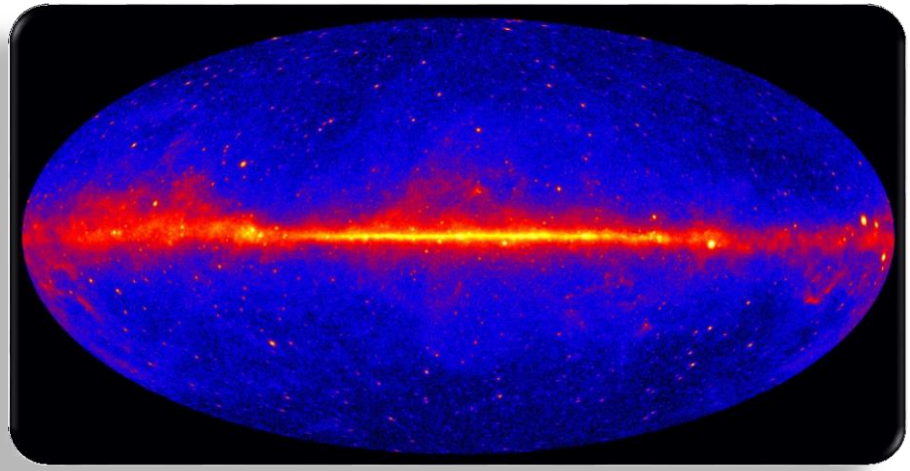
Energy Peak: Back to cosmic γ-ray excess

Doojin Kim & **JCP** [arXiv: 1507.07922]



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October 13, 2015

CosPA 2015

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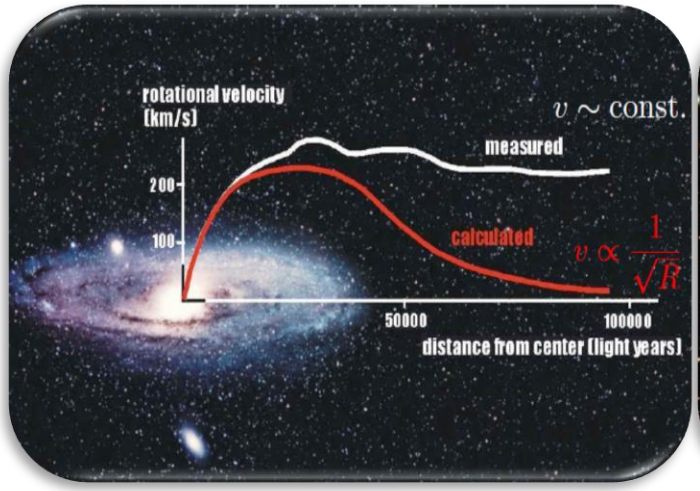
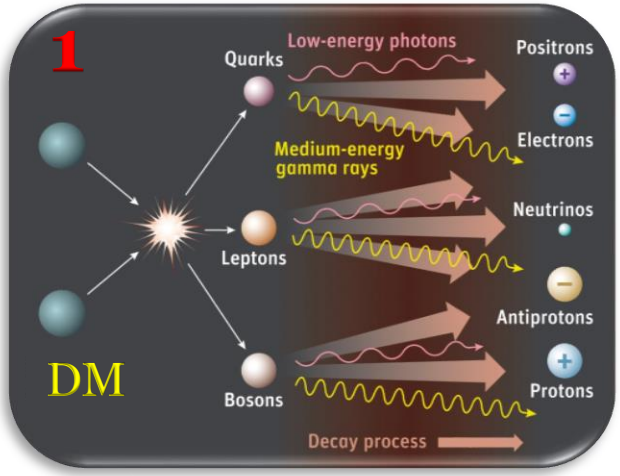
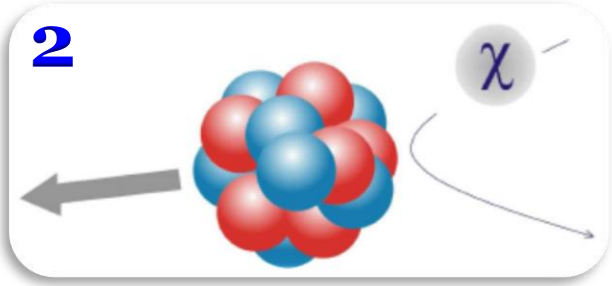
Dark Matter (DM)

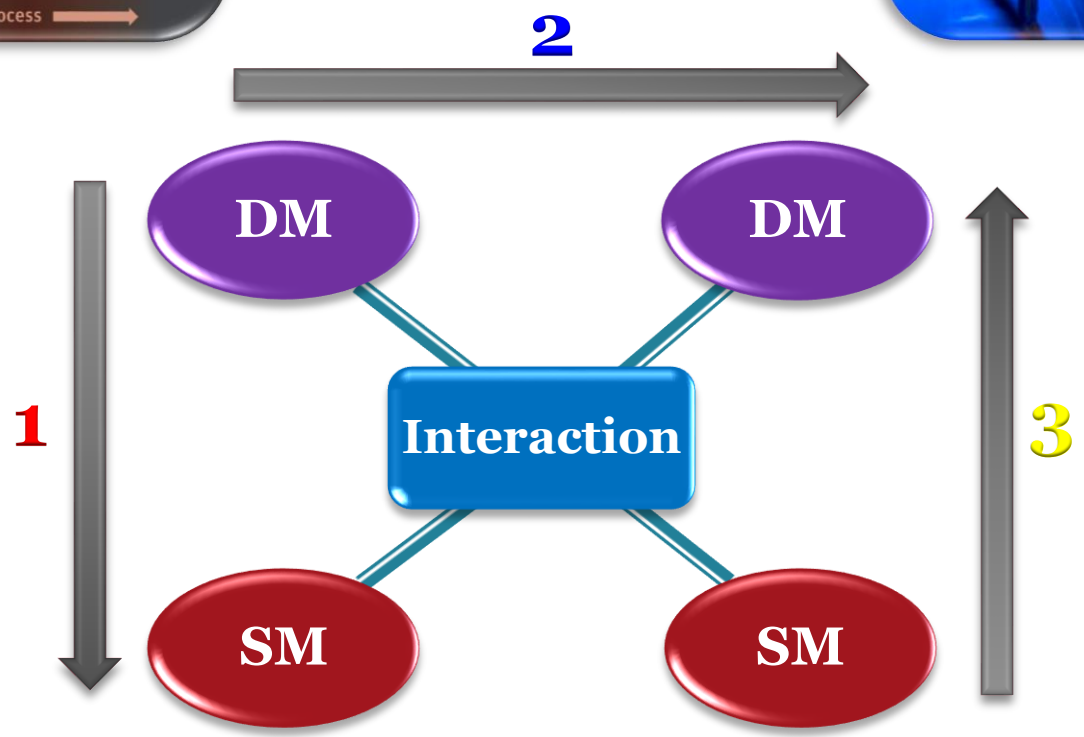
- **DM**: ~25% of our Universe
- **Compelling paradigm**:
  massive, non-luminous & stable particles
- **Evidence**
  - ✓ Galaxy rotation curve
  - ✓ Bullet cluster
  - ✓ Gravitational lensing
  - ✓ Structure formation
  - ✓ CMB
  - ✓ Coma Cluster
  - ✓ Sky surveys
  - ✓ …



