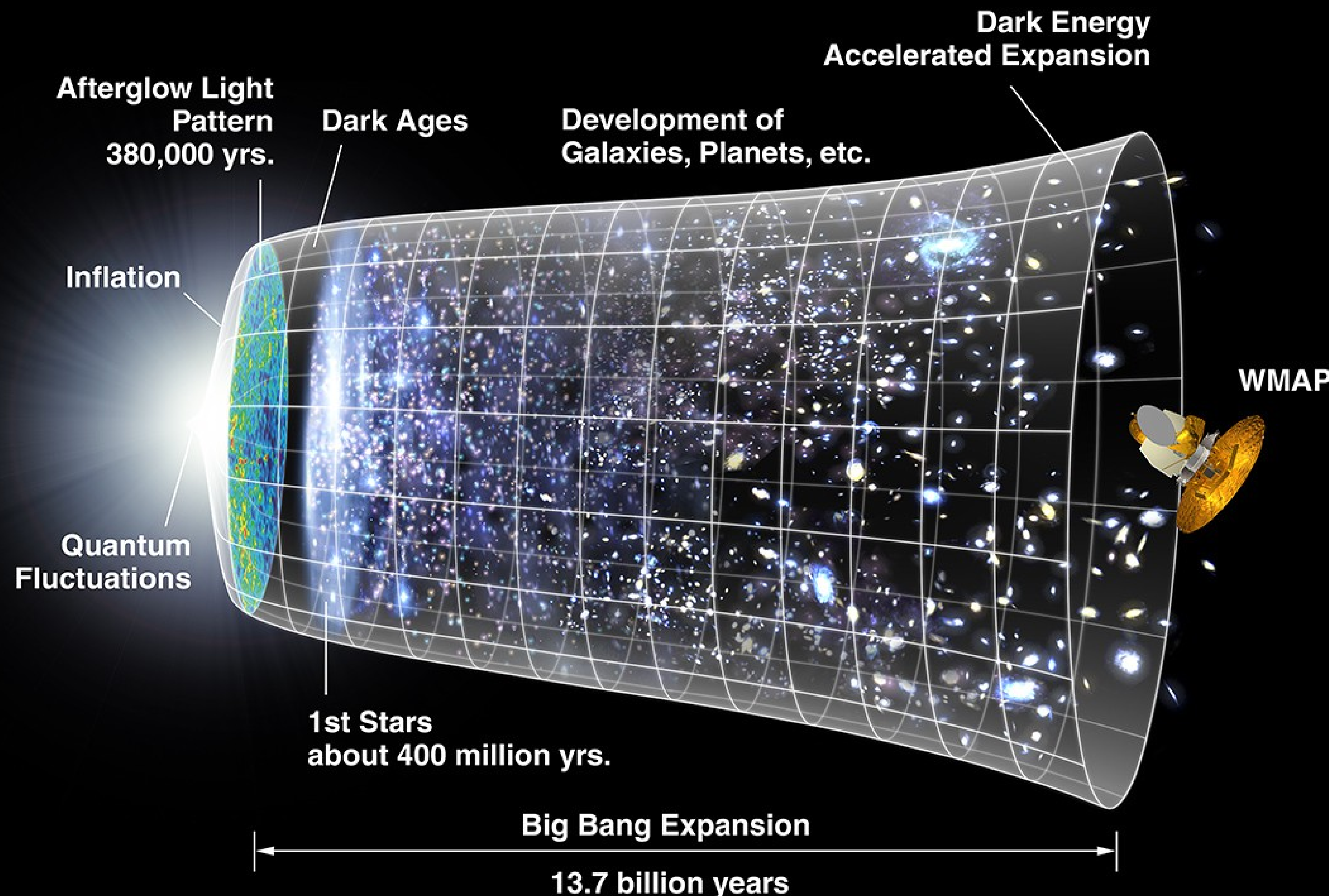
Dark matter decay via the gravity portal

Alejandro Ibarra

In collaboration with Oscar Catà and Sebastian Ingenhütt
Phys.Rev.Lett. 117 (2016) no.2, 021302 (arXiv:1603.03696)
Phys.Rev. D95 (2017) no.3, 035011 (arXiv:1611.00725)
JCAP 1711 (2017) no.11, 044 (arXiv:1707.08480)

Tallinn
19th June 2018

Introduction: the dark matter stability puzzle



Introduction: the dark matter stability puzzle

Among the many particles species produced after inflation, only very few have survived until today

particle	Lifetime	Decay channel	Theoretical justification
proton	$\tau > 8.2\times10^{33}$ years	$p \to e^+ \pi^0$	Baryon number conservation
electron	$\tau > 4.6\times10^{26}$ years	$e \to \gamma\, \nu$	Electric charge conservation
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Accidental symmetry

Local symmetry

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dark matter	$\tau \gtrsim 10^{9}$ years	???	???

Accidental symmetry

Local symmetry

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Some possible solutions:

- The dark matter is very light. Lifetime naturally long due to the small phase space available for the decay (axion, sterile neutrino)

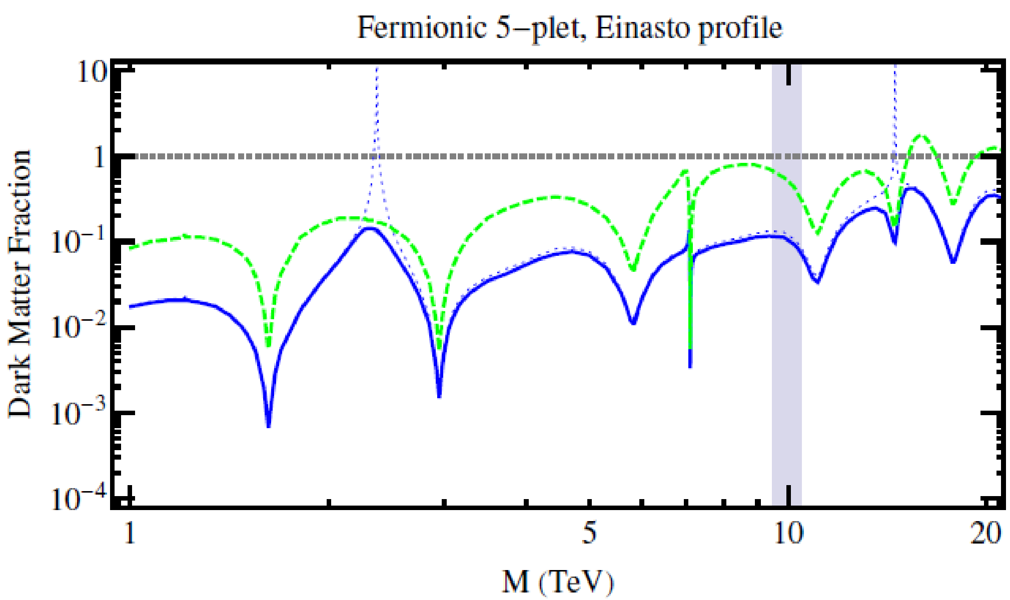
- Dimension 4 operators inducing decay accidentally not present in the Lagrangian (as is the case of the proton in the Standard Model)

  Higher dimensional operators may induce the dark matter decay. For a dimension six operator suppressed by a large scale M,

$$\tau_{\rm DM} \sim 10^{26}{\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M}{10^{15}{\rm GeV}}\right)^4$$

- The dark matter is in a specific gauge representation (fermionic 5-plet).

Cirelli et at.'05



Tension with γ-ray observations?

Garcia-Cely et at.'15

Cirelli et at.'15

Introduction: the dark matter stability puzzle

However, none of these schemes apply for the simplest WIMP scenarios:

- Real scalar singlet ϕ: $\mathcal{L} \supset \mu\phi(H^\dagger H)$
- Scalar doublet η: $\mathcal{L} \supset \mu^2(H^\dagger \eta + \eta^\dagger H)$
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Common approach: impose that the DM is charged under some conserved global symmetry.

