Energy Peak: Back to the Galactic Center GeV Gamma-ray Excess

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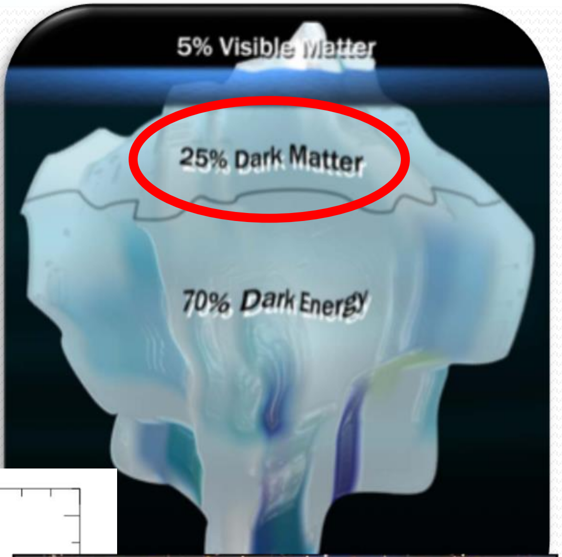
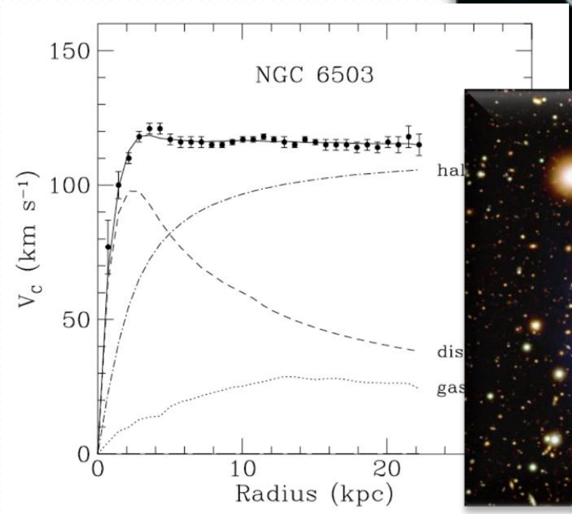
DK, Jong-Chul Park, arXiv:1507.07922

Introduction

Existence of dark matter

- Dark Matter (DM): ~25% of our universe
- Evidence (e.g., rotation curve)
- Known properties
  - Gravitationally interacting, not hot, not short-lived, not baryonic, neutral
- **Compelling paradigm, but no DM particle in the SM**

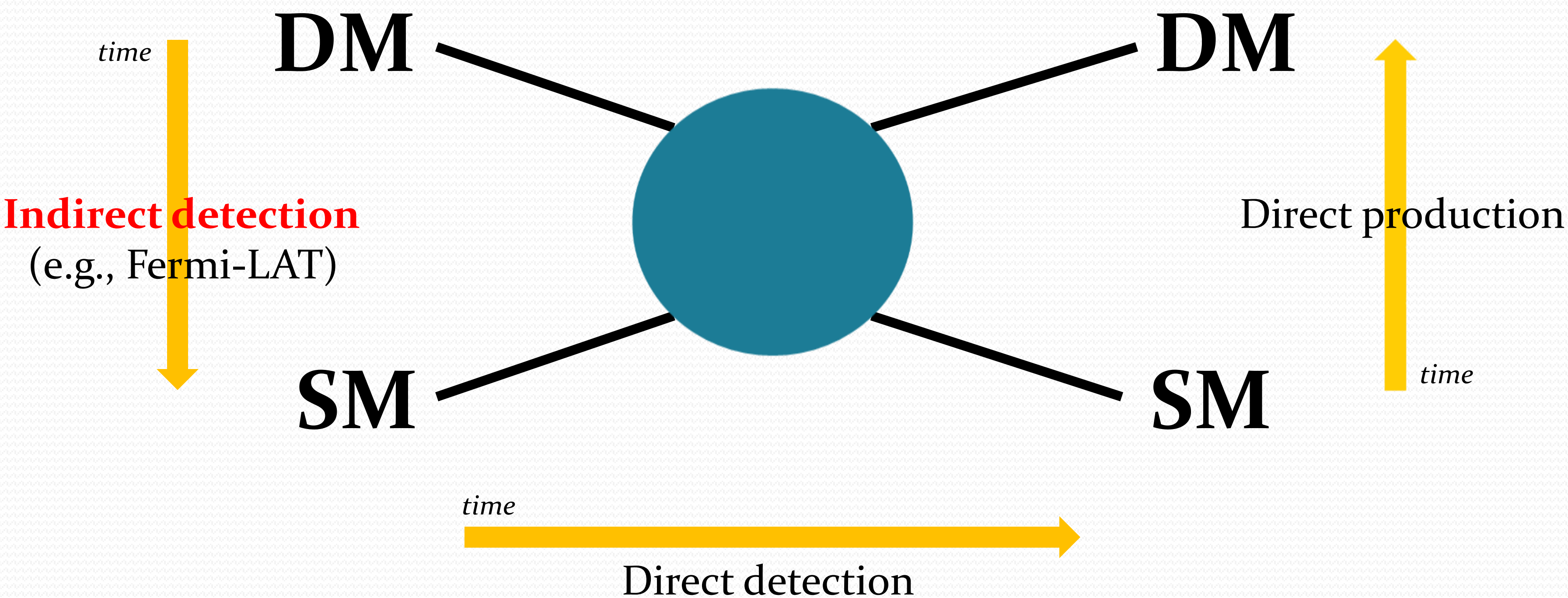




Introduction

Dark matter detection

- Assuming that dark matter is interacting with the known particles (Standard Model)…

