Kaluza-Klein Dark Matter

Jonathan Feng
UC Irvine

KITP, Santa Barbara
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Dark Matter

- Our best evidence for new particle physics

- We live in interesting times
  - we know how much there is ($\Omega_{DM} \sim 0.3$)
  - but not what it is (non-baryonic, cold)

- WIMPs are attractive
  - predicted in many particle theories (EWSB)
  - naturally give thermal relic density $\Omega_{DM} \sim O(1)$
  - $\Omega_{DM} < 1$ ➔ $\chi\chi \to f\,f$ not small ➔ $\chi f \to \chi f$ not small, so testable: promising for direct, indirect detection

Candidates from Particle Physics

- Supersymmetry
  - Neutralinos – partners of γ, Z, W, h
  - Requirements:

    high supersymmetry-breaking scale (supergravity)

    R-parity conservation
- Extra Dimensions
  - Kaluza-Klein particles – partners of γ, Z, W, h, $G_{\mu\nu}$,…
  - Requirements:

    universal extra dimensions

Cheng, Feng, Matchev (2002)
Feng, Rajaraman, Takayama

Universal Extra Dimensions

- Kaluza (1921) and Klein (1926) considered D=5, with 5th dimension compactified on circle S^1 of radius R:

D=5 gravity → D=4 gravity + EM + scalar

$$G_{MN} \rightarrow G_{\mu\nu} + G_{\mu 5} + G_{55}$$

- Kaluza: “virtually unsurpassed formal unity...which could not amount to the mere alluring play of a capricious accident.”

- Problem: gravity is weak

- Solution: introduce extra 5D fields: G_{MN} , V_M , etc.

- New problem: many extra 4D fields; some with mass *n*/*R*, but some are massless! E.g., 5D gauge field:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu)\cos(ny/R) + \sum_m V_\mu^m(x^\mu)\sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu)\cos(ny/R) + \sum_m V_5^m(x^\mu)\sin(my/R)$$

- A new solution…

- Compactify on S^1/Z_2 instead (orbifold); require

$$y \to -y \;:\quad V_\mu \to V_\mu \quad V_5 \to -V_5$$

- Unwanted scalar is projected out:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu)\cos(ny/R) + \cancel{\sum_m V_\mu^m(x^\mu)\sin(my/R)}$$

$$V_5(x^\mu, y) = \underbrace{\cancel{V_5(x^\mu)}}_{\text{bad}} \cancel{+ \sum_n V_5^n(x^\mu)\cos(ny/R)} + \sum_m V_5^m(x^\mu)\sin(my/R)$$

- Similar projection on fermions → 4D chiral theory, …

- Very simple (requires UV completion at $\Lambda >> R^{-1}$)

Appelquist, Cheng, Dobrescu (2001)

KK-Parity

- An immediate consequence: conserved KK-parity $(-1)^{KK}$
  Interactions require an even number of odd KK modes

- 1st KK modes must be pair-produced at colliders

Macesanu, McMullen, Nandi (2002)

- weak bounds: $R^{-1} > 200$ GeV

Appelquist, Yee (2002)

- LKP (lightest KK particle) is stable – dark matter

Kolb, Slansky (1984)
Saito (1987)

Other Extra Dimension Models

- SM on brane; gravity in bulk (brane world)
  - Requires localization mechanism
  - No concrete dark matter candidate

- fermions on brane; bosons and gravity in bulk
  - Requires localization mechanism
  - R^{-1} > few TeV from $f\bar{f} \rightarrow V_\mu^1 \rightarrow f\bar{f}$
  - No concrete dark matter candidate

- everything in bulk (UED)
  - No localization mechanism required
  - Natural dark matter candidate – LKP

UED and SUSY

Similarities:

- Superpartners → KK partners
- R-parity → KK-parity
- LSP → LKP
- Bino dark matter → B^1 dark matter

