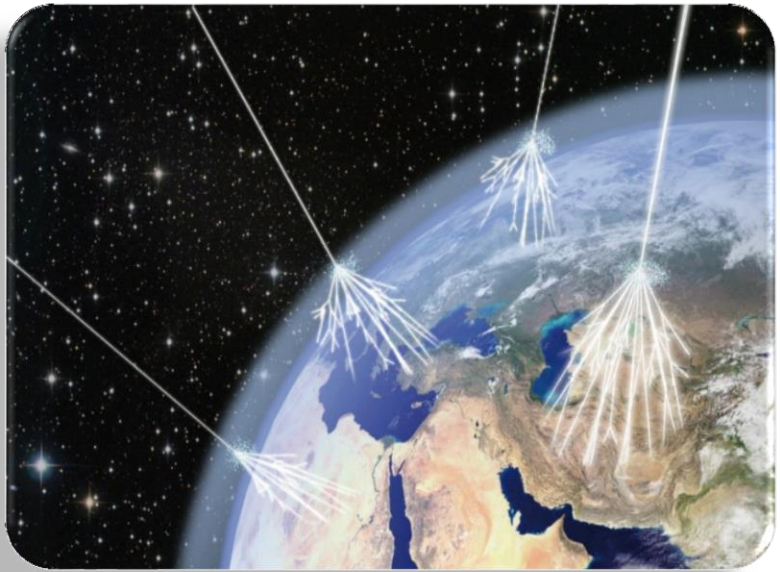
Cosmic Rays from Dark Matter

D. Kim & **JCP** [arXiv:1507.07922] & [arXiv:1508.06640]
&
K. Boddy, K. Dienes, D. Kim, J. Kumar, **JCP** & B. Thomas
[arXiv:1606.07440] & [arXiv:1609.09104]



Jong-Chul Park

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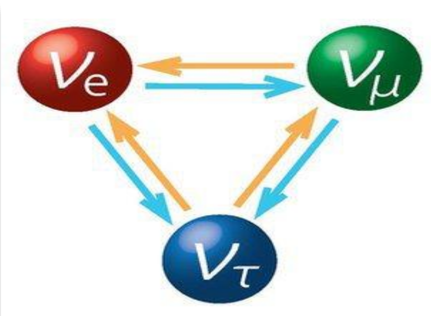
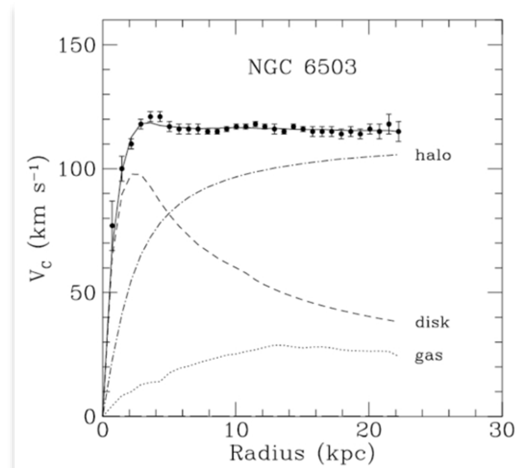
The 6th KIAS Workshop on Particle Physics & Cosmology
The 2nd Durham-KEK-KIPMU-KIAS Joint Workshop
October 25 (2016)

Need for New Physics

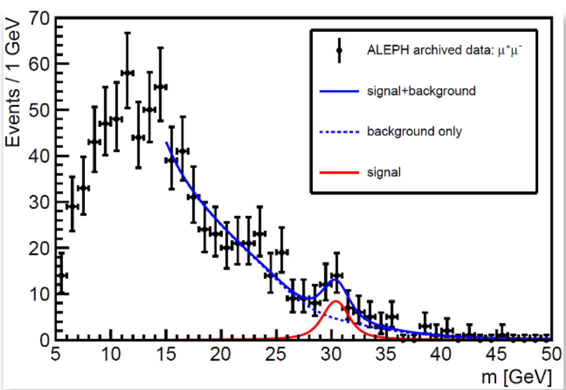
- On top of theory motivation, there are real & hopefully-real motivations for new physics.

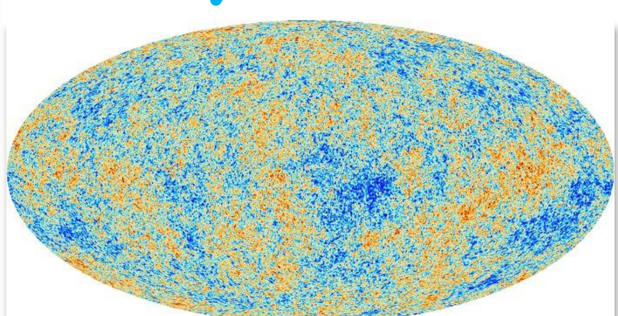
Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, …

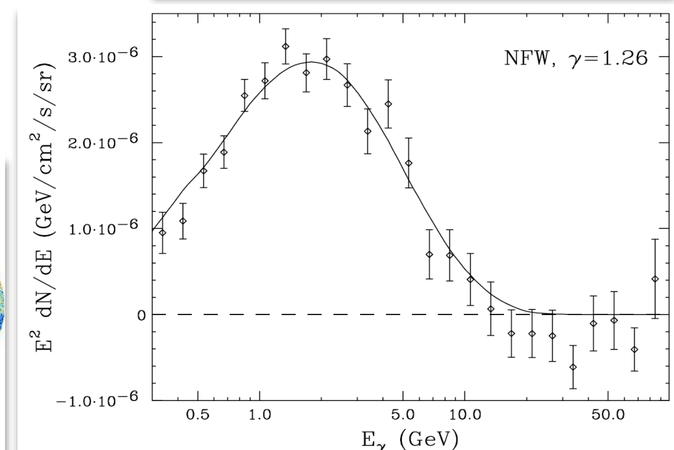




Beyond the Standard Model







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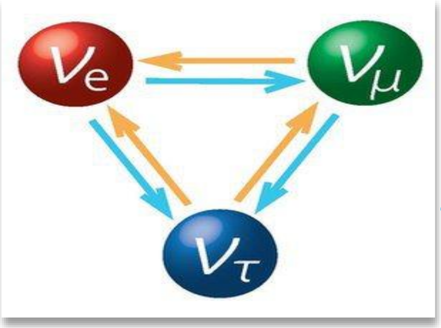

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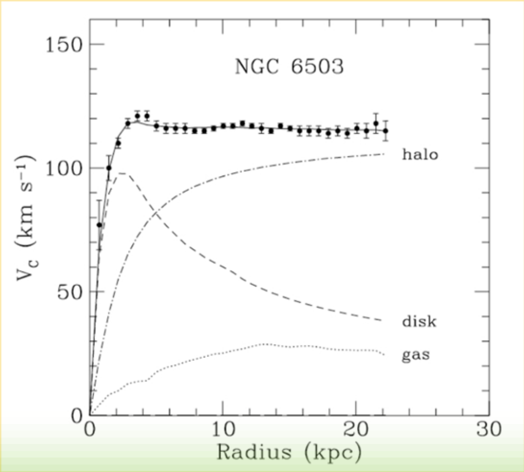
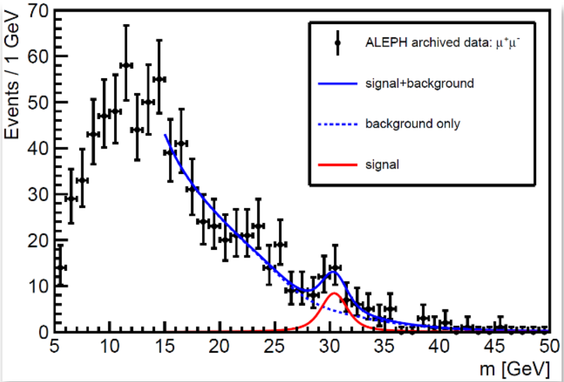
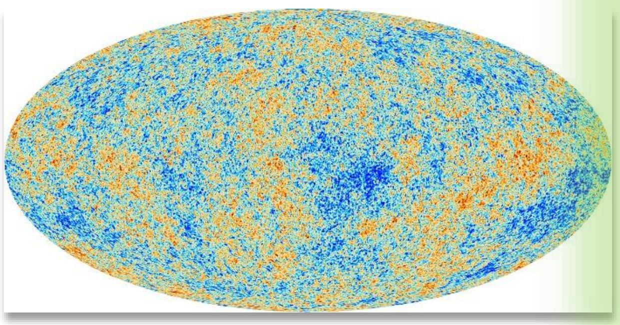
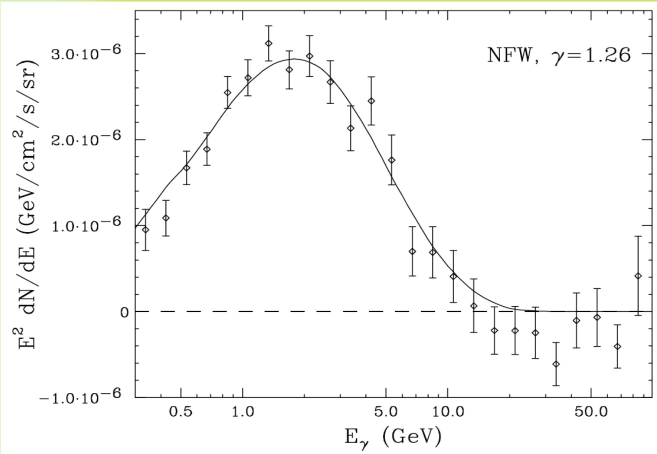








