WIMPs:
The Non-SUSY Grab Bag

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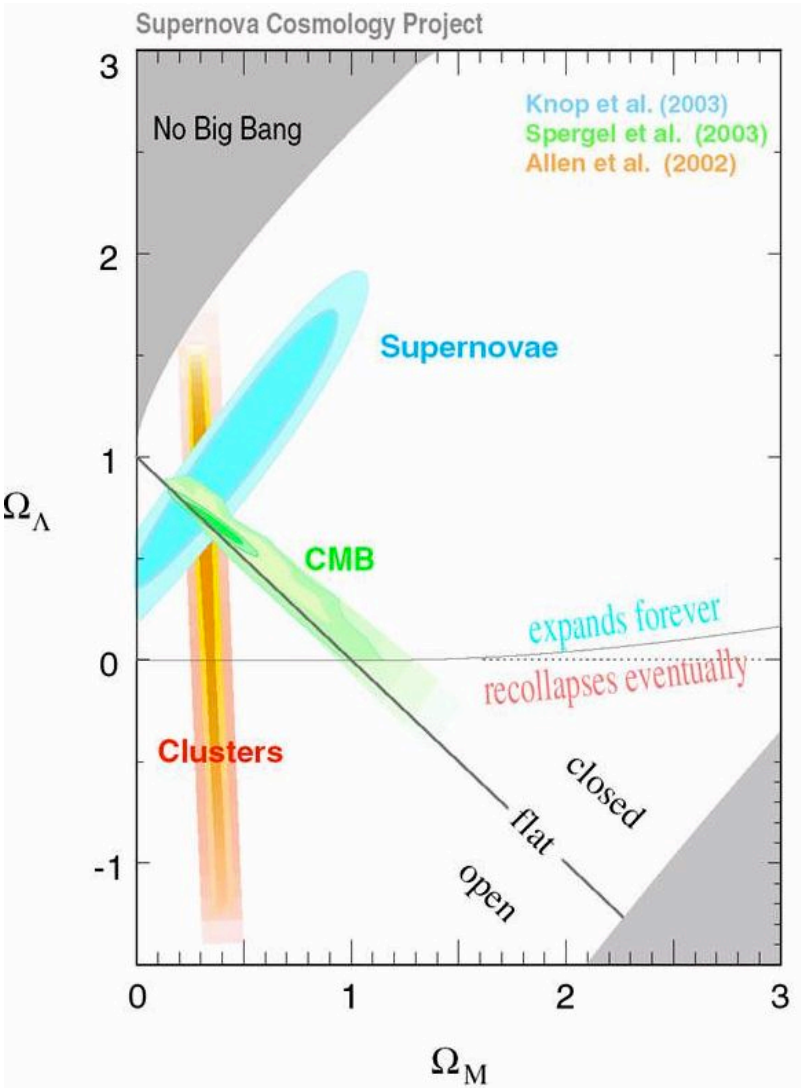
The Hunt for Dark Matter
Fermilab
May 10, 2007

Outline

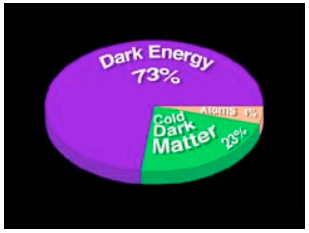
- Dark Matter from Particle Physics
- Particle Physics in Extra Dimensions
  - Universal Extra Dimensions: the KK “photon”
  - Warped Extra Dimensions: the KK “neutrino”
  - Extra dimensional “Gravity”: the light radion
- Little Higgs with T Parity
- Outlook

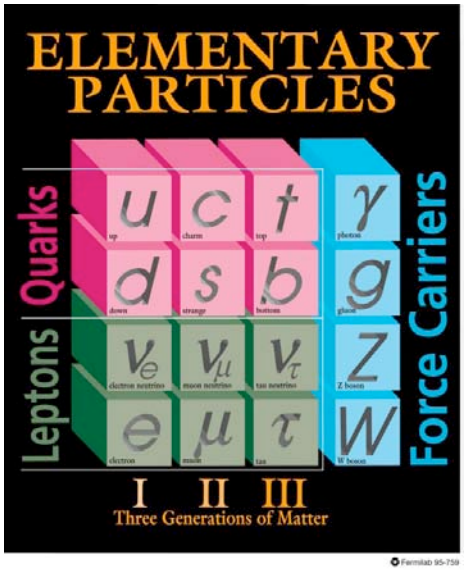
No discussion of axions... we’ll hear about them on Saturday!

The Dark Side



The supernova data combined with the CMB points to a universe which is roughly 73% dark energy, **23% cold matter**, and only a few % baryons.





"Cold Dark Matter: An Exploded View"
by Cornelia Parker

What is this stuff?

Particle physics as we know it has no answer.

Miracle and Mystery

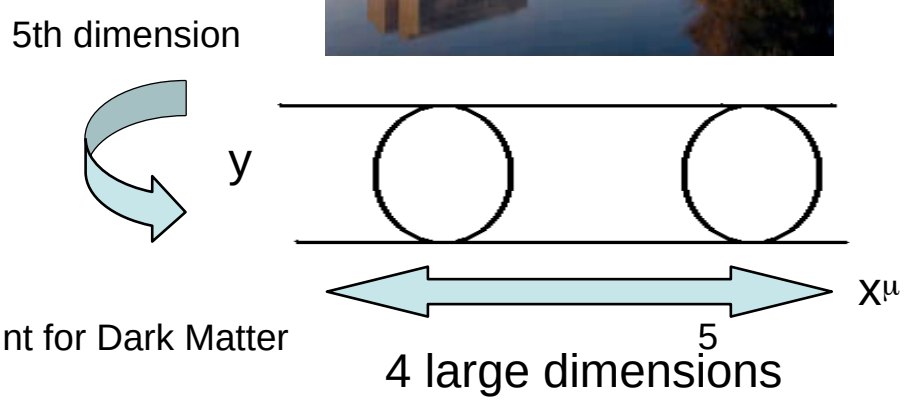
- It is both miraculously easy and mysteriously difficult to get dark matter out of a typical theory of physics beyond the SM.
- The miracle is related to the relic density. We expect there is new structure to explain EWSB at the TeV mass scale. If we put in a typical gauge coupling of order one, we arrive at a non-relativistic cross section of order:

$$\langle \sigma v \rangle \sim \frac{g^2}{m^2} \sim \mathrm{pb}$$

- Leading to a thermal relic density of order: $\Omega h^2 \simeq 0.1$!
- The mystery is the fact that to be dark matter, such a new state must be stable at least on the order of the lifetime of the Universe. Generically, such massive objects would have decayed away long ago.

Extra Dimensions?

- In recent years, HEP theory has begun to explore theories with weak scale extra dimensions.
  - The picture is that our familiar large **3 + 1** dimensions may be supplemented with more space-like directions.
  - An immediate question is: why do the force laws we observe scale like $1 / r^2$? In more dimensions, they should fall off more quickly.
  - This forces us to consider extra dimensions which are small (of order $\mathrm{TeV}^{-1} \sim 10^{-17}\mathrm{cm}$), or a brane world scenario.
- How to define a model with extra dimensions..
  - Number of Extra Dimensions
  - Topology: Line, circle, torus,…
  - Geometry : Flat, warped,…



Field Theory in 5 Dimensions

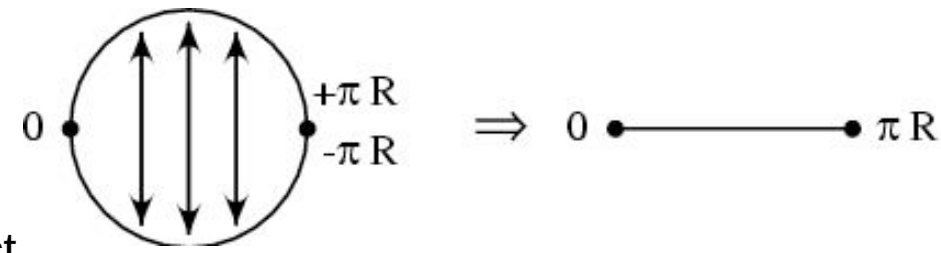
- To begin with, imagine our extra dimension is a circle (S^1).
- This requires wave functions of any states to be periodic as one traverses the extra dimension.
- Mathematically, this is the particle-in-a-box problem familiar from basic Quantum Mechanics.
- The 5th component of Momentum (p_5) is quantized in units of $1 / R$:

$$p_0^2 - \vec{p}^{\,2} - p_5^2 = 0 \quad \Rightarrow \quad p_0^2 - \overrightarrow{p^2} = p_5^2 = m_{eff}^2$$

- States with p_5 different from zero appear massive to an observer who does not realize the extra dimension is there.
- We (and all low energy physics) are composed of the lowest modes.
- Each field has a tower of massive states with the same charge and spin as the zero mode, but with masses given by n / R.

Orbifold

- 5d vector bosons contain a 4d vector V_μ and scalar V_5.
- Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- Orbifold boundary conditions project out the unwanted degrees of freedom.
- Instead of a circular extra dimension, we fold the circle, identifying y with $-y$.
- This results in a line segment, with the points 0 and πR at the end-points.
- Chiral fermions result from boundary conditions:



$$V_\mu(-y) = V_\mu(y)$$

$$V_5(-y) = -V_5(y)$$

$$\Psi(-y) = \gamma_5 \Psi(y)$$

KK Decomposition

- We expand fields in KK modes:

$$\Phi(x^\mu, y) = \sum_n f^n(y)\Phi^n(x^\mu)$$

- Even fields (A_μ, Ψ_L) have zero modes:

$$\Phi(x^\mu, y) = \sqrt{\frac{1}{\pi R}}\Phi^0(x^\mu) + \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\cos(\frac{ny}{R})\Phi^n(x^\mu)$$

- Odd fields (A_5, Ψ_R) don't:

$$\Phi(x^\mu, y) = \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\sin(\frac{ny}{R})\Phi^n(x^\mu)$$

- Each SM field has a tower of "partner fields" with mass n / R but the same charge and spin.

