Dark matter decays from non-minimal coupling to gravity

(based on arXiv:1603.03696 & work in progress)

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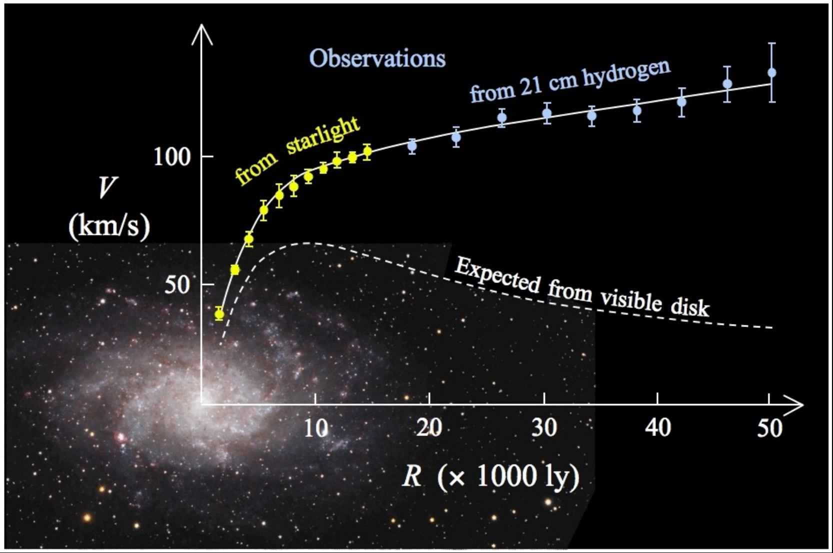
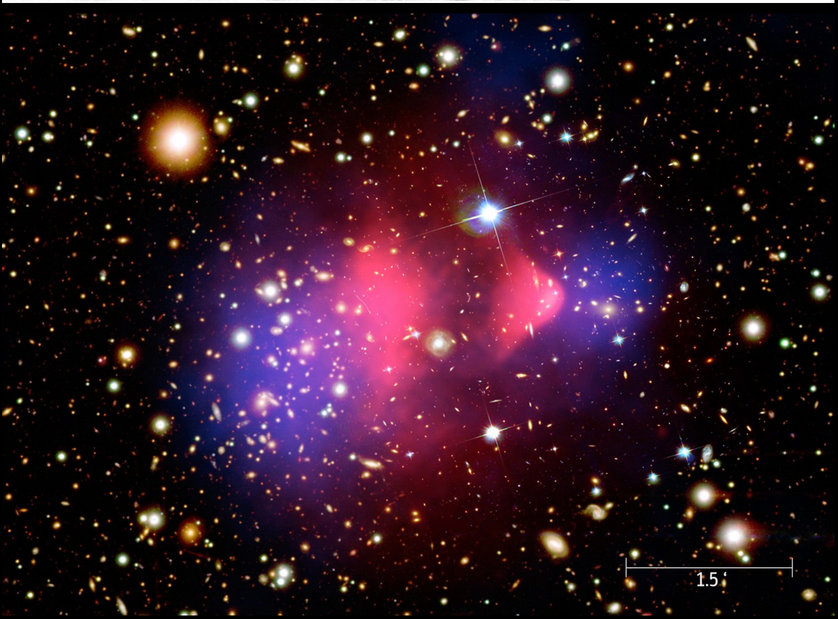
Motivation

- Evidence for DM on multiple scales
- DM either absolutely stable or very long-lived

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

- Stability often achieved by introducing global symmetry by hand





Motivation

- Gravitational interactions of DM evident
- Gravity not expected to respect global symmetries

➔ Consider unstable DM that can decay through non-minimal coupling to gravity

- EFT approach: find lowest-dimensional operator, constrain coefficient through resulting decay rate

Non-minimal coupling to gravity

- Lowest-dimensional operators:
  - Scalar singlet: $\mathcal{L}_\xi = -\xi \bar{M}_{\mathrm{P}} R\, \phi$
  - Scalar doublet: $\mathcal{L}_\xi = -\xi R \left(\eta^\dagger \Phi + \mathrm{h.c.}\right)$
  - Fermion singlet: $\mathcal{L}_\xi = -\frac{\xi R}{\bar{M}_{\mathrm{P}}^2} \left(\bar{L}_L \widetilde{\Phi} \chi + \mathrm{h.c.}\right)$