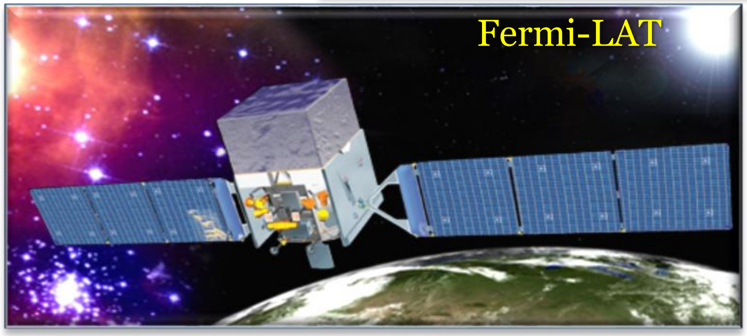
Cosmic-Ray Experiments

❖ Ground-based
MAGIC, HESS, CTA, IceCube, Super-K, Hyper-K, …

❖ Balloon-based
ATIC, PPB-BETS, …

❖ Satellite-based
AMS, DAMPE, Fermi-LAT, PAMELA, INTEGRAL, ASTROGAM, CALET, …

- ✓ Great sensitivity to cosmic-ray signals
- ✓ Better chance to have the information for extracting DM properties



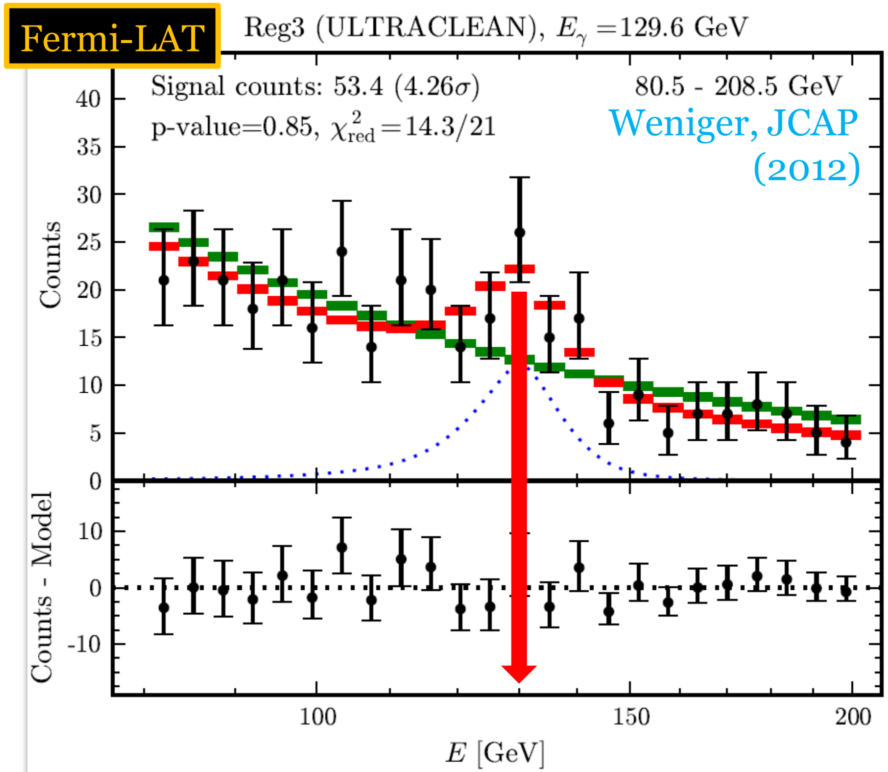
Hints from Cosmic Rays?

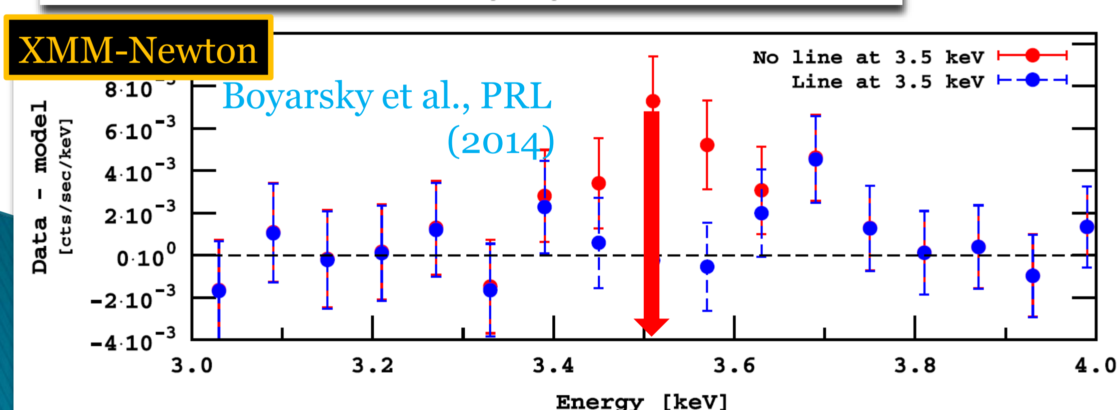
❖ DM signatures in cosmic-ray observations?

- SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line
- PAMELA ($e^\pm$, $p^\pm$, …): e^+ excess
- ATIC (e^-e^+): e^-e^+ excess
- Fermi-LAT (e^-e^+, γ): e^-e^+ excess, 130 GeV line, GeV excess
- AMS-02 ($e^\pm$, $p^\pm$, …): e^+ excess
- XMM-Newton (X-ray): 3.5 keV line
- IceCube (ν): PeV events
- …

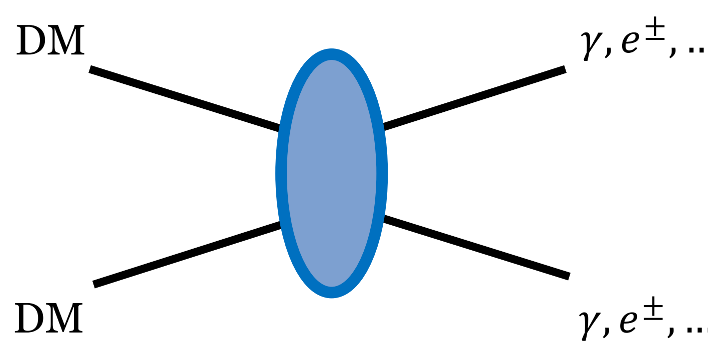
Conventional Approaches

Line-Like Excesses

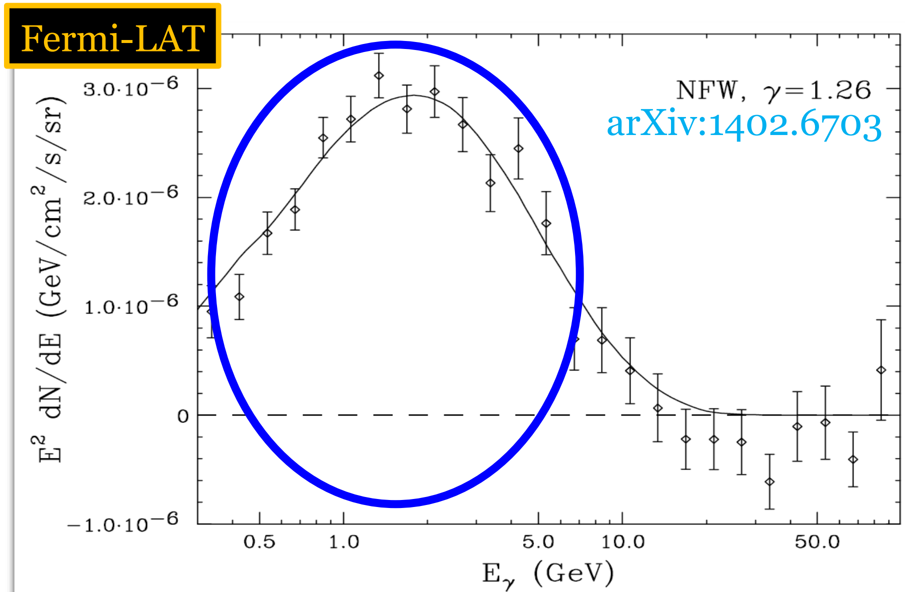


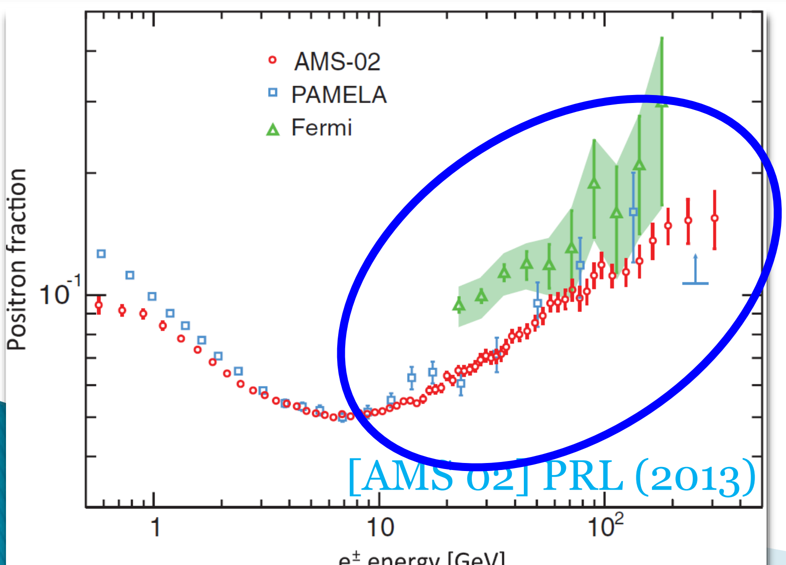


- 3.5 keV line, 511 keV line, 130 GeV line, …
- **Typical DM interpretation**
  - ✓ DM: directly annihilates/decays into 2 (stable) SM particles, γ+X
  - ✓ The location of the line is identified as the (double) mass of DM
  - ✓ Width of the line is instrumental

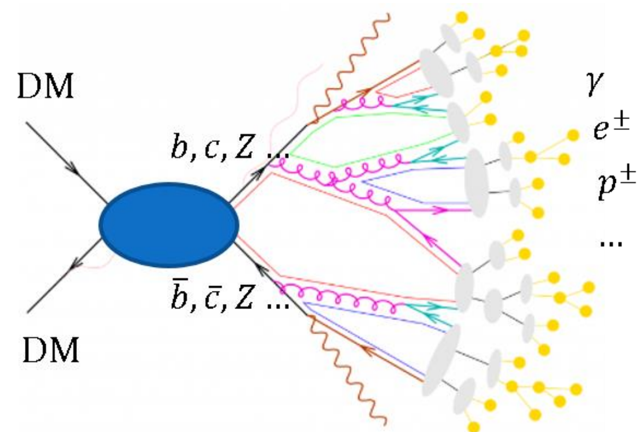


Bump-Like Excesses





- GC GeV γ-ray excess, e^+ excess, …
- **Typical DM interpretation**
  - ✓ DM: directly annihilates/decays into 2 (unstable) SM particles which further goes to stable SM particles through secondary processes
  - ✓ Diffusion mechanism for charged particles
  - ✓ Shape information (including the peak position): highly model-dependent



