Dark matter, black holes, and the Fermi-LAT GeV excess

Jessie Shelton

University of Illinois, Urbana-Champaign

Mainz Institute for Theoretical Physics

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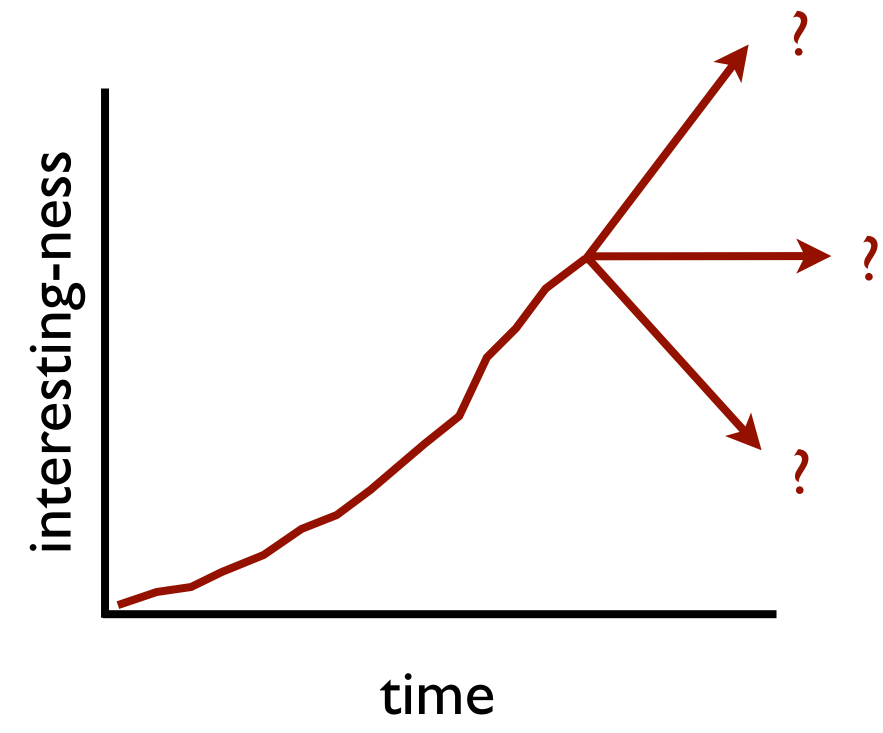
Abbreviated history of the excess

- Goodenough & Hooper (2011): excess over power-law background models in the Galactic Centre



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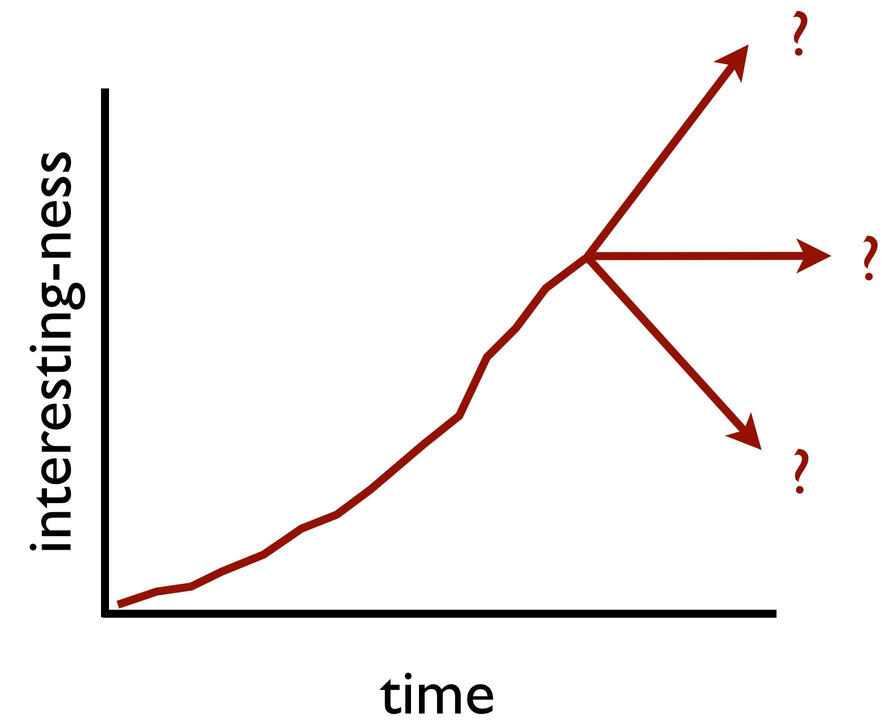

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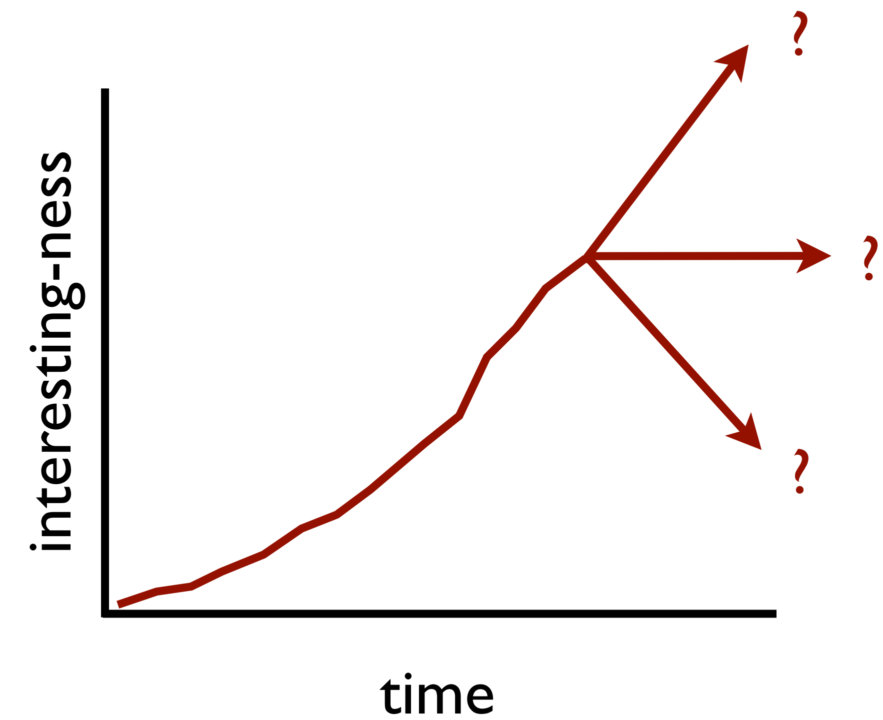

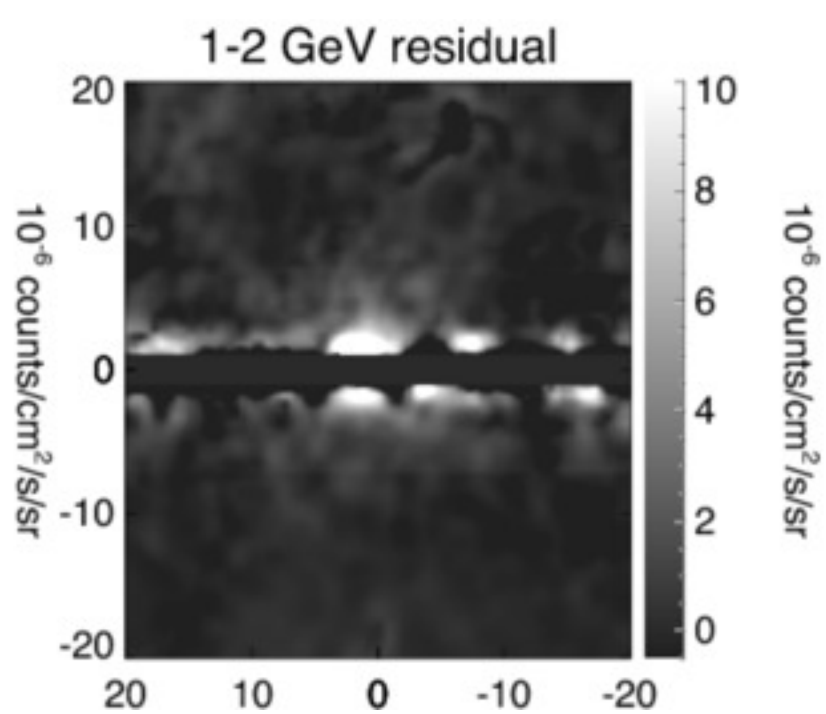

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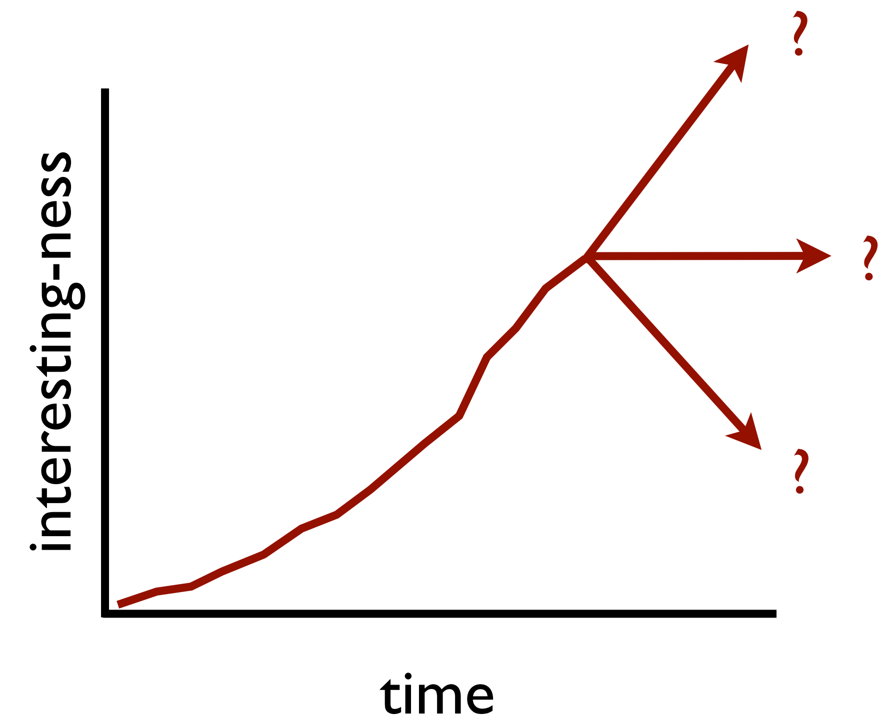
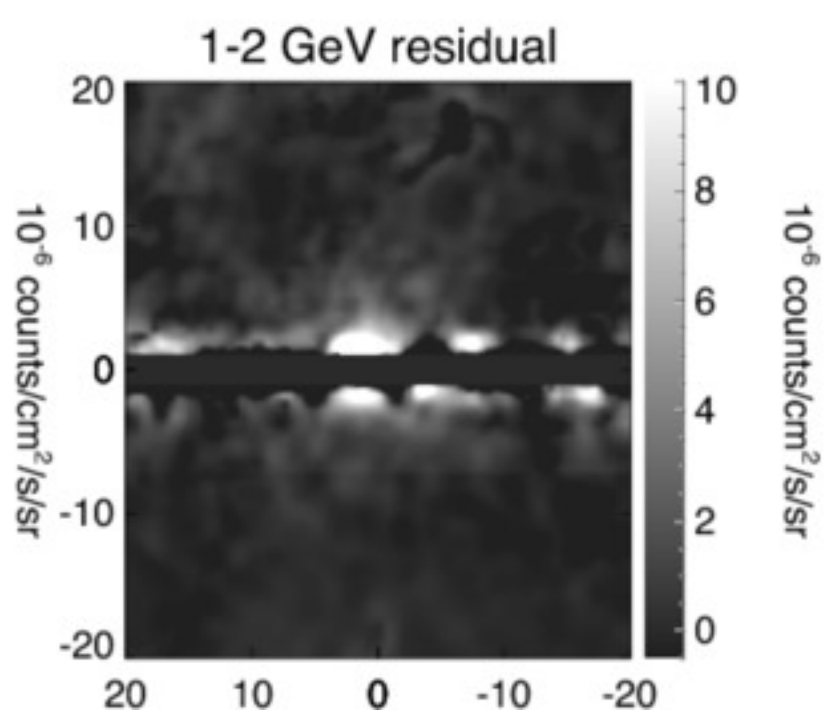




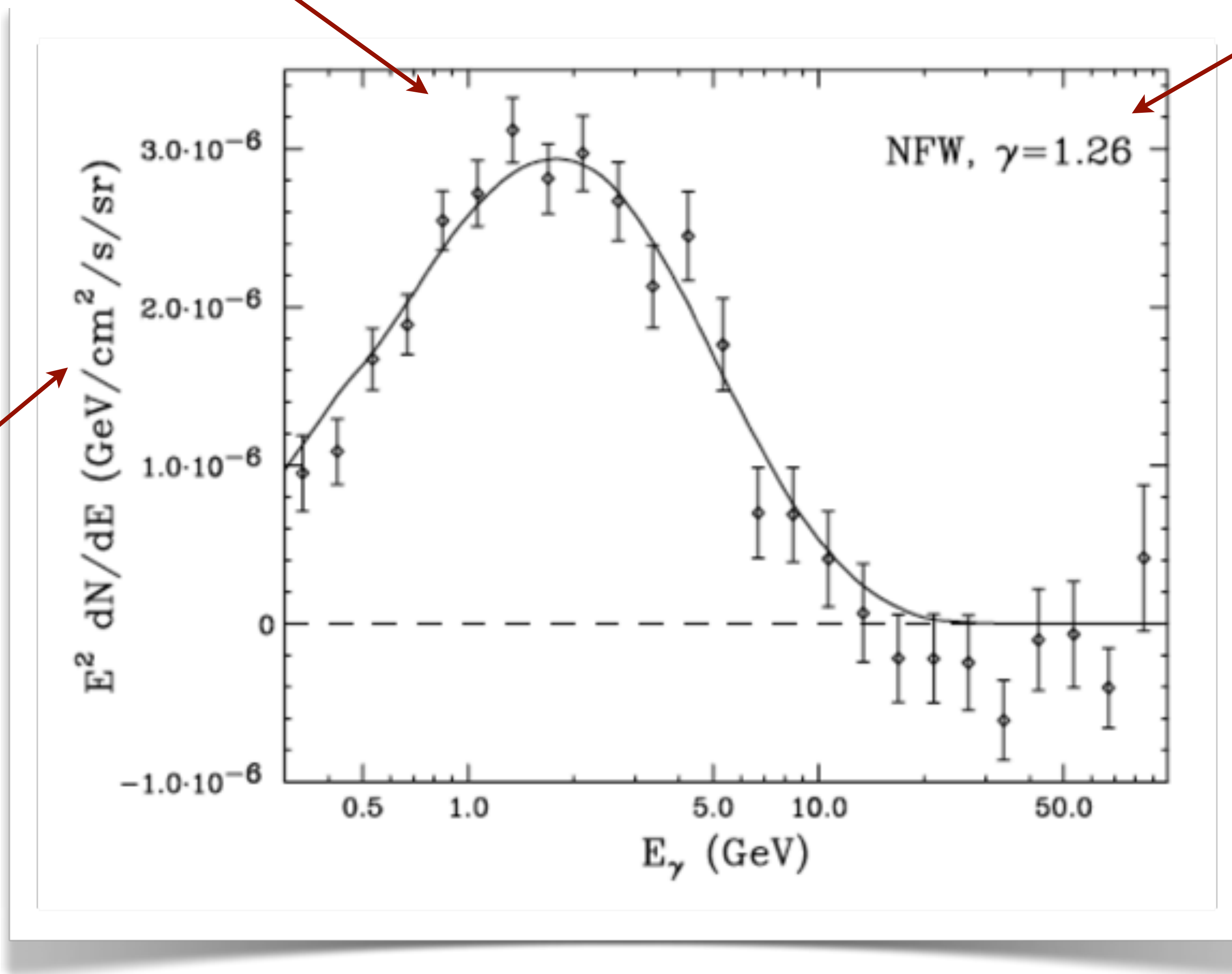
- Hooper & Slatyer (2013) establish spatial extent out to ~10° from the GC

- Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, & Slatyer (2014): increased angular resolution tightens DM case

