Dark Matter: Candidates II

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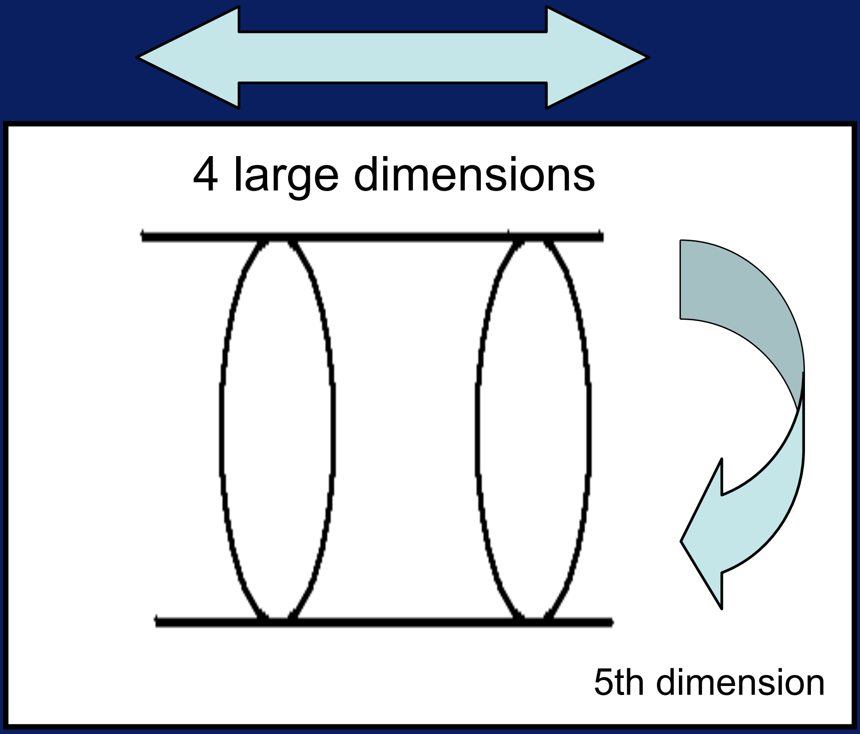
Outline for Lecture II

- KK parity: UED Dark Matter
  - 5d UED Dark Matter
  - The 6d Chiral Square
- T-parity
- Super-WIMPs
- “Designer” Dark Matter

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 (S^1), requiring wave functions to be periodic as one traverses the extra dimension.
  - Mathematically, this is the particle-in-a-box problem familiar from basic QM.
  - The 5th component of Momentum (p_5) is quantized in units of 1 / R.
- States with p_5 different from zero appear massive to an observer who does not realize the extra dimension is there.

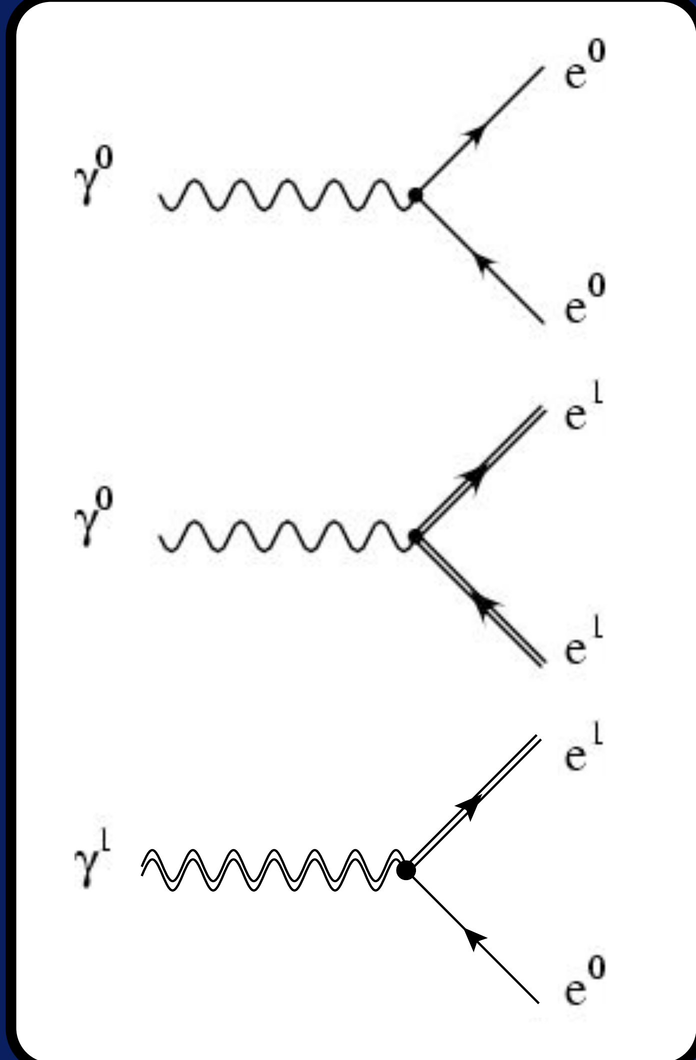
$$p_0^2 - \vec{p}^{\,2} - p_5^2 = 0 \quad \Longrightarrow \quad p_0^2 - \overrightarrow{p}^{\,2} = p_5^2 = m_{eff}^2$$

- 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 p_5, 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.
- TeV extra dimensions provide a natural setting for top condensation:
  - A theory without a Higgs can still exhibit spontaneous symmetry-breaking driven by KK modes of gluons.

Arkani-Hamed, Cheng, Dobrescu, Hall
PRD62, 096006 (2000)

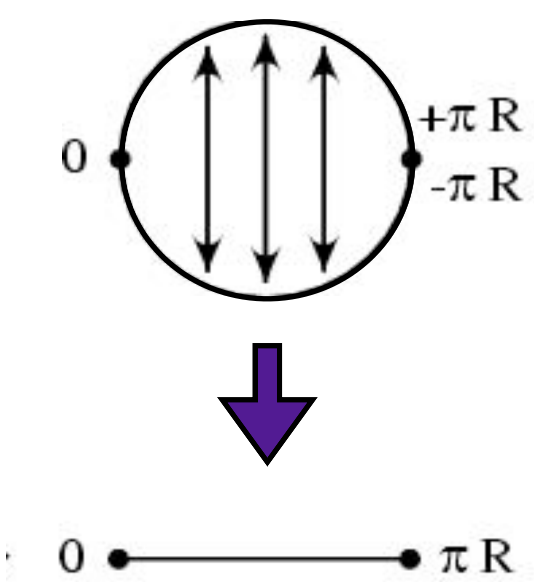
- Number of generations:
  - Cancellation of anomalies in six dimensions requires the number of families to be a multiple of three!

Dobrescu, Poppitz
PRL87, 031801 (2001)

- Dark Matter!

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.



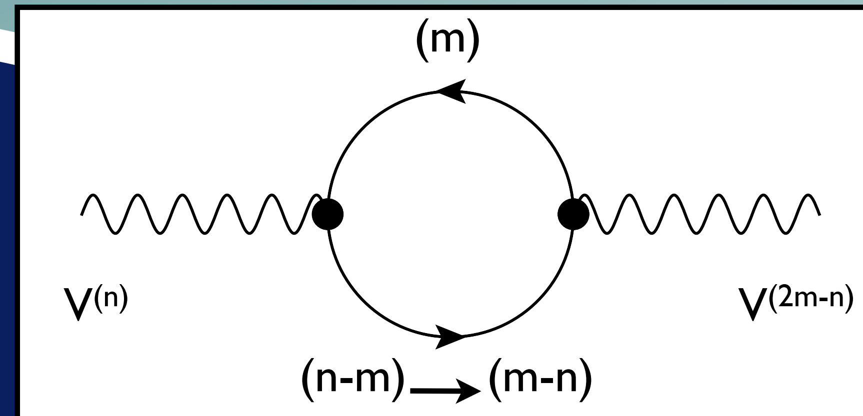
$$V_\mu(-y) = V_\mu(y)$$

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

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

Orbifolds are Opaque

- Even theories without localized fields have 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 p_5 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)

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

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

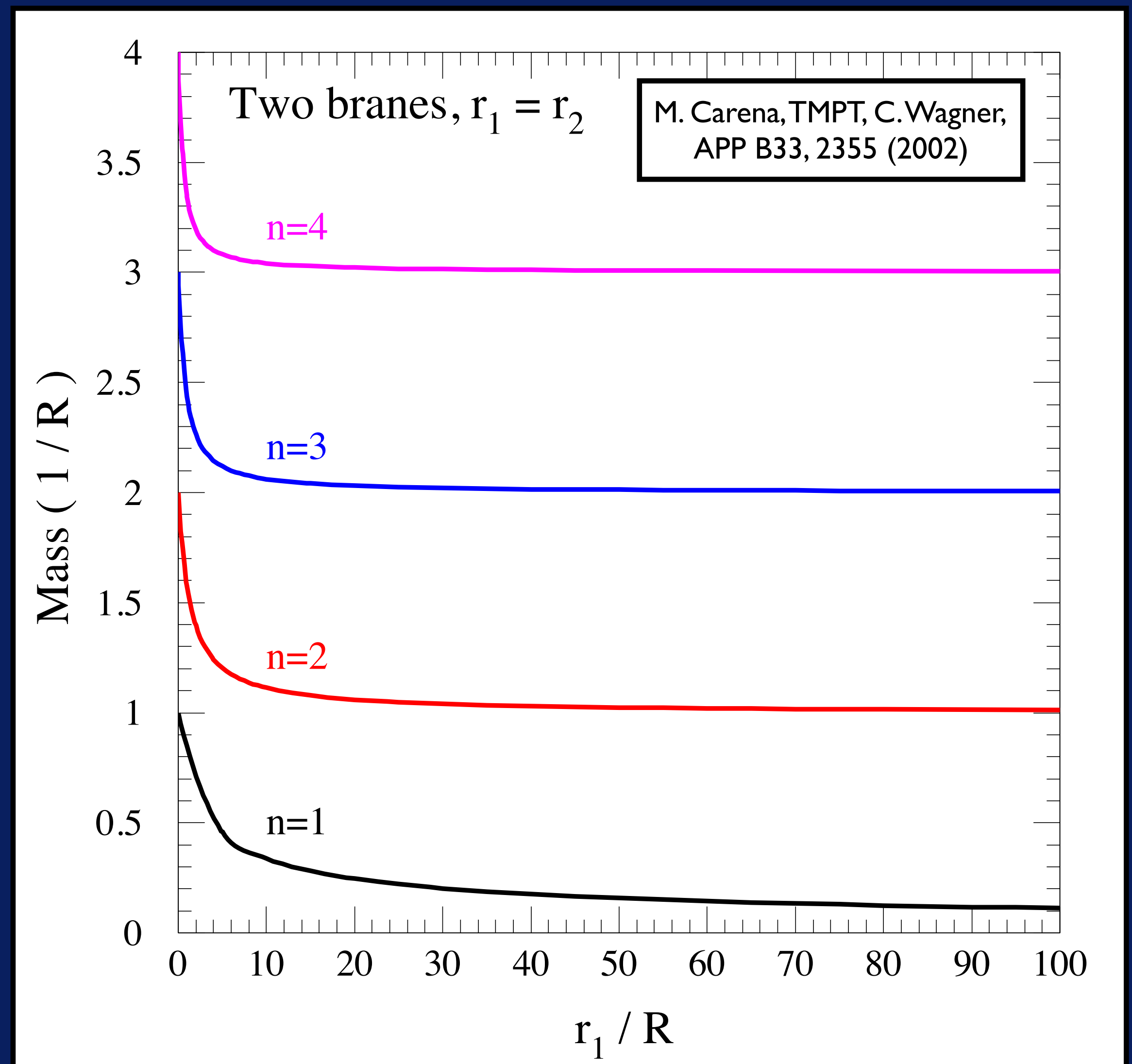
Opaque Orbifolds

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

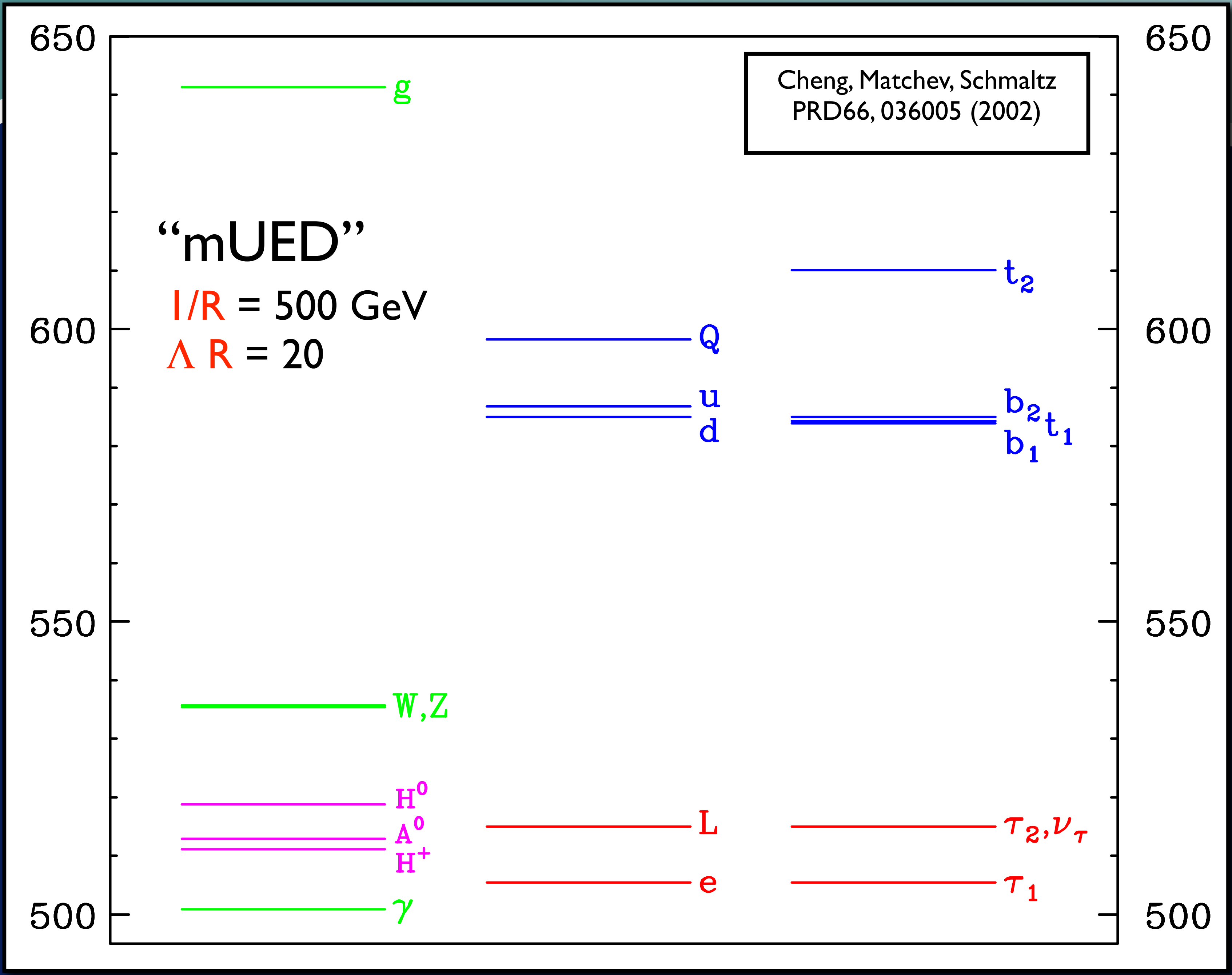
This has the effect of changing the KK mass spectrum.

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

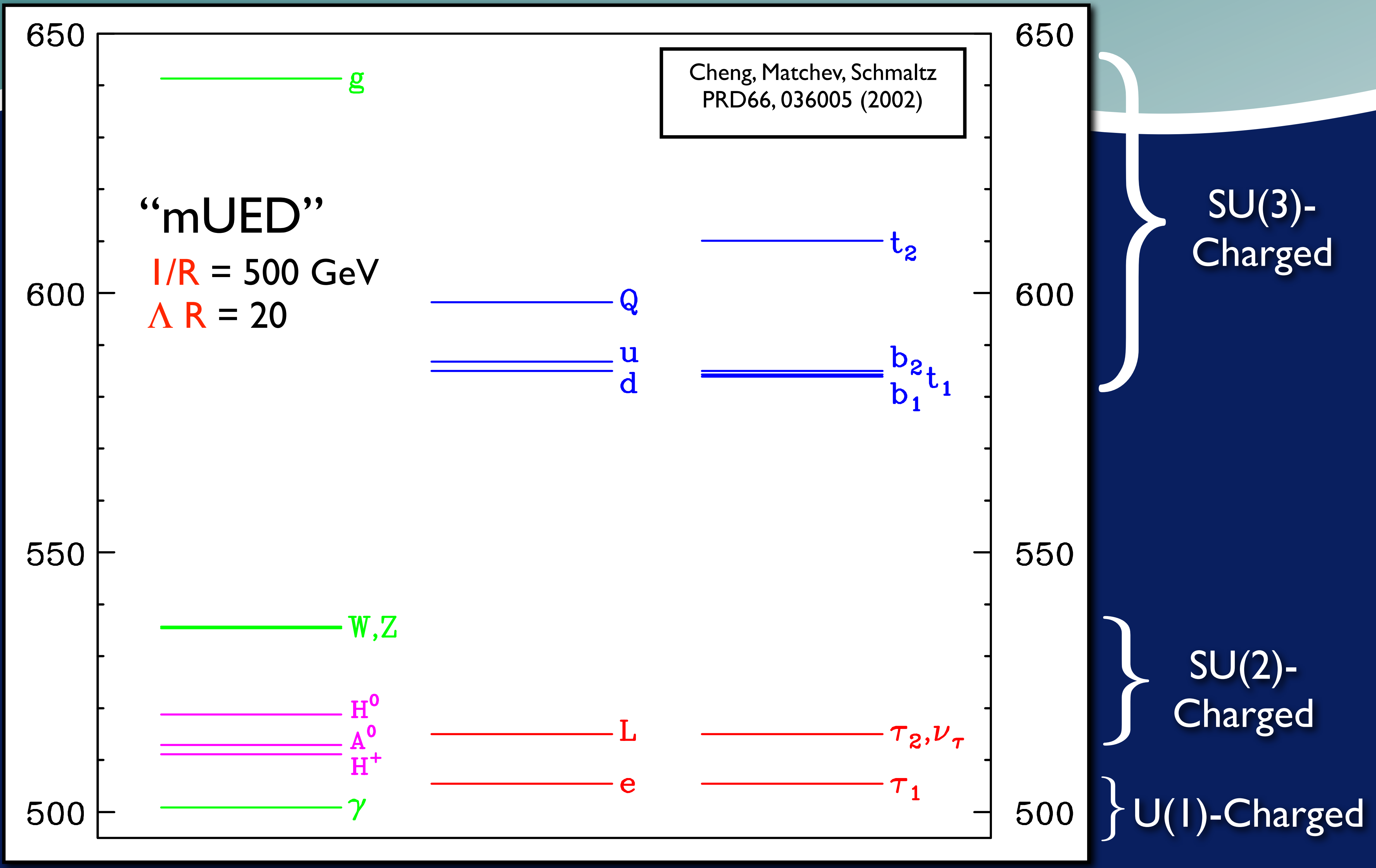
Much like R-parity, the lightest odd mode is stable, and odd modes are produced in pairs.