Minimal vs Non-minimal

❖ Scenario with a single DM species

✓ Simplest & well-motivated scenario

✓ Stability of DM ensured (typically) by a discrete symmetry

✓ Popular models having a single type of DM candidate:

- SUSY models with R-parity

- Extra-D models with KK-parity

- Little Higgs models with T-parity

Minimal vs Non-minimal

- Scenario with multiple DM species
  - ✓ Nothing stops from having more stable particles
    - \- Visible sector (SM) has many stable particles
    - \- Rising interest in non-minimal scenarios

Minimal vs Non-minimal

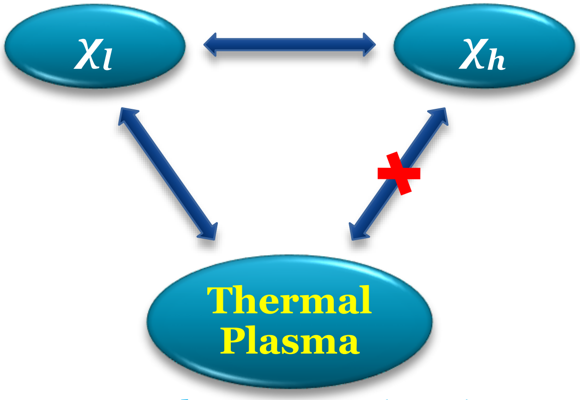
❖ Scenario with multiple DM species

✓ Nothing stops from having more stable particles

- Visible sector (SM) has many stable particles

- Rising interest in non-minimal scenarios

✓ Assisted freeze-out



E. J. Chun & **JCP** (2011)
G. Belanger & **JCP** (2011)

Minimal vs Non-minimal

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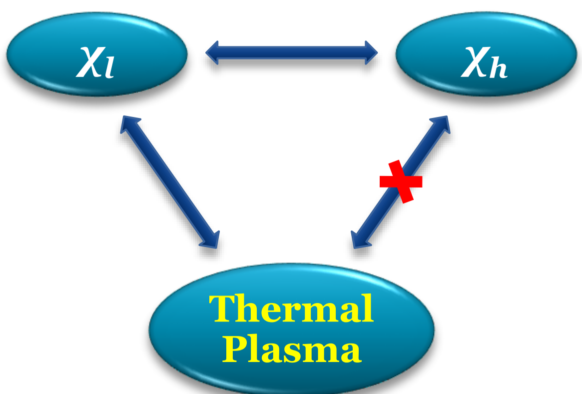
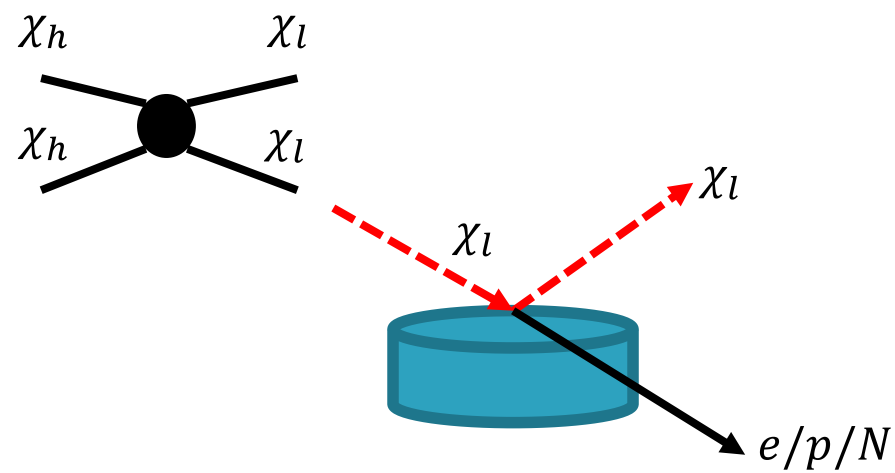


E. J. Chun & **JCP** (2011)
G. Belanger & **JCP** (2011)

✓ Boosted DM



K. Agashe, Y. Cui, L. Necib, J. Thaler (2014)
KC Kong, G. Mohlabeng & **JCP** (2014)

Minimal vs Non-minimal

❖ Scenario with multiple DM species: Dynamical DM framework

- ✓ DDM framework: the dark sector comprises a potentially vast ensemble of individual particle species χ_n whose cosmological abundances Ω_n are balanced against their decay width Γ_n in such a way as to ensure consistency with observational data.

K. Dienes & B. Thomas (2011)

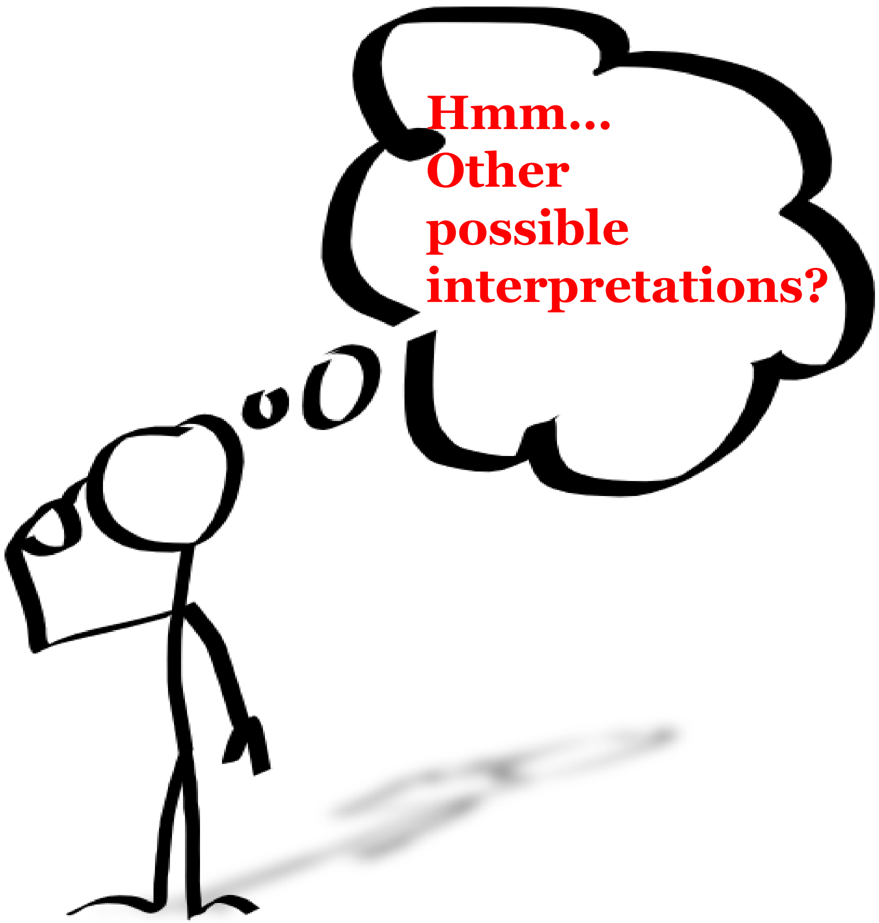
- ✓ Mass parameters (generic parameterization)

$$m_n = m_0 + n^{\delta} \Delta m$$

δ:mass scaling parameter, Δm: mass splitting/gap

- ✓ Parameterizing the fluxes Φ_n by a single power law with a scaling parameter ξ

$$\Phi_n = \Phi_0 \left(\frac{m_n}{m_0}\right)^{\xi} = \Phi_0 \left(\frac{\sqrt{s_n}}{\sqrt{s_0}}\right)^{\xi}$$

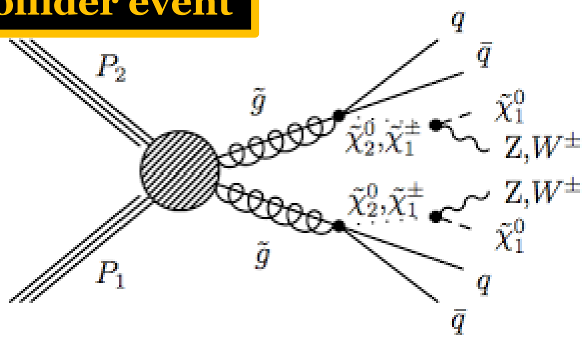

Hmm…
Other
possible
interpretations?

Energy Peak in Cosmic-Rays

❖ With DM interpretation in mind, we propose alternative mechanisms based on the observation of the "*Energy-Peak*" in collider physics to explain cosmic-ray excesses.

❖ Why E-Peak?

