Gamma Ray Lines as Dark Matter Signals

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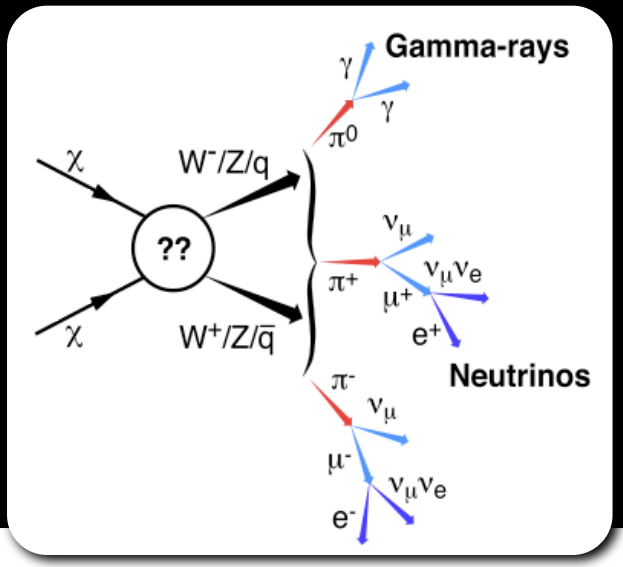
Outline

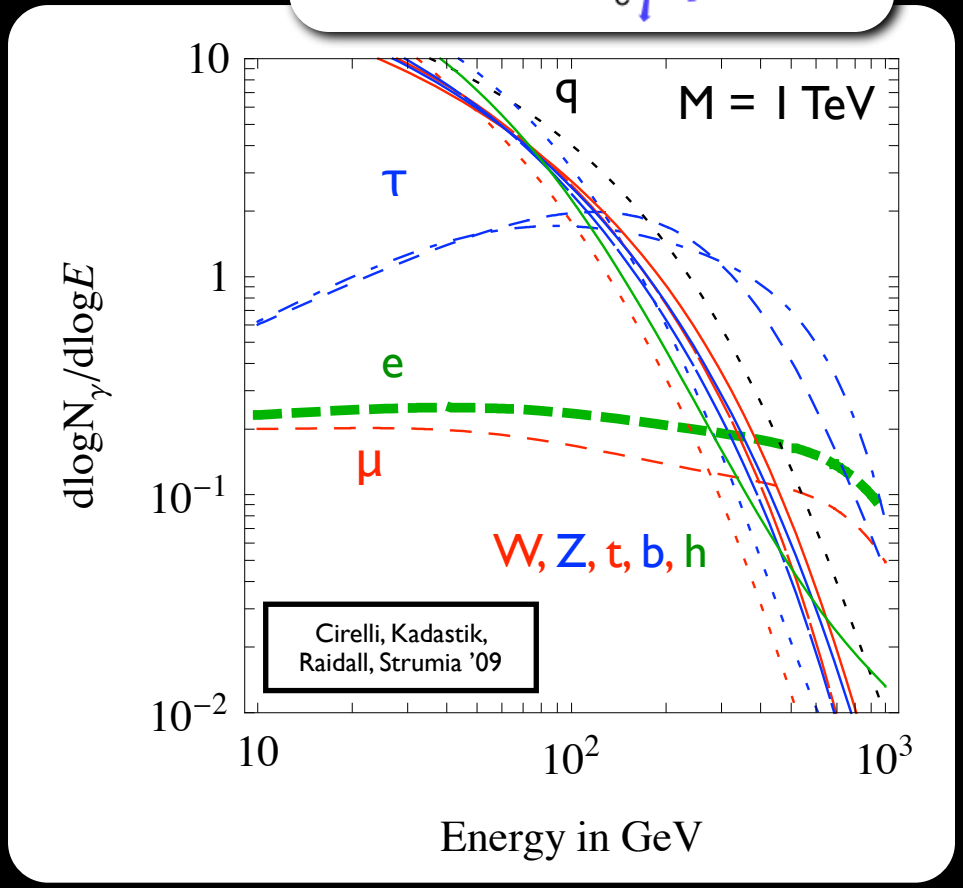
- Motivation for Gamma ray line searches
- Gamma ray Lines - basic implications
- What a Line can tell us
- The ``Weniger'' Line in the Fermi-LAT data
- Outlook

Gamma Rays from WIMPs

- If WIMPs can interact sufficiently with the Standard Model, they can annihilate, producing gamma rays as secondary products.
- Such photons tend to have low energies, because they take only a small fraction of the energy of the primary annihilation product.
- Searching for such photons is very challenging, because the spectrum of astrophysical backgrounds is not perfectly understood (and not radically different).

For more details, see the lectures by Dan Hooper about indirect searches for DM and Eric Charles about Fermi LAT dark matter searches...



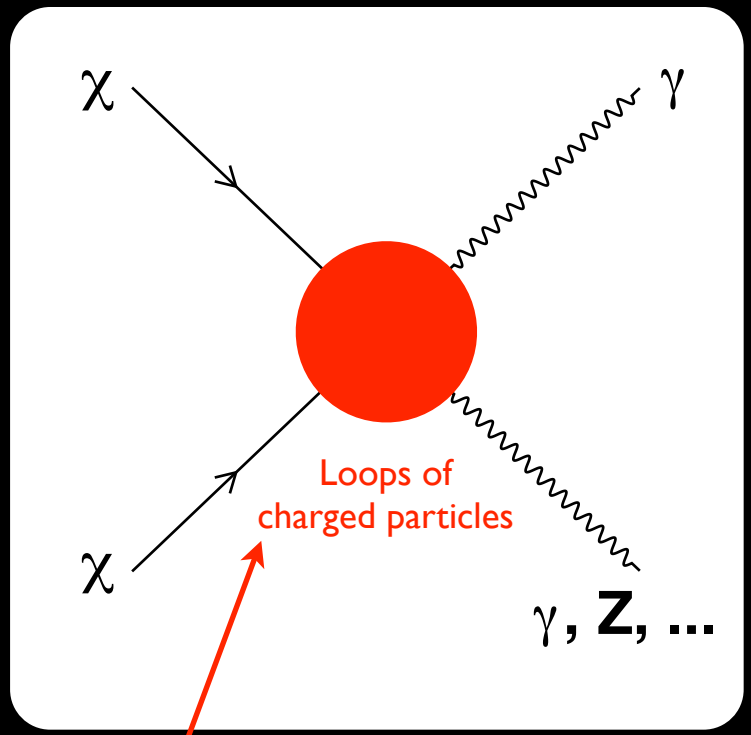


Gamma Ray Lines

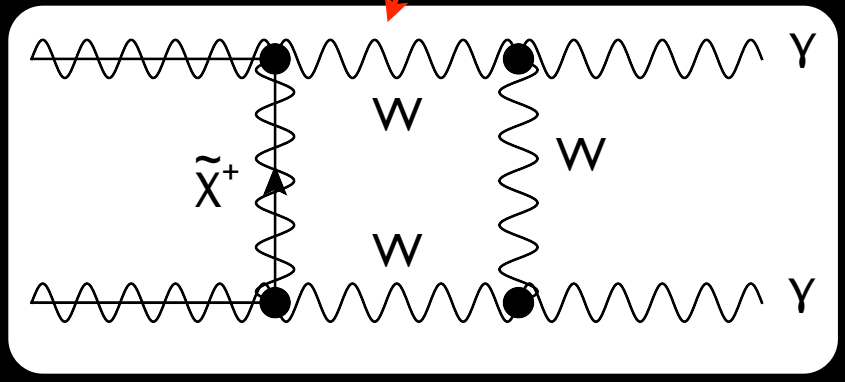
- WIMP annihilation into a two body final state containing a photon can result from loop processes, with charged particles running in the loop.
- Since WIMPs are thought to be highly non-relativistic in the galaxy, energy conservation predicts the energy of the photon in the reaction XX -> γY to be approximately:

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

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



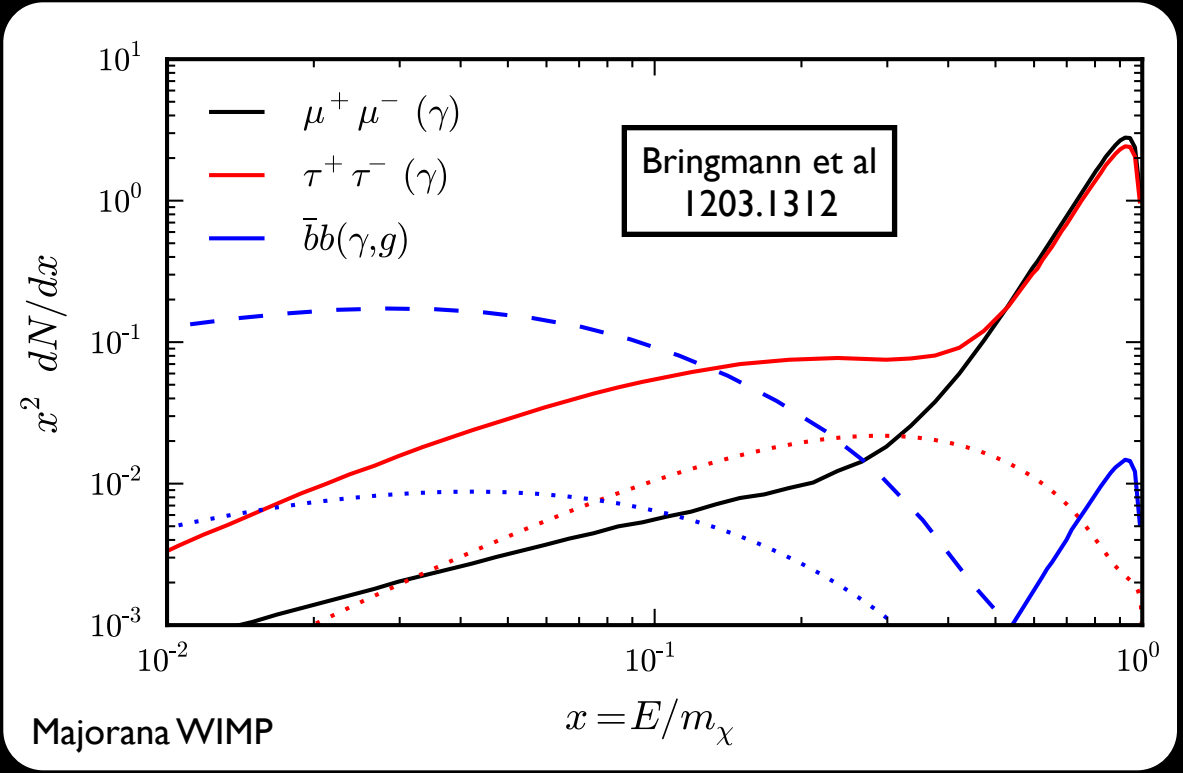
What goes in the loop may be a mixture of SM and/or exotic charged particles

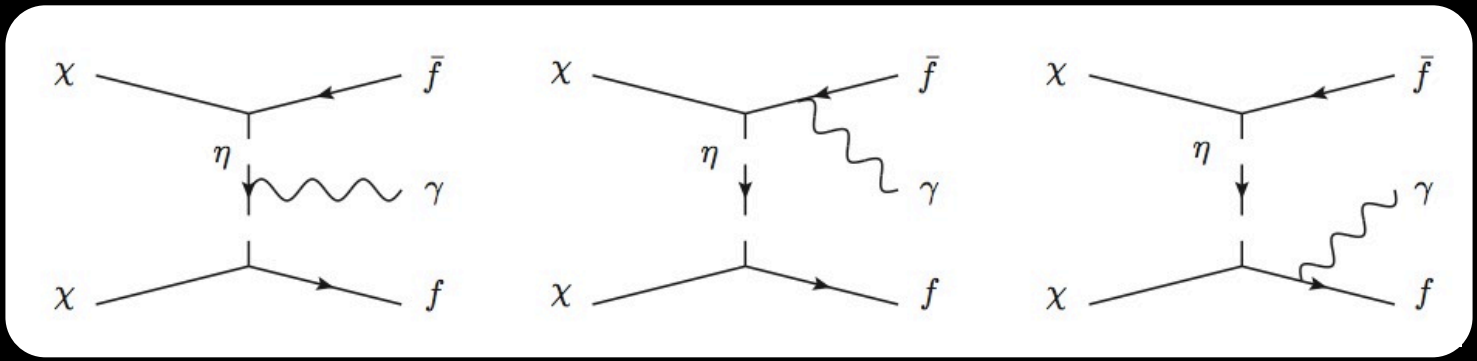


Internal Bremsstrahlung

- A sharp feature can also appear from radiative processes where a photon is radiated from a final state lepton or exchange particle.

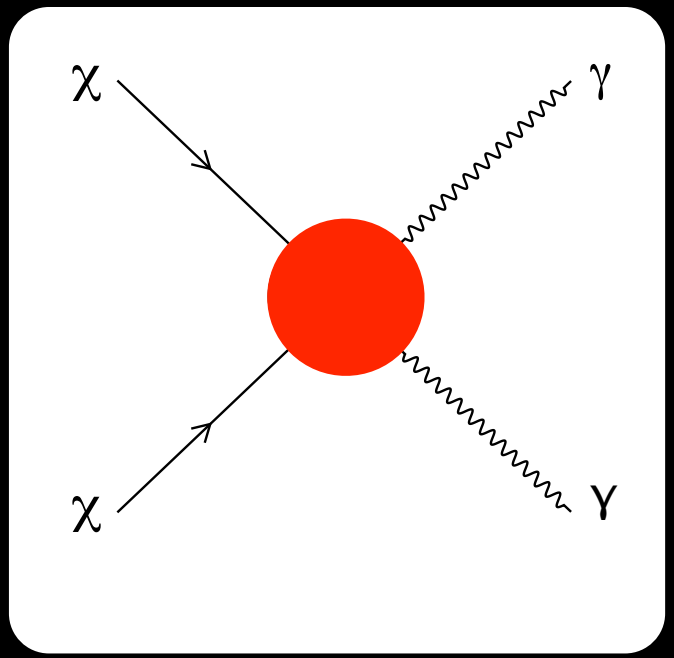
- The resulting bump is typically less sharp than a line, but in many theories (particularly those with suppressed continuum annihilation) can be quite peaked around the dark matter mass.