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 $\alpha_1 << \alpha_2 << \alpha_3$, 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, $e^{(1)}_R$.

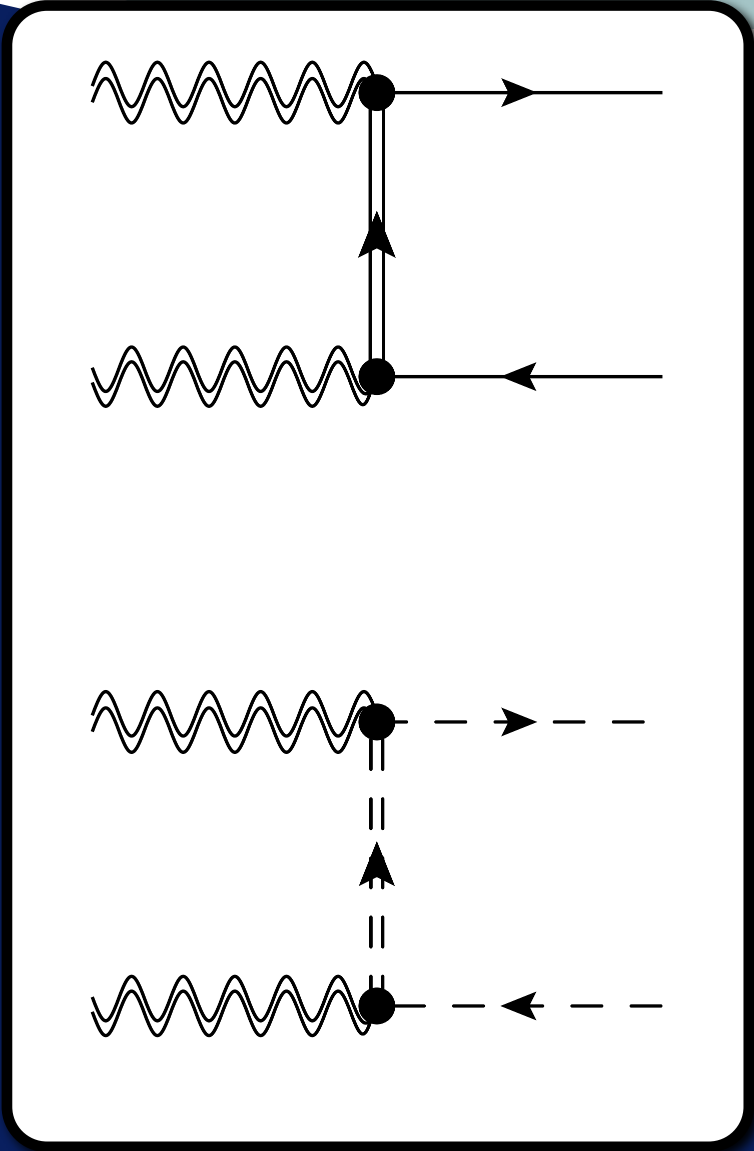
$B^1 - W_3^1$ Mass^2 matrix

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

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

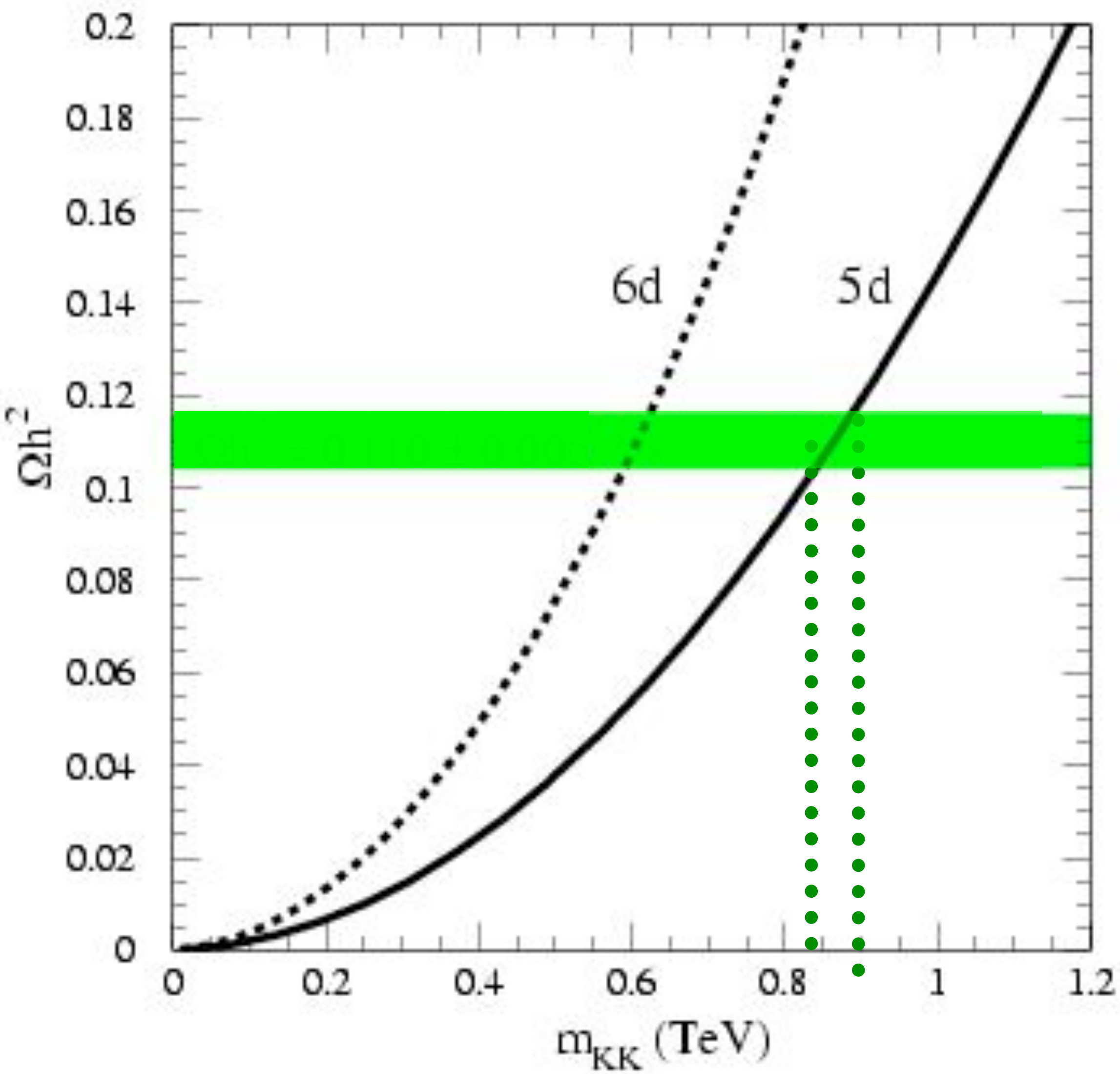
LKP Annihilations

- 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 WIMPs.



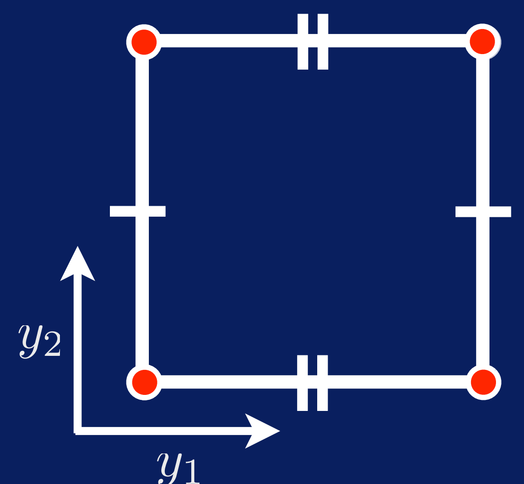
LKP Relic Density

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



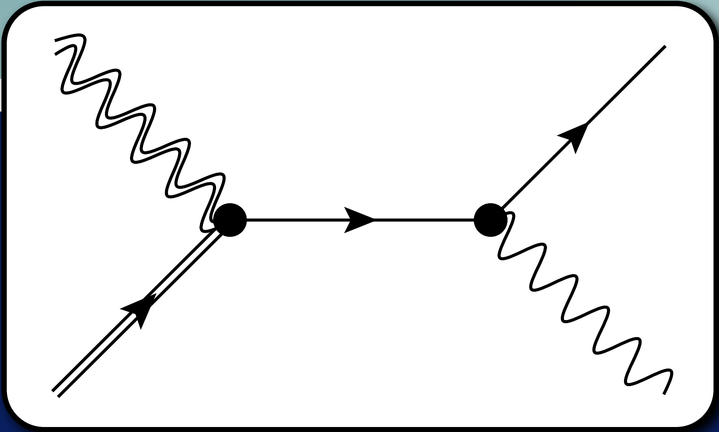
With no helicity suppression for annihilation, the LKP realizes the correct relic density for larger WIMP masses.

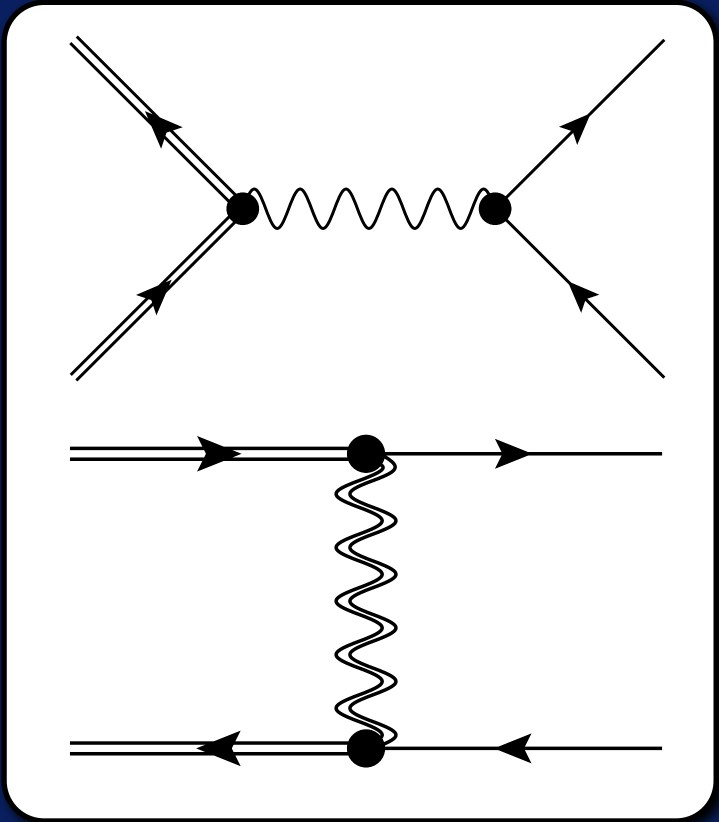
The 6d curve is for a 2-torus with equal radii (2 LKPs):



Co-annihilation

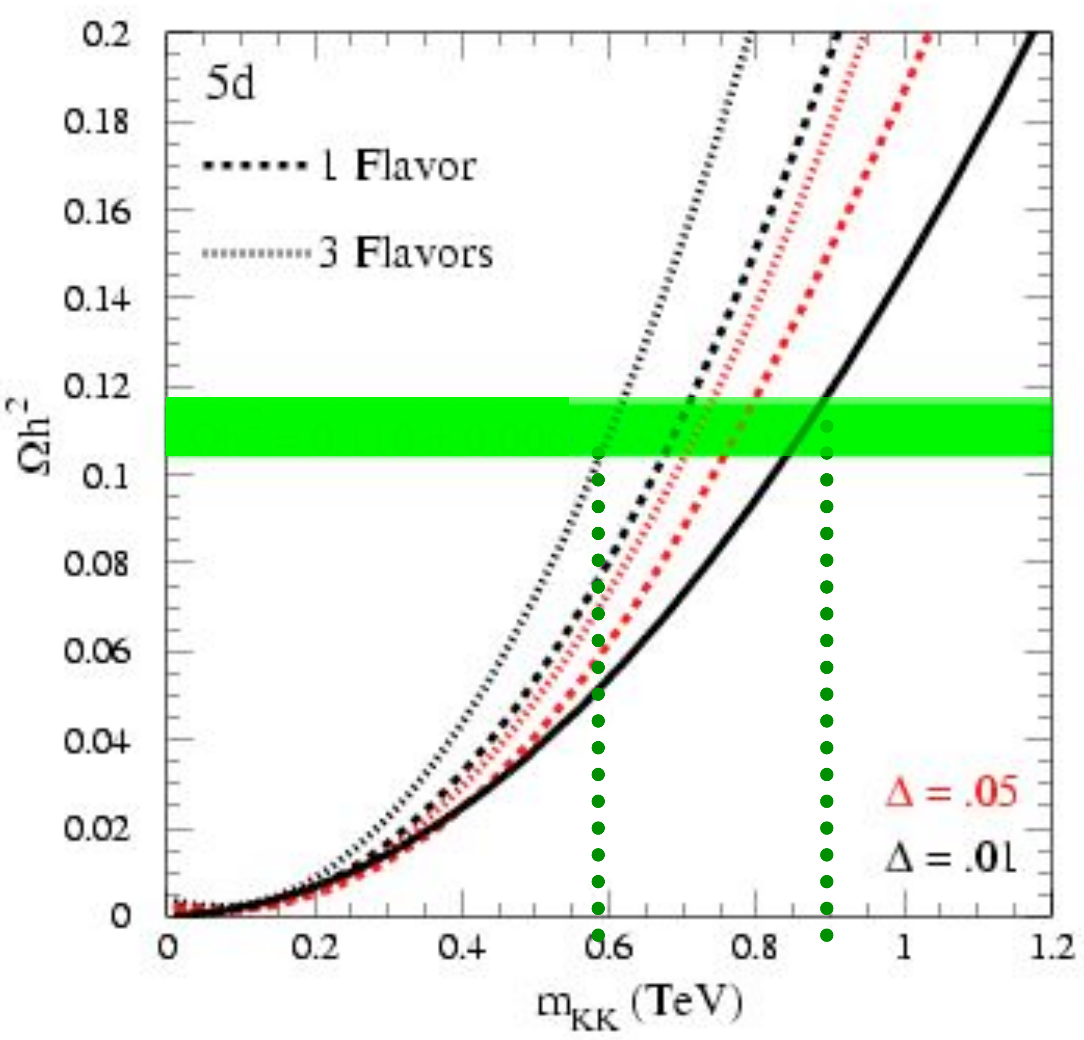
- Just like in SUSY, nearby particles can affect the relic density. In particular, we saw that the mass of $e^{(1)}_R$ is close to $B^{(1)}$ in mUED.
- However unlike SUSY, both particles interact with roughly with the same cross section, and the freeze-out temperature is basically unchanged,
- Some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

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



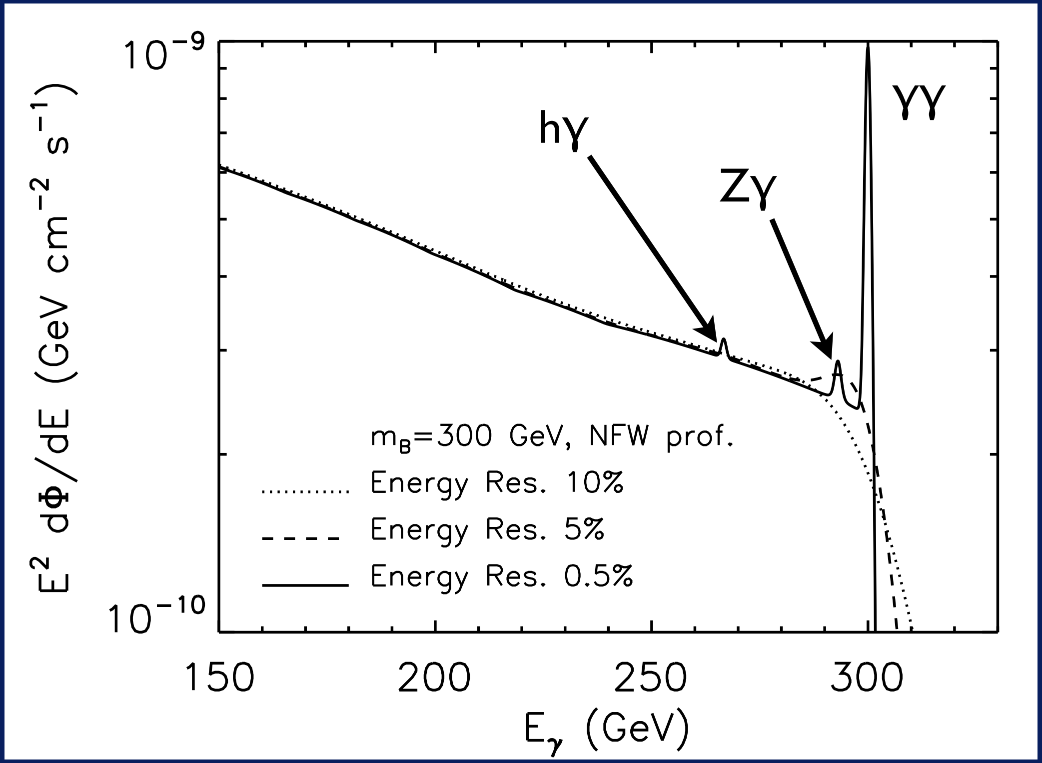
Coannihilation leads to an increase in the number of LKPs after freeze-out. To compensate, we dial down the mass of the LKP so that the correct energy density results.

