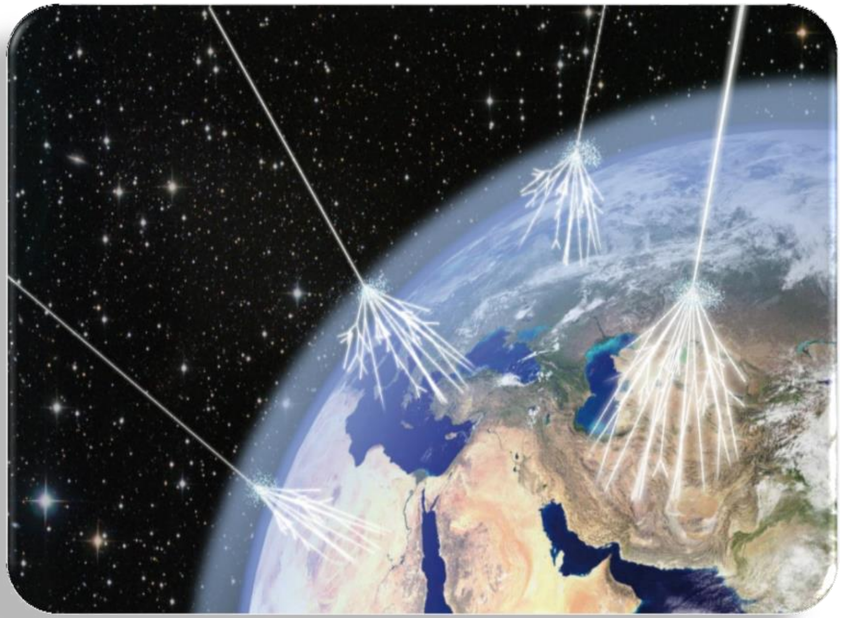
How can we get cosmic-rays from dark matter?

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]



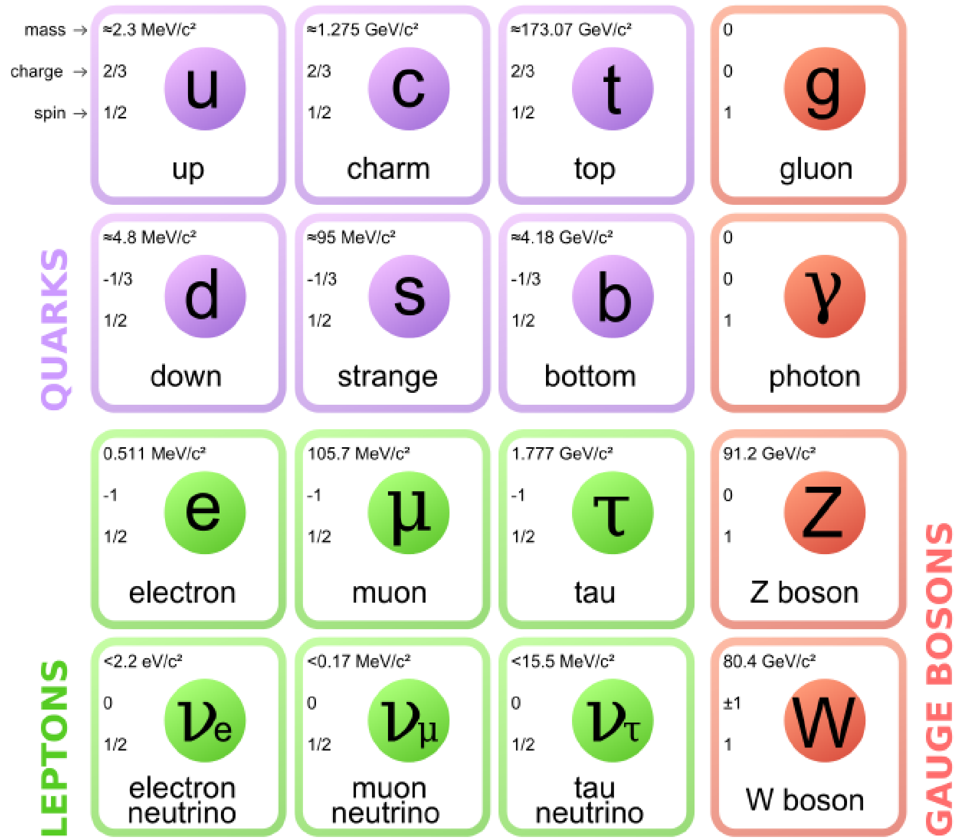
Jong-Chul Park

CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

DM from aeV to ZeV: IBS-MultiDark-IPPP Workshop

November 24 (2016)

Standard Model (SM)



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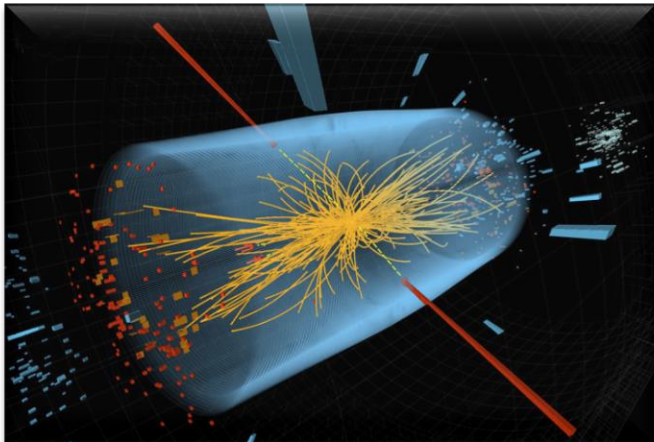

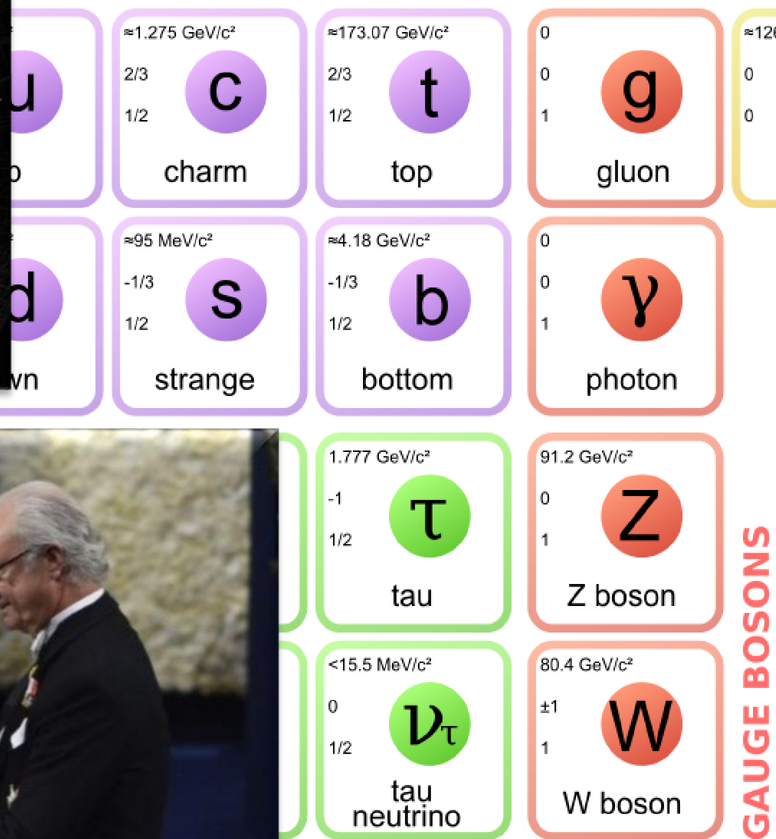


NEED
ORK!

SM is not the end of the story

Need for New Physics

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

Beyond the Standard Model

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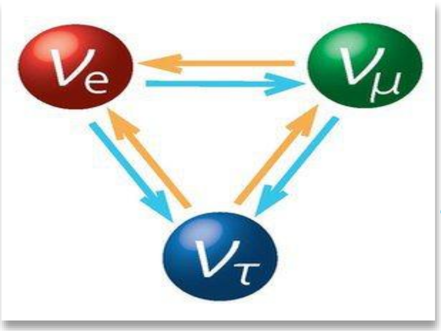
Neutrino



Beyond the Standard Model

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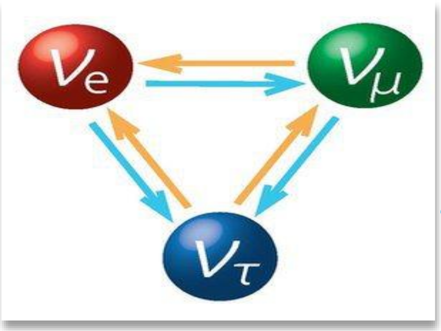
Neutrino, Dark Matter



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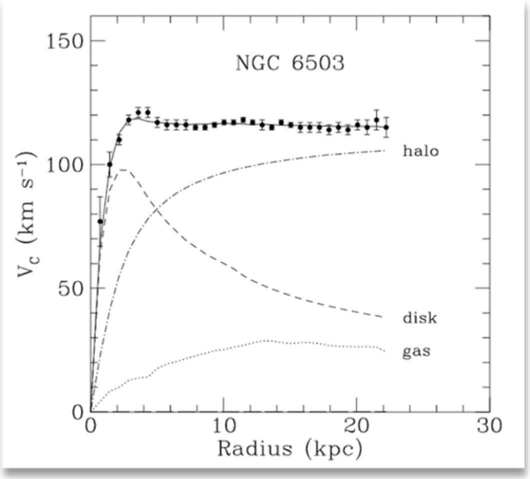

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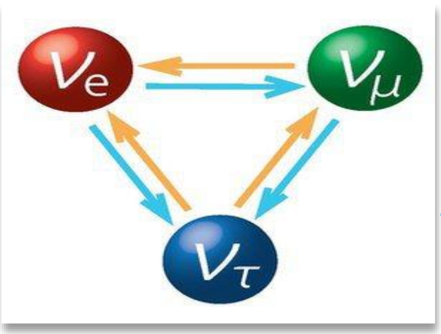
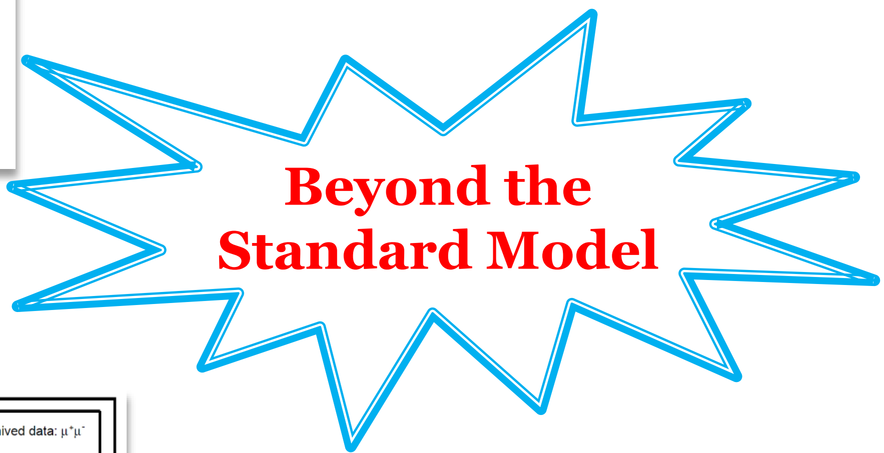
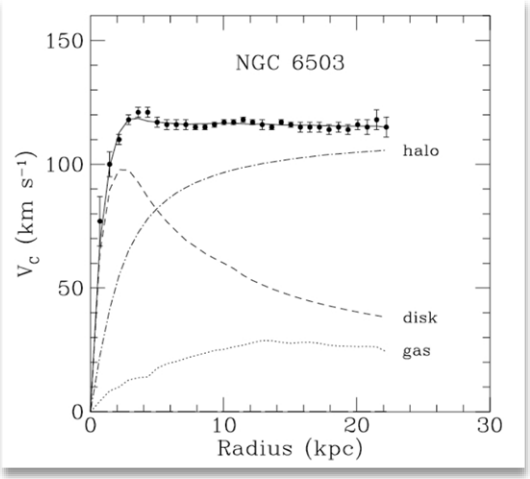
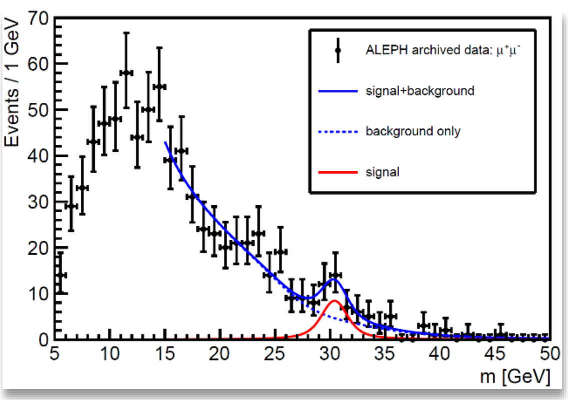
Neutrino, Dark Matter, Collider









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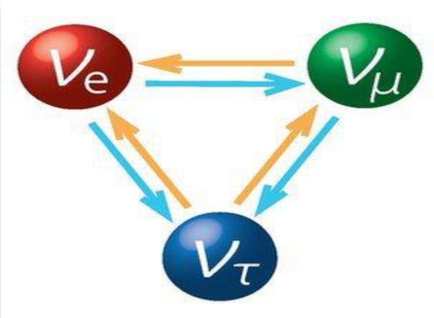
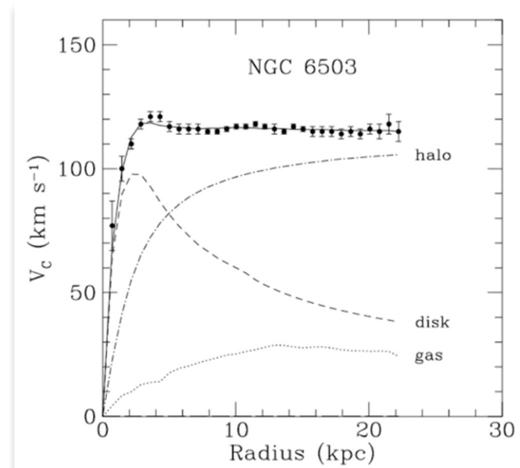
Neutrino, Dark Matter, Collider, Cosmic-Ray





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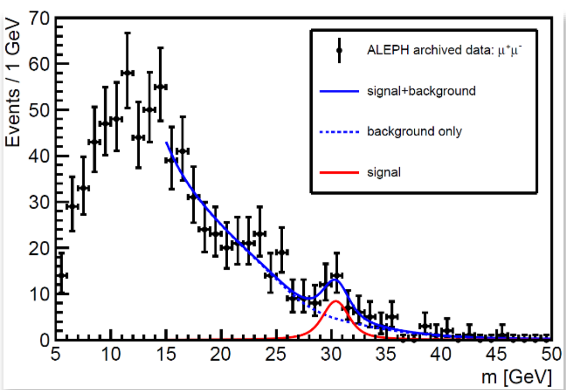

