Gamma Ray Lines and a WIMP Forest

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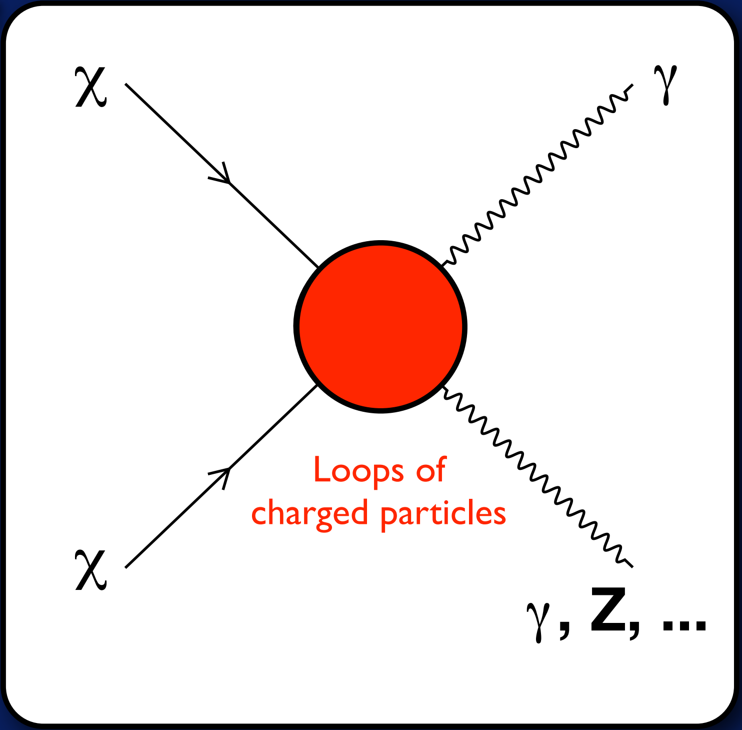
Outline

- Gamma ray lines from WIMP annihilation.
- A Forest of Lines
- Examples
- The `Weniger' Line in the Fermi data
- Outlook

Gamma Ray Lines

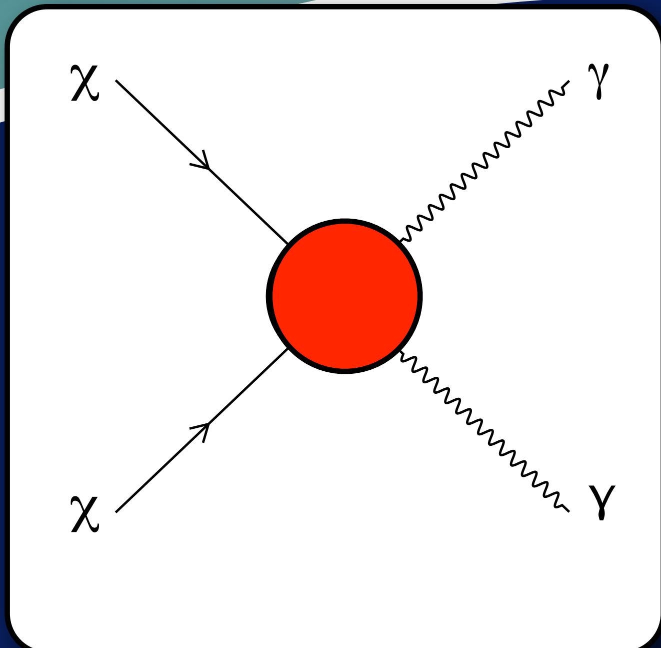
- WIMP annihilation into a two body final state containing a photon can result from loop processes, with charged particles running in the loop.
- Since WIMPs are thought to be highly non-relativistic in the galaxy, energy conservation predicts the energy of the photon in the reaction $\chi\chi \rightarrow \gamma X$ to be:

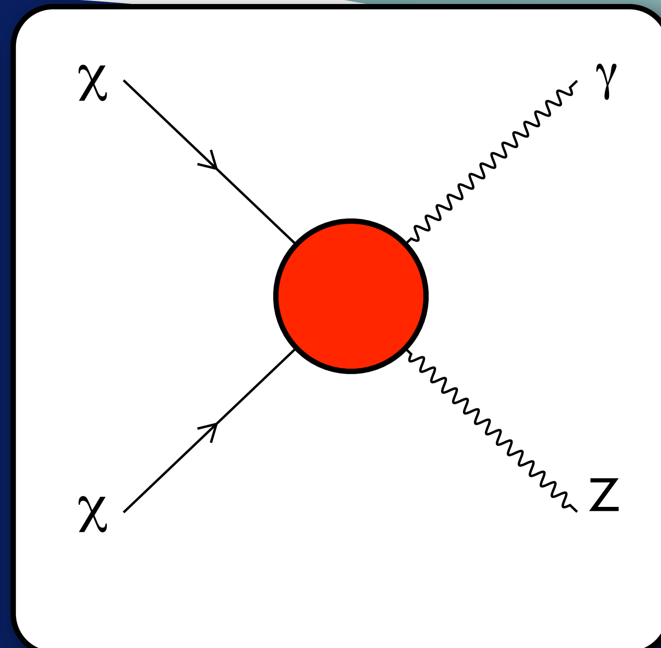
$$E_\gamma = M_\chi \left(1 - \frac{M_X^2}{4M_\chi^2}\right)$$

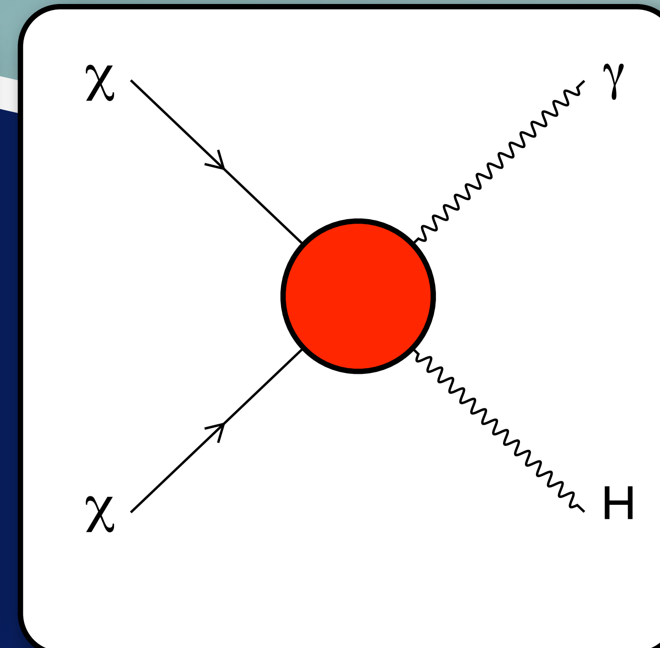


- The line feature allows backgrounds to be more easily fit from data, perhaps compensating for a smaller, loop-suppressed rate.

Lines Can Tell Us Something







$J=0,\cancel{1},2$

Forbidden by the Landau-Yang theorem

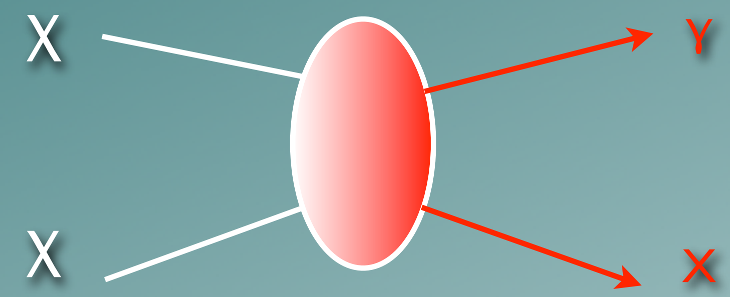
$J=0,1,2$

$J=1$

v-suppressed for Majorana χ

- The initial J should arise from the WIMP spin, or the process will be suppressed by the small WIMP velocity.
- Since whatever is in the loop carries hypercharge or SU(2), generically both $\gamma\gamma$ and γZ will occur unless something like Landau-Yang prevents $\gamma\gamma$.

A WIMP Forest?



- In supersymmetry, the 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.
- Any ‘even’ particle in the theory whose mass is less than twice the WIMP mass can be produced together with a photon in WIMP annihilation.
- Each such particle produces its own line at a different energy, potentially resulting in a forest of lines.

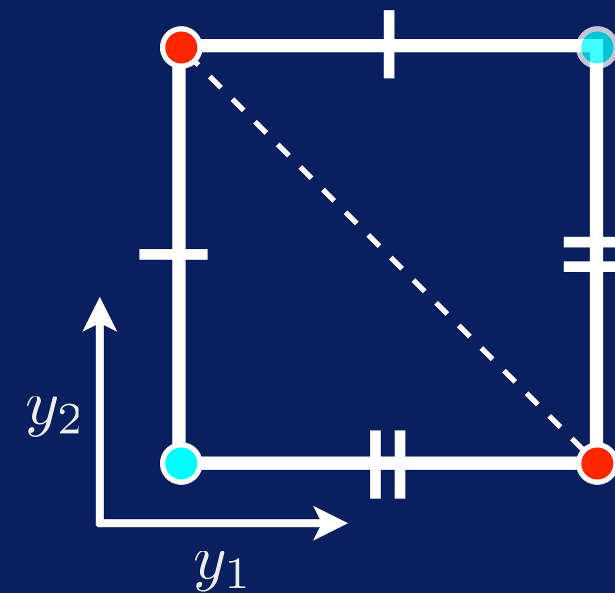
Example: The Chiral Square

- 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".

