Title: A Few Interesting Trees in the WIMP Forest

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Abstract: Gamma rays from WIMP annihilation are an important signal through which we search for non-gravitational interactions of dark matter. In particular, lines in the energy spectrum of gamma rays provide a signal which is difficult for conventional astrophysics to fake, and are thus promising despite the fact that such lines are generically expect to be suppressed, arising from one loop processes. I will discuss two theories which have an interesting family of gamma ray lines and discuss how such lines can reveal information about the WIMPs and the dark sector.

A Few Interesting Trees of the WIMP Forest

Tim M.P. Tait

University of California, Irvine

Work done with:
Bertone, Jackson, Shaughnessy, Vallinotto, [0904.1442]
and
Jackson, Servant, Shaughnessy,

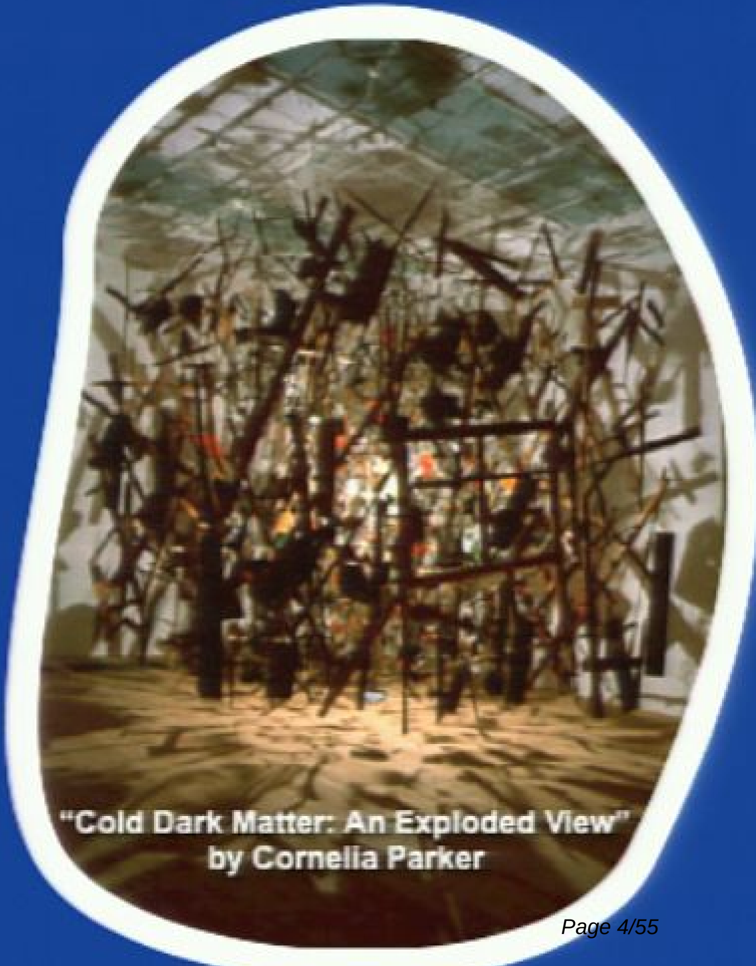
Perimeter Institute
March 26, 2010

Outline

- Introduction / Motivation
- Gamma rays from WIMP Annihilations
- The WIMP Forest
- Some interesting Trees...
  - The 6d Chiral Square
  - The Higgs in Space
- Outlook

Dark Matter: WIMPs

- Dark matter is physics beyond the SM.
- A particularly compelling realization is a Weakly Interacting Massive Particle.
  - Relic density -- WIMP Miracle.
- Some properties are required:
  - Neutral
  - Massive
  - (At least approximately) stable
- That still leaves a lot unknown:
  - Mass
  - Spin
  - Electroweak charge
  - Real/Majorana or Complex/Dirac...



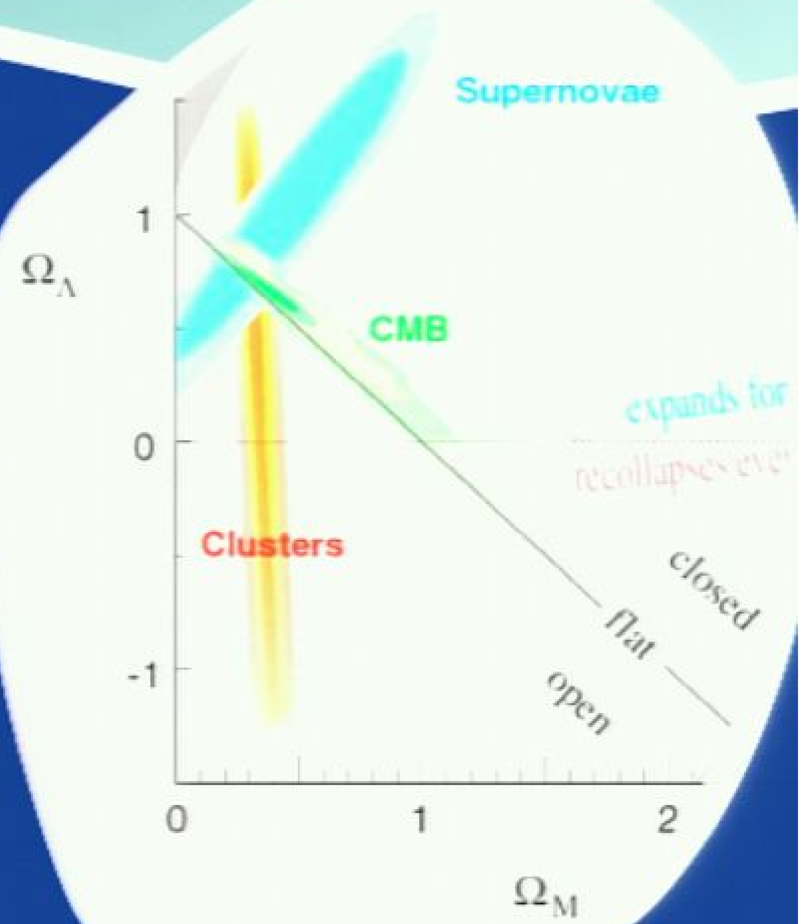
"Cold Dark Matter: An Exploded View" by Cornelia Parker

Interactions with the SM

- We usually infer the annihilation cross section from the relic density:

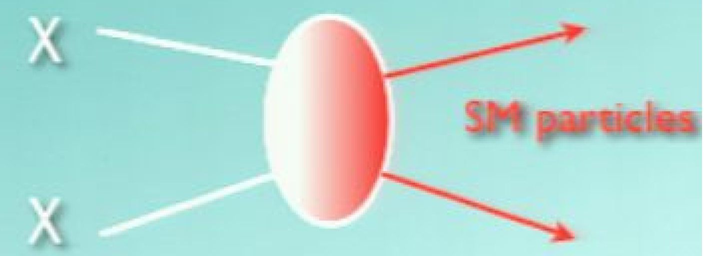
$$\langle \sigma v \rangle \propto \frac{g^4}{M^2} \sim 1 \text{ pb}$$

- This constrains a surface in the space of couplings and mass.
- It would be great, because large (electroweak strength) interactions with the SM would provide all sorts of new avenues to detect WIMPs.



- Ordinary Matter
- Dark Matter
- Dark Energy

Indirect Detection



- WIMPs may still be annihilating today, producing particles we can detect here such as photons, neutrinos, or charged particles.
- The search for these particles is an important search for dark matter:
  - Since it involves the cosmological relic WIMPs themselves, the signals can be directly traced back to dark matter. (Unlike at colliders where we may find even more exotic sources of missing momentum).
  - It offers a glimpse into some of the same annihilations we think drove the relic density, and thus would be the first step toward verifying our hypothesis for the thermal picture of the Universe.
- Ultimately, together with a picture of WIMP interactions, we can use this process to learn about the distribution of dark matter in the galaxy.

Indirect Detection

- The rate of production is described by a cross section which depends on the WIMP model, and the density of WIMPs along the line of sight, squared.

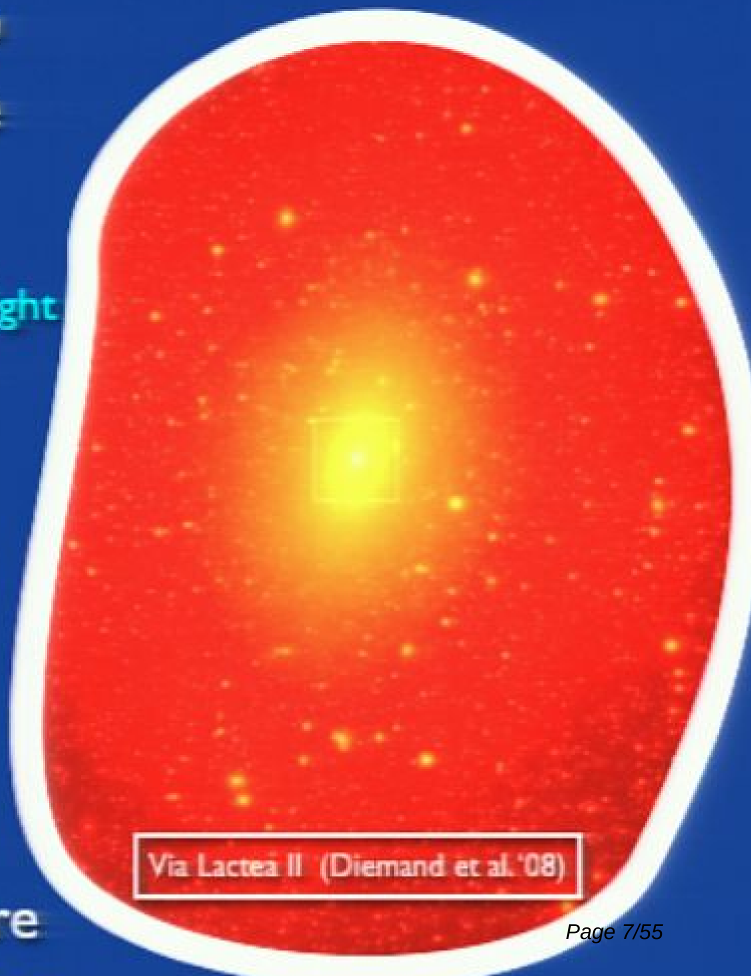
Microphysics

Distance along line of sight

DM density

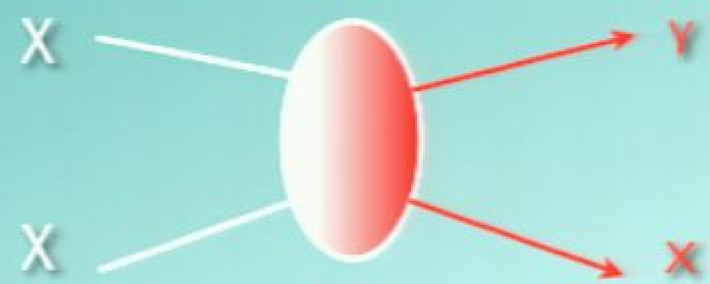
$$\frac{dN}{dE} = \frac{d\langle \sigma v \rangle}{dE} \int dl\; \rho_{DM}^2(l)$$

- Simulations of the dark matter density provide clues as to where to look. The center of the galaxy has the largest concentrations of dark matter (but also the most ferocious backgrounds). There are also dwarf galaxies & perhaps dark subhaloes.



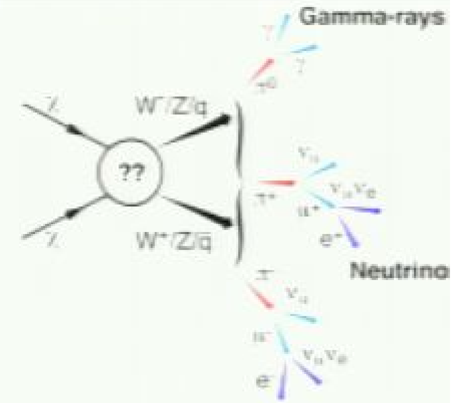
Via Lactea II (Diemand et al. '08)

Gamma Rays



- I'll focus on gamma rays:
  - Gamma rays do not get highly scattered over galactic distances, so they generally point back to their source.
    - Unlike charged particles, which get scattered by galactic magnetic fields, we can ask if gamma rays come from regions of the sky where we expect dark matter, and what the backgrounds in that region are expected to look like.
  - Gamma rays are produced from almost any SM final states, and offer some hope of reconstructing the primary annihilation products.
  - The Fermi/GLAST satellite is rapidly increasing our understanding of the gamma ray sky in the energy range from a few MeV to 100's of GeV.

Continuum Gammas



- Since WIMPs are neutral, they don't couple directly to photons. The rates into photons can be expressed as a convolution of the rates into other particles with the rate for those particles to produce gammas.

$$\frac{d\langle \sigma v \rangle}{dE_\gamma} = \sum_F \frac{d\langle \sigma v(\chi\chi \to F)\rangle}{dE_F} \, f_{\gamma/F}\left(\frac{E_\gamma}{E_F}\right)$$

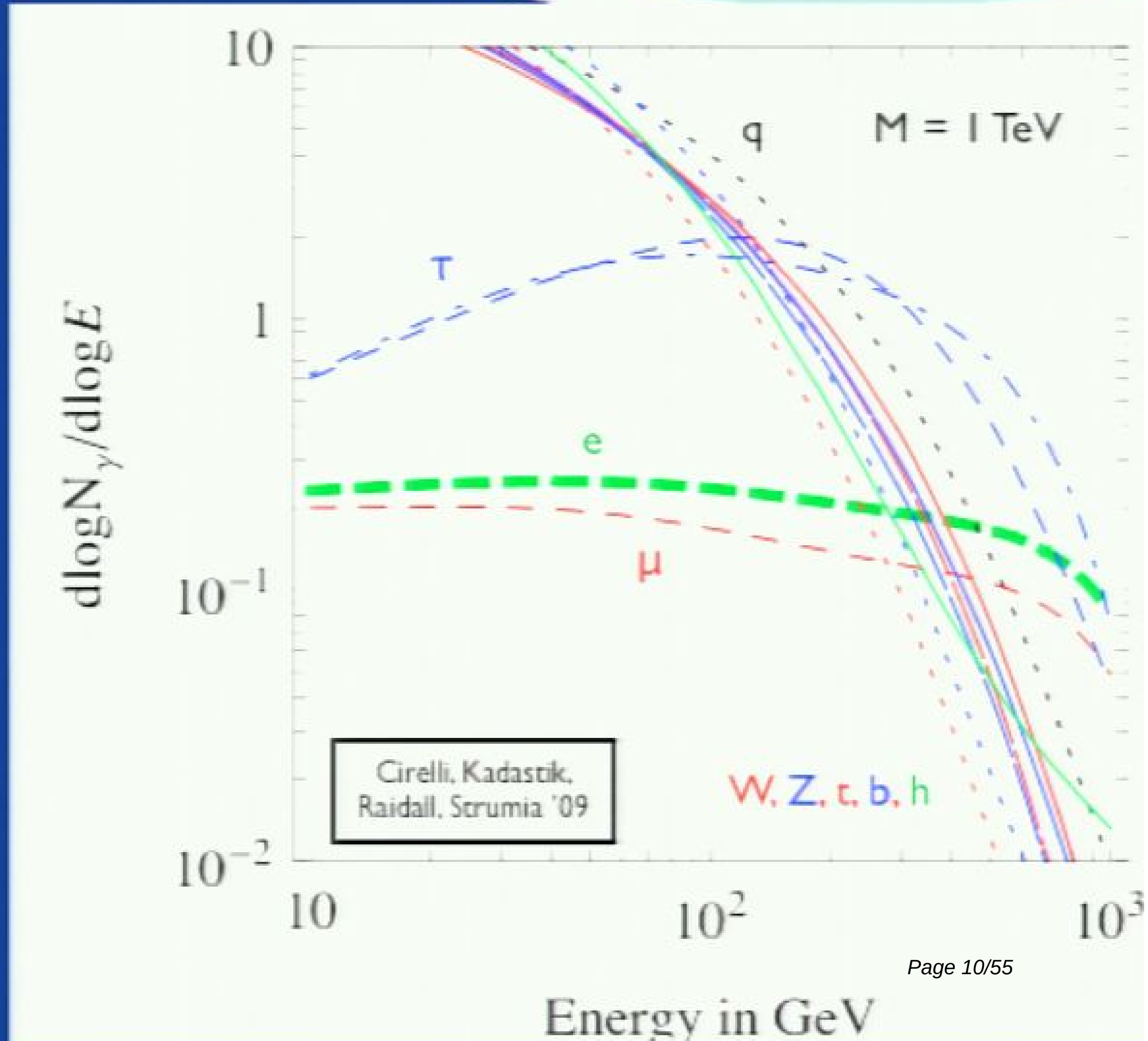
Sum over perturbative final states F

Gamma yield from final state F

- The final E_γ are complicated and smeared out:
  - Some gammas are produced as radiation from charged final states.
  - Hadronic final states undergo corrections from parton showering.
  - Heavy particles share energy among many final state decay products.

