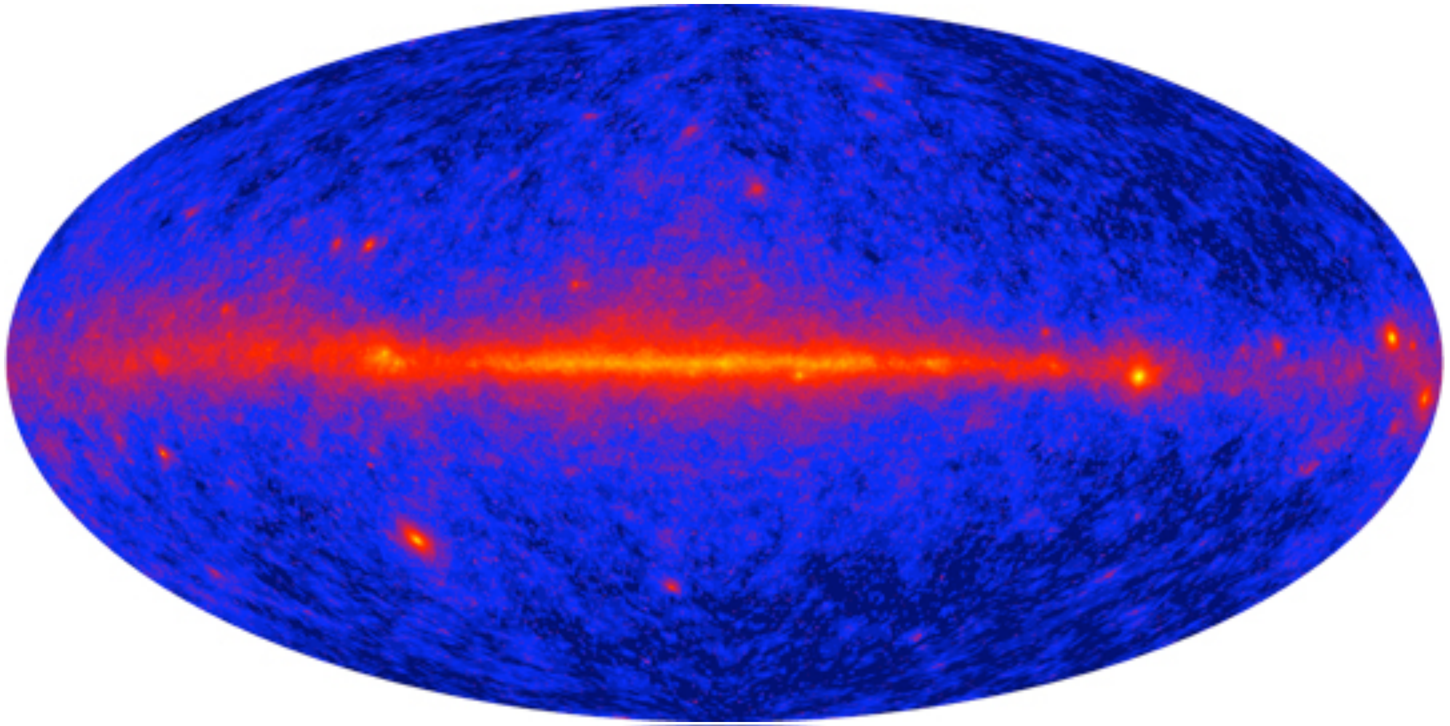

The WIMP Forest

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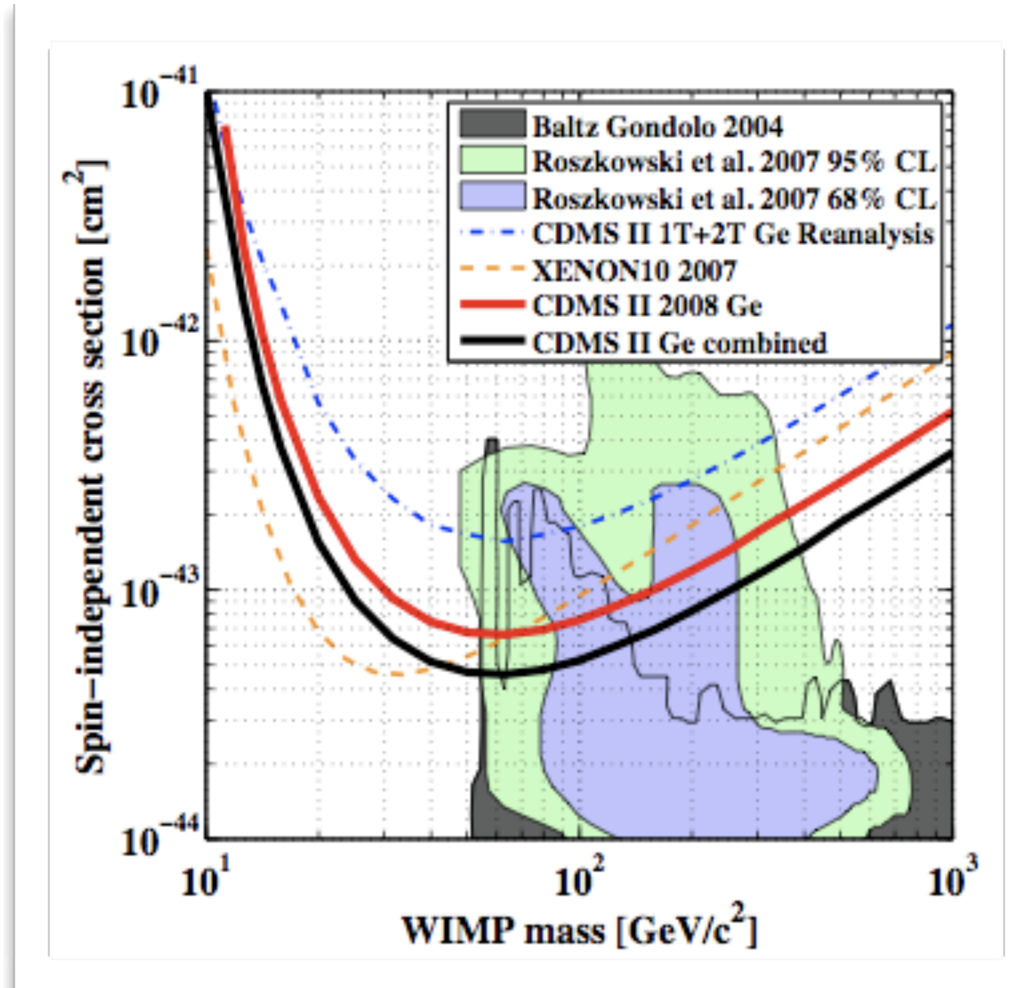
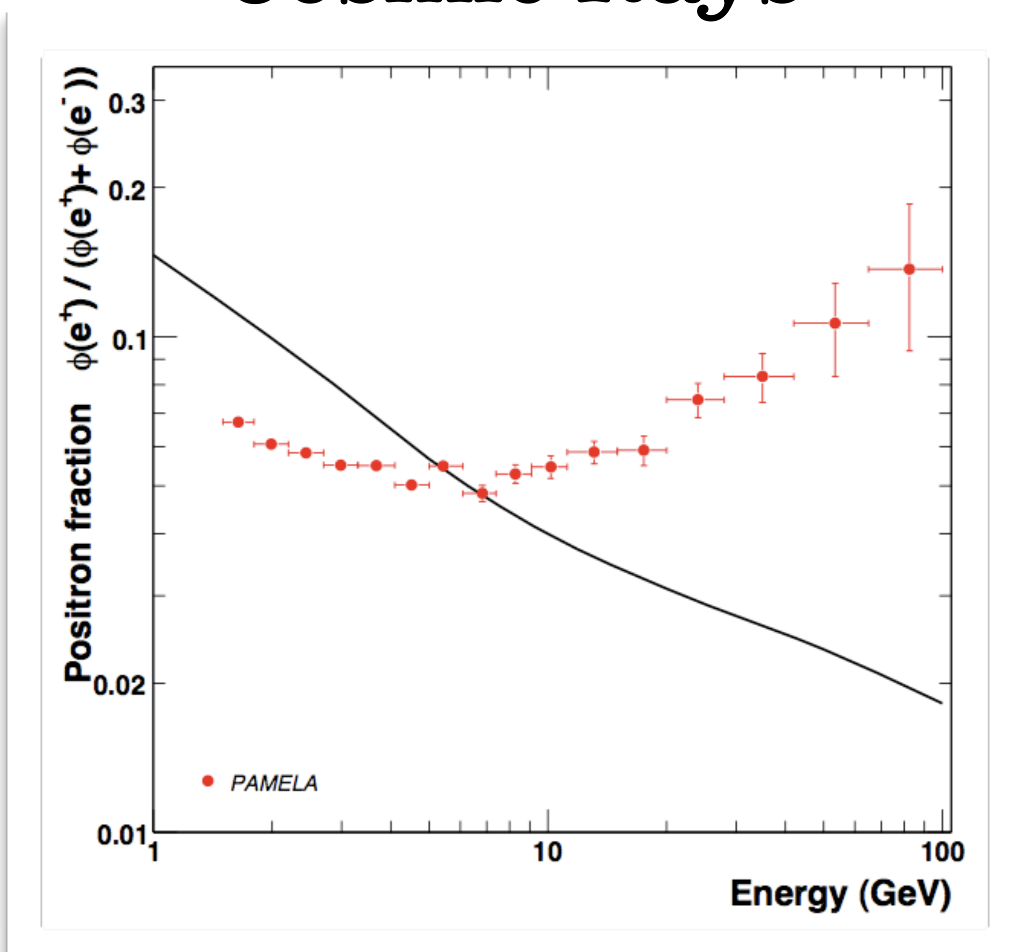
with: G. Bertone, G. Shaughnessy, T. Tait and A. Vallinotto

Based on arXiv:0904.1442

Direct Detection



Cosmic Rays



Colliders

(?)

Seeing the Light... from Dark Matter

- One way to (indirectly) detect Dark Matter is via annihilations into photons.
  - Searches performed with Fermi/GLAST and/or ground-based ACT's.
  - Advantage of γ's $\rightarrow$ travel in straight lines w/o much energy loss... identify sources and/or trace dark matter distribution?
- Expected spectrum of γ's from DM annihilation has two main components:
  - "Secondary" γ's from annihilation into charged SM particles which then radiate γ's OR hadronize and decay into γ's ($\pi^0 \rightarrow \gamma\gamma$).

The result is a CONTINUUM of γ's.

  - "Primary" γ's from LOOP-LEVEL annihilations into final states involving γ's (DM + DM $\rightarrow \gamma$ + X).

The result is (are) mono-energetic line(s) super-imposed onto continuum.

- Generally, lines are expected to be small (loop-suppressed) compared to the continuum.
- However, if observable, lines provide a nice discriminant against astrophysical backgrounds.

The WIMP Forest

- What if the nature of DM is such that continuum emission is suppressed while production of “direct” photons is via “large-ish” couplings?
  - The former can occur if DM annihilates mainly into “photon-unfriendly” states (such as Z’s or Higgs)
  - The latter can occur, for example, in models where the WIMP is related to the SM hypercharge gauge boson.
- The position/strength of lines can provide a wealth of information about DM.