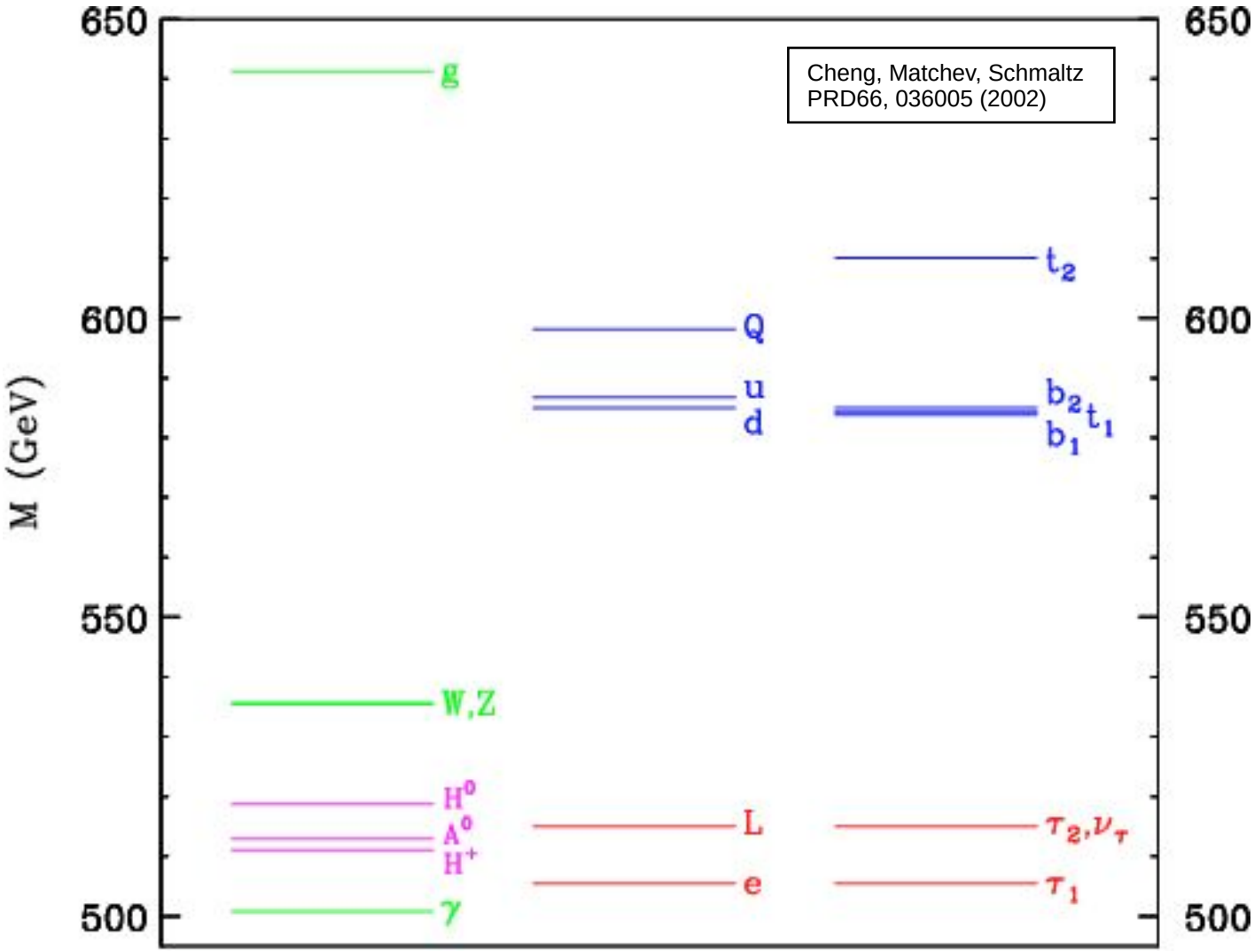
Universal Extra Dimensions

- The framework is that all fields live in all dimensions:
  - Quarks & Gluons
  - Leptons
  - Photons and Gauge Bosons
  - Higgs
  - Gravity
- This is unlike the "brane world" scenario where everything except gravity is stuck to some point.
- This universality implies a translational invariance along the 5th dimension, and thus conservation of momentum in that direction.
- The result is a stable particle, necessary to have a dark matter candidate.

Why Universal Extra Dimensions?

- **Proton Decay** Appelquist, Dobrescu, Ponton, Yee PRL87, 181802 (2001)
  - Generically, extra dimensional models are non-renormalizable, and have a low cut-off scale.
  - Dangerous operators mediating proton decay can be automatically suppressed by considering UED models in 6d.
- TeV extra dimensions provide a natural setting for **top seesaw** models: Arkani-Hamed, Cheng, Dobrescu, Hall PRD62, 096006 (2000)
  - A theory without a Higgs can still exhibit spontaneous symmetry-breaking driven by KK modes of gluons.
  - At high energies, the bound state Higgs breaks into quarks and gluons with no quadratic divergences.
- **Number of generations:** Dobrescu, Poppitz PRL87, 031801 (2001)
  - Cancellation of anomalies in six dimensions requires the number of families to be a multiple of three!

KK Mode Spectrum



Cheng, Matchev, Schmaltz
PRD66, 036005 (2002)

$1/R = 500$ GeV
$\Lambda R = 20$

Terms living on the boundaries of the extra dimension modify the spectrum. Such terms will be induced at the loop level, even if they vanish at some fundamental scale.

KK Parity

- Conservation of KK number is broken to conservation of KK parity: $(-1)^n$ by the boundary terms.

- KK parity requires odd KK modes to couple in pairs:
  - The lightest first level KK mode is stable.
  - First level KK modes must be pair-produced.

- The Lightest Kaluza-Klein Particle plays a crucial role in phenomenology, similar to the LSP of SUSY:
  - All relic KK particles decay to LKPs.
  - Any first level KK mode produced in a collider decays to zero modes and an LKP.

Identity of the LKP

- Boundary terms play a role similar to soft masses, determining masses and couplings for the entire KK tower.
- If we imagine the terms are zero at the cut-off, they will be induced at loop size.
- Since $\alpha_1 << \alpha_2 << \alpha_3$, we imagine the smallest corrections will be to the U(1) gauge boson.
- Since $\delta M \sim 1 / R >> v$, the LKP is (almost) purely a KK mode of the U(1) gauge boson, $B_\mu^{(1)}$.
- Following this line of reasoning, the NLKP is the right-handed electron, $e^{(1)}_R$.

$$\delta M^2 : \frac{1}{R^2}\frac{\alpha}{4\pi}\log(\Lambda R)$$

$$\begin{pmatrix} \frac{1}{R^2}+\frac{1}{4}g_1^2v^2+\delta M_1^2 & \frac{1}{4}g_1g_2v^2 \\ \frac{1}{4}g_1g_2v^2 & \frac{1}{R^2}+\frac{1}{4}g_2^2v^2+\delta M_2^2 \end{pmatrix}$$

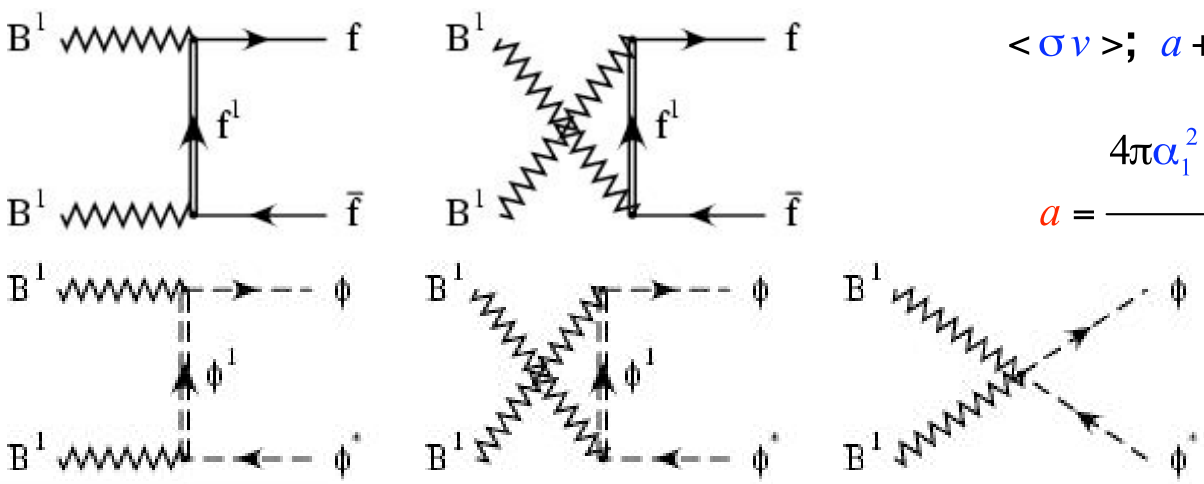
$B^1 - W_3^1$ Mass^2 matrix

LKP as Dark Matter

- We know how much dark matter the universe seems to require.
- The question, then, is for which regions of parameter space the LKP is a good dark matter candidate.
- The couplings of the LKP to matter are fixed by the structure of the theory.
- The LKP couples to one zero-mode matter particle, and one KK mode matter particle, with coupling given by the (measured) U(1) coupling of the Standard Model, g_1, times the corresponding hyper-charge, Y.
- What remains is to explore the mass spectra which lead to a relic abundance consistent with observation.

Thermal Production & Freeze Out

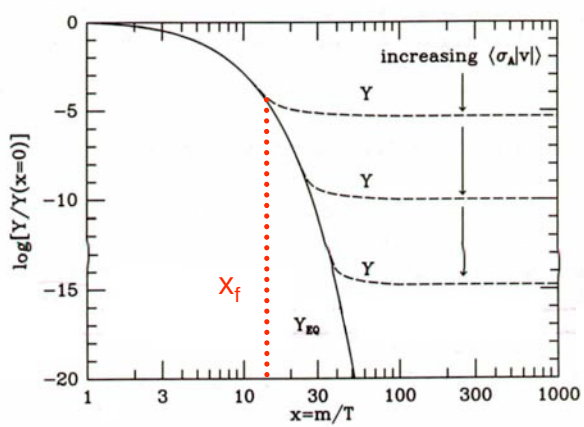
- To estimate the relic density of the LKP, we assume it was originally in thermal equilibrium in the early universe.
- As the universe expands, eventually the density is small enough that they can no longer interact with one another, and fall out of equilibrium.
- Below this *freeze-out temperature*, the density of WIMPs per co-moving volume is fixed.



$$<\sigma v>;\ a + b < v^2 > + \ldots = a + 6b/x + \ldots$$

$$a = \frac{4\pi\alpha_1^2\left(2\sum_F Y_F^{\,4} + 3Y_H^{\,4}\right)}{9m_{KK}^2}$$

