

Axions in the Lab and in the Cosmos

15-19 July 2019 CERN

Relic abundance of QCD axion DM

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Based on works w/ M. Gorgetto and E. Hardy

QCD Axion

Axion Solution to the Strong CP Problem!

$$\det[y_u y_u^\dagger, y_d y_d^\dagger]$$

$$\Rightarrow \delta \approx 1.2$$

$$\det(y_u y_d) e^{i\theta_0}$$

$$\Rightarrow \theta \lesssim 10^{-10}$$

$$\theta \rightarrow \frac{a(x)}{f_a}$$

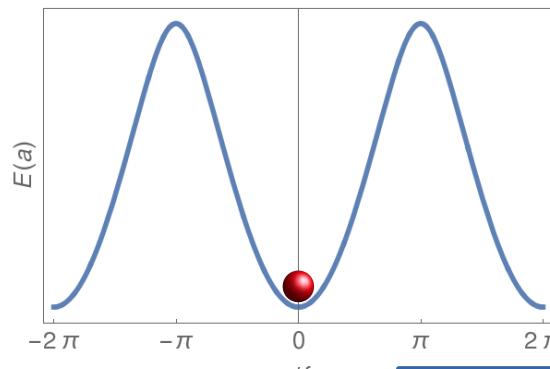
Peccei Quinn '77
 Weinberg, Wilczek '78
 (KSVZ, DSFZ...)

$$\mathcal{L}_{\text{top}} = \frac{\theta_0}{32\pi^2} G\tilde{G}$$

$$\mathcal{L}_{SM}^{\theta=0} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$10^8 \lesssim \frac{f_a}{\text{GeV}} \lesssim 10^{17}$$

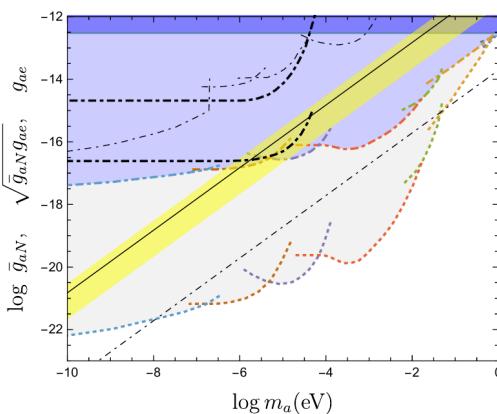
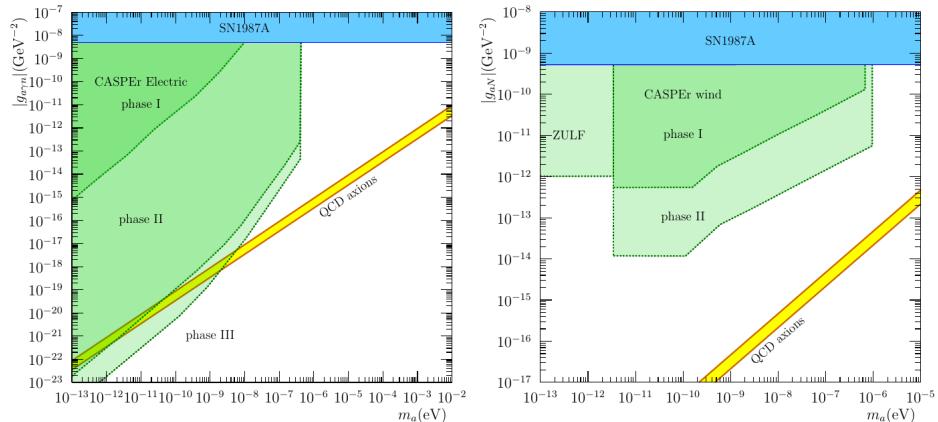
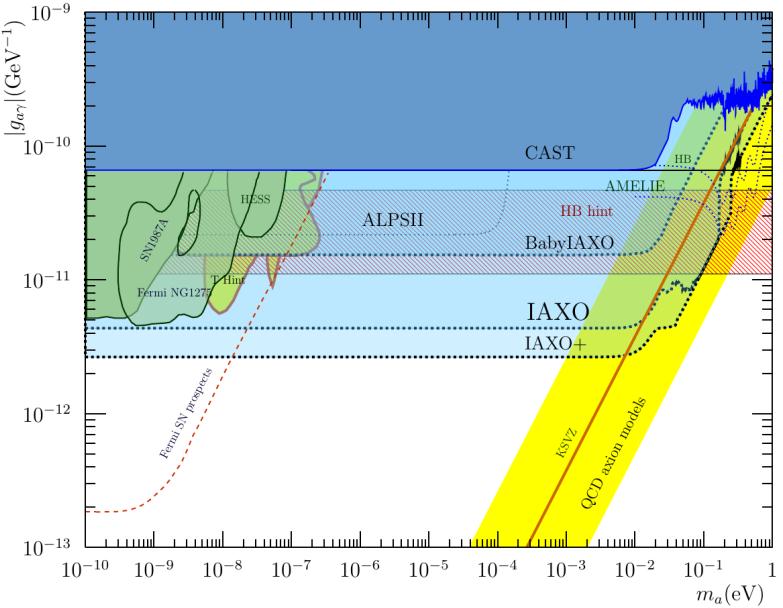
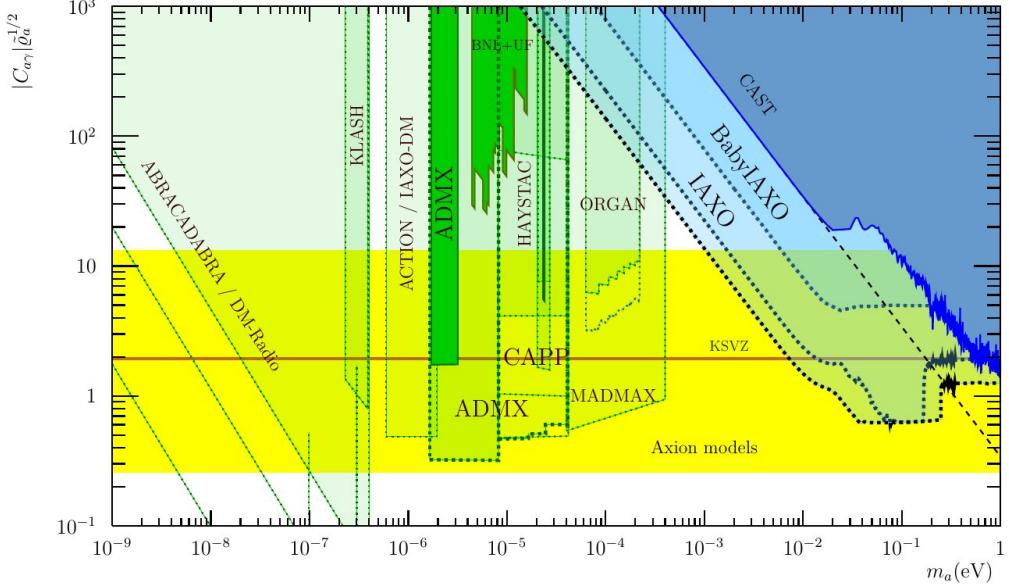
$$10^{-10} \lesssim \frac{m_a}{\text{eV}} \lesssim 10^{-1}$$



Vafa Witten '84

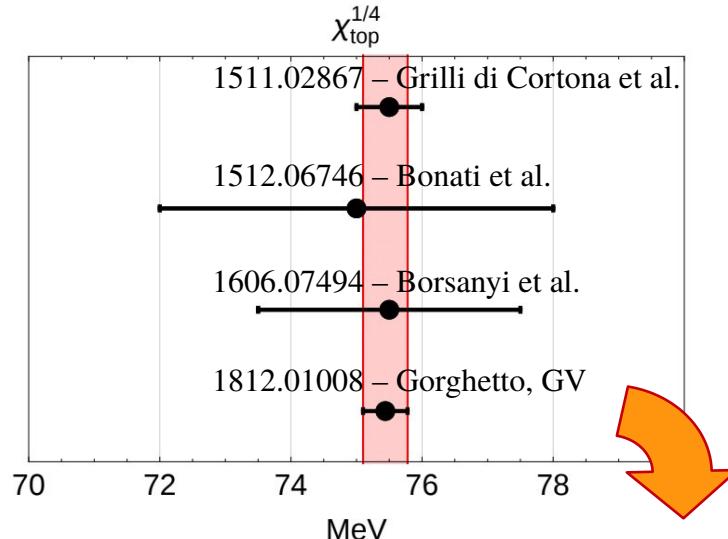
$$m_a \approx \frac{\Lambda_{\text{QCD}}^2}{f_a}$$





from 1801.08127
Irastorza. Redondo

$$m_a = \frac{\chi_{\text{top}}^{1/2}}{f_a}$$



$$m_a = \left[\underbrace{5.815(22)_z(04)_{f_\pi}}_{\text{LO}} - \underbrace{0.121(38)_{\ell_i^r}}_{\text{NLO}} - \underbrace{0.022(07)_{\ell_i^r}(05)_{c_i^r}}_{\text{NNLO}} + \underbrace{0.019(06)_{k_i^r}}_{\text{EM}} \right] \mu\text{eV} \frac{10^{12} \text{ GeV}}{f_a}$$

$$m_a = 5.691(51) \mu\text{eV} \frac{10^{12} \text{ GeV}}{f_a}$$

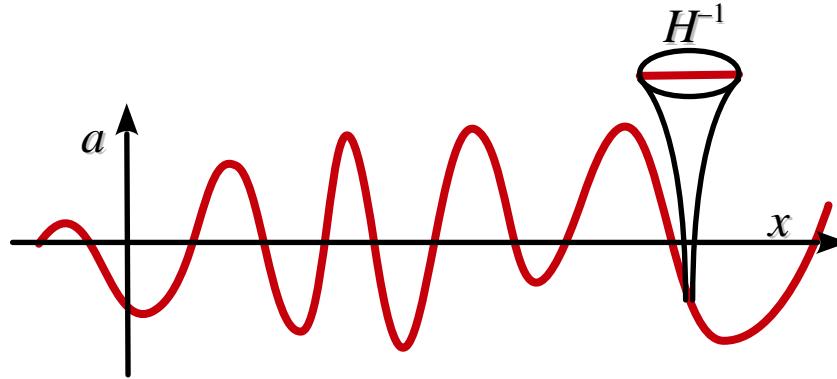
$$\chi_{\text{top}}^{1/4} = 75.44(34) \text{ MeV}$$