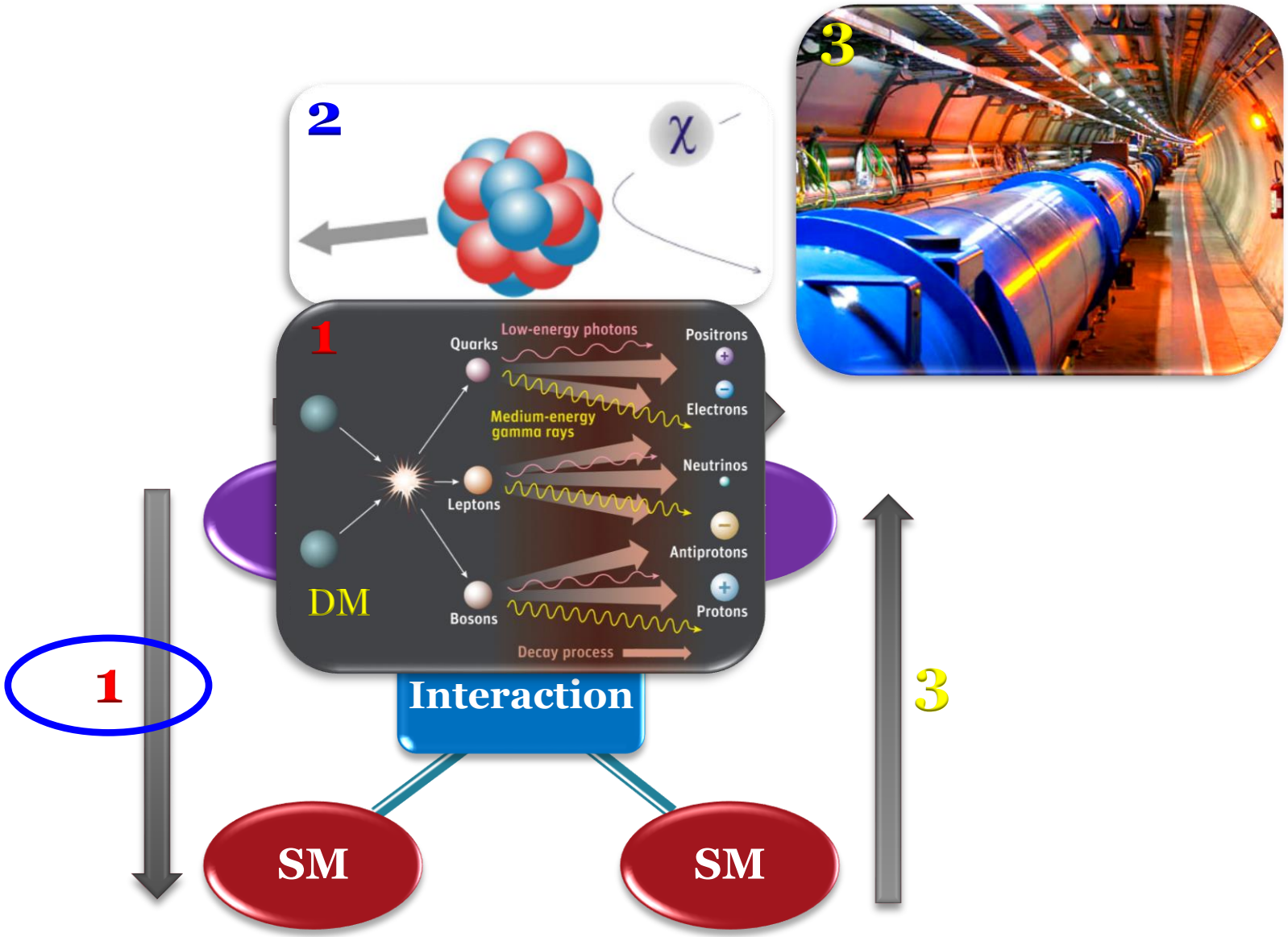
DM Search Strategies



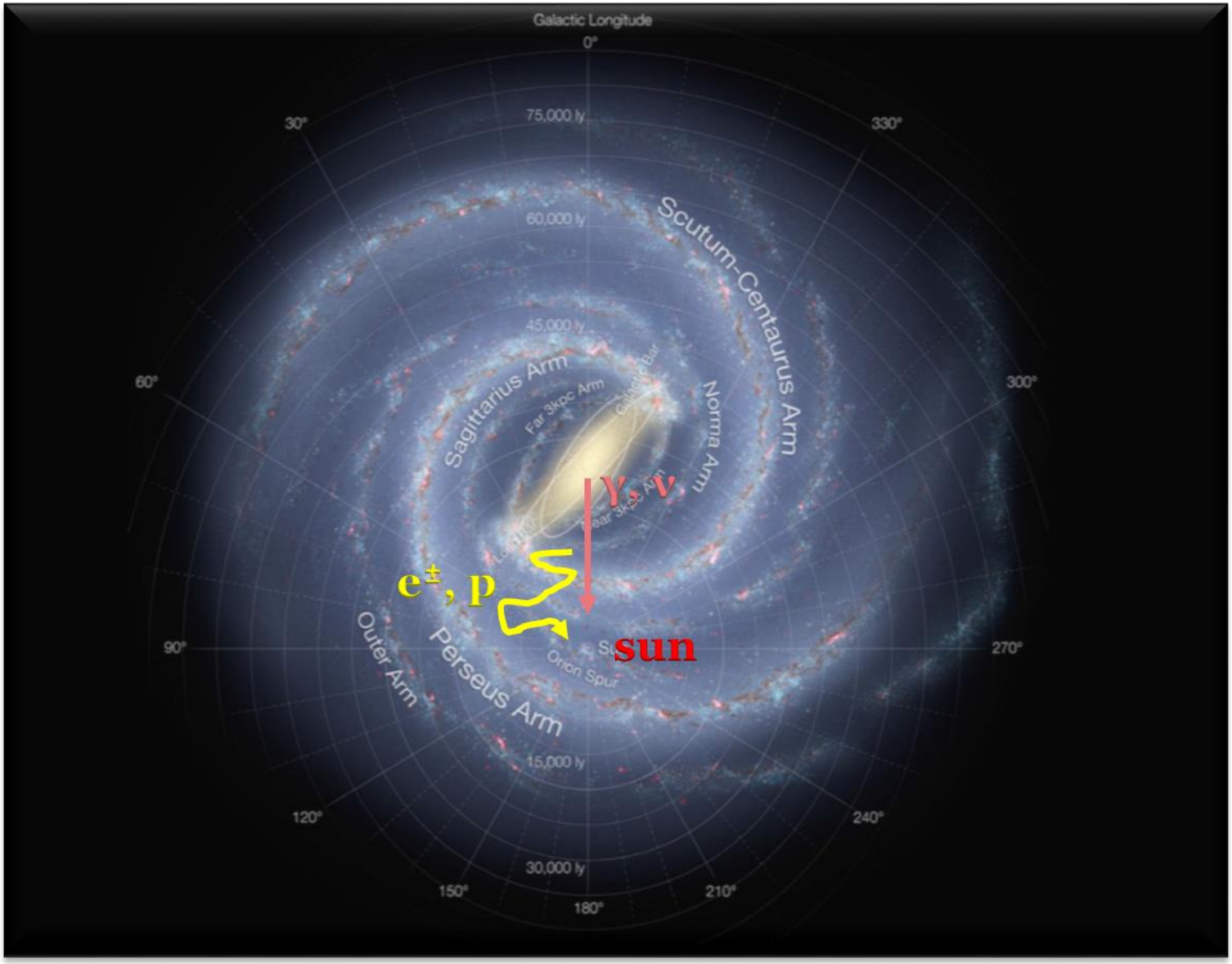




DM Indirect Detection



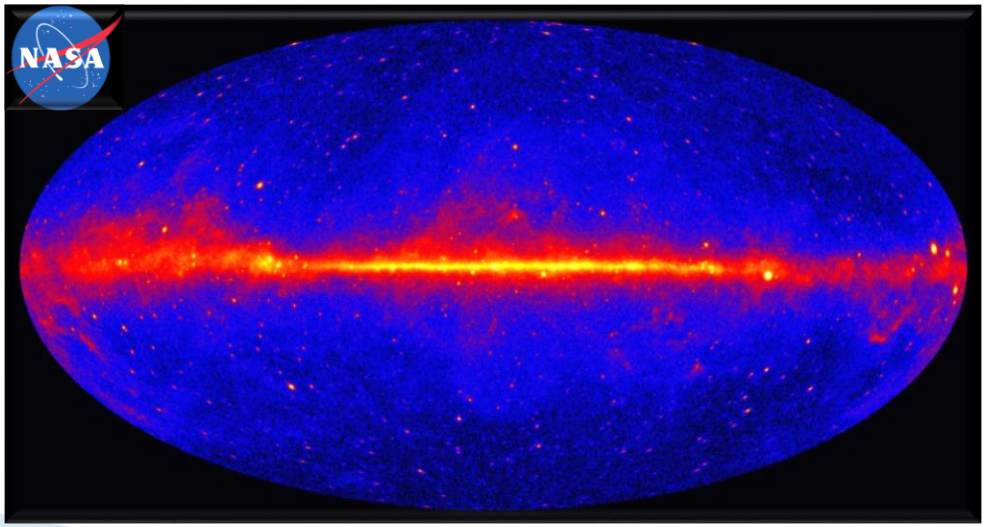
Indirect Detection: Cosmic-rays



Hints from Cosmic-ray?

❖ DM signatures in cosmic-ray observations?

- SPI/INTEGRAL ($\gamma \rightarrow e^+$)
- PAMELA ($e^\pm$, $p^\pm$, …)
- ATIC ($e^- e^+$)
- Fermi-LAT (γ)
- AMS-02 ($e^\pm$, $p^\pm$, …)
- XMM-Newton (X-ray)
- IceCube (ν)
- …



Importance of γ-rays

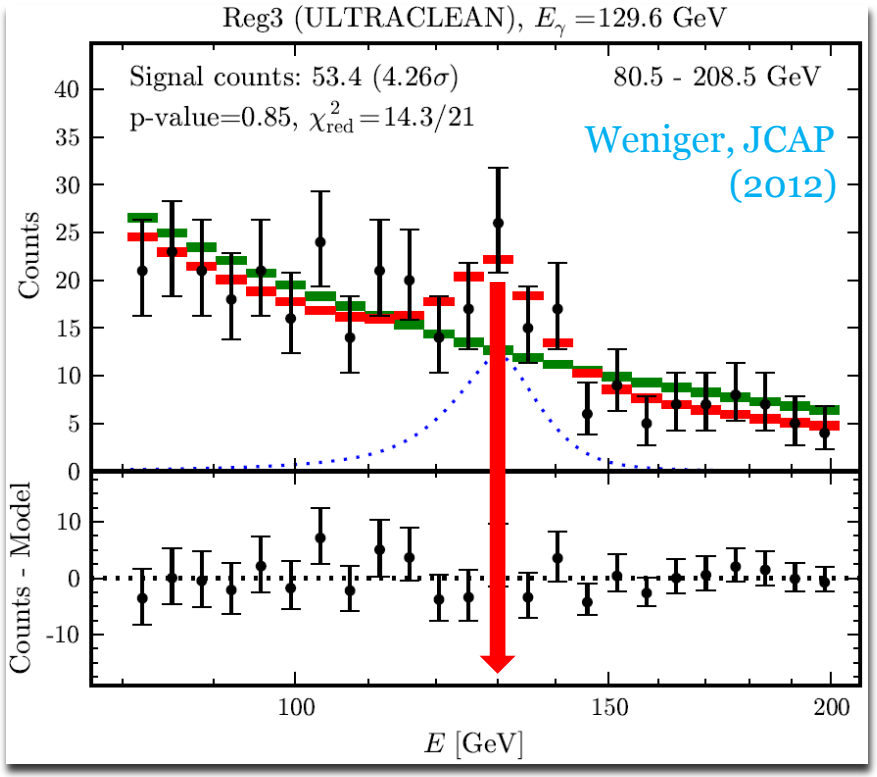
- Preserve spatial information about their sources

  & travel long distance (vs. $e^{\pm}$, $p^{\pm}$, …)

- Spectrum at the detector similar to the injection spectrum
- Photons can be measured very easily & precisely (vs. ν's)
- Relatively efficient S/B discrimination in searches for γ-ray signatures
- Signatures in E_γ play a major role in DM searches.