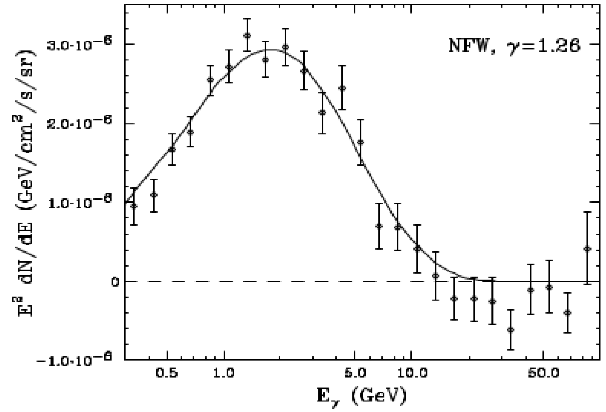


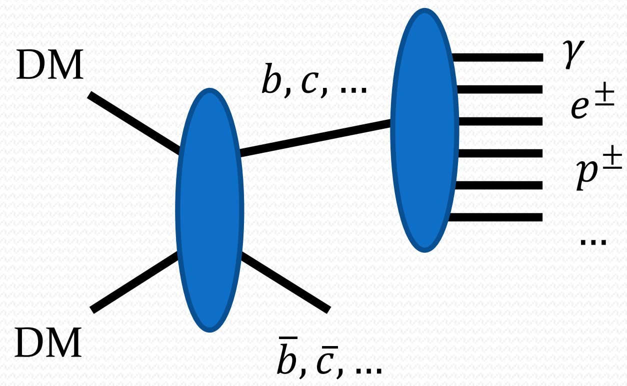
Introduction

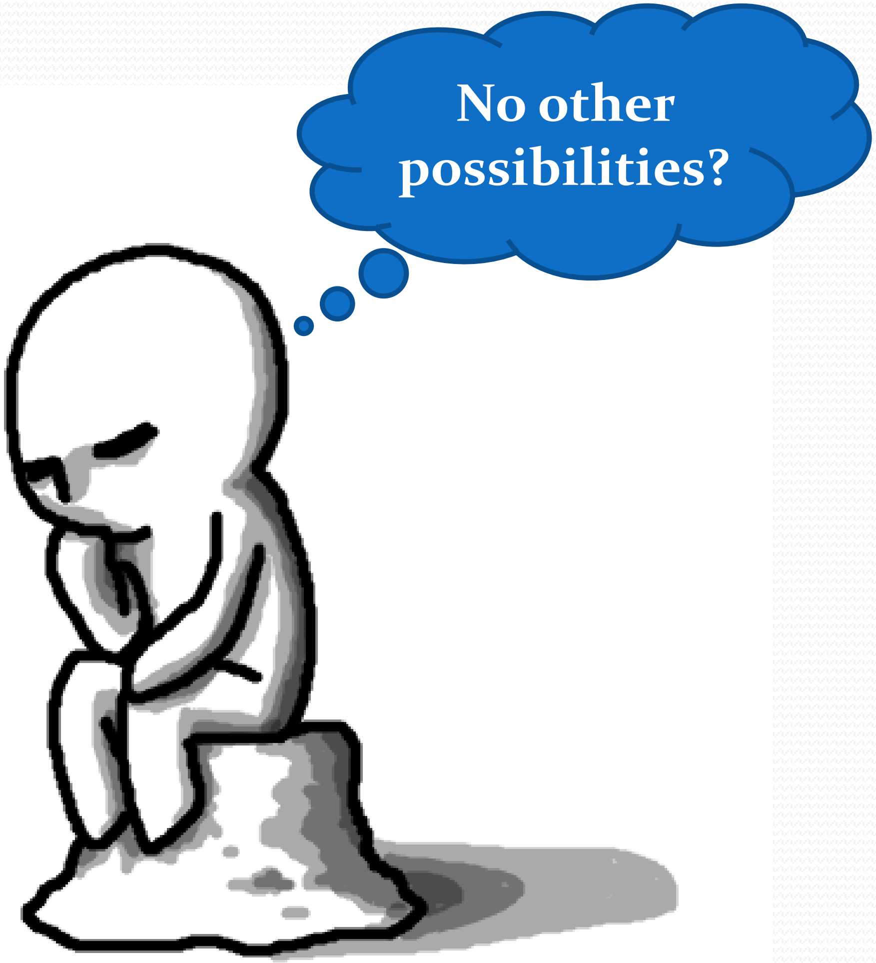
GC gamma-ray excess

- ❑ Continuum bump signature
- ❑ Typical DM interpretation
  - ❖ DM pair annihilation into 2 (unstable) SM which further goes through secondary processes to stable SM particles

    [Goodenough and Hooper (2009)]
  - ❖ Shape information (including the peak position) is highly model-dependent






No other possibilities?

Energy Peak

Why energy peak?

