

Gamma-rays from light dark matter decaying through a gravity portal

(JCAP 1711 (2017) no.11, 044,
Phys.Rev. D95 (2017) no.3, 035011,
Phys.Rev.Lett. 117 (2016) no.2, 021302)

with Oscar Catà, Alejandro Ibarra



Max-Planck-Institut für Physik
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Gamma-rays from decaying dark matter

(with a pinch of 'gravity portal' in the end)

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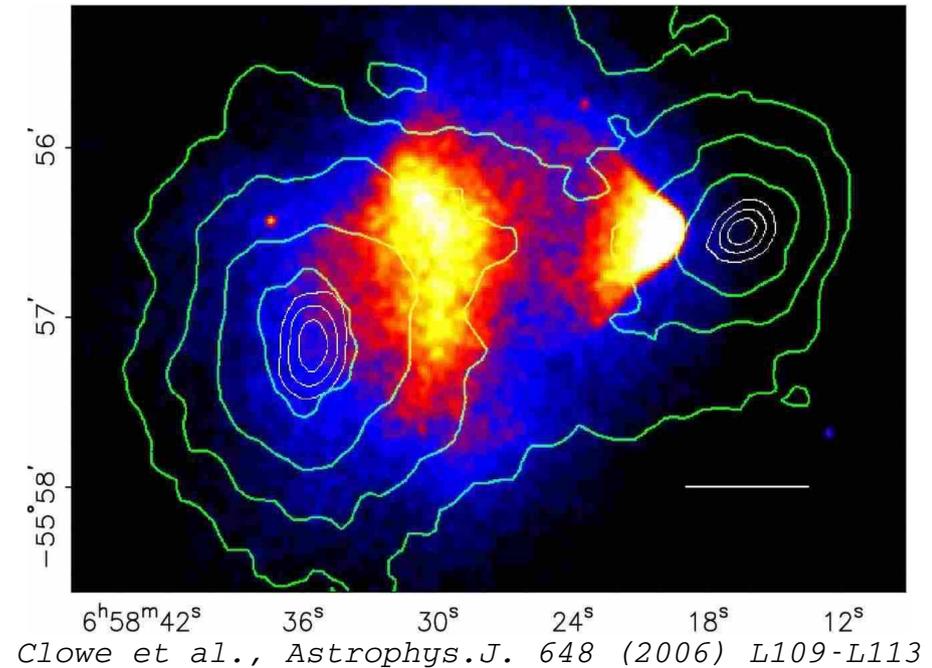


Outline

- ◆ Motivation: dark matter stability
- ◆ Observables: gamma-rays, cosmic rays, CMB
- ◆ Example: DM decay via “gravity portal” interactions
- ◆ Results: constraints on non-minimal coupling

The dark universe

- Since 1930s: evidence for dark matter (DM) on multiple length scales
 - Galaxies (→ rotation curves)
 - Galaxy clusters
 - Universe at large (→ CMB, large-scale structure)
- So far, only “seen” through gravitational interactions
 - What does a dark matter particle look like?



Dark matter properties

- Λ CDM: DM cold, uncharged, collisionless, stable
 - Created in the early Universe (\rightarrow freeze-out/freeze-in?)
 - Cools down as the Universe expands
 - Clumps together gravitationally to seed structure formation (visible matter falls into DM potential wells)

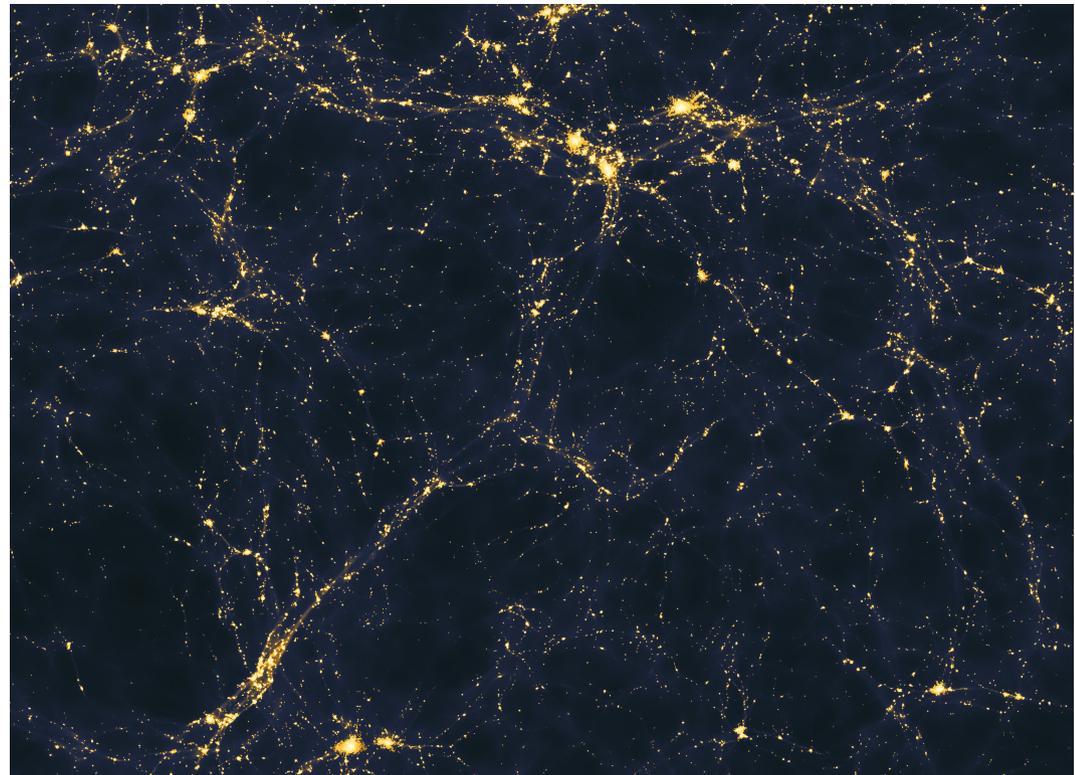


Image: Andrew Pontzen, Fabio Governato

Dark matter interactions

- Λ CDM: DM cold, uncharged, collisionless, *stable*
- In this (worst-case) scenario: virtually undetectable other than through its gravitational effects
- Departure from simplest case: DM self-interactions?
Interactions with visible sector?
 - Annihilations/*decays*? (“indirect detection”)
 - Scattering? (“direct detection”)
 - Production at colliders?

Dark matter stability

- Observational evidence: DM particle very long-lived

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

- Is dark matter absolutely stable or merely long-lived?

- Visible sector: only very few stable particles, stability due to symmetry

- Is there a symmetry in place to stabilize dark matter?

- Popular choice: global Z_2 ($\varphi \rightarrow -\varphi, X_{\text{SM}} \rightarrow X_{\text{SM}}$)

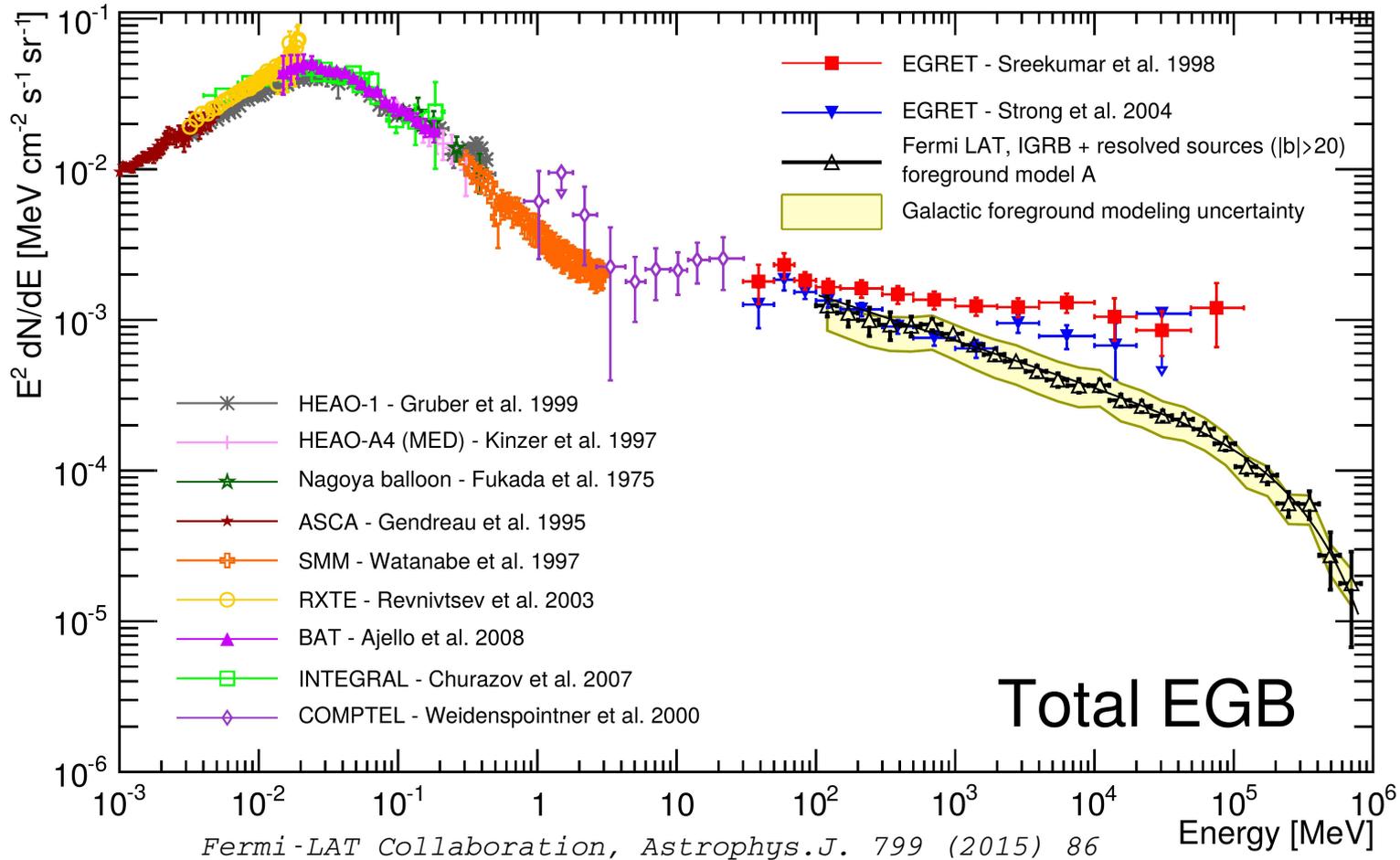
Decaying dark matter 101

- Alternatively: kinematical reasons for its long lifetime
 - *E.g.* axion – can decay in principle, but tiny decay width
- In this case: potentially observable decay products (cosmic rays / gamma-rays / neutrinos)

- Signals from decaying dark matter from
 - The galactic center
 - DM-dominated objects (*e.g.* dwarf spheroidal galaxies)
 - All around us (average DM density in the Universe)

DM decay signals

- Problem: astrophysical backgrounds



- Identify DM signal through morphology & spectrum

Gamma-ray flux from DM decay

- Cosmological DM: isotropic flux

$$\frac{d\Phi_{\text{EG}}}{dE} = \frac{\Omega_{\text{DM}}\rho_c}{m_{\text{DM}}} \int_0^\infty \frac{dz}{H(z)} \sum_f \Gamma_f \frac{dN^{(f)}}{dE} ((1+z)E)$$

- Halo component: integrate over line of sight

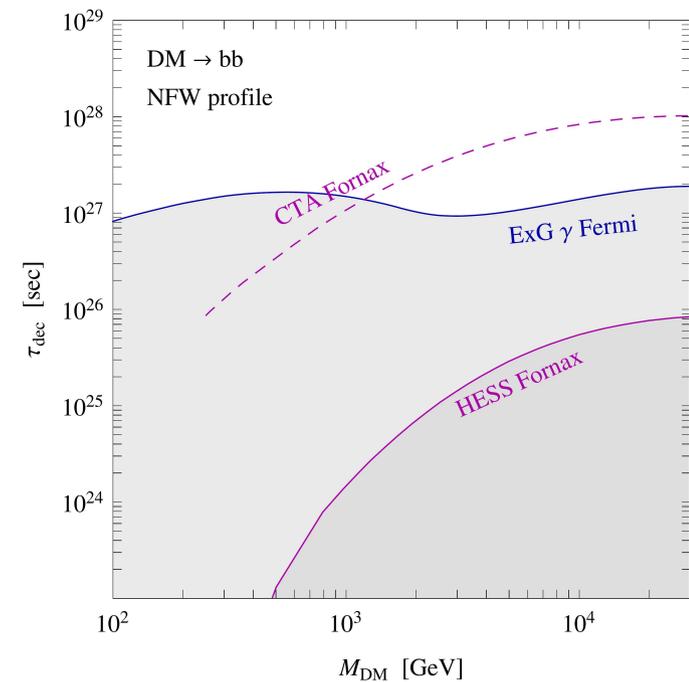
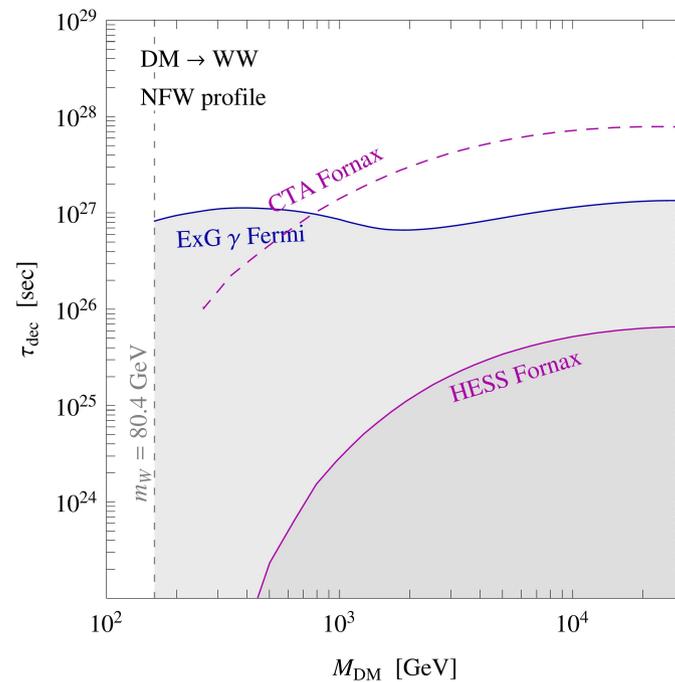
$$\frac{d\Phi_{\text{halo}}}{dE d\Omega}(\psi) = \frac{1}{4\pi} \frac{1}{m_{\text{DM}}} \sum_f \Gamma_f \frac{dN^{(f)}}{dE} \int_0^\infty ds \rho_{\text{halo}}(s, \psi)$$

Ibarra, Tran, Weniger, Int.J.Mod.Phys. A28 (2013) 1330040
Cirelli et al, Phys.Rev. D86 (2012) 083506

Constraints on decaying dark matter

- So far: no conclusive signal
 - Derive limit on DM lifetime for specific decay scenario, under certain astrophysical assumptions

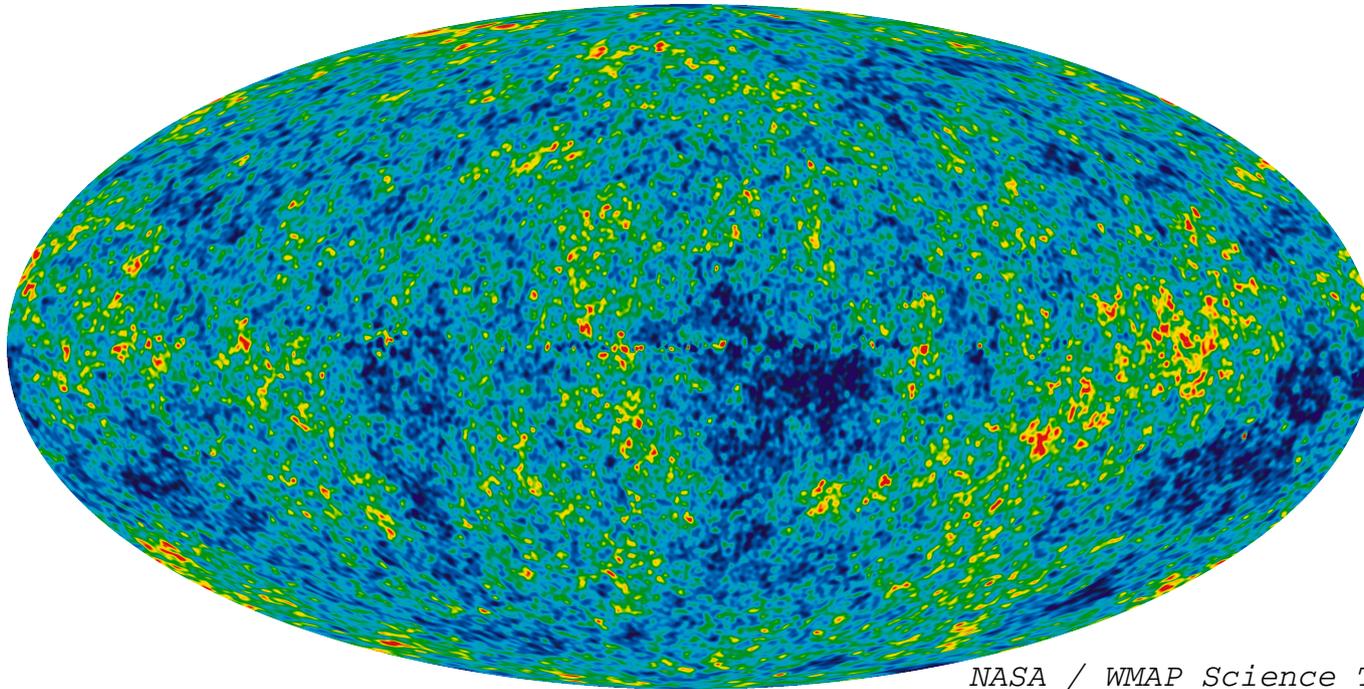
- Complimentary limits from cosmic rays and neutrinos



Cirelli, Moulin, Panci, Serpico, Viana, *Phys.Rev. D86 (2012) 083506*

Additional constraints: CMB

- Cosmic microwave background: sensitive probe of Universe at the time of decoupling



- DM decay in the early universe injects energy into intergalactic medium and distorts measured CMB

Taking stock

- ◆ Dark matter required to be very long-lived, but not absolutely stable
- ◆ Does DM interact with the observable sector? Does it decay into standard model particles?
- ◆ Cosmic ray / gamma-ray / neutrino fluxes at Earth might feature DM component
 - However, can be difficult to distinguish from background
 - So far no signal, only limits on DM lifetime
- ◆ CMB can also be used to constrain DM models

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

Witten, arXiv:1710.01791

- What if the DM particle is stabilized by a global symmetry that is only broken by gravity?

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

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

- Scenario:

- DM stable under non-gravitational interactions (as usual)
- DM decays via “gravity portal” only
- Long lifetime due to Planck suppression of gravitational interactions

Light (below 700 MeV) scalar dark matter

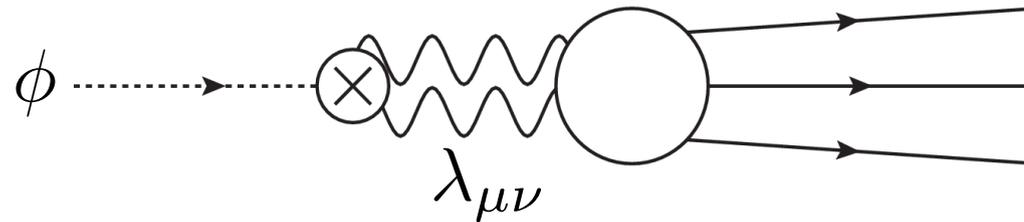
- Classical action ($\mathcal{L}_\xi = -\xi M R \phi$):

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

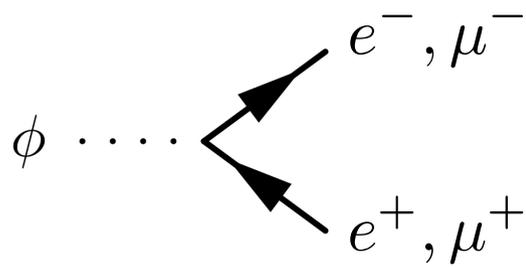
- **Observable sector**: effective Lagrangian for photons, neutrinos, light leptons, pions (χ PT)
- DM assumed to be stable in the absence of gravitational interactions (Z_2 conserved in \mathcal{L}_{DM})

Gravity portal

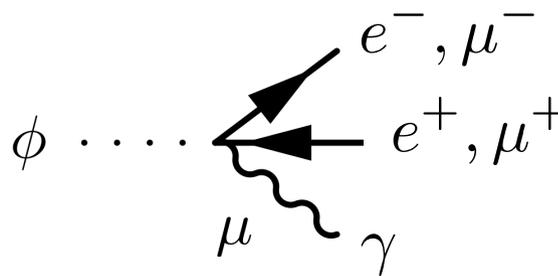
- Schematically: DM-graviton mixing



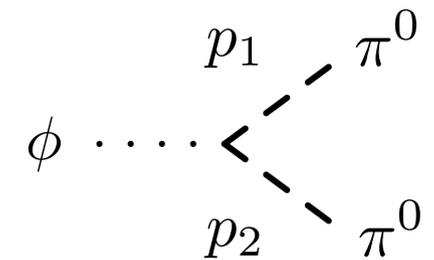
- In practice: perform field redefinition to read off vertices



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

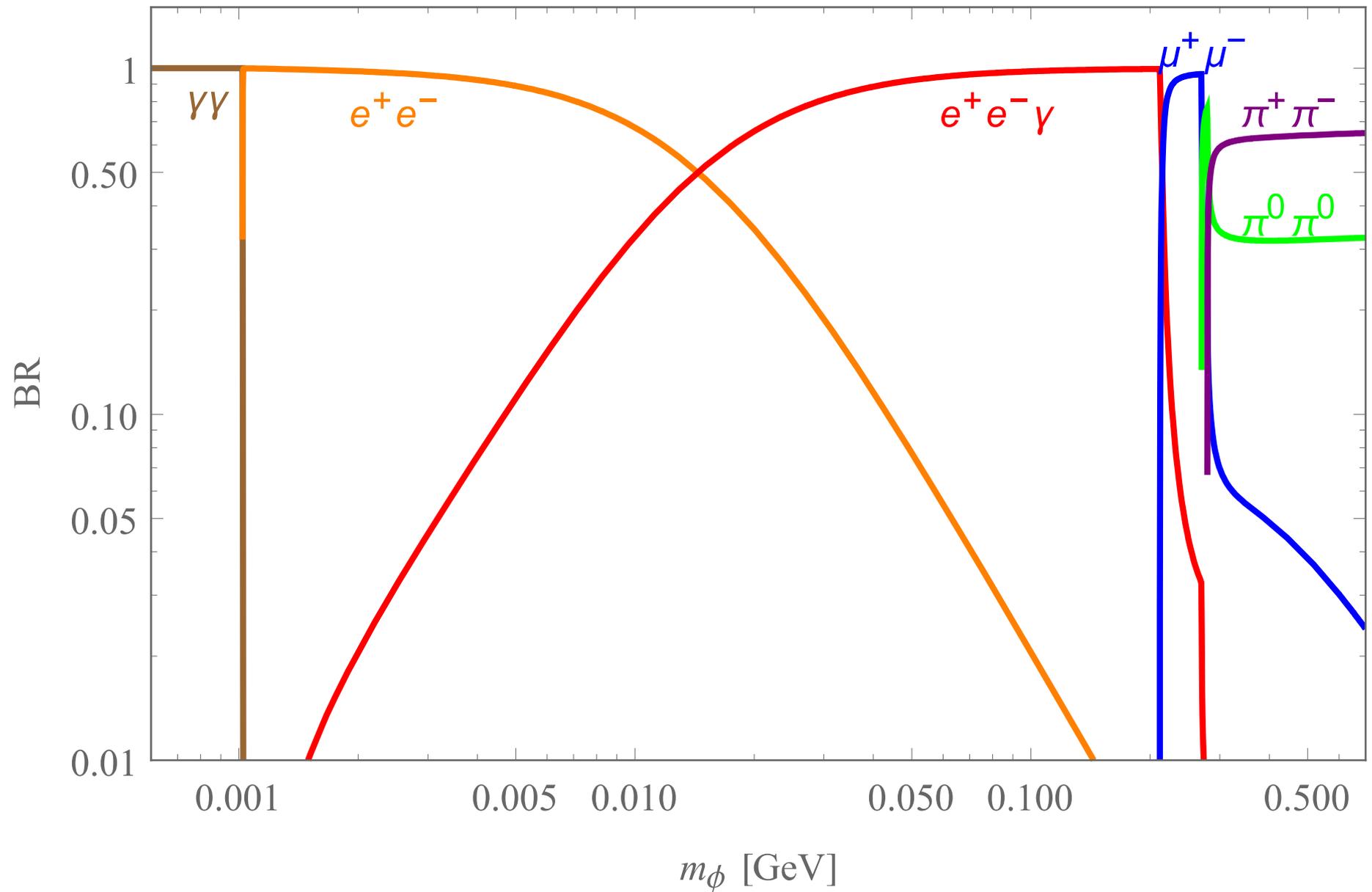


$$3i\kappa^2 \xi M e \gamma_\mu$$



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

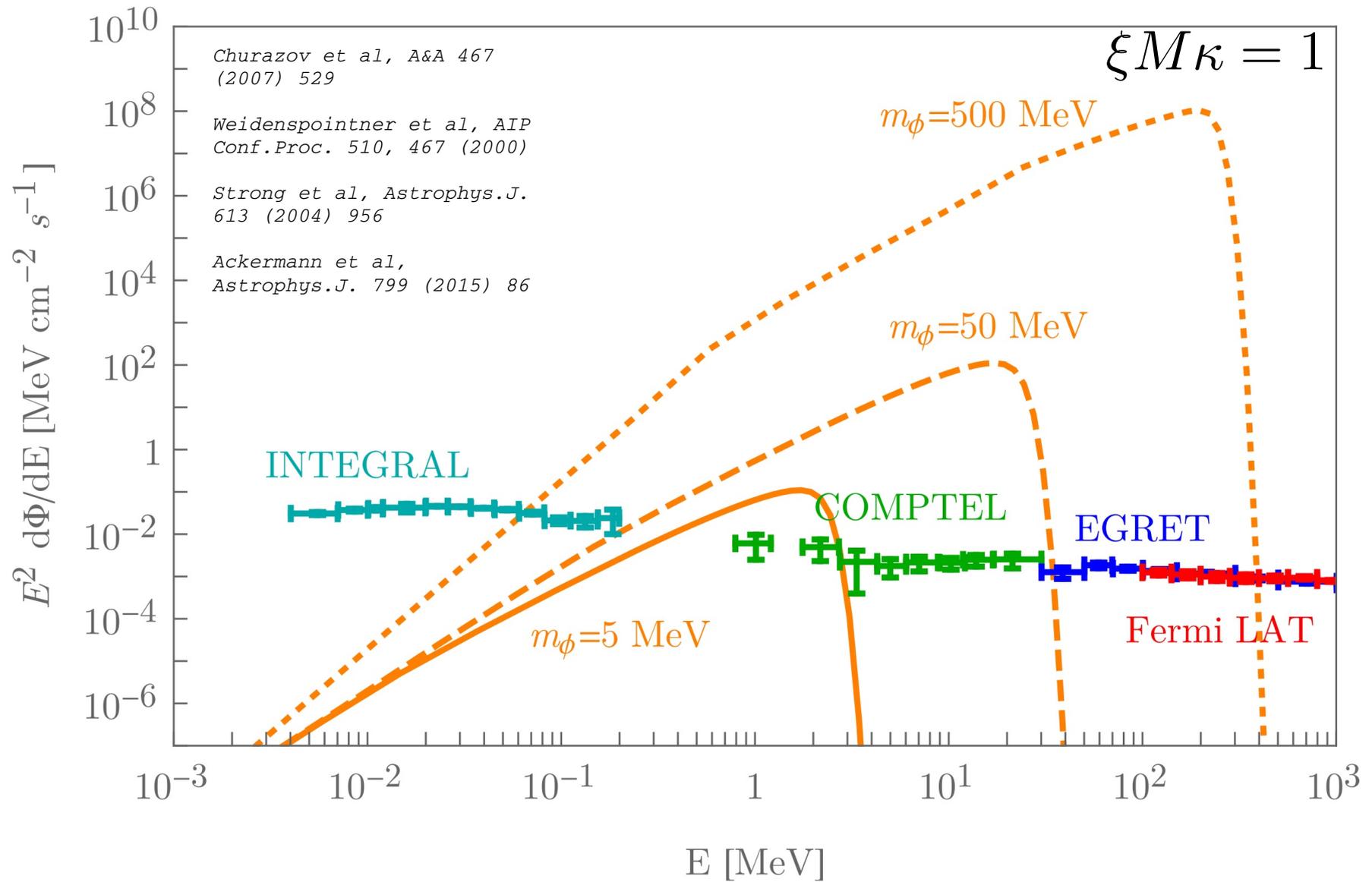
Light scalar singlet: branching ratios



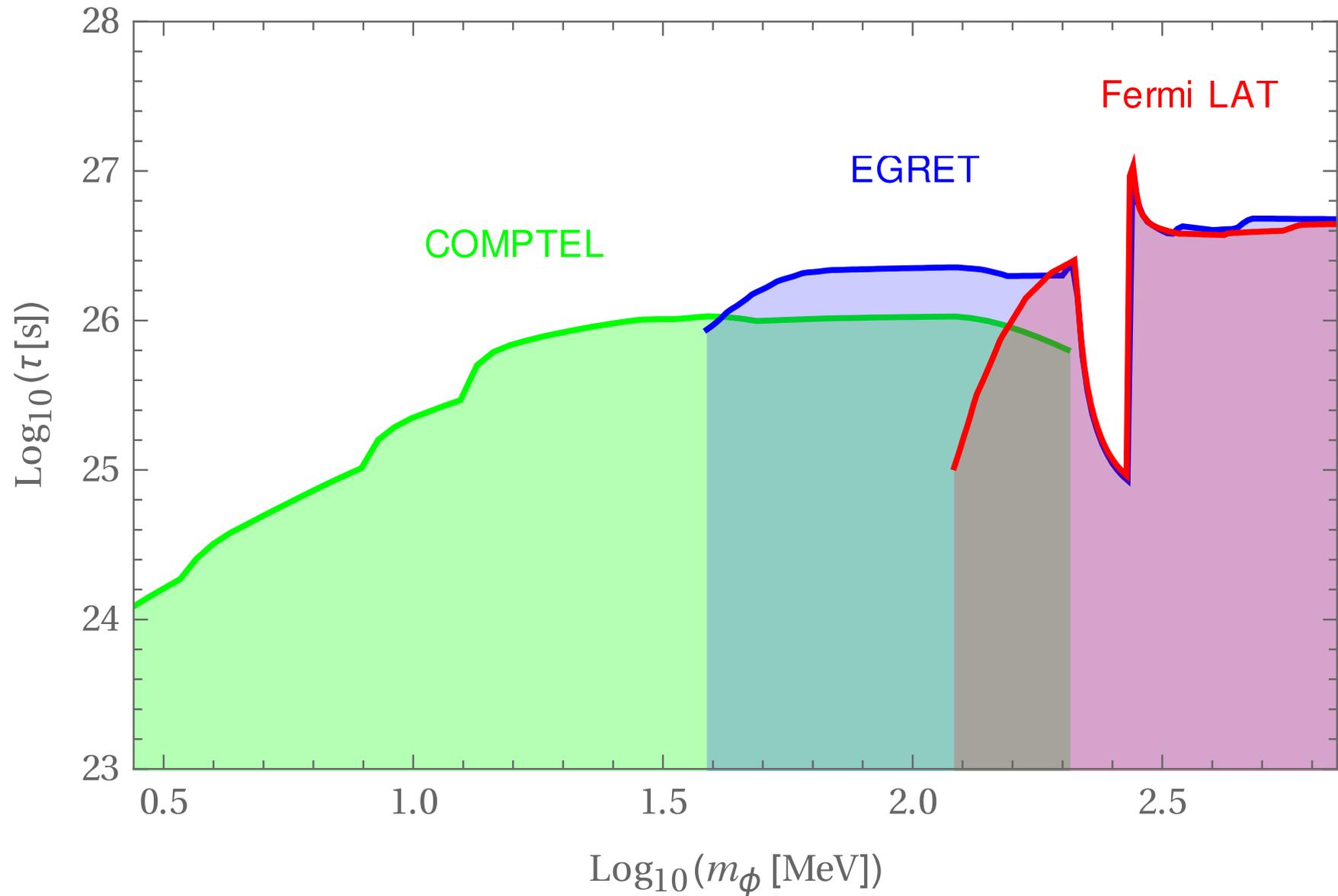
Spectral features

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

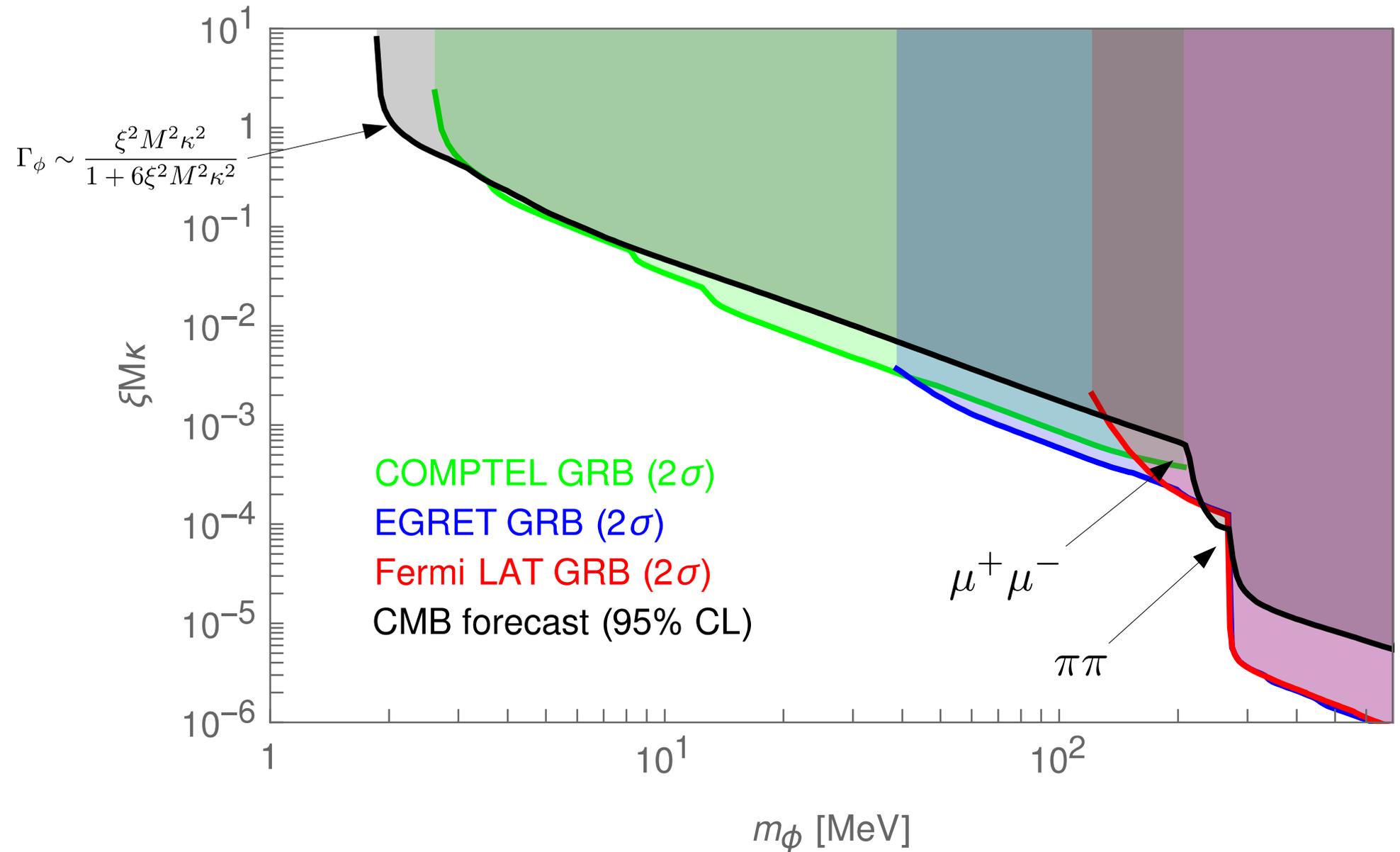
Gamma-ray spectra



Gamma-ray constraints: lifetime



Constraints on non-minimal coupling



Conclusions I

- DM particles are extremely long-lived
 - Absolute stability or decaying dark matter?
 - DM component in cosmic ray / gamma-ray / neutrino flux?
- Strength and shape of DM decay signal depends on
 - Model specifics (→ decay channels, total width)
 - Target region in the sky (→ astrophysical backgrounds, origin of signal)
- So far, no conclusive signals, only limits
- Additional constraints from CMB

Conclusions II

- “Gravity portal” scenario:
 - Non-minimal coupling to Ricci curvature tensor
 - Universal coupling to visible sector → final states predictable
- DM candidate in the MeV-GeV mass range: γ, e, μ, π
- Present data: $\xi M \kappa \lesssim 10^{-2}$ for scalar singlet with $m_\phi \gtrsim 15$ MeV, in line with CMB limits
- Open questions:
 - Production mechanism?
 - Expected size of non-minimal coupling?

Thanks for your attention!



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Backup: Weyl transformation details

- Ricci scalar, expanded: $g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa\lambda_{\mu\nu}$, $\kappa = \bar{M}_{\text{P}}^{-1}$

$$R = \kappa \left(2\partial^\alpha \partial^\beta \lambda_{\alpha\beta} - 2\partial^2 \lambda \right) + \mathcal{O}(\kappa^2 \lambda^2)$$

- Non-minimal coupling: $\mathcal{L} \supset -\xi R M \varphi$

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

- Weyl transform metric tensor:

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} = \left(1 + 2\kappa^2 \xi f^{(1)}(\varphi) \right) g_{\mu\nu}$$

- Einstein frame action:

$$\mathcal{S} = \int d^4x \sqrt{-\hat{g}} \left[-\frac{\hat{R}}{2\kappa^2} + \Omega^{-4} \mathcal{L}_{\text{m}} \left(\varphi, \hat{\nabla}_\mu \varphi, \Omega^{-2} \hat{g}_{\mu\nu} \right) \right]$$

Backup: EF field renormalization

- DM Lagrangian:

$$\hat{\mathcal{L}}_{\text{DM}} = \frac{3}{\kappa^2} \frac{\hat{\nabla}_\mu \Omega \hat{\nabla}^\mu \Omega}{\Omega^2} + \frac{1}{\Omega^2} \hat{\mathcal{T}}_\phi - \frac{1}{\Omega^4} \hat{\mathcal{V}}_\phi$$

- Define canonically normalized scalar field:

$$\hat{\phi} \simeq \sqrt{1 + 6\kappa^2 \xi^2 M^2} \phi + \mathcal{O}(\kappa^2 \phi^2)$$

- Modification in large-coupling limit:

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

Non-minimal coupling to gravity

- DM remains stable under minimal coupling to gravity
 - Lowest-dimensional *non-minimal* operator that conserves Lorentz and SM symmetries, but allows for DM decay?

$$\mathcal{L}_\xi = -\xi \mathbf{R} \cdot \mathbf{f}(\varphi)$$

$$g_{\mu\nu} \sim \eta_{\mu\nu} + \frac{\lambda_{\mu\nu}}{\bar{M}_\text{P}}, \quad R_{\mu\nu} \sim \left(\frac{\lambda_{\mu\nu}}{\bar{M}_\text{P}} + \frac{\lambda_{\mu\nu}^2}{\bar{M}_\text{P}^2} + \dots \right)$$

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

Non-minimal coupling: leading operators

- DM remains stable under minimal coupling to gravity
- Lowest-dimensional non-minimal operators:

➤ Scalar singlet DM

$$-\xi R M \phi$$

➤ Scalar SU(2)-doublet DM

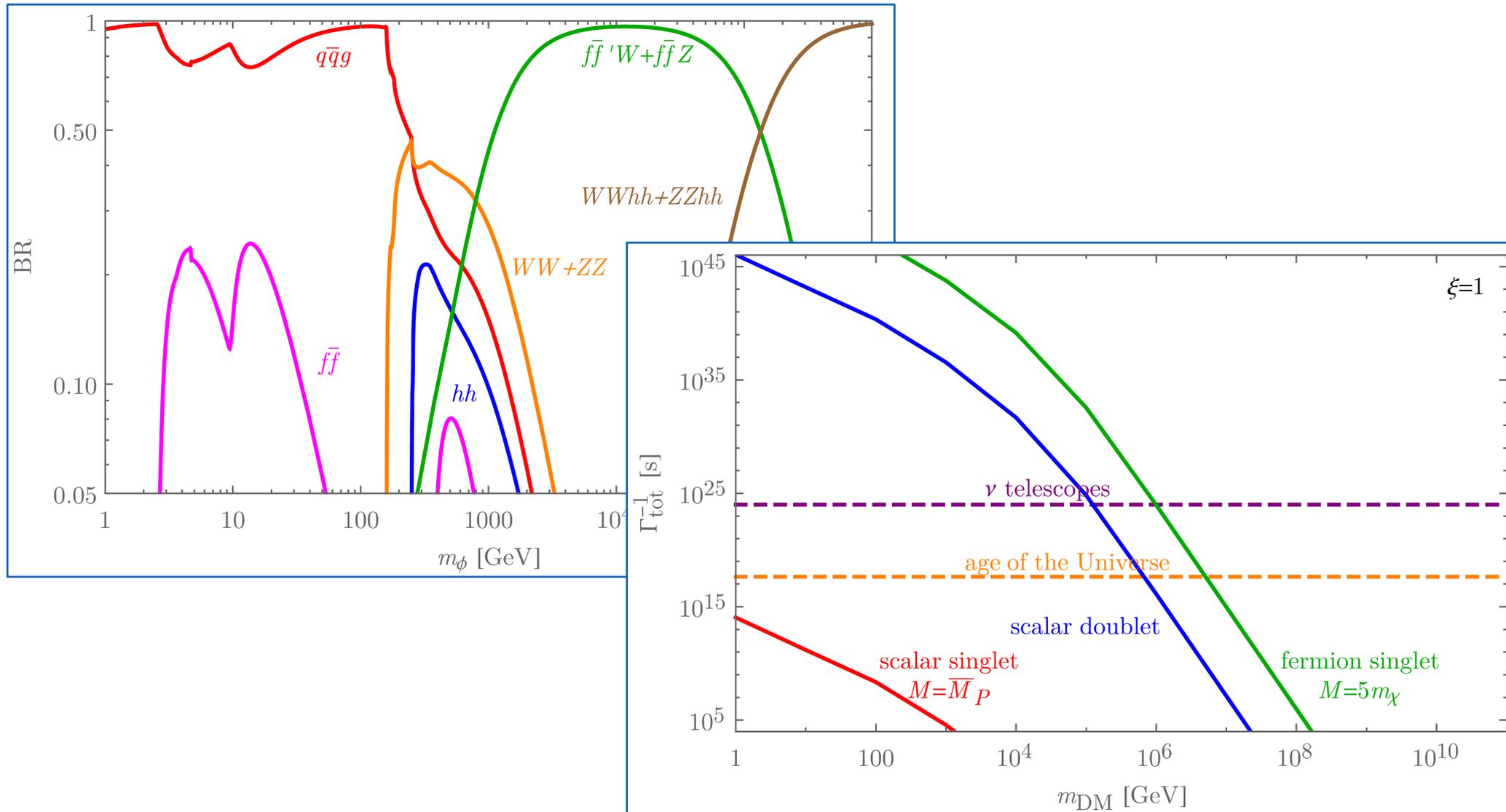
$$-\xi R \left(H_1^\dagger H_2 + H_2^\dagger H_1 \right)$$

➤ Fermionic singlet DM

$$-\frac{\xi}{M^2} R \left(\bar{\ell} \tilde{H}_1 \chi + \bar{\chi} \tilde{H}_1^\dagger \ell \right)$$

Backup: toy scenarios at $m_{\text{DM}} \gtrsim 1 \text{ GeV}$

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



Backup: nm coupling sensitivity

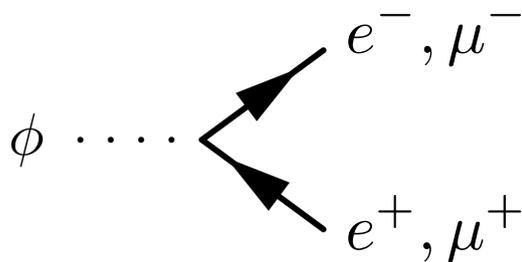
- Scalar SU(2)-doublet (fermion) DM: additional protection from gauge/Lorentz symmetry allows for $\xi \sim \mathcal{O}(1)$ up to $m_{\text{DM}} \lesssim 10^5$ (10^6) GeV
 - Constraints only powerful for very heavy DM
- Catà, Ibarra, SI, Phys. Rev. D95 (2017) 035011
- Scalar singlet ϕ : experiments sensitive to $\xi M \kappa \sim \mathcal{O}(1)$ even at sub-GeV DM masses
 - Potential for a signal in gamma-ray flux
 - Imprint on CMB from decays in the early Universe?

Backup: decay vertices

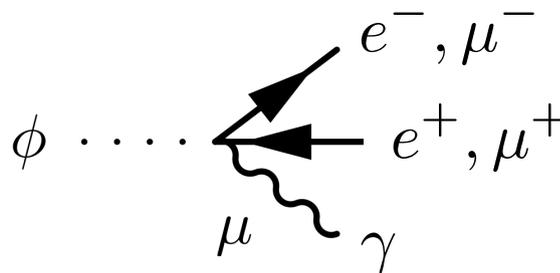
- Transformed Lagrangian:

$$\hat{\mathcal{L}}_{\text{obs}}^{\text{eff}} = \frac{1}{\Omega^3} \hat{\mathcal{T}}_f + \frac{1}{\Omega^2} \hat{\mathcal{T}}_\pi + \hat{\mathcal{T}}_\gamma - \frac{1}{\Omega^4} \hat{\mathcal{V}}$$

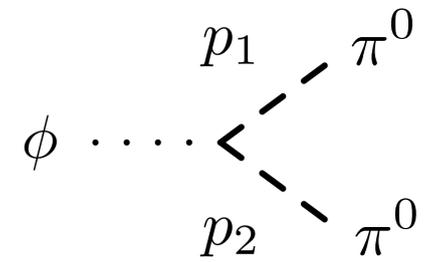
$$\Omega^{-n} = 1 - n\kappa^2 \xi M \phi + \mathcal{O}(\xi^2 M^2 \kappa^4 \phi^2)$$



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



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



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

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

Backup: CMB basis models

Slatyer, Wu, Phys.Rev. D95 (2017) no.2, 023010

MIT-CTP/4842

General Constraints on Dark Matter Decay from the Cosmic Microwave Background

Tracy R. Slatyer^{1,*} and Chih-Liang Wu^{1,†}

¹*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

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

- DM decay in the early universe injects energy into IGM
- Main impact of generic DM model: electrons/photons
- Define set of “basis models” (e.g. species, energy)
- Effect of basis models on CMB known, interpolation tables provided online

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

Backup: CMB limits on generic DM model

Slatyer, Wu, Phys.Rev. D95 (2017) no.2, 023010

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- Constraint on generic DM model:
 - Decompose into linear combination of basis models: compute electron/photon spectra (including cascade decays!)
 - Convolve with detectability functions for e^{\pm}, γ
 - Approximate limit on DM lifetime is given by weighted sum over limits on basis models

Backup: CMB constraints on DM lifetime

- Channels:

$$\phi \rightarrow \gamma\gamma$$

$$\phi \rightarrow e^+e^-(\gamma)$$

$$\phi \rightarrow \mu^+\mu^-(\gamma)$$

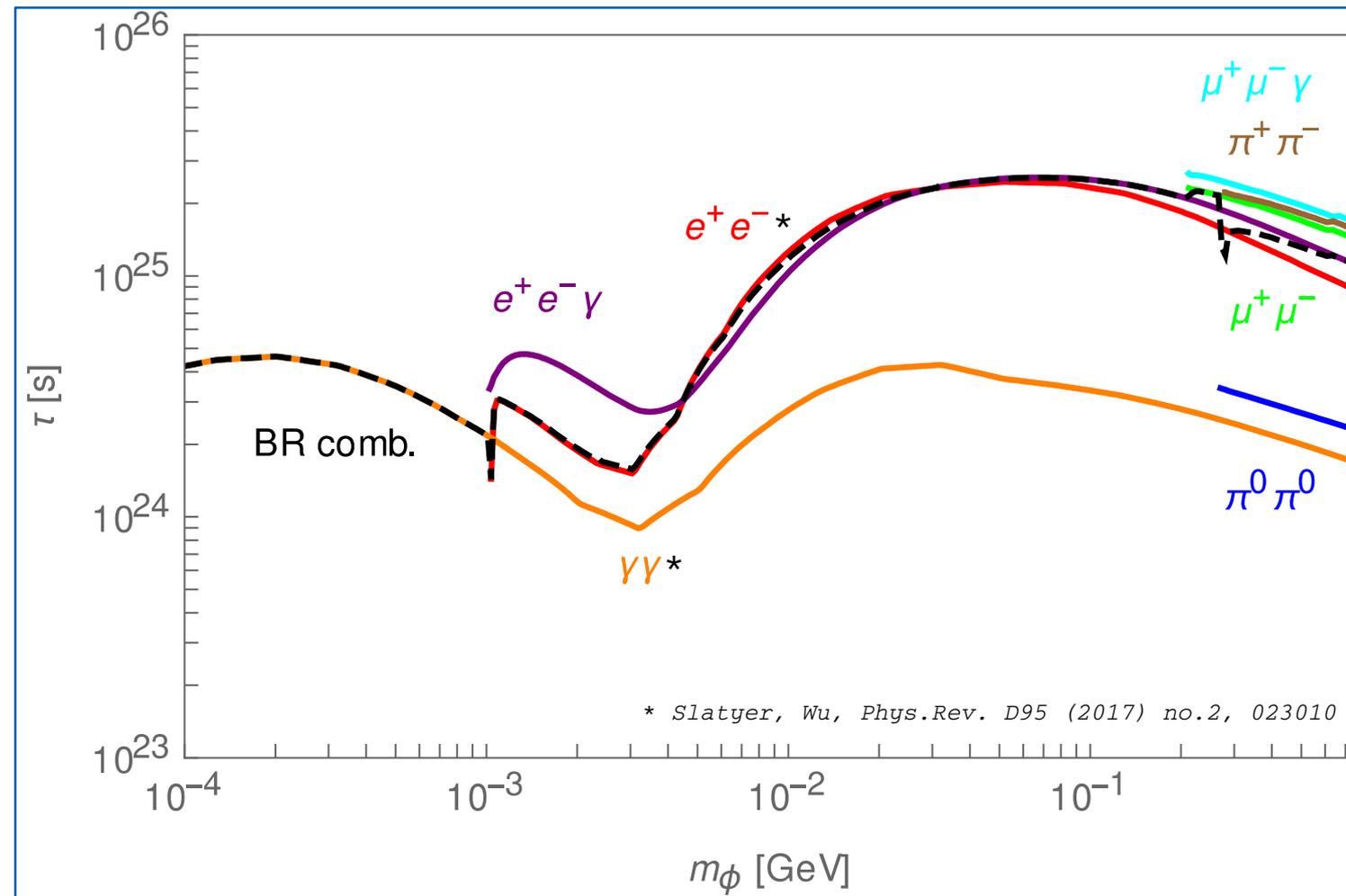
$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

$$\phi \rightarrow \pi^+\pi^-$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

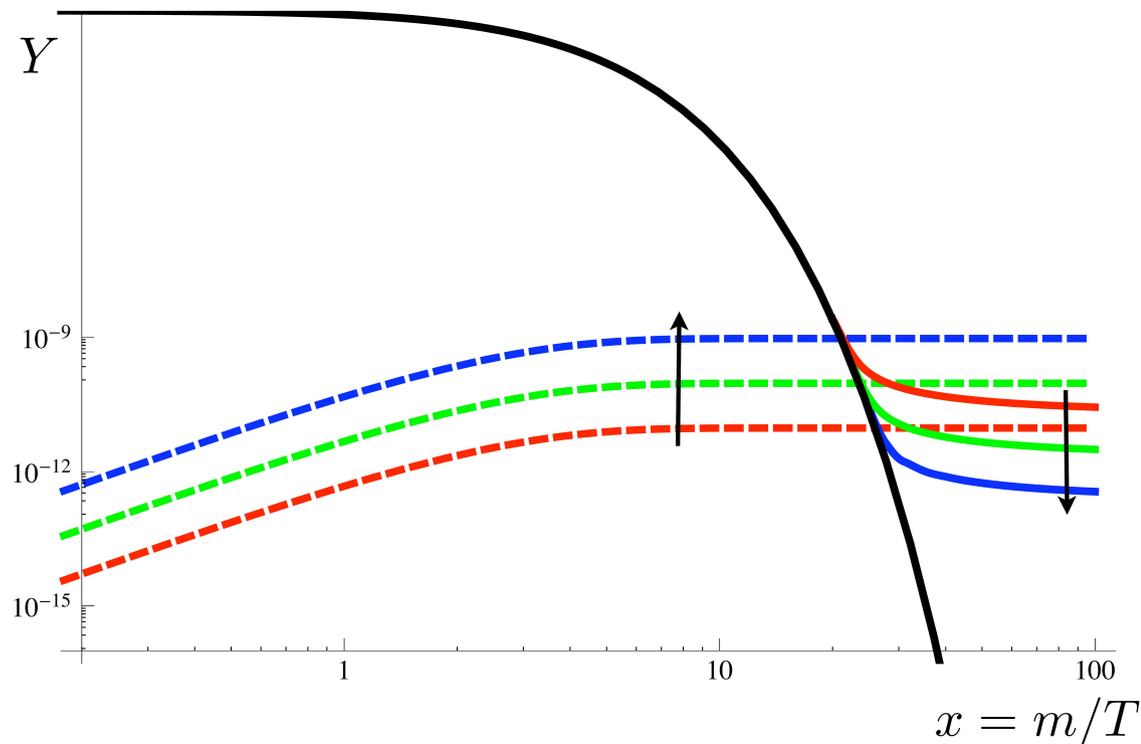
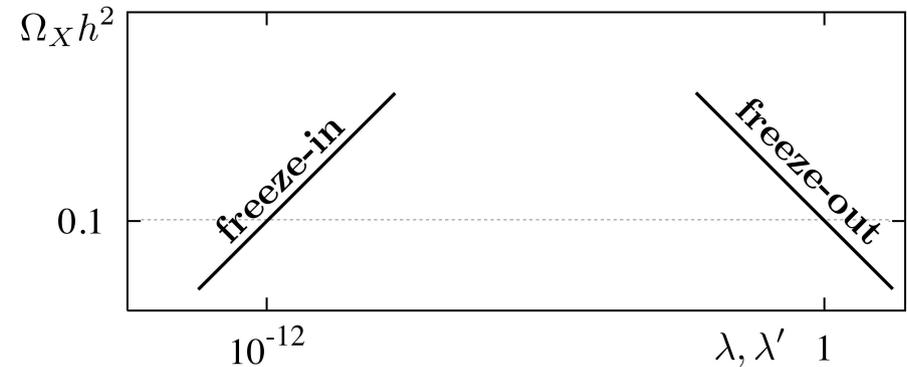
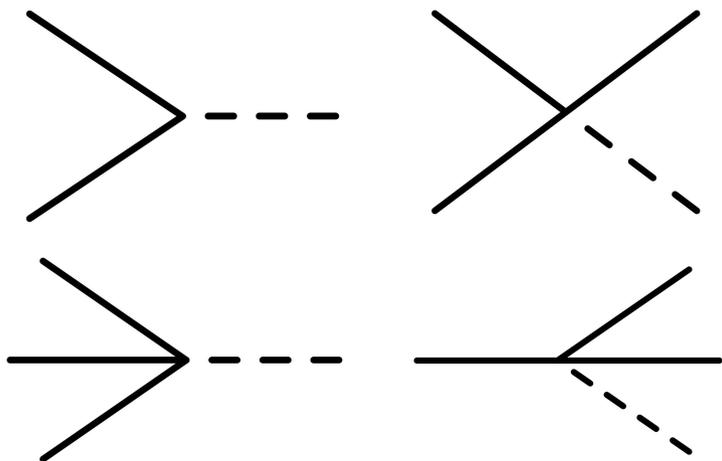
$$\phi \rightarrow \pi^0\pi^0$$

$$\pi^0 \rightarrow \gamma\gamma$$



Backup: DM production

- DM production in the early Universe: freeze-in versus freeze-out
- Non-minimal gravitational production: freeze-in



Hall, Jedamzik, March-Russell, West, JHEP 1003 (2010) 080

Backup: DM production

