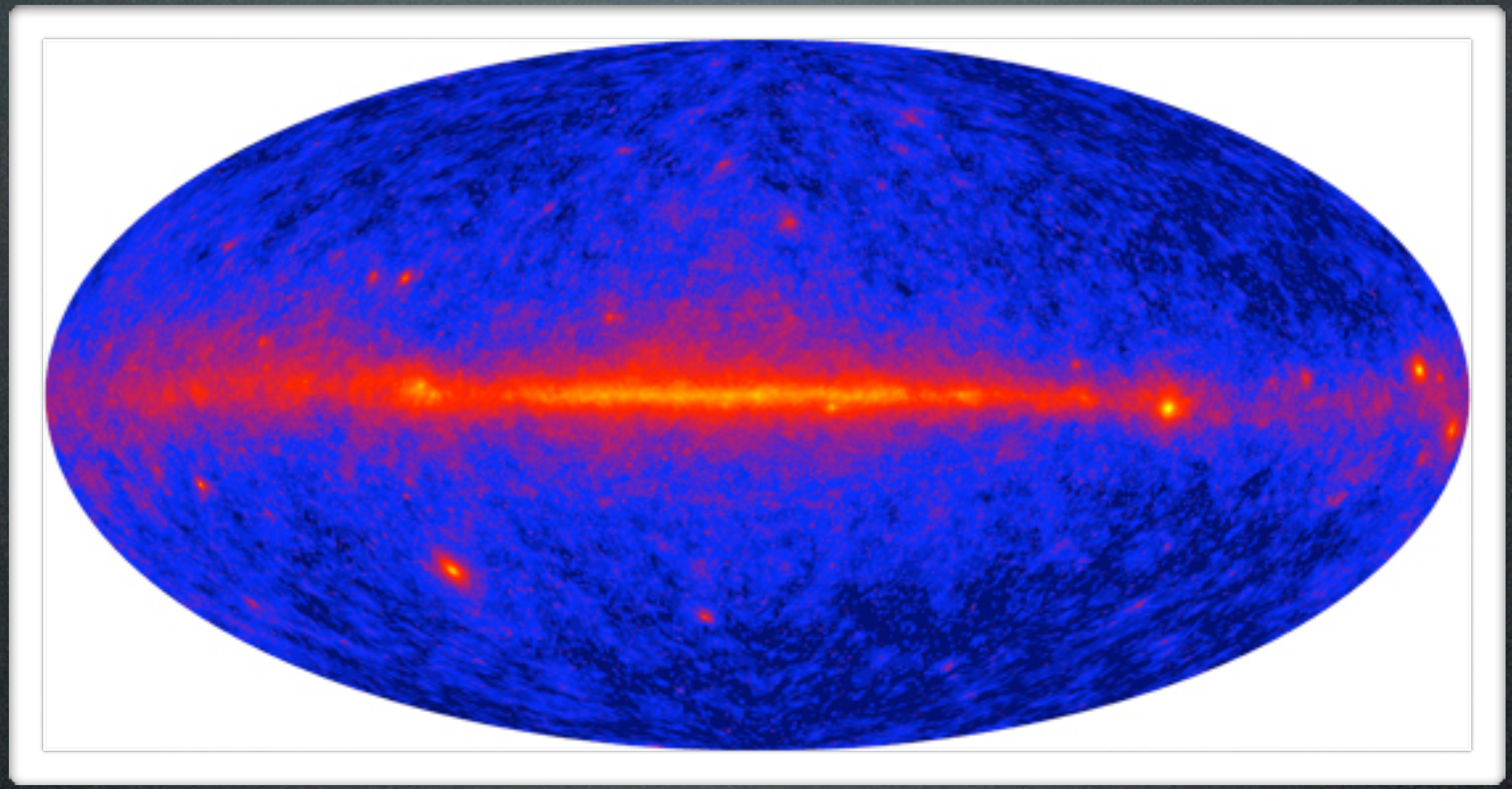
The WIMP Forest



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Based on arXiv:0904.1442

Preface

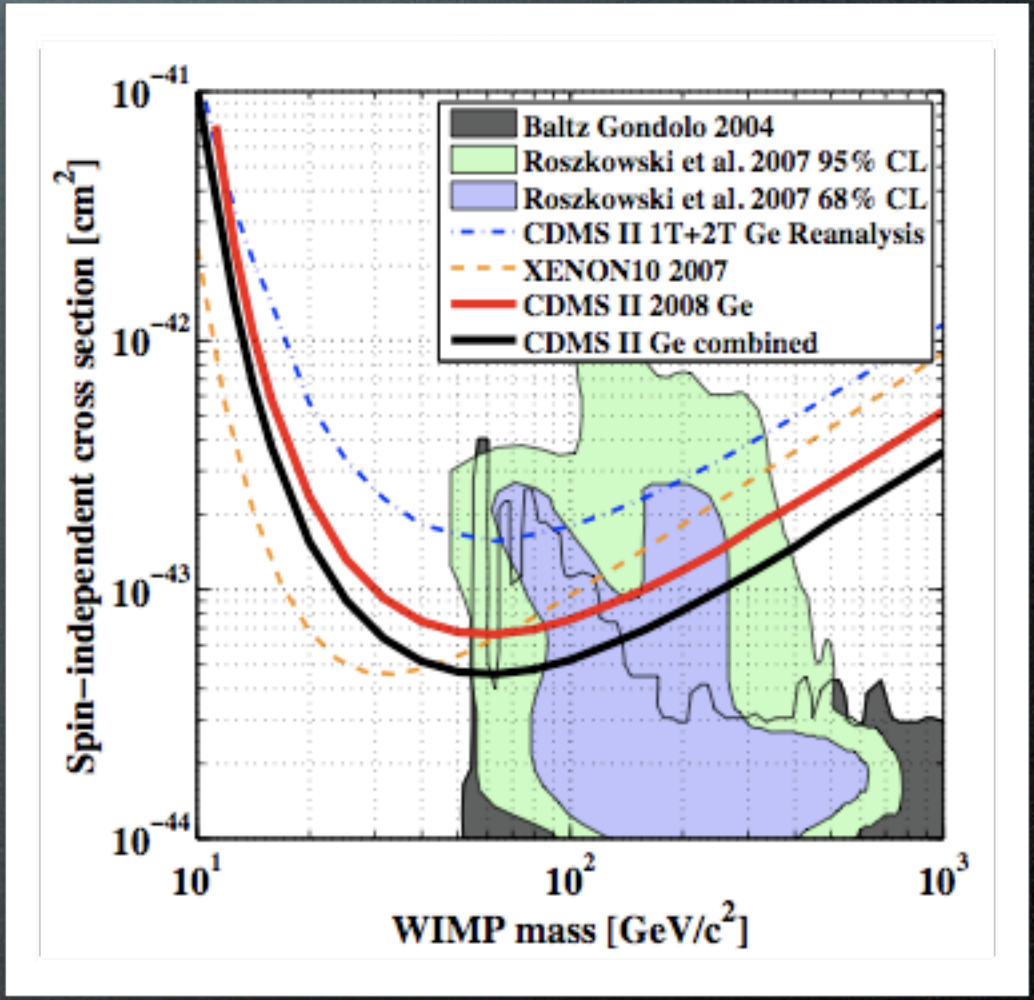
- Yes, this is a Dark Matter Talk.
- No, it's not a talk on PAMELA/ATIC
- My apologies...
- However, ...

BSM + Astro + Loops = Fun!

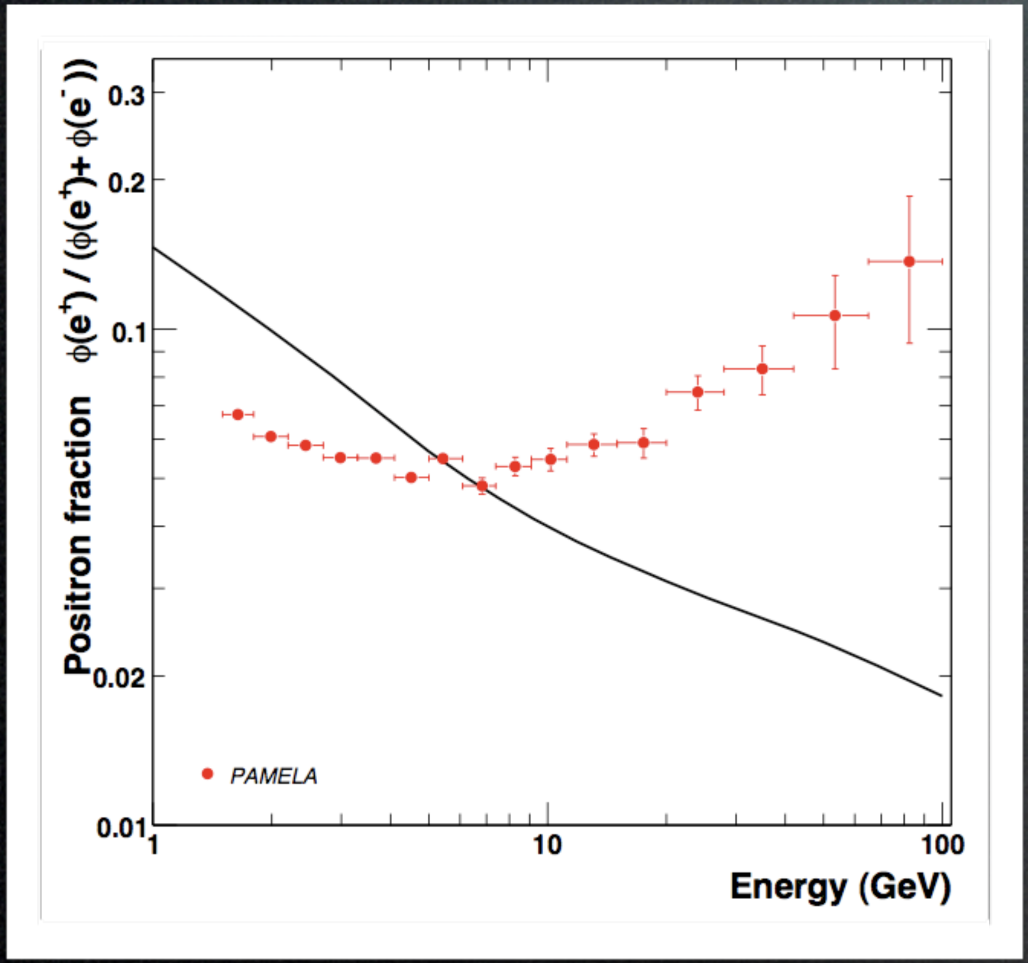
Outline

- Indirect detection of Dark Matter (DM) via gamma rays
- Spectral lines... i.e., the "WIMP Forest"
- Past studies
  (SUSY, Inert Doublet Model)
- Signals from the "Chiral Square"
- Conclusions and Outlook

