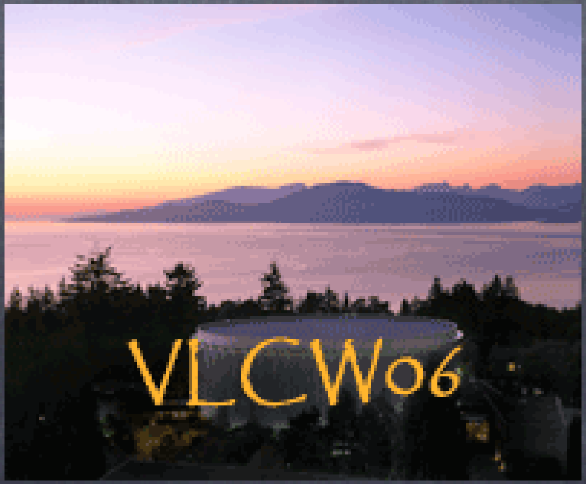
Little Higgs Dark Matter

Andrew Noble
in collaboration with
Andreas Birkedal, Maxim Perelstein, and Andrew Spray
arxiv:hep-ph/0603077



The Littlest Higgs Model with T Parity (LHT)

Evolution of the LHT Idea

- The "Little Higgs" question: Could the Higgs be a pseudo-GSB of a global symmetry broken at a scale $f \sim 1$TeV?
  Georgi, et. al. (1974)
- Higgs mass unstable: With 1-loop corrections, $m_h \to f$. Solution: Collective Symmetry Breaking.
  Arkani-Hamed, Cohen, Georgi (2002)
- An economical implementation: The "Littlest Higgs" model.
  a) EW sector embedded in an SU(5)/SO(5) nlsm.
  b) Heavy vector quark, triplet scalar, and four GB's.
  Arkani-Hamed, Cohen, Katz, Nelson (2002)
- Little Hier. Problem: Violates EWPM without fine-tuning. Solution: A Z_2 symmetry dubbed "T Parity" (LH's R Parity).
  Cheng and Low (2004)

600GeV < f < 3TeV OK!

Hubisz, Meade, AN, and Perelstein (2005)

Why study the LHT?

- Stabilizes the Higgs mass with perturbative physics at the TeV scale and radiative EWSB.

- Satisfies EW constraints without fine-tuning.

- Provides a WIMP dark matter candidate.

- Predicts the pair production of new heavy particles and a generic missing energy signal that could fake SUSY at the LHC.

LHT Structure

Globally $SU(5) \rightarrow SO(5)$ by $\Sigma_0 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix}$

Gauged subgroup $[SU(2) \times U(1)]_{1,2} \rightarrow SU(2)_L \times U(1)_Y$

Higgsing generates W^a_H and B_H.

Explicitly breaks SU(5)!

T Parity $[SU(2) \times U(1)]_1 \leftrightarrow [SU(2) \times U(1)]_2$

Gauged generators $Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ $Y_1 = \mathrm{diag}(3,3,-2,-2,-2)/10$

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix} \qquad Y_2 = \mathrm{diag}(2,2,2,-3,-3)/10$$

A Non-Linear Sigma Model

Goldstone Expansion

$$\Sigma = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f}$$

where $\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$

Low Energy Dynamics

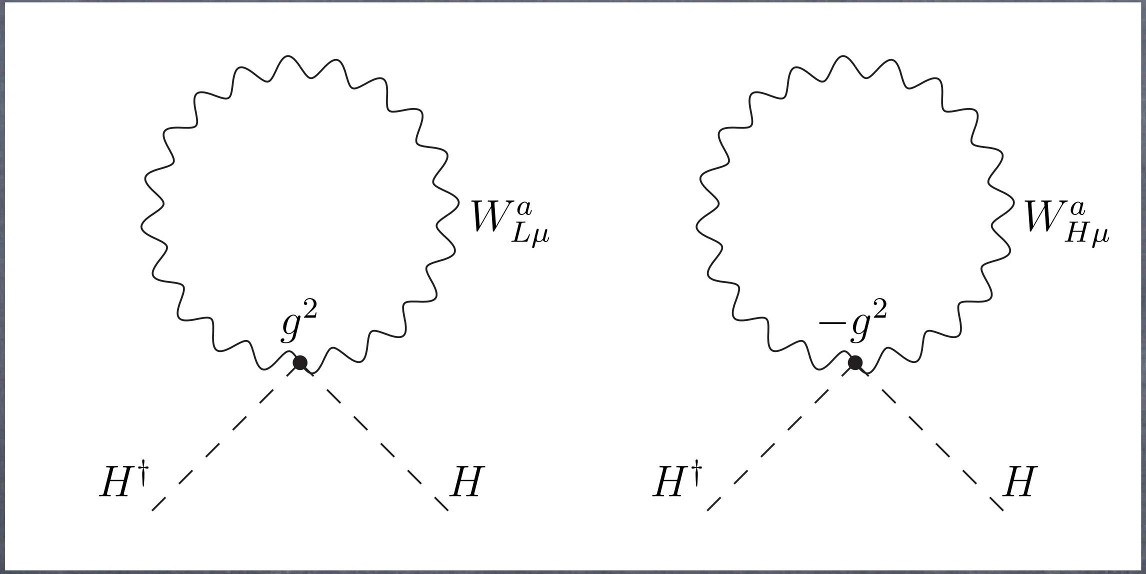
$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}{\rm Tr} D_\mu\Sigma(D^\mu\Sigma)^\dagger$$

with $\Lambda_{\rm NDA} \sim 4\pi f$

"Bosonic SUSY!"

- At one-loop order, quadratic divergences in the Higgs mass due to SM particles are cancelled by heavy particles of the same spin-statistics running in the loop.

"Collective Symmetry Breaking"



- At two-loop order, the Higgs mass will receive quadratic corrections, but no fine-tuning required if Λ~10TeV.

$$\Delta m_h^2 \sim \frac{g^4}{(4\pi)^4}\Lambda^2$$

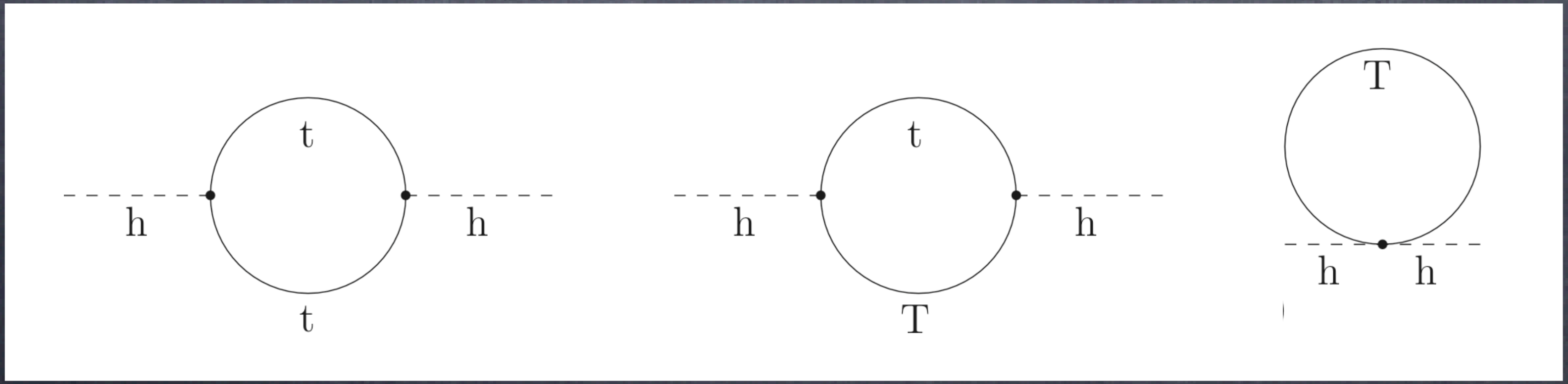
Radiative EWSB

- Implementing the collective symmetry breaking pattern in the top sector introduces a T-even heavy Dirac fermion.

"T"

- Top sector gives leading contribution in the CW potential.

$$m_h^2 = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2}$$



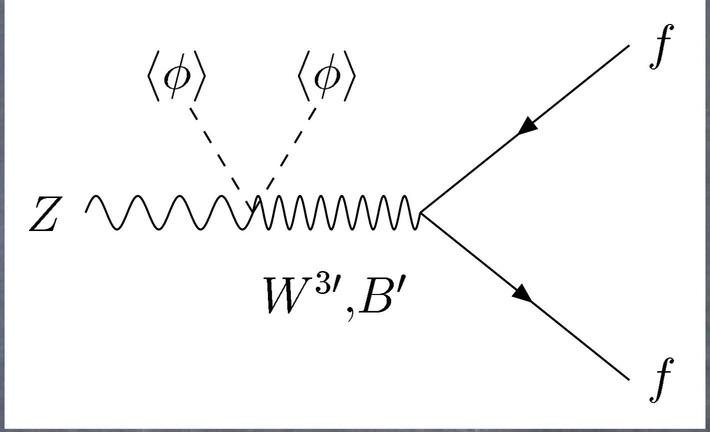
Electroweak Constraints

Hewett, Petriello, Rizzo (2002)
Csaki, Hubisz, Kribs, Meade, Terning (2003)

- Problems without T Parity

1) A small but non-vanishing $<\phi>$ due to $h\phi h$ tadpole.

2) The tree-level exchange of heavy gauge bosons.