Axion DM

Abbott, Dine, Fischler,
Preskill, Sikivie, Wise,
Wilczek ‘83

Scenario I: no PQ restoration after inflation

$$f_a > \max\{H_I, T_R\}$$



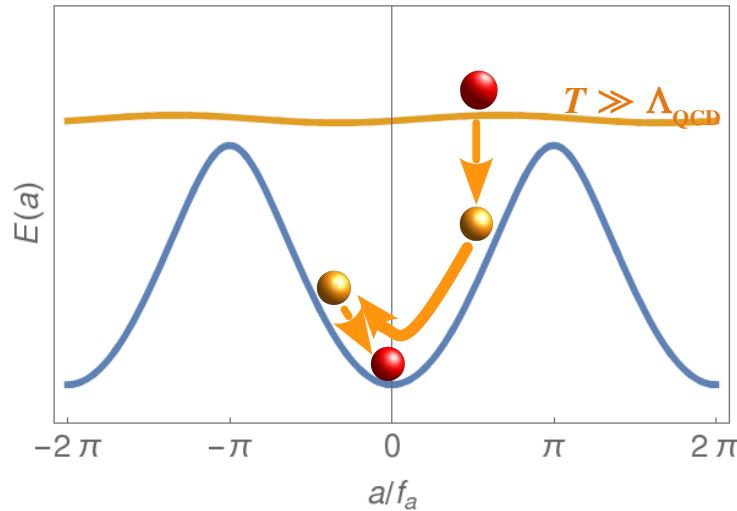
$$a(t_0) = \text{const} \text{ (within Hubble)}$$

after inflation

Scenario I:

$$a(t_0) = \text{const} \equiv \theta_0 f_a$$

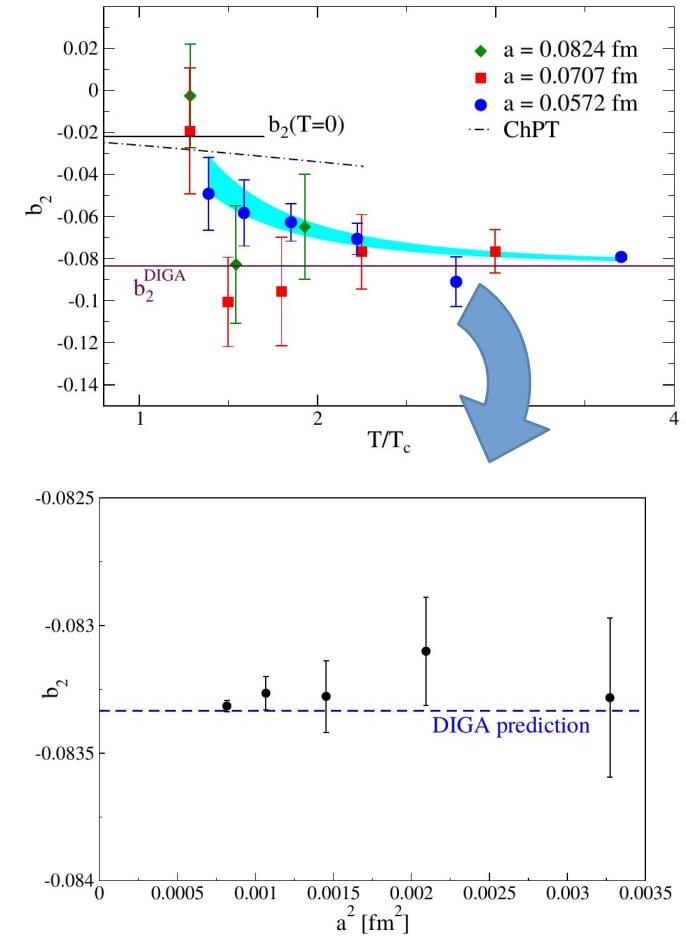
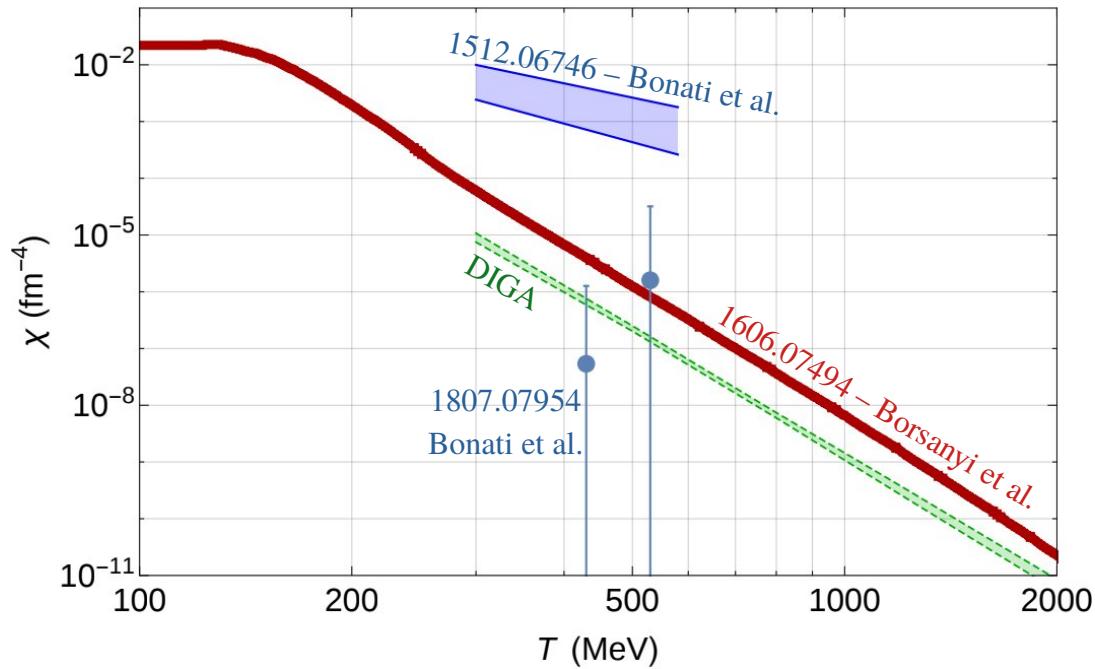
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

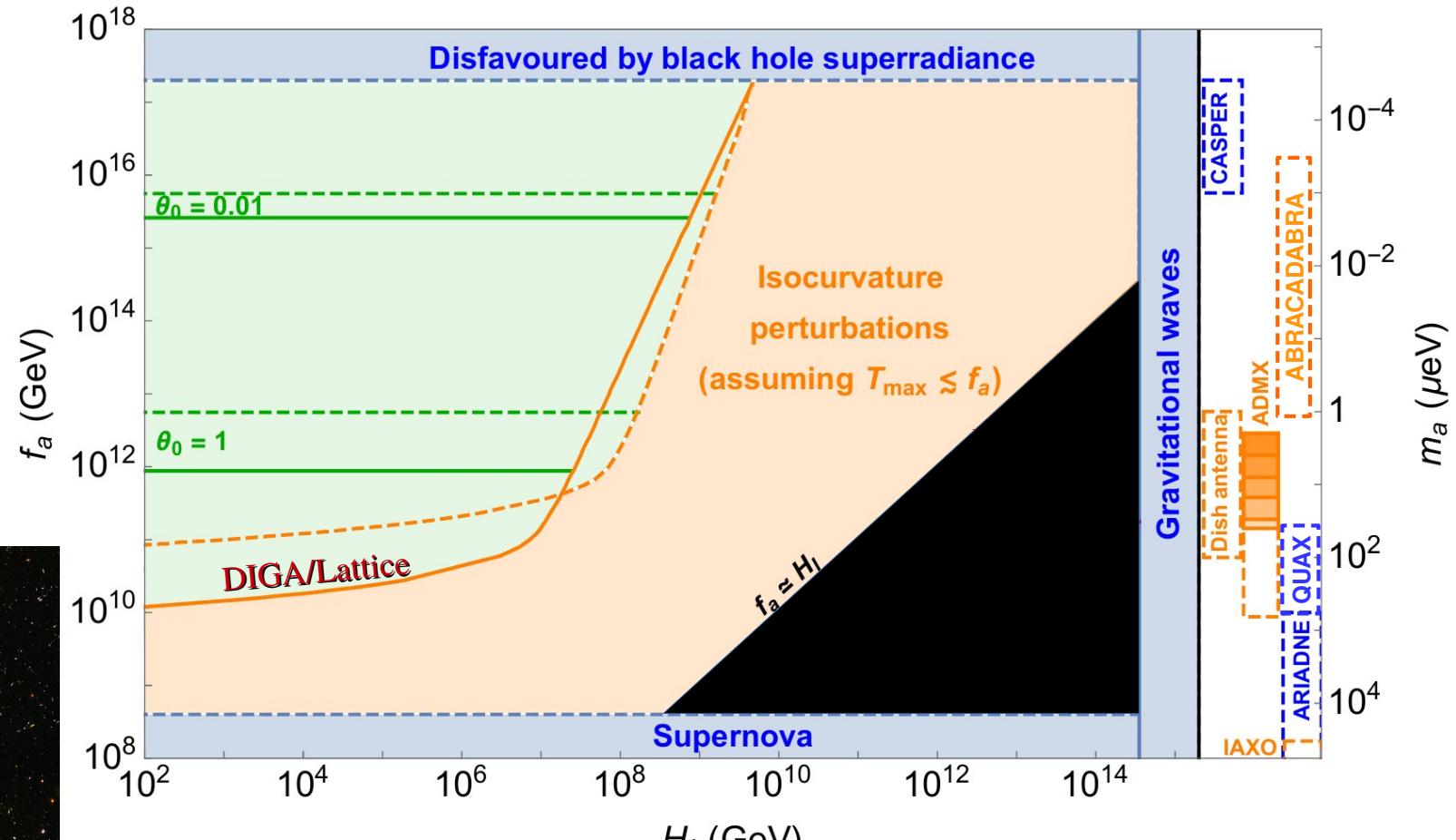
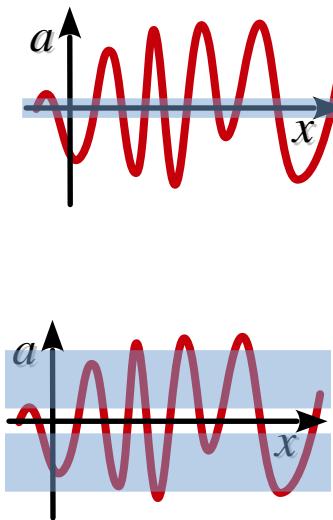


$$\rho_a = m_a^2 a^2$$

$$\Omega_a = 0.1 k \theta_0^2 \left[\frac{f_a}{10^{12} \text{GeV}} \right]^{1+\epsilon}$$

Finite Temperature QCD Axion Mass





$$\rho_{dm} \sim 10^{-5} \rho_{dm}^{loc}$$

Scenario II: PQ restoration after inflation

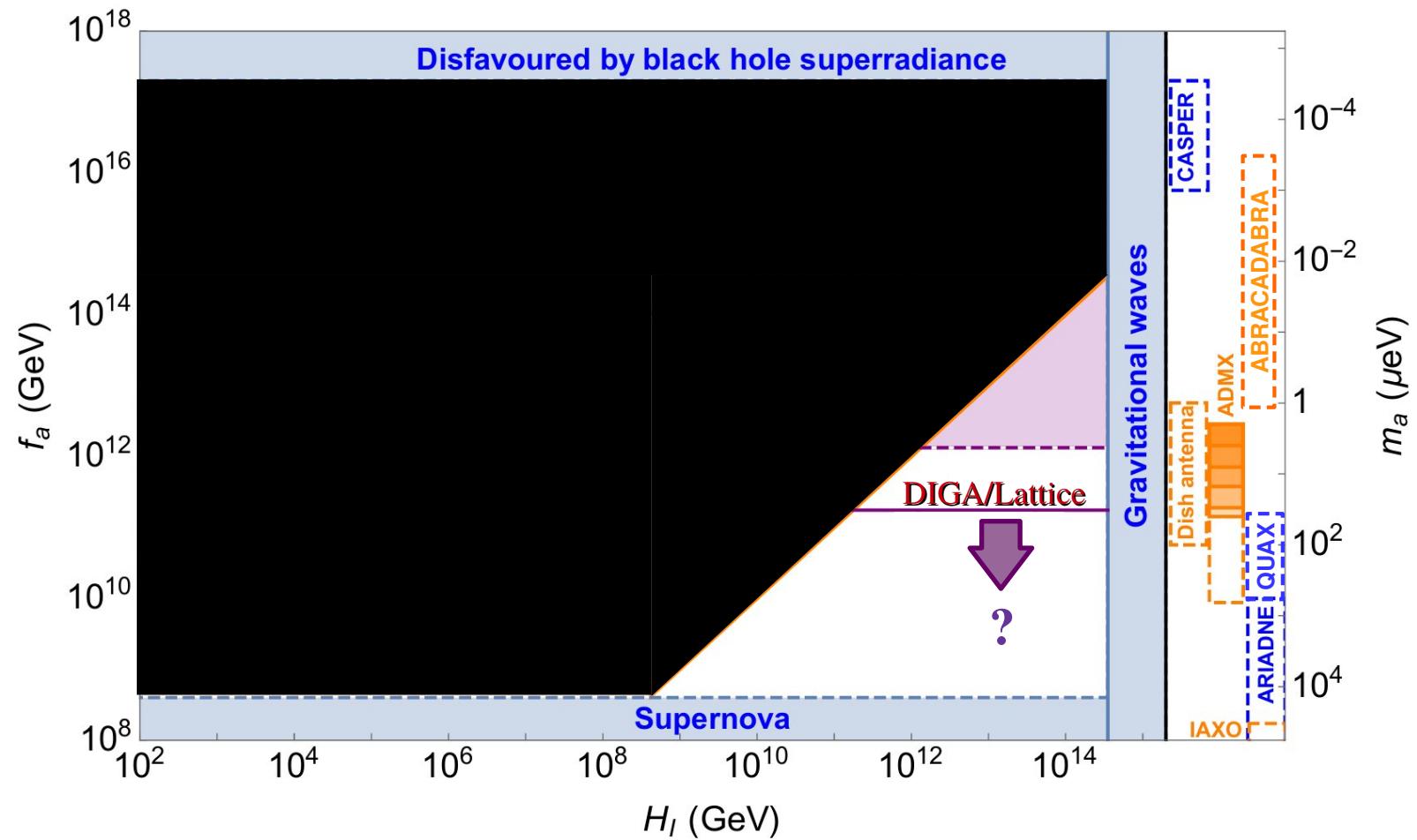
$$f_a < \max\{H_I, T_R\}$$

$$\theta_0^2 \approx \frac{\langle a^2 \rangle}{f_a^2} \approx (2.2)^2$$

no free parameters from initial conditions
abundance calculable! (*in principle*)