The Galactic Centre Excess

Spatially uniform continuum spectrum

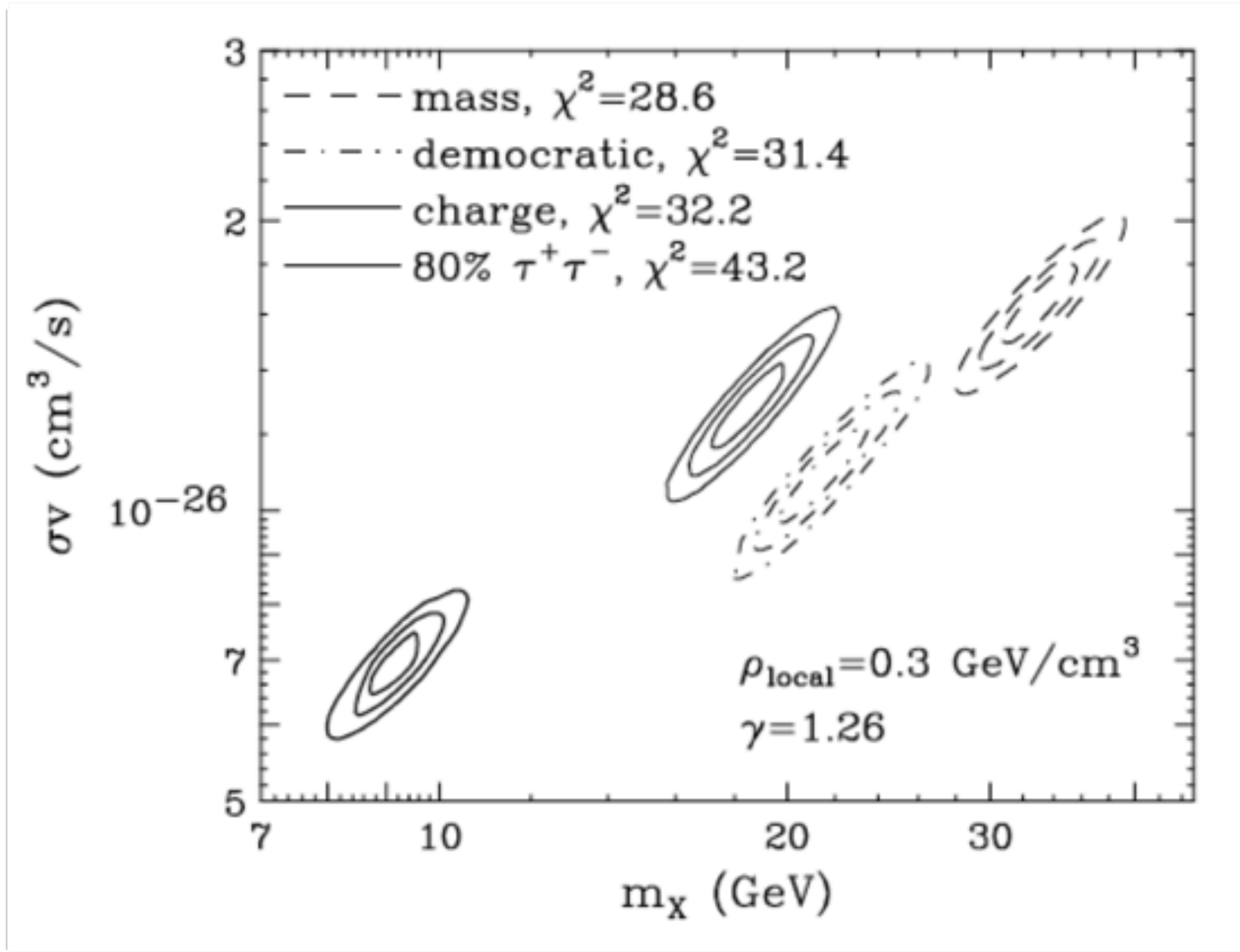
Annihilation in an adiabatically contracted NFW halo



Overall rate

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer

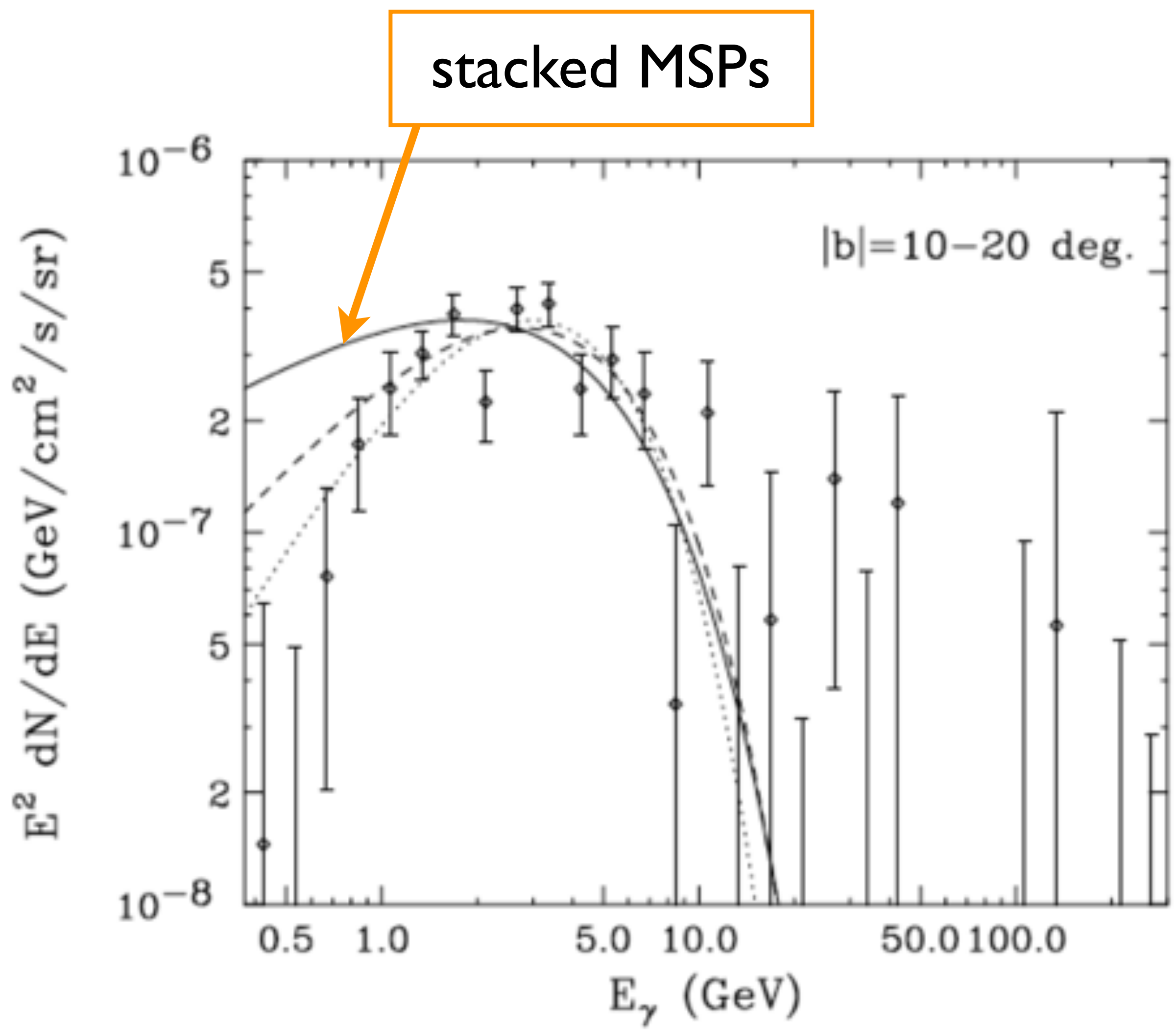
Mass, cross section, final states:



Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer

A cautionary note

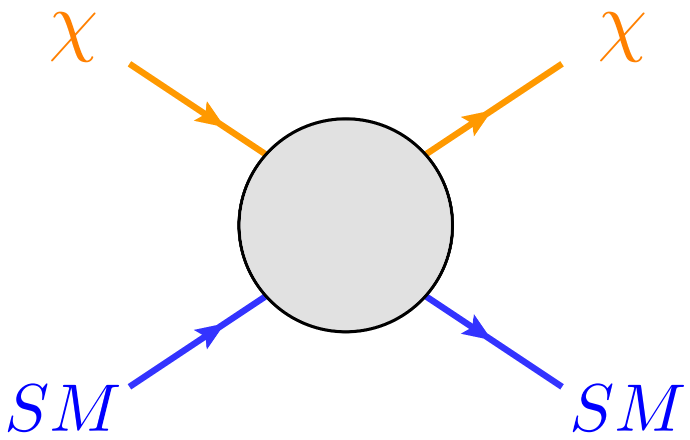
- Known astrophysical objects with similar energy cutoff: millisecond pulsars
- Energy spectrum?
- Spatial distribution?



- Need novel luminosity distribution to avoid over-predicting resolved MSPs at high latitude
  - By this argument: < 5-10 % of excess

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer

Mediating annihilations in the GC



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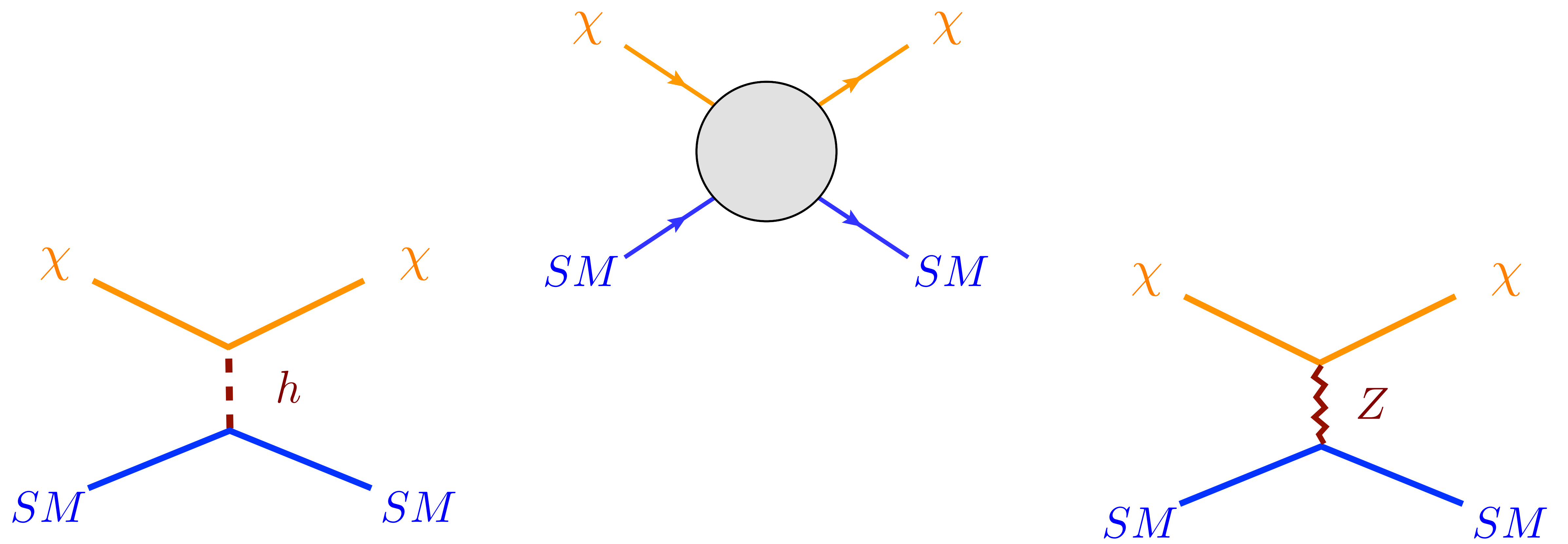

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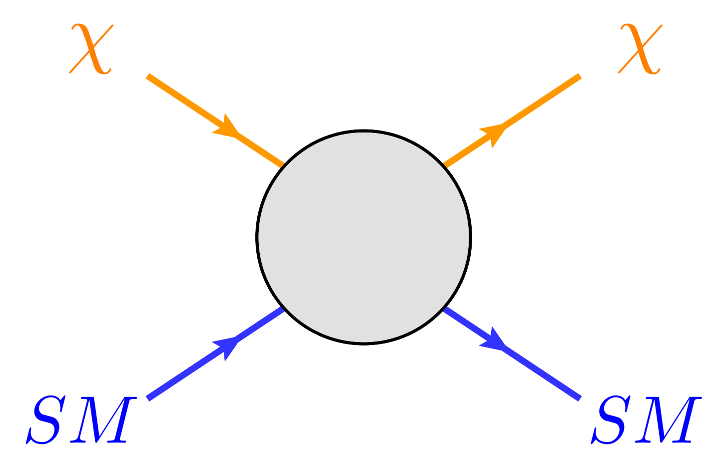
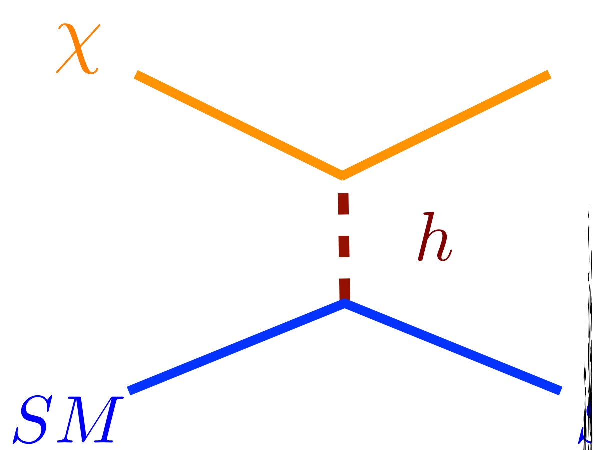
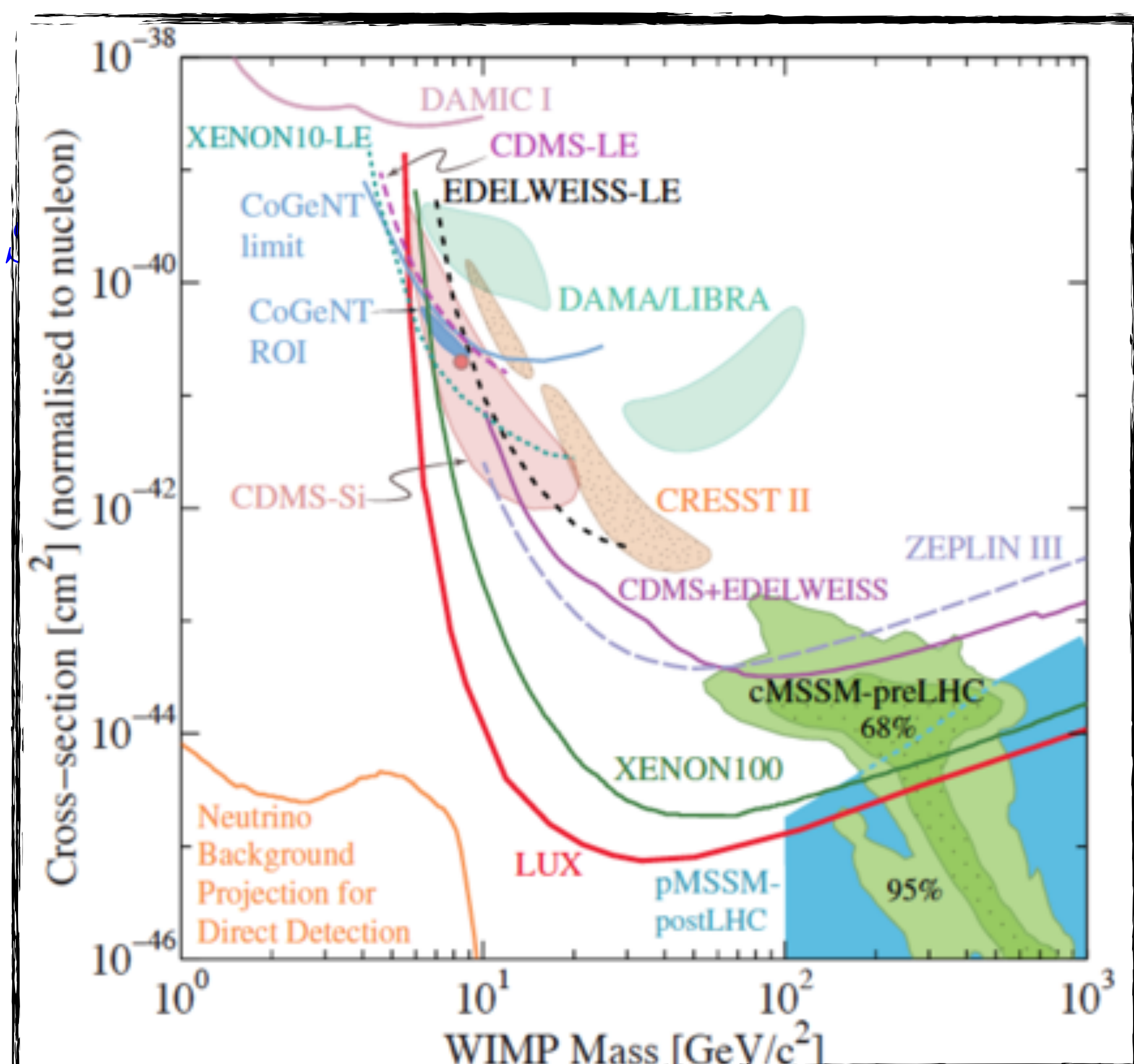
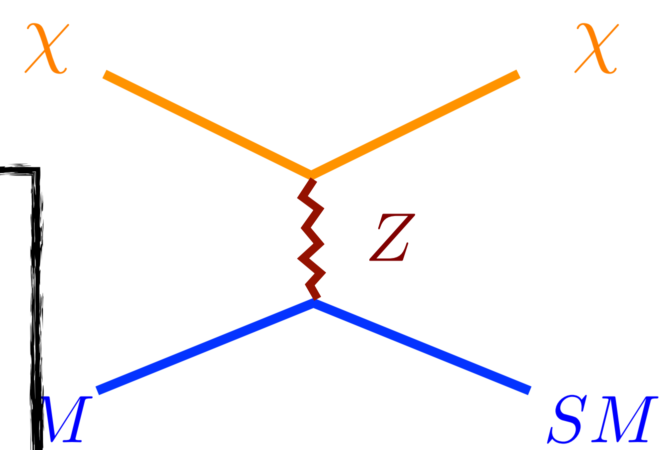