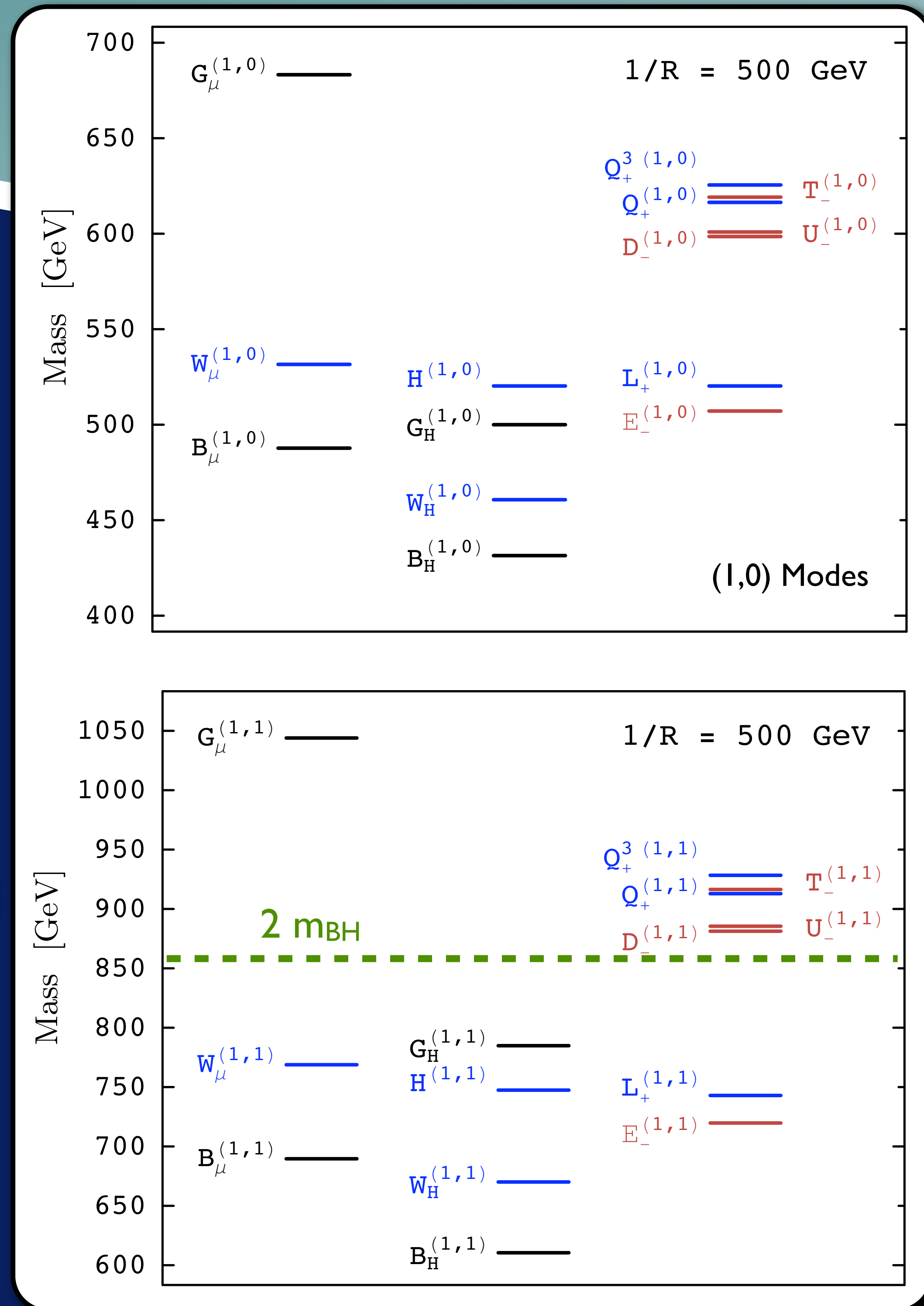
Ponton, Wang '06



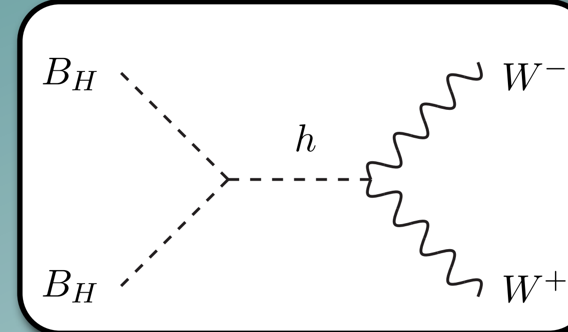
KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

Spectrum

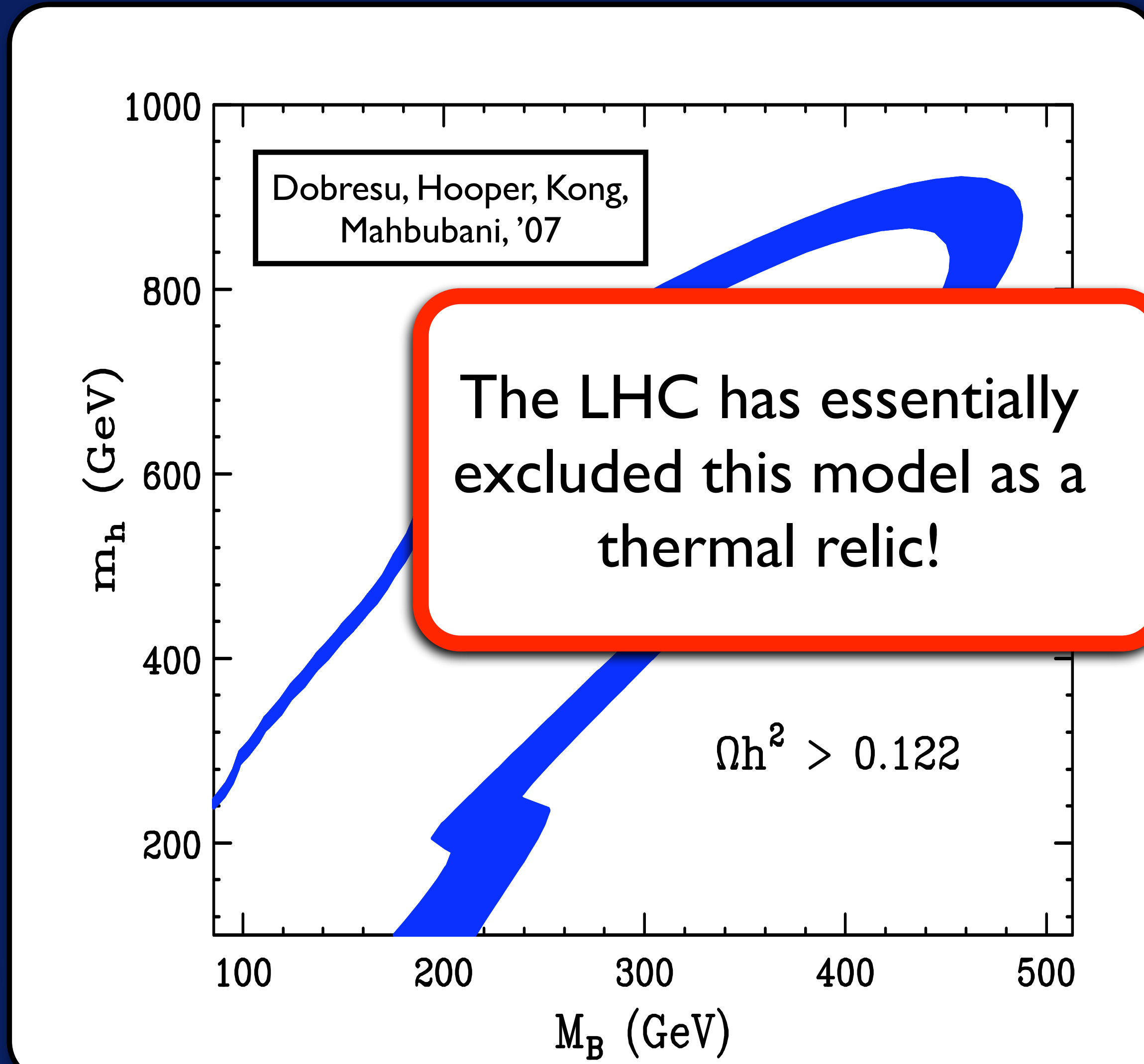
- The boundary terms modify the masses of the fields at a given (j,k) level. They control the systematics of the spectrum of states.
  - The LKP is usually the scalar (1,0) KK mode of the Hypercharge gauge boson, B_H.
  - Colored states are the heaviest of a given (j,k).
- The (1,1) modes are KK even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



Relic Density

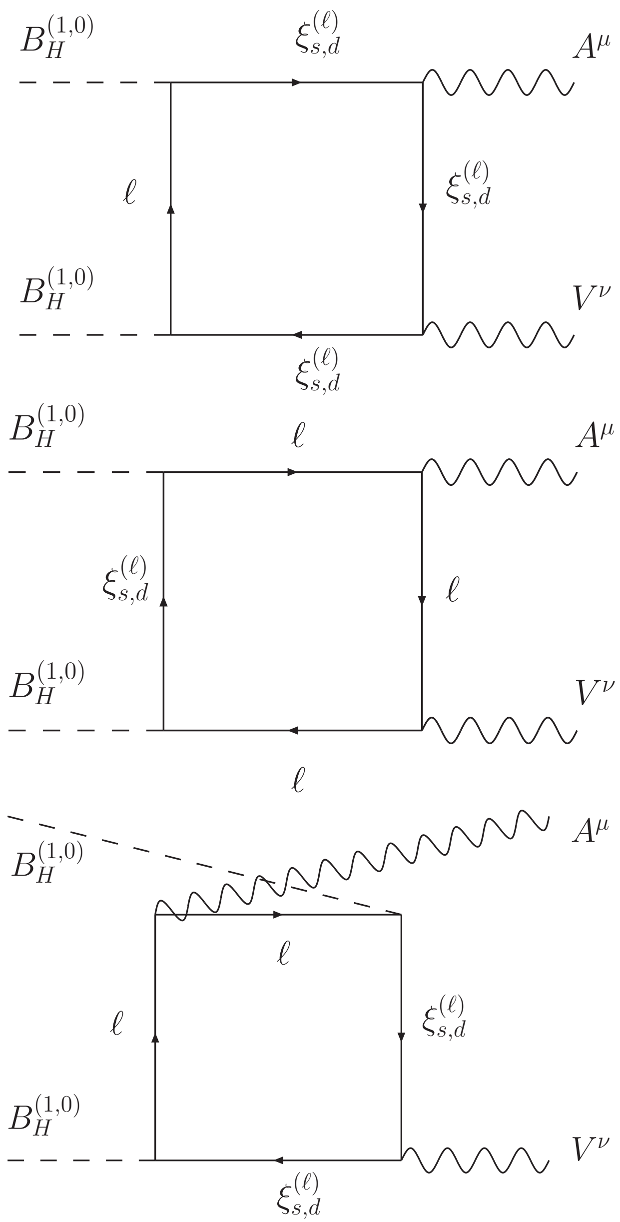


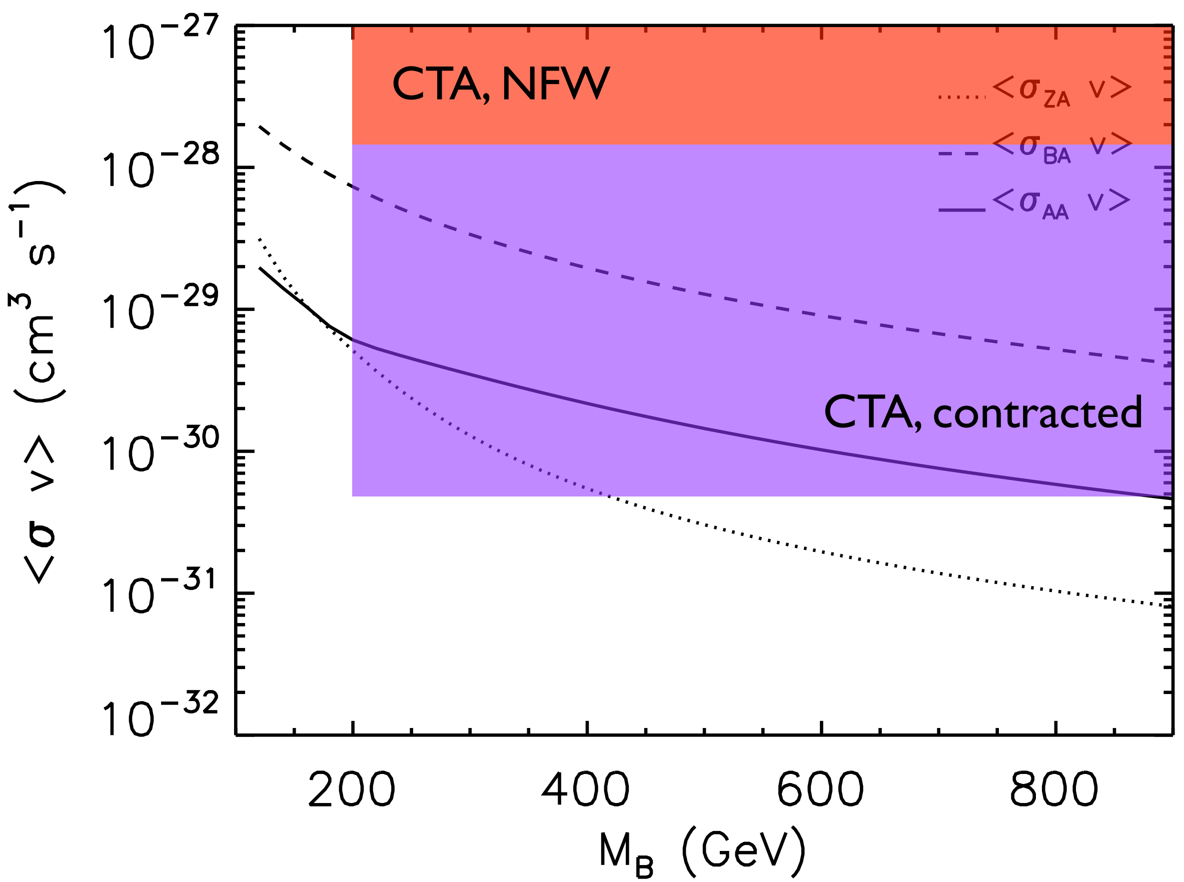
- Annihilation typically goes through an s-channel SM Higgs boson.
- Generally, the relic density favors LKP masses between 100 - about 500 GeV, provided the Higgs mass is chosen to match.
- This model might be salvageable as a thermal relic by using the level (1,1) or (2,0) Higgs modes as the resonance, probably only with nonminimal boundary terms.