Multiple contributions:

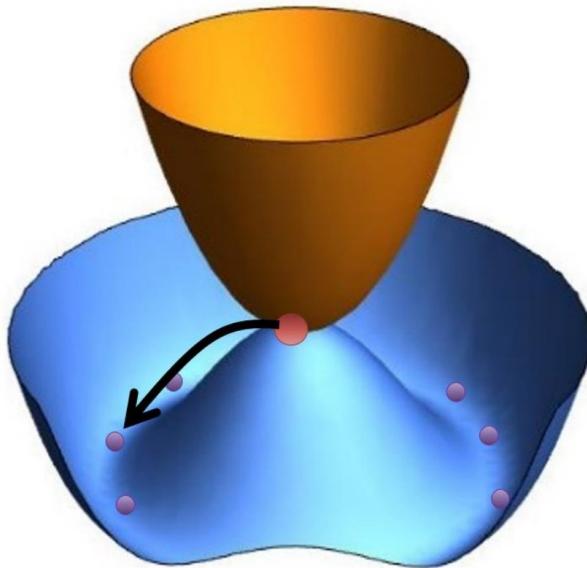
- misalignment (0-mode) $\Omega_a^{(0)} = 0.1 k_\alpha \left[\frac{\theta}{2.15} \right]^2 \left[\frac{f_a}{10^{12} \text{ GeV}} \right]^{1+\epsilon}$
- misalignment (k -modes) $\ddot{a}_k + 3H\dot{a}_k + \left(m_a^2 - \frac{k^2}{R^2} \right) a_k = 0$ $\Omega_a^{(k)} \sim \Omega_a^{(0)}$
- topological defects (strings and domain walls)



PQ phase transition

$$T \gtrsim f_a$$

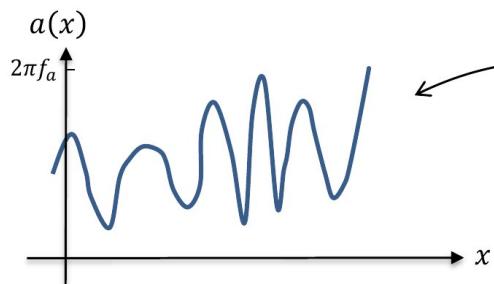
$$T \lesssim f_a$$



$$\phi = |\phi| e^{i \frac{a}{f_a}}$$

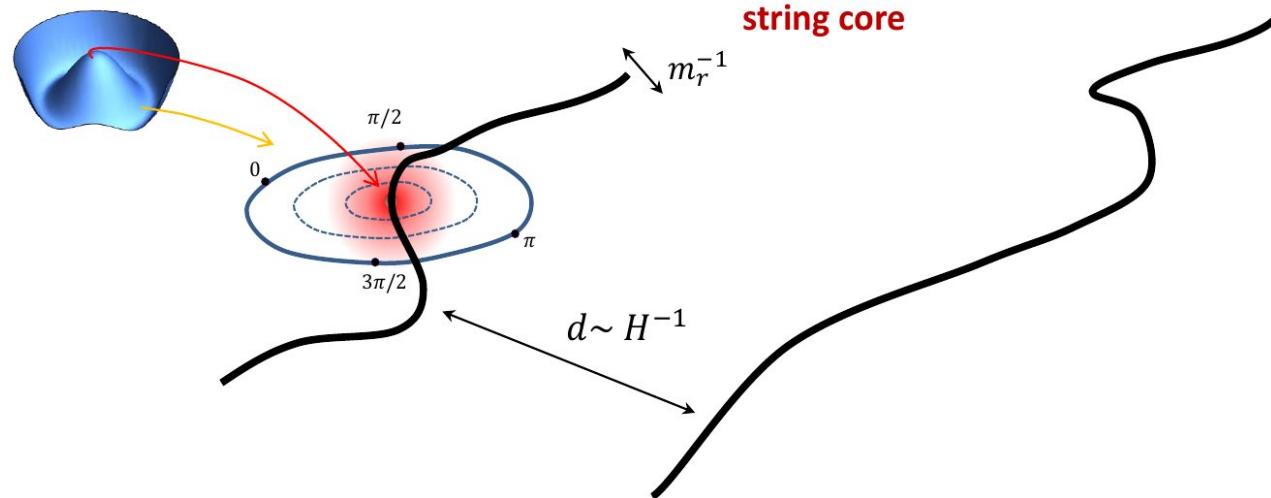
similarly if

$$H \gtrsim f_a$$



after PQ axion field has random
fluctuations over the observable universe

Axionic Strings



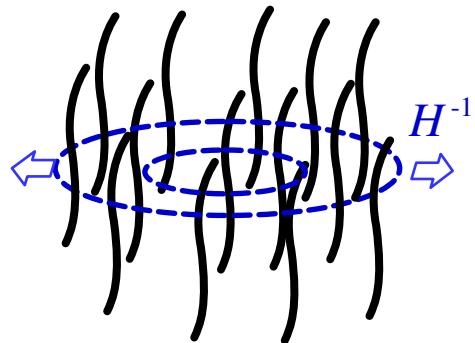
string tension

$$\mu = \frac{E}{L} \sim \boxed{\pi f_a^2} \log \frac{d}{m_r^{-1}} \sim \pi f_a^2 \log \frac{m_r}{H}$$

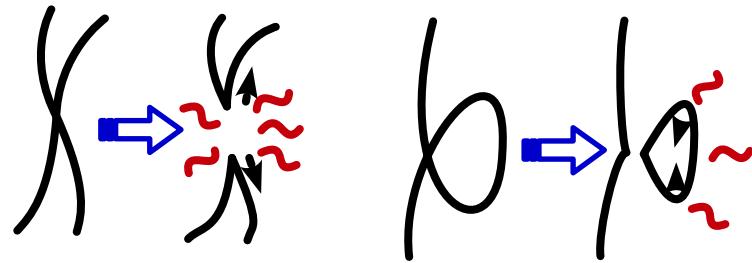
radial
core

axion
field

free strings



string recombination



$$\rho_{\text{free}} \propto \frac{1}{R^2(t)} = \frac{1}{t}$$

scaling solution

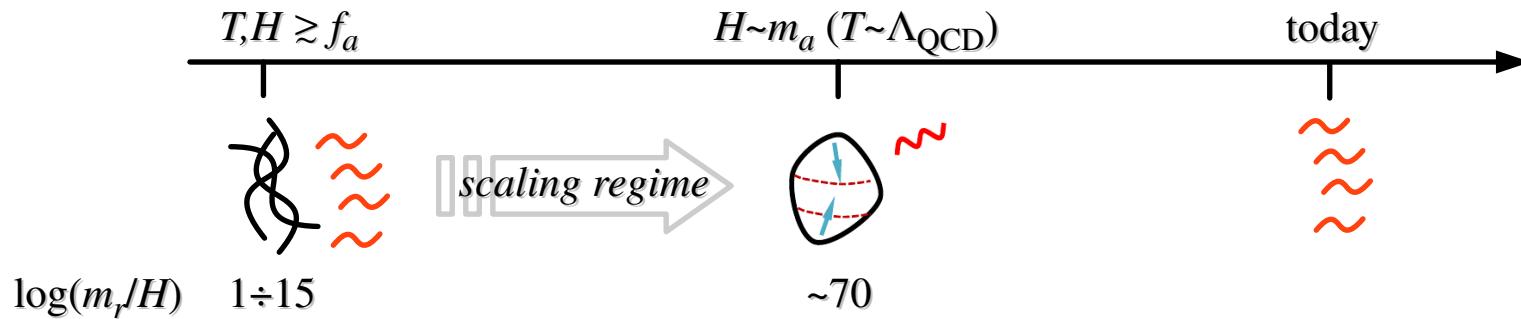
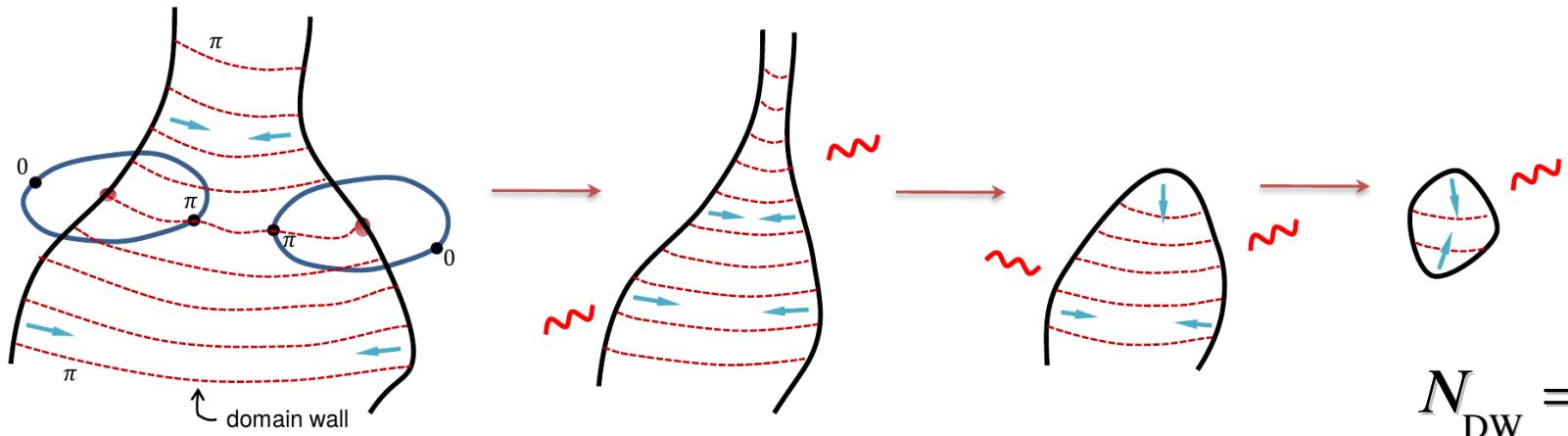
$$\rho_s = \xi \frac{\mu}{t^2}$$

$$\xi = (\# \text{ strings}) / (\text{Hubble Patch})$$



difference goes in radiation

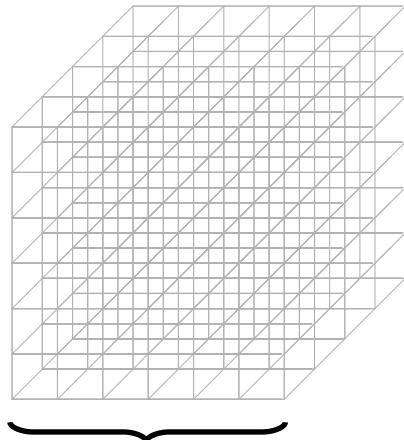
@ $H \sim m_a$ ($T \sim \Lambda_{\text{QCD}}$)



