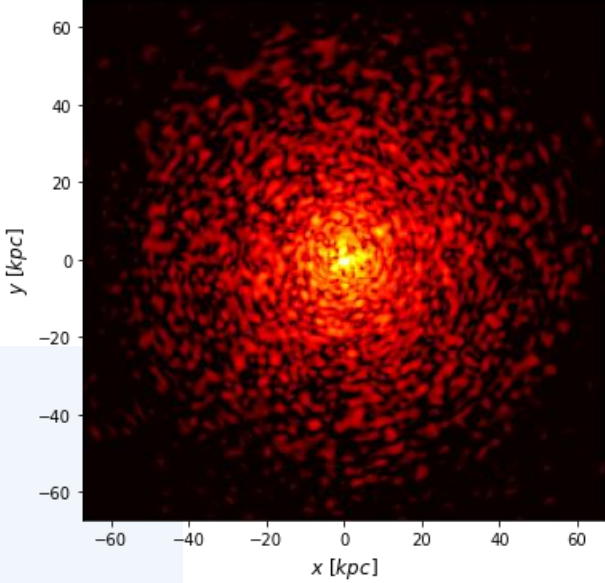
2025 Cargèse – BSM Odyssey

Climbing



DM, Bootstrapping, …

Revisiting Axion Strings

Frisbee

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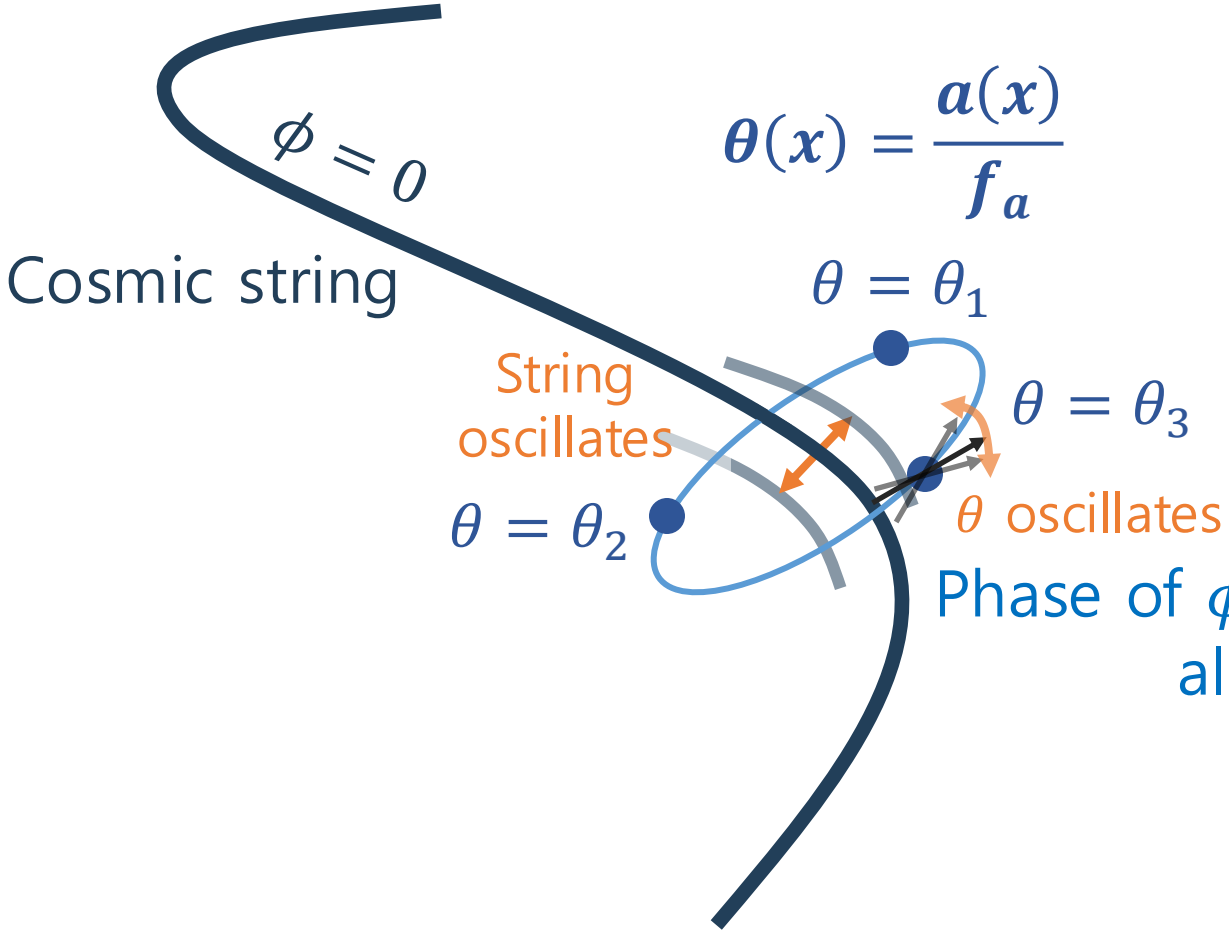
Based on **Kim, H.,** Park, J. & Son, M. (2024) JHEP07(2024)150
Kim, H. & Son, M. (2025) JHEP07(2025)052