This argument holds in flat spacetime

Introduction: the dark matter stability puzzle

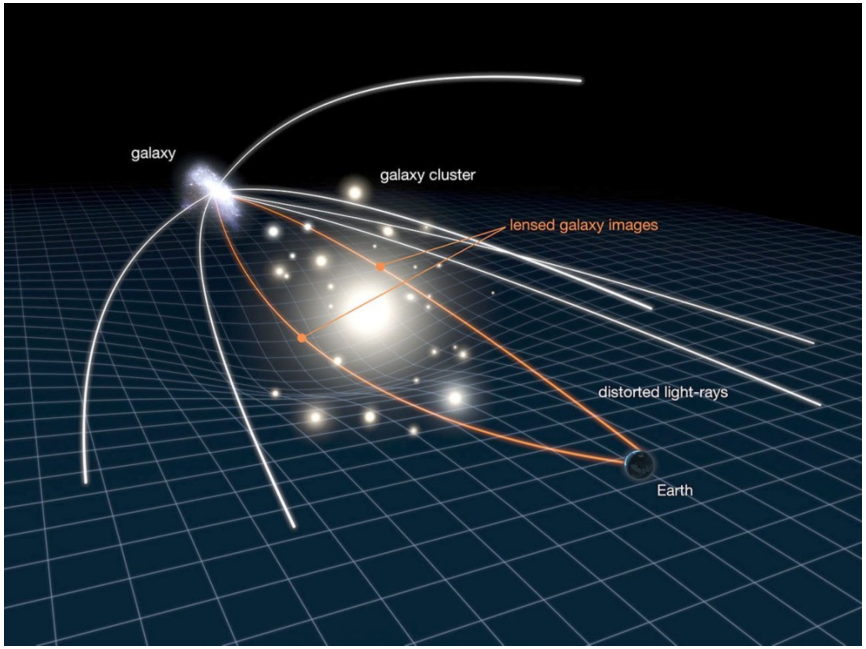
Potential caveat:

- Any dark matter model *must* be embedded in curved spacetime.

- Global symmetries might not be exact in curved spacetime.

  (no-hair theorem, Hawking radiation...)

→ Dark matter decay



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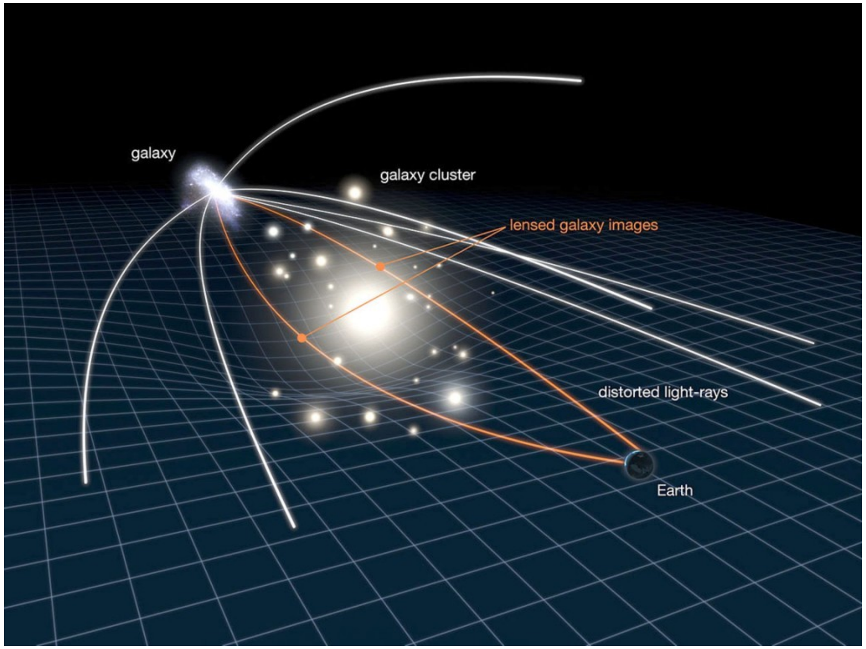

What is the impact of curvature on the dark matter stability?

Dark Matter in curved spacetime

Classical action of the SM extended with a DM field in flat spacetime

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For a singlet real scalar

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We assume that the DM transforms under an unbroken global symmetry ⇒ the DM is stable *in flat spacetime*.

Dark Matter in curved spacetime

Simplest extension to curved spacetime

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(-\frac{R}{2\kappa^2} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} \right)$$

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With this extension, the DM is still absolutely stable

Dark Matter in curved spacetime

The extension to curved spacetime is *not* unique. The action could also include a non-minimal coupling term to gravity.

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{R}{2\kappa^2} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} - \xi R F(\underset{\text{DM}}{\varphi}, \underset{\text{SM}}{X})\right)$$

In the limit of flat spacetime, $g_{\mu\nu} \to \eta_{\mu\nu}$, $R \to 0$

$$\mathcal{S} = \int d^4x \left(\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM}\right)$$

We consider the case where $F(\varphi, X)$ is linear in φ

$\Longrightarrow$ Dark matter decay via a "gravity portal".

(Other non-minimal coupling terms, such as R^2F, $R^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$ are higher dimensional and will not be considered here.)

Dark Matter in curved spacetime

Action in the Jordan frame:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{R}{2\kappa^2} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} - \xi R F(\varphi, X)\right)$$

Dark Matter in curved spacetime

Action in the Jordan frame:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{R}{2\kappa^2}\Omega^2(\varphi, X) + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM}\right)$$

$$\Omega^2(\varphi, X) = 1 + 2\kappa^2\xi F(\varphi, X)$$

Field equations in the Jordan frame:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{1}{\Omega^2}(\kappa T_{\mu\nu} + g_{\mu\nu}\nabla^2\Omega^2 - \nabla_\mu\nabla_\nu\Omega^2)$$

$$\nabla_\mu\frac{\partial\mathcal{L}}{\partial\nabla_\mu\phi} - \frac{\partial\mathcal{L}}{\partial\varphi} = \frac{1}{2\kappa}R\frac{\partial\Omega^2}{\partial\varphi}$$

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Redefine the metric

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

Dark Matter in curved spacetime

Action in the Einstein frame:

$$\mathcal{S} = \int d^4x\sqrt{-\widetilde{g}}\left(-\frac{\widetilde{R}}{2\kappa^2} + \frac{3}{\kappa^2\Omega^2}(\widetilde{\nabla}_\mu\Omega)(\widetilde{\nabla}^\mu\Omega) + \widetilde{\mathcal{L}}_{\rm SM} + \widetilde{\mathcal{L}}_{\rm DM}\right)$$

The DM field decouples from the curvature operator.

$$\widetilde{R}_{\mu\nu} - \frac{1}{2}\widetilde{R}\widetilde{g}_{\mu\nu} = \kappa^2\widetilde{T}_{\mu\nu}$$

$$\widetilde{\nabla}_\mu\frac{\partial\widetilde{\mathcal{L}}}{\partial\widetilde{\nabla}_\mu\varphi} - \frac{\partial\widetilde{\mathcal{L}}}{\partial\varphi} = 0$$

The field equations take the familiar form in the Einstein frame

Dark Matter in curved spacetime

The SM Lagrangian $\widetilde{\mathcal{L}}_{\rm SM}$ in the Einstein frame

$$\widetilde{e}^a_\mu = \Omega e^a_\mu$$

$$\widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \qquad \sqrt{-\widetilde{g}} = \Omega^4 \sqrt{-g}$$

	Jordan Frame	Einstein Frame
$\mathcal{T}_F = -\frac{1}{4} g^{\mu\nu} g^{\lambda\rho} F^a_{\mu\lambda} F^a_{\nu\rho}$	$\sqrt{-g}\,\mathcal{T}_F$	$\sqrt{-\widetilde{g}}\,\widetilde{\mathcal{T}}_F$
$\mathcal{T}_f = \frac{i}{2} \bar{f} \overleftrightarrow{\nabla} f$	$\sqrt{-g}\,\mathcal{T}_f$	$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^3}\widetilde{\mathcal{T}}_f$
$\mathcal{T}_H = g^{\mu\nu} (D_\mu H)^\dagger (D_\nu H)$	$\sqrt{-g}\,\mathcal{T}_H$	$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^2}\widetilde{\mathcal{T}}_H$
$\mathcal{L}_Y = -\bar{f}_L H f_R + \text{h.c.}$ $\mathcal{V}_H = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$	$\sqrt{-g}\,(\mathcal{L}_Y - \mathcal{V}_H)$	$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^4}(\mathcal{L}_Y - \mathcal{V}_H)$

Dark Matter in curved spacetime

The SM Lagrangian $\widetilde{\mathcal{L}}_{\rm SM}$ in the Einstein frame

Upon expanding $\Omega^2(\varphi, X) = 1 + 2\kappa^2 \xi F(\varphi, X)$ for small values of the DM field φ, one finds terms inducing decay into SM particles.

