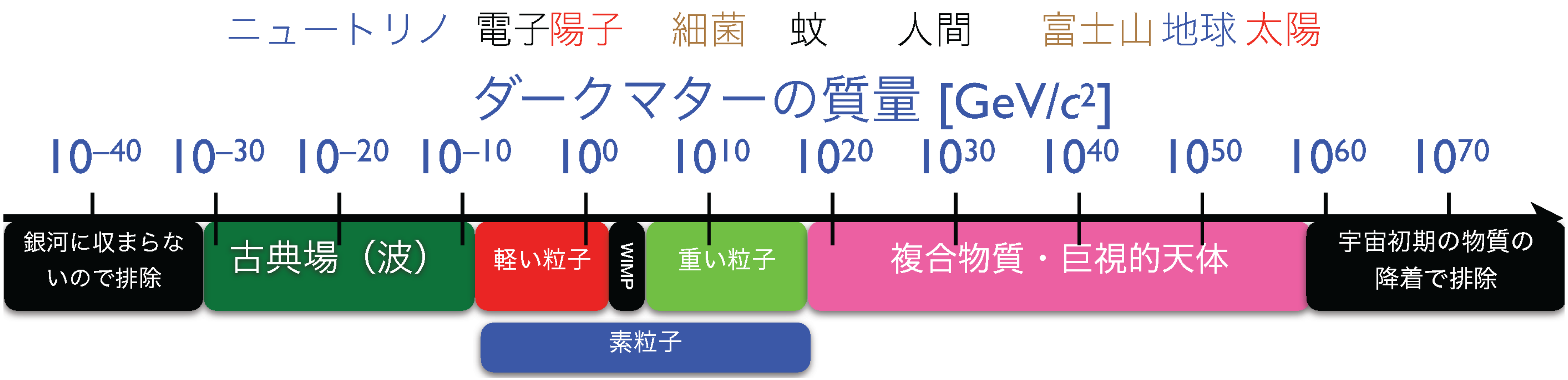
初期宇宙における軽いダークフォトンダークマターの生成

北嶋直弥

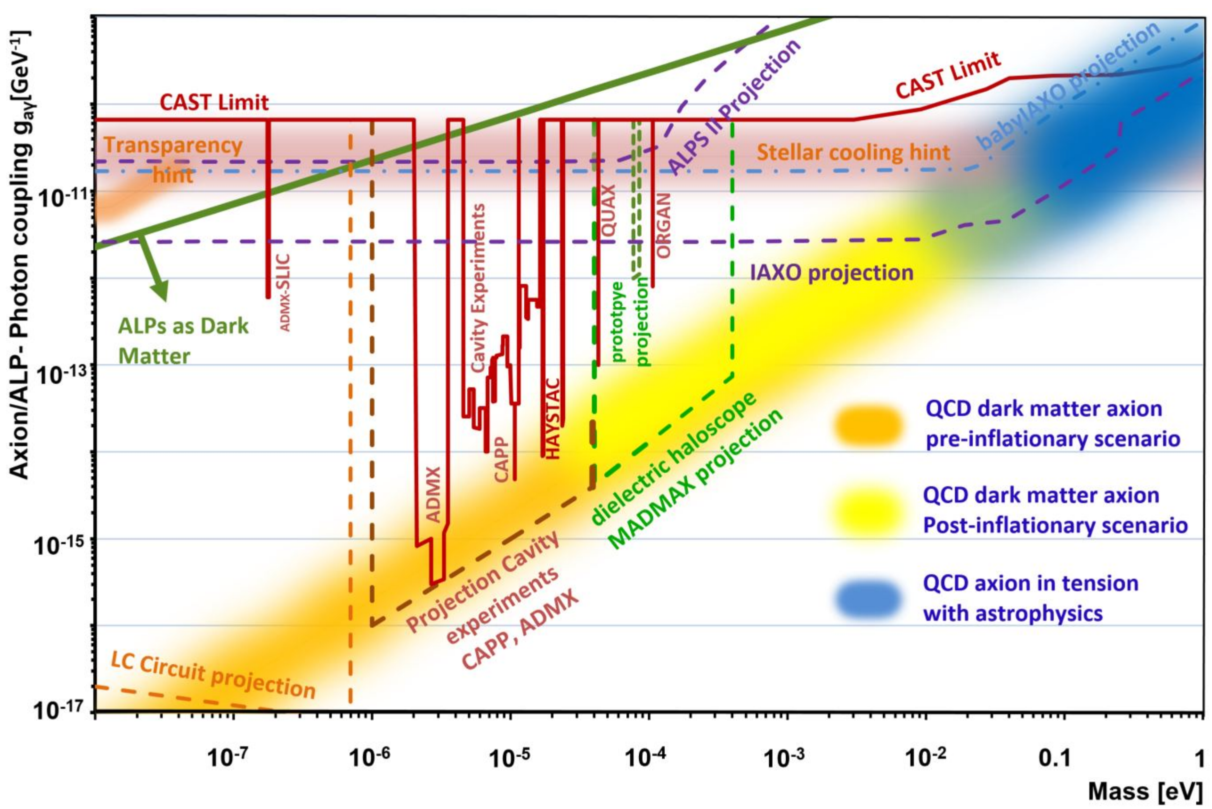
FRIS
TOHOKU UNIVERSITY

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

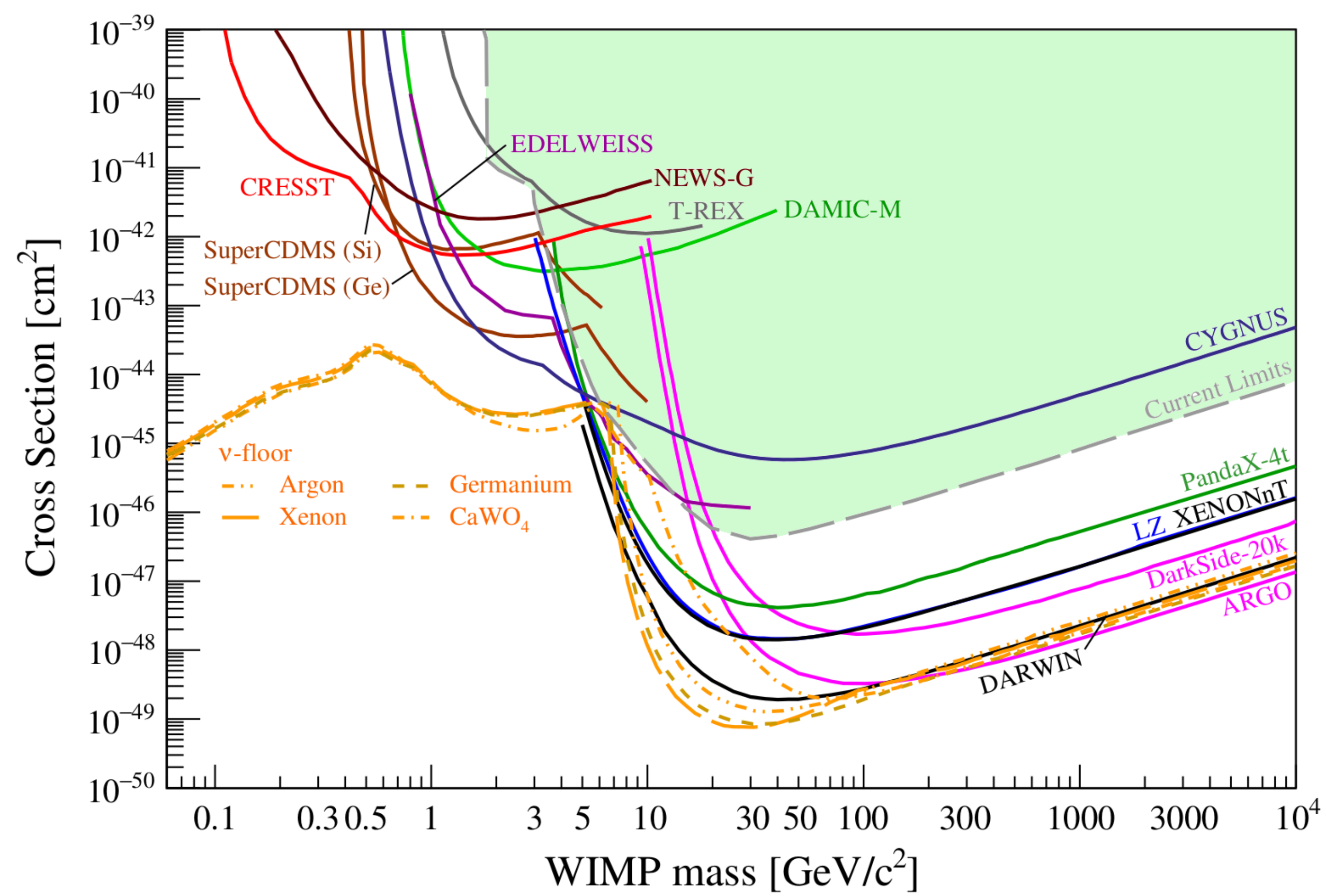
素粒子現象論研究会 2022, 3/16-18, 大阪公立大学



Axion search

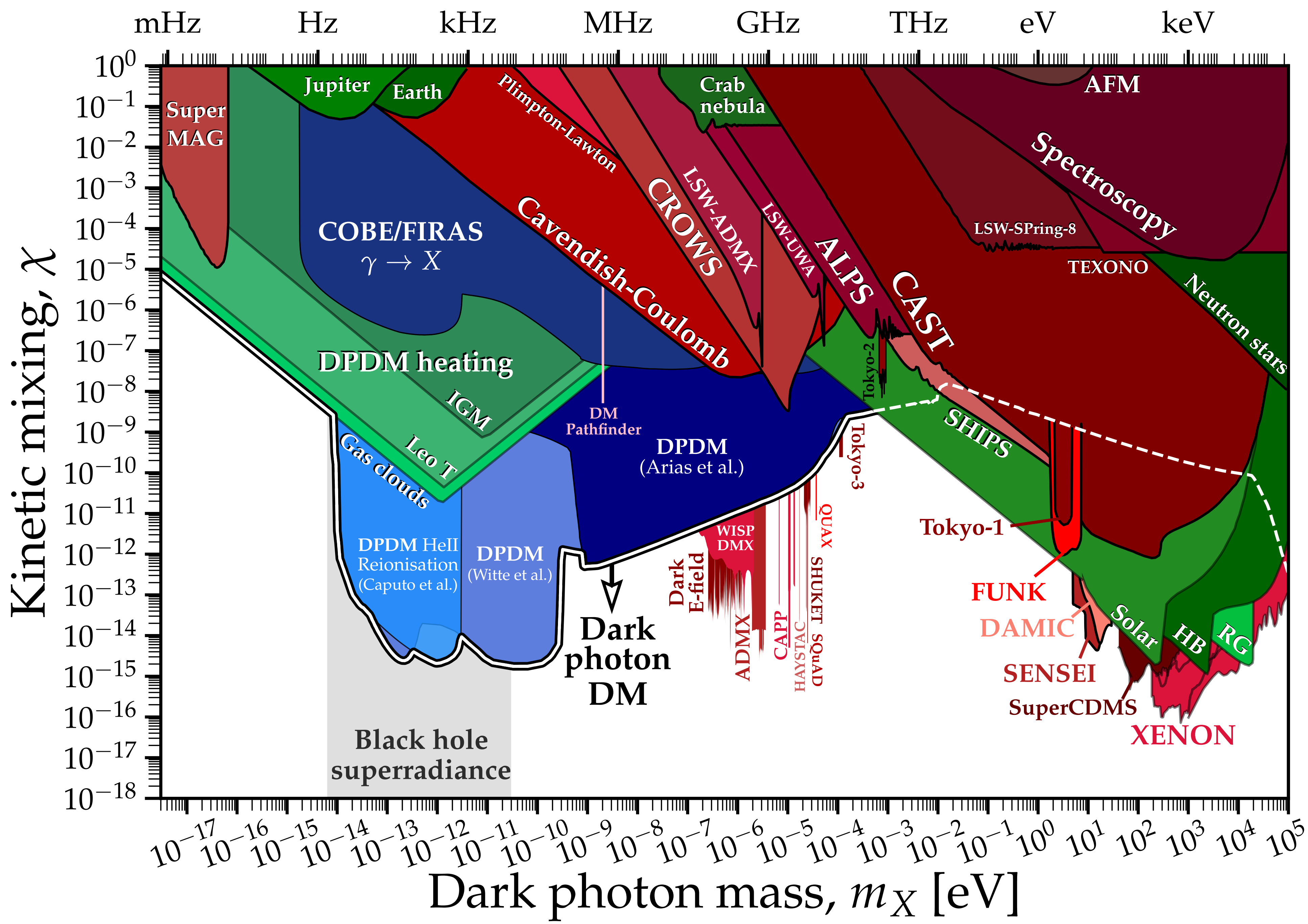


WIMP search



APPEC report 2104.07634

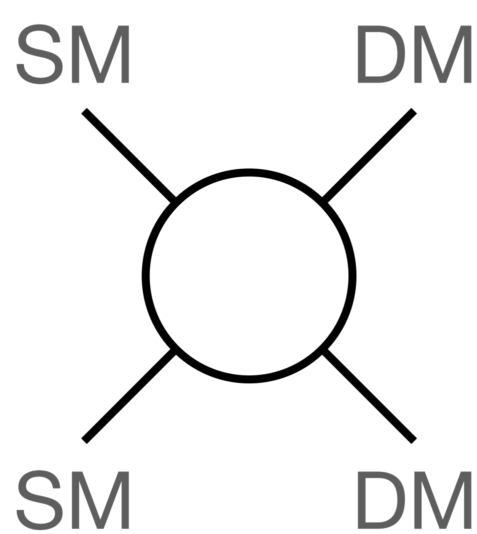
Dark photon search $\mathcal{L} \ni \frac{1}{2}\chi F^{\mu\nu} X_{\mu\nu}$

