Production of dark matter axions from global strings

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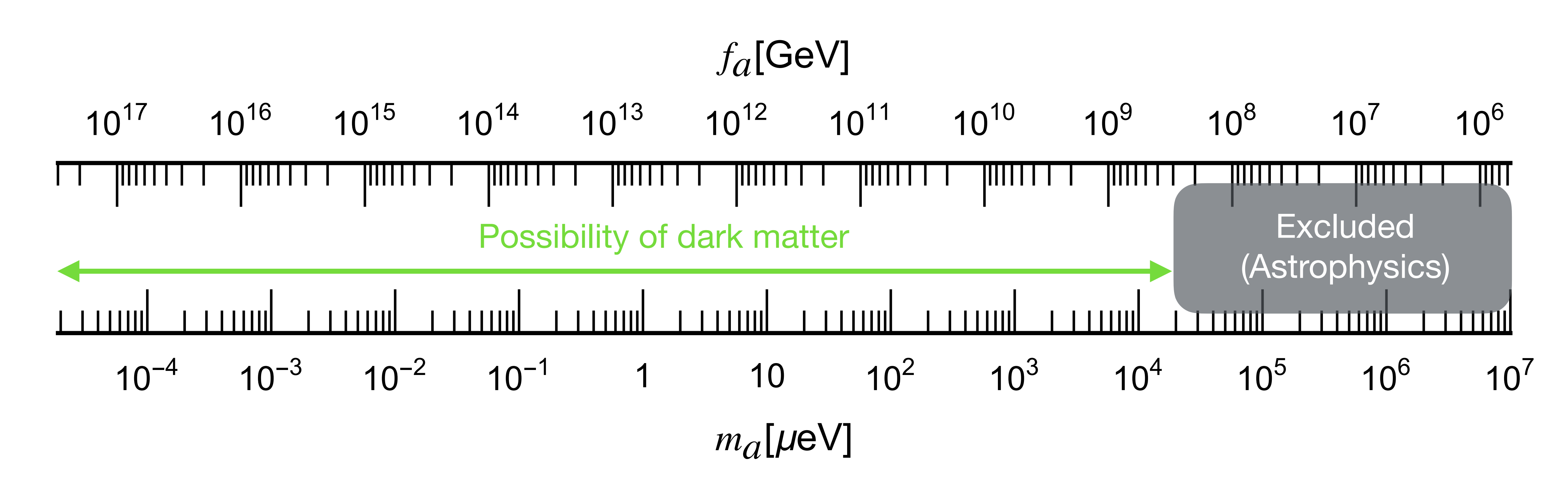
Axion dark matter mass



- Experiments will cover many orders of magnitudes in the axion mass…
- What is the "typical" theoretical prediction for axion dark matter mass?
- How to interpret experimental results?

Axion dark matter mass

- Relic axion abundance depends on the Peccei-Quinn scale, and hence on the axion mass.

$$\Omega_a = \Omega_a(f_a), \quad m_a \simeq 57\,\mu\mathrm{eV}\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)$$

- Assuming axions are the dominant component of dark matter, one can guess what is their mass.

$$\Omega_a h^2 = 0.12 \quad \Longrightarrow \quad m_a = ???\,\mu\mathrm{eV}$$

- How axions are produced in the early universe ?

Assumptions in cosmology

- Many different theoretical possibilities and different consequences.

- A simple scenario based on three assumptions:

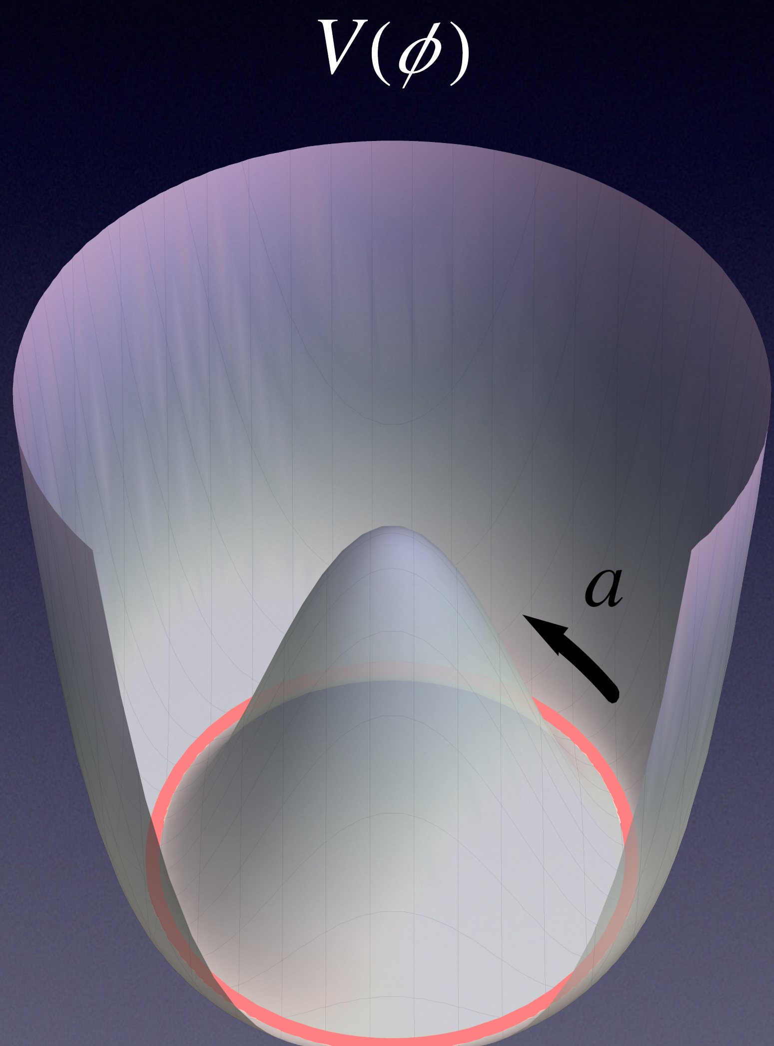
1. PQ symmetry has been broken after inflation.
2. Standard expansion history (i.e. radiation domination) after axion number is fixed ($T \lesssim 1\,\mathrm{GeV}$).
3. Domain wall (DW) number (# of degenerate vacua) is $N_{DW} = 1$.

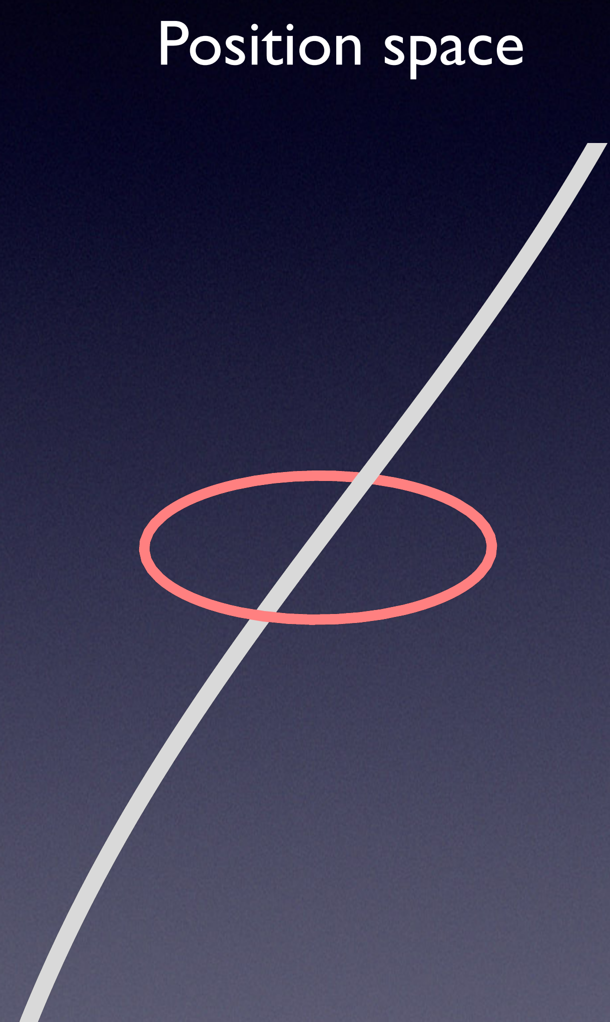
- In the scenario based on the above assumptions…
    - there *should* be one-to-one correspondence between the axion abundance and decay constant (and hence its mass).
    - we must take account of axions produced from global strings.

[Davis (1986)]

Axionic strings

$$\mathcal{L} = |\partial_\mu \phi|^2 - V(\phi), \quad V(\phi) = \lambda \left(|\phi|^2 - \frac{f_a^2}{2} \right)^2$$



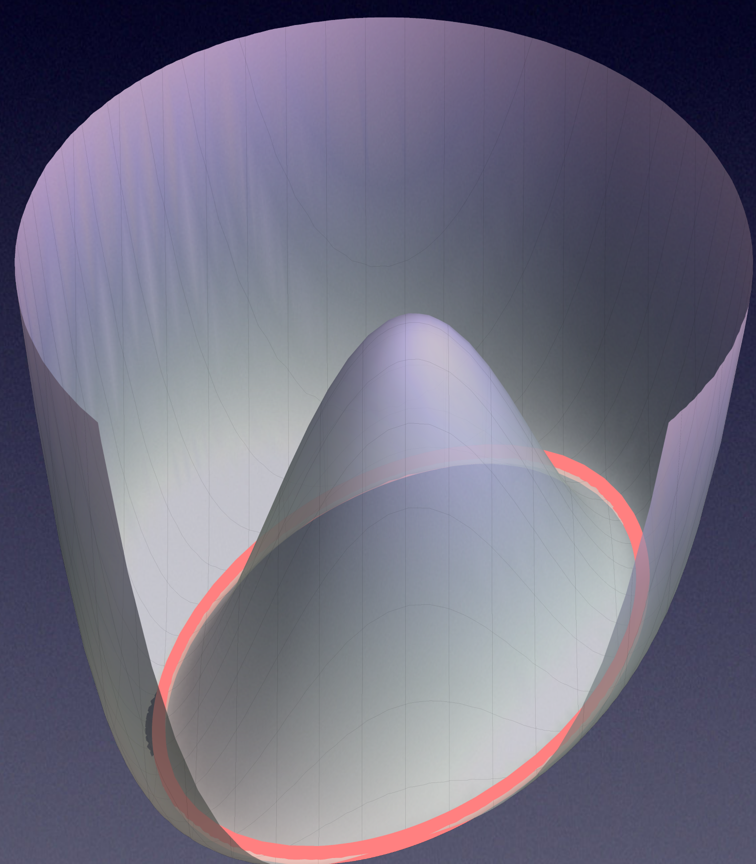


- Form when $U(1)_{PQ}$ symmetry is spontaneously broken.
- Disappear around the epoch of the QCD phase transition (if $N_{DW} = 1$).

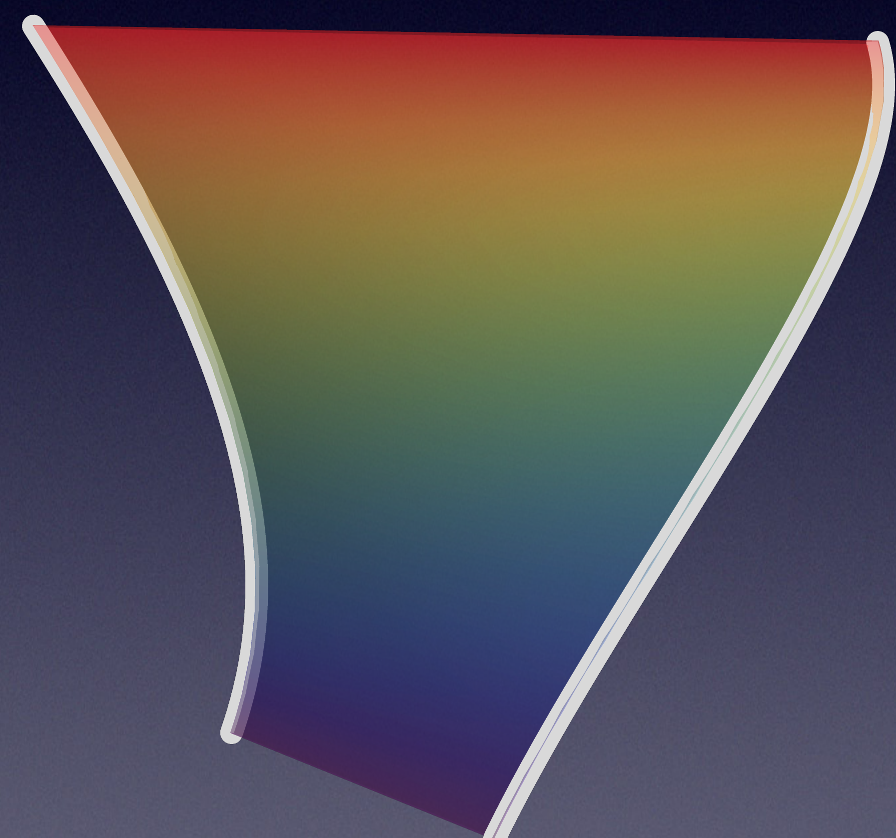
Axionic strings

$$\mathcal{L} = |\partial_\mu \phi|^2 - V(\phi), \quad V(\phi) = \lambda \left(|\phi|^2 - \frac{f_a^2}{2} \right)^2 + \chi(T) \left(1 - \cos\left(\frac{a}{f_a} \right) \right)$$

$V(\phi)$



Position space

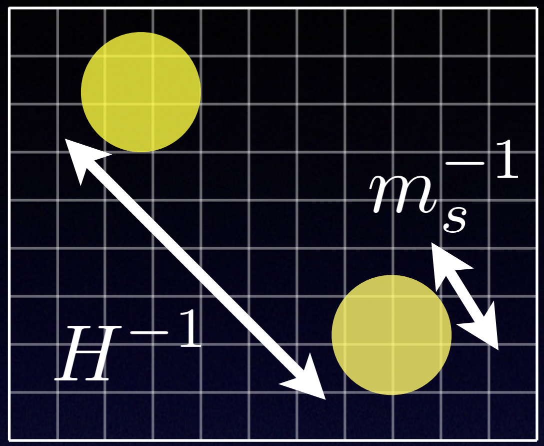


- Form when U(1)$_{PQ}$ symmetry is spontaneously broken.
- Disappear around the epoch of the QCD phase transition (if N_{DW} = 1).

Difficulty in string dynamics

- Two extremely different length scales.
  - String core radius $r_{\rm core} \sim m_s^{-1} \sim f_a^{-1}$

    m_s : mass scale of the UV completion
  - Hubble radius H^{-1}



- String tension acquires a logarithmic correction:

$$\mu = \frac{\text{energy}}{\text{length}} = \int r dr \int_0^{2\pi} d\varphi \left[\left| \frac{\partial \phi}{\partial r} \right|^2 + \left| \frac{1}{r} \frac{\partial \phi}{\partial \varphi} \right|^2 + V(\phi) \right]$$

$$\approx 2\pi \int r dr \left| \frac{1}{r} \frac{\partial \phi}{\partial \varphi} \right|^2 \simeq \pi f_a^2 \log\left(m_s/H\right)$$

- At the QCD phase transition, $m_s/H_{\rm QCD} \sim 10^{30}$!

  The large enhancement $\log\left(m_s/H_{\rm QCD}\right) \sim 70$ is challenging for simulations with $\log\left(m_s/H\right) \lesssim 5$–$6$.

Scaling solution

- $\mathcal{O}(1)$ strings per horizon volume:

$$\rho_{\rm string} = \xi \frac{\mu}{t^2} \sim \left. \frac{\mu \ell}{\ell^3} \right|_{\ell \sim H^{-1} \sim t}$$

- The net energy density of radiated axions should be the same order.

$$\rho_a \sim \xi \frac{\mu}{t^2} \sim \xi H^2 f_a^2 \log(m_s/H)$$

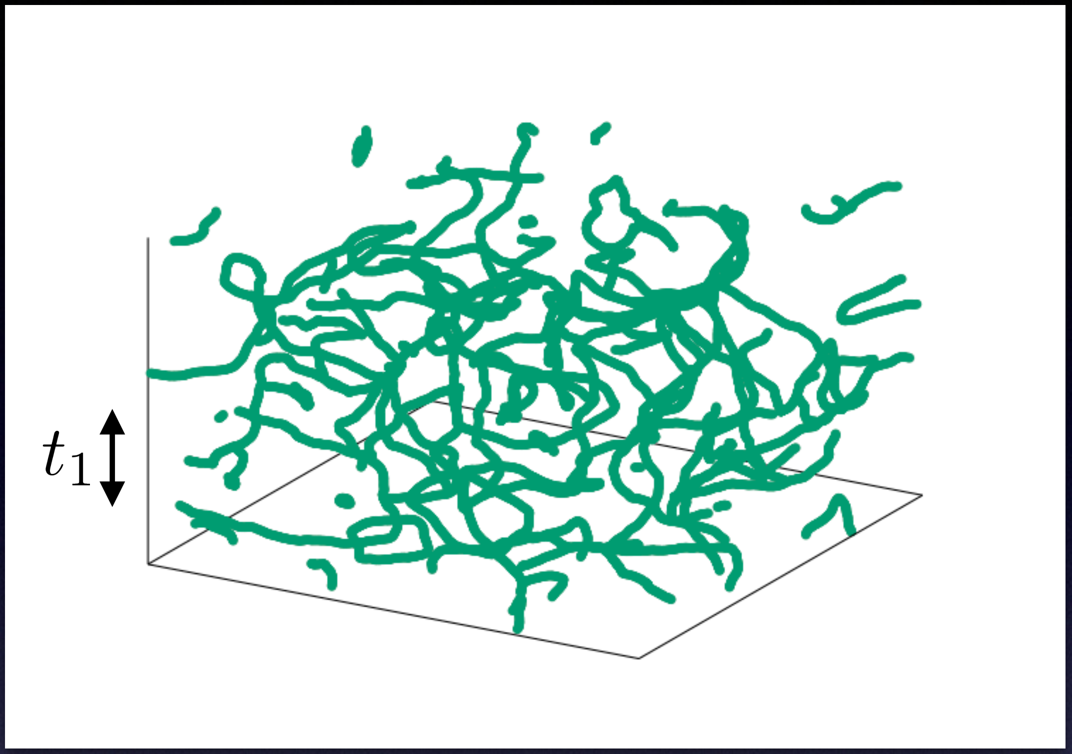
- Axion number is sensitive to the (instantaneous) spectrum:

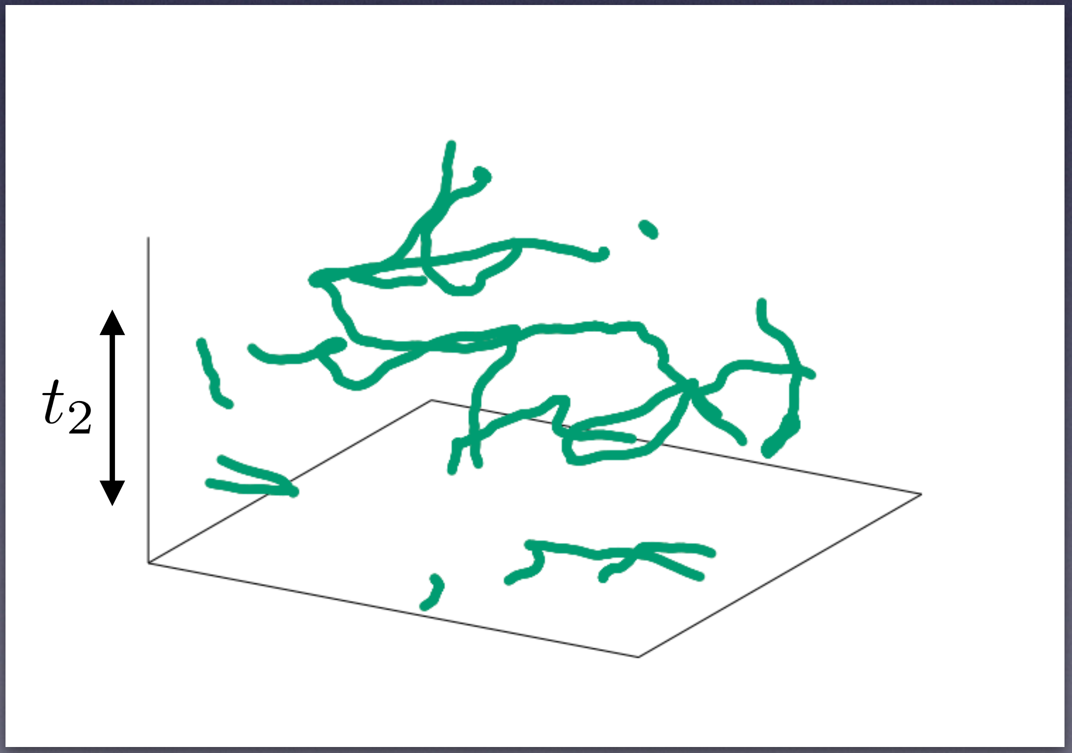
$$\boxed{F\left(\frac{k}{H}, \frac{m_s}{H}\right) = \frac{1}{R^3} \frac{H}{\Gamma_{{\rm str}\to a}} \frac{\partial}{\partial t} \left(R^3 \frac{\partial \rho_a}{\partial k} \right)}$$

[Gorghetto, Hardy and Villadoro (2018)]

$\Gamma_{{\rm str}\to a} \simeq \dfrac{\xi \mu}{t^3}$: energy transfer rate from strings

R : scale factor of the universe





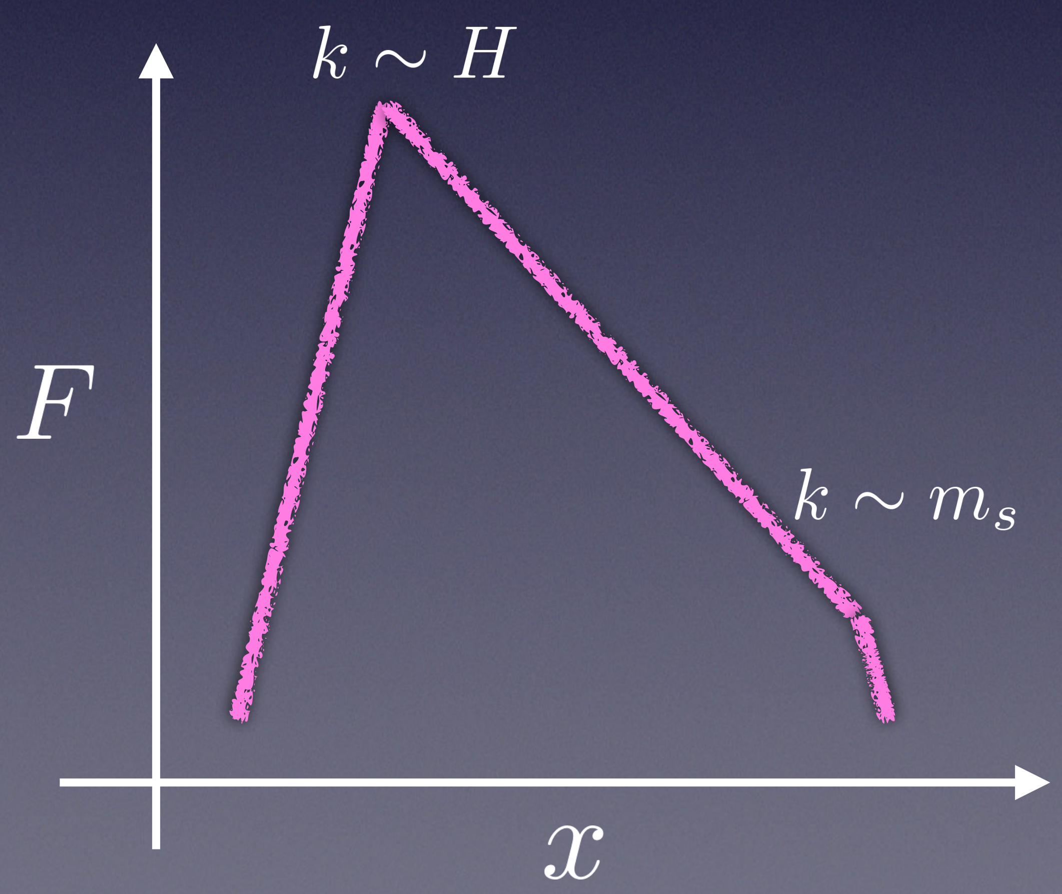
Controversy on the spectrum

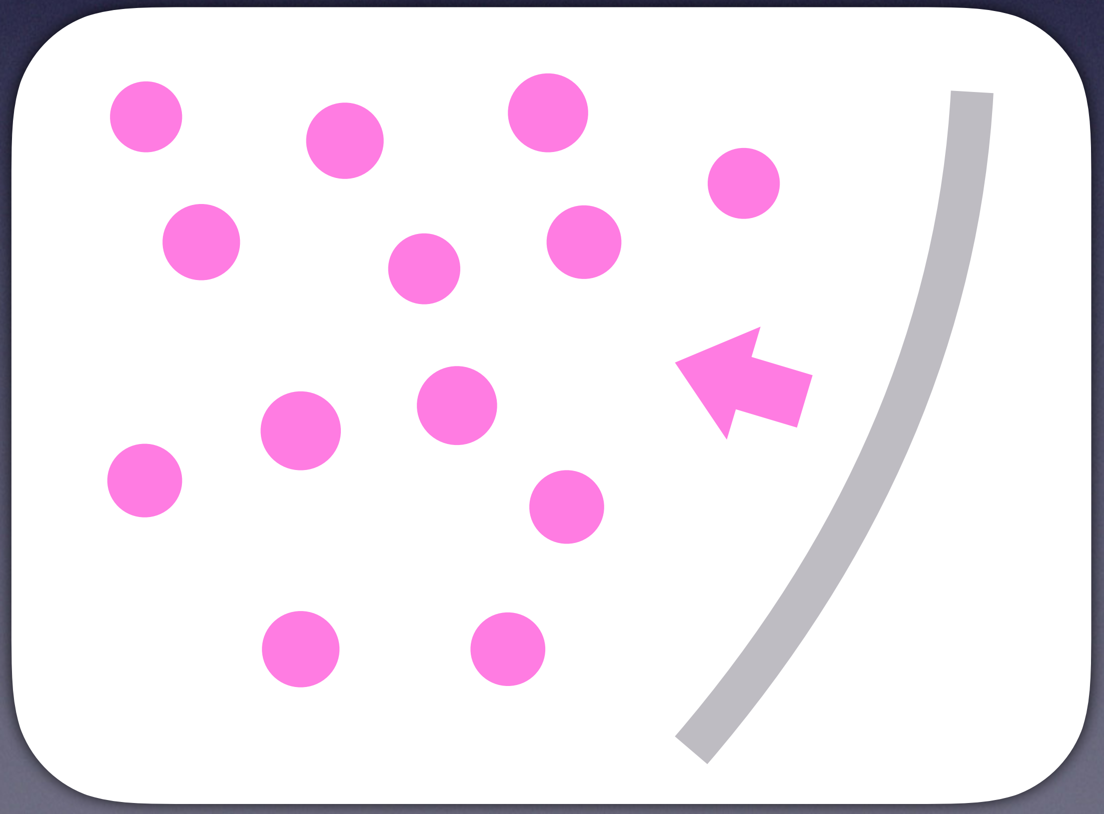
Assume a single power law in the intermediate range:

$$F \propto 1/k^q \quad \text{for} \quad H \lesssim k \lesssim m_s$$

If q > 1, IR modes dominate.
Many soft axions → Higher mass is predicted.

[Davis (1986); Davis and Shellard (1989); Battle and Shellard (1994); Yamaguchi, Kawasaki and Yokoyama (1999); Hiramatsu et al. (2011); Kawasaki, KS and Sekiguchi (2015); Kawasaki et al. (2018)]





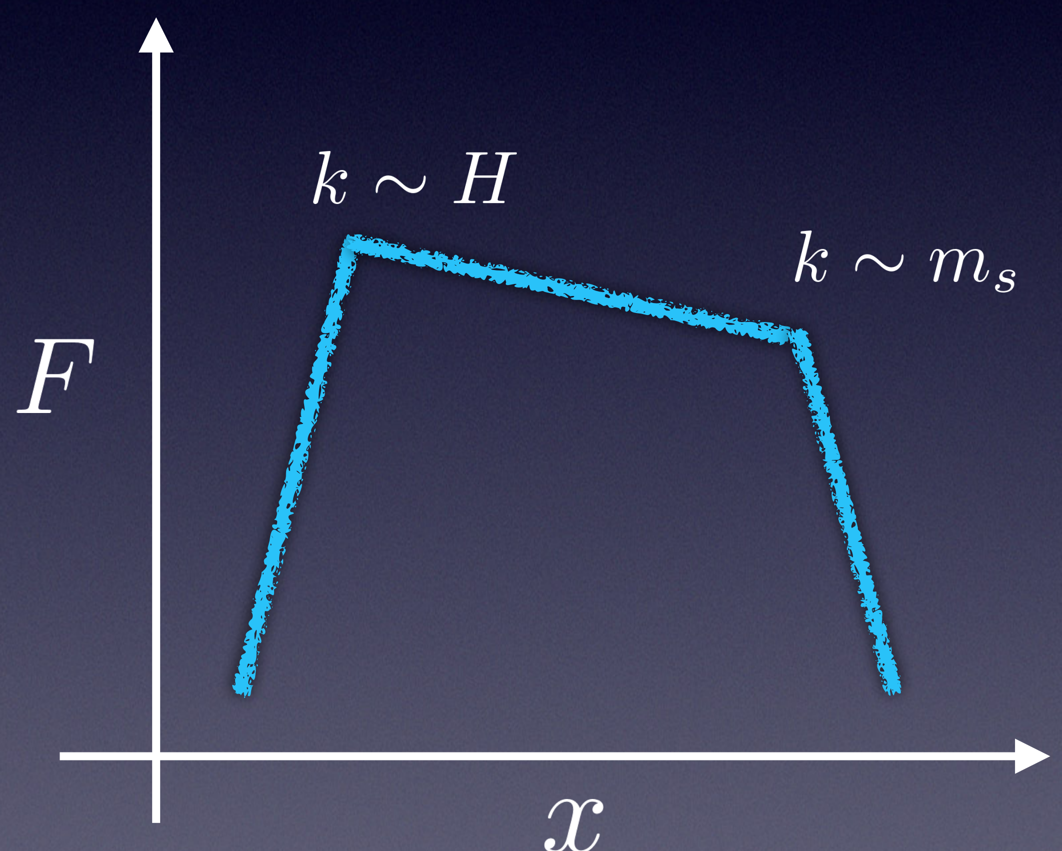
Controversy on the spectrum

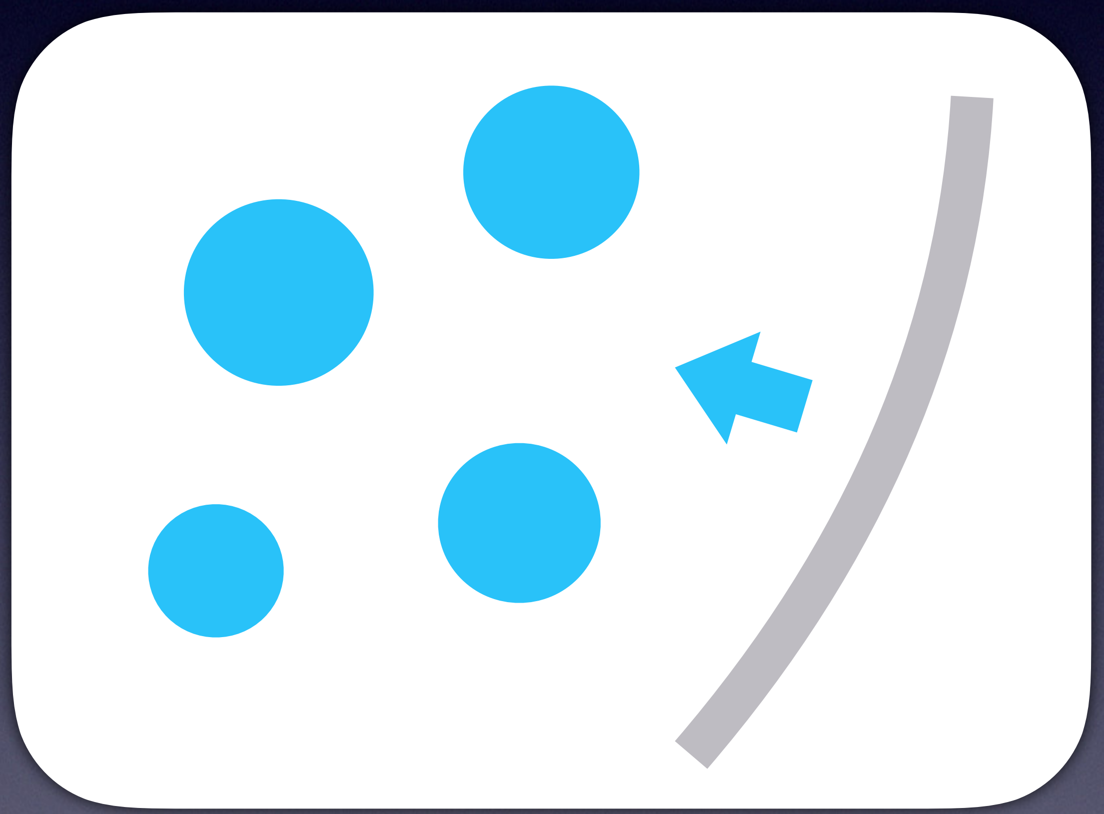
If q ≤ 1, spectrum becomes hard.

Few hard axions → Lower mass is predicted.

q = 1 in [Harari and Sikivie (1987); Hagmann and Sikivie (1991); Hagmann, Chang and Sikivie (2001)]

q < 1 in [Fleury and Moore (2016); Klaer and Moore (2017)]





Note:

- Value of q may depend on $\log(m_s/H)$.
- Careful extrapolation to large $\log(m_s/H)$ is required.

[Gorghetto, Hardy and Villadoro (2018)]

Field theoretic lattice simulation

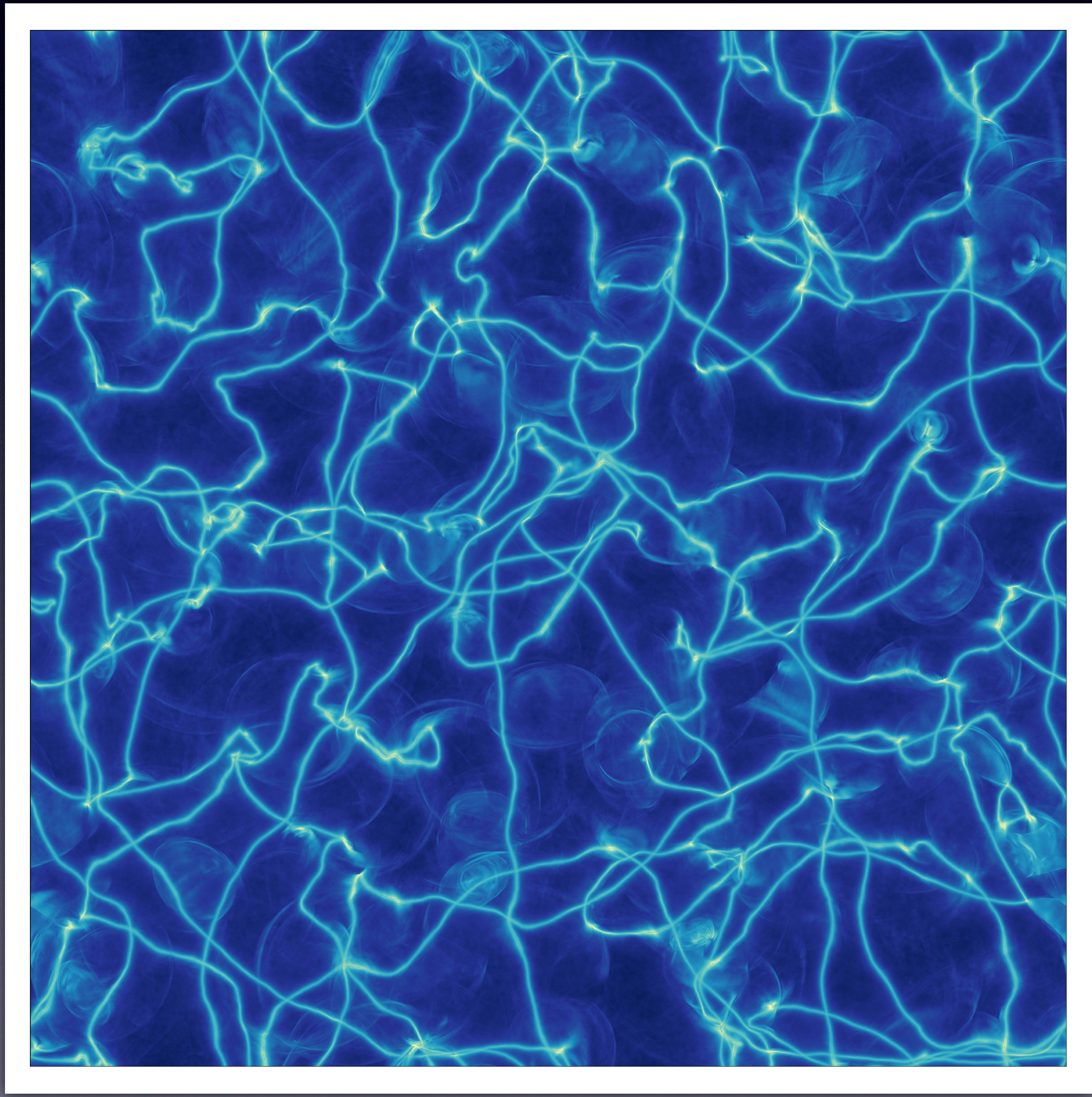
- Solve EOM for a complex scalar field ϕ numerically.

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{R^2}\nabla^2\phi + \lambda\phi(|\phi|^2 - v^2) = 0$$

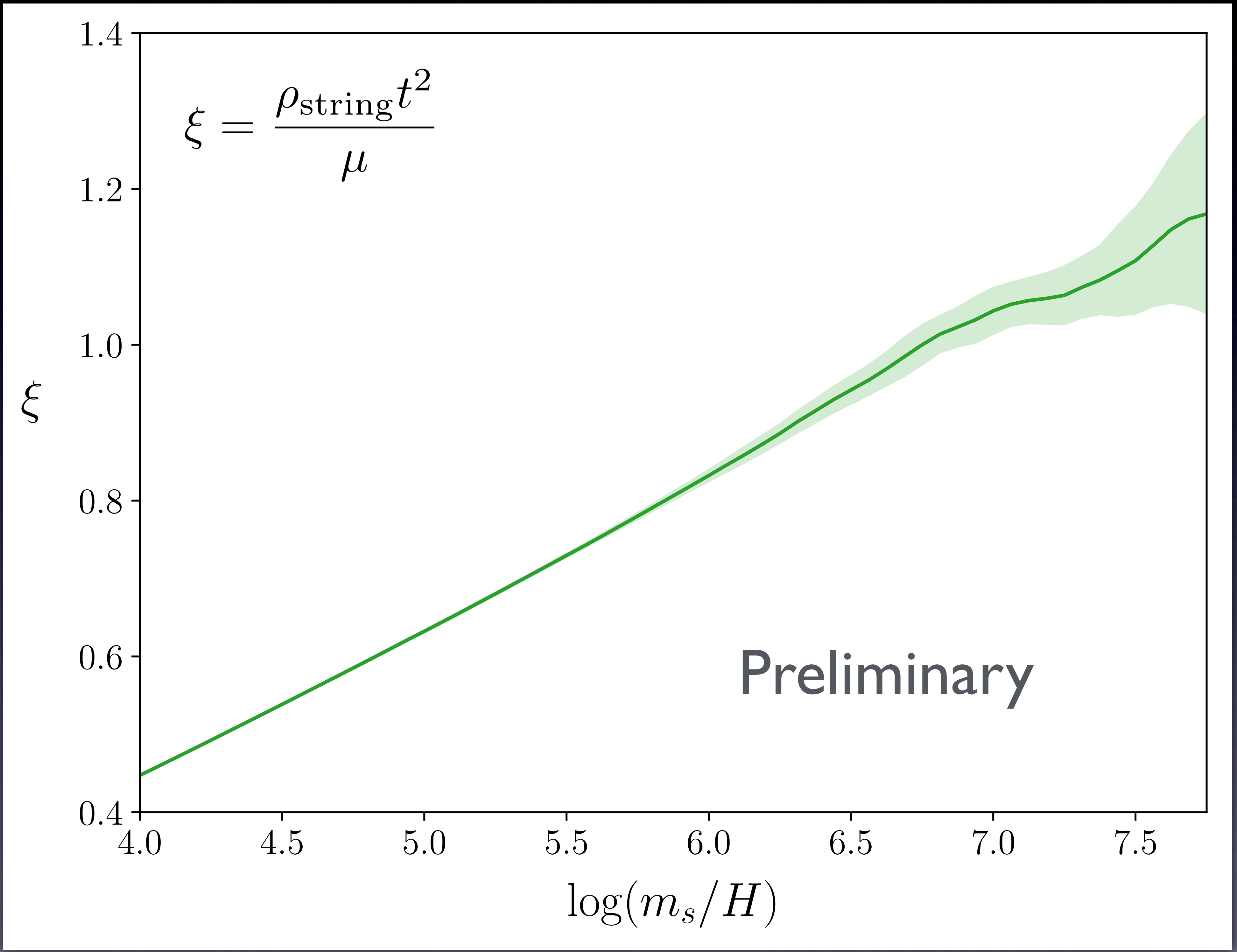
- The largest number of grids N = 8192^3 at the COBRA cluster (MPCDF, Garching).

➡ $\log(m_s/H) \lesssim 7\text{–}8$ is feasible.

cf.
N = 512^3 in Hiramatsu et al. (2011)
N = 1600^3 in Fleury and Moore (2016)
N = 1250^3 in Gorghetto et al. (2018)
N = 4096^3 in Kawasaki et al. (2018)



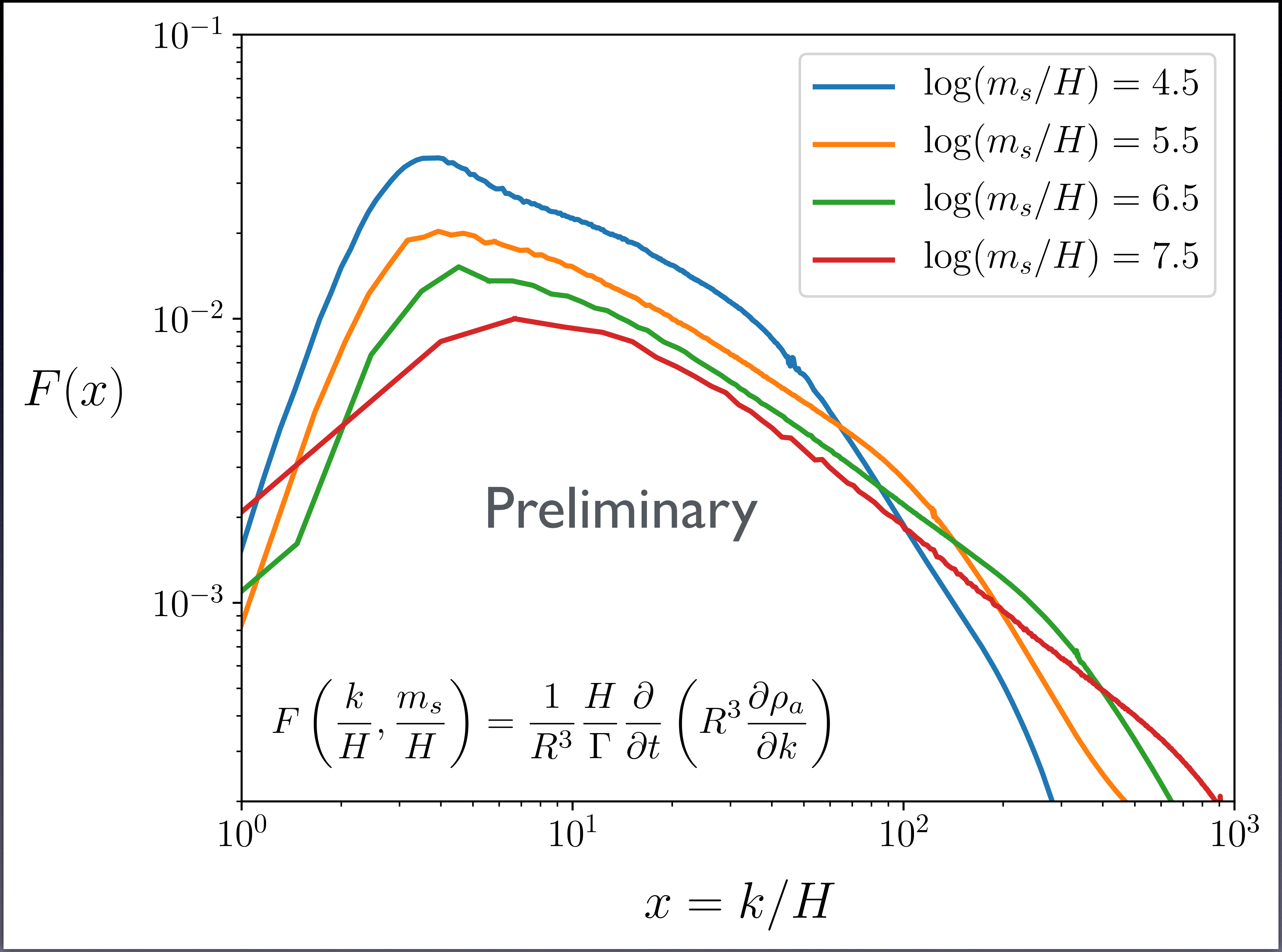
String density



Logarithmic growth compatible with previous results.

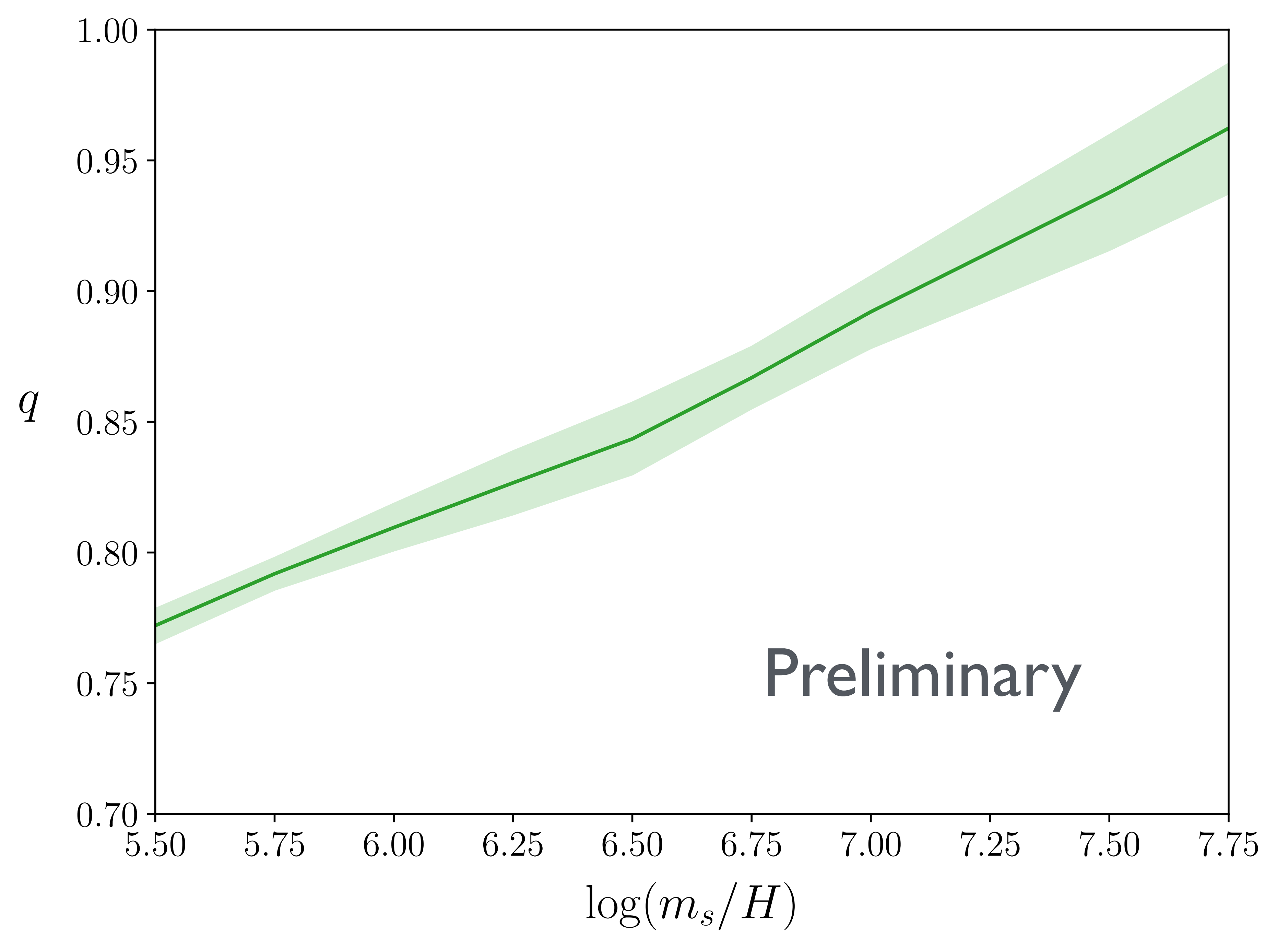
[Fleury and Moore (2016); Gorghetto, Hardy and Villadoro (2018)]

Spectrum of radiated axions



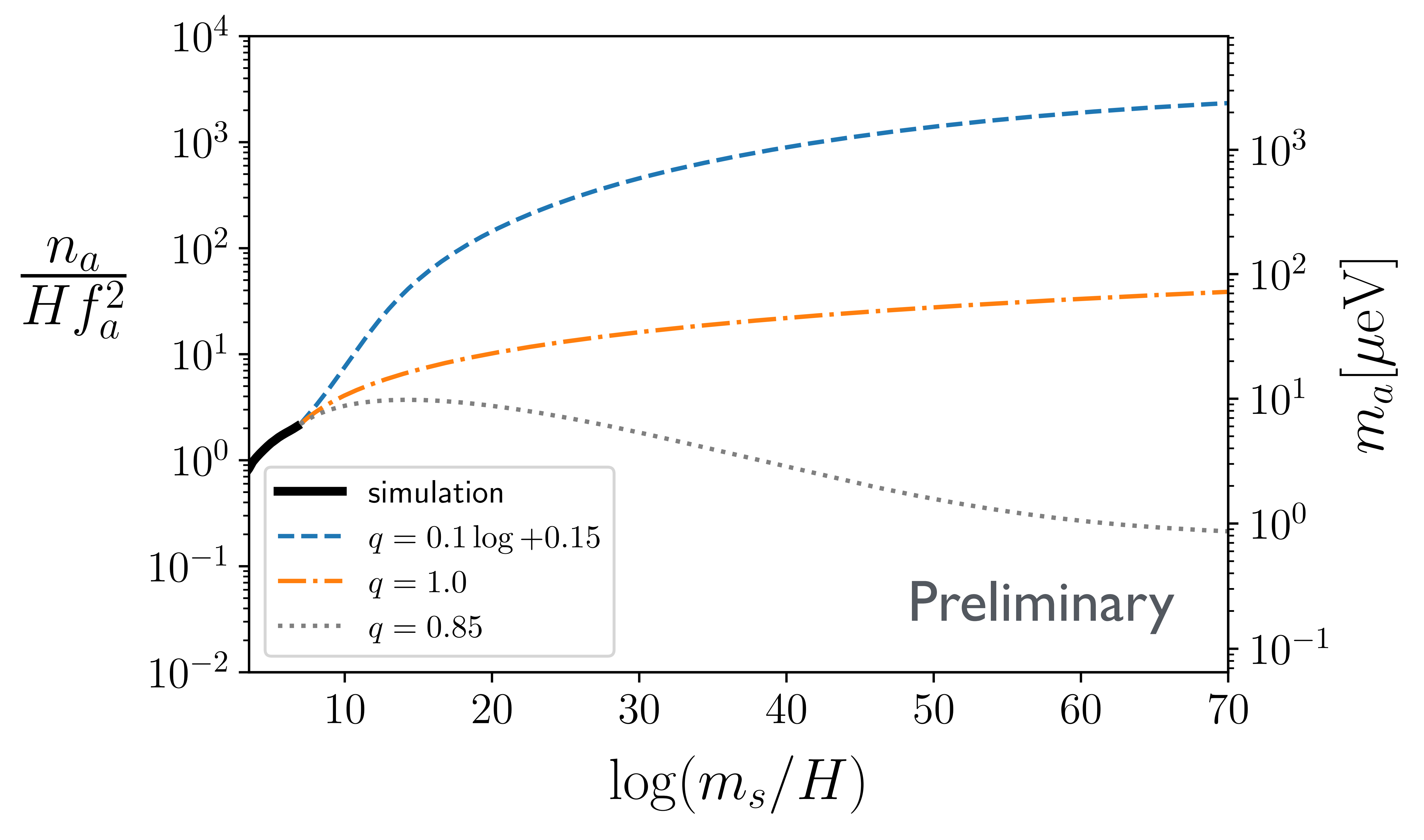
Fitting to a power law

Assume $F \propto 1/x^q$ in the intermediate range…



q seems to grow with log.

Extrapolation to large log



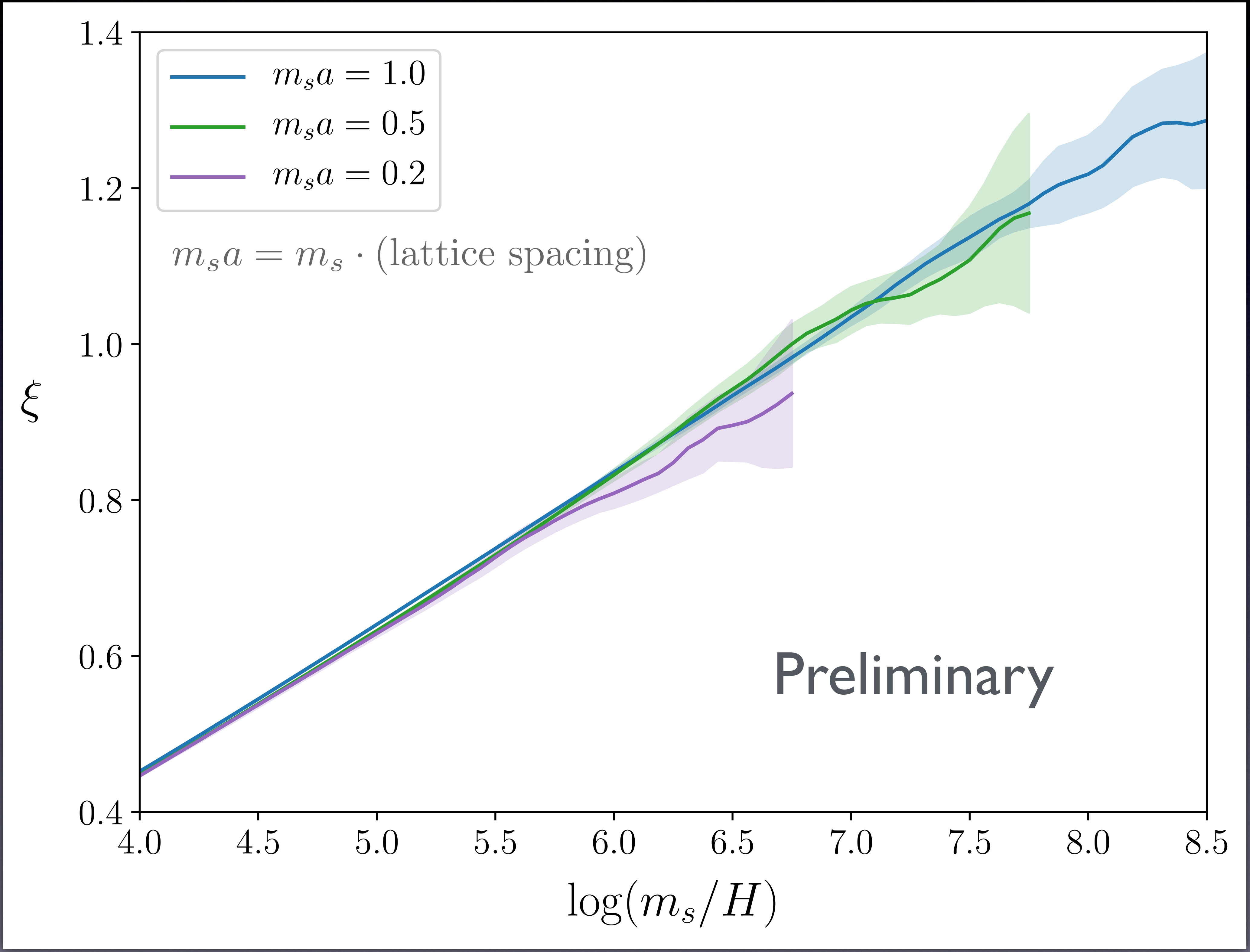
Summary

- Typical scenario for axion dark matter production:
  - Post-inflationary PQ symmetry breaking
  - Standard expansion history during/after QCD phase transition
  - No domain wall problem ($N_{DW} = 1$)
- Relic abundance is sensitive to the detailed shape of the spectrum of axions produced by strings.
- Current simulation results indicate that
  - The spectrum evolves towards the IR-dominated shape.
  - A naive extrapolation gives higher axion dark matter mass (?)
- Two independent results appear to show a similar trend.

(see talk by *Marco Gorghetto*)

Backup slides

String density



Fitting to a power law