Dark Matter: Models

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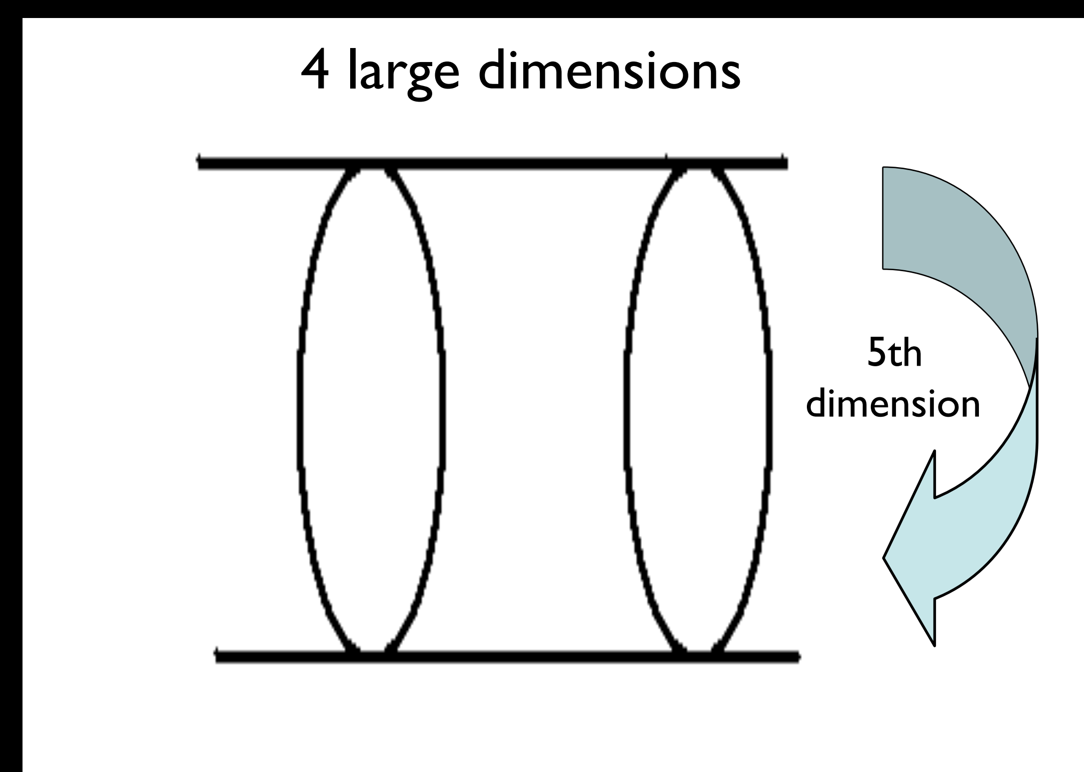
Outline

- More WIMPs:
  - KK parity: UED Dark Matter
    - 5d UED Dark Matter
    - The 6d Chiral Square
  - T-parity (Little Higgs)
- Super-WIMPs:
  - Gravitinos,
  - Axions
  - Sterile Neutrinos

Universal Extra Dimensions

- Our next entry in the catalogue has "Universal Extra Dimensions"
- The basic premise is that in addition to the large dimensions we are familiar with, there is one or more small, curled up dimensions.
    - R smaller than (a few hundred GeV)$^{-1}$.
- All of the quantum fields are functions of the four large (ordinary) coordinates x as well as the extra (compact) coordinates y.
- We'll take a look at both 5d and 6d versions.



Field Theory in 5 Dimensions

- To begin with, imagine our extra dimension is a circle (S1), requiring wave functions to be periodic as one traverses the extra dimension.
  - Mathematically, this is the particle-in-a-box (with periodic boundary conditions) problem familiar from basic QM.
  - The 5th component of Momentum (p5) is quantized in units of 1 / R.
- States with p5 different from zero appear massive to an observer who does not realize the extra dimension is there.

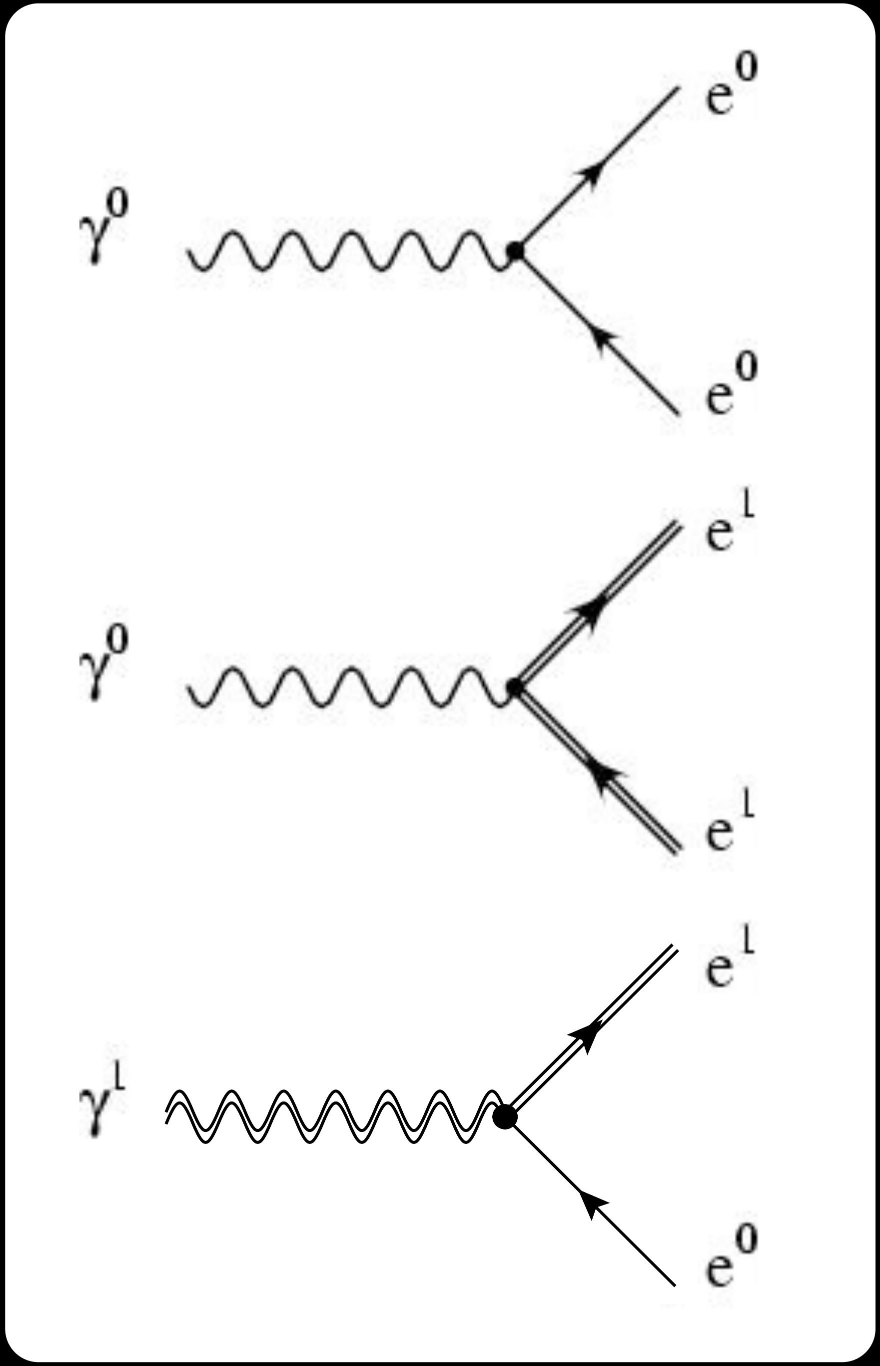
$$p_0^2 - \vec{p}^{\,2} - p_5^2 = 0 \quad \Longrightarrow \quad p_0^2 - \overrightarrow{p}^{\,2} = p_5^2 = m_{eff}^2$$

- We (and all low energy physics) are composed of the lowest (n=0) modes.
- Each SM field comes with a tower of massive states with the same charge and spin as the zero mode, but with masses given by n / R.

Kaluza-Klein Particles

- The translational invariance along the extra dimensional direction implies conservation of p5, or in other words, of KK mode number.
- Clearly, all fields must "live" universally in the extra dimension for there to be translational invariance -- this is not a brane world.
- The conserved KK number implies that the Lightest Kaluza-Klein Particle is stable.
  - Usually the n=1 KK "Photon".
- From the extra dimensional point of view: a photon is massless and cannot be dark matter, but if one is circulating around in a hidden dimension, to an outside observer, it appears to be a massive particle at rest.

Sample Interactions



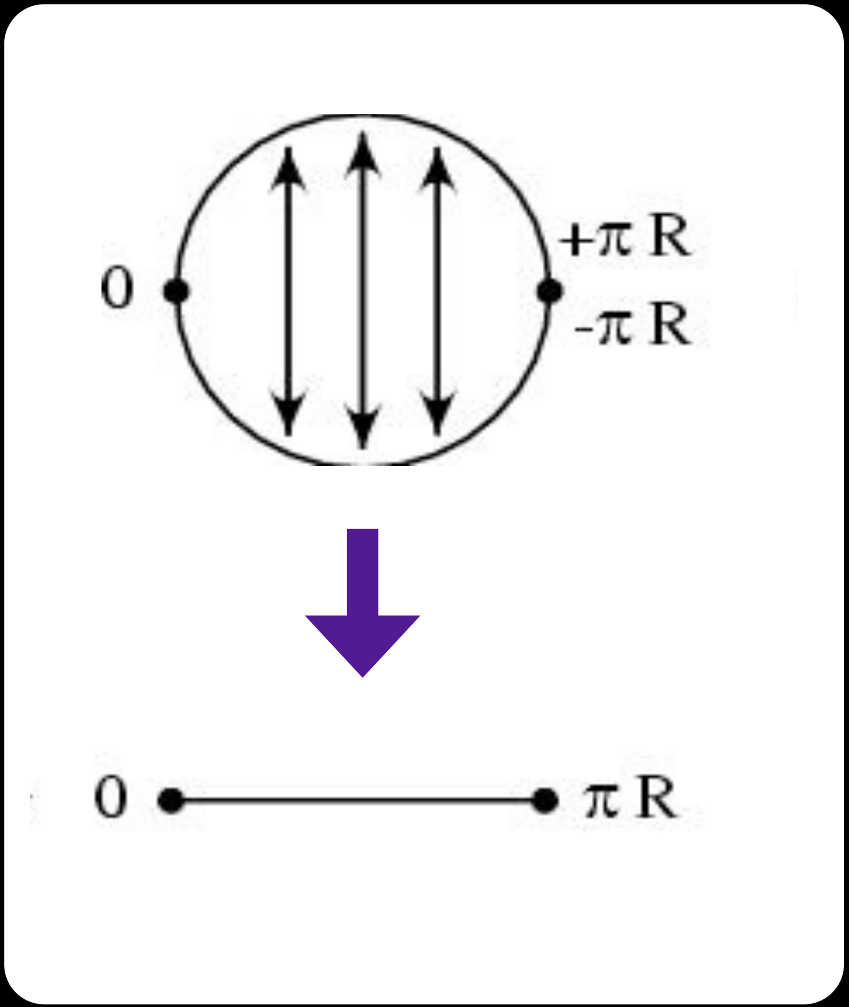
Why Universal Extra Dimensions?

- String Theory:
  - String theories require supersymmetry and extra dimensions to be consistent. So extra dimensions are (from a low energy point of view), the "other half" of stringy phenomenology.
- Number of generations:
  - Cancellation of anomalies in six dimensions requires the number of families to be a multiple of three!
- Dark Matter!

Dobrescu, Poppitz
PRL87, 031801 (2001)

Orbifold

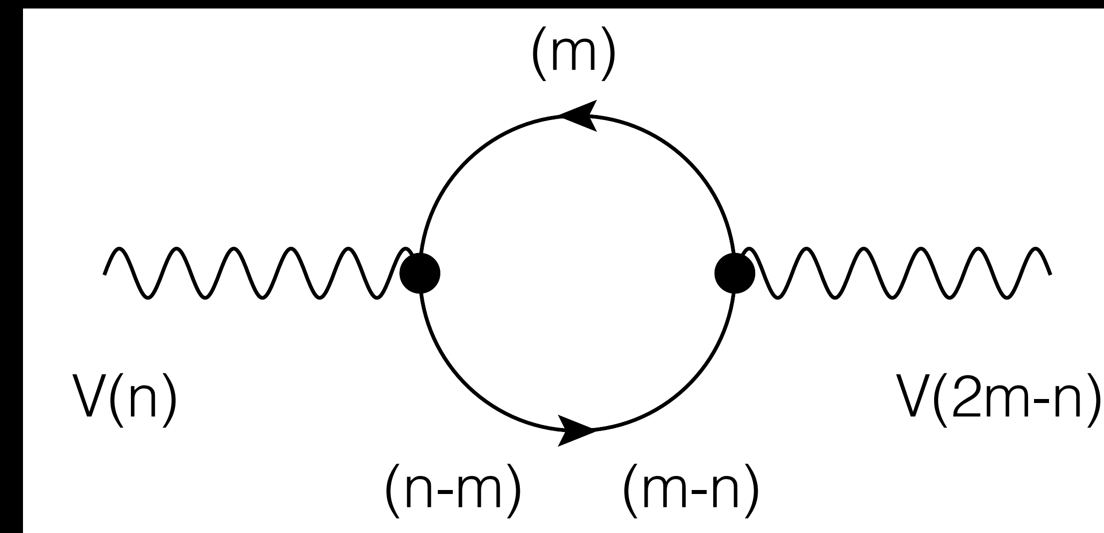
- Our circular extra dimension is not quite realistic. It contains unwanted zero-mode degrees of freedom:
  - 5d vector bosons contain a 4d vector V_μ and scalar V_5.
  - Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- Orbifold boundary conditions project out the 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.
  - Boundary conditions forbid the unwanted zero modes.



$$V_\mu(-y) = V_\mu(y)$$
$$V_5(-y) = -V_5(y)$$
$$\Psi(-y) = \gamma_5 \Psi(y)$$

Orbifolds are Opaque

- Even theories without localized fields have Lagrangian terms living on their boundaries.
- The orbifold, identifying (y and –y), implies the theory can't tell one direction from another.
- Loops of bulk fields generate p5 non-conserving terms.
- In position space, these are equal size terms living on the boundaries.
- The loops are log-divergent, indicating that they are not calculable -- they are parameters of the effective theory.



Georgi, Grant, Hailu, PLB506, 207 (2001)

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

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

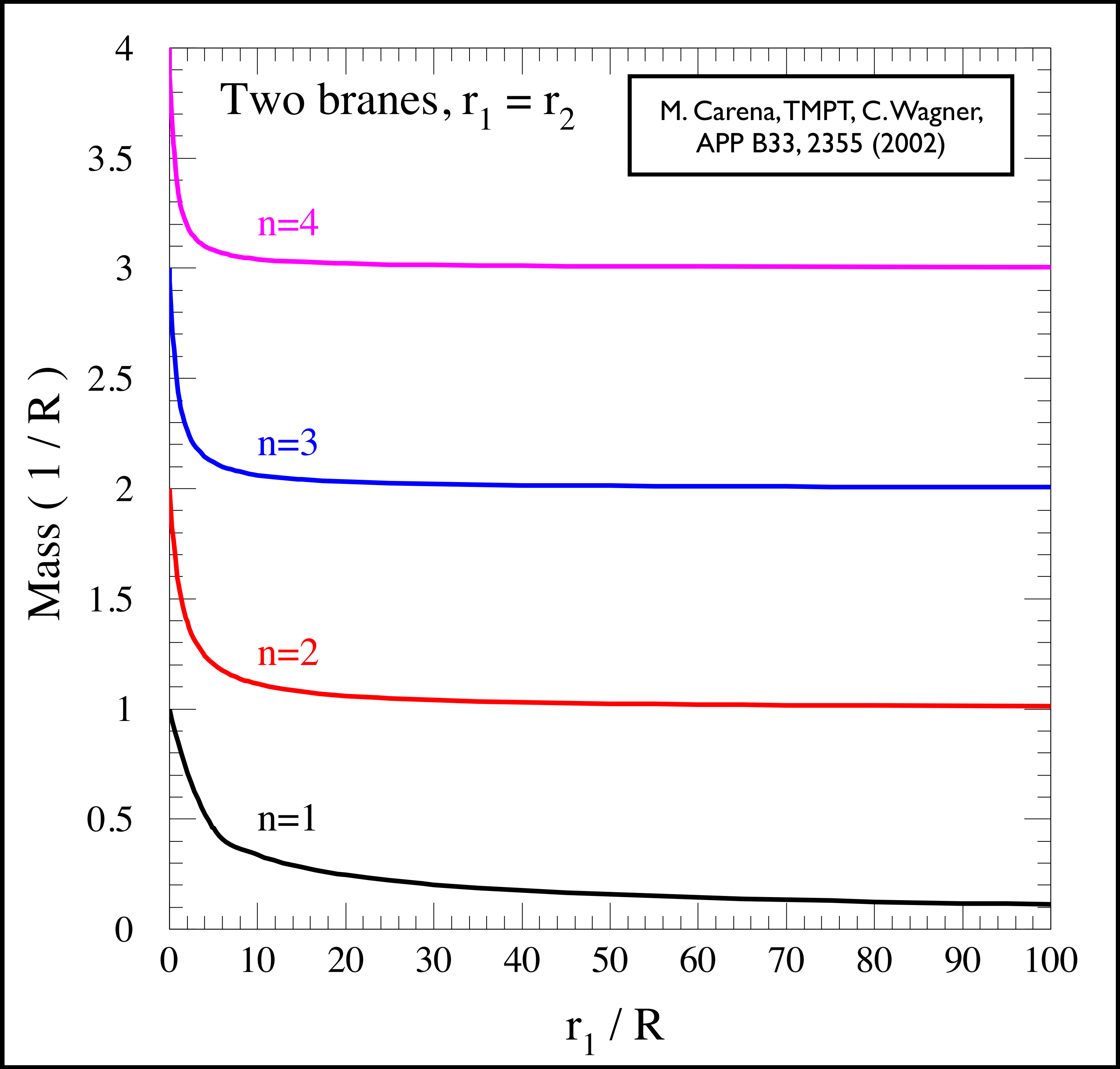
Opaque Orbifolds

The boundary terms modify the KK expansion, reshuffling modes in the expansion.

