Lines, Boxes, and Energy Duality: Unmasking Dynamical Dark Matter in Indirect-Detection Data

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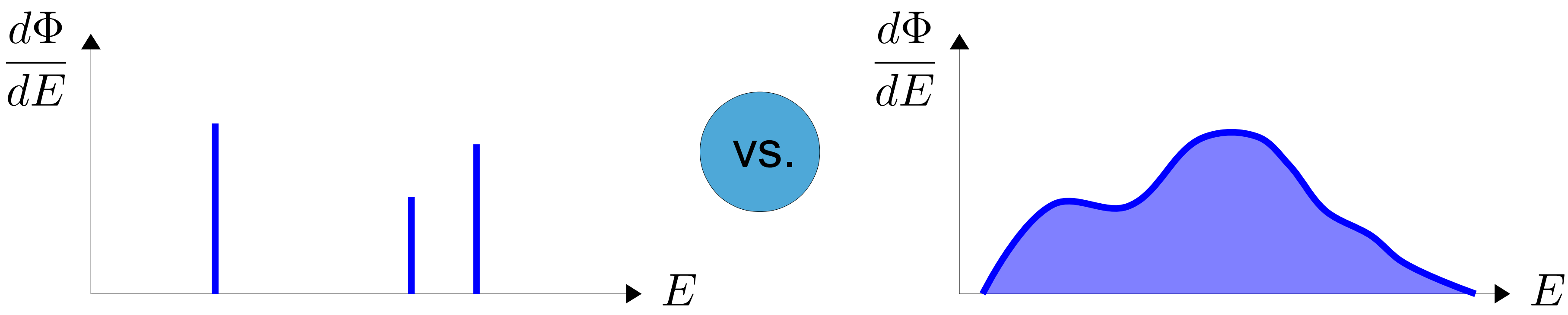
Based on work done in collaboration with:

- Kimberly Boddy, Keith Dienes, Doojin Kim, Jason Kumar, and Jong-Chul Park [arXiv:1609.07440, arXiv:1609.09104].

A General Observation:

- Extracting infromation about the dark matter from **continuum features** observed at indirect-detection experiments is notoriously challenging.



- Complicated **showering/cascade dynamics** obscures the relationship between the shape of the signal spectrum and the properties of the underlying dark sector.
- Moreover, it's not easy to tell conclusively that such a signal spectrum has a dark-matter origin and isn't due to more **mundane astrophysics** (e.g., pulsars).

It's important to identify techniques which can serve to distinguish between dark-matter models on the basis of continuum features in indirect-detection spectra!

- One natural context in which continuum features with characteristic (and particularly simple) kinematics arise is the **Dynamical Dark Matter** (DDM) framework. [Dienes, BT, '11]

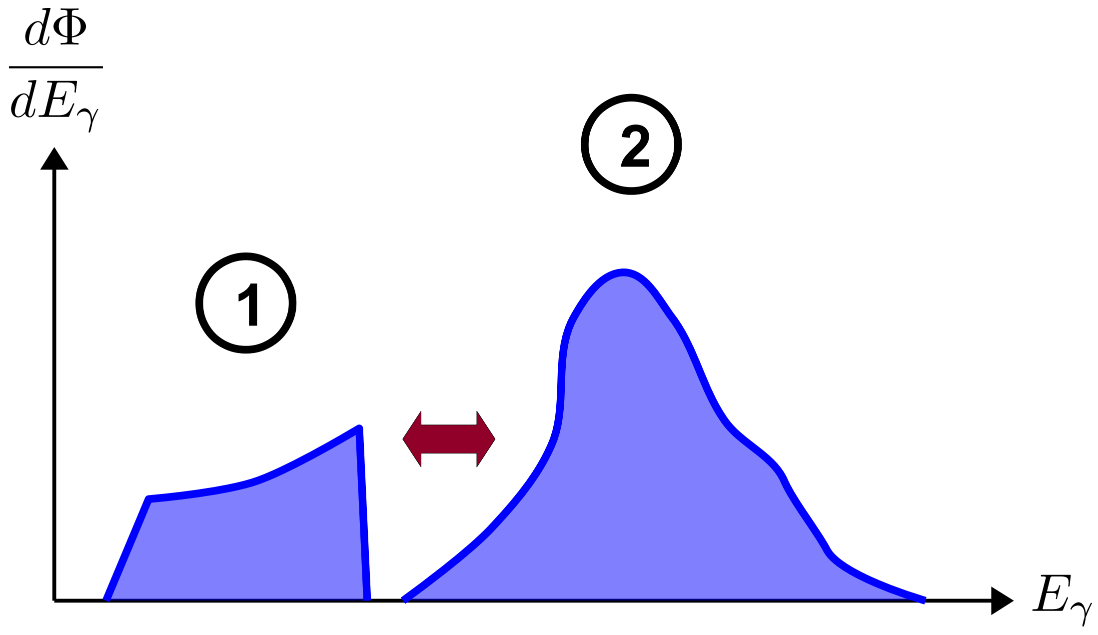
In DDM scenarios...

- The dark-matter candidate is an **ensemble** consisting of a potentially vast number of constituent particle species.
- The individual abundances of the constituents are **balanced against decay rates** across the ensemble such that constraints are satisfied.
- The DM abundance and equation of state also exhibit a **non-trivial time-dependence** beyond that associated with Hubble expansion.

- Continuum signals can arise from a decaying (or annihilating) DDM ensemble wherein the mass splittings between the constituents are smaller than the energy resolution of the detector.
- Since the continuum nautre of these spectral features results from a spearing of the total DM abundance features across the ensemble, the **annihilation/decay kinematics** can nevertheless be **straightforward**.

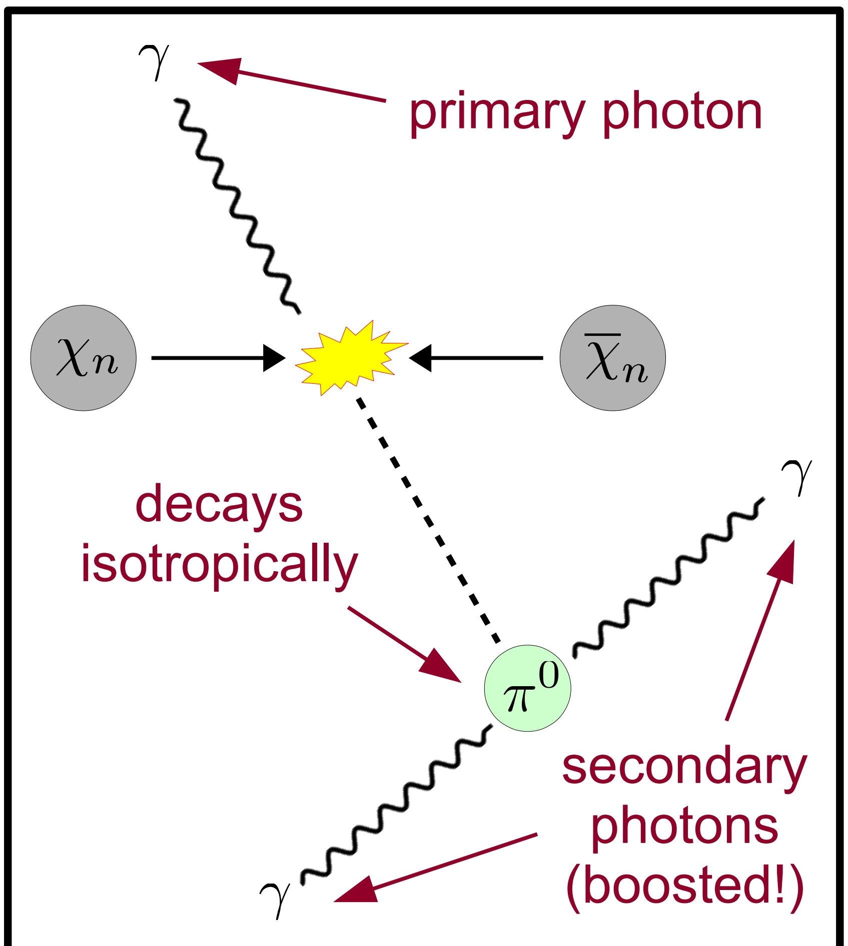
Technique I: Correlating Spectral Features

