Dark Matter from Hidden Dimensions

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TeV Particle Astrophysics
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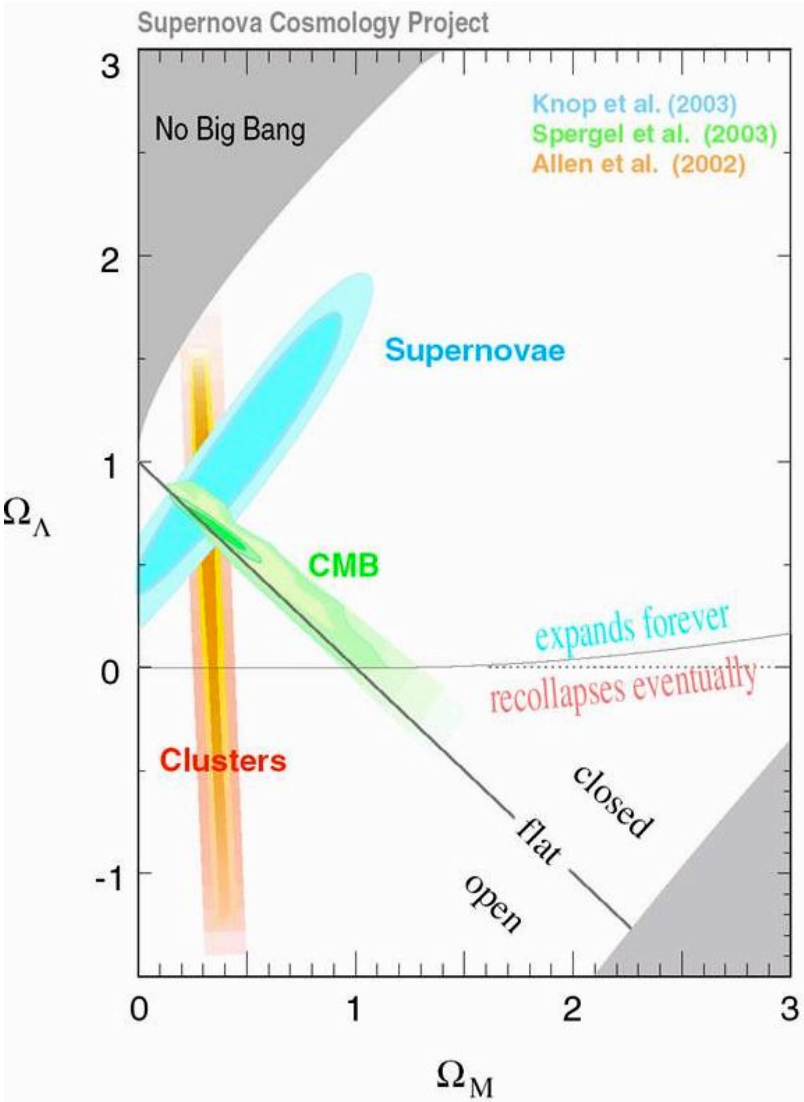
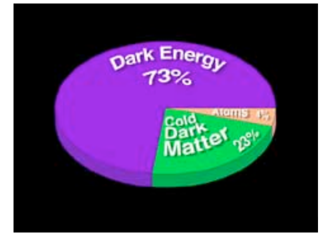
Outline

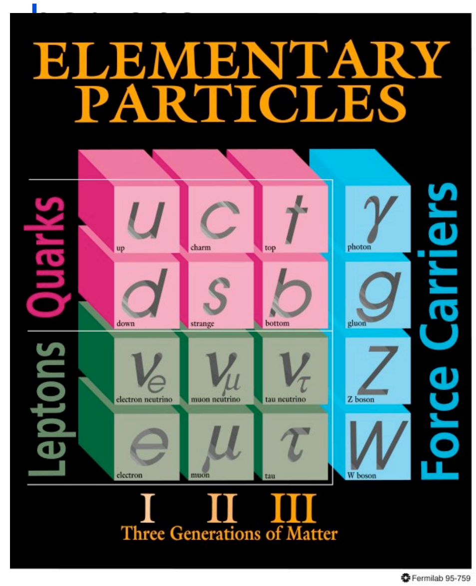
- Particle Physics in Extra Dimensions
- Universal Extra Dimensions
  - KK "photon" as Dark Matter.
- Warped Extra Dimensions
  - KK "neutrino" as Dark Matter.
- The Light Radion
  - Extra dimensional "Gravity" as Dark Matter.
- Outlook

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 %





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

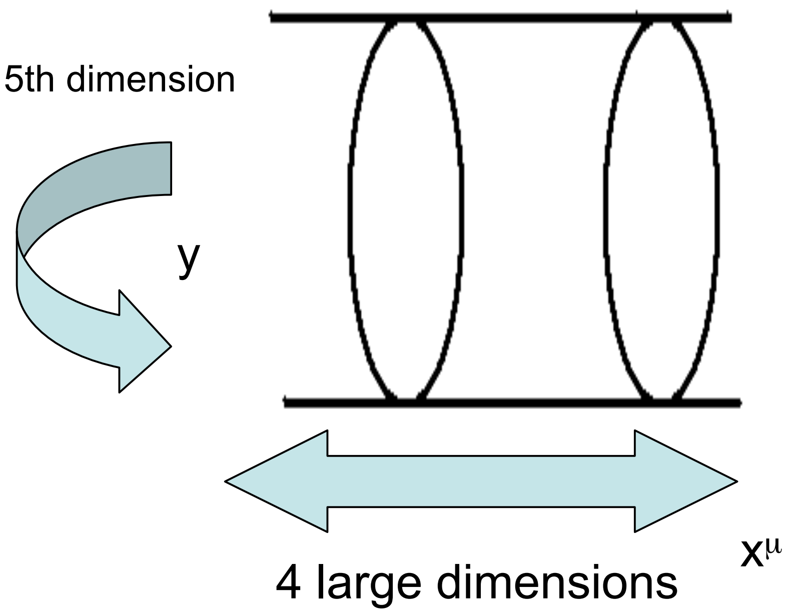
What is this stuff?

Particle physics as we know it has no answer.

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.
- The main challenge extra dimensions face in making contact with dark matter is explaining why the new states should still exist in the universe today.
  - Naively, we expect such heavy new states should be very short-lived.
  - This expectation can be over-turned either by a symmetry which prevents the new states from decaying, or from a particle which is so weakly coupled that the dark matter does decay, but it has not had time to do so in large quantities today.
  - Extra dimensional theories will exploit both of these possibilities in presenting dark matter candidates.

Life on a Circle



- How to define a model with extra dimensions..
  - Number of Extra Dimensions
  - Topology
    - Line, circle, torus,…
  - Geometry
    - Flat, warped,…
  - I will confine myself to 5d
    - Most results easily extrapolated to more
    - Simple, only one real choice for the topology.

Field Theory in 5 Dimensions

- 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:

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

- 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.

