Three (+) Exceptions for Thermal Dark Matter

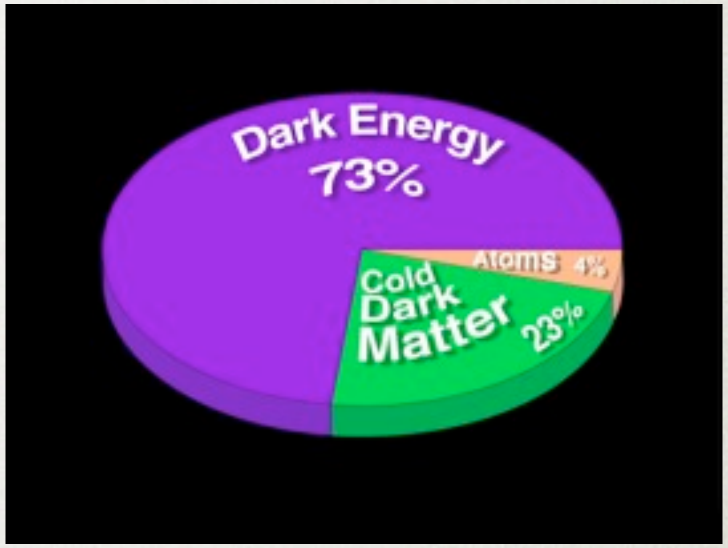
and the 130 GeV Fermi Line

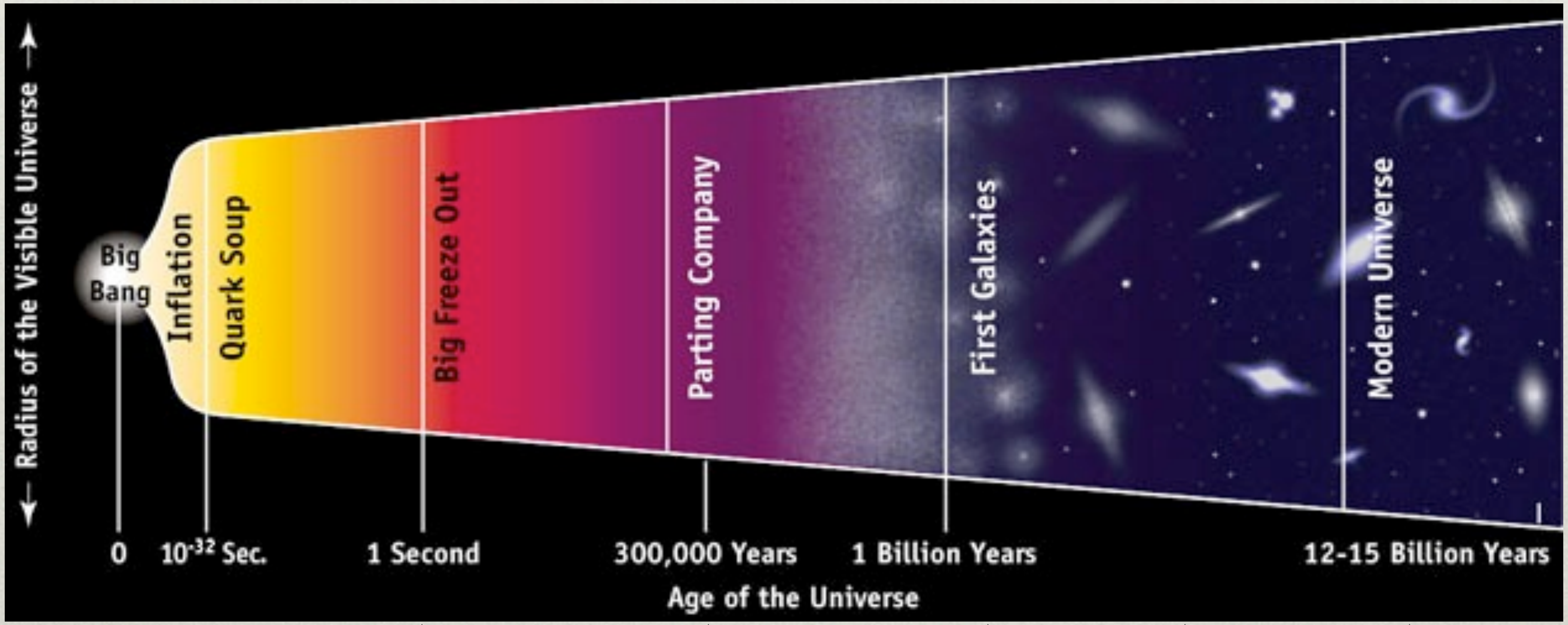
Based on 1208.0009 with S. Tulin and H. Yu

Kathryn M. Zurek
University of Michigan

Evidence for DM Overwhelming

All evidence points toward





BBN (baryons)

CMB (curvature)

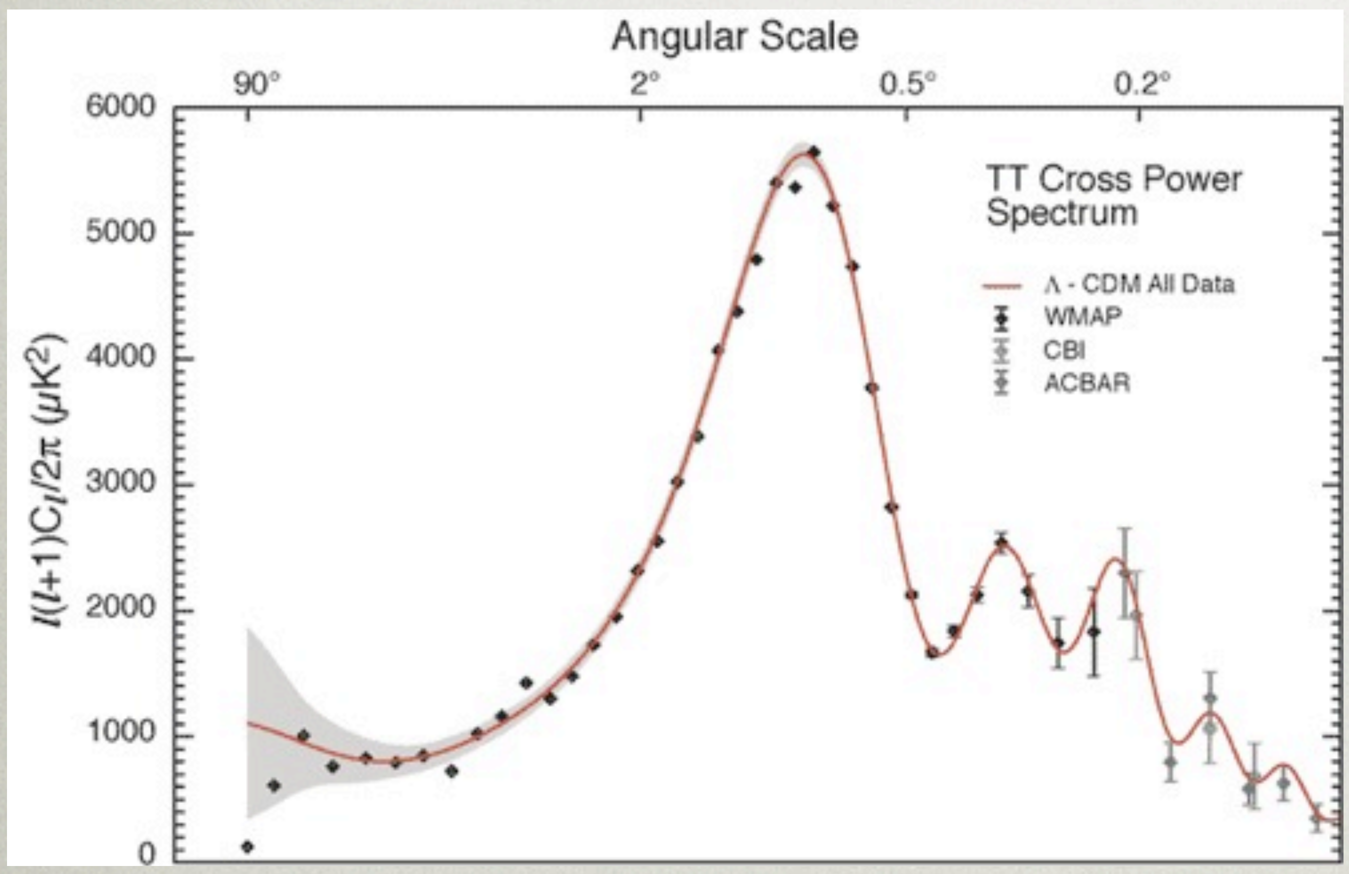
LSS (matter)

Supernovae (DE)

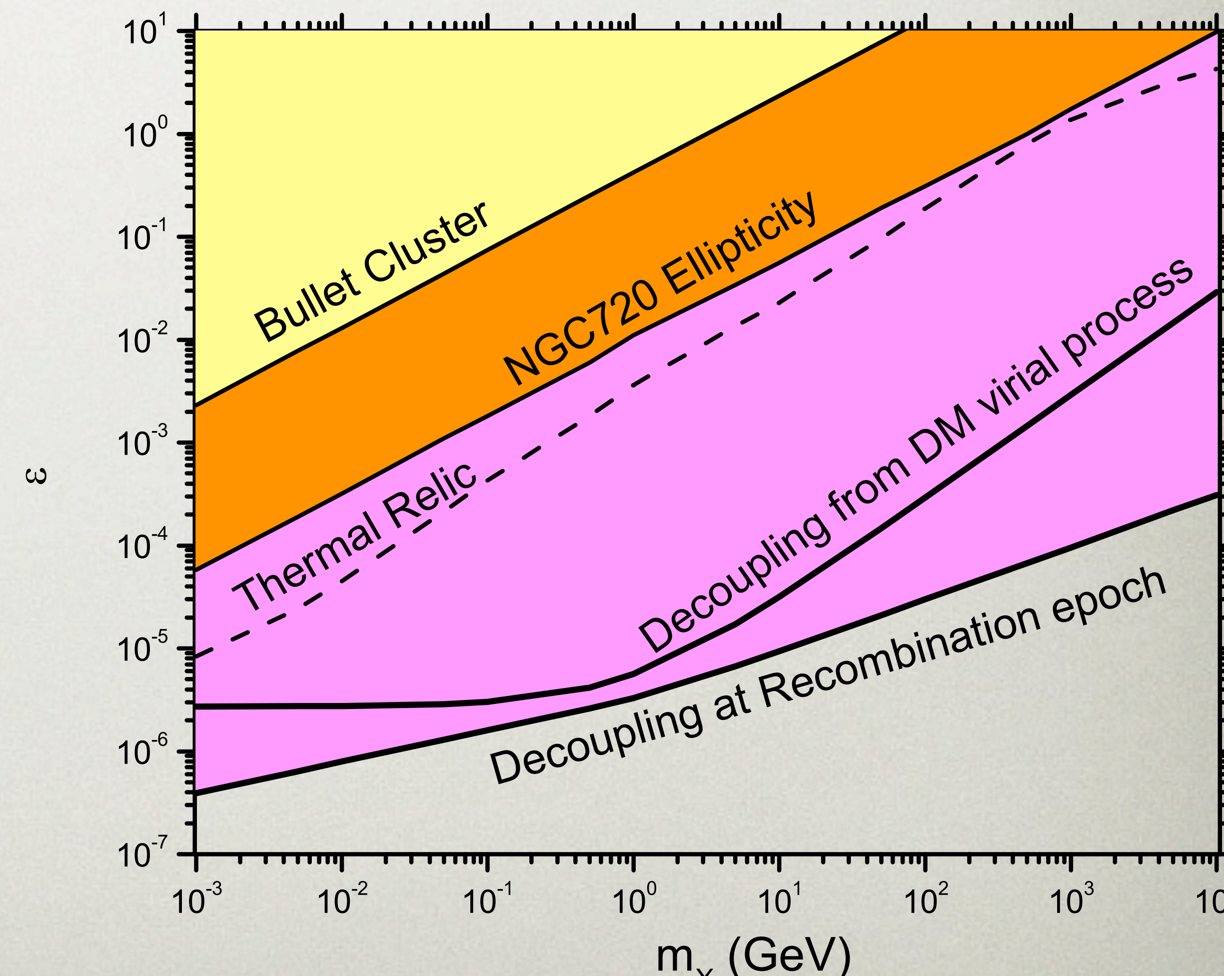
Galaxy curves (matter)

How Dark is Dark Matter?