➔ DM stable in flat-space limit $(R \to 0)$

Jordan frame action (scalar singlet)

- Non-minimal gravitational sector + matter Lagrangian:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(\mathcal{L}_{\mathrm{GR}} + \mathcal{L}_\xi + \mathcal{L}_\phi + \mathcal{L}_{\mathrm{SM}} \right)$$

$$\mathcal{L}_{\mathrm{GR}} + \mathcal{L}_\xi = -\frac{\bar{M}_{\mathrm{P}}^2}{2} R \left(1 + \frac{2\xi\phi}{\bar{M}_{\mathrm{P}}} \right)$$

- Perform Weyl transformation

$$\widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

with

$$\Omega^2 = 1 + \frac{2\xi\phi}{\bar{M}_{\mathrm{P}}}$$

Einstein frame action (scalar singlet)

- Gravitational sector (GR) decoupled

$$\mathcal{S} = \int d^4x \sqrt{-\widetilde{g}} \left(\widetilde{\mathcal{L}}_{\mathrm{GR}} + \Omega^{-4} \left(\mathcal{L}_\phi + \mathcal{L}_{\mathrm{SM}} \right) + \widetilde{\mathcal{L}}_{\mathrm{kin},\phi} \right)$$

- Decay vertices from prefactor expansion:

$$\Omega^{-4} \mathcal{L}_{\mathrm{SM}} \supset -\frac{2\xi\phi}{\bar{M}_P} \left(\frac{3}{2} \widetilde{\mathcal{T}}_f + \widetilde{\mathcal{T}}_H + 2 \left(\mathcal{L}_Y - \mathcal{V}_H \right) \right)$$

Non-minimal gravitational sector + DM + SM

⇔ Weyl trafo ⇔

General relativity + DM couplings to SM + DM + SM

DM decay channels (scalar singlet)

- Tree-level couplings to all massive SM particles
- Scalar doublet / fermion: additional five- and six-body decays

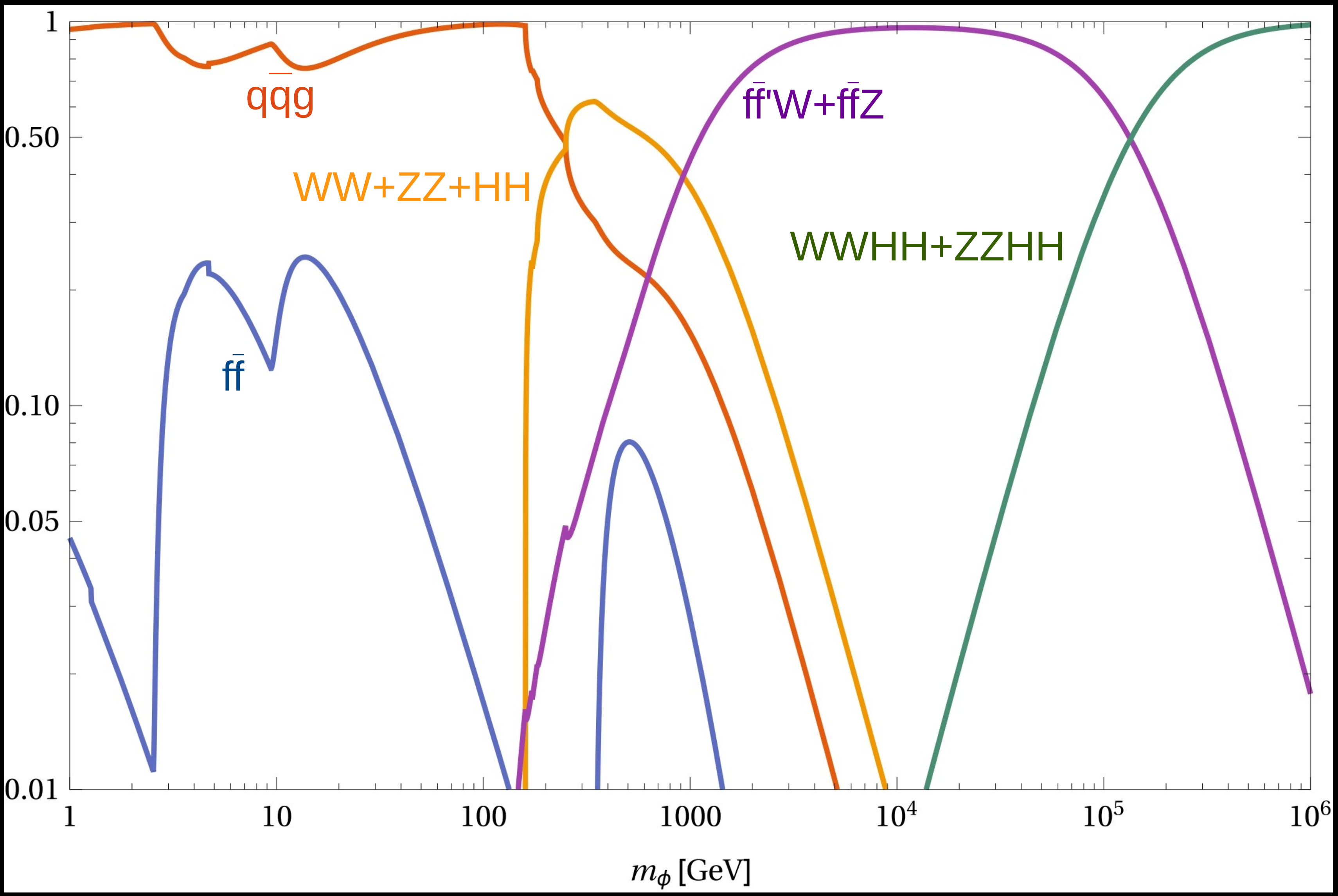
Scalar singlet ϕ	
$\phi \to HH$	m_ϕ^3
$\phi \to W^+W^-$	m_ϕ^3
$\phi \to ZZ$	m_ϕ^3
$\phi \to f\bar{f}$	$m_f^2 m_\phi$
$\phi \to HHH$	$m_H^2 m_\phi$
$\phi \to W^+W^-H$	m_ϕ^5/v^2
$\phi \to ZZH$	m_ϕ^5/v^2
$\phi \to f\bar{f}H$	$m_f^2 m_\phi^3/v^2$
$\phi \to f\bar{f}'W^\pm$	m_ϕ^5/v^2
$\phi \to f\bar{f}Z$	m_ϕ^5/v^2
$\phi \to f\bar{f}\gamma$	m_ϕ^3
$\phi \to q\bar{q}g$	m_ϕ^3
$\phi \to HHHH$	m_ϕ^3
$\phi \to W^+W^-HH$	m_ϕ^7/v^4
$\phi \to ZZHH$	m_ϕ^7/v^4

