HIGGS IN SPACE!

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Preface

- Yes, this is a Dark Matter talk.
- No, it’s not a talk on PAMELA/ATIC
- My apologies...
- However, ...

BSM + Astro + Loops = Fun!

Outline

- Indirect detection of dark matter from γ rays... from spectral lines!

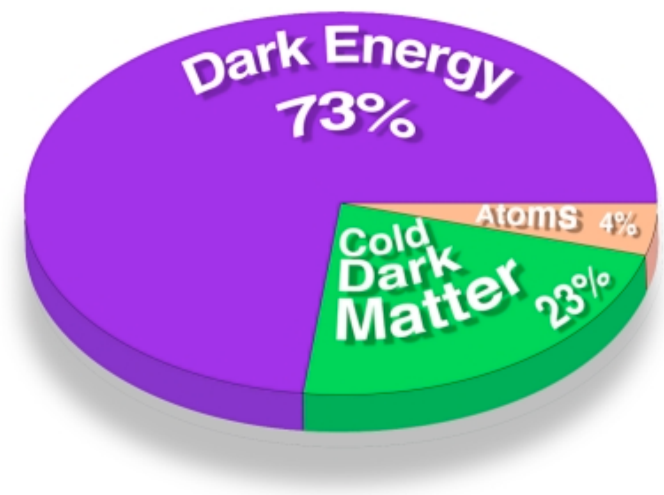
- Past results:
    - SUSY
    - Inert Doublet Model
    - A “WIMP Forest” from Universal Extra Dimensions(?)

- Higgs in Space!
    - Dark matter - top quark connection?
    - Signals of a Higgs from γ rays

- Conclude/Outlook

The WIMP Miracle and a Dark Sector(?)

- Over 20 percent of the Universe is made up of non-luminous “stuff” (dark matter)



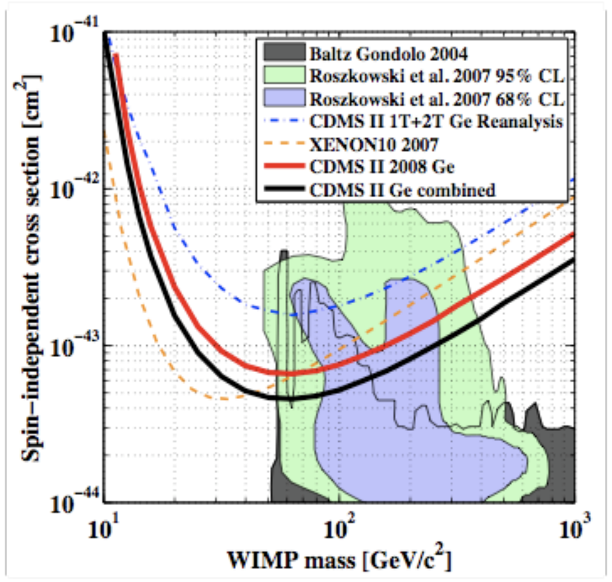
Source: Robert Kirshner
Source: NASA/WMAP Science Team

- If DM is a thermal relic, we know that electroweak-scale masses/couplings can correctly reproduce the measured relic abundance (“WIMP Miracle”)

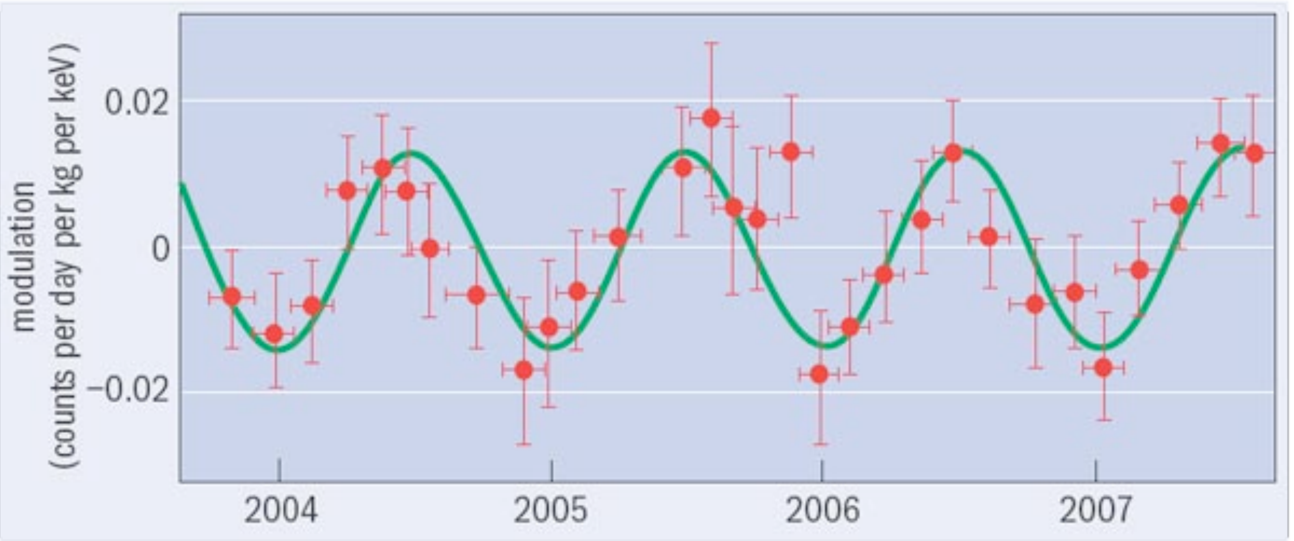
- Most (serious) models which contain WIMP candidates do so as a by-product
  - WIMP = lightest stable particle which interacts with a “dark sector”
  - In our search/discovery of DM, might we also discover evidence for this “dark sector”?
  - More later...

Direct and Collider Searches for DM

CDMS

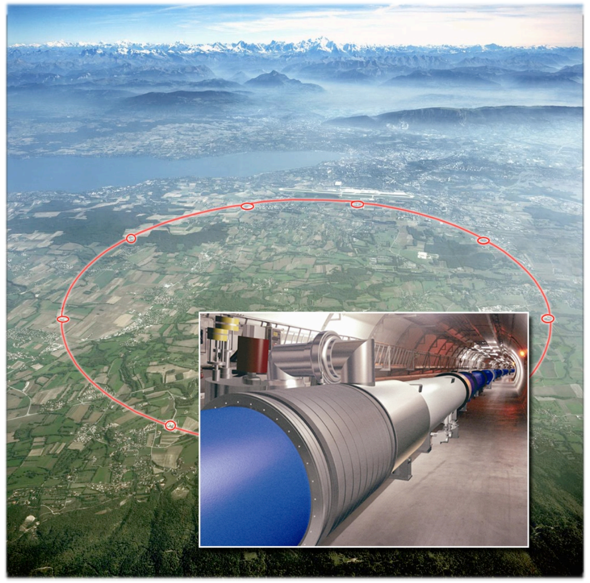


DAMA



Tevatron

LHC



A word from Carlos...

A word from Carlos...

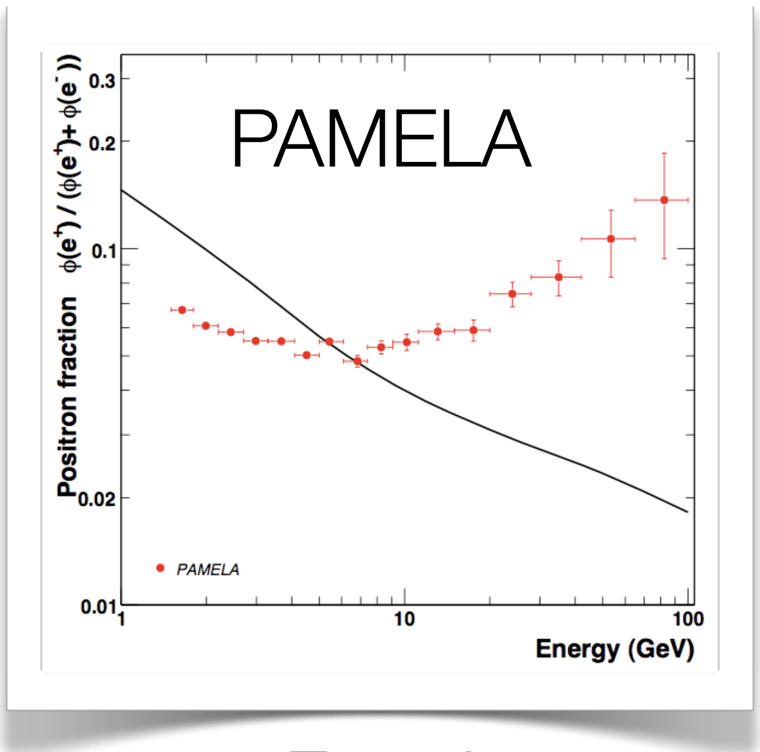
“Did you know that, last year, the LHC achieved the highest collisions ever?”

A word from Carlos...

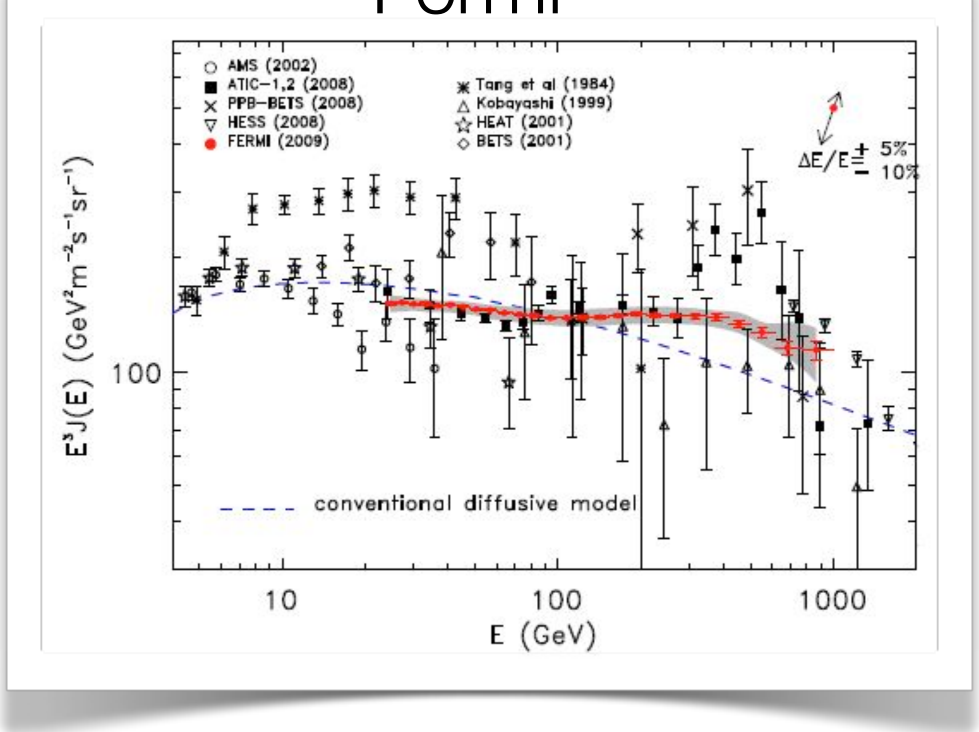
“Did you know that, last year, the LHC achieved the highest collisions ever?”

“Yes, but unfortunately, the collisions were between two magnets and not two protons.”

