOD 2, $B^{(0,1)}$ and $B^{(1,0)}$ DO NOT TALK TO EACH OTHER AND ANNIHILATE INDEPENDENTLY AT TREE LEVEL.

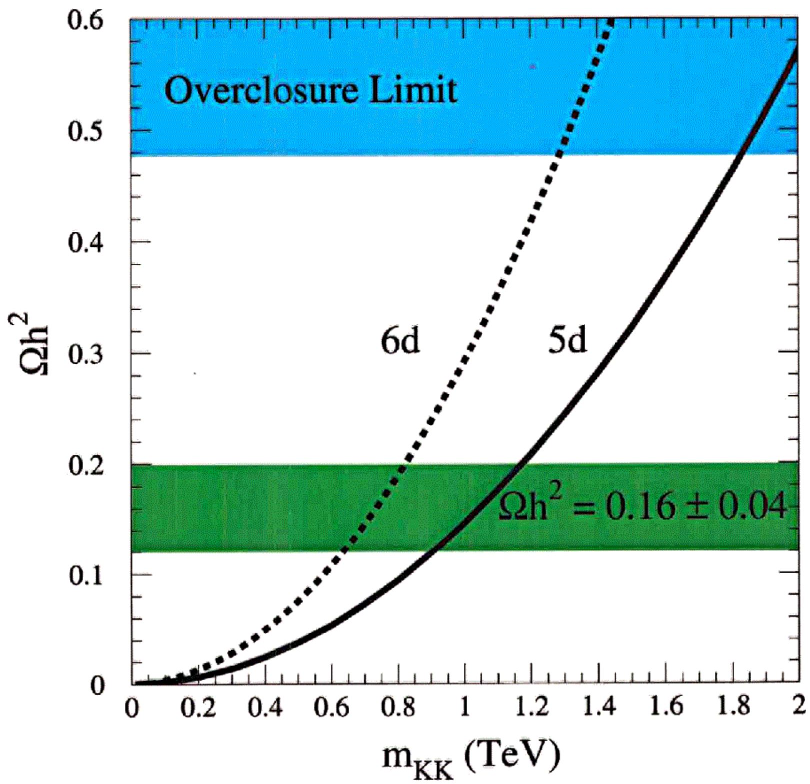
TWICE AS MANY LKP
SAME # of ZERO MODES } ⇒ Relic density multiplied by 2.

$$\Omega h^2 \sim \frac{10^9}{M_{pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{\langle \sigma v \rangle} \propto m^2$$

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

- T^2/Z_4 : 2 STABLE PARTICLES: $B^{(0,1)}$ & $B^{(1,1)}$
same as 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.
(CHENG-FENG-MATCHEV ; SERVANT-TAIT)

→ 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 km³ neutrino telescopes.
(Hooper & Kribs)

BERTONE-SERVANT-SIGL

WIMP-NUCLEUS ELASTIC SCATTERING

For $m \sim 1$ TeV and $v \sim 270\ km\, s^{-1}$

↳ 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 : $\frac{dR}{dE_r} \propto \sigma(q^2=0) \times F^2(q)$

↑ nuclear form factor

NUCLEAR FORM FACTOR EFFECTS :

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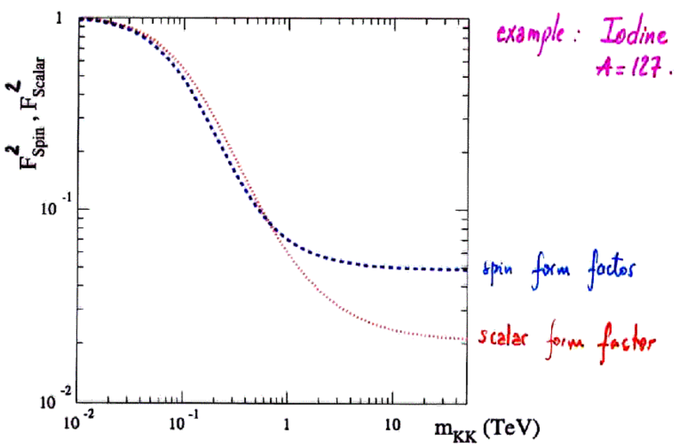
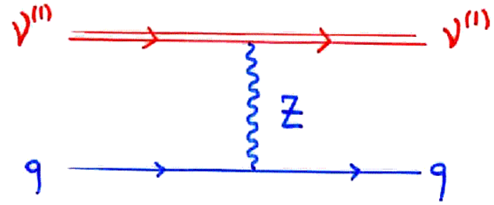