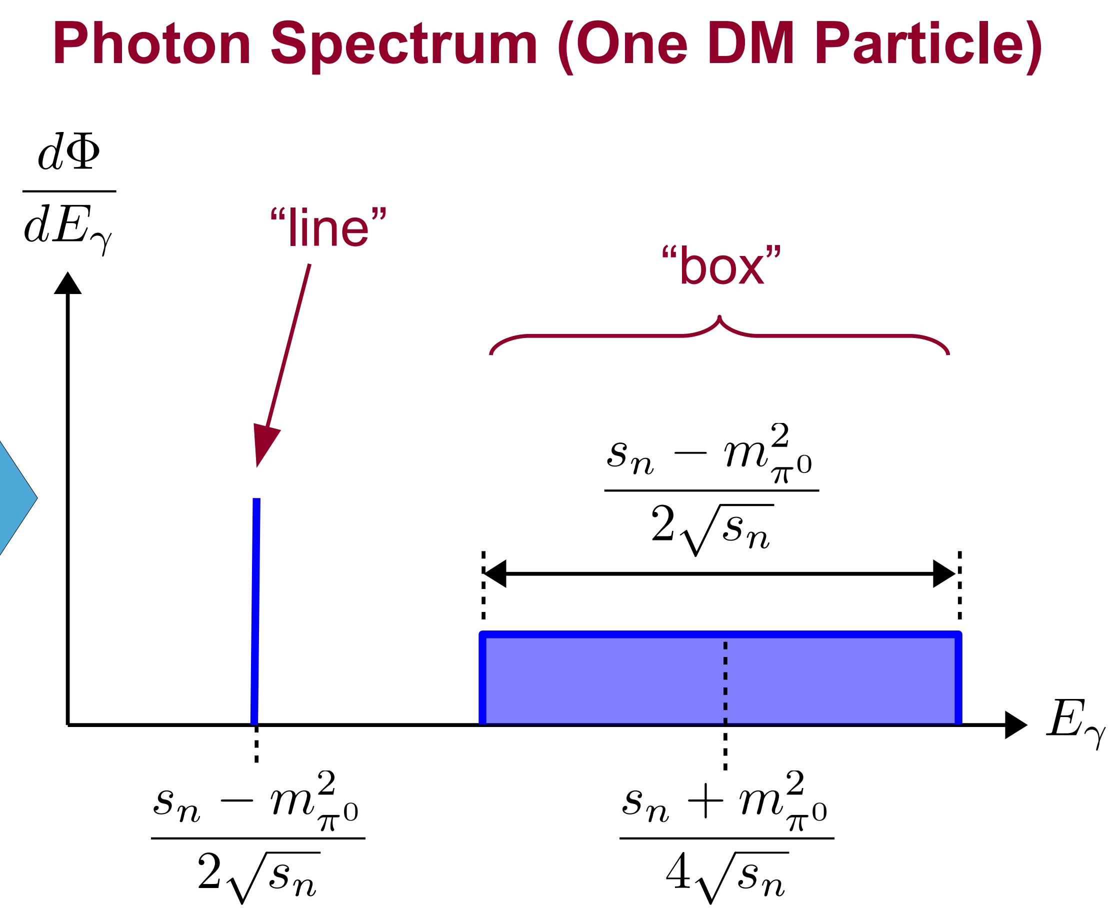
- One technique which can potentially uncover information about the origin of a continuum signal is to look for **correlations** between the shapes (and normalizations) of **different spectral features** within the same signal spectrum.
- Such correlations can arise when the features are produced via the same underlying annihilation/decay process.
- They can also be analyzed even if the spectral features in question overlap.



Decay Kinematics: Lines and Boxes

- Ensemble of DM particles χ_n with masses m_n, where $n = 0, 1, 2, ..., N$.
- Each annihilates via $\chi_n \overline{\chi}_n \to \pi^0 \gamma \to \gamma\gamma\gamma$
- Secondary photons produced by π^0 decay are **boosted**. Resulting photon spectrum includes both a line-like feature and a spectral "box."





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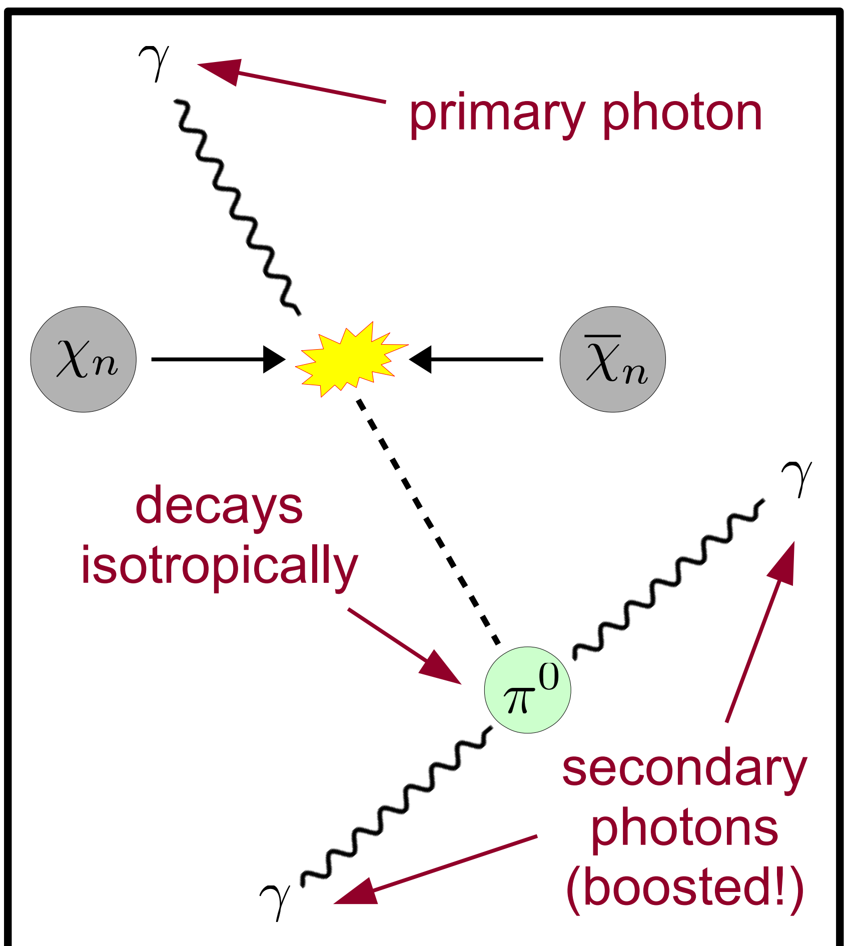
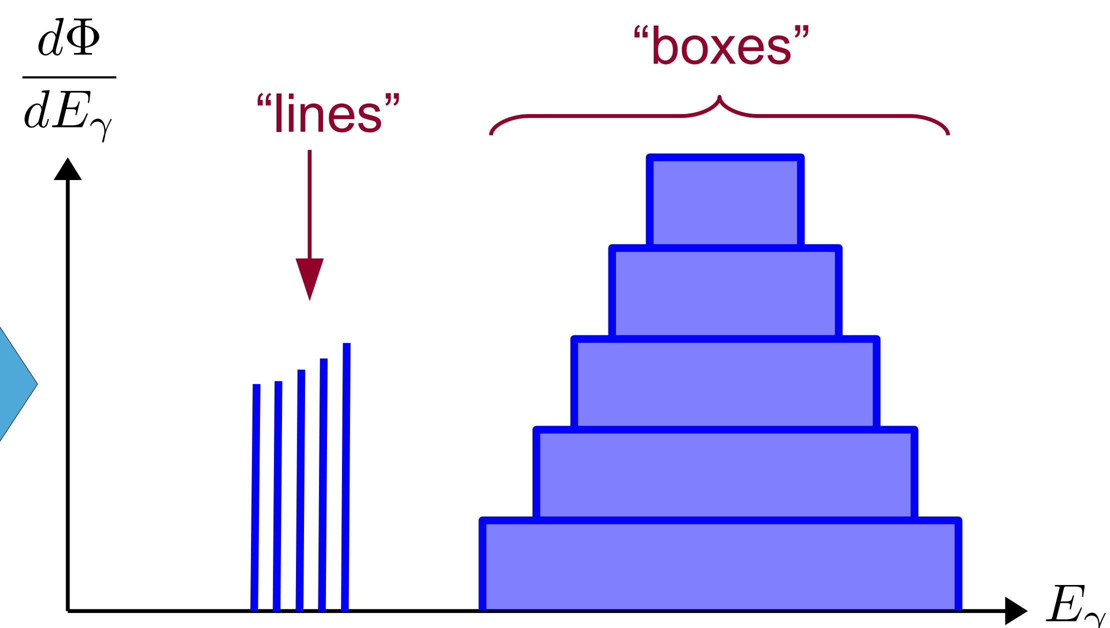