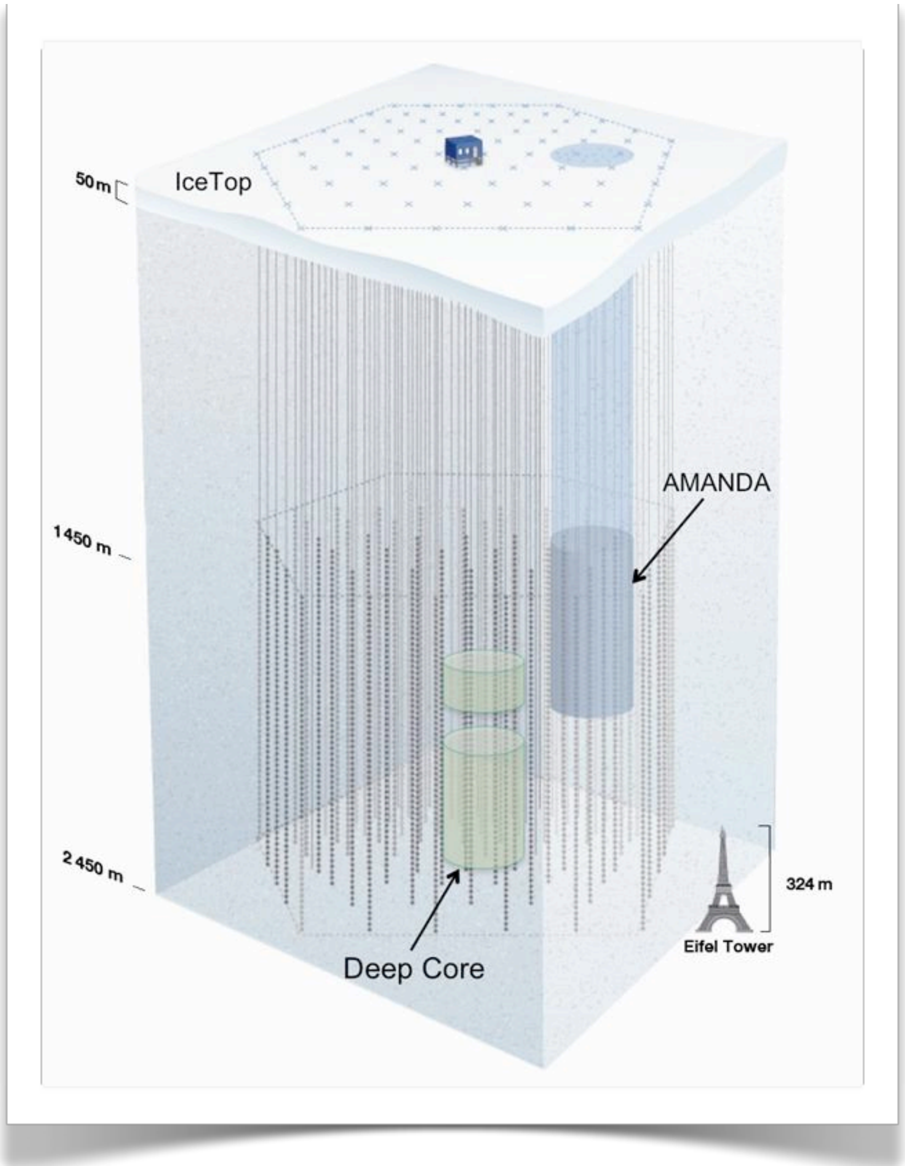
Indirect Searches for Dark Matter



Fermi



IceCube

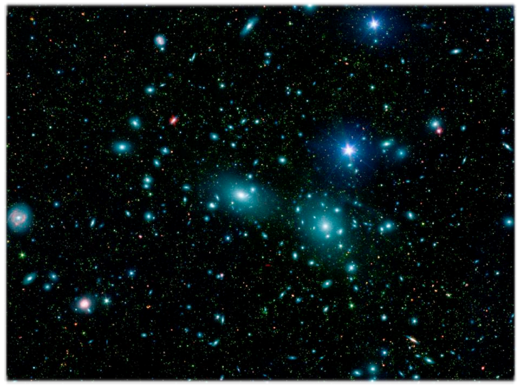


Seeing the light... from Dark Matter

- WIMP annihilations also produce photons!
  - Through charged SM particles which then radiate or hadronize/decay
  - Direct (through loops) annihilation
- Expected flux:

$$\phi_{WIMP}(E,\psi) = \frac{1}{2}\frac{<\sigma v>}{4\pi}\sum_f \frac{dN_f}{dE}B_f \int_{\rm l.o.s} dl(\psi)\frac{\rho(l)^2}{m_{WIMP}^2}$$

- Searches typically focus on regions of the sky where we expect Dark Matter to “clump” (e.g., “towards” the GC, dwarf galaxies, etc.)

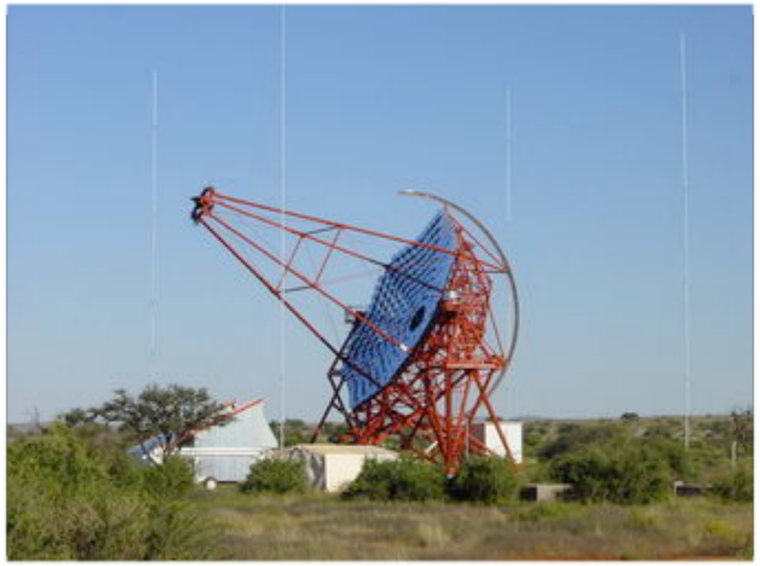


Searching for the light

Fermi Space Telescope

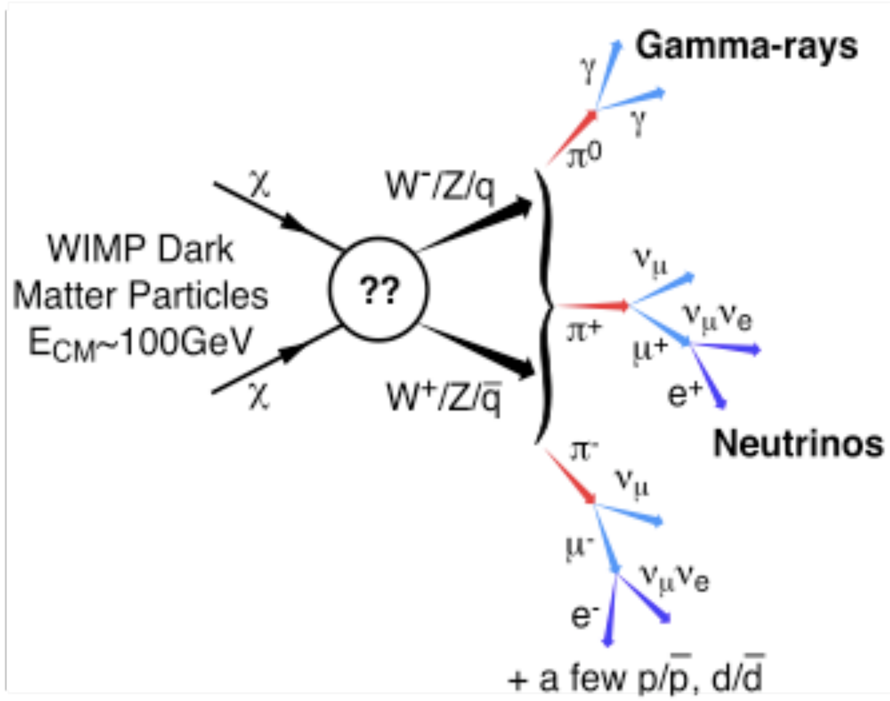
- Scans entire sky
- LAT sensitive up to 100's GeV
- $\Delta E/E \sim 10\%$
- See arXiv:0806.2911

Air Cerenkov Telescopes



- Observes small sections of the sky
- Most sensitive to TeV scales
- $\Delta E/E \sim 15 - 20\ \%$

The Continuum

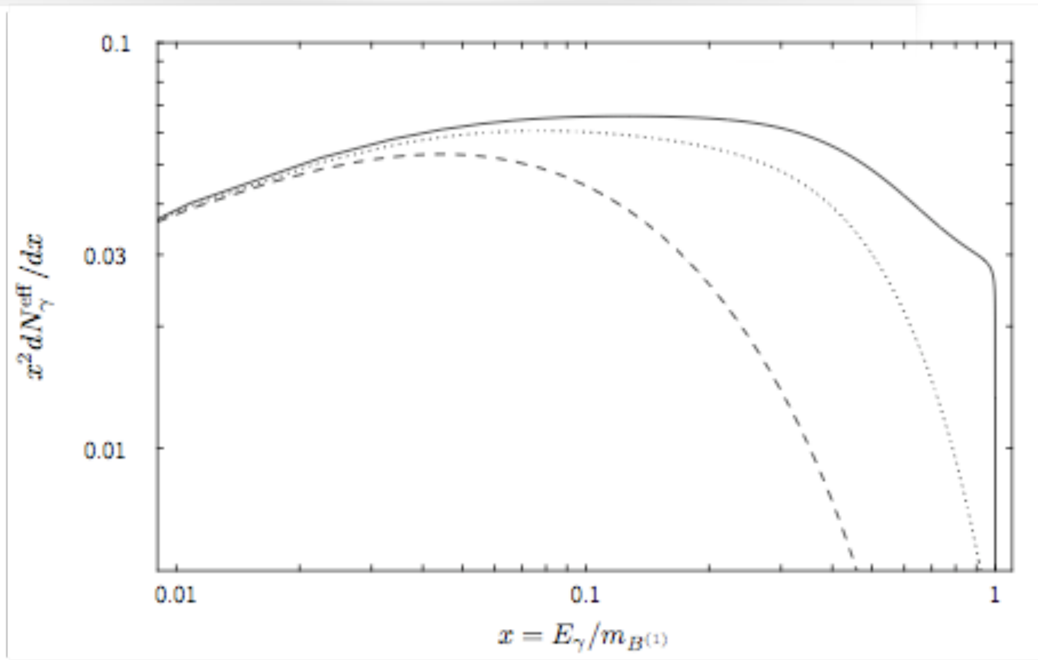


- Annihilation into charged SM particles
- Light quark hadronization ($\pi^0 \rightarrow \gamma\gamma$)
- Final-state radiation:

$$\frac{dN_{X\bar{X}}}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right)$$

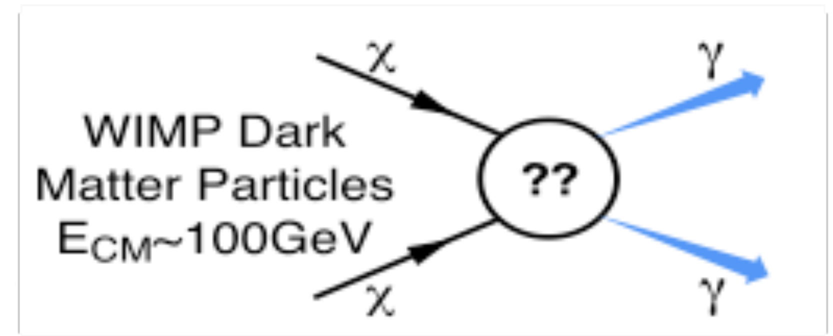
($\sqrt{s} \simeq 2M_{WIMP}$)

($x = E_\gamma / M_{WIMP}$)



- $\pi^0 \rightarrow \gamma\gamma$: featureless and soft
- FSR: harder spectrum w/ a sharp cutoff at WIMP mass
- Results from PYTHIA (If you've seen one spectrum...)

Spectral Lines



- Loop-induced annihilation into γ + X final states
- Suppressed... but a "smoking gun" compared to astro. backgrounds
- For a γ + X final, photons emitted mono-energetically:

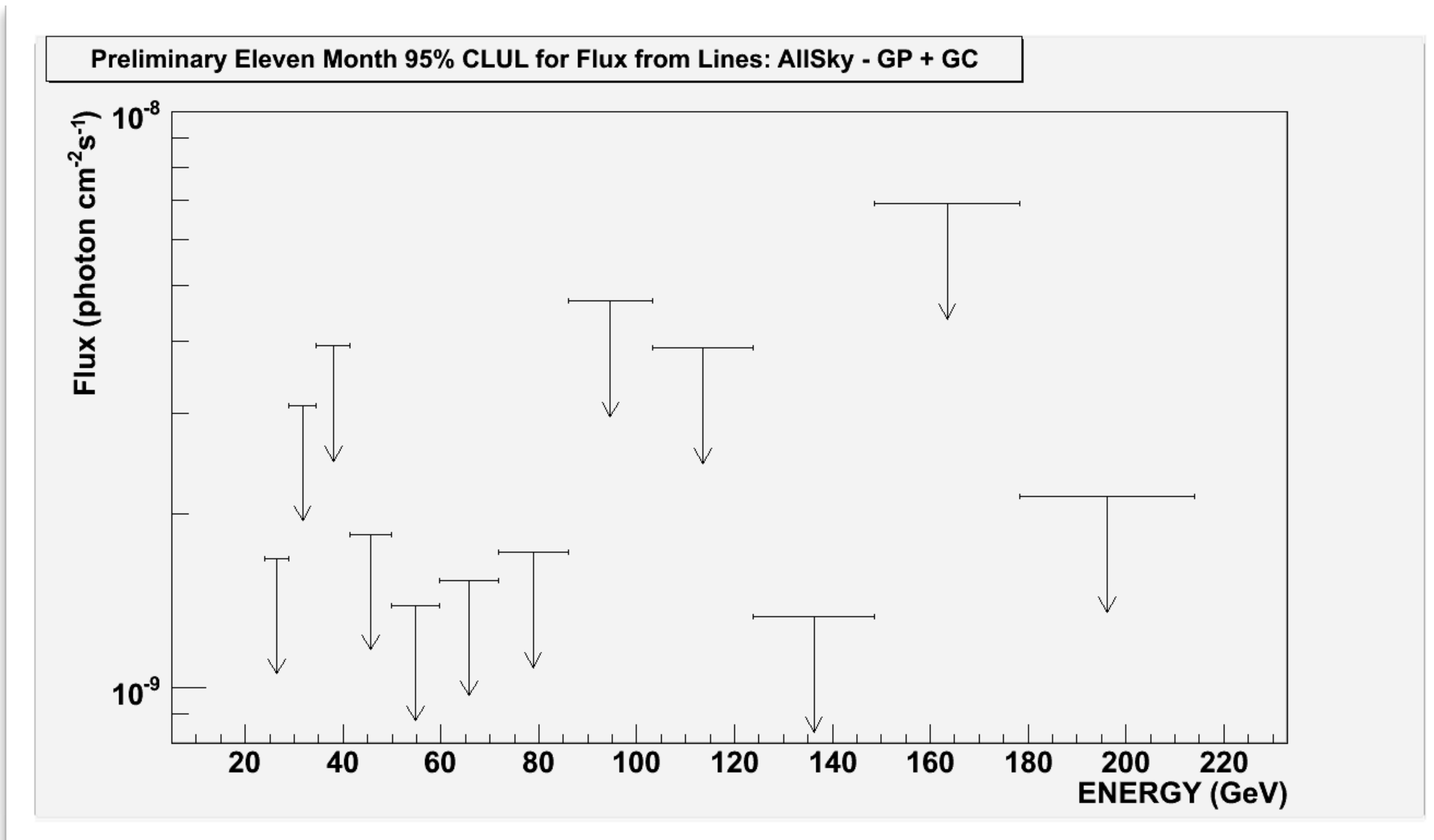
$$E_\gamma = m_{DM}\left(1 - \frac{M_X^2}{4m_{DM}^2}\right)$$

