Sharp spectral features from light dark matter decay via gravity portals

(arXiv:1707.08480)

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Motivation

- Observational evidence: DM particle very long-lived

$$\tau_{\mathrm{DM}} \gtrsim \tau_{\mathrm{U}} \sim 4 \times 10^{17}\ \mathrm{s}$$

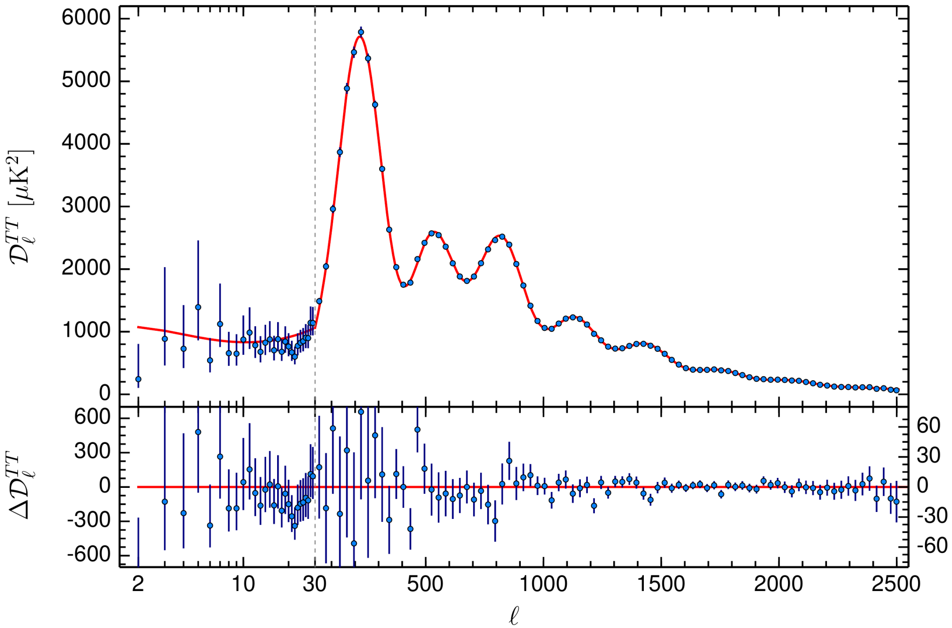
- DM particle could be absolutely stable, protected by some symmetry

  (*e.g.* scalar "inert" doublet – stabilized by global Z_2)

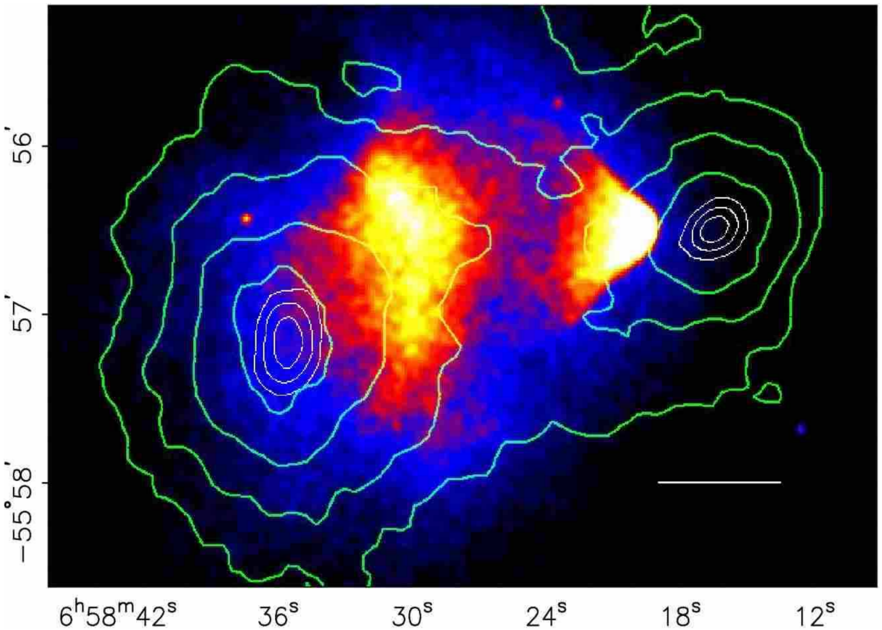
- Alternatively: kinematical reasons for its long lifetime (*e.g.* axion – tiny decay width)

