Production of ultralight dark photon dark matter

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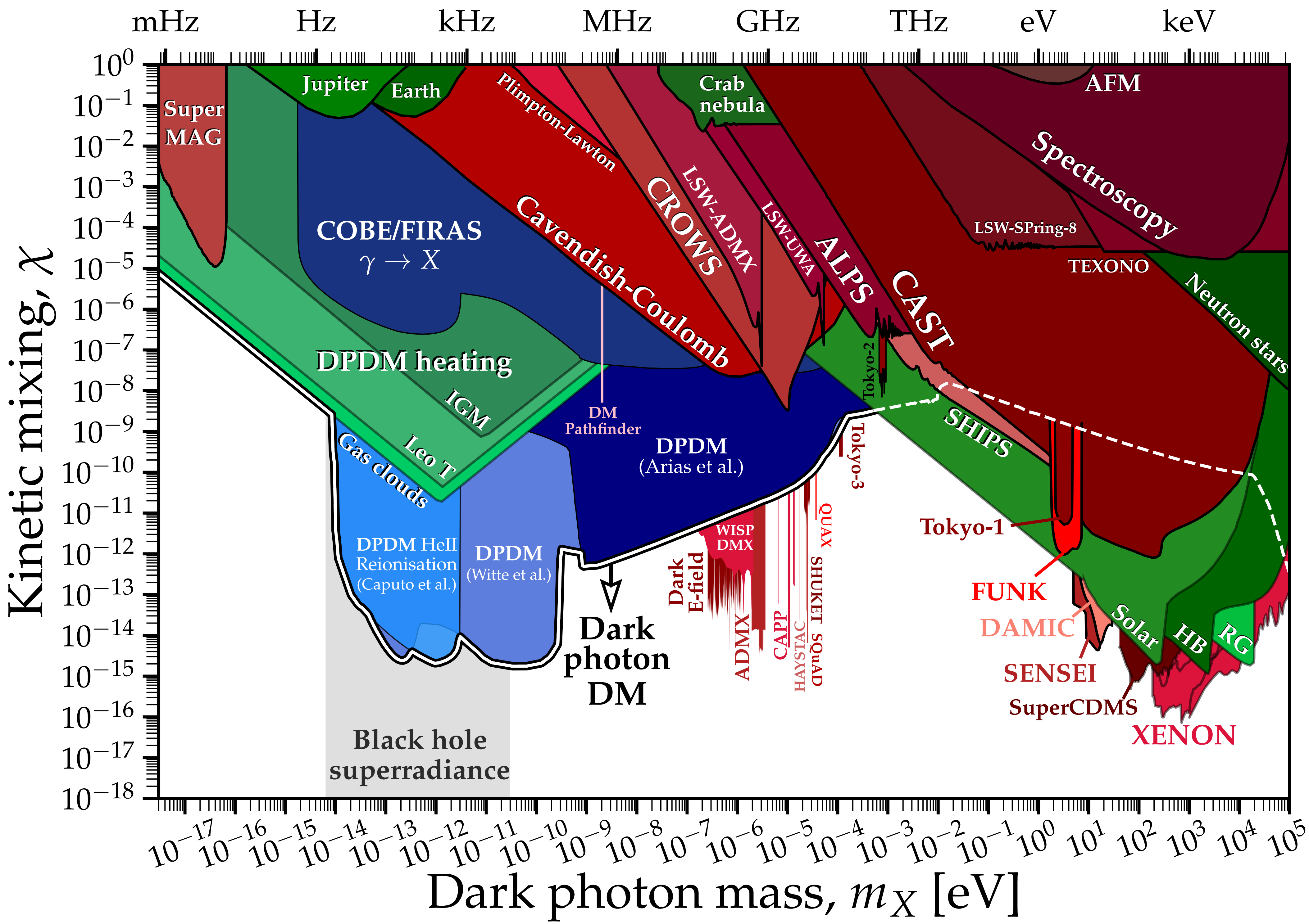
TOHOKU UNIVERSITY

NK, Fuminobu Takahashi, 2303.05492
NK, Kazunori Nakayama, 2212.13573, 2303.04287, 2306.17390

FY2023 “What is dark matter? - Comprehensive study of the huge discovery space in dark matter”, March 7-8, 2024, YITP

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)

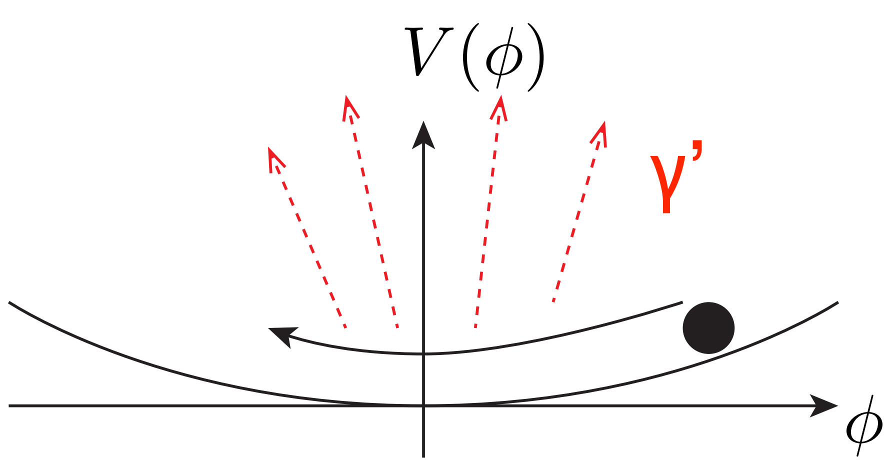
- Production from cosmic strings   Long, Wang (2019), NK, Nakayama (2022)

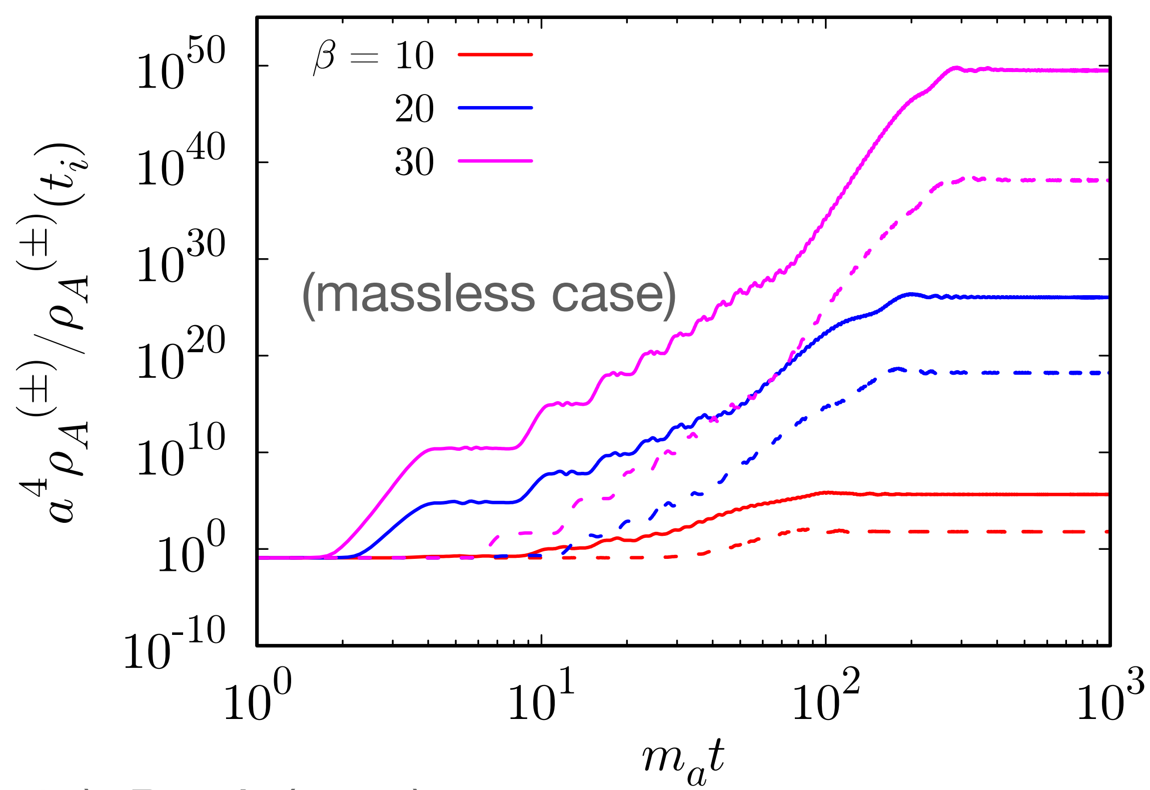
Resonant dark photon (DM) production from axion