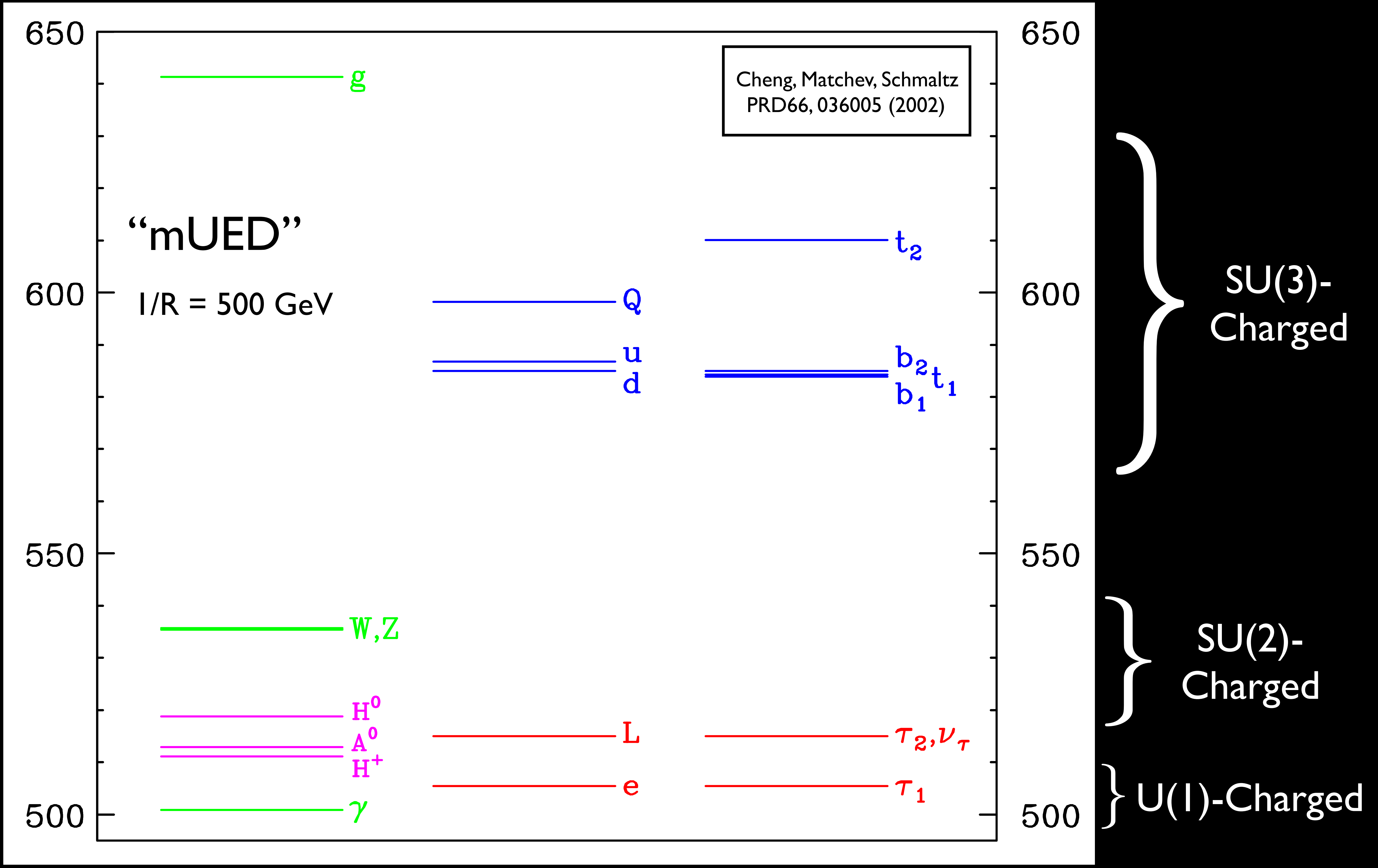
This has the effect of changing the KK mass spectrum.

It breaks conservation of KK number down to a KK parity under which odd KK number modes are odd.

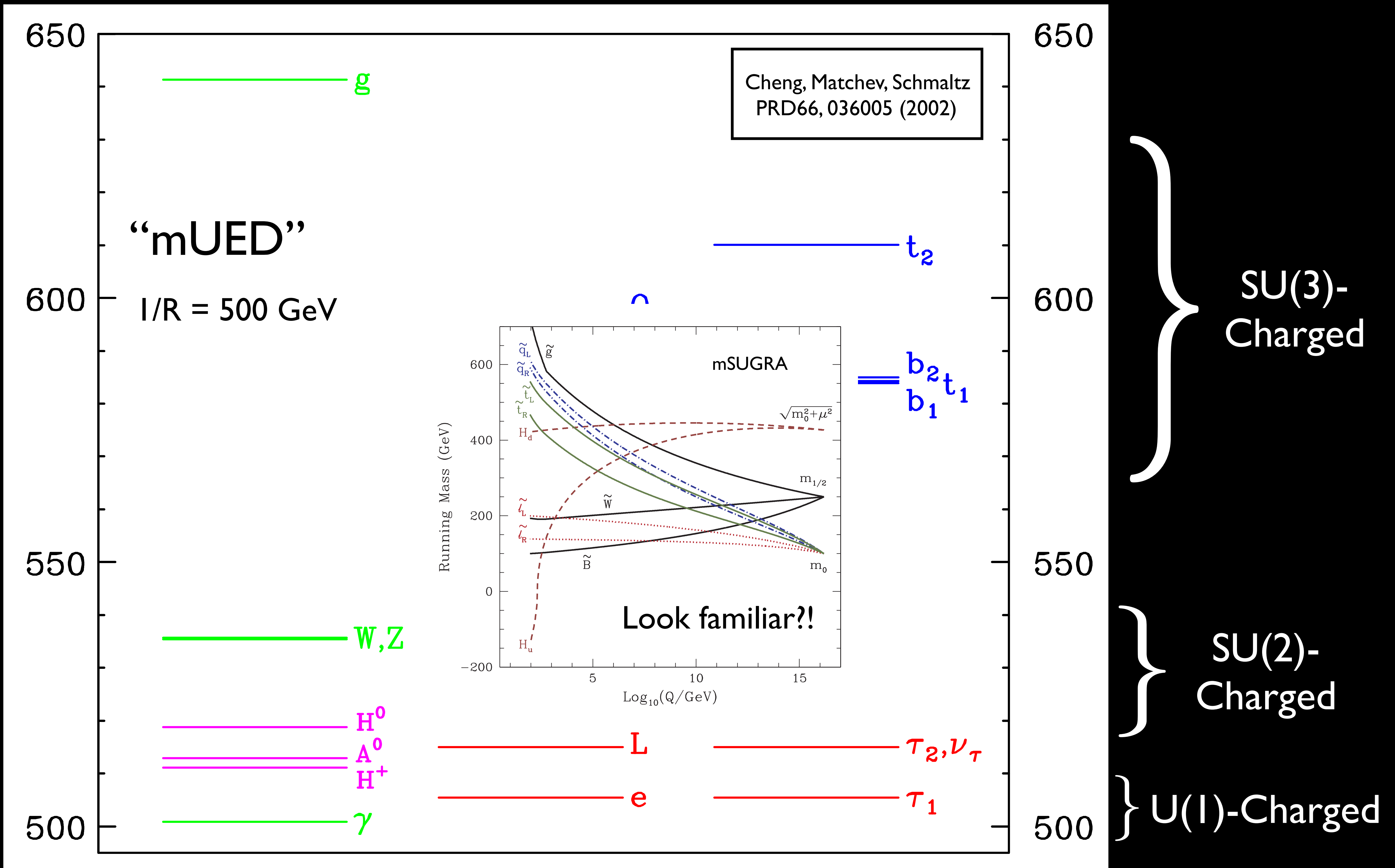
Much like R-parity, the lightest odd mode is stable, and odd modes are produced in pairs.



KK Mode Spectrum



KK Mode Spectrum



Identity of the LKP

- Boundary terms play a role similar to SUSY 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 α1 << α2 << α3, we imagine the smallest corrections will be to the U(1) gauge boson.
- Since δM ~ 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, $e^{(1)}_R$.

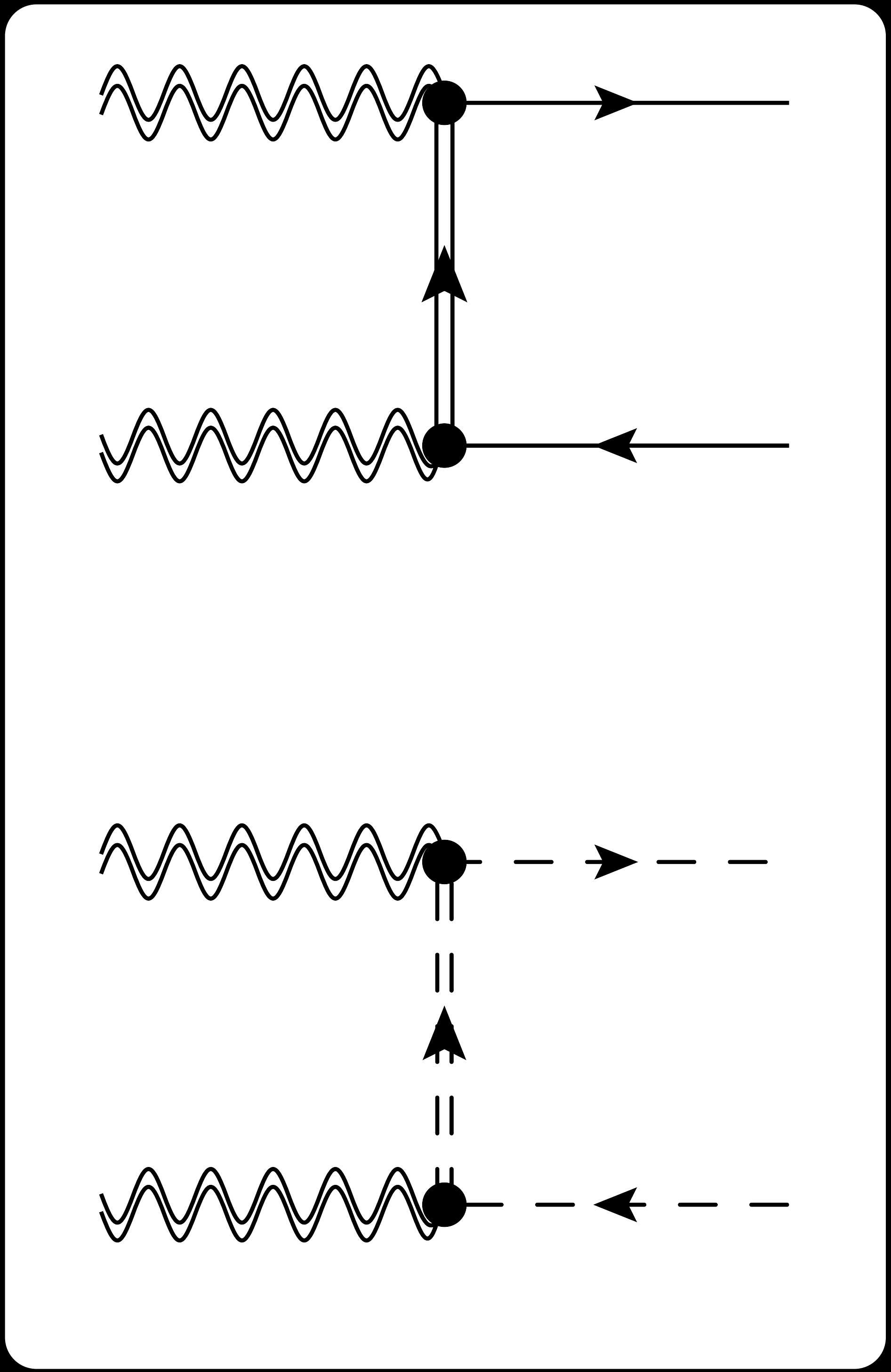
$\boxed{B^{(1)} - W_3^{(1)} \text{ Mass}^2 \text{ matrix}}$

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

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

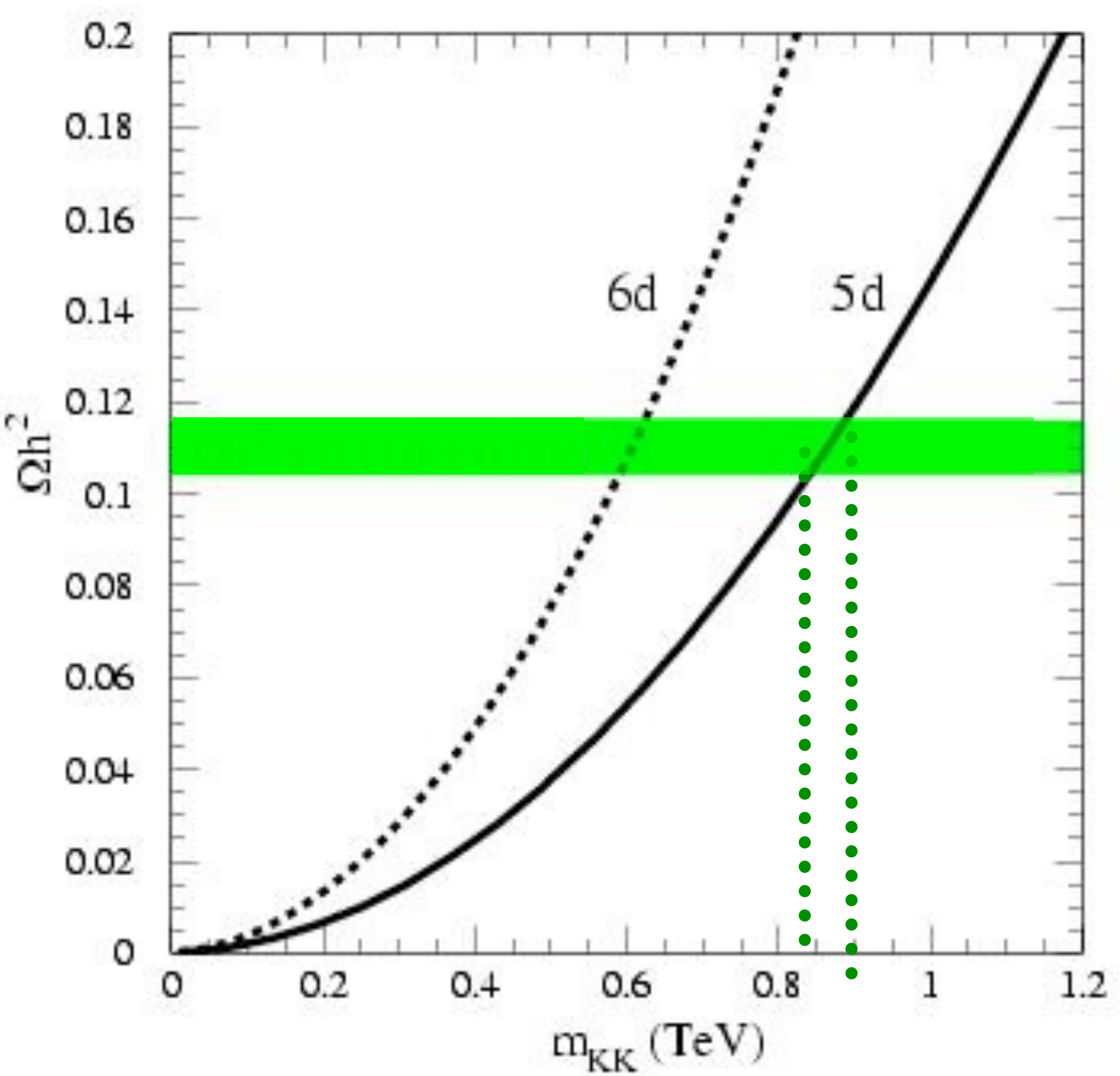
LKP Annihilations

- For a pure $B^{(1)}$ LKP, we know couplings are controlled by the hypercharges.
- There are annihilations into SM fermions and Higgs bosons.
  - 59% Charged Leptons
  - 35% Hadrons
  - 4% Neutrinos
  - 2% Higgs/Goldstone bosons
- As bosons, there are no restrictions from Fermi statistics: cross sections are generally larger than for SUSY bino WIMPs.



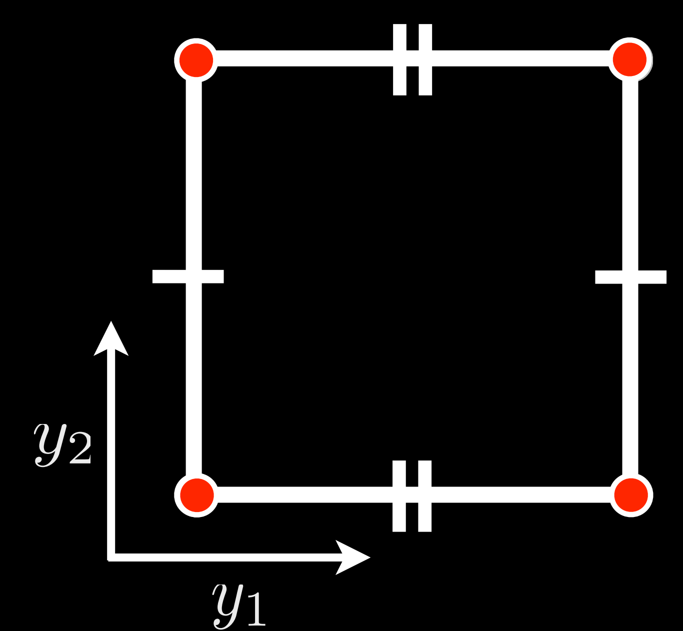
LKP Relic Density

G. Servant, TMPT, NPB650, 351 (2003)



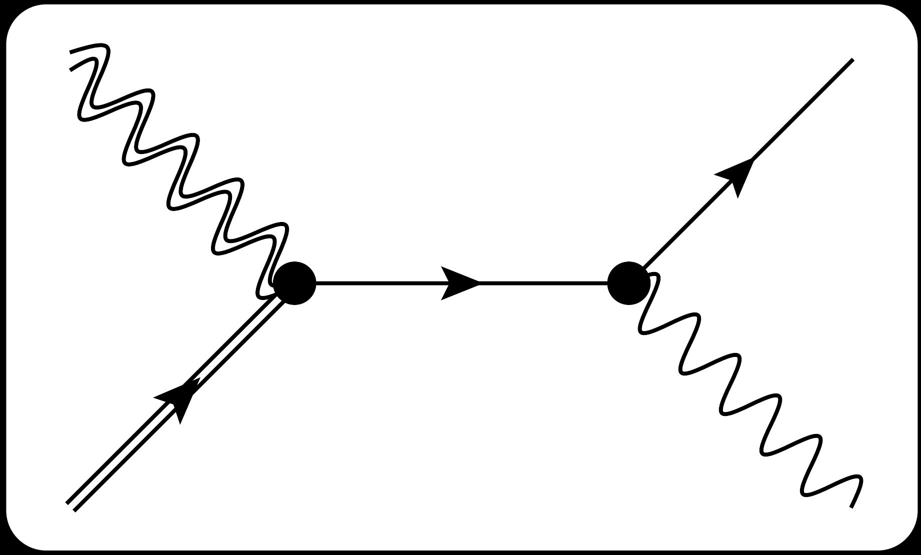
With no helicity suppression for annihilation, the LKP realizes the correct relic density for larger WIMP masses.

