The Galactic Centre Excess: Review, Interpretation and Future Directions

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Intense Electron Beams Workshop
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Image Courtesy of NASA Goddard/A. Mellinger (Central Michigan Univ.) and T. Linden (Univ. of Chicago)

- Fermi Large Area Telescope (LAT)

  - Wide field of view - covers the entire sky in 2 orbits

  - Energy range: 20 MeV - 300 GeV

  - Data publicly available

The Gamma-Ray Sky
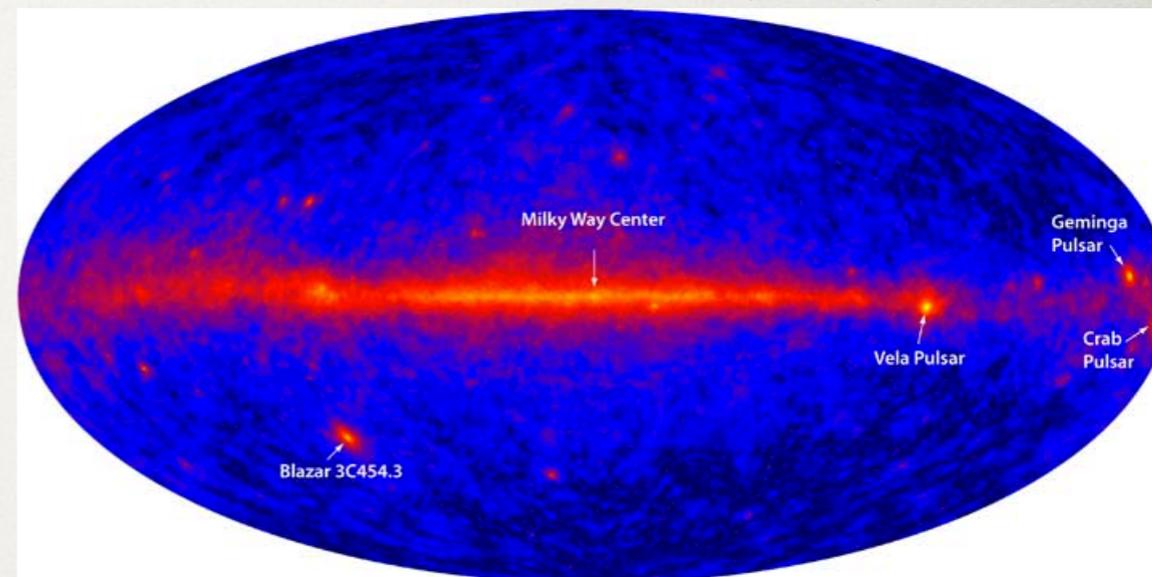
- Where should we look for signs of DM annihilation? Recall photon flux from DM annihilation:

$$\Phi(E_\gamma, l, b) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} J(l, b)$$

Particle physics: what the DM is

Astrophysics: how the DM is distributed

- Galactic centre has the largest value of J on the sky - good place to look

- Find an excess over the expected background: **Galactic Centre Excess**

GCE Review: Timeline

- **2008:** Fermi launched

- **2009:** First hint of a DM like signal in galactic centre (inner few degrees); Goodenough and Hooper (0910.2998)

- **2013:** Signal seen to extend into the inner galaxy (10s of degrees from the centre); Hooper and Slatyer (1302.6589)

- **2014:**
  - **Feb:** Combined analysis showing consistency between GC and IG, and that the spatial properties are more in line with what would be expected from DM than astrophysics; Daylan, Finkbeiner, Hooper, Linden, Portillo, NLR, Slatyer (1402.6703)
  - **Aug:** Existence of the excess and spatial properties appear robust to inclusion of systematic uncertainties; Calore, Cholis and Weniger (1409.0042)
  - **Oct:** Fermi collaboration confirm the presence of an excess; Simona Murgia talk at the Fifth Fermi Symposium

- **Today:** GCE as point sources (1506.05104, 1506.05124) or leptonic outflow (1506.05119)

- **GCE is highly significant - test statistic (like $\Delta\chi^2$) is O(1000) - not a fluctuation**

- This is an incomplete list - see backup slides for more

GCE Review: Spectral Properties

Spectrum is the emission correlated with a generalized
NFW squared profile integrated along the line of sight,
as determined by a template fit

$$\rho(r, \gamma) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$
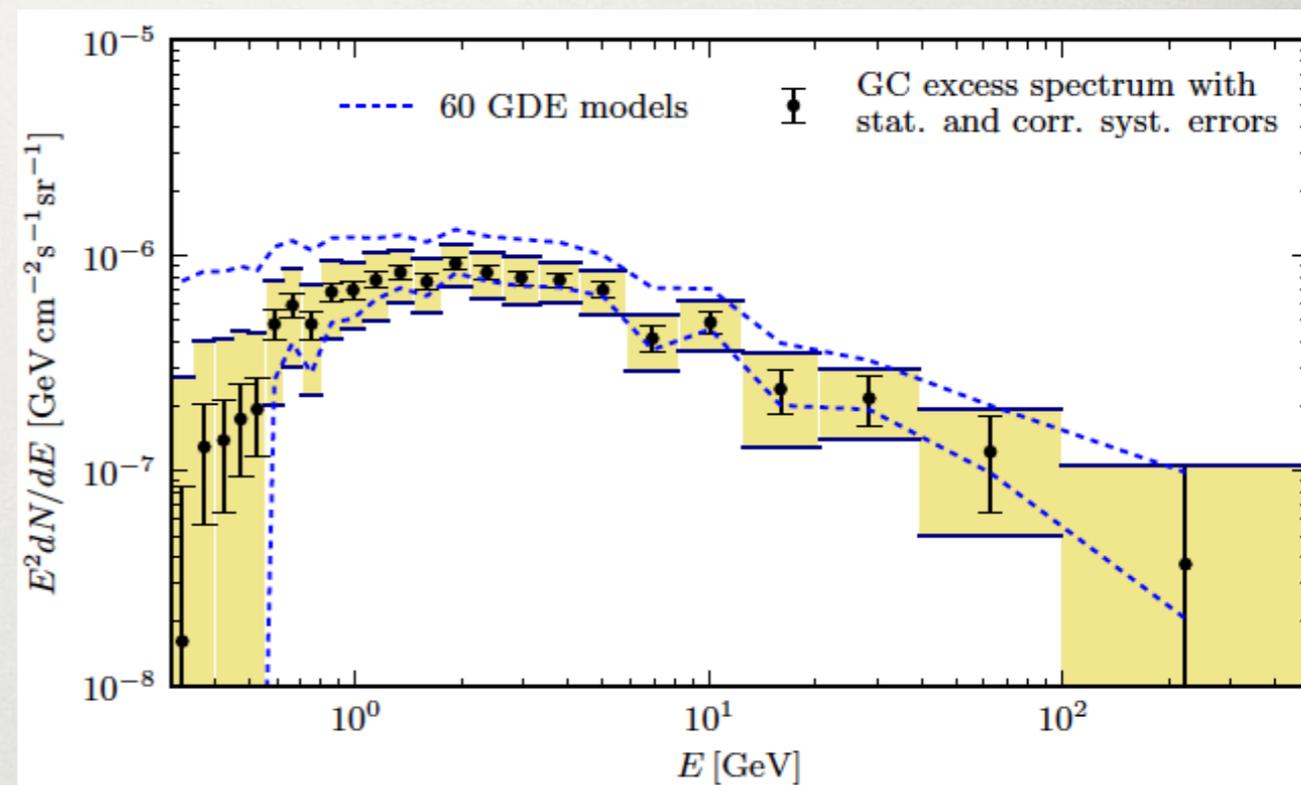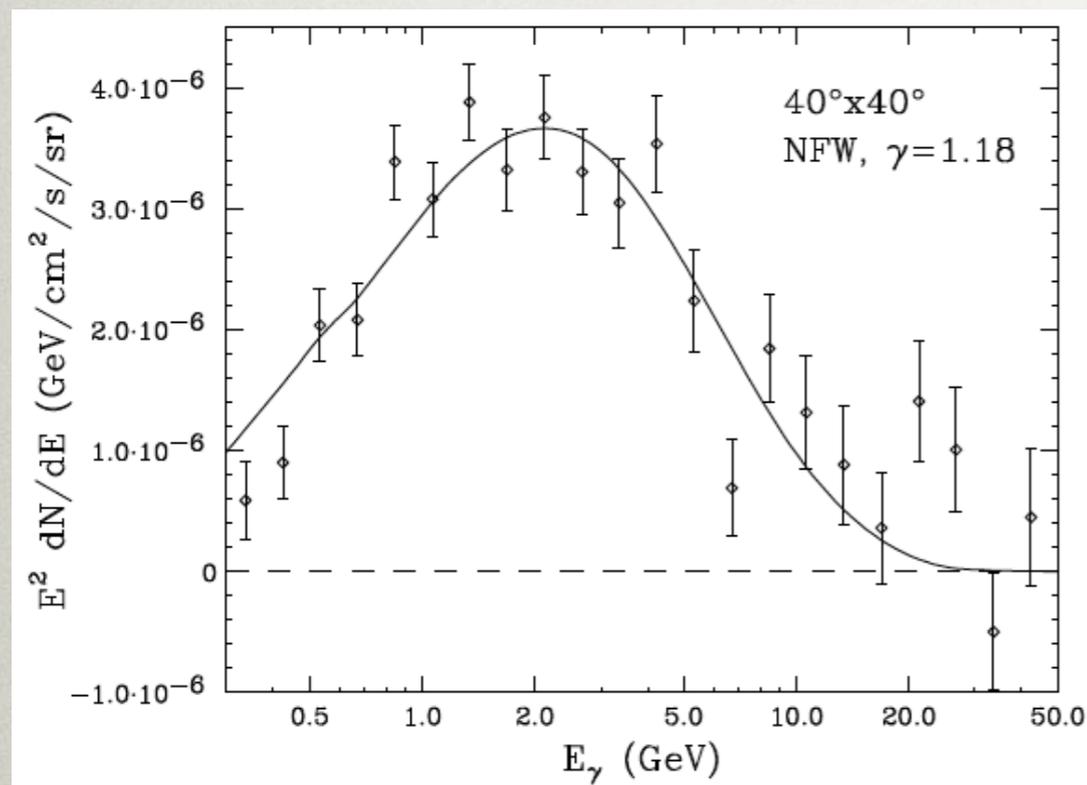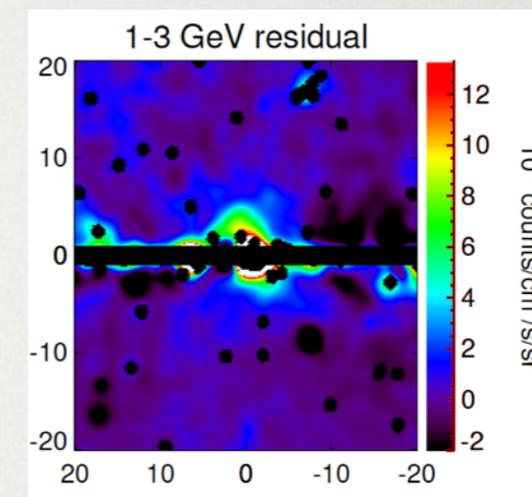
Result from Daylan, NLR et al - overlaid
is spectrum of 43.0 GeV DM annihilating
into b-quarks with $\sigma v = 2.25 \times 10^{-26}$ cm^3/s

Result from CCW - includes systematics

NB: NFW templates normalized differently   4

GCE Review: Spatial Properties

- At small radii, scales with a power law slope of r$^{-2.2-2.8}$, corresponding to an NFW with a γ~1.1-1.4

- Roughly spherically symmetric - can exclude any significant stretch along the plane

$$\rho(r, \gamma) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

- Appears centred at Sagittarius A*, the dynamical centre of the Milky Way

- Extends to at least 10 degrees (~1.5 kpc) from the galactic centre
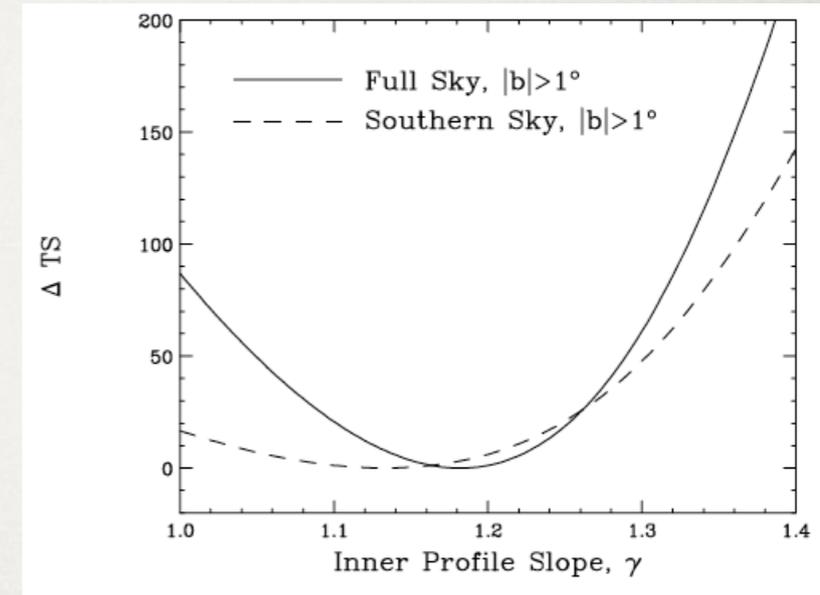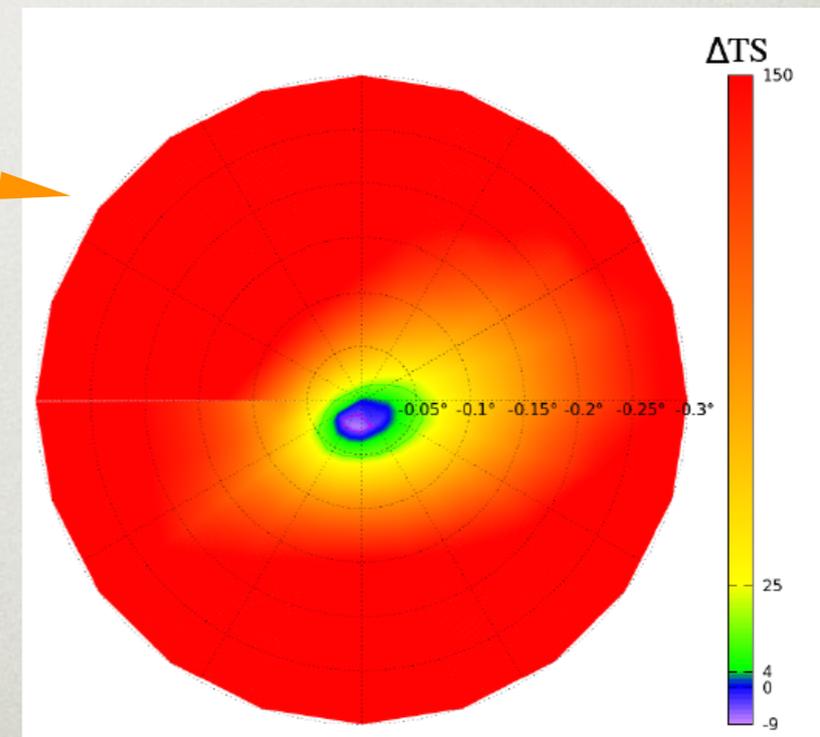
GCE Review: Astrophysics?

Unresolved Point Sources
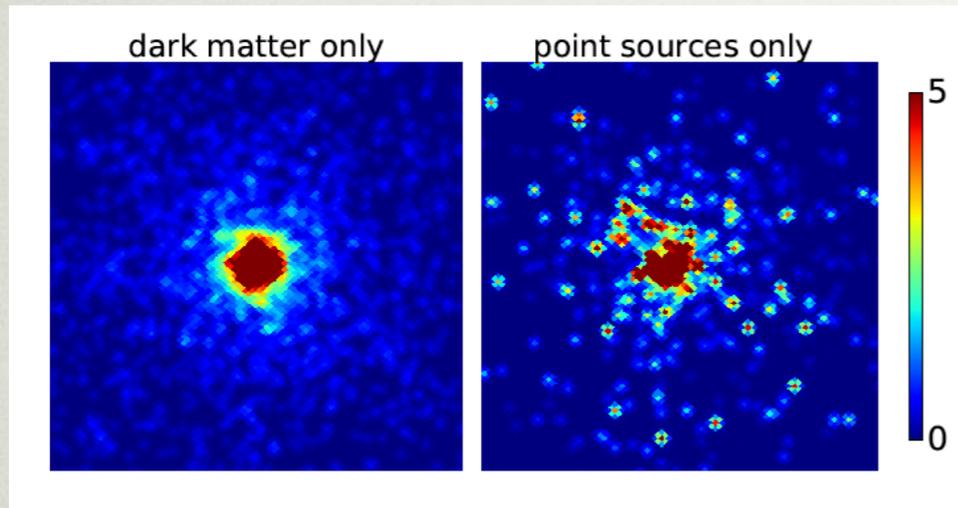
Can distinguish uniform and point source
emission just with photon statistics
See 1104.0010, 1412.6099 and 1506.05124
Wavelet analysis: 1506.05104

e.g. Pulsars

Spectrally similar, yet spherical
symmetry unexpected
See e.g. 1305.0830 or 1407.5625

Cosmic Ray Outflow

Such events have occurred, but hard to
match spectrum and morphology
See e.g. 1405.7685, 1405.7928 or 1506.05119

Something unexpected
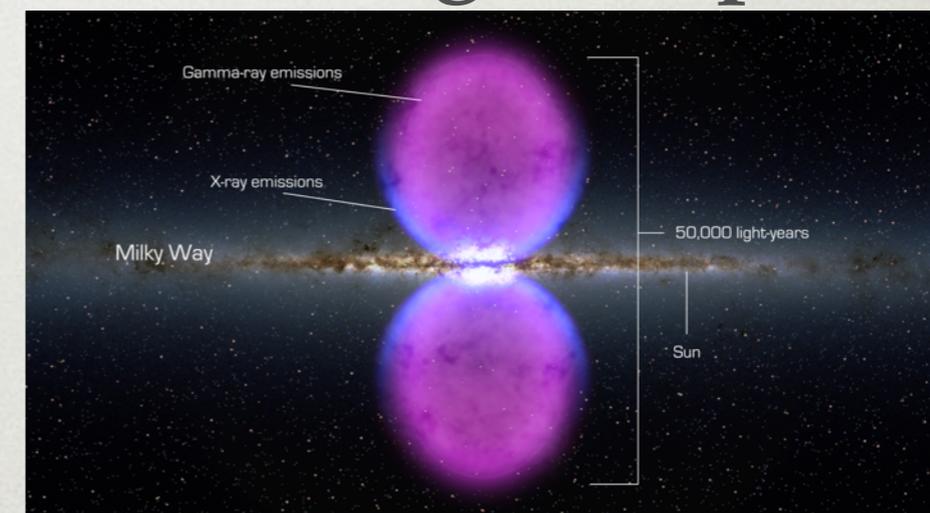
Never underestimate the power of the
universe to produce something new -
classic example: Fermi Bubbles

- Dark matter naturally explains the observed GCE properties

- ~40 GeV DM annihilating directly into b-quarks with a thermal relic cross-section, gives a very good fit

- Need to keep in mind constraints from non-observation of DM in other searches: constrains model space

- Extending beyond direct annihilation to dark photon/ cascade scenarios can alleviate such constraints