  Sneutrino dark matter → ν^1 dark matter

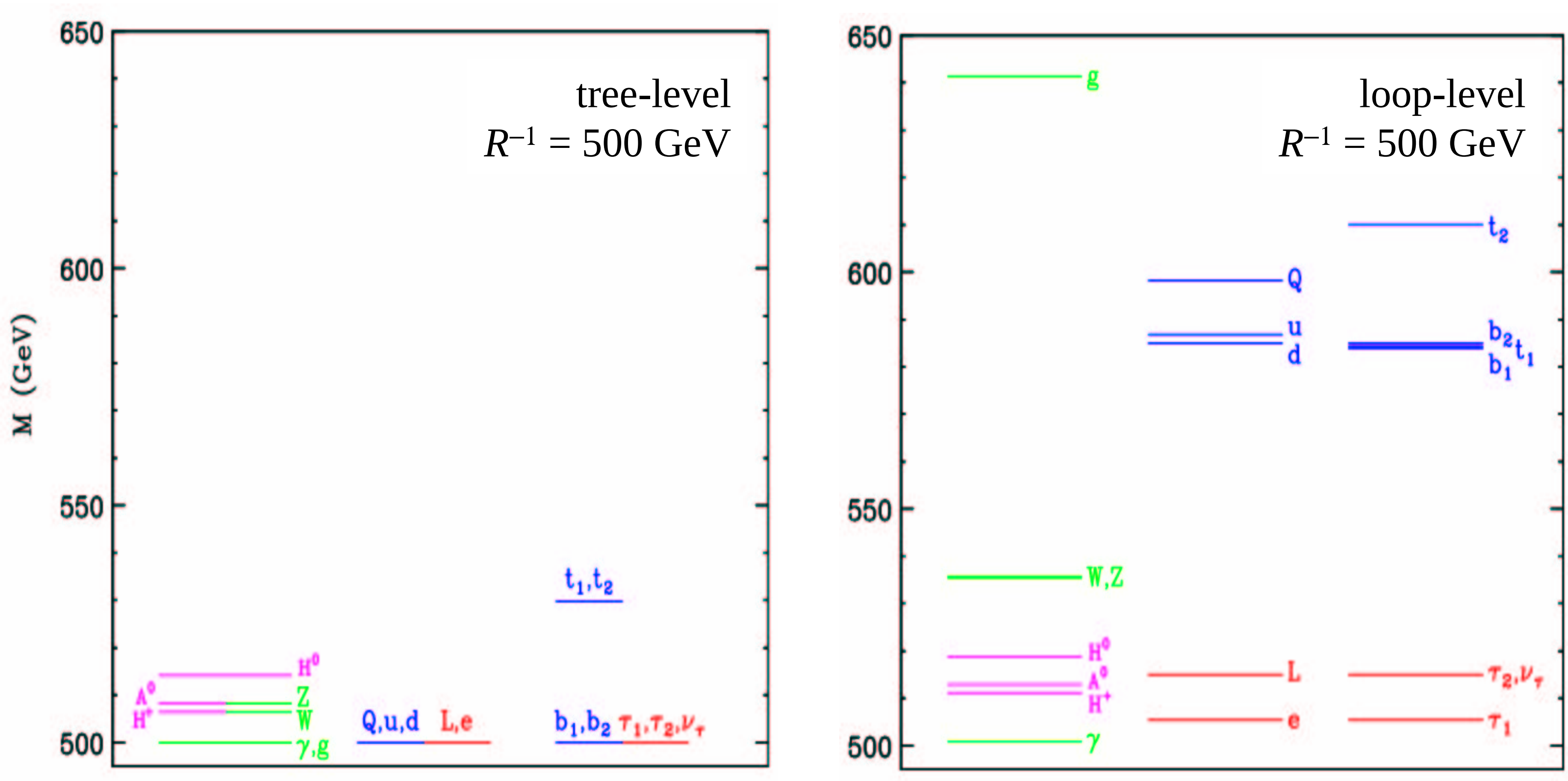
  …

Not surprising: SUSY is also an extra (fermionic) dimension theory

Differences:

- KK modes highly degenerate, split by EWSB and loops
- Fermions → Bosons

Minimal UED KK Spectrum

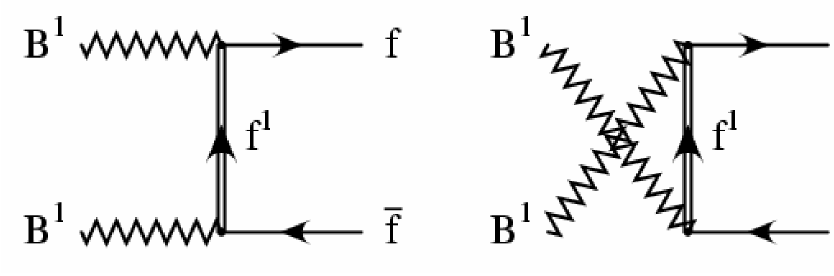


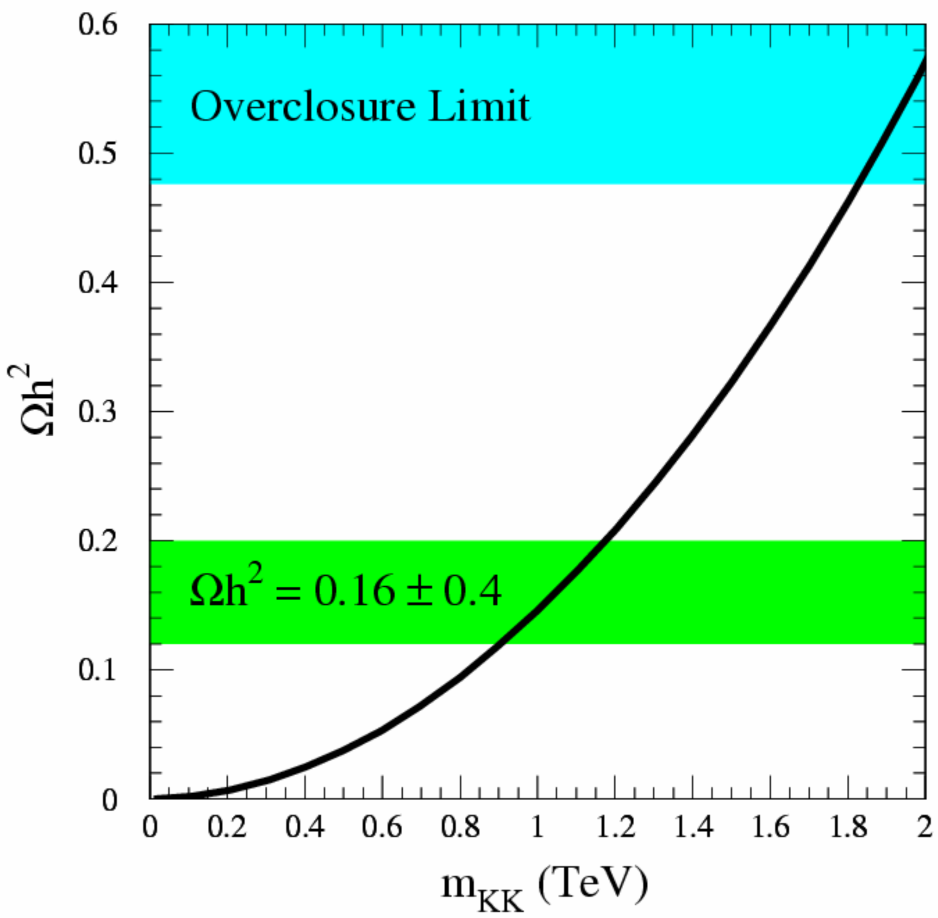
Cheng, Matchev, Schmaltz (2002)

B^1 Dark Matter

- LKP is nearly pure B^1 in minimal model (more generally, a B^1-W^1 mixture)

- Relic density:

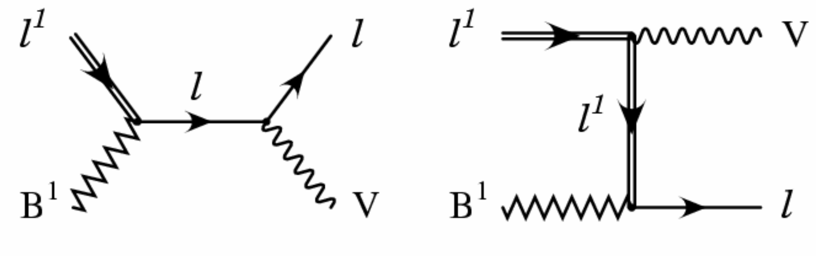




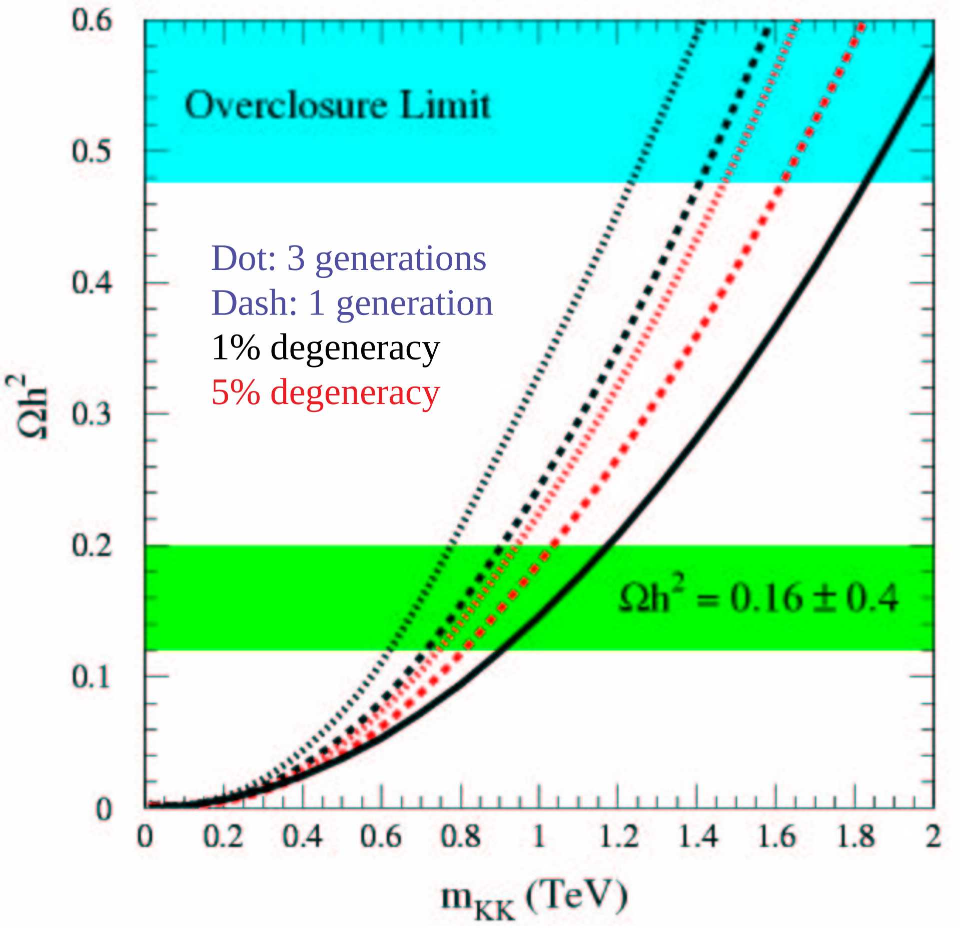
Servant, Tait (2002)