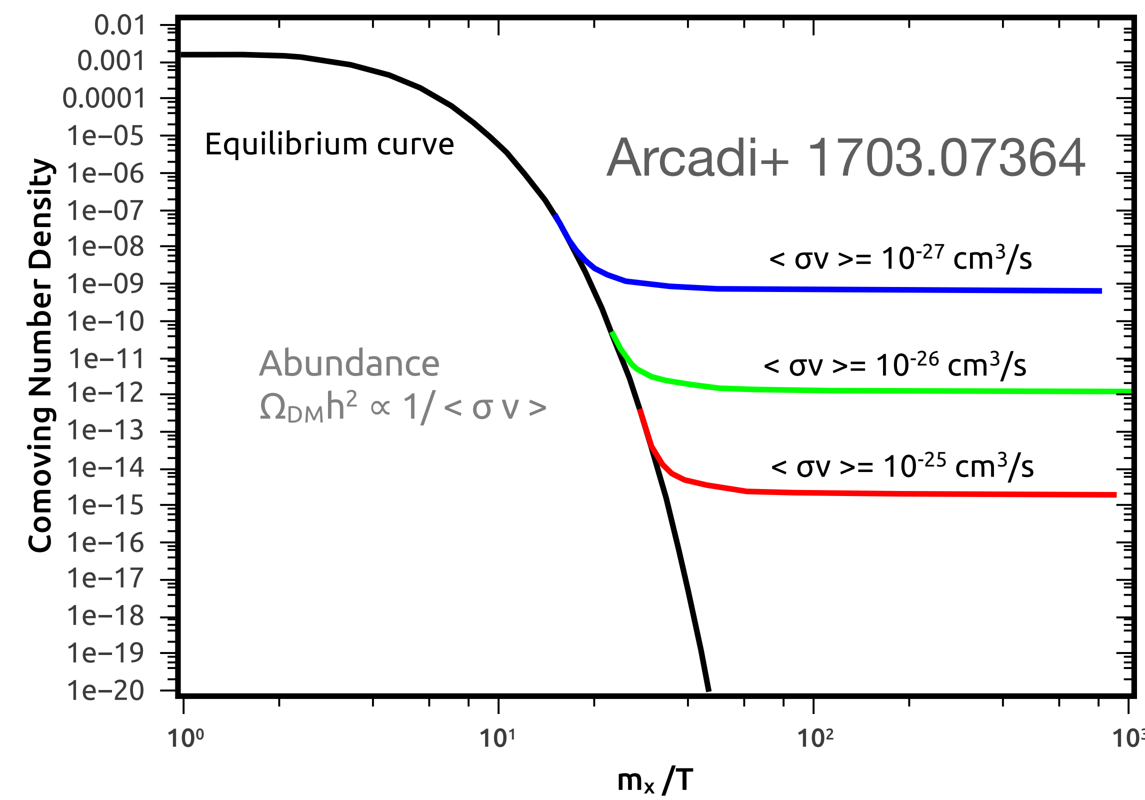


Caputo et al 2105.04565

Dark matter production

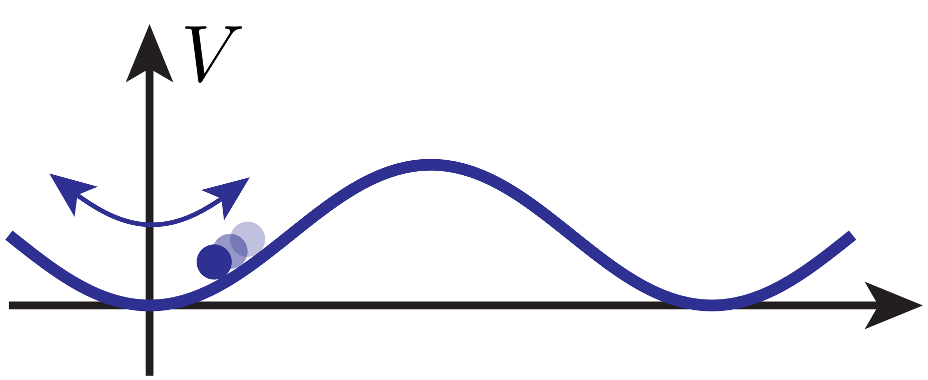
WIMP DM : thermal freeze-out



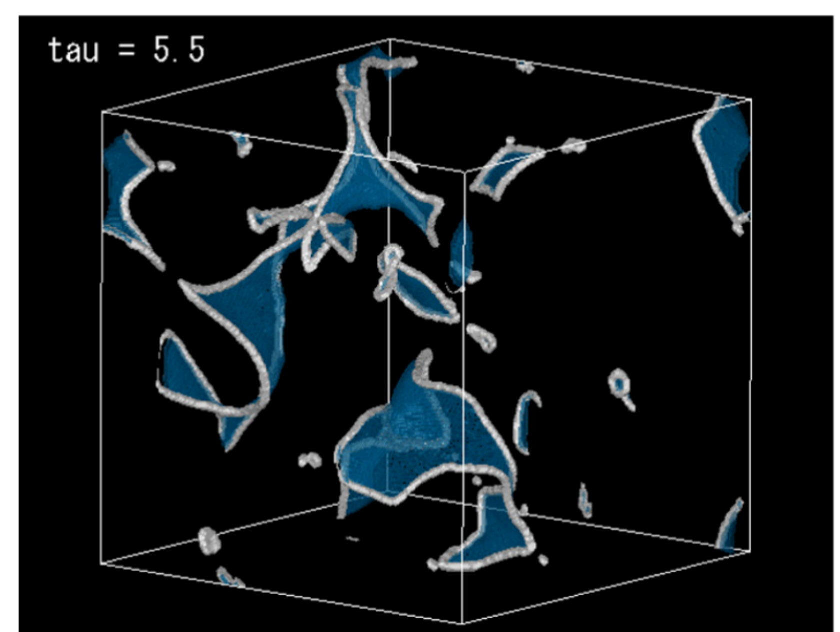


Axion DM : non-thermal production

- misalignment production



- topological defect



Hiramatsu et al 1202.5851

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)
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)

