Production of dark photon DM in the early universe

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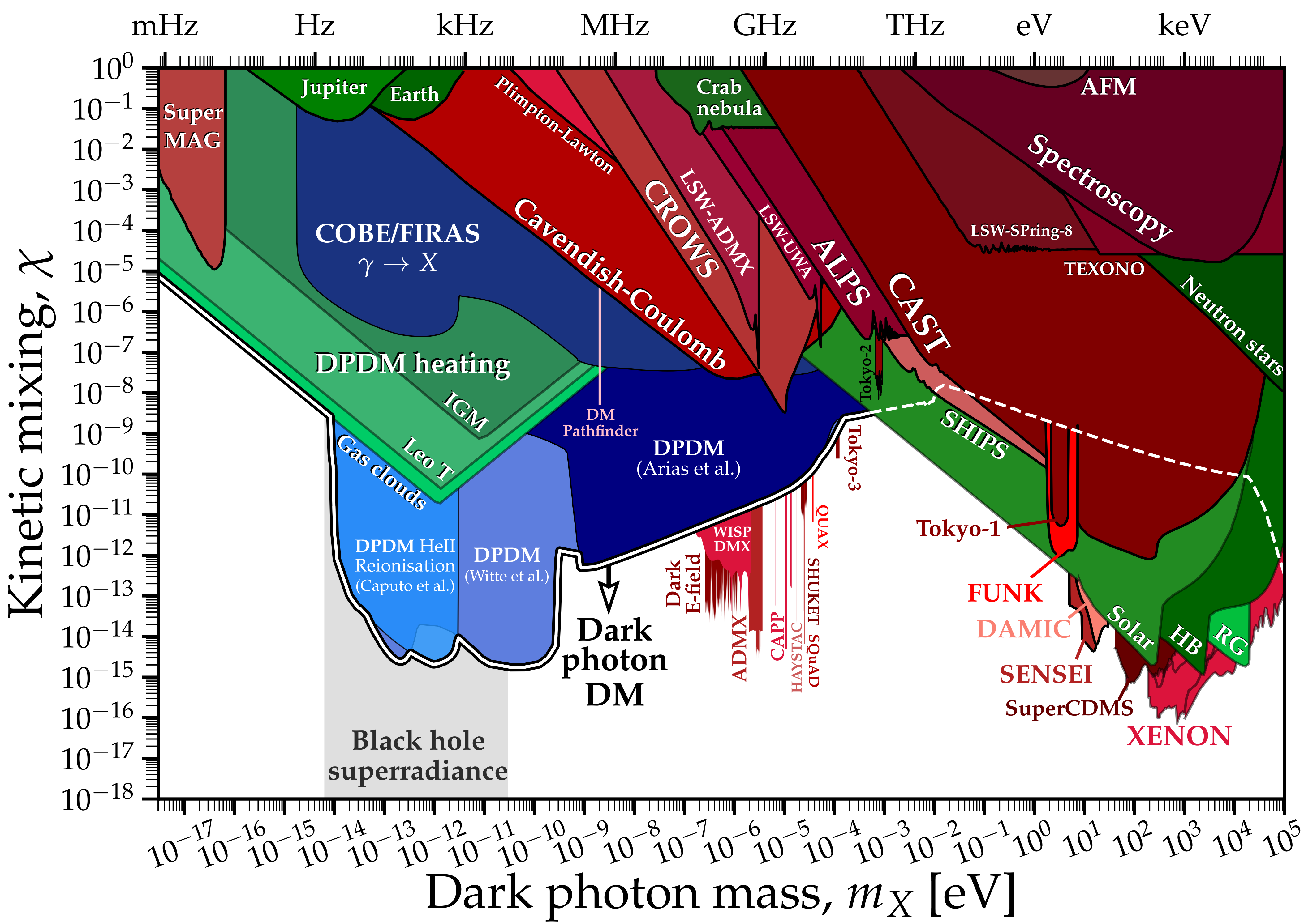
NK, F. Takahashi, 2303.05492

NK, K. Nakayama, 2212.13573, 2303.04287, 2306.17390

"What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

Apr 24-25, 2025, Online

Dark photon dark matter : current status



$$\mathcal{L} \ni \frac{1}{2}\chi F^{\mu\nu} X_{\mu\nu}$$

Caputo et al 2105.04565

Dark photon DM production

- Gravitational particle production during inflation / reheating

Graham, Mardon, Rajendran (2016) / Ema, Nakayama, Tang (2019)

$$\Omega_{\gamma'} \simeq \Omega_{\rm DM}\sqrt{\frac{m_{\gamma'}}{6\,\mu{\rm eV}}}\left(\frac{H_{\rm inf}}{10^{14}\,{\rm GeV}}\right)^2$$ —> lower limit on dark photon mass

- Resonant production from scalar field

Axion : Agrawal, NK, Reece, Sekiguchi, Takahashi (2020), NK, Takahashi (2023)
Co, Pierce, Zhang, Zhao (2019), Bastro-Gil, Santiago, Ubaldi, Vega-Morales (2019)

Higgs : Harigaya, Narayan (2019)

- Misalignment production Nakayama (2019), Nakayama (2020), NK, Nakayama (2023)

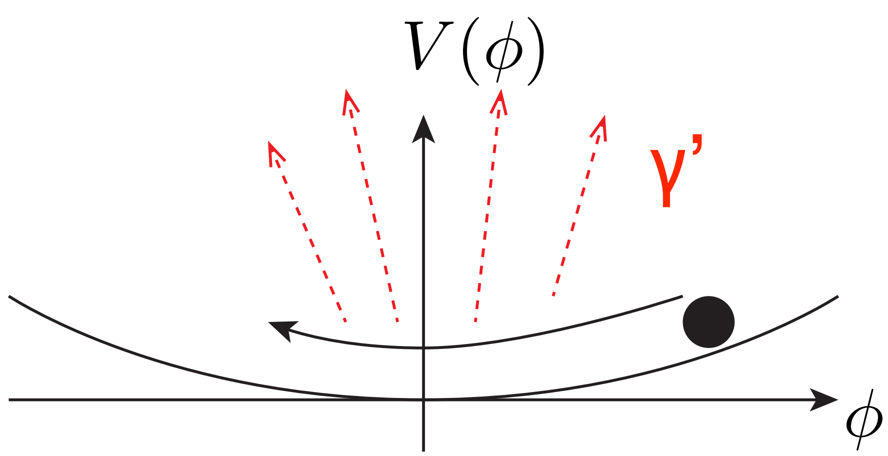
- Production from cosmic strings Long, Wang (2019), NK, Nakayama (2022,2023)