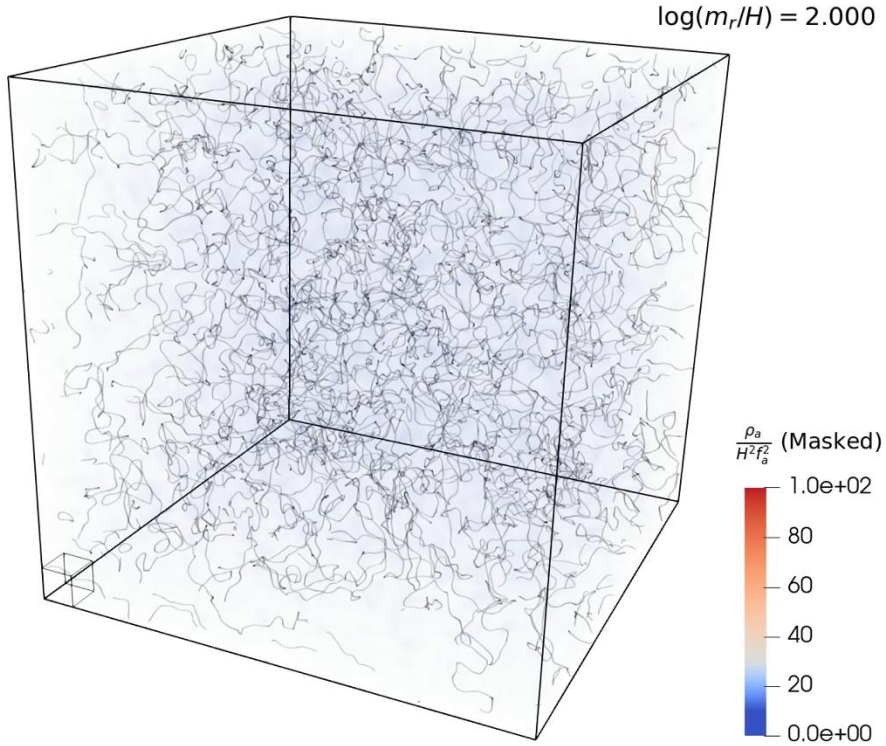
Brief Description of Axion String



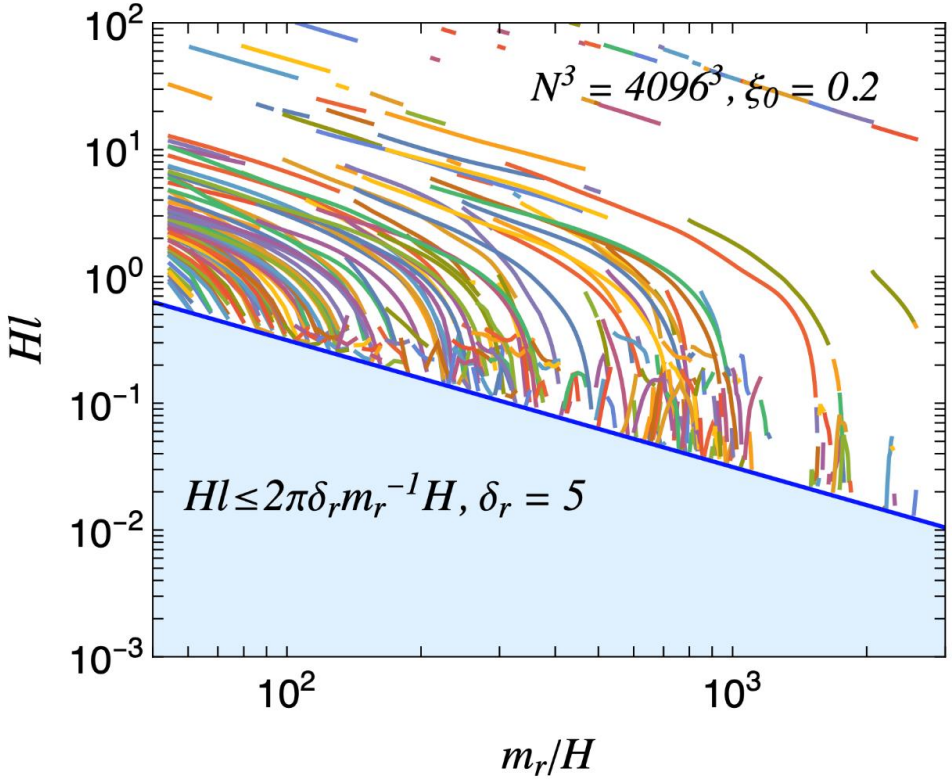
$$\phi(x) = |\phi(x)|e^{ia(x)/f_a} \quad \textbf{(Axion)}$$

$$\mathcal{L} = \partial_\mu \phi^\star \partial^\mu \phi - \frac{m_r^2}{2f_a^2}\left(|\phi|^2 - \frac{f_a^2}{2}\right)^2$$

Axion Radiation from String Dynamics



- Strings get shorten
- Release energy into axion



- Number of string segments per Hubble patch seems to grow in time.
- Axion radiation seems to evolve toward more IR dominated spectrum.