$f_{\gamma/F}(E_\gamma/E_F)$

- WIMPs which annihilate into pairs of leptons produce a relatively hard spectrum of gammas from FSR. (e's and μ's are even somewhat harder than τ's).
- Annihilation into quarks ultimately produces π^0s which decay into pairs of γs.
- Heavy particles (W, Z, h, t, b) produce a mixture, sharing their energy among decay products, looking much like



Challenges

- While the signals for WIMPs annihilating into gamma rays can have large rates, observing a signal is challenging.
- Backgrounds (especially from the galactic center) are complicated, coming from many different kinds of objects, and the spectrum and distribution of these objects are not always well understood.
- The WIMP signal has a cut-off at the mass of the WIMP, but, especially without knowing which final states the compromise the primary annihilations, the shape of the signal, and the prominence of the cut-off is difficult to know.
- Most of the experimental searches currently focus on a bb final state, motivated by supersymmetry.

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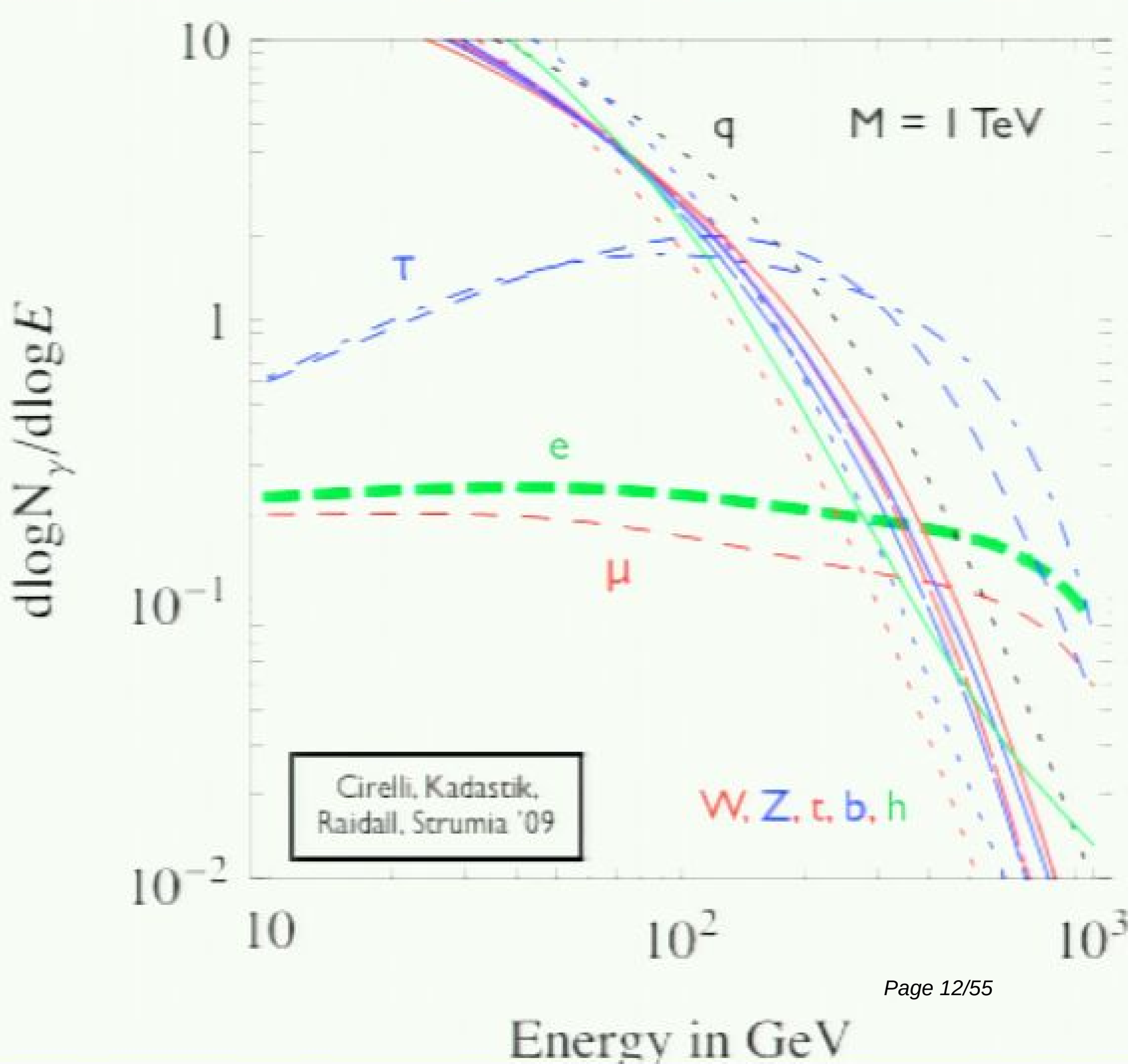

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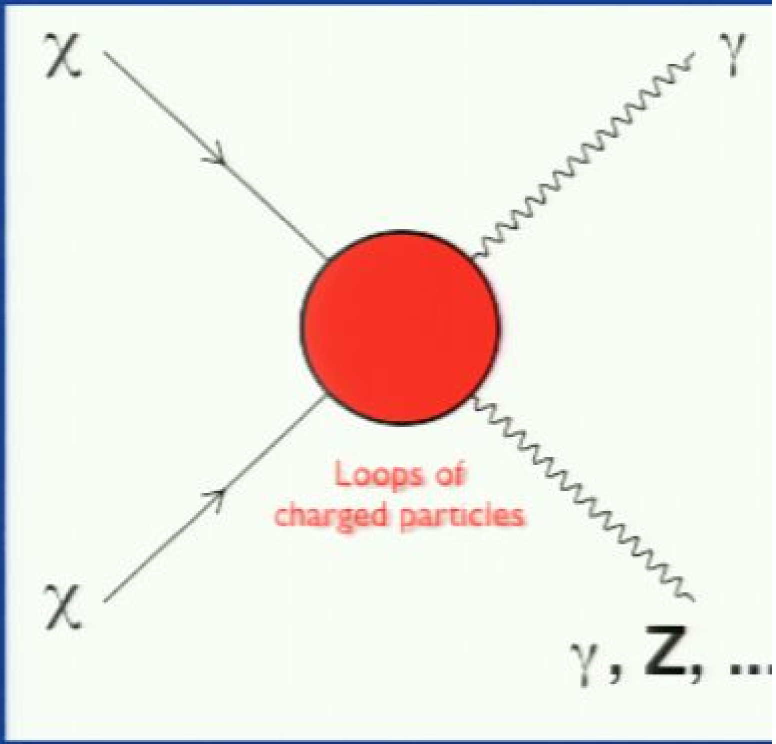
Gamma Ray Lines

- The spectrum of gamma rays may also contain spectral lines. They occur when WIMPs produce gammas in a two-body final state.

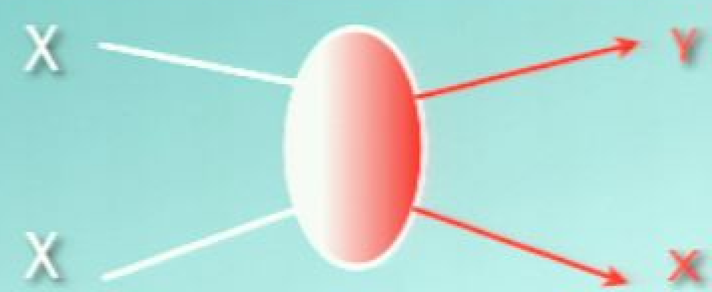
- Since WIMPs are thought to be highly non-relativistic in the galaxy, energy conservation predicts the energy of the photon in the reaction $\chi\chi \to \gamma X$ to be:

$$E_\gamma = M_\chi \left(1 - \frac{M_X^2}{4M_\chi^2}\right)$$

- This is a feature that conventional astrophysics has great difficulty producing, perhaps compensating for a loop level rate.



A WIMP Forest?



- In supersymmetry, gamma ray lines from annihilation into γγ and γZ have been well known for many years.
- The WIMP forest refers to the possibility that there may be a richer structure of gamma ray lines.
- Today, I'm going to explore two theories with interesting line structures:
  - A model of (two) Universal Extra Dimensions : the 6d Chiral Square.
  - A Randall-Sundrum model with a KK neutrino dark matter candidate.

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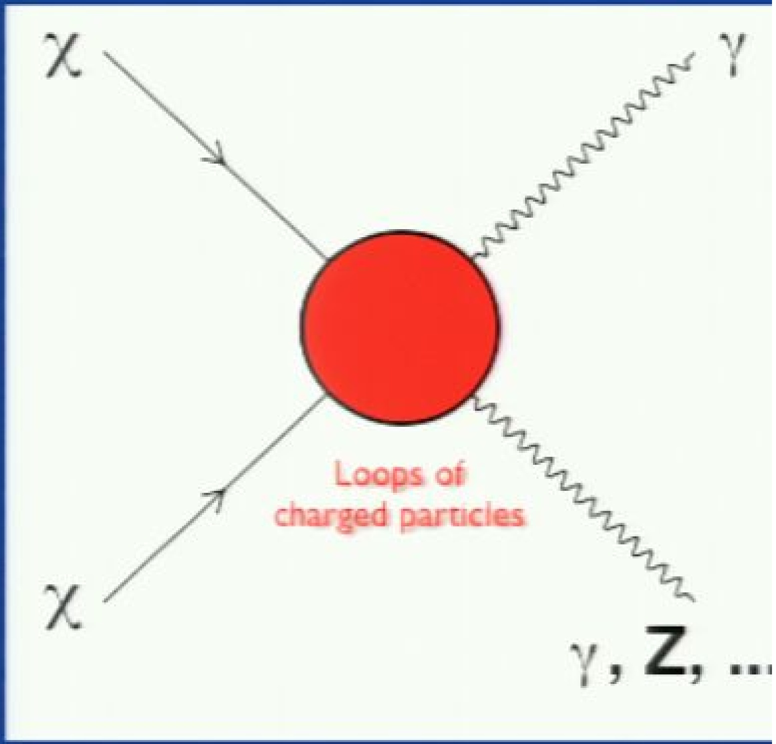

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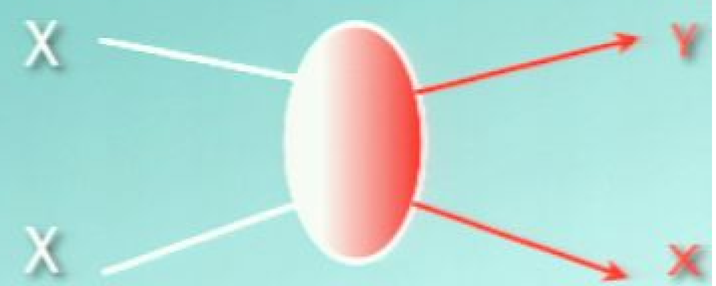

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The 6d Chiral Square

Universal Extra Dimensions

- The Chiral Square is an example of a theory with Universal Extra Dimensions (UED), which treat all fields of the theory democratically : living equally in all of the dimensions.

  Appelquist, Cheng, Dobrescu '01

- The zero mode fields are identified with the usual SM particles; every SM field thus has a KK tower associated with it.
- This is particularly interesting for a theory of dark matter, because it implies a translational invariance along the extra dimensional directions, which leads to a conserved quantity: momentum (KK number) in the extra dimensions.
- The boundary effects break KK number conservation down, but a parity usually remains, and is usually sufficient to guarantee that the lightest KK mode is stable, and thus a possible WIMP.

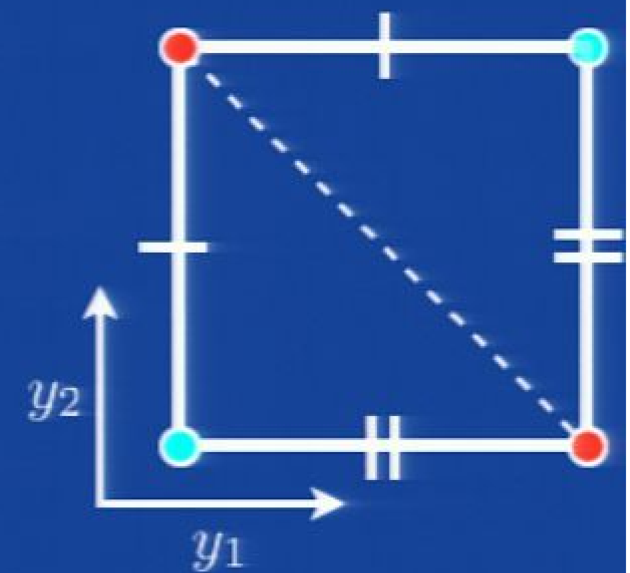
The Chiral Square

- 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 orbifold compactification has chiral fermions, and its low energy physics can be engineered to match the Standard Model.
- 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



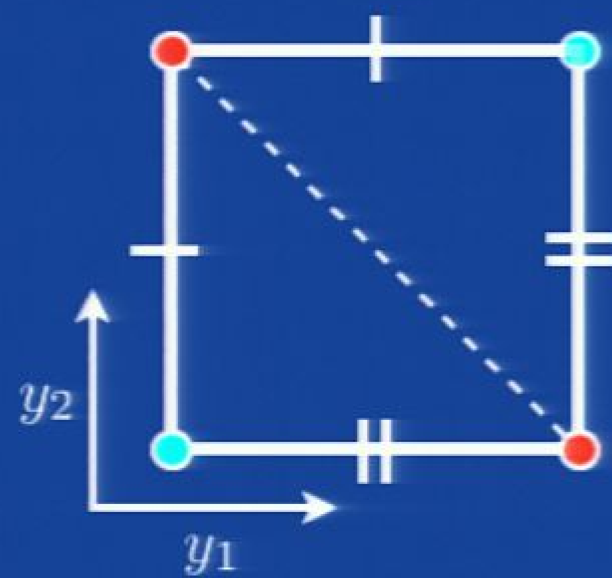
KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

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).