(from phase space)

  - γγ line: precise determination of WIMP mass
  - $M_X \sim M_{WIMP}$: multiple AND distinct lines!
- Lines contain a wealth of information:
  - DM Spin: vector "X" can be produced by all types of DM, but scalar "X" can only be produced by vector or Dirac fermion Dark matter
  - γγ vs. Zγ: $SU(2)_L$ couplings of WIMP to SM singlets/doublets

Early Results from Fermi...

- See recent talks by S. Murgia and Y. Edmonds at TeV PA meeting



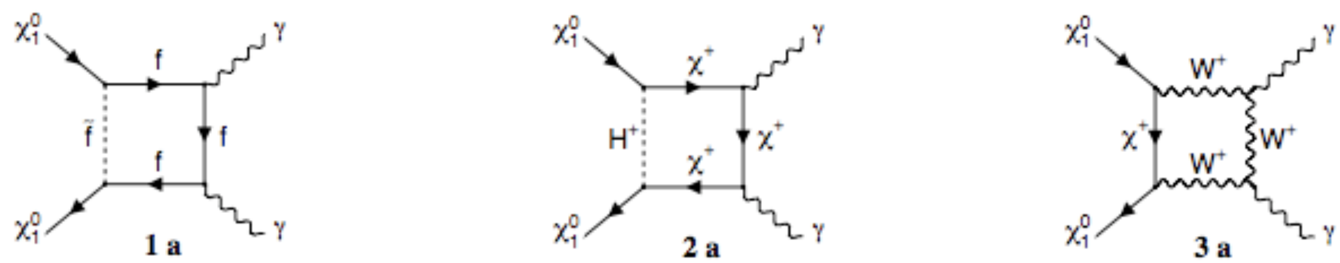
(from Y. Edmonds, TeV PA meeting)

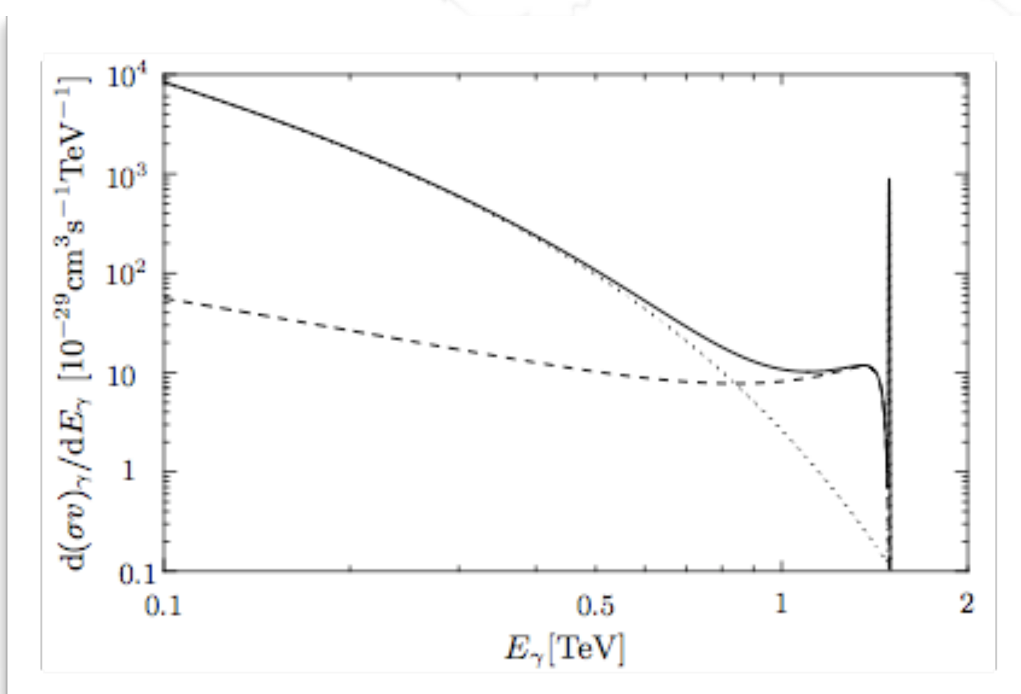
- Results from 1st year of data expected soon!

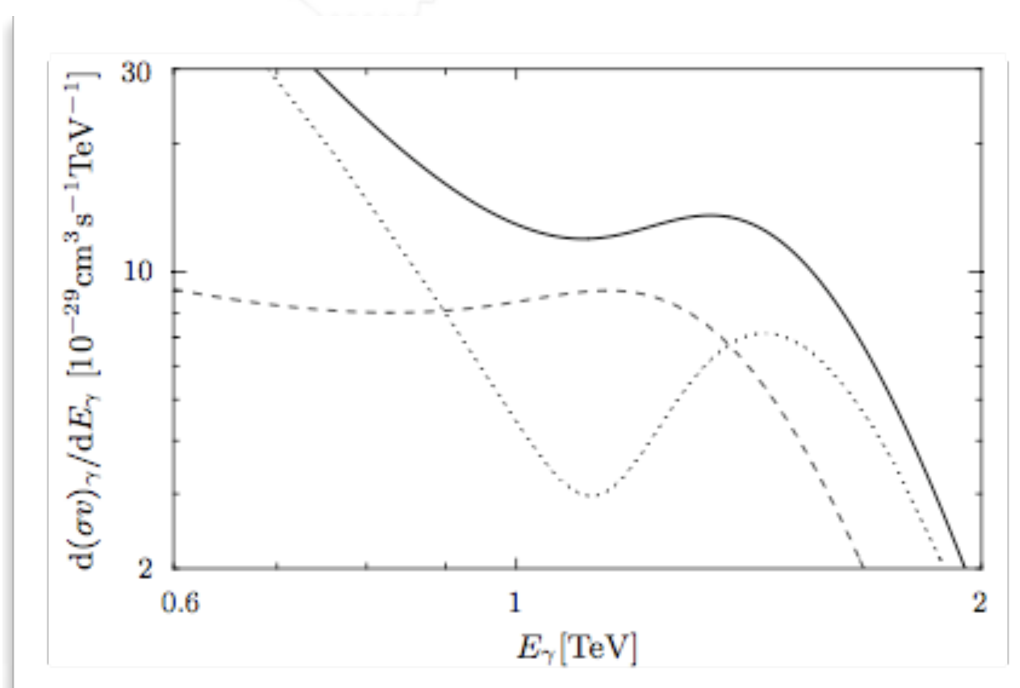
Results from past studies...

Lines from SUSY (e.g., see series of papers by L. Bergstrom et al.)

- Majorana nature of WIMP implies two things:
  - Continuum suppressed (light fermion final states chirally-suppressed)
  - Only possible “lines”: γγ and Z γ

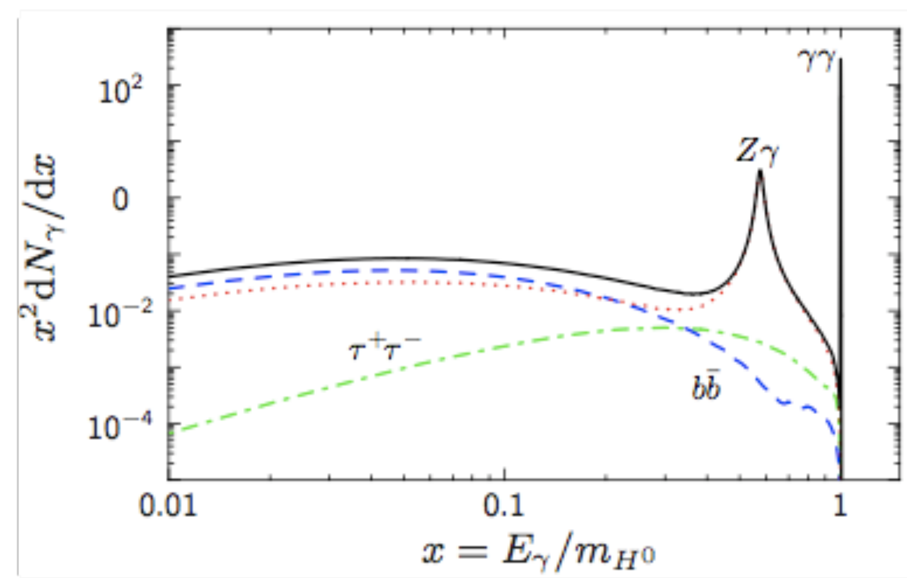


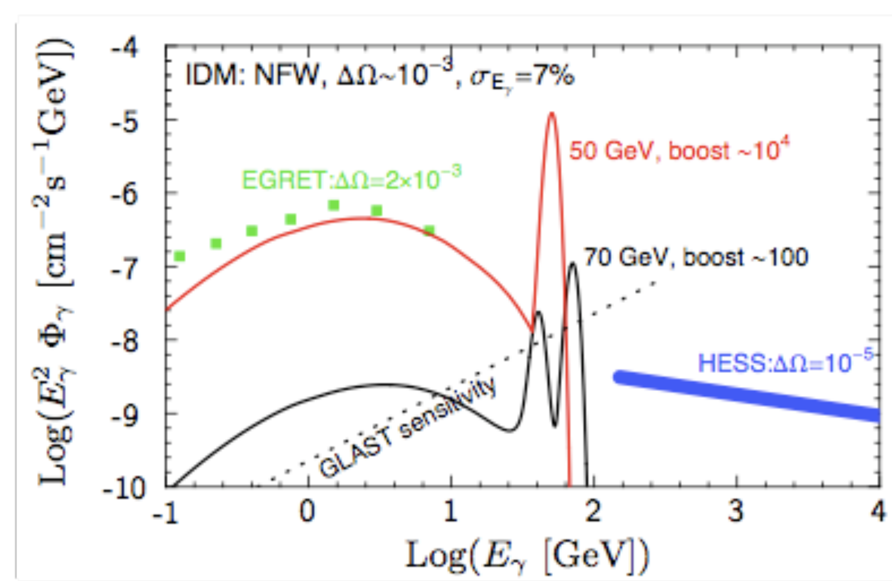




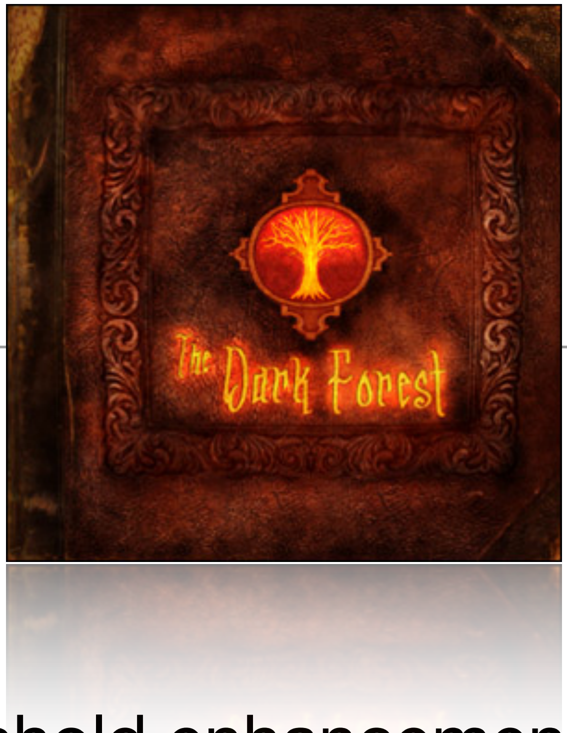
Lines from an "Inert" Higgs (Gustaffson et al., PRL99:041301 (2007))

- Add a 2nd Higgs doublet to SM w/ additional Z_2 symmetry
- Scalar WIMP:
  - (Chirally-) suppressed continuum
  - Only γγ and Zγ lines possible
- Relic density: $M_{DM} \sim M_W$
- Annihilations mainly through loops of W's
  - Virtual W's are nearly on-shell
  - Threshold enhancements!
- Extremely pronounced peak(s)!!!
  (Beware: line-shapes VERY sensitive to
  detector resolutions!)





