Effects of a hidden-photon dark matter background in axion-photon interactions

In coll with A. Arza, J. Jaeckel, D. Vargas-Arancibia

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Several ways to produce HP DM in the early universe

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→ **misalignment mechanism** (Nelson11, Arias12)**, resonant decays of a precursor field** (Co19, Dror19, Bastero-Gil2019, Agrawal20…etc)**, quantum fluctuations grown during inflation** (Graham16, Ema19, Alonso-Álvarez20)**, topological defects** (Long19)**, among others.**

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A distinction with popular models for WIMP DM is that their **sufficient production does not require messenger particles**, and their cosmological stability is a consequence of **very small masses and couplings**.

But what if these light particles do interact with the SM through a messenger?

Coupling axion-hidden photon

There have been several works elaborating on the idea of coupling between axions and hidden photons (among others):

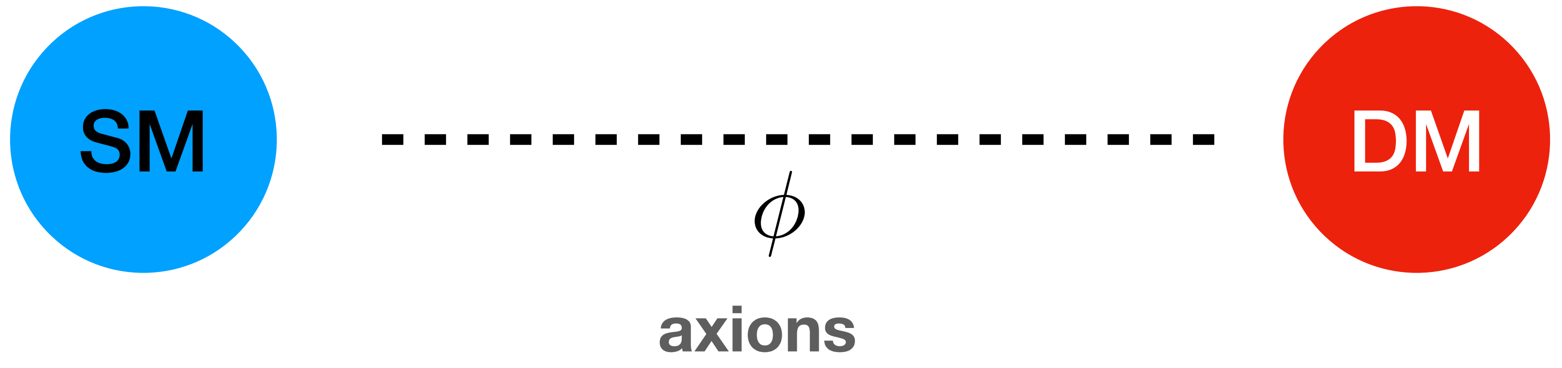
Alleviate puzzling observations such as 3.5 keV line (Jaeckel14), Xenon1T (Aprile20), Cosmic IR background (Kalashev19).

Axion dark matter to convert into HP dark matter (Takahashi18, Agrawal18, Co19, Agrawal20).

The coupling of QCD axion with a HP does not spoil the solution to the strong CP problem (Kaneta et al. 17).

- The golden precision era we are entering encourages to look for more involved particle physics models. They can be constrained!
- The search for new models can be done parasitically to existing ones.

Our model



We consider the DM to be composed of light hidden photons γ'

Properties:

Huge occupation number in the DM condensate

$$N_{\gamma'} \sim \frac{\rho_{\gamma'}}{m_{\gamma'} H^3} \sim 10^{40} \left(\frac{\mathrm{eV}}{m_{\gamma'}}\right)^2 \left(\frac{X_{ini}}{10^{11}\,\mathrm{GeV}}\right)$$

permeates a hidden oscillating electric field.

$$\mathbf{E}'_{dm} = E'_0 \cos(m_{\gamma'} t)\hat{\varepsilon}_{dm}$$

$$|\mathbf{E}'_{dm}| = \sqrt{2\rho_{\mathrm{dm,local}}} = 3 \times 10^3\,\frac{\mathrm{V}}{\mathrm{m}} \left(\frac{\rho_{\mathrm{dm,local}}}{300\,\mathrm{MeV/cm^3}}\right)^{1/2}$$

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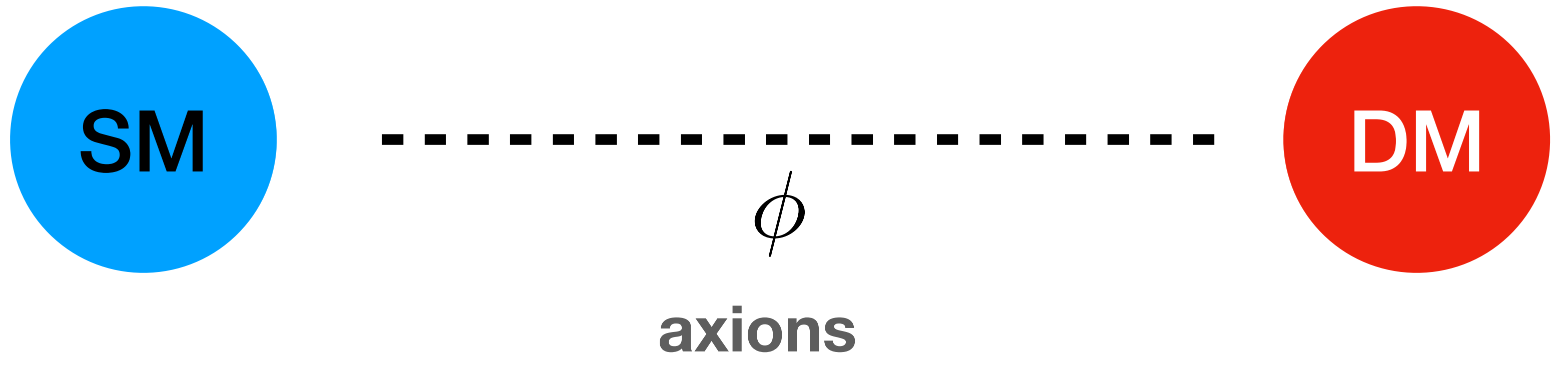

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We introduce a Z_2 symmetry in the hidden sector that forbids

$$\sim \chi F_{\mu\nu} F'^{\mu\nu}$$

$$\sim \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \phi F'_{\mu\nu} \tilde{F}'^{\mu\nu}$$

Our model

Thus, we end up with:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m_\phi^2}{2}\phi^2 + \frac{g_{\phi\gamma\gamma'}}{2}\phi F_{\mu\nu}\tilde{F}'^{\mu\nu}$$

We consider the HP-DM condensate as a background field: $\mathbf{E}'_{dm} = E'_0 \cos(m_{\gamma'}t)\hat{\varepsilon}_{dm}$

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We consider the HP-DM condensate as a background field: $\mathbf{E}'_{dm} = E'_0 \cos(m_{\gamma'}t)\hat{\varepsilon}_{dm}$

And study the evolution of photons and axions in this background:

$$\begin{aligned} \left(\partial_t^2 - \nabla^2\right)\mathbf{A} &= -g_{\phi\gamma\gamma'}\nabla\phi \times \mathbf{E}'_{dm} \\ \left(\partial_t^2 - \nabla^2 + m_\phi^2\right)\phi &= -g_{\phi\gamma\gamma'}\,\mathbf{E}'_{dm}\cdot\mathbf{B}, \end{aligned}$$