(monochromatic peak and/or continuous bump signals)

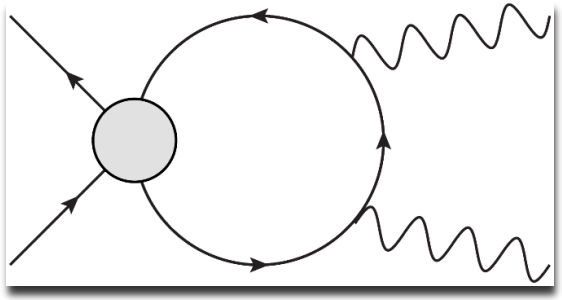
Peaks: 130 GeV/3.5 keV Lines

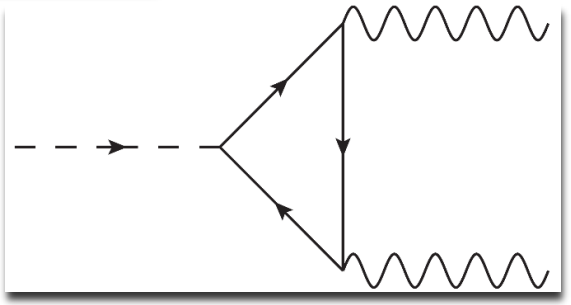


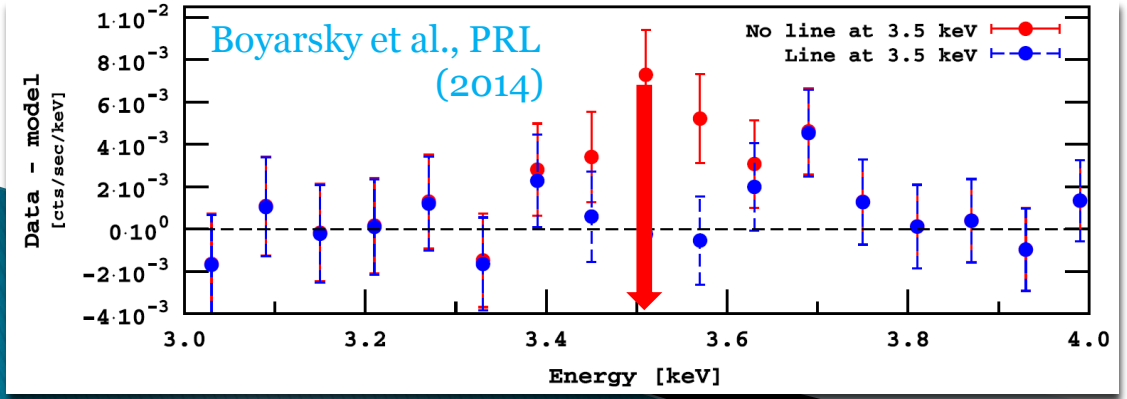
- γ line (Gaussian peak)

  at $E_\gamma \approx 130$ GeV/3.5 keV

→ DM: directly annihilate/decay into photon + X







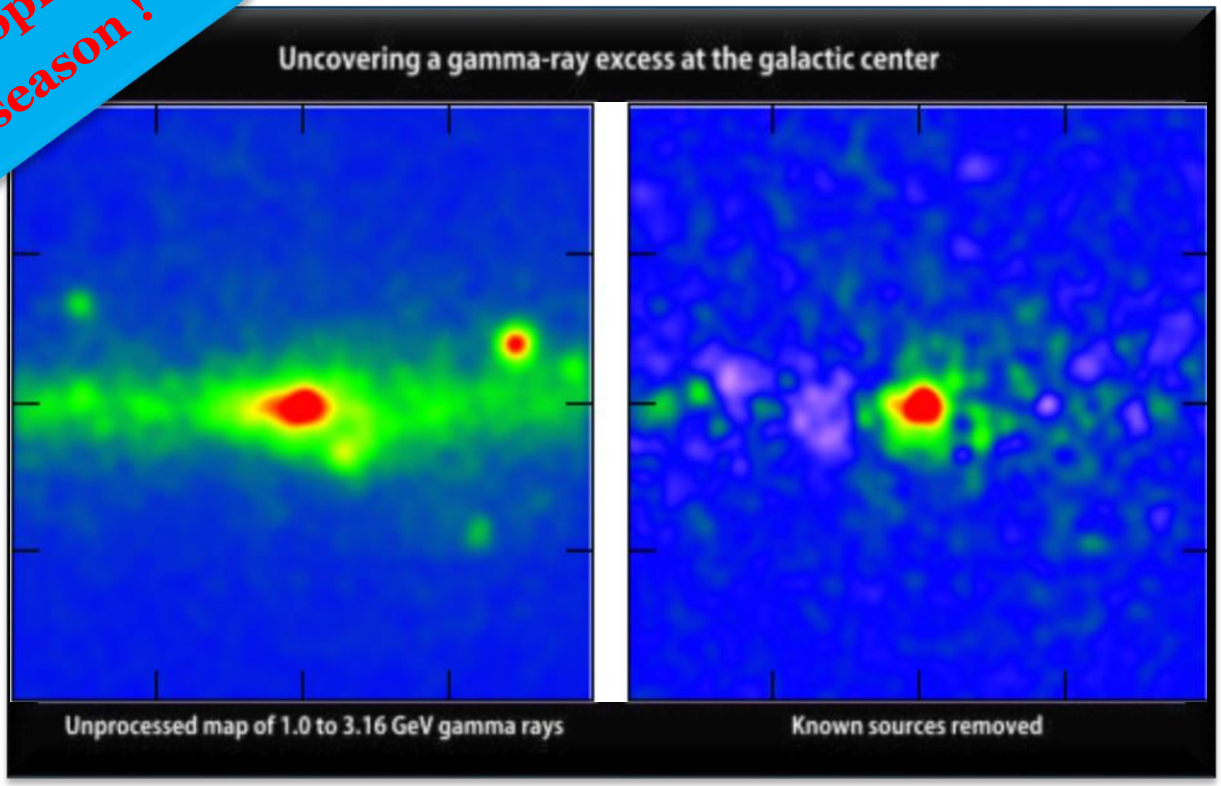
Alternative mechanism for cosmic-ray peaks based on extended DM:

Doojin Kim & **JCP** [1508.06640]

GeV γ-rays from Galactic Center

See Simona Murgia's Talk

Hot Topic of the season !