1) Neutrino Case

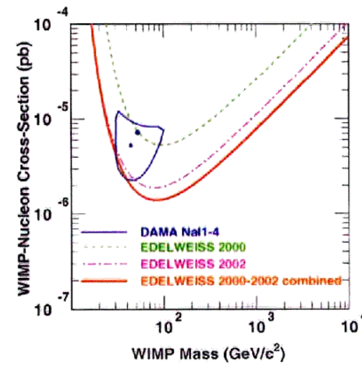


AT THE QUARK LEVEL : $\mathcal{L}_{eff} \sim \bar{u}_{\nu^{(1)}} \gamma^\mu u_{\nu^{(1)}} \; \bar{q} \gamma_\mu q$

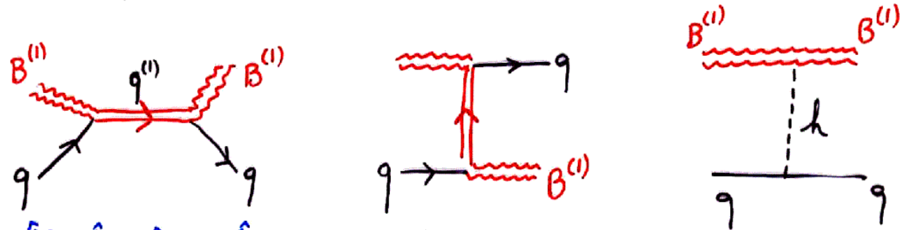
↳ $\sigma_0^{vector} \sim \mu^2 G_F^2 \frac{A^2}{8\pi}$ ➞ WIMP-NUCLEON CROSS SECTION : $\sigma_n \sim 2 \times 10^{-39}$ cm^2 = 2×10^{-3} pb

EXCLUDED !

unless $m_{\nu^{(1)}} \gtrsim 50$ TeV



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



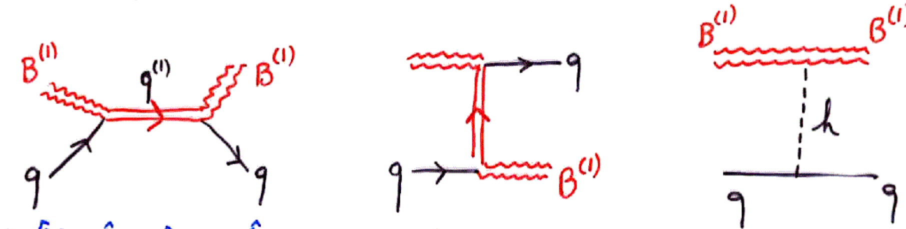
↳ "SPIN" & "SCALAR" CROSS SECTIONS

$\mathcal{M}_{scalar} \propto \epsilon^*_\mu \epsilon^\mu \bar{u} u \rightsquigarrow \sigma_p^{scalar} \sim 10^{-10}$ pb

$\mathcal{M}_{spin} \propto \epsilon^*_\mu \epsilon_\nu \; \epsilon^{0ijk} \bar{u} \gamma_k \gamma_5 u \rightsquigarrow \sigma_p^{spin} \sim 10^{-7}$ pb