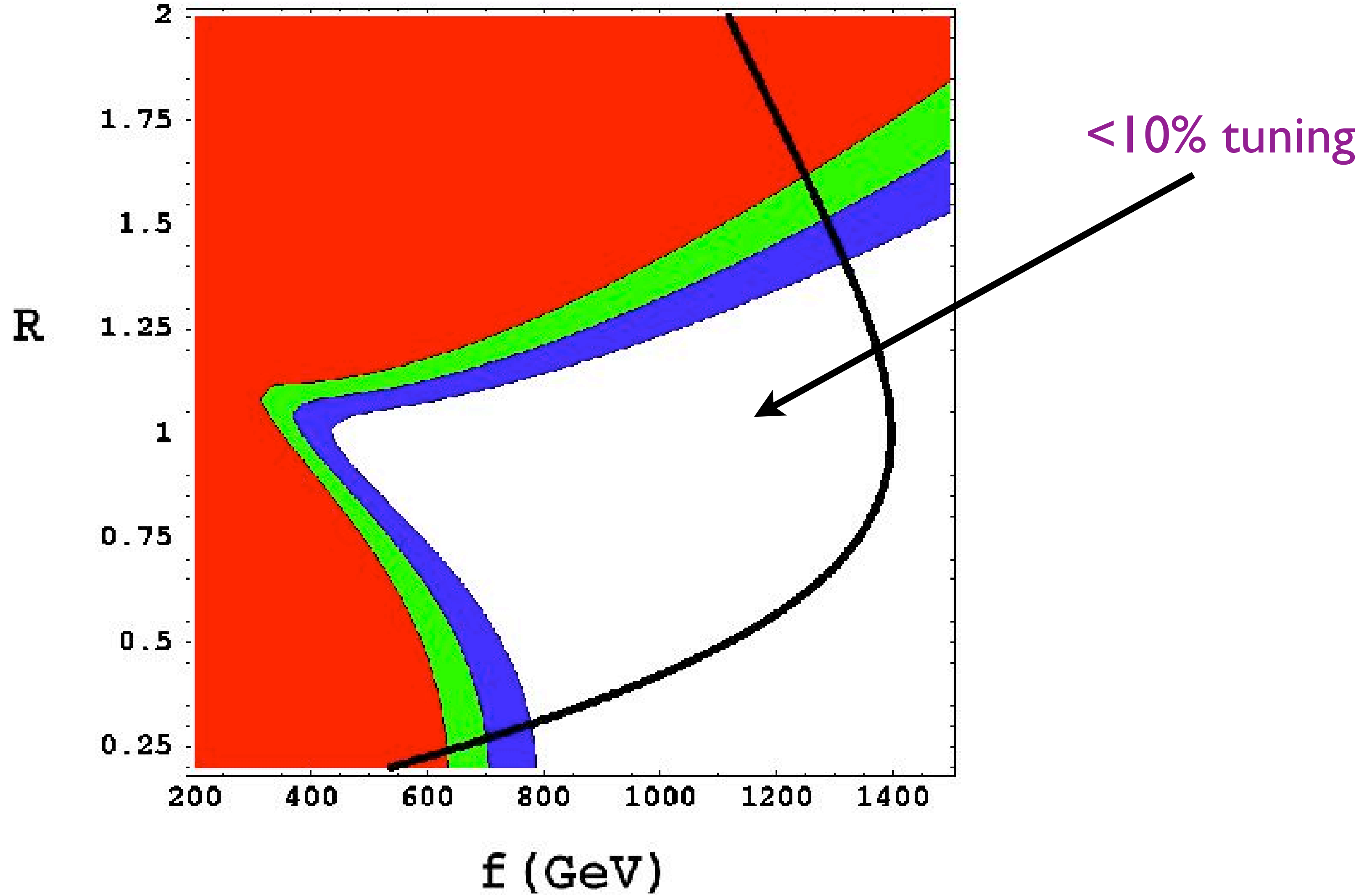
- T Parity saves the Littlest Higgs in the same way that R Parity saves Supersymmetry.

1) Leading corrections to EWPM occur at one-loop order.

2) Heavy top contributions to the T parameter dominate EWP fits.

LHT Fit to EWPM

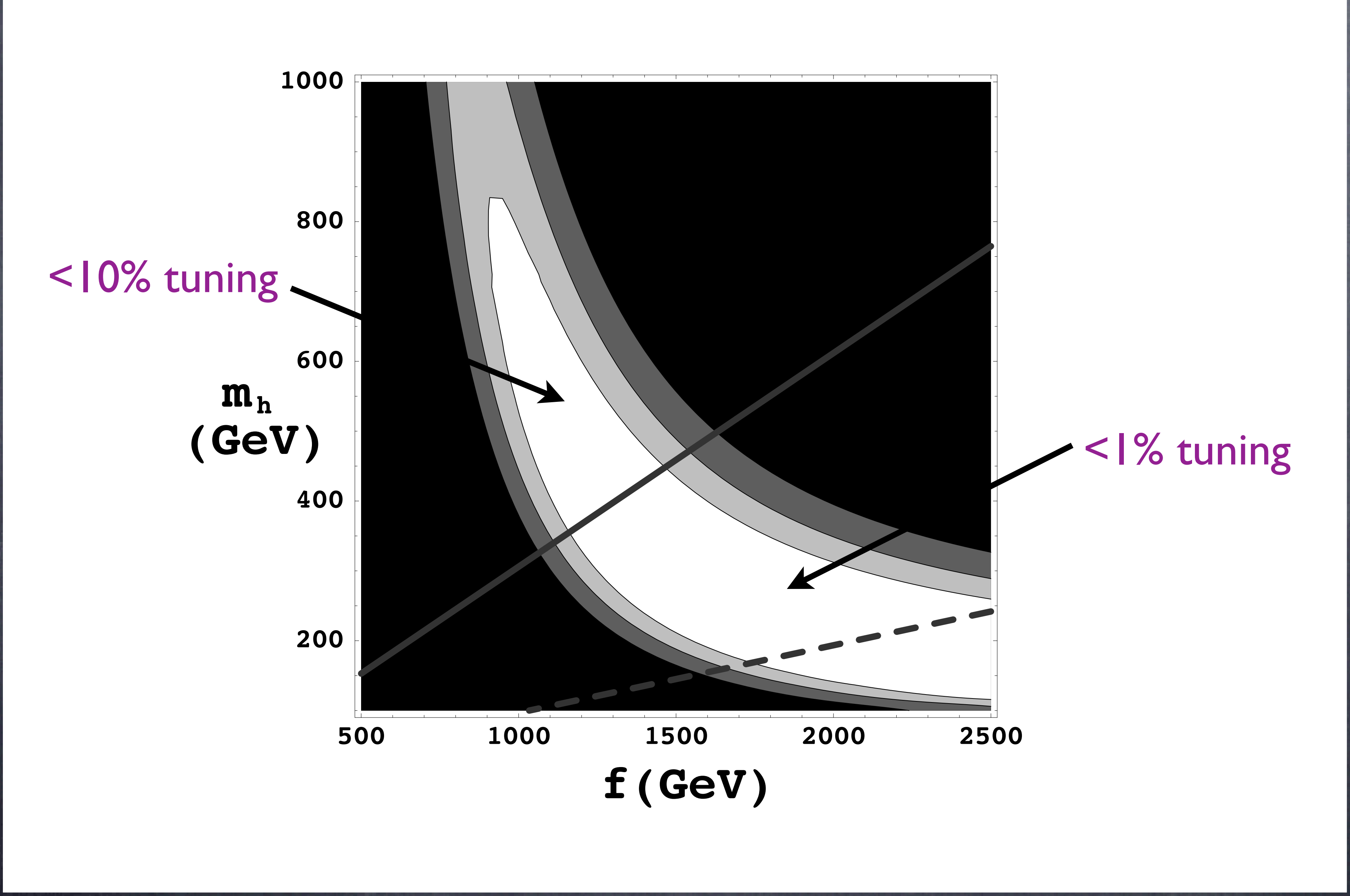
Hubisz, Meade, AN, and Perelstein (2005)



$$m_{h,ref} = 113\text{GeV}$$

A Heavy Higgs Region

Hubisz, Meade, AN, and Perelstein (2005)



$R = 2$

The LHT Fermion Content

SM T-even Fermions

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L^c \begin{pmatrix} c \\ s \end{pmatrix}_L^c \begin{pmatrix} t \\ b \end{pmatrix}_L^c$$