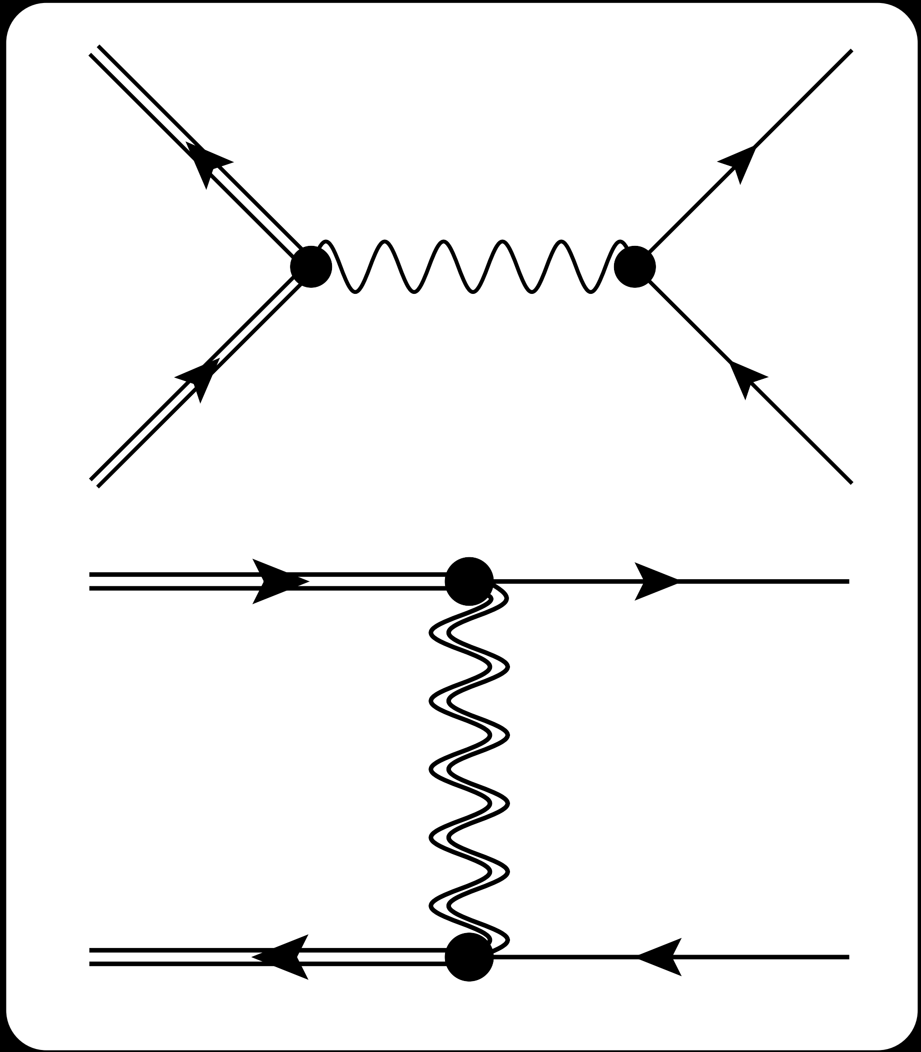
The 6d curve is for a 2-torus with equal radii (2 LKPs):



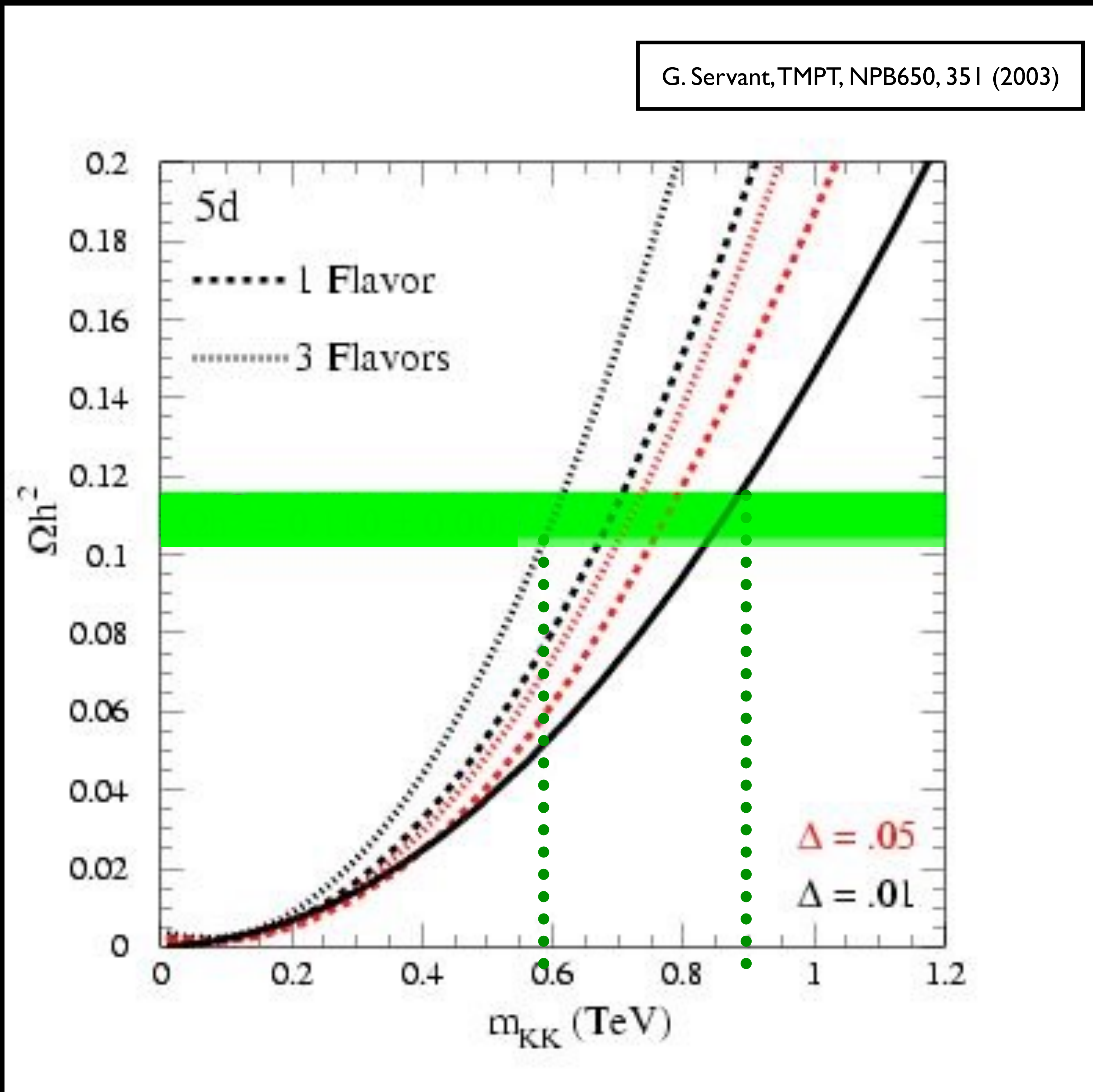
Co-annihilation

- Just like in SUSY, nearby particles can affect the relic density. In particular, we saw that the mass of $e^{(1)}{}_R$ is close to $B^{(1)}$ in mUED.
- However unlike SUSY, both particles interact with roughly with the same cross section, 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, rather than reduced.





Relic Density with Co-annihilation



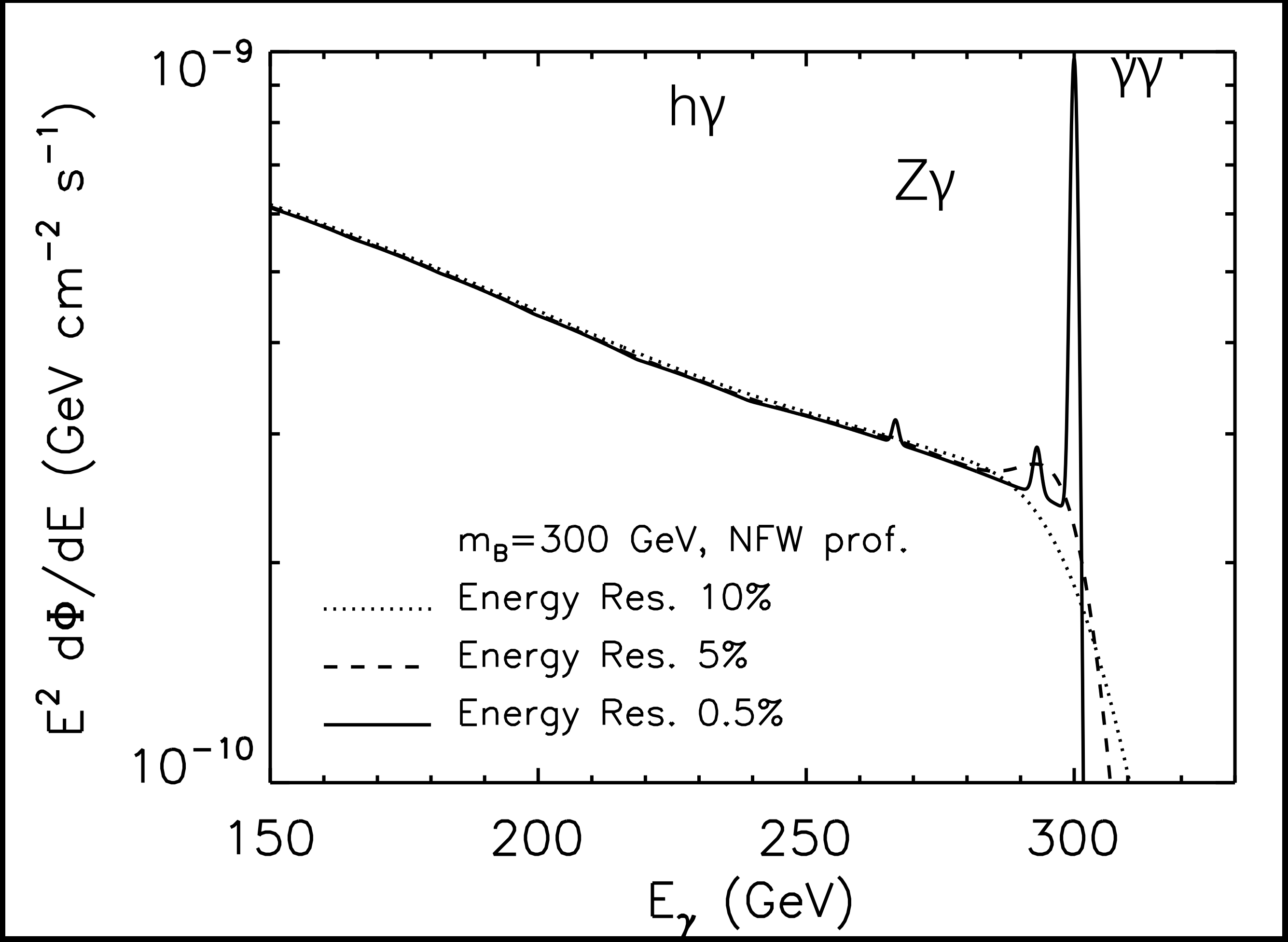
Coannihilation leads to an increase in the number of LKPs after freeze-out. To compensate, we dial down the mass of the LKP so that the correct relic DM energy density results.

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

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

Gamma Rays from UED

- There is a large rate for continuum γ's with a harder (than, say, SUSY) spectrum, because the LKP likes to annihilate into e^+e^-.
- There are γγ, γZ, and γ Higgs lines.
- Over-all, the lines are relatively faint, and tend to merge into the continuum photons from WIMP annihilations.
- Resolving them is possible for a very light LKP, and would require a next- (or next to next) generation gamma ray observatory.

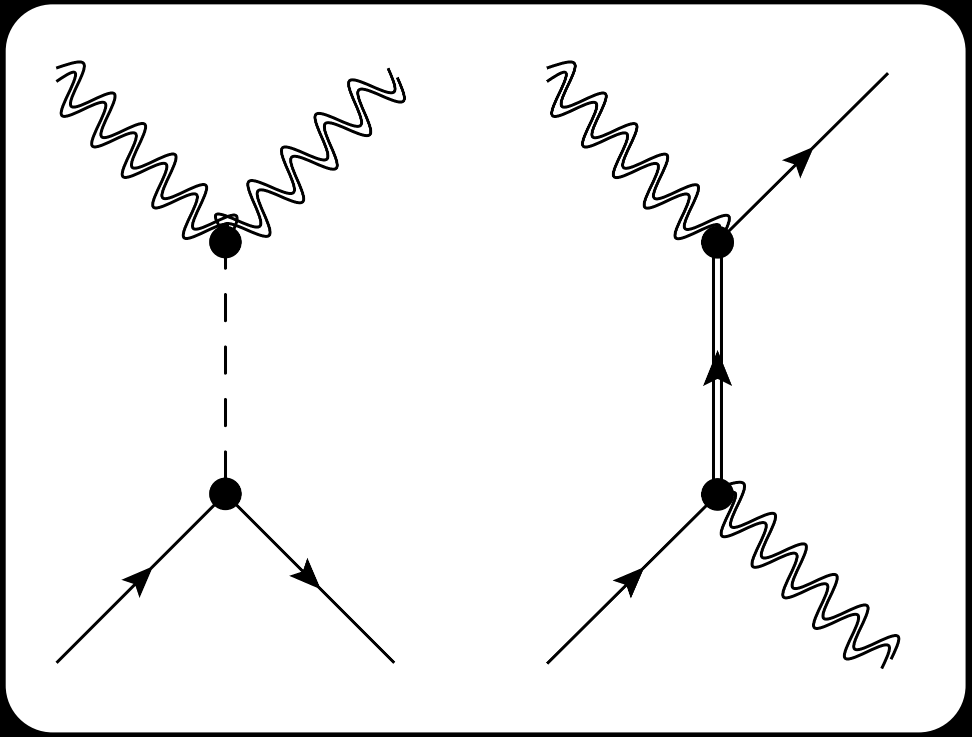


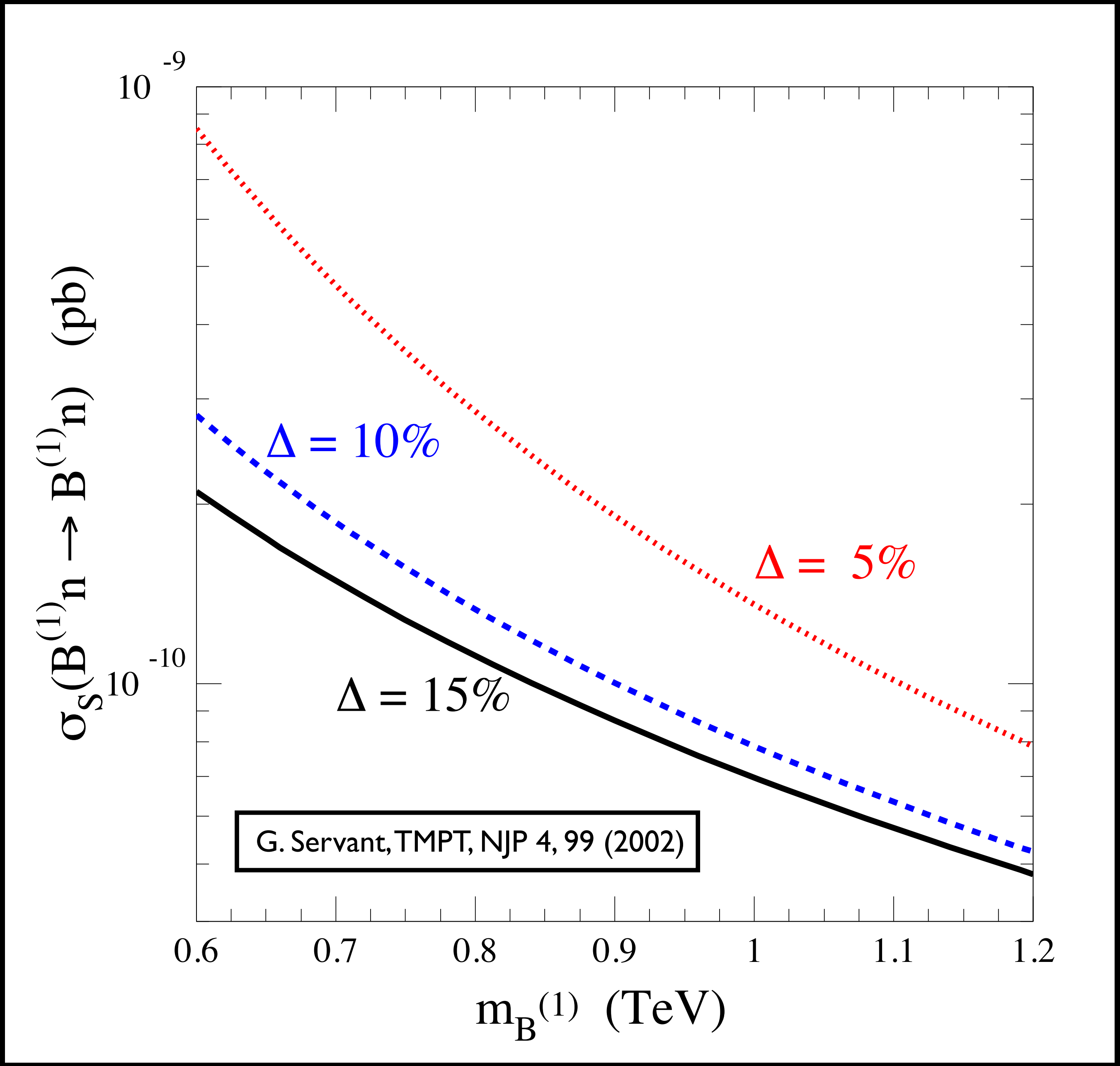
Bertone, Jackson, Shaughnessy, TMPT, Vallinotto 1009.5197

Direct Detection

- Much like the case of SUSY models, UED dark matter interacts with nuclei largely by exchanging Higgs (zero mode) bosons.