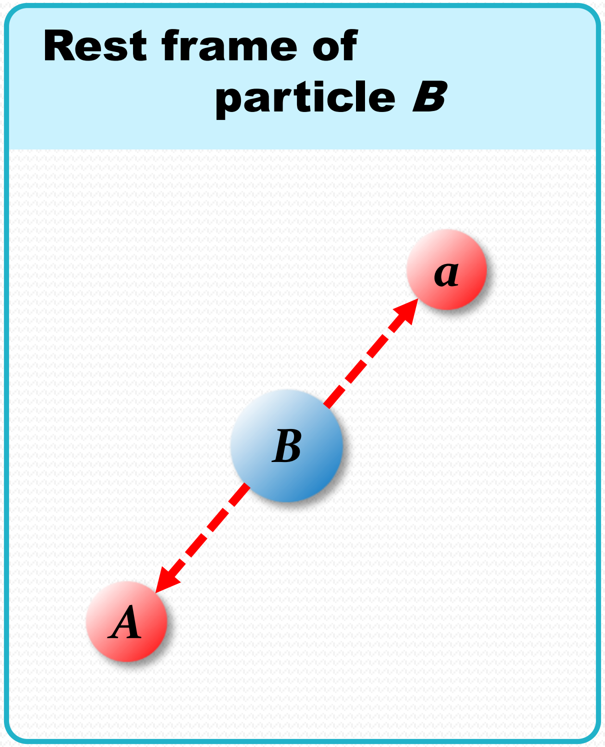
- With DM interpretation in mind, I propose alternative mechanisms based on the observation of the "**energy-peak**" in **collider physics** to explain GC GeV gamma-ray excess (cf. other explanations by astrophysical activities such as millisecond pulsars, unresolved point-like sources are available)

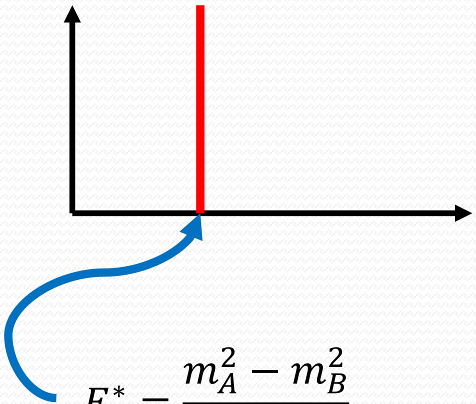
- Why energy peak?
  - Energy is the **only** available quantity (vs. large multiplicity, momentum w.r.t. the beam line in collider events)
  - **Unique morphological features** irrespective of underlying DM model details (vs. highly model-dependent in the standard interpretation)

Energy Peak

Existence of energy peak: a quick review

- A simple 2-body decay of a heavy resonance B into A and ***massless*** visible a





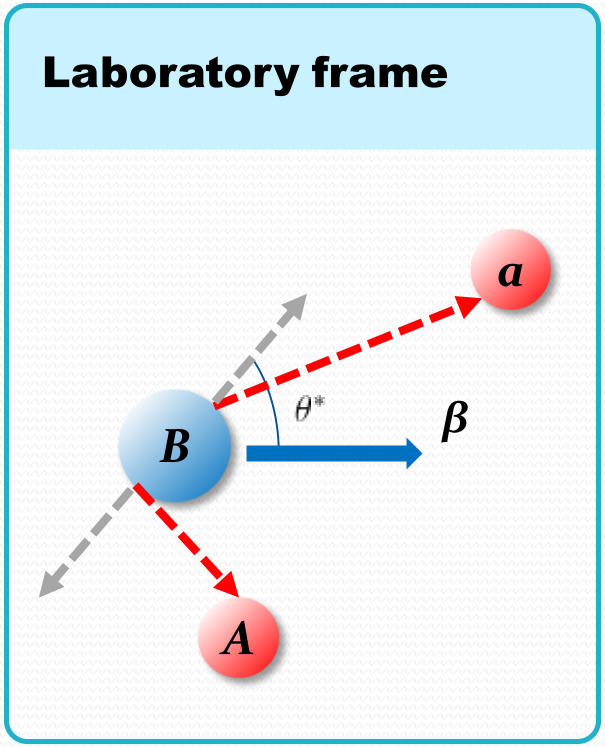
$$E^* = \frac{m_A^2 - m_B^2}{2m_A}$$

- Energy of visible particle a is **monochromatic** and **simple** function of masses in the rest frame of particle
- E^*, m_A known $\rightarrow$ measurement of m_B, vice versa
- Great to be on this **special** frame!

Energy Peak

Existence of energy peak: a quick review

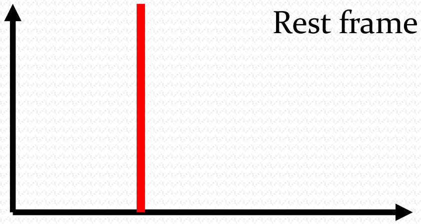
- ❑ Energy (not a Lorentz-invariant) of particle a should be Lorentz-transformed

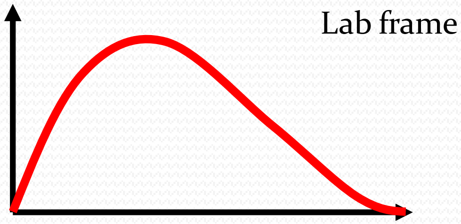


- ❑ Energy of particle a should be Lorentz-transformed!

$$E = E^*\gamma(1 + \beta\cos\theta^*)$$

- ❑ No longer δ-functionlike spectrum, but a function of $\gamma, \theta^* \rightarrow$ becoming a distribution due to variation in them $\rightarrow$ information **loss**?!