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

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

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





- 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)

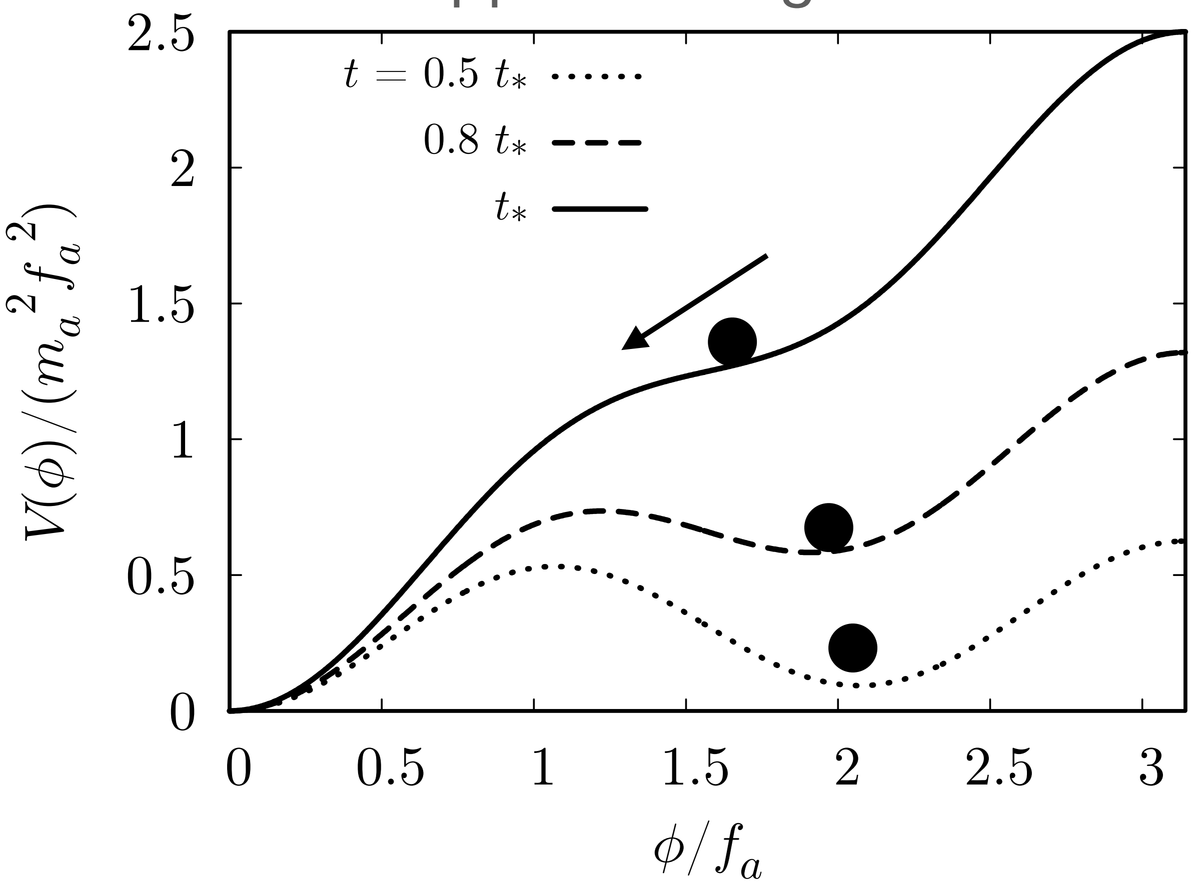
Resonant dark photon production w/o large coupling

NK, Takahashi, 2303.05492

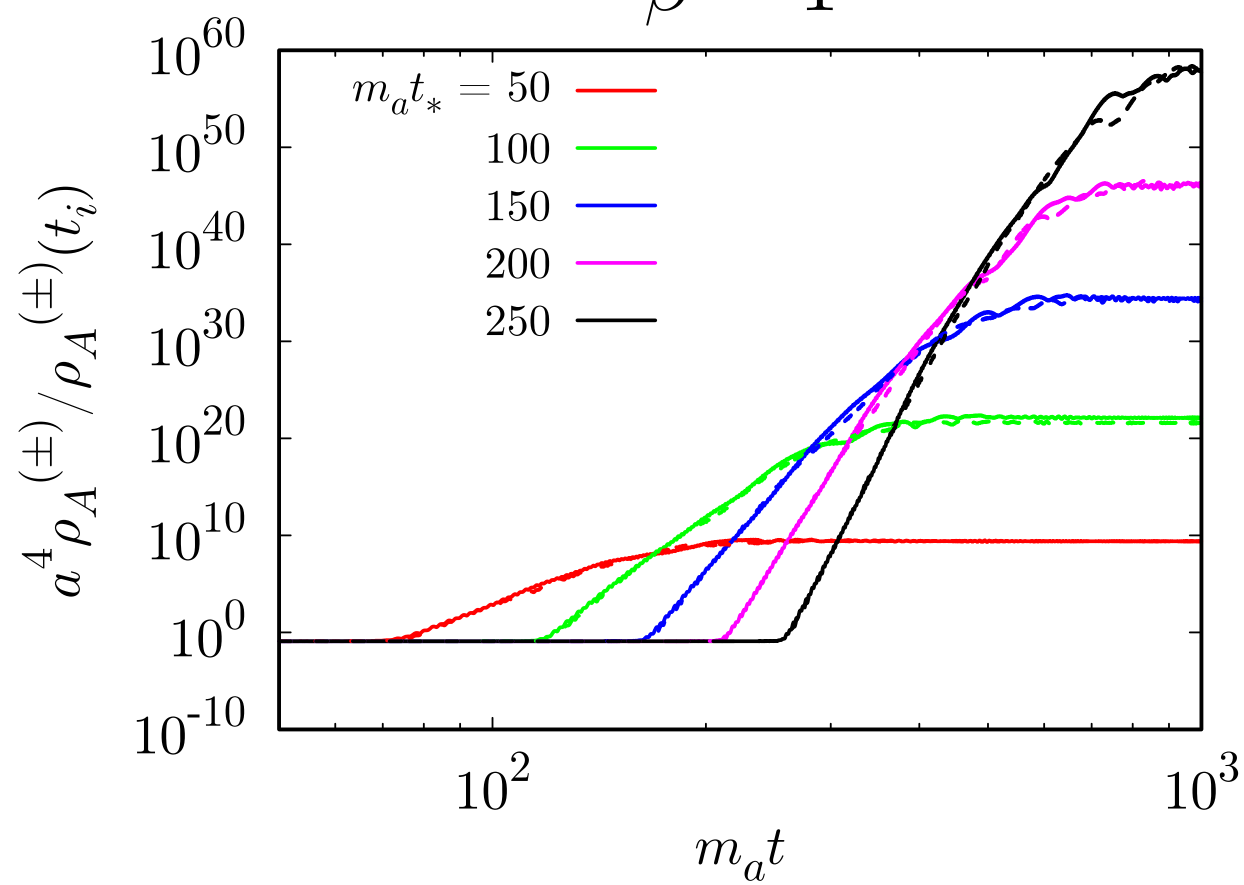
$$V(\phi) = m_a(t)^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right] + \Lambda_H^4 \left[1 - \cos\left(\frac{N_H \phi}{f_a}\right)\right]$$