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

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



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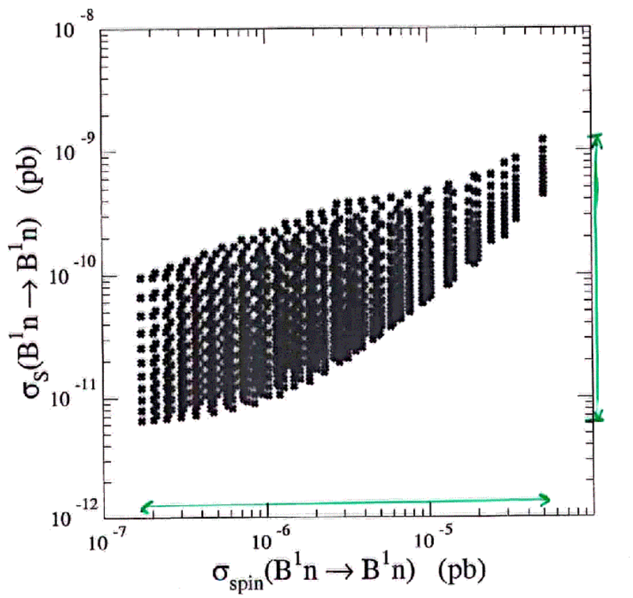
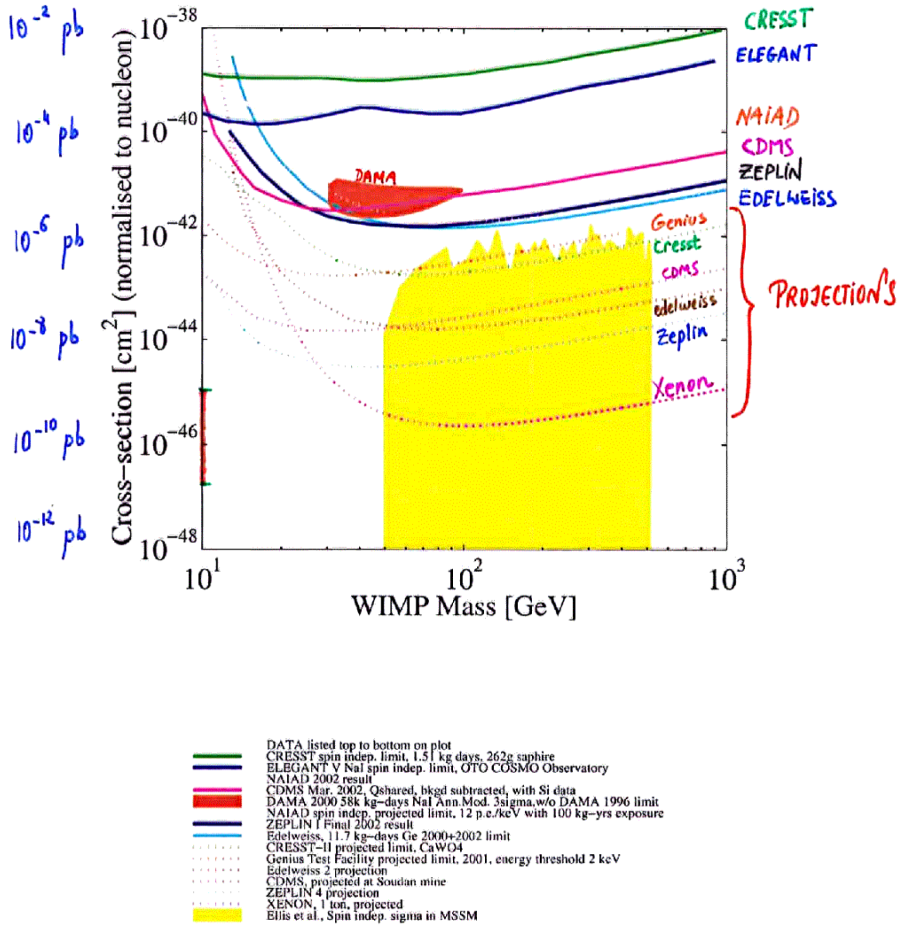
SCALAR & SPIN-DEPENDENT $B^{(1)}$-nucleon CROSS SECTIONS