Direct Detection

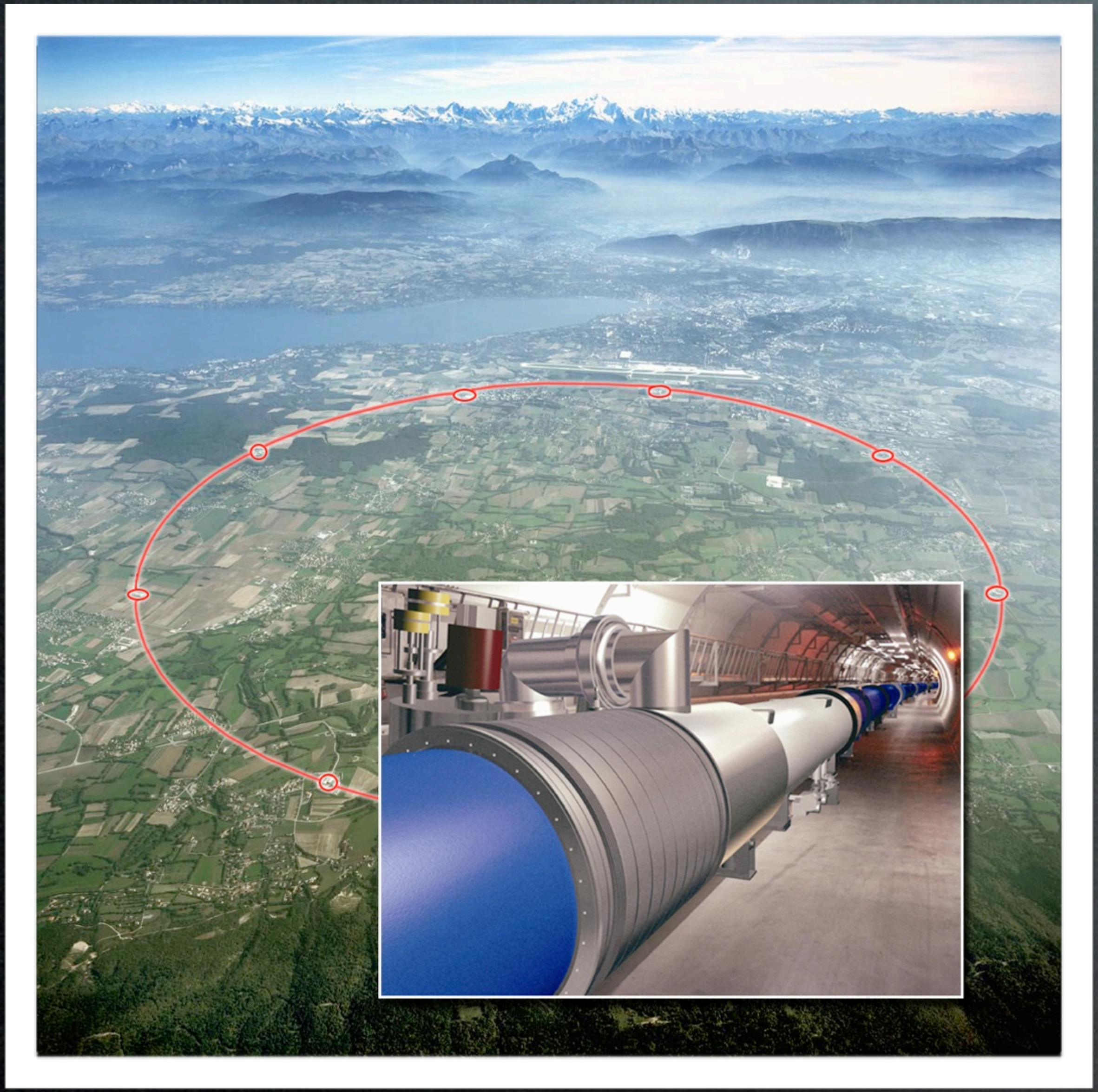


Cosmic Rays(?)

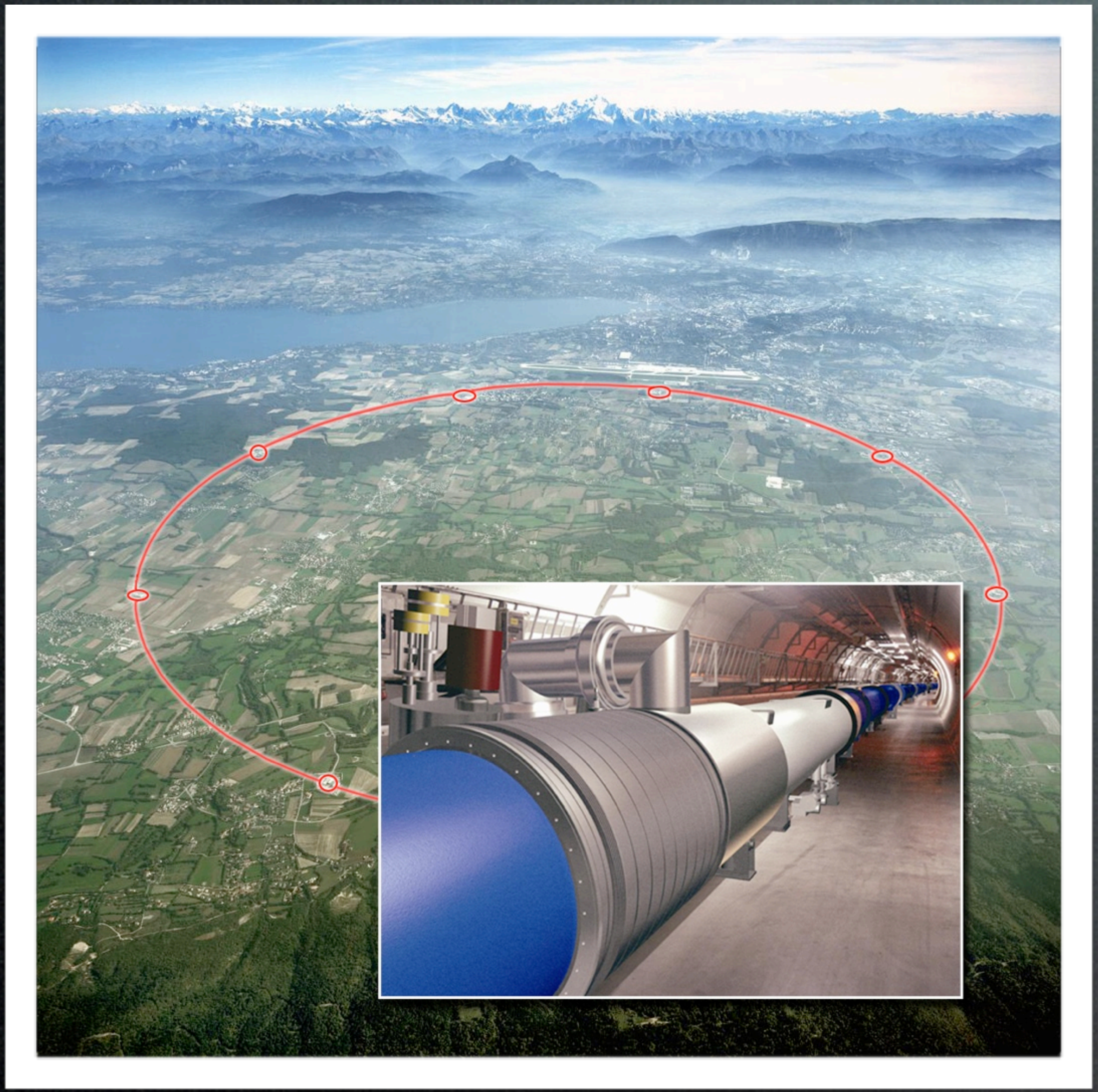


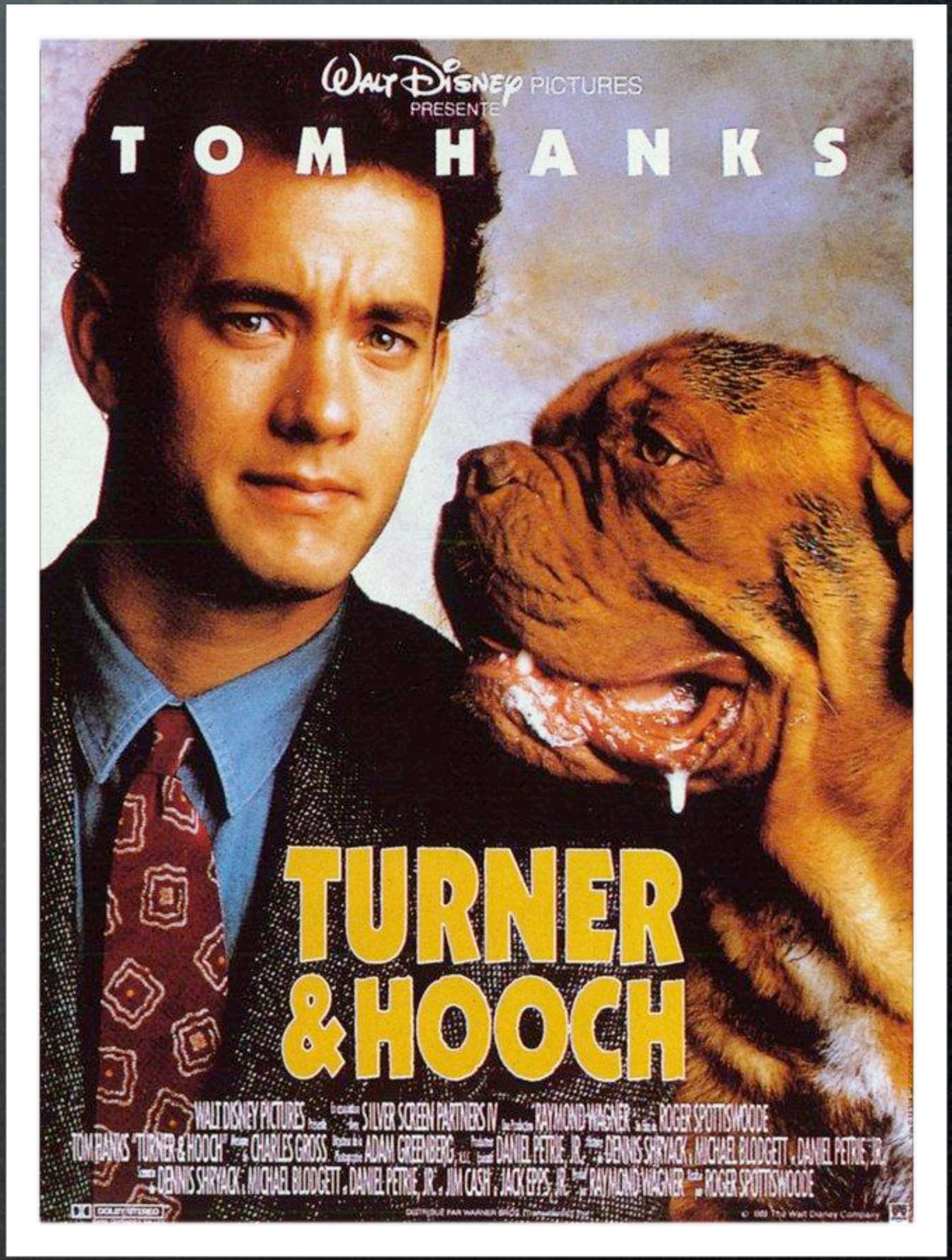
and...