- Which probe is the most constraining?



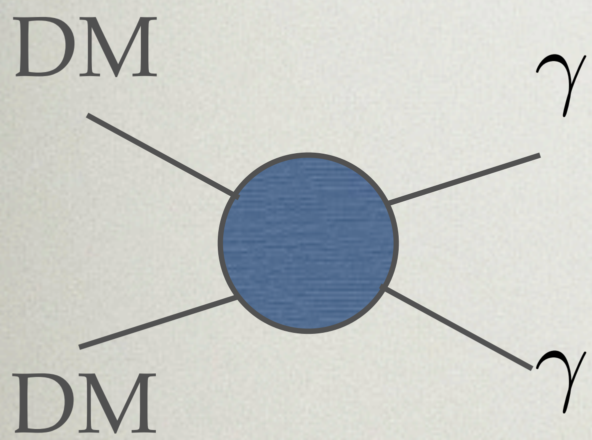
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{v^4}!$$



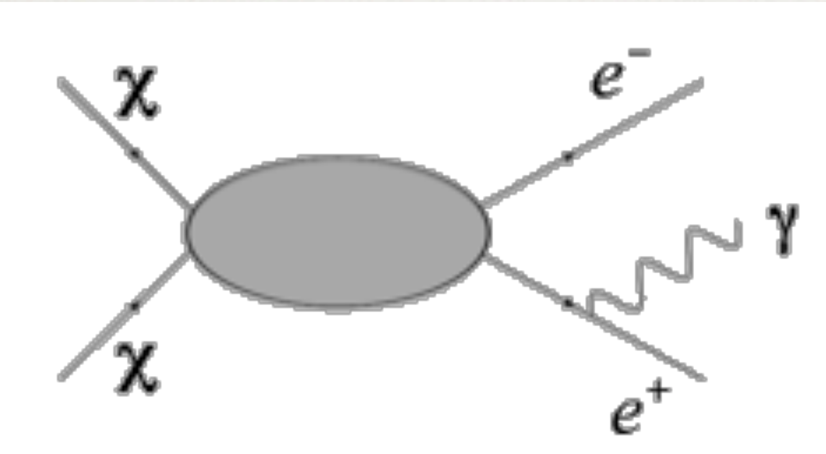
McDermott, Yu, KZ '10

Search Via Annihilations

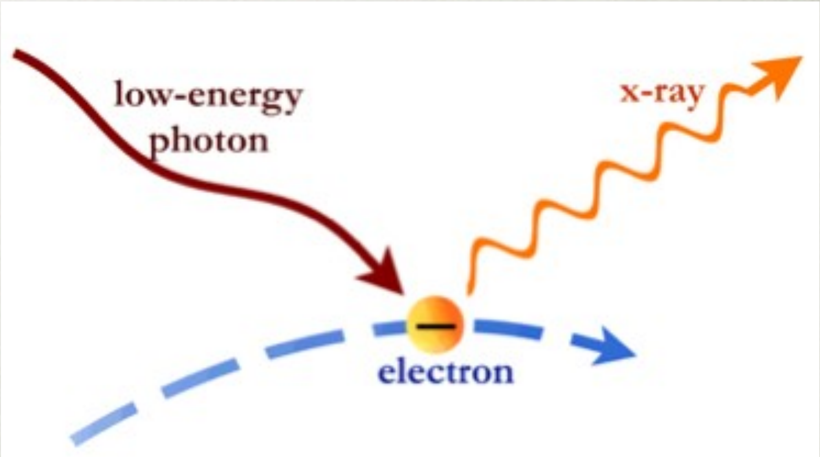
- How do we get photons from DM annihilation?



1. Direct

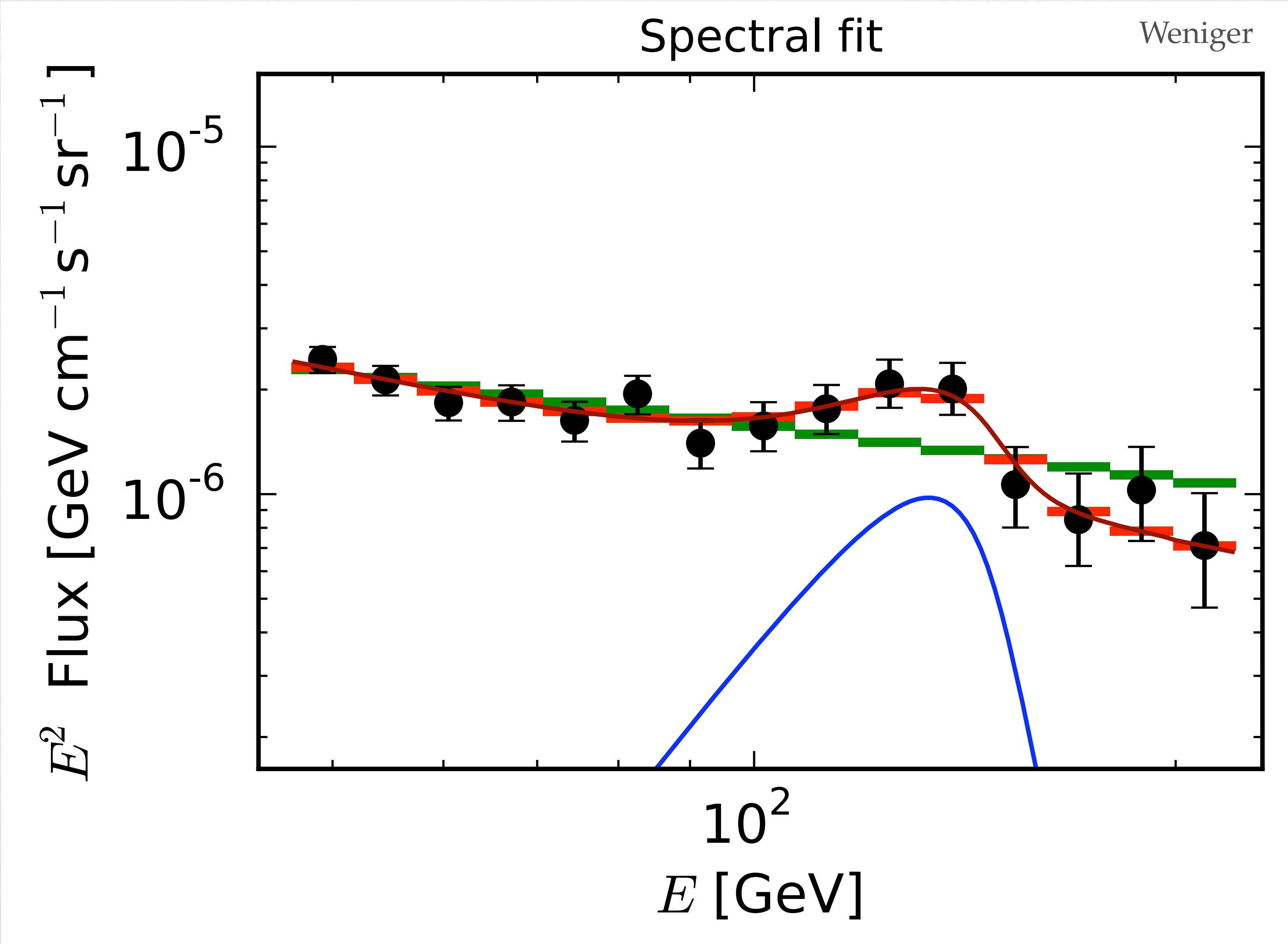


2. Final State Radiation



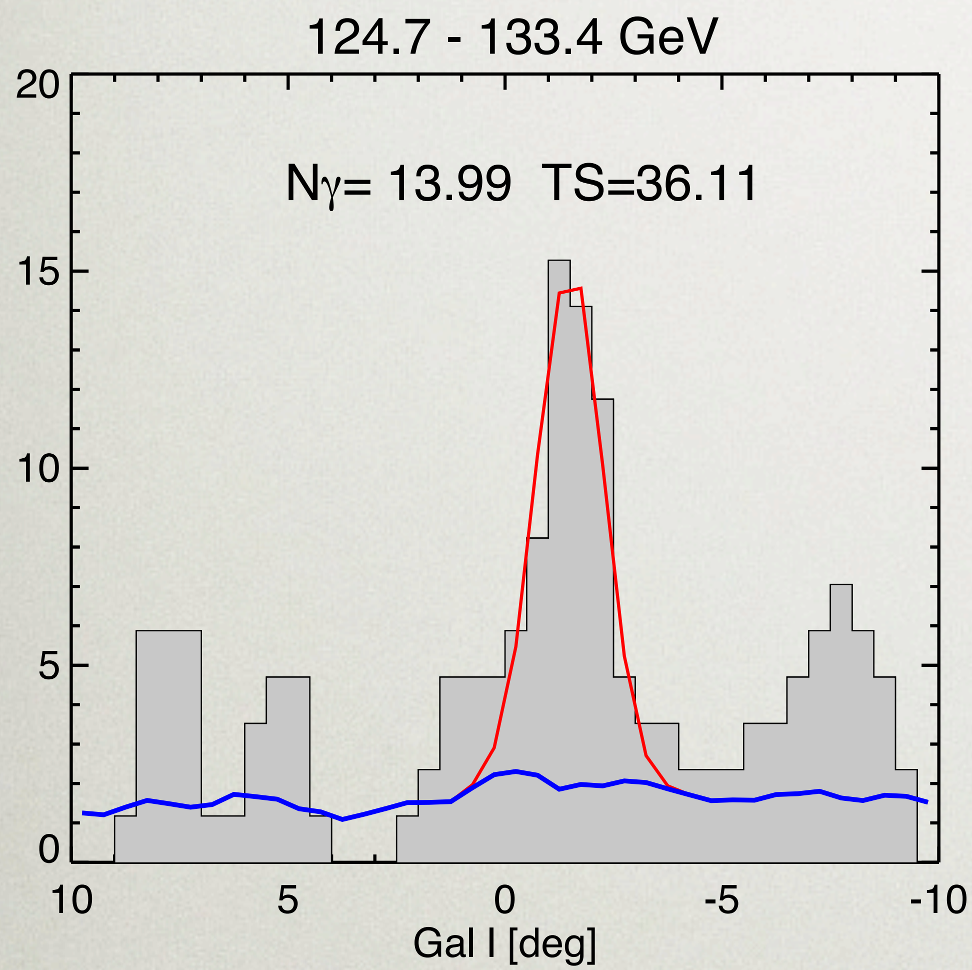
3. Inverse Compton

A Fermi Line?