KK Decomposition

5d action:

$$\int d^5x \;\; \partial_M \Phi \, \partial^M \Phi \;\Rightarrow\; \int d^5x \left\{ \partial_\mu \Phi \, \partial^\mu \Phi - \partial_5 \Phi \, \partial_5 \Phi \right.$$

We perform a Kaluza-Klein decomposition of the 5d field:

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

Resulting in:

$$\int d^4x \sum_{n,m} \partial_\mu \Phi^n \partial^\mu \Phi^m \times \underbrace{\left(\int dy \;\; f^n f^m \right)}_{\delta_{nm}} - \Phi^n \Phi^m \times \underbrace{\left(\int dy \;\, \partial_5 f^n \partial_5 f^m \right.}_{M_n^2 \;\, \delta_{nm}}$$

With 4d action:

$$\int d^4x \sum_n \partial_\mu \Phi^n \partial^\mu \Phi^n - M_n^2 \Phi^n \Phi^n$$

Kaluza-Klein Particles

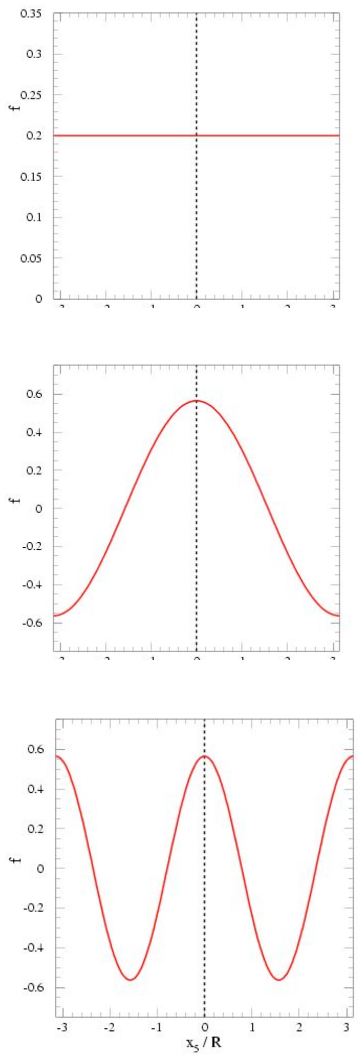
- Particles:
  - $p_5 = 0$

    M = 0
  - $p_5 = 1 / R$

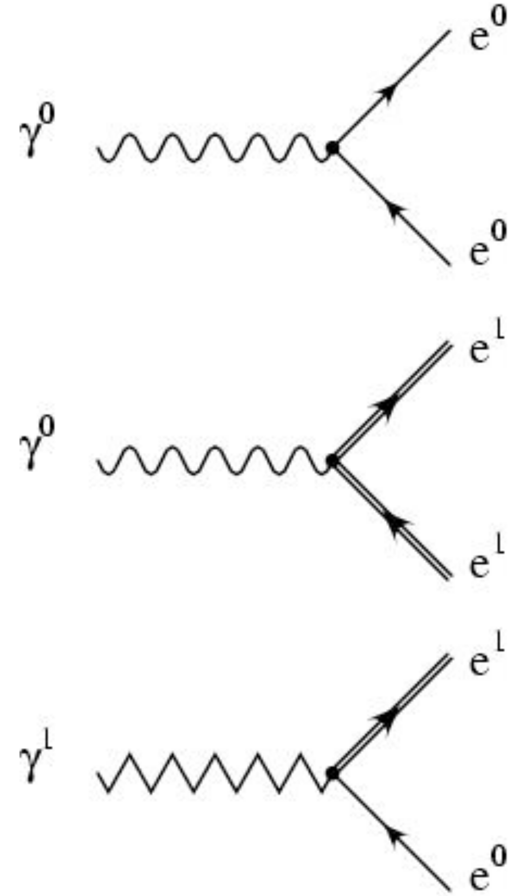
    M = 1/R
  - $p_5 = 2 / R$

    M = 2/R

…and so on!

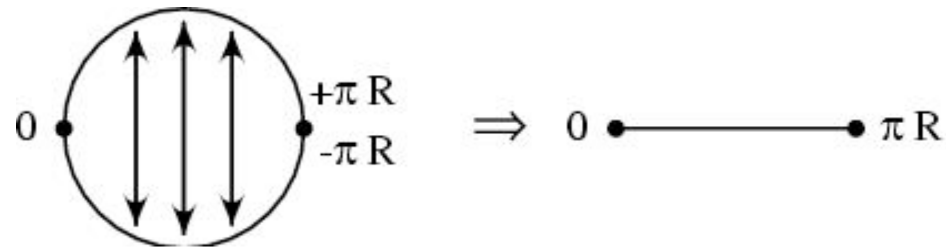


- Interactions:
  - Conservation of p_5 becomes conservation of **KK number**.



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 (II)

- 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:

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

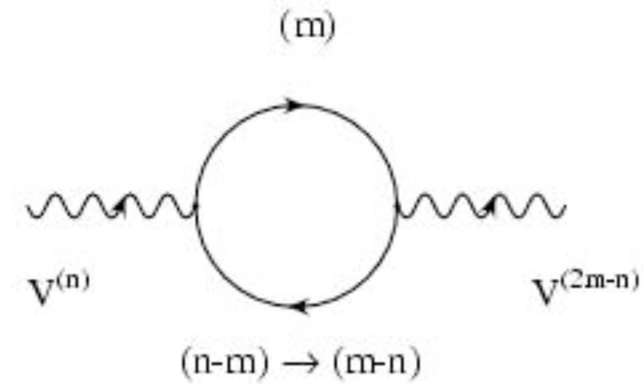
- Odd fields (A_5, Ψ_R) don't:

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

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

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.



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

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

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

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

Boundary Kinetic Terms

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

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

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

- 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)

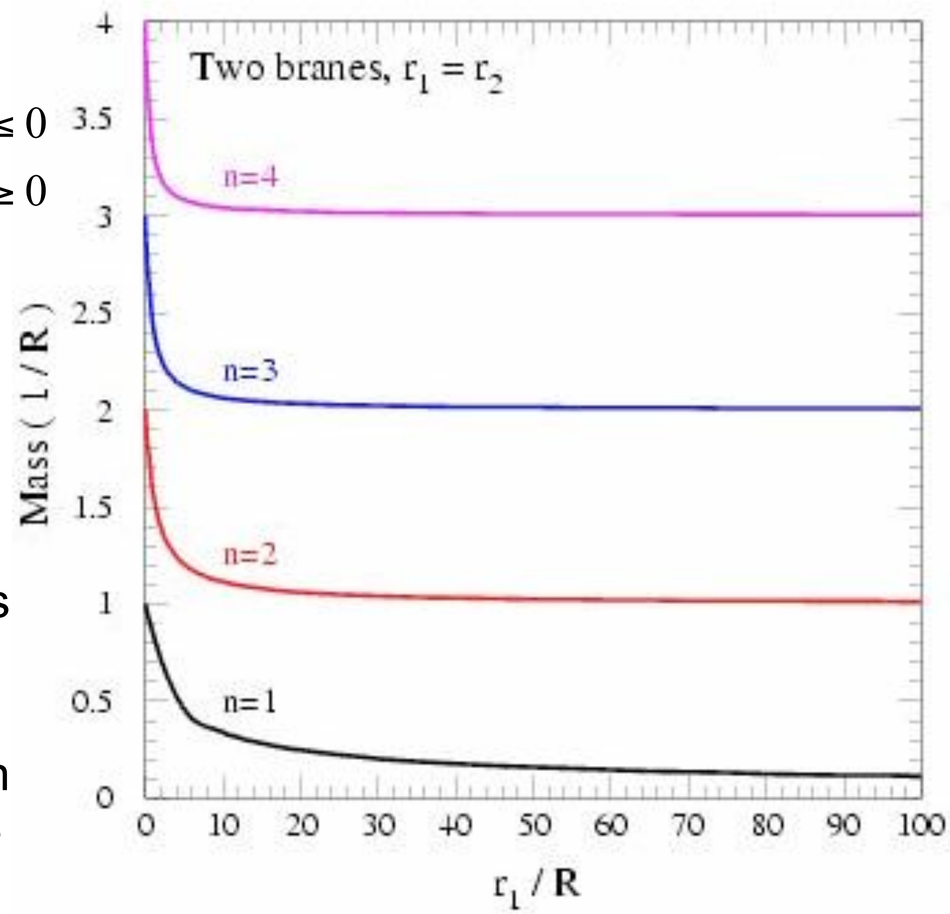
The wave functions are:

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

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.



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 5^{th} 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?

- **String Theory:**
  - String theories require supersymmetry and 10 dimensions to be consistent.
  - So, extra dimensions are (from a low energy point of view), the "other half" of stringy phenomenology.
- TeV extra dimensions provide a natural setting for **top seesaw** models:
  - 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:**
  - Cancellation of anomalies in six dimensions requires the number of families to be a multiple of three!

