# On Gravitational Portal to Dark QED

**Simon Cléry, TUM**

Paris-Saclay Astroparticle Symposium 2026

***Based on***

- *On the gravitational portal to Dark QED,* SC, Kachanovich, Tytgat, **2611.XXXXX**

***See also***

- *Asymmetric Reheating of Dark QED,* SC, Kimus, Tytgat, **2605.09686**
- *Gravitational portals in the early Universe,* SC, Mambrini, Olive, Verner, **2112.15214**

Technische Universität München

UNTERSTÜTZT VON / SUPPORTED BY
Alexander von HUMBOLDT STIFTUNG

# Hidden Sector Dark Matter and Reheating

DM may live in a **Hidden Sector (HS)** with feeble couplings to the SM or even **completely secluded**

➜ **Dark QED** as a HS model:

**Dark electron χ + Dark photon γ′** with $\mathbf{m_{\gamma'} \ll m_\chi \ll m_\phi}$

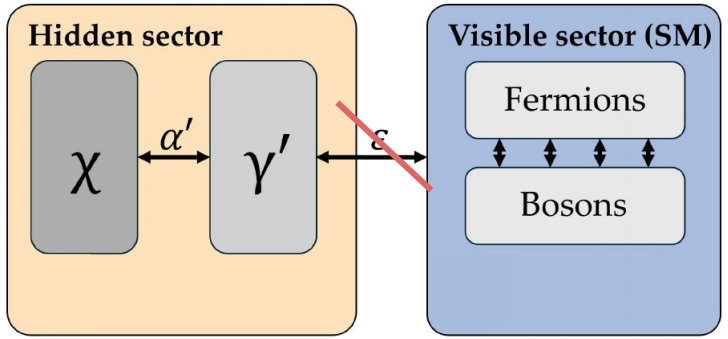
$$\mathcal{L} \supset \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu},\ D_\mu = \partial_\mu - ie'A'_\mu$$

If the portal $\boldsymbol{\varepsilon \to 0}$, **how is the HS populated at all?**

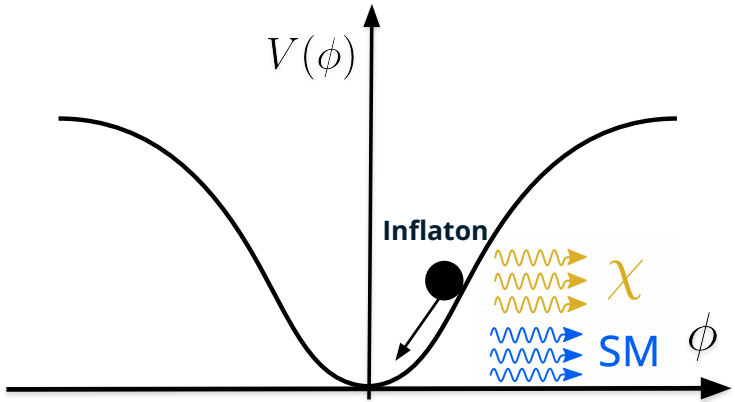
➜ **Reheating**: cold inflaton condensate has to populate both the visible sector and the HS

➜ **Gravity couples to everything**: irreducible HS production together with SM

*This talk:* **minimal gravitational production** of a dark fermion **charged** under a **dark U(1)′** and why quantum effects matter




SC, Kimus, Tytgat, **2605.09686**



# Gravitational portals after inflation

**Minimal gravitational interactions** sets a **minimal, irreducible abundance** of cosmological relics

After inflation: the inflaton condensate **oscillates coherently**

$$V(\phi) \simeq \tfrac{1}{2} m_\phi^2 \phi^2, \qquad \rho_\phi \propto a^{-3}$$

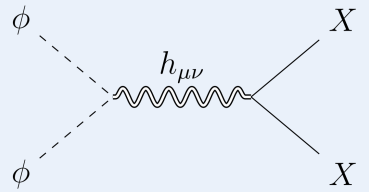
Inflaton quanta at rest annihilate through **s-channel graviton exchange**

$$\sqrt{-g}\,\mathcal{L} \supset -\frac{1}{M_P}\, h_{\mu\nu}\left(T^{\mu\nu}_\phi + T^{\mu\nu}_\chi + T^{\mu\nu}_{\gamma'}\right) \qquad g_{\mu\nu} \simeq \eta_{\mu\nu} + 2h_{\mu\nu}/M_P$$

➜ Rate set by the squared energy density: $R \sim \dfrac{\rho_\phi^2}{M_P^4}$ $\quad R_{\rm bath}(T) \sim \dfrac{T^8}{M_P^4}$

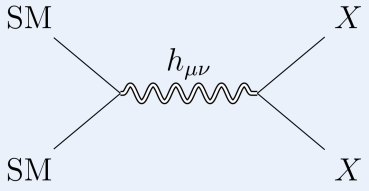
➜ **UV "freeze-in"**: production dominated by the earliest stages of reheating

**Inflaton condensate**




$m_\phi \simeq 3 \times 10^{13}\,\mathrm{GeV}\,,\ R \propto \rho_\phi^2$

**Thermal bath (during reheating)**




requires large $T_{RH}$ $\quad \Omega \propto m_X T_{\rm RH}^3$

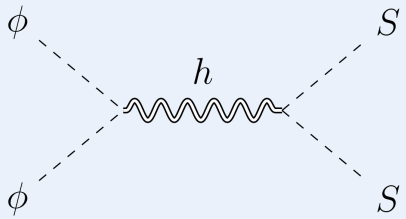
Bernal, Dutra, Mambrini, Olive, Peloso, Pierre **1803.01866** · Mambrini, Olive, **2102.06214** · SC, Mambrini, Olive, Verner, **2112.15214** · Kolb, Long, **2312.09042**

# Inflaton condensate only sees the trace

Homogeneous **inflaton condensate at rest** (s-wave) **couples only to the trace of stress-energy tensor**

$$\frac{1}{M_P^2} T^{\phi}_{\mu\nu} \Pi^{\mu\nu\rho\sigma} T^{X}_{\rho\sigma} \overset{P=(m_\phi,\vec{0})}{\longrightarrow} (2P^\mu P^\nu + m_\phi^2 \eta^{\mu\nu}) T^{X}_{\mu\nu} \overset{P^\mu T^X_{\mu\nu}=0}{\longrightarrow} \frac{1}{M_P^2} \langle f | T^{X\mu}{}_{\mu} | 0 \rangle$$