Phenomenologically interesting processes

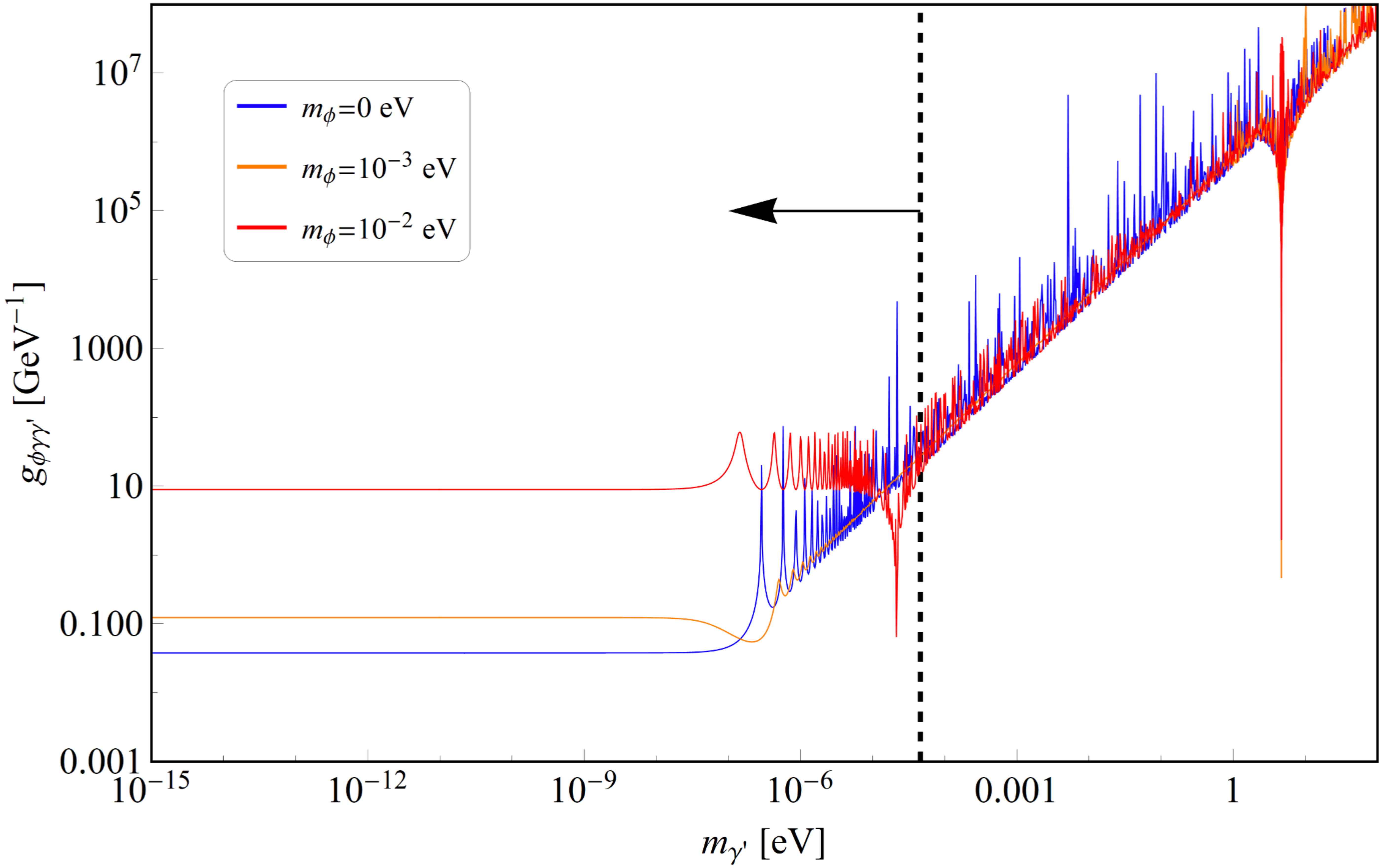
Process	Reaction	process favored when	Momentum transfer
Photon-HP annihilation CMB distortion bounds, LSW	$\gamma' + \gamma \to \phi$	$\omega = \omega_\phi - m_{\gamma'}$	$\Delta k \approx m_{\gamma'}$ $m_\phi \ll m_{\gamma'}, \omega$ $\Delta k \approx 0$ when $m_\phi > m_{\gamma'} = \frac{m_\phi^2}{2\omega}$
(Stimulated) HP decay Stability, CMB distortion, LSW	$\gamma' \to \gamma + \phi$	$\omega = m_{\gamma'} - \omega_\phi$	$\Delta k \approx m_{\gamma'}$ $m_\phi \ll m_{\gamma'}, \omega$ $\Delta k \approx 0$ when $\omega = \frac{m_{\gamma'}^2 - m_\phi^2}{2m_{\gamma'}},$
(Stimulated) Photon decay Stellar, helioscope, X-ray, LSW	$\gamma \to \gamma' + \phi$	$\omega = m_{\gamma'} + \omega_\phi$	$\Delta k \approx m_{\gamma'}$ $m_\phi \ll m_{\gamma'}, \omega$ $\Delta k \approx \frac{m_\phi^2}{2\omega}$ $m_\phi > m_{\gamma'}$

uncertainty in photon momentum prevents full momentum transfer.

LSW-type experiments

2nd cavity \ 1st cavity	$A_{\gamma\phi}$	SD_γ	$SD_{\gamma'}$
$A_{\phi\gamma}$	$\omega + 2m_{\gamma'}$	ω	$2m_{\gamma'} - \omega$
SD_ϕ	ω	$\omega - 2m_{\gamma'}$	-
$SD_{\gamma'}$	-	-	ω

Highly tuned detectors might miss some of these processes



$\omega = 2.33\,\text{eV}$ $\quad L = 4.3\,\text{m}$

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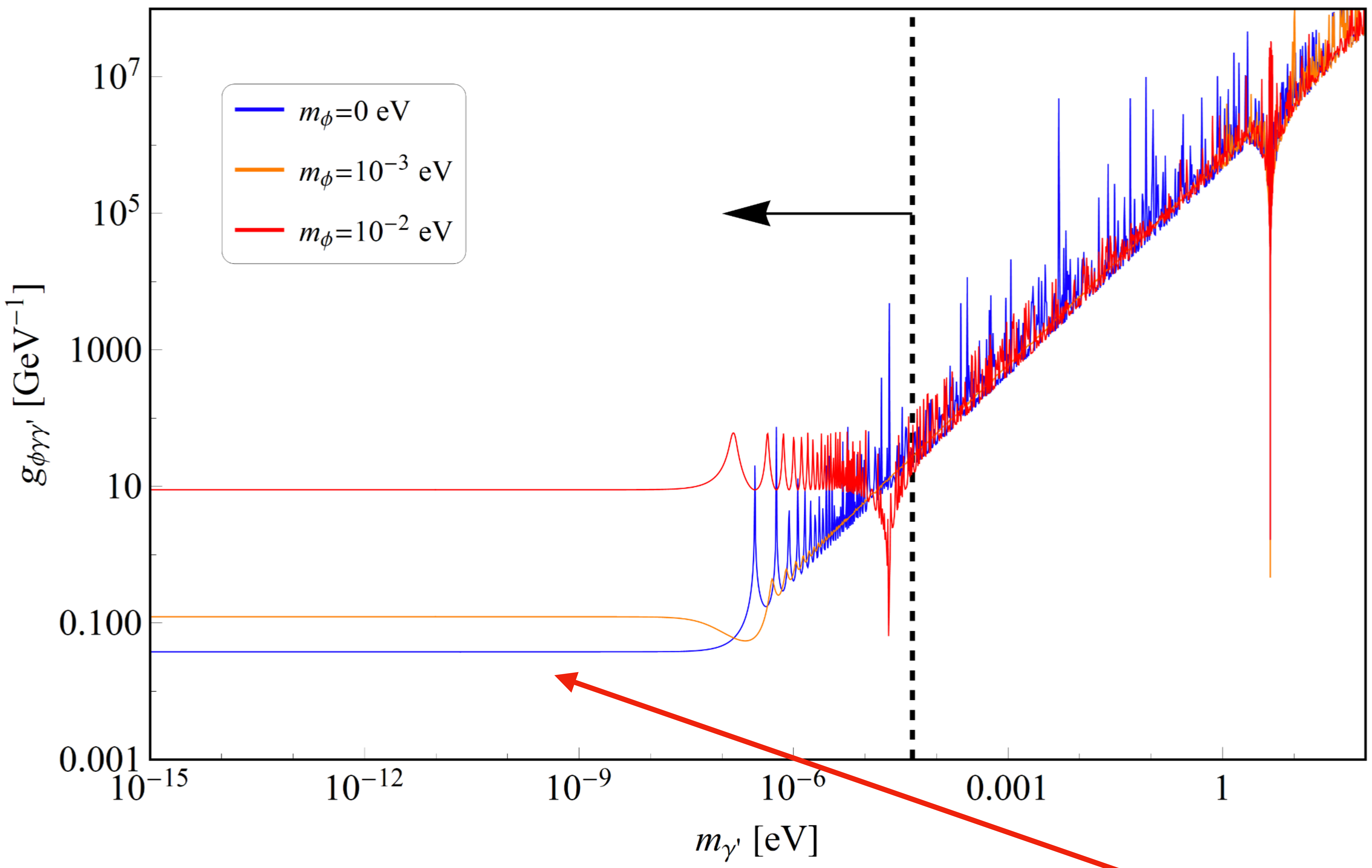