A Dark Forest?



- Ingredients for a successful line search:
  - Suppression of continuum
  - Loop-annihilation via “largish” couplings and/or threshold enhancements
  - For good separation between lines, you need $M_X \sim M_{WIMP}$ (detector res.)
- What if there are other particles in the “dark sector” with appreciable masses compared to the WIMP mass (but $< 2M_{WIMP}$)?

- A series of lines...
  or a “WIMP Forest”!!!
- Dark matter spectroscopy?

Universal Extra Dimensions (Appelquist, Cheng & Dobrescu)

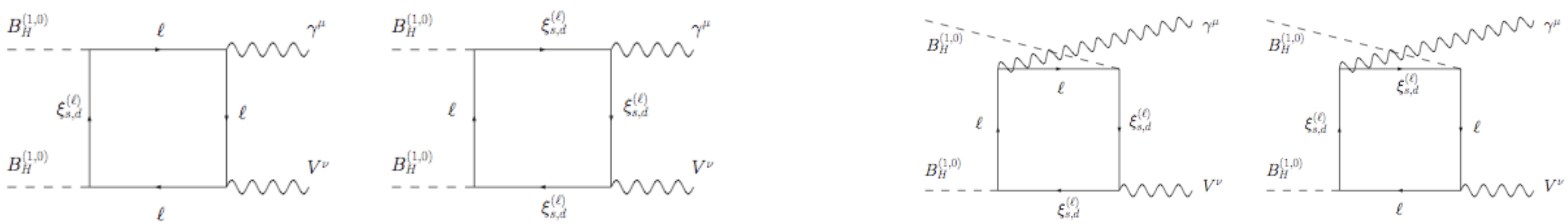
- ALL SM fields propagate in flat extra dimension(s)
- KK parity → stable WIMP candidate (LKP)

	5-d	6-d
Compactification	Line	Square
KK Masses	$m^{(n)} = \sqrt{(n/R)^2 + m_{\rm EW}^2}$	$M_{(j,k)}^2 = M_0^2 + \pi^2 \frac{j^2+k^2}{L^2}$
WIMP candidate	Vector ($B^{(1)}$)	Scalar (B_H)
Preferred WIMP mass	≈ 0.5 - 1 TeV	≈ 200 - 500 GeV
γ+X final states	γγ, γZ & γH	γγ, γZ & γ$B^{(1,1)}$

G. Bertone, CJ, G. Shaughnessy, T. Tait
and A. Vallinotto
5-d in preparation
6-d, PRD80, 023512 (2009)

The γ-ray Flux from UEDs

- Use micrOMEGAs to compute continuum
- Annihilation to γ+V final states, proceeds via box diagrams:



- The amplitude:

$$\mathcal{M} = \epsilon_A^{\mu *}(p_A)\epsilon_B^{\nu *}(p_B)\mathcal{M}^{\mu\nu}(p_1, p_2, p_A, p_B) \longrightarrow$$

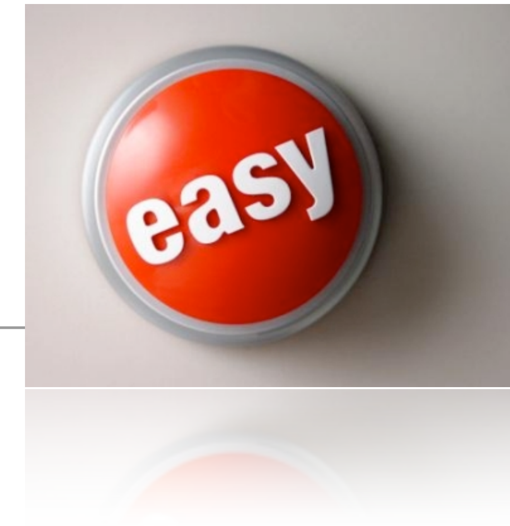
$$\begin{aligned}\mathcal{M}^{\mu\nu} &= A_1\, g^{\mu\nu} + B_1\, p_1^\mu p_1^\nu + B_2\, p_2^\mu p_2^\nu + B_3\, p_1^\mu p_2^\nu \\ &+ B_4\, p_1^\nu p_2^\mu + B_5\, p_A^\nu p_B^\mu + B_6\, p_1^\mu p_A^\nu + B_7\, p_1^\nu p_B^\mu \\ &+ B_8\, p_2^\mu p_A^\nu + B_9\, p_2^\nu p_B^\mu\,.\end{aligned}$$

- Tricks:
  - WIMPs are non-relativistic
  - Cons. of momentum ⟶
  - Choosing the z-axis

A$_1$ is the dominant term

- For details of 5-d γγ calculation, see Bergstrom et al., hep-ph/0412001

Nothing's ever easy



- NR nature of WIMPs causes havoc in loops
- Passarino-Veltman tensor integral coefficients depend INVERSELY on Gram Determinant (GD):

$$\mathrm{GD} = \det(p_i \cdot p_j)$$

- Implemented a technique developed by R. Stuart (Comput. Phys. Commun. 48, 367 (1988))
- Based on extension of usual P-V formalism... assuming the "usual" GD vanishes:

$$\begin{aligned} D_{27} &= \alpha_{123} C_{24}(123) + \alpha_{124} C_{24}(124) \\ &+ \alpha_{134} C_{24}(134) + \alpha_{234} C_{24}(234)\,, \end{aligned}$$

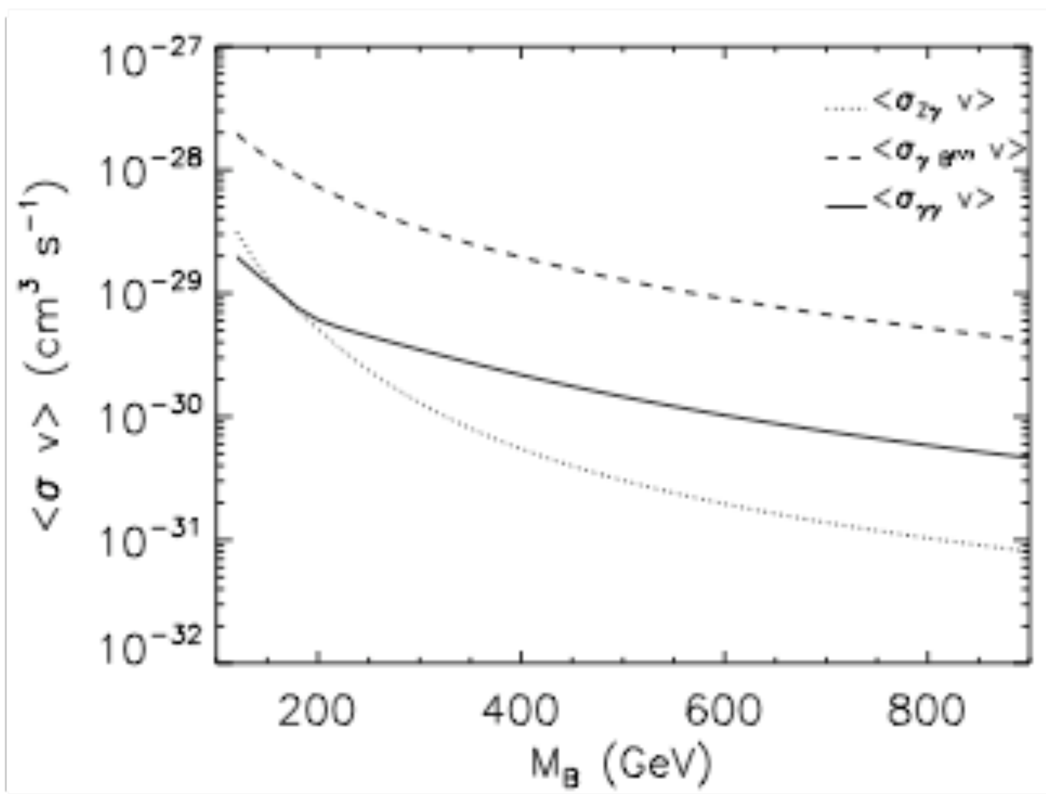
$$\downarrow$$

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & p_1^2 & (p_1^2 - p_2^2 + p_5^2)/2 & (p_1^2 + p_4^2 - p_6^2)/2 \\ 0 & (-p_1^2 - p_2^2 + p_5^2)/2 & (-p_1^2 + p_2^2 + p_5^2)/2 & (-p_1^2 - p_3^2 + p_5^2 + p_6^2)/2 \\ -m_1^2 & p_1^2 - m_2^2 & p_5^2 - m_3^2 & p_4^2 - m_4^2 \end{pmatrix} \begin{pmatrix} \alpha_{234} \\ \alpha_{134} \\ \alpha_{124} \\ \alpha_{123} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Line Cross sections

Summing over 24 diagrams...

$$
\begin{aligned}
A_1^{(\ell)} \;=\; & -\alpha_Y \alpha_{em} Q_\ell^2 (Y_L^2 + Y_R^2) \Big\{ 2 + \frac{2}{1-\eta} B_0(M_{B_H}^2; M_L^2, 0) - B_0(4M_{B_H}^2; 0, 0) - \frac{1+\eta}{1-\eta} B_0(4M_{B_H}^2; M_L^2, M_L^2) \\
& + M_{B_H}^2 \Big[-(1+\eta)(C_0(M_{B_H}^2, 4M_{B_H}^2, M_{B_H}^2; M_L^2, 0, 0) + C_0(M_{B_H}^2, 4M_{B_H}^2, M_{B_H}^2; 0, M_L^2, M_L^2)) \\
& - 2C_0(M_{B_H}^2, 0, M_{B_H}^2; 0, M_L^2, M_L^2) + 4\eta C_0(0, 0, 4M_{B_H}^2; M_L^2, M_L^2, M_L^2) \Big] \Big\}, \qquad (13)
\end{aligned}
$$



- Threshold enhancements!
- Significant cancellations in $\gamma\gamma$ and γZ amplitudes
- $B^{(1,1)}$ has loop suppressed couplings to SM fermions... less cancellation!
- Enhanced $\gamma B^{(1,1)}$ cross sections

Known unknowns

- Largest uncertainties due to ignorance of DM distributions

$$J \equiv \int_{\mathrm{l.o.s.}} \frac{ds}{r_\odot} \left[\frac{\rho[r(s,\psi)]}{\rho_\odot}\right]^2$$

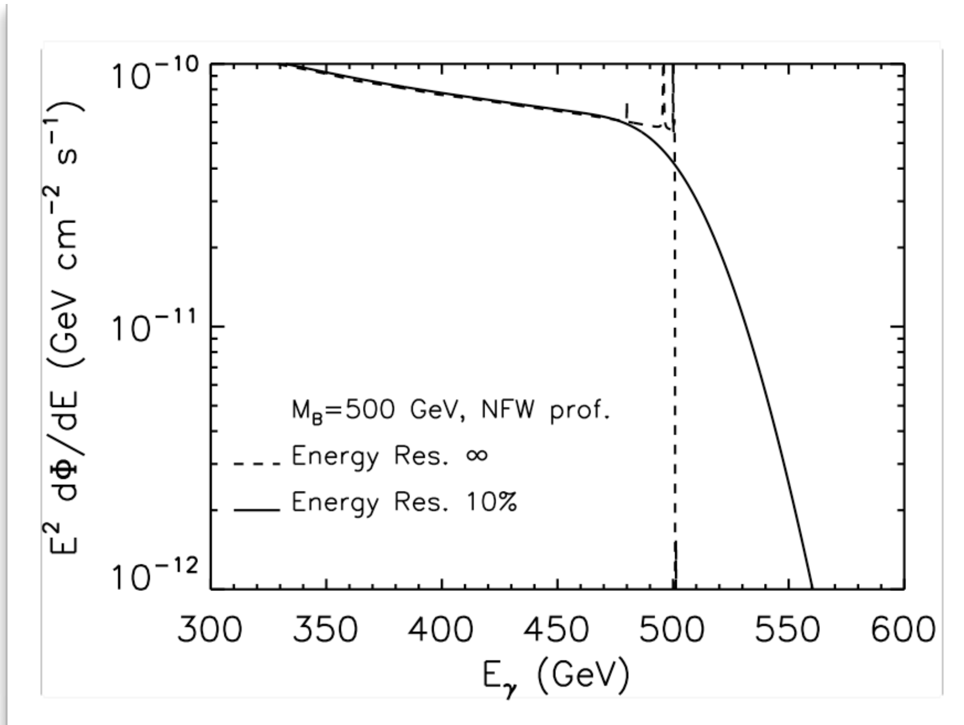
- Two “benchmarks”:
  - Navarro-Frenk-White (NFW)
  - “Adiabatic”: include baryons in DM simulations