Photon Spectrum (Whole Ensemble)



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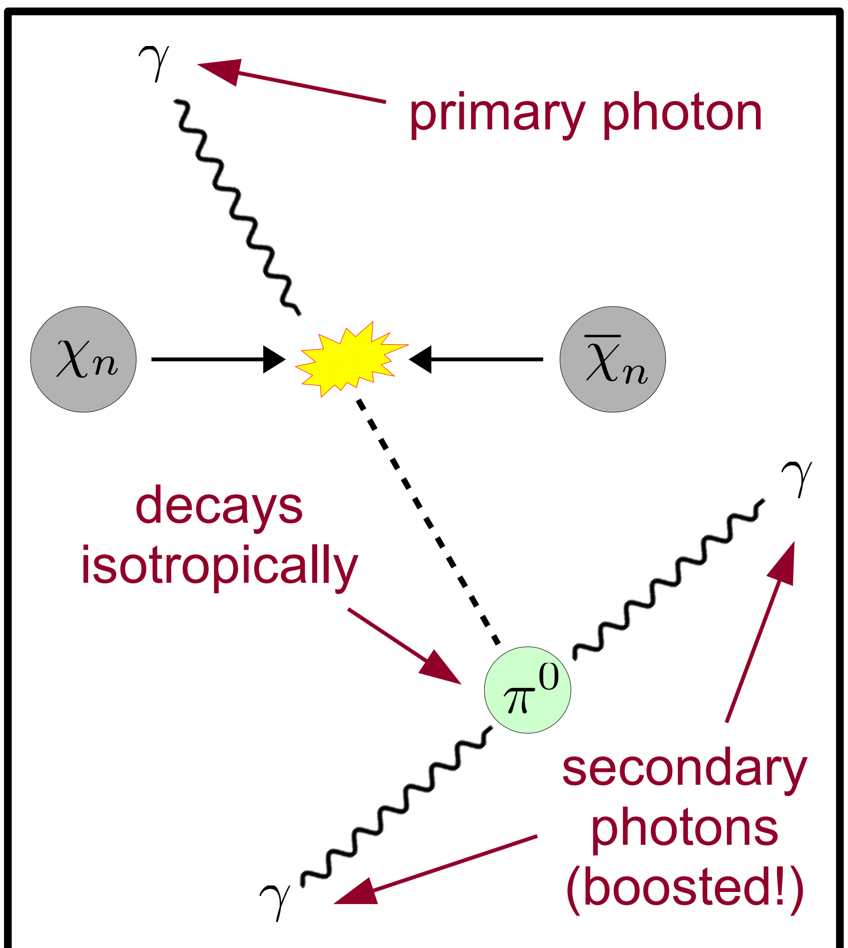