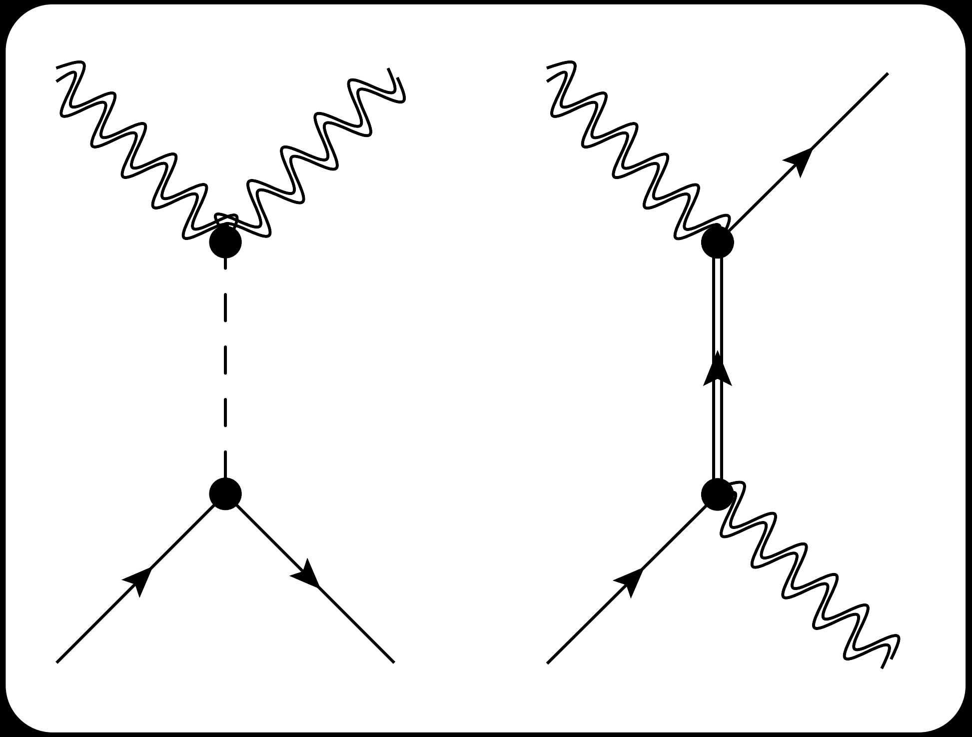
- KK quarks also contribute, but are expected to be heavier and thus less important.

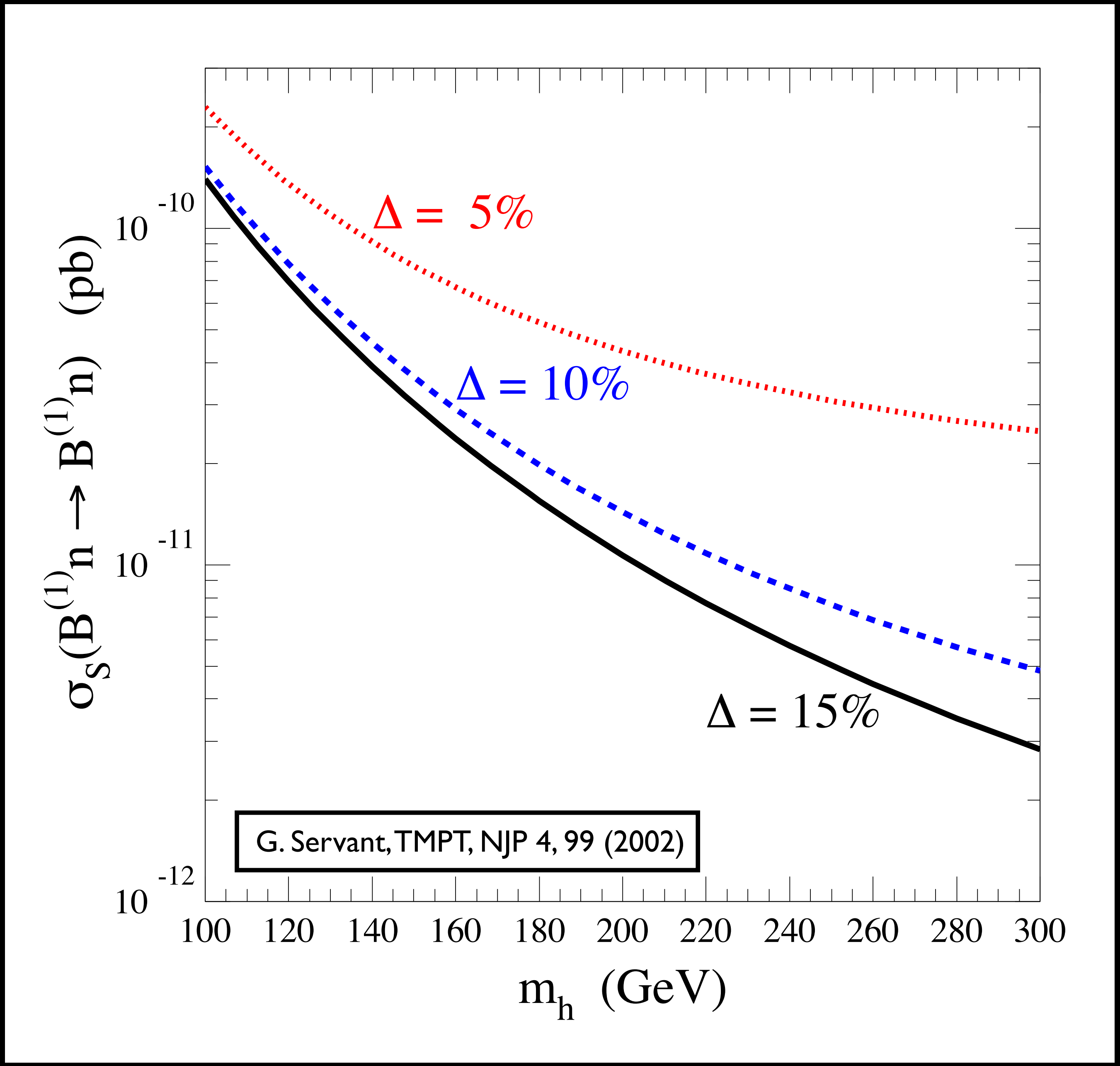




Direct Detection

- Higgs exchange usually dominates, because the Higgs is much lighter than the expected KK scale.
- At very low energies, the cross section goes like 1 / mass of the exchanged particle to the 4th power.

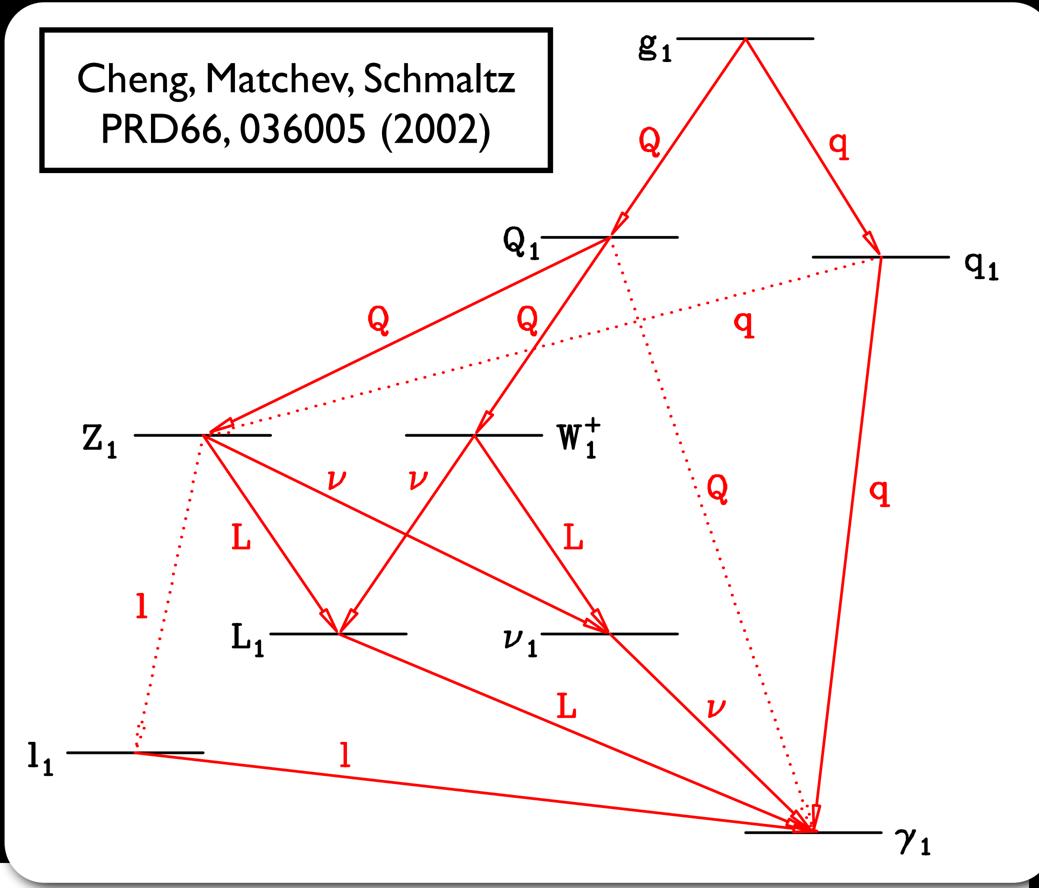


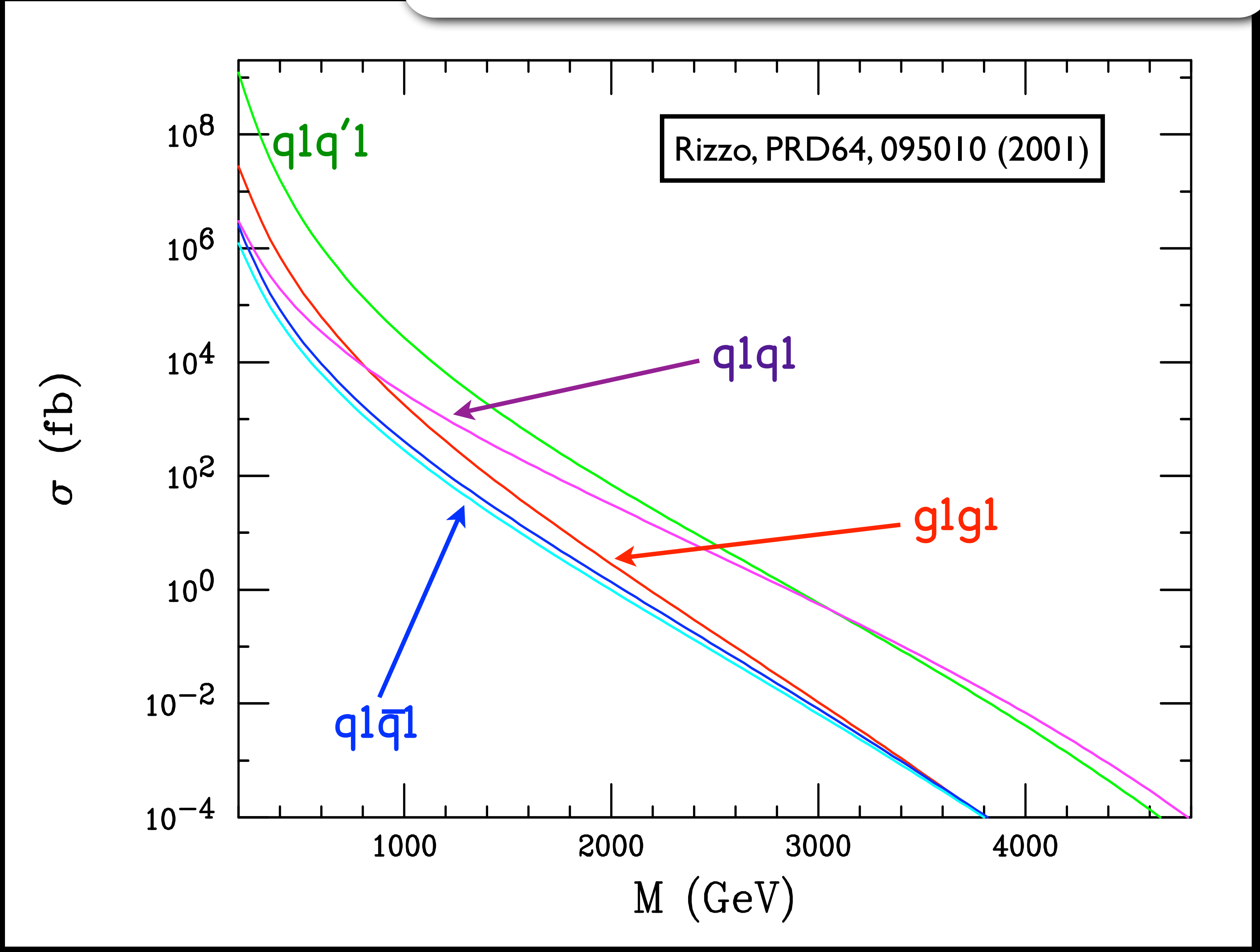


UED at the LHC

- At the LHC, one can expect cascade decays very much like we find in SUSY models, where we produce colored KK particles and they decay down through the weakly interacting ones into the LKP.

- This raises an interesting and important question: how do we measure the spins of particles when we can't observe some of their decay products directly?





6d UED: The Chiral Square

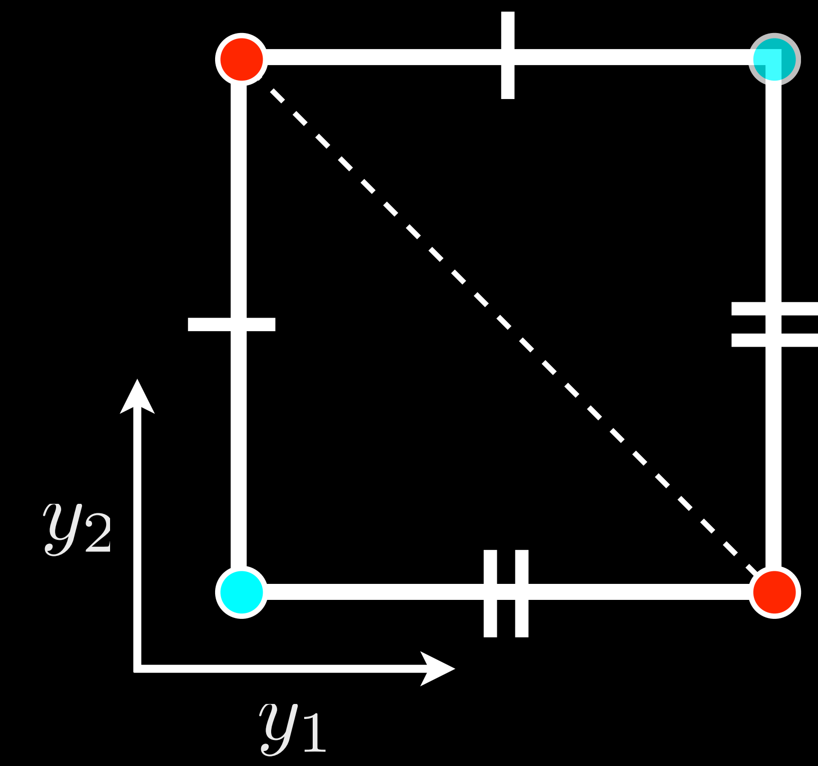
- Let's look at another example of a 6d model. The Chiral Square is a UED theory with two extra dimensions.

Burdman, Dobrescu, Ponton '04, '05

- The adjacent sides are identified as the same, which can be visualized as a square region folded along a diagonal. This is another orbifold compactification with chiral fermions.

- There are three "fixed points", where boundary terms can live which preserve KK parity.

- I'll follow the usual practice and assume the size of the boundary terms is consistent with their being generated by loops -- ``minimal UED".

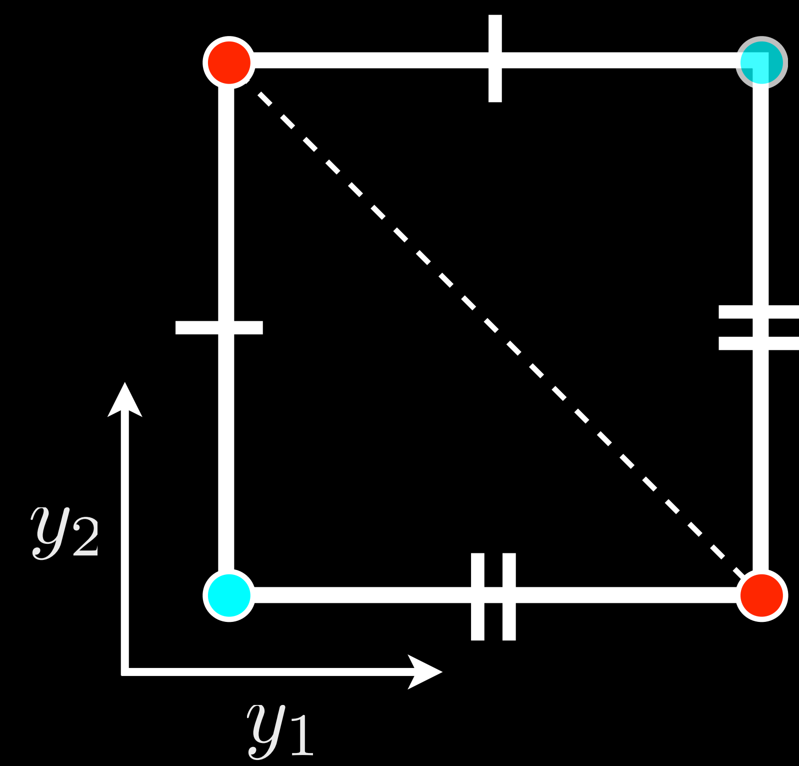


KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

Ponton, Wang '06

KK Decomposition

- In the case of a 6d UED model, KK modes are labelled by a pair of integers (j,k) indicating momentum flow in the extra dimensions.