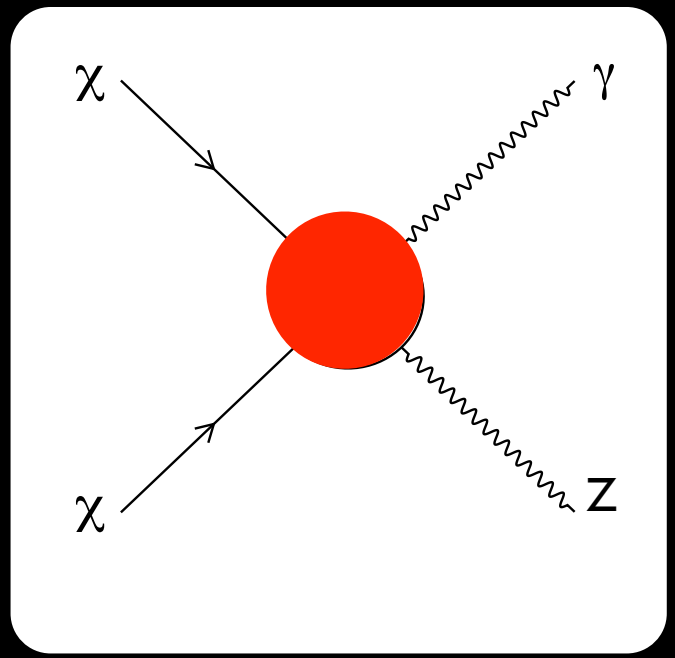
Line Final States

- In the Standard Model, a gamma ray can be produced in association with another gamma, a Z boson, or a Higgs boson.
- Other theories may have richer line structures... Bertone, Jackson, Shaughnessy, TMPT, Vallinotto 0904.1442 & PRD
- Angular momentum conservation tells us something! The initial J should arise from the spin, or the rate will be suppressed by the small WIMP velocity.

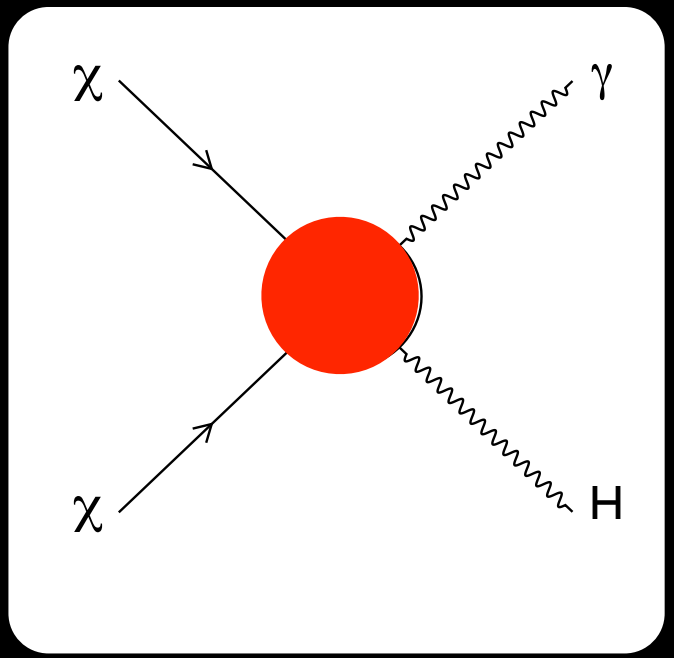


J=0,~~1~~,2

Forbidden by the Landau-Yang theorem



J=0,1,2

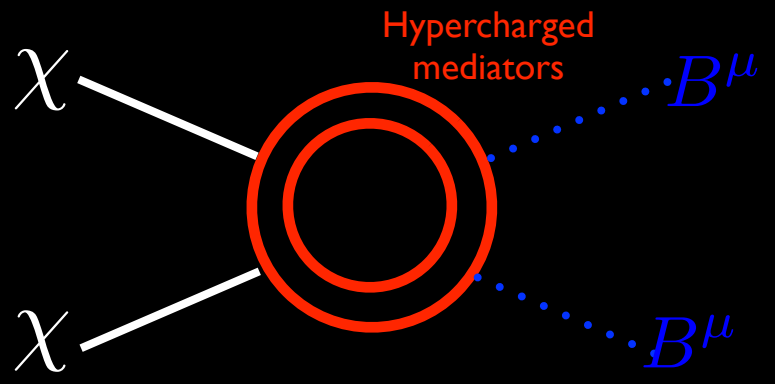


J=1

v-suppressed for Majorana χ

Line Operators

- We can express the possible terms in the effective action of the quantum field theory to describe line processes.



- SU(2) x U(1) invariance tells us a lot: at its heart, the WIMP must couple to either B or W_3, both of which are a linear combination of γ and Z.

Rajaraman, TMPT, Whiteson, 1205.4723

- So a generic prediction (modulo interference) is that a γγ line is generically accompanied by γZ.

$$\frac{1}{M_*^2}|\chi|^2 B^{\mu\nu}B_{\mu\nu}$$

$$\rightarrow \quad \frac{c_W^2}{M_*^2}|\chi|^2 F_{\mu\nu}F^{\mu\nu}$$

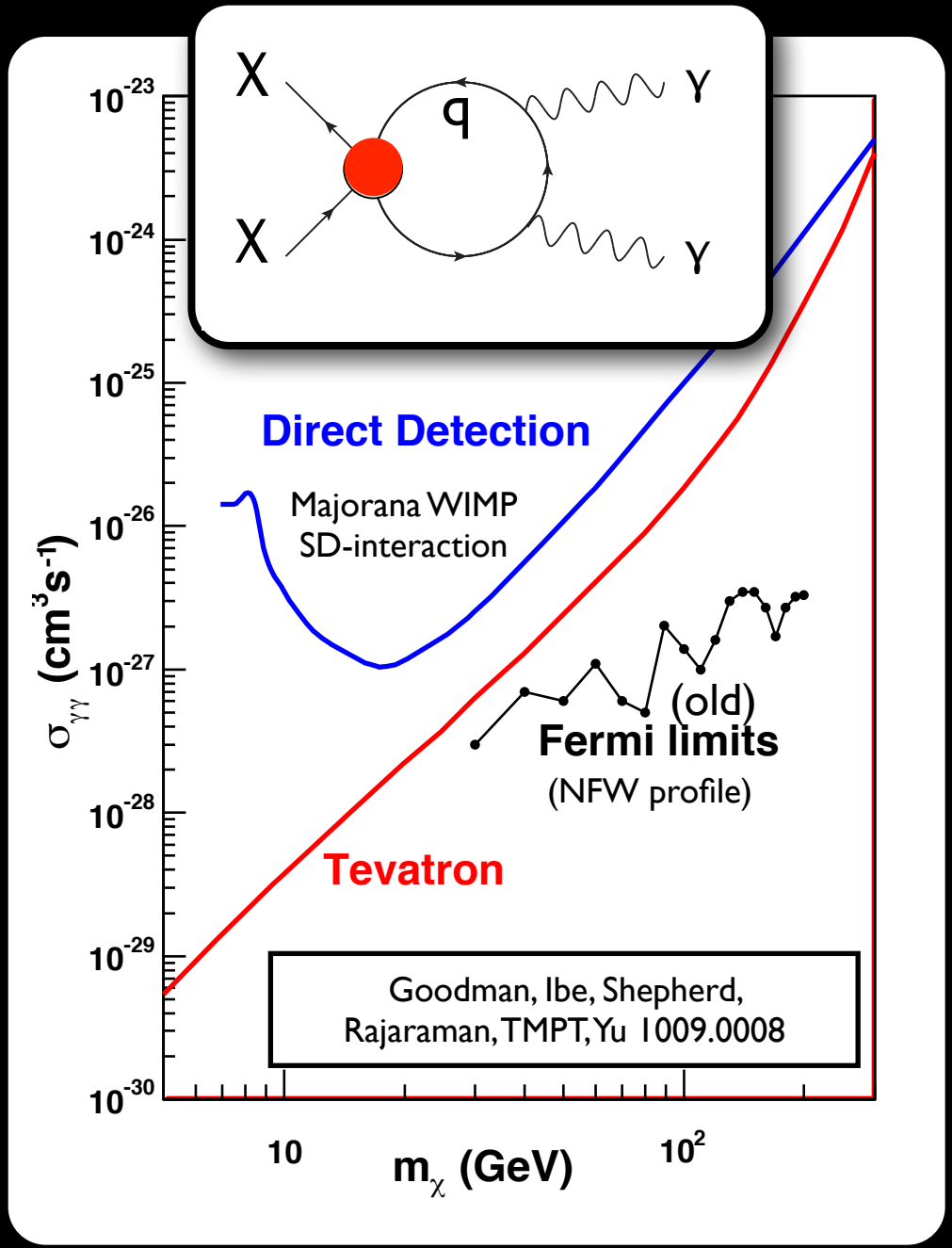
$$+\frac{2s_W c_W}{M_*^2}|\chi|^2 F_{\mu\nu}Z^{\mu\nu}$$

$$+\frac{s_W^2}{M_*^2}|\chi|^2 Z_{\mu\nu}Z^{\mu\nu}$$

- A similar argument applies to γh -- because the longitudinal Z is part of the Higgs doublet, a γZ line is implied by a γh one.

Bounds from Lines

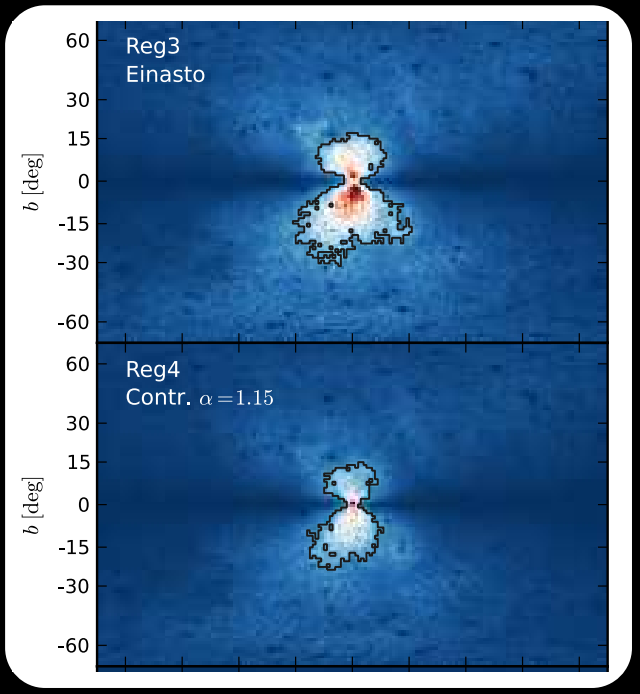
- Lines could also be generated indirectly from coupling to quarks and/or leptons.
- Null searches for gamma ray lines are a powerful probe of dark matter.
- For example, for a WIMP coupling to quarks in a spin-dependent way, the Fermi line search can provide more stringent constraints that direct searches for WIMP scattering or LHC production of WIMPs.
- Gamma ray lines are complementary to other searches for dark matter, and an important contribution to our over-all understanding of dark matter.



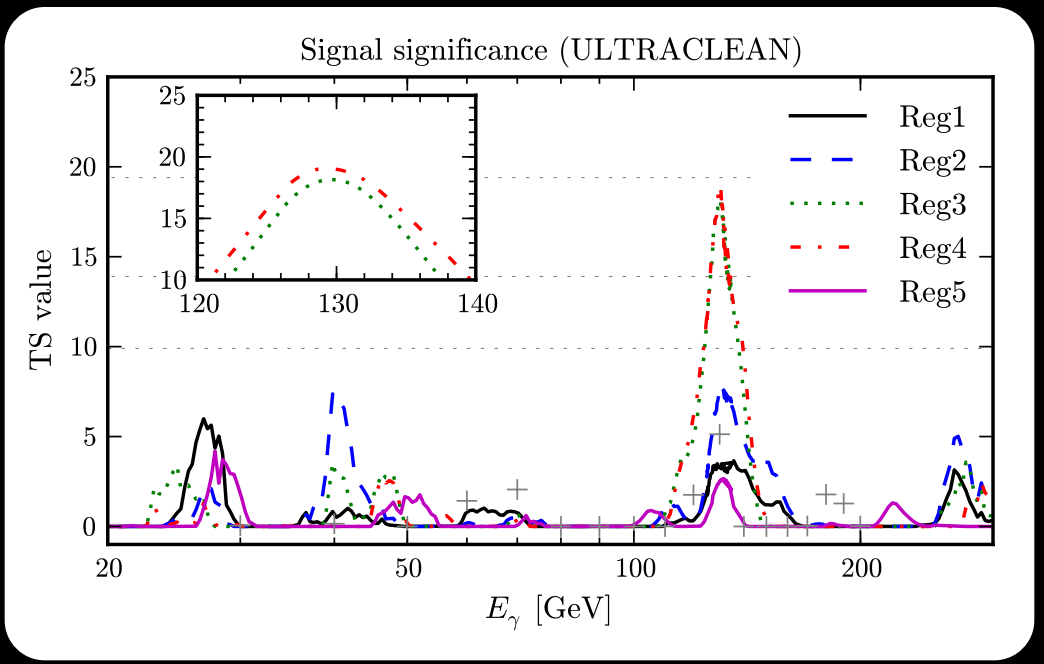
The 'Weniger' Line

- 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.
- The feature is more prominent in regions 3 and 4, focused on the galactic center (with the galactic plane removed).
- Weniger quotes a statistical significance a little above 3 sigma, when the trials factor is included.
- The question now is: is this real? is it instrumental? Astrophysics? Dark matter...?!?!