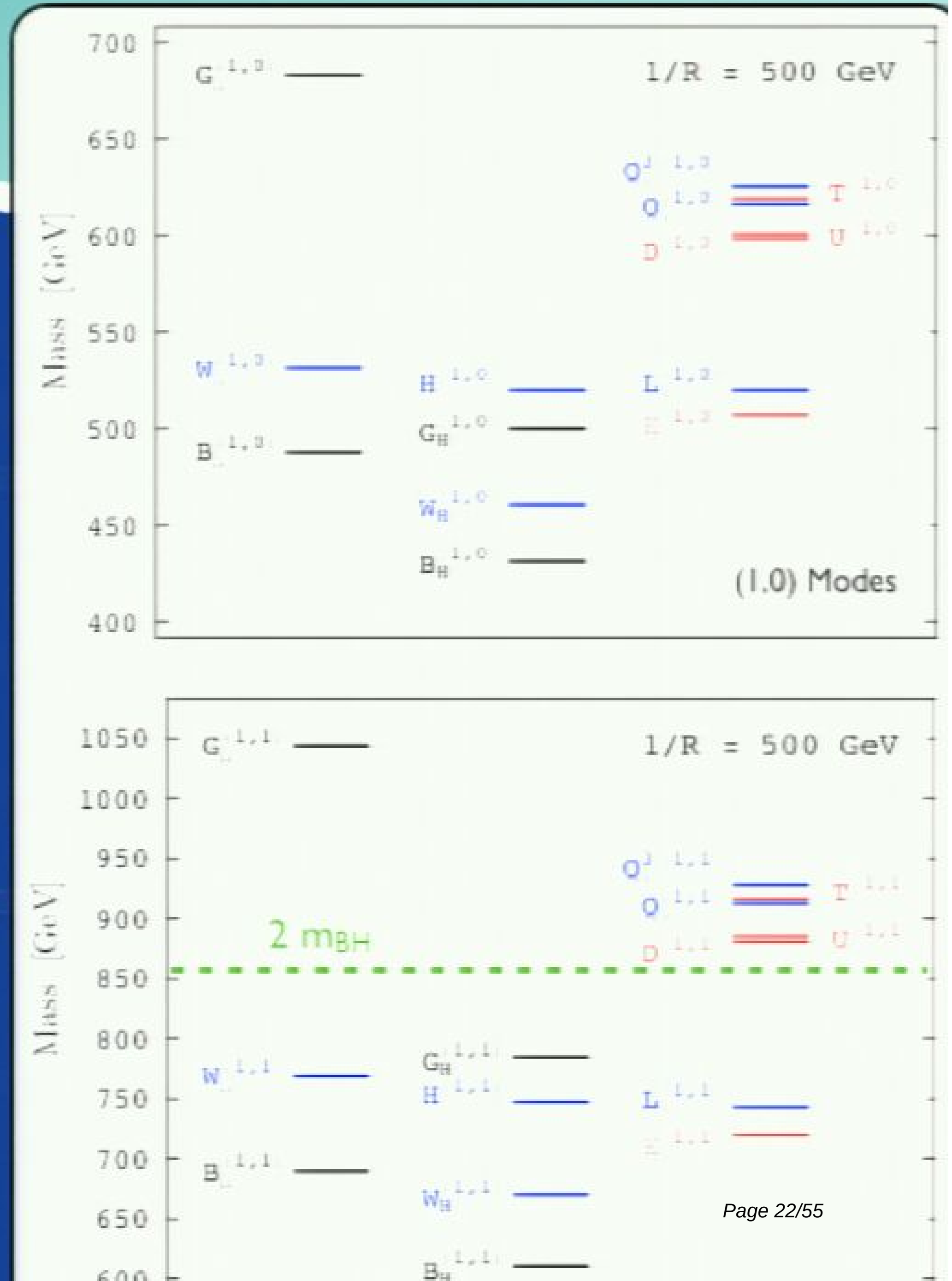


$$V_M \rightarrow \{V_\mu, V_5, V_6\}$$

One combination eaten by massive V_μ, the other

Spectrum

- The boundary terms modify the masses of the fields at a given (j,k) level. They control the systematics of the spectrum of states.
  - 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 $2 M_B$.



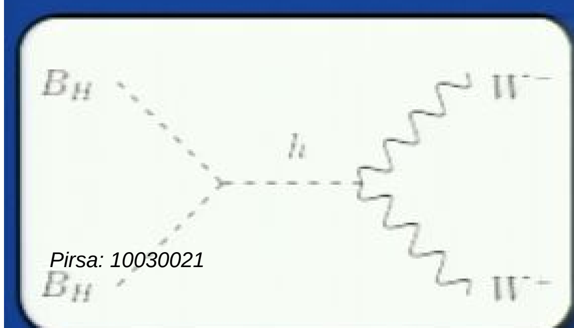
(1,1) States

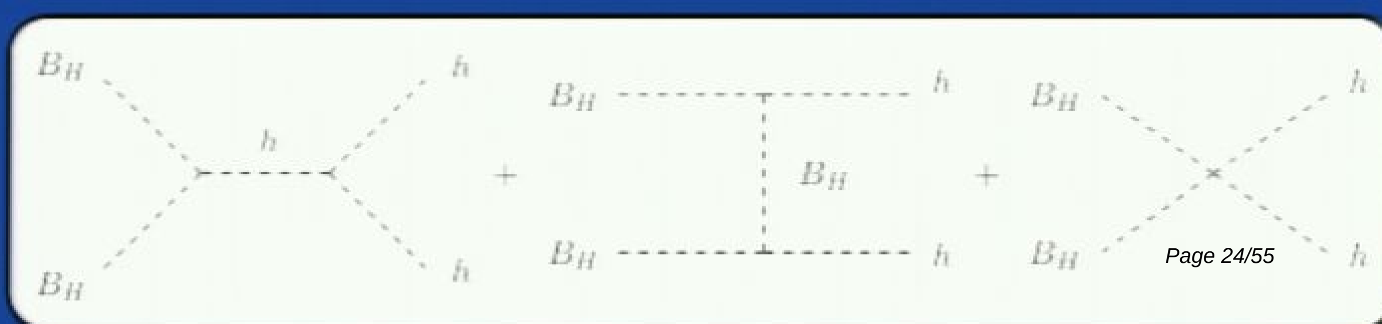
- The presence of the (1,1) states is what makes the chiral square particularly interesting in the context of the WIMP forest.
  - Their masses are roughly $\sqrt{2}M_B$, implying processes like $B_H B_H \to B_\mu^{(1,1)}\gamma$ and $B_H B_H \to W_\mu^{(1,1)}\gamma$ are kinematically allowed.
  - They produce lines at $E_\gamma \sim M_B / 2$, far away from the $\gamma\gamma$ line.
    $$E_\gamma = M_\chi \left(1 - \frac{M_X^2}{4M_\chi^2}\right)$$
  - A 5d UED theory has its next highest states at about 2 MB - slightly too heavy to be produced in annihilation of two LKPs.
- The (1,1) states are even under KK-parity.
  - They have small (boundary-term induced) couplings to pairs of SM fields, allowing them to be singly produced at colliders, and they can

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

Dobresu, Hooper, Kong, Mahbubani, '07





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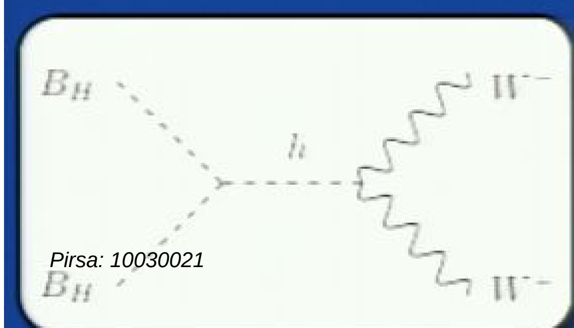
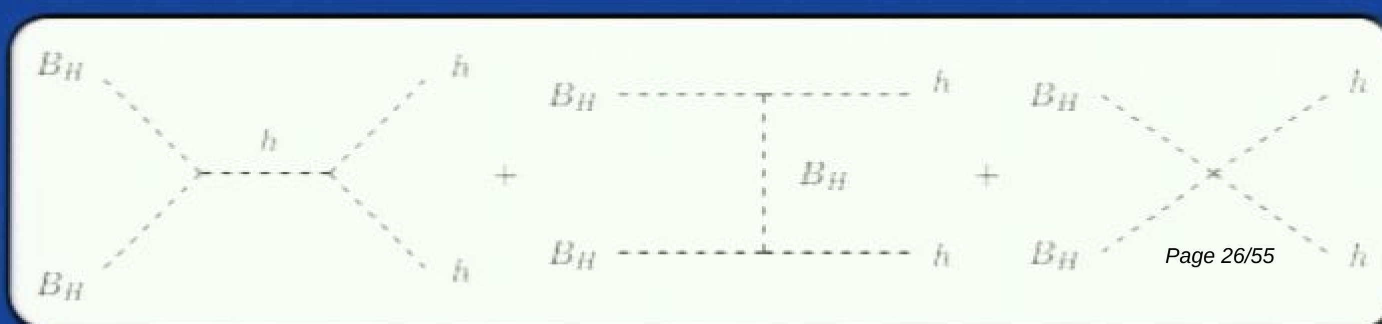
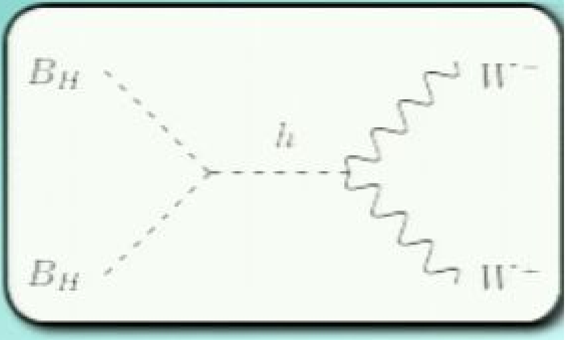
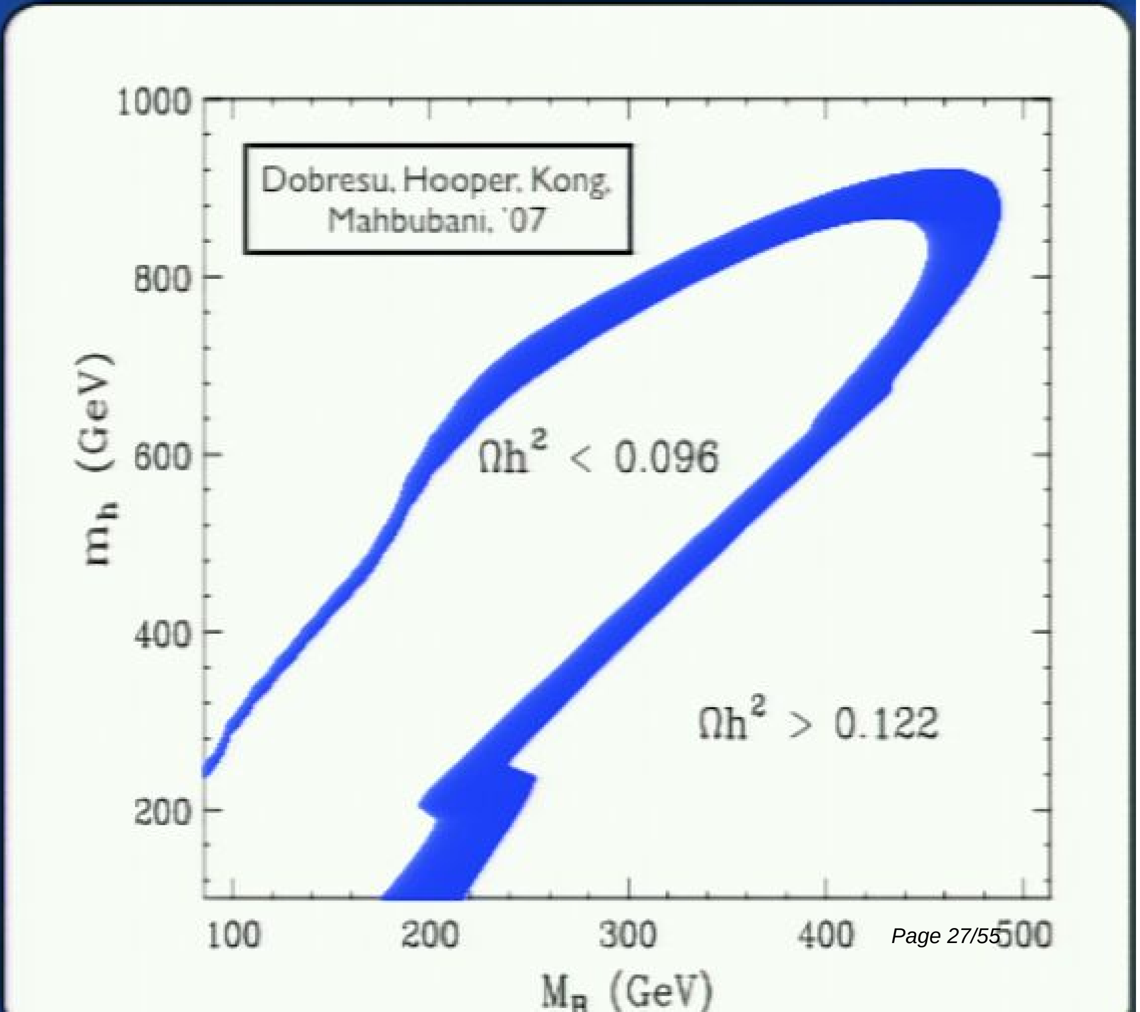