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

trapped misalignment



$\beta = 1$



Coherent vector DM production

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

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

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

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

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

$\& \quad g_k \propto R_A$

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

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

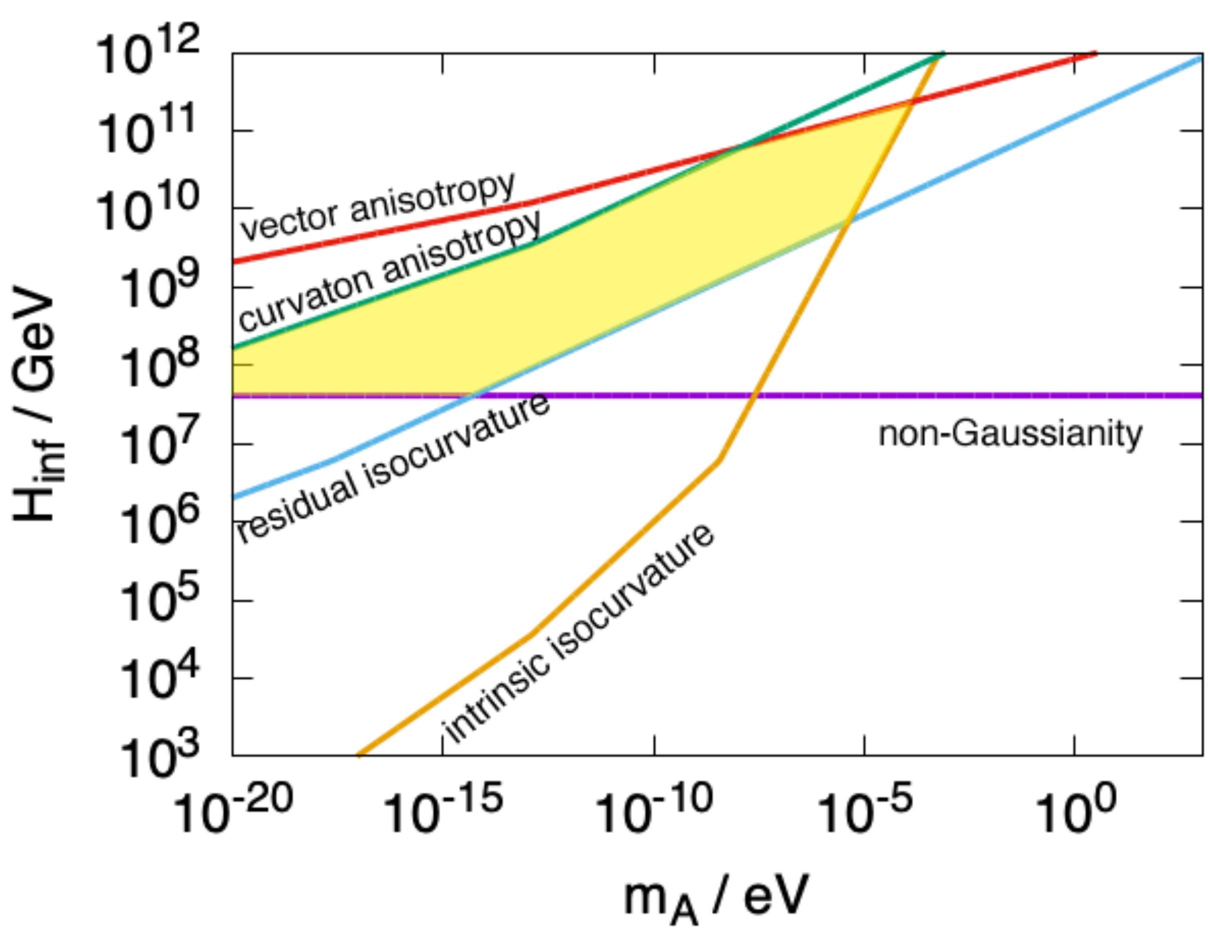
“Viable” coherent vector DM scenario
— curvaton scenario