Axion abundance and mass bound

The string network evolution may matter

🤔 $\dfrac{\Omega_a^{\rm str}}{\Omega_a^{\rm mis}} \approx 30$ ⇒ $m_a \geq 400\ \mu\text{eV}$

c.f. Misalignment bound: $m_a \geq 30\ \mu\text{eV}$

String of length l

$n^{\rm th}$ fluctuation mode has wavenumber

$$k_n = \frac{2\pi n}{l}$$

(Fluctuation amplitude)^2 $\propto \dfrac{1}{k^p}$

- **Evolution of super-horizon string fluctuation spectrum**

Seems to (roughly) match
(analysed with **Kalb-Ramond** theory)

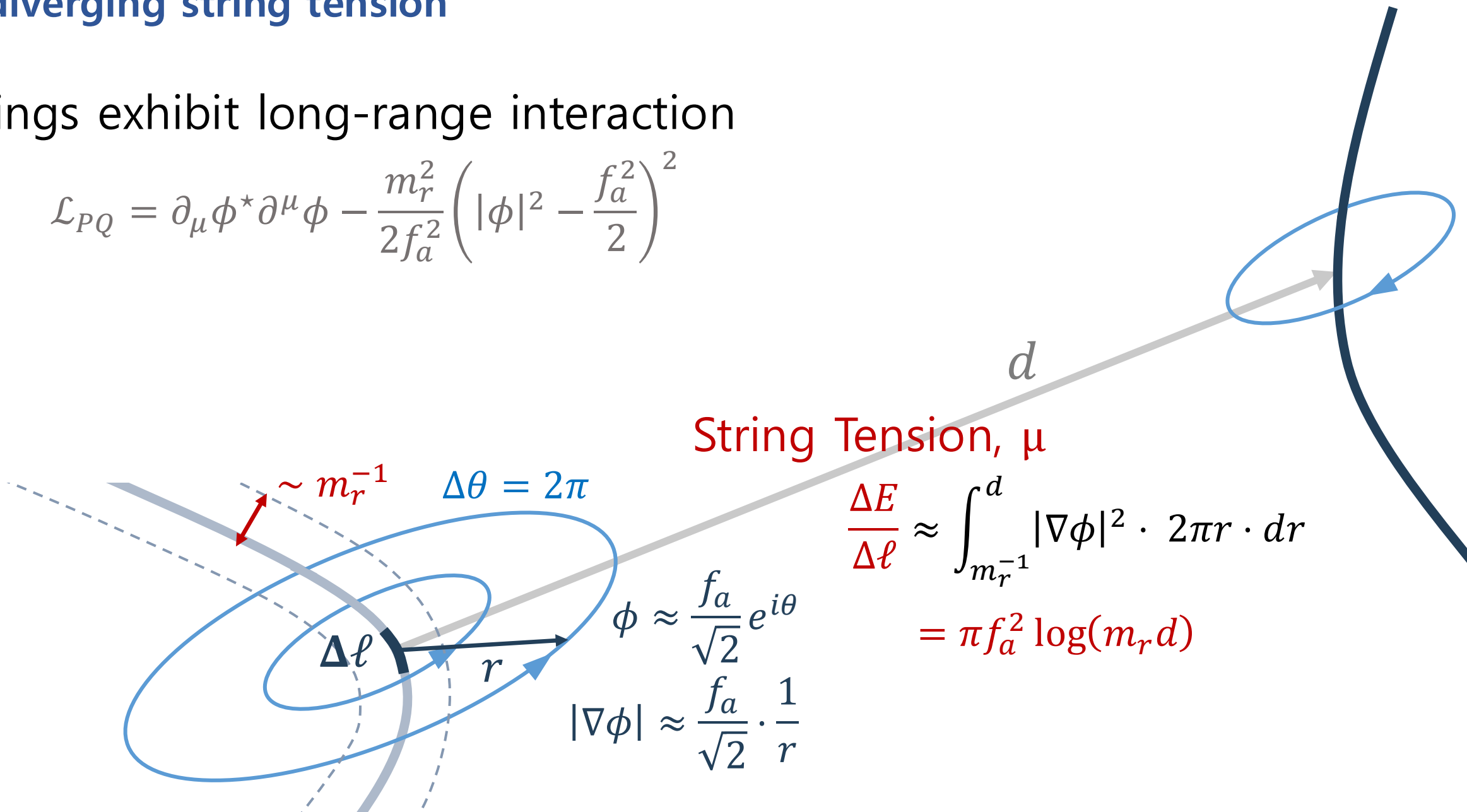
- **Evolution of axion radiation spectrum**

Backup Slides

IR diverging string tension

Strings exhibit long-range interaction

$$\mathcal{L}_{PQ} = \partial_\mu \phi^\star \partial^\mu \phi - \frac{m_r^2}{2f_a^2}\left(|\phi|^2 - \frac{f_a^2}{2}\right)^2$$