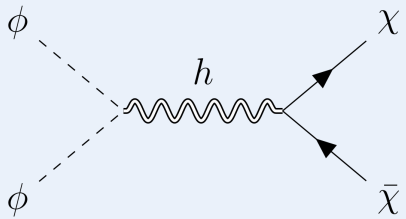
**Scalar S**




$T^{\mu}{}_{\mu} \neq 0$

**unsuppressed**

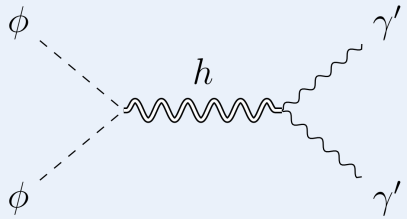
**Dirac fermion χ**




$T^{\mu}{}_{\mu} \propto m_\chi \bar{\chi} \chi$

**suppressed** $\propto m_\chi^2 / m_\phi^2$

**Gauge boson γ′**




**classically** conformal

**vanishes for** $m_{\gamma'} = 0$

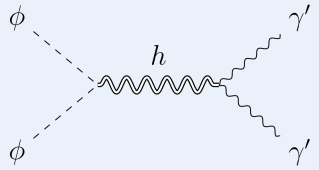
➜ **Conformal fields decouple**: massless χ and γ′ are **classically** not produced

$$\text{FLRW: } g_{\mu\nu} \to e^{2\Omega} g_{\mu\nu} : \quad \delta S = \int d^4x \sqrt{-g}\, T^{\mu}_{\mu}\, \delta\Omega$$

# Gravitational production of Dark Photons

What about the **gravitational production** of the (effectively massless) **dark photon** ?

## Transverse polarizations




$$i\mathcal{M}^{01}_{\text{s-wave}} = -i\,\frac{m^2_{\gamma'}}{2M_P^2}\,\epsilon_1^*\cdot\epsilon_2^* \xrightarrow{m_{\gamma'}\to 0} 0$$

Maxwell action conformal $T^{\mu}{}_{\mu} = 0$

**No production from the condensate**

## Massive γ′: longitudinal mode

$$\epsilon^{\mu}_L \simeq \frac{k^{\mu}}{m_{\gamma'}} \;\Rightarrow\; m^2_{\gamma'}\,\epsilon_L\cdot\epsilon_L \sim m^2_{\phi}$$

$$|\mathcal{M}^{01}_{\text{s-wave}}|^2_{\text{Proca}} = \frac{3m^4_{\gamma'} - 4m^2_{\gamma'}m^2_{\phi} + 4m^4_{\phi}}{16M_P^4} \xrightarrow{m_{\gamma'}\to 0} \frac{m^4_{\phi}}{4M_P^4} \neq 0$$

**Longitudinal mode $\gamma'_L$** ≈ one (Goldstone) scalar d.o.f.
**unsuppressed, finite as $m_{\gamma'} \to 0$**

Garcia, Kaneta, Ke, Mambrini, Olive, Verner, **2311.14794** · Kolb, Long, **2009.03828**

➜ **Effectively massless γ′** ($m_{\gamma'} \ll m_{\phi}$): **no gravitational production of transverse modes**

➜ No continuous massless limit: **$\gamma'_L$ produced like a (massless) scalar**

# Gravitational production of fermionic Dark Matter

$$R^{\chi}_{\rm min} = \frac{\rho_\phi^2}{128\pi M_P^4}\,\frac{m_\chi^2}{m_\phi^2}\left(1-\frac{m_\chi^2}{m_\phi^2}\right)^{3/2}$$

$$R^{\chi}_{\rm min} \propto \frac{m_\chi^2}{m_\phi^2} \xrightarrow{m_\chi \to 0} 0$$

SC, Mambrini, Olive, Verner, **2112.15214**

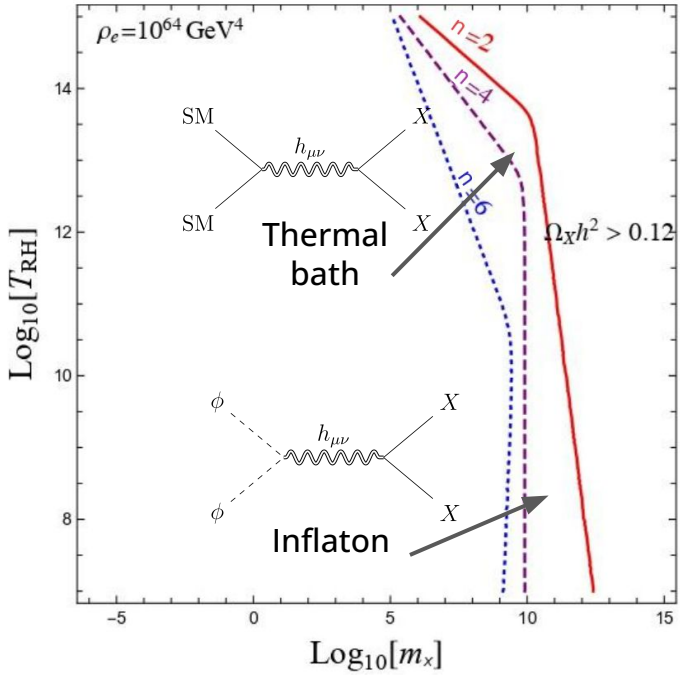
➜ Inflaton to $\chi\bar{\chi}$ pair requires a **chirality flip**

➜ Light fermions are **not produced** gravitationally from the condensate

➜ To get the observed relic DM must be **super heavy**

$$\Omega_\chi h^2 \simeq 0.12 \;\Rightarrow\; m_\chi \gtrsim 10^{10}\,\text{GeV}$$

**or** produced at **very high temperatures** during reheating

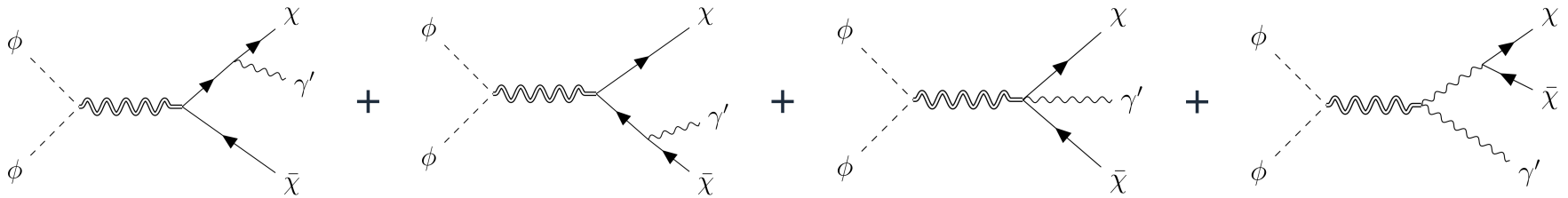



$\Omega_X h^2 = 0.12$ in the case of a **spin ½ DM**

What if χ is **charged** under a dark U(1)′ ? Can the gauge interaction lift the suppression?

# Bremsstrahlung does not help

Could **bremsstrahlung** of dark photon **lift helicity suppression**, as in DM annihilation ?