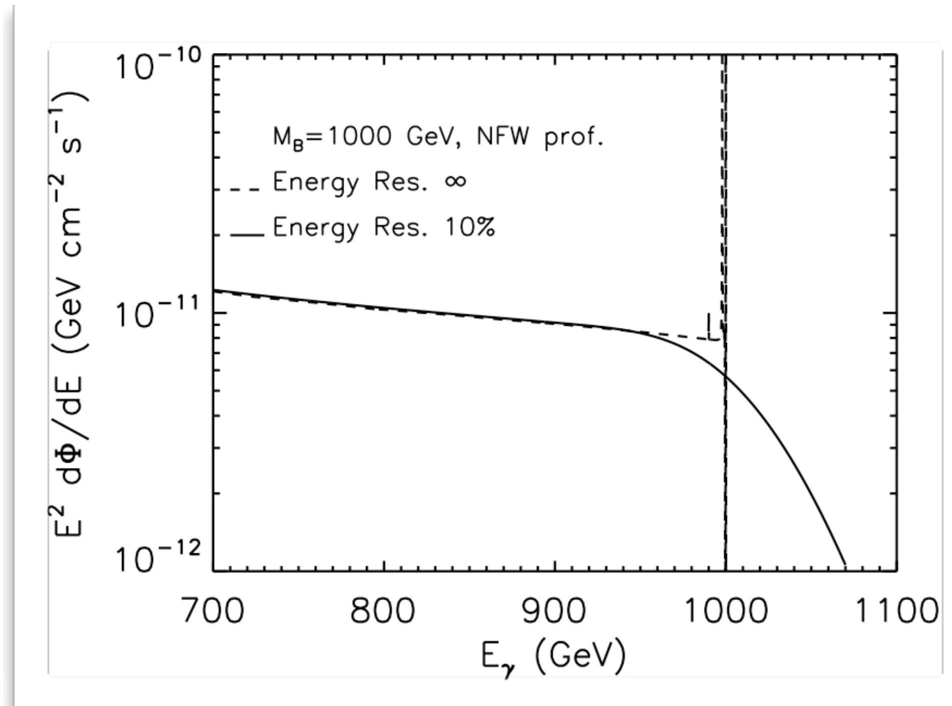
Model	$\bar{J}\,(10^{-5})$
NFW	1.5×10^4
Adiabatic	4.7×10^7

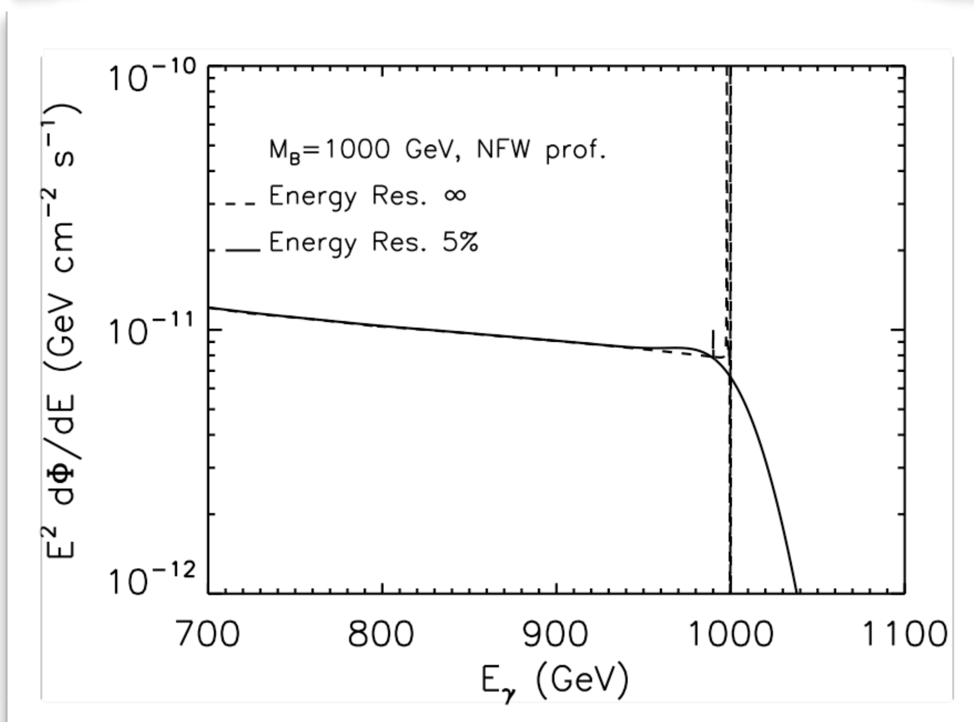
← Spans three orders of magnitude!!!

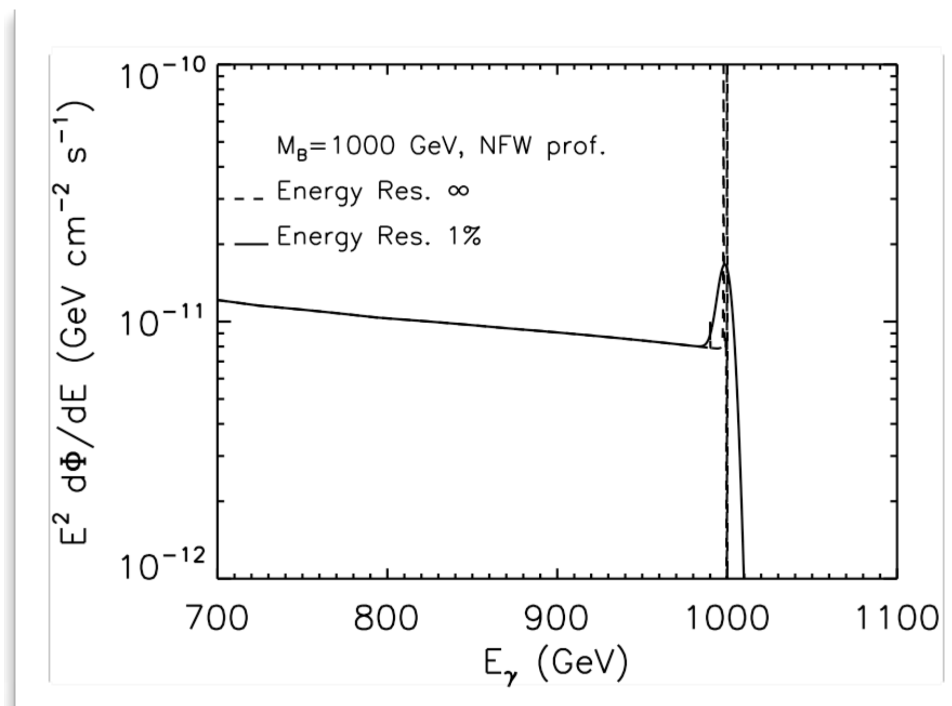
- Good news:
  - Identify sources
  - With help from LHC (WIMP mass, couplings), trace DM density? (see Hooper and Serpico, arXiv:0902.2539)

Results for the 5-d case

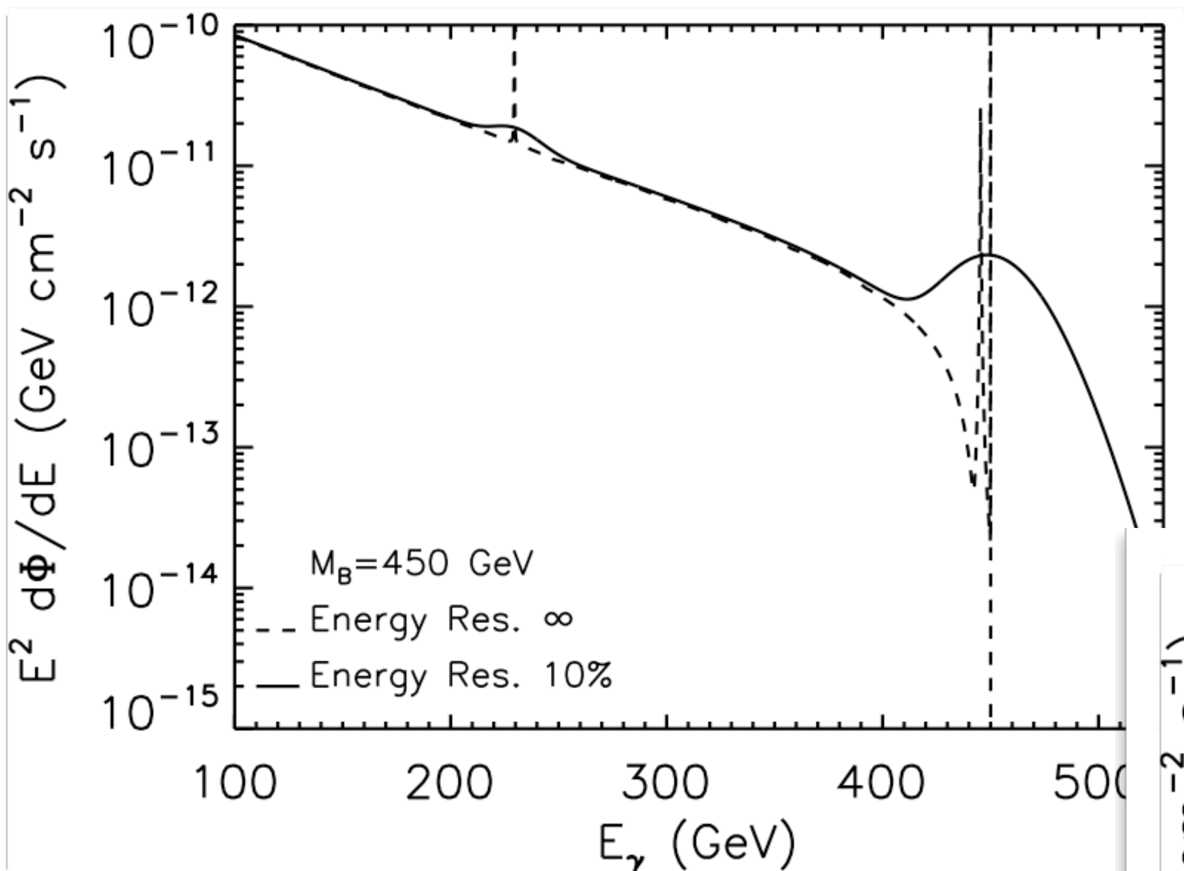




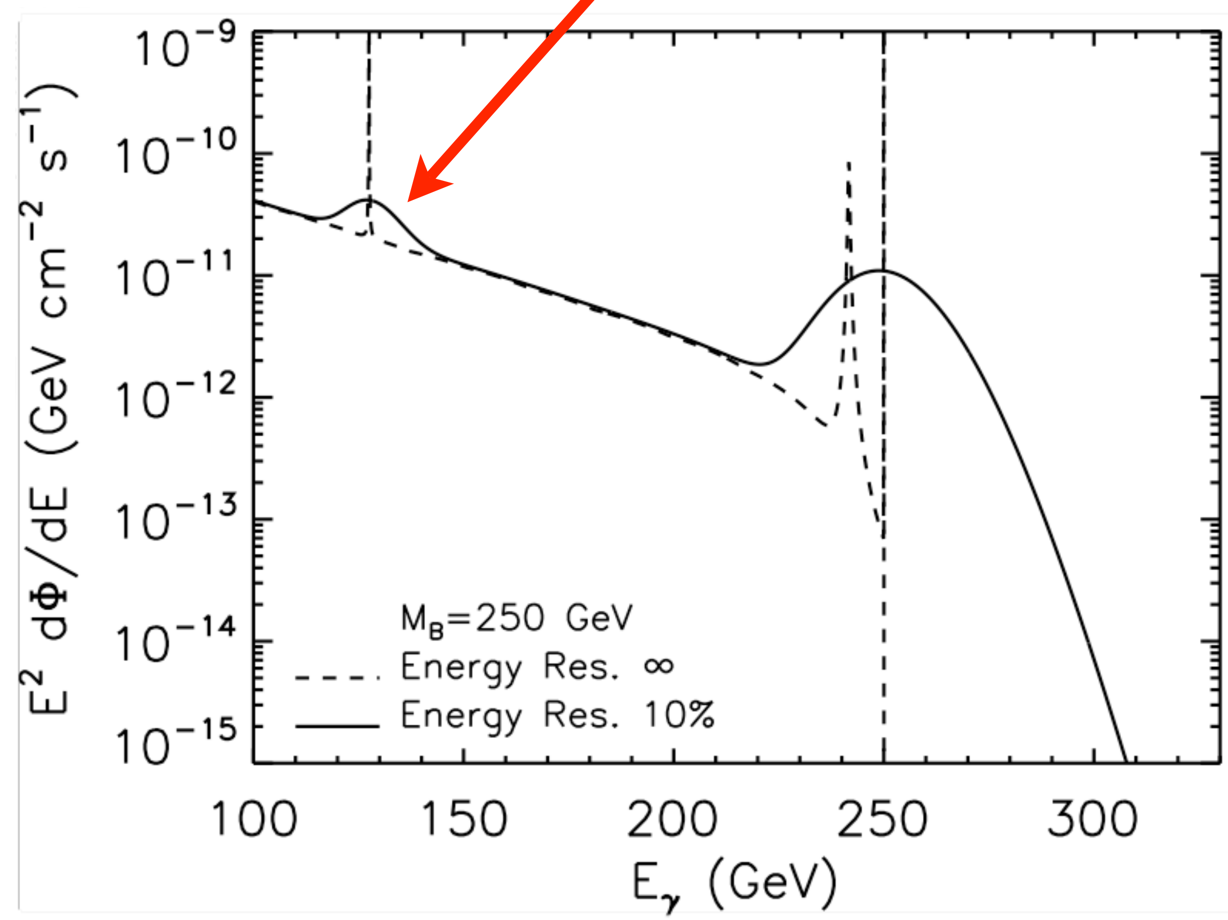




Results for the 6-d case



- Three lines: γγ, γZ and γ$B^{(1,1)}$
- After detector resolution effects, two "bumps" are distinct!
- Well-separated γ$B^{(1,1)}$ bump!