$$e_R, \mu_R, \tau_R, u_R, d_R, c_R, s_R, t_R, b_R$$

Composite T-odd Fermions

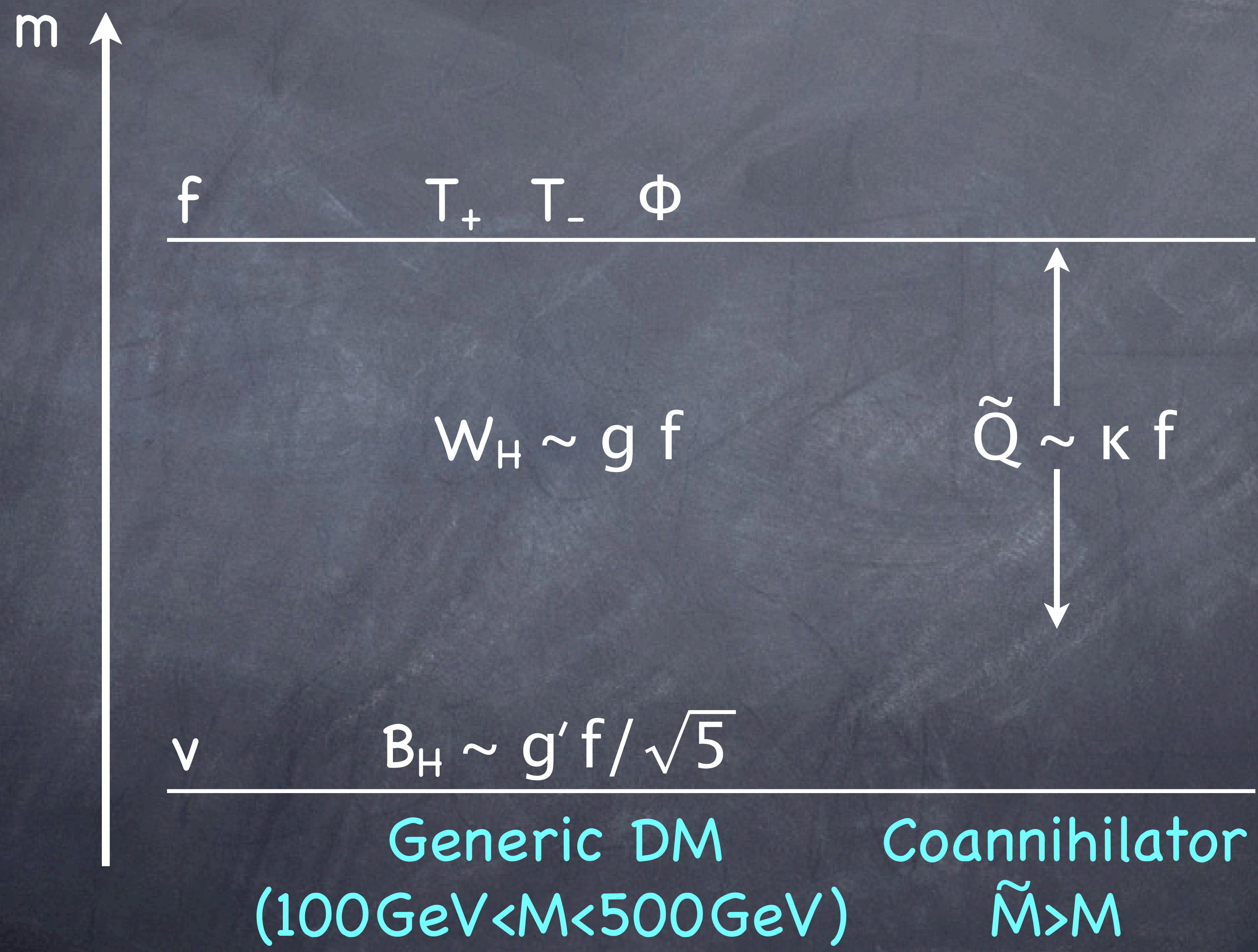
$$\begin{pmatrix} \nu_{e_-} \\ e_- \end{pmatrix}_L \begin{pmatrix} \nu_{\mu_-} \\ \mu_- \end{pmatrix}_L \begin{pmatrix} \nu_{\tau_-} \\ \tau_- \end{pmatrix}_L$$

$$\begin{pmatrix} u_- \\ d_- \end{pmatrix}_L^c \begin{pmatrix} c_- \\ s_- \end{pmatrix}_L^c \begin{pmatrix} t_- \\ b_- \end{pmatrix}_L^c$$

$$T_{L+}, T_{L-}, T_{R+}, T_{R-}$$

For our purposes, assume a common mass ~κf.

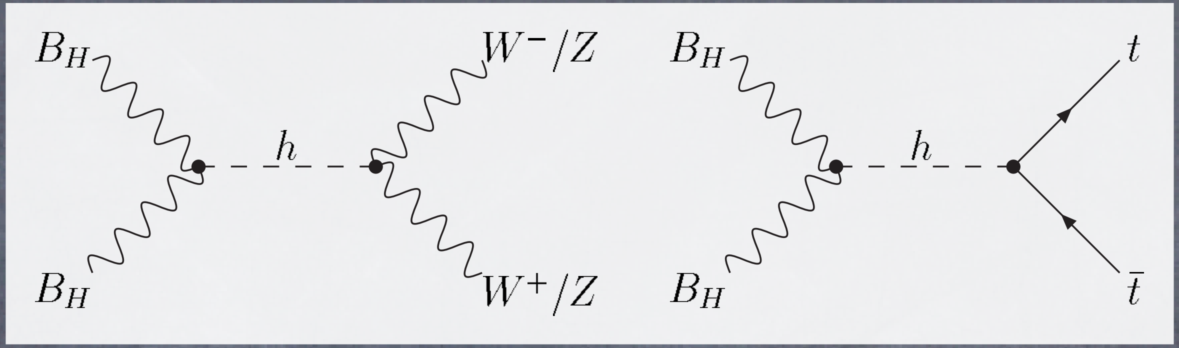
Heavy Particle Spectrum



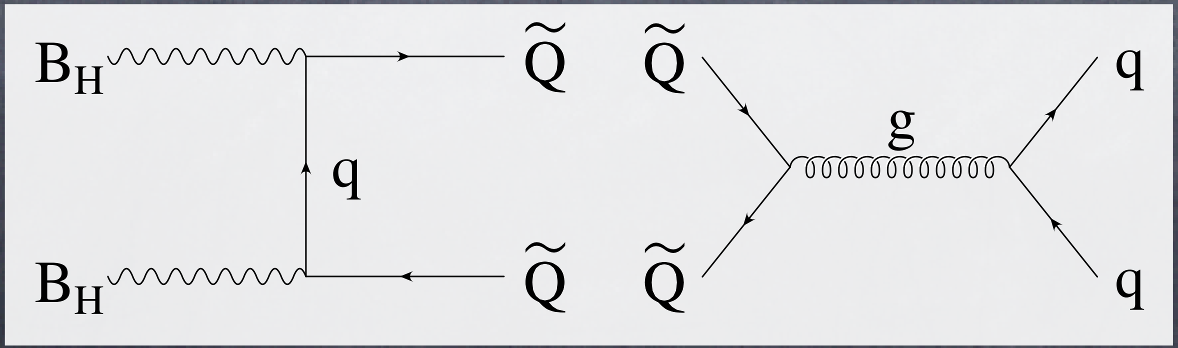
LHT Dark Matter

Relic Density

- Pair annihilation: $\langle \sigma v \rangle$ gives $\Omega_{dm} h^2$. B_H is an s-annihilator!

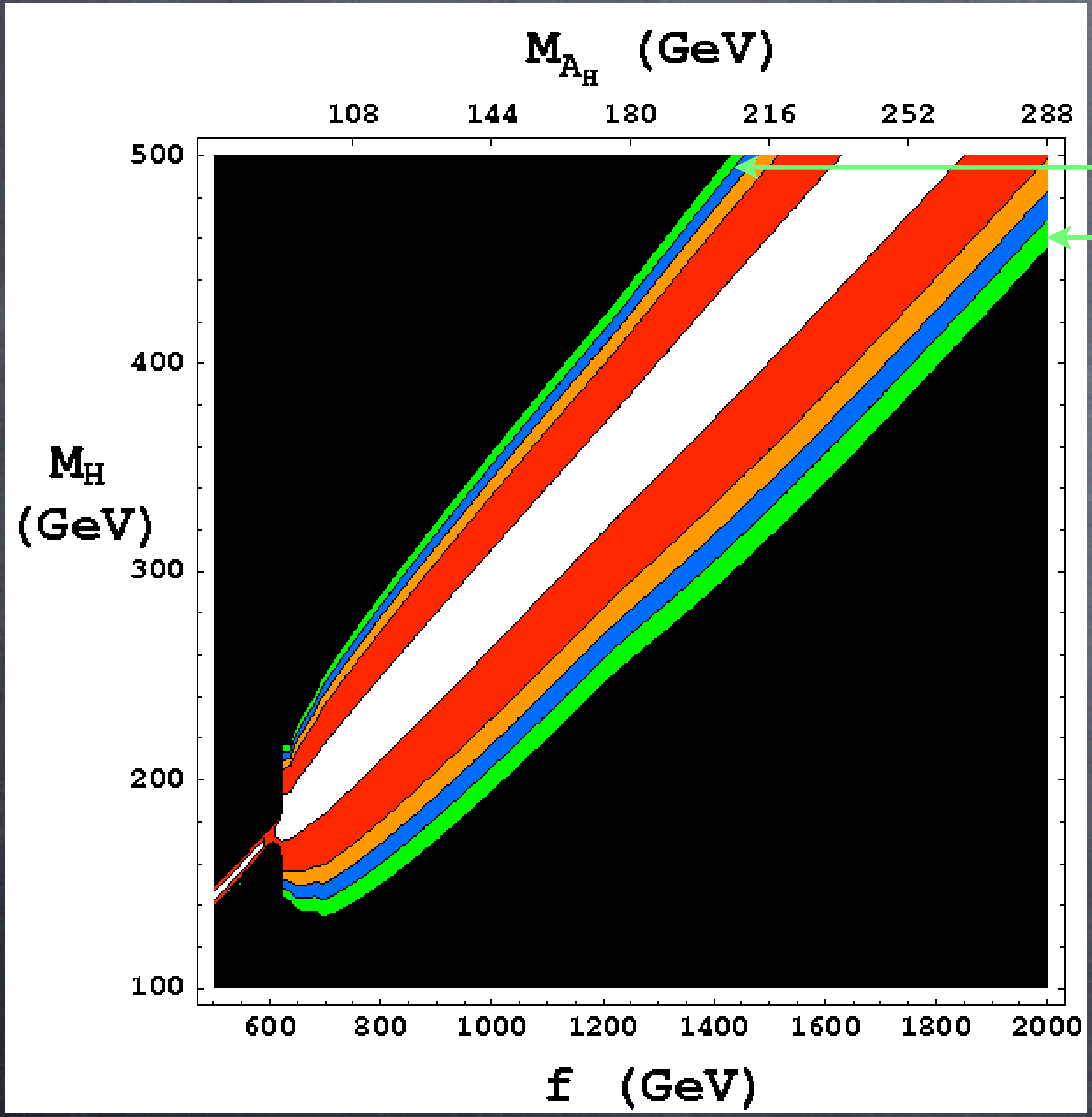


- Coannihilation: Solve two coupled Boltzmann equations.