(common factor of $\frac{\xi^2}{\bar{M}_{\rm P}^2}$)

Branching ratios

- BRs fully calculable (consequence of SM Lagrangian structure)
- Only free parameter: DM mass
- Generically: multi-body final states dominate the rate once kinematically accessible

Branching ratios (scalar singlet)



Constraints: overview

- Require DM stability on cosmological timescale

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

- Additional constraints from cosmic ray experiments:
  - Gamma-rays: $\tau_{\mathrm{DM}}^{(WW)} \gtrsim 10^{27}\ \mathrm{s}$ $m_{\mathrm{DM}} \in (200\ \mathrm{GeV}, 30\ \mathrm{TeV})$
  - Neutrinos: $\tau_{\mathrm{DM}}^{(\nu)} \gtrsim 10^{26}\ \mathrm{s}$ $m_{\mathrm{DM}} \in \left(10\ \mathrm{TeV}, 10^{15}\ \mathrm{GeV}\right)$
  - Antimatter: $\tau_{\mathrm{DM}}^{(b\bar{b})} \gtrsim 10^{27}\ \mathrm{s}$ $m_{\mathrm{DM}} \in (10\ \mathrm{GeV}, 10\ \mathrm{TeV})$

Constraints: light DM *(preliminary)*

- Light scalar singlet case $(1\ \mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 700\ \mathrm{MeV})$: gamma-ray spectrum from