String Tension, μ

$$\frac{\Delta E}{\Delta \ell} \approx \int_{m_r^{-1}}^{d} |\nabla\phi|^2 \cdot 2\pi r \cdot dr$$

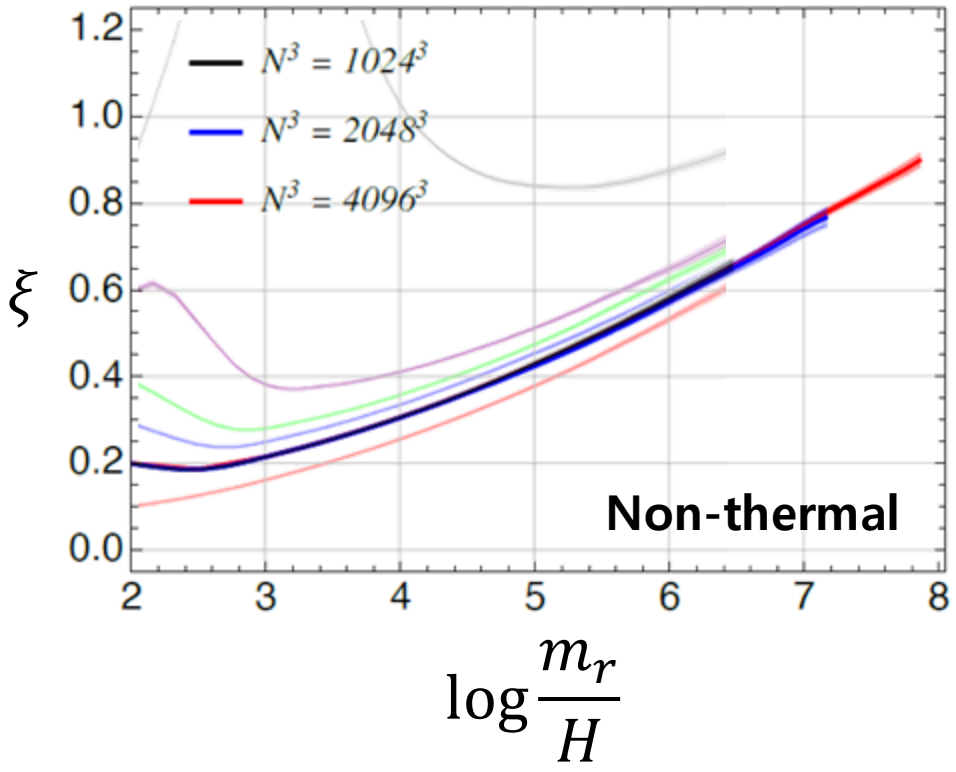
$$= \pi f_a^2 \log(m_r d)$$

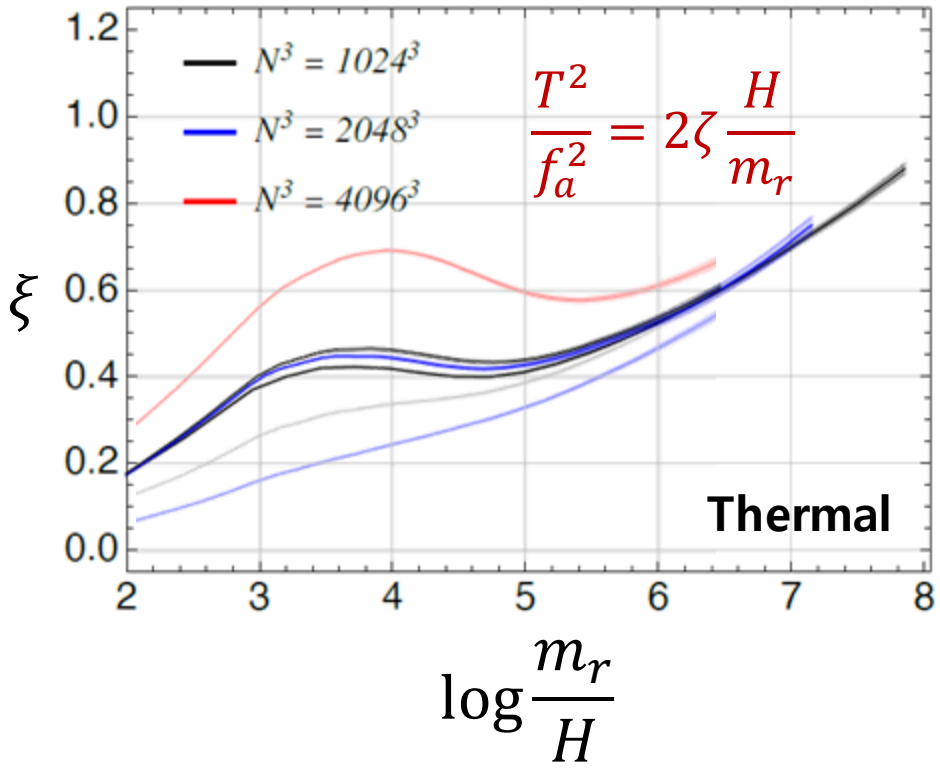
$$\phi \approx \frac{f_a}{\sqrt{2}} e^{i\theta}$$

