Production of light dark photon dark matter in the early universe

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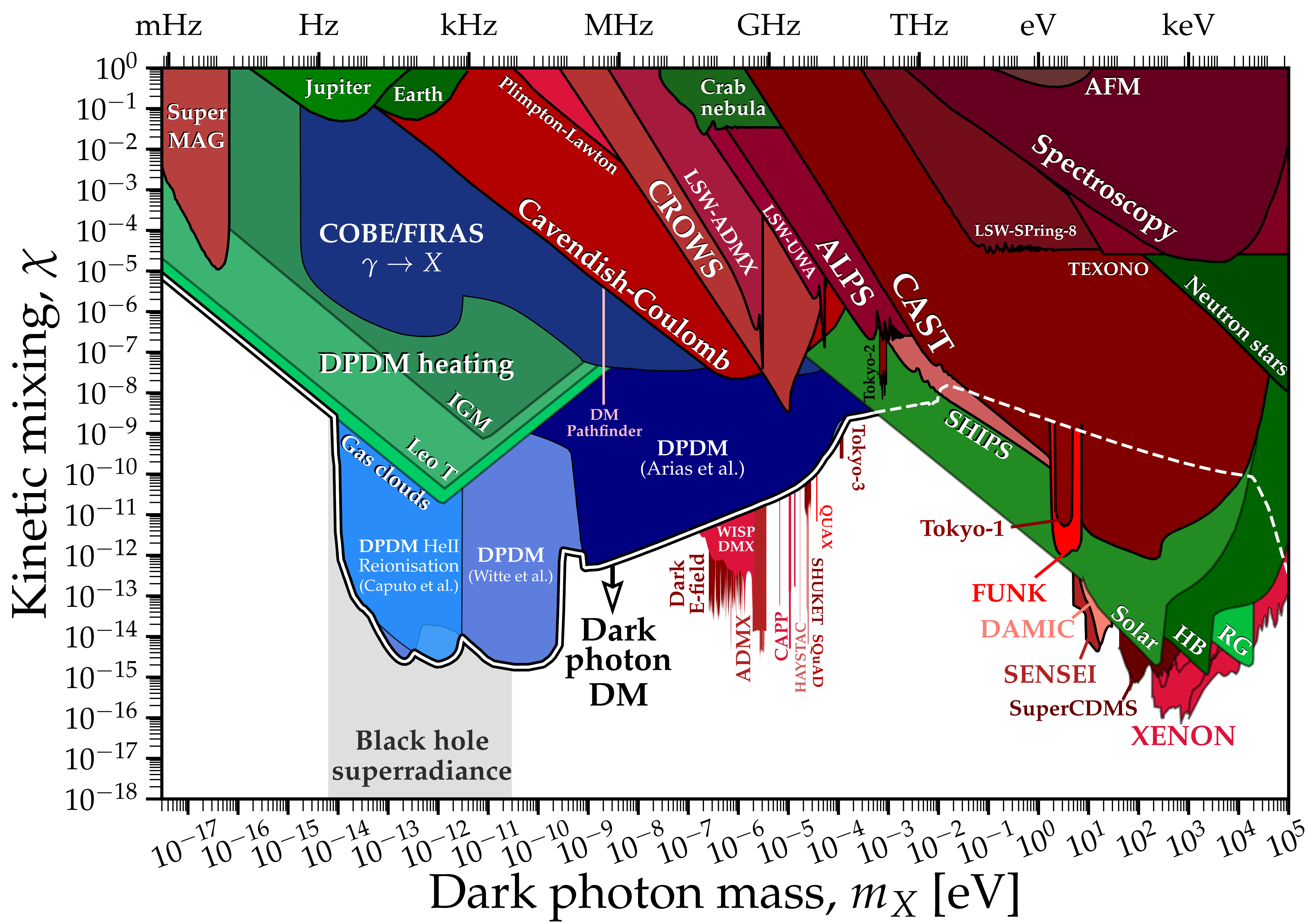
Dark photon dark matter : current status



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

Caputo et al 2105.04565

Dark photon dark matter production

- Gravitational particle production during inflation / reheating

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

Requirement : High scale inflation / high reheating temperature

- Resonant production from axion oscillation

Agrawal, NK, Reece, Sekiguchi, Takahashi (2020)

Co, Pierce, Zhang, Zhao (2019), Bastro-Gil, Santiago, Ubaldi, Vega-Morales (2019)

Requirement : Large axion-dark photon coupling

- Resonant production from dark Higgs oscillation Harigaya, Narayan (2019)

Requirement : Extremely small Higgs self-coupling and gauge coupling

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

Requirement : non-trivial dynamics of gauge kinetic function during inflation

- Production from the decay of cosmic string loop

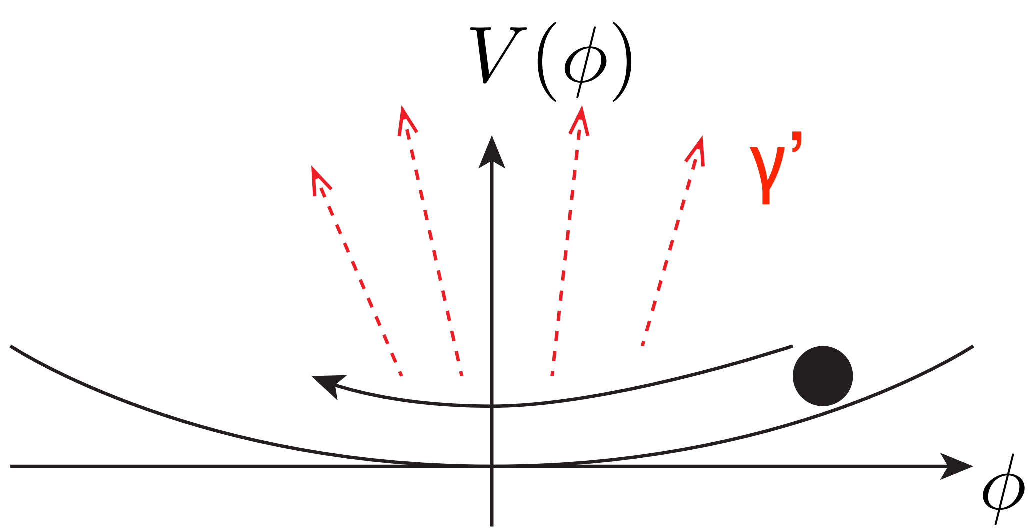
Long, Wang (2019), NK, Nakayama (2022)

Resonant dark photon DM production from axion

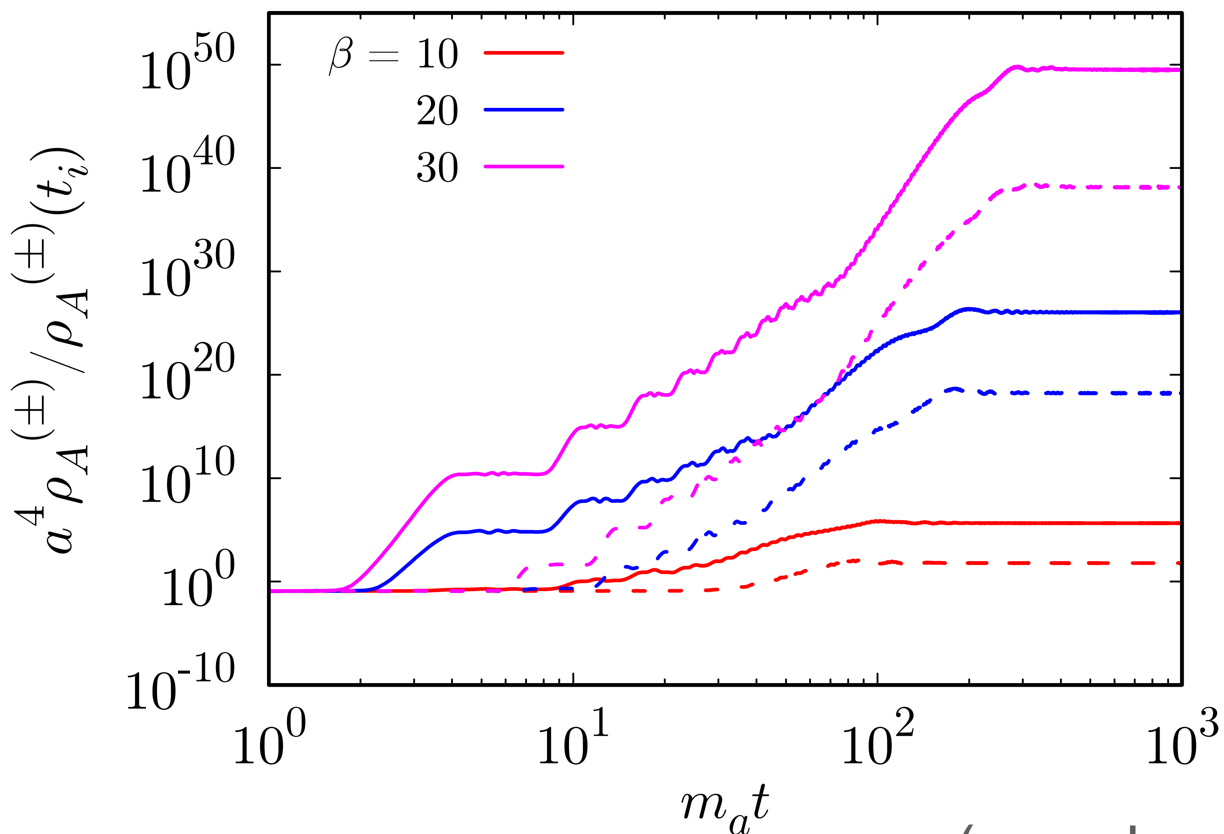
Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188
Co, Pierce, Zhang, Zhao, 1810.07196
Bastero-Gil, Santiago, Ubaldi, Vega-Morales, 1810.07208

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

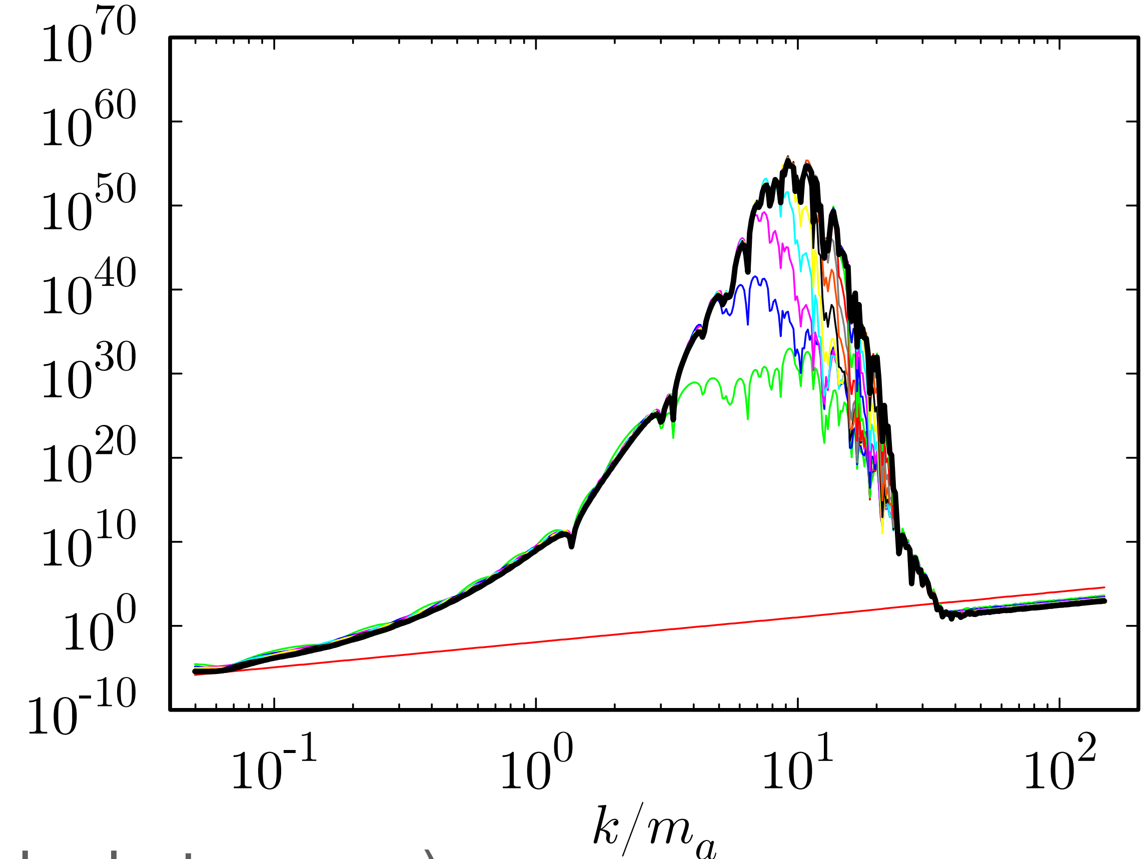
$$\longrightarrow \quad \ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a}\right)\mathbf{A}_{\mathbf{k},\pm} = 0$$



resonant amplification



spectrum



(massless dark photon case)