Pair-Annihilation

Hubisz and Meade (2004)



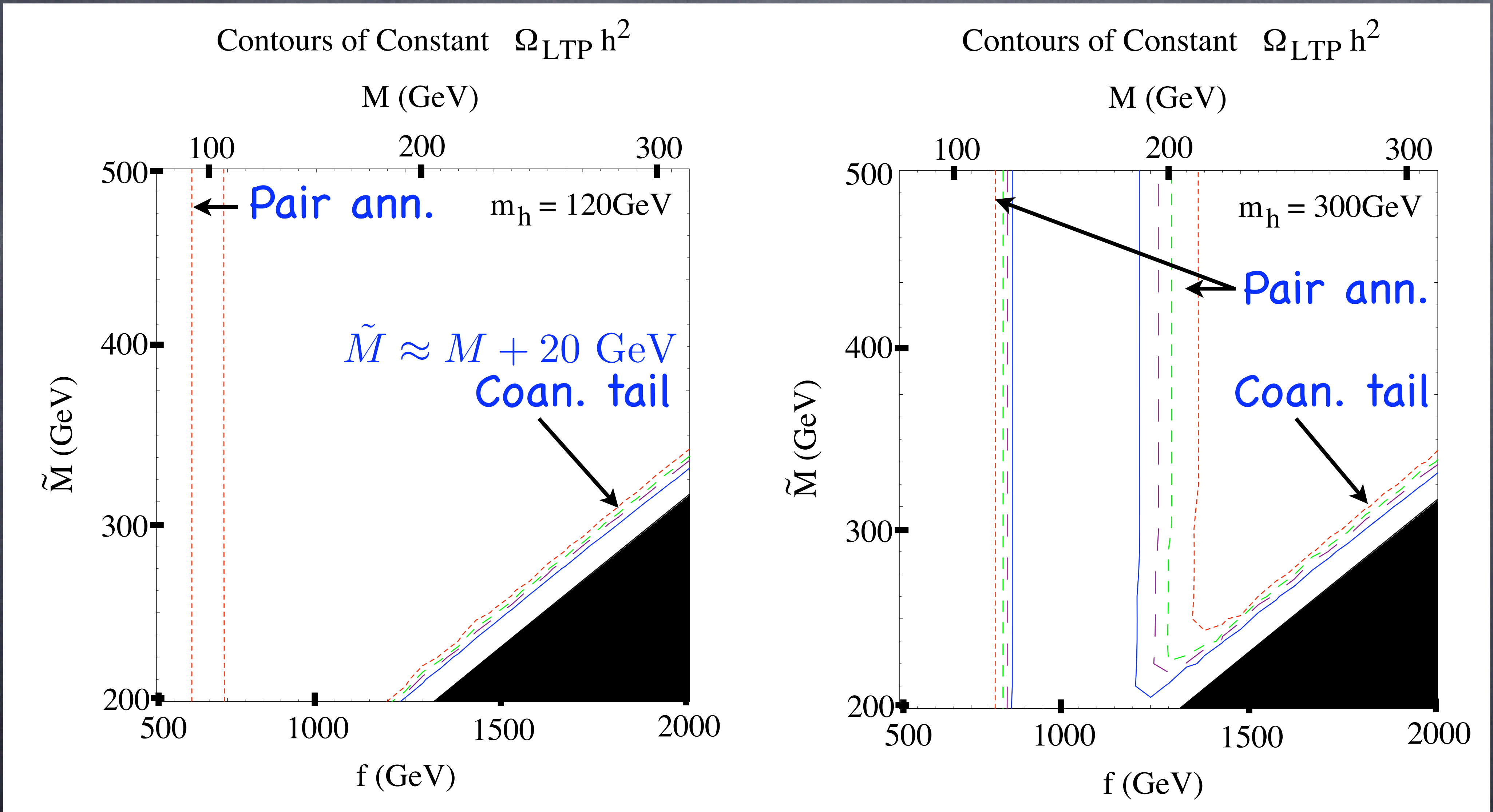
"High" $m_h \approx 2.38M + 24\text{GeV}$

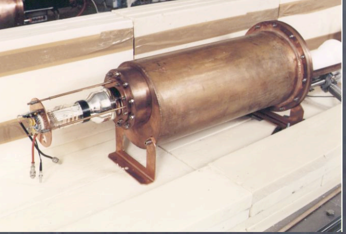
"Low" $m_h \approx 1.89M - 83\text{GeV}$

Regions where B_H accounts for 100% of the WMAP DM value.

$$\Omega_{dm}h^2 = 0.111 \pm 0.018$$

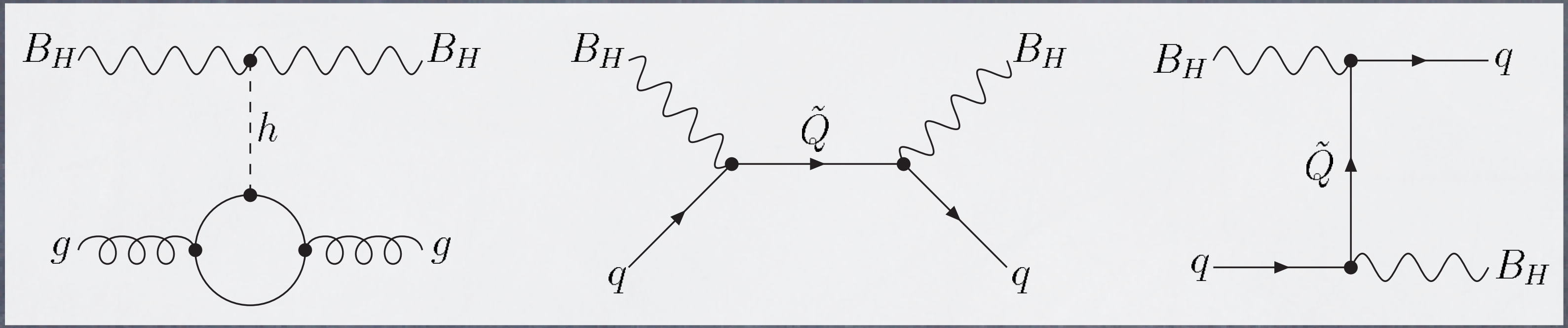
Coannihilation





Direct Detection

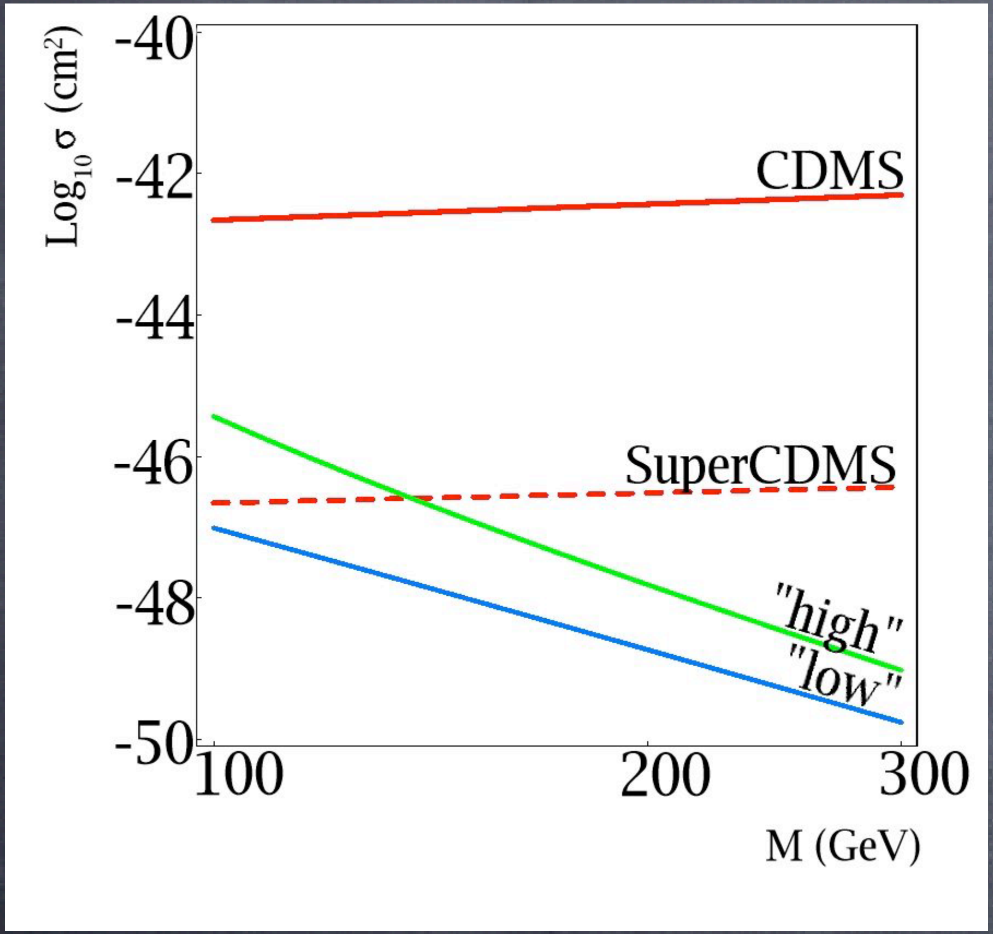
- Measuring the recoil energy of a nucleus due to an elastic collision with a WIMP.