59% charged leptons
35% hadrons
4% neutrinos
2% Higgs



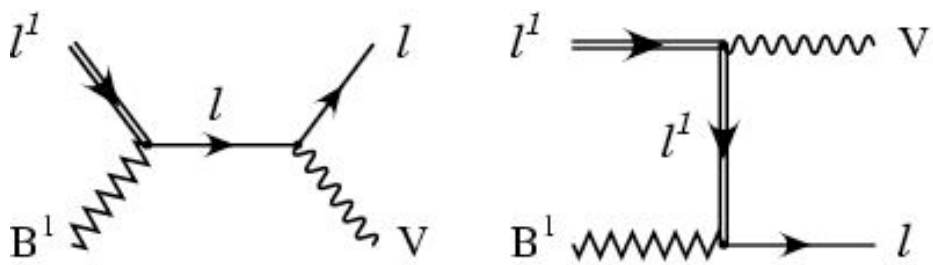
$x_f \sim 25$

For $m_{KK} \sim 1$ TeV : $T_f \sim 40$ GeV

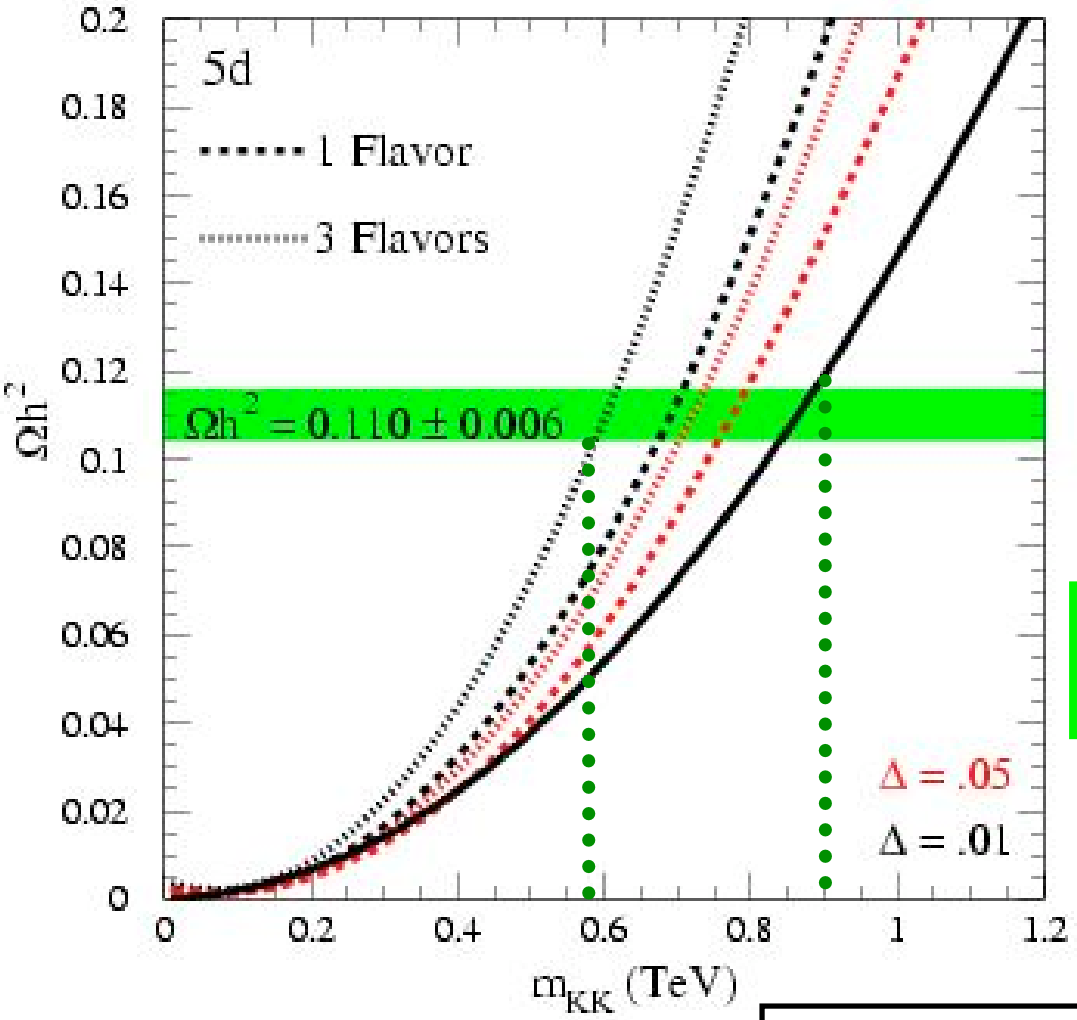
From Kolb & Turner, "The Early Universe"

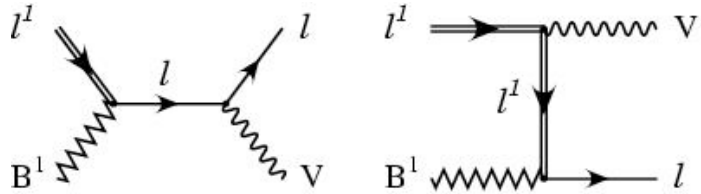
Co-annihilation

- If the mass of $e^{(1)}_R$ (or any other level 1 KK mode) is close to $B^{(1)}$, it may substantially affect the relic density.
- They interact roughly with the same efficiency, and the freeze-out temperature is basically unchanged,
- Some $e^{(1)}_R$ are left over after freeze-out, and eventually decay into $B^{(1)}$ and $e^{(0)}$.
- The net relic density of $B^{(1)}$ is increased!
- This is quite different from SUSY, where the neutralino is usually so feeble compared to everything else that coannihilation keeps it in equilibrium longer, and reduces the relic density.



Relic Density





Δ is the splitting between the $B^{(1)}$ and $e^{(1)}_R$ masses.

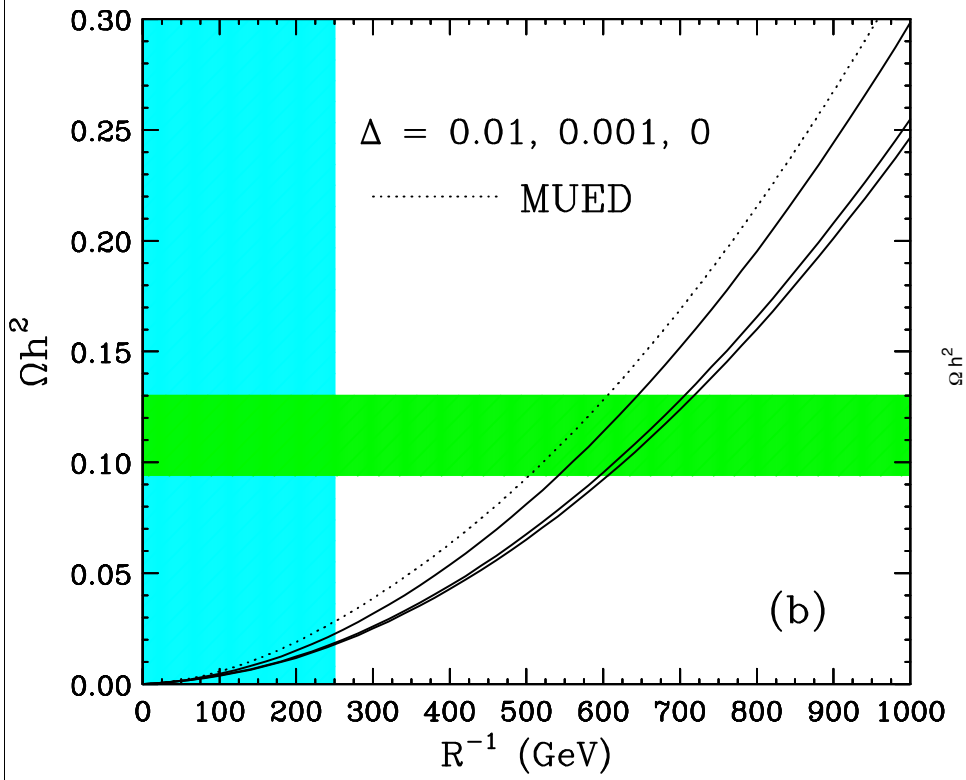
$$\Delta \equiv \frac{m_{e_R^{(1)}} - m_{B^{(1)}}}{m_{B^{(1)}}}$$

e^1_R Coannihilation favors the 5d range **600-900 GeV**.

The 6d range is **425-625 GeV**.

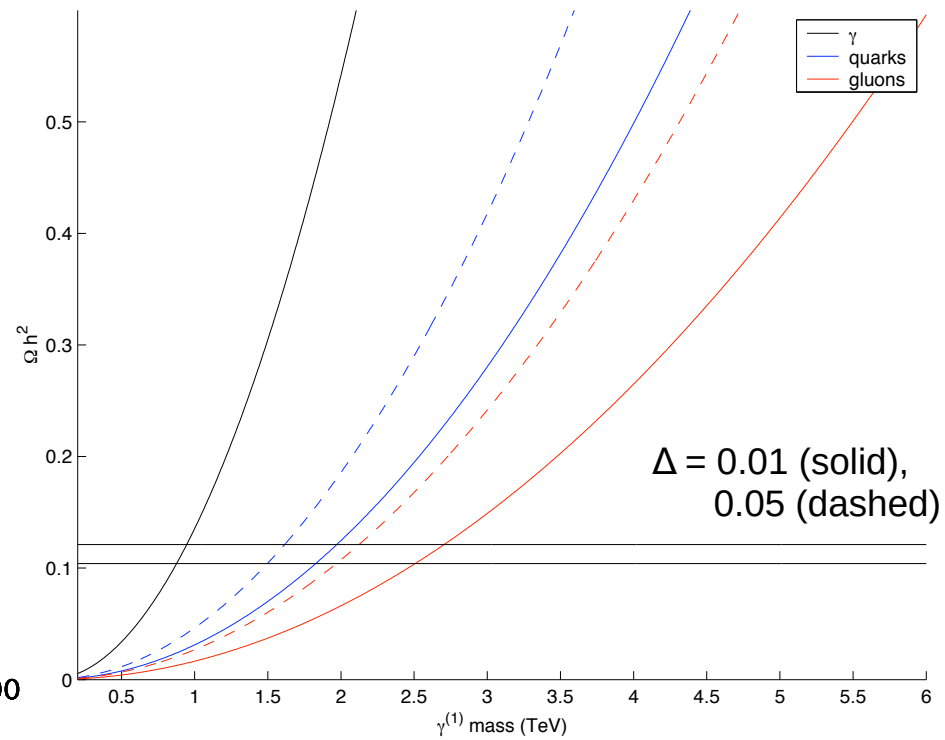
G. Servant, T. Tait, NPB650, 351 (2003)

More Complete Calculations...



Kong, Matchev JHEP 0601, 038 (2006)