Co-annihilation

- But degeneracy → co-annihilations important
- Co-annihilation processes:



- Preferred m_{B^1}: l^1 lowers it, q^1 raises it; 100s of GeV to few TeV possible

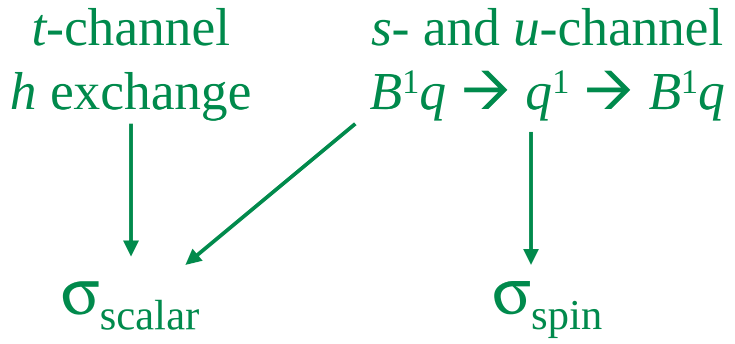


Dot: 3 generations
Dash: 1 generation
1% degeneracy
5% degeneracy

Servant, Tait (2002)

B^1 Dark Matter Detection

Direct Detection

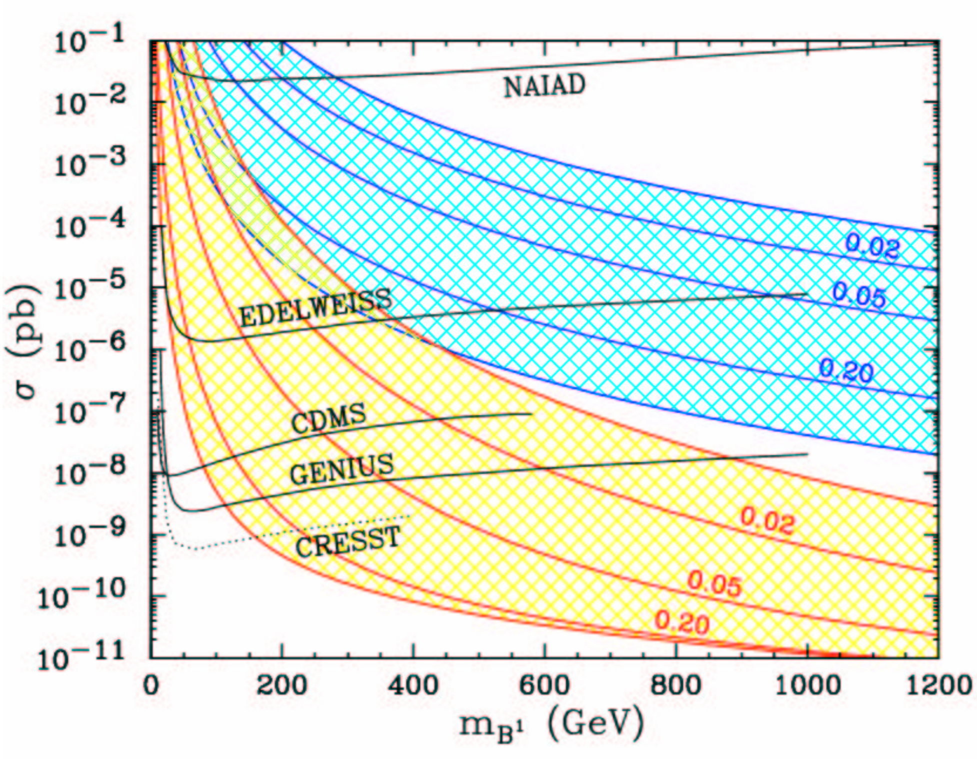


t-channel
h exchange

s- and *u*-channel
$B^1q \rightarrow q^1 \rightarrow B^1q$

σ_{scalar}

σ_{spin}



Cheng, Feng, Matchev (2002)