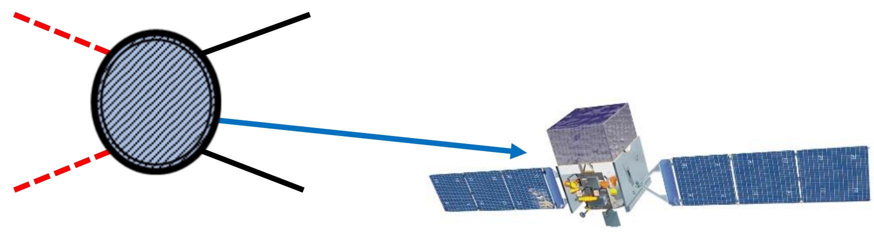
A collider event



- Large multiplicity

- Momentum w.r.t. the beam line

A DM indirect detection event



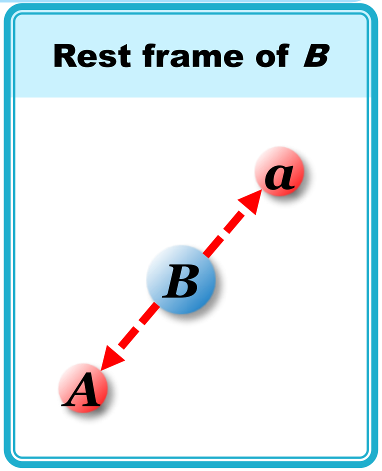
- Energy is the only available quantity

✓ Unique spectral features from 1st principle irrespective of underlying DM model details (vs. highly model-dependent in the conventional interpretation)

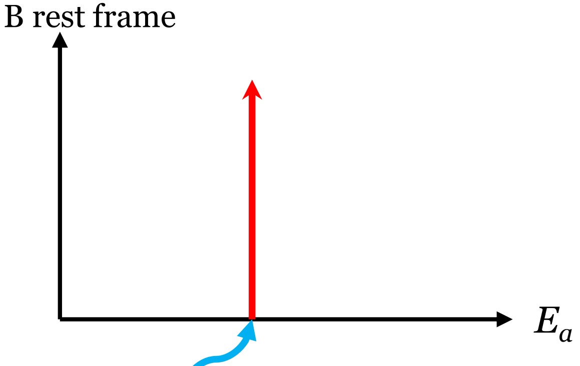
E-Peak: a Quick Review

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



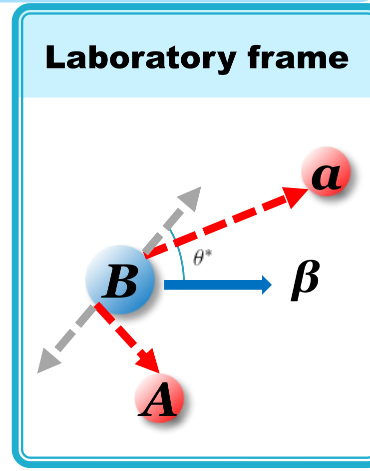
$$E_a^* = \frac{m_B^2 - m_A^2}{2m_B}$$

- E_a^* measured & m_A known, → m_B determined, vice versa

Based on Doojin Kim's talk @ Brookhaven Forum 2015

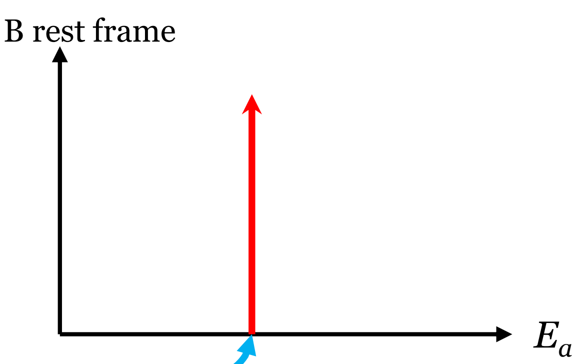
E-Peak: a Quick Review

Two-body decay kinematics



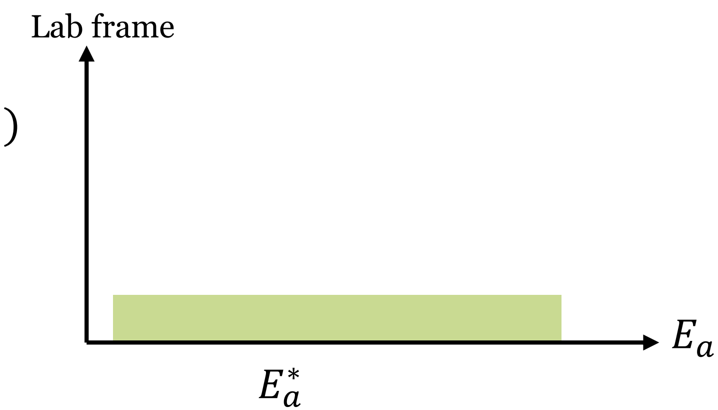
A simple 2-body decay of a heavy resonance B into A and massless visible a

- ❑ Energy of visible particle a is monochromatic & simple function of masses



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

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



- ❑ E_a^* measured & m_A known,
  → m_B determined, vice versa

- ❑ Rectangular spectrum containing E_a^* for any B boost γ

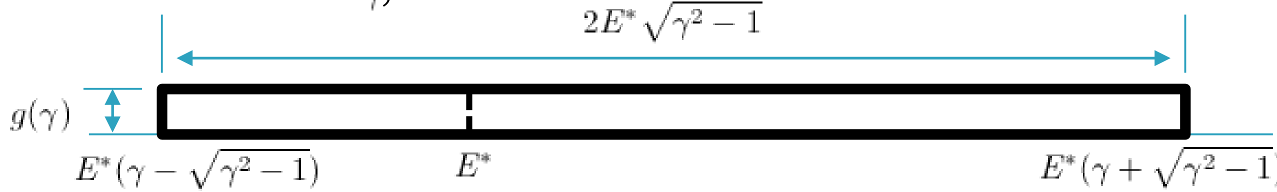
Based on Doojin Kim's talk @ Brookhaven Forum 2015

E-Peak: a Quick Review

"stacking up" rectangles

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

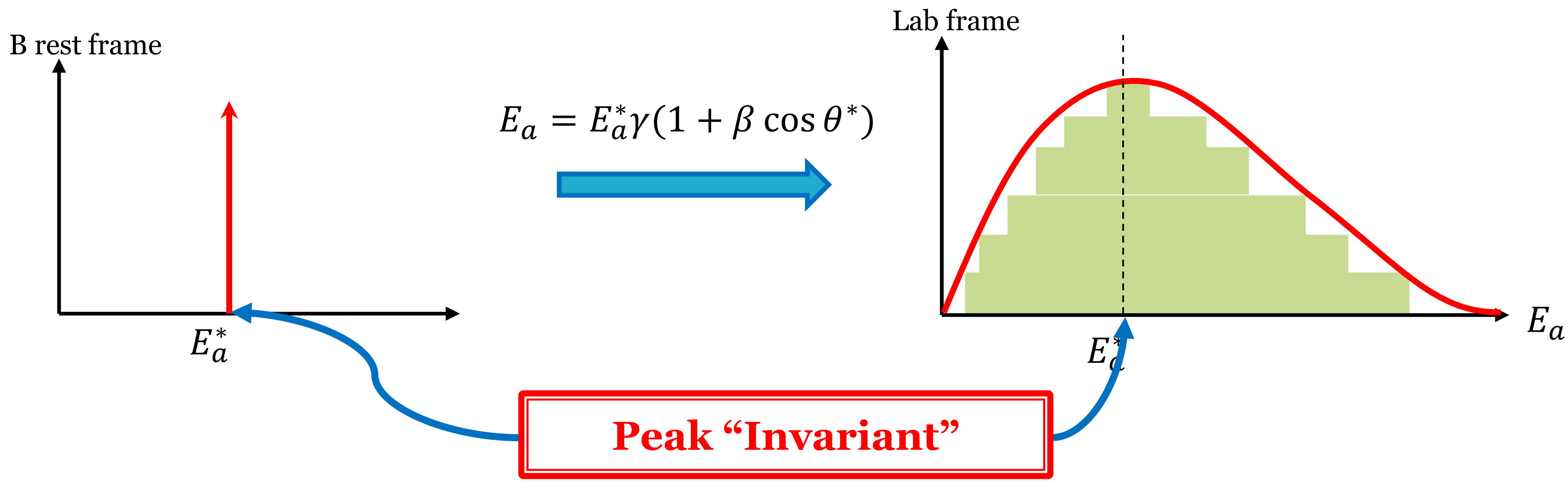
- ❑ For any given Lorentz factor γ,



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

  → ***"Stacking up" rectangles*** weighted by boost distribution of particle B

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

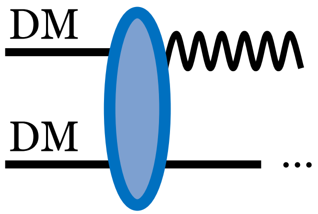


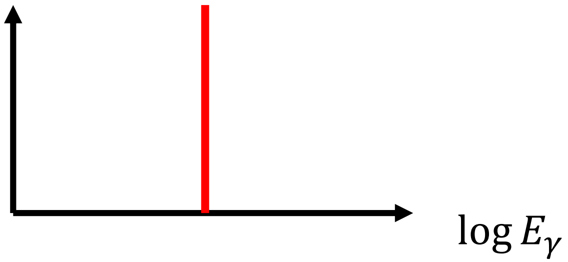
Based on Doojin Kim's talk @ Brookhaven Forum 2015

Applications

Dark Sector Cascade

o-step cascade

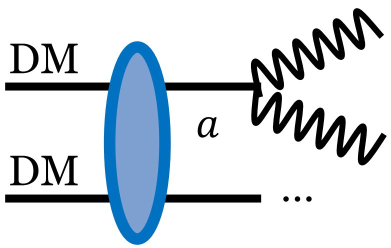


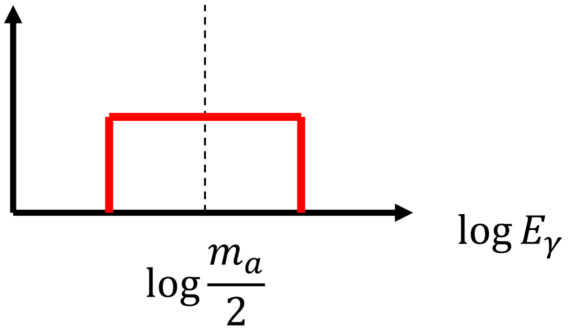


- ❑ Simplest and conventional model
- ❑ Featured by a sharp peak

Dark Sector Cascade

1-step cascade

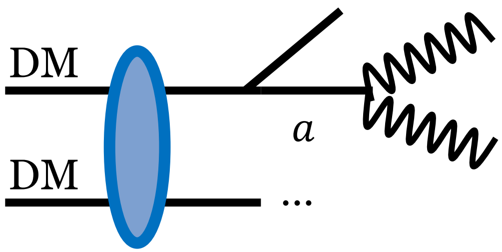


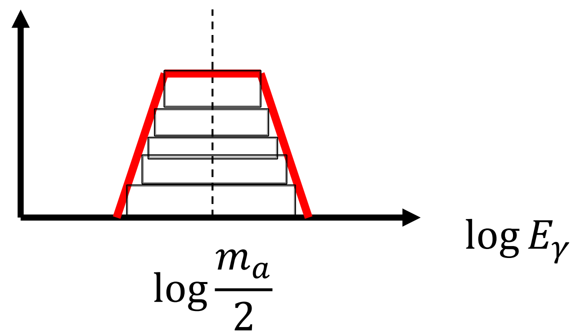


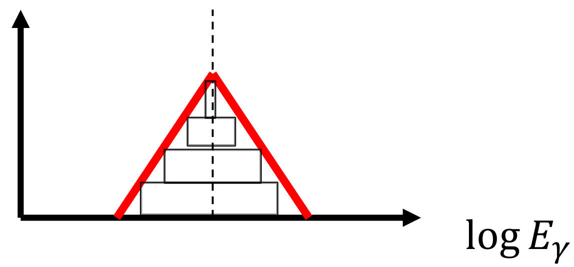
- ❑ Introducing an on-shell intermediary state directly decaying into two photons (e.g. dark pion, ALP)
- ❑ Featured by a box-like distribution