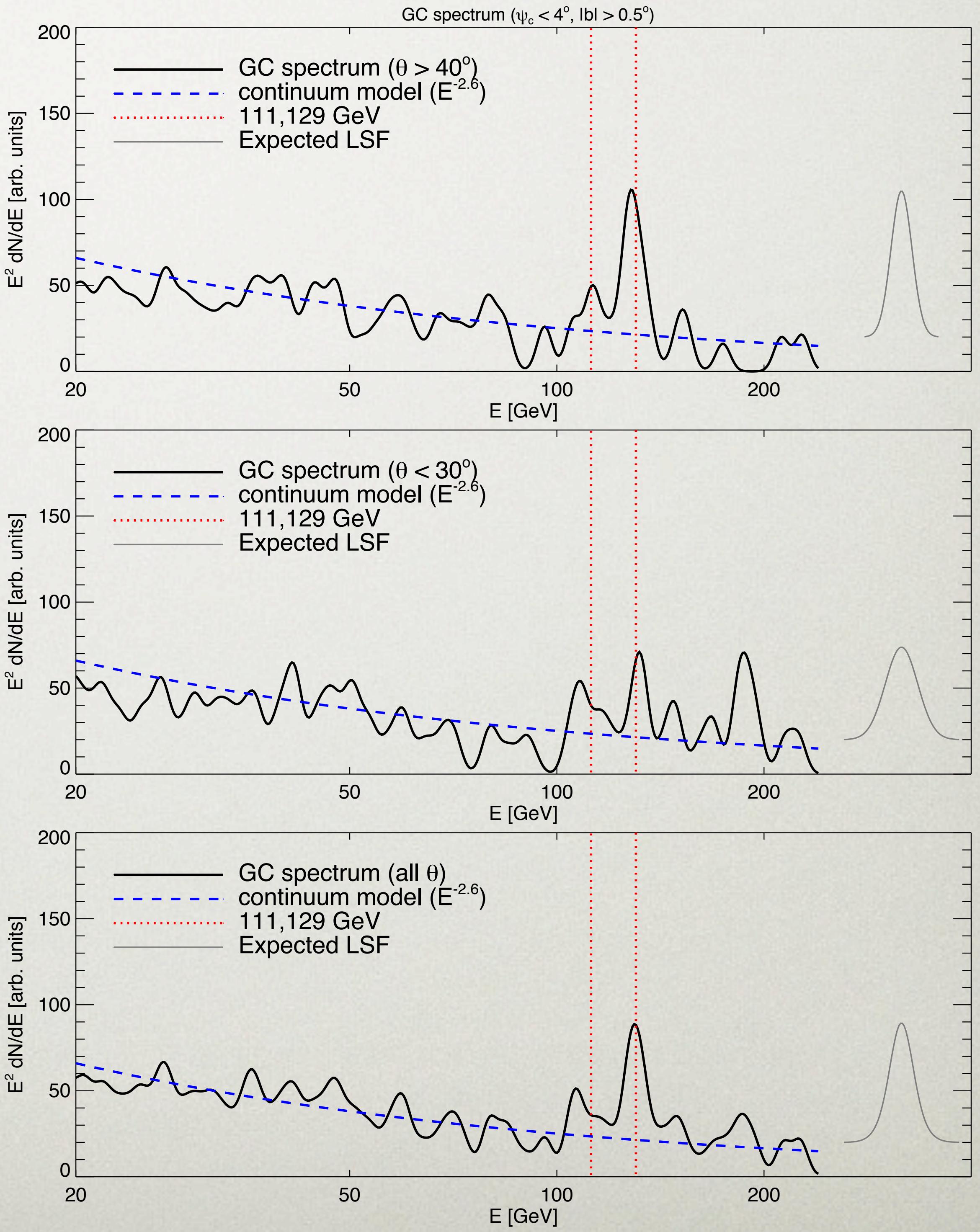


A Fermi Line(s)?

Su and Finkbeiner

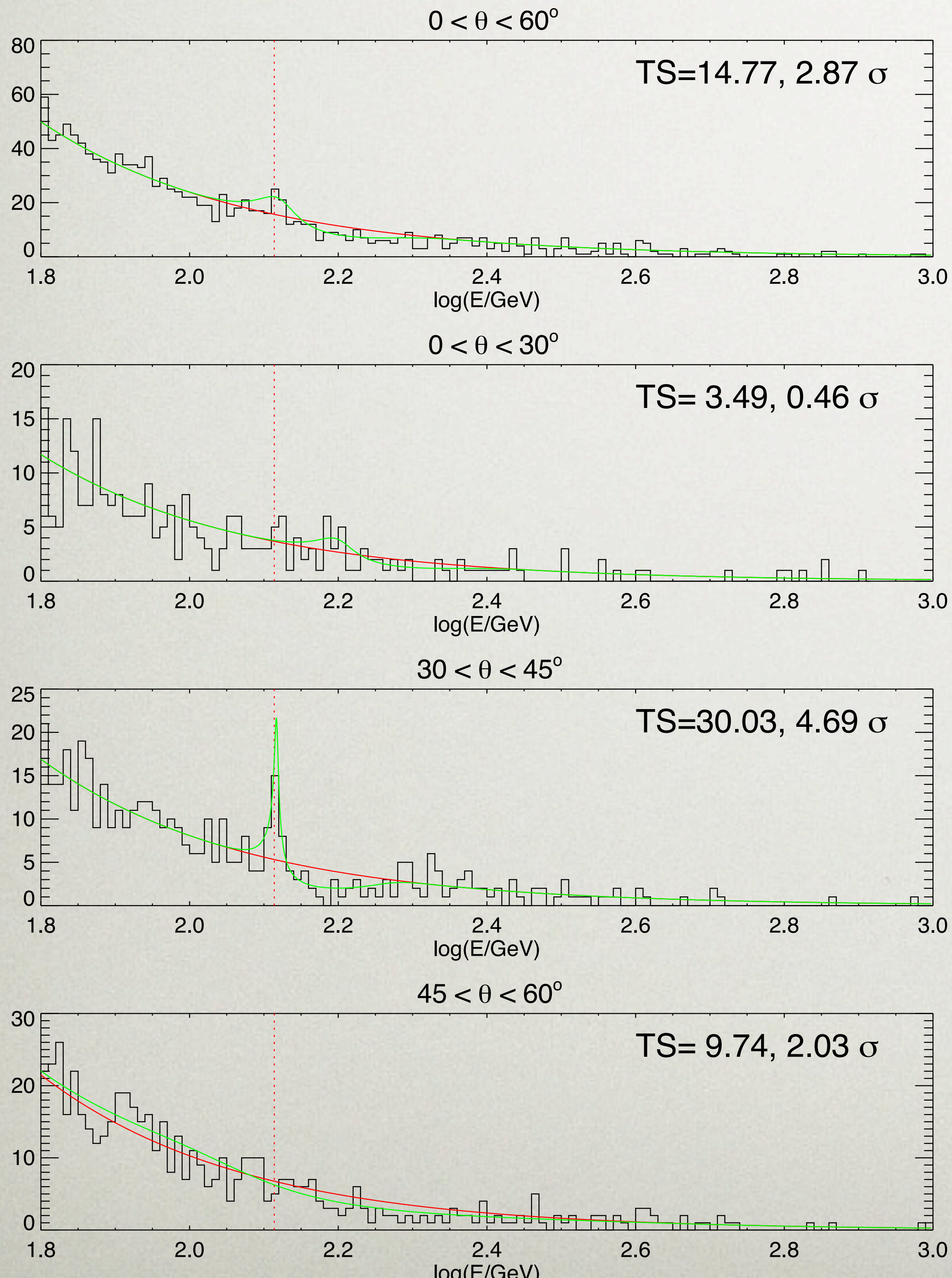


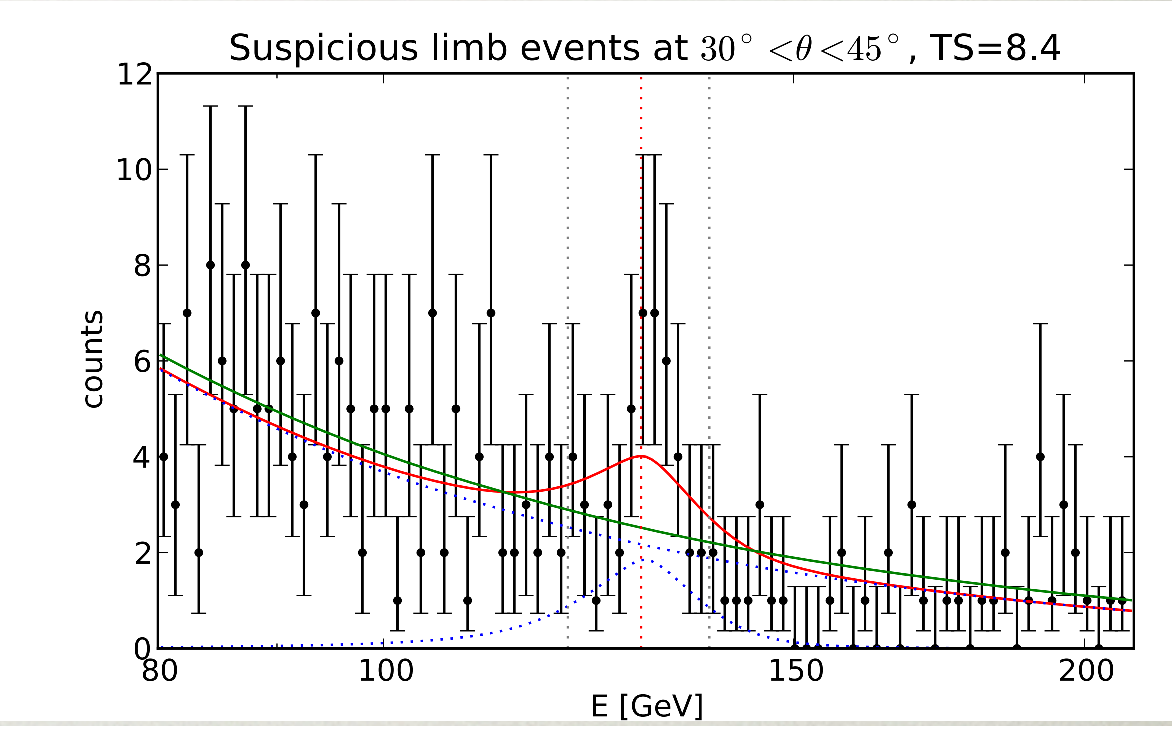
$$E_\gamma = m_\chi \left(1 - \frac{M_Y^2}{4m_\chi^2}\right)$$



A Systematic?

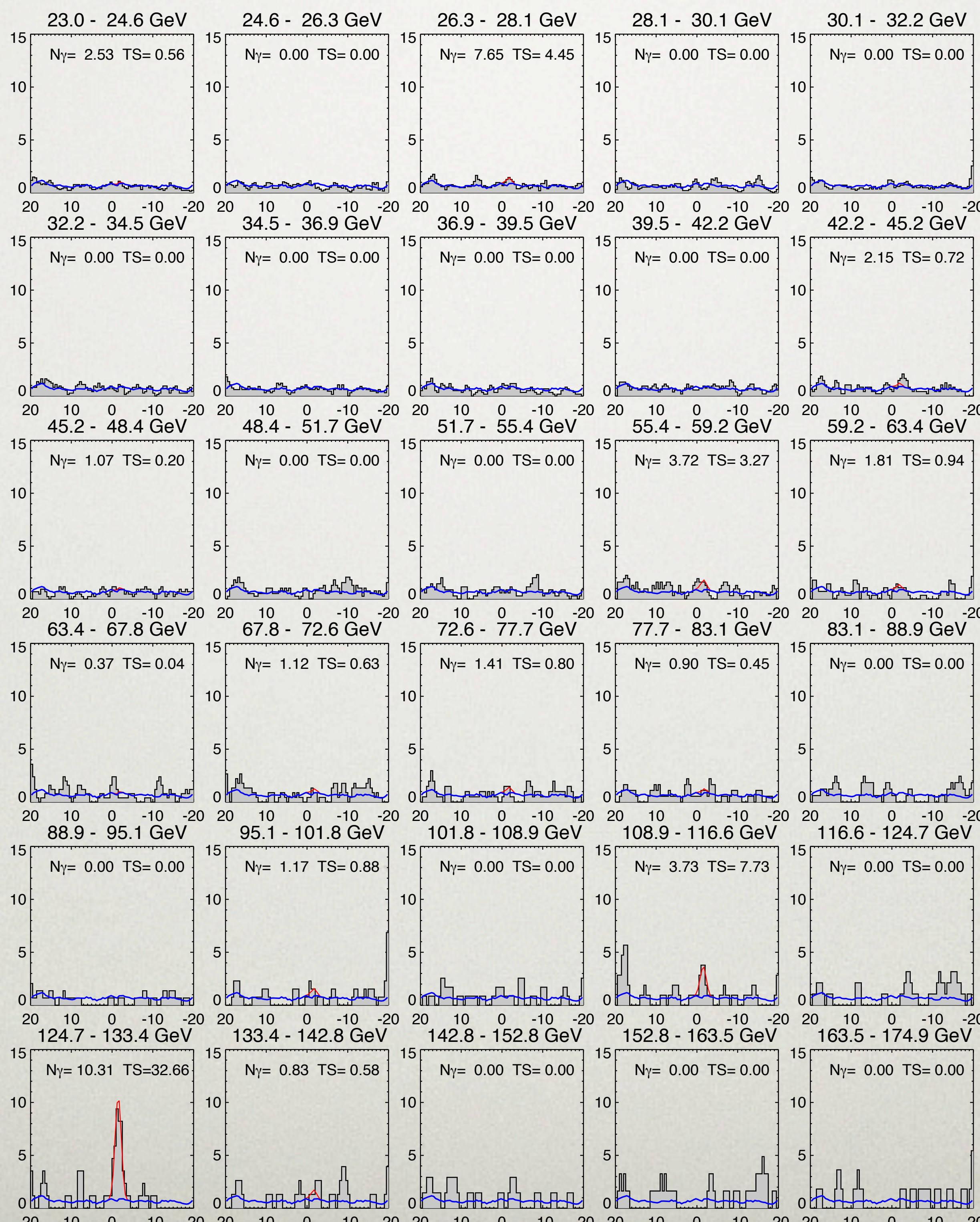
Finkbeiner and Weniger





A Systematic?