- Produced dark photons can stabilize the dark Higgs

  —> secondary inflation (like thermal inflation) or early dark energy

  NK, Nakagawa, Takahashi, 2111.06696

  Nakagawa, Takahashi, Yin, 2209.01107

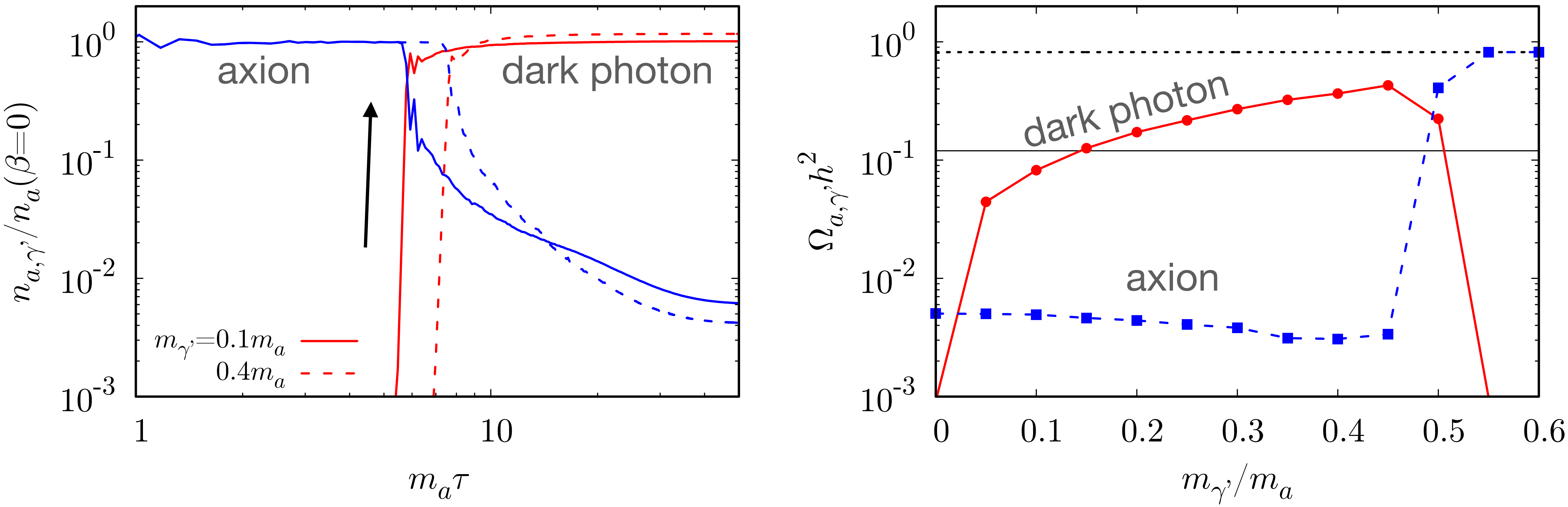
  next talk by S. Nakagawa

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

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)

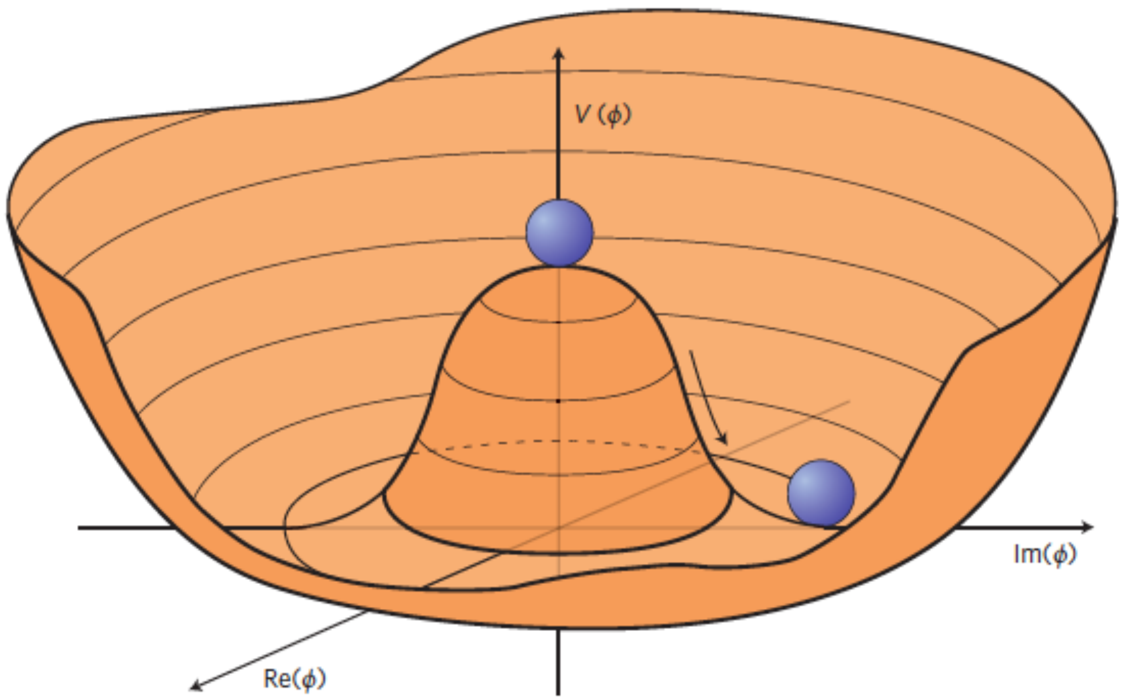
& dark photon can be the dominant DM component

Dark photon DM from Abelian-Higgs cosmic strings

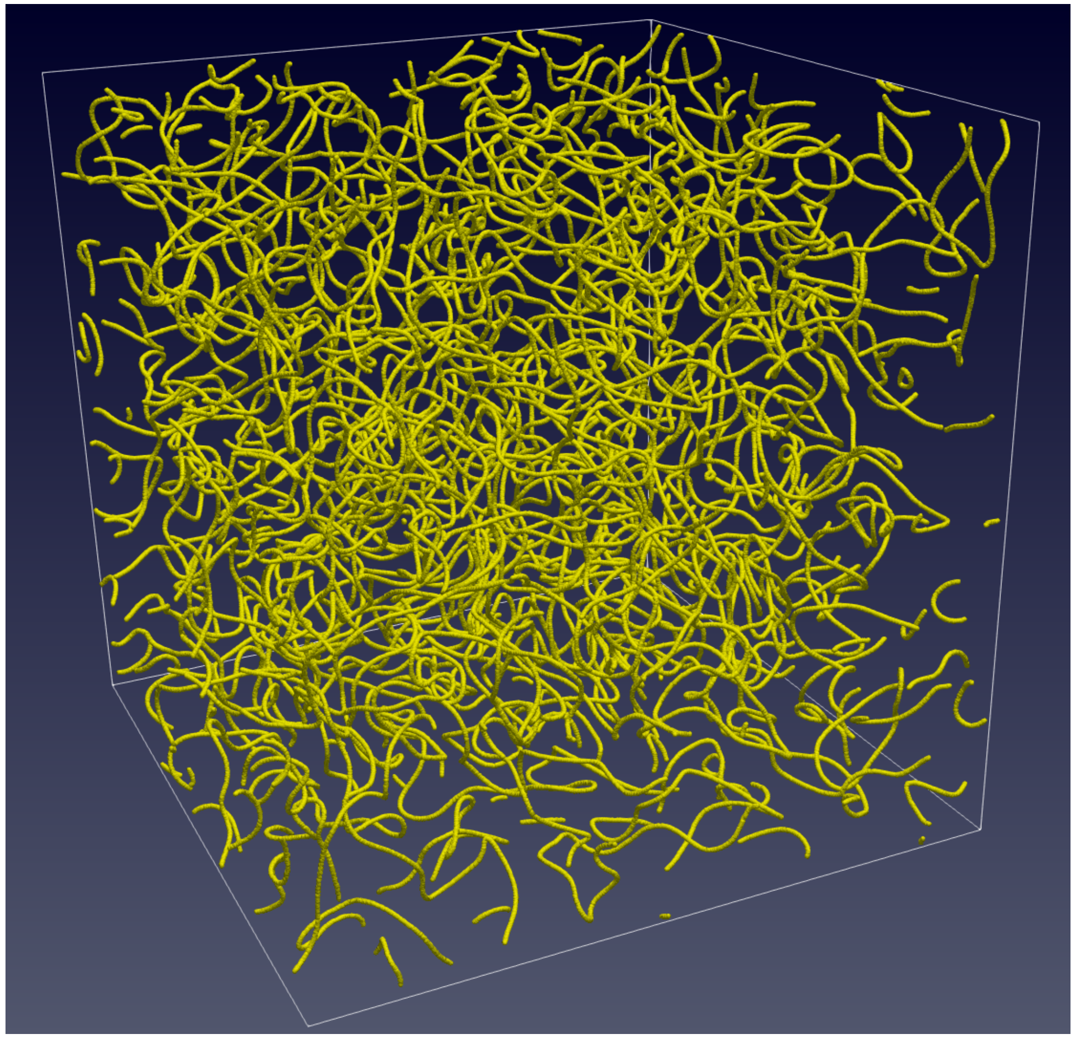
Long, Wang 1901.03312, NK, Nakayama 2212.13573

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

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



Ellis, Gaillard, Nanopoulos 1504.07217



Scenario

- We are interested in very light dark photon (i.e. extremely small gauge coupling) in order to give the observed relic abundance.