Gamma Ray Lines

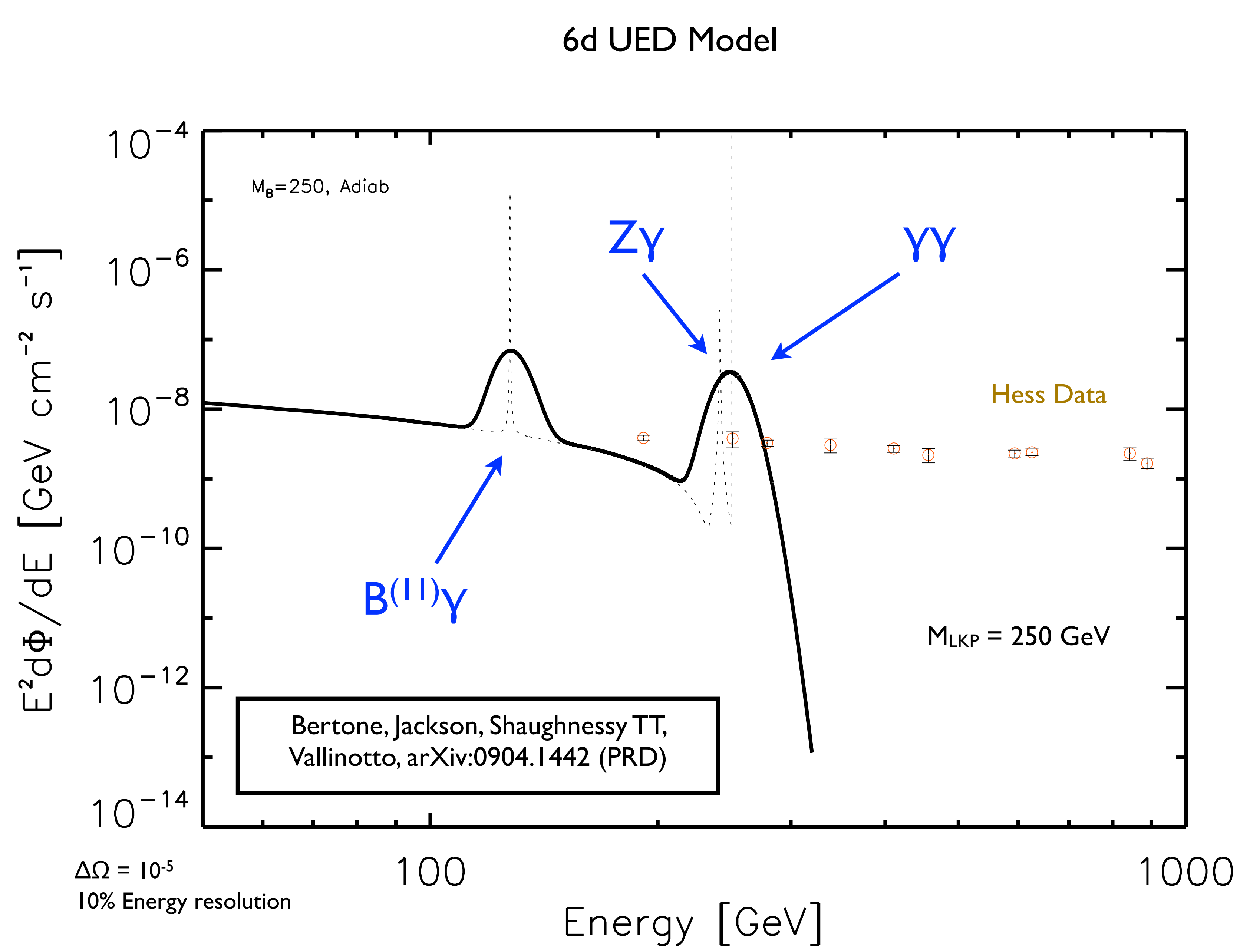
Bertone, Jackson, Shaughnessy, TT, Vallinotto, [0904.1442] (& PRD)





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

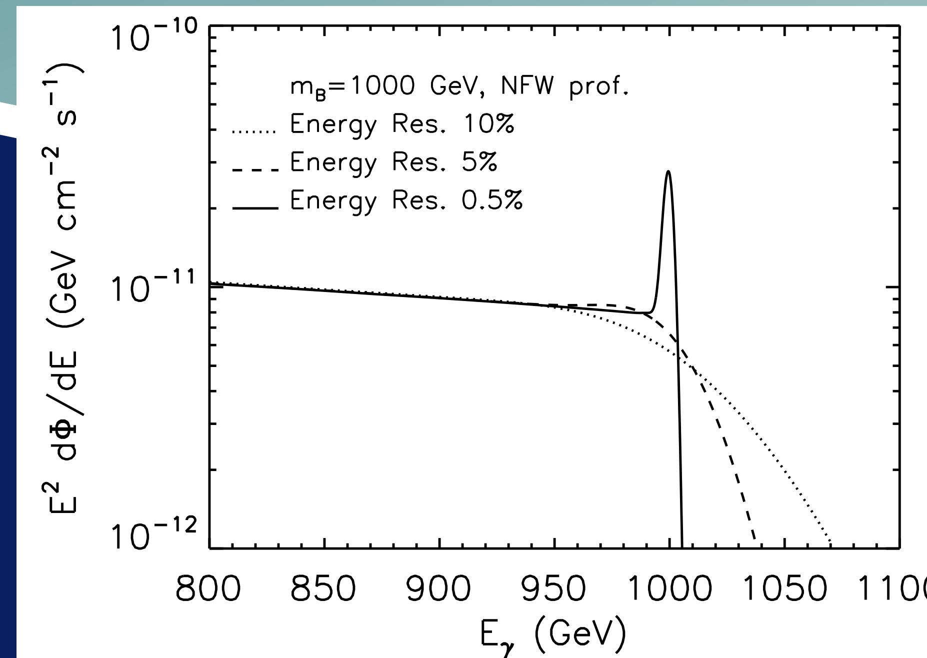
Lines of the Chiral Square

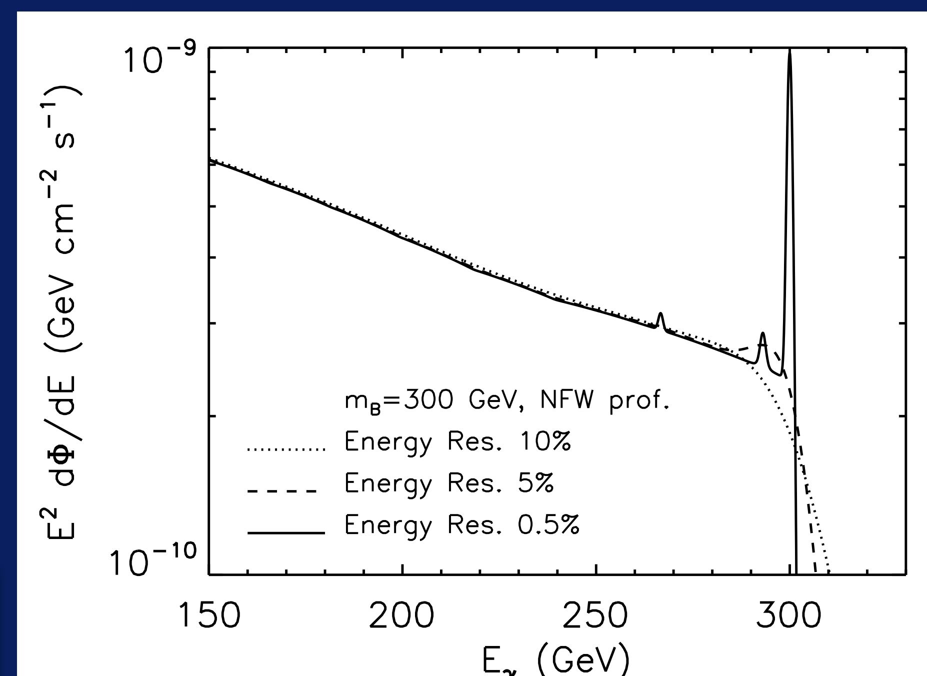


Contrasting with 5d UED

- The 5d theory has a large continuum because the LKP likes to annihilate into e^+e^-.
- There are γγ, γZ, and γ Higgs lines.
  - γγ also previously computed by Bergstrom et al hep-ph/0412001.
- Over-all, the lines are relatively faint, and tend to merge into the continuum photons from WIMP annihilations.
- Resolving them requires a next- (or next to next) generation gamma ray observatory.

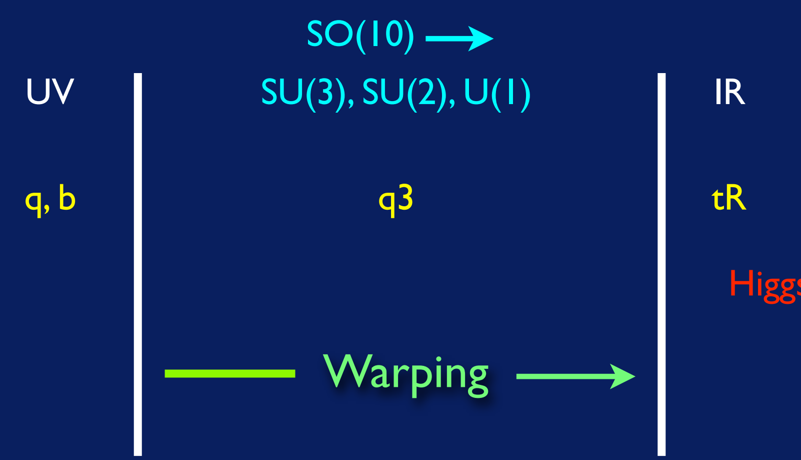
Bertone, Jackson, Shaughnessy, TT, Vallinotto, [1009.5197] (& JCAP)]