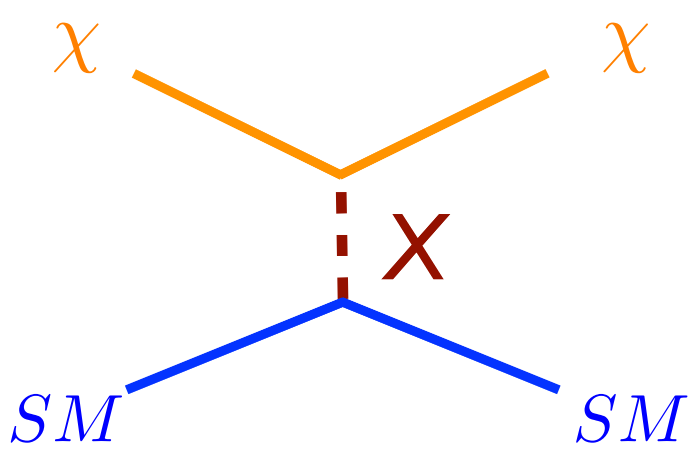






PDG

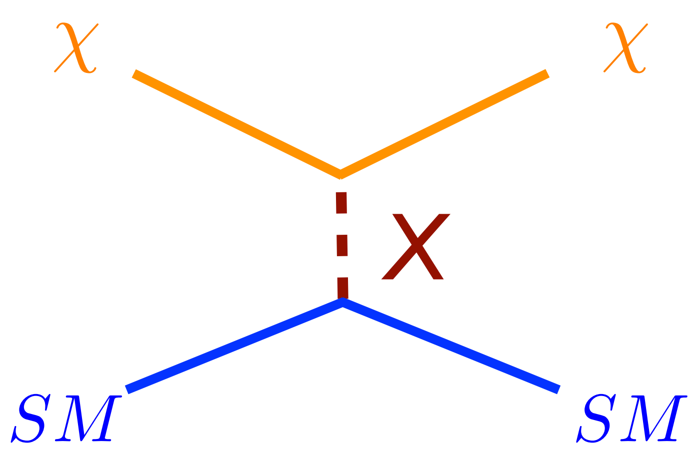
New mediators



$$m_X > m_\chi$$

- annihilation, direct detection amenable to contact operator description
- collider signals may require explicit introduction of new d.o.f.
- pseudoscalar X requires 2HDM or similar

New mediators



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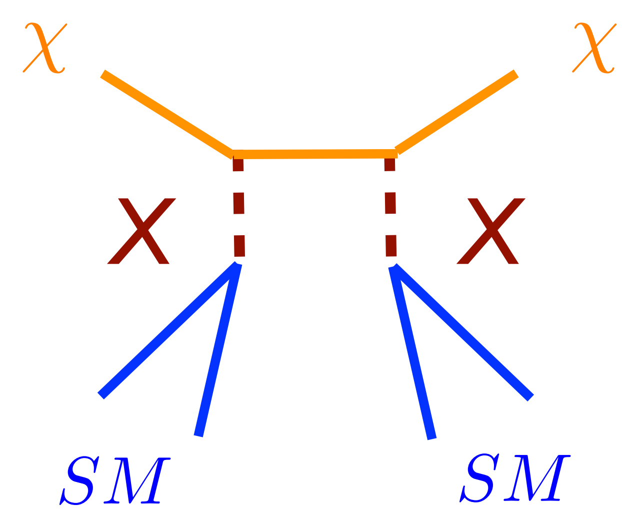
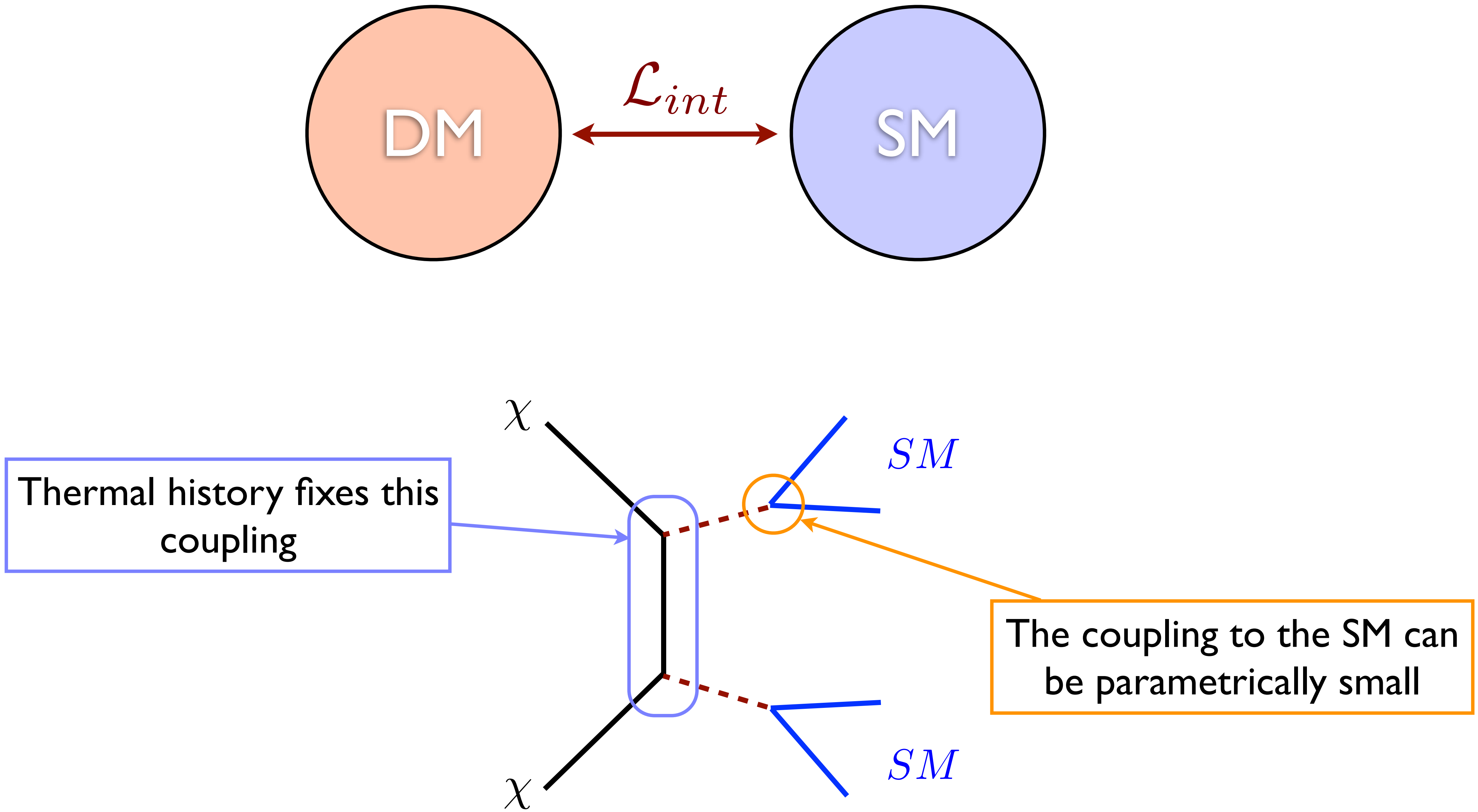


$$m_X < m_\chi$$

- dominant DM annihilation mode is to mediators
- lifetime of mediators bounded by BBN

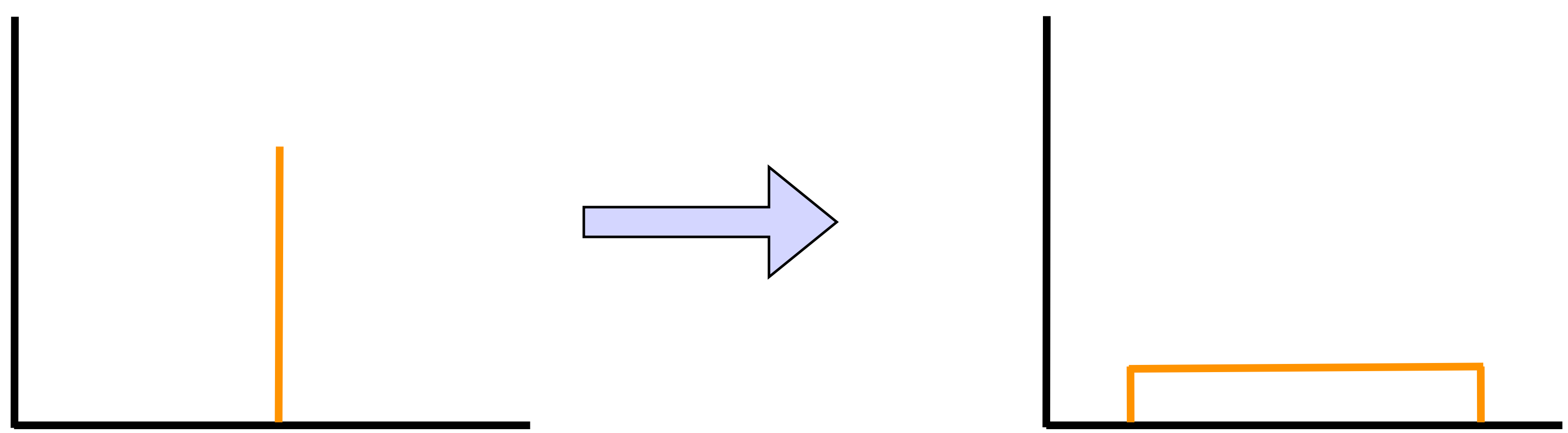
New mediators



Pospelov, Ritz

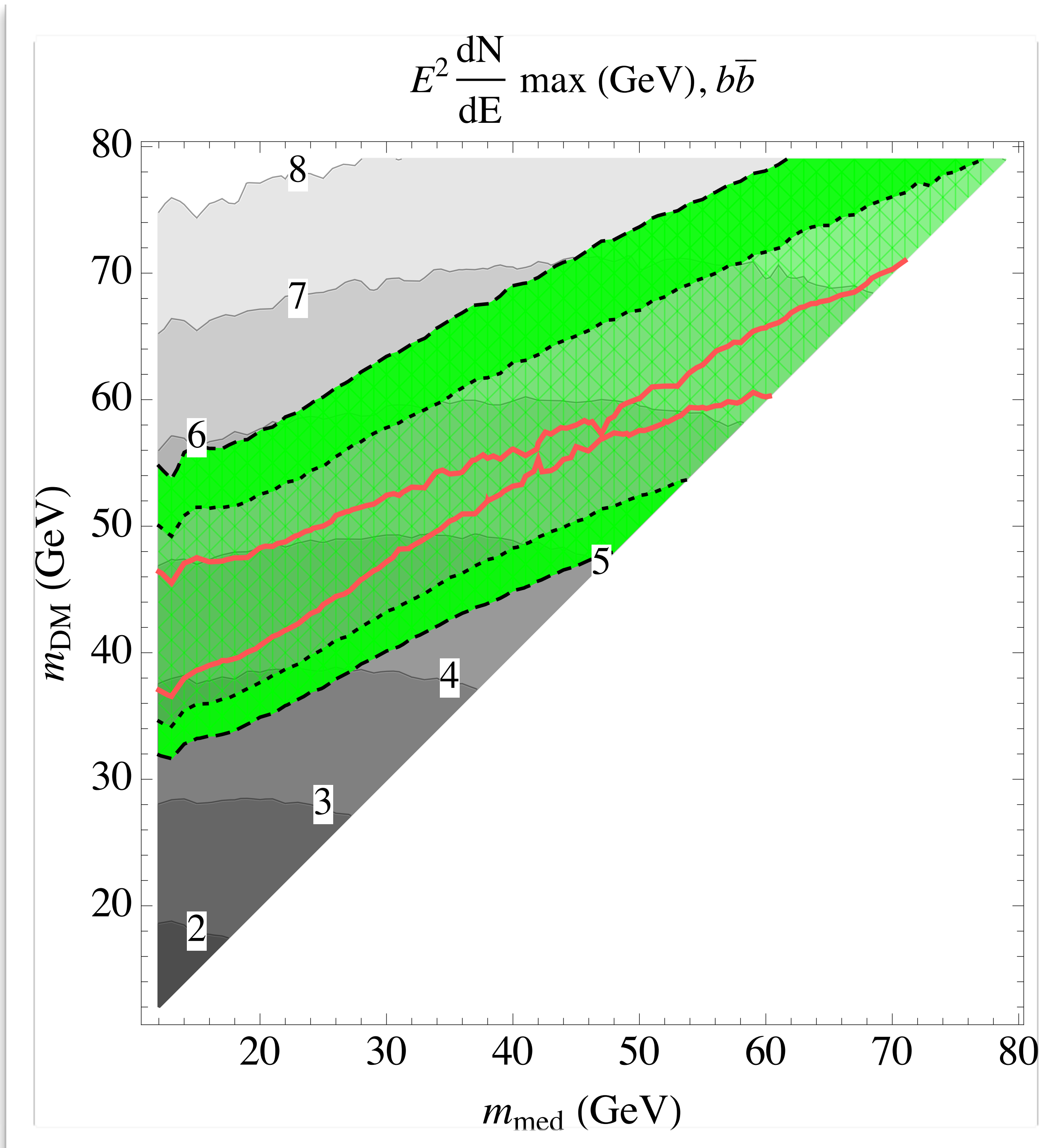
Final states in cascade annihilations

- SM singlets couple through portals:
  - Higgs: $\lambda |H|^2 s^2$
  - hypercharge: $\epsilon B_{\mu\nu} V^{\mu\nu}$
  - gluons: $\frac{1}{M}\, s\, G^{\mu\nu} G_{\mu\nu},\ \frac{1}{M}\, a\, G^{\mu\nu} \widetilde{G}_{\mu\nu}$
  - ...