Einstein Frame
$\sqrt{-\widetilde{g}}\,\widetilde{\mathcal{T}}_F$
$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^3}\widetilde{\mathcal{T}}_f$
$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^2}\widetilde{\mathcal{T}}_H$
$\sqrt{-\widetilde{g}}\,\frac{1}{\Omega^4}(\mathcal{L}_Y - \mathcal{V}_H)$

Singlet scalar dark matter

We consider a singlet real scalar field ϕ in flat spacetime

$$\mathcal{L} = \frac{1}{2}\eta_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi, H)$$

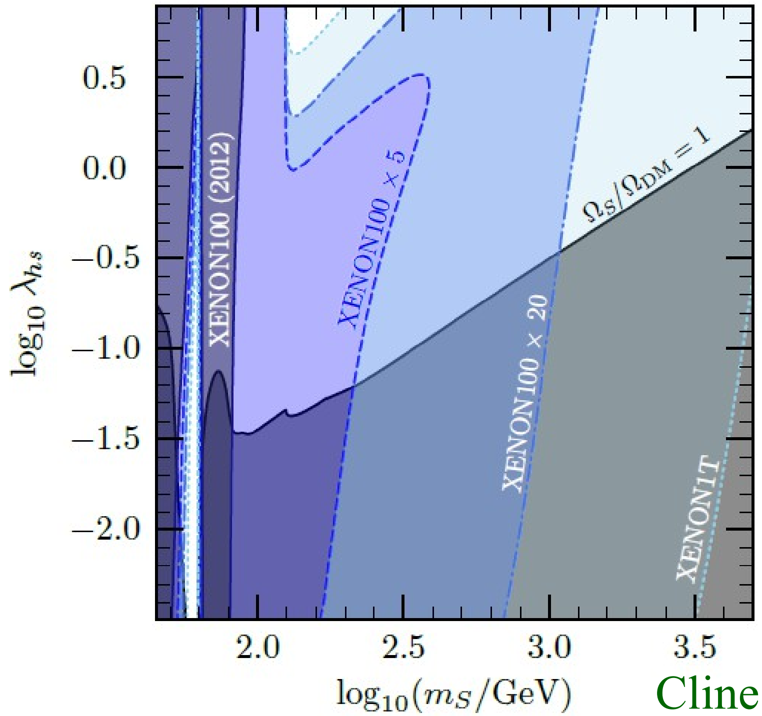
Silveira, Zee '85
McDonald '07

We assume that the potential V is invariant under the transformation $\phi \to -\phi$

$$V(\phi, H) = \frac{1}{2}\mu_\phi^2\phi^2 + \frac{1}{4!}\lambda_\phi\phi^4 + \frac{1}{2}\lambda_{\phi H}\phi^2(H^\dagger H)$$

ϕ is absolutely stable and constitutes a dark matter candidate

For reasonable choices of the parameters, the predicted relic abundance from thermal freeze-out is in agreement with the observed DM abundance $\Omega_{\rm DM}h^2$=0.12.



Cline et al. '13

Singlet scalar dark matter

We consider the following extension of the singlet DM model to curved spacetime

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(\underbrace{-\frac{R}{2\kappa^2} + \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}}}_{\text{preserve } Z_2} \underbrace{-\xi M R \phi}_{\text{break } Z_2} \right)$$

In the limit of flat spacetime, $g_{\mu\nu} \to \eta_{\mu\nu}$, $R \to 0$, the Z_2 symmetry becomes exact

Impact of the term $-\xi M R \phi$ on the DM stability?

Singlet scalar dark matter

Action in the Jordan frame:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(-\frac{R}{2\kappa^2} \Omega^2(\varphi, X) + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} \right)$$

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

Action in the Einstein frame:

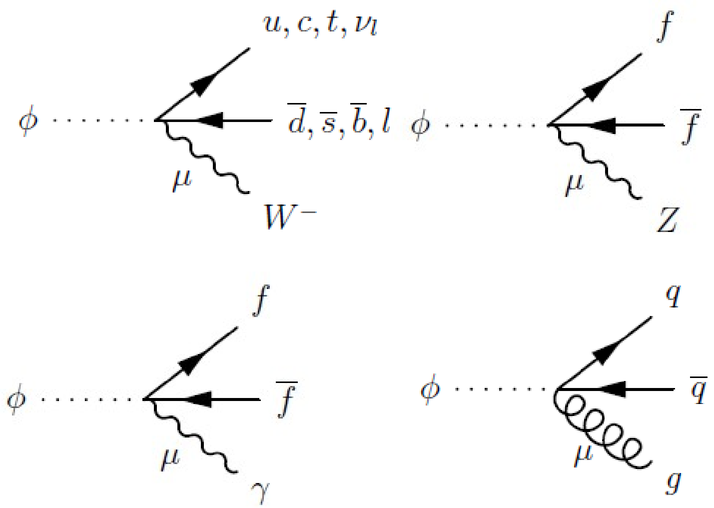
$$\mathcal{S} = \int d^4x \sqrt{-\tilde{g}} \left(-\frac{\tilde{R}}{2\kappa^2} + \frac{3}{\kappa^2 \Omega^2} (\tilde{\nabla}_\mu \Omega)(\tilde{\nabla}^\mu \Omega) + \tilde{\mathcal{L}}_{\rm SM} + \tilde{\mathcal{L}}_{\rm DM} \right)$$

$$\tilde{\mathcal{L}}_{\rm SM} = \tilde{\mathcal{T}}_F + \frac{1}{\Omega^3} \tilde{\mathcal{T}}_f + \frac{1}{\Omega^2} \tilde{\mathcal{T}}_H + \frac{1}{\Omega^4} (\mathcal{L}_Y - \mathcal{V}_H)$$

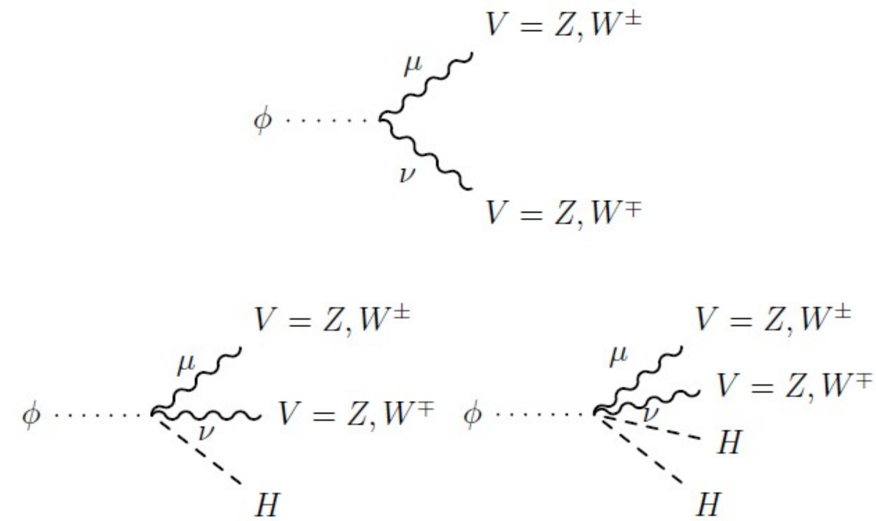
$$\boxed{\tilde{\mathcal{L}}_{\rm SM} \supset -2\kappa^2 \xi M \phi \left[\frac{3}{2} \tilde{\mathcal{T}}_f + \tilde{\mathcal{T}}_H + 2(\mathcal{L}_Y - \mathcal{V}_H) \right]}$$

Singlet scalar dark matter: decay channels

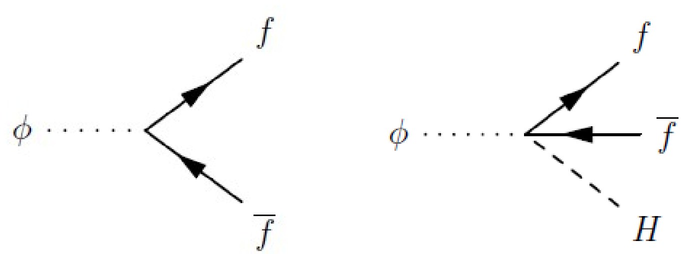
From fermion kinetic term: $\sim \phi\,\mathcal{T}_f$