—> cosmic string is almost global (Type-II string)

e = 0 limit corresponds to the global string case

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

(similar to the axion emission from global strings)

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

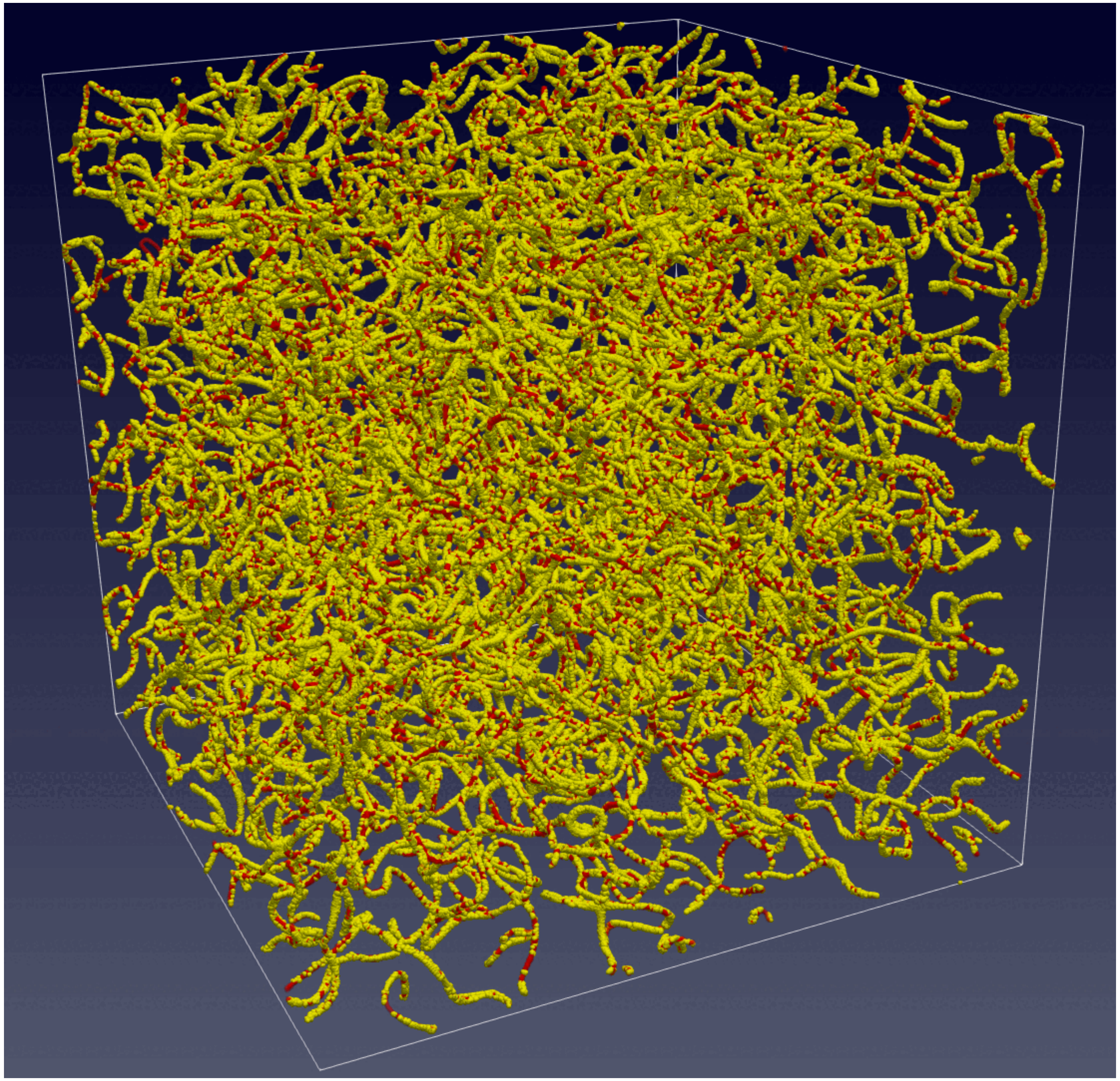
(i.e. loop oscillation frequency becomes smaller than the mass) or $H \lesssim m_A$

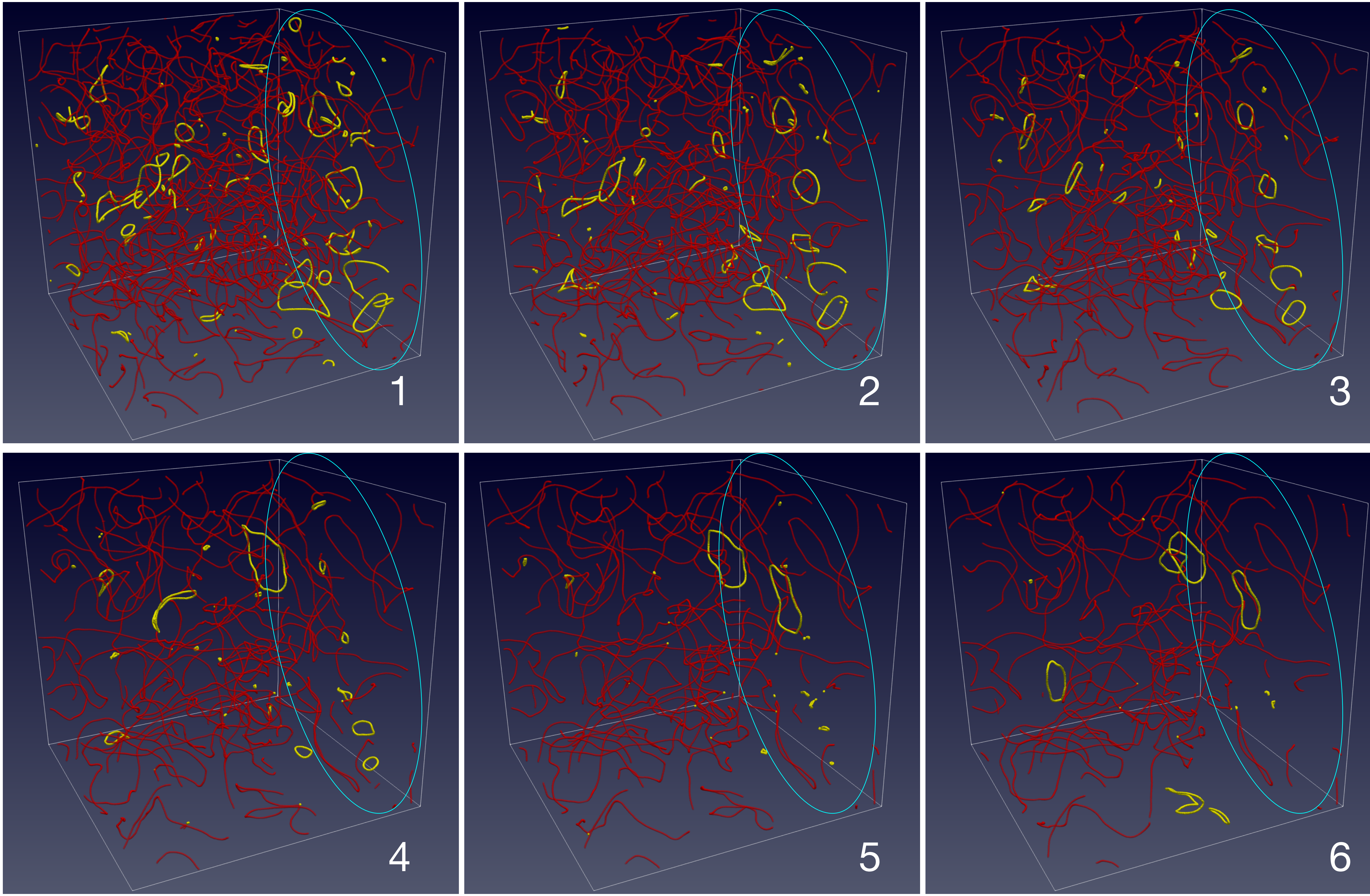
- After that, string behaves like local string

(network loses the energy only through the GW emission)

Loop production & decay

Type-II string with $e=0.01$ and $\lambda=2$



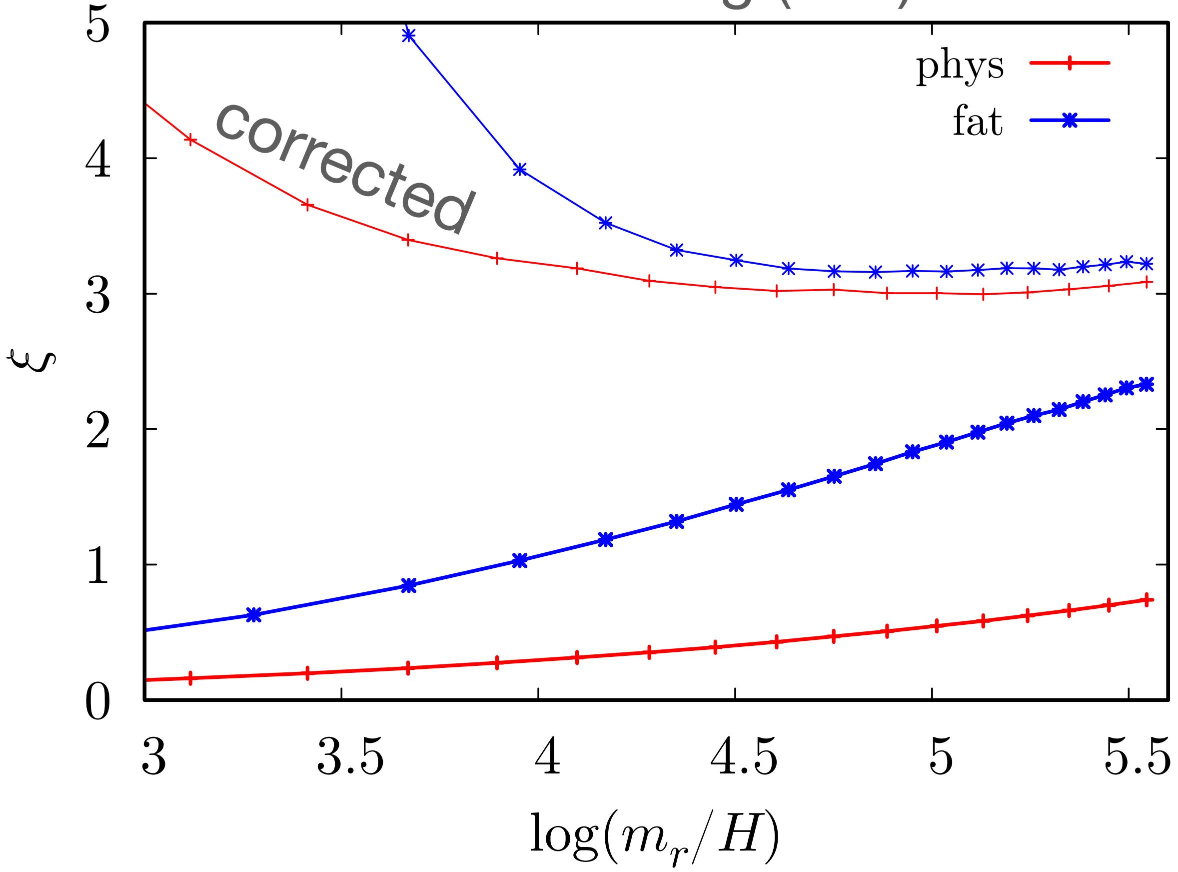

1
2
3
4
5
6

Scaling law/violation

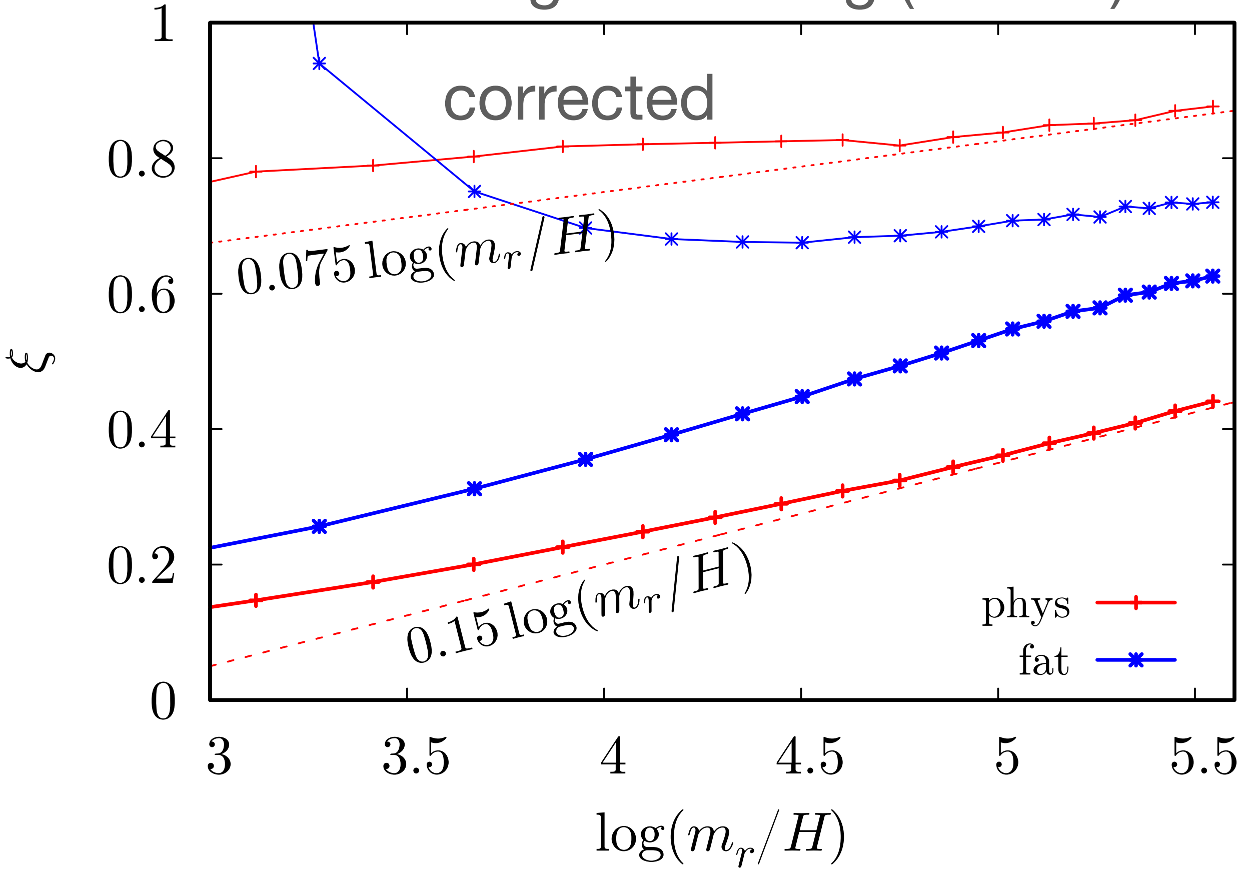
number of strings per Hubble patch: $\xi = \frac{\ell_{\rm str} t^2}{V}$