Dark photon DM production

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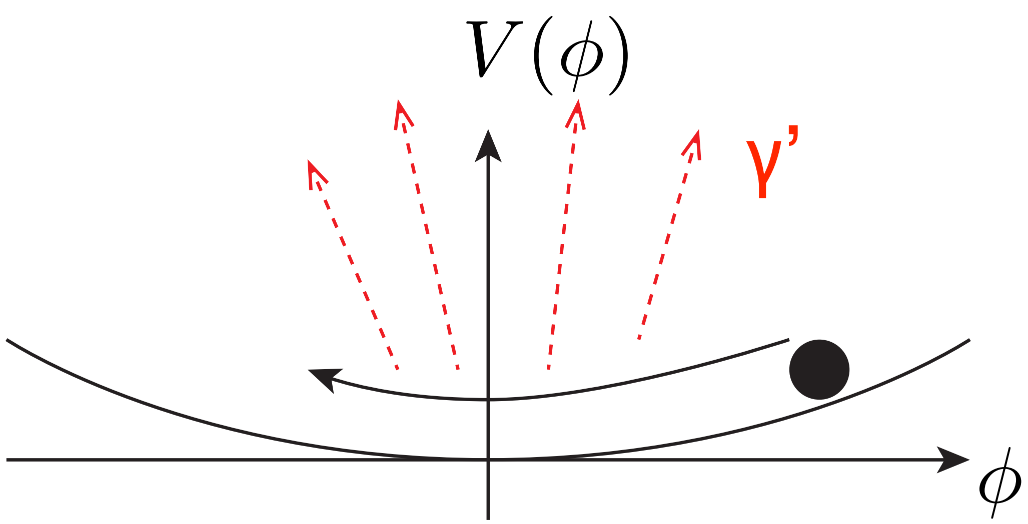
- Production from cosmic strings Long, Wang (2019), NK, Nakayama (2022)

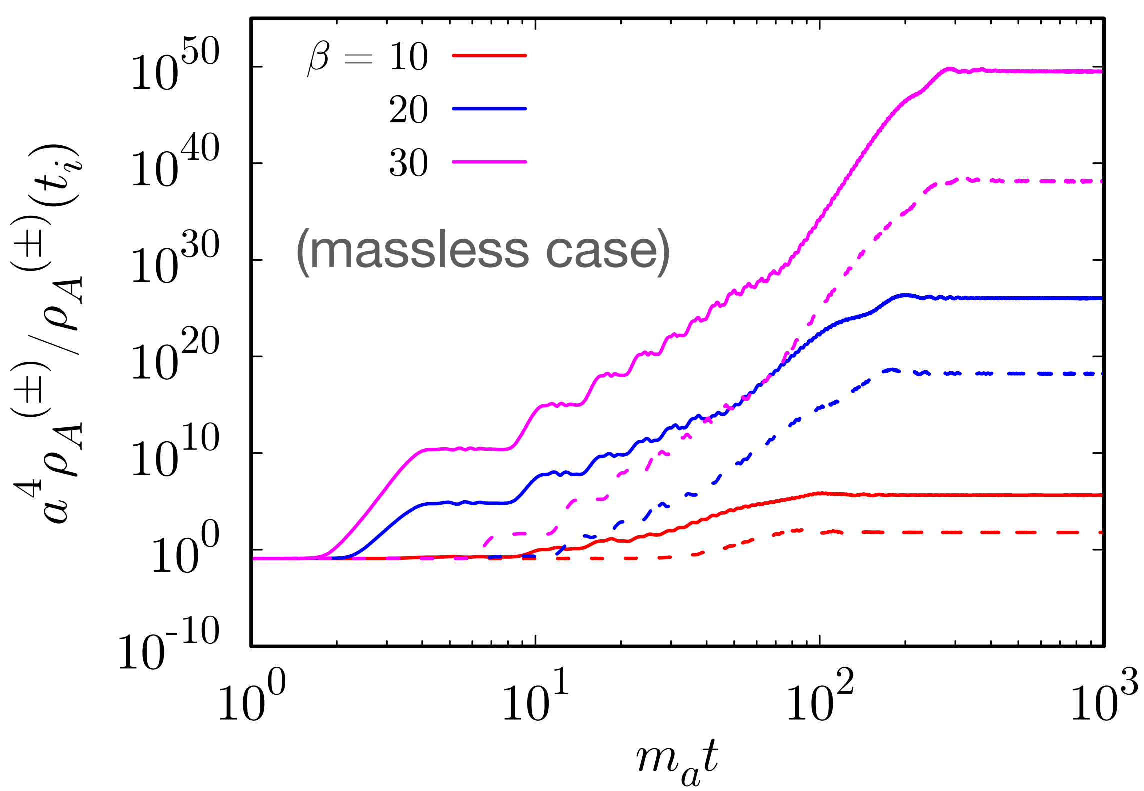
Resonant dark photon production from axion

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

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

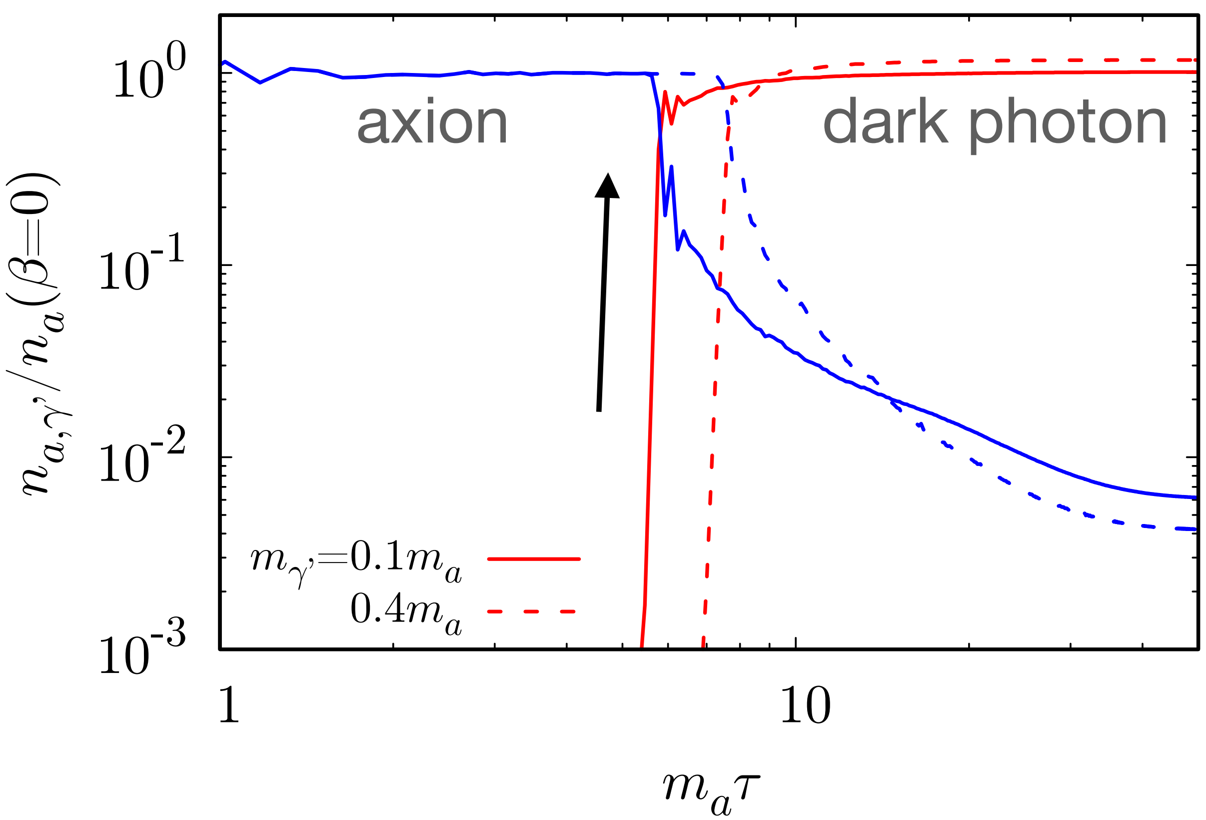
$$\longrightarrow \ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a}\right)\mathbf{A}_{\mathbf{k},\pm} = 0$$