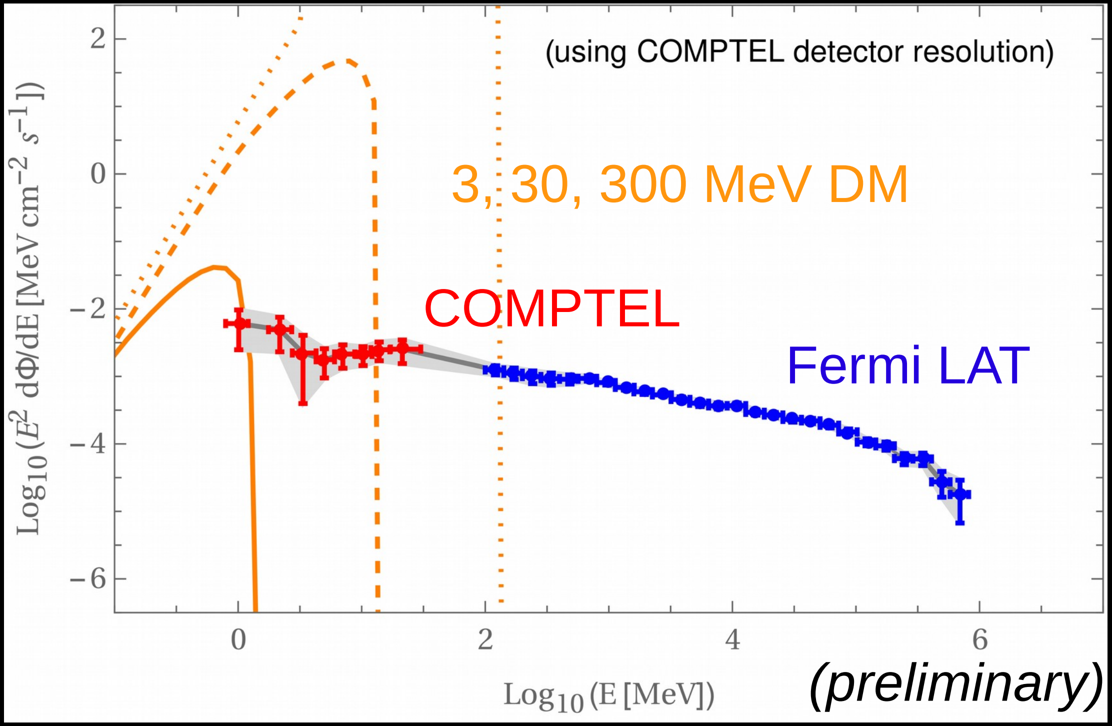
$$\phi \to e^+ e^- \gamma$$

$$\phi \to \mu^+ \mu^- \gamma$$

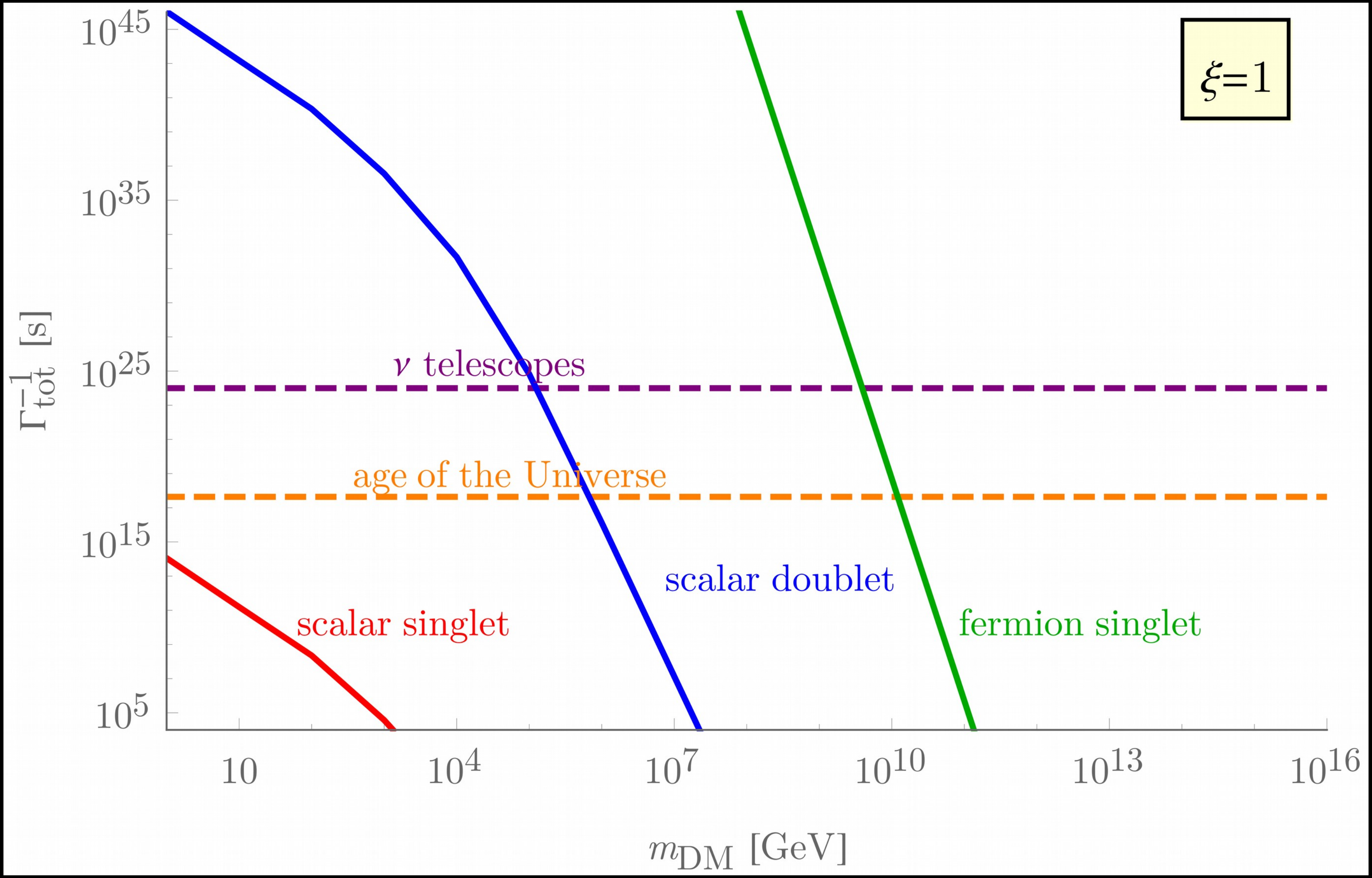
$$\phi \to 2\pi^0 \to 4\gamma$$

➔ Hard photons produce visible spectral features