- Contributing factors:
  - Mass of $B^{(1,1)}$ ~ M_{WIMP}
  - Large γ$B^{(1,1)}$ cross section

Higgs in Space!

with G. Servant, G. Shaughnessy, T. Tait & M. Taoso

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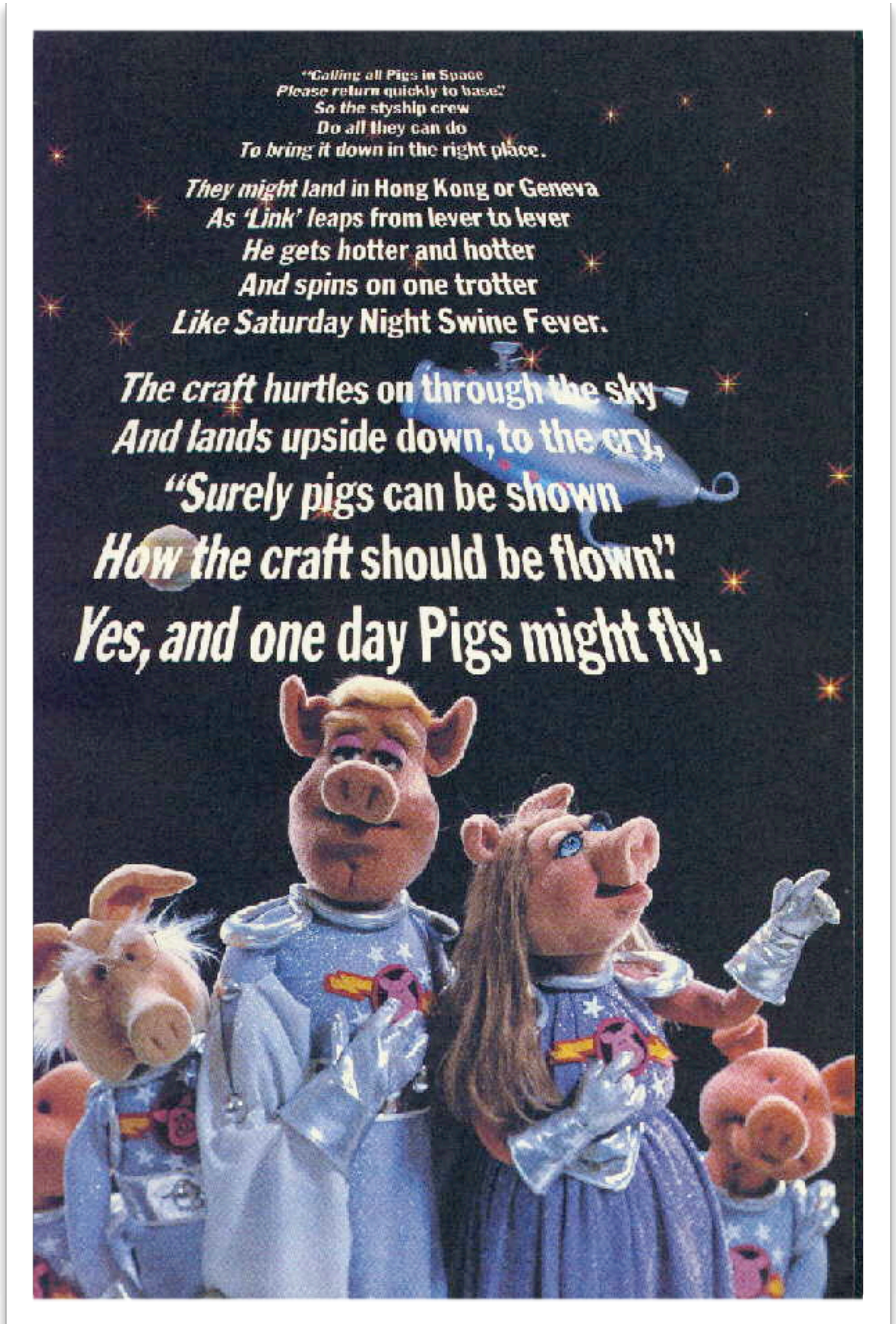

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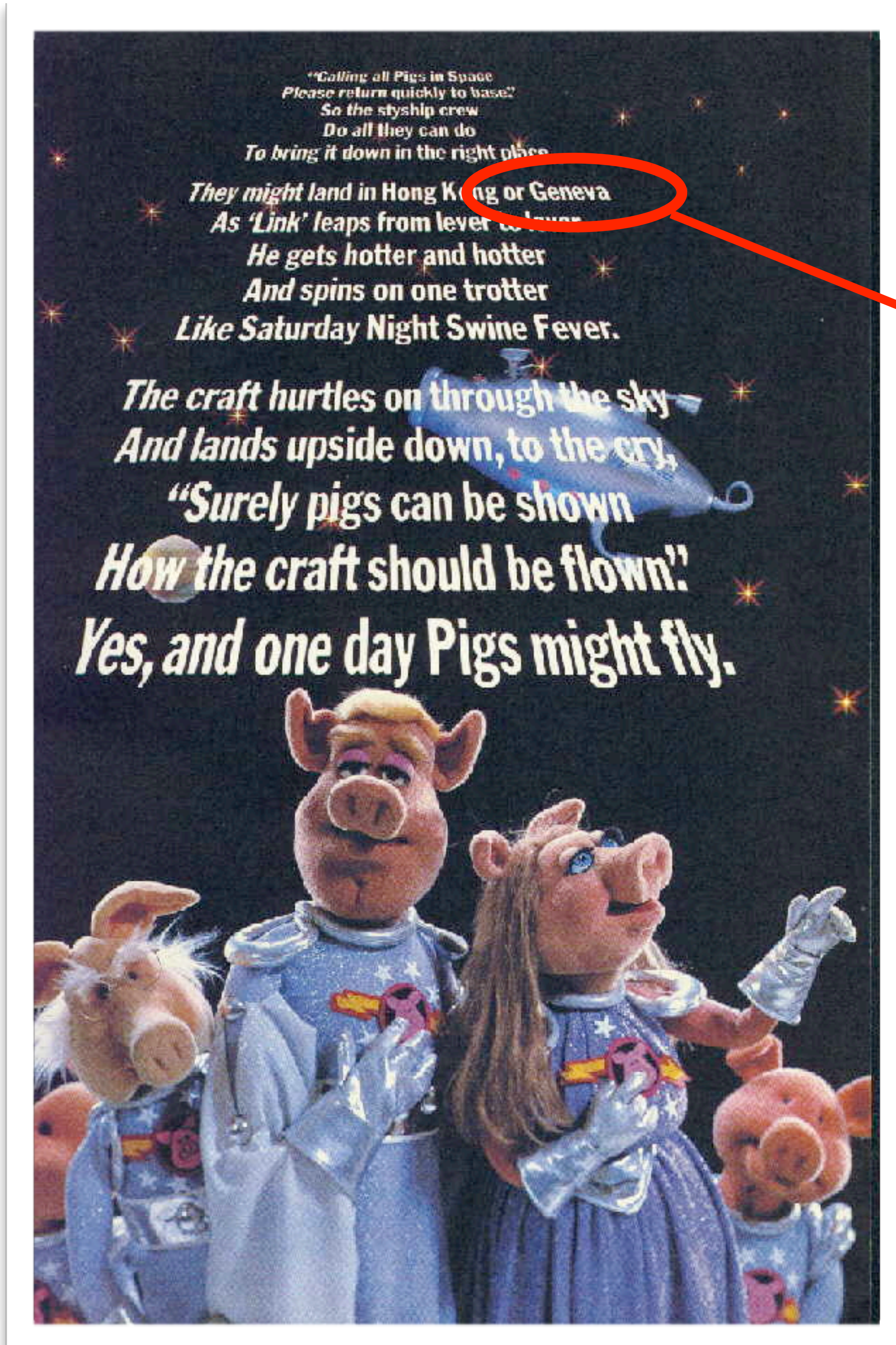


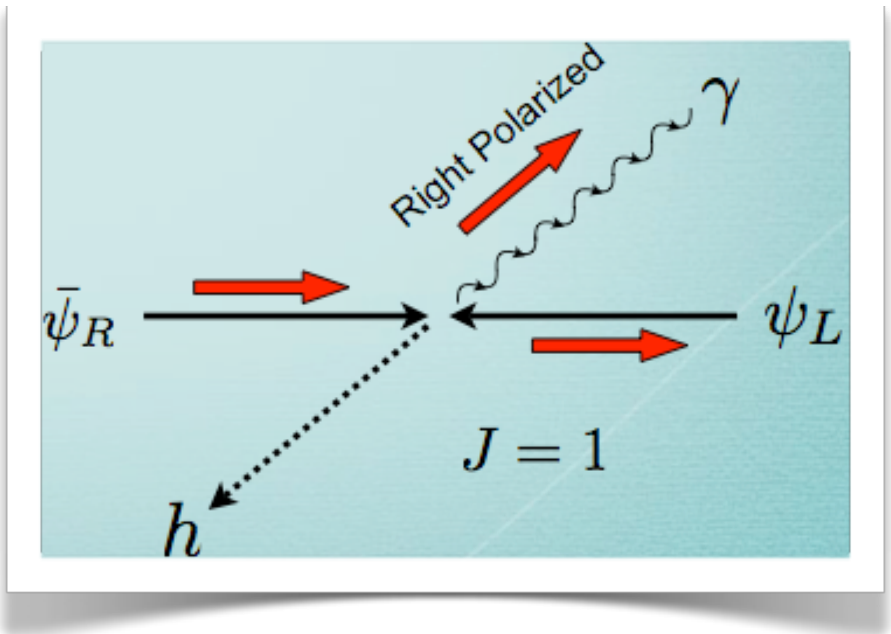
Geneva!

Higgs in Space!

- "WIMP Miracle": EW-size scales and couplings can naturally account for measured thermal relic abundance

- DM and EWSB dynamics related? If so, WIMPs may have enhanced couplings to massive states (tops, W/Z's, Higgs, etc.)

- Could DM annihilations already be producing Higgs bosons... in space?!?
- Could the Fermi telescope "scoop" the Tevatron and/or the LHC?!?
- Identification of a γH line:
  - Spin determination?
    (WIMP = fermion and vector only)
  - Give credence to DM-EWSB relation



A DM-Top Quark Connection

- Consider the case where WIMPs have sizable (albeit indirect) couplings to top quarks.
- Simple example: WIMP is a Dirac fermion (ν)
  - Usual SM gauge group with an additional U(1)´
  - ONLY the new Dirac fermion and the top quark are charged under U(1)´
  - U(1)´ is broken: Z´ acts as "portal" between SM and "dark sector"
- Effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + M^2_{Z'}Z'_\mu Z'^\mu + i\bar{\nu}\gamma^\mu D_\mu \nu + \bar{t}\gamma^\mu \left(g^t_R P_R + g^t_L P_L\right) Z'^\mu)t + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}_Y$$

$$D^\mu \equiv \partial_\mu - i\left(g^\nu_R P_R + g^\nu_L P_L\right) Z'^\mu$$

- "UV completion": see Agashe and Servant, PRL93, 231805 (2004).

Hypercharge-Z´ Mixing

- ε (η) term consistent w/ gauge symmetries (even if absent in UV... it would appear in the IR from loops of top quarks)

- Gauge anomalies? Cancelled by additional massive fermions... which also contribute to ε (η) term.