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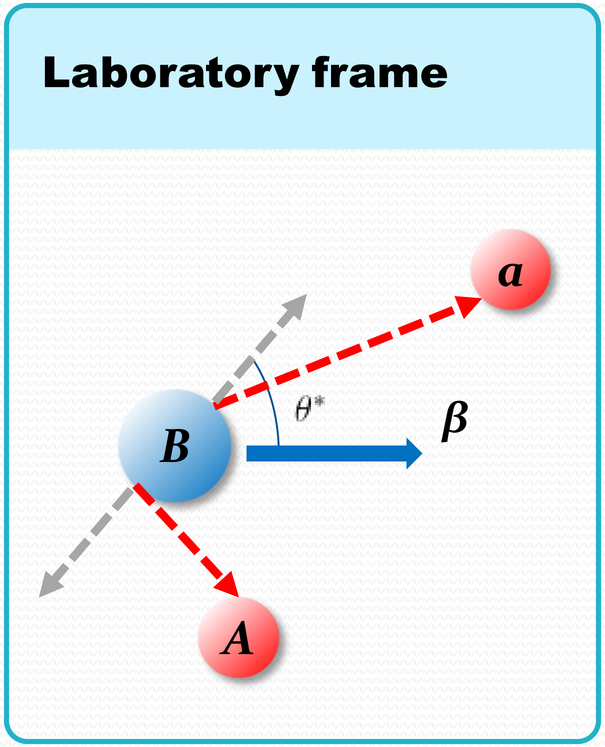

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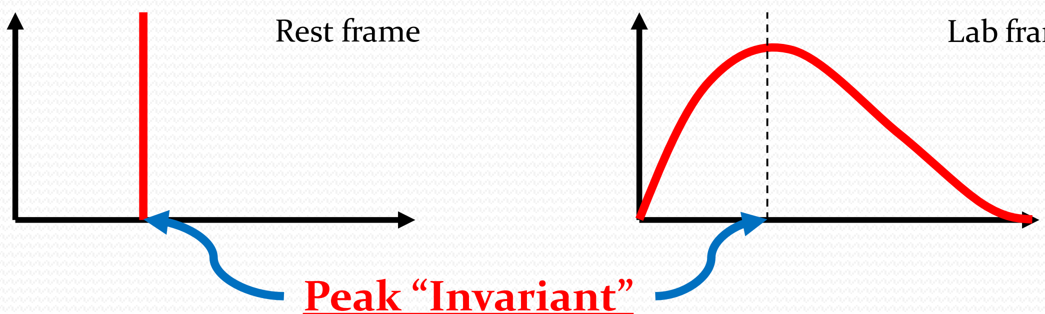
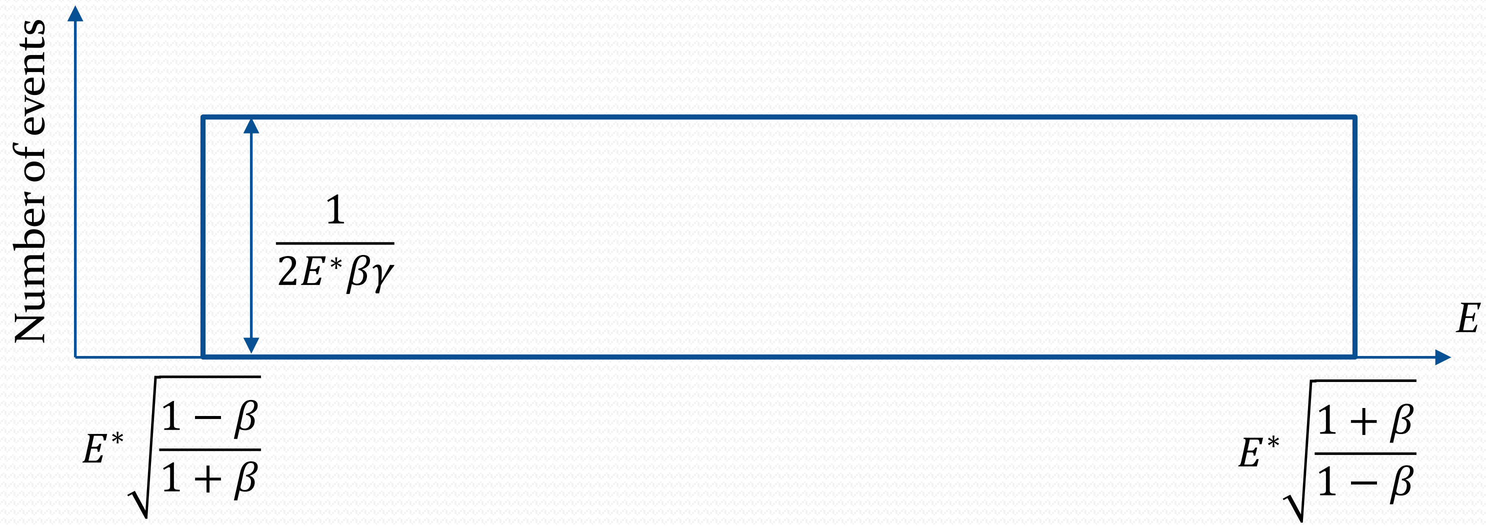


