# Axion strings and dark matter

UNSW SYDNEY

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# QCD axion and dark matter

$$\mathcal{L}_{\rm CPV} = \bar{\theta}\frac{\alpha_s}{8\pi}G_{a,\mu\nu}\tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta - \arg\det M$$

$$d_n \simeq 1.52(71) \times 10^{-16}\,\bar{\theta}\; e\;\mathrm{cm}$$

[1902.03254]

$$\bar{\theta} < 10^{-10}$$

# QCD axion and dark matter

$$\mathcal{L}_{\rm CPV} = \bar{\theta}\frac{\alpha_s}{8\pi}G_{a,\mu\nu}\tilde{G}^{\mu\nu}_a$$

$$\bar{\theta}(x) \to a(x)/f_a$$

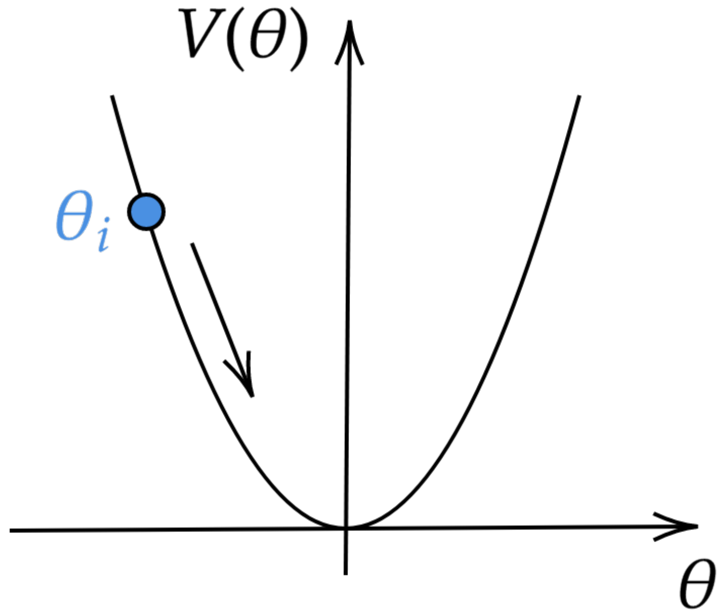
$$\bar{\theta} = \theta - \arg\det M$$

$$d_n \simeq 1.52(71)\times 10^{-16}\,\bar{\theta}\; e\;{\rm cm}$$

[1902.03254]

$$\bar{\theta} < 10^{-10}$$

- Assume an abelian global symmetry, spontaneously broken at high scale $f_a$
- Axion appears as Goldstone boson, but mass term is generated at QCD era $m_a \propto f_a^{-1}$
- Oscillation around QCD potential behaves like NR condensate




Clears strong CP problem and provides DM candidate!

# Post-inflationary scenario

$$f_a \lesssim \frac{H_I}{2\pi} \longrightarrow$$

Formation of topological defects
(strings, domain walls)

- Evolution of string network in the ‘scaling’ regime
- *Domain wall problem*
- *Fate of miniclusters in late time Cosmology*
- *Uncertainty in the topological susceptibility*

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- Evolution of string network in the 'scaling' regime — This talk
- *Domain wall problem*
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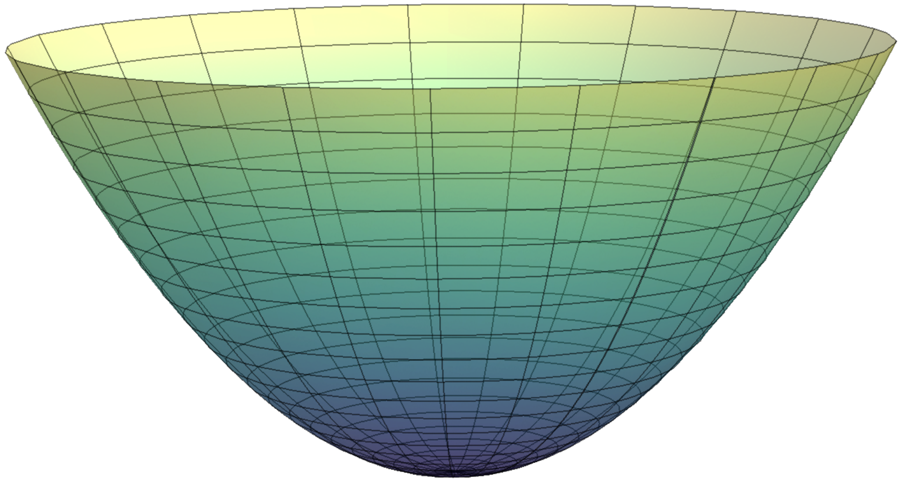
# Global $U(1)$ field theory