Relic Density

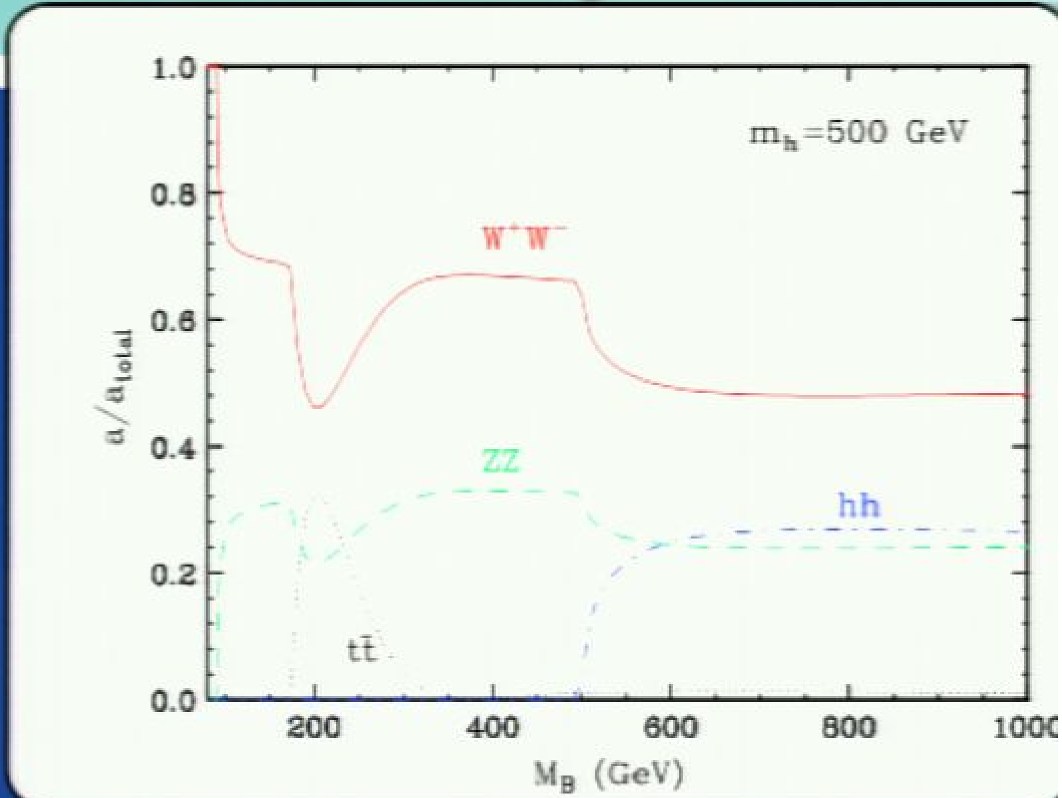


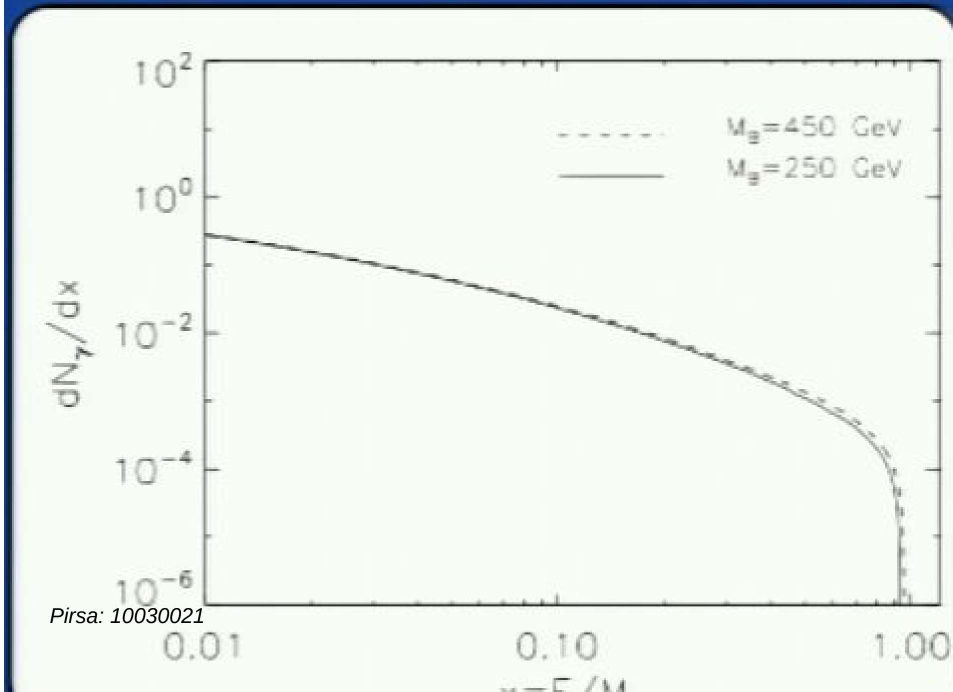
- Because of the s-channel Higgs-mediate graphs, the annihilation cross section is very sensitive to the interplay between the LKP and Higgs masses.
- Generally, the relic density favors LKP masses between 100 - about 500 GeV, provided the Higgs mass is chosen to match.
- Collider bounds require the LKP mass to be greater than about 200 GeV.



Continuum Gamma Rays

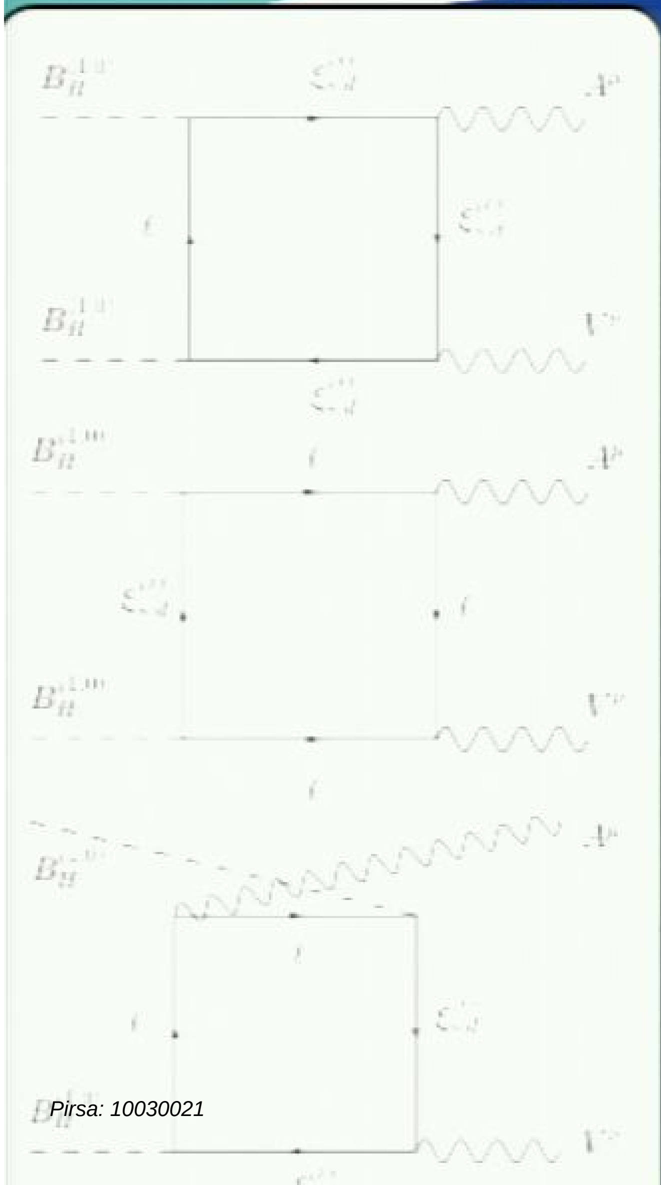
At large LKP masses, the relative annihilation into charged and neutral (ZZ + hh) channels become equal, as dictated by the Goldstone equivalence theorem.





These annihilation modes are "photon unfriendly" - they do lead to continuum gamma rays, but only after the (pairs of) heavy direct particles decay, resulting in many very low energy gammas, but not many hard photons.

Gamma Ray Lines



- LKP annihilations leading to gamma ray lines include $\gamma\gamma$, γZ, $\gamma B^{(1,1)}$, and $\gamma W^{(1,1)}$ final states.
- All fields carrying hypercharge and electric charge run in the loops.
- In the case of $W^{(1,1)}$, the internal fields also need to be SU(2)-charged, resulting in a somewhat smaller cross section than for $B^{(1,1)}$.
- We compute the full set of graphs, using Passarino-Veltman to decompose the tensor integrals into scalar functions. Passarino, Veltman '79
- Special technology is needed for non-relativistic scattering, where PV becomes singular. Stuart '88

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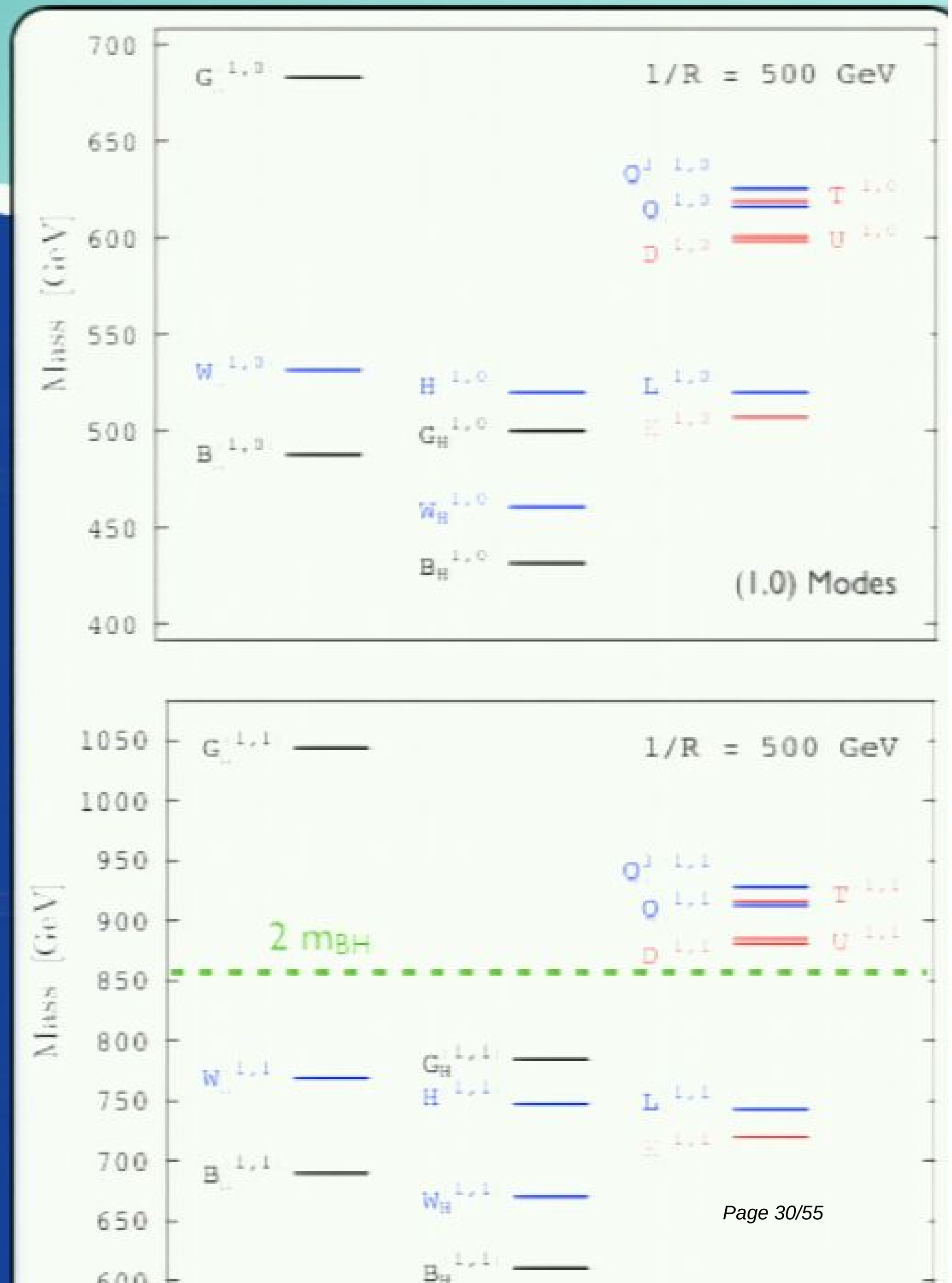

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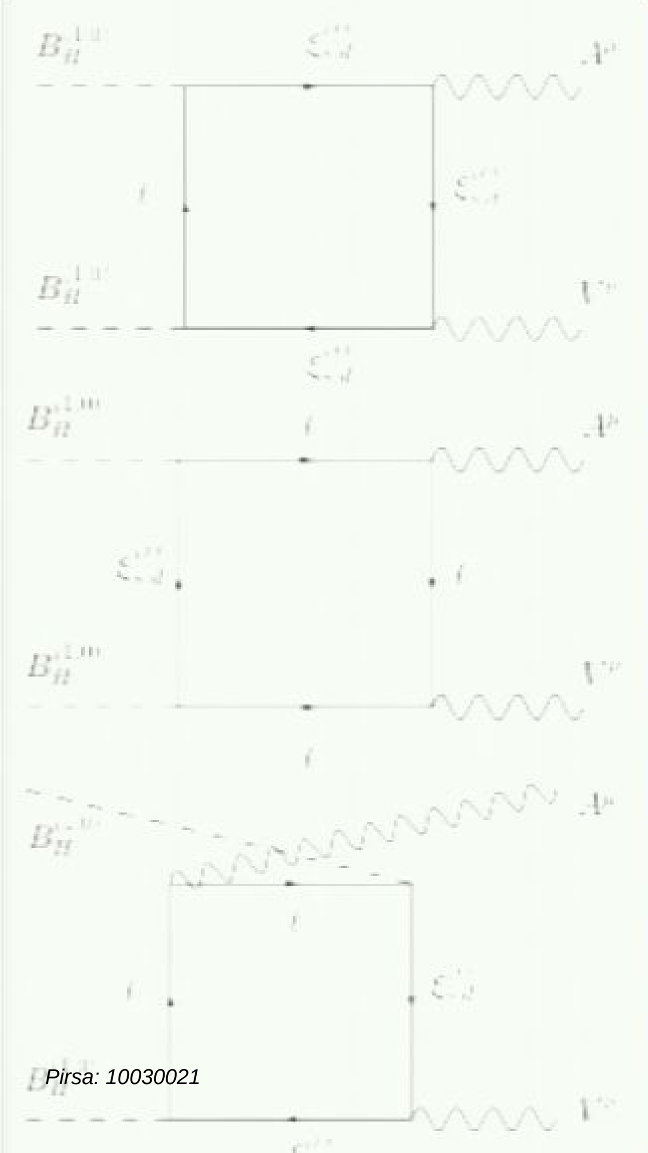