- Masses are given (up to corrections from boundary terms) in terms of (j,k):

$$M^2_{(j,k)} \simeq \frac{1}{L^2}\left(j^2 + k^2\right)$$

- KK parity leaves the lightest of the j+k = odd modes stable, providing our stable WIMP.

$$V_M \to \{V_\mu, V_5, V_6\}$$

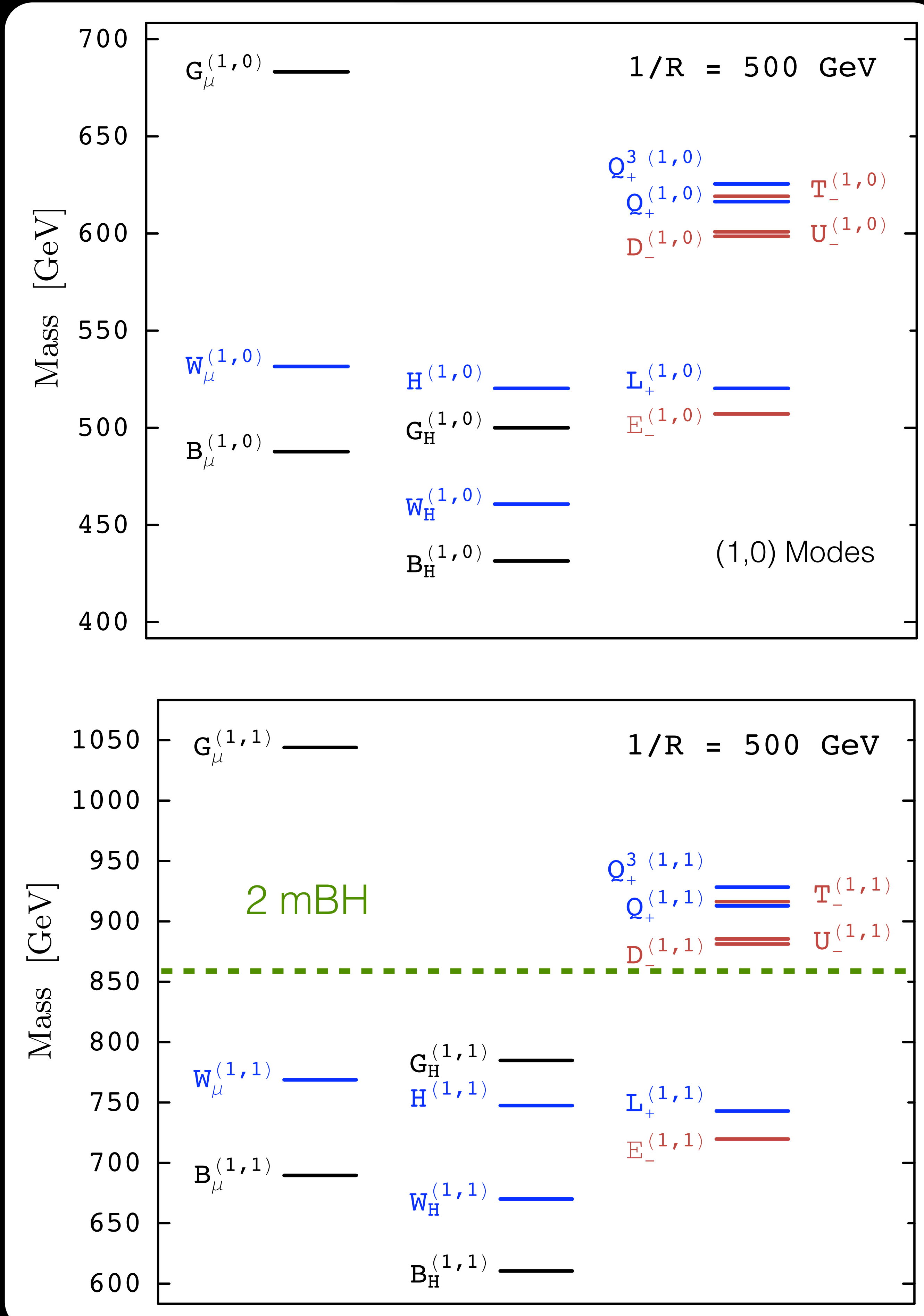
One combination eaten by massive Vμ, the other combination is physical.

- The vector bosons have KK towers corresponding to 4d vector particles (which contain a zero mode) and a combination of the 5 and 6 components which looks like a 4d scalar (without a zero mode).

Burdman, Dobrescu, Ponton '04

Spectrum

- As in the 5d theory, boundary terms modify the masses of the fields at a given (j,k) level.
- The LKP is usually the scalar (1,0) KK mode of the Hypercharge gauge boson, B_H.
    - Colored states are the heaviest of a given (j,k).
- The (1,1) modes are KK even and many have masses above M_B but below $2 \times M_B$.



BH Annihilations

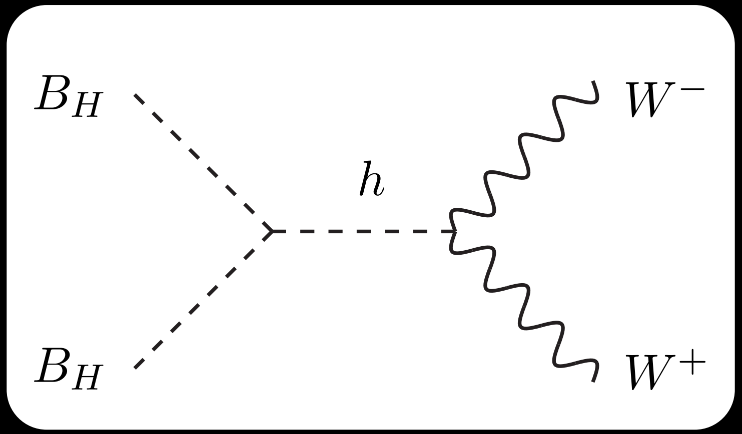
- Both the regions of parameter space and the continuum gamma ray emission spectra and rates are controlled by the tree level LKP annihilation channels.

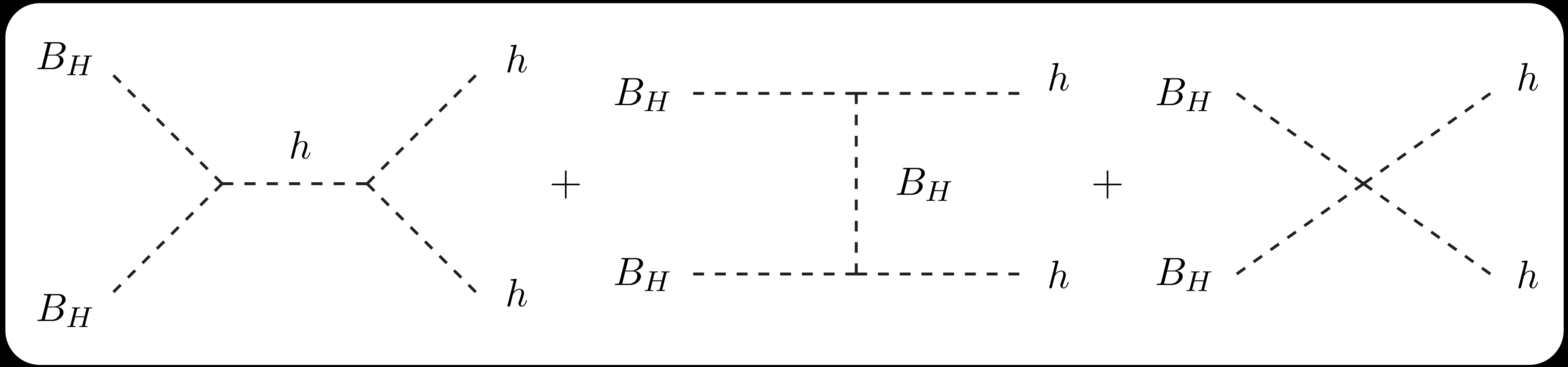
- BH is a real scalar and an electroweak singlet:

  - BH BH into fermions is suppressed by the final state fermion mass (more like what we saw in the MSSM than the 5d UED model).

  - Annihilation into weak boson and Higgs pairs are mediated by the Higgs boson itself.

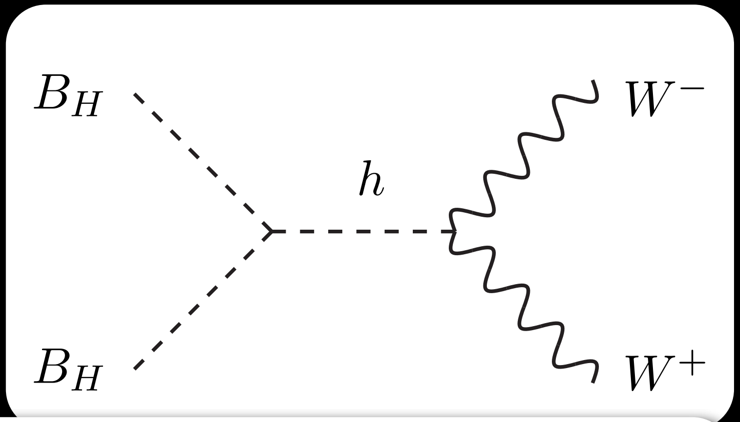
Dobresu, Hooper, Kong, Mahbubani, '07

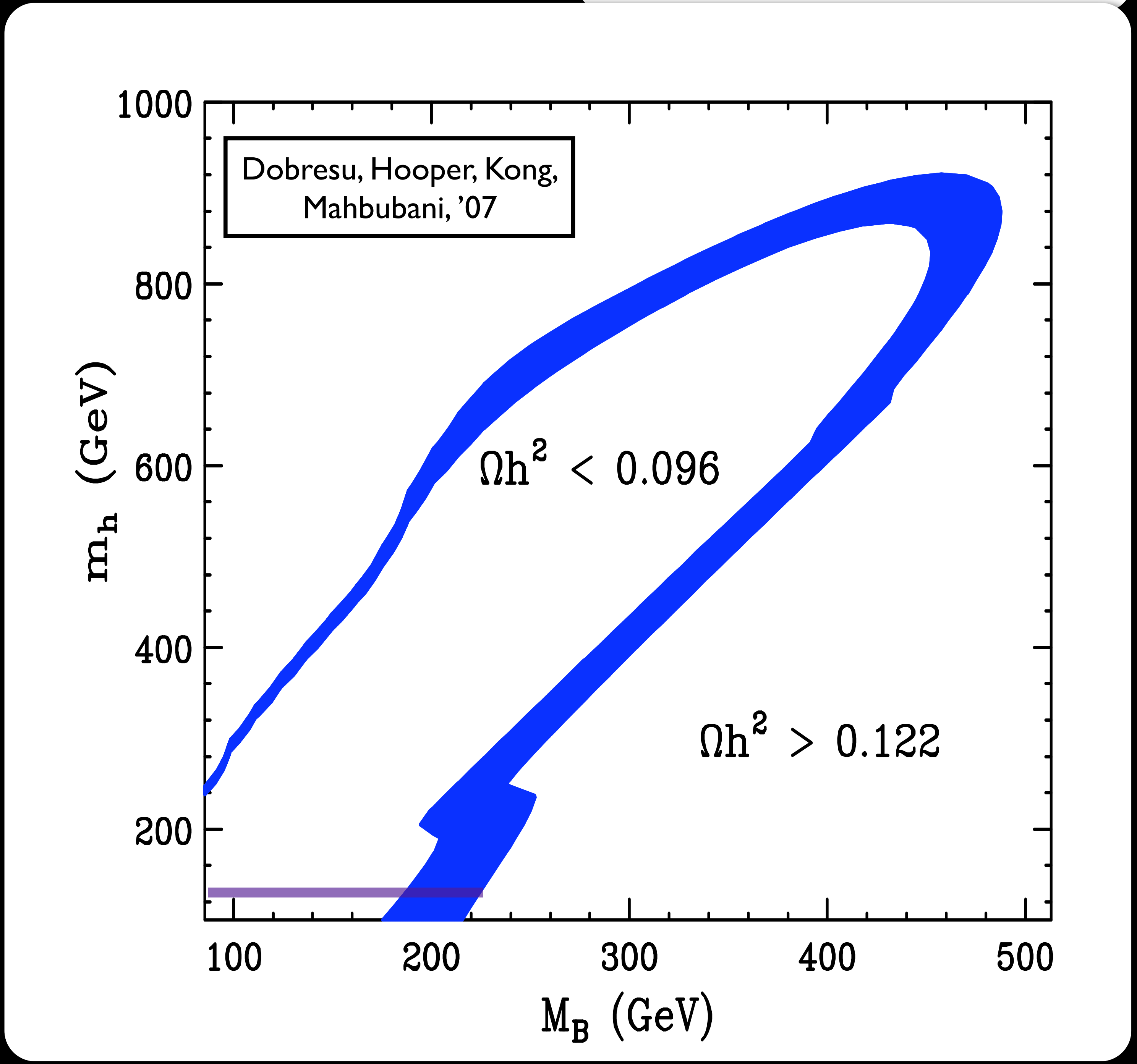




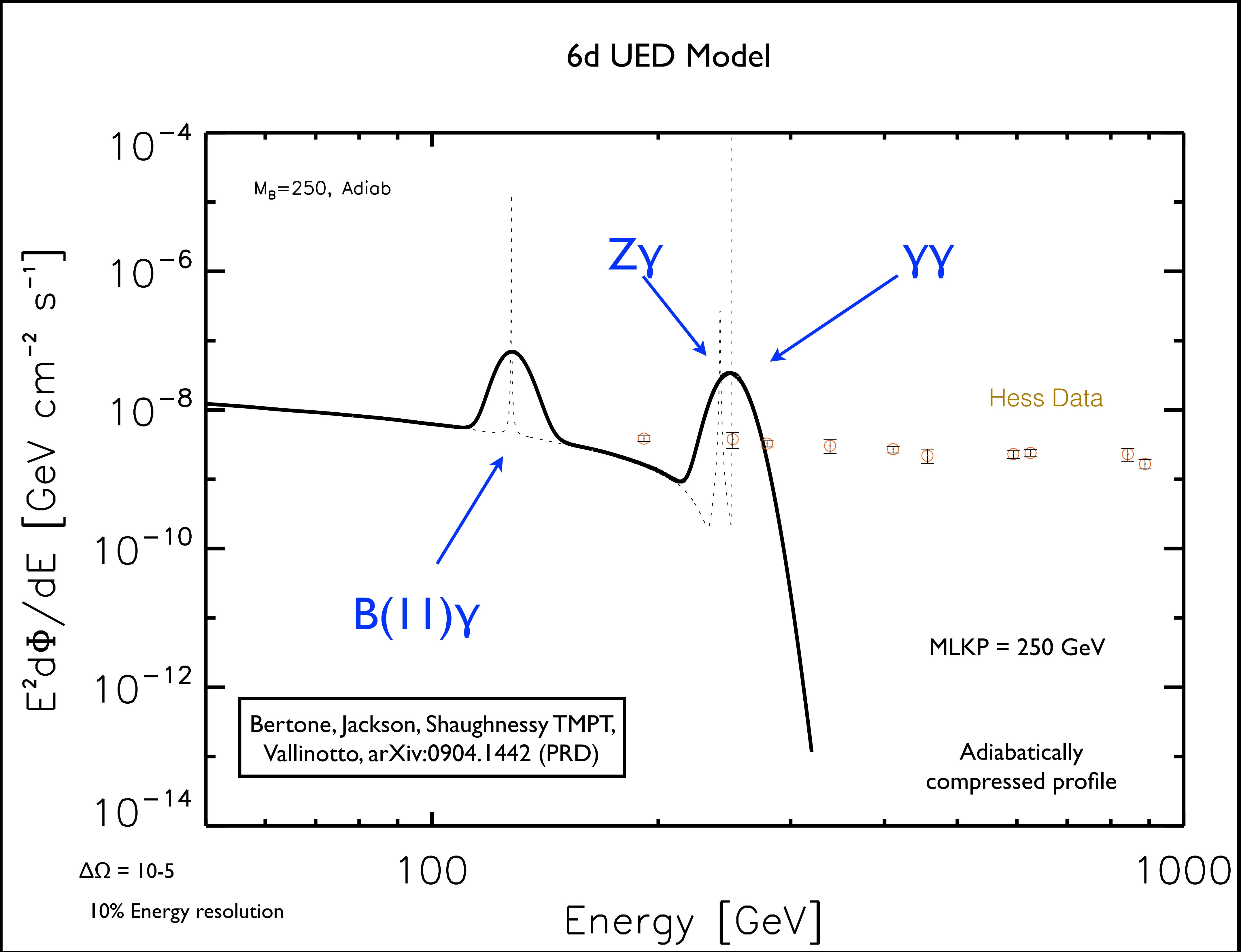
Relic Density

- Because of the s-channel Higgs-mediated graphs, the annihilation cross section is very sensitive to the interplay between the LKP and Higgs masses.
  - This is another example of a funnel region, like the ones we saw in the MSSM.
- The Higgs discovery at the LHC has severely collapsed the parameter space down to LKP masses around 200 GeV.