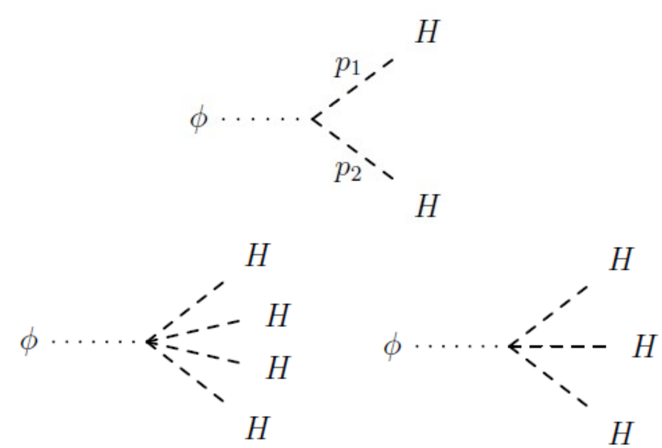
From Higgs kinetic term: $\sim \phi\,\mathcal{T}_H$



From Yukawa term: $\sim \phi\,\mathcal{L}_Y$



From Higgs potential term: $\sim \phi\,\mathcal{V}_H$

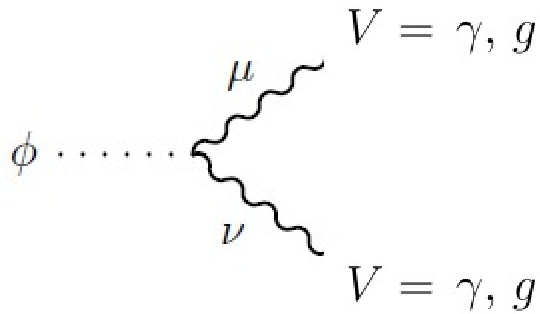


Singlet scalar dark matter: some remarks

① In the Einstein frame, the gauge kinetic terms do not pick a factor Ω.

$$\widetilde{\mathcal{L}}_{\rm SM} = \widetilde{\mathcal{T}}_F + \frac{1}{\Omega^3}\widetilde{\mathcal{T}}_f + \frac{1}{\Omega^2}\widetilde{\mathcal{T}}_H + \frac{1}{\Omega^4}(\mathcal{L}_Y - \mathcal{V}_H)$$

⇒ No tree-level decays into massless gauge bosons.



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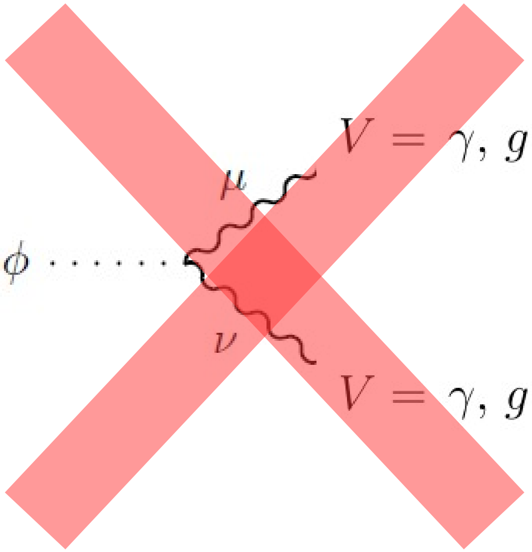
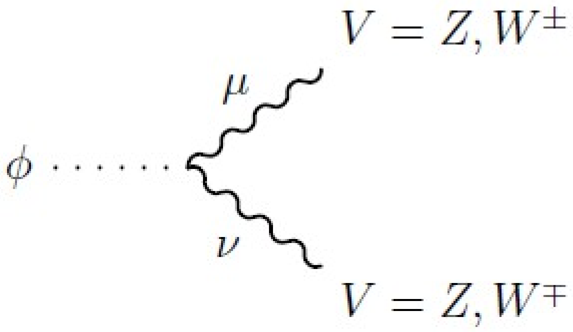


However, there are decays into massive gauge bosons through the Higgs kinetic terms, and after symmetry breaking.



Singlet scalar dark matter: some remarks

2 The non-minimal coupling to gravity provides a theory of DM decays

Effective field theory

$$\frac{\lambda_{\gamma\gamma}}{\bar{M}_P}\phi F_{\mu\nu}F^{\mu\nu}$$

$$\frac{\lambda_{gg}}{\bar{M}_P}\phi G_{\mu\nu}G^{\mu\nu}$$

$$\frac{\lambda_{ZZ}}{\bar{M}_P}\phi Z_{\mu\nu}Z^{\mu\nu}$$

$$\frac{\lambda'_{ZZ}}{\bar{M}_P}\phi Z_{\mu}Z^{\mu}$$

$$\frac{\lambda_{f\bar{f}}}{\bar{M}_P}\phi \bar{f}\partial\!\!\!/ f + \text{h.c.}$$

Singlet scalar dark matter: some remarks

② The non-minimal coupling to gravity provides a theory of DM decays

Effective field theory

$$\phi \to \gamma\gamma \qquad \frac{\lambda_{\gamma\gamma}}{\bar{M}_P}\phi F_{\mu\nu}F^{\mu\nu}$$

$$\phi \to gg \qquad \frac{\lambda_{gg}}{\bar{M}_P}\phi G_{\mu\nu}G^{\mu\nu}$$

$$\phi \to ZZ \qquad \frac{\lambda_{ZZ}}{\bar{M}_P}\phi Z_{\mu\nu}Z^{\mu\nu}$$

$$\phi \to ZZ \qquad \frac{\lambda'_{ZZ}}{\bar{M}_P}\phi Z_{\mu}Z^{\mu}$$

$$\phi \to f\bar{f} \qquad \frac{\lambda_{f\bar{f}}}{\bar{M}_P}\phi \bar{f}\not{\partial} f + \text{h.c.}$$

Singlet scalar dark matter: some remarks

2 The non-minimal coupling to gravity provides a theory of DM decays

	Effective field theory	Non-minimal coupling to gravity
$\phi \to \gamma\gamma$	$\frac{\lambda_{\gamma\gamma}}{\bar{M}_P}\phi F_{\mu\nu}F^{\mu\nu}$	$\lambda_{\gamma\gamma} = 0 \quad (\mathrm{tree-level})$
$\phi \to gg$	$\frac{\lambda_{gg}}{\bar{M}_P}\phi G_{\mu\nu}G^{\mu\nu}$	$\lambda_{gg} = 0 \quad (\mathrm{tree-level})$
$\phi \to ZZ$	$\frac{\lambda_{ZZ}}{\bar{M}_P}\phi Z_{\mu\nu}Z^{\mu\nu}$	$\lambda_{ZZ} = 0 \quad (\mathrm{tree-level})$
$\phi \to ZZ$	$\frac{\lambda'_{ZZ}}{\bar{M}_P}\phi Z_{\mu}Z^{\mu}$	$\lambda'_{ZZ} = 2\kappa^2\xi M m_Z^2$
$\phi \to f\bar{f}$	$\frac{\lambda_{f\bar{f}}}{\bar{M}_P}\phi \bar{f}\partial\!\!\!/ f + \mathrm{h.c.}$	$\lambda_{f\bar{f}} = \kappa^2\xi M m_f$

No new mediators: only gravity

Singlet scalar dark matter: some remarks

2 The non-minimal coupling to gravity provides a theory of DM decays

$$\frac{\Gamma(\phi \to f\bar{f})}{\Gamma(\phi \to ZZ)} \simeq 4N_c^{(f)}\frac{m_f^2}{m_\phi^2}$$