V : volume
l_{str} : total string length

Local string (e=1)

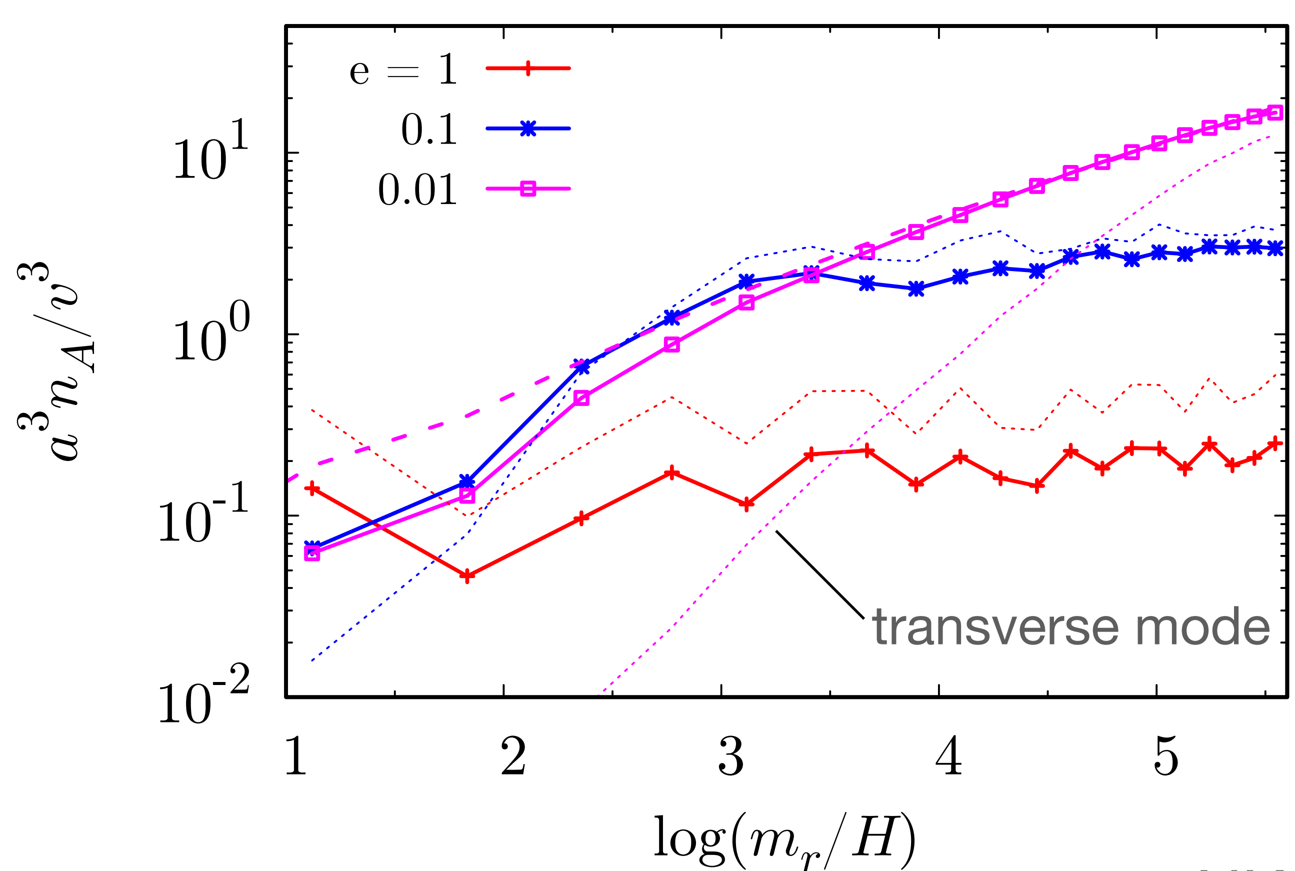


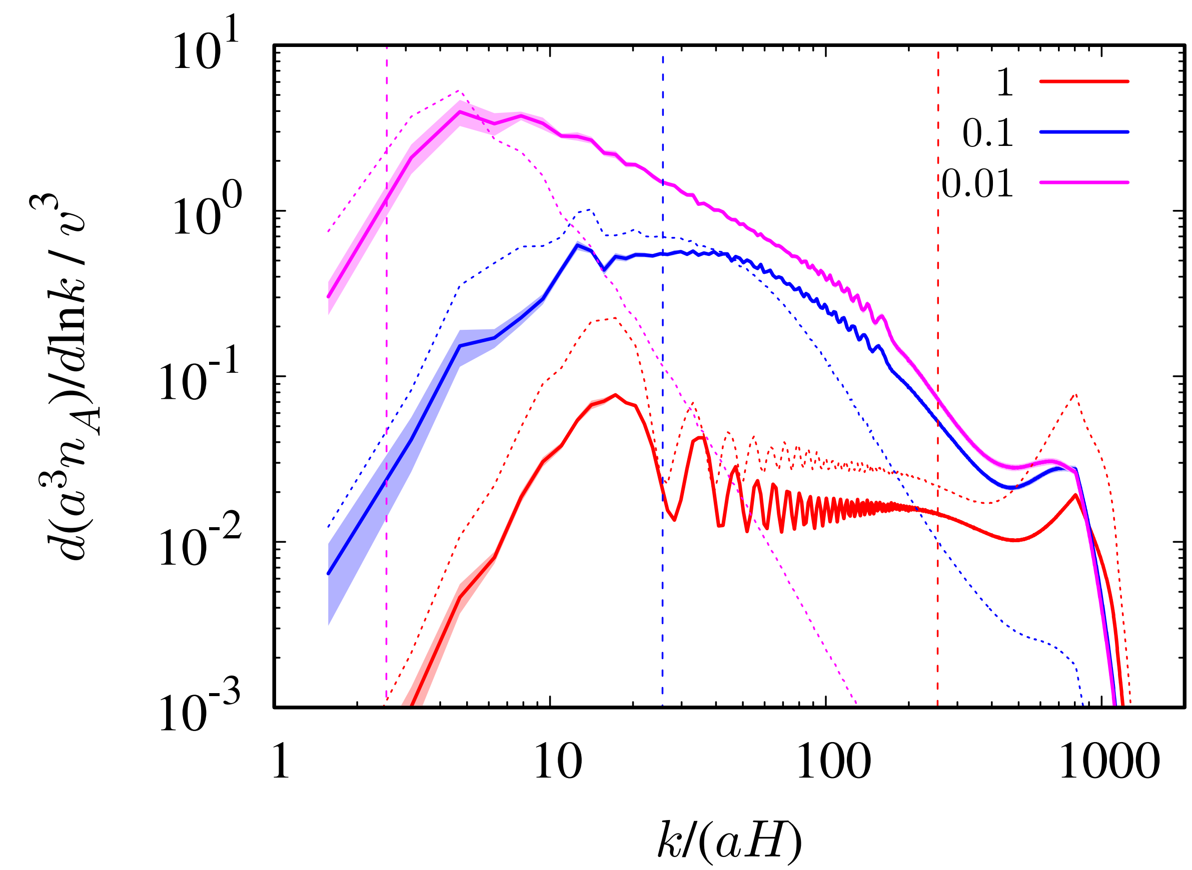
Near-global string (e=0.01)



scaling violation can be seen (similar to the axion string case)

