Cosmological Implications of Kalb-Ramond Fields

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Main Takeaways

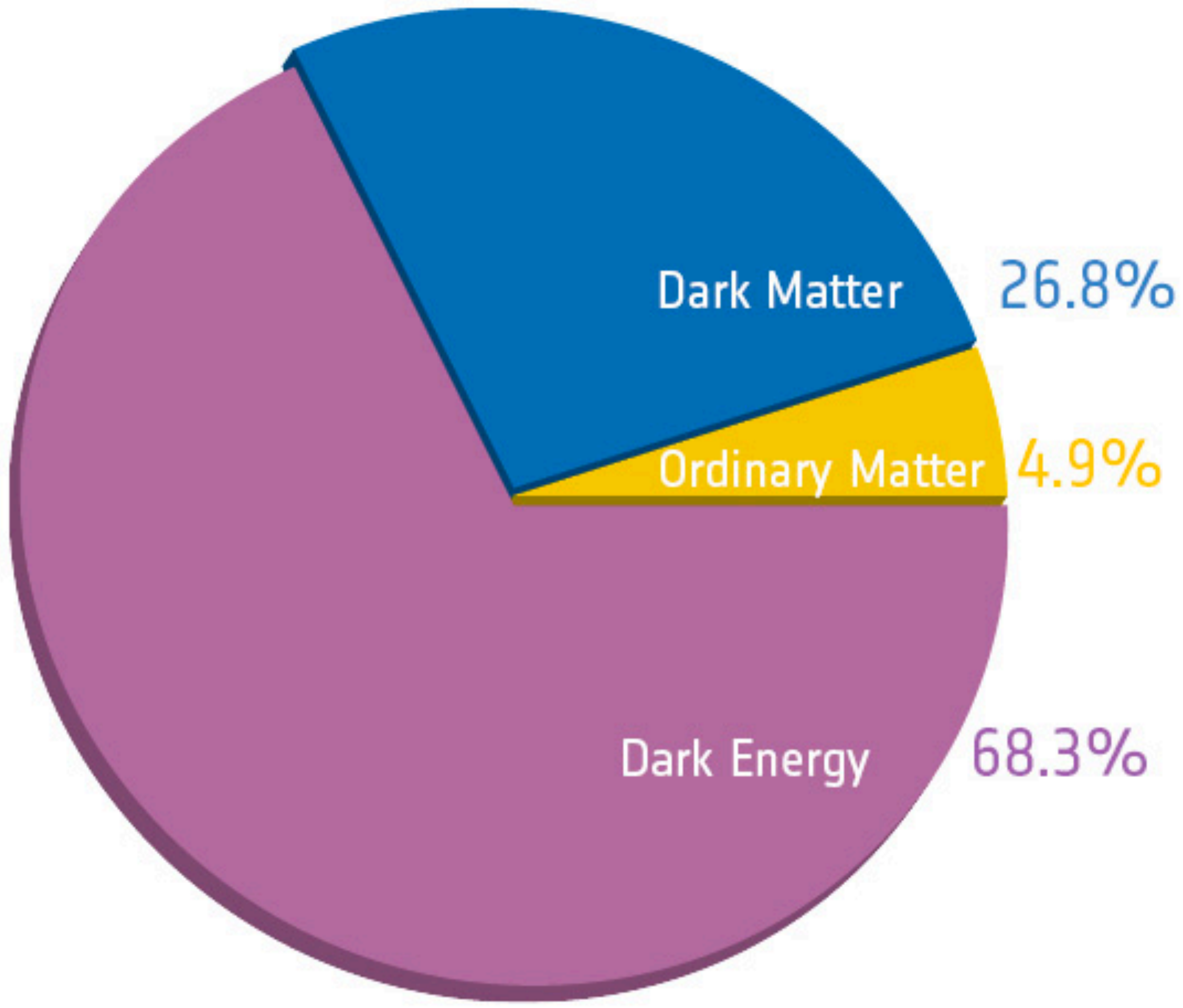
1. Kalb-Ramond fields have related, but distinct properties to axions and dark photons

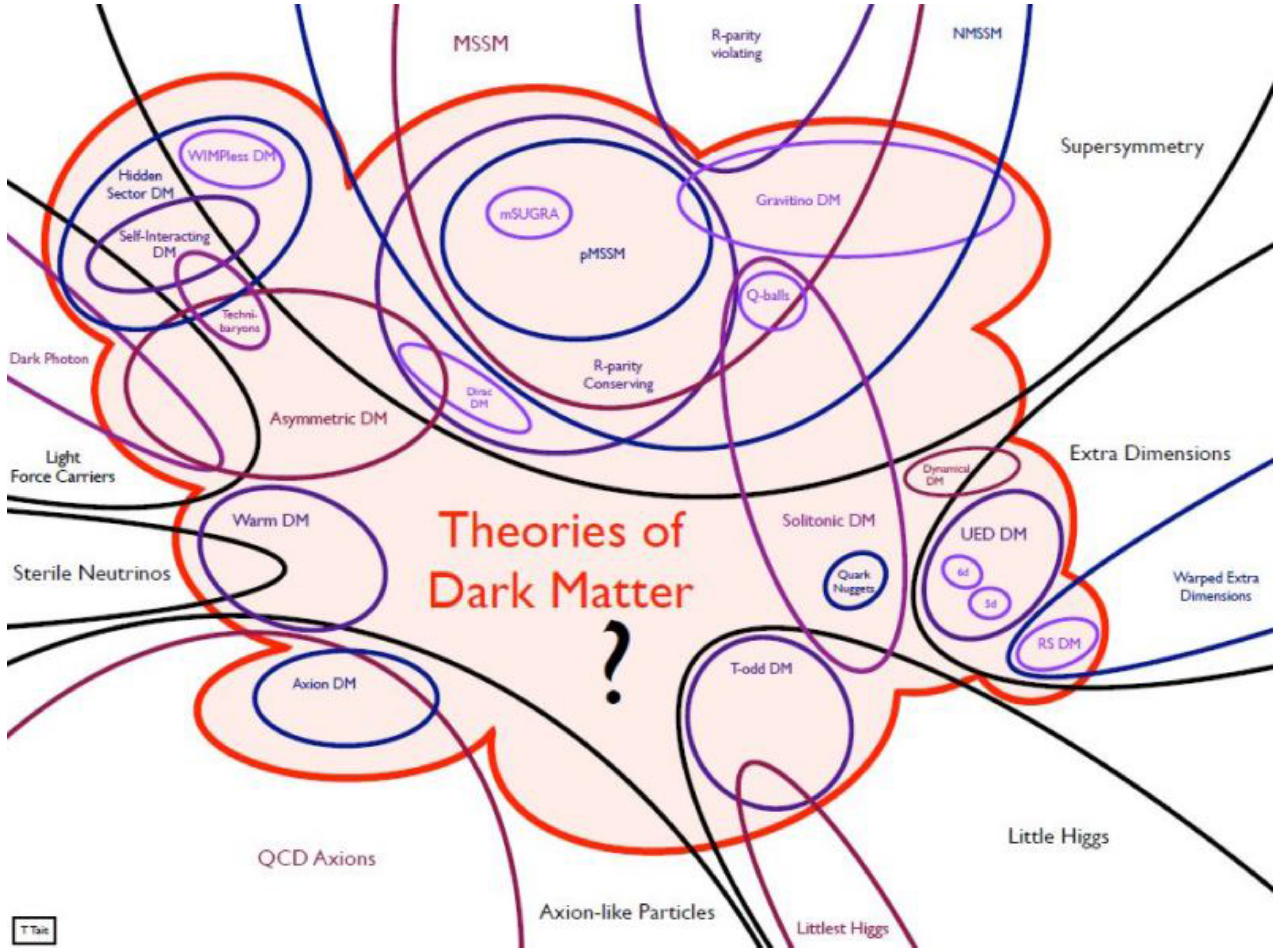
2. Kalb-Ramond-like-particles (KRLPs) are a viable dark matter candidate