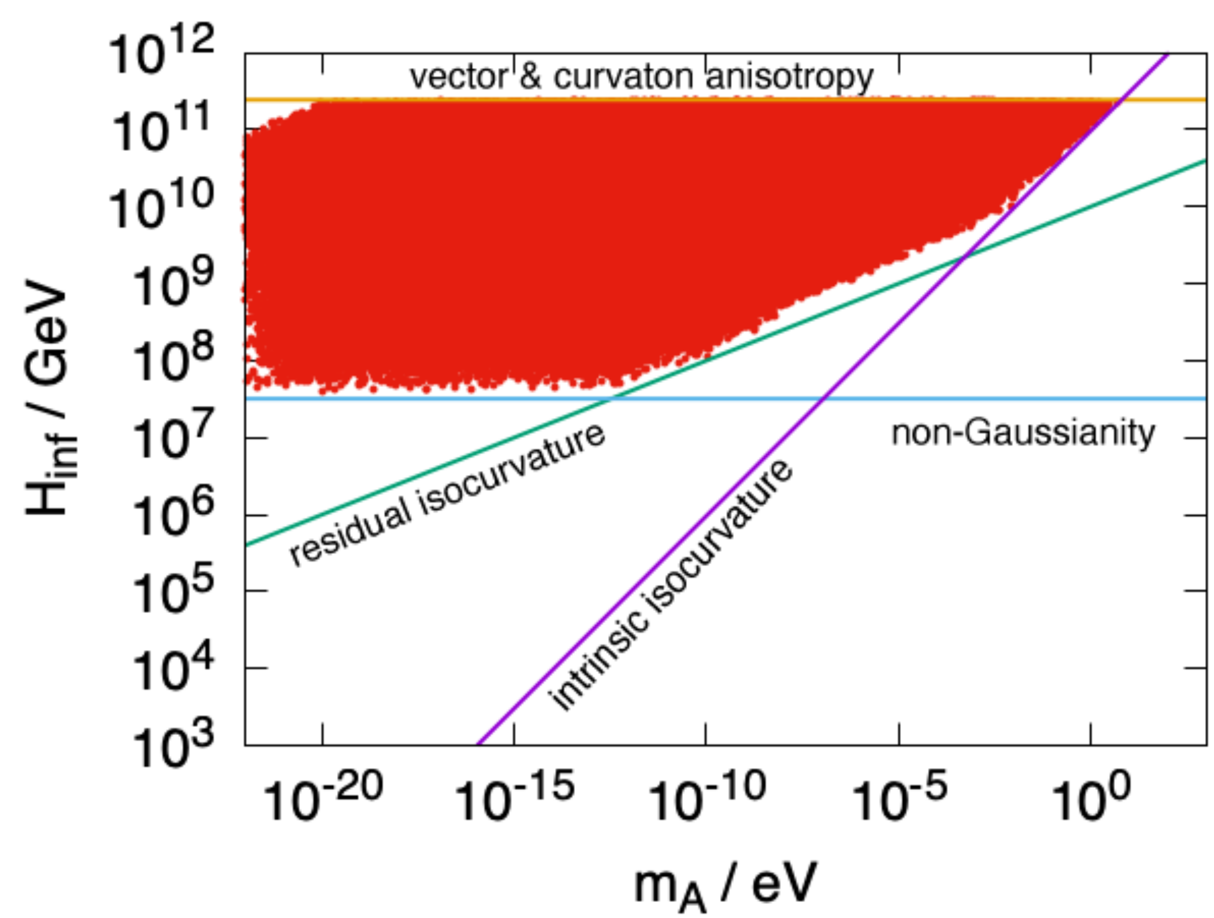
NK, Nakayama 2303.04287

additional constraints: non-Gaussianity & residual isocurvature

curvaton domination before curvaton decay & dark photon oscillation

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





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

Dark photon DM from Abelian-Higgs cosmic strings

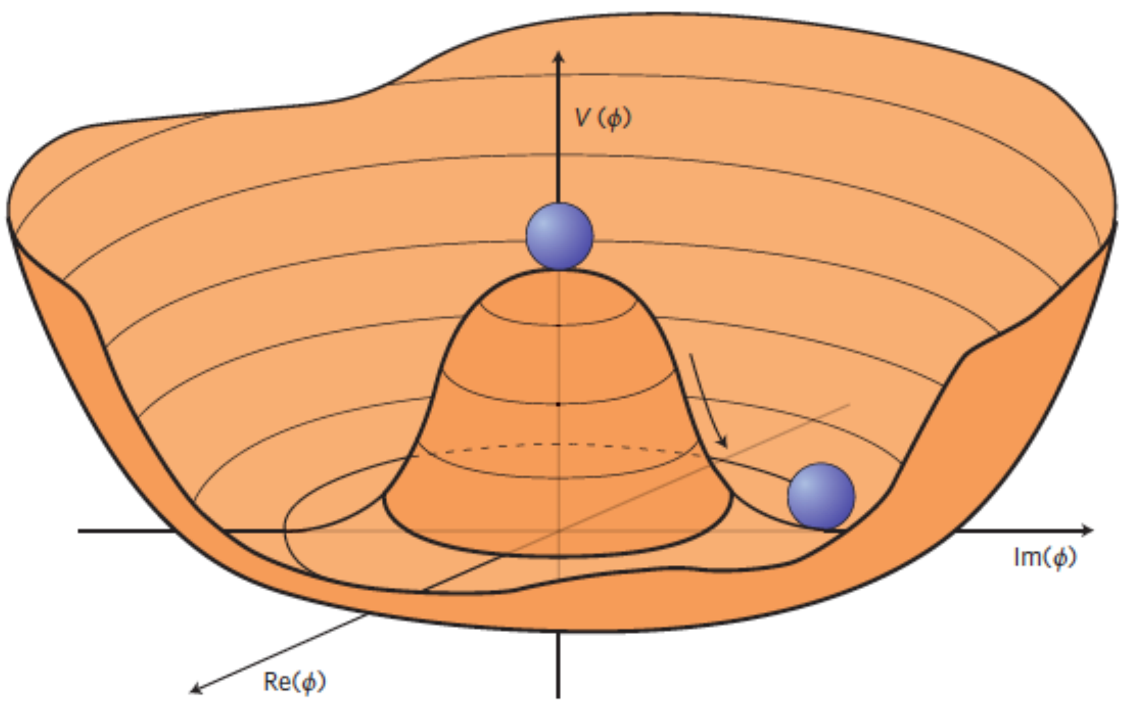
Long, Wang 1901.03312, NK, Nakayama 2212.13573

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

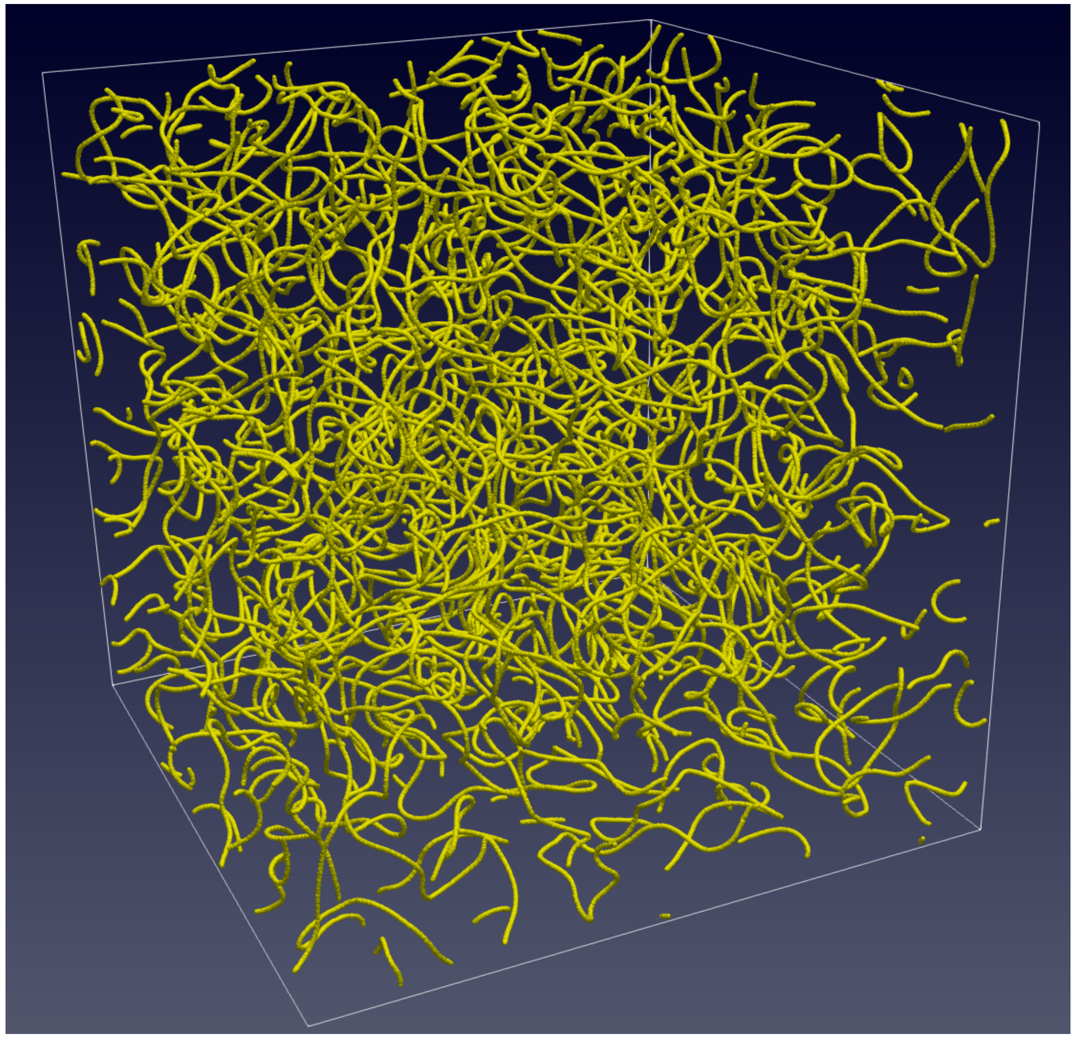
$$(\mathcal{D}_\mu = \partial_\mu - ieA_\mu, \ \ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$$

spontaneous U(1) symmetry breaking

—> formation of cosmic strings



Ellis, Gaillard, Nanopoulos 1504.07217



Scenario

Long, Wang 1901.03312
NK, Nakayama 2212.13573

- "Light" vector bosons can be produced by cosmic strings

  small gauge coupling i.e. $m_A \ll m_\Phi \quad (e \ll \sqrt{\lambda})$ (Type II string)

  e = 0 limit corresponds to the massless NG boson emission (global string case)

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

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

  <u>Vector boson (dark photon) abundance is fixed</u>

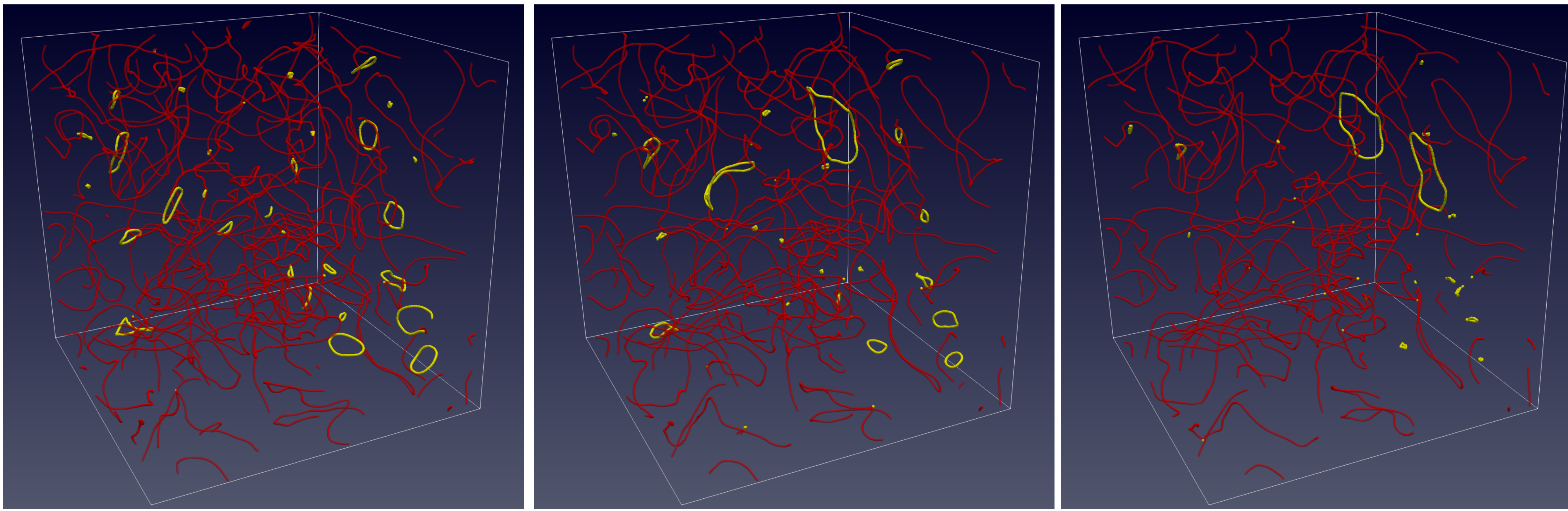
- After that, string evolves like "local" string (Type I string)