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best sensitivity for small WISP masses

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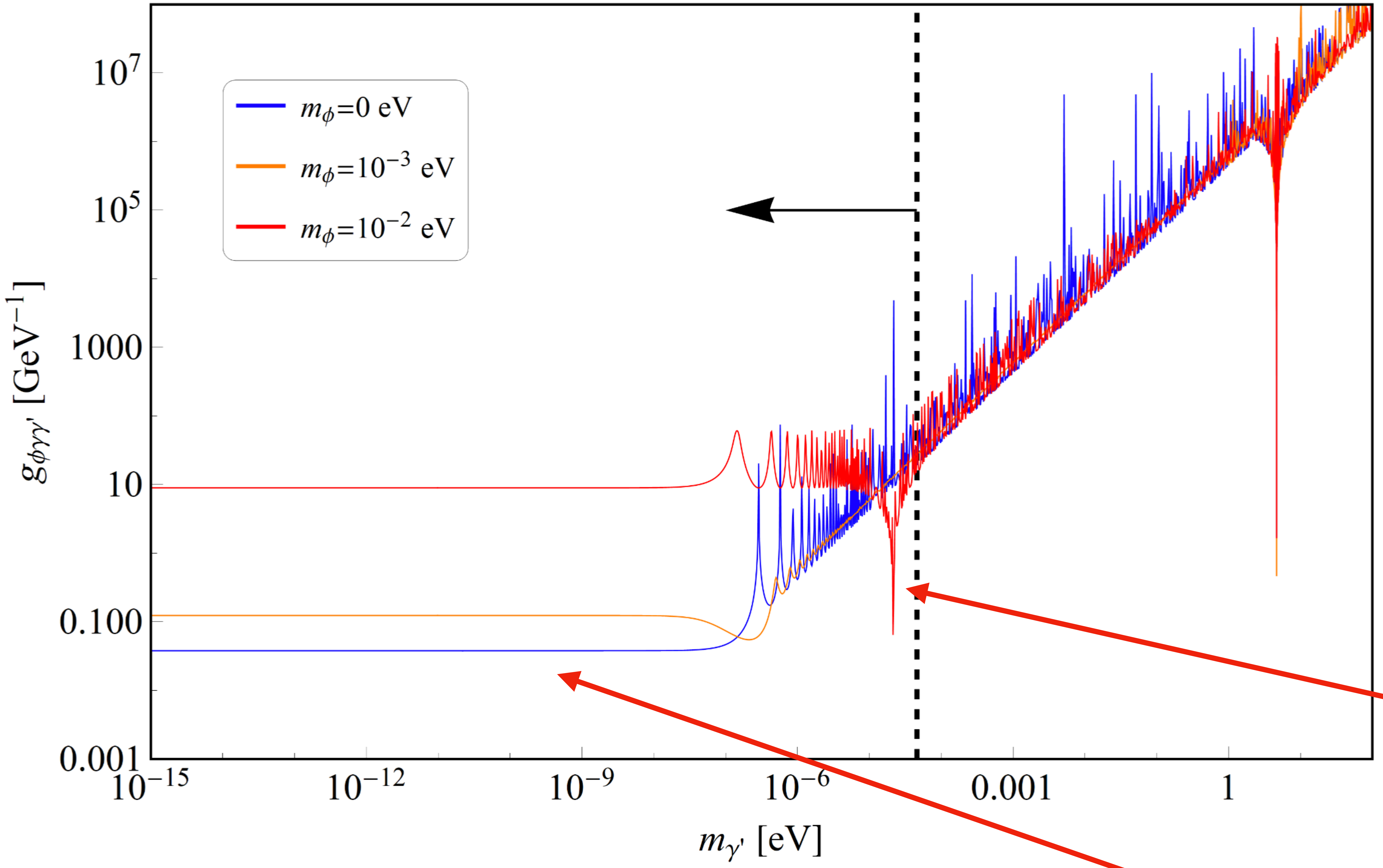

resonance $\gamma' + \gamma \to \phi$

at $m_{\gamma'} = \frac{m_\phi^2}{2\omega}$

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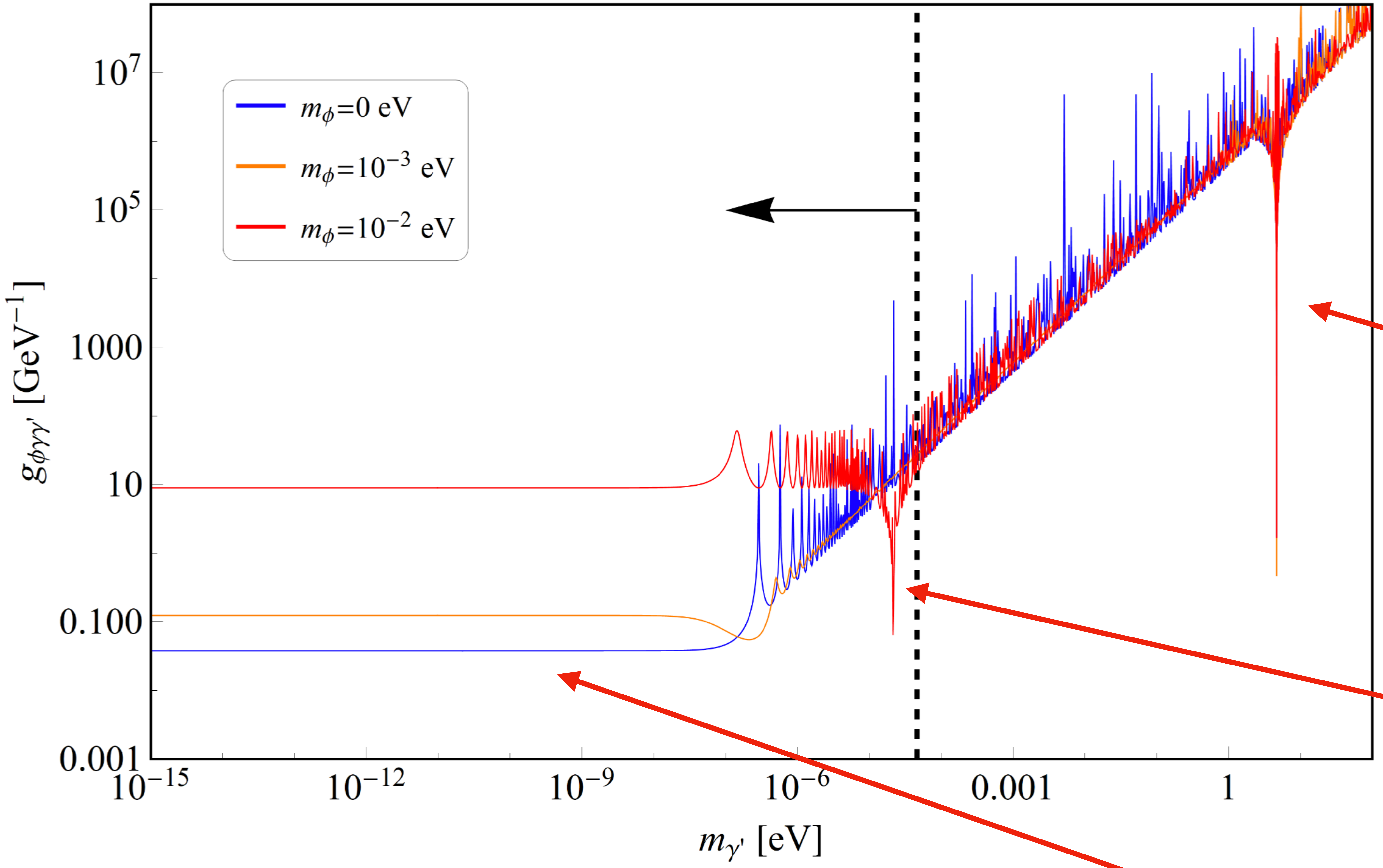