$$|\nabla\phi| \approx \frac{f_a}{\sqrt{2}} \cdot \frac{1}{r}$$

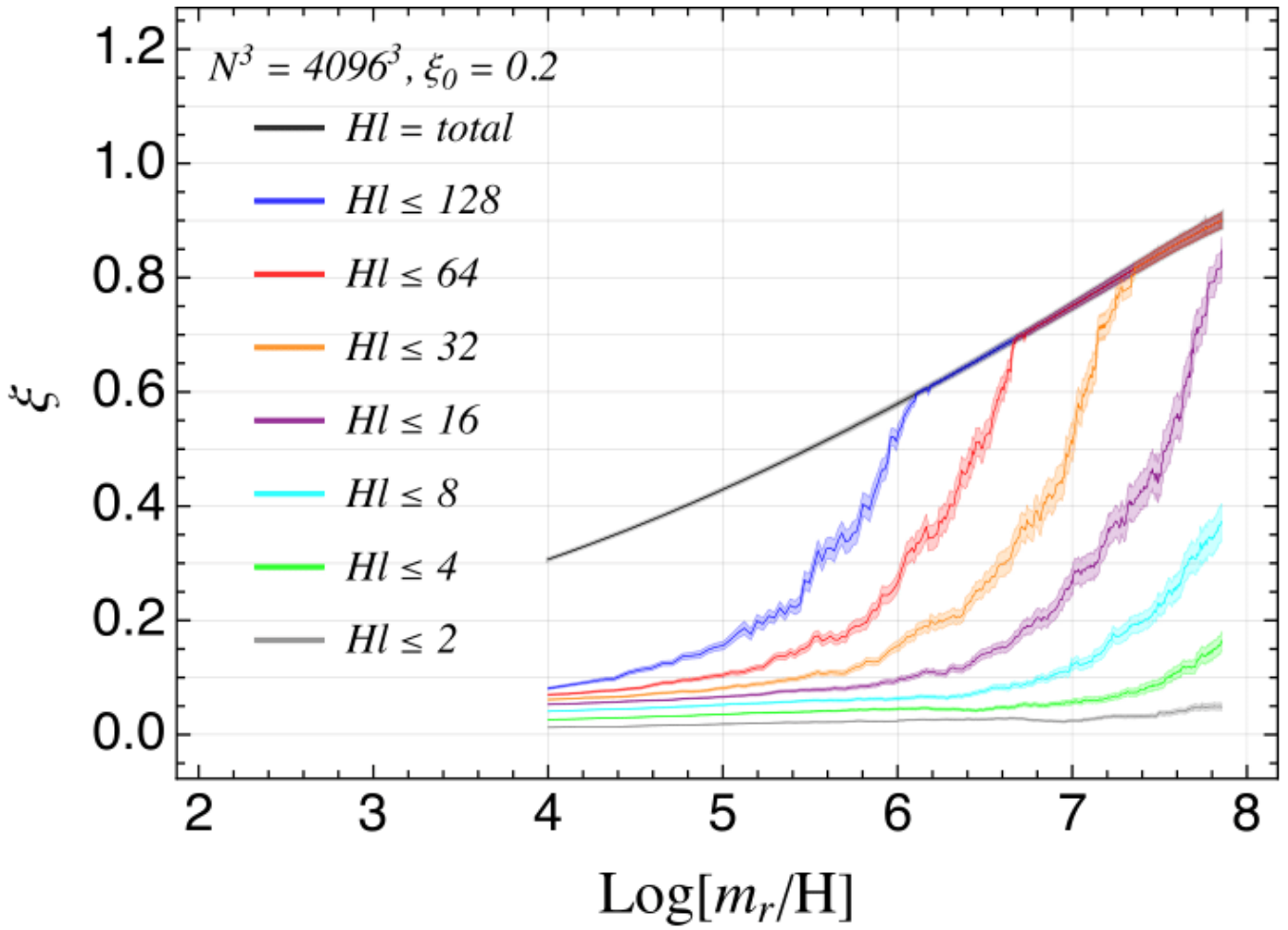
Strings May Be More Abundant Than Expected