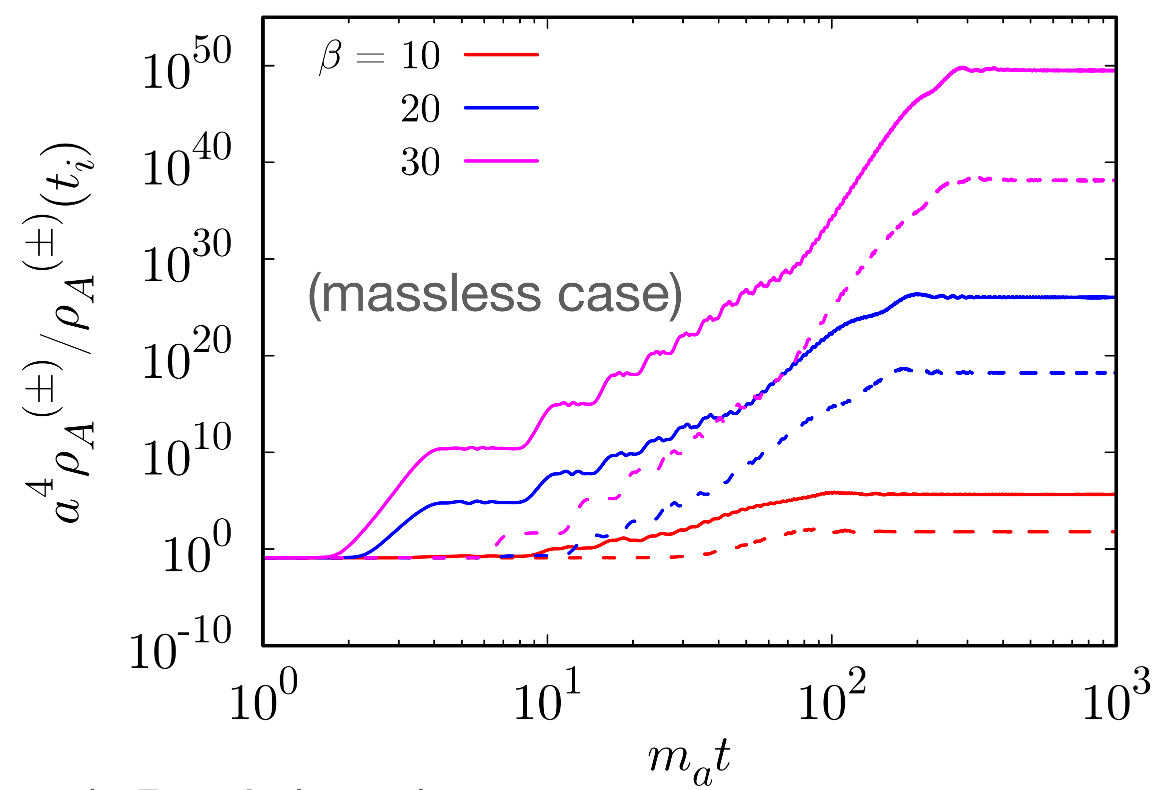
Resonant dark photon (DM) production from axion

Agrawal, NK, Reece, Sekiguchi, Takahashi (2018)
Co, Pierce, Zhang, Zhao (2018), Bastero-Gil, Santiago, Ubaldi, Vega-Morales, (2018)

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_{\gamma'}^2 A_\mu A^\mu - \frac{\beta}{4 f_a}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\longrightarrow \quad \ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a} \right)\mathbf{A}_{\mathbf{k},\pm} = 0$$