resonance $\gamma' \to \gamma + \phi$

at $m_{\gamma'} = \omega + \sqrt{\omega^2 + m_\phi^2}$

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best sensitivity for small WISP masses

Stability of the DM condensate

$$\gamma' \to \gamma + \phi$$

Spontaneous decay
Stimulated decay

$$\tau = \frac{1}{\Gamma_{\gamma' \to \phi\gamma}} = \frac{96\pi}{g^2_{\phi\gamma\gamma'} m^3_{\gamma'}} \left(1 - \frac{m^2_\phi}{m^2_{\gamma'}}\right)^{-3} \approx 2 \times 10^{17}\,\mathrm{s} \left(\frac{g_{\phi\gamma\gamma'}}{10^{-6}\,\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_{\gamma'}}{1\,\mathrm{eV}}\right)^{-3} .$$

perturbative decay

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With huge occupation numbers in HP condensate, it is also possible to have a spontaneous **Bose enhanced** decay.

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$$\epsilon(k) = m'_{\gamma'} - \omega - \omega_\phi \approx 0$$

$$\mathbf{k}_\phi + \mathbf{k} \approx 0$$

$$\omega = \frac{m^2_{\gamma'} - m^2_\phi}{2 m_{\gamma'}},$$

Resonance condition

Stability of the DM condensate

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$$n_\gamma(t) = \int \frac{d^3k}{(2\pi)^3}\left(f_{\gamma,\mathbf{k}}(0)\left(\cosh(s_{\mathbf{k}}t)^2 + \frac{\epsilon_k^2}{4s_{\mathbf{k}}^2}\sinh(s_{\mathbf{k}}t)^2\right) + f_{\phi,-\mathbf{k}}(0)\frac{\Omega_{\mathbf{k}}^2}{s_{\mathbf{k}}^2}\sinh(s_{\mathbf{k}}t)^2 + \frac{\Omega_{\mathbf{k}}^2}{s_{\mathbf{k}}^2}\sinh(s_{\mathbf{k}}t)^2\right).$$

stimulated decay by initial photon population

stimulated decay by initial axion population

spontaneous Bose enhanced decay

Stability of the DM condensate

$$\gamma' \to \gamma + \phi$$

Spontaneous decay
Stimulated decay

$$n_\gamma(t) = \frac{m_{\gamma'}^2 \eta}{16\pi} \frac{e^{2\eta t}}{2\eta t} \left(f_{m_{\gamma'}/2} + \frac{1}{2} \right)$$

for nearly massless axions

$$\eta \equiv \frac{g_{\phi\gamma\gamma'} E_0'}{4}$$

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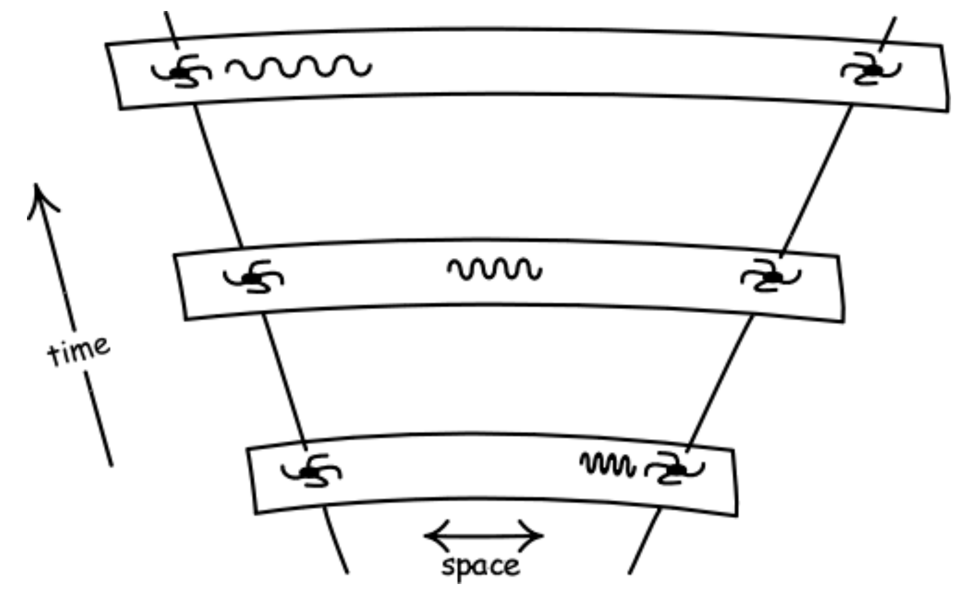

A photon of energy $\omega = k$ will be **redshifted away** from the parametric resonance window

after an interval of time $2\eta\delta t \ = \ g_{\phi\gamma\gamma'}^2 \rho_{dm}/(m_{\gamma'} H).$

Stability of the DM condensate

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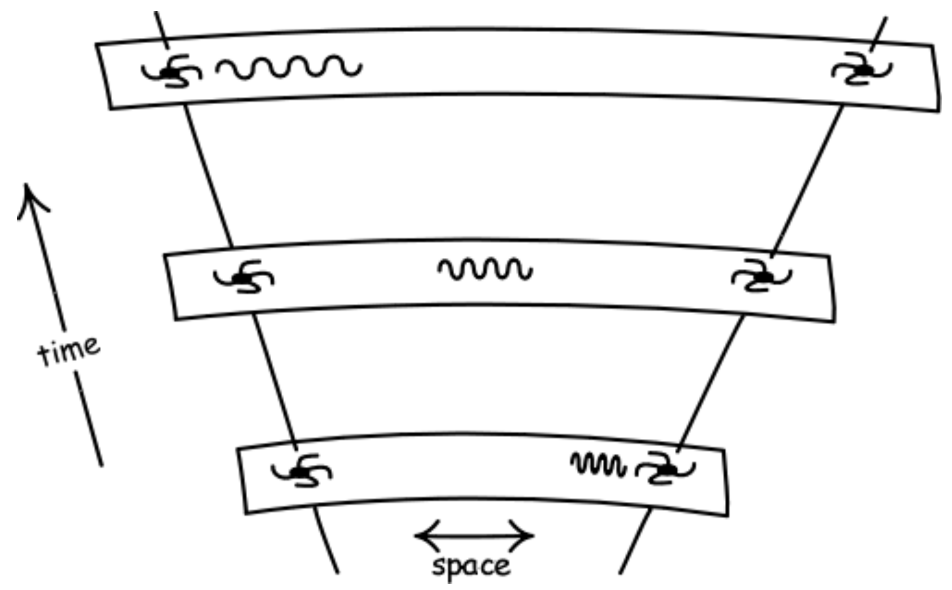