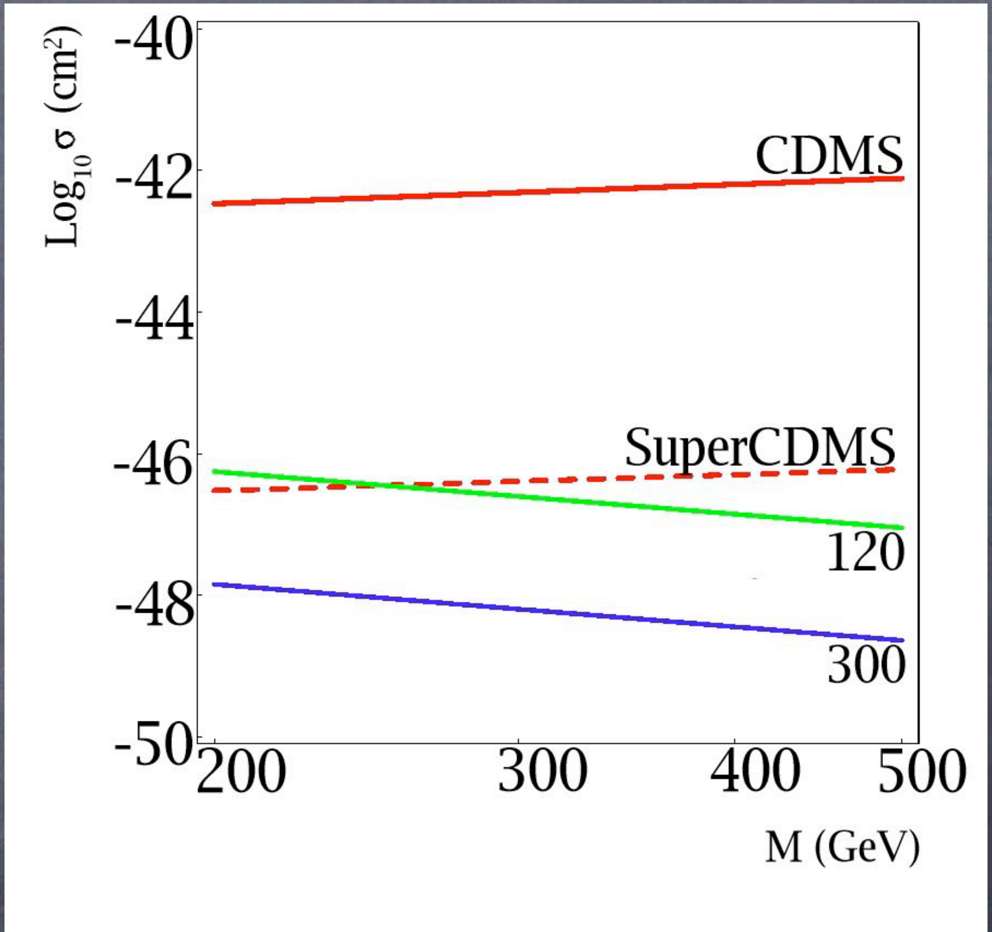
- In the NRL, the cross-sections can be divided into spin-independent and spin-dependent contributions.

- The small couplings of B_H to partons result in DD cross-sections significantly below current sensitivities.

Spin-Independent

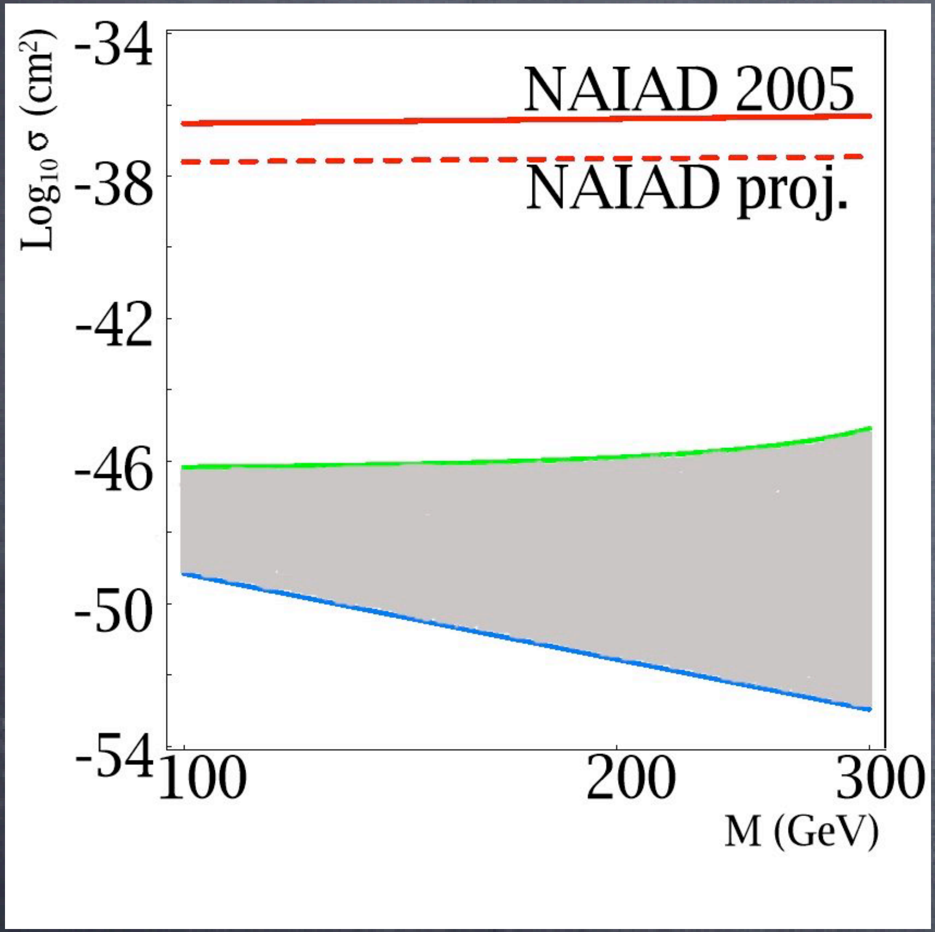


Pair annihilation

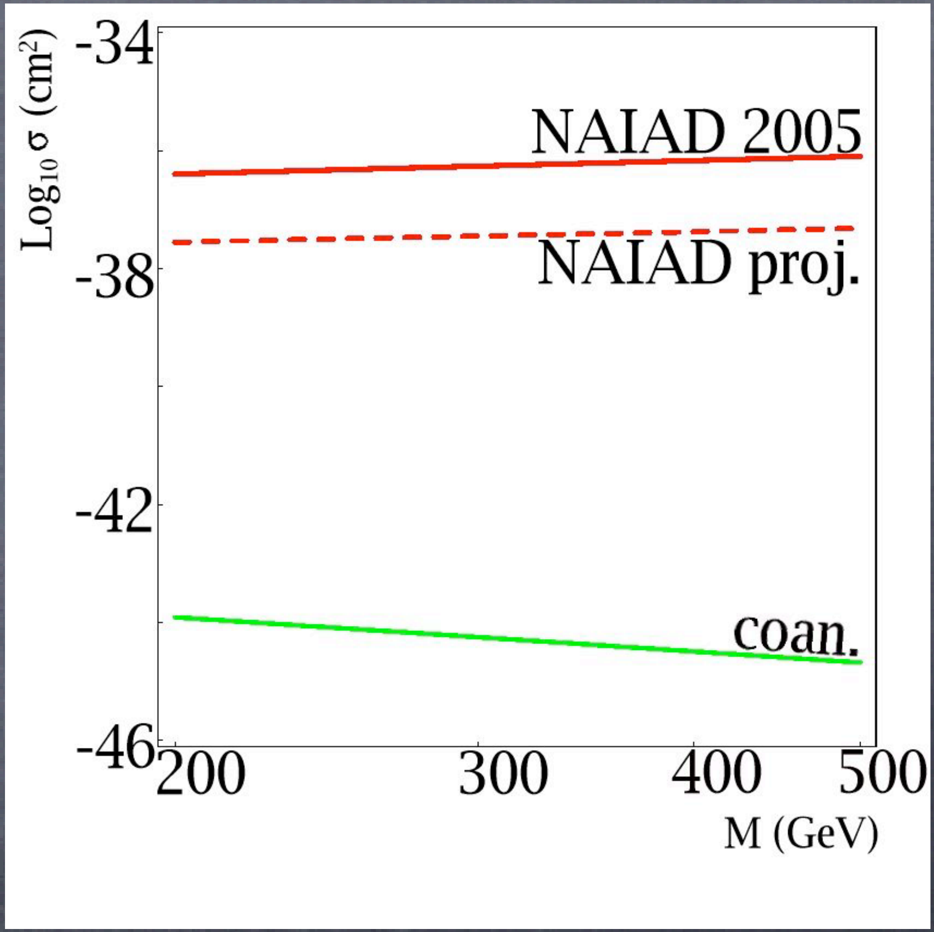


Coannihilation Tail

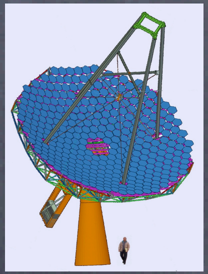
Spin-Dependent



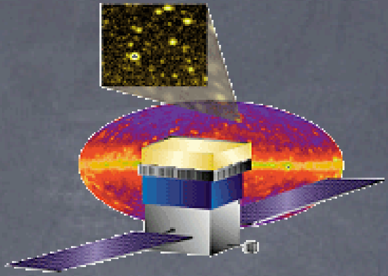
Pair annihilation



Coannihilation Tail



Gamma Ray Indirect Detection



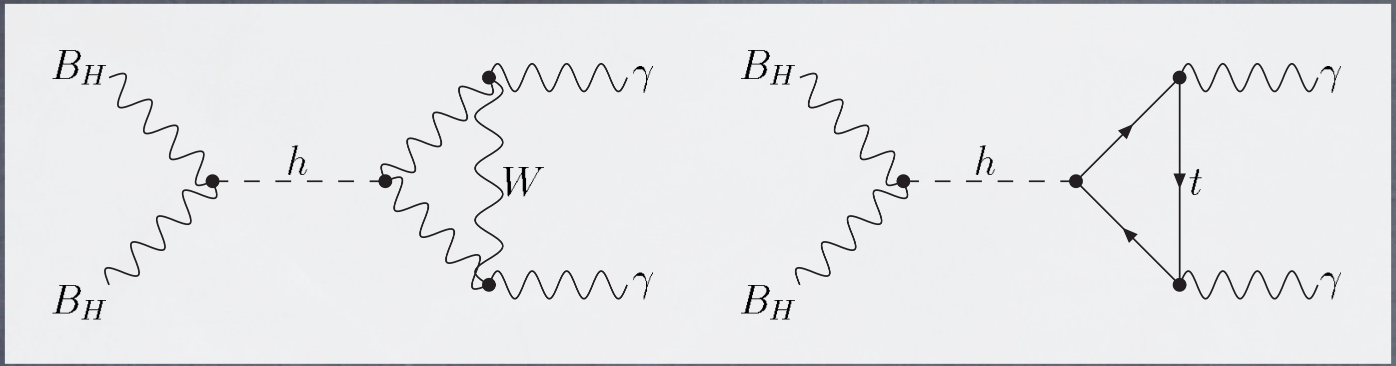
- Goal: Distinguish fluxes due to WIMP annihilation in the galactic center from astrophysical backgrounds.