String number density $\xi = \dfrac{l_{\text{string}}/t}{V_{\text{univ}}/t^3}$

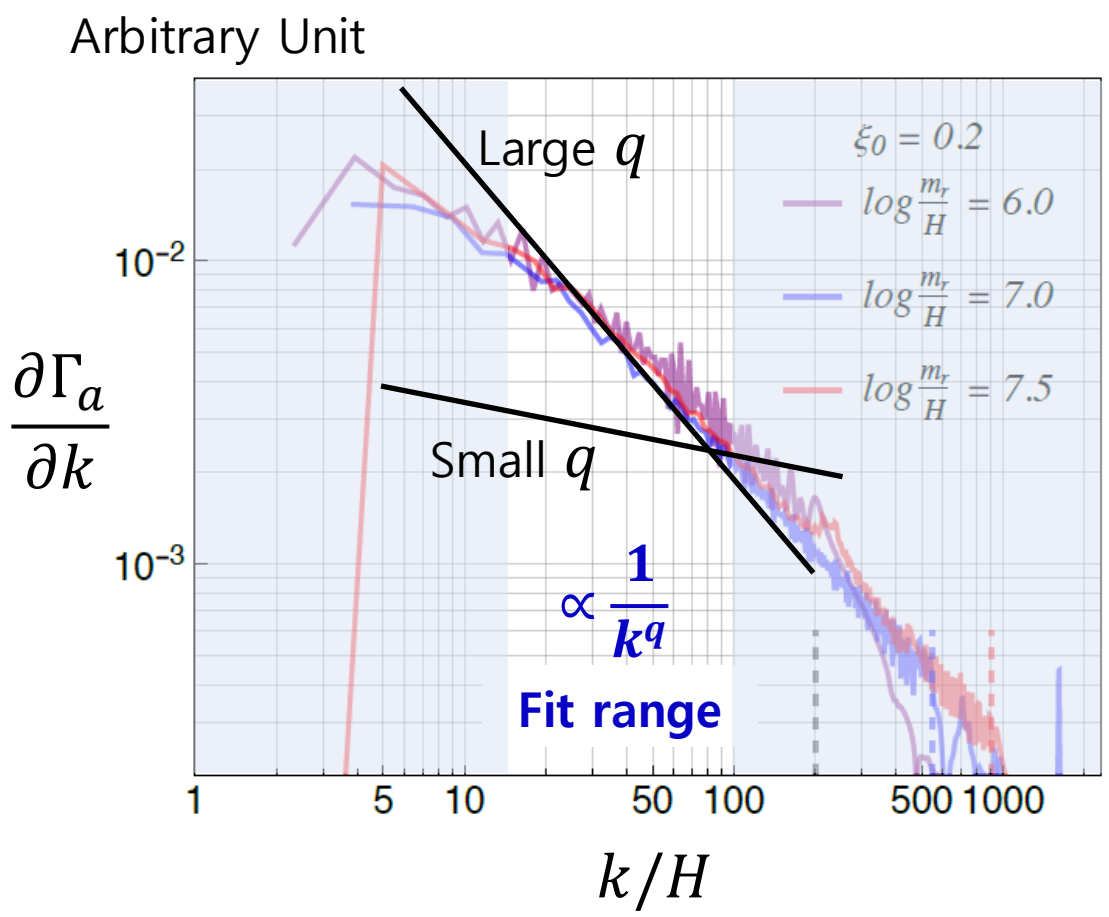


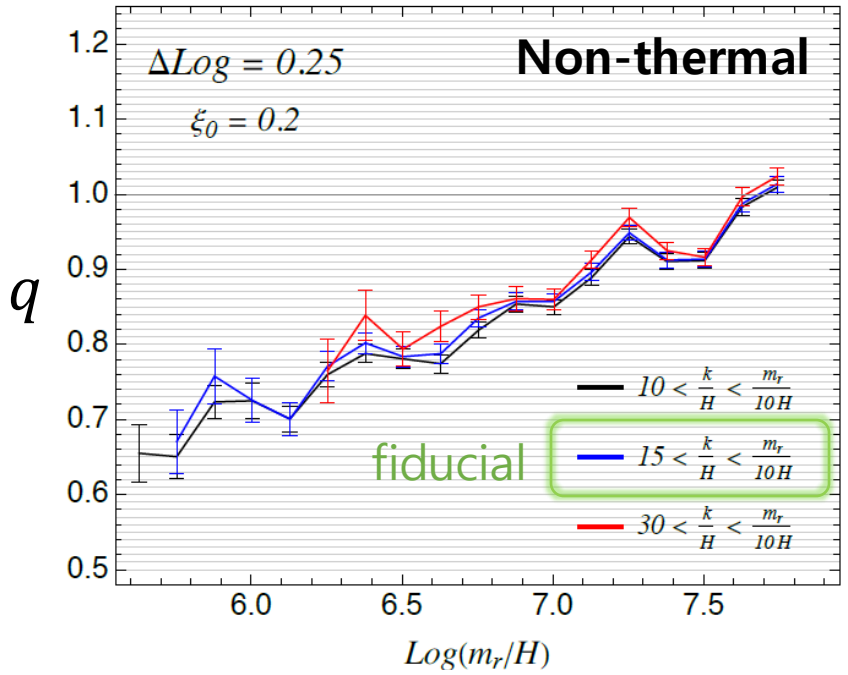


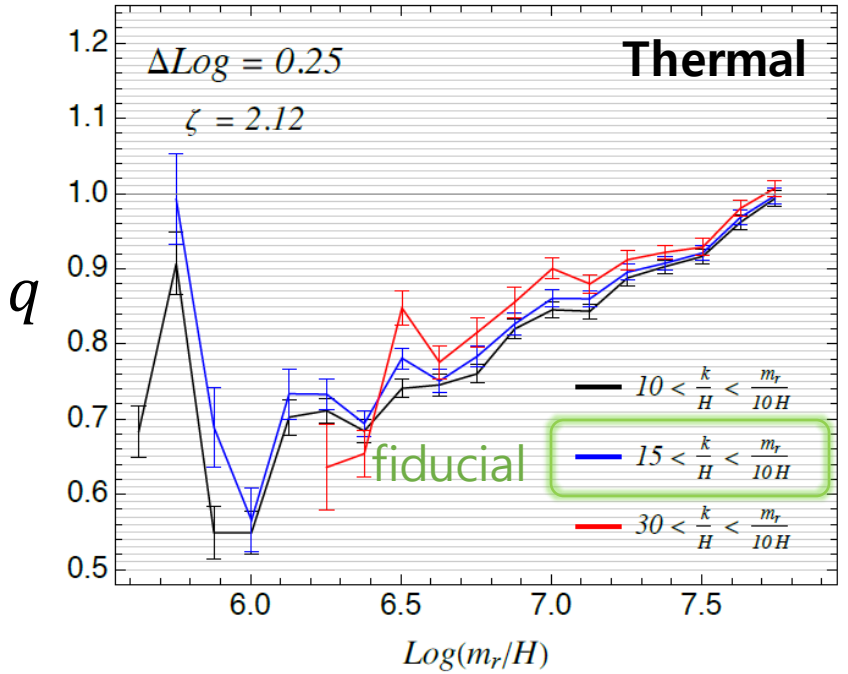
Dominance of Super-Horizon strings



Axion Radiation is getting Softer







Radiation from String

String releases energy while getting shortened

If strings do not constantly disappear:

$$\xi = \frac{l_{tot}t^2}{V_{\text{univ}}} \propto \frac{R(t)t^2}{R(t)^3} \propto t$$

Radiation dominated universe ($R \propto \sqrt{t}$)

$$\xi \sim c_0 + c_1 \log(m_r/H)$$

Saikawa et al. [2401.17253]

Kim et al. [2402.00741]

Safdi et al. [2412.08699], [2108.05368]

Gorghetto et al. [2007.04990]

String releases its energy