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

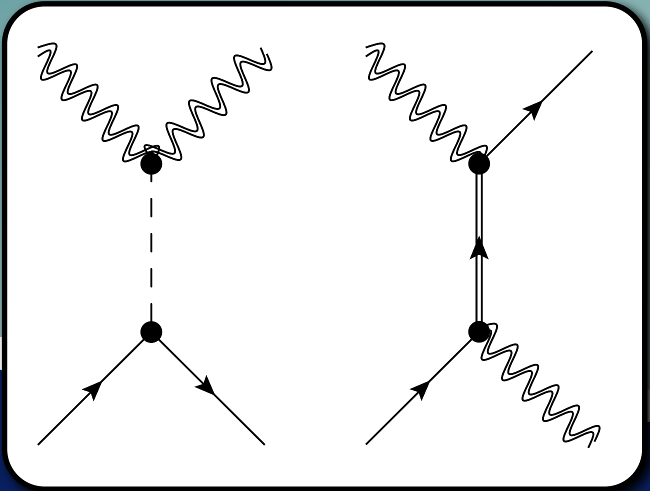
- There is a large rate for continuum γ's with a harder (than, say, SUSY) spectrum, because the LKP likes to annihilate into e^+e^-.
- There are $\gamma\gamma$, γZ, and γ Higgs lines.
- Over-all, the lines are relatively faint, and tend to merge into the continuum photons from WIMP annihilations.
- Resolving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

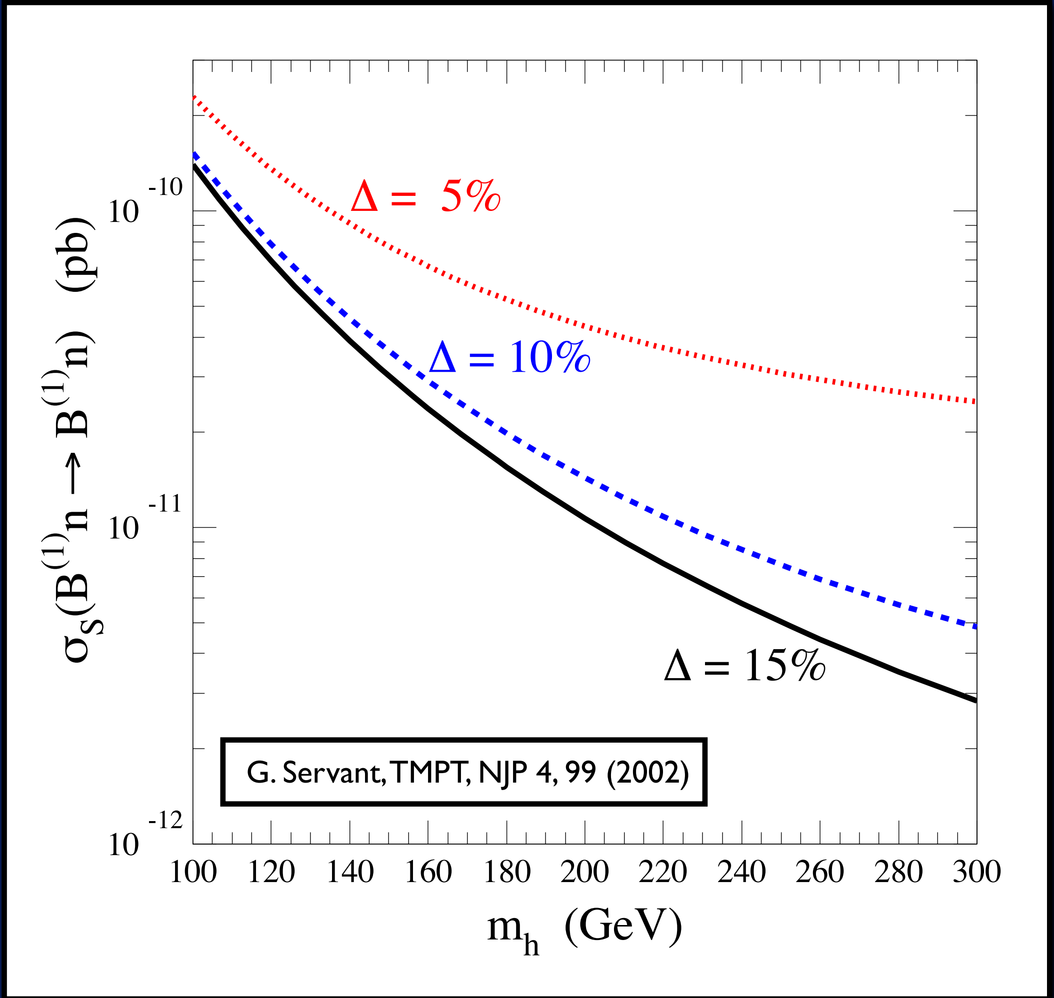


Bertone, Jackson, Shaughnessy, TMPT, Vallinotto 1009.5197

Direct Detection

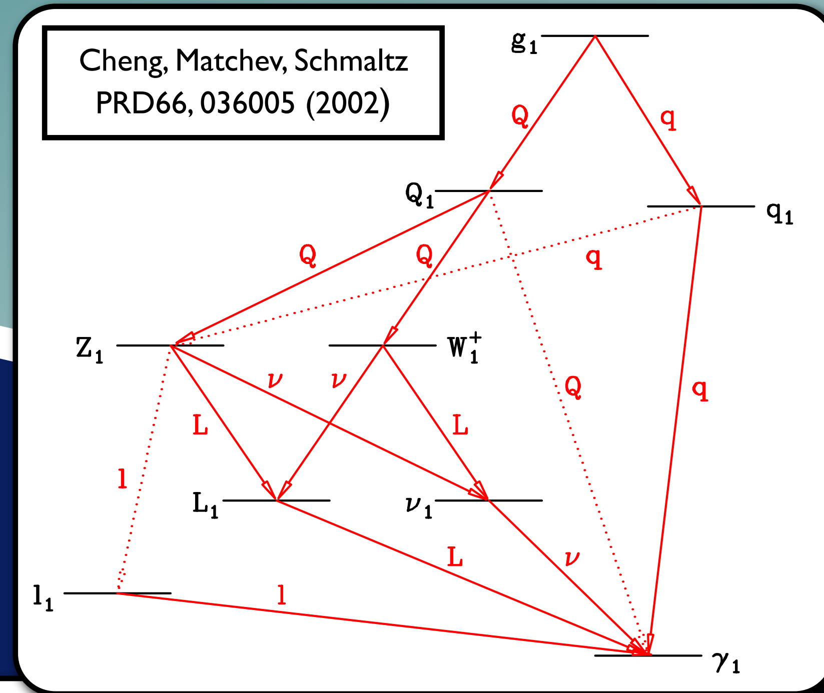
- Much like the case of SUSY models, UED dark matter interacts with nuclei largely by exchanging Higgs (zero mode) bosons.
- KK quarks also contribute, but are expected to be heavier.
- Because UED has no structural reason to have a light Higgs boson (and precision electroweak data generally disfavors one), one expects direct detection cross sections will turn out to be smaller in UED than in SUSY.

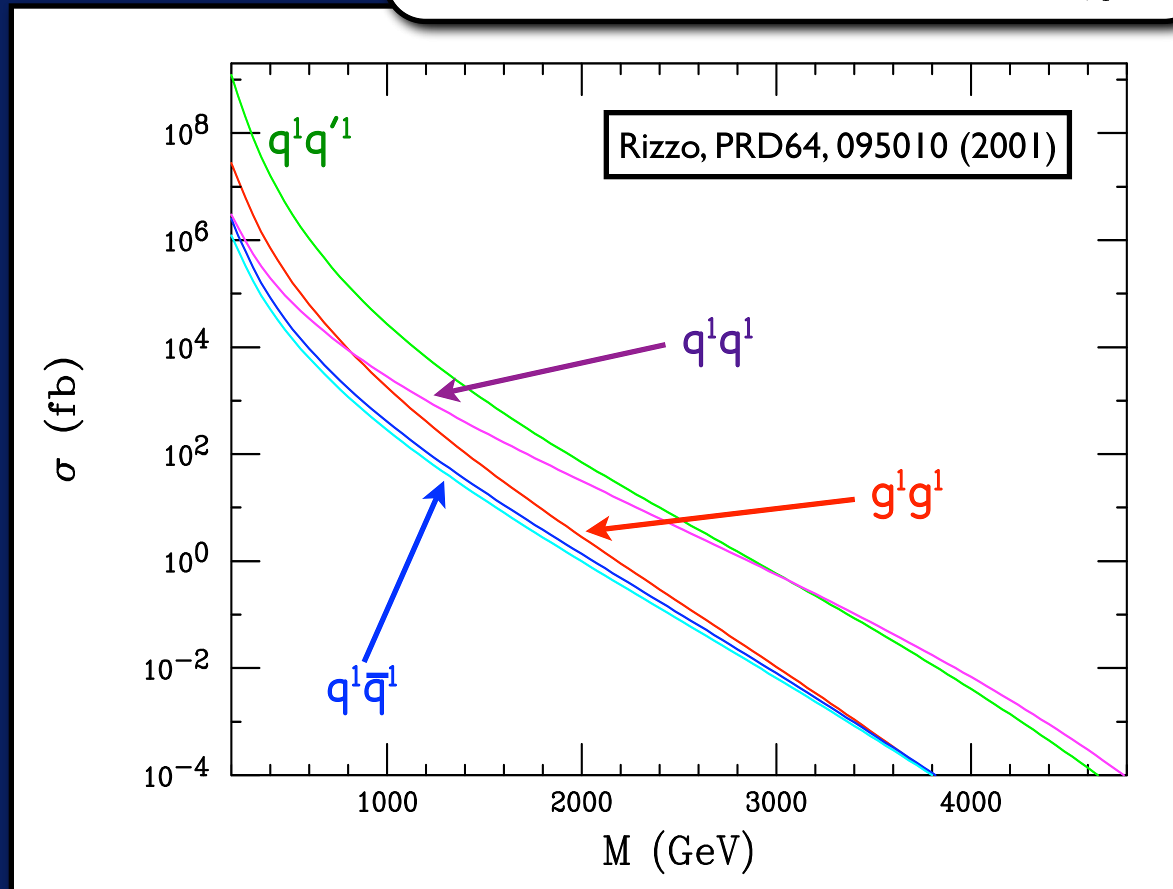




UED at the LHC

- 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?





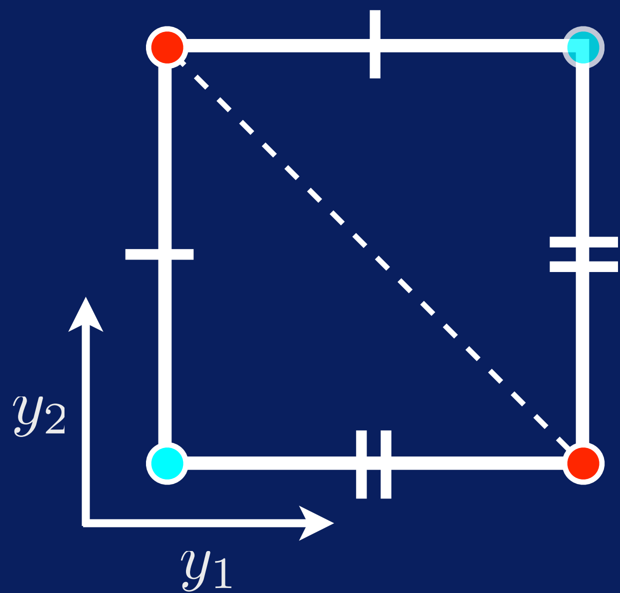
6d UED: The Chiral Square

- 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".

Ponton, Wang '06



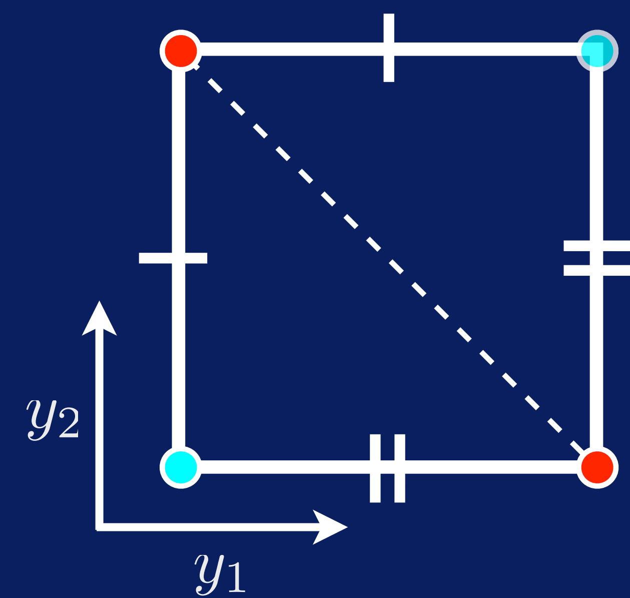
KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

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.
- 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).

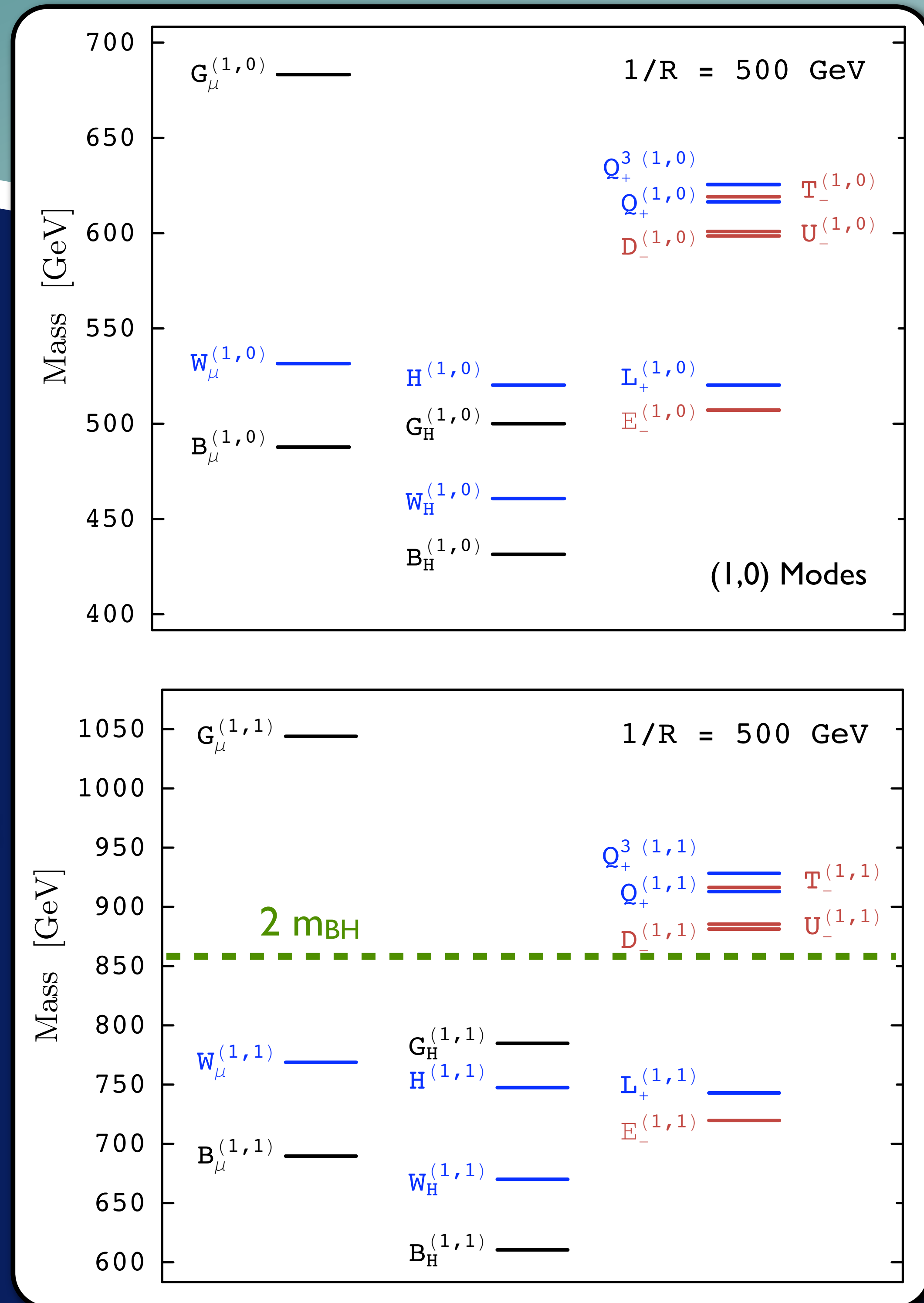


$$V_M \longrightarrow \{V_\mu, V_5, V_6\}$$

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

Spectrum

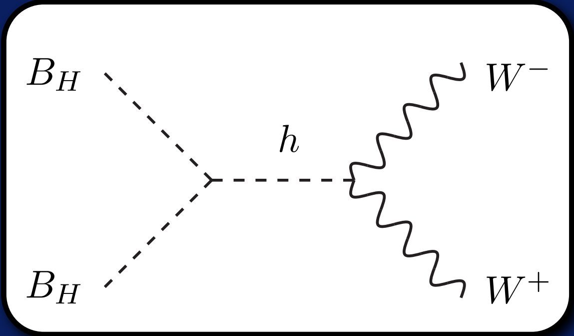
- As in the 5d theory, boundary terms modify the masses of the fields at a given (j,k) level.
- The LKP is usually the scalar (1,0) KK mode of the Hypercharge gauge boson, B_H.
  - Colored states are the heaviest of a given (j,k).
- The (1,1) modes are KK even and many have masses above M_B but below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