$$\mathcal{L} = (\partial_\mu \Phi)^* (\partial^\mu \Phi) - V(\Phi)$$

$$V(\Phi) = \frac{\lambda}{4}(\Phi^*\Phi - f_a^2)^2 + \frac{\lambda}{6} T^2 \Phi^2$$



$T \gg f_a$

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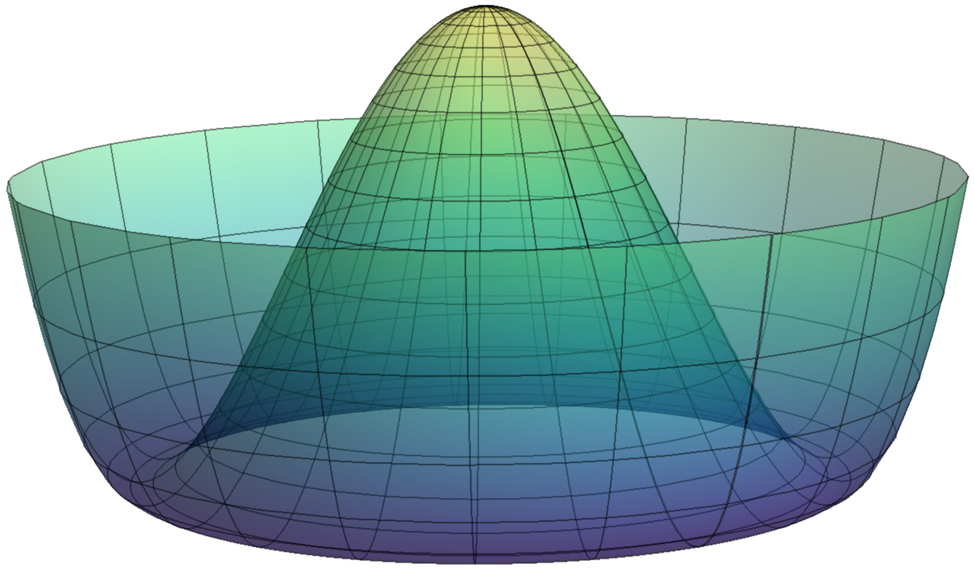