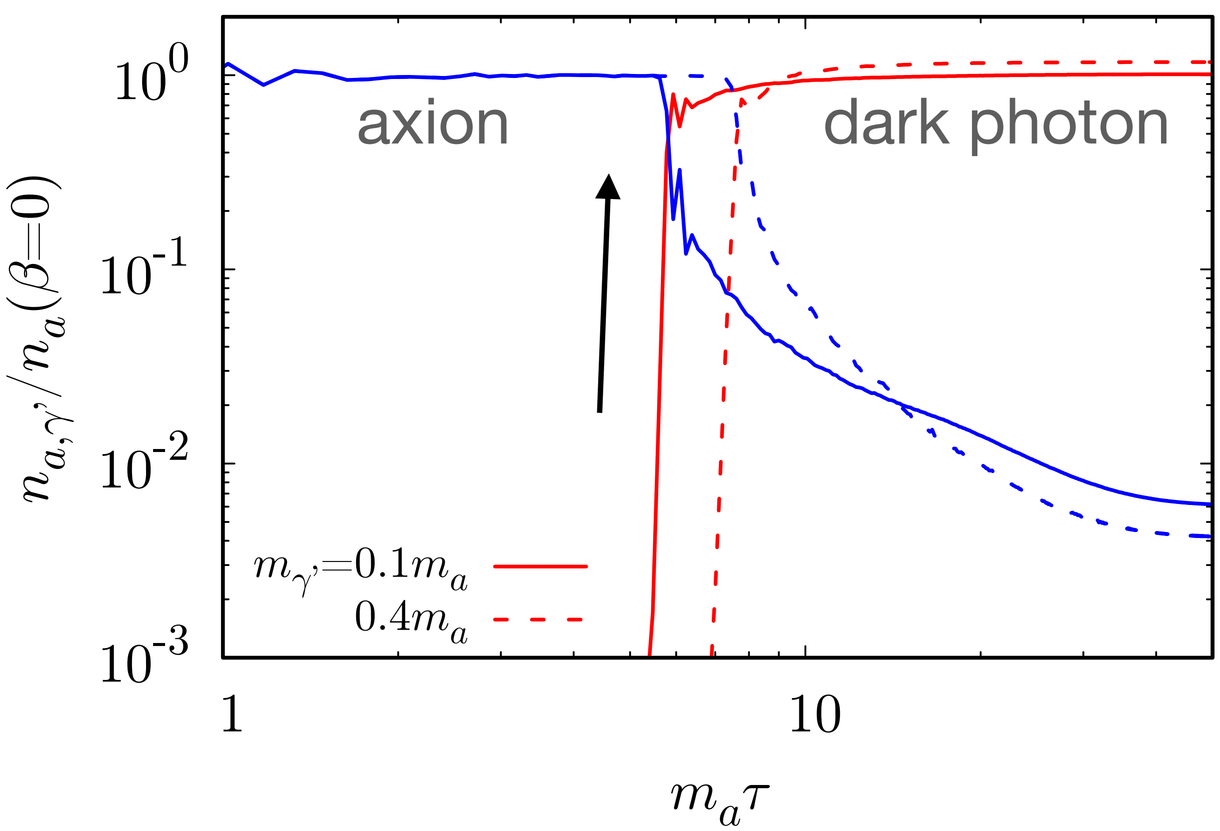


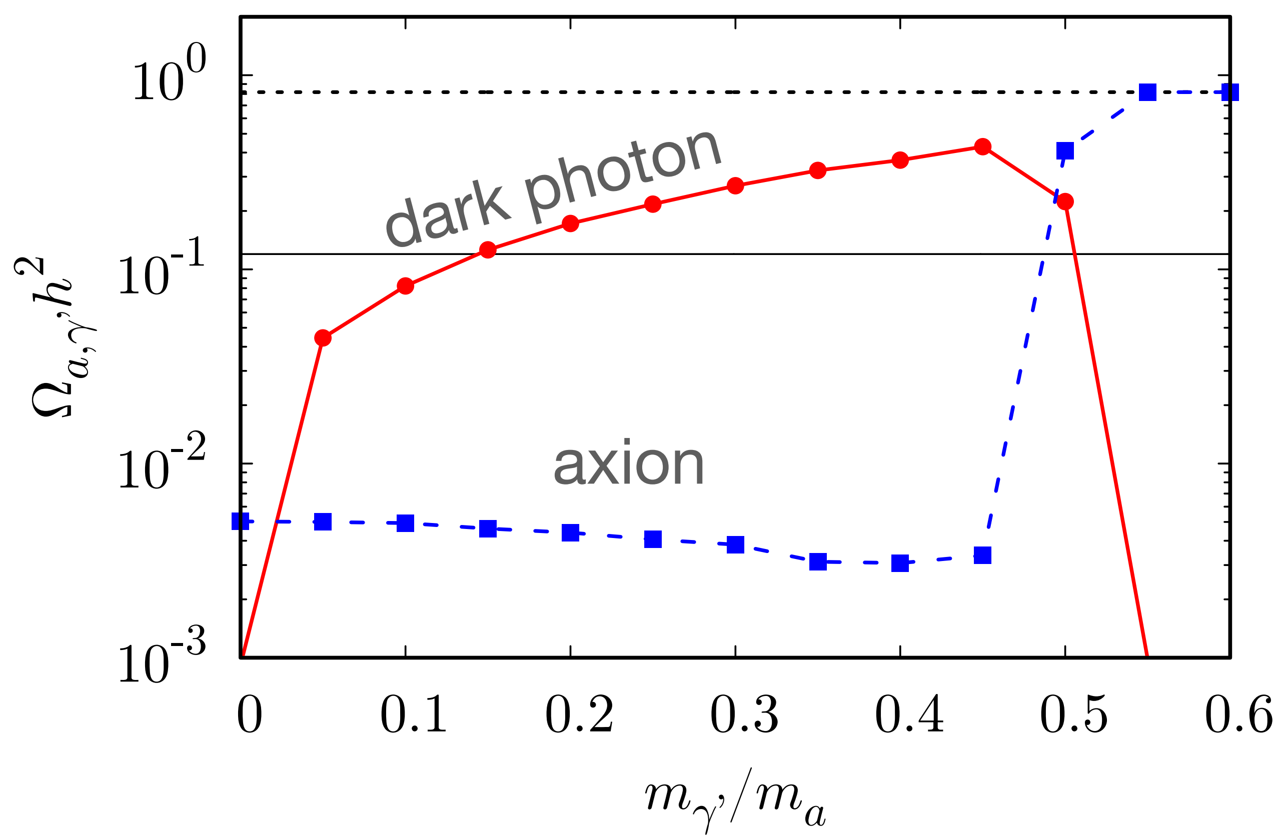
- magnetogenesis Fujita+(2015), Kamada+(2016), Patel+(2020), …
- GW emission with circular polarization NK, Soda, Urakawa (2020), …

see also Machado+ (2019), Salehian+ (2020), Ratzinger+ (2020), Namba+ (2020)

Relic abundance of dark photon DM and axion

Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188





Axion abundance is suppressed due to the backreaction

(see also NK, T. Sekiguchi, F. Takahashi, 1711.06590)

& dark photon can be the dominant DM component

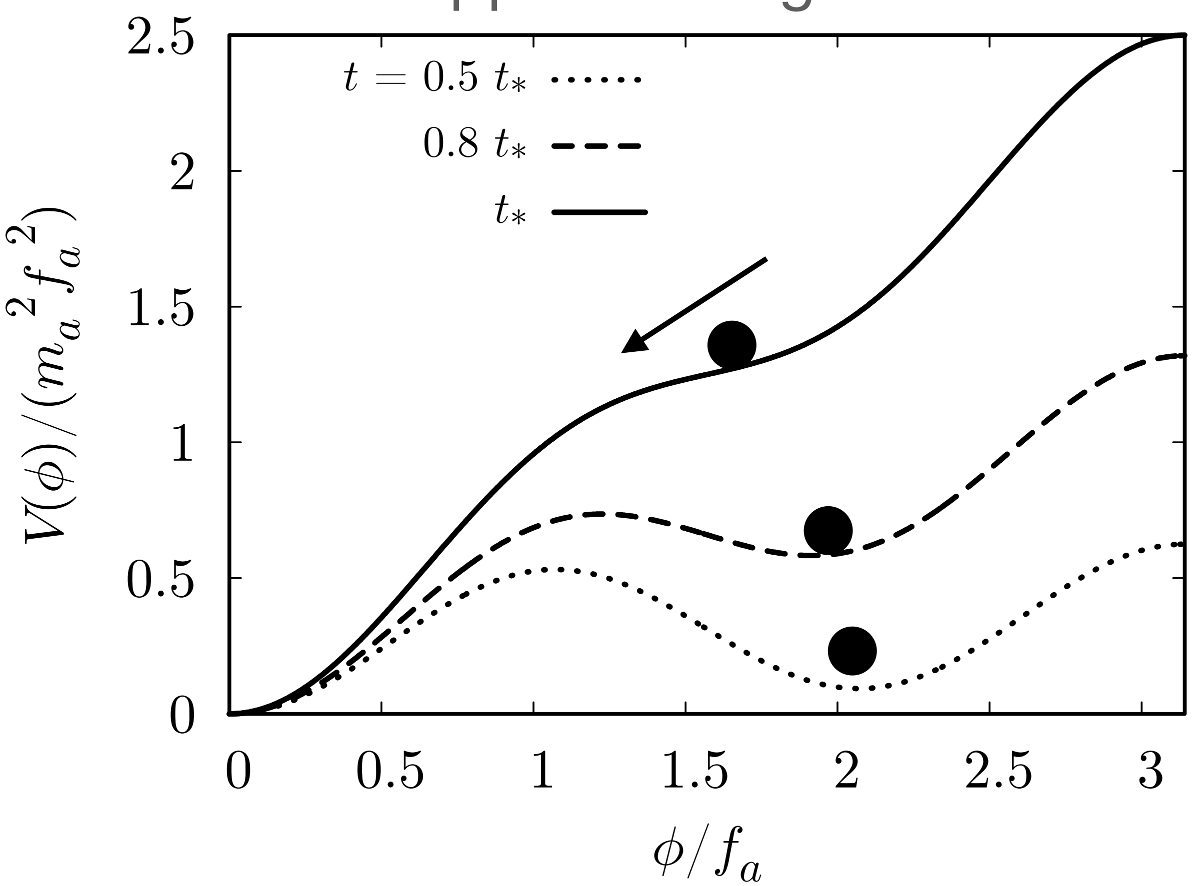
Resonant dark photon production w/o large coupling