Numerical Simulation

$$V(\Phi) = \frac{\lambda}{4} \left(|\Phi|^2 - \frac{f_a^2}{2} \right)^2$$

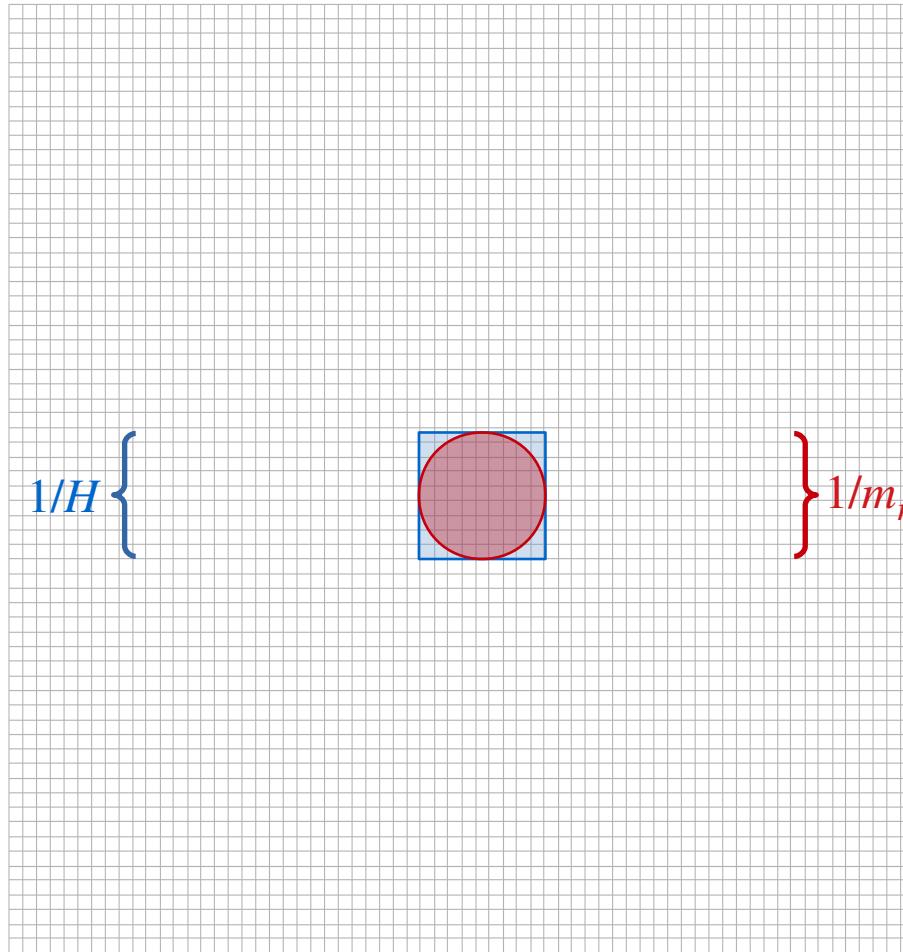
 $\Phi = \frac{f_a + r}{\sqrt{2}} e^{ia/f_a}$



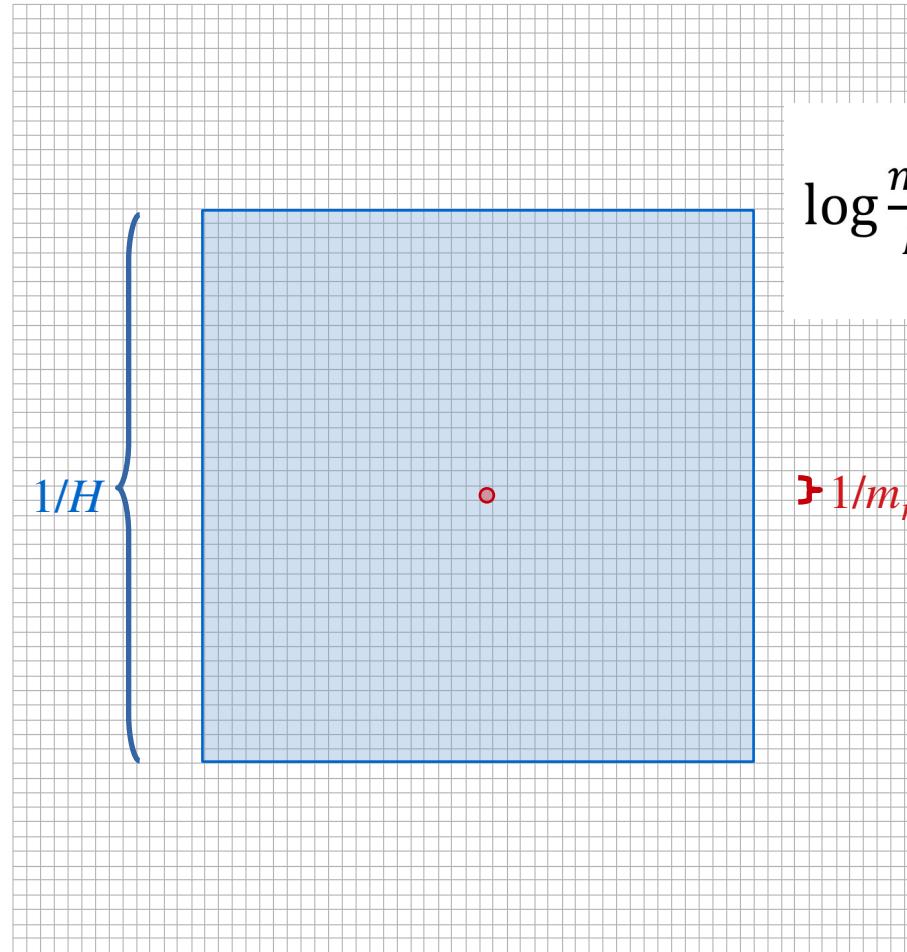
$$N \approx 1k - 4k - 8k$$



The Bottle Neck

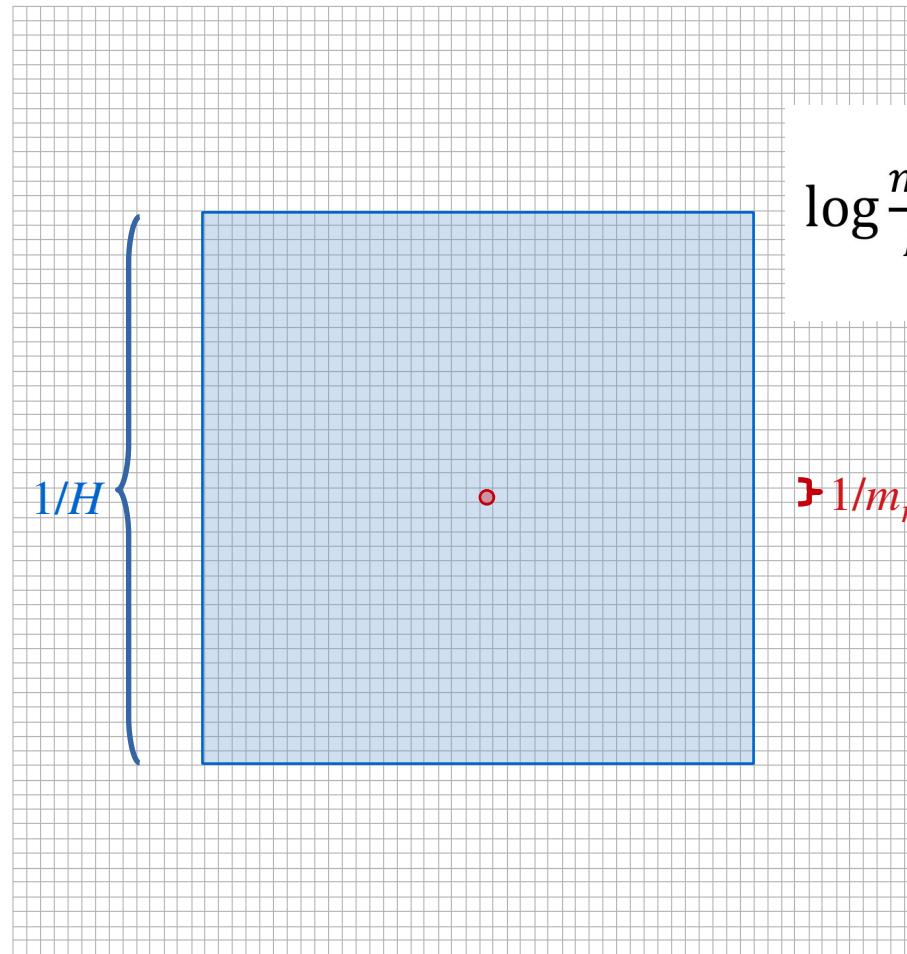


The Bottle Neck



$$\log \frac{m_r}{H} \leq \log\left(\frac{\text{blue square}}{\text{red circle}}\right) \sim 7 \ll 70$$