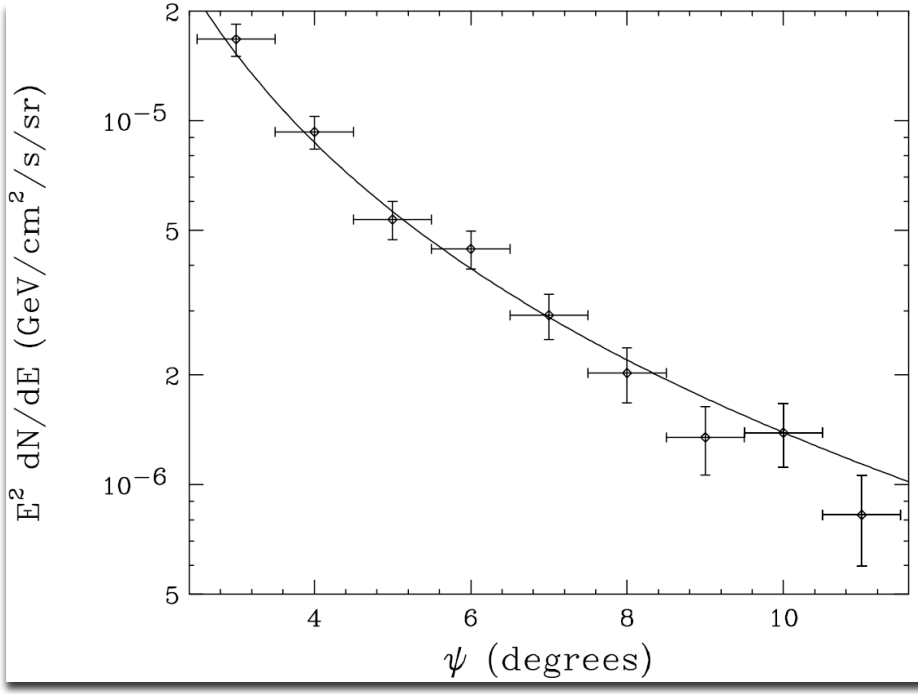
Before

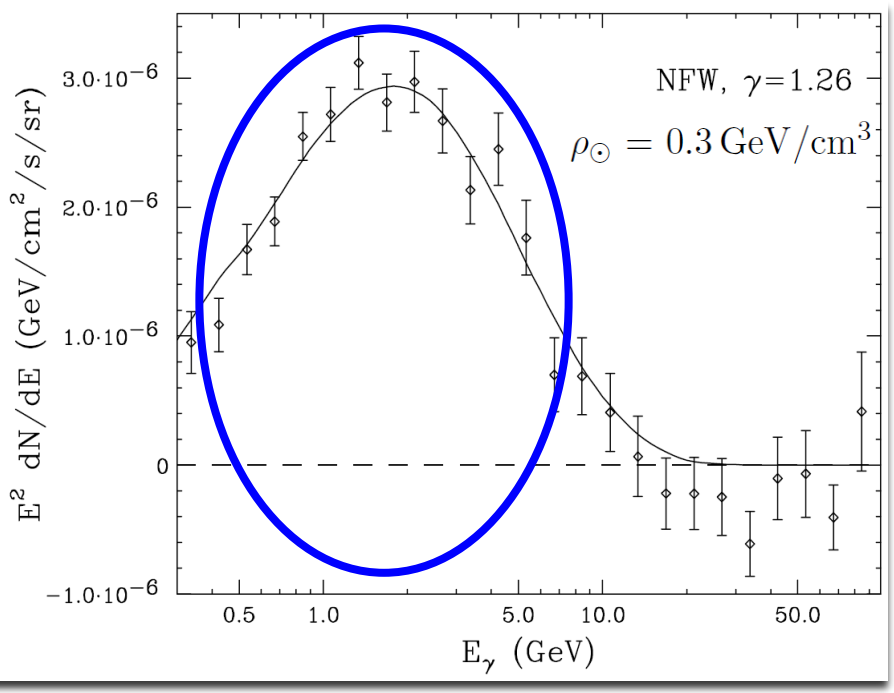
After

arXiv:1402.6703

Bump: GC GeV Excess

See Simona Murgia's Talk

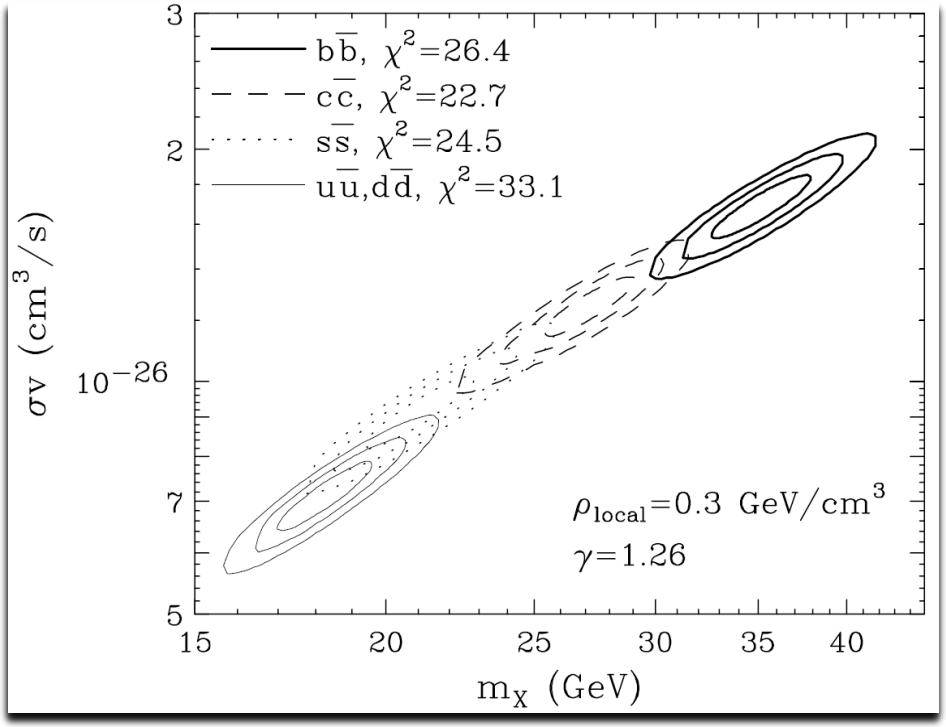


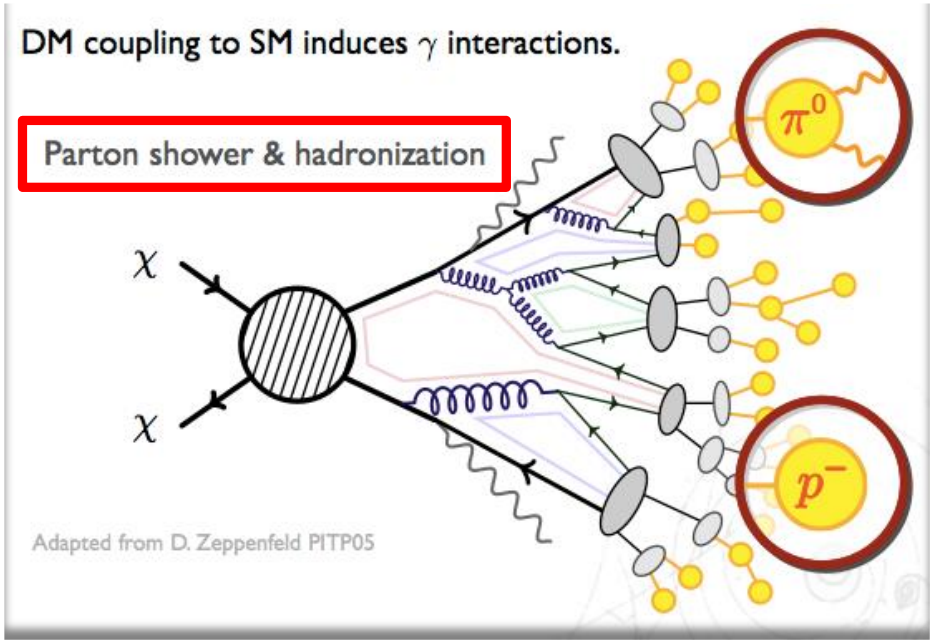


- Signal: extended to > 10° from the GC
- Consistent with the dynamical center of the Milky Way (< 0.05°)
- The spectrum of the excess peaks at 1-3 GeV.

arXiv:1402.6703

Bump: Preferred Final States





- The spectrum is in good agreement with the predictions from 20-40 GeV DM mostly annihilating to quarks (fragmentation, IC, bremsstrahlung, …).
- Required cross section is ~ $0.7\text{-}2.1 \cdot 10^{-26}$ cm^3/s

arXiv:1402.6703

DM Models for GeV Excess

- GeV excess & direct detection signals: B. Kyae & **JCP** (1310.2284) m~10GeV
- Higgs portal DM: N. Okata & O. Seto (1310.5991: bb or ττ, 1404.1373: bb), …
- Flavored DM: C. Boehm et al. (1401.6458), P. Agrawal, B. Batell, D. Hooper & T. Lin (1404.1373), …
- Effective Ops.: W. Huang, A. Urbano & W. Xue (1310.7609), A. Alves, S. Profumo, F. Queiroz & W. Shepherd (1403.5027), A. Berlin, D. Hooper & S. McDermott (1404.0022), E. Izaguirre, G. Krnjaic & B. Shuve (1404.2018), …

  "Slight variation of the typical mechanism: directly into SM *f*'s"

- On-shell mediator: C. Boehm, M. Dolan & C. McCabe (1404.4977), P. Ko, W. Park & Y. Tang (1404.5257), Tim Tait et al. (1404.6528), A. Martin, J. Shelton & J. Unwin (1405.0272), …
- Model-independent constraints: KC. Kong & **JCP** (1404.3741)

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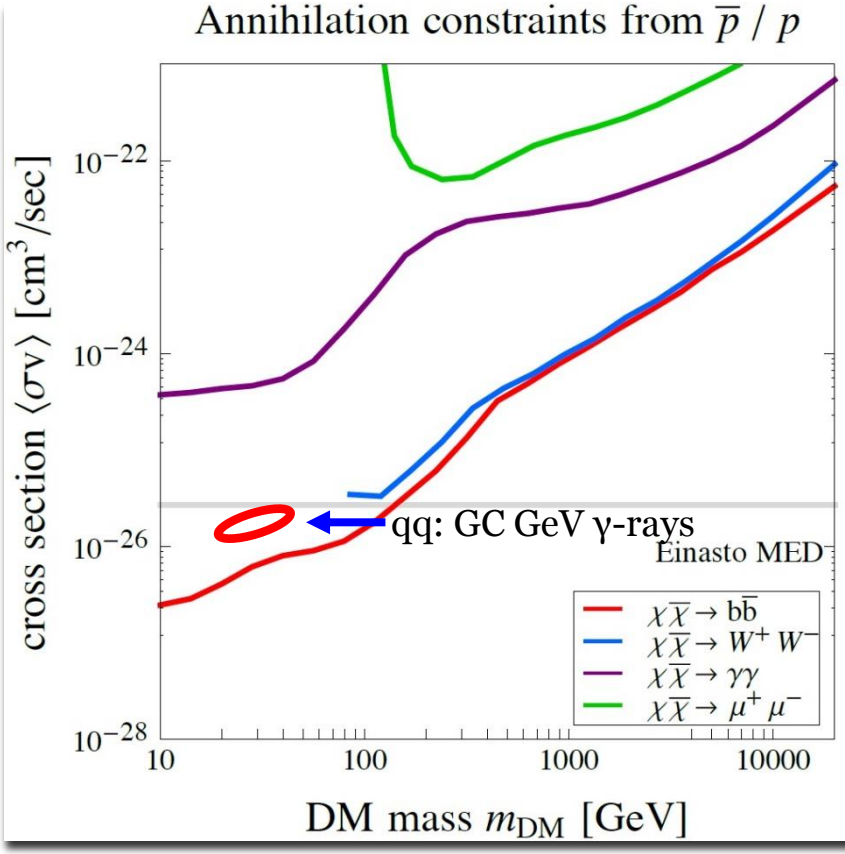
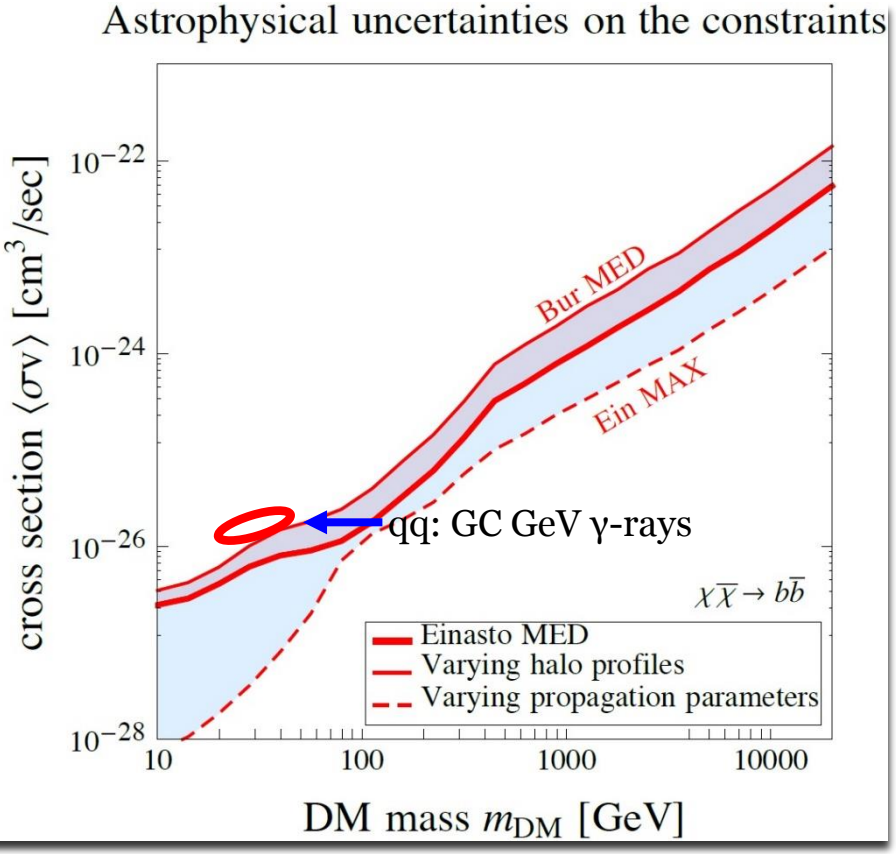
DM couplings to 1st (2nd) generation of SM *f*s: disfavored! (Maybe even not b-quark)

