Axion dark matter mass: Towards a reliable estimate

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Work in progress, with
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Abstract

- Discuss possible uncertainties on the prediction for the axion dark matter mass by considering the axion production from cosmic strings in the early universe.
- Present some new results of large scale numerical simulations of axionic strings and discuss their implication for the axion mass prediction.

Plan

- Brief introduction of axions
- Issue of axion dark matter mass predictions
  - Post-inflationary Peccei-Quinn symmetry breaking scenario
  - Axionic strings: controversies
- Up-to-date results of large scale numerical simulations
- Some more issues on analysis methods
- Summary

Strong CP problem and axion

- Strong CP problem
  - Quantum chromodynamics (QCD) allows a CP violating term:

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \theta G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Physical observable: $\bar{\theta} = \theta + \arg\, \det M_q$

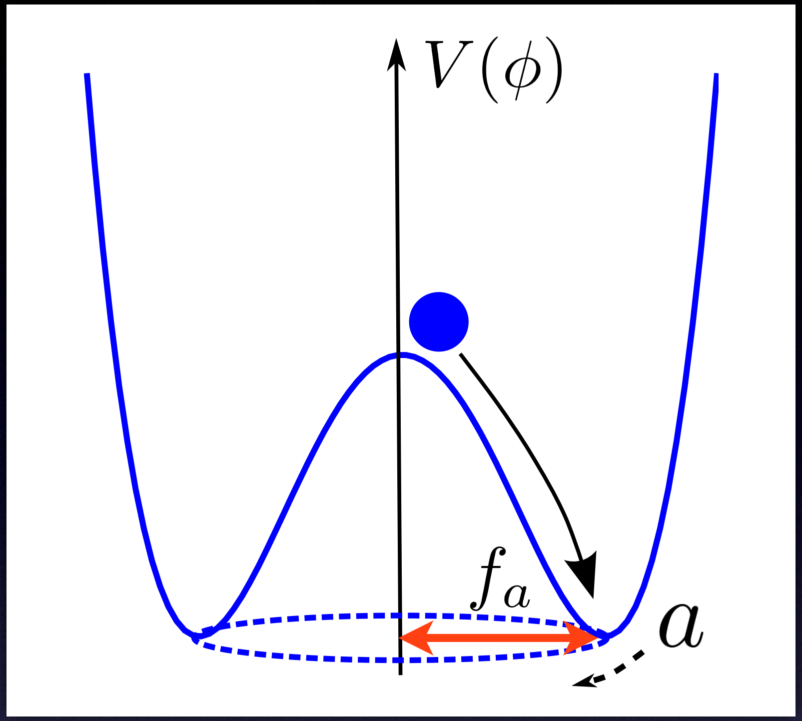
  - Non-observation of neutron electric dipole moment implies

$$|\bar{\theta}| < \mathcal{O}(10^{-11})$$ "Why it is so small ?"

- Peccei-Quinn (PQ) mechanism
  - Take $\bar{\theta}$ as a dynamical variable that explains its smallness, i.e. $\bar{\theta} \to \bar{\theta}_{\rm eff}(x) = a(x)/f_a$
  - Predicts the existence of light particle $a(x)$ = axion.

Axion as a Nambu-Goldstone boson

- Axions can be identified as Nambu-Goldstone bosons arising from breaking of global symmetry. (Peccei-Quinn (PQ) symmetry)

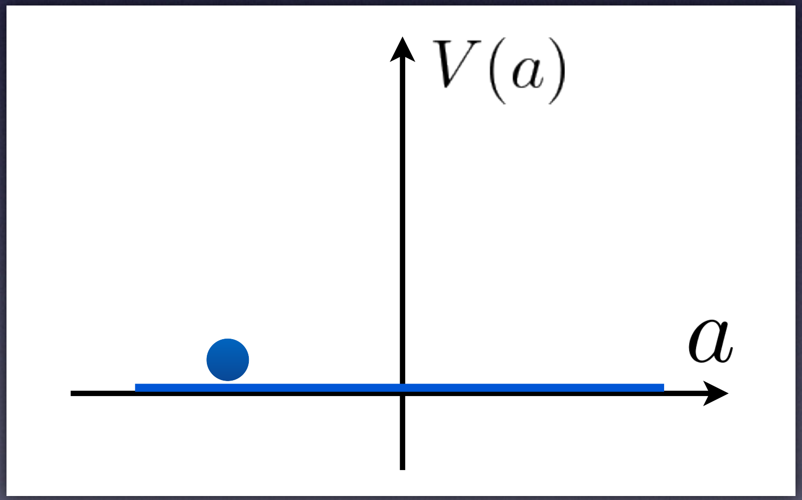


- Hidden scalar field:

$$\phi(x) = \frac{1}{\sqrt{2}}[f_a + \rho(x)]e^{ia(x)/f_a}$$

Massive modulus, massless phase:

$$m_\rho \sim f_a, \quad m_a = 0$$



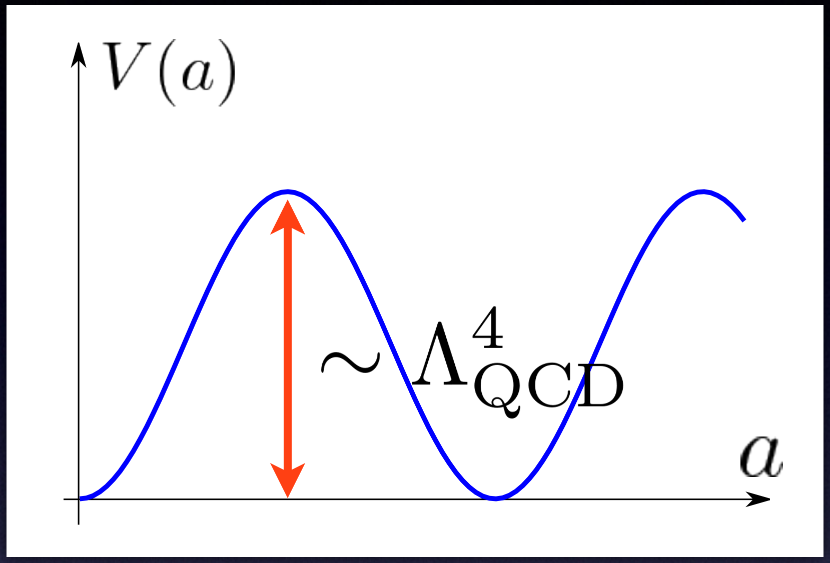
- Interactions with standard model particles are suppressed by assuming a large symmetry breaking scale.

$$f_a \gg v_{\text{electroweak}} \approx \mathcal{O}(100)\ \text{GeV}$$

Coupling to QCD

- Axions couple to gluons via

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



- Below the QCD scale $\Lambda_{\rm QCD} \sim \mathcal{O}(100\,{\rm MeV})$, topological charge fluctuations in QCD vacuum induce the potential energy:

$$V_{\rm QCD}(a) \sim \Lambda^4_{\rm QCD}\left(1 - \cos\frac{a}{f_a}\right)$$

➡ $\langle a \rangle = 0$ at the minimum, solving the strong CP problem

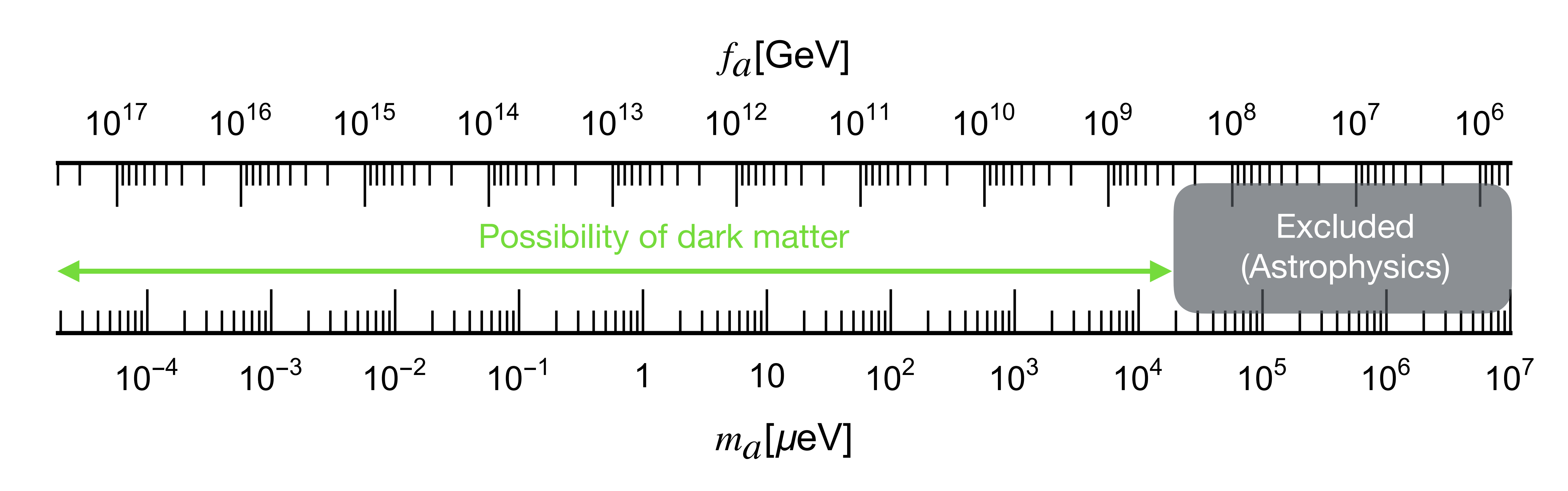
- Mass of QCD axions $m_a \sim \Lambda^2_{\rm QCD}/f_a$:

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

- Tiny coupling with matter + non-thermal production

→ good candidate of cold dark matter

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.

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

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

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

- How axions are produced in the early universe ?

Assumptions in cosmology

- Many different theoretical possibilities and different consequences.

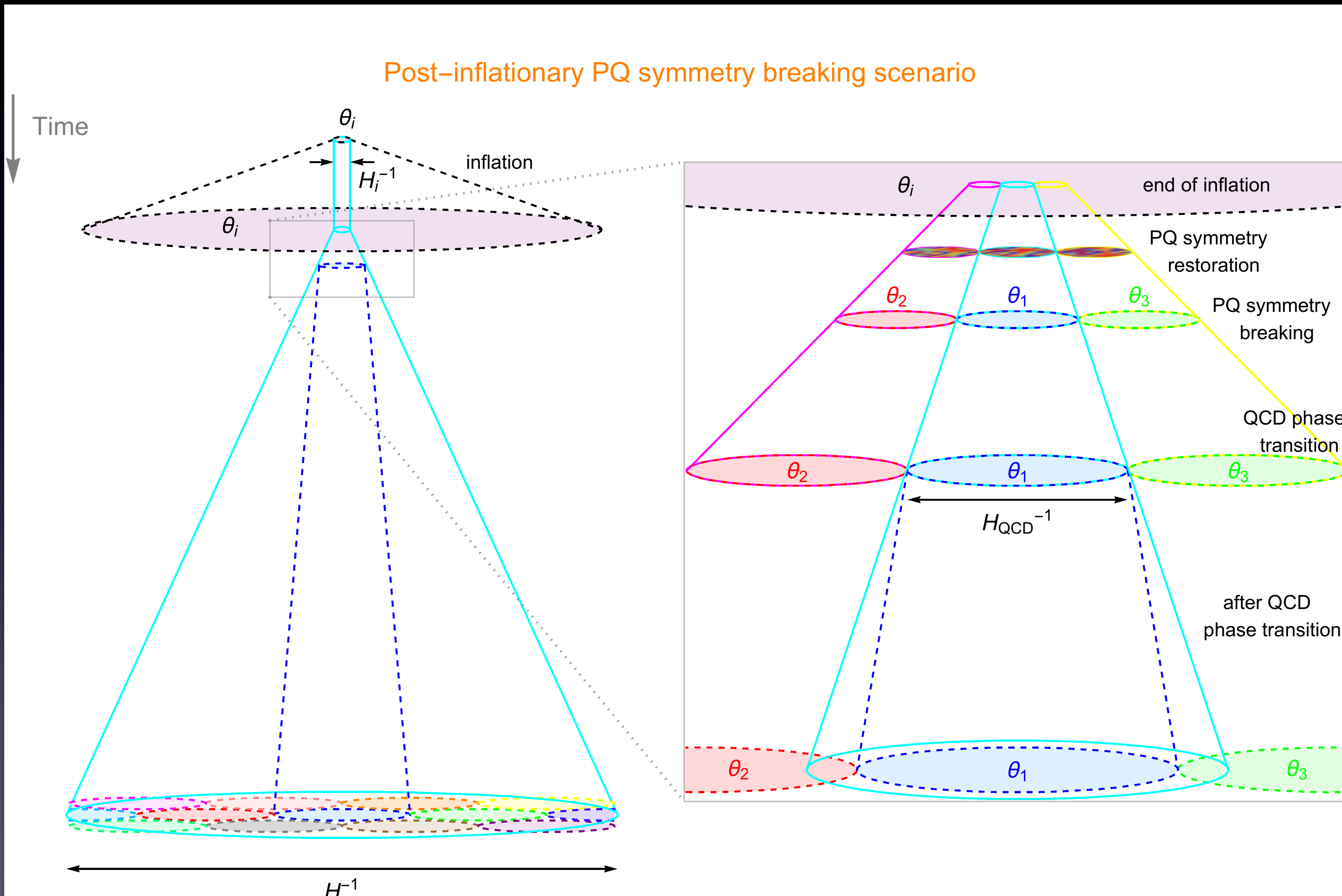
- A simple scenario based on three assumptions:

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)]

Post-inflationary PQ symmetry breaking scenario

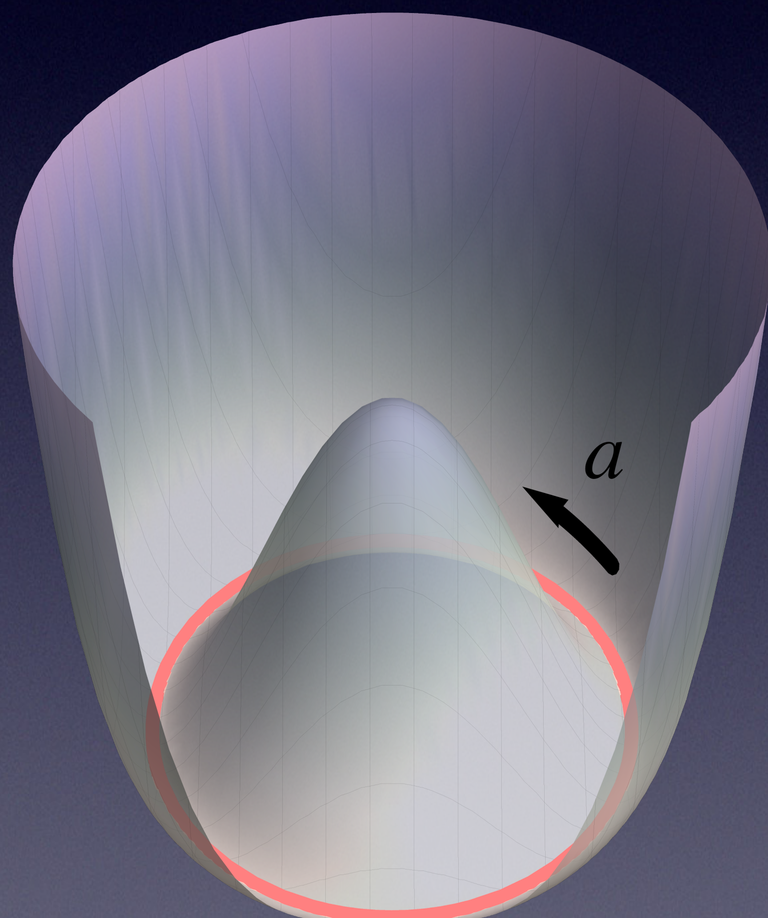


Precise knowledge about the field configurations around the epoch of QCD phase transition is crucial for a reliable estimate of the relic axion abundance.

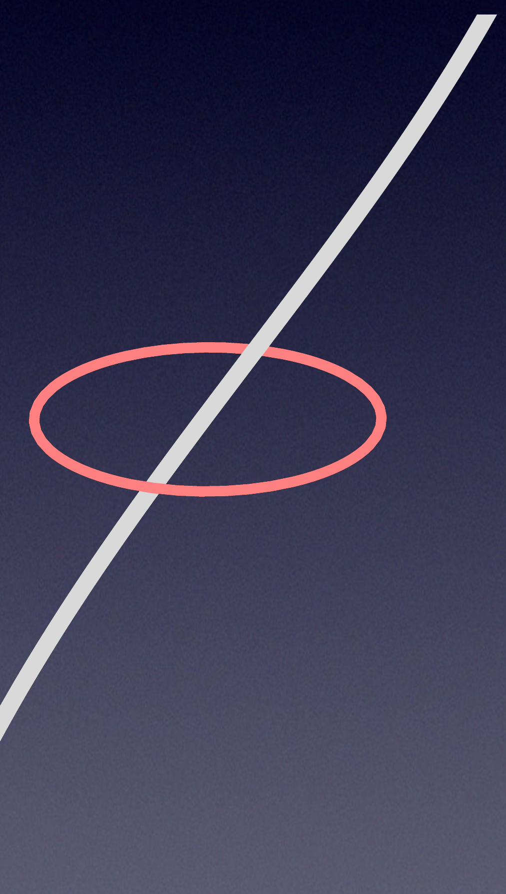
Axionic strings

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

$V(\phi)$



Position space

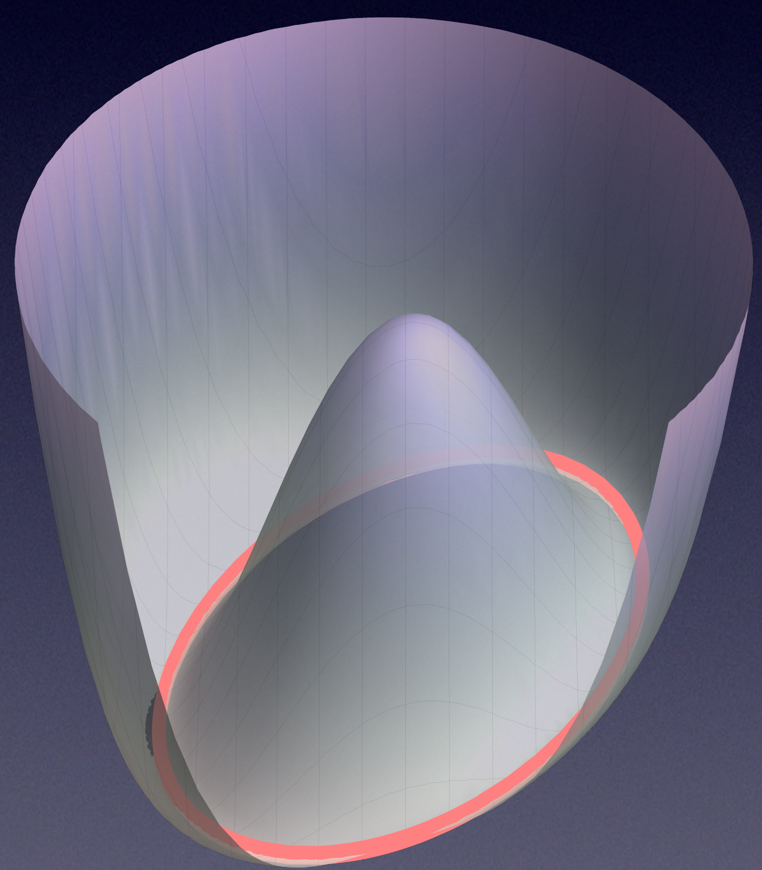


- Form when U(1)$_{PQ}$ symmetry is spontaneously broken.
- Disappear around the epoch of the QCD phase transition (if N_{DW} = 1).

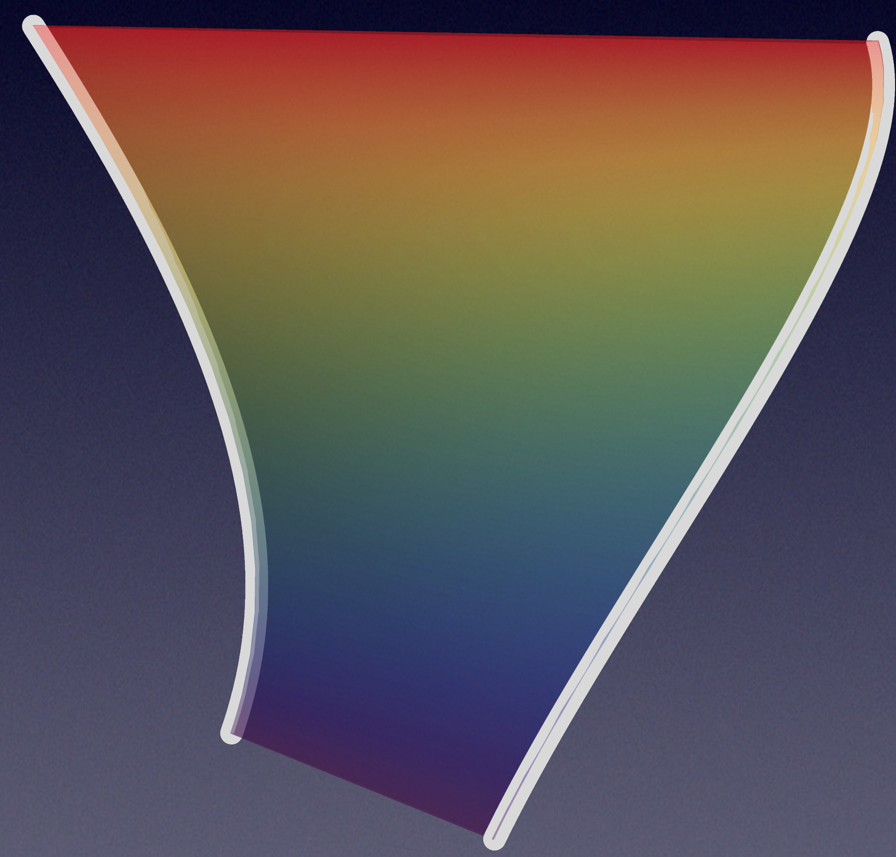
Axionic strings

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

$V(\phi)$



Position space

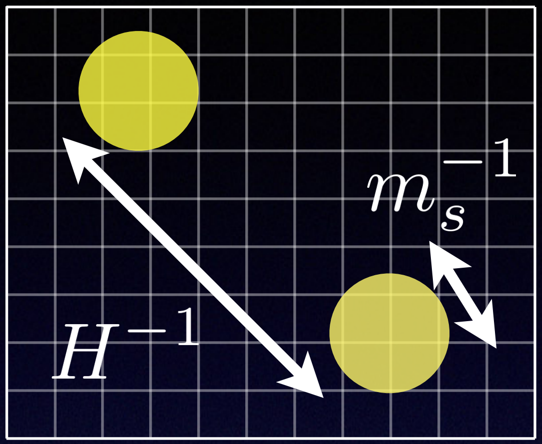


- Form when U(1)$_{PQ}$ symmetry is spontaneously broken.
- Disappear around the epoch of the QCD phase transition (if N_{DW} = 1).

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 $\log\left(m_s / H \right) \lesssim 5\text{–}6$.

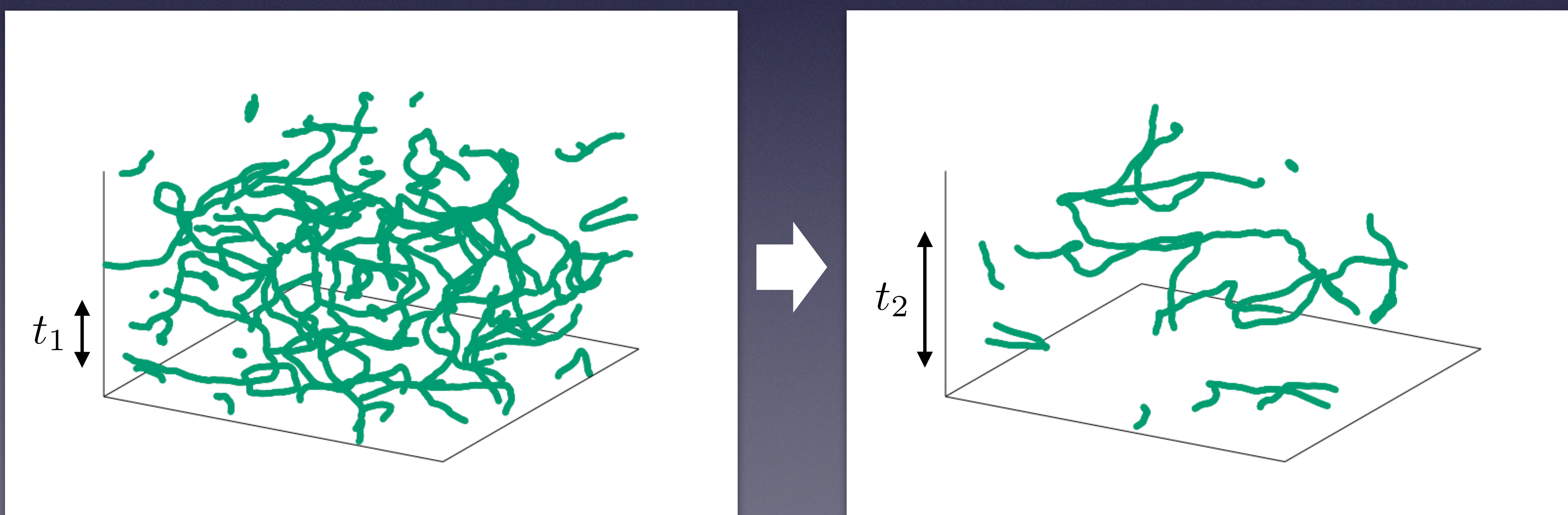
Scaling solution

- $\mathcal{O}(1)$ 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 production from strings

- Energy transfer from strings in the scaling regime

$$\dot{\rho}_a + 4H\rho_a = \Gamma_{\mathrm{str}\to a}, \quad \Gamma_{\mathrm{str}\to a} = \frac{\xi\mu}{t^3}$$

- Differential energy transfer rate [Gorghetto, Hardy and Villadoro (2018)]

$$\frac{\partial \Gamma}{\partial k}(k,t) = \frac{\Gamma(t)}{H(t)} F\left(\frac{k}{H}, \frac{m_s}{H}\right), \quad \int dx F(x,y) = 1$$

$$F\left(\frac{k}{H}, \frac{m_s}{H}\right) = \frac{1}{R^3}\frac{H}{\Gamma}\frac{\partial}{\partial t}\left(R^3 \frac{\partial \rho_a}{\partial k}\right)$$

"Instantaneous spectrum"

Information on the amount of energy injected for each mode at a given instant.

R : scale factor of the universe

- Axion number

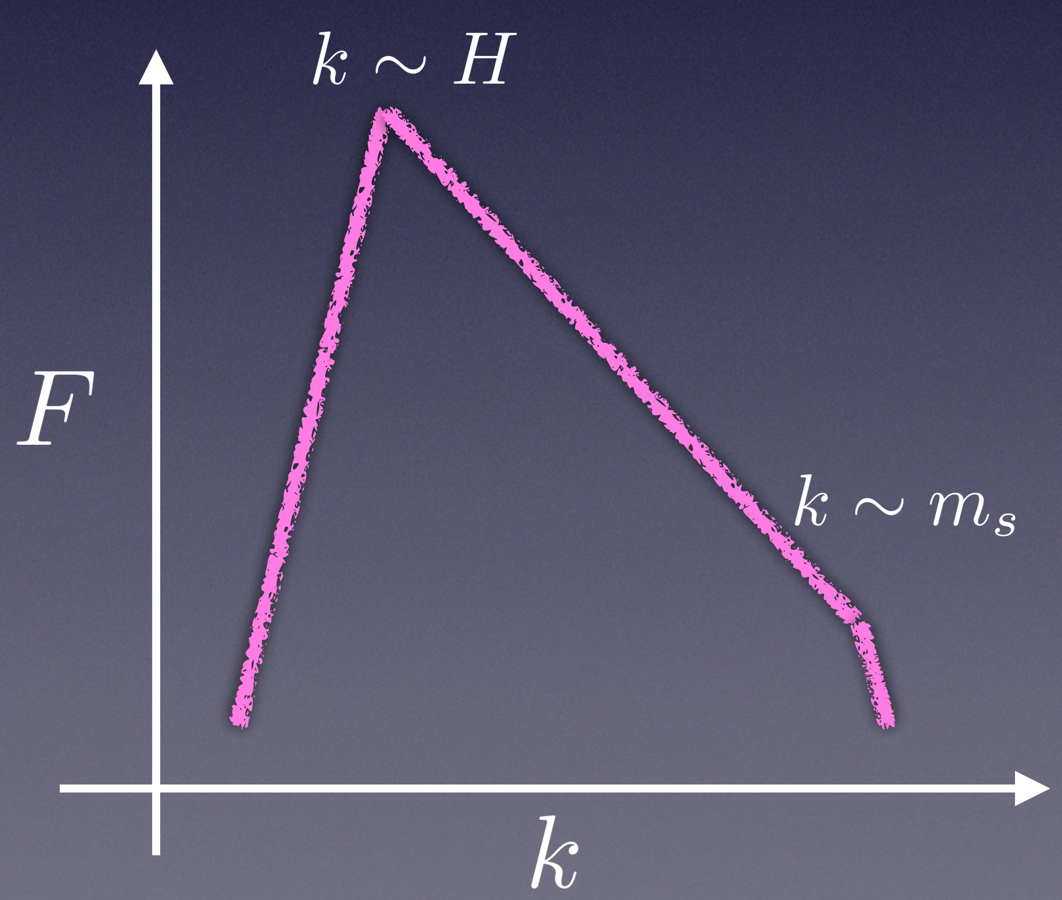
$$n_a = \int \frac{dk}{k}\frac{\partial \rho_a}{\partial k} = \int^t dt' \frac{\Gamma'}{H'}\left(\frac{R'}{R}\right)^3 \int \frac{dx}{x} F(x, y')$$

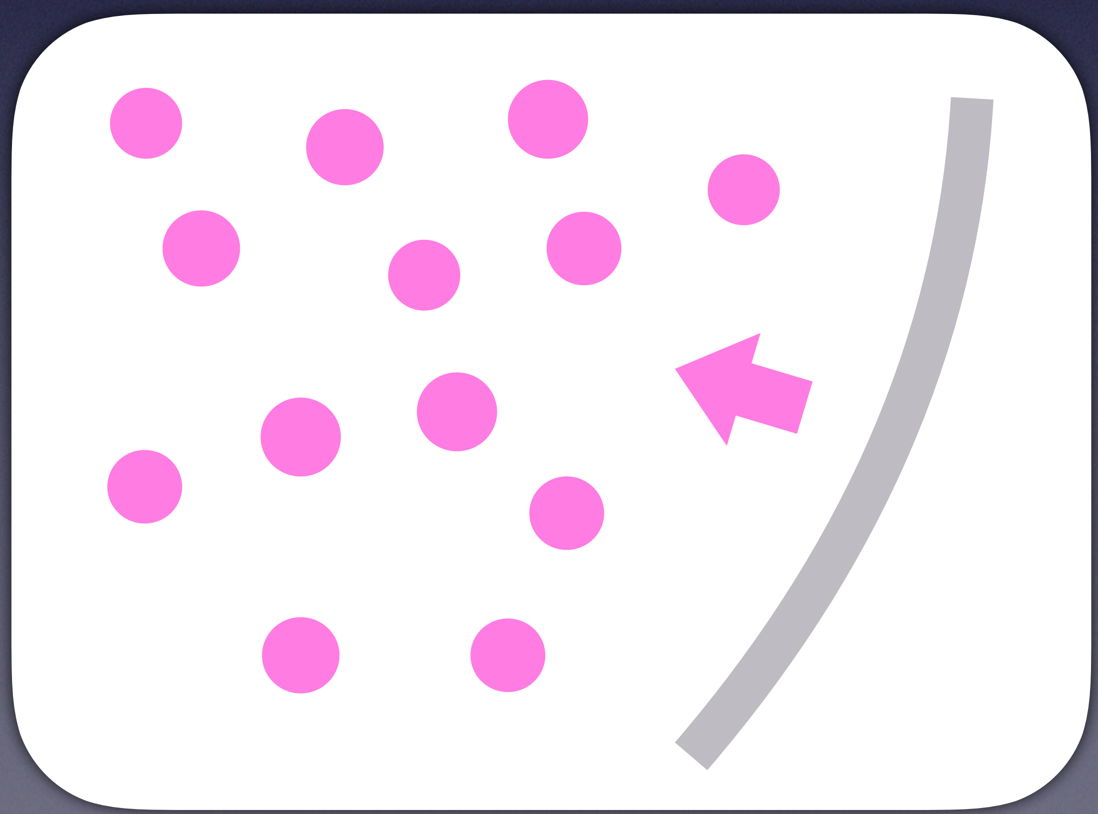
Controversy on the spectrum

Important to know about the shape of the spectrum of axions radiated at a given instant.

If 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)]

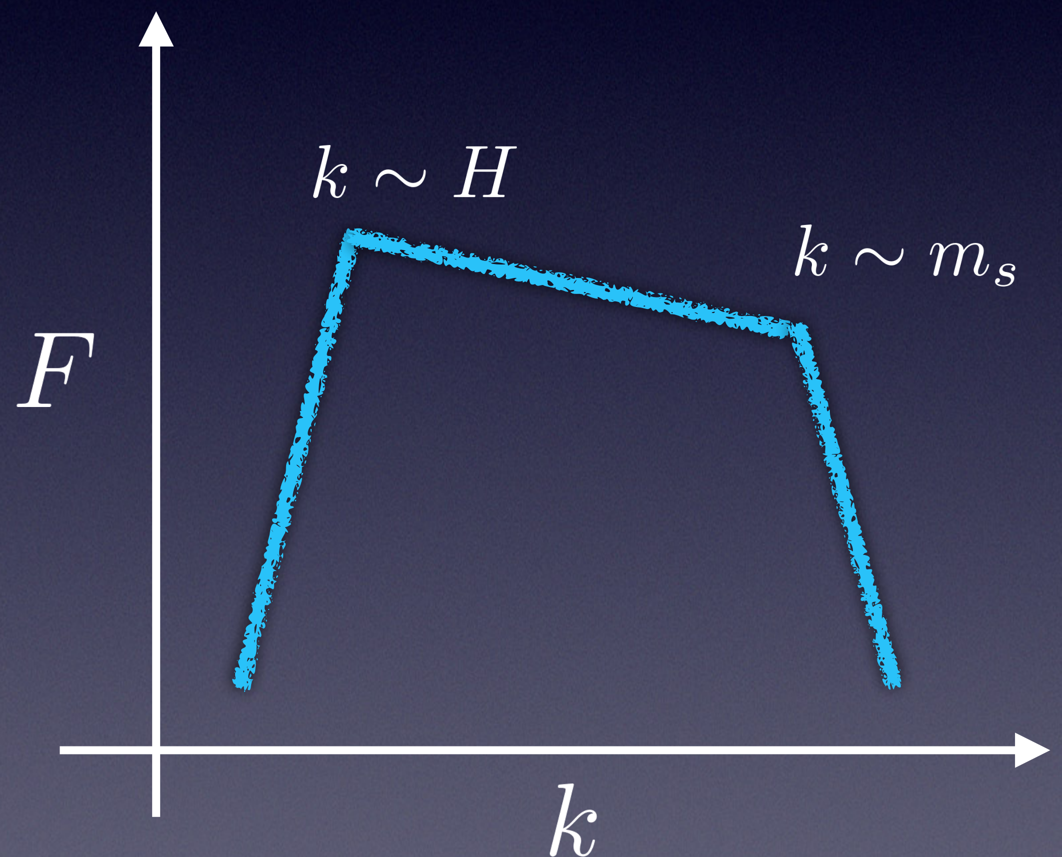


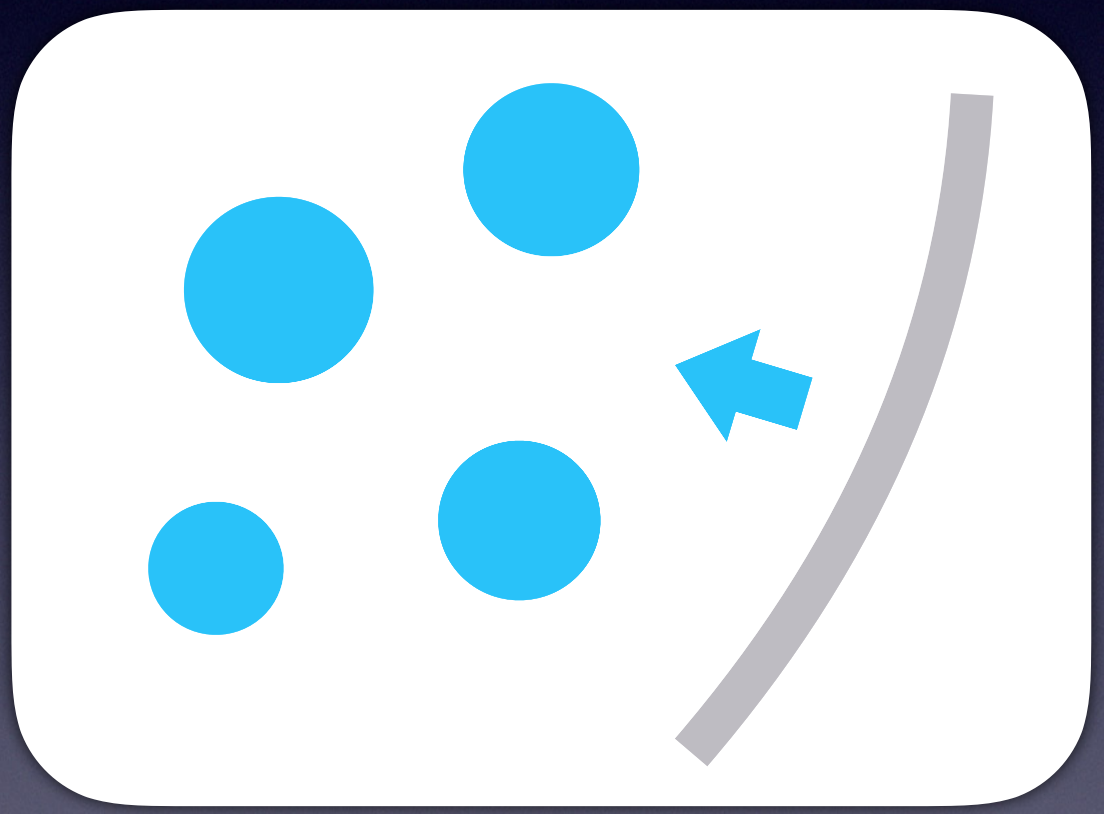


Controversy on the spectrum

If UV modes dominate,
few hard axions → Lower mass is predicted.

[Harari and Sikivie (1987); Hagmann and Sikivie (1991); Hagmann, Chang and Sikivie (2001); Fleury and Moore (2016); Klaer and Moore (2017)]



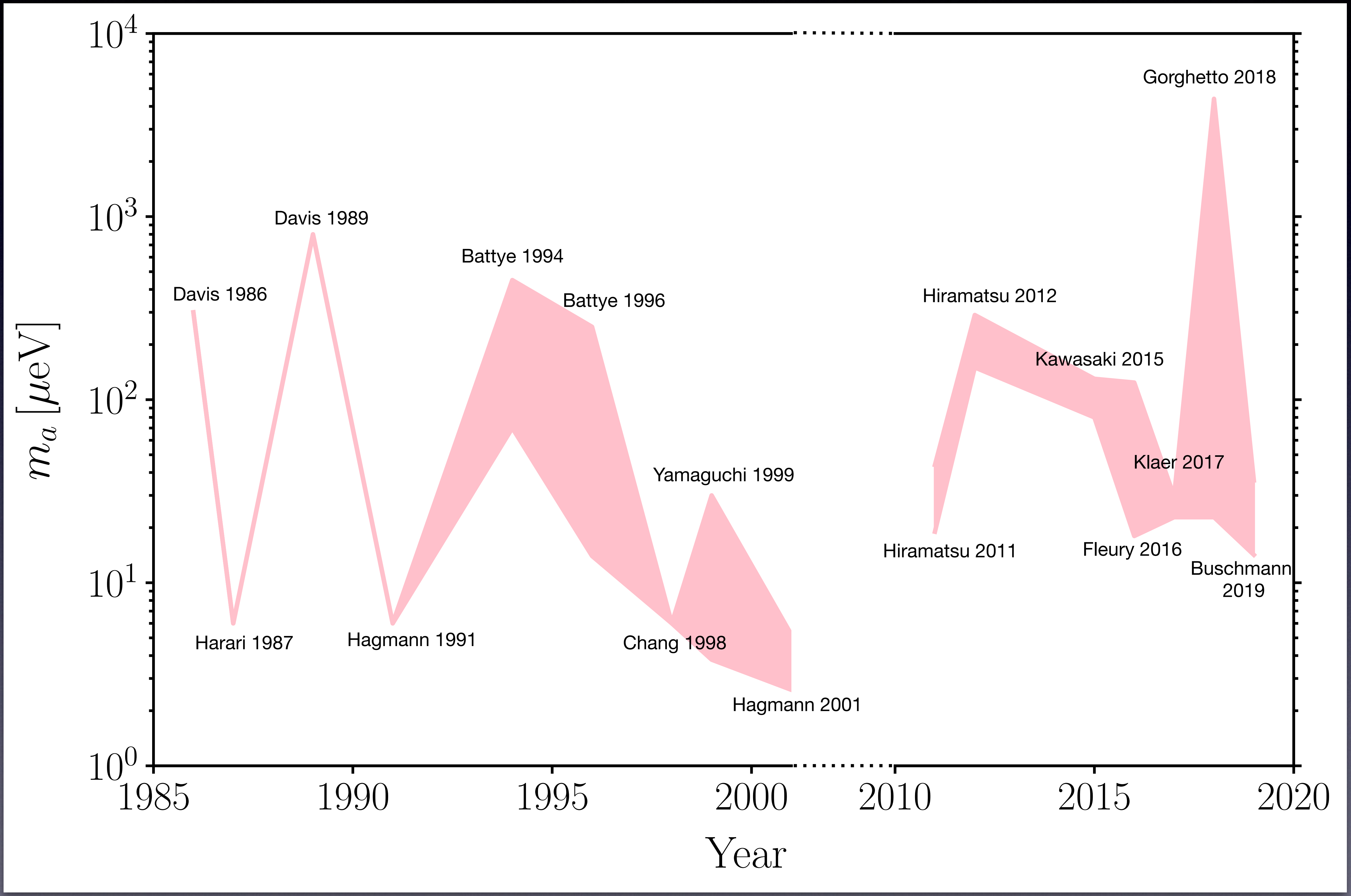


Note:

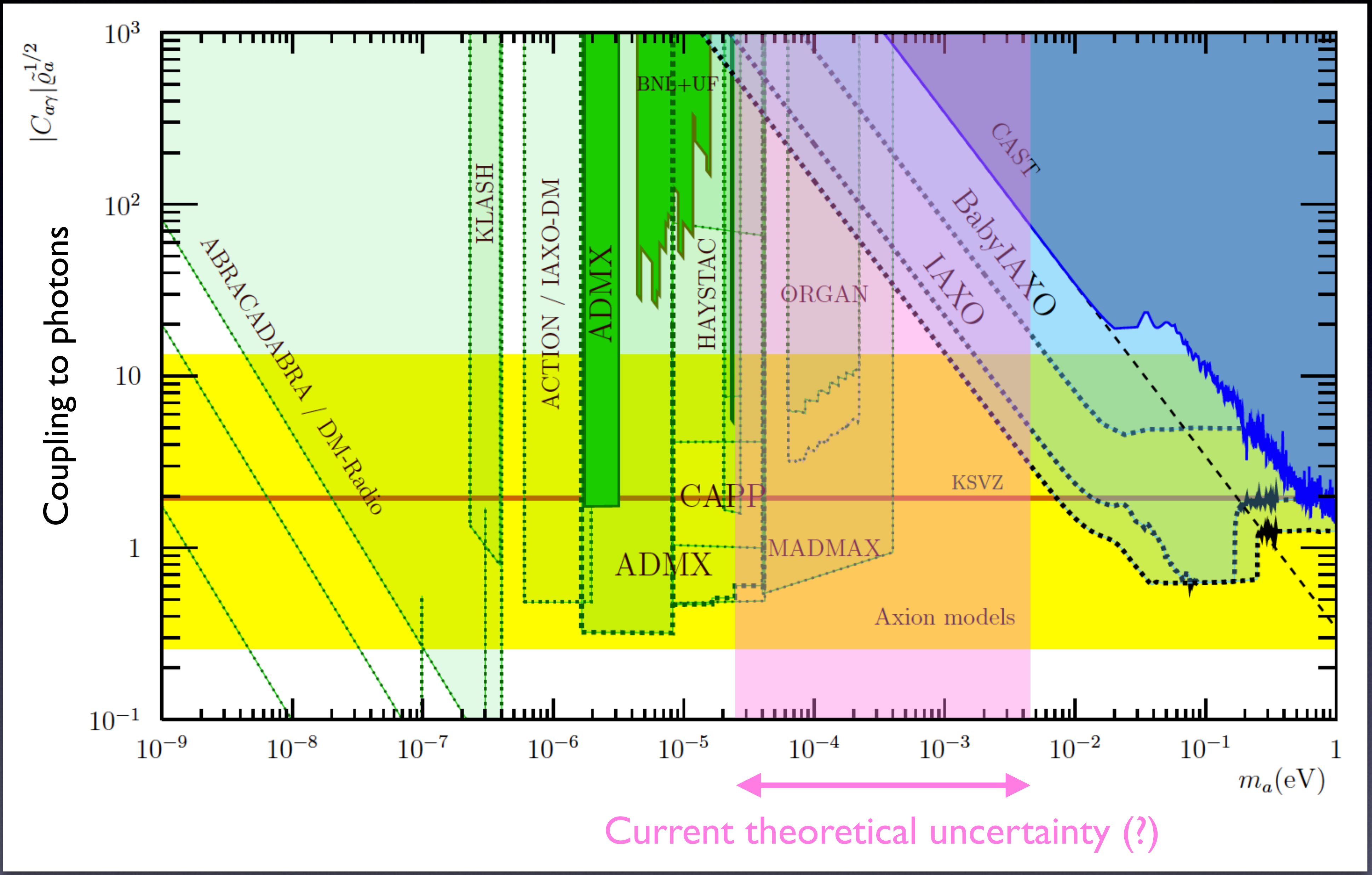
- Shape of the spectrum may depend on $\log(m_s/H)$.
- Careful extrapolation to large $\log(m_s/H)$ is required.

[Gorghetto, Hardy and Villadoro (2018)]

Axion DM mass prediction: discrepancies



Current & future experiments



[Irastorza and Redondo (2018)]

It is important to reduce the uncertainty of theoretical prediction for the "Vanilla" scenario in light of future developments of experimental searches.

Recent simulation results

Field theoretic lattice simulation

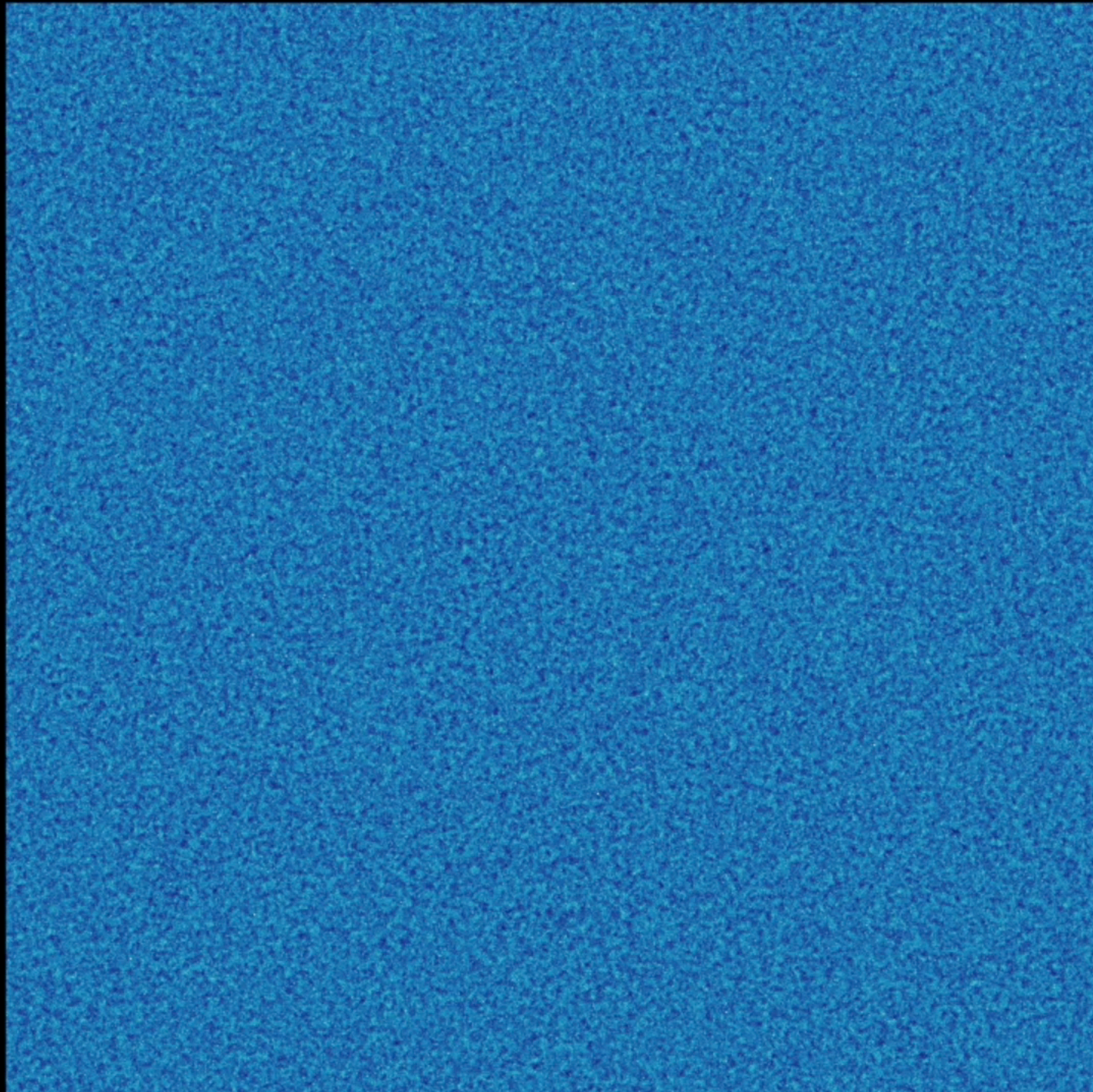
- Solve EOM for a complex scalar field ϕ numerically.

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

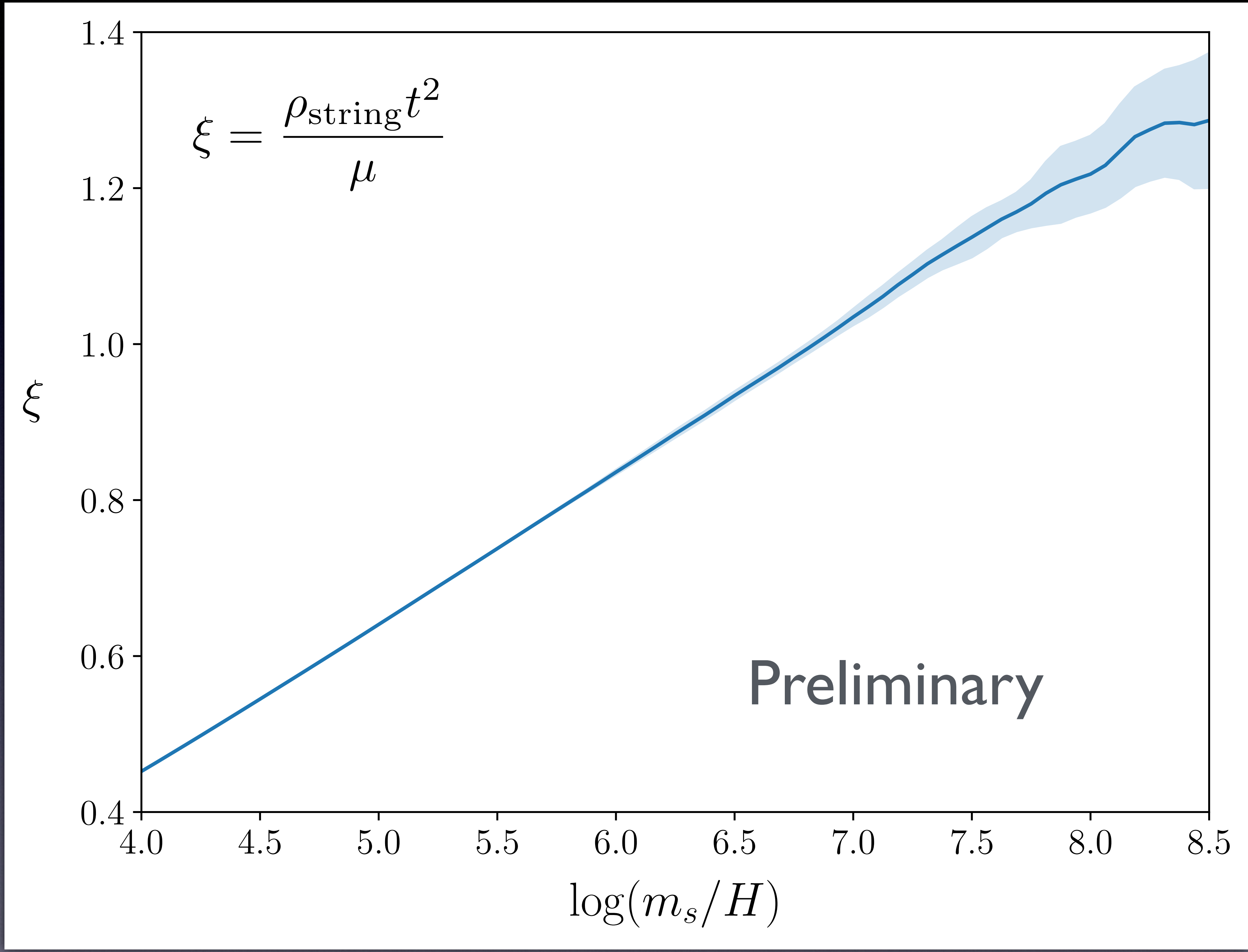
- The largest number of grids N = 8192^3 at the COBRA cluster (MPCDF, Garching).

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

https://www.mpcdf.mpg.de/services/computing/cobra/about-the-system



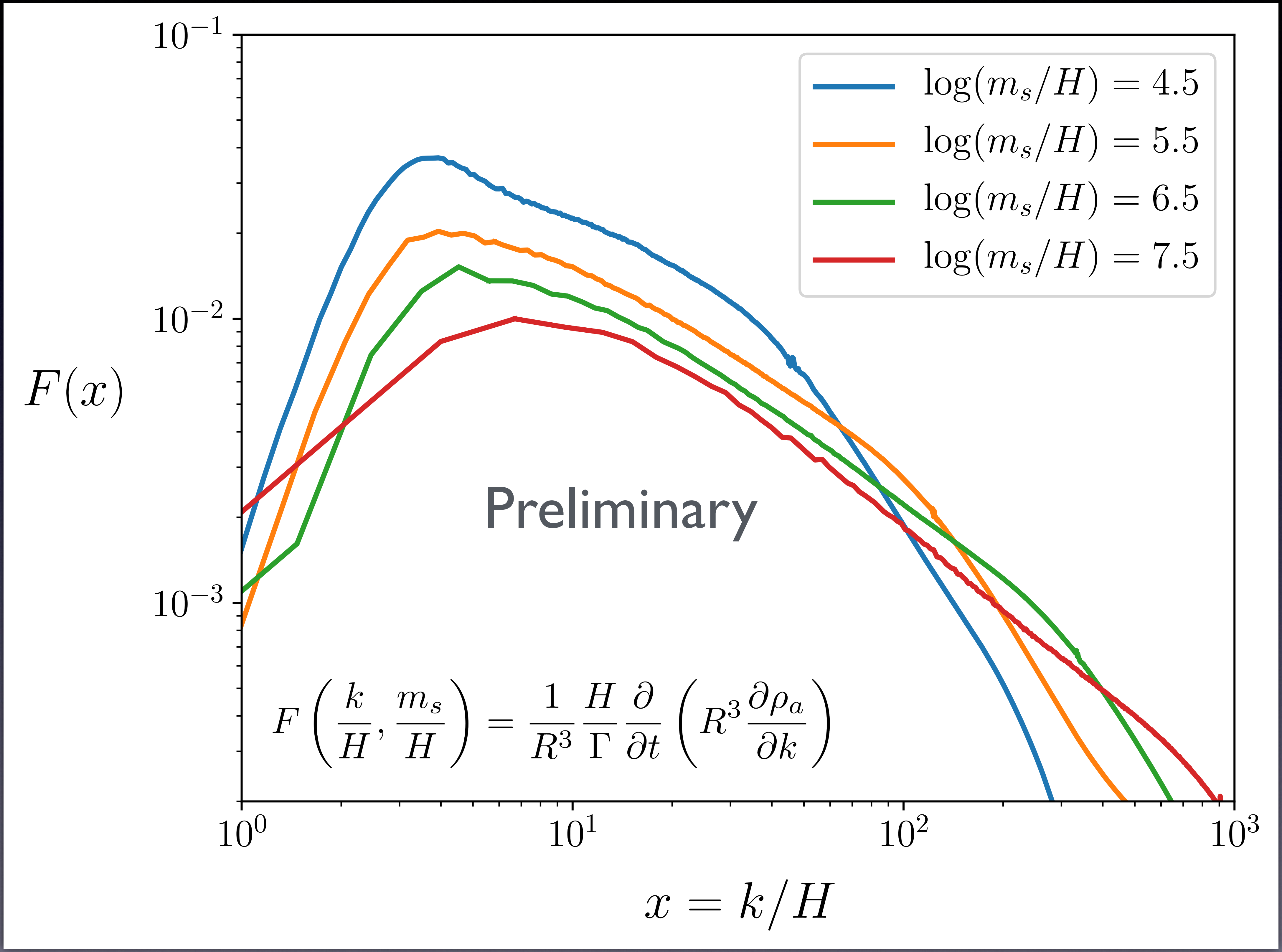
String density



Logarithmic growth compatible with previous results.

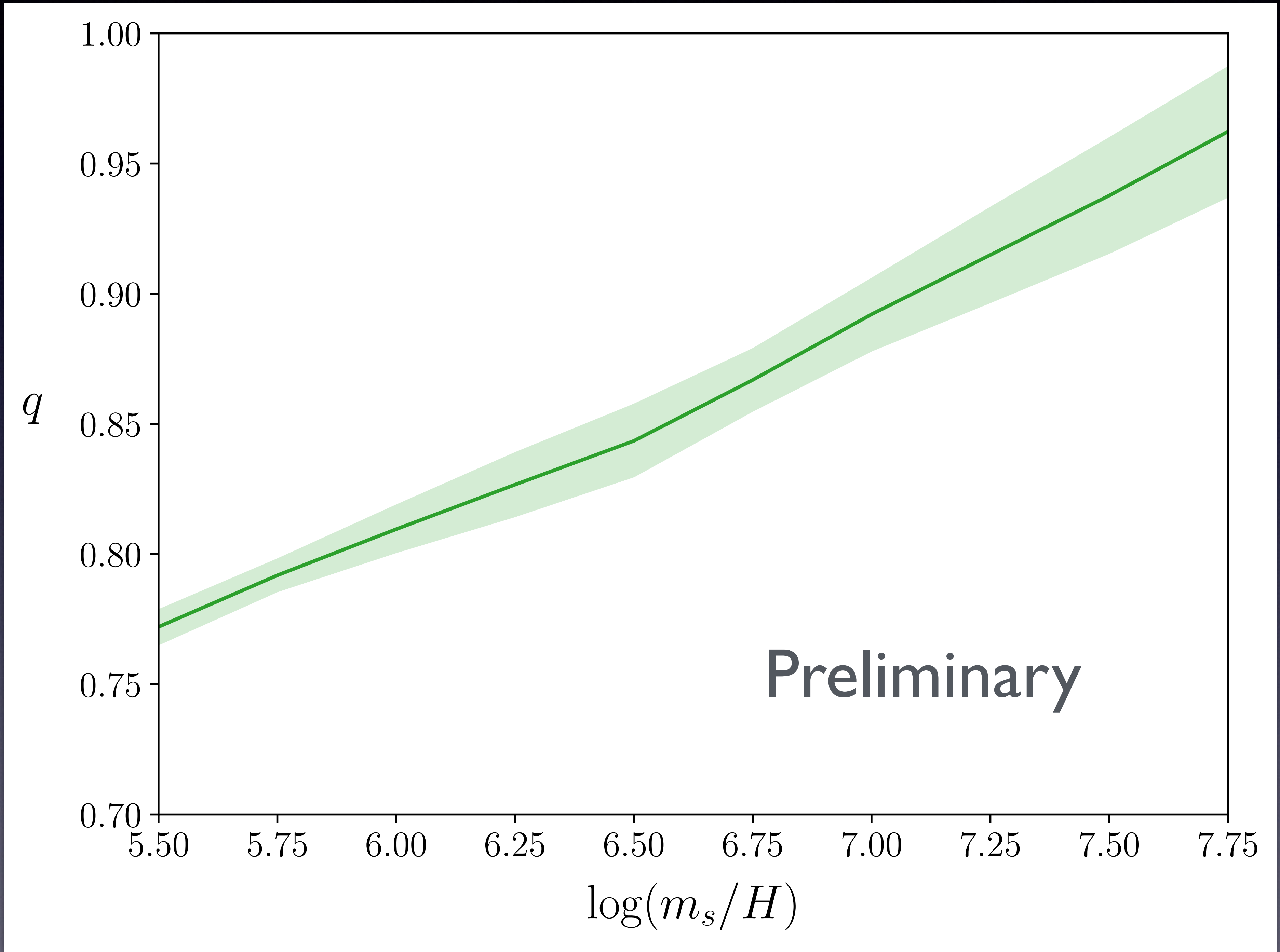
[Fleury and Moore (2016); Gorghetto, Hardy and Villadoro (2018); Kawasaki, Sekiguchi, Yamaguchi and Yokoyama (2018)]

Spectrum of radiated axions



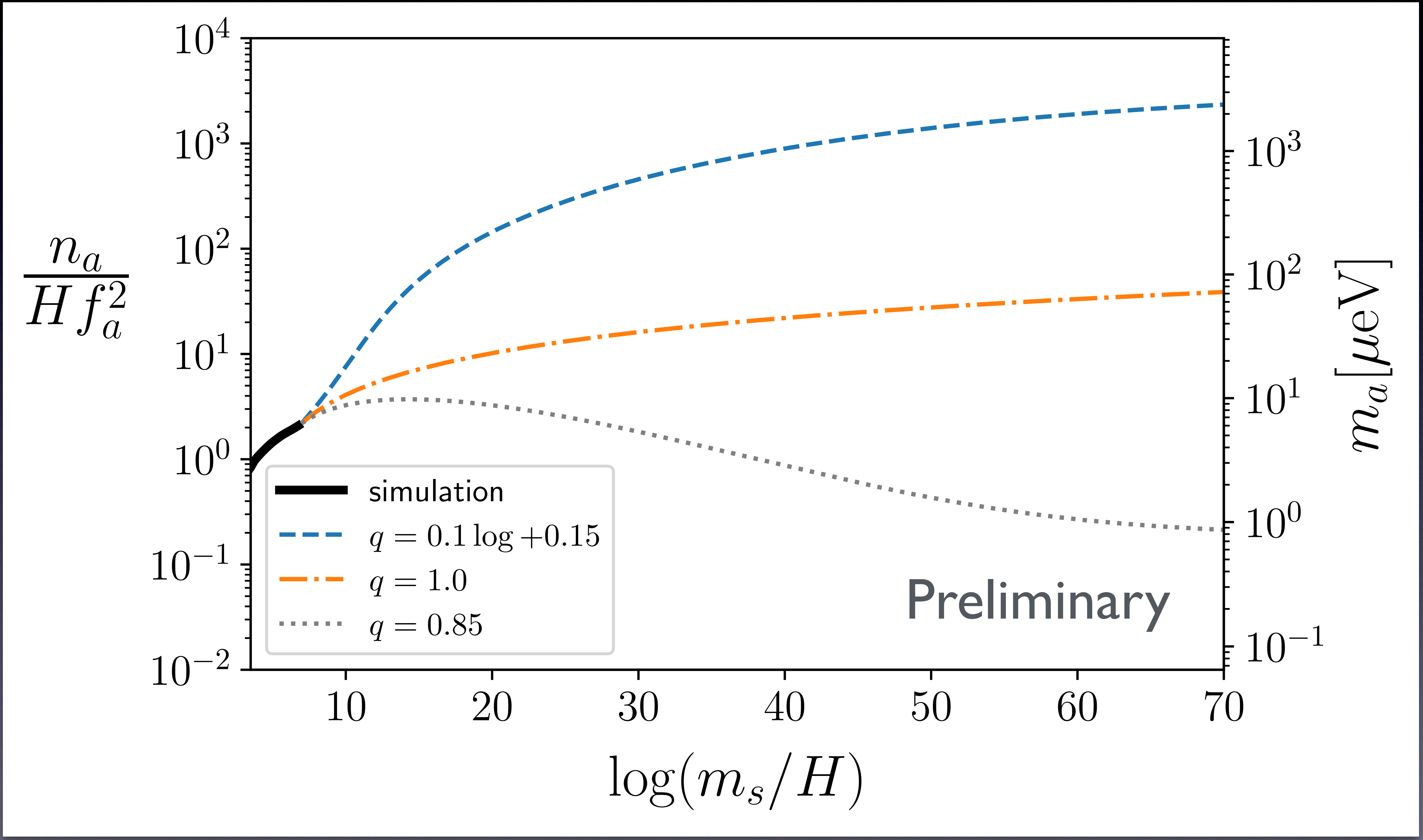
Fitting to a power law

Assume $F \propto 1/x^q$ in the intermediate range $H \lesssim k \lesssim m_s$



q seems to grow with log.

Extrapolation to large log



More issues on analysis methods

PRS vs physical strings

- Results in the previous slides are obtained based on the Press-Ryden-Spergel (PRS) trick (or "fat string" trick):

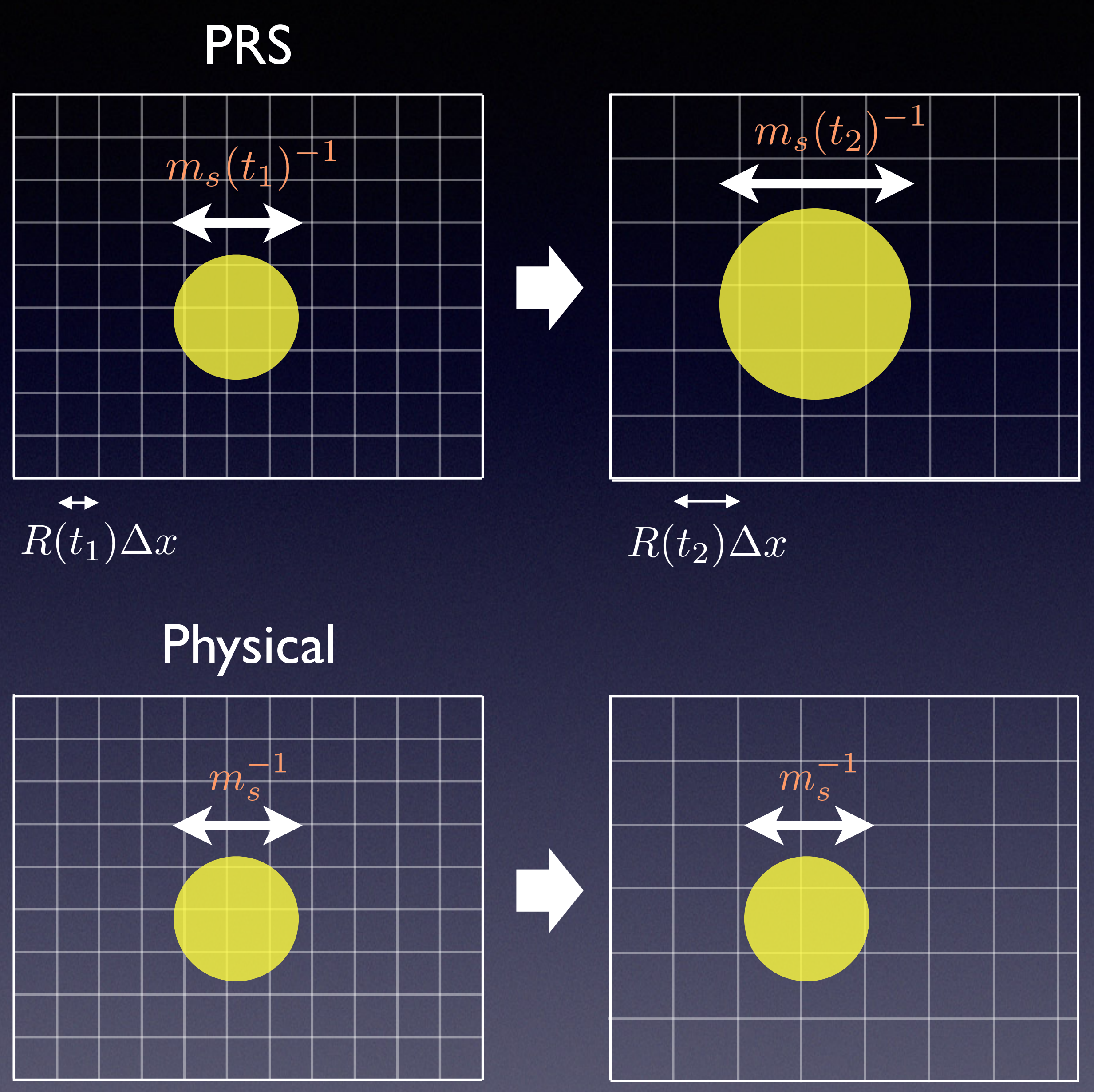
  [Press, Ryden and Spergel (1989)]

  Modifying the action such that

$$m_s \to m_s(t) = \left(\frac{R(t_{\rm ini})}{R(t)}\right) m_s(t_{\rm ini})$$

- PRS strings take a longer time to reach the same value of $\log(m_s/H)$ than physical strings.

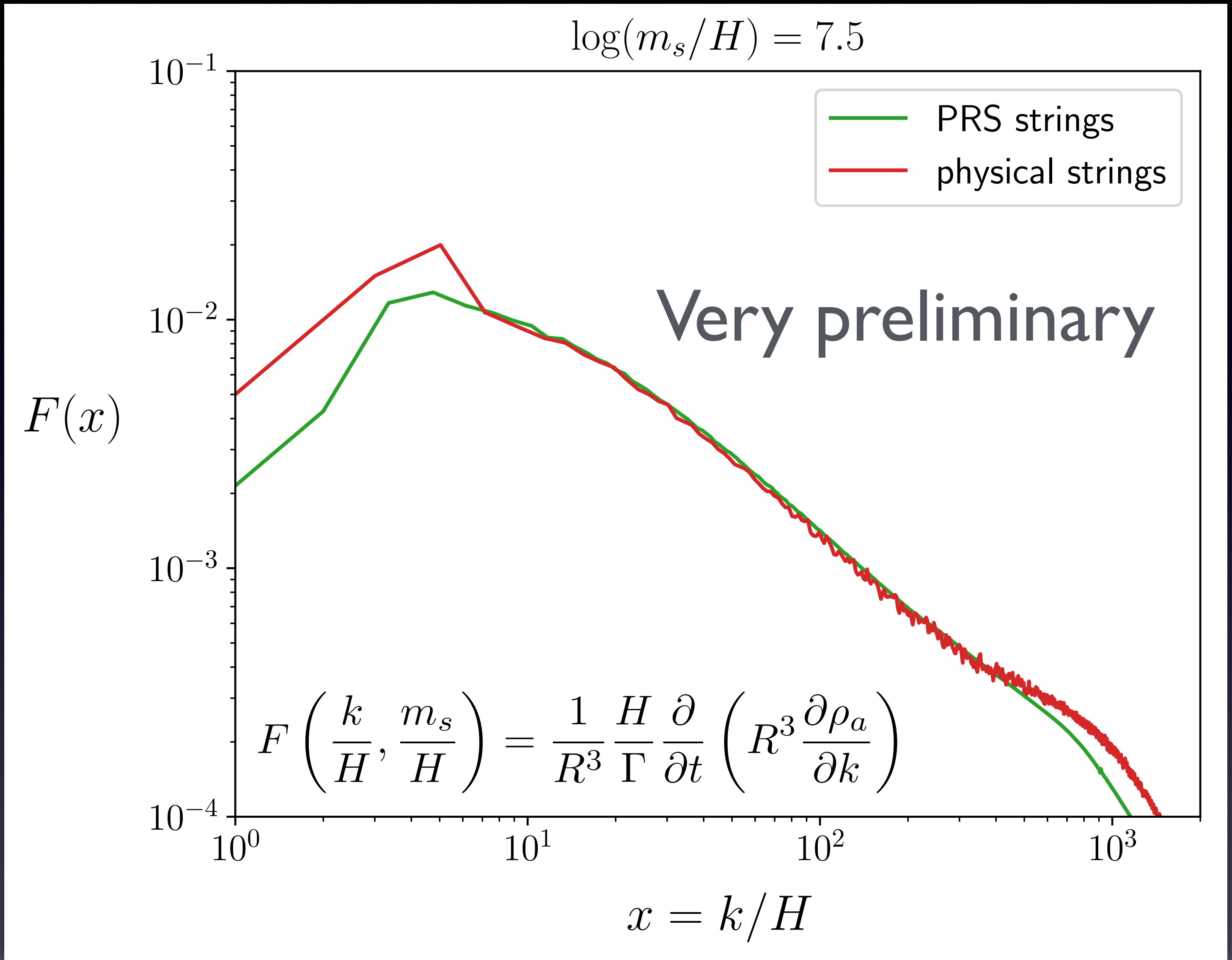
$$\log(m_s/H) \propto \begin{cases} \log(\tau) & \text{(PRS)} \\ \log(\tau^2) & \text{(physical)} \end{cases}$$



➡ PRS strings are less sensitive to the contamination from initial conditions.
i.e. Results are relatively easy to understand.

- In the end we must consider physical strings. How will the results be different?

Spectrum from physical strings



- Instantaneous quantities may depend solely on $\log(m_s/H)$ (TBC).
- Difference should appear when integrated over time.

cf. $\log(m_s/H) \propto \begin{cases} \log(\tau) & \text{(PRS)} \\ \log(\tau^2) & \text{(physical)} \end{cases}$

Interpretation of string density evolution

arXiv:1908.03522 **The scaling density of axion strings**

Mark Hindmarsh,[1,2,*] Joanes Lizarraga,[3,†] Asier Lopez-Eiguren,[1,‡] and Jon Urrestilla[3,§]

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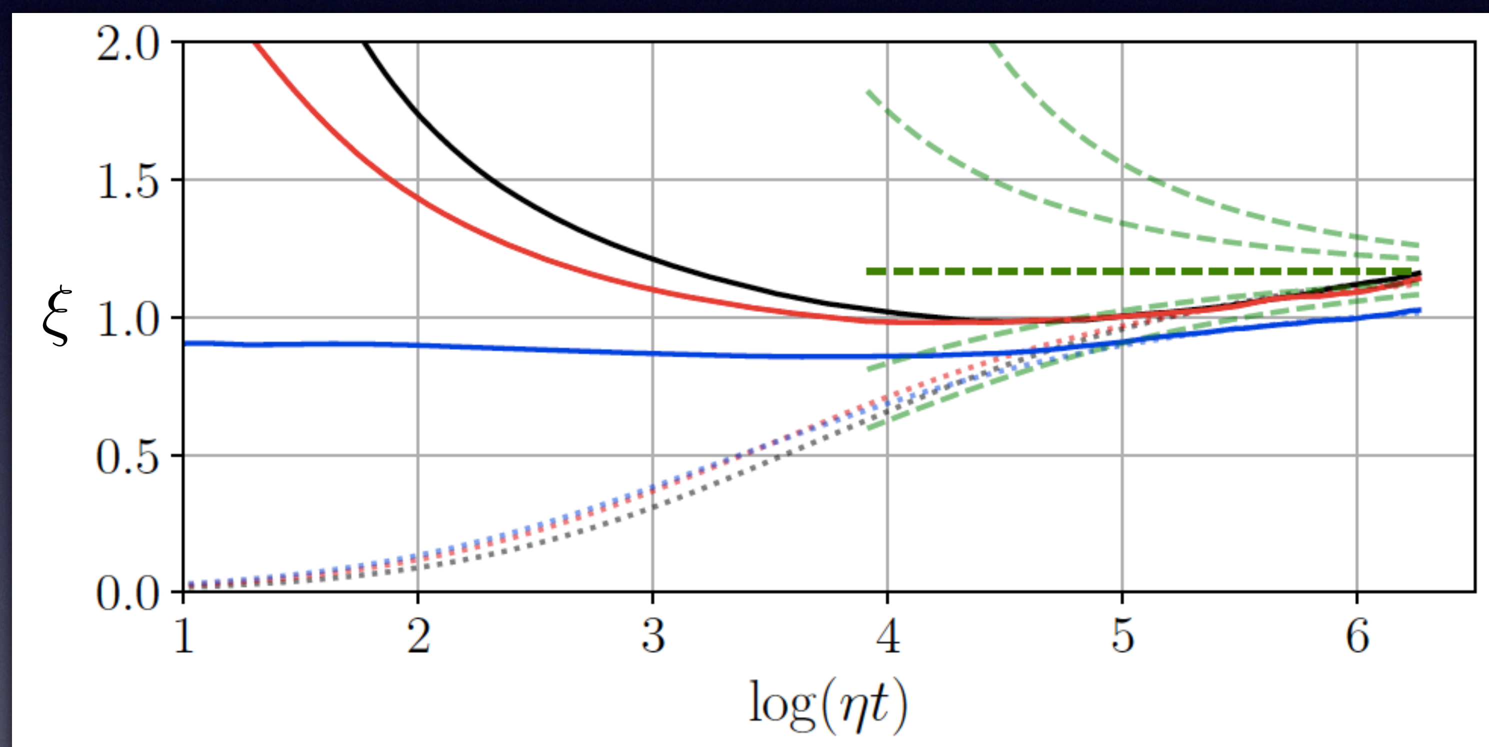
[2] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, U.K.*
[3] *Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain*

(Dated: August 12, 2019)



- Better fits are obtained for $\xi \propto (1 - t_0/t)^{-2}$ rather than $\xi \propto \log(m_s/H)$, implying that $\xi \simeq 1\ (\text{const.})$ at large $\log(m_s/H)$ … a new controversy?

- Should be checked in simulations with larger dynamical ranges!

Summary

- Typical scenario for axion dark matter production:
  - Post-inflationary PQ symmetry breaking
  - Axions produced from strings
- We should be careful about potentially large uncertainty on the relic axion dark matter abundance.
- A naive extrapolation of the simulation results show a preference for higher mass ranges, but there remain several issues on the systematics.