RS Dark Matter

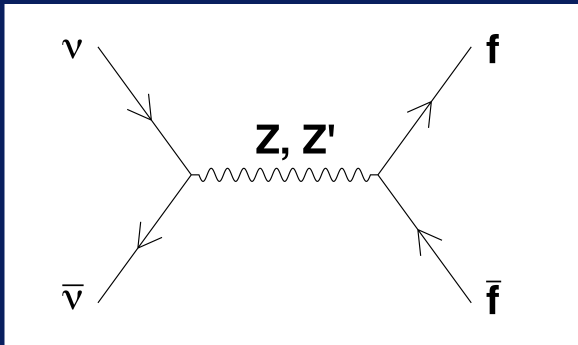
- As another example, I'll consider dark matter in an warped extra dimension.
- The models of interest have the Standard Model in the bulk and gauge coupling unification.
- These models need extra structure to avoid constraints from rapid proton decay.
- A particular realization results in a gauge singlet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

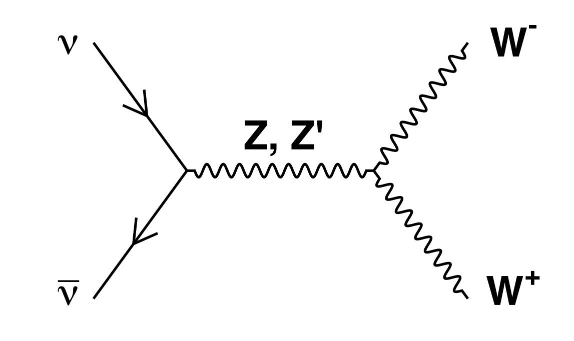


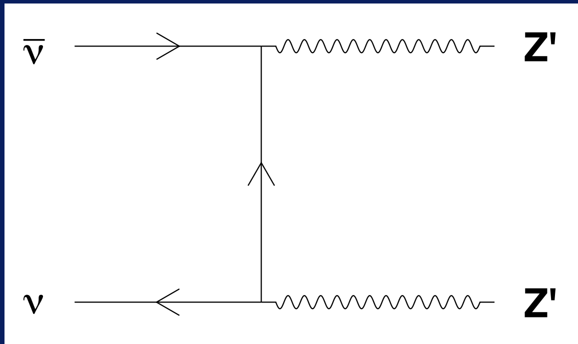
Agashe, Servant, '04

RS Dark Matter

- The LKP has no SM gauge interactions, but it interacts with a neutral Z' boson corresponding to the broken SO(10) generators.
- The Z' itself is a KK mode, and interacts strongly with the right-handed top, as the only fermion localized close to the IR brane.
- It has small coupling to the light fermions, and a small amount of mixing with the Z (small enough to be consistent with precision EW bounds).
- 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.

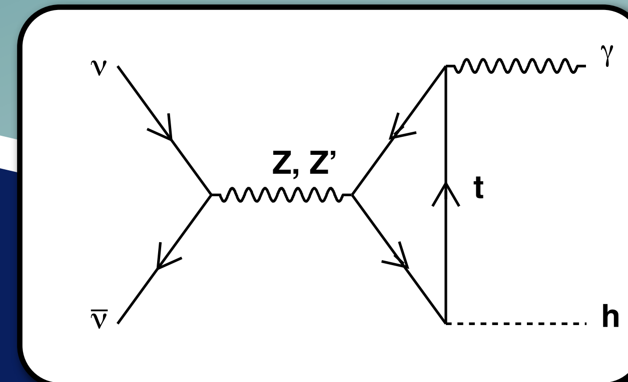




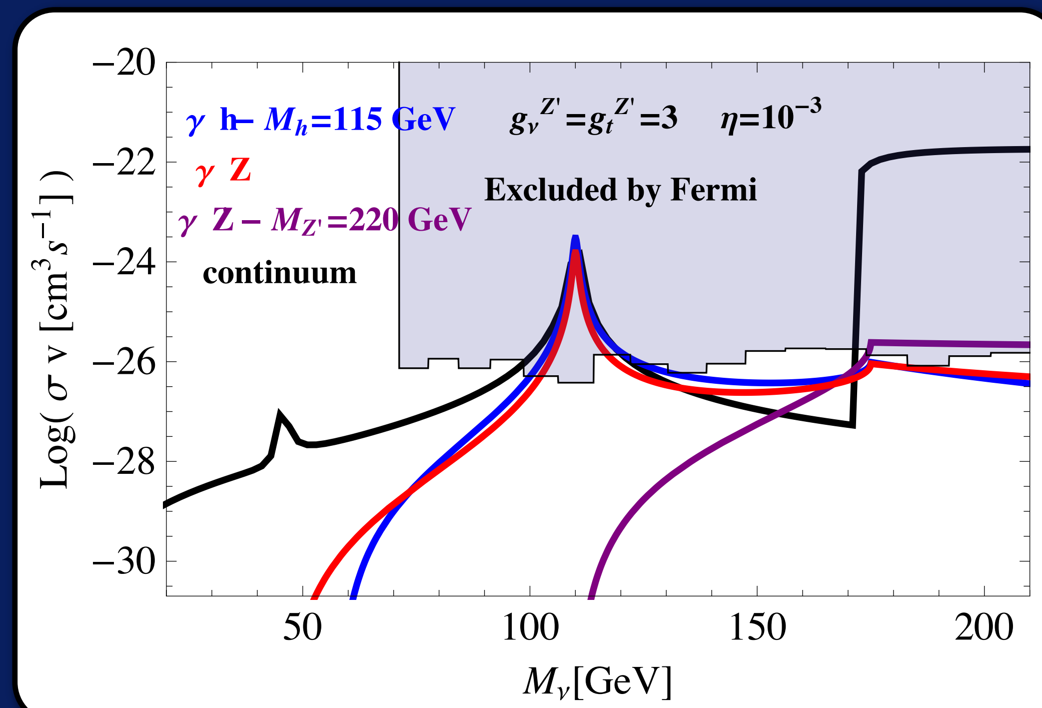


Loop Annihilations

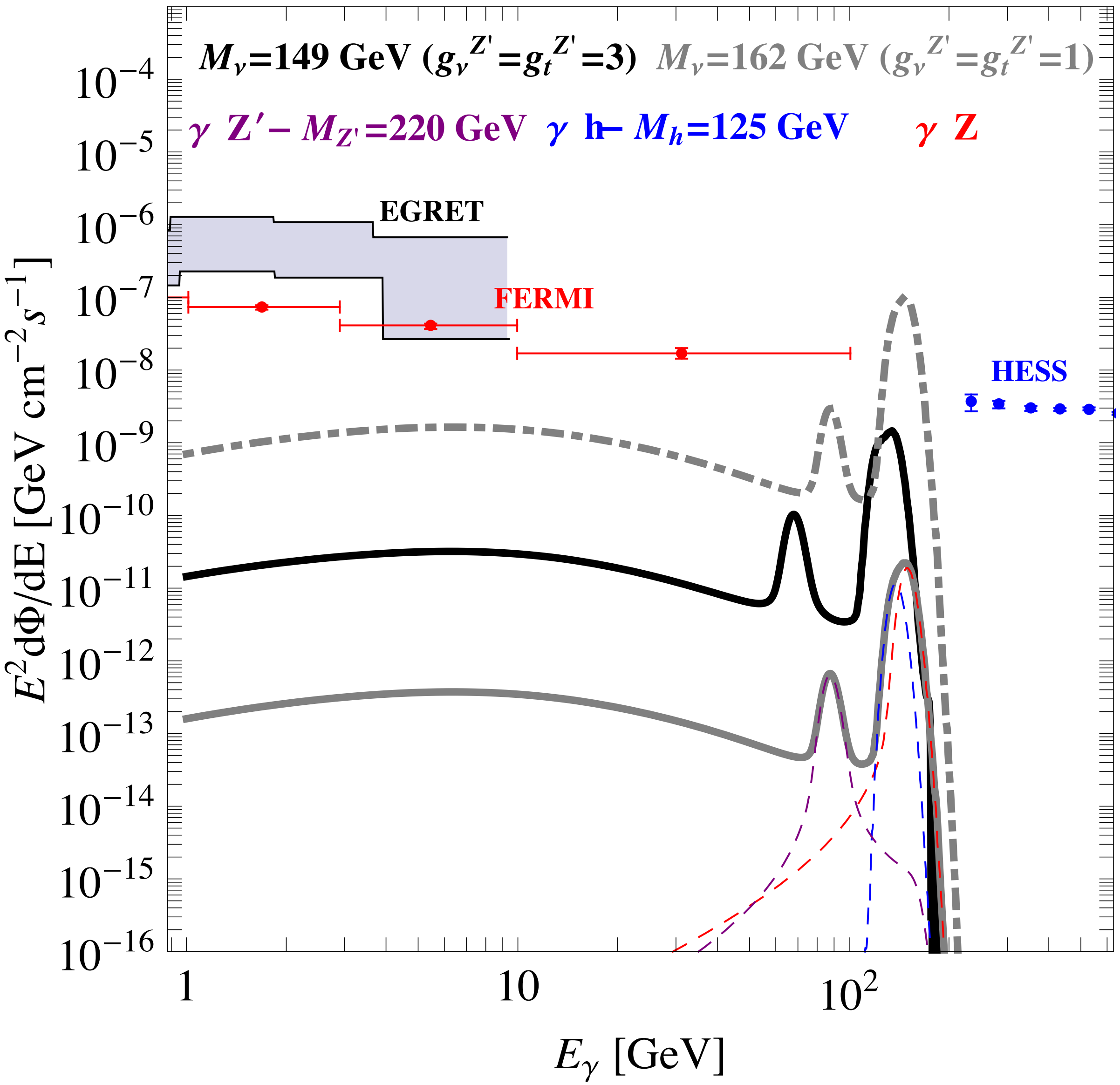
- Loop annihilations can lead to γZ, γh, and (if light enough) γZ’ final states.
  - A γγ final state is forbidden by the Landau-Yang theorem.
  - We produce the Higgs in space with a large rate!
- Why did the possibility of a Higgs gamma ray line show up here?
  - We needed a Dirac WIMP which can have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



Jackson, Servant, Shaughnessy, TMPT, Taoso, [0912.0004] (& JCAP)