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$\sim t^{-1/2}$ RD

$\sim t^{-1}$ MD

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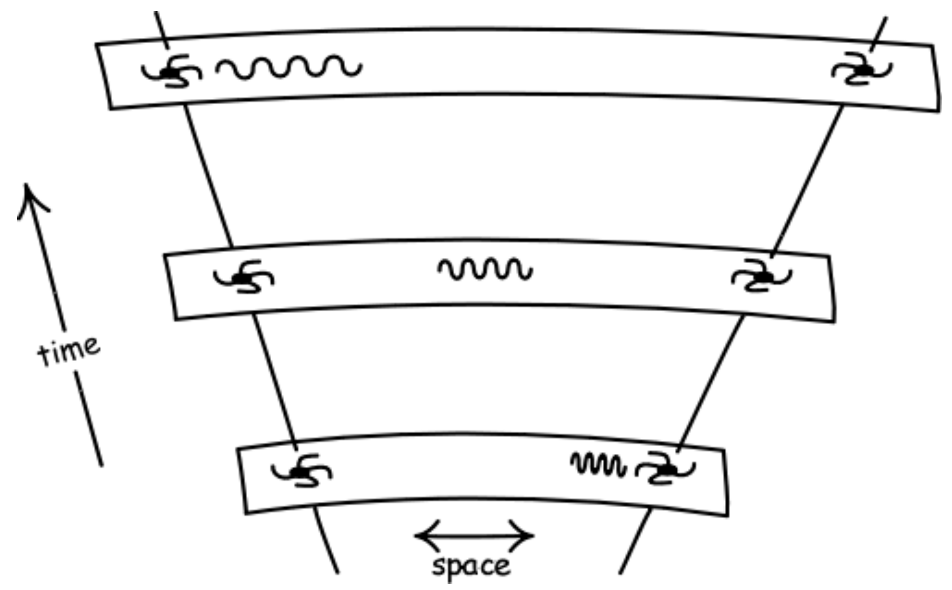

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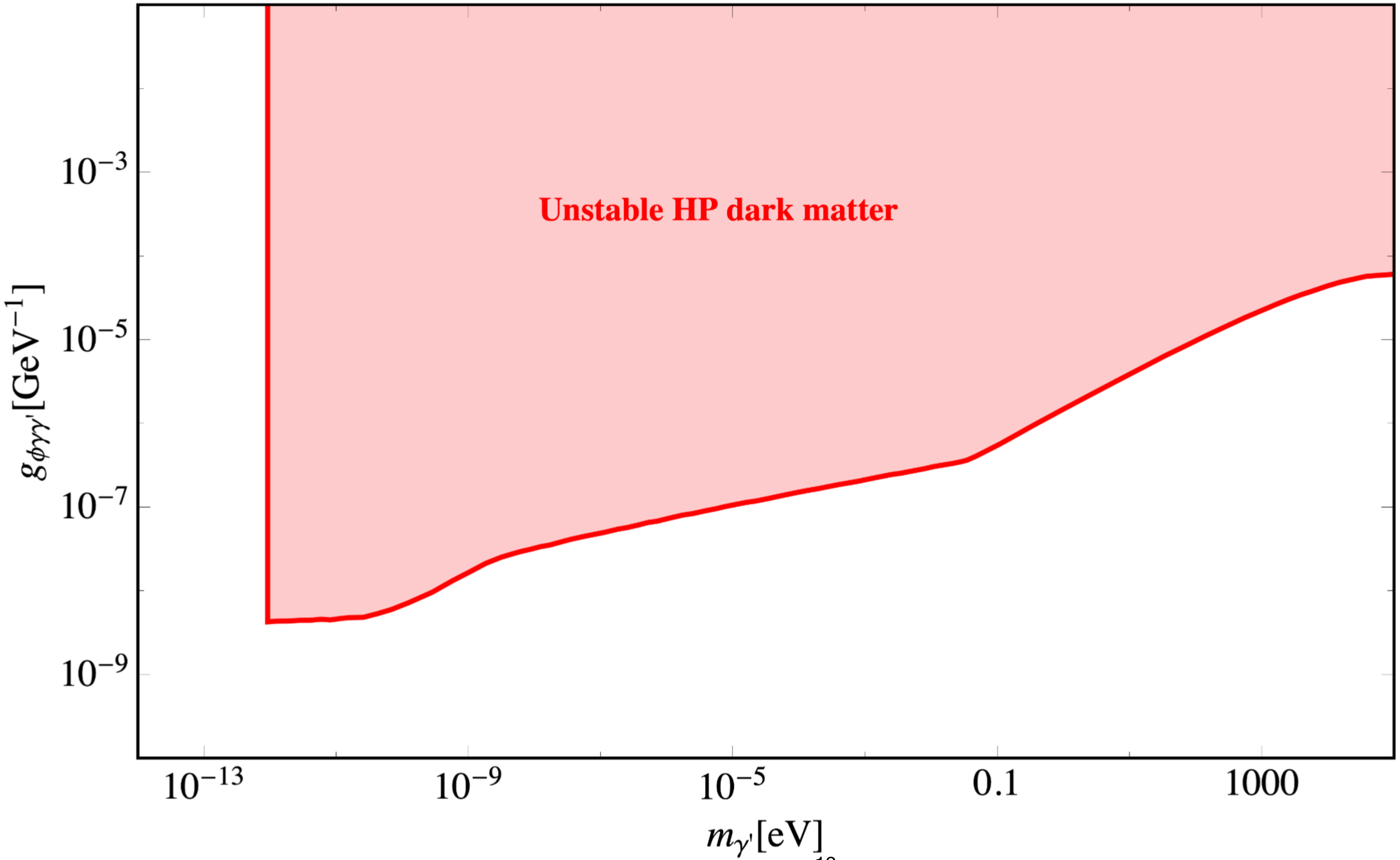
all in all, by $\rho_\gamma < \rho_{\rm dm}$

$$g_{\phi\gamma\gamma'}^2 < \frac{m_{\gamma'} H}{\rho_{dm}} \ln\left(\frac{64\pi \rho_{dm}}{\sqrt{2Hm_{\gamma'}^5 T}} \right).$$

We include plasma effects by evaluating at times such that $m_{\gamma'} \gtrsim m_{pl}$

HP-DM Stability



Bounds from CMB distortion

Two processes contribute to CMB distortion

$$\gamma' \to \phi + \gamma$$

stimulated HP decay from CMB photons satisfying

$$\omega = \frac{m_{\gamma'}^2 - m_\phi^2}{2m_{\gamma'}},$$

$$\gamma' + \gamma \to \phi$$

Photon - HP annihilation with

$$\omega = \frac{m_\phi^2 - m_{\gamma'}^2}{2m_{\gamma'}}$$

We compute the spectral photon energy density and its corrections, to obtain the distortion of the CMB spectrum as