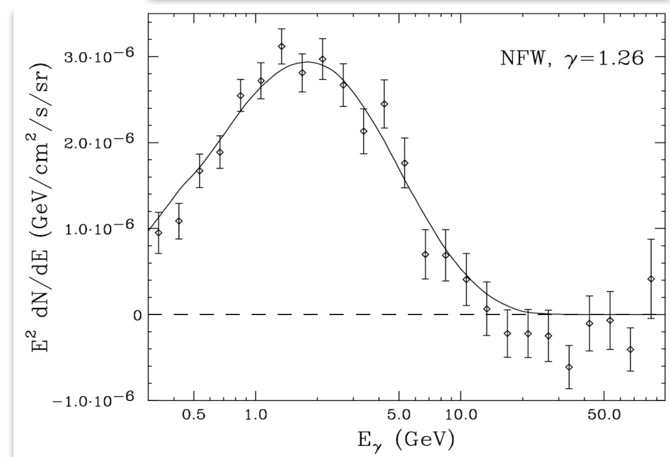

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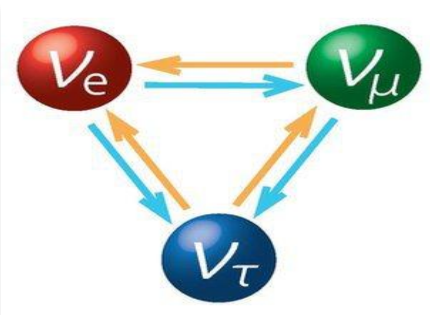
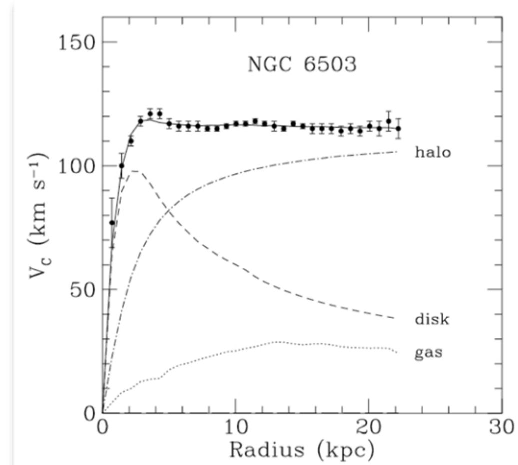
Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, …





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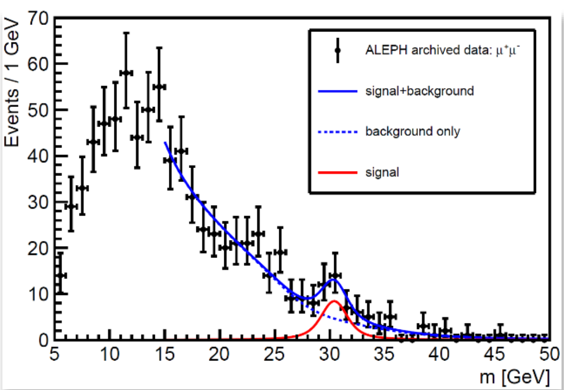

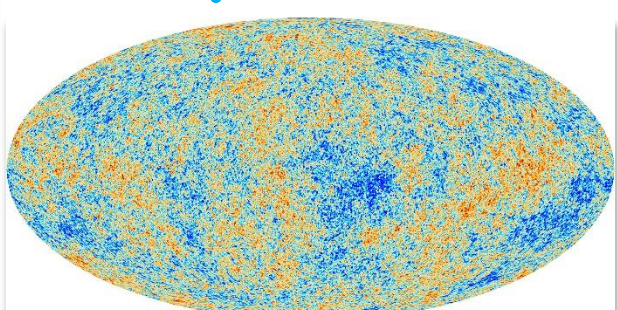

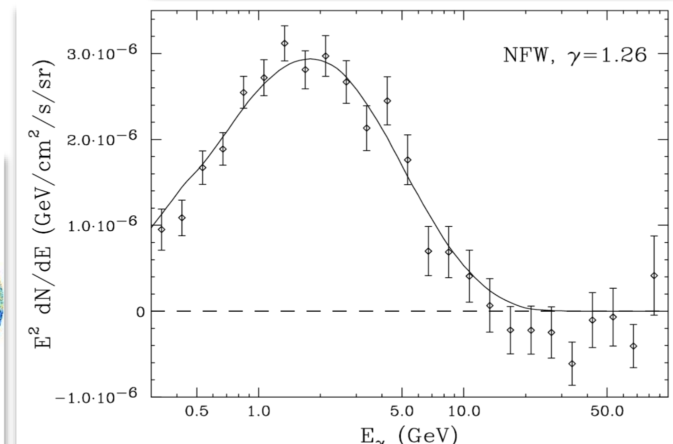

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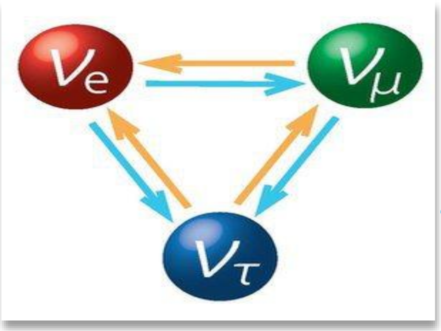
Neutrino, <u>Dark Matter</u>, Collider, <u>Cosmic-Ray</u>, Cosmology, …



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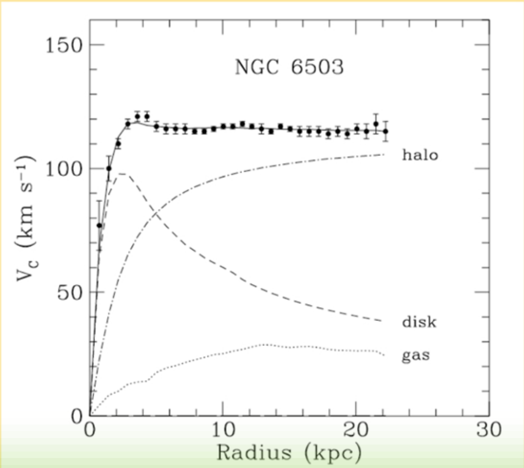
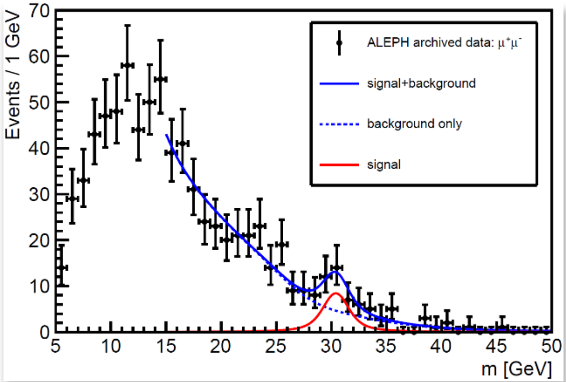
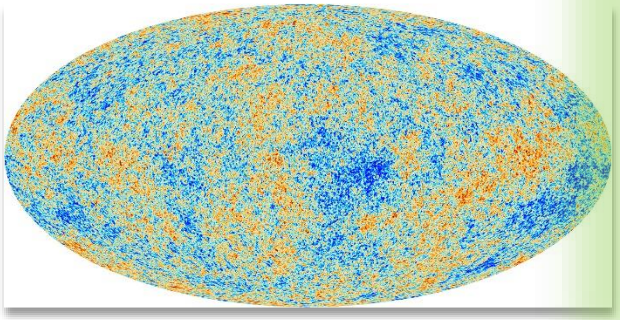
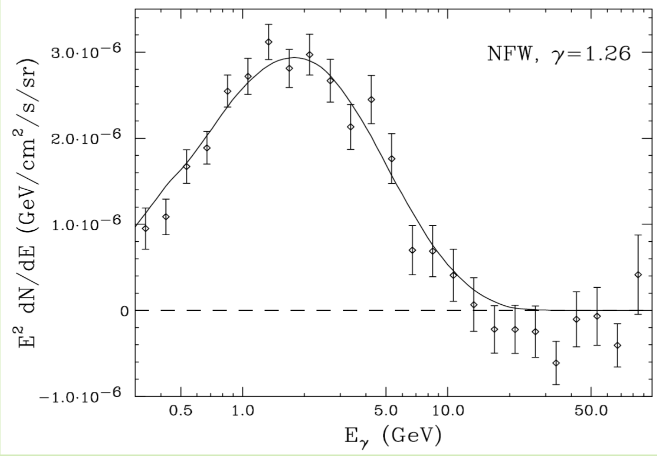


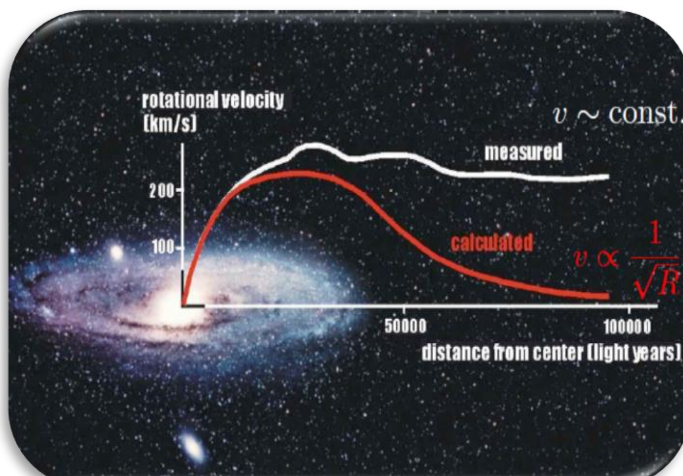




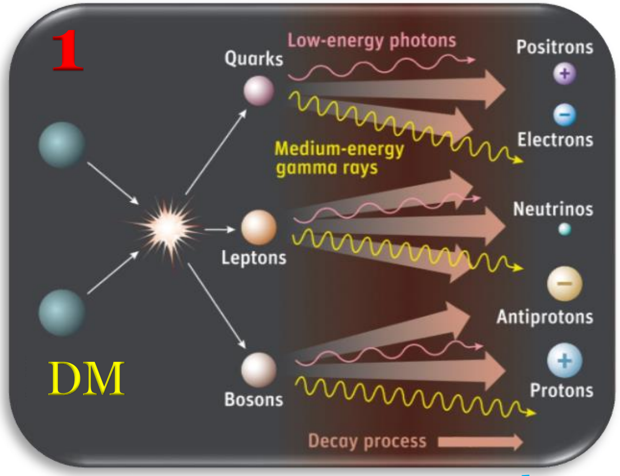


Dark Matter (DM)

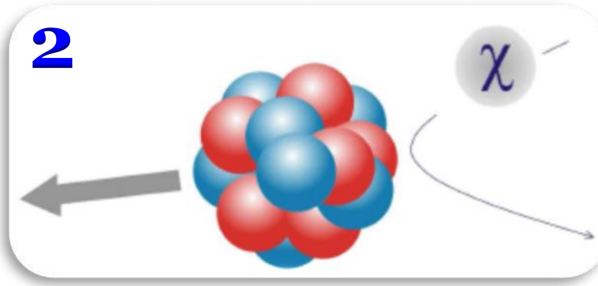
- **DM**: ~25% of our Universe
- **Compelling paradigm**:
  massive, non-luminous & stable particles
- **Evidence**
  - ✓ Galaxy rotation curve
  - ✓ Bullet cluster
  - ✓ Gravitational lensing
  - ✓ Structure formation
  - ✓ CMB
  - ✓ Coma Cluster
  - ✓ Sky surveys
  - ✓ …



DM Search Strategies

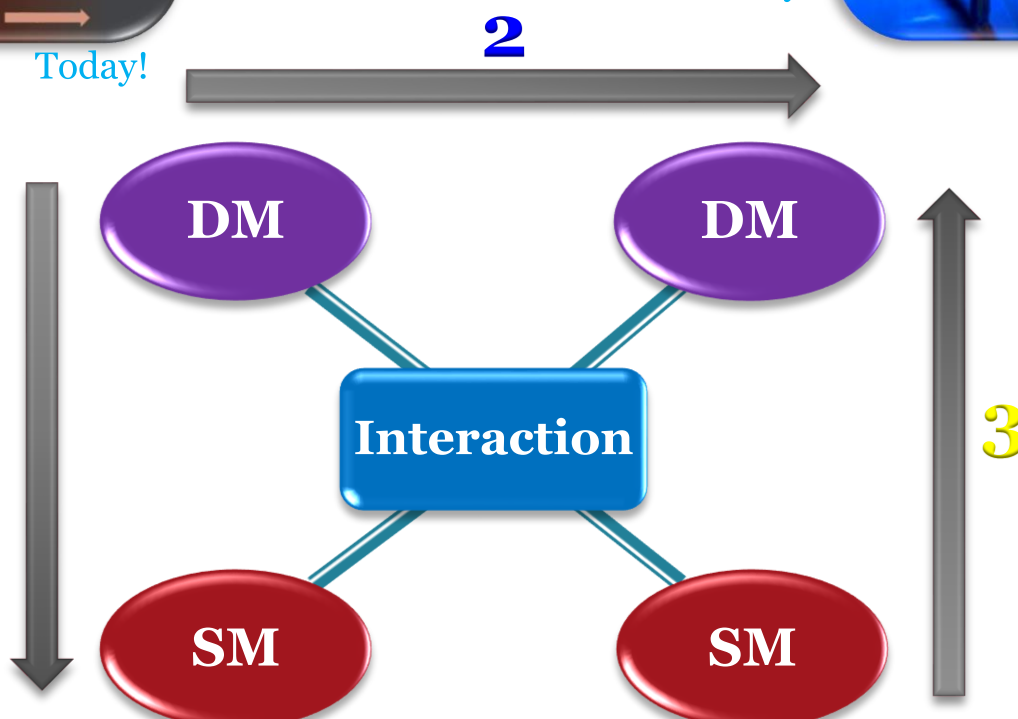


Today!