Effective Theory for UED

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

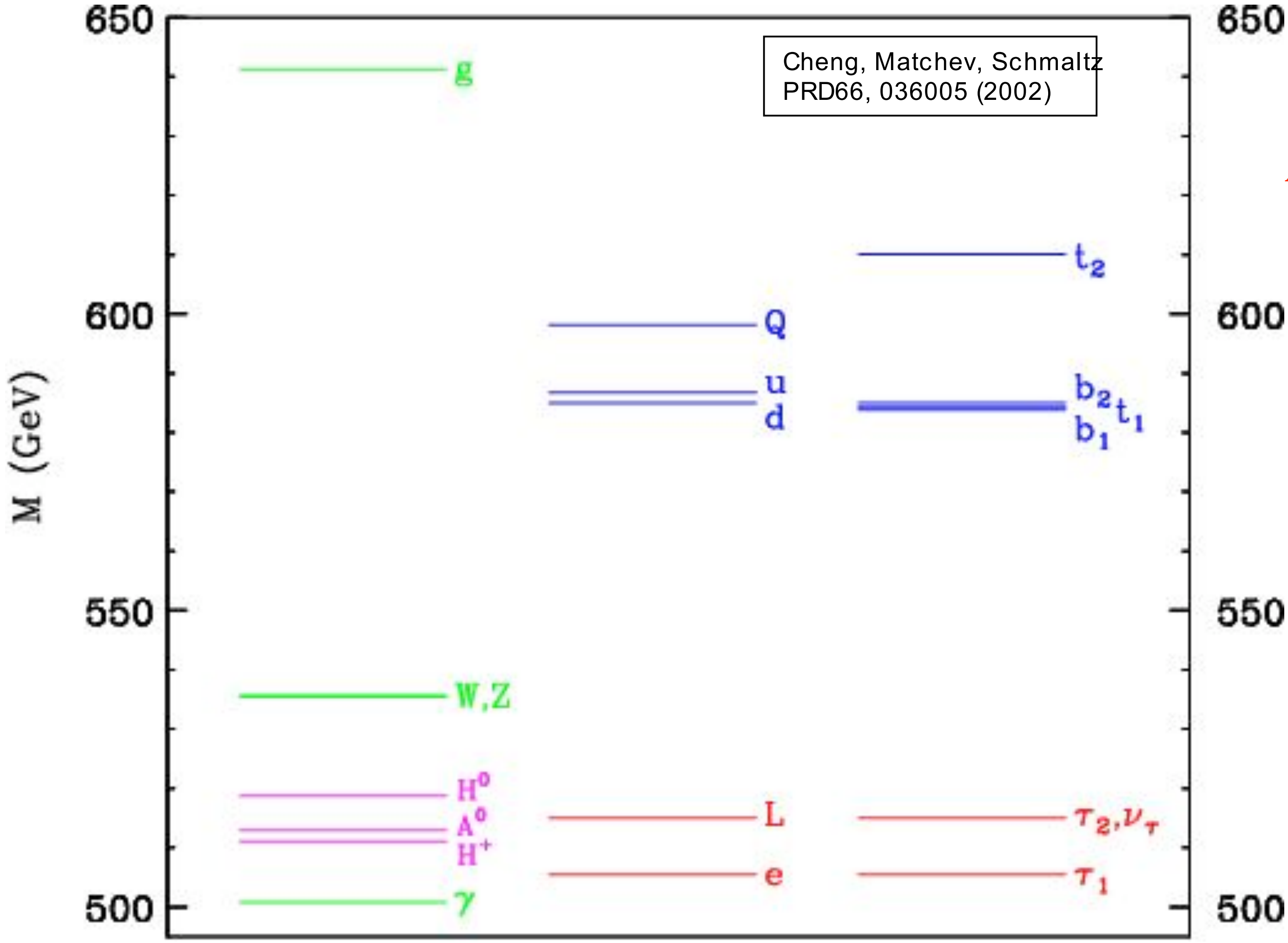
$$\frac{1}{g_5^2} F_{\mu\nu}\left(x^\mu, y\right) F^{\mu\nu}\left(x^\mu, y\right)$$

  - Boundary terms, i.e.:

$$\frac{r_c}{g_5^2} F_{\mu\nu}\left(x^\mu\right) F^{\mu\nu}\left(x^\mu\right)\left[\delta\left(y\right)+\delta\left(y-L\right.\right.$$

  - 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.

KK Mode Spectrum



1/R = 500 GeV
Λ R = 20

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

KK Parity

- Conservation of KK number is broken to conservation of KK parity: $(-1)^n$.
- 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, $e^{(1)}_R$.

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

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

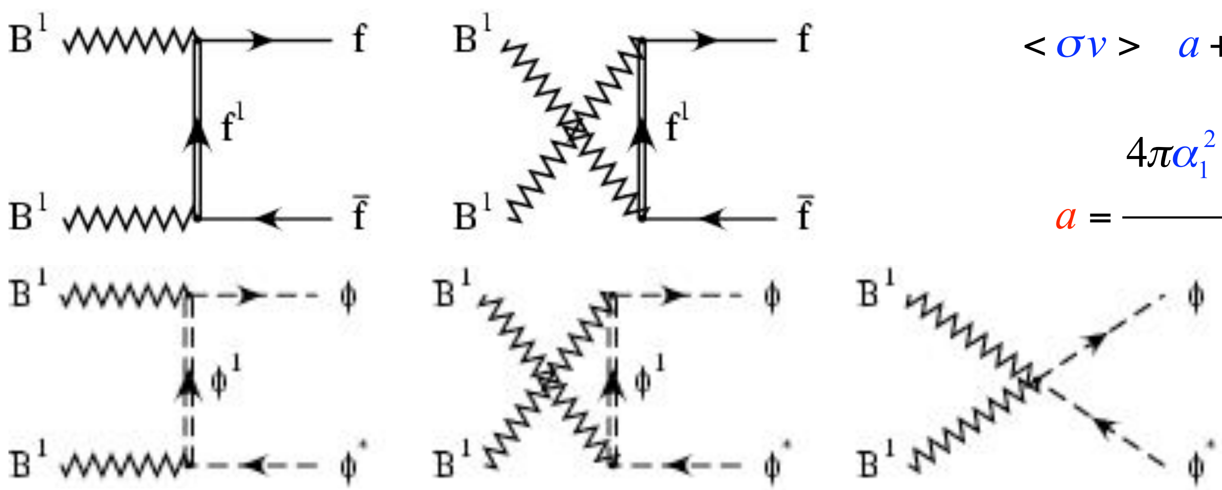
$B^1 - W_3{}^1$ Mass^2 matrix

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.
- Thus, the only parameter we don't already know is the size of the extra dimension, or in other words, the masses of the KK particles.
- I will explore this single parameter to find the cosmologically interesting values.

Thermal Production & Freeze Out

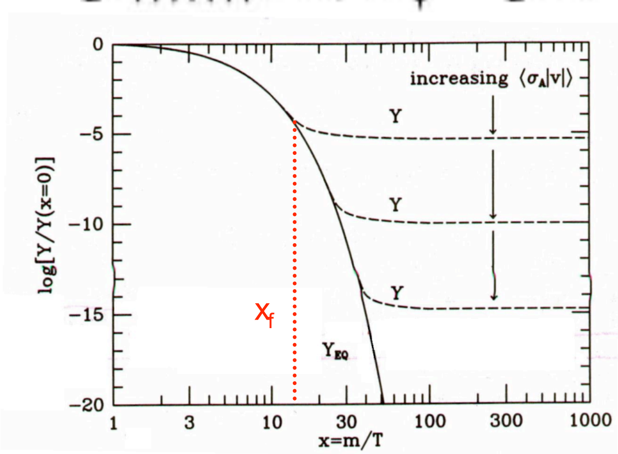
- To estimate the relic density of the LKP, we assume it was originally in thermal equilibrium in the early universe.
- As the universe expands, eventually the density is small enough that they can no longer interact with one another, and fall out of equilibrium.
- Below this *freeze-out temperature*,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