LHC *Alive!*



LHC Alive! ?





"Higgins Bosun"?!?

Seeing the Light... from Dark Matter

- Indirect detection of DM via its annihilations into γ rays

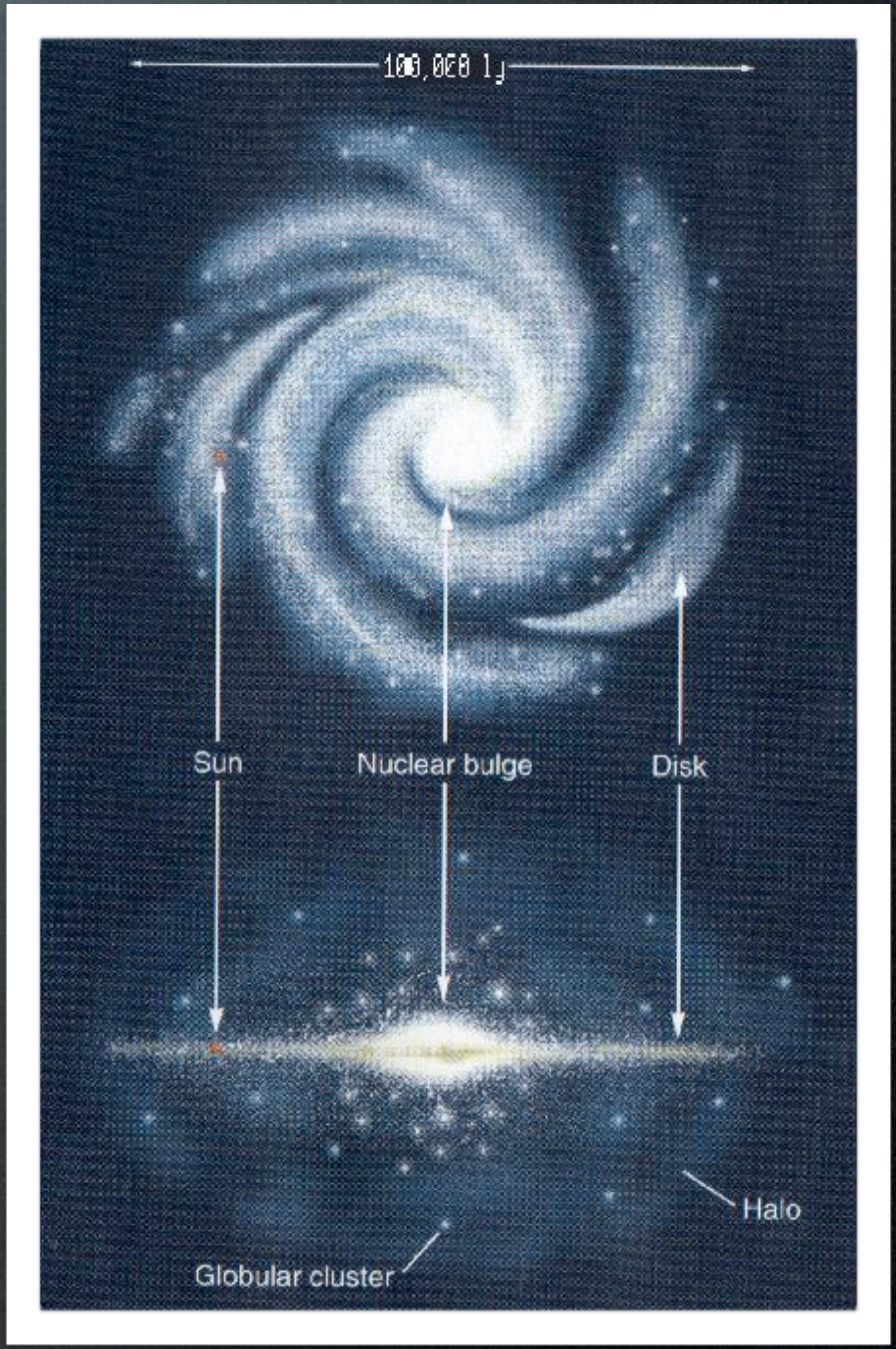
- Basic idea:

  - Look towards GC

  - Anomalous signals over astrophysical backgrounds (power laws)

  - γ rays travel in straight lines

- Flux (on the theory side):



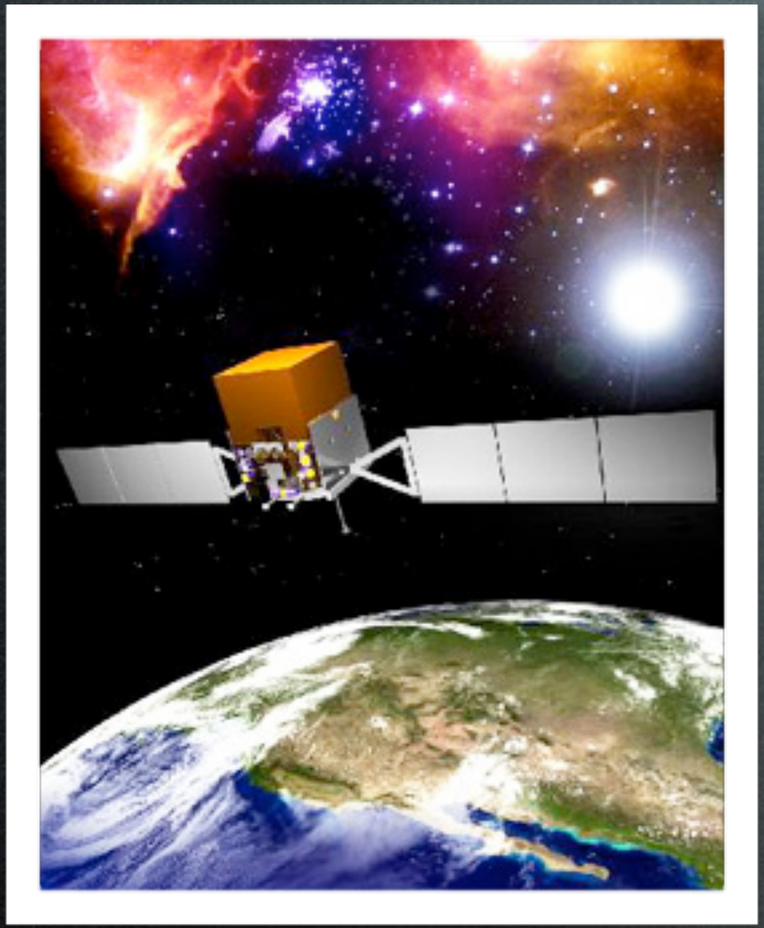
$$\frac{d\Phi_\gamma}{d\Omega dE}(\psi, E) = \frac{r_\odot \rho_\odot^2}{4\pi M_{B_H}^2} \frac{dN_\gamma}{dE} \int_{\mathrm{l.o.s.}} \frac{ds}{r_\odot} \left[\frac{\rho[r(s,\psi)]}{\rho_\odot}\right]^2$$

$\longrightarrow$

$$\frac{dN_\gamma}{dE} = \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE},$$