Bringmann et al 1203.1312

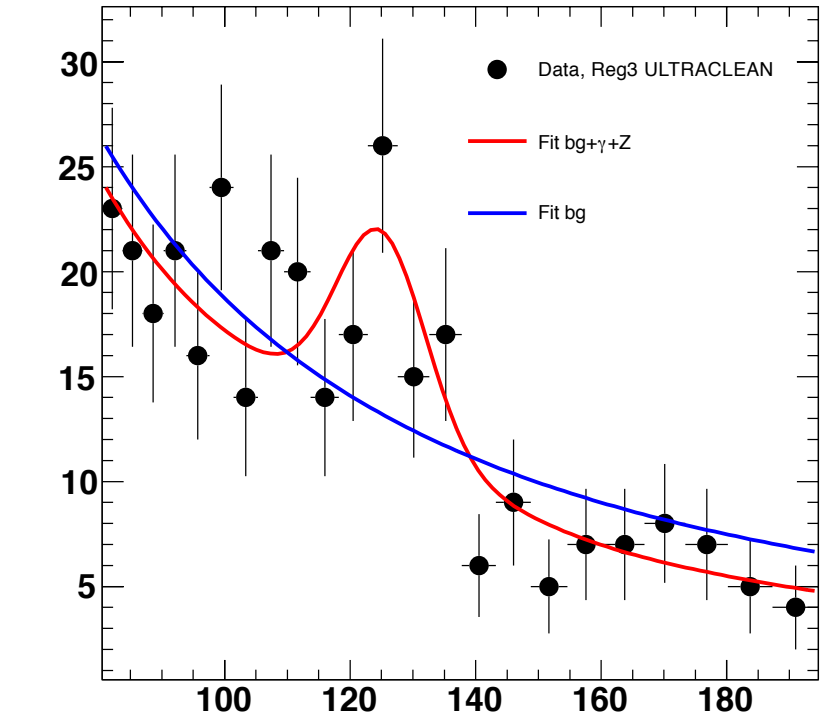


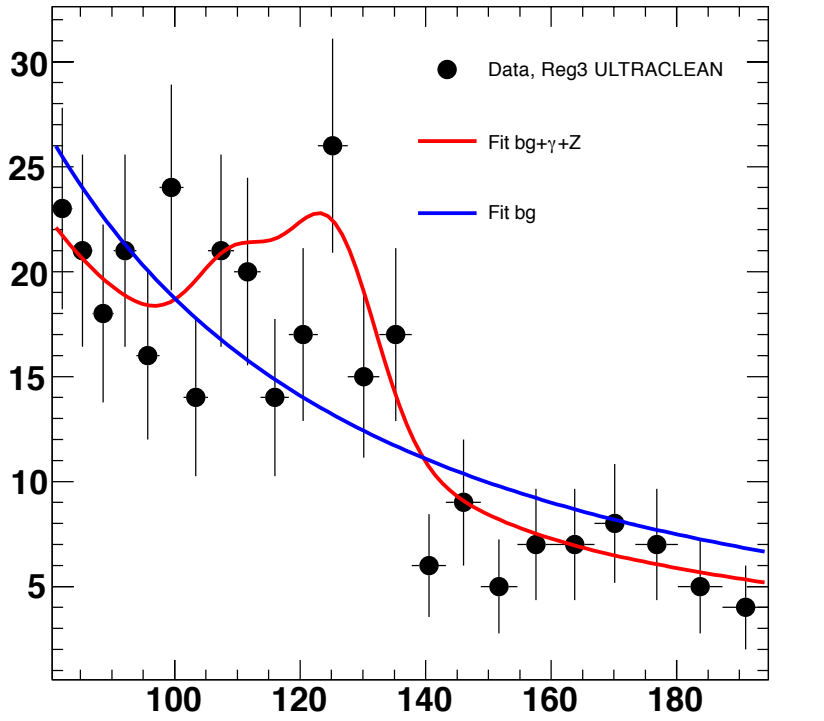
Weniger, 1204.2797



Two lines?

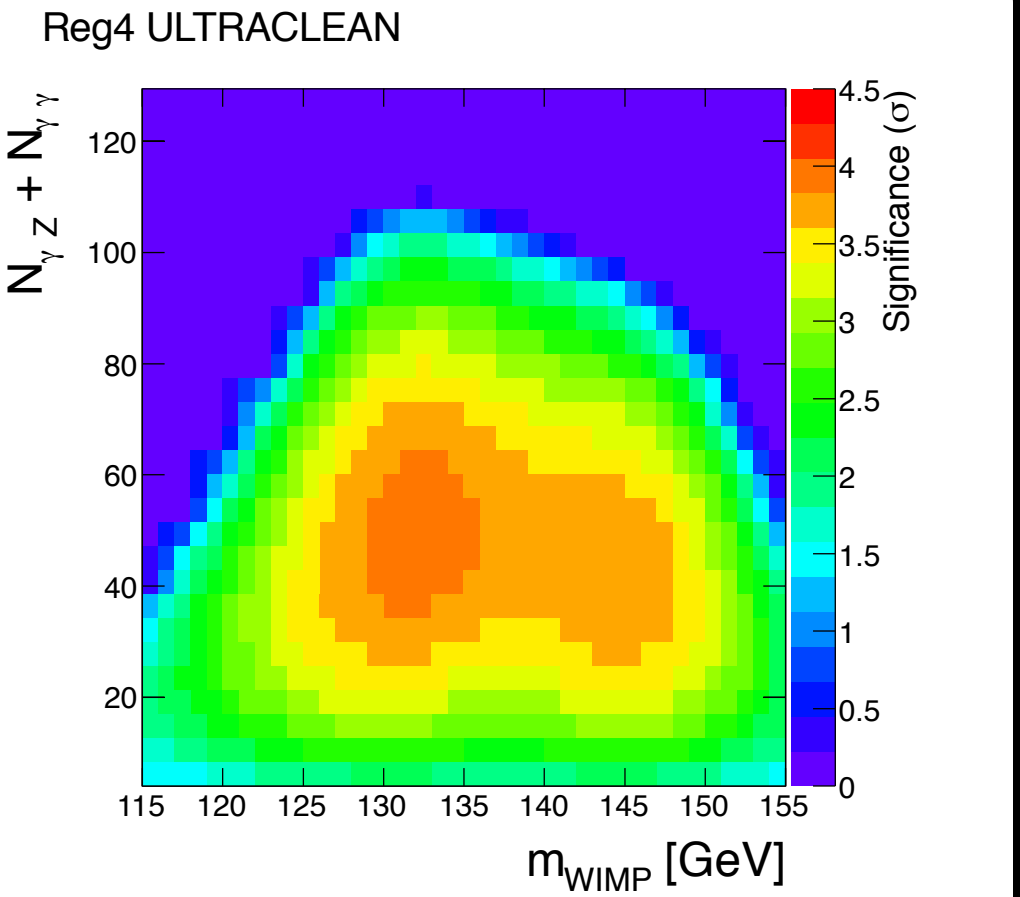
Rajaraman, TMPT, Whiteson, 1205.4723

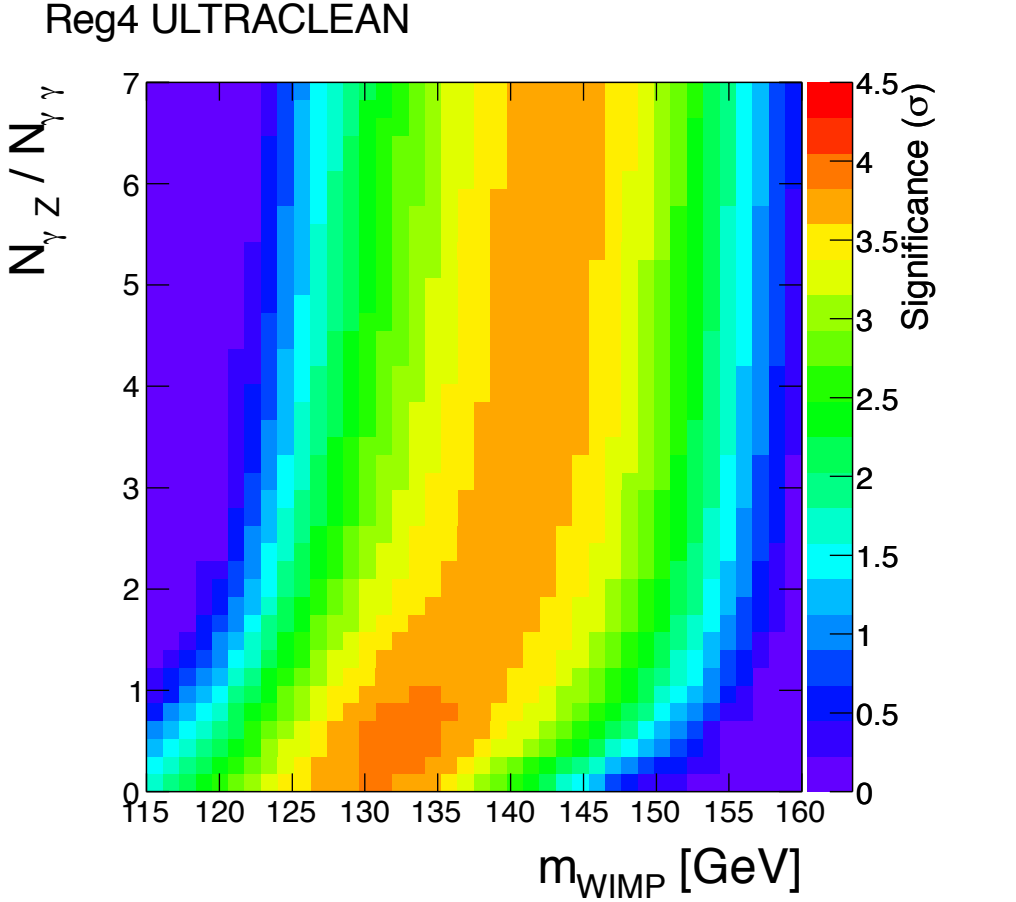




- We can fit the data to the two line hypothesis, varying WIMP mass and relative fraction of γγ and γZ, to see if there is any hint of two lines.
- We find that there is a (very) mild preference for two lines, with the γZ line somewhat subdominant to the γγ one.

Fit to γγ and/or γZ



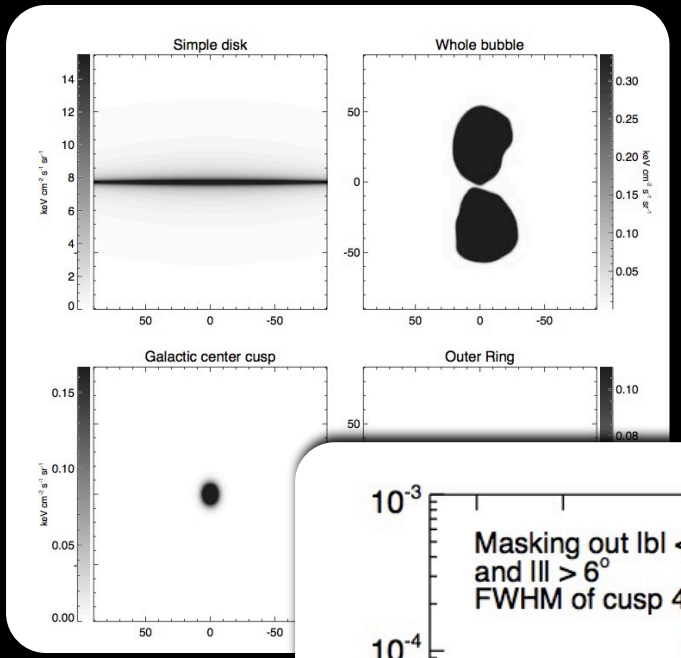


Rajaraman, Tait, Whiteson, 1205.4723

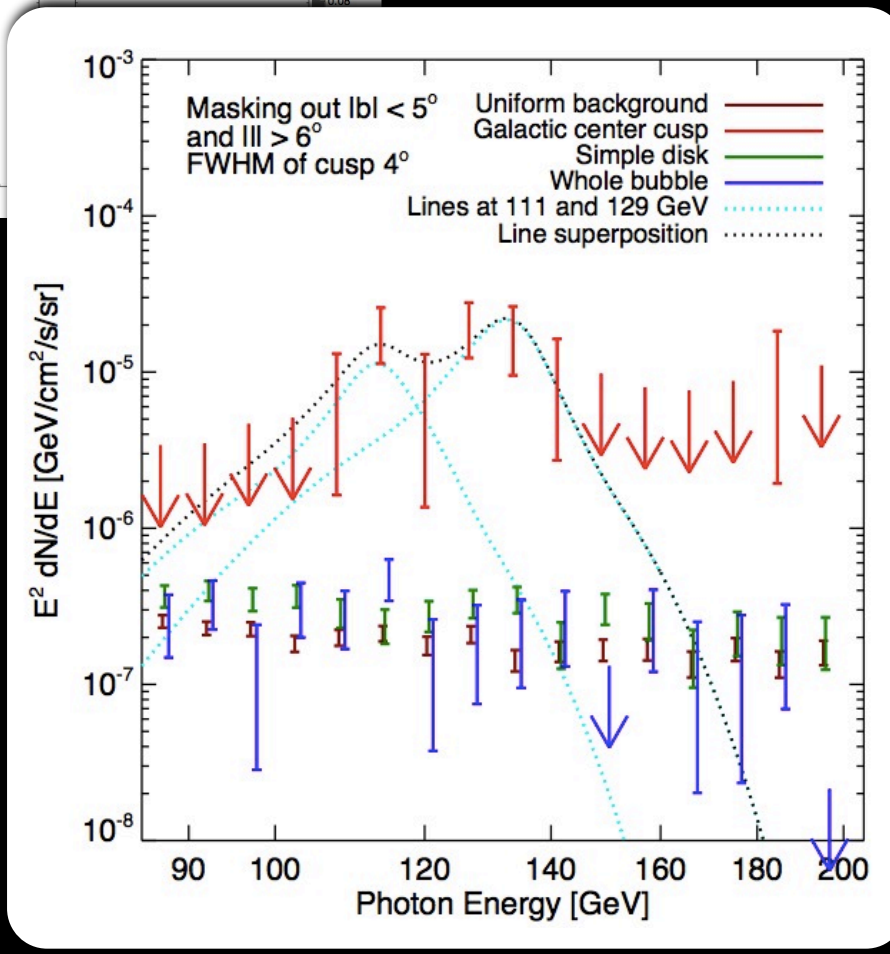
See also: Cohen, Lisanti, Slatyer, Wacker, 1207.0800

Template Analysis

- A follow-up by Finkbeiner and Su uses a template analysis to try to tease the feature out of the data.
- They find evidence for a ~circular excess slightly (~1°) offset from the galactic center.
- They design templates to cover the morphology of the diffuse background, the galactic plane, the Fermi "bubbles", and the putative extra spot near the center.
- They fit the coefficients of these templates in bins of energy.