Wednesday

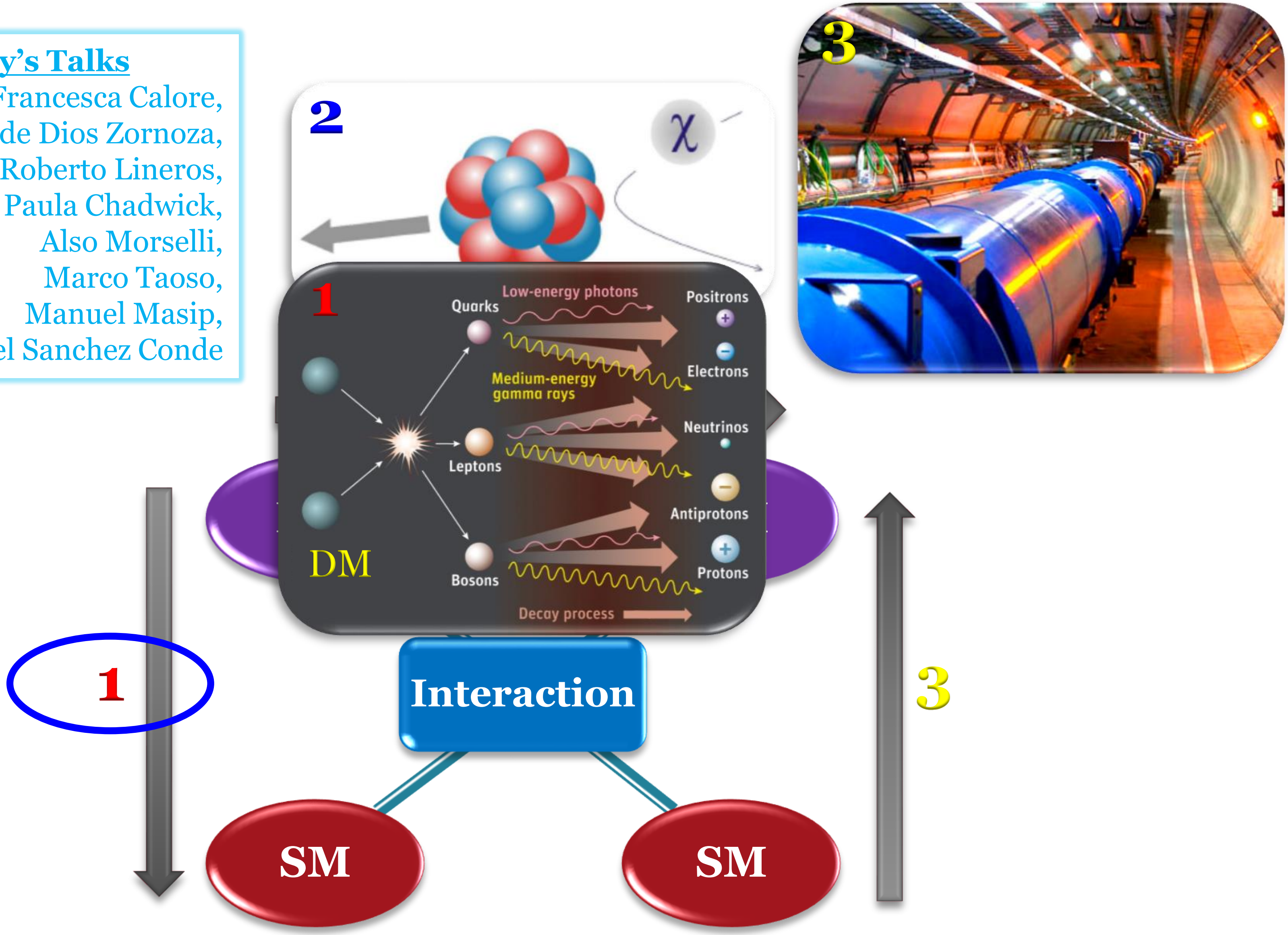
Tuesday



Indirect Detection: Cosmic-Rays

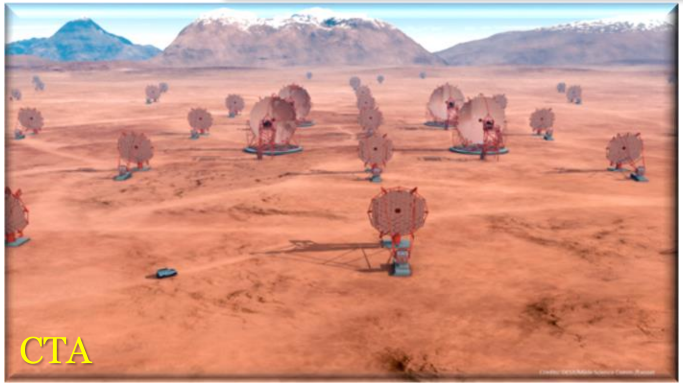
Today's Talks

Francesca Calore,
Juan de Dios Zornoza,
Roberto Lineros,
Paula Chadwick,
Also Morselli,
Marco Taoso,
Manuel Masip,
Miguel Angel Sanchez Conde



Cosmic-Ray Experiments

- **Ground-based**
  MAGIC, HESS, CTA, IceCube, Super-K, Hyper-K, …
- **Balloon-based**:
  ATIC, PPB-BETS, …
- **Satellite-based**:
  AMS, Chandra, Fermi-LAT, PAMELA, XMM-Newton, Hitomi, ASTROGAM, …
  - ✓ Great sensitivity to cosmic-ray signals
  - ✓ Better chance to have the information for extracting DM properties



Hints from Cosmic-Rays?

❖ Anomalies in cosmic-ray measurements ⇔ DM signature ?

- 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
- …

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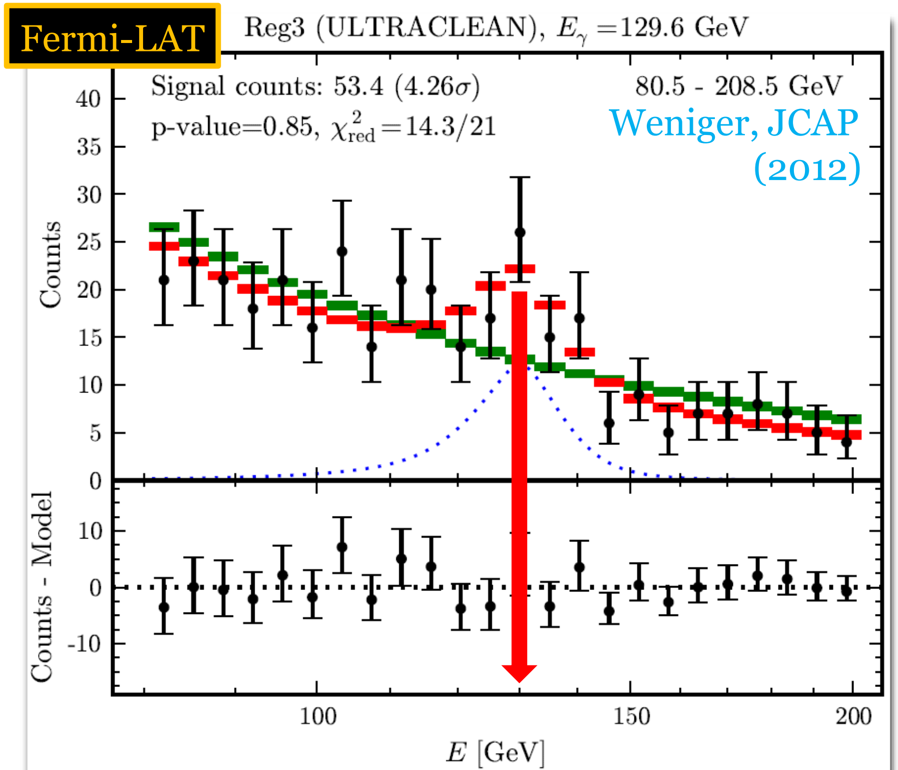
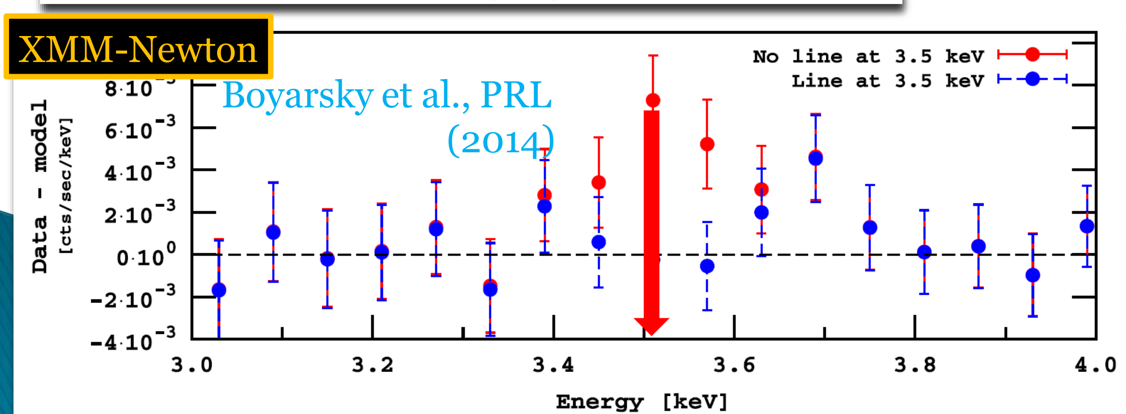
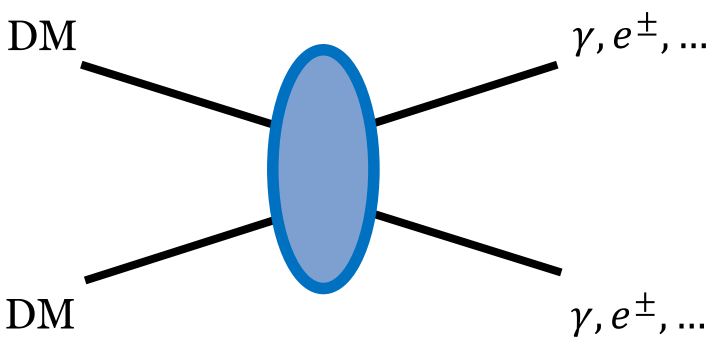
Conventional Approaches

Line-like Excesses

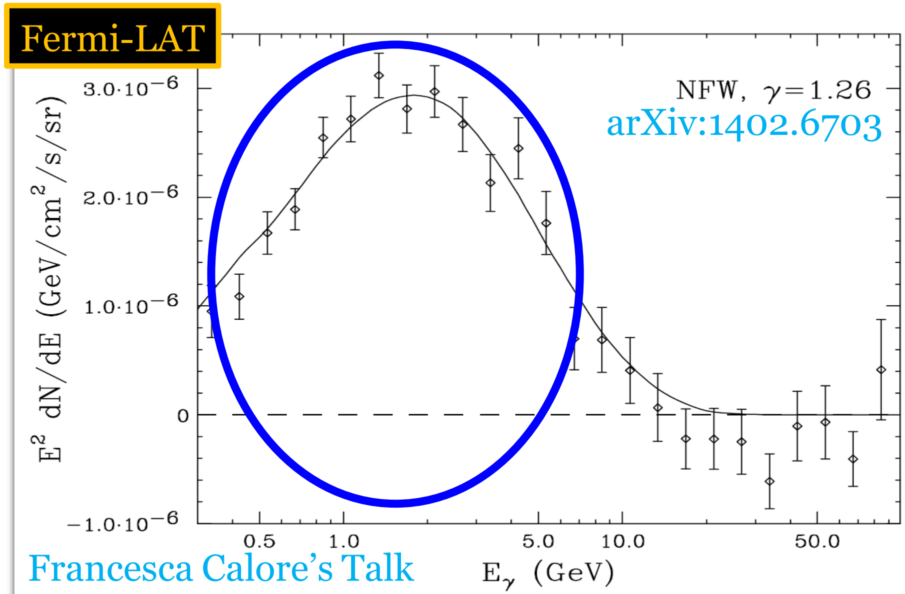


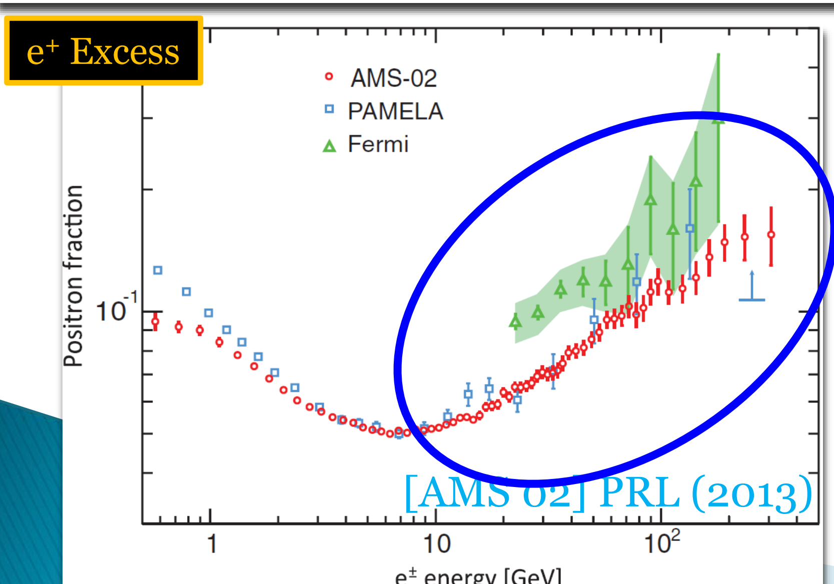


- 3.5 keV line, 511 keV line, 130 GeV line, …
- **Typical DM interpretation**
  - ✓ DM: directly annihilates/decays into 2 (stable) SM particles, γ+X
  - ✓ The location of the line is identified as the (double) mass of DM
  - ✓ Width of the line is instrumental

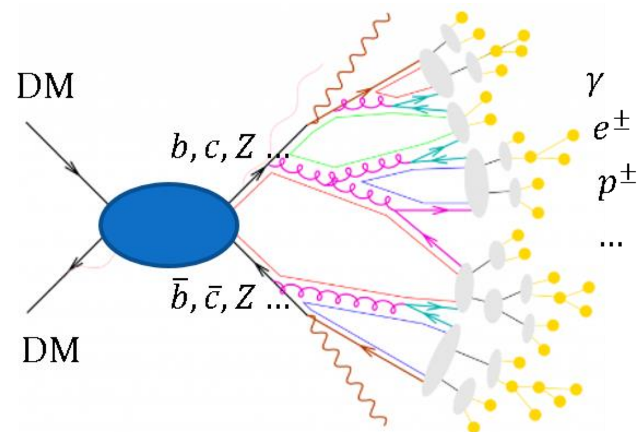


Bump-Like Excesses





- 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

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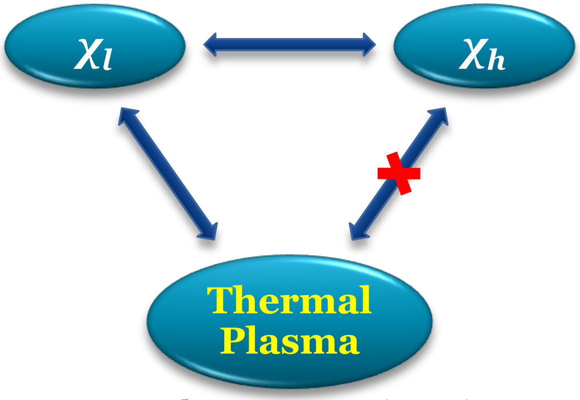
- Rising interest in non-minimal scenarios

✓ Assisted freeze-out



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

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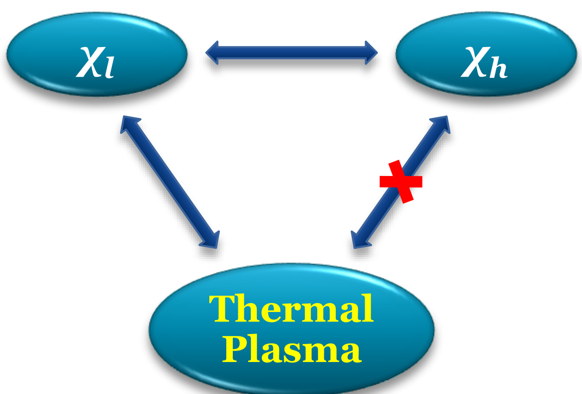