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

→ $\gamma\gamma$ line measures mass of DM

→ Relative strengths γZ and $\gamma\gamma$ lines provides info on SU(2) couplings of WIMP

→ Observation of γH would indicate WIMP is not a scalar or Majorana fermion

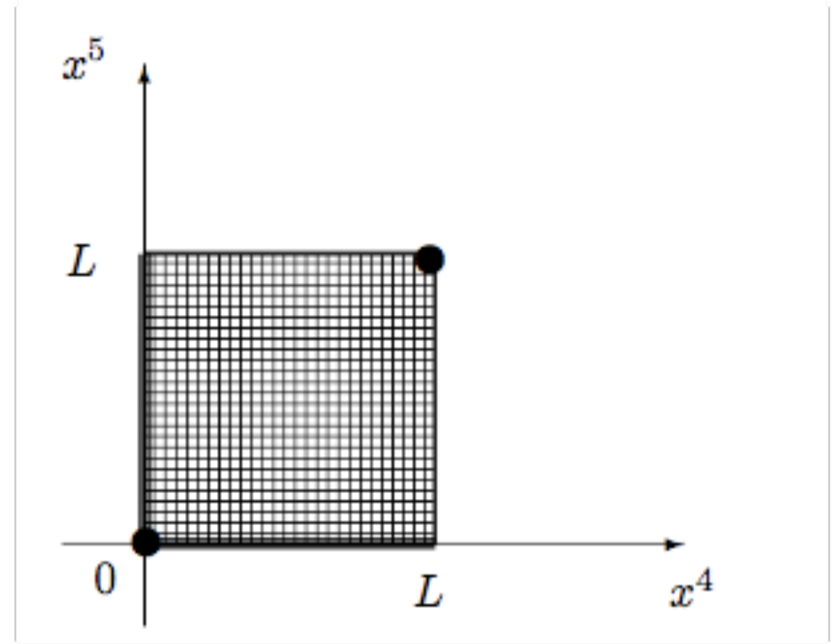
- If there are other particles in the “dark sector” with masses appreciable to the WIMP mass (but ≤ $2m_{DM}$), you could possibly observe a SERIES of LINES… i.e., a WIMP FOREST!!!

Case Study: The Chiral Square

- Model of Universal Extra Dimensions (UEDs) with TWO extra dimensions
  (Dobrescu & Ponton, JHEP 0403 (2004) 071)

- Identify adjacent sides of square:

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



- Kaluza-Klein (KK) modes identified by TWO indices (j,k)

$$k \geq 0 \;, \quad j \geq 1 - \delta_{k,0}$$

- Mass eigenvalues:

$$M^2_{(j,k)} \; = \; M_0^2 + \pi^2 \frac{j^2 + k^2}{L^2} \, ,$$

- Important for us: the lightest (non-SM) modes are the (1,0) modes, while the next-to-lightest modes are the (1,1) with masses ≃ √2 times heavier!
  (Compare to 5-d model where level-2 modes are TWICE as heavy)

The WIMP Candidate

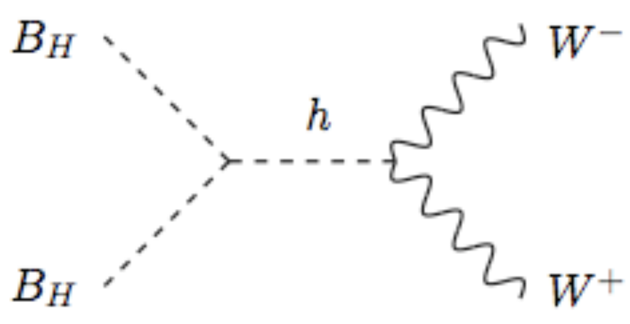
(Dobrescu et al., JCAP 0710:012,2007)

- Residual spacetime symmetry → lightest KK particle (LKP) is stable
  (j + k = odd (even) → state is odd (even) under symmetry)

- LKP expected to be SCALAR partner of the hypercharge gauge boson (a.k.a. “spinless photon”) $B^{(1,0)} \equiv B_H$

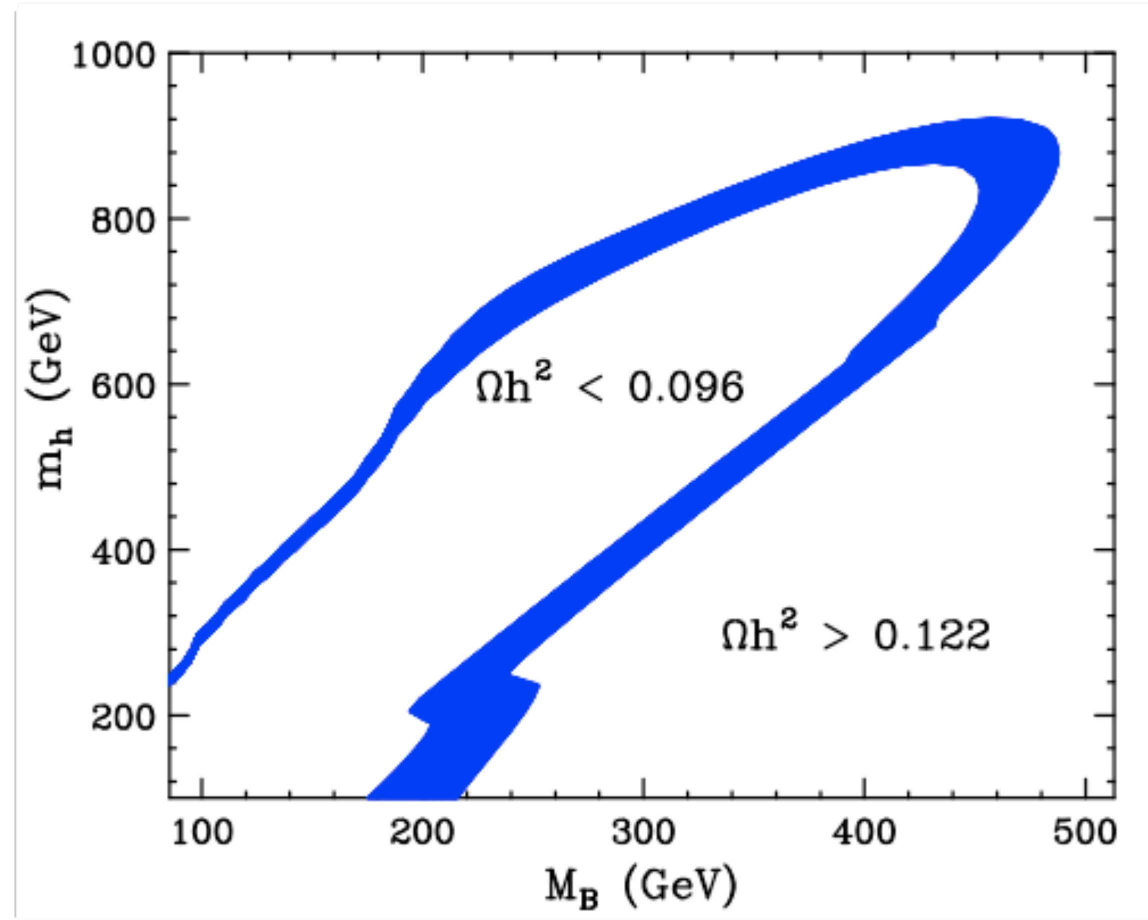
- Scalar LKP = suppressed annihilation to fermions...
  annihilates mainly into W’s, Z’s and Higgs.