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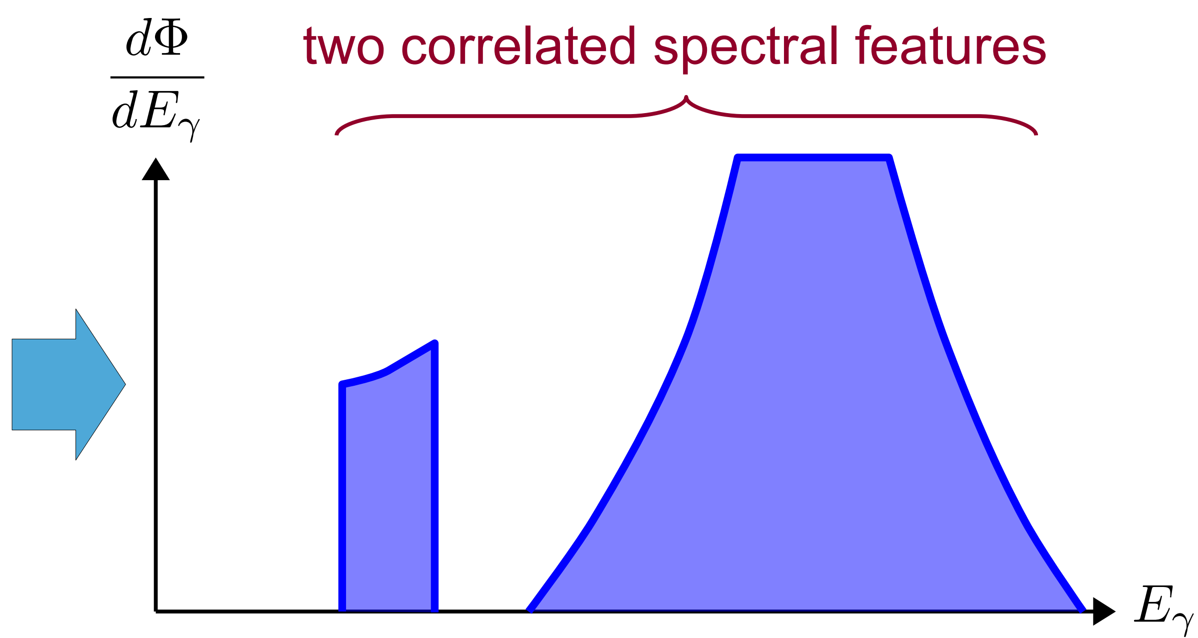
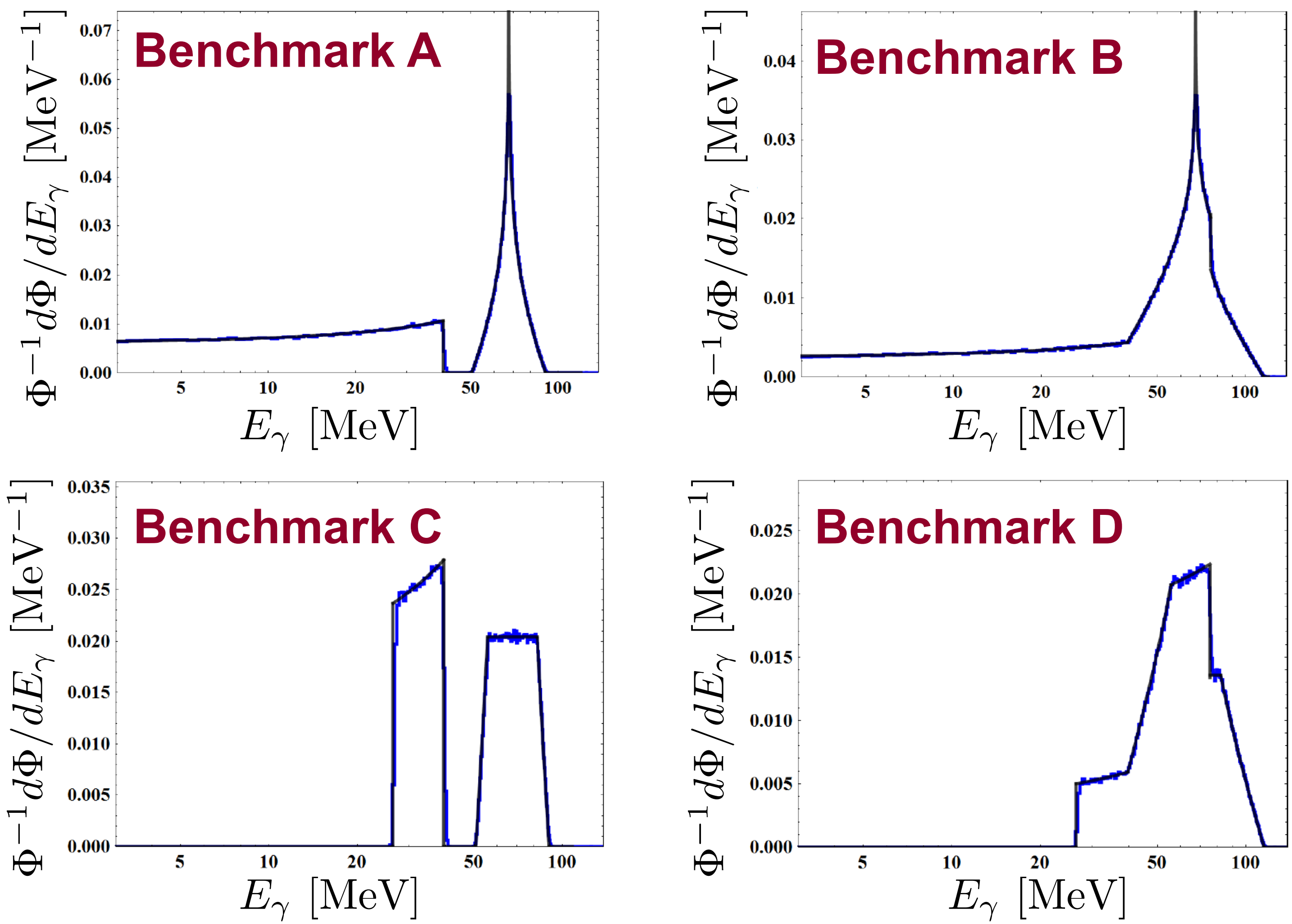


- We adopt four **benchmark scenarios** which represent four qualitatively different cases of interest:

Benchmark	$\sqrt{s_0}$ (MeV)	$\sqrt{s_N}$ (MeV)	N	Behavior at $E_\gamma = m_{\pi^0}/2$	Spectral overlap
A	135	181	23	spike	negligible
B	135	231	48	spike	significant
C	164	180	8	plateau	negligible
D	164	230	33	plateau	significant



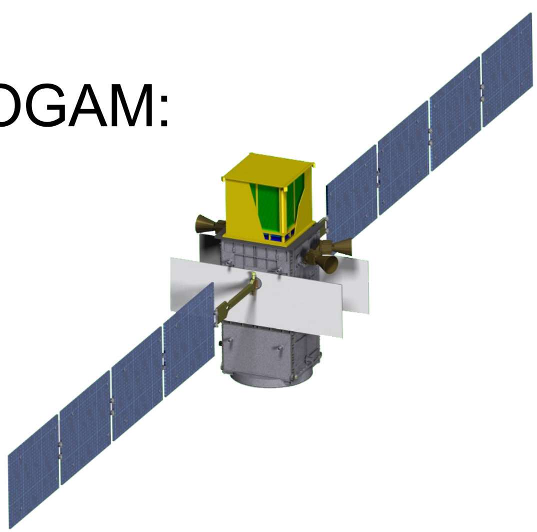
Looking for a Signal

- Dwarf galaxies:
  - Dark-matter dominated [Mateo, '98; McConnachie, '12].
  - More reliable estimates of astrophysical backgrounds/foregrounds
- For concreteness, we choose...

Draco Dwarf

$$\begin{cases} \log_{10}(J/\mathrm{GeV}^2\mathrm{cm}^{-5}) = 19.05^{+0.22}_{-0.21} \ \text{(annihilation)} \\ \log_{10}(J/\mathrm{GeV}^2\mathrm{cm}^{-2}) = 18.97^{+0.17}_{-0.24} \ \text{(decay)} \end{cases}$$

- Hypothetical space-based detector similar to ASTROGAM:
  - Energy range: $0.3\ \mathrm{MeV} \lesssim E_\gamma \lesssim 3000\ \mathrm{MeV}$
  - Energy resolution: 1% over full range of E_γ
  - Effective area: $500\ \mathrm{cm}^2$
  - One year of continuous running



Parametrizing the Ensemble

- For concreteness, we consider an annihilating DDM scenario in which the individual masses m_n and flux contributions Φ_n associated with the ensemble constituents scale as follows:

$$\boxed{\mathrm{m}_n = m_0 + n\Delta m}$$

$$\boxed{\Phi_n = \Phi_0 \left(\frac{\sqrt{s_n}}{\sqrt{s_0}} \right)^{\xi}}$$

Where: $$\sqrt{s_n} \approx \begin{cases} 2m_n & \text{(annihilation)} \\ m_n & \text{(decay)} \end{cases}$$