Dark photon DM abundance & spectrum



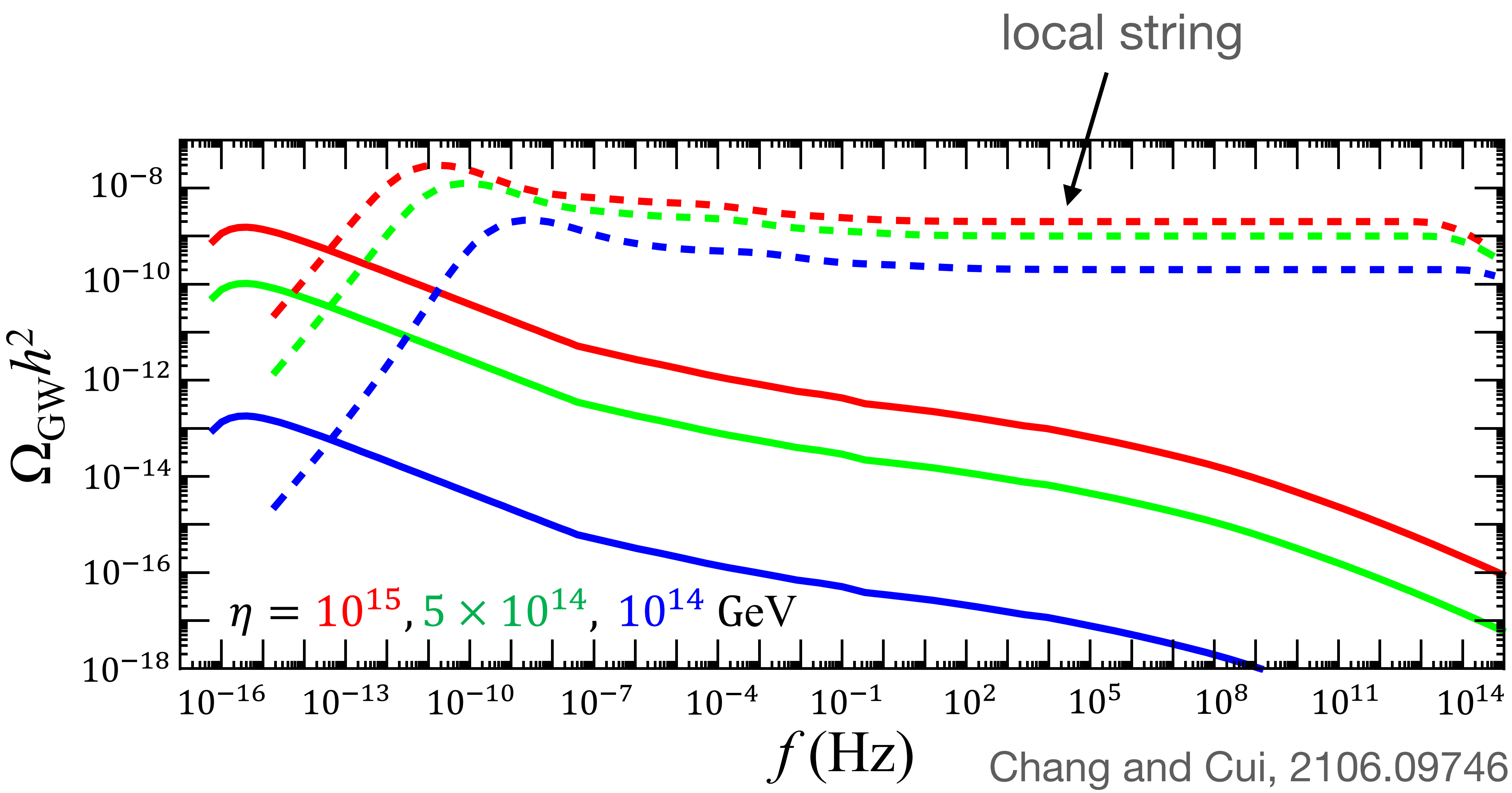


NK, Nakayama 2212.13573

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

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

GW spectrum from local/global strings



Chang and Cui, 2106.09746

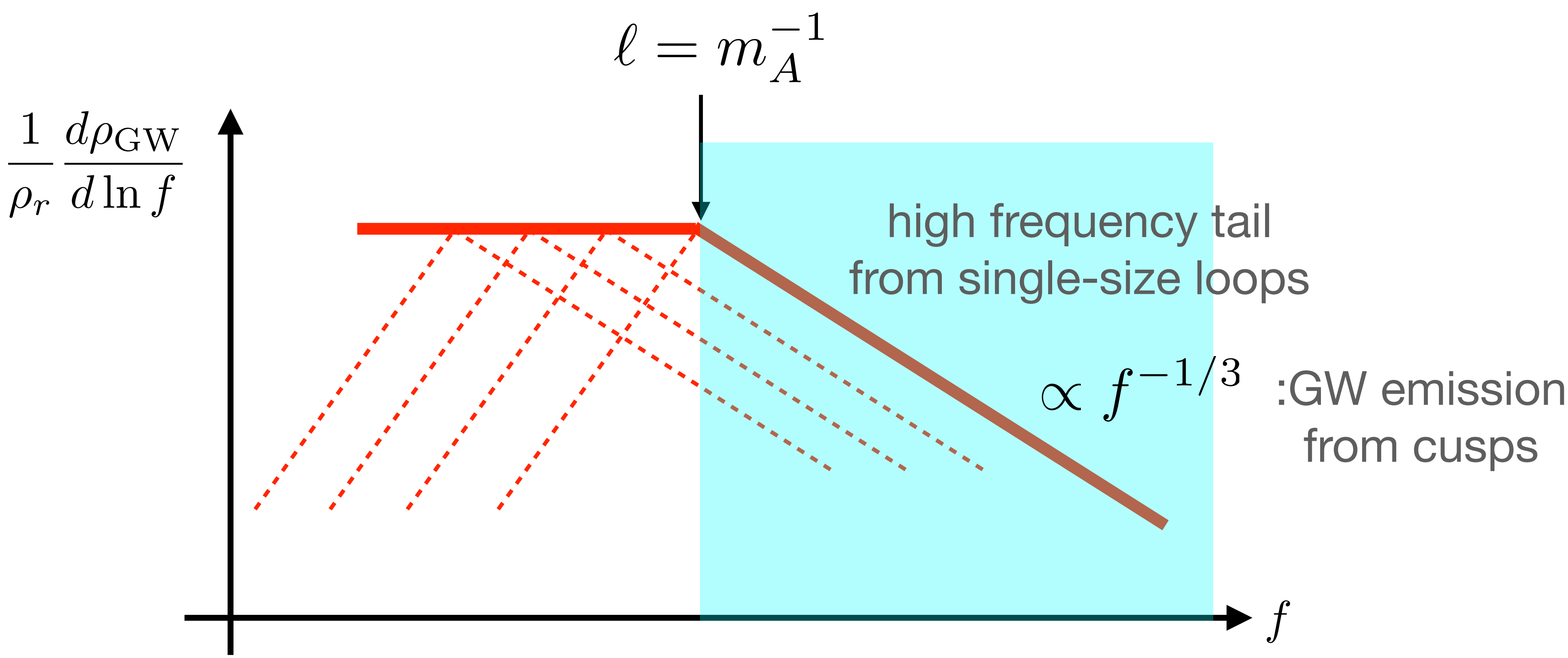
(see also Gorghetto et al, 2101.11007)

Energy loss of loops = GW emission + vector boson emission

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

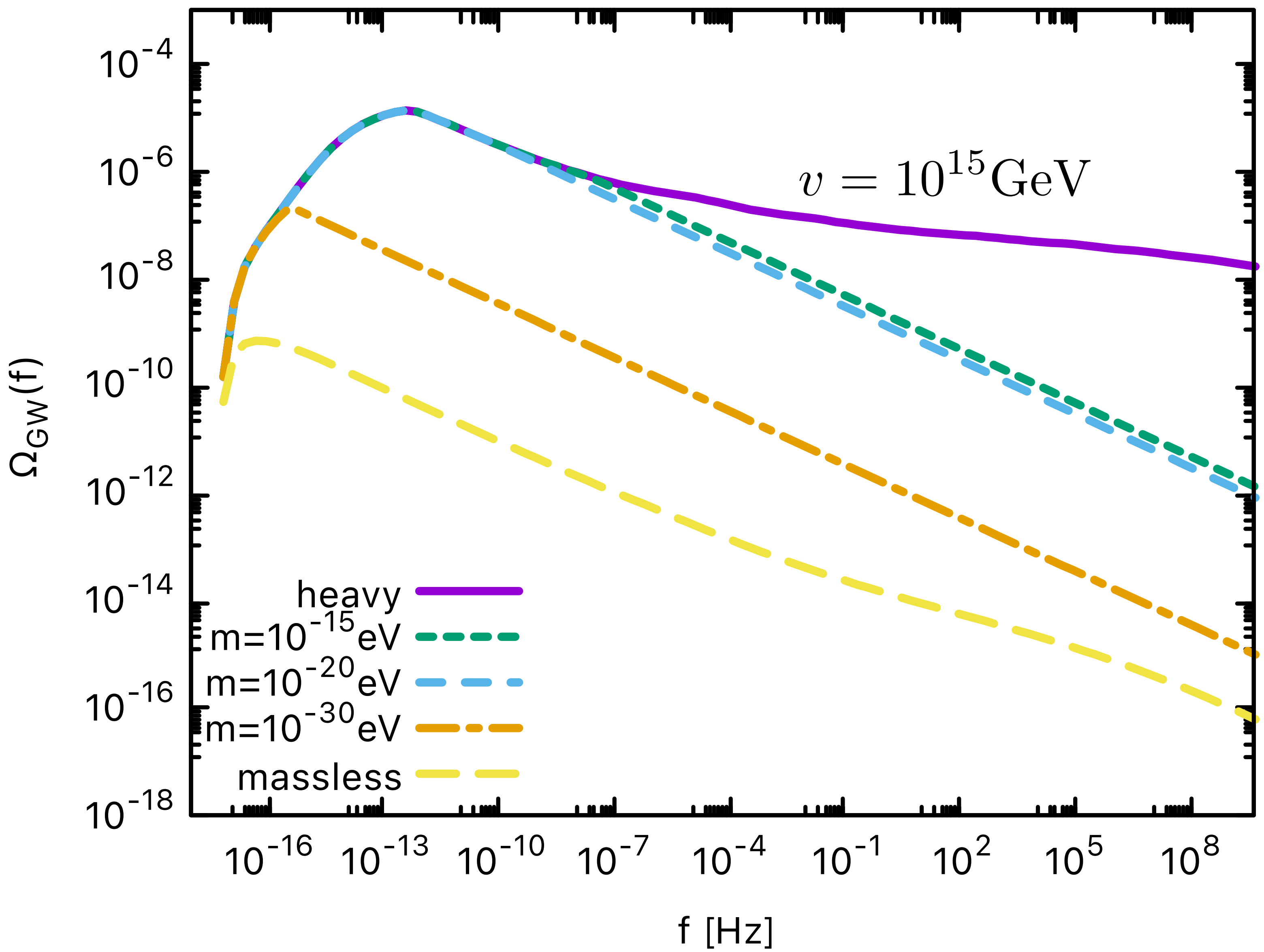
Loops shorter than m_A^{-1} can emit dark photons

—> short lived & GW emission is suppressed



GW spectrum

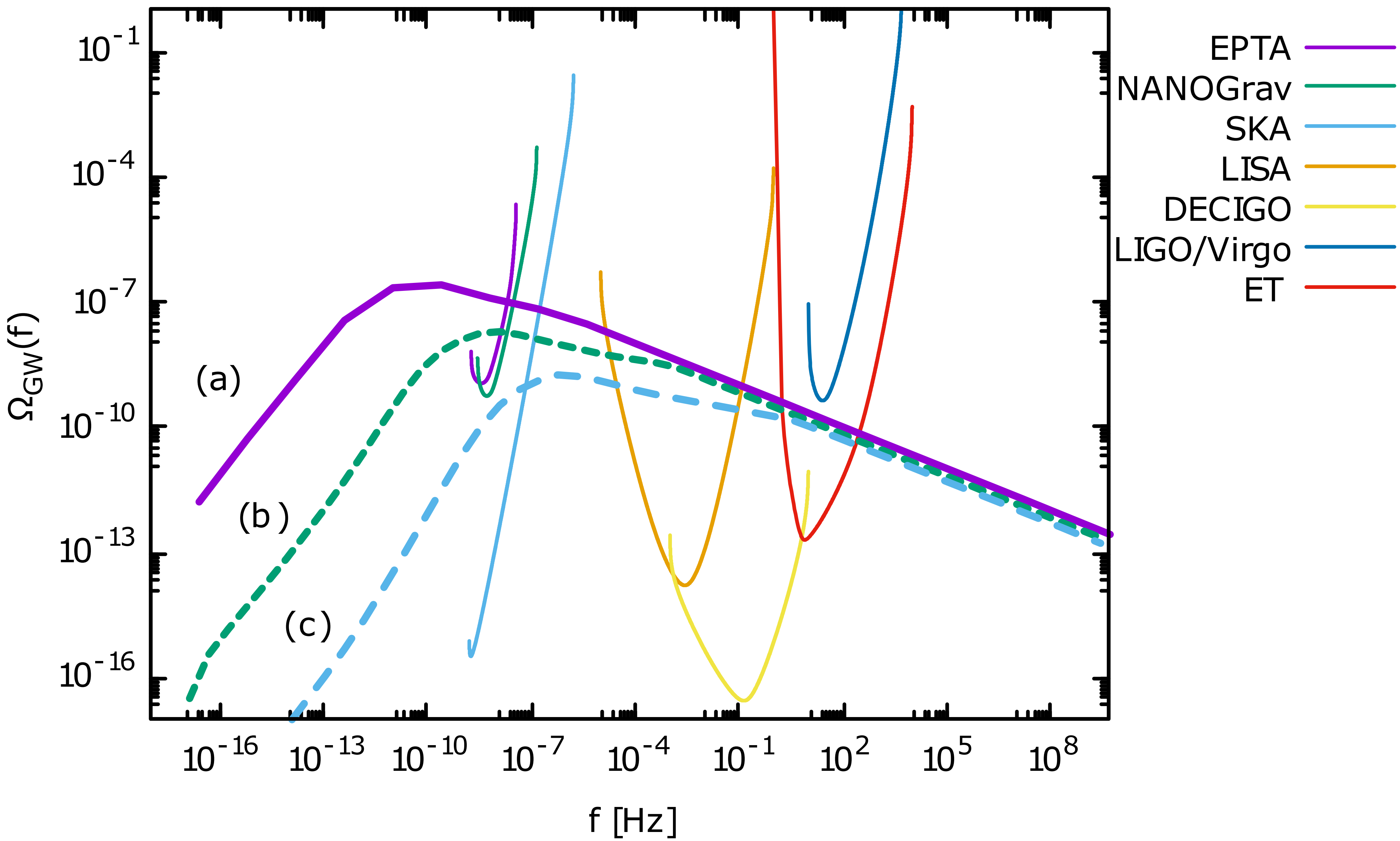
NK, Nakayama 2212.13573



scaling violation (Log-dependence) is taken into account

Detectability

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

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

efficient loop collapse continuously produces dark photons

dark photon production stops when $H < m_A$

(i.e. the dark photon emission is kinematically suppressed)

—> relic abundance is fixed at that time

observed abundance can be obtained for e.g.