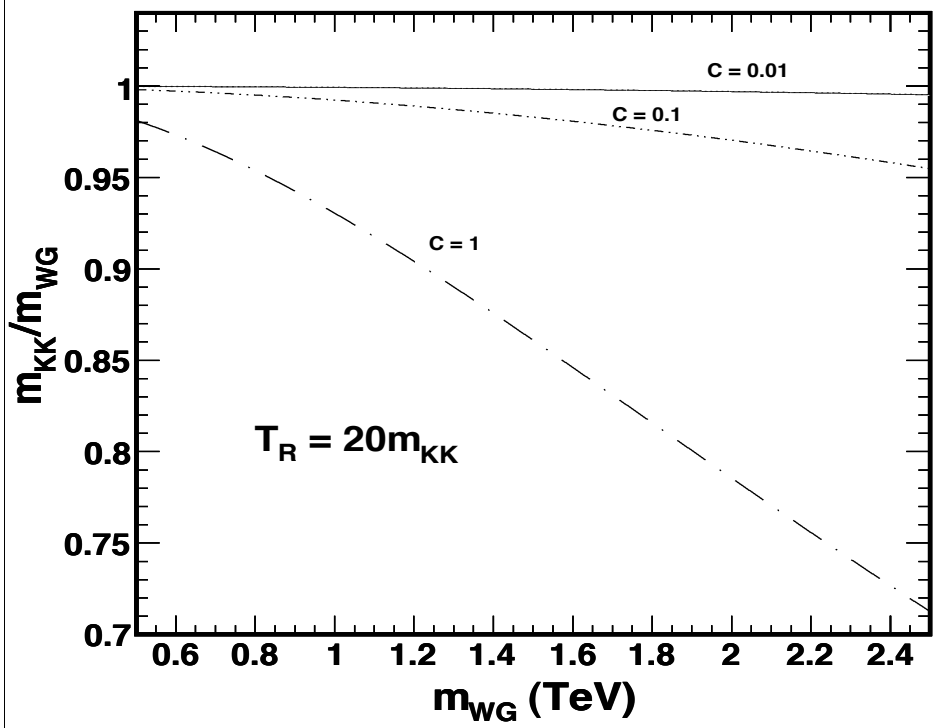
Quasi-degenerate KK e^1_L



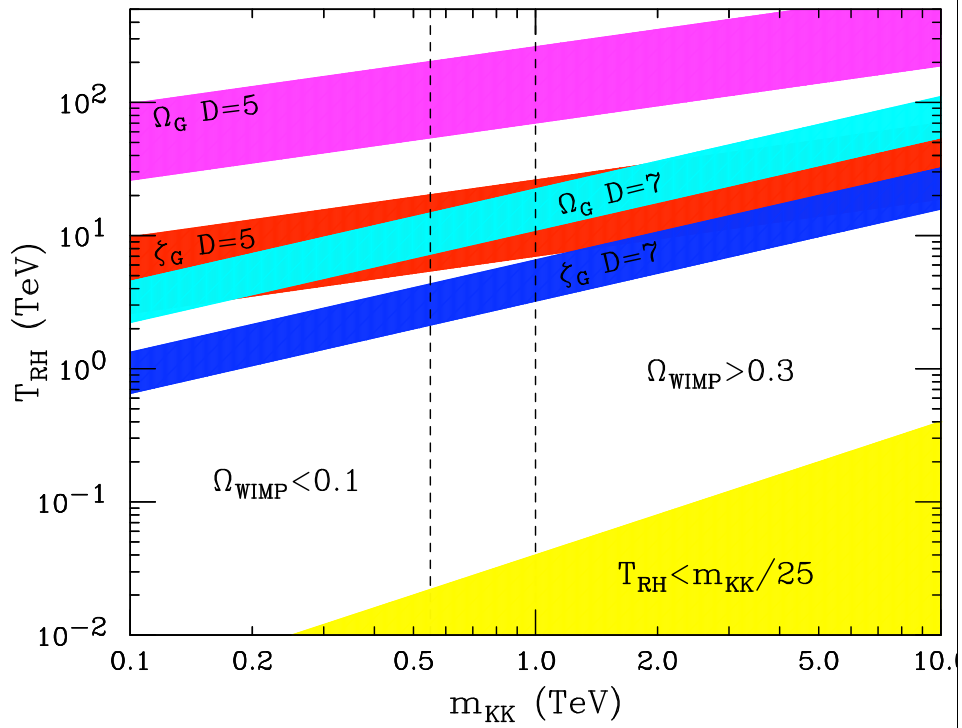
Burnell, Kribs PRD73, 015001 (2006)

Quasi-degenerate KK gluons and quarks

KK Gravitons



$10^{-3} < c < 10^{-1}$



$m_{G1} > m_{B1}$: A new source of B1!
(ratio of the actual required KK mass to the value without gravitons contributing)

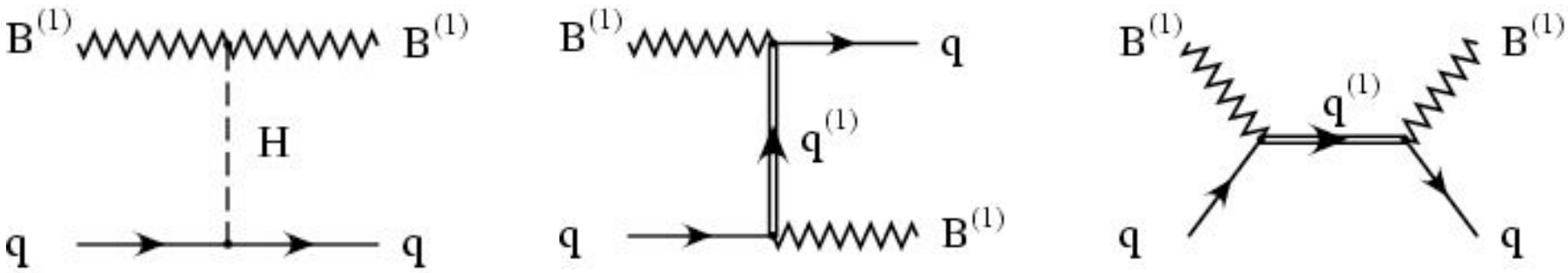
Shah, Wagner PRD74, 104008 (2006)

$m_{G1} < m_{B1}$: Super-WIMPs!

Feng, Rajaraman, Takayama PRD68, 085018 (2003)

Direct Detection

- Direct detection of dark matter attempts to see WIMP-nuclei scattering.
- At the fundamental level, the LKP scatters with quarks.

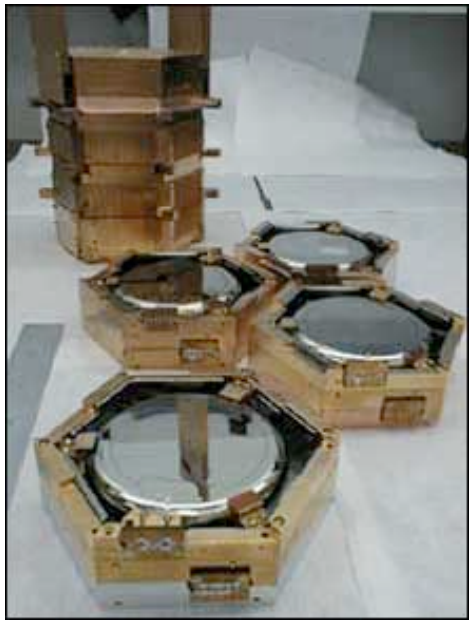


- Form factors relate quark interactions to nucleon scattering.
- Nuclear physics relates nucleon scattering to nuclear interactions.
- Energy is deposited in the nucleus target:

$$\frac{dR}{dE_r} = \frac{\rho}{m_{KK}} \frac{\sigma_0}{2\mu^2 v^2} F^2(E_r, v) f(v) v dv$$

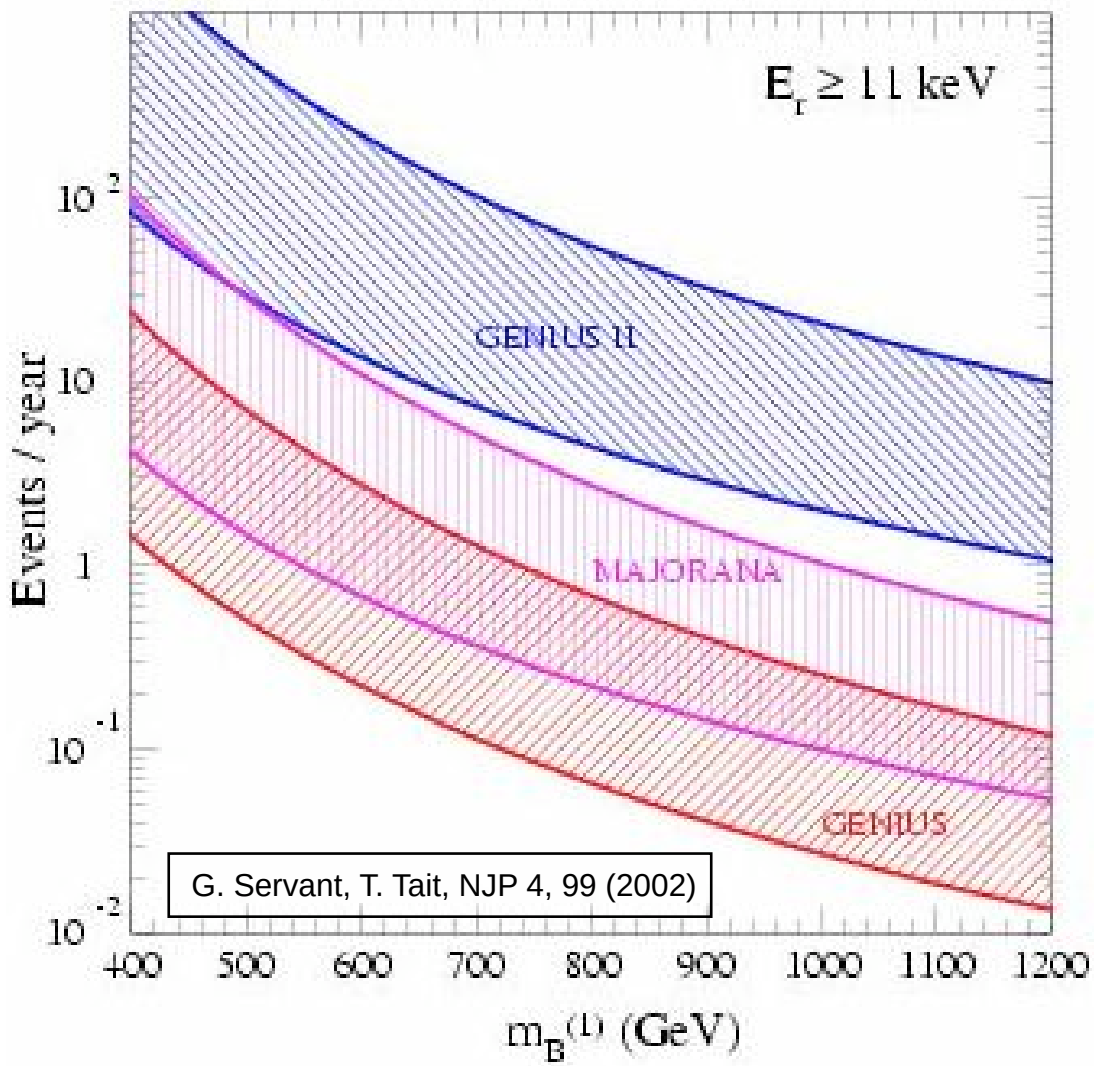
ρ : WIMP halo density
v : WIMP velocity
f : WIMP v distribution
σ_0 : nucleon σ
F : nuclear form factor

Germanium Detectors



Very precise calorimeter, in order to see a clear excess.