- Gilly Elor, Tracy Slatyer and myself recently showed how to understand cascades in a model independent way - 1503.01773
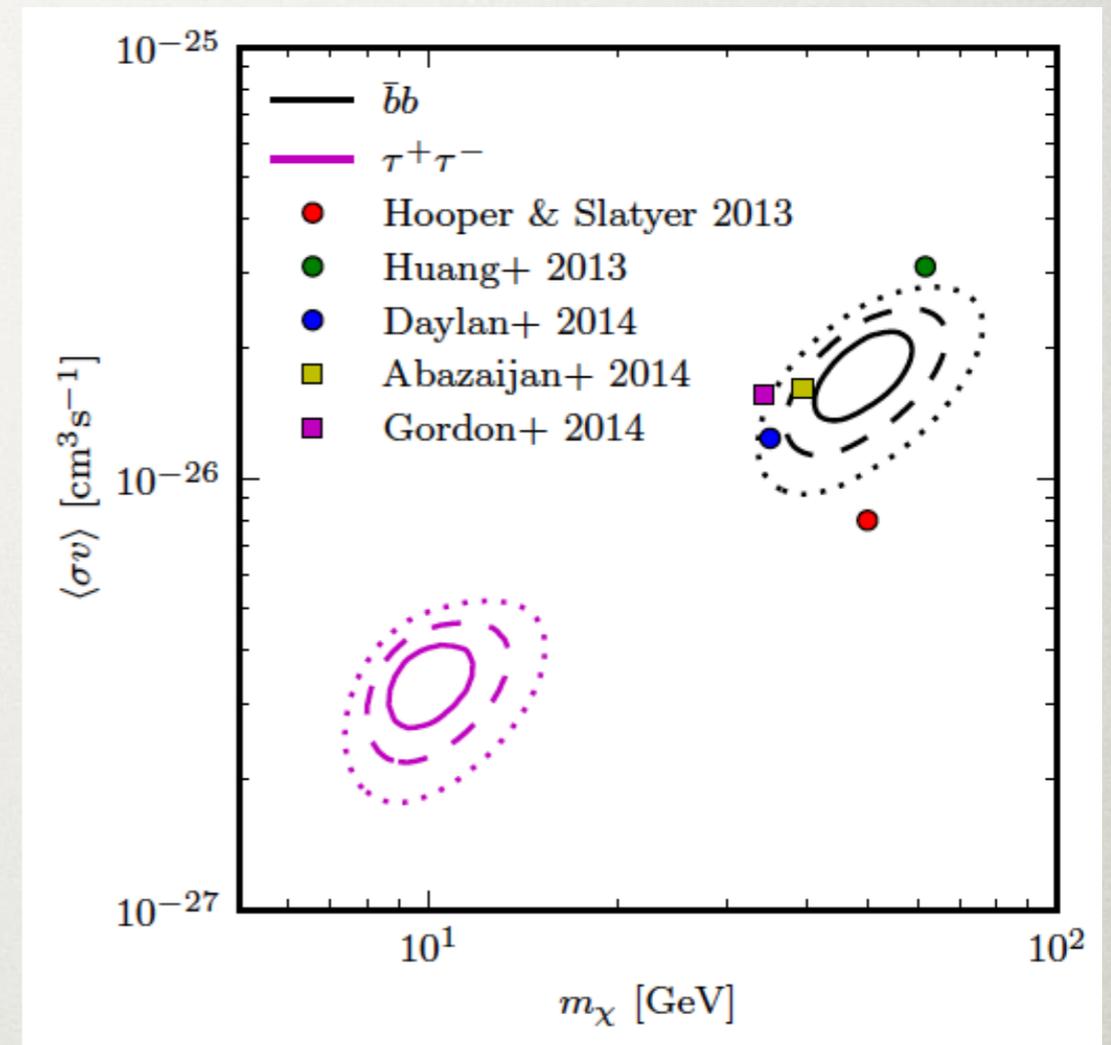
Fits from 1409.0042 - includes systematic uncertainties

Direct or 0-Step Spectra

$$\chi\chi \rightarrow f\bar{f}$$

- Photons come from the decay of standard model particles

- The photon spectrum depends on the identity of f and $\varepsilon_f = m_f / m_\chi$ (controls final state radiation, fragmentation and hadronization)

- To compare spectra use dimensionless variables: $x = E_\gamma / m_\chi$
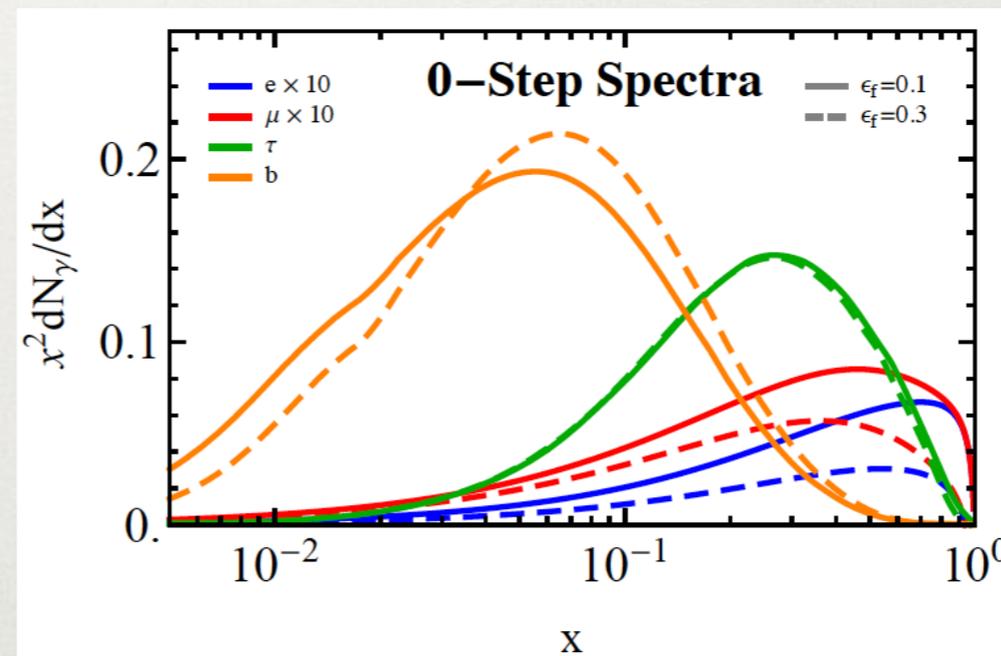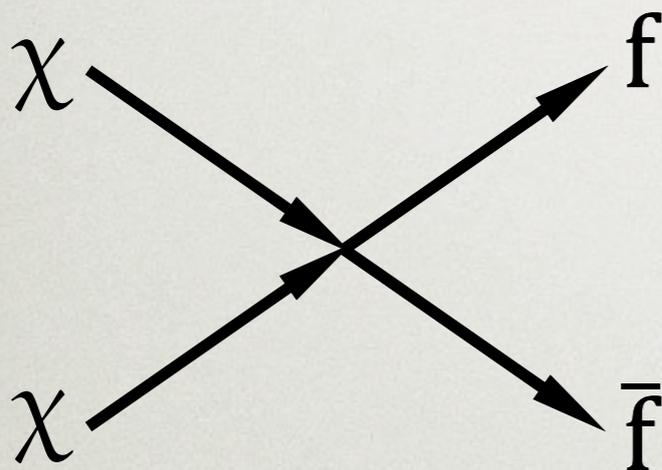
- Spectra peaked at lower x require a higher m_χ to fit the GCE

- Note we consider the FSR spectra of e and μ as examples of sharply peaked spectra rather than viable explanations of the excess

Cascade Spectra

Add a step in the dark sector

$$\underbrace{\chi\chi \to}_{\epsilon_1 = m_1/m_\chi} \phi_1\phi_1 \underbrace{\to 2f\bar{f}}_{\epsilon_f = 2m_f/m_1}$$

f

Φ_1

χ

$\bar{f}$

f

χ

Φ_1

$\bar{f}$
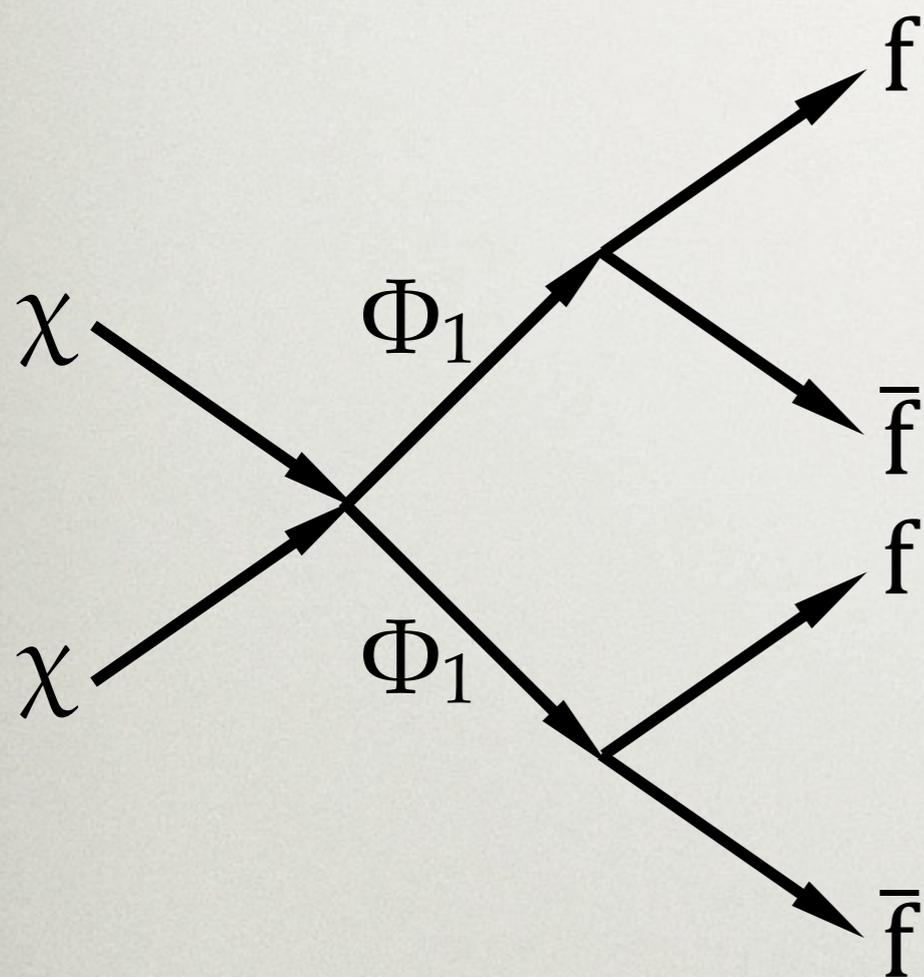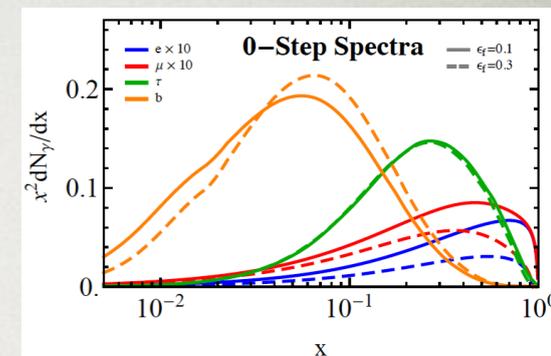
NB: Not a Feynman diagram
- all decays on shell

- The direct spectrum now describes the scalar decay $\Phi_1\to f\bar{f}$, and we simply need to Lorentz boost this to move back to the $\chi\chi$ rest frame

- If $\epsilon_1 \ll 1$, i.e. there is a large hierarchy between χ and Φ_1, then this is particularly simple and it turns out the missing information can be easily recovered

- The logic can then be iterated for additional steps

Cascade Spectra

Add a step in the dark sector

$$\underbrace{\chi\chi \rightarrow}_{\epsilon_1 = m_1/m_\chi} \phi_1\phi_1 \underbrace{\rightarrow 2f\bar{f}}_{\epsilon_f = 2m_f/m_1}$$
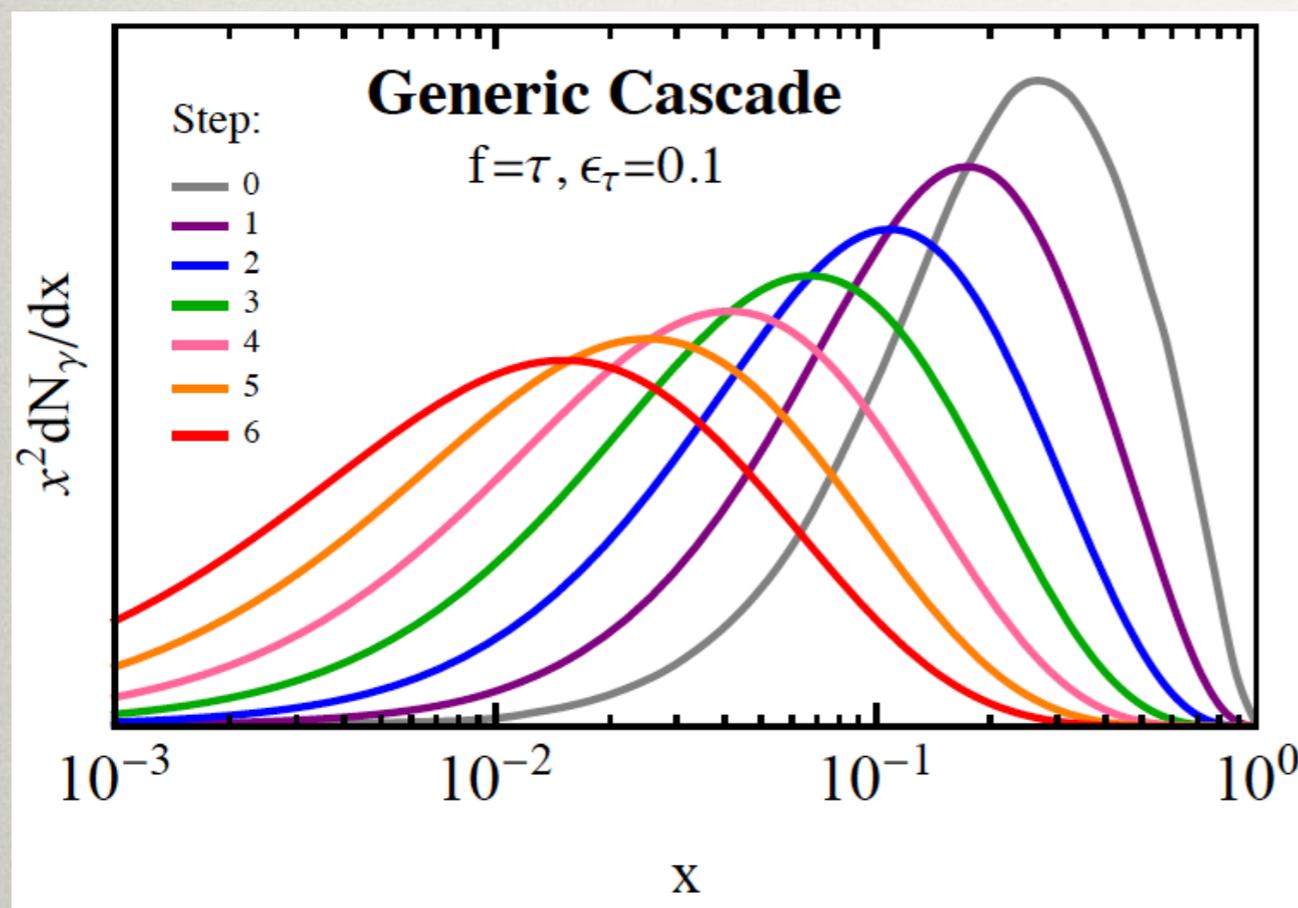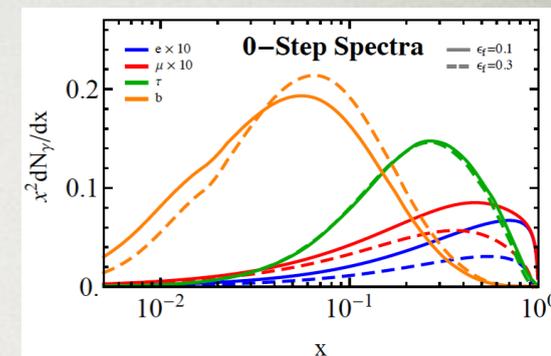
Generically cascade spectra:

- are described by just f, ϵ_f and the number of steps in the large hierarchies regime

- are peaked at lower x, allowing higher mass DM to fit the GCE

- are broader, opening the way for final states with sharper direct spectra

- can ease tension with direct detection and collider bounds (see e.g. 1405.0272 or 1404.6528)

- can provide an approximation to more complex dark sectors that might involve hadronization

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Fitting to the GCE

- Fit spectra to the data and systematic uncertainties determined by Calore et al:

Scale to determine $\langle \sigma v \rangle$

Scale by m_χ
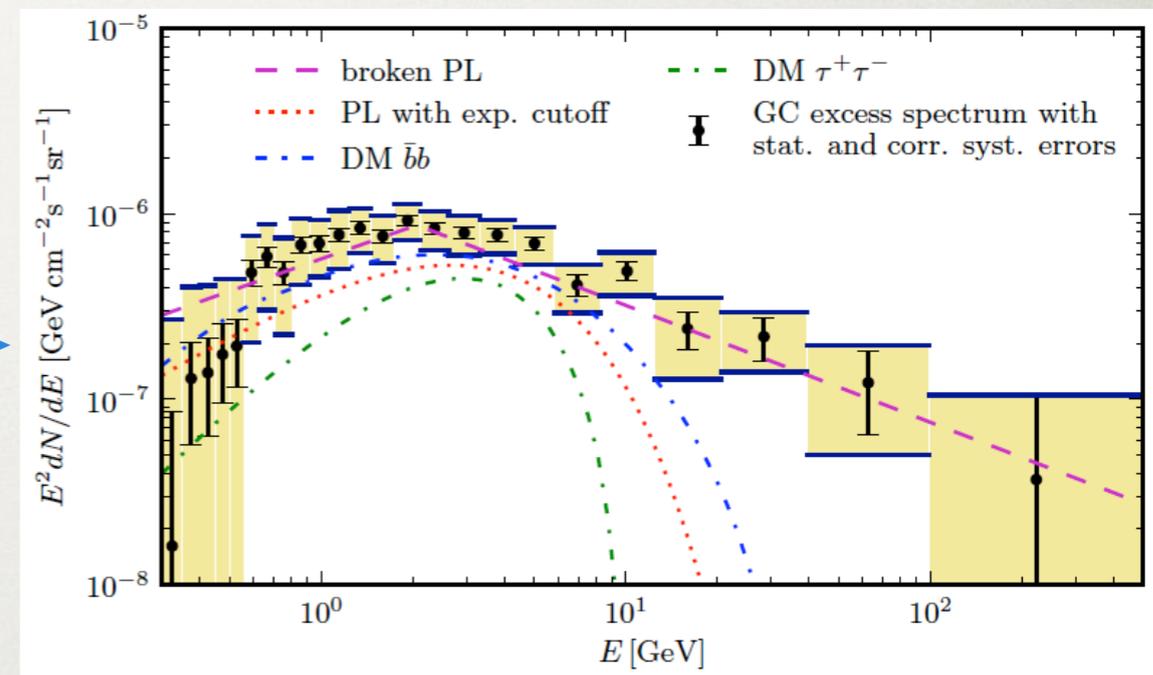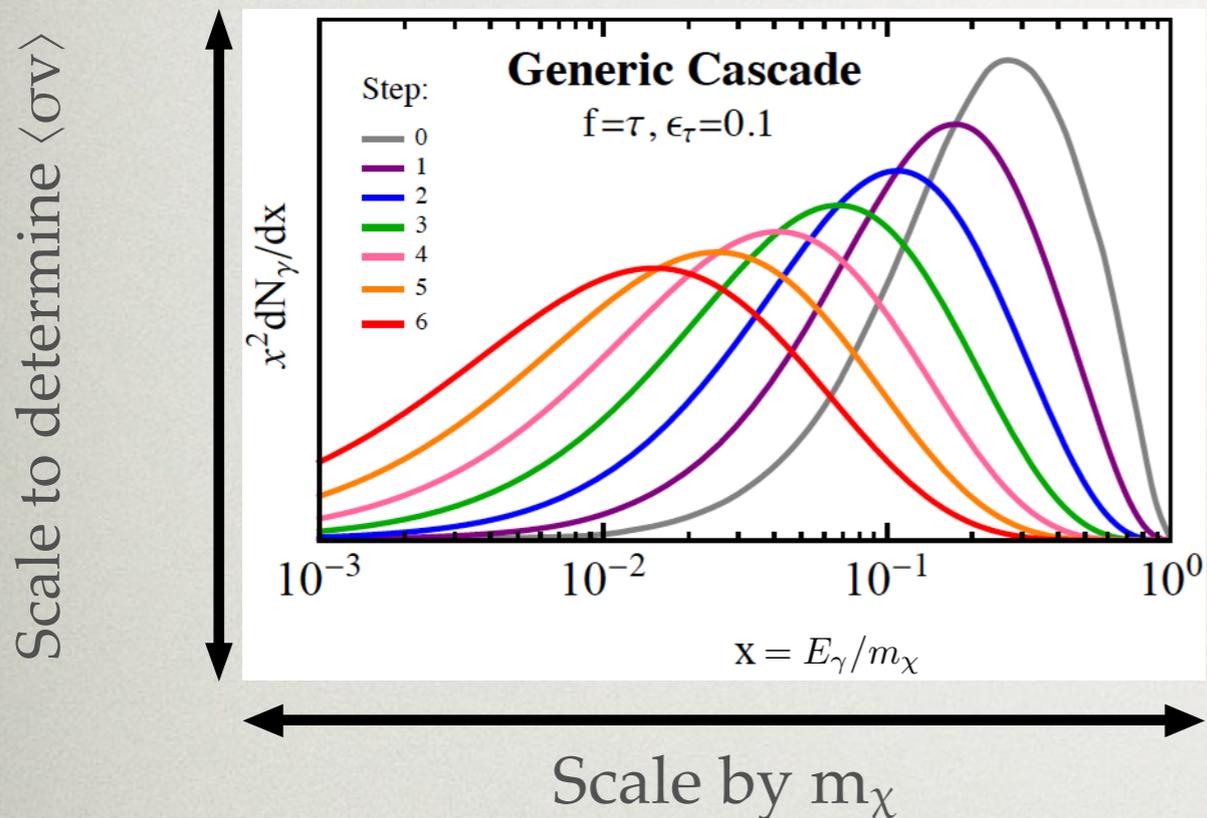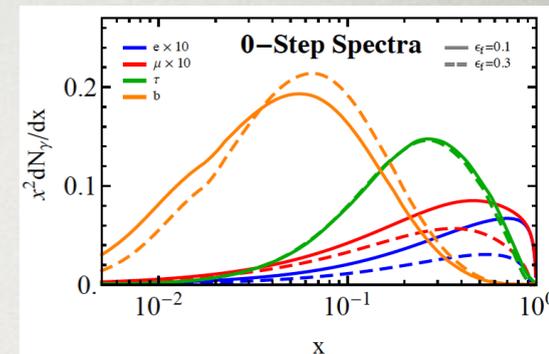
- For each cascade step determine the preferred m_χ-$\langle \sigma v \rangle$

- There is some disagreement in the literature as to whether the points above 10 GeV are part of the GCE

- For now we fit including these points, return to this issue later

Observe fits exhibit power law scaling approximately as

$$\langle \sigma v \rangle \propto m_\chi^{1.3}$$

Higher step can allow much higher masses
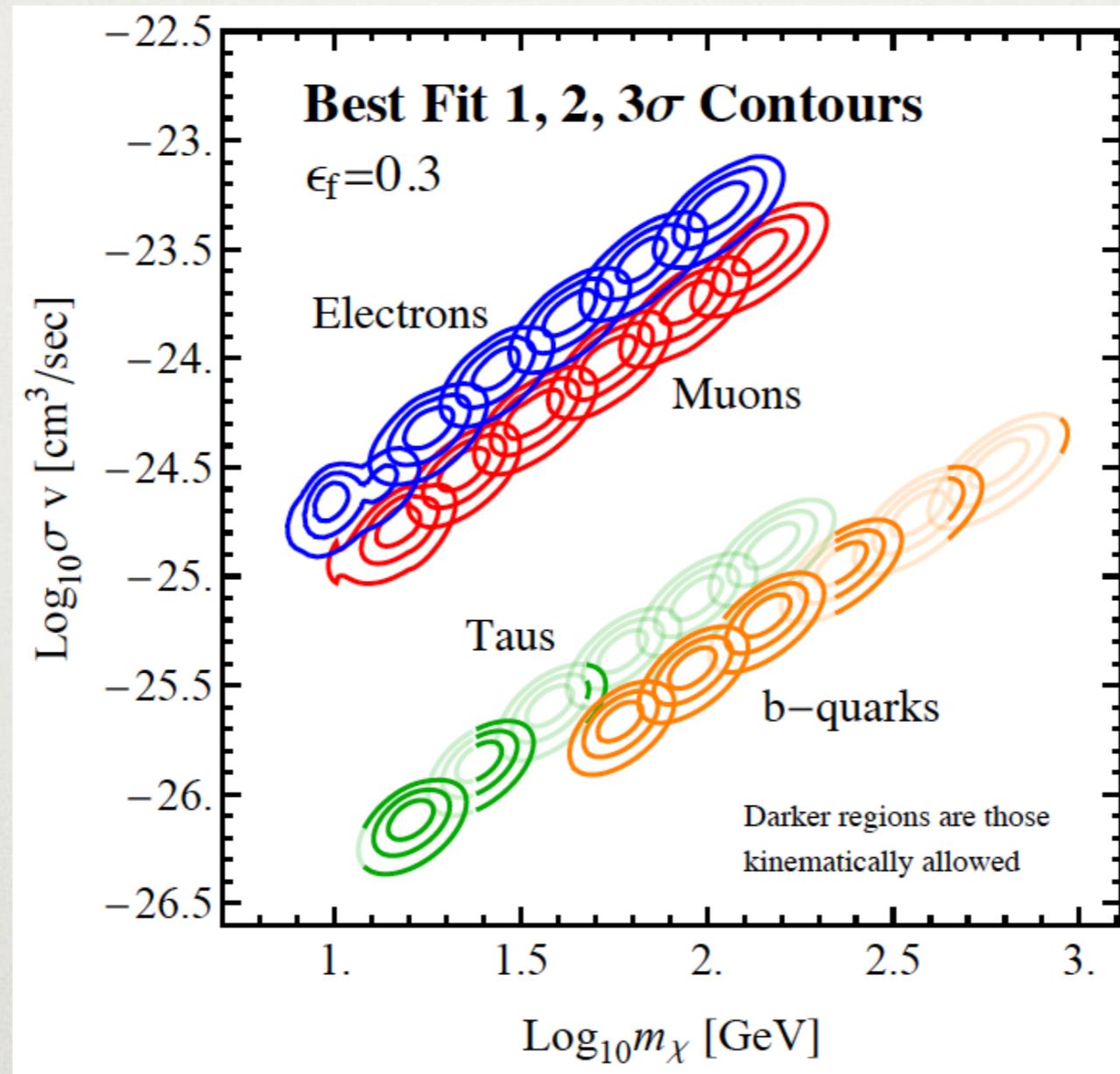
Position of 1-step clear from direct spectra
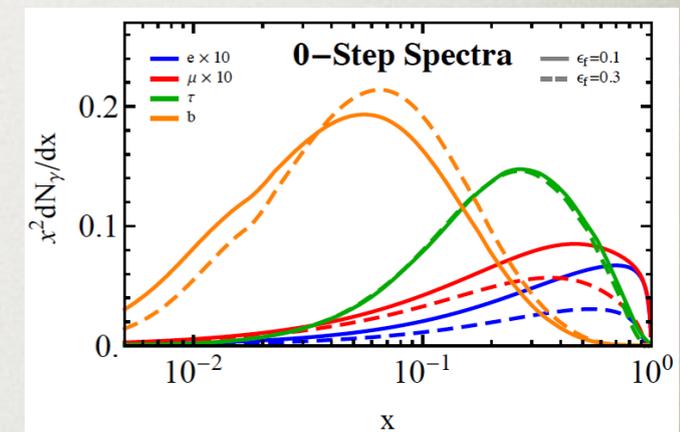
Dependence on ϵ_f is easily understood from the direct spectra - only show one value

Kinematically allowed: $m_\chi \geq 2^n m_f / \epsilon_f$

and is violated when it becomes impossible to fit the intermediate masses between m_χ and m_f

BEST FIT SPECTRA FOR EACH FINAL STATE

Best Fit Spectra

$\epsilon_f = 0.3$

- - - e
— μ
— τ
— b
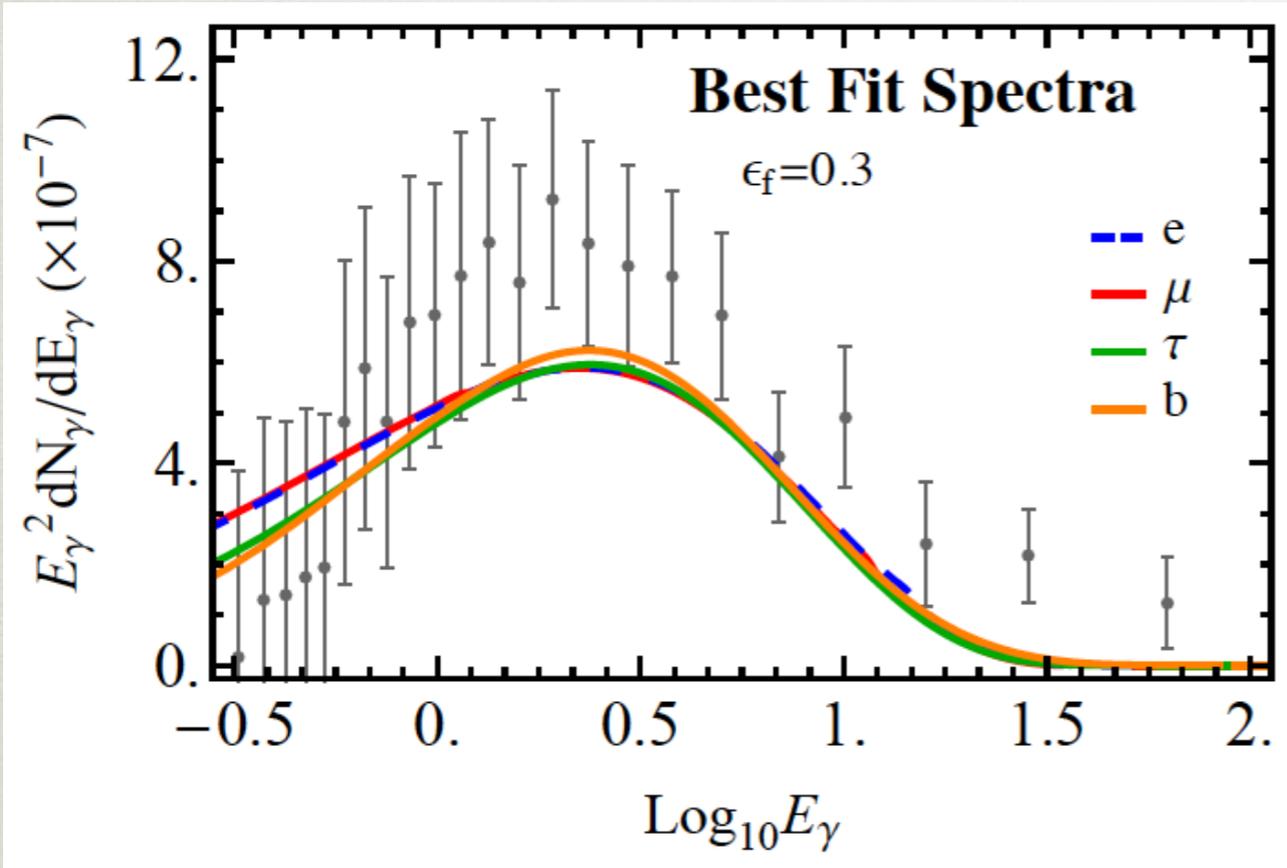
- With the extra degree of freedom provided by cascades a similar best fit spectrum is picked out in each case

- NB: the errors are correlated

Final State	n-step	m_χ (GeV)	σv (cm^3/sec)	χ^2
e	5	67.2	2.9×10^{-24}	26.82
μ	4	53.0	9.9×10^{-25}	26.94
$\tau_{\text{unphysical}}$	4	59.4	4.6×10^{-26}	24.13
τ_{physical}	2	24.1	1.4×10^{-26}	25.59
b	2	91.2	3.9×10^{-26}	22.42

- Fits are performed over 20 degrees of freedom

Scaling Results by Power into Photons

- Looking back at the fits, there are many similarities between the different final states

- If we rescale cross-section by the fraction of power into photons, all results collapse into a single cone. Best fit mass and cross-section determined by two parameters:

  - **Cross-section:** the fraction of power into photons

  - **Mass:** the width of the spectrum
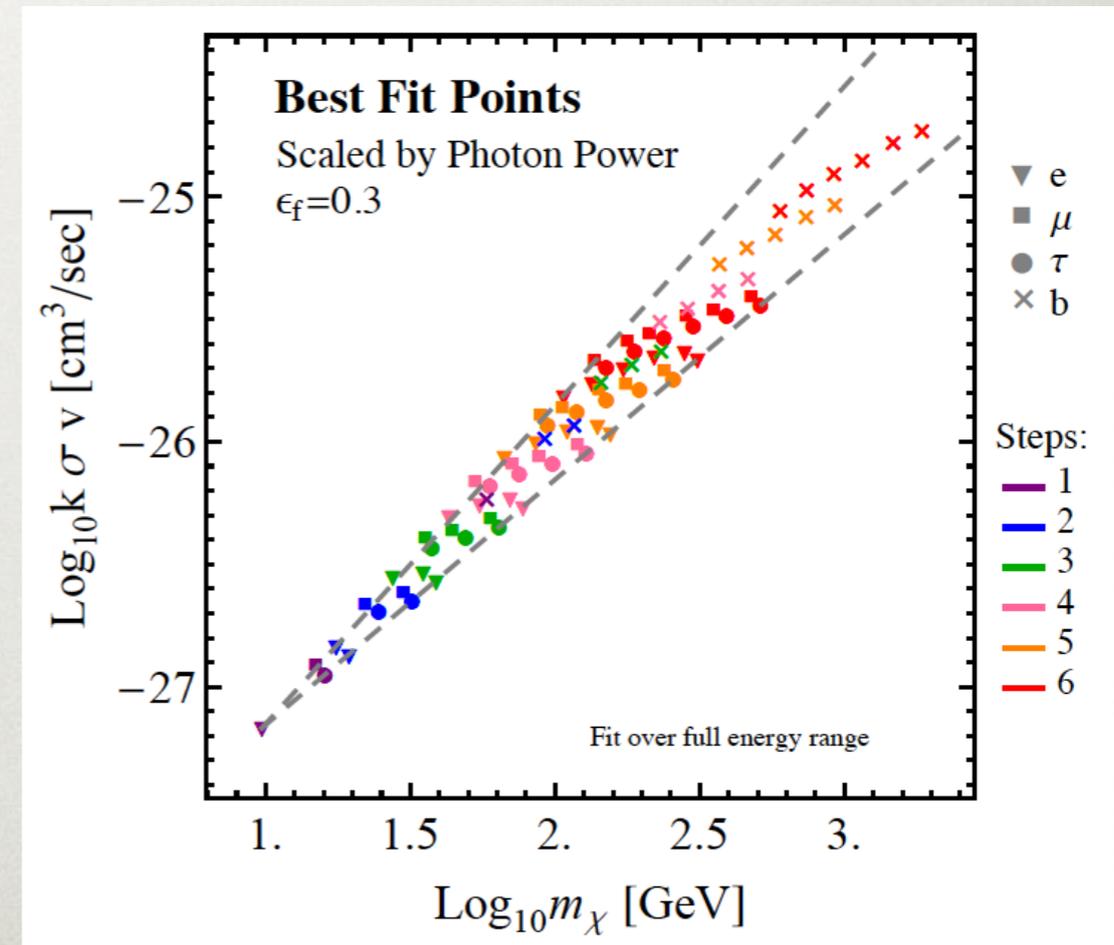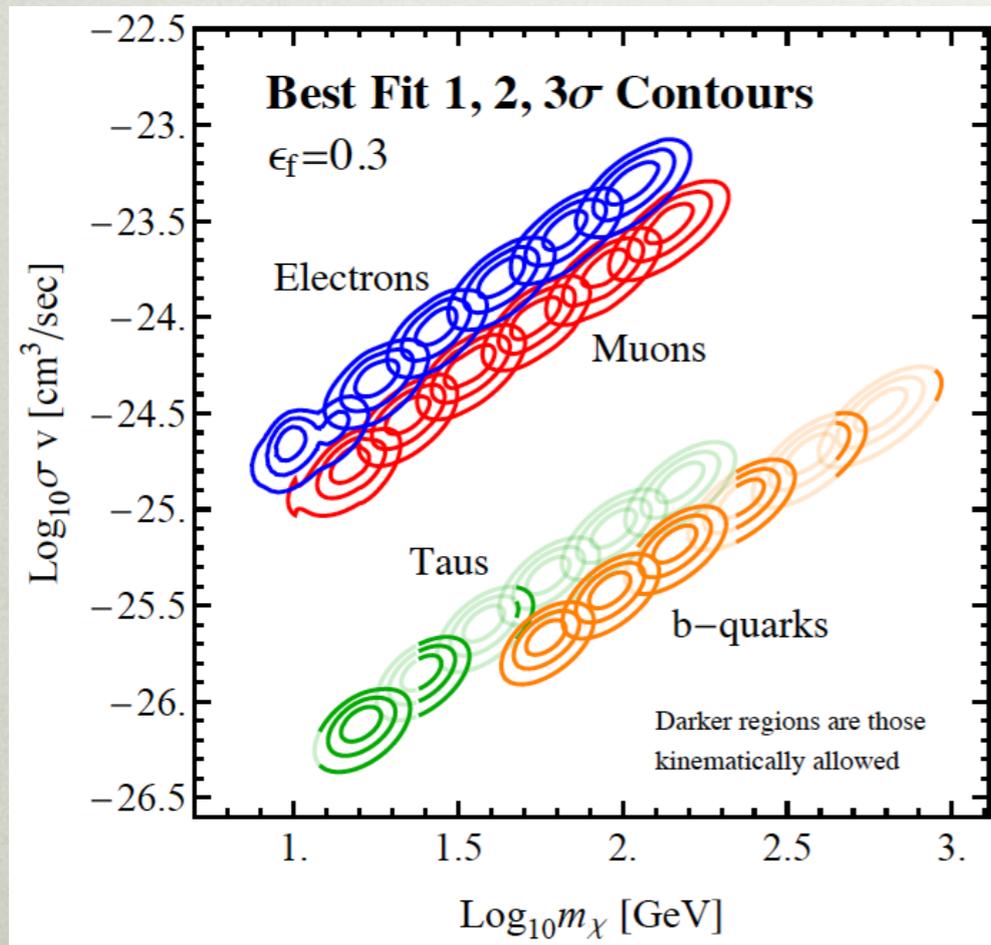
Dependence on High E Points