Finkbeiner and Su



Should we Build Models for the Fermi Line?

- Unlikely a statistical fluke
- However, like other anomalies, we learn about models of DM by being faced with an unconventional anomaly
- Take the line seriously and see what it takes to build a model

Su and Finkbeiner

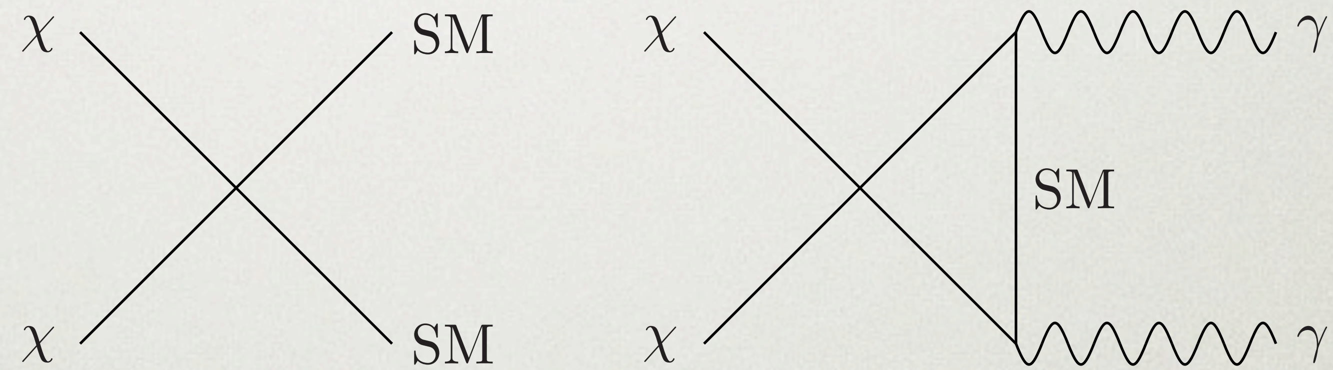
Models	Before trials	After trials (one line)
Gaussian (centered)	5.0σ	3.7σ
Gaussian (off center, $\theta > 40°$)	5.5σ	3.7σ
unbinned ℓ	5.2σ	3.2σ
unbinned ℓ ($\theta > 40°$)	4.9σ	2.8σ
unbinned b	4.8σ	3.5σ
unbinned b ($\theta > 40°$)	4.6σ	3.2σ
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ
NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ
Einasto (off center)	$\mathbf{6.6}\sigma$	$\mathbf{5.1}\sigma$

What Does a Model for the Fermi Line Do?

- Avoid continuum constraints
- Give a *large* rate
- Obtain correct relic density (if interested in thermal DM)

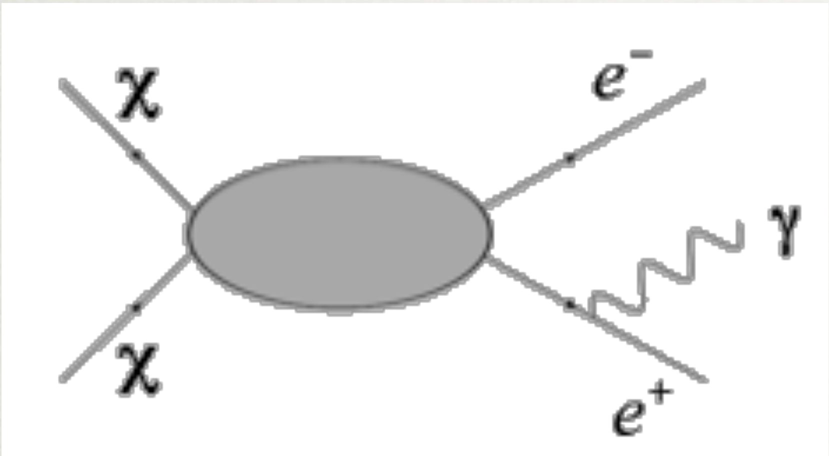
1. Avoid Continuum Constraint

- DM doesn't carry a charge; coupling to photons comes through loops of charge particles

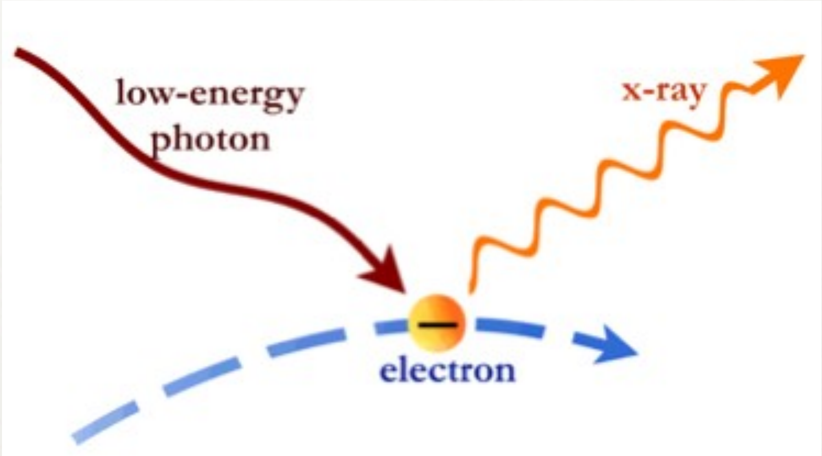


- Cut the loop and you get continuum photons

1. Avoid Continuum Constraint



2. Final State Radiation

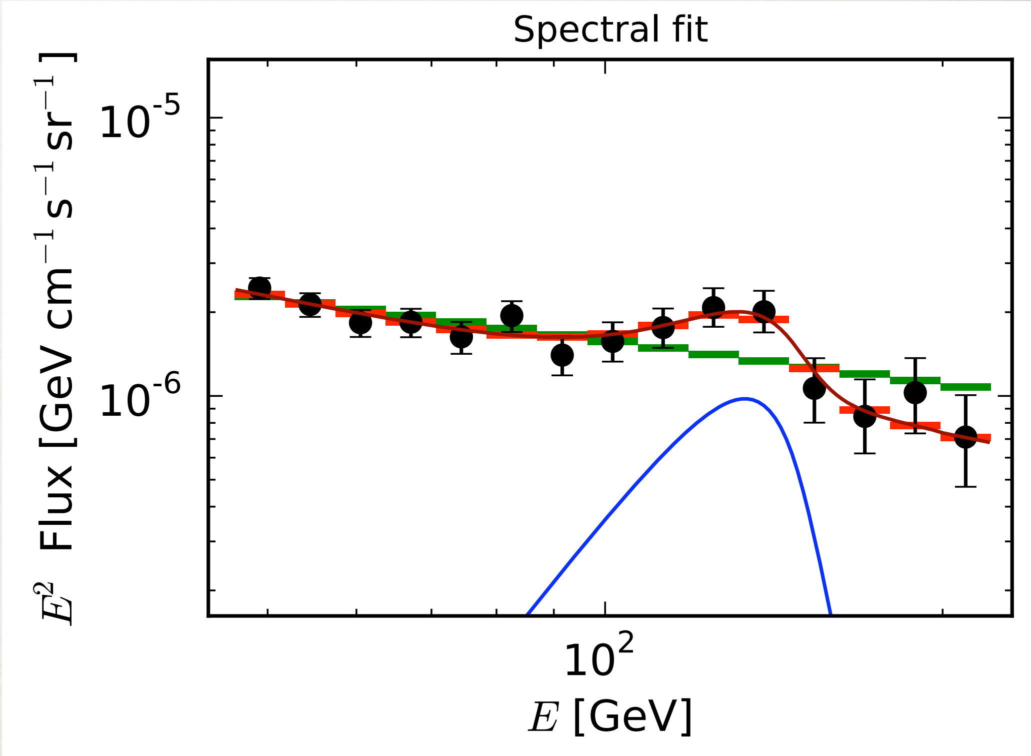


3. Inverse Compton

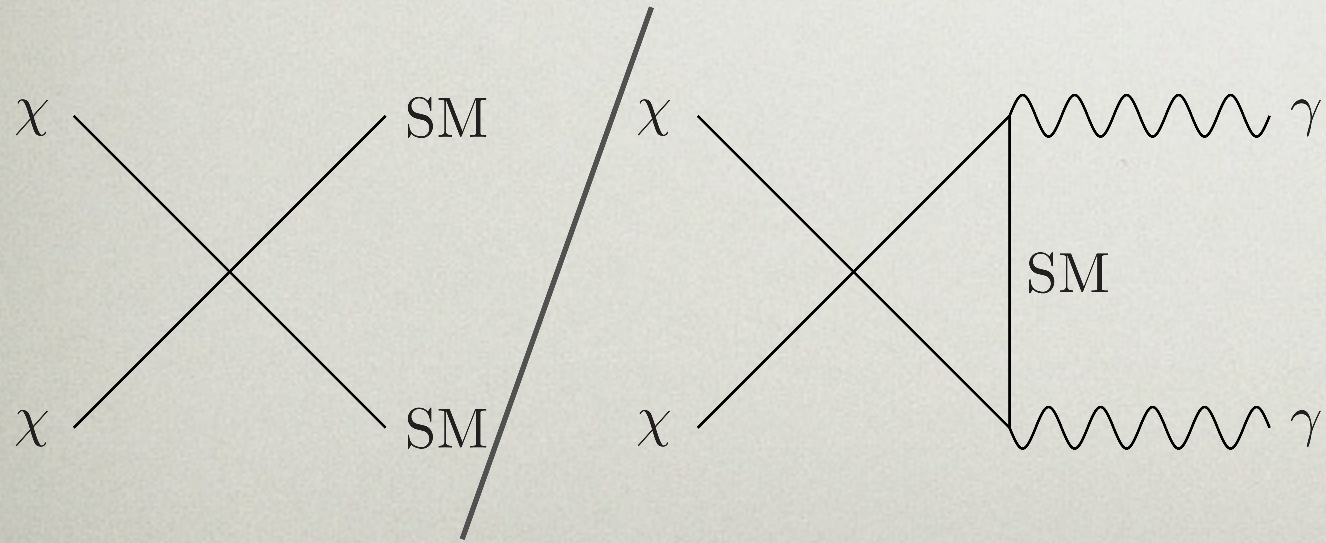
- Annihilation to charged states dominates by $\frac{R_{SM}}{R_{\gamma\gamma}} \sim (\pi/\alpha)^2 \approx 10^5$