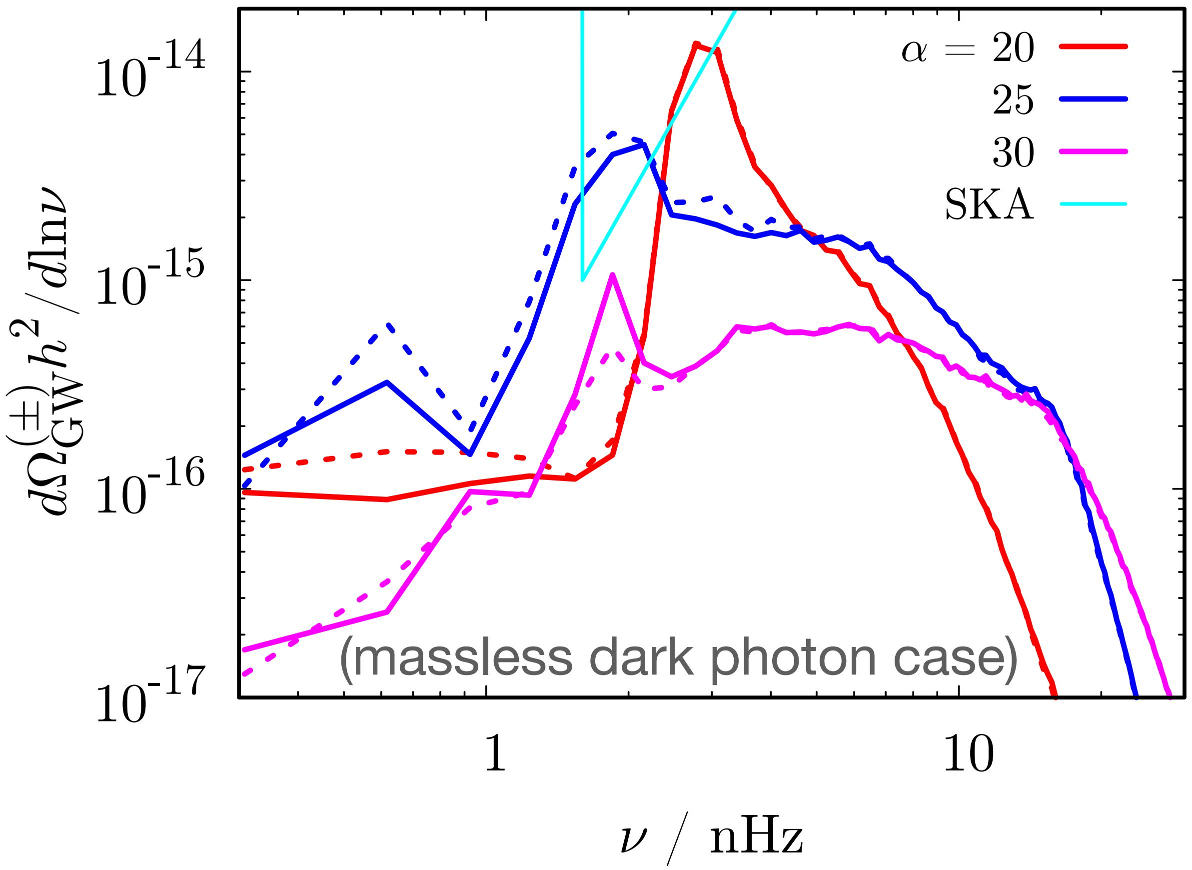


—> magnetogenesis Fujita+(2015), Kamada+(2019), Patel+(2020), …

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

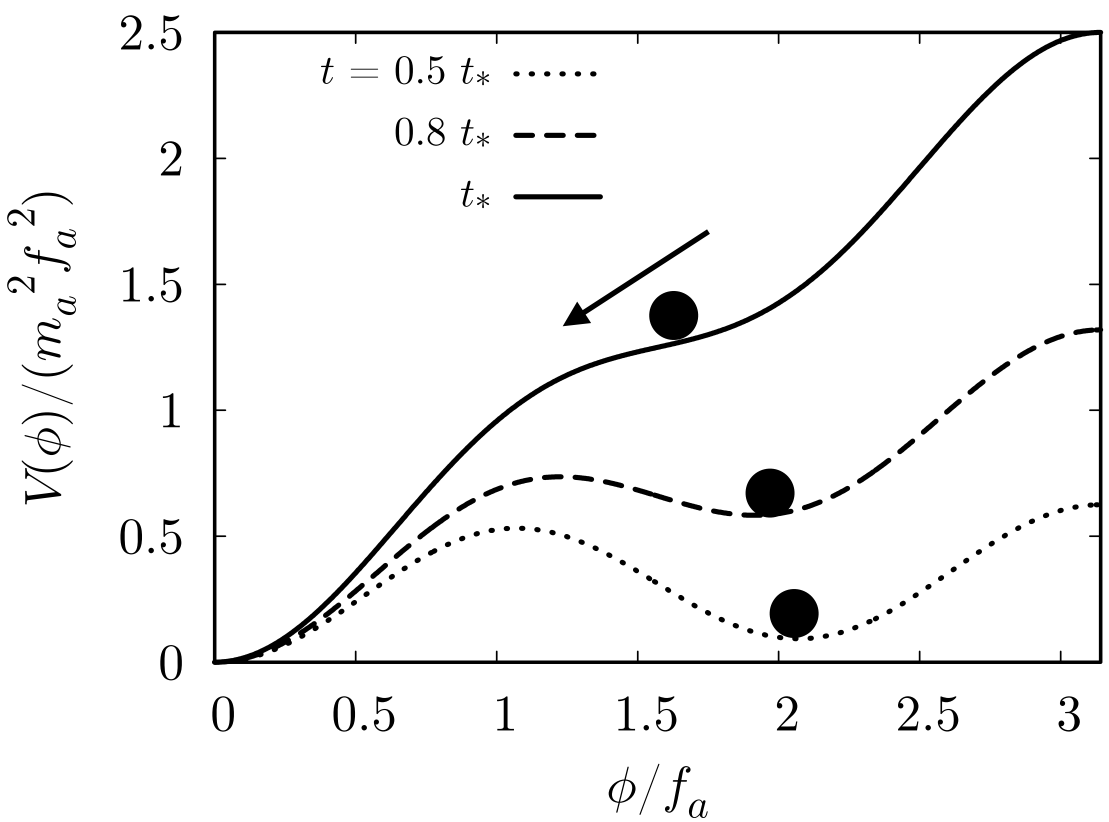
see also Machado+ (2019), Salehian+ (2020), Ratzinger+ (2020), Namba+ (2020)

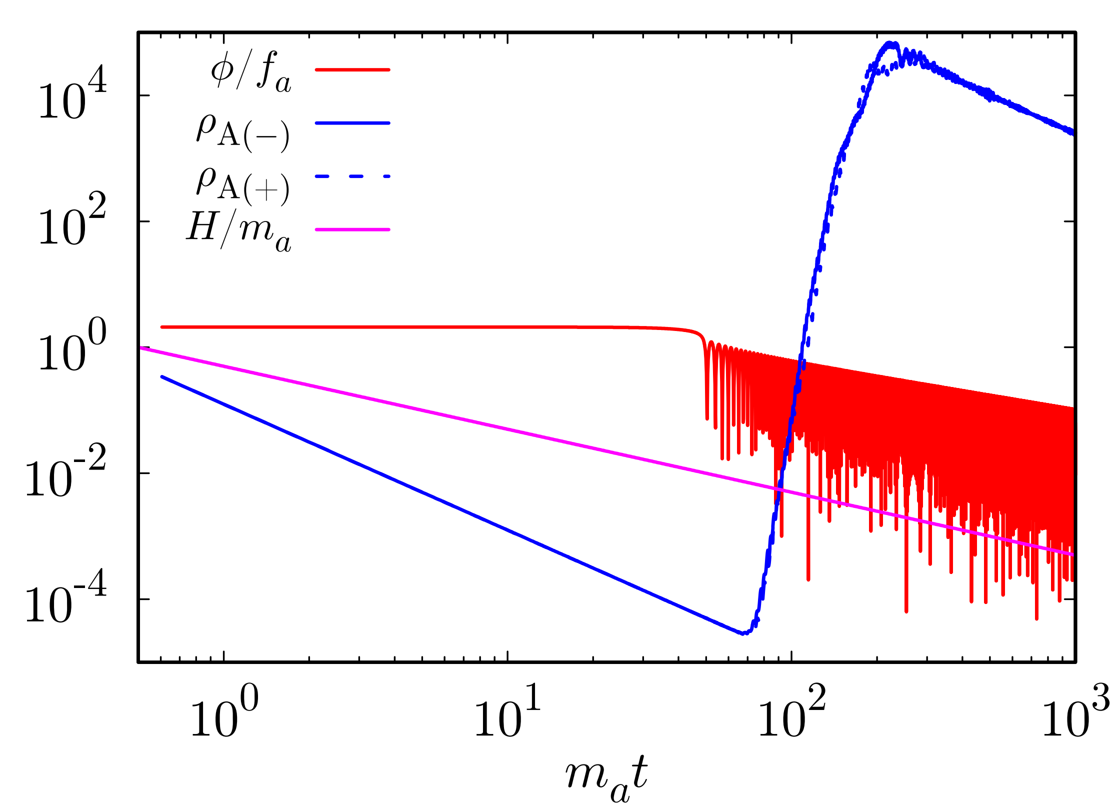
Resonant dark photon production w/o large coupling

NK, Takahashi, 2303.05492

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

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





Application for QCD axion cosmology —> next talk by Shota Nakagawa

Coherent vector DM production

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

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

$$f^2 \propto a^\alpha, \ \bar{A}_i = f A_i / a, \ R_A = \frac{\rho_A}{\rho_\phi}$$