Motivation

- DM interacts gravitationally



Planck Coll., Astron.Astrophys. 594 (2016) A13



Clowe et al., Astrophys.J. 648 (2006) L109-L113

- Gravity not expected to respect global symmetries

Banks, Seiberg, Phys.Rev. D83 (2011) 084019
Kallosh, Linde, Linde, Susskind, Phys.Rev. D52 (1995) 912-935

➔ DM stabilized by global symmetry that is however broken by non-minimal gravitational interactions?

Motivation

- Scenario:
  - Non-gravitational interactions preserve global symmetry
  - DM decays via “gravity portal” only

➔ Long lifetime due to Planck-mass suppression of gravitational interactions

Phys. Rev. Lett. 117 (2016) 021302
Phys. Rev. D95 (2017) 035011

- Simplest case: scalar singlet DM

Silveira, Zee, Phys.Lett. 161B (1985) 136-140
McDonald, Phys.Rev. D50 (1994) 3637-3649

- Lowest-dimensional operator: $\mathcal{L}_\xi = -\xi M R \phi$

Light dark matter (here: $m_\phi \lesssim 700\ \mathrm{MeV}$)

- Jordan frame action:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[-\frac{R}{2\kappa^2}\left(1+2\kappa^2\xi M\phi\right)+\mathcal{L}_{\mathrm{obs}}^{\mathrm{eff}}+\mathcal{L}_{\mathrm{DM}}\right]$$

  - Observable sector: effective Lagrangian for photons, neutrinos, light leptons, pions (χPT)
  - DM assumed to be stable in the absence of gravitational interactions (Z_2 conserved in $\mathcal{L}_{\mathrm{DM}}$)

➔ Mixing of gravitational and DM sectors:

$$\mathcal{L}^{(2)}_{\lambda,\phi} \supset \text{“}\lambda\Box\lambda+\phi\Box\phi+\xi\phi\Box\lambda\text{”}$$

$$\left(g_{\mu\nu}=\eta_{\mu\nu}+2\kappa\lambda_{\mu\nu},\quad \kappa=M_{\mathrm{P}}^{-1}\right)$$

Weyl transformation

- Diagonalize quadratic Lagrangian via

$$\widehat{g}_{\mu\nu} = \left(1 + 2\kappa^2 \xi M \phi\right) g_{\mu\nu}$$

➔ Einstein frame: gravitational action canonical

➔ DM interactions with observable sector explicit

➔ Universal coupling $\xi M \kappa$, introduced via Weyl factor $\Omega^2 = 1 + 2\kappa^2 \xi M \phi$

$$\mathcal{S} = \int d^4x \sqrt{-\widehat{g}} \left[-\frac{\widehat{R}}{2\kappa^2} + \widehat{\mathcal{L}}_{\text{obs}}^{\text{eff}} + \widehat{\mathcal{L}}_{\text{DM}} + ... \right]$$

Light dark matter: decay channels

- Example: transformed fermion Lagrangian

$$\widehat{\mathcal{L}}^{\text{eff}}_{\text{obs}} \supset \sum_f \left(\frac{i}{\Omega^3} \bar{f} \gamma^\mu \widehat{\nabla}_\mu f - \frac{m_f}{\Omega^4} \bar{f} f \right)$$