Energy Peak

Existence of energy peak: a quick review

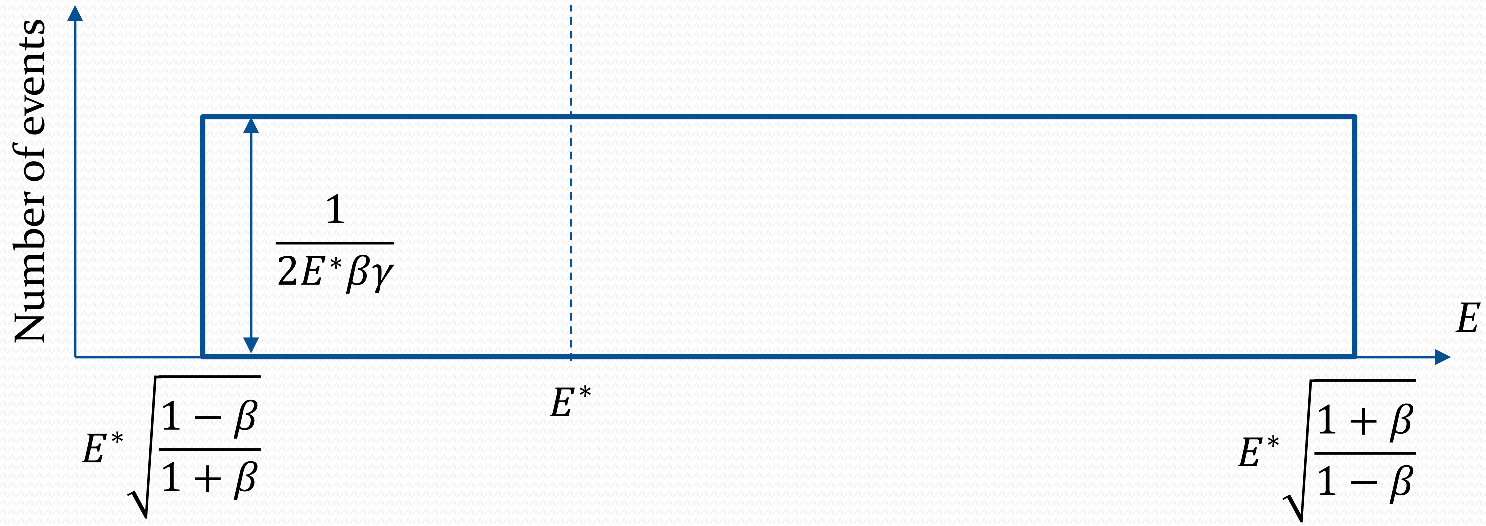
- Lorentz transformation: $E = E^*\gamma(1 + \beta\cos\theta^*)$
- Unpolarized/scalar mother particles
  - ✓ $\cos\theta^*$ becomes flat → E is also flat (simple chain rule)



Energy Peak

Existence of energy peak: a quick review

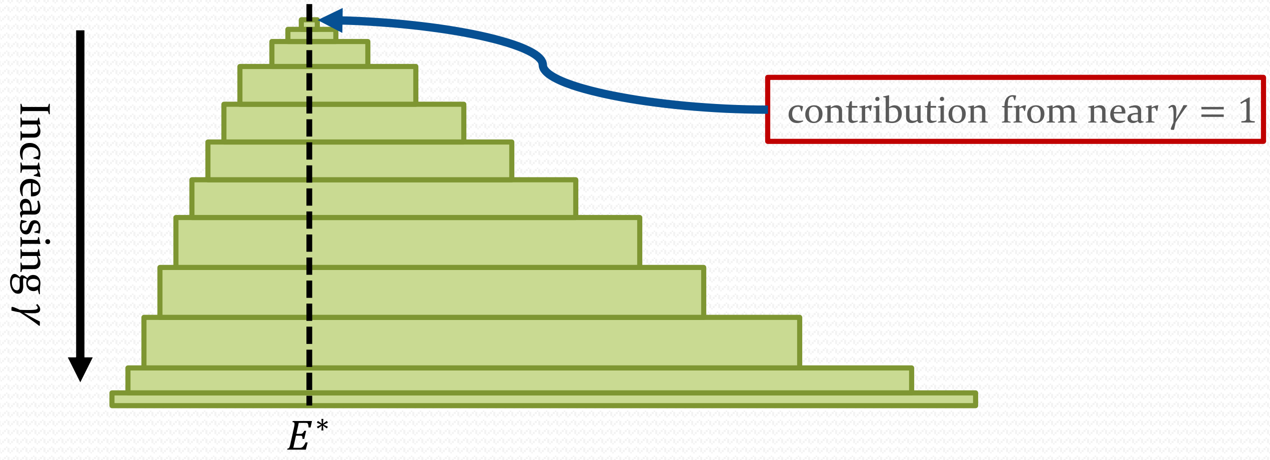
- Lower bound (upper bound) smaller (bigger) than E^* (for **any** boost)
  - ✓ **No other** E gets **larger** contribution from a given boost than does $E = E^*$
  - ✓ **No other** E is contained in **every** rectangle
- Asymmetric on linear E (**symmetric on logarithmic E**) with respect to E^*



Energy Peak

Existence of energy peak: a quick review

- Distribution in E: summing up the contributions from all relevant boost factors
  - ✓ **"Stacking up" rectangles** weighted by boost distribution (Lebesque-type integral)
  - ✓ Energy distribution has a unique **peak** at $E = E^*$ [Agashe, Franceschini, and **DK** (2012)]



- Details of the boost distribution (depending on production mechanism, PDFs, mother masses…) **NOT** matters

Energy Peak

Analysis: introduction of an ansatz

$$f(E) = \int_{\frac{1}{2}\left(\frac{E}{E^*}+\frac{E^*}{E}\right)}^{\infty} d\gamma \frac{g(\gamma)}{2E^* \sqrt{\gamma^2 - 1}}$$

- Generic distributions are obtained by an integration over the boost factor with **unknown** boost distribution $g(\gamma)$, generally, not doable
- Nevertheless, there are common features of $f(E)$
  - Even under $E/E^* \leftrightarrow E^*/E$
  - Maximized at $E = E^*$
  - Vanishing as E goes to $0/\infty$
  - Returning a δ-function for some limiting parameter choice
- Proposal of an ansatz:

$$\boxed{f(E) = \frac{1}{K_1(w)} \exp[-\frac{w}{2}\left(\frac{E}{E^*} + \frac{E^*}{E}\right)]}$$