**Soft part**: photon emission factorizes $\mathcal{M}_{\rm soft} = -ie' \left( \frac{p_3 \cdot \epsilon^*}{p_3 \cdot k} - \frac{p_4 \cdot \epsilon^*}{p_4 \cdot k} \right) \mathcal{M}^{1/2}_{\text{s-wave}}, \qquad \mathcal{M}^{1/2}_{\text{s-wave}} \propto m_\chi$

**Hard part**: **4th amplitude is traceless** for massless photon and **remaining gauge invariant sum** $\propto \mathcal{O}(m_\chi)$

Full gauge-invariant amplitude: conserved $T_{\mu\nu}$ + condensate source ➜ **projected onto the trace**

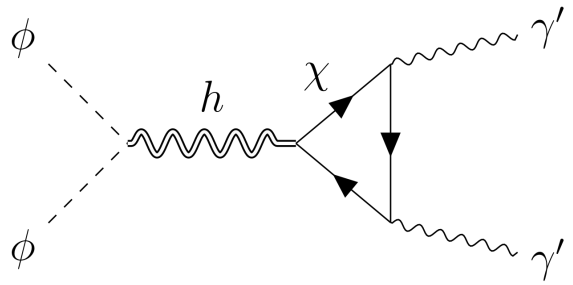
$$P_\mu T^{\mu\nu}_{\rm DQED} = 0 \;\Rightarrow\; \mathcal{M} \propto (2P^\mu P^\nu + m_\phi^2 \eta^{\mu\nu}) T^{\mu\nu}_{\rm DQED} \propto T^\mu_{\ \mu} \qquad \sum_{i=1}^{4} \mathcal{M}_i \xrightarrow{m_\chi, m_{\gamma'} \to 0} 0$$

➜ Tree-level stress tensor of **dark QED is traceless in the massless limit** : classical **conformal invariance survives the gauge interaction ⇒ no gravitational production** from the condensate
➜ We need a **breaking of conformal invariance:** trace of stress energy tensor

# Trace anomaly

Classical conformal invariance is **broken by quantum effects**: running coupling of the dark U(1)′

$$T^{\mu}_{\ \mu} \supset \frac{\beta(e')}{2e'} F'_{\rho\sigma} F'^{\rho\sigma}, \qquad \beta(e') = \frac{e'^3}{12\pi^2}$$




Gravity couples to the **anomaly ➜** massless **dark photons**

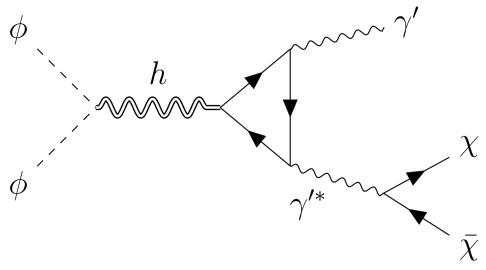
$$\mathcal{M}^{01}_{\rm TA} = -i \frac{\beta(e')}{e'} \frac{m_\phi^2}{M_P^2} \epsilon_1^* \cdot \epsilon_2^*, \qquad \sum_{\rm pol} |\mathcal{M}^{01}_{\rm TA}|^2 = \frac{e'^4 m_\phi^4}{72\pi^4 M_P^4}$$

$$R_{\gamma'\gamma'} = \frac{e'^4 \rho_\phi^2}{9216\,\pi^5 M_P^4} = \frac{e'^4}{1024\,\pi^5} H^4$$

**Gravity + trace anomaly ➜ massless dark photons** (cf. analogy with the chiral anomaly in $\pi^0 \to \gamma\gamma$)

Adler, Collins, Duncan, **PRD (1977)** · Collins, Duncan, Joglekar, **PRD (1977)** · Dolgov, **Sov. Phys. JETP (1981)** · Giannotti, Mottola, **0812.0351** ·

# Gravitational Dalitz process




One off-shell **dark photon can convert into a χχ̄ pair**:

**ϕϕ → h* → γ′γ′* → γ′χχ̄**

analogue of the **Dalitz decay** $\pi^0 \to \gamma\, e^+e^-$

Dalitz (1951) · Kroll and Wada (1955) · Landsberg (1985)

$$i\mathcal{M}_{\rm D} = i\,\frac{\beta(e')}{2M_P^2}\,\frac{1}{q^2}\left(q\cdot k\,\eta^{\alpha\beta} - q^\beta k^\alpha\right)\epsilon^*_\beta(k)\,\bar{u}(p_3)\gamma_\alpha v(p_4) \;\propto\; e'^3$$

The 3-body rate factorizes: **anomalous γ′γ′ production × conversion probability**

$$\frac{dI_D}{dz} = I_{\gamma'\gamma'} \times \underbrace{\frac{2\alpha'}{3\pi}\,\frac{(1-z)^3}{z}\left(1+\frac{r^2}{2z}\right)\sqrt{1-\frac{r^2}{z}}}_{\text{internal conversion } \gamma'^*\to\chi\bar{\chi}}, \qquad \alpha' = \frac{e'^2}{4\pi} \qquad z = \frac{q^2}{s}, \quad r = \frac{m_\chi}{m_\phi}, \quad r^2 \le z \le 1, \qquad s = 4m_\phi^2$$

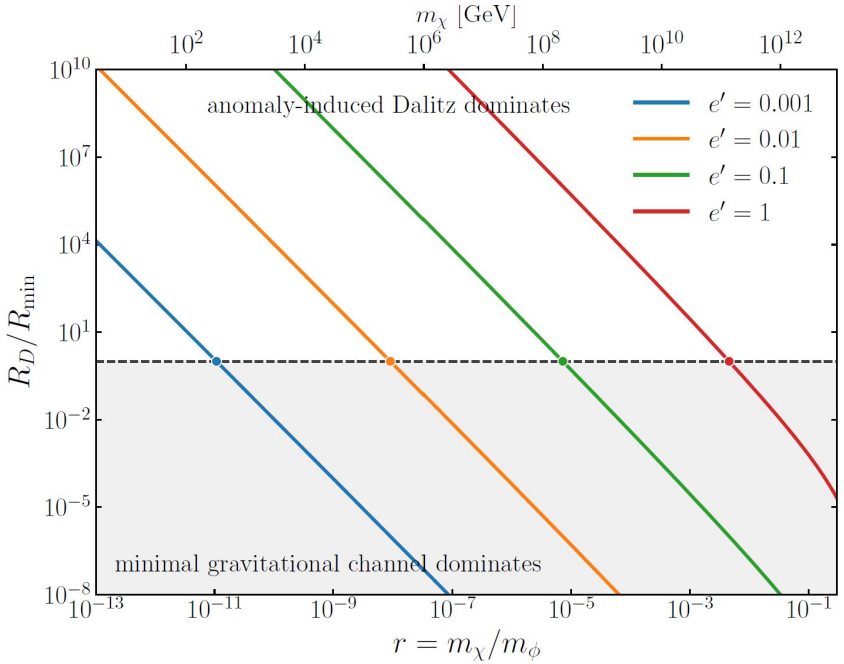
➜ Loop suppressed but $m_\chi$ only enters through $\log(4m_\phi^2/m_\chi^2)$, from quasi-collinear χχ̄ pairs (small $q^2$)