- Thermal relic abundance very sensitive to B_H mass... as well as Higgs mass...



- WMAP constraints:

200 GeV ≲ M_B ≲ 500 GeV

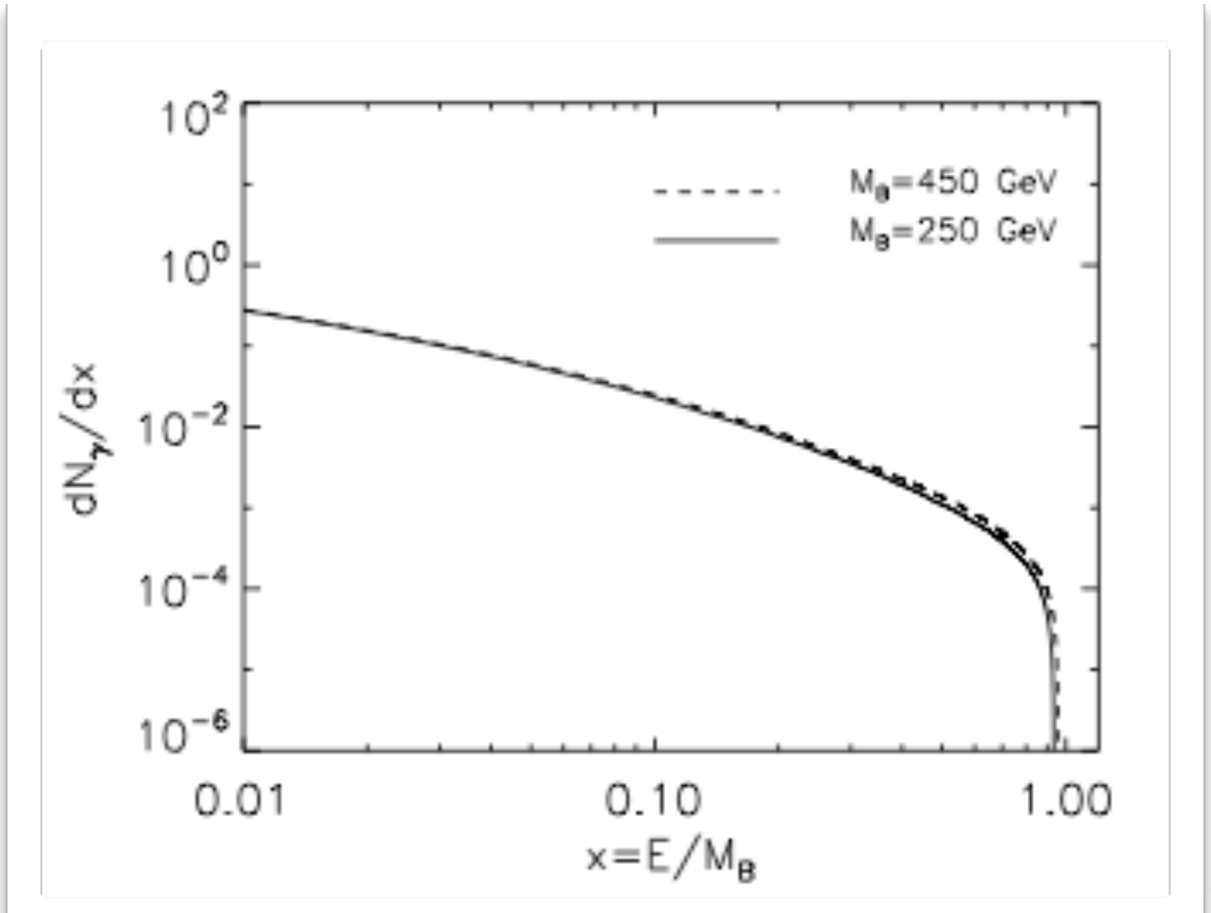


Gamma Ray Continuum

- In general, continuum consists of two components:
  - quark fragmentation/decay ($\pi^0 \rightarrow \gamma\gamma$): featureless, SOFT spectrum
  - final-state radiation: harder component of the form...