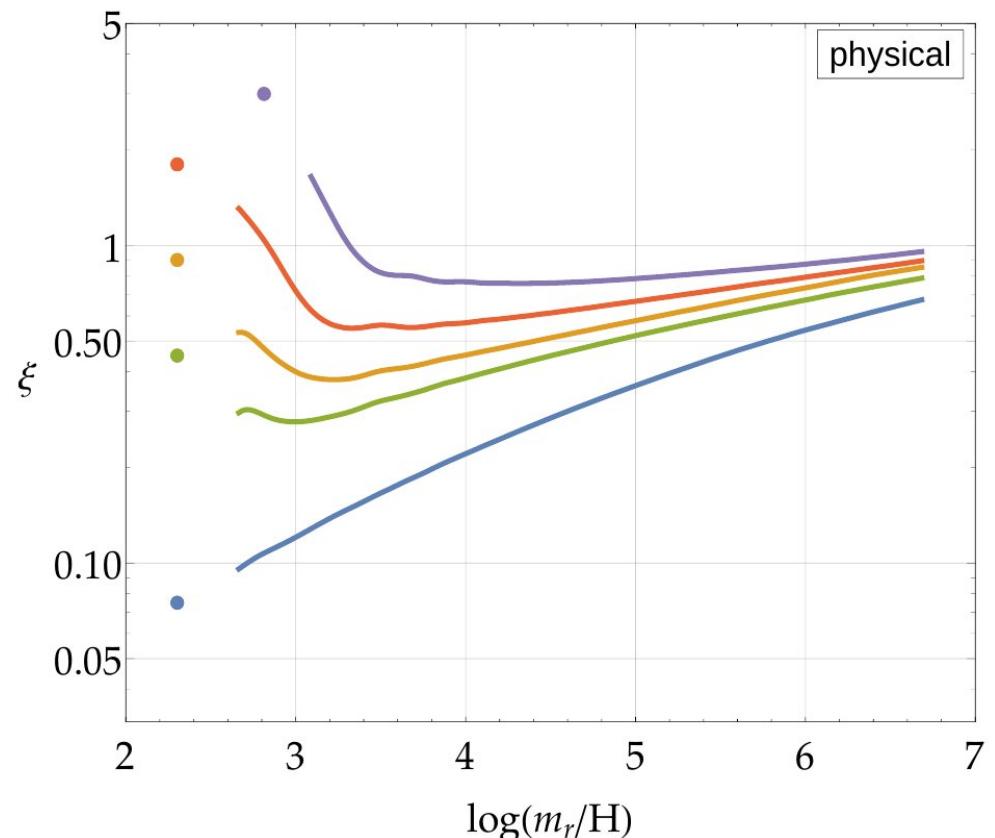
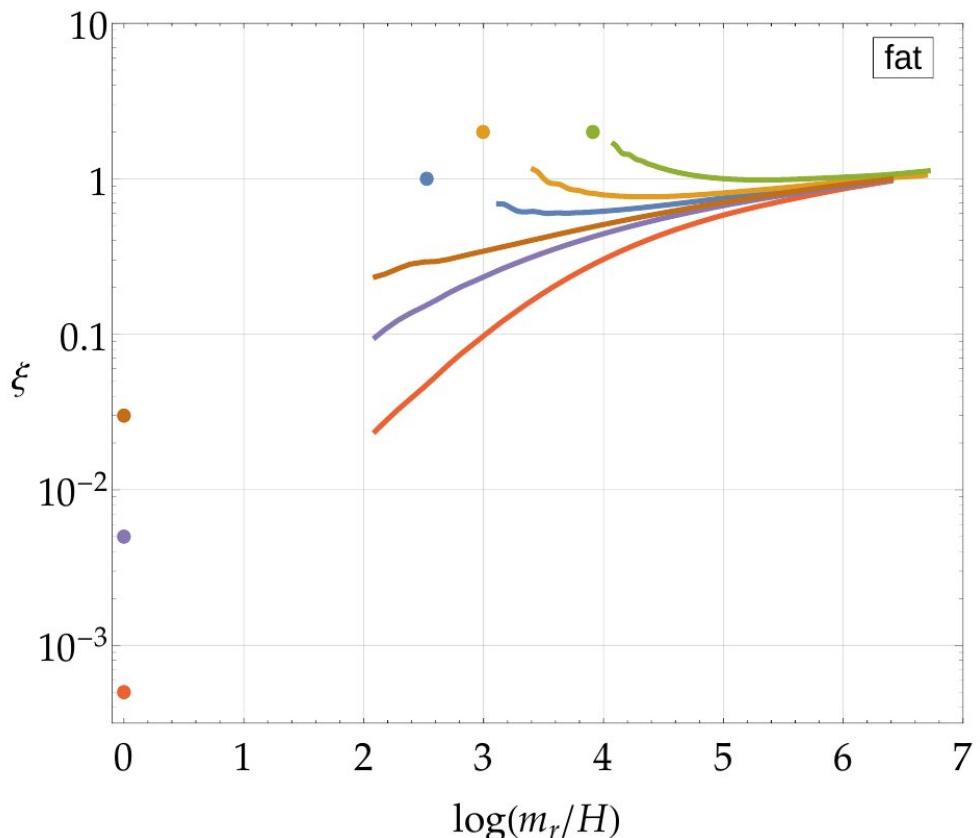
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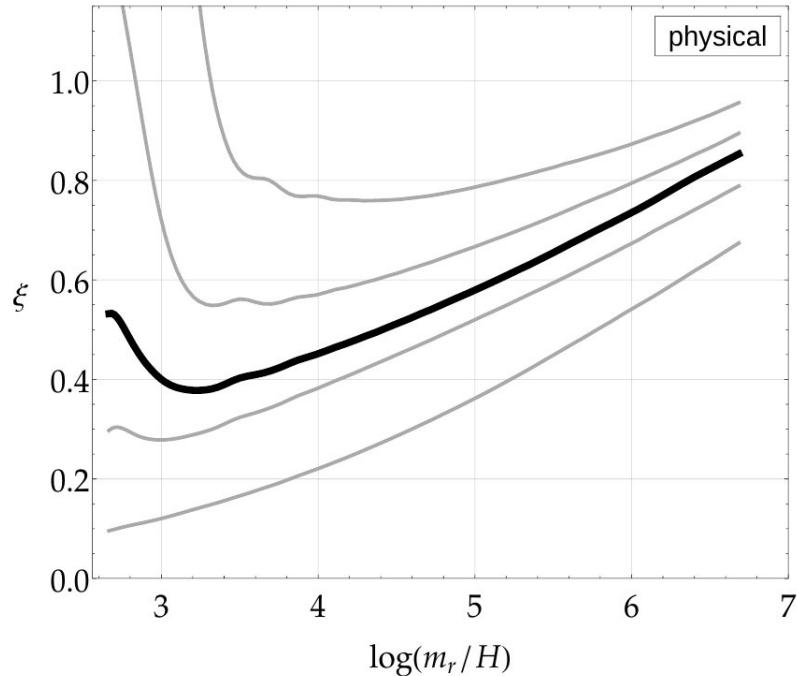
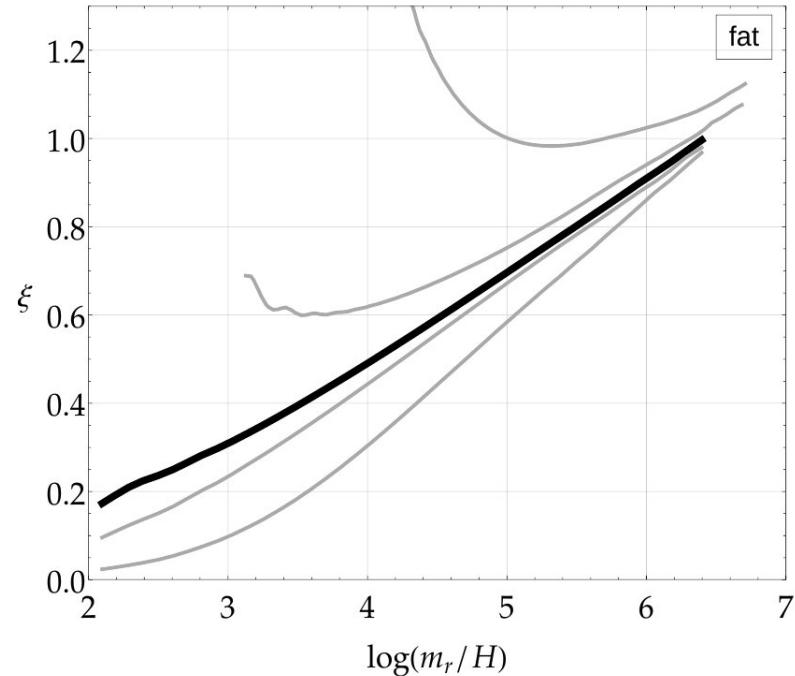
fat string trick
 $\Im 1/m_r \sim R \sim t^{1/2}$

The Scaling Solution is an Attractive Solution



Scaling Violation

1806.04677 – Gorgetto, Hardy, GV



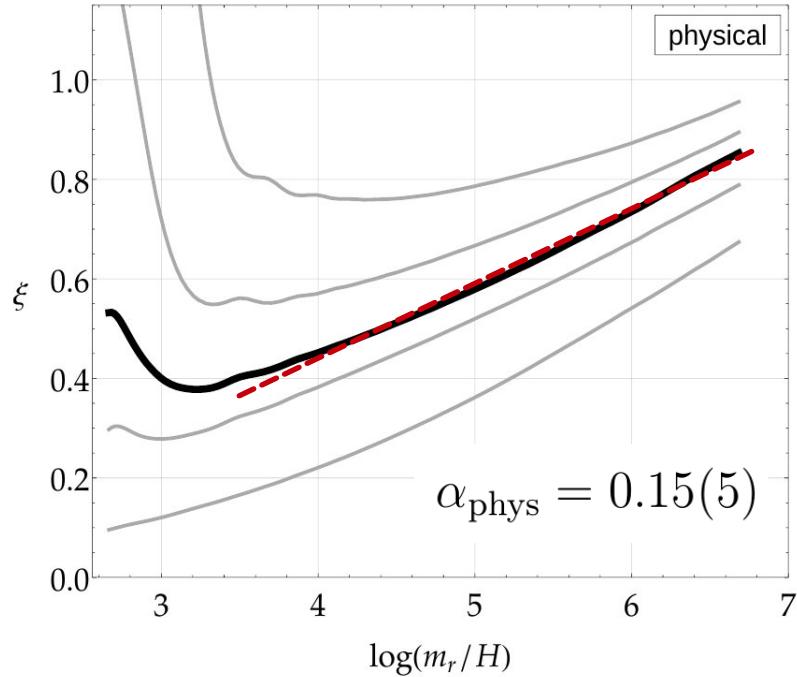
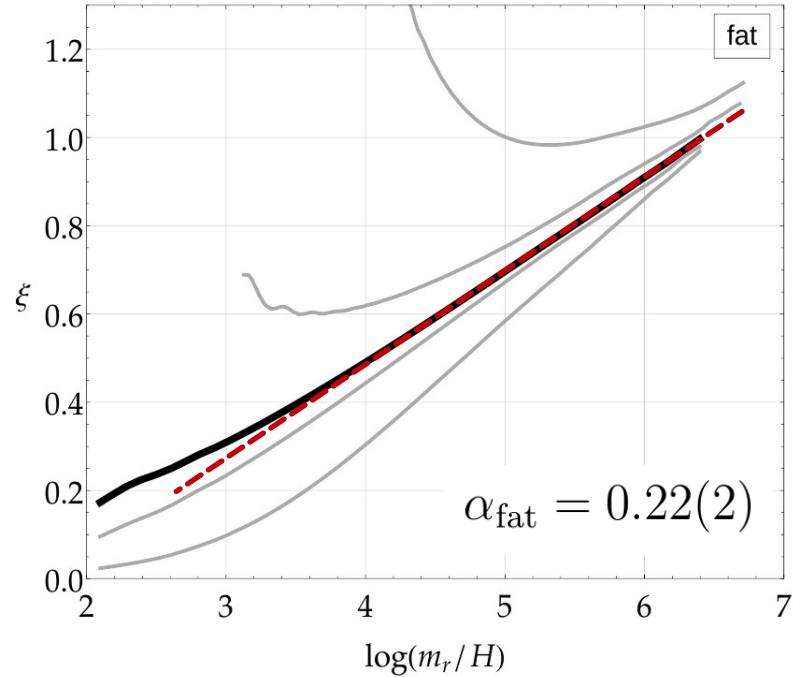
Also observed in:

1509.00026 – Fleury, Moore

1806.05566 – Kawasaki et al.

1906.00967 – Buschmann, Foster, Safdi
preliminary – Redondo, Saikawa, ...