E. J. Chun & **JCP** (2011)
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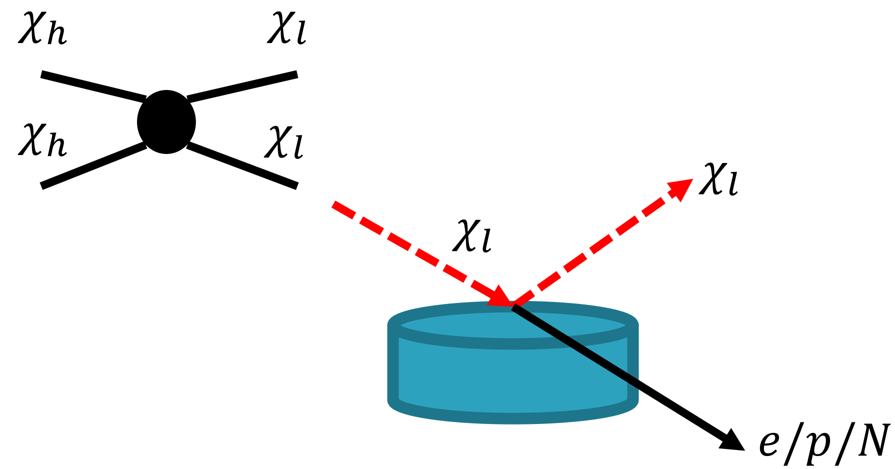
✓ Boosted DM



K. Agashe, Y. Cui, L. Necib, J. Thaler (2014)
KC Kong, G. Mohlabeng & **JCP** (2014)
H. Alhazmi, KC Kong, G. Mohlabeng & **JCP** (2016)

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)

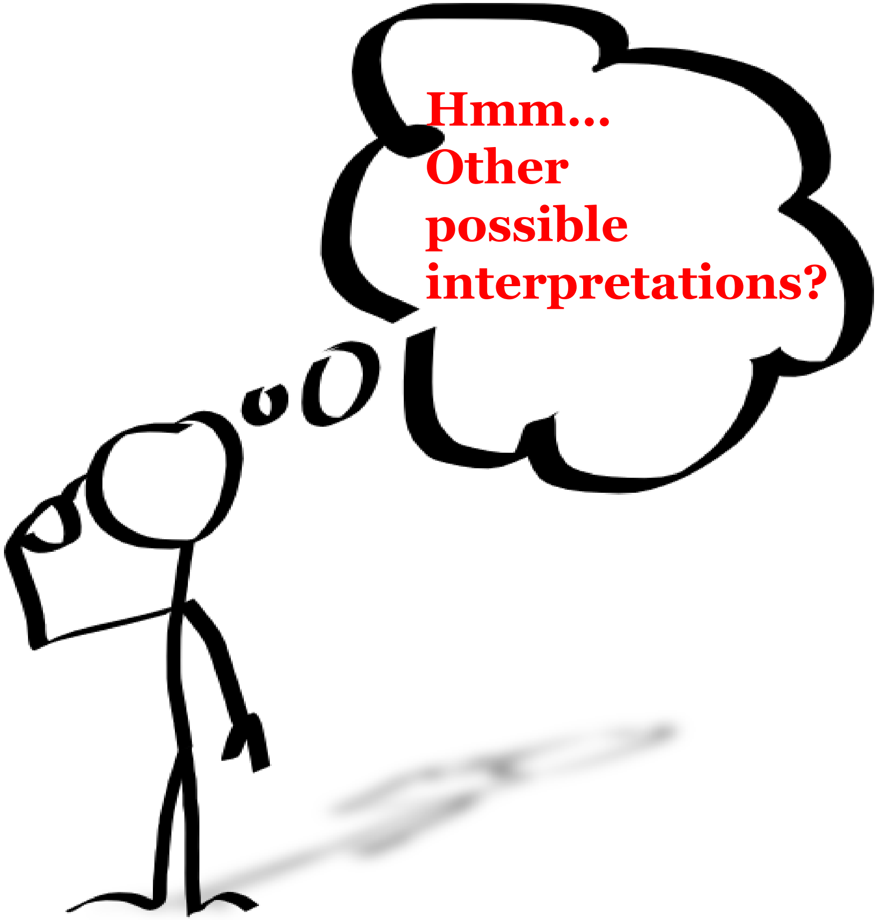
✓ Mass parameters (generic parameterization)

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

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

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

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

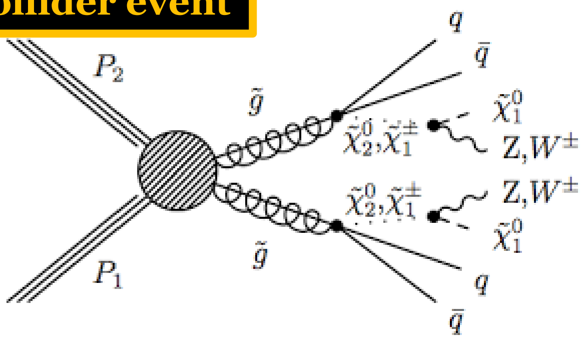

Hmm…
Other
possible
interpretations?

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.

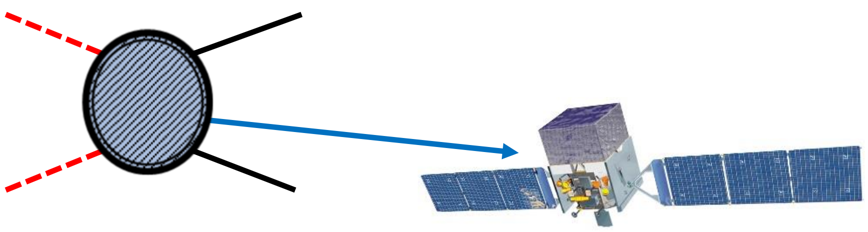
❖ Why E-Peak?

A collider event



- Large multiplicity
- Momentum w.r.t. the beam line

A DM indirect detection event



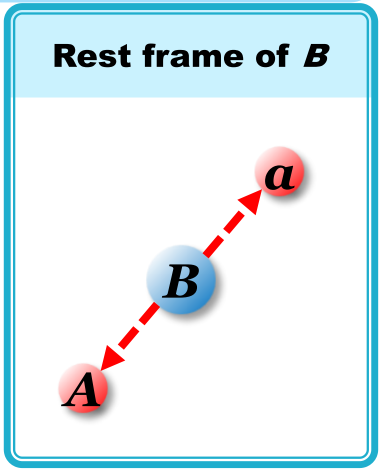
- Energy is the only available quantity

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

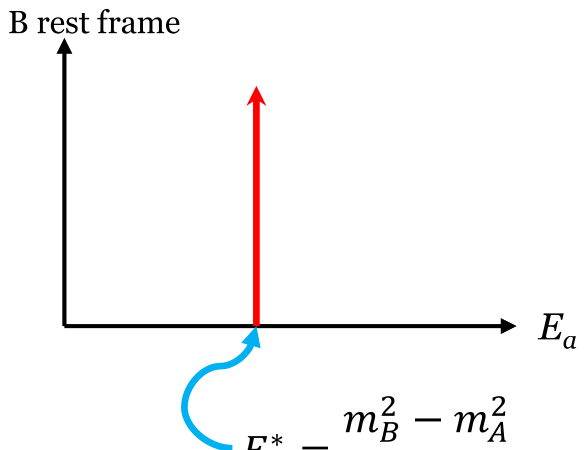
E-Peak: a Quick Review

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

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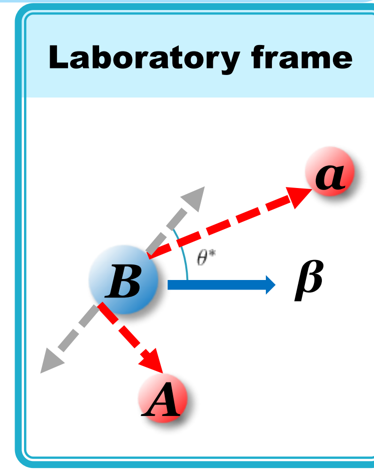

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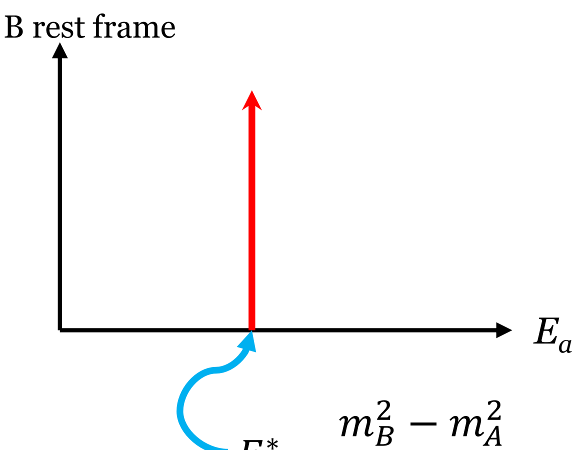
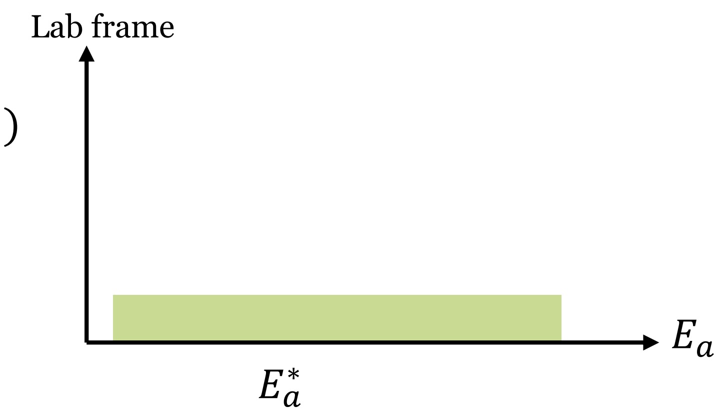


$$E_a^* = \frac{m_B^2 - m_A^2}{2m_B}$$

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



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

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

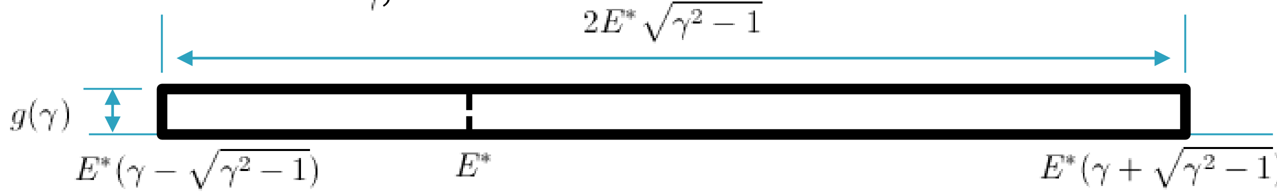
Based on Doojin Kim's talk @ Brookhaven Forum 2015

E-Peak: a Quick Review

"stacking up" rectangles

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

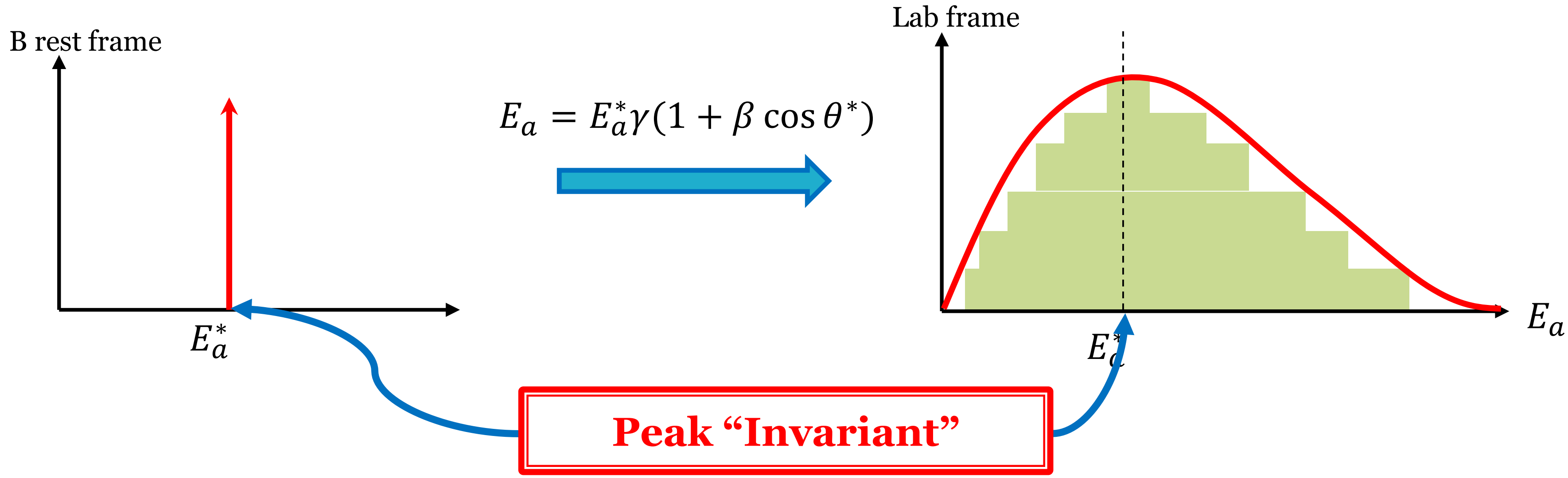
- For any given Lorentz factor γ,



- 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^*

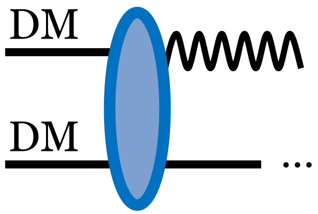


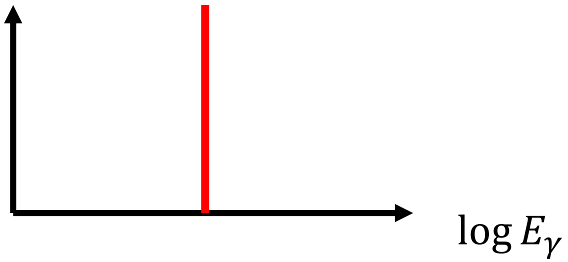
Based on Doojin Kim's talk @ Brookhaven Forum 2015