Dark Sector Cascade

2-step cascade







- Introducing an on-shell intermediary 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
- Alternative mechanism for cosmic-ray peaks

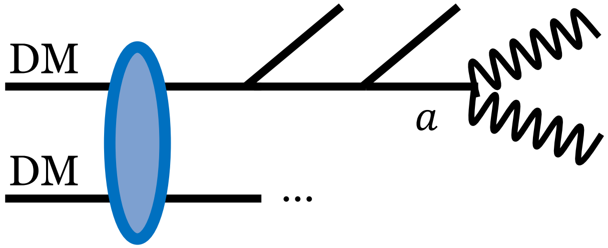
  e.g. 130 GeV/3.5 keV lines

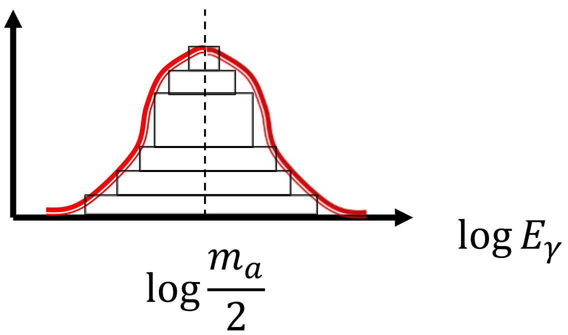
  D. Kim & **JCP** [PLB (2015)]

Later

Dark Sector Cascade

3-step cascade



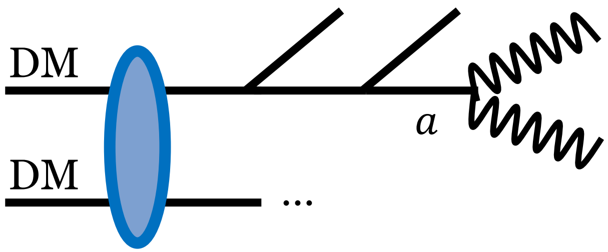


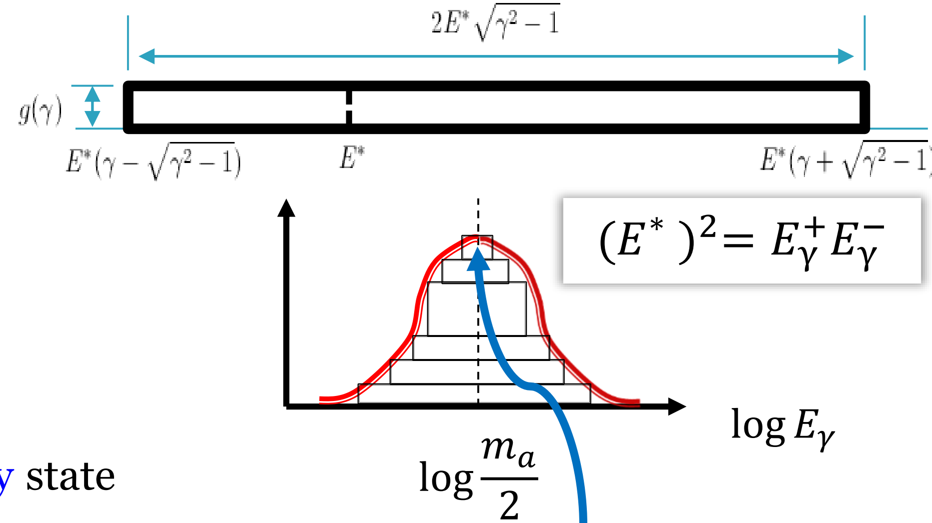
- Introducing one more on-shell intermediary state before the state decaying into two photons
- Developing a smoothly rising-and-falling shape
- Generic distribution function:

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

Dark Sector Cascade

3-step cascade



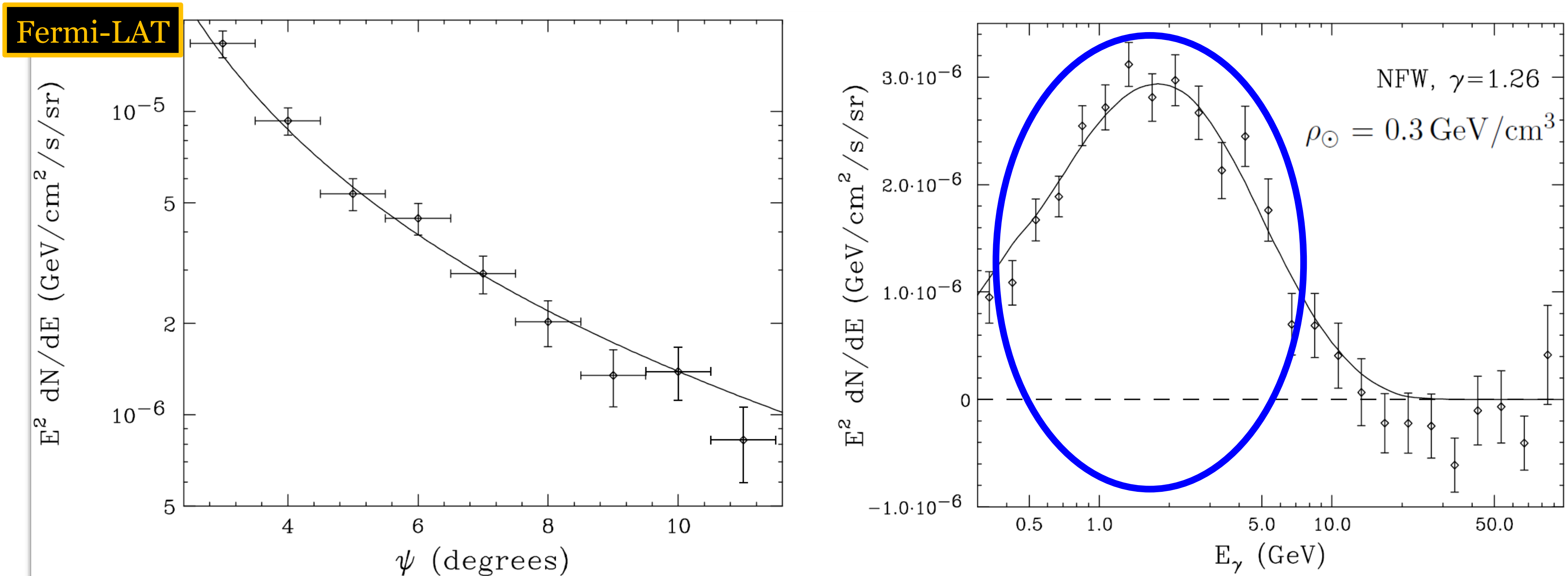


Symmetric w.r.t the peak in **logarithmic E_γ**

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

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

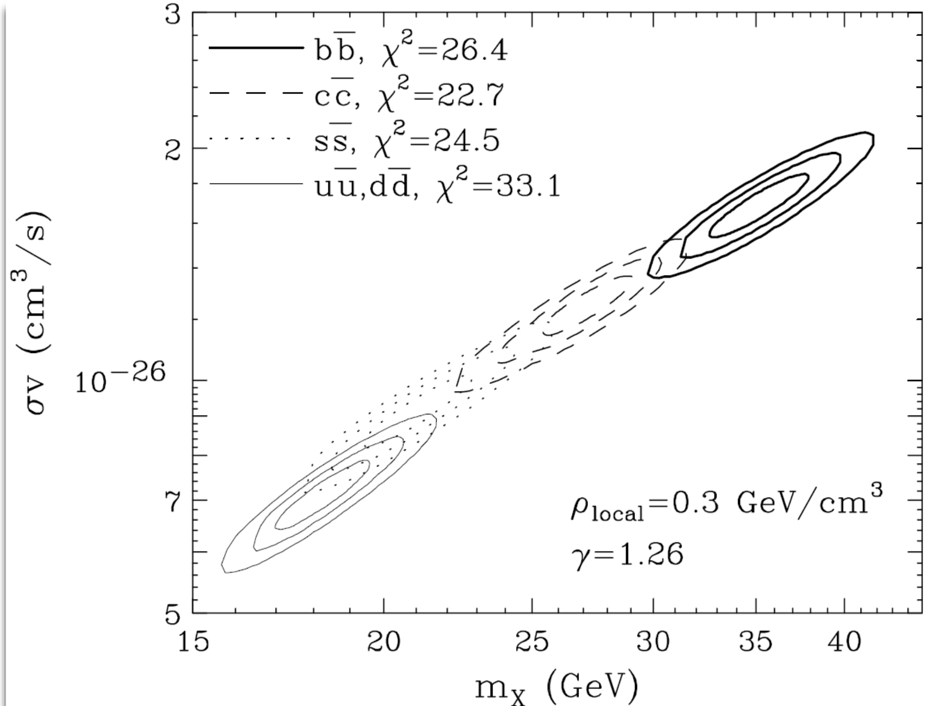
Bump: Features of GeV Excess

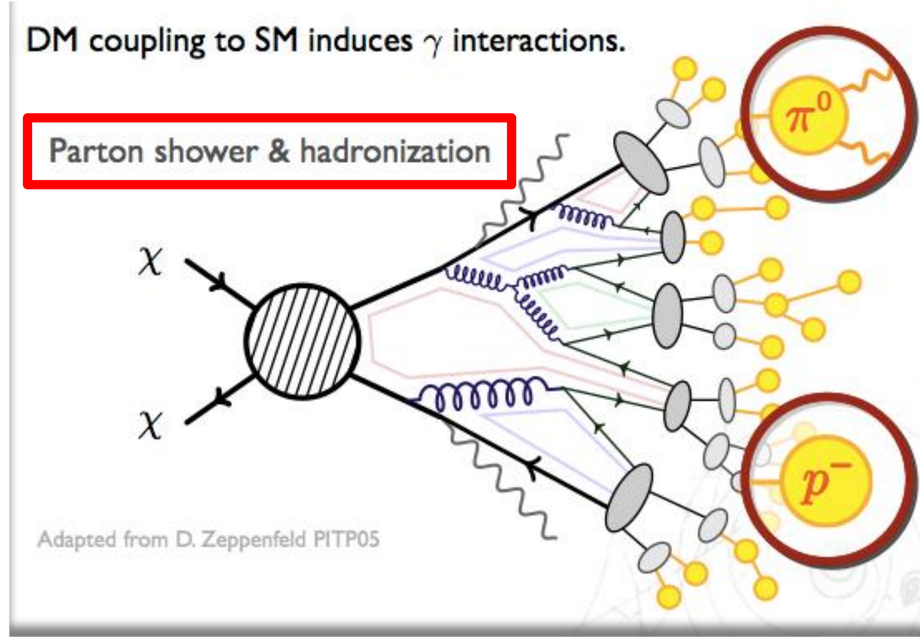


- Signal: extended to > 10° from the GC → disfavor point sources
- Consistent with the dynamical center of the Milky Way (< 0.05°)
- The spectrum of the excess peaks at 1-3 GeV.

arXiv:1402.6703

Bump: Conventional Approach

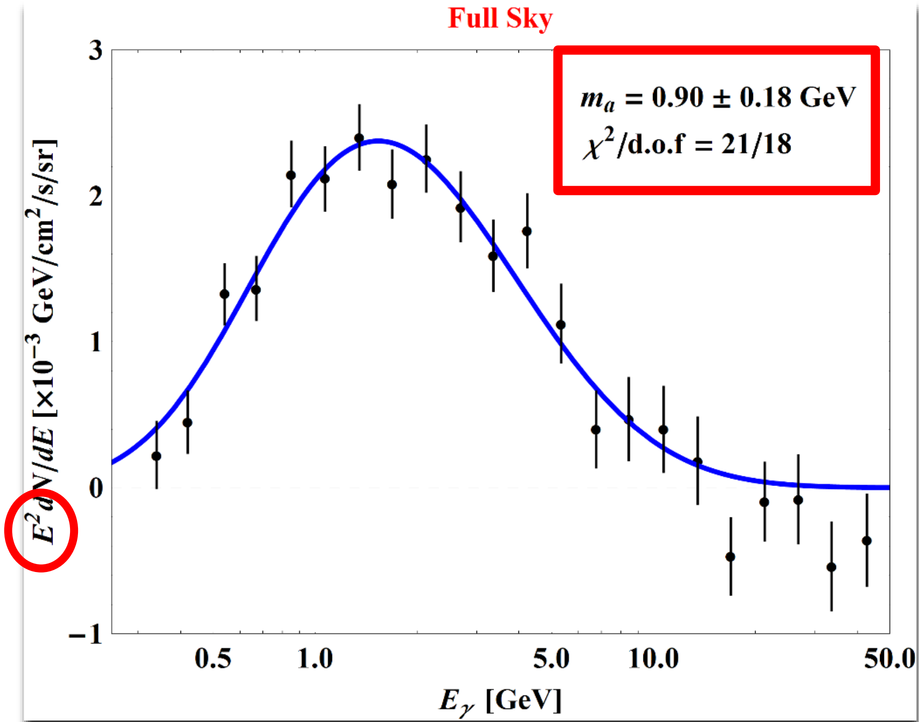




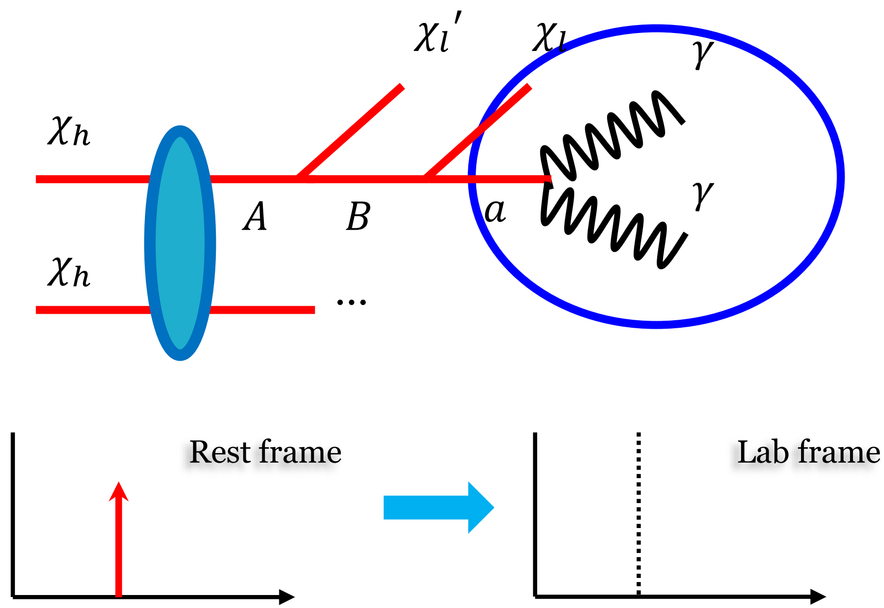
- The spectrum is in good agreement with the predictions from 20-40 GeV DM mostly annihilating to quarks (fragmentation, IC, bremsstrahlung, ...).
- Required cross section is ~ 0.7-2.1 · 10^{-26} cm³/s

arXiv:1402.6703

Dark Cascade: GeV γ-ray Bump



- Multi-step cascade decay!



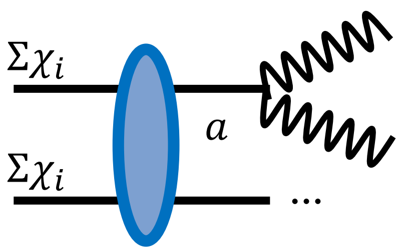
- Fitting function: $f_M(E_\gamma) = N \exp\left[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*} + \frac{E_\gamma^*}{E_\gamma}\right)^p\right]$ with $E_\gamma^* = m_a/2$
- cf. arXiv:1402.6703 (bb) → χ^2 /d.o.f.= 44/20 with $m_{\rm DM}$=36.6 GeV

D. Kim & **JCP**, Phys Dark Univ (2016)

Multi-Component DM Models

Mechanism

- What if there exist multiple DM species? What if the collection of DM particles have sufficiently small mass gaps (smaller than relevant energy resolution)?

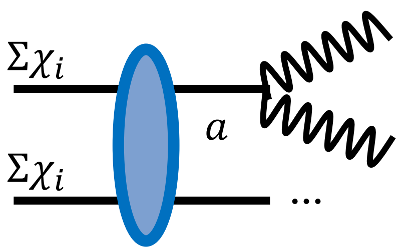


K. Boddy, K. Dienes, D. Kim, J. Kumar,
JCP, and B. Thomas (2016)

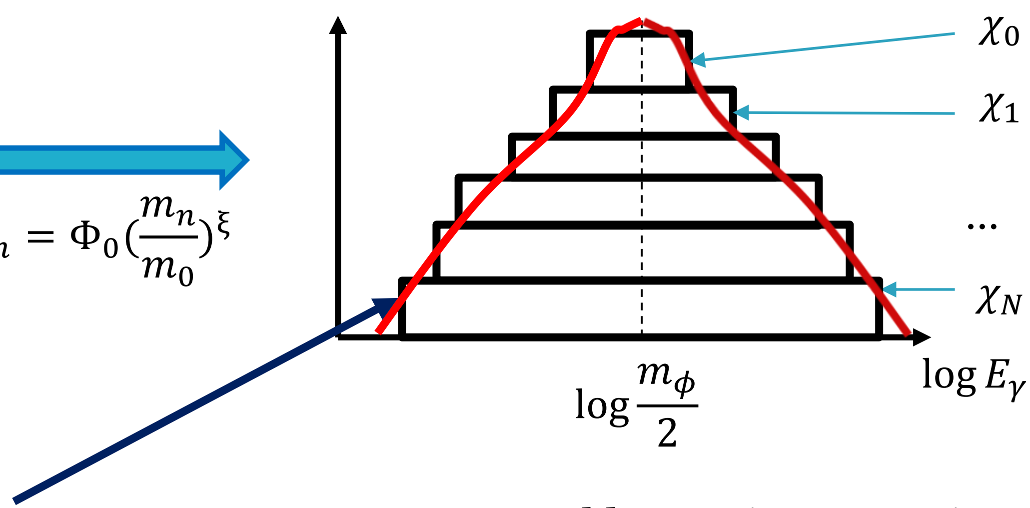
Multi-Component DM Models

Mechanism

- What if there exist multiple DM species? What if the collection of DM particles have sufficiently small mass gaps (smaller than relevant energy resolution)?
- Obtaining continuum energy spectra not by cascade decays, but by **increasing the number of DM species**