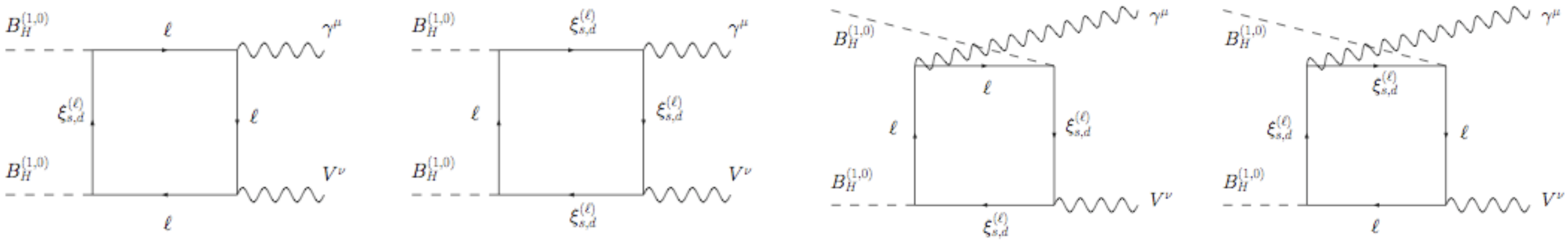
$$\frac{dN_{X\bar{X}}}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \quad \longleftrightarrow \quad \mathcal{F}_{\rm fermion}(x) = \frac{1+(1-x)^2}{x}, \quad \mathcal{F}_{\rm boson}(x) = \frac{1-x}{x}$$

- Scalar nature of LKP suppresses continuum...
- Annihilation into "photon-unfriendly" states (ZZ + HH) 50% of the time.
- Continuum spectrum reminiscent of neutralino



Calculation of the "Lines"

- Annihilation to γ + V final states proceed via box diagrams:



where V = γ , Z or $B^{(1,1)}$ mode.

- In general, the amplitude takes the form:

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

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

- Use the fact that WIMPs are non-relativistic (NR): $p_1 \simeq p_2 \simeq p \equiv (M_B, \mathbf{0})$... and other tricks... A_1 is the dominant contribution.

- "NR-ness" of WIMPs causes problems when computing the loops... specifically the Passarino-Veltman (PV) TENSOR coefficients.

- Reason: PV coefficients depend INVERSELY on Gram Determinant (GD):

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

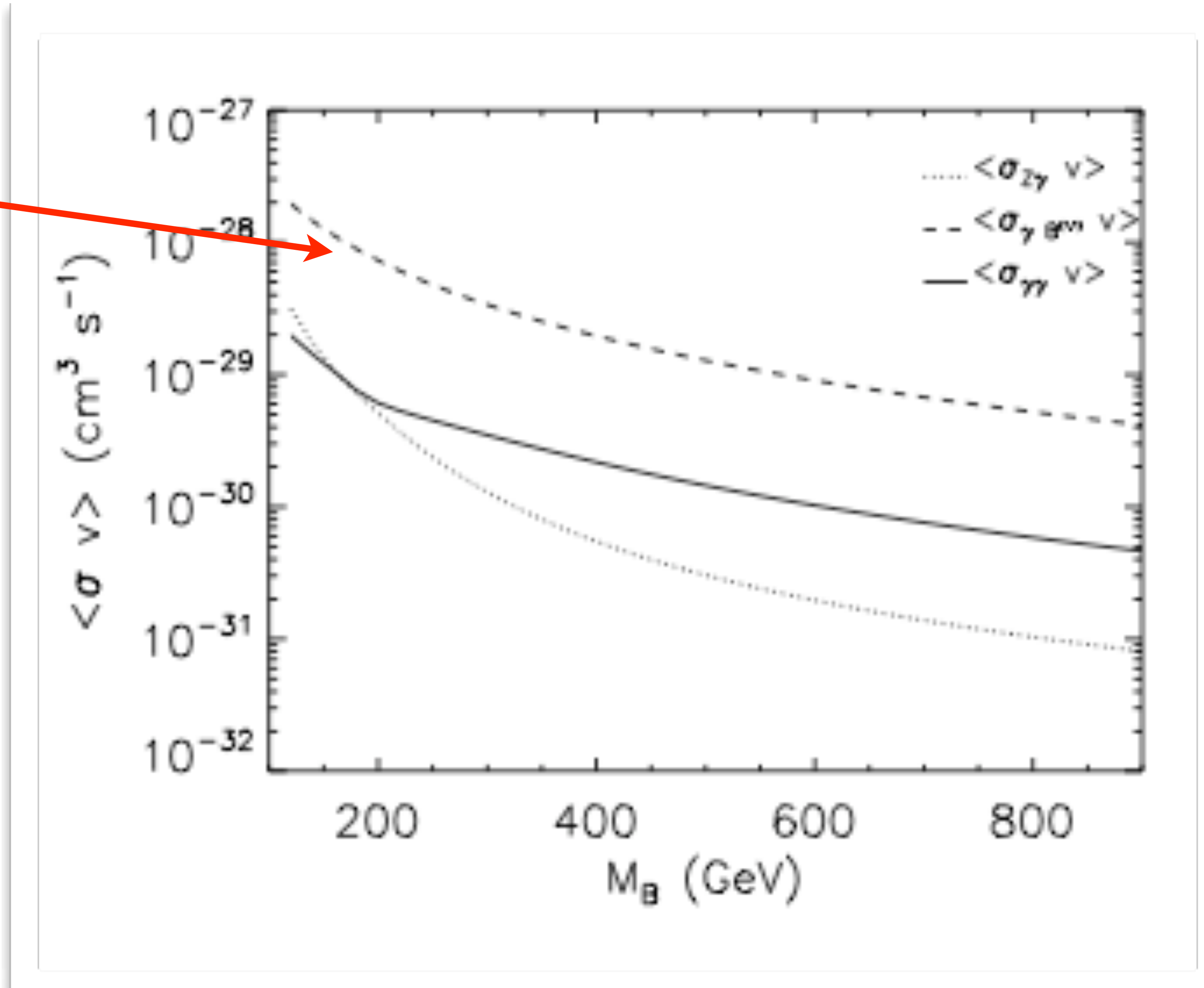
Line Cross Sections

- Used technique developed by R. Stuart (Comput. Phys. Commun. 48, 367 (1988))

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

and α's are solved for assuming GD exactly vanishes.

Note relative size of $B^{(1,1)}$ cross section!