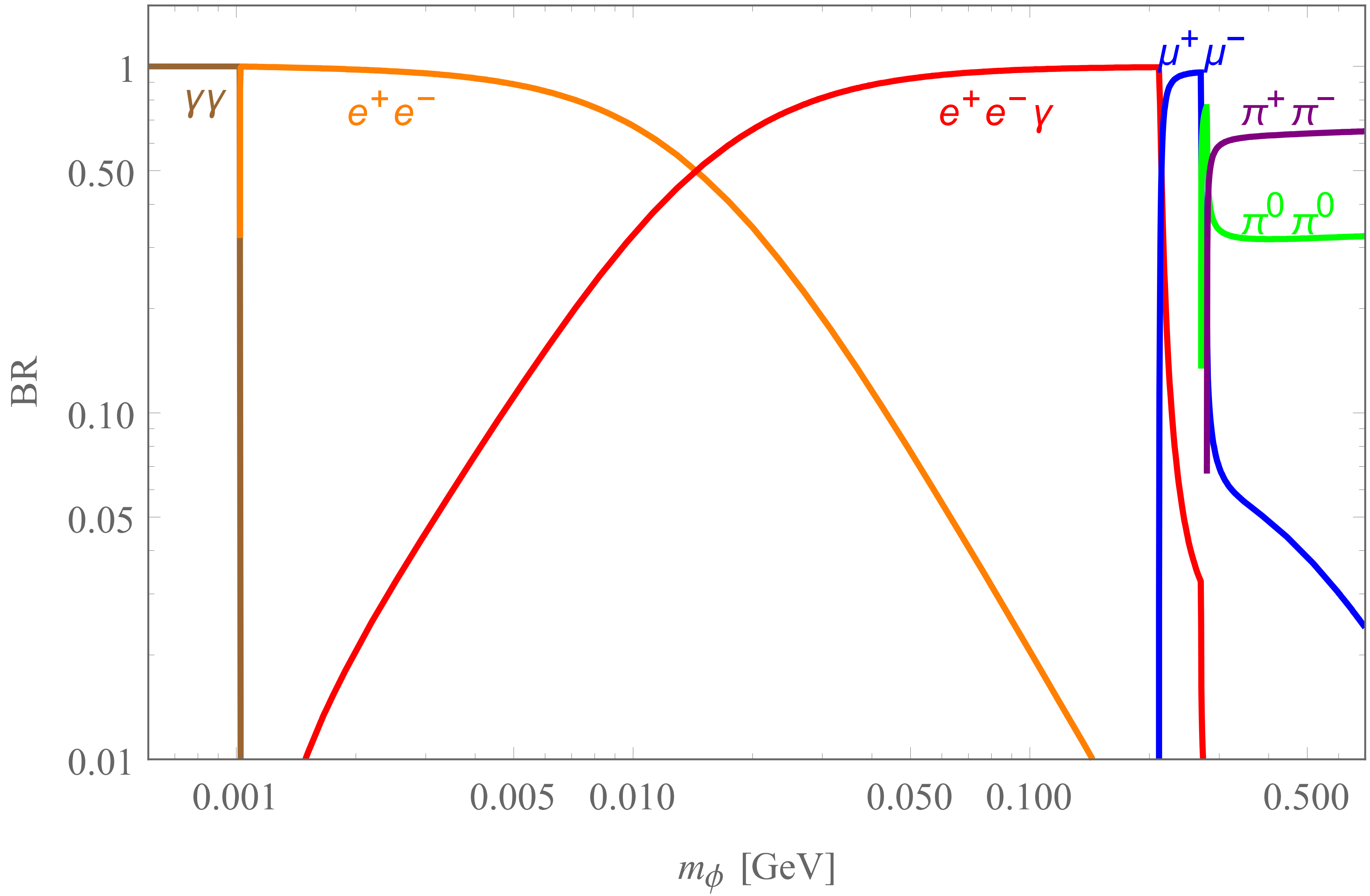
$$\Omega^2 = 1 + 2\kappa^2 \xi M \phi$$

→ Expand prefactors to first order in DM field, read off decay vertices

- Decay modes below GeV scale:

$$\phi \to \gamma\gamma, \nu\bar{\nu}, e^+e^-(\gamma), \mu^+\mu^-(\gamma), \pi\pi, \ldots$$