3. KRLPs can be produced via freeze-in and cosmological gravitational particle production

4. Many directions for future follow up

Dark Matter





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Ultralight axions: 10^{-22} eV

WIMPs: GeV - TeV

Black holes: $10^4 M_\circ \sim 10^{60}$ GeV

DM Candidate: Dark Photons

$$\mathscr{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + eA_\mu J^\mu_{EM} + \frac{1}{2}m^2 A'_\mu A'^\mu - \epsilon\frac{1}{4}F^{\mu\nu}F'_{\mu\nu}$$

- SM photon kinetically couples to a dark U(1) A'_μ
- Diagonalize kinetic term to obtain $A'_\mu J^\mu_{EM}$
- A'_μ can be portal to dark sector or DM itself
- Can be produced via freeze-in, gravitational particle production

DM Candidate: Axions

$$\mathscr{L} \supset g_{\theta\gamma\gamma}\theta F\tilde{F} + \frac{g_{\theta ff}}{2m_f}\partial_\mu\theta\bar{\psi}\gamma^\mu\gamma^5\psi$$

- Originally introduced to solve strong CP problem (Peccei & Quinn, 1977)
- Extended to a class of 'axion like particles' as a DM candidate
- Can be produced via freeze-in, misalignment

Kalb-Ramond Field: $B_{\mu\nu}$

- Proposed in string theory by Kalb & Ramond
  (Kalb & Ramond, 1974)

$$S = \int d^4x H_{\mu\nu\rho} H^{\mu\nu\rho}$$

$$H = dB$$

- Antisymmetric, *massless* two-form field, $B_{\mu\nu}$

- Analogous to EM potential A_μ

Kalb-Ramond-Like-Particles (KRLPs)

Kalb-Ramond-Like-Particles

$$S = \int d^4x \left(H_{\mu\nu\rho} H^{\mu\nu\rho} - m^2 B_{\mu\nu} B^{\mu\nu} \right)$$

$$H = dB$$

- Antisymmetric, *massive* two-form field, $B_{\mu\nu}$
- EFT-inspired, $B_{\mu\nu}$-like objects appear in many areas of physics
- $(1,0) \oplus (0,1)$ representation of the Lorentz group

Massless KR

"Kalb-Ramond axion"

(Svrcek & Witten, 2006)

$$d\theta = \star\, dB$$

$$S = \int d^4x H_{\mu\nu\rho} H^{\mu\nu\rho}$$

↓

$$S = \int d^4x \partial_\mu \theta \partial^\mu \theta$$

= axion

Dualities

Massless KR

"Kalb-Ramond axion"

(Svrcek & Witten, 2006)

$$d\theta = \star\, dB$$

$$S = \int d^4x H_{\mu\nu\rho} H^{\mu\nu\rho}$$

↓

$$S = \int d^4x \partial_\mu \theta \partial^\mu \theta$$

= axion

Massive KR

Dual to a *pseudovector*

(e.g. Smailagic & Spalluci, 2001; Hell, 2022)

$$B_{ij} = \epsilon_{ijk} B^k$$

$$S = \int d^4x \left(H_{\mu\nu\rho} H^{\mu\nu\rho} - m^2 B_{\mu\nu} B^{\mu\nu} \right)$$

↓

$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu \right)$$

≠ Proca

Distinguishing KRLP and Proca

The KRLP and Proca fields are distinct objects

KRLP

- Pseudovector
- `Stueckelberg trick' massless limit: U(1) + vector
- Massless KRLP → axion

Proca

- Vector
- `Stueckelberg trick' massless limit: U(1) + scalar
- Massless Proca → spin-1

Interactions built from symmetry properties

- KRLP is an antisymmetric matrix
- $B_{\mu\nu}$ a pseudovector (parity even)
- $H_{\mu\nu\rho}$ parity odd
- $\star B$ parity even

Dark photon-like portal

$$\mathscr{L}_{int} = gB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$$

$$\sigma^{\mu\nu} = [\gamma^{\mu}, \gamma^{\nu}]$$

Axion-like portal

$$\mathscr{L}_{int} = \tilde{g}\tilde{H}_{\mu}\bar{\psi}\gamma^{\mu}\gamma^{5}\psi$$