$T \lesssim f_a$

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

Saxion

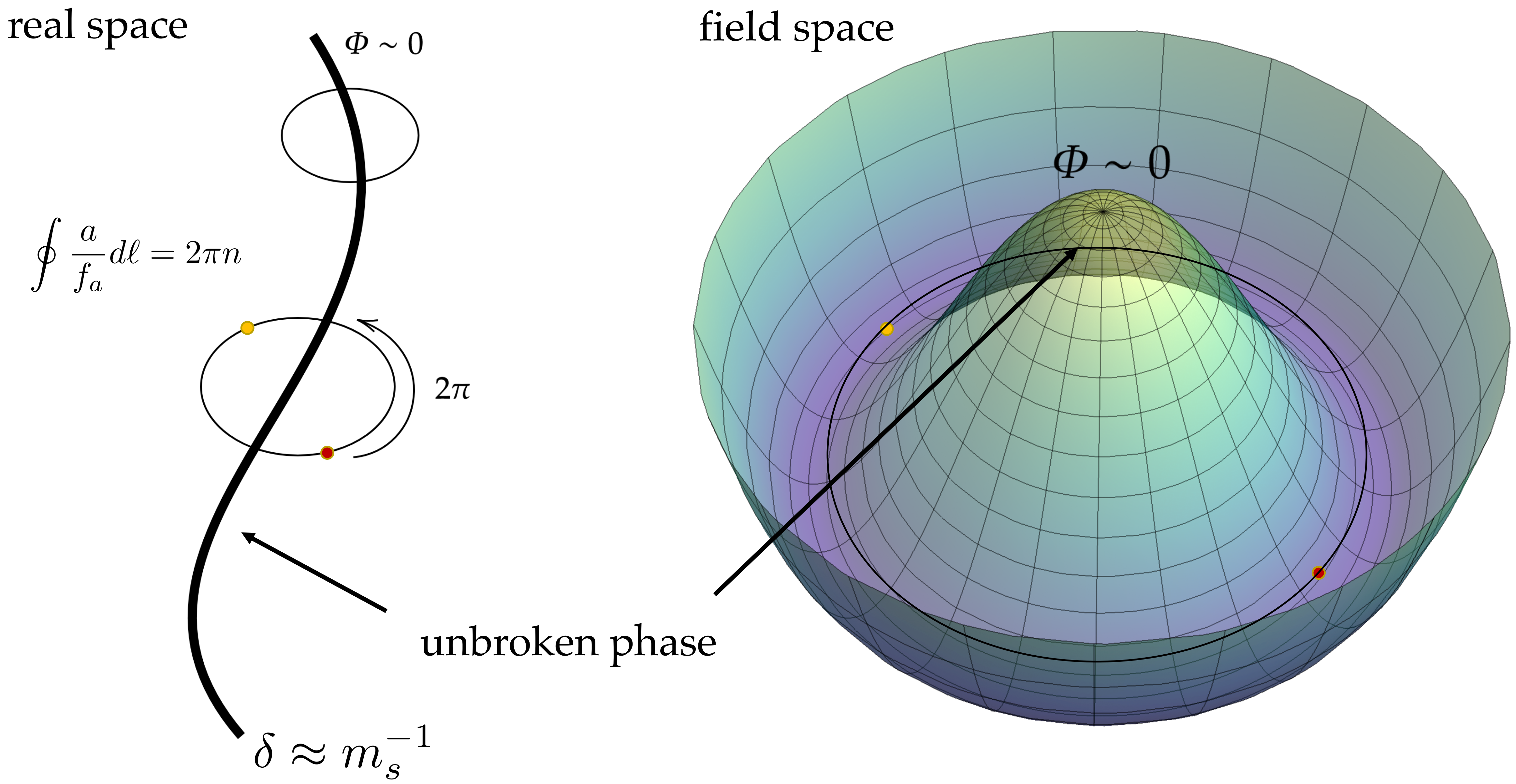
Axion

Heavy radial mode with mass

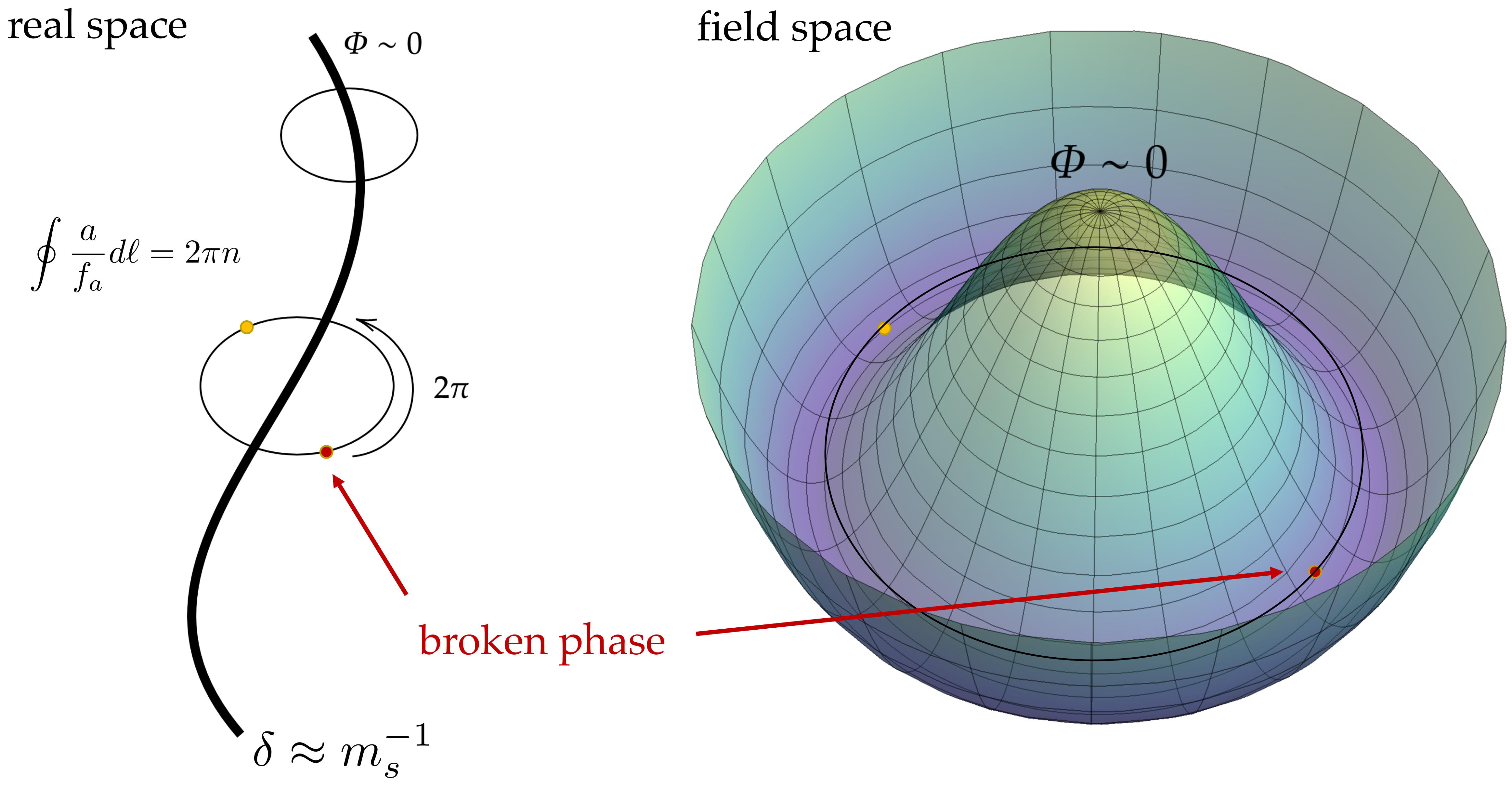
$$m_s = \sqrt{2\lambda} f_a$$

Massless goldstone boson with shift symmetry

$$a(x) \to a(x) + 2\pi f_a$$



real space
$\Phi \sim 0$
$\oint \frac{a}{f_a} d\ell = 2\pi n$
$2\pi$
$\delta \approx m_s^{-1}$
unbroken phase
field space
$\Phi \sim 0$



