Production of very light dark photon dark matter

Naoya Kitajima

FRIS

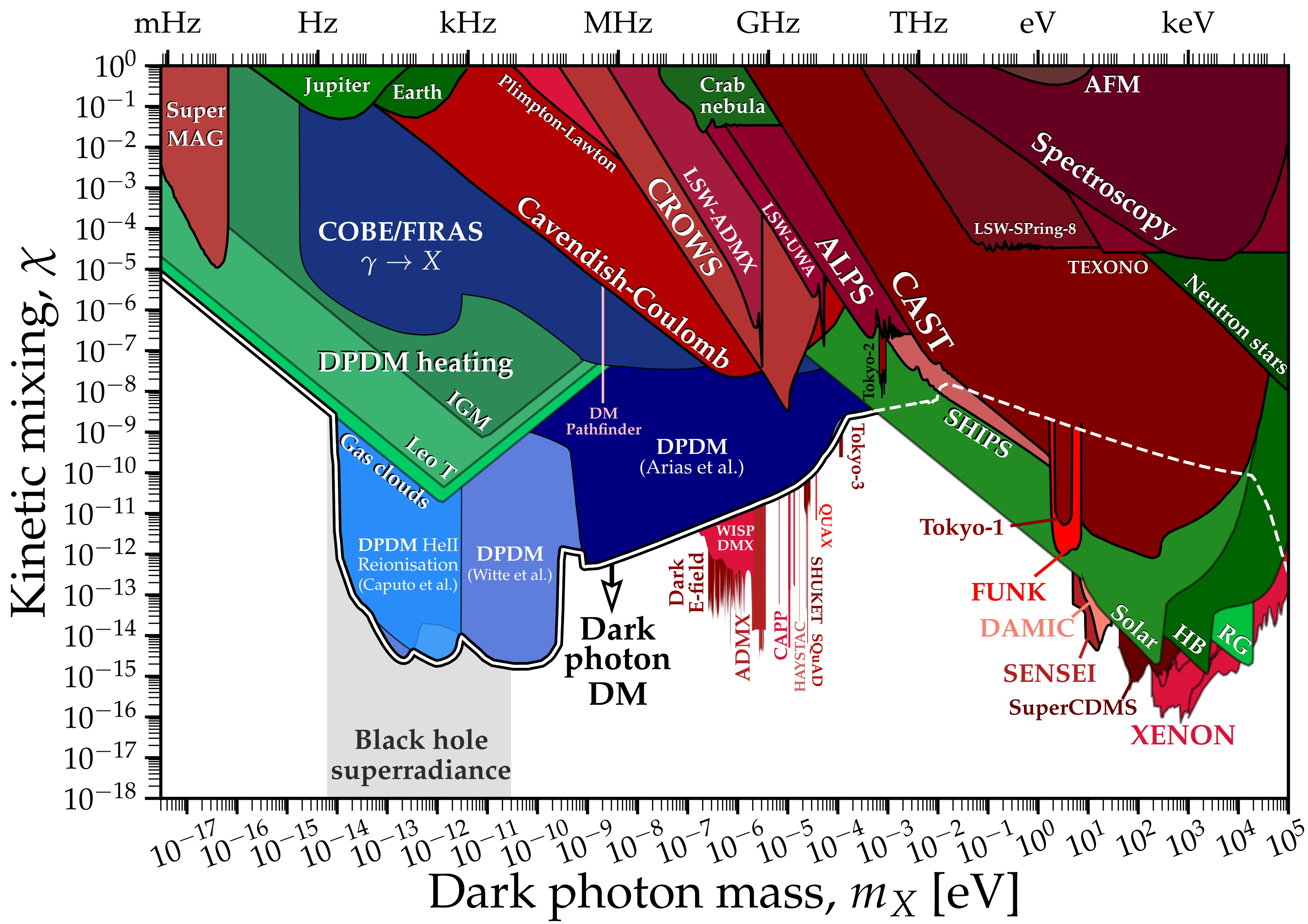
TOHOKU UNIVERSITY

NK, Kazunori Nakayama (Tohoku U.), 2212.13573, 2303.04287
NK, Fuminobu Takahashi (Tohoku U.), 2303.05492

Workshop on Very Light Dark Matter 2023, Chino, 3.28-30

Dark photon search

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



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)

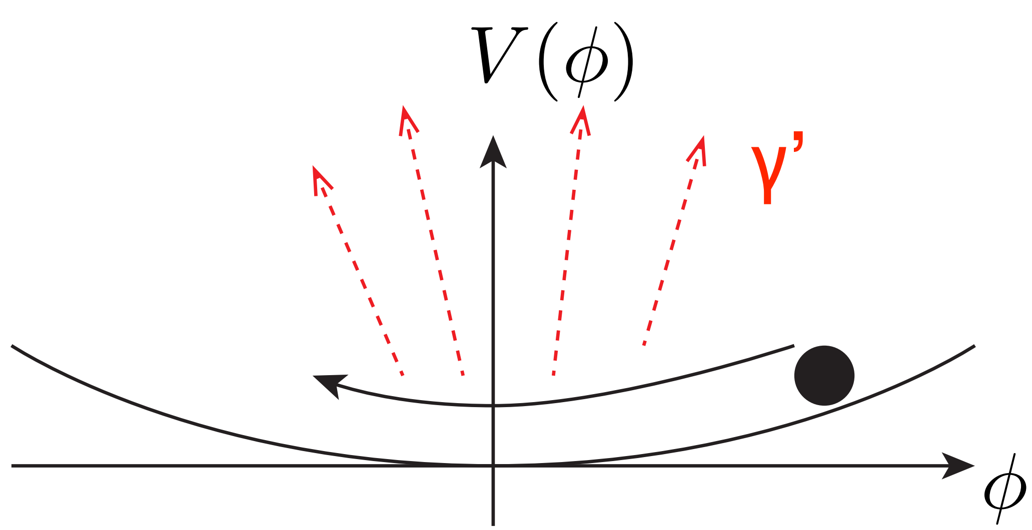
- Production from cosmic strings Long, Wang (2019), NK, Nakayama (2022)

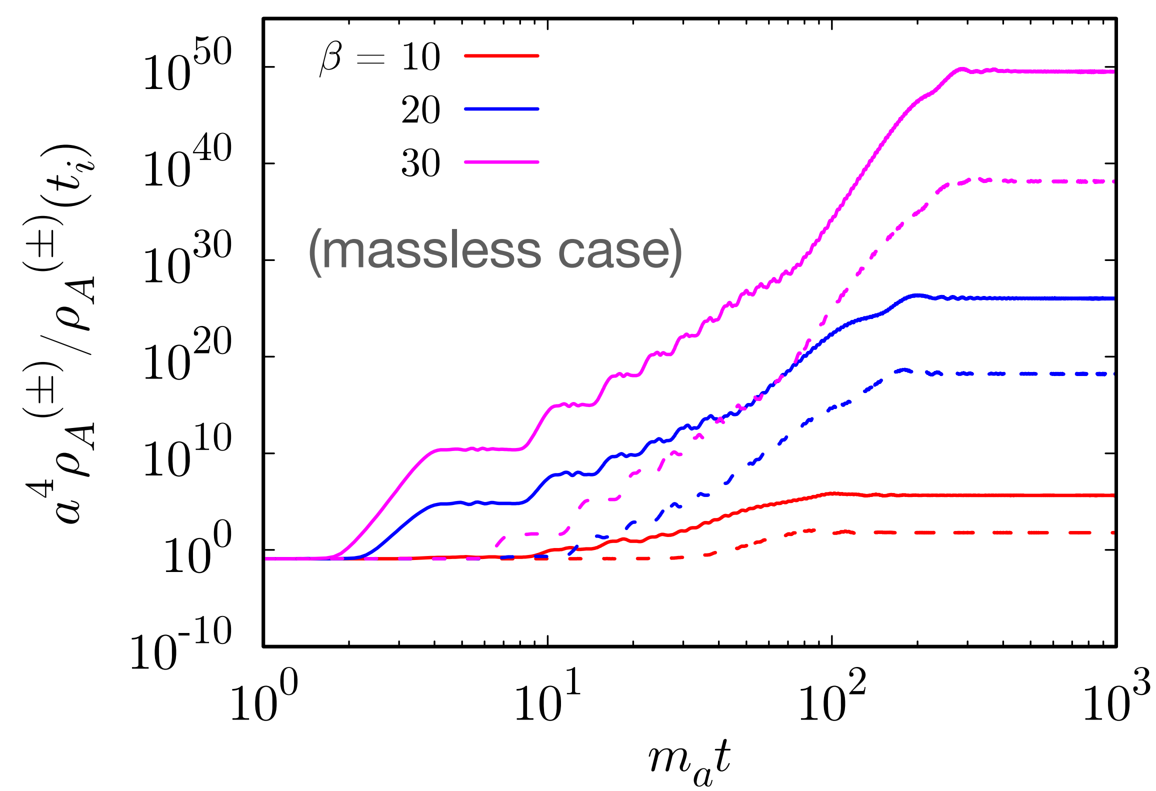
Resonant dark photon production from axion

Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188
Co, Pierce, Zhang, Zhao, 1810.07196
Bastero-Gil, Santiago, Ubaldi, Vega-Morales, 1810.07208

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

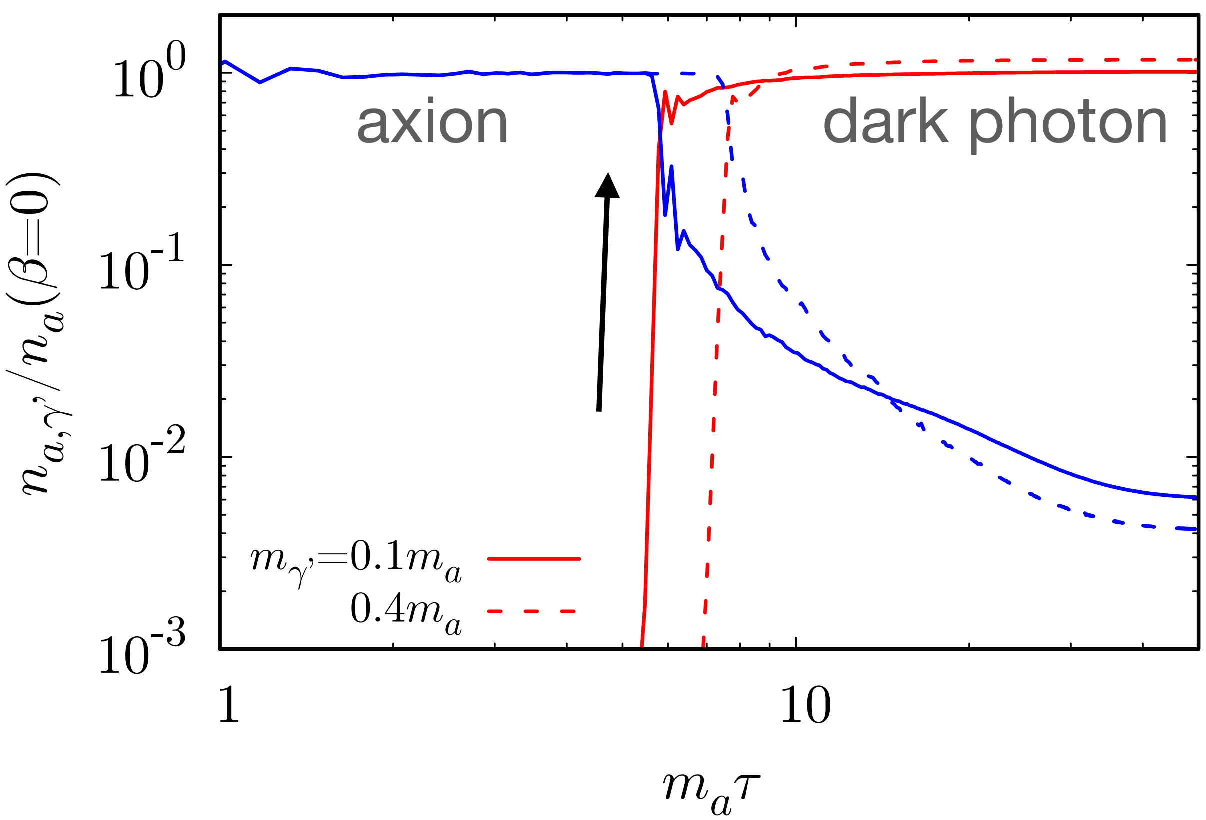
$$\longrightarrow \ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a}\right)\mathbf{A}_{\mathbf{k},\pm} = 0$$



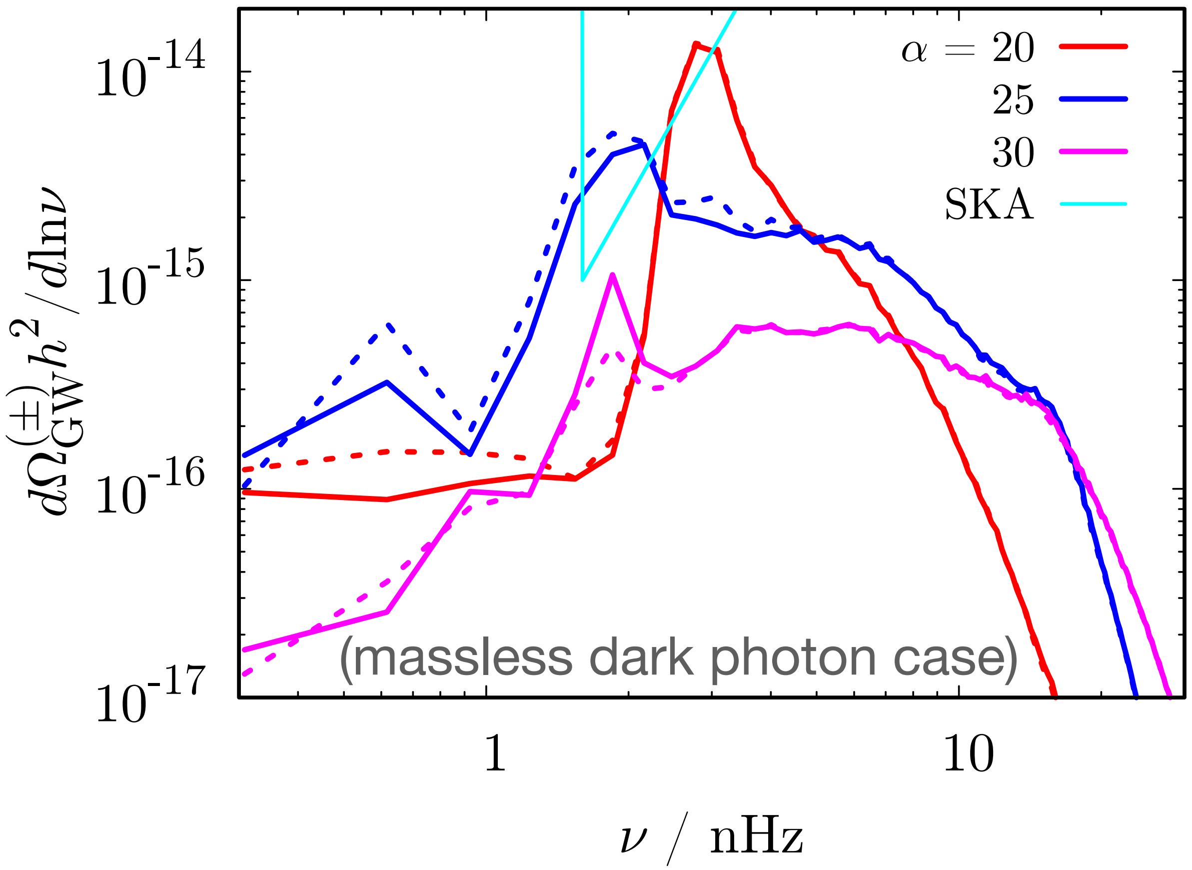


—> magnetogenesis Fujita+(2015), Kamada+(2016), Patel+(2020), …

non-linear evolution



gravitational wave



- Axion abundance is suppressed & dark photon is dominant

  Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188
  (see also NK, T. Sekiguchi, F. Takahashi, 1711.06590)

- Produced dark photons can stabilize the dark Higgs $V(\Phi) \ni |\boldsymbol{A}|^2|\Phi|^2$

  —> secondary inflation, early dark energy

  NK, Nakagawa, Takahashi, 2111.06696 Nakagawa, Takahashi, Yin, 2209.01107

- GW emission with circular polarization NK, Soda, Urakawa, 2010.10990

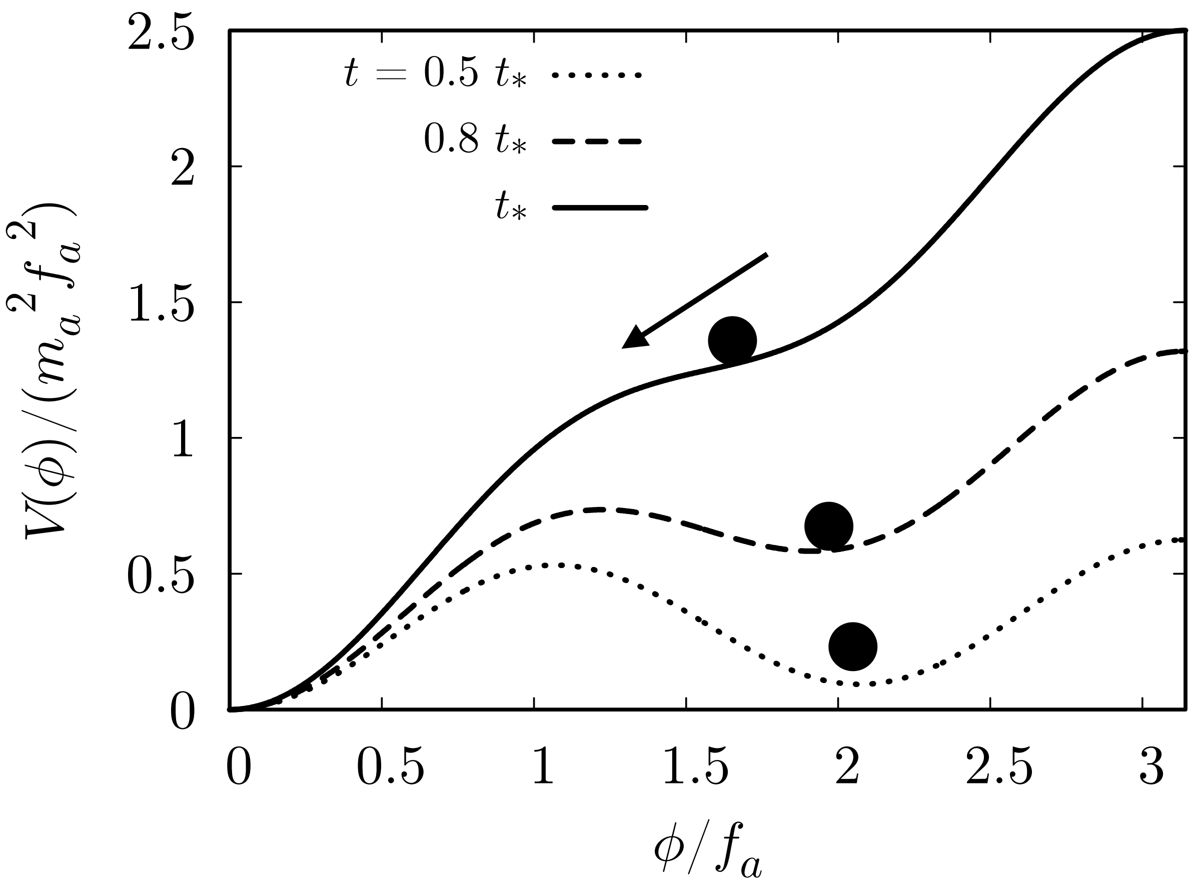
see also Machado+ (2019), Salehian+ (2020), Ratzinger+ (2020), Namba+ (2020)

Resonant dark photon production w/o large coupling

NK, Takahashi, 2303.05492

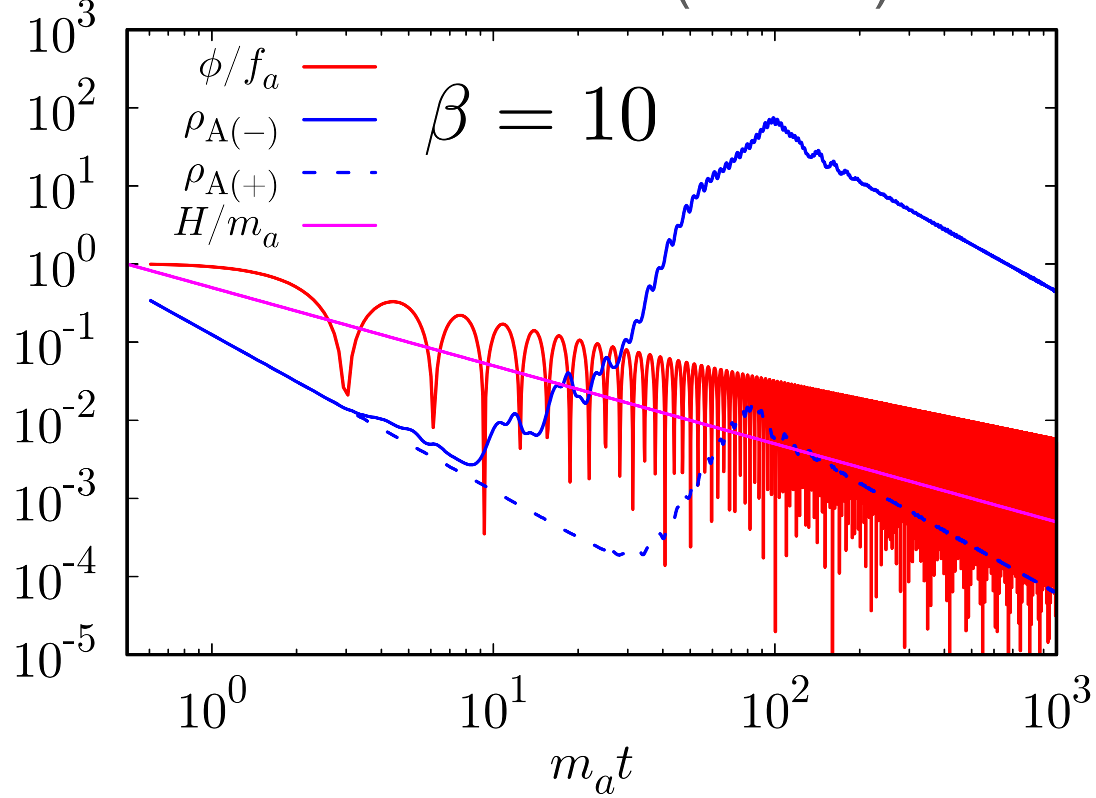
$$V(\phi) = m_a(t)^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right] + \Lambda_H^4 \left[1 - \cos\left(\frac{N_H \phi}{f_a}\right)\right]$$

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

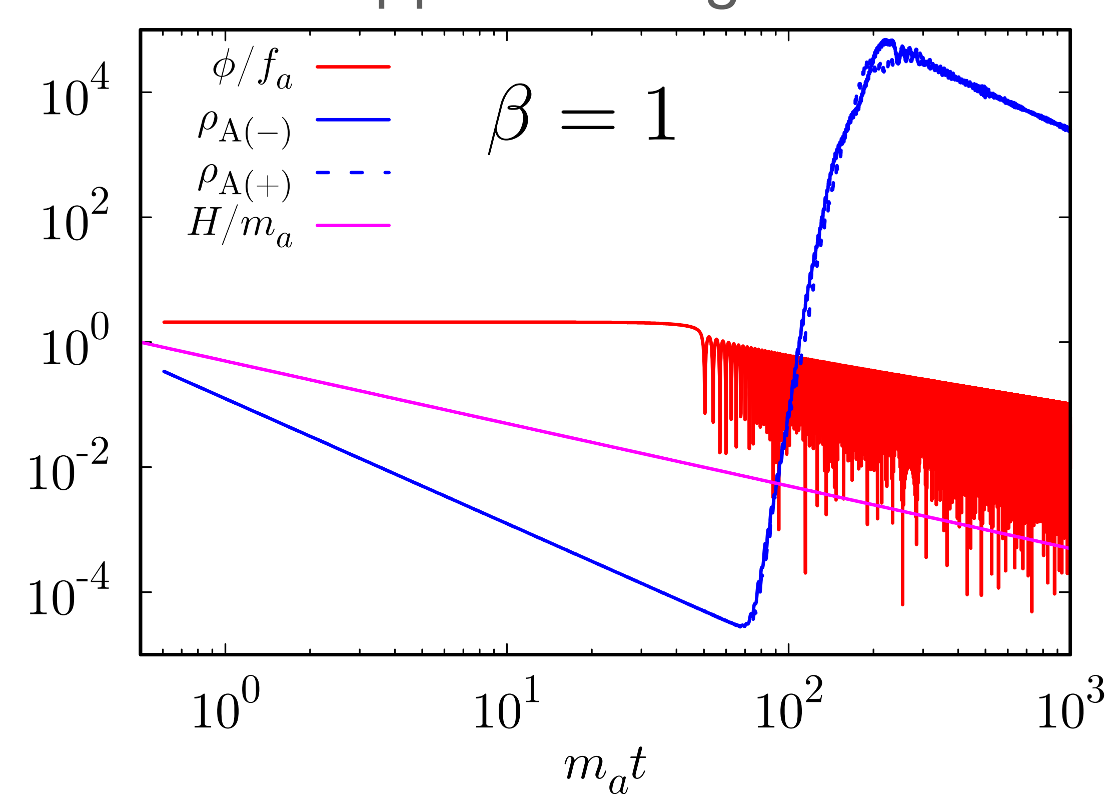


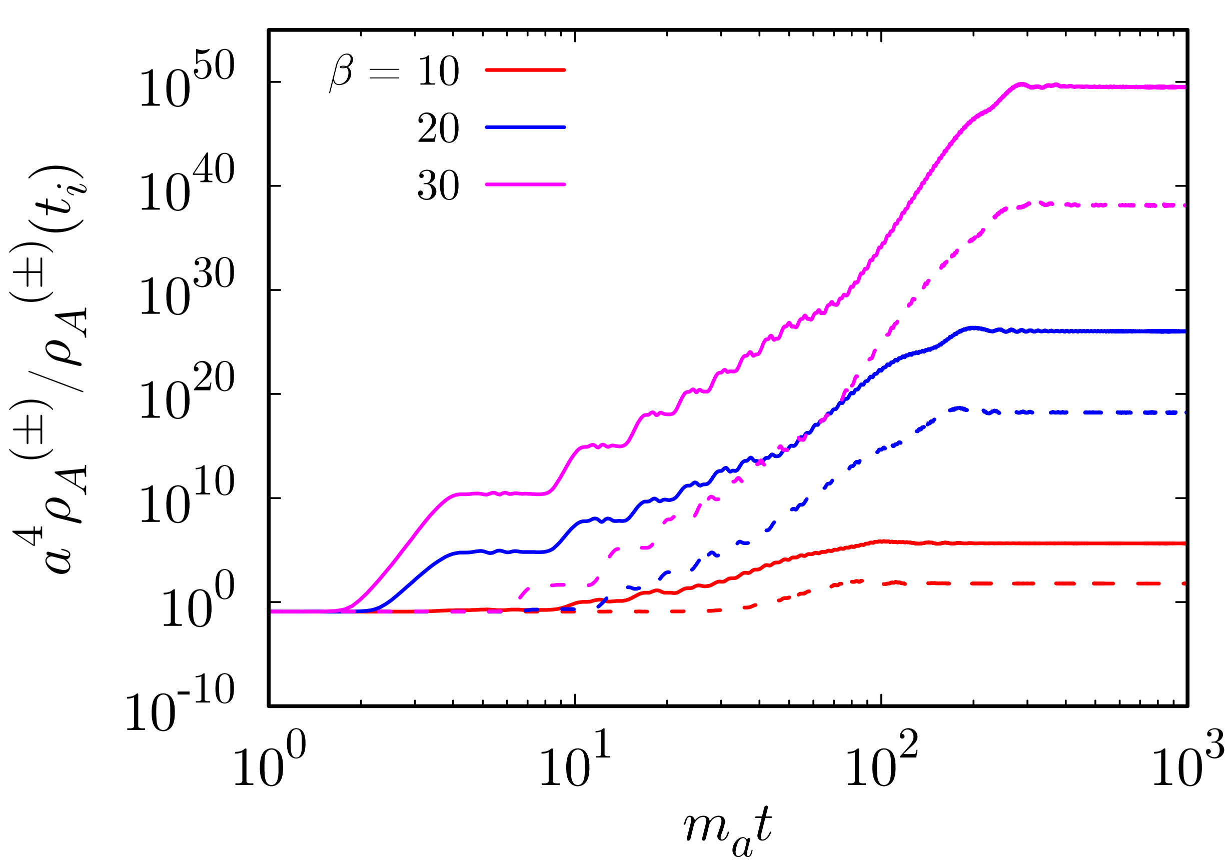
Application for QCD axion cosmology

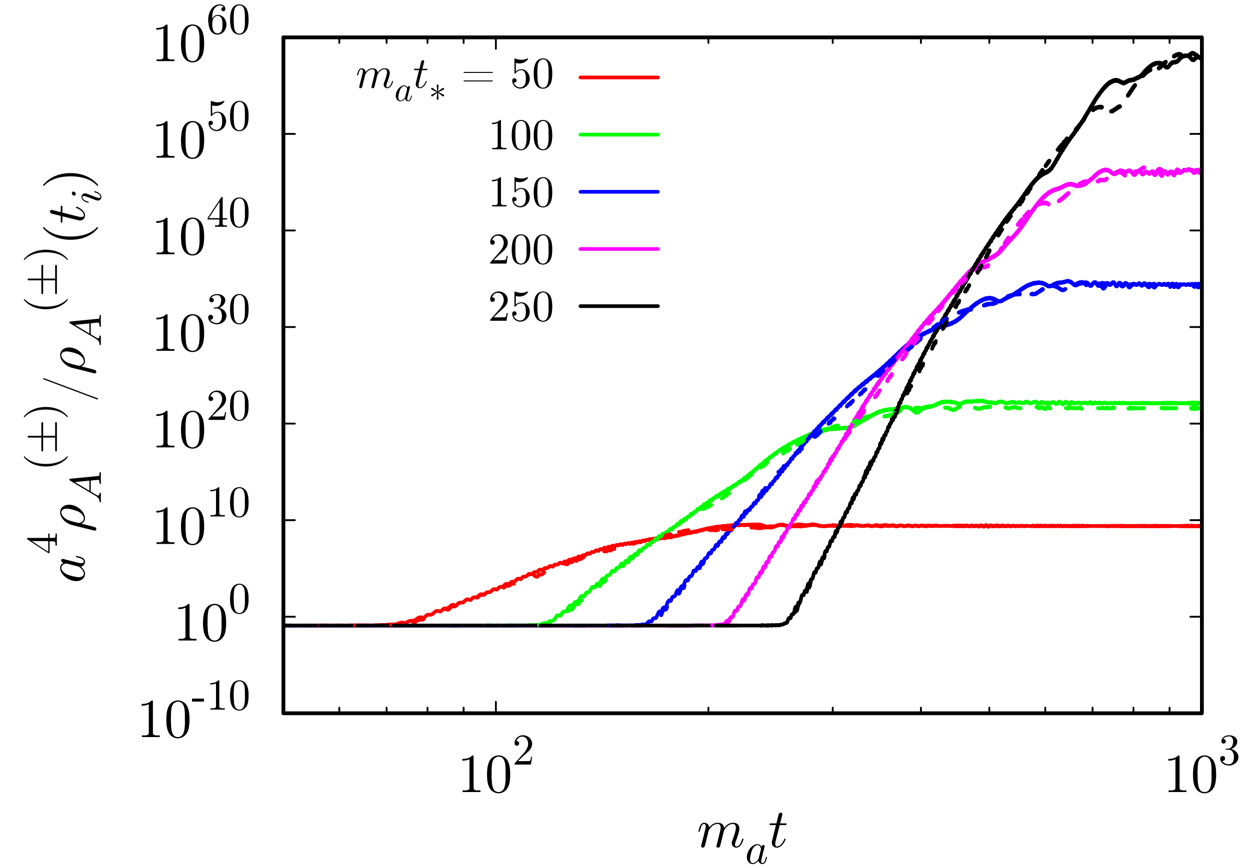
—> Jeong, Matsukawa, Nakagawa, Takahashi 2201.00681 conventional (cosine)



trapped misalignment







NK, Takahashi, 2303.05492

- growth is due to narrow resonance
—> no circular polarization

Coherent vector DM production

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

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

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

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

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

$\& \quad g_k \propto R_A$

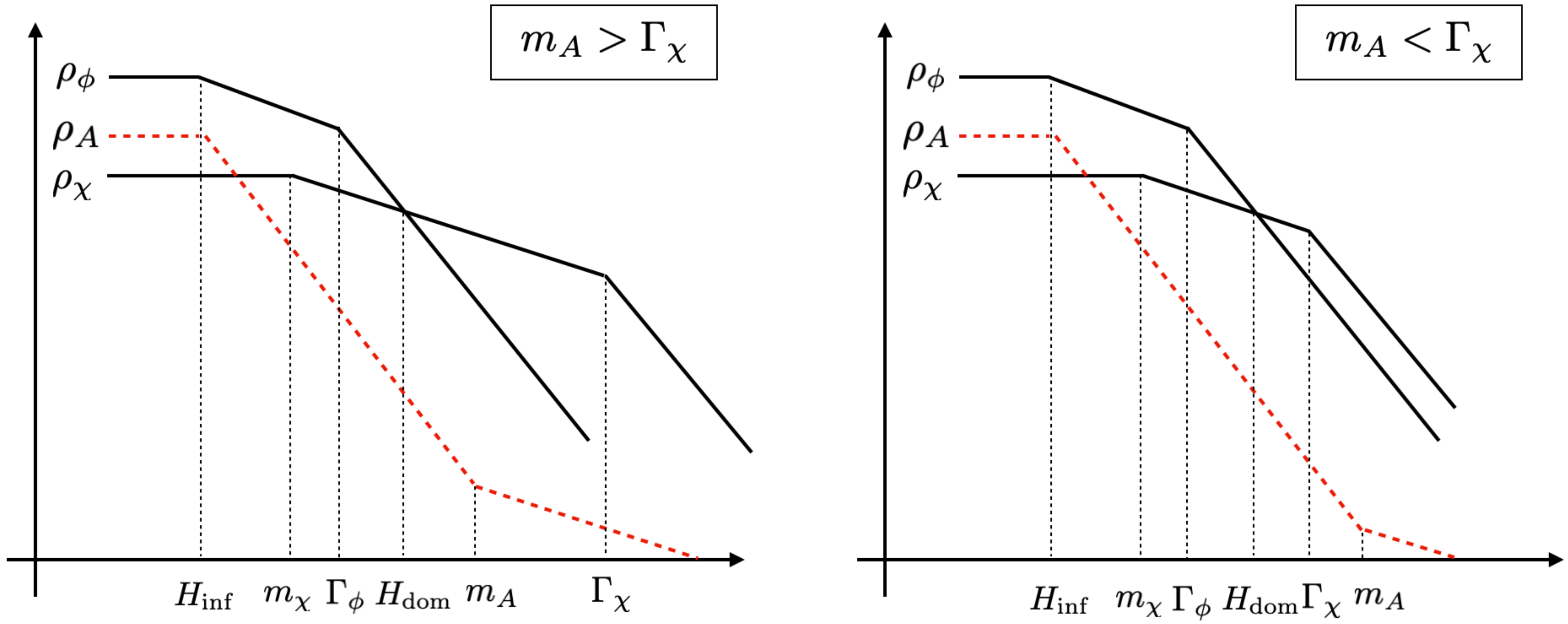
DM isocurvature perturbation $\quad S = \frac{\delta\rho_A}{\bar{\rho}_A} \sim \frac{H_{\mathrm{inf}}}{\pi\bar{A}_i} \propto R_A^{-1}$

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

“Viable” coherent vector DM scenario

NK, Nakayama, 2303.04287

curvaton scenario : introduction of an additional scalar field (χ) responsible for the curvature perturbation



additional constraints: $\Gamma_\chi \lesssim H_{\rm dom}$ (non-Gaussianity)

$m_A \lesssim H_{\rm dom}$ (residual isocurvature)

Anisotropic background metric (Bianchi-I universe)

$$ds^2 = -dt^2 + a^2(t)\left[e^{-4\sigma}dx^2 + e^{2\sigma}(dy^2 + dz^2)\right]$$

Cosmic expansion (Einstein equation):

$$H^2 = \Sigma^2 + \frac{1}{3M_{\rm Pl}^2}(\rho_\phi + \rho_A), \quad \dot{\Sigma} + 3H\Sigma = \frac{1}{3M_{\rm Pl}^2}\left(\frac{f\dot{A}_x}{a}\right)^2 e^{4\sigma}$$

$$(\Sigma \equiv \dot{\sigma})$$

Mode equation of curvaton:

$$\widetilde{\chi}''_{\vec{k}} + \left(a^2(\tau)p^2(\tau) - \frac{a''}{a} + a^2 m_\chi^2\right)\widetilde{\chi}_{\vec{k}} = 0, \quad p^2(\tau) = a^{-2}(\tau)\left(e^{4\sigma}k_x^2 + e^{-2\sigma}\vec{k}_\perp^2\right),$$

Anisotropic curvature perturbation

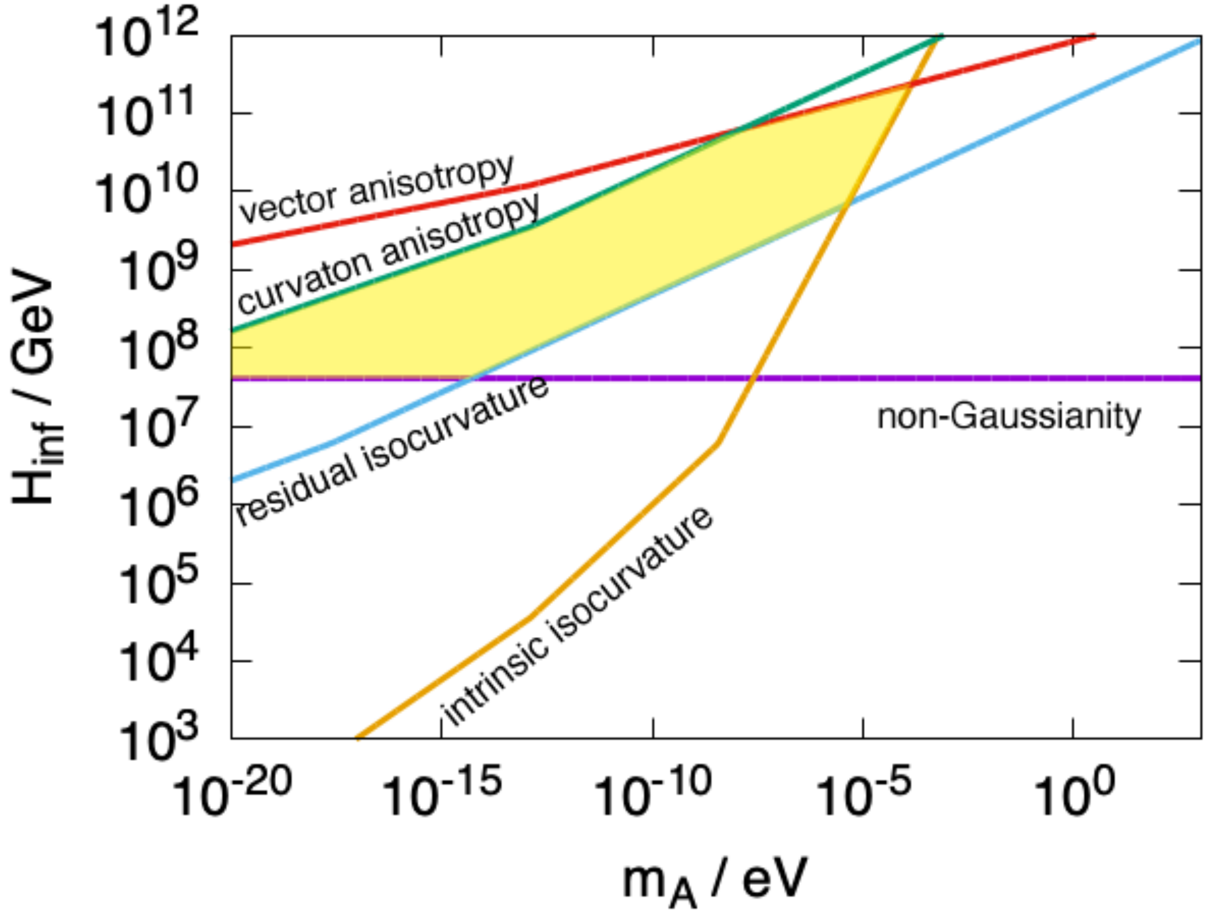
$$\mathcal{P}_\zeta^{(\rm curv)}(\vec{k}_{\rm end}) \simeq \mathcal{P}_{\zeta 0}^{(\rm curv)}(k_{\rm end})\left[1 + g^{(\rm curv)}\sin^2\theta_k\right]$$

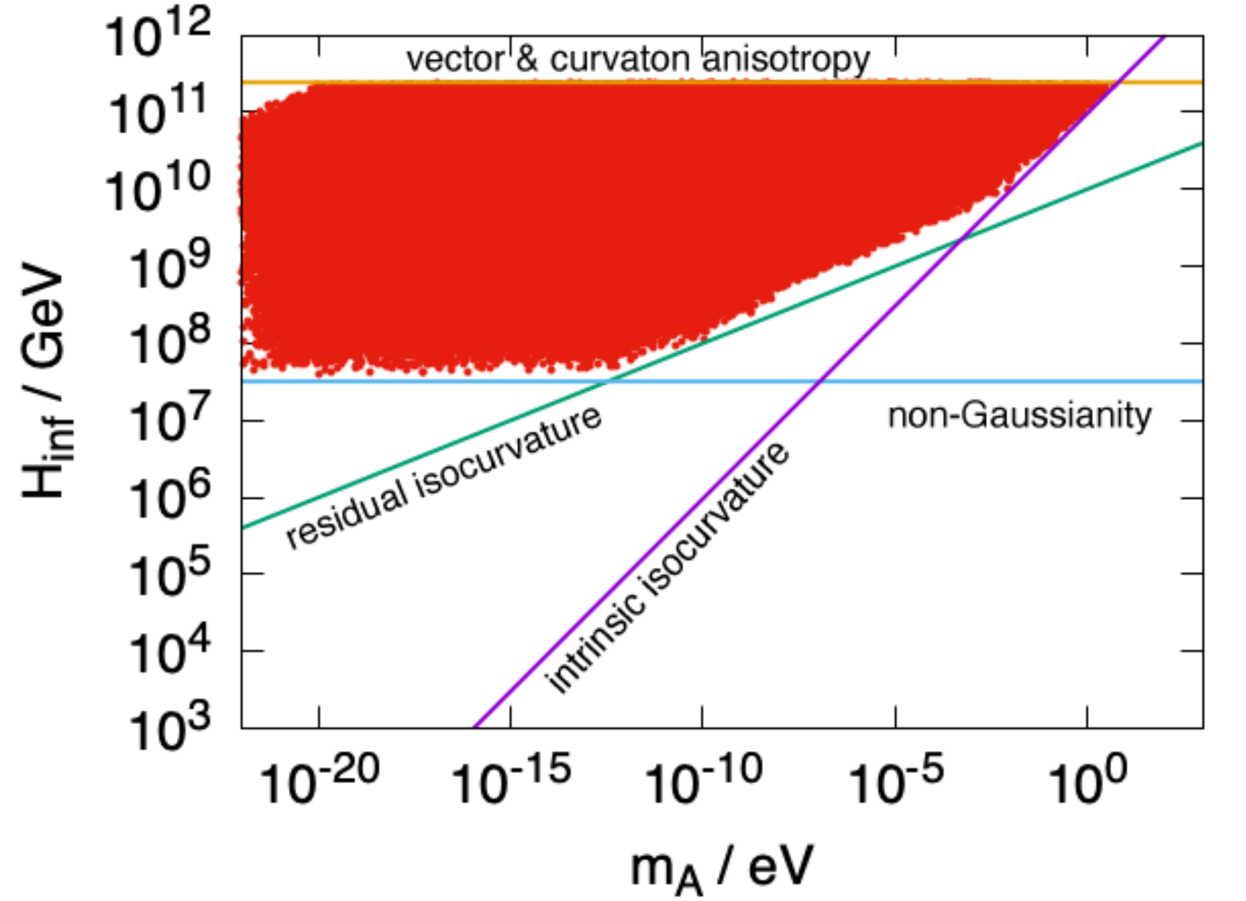
$$g^{(\rm curv)} = 3(n_s - 1)(\sigma_{\rm end} - \sigma_k) + 9\sigma_k$$

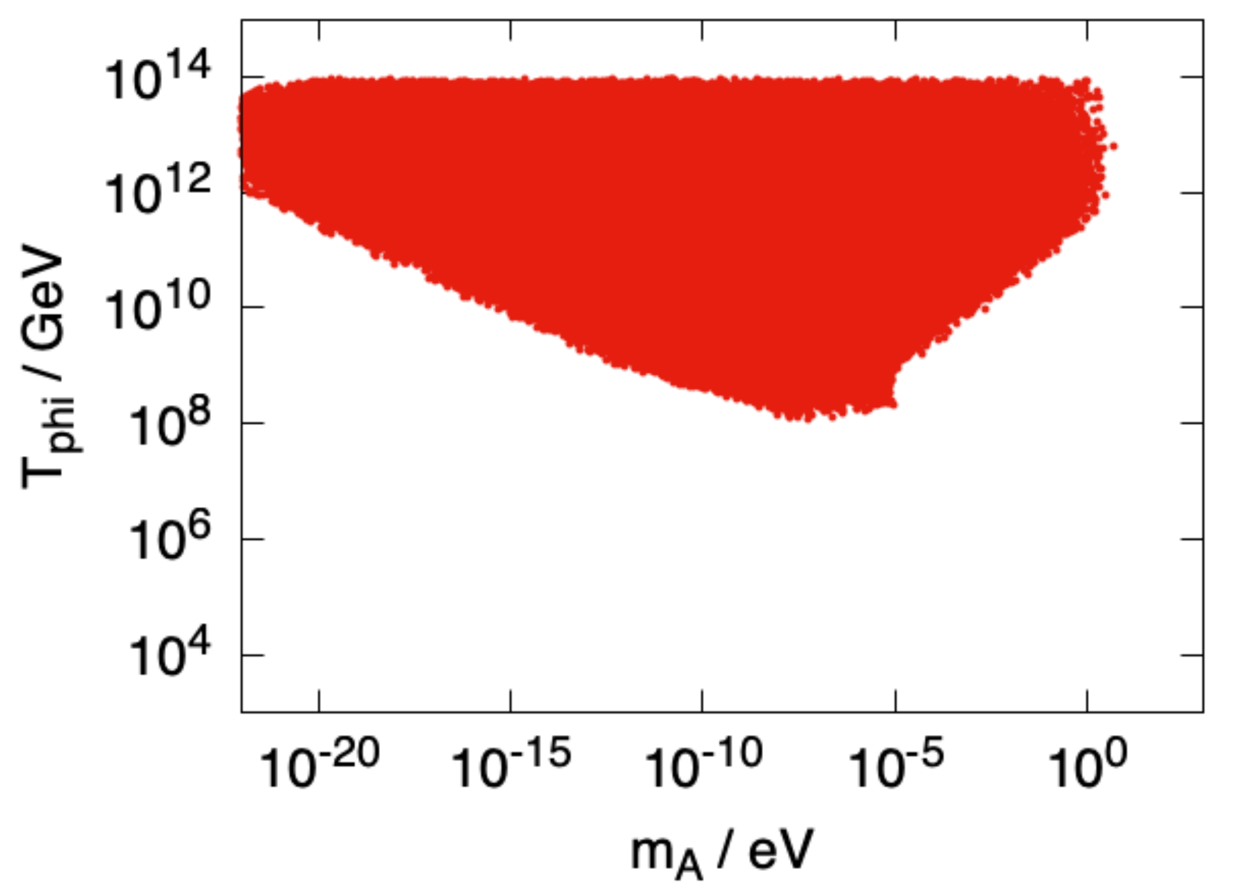
viable parameter region

NK, Nakayama, 2303.04287

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







Dark photon DM from Abelian-Higgs cosmic strings

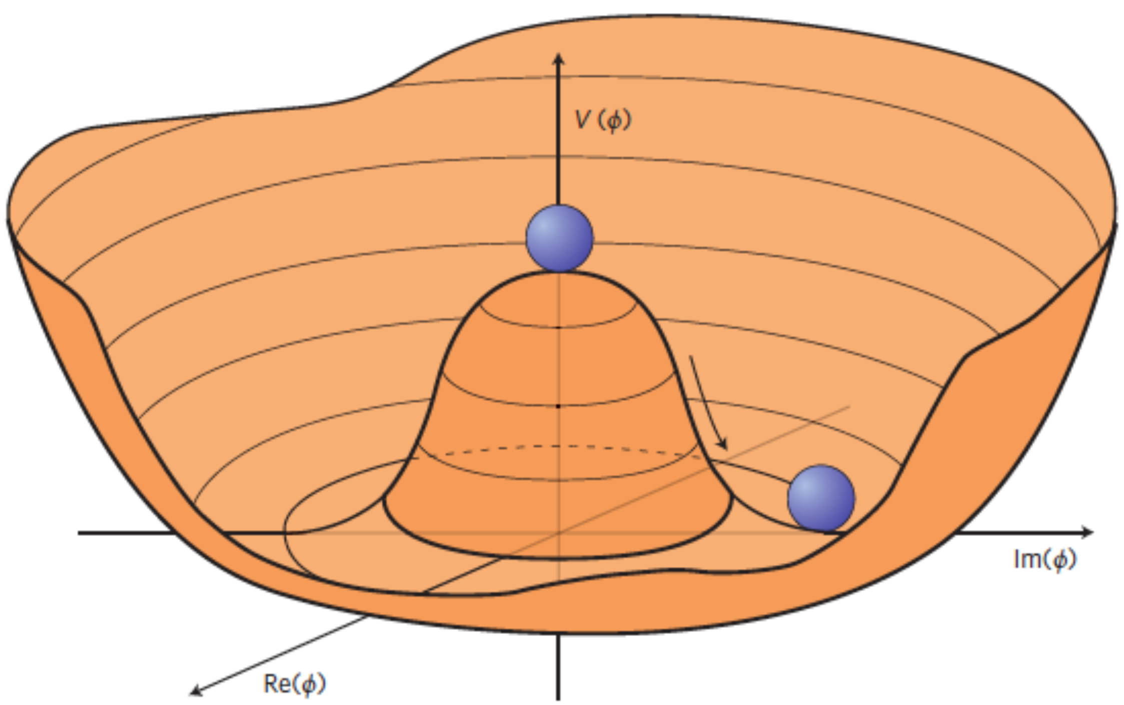
Long, Wang 1901.03312, NK, Nakayama 2212.13573

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

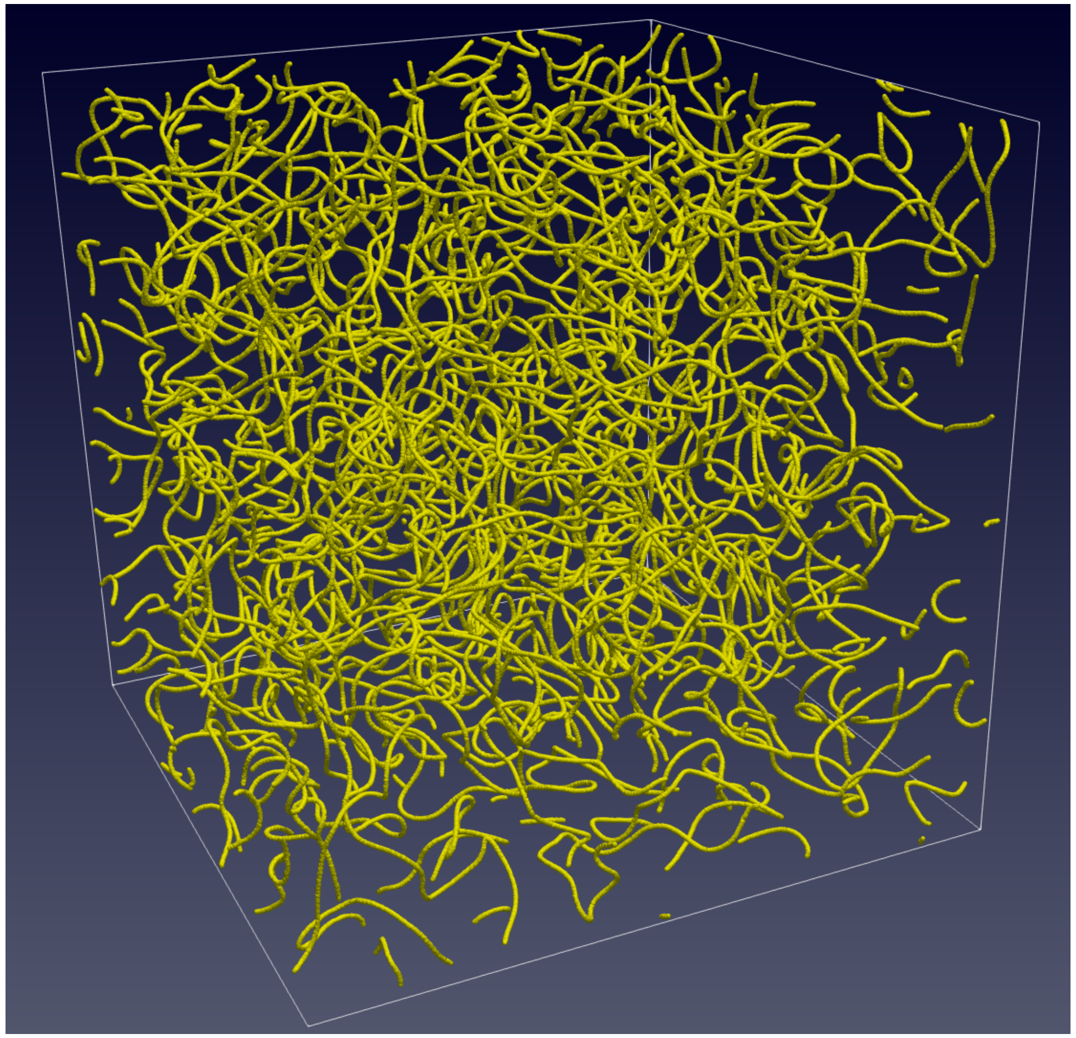
$$(\mathcal{D}_\mu = \partial_\mu - ieA_\mu, \;\; F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$$

spontaneous U(1) symmetry breaking

—> formation of cosmic strings



Ellis, Gaillard, Nanopoulos 1504.07217



Scenario

- “Light” dark photons can be produced by cosmic strings

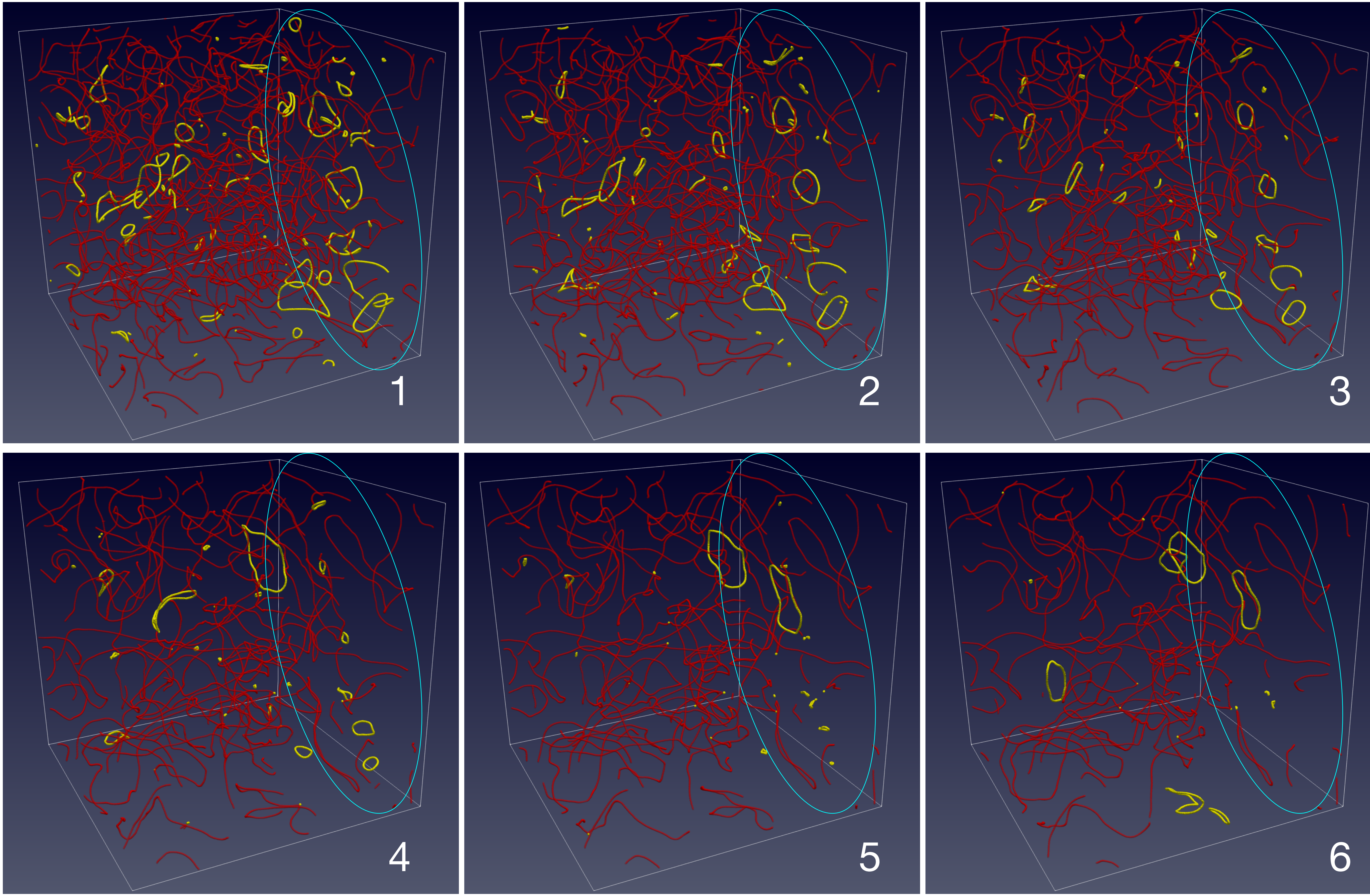
  small gauge coupling
  e = 0 limit corresponds to the axion emission (global string case)

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

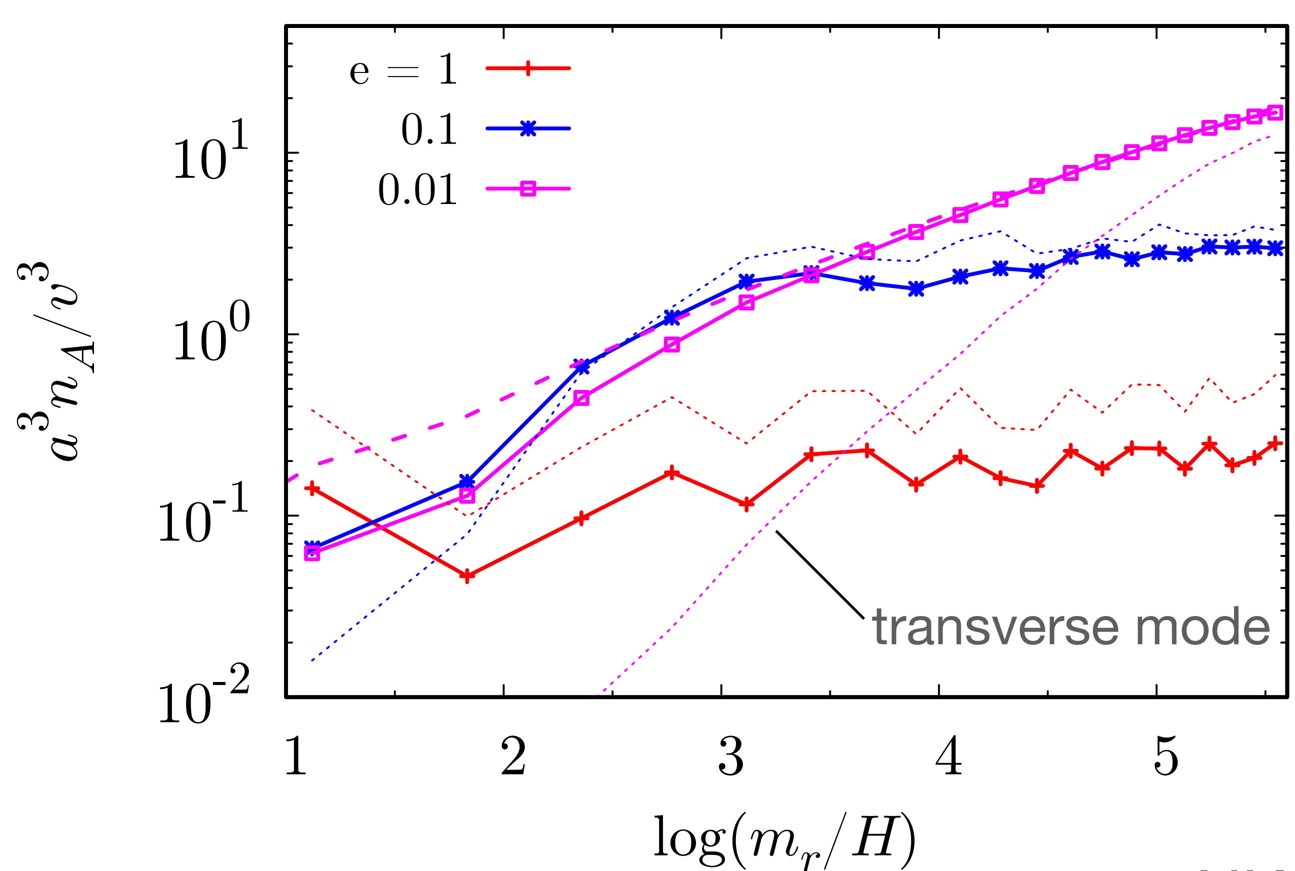
  (i.e. loop oscillation frequency becomes smaller than the mass) $\rightarrow \quad H \lesssim m_A$

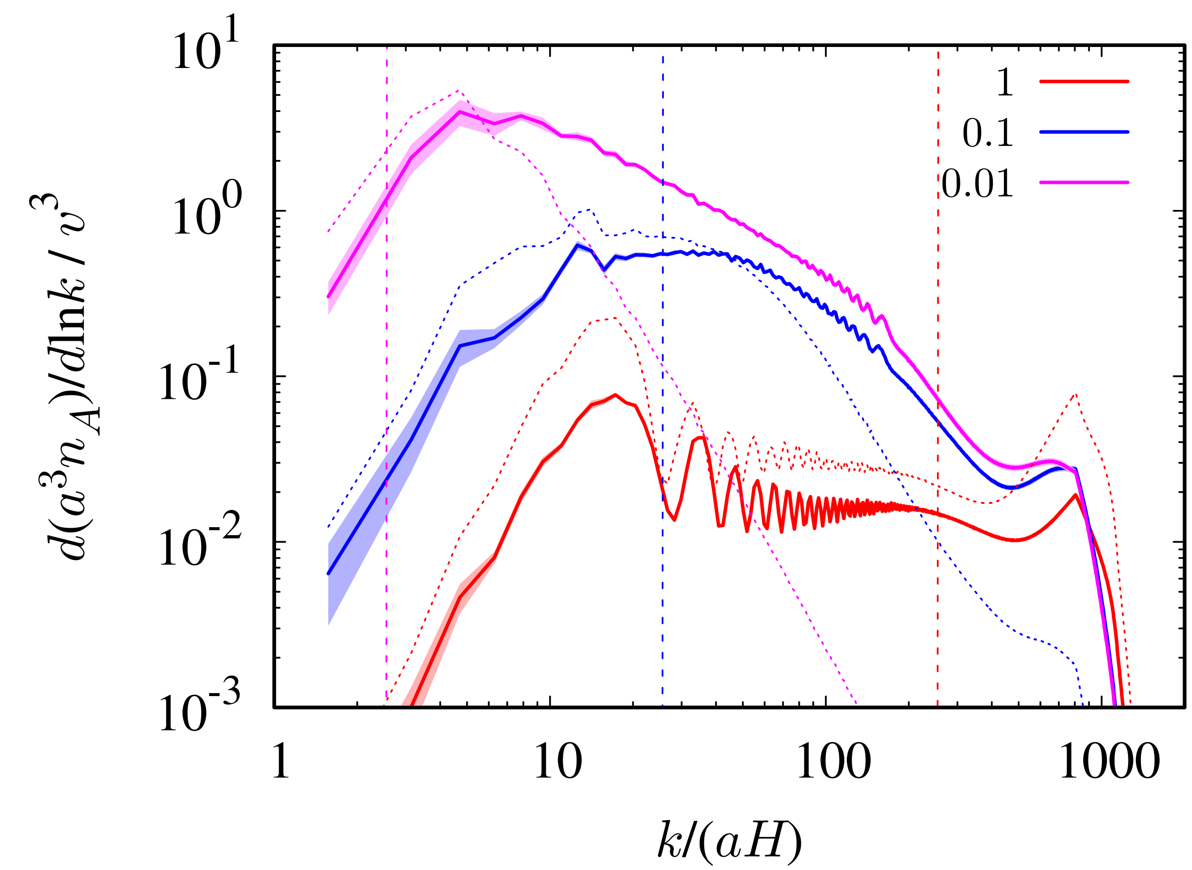
- After that, string evolves like “local” string

  (network loses the energy only through the GW emission) e=0.01 and λ=2



Dark photon DM abundance & spectrum





NK, Nakayama 2212.13573

$$\Omega_A h^2 = \frac{m_A (n_{A,0}/s_0) h^2}{\rho_{\rm cr,0}/s_0} \simeq 0.091 \left(\frac{\xi}{12}\right) \left(\frac{m_A}{10^{-13}\,{\rm eV}}\right)^{1/2} \left(\frac{v}{10^{14}\,{\rm GeV}}\right)^2$$

$$\xi = 0.15 \log\left(\frac{m_r}{m_A}\right) \simeq 12 + 0.15 \log\left[\left(\frac{m_r}{10^{14}\,{\rm GeV}}\right)\left(\frac{10^{-13}\,{\rm eV}}{m_A}\right)\right]$$

GW emission from cosmic strings

Credit: Daniel Dominguez/CERN

Energy loss of loops = GW emission + vector boson emission

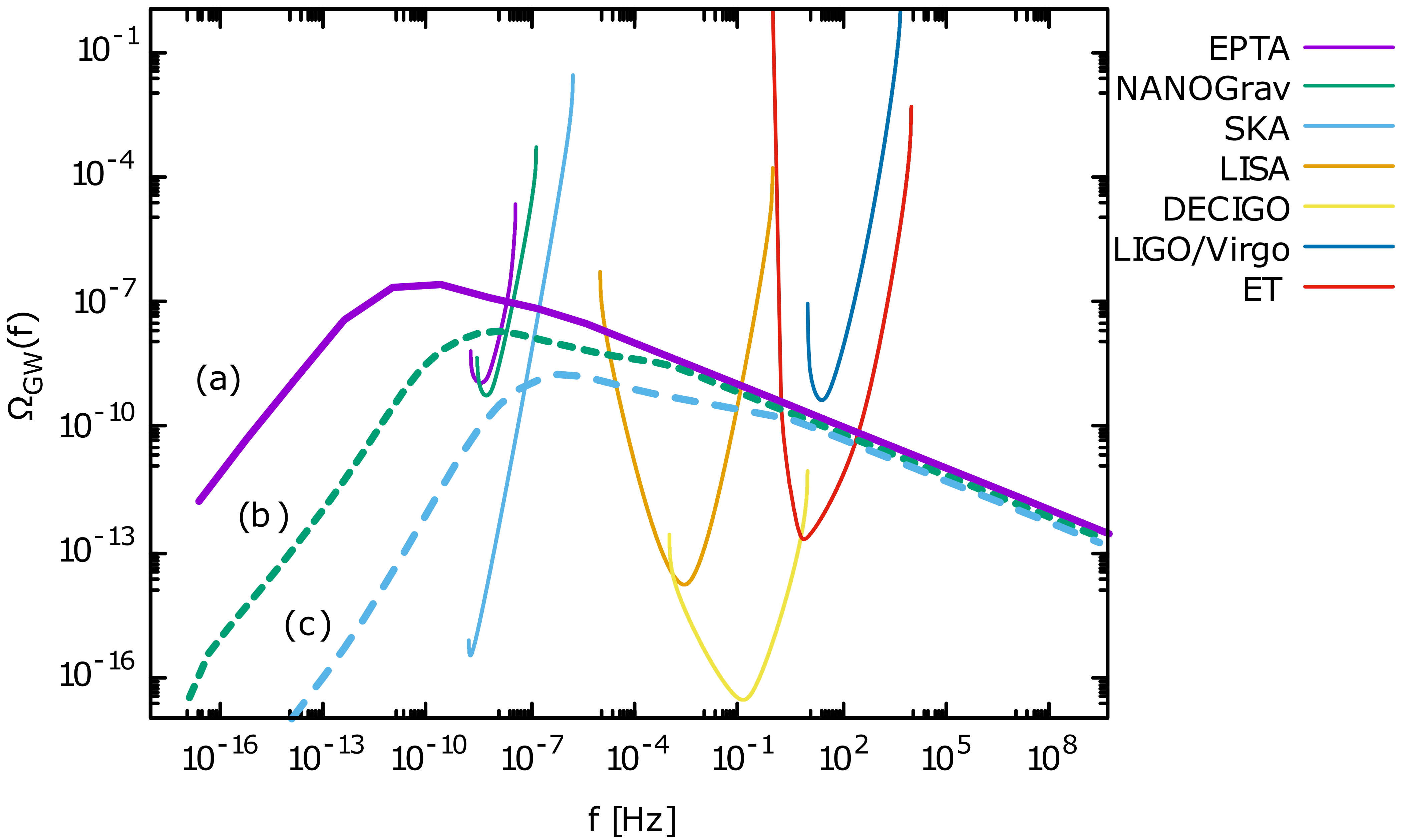
$$\frac{dE_\ell}{dt} = -\Gamma_{\rm GW} G\mu^2 - \Gamma_{\rm vec} v^2 \theta(1 - m_A \ell) \quad (\Gamma_{\rm GW} \sim \Gamma_{\rm vec} \sim 50)$$

Loops shorter than m_A^{-1} can emit dark photons

—> short lived & GW emission is suppressed

GW spectrum

NK, Nakayama 2212.13573



$(a)\ v = 10^{15}\,\mathrm{GeV},\ m_A = 10^{-14}\,\mathrm{eV}$

$(b)\ v = 10^{13}\,\mathrm{GeV},\ m_A = 10^{-10}\,\mathrm{eV}$

$(c)\ v = 10^{12}\,\mathrm{GeV},\ m_A = 10^{-5}\,\mathrm{eV}$

Summary

- Light dark photon DM can be produce by

  - axion oscillation (even w/o large coupling)
  - misalignment mechanism (still viable)
  - decay of cosmic string loops

- Gravitational waves can be a signature of this scenario

  - circular polarization (tachyonic production)
  - mildly tilted spectrum (cosmic string)
  - statistically anisotropic tensor mode