New Limits from AMS-02

Cirelli et al., arXiv:1504.04276





- Based on the recent AMS-02 anti-p/p data
- **q-final states are disfavored!** (**regardless of mediator**)

No Other
Possibility?

Energy Peak in Cosmic γ-rays

❖ With DM interpretation in mind, we propose alternative mechanisms based on the observation of the "energy-peak" in collider physics to explain the GC GeV γ-ray excess.

❖ Why energy peak?

- ✓ Energy is the only available quantity

  (vs. large multiplicity, momentum w.r.t. the beam line in collider events)

- ✓ Unique spectral features irrespective of underlying DM model details

  (vs. highly model-dependent in the standard interpretation)

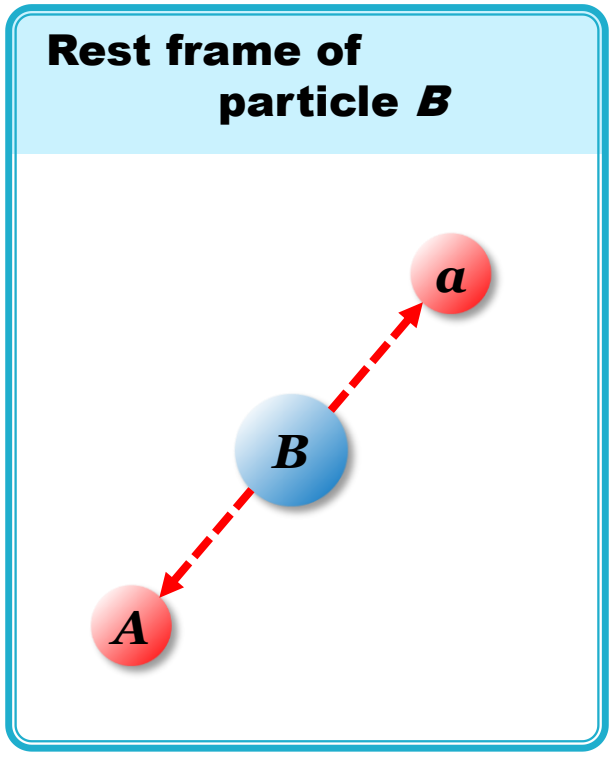
Doojin Kim & **JCP**, arXiv: 1507.07922

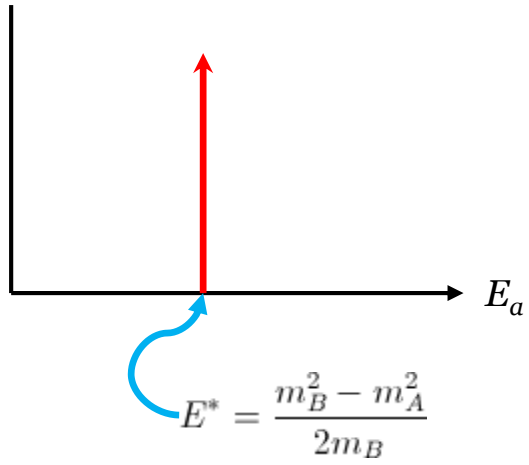
E-Peak: a Quick Review I

arXiv: 1209.0772

Two-body decay kinematics

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





- Energy of visible particle *a* is monochromatic & simple function of masses
- E^* measured & m_A known, → m_B determined, vice versa
- Great to be on the special frame!

Based on Doojin Kim's talk @ Brookhaven Forum 2015

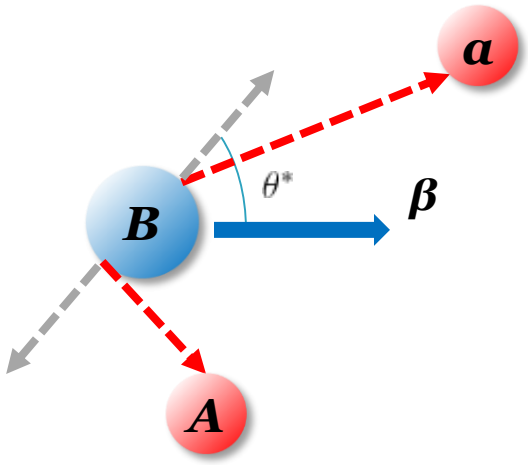
E-Peak: a Quick Review II

arXiv: 1209.0772

Two-body decay kinematics

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

Laboratory frame

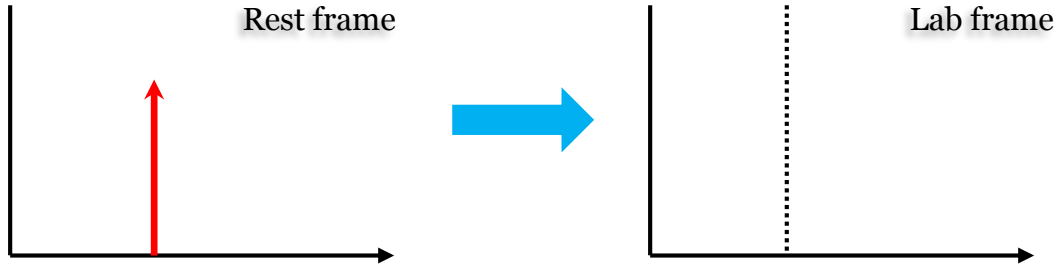


❑ Energy of particle *a* should be Lorentz-transformed!

$$E = E^*\gamma(1+\beta\cos\theta^*) = E^*(\gamma+\sqrt{\gamma^2-1}\cos\theta^*)$$

❑ No more δ-function-like spectrum, but a function of γ, θ^*

→ becoming a distribution due to variation in them



Peak "Invariant"

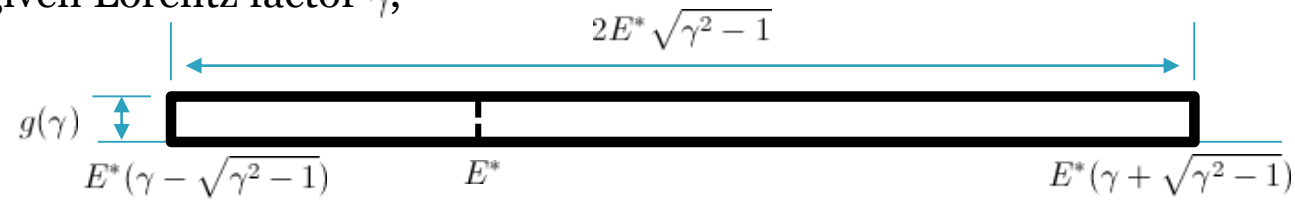
Based on Doojin Kim's talk @ Brookhaven Forum 2015