Light dark matter: branching fractions



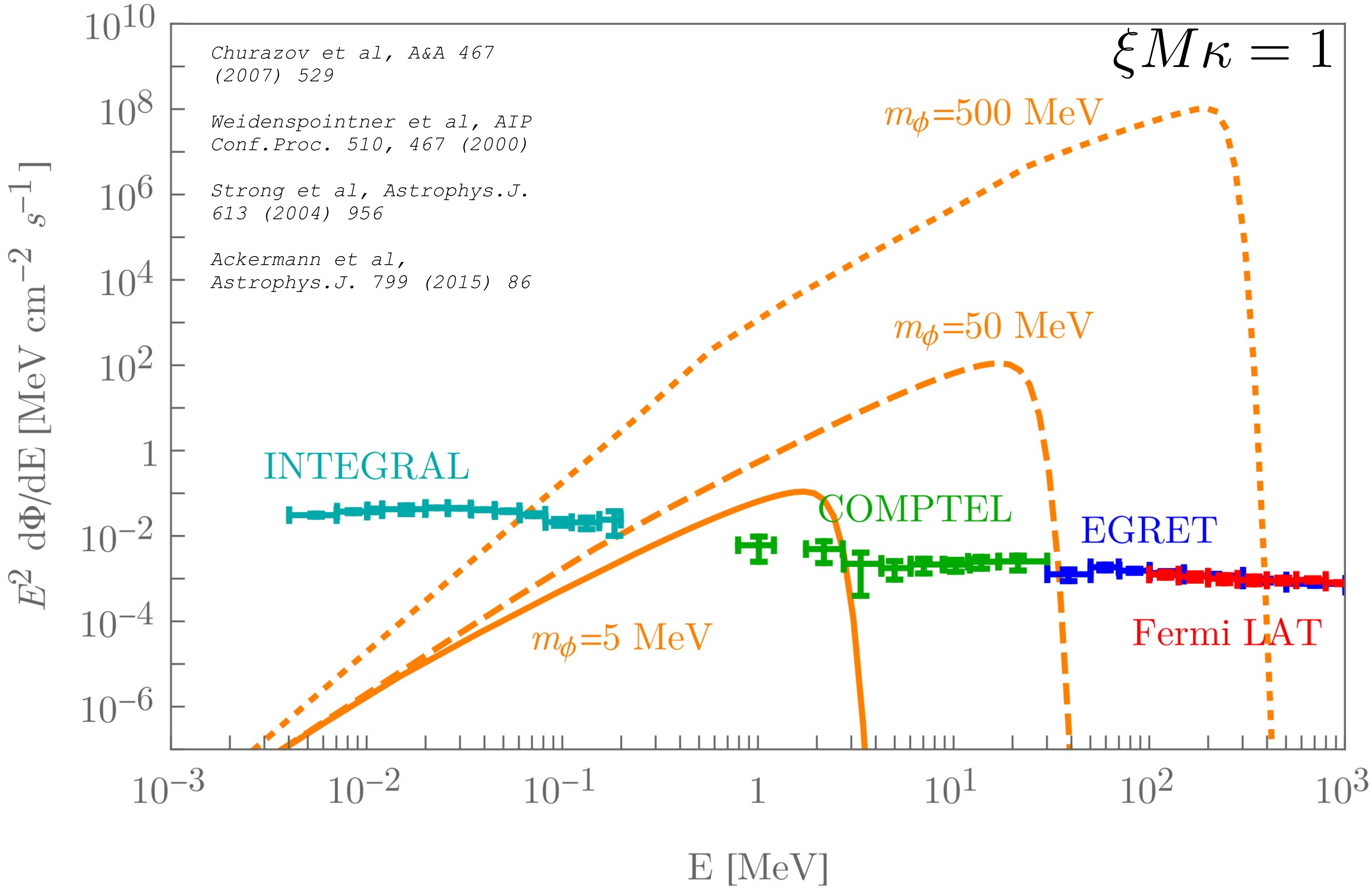
Spectral features

- "Gravity portal" coupling to observable sector & MeV to GeV-scale mass
  - ➔ Decays into $\gamma\gamma, f\bar{f}\gamma, 2\pi^0 \to 4\gamma, ...$
  - ➔ Radiation of gamma-/x-rays at corresponding energies
  - ➔ Spectral features (line, box,…): in principle detectable over smooth background (cosmological DM + NFW halo)