Searching for the Light

Fermi Space Telescope

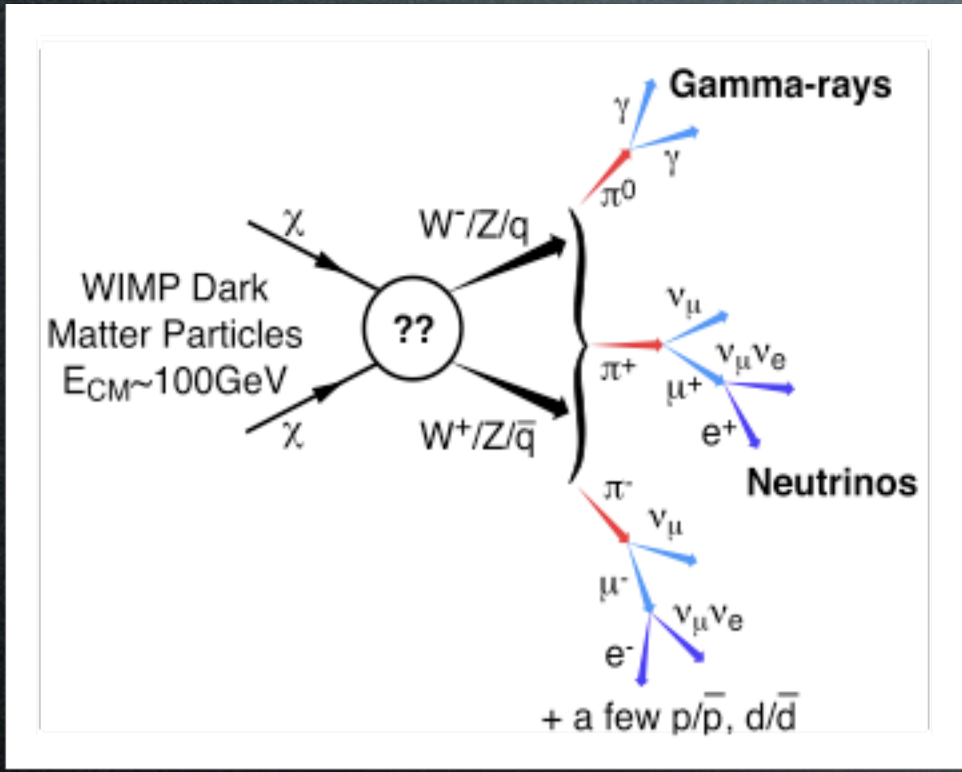


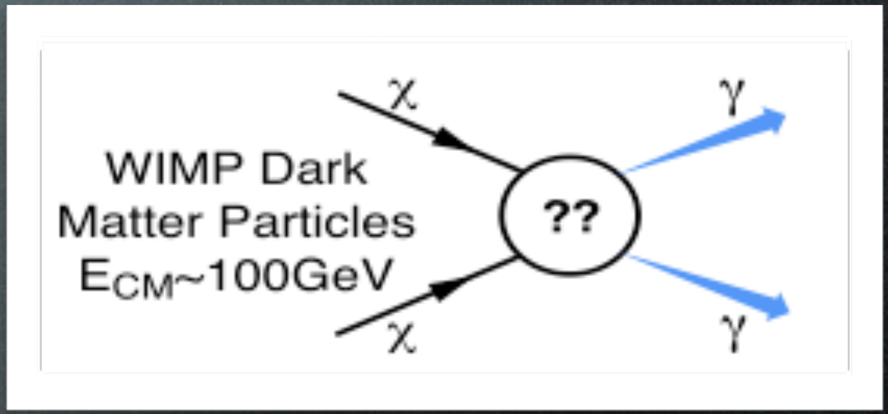
Air Cerenkov Telescopes

- Scans entire sky
- LAT sensitive up to 100's GeV
- $\Delta E/E \sim 10\%$
- See Baltz et al., arXiv:0806.2911 or Pheno talk by Simona Murgia

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

Contributions to γ flux from DM





- Continuous spectrum
- Hadronization/decay of quarks
- Final-state radiation from charged SM particles
- Hard cut-off at WIMP mass

- Loop-induced process into γ + X final states
- Spectral “lines”
- Suppressed compared to continuum
- “Smoking gun”

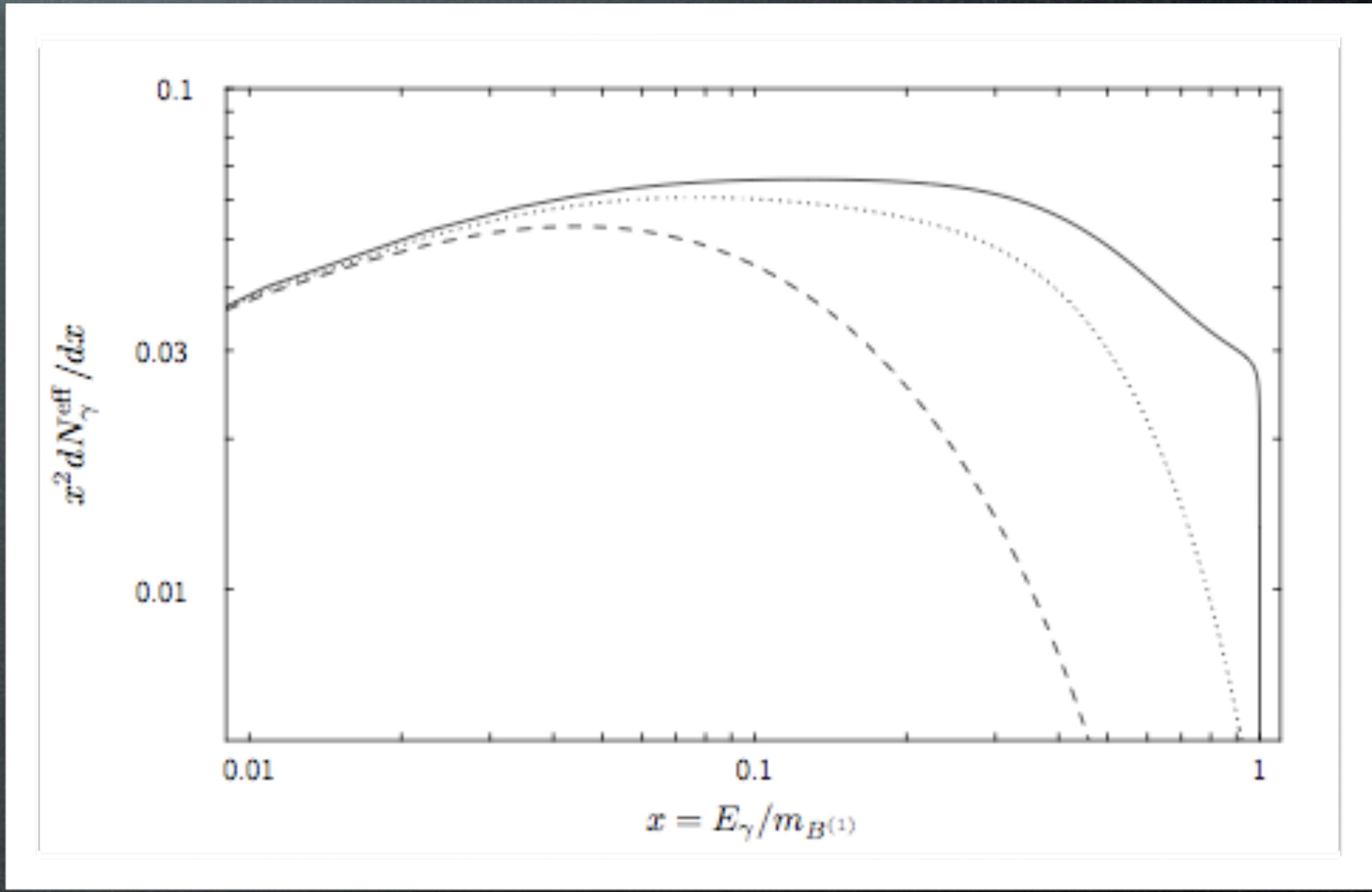
Continuous Spectrum

- Light quark hadronization ($\pi^0 \to \gamma\gamma$ decays)
  - Featureless and soft
- Bottom quark and tau decays
- Final-state radiation:

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

  - "Collinear" log
  - "Hard" cutoff @ WIMP mass
  - Some cases, "rise" in spectrum
- In practice, spectra obtained with Pythia... hard to tell models apart!

Distribution of Photons



Direct Annihilation into Photons

- Loop-level processes (since WIMPs are electically neutral)
- Strong discriminant against astrophysical backgrounds
- For γ + X final states, photons emitted mono-energetically:

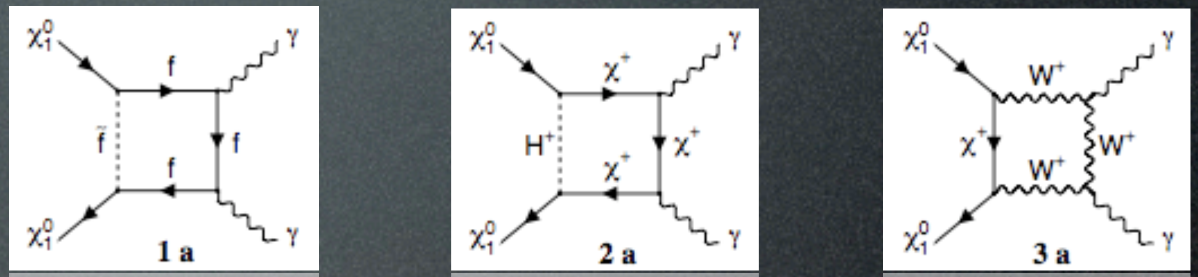
$$E_\gamma = m_{DM}\left(1 - \frac{M_X^2}{4m_{DM}^2}\right)$$

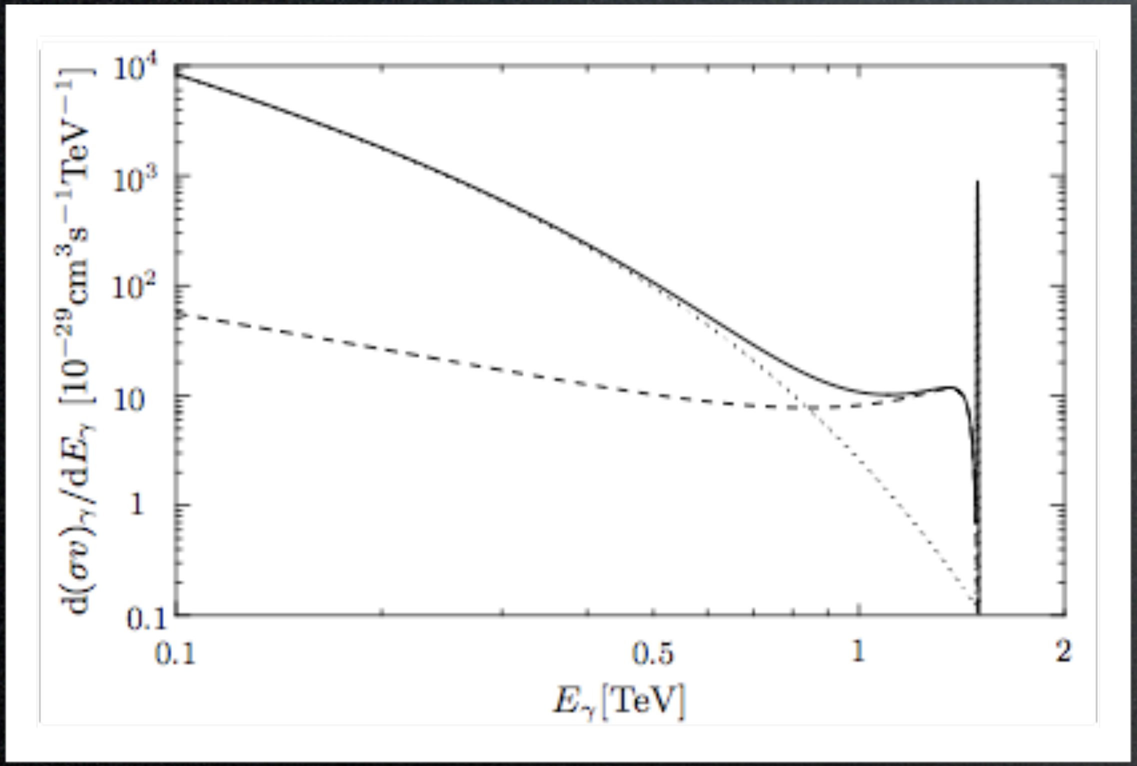
- Position/strengths of lines contain a wealth of information:
  - Position of $\gamma\gamma$ line → precise determination of WIMP mass
  - $\gamma\gamma$ vs. Z γ lines → $SU(2)_L$ couplings to singlets/doublets of WIMP
  - Observation of H γ line → WIMP cannot be Majorana or Scalar