Energy Peak

- **Top mass measurement by CMS**

Available on the CERN CDS information server **CMS PAS TOP-15-002**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch 2015/09/16

Measurement of the top-quark mass from the b jet energy spectrum

The CMS Collaboration

Energy Peak

Many more collider studies with energy-peak

- Distinguishing DM stabilization symmetries [Agashe, Franceschini, **DK**, and Wardlow (2012)]
- Distinguishing signal from background in searching for superpartners of the top quark [Low (2013)]
- Mass measurement of new particles in 2-step on-shell cascade of 2-body decays [Agashe, Francheschini, and **DK** (2013)]
- Mass measurement of Kaluza-Klein gravitons in warped RS models [Chen, Davoudiasl, and **DK** (2014)]
- Mass measurement of new particles in 3-body decays [Agashe, Franceschini, **DK**, and Wardlow (2015)]
- Mass measurement of new particles in the case with massive visible particles [Agashe, Franceschini, Hong, and **DK**, in progress]
- Top quark mass measurement in NLO [Agashe, Franceschini, **DK**, and Schulze, in progress]
- …

GC GeV Excess

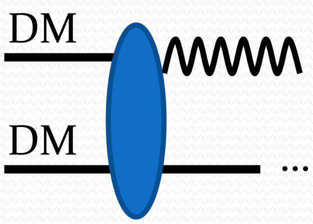
Continuum Energy Spectrum

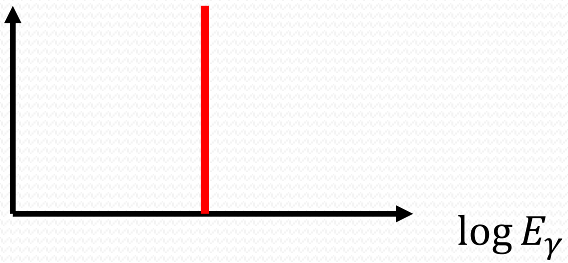
DM model under consideration

- How to obtain broadly distributed energy spectrum?
- A lesson from collider physics: getting through **multiple cascade decays** easily generates a continuum energy spectrum
  - Assuming a **simple** event topology (vs. collection of cascade decays, bremsstrahlung, Compton scattering, etc.)

Continuum Energy Spectrum

DM model under consideration

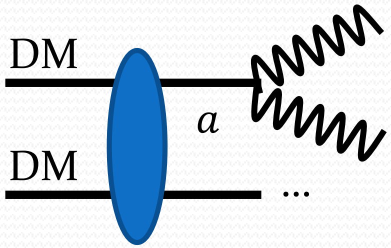


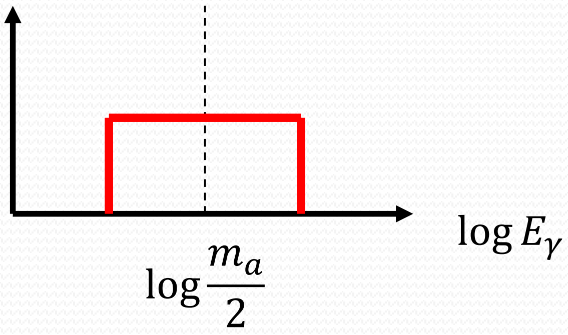


- ❑ Simplest and conventional model
- ❑ Featured by a sharp peak

Continuum Energy Spectrum

DM model under consideration

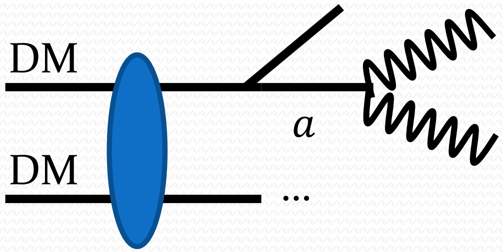


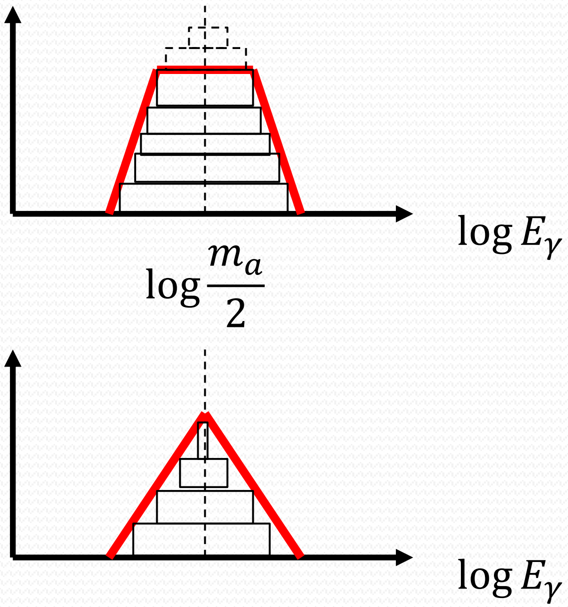


- ❑ Introducing on-shell mediator state
- ❑ Featured by a box-like distribution

Continuum Energy Spectrum

DM model under consideration

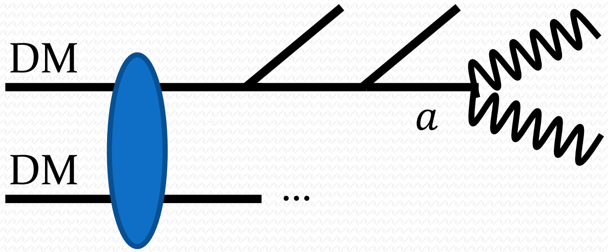


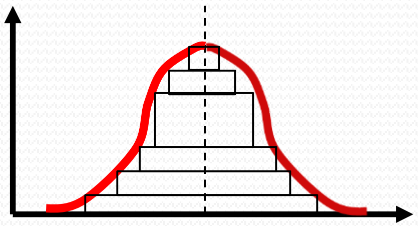


- Introducing an on-shell intermediate state before the state decaying into two photons
- Developing a plateau or a peak depending on model details
- Morphologically constrained: analytic expression for the shape available