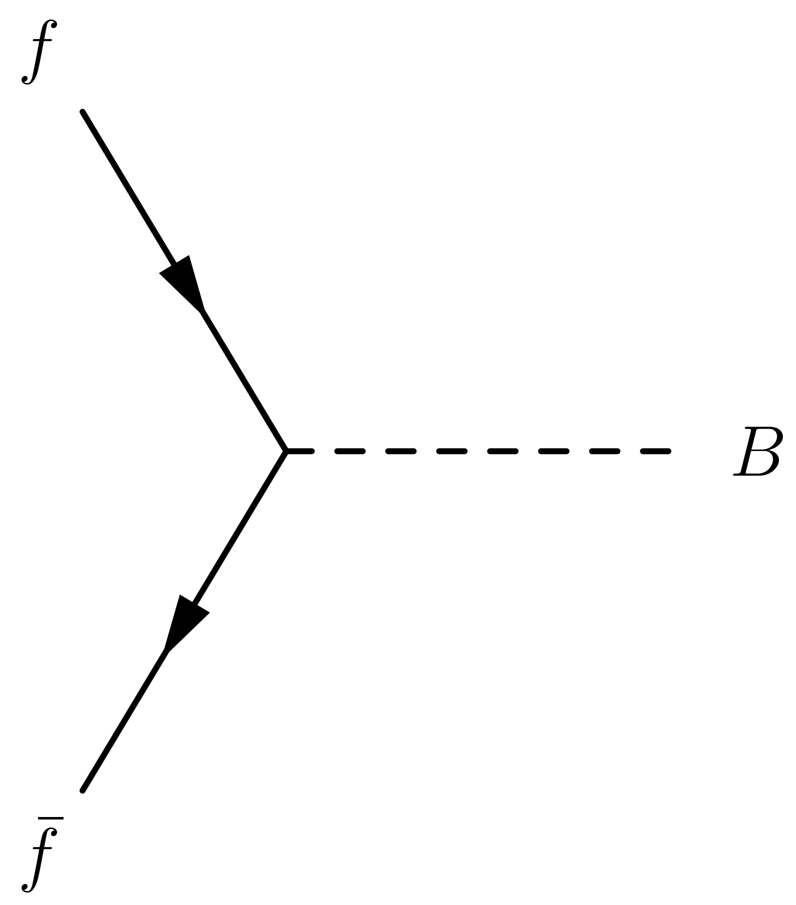
$$\tilde{H} = \star H$$

Freeze-in Production

Freeze-In

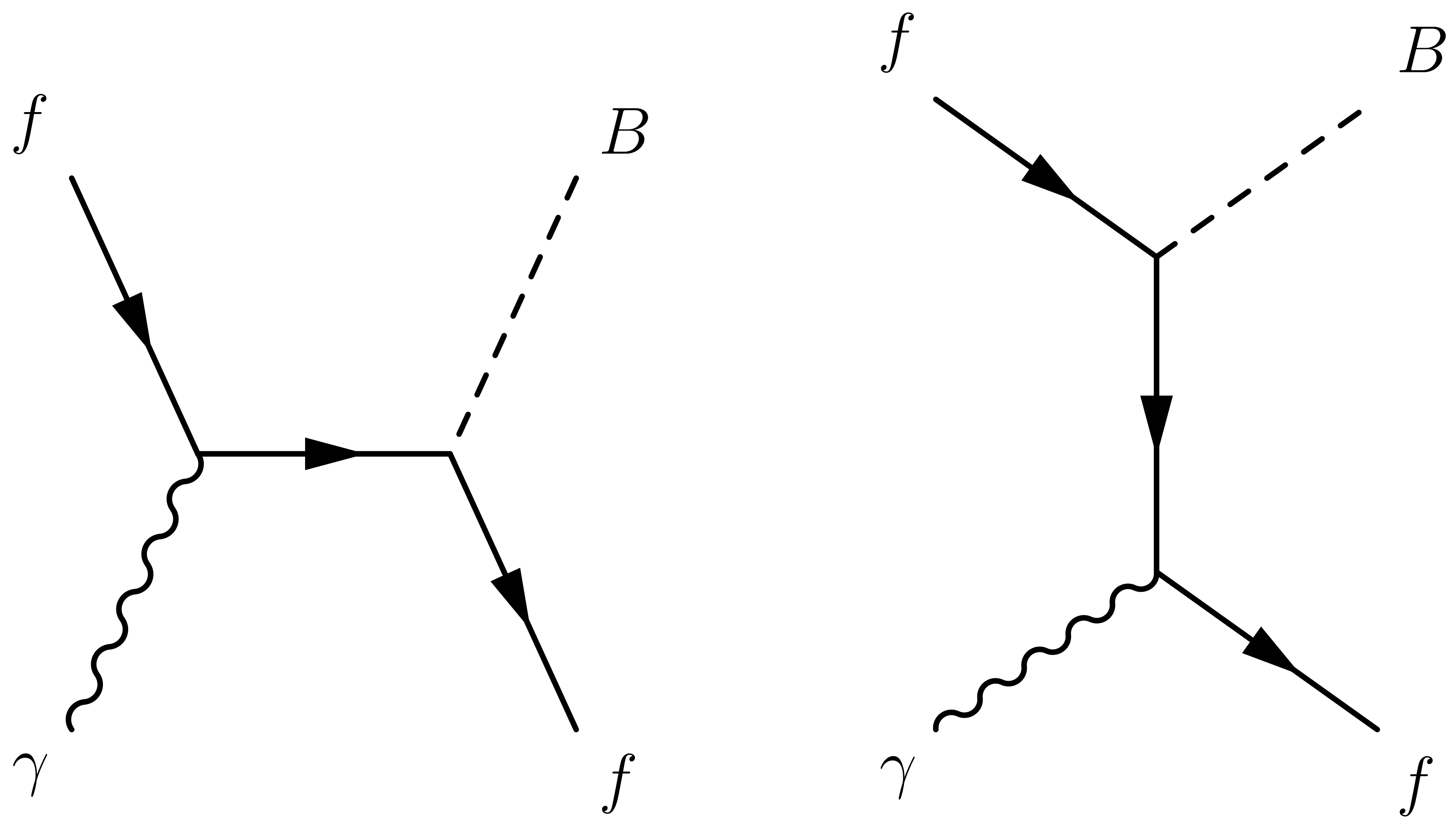
$$\dot{n}_B + 3Hn_B \approx \bar{n}_1\bar{n}_2\langle\sigma v\rangle$$