Continuum and Lines

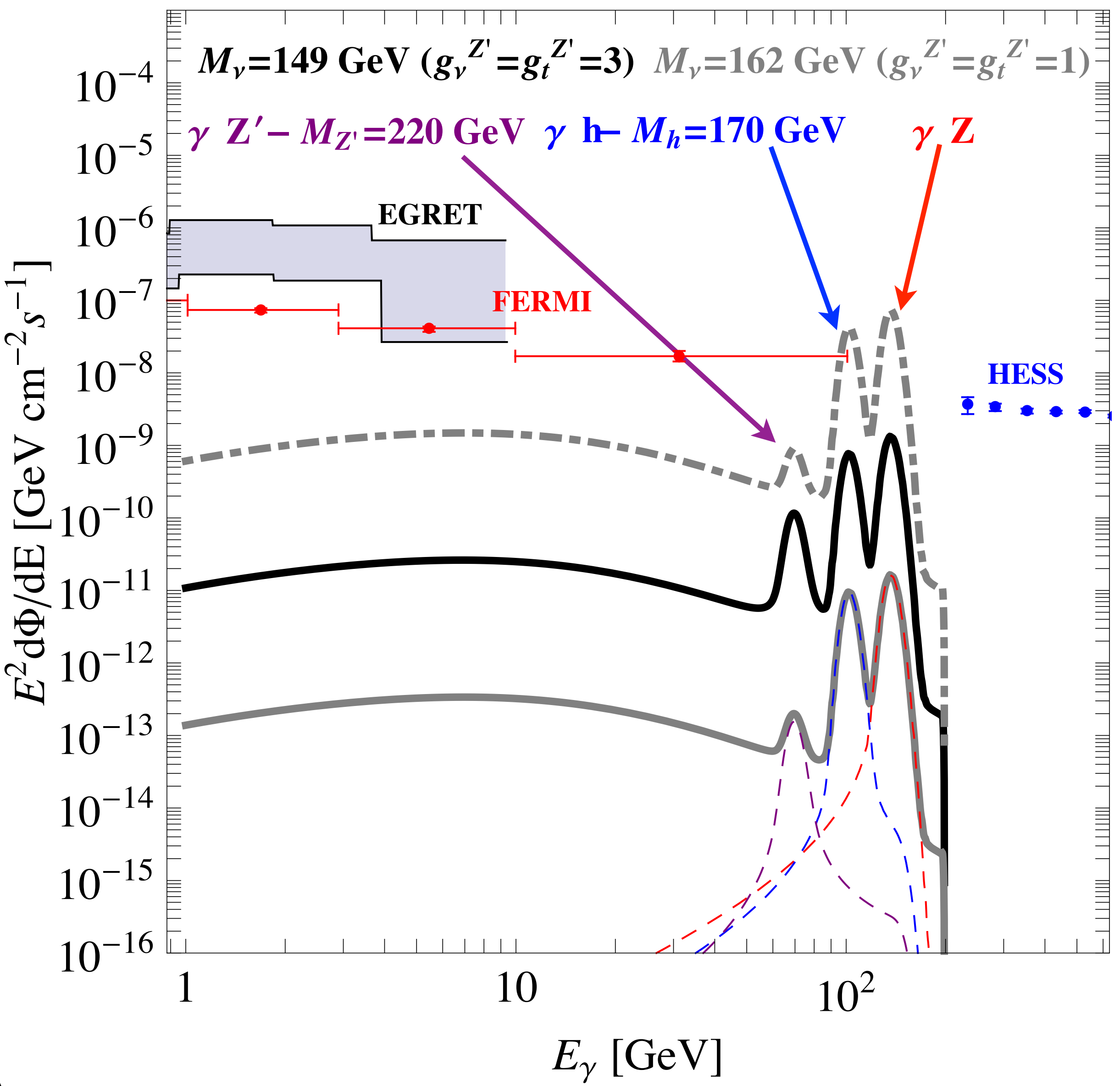


For this set of parameters, γZ and γh merge into a single line around 130 GeV.

A distinct smaller line appears around 50 GeV due to γZ'.

Jackson, Servant, Shaughnessy, TMPT, Taoso, [0912.0004] (& JCAP)

Multiple Lines



For particularly favorable parameters, we can resolve three lines!

Their energies would suggest that one is γγ or γZ, one is γH, and is something exotic...

This might be the ealiest way to infer the Z' in such a model.

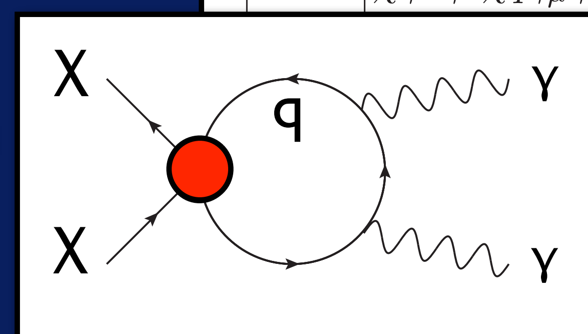
Jackson, Servant, Shaughnessy, TMPT, Taoso, [0912.0004] (& JCAP)

Lines in EFTs of DM

Dirac WIMPs

- We can also compute lines in effective field theories describing WIMPs which couple to SM particles. (E.g. SM quarks).
- In one very simple description, we looked at the impact collider and line searches could have in the space of direct detection.
- We write down a set of leading operators (consistent with Lorentz and SM gauge invariance).
- We use the Fermi line search limits and map these using the EFT into the parameter space of direct or indirect detection.

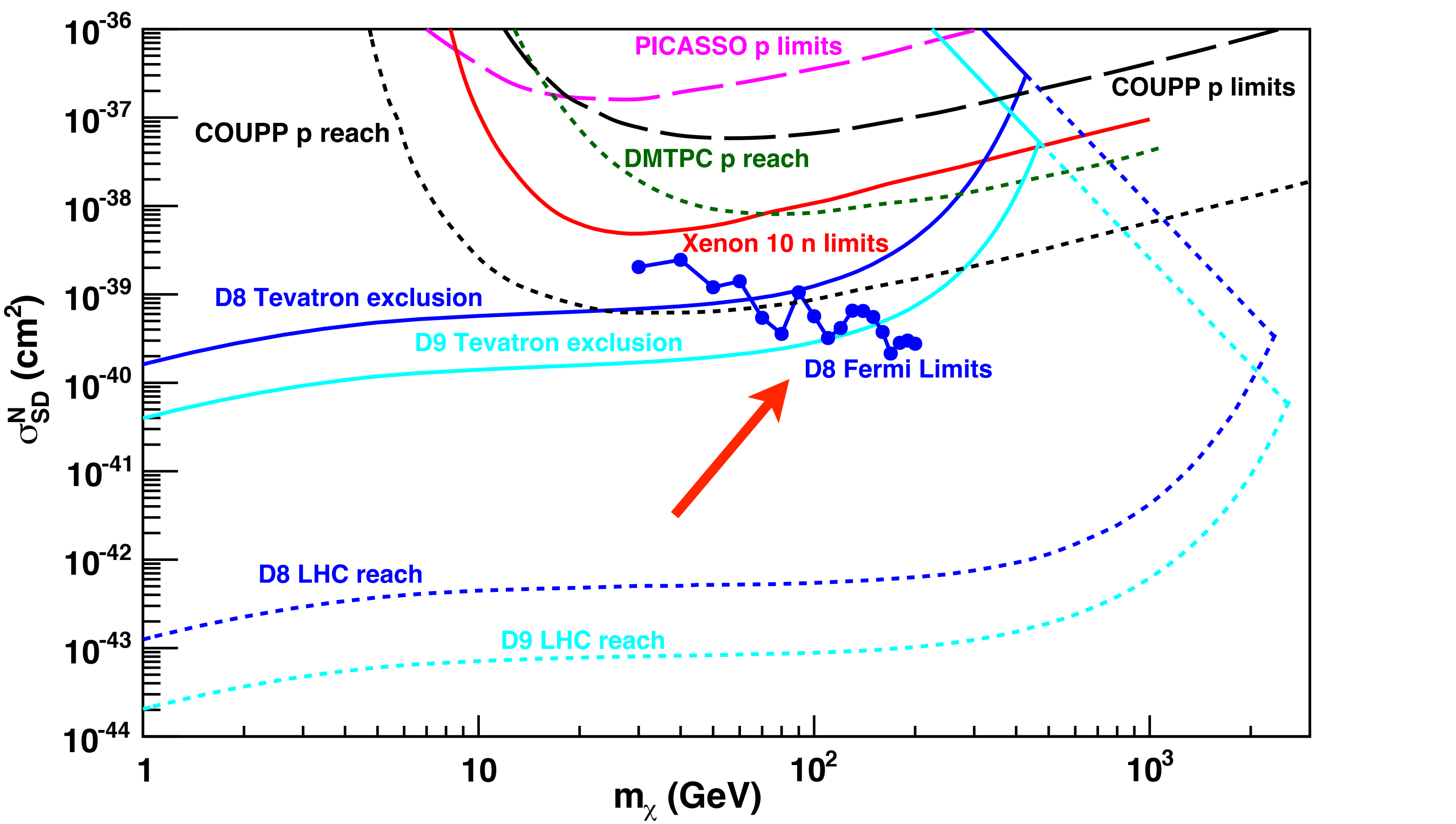
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
[illegible]	[illegible]	$1/M_*^2$
[illegible]	[illegible]	i/M_*^2
[illegible]	[illegible]	$\alpha_s/4M_*^3$
[illegible]	[illegible]	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D



Goodman, Ibe, Rajaraman, Shepherd, TT, Yu [1009.0008] & NPB

Fermi and Direct Detection

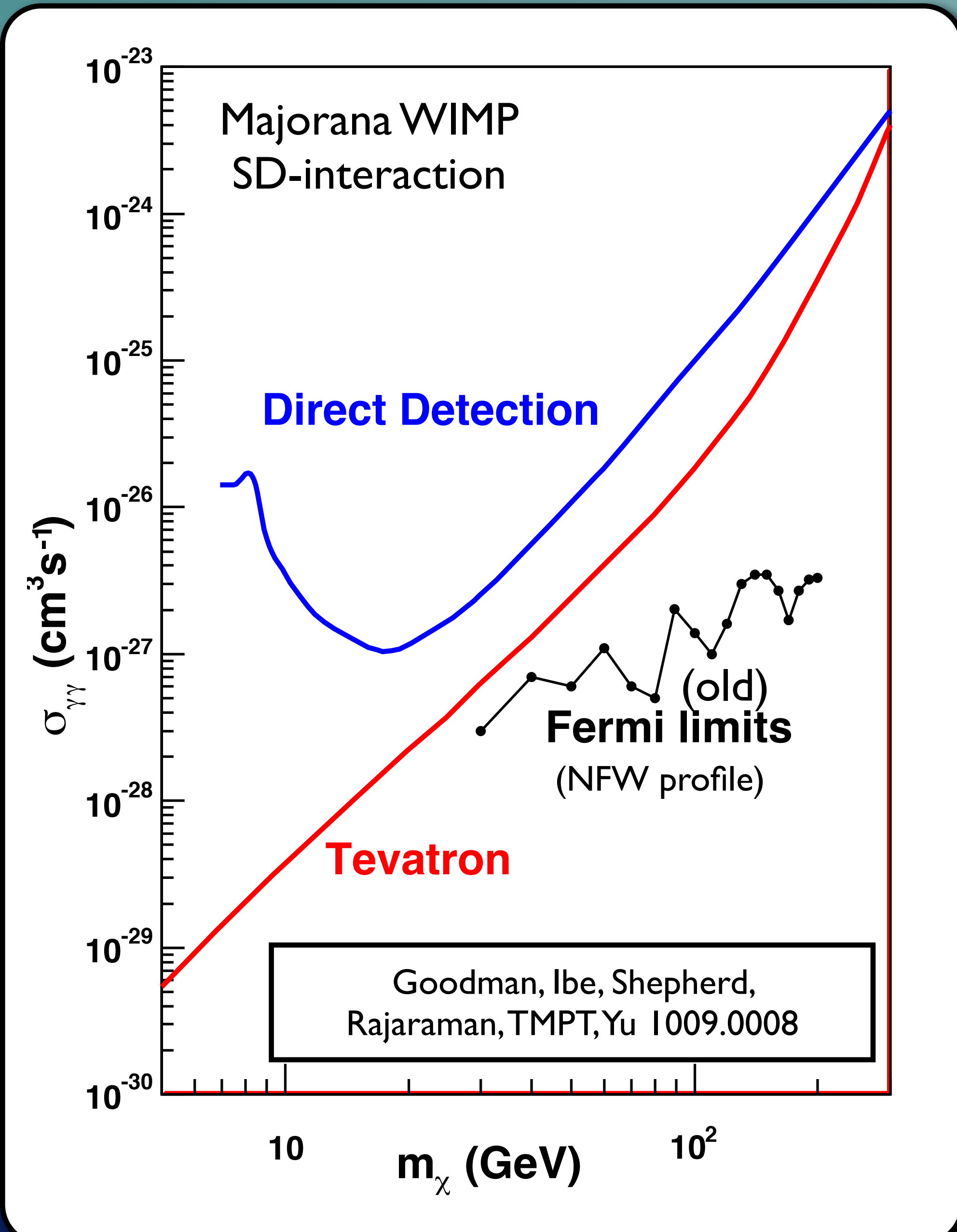
Axial vector interaction of a Dirac WIMP