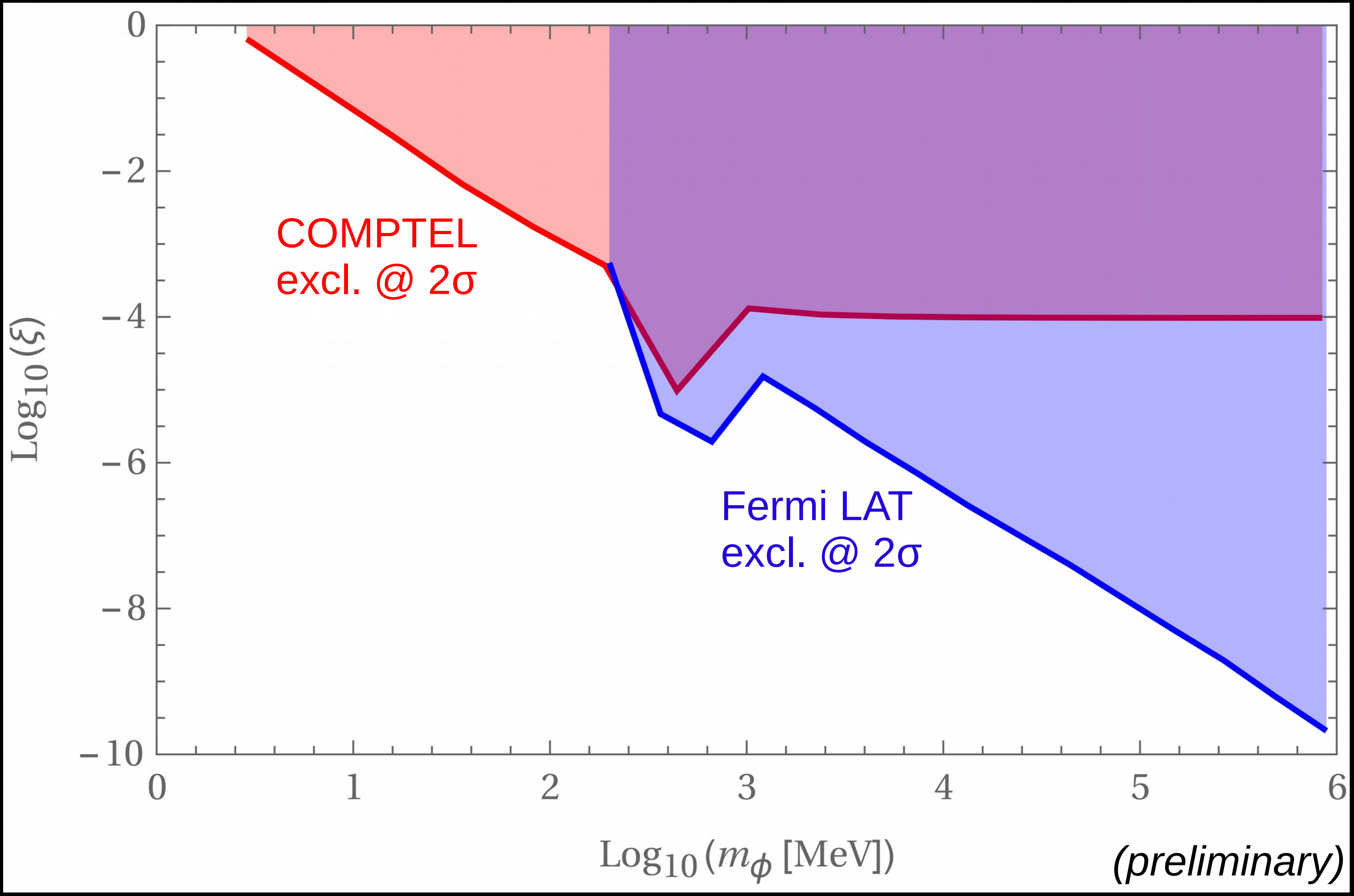
➔ Use diffuse gamma-ray flux



Constraints: different scenarios



Constraints: scalar singlet *(preliminary)*



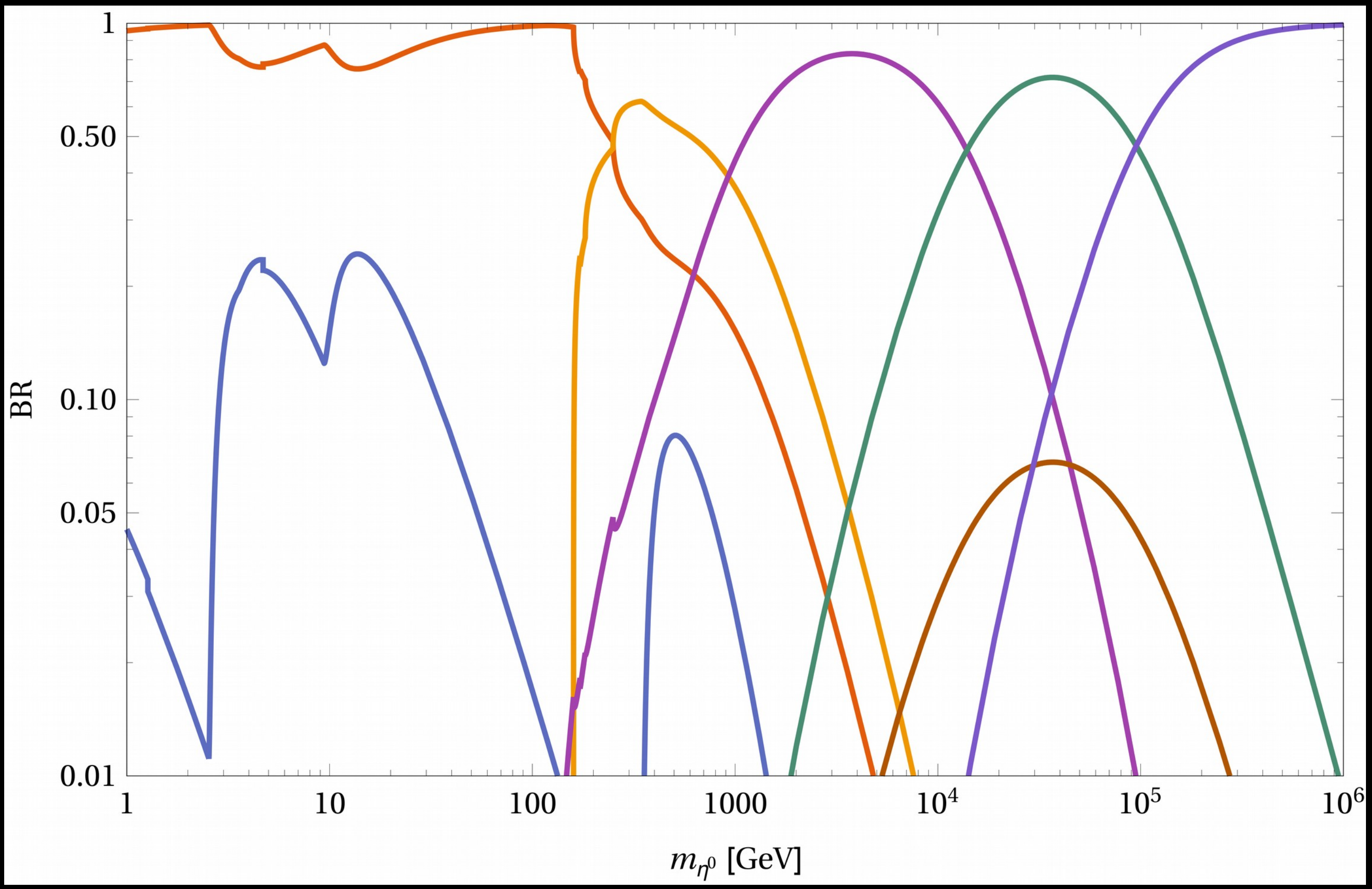
Conclusions