(for $\xi \sim c_0 + c_1 \log\frac{m_r}{H}$)

$$\underset{\text{radiation power}}{\Gamma} \sim \frac{\xi \times \mu_{eff}}{t^3}$$

string number density string tension

Axion Radiation Spectrum from Super-Horizon String Fluctuations

Kalb-Ramond theory

$$H^{\alpha\beta\gamma} = \frac{f_a}{\sqrt{2}} \epsilon^{\mu\alpha\beta\gamma} \partial_\mu \left(\frac{a}{f_a}\right)$$

$$S = \int -\mu\sqrt{-\gamma} d^2\zeta + \frac{1}{6}\int H^2 d^4x + \sqrt{2}\pi f_a \int B_{\mu\nu} d\sigma^{\mu\nu}$$

$$H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu B_{\rho\mu} + \partial_\rho B_{\mu\nu}$$

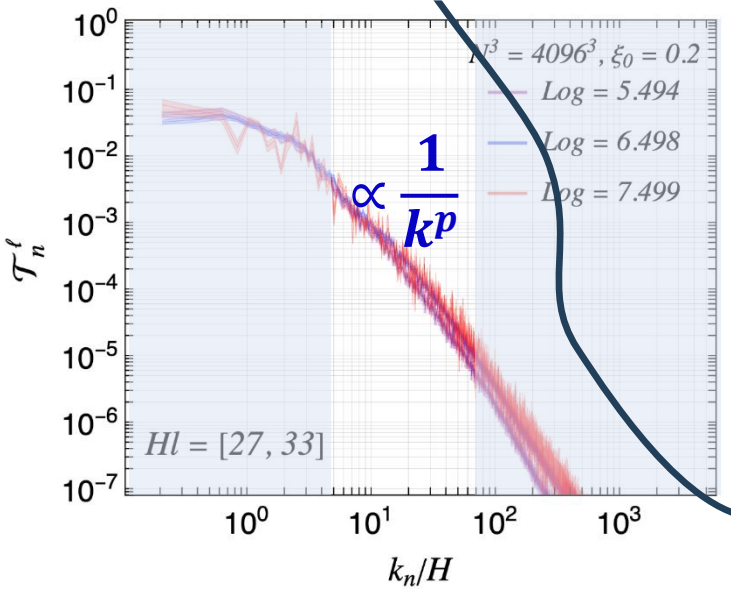
$$\frac{\partial \Gamma_a}{\partial k} \propto \frac{1}{k^{p-1-O(0.\#)}} \text{ correction}$$