NK, Takahashi, 2303.05492

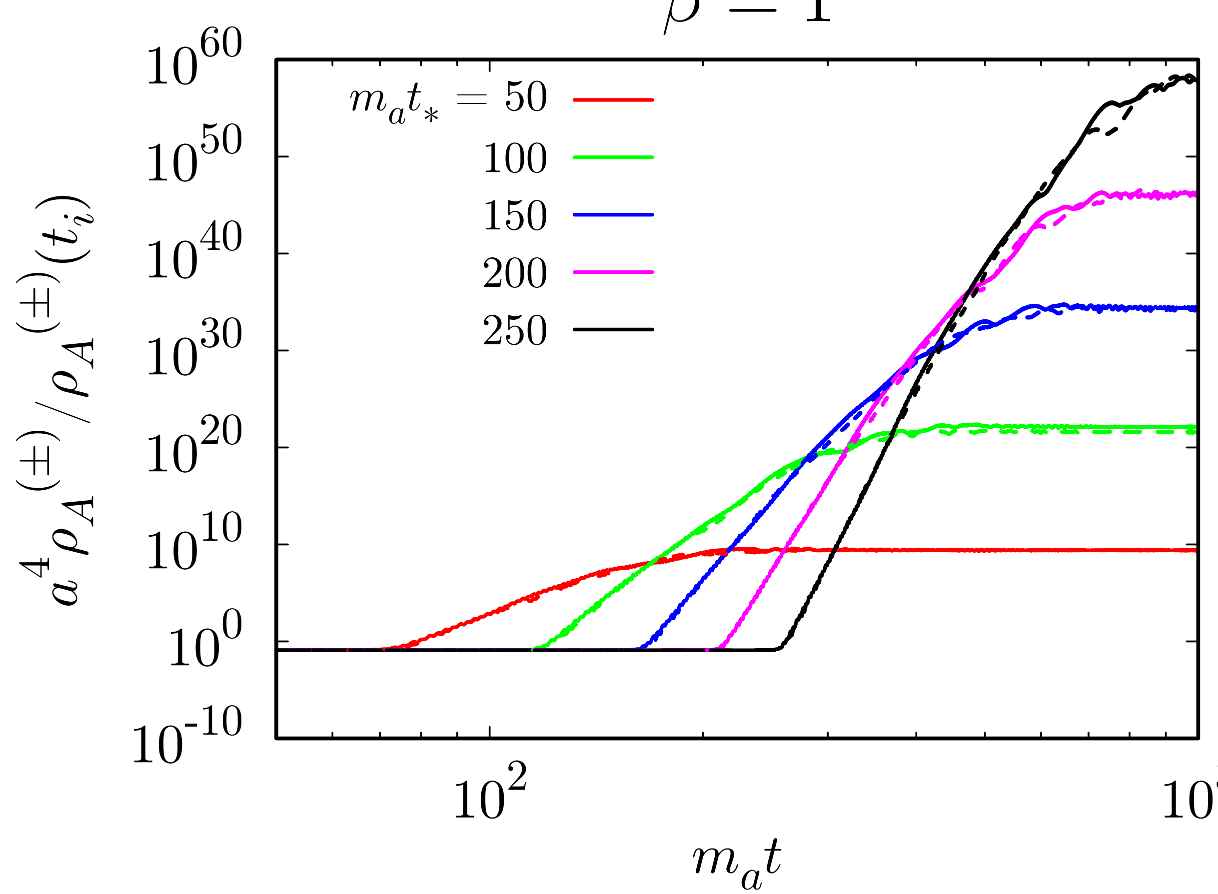
$$V(\phi) = m_a(t)^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right] + \Lambda_H^4 \left[1 - \cos\left(\frac{N_H \phi}{f_a}\right)\right]$$

$$m_a(t) = \begin{cases} m_{a0}(t/t_*)^{b/2} & \text{for} \quad t < t_* \\ m_{a0} & \text{otherwise} \end{cases}$$

trapped misalignment



$\beta = 1$



axion starts to oscillate even when H << m (delayed onset of oscillation)

Coherent vector DM production

Nakayama (2019), Nakayama (2020), NK, Nakayama (2023)

$$\mathcal{L} = -\frac{f^2(\phi)}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2} m_A^2 A_\mu A^\mu - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$(f \to 1 \ \text{ after inflation})$ $\qquad f^2 \propto a^\alpha, \ \bar{A}_i = f A_i / a, \ R_A = \frac{\rho_A}{\rho_\phi}$

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V \left(1 + \frac{\alpha R_A}{2\epsilon_V}\right) = 0 \qquad \epsilon_V = \frac{M_P^2}{2}\left(\frac{\partial_\phi V}{V}\right)^2$$

(slow-roll parameter)

$$\ddot{\bar{A}}_i + 3H\dot{\bar{A}}_i + \left(\frac{m_A^2}{f^2} - \frac{(\alpha+4)(\alpha-2)}{4}H^2 + \frac{2-\alpha}{2}\dot{H}\right)\bar{A}_i = 0$$

Statistical anisotropy $\quad \mathcal{P}_\zeta(\boldsymbol{k}) = \mathcal{P}_\zeta^{(\mathrm{iso})}(k)(1 + g_k \sin^2\theta_k), \quad \hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{A}} = \cos\theta_k$

$\& \quad g_k \propto R_A$

DM isocurvature perturbation $\quad S = \frac{\delta\rho_A}{\bar{\rho}_A} \sim \frac{H_{\mathrm{inf}}}{\pi \bar{A}_i} \propto R_A^{-1}$

CMB observation —> $\quad g_k \lesssim 0.01, \quad S \lesssim 0.1\zeta$

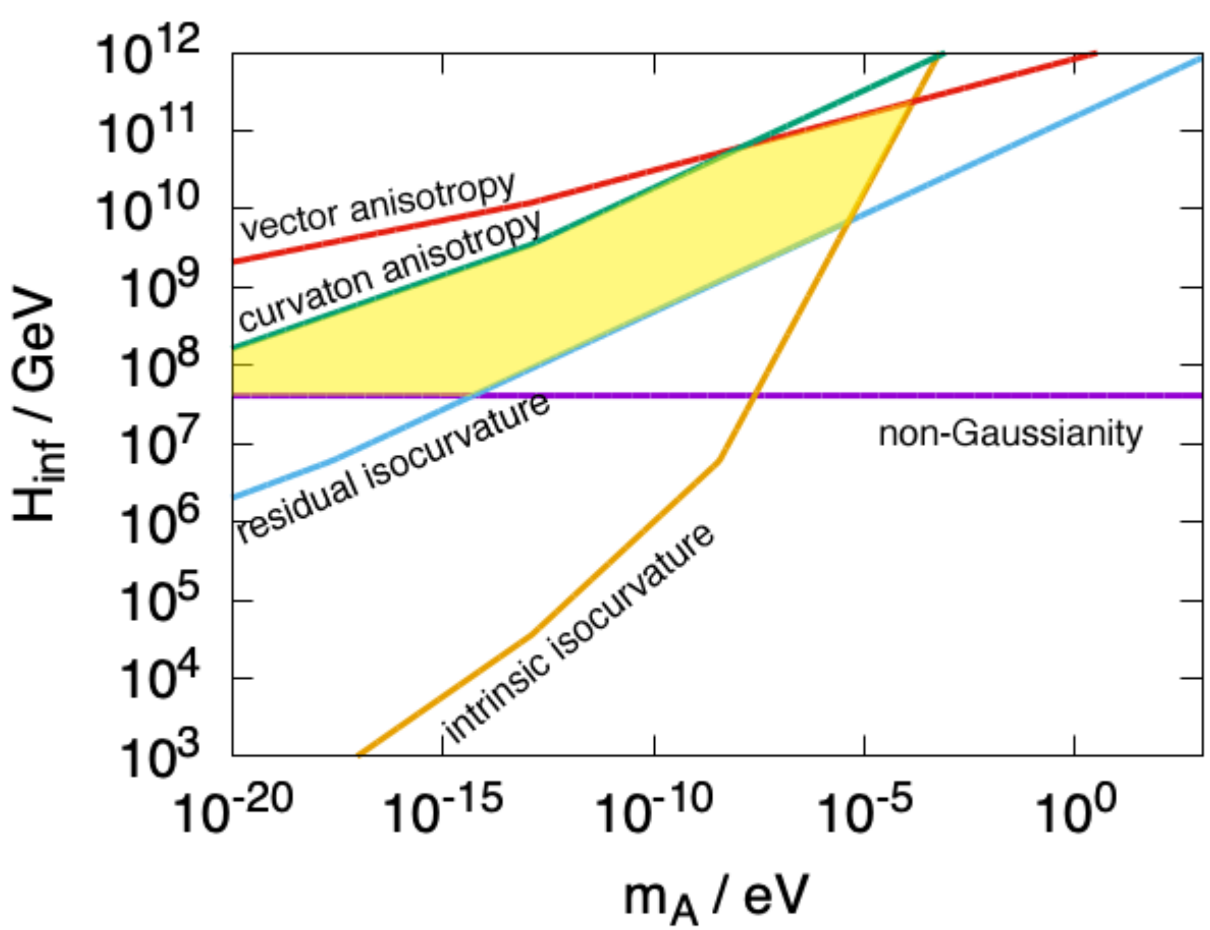
“Viable” coherent vector DM scenario
– curvaton scenario