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

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

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

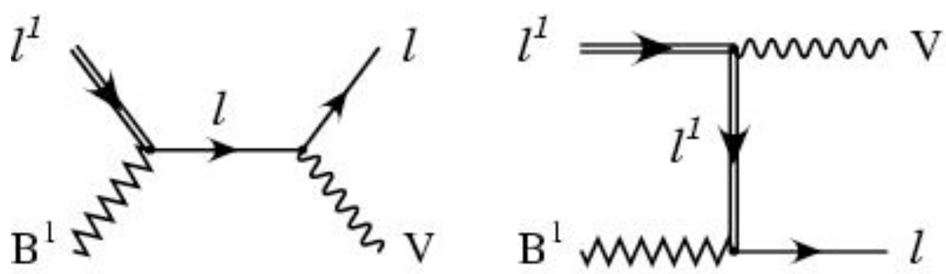


$x_f \sim 25$

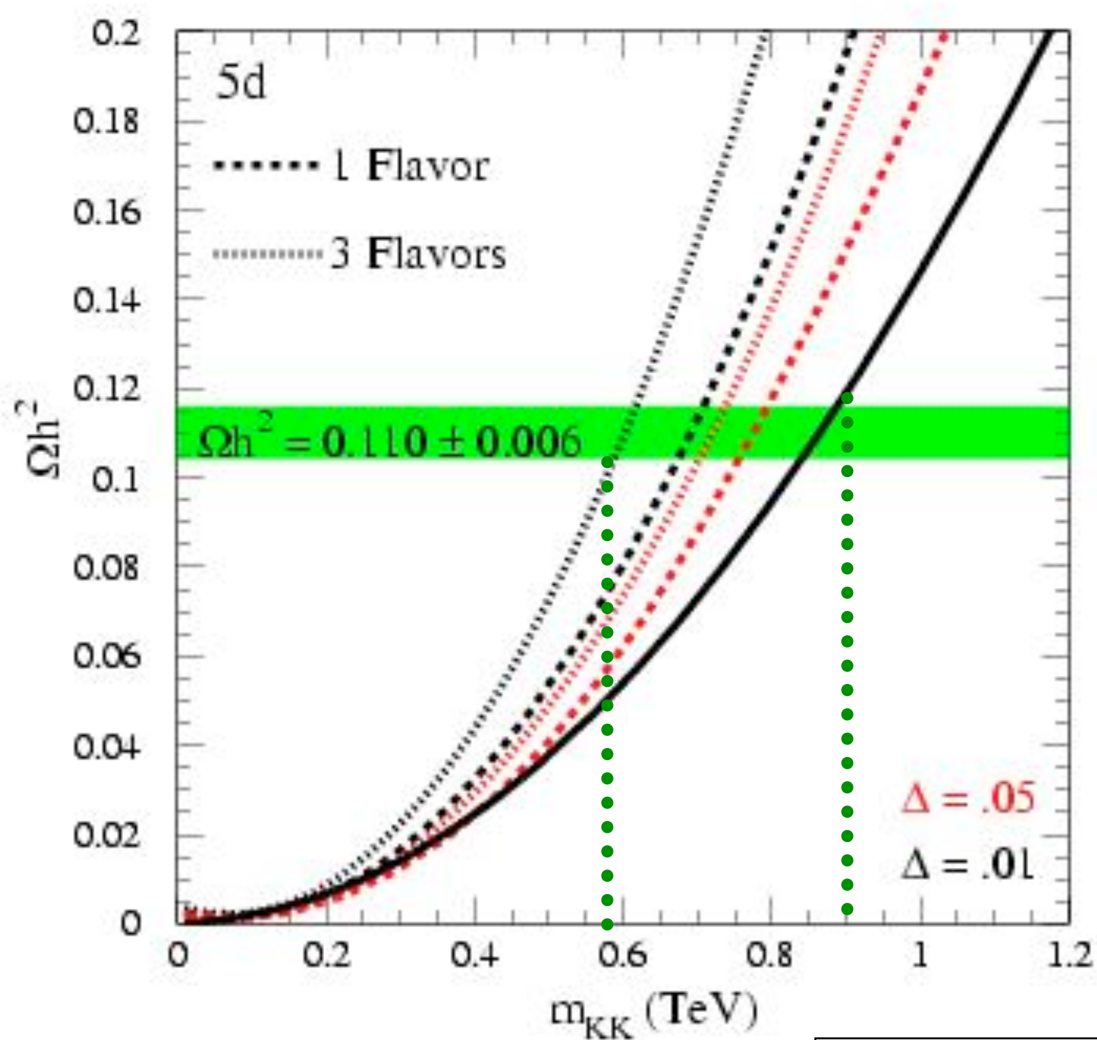
For $m_{KK} \sim 1$ TeV : $T_f \sim 40$ GeV

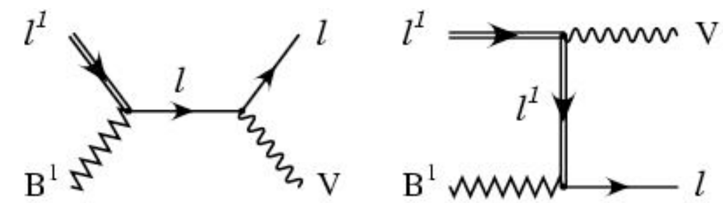
Coannihilation

- If the mass of $e^{(1)}_R$ is close to $B^{(1)}$, it may substantially affect the relic density.
- They interact roughly with the same efficiency.
- The freeze-out temperature is basically unchanged,
- Some $e^{(1)}_R$ left over after freeze-out, and eventually decay into $B^{(1)}$ and $e^{(0)}$.
- The net relic density of $B^{(1)}$ is increased.
- Quite different from SUSY.



Relic Density





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

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

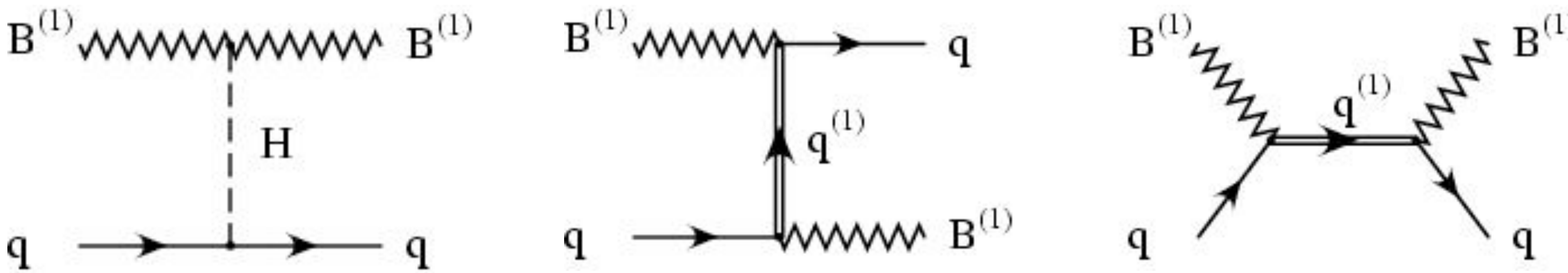
Coannihilation favors the 5d range **600-900 GeV**.