With some caveats

String of length l

n^{th} mode has wavenumber

$$k_n = \frac{2\pi n}{l}$$

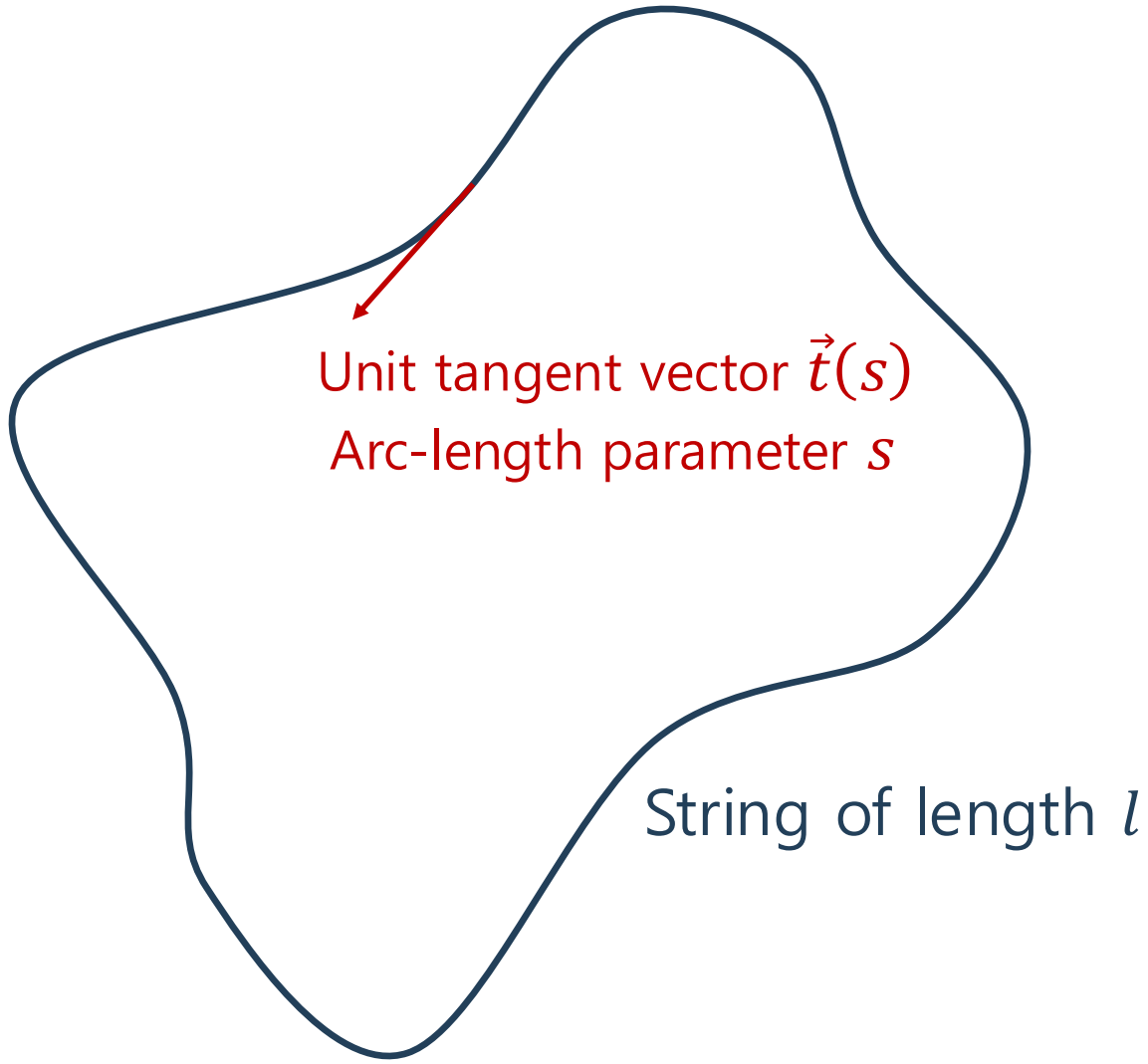


Closer look at String fluctuation

String Fluctuation profile (spectrum) $\vec{T}_n^l$

$$\vec{T}_n^l = \int_0^l \frac{ds}{l} \vec{t}(s) e^{-2\pi i n s/l}$$

$$\langle \vec{T}_{n_1}^l \cdot \vec{T}_{n_2}^l \rangle = \mathcal{T}_{|n_1|}^l \, \delta_{n_1+n_2}$$



Connecting Spectrum: “string” & “axion”

Caveats in our analytic calculation

$$\frac{1}{m_r^2 f_a^2}\frac{\partial \Gamma_a}{\partial k} = 8\pi^3 \xi \left(\frac{m_r}{H}\right)^{-2} \int_0^\infty \frac{d(Hl)}{H l_{avg}} \frac{\rho(l)}{H} \sum_{n=1}^{\infty} nH\delta\left(k - \frac{2\pi n}{l}\right) \sum_{\substack{|m|<n \\ m+n\ even}} \mathcal{T}^l_{\frac{n+m}{2}} \mathcal{T}^l_{\frac{n-m}{2}}$$

- Low momentum fluctuation modes are involved even for high momentum axion radiation
- Neglected Hubble expansion plays significant role in low momentum fluctuation mode dynamics
- Small fluctuation assumption may break down for low momentum modes