Coalescence



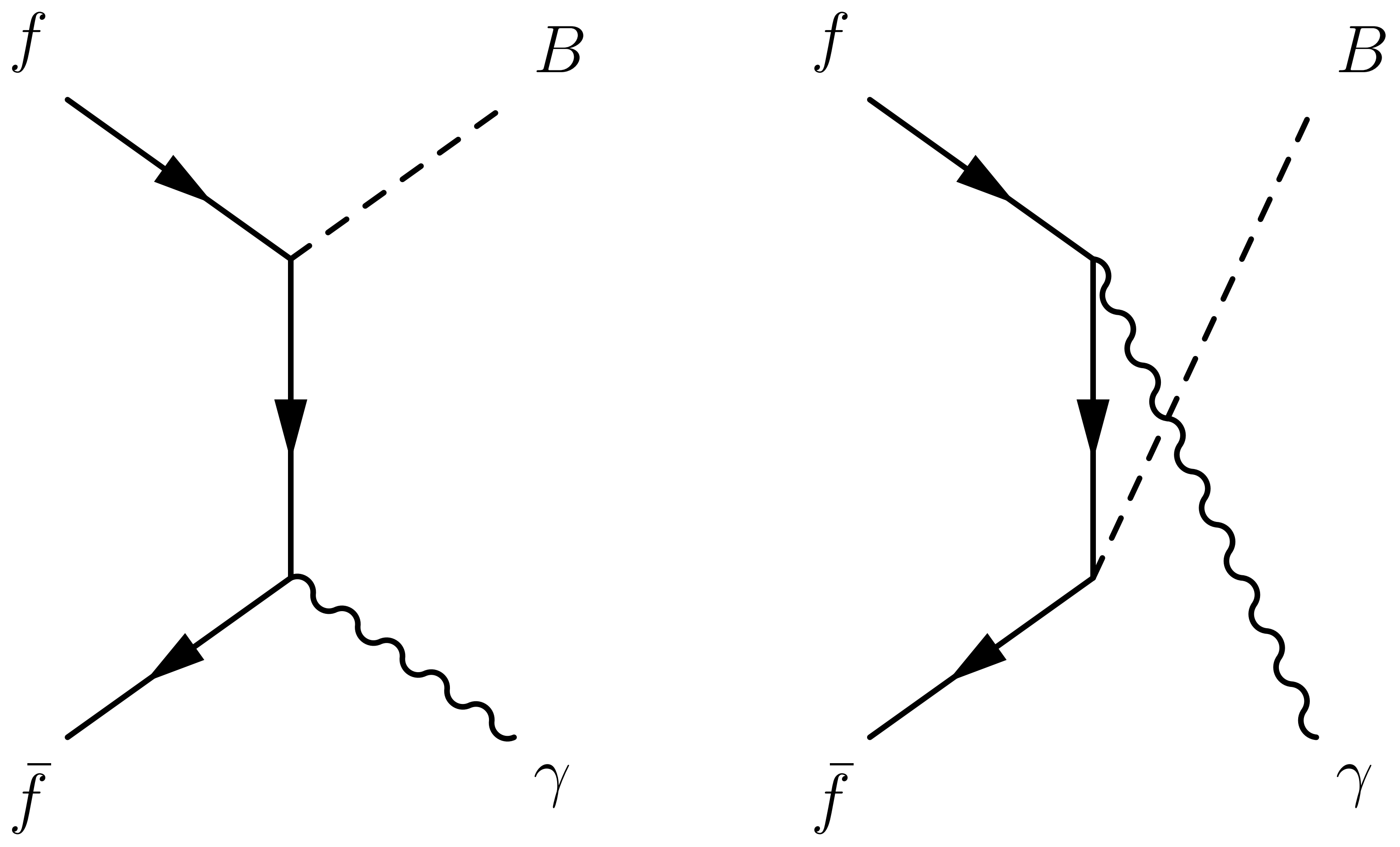
$f\bar{f} \to B$

Compton



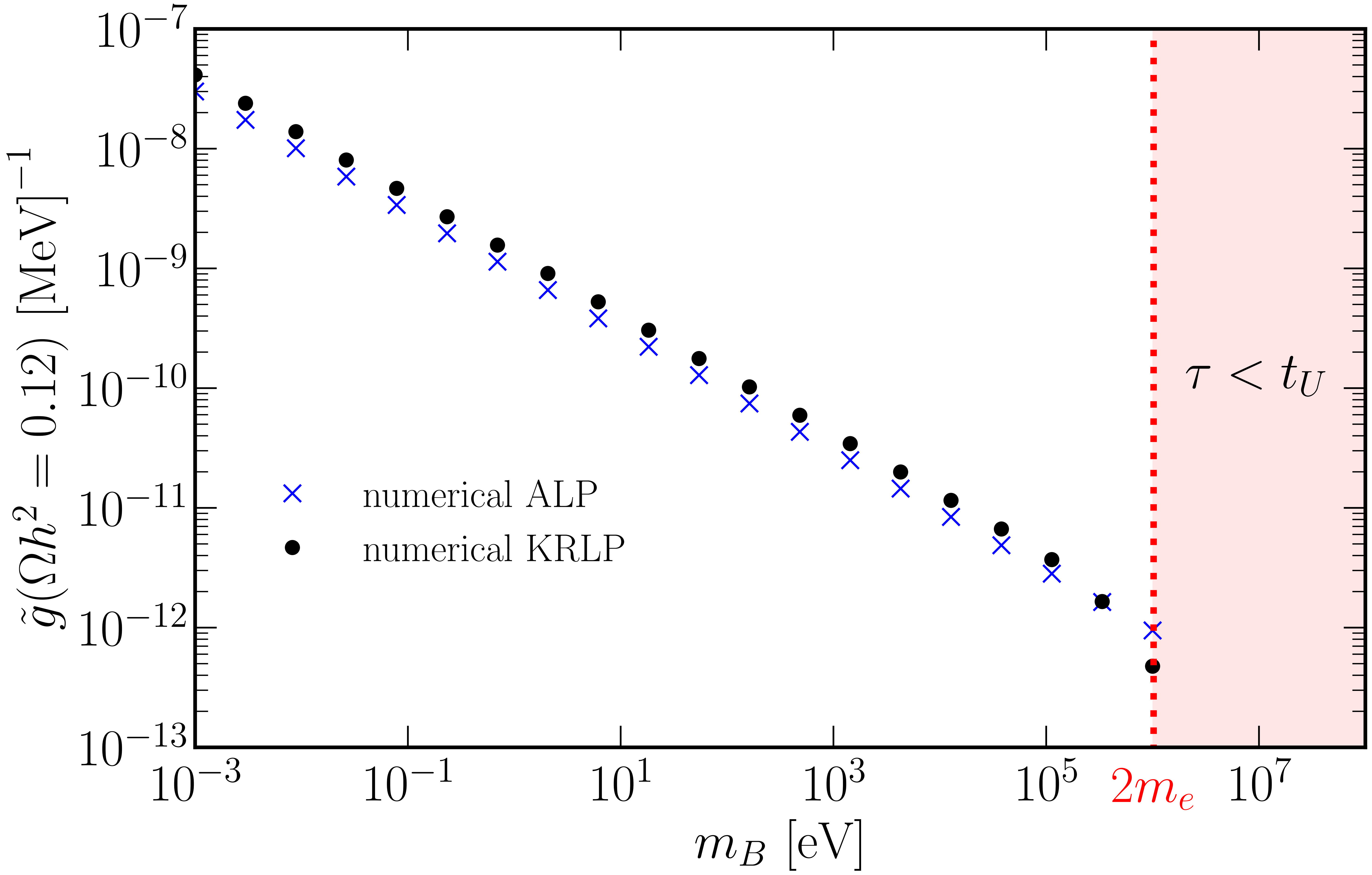
$\gamma f \to \gamma B$

Annihilation



$ff \to \gamma B$

Freeze-in: Axion-like Portal



KRLP

$$\mathcal{L}_{int} = \tilde{g}\tilde{H}_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$$

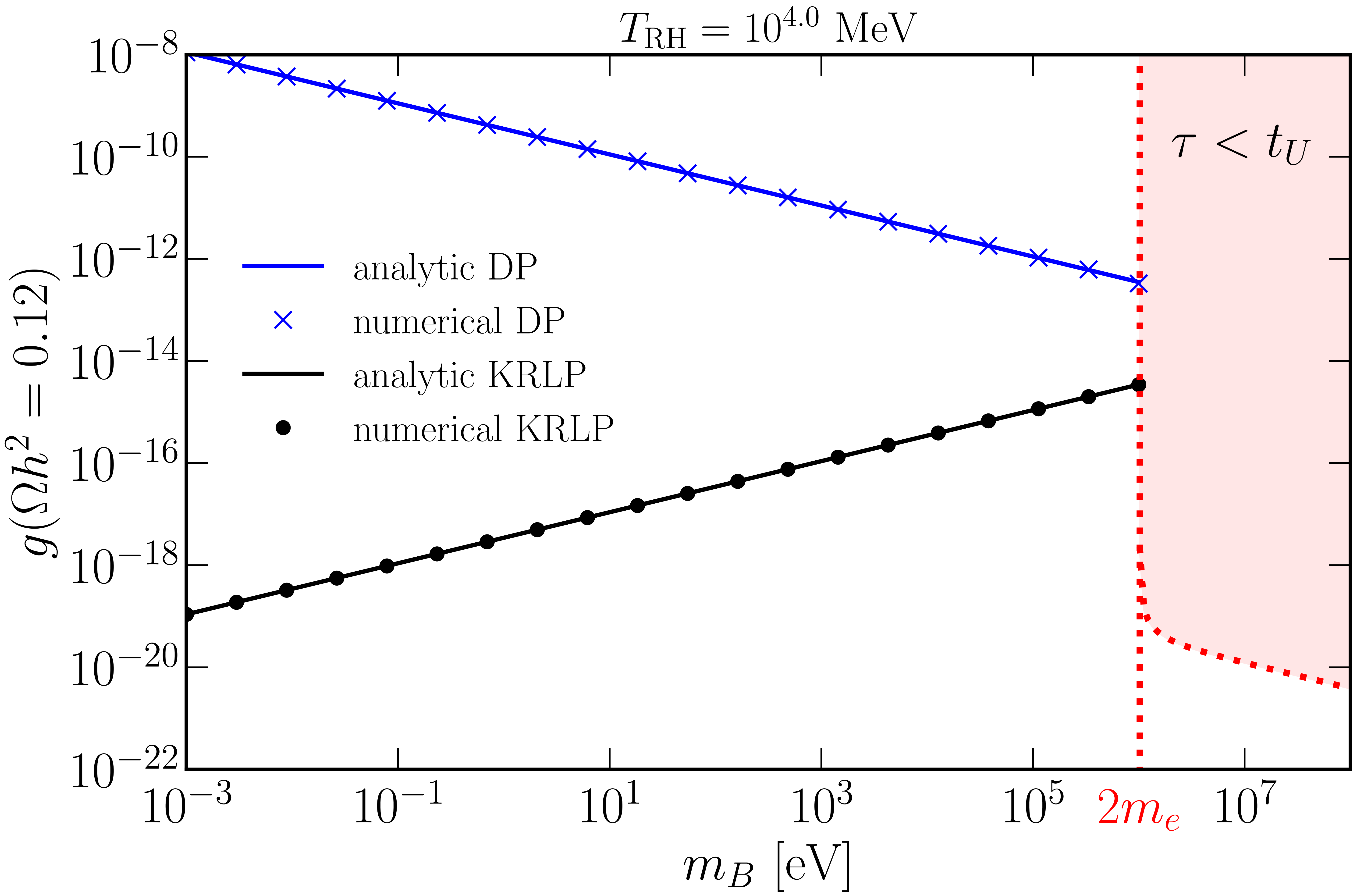
Axion (Langhoff et al., 2022)

$$\mathcal{L}_{int} = \tilde{g}\partial_\mu \theta \bar{\psi}\gamma^\mu\gamma^5\psi$$

- Scales like $\sim m_f^{1/2}$
- Independent of T_{RH}

C. Capanelli, LJ, E. Kolb, E. McDonough

Freeze-in: Dark-Photon-like portal



KRLP

$$\mathscr{L}_{int} = gB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$$

- Independent of m_f
- Scales like ~$T_{RH}^{1/2}$

Dark Photon Redondo & Postma, 2008)

$$\mathscr{L}_{int} = gA_{\mu}\bar{\psi}\gamma^{\mu}\psi$$

- Scales like $\sim m_f^{1/2}$
- Independent of T_{RH}

Capanelli, LJ, Kolb, McDonough 2023

Cosmological Gravitational Particle Production

- Expansion of universe → particle production

(e.g. Schrodinger, 1939; Parker 1965; Kuzmin & Tkachev, 1998; Chung, Kolb & Riotto, 1998)

$$n_k = \frac{k^3}{2\pi^2} |\beta_k|^2$$

$$na^3 = \int \frac{dk}{k} n_k$$

- DM production for a wide range of masses & spins

(e.g. Chung, Kolb & Riotto, 1998+
Graham, Mardon & Rajendran, 2015
Kolb & Long, 2018
Alexander, LJ & McDonough, 2020
Kolb, Ling, Long & Rosen, 2022)

CGPP of Spin-1 Fields

- CGPP Studied in detail for spin-1 fields

(e.g. Graham, Mardon & Rajendran, 2015; Kolb & Long, 2018)

Recall:

$$S = \frac{1}{12}\int d^4x\sqrt{-g}\left(H_{\mu\nu\rho}H^{\mu\nu\rho} - 3m^2 B_{\mu\nu}B^{\mu\nu}\right)$$

$$\downarrow$$

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu\right)$$

GPP of minimally coupled KRLPs identical to Proca

CGPP of KRLPs

Add non minimal couplings?