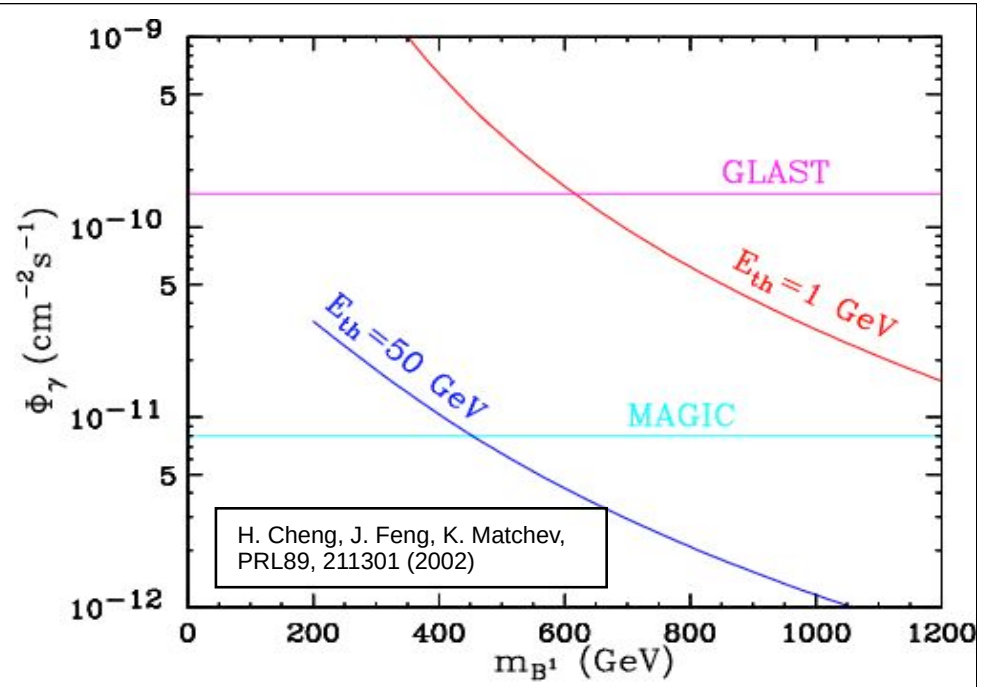
GENIUS : 100 kg ^{73}Ge
GENIUS-2 : 10^4 kg ^{76}Ge
MAJORANA : 500 kg ^{76}Ge

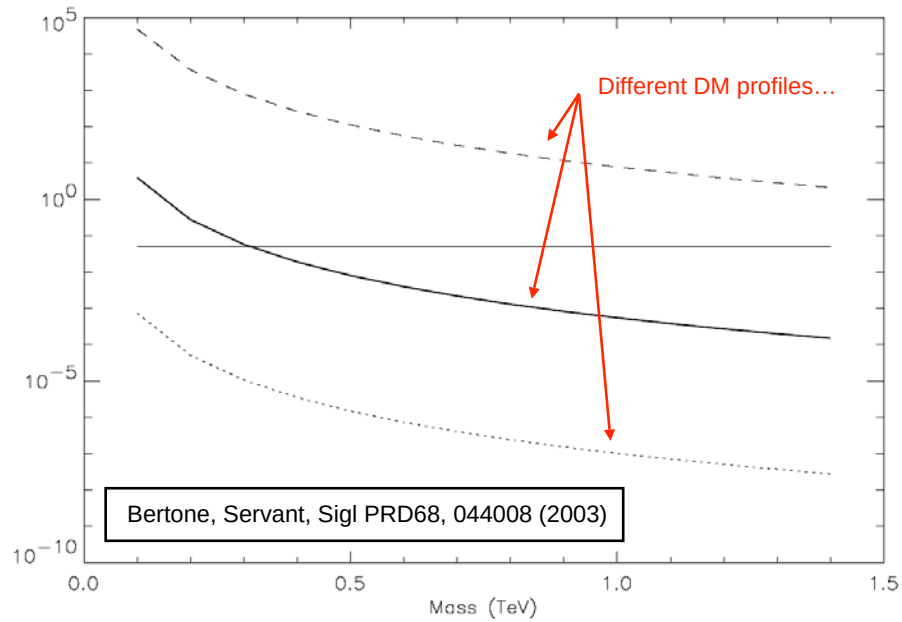


G. Servant, T. Tait, NJP 4, 99 (2002)

Indirect Detection: γ

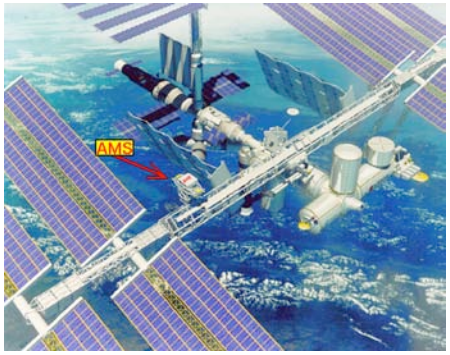
- WIMPs can annihilate into high energy gamma rays.
- Rates are rather sensitive to the profile of dark matter along the line of sight.
- Energetic photons from synchrotron radiation of charged particles is also possible, though this further depends on galactic magnetic fields.
- This may be observable at GLAST, MAGIC, or VERITAS for the lower range of LKP masses.



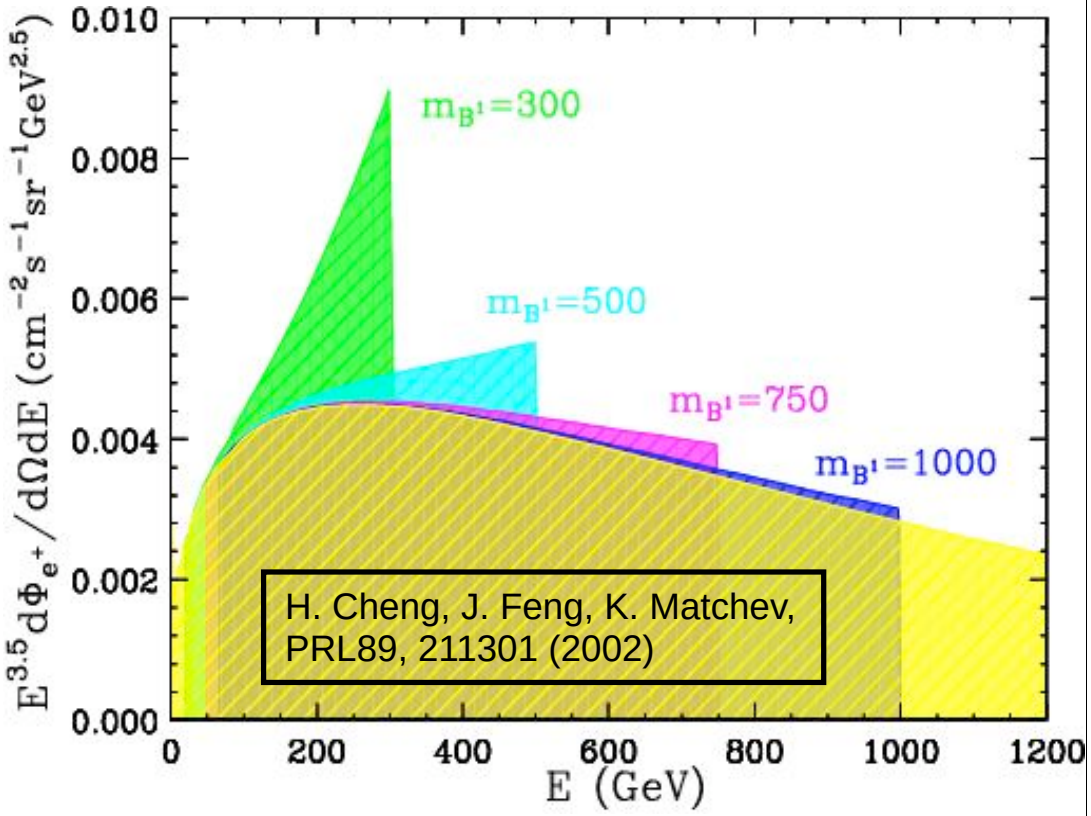


See also: Line emission: Bergstrom, Bringmann, Eriksson, Gustofsson, hep-ph/0412001

Indirect Detection: e^+



- WIMPs in the galactic halo can annihilate into $e^+ e^-$.
- The e^+ can be detected by space-based experiments, such as AMS.
- LKPs *prefer* to annihilate into $e^+ e^-$, and produce mono-energetic positrons.
- This is a striking signal, clearly visible against backgrounds for m_{KK} less than about **500 GeV**.



H. Cheng, J. Feng, K. Matchev, PRL89, 211301 (2002)

See also: Baltz, Hooper **JCAP 0507, 001 (2005)**

Another interesting signal: neutrinos from the sun! Hooper, Kribs PRD67, 055003 (2003)

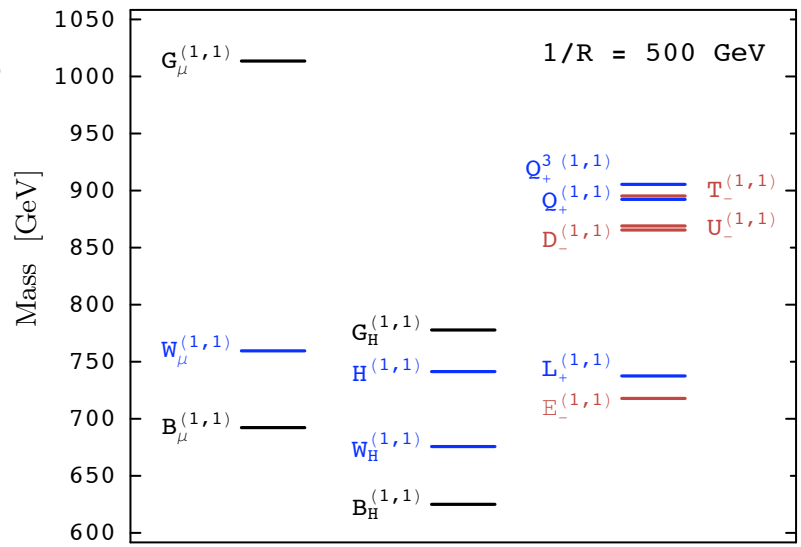
More Dimensions?

- More dimensions allow for more complicated compactifications and orbifolds.
- An interesting 6d example is the "chiral square".

Burdman, Dobrescu, Ponton
JHEP 0602, 033 (2006)

- This theory has a different LKP (a scalar $B_H^{(1,1)}$).
- We still don't have a complete relic density computation, or direct/indirect search prospects, though we have some collider results.

Burdman, Dobrescu, Ponton PRD74, 075008 (2006)
Dobrescu, Kong, Mahbubani hep-ph/0703231

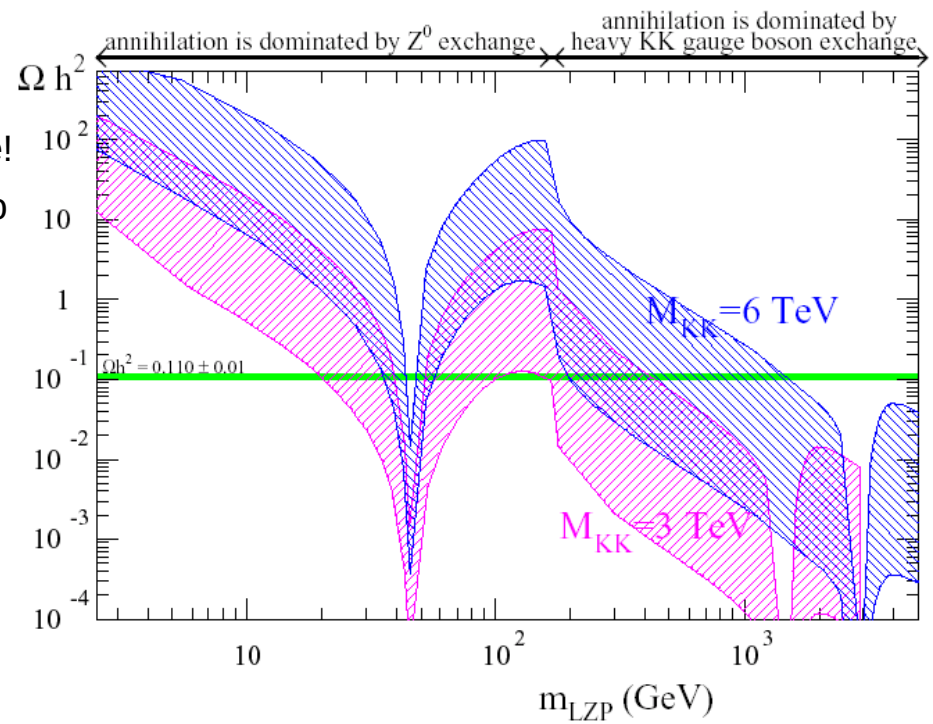


Warped Extra Dimension?