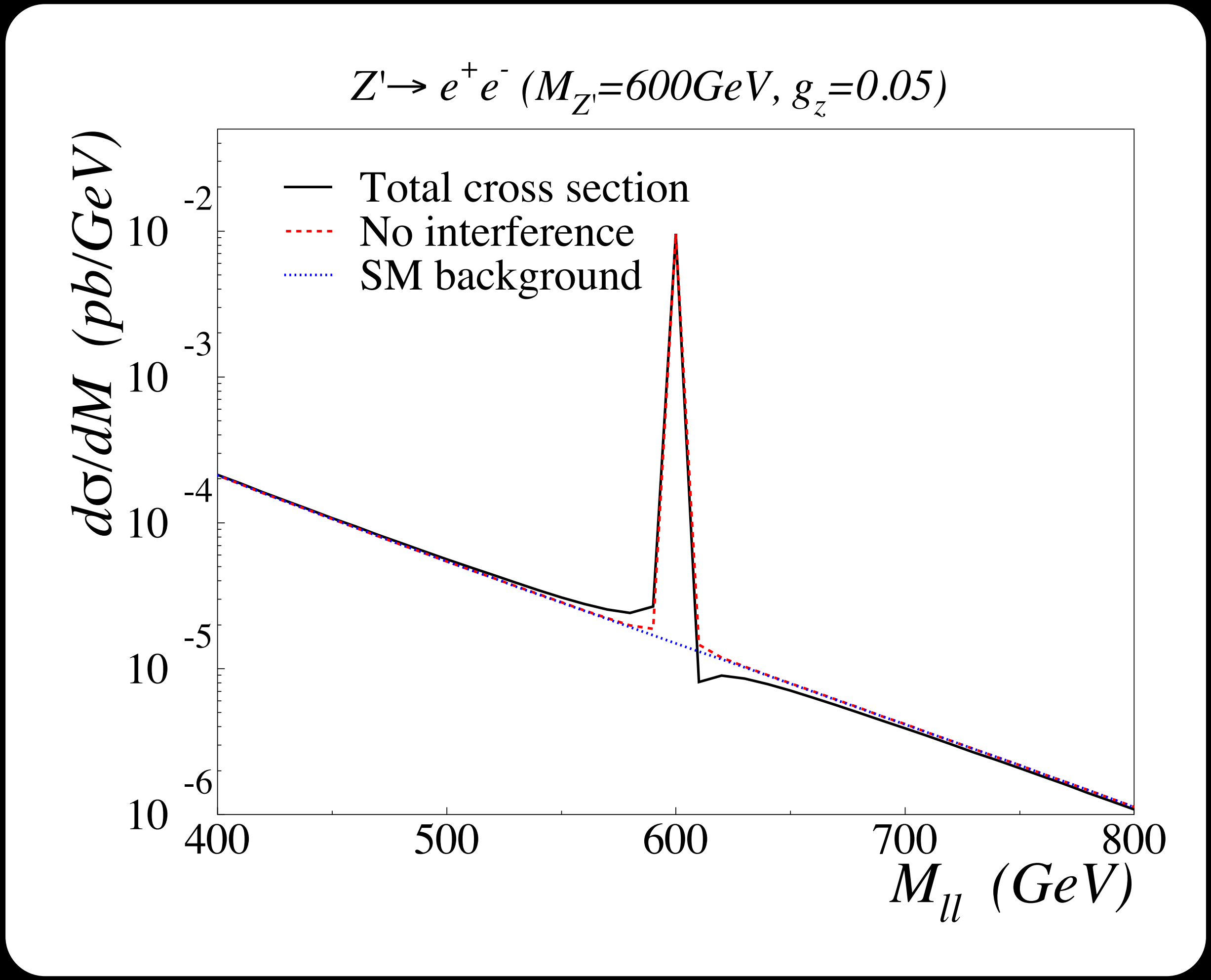
Chiral Square: γ-Rays

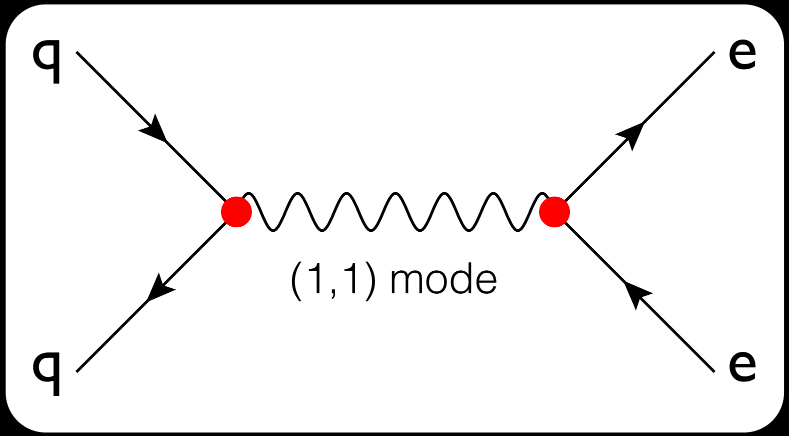


Note: The background is not well understood, so the HESS data should not be understood as a constraint, and is only shown for comparison.

B(1,1) at the LHC

- At the LHC, B(1,1), can be produced from a q qbar initial state (with reduced but substantial couplings proportional to hypercharge).
- It decays into ordinary leptons and quarks, providing a classic Z' signature.
- γ-ray observations can observe the secondary line, and measure the mass - telling the LHC where to look.
- LHC data severely constrains the potential size of the brane terms, limiting the coupling of the (1,1) state to zero mode (SM) fermions.



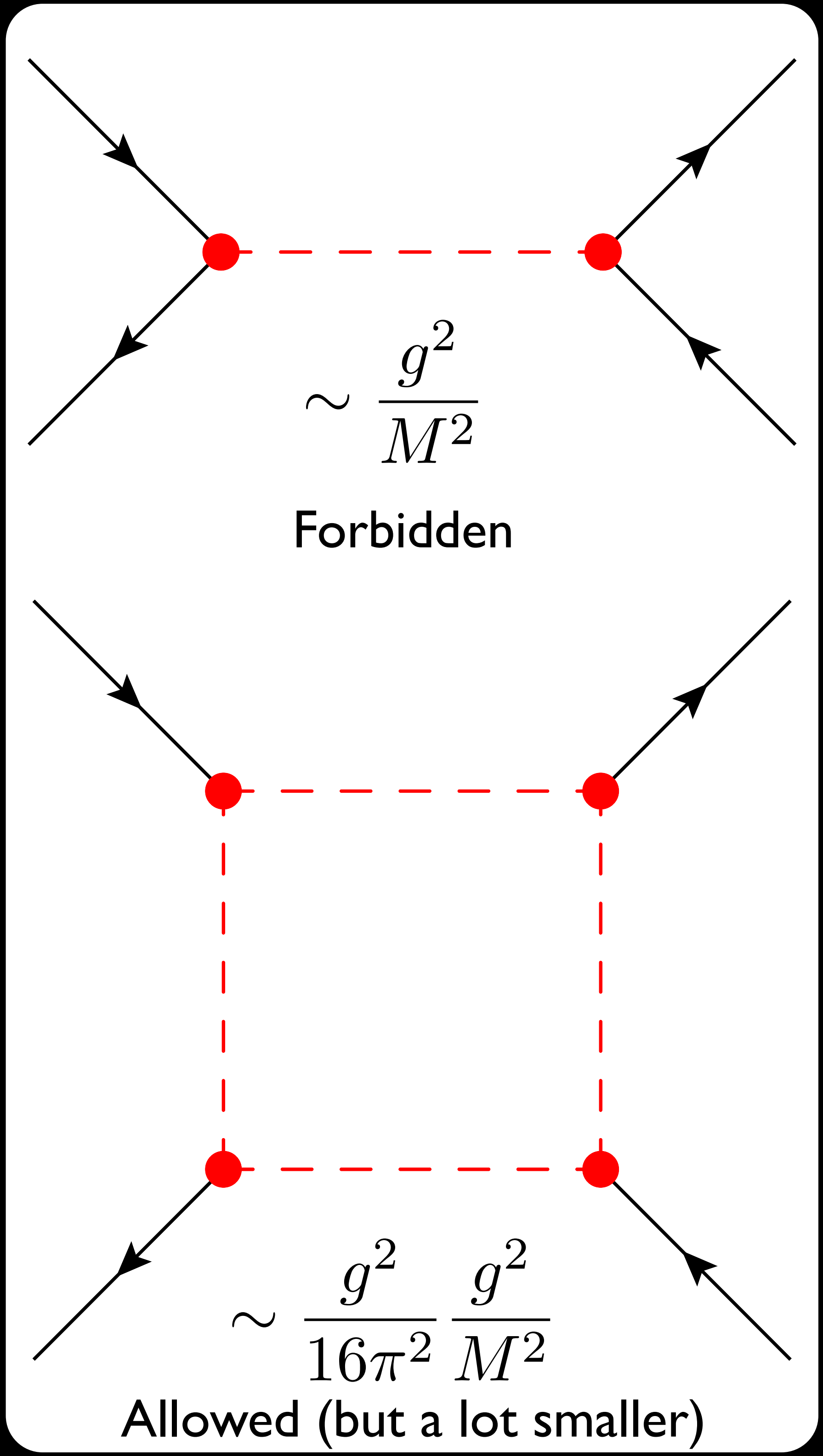


T-Parity

- Another symmetry which can stabilize dark matter is "T-parity".

Cheng, Low hep-ph/0308199

- T-parity is a phenomenological symmetry which can be invoked to protect precision measurements from large contributions from new physics.
- If one requires the new particles to couple in pairs, they can't contribute to SM processes at tree level, and first appear at loop level.
- This implies the lightest new particle is stable.
    - R-parity and KK-parity are both examples!
- We can still address the hierarchy problem which is a problem with loop diagrams.

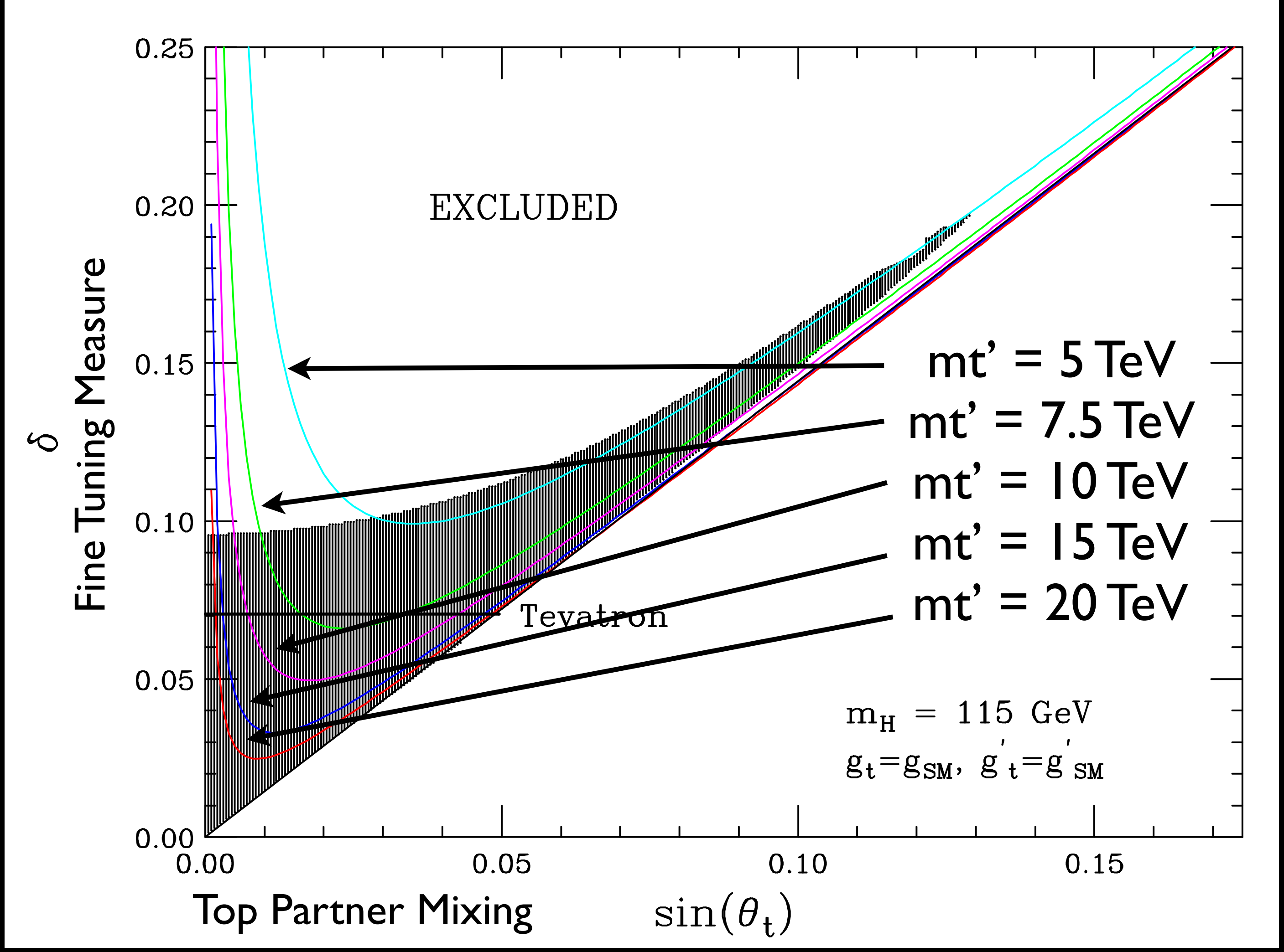


Little Higgs with T-parity

- Little Higgs theories attempt to create a gap between whatever stuff solves the hierarchy problem and the Higgs itself by engineering the Higgs to be a pseudo-Goldstone boson.

- It's a very nice idea, but it faltered in practice when it was found that precision electroweak data made it difficult to realize in practice.

- T-parity allows the extra new particles ("partners") to have light enough masses to make the Little Higgs idea workable.



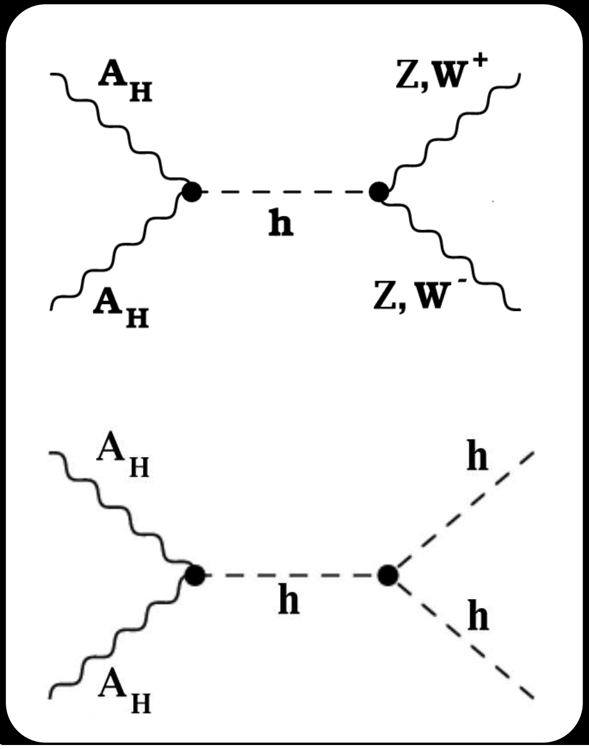
$$\delta \equiv \frac{v}{f}$$

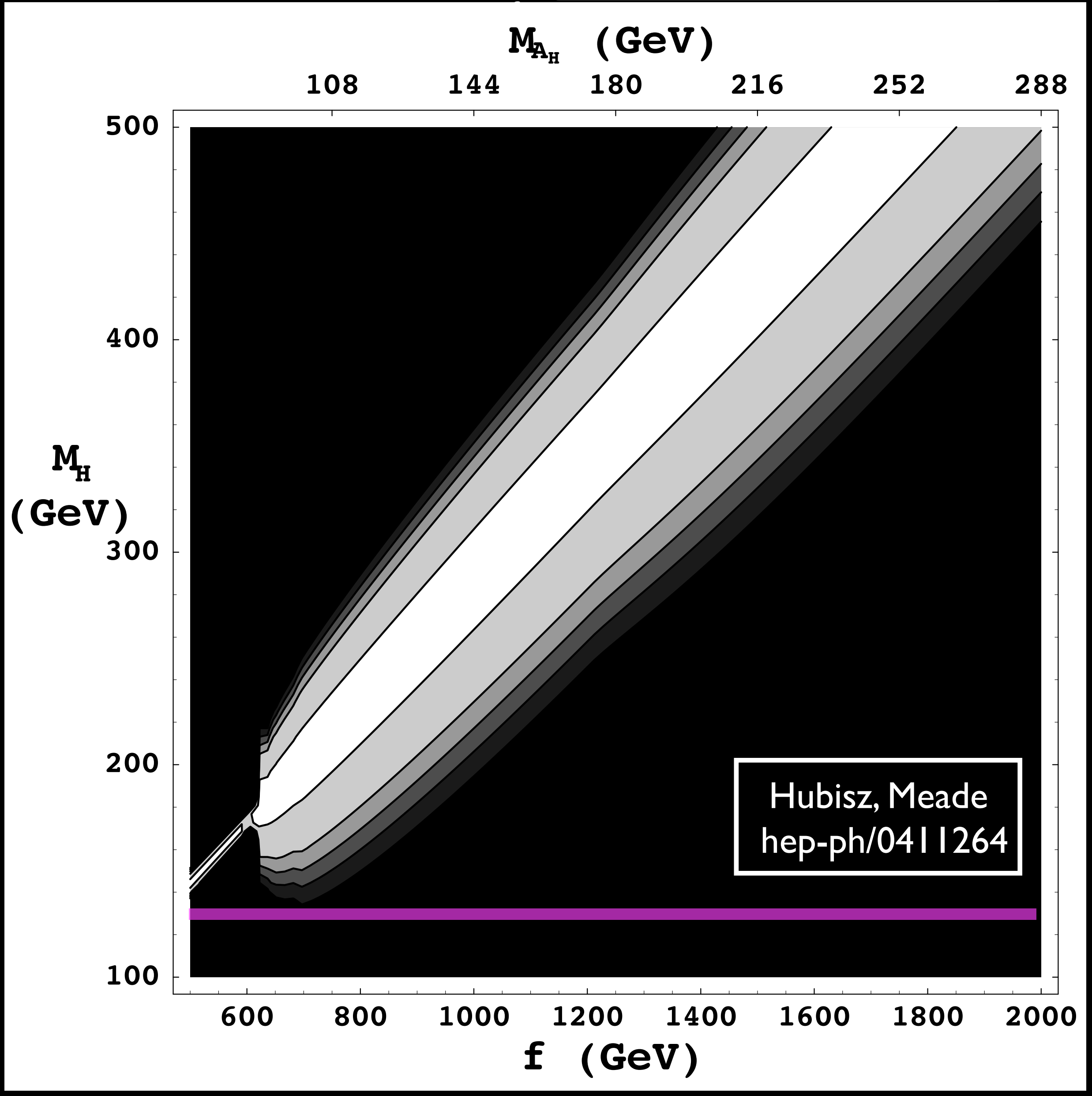
Hewett, Petriello, Rizzo
hep-ph/0211218
See Also: Terning et al
hep-ph/0211124

Less fine-tuned theories result, with new states coupling in pairs -- the Lightest T-odd Particle is DM!