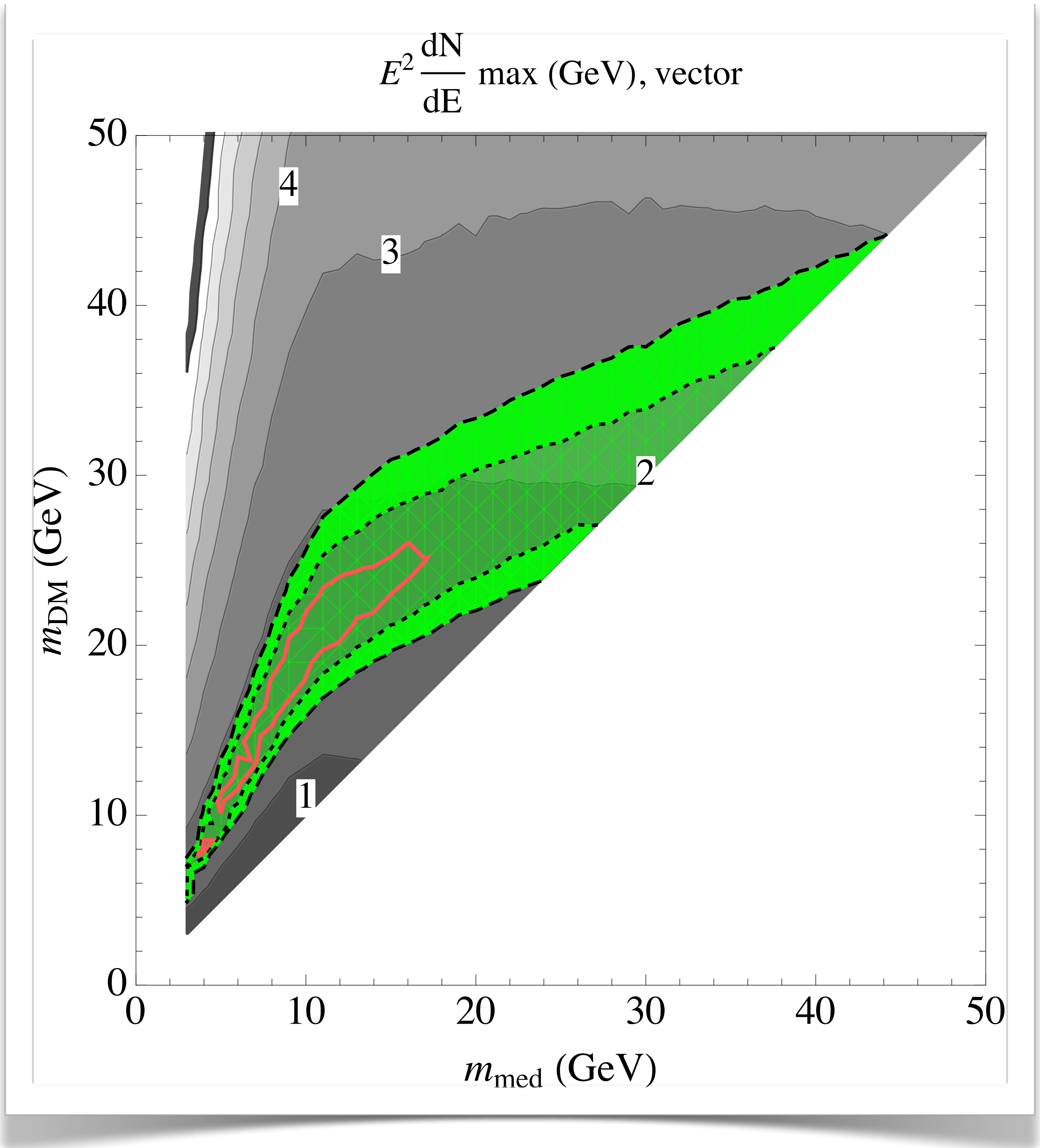
$$\frac{m_{DM}}{2} \qquad\qquad \frac{m_{DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_{med}}{m_{DM}}}\right)$$

Cascade annihilation spectra



Martin, JS, Unwin

Portals into the SM:
Hypercharge

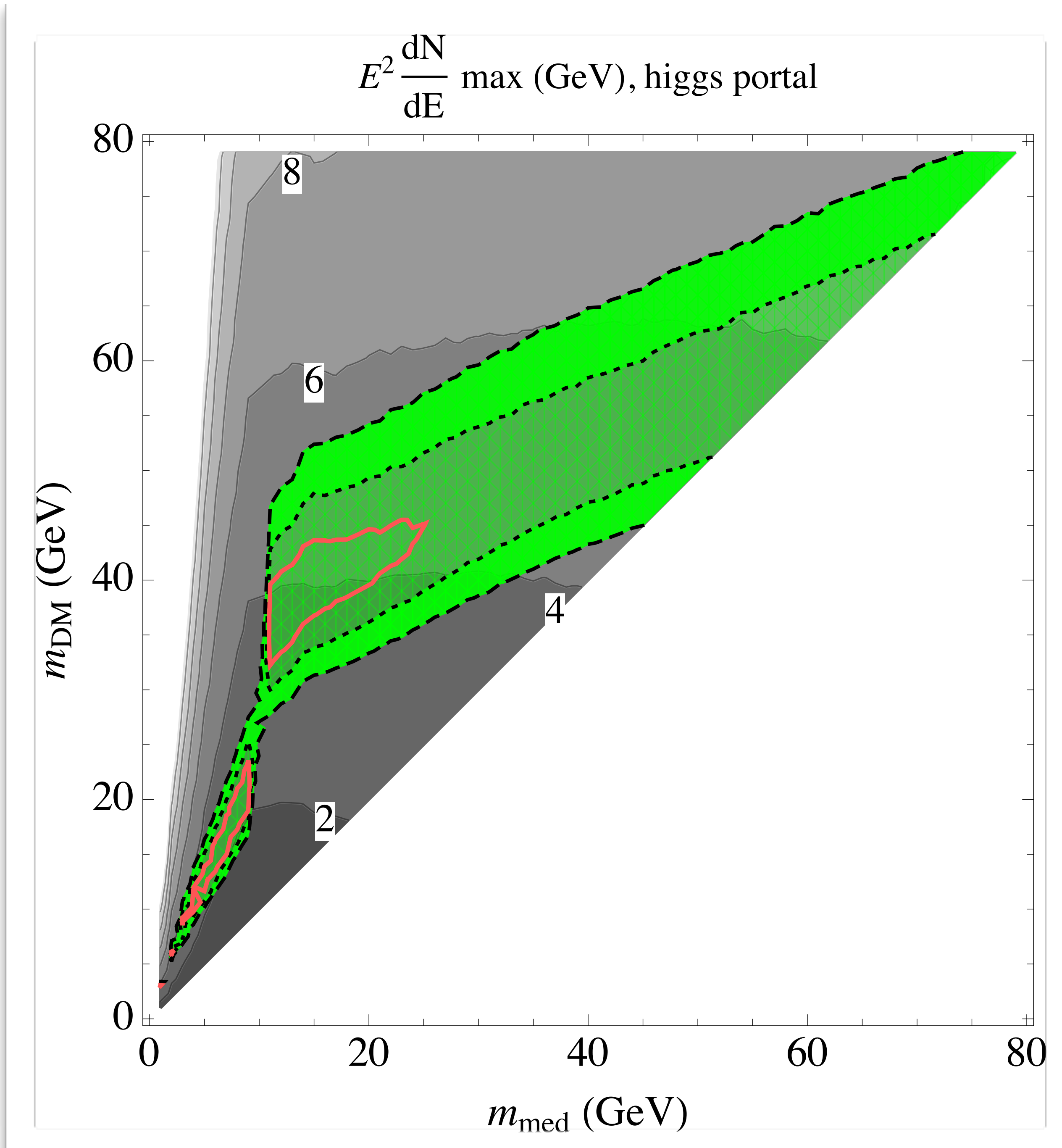


$$\mathcal{L}_{int} = \epsilon V_{\mu\nu} B^{\mu\nu}$$

- kinetically mixed *U*(1) gets mass from dark SSB
- for $m \lesssim 20$ GeV, coupling to SM fermions approximately proportional to charge

Martin, JS, Unwin

Portals into the SM:
Higgs



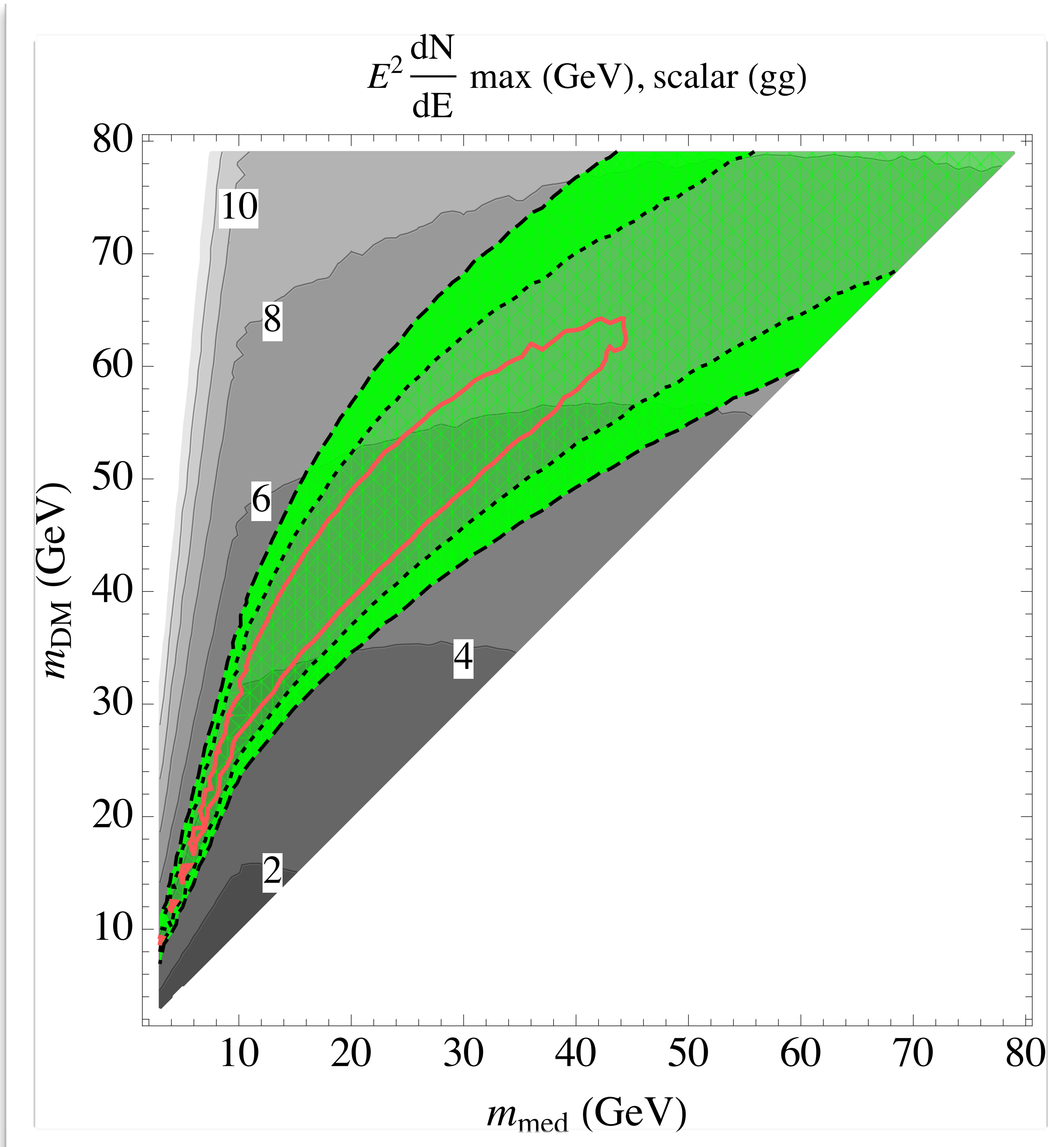
$$\mathcal{L}_{int} = \epsilon s^2 |H|^2$$

- s inherits Yukawa couplings through Higgs mixing after SSB
- radiative corrections: HDECAY for branching fractions
- fit results also apply to pseudoscalar a

Martin, JS, Unwin

Portals into the SM:

gluons



$$\mathcal{L}_{int} = \frac{1}{\Lambda}\phi G_{\mu\nu}G^{\mu\nu},\ \frac{1}{\Lambda}aG_{\mu\nu}\tilde{G}^{\mu\nu}$$

- new colored matter at high scales
- similar operators with electroweak field strengths can generate gamma ray boxes: potentially interesting signal for future

Martin, JS, Unwin

Many ways to fit a spectrum

$m_{DM} = 22\,\mathrm{GeV}$

$m_{med} = 12\,\mathrm{GeV}$

$\langle \sigma v \rangle = 3.4 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$

$m_{DM} = 40\,\mathrm{GeV}$

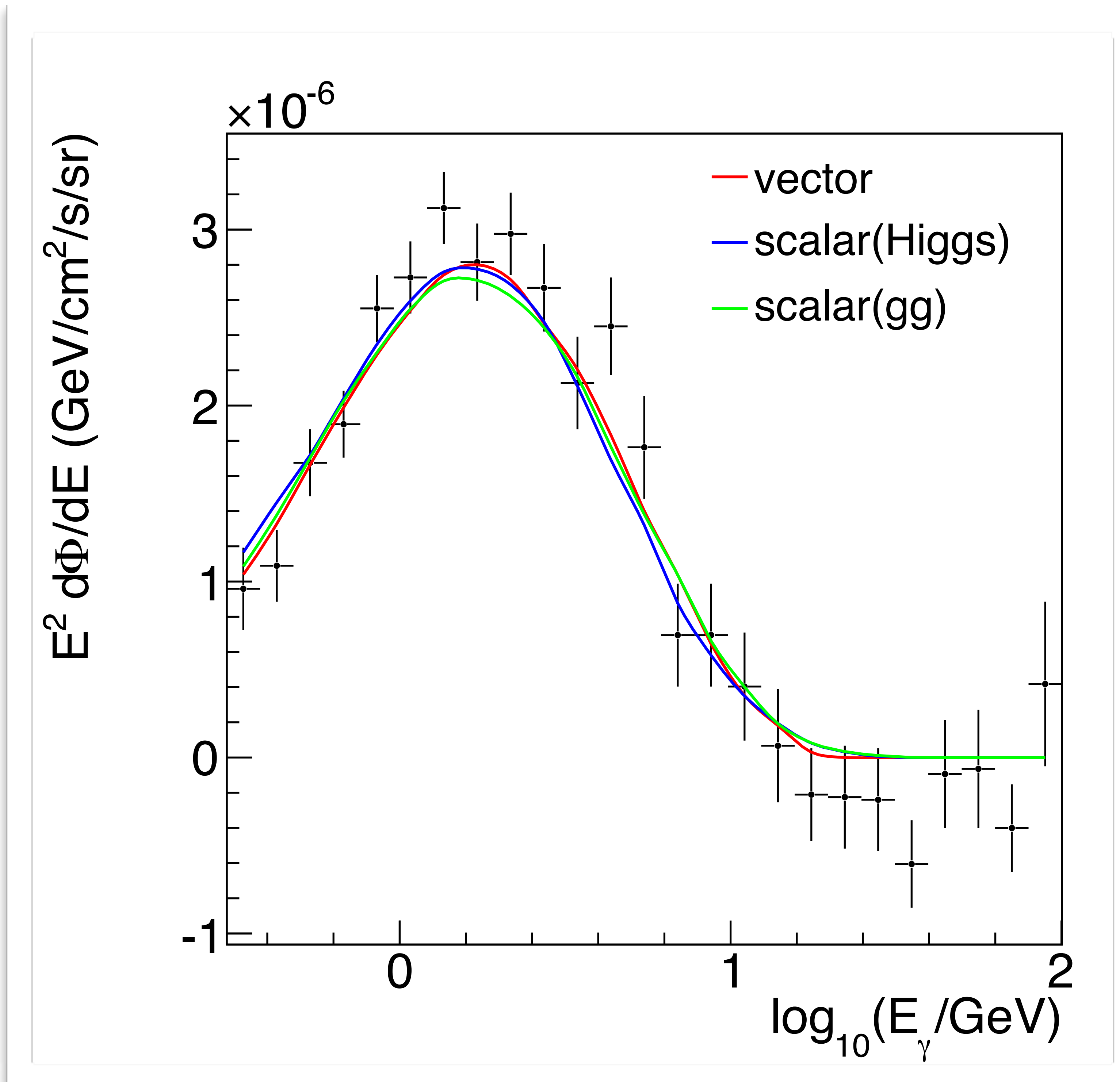
$m_{med} = 20\,\mathrm{GeV}$

$\langle \sigma v \rangle = 4.4 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$