Agashe, Servant PRL93, 231805 (2004)

- Another possibility is that the extra dimension is warped (Randall-Sundrum), with non-zero bulk curvature.
  - Such theories naturally solve the hierarchy problem and lead to GUTs.
  - However, they generically lead to much too rapid proton decay, requiring the imposition of more symmetries.
  - A particular SO(10) model splits the families among three 16s of SO(10), with different Z_3 charges. The lightest Z-odd particle is stable!
  - This turns out to be the right-handed neutrino (KK mode) which lives in the same multiplet as the right-handed top quark (zero mode).
  - It can have the correct thermal relic density for a wide range of masses. The processes maintaining equilibrium can proceed either through the ordinary Z or a Z' KK mode from the broken part of SO(10).
  - Preferred coupling is to the LZP's GUT partner, the ordinary RH top quark.

$$\begin{pmatrix} \mathbf{u_L}\ ,\mathbf{d_L} \\ u'^c_R \\ d'^c_R \\ \nu'_L\ ,e'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}_{B=1/3} , \quad \begin{pmatrix} u'_L\ ,d'_L \\ \mathbf{u^c_R} \\ \mathbf{d^c_R} \\ \nu'_L\ ,e'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}_{-1/3} , \quad \begin{pmatrix} u'_L\ ,d'_L \\ u'^c_R \\ d'^c_R \\ \nu_\mathbf{L}\ ,\mathbf{e_L} \\ \mathbf{e^c_R} \\ \nu^\mathbf{c}_\mathbf{R} \end{pmatrix}_{0}$$



Light Radion?

- Any theory with an extra dimension contains a scalar field, the radion, which is the modulus describing the size of the extra dimension.

$$ds^2 = \left(e^{-1/3\tilde{\phi}} g_{\mu\nu} + e^{2/3\tilde{\phi}} \widetilde{A}_\mu \widetilde{A}_\nu\right) dx^\mu dx^\nu + 2e^{2/3\tilde{\phi}} \widetilde{A}_\mu dx^\mu dy + e^{2/3\tilde{\phi}} dy^2$$

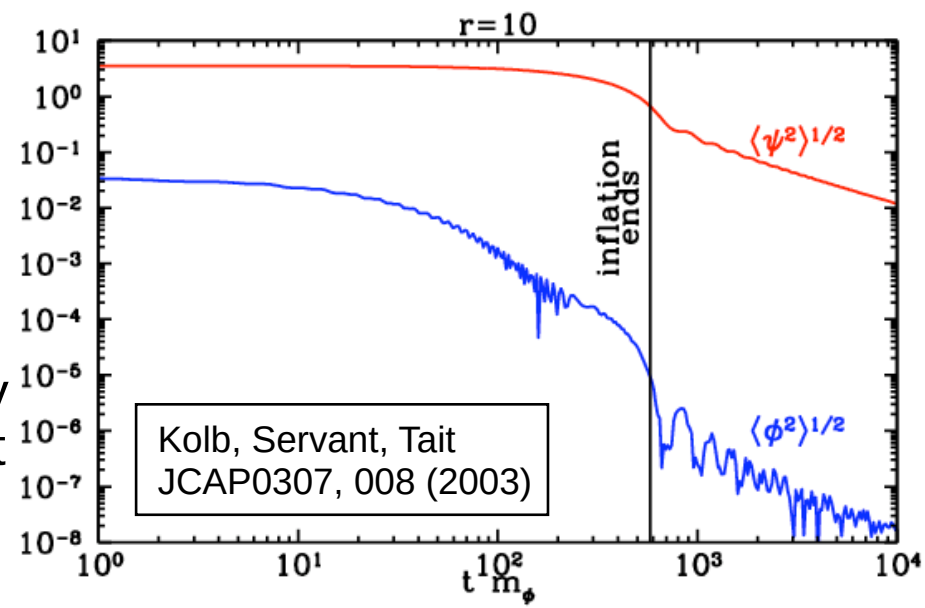
- In 5d, the KK modes of g_{55} are eaten by the massive spin-2 modes.
- The massless mode is a physical degree of freedom, but it must gain a mass to stabilize the size of the extra dimension.

$$m_r \sim \sqrt{3}\frac{M_c^2}{m_{Pl}}$$

- Its couplings are gravitational, and thus highly suppressed, allowing for the possibility that it is long lived.

$$\Gamma = \tau^{-1} \simeq \frac{m_r^3}{192\pi m_{Pl}^2} \sim \frac{\sqrt{3}M_c^6}{64\pi m_{Pl}^5},$$

- It can be produced non-thermally through a coherent misalignment during inflation (like the axion).



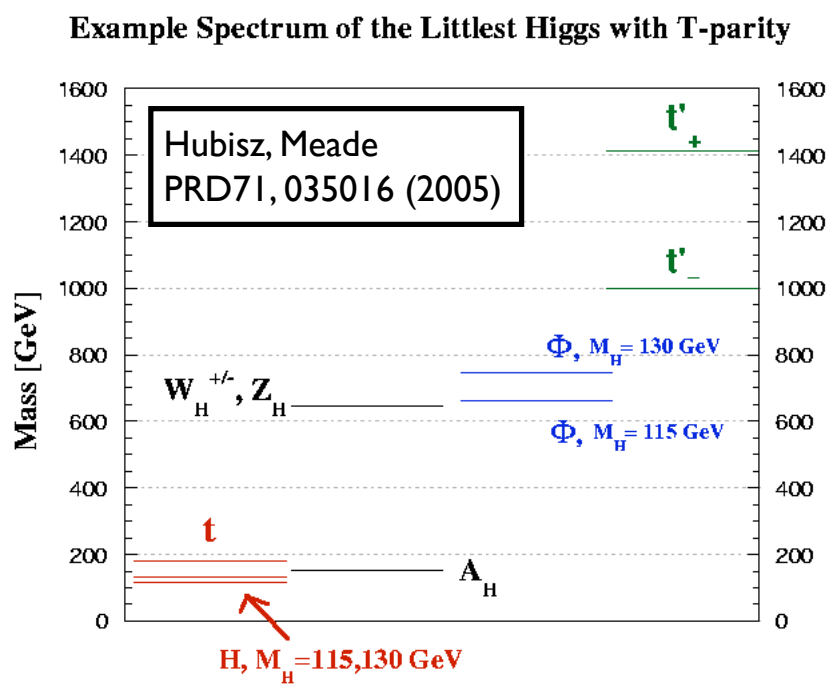
Little Higgs with T-Parity

- A class of models solves the little hierarchy problem by proposing that the Higgs is a pseudo-Nambu-Goldstone boson.
- The idea is beautiful, but early efforts were strongly constrained by precision EW data, because of tree level effects from heavy states.
- A cure is to introduce a new discrete symmetry, T-parity, which forces the new states to couple in pairs, and thus leads to pair production at colliders, and the lightest of them to be stable: dark matter!

  Cheng, Low JHEP 0408, 061 (2004)
- Some UV completions may not respect T-parity, and would affect collider physics and remove the dark matter candidate...

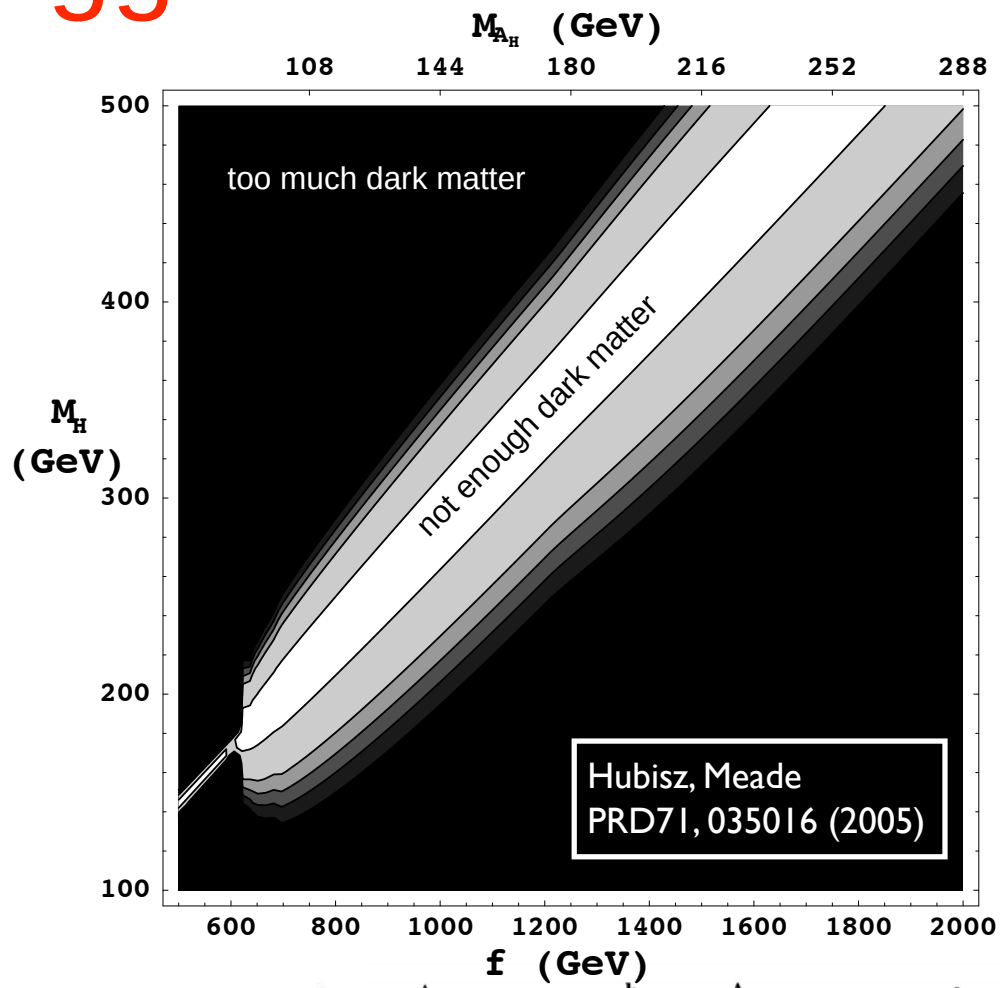
  Hill, Hill arXiv:0705.0697 [hep-ph]

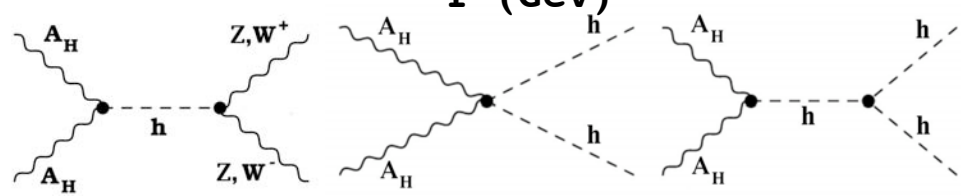
i.e. "The Littles Higgs"
Arkani-Hamed, Cohen, Katz, Nelson JHEP 0207, 034 (2002)



T-parity, Little Higgs: Dark Matter!