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

- Gravitational waves are emitted as a signal of this scenario

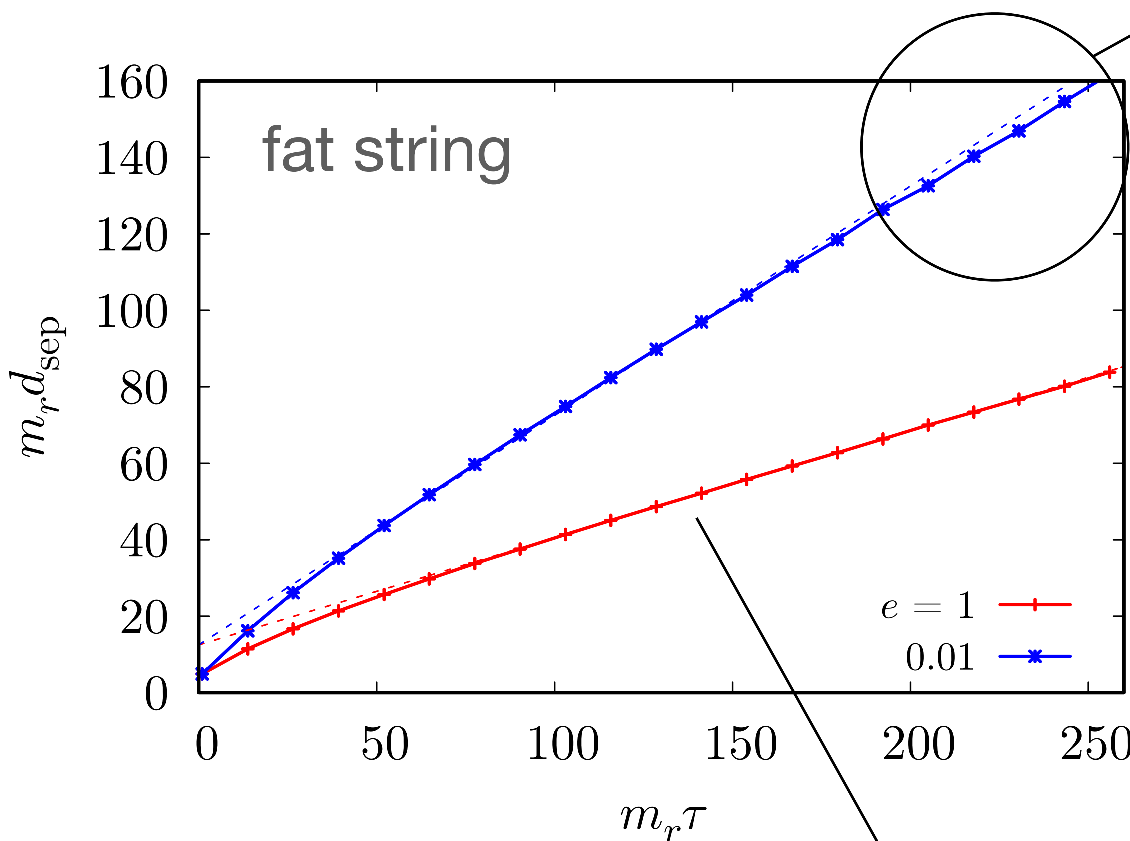
Spectrum is different from both local and global one

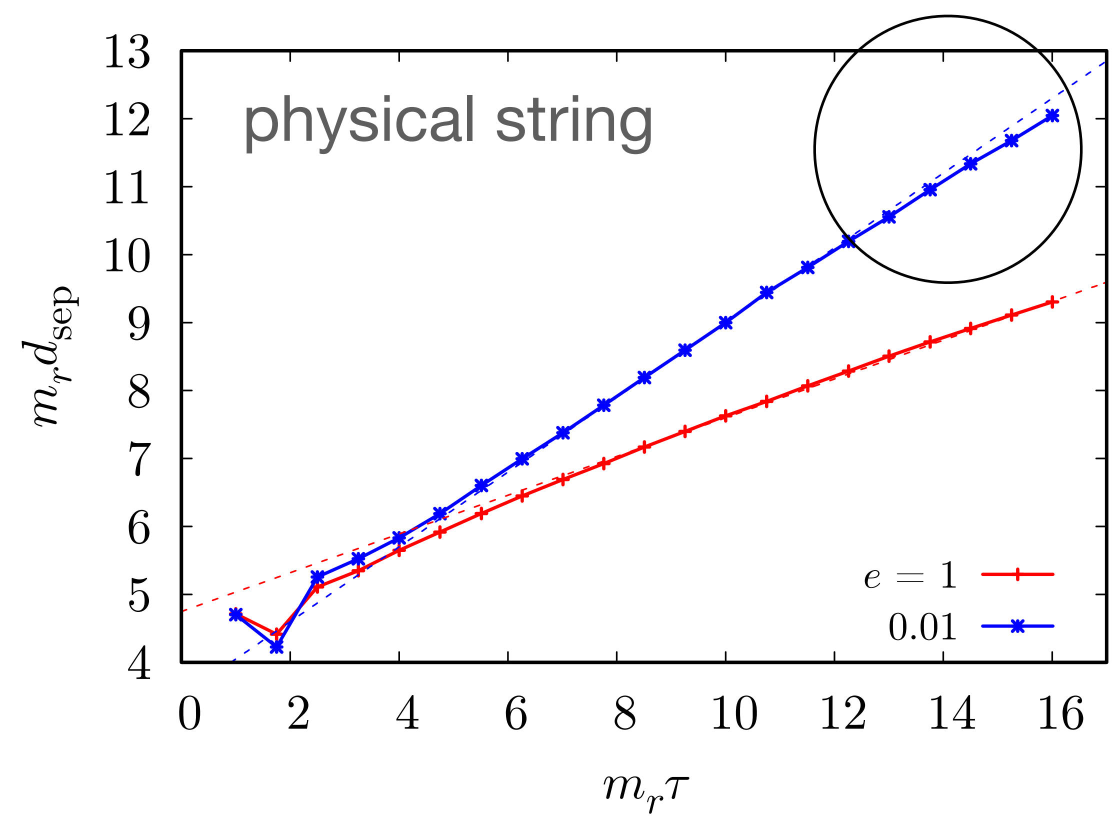
It can be tested by combining pulsar timing and direct detection

Mean separation of neighboring strings

$$d_{\text{sep}} = \sqrt{\frac{V^{(c)}}{\ell_{\text{str}}^{(c)}}}$$

deviation from the scaling regime





$d'_{\text{sep}} \simeq 0.28$ (consistent with previous works)

Near-global string is more sparse than local string
(as pointed out by Yamaguchi at al (1999))

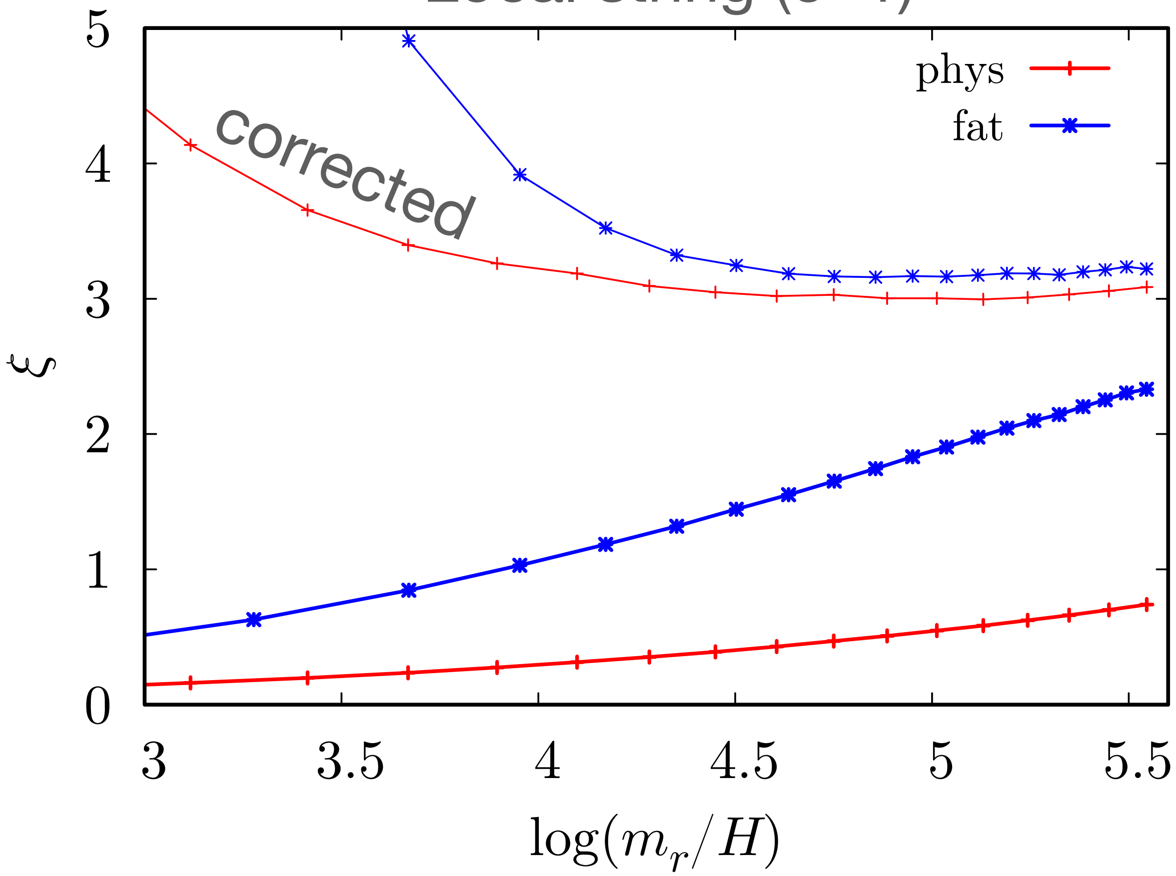
Number of strings per Hubble patch

$$\xi = \frac{\ell_{\rm str} t^2}{V}$$

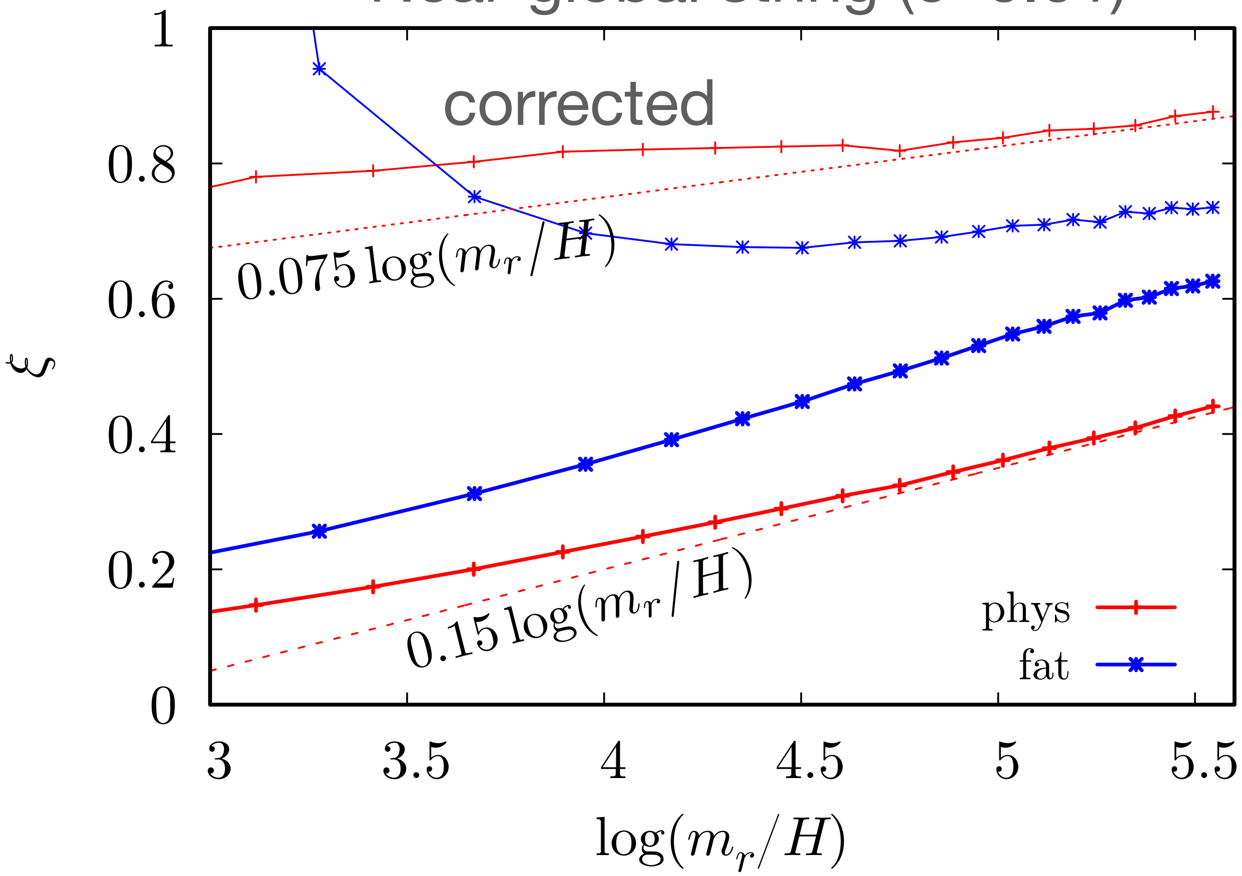
correction: $d_{\rm sep} = a\tau + b \quad \rightarrow \quad \tilde{d}_{\rm sep} \equiv d_{\rm sep} - b = a\tau$

$$\tilde{d}_{\rm sep} = \sqrt{\frac{V^{(c)}}{\tilde{\ell}^{(c)}_{\rm str}}} \longrightarrow \tilde{\xi} = \frac{\tilde{\ell}_{\rm str} t^2}{V}$$