Proca (Kolb & Long, 2018)

$$\xi_1 R A_\mu A^\mu$$

$$\xi_2 R^{\mu\nu} A_\mu A_\nu$$

↓

$$m^2_{eff,t} = m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2$$

$$m^2_{eff,x} = m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2$$

KRLP

$$\xi_3 R B^{\mu\nu} B_{\mu\nu}$$

$$\xi_4 R^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}$$

↓

$$m^2_{eff,t} = m^2 - \frac{2}{3}\xi_3 R - \frac{2}{9}\xi_4 R - \frac{4}{3}\xi_4 H^2$$

$$m^2_{eff,x} = m^2 - \frac{2}{3}\xi_3 R - \frac{2}{27}\xi_4 R + \frac{4}{3}\xi_4 H^2$$

CGPP of KRLPs

Add non minimal couplings?

Redefine:

$$\xi_3 \to \frac{3}{2}\xi_1$$

$$\xi_4 \to \frac{9}{4}\xi_2$$

⟶ Effective masses are the same (on FRW)

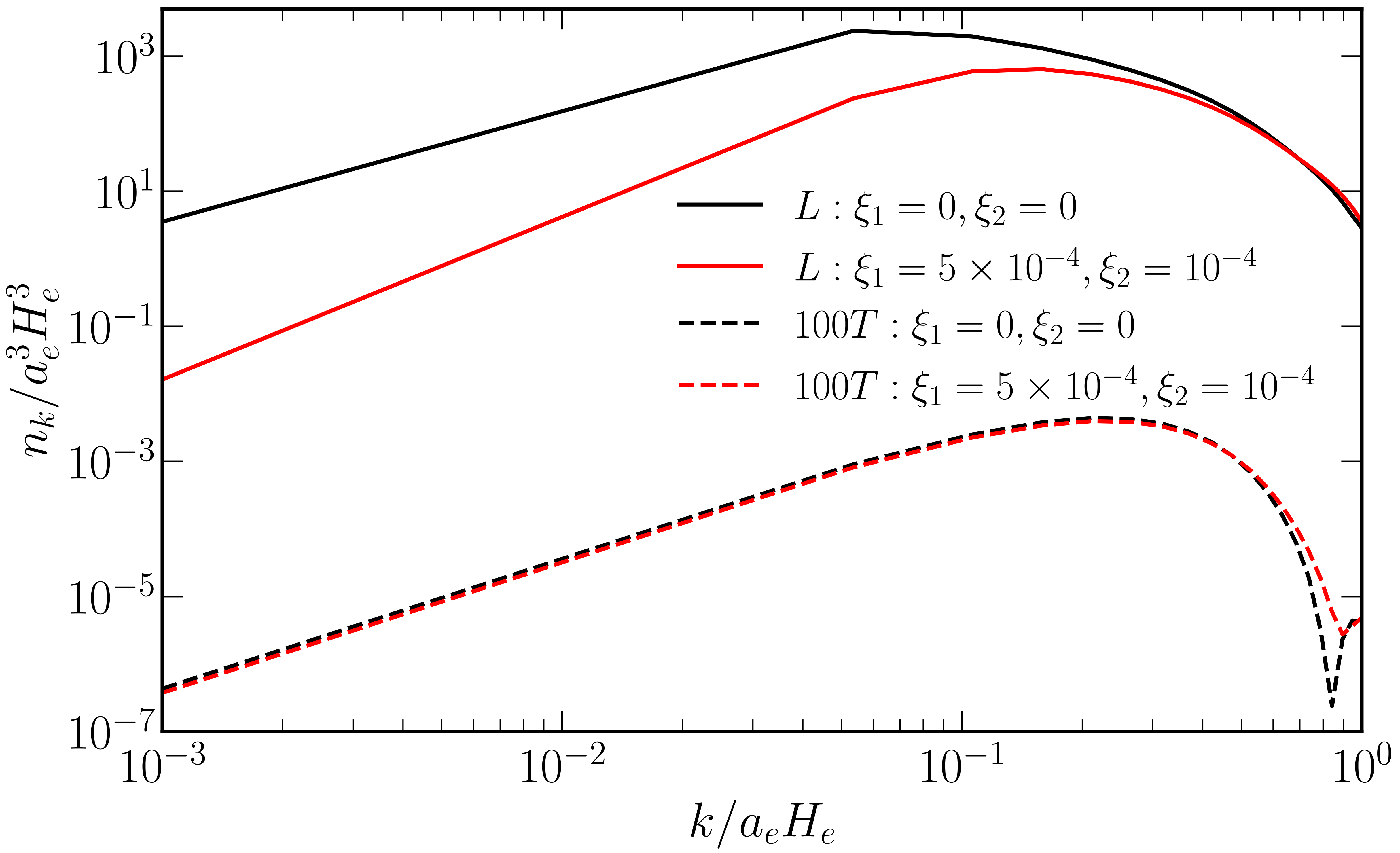
We get GPP of non minimally coupled KRLPs from non minimally coupled spin-1