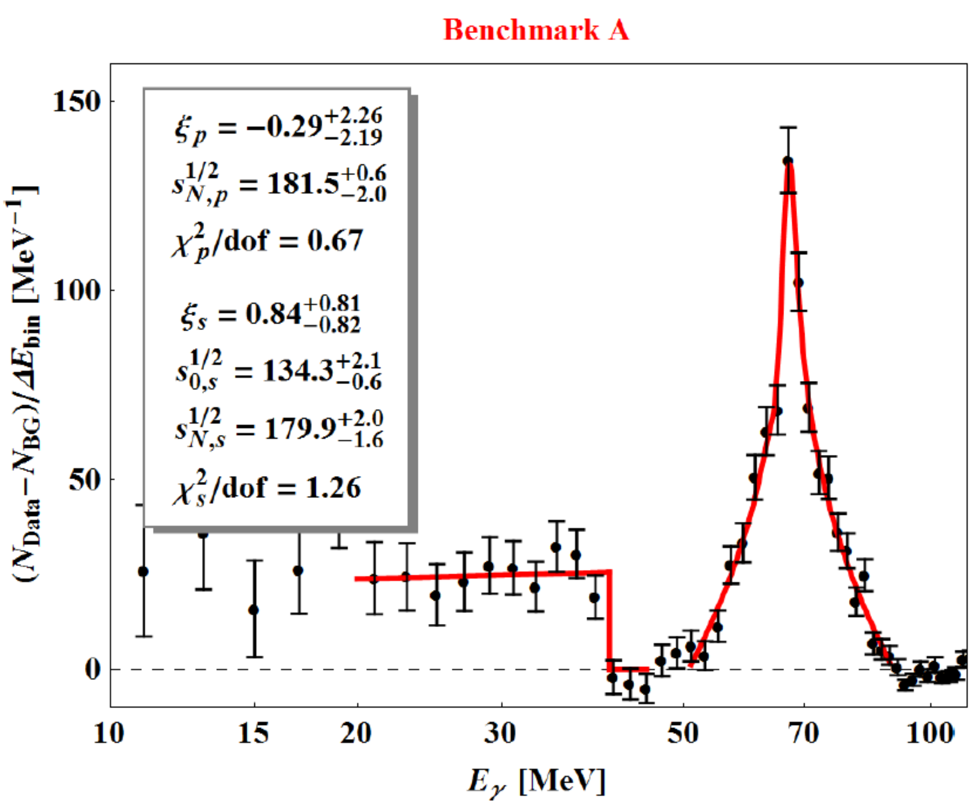
- Background N_B: diffuse background model based on COMPTEL, EGRET data.
- Signal N_S: minimum number of events necessary for initial 5σ discovery based on simple counting analysis.

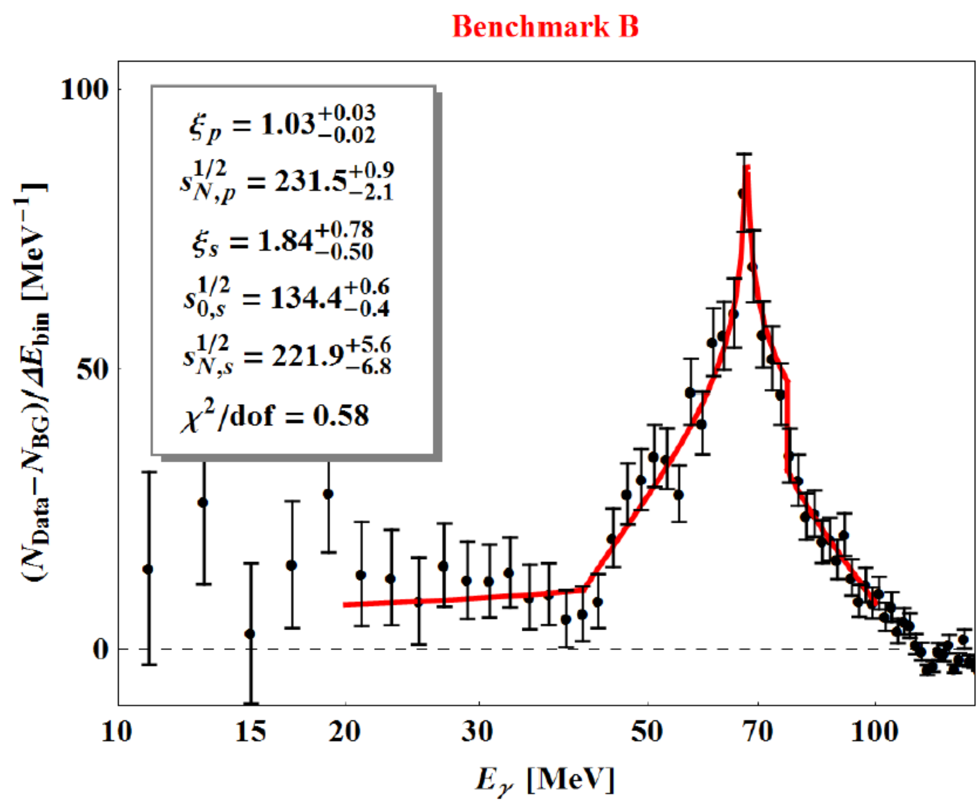
- Primary and secondary spectra fit separately when they don't overlap, each with its own normalization factor Ψ:

Fit parameters: $\{\sqrt{s_{0p}}, \sqrt{s_{Np}}, \xi_p, \Psi_p\}$ and $\{\sqrt{s_{0s}}, \sqrt{s_{Ns}}, \xi_s, \Psi_s\}$

- Both spectra fit together with a common normalization factor when there is significant overlap:

Fit parameters: $\{\sqrt{s_{0p}}, \sqrt{s_{Np}}, \xi_p, \sqrt{s_{0s}}, \sqrt{s_{Ns}}, \xi_s, \Psi\}$





Technique II: Exploiting Energy Duality

- An interesting duality arises in the gamma-ray signal spectra associated with certain dark-matter annihilation/decay topologies. In particular, whenever...
  - The DM particles annihilate/decay down to **on-shell intermediaries**
  - Each intermediary decays **isotropically** to photons within its own, proper frame
  - These photons are line-like (i.e., produced only with certain specific energies) in the frame of the decaying intermediary.

…the resulting photon spectrum is **invariant** under:

$$\boxed{E_\gamma \to \frac{E_*^2}{E_\gamma}}$$

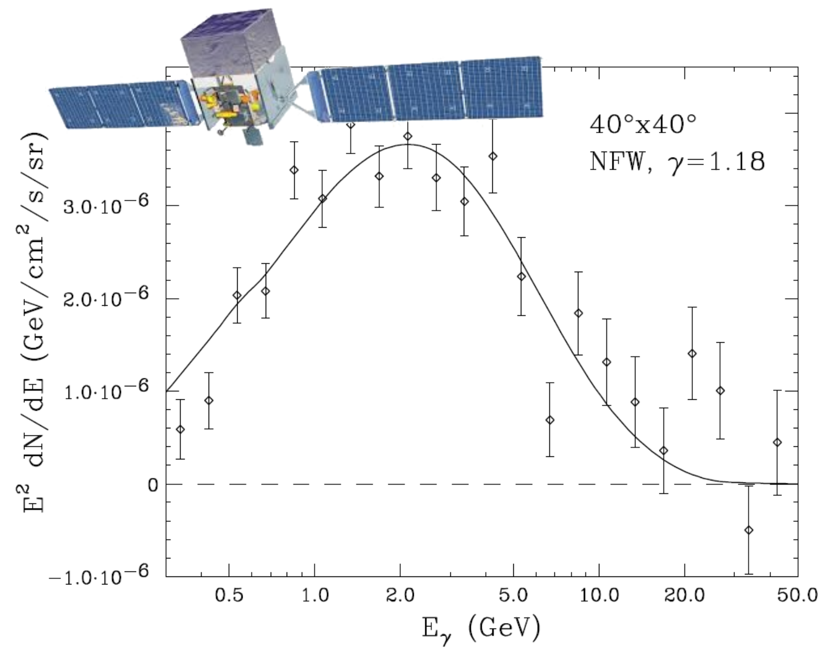
"**Energy duality**"

- Such a duality has been discussed before in other contexts
  - Cosmic-ray pion decay [Stecker, '71]
  - Particle production at colliders [Agashe, Franceschini, Kim, '12]
- It can also be exploited to distinguish certain dark matter models on the basis of indirect-detection data.