	Effective field theory	Non-minimal coupling to gravity
$\phi \to \gamma\gamma$	$\frac{\lambda_{\gamma\gamma}}{\bar{M}_P}$	(tree − level)
$\phi \to gg$	$\frac{\lambda_{gg}}{\bar{M}_P}\phi G_{\mu\nu}G^{\mu\nu}$	$\lambda = 0$ (tree − level)
$\phi \to ZZ$	$\frac{\lambda_{ZZ}}{\bar{M}_P}\phi Z_{\mu\nu}Z^{\mu\nu}$	$\lambda_{ZZ} = 0$ (tree − level)
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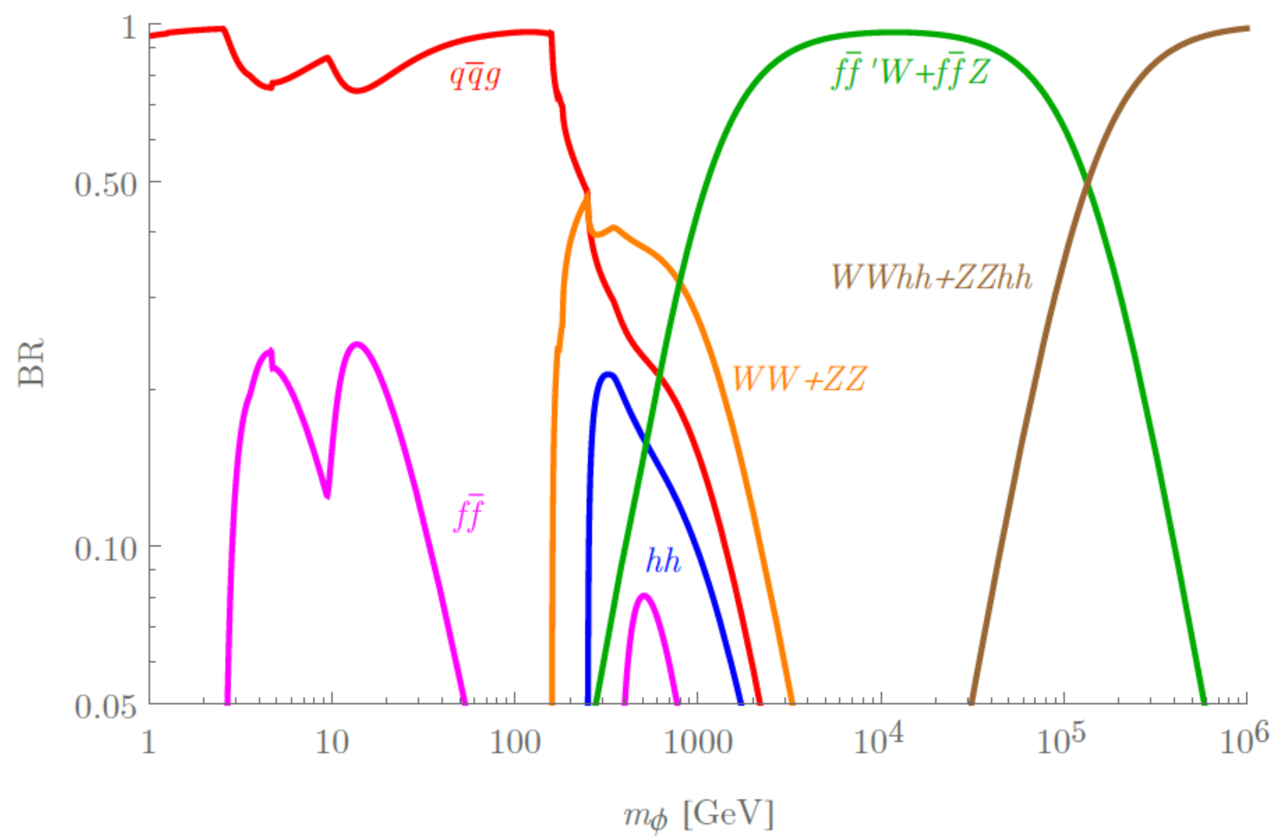
$\phi \to f\bar{f}$	$\frac{\lambda_{f\bar{f}}}{\bar{M}_P}\phi\bar{f}\partial\!\!\!/ f + \mathrm{h.c.}$	$\lambda_{f\bar{f}} = \kappa^2\xi M m_f$

Singlet scalar dark matter: branching ratios

Decay mode	Rate proportional to
$\phi \to hh, WW, ZZ$	m_ϕ^3
$\phi \to f\bar{f}$	$m_f^2 m_\phi$
$\phi \to hhh$	$v^2 m_\phi$
$\phi \to WWh, ZZh$	m_ϕ^5/v^2
$\phi \to f\bar{f}h$	$m_f^2 m_\phi^3/v^2$
$\phi \to f\bar{f}'W, f\bar{f}Z$	m_ϕ^5/v^2
$\phi \to f\bar{f}\gamma, q\bar{q}g$	m_ϕ^3
$\phi \to hhhh$	m_ϕ^3
$\phi \to WWhh, ZZhh$	m_ϕ^7/v^4



Singlet scalar dark matter: limits

Decay rate:

$$\Gamma_{\rm tot} \gtrsim \frac{\xi^2}{8\pi}\frac{M^2 m_\phi^3}{\bar{M}_P^4} \times \begin{cases} 2n_q\,\dfrac{\alpha_s}{\pi}, & m_\phi \sim 1-200 \text{ GeV}, \\ 1+2n_q\,\dfrac{\alpha_s}{\pi}, & m_\phi \sim 0.2-1 \text{ TeV}, \\ \dfrac{3}{(2\pi)^2}\dfrac{m_\phi^2}{v^2}, & m_\phi \sim 1-100 \text{ TeV}, \\ \dfrac{1}{10(8\pi)^4}\dfrac{m_\phi^4}{v^4}, & m_\phi \gtrsim 100 \text{ TeV}, \end{cases}$$

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$$\boxed{\sim \frac{1}{10^8\,\mathrm{s}}\left(\frac{\xi M}{\bar{M}_p}\right)^2\left(\frac{m_\phi}{100\,\mathrm{GeV}}\right)^3}$$

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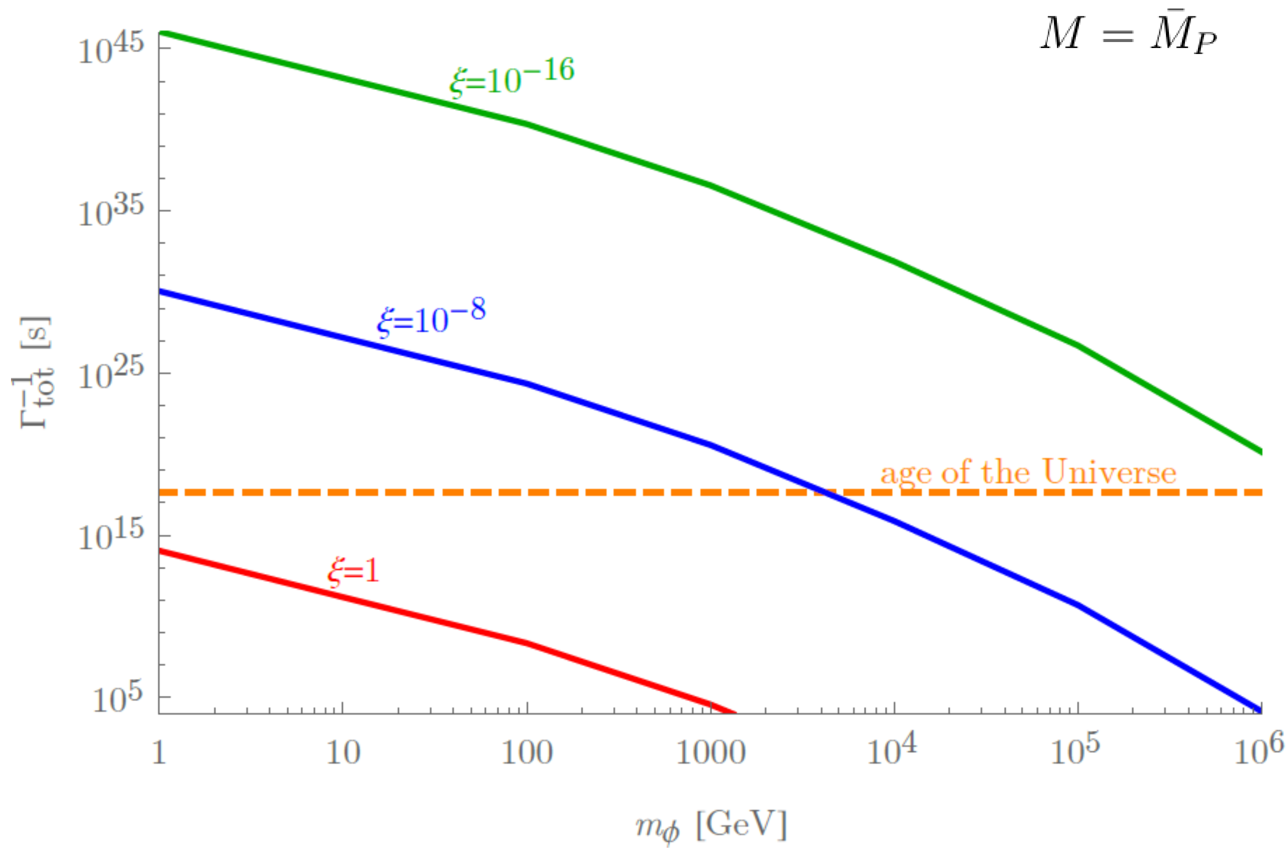
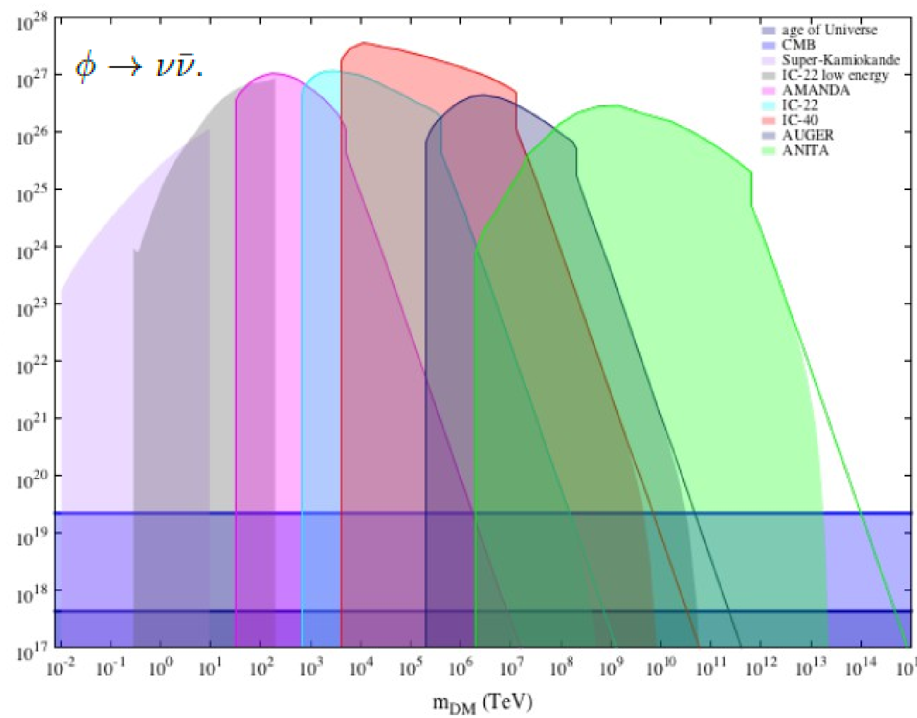