  <u>network loses energy only through the GW emission (Nambu-Goto limit)</u>

Global string —> Local string
$H \sim m_A$

String network evolution

$\lambda = 2, \ e = 0.01$



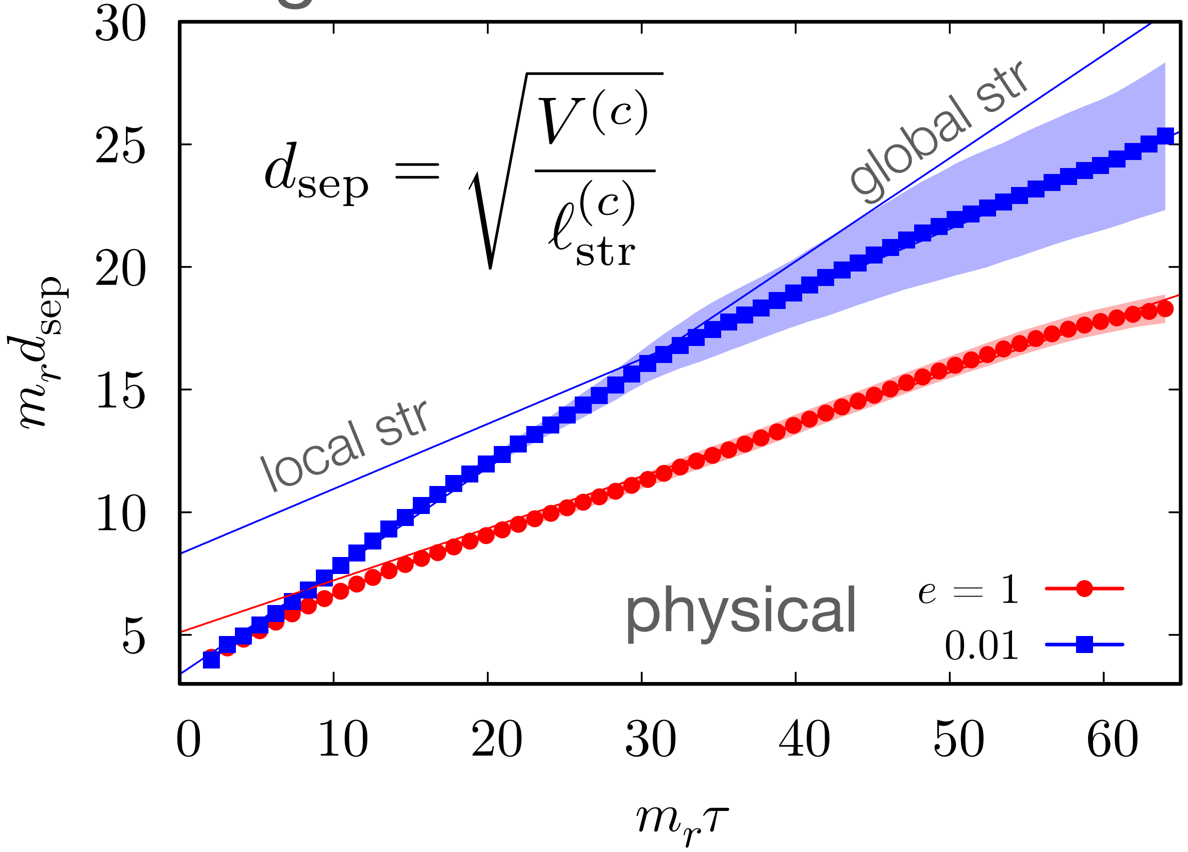
Lattice simulation with 1024^3 - 4096^3 grids

by AOBA supercomputing system
(SX-Aurora TUBASA) in Tohoku U.

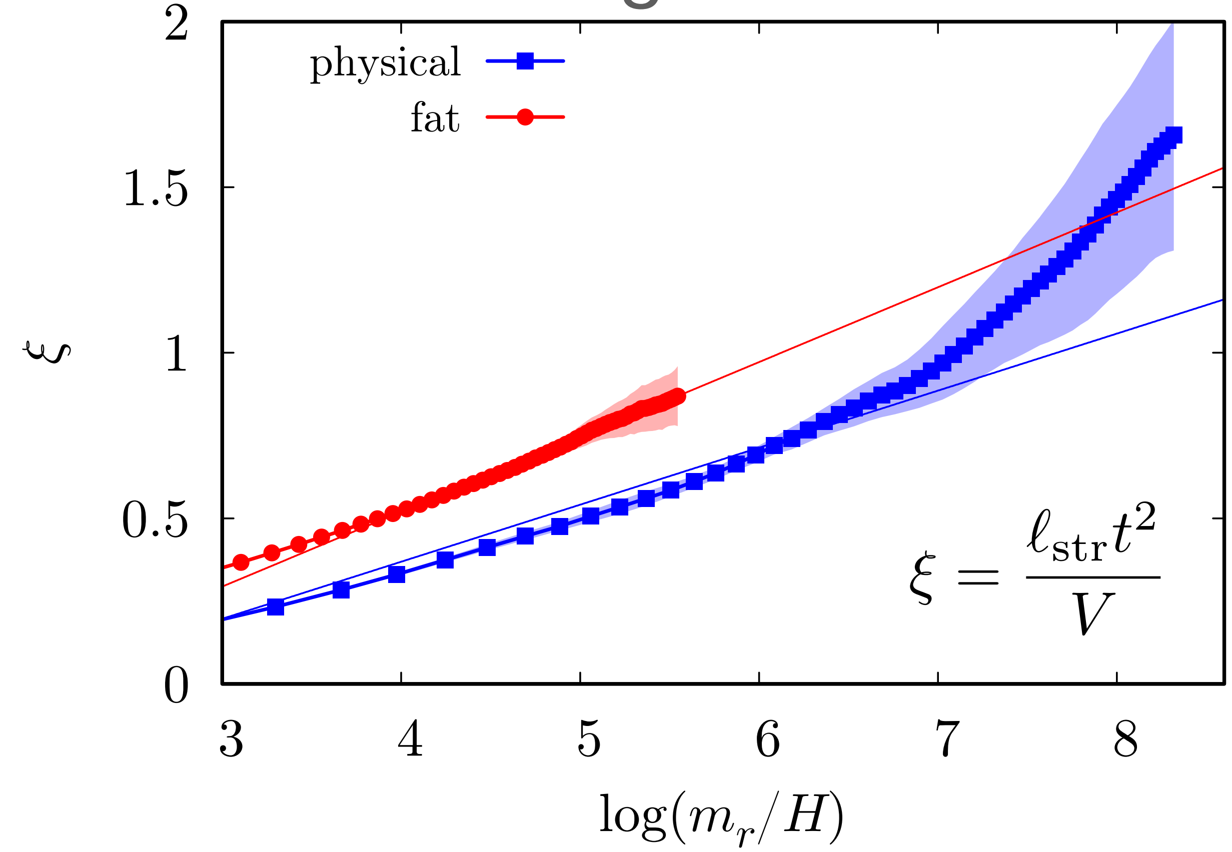
Mean separation

NK, Nakayama 2212.13573(v2)

global str —> local str



scaling violation?