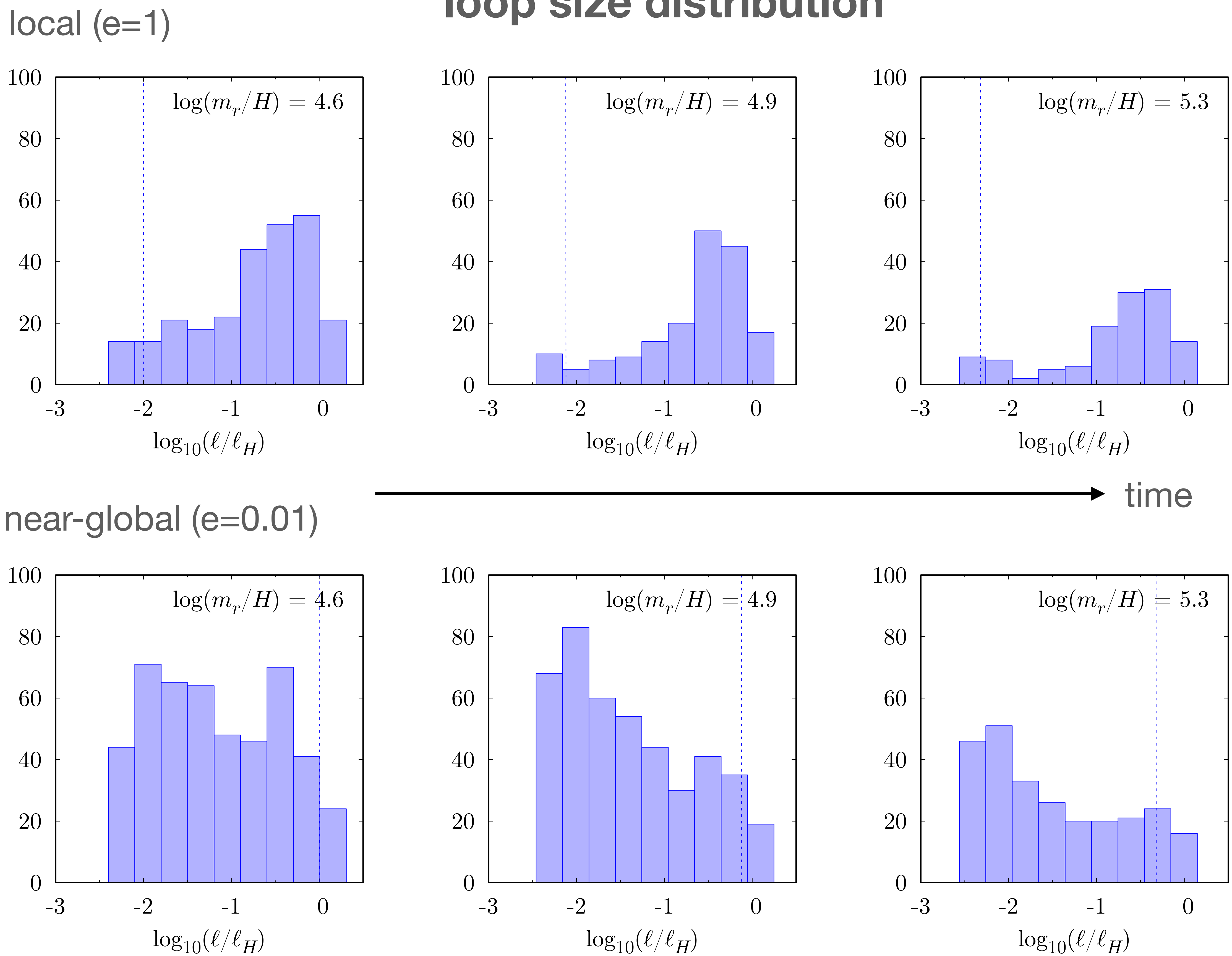
Local string (e=1)



Near-global string (e=0.01)

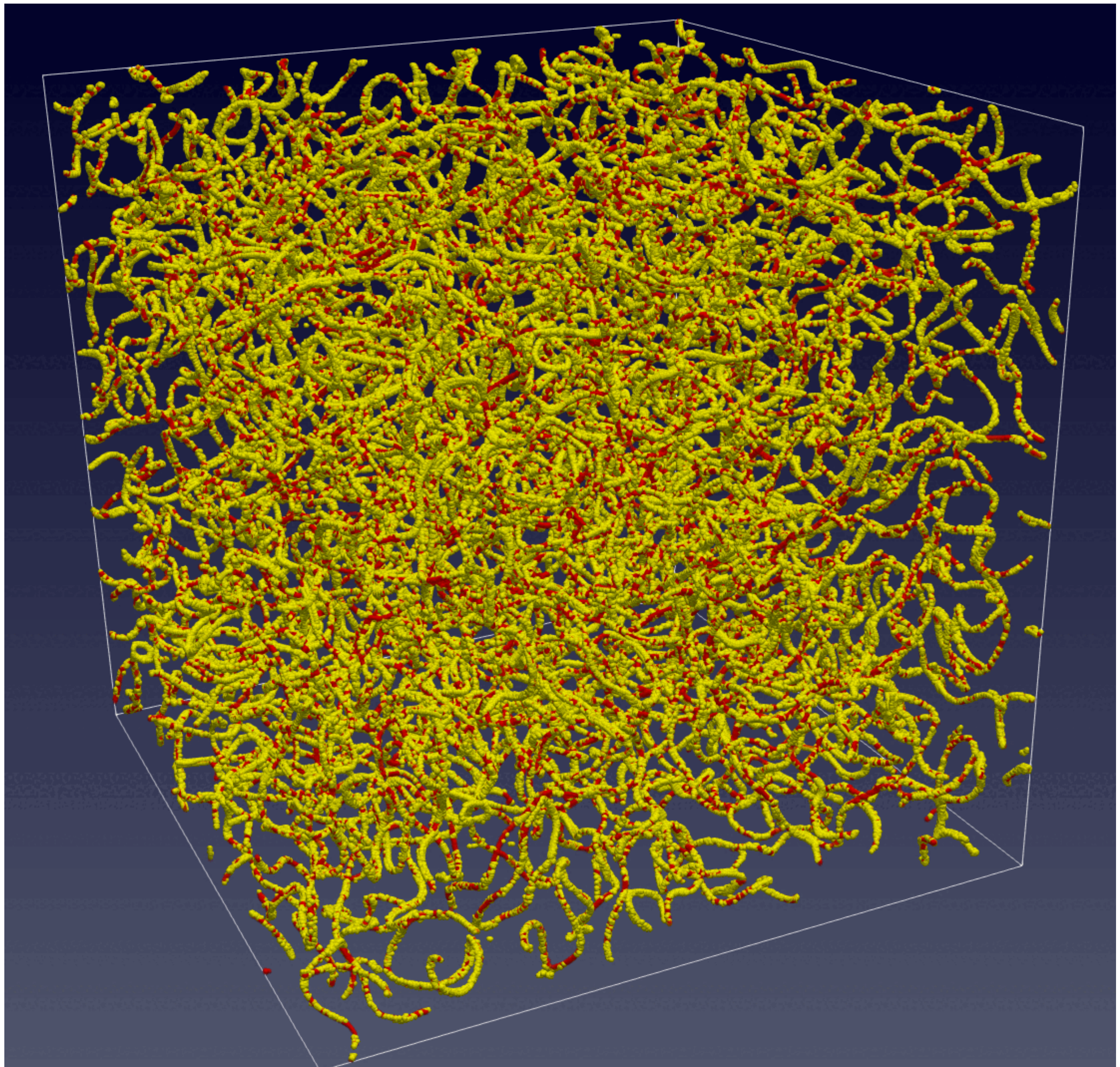


loop size distribution

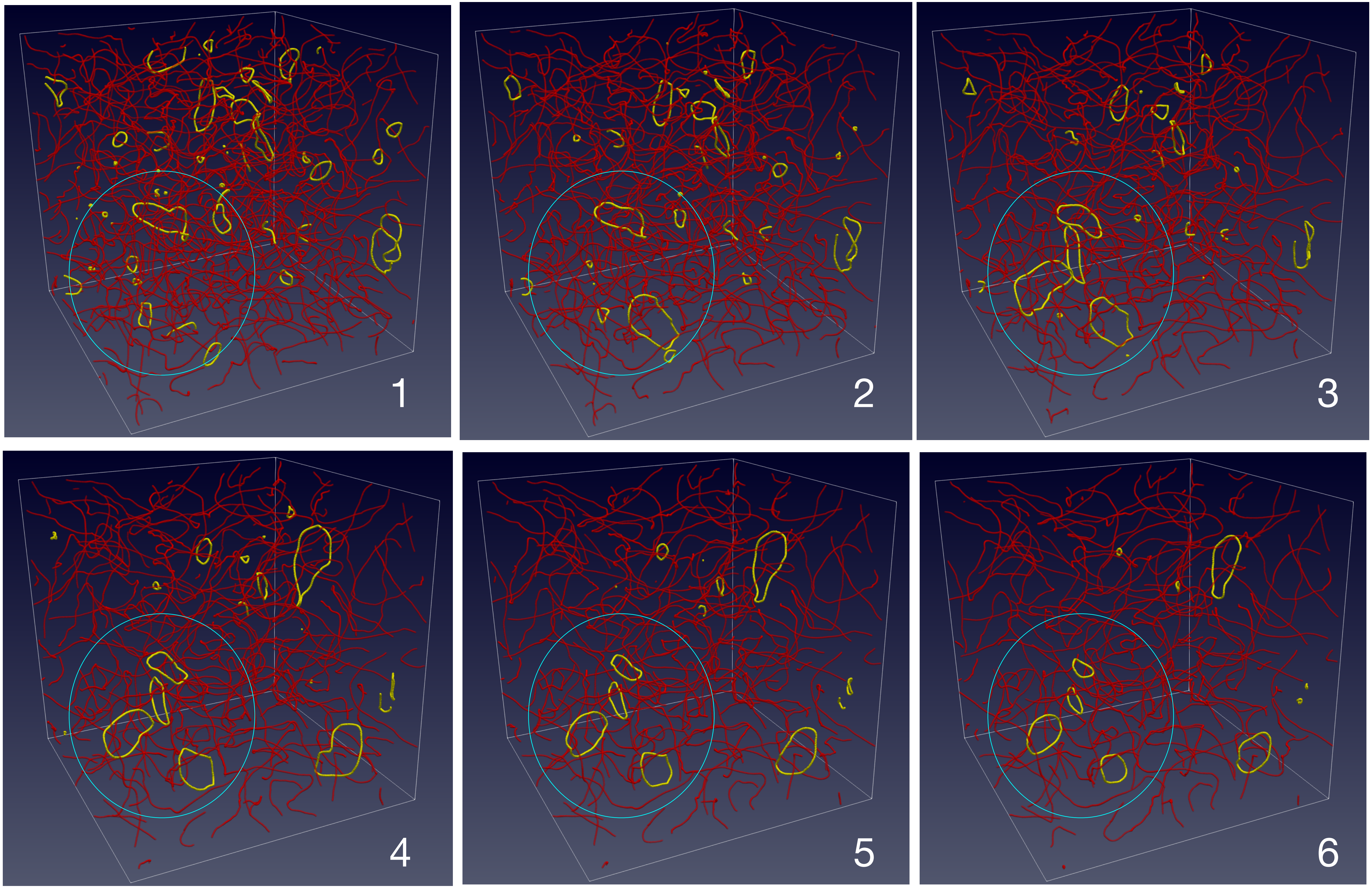


Loop production & decay

local string (e=1)



local string (e=1)