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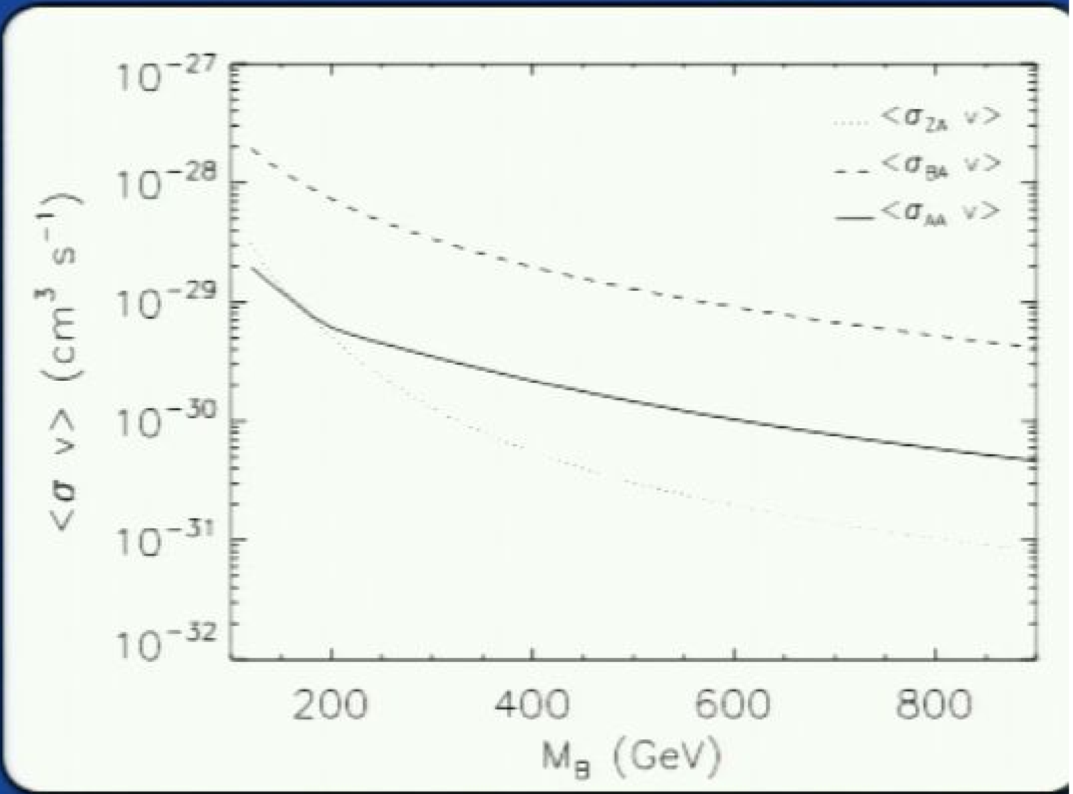
Line Cross Sections

- The resulting cross sections are roughly what one would expect for a process whose amplitude is one-loop: they're tiny.
- Interestingly, the cross section for $\gamma B^{(1,1)}$ is considerably larger than for $\gamma\gamma$ or γZ.
- This appears to be mostly an accidental effect related to (partial) internal cancellations between graphs which reduce the $\gamma\gamma$ and γZ rates by comparison.



KK masses inspired by minimal boundary terms: (1,0) lepton modes are about 20% heavier than the LKP.

Line Shapes and Resolutions

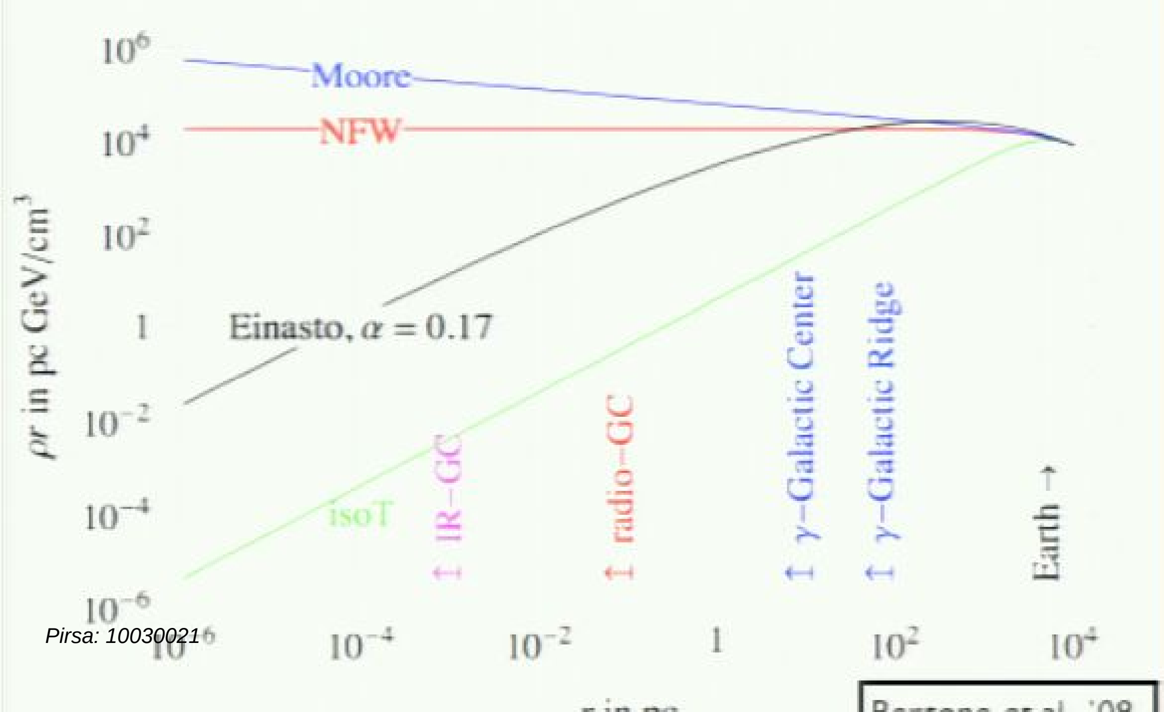
- The Z and (1,1)-state lines have intrinsic spread set by their decay widths.
- However, the current generation of experiments (both the Fermi satellite and the Air Cherenkov Telescopes) have energy resolutions which are much greater:

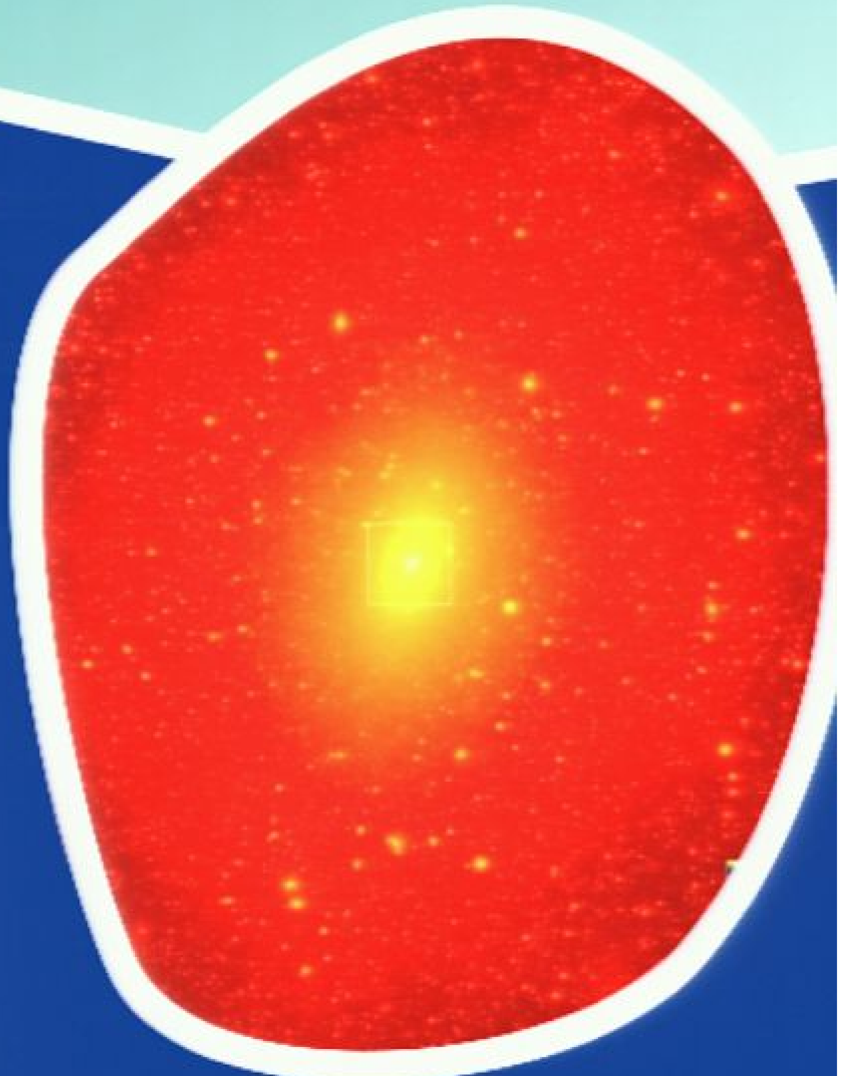
$$\frac{\Delta E}{E} \sim 10\% \qquad\qquad (E \sim 100\ \mathrm{GeV})$$

- As a result, the lines broaden into "bumps" and the $\gamma\gamma$ and γZ lines merge into a single peak.
- The (1,1) modes will similarly end up merged together, but remain distinct from the $\gamma\gamma+\gamma Z$ peak.

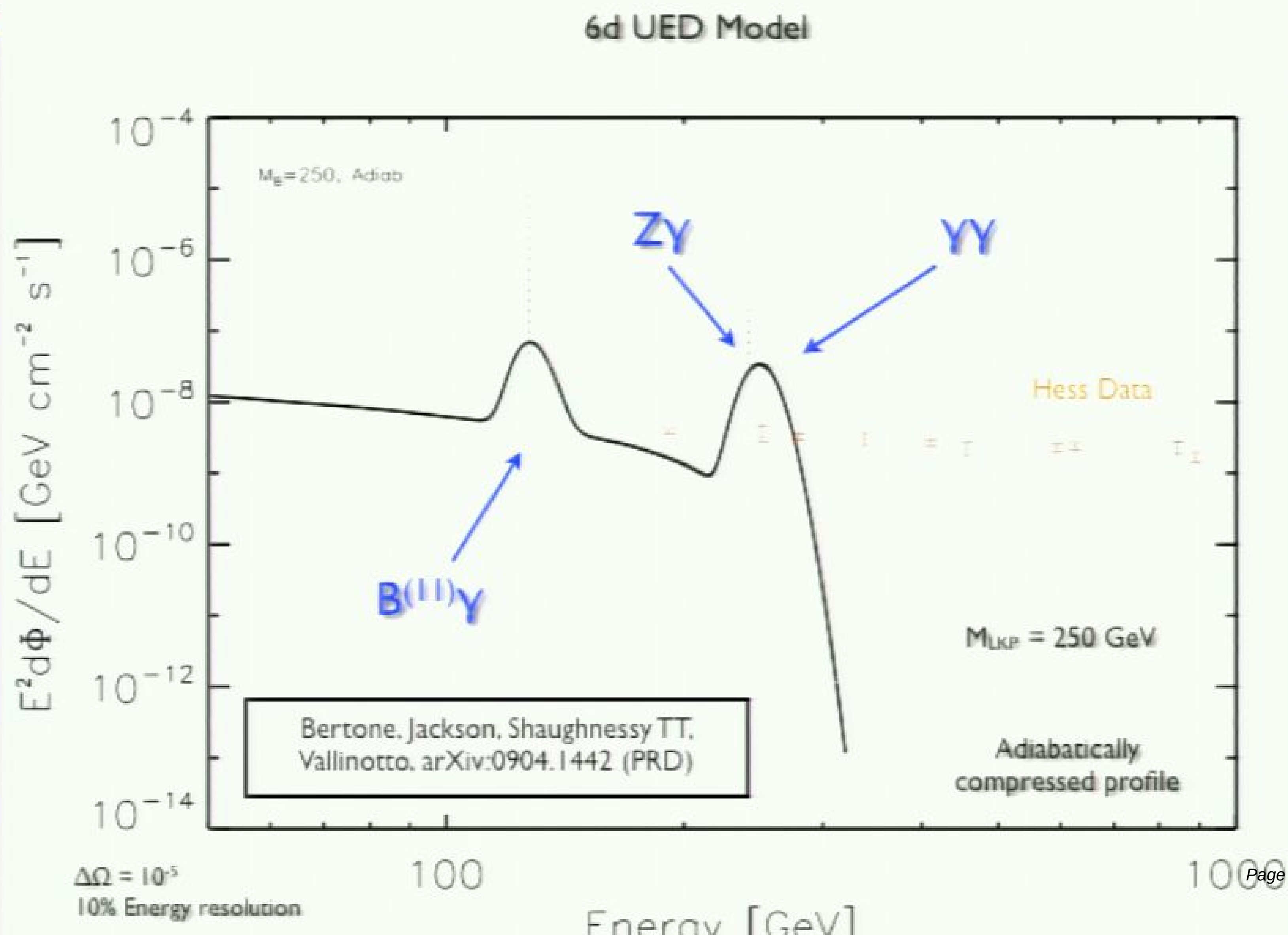
Dark Matter Profiles

The strength of the signal depends on the square of the dark matter density. Especially at the center of the galaxy, that quantity has large uncertainties.