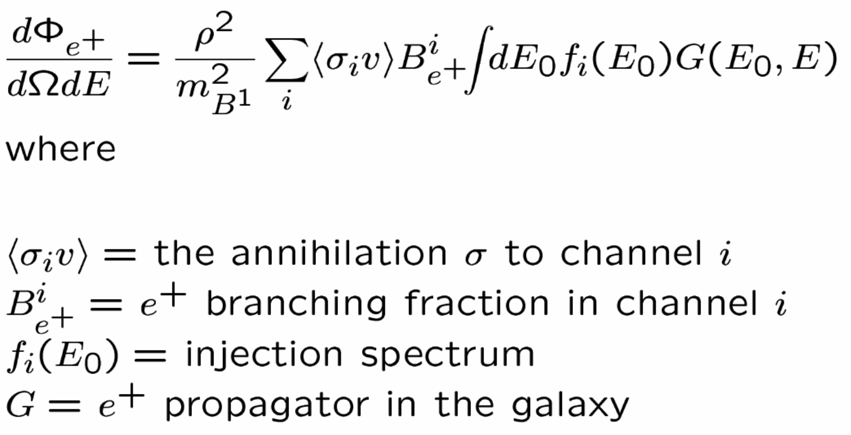
- *s*-channel enhanced by B^1-q^1 degeneracy

- Constructive interference: lower bound on both σ_{scalar} and σ_{spin}

B^1 Dark Matter Detection

- Indirect Detection:
  - Positrons from the galactic halo
  - Muons from neutrinos from the Sun and Earth
  - Gamma rays from the galactic center
- All rely on annihilation, very different from SUSY
  - For neutralinos (Majorana fermions), $\chi\chi \rightarrow f\bar{f}$ is chirality suppressed
  - $B^1B^1 \rightarrow f\bar{f}$ isn't; generically true for bosons

Positrons

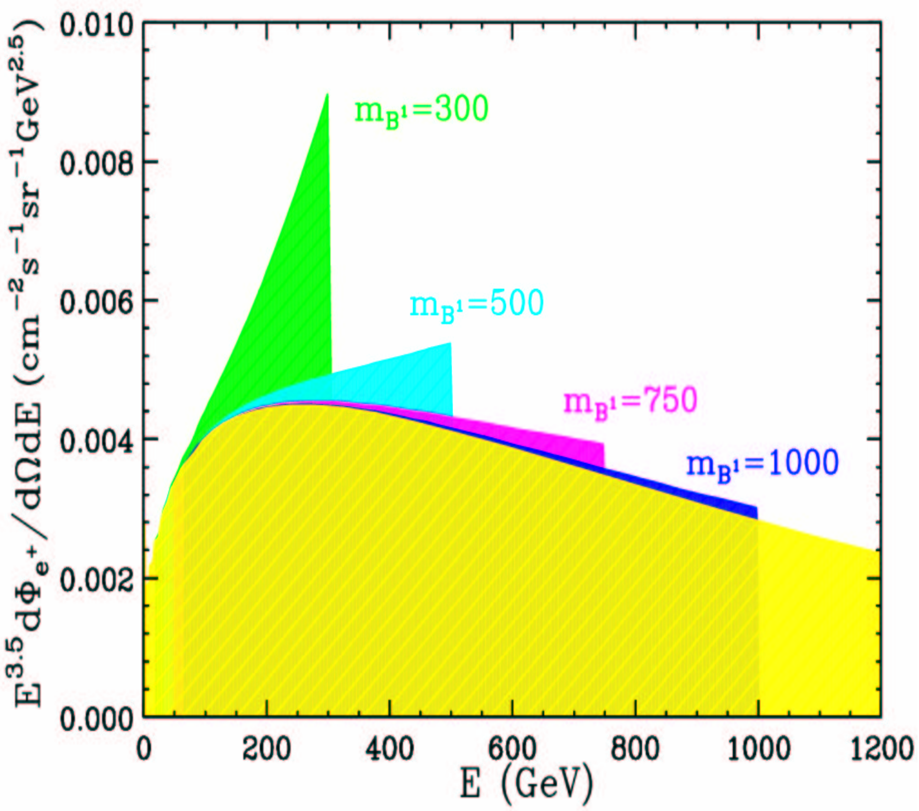


$$\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho^2}{m_{B^1}^2}\sum_i \langle\sigma_i v\rangle B^i_{e^+}\int dE_0 f_i(E_0) G(E_0,E)$$

where

$\langle\sigma_i v\rangle$ = the annihilation σ to channel i
$B^i_{e^+}$ = e^+ branching fraction in channel i
$f_i(E_0)$ = injection spectrum
G = e^+ propagator in the galaxy