LTP

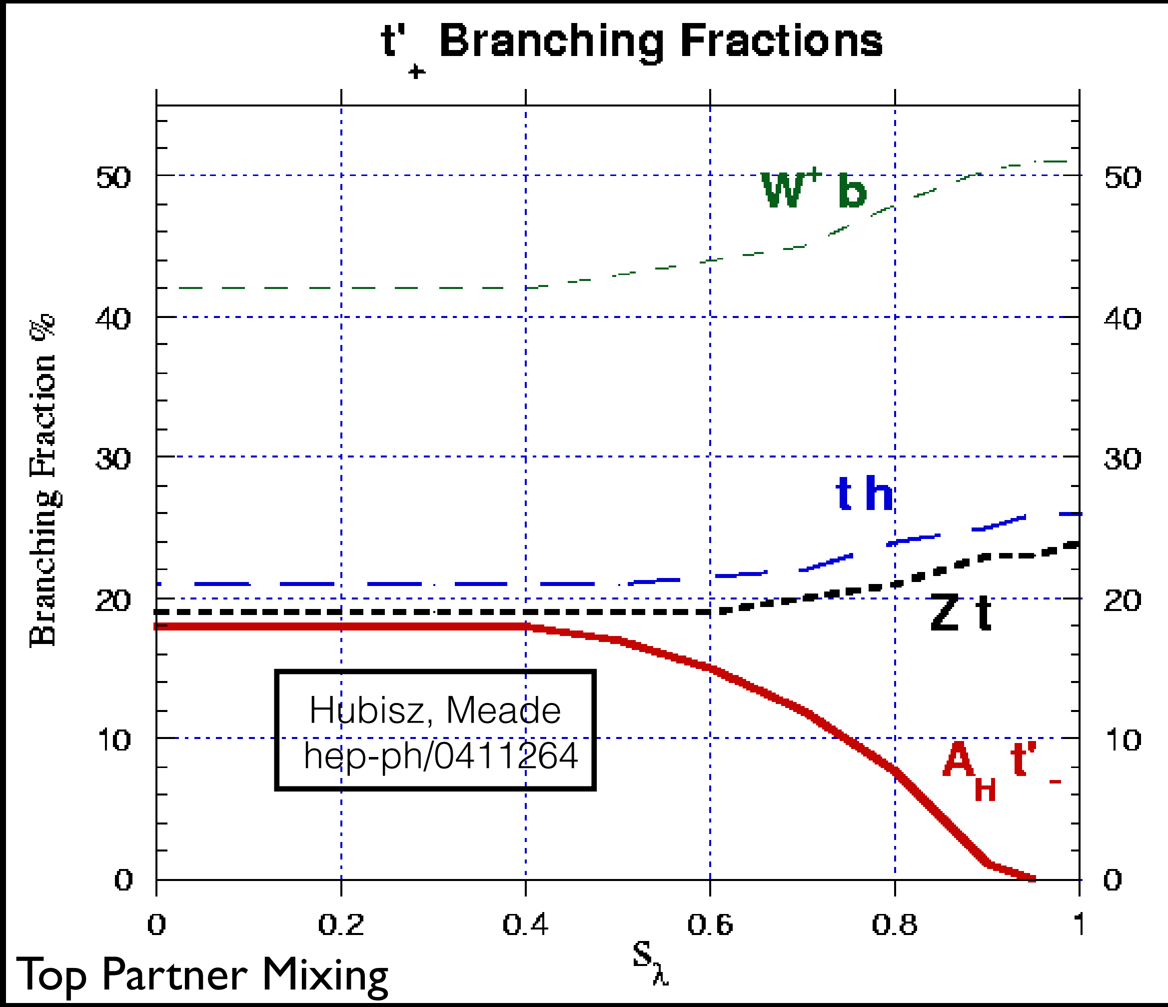
- A simple LH model with dark matter is the "Littlest Higgs with T-parity".
- The lightest particle is often a U(1) gauge boson, very similar to the LKP.
- The key difference is that the model only needs light partners for particles which couple strongly to the SM Higgs.
  - The t, W, Z, h partners are all light.
  - All other partners are assumed very heavy.
  - As a result, the cross section away from the SM Higgs funnel is always way too small to give us the correct relic density for a Standard Cosmology.
- This simplest model is ruled out by the LHC because the SM Higgs is too light.

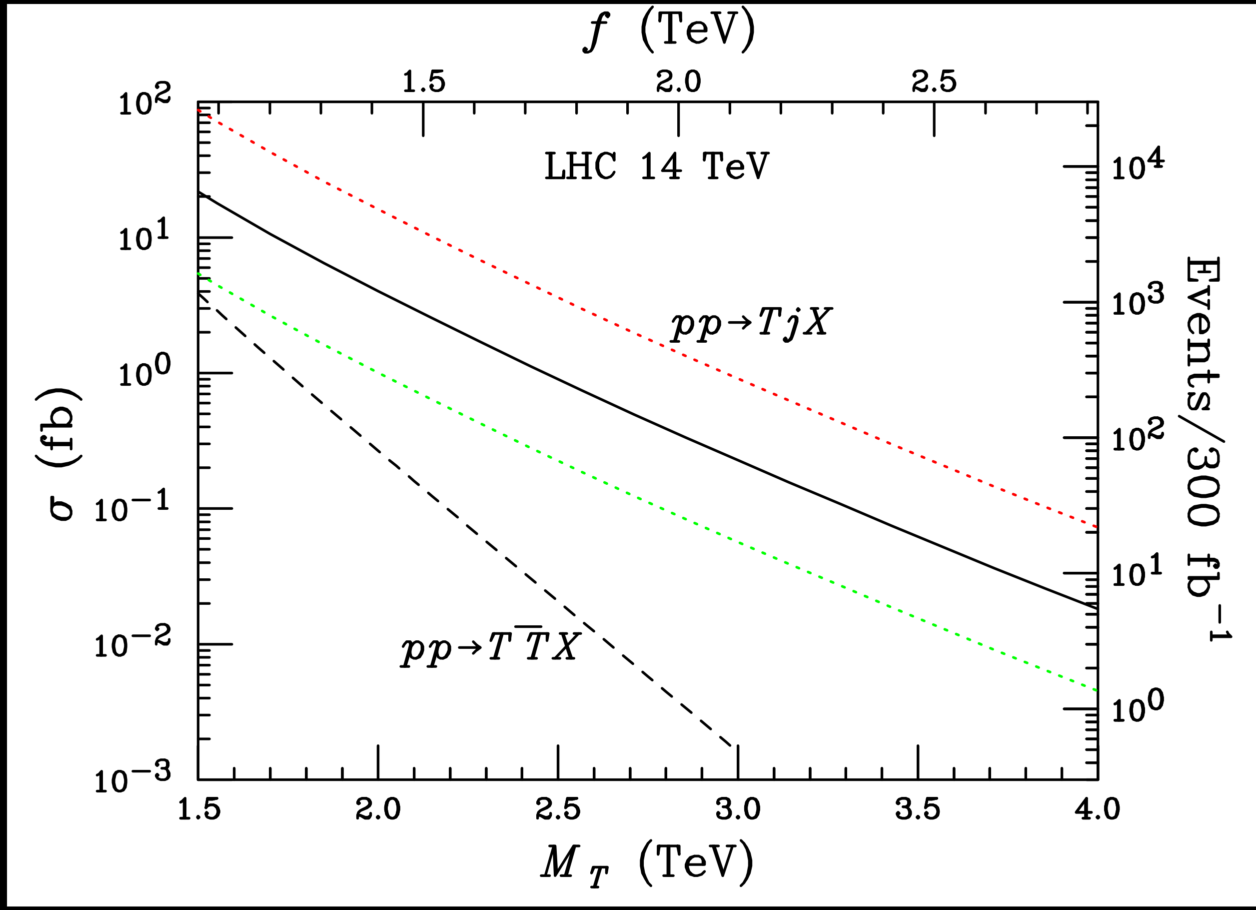




LHC Signals

- The LHC signals are dominated by the light colored partner (the top-partner).
- It turns out there are two:
  - A T-odd one which decays into t + LTP.
  - A T-even one which decays to W + b, Z + t, and/or h + t.
- The cross section for pair production of the top partners is QCD : depends on the mass & αS.
- Single production of the T-even partner can dominate.





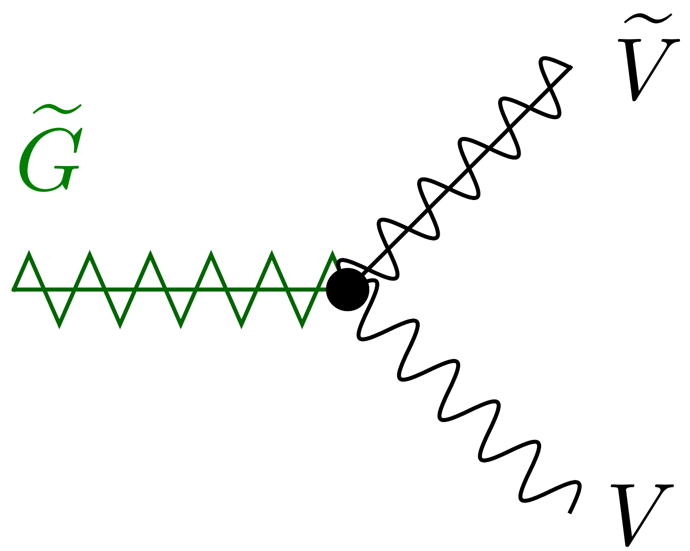
Han, Logan, McElrath, Wang
hep-ph/03o1040

Recap: UED and T-parity

- Other theories of dark matter arise when the Standard Model is extended in such a way that there are "partner" fields and something makes the lightest of such states stable.
    - SUSY: R-parity (imposed by hand to forbid proton decay)
    - UED: KK-parity (remnant of the 5 or 6d Poincare symmetry)
    - T-parity: Imposed by hand to help avoid precision electroweak constraints.
- Since the new particles feel the same SM interactions, generically they must have ~ TeV scale masses, and will behave like WIMPs.
- Nonetheless, there is a lot of phenomena which is distinct from supersymmetric models.
    - The most dramatic example is when the dark matter is not a Majorana fermion, and as a result has different statistical behavior, which can dramatically upset the annihilation channels and cross section.
    - At the same time, many features show similarity: generically there is a good chance to make an observation in direct detection and collider signals often involve cascade decays.

Super-WIMPs

- Dark matter could be super-weakly interacting.
- In general, this allows us to consider a particle which can decay, as long as its lifetime is long enough that it lives for more than the current age of the Universe.
- This gives up the beauty of the WIMP miracle, but is still an interesting possibility.
- In fact, both SUSY and UED theories naturally have a particle which could be dark matter and falls into this category:
  - SUSY: spin 3/2 gravitino
  - UED: spin 2 KK graviton
- I'll focus on the gravitino here, but the generalization to the KK graviton is rather straightforward.



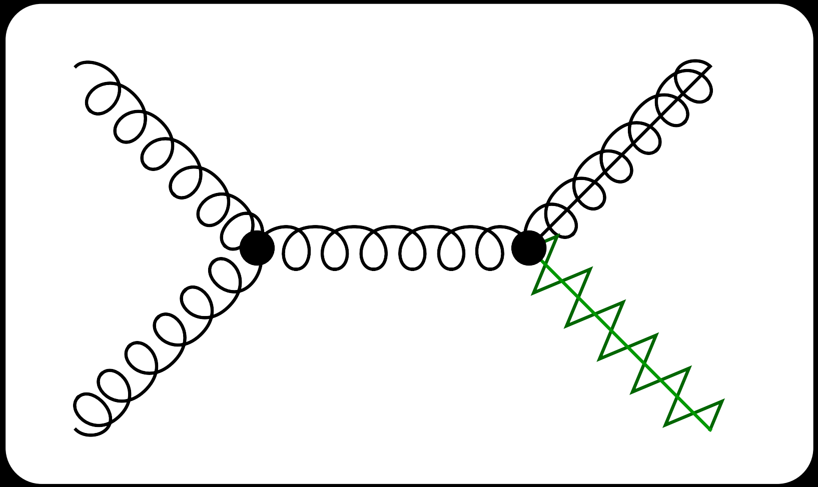
$$\sim \frac{M_{\widetilde{V}}}{F} \sim \frac{M_{\widetilde{V}}}{m_{\widetilde{G}} M_{\rm Pl}}$$

Dominant Coupling through the Goldstino component

For more UED details, see:
Feng, Rajaraman, Takayama
hep-ph/0302215 & 0307375

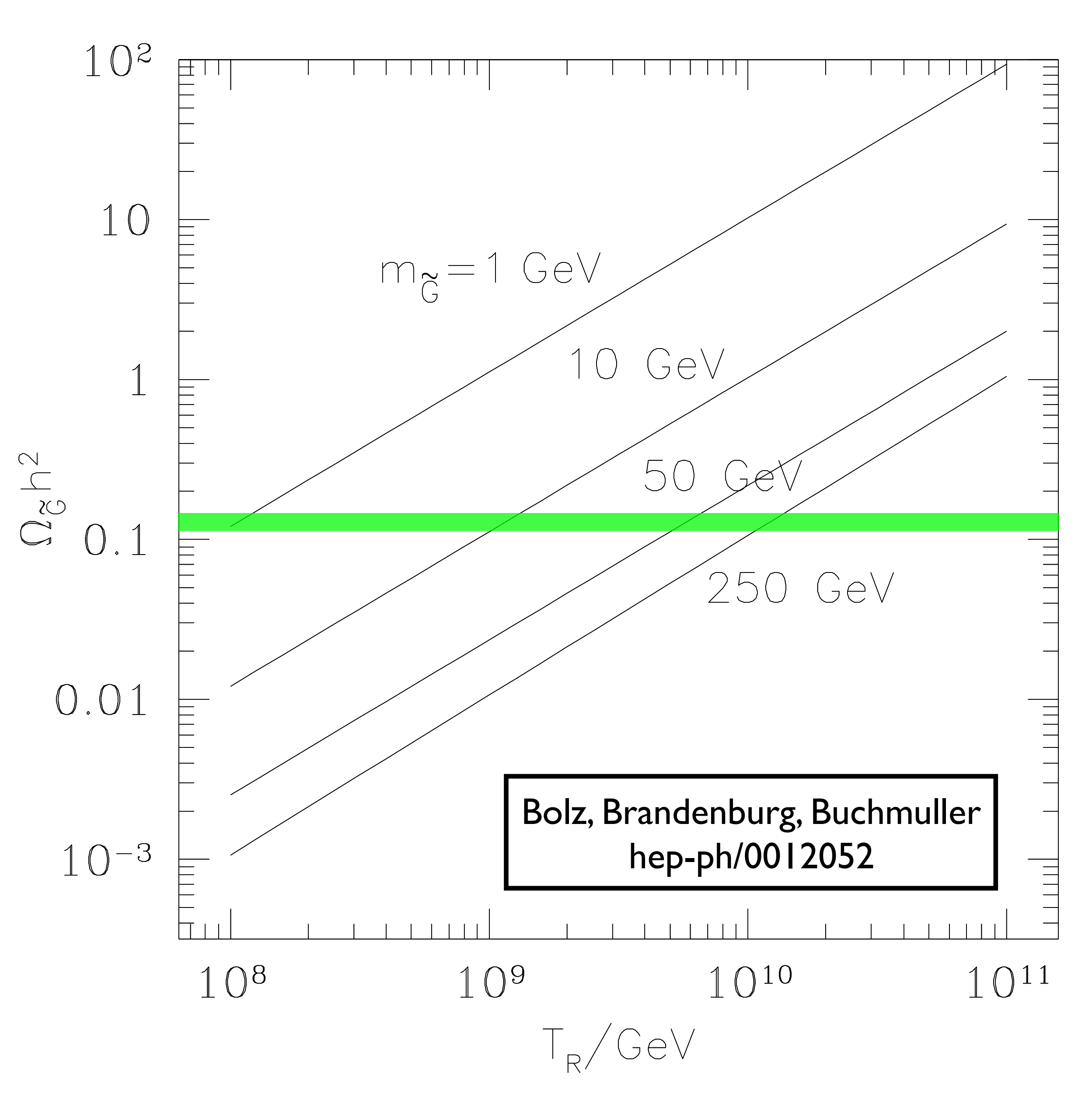
Relic Gravitinos

- Though they are never in equilibrium, we can still produce relic gravitinos:



- One mechanism is to have them *freeze-in*.

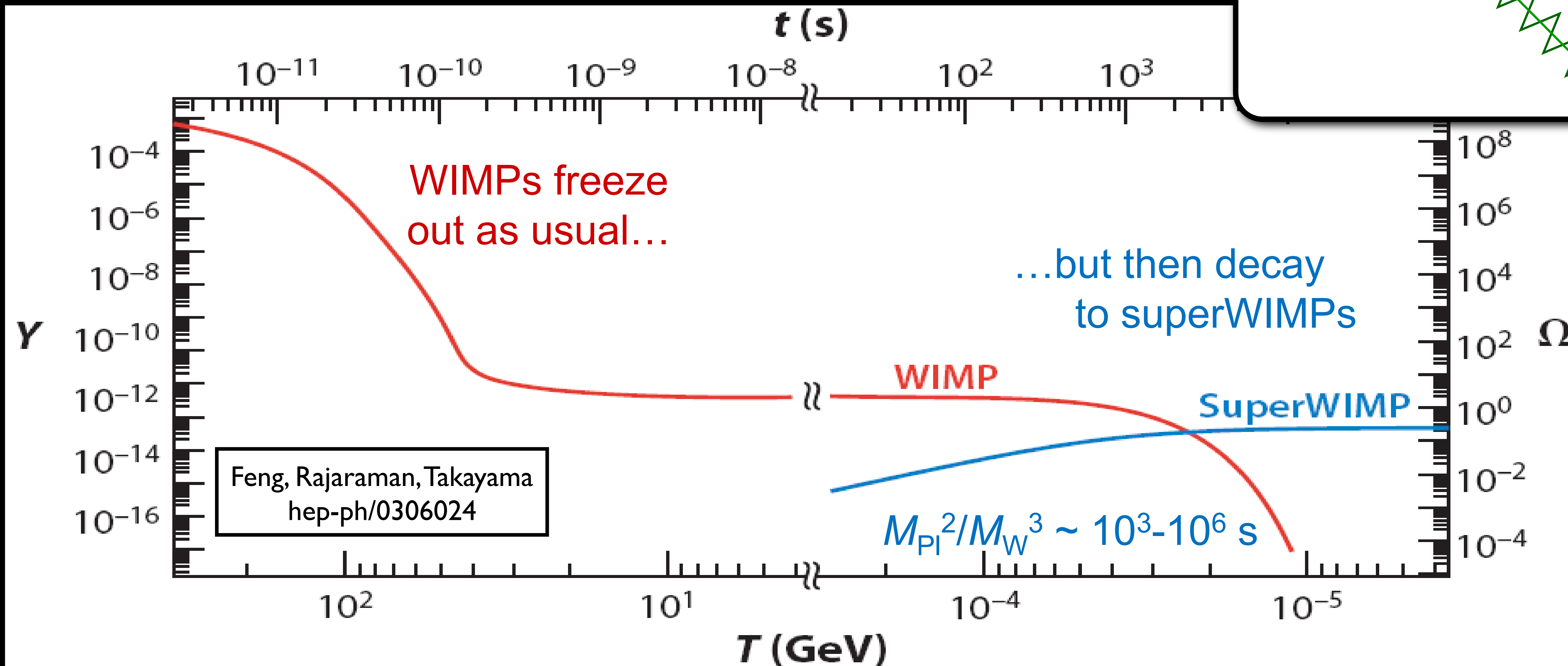
- Since they fail to reach equilibrium and their interactions are non-renormalizable, the quantity generated depends very sensitively on the reheating temperature at the end of inflation.