- So what happens if we exclude points above 10 GeV from the fit?
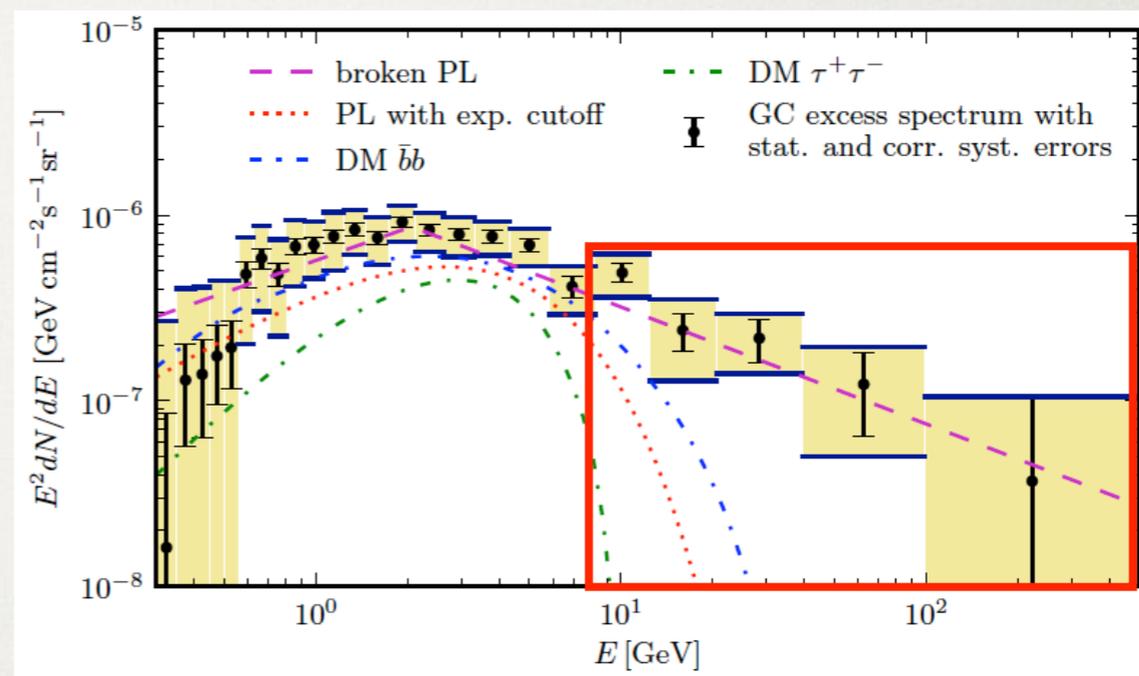
- Removing the high E points noticeably impacts the preferred number of steps and consequently the viable DM mass range for the GCE
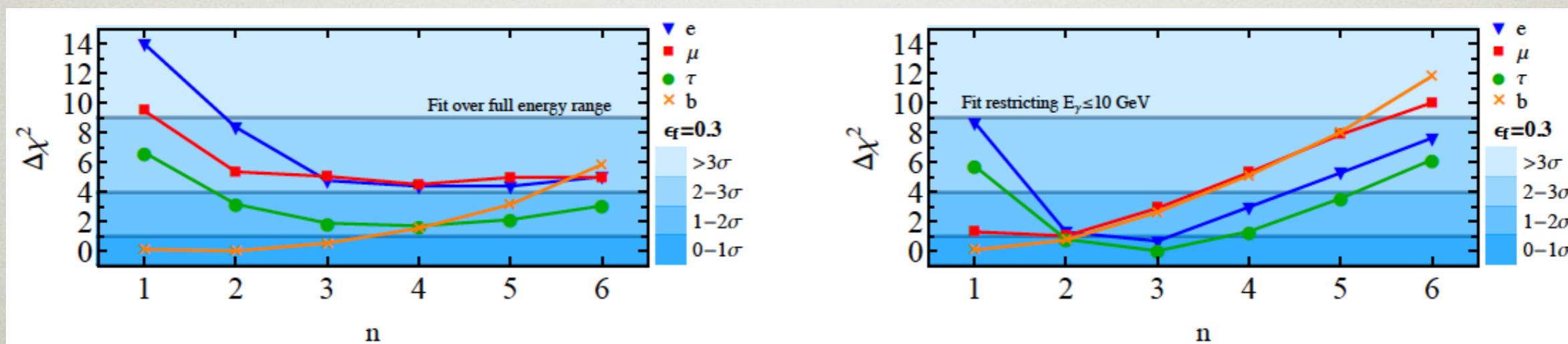
High Energy Tail of the GCE

- **Central question:** is the emission above 10 GeV part of the GCE or not?

- Ongoing work with Tim Linden and Tracy Slatyer
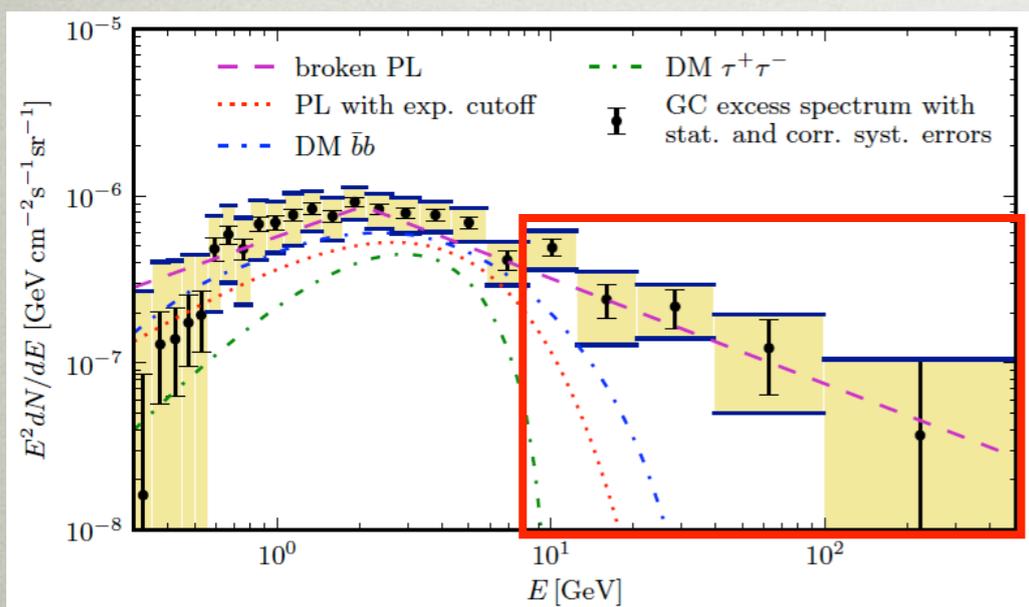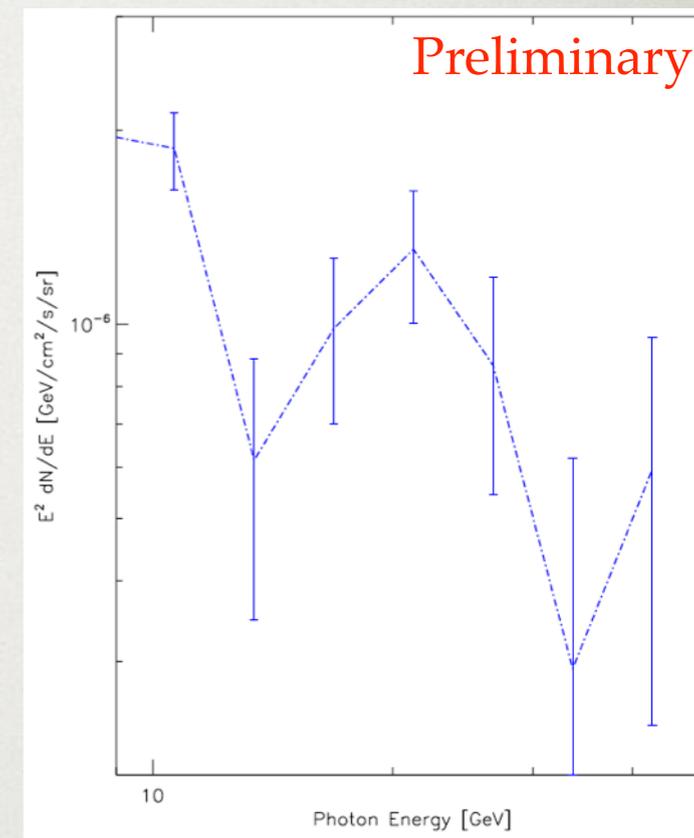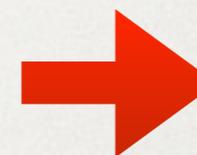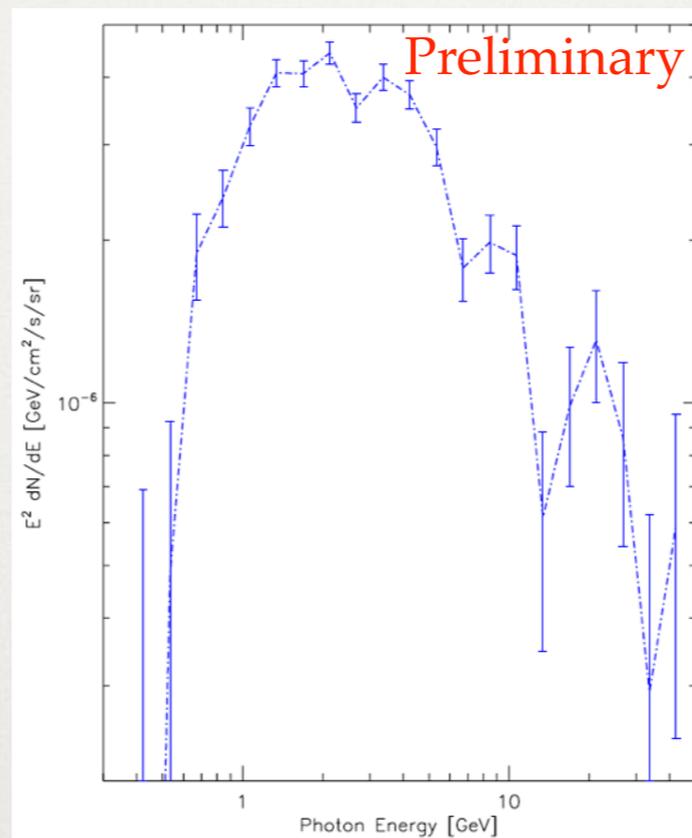
- Cascades highlight the importance of this question for a dark matter interpretation of the GCE

- More fundamentally though, independent of any interpretation of the GCE, understanding how high its emission extends is important

NB: NFW templates normalized differently

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HIGH ENERGY TAIL: STRATEGY

- Basic idea: there is more information in the tail of the GCE than simply the overlap with an NFW template in a template fit - want to tease this out

- Strategy:
  - Use template fitting analysis
  - Use source class P7REP data with front and back converting photons to maximise statistics
  - Focus on a 30x30 degree region around the GC, masking the plane at 1 degree - the smaller region helps with over subtraction issues identified in 1402.6703
  - Use four different background models: p6v11, p7 and two generated in Galprop - only show p6 results today, but find qualitative agreement between models
  - Independent analysis performed using the Fermi tools in a 5x5 regions around the GC, which does not mask the plane - results not shown today
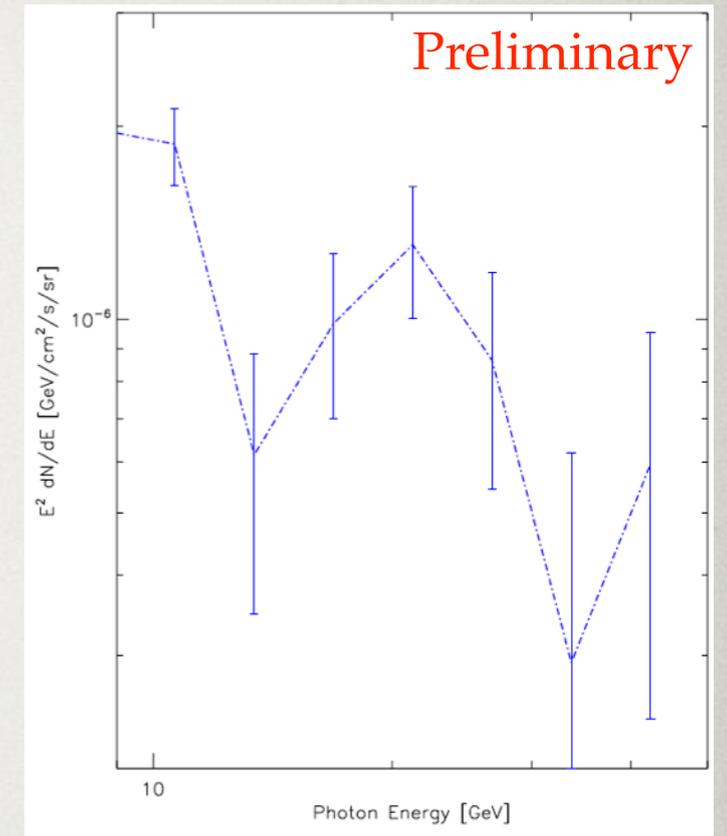
High Energy Tail: the Challenge

- Below we show the high energy residual of the fit with (left) and without (right) the NFW added back in
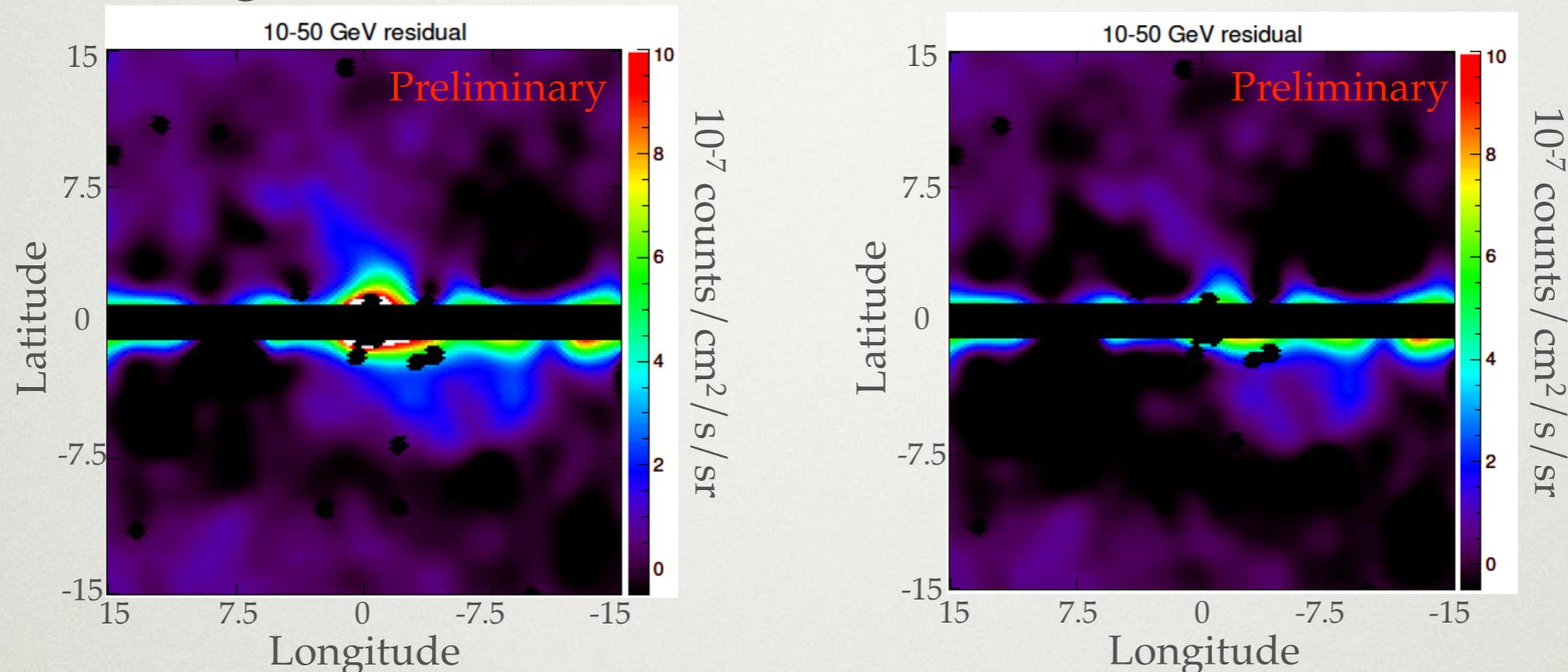
- The size of the background residuals are similar to the signal at high E, but there still appears to be a concentrated emission at the centre

- Background mismodelling at high energy could hide a signal

- The background could easily give a non-zero overlap with the NFW, but it is less likely for it to mimic the exact spatial properties of the GCE

SPATIAL PROPERTIES OF THE TAIL

- Bin by bin we determine the best fit power law slope of the generalized NFW, and also look for a preference for spherical symmetry using the axis ratio (which is greater than 1 for a stretch perpendicular to the plane)

- Both of these can then be compared to the properties of the excess over all energies
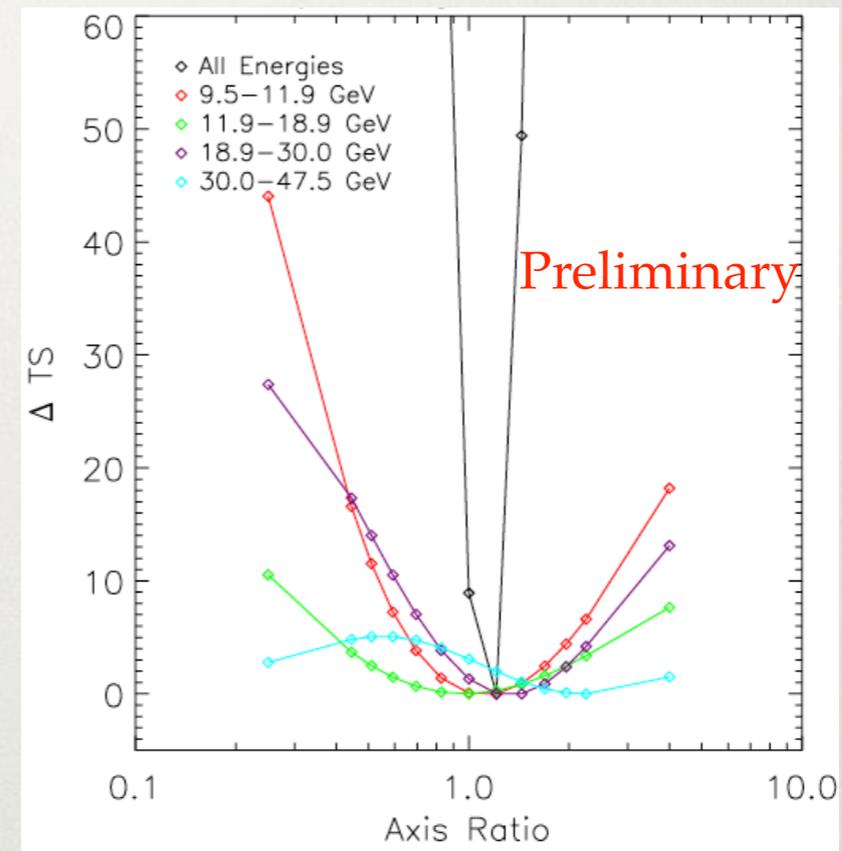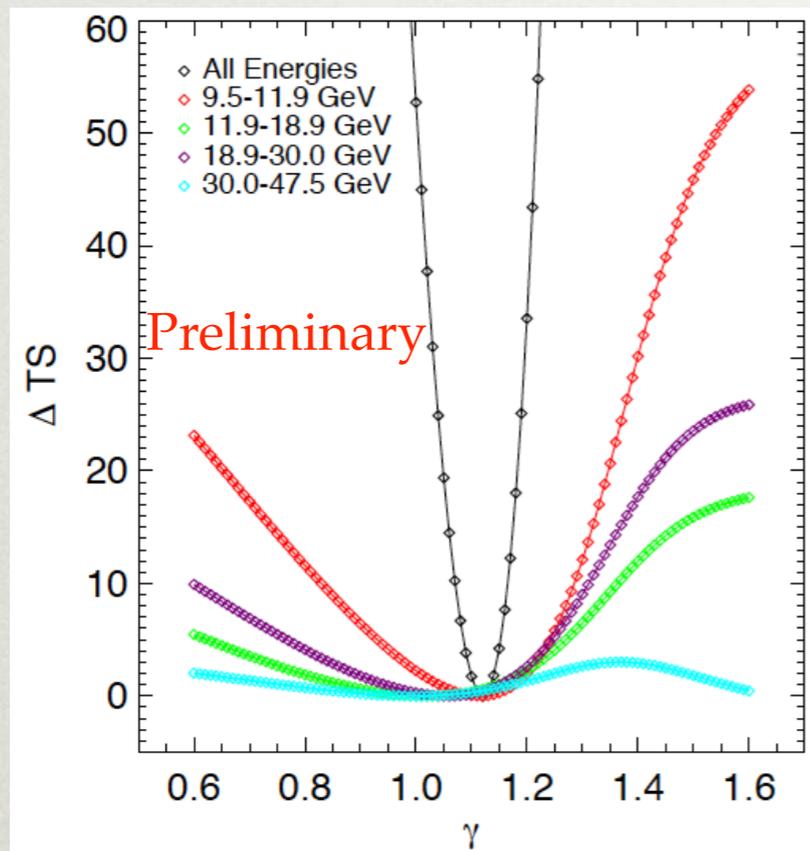
- First high energy bin certainly appears to have similar features to the GCE