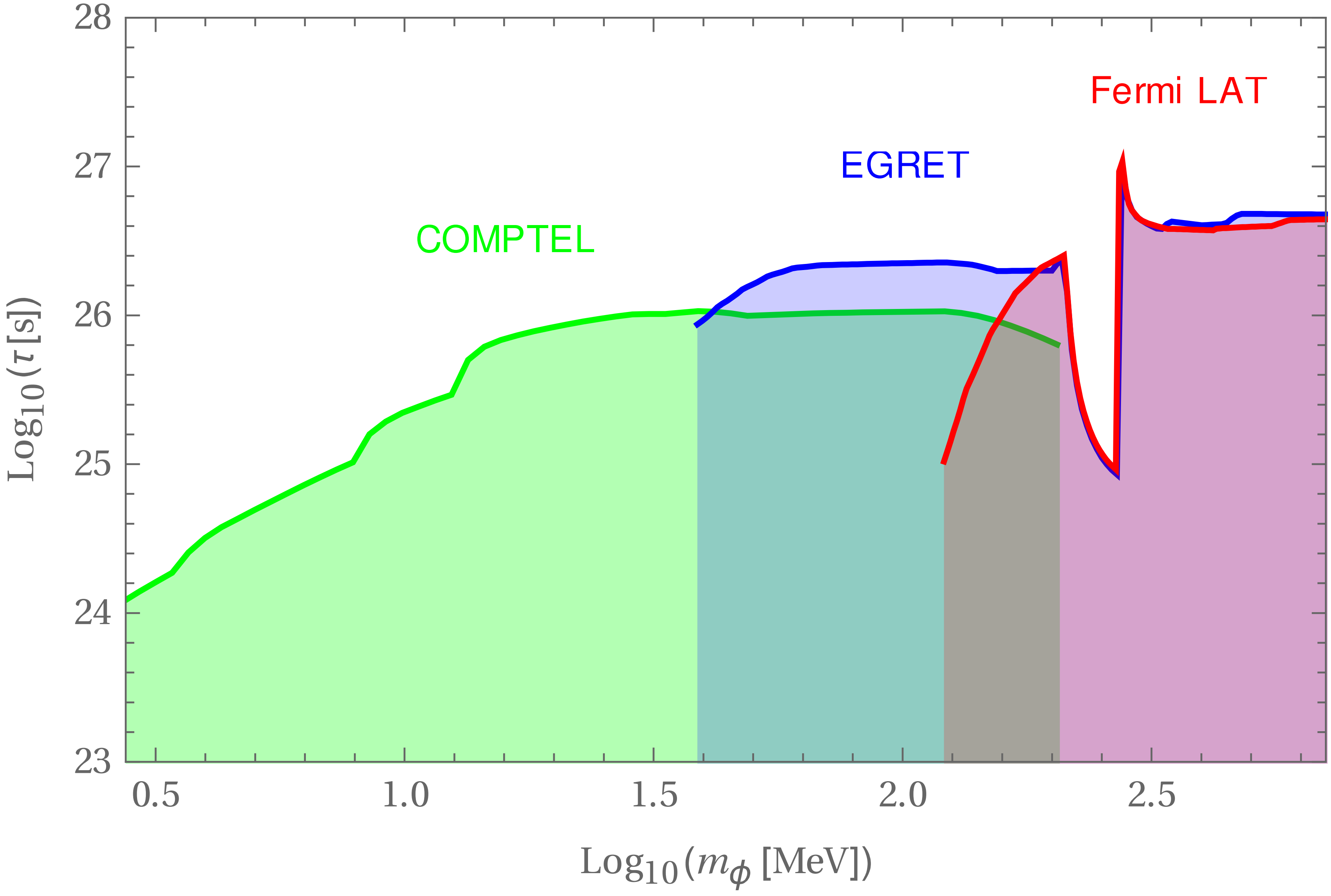
- Scalar singlet: observable decays in spite of Planck-mass suppression for $\xi M \kappa \lesssim \mathcal{O}(1)$, $m_\phi \gtrsim 1\ \mathrm{MeV}$