$m_{DM} = 60\,\mathrm{GeV}$

$m_{med} = 40\,\mathrm{GeV}$

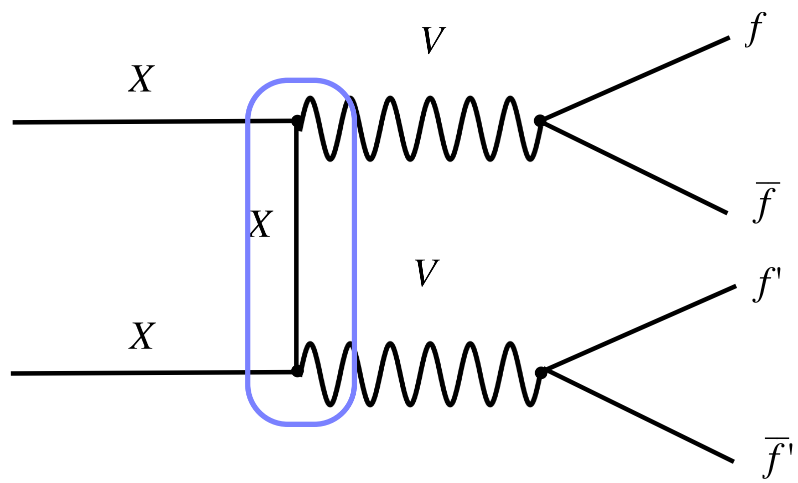
$\langle \sigma v \rangle = 6.1 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$



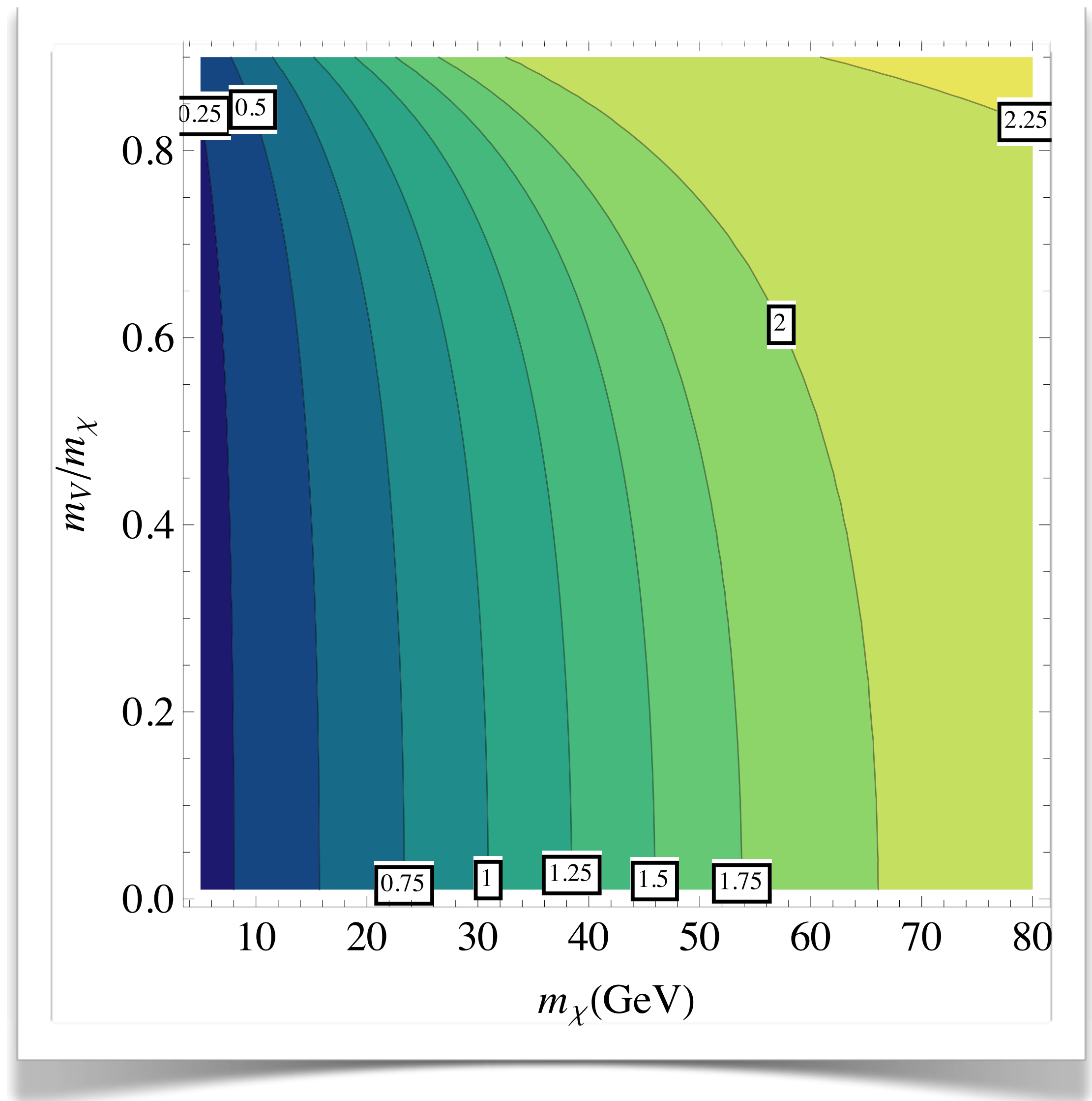
Martin, JS, Unwin

A sample model

Consider fermionic DM and a dark vector mediator:



Requiring $\Omega h^2 = 0.11$ determines α_D



$\alpha_D(10^{-3})$

Martin, JS, Unwin

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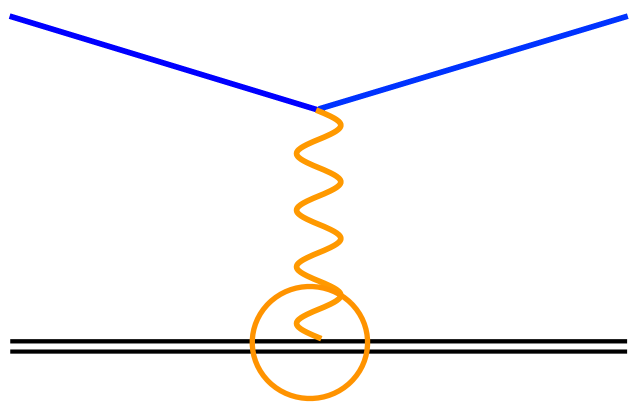

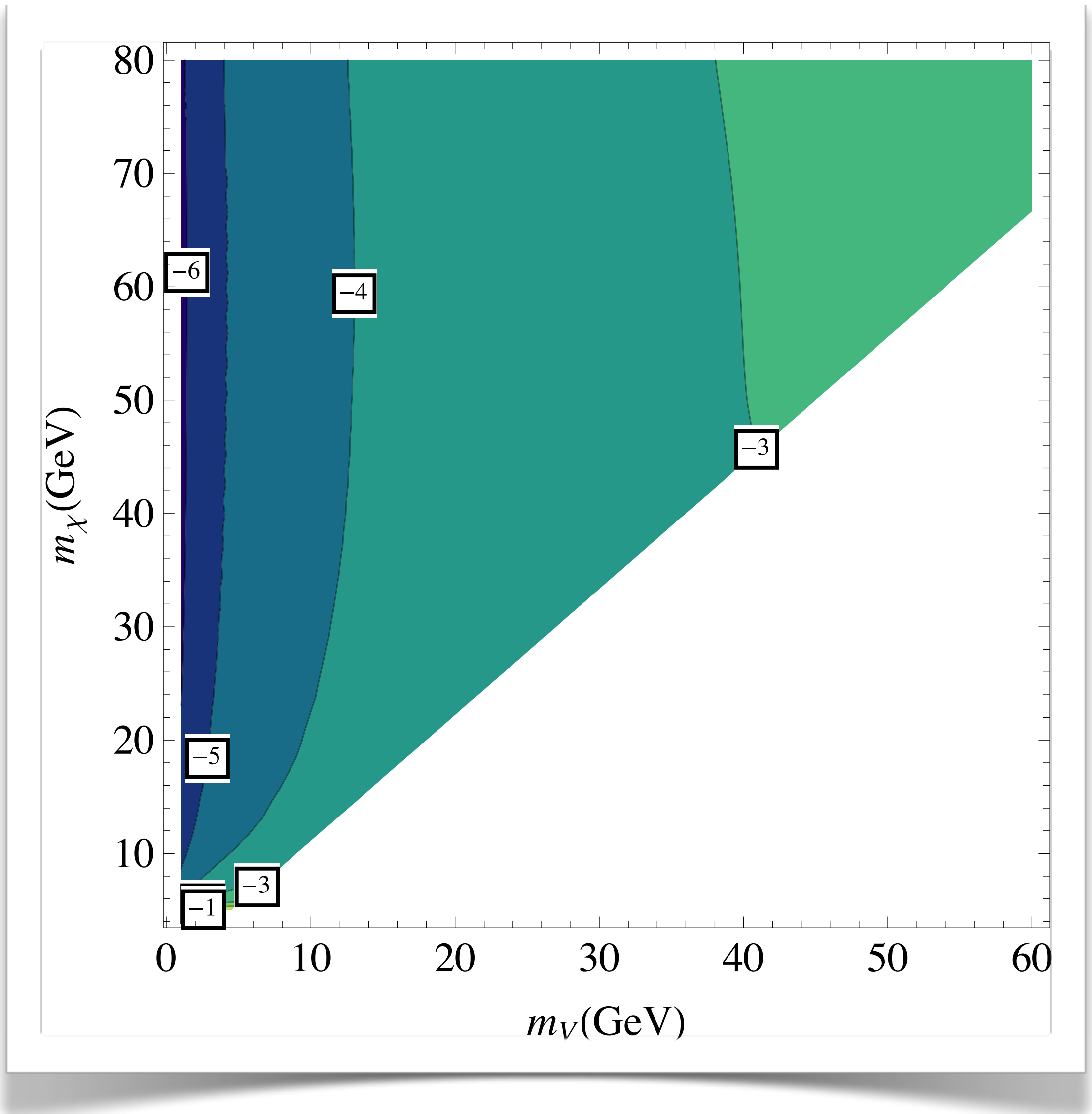

$\log_{10} \epsilon$

- LUX then constrains admissible kinetic mixing

Martin, JS, Unwin

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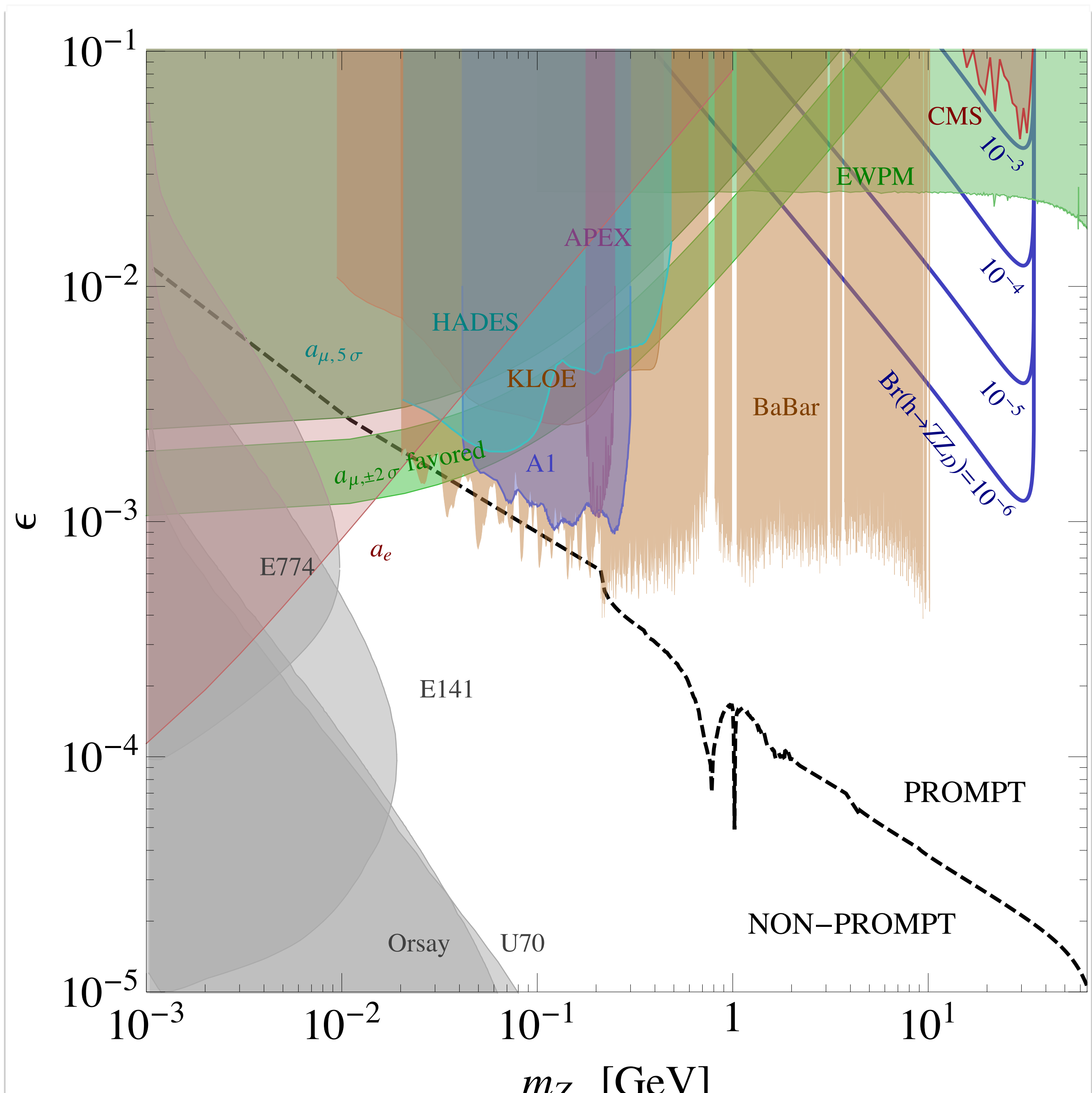


Collider constraints

- Strongest bounds: quarkonia
- LHC signals: exotic Higgs decays?
- competiveness with LUX depends on structure of dark Higgs sector, model dependent

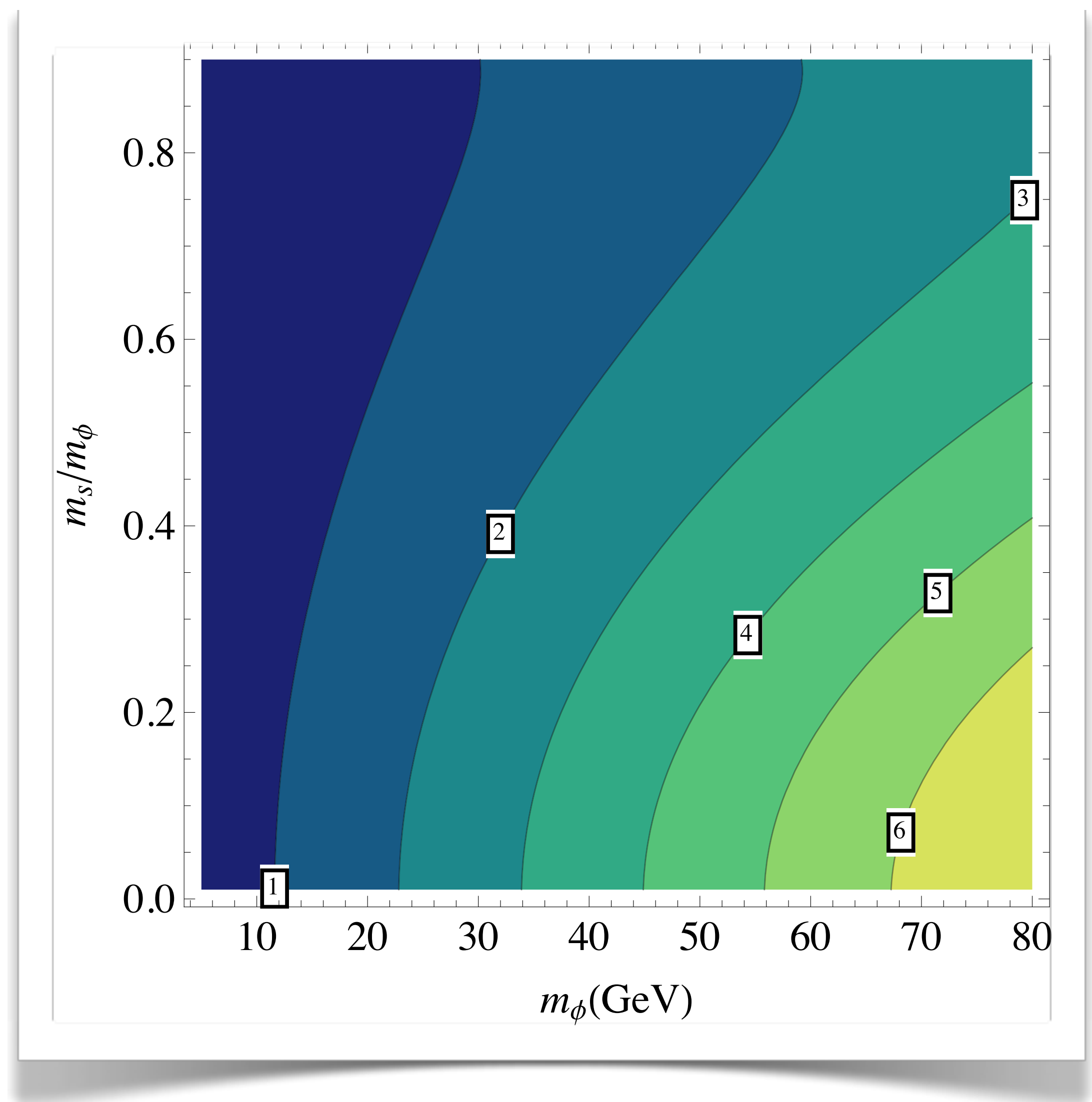
Curtin, Essig, Gori, Jaiswal, Katz, T. Liu, Z. Liu, McKeen, JS, Strassler, Surujon, Tweedie, Zhong