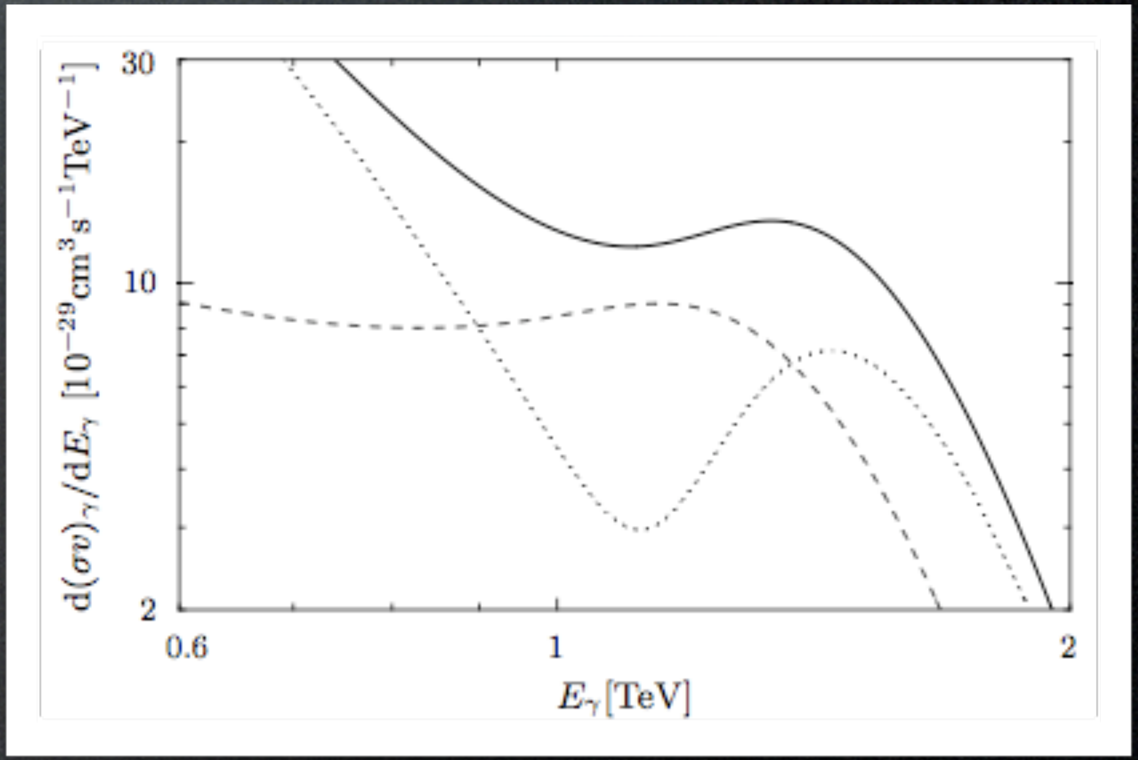
Lines from SUSY

(e.g., see series of papers by Bergstrom et al.)

- Majorana nature of neutralino:
  - Reduces continuum emission (chiral suppression)
  - Only accessible final states = $\gamma\gamma$ and Z γ (cons. of spin ang. mom.)
- Feynman diagrams:



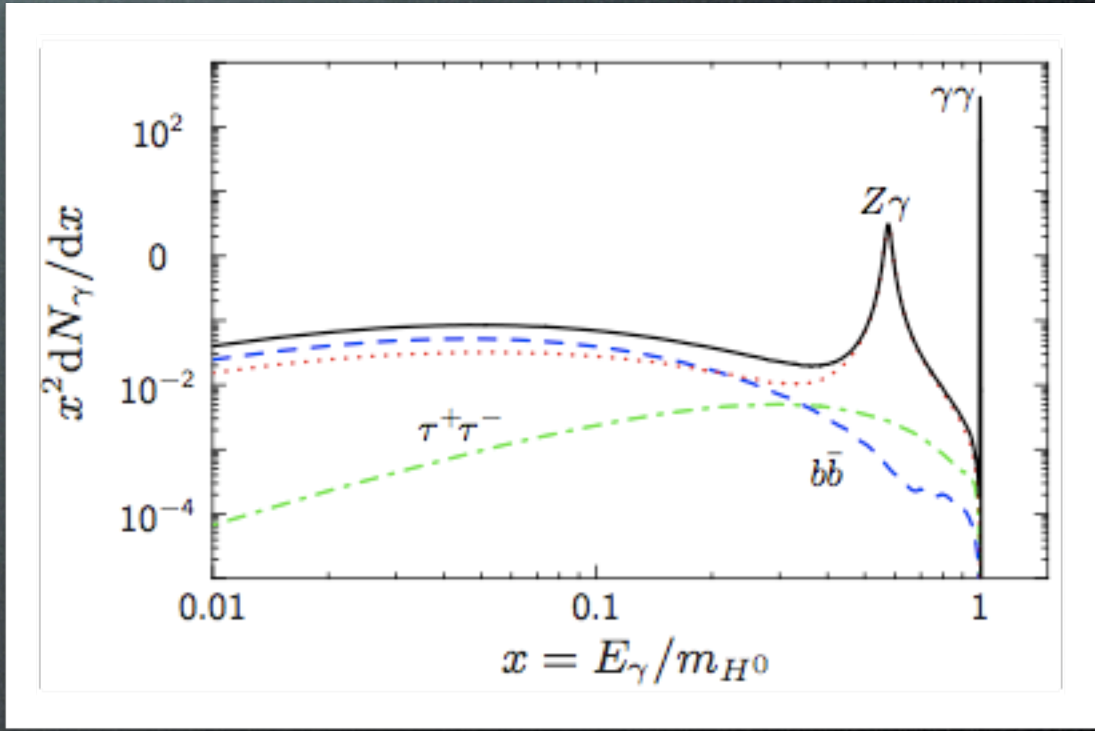


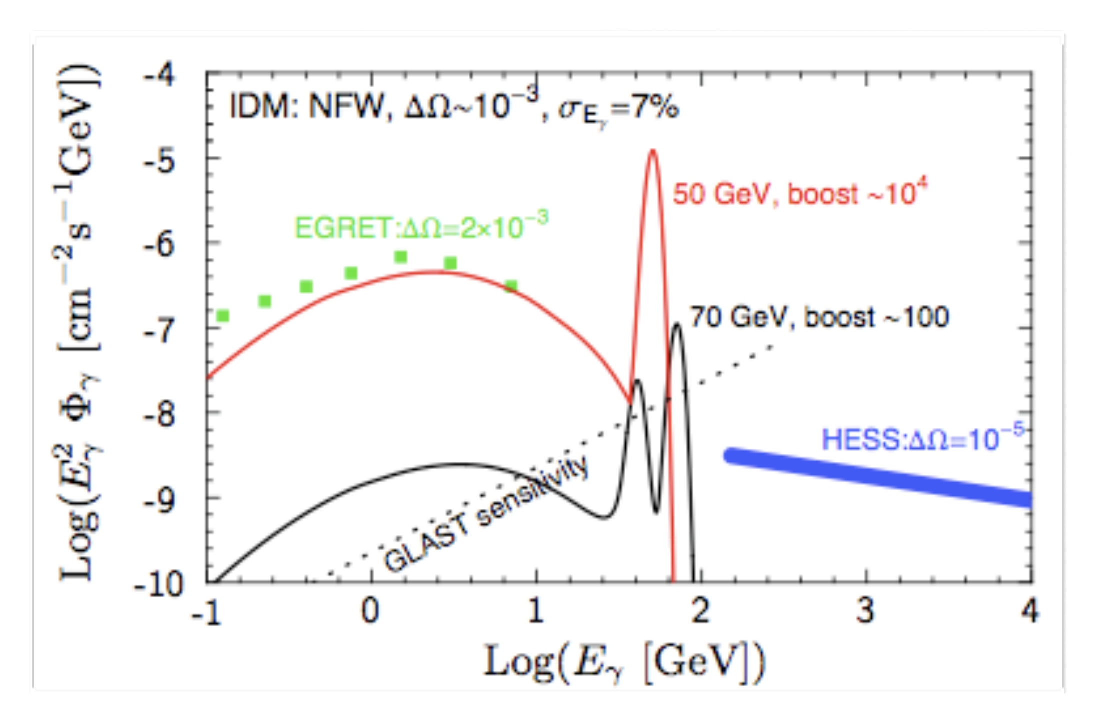


Lines from an "Inert" Higgs

(Gustafsson et al., PRL99:041301 (2007))

- Add a second Higgs doublet to SM w/ additional Z_2 symmetry (push PEW constraint on M_H up to 500 GeV or so)
- WIMP candidate = scalar
- Relic density: $M_{DM} < M_W$ (ideal mass range for Fermi)
- Virtual W's close to threshold enhance loop effects
- $\gamma\gamma$ and Z γ final states
- Chirally-suppresed couplings to fermions (suppressed continuum)
- Extremely pronounced peak(s)!!!