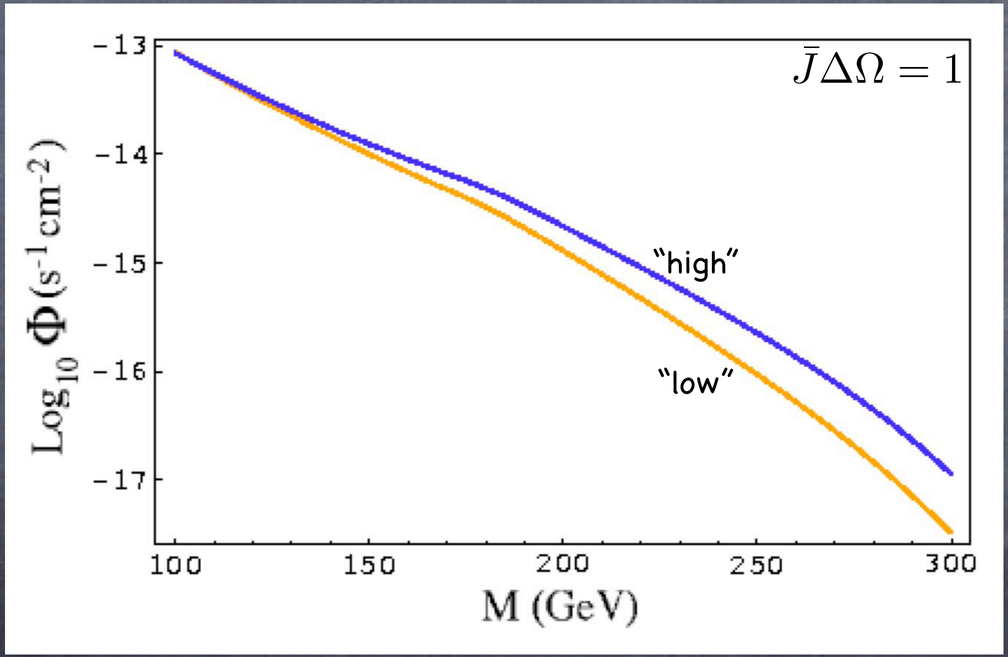
$$\Phi \sim \frac{\sigma v}{M^2} \bar{J}(\theta, \phi, \Delta\Omega)\Delta\Omega$$

- $\bar{J}$ contains the dependence on the halo dark matter density squared.

- For $\Delta\Omega = 10^{-3}\mathrm{sr}$, typical of ACTs, estimates of $\bar{J}$ near the galactic center range from 10^3 to 10^7.

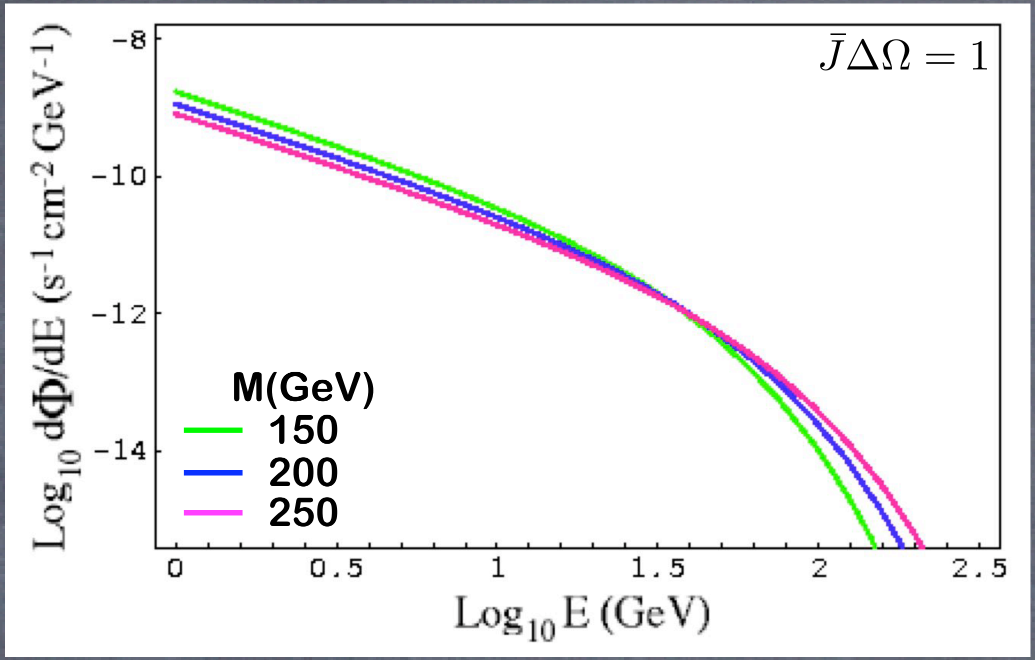
Monochromatic "Line" Flux





ACT sensitivity $\Phi \sim (1-5)\times 10^{-12}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