Another sample model

Consider scalar DM annihilating to a dark scalar:

$$V(\phi, s, H) = V(|\phi|^2) + V(|H|^2) + \frac{\lambda_4}{2}|\phi|^2 s^2 + \epsilon s^2 |H|^2 + \left(-\frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4!}s^4\right)$$

- Let s get a VEV; induces Higgs mixing
- After SSB: $\lambda_4,\ m_s,\ \epsilon,\ \sigma$
- Freezeout sets λ_4 (insensitive to $y \equiv \sigma/m_s$)



$\lambda_4\,(10^{-2})$

Martin, JS, Unwin

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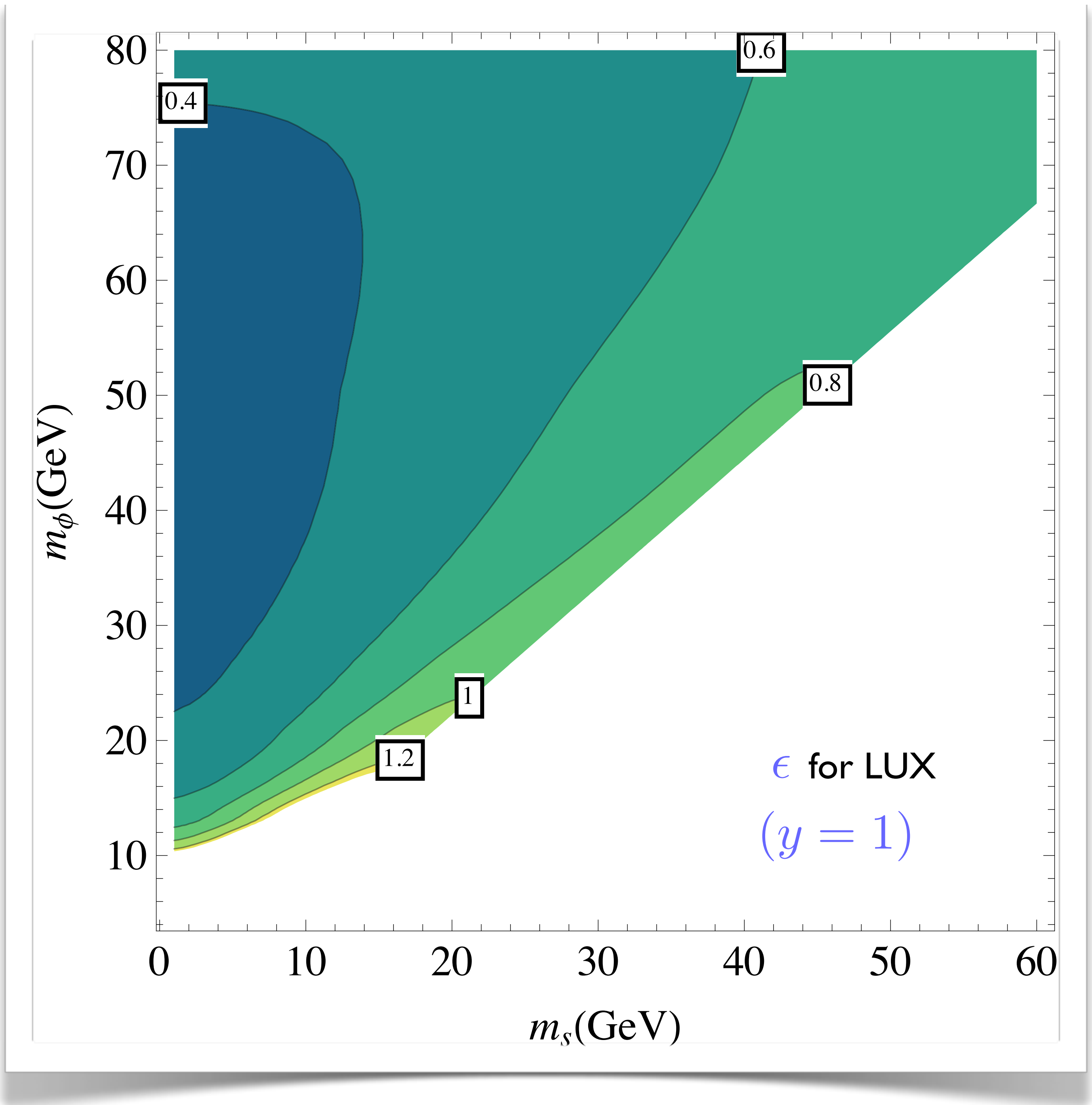
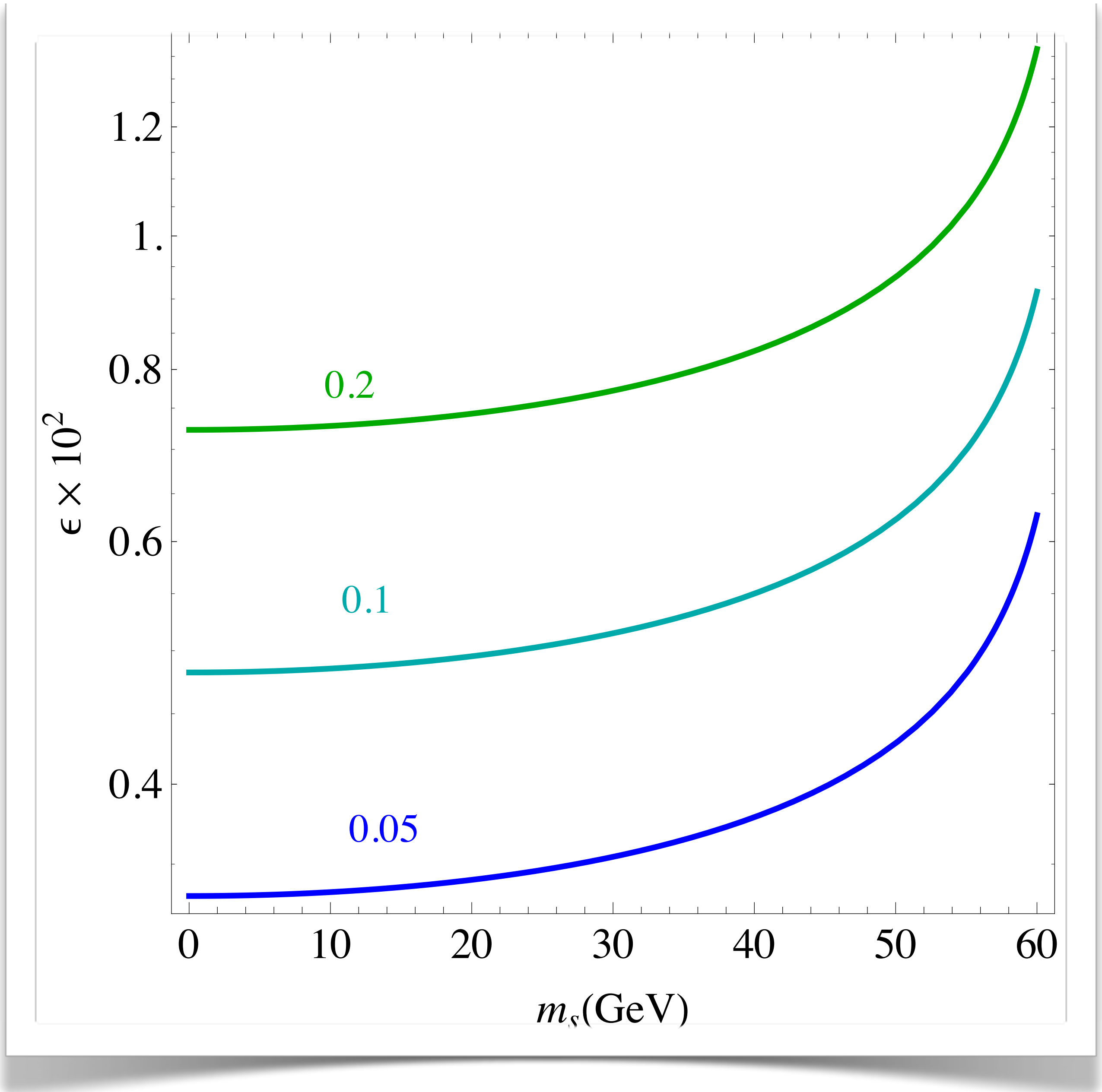


- Direct detection less constraining than in vector case (and $\propto y^4$)

Martin, JS, Unwin

Another sample model

- In fact, the most stringent limits come from exotic Higgs decays
- Constraint on total exotic branching fraction assuming SM production
- (direct observation will be hard at LHC)



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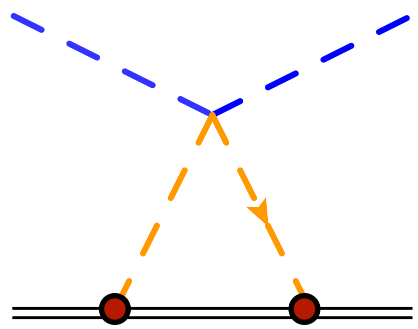
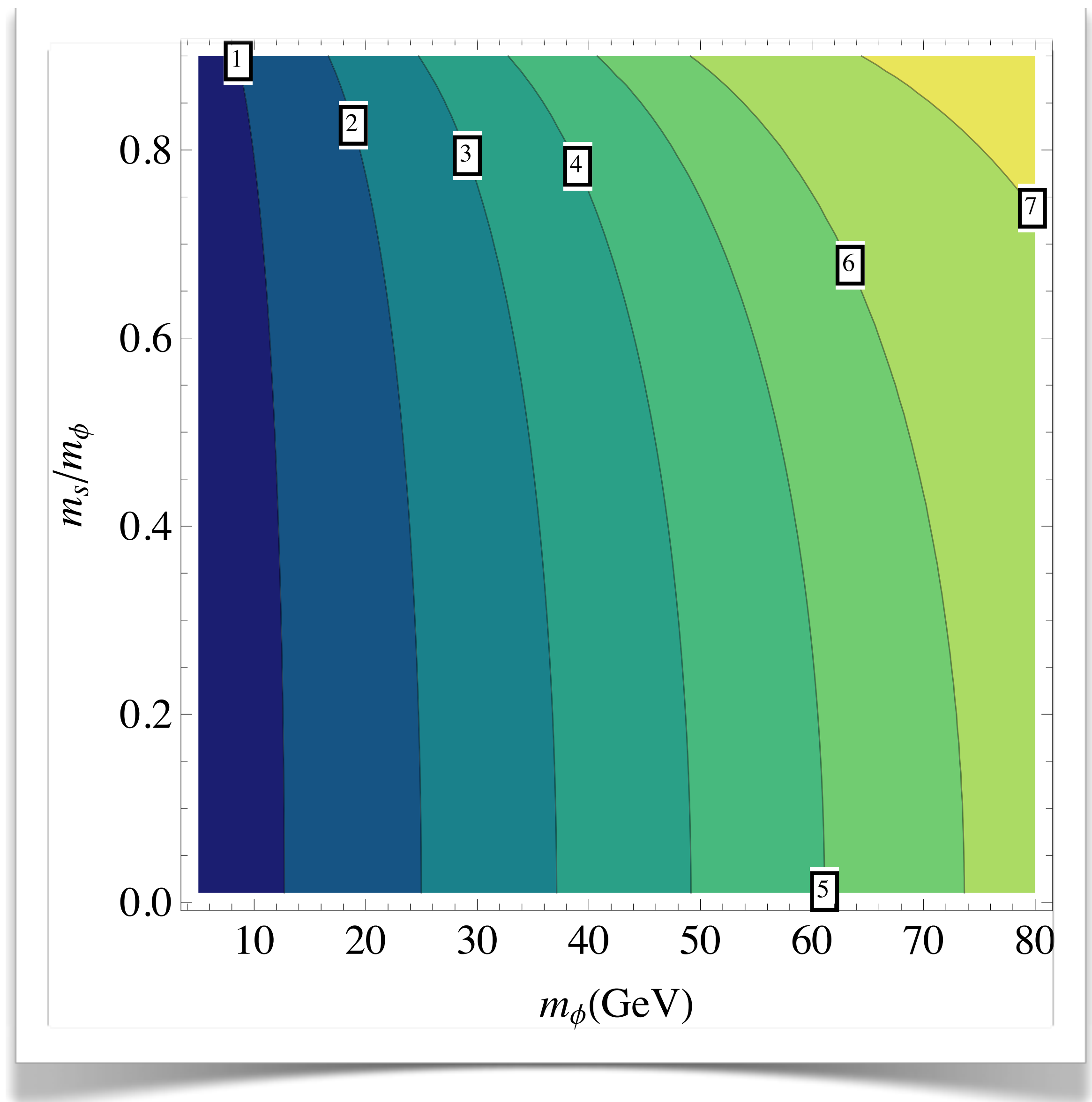
And another sample model

Scalar DM annihilating to a dark scalar, no condensation:



- Direct detection proceeds at one loop: no signals
- Higgs portal coupling could mediate $h \to 4g$



$\lambda_4\ (10^{-2})$

Martin, JS, Unwin

No silver bullets soon

- Many proposed models predict signals right around the corner at LHC and/or LUX (and/or flavour), but others (e.g. ours) do not

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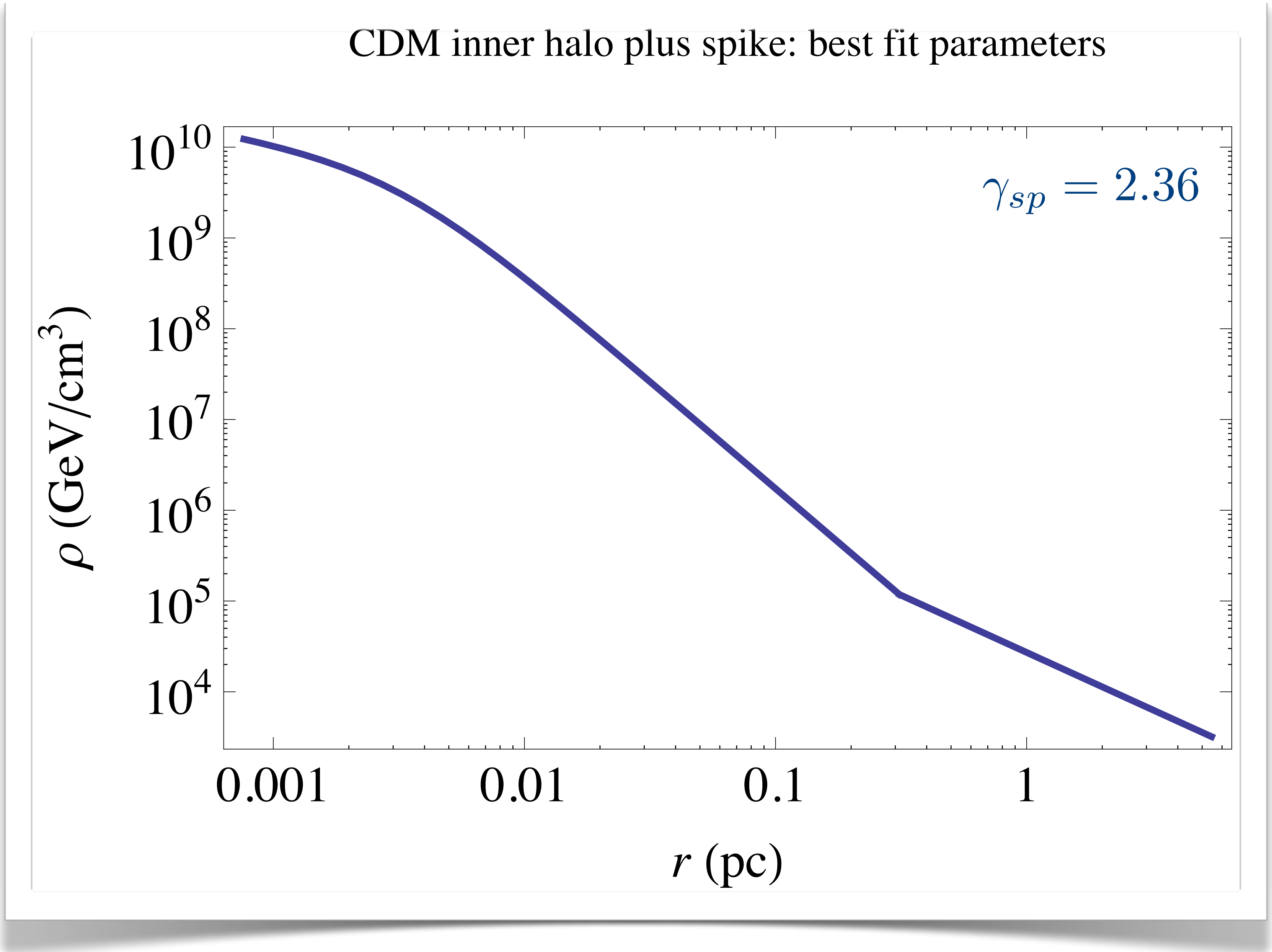
- Antiprotons potentially powerful discriminant, but systematics are challenging
- DM gamma ray signal from Sagittarius A*