Application: Galactic Center Gamma-Ray Excess

- Observed excess of gamma rays coming from the Galactic Center.
  [Hooper, Goodenough, '09]

  - Roughly spherical emission region
  - **Continuum feature** spanning the energy range $0.3\ \mathrm{GeV} \lesssim E_\gamma \lesssim 50\ \mathrm{GeV}$
  - Peaked around $E_\gamma \sim 1\ \mathrm{GeV}$

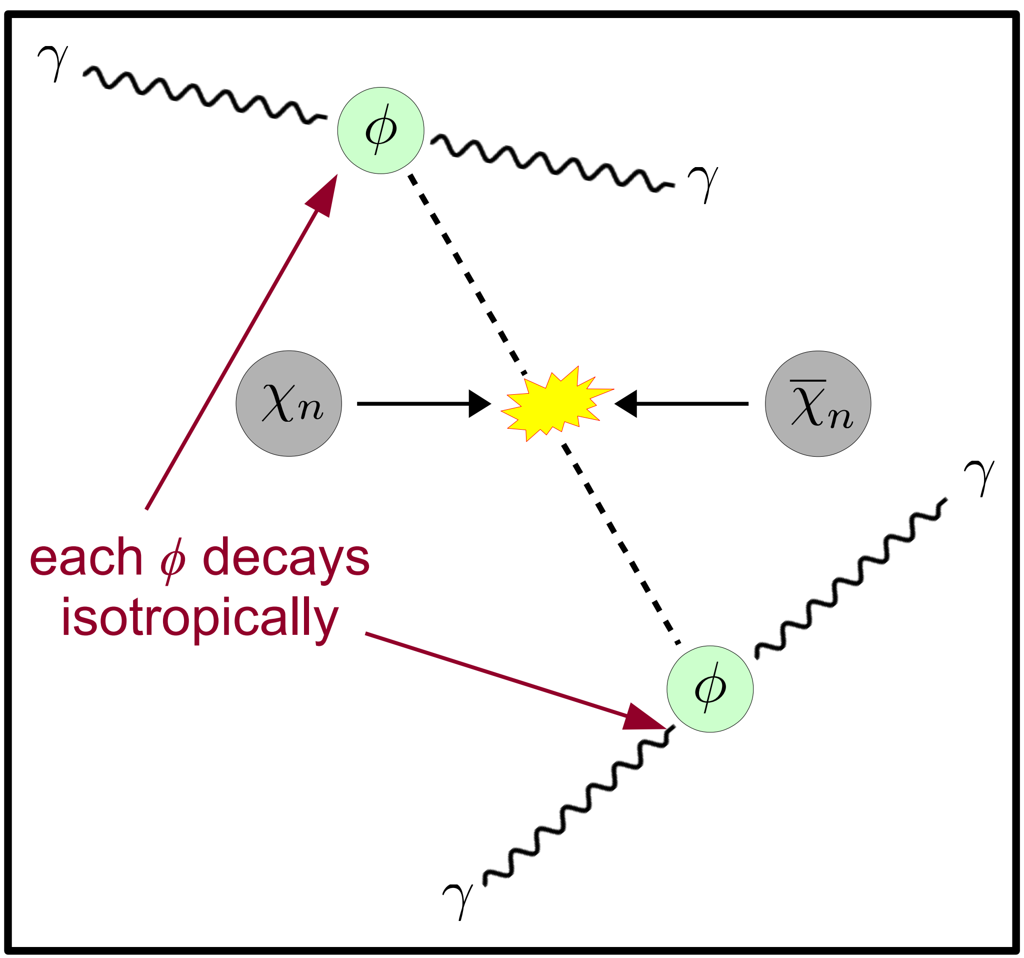


[Daylan et al., '14]

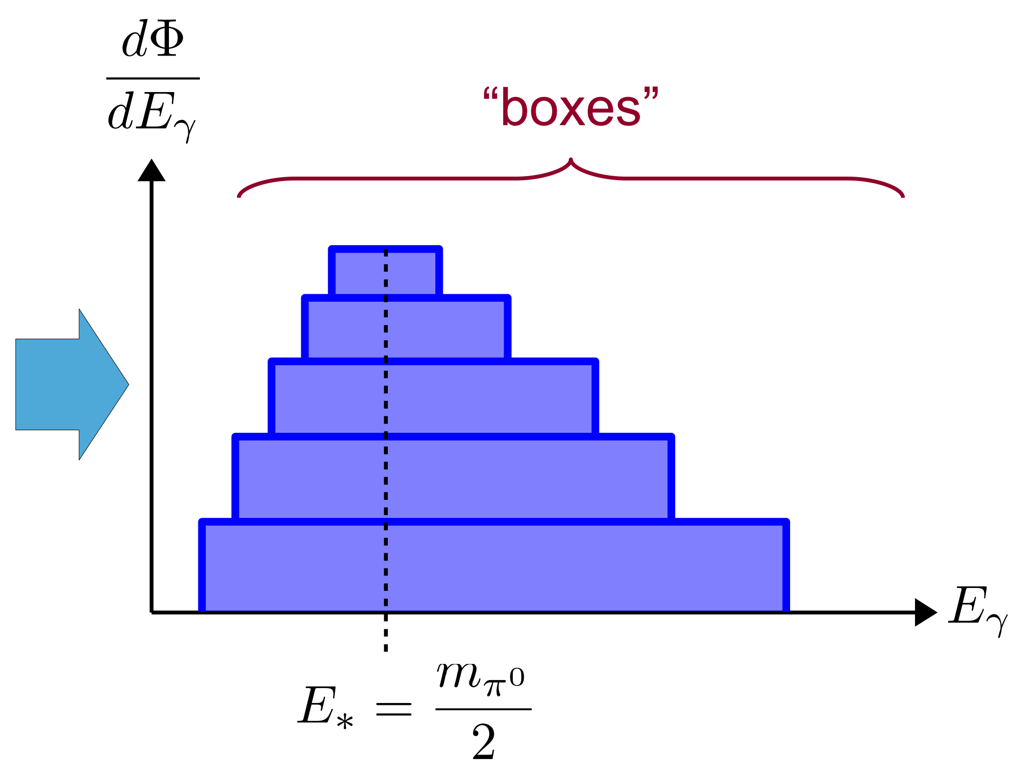
- Potential signal of annihilating/decaying **dark matter**...
  - ...or milisecond pulsars
    [Bartels, Krishnamurthy, Weniger, '15; Lee, Lisanti, Safdi, Slatyer, Xue, '15]
  - … or π^0 produced by collisions of cosmic-ray particles with interstellar gas
    [Hooper, Goodenough, '10; Abazajian, Kaplinghat, '12; Gordon, Macias, '13]
  - ...or leptonic cosmic-ray bursts
    [Petrovic, Serpico, Zaharijas, '14; Cholis, Evoli, Calore, Linden, Weniger, Hooper, '15]

Decay Kinematics: Stacking Boxes

- Ensemble of DM particles χ_n with masses m_n, where $n = 0, 1, 2, ..., N$.
- Each annihilates via $\chi_n \overline{\chi}_n \to \phi\phi \to 4\gamma$, where ϕ is a light scalar.
- The resulting photon spectrum is energy-dual around $\boxed{E_* = m_\phi/2}$



Photon Spectrum (Whole Ensemble)