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

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

Direct Detection

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

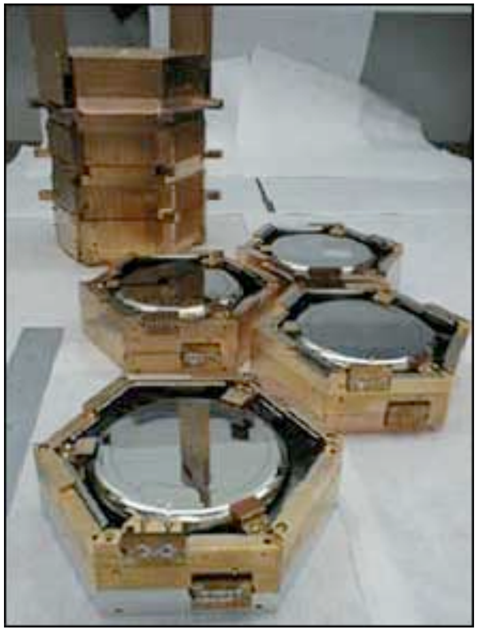


- Form factors relate quark interactions to nucleon scattering.
- Nuclear physics relates nucleon scattering to nuclear interactions.
- Energy is deposited in the nucleus target:

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

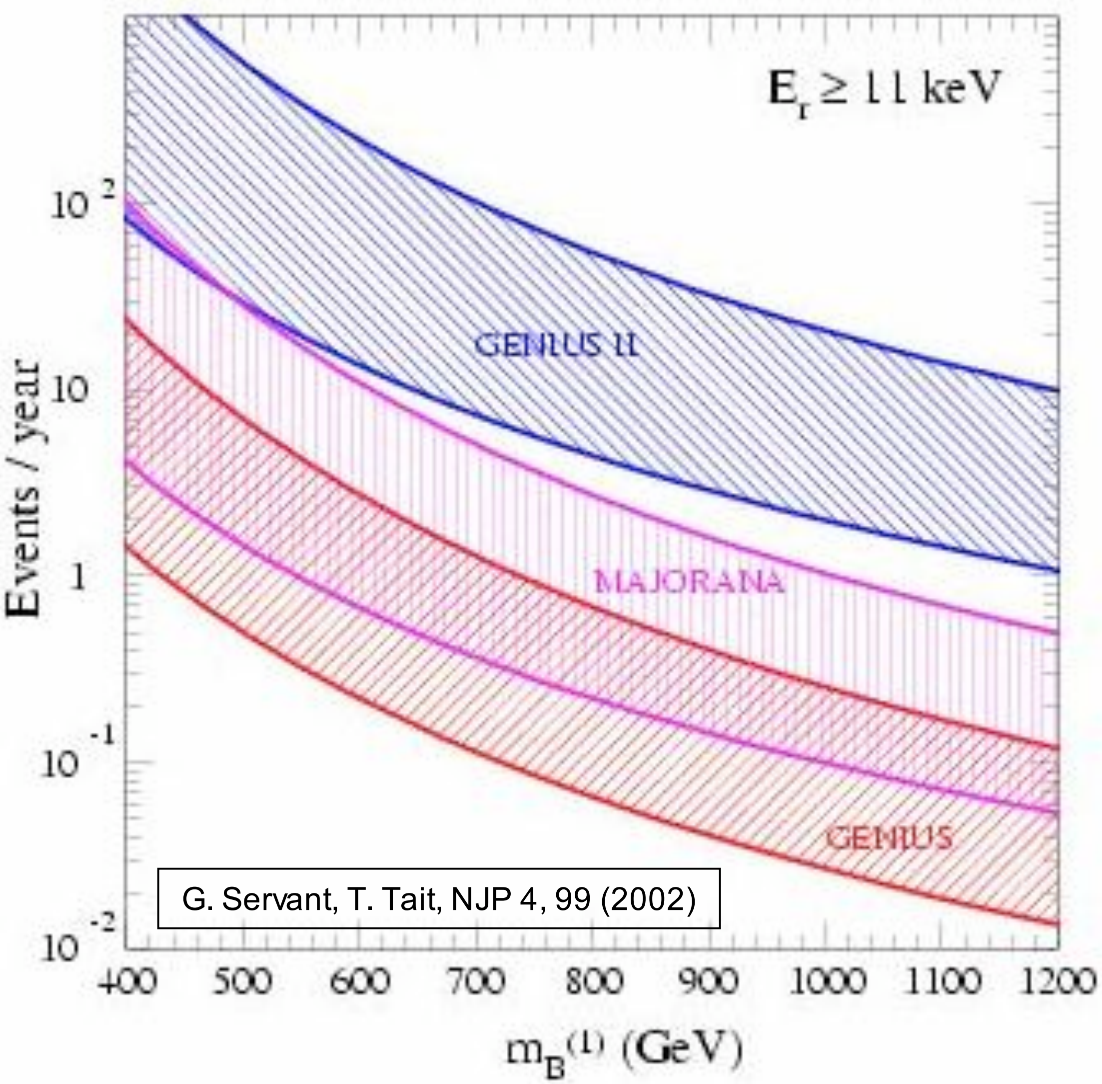
ρ : WIMP halo density
v : WIMP velocity
f : WIMP v distribution
σ_0 : nucleon σ
F : nuclear form factor

Germanium Detectors



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

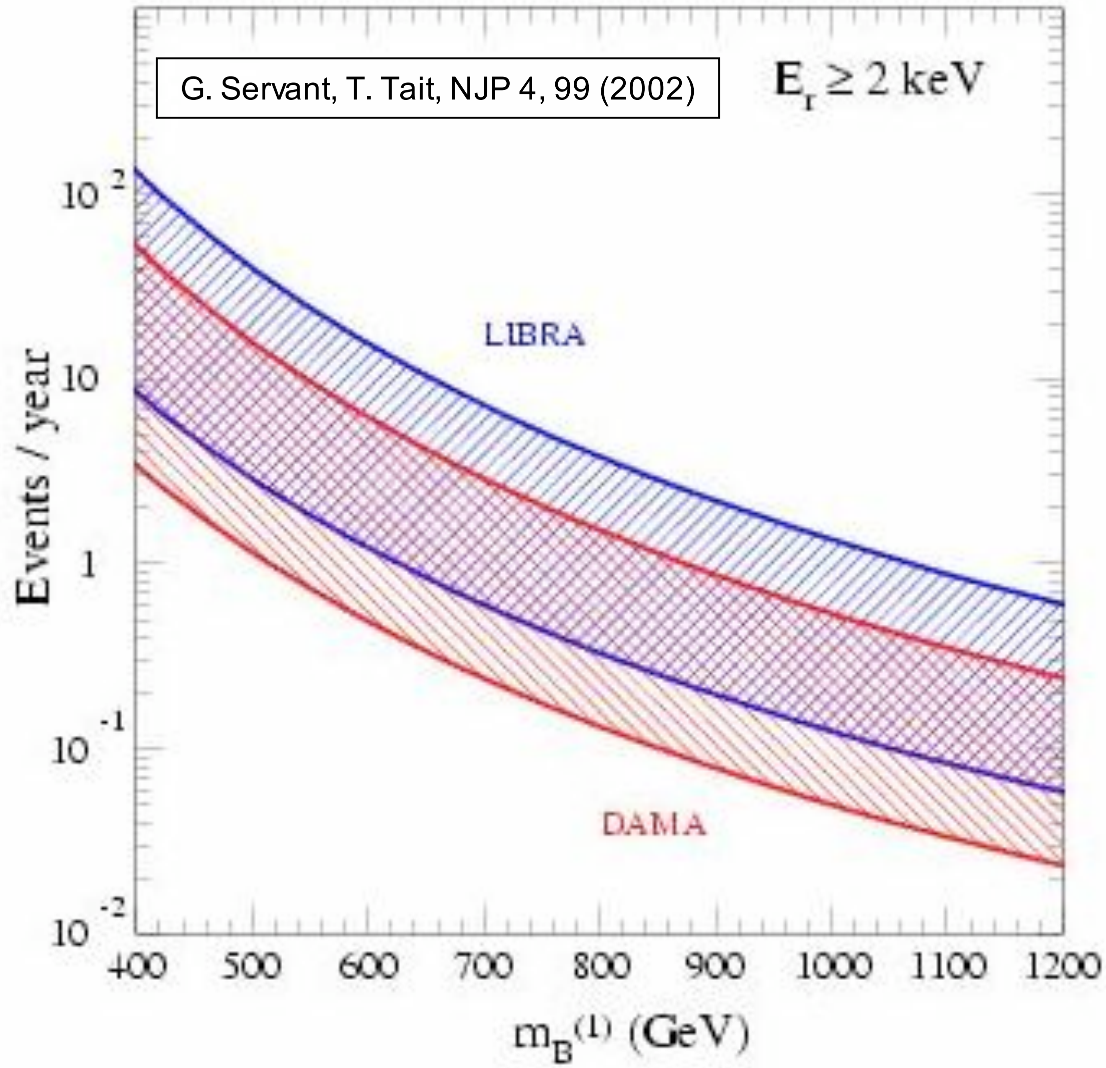
GENIUS : 100 kg ^{73}Ge
GENIUS-2 : 10^4 kg ^{76}Ge
MAJORANA : 500 kg ^{76}Ge