Singlet scalar dark matter: limits

Stronger limits on the decay width from the non-observation of an exotic component in the cosmic gamma-ray, antimatter and neutrino fluxes.

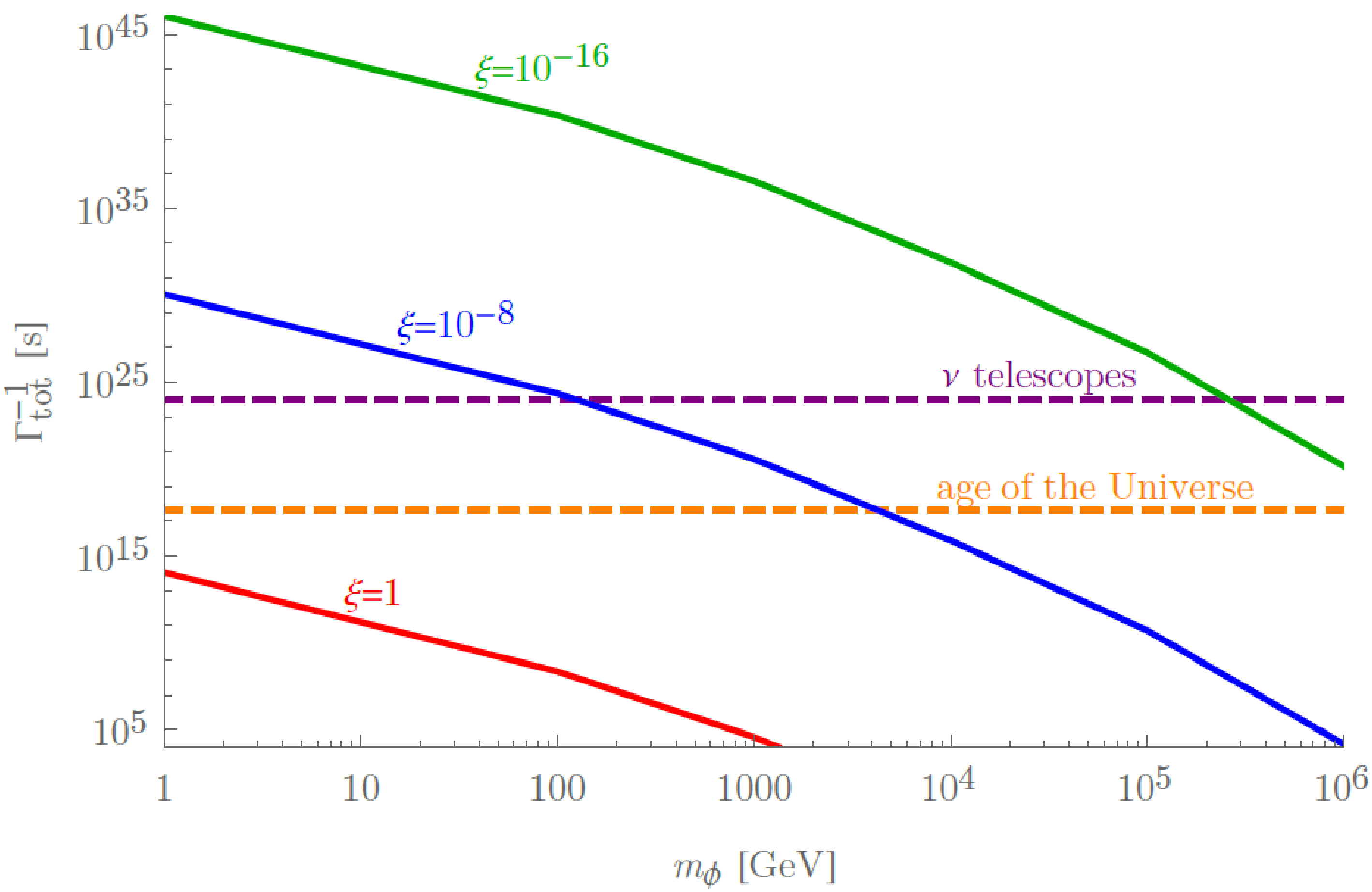
We conservatively impose a lower limit on the rate $\Gamma^{-1} \gtrsim 10^{24}$ s, for DM masses between 1 GeV and 10^{16} GeV.

	$E_\nu^{\min} - E_\nu^{\max}$ (TeV)	$N_{\rm bg}$	$N_{\rm sig}$	$N_{\rm limit}$
AMANDA	$16 - 2.5 \times 10^3$	6	7	5.4
IceCube-22	$340 - 2 \times 10^5$	0.6	3	6.1
IceCube-40	$2 \times 10^3 - 6.3 \times 10^6$	0.1	0	2.3
Auger	$10^5 - 10^8$	0	0	2.3
ANITA	$10^6 - 3.2 \times 10^{11}$	0.97	1	3.3