$$\rho_{\rm dm,0} \sim 1{\rm keV/cm^3}$$

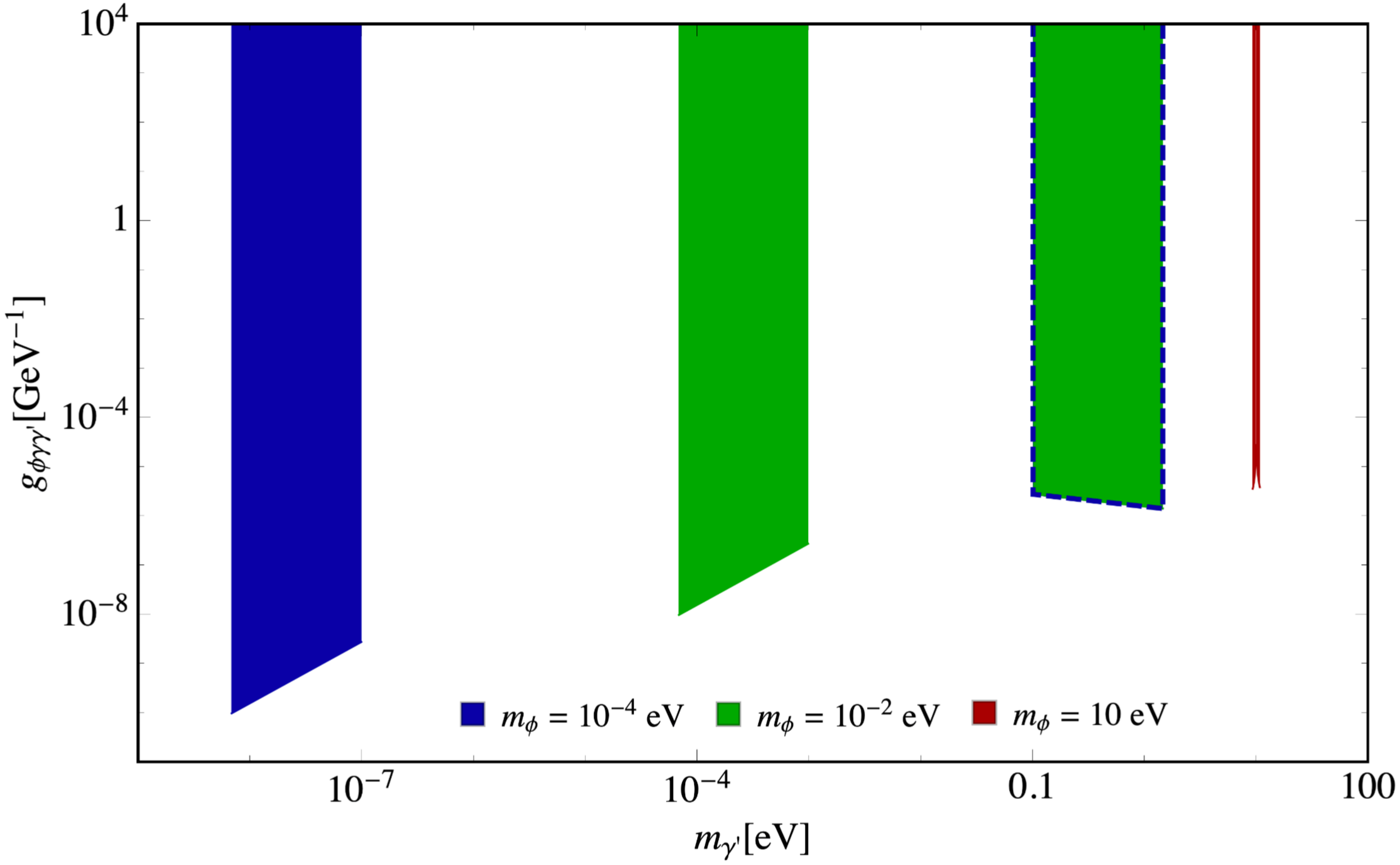
$$t_0 \sim 14 \times 10^9 {\rm yr}$$

$$\chi_\omega \sim \left(10^{-3} - 1\right)$$

$$\delta_\omega = \frac{\delta\rho_{\mathbf{k},\mathbf{0}}}{\rho_{\mathbf{k},\mathbf{0}}} = \pm\frac{\pi}{8}\frac{g_{\phi\gamma\gamma'}^2 \rho_{\rm dm,0}\, t_0}{m_{\gamma'} \chi_\omega^{3/2}}$$

Using the accuracy of FIRAS (Fixsen93) $\delta_\omega < 10^{-4}$.

CMB Constraints

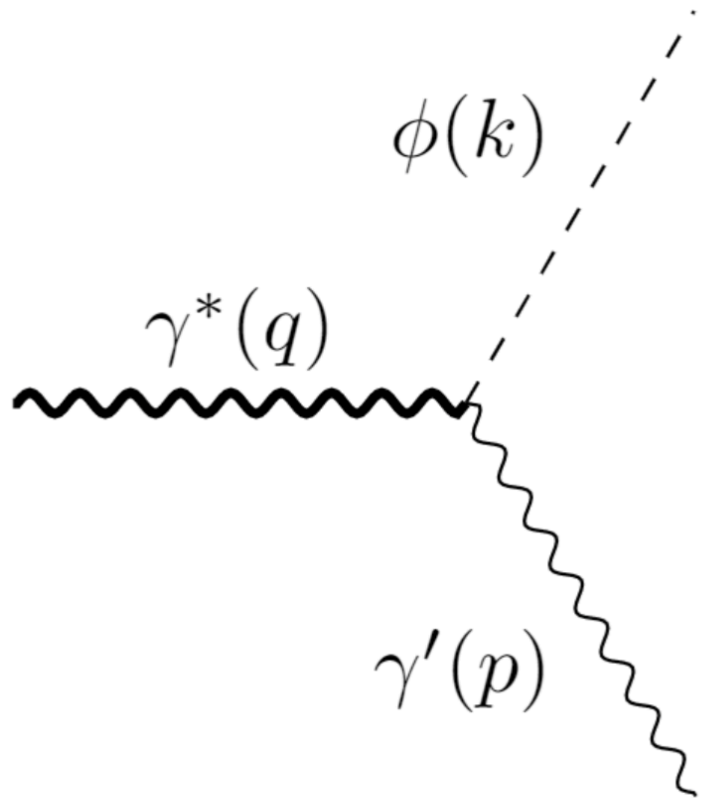


Stellar constraints

Energy loss arguments have been widely invoked to study novel particles. A new energy loss channel will perturb the stellar object, enforcing it to become more compact, luminous and hotter than the unperturbed configuration **(Raffelt87, Gondolo09, An13)**

The vertex in our model allows for the decay of a transverse plasmon into a hidden-photon and an axion in a plasma.

We start looking the anomalous **solar luminosity** produced by this process, using that $L_x < 0.1 L^{std}$



$$L_x = \int_{V_{\rm sun}} dV\, g_d \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{\Gamma_x\, \omega(q)}{e^{\omega(q)/T} - 1}$$

$$\Gamma_{\gamma^* \to \phi\gamma'} = \frac{1}{3} \frac{g^2_{\phi\gamma\gamma'}}{32\pi} \frac{\omega^4_{pl}}{\omega}$$ massless