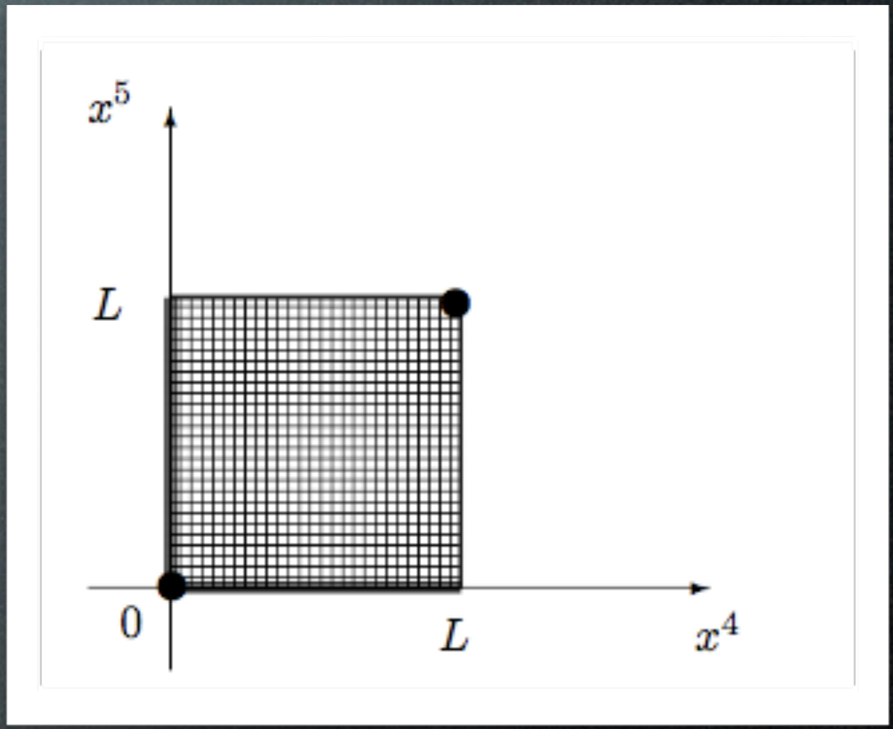
A Dark Forest?

- Ingredients for a successful line search:
  - Suppression of continuum
  - Loop-annihilation via "largish" couplings
  - Lines close together tend to be "blended" together (detector resolutions)
- What if there are other particles in the "dark sector" with appreciable masses compared to the DM mass (but $\leq 2\ M_{DM}$)?
- A series of lines... or a WIMP Forest!!!
- Dark matter spectroscopy?

Case Study: The Chiral Square

(Dobrescu & Ponton)

- Universal Extra Dimensions (UEDs)



- Two extra-d's compactified on a square
- Adjacent sides identified:

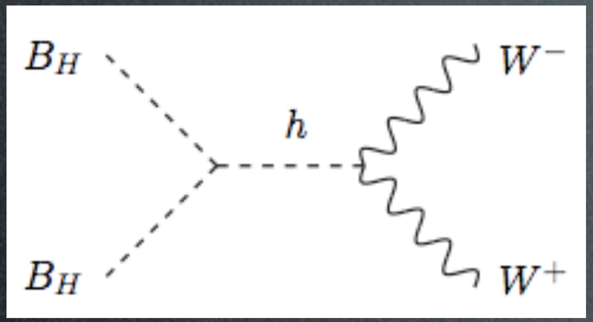
$$(y, 0) \equiv (0, y) \qquad (y, L) \equiv (L, y)$$

- Residual spacetime symmetry
- KK modes identified by TWO indices $V^{(j,k)}$
- Under KK parity, particles are odd (even) if (j+k) = odd (even)
- Mass eigenvalues: $$M^2_{(j,k)} = M^2_0 + \pi^2 \frac{j^2 + k^2}{L^2},$$
- After zero-modes, lightest modes are (1,0)'s while (1,1)'s are √2 times heavier
- Collider study: Burdman, Dobrescu & Ponton, PRD74:075008 (2006))

The “Spinless Photon”

(Dobrescu et al., JCAP 0710:012,2007)

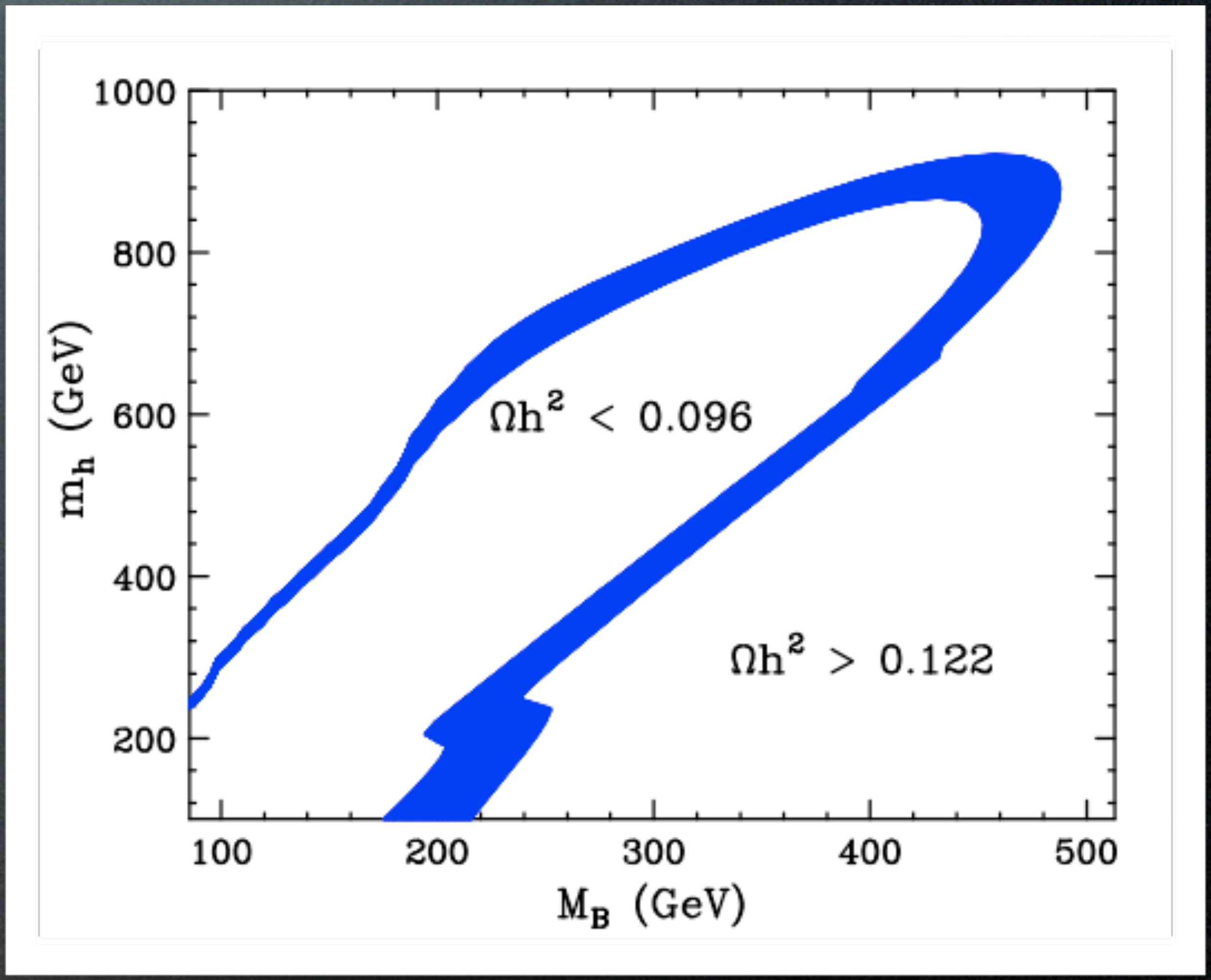
- WIMP = scalar partner of SM hypercharge gauge boson ($B^{(1,0)} \equiv B_H$)
- Annihilates mainly into pairs of WW, ZZ and HH



- Thermal relic abundance very sensitive to both B_H and SM Higgs masses
- Allowed mass range (neglecting coannihilations):

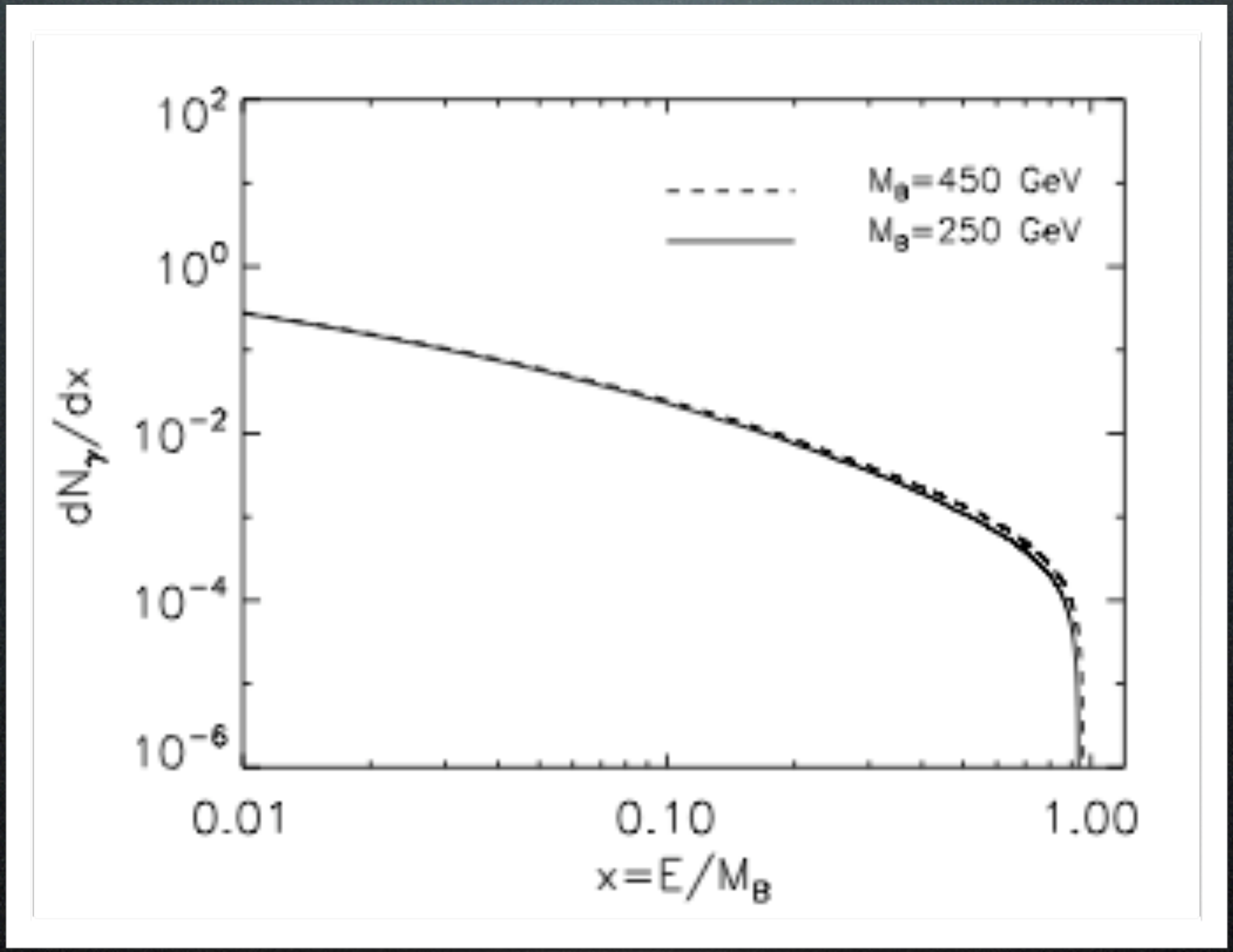
$$200 \text{ GeV} \lesssim M_B \lesssim 500 \text{ GeV}$$