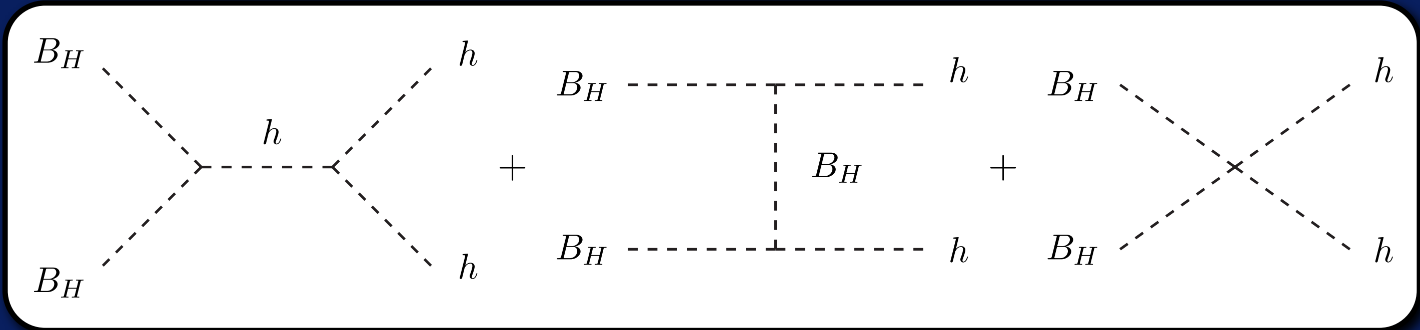


B_H Annihilations

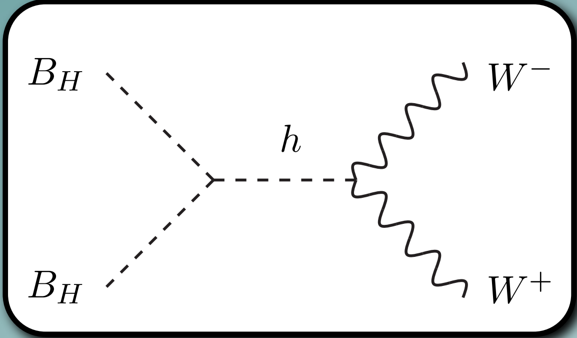
- Both the regions of parameter space and the continuum gamma ray emission spectra and rates are controlled by the tree level LKP annihilation channels.
- B_H is a real scalar and an electroweak singlet:
  - B_H B_H into fermions is suppressed by the final state fermion mass (more like what we saw in 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

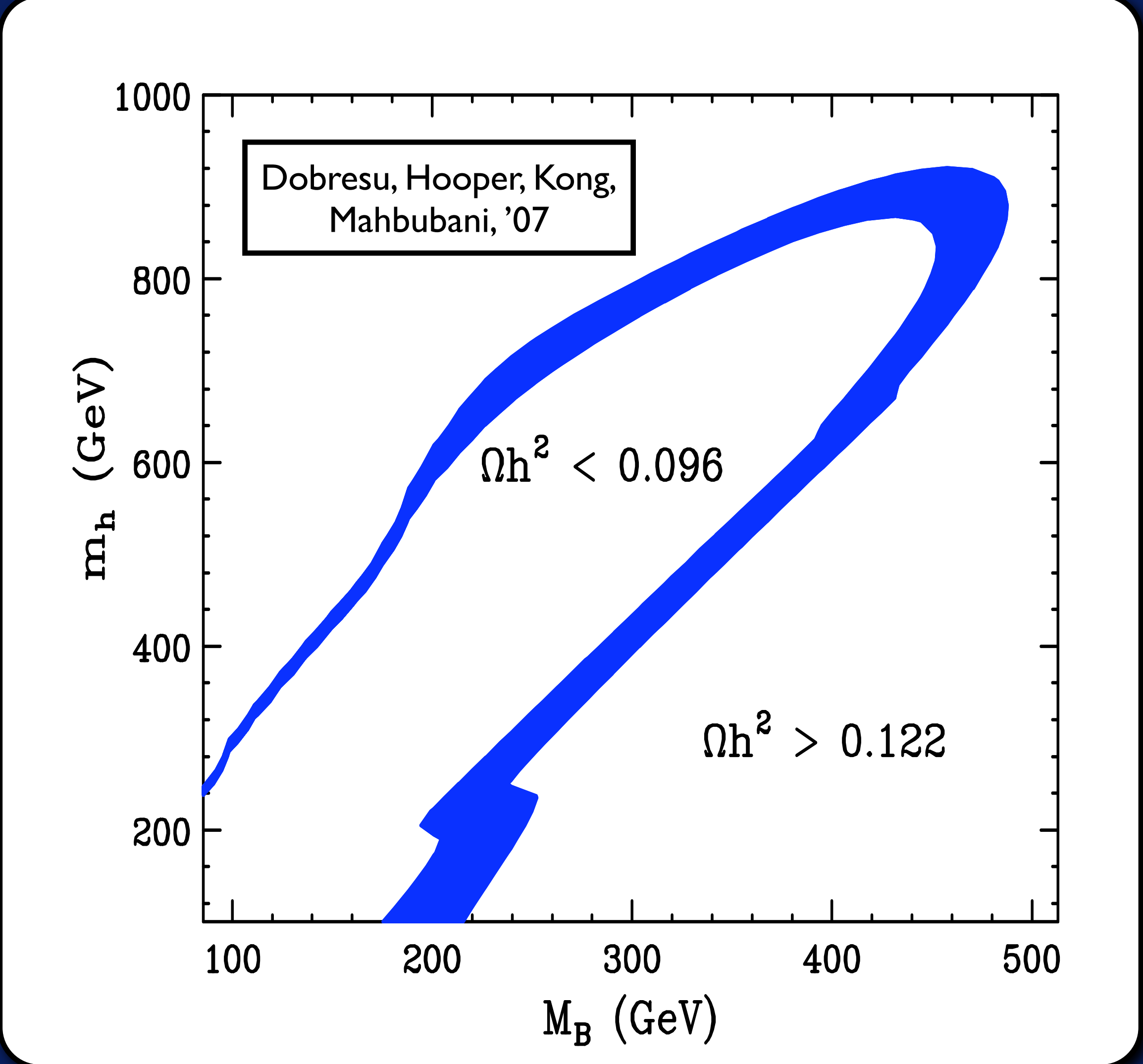




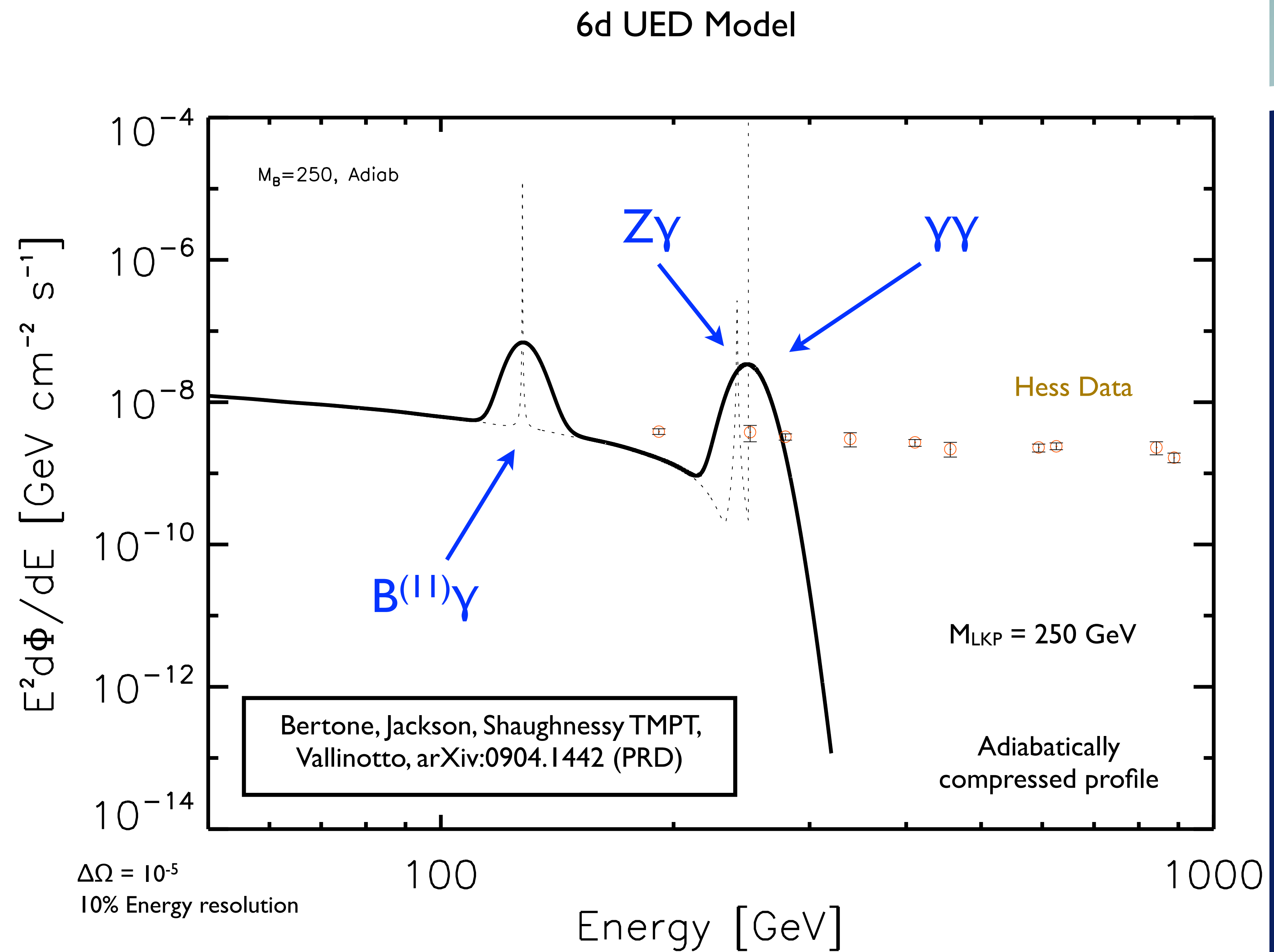
Relic Density



- 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.
- Generally, the relic density favors LKP masses between 100 - about 500 GeV, provided the Higgs mass is chosen to match.



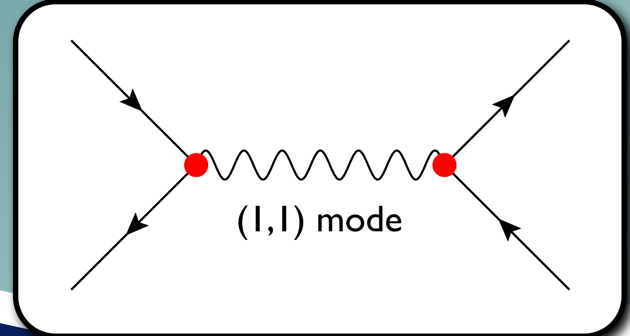
Chiral Square: γ-Rays



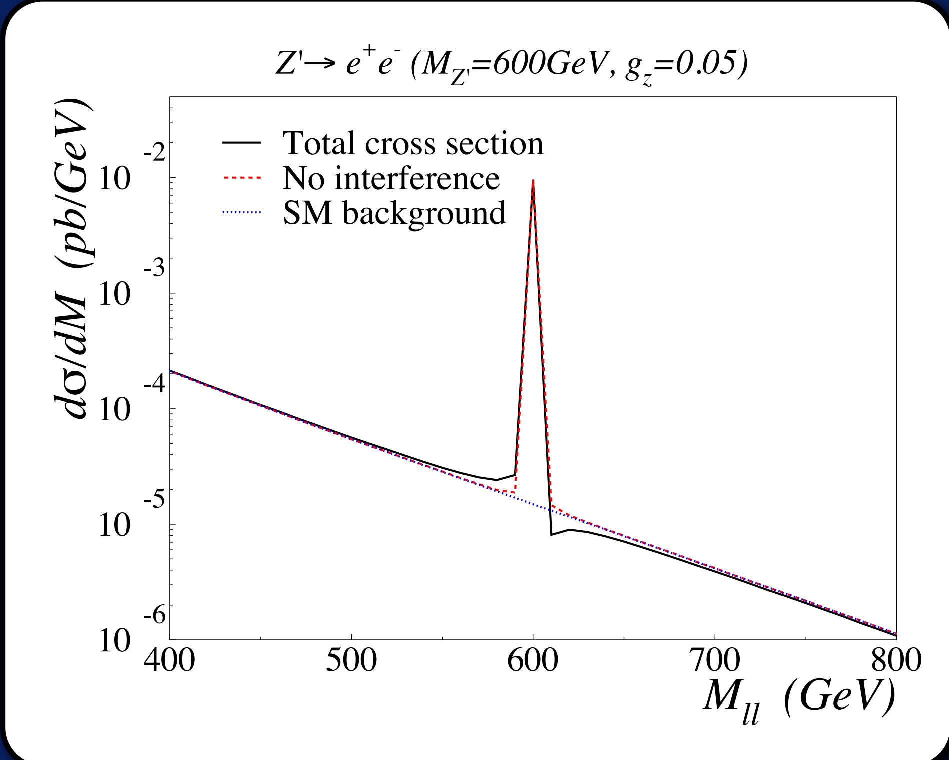
$\Delta\Omega = 10^{-5}$

10% Energy resolution

$B^{(1,1)}$ at the LHC



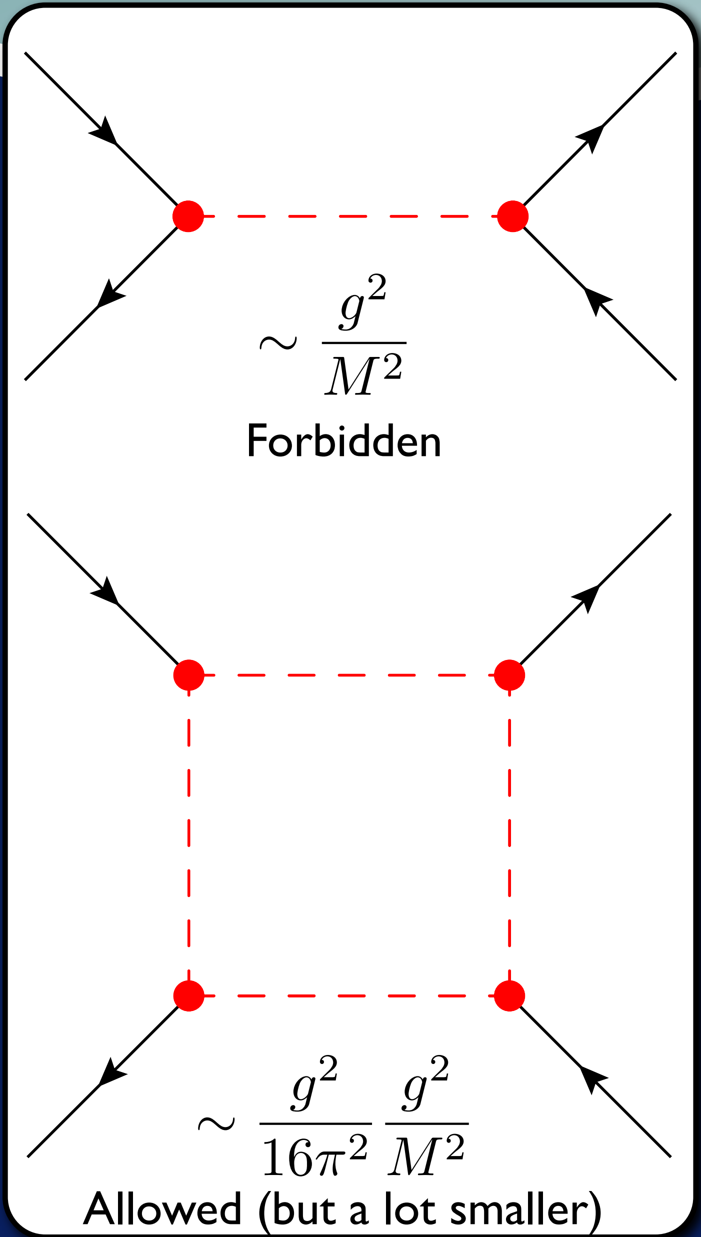
- At the LHC, B(1,1), can be produced from a q qbar initial state (with reduced but substantial couplings proportional to hypercharge).
- It decays into ordinary leptons and quarks, providing a classic Z' signature.
- γ-ray observations can observe the secondary line, and measure the mass - telling the LHC where to look.
- The LHC is needed to fit the additional state into the big picture, measuring its spin and coupling to SM states.