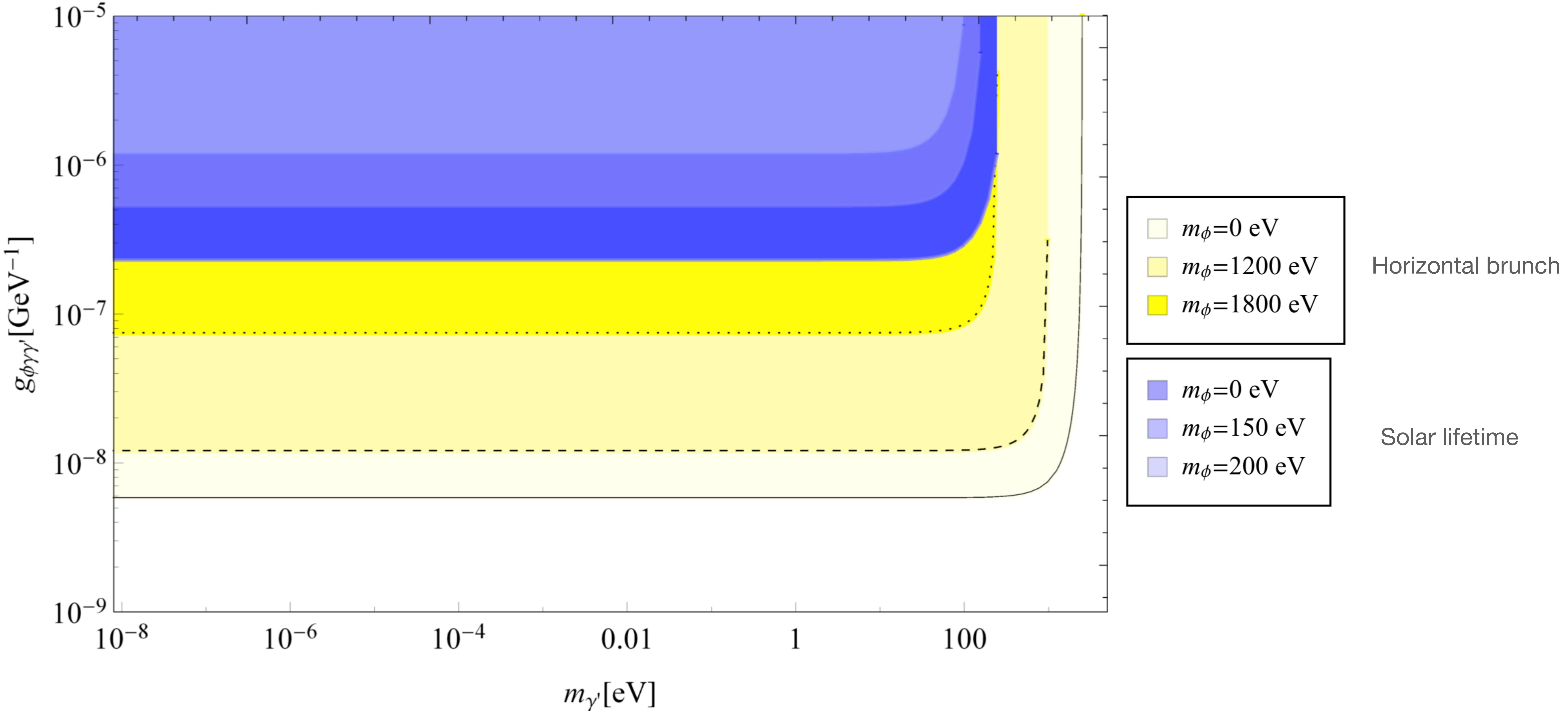
$$\Gamma_{\gamma^* \to \phi\gamma'} = \frac{1}{3} \frac{g^2_{\phi\gamma\gamma'}}{32\pi} \frac{1}{\omega\, \omega^2_{pl}} \left[\left(\omega^2_{pl} - (m_\phi + m_{\gamma'})^2\right)\left(\omega^2_{pl} - (m_\phi - m_{\gamma'})^2\right)\right]^{\frac{3}{2}}$$ massive

Horizontal Branch stars are denser and hotter than the sun, so improved limits are expected.

Stellar constraints

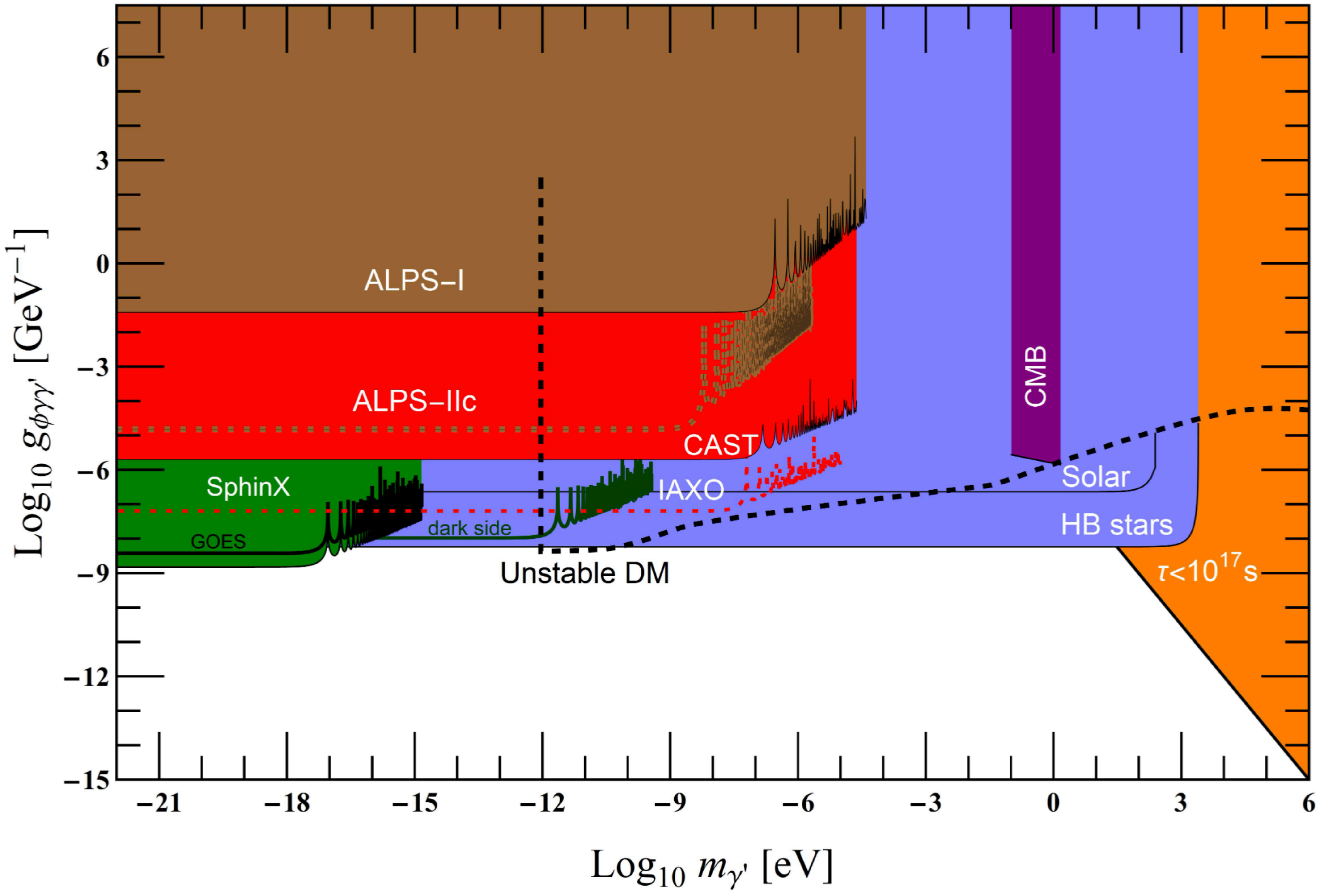
$$\omega_{\rm pl}^{\rm sun} \sim 0.3\,{\rm keV}$$