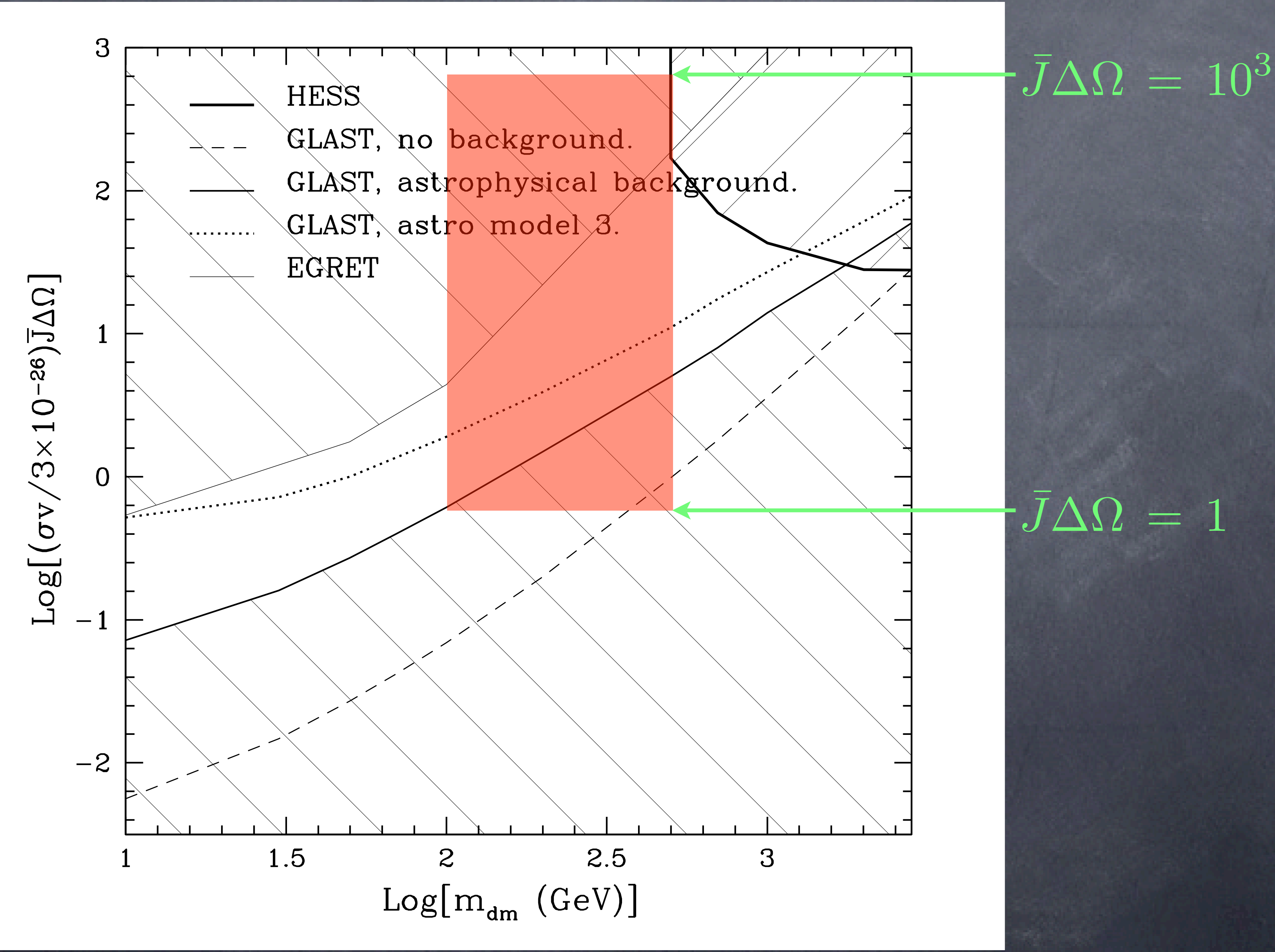
Fragmentation Flux



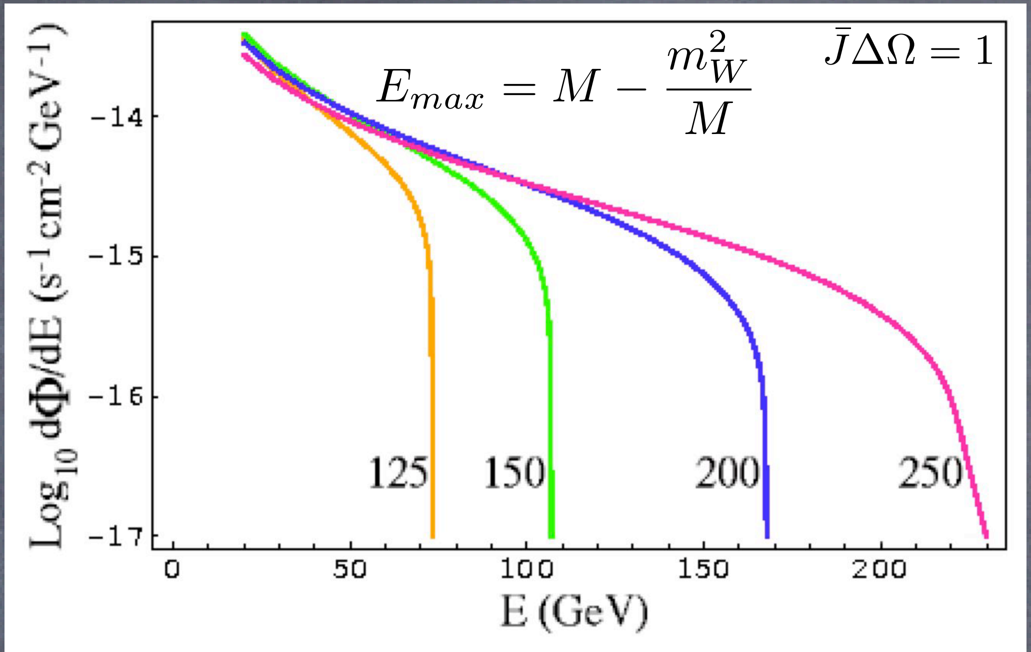
- Dominant production process:
  $B_H + B_H \to W^+W^-, ZZ \ / \ W, Z \to q\bar{q} \ / \ q \to \pi^0 \ldots \ / \ \pi^0 \to \gamma\gamma$
- GLAST should see ~50 events above 2GeV.
- But a soft, featureless spectrum makes this signal difficult to distinguish from astrophysical backgrounds.

Visible Against GC Bkg

Hooper and Zaharijas (2006)



Final State Radiation Flux

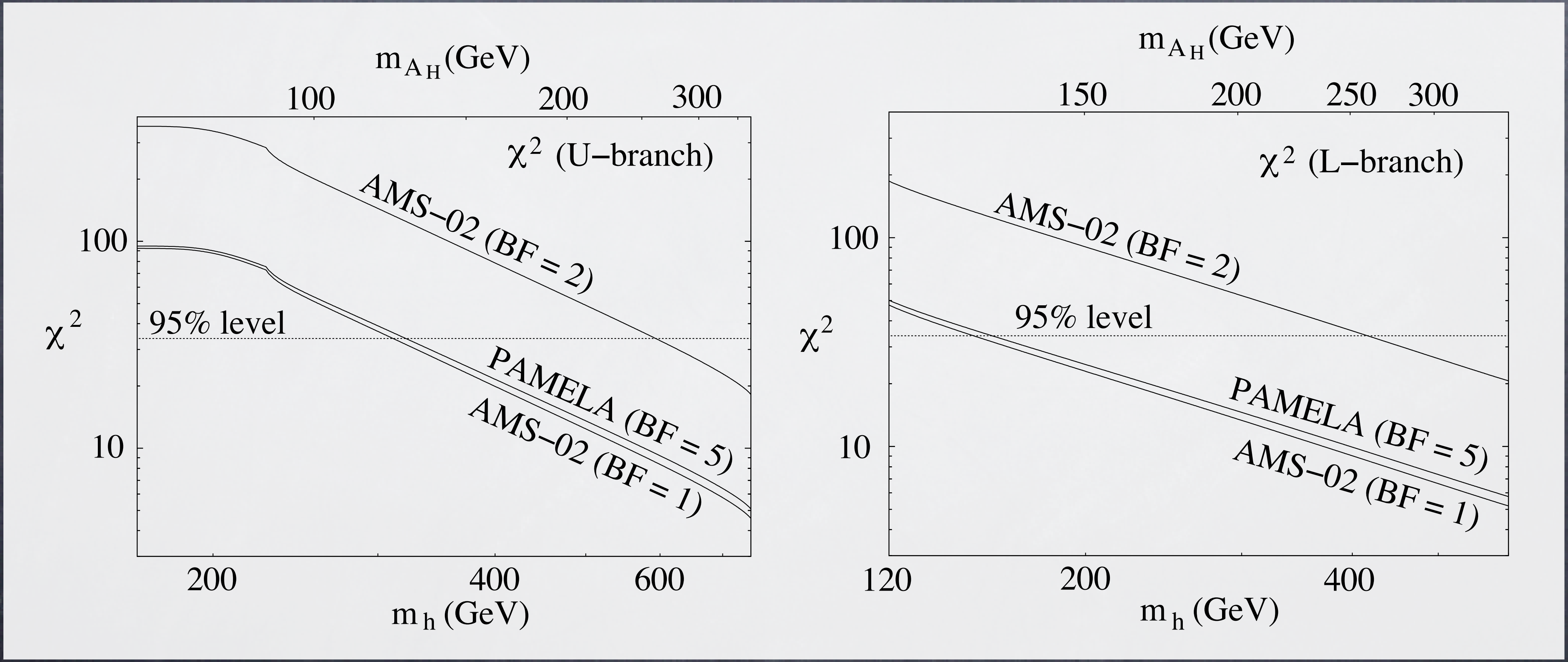


- Dominant production process: $B_H + B_H \to W^+W^-\gamma$
- Flux reduced by a factor of α compared to fragmentation photons.
- Observation of the edge feature would strengthen the case for WIMPs and provide a measurement of M.

Birkedal, Matchev, Perelstein, and Spray (2005)

Positron
Indirect Detection

Asano, Matsumoto, Okada, Okada (2006)



Conclusions

- The "heavy photon" B_H in the Littlest Higgs with T Parity provides a potential DM candidate.
- B_H can account for 100% of observed DM in both the pair annihilation and coannihilation scenarios.
- Current direct detection prospects are low, but SuperCDMS would be sensitive to these cross-sections.
- Indirect detection with the current ACT sensitivities would require $\bar{J} \gtrsim 10^5 - 10^6$.
- GLAST has the sensitivity to observe ~50 anomalous gamma rays due to the fragmentation flux.

New Parameters: R=λ$_1$/λ$_2$, f, and κ

m

f $\quad T_+ \sim f\sqrt{\lambda_1^2+\lambda_2^2} \quad T_- \sim f\lambda_2$

$$\phi \sim \frac{\sqrt{2}m_h f}{v}$$

$W_H \sim gf \qquad \tilde{Q} \sim \kappa f$

v $\quad B_H \sim g' f/\sqrt{5}$

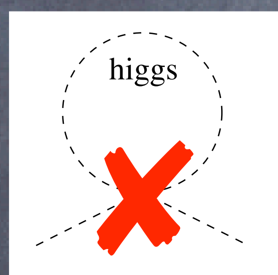
$$m_t \sim \lambda_1\lambda_2 v/\sqrt{\lambda_1^2+\lambda_2^2}$$

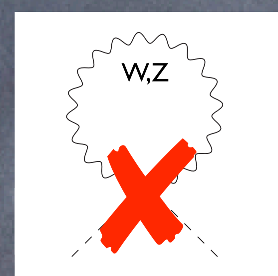
Collective Symmetry Breaking

Idea from Arkani-Hamed, Cohen, Georgi (2001)

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_j \left[g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + g_j' B_j (Y_j \Sigma + \Sigma Y_j) \right]$$

g_1 turned off → only gauge $Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$





SU(3)$_1$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

SU(3)$_2$

g_2 turned off → only gauge $Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

The Top Sector

To the third-family quark doublet add a new Weyl fermion.

$$\chi = (d_3, u_3, \tilde{t})$$

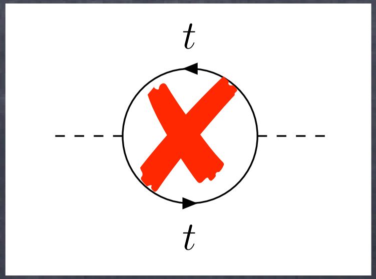
Explicitly breaks SU(5)!

Write down a Lagrangian that follows the collective symmetry breaking pattern.

$$\mathcal{L}_t = \lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i \Sigma_{jx}\Sigma_{ky} u_3^c + \lambda_2 f \tilde{t}\tilde{t}^c + h.c$$

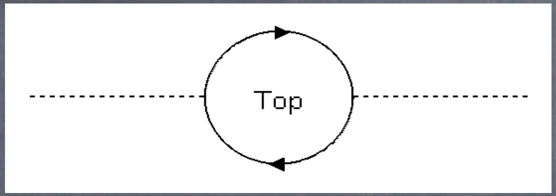
$\downarrow$ Breaks $SU(3)_2$ $\qquad$ $\downarrow$ Breaks $SU(3)_1$

In the mass eigenbasis, we find the SM top Yukawa coupling and a new "heavy top" T with an f-scale Dirac mass.