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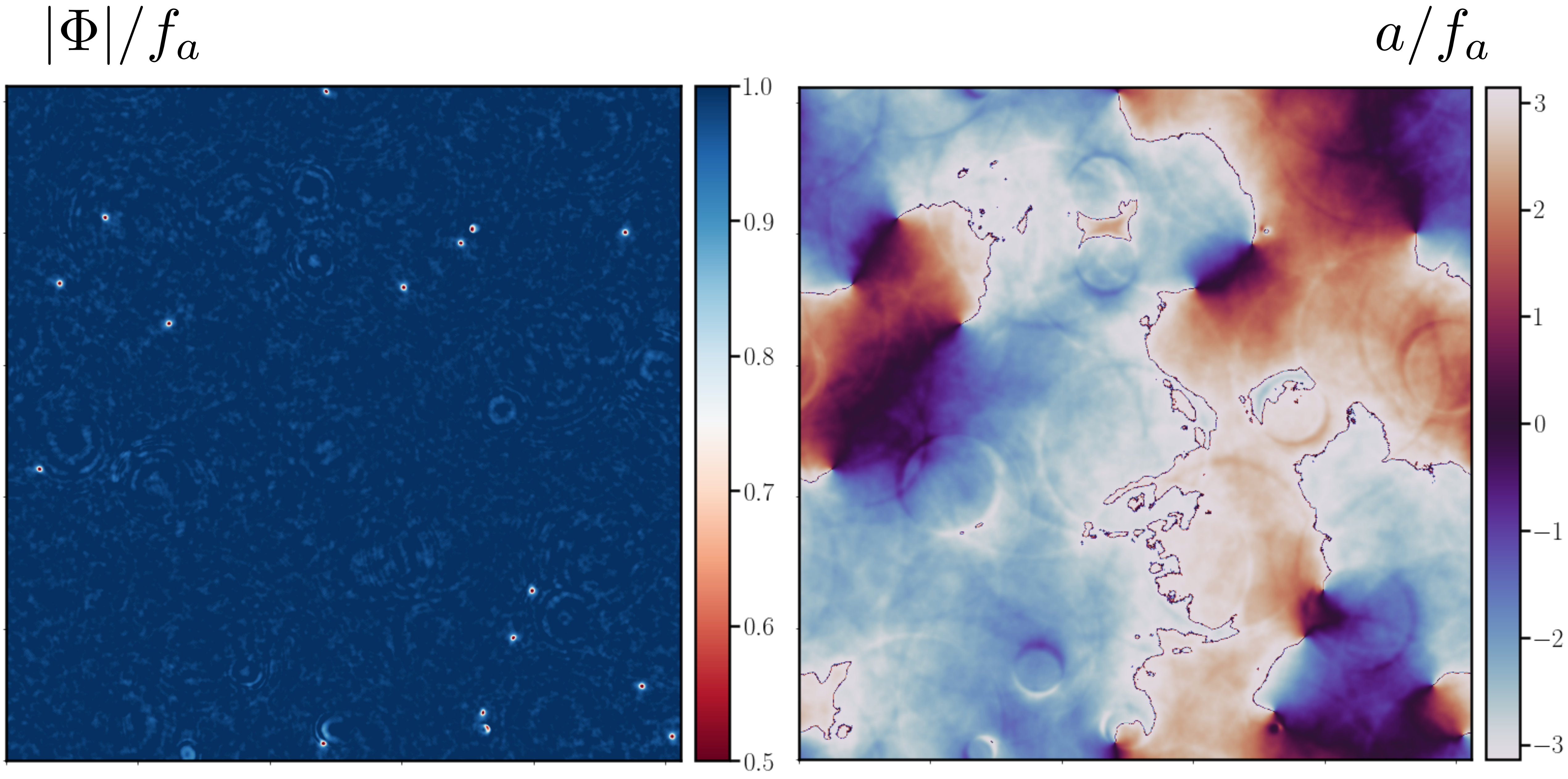


$|\Phi|/f_a$
$a/f_a$
1.0
0.9
0.8
0.7
0.6
0.5
3
2
1
0
−1
−2
−3

$$\ddot{\Phi} + 3H\dot{\Phi} - \nabla^2\Phi + \frac{m_s^2}{2f_a^2}(|\Phi|^2 - f_a^2) = 0$$

2D: vortex solution
3D: line-like solution

*Ansatz:* $\varphi_{\text{string}} = \underbrace{f(r)}_{\text{core profile}} e^{in\theta}$ ← winding number