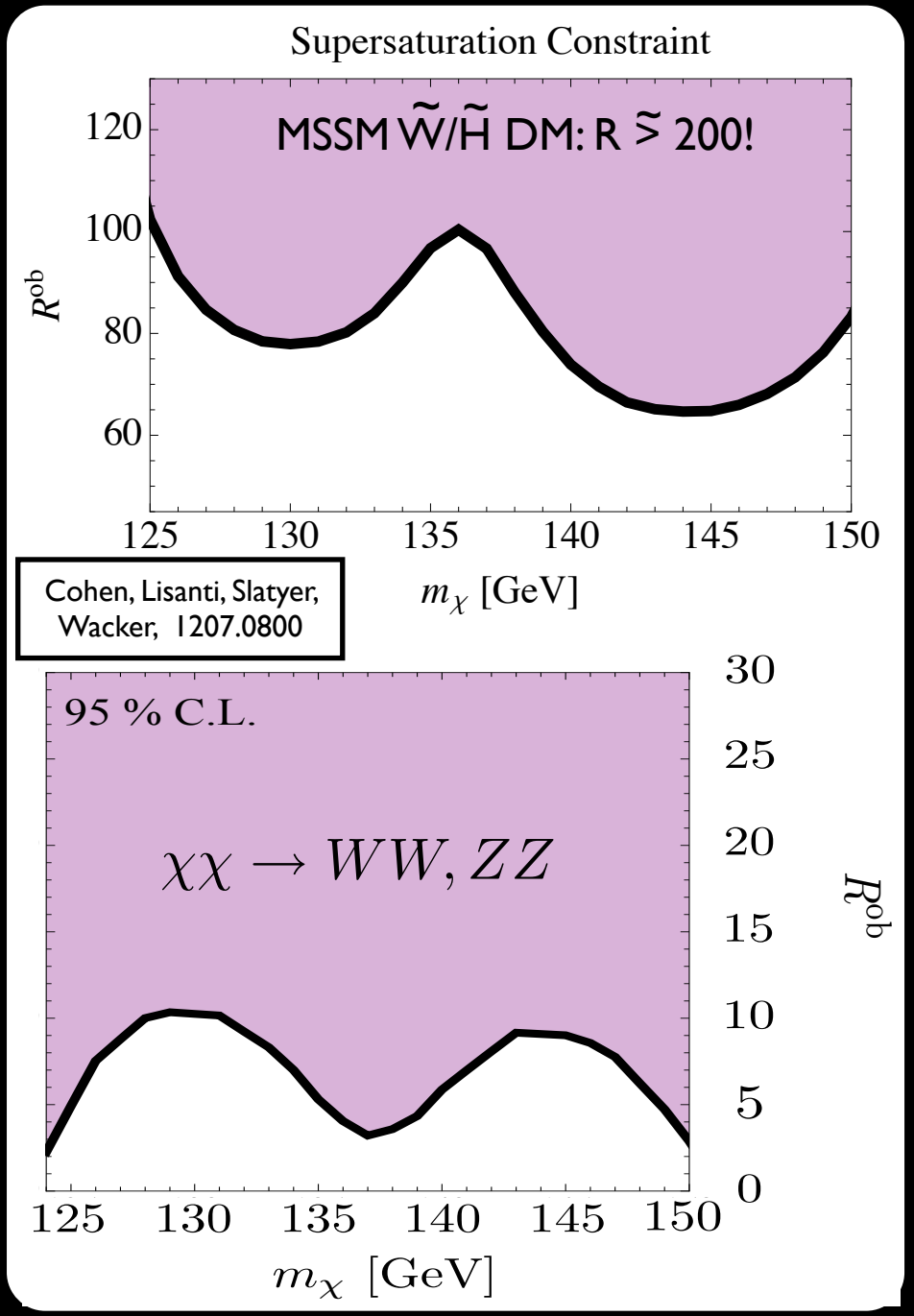


Su, Finkbeiner
1206.1616



Continuum Constraints

- If the line really is dark matter annihilating, it should be accompanied by continuum gammas from annihilation too.
- One can remove the astrophysical uncertainty from the dark matter distribution by using the line signal to define the region of interest, and study the relative size of the ratio of continuum / line emission.
- Very robust limits can be derived by just asking that the WIMP annihilaiton not over-produce photons at lower energies.
- Somewhat more assumptions are built into a shape analysis which assumes a purely power law background.



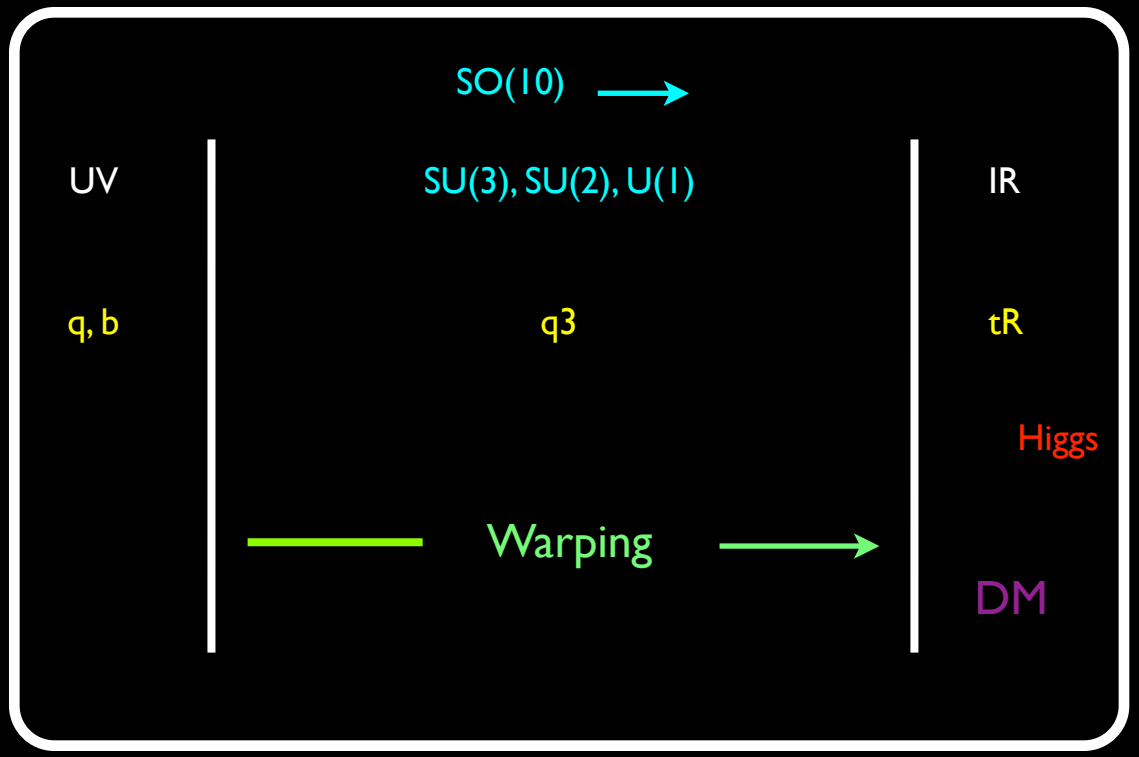
See also: Buckley, Hooper 1205.6811

If the 130 GeV feature is indeed dark matter, it is telling us something very interesting...

This is not vanilla dark matter...

RS Dark Matter

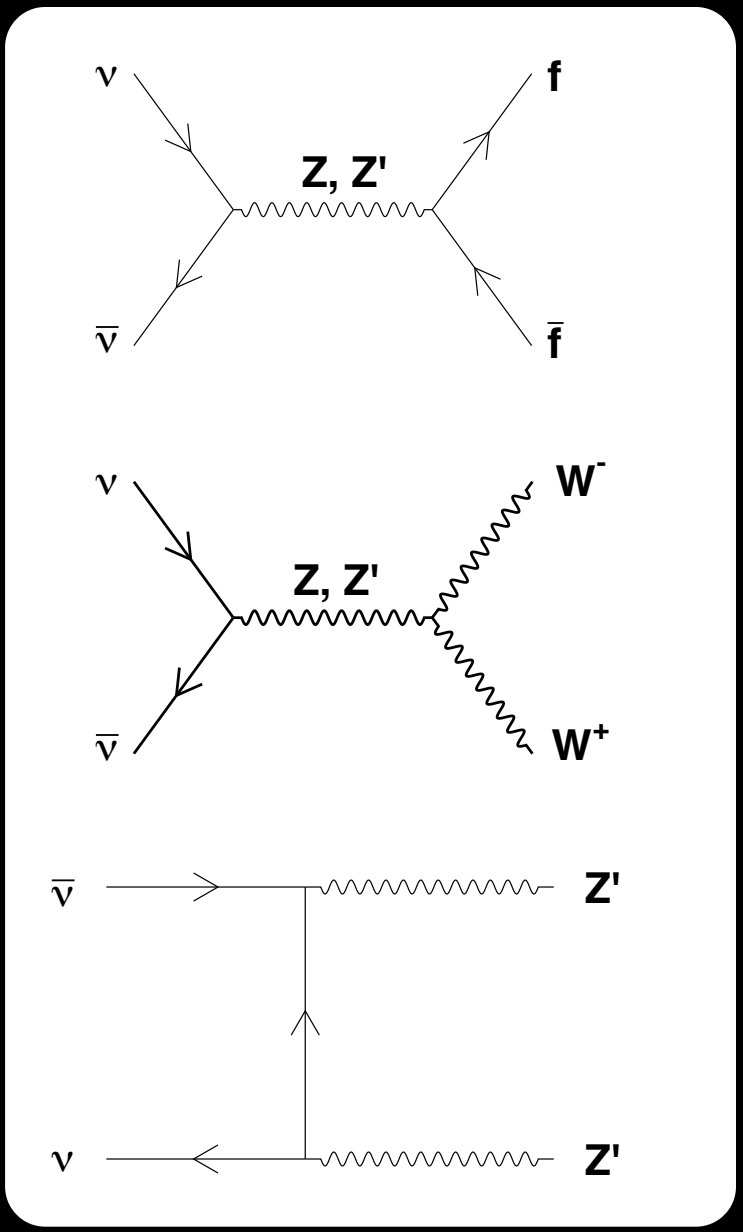
- An example with a naturally suppressed continuum comes from dark matter in an warped extra dimension.
- The models of interest have the Standard Model in the bulk and gauge coupling unification.
- These models need extra structure to avoid constraints from rapid proton decay.
- A particular realization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



Agashe, Servant, '04

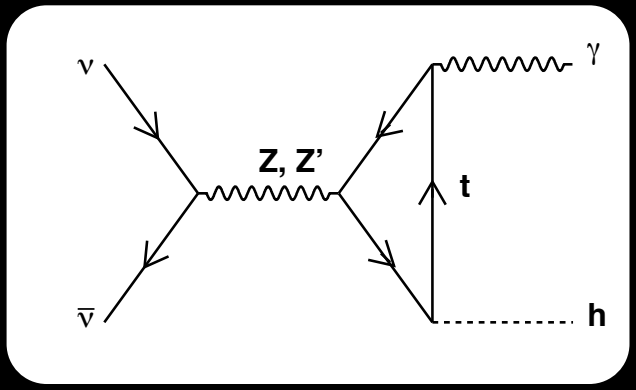
RS Dark Matter

- 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 is dominated by 3 body annihilation into tWb and loop processes.

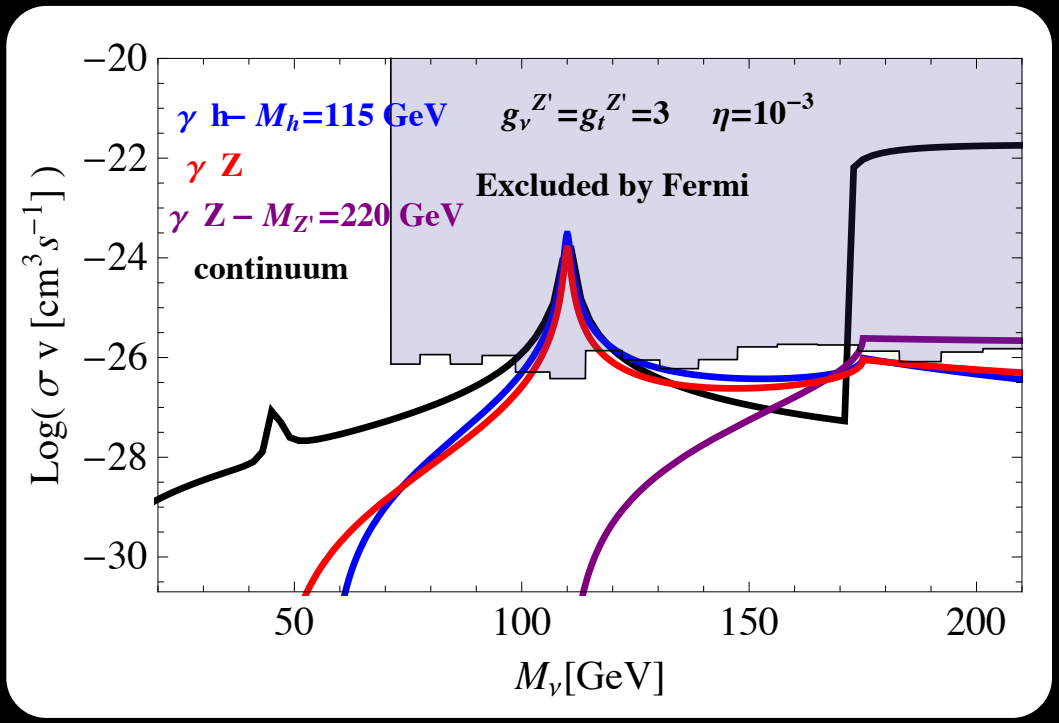


Loop Annihilations

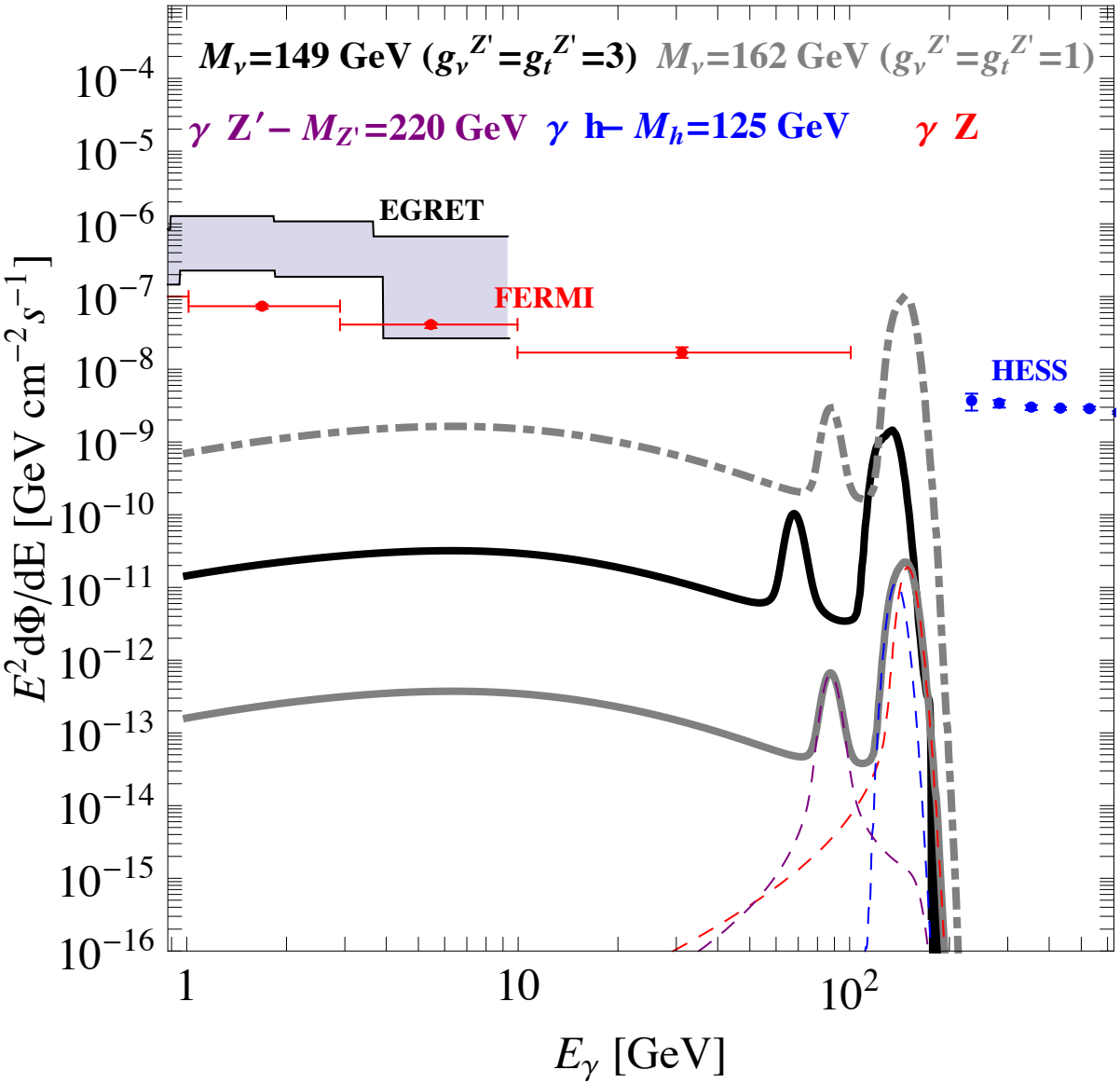
- Loop annihilations can lead to γZ, γh, and (if light enough) γZ' final states.
  - A γγ final state is forbidden by the Landau-Yang theorem.
  - We produce the Higgs in space with a large rate!
- Why did the possibility of a Higgs gamma ray line show up here?
  - We needed a Dirac WIMP which can have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