Moskalenko, Strong (1999)



Cheng, Feng, Matchev (2002)

- Here $f_i(E_0) \sim \delta(E_0 - m_{B^1})$, and the peak is not erased by propagation (cf. $\chi\chi \rightarrow W^+W^- \rightarrow e^+\nu\, e^-\nu$)
- AMS will have e^+/e^- separation at 1 TeV and see ~1000 e^+ above 500 GeV

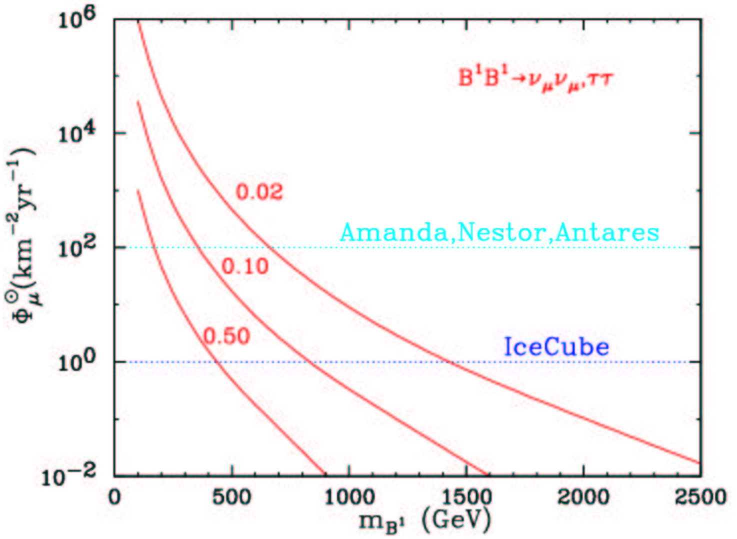
Muons from Neutrinos

- Muon flux is

$$\Phi_\mu \propto \sum_{F,i} B_F \langle N z^2 \rangle_{F,i}$$

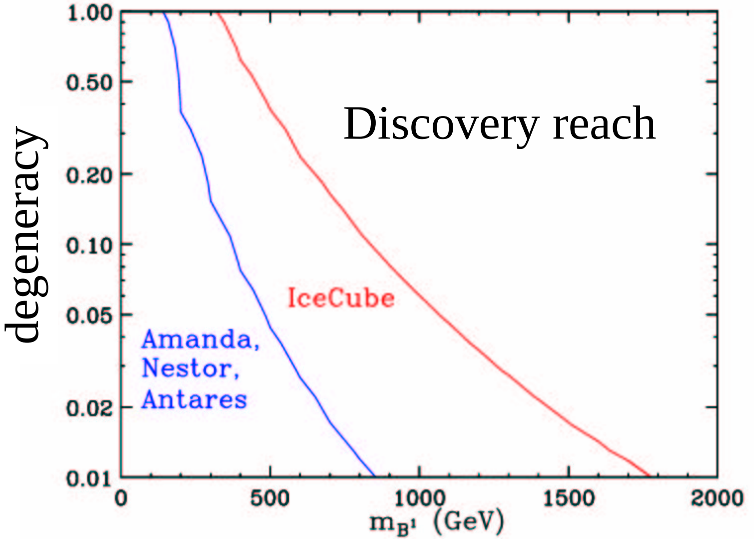
where $i = \nu, \bar{\nu}$, F labels final states, and $z \equiv E_\nu / E_{\text{in}}$.