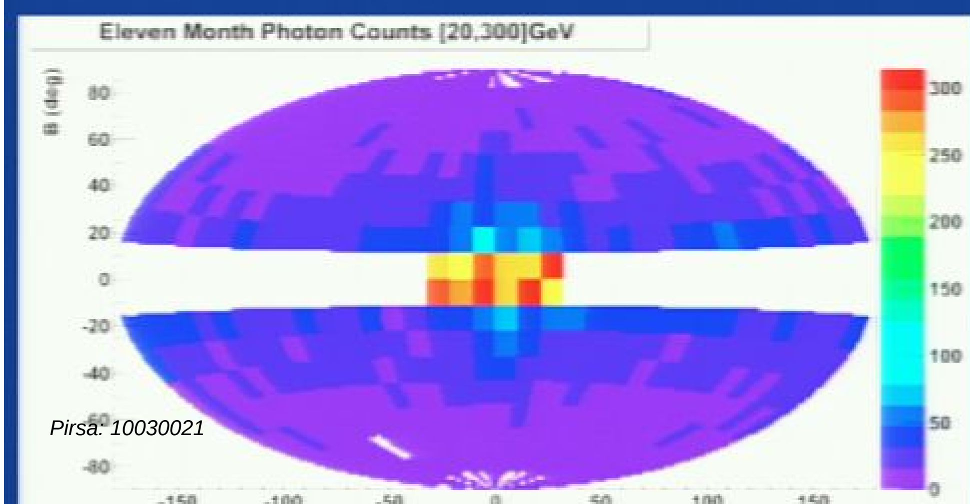


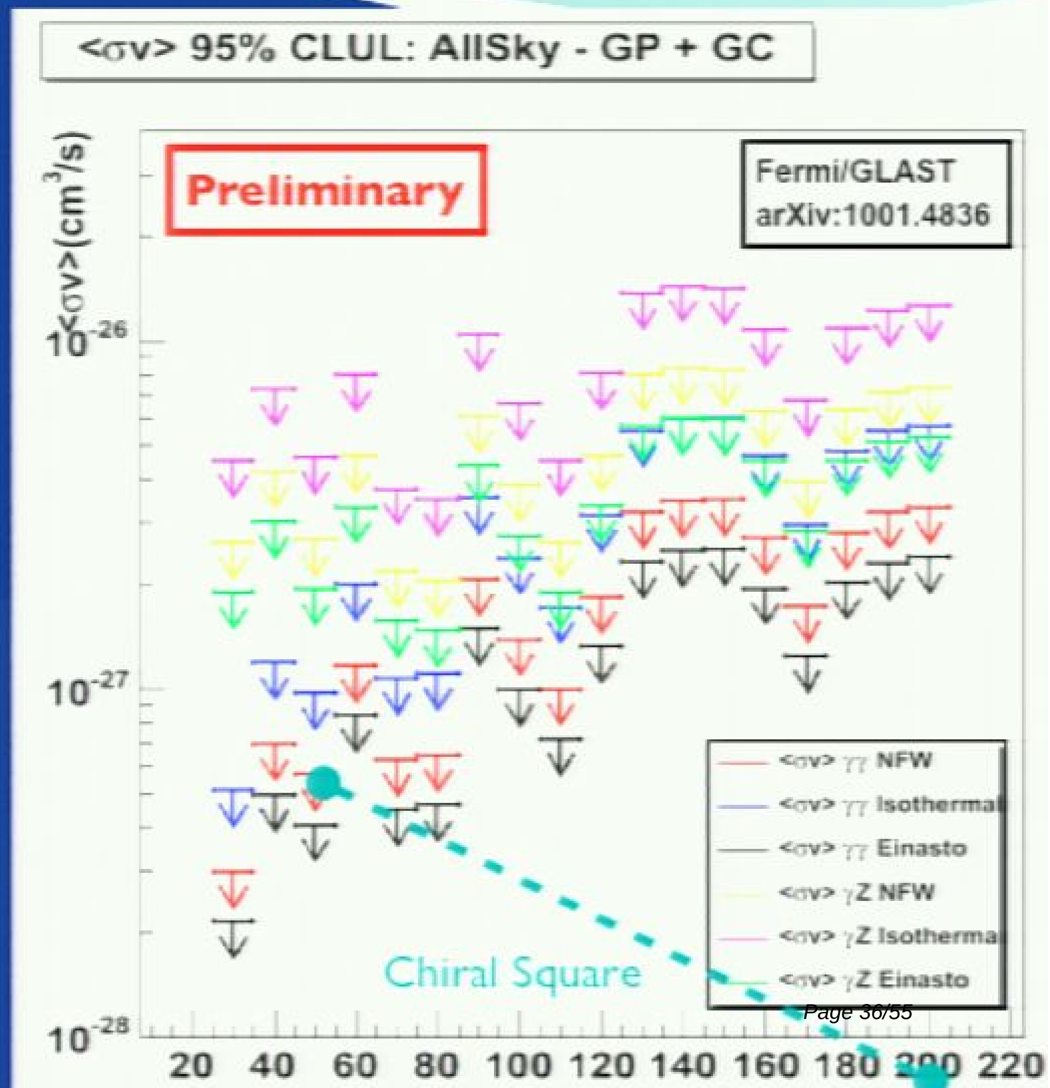
Lines of the Chiral Square



Fermi Line Search

- Fermi/GLAST has searched for lines in the gamma ray spectrum with energies between 30 - 200 GeV in a "shape analysis".
- Search region includes |b| > 10° and 30° around the galactic center.





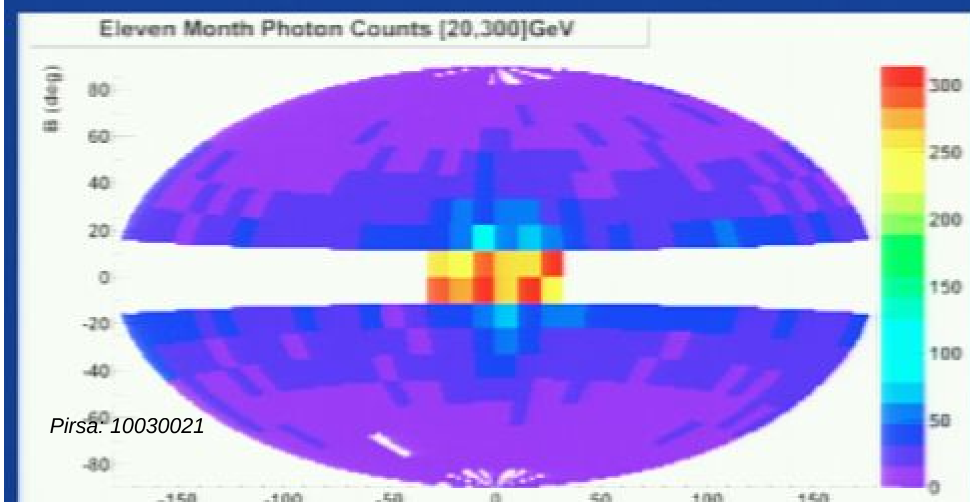
Fermi vs the Chiral Square

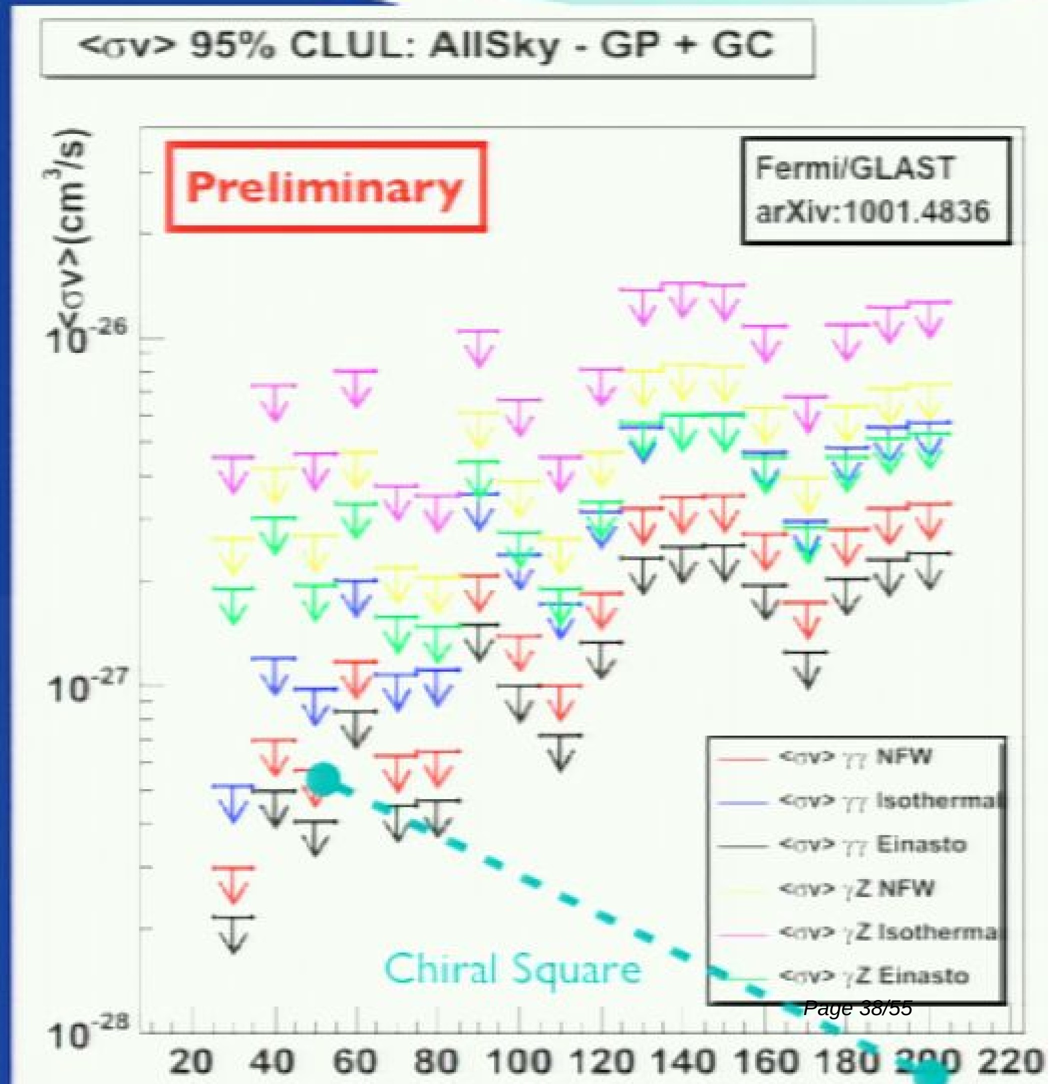
- The Fermi search is still about an order of magnitude away from the chiral square predictions for $\gamma B^{(1,1)}$. Expected improvements in control over the background, and more statistics will bring it into reach, at least for the lower range of LKP masses.
- If we end up with a discovery, one can imagine the initial observation will be of the $\gamma B^{(1,1)}$, which for a vanilla WIMP will be interpreted as $\gamma\gamma/\gamma Z$ at the WIMP mass.
- Later observation of the true $\gamma\gamma/\gamma Z$ peaks could help clarify the situation.
  - But the $\gamma\gamma$ line may be too faint to be observed by Fermi.
  - Fermi rapidly loses energy resolution above 300 GeV; for more massive LKPs, the $\gamma\gamma$ line may be beyond its reach.

- If we do understand the full line structure, it tells LHC where $B^{(1,1)}$ is!

Fermi Line Search

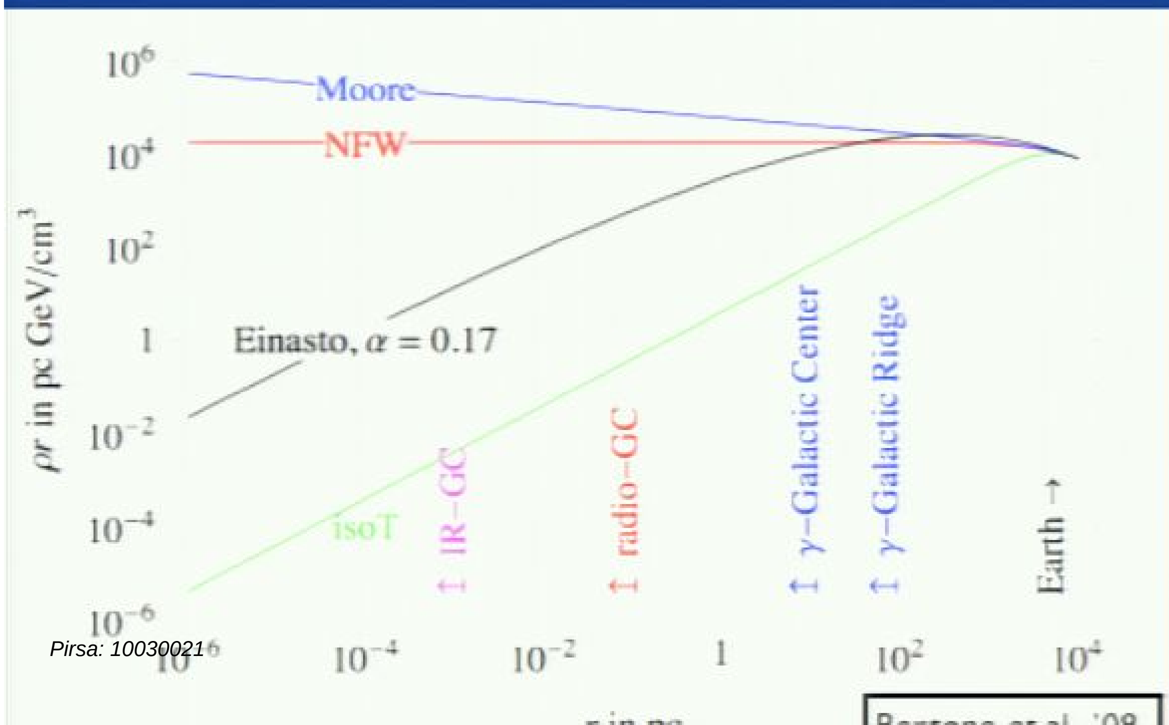
- Fermi/GLAST has searched for lines in the gamma ray spectrum with energies between 30 - 200 GeV in a "shape analysis".
- Search region includes |b| > 10° and 30° around the galactic center.

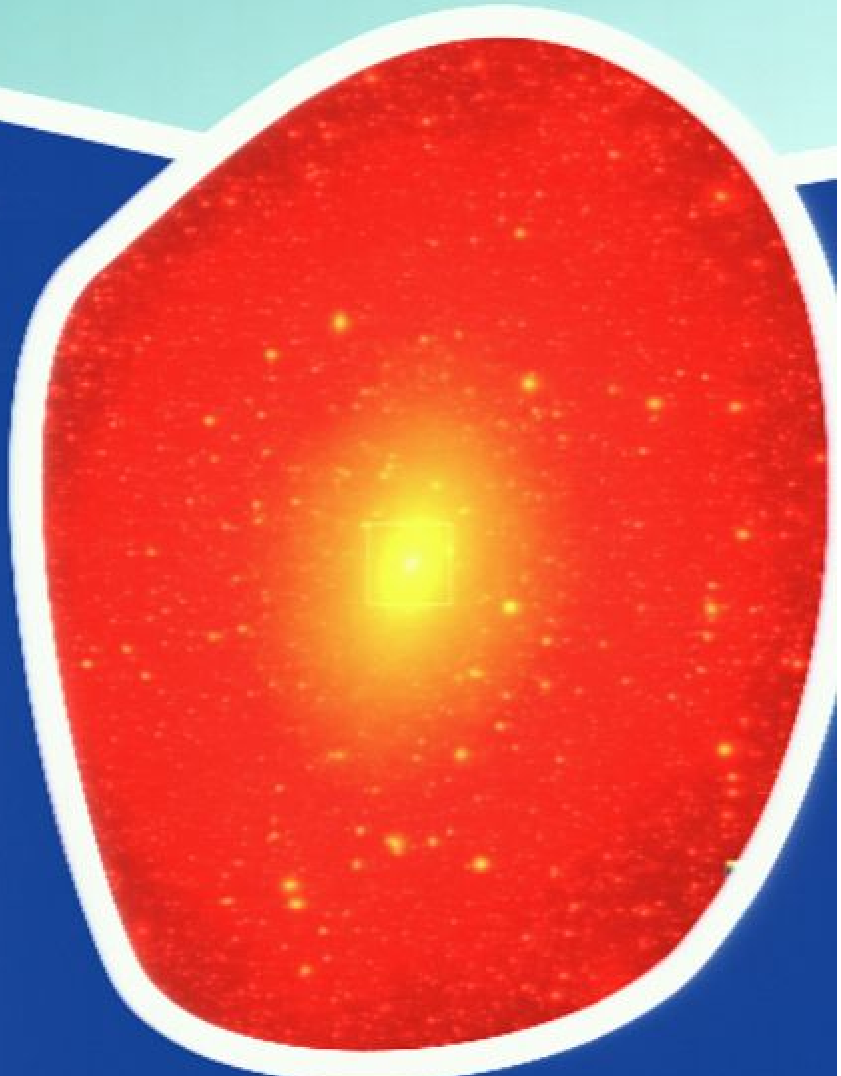




Dark Matter Profiles

The strength of the signal depends on the square of the dark matter density. Especially at the center of the galaxy, that quantity has large uncertainties.