- Annihilation is (mostly) through Higgs bosons, implying a strong correlation between the Higgs mass and the relic density.
- When $M_H \sim 2\, M_{AH}$, there is a resonant enhancement of the annihilation, and the relic density is highly damped.
- Direct detection will probably be similar to the LKP. (The LKP was also dominated by a Higgs exchange for most of parameter space). It would be nice to have explicit calculations, results for indirect detection, and exploration of other models.





Outlook

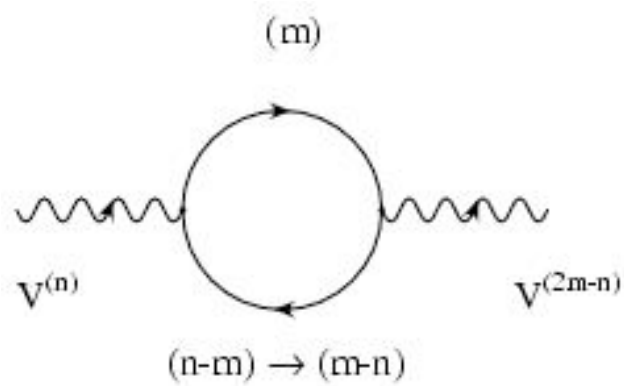
- Many theories of physics beyond the Standard Model predict new massive weakly interacting particles.
- Many of them also invoke new symmetries, to avoid inconvenient effects such as proton decay, flavor-violation, or large contributions to precision electroweak data, leading to stable or long-lived particles.
- There is a rich interplay between potential signals from direct detection, indirect detection, and colliders.
- Most likely, we need a combination of all three to really unravel the identity of dark matter, and there is a lot of potential for one type of measurement to benefit from another one.

- **Whatever** the nature of dark matter, particle physics will expand to include it, and hopefully provide a context to understand it...

Supplementary

Orbifolds are Opaque

- Even theories without localized fields have terms on boundaries.
- The orbifold, identifying (y and $-y$), implies the theory can't tell one direction from another.
- Loops of fields generate p_5 non-conserving terms.



$$-\frac{r_c}{4}\left[\delta(y)+\delta(y-L)\right]F_{\mu\nu}F^{\mu\nu}$$

- In position space, these are equal terms on both boundaries.

$$r_c : \frac{\alpha_5}{4\pi}\log\left[\frac{\Lambda}{\mu}\right]$$

- The loops are log-divergent, indicating that they are incalculable parameters of the effective theory.

Boundary Kinetic Terms

- The terms living on the boundaries change the physics.
- They alter the KK decomposition:

$$\frac{1}{g_5^2}\int dy\left\{1+r_c\left[\delta(y)+\delta(y-L)\right]\right\}f_n(y)f_m(y)=\delta_{nm}$$

$$\frac{1}{g_5^2}\int dy\, f_n'(y)f_m'(y)=m_n^2\delta_{nm}$$

- KK wave functions satisfy:

$$\left[\partial_5^2+m_n^2+r_c m_n^2\left\{\delta(y)+\delta(y-L)\right\}\right]f_n=0$$

Opaque Orbifolds

M. Carena, T. Tait, C. Wagner, APP B33, 2355 (2002)

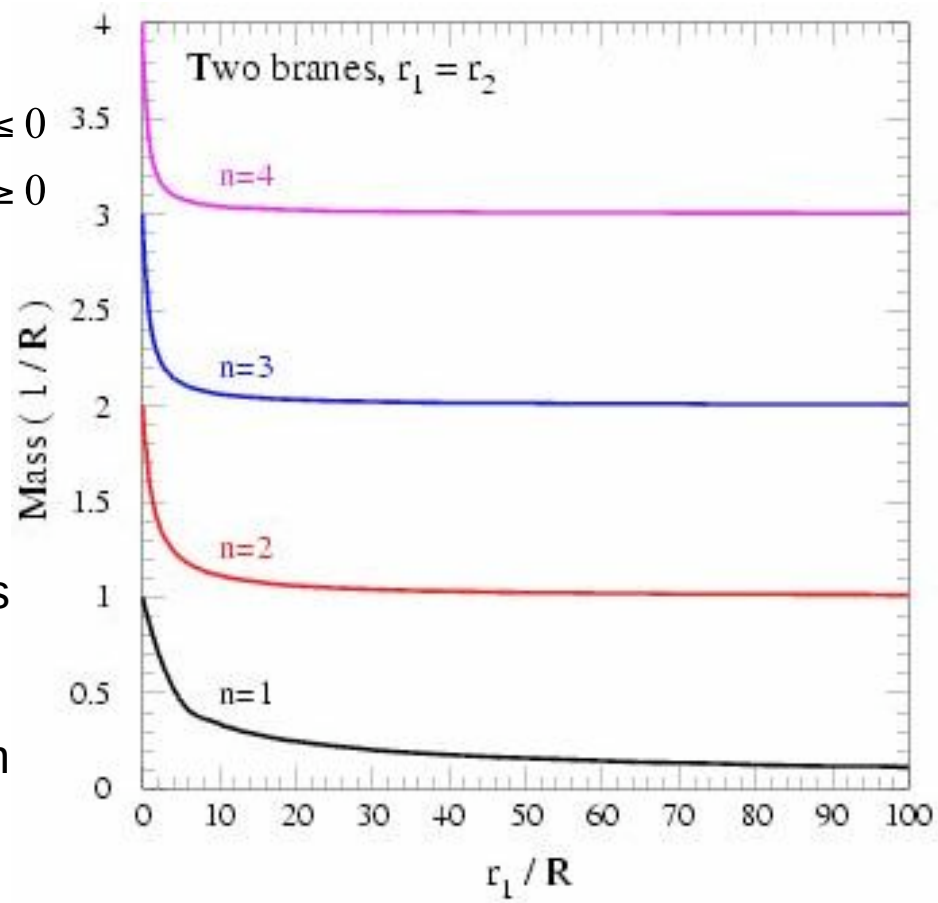
The wave functions are:

$$f_n(y) = \begin{cases} \cos(m_n y) + (m_n r_c/2)\sin(m_n y) & y \le 0 \\ \cos(m_n y) - (m_n r_c/2)\sin(m_n y) & y \ge 0 \end{cases}$$

With quantized masses:

$$0 = \left(r_c^2 m_n^2 - 4\right)\tan\left[m_n \pi R\right] - 4 r_c m_n$$

The boundary terms change the masses and wave functions. Since each field has a potentially different boundary term, this splits the degeneracy between the entire KK level and allows i.e., some KK modes of the first level to decay.



Effective Theory for UED

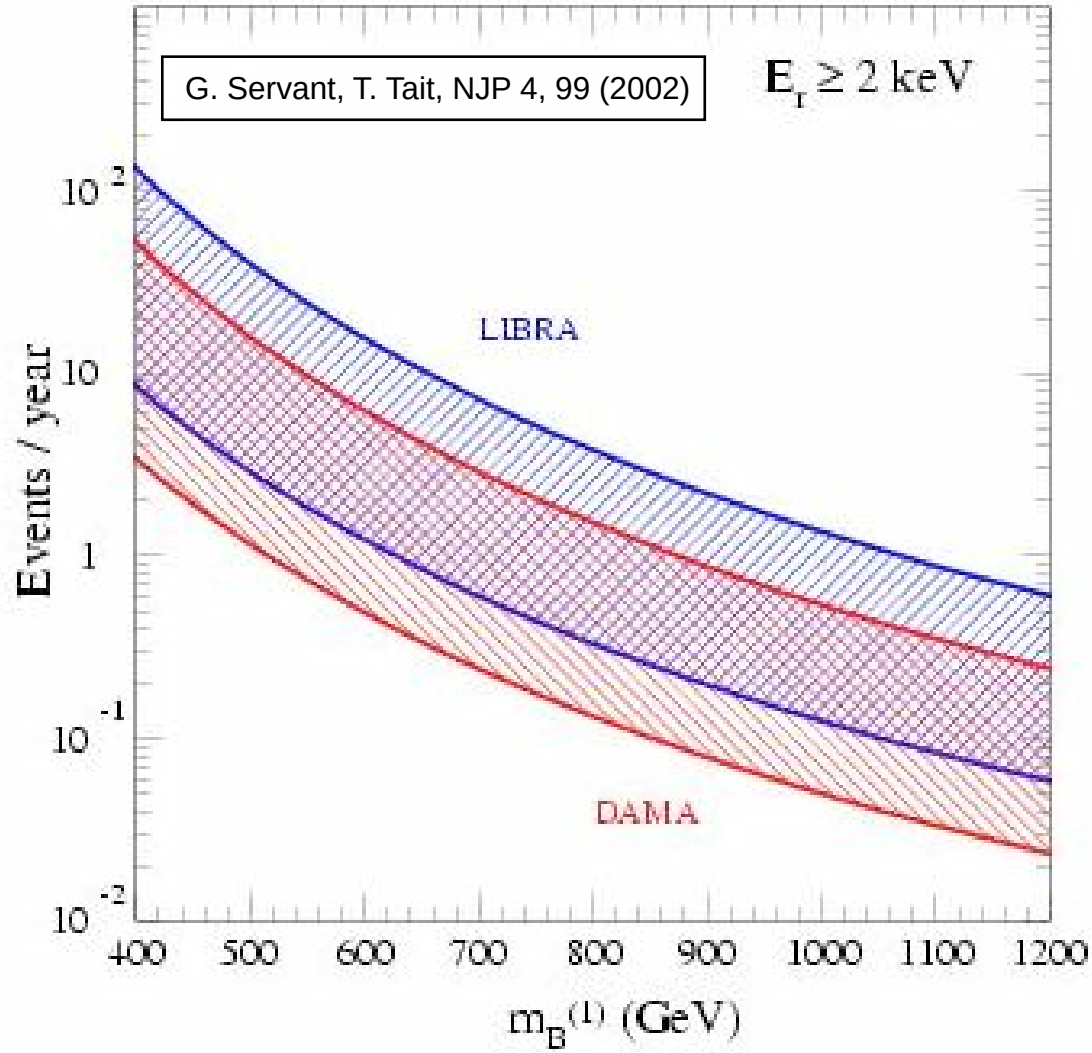
- To define a model of UED, one **must** specify:
  - Bulk Interactions, i.e.:

$$\frac{1}{g_5^2} F_{\mu\nu}\left(x^\mu, y\right) F^{\mu\nu}\left(x^\mu, y\right)$$

  - Boundary terms, i.e.:

  - Each field has a (potentially different) kinetic term living on the boundaries of the extra dimension. These free parameters play an important role in the resulting phenomenology of the universal extra dimension.