- Considered unstable DM that decays through non-minimal coupling to gravity, stable in flat space
- Couplings to SM explicit after Weyl transformation
- Branching ratios fixed by SM structure

Conclusions

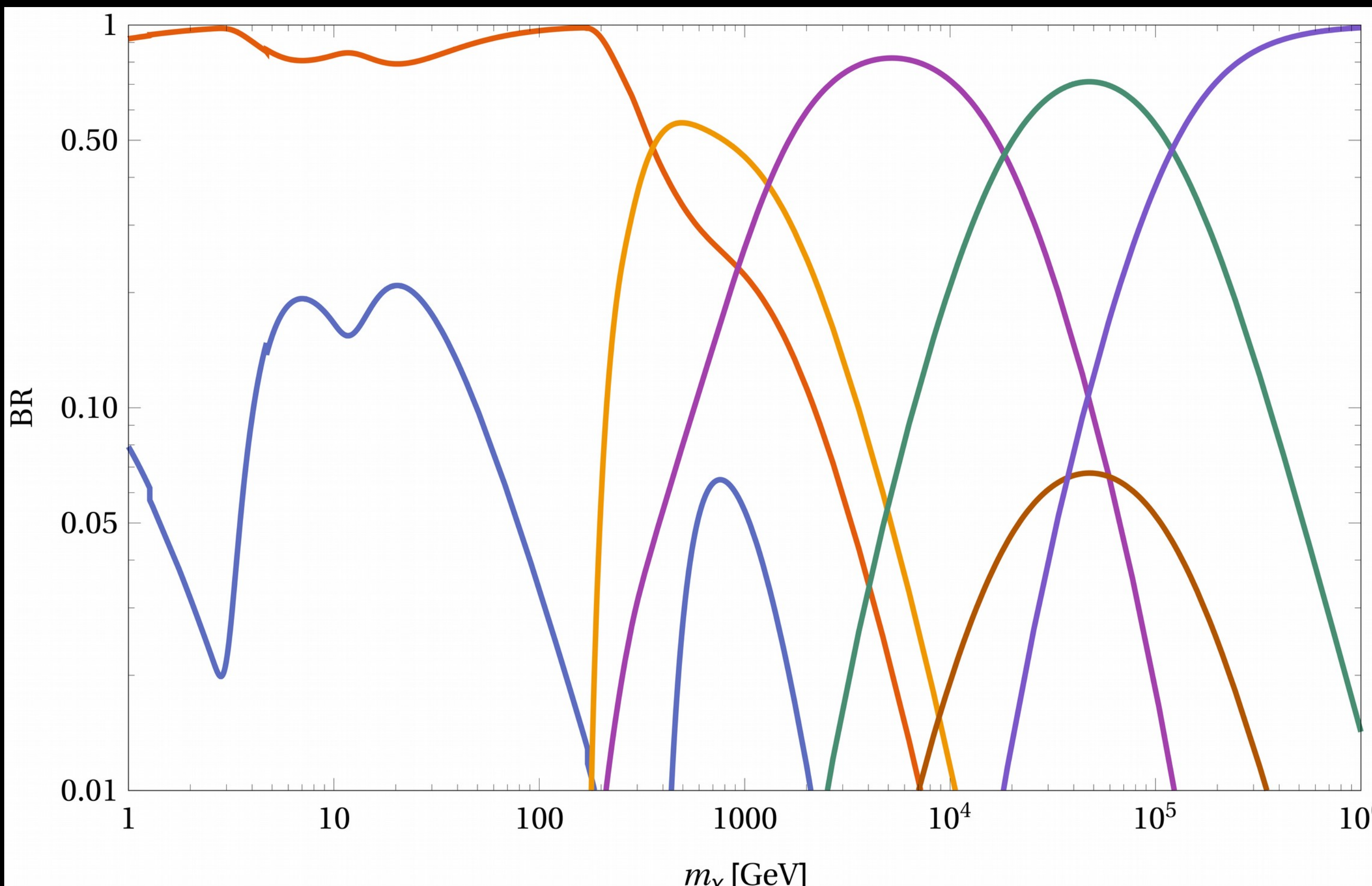
- Use CR experiments to constrain coupling:
  - Neutrinos (high mass)
  - Gamma-rays (low mass)
- Heavy suppression needed in case of scalar singlet
- Weaker constraints for scalar doublet and fermion singlet (work in progress)