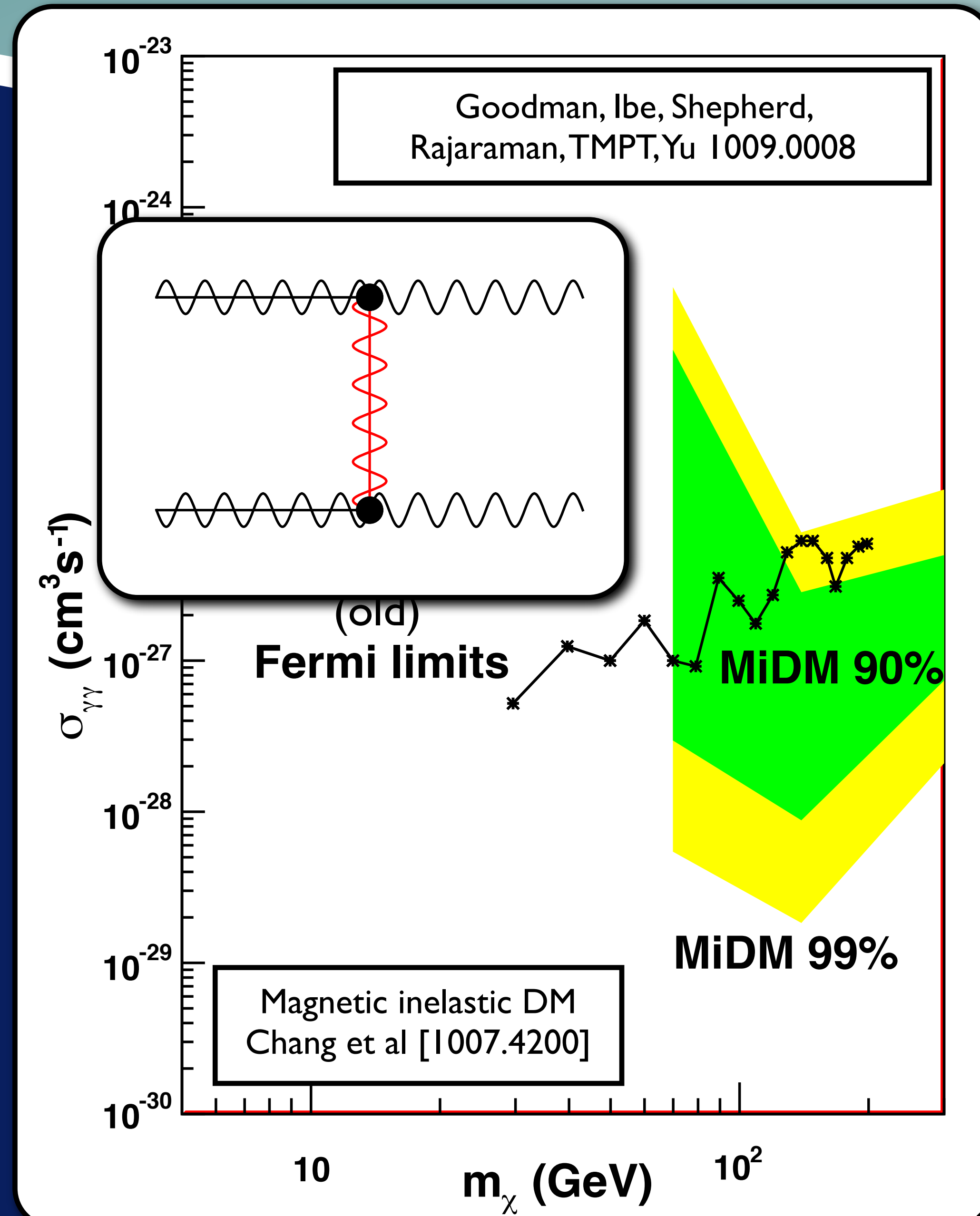


Goodman, Ibe, Rajaraman, Shepherd, TT, Yu [1009.0008] & NPB

- For dark matter theories amenable to an effective theory description, the line search can be a powerful probe of dark matter interacting with quarks, comparable to bounds from colliders.

Bounds from Lines

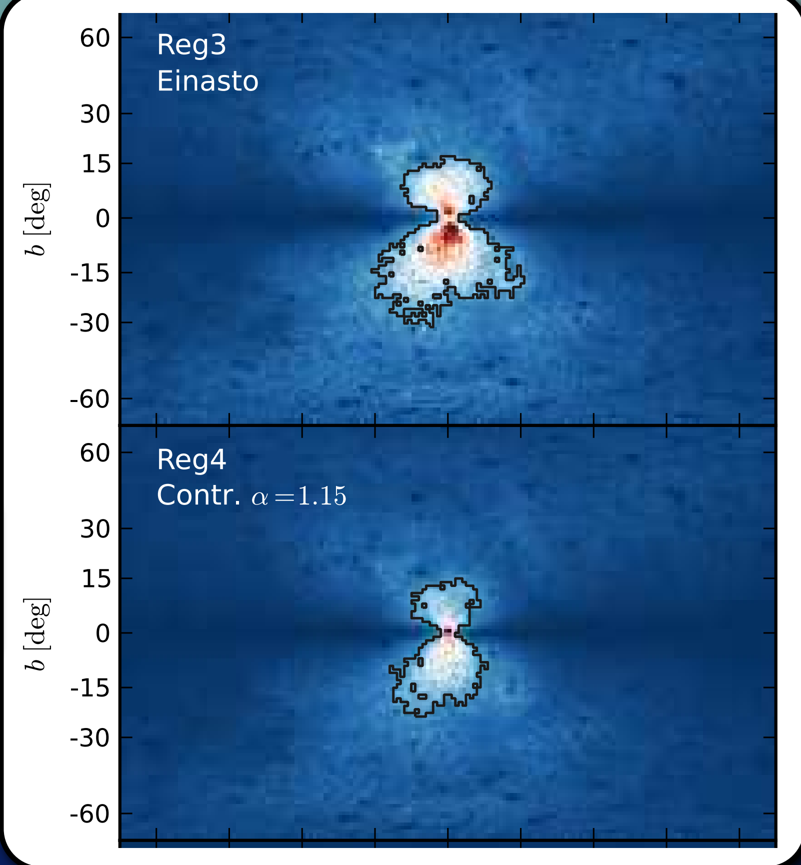


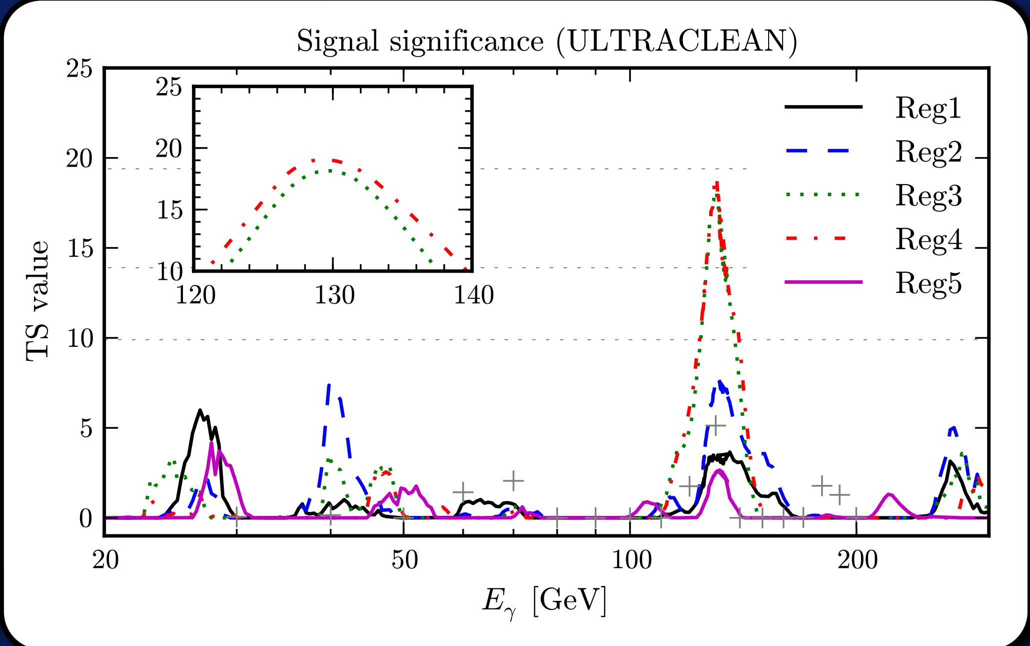


The 'Weniger' Line

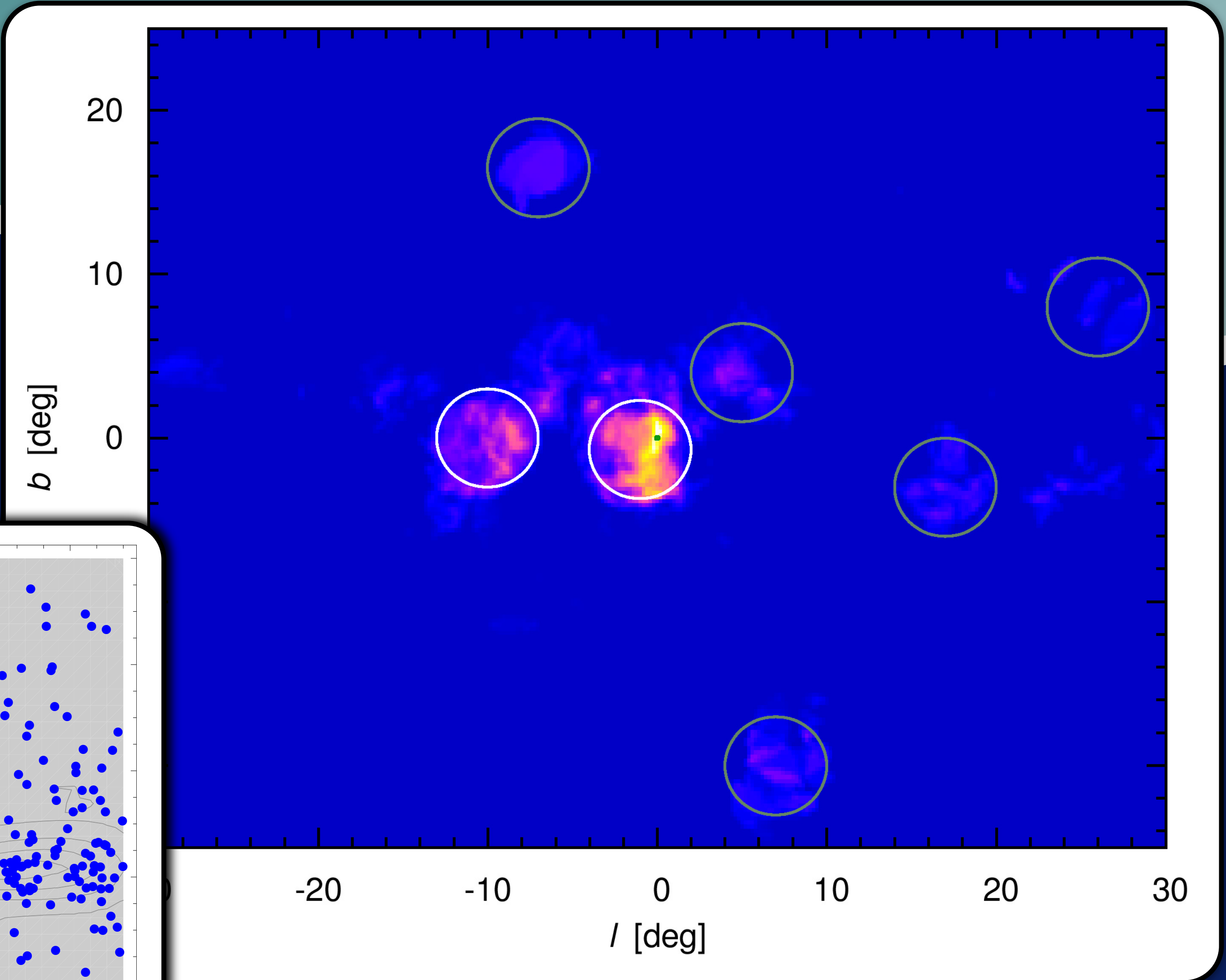
- Recently, Weniger (et al) claim observation of a feature around ~130 GeV corresponding to a cross section around ~10^{-27} cm^3/s in the Fermi public data.
- While it is premature to take the viewpoint that this feature is due to dark matter, we can take a look at what the data would be telling us, if it eventually is realized as something iron clad.