1. Avoid Continuum Constraint

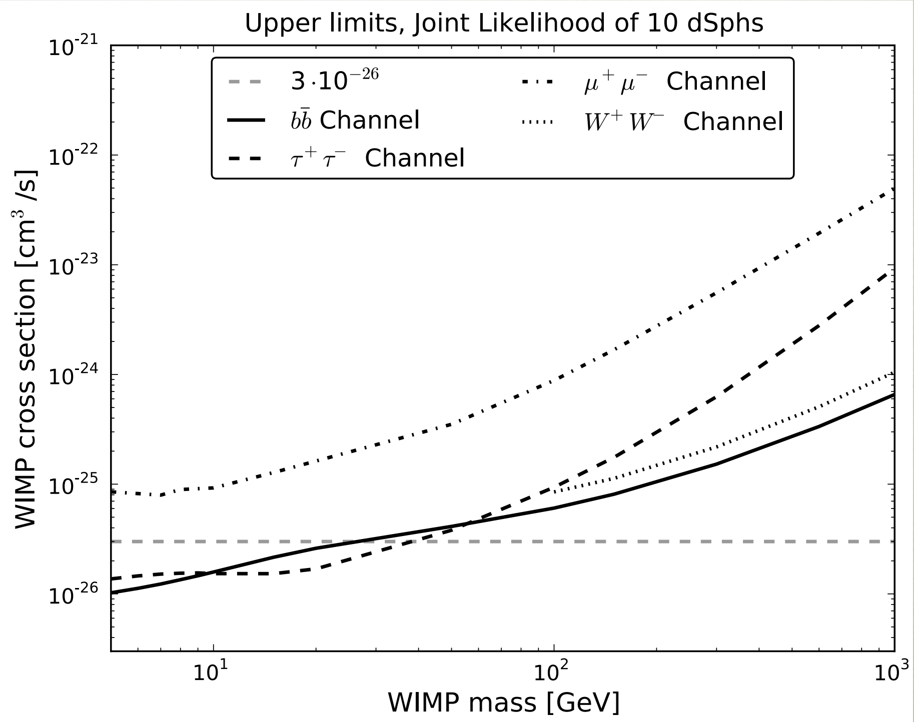
Weniger



$$\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$



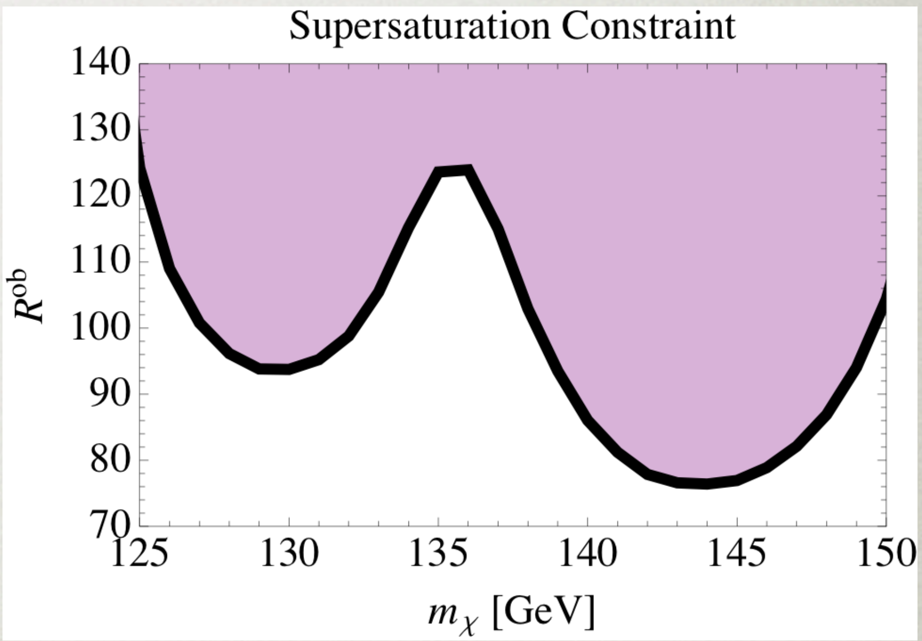
$$\approx 10^5$$

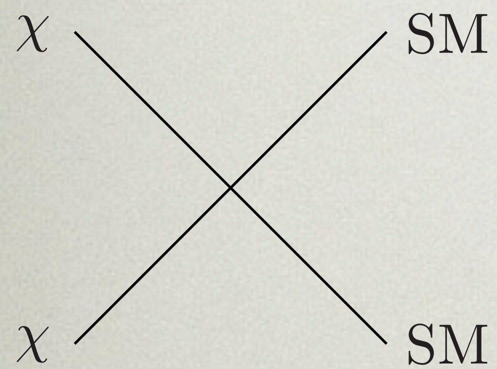


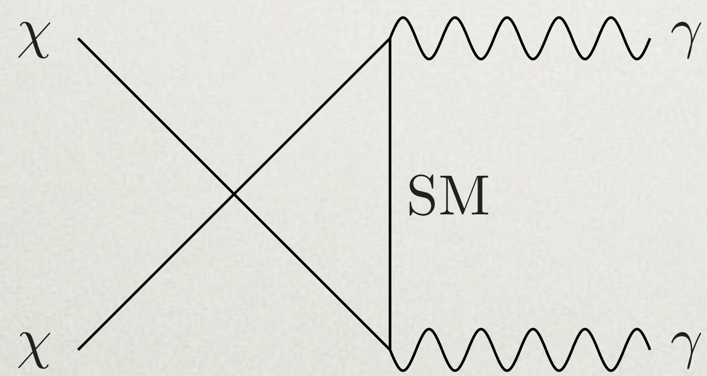
MSSM Does Not Work (Perhaps)

- Charged states in the loop tend to be W's; Annihilation to W's strongly constrained

Cohen, Lisanti, Slatyer, Wacker





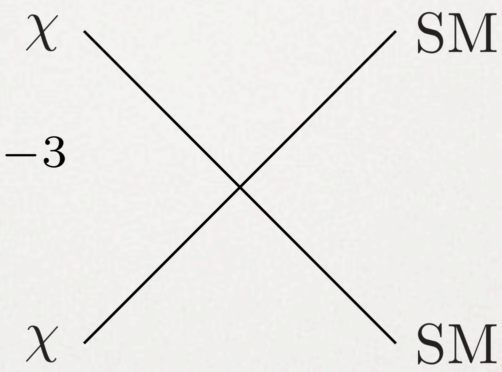


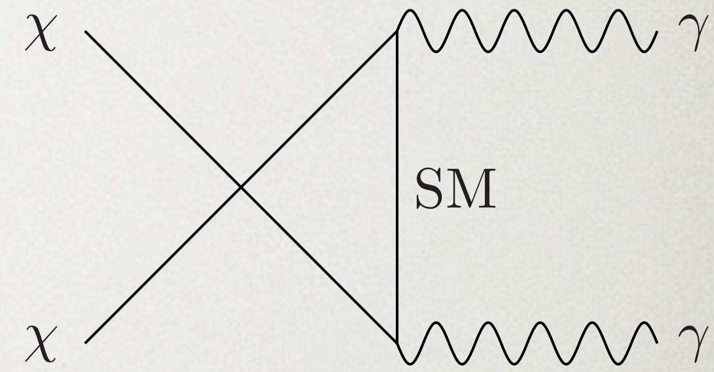
$$R^{\rm th} \equiv \frac{\sigma_{\rm ann}}{2\,\sigma_{\gamma\gamma} + \sigma_{\gamma Z}}$$

$$R^{\rm th}_{\rm wino} \simeq 200 \text{ and } R^{\rm th}_{\rm Higgsino} \simeq 700$$

Simplest Fix ....

- p-wave! $v_{MW} \sim 10^{-3}$





$$\langle \sigma v \rangle \sim v^2 \qquad \sigma v \sim \text{ const}$$

- A toy model:

$$\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-27} \text{ cm}^3/\text{s}$$

$$\sigma(\chi\chi^\dagger \to f\bar{f})v \approx \frac{|g_R|^4(3m_f^2 + m_\chi^2 v^2)}{48\pi(m_\chi^2 + m_F^2)^2} \qquad \langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha^2 Q_f^4(|g_L|^2 + |g_R|^2)^2}{64\pi^3 m_\chi^2}|\mathcal{A}|^2$$

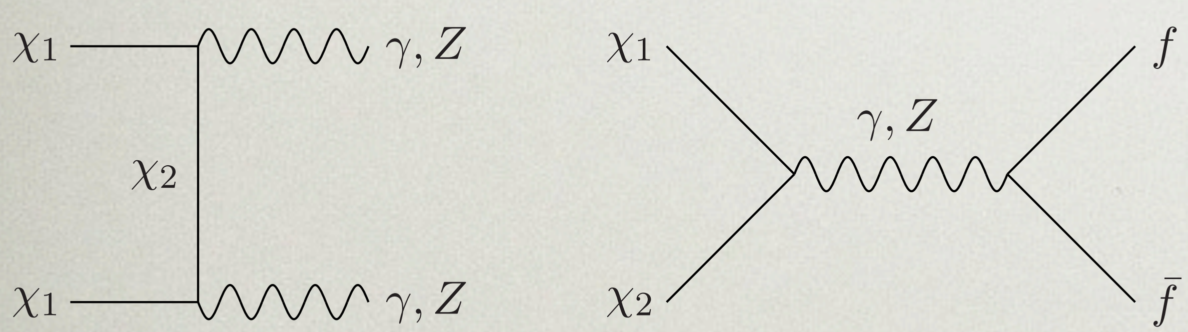
- However, p-wave does not allow one to obtain thermal DM $v \sim 0.3$

$$\langle \sigma v \rangle_{tree,p-wave} \sim 10^{-27} \text{ cm}^3/\text{s} \times 10^5 \times 0.3^2 \neq 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

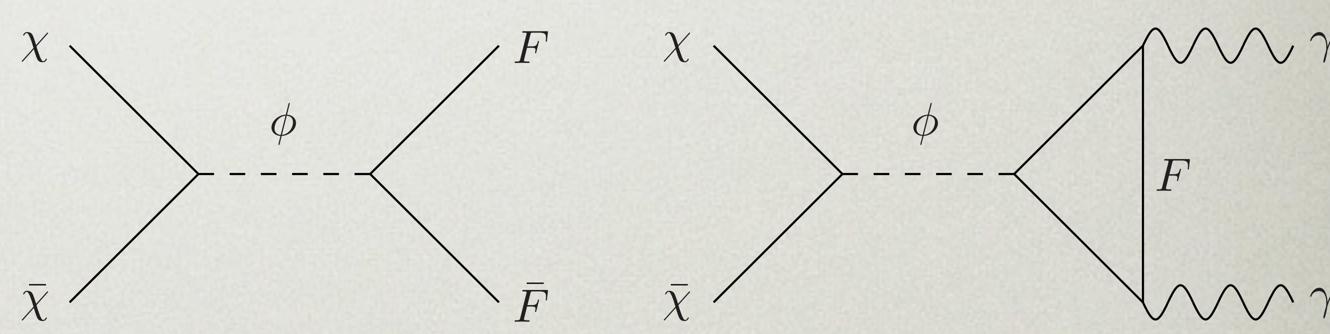
Three Exceptions

Tulin, Yu, KZ '12

- Some way to:
  - suppress continuum photons
  - obtain the observed abundance of DM



1. Coannihilation



2. Forbidden Channels

Three Exceptions

Tulin, Yu, KZ '12

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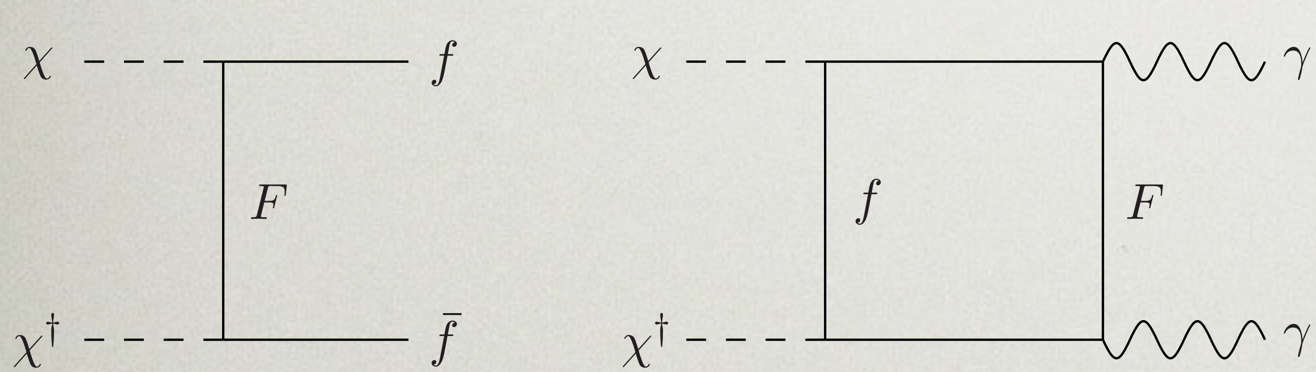
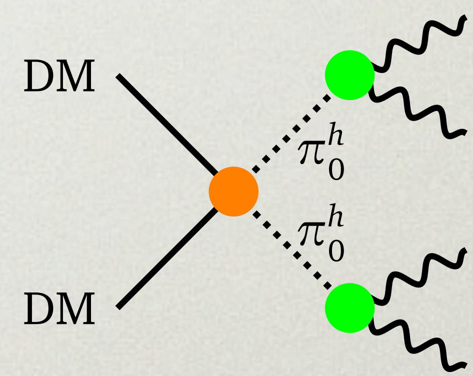