# When does the anomaly dominate fermion production ?

Production rate of $\chi\bar{\chi}$ from the inflaton via Dalitz

$$R_{\rm D} \simeq \frac{e'^6\,\rho_\phi^2}{55296\,\pi^7 M_P^4}\left[\log\frac{4m_\phi^2}{m_\chi^2} - \frac{7}{2}\right]$$

Compared with the minimal gravitational portal:




**Critical mass** ($R_D > R_{min}$) :

| e′ | $r_{crit}$ | $m_\chi$ [GeV] |
|---|---|---|
| 0.001 | $10^{-11}$ | $10^2$ |
| 0.1 | $10^{-5}$ | $10^8$ |
| 1.0 | $10^{-2}$ | $10^{11}$ |

➜ Despite loop suppression **anomaly dominates** for **lower $m_\chi$**

➜ In the **mass range where the minimal gravitational channel can fail** to give the **DM abundance**

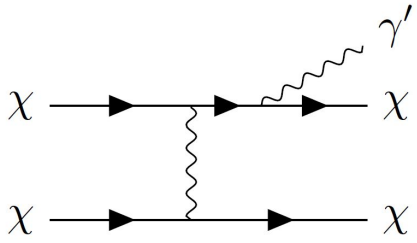
# Thermalization of the Hidden Sector

Non-thermal production requires the dark sector to **stay out of equilibrium**

Abelian plasma: **thermalization** via **LPM-suppressed splittings**

$$t_{\rm th} \sim \frac{1}{\alpha'^2 m_\phi} \left( \frac{m_\phi^3}{n_\chi} \right)^{1/2}$$

SC, Kimus, Tytgat, **2605.09686**




Here: **hard populations** injected by the condensate $E_i = m_\phi$

$$\Gamma_{\rm th} \simeq \alpha'^2 \left[ \sum_i \frac{n_i}{E_i} \right]^{1/2}$$

Momenta of condensate products **redshift** after production:

$$E_i(a_{\rm RH}) \simeq m_\phi \left( \frac{H_{\rm RH}}{H_{\rm end}} \right)^{2/3}$$

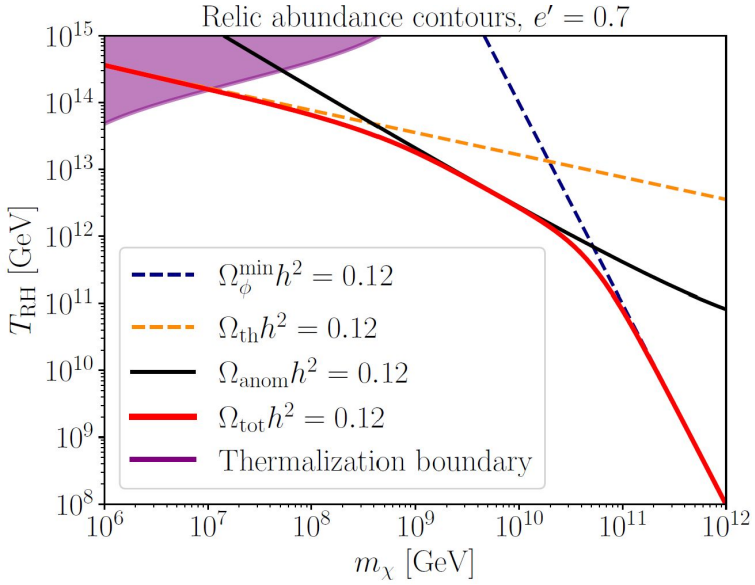
**Fast splittings** before χ becomes non-relativistic:

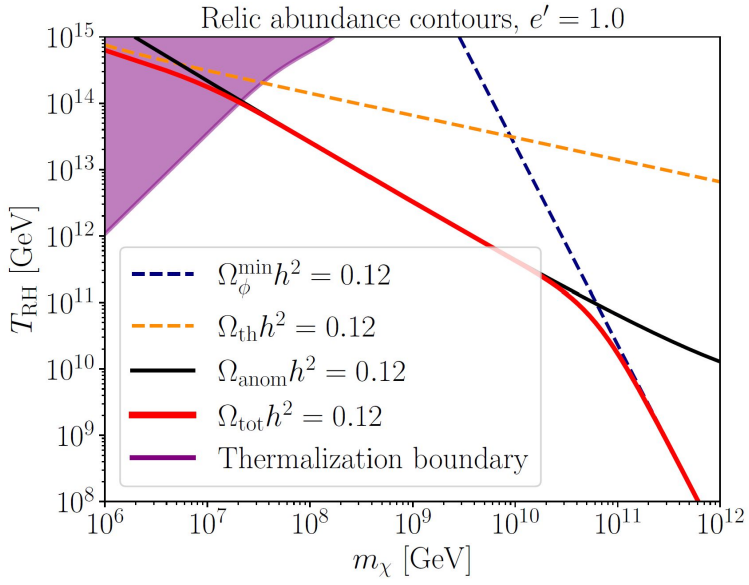
$$\frac{\Gamma_{\rm th}}{H_{\rm RH}} \gtrsim \frac{m_\chi}{E_i}$$

➜ **Dark sector thermalized**

# DM relic abundance

$$\Omega_\chi^{\rm D} h^2 \;\propto\; e'^6\, m_\chi\, T_{\rm RH}\sqrt{\rho_{\rm end}}\left[2\log\frac{4m_\phi^2}{m_\chi^2}-7\right] \qquad \Omega_\chi^{\rm tot} h^2 = \Omega_\chi^{\rm D} h^2 + \Omega_\chi^{\rm min} h^2 + \Omega_\chi^{\rm bath} h^2$$




➜ **Large e′, lighter χ: anomaly dominates** and gives $\Omega_\chi h^2 \simeq 0.12$ possibly down to $m_\chi \sim 10^7$ **GeV**

# Summary

**Homogeneous condensate**

Sees only $T^{\mu}{}_{\mu}$

→

**Trace of stress-energy**

$T^{\mu}{}_{\mu} = m_{\chi}\,\bar{\chi}\chi$
mass-suppressed

→

**Trace anomaly**

$(\beta/2e')\,F'F'$
➜ Dark radiation $\gamma'\gamma'$

→

**Dalitz conversion**

$\gamma'^{*} \to \chi\bar{\chi}$ : Fermionic DM without mass suppression

- Loop suppressed $O(e'^{6})$ yet **dominates for** $m_{\chi} \lesssim 10^{10}$–$10^{11}$ GeV for $e' \sim 0.5 - 1$
- $\Omega_{\chi}h^{2} \simeq 0.12$ with $\chi$ **lighter** than minimal gravitational DM at the same $T_{RH}$ (still large $T_{RH}$ required)
- $\gamma'$ abundant but **negligible dark radiation**; rate matches earlier results using Bogoliubov approach