Ritz, Seckel (1988)
Jungman, Kamionkowski, Griest (1995)



- B^1B^1 → ν ν is also unsuppressed, gives hard neutrinos, enhanced μ flux

Cheng, Feng, Matchev (2002)
Hooper, Kribs (2002)
Bertone, Servant, Sigl (2002)

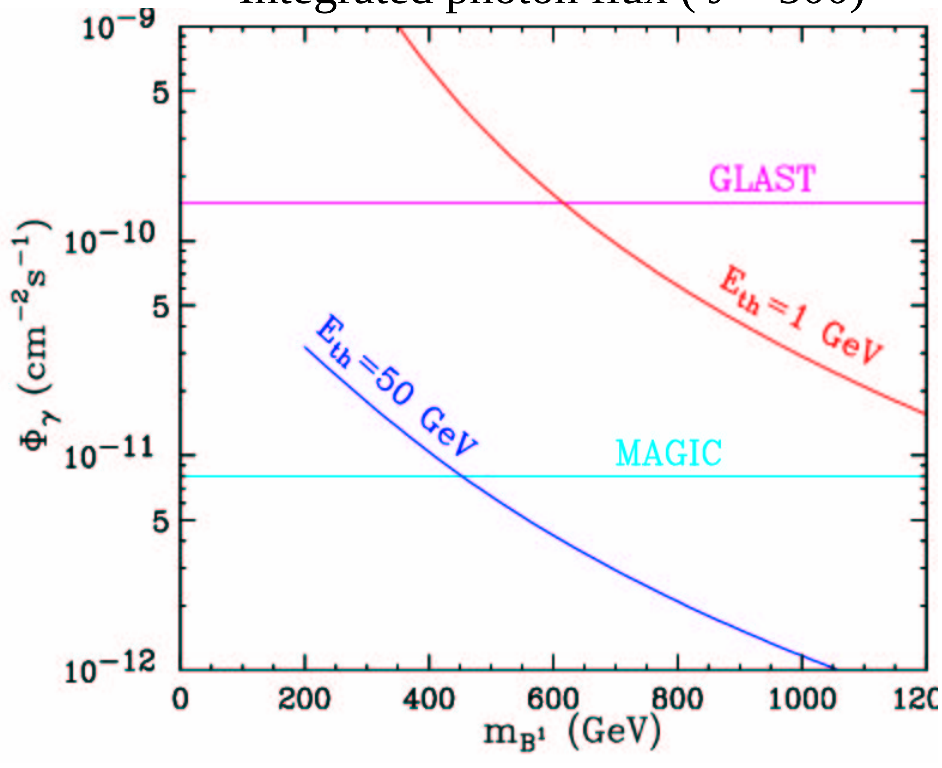


Gamma Rays

- $B^1 B^1 \to \gamma\gamma$ is loop-suppressed, but light quark fragmentation gives hardest photons, so absence of chirality suppression helps again
- Results sensitive to halo clumpiness; choose moderate value

Bergstrom, Ullio, Buckley (1998)

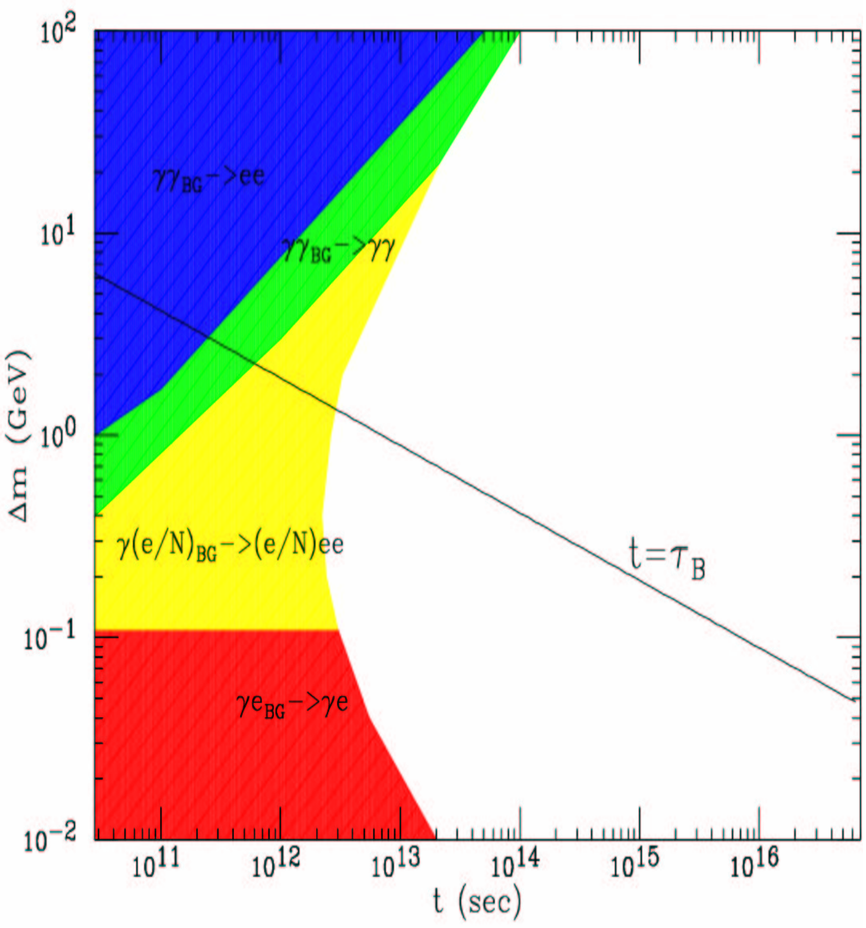
Integrated photon flux ($\bar{J}$ = 500)