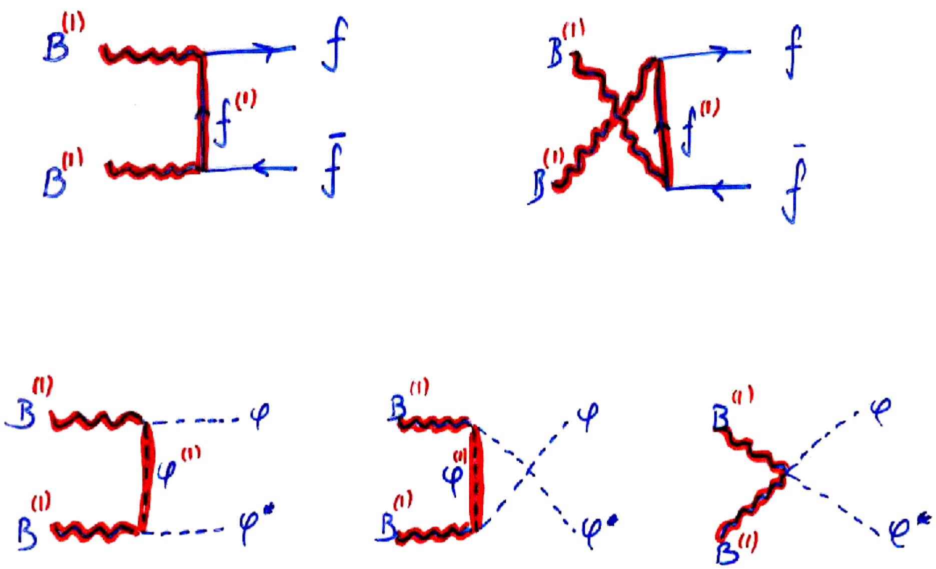


Limits on Spin-independent cross sections

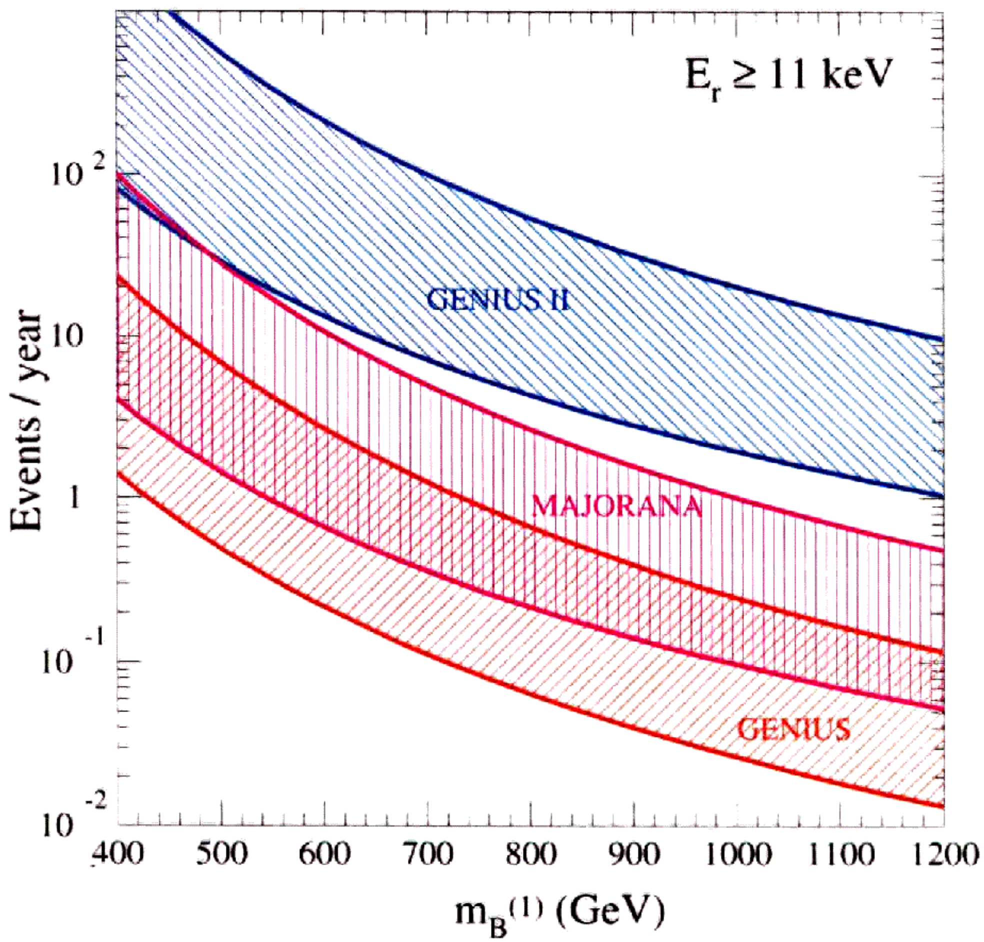


① L.K.P is $B^{(1)}$

Annihilation cross sections

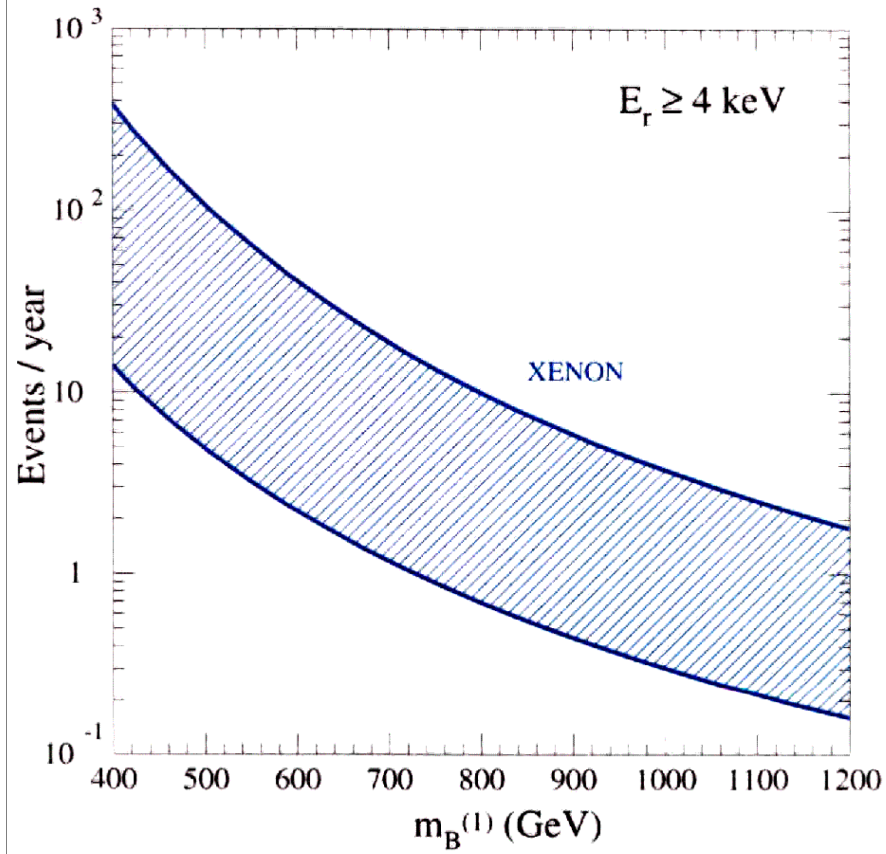


Germanium Detectors



- GENIUS: 100 kg ^{73}Ge
- MAJORANA: 500 kg ^{76}Ge and ^{74}Ge
- GENIUS II: 10^4 kg ^{76}Ge and ^{74}Ge

Xe Detectors

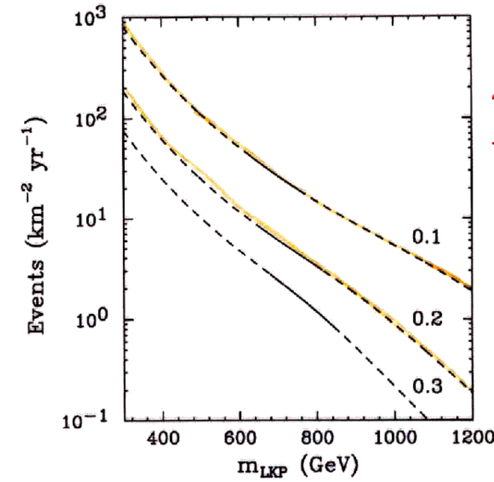


- XENON: 1000 kg ^{131}Xe

INDIRECT DETECTION :

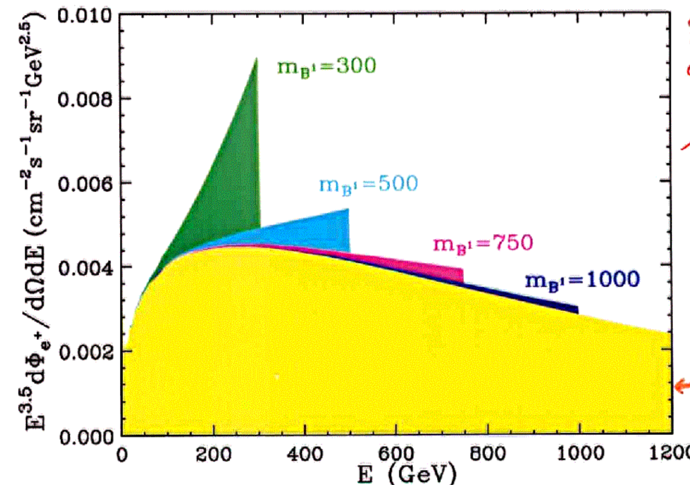
- Signal from LKP annihilation in the Sun.
  → HOOPER - KRIBS '02.
  (ν spectrum)

- Signal from LKP annihilation in the Center of the Galaxy.
  → positron spectrum } CHENG - FENG - MATCHEV '02
  → γ spectrum
  → ν spectrum
  → synchrotron radiation } Bertone - Sigl - Servant '02.



Detection of cosmic neutrinos coming from LKP annihilation in the Sun.

Hooper - Kribs '02.



POSITRON SIGNAL due to LKP annihilation in the galactic center

← "NOISE"

$\bar{J} = 500$ (Halo parameter)

Cheng et al '02.

Conclusion

- Nature of Dark Matter: a major puzzle in particle physics / Cosmology.

  WIMP: LSP, axion, LKP ... ?

- A major exp^{al} program to search for these objects
- We studied an interesting alternative to the extensively studied standard neutralino LSP in SUSY models

  ↳ L.K.P: well motivated in a large class of theories with extra dimensions.

  we found that the LKP can account for DM if $m_{KK} \sim R^{-1} \sim$ TeV : at frontier of current collider & direct detection constraints.

- Advantage over LSP: more predictive

  ~ 1 parameter: R

- Future experiments should study a significant region of parameter space. At same time, Tevatron & LHC will study a similar range.
- Indirect detection: might be more promising