➜ Gravitational production of an **interacting** hidden sector can be **dominated by trace anomaly**

**Outlook:** Steep potential · Massive dark photons and late time decays

# Summary

**Homogeneous condensate**
Sees only $T^{\mu}{}_{\mu}$

→

**Trace of stress-energy**
$T^{\mu}{}_{\mu} = m_{\chi}\,\bar{\chi}\chi$
mass-suppressed

→

**Trace anomaly**
$(\beta/2e')\,F'F'$
➜ Dark radiation $\gamma'\gamma'$

→

**Dalitz conversion**
$\gamma'^{*} \to \chi\bar{\chi}$ : Fermionic DM without mass suppression

- Loop suppressed $O(e'^{6})$ yet **dominates for** $m_{\chi} \lesssim 10^{10}$–$10^{11}$ GeV for $e' \sim 0.5 - 1$
- $\Omega_{\chi}h^{2} \simeq 0.12$ with $\chi$ **lighter** than minimal gravitational DM at the same $T_{RH}$ (still large $T_{RH}$ required)
- $\gamma'$ abundant but **negligible dark radiation**; rate matches earlier results using Bogoliubov approach

➜ Gravitational production of an **interacting** hidden sector can be **dominated by trace anomaly**

**Outlook:** Steep potential · Massive dark photons and late time decays

# Thank you for your attention !

# Backup

# Mass suppression is an effect of the homogeneous background

Massless final states, **generic kinematics** for the graviton exchange processes:

$$|\bar{\mathcal{M}}^{0\,\frac{1}{2}}|^2 = \frac{\left(s+2t-2m_\phi^2\right)^2\left(2m_\phi^2 t - m_\phi^4 - t(s+t)\right)}{4M_P^4\, s^2} \qquad (m_\chi = 0)$$

$$|\bar{\mathcal{M}}^{01}|^2 = \frac{\left(m_\phi^4 - 2m_\phi^2 t + t(s+t)\right)^2}{2M_P^4\, s^2} \qquad (m_{\gamma'} = 0)$$

$$p_1 = p_2 = (m_\phi, \vec{0}) : \; s = 4m_\phi^2,\; t = -m_\phi^2 \;\Rightarrow\; \text{both vanish}$$

- **Inflaton condensate** (s-wave, isotropic source): only the trace is probed → massless χ, γ′ **not produced**
- **Thermal bath** SM SM → h* → $\chi\bar{\chi}$: no such suppression
- Weyl invariance of the Dirac and Maxwell actions in semi-classical cosmological production from homogeneous and isotropic background (FLRW)

SC, Mambrini, Olive, Verner, **2112.15214**

# Massive dark photons case

Proca / Stueckelberg vector: the **longitudinal mode** behaves like a **scalar** (Goldstone)

$$|\mathcal{M}^{01}_{\text{s-wave}}|^2_{\text{Proca}} = \frac{3m^4_{\gamma'} - 4m^2_{\gamma'}m^2_\phi + 4m^4_\phi}{16M^4_P} \xrightarrow{m_{\gamma'}\to 0} \frac{m^4_\phi}{4M^4_P} \neq 0$$

$$\frac{|\mathcal{M}_{LL}|^2}{\sum_{\text{pol}}|\mathcal{M}^{01}_{\text{TA}}|^2} \simeq \frac{18\pi^4}{e'^4} \sim 10^3\text{–}10^4, \qquad |\mathcal{M}|^2_{\text{Stueck.}} - |\mathcal{M}|^2_\sigma = |\mathcal{M}|^2_{\text{Proca}}$$

Garcia, Kaneta, Ke, Mambrini, Olive, Verner, **2311.14794**

- ✦ $\chi$ couples to the **conserved current** $J^\mu = \bar{u}\,\gamma^\mu\,v$: the $k^\mu/m_{\gamma'}$ part of $\varepsilon_L$ and $q_\mu q_\nu/m^2$ in $\gamma'^*$ drop out
  - ➜ each $\gamma'_L$ leg costs $m_{\gamma'}/E$: $\boldsymbol{\gamma'_L\gamma'_L \to \chi\bar{\chi} \propto (m_{\gamma'}/E)^4}$
- ✦ Free propagation in FLRW **conserves helicity**: $\gamma'_L$ stays longitudinal until non-relativistic

# Dalitz phase space and rate

Two inflaton quanta at rest, $s = 4m_\varphi^2$. Three body phase space for invariant mass of the pair $z = q^2/s$:

$$d\Phi_3 = \frac{m_\phi}{32\pi^3}\, dE_3\, dz, \qquad E_3^\pm = \frac{m_\phi}{2}\left[1 + z \pm (1-z)\sqrt{1 - \frac{r^2}{z}}\right]$$

Differential and two-body results:

$$\frac{dI_D}{dz} = \frac{e'^6 m_\phi^4}{6912\pi^7 M_P^4}\,\frac{(1-z)^3}{z}\left(1 + \frac{r^2}{2z}\right)\sqrt{1 - \frac{r^2}{z}}, \qquad I_{\gamma'\gamma'} = \frac{e'^4 m_\phi^4}{1152\pi^5 M_P^4}$$

Integrated three-body result:

$$I_D = \frac{e'^6 m_\phi^4}{9216\pi^7 M_P^4} J(r), \quad J(r) = \frac{2}{3}\int_{r^2}^1 dz\,(1-z)^3(r^2+2z)\frac{\sqrt{z-r^2}}{z^{5/2}} \simeq \frac{4}{3}\left[\log\frac{4}{r^2} - \frac{7}{2}\right]$$

Production rate from the oscillating condensate ($N_X$ particles per event):

$$R_X = N_X\,\frac{\rho_\phi^2}{16\, m_\phi^4}\int d\Phi\,|\mathcal{M}|^2 \qquad (\text{oscillating condensate},\ \sqrt{s} = 2m_\phi)$$

# Gravity induced kinetic mixing ?

$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$ A gravitational portal **does not by itself imply ε ≠ 0**

### Minimal Dark QED

$$C_D: \; A'_\mu \to -A'_\mu, \;\; \chi \to \chi^c \;\; \Rightarrow \;\; B_{\mu\nu} F'^{\mu\nu} \to -B_{\mu\nu} F'^{\mu\nu}$$

$$\frac{1}{M_P} h_{\mu\nu} \left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{D}\right) \; : \; C_D\text{-even}$$

- Exact **dark charge conjugation** $C_D$
- Kinetic mixing operator is **$C_D$-odd**
- Gravity couples to $T^{\mu\nu}$, **preserves $C_D$**

➜ **ε = 0 is radiatively stable**

### If charge conjugation is broken

- Gravity-induced ε only at **≥ 6 loops**: **$\varepsilon_{\rm grav} \lesssim 10^{-13}$ (Planck scale)**
- Freeze-in through ε needs a millicharge Q = εe′/e **~ $10^{-11}$**