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

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

$\& \quad g_k \propto R_A$

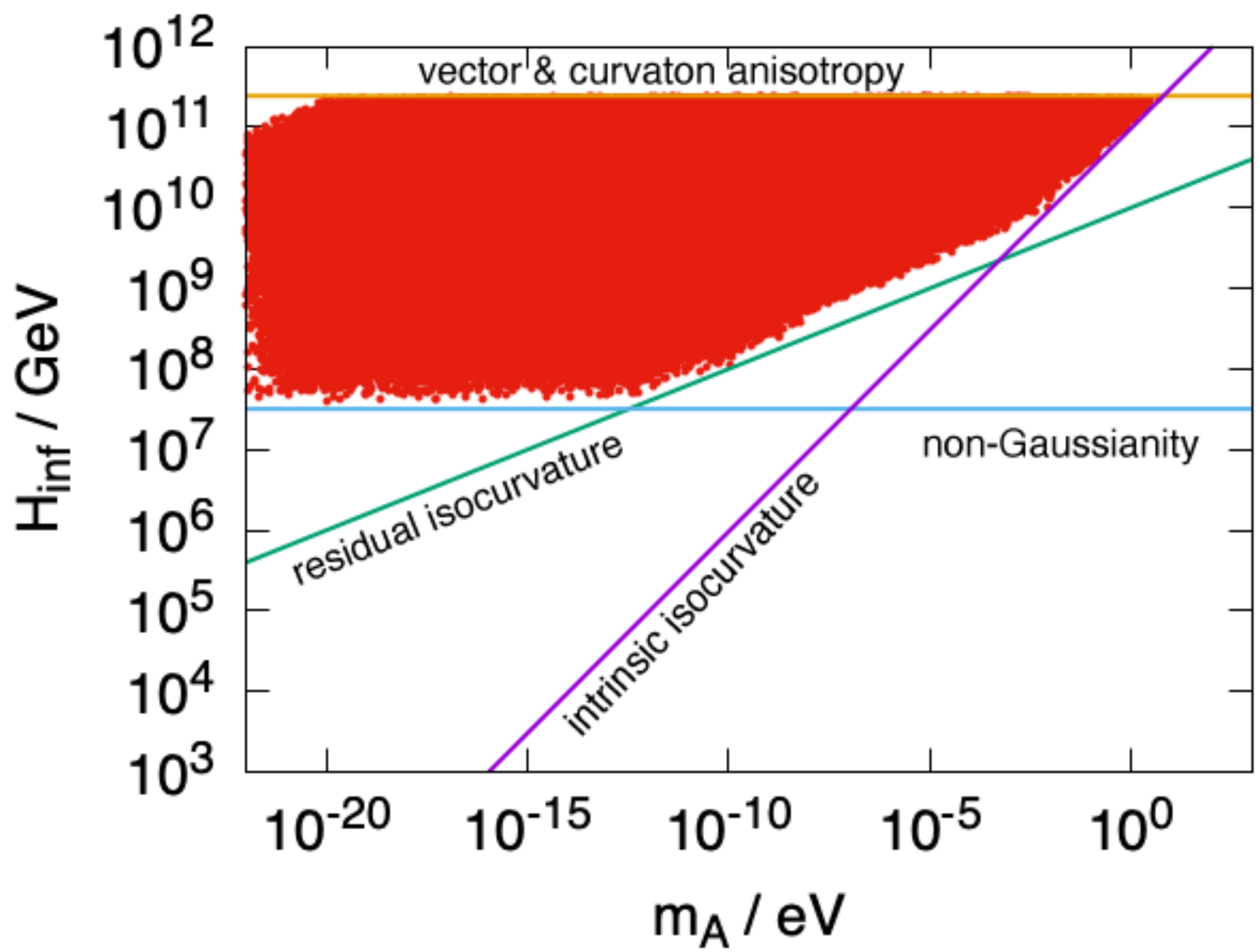
DM isocurvature perturbation $S = \frac{\delta \rho_A}{\bar{\rho}_A} \sim \frac{H_{\mathrm{inf}}}{\pi \bar{A}_i} \propto R_A^{-1}$

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 responsible for the curvature perturbation



Dark photon DM from Abelian-Higgs cosmic strings

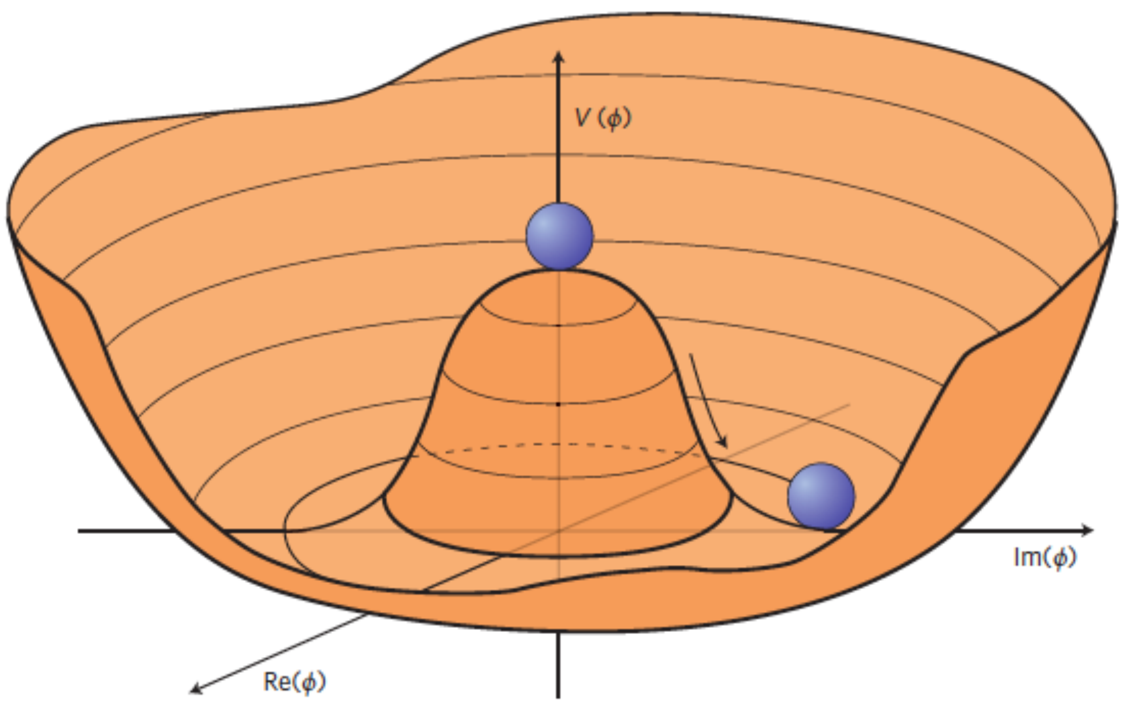
Long, Wang 1901.03312, NK, Nakayama 2212.13573

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

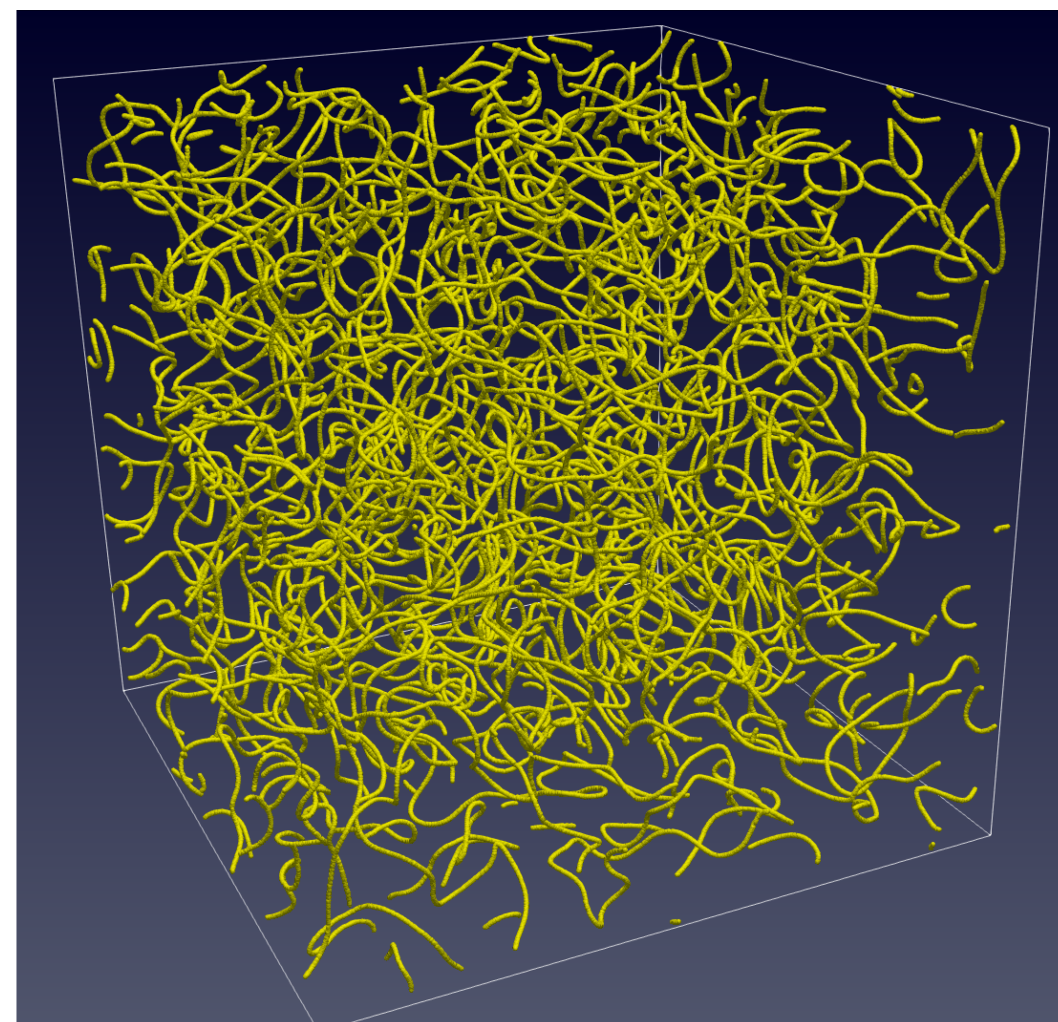
$$(\mathcal{D}_\mu = \partial_\mu - ieA_\mu, \;\; F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$$