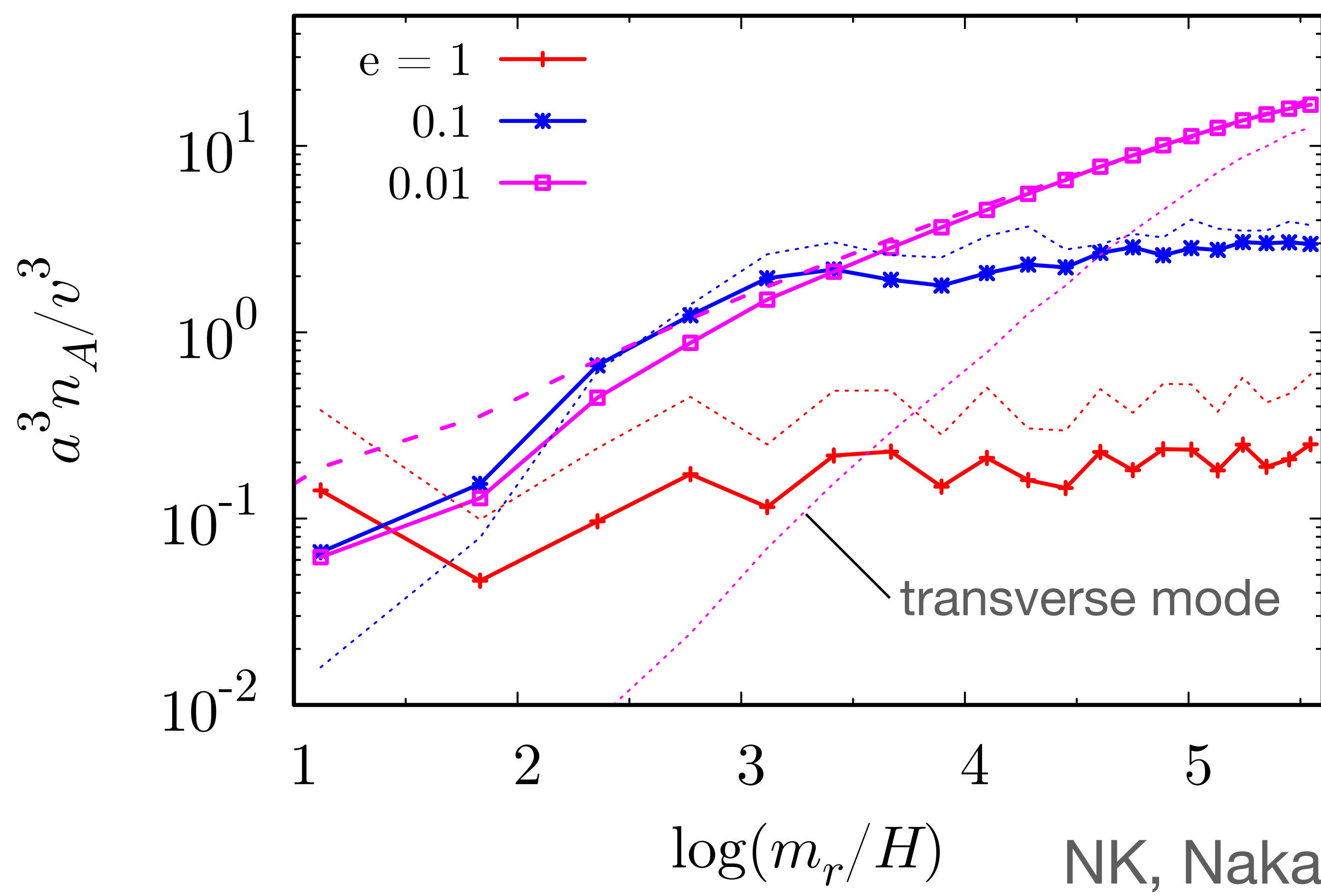


Emission of longitudinal vector boson

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

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

(analytic estimation)

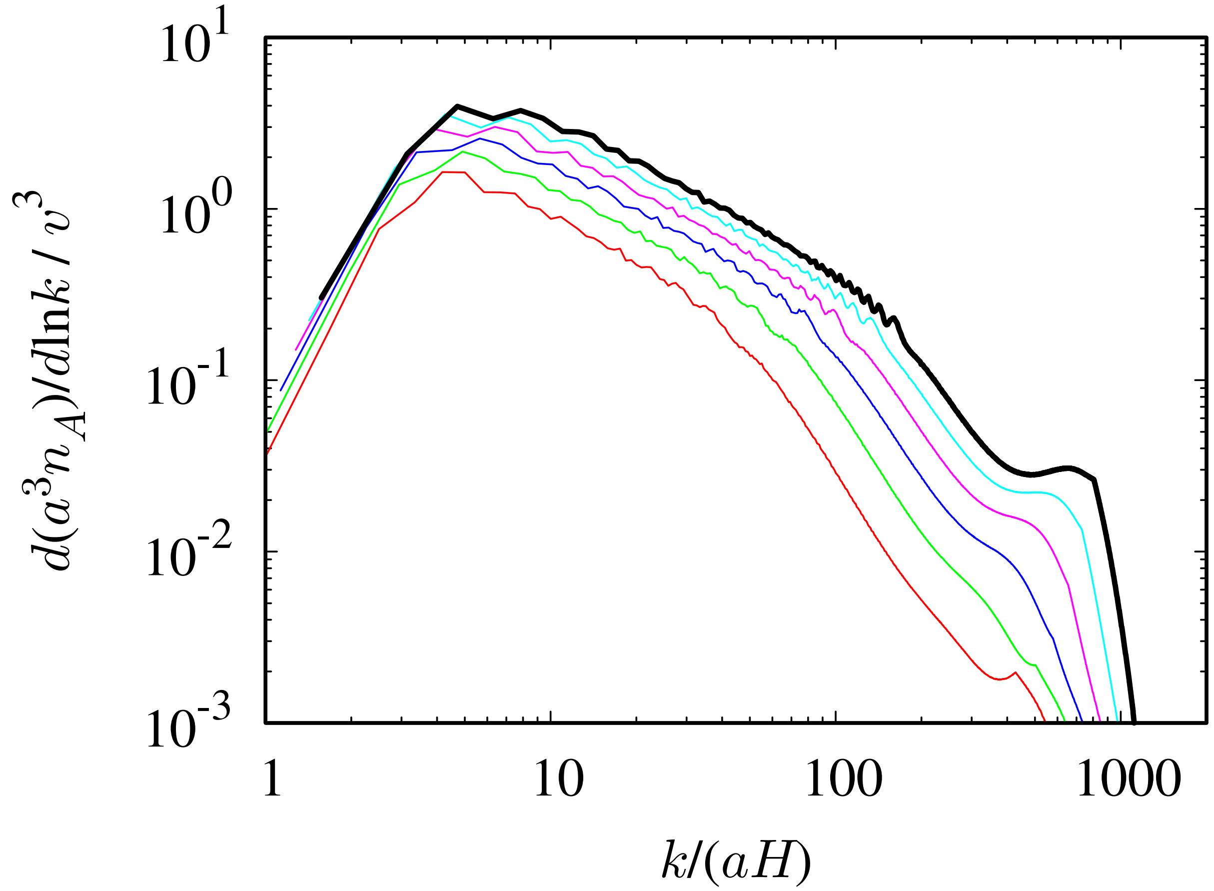


NK, Nakayama 2212.13573

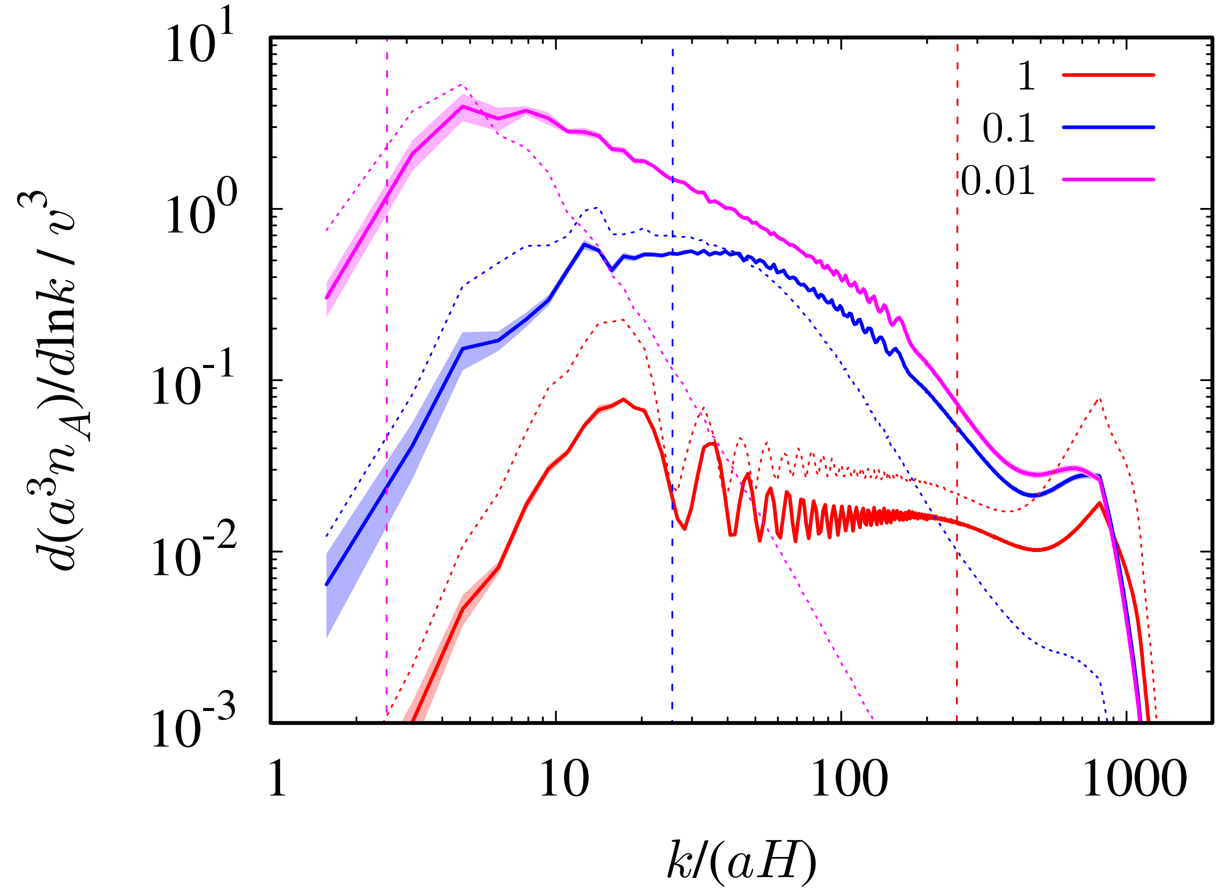
Spectrum of emitted dark photon

NK, Nakayama 2212.13573

time evolution (from bottom to top)



final value



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