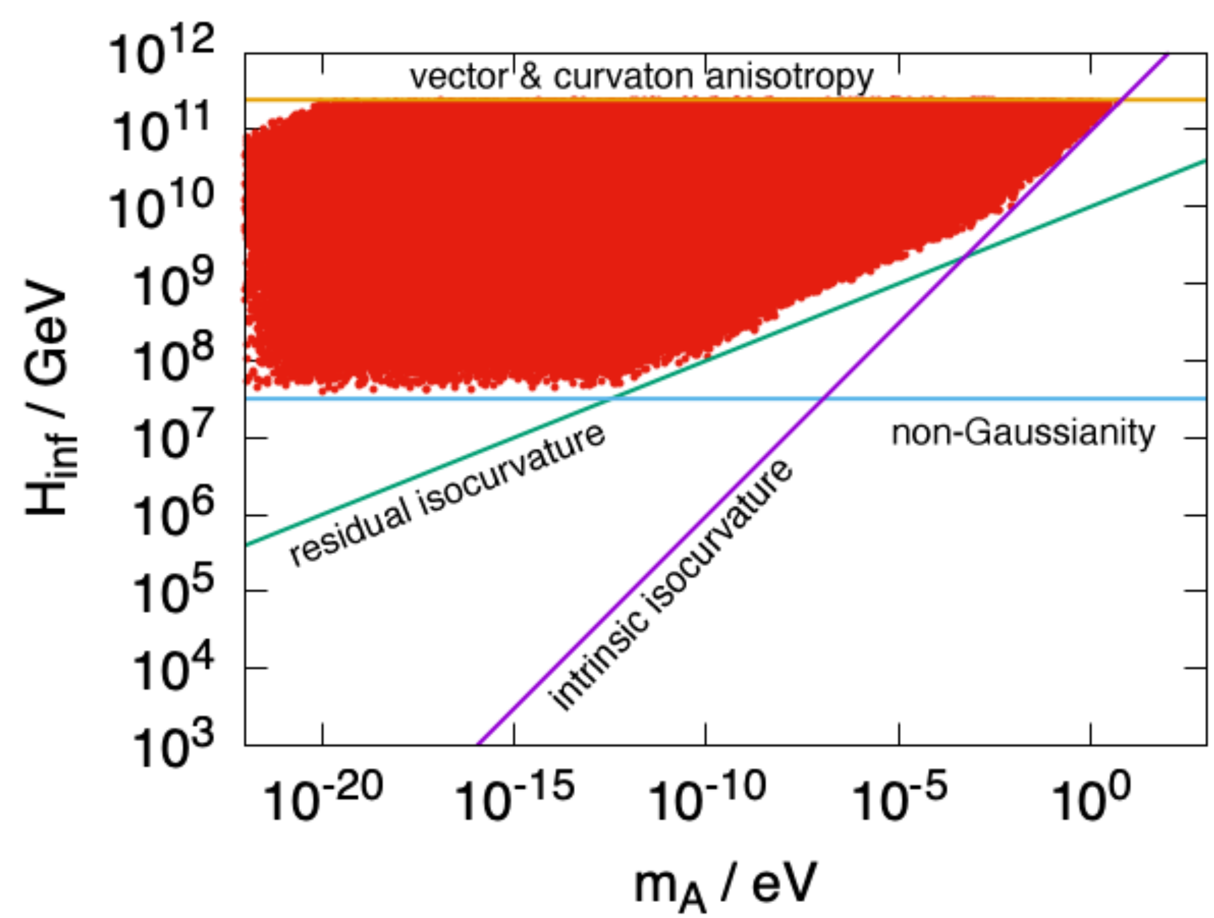
NK, Nakayama 2303.04287

additional constraints: non-Gaussianity & residual isocurvature

curvaton domination before curvaton decay & dark photon oscillation

$\Gamma_\chi \lesssim H_{\rm dom}$ $\quad$ $m_A \lesssim H_{\rm dom}$





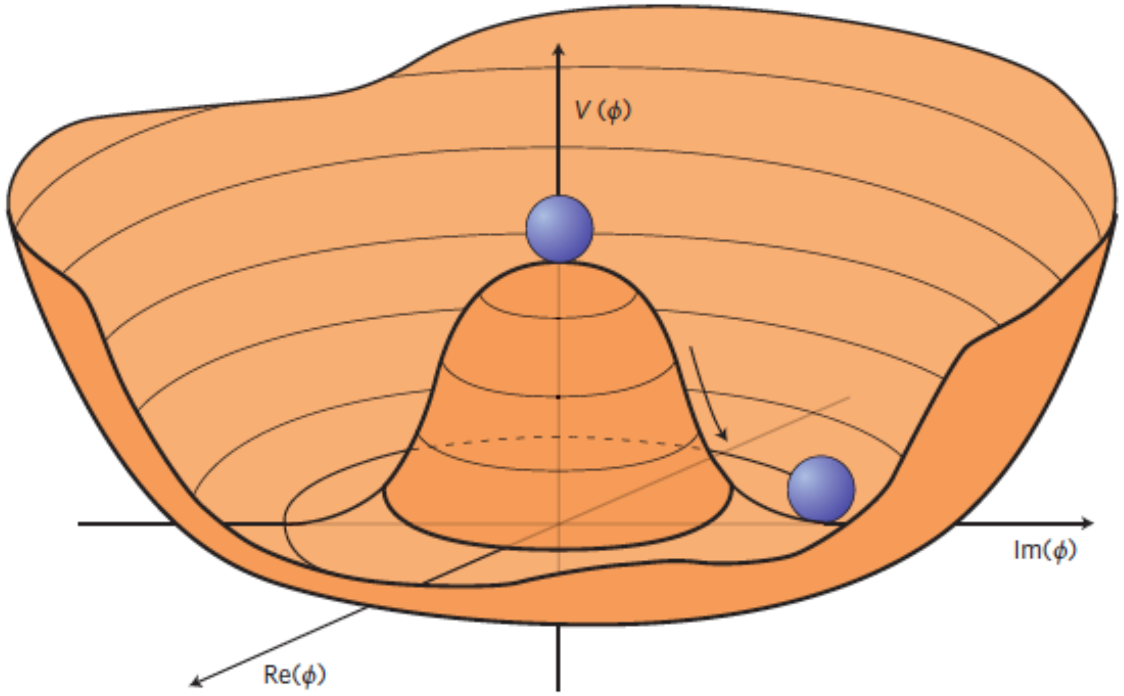
$m_\chi = 10^6 {\rm GeV},\ T_\chi = 10 {\rm MeV},\ \Gamma_\phi = m_\phi$