Black hole-induced density spikes

- A black hole growing adiabatically in an NFW halo gives rise to a steep spike:
  - inside zone of influence $r_b = 0.2 \times \frac{M_{BH}}{v_0^2}$
  - density rises like $\left(\frac{r_b}{r}\right)^{\gamma_{sp}}$
  - where spike index depends on NFW profile $\gamma_{sp} = \frac{9 - 2\gamma_c}{4 - \gamma_c}$
  - when annihilation becomes important, $r_{in} : \rho(r) = \frac{m}{\langle \sigma v \rangle \tau}$
  - spike levels out to a shallow $\left(\frac{r_{in}}{r}\right)^{1/2}$

Gondolo and Silk
Vasiliev

A fiducial model for the spike



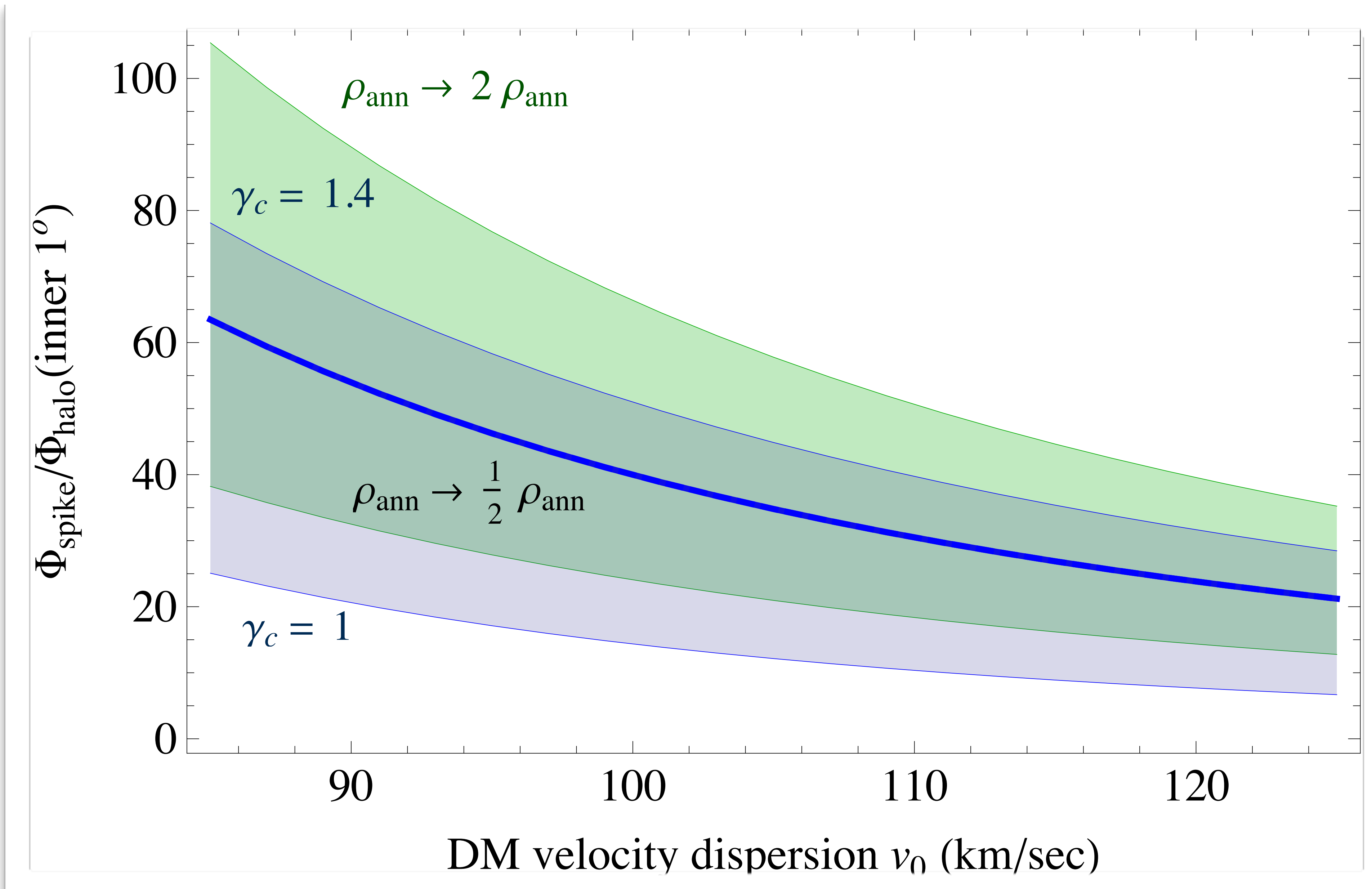
assume 35.25 GeV reference DM candidate, annihilating to *bb*

Fields, Shapiro, JS

Parametric dependence

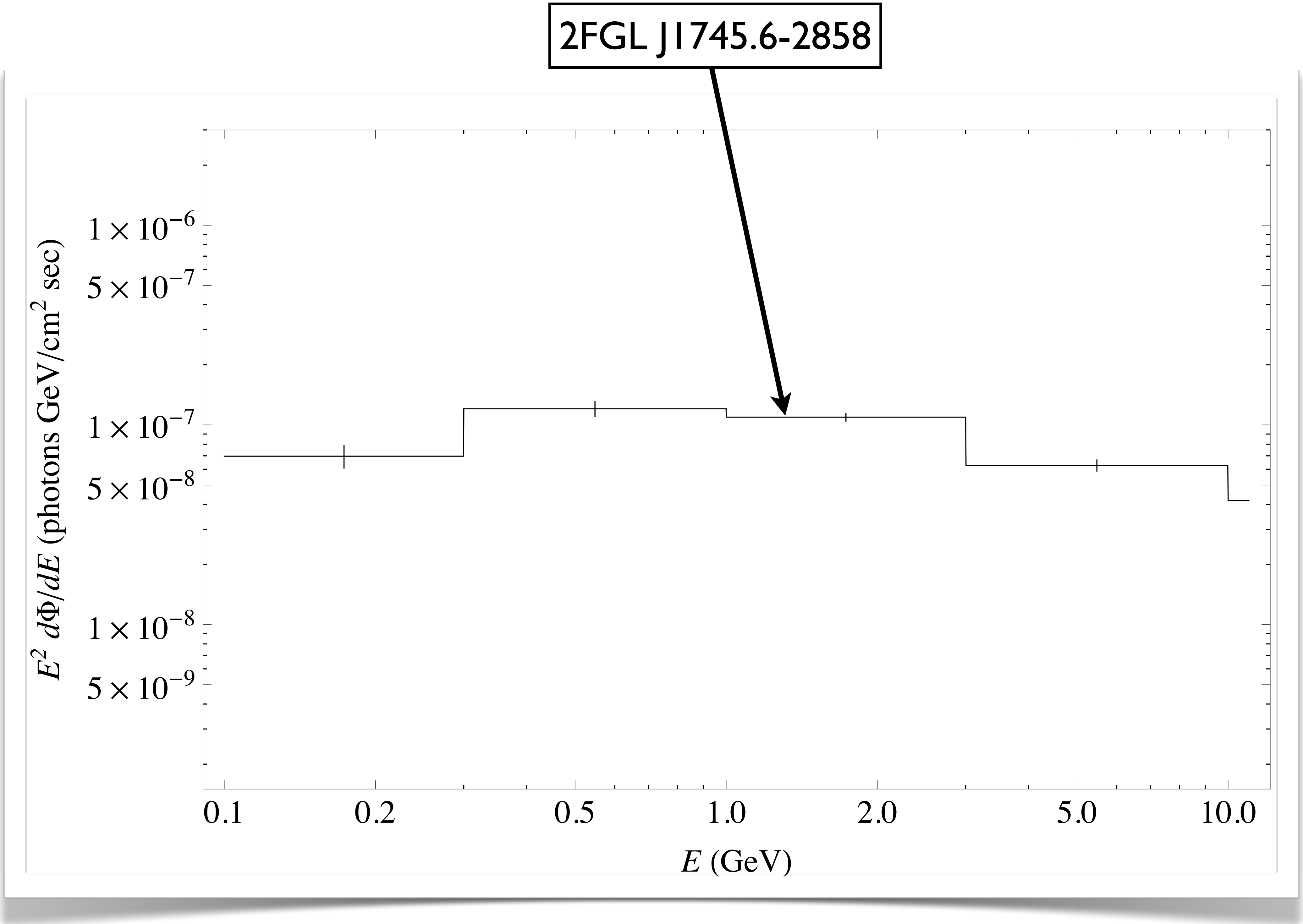
- steep power law $\Longrightarrow$ strong dependence on inputs
  - M_{BH}
  - v_0
  - inner NFW index γ_c
  - DM properties: $\rho_{ann} = \dfrac{m}{\langle \sigma v \rangle \tau}$
- potential DM signal allows (relatively) precise statements: γ_c, ρ_{ann}

Parametric dependence



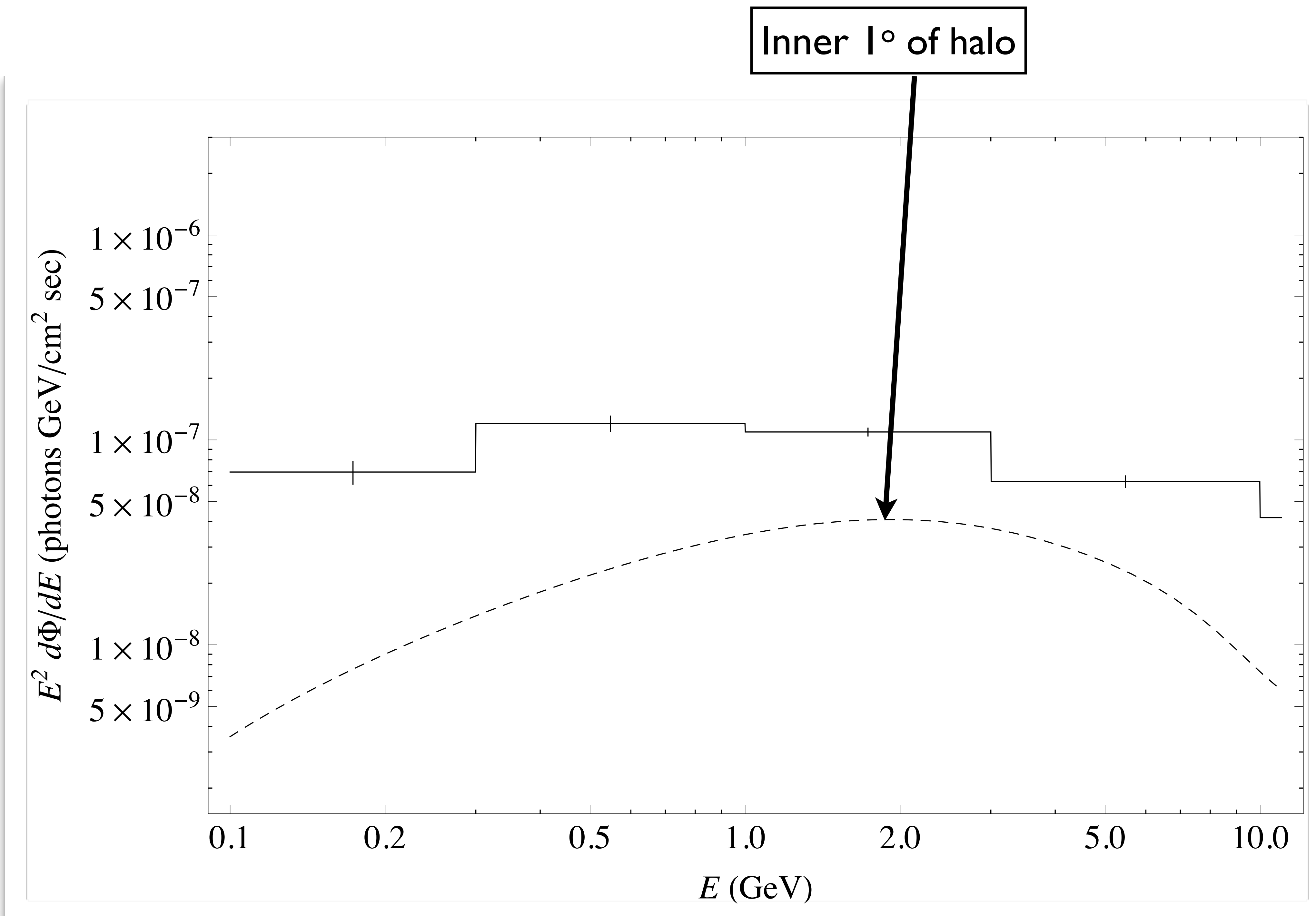
Fields, Shapiro, JS

The point source at the centre of the galaxy



Second Fermi Point Source Catalog

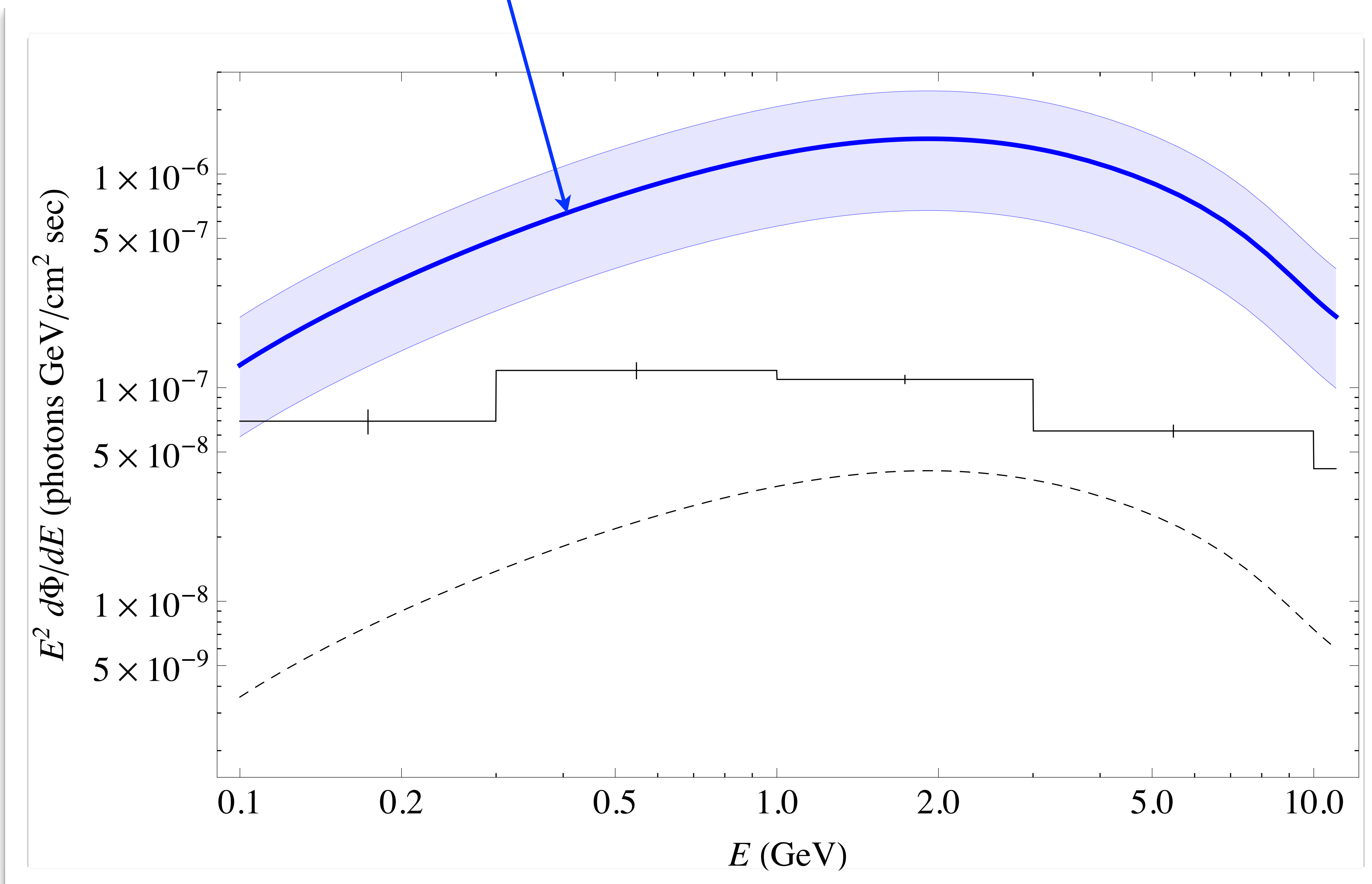
The point source at the centre of the galaxy