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



Continuum and Lines

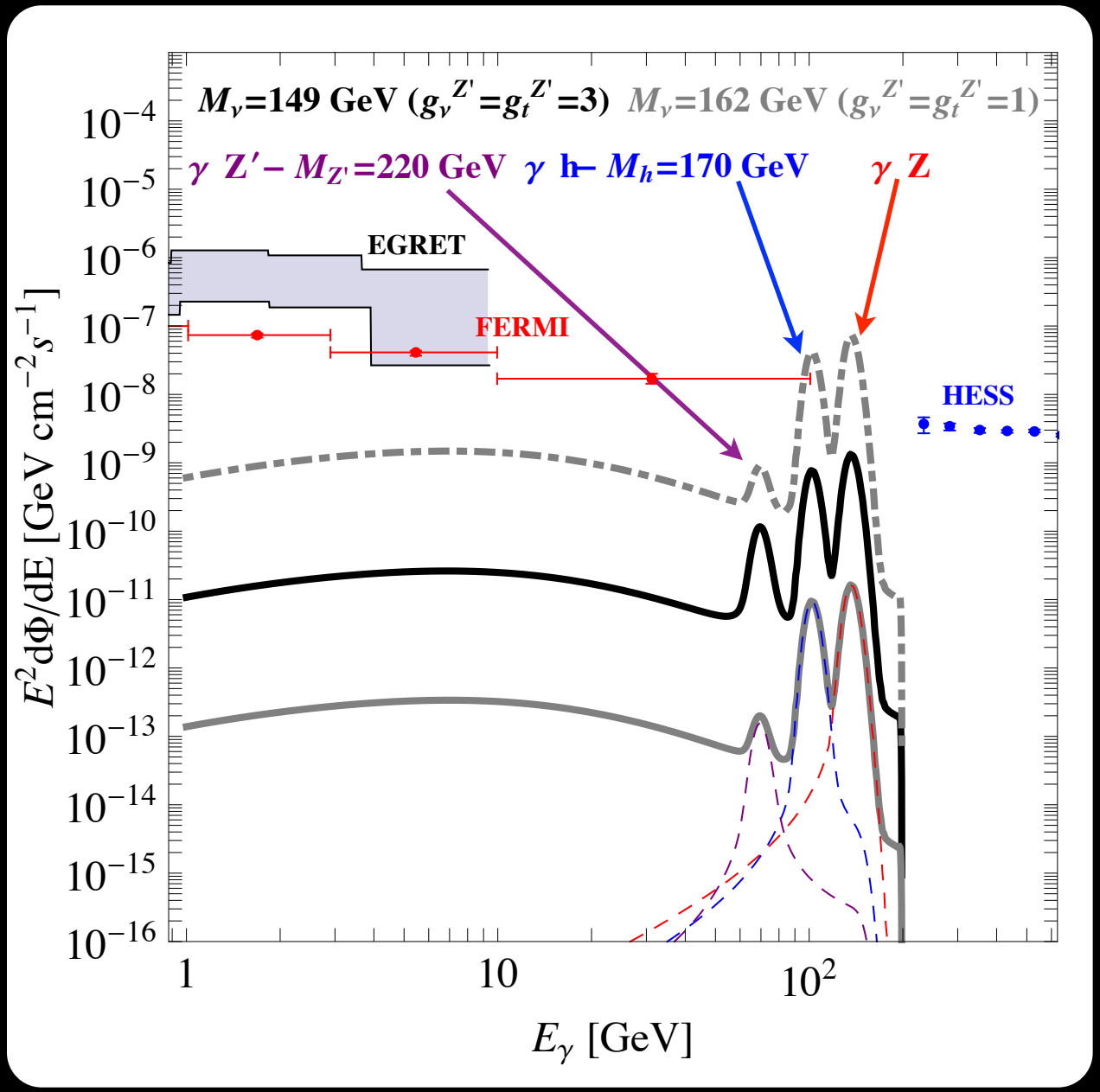


For this set of parameters, γZ and γh are hard to distinguish.

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)

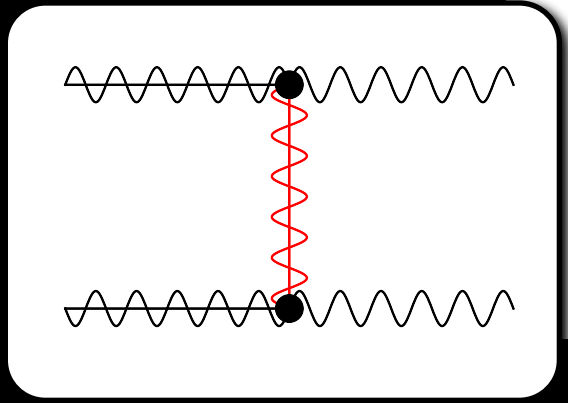
MiDM

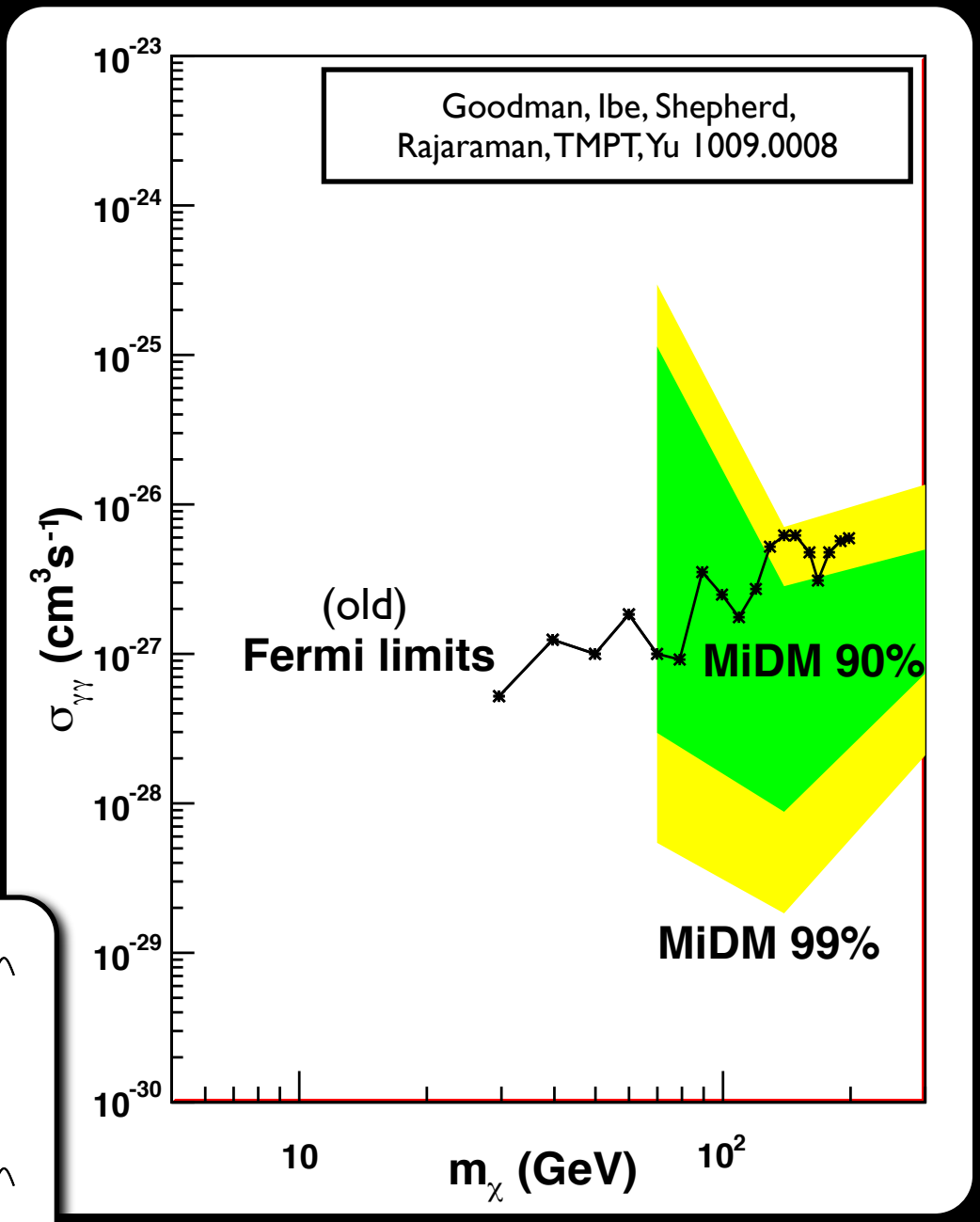
- A line can arise from an inelastic scattering WIMP whose main interaction is "through the photon portal".
- These models were proposed to reconcile DAMA with null results from other experiments.

Chang, Weiner, Yavin
PRD & 1107.4200

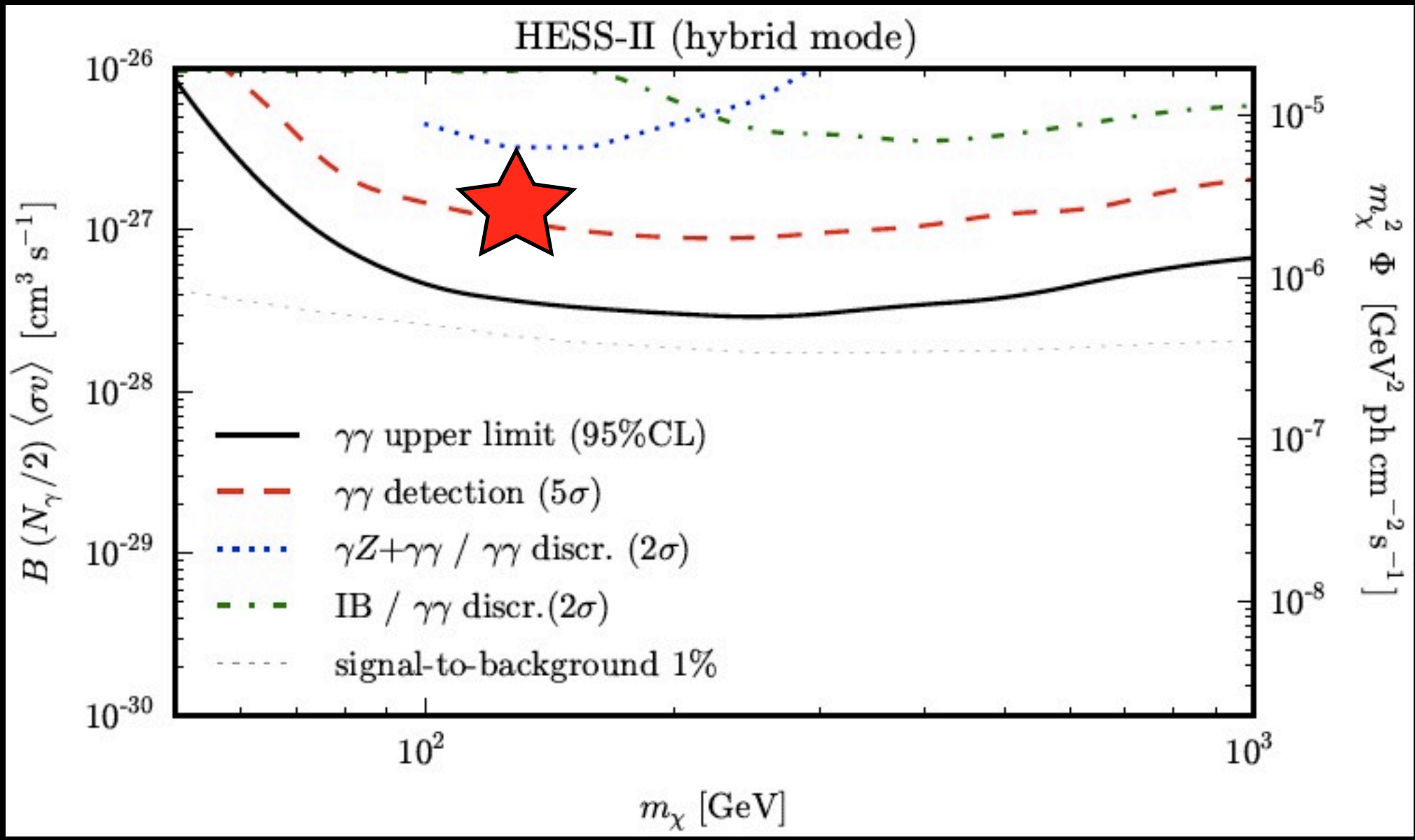
- Amazingly enough, they also seem to work for similar parameters to explain the ~130 GeV feature in the Fermi gamma rays.

Weiner, Yavin
1206.2910





Hess II ?!