Continuum Energy Spectrum

DM model under consideration



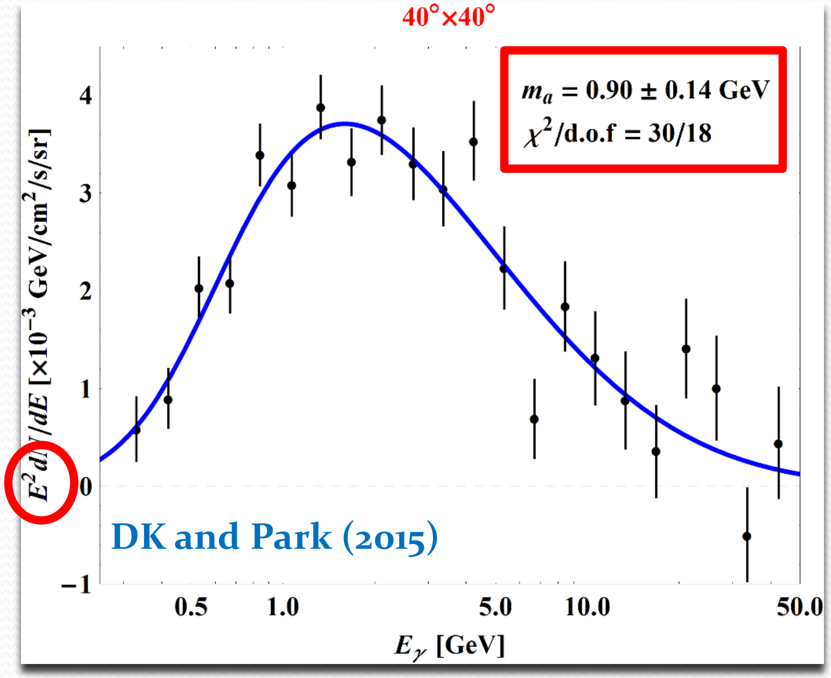


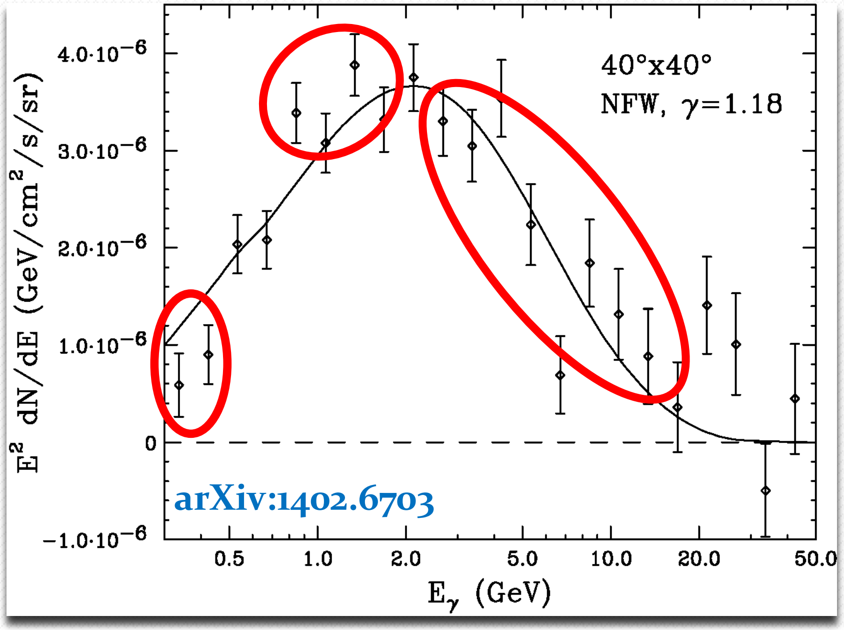
- Introducing one more on-shell intermediate state before the state decaying into two photons
- Developing a smoothly rising-and-falling shape
- Analytic expression for the shape generally not available $\rightarrow$ Employ ansatz with a slight modification (another fit parameter)!

$$\boxed{f(E_\gamma) \propto \exp\left[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*}+\frac{E_\gamma^*}{E_\gamma}\right)^p\right]}$$