- There are tentative hints this might extend up to the bin at 18.9-30 GeV, but not higher

- For these higher bins a careful consideration of the backgrounds and residuals is required before reaching any conclusions here

Conclusions

- The Galactic Centre Excess is an interesting potential DM signal - still a long way from a conclusive answer though
- Cascade spectra are much simpler than one might expect:
  - Spectrum determined by three parameters: n, ε_f and f
  - The preferred m_χ-$\langle \sigma v \rangle$ for GCE is determined by the power into photons and the width of the spectrum
- Cascades in the dark sector increases the viable mass and cross section parameter space for the GCE
- Exactly how much depends on whether we attribute high energy data points to the excess
- Initial results of looking at the high energy tail of the GCE suggest the excess extends to at least 10 GeV and maybe higher, but these results are still preliminary

Backup Slides

- Galactic Centre:
  - Goodenough and Hooper; 0910.2998
  - Goodenough and Hooper; 1010.2752
  - Boyarsky, Malyshev, and Ruchayskiy; 1012.5839
  - Hooper and Linden; 1110.0006
  - Abazajian and Kaplinghat; 1207.6047
  - Gordon and Macias; 1306.5725
  - Abazajian, Canac, Horiuchi, and Kaplinghat; 1402.4090
- Inner Galaxy:
  - Hooper and Slatyer; 1302.6589
  - Huang, Urbano and Xue; 1307.6862
  - Calore, Cholis and Weniger; 1409.0042
- GC and IG:
  - Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd and Slatyer; 1402.6703
- Discussion of why pulsars aren't a good fit:
  - Cholis, Hooper, Linden, Siegal-Gaskins, and Slatyer; 1302.6589

Template Fitting

- How the method works:
  - Describe the expected contributions by spatial templates at each energy (relative normalisations unknown)
  - Determine the normalisations by a pixel-based maximum likelihood analysis, fitting the data to a weighted sum of the spatial templates
  - Returns coefficients for the various templates (see plot for an example)
  - Repeat this independently for 30 energy bins between 300 MeV and 300 GeV
  - The fit is characterised by the likelihood and the spatial residual
- Input:
  - Spatial templates of the backgrounds
  - No spectral information is inserted - recovering expected spectrum for backgrounds is a cross check

NB: templates normalised to different regions of the sky

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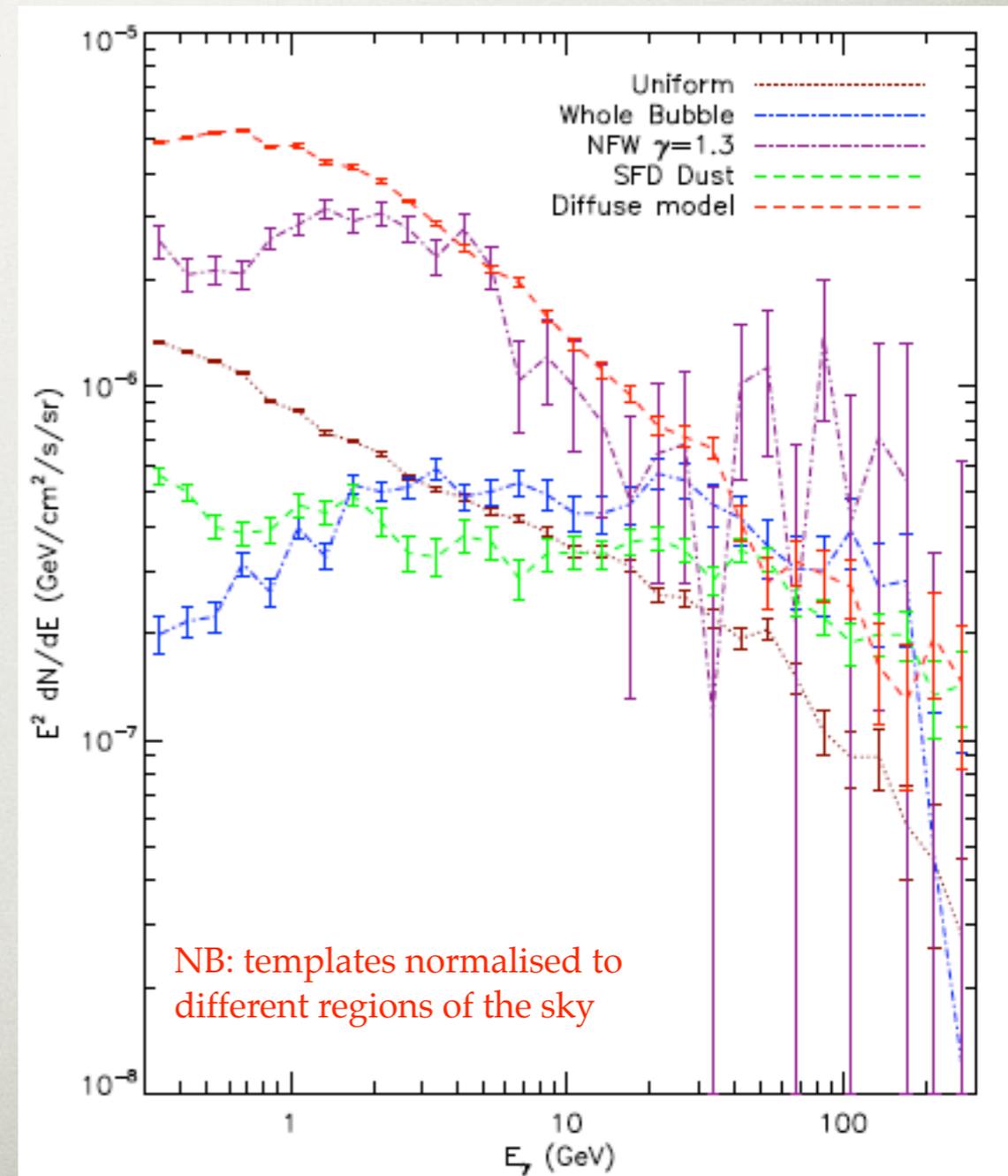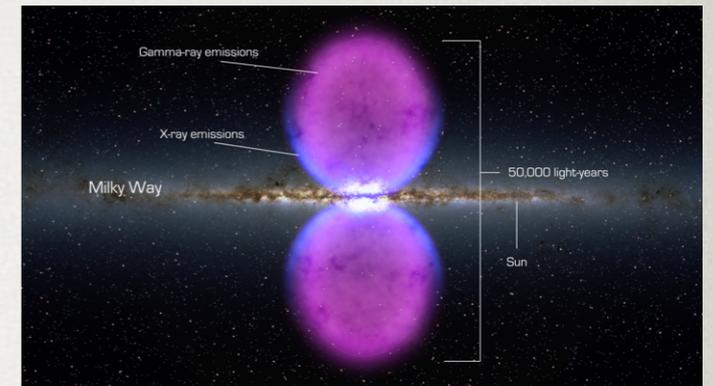
Template Fitting: Inputs

- Isotropic map: Absorbs extragalactic background and any residual contamination
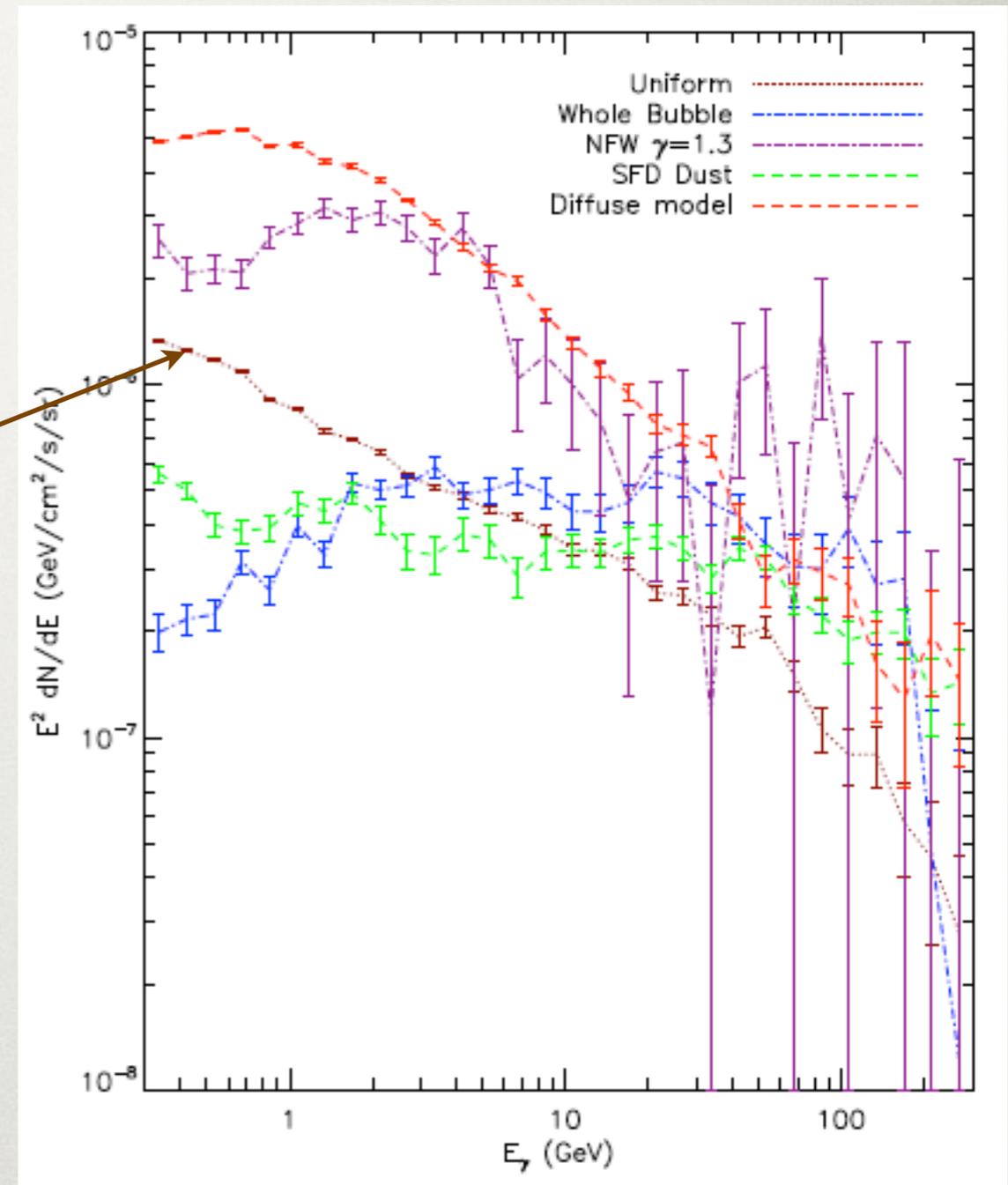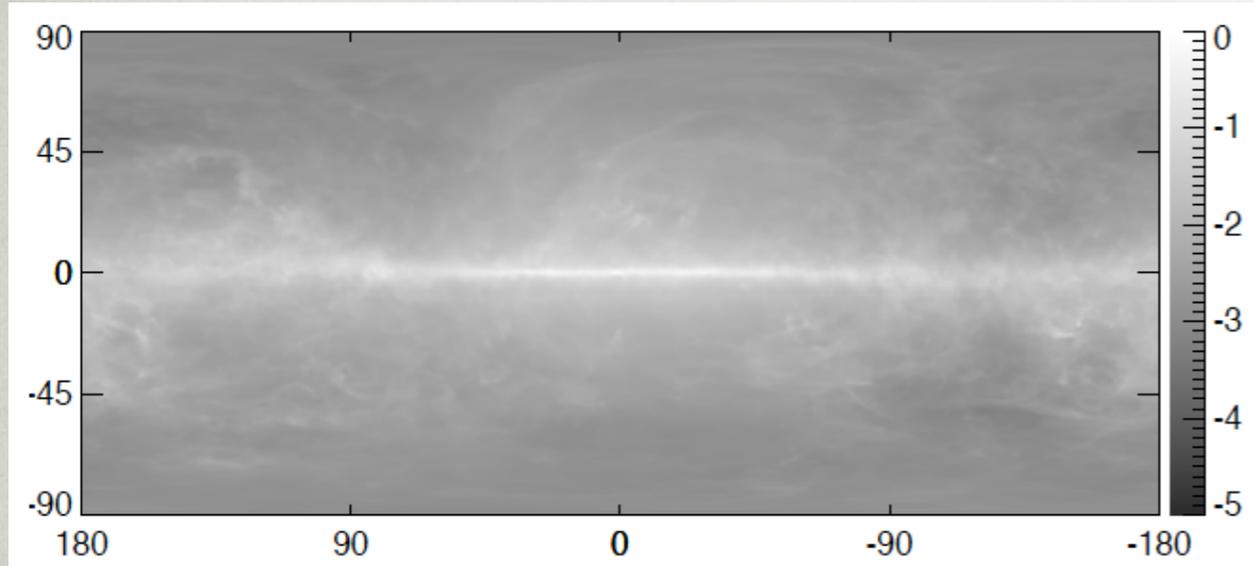
- Fermi Diffuse Model (p6v11): model of π^0 decay, inverse Compton scattering and bremsstrahlung

  - π^0 and brem: arises from interactions of cosmic rays with the gas; modelled by gas maps divided into galactocentric rings to account for variations in the cosmic ray (CR) population

  - Inverse Compton: arises from the scattering of CR electrons on the radiation field; modelled using GALPROP

- Describes the diffuse emission well but there are systematic residuals above the expected level of Poisson noise