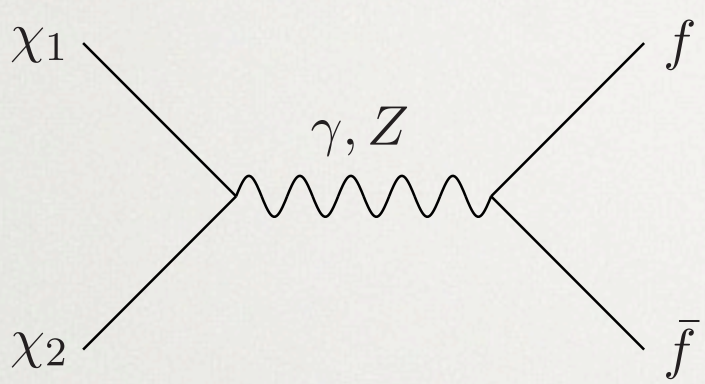
3. Asymmetric Dark Matter

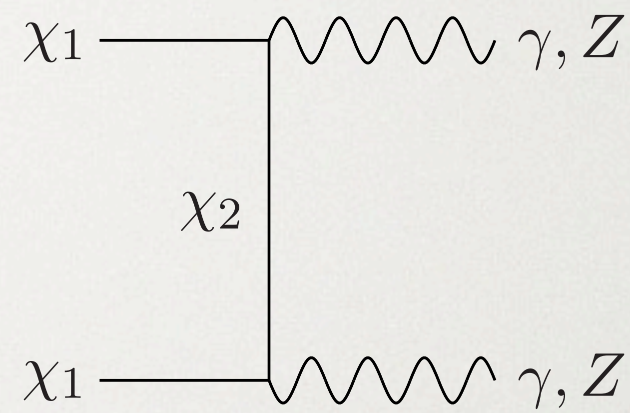


Buckley, Hooper
Bai, Shelton
Fan, Reece

(4.) Degenerate States

Exception 1: Coannihilation



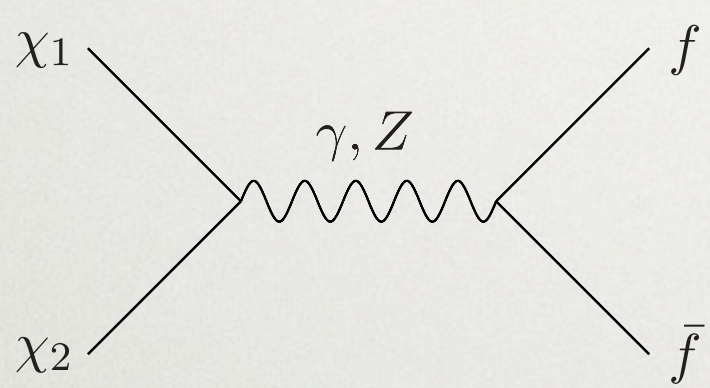


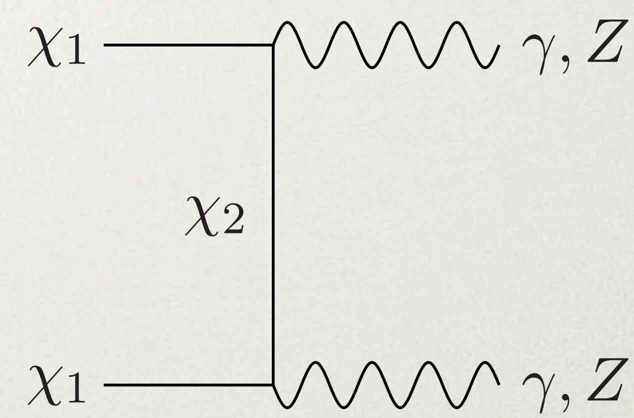
- Relic density set by annihilation with heavier state; relic abundance fixed by mass splitting
- Heavier state not present today; must annihilate through virtual state
- Natural example is dipole moment

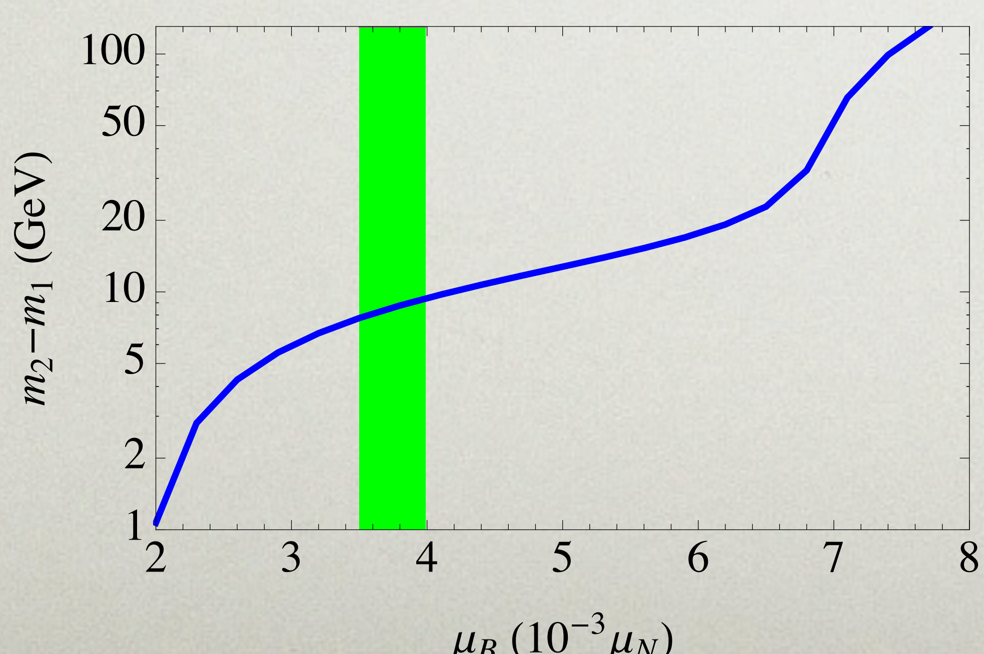
Exception 1: Coannihilation

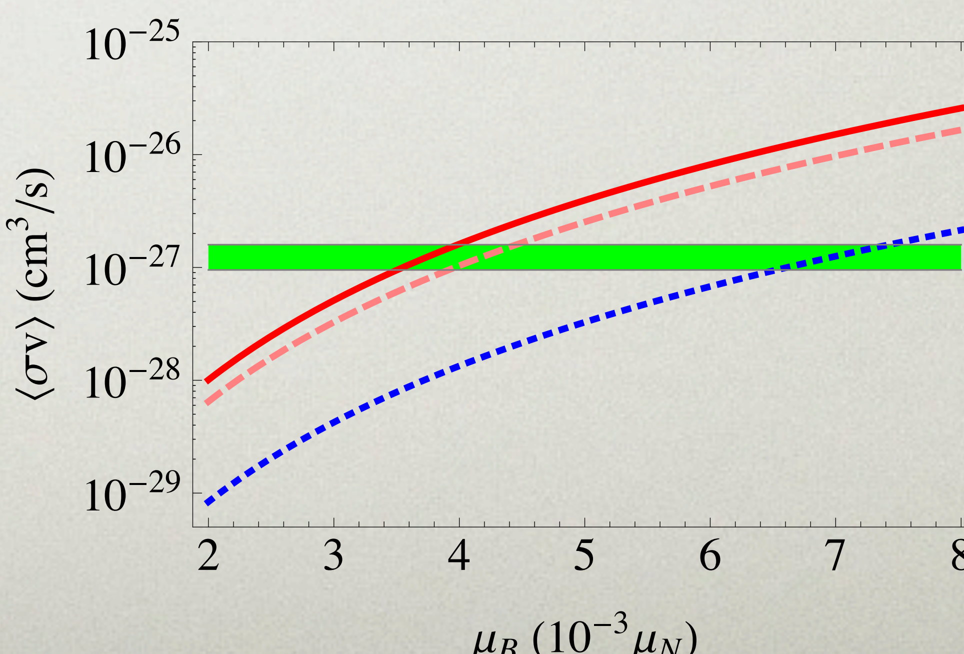
$$\mathscr{L}_{\mathrm{int}} = \frac{\mu_\gamma}{2}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 F_{\mu\nu} + \frac{\mu_Z}{2}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 Z_{\mu\nu}$$

- Natural place to look is in monopoles



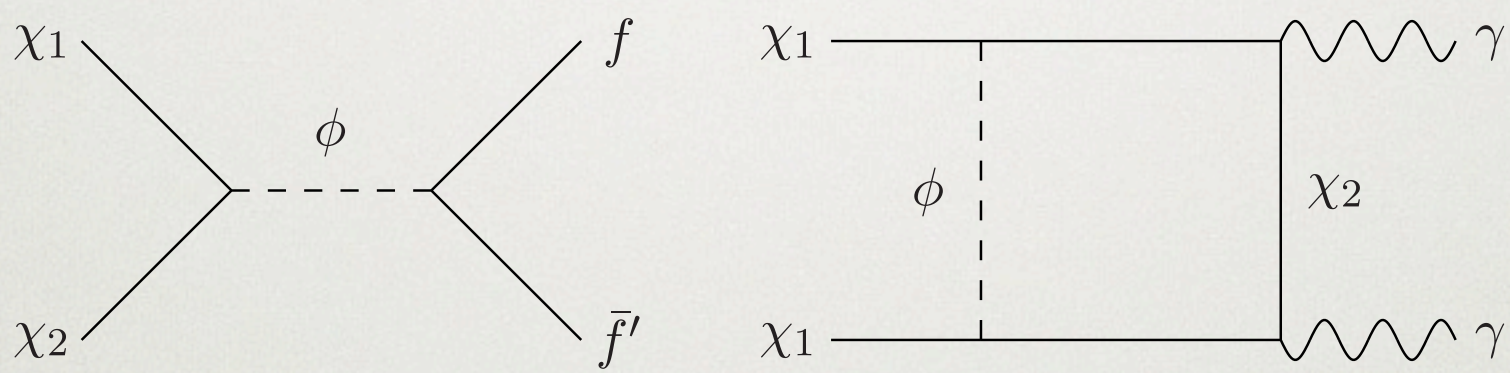






Exception 1: Coannihilation

- Other toy models are realizable



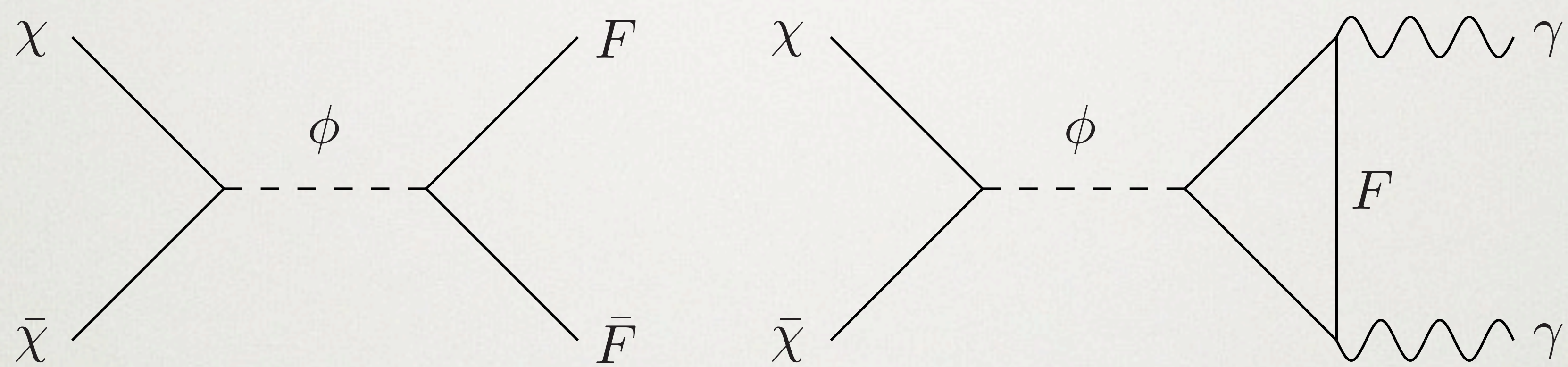
$$\mathscr{L}_{\rm int} = \bar{\chi}_2 (g_S + g_P \gamma_5)\chi_1 \phi + \bar{f}(g'_S + g'_P \gamma_5) f' \phi + \text{h.c.}$$