Dark photon DM from Abelian-Higgs cosmic strings

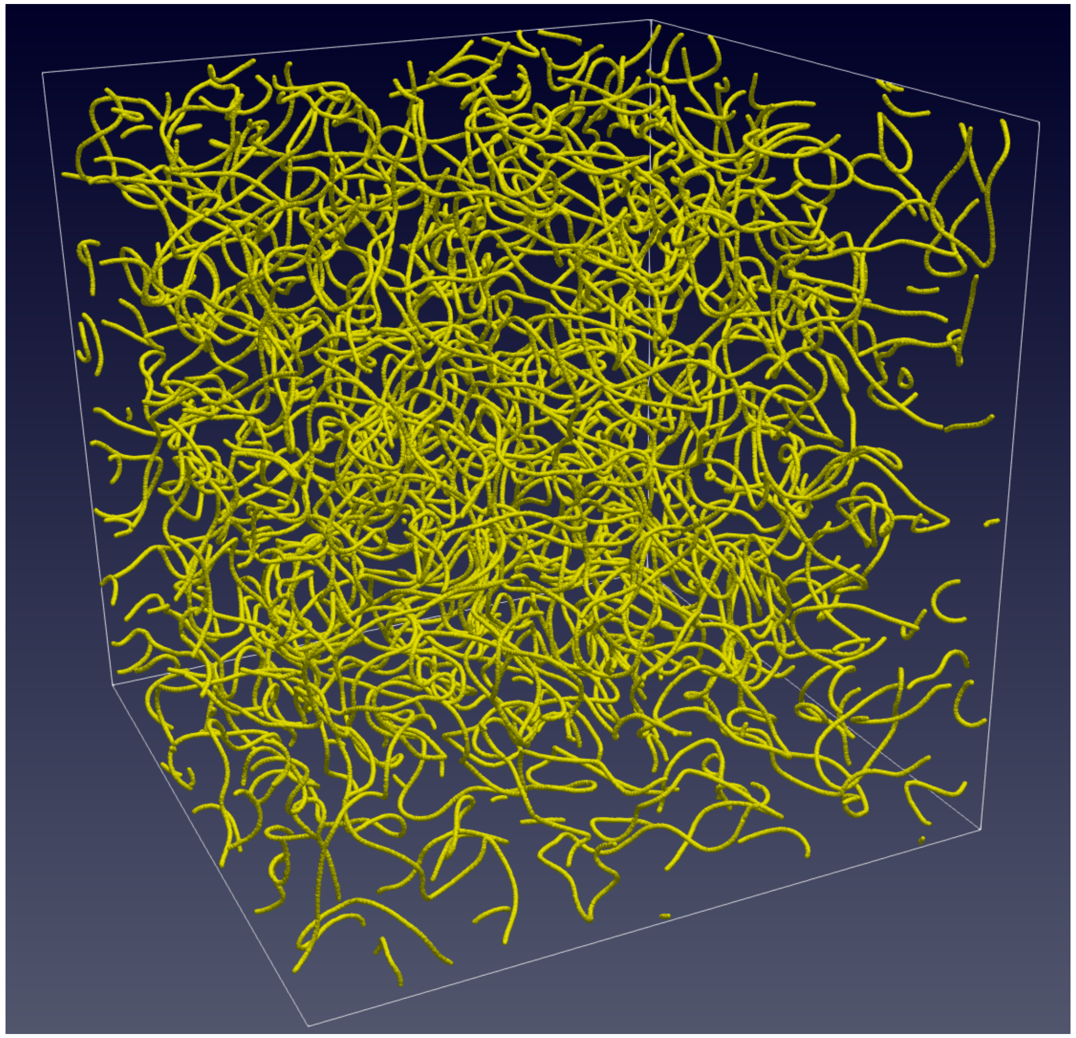
Long, Wang 1901.03312, NK, Nakayama 2212.13573

$$\mathcal{L} = (\mathcal{D}_\mu \Phi)^* \mathcal{D}^\mu \Phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\Phi),\ V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - v^2)^2$$

$$(\mathcal{D}_\mu = \partial_\mu - ieA_\mu,\ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$$



Ellis, Gaillard, Nanopoulos 1504.07217



Scenario

- We are interested in light dark photon (i.e. small gauge coupling)

  —> cosmic string is almost global (Type-II string) $e = 0$ —> global (axion) string

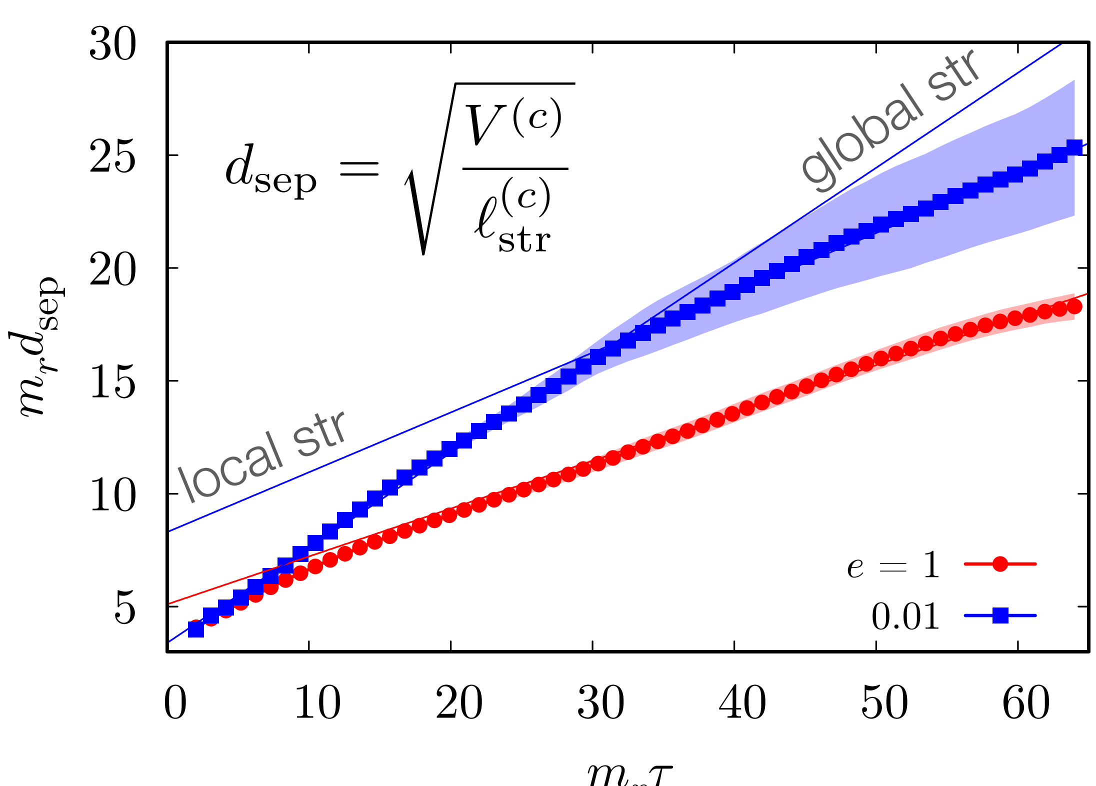
- Dark photon is continuously produced by the collapse of loops.