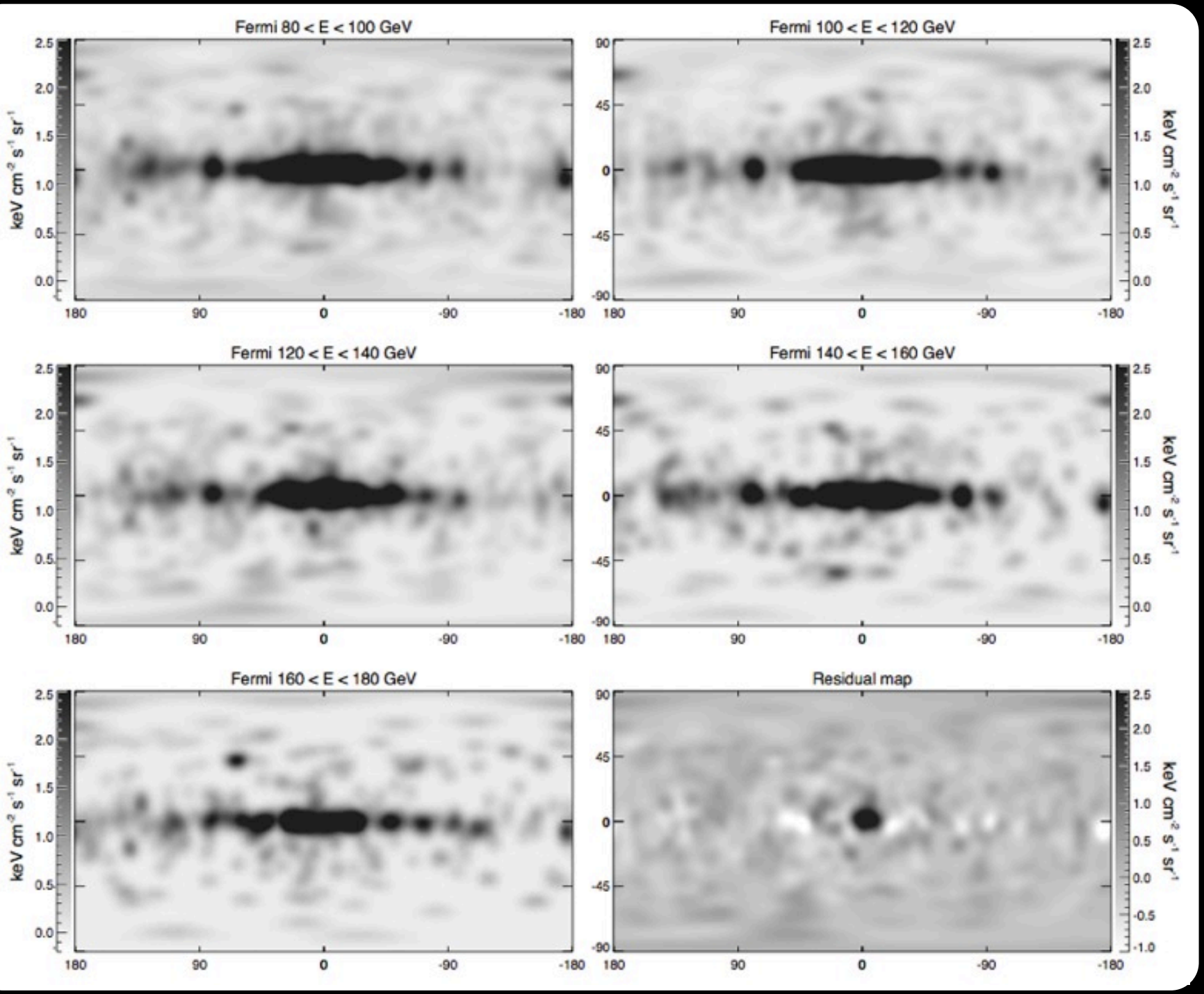


Bertone et al, coming soon...

Outlook

- Lines in the spectrum of gamma ray are an interesting feature that can occur in any theory of dark matter which has coupling to charged particles.
  - Astrophysics has difficulty producing sharp line features (but it is not impossible)
- Generically, we expect two or more lines, with energies related to one another by the WIMP mass and the Z and/or Higgs masses.
- Amazingly, we see an interesting feature in the Fermi LAT data which might even be the first hints of such a feature emerging.
  - More study is needed to confirm...
  - If this feature is indeed dark matter annihilating, it is pointing us away from vanilla WIMPs toward theories where the line is enhanced with respect to tree level annihilation into the continuum.

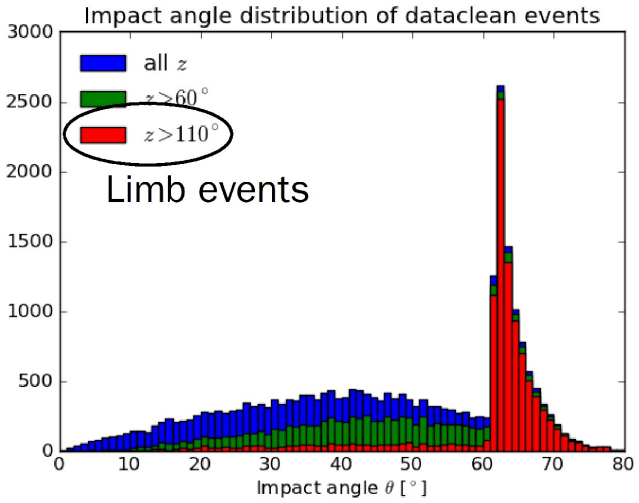
Bonus Material

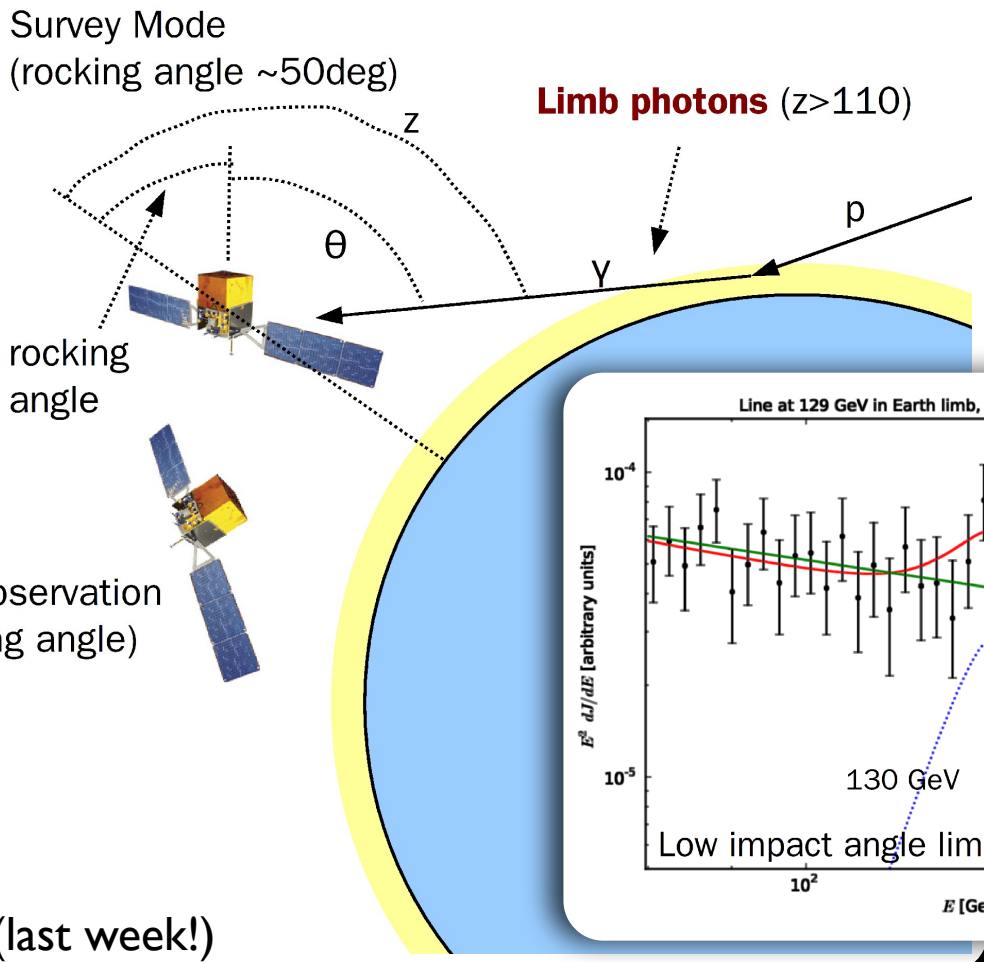


Su, Finkbeiner
1206.1616

Earth Limb Photons?

The Earth limb/albedo as test sample



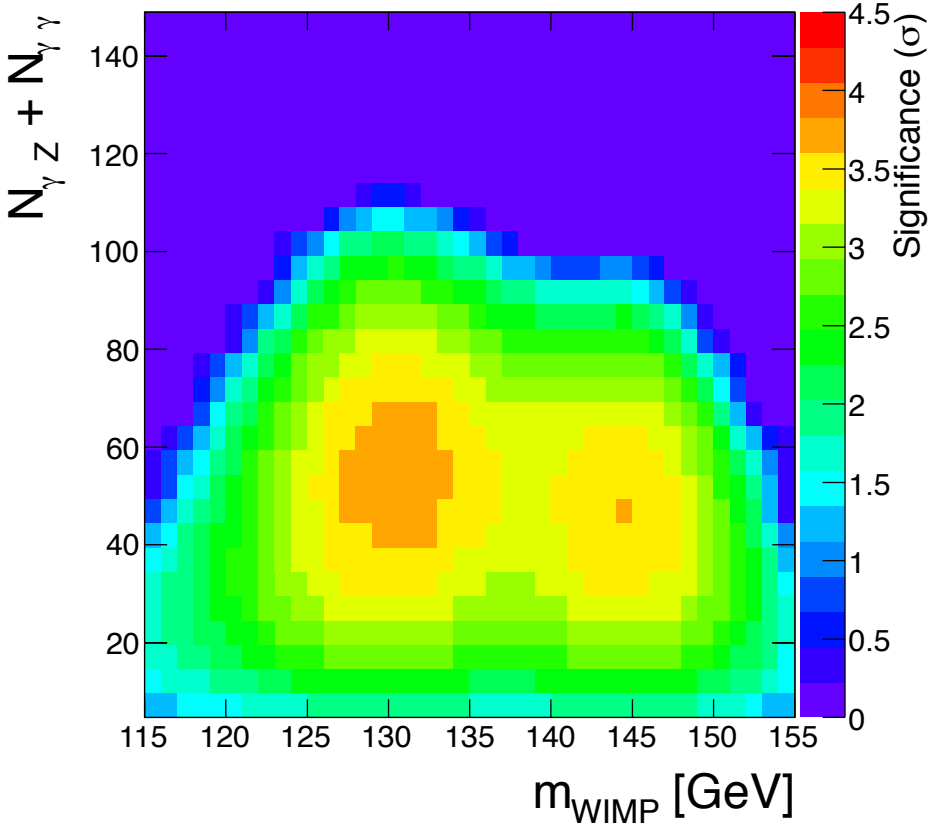


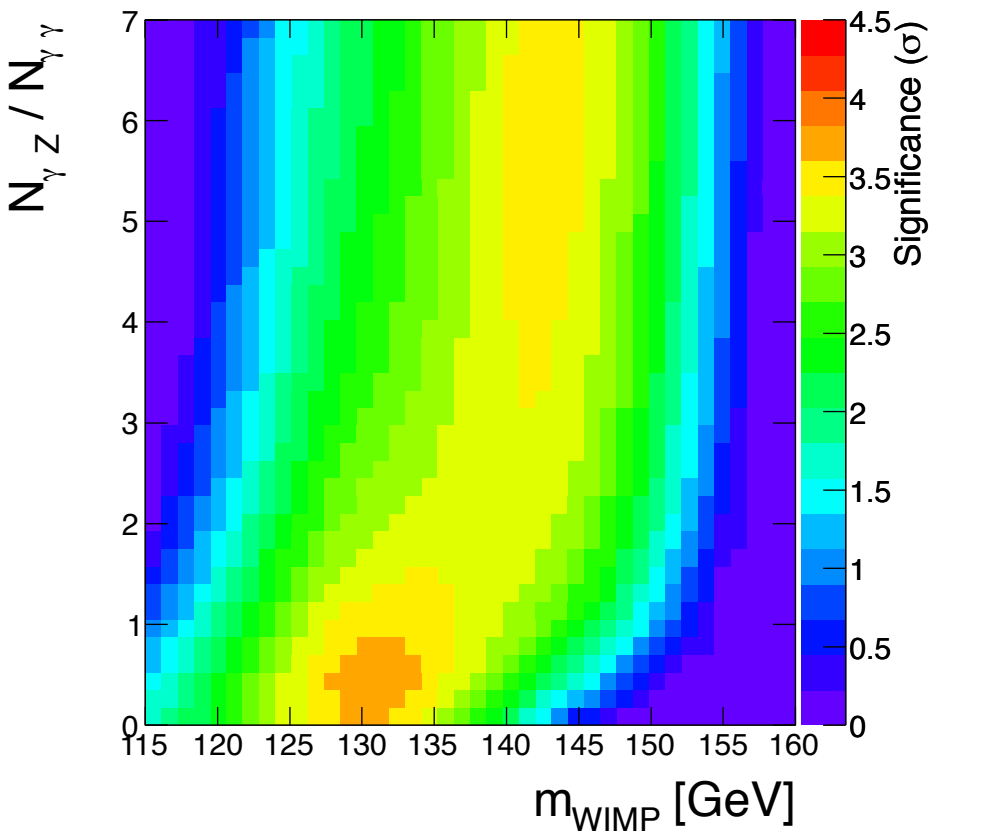
Target-of-opportunity observation
(potentially large rocking angle)

Slide from C. Weniger, IDM Chicago (last week!)

Uh oh...?

Region 3 is Similar





Rajaraman, Tait, Whiteson, 1205.4723

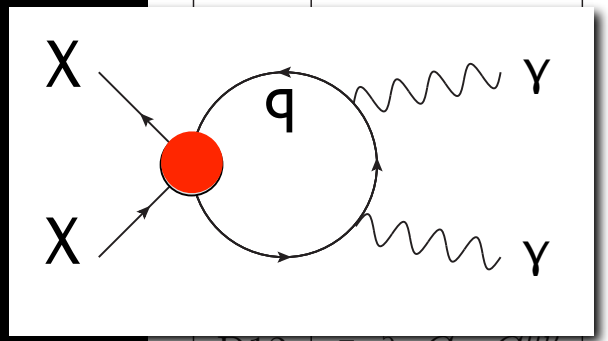
See also: Cohen, Lisanti, Slatyer, Wacker, 1207.0800

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.