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

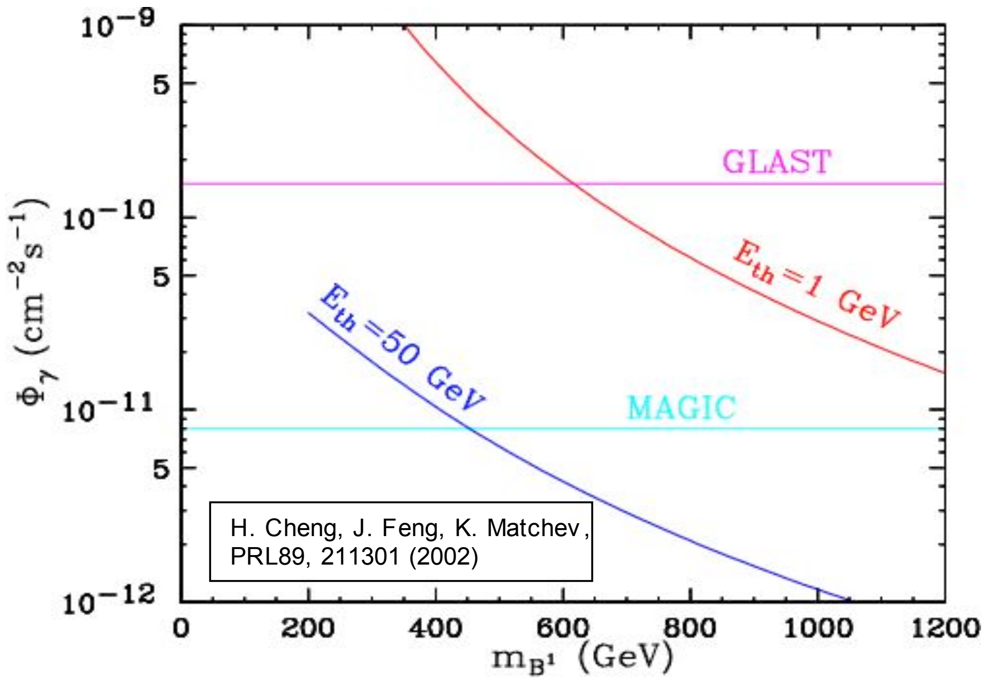
NaI Detectors

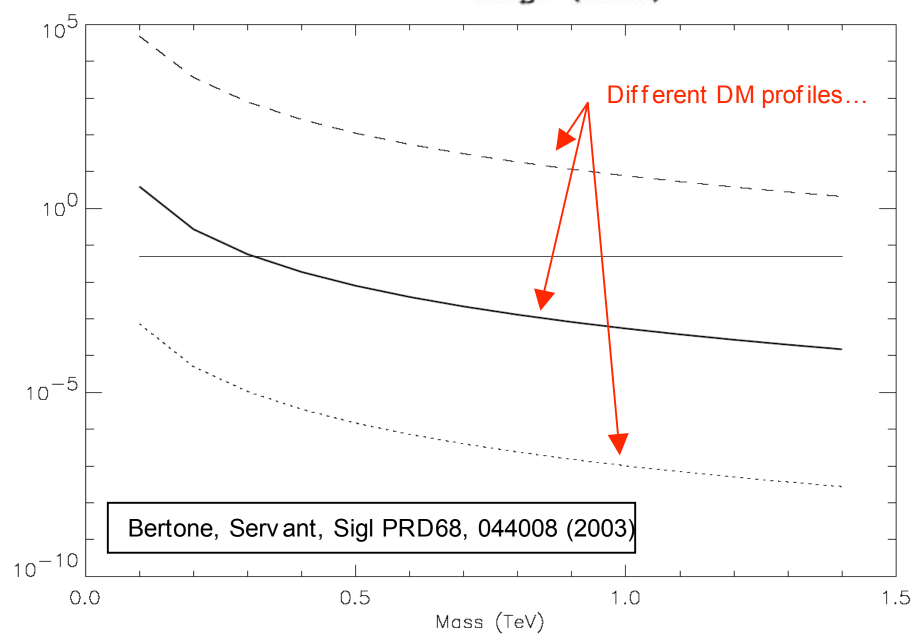
Search strategy is to see an annual modulation of events as the earth revolves around the sun.
DAMA: 100 kg NaI
LIBRA: 250 kg NaI



Indirect Detection: γ

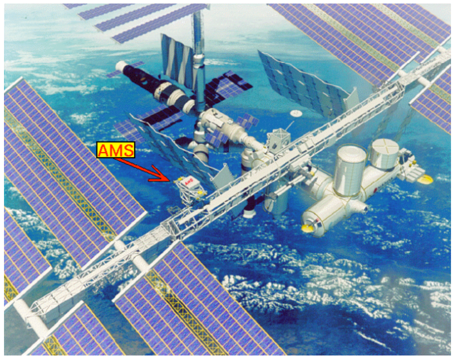
- WIMPs in the galactic halo can annihilate into high energy gamma rays.
- Rates are rather sensitive to the profile of dark matter in our galaxy, which is not very well understood.
- Energetic photons from synchrotron radiation of charged particles is also possible, though this further depends on galactic magnetic fields.
- This may be observable at GLAST or MAGIC for the lower range of LKP masses.