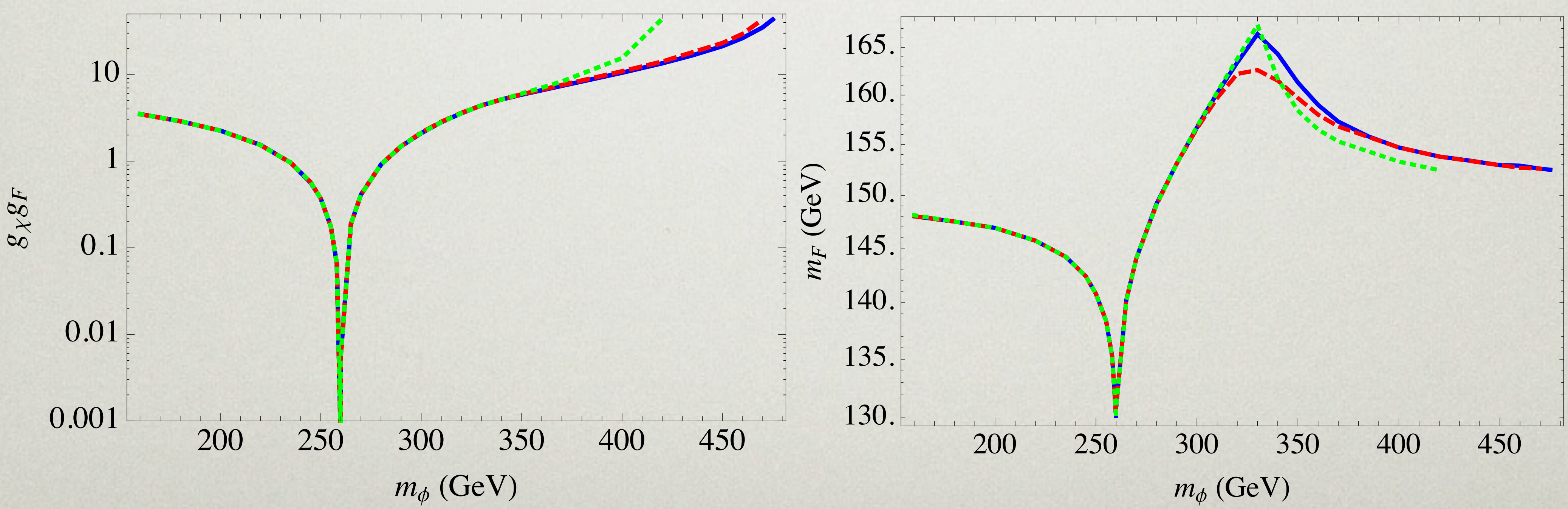
Exception 2: Forbidden Channels

- Make the charged particle in the loop heavier than the DM
- No direct annihilation; avoid continuum constraints
- Dial neutral-charged mass splitting to obtain correct relic abundance

Exception 2: Forbidden Channels

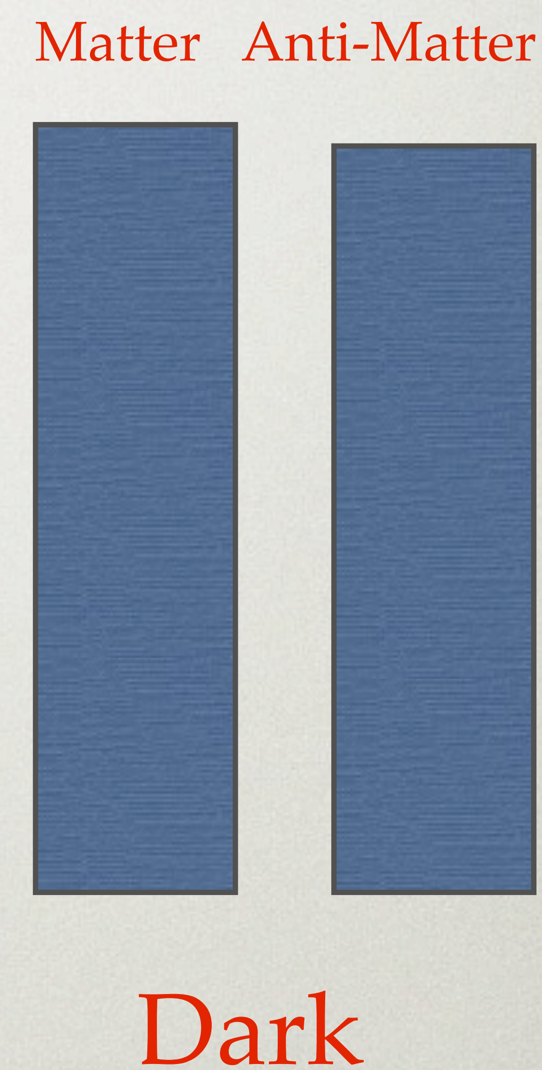
Tulin, Yu, KZ '12





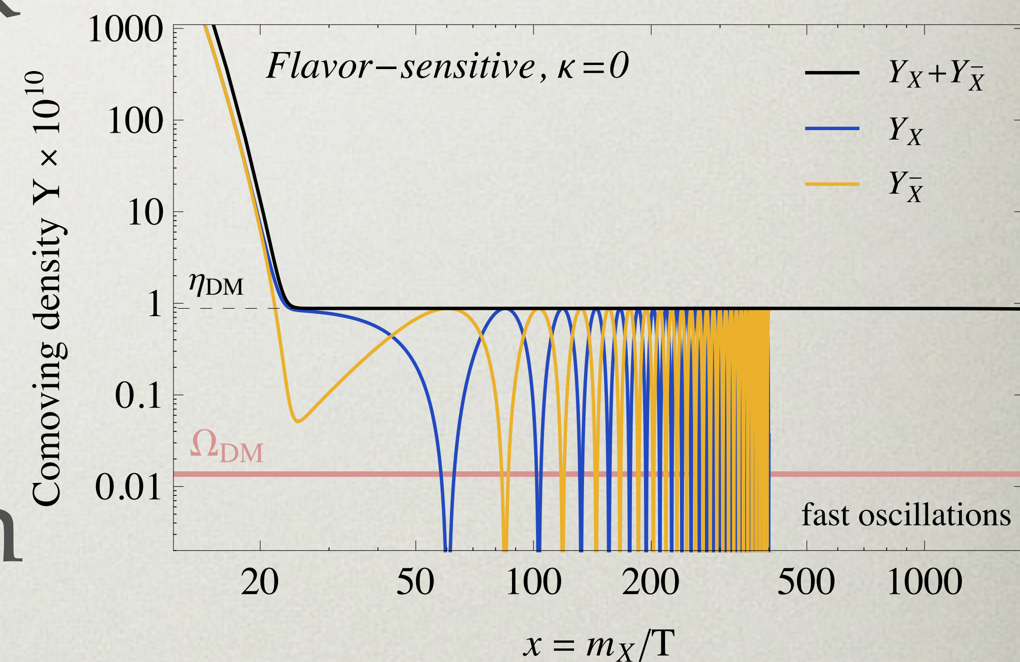
Exception 3: Asymmetric Dark Matter

- Stop the annihilation in the early universe dead in its tracks: remove the anti-matter
- How do we regain annihilations today? Oscillations!



Oscillating ADM

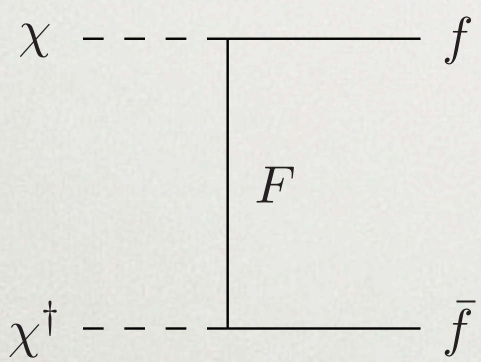
- Asymmetry may be erased
- Any violation of DM number can lead to dark-anti-dark oscillations
- Like ν oscillations
- Become important when mass exceeds Hubble expansion

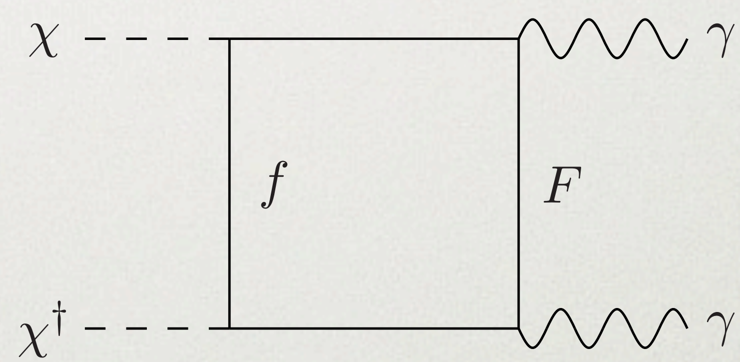


Tulin, Yu, KZ, '12

Exception 3: Asymmetric Dark Matter

- Still need to suppress continuum today
- Make use of p-wave





$$\sigma(\chi\chi^\dagger \to f\bar{f})v \approx \frac{|g_L|^2|g_R|^2 m_F^2}{4\pi(m_\chi^2 + m_F^2)^2}$$

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha^2 Q_f^4 (|g_L|^2 + |g_R|^2)^2}{64\pi^3 m_\chi^2} |\mathcal{A}|^2$$

$$\sigma(\chi\chi^\dagger \to f\bar{f})v \approx \frac{|g_R|^4 (3m_f^2 + m_\chi^2 v^2)}{48\pi(m_\chi^2 + m_F^2)^2}$$