Top Sector Modification:

$\mathcal{L}_{Teven}$ must follow the collective symmetry breaking pattern to cancel,



Extend the two fermion doublets in this sector to SU(3) representations.

$$\mathcal{Q}_1 = \begin{pmatrix} q_1 \\ U_{L1} \\ 0 \end{pmatrix}, \mathcal{Q}_2 = \begin{pmatrix} 0 \\ U_{L2} \\ q_2 \end{pmatrix}$$ where, under T Parity, $U_{L1} \leftrightarrow -U_{L2}$

Then the top sector Lagrangian supporting collective symmetry breaking is,

$$\mathcal{L}_t = \frac{1}{2\sqrt{2}}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\left[(\bar{\mathcal{Q}}_1)_i \Sigma_{jx}\Sigma_{ky} - (\bar{\mathcal{Q}}_2\Sigma_0)_i \tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right] u_R + \lambda_2 f(\bar{U}_{L1}U_{R1} + \bar{U}_{L2}U_{R2}) + \text{h.c.}$$

↓ Breaks one T-even SU(3) ↓ Breaks other T-even SU(3)

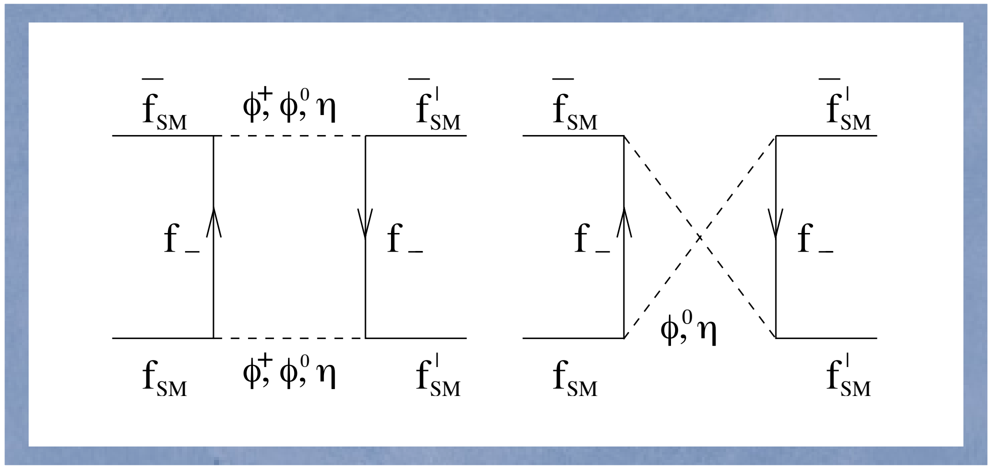
In the mass eigenbasis, we find,

$$t_L = u_{L+} - s_\lambda^2 \frac{v}{f} U_{L+} \qquad T_{L+} = U_{L+} + s_\lambda^2 \frac{v}{f} u_{L+}$$

$$t_R = c_\lambda u_R - s_\lambda U_{R+} \qquad T_{R+} = c_\lambda U_{R+} + s_\lambda u_R$$

T-odd Fermion Corrections

The leading contributions to four-fermion operators, in the limit where κ >> g, come from,



$$\mathcal{O}_{4-\mathrm{f}} = -\frac{\kappa^2}{128\pi^2 f^2}\, \bar{f}_L \gamma^\mu f_L \bar{f}'_L \gamma_\mu f'_L$$

Strongest constraint comes from eedd coefficient.

$$\delta_{eedd} < \frac{2\pi}{(26.4TeV)^2} \quad \Rightarrow \quad M_{\mathrm{TeV}}^{T-odd} = \sqrt{2}\kappa f < 4.8 f_{\mathrm{TeV}}^2$$

Assuming a universal, flavor-diagonal κ, the 12 T-odd fermion doublets contribute,

$$T_{\mathrm{T-odd}} = -12 \times \frac{\kappa^2}{192\pi^2\alpha}\left(\frac{v}{f}\right)^2$$

Relic Abundance

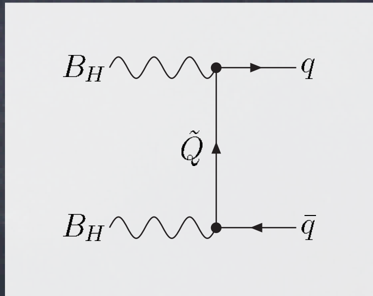
$$a(W^+W^-) = \frac{2\pi\alpha^2}{3\cos^4\theta_W}\frac{M^2}{(4M^2-m_h^2)^2+m_h^2\Gamma_h^2}\left(1-\mu_w+\frac{3}{4}\mu_w^2\right)\sqrt{1-\mu_w}$$

$$a(ZZ) = \frac{\pi\alpha^2}{3\cos^4\theta_W}\frac{M^2}{(4M^2-m_h^2)^2+m_h^2\Gamma_h^2}\left(1-\mu_z+\frac{3}{4}\mu_z^2\right)\sqrt{1-\mu_z}$$

$$a(t\bar{t}) = \frac{\pi\alpha^2}{4\cos^4\theta_W}\frac{M^2}{(4M^2-m_h^2)^2+m_h^2\Gamma_h^2}\mu_t(1-\mu_t)^{3/2}$$

$$a(hh) = \frac{\pi\alpha^2 M^2}{2\cos^4\theta_W}\left[\frac{\mu_h(1+\mu_h/8)}{(4M^2-m_h^2)^2+m_h^2\Gamma_h^2}+\frac{1}{24M^4}\right]\sqrt{1-\mu_h}$$

$$a(f\bar{f}) = \frac{16\pi\alpha^2\tilde{Y}^4 N_c^f}{9\cos^4\theta_W}\frac{M^2}{(M^2+\tilde{M}^2)^2}$$



Direct Detection: SI

$$\mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{\alpha_s \alpha}{6\cos^2\theta_W} \frac{1}{m_h^2} B_{\mathrm{H}\alpha} B^{\alpha}_{\mathrm{H}} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{e^2}{27\cos^2\theta_W} \frac{m_n}{m_h^2} B_{\mathrm{H}\alpha} B^{\alpha}_{\mathrm{H}} \bar{\Psi}_n \Psi_n$$

$$\sigma_{\mathrm{SI}} = \frac{4\pi\alpha^2}{729\cos^4\theta_W} \frac{m_n^4}{m_h^4} \frac{1}{(M + m_n)^2}$$

Direct Detection: SD

$$-i\,\frac{e^2\tilde{Y}^2}{\cos^2\theta_W}\varepsilon^*_\mu(p_3)\varepsilon_\nu(p_1)\;\bar{u}(p_4)\left[\frac{\gamma^\mu\,\not{k}_1\gamma^\nu}{k_1^2-\tilde{M}^2}+\frac{\gamma^\nu\,\not{k}_2\gamma^\mu}{k_2^2-\tilde{M}^2}\right]P_L\,u(p_2)$$

$$\frac{e^2\tilde{Y}^2}{\cos^2\theta_W}\,\frac{M}{M^2-\tilde{M}^2}\,\epsilon_{ijk}\varepsilon_1^i\varepsilon_3^j\bar{u}_4\gamma^k(1-\gamma^5)u_2$$

$$\langle N|\bar{q}\gamma^\mu\gamma^5 q|N\rangle\;=\;2s_N^\mu\lambda_q \qquad\qquad \lambda_q=\Delta q_p\frac{\langle S_p\rangle}{J_N}+\Delta q_n\frac{\langle S_n\rangle}{J_N}$$

$$\frac{2e^2\tilde{Y}^2M}{\cos^2\theta_W(M^2-\tilde{M}^2)}\,\epsilon_{ijk}B_H^iB_H^j\bar{\Psi}_N s_N^k\Psi_N\sum_{q=u,d,s}\lambda_q$$

$$\sigma_{\rm SD}\;=\;\frac{16\pi\alpha^2\tilde{Y}^4}{3\cos^4\theta_W}\,\frac{m_N^2}{(M+m_N)^2}\,\frac{M^2}{(M^2-\tilde{M}^2)^2}\,J_N(J_N+1)\left(\sum_{q=u,d,s}\lambda_q\right)^2$$

ID: Line Flux

$$\sigma_{\gamma\gamma} u \equiv \sigma\left(B_H B_H \to \gamma\gamma\right) u = \frac{g'^4 v^2}{72 M^4} \frac{s^2 - 4sM^2 + 12M^4}{(s-m_h^2)^2 + m_h^2\Gamma_h^2} \frac{\hat{\Gamma}\left(h \to V_1 V_2\right)}{\sqrt{s}}$$

$$\hat{\Gamma}(h \to \gamma\gamma) \;=\; \frac{\alpha^2 g^2}{1024\pi^3} \frac{s^{3/2}}{m_W^2} \left|\mathcal{A}_1 + \mathcal{A}_{1/2} + \mathcal{A}_0\right|^2$$

$$\Phi \;=\; (1.1 \times 10^{-9} \mathrm{s}^{-1} \mathrm{cm}^{-2}) \left(\frac{\sigma_{\gamma\gamma} u}{1\ \mathrm{pb}}\right) \left(\frac{100\ \mathrm{GeV}}{M}\right)^2 \bar{J}(\Psi, \Delta\Omega)\Delta\Omega$$

$$\bar{J}(\Psi, \Delta\Omega) \equiv \frac{1}{8.5\ \mathrm{kpc}} \left(\frac{1}{0.3\ \mathrm{GeV/cm}^3}\right)^2 \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\Psi} \rho^2 dl$$

ID: Fragmentation Flux

$$\frac{dN_\gamma}{dx} \approx \frac{0.73}{x^{1.5}} e^{-7.8x}$$

$$\frac{d\Phi}{dE} = \left(3.3 \times 10^{-12} \mathrm{s}^{-1} \mathrm{cm}^{-2} \mathrm{GeV}^{-1}\right) x^{-1.5} e^{-7.8x} \left(\frac{100 \text{ GeV}}{M}\right)^3 \bar{J}(\Psi, \Delta\Omega)\Delta\Omega,$$

ID: FSR Flux

$$\frac{d\sigma}{dx}\left(B_H B_H \to W^+W^-\gamma\right) = \sigma\left(B_H B_H \to W^+W^-\right)\mathcal{F}(x;\mu_w)$$

$$\mathcal{F}(x;\mu) = \frac{\alpha}{\pi}\frac{1}{\sqrt{1-\mu}}\frac{1}{x} \times \left[(2x-2+\mu)\log\frac{2(1-x)-\mu-2\sqrt{(1-x)(1-x-\mu)}}{\mu} \right.$$
$$\left. +2\left(\frac{8x^2}{4-4\mu+3\mu^2}-1\right)\sqrt{(1-x)(1-x-\mu)}\right]$$

$$\mathcal{F}(x) = \frac{2\alpha}{\pi}\frac{1-x}{x}\left[\log\frac{s(1-x)}{m_W^2} + 2x^2 - 1 + \mathcal{O}(\mu)\right]$$

$$\frac{d\Phi}{dE} = \left(5.6\times10^{-12}\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{GeV}^{-1}\right)\left(\frac{a(W^+W^-)}{1\ \mathrm{pb}}\right)\mathcal{F}(x;\mu_w)\left(\frac{100\ \mathrm{GeV}}{M}\right)^3\bar{J}(\Psi,\Delta\Omega)\Delta\Omega,$$