Applications

Dark Sector Cascade

o-step cascade

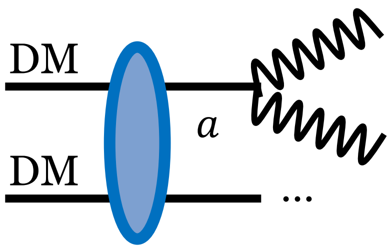


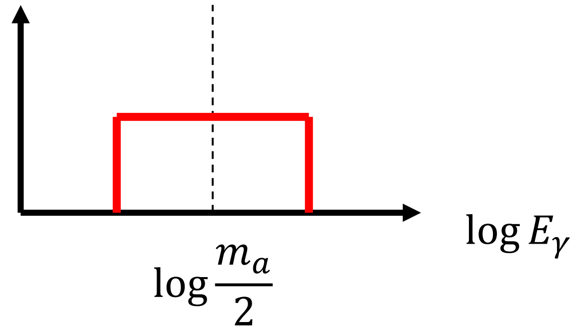


- ❑ Simplest and conventional model
- ❑ Featured by a sharp peak

Dark Sector Cascade

1-step cascade

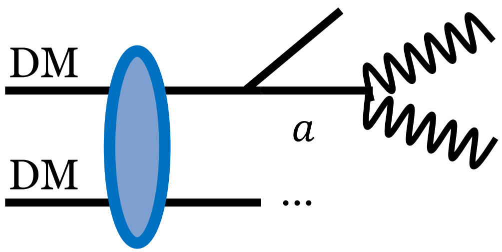


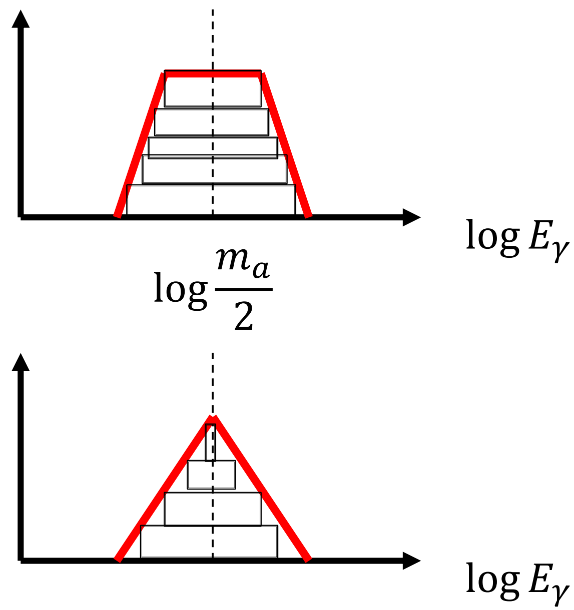


- Introducing an on-shell intermediary state directly decaying into two photons (e.g. dark pion, ALP)
- Featured by a box-like distribution

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

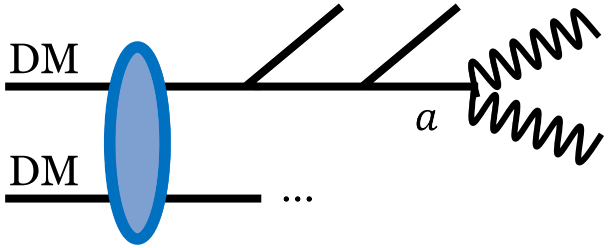
  e.g. 130 GeV/3.5 keV lines

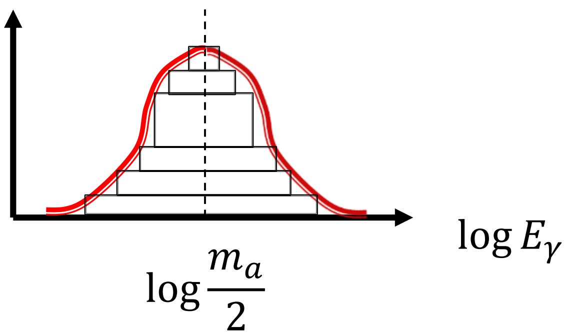
  D. Kim & **JCP** [PLB (2015)]

Later

Dark Sector Cascade

3-step cascade



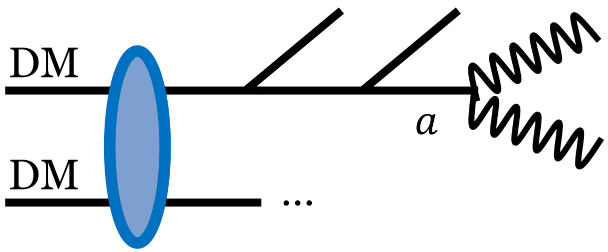


- ❑ Introducing one more on-shell intermediary state before the state decaying into two photons
- ❑ Developing a smoothly rising-and-falling shape
- ❑ Generic distribution function:

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

Dark Sector Cascade

3-step cascade



- Introducing one more on-shell intermediary state before the state decaying into two photons
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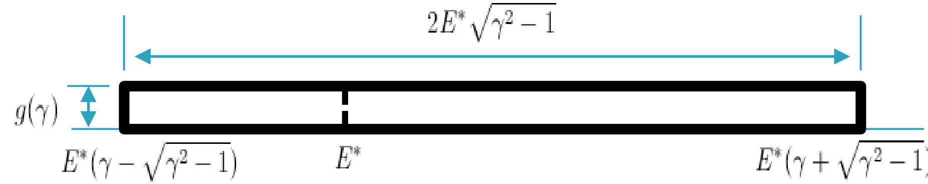
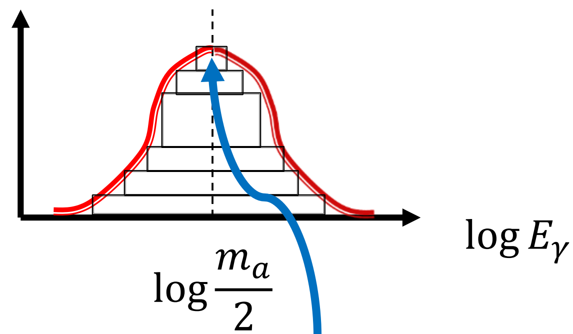


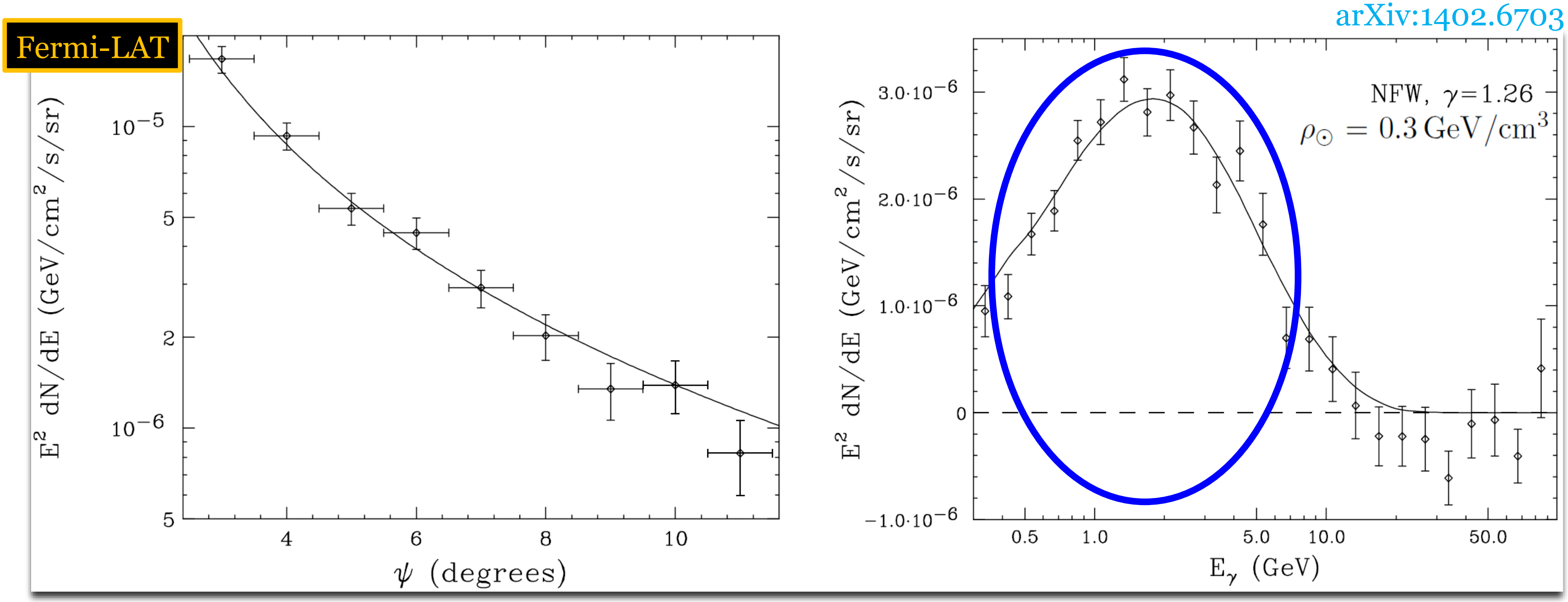


Symmetric w.r.t the peak in **logarithmic E_γ**

$$(E^*)^2 = E_\gamma^+ E_\gamma^-$$

Bump: Features of GeV Excess

arXiv:1402.6703

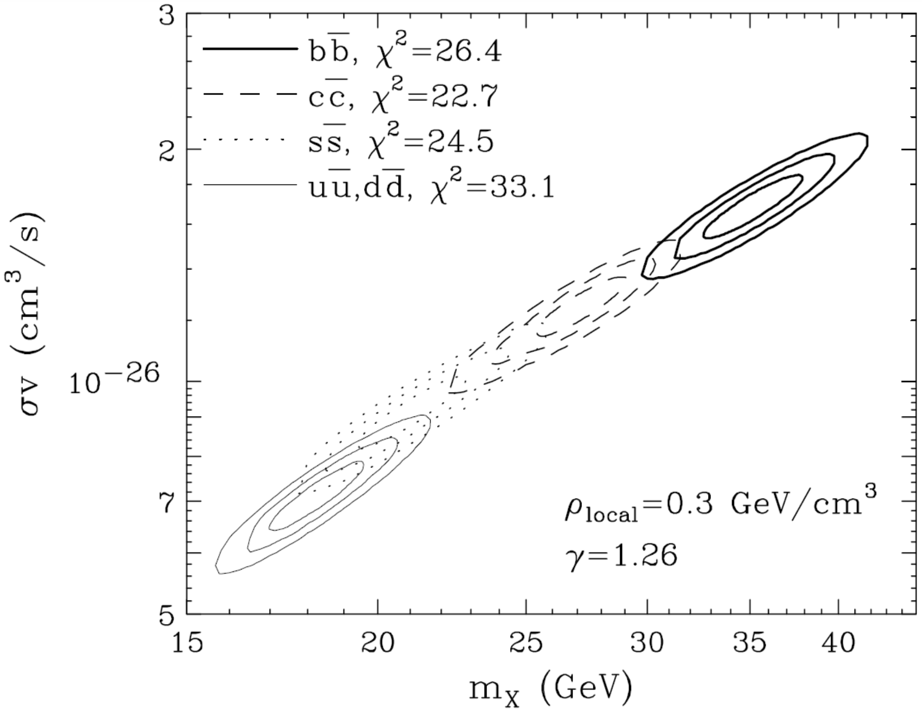


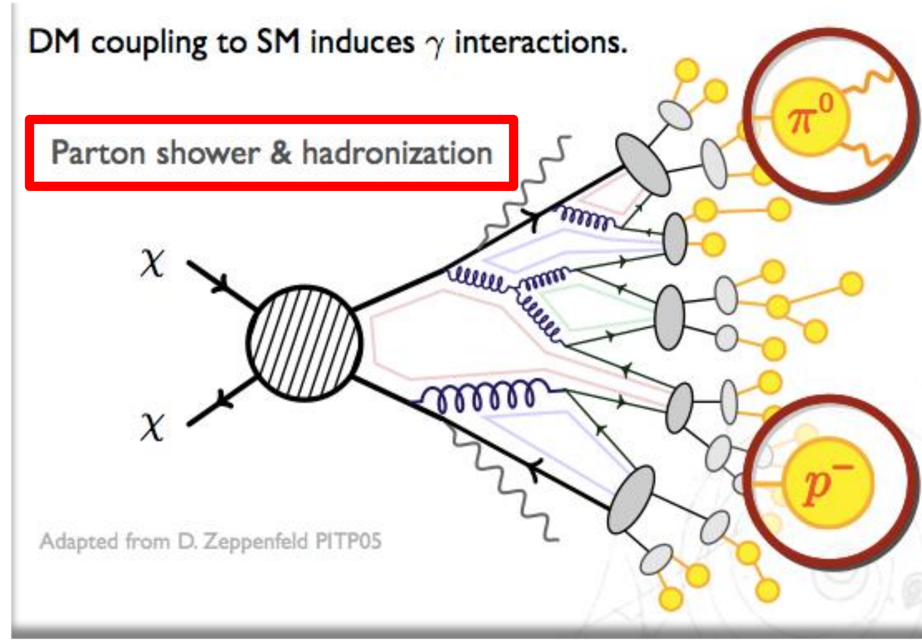
- Signal: extended to > 10° from the GC
- Consistent with the dynamical center of the Milky Way (< 0.05°)
- The spectrum of the excess peaks at 1-3 GeV.

Francesca Calore's Talk

Bump: Conventional Approach

arXiv:1402.6703

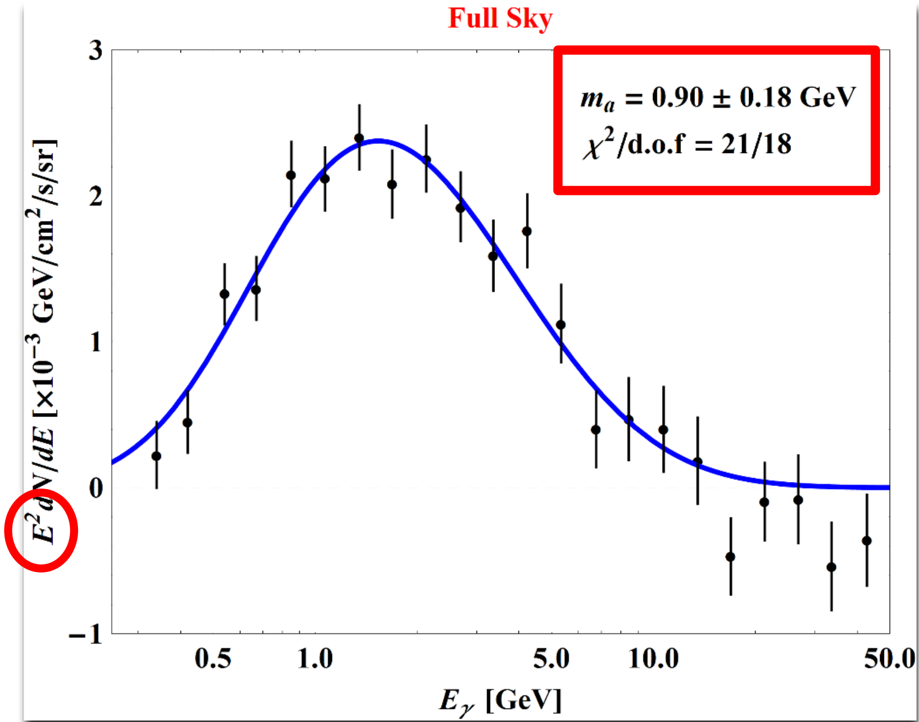




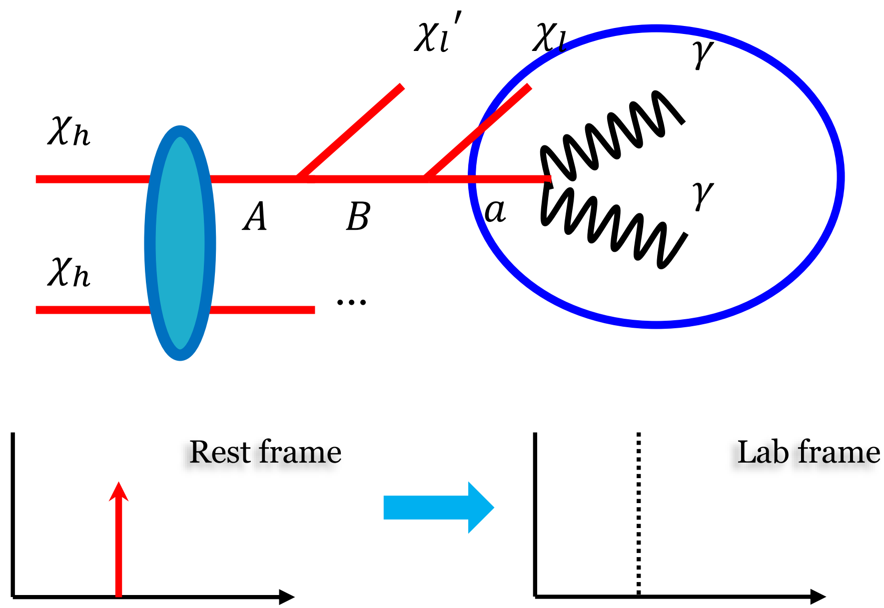
- The spectrum is in good agreement with the predictions from 20-40 GeV DM mostly annihilating to quarks (fragmentation, IC, bremsstrahlung, …).
- Required cross section is ~ 0.7-2.1 · 10^{-26} cm^3/s

Francesca Calore's Talk

Dark Cascade: GeV γ-ray Bump



- Multi-step cascade decay!