Cheng, Feng, Matchev (2002)

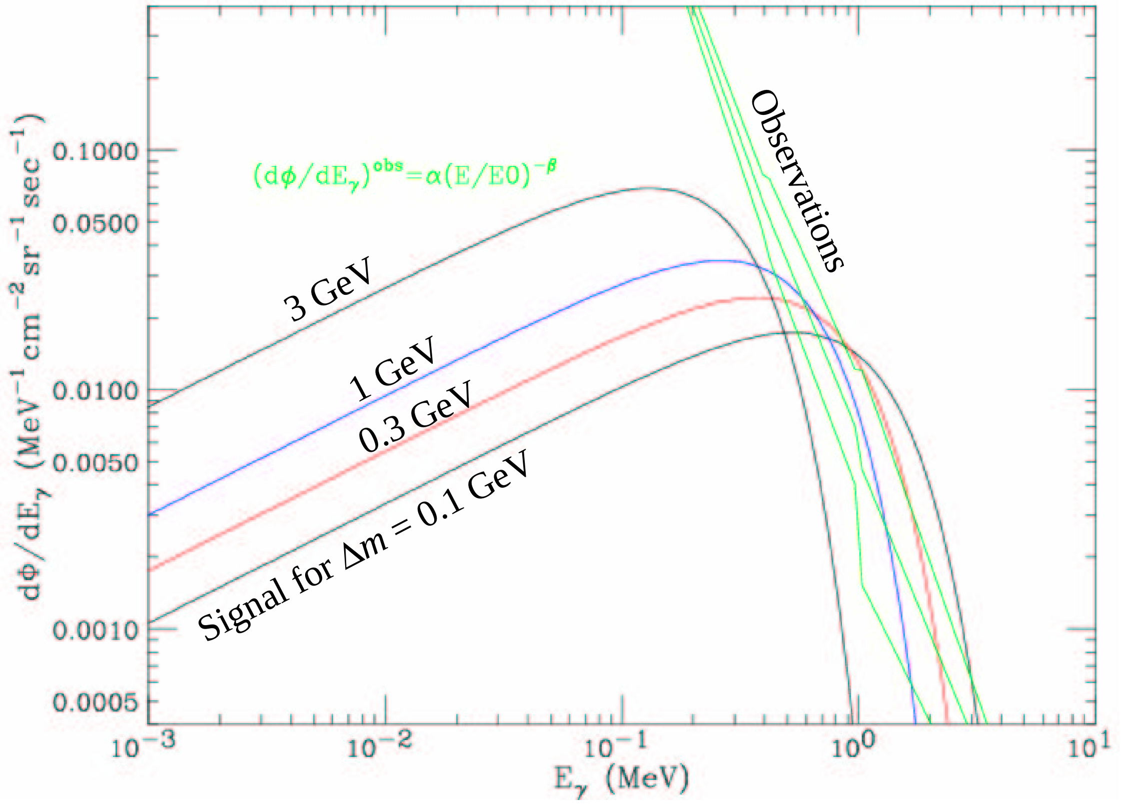
Graviton Dark Matter

- LKP may be 1st KK graviton G^1
- If NLKP is B^1, B^1 freezes out, then decays via $B^1 \rightarrow \gamma\, G^1$ with lifetime ~ 10^{12} sec [1 GeV / Δm]^3; get very late, very soft decays
- Evades BBN constraints for small Δm (or if NLKP is ν^1)
- G^1 DM retains WIMP virtues, but is undetectable by all conventional dark matter searches


Feng, Rajaraman, Takayama

Diffuse Photon Flux

- Late $B^1 \rightarrow \gamma G^1$ implies a novel WIMP signal: diffuse photon flux
- Large Δm implies larger initial energy, but also more red shifting; latter dominates
- Present flux peaks ~ 1 MeV, yields observable signal



Feng, Rajaraman, Takayama

Conclusions

- Extra Dimensions yield natural dark matter candidates
- Much work to be done: h^1, W^1, G^1, non-minimal models, …, but already several novel features:
  - *s*-channel enhancements from degeneracy
  - Annihilation not chirality suppressed
  - Graviton dark matter – naturally desired thermal relic density, but inaccessible to all conventional searches
- Direct detection, μ from ν, e^+, γ rays, may all push sensitivity beyond collider reach
- KKDM – escape from the tyranny of neutralino dark matter!