Scaling Violation

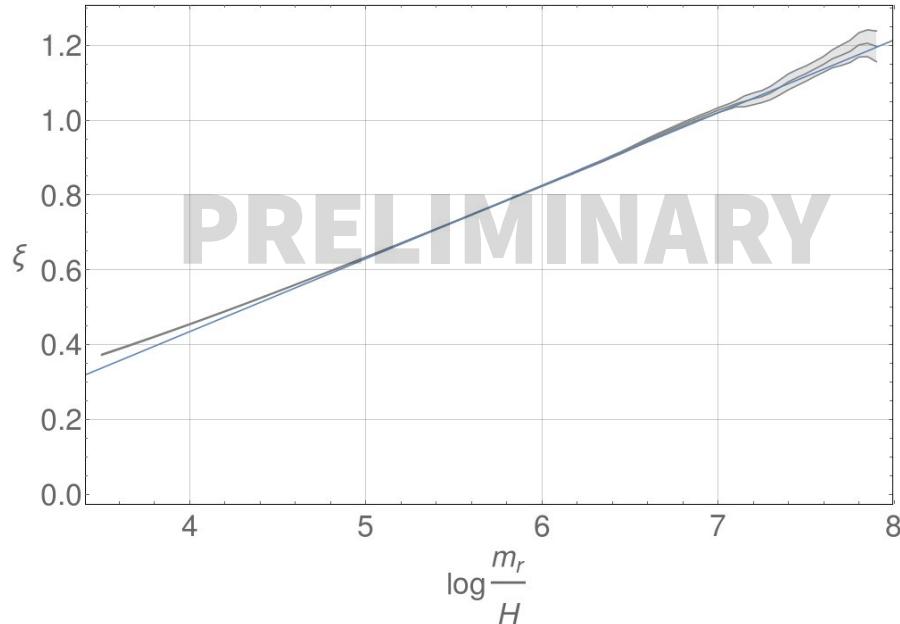


$$\xi(t) = \alpha \log \left(\frac{m_r}{H} \right) + \beta$$

$$\xi \xrightarrow{\log=70} 10$$

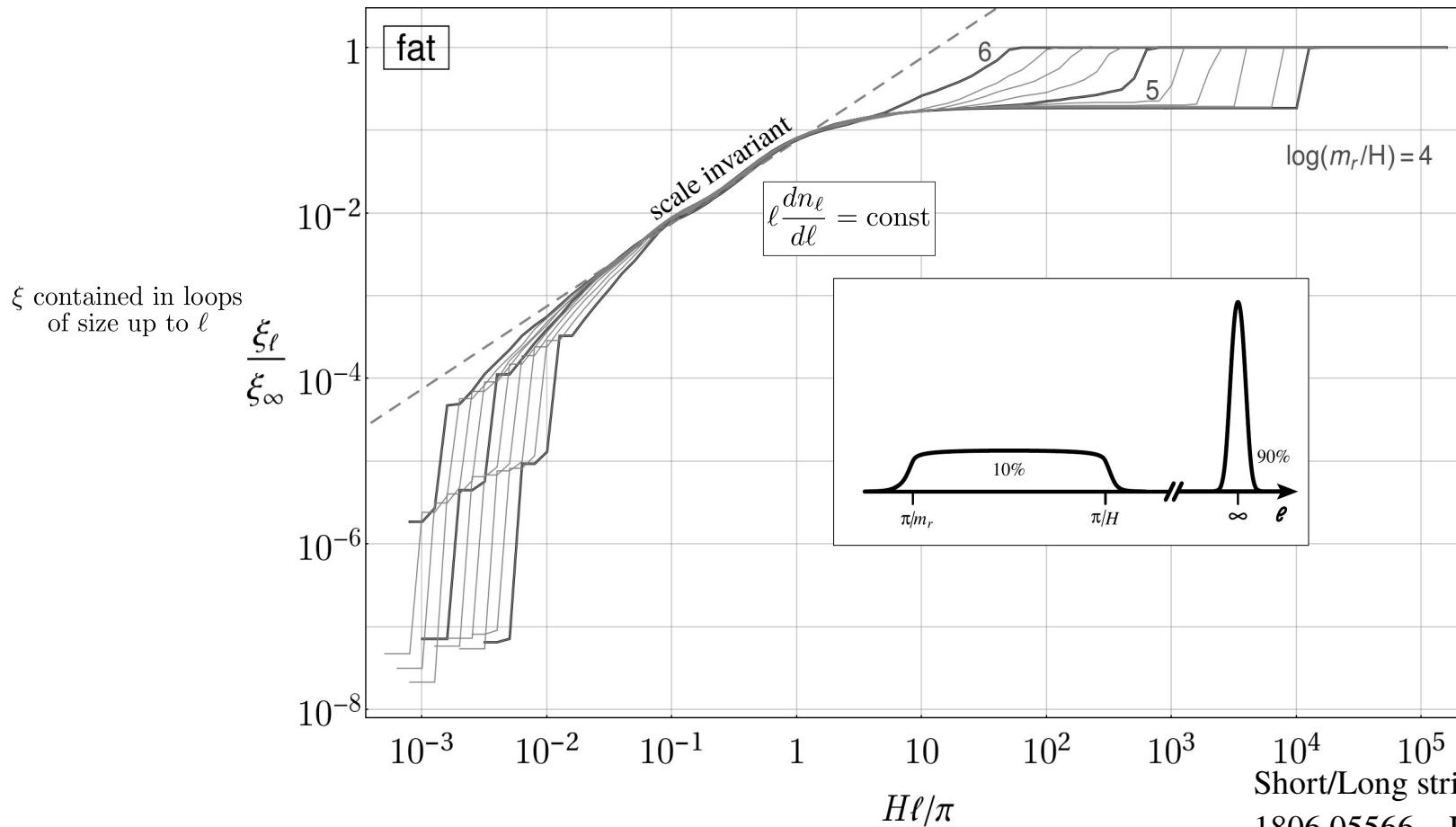
Scaling Violation (4k simulation)

Gorghetto, Hardy, GV



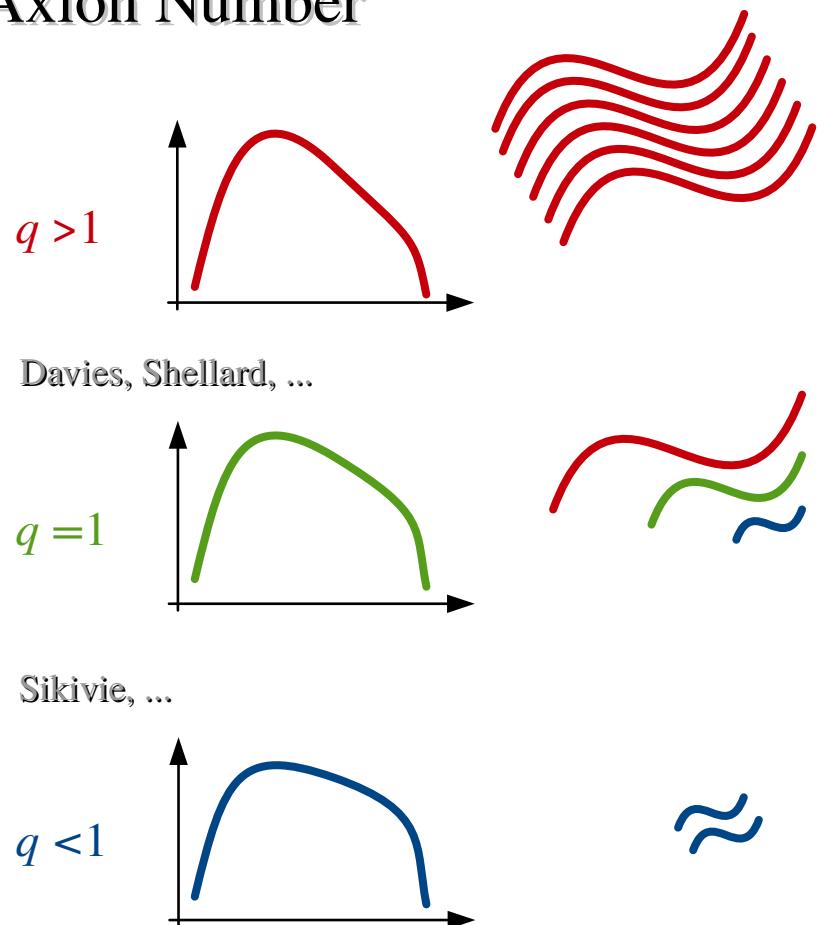
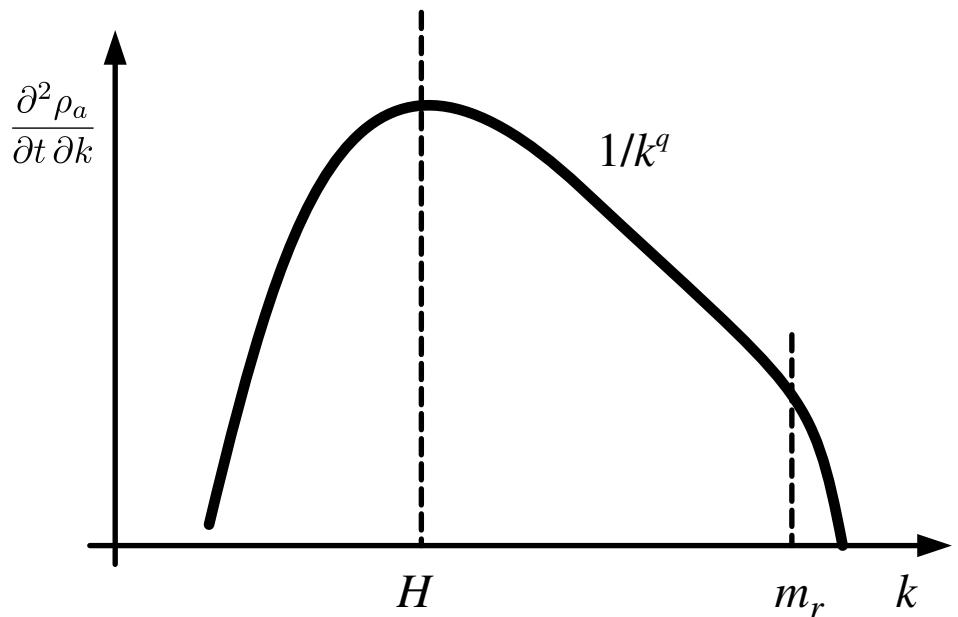
Loop Distribution

1806.04677 – Gorgetto, Hardy, GV

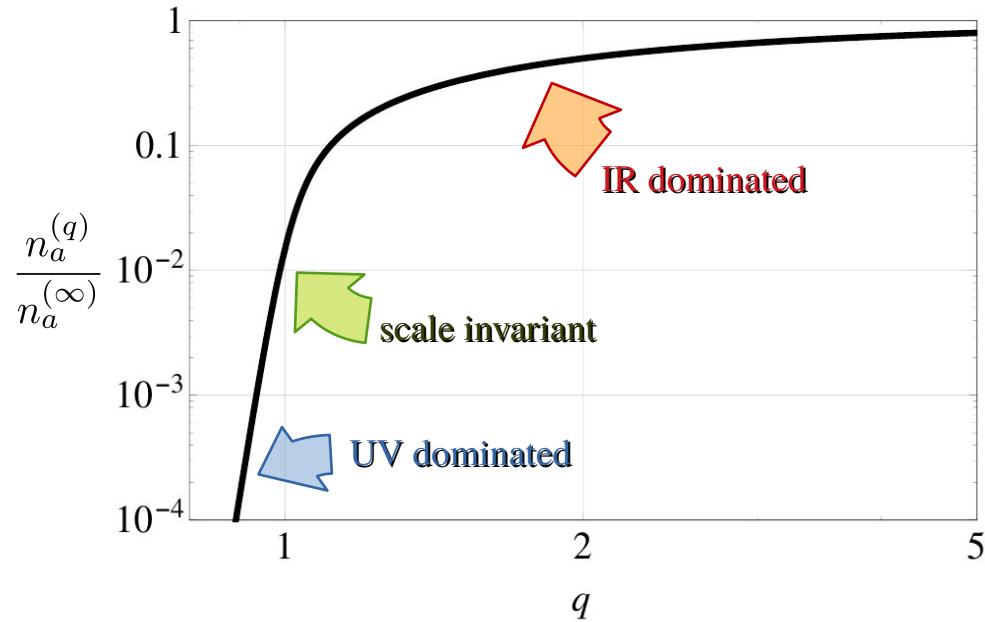


Short/Long string ratio also observed by:
 1806.05566 – Kawasaki et al.
 1906.00967 – Buschmann, Foster, Safdi