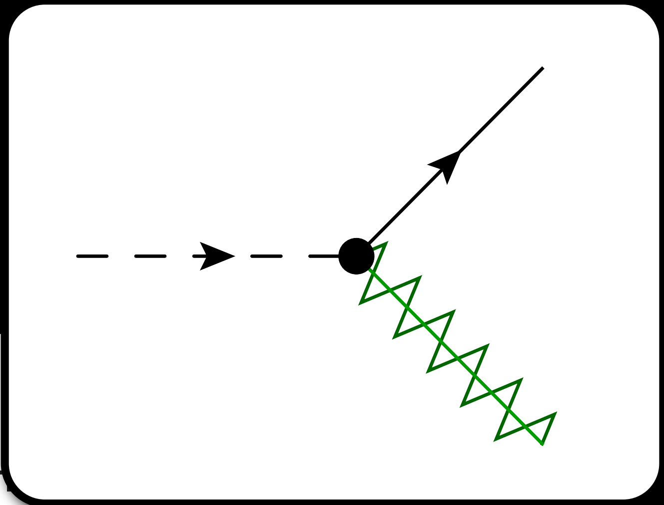


- This can be a problem -- if they are overproduced, we can end up with too much dark matter, leading to a bound on T_R.

- For just the right T_R, we get $\Omega h^2 \sim 0.1$.

Late Decay





- A gravitino LSP can also be produced by the late decay of a more conventional WIMP, inheriting its relic density.
  - The NLSP need not even be neutral!
- Some care is needed to have the decay not destroy light elements.

Axion Dark Matter

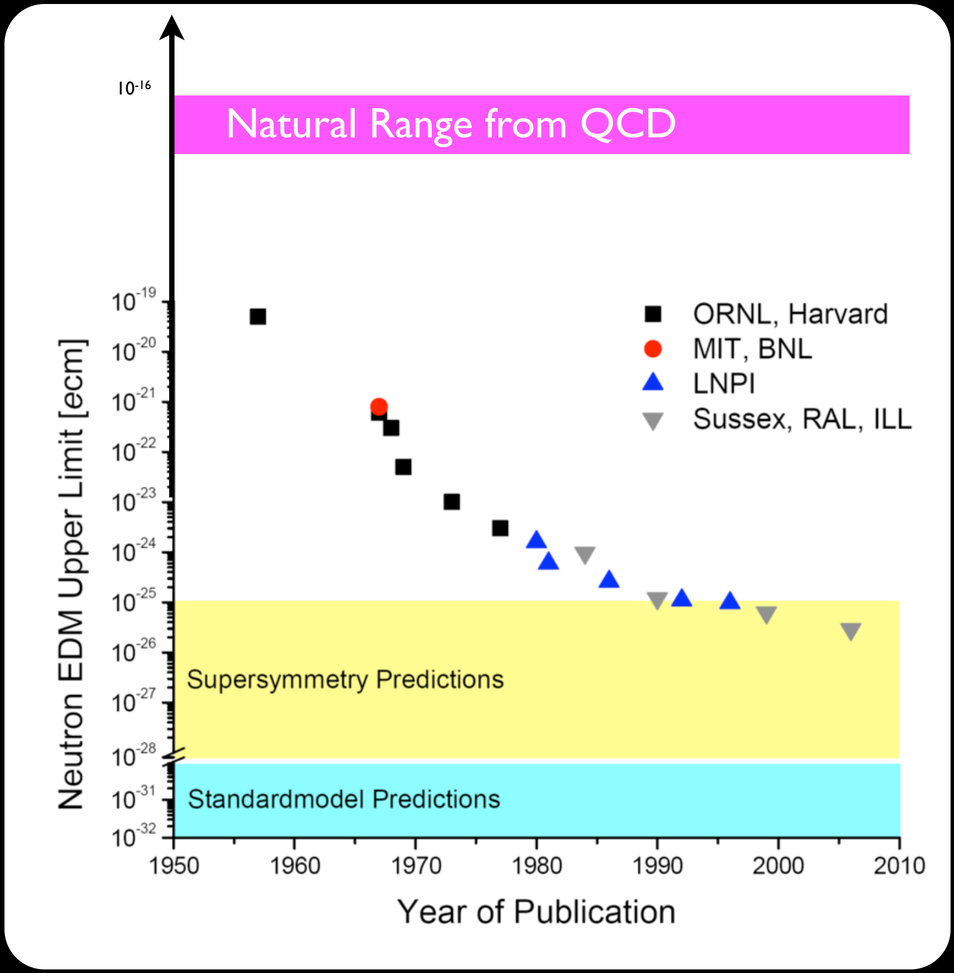
- The axion is motivated by the strong CP-problem, where the QCD θ term is cancelled by introducing a scalar field -- the QCD axion. Peccei, Quinn ’77

- The axion’s mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

$$m_a \sim f_\pi / f_a \times m_\pi$$

- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

- More generally, string theories often contain axion-like particles which are long-lived and can play the role of dark matter but have less tight correlations between their masses and couplings.

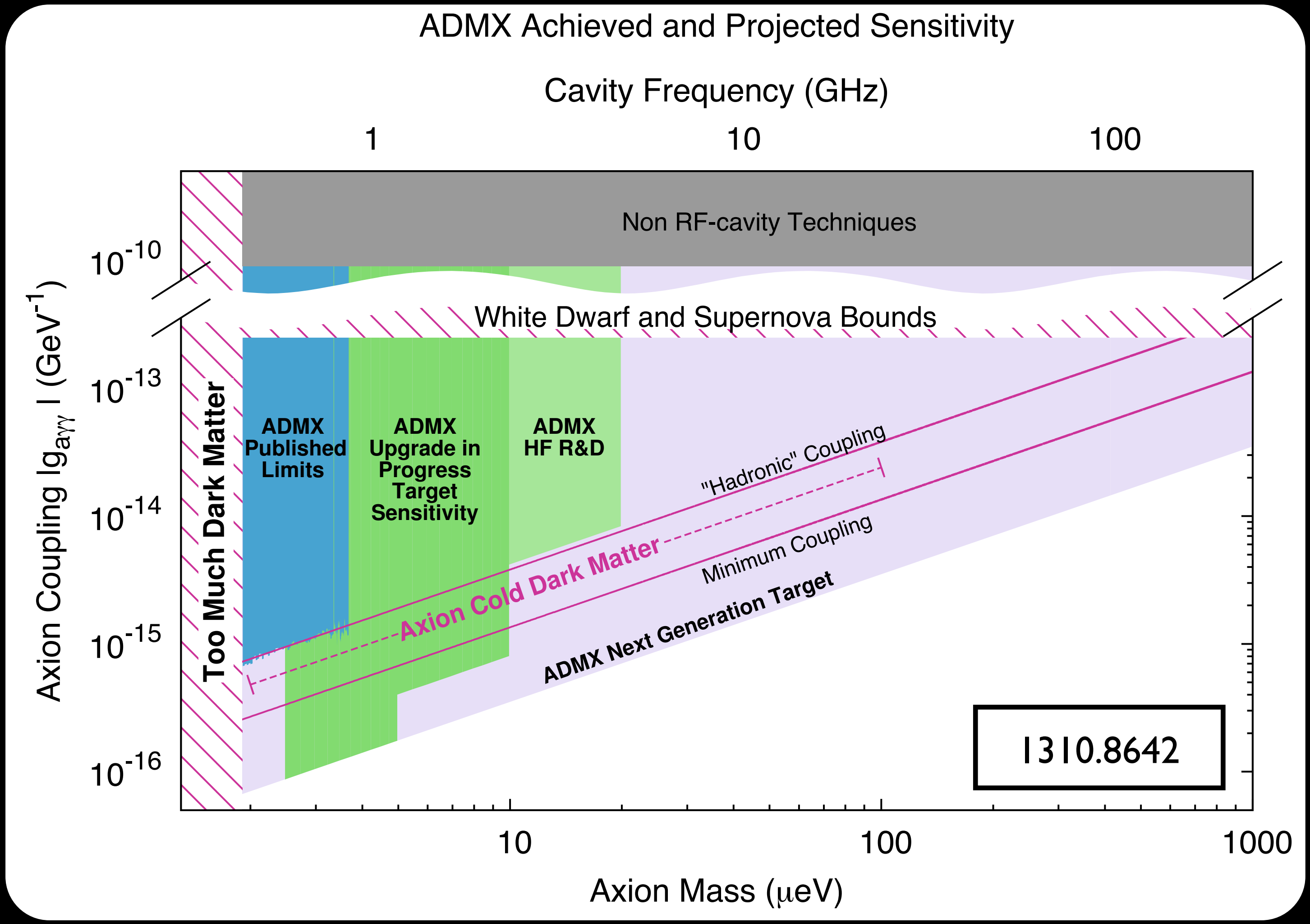


Preskill, Wise, Wilczek ’83
Abbott, Sikivie ’83
Dine, Fischler ’83

Axion Conversion

$$\frac{1}{f_a}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu} \longrightarrow \frac{1}{f_a}\, a\, \vec{E}\cdot\vec{B}$$

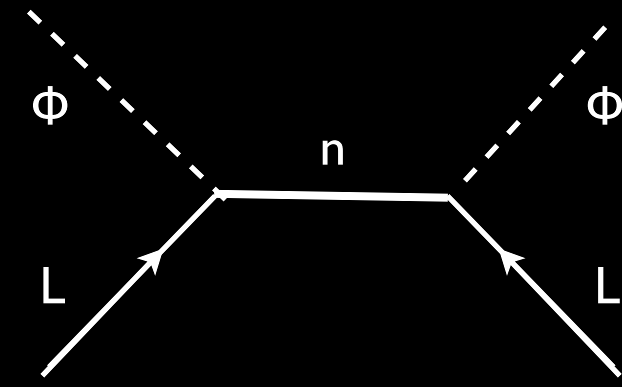
- The axion has a model-dependent coupling to electromagnetic fields that is somewhat smaller than 1 / f_a.
- There is a rich and varied program of axion searches based on this coupling.
- One particular search looks for ambient axions converting into EM signals in the presence of a strong background magnetic field.
- Other very interesting new ideas are to look for time variation in the neutron EDM or the induced current in an LC circuit.

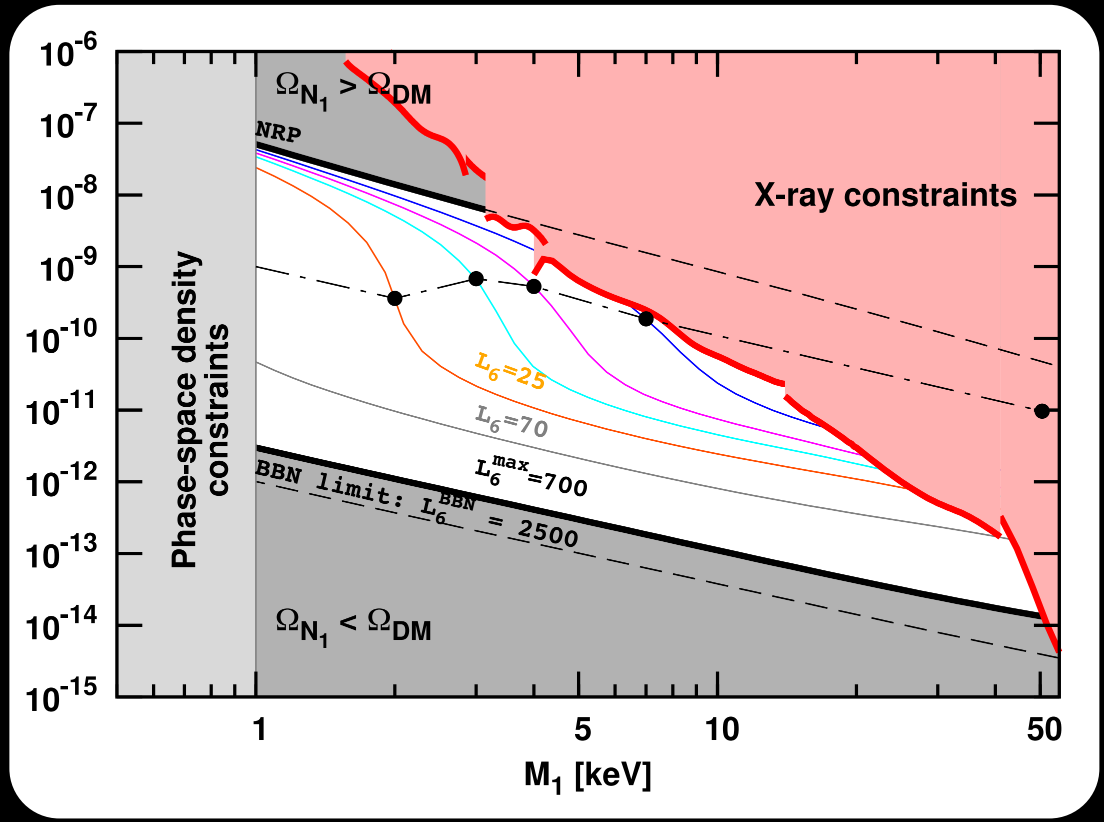


1306.6088 & 1310.8545

Sterile Neutrino DM

- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.
- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.
- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision electroweak data), they can be stable on the scale of the age of the Universe and play the role of dark matter.
- Arriving at the right amount of dark matter via oscillations typically requires delicately choosing the mass and mixing angle, or invoking some other new physics.





1310.8642

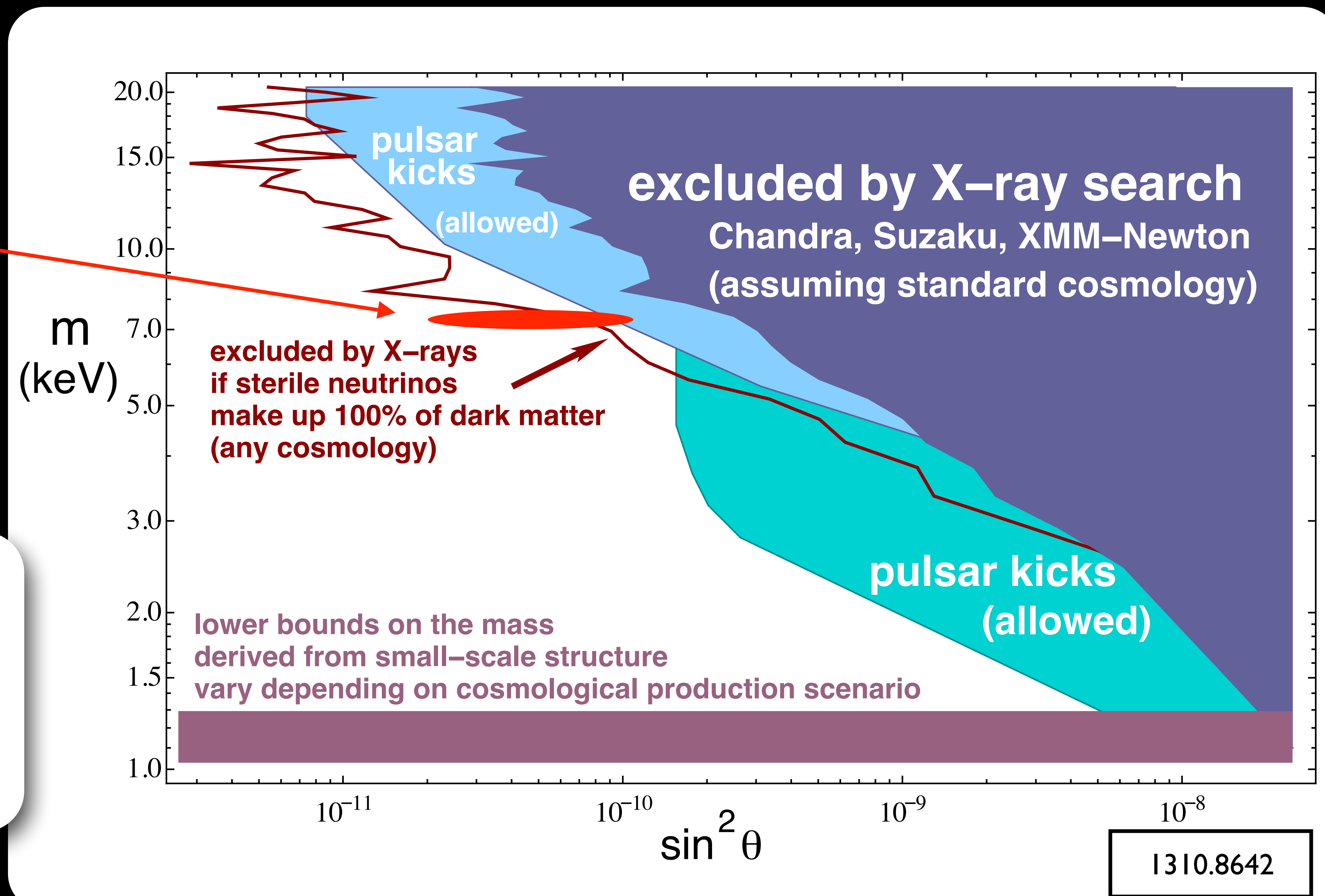
Y-axis: $\sin^2 \theta$, mixing angle with active neutrinos.

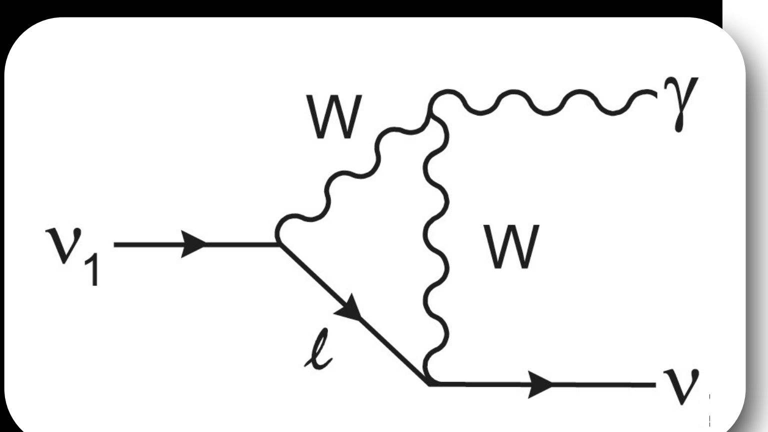
Sterile Neutrino Decay

- Though rare, sterile neutrinos can decay into ordinary neutrinos and a photon, resulting in (mono-energetic) keV energy photons.
- Constraints from the lack of observation of such a signal put limits in the plane of the mass versus the mixing angle.

Possible X-ray Signal
[Bulbul et al 2014]

(Extracted from
Abazajian 2014)





Recap: Super-WIMPs

- Super-WIMPs (including axions and sterile neutrinos) are particles which are not generally stable, but have such weak interactions (and sometimes small masses) that their lifetimes are of the order of the age of the Universe.
  - Axions arise as solutions to the strong CP problem.
  - Sterile neutrinos occur in some models of neutrino mass.
  - Gravitinos are the super-partners of gravitons in theories with SUSY.
- They are typically much harder to probe than WIMPs, since they tend to couple much more weakly to the SM.
  - Nonetheless, there are often astrophysical probes, such as axion conversion into an EM field or sterile neutrino decays producing X-rays.