$$\omega_{\rm pl}^{\rm HB} \sim 2\,{\rm keV}$$



Constrained parameter space

Summary



massless ALP

$m_\phi \ll m_{\gamma'}$

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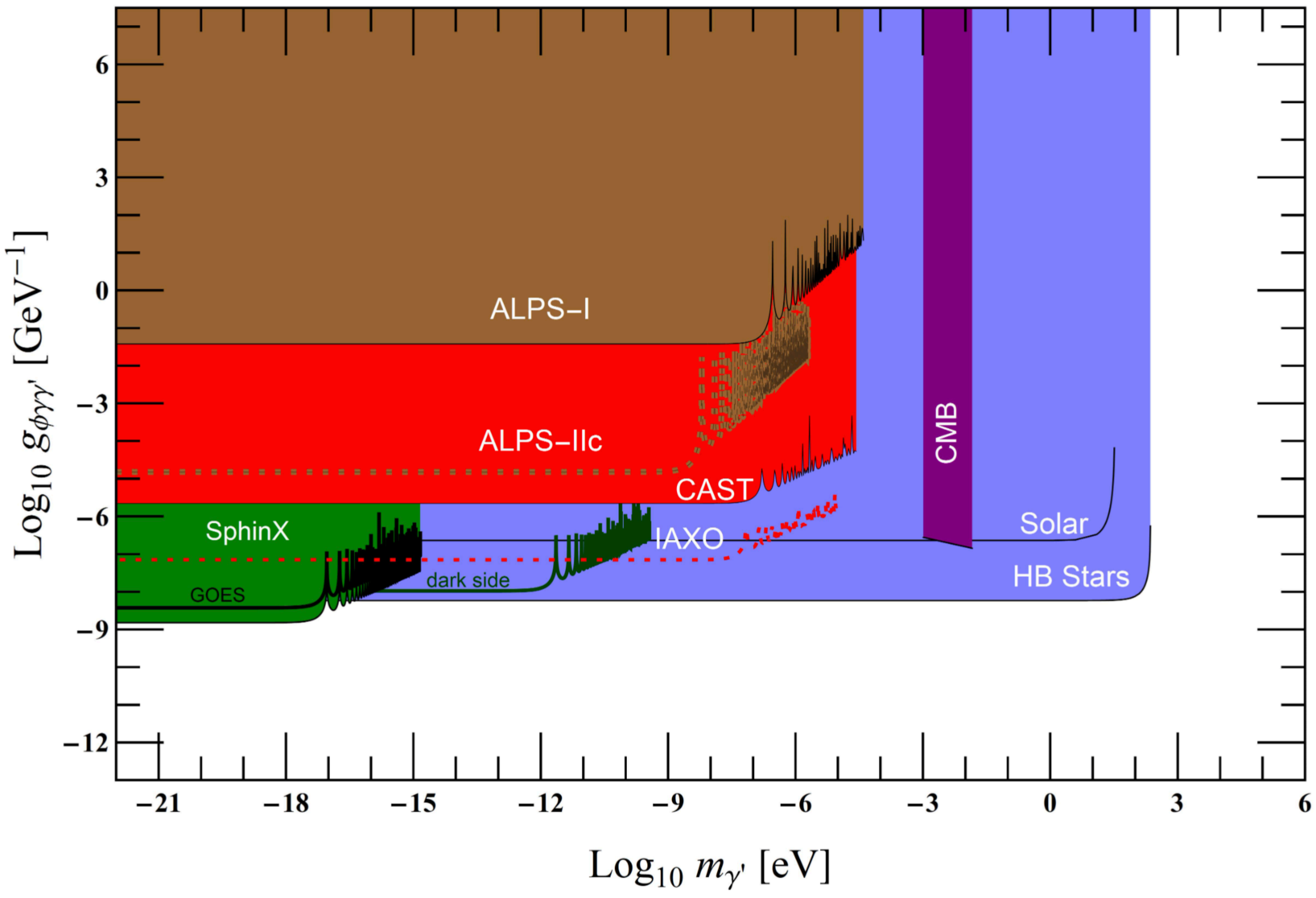


massive ALP

$$m_\phi = 10\, m_{\gamma'}$$

Outlook

- We studied a model of very light dark matter particles (HPs) interacting only under the inclusion of an additional light "messenger" with the Standard Model (the ALP).
- For ALP masses higher than the HP, the DM is stable.
- For HP heavier than ALPs, the decay of DM can exhibit parametric resonance, constraining the parameter space where the HP can be the DM.
- Best bounds from astrophysical observations.
- Direct detection becomes harder, but still possible. A different tune of the detectors could help to distinguish between different physical models.

Coherence of DM

The coherence length of the DM goes by the inverse width in momentum space of the hidden photon distribution

$$L_{\rm coh} \sim \frac{1}{\Delta k_{\rm coh}}$$ and $$\Delta k_{\rm coh} = m_{\gamma'} \Delta v$$

During early times we use linear perturbation theory to obtain

$$\Delta k_{\rm coh} \sim \sqrt{H m_{\gamma'} \delta}.$$

$$\delta \sim \delta\rho/\rho \sim 10^{-4} < 1$$

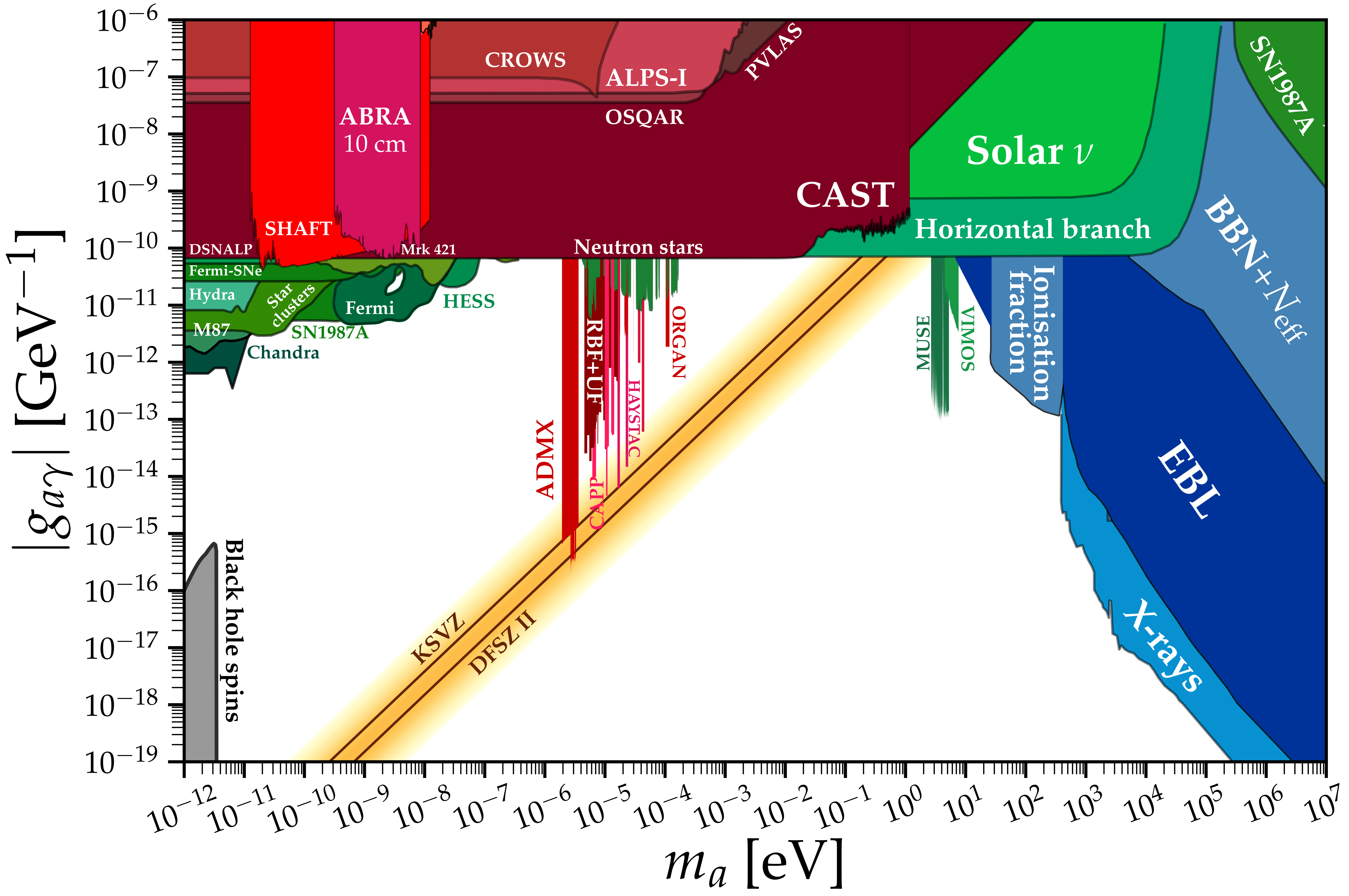
No longer applicable during matter domination. Fluctuations start to grow and become non-linear

$$\delta \sim 1$$

$$\int_0^{k_{NL}} dk\, \frac{k^2 P_{\rm lin}(k,z)}{2\pi^2} \sim 1.$$

we estimate the scales are linear for $z \gtrsim 75$

Several observations and experiments constrain their parameter space



Compilation made by C. O'Hare.
Available at: https://github.com/cajohare

Caputo, O'Hare, Millar, Vitagliano arxiv: 2105.04565 [hep-ph]