  (Below electron threshold: $\phi \to \gamma\gamma$ via e^-, μ^- loops + effective vertex, but rate too low to be detectable)

Gamma-ray spectra



Gamma-ray constraints: lifetime



CMB constraints: approach

Slatyer, Wu, Phys.Rev. D95 (2017) no.2, 023010 MIT-CTP/4842

General Constraints on Dark Matter Decay from the Cosmic Microwave Background

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Precise measurements of the temperature and polarization anisotropies of the cosmic microwave background can be used to constrain the annihilation and decay of dark matter. In this work, we demonstrate via principal component analysis that the imprint of dark matter decay on the cosmic microwave background can be approximately parameterized by a single number for any given dark matter model. We develop a simple prescription for computing this model-dependent detectability

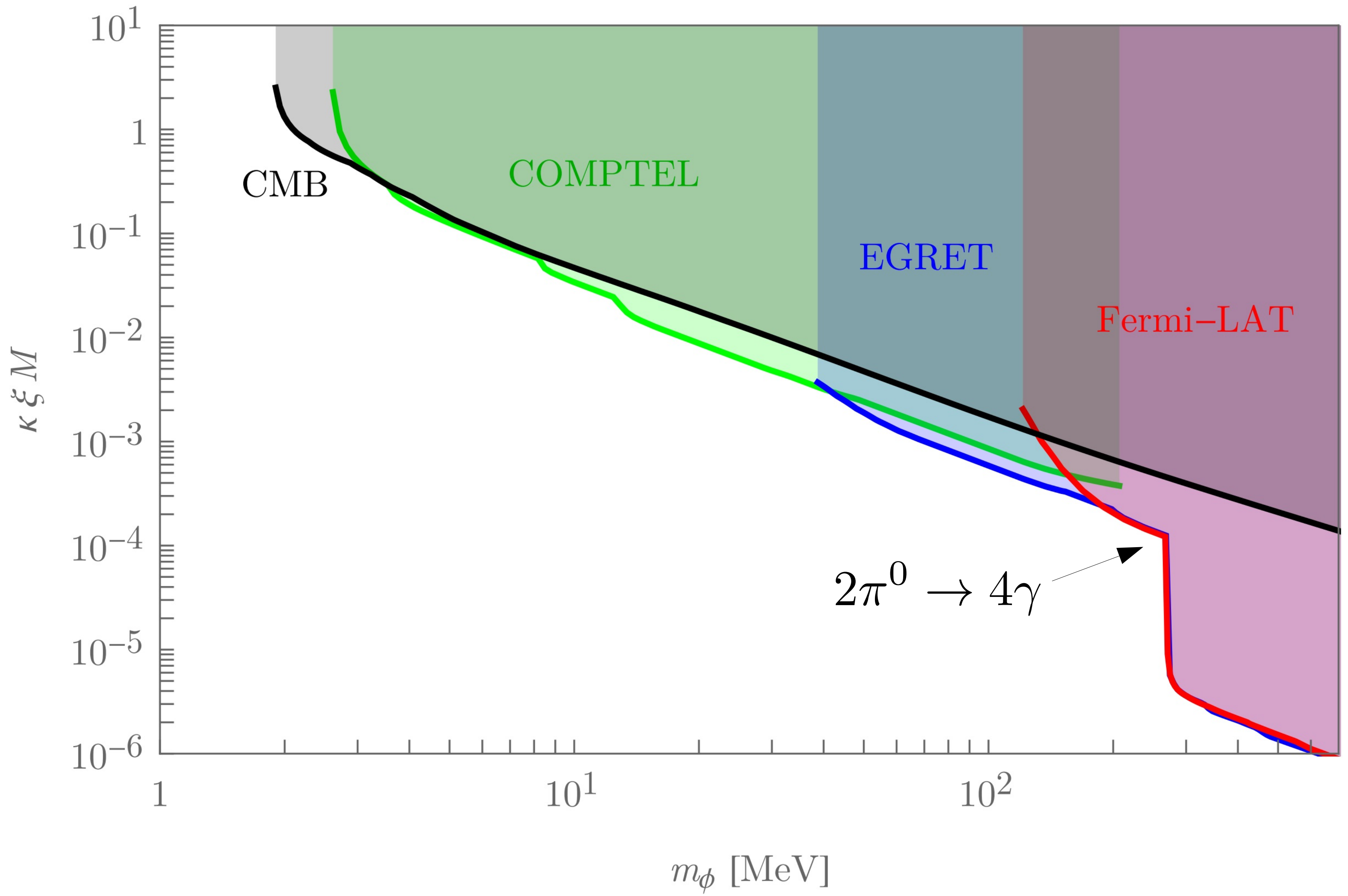
- Impact of DM "basis models" on CMB known, interpolation tables provided online