Synergy between indirect detection and the LHC can teach us more about WIMPs

T-Parity

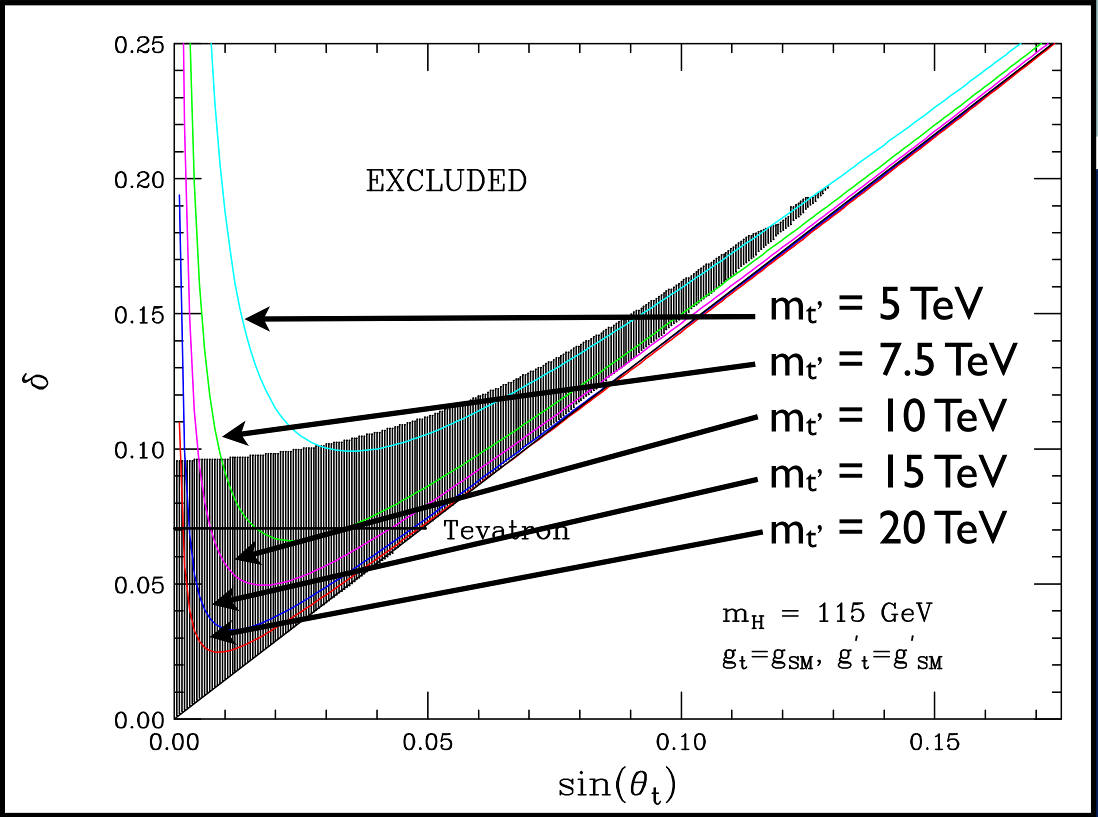
- Another symmetry which can stabilize dark matter is "T-parity". Cheng, Low hep-ph/0308199
- T-parity is a phenomenological symmetry which can be invoked to protect precision measurements from large contributions from new physics.
- If one requires the new particles to couple in pairs, they can't contribute 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

Lectures by M. Peskin

- 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.



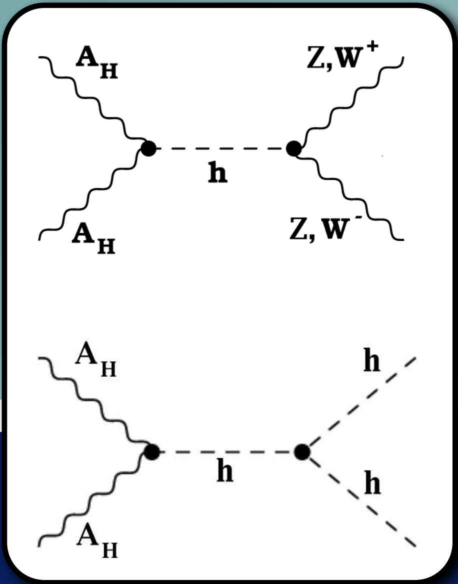
$$\delta \equiv \frac{v}{f}$$

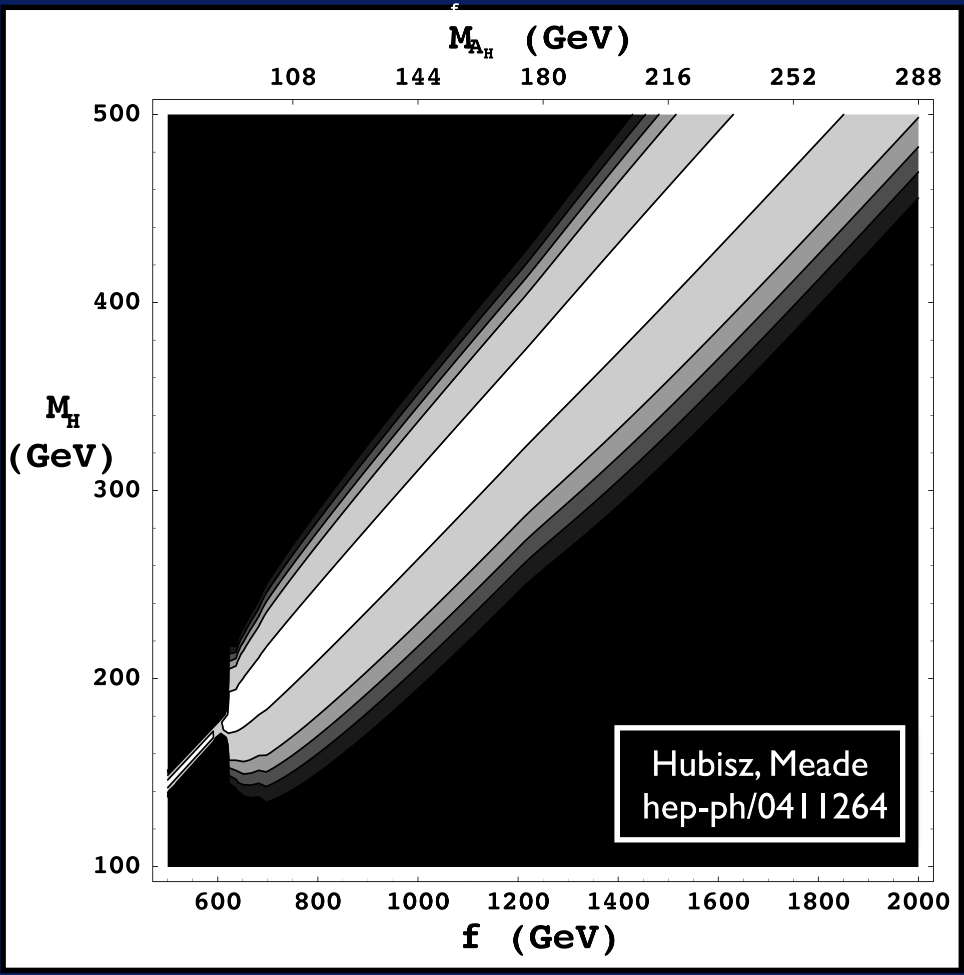
Hewett, Petriello, Rizzo
hep-ph/0211218

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 the other partners are assumed to be very heavy.
- As a result, only the heavy SM particles matter for annihilation, and SM Higgs exchange becomes very important.

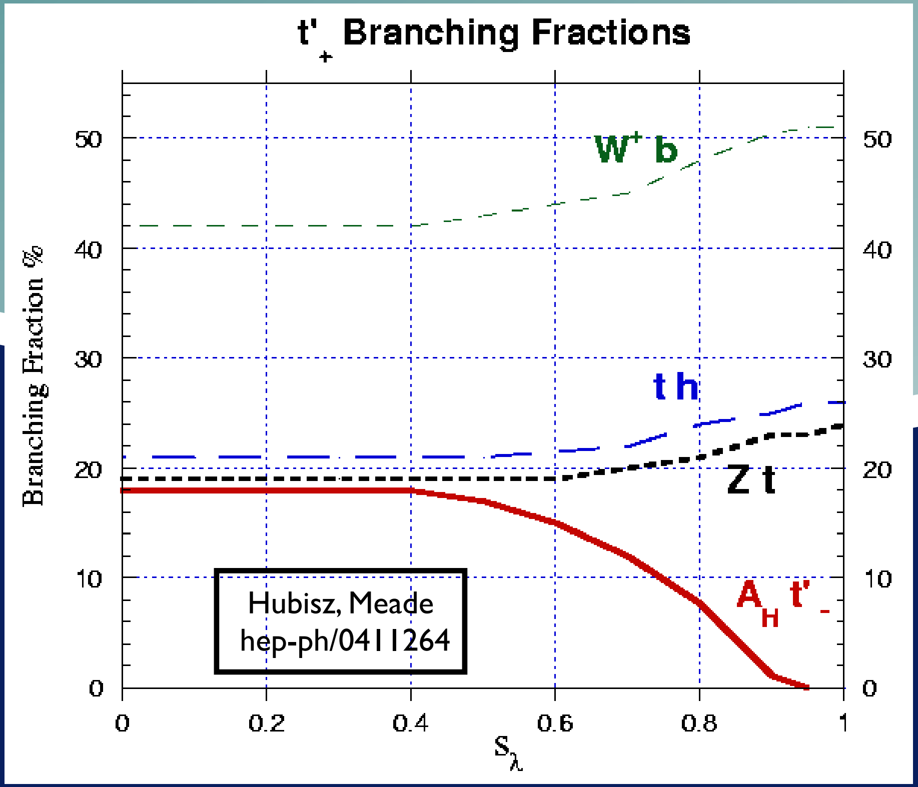


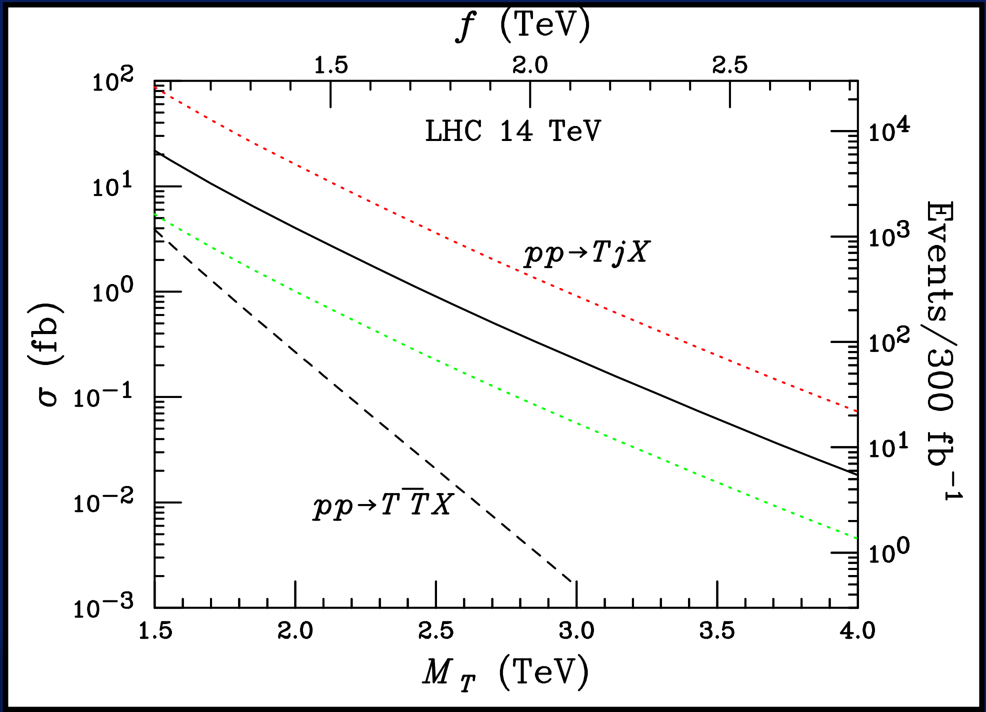


LHC Signals

- 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.
- The cross section for pair production of the top partners is QCD : depends on the mass & α_S.
- Single production of the T-even partner can dominate.

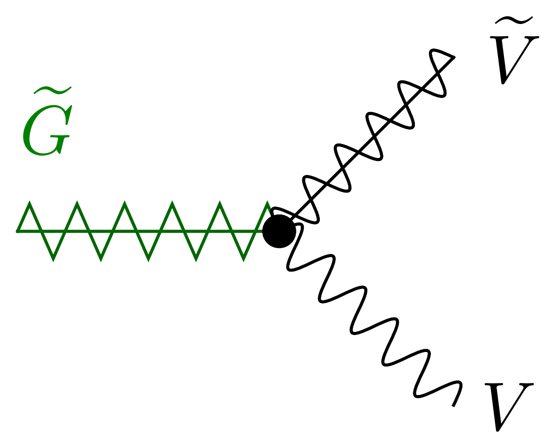
Han, Logan, McElrath, Wang
hep-ph/03o1040





Super-WIMPs

- Dark matter could be super-weakly interacting.
- 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.

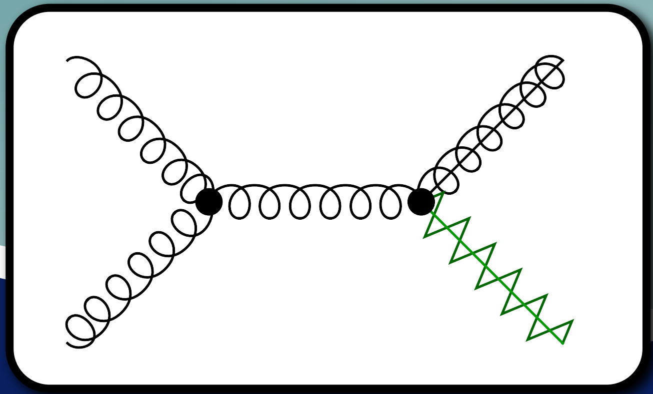


$$\sim \frac{M_{\widetilde{V}}}{F} \sim \frac{M_{\widetilde{V}}}{m_{\widetilde{G}} M_{\rm Pl}}$$

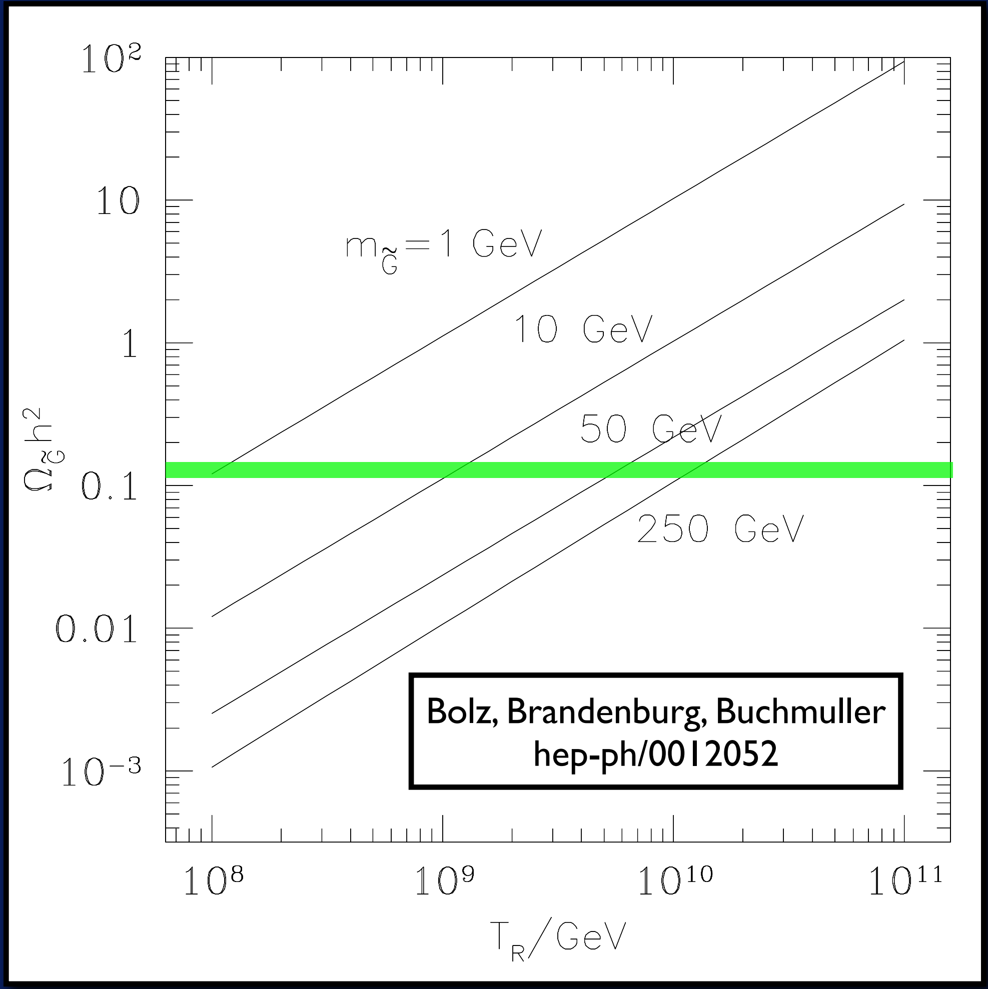
Dominant Coupling through the Goldstino component