25
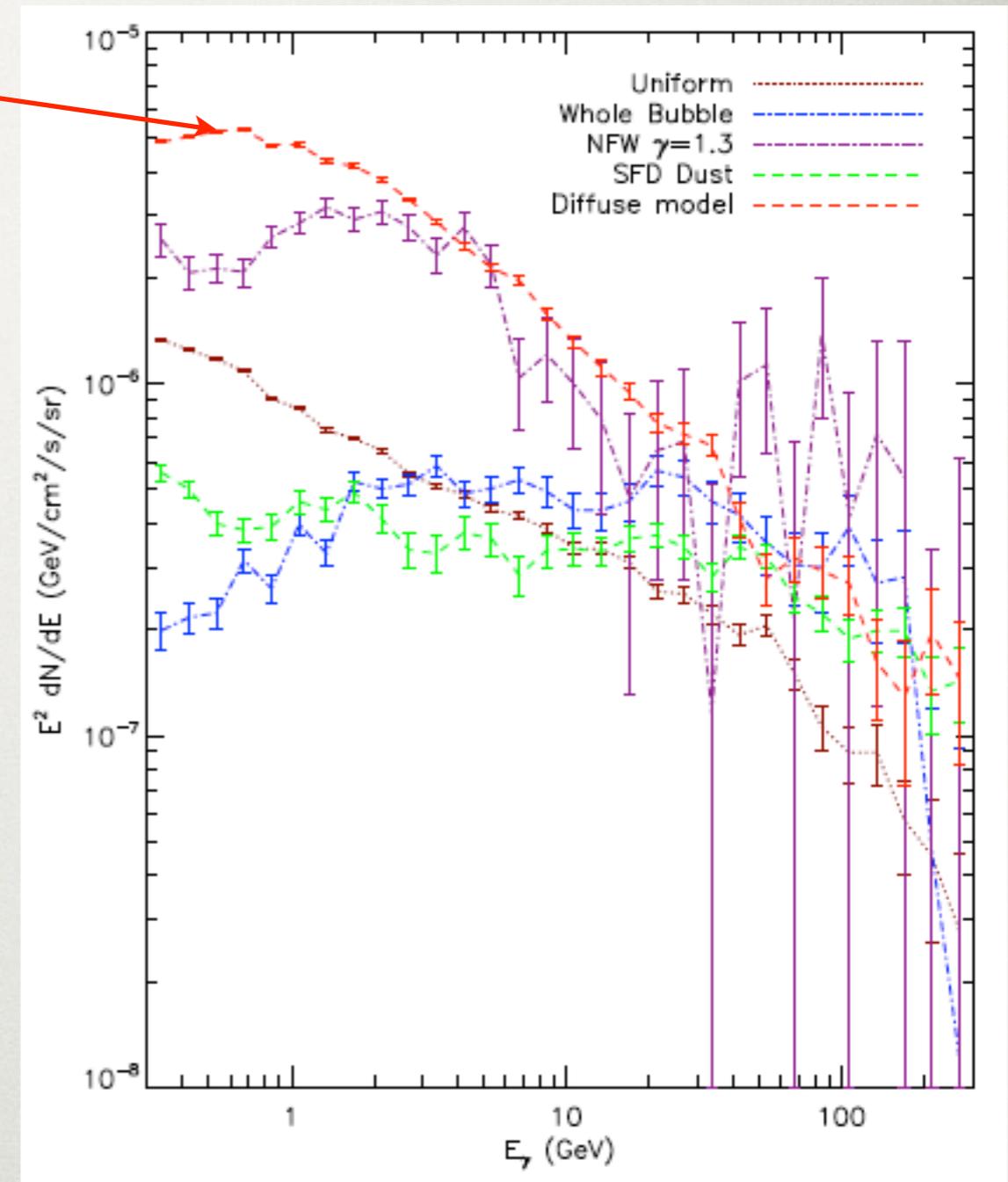
Template Fitting: Inputs

- Fermi bubbles (version of the diffuse model used does not include these)
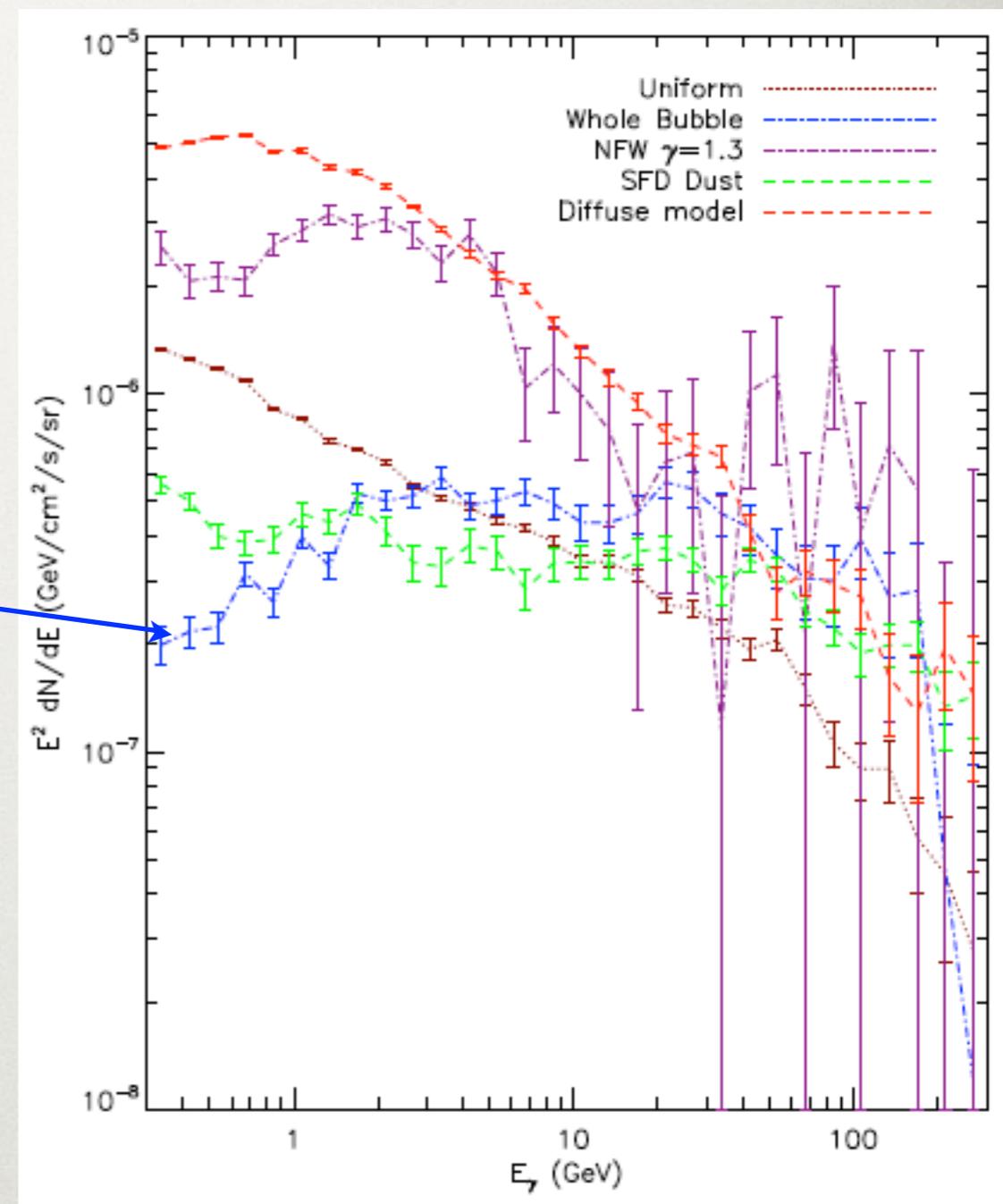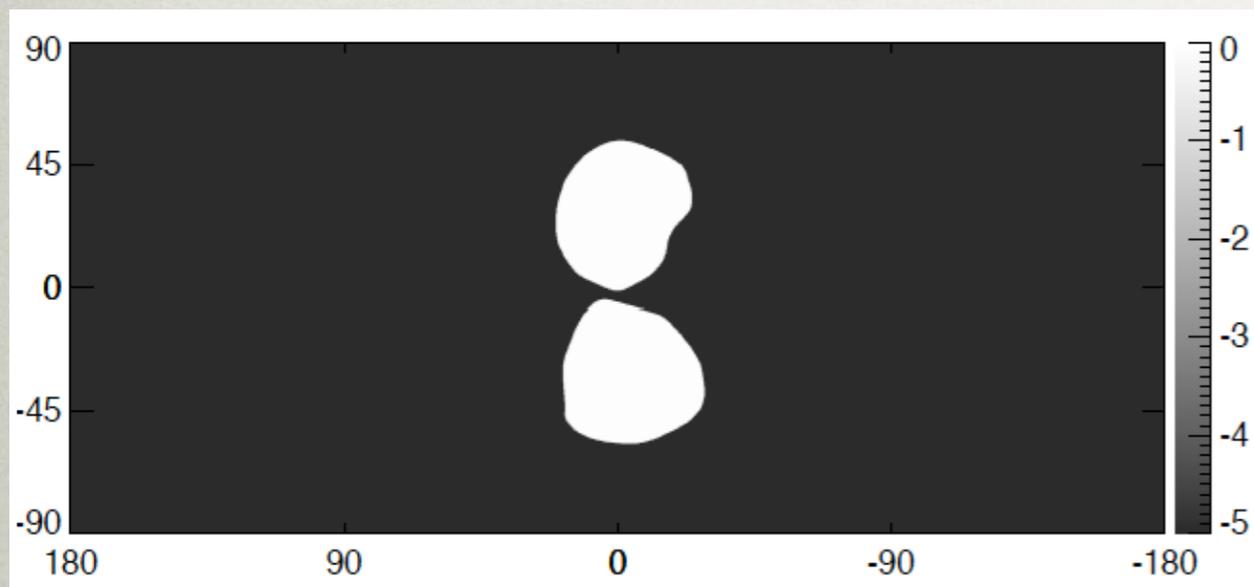
Template Fitting: Inputs

- Template for the excess in the form of a generalized Navarro-Frenk-White (NFW) halo profile (squared and projected along the line of sight), remaining agnostic as to γ

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$r_s = 20 \text{ kpc}$$
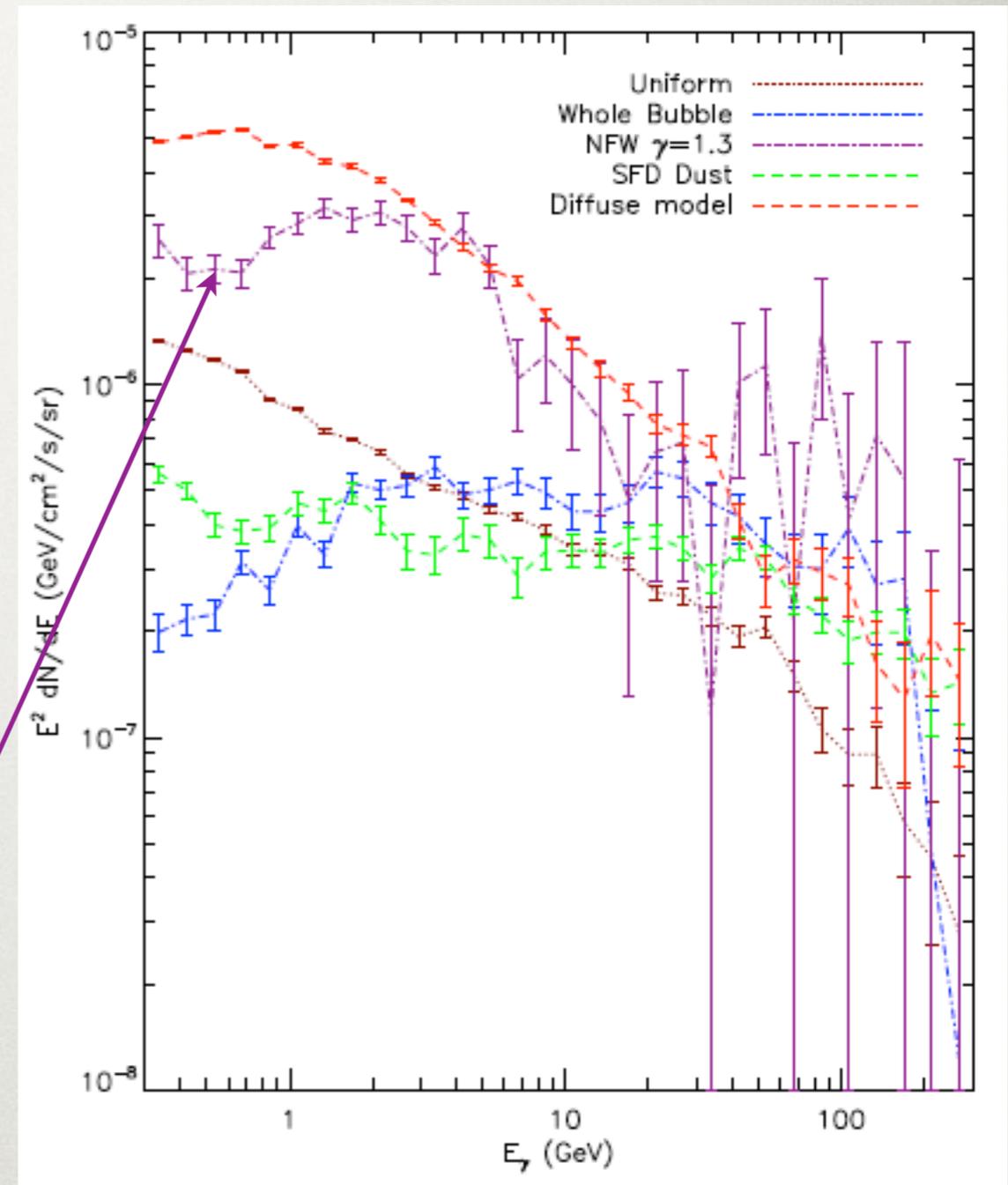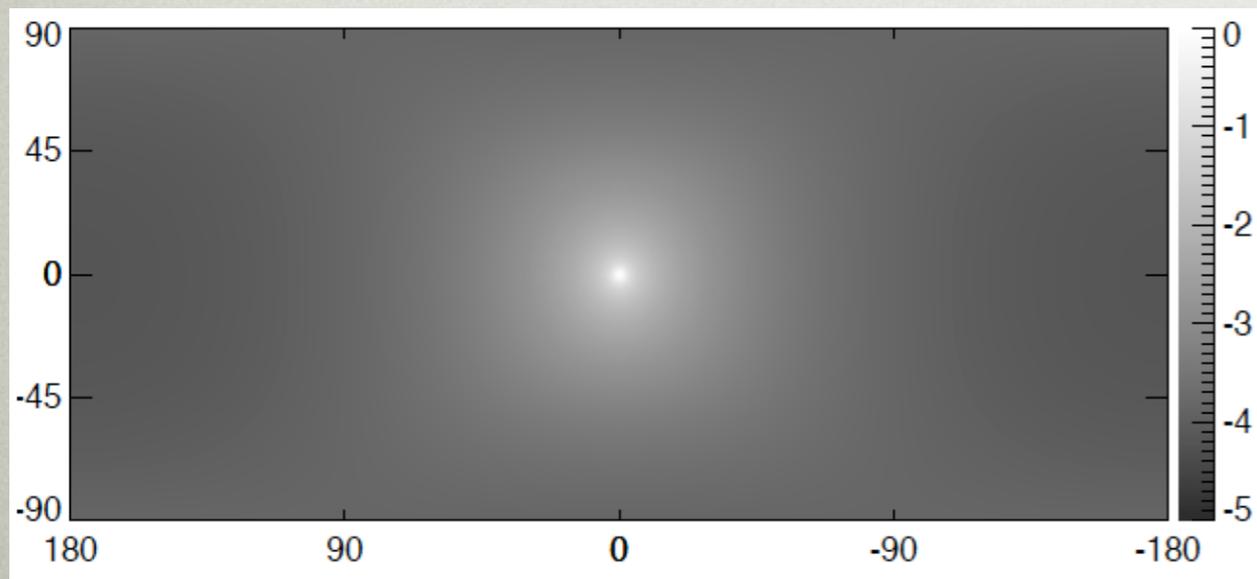
A Simplified Picture for the Spectra

- Can approximate 0-step spectra as "effective n-step" cascades in the visible sector terminating in $\Phi_1 \rightarrow \gamma\gamma$

- Best fit "effective n"

  - e: 2-3

  - μ: 3-4

  - τ: 3-4

  - b: 6-7

- Combining with preferred n in the dark sector, find the GCE roughly modelled by an effective 7-9 step cascade ending in $\Phi_1 \rightarrow \gamma\gamma$

0−Step vs $\gamma\gamma$ Cascade

$\epsilon_f=0.3$; lighter gray corresponds to longer cascades, ranging from n=1−7

- e
- μ
- τ
- b
- δ−fn

y-axis: $x^2 dN_\gamma/dx$

x-axis: x
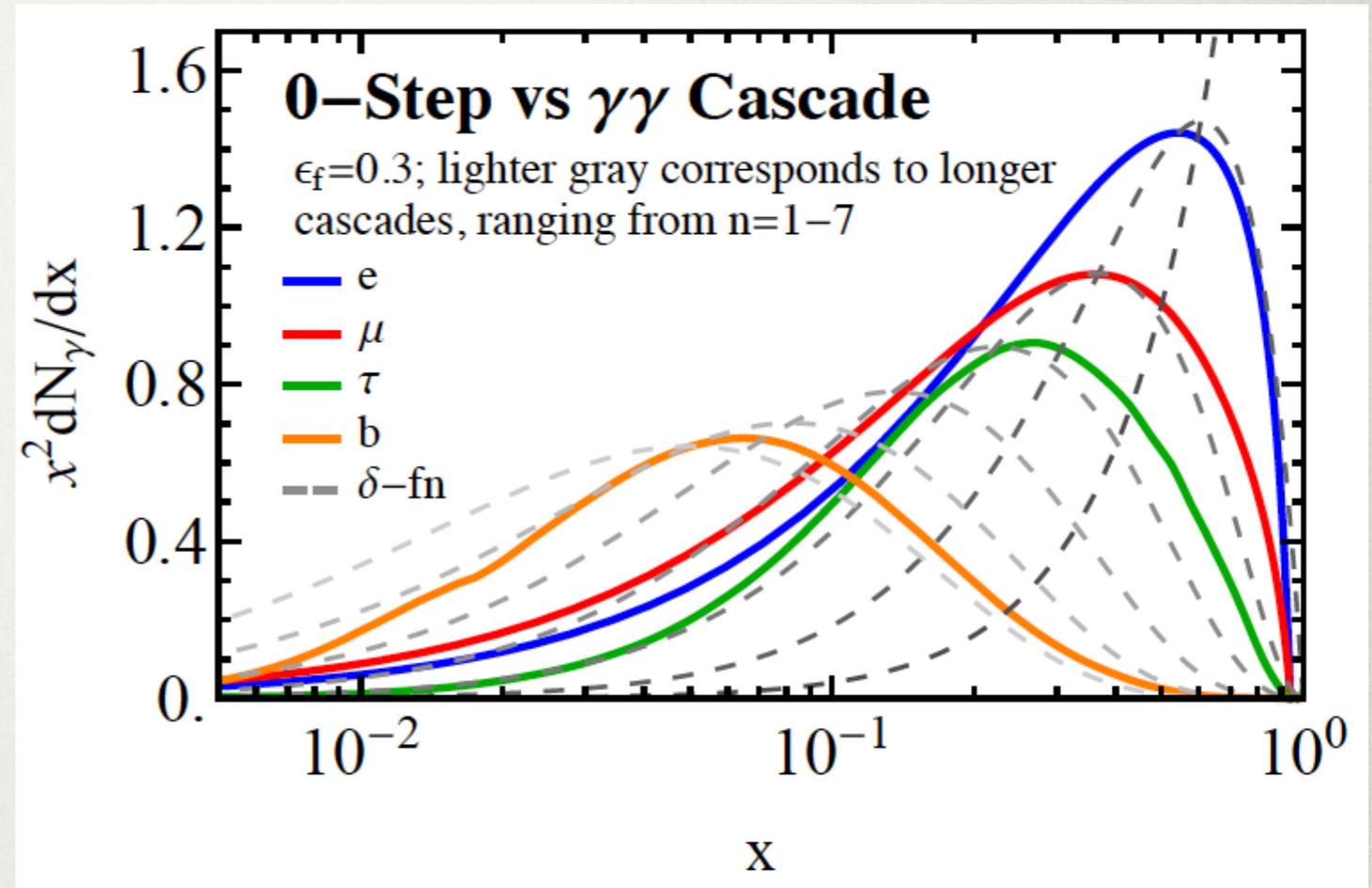
Heights of the 0-step spectra have been rescaled

Final State	n-step	m_χ (GeV)	σv (cm^3/sec)	χ^2
e	5	67.2	2.9×10^{-24}	26.82
μ	4	53.0	9.9×10^{-25}	26.94
$\tau_{\text{unphysical}}$	4	59.4	4.6×10^{-26}	24.13
τ_{physical}	2	24.1	1.4×10^{-26}	25.59
b	2	91.2	3.9×10^{-26}	22.42

What was lost in assuming a Large Hierarchy?

$$\underbrace{\chi\chi\to}_{\epsilon_1=m_1/m_\chi}\quad \phi_1\phi_1 \quad \underbrace{\to 2 f\bar{f}}_{\epsilon_f=2m_f/m_1}$$

- If $\epsilon_1 = 1$, then there is no boost as the Φ_1's are produced at rest

- So if a step goes degenerate, an n-step cascade reduces to an (n-1)-step spectrum; we just have to adjust for the increased multiplicity and m_χ

- The more general case of non-hierarchical cascades can be obtained from our hierarchical results

- Can calculate analytically the transition between the two cases:

Spectra for Varying ϵ
$n=2, f=\tau, \epsilon_\tau=0.1$

— $\epsilon=0$
— $\epsilon=1$
- - $0<\epsilon<1$

Dashed lines move bet–ween the two cases via $\epsilon=\{0.3,0.5,0.7,0.9,0.99\}$

$x^2 dN_\gamma/dx$

x
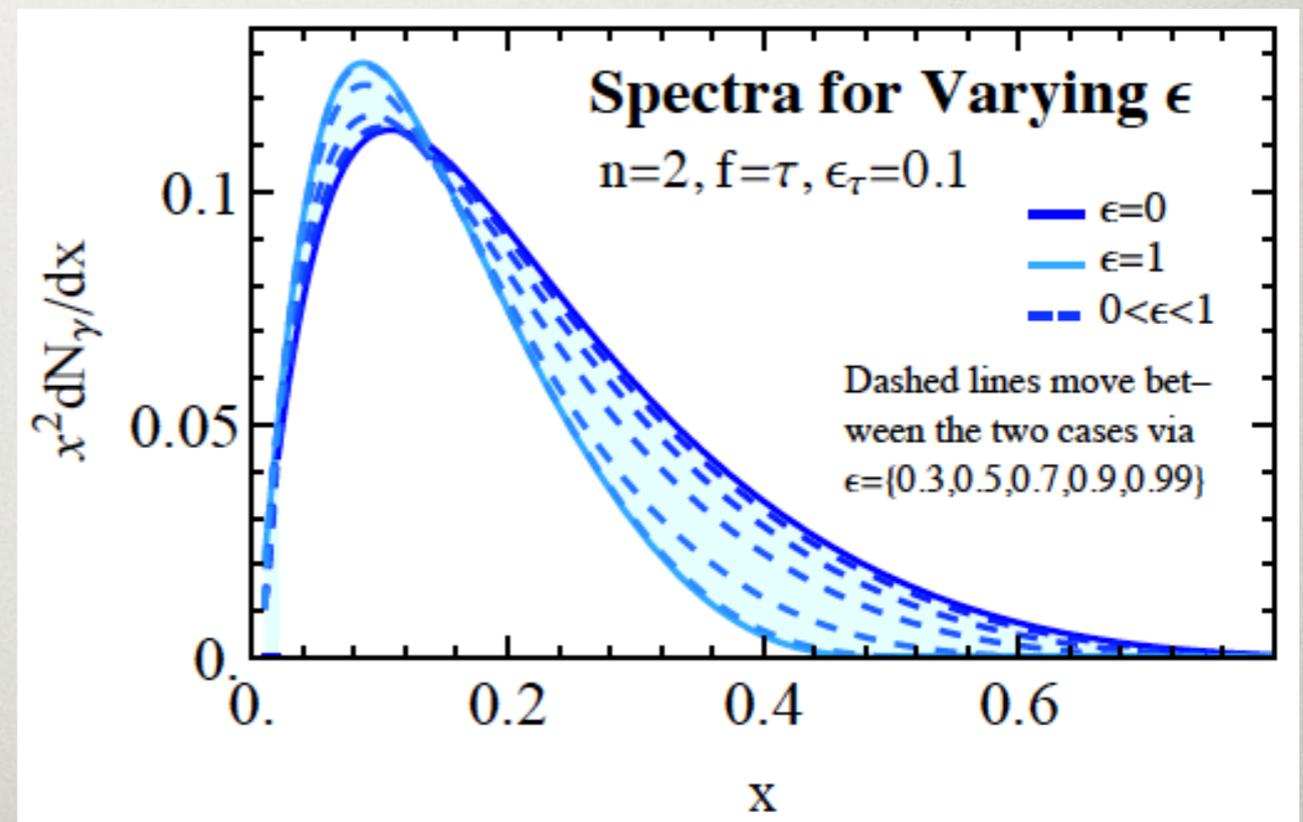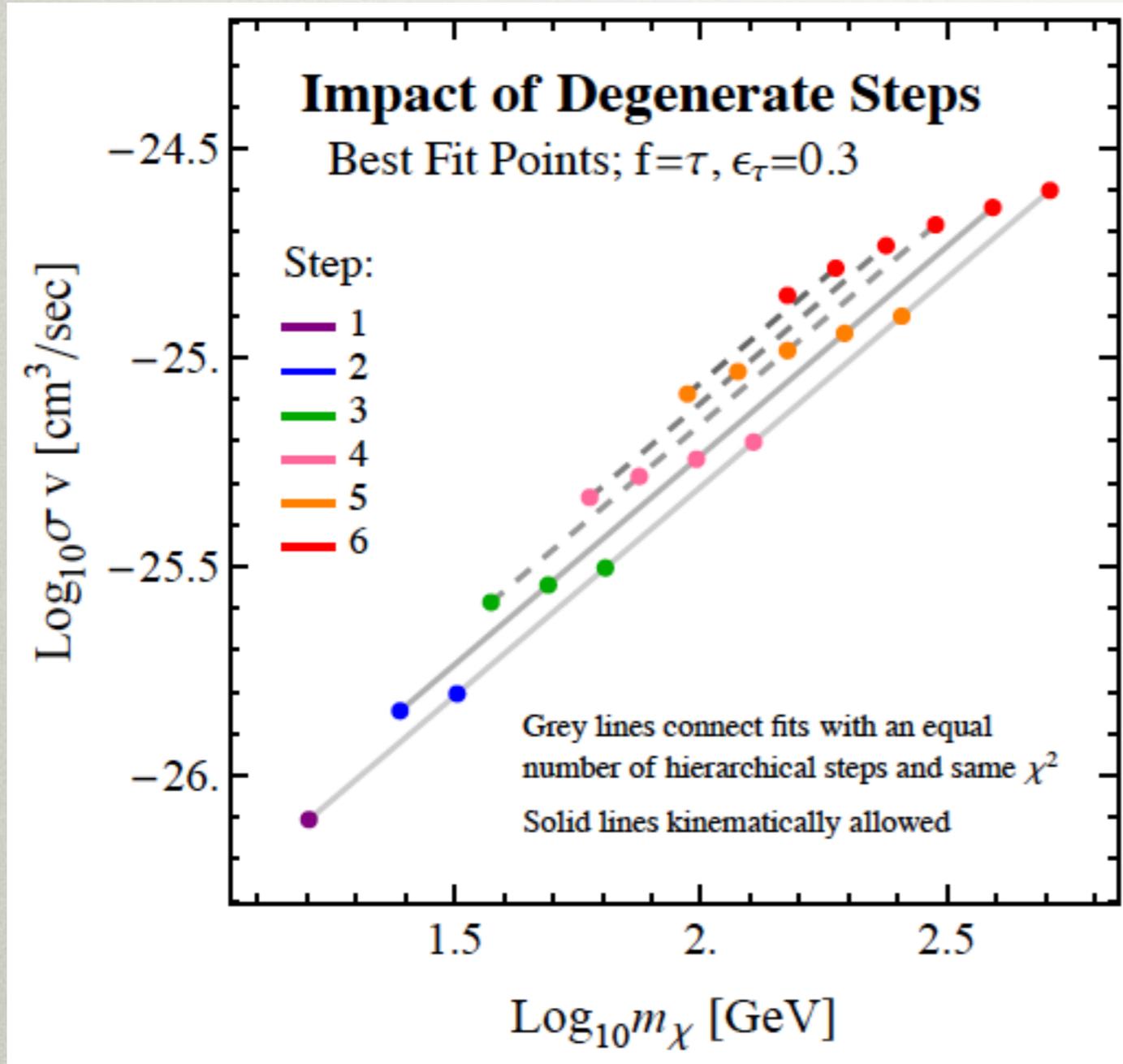
Hierarchical steps:

$$\langle \sigma v \rangle \propto m_\chi^{1.3}$$

Degenerate steps:

$$\langle \sigma v \rangle \propto m_\chi$$
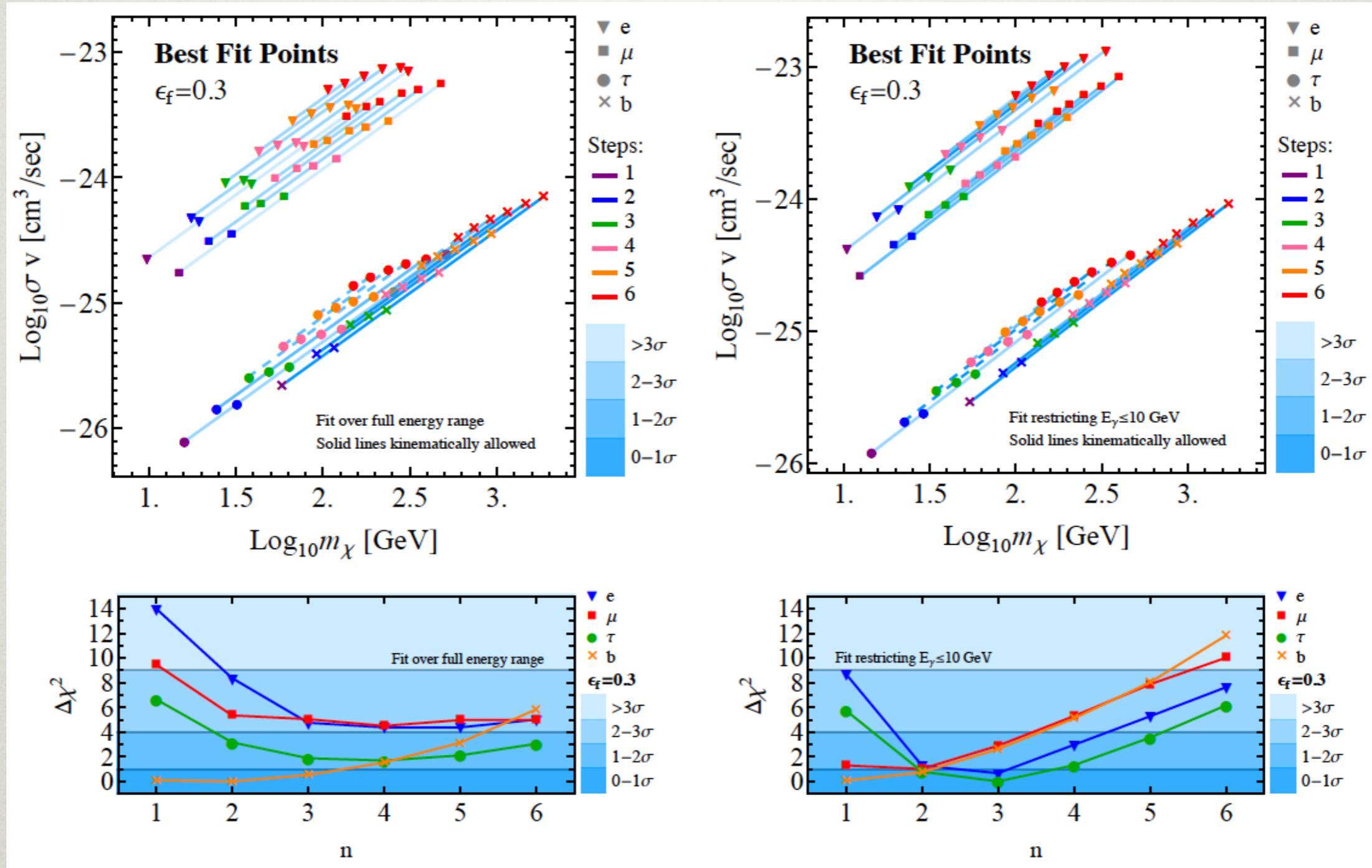
- Removing the high E points noticeably impacts the preferred number of steps and consequently the viable DM mass range for the GCE

- Difference in preferred $\langle \sigma v \rangle$ for various final states is mainly due to the fraction of power the annihilation puts into photons

- We can rescale results by this factor to obtain a single region of preferred parameter space bounded by $\langle \sigma v \rangle \propto m_\chi$ and $\langle \sigma v \rangle \propto m_\chi^{1.3}$
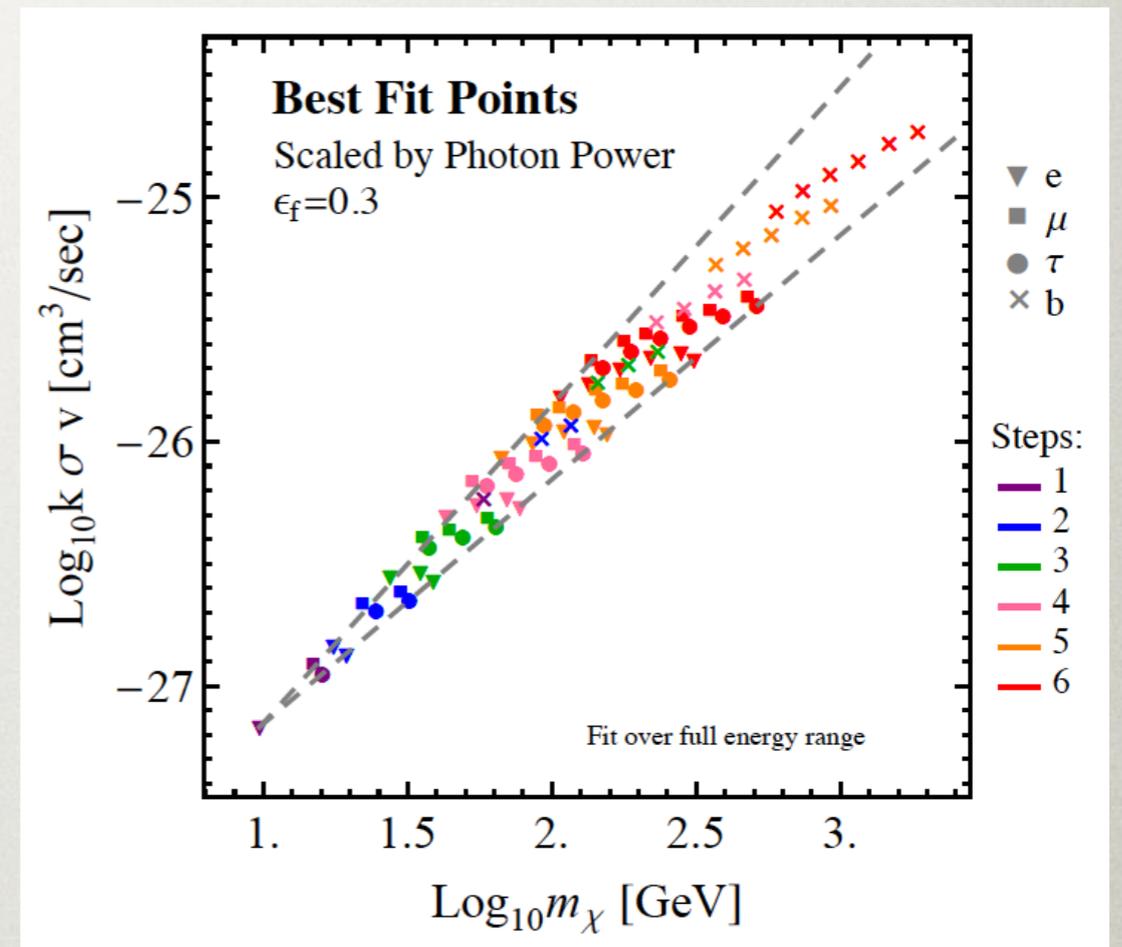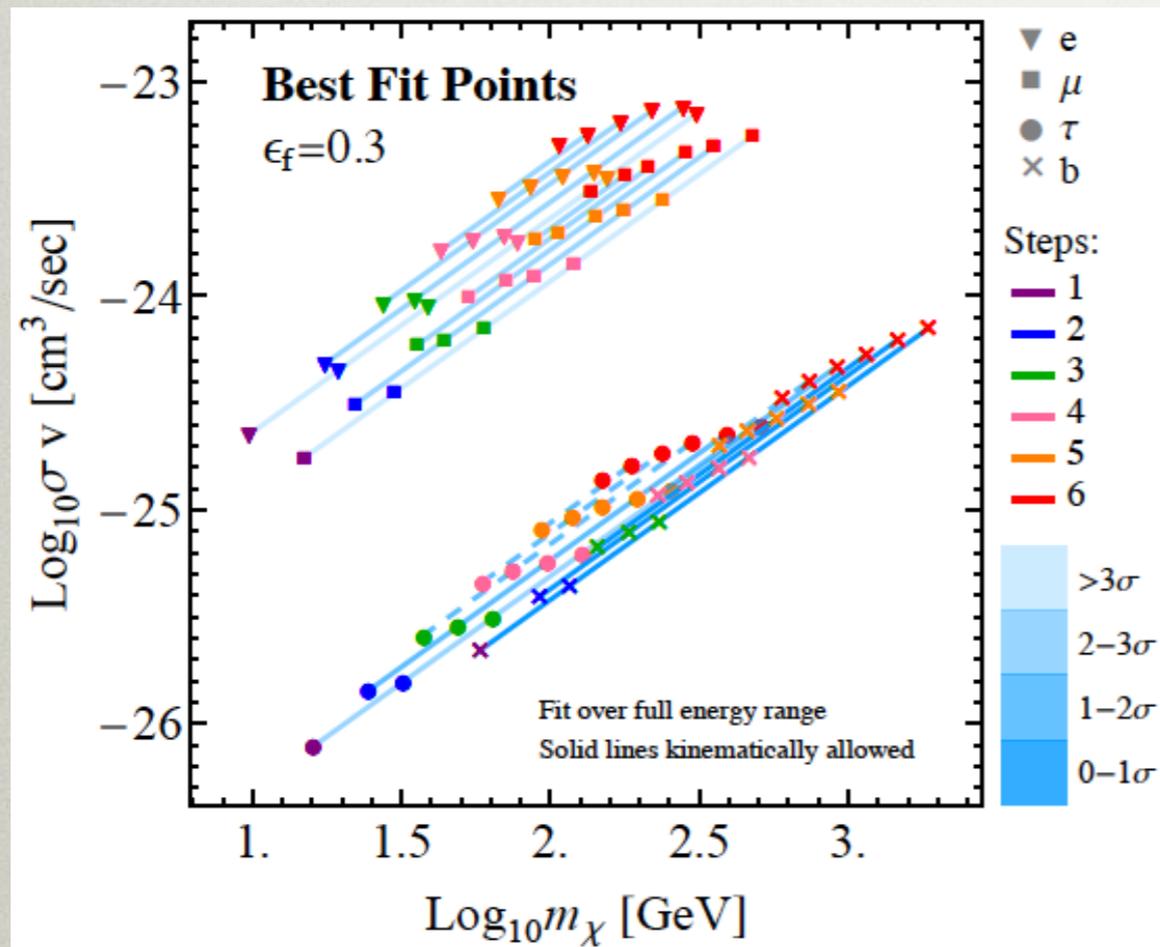
- For a given model, the preferred mass is largely dictated by "effective n," whilst the cross section is then roughly set by the power into photons - specific details of the cascade are captured by the width of the cone

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Consider $\quad \phi_2 \to \phi_1 \phi_1 \to 2f\bar{f}\,(+\gamma)$

We have $\quad \dfrac{dN_\gamma}{dx_0} \quad x_0 = 2E_0/m_1 \in (0,1) \quad E_0 =$ Photon energy ϕ_1 rest frame

We want $\quad \dfrac{dN_\gamma}{dx_1} \quad x_1 = 2E_1/m_2 \quad E_1 =$ Photon energy ϕ_2 rest frame

Just integrate the known spectrum over all energies and angles

$$\frac{dN_\gamma}{dx_1} = 2\int_{-1}^{1} d\cos\theta \int_0^1 dx_0 \frac{dN_\gamma}{dx_0} \delta\left(2x_1 - x_0 - \cos\theta\, x_0 \sqrt{1-\epsilon_1^2}\right)$$

Kinematics of Lorentz-Boost

The angular integral is easily performed, yielding a simple formula for boosts

$$\frac{dN_\gamma}{dx_1} = 2\int_{x_0}^1 \frac{dx_0}{x_0} \frac{dN_\gamma}{dx_0} + \mathcal{O}(\epsilon_1^2)$$

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HOW DO THE FITS DEPEND ON ε_f?