Application: GC GeV Excess

- **Results: $40^\circ \times 40^\circ$**

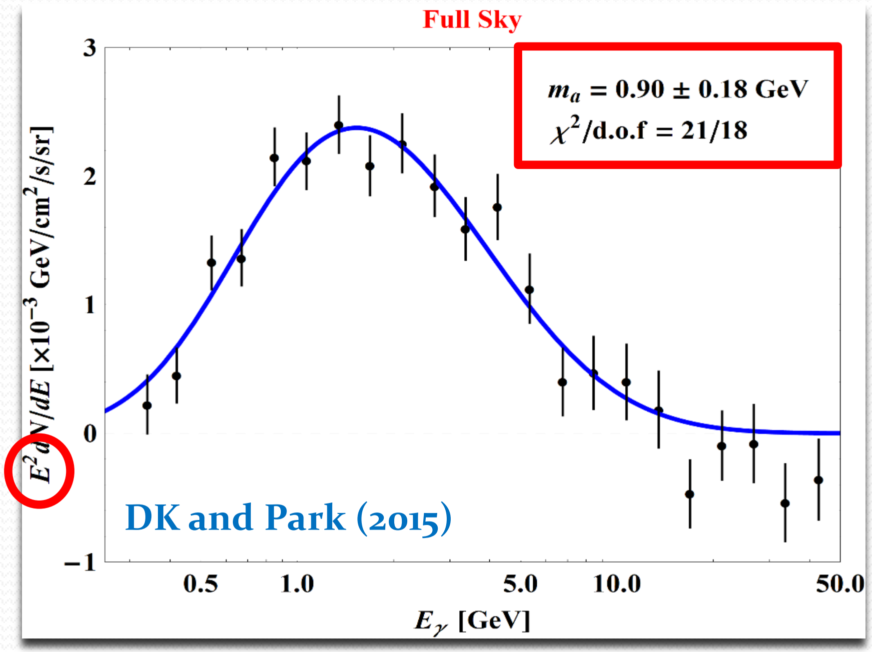


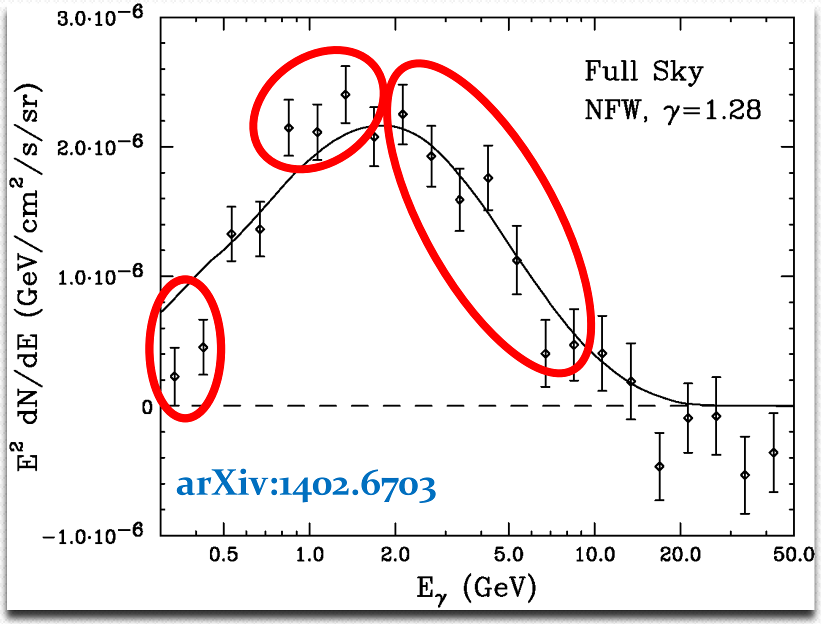


- cf. arXiv:1402.6703 → χ^2/d.o.f. = 64/20 with m_{DM} = 43.0 GeV

Application: GC GeV Excess

Results: Full sky





- cf. arXiv:1402.6703 → χ^2/d.o.f. = 44/20 with m_{DM} = 36.6 GeV

Take-home Lesson

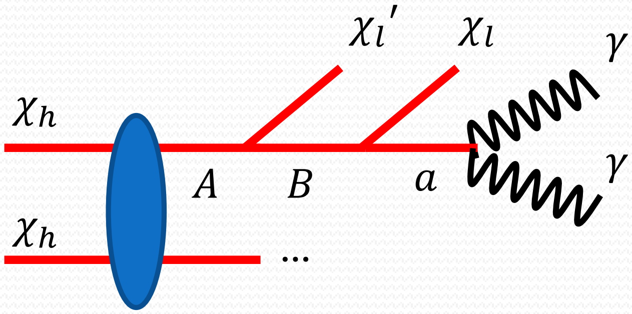
Summary

- Fit results with **reasonable chi square** (i.e., χ^2/d.o.f $\sim$1) suggest that the GC GeV gamma-ray energy spectrum has a **unique structure** (i.e., symmetric with respect to the peak in logarithmic E_γ)
- The **peak position** is identified as **half the mass of an on-shell mediator** decaying into photons
- Such structural features are easily realized by a **2-body decay** of the **on-shell mediator** into 2 photons
- **Continuum energy spectrum** can be realized when the on-shell mediator comes along with a **sequential cascade decay**
- (In addition,) **non-trivial dark sector** could be favored to accommodate the above observations

Thank you!

Back-up

More on DM scenario



[**DK** and Park (2015)]

- Two dark matter particles introduced, heavier one (χ_h) and lighter one (χ_l) → **non-trivial** dark sector (e.g., boosted DM [Agashe, Cui, Nevib, and Thaler (2014); Berger, Cui, and Zhao (2014); Kong, Mohlabeng, and Park (2014)])
- Heavier one: **dominant** DM component, **no direct coupling** to SM → relic abundance realized by **Assisted Freeze-out** [Belanger and Park (2011)]
- Lighter one: **subdominant** DM component, **direct coupling** to SM
- a: dark pion or axion-like particle
- In general, various DM models are allowed as far as experimental constraints are satisfied: more detailed DM model building in progress [with Kong and Park]

Back-up

- Unweighted energy spectrum