Fields, Shapiro, JS

The point source at the centre of the galaxy

canonical adiabatic spike: $\gamma_{sp} = 2.36$



Fields, Shapiro, JS

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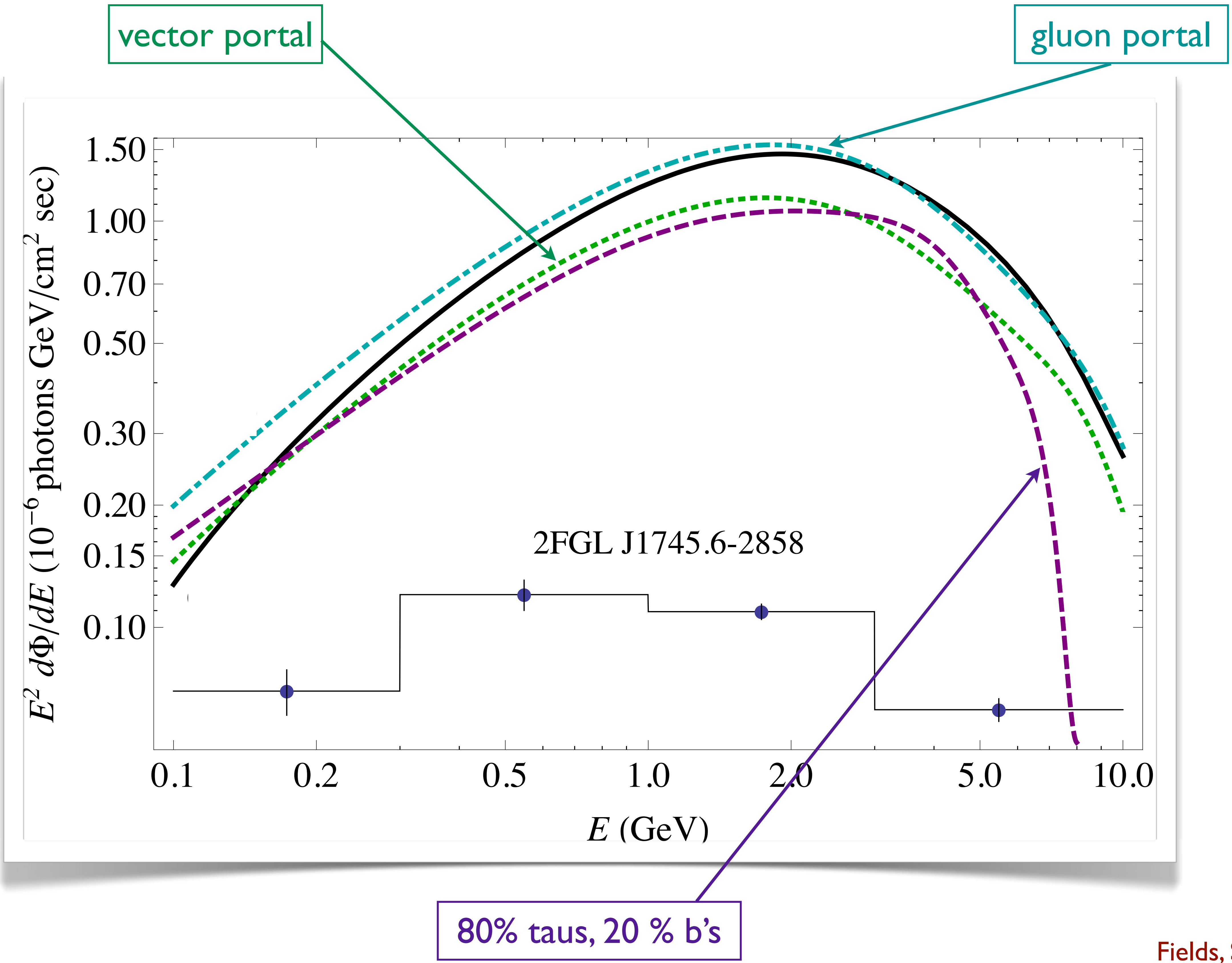


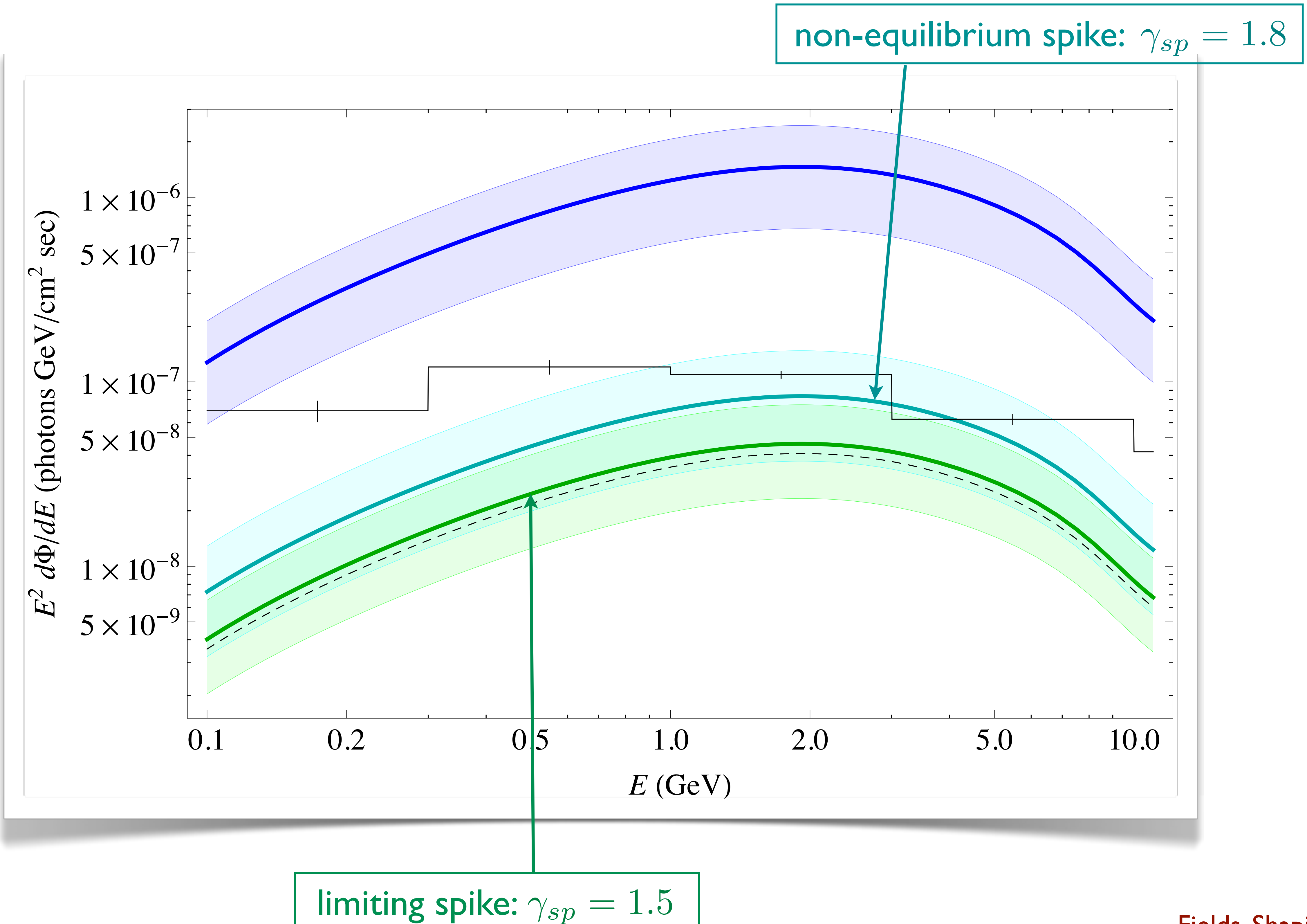
Fields, Shapiro, JS

Stellar Heating

- dense stellar population in Galactic nucleus could alter spike:
  - heating
  - enhanced DM capture by BH
  - limiting spike: $\gamma_{sp} = 1.5$
- existence of such a stellar cusp still unsettled

Merritt
Primack and Gnedin

The point source at the centre of the galaxy



Fields, Shapiro, JS

The spiky takeaway

- You can't have *both*
  - a DM interpretation of the excess
  - a canonical adiabatic spike
- GeV-range spectrum of Sgr A* is interestingly close to a heated spike + halo
- DM interpretations of excess don't harmonize well with other spiky scenarios (cores, sudden)
- Discovery of e.g. a pulsar associated with 2FGL J1745.6-2858 would significantly weaken case for DM spike

Conclusions

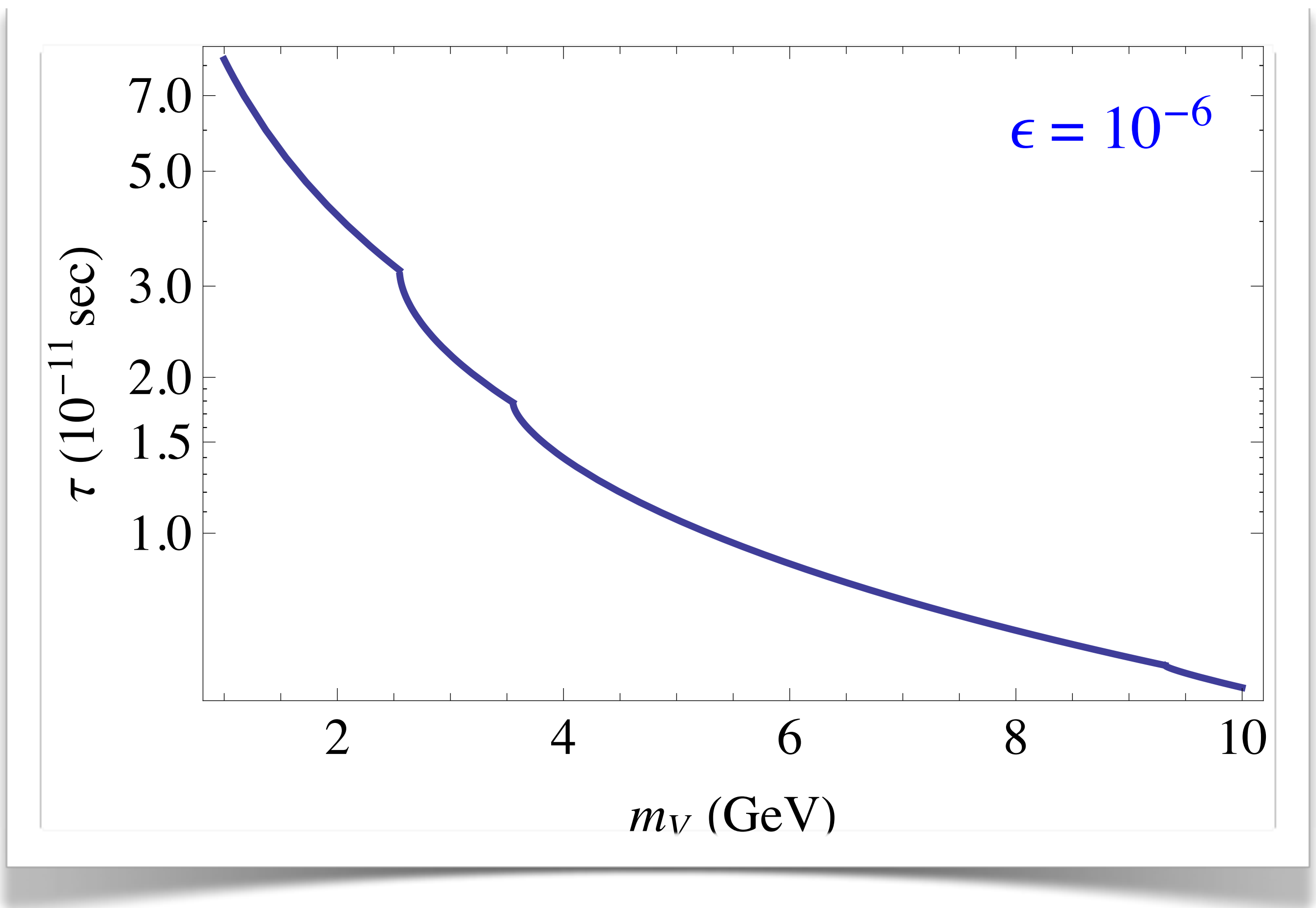
- GC excess, if due to DM, suggests new interactions
  - Minimal cascade possibilities: fermionic DM + vector; scalar DM + (pseudo-)scalar mediators; make more natural but less minimal models by adding additional new species
- Cascade annihilations:
  - parametrically "explain" lack of deviations from SM
  - ...at the cost of making terrestrial confirmation harder
  - weakest couplings may be best constrained astrophysically
- Milky Way's SMBH spike adds point-like contribution to DM gamma-ray signal
  - Pick at least one: not DM, or: no canonical adiabatic spike

Backup

A sample model

Cosmological history:

- V still decays long before BBN



- For $m_V \gtrsim$ GeV, values of mixing down to $\epsilon \sim 10^{-12}$ are safe

A sample model

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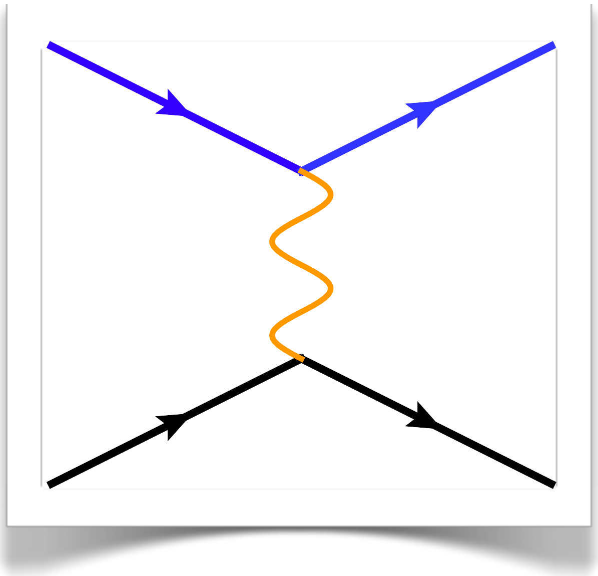

Thermal decoupling?

- estimate thermal decoupling at:

$$T_{\rm dec}^2 \approx (10\,{\rm MeV})^2 \left(\frac{0.003}{\alpha_D}\right)\left(\frac{m_V}{10\,{\rm GeV}}\right)^4 \times \left(\frac{20\,{\rm GeV}}{m_\chi}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{4}{\sum g_i Q_i^2}\right)$$

- assume reheating yields $T_{DM} = T_{SM}$ initially
- provided $T_{fo} > T_{\chi PT}$, relatively insensitive