➜ $\Omega/\Omega_{\rm DM} \lesssim$ **$10^{-4}$-$10^{-3}$ negligible**

Gherghetta, Kersten, Olive, Pospelov, **1909.00696**

Chu, Hambye, Tytgat, **1112.0493**

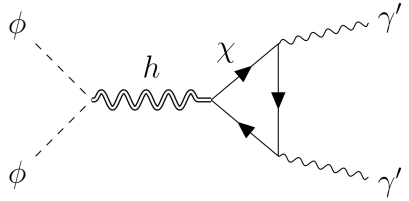
➜ Gravity-only setup **consistent with ε = 0** and even gravity-induced ε is **too small for freeze-in**

# Dark Photons abundance

**Trace anomaly** $\phi\phi \to \gamma'\gamma'$ → **Dark radiation** $\gamma'$ — **Dalitz conversion** $\gamma'^* \to \chi\bar{\chi}$ → **Fermionic massive DM** $\chi$

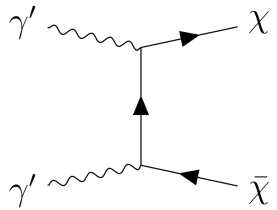
➜ Dark photons **outnumber** the fermions produced through the anomaly

$$n_{\gamma'}(a_{\rm RH}) \simeq \frac{e'^4 \rho_{\rm RH}\sqrt{\rho_{\rm end}}}{4608\sqrt{3}\,\pi^5 M_P^3}, \qquad \frac{R_{\gamma'\gamma'}}{R_{\rm D}} \simeq \frac{6\pi^2}{e'^2 L} \gg 1$$




➜... but carry a **negligible energy density as dark radiation**

$$\frac{\rho_{\gamma'}(a_{\rm RH})}{\rho_{\rm RH}} \simeq \frac{e'^4}{1536\sqrt{3}\pi^5}\frac{m_\phi}{M_P^3}\rho_{\rm end}^{1/6}\rho_{\rm RH}^{1/3} \ll 1$$




➜ **Secondary fermions production** $\gamma'\gamma' \to \chi\bar{\chi}$ is also negligible:

$$\frac{R_{\rm sec}}{R_{\rm D}} \sim \frac{e'^6}{3072\pi^4}\frac{\log(4E_{\gamma'}^2/m_\chi^2)-1}{\log(4m_\phi^2/m_\chi^2)-7/2}\left(\frac{H_{\rm end}}{E_{\gamma'}}\right)^2 \ll 1$$

**Massive γ' :** longitudinal modes produced but strongly suppressed interaction with the conserved fermions current (decoupled from Dalitz)

# Long-range dark force ?

Massless γ′ ➜ **long-range force** between dark matter particles

### Constraints (exactly massless γ′)

- **Hard 2→2 scattering** (halo shapes, clusters):
  $e' \lesssim 4\times10^{-3}\ (m_\chi/\mathrm{GeV})^{3/4}$
  ➜ irrelevant for $m_\chi \gtrsim$ TeV
- **Dark plasma instabilities** (Bullet Cluster):
  $e'/m_\chi \lesssim 2\times10^{-14}\ \mathrm{GeV}^{-1}$
  ➜ $e' \sim 0.5$ would need $m_\chi \gtrsim 10^{13}$ GeV ✗

Lasenby, **2007.00667** · DeRocco, Giffin, **2411.11958**

### A small dark photon mass

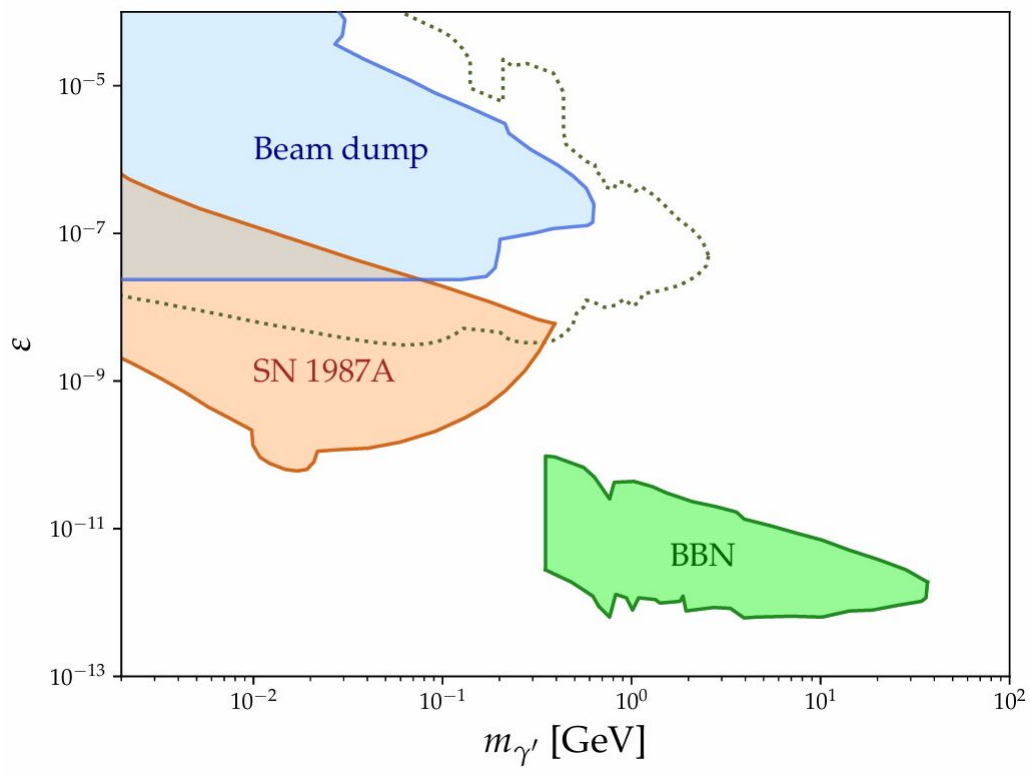
- $m_{\gamma'} \gtrsim \omega_{p,D} \sim 10^{-22}$ **eV** expected to screen collective effects; production unchanged ($m_{\gamma'} \ll m_\varphi$)
- $\gamma'_L$ produced like one scalar: $n_L/n_\chi \sim 10^6$

➜ **dark radiation** (ultralight) or **subdominant DM relic**
$m_{\gamma'} \lesssim 10^{-6}\text{-}10^{-7}\ (e'/0.5)^6\ m_\chi$

➜ Results hold for small $m_{\gamma'} \ll m_\varphi$; the **dark photon mass** is an **open model-building question**

# Observational/Experimental constraints on massive Dark Photons

- Beam dump : absence of additional feeble interaction channels for fixed target experiments (E137, LSND, CHARM, NuCal, and projected as SHiP)
- SN 1987 A : absence of additional energy loss processes in observed ν flux from Supernovae
- BBN : Nucleosynthesis abundances not disrupted by frozen-in Dark Photons