    - Keep ε (η) as a free parameter (although it has little effect on γ-ray signals)

- Simplified parameter space (motivated by RS model):

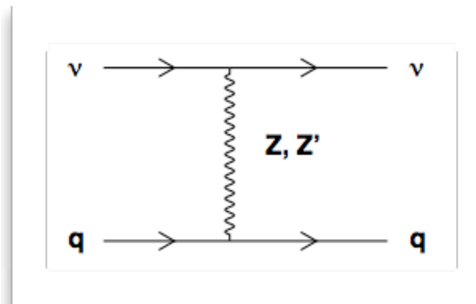
$$g_L^\nu = 0,\ g_R^\nu = g_{Z'}^\nu$$

$$g_R^t = g_{Z'}^t,\ g_L^t = 0.$$

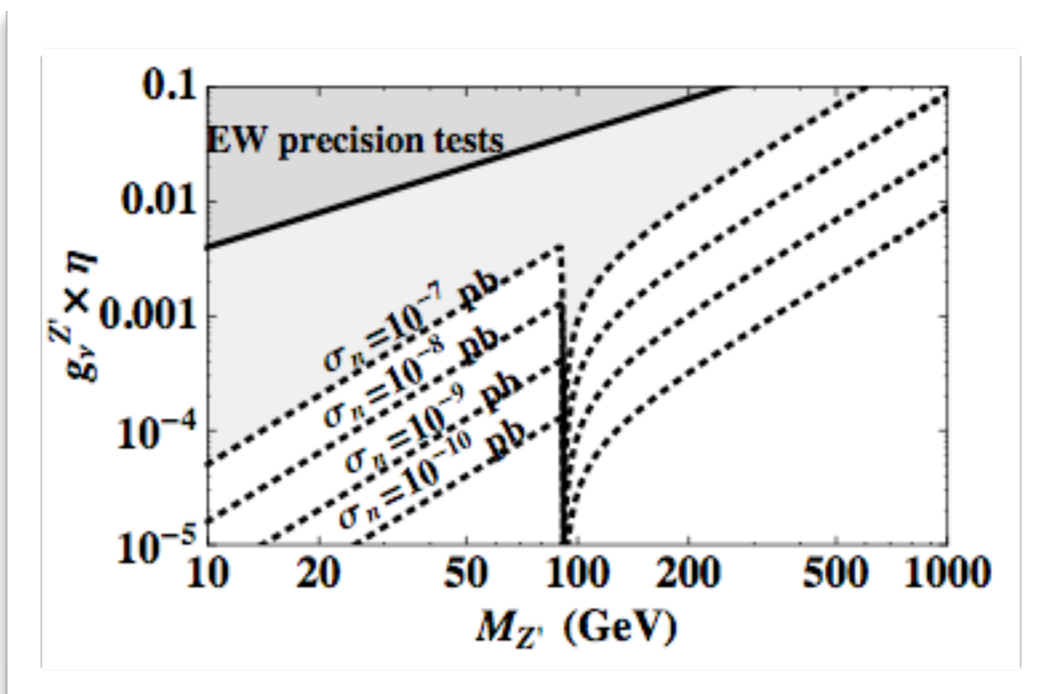
- Free parameters = (M, $M_{Z'}$, ε (η), Z´ couplings to ν and top quarks)

Elastic scattering constraints

- Use elastic scattering of WIMPs with nuclei to constrain ε (η):

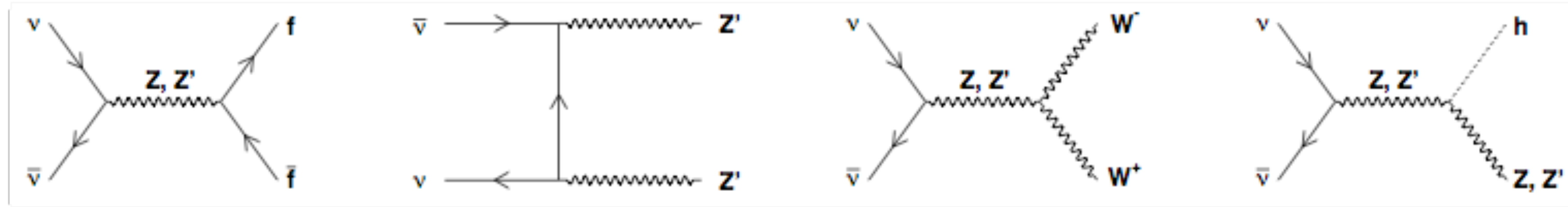


- Dirac WIMPs (unlike Majorana) have vector interactions which remain large in NR limit... strong constraints on cross section ($\sigma \sim \varepsilon^2$)

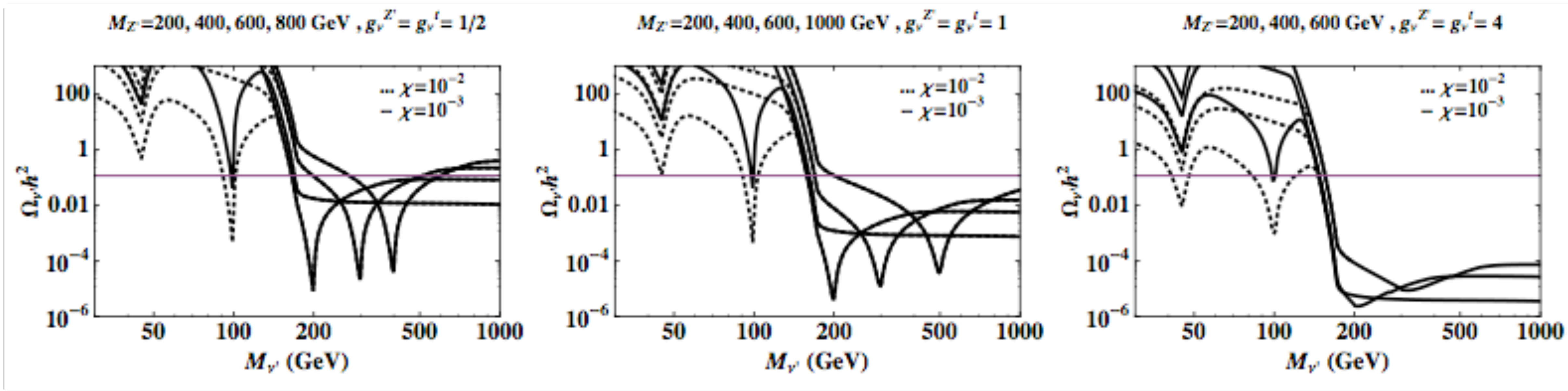


- For $M_{Z'}$ > few 10's GeV, constraints are consistent with:
  - Order one coupling between ν and Z´
  - Loop-suppressed ε (η)

Relic Density



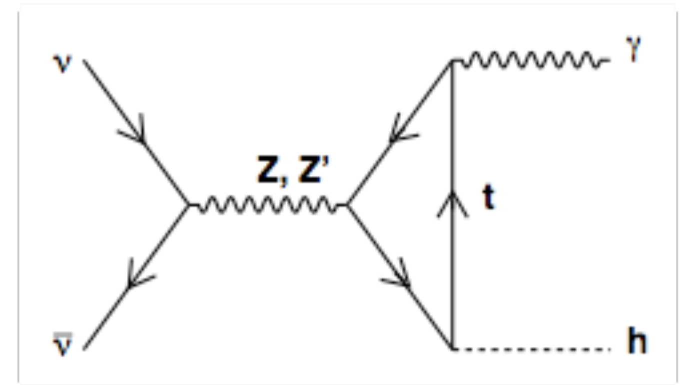
- Relic abundance controlled by annihilation into SM particles (and Z´)



- For M < mt and M ≲ $M_{Z'}$, *ff* mode dominates.... need annihilation to be on Z´ resonance
- For M ⋠ MZ´/2, annihilation into *tt* opens up... continuum of allowed values of M
- As couplings are dialed stronger, “continuum of values” reduces to M ≈ 150 GeV

The Lines

- Annihilation proceeds via an s-channel Z´:
- As a consequence, (in the NR limit) no γγ line! (Landau-Yang theorem)



- The cross sections:

$$\sigma v = \frac{1}{64\pi M^2}\left(1 - \frac{M_X^2}{4M^2}\right)\overline{|\mathcal{M}|^2}$$

$$\overline{|\mathcal{M}|^2} = \frac{2\alpha\alpha_t N_c^2}{9\pi^2}\mathcal{V}^2 \frac{(g_t g_\nu)^2 M^2 m_t^2}{(4M^2 - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2}$$

$$\overline{|\mathcal{M}|^2}_{\gamma Z} = \frac{\alpha^2 N_c^2}{144\pi^2 s_w^2 c_w^2}\mathcal{V}_{\gamma Z}^2 \frac{(g_\nu)^2 M^2}{(4M^2 - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2},$$

$$\overline{|\mathcal{M}|^2}_{\gamma Z'} = \frac{\alpha N_c^2}{36\pi^3}\mathcal{V}_{\gamma Z'}^2 \frac{(g_\nu)^2 M^2}{(4M^2 - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2}$$

- Account for finite width effects:

$$\frac{dN_\gamma^X}{dE} = \frac{4M_\nu M_X \Gamma_X}{f_1 f_2}$$

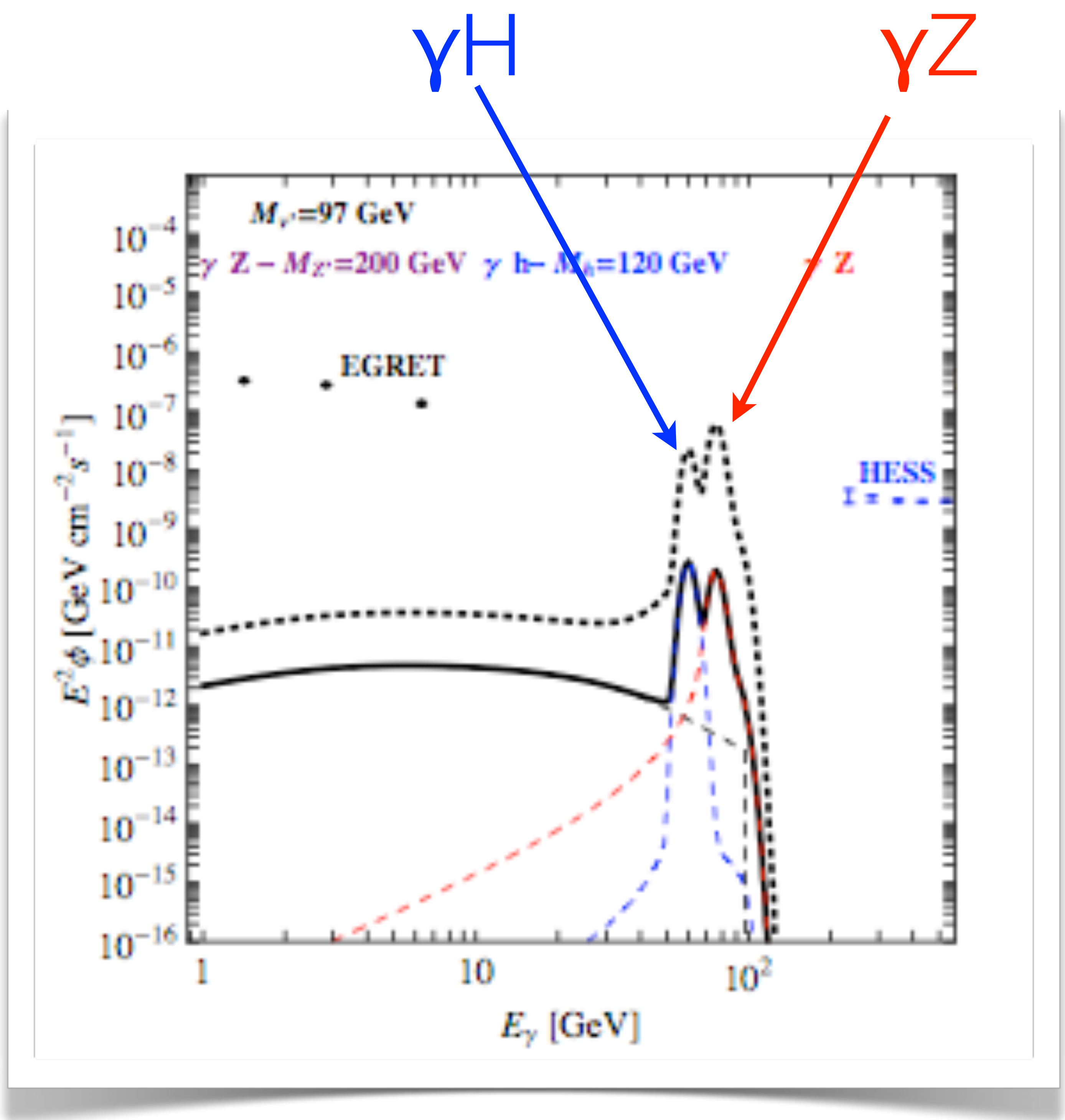
$$f_1 = \tan^{-1}\left(\frac{M_X}{M_\nu}\right) + \tan^{-1}\left(\frac{4M - M_X^2}{M_X\Gamma_X}\right)$$
$$f_2 = (4M^2 - 4ME_\gamma - M_X^2)^2 + \Gamma_X^2 M_X^2$$