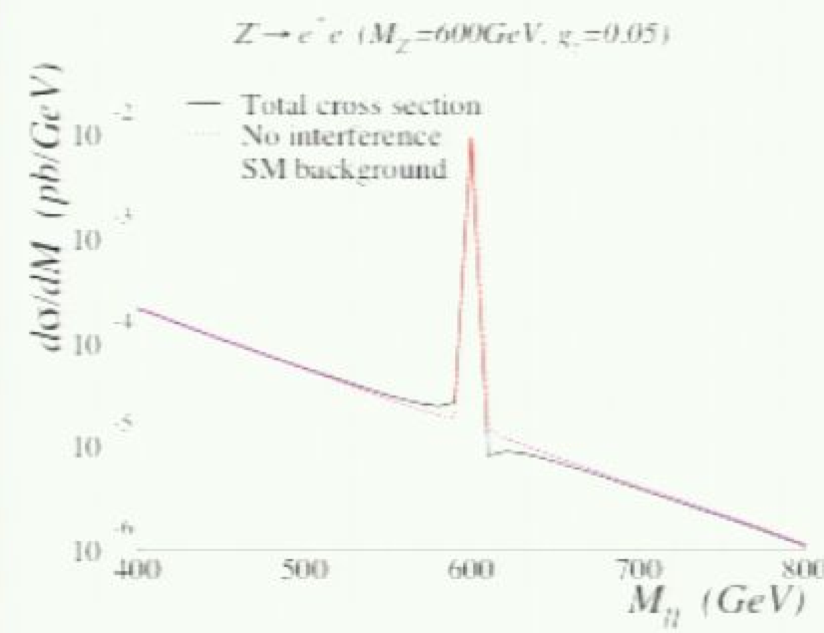
Fermi vs the Chiral Square

- The Fermi search is still about an order of magnitude away from the chiral square predictions for $\gamma B^{(1,1)}$. Expected improvements in control over the background, and more statistics will bring it into reach, at least for the lower range of LKP masses.
- If we end up with a discovery, one can imagine the initial observation will be of the $\gamma B^{(1,1)}$, which for a vanilla WIMP will be interpreted as $\gamma\gamma/\gamma Z$ at the WIMP mass.
- Later observation of the true $\gamma\gamma/\gamma Z$ peaks could help clarify the situation.
  - But the $\gamma\gamma$ line may be too faint to be observed by Fermi.
  - Fermi rapidly loses energy resolution above 300 GeV; for more massive LKPs, the $\gamma\gamma$ line may be beyond its reach.

- If we do understand the full line structure, it tells LHC where $B^{(1,1)}$ is!

$B^{(1,1)}$ 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. (Which given the narrow width may be important).
- The LHC is needed to fit the additional state into the big picture, measuring its spin and coupling to SM states.

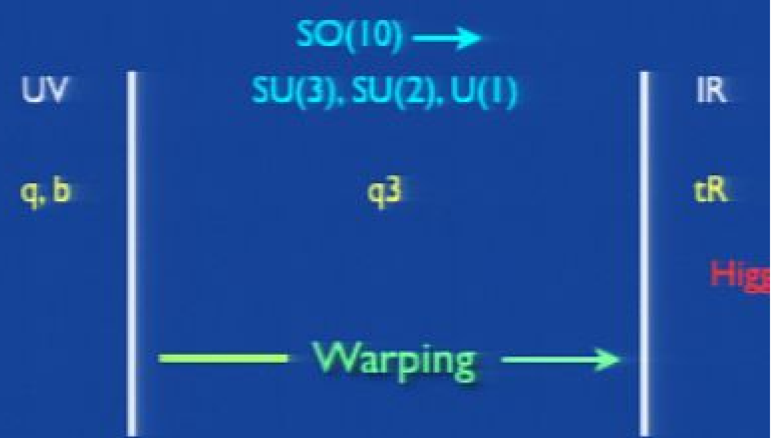


Synergy between indirect detection and the LHC can teach us more about WIMPs

The Higgs in Space?!

RS Dark Matter

- As a second example (which I'll go through much more quickly than the chiral square), I'll consider dark matter in an warped extra dimension.
- The models of interest have the Standard Model in the bulk and gauge coupling unification.
- These models need extra structure to avoid constraints from rapid proton decay.
- A particular realization results in a gauge singlet Dirac fermion ("right-handed neutrino") KK mode as the LKP WIMP.



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- The LKP has no SM gauge interactions, but it interacts with a neutral Z' boson corresponding to the broken SO(10) generators.
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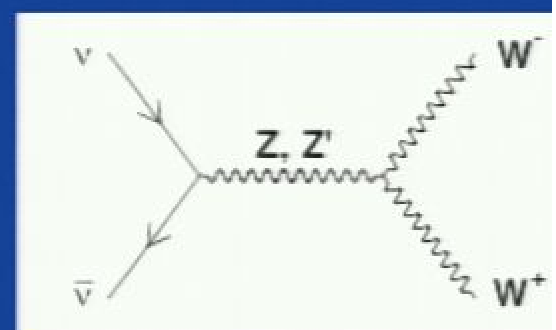
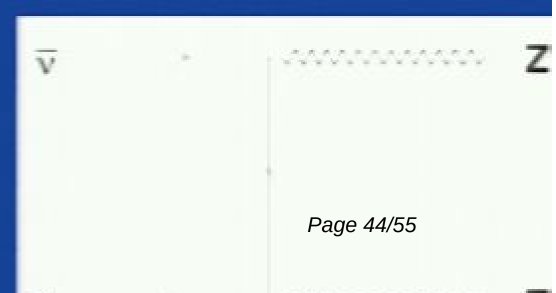
- For WIMPs above the top mass, most of the continuum emission is from a tt final state. Below the top mass, the continuum is highly suppressed, and can be dominated by loop processes.





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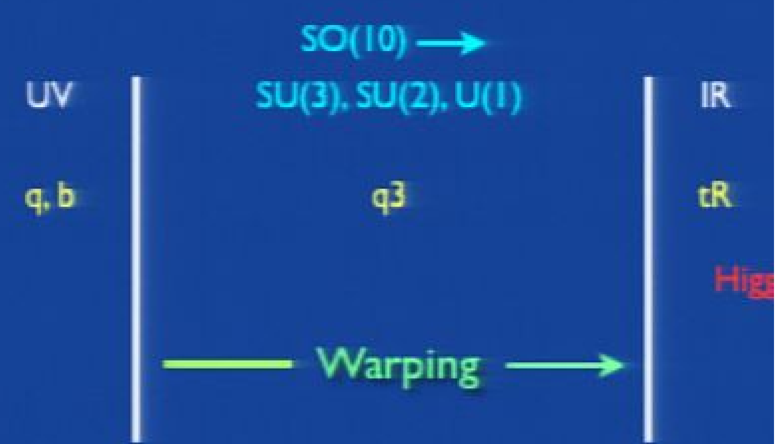

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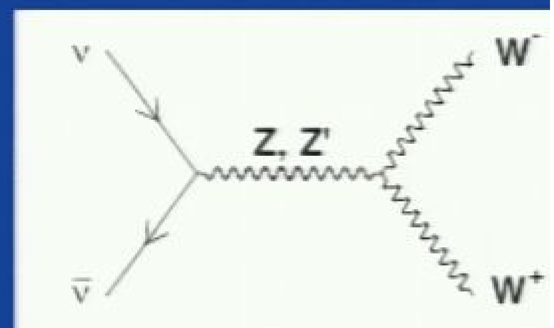
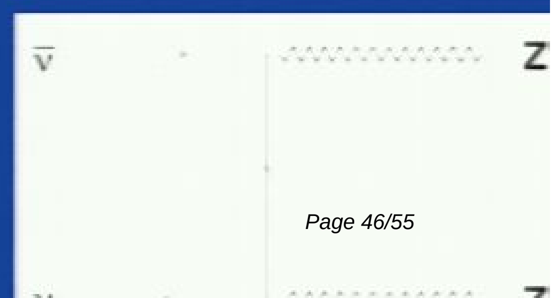
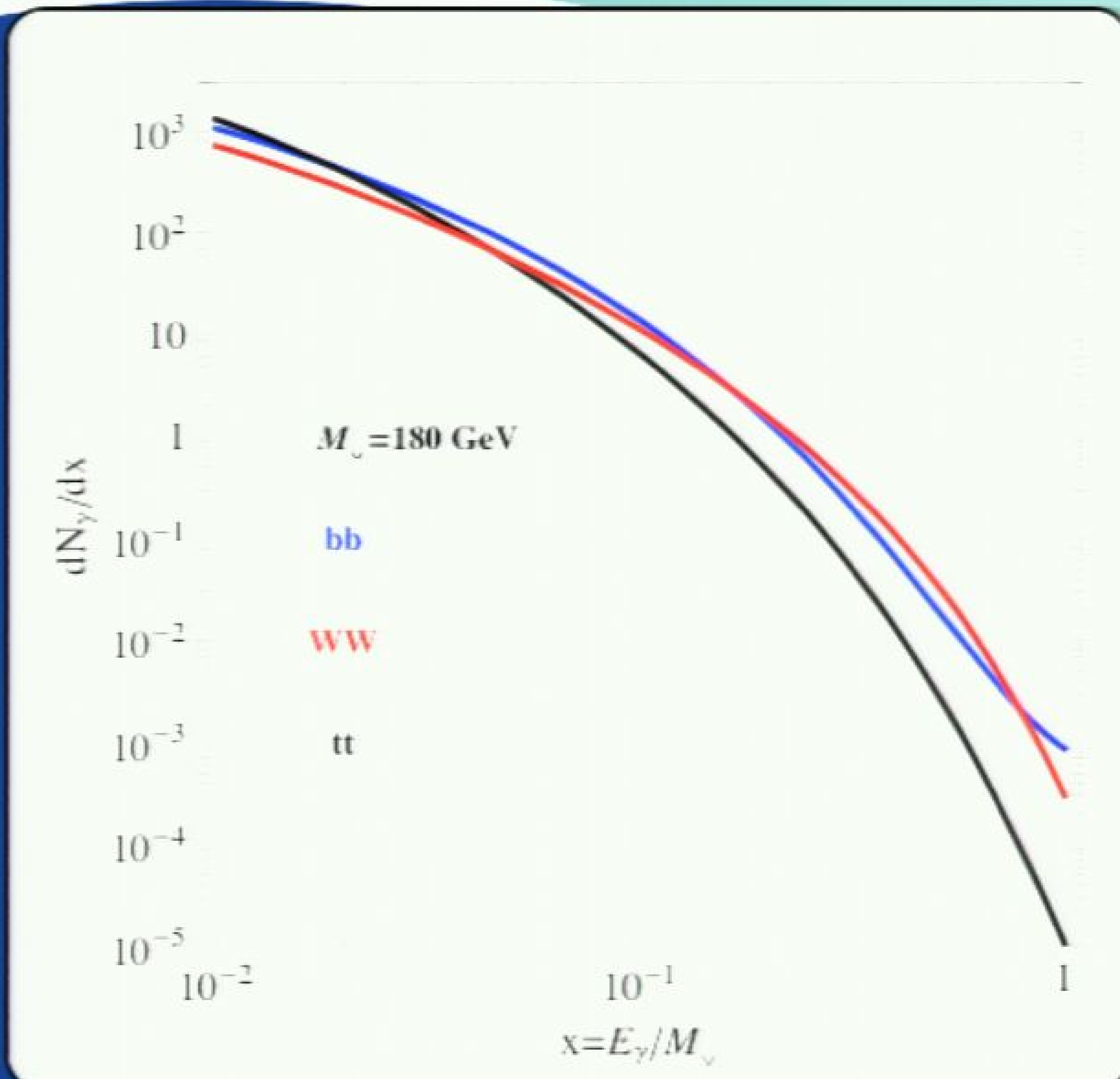