E-Peak: a Quick Review III

arXiv: 1209.0772

"stacking up" rectangles

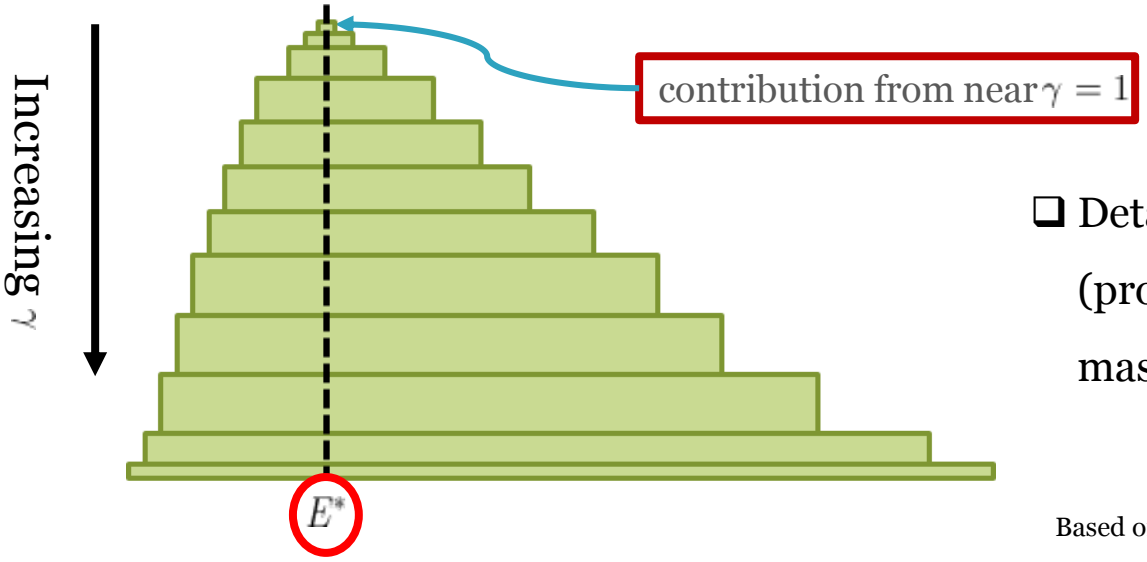
- For any given Lorentz factor γ,



- Distribution in E → summing up the contributions from all relevant boost factors

  → ***"Stacking up" rectangles*** weighted by boost distribution $g(\gamma)$ (Lebesque-type integral)

- Energy distribution has a unique peak at $E=E^*$



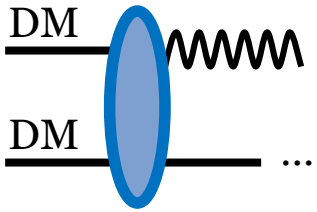
- Details of the boost distribution (production mechanism, mother masses, …) NOT matter

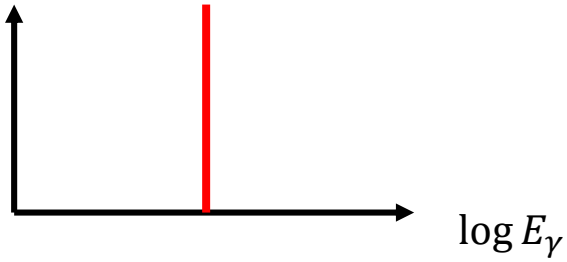
Based on Doojin Kim's talk @ Brookhaven Forum 2015

GC GeV Excess

Continuum E Spectrum

- **DM model under consideration**



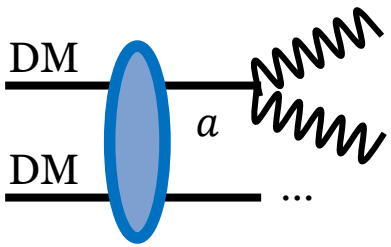


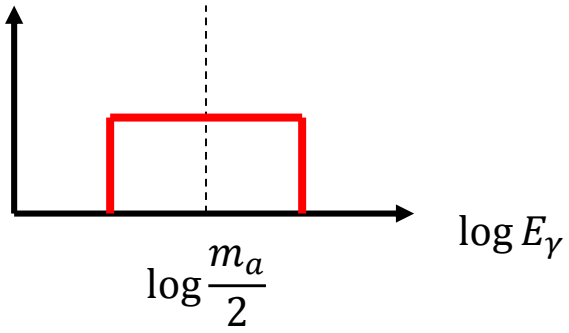
- ❑ Simplest and conventional model
- ❑ Featured by a sharp peak

Based on Doojin Kim's talk @ Brookhaven Forum 2015

Continuum E Spectrum

- **DM model under consideration**



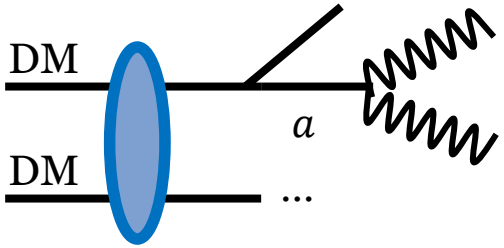


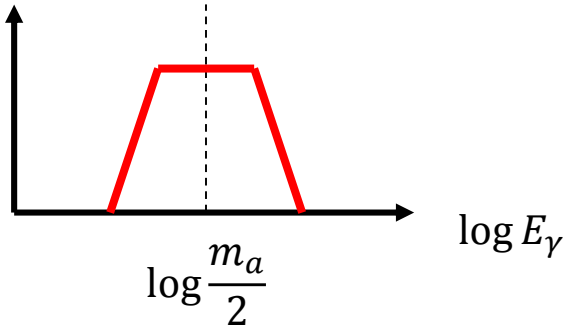
- ❑ Introducing on-shell mediator state
- ❑ Featured by a box-like distribution

Based on Doojin Kim's talk @ Brookhaven Forum 2015

Continuum *E* Spectrum

DM model under consideration





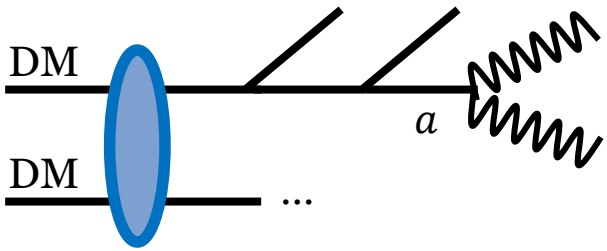
- Introducing an on-shell intermediate state before the state decaying into two photons
- Developing a plateau or a peak depending on model details
- Morphologically constrained: analytic expression for the shape available
- Doojin Kim & **JCP** [arXiv:1508.06640]

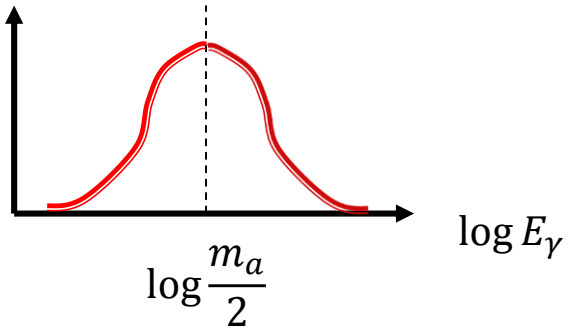
  → Cosmic-ray peaks: e.g. 130 GeV/3.5 keV lines

Based on Doojin Kim's talk @ Brookhaven Forum 2015

Continuum E Spectrum

- **DM model under consideration**



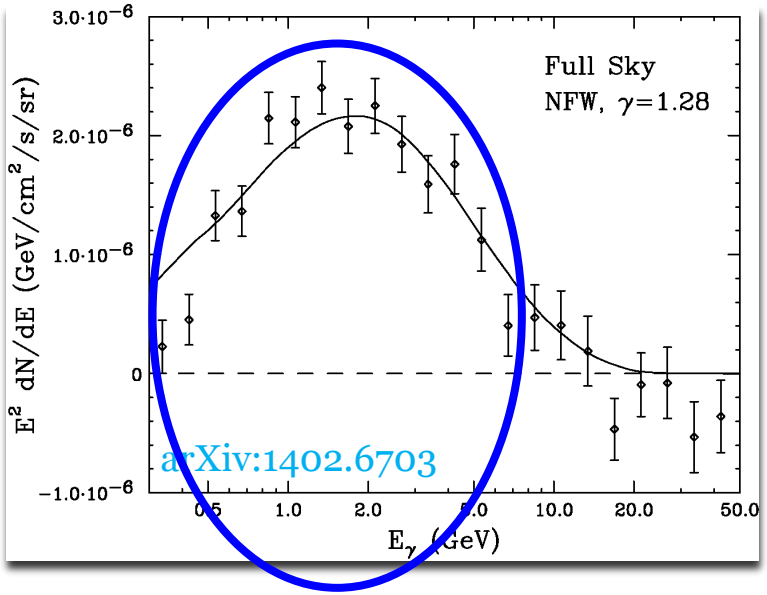


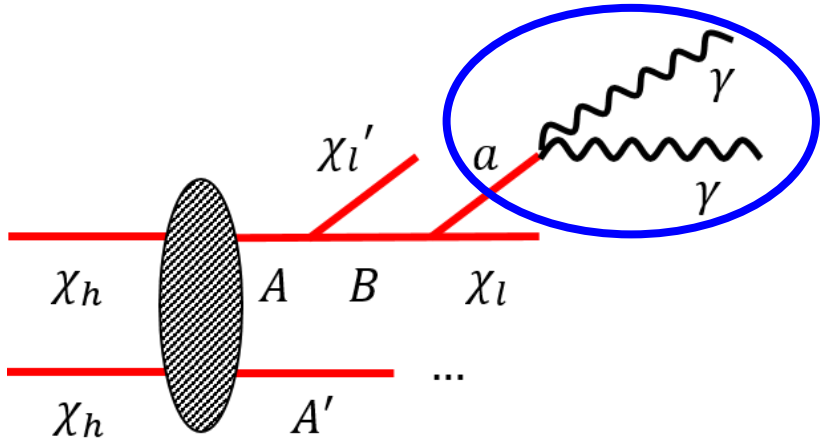
- ❑ Introducing one more on-shell intermediate state before the state decaying into two photons
- ❑ Developing a smoothly rising-and-falling shape
- ❑ Generic distribution function:

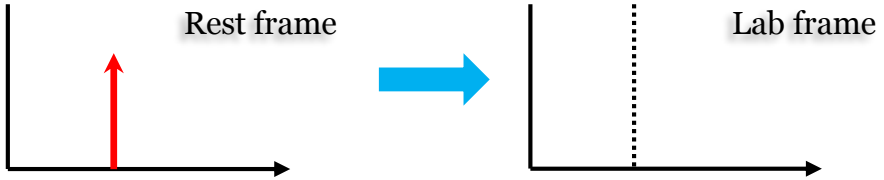
$$f(E_\gamma) \propto \exp[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*}+\frac{E_\gamma^*}{E_\gamma}\right)^p]$$

Based on Doojin Kim's talk @ Brookhaven Forum 2015

Dark Cascade ➔ γ-ray Bump!