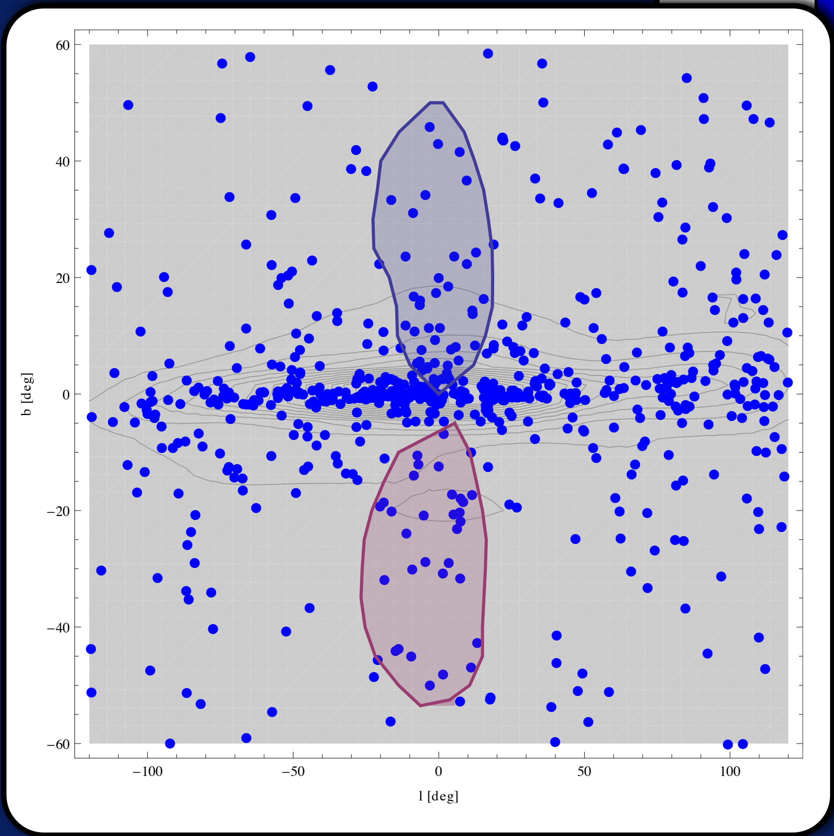
Bringmann et al 1203.1312





Weniger, 1204.2797



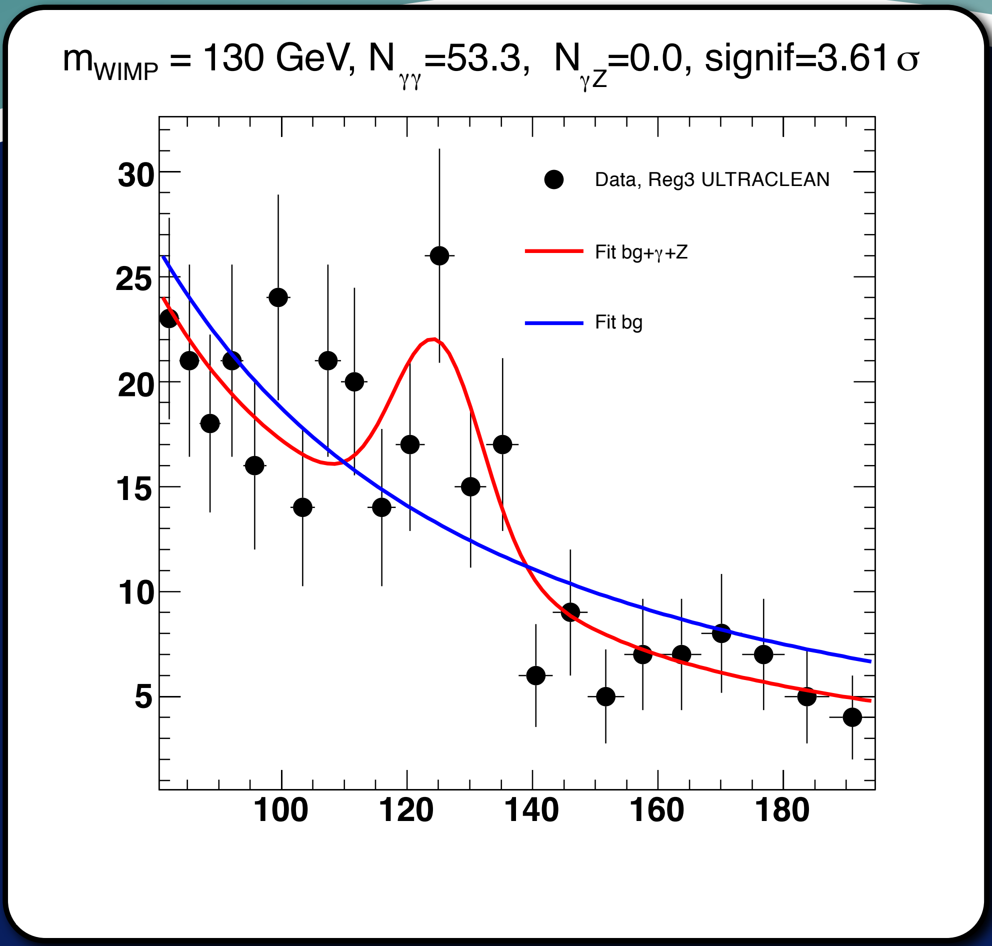


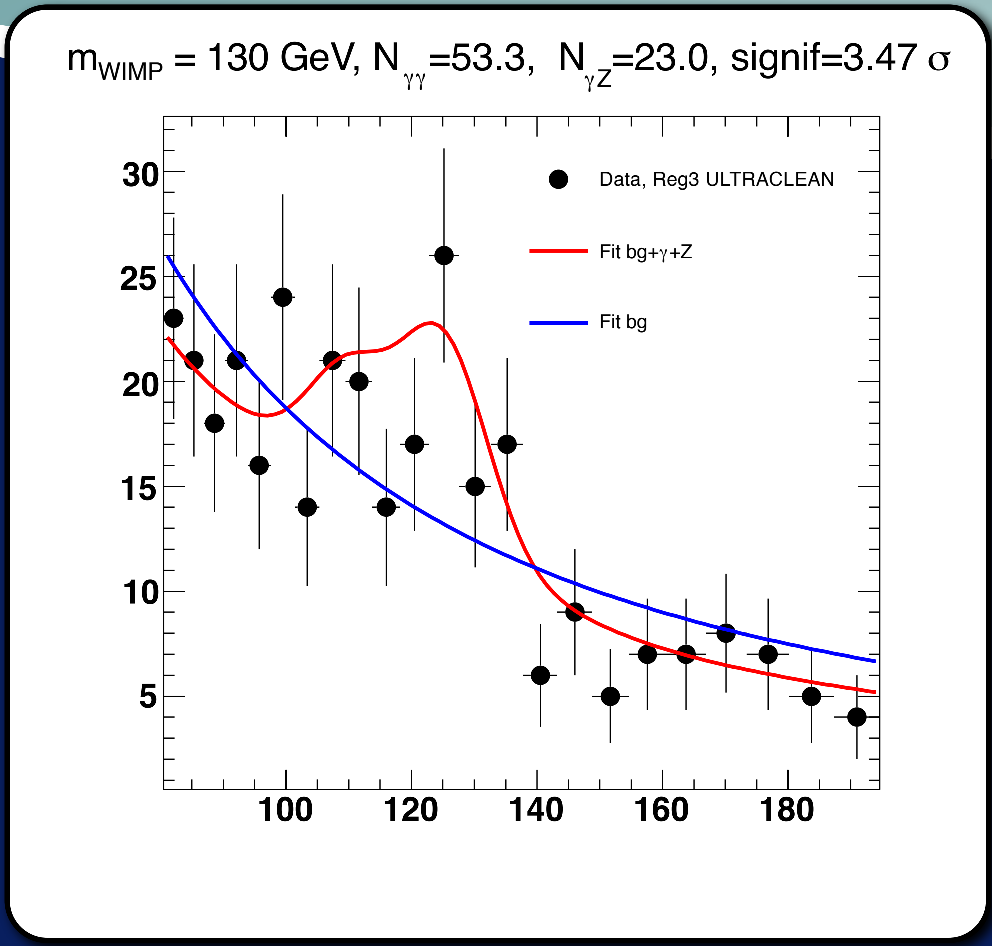
Tempel et al 1205.1045

- The morphology looks a little weird, clearly more statistics are needed...

Two lines?