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

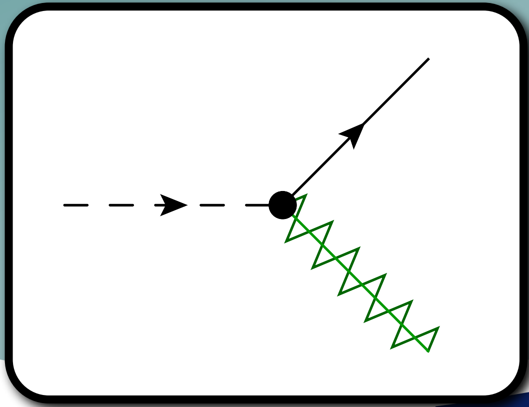
Relic Gravitinos

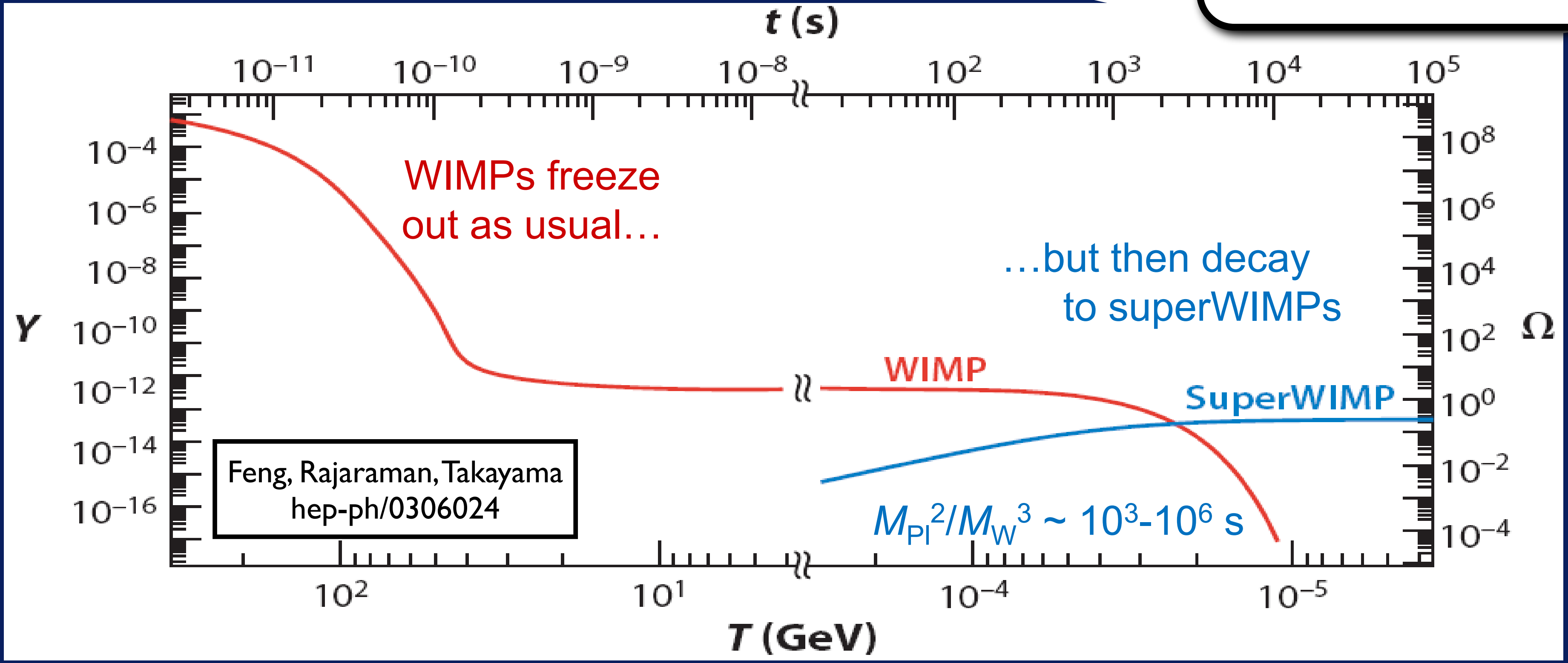


- Though they are never in equilibrium, we can still produce relic gravitinos:
- One mechanism is from reheating (freeze-in).
- Since they fail to reach equilibrium, the quantity generated depends very sensitively on the reheating temperature at the end of inflation.
- This can be a problem -- if they are overproduced, we can end up with too much matter, leading to a bound on T_R.
- For just the right T_R, we get Ωh^2.



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.

Axions

- Axions appear as a solution to the strong CP problem, in which one promotes the coefficient of the theta term to a field, allowing it to relax to zero.

  Peccei, Quinn '77

$$\frac{g^2}{32\pi^2}\left(\theta + \frac{a}{f}\right) G_{\mu\nu}\widetilde{G}_{\mu\nu}$$

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

- A pseudoscalar particle is predicted, derivatively coupled with coupling 1 / f.
  - Its relic density occurs through freeze-in, and also through a misalignment mechanism.

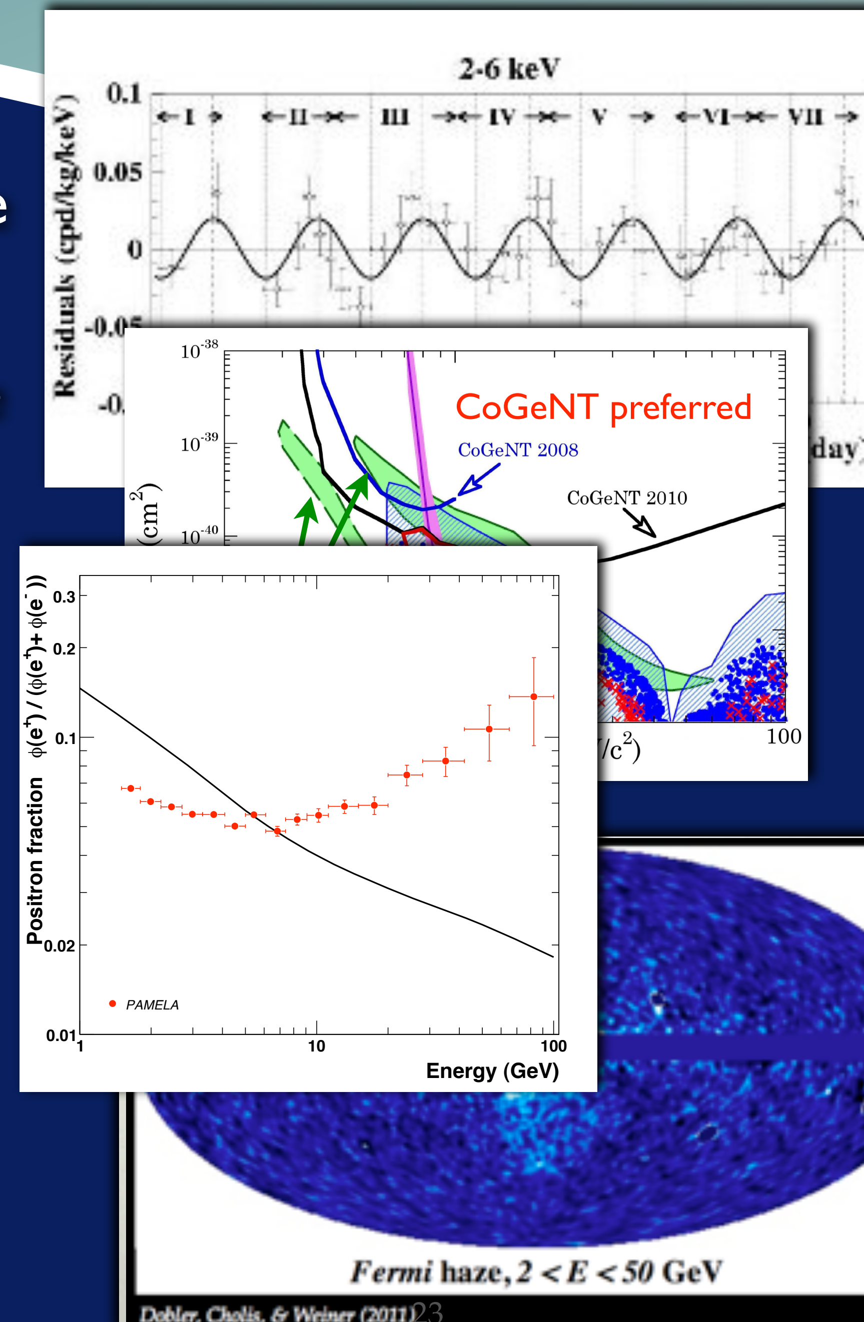
$$m_a \simeq 6 \text{ eV } \frac{10^6 \text{ GeV}}{f}$$

- Axions decay, but their interactions are feeble enough that they can live long enough to be dark matter.
  - This DM particle is quasi-stable by virtue of being superweakly coupled!

This slide falls far from doing justice to the subject. For a more comprehensive discussion and review: Sikivie, hep-ph/0610440

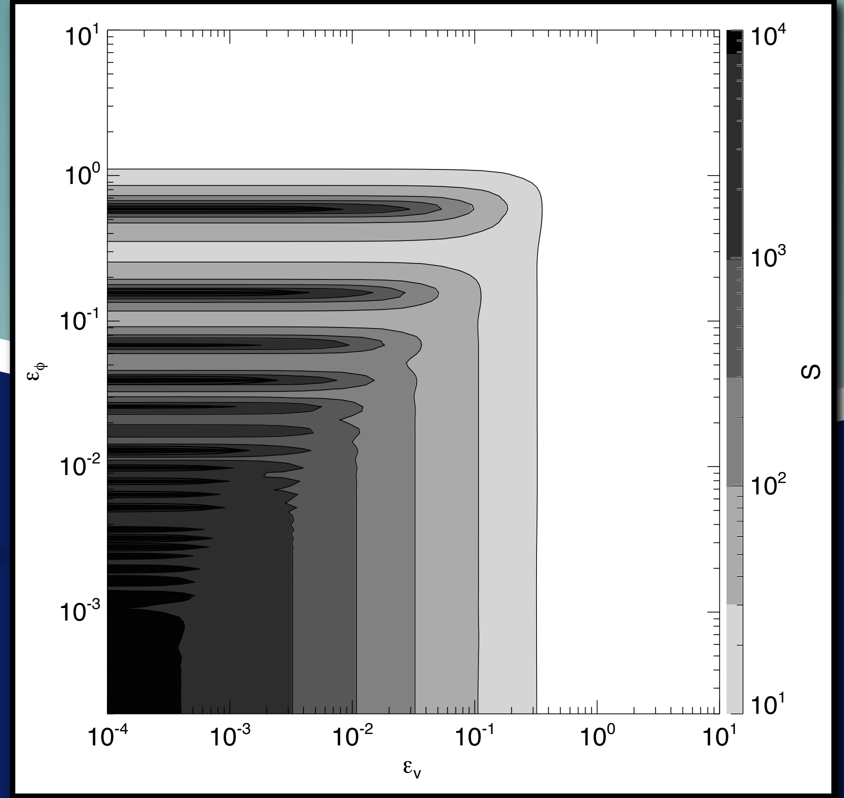
Designer Dark Matter

- As our searches for dark matter mature, we hope to eventually see a hint for a signal.
- There is no completely compelling evidence for an observation, but there are some tantalizing hints for things we don't understand. They might even be WIMPs!
- We can hope to eventually construct a theory of dark matter from observation.
- Even if the hints don't stand the test of time, they may inspire unconventional visions for how dark matter could work. They're still valuable to inspire new experiments and analyses.



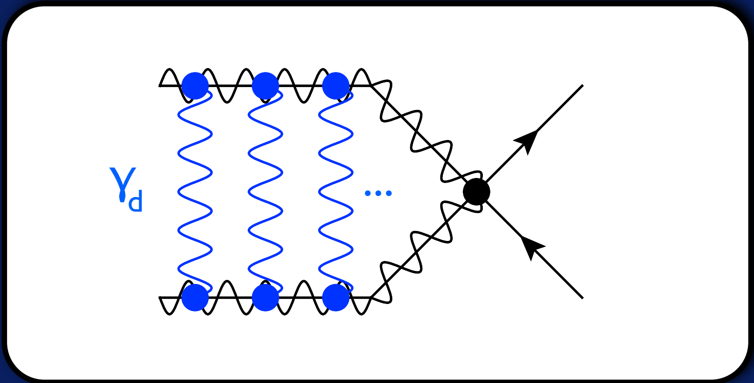
Light Mediators

- The PAMELA (and now Fermi) positron excess was already mentioned several times.
- We also heard about the tension between the rate of annihilation required to produce a large enough signal compared with the relic density.
- A popular idea to reconcile the two is to introduce a light mediator (such as a dark photon) to invoke a Sommerfeld-like enhancement at small WIMP velocities.
- Andy Haas showed us how light mediators lead to unique accelerator/collider signatures and searches, including lepton jets and interesting cascade decays.

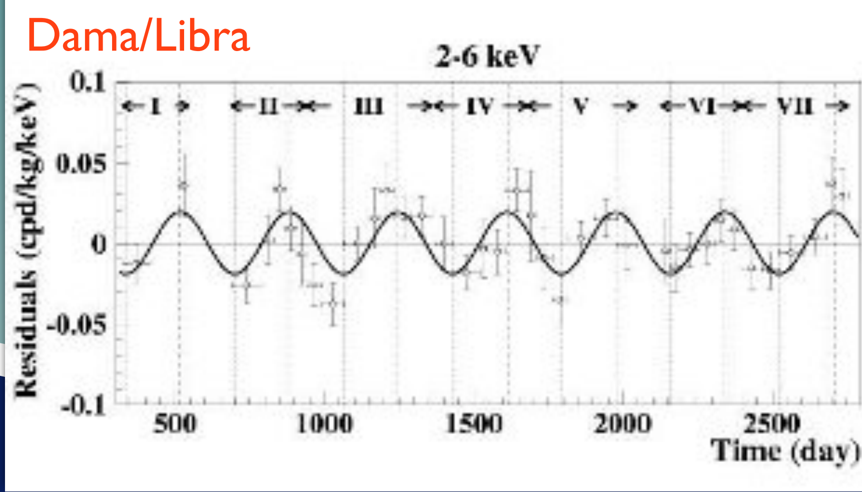


$$\epsilon_\phi \equiv \frac{m}{\alpha M} \qquad \epsilon_v \equiv \frac{v}{\alpha}$$

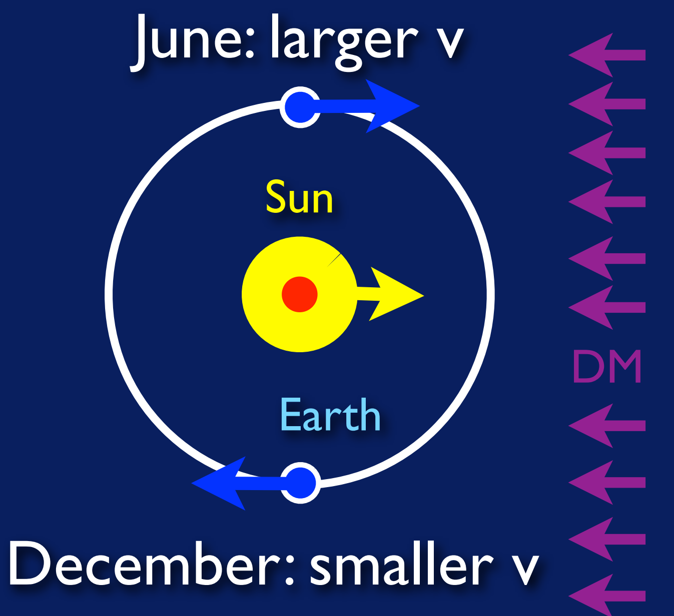
Cirelli, Kadastik, Raidal, Strumia 0809.2409
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
...



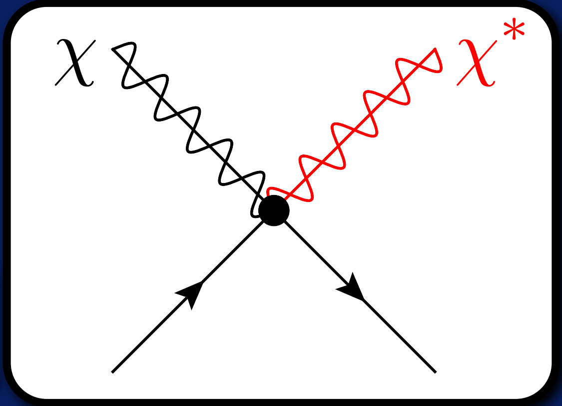
iDM



- Dama/Libra looks for Dark Matter on a NaI target, by looking for an annual modulation caused by the relative motion of the Earth to the Sun.
- After more than a decade, they find 9σ evidence of an annual modulation.
- Already early on, the favored parameter space was tightly constrained for generic WIMPs by null searches by CDMS (and others).
- One interesting proposal to use an underlying particle model to try to reconcile the two was to posit a WIMP which can only scatter inelastically into a very slightly more massive state.