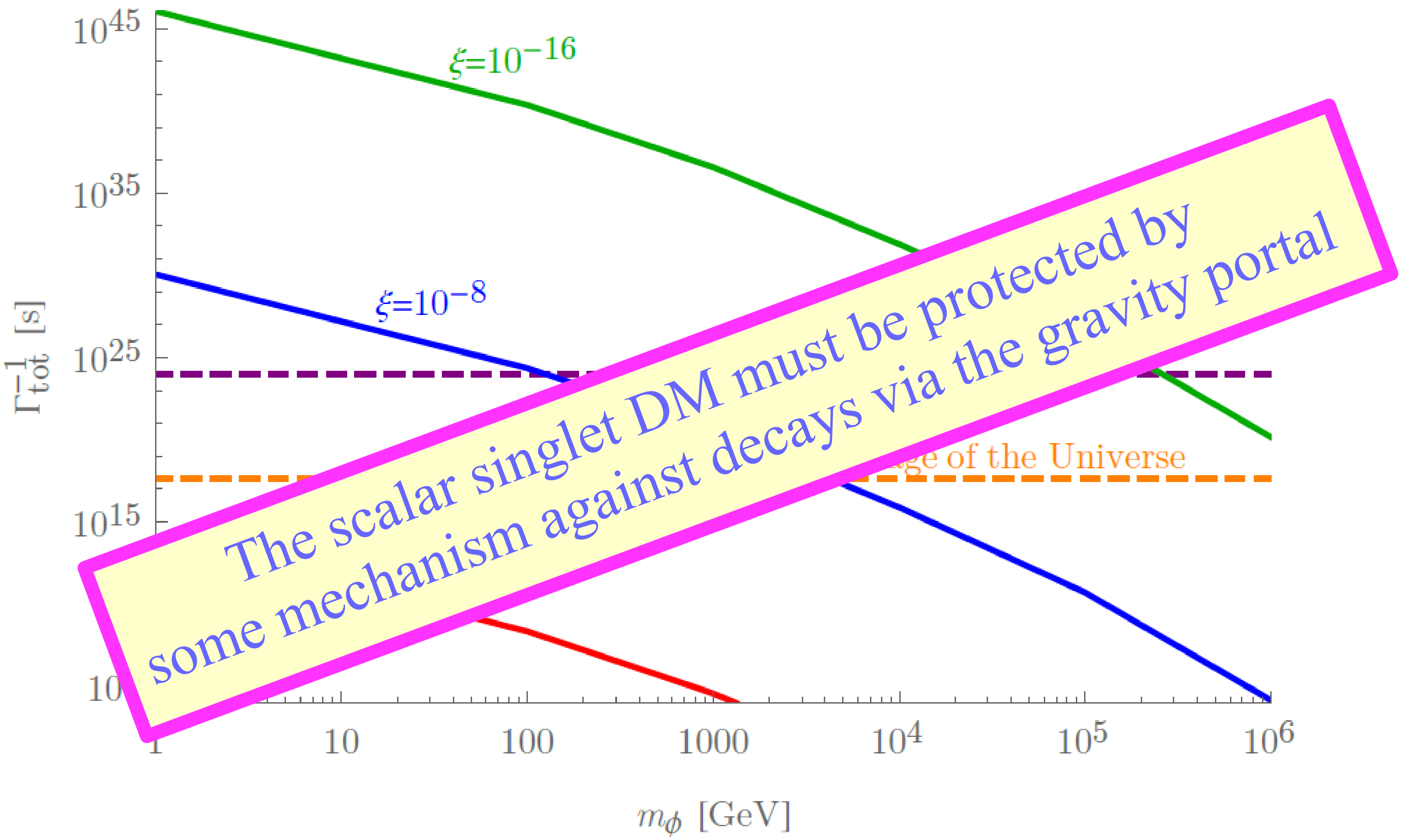
Esmaili et al'12

Singlet scalar dark matter: limits



$$\left|\frac{\xi M}{\bar{M}_P}\right| \lesssim \begin{cases} 2\times 10^{-8}\,\left(\frac{m_\phi}{100\ \mathrm{GeV}}\right)^{-3/2}, & m_\phi \sim 1-200\ \mathrm{GeV}, \\ 8\times 10^{-10}\,\left(\frac{m_\phi}{500\ \mathrm{GeV}}\right)^{-3/2}, & m_\phi \sim 0.2-1\ \mathrm{TeV}, \\ 2\times 10^{-14}\,\left(\frac{m_\phi}{50\ \mathrm{TeV}}\right)^{-5/2}, & m_\phi \sim 1-100\ \mathrm{TeV}, \\ 4\times 10^{-15}\,\left(\frac{m_\phi}{100\ \mathrm{TeV}}\right)^{-7/2}, & m_\phi \gtrsim 100\ \mathrm{TeV}. \end{cases}$$

Singlet scalar dark matter: limits



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Some ways-out

- ξ small. What is the theory behind non-minimal coupling to gravity?

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- M small. E.g. inert doublet dark matter model

  Consider a scalar field, η, with identical gauge quantum numbers as the Standard Model Higgs boson, and charged under a discrete Z_2 symmetry

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\underbrace{-\frac{R}{2\kappa^2} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM}}_{\text{preserve } Z_2}\underbrace{-\xi R(H^\dagger\eta + \eta^\dagger H)}_{\text{break } Z_2}\right)$$

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In the Einstein frame, one finds

$$\widetilde{\mathcal{L}}_{\rm SM} \supset -2\kappa^2\xi(H^\dagger\eta + \eta^\dagger H)\left[\frac{3}{2}\widetilde{\mathcal{T}}_f + \widetilde{\mathcal{T}}_H + 2(\mathcal{L}_Y - \mathcal{V}_H)\right]$$

$$M = \langle H^0\rangle \ll \overline{M}_P$$

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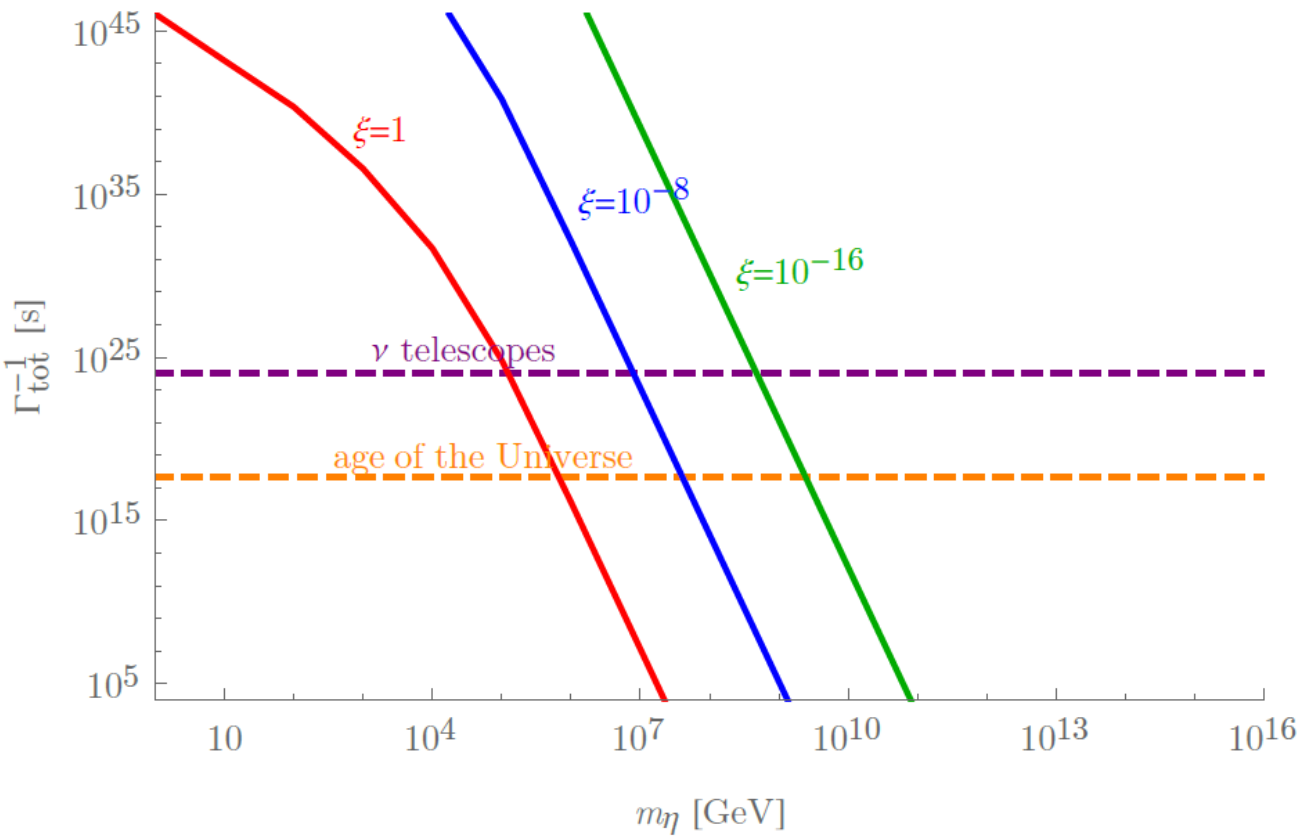

(If $\xi \gg 1$, indirect signals might be detected)