- Good for Fermi!



Continuum Spectrum

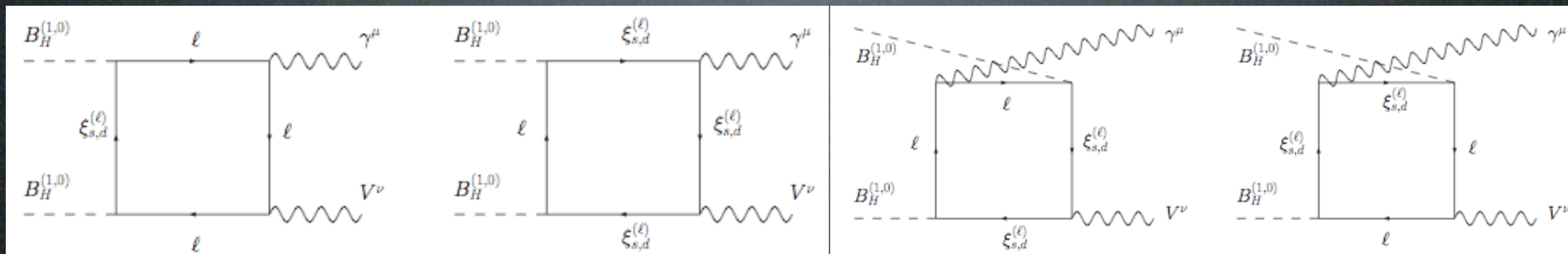
- Scalar WIMP → soft, featureless continuum



- Very reminiscent of the neutralino continuum!

Calculation of the “Lines”

- Annihilation to γ + V final states proceeds through box diagrams:



where V = γ , Z or $B^{(1,1)}$ mode.

- The amplitude:

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

$\longrightarrow$

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

- WIMP’s are highly non-relativistic (NR): $p_1 \simeq p_2 \simeq p \equiv (M_B, \mathbf{0})$

- Tricks:
  - Cons. of Momentum
  - Choosing the z-axis

$\longrightarrow$ A_1 is the dominant term

Nothing's Ever Easy

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

$$GD = \det(p_i \cdot p_j)$$

- 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 exactly vanishes

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

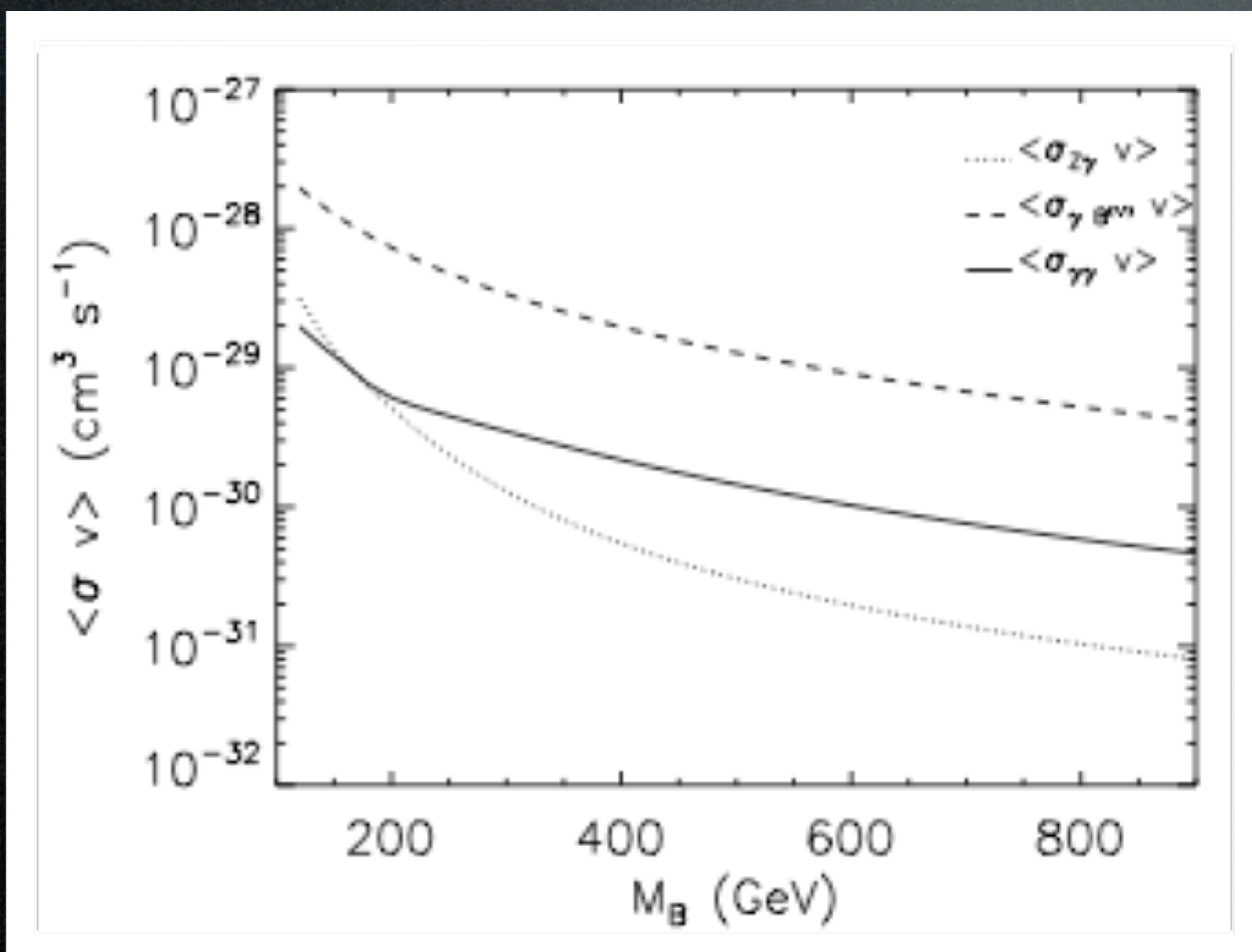
$$\downarrow$$

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

Line Cross Sections

- Summing over 24 diagrams (for massless SM fermions):

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



- Significant cancellations in $\gamma\gamma$ and Z γ amplitudes
- $B^{(1,1)}$ mode has suppressed couplings to SM fermions
- Less cancellation at amplitude level
- Enhanced $\gamma B^{(1,1)}$ cross section!

Astrophysical Uncertainties

- Largest uncertainties due to ignorance of DM distribution

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

- Two "benchmarks":
  - Navarro-Frenk-White (NFW): simulations with DM only
  - "Adiabatic": include baryons in simulations

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

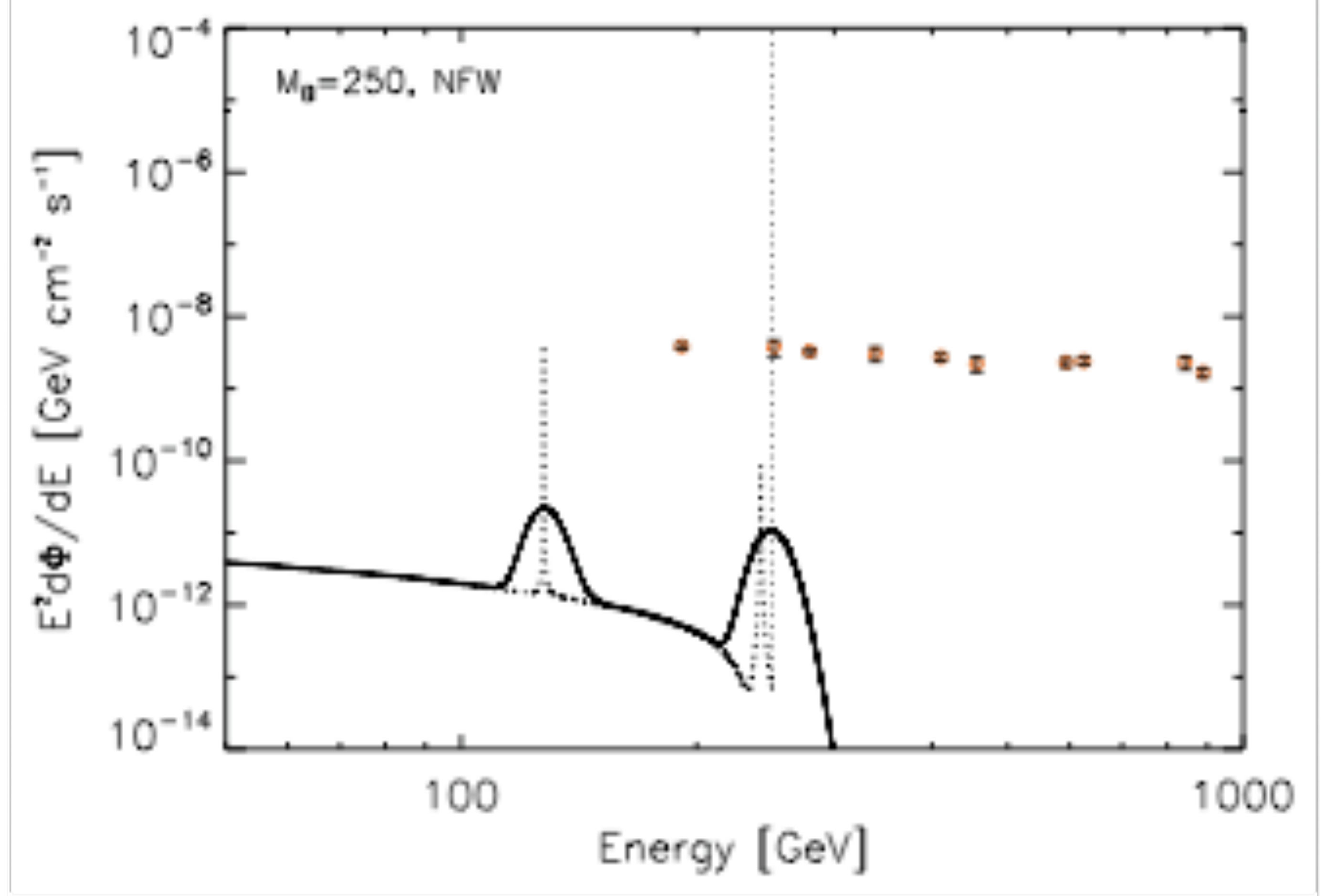
← Spans three orders of magnitude!