NaI Detectors



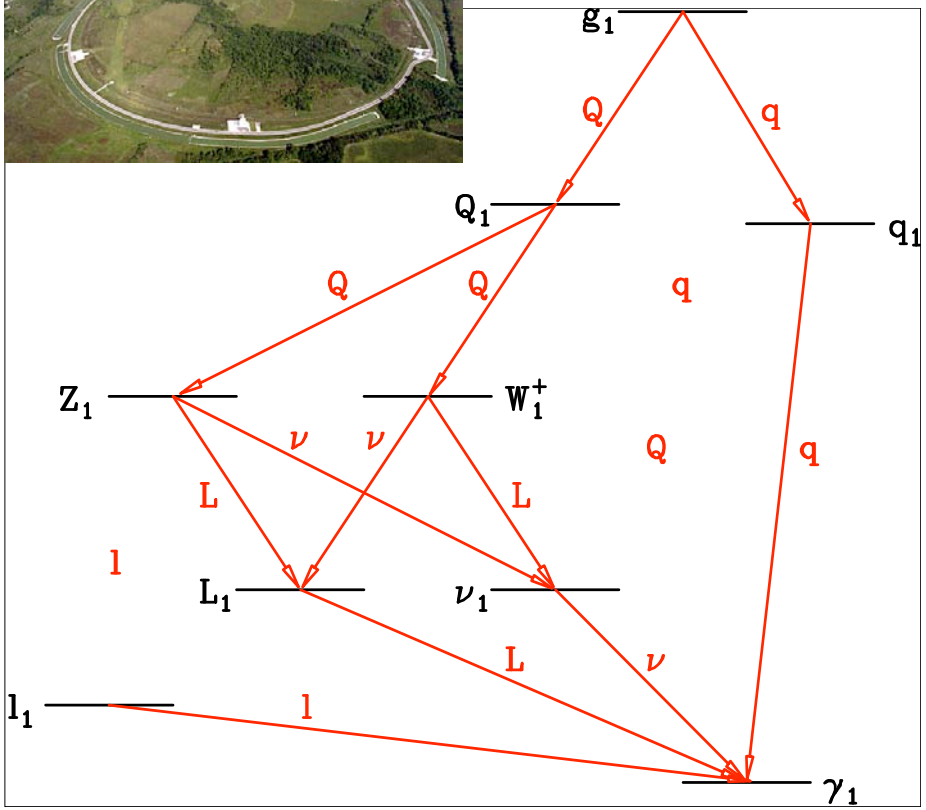
Search strategy is to see an annual modulation of events as the earth revolves around the sun.

DAMA: 100 kg NaI

LIBRA: 250 kg NaI

Collider Signatures

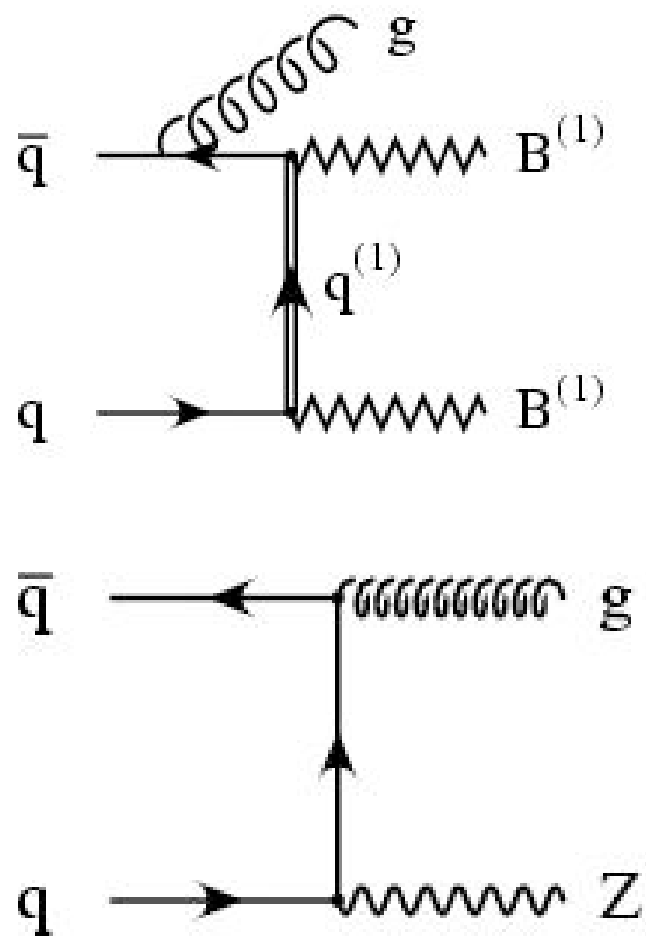
Fermilab



- Another interesting avenue would be to discover LKPs (and other KK modes) at high energy colliders.
- Current precision bounds are **1 / R > 200 GeV**.
- One would expect Tevatron limits are on the same order, though no detailed analysis exists.
- Complicated cascade decays are possible, especially for coloured KK modes of q and g.
- In order to study the dark matter scenario more directly, I will focus on $B^{(1)}$ and $e^{(1)}_R$, though cross sections may be smaller.

Monojet Signature

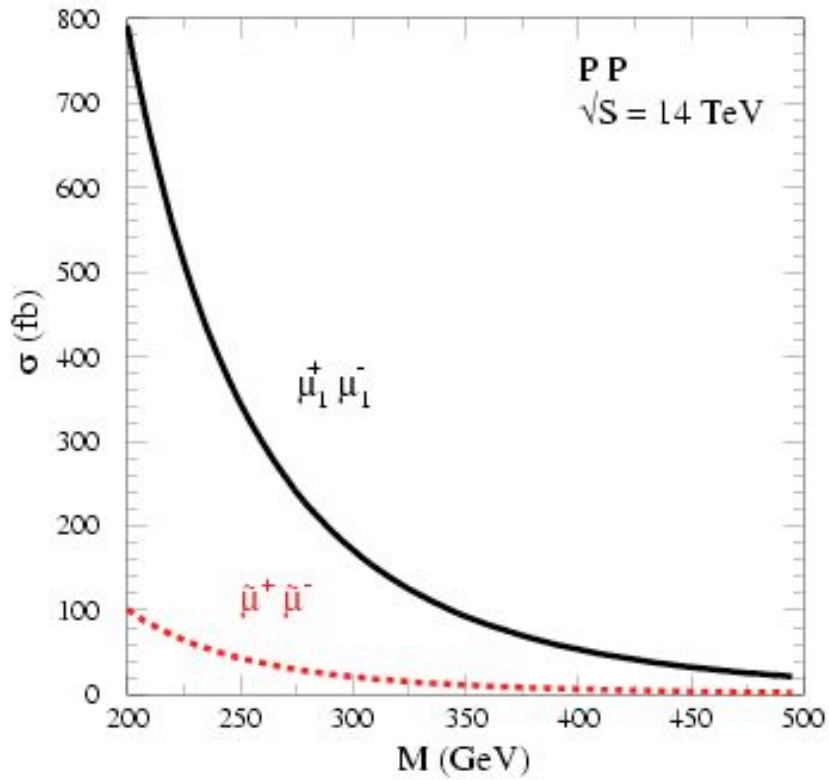
- One could look for pairs of LKPs accompanied by initial state radiation.
- The LKPs themselves escape from the detector.
- Unfortunately, this is sensitive to the KK quark masses.
- Physics backgrounds come from Z + jet production, with Z decaying into neutrinos.
- Fake backgrounds are from missed jets, energy mismeasurement, etc.
- At an $e^+ e^-$ collider: γ + missing energy.

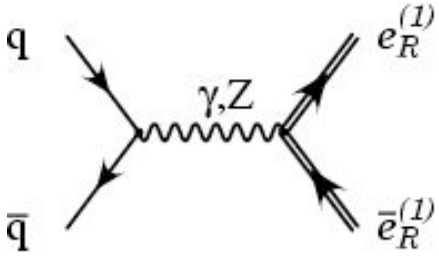


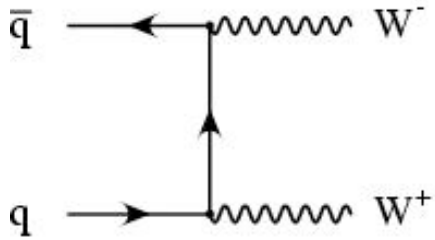
Leptons + Missing Energy

- Another mode is pair production of $e^{(1)}_R$, followed by its decay into $e^{(0)} + B^{(1)}$.
- This process is not sensitive to KK quark masses.
- Physics backgrounds are diboson production, dominantly W pairs.
- Fake backgrounds are from Drell-Yan + missed jets, etc.
- A linear collider is limited by kinematics, but can also search effectively.

J. Hewett, T. Rizzo, T. Tait, in progress

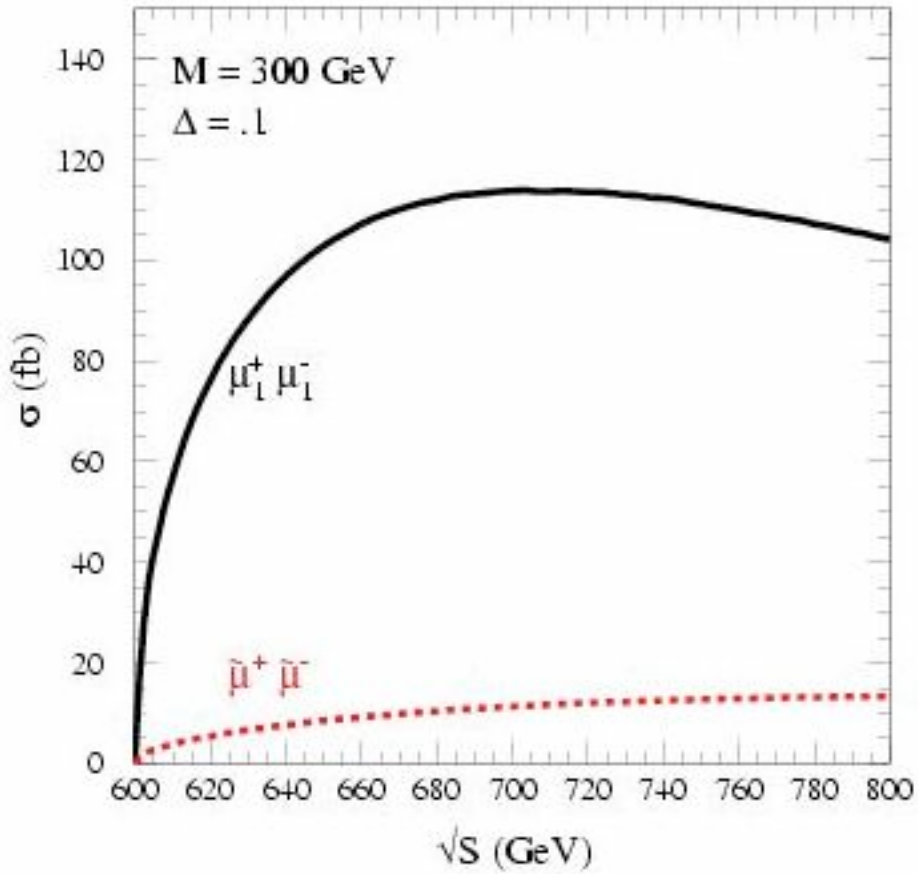






e^+e^- Linear Collider

J. Hewett, T. Rizzo, T. Tait, in progress



- One pressing question for particle physics is how we will be able to tell one theory from another.
- In particular, the theory with universal extra dimensions can be very similar to supersymmetry.
- Each theory has partner fields for each SM particle. The difference is the spin of the partner.
- A high energy e+ e- collider can distinguish the spins.