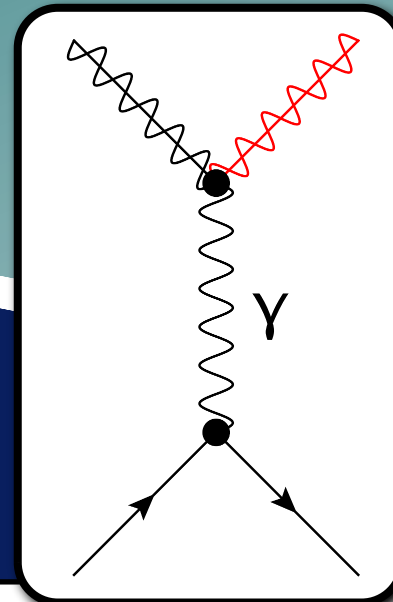


Tucker-Smith, Weiner
hep-ph/0101138

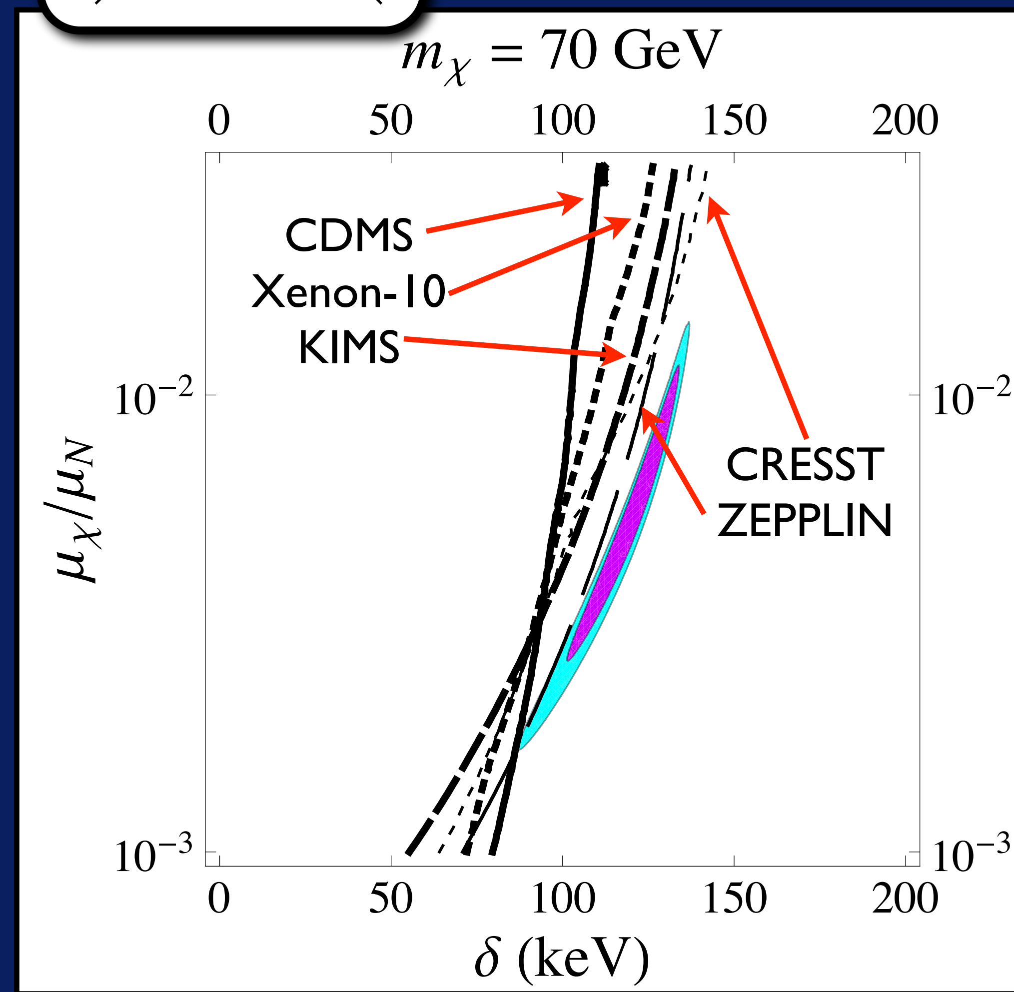


MiDM

- Just as the DAMA signal did not disappear, also CDMS kept improving its limits, and eventually largely ruled out the original iDM as well (with some help).
- But this was just the most naive vision of iDM. A new idea is to have the inelastic scattering mediated by a magnetic moment.
  - Both I and Na have large μ_M (compared to Xe or Ge).
  - Could be mediated either by an ordinary or "dark" photon.



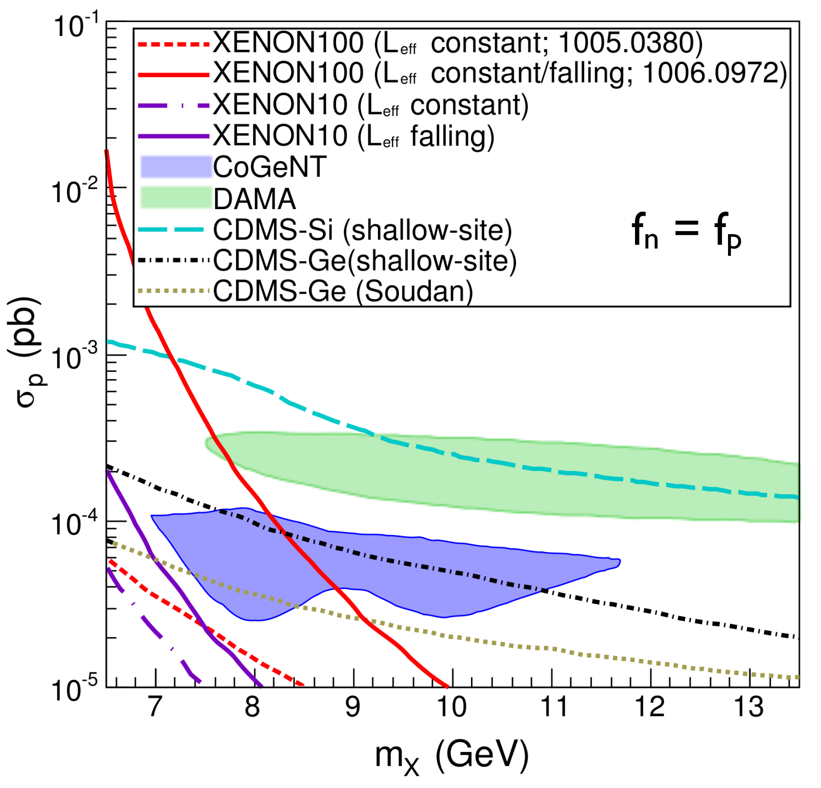
Magnetic inelastic DM
Chang et al [1007.4200]

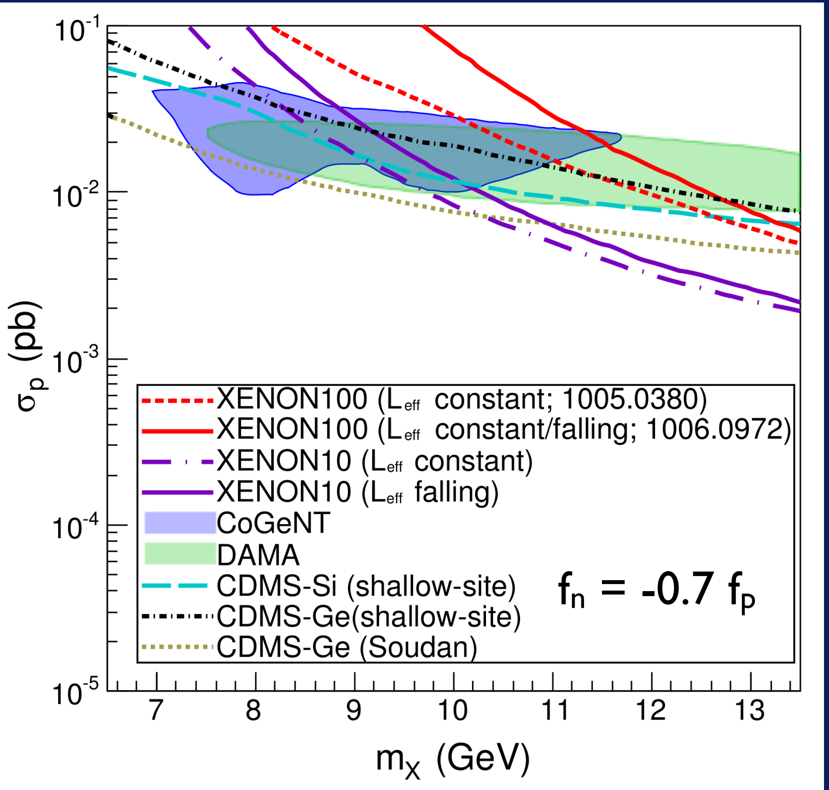


Isopin-Violating DM

Feng, Kumar, Marfatia, Sanford 1102.4331
Chang, Pierce, Weiner 1004.0697

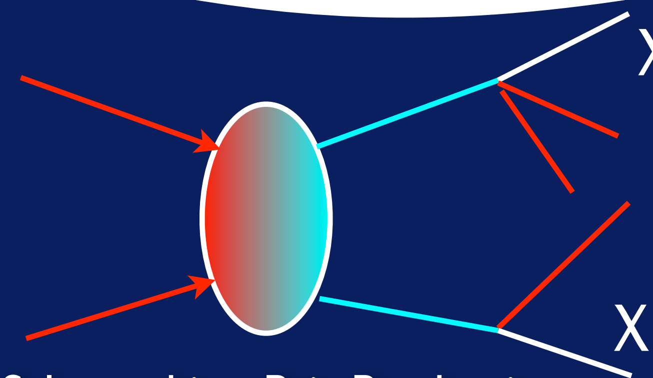
- CoGeNT is a low threshold Germanium detector which sees a (so far not very significant) signal that can be ascribed to low mass dark matter.
    - Not quite where DAMA lives.
- Xenon-100 would seem to naively exclude the CoGeNT signal.
- (Perhaps more seriously, so does the CDMS low threshold analysis).
- Somewhat amazingly, adjusting the couplings such that $f_n / f_p \sim -0.7$ severely weakens the Xenon bound, and causes CoGeNT to line up with DAMA.



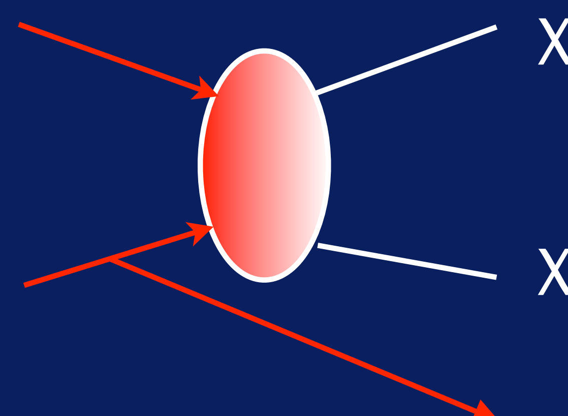


Effective Theories of DM

- Yesterday we discussed how to parameterize a big class of WIMP models in terms of effective theories.
- We can't describe every theory of dark matter this way, but it can accurately describe limits of theories like SUSY or UED.
- An additional advantage is that by working with a more model-independent description, we can translate collider bounds into the language of direct or indirect detection.



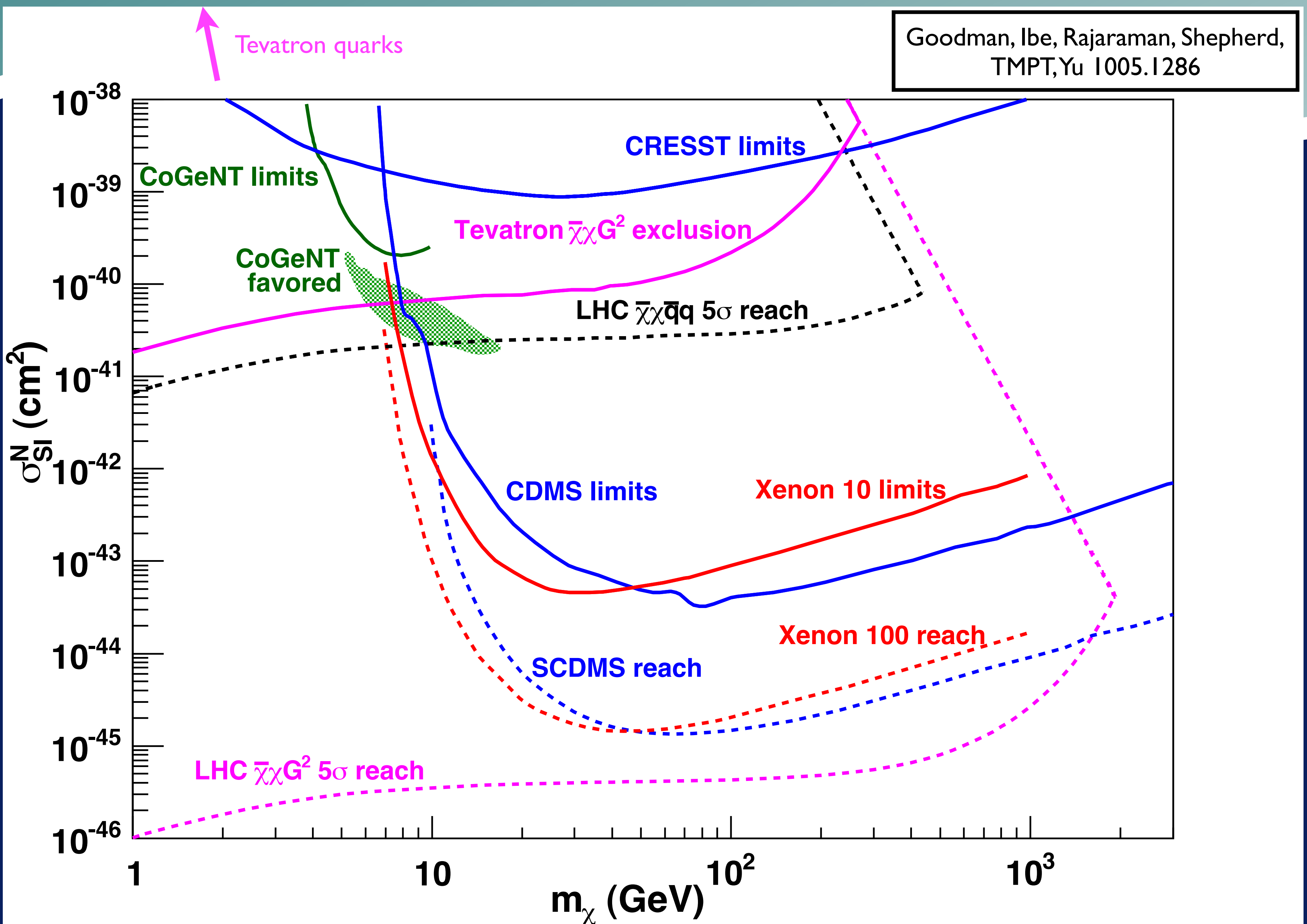
"KK Sgluquarkino Pair Production Followed by Decay into WIMPs"



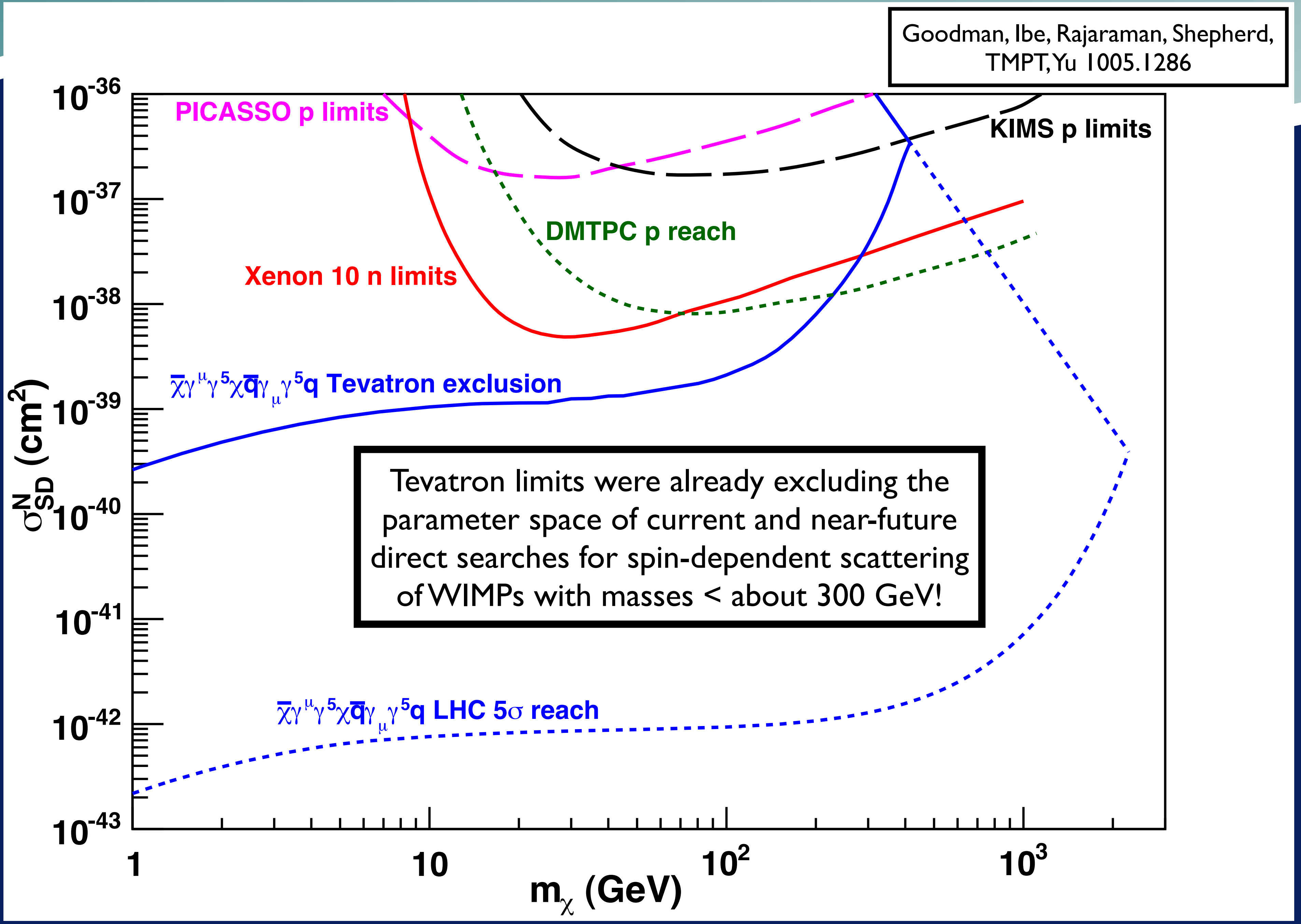
"Maverick Production"