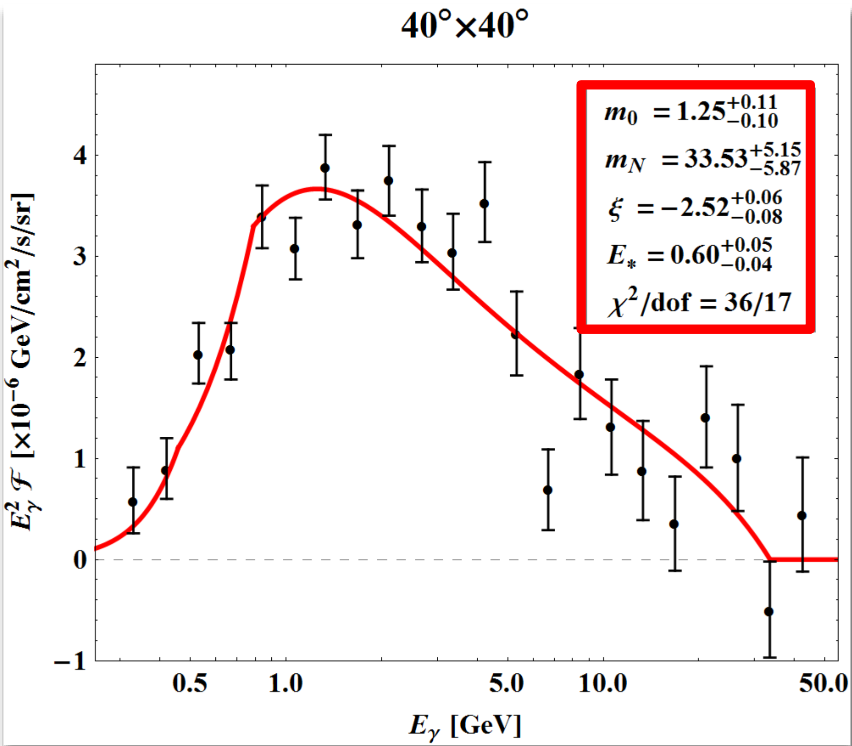
$$\Phi_n = \Phi_0 \left(\frac{m_n}{m_0}\right)^{\xi}$$

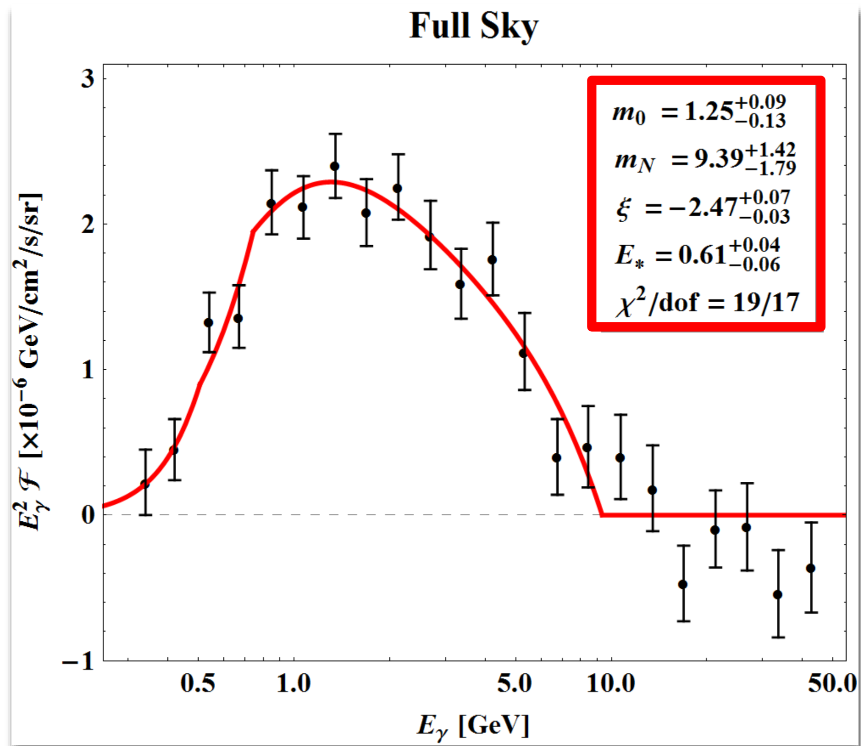


mass gap ≪ energy resolution

K. Boddy, K. Dienes, D. Kim, J. Kumar, **JCP**, and B. Thomas (2016)

Fit Results to GeV γ-ray Bump





- Data reproduced well enough (see χ^2 values)
- cf. arXiv:1402.6703 (bb) → χ^2 /d.o.f.= 64/20 (44/20) with $m_{\rm DM}$=43.0 (36.6) GeV

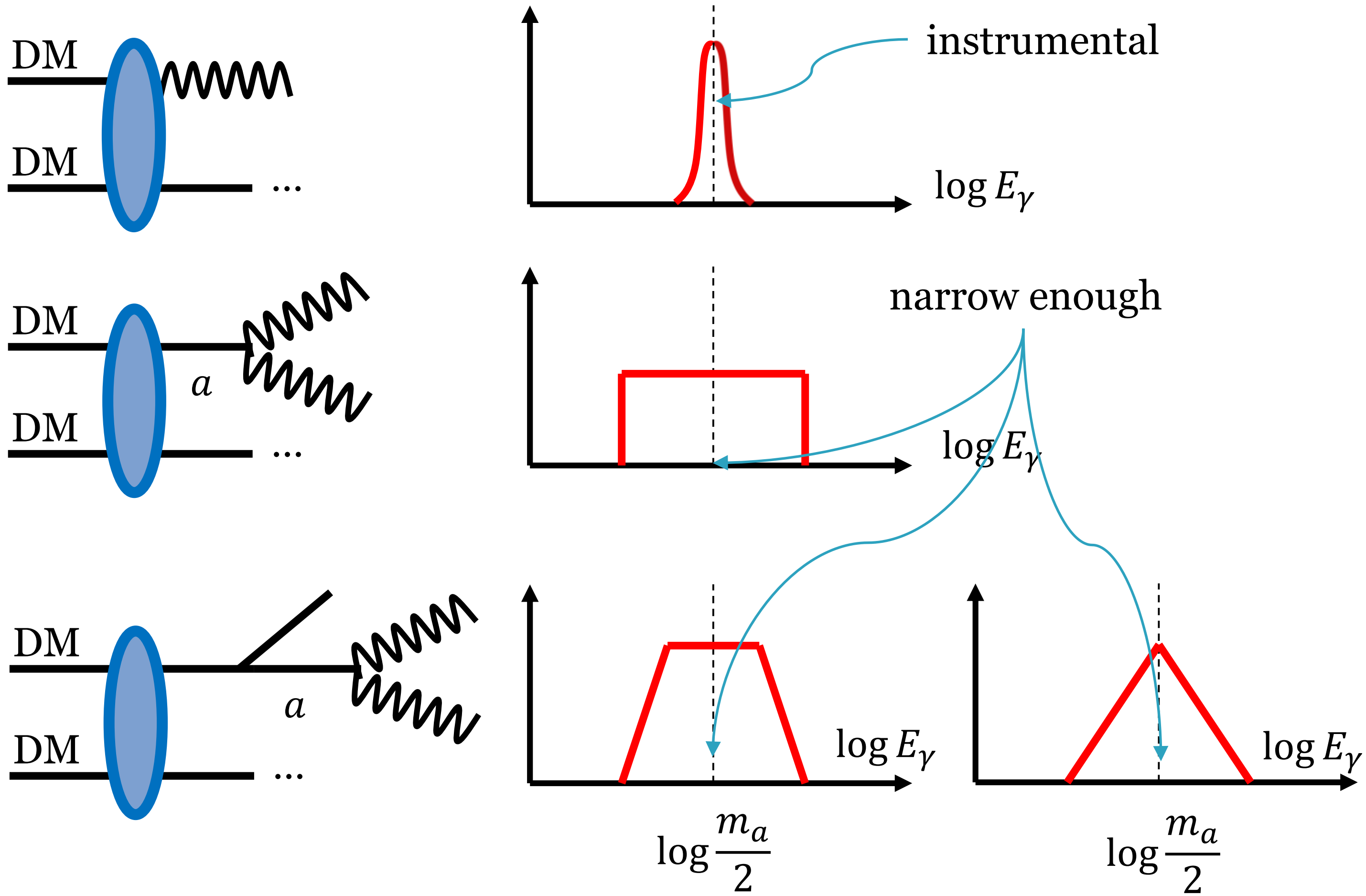
K. Boddy, K. Dienes, D. Kim, J. Kumar, **JCP**, and B. Thomas (2016)

Line-like Excesses

Models explaining line-like signals

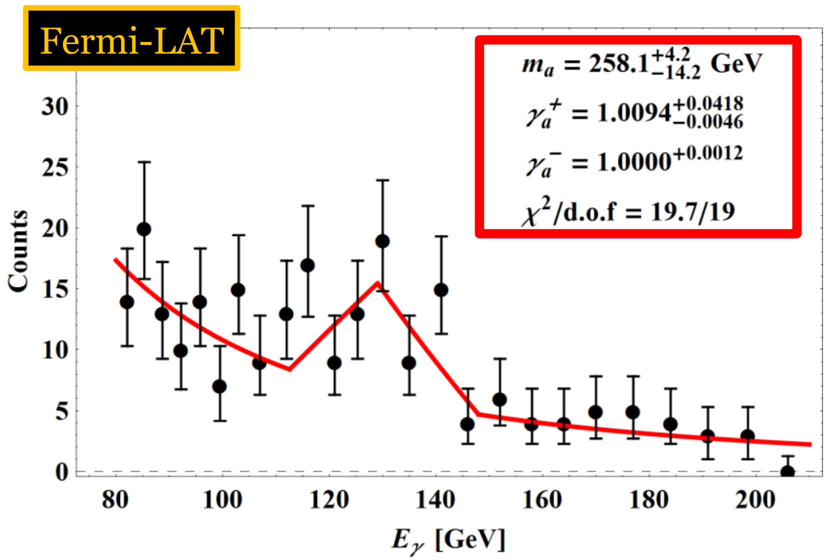
- ❑ Scenario I
- ❑ Scenario II
- ❑ **Scenario III**