Due to less cancellation at the amplitude level

Z and $B^{(1,1)}$ particles decay (broadening of line)

Putting it All Together

- The differential flux (@ angle ψ w.r.t. GC) :

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

- Separate particle physics from astrophysics:

$$J \equiv \int_{\text{l.o.s.}} \frac{ds}{r_\odot} \left[\frac{\rho[r(s,\psi)]}{\rho_\odot}\right]^2 \longrightarrow \bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} J(\psi)\, d\Omega.$$

- Consider two profiles: Navarro-Frenk-White (NFW) and "Adiabatic"

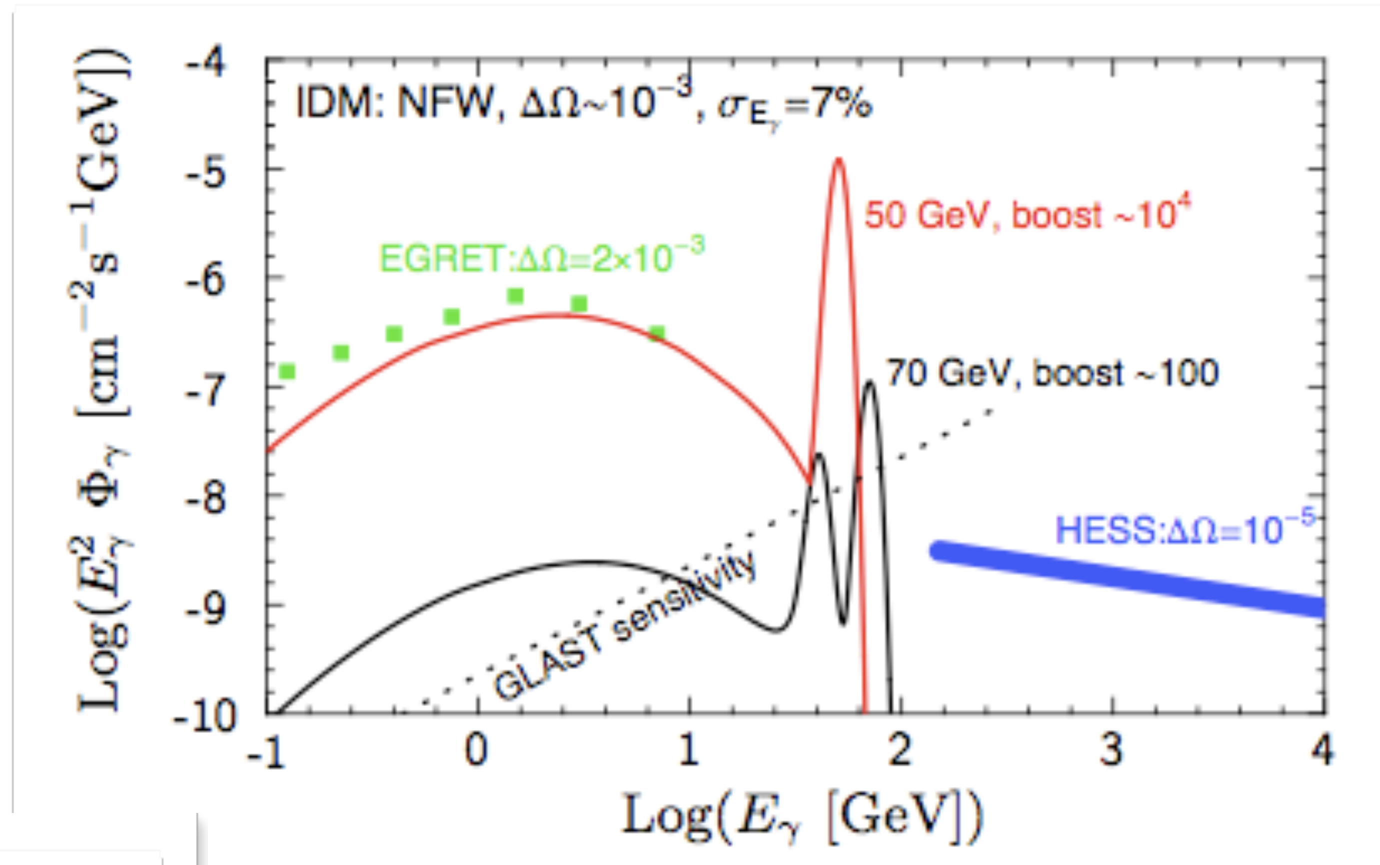
Model	$\bar{J}\ (10^{-5})$
NFW	1.5×10^4
Adiabatic	4.7×10^7

- Good news: signals like the ones considered here will "trace" DM distribution!

- To account for detector resolutions, convolve "signal" with Gaussian:

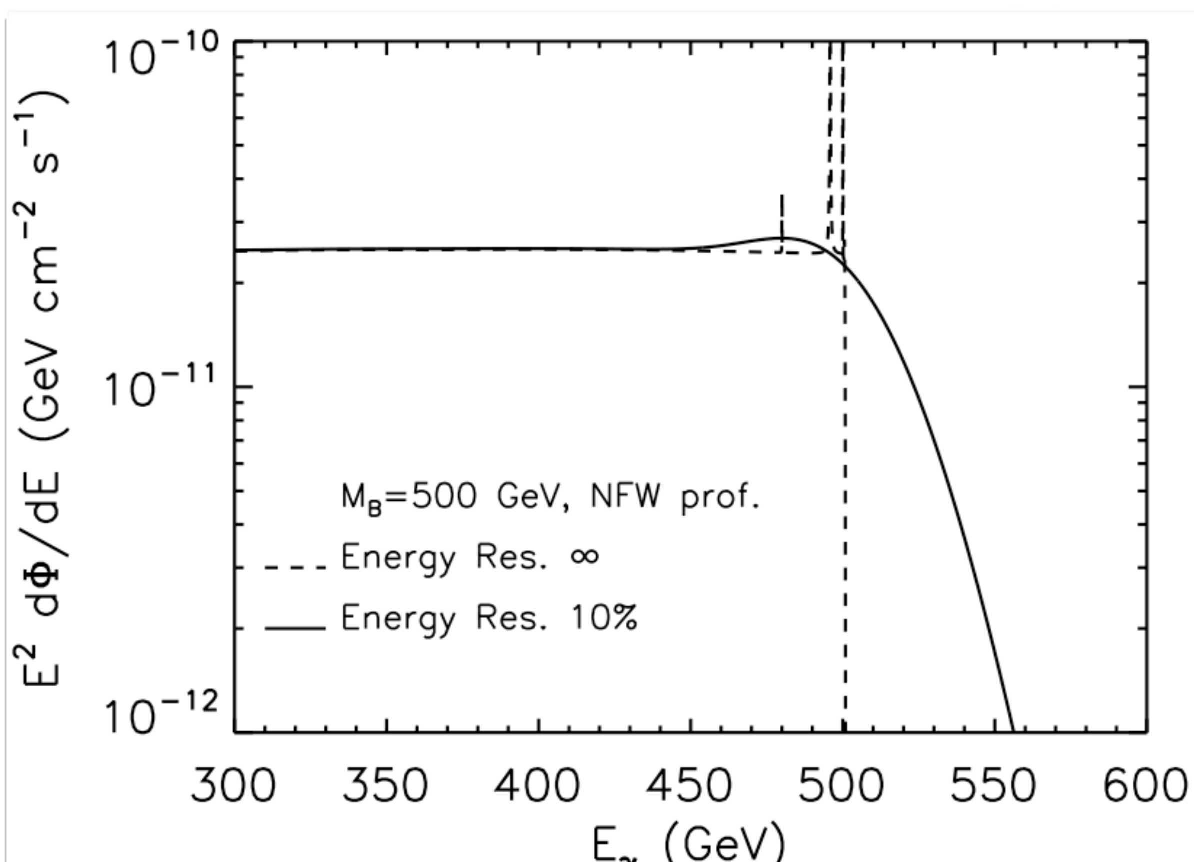
$$S_M(E_0) = \int dE\, G(E, E_0)\, S(E). \longrightarrow G(E, E_0) = \frac{1}{\sqrt{2\pi} E_0 \sigma} \exp\left[-\frac{(E - E_0)^2}{2\sigma^2 E_0^2}\right]$$

Setting the Stage



"The Inert Doublet Model"
(Gustafsson et al., PRL99: 041301, 2007)

WIMP = scalar
Lines = γγ and γZ



"5-d UED Model"
(Work in progress)