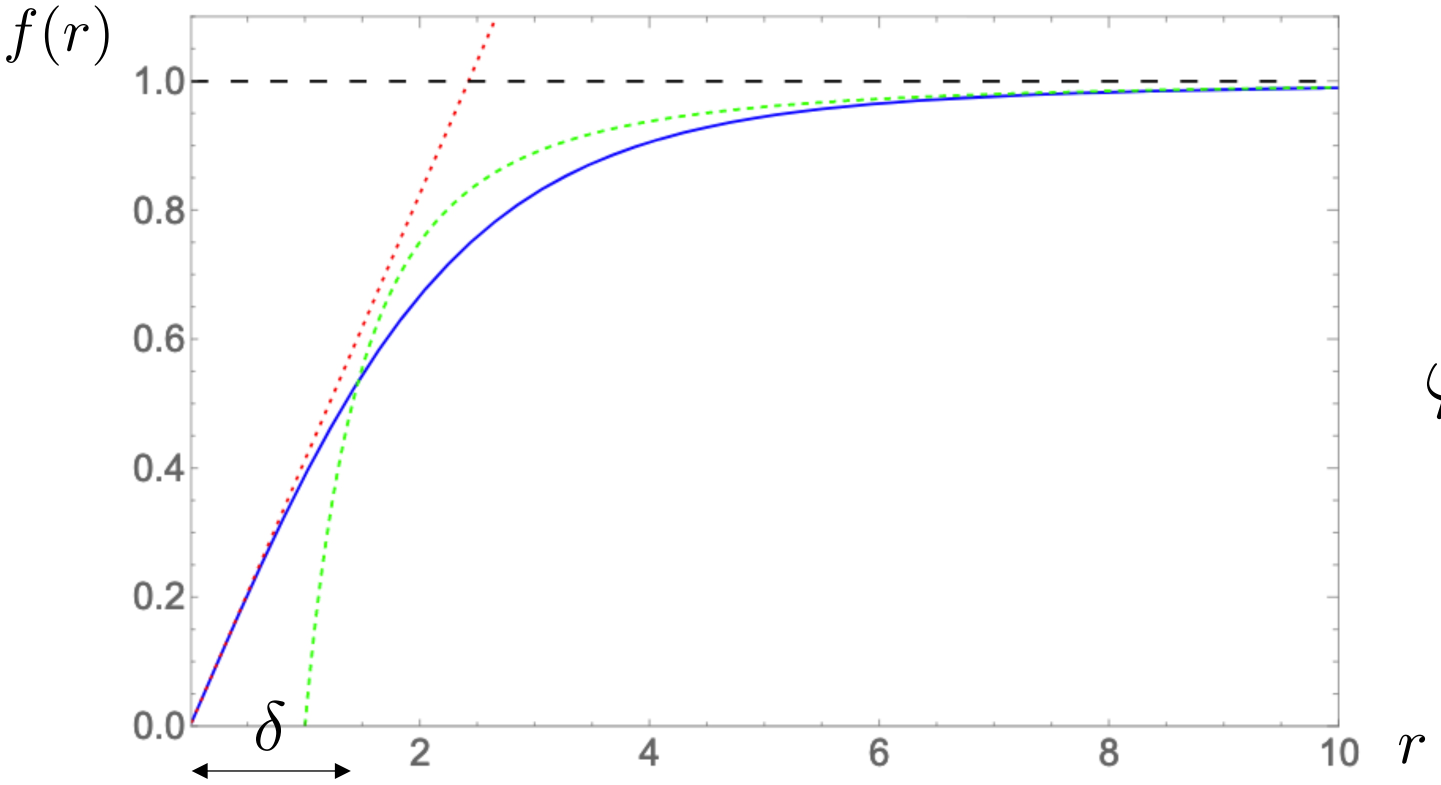
Boundary conditions: $f(0) = 0$

$$f(r) \xrightarrow{r\to\infty} 1$$

Drew, Shellard [1910.01718]

String core

$$\mathcal{O}(1)f_a^{-1}$$
$$\simeq \mathcal{O}(1)m_s^{-1}$$




Away from string core

$$\varphi_{\text{string}} \simeq f_a e^{in\theta}$$

$$(\partial_\mu\partial^\mu + m_s^2)s(x) = 0$$
$$\partial_\mu\partial^\mu a(x) = 0$$

# Two scale model

$$\varphi_{\text{string}} = f(r)e^{in\theta}$$

winding around the core

$$\rho_{\text{string}}(r) = \underbrace{(\partial_r f)^2 + \frac{\lambda}{4}(f^2-1)^2}_{\text{local core}} + \boxed{\left(\frac{f}{r}\right)^2}$$

# Two scale model

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String tension:

