Spectral features from light dark matter decay via gravity portal interactions

(arXiv:1707.08480)

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DESY Theory Workshop 2017, Hamburg

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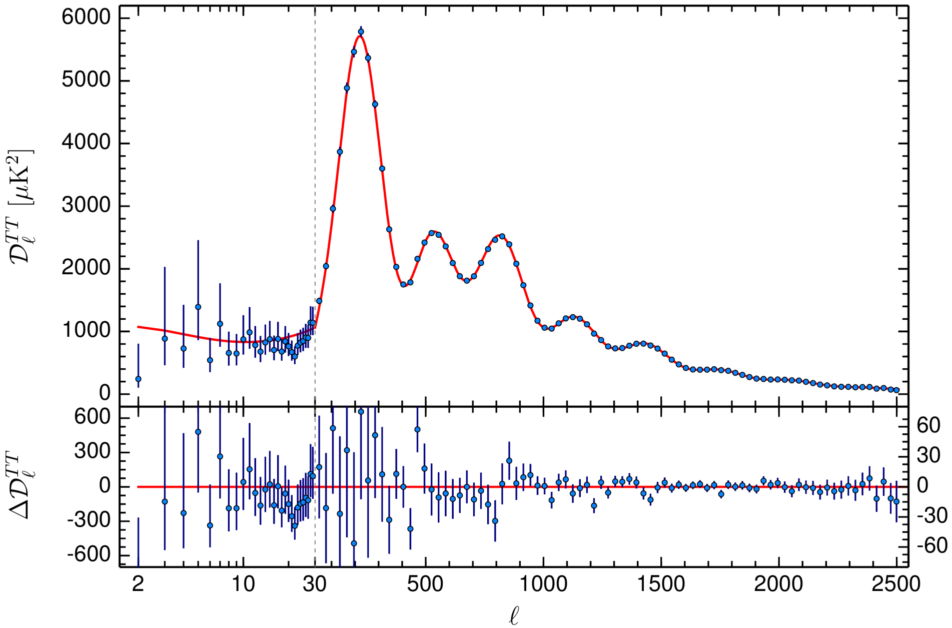
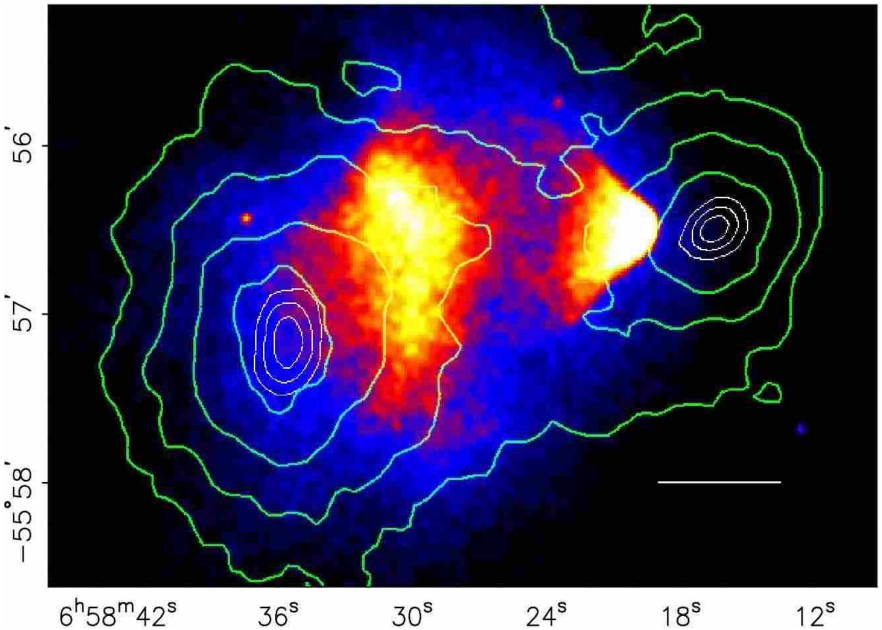
The dark sector

- Evidence for dark matter (DM) on multiple scales, based on its gravitational interactions



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



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

- Properties: uncharged (?), collisionless (?), ***stable (?)***

Dark matter stability

- 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

Decay via "gravity portal"

- Does gravity conserve global symmetries?

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

  - What if the DM particle is stabilized by a global symmetry that is only broken by gravity? (Lifetime large enough?)

Catà, Ibarra, SI, Phys. Rev. Lett. 117 (2016) 021302
Catà, Ibarra, SI, Phys. Rev. D95 (2017) 035011

- Scenario:
  - Non-gravitational interactions preserve global symmetry
  - DM decays via "gravity portal" only
  - Long lifetime due to Planck suppression of gravitational interactions

Non-minimal coupling to gravity

- DM remains stable under minimal coupling to gravity

$$\mathcal{L}\left(\varphi, \partial_\mu \varphi, \eta_{\mu\nu}\right) \to \sqrt{-g}\,\mathcal{L}\left(\varphi, \nabla_\mu \varphi, g_{\mu\nu}\right)$$

  - ➢ Lowest-dimensional *non-minimal* operator that conserves Lorentz and SM symmetries, but breaks stabilizing Z_2?

$$\mathcal{L}_\xi = -\xi R f^{(1)}(\varphi)$$

- (Kinetic) mixing between DM candidate and graviton
  - ➢ Universal nature of gravity leads to universal coupling between DM and observable sector (→ DM decays into SM!)

Non-minimal coupling: detectability

- Scalar SU(2)-doublet / fermion DM: additional protection from gauge/Lorentz symmetry allows for $\xi \sim \mathcal{O}(1)$ up to $m_{\mathrm{DM}} \lesssim 10^5 \div 10^6\ \mathrm{GeV}$

  Catà, Ibarra, SI, Phys. Rev. D95 (2017) 035011

- Scalar singlet ϕ: experiments sensitive to $\xi \sim \mathcal{O}(1)$ even at sub-GeV DM masses
  - Potential for a signal in gamma-ray flux
  - Imprint on CMB from decays in the early Universe?

Light (below $700\ \mathrm{MeV}$) scalar dark matter

- Jordan frame action $(\mathcal{L}_\xi = -\xi M R \phi)$:

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

  - ➢ 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:

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

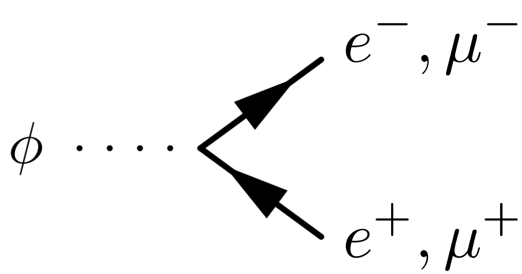
$$\left(g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa\lambda_{\mu\nu}, \quad \kappa = \bar{M}_{\mathrm{P}}^{-1}\right)$$

Weyl transformation

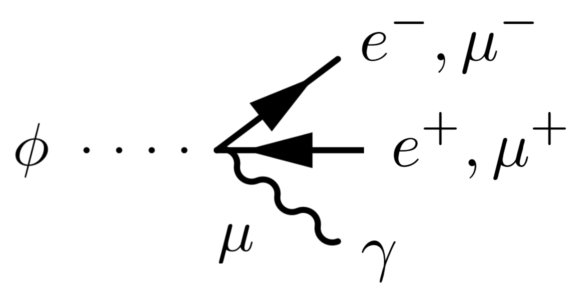
- Decouple gravitational and dark sectors via

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

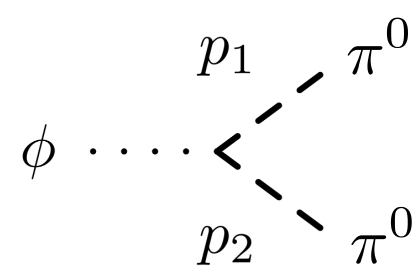
  - ➢ Einstein frame: gravitational action canonical
  - ➢ DM interactions with visible sector can be read off directly



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



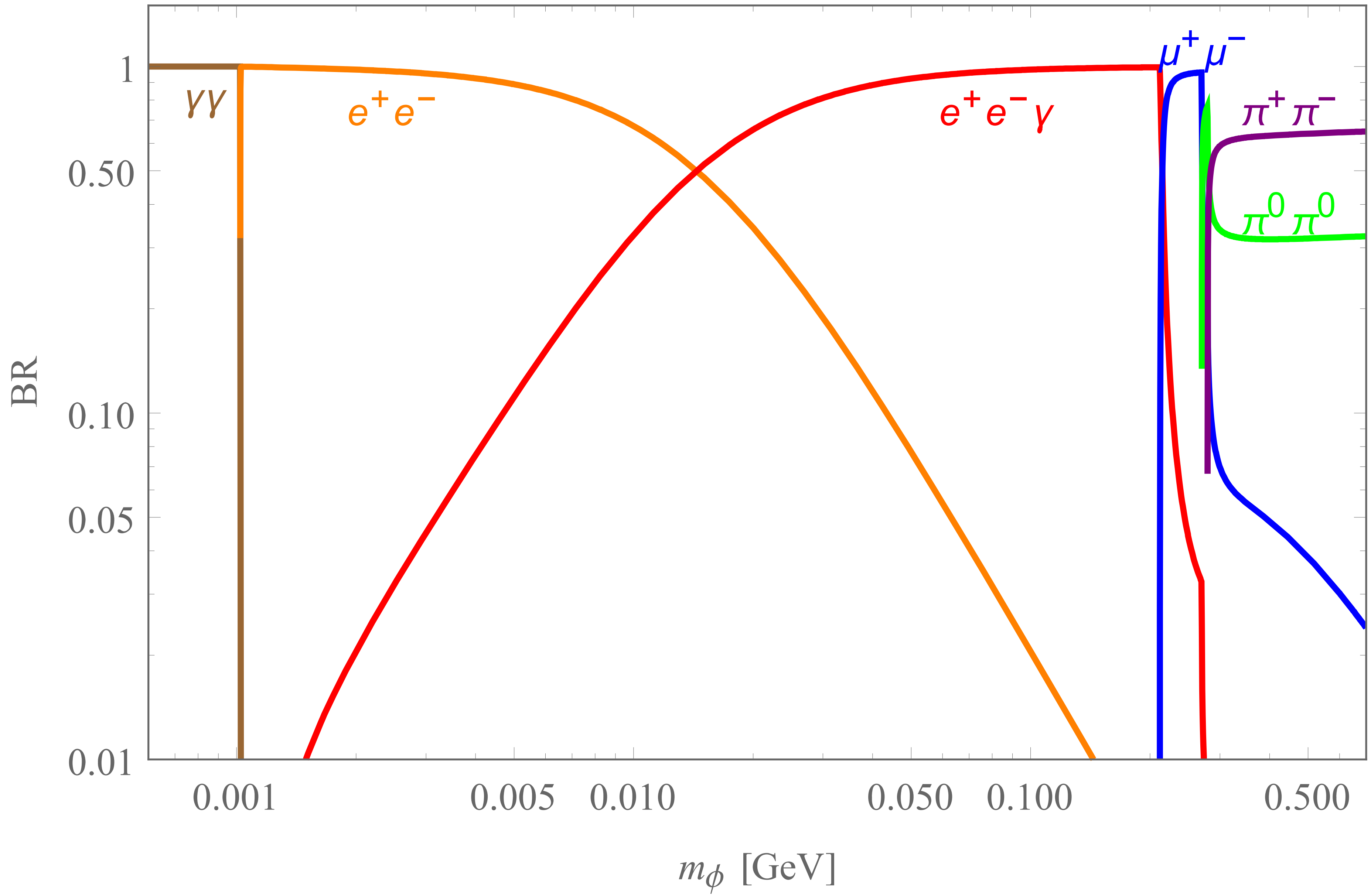
$3i\kappa^2 \xi M e \gamma_\mu$



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

- Decay modes: $\phi \to \gamma\gamma, \nu\bar{\nu}, e^+e^-(\gamma), \mu^+\mu^-(\gamma), \pi\pi,$ ...

Branching fractions

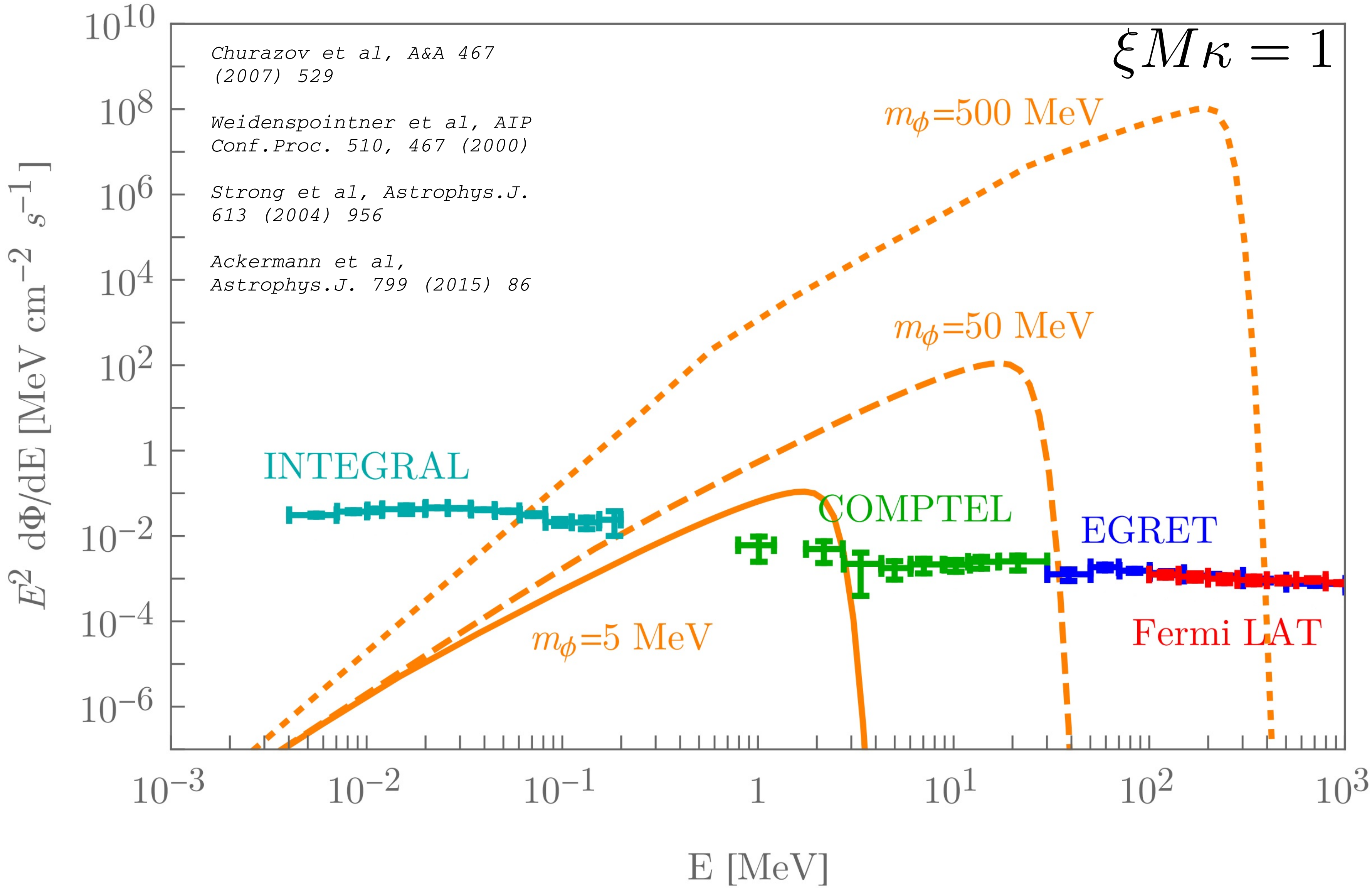


Spectral features

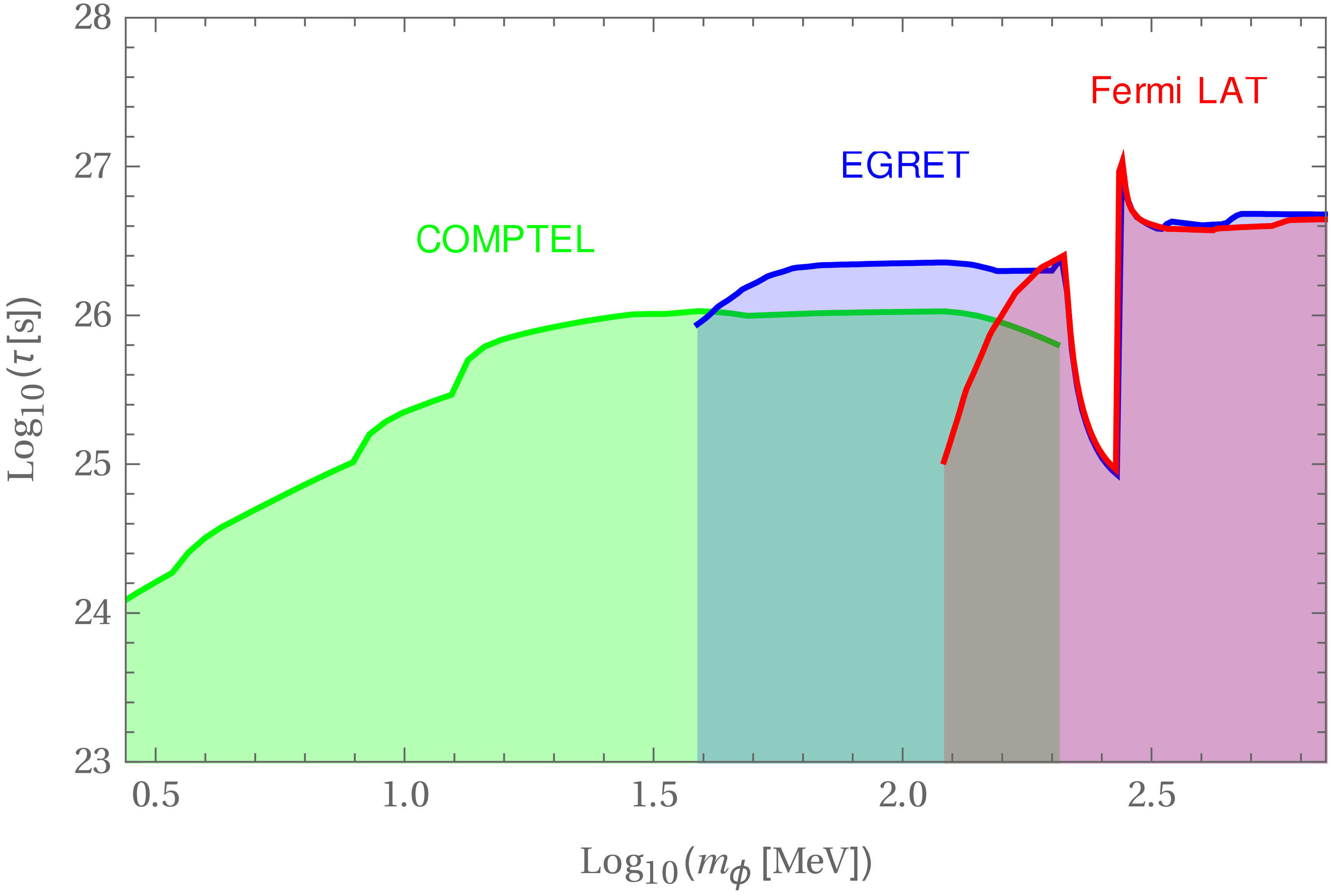
- "Gravity portal" coupling to observable sector, MeV to GeV-scale mass → decays into $\gamma\gamma, l^+l^-(\gamma), 2\pi^0, \pi^+\pi^-$
  - $\phi \to \gamma\gamma$: gamma-ray line, but loop suppressed
  - $\phi \to 2\pi^0 \to 4\gamma$: gamma-ray box, visible for $\xi M\kappa \lesssim \mathcal{O}(1)$
  - $\phi \to l^+l^-\gamma$: additional "bump-like" feature from 3-particle vertex

- Spectral features in principle detectable over smooth background (cosmological + halo components)
  - Confront with measured x-ray / gamma-ray flux!

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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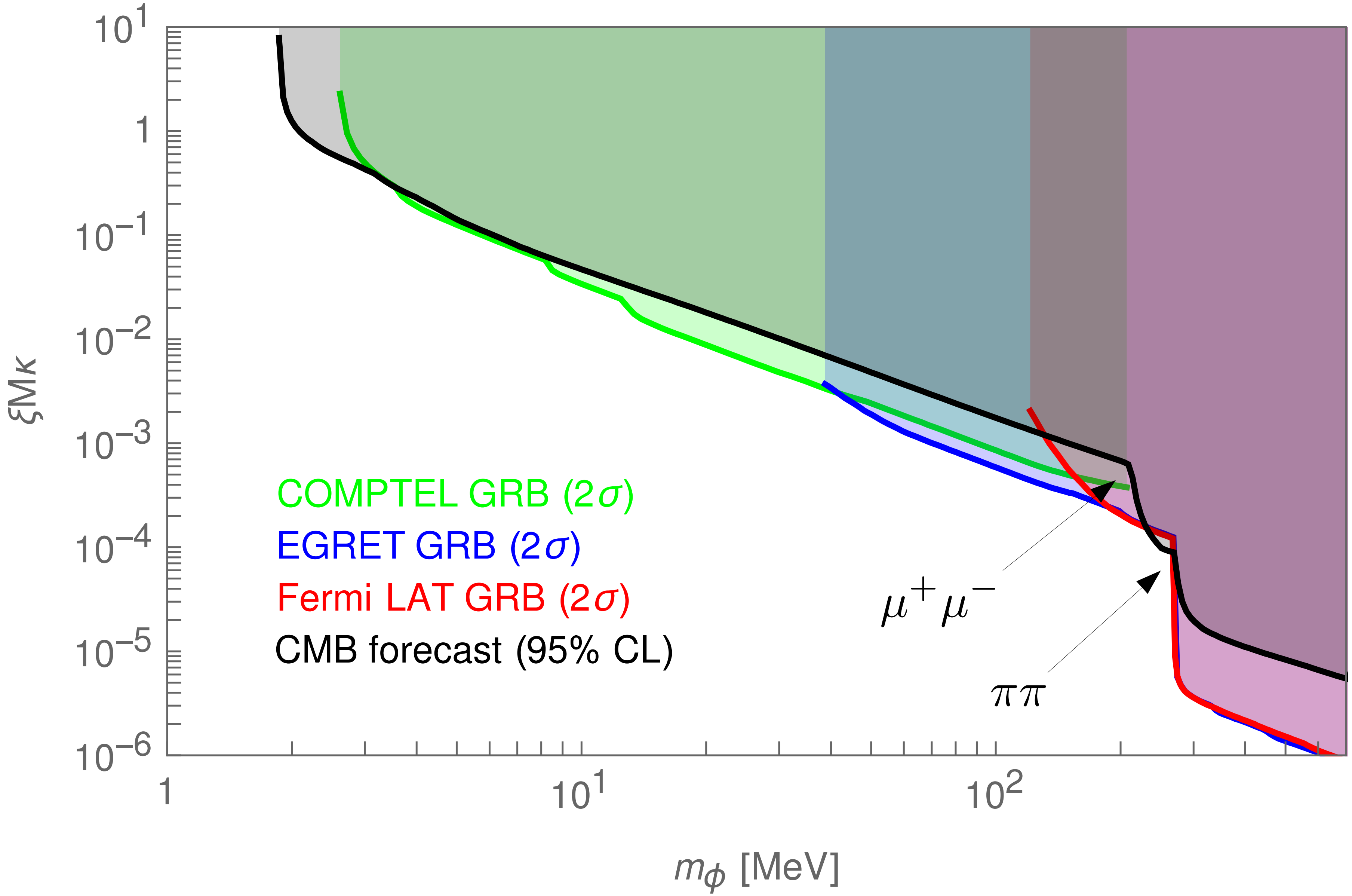
Precise measurements of the temperature and polarization anisotropies of the cosmic microwave background can be used to constrain the annihilation and decay of dark matter. In this work, we demonstrate via principal component analysis that the imprint of dark matter decay on the cosmic microwave background 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

Constraints on non-minimal coupling



Conclusions

- DM stabilized by global symmetry might become unstable via "gravity portal"
  - Universal coupling to visible sector leads to decay
- Specifically, a DM candidate in the MeV-GeV mass region could produce copious amounts of γ, e, μ, π
  - Sharp spectral feature in gamma-ray flux
  - Imprint on CMB

$(\xi M \kappa \sim 1)$

- Present data: $\xi M \kappa \lesssim 10^{-2}$ for scalar singlet with $m_\phi \gtrsim 15 \text{ MeV}$, in line with CMB limits

Backup – vertex from Weyl trafo

- 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

$$\Omega^{-3} = 1 - 3\kappa^2 \xi M \phi + \mathcal{O}(\phi^2)$$

- Decay modes below GeV scale:

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

Backup: CMB constraints, DM lifetime

- Here: prompt electrons & $\mu^{\pm}, \pi^{\pm}$ decays, photons