Feng, Su, Takayama PRL hep-ph/0503117;
Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037

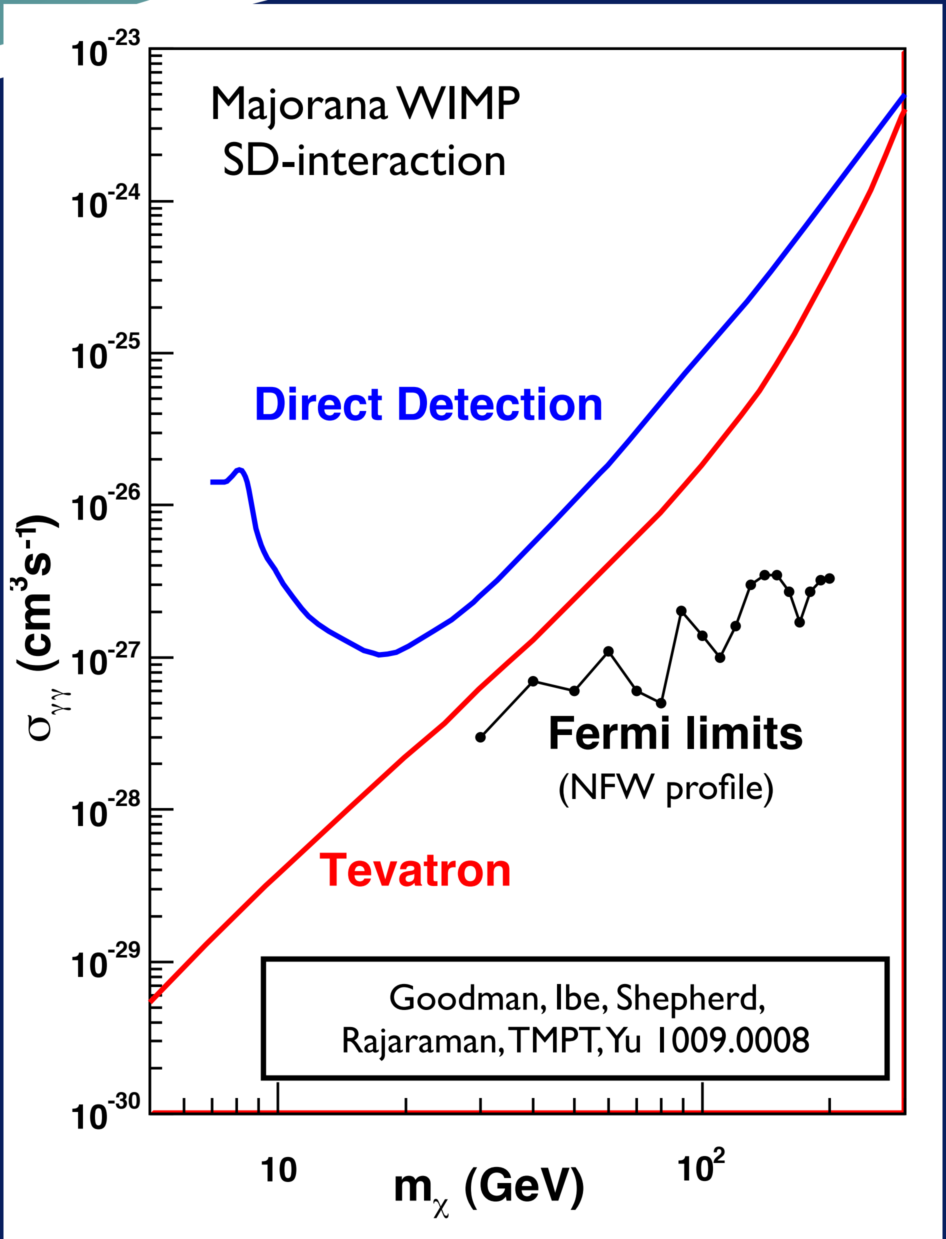
Colliders - Direct Detection



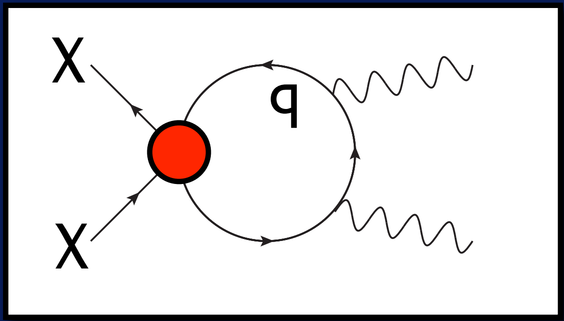
Spin-Dependent



Gamma-Ray Lines

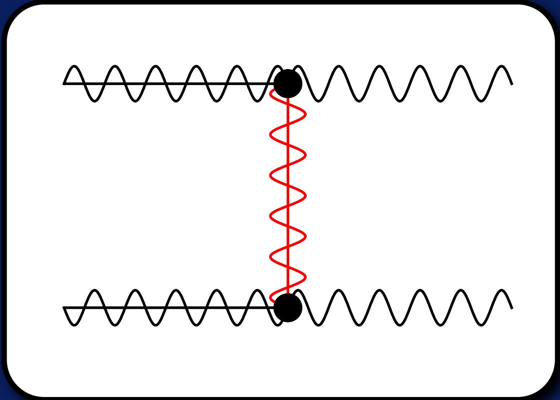


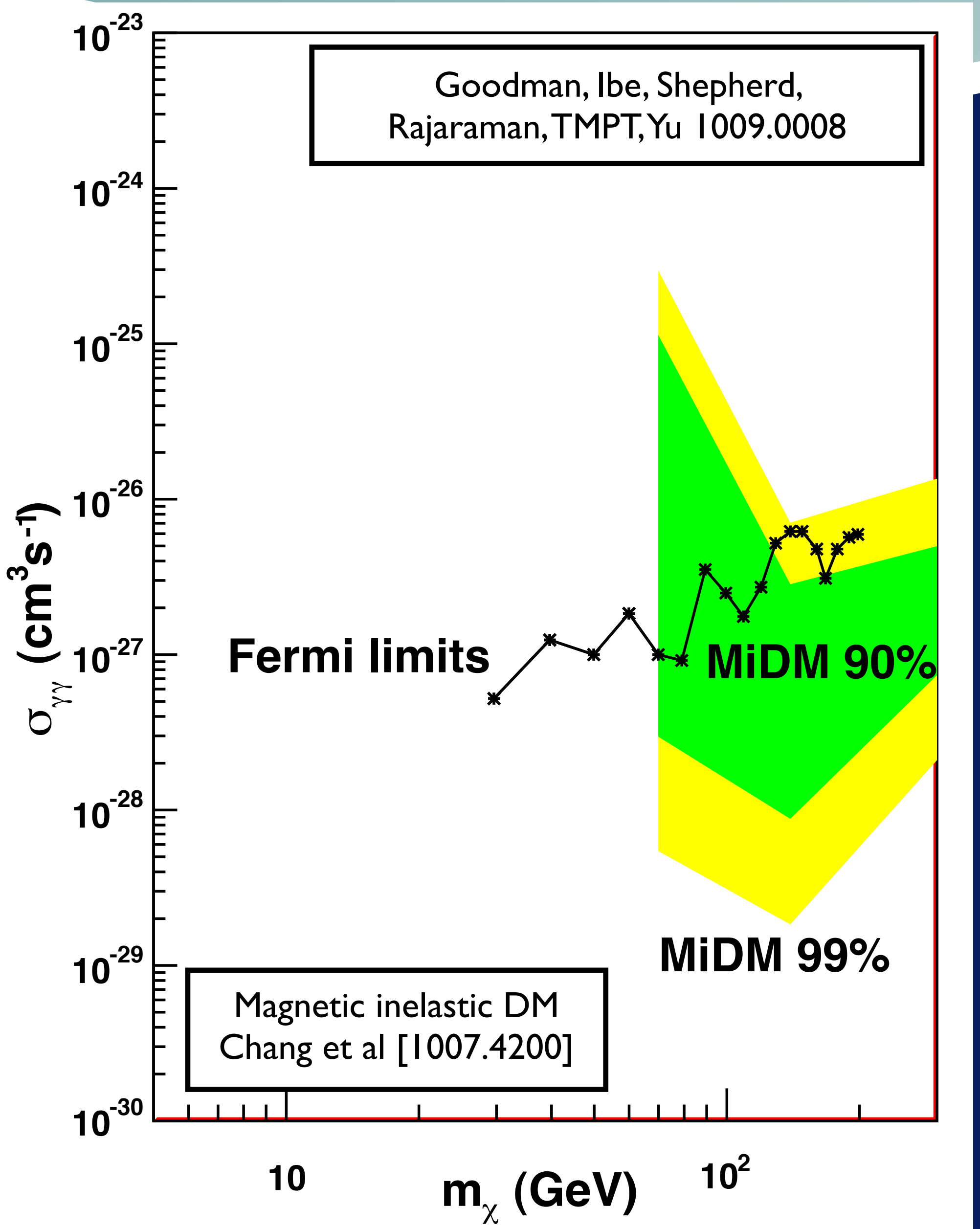
- The effective theory language can also be effectively mapped into indirect searches for dark matter.
- For example, interactions with quarks can be closed into loops and turned into annihilation into gamma ray lines.
- The Fermi limits are actually the best ones for some operators (such as for spin-dependent interactions).



Gamma ray Lines and MiDM

- Gamma ray line bounds also have something interesting to say about the MiDM model!
- In this case, WIMPs can annihilate into a two photons at tree level through their magnetic moment interactions.
- The Fermi line constraints are particularly relevant for lower mass WIMPs.





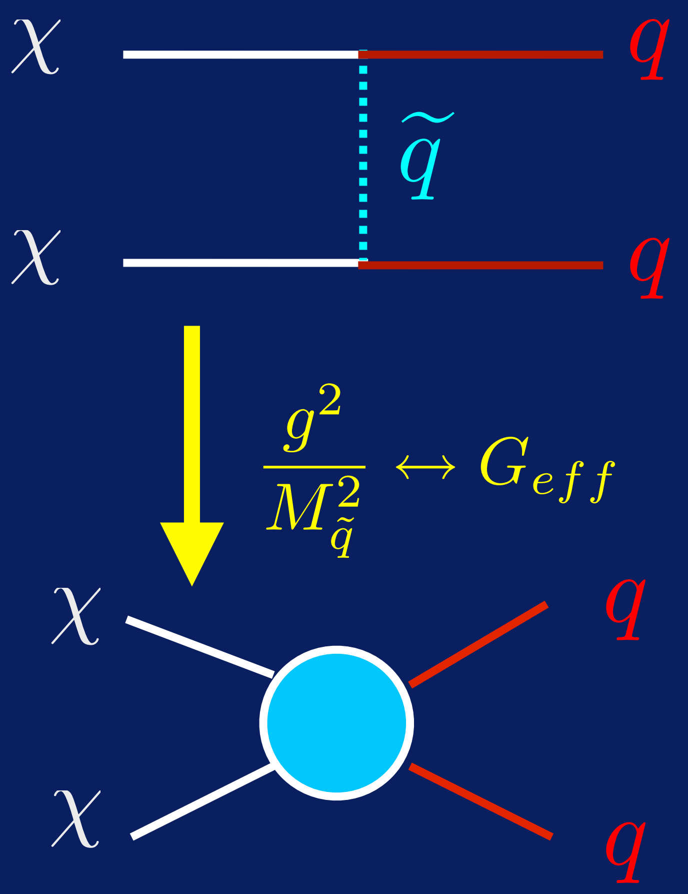
Recap

- In lecture 2, we saw more examples of theories of dark matter.
  - The UED WIMP serves to illustrate the case in which dark matter is a boson, either a vector (5d) or a scalar (6d).
  - Little Higgs theories with T-parity also have a vector WIMP, but one which prefers to couple to massive particles.
  - Both show big differences compared to a SUSY Majorana WIMP!
- Super-WIMPs are harder to search for, and may be a hint of a nonstandard thermal history.
- Designer dark matter tries to fit the dark matter to the observations, rather than the other way around.
  - Eventually, we can hope to assemble a designer theory of dark matter into a more fundamental theory with connections to deep questions.

Bonus Material

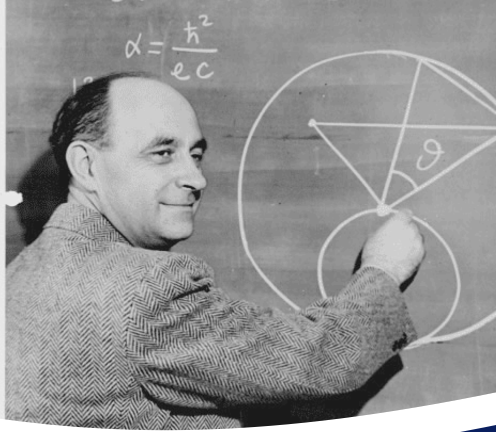
Effective Field Theory

- Effective Field theories are a powerful tool to describe physics at a particular energy scale.
- Only the degrees of freedom relevant at the energy scale at hand are included in the description. Heavier particles are "integrated out".
- Theories which look very different at high energies lead to a smaller range of low energy phenomena, because their form is dictated by the particles and symmetries present at low energies.
- Capitalizing on these strengths, we construct the most general effective theories describing WIMP interactions.

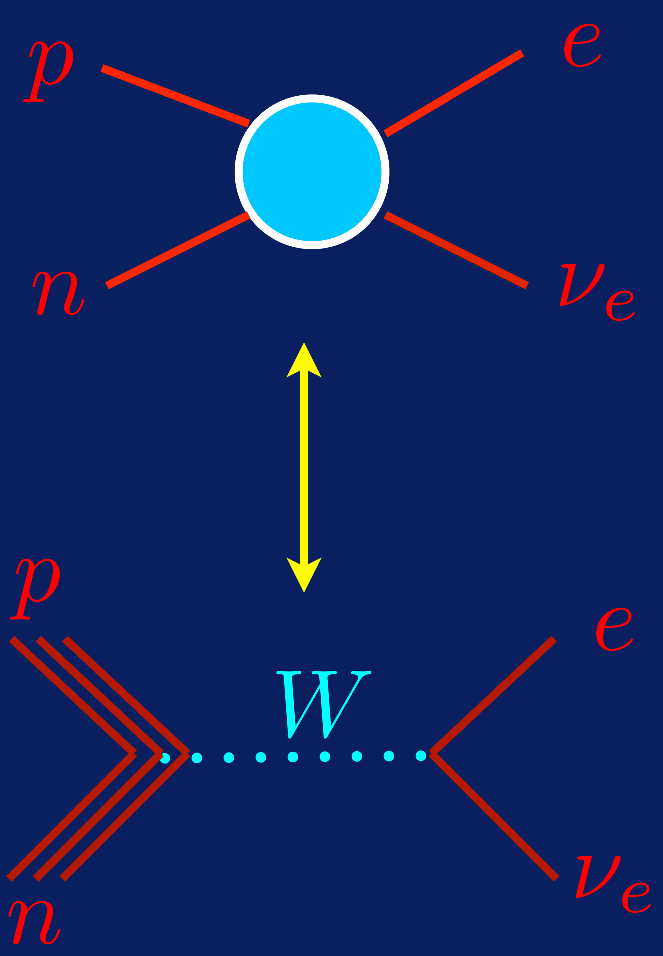


Shepherd, TMPT, Zaharijas, Phys Rev D79, 055022 (2009)

Historical Perspective

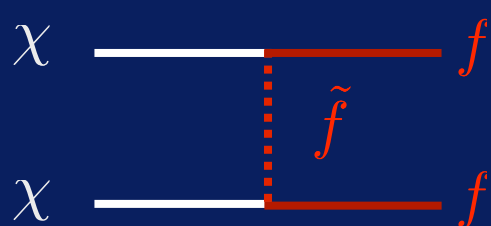


- Effective field theories have a fruitful history:
  - Fermi proposed his theory of beta-decay without knowing about the existence of the W boson (or quarks!).
  - Feynman and Gell-Mann deduced its V - A structure.
  - With the advent of the Standard Model, we resolve the interaction into the W boson, resulting in a UV complete description.
- At low energies, the Fermi theory is a perfectly fine description of the physics.
- Quantifying it provides the first hints to construct a more complete high energy theory.

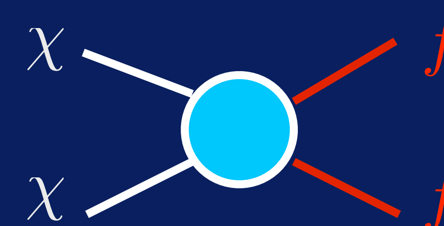


Example EFT: Majorana WIMP

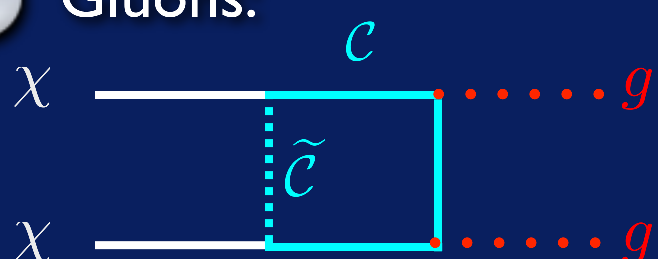
- Here are pictures for how a Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



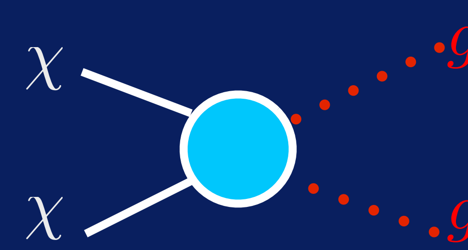
$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



  - Gluons:



$$\sim \alpha_S \frac{g^2}{M_{\mathcal{C}} M_{\tilde{\mathcal{C}}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



  - Each requires new states with masses heavier than the WIMP.

SI: Zoomed Out