The γ-ray spectrum

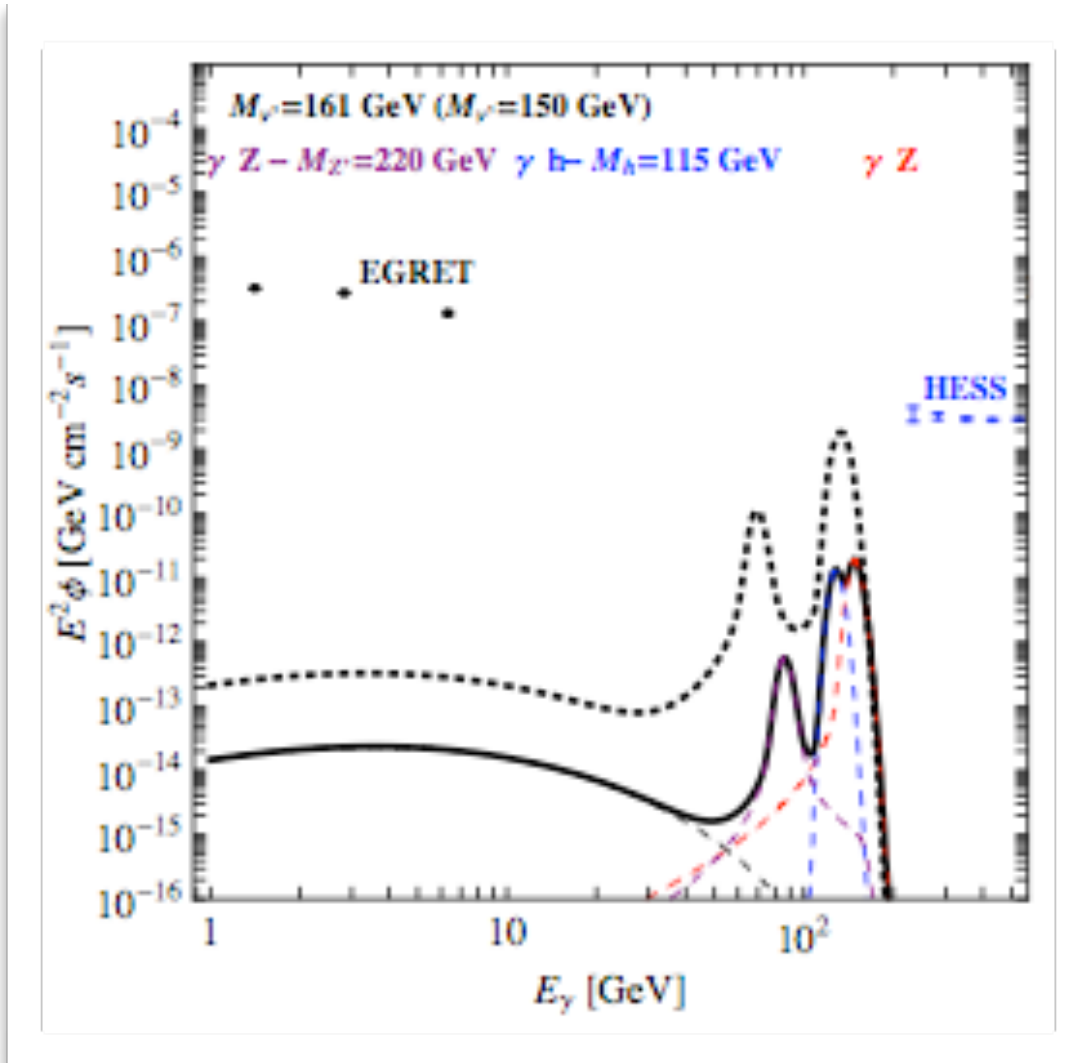
- “Source” = galactic center
- Use NFW dark matter profile:

MW halo model	r_s in kpc	ρ_s in GeV/cm^3	$\bar{J}$ (10^{-5})
NFW [20]	20	0.26	$15 \cdot 10^3$
Einasto [21]	20	0.06	$7.6 \cdot 10^3$
Adiabatic[22]			$4.7 \cdot 10^7$

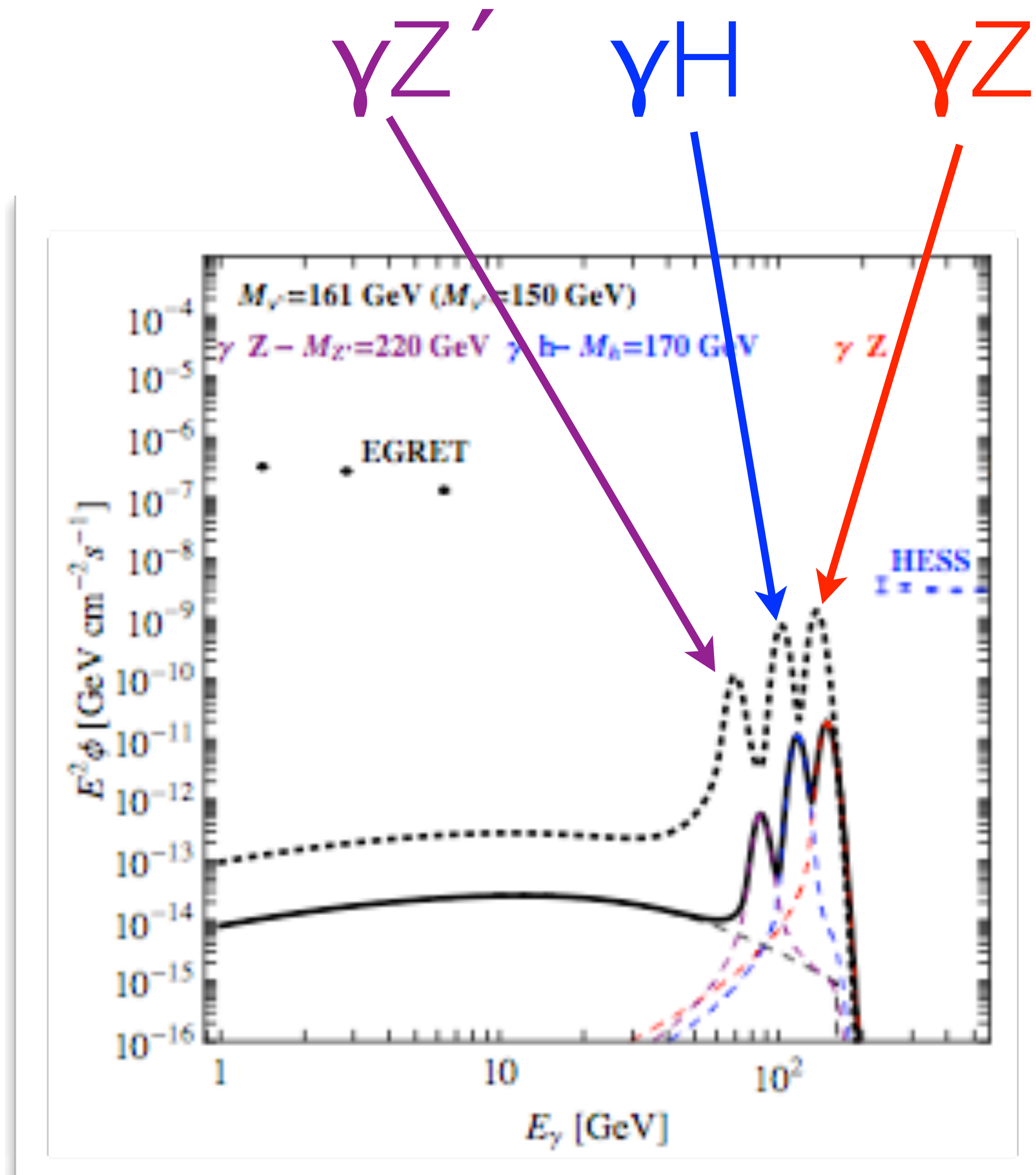
- Detector resolution = 10%
- Solid line: ν couplings = 1
  Dashed line: ν couplings = 3



The γ-ray spectrum (cont.)

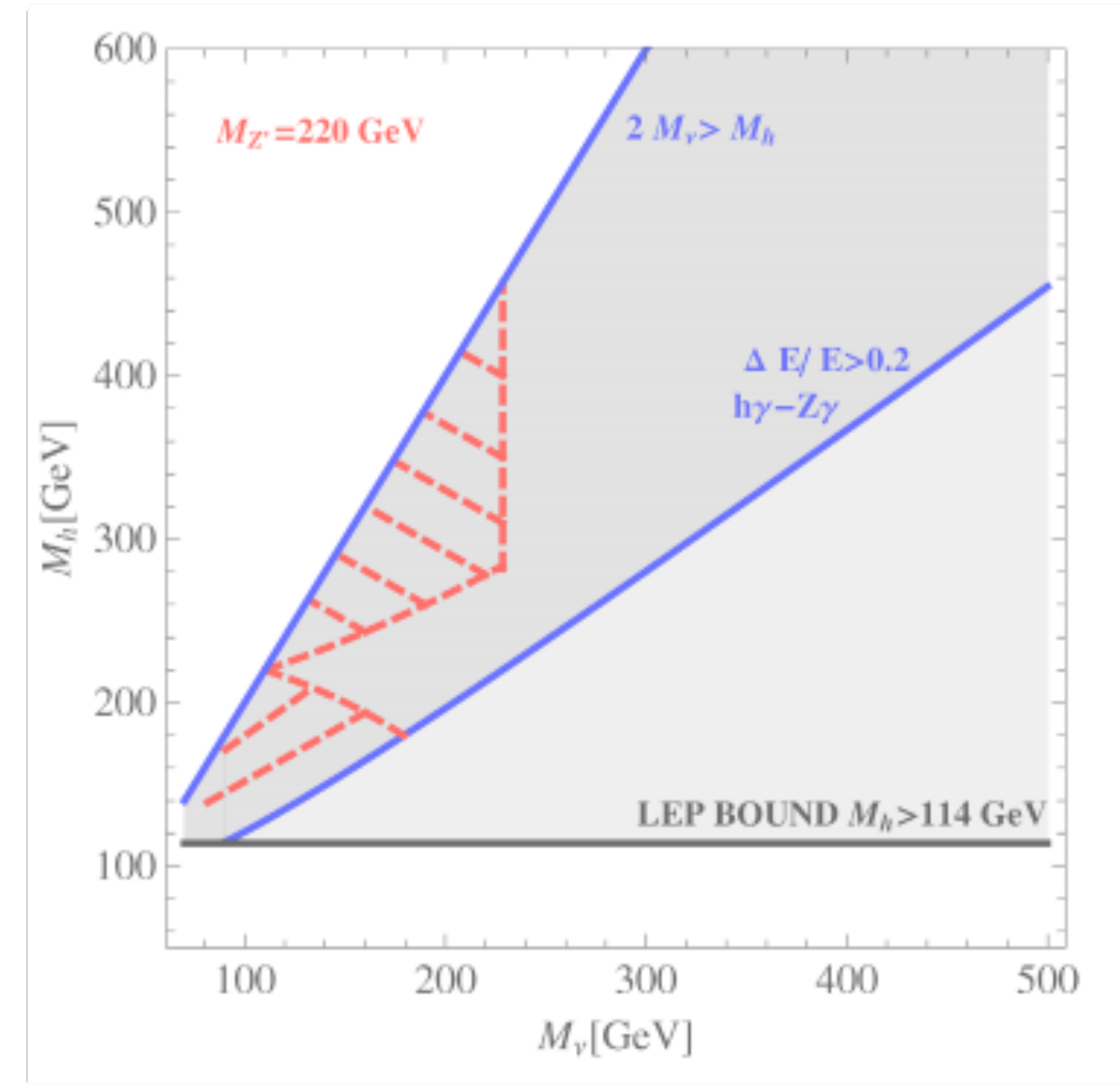


Three lines!



How many lines?

- Scan over parameter space to see when γH can be resolved
- γH discernible from γZ when energy separation ~ 2(ΔE/E)
- Anything below this, only one line observable (light grey)
- Huge part of parameter space produces (at least) two lines! (dark grey)
- Significant part of parameter space produces three lines! (red dashed)



Conclusions/Outlook

- Exciting times in the "Amazing Race" for dark matter!
- The search for γ-ray lines can play an integral part.
- In our search for dark matter, we might discover a whole "dark sector"
- A "WIMP Forest"? Dark Matter spectroscopy?
  (best examples: Inert Doublet Model, 6-d Chiral square)

- Higgs in Space!
  - The dynamics of EWSB and dark matter related?
  - If so, WIMPs may have enhanced couplings to massive states
  - Dark matter - top quark connection (RS inspired)
  - Huge region of parameter space allows observation of γH line!

Backup slides...

Mapping to RS

- EFT inspired by an RS model studied by Agashe and Servant (PRL93, 231805 (2004), JCAP 0502, 002 (2005))
- SUSY Paradigm: R-parity (which is imposed to conserve baryon number) results in a stable LSP
- RS setup w/ bulk (gauged) baryon number symmetry (Z_3)
- ν is a bulk field with (-,+) BC's...
  - anomalously low mass for ν (compared to KK modes)
  - stability of ν related to suppression of rapid proton decay
- Z' represents the lowest KK mode of the U(1) contained in SO(10)
  - Z' has enhanced couplings to KK modes (such as ν) and fermions