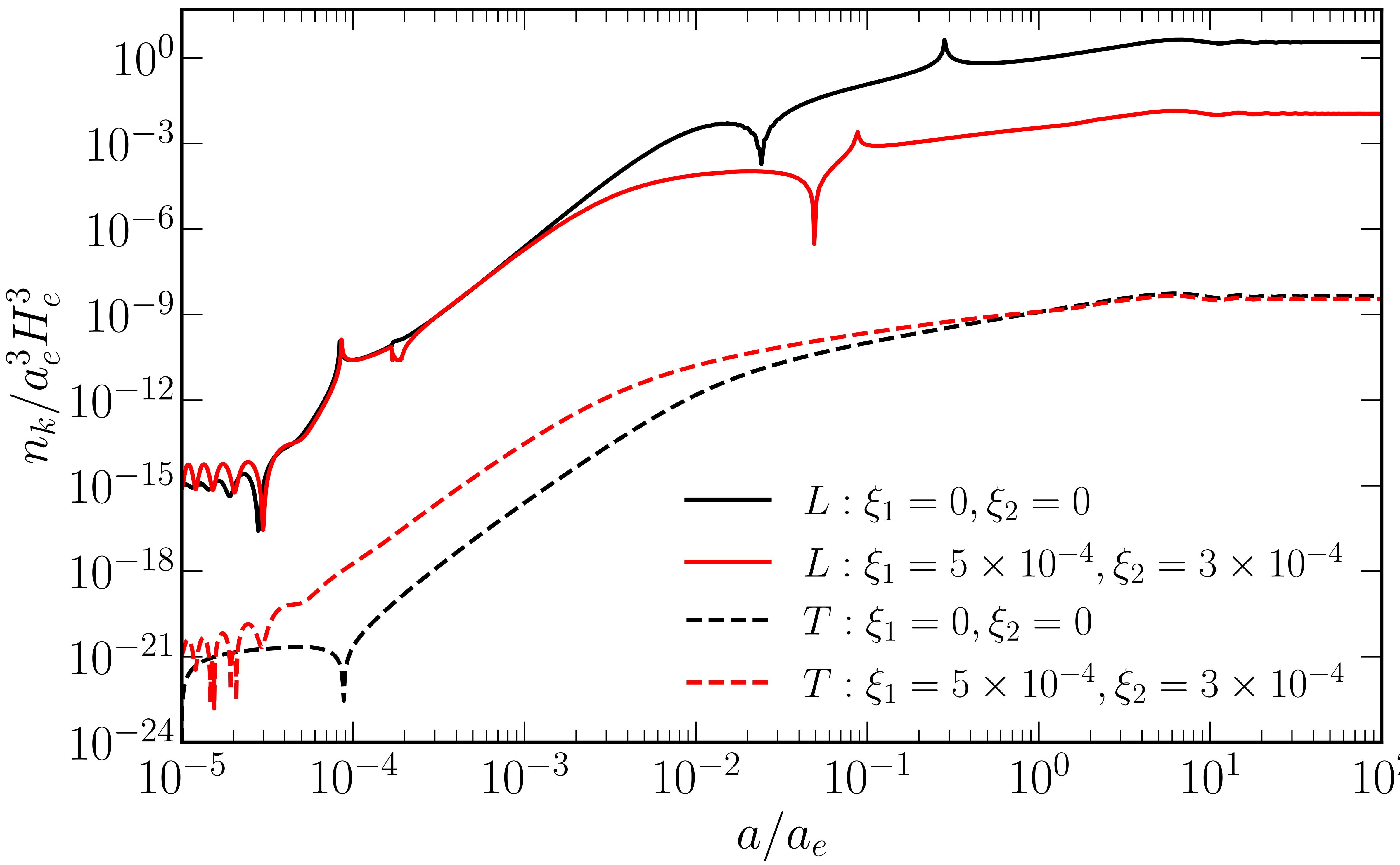
Capanelli, LJ, Kolb, McDonough in prep

See also: Ozsoy & Tasinato, 2023, Cembranos et al., 2023

Cosmological Gravitational Particle Production

Compare: minimal and non-minimal coupling





Full parameter space in progress

Capanelli, LJ, Kolb, McDonough, 2023
Capanelli, LJ, Kolb, McDonough, in prep

Future Directions

- Experimental prospects: dark photon and axion experiments (Belle-II, DarkLight)

- Couplings to cosmic strings

(e.g. Vilenkin & Vachaspati, 1987)

- Cosmological collider signaturess

(e.g. Chen & Wang, 2010; Arkani-Hamed & Maldecena, 2015; Lee et al., 2016)

- Terrestrial collider signatures

- Primordial gravitational waves

- & much more!

Summary & Conclusions

- KRLPs are a well-motivated particle which share properties with axions and dark photons
- As a dark matter candidate, KRLPs can account for the relic density of dark matter
- Production possible via freeze-in and CGPP
- Much more to be done!

Thank you!

Extra Slides

CGPP of KRLPs

Add non minimal couplings?

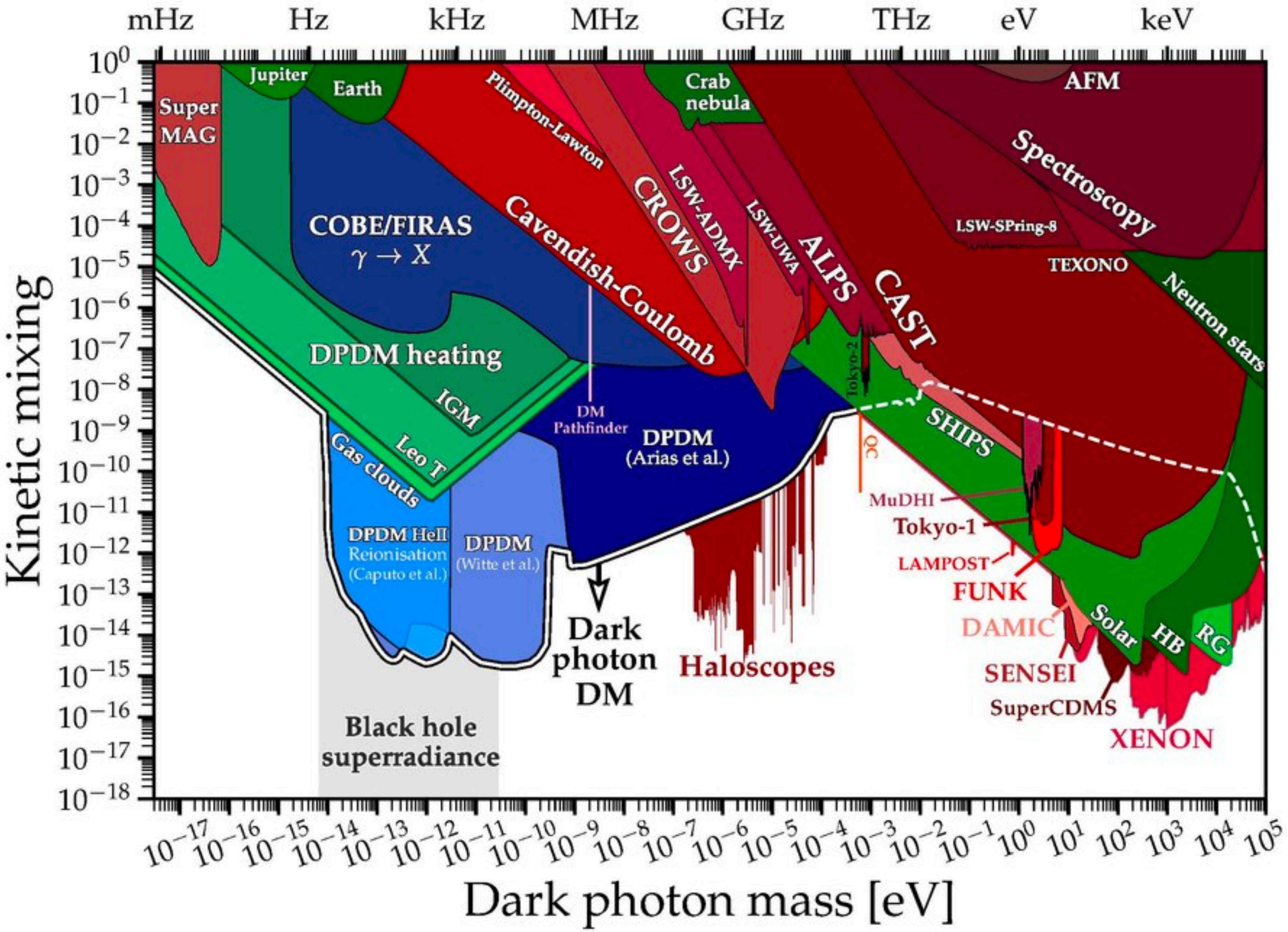
$$S = \frac{1}{12}\int d^4x\sqrt{-g}\left(H_{\mu\nu\rho}H^{\mu\nu\rho} - 3m^2 B_{\mu\nu}B^{\mu\nu} - \xi_1 R B^{\mu\nu}B_{\mu\nu} - \xi_2 R^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma}\right)$$