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

Results for the Chiral Square

- Three lines!
- Detector resolution (10%) "smears" $\gamma\gamma$ + Z γ into one "bump"
- Distinctive feature is the well-separated $\gamma B^{(1,1)}$ "bump"
- Contributing factors:
  - Mass of $B^{(1,1)} \sim O(M_{DM})$
  - Large $\gamma B^{(1,1)}$ cross section
  - Suppression of continuum

NFW Profile



Data = HESS point source J1745-290
(foreground for our signal)

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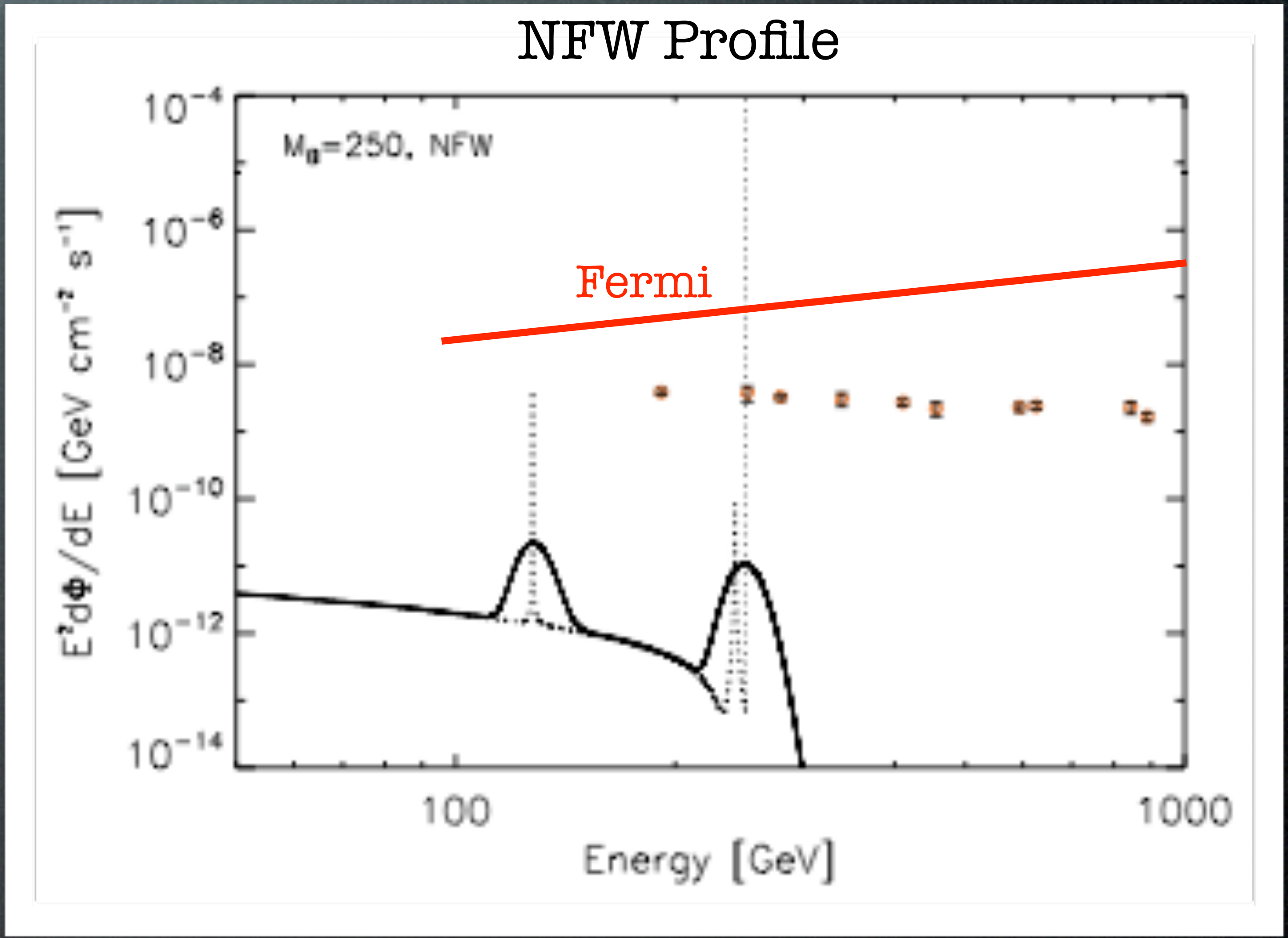

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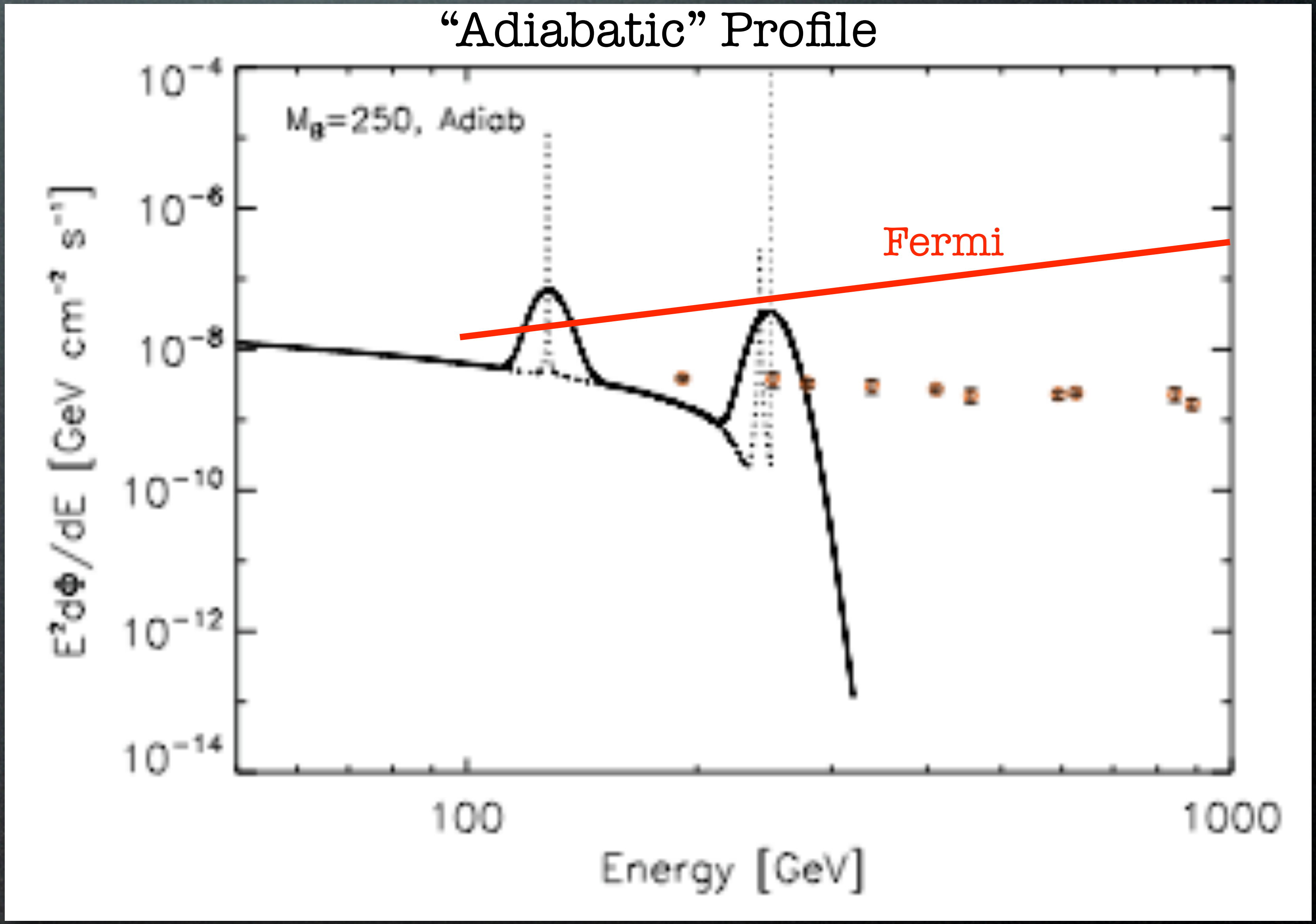
Large "Boost" Factors?

Note change in scale



Conclusions

- The “Amazing Race” is on!
- Indirect detection of DM via gamma rays can play an integral part:
    - WIMP mass
    - Spin, couplings, etc.
- “WIMP Forest”: a series of lines from the “dark sector”?
- Results from the “Chiral Square”
    - VERY DISTINCTIVE “two-bump” feature
    - Easily distinguishable from SUSY or IDM scenarios
- Future directions:
    - Counting extra-dimensions?
    - “Higgs in Space”?