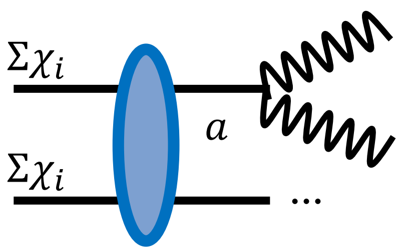
- Fitting function: $f_M(E_\gamma) = N \exp\left[-\frac{w}{2}\left(\frac{E_\gamma}{E_\gamma^*} + \frac{E_\gamma^*}{E_\gamma}\right)^p\right]$ with $E_\gamma^* = m_a/2$
- cf. arXiv:1402.6703 (bb) → χ^2 /d.o.f.= 44/20 with m_{DM}=36.6 GeV

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

Multi-Component DM Models

Mechanism

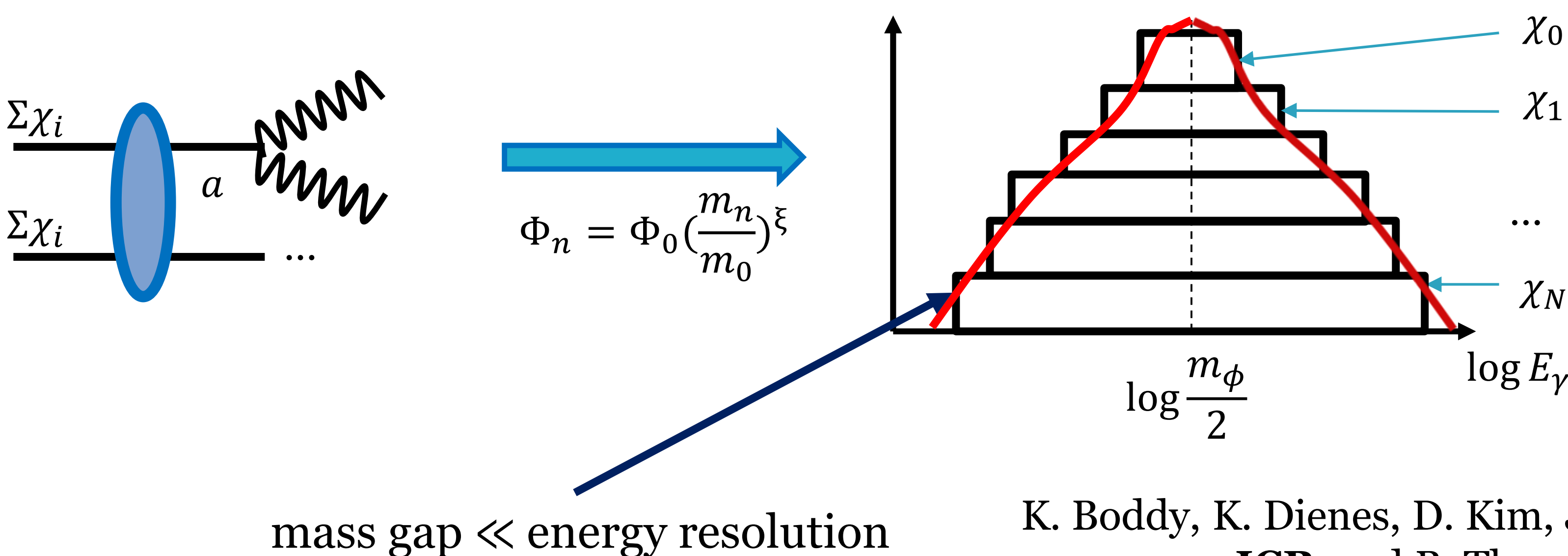
- What if there exist multiple DM species? What if the collection of DM particles have sufficiently small mass gaps (smaller than relevant energy resolution)?



Multi-Component DM Models

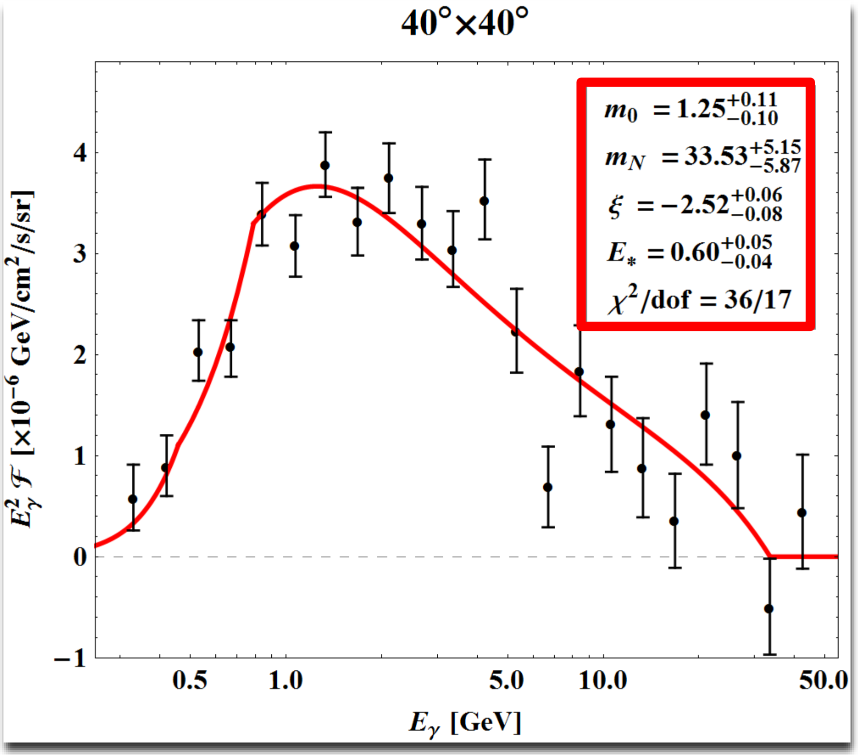
Mechanism

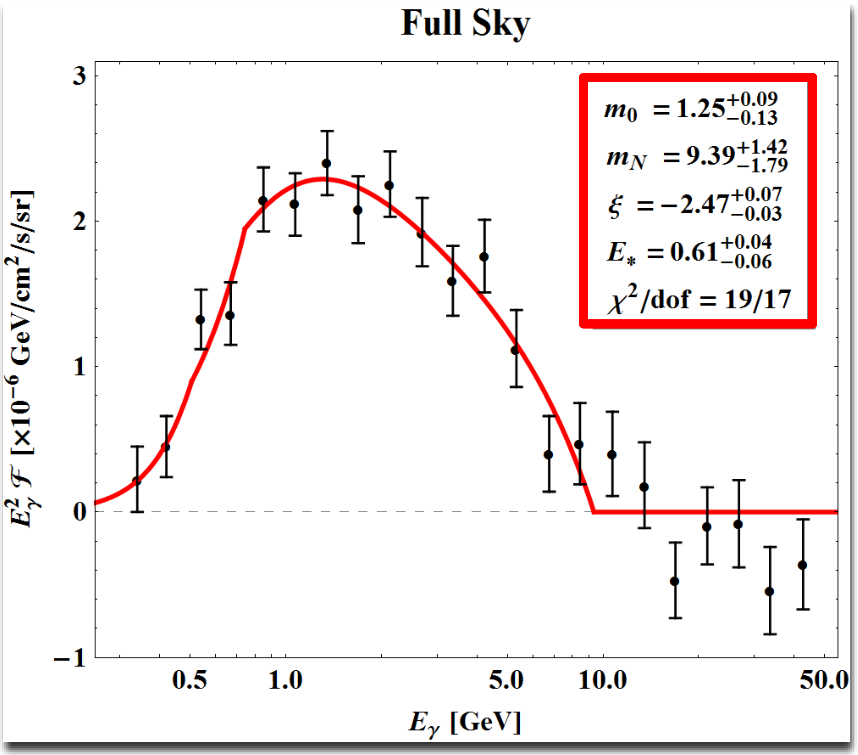
- What if there exist multiple DM species? What if the collection of DM particles have sufficiently small mass gaps (smaller than relevant energy resolution)?
- Obtaining continuum energy spectra not by cascade decays, but by **increasing the number of DM species**



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

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_{DM}=43.0 (36.6) GeV

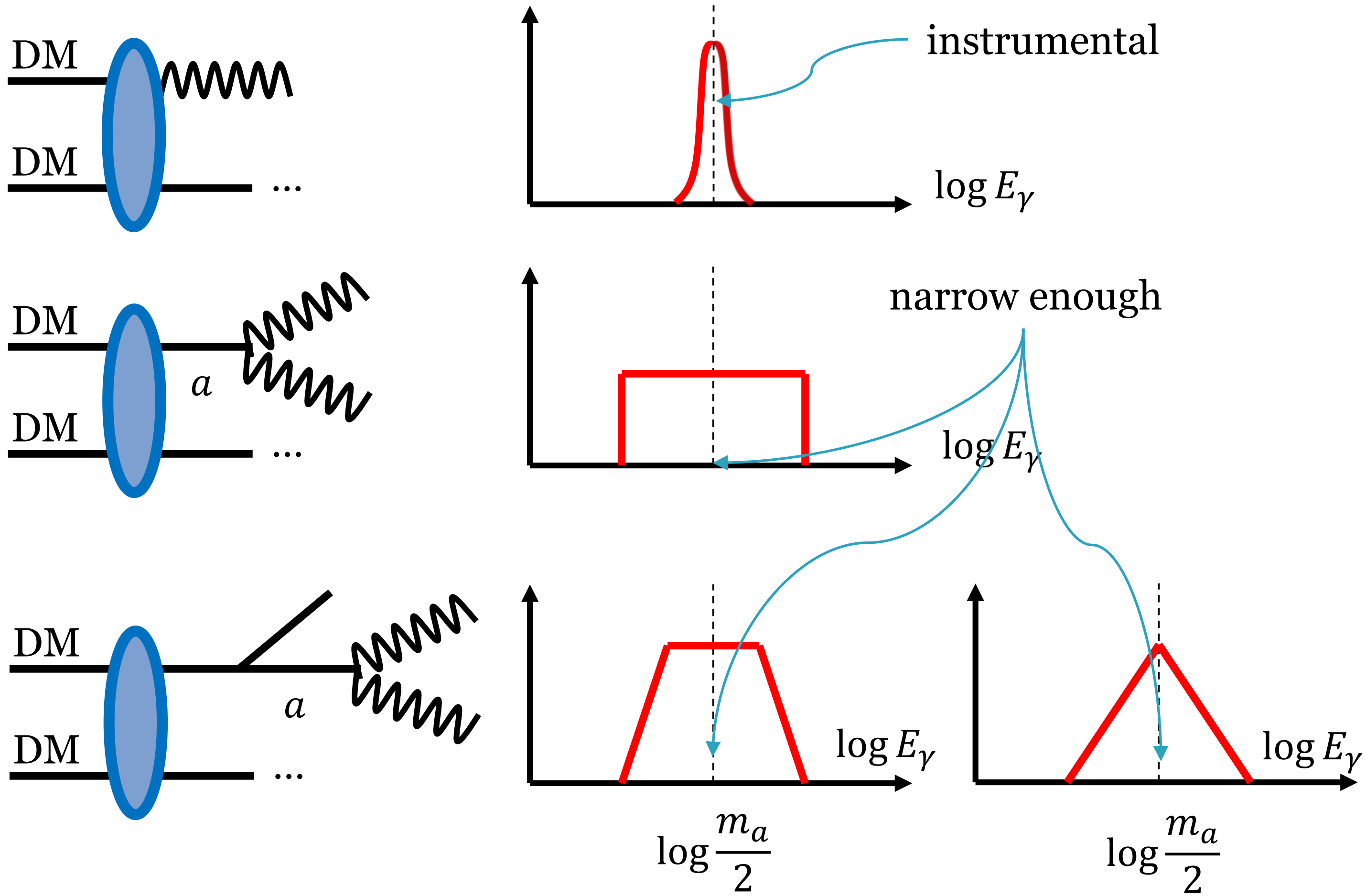
K. Boddy, K. Dienes, D. Kim, J. Kumar, **JCP**, and B. Thomas (2016)

Line-like Excesses

Models explaining line-like signals

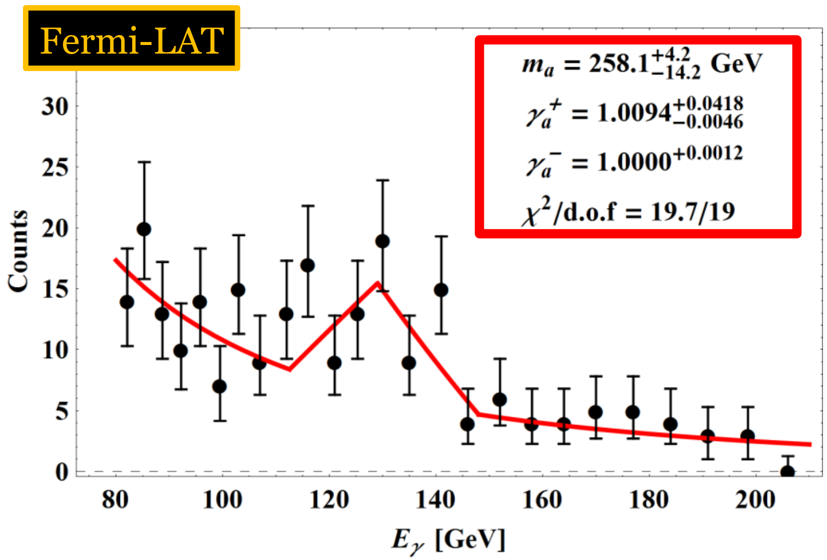
- ❑ Scenario I
- ❑ Scenario II
- ❑ **Scenario III**