Gorghetto et al, 1806.04677, Kawasaki et al, 1806.05566
Buschmann et al, 2108.05368, Saikawa et al, 2401.17253

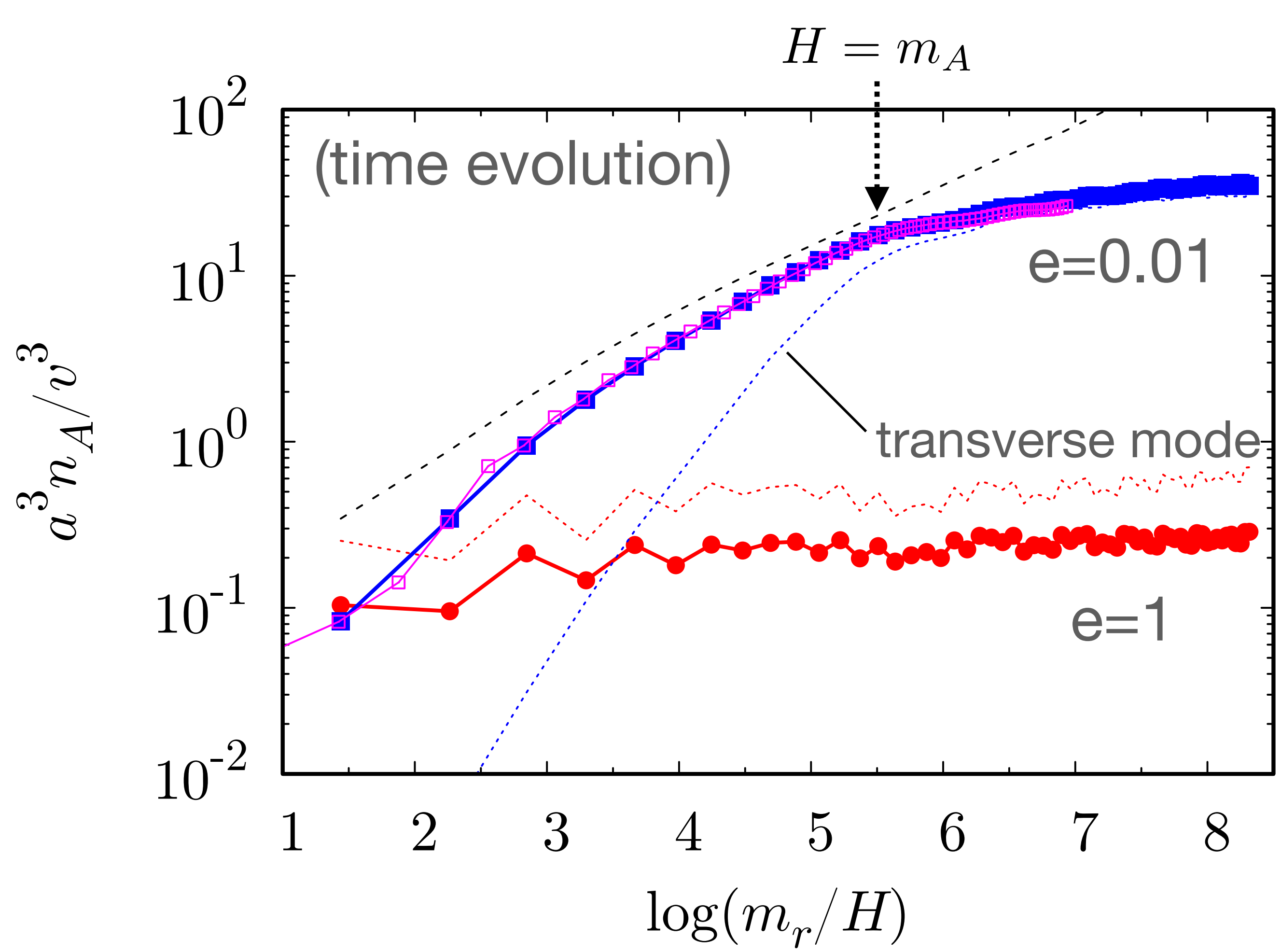
	grid	$m_r L$	$m_r \Delta x$	e	$m_r \tau$	a	b
physical string	4096^3	64	1/64	1	33.6 - 64.0	0.21 ± 0.0043	5.1 ± 0.21
physical string	4096^3	64	1/64	0.01	2.05 - 32.5	0.42 ± 0.0038	3.4 ± 0.073
physical string	4096^3	64	1/64	0.01	33.6 - 64.0	0.27 ± 0.019	8.4 ± 0.96
fat string	1024^3	512	1/2	1	133 - 256	0.24 ± 0.0013	11 ± 0.25
fat string	1024^3	512	1/2	0.01	133 - 256	0.47 ± 0.0081	18 ± 1.6

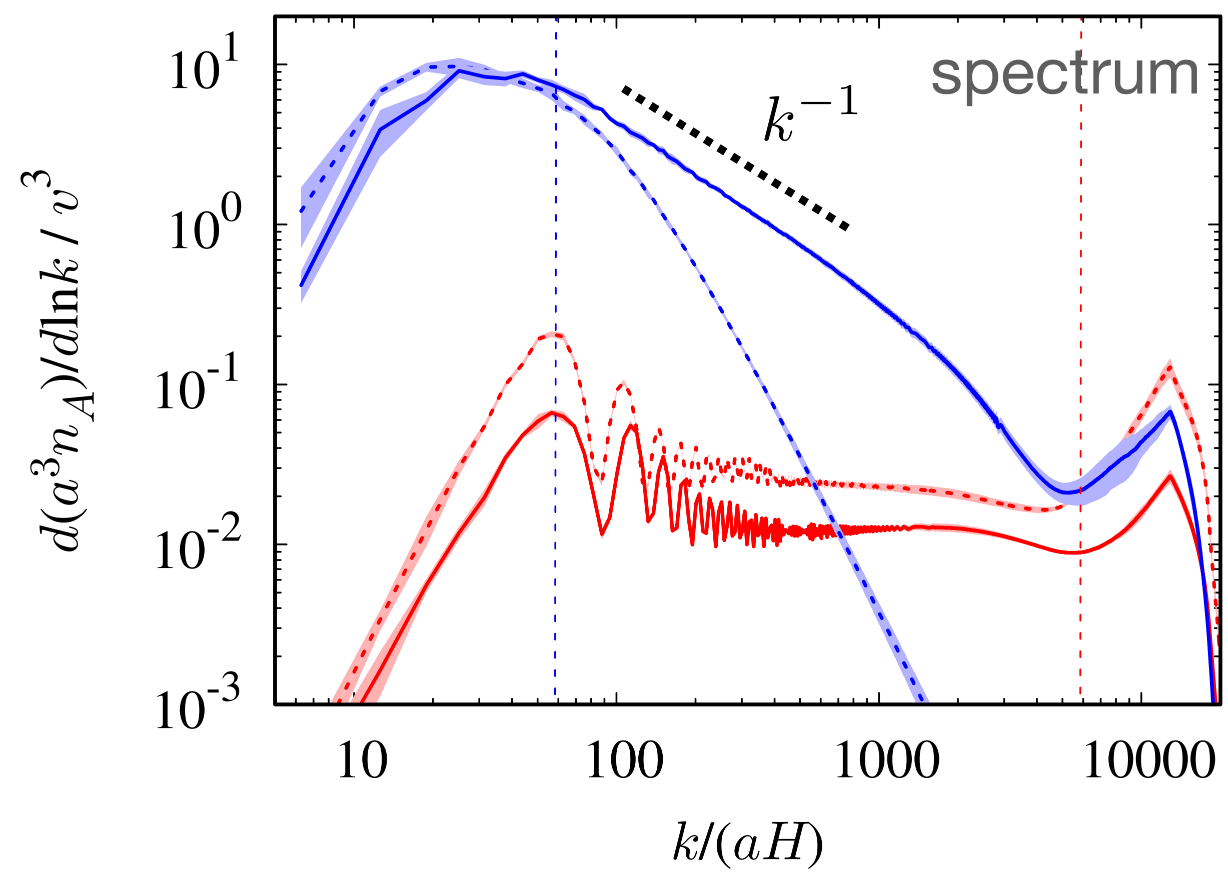
Emission of (longitudinal) vector boson

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

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

analytic estimation by Long, Wang 1901.03312





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

Relic abundance

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

$\xi = \mathrm{const}$ (scaling law)

Hindmarsh et al, 1908.03522

Hindmarsh et al, 2102.07723

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

(scaling violation)