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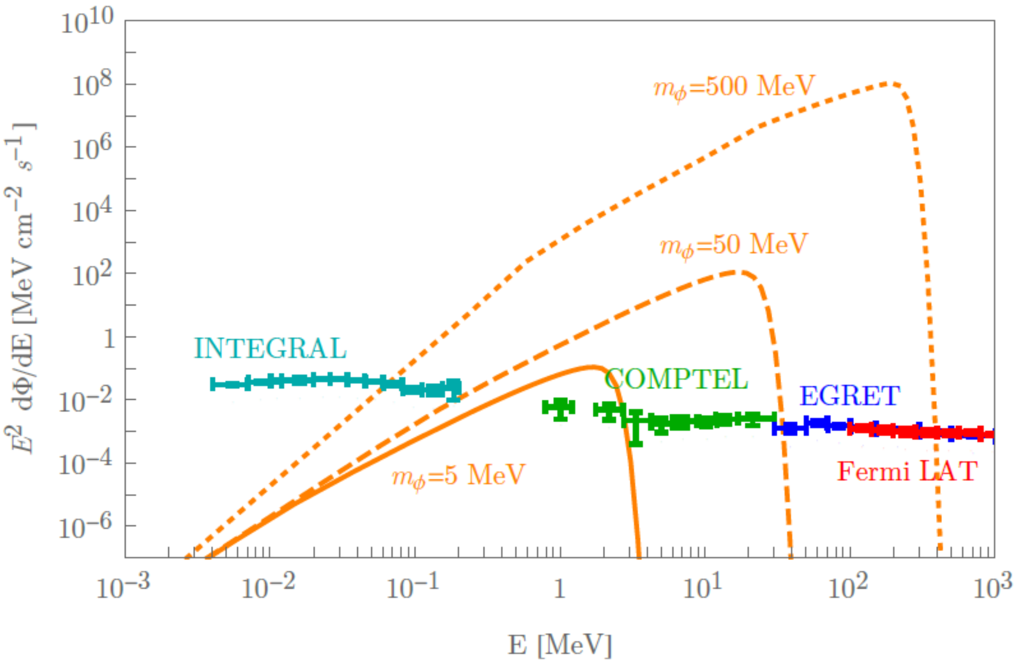
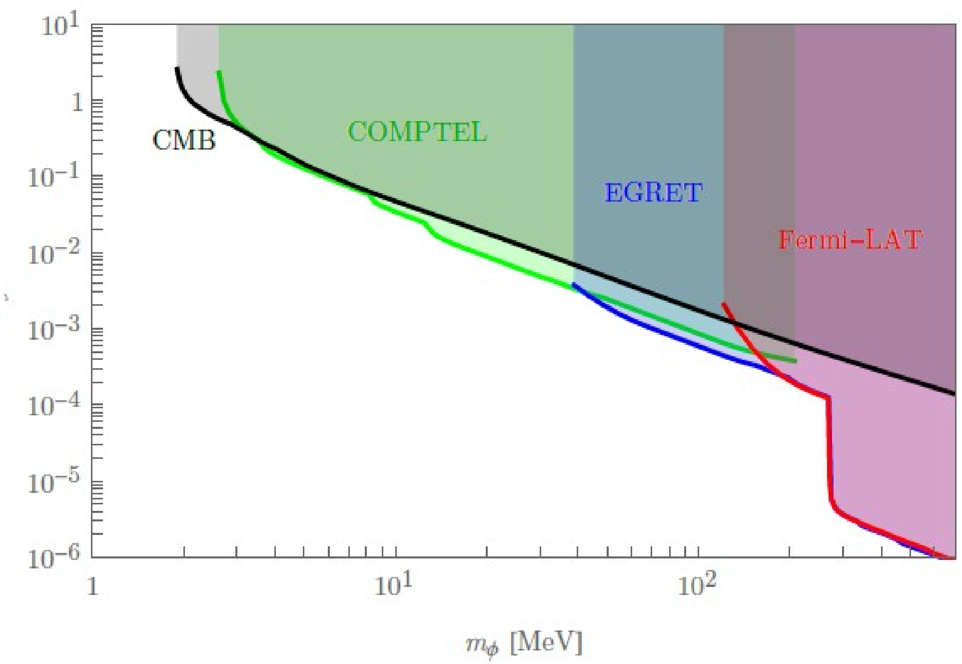
- Low mass dark matter. Decay rate suppressed by the DM mass. But decays lead to sharp gamma-ray spectral features $\hookrightarrow$ strong limits.





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- Low mass dark matter. Decay rate suppressed by the DM mass. But decays lead to sharp gamma-ray spectral features $\hookrightarrow$ strong limits.

- DM stability due to a gauge symmetry (not by a global symmetry).

  $\hookrightarrow$ Dark matter production and signals also determined by the gauge interactions

Conclusions

- Global symmetries are usually invoked to stabilize DM particles. However, gravitational effects might violate global symmetries. What is the impact of space-time curvature on the DM stability?

- We have investigated the impact on the DM stability of a non-minimal coupling term to gravity, proportional to the scalar curvature.

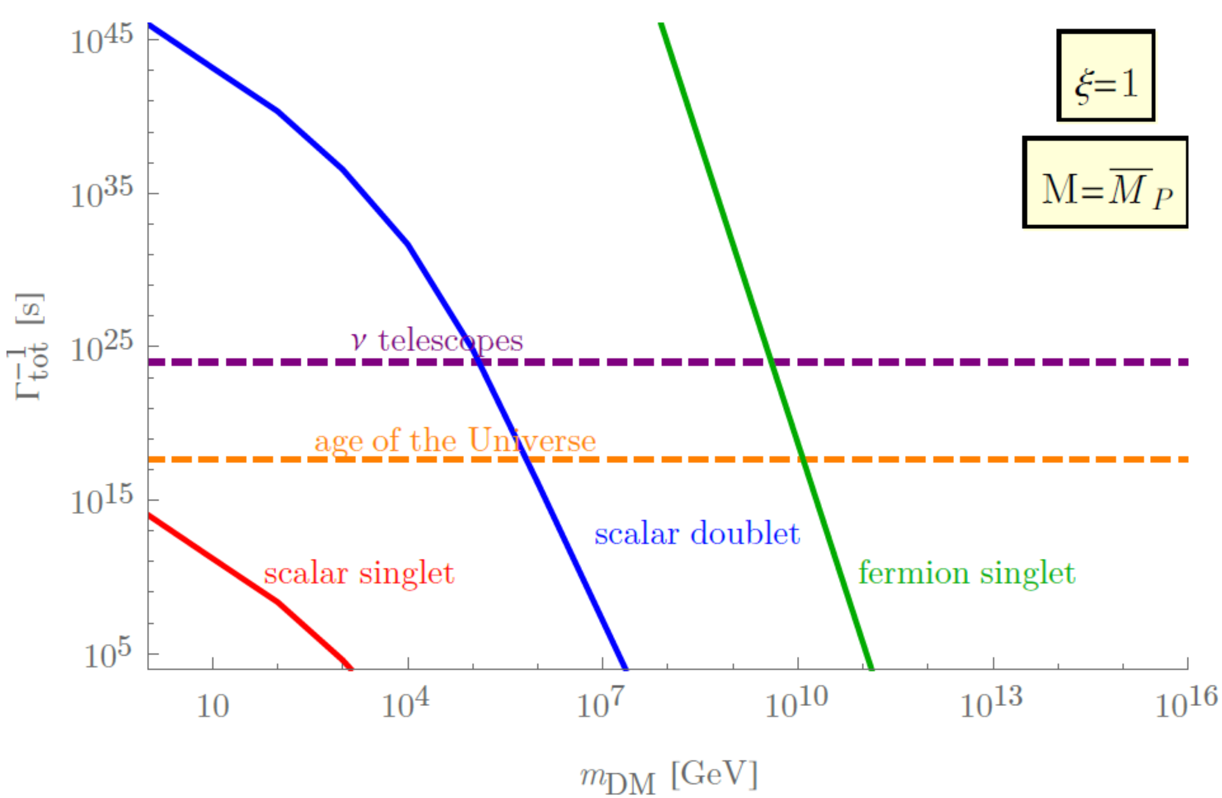
- This scenario leads to DM decay with decay branching ratios which only depend on the DM mass.

- For singlet scalar DM, observations require the non-minimal coupling parameter to be tiny, especially for large masses. The doublet scalar and the fermion singlet are naturally more protected against decay.

Comparison among models

dim. 2 dim. 2

$$\mathcal{L}_\xi = \begin{cases} -\xi R\,(M\phi) & \text{for scalar singlet} \\ -\xi R\,(H^\dagger \eta + \text{h.c.}) & \text{for scalar doublet} \\ -\xi R\,\frac{1}{M^2}(\bar{L}\tilde{H}\chi + \text{h.c.}) & \text{for fermion singlet} \end{cases}$$



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