Rajaraman, TMPT, Whiteson, work in progress

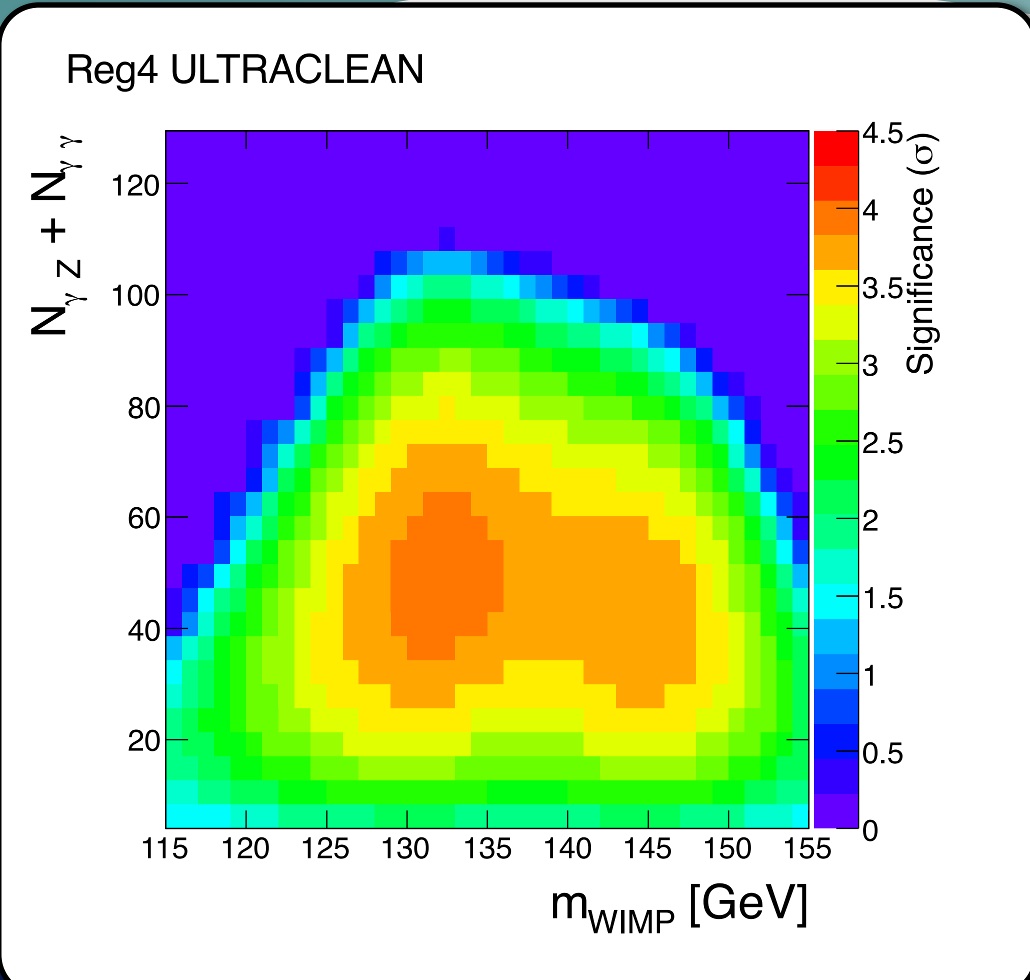


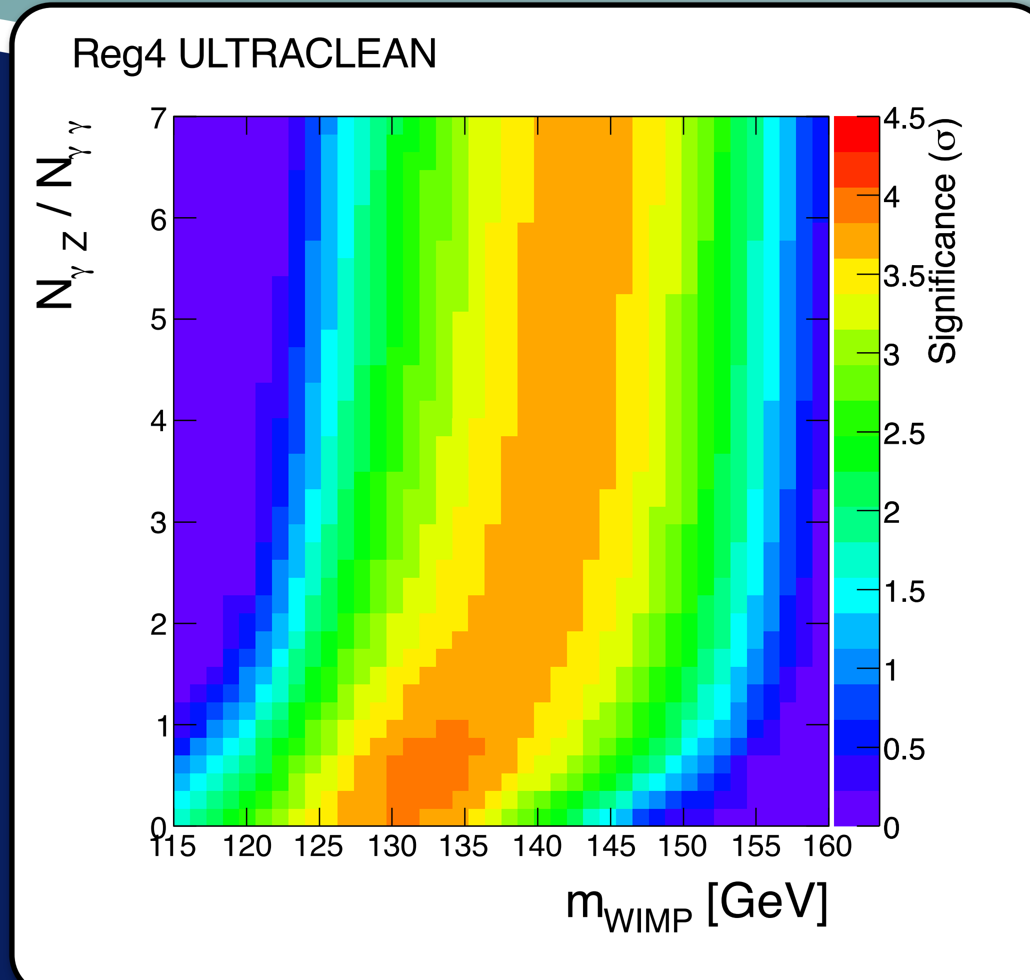


- Generically, we expect a γγ line to come along with a γZ line.
- We can fit the data to the two line hypothesis, varying WIMP mass and relative fraction of γγ and γZ, to see if there is any mild preference.

Fit to γγ and/or γZ

Rajaraman, Tait, Whiteson, work in progress

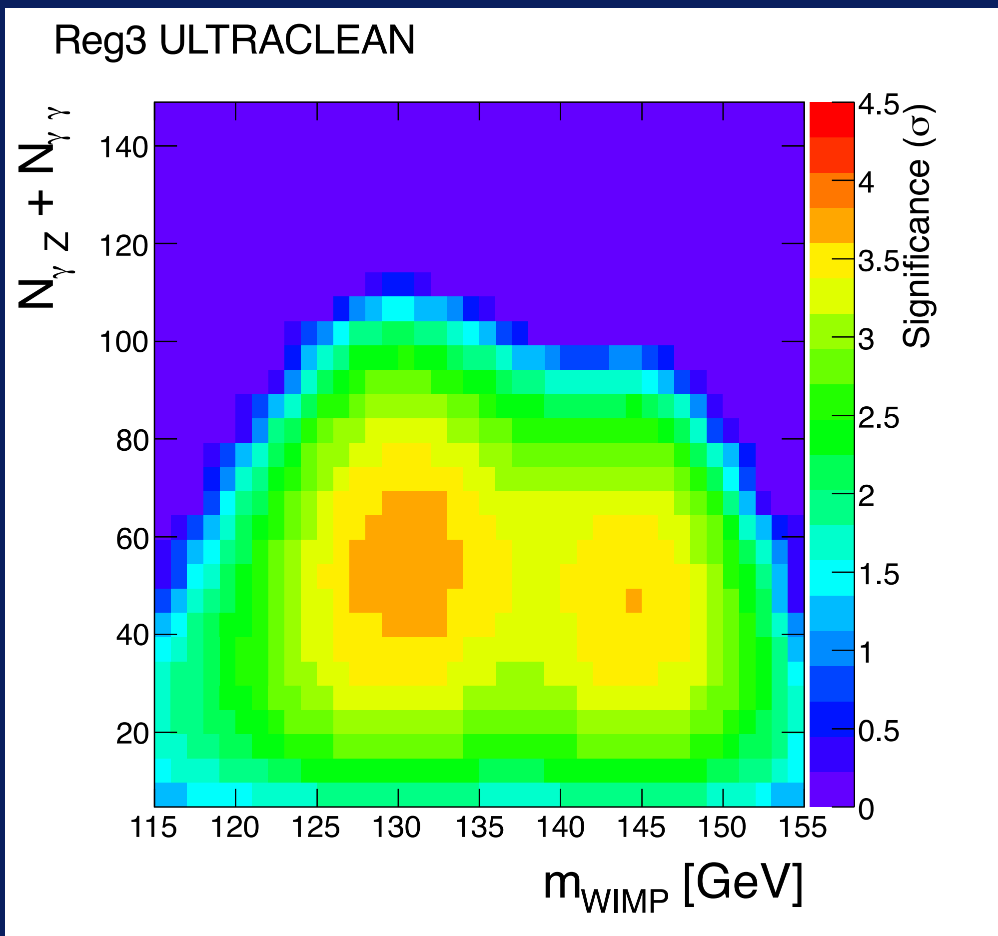


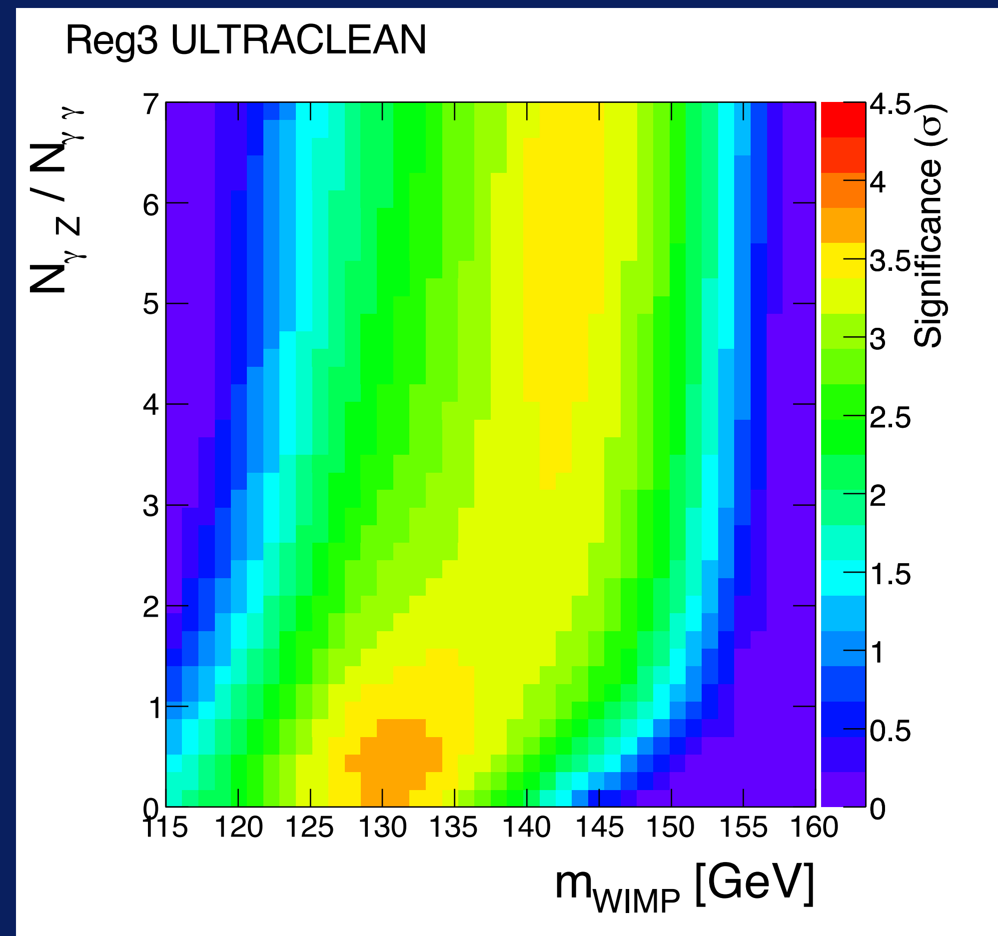


- Note: These significances are not look-elsewhere corrected!
- The data shows a very mild preference for a single line interpretation, but does not significantly exclude the γγ + γZ hypothesis.

Region 3 is Similar

Rajaraman, Tait, Whiteson, work in progress





Outlook

- WIMP annihilations into gamma ray lines are an interesting and important way to search for WIMPs and learn about them, especially in tandem with a signal from somewhere else.
- 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.
- Finite energy resolutions may merge lines together, but in some cases, distinctly observable lines may result.
- If we do find a concrete signal, the next step is to disentangle how many lines there are, and to try to identify the actual final states. This can give us very interesting information about the WIMP properties, which may be difficult to extract from other observations.