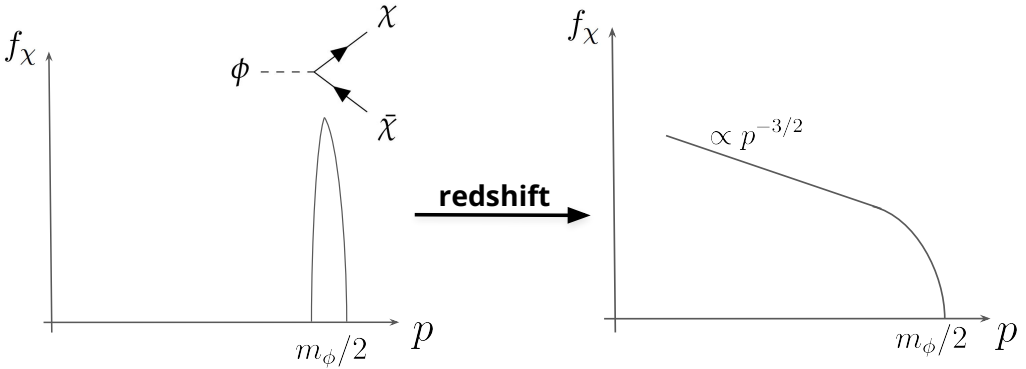

For more see *The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds,* Caputo, Park, Yun **2511.15785**

# Non-thermal, under abundant HS from inflaton decays

**Inflaton decays** inject a **hard, non-thermal population**

$$f_\chi \simeq 24\pi^2 \frac{n_\chi}{m_\phi^3} \left(\frac{m_\phi}{2p}\right)^{3/2} \Theta(m_\phi/2 - p)$$

Harigaya, Mukaida, **1312.3097**
Garcia, Amin, **1806.01865**



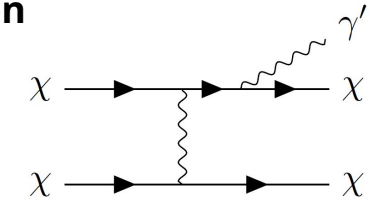

Typical momentum $\langle p \rangle \sim O(m_\phi)$

**Underabundant population : Kinetic ≠ Chemical equilibrium**

$$\frac{n_\chi}{n_\chi^{\rm th}} \sim \frac{(\Gamma_\phi^\chi H M_P^2)^{1/4}}{m_\phi} \sim \frac{T'}{m_\phi} \lesssim 1$$

2-2 processes redistribute momenta but **chemical equilibration** must involve **particle number changing processes**

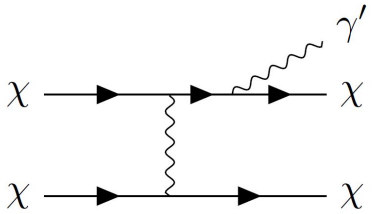
➜ **finite thermalization time** through **splitting processes**



# Thermalization of the Hidden Sector : Splittings

Gauge boson emission dominated by **soft t-channel collision of hard fermions** of density $n_h$

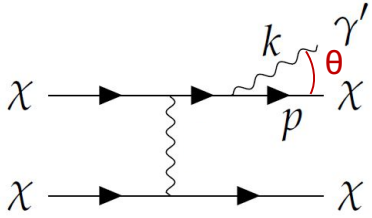
➜ slightly off-shell parent fermion radiating a gauge boson
➜ splitting rate from soft collision cut off in the medium by the Debye mass $m_D^2 \sim \alpha' \int d^3k \frac{f(k)}{k}$




$$\Gamma_{2\to3} \sim \alpha' \Gamma^s_{2\to2} \longleftarrow \Gamma^s_{2-2} \sim \begin{cases} \alpha' m_\phi & m_D \gtrsim m_{\gamma'} \\ \alpha'^2 n_h / \bar{m}^2_{\gamma'} & m_{\gamma'} \gtrsim m_D \end{cases}$$

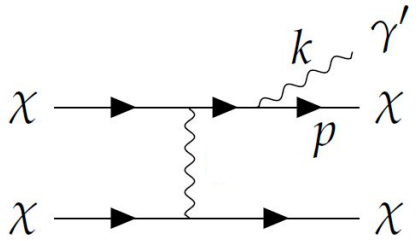
Emitted soft gauge bosons are **collinear** with their parent particle
➜ a finite time before the particles are **"separated"**

Several amplitudes interfering destructively can **suppress the splitting rate ➜ Landau–Pomeranchuk–Migdal (LPM) effect**



# Thermalization in an Abelian plasma

In an **abelian plasma** thermalization proceeds through **gauge boson emission**




Multiple soft scatterings broaden the parent fermion transverse momentum, while the dark photon does not undergo efficient soft rescattering ➜ **Landau-Pomeranchuk-Migdal (LPM) suppression**

$$\Gamma^{A}_{2-3} \sim \alpha' \, \Gamma^{s}_{2-2} \sqrt{\frac{k}{k^{A}_{\rm LPM}}}$$

$$k^{A}_{\rm LPM} \sim \frac{p^4}{n_\chi}$$

*LPM-suppressed splittings*

Abelian thermalization: **relatively hard gauge bosons are produced first**, followed by a **cascade toward lower momenta** through repeated splittings

➜ **Bottleneck : LPM suppressed gauge boson emission**

$$t^{\rm A}_{\rm th} \sim 1/\Gamma_{2\to3} \sim \frac{1}{\alpha'^2 m_\phi} \left( \frac{m_\phi^3}{n_\chi} \right)^{1/2}$$