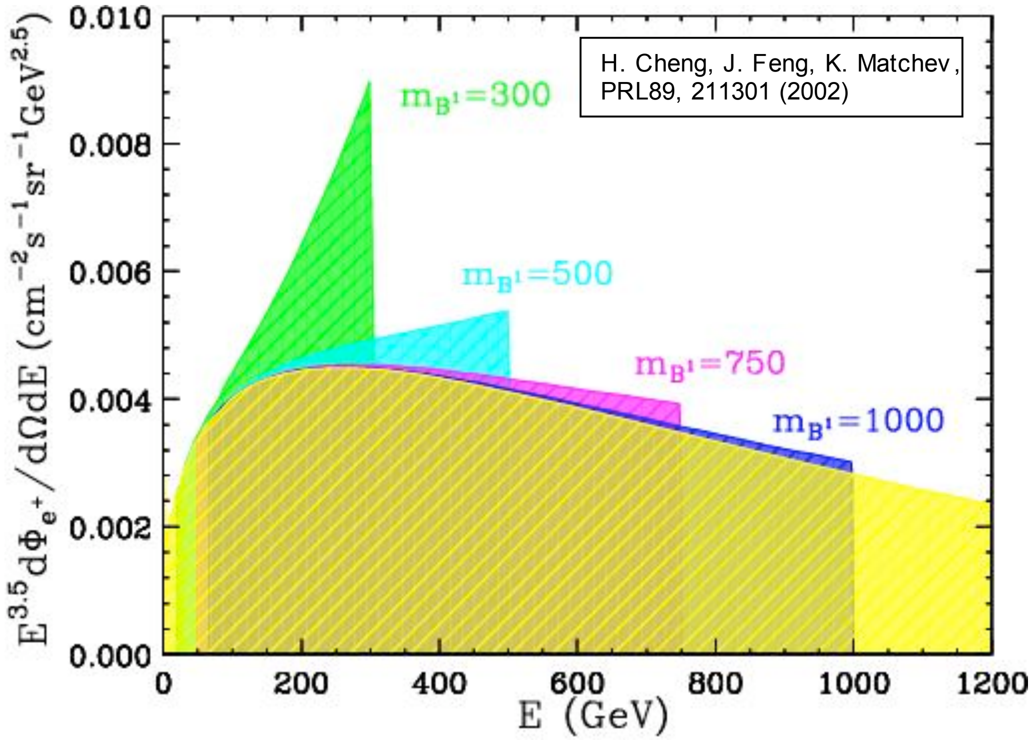


Line emission: Bergstrom, Bringmann, Eriksson, Gustofsson, hep-ph/0412001

Indirect Detection: e^+



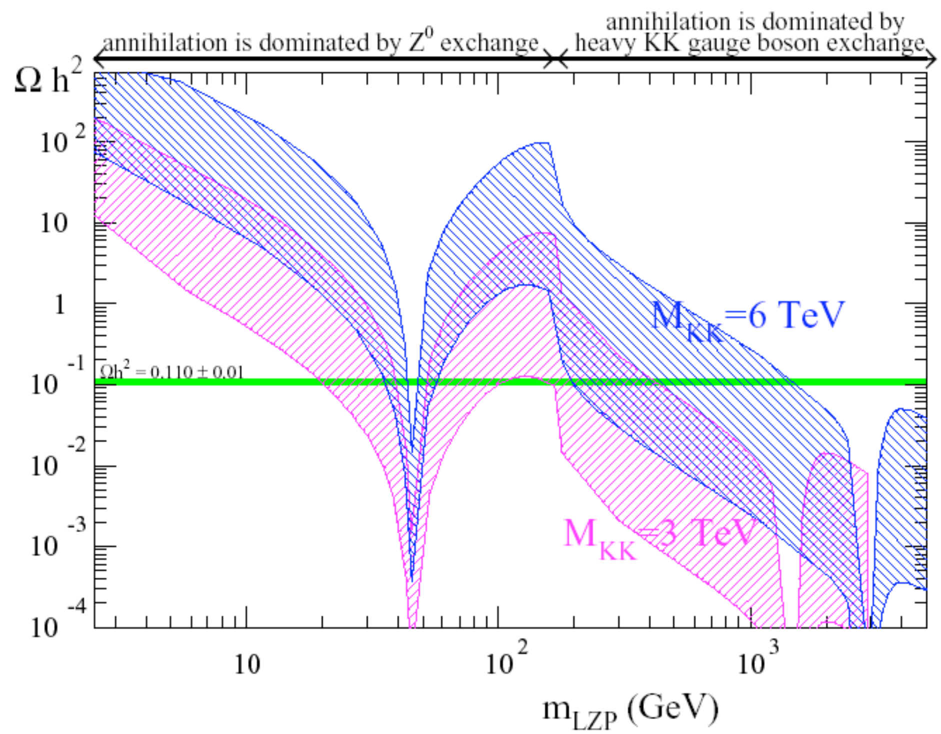
- WIMPs in the galactic halo can annihilate into $e^+ e^-$.
- The e^+ can be detected by space-based experiments, such as AMS.
- LKPs *prefer* to annihilate into $e^+ e^-$, and produce mono-energetic positrons.
- This is a striking signal, clearly visible against backgrounds for m_{KK} less than about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



Warped Extra Dimension?

- 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.

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



Light Radion?

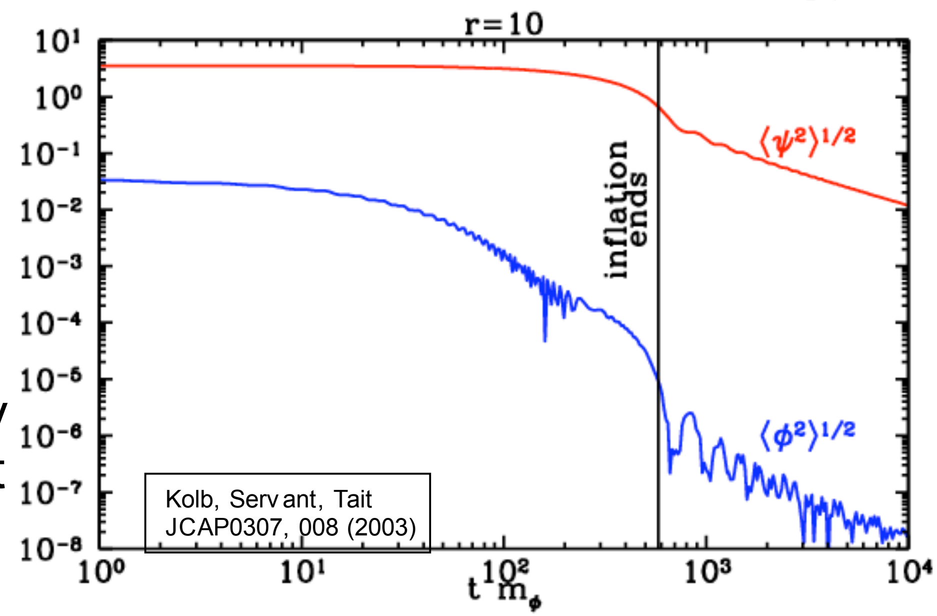
- Any theory with an extra dimension contains a scalar field, the radion, which is the modulus describing the size of the extra

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

- 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 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

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

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

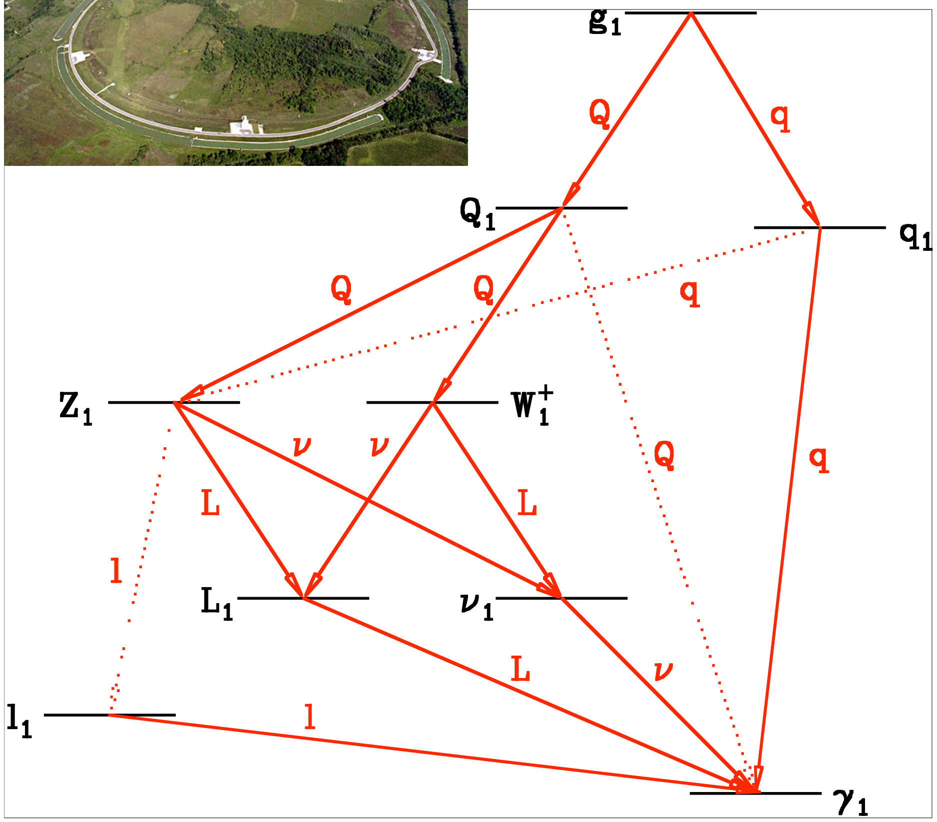


Outlook

- Extra Dimensions allow us to address many puzzles of particle physics: now including **dark matter**!
- In UED, the dark matter candidate is a massive vector particle, stable because of a remnant of the extra-dimensional space-time symmetries.
- RS has a right-handed neutrino which is stable because of a symmetry which is imposed to avoid too rapid proton decay.
- Both theories produce WIMPs thermally in the correct abundance if the WIMP mass is at the TeV scale.
- Any theory can have a light radion which may survive to the present day because it interacts very weakly. It may be produced non-thermally through vacuum misalignment during inflation.
- All of these theories have interesting experimental signatures allowing us to explore the nature of dark matter.
- **Let the exploration of the 5th dimension begin!**