- The dependence on ε_f is generally not strong, which is why we picked a single representative value for most fits
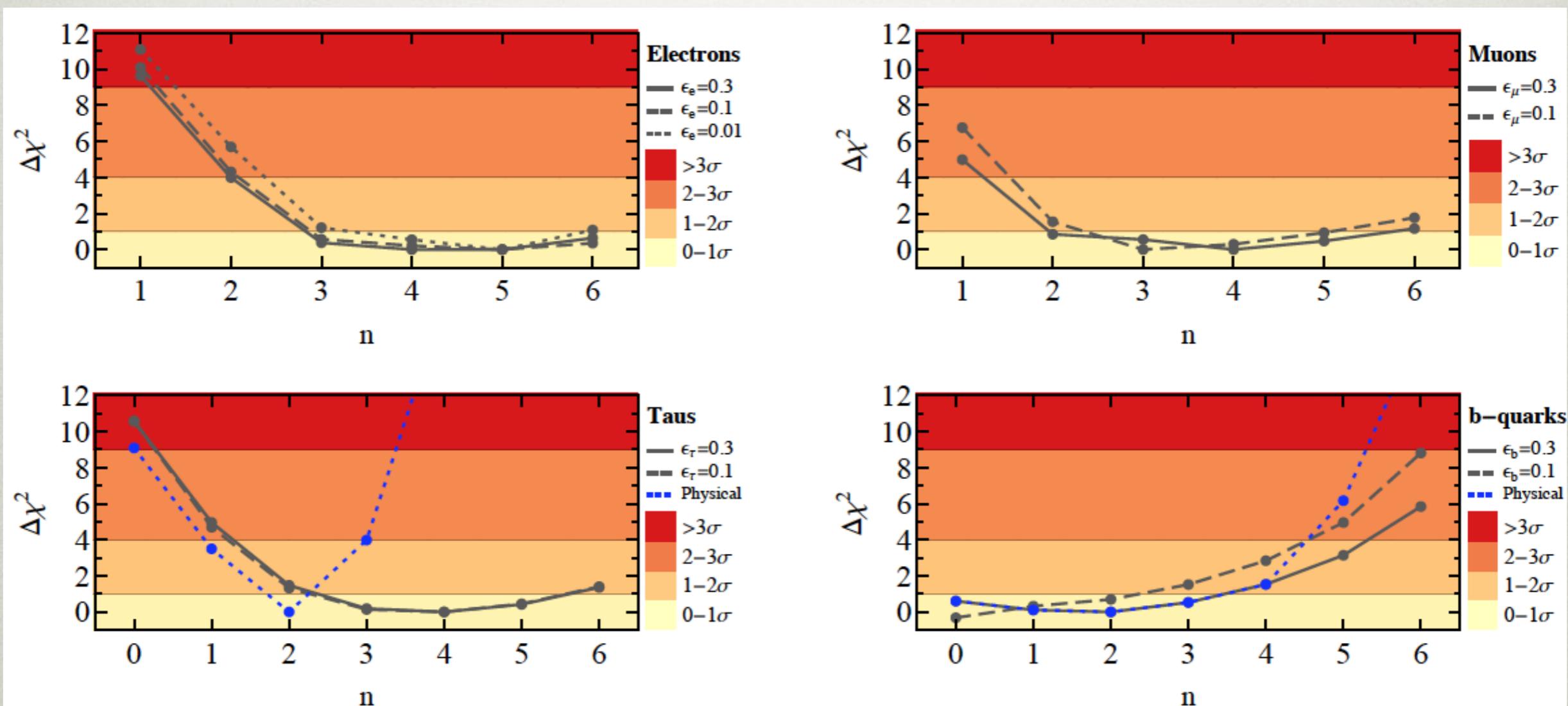
Vector Cascades

- In the case of vector cascades, additional angular dependence needs to be accounted for at each step

- Despite this, it appears that in the case of two common angular dependencies, the shape of the resulting spectrum does not vary significantly

Cascade with a Vector Step

$f = \tau, \epsilon_\tau = 0.1$

$f(\theta)$:
— 1
-- $\frac{3}{2}\sin^2\theta$
--- $\frac{3}{4}(1 + \cos^2\theta)$

Step:
— 1
— 2
— 3

$x^2 dN_\gamma/dx$

x
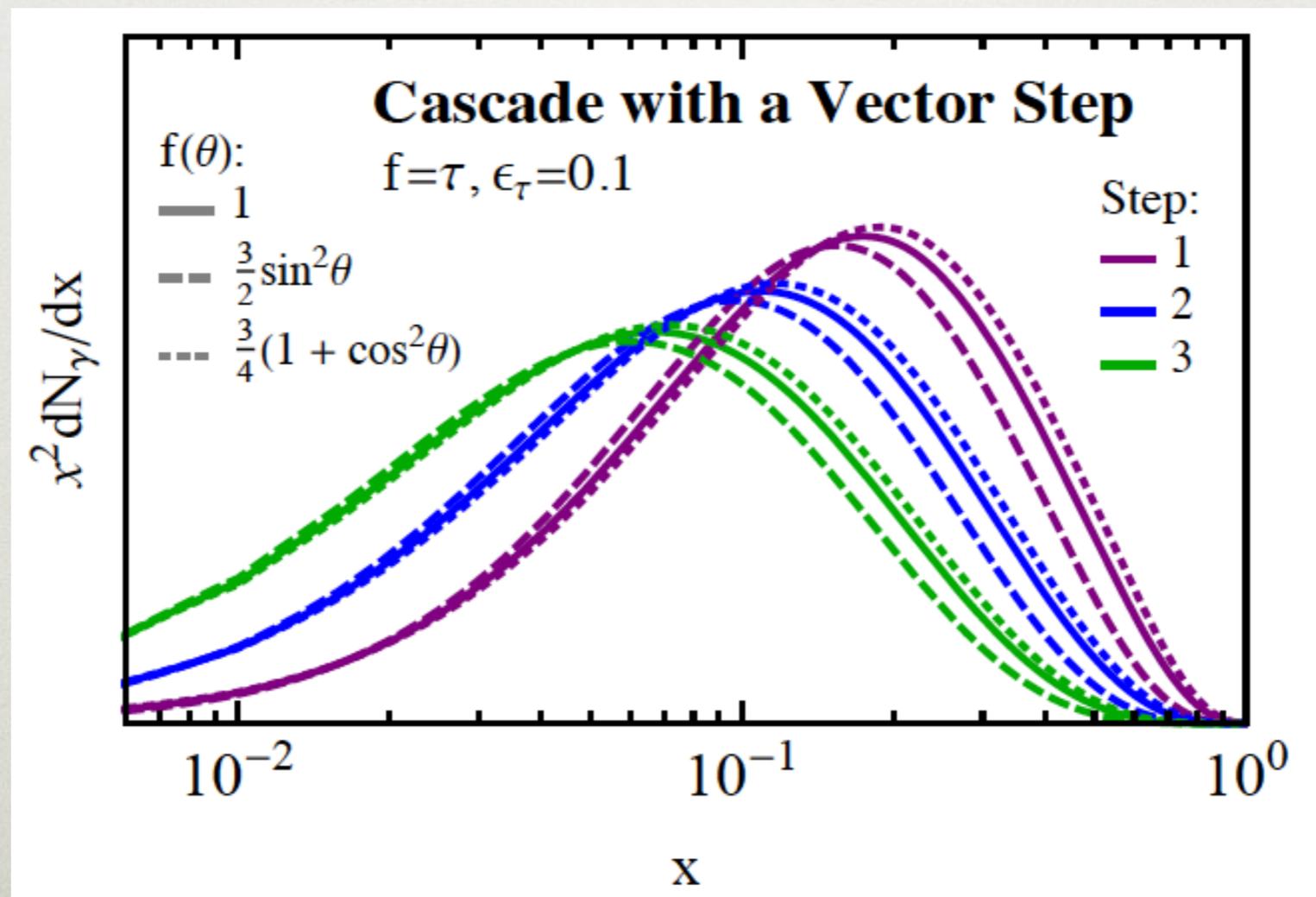
Systematic vs Statistical Errors
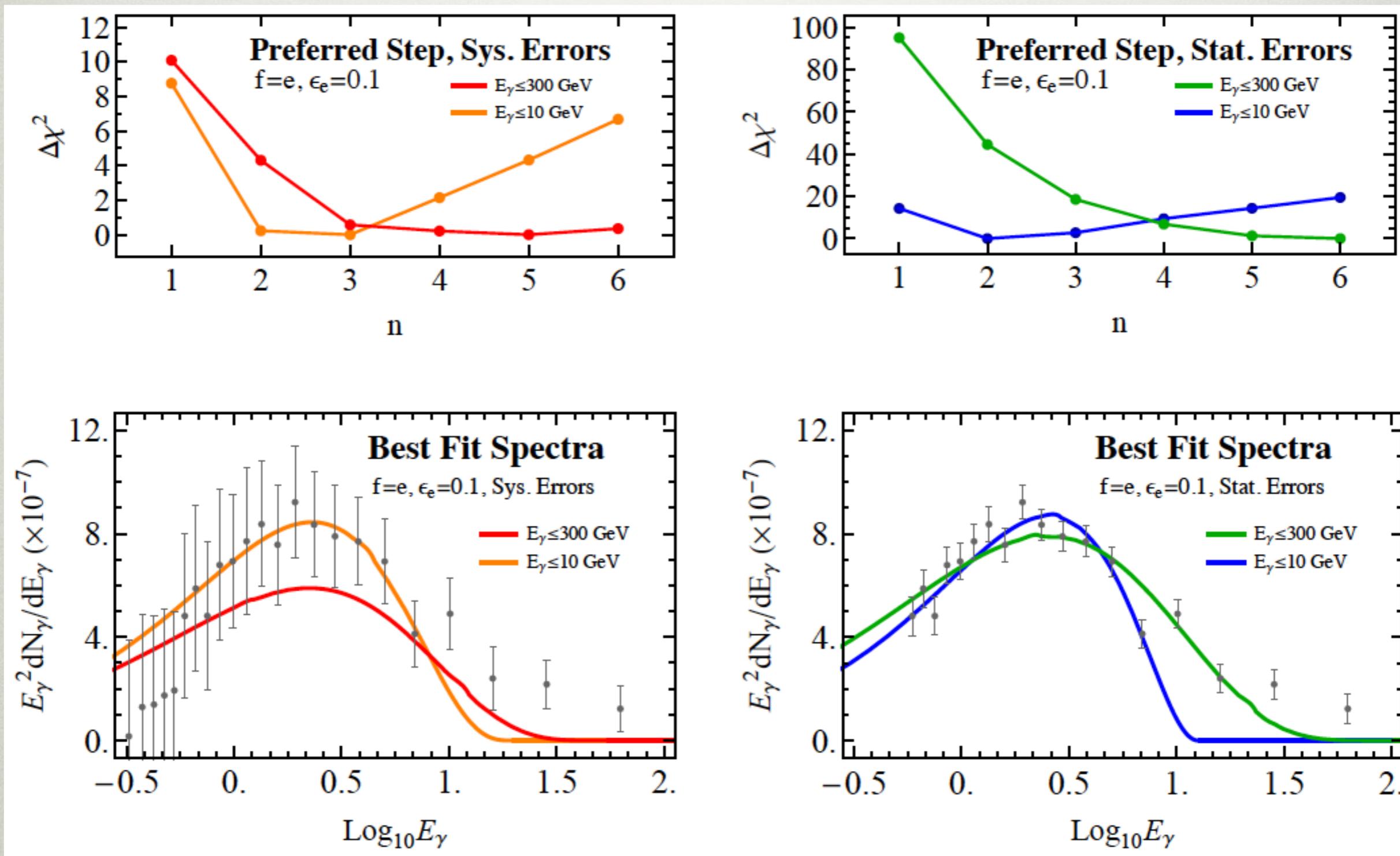
Fitting to the GCE - m_χ-$\langle\sigma v\rangle$ Relation
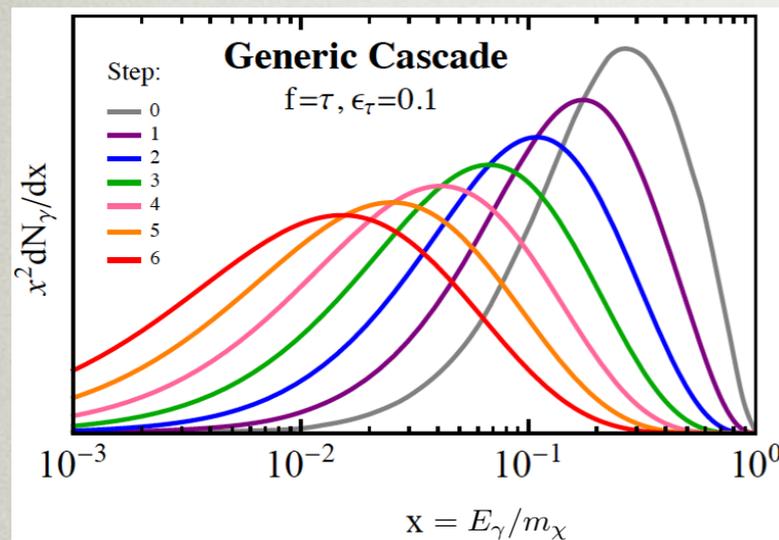
$$\times \frac{\langle\sigma v\rangle J_{\text{norm}}}{8\pi m_\chi}$$
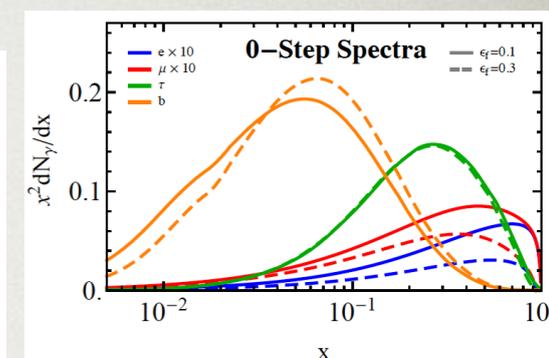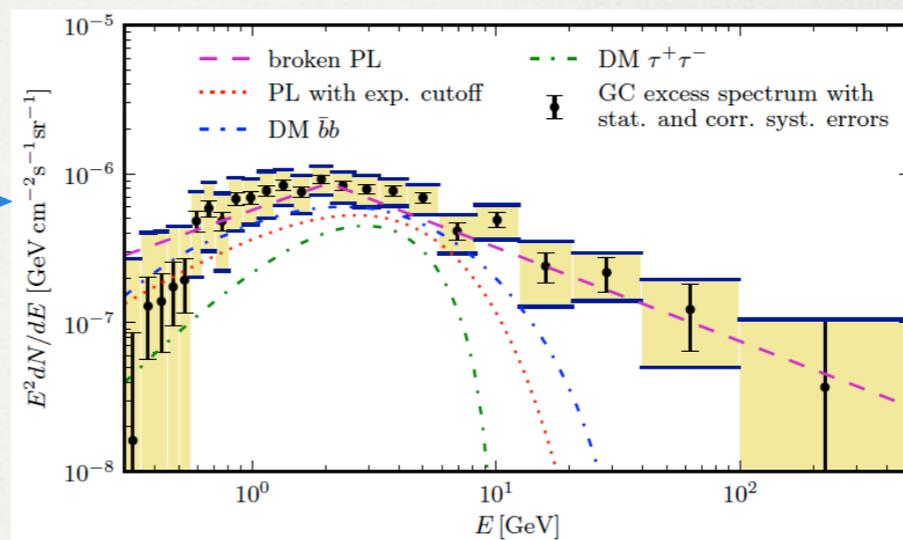
Scale by m_χ

- What happens to the preferred m_χ-$\langle\sigma v\rangle$ as we add steps in the cascade?

- **Mass:** each step is peaked at a lower x, so is better fit by a larger m_χ

- **Cross-Section:** 1. increased m_χ means to keep the conversion constant, $\langle\sigma v\rangle$ must scale as m_χ; 2. an additional scaling of $\sim m_\chi^{0.3}$ is required to adjust for the decreased height of the peak

- So we expect: $\langle\sigma v\rangle \propto m_\chi^{1.3}$

Integral of J over ROI/Ω

$$\Phi(E_\gamma, l, b) = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE_\gamma}J(l,b) \implies \frac{E^2\Phi}{\Omega} = \frac{\langle\sigma v\rangle J_{\text{norm}}}{8\pi m_\chi}\left[x^2\frac{dN}{dx}\right]$$
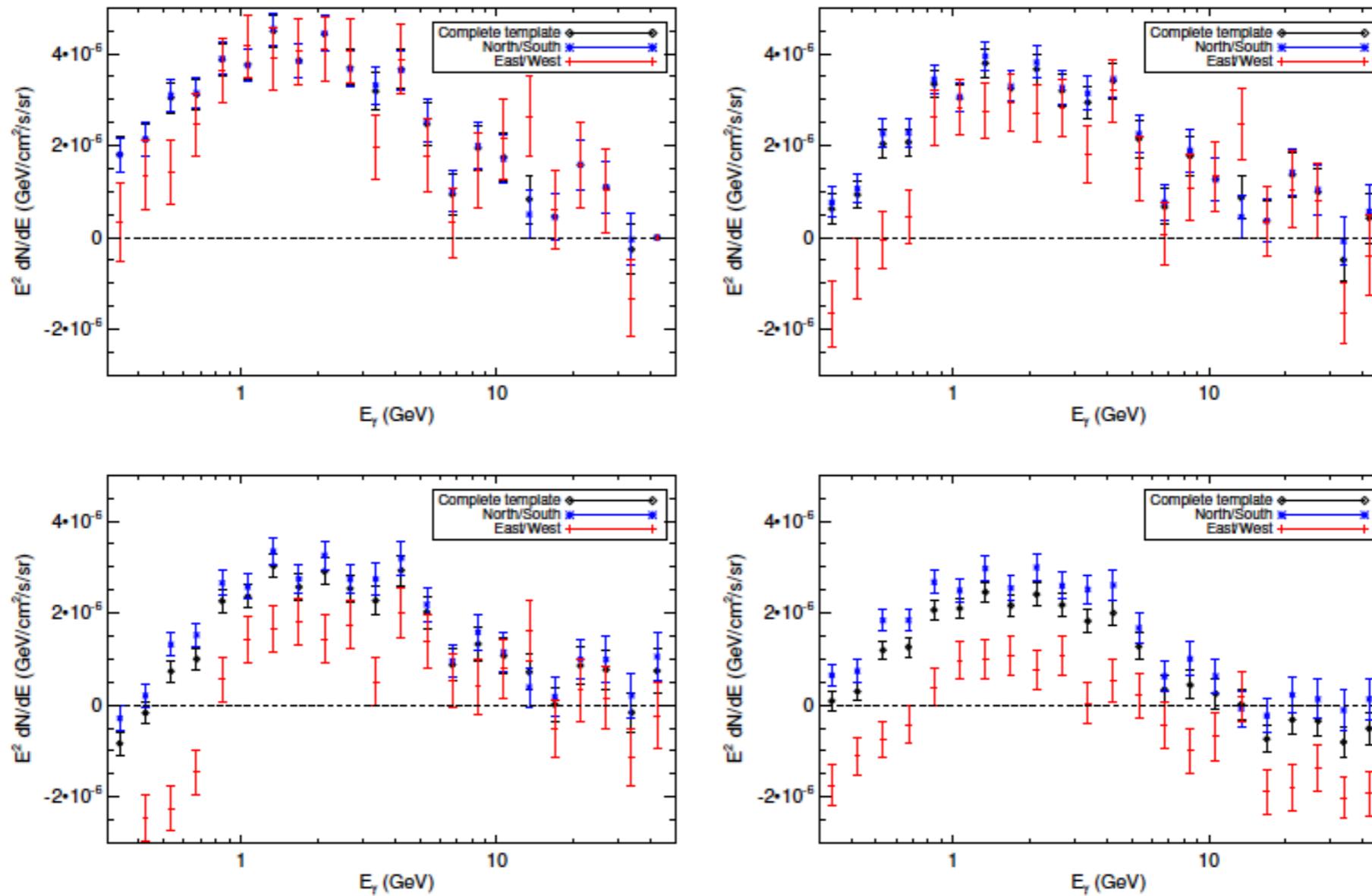
FIG. 23: As the upper panel of Fig. 22, but for ROIs given by (upper left frame) $|b|, |l| < 15°$, (upper right frame) $|b|, |l| < 20°$, (lower left frame) $|b|, |l| < 40°$, (lower right frame) full sky. In all cases the Galactic plane is masked for $|b| < 1°$. We attribute the lower emission in the East/West quadrants in the larger ROIs to oversubtraction by the Galactic diffuse model along the Galactic plane. The slope parameter for the dark matter template is set to $\gamma = 1.2$ in all cases.

Taken from 1402.6703