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 $\ell_{\rm loop} \gtrsim m_A^{-1}$

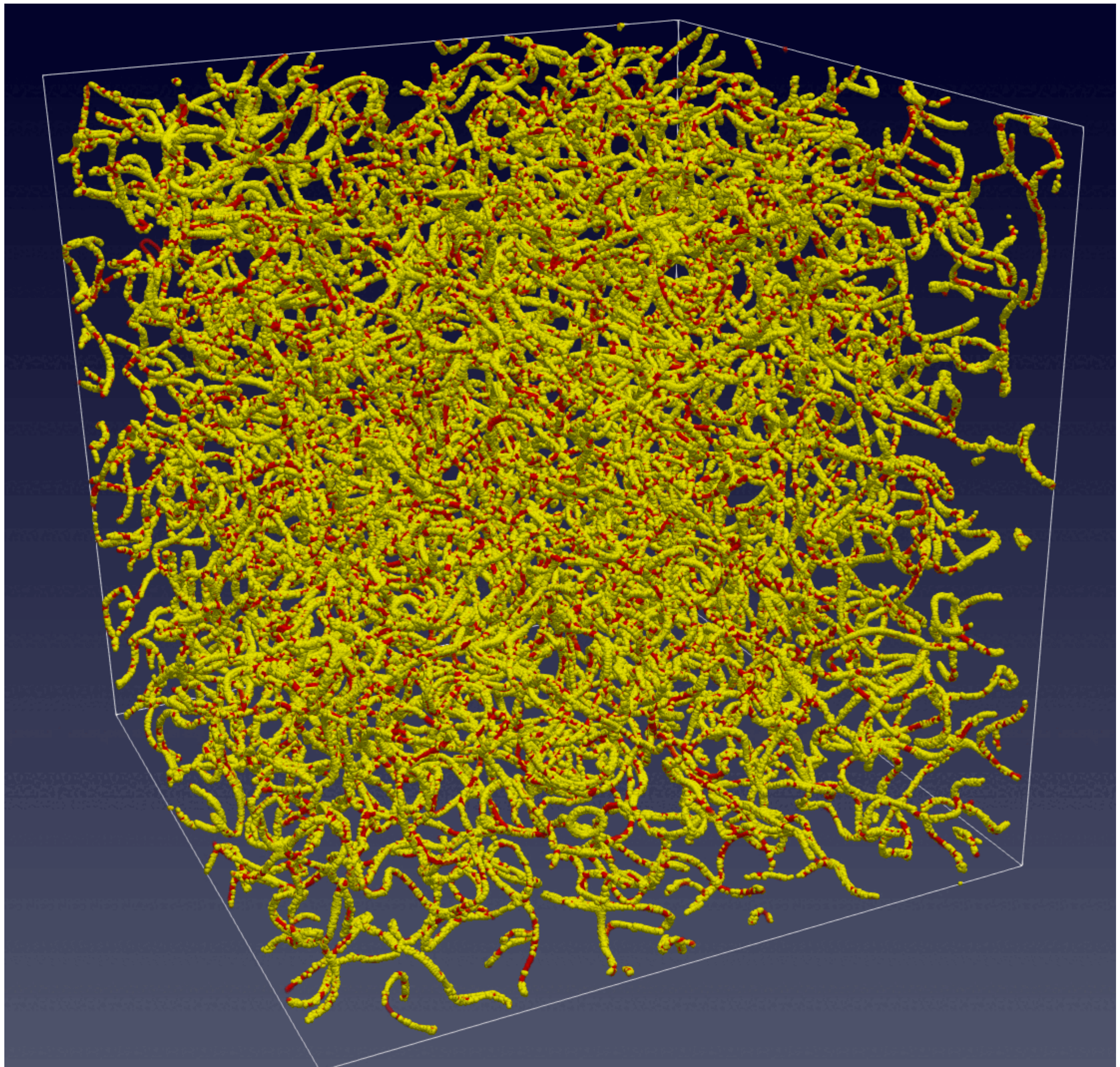
  (i.e. loop oscillation frequency becomes smaller than the mass) $\rightarrow \quad H \lesssim m_A$

- After that, string evolves like "local" string

  (network loses the energy only through the GW emission)