Collider Signatures

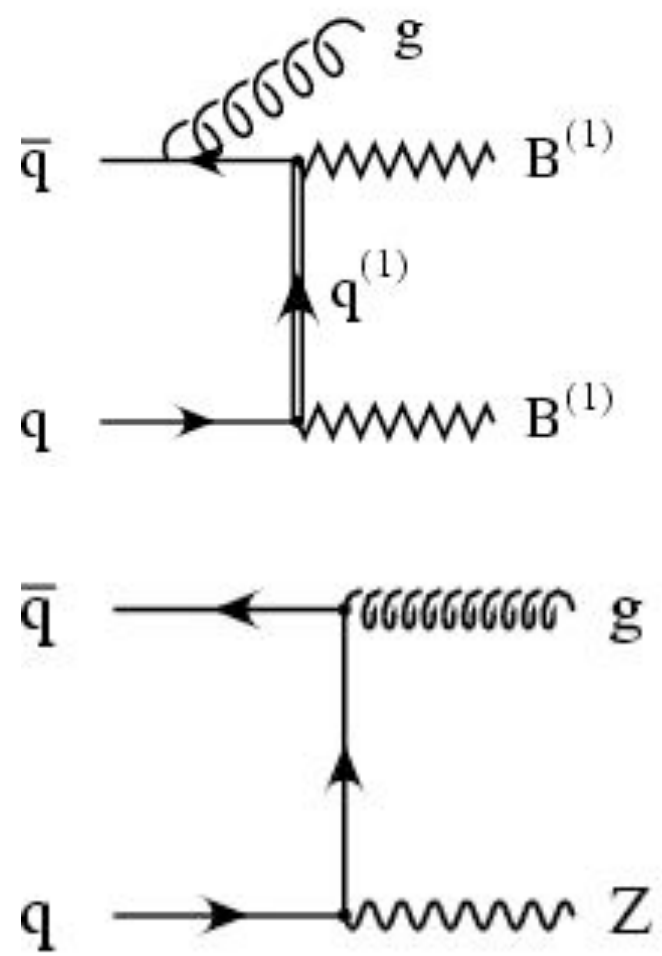
Fermilab



- 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

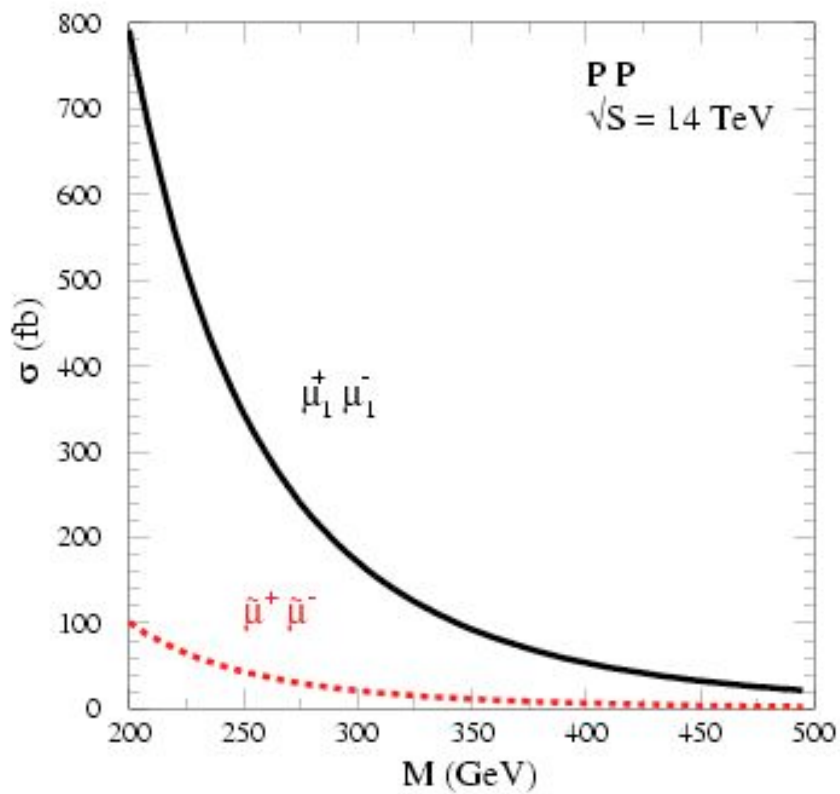
- One could look for pairs of LKPs accompanied by initial state radiation.
- The LKPs themselves escape from the detector.
- Unfortunately, this is sensitive to the KK quark masses.
- Physics backgrounds come from Z + jet production, with Z decaying into neutrinos.
- Fake backgrounds are from missed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

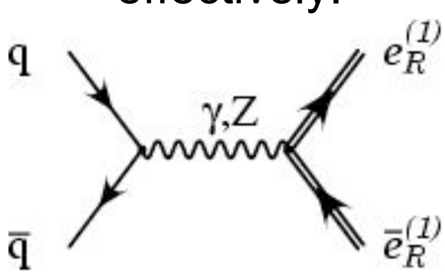


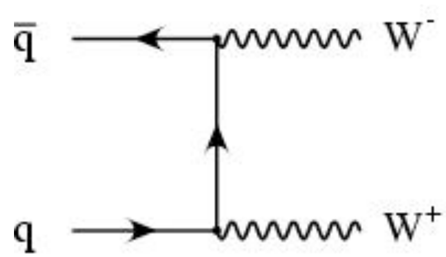
Leptons + Missing Energy

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

- 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.

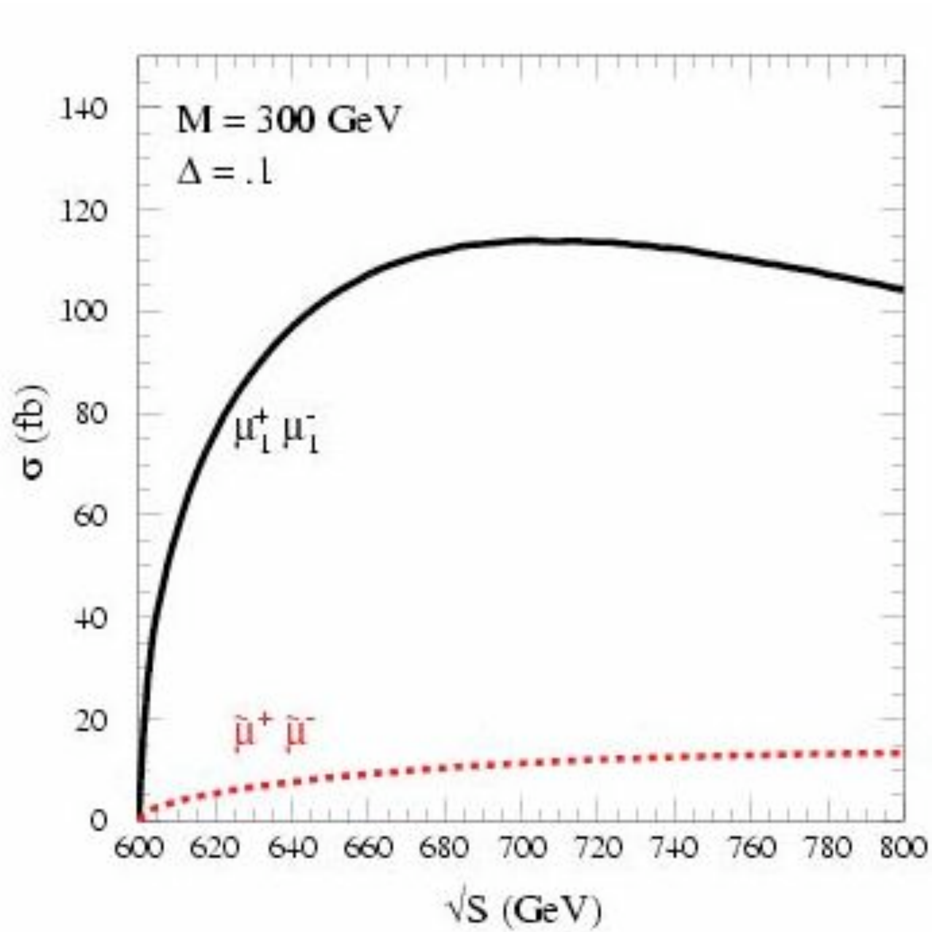






e^+e^- Linear Collider

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.