Axion Spectra VS Axion Number

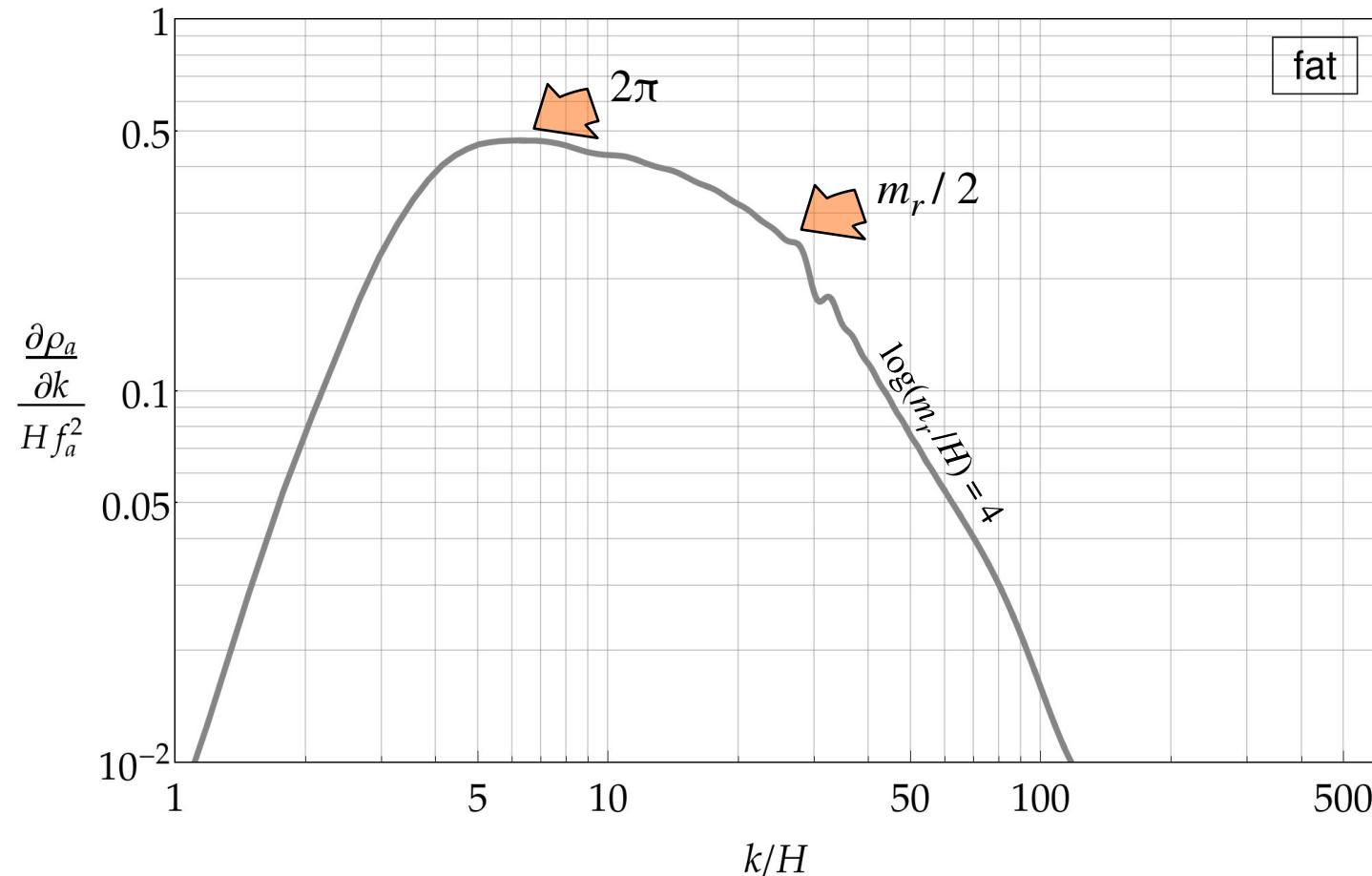


Axion Spectra VS Axion Number



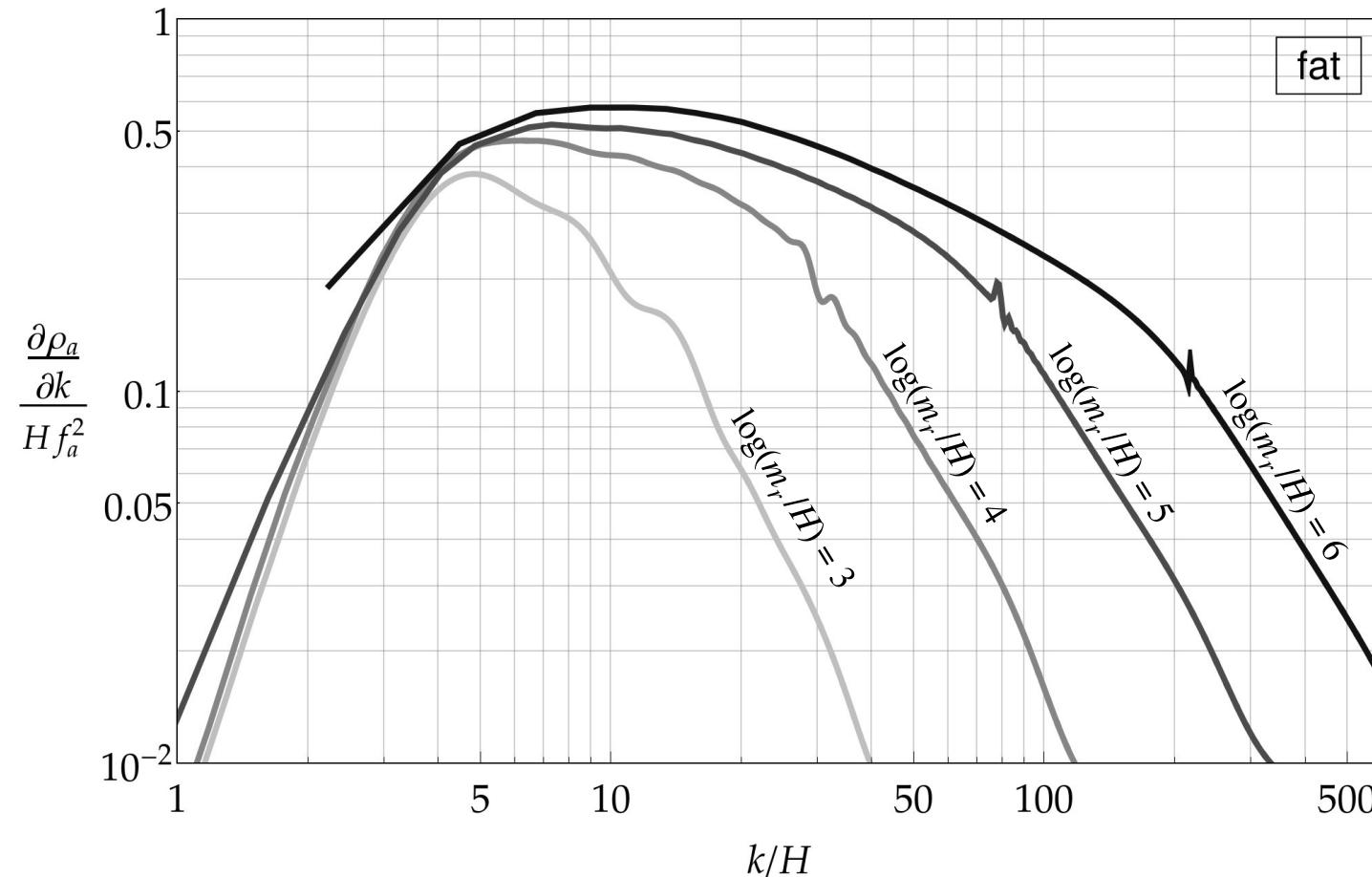
Axion Spectrum

1806.04677 – Gorgetto, Hardy, GV

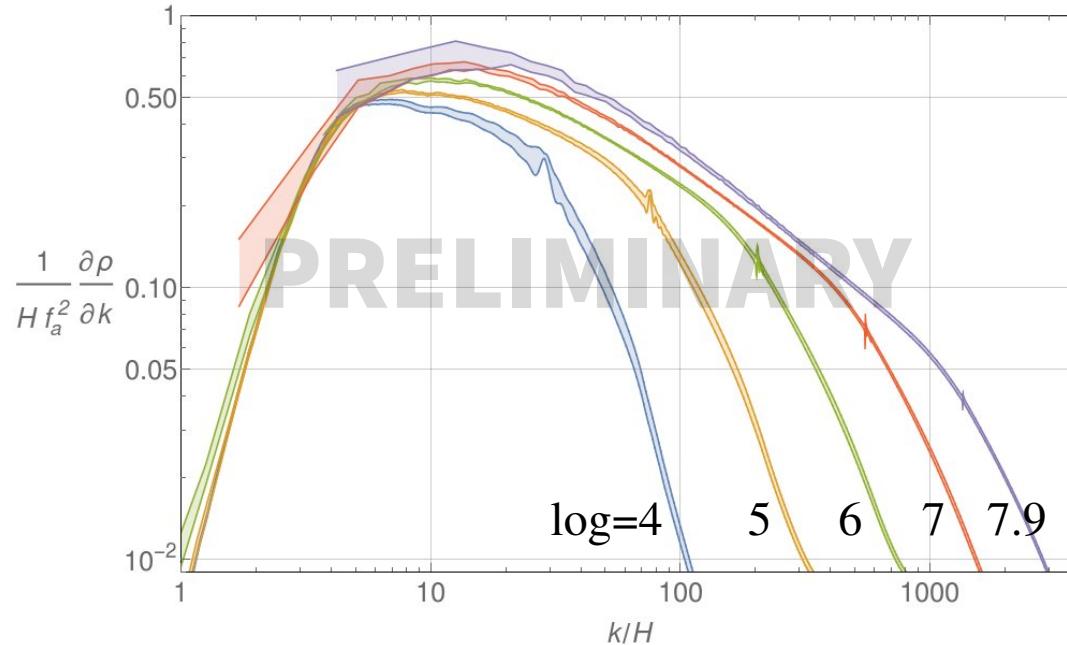


Axion Spectrum

1806.04677 – Gorgetto, Hardy, GV

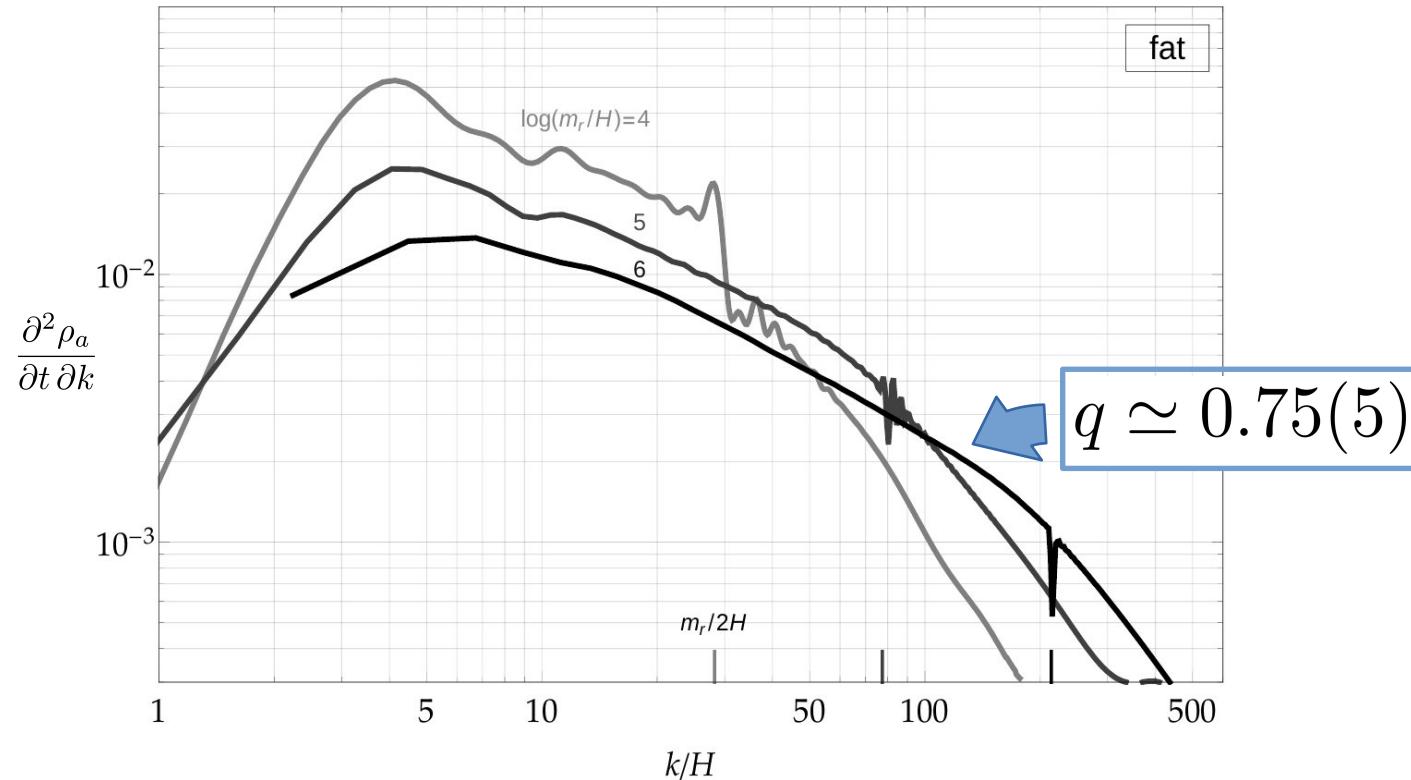


Axion Spectrum @ 4k

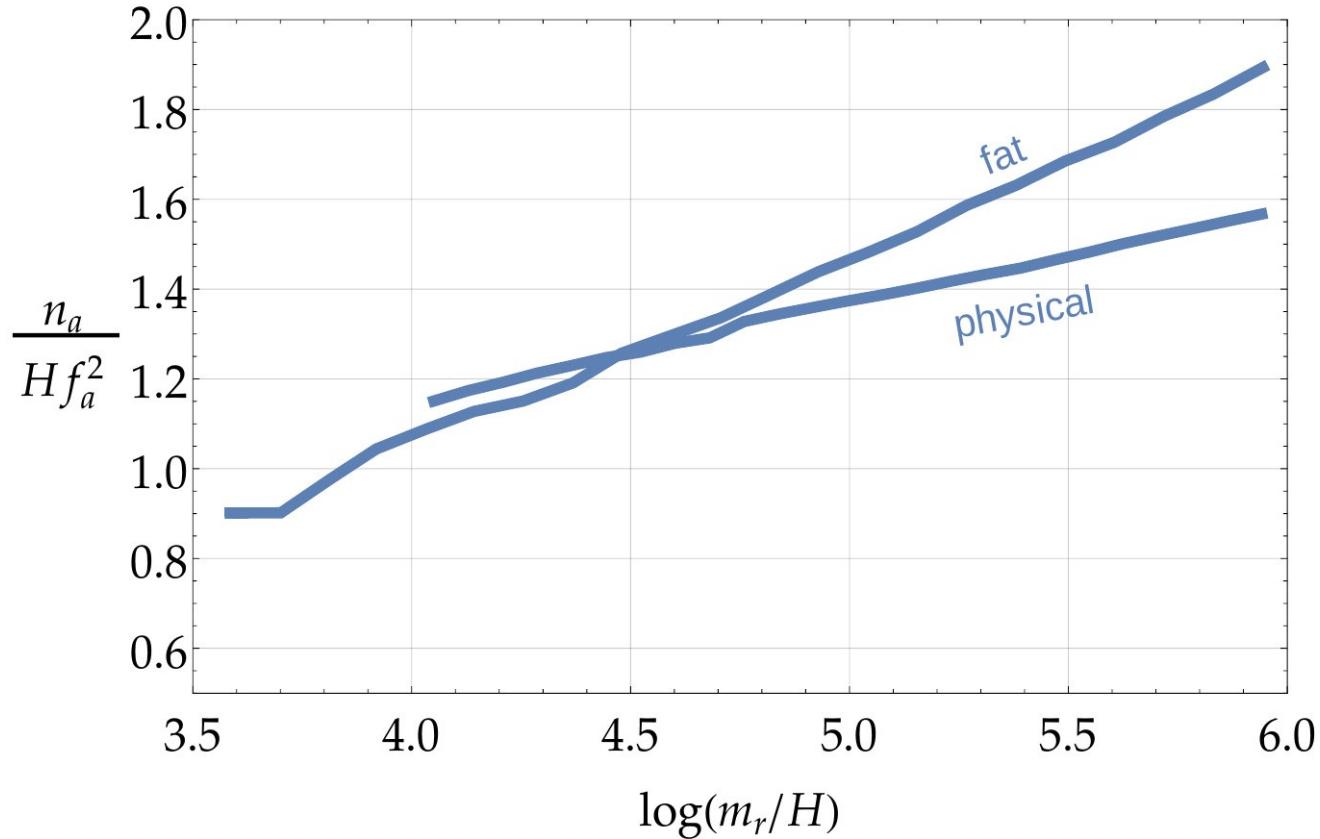


Gorghetto, Hardy, GV

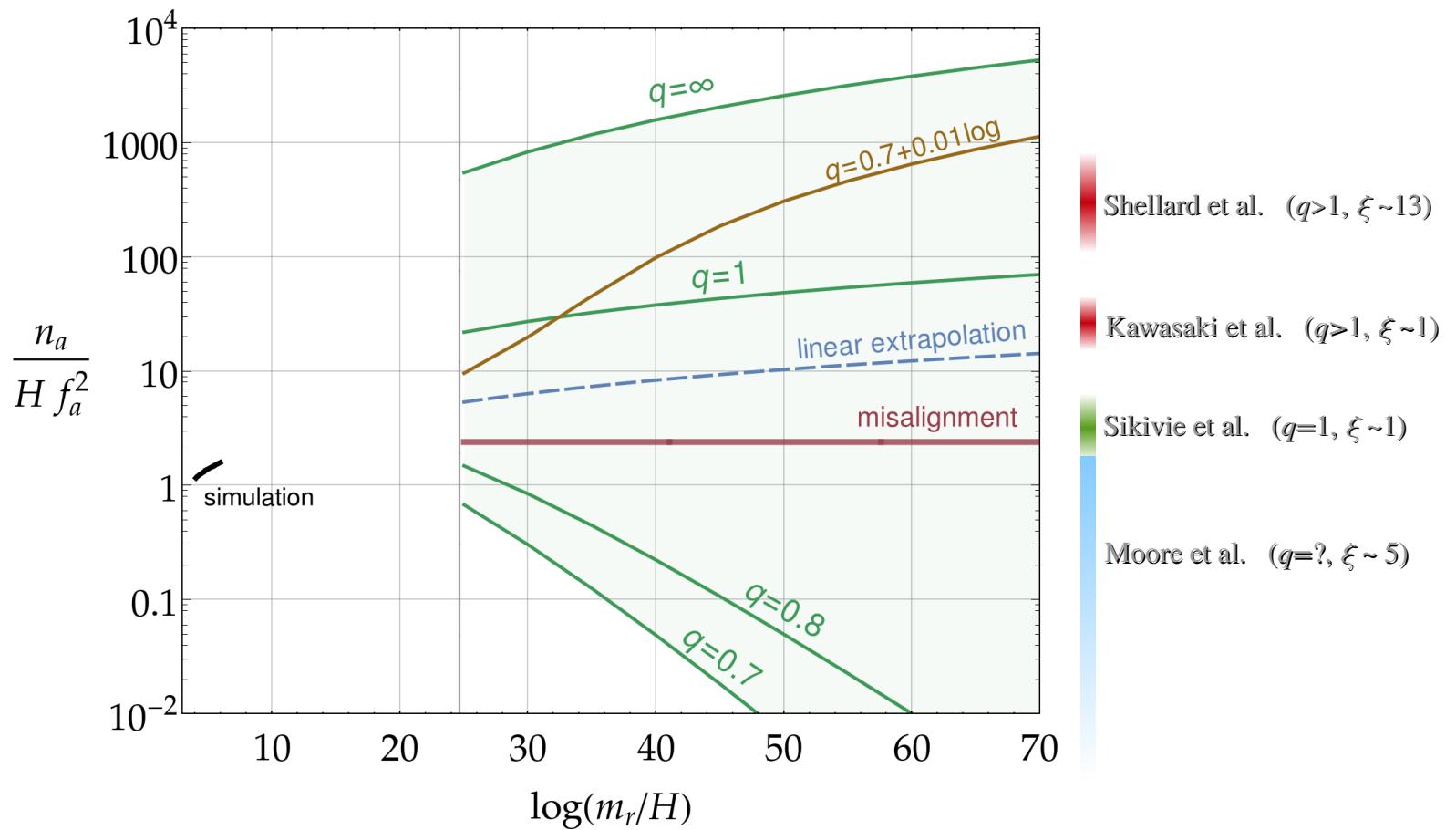
Axion Instantaneous Spectrum



Axion Number Density

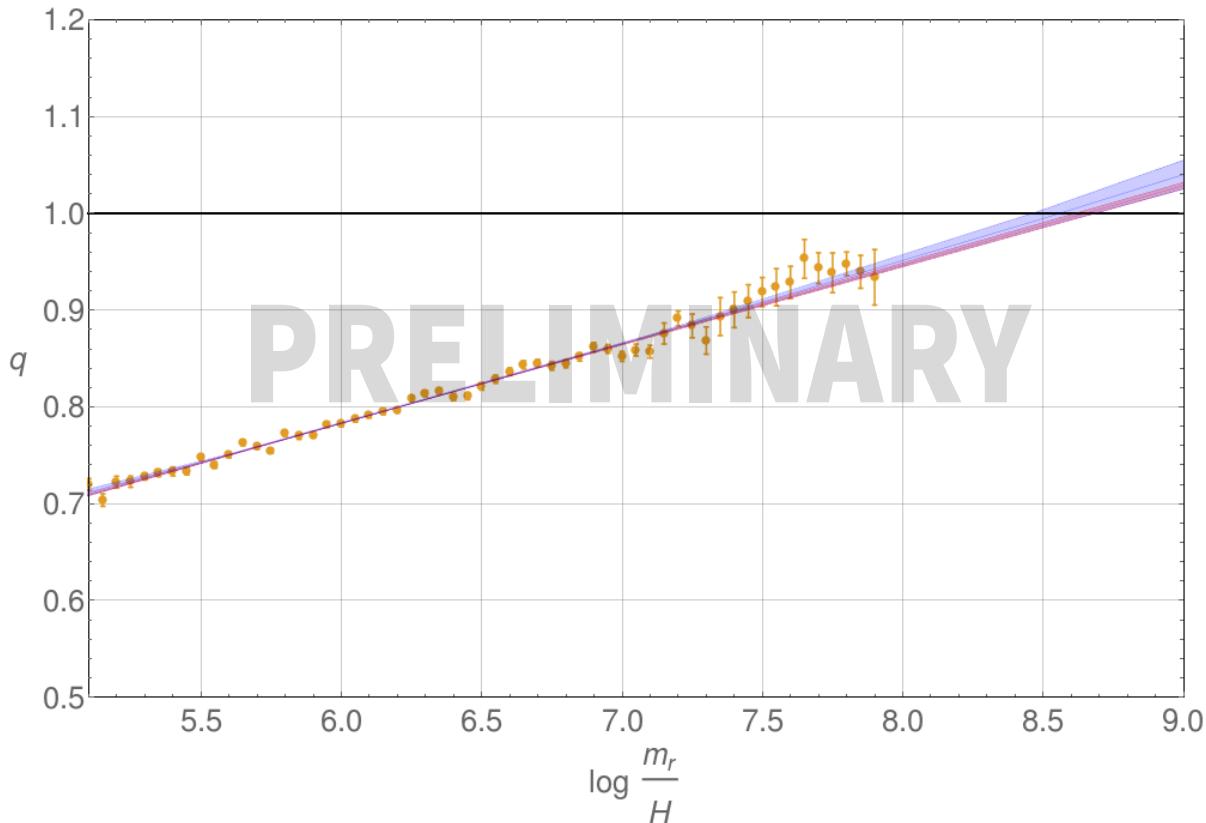


Axion Number Density → Extrapolation



Running of the spectral index (in 4k)

Gorghetto, Hardy, GV



Parameters at DW formation time: simulations vs physical case

$$\log(m_r/H) \sim 7$$

$$\log(m_r/H) \sim 70$$

$$\mu_{ph} \sim 10\mu_{sim}$$

$$\xi_{ph} \sim (10?)\xi_{sim}$$

$$(\rho_a/H^2)_{ph} \sim 10^4 (\rho_a/H^2)_{sim} \sim 10^4 (\rho_a/H^2)_{mis}$$

$$\delta_{wall}/\delta_{string} \sim 10^{30}$$

(Preliminary) Conclusions:

- Towards reasonable understanding of string evolution and axion spectrum
- String dynamics is evolving during scaling regime (\rightarrow NG strings)
- Strings/DW behavior @ physical parameters could be completely different from the simulated (or naively extrapolated) one

Some Open Questions:

- What is the initial field configuration at the QCD time?
- How many relic axions are produced from the radiation of strings?
- How can we reliably reconstruct
the right dynamics of the DW/string network ?