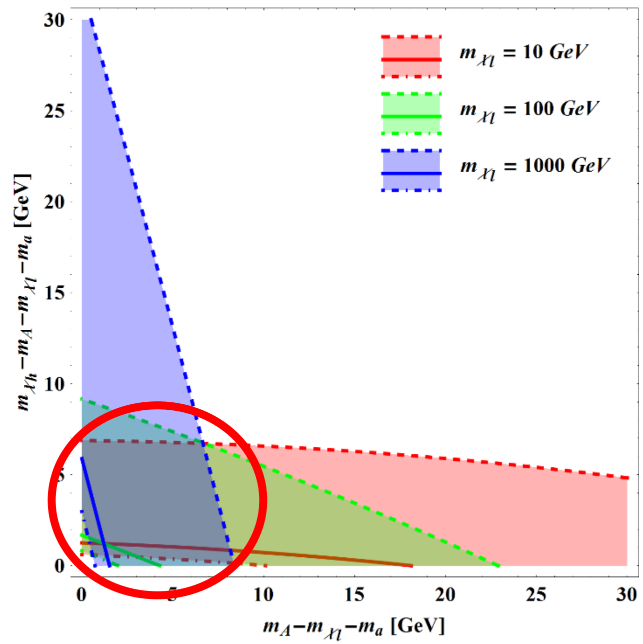
[D. Kim & **JCP**, PLB (2015)]



Line-like Excesses

Application to 130 GeV line



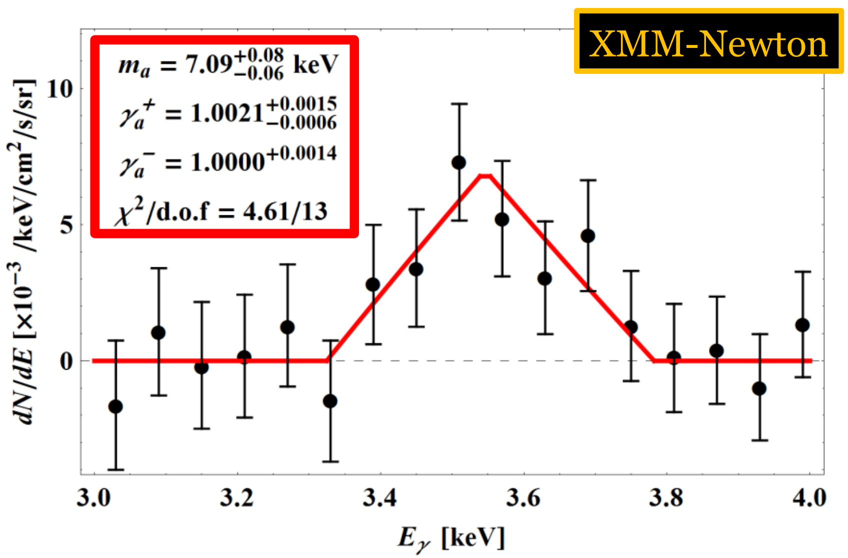


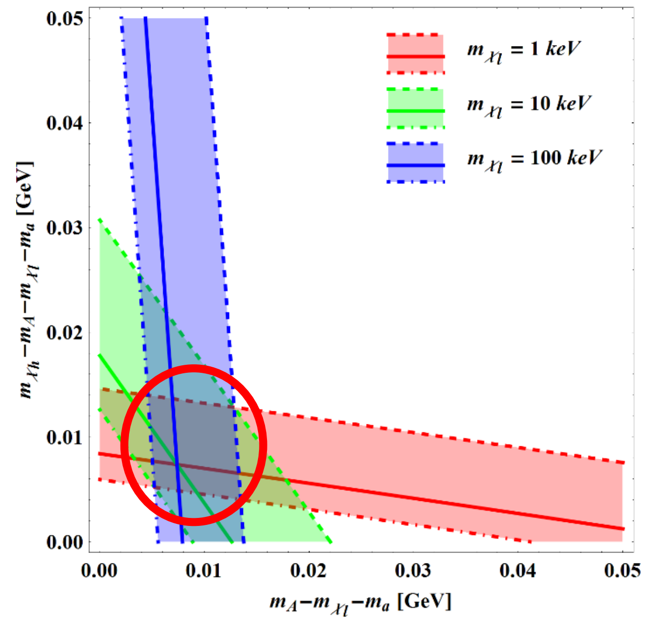
- Data extracted from the ULTRACLEAN event class in arXiv:1204.2797
- Power-law background template considered simultaneously

Doojin Kim & **JCP**, PLB (2015)

Line-like Excesses

Application to 3.5 keV line





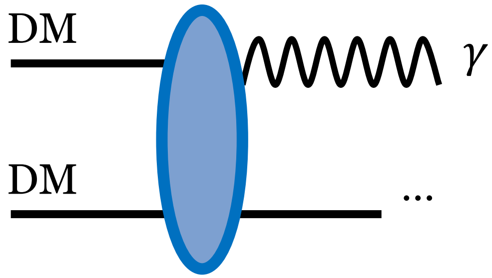
- Data extracted from the MOS spectrum of the central region of the galaxy M31 in arXiv:1402.4119
- Signal template only considered

Doojin Kim & **JCP**, PLB (2015)

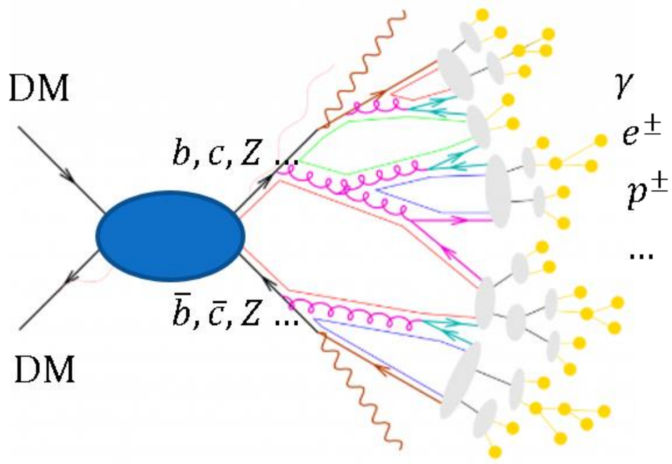
Conclusions

➢ Conventional DM interpretations on cosmic/γ-ray excesses:

1. Line: directly into γ + X



2. Bump: into SM particle pairs → γ's



Conclusions

- Conventional DM interpretations on cosmic/γ-ray excesses:

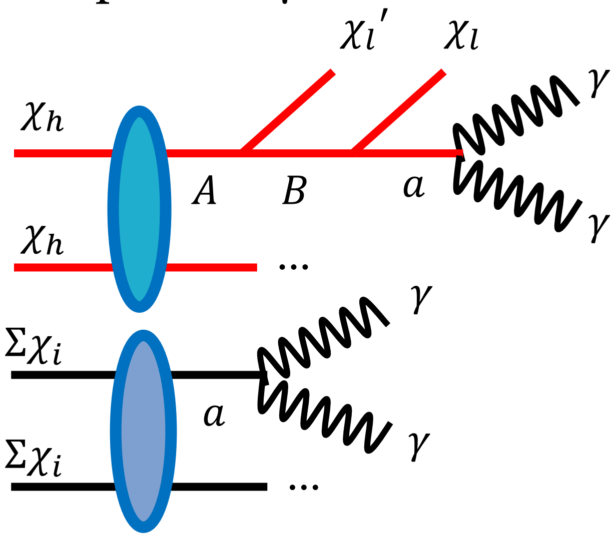
  1. Line: directly into γ + X 2. Bump: into SM particle pairs → γ's

- **Alternative mechanisms** using **E-peak idea**:

  Non-minimal DM sector (e.g., Assisted FO, DDM, …)

  1. χ_h finally into χ_l + a(→ 2γ) via ≥ 1(2) step cascade

  2. $\Sigma\chi_i$ into X + a(→ 2γ)

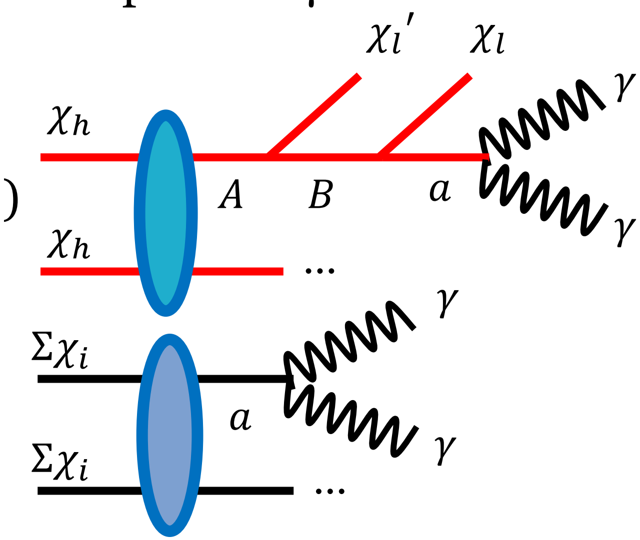


- Reasonable χ^2 fits (χ^2/d.o.f.~1)

Conclusions

- Conventional DM interpretations on cosmic/γ-ray excesses :

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



- **Alternative mechanisms** using **E-peak idea**:

  Non-minimal DM sector (e.g., Assisted FO, DDM, …)

  1. χ_h finally into χ_l + a(→ 2γ) via ≥ 1(2) step cascade

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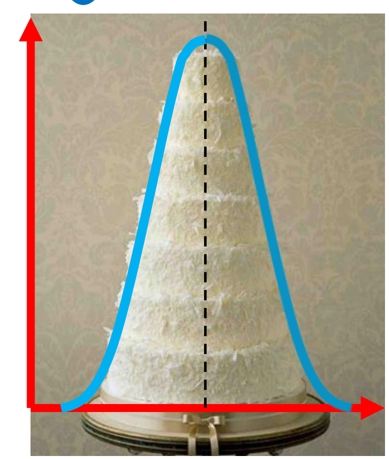
- Reasonable χ^2 fits (χ^2/d.o.f.~1)

- Symmetric w.r.t the peak in logarithmic E_γ

  → prediction: m_a



Thank you