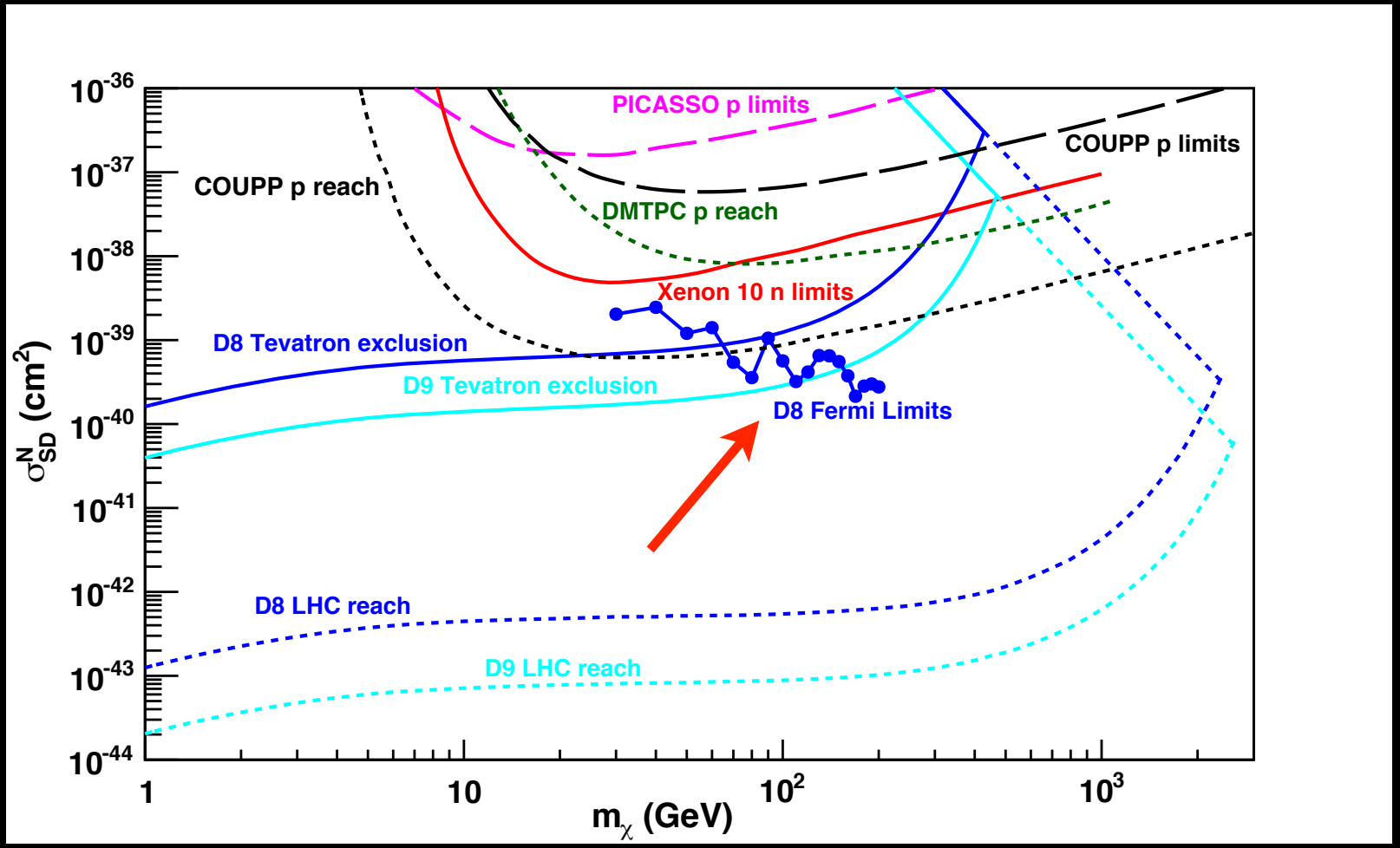
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
		$1/M_*^2$
		$1/M_*^2$
		i/M_*^2
		$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
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

Axial vector interaction of a Dirac WIMP



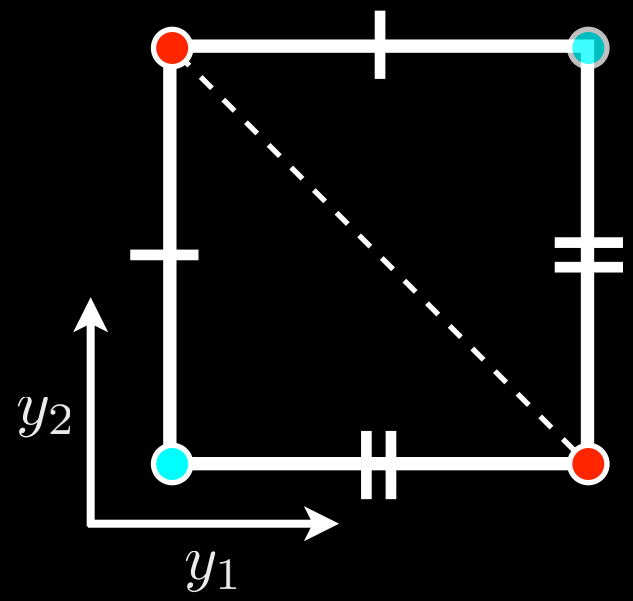
Goodman, Ibe, Rajaraman, Shepherd, TT, Yu [1009.0008] & NPB

Example: The Chiral Square

- The Chiral Square is a UED theory with two extra dimensions.
- 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

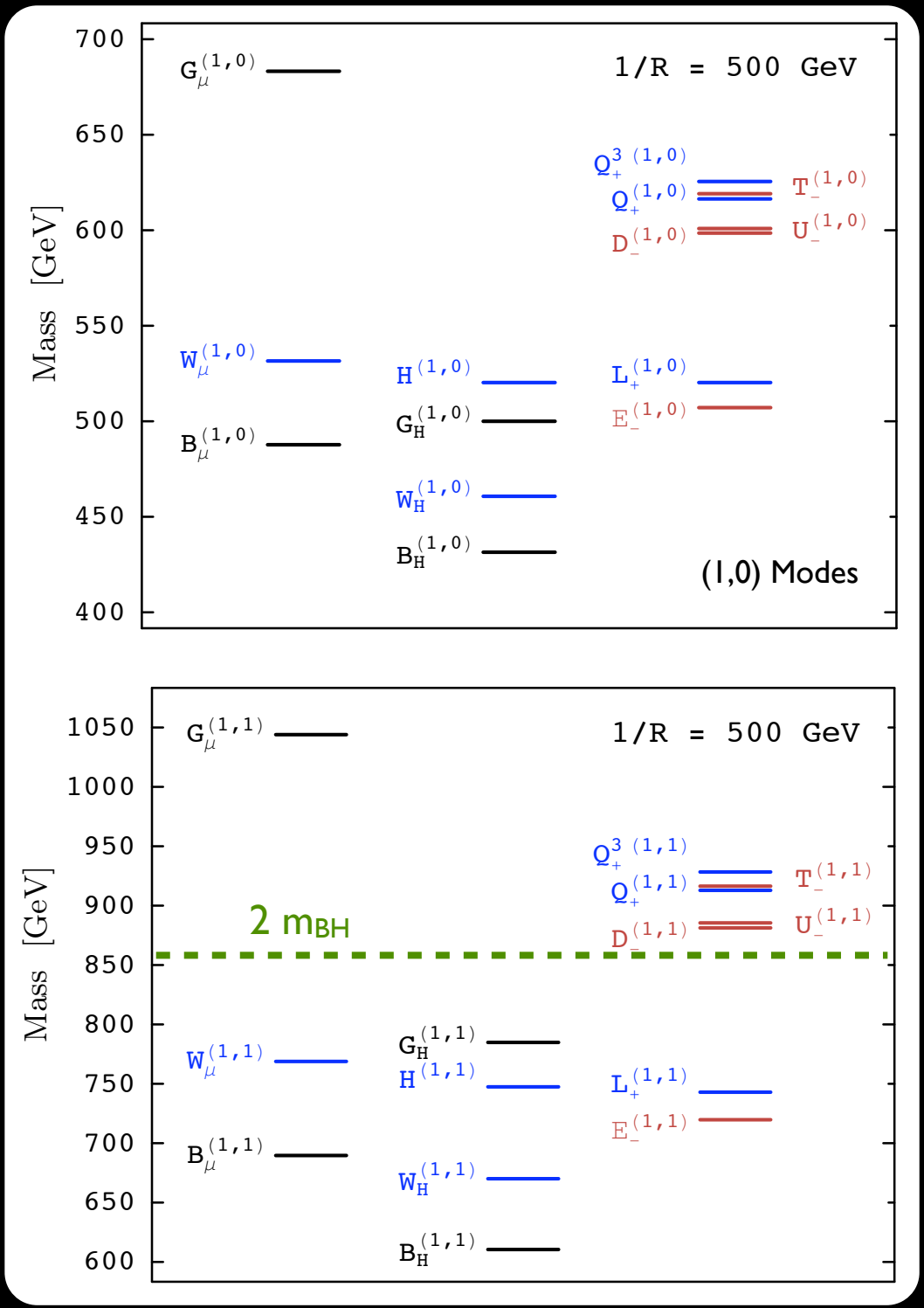
Burdman, Dobrescu, Ponton '04, '05



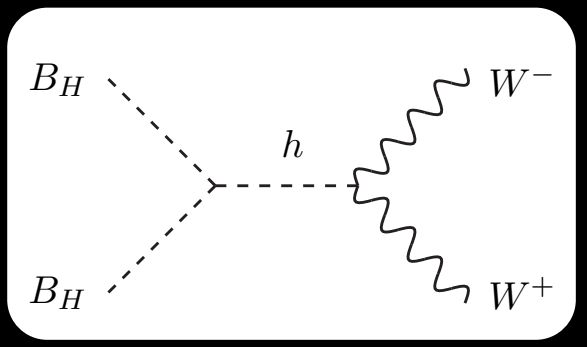
KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

Spectrum

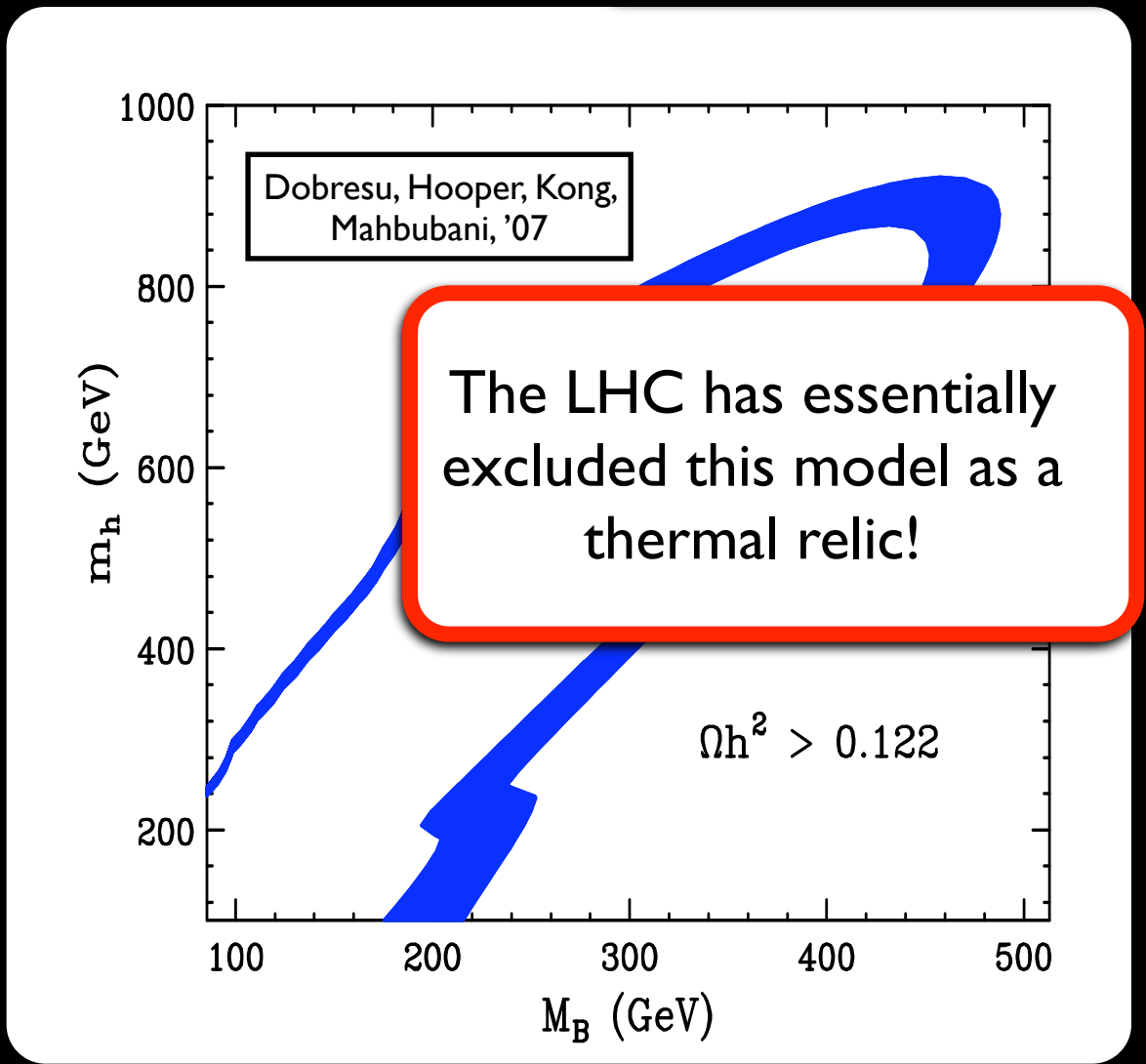
- The boundary terms modify the masses of the fields at a given (j,k) level. They control the systematics of the spectrum of states.
  - The LKP is usually the scalar (1,0) KK mode of the Hypercharge gauge boson, B_H.