Dualize

↓

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu - \frac{1}{2}\xi_1 R A_\mu A^\mu - \frac{1}{2}\xi_2 R^{\mu\nu}A_\mu A_\nu\right)$$

GPP of nonminimally coupled KRLPs identical to Proca!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Earth
Plimpton-Lawton
Crab nebula
AFM
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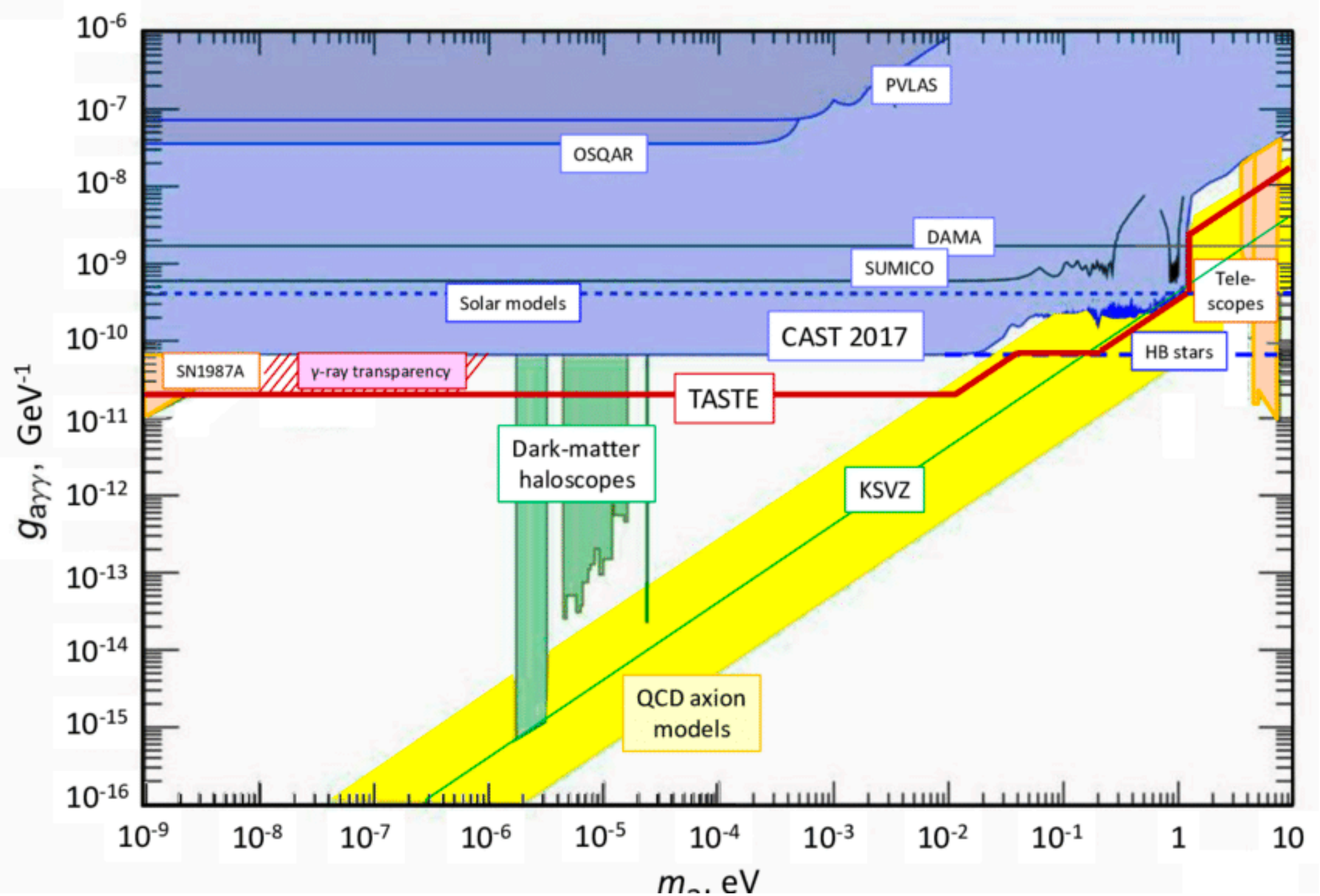
$\gamma \to X$
Cavendish-Coulomb
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
LSW-SPring-8
TEXONO
Neutron stars
DPDM heating
IGM
Leo T
Gas clouds
DM Pathfinder
DPDM (Arias et al.)
Tokyo-2
SHIPS
QC
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
XENON
Solar
HB
RG
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
Black hole superradiance
Kinetic mixing
Dark photon mass [eV]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