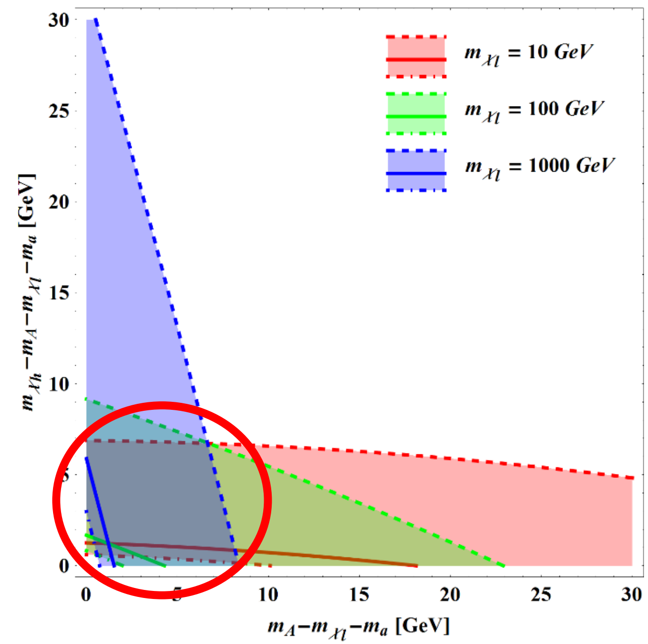
[D. Kim & **JCP**, PLB (2015)]



Line-like Excesses

Application to 130 GeV line



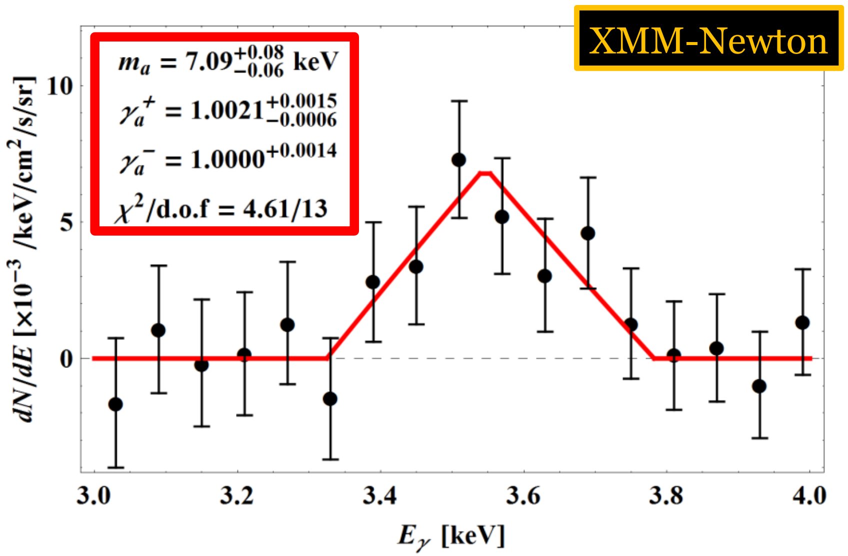


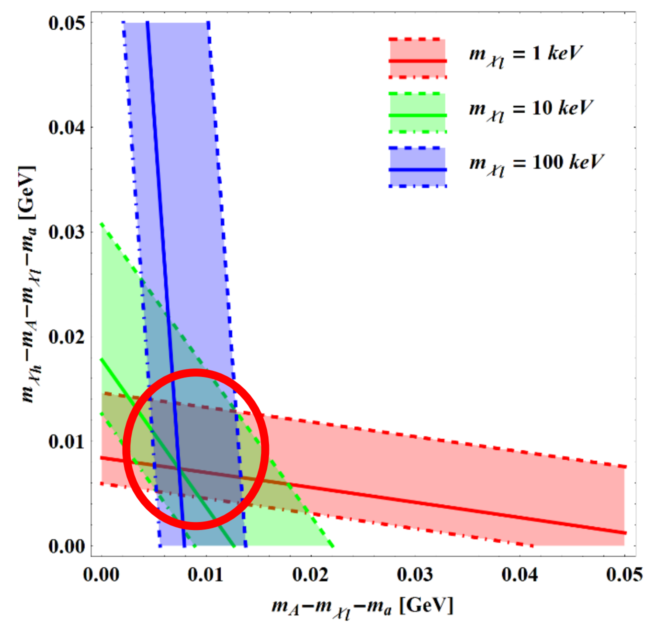
- Data extracted from the ULTRACLEAN event class in arXiv:1204.2797
- Power-law background template considered simultaneously

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

Line-like Excesses

Application to 3.5 keV line





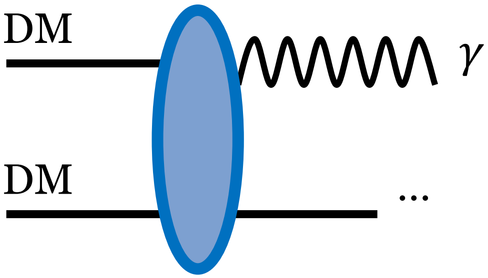
- Data extracted from the MOS spectrum of the central region of the galaxy M31 in arXiv:1402.4119
- Signal template only considered

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

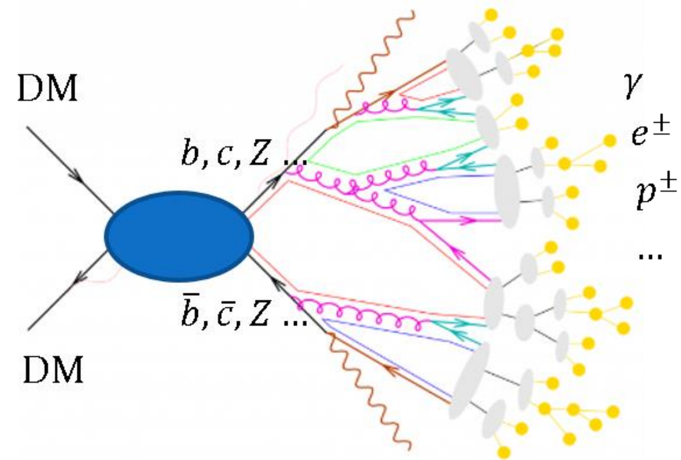
Conclusions

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

1. Line: directly into γ + X



2. Bump: into SM particle pairs → γ's, e's, ...



Conclusions

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

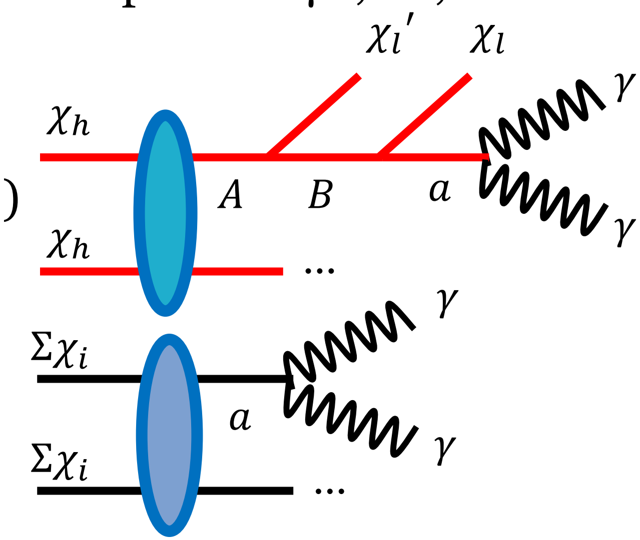
  1. Line: directly into γ + X 2. Bump: into SM particle pairs → γ's, e's, ...

- **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

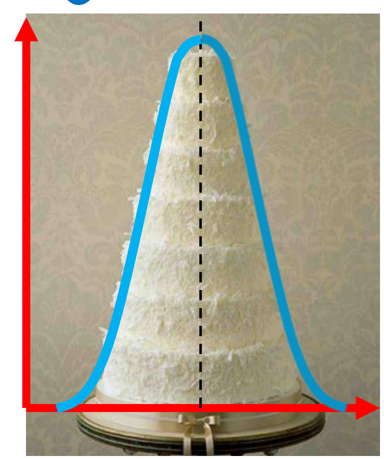
  2. $\Sigma\chi_i$ into X + a(→ 2γ)



- Reasonable χ^2 fits (χ^2/d.o.f.~1)

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

  → prediction: m_a



Conclusions

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

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

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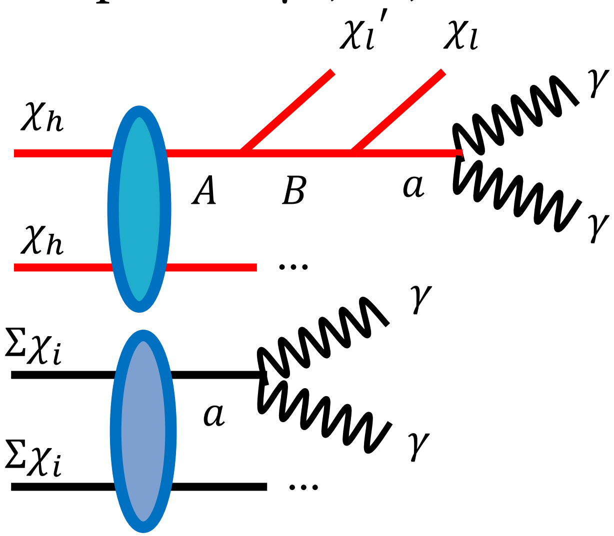

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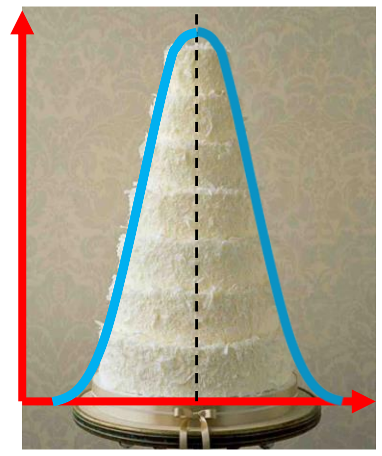
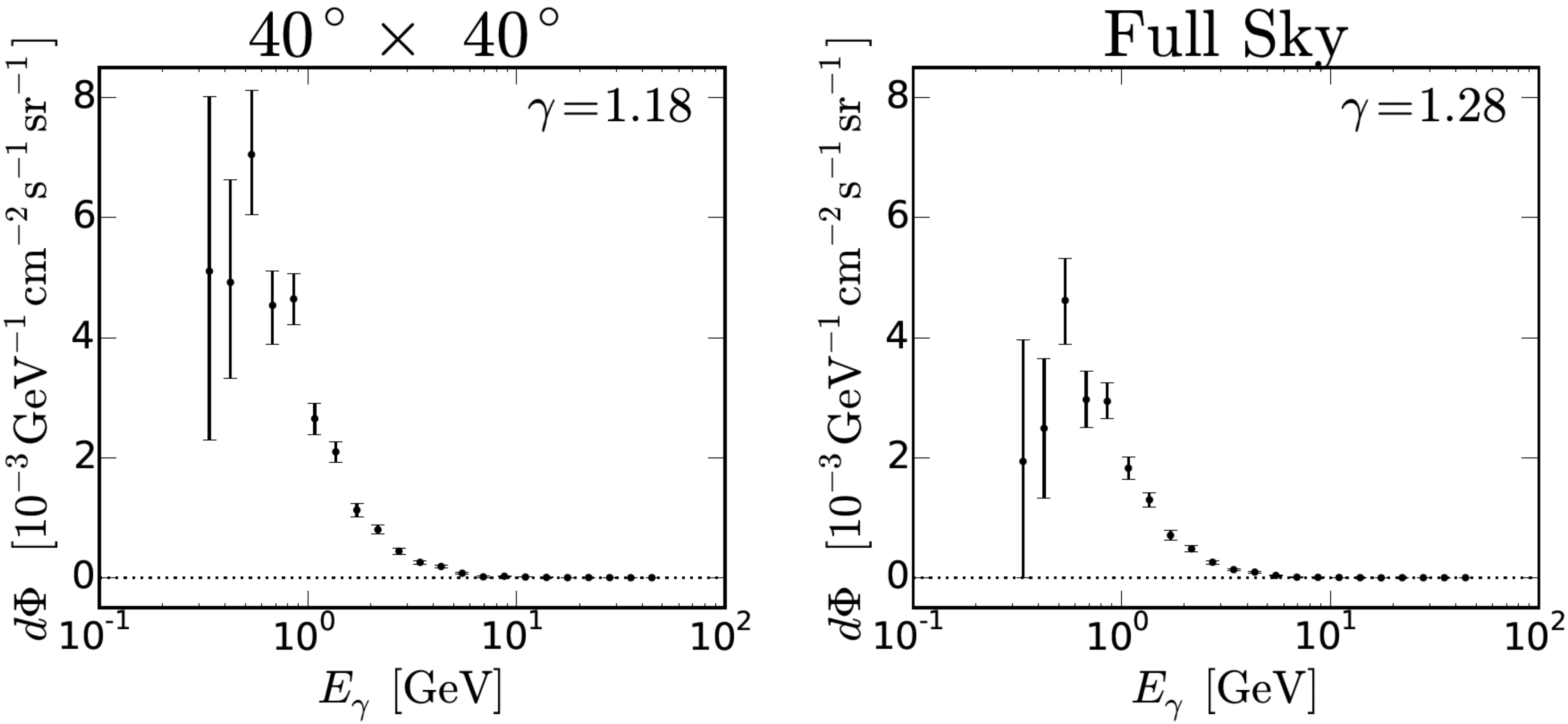