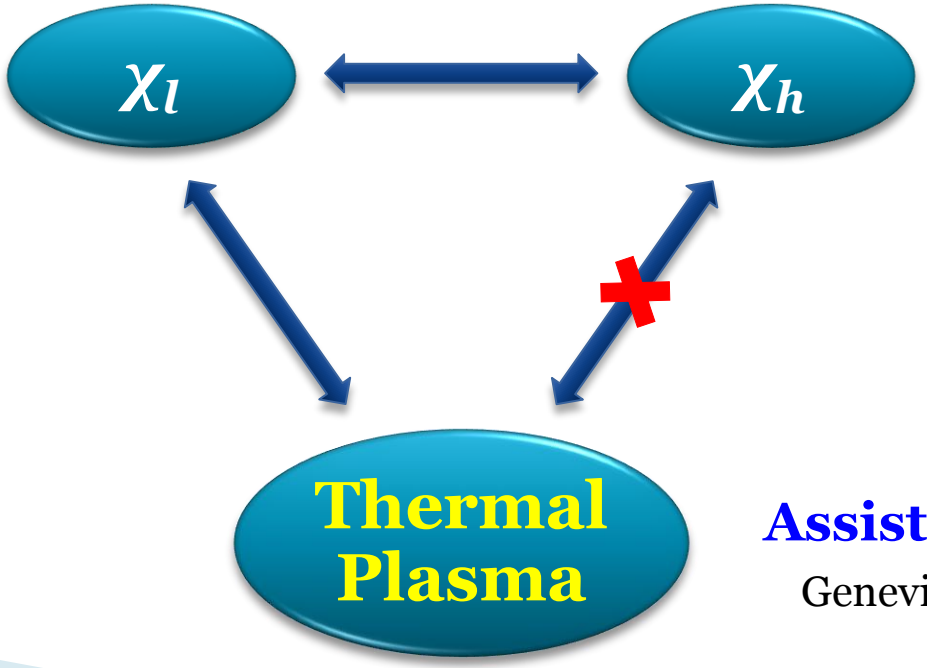


- More-than-one step cascade decay!

Doojin Kim & **JCP**, arXiv: 1507.07922

Multi-DM Set-up: Assisted FO

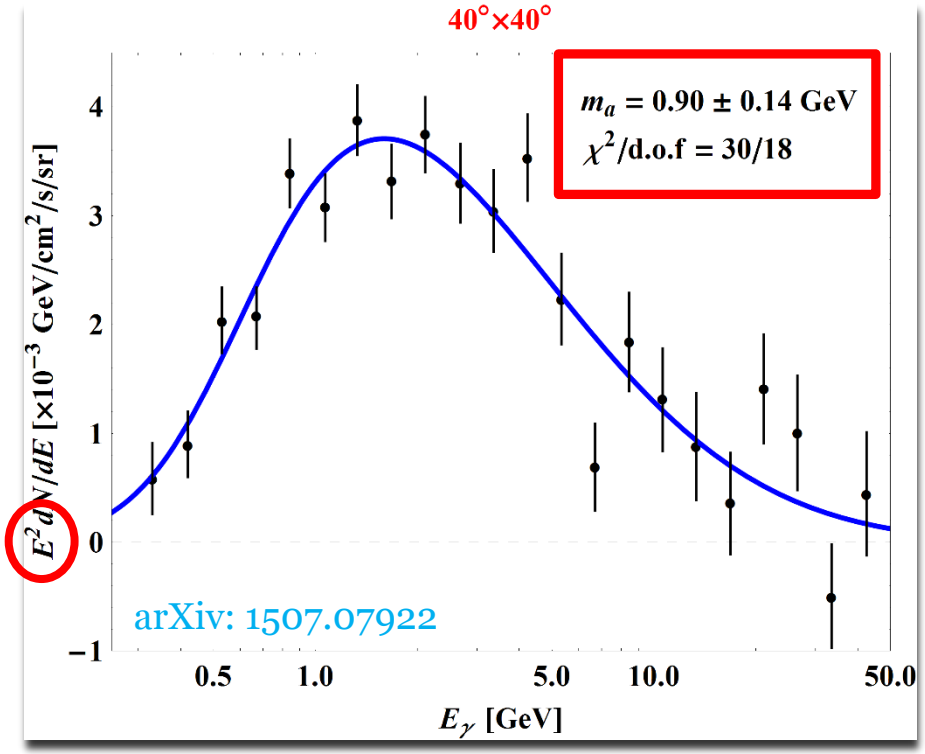
- Two species of DM: χ_h, χ_l with $m_h > m_l$ (e.g. $\mathrm{U}(1)' \otimes \mathrm{U}(1)''$, $Z_2' \otimes Z_2''$)
- χ_h : dominant DM component, no direct coupling to the SM
  - ➔ Assisted Freeze-Out
- χ_l: sub-dominant, direct coupling to the SM ($\mathcal{L} \supset -\frac{1}{2} \sin\epsilon X_{\mu\nu} F^{\mu\nu}$)

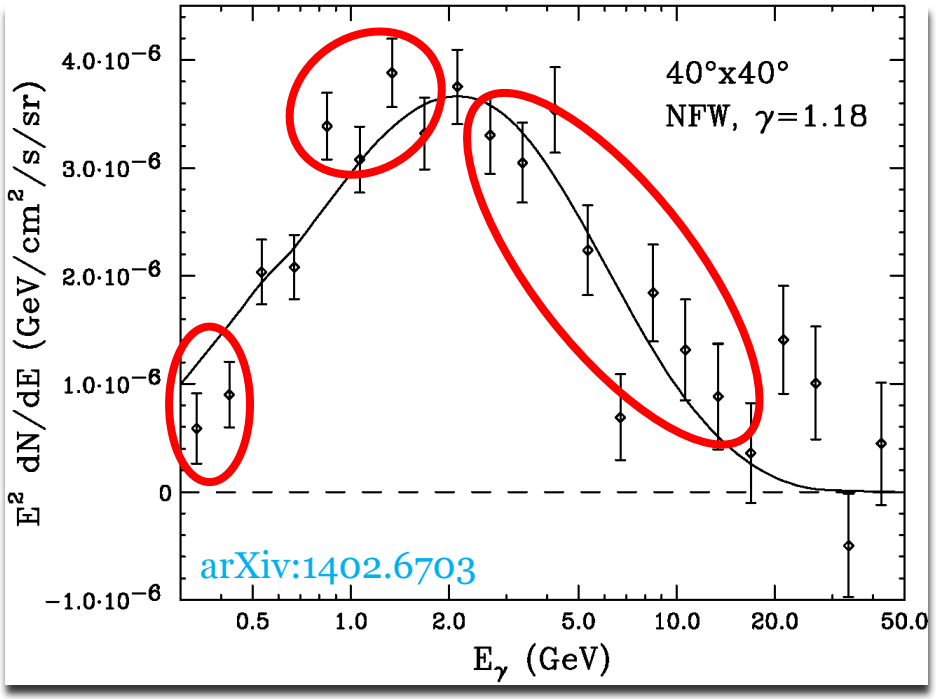


Assisted Freeze-Out

Genevieve Belanger & **JCP**
(arXiv:1112.4491)