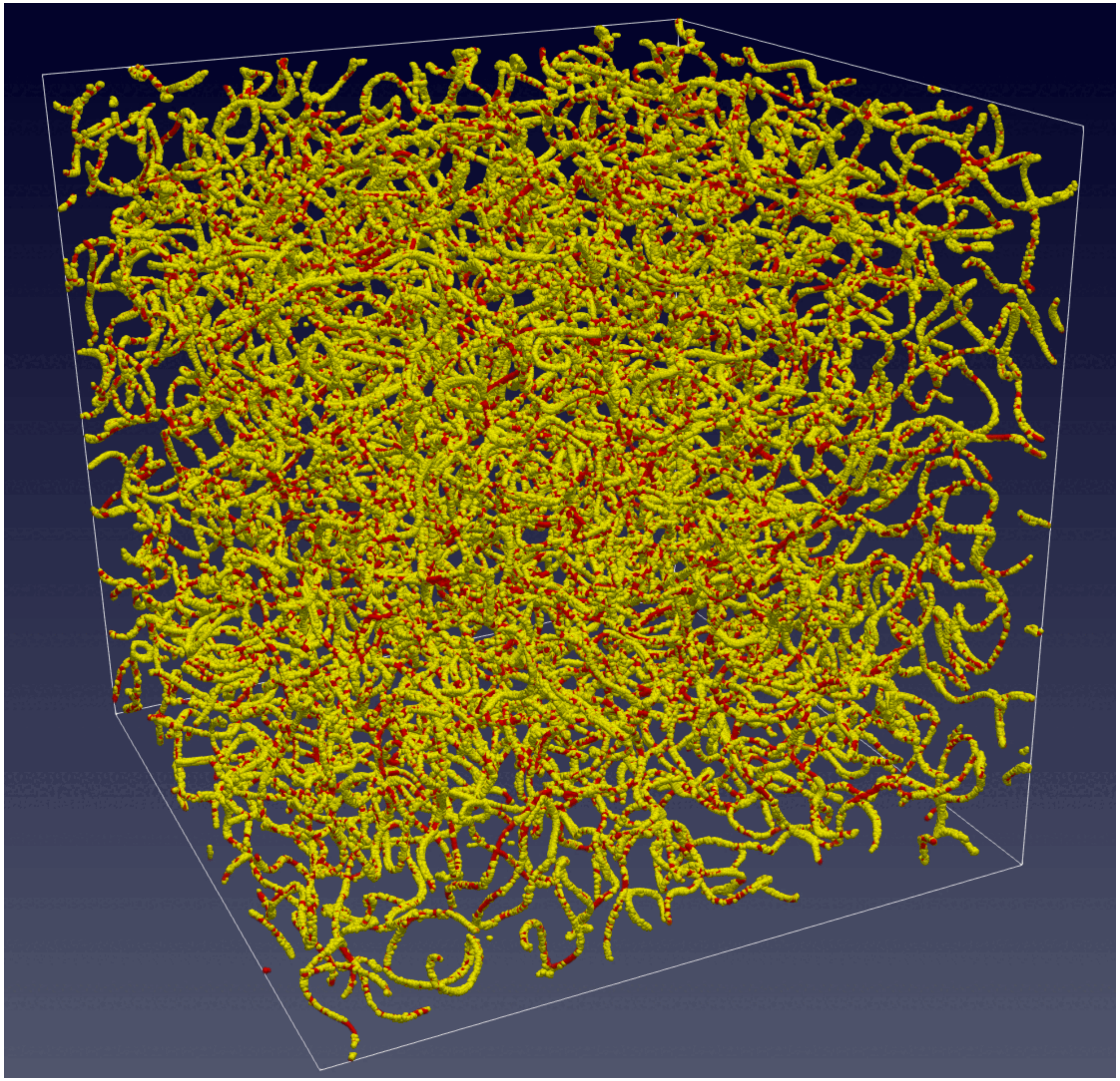
Loop production & decay

Type-II string with e=0.01 and λ=2

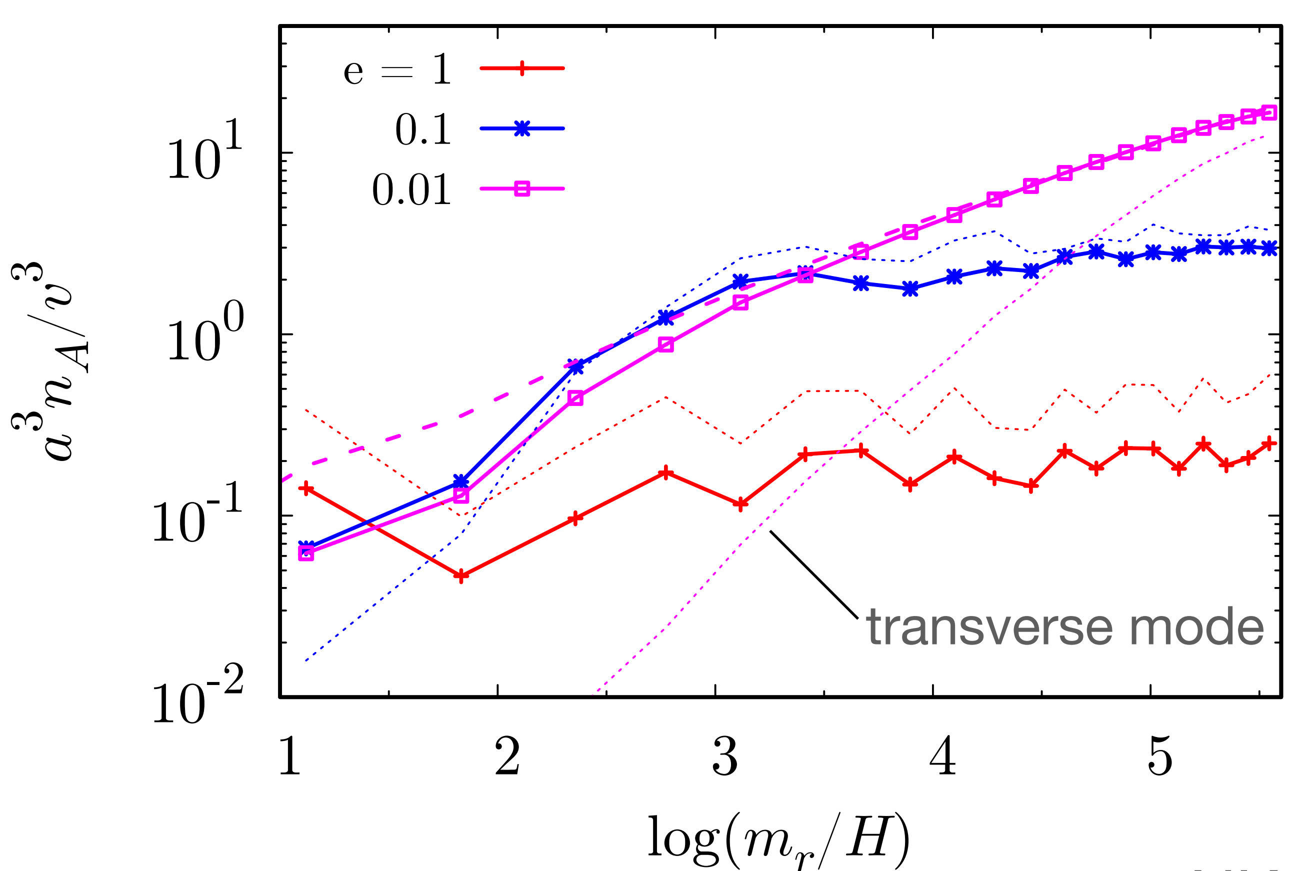


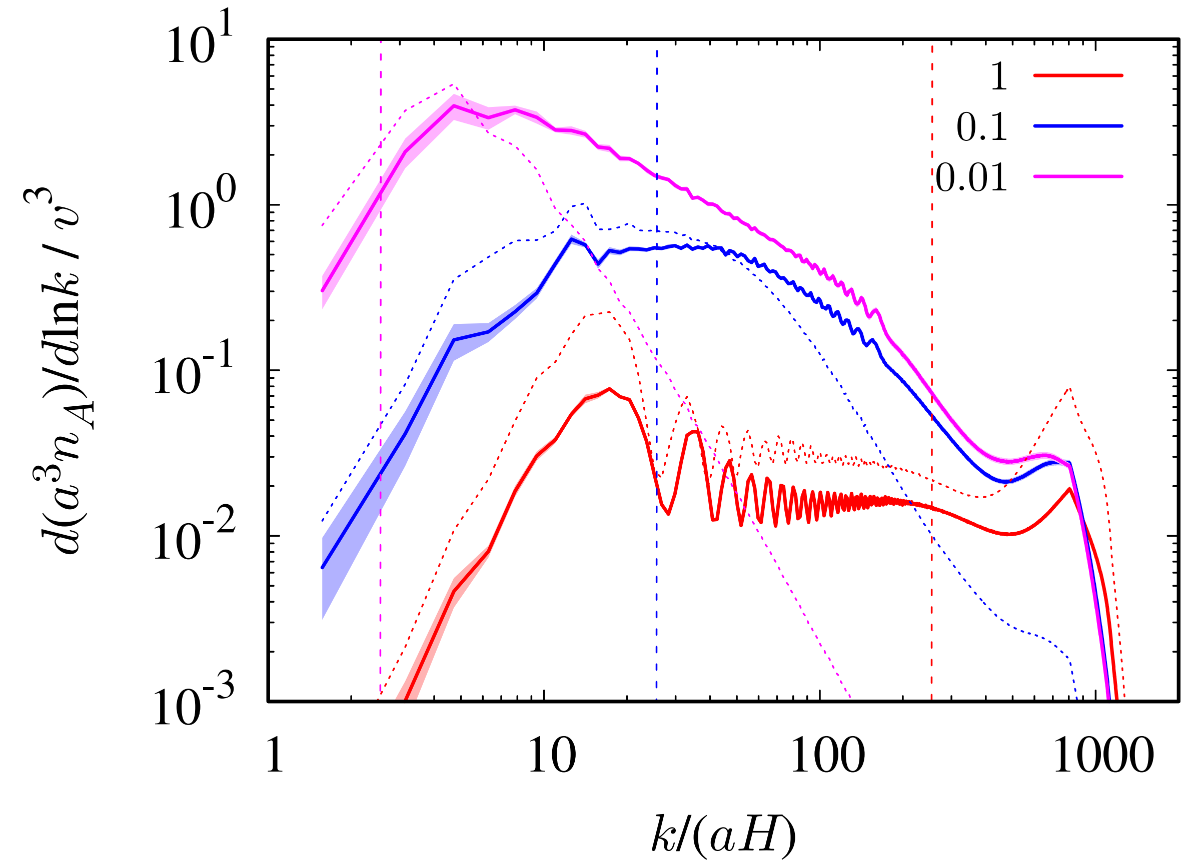
Loop production & decay

Type-I string with e=1 and λ=2



Dark photon DM abundance & spectrum





NK, Nakayama 2212.13573

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

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

GW emission from cosmic strings

Credit: Daniel Dominguez/CERN

Quadrupole formula for GW emission: $\dot{E}_{\rm GW} \sim G(\dddot{D})^2$

quadrupole moment: $D \sim ML^2 \sim \mu L^3, \quad \dddot{D} \sim \omega^3 D \sim L^{-3} D$

L : typical loop size ~ (typical oscillation frequency)$^{-1}$

GW emission rate: $\dot{E}_{\rm GW} \sim G\mu^2 \equiv \Gamma_{\rm GW} G\mu^2$

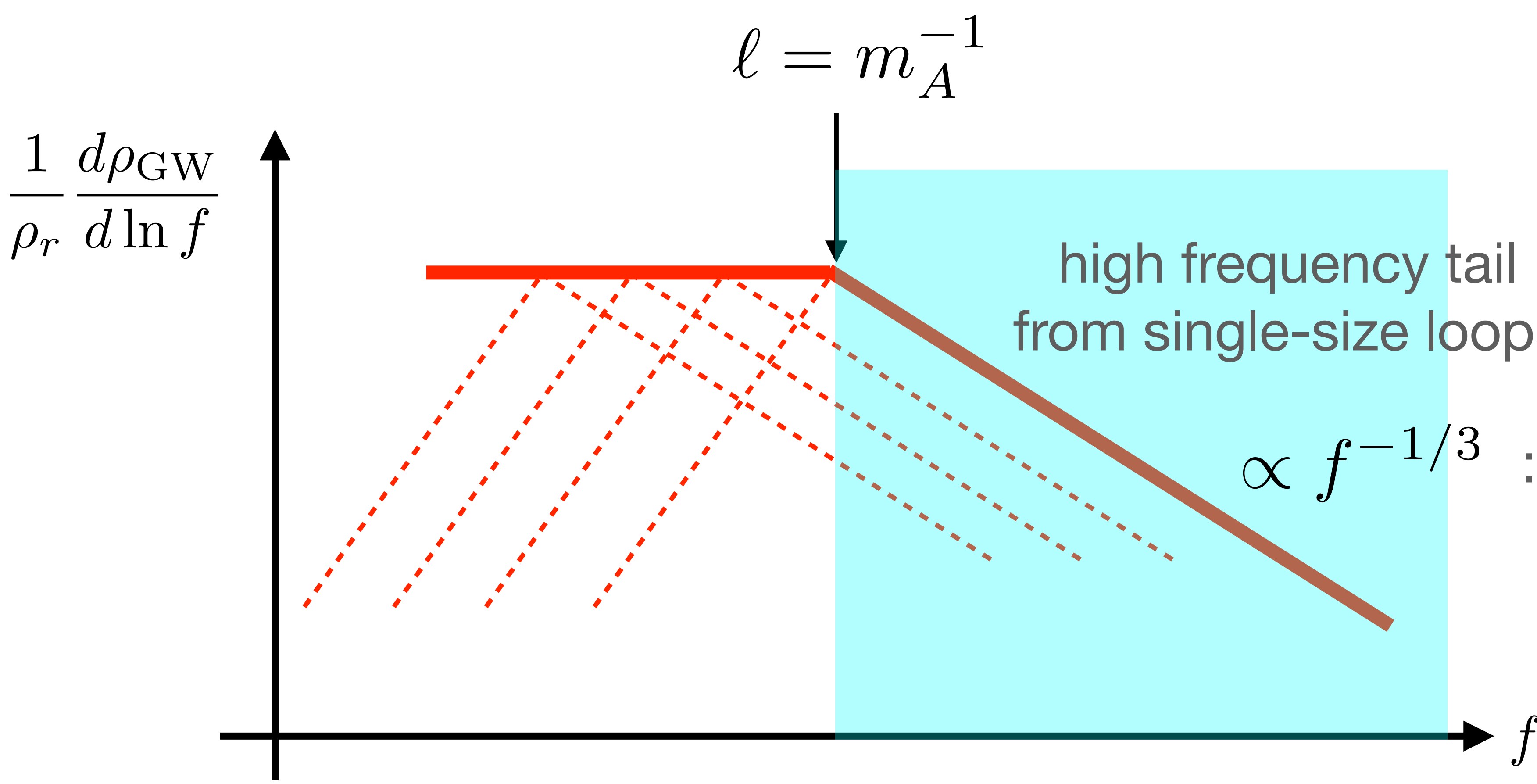
$$G\mu \sim (v/M_P)^2 \sim 10^{-7}(v/10^{15}{\rm GeV})^2$$