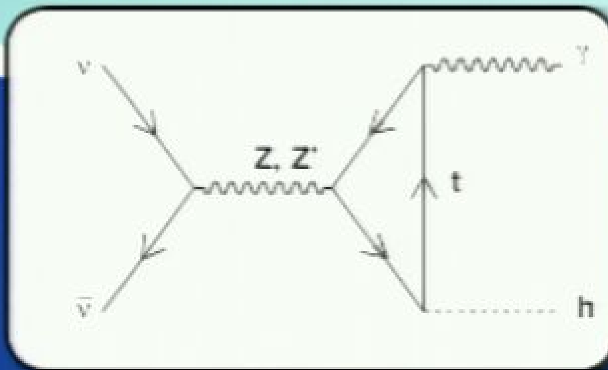


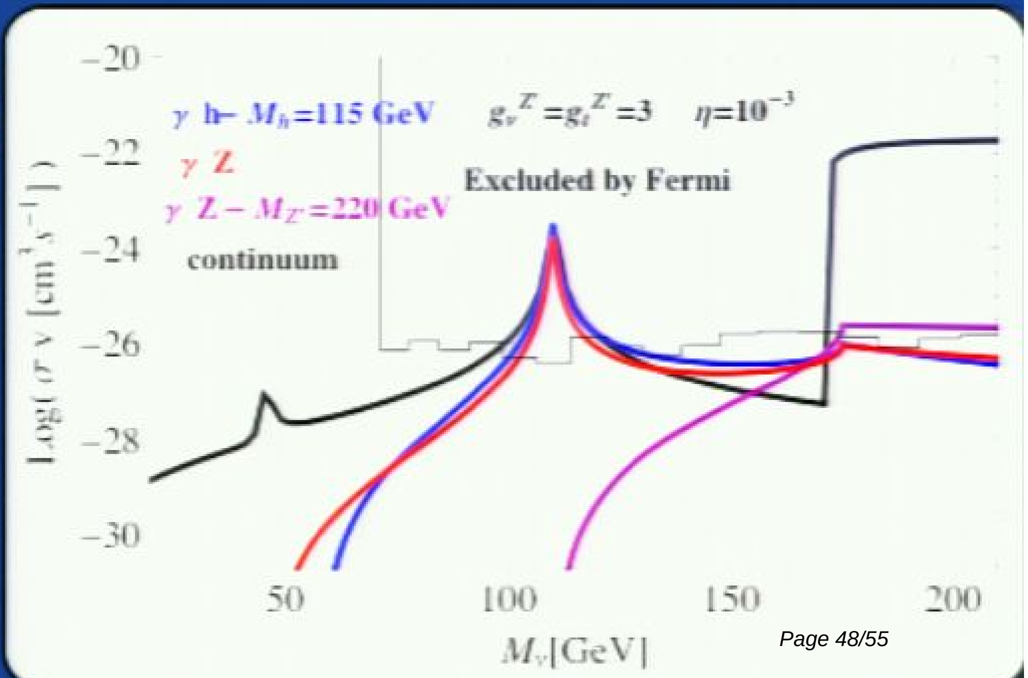
Continuum Spectrum



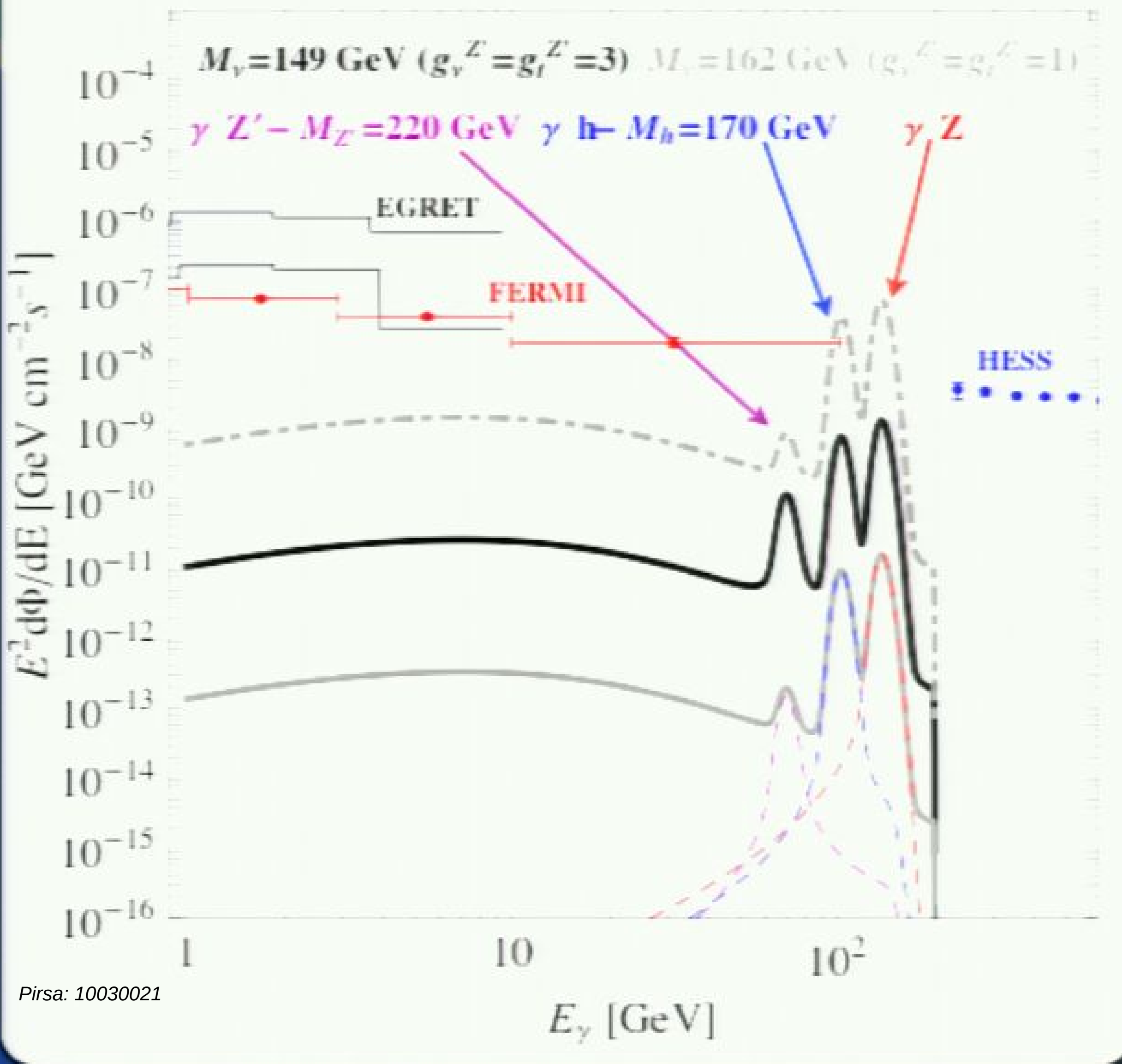
Loop Annihilations

- Loop annihilations can lead to γZ, γh, and (if light enough) γZ' final states.
  - A γγ final state is forbidden by the Landau-Yang theorem.
  - We produce the Higgs in space!
- Why did the possibility of a Higgs gamma ray line show up here?
  - We needed a Dirac WIMP which can have a net S=1 spin configuration even in the NR (s-wave) limit.





Continuum and Lines



For particularly favorable parameters, we can resolve three lines!

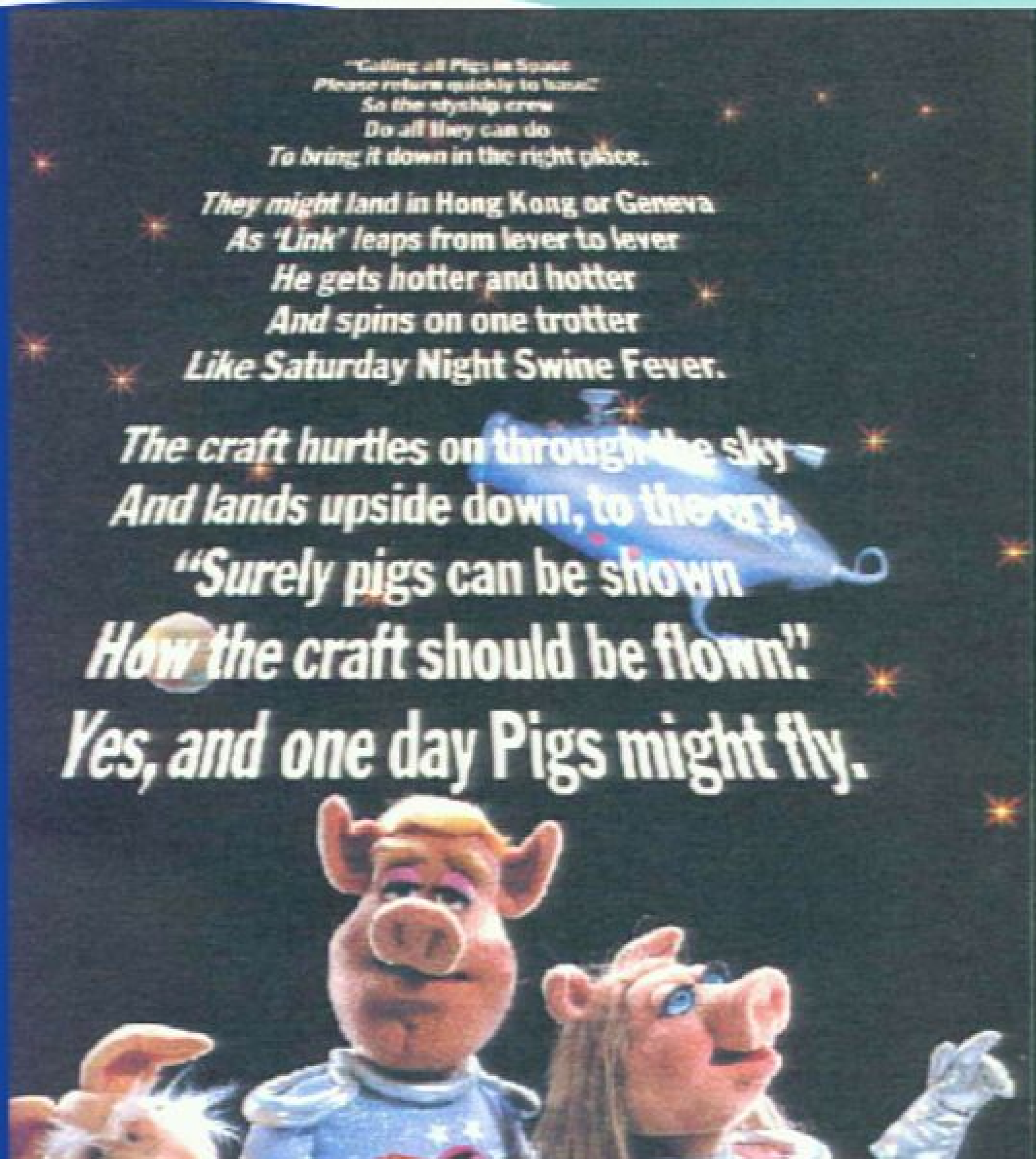
Of course, all gamma ray observatories can see is a line in the spectrum of γ-rays.

We need colliders to unravel the identity of these new states!

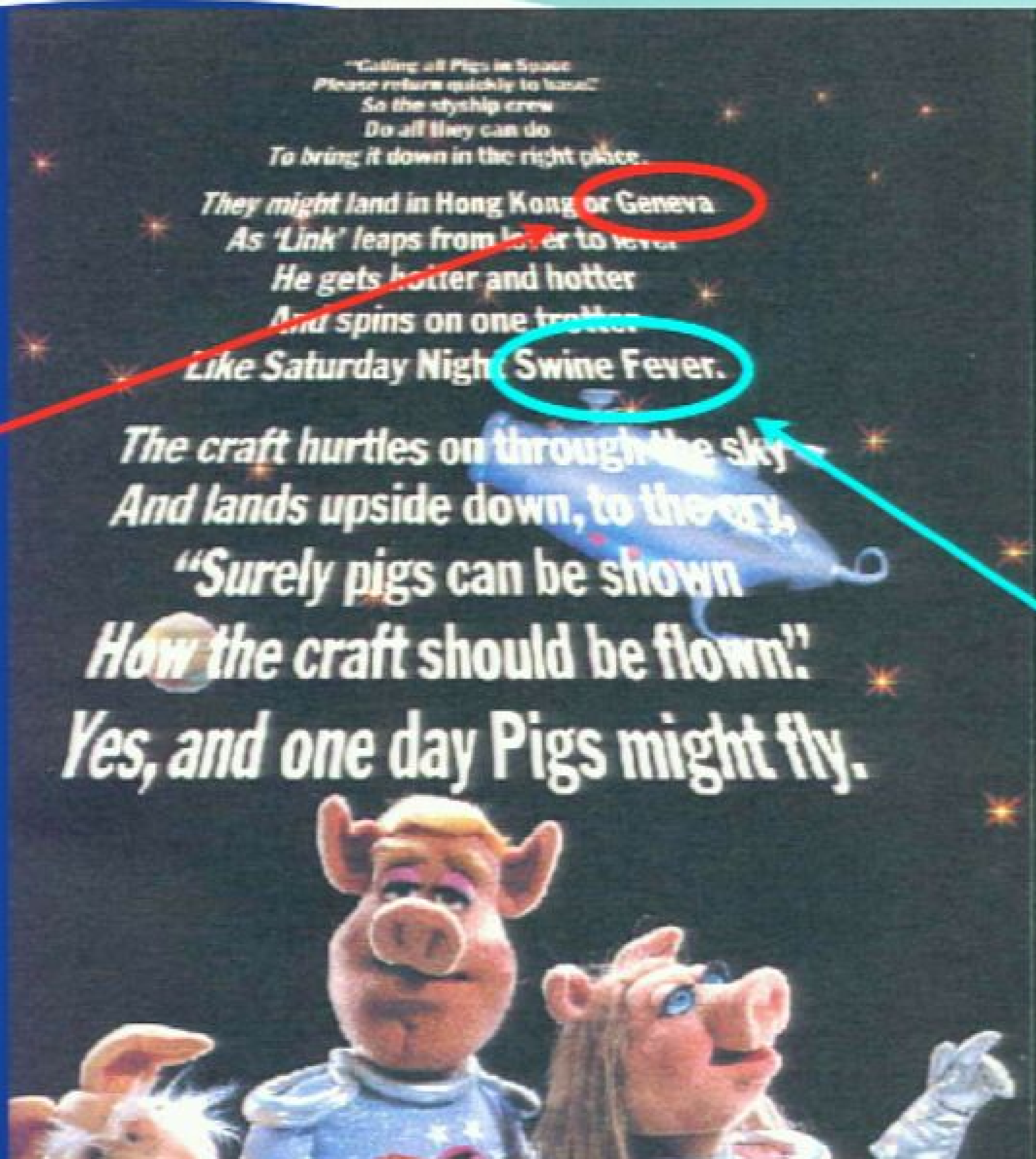
One Last Key Question:

What happens when Higgses are produced in space and travel backward in time?

Maybe they could influence 1970s televsion...



Pigs in Space!



Sounds like they're taunting the LHC to me...

Foreshadowing the swine flu?!

Outlook

- WIMP annihilations into gamma rays are an interesting and important way to search for WIMPs and learn about them, especially in tandem with collider signals.
- Annihilation into $\gamma\gamma$ and γZ have received a lot of attention. However, there may be more particles in the "dark sector" which can be produced as well. In some cases, distinctly observable lines may result.
- We may learn interesting things such as the mass of a super-weakly coupled Z' or even have an indirect view of the Higgs boson which can have huge interplay with the LHC.
- We've studied the rates expected in two different extra-dimensional theories of dark matter - but this phenomenon is much more general, and can occur in many models of dark matter!

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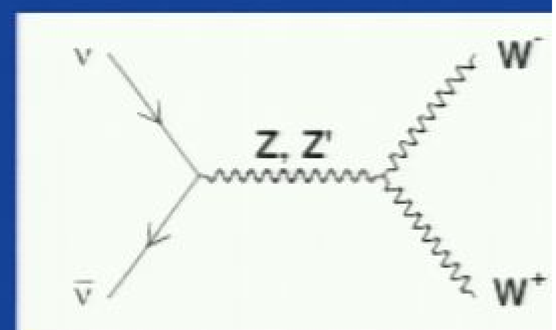

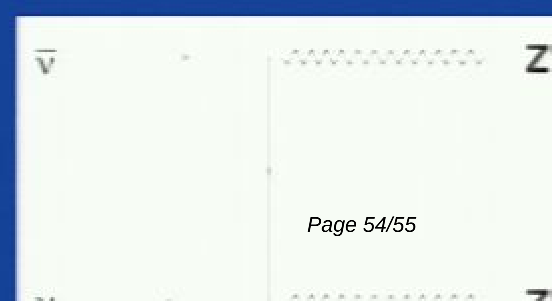

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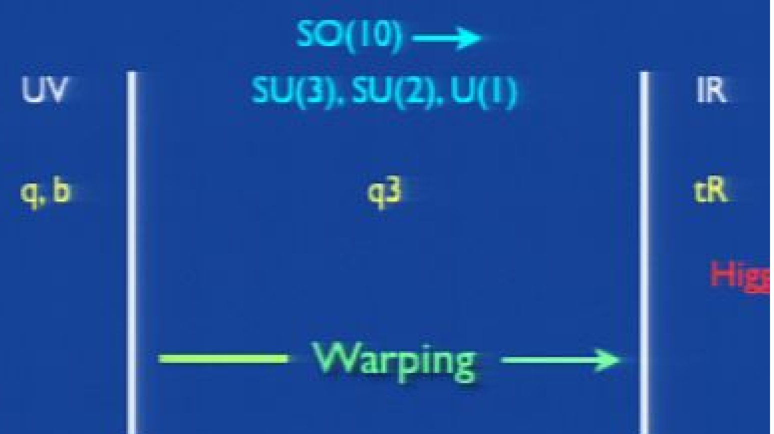

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