Gorghetto et al, 1806.04677

Kawasaki et al, 1806.05566

Buschmann et al, 2108.05368

Saikawa et al, 2401.17253

GW emission from cosmic strings

Credit: Daniel Dominguez/CERN

Energy loss of loops = GW emission + vector boson emission

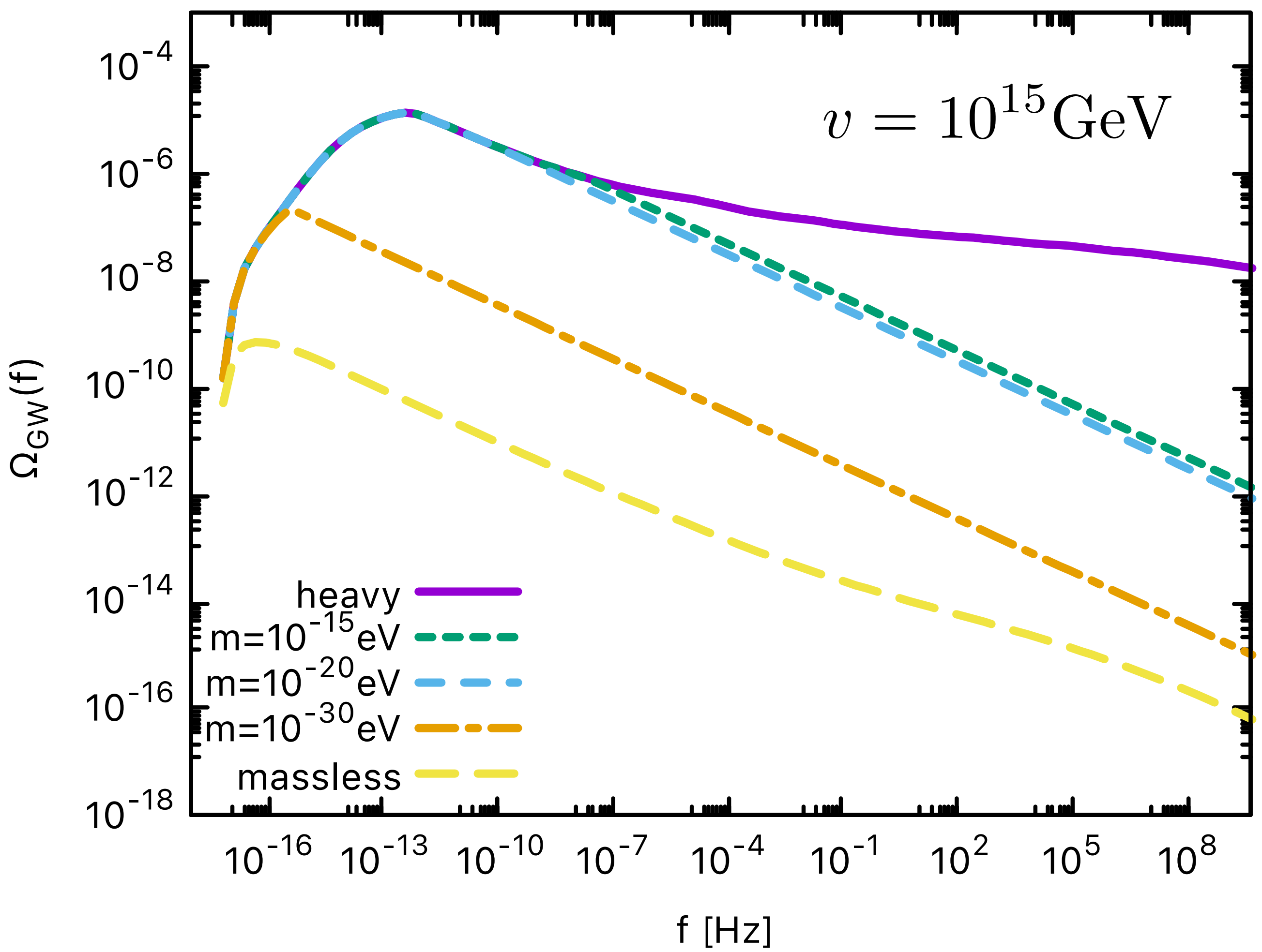
$$\frac{dE_\ell}{dt} = -\Gamma_{\rm GW} G\mu^2 - \Gamma_{\rm vec} v^2 \theta(1 - m_A \ell) \quad (\Gamma_{\rm GW} \sim \Gamma_{\rm vec} \sim 50)$$

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

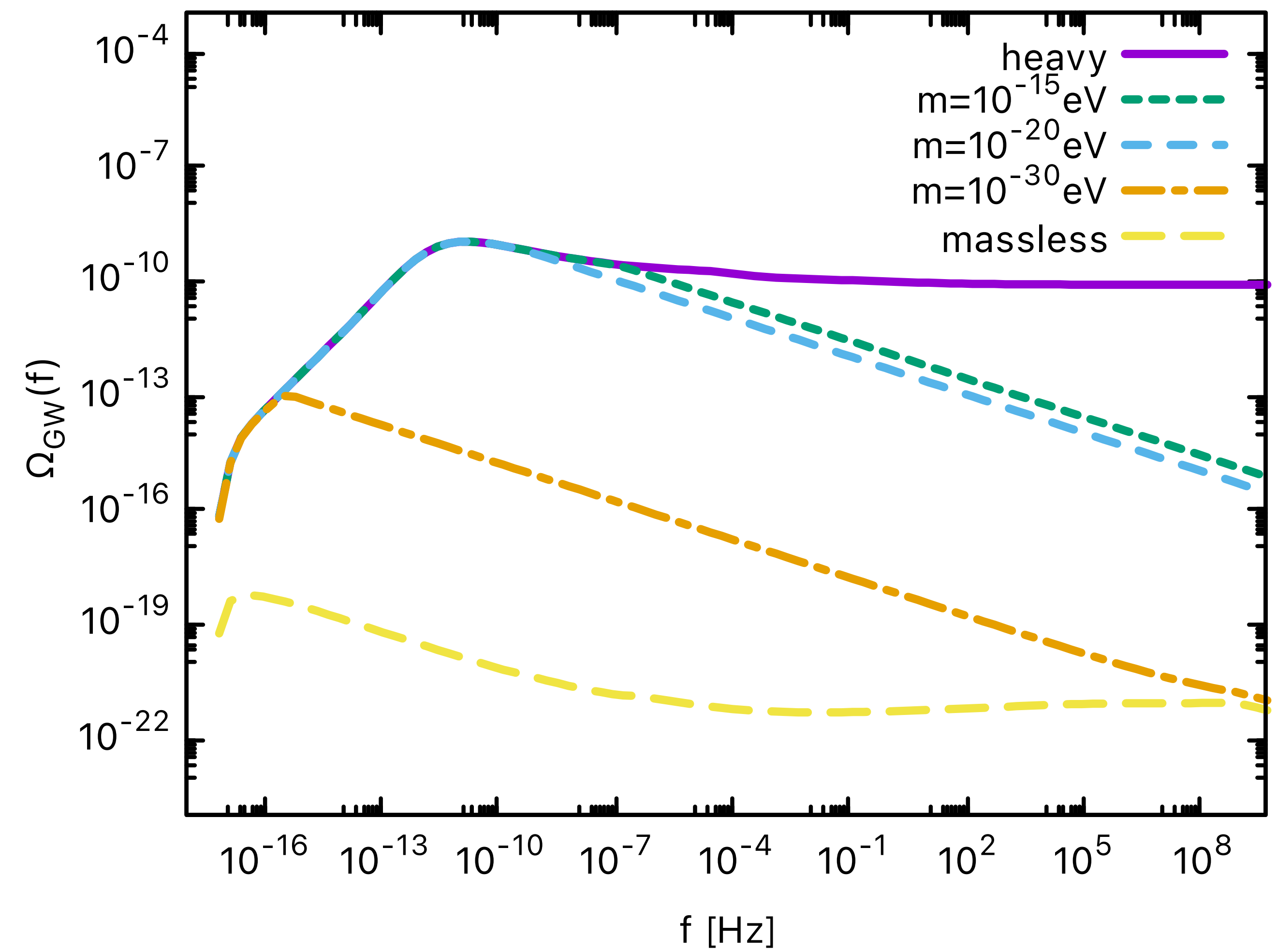
—> short lived & GW emission is suppressed

GW spectrum

NK, Nakayama 2212.13573

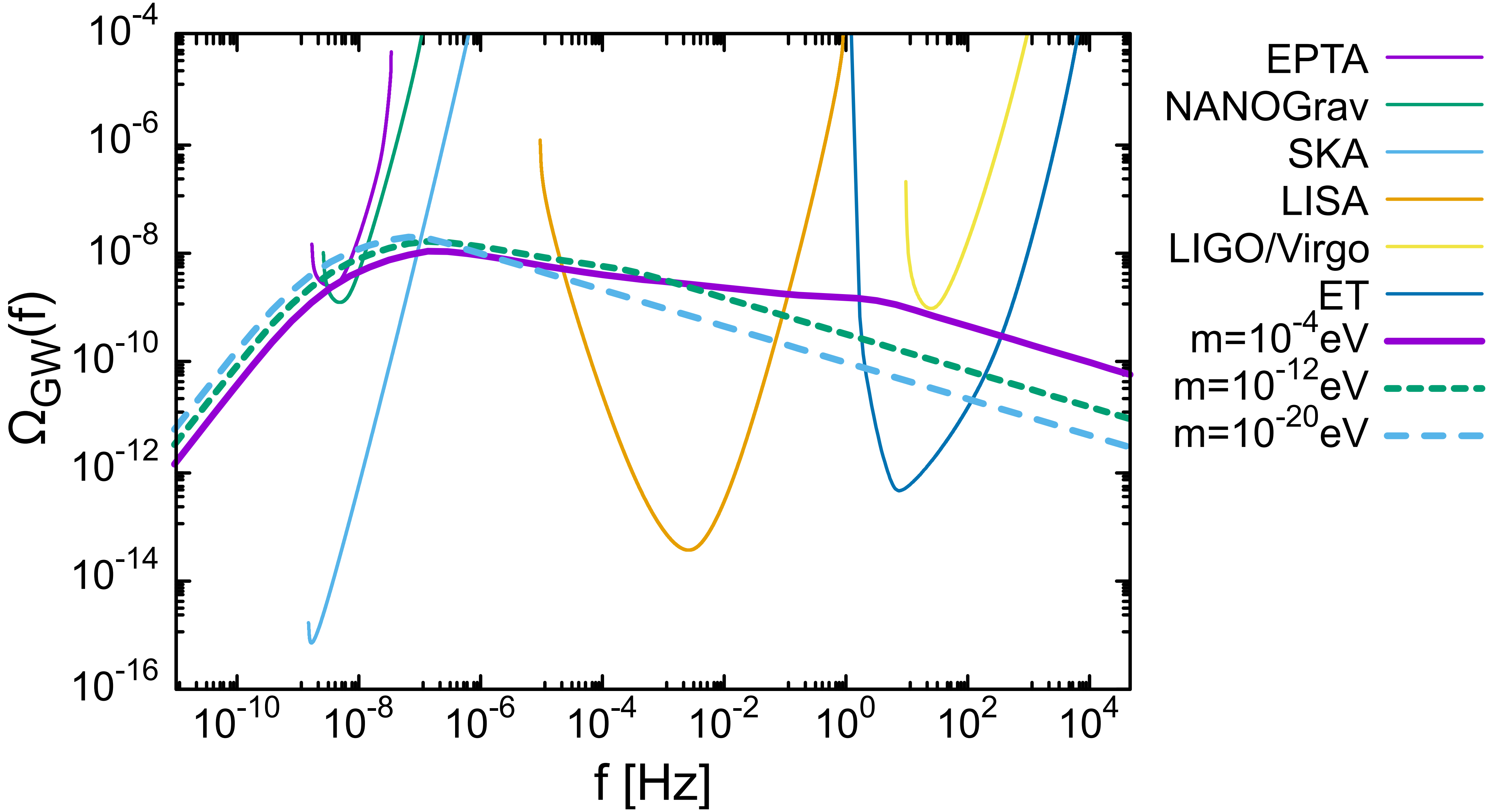


log-enhanced (scaling violation)



no-scaling violation

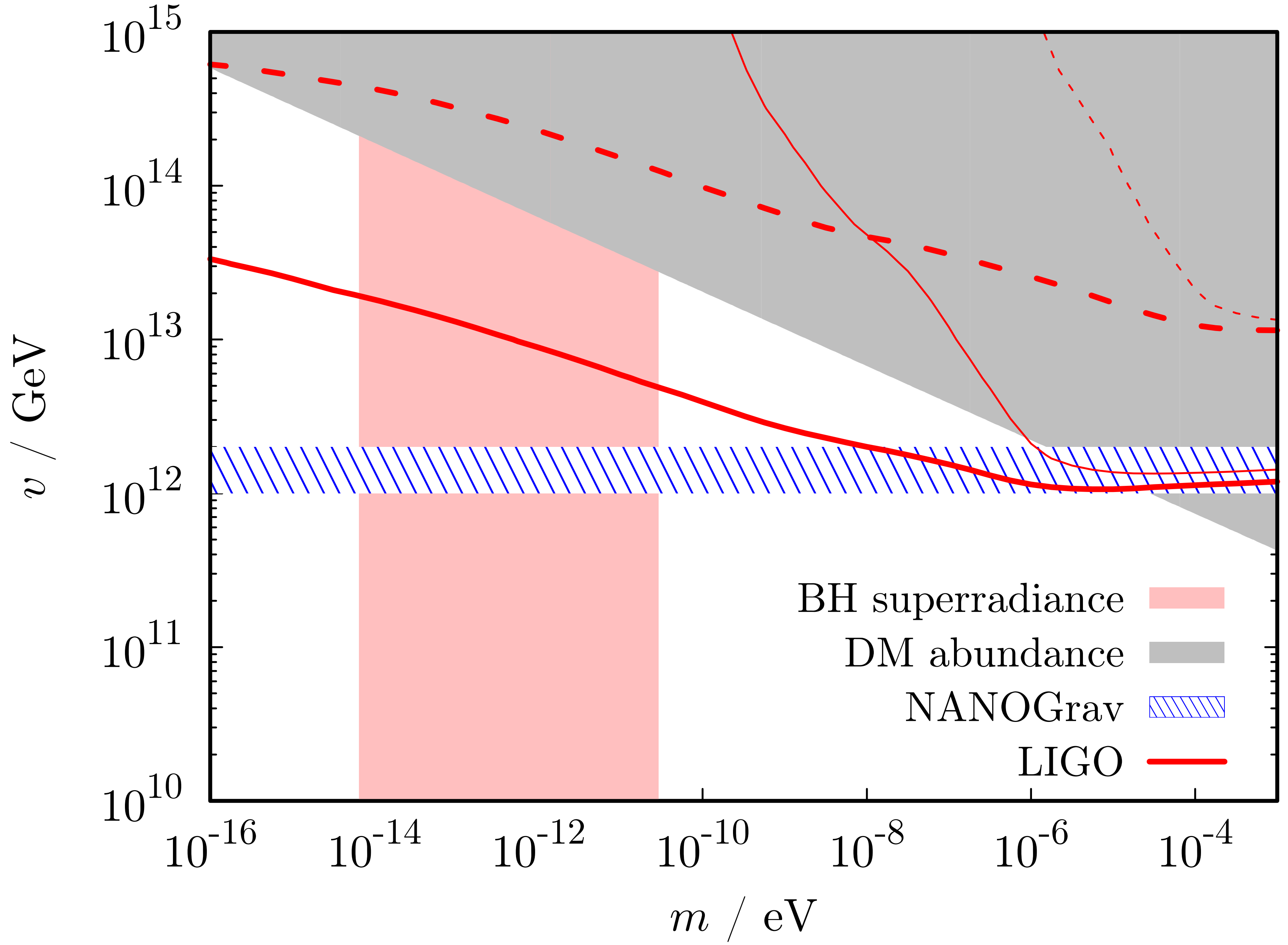
GW spectrum with log-enhancement



NK, Nakayama 2306.17390

Dark photon DM abundance

NK, Nakayama 2306.17390



m_A ~ 1-10μeV

Summary

- Dark photon can be produced from the network of cosmic strings

  but the production stops when $H < m_A$

  —> relic abundance is fixed at that time

  observed DM abundance can be obtained for e.g.

$$v \sim 10^{12}\text{-}10^{14}\mathrm{GeV},\ m_A \sim 10^{-14}\text{-}10^{-5}\mathrm{eV}$$

- Gravitational waves are emitted as a signal of this scenario

  Spectrum is different from both local and global one

- NANOGrav data can be explained & tested by future aLIGO

  with dark photon mass m_A ~ 1-10μeV