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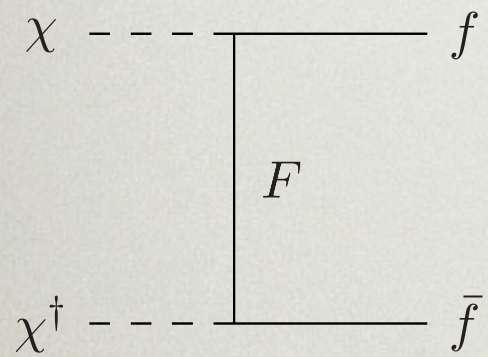
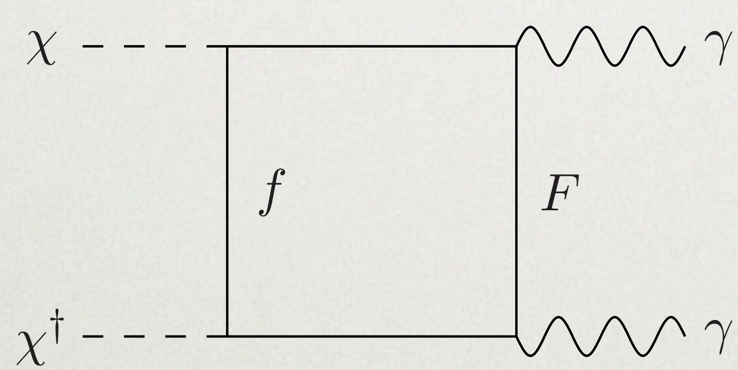
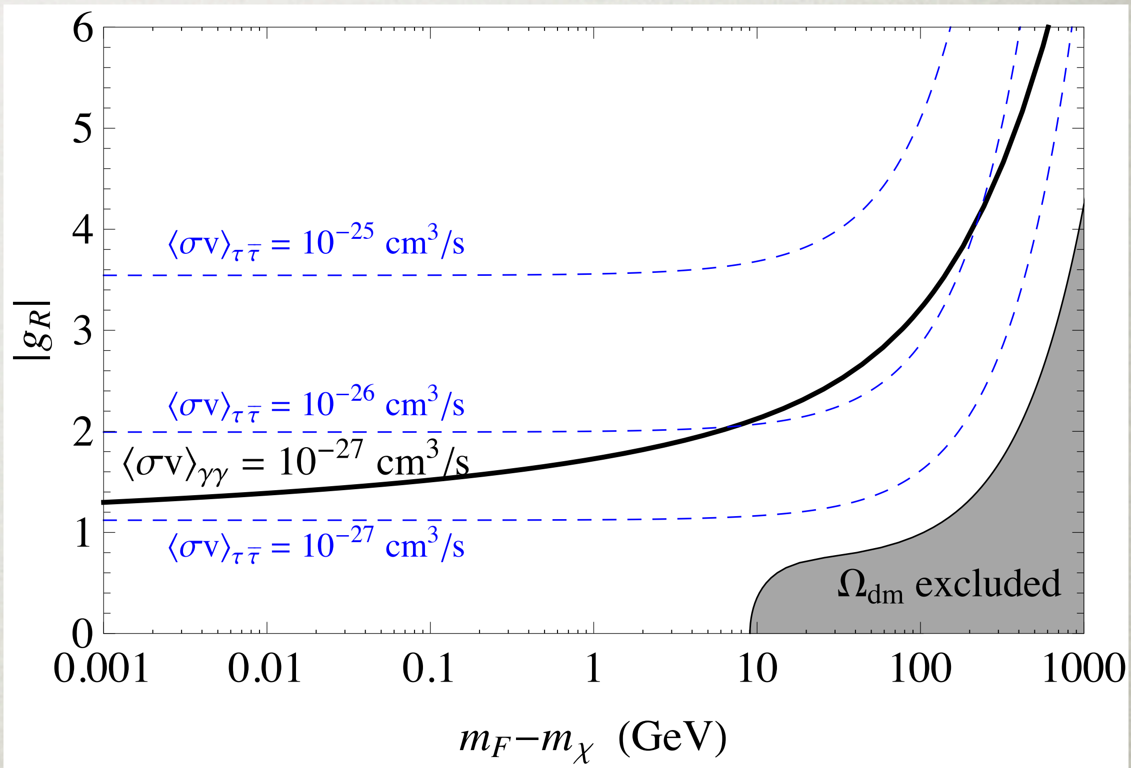
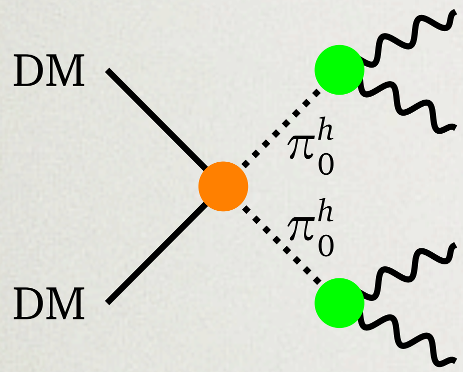






Exception 4: Annihilate to Degenerate States



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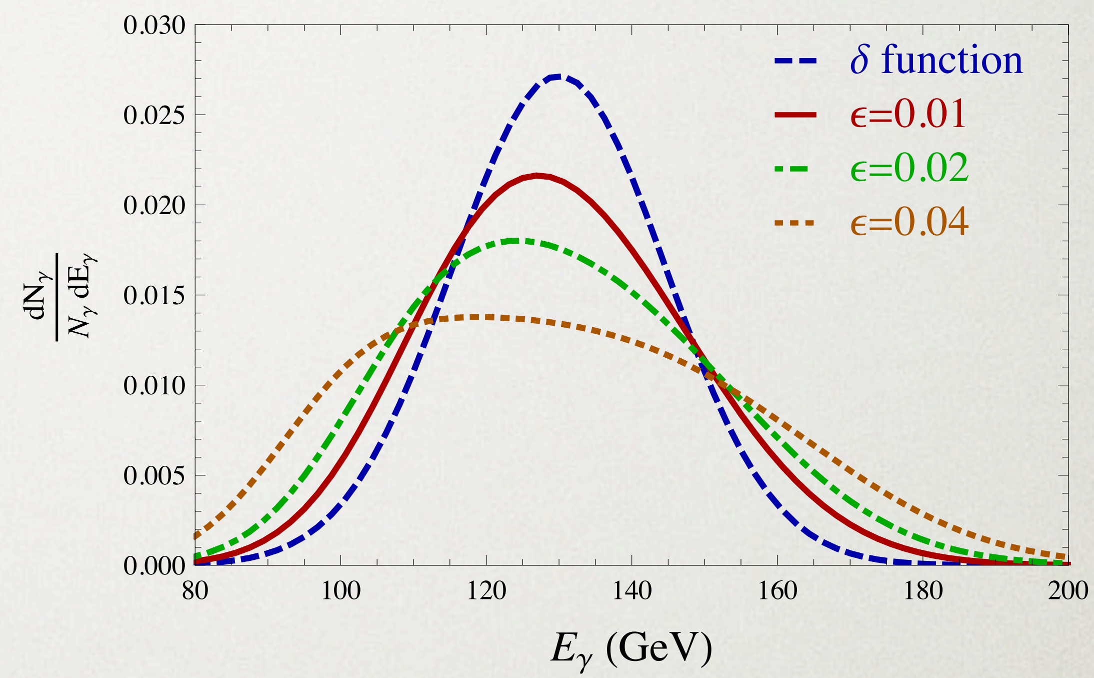


- Why is the mass splitting so small?
- A symmetry? Flavor symmetry?

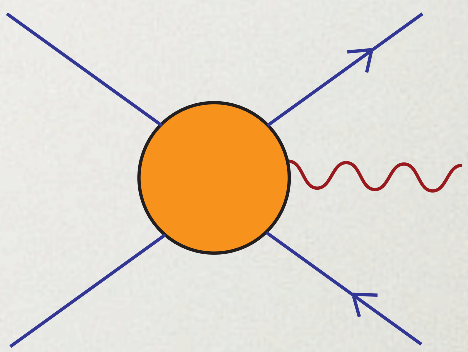
$$m^2_{\pi_\pm} = (m_p + m_q)\mu$$

$$\delta m_\pi = \frac{(m_p - m_q)^2 \mu^2}{2 m_{\pi_\pm} m^2_{\eta_0}}$$

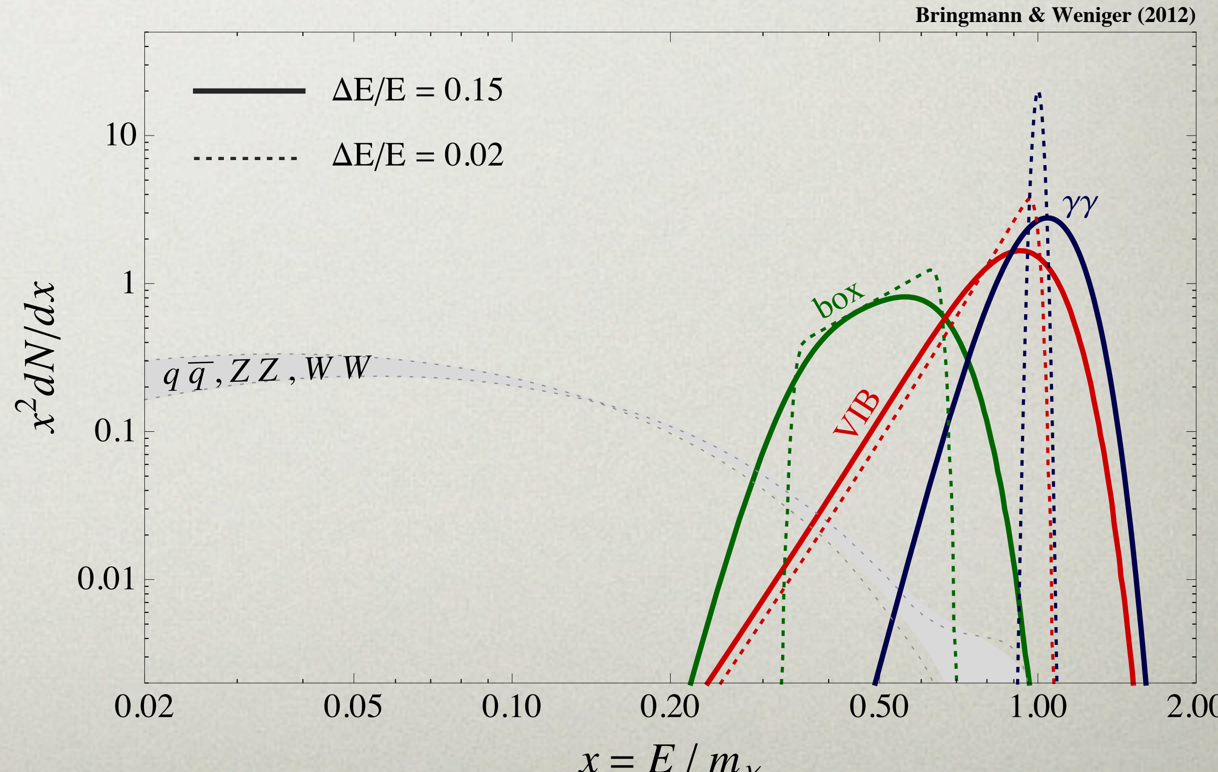
$$\pi^h_+ \pi^h_- \to \pi^h_0 \pi^h_0, \quad \pi^h_0 \to \gamma\gamma,\ \gamma Z$$

Exception 5: Internal Bremstrahlung

- Photon from IB can look nearly mono-chromatic
- Annihilation to charged fermions p-wave suppressed

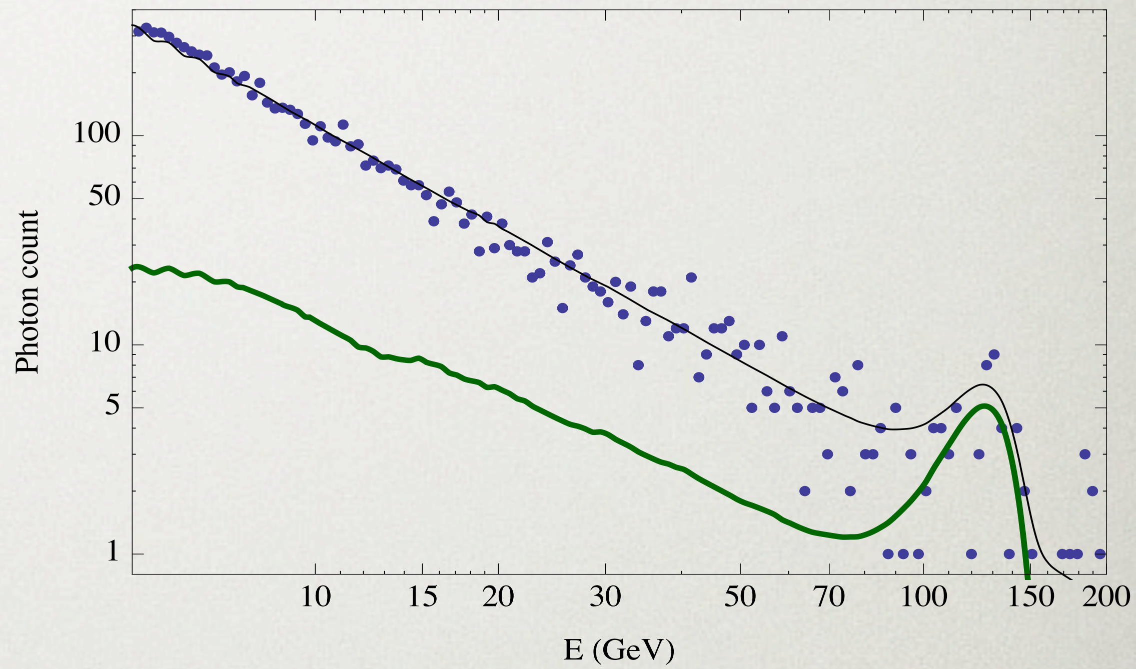


(c)



Exception 5: Internal Bremstrahlung

B. Shakya



- Classic case: neutralino annihilation to charged leptons
- p-wave suppressed
- With IB photon, it becomes s-wave

Summary

- Fermi line: compelling signal for DM or a systematic?
- General take home message: not very difficult to construct models that fit this feature, though MSSM-type models must be very particular
- Good news: experimentally resolvable on a short time scale