Fit to the GeV γ-ray excess I

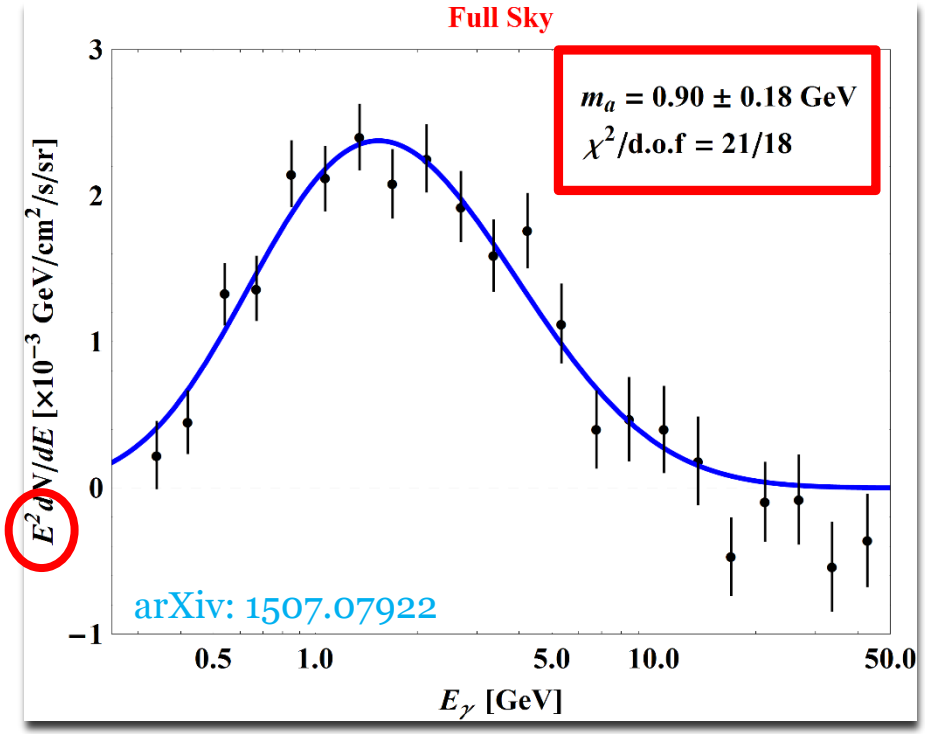


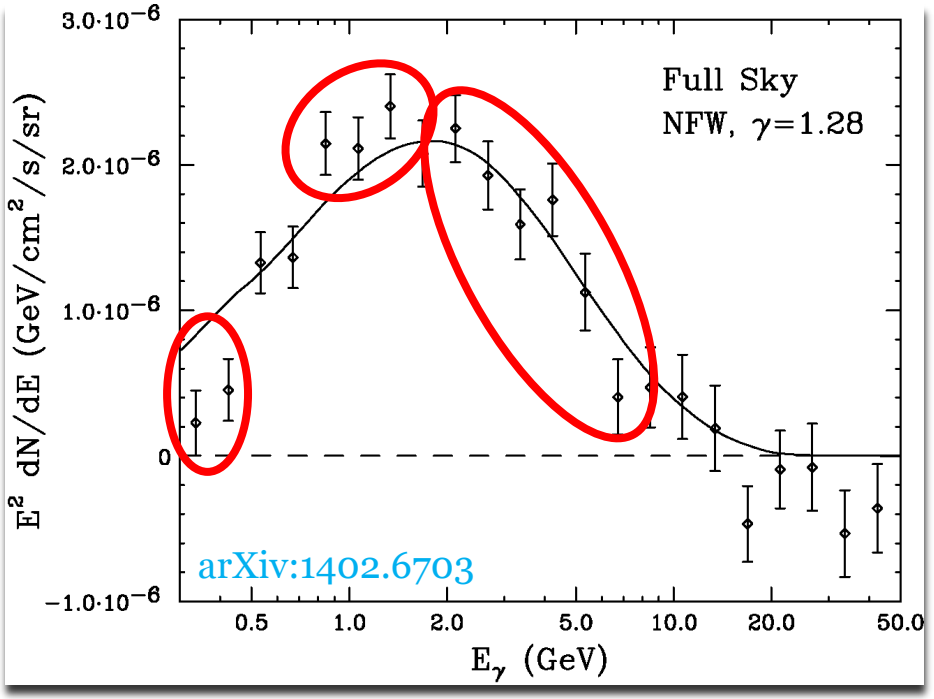


- Fitting function: $f_M(E_\gamma) = N \exp\left[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*} + \frac{E_\gamma^*}{E_\gamma}\right)^p\right]$ with $E_\gamma^* = m_a/2$
- cf. arXiv:1402.6703 → χ^2 /d.o.f.= 64/20 with m_{DM}=43.0 GeV

Doojin Kim & **JCP**, arXiv: 1507.07922

Fit to the GeV γ-ray excess II





- Fitting function: $f_M(E_\gamma) = N \exp\left[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*} + \frac{E_\gamma^*}{E_\gamma}\right)^p\right]$ with $E_\gamma^* = m_a/2$
- cf. arXiv:1402.6703 → χ^2 /d.o.f.= 44/20 with m_{DM}=36.6 GeV

Doojin Kim & **JCP**, arXiv: 1507.07922

Conclusion

- Conventional interpretations on excess in cosmic γ-ray measurements:

  1. Peak: directly into γ + X 2. Bump: into SM particle pairs → γ's

- A novel mechanism enabling us to have a **"continuum bump"**:

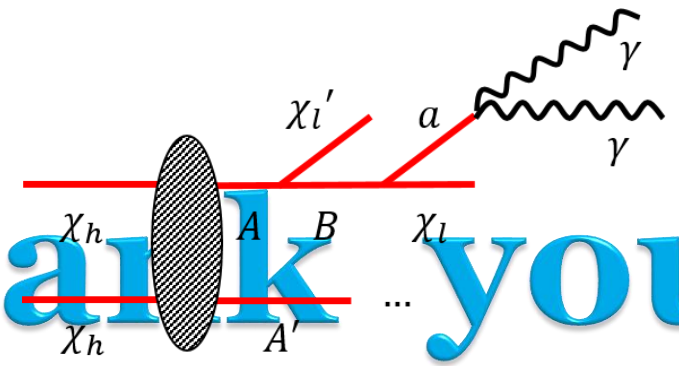
  Dark sector w/ multi-DM's (at least two, e.g., Assisted FO)

  χ_h finally into χ_l + a(→ 2γ), via > 1 step cascade

- Fermi-LAT data ➔ GeV γ-ray excess around the GC:

  reasonable chi square (χ^2/d.o.f.~1)

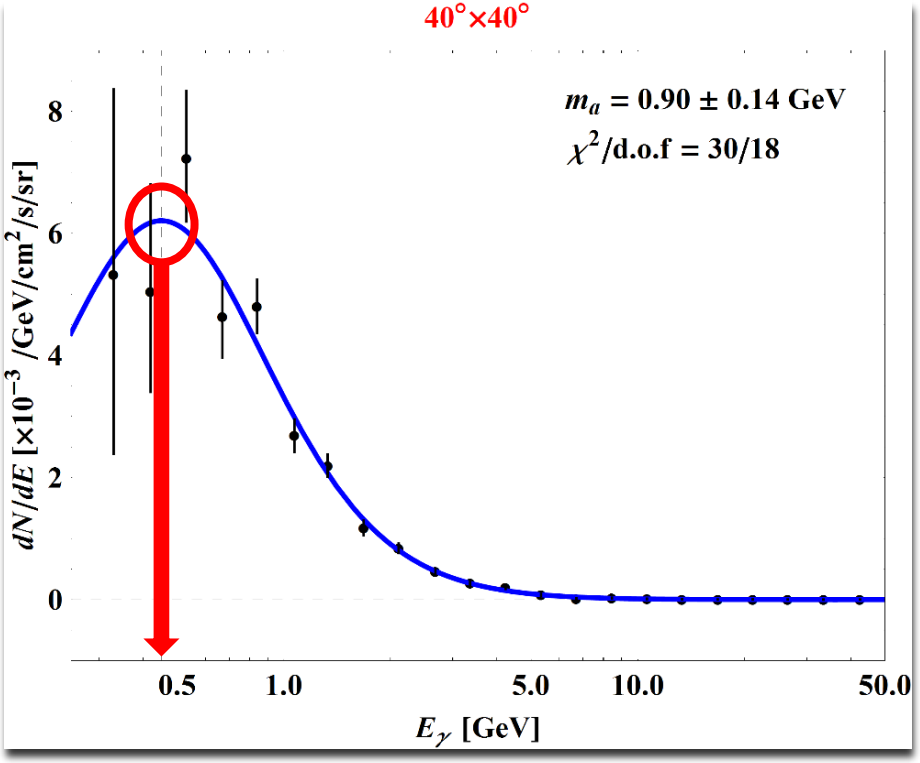
  prediction: m_a ~ 0.9 GeV

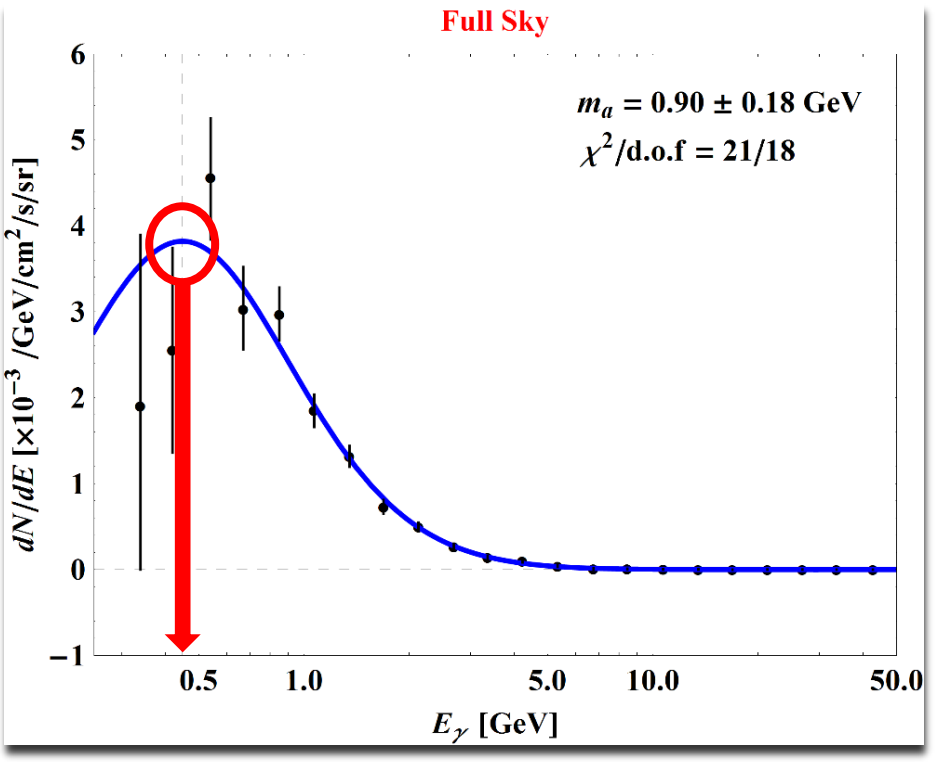


Thank you

Back-Up

Unweighted *E* Spectrum





Doojin Kim & **JCP**, arXiv: 1507.07922