WIMP = vector gauge boson
Lines = γγ, γZ and γH

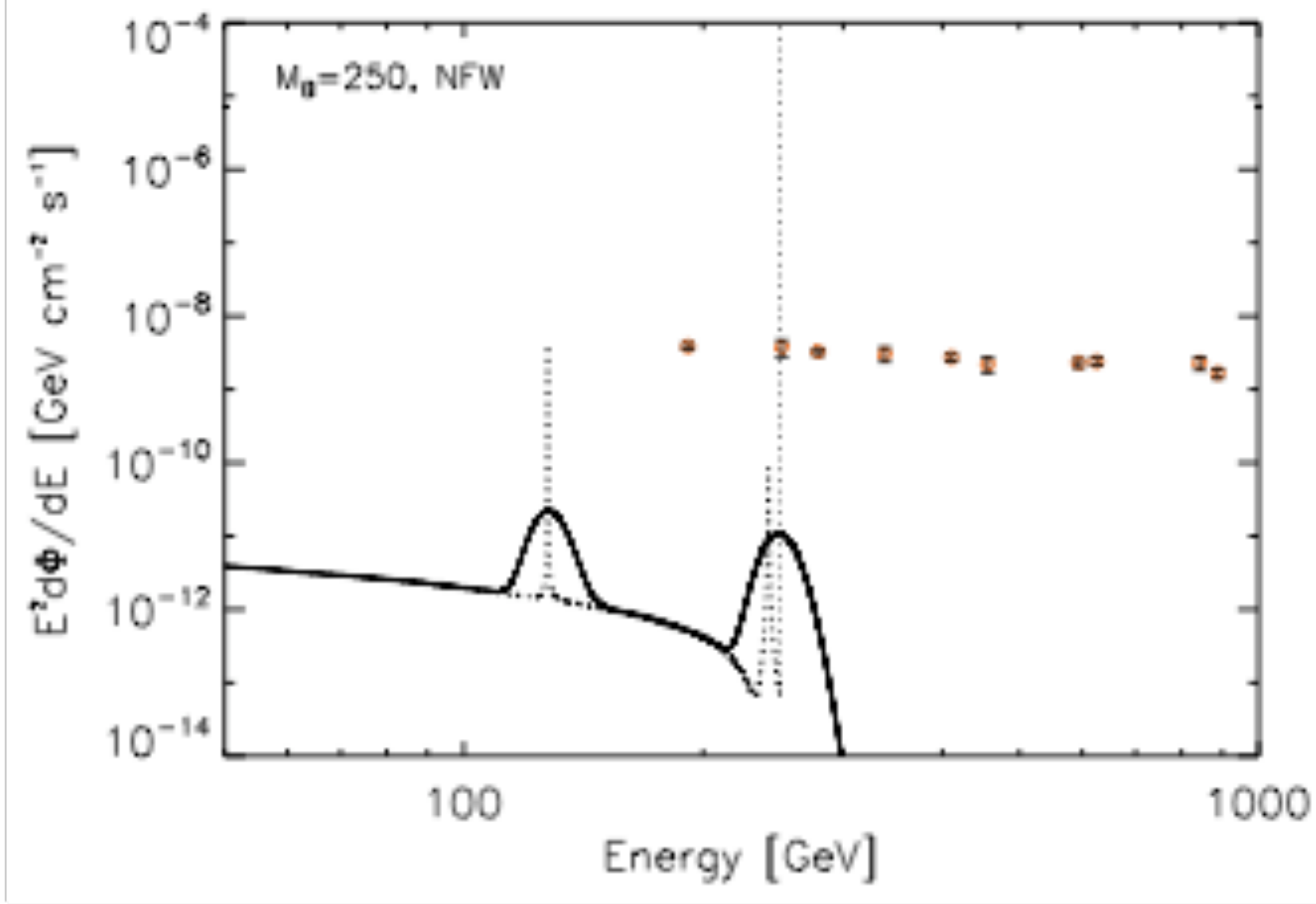
Results for the Chiral Square

- "WIMP Forest" characterized by 3 lines (and suppression of continuum)
- $\gamma\gamma$ line (@ $E_\gamma = M_B$), $Z\gamma$ (very close to M_B) and $B^{(1,1)}\gamma$ line
- Detector resolution ($\Delta E/E$ = 10%) effects smear $\gamma\gamma$ and $Z\gamma$ lines into one "bump"
- Distinctive feature of the Chiral Square model is the $B^{(1,1)}\gamma$ line!
- Since $B^{(1,1)}$ mass is comparable to WIMP mass...

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

is well-separated from $\gamma\gamma$ + $Z\gamma$ bump and distinguishable... even after detector resolution effects are accounted for!

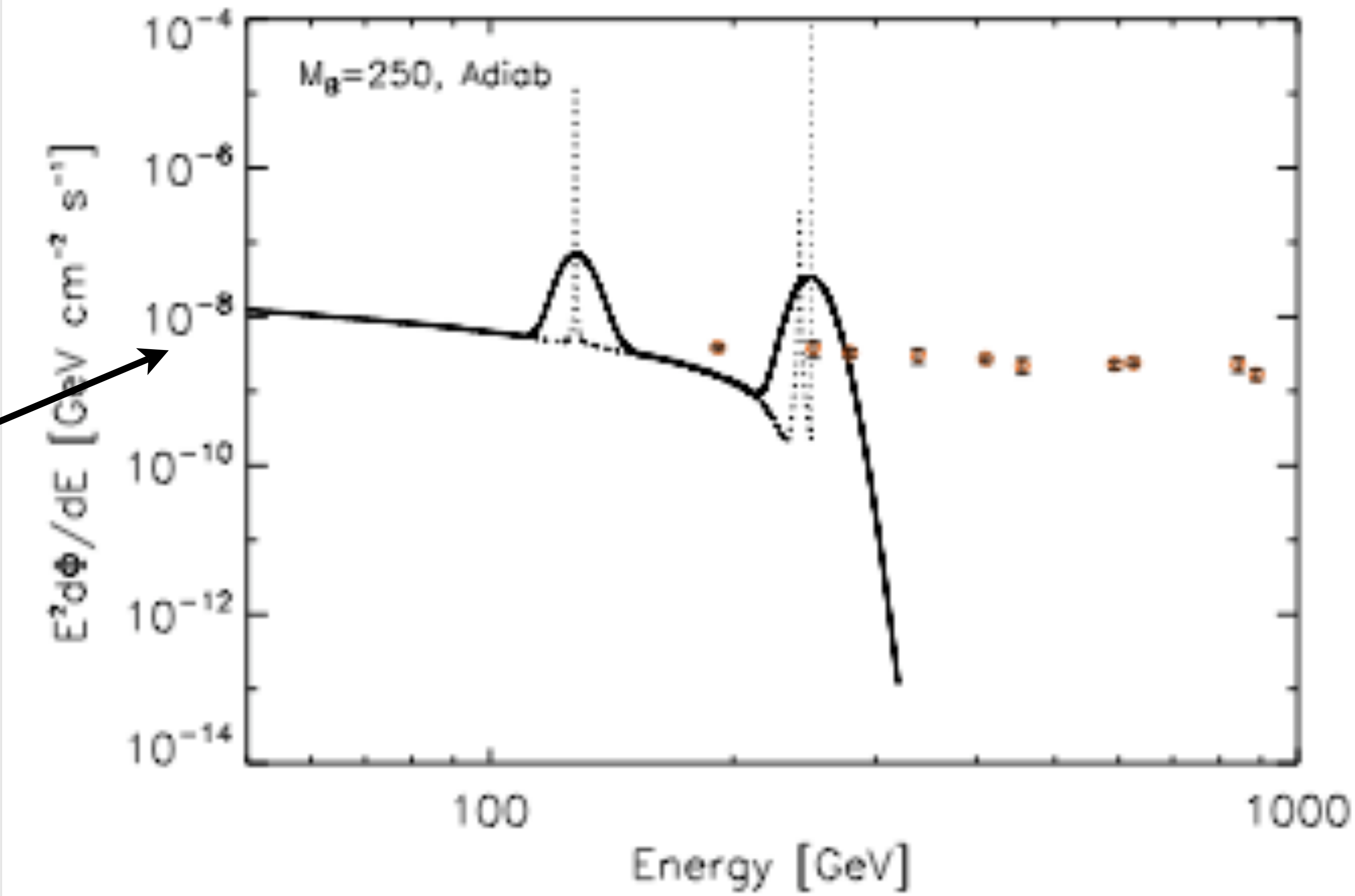
NFW Profile



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

Large Boost Factors?

"Adiabatic" Profile



Note change in scale

Conclusions

- I can’t believe I made it this far in 13 minutes!
- Search for DM via annihilation into photons:
  - Particle physics: information on DM properties(?)
  - Astrophysics: trace out DM distribution!
- “WIMP Forest”: if there are other particles in the “dark sector” with masses appreciable to the WIMP mass (but $\leq 2m_{DM}$), you could possibly observe a SERIES of lines!
- Case study: 6-d UED “Chiral Square”
  - WIMP = scalar (“spinless”) photon
  - Relic Density: $200 \text{ GeV} \lesssim M_B \lesssim 500 \text{ GeV}$
- Gamma-ray Spectrum:
  - Suppressed continuum spectrum
  - VERY DISTINCTIVE TWO-BUMP FEATURE!