SC, Kimus, Tytgat, **2605.09686**

# Thermalization timescales : Abelian vs Non-Abelian

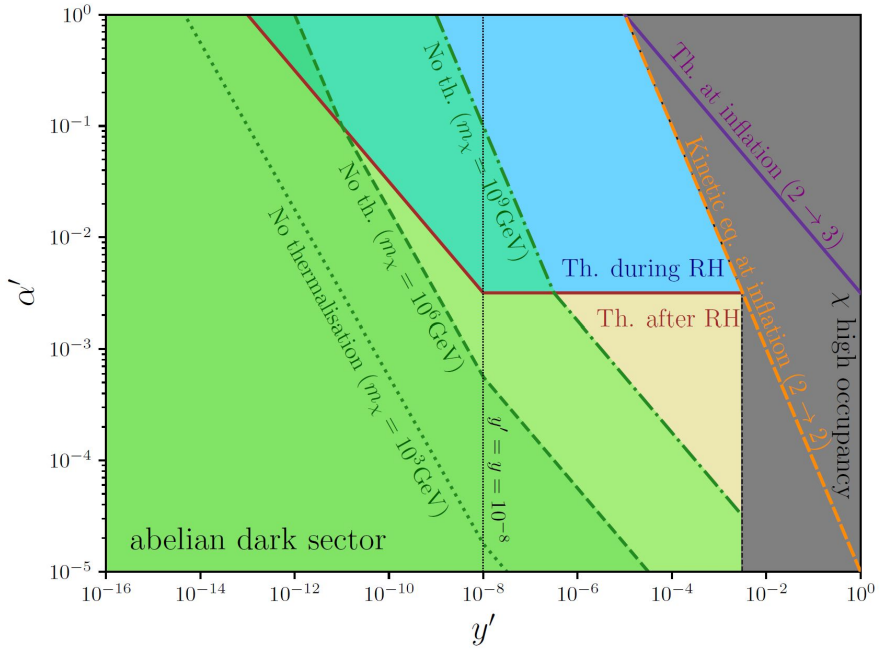
| | abelian | non-abelian |
|---|---|---|
| LPM | $k \gtrsim k_{\rm LPM}$ | $k \lesssim k_{\rm LPM}$ |
| $k_{\rm LPM}$ | $\frac{m_\phi^4}{n_h} \gg m_\phi$ | $\frac{n_h}{m_\phi^2} \ll m_\phi$ |
| $\Gamma^{\rm LPM}_{2\to3}$ | $\alpha' \Gamma^s_{2-2} \sqrt{\frac{k}{k_{\rm LPM}}}$ | $\alpha' \Gamma^s_{2-2} \sqrt{\frac{k_{\rm LPM}}{k}}$ |
| $t_{\rm th}$ | $\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{1/2}$ | $\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{3/8}$ |
| $H_{\rm th}$ | $m_\phi \alpha'^4 \left(\frac{\Gamma^\chi_\phi M_P^2}{m_\phi^3}\right)$ | $m_\phi \alpha'^{16/5} \left(\frac{\Gamma^\chi_\phi M_P^2}{m_\phi^3}\right)^{3/5}$ |

**Thermalization timescales**, to compare with reheating time scale

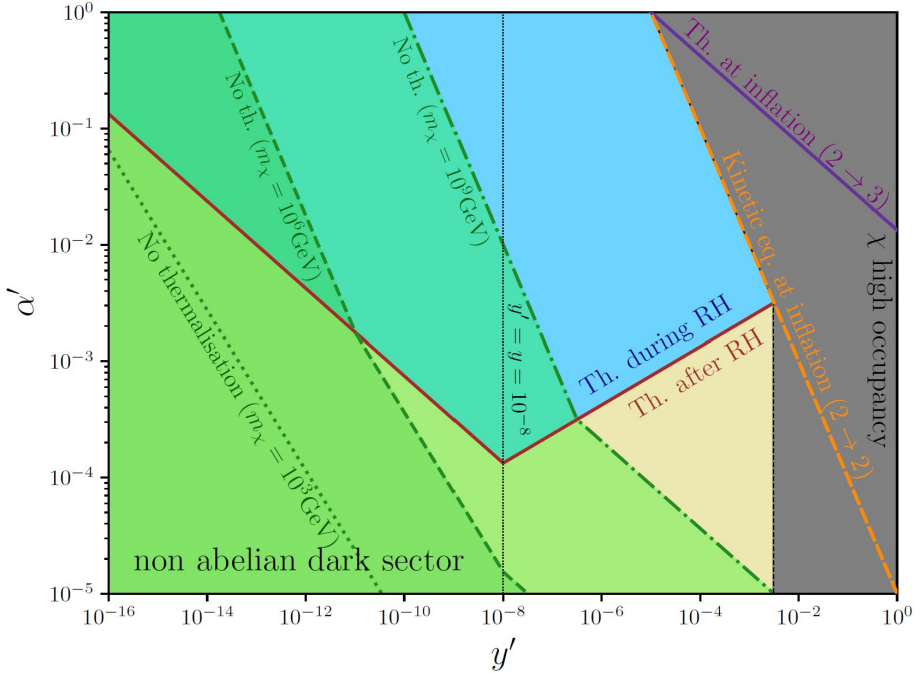
SC, Kimus, Tytgat, **2605.09686**

Harigaya, Mukaida, **1312.3097**

# Constraints from Thermalization of the Hidden Sector



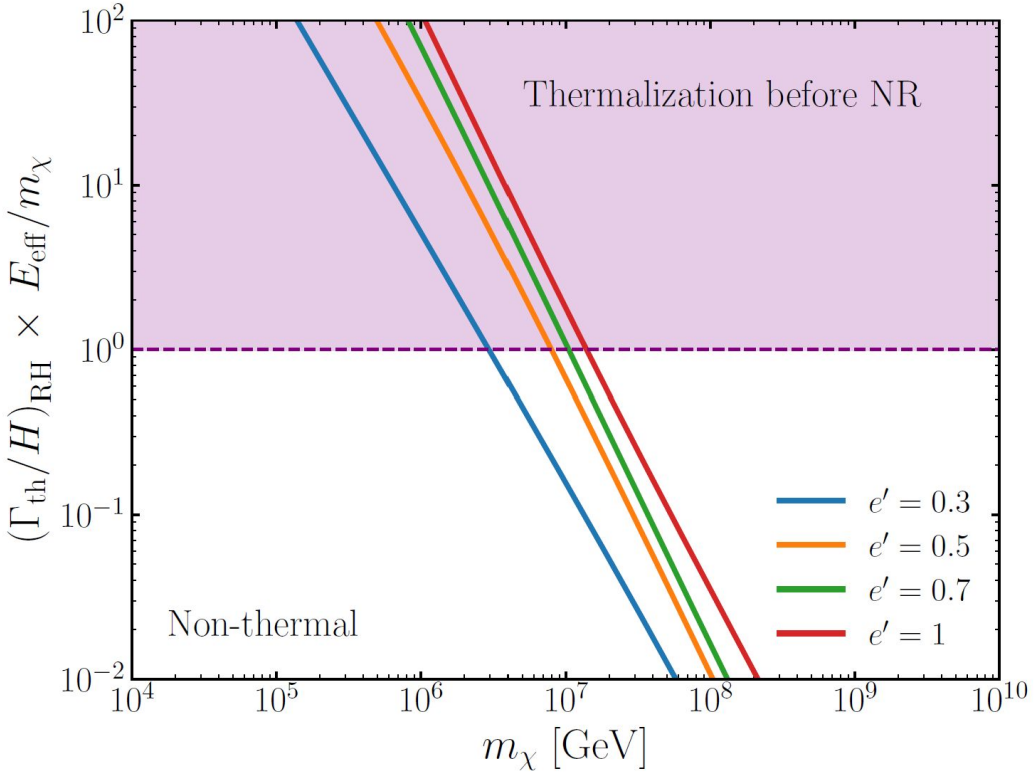

Domain of thermalization during/after reheating
**Abelian plasma**




Domain of thermalization during/after reheating
**Non-Abelian plasma**

SC, Kimus, Tytgat, **2605.09686**

# Gravitationally produced dark sector thermalization




Thermalization parameter evaluated along the DM iso relic abundance lines, for several e′

➜ Horizontal dashed line marks the condition for thermalization before the non-relativistic transition