Thank you

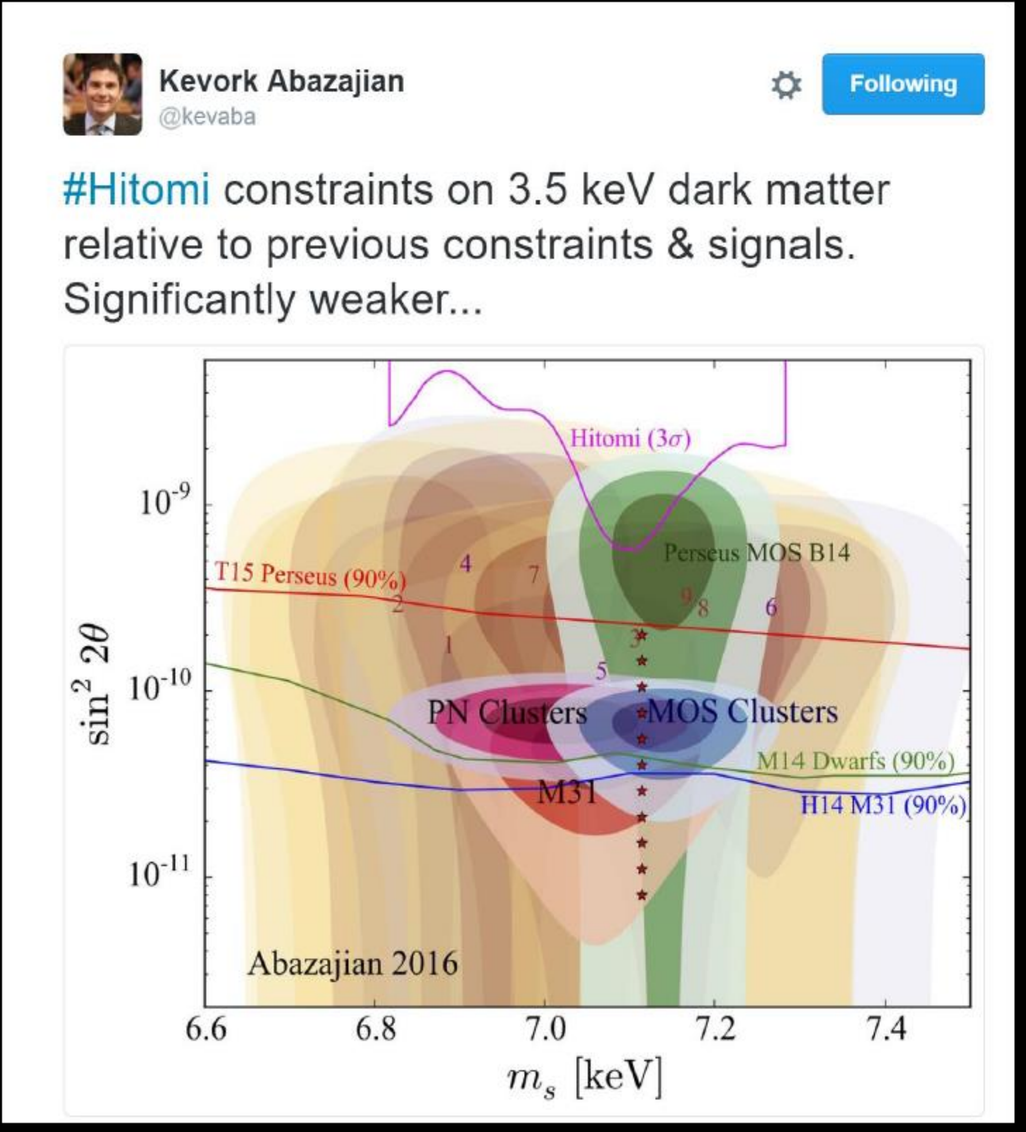
Back-Up

Unweighted E Spectrum



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

Hitomi Perseus



Line-like Excesses

Scenario III

- **Analytic expression** for E spectrum available

$$f(E_\gamma) = \int_{\gamma_a^{\min}}^{\gamma_a^{\max}} d\gamma_a \frac{g(\gamma_a)}{2E_\gamma^* \sqrt{\gamma_a^2 - 1}} \qquad (11)$$

$$= \frac{m_a}{4E_{\gamma^*} p_a^* \sqrt{\gamma_A^2 - 1}} \left\{ \log\left[\sqrt{(\gamma_a^{\max})^2 - 1} + \gamma_a^{\max}\right] - \log\left[\sqrt{(\gamma_a^{\min})^2 - 1} + \gamma_a^{\min}\right] \right\}, \qquad (12)$$

where $\gamma_a^{\min}$ and $\gamma_a^{\max}$ are defined as

$$\gamma_a^{\min} \equiv \max\left[\gamma_a^-, \frac{1}{2}\left(\frac{E_\gamma}{E_\gamma^*} + \frac{E_\gamma^*}{E_\gamma}\right)\right], \quad \gamma_a^{\max} \equiv \gamma_a^+. \qquad (13)$$

$$\gamma_a^\pm \equiv \frac{E_a^*}{m_a}\gamma_A \pm \frac{p_a^*}{m_a}\sqrt{\gamma_A^2 - 1}.$$

- Fit parameters: $E_\gamma^*, \gamma_a^+, \gamma_a^-$

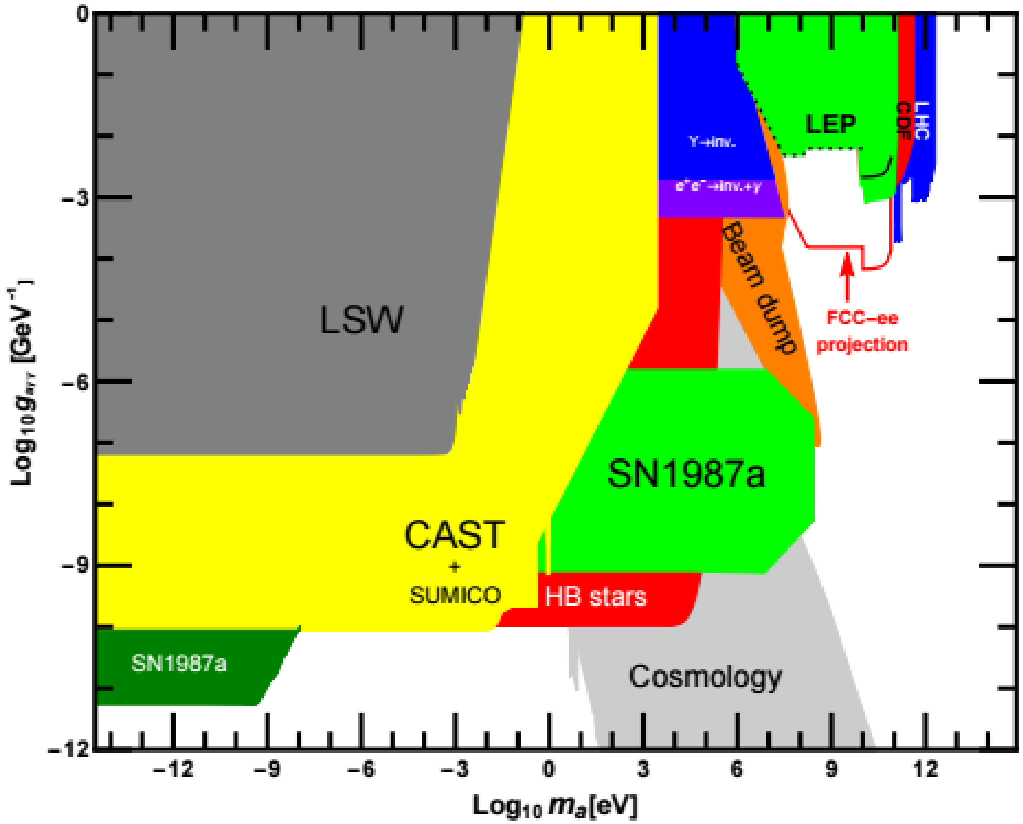
- Possible to **distinguish DM models** to give a line-like signature using morphological features

	Scenario i)	Scenario ii)	Scenario iii)
Peak existence	Always	Absent	Sometimes
Plateau existence	Absent	Always	Sometimes
Width	Instrumental	Physical	Physical
Symmetry in E	Symmetric	Not available	Asymmetric
Symmetry in $\log E$	Asymmetric	Not available	Symmetric
Shape in E	Curved	Rectangular	Curved
Shape in $\log E$	Curved	Rectangular	Oblique

Doojin Kim & **JCP**, arXiv:1508.06640

Bounds of Axion-Like Particles

- Limits from current experiments



Jaeckel et al. (2015)

Energy Peak

- **Advertisement**

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

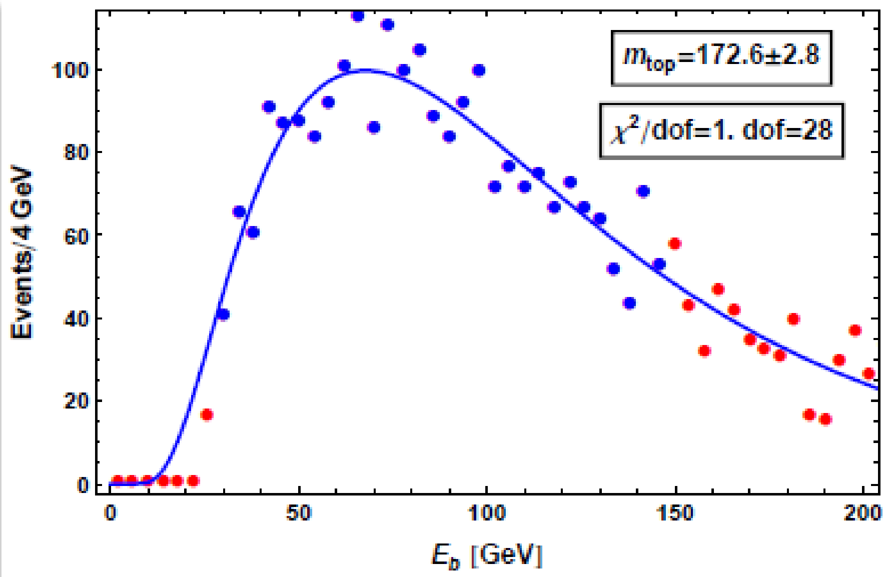
Example: M_{top} Measurement

arXiv: 1209.0772

Detector level test

- ❑ (Assuming W mass is well-known,) the result is quite good.

$$<m_{top}>=173.1\pm 2.5\text{ GeV}$$



- ❑ Compared with the traditional method, o urs is simpler.: **purely based on the kinematics** and not rely at all on the detailed knowledge of underlying dynamics of top decay such as matrix element of the process.

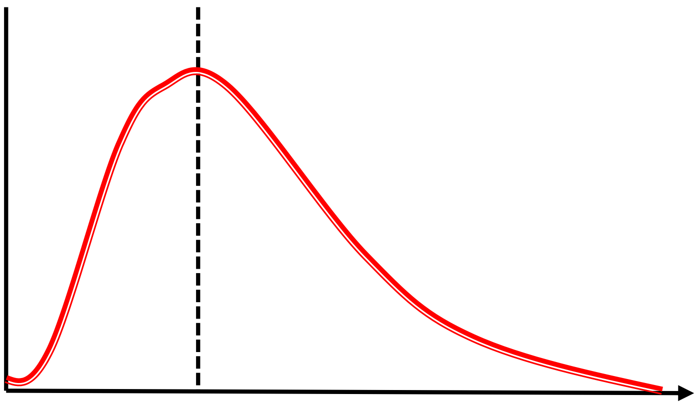
Energy Peak

arXiv: 1209.0772

Analysis: introduction of an ansatz

- Generic distributions are obtained by an integration over the boost factor with **unknown** boost distribution $g(\gamma)$, generally, not doable

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



- 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:

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

Energy Peak

arXiv: 1209.0772

Proposal of a "simple" *ansatz*

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

- ❑ $K_1(p)$: modified Bessel function of the second kind of order 1
- ❑ p : fitting parameter which encodes the width of the peak
- ❑ E^* as a ***fitting parameter*** can be extracted by fitting!
- ❑ All four properties are satisfied. → for the last property, use the asymptotic behavior of $K_1(p)$

$$K_1(p) \overset{p\to\infty}{\to} \sim \frac{e^{-p}}{\sqrt{p}}\left(1 + \mathcal{O}\left(\frac{1}{p}\right)\right)$$

- ❑ Proposed ansatz does not develop a cusp so that it is more suitable for the case of $g(1)=0$, e.g., pair-production of mothers

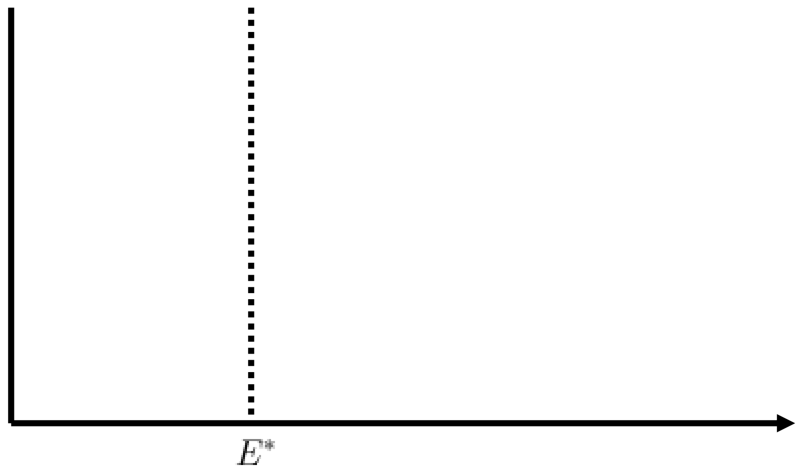
Based on Doojin Kim's talk @ KVNP Workshop at Caltech, 2013

Fitting Function

arXiv: 1209.0772

Functional properties of generic $f(E)$

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



1) Even under $\frac{E}{E^*} \leftrightarrow \frac{E^*}{E}$ or $E \rightarrow \frac{E^{*\,2}}{E}$

2) Maximized at $E=E^*$

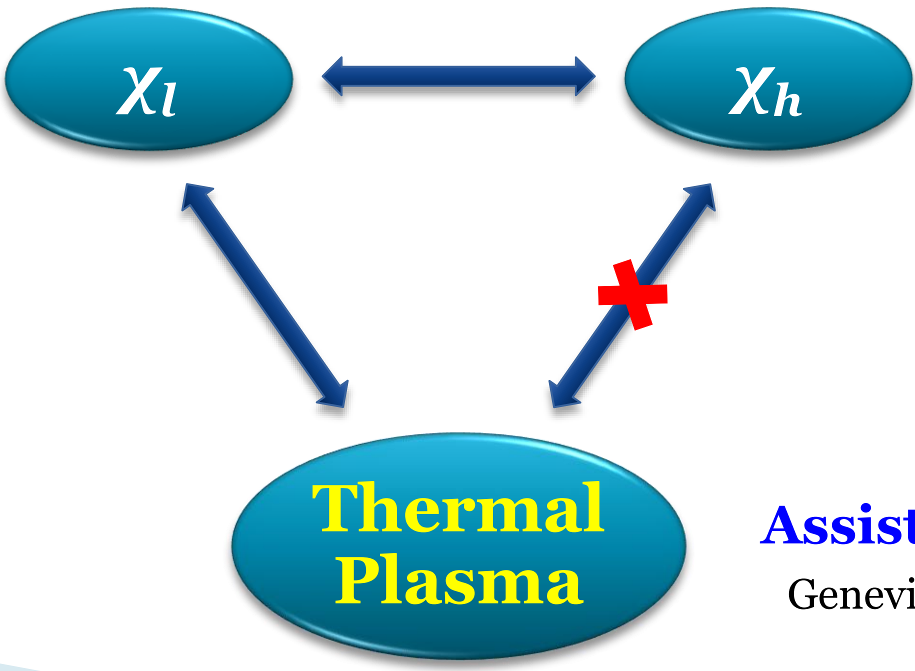
3) Vanishing as E goes to zero or infinity

4) Returning a δ-function for some limiting par ameter choice

Based on Doojin Kim's talk @ KVNP Workshop at Caltech, 2013

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**, JCAP (2012)