  https://faun.rc.fas.harvard.edu/epsilon//

- Constraint on generic DM model:
  - Decompose into linear combination of basis models
  - Approximate limit is given by weighted sum over limits on basis models

Details: see Chih-Liang Wu's talk on Friday!

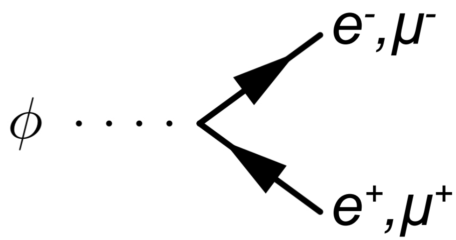
Constraints on non-minimal coupling



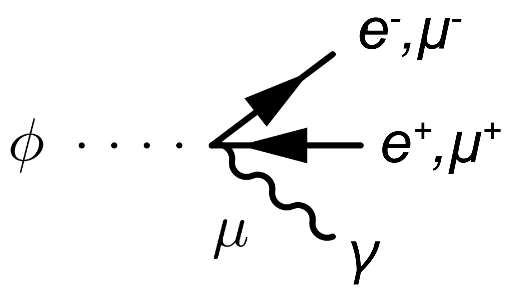
Conclusions

- DM stabilized by global symmetry might become unstable via “gravity portal”
  - ➔ Universal coupling to visible sector
- Specifically, a DM candidate in the MeV-GeV mass region could produce copious amounts of γ, e, μ, π
  - ➔ Expect sharp spectral feature in gamma-ray flux
  - ➔ Scalar singlet DM: fluxes at observable level $(\xi M \kappa \lesssim 1)$
- Present data constrains non-minimal coupling to values $\xi M \kappa \lesssim 10^{-2}$ for scalar singlet with $m_\phi \gtrsim 15 \text{ MeV}$, in line with CMB limits

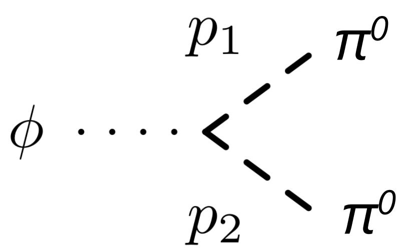
Backup – decay vertices



$$i\kappa^2\xi M m_{e,\mu}$$



$$3i\kappa^2\xi M e\gamma_\mu$$



$$2i\kappa^2\xi M\left(2m_\pi^2 + p_1\cdot p_2\right)$$

Backup – constraints: overview

- Decays into photons, electrons/positrons
  1) Today: spectral features over gamma-ray background
  2) In the early Universe: impact on CMB spectrum
- Sensitivity to non-minimal coupling parameter: saturates at large coupling

$$\Gamma_{\widehat{\phi}} \sim \frac{\xi^2 M^2 \kappa^2}{1 + 6\kappa^2 \xi^2 M^2}$$

➔ Can only constrain small-coupling regime

Backup – CMB constraints: lifetime