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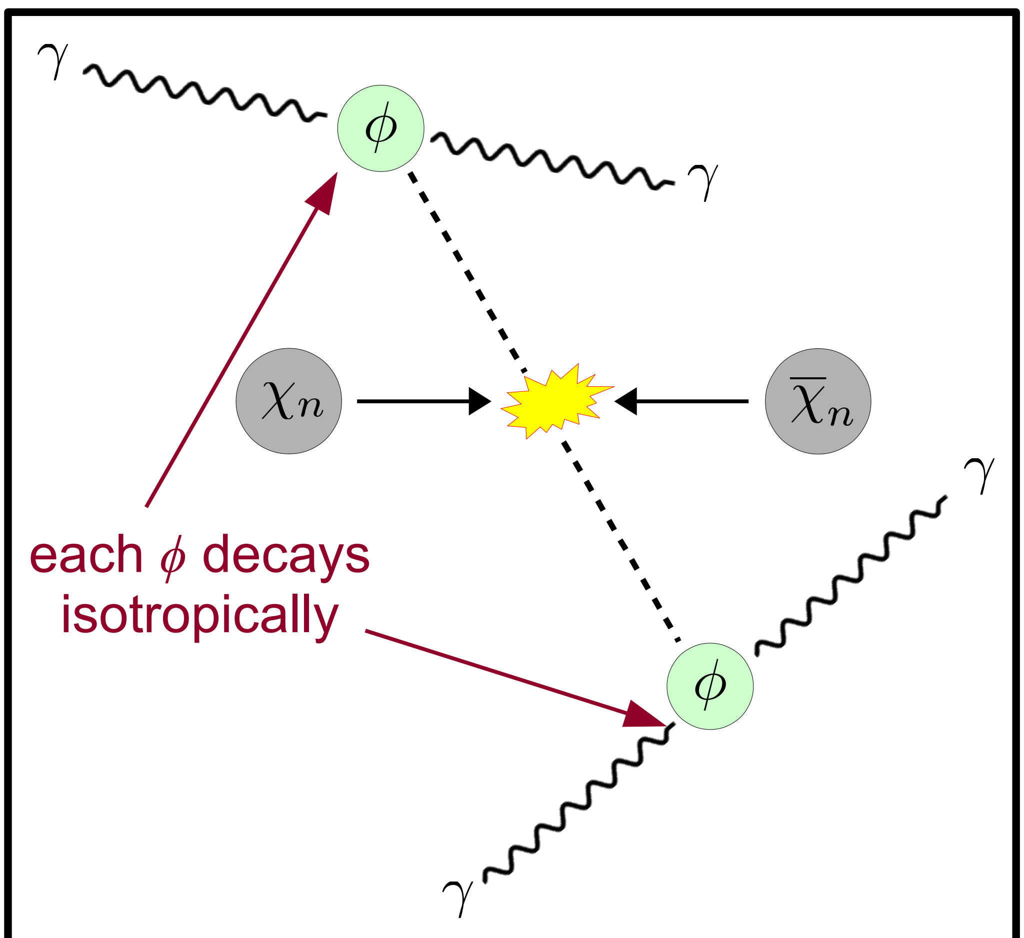
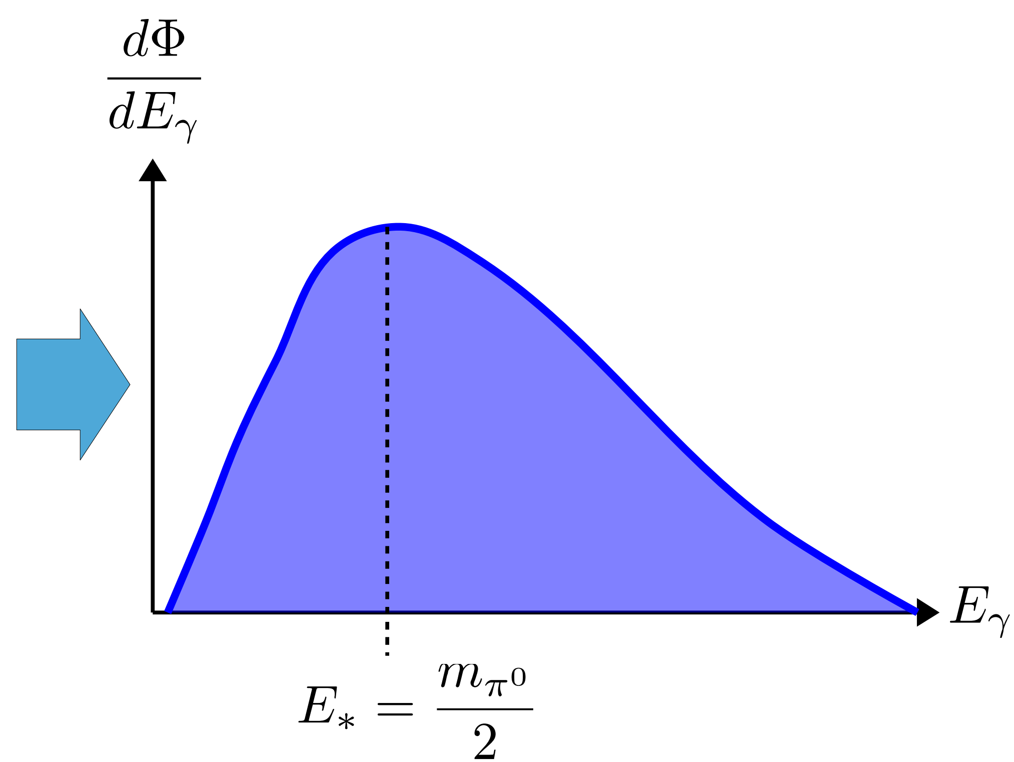


Photon Spectrum (What We See)



Signal Spectrum

- For concreteness, we consider an annihilating DDM scenario in which the individual masses m_n and flux contributions Φ_n associated with the ensemble constituents scale as follows:

$$\boxed{\mathrm{m}_n = m_0 + n\Delta m}$$

$$\boxed{\Phi_n = \Phi_0 \left(\frac{m_n}{m_0}\right)^{\xi}}$$

Closed-form solution for the signal spectrum!

- … and here is is:

Euler beta functions

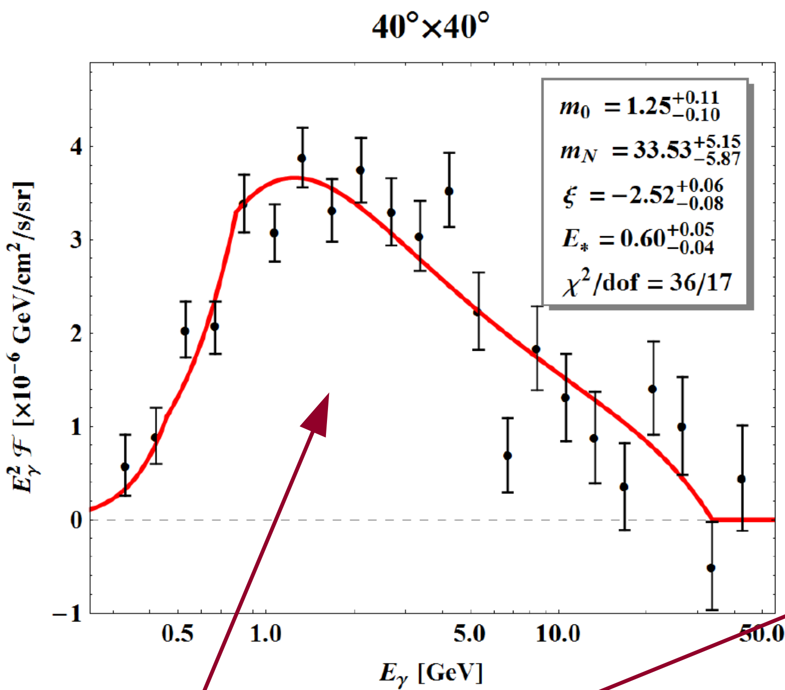
$$\boxed{E_\gamma^2 \frac{d^2\Phi}{dE_\gamma d\Omega} = \frac{E_\gamma^2}{\Delta\Omega} \Xi \left(\frac{4E_*}{\sqrt{s_0}}\right)^{\xi} \left[B_{z_+}\left(-\frac{\xi}{2}, \frac{1}{2}\right) - B_{z_-}\left(-\frac{\xi}{2}, \frac{1}{2}\right)\right]}$$

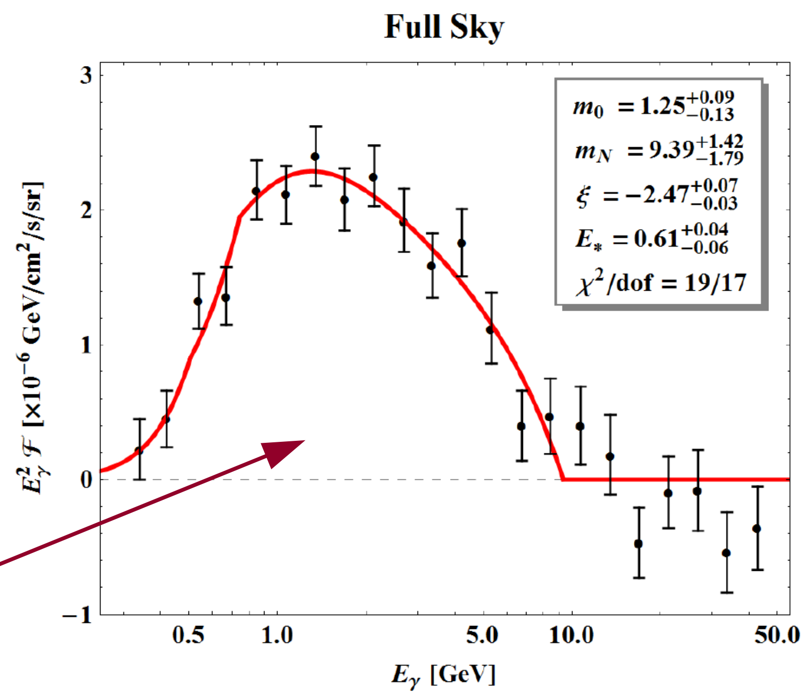
With:
$$\begin{cases} z_+ = \max\left(\dfrac{8E_*^2}{m_N}, \min\left[\dfrac{8E_*^2}{m_0}, \dfrac{4}{(E_*/E_\gamma + E_\gamma/E_*)^2}\right]\right) \quad , \quad z_- = \dfrac{8E_*^2}{m_N} \\ \Xi \equiv \dfrac{\Phi_0}{2\Delta m} \end{cases}$$

Fitting the Observed Excess

- We fit this spectrum to the residual signal spectrum of the observed GC gamma-ray excess two different ROI (40° × 40° and full sky).

Fit parameters: $\{m_0, m_N, \xi, E_*, \Xi\}$





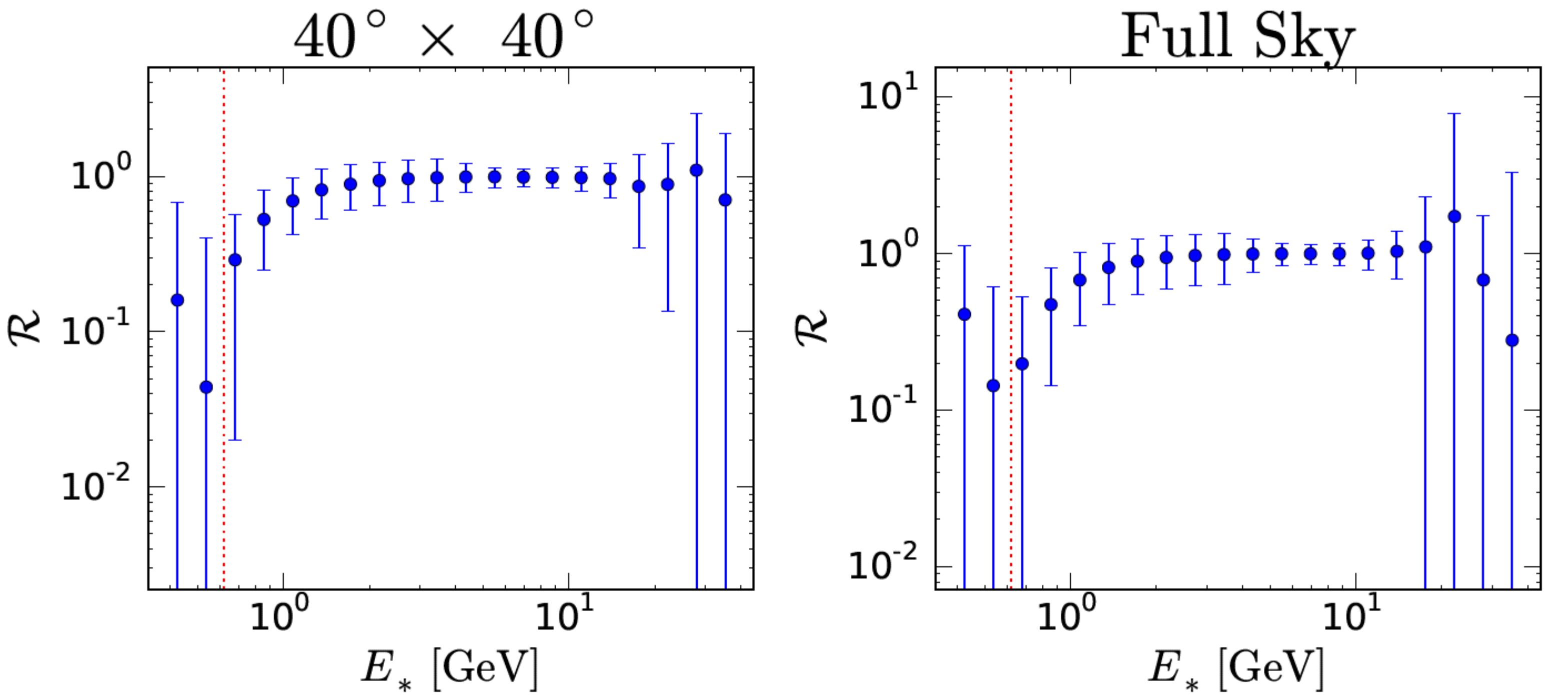
Good agreement with data and with each other (save for m_N)

GC signal excess [Daylan et al., '14]

Best fit

But Is the GC Gamma-Ray Excess ***Really*** Energy-Dual?

- Very possibly... but at this point, it's a bit hard to tell.



$$\boxed{\mathcal{R}(n_*) \equiv \frac{\sum_{n=1}^{n_{\max}} \left|\mathcal{F}_{n_*+n} - \mathcal{F}_{n_*-n}\right|}{\sum_{n=1}^{n_{\max}} \left|\mathcal{F}_{n_*+n} + \mathcal{F}_{n_*-n}\right|}}$$

antisymmetric part of the flux

symmetric part of the flux

- Future gamma-ray telescopes such as GAMMA-400 or ASTROGAM should provide better **energy resolution**, better **statistics** for energies in the range $10 \text{ MeV} \lesssim E_\gamma \lesssim 1 \text{ GeV}$, or both.

Summary

- Extracting detailed information about the dark matter from indirect detection data is challenging – especially when the signal is a **continuum feature** rather than a narrow line.
- Nevertheless, techniques for extracting information from continuum features do exist. In this talk, we have highlighted two of them.
- **Correlations** between the shapes (and normalizations) of different spectral features produced via the same underlying physical process can
- Particular classes of dark-matter annihilation/decay processes give rise to spectral features invariant under $E_\gamma \rightarrow E_*^2/E_\gamma$. Such an **energy duality** can be used to distinguish between different dark-sector models.
- Indeed, an energy duality of this sort may even be lurking in the signal spectrum for the observed **Galactic-Center excess**!