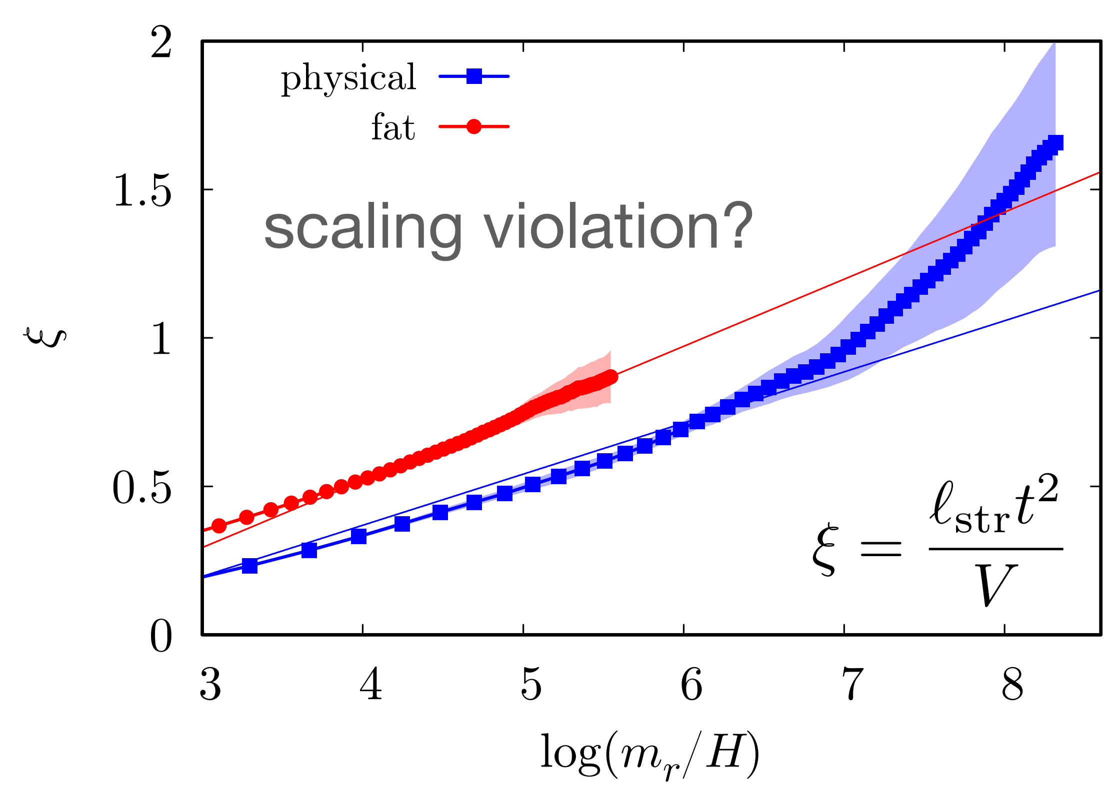
  (similar to the axion emission from global strings)

- Dark photon production becomes inefficient for $\ell_{\rm loop} \gtrsim m_A^{-1}$

  (i.e. loop oscillation frequency becomes smaller than the mass) or $H \lesssim m_A$

- After that, string behaves like local string (GW emission is dominant)



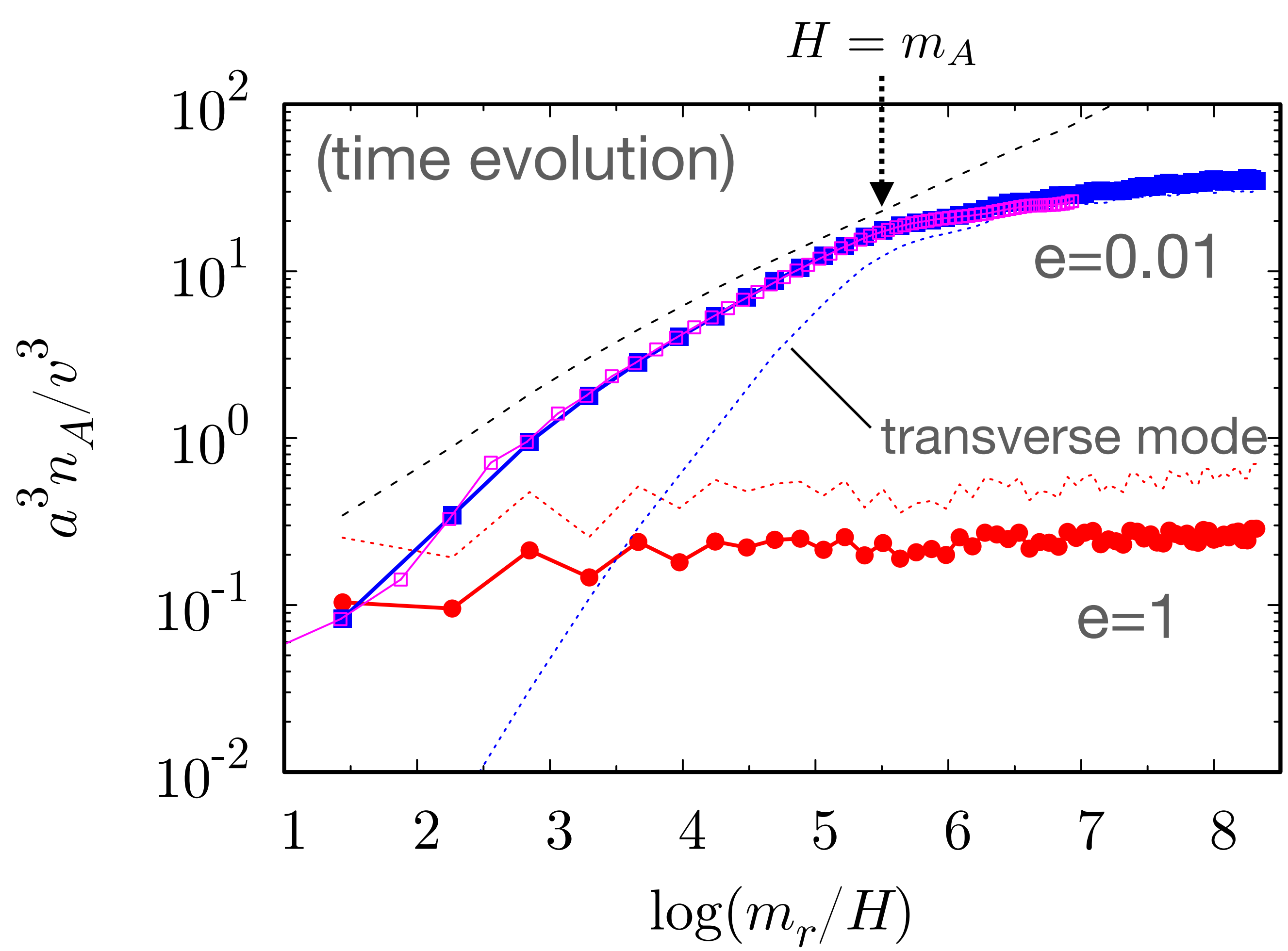


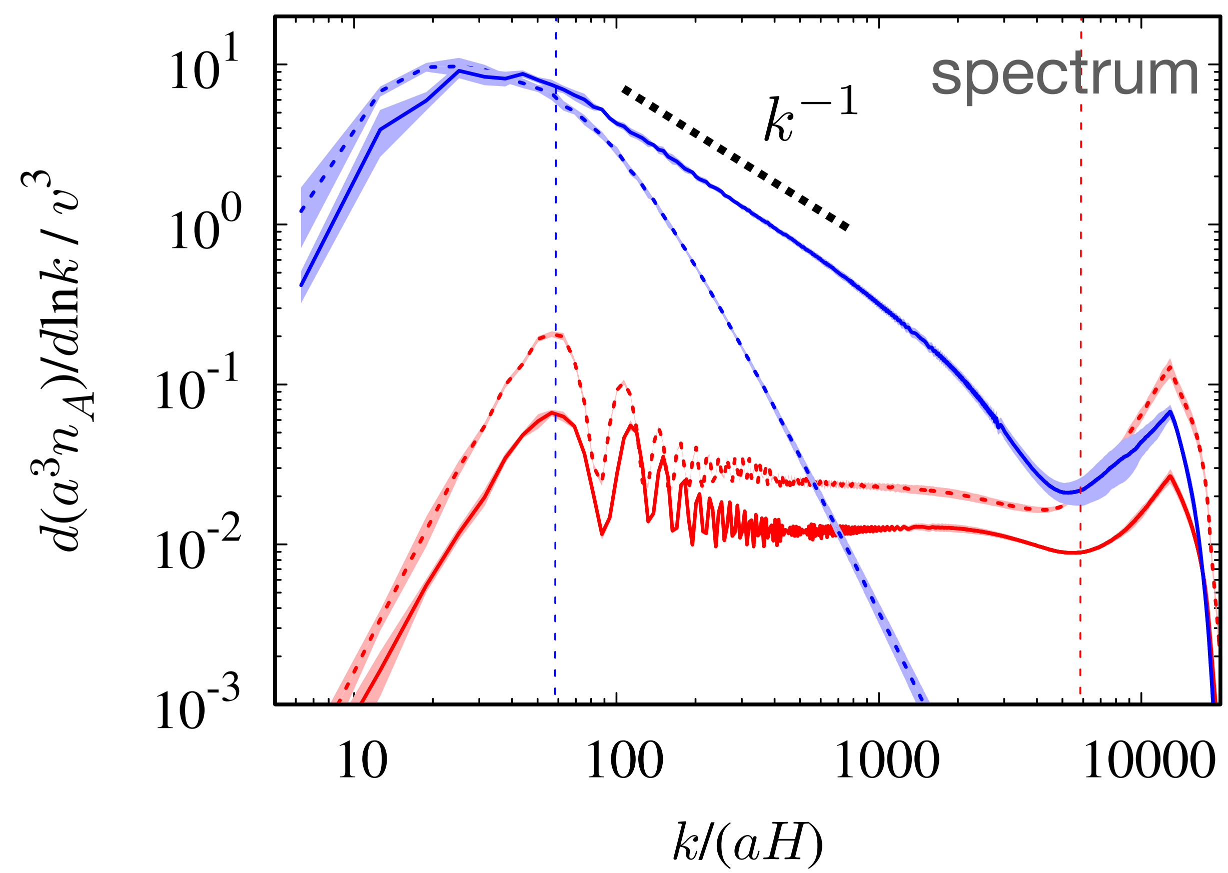
Emission of (longitudinal) vector boson

$$\rho_A^{(\mathrm{L})} = \frac{|\Phi|^2}{v^2}\left[\frac{2}{a^2}\left(\frac{\mathrm{Im}(\Phi^*\Phi')}{|\Phi|}\right)^2 + \frac{1}{a^4}\left(E_i^{(\mathrm{L})}\right)^2\right].$$

$$n_A = \int dk \frac{dn_A}{dk} = \int dk \frac{1}{E_A(k)}\frac{d\rho_A}{dk}, \quad n_A^{(\mathrm{L})}(t) \simeq \frac{8\xi\mu H}{\bar{E}_A/H}$$

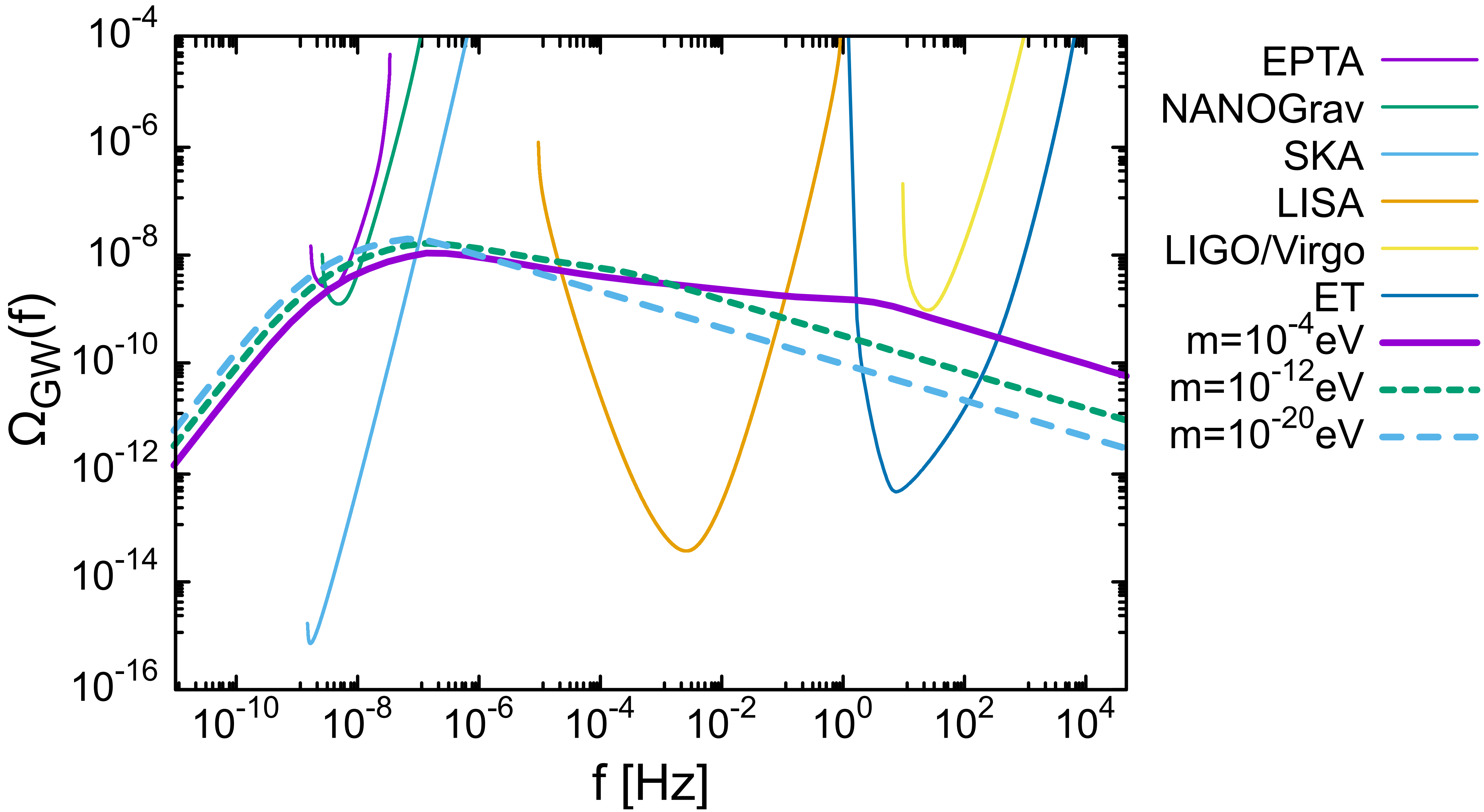
analytic estimation by Long, Wang 1901.03312





peak wavenumber: $k/a \sim 10H$ ⟷ typical loop size: $\ell \sim 0.1 H^{-1}$

GW spectrum with log-enhancement



NK, Nakayama 2306.17390

Summary

- Resonant production from scalar (axion) field

  Dark photon can be the dominant DM component
  (axion abundance is suppressed due to the nonlinear effect)

  We have shown that the efficient production of dark photon can be realized even if the axion-gauge coupling is small (<<O(1))

- Misalignment production

  Coherent dark photon DM is viable in the curvaton scenario

- Production from cosmic strings

  Cosmic strings can be efficient source of light dark photon DM
  and this scenario can be tested by gravitational wave observations
  (spectrum is “tilted”)