Relic Density

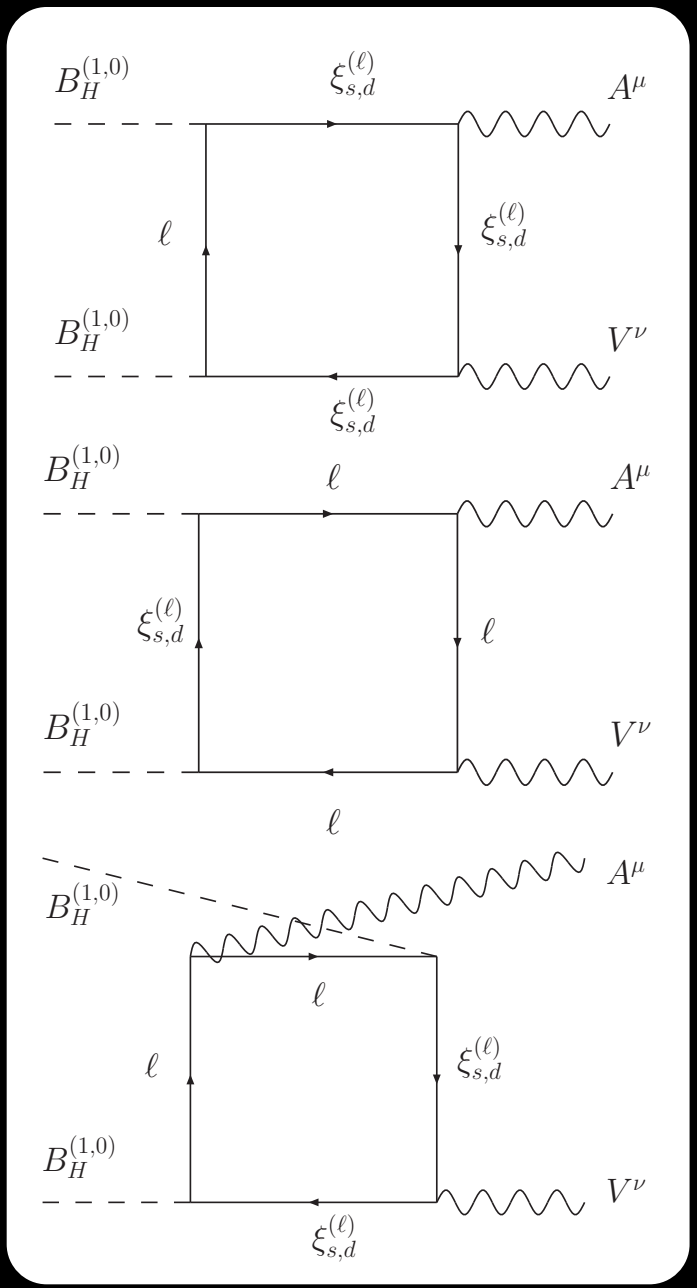


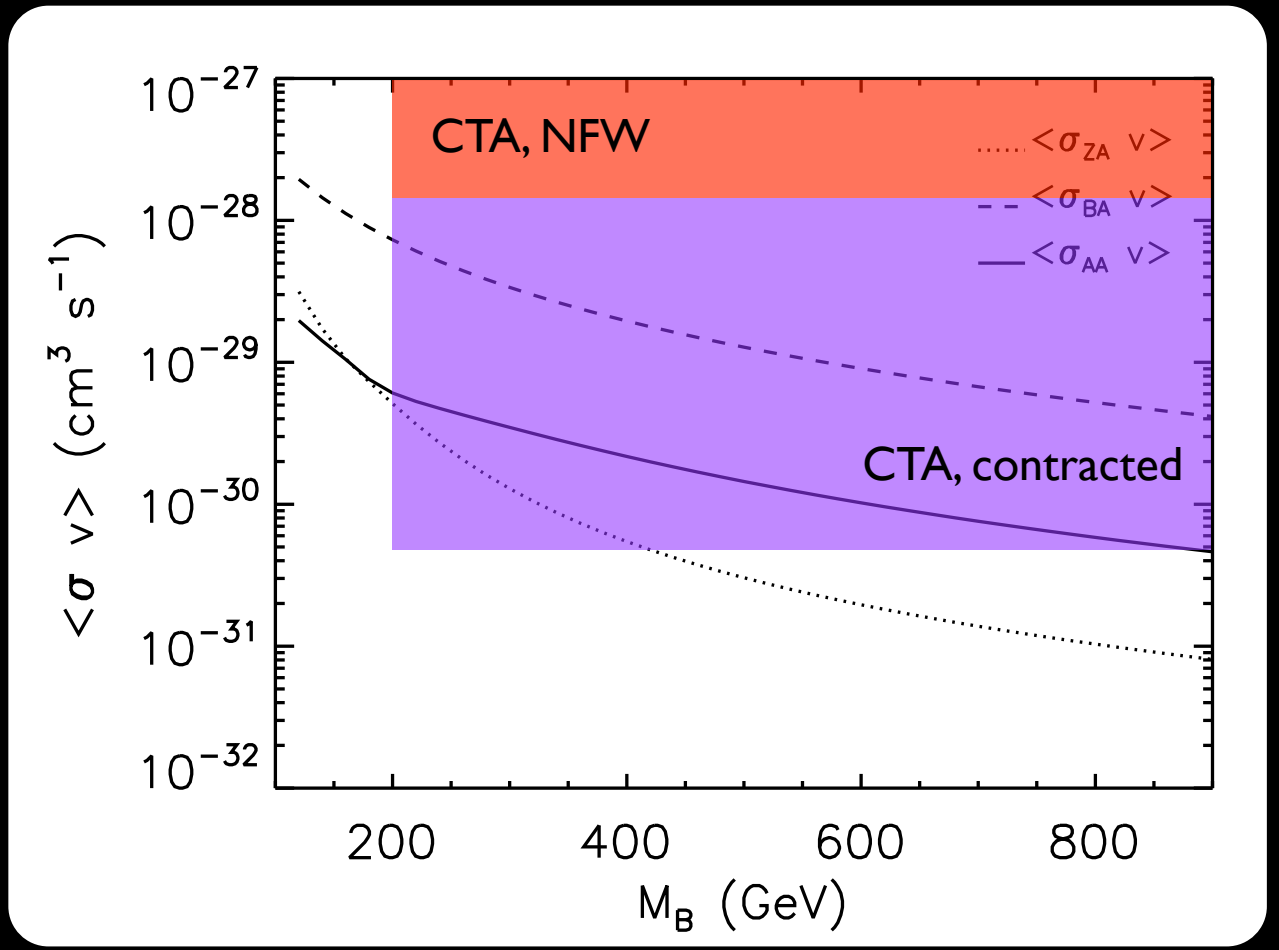
- Annihilation typically goes through an s-channel SM Higgs boson.
- Generally, the relic density favors LKP masses between 100 - about 500 GeV, provided the Higgs mass is chosen to match.
- This model might be salvageable as a thermal relic by using the level (1,1) or (2,0) Higgs modes as the resonance,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



Gamma Ray Lines

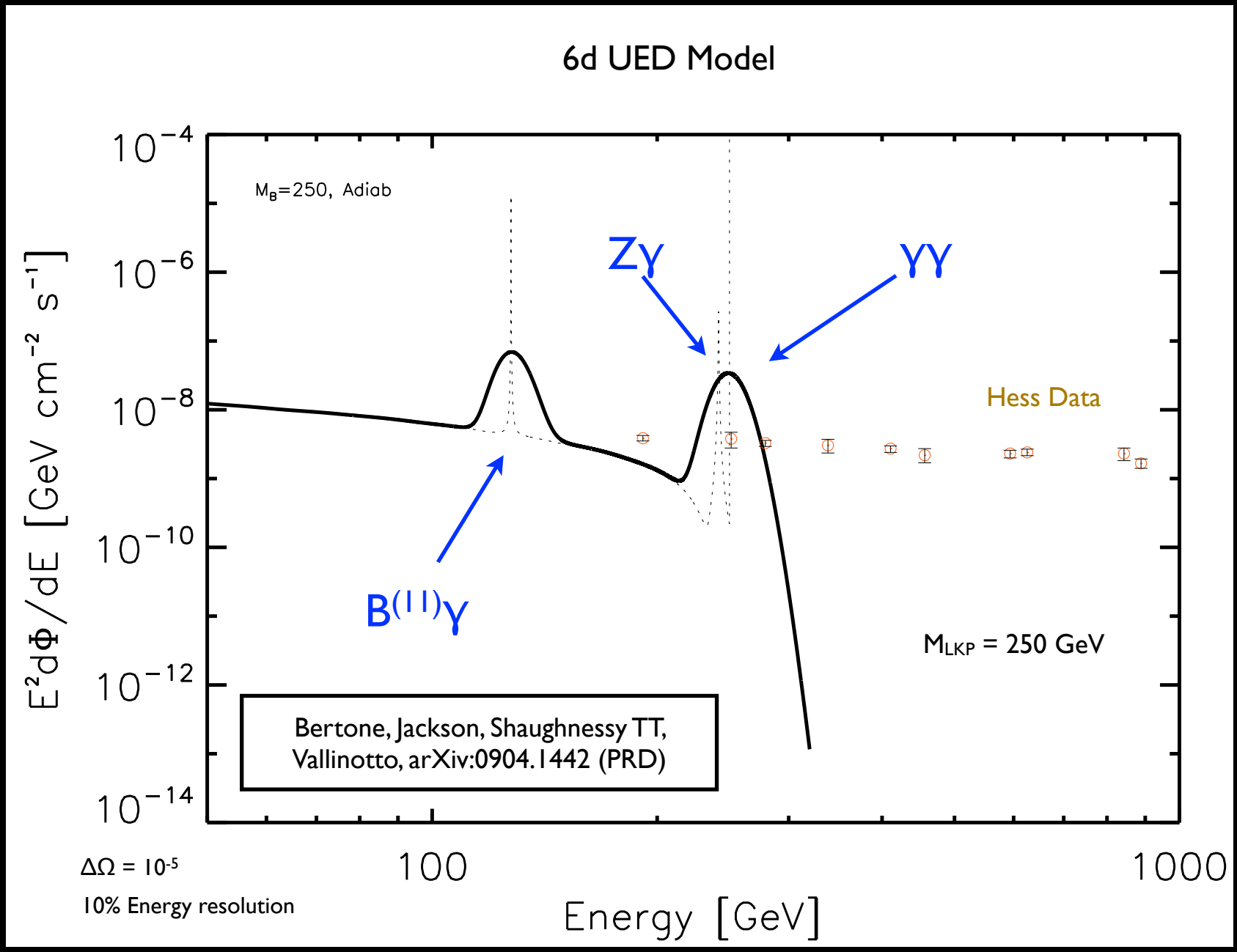
Bertone, Jackson, Shaughnessy, TT, Vallinotto, [0904.1442] (& PRD)





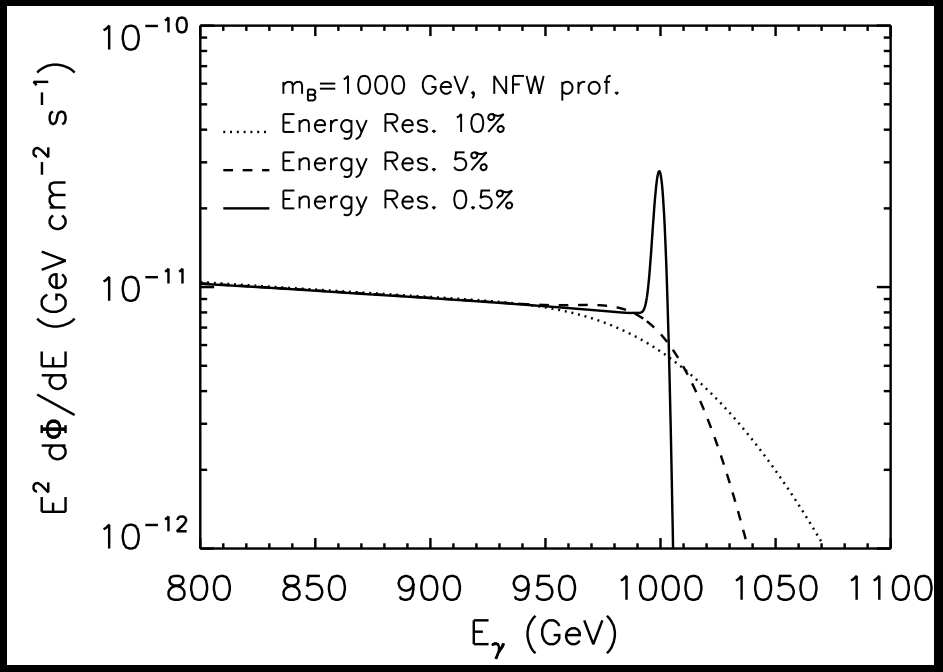
KK masses inspired by minimal boundary terms: (1,0) lepton modes are about 20% heavier than the LKP.

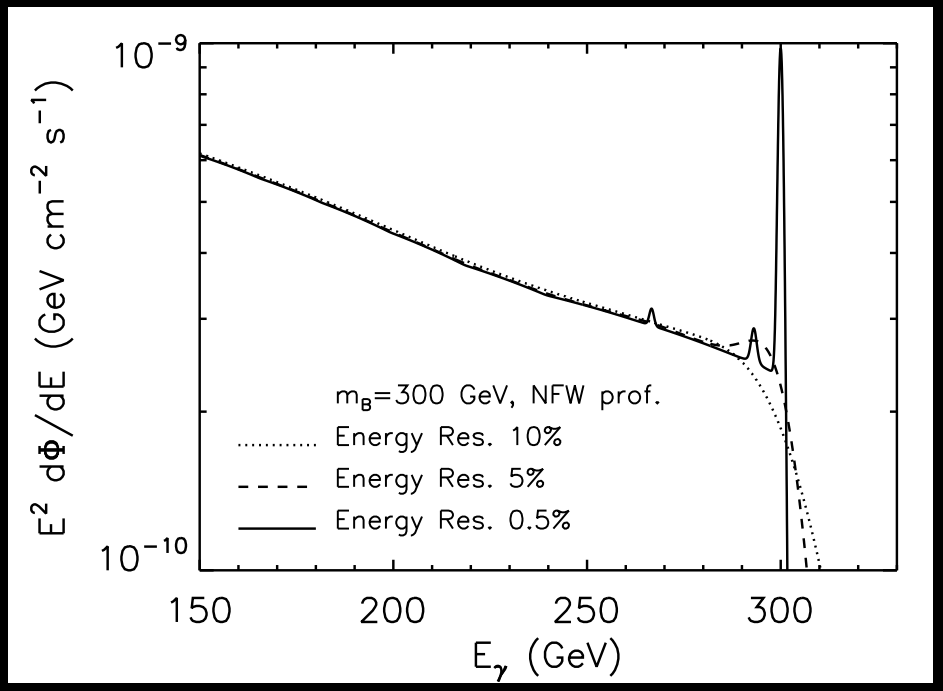
Lines of the Chiral Square



Contrasting with 5d UED

- The 5d theory has a large continuum because the LKP likes to annihilate into e^+e^-.
- There are $\gamma\gamma$, γZ, and γ Higgs lines.
  - $\gamma\gamma$ 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)]