Energy loss of loops = GW emission + vector boson emission

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

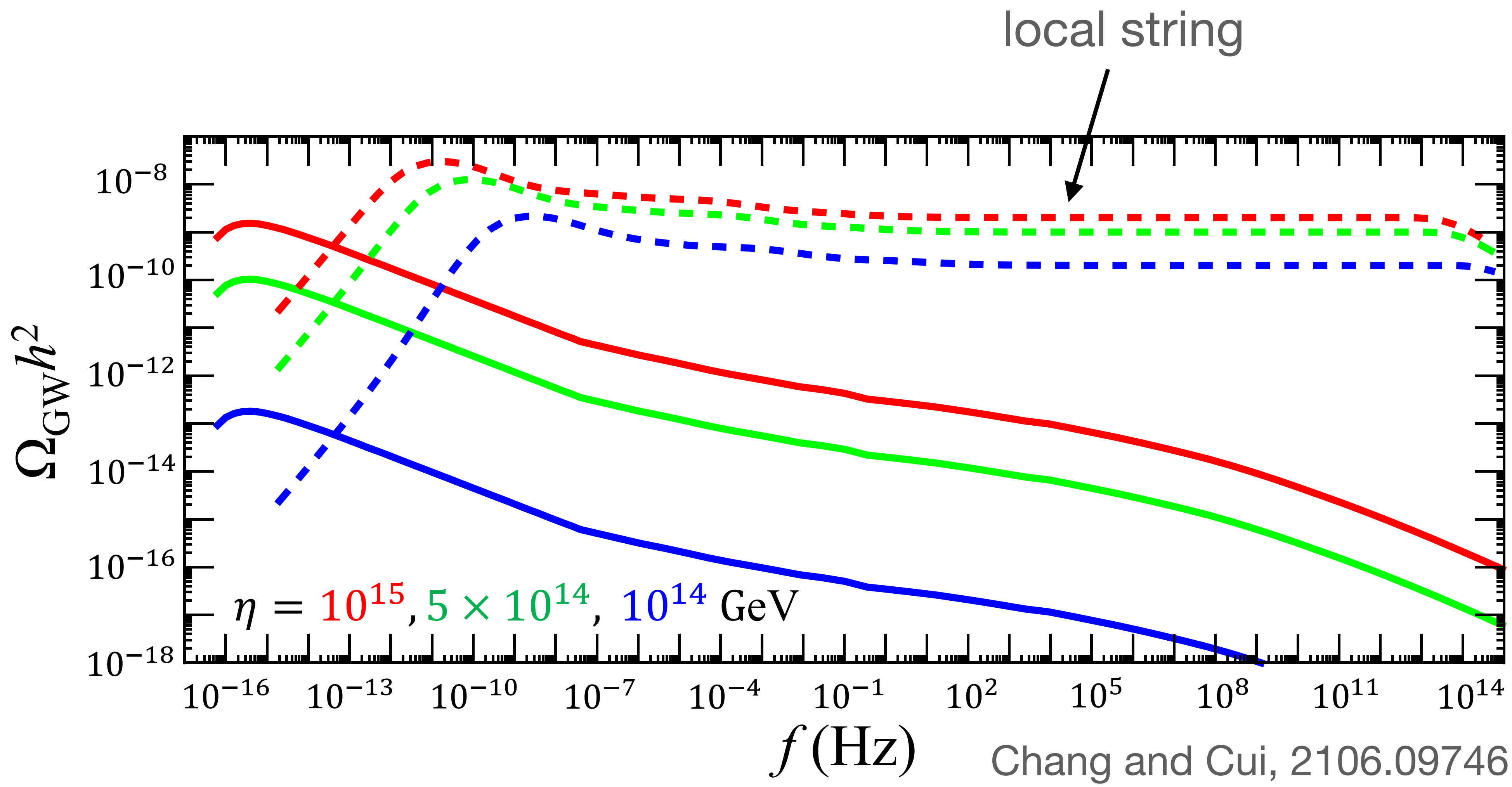
Loops shorter than m_A^{-1} can emit dark photons

—> short lived & GW emission is suppressed



GW spectrum from local/global strings

(conventional models)

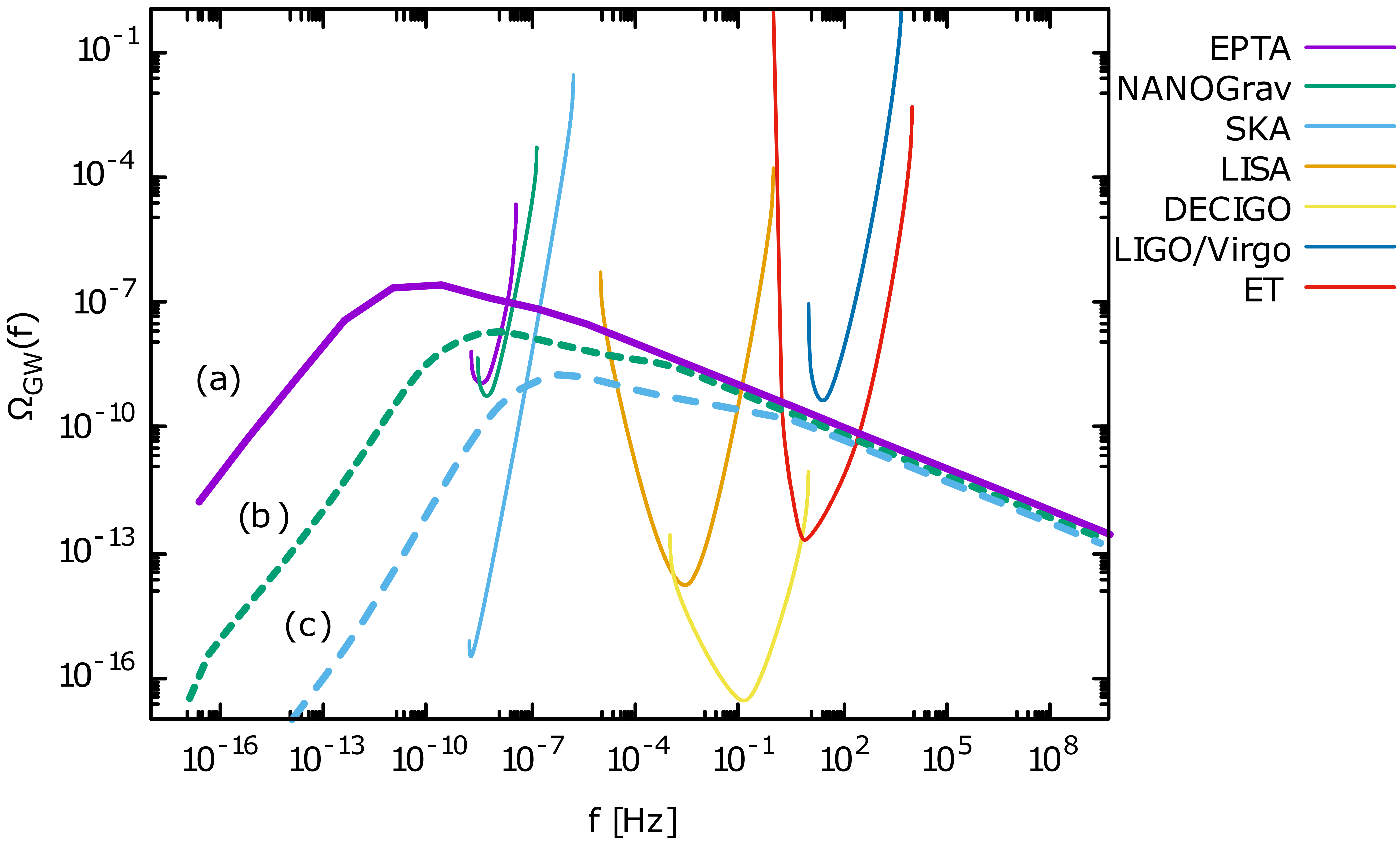


Chang and Cui, 2106.09746

(see also Gorghetto et al, 2101.11007)

GW spectrum

NK, Nakayama 2212.13573



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

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

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

Discussion

More precise study is necessary for

- Scaling violation
- Time-dependence of the tension
- Loop and dark photon production rate
  especially near the transition : global —> local
- Initial loop size distribution (monochromatic or extended?)
- Spectral function of GW from individual loop (cusp- or kink-like?)
  (because it is crucial for high frequency region)
- Loop lifetime (deviation from Nambu-Goto string)

discussed in Hindmarsh et al (2017), Matsunami et al (2019)

Summary

- Light dark photon DM can be produce by

    - axion oscillation
    - misalignment mechanism (still viable)
    - decay of cosmic string loops

- Gravitational waves can be a signature of this scenario

    - circular polarization
    - mildly tilted spectrum