Backup slides



Scalar doublet η^0	
$\eta^0 \to HH$	$v^2 m_\eta^3$
$\eta^0 \to W^+W^-$	$v^2 m_\eta^3$
$\eta^0 \to ZZ$	$v^2 m_\eta^3$
$\eta^0 \to f\bar{f}$	$v^2 m_f^2 m_\eta$
$\eta^0 \to HHH$	m_η^5
$\eta^0 \to W^+W^-H$	m_η^5
$\eta^0 \to ZZH$	m_η^5
$\eta^0 \to f\bar{f}H$	$m_f^2 m_\eta^3$
$\eta^0 \to f\bar{f}'W^\pm$	m_η^5
$\eta^0 \to f\bar{f}Z$	m_η^5
$\eta^0 \to f\bar{f}\gamma$	$v^2 m_\eta^3$
$\eta^0 \to q\bar{q}g$	$v^2 m_\eta^3$
$\eta^0 \to HHHH$	$v^2 m_\eta^3$
$\eta^0 \to W^+W^-HH$	m_η^7/v^2
$\eta^0 \to ZZHH$	m_η^7/v^2
$\eta^0 \to f\bar{f}HH$	$m_f^2 m_\eta^5/v^2$
$\eta^0 \to f\bar{f}'W^\pm H$	m_η^7/v^2
$\eta^0 \to f\bar{f}ZH$	m_η^7/v^2
$\eta^0 \to f\bar{f}\gamma H$	m_η^5
$\eta^0 \to q\bar{q}gH$	m_η^5
$\eta^0 \to HHHHH$	m_η^5
$\eta^0 \to W^+W^-HHH$	m_η^9/v^4
$\eta^0 \to ZZHHH$	m_η^9/v^4

Backup slides



Fermionic singlet χ	
$\chi \to HH\nu$	$v^2 m_\chi^7$
$\chi \to W^+W^-\nu$	$v^2 m_\chi^7$
$\chi \to ZZ\nu$	$v^2 m_\chi^7$
$\chi \to f\bar{f}\nu$	$v^2 m_f^2 m_\chi^5$
$\chi \to HHH\nu$	m_χ^9
$\chi \to W^+W^-H\nu$	m_χ^9
$\chi \to ZZH\nu$	m_χ^9
$\chi \to f\bar{f}H\nu$	$m_f^2 m_\chi^7$
$\chi \to f\bar{f}'W^\pm\nu$	m_χ^9
$\chi \to f\bar{f}Z\nu$	m_χ^9
$\chi \to f\bar{f}\gamma\nu$	$v^2 m_\chi^7$
$\chi \to q\bar{q}g\nu$	$v^2 m_\chi^7$
$\chi \to HHHH\nu$	$v^2 m_\chi^7$
$\chi \to W^+W^-HH\nu$	m_χ^{11}/v^2
$\chi \to ZZHH\nu$	m_χ^{11}/v^2
$\chi \to f\bar{f}HH\nu$	$m_f^2 m_\chi^9/v^2$
$\chi \to f\bar{f}'W^\pm H\nu$	m_χ^{11}/v^2
$\chi \to f\bar{f}ZH\nu$	m_χ^{11}/v^2
$\chi \to f\bar{f}\gamma H\nu$	m_χ^9
$\chi \to q\bar{q}gH\nu$	m_χ^9
$\chi \to HHHHH\nu$	m_χ^9
$\chi \to W^+W^-HHH\nu$	m_χ^{13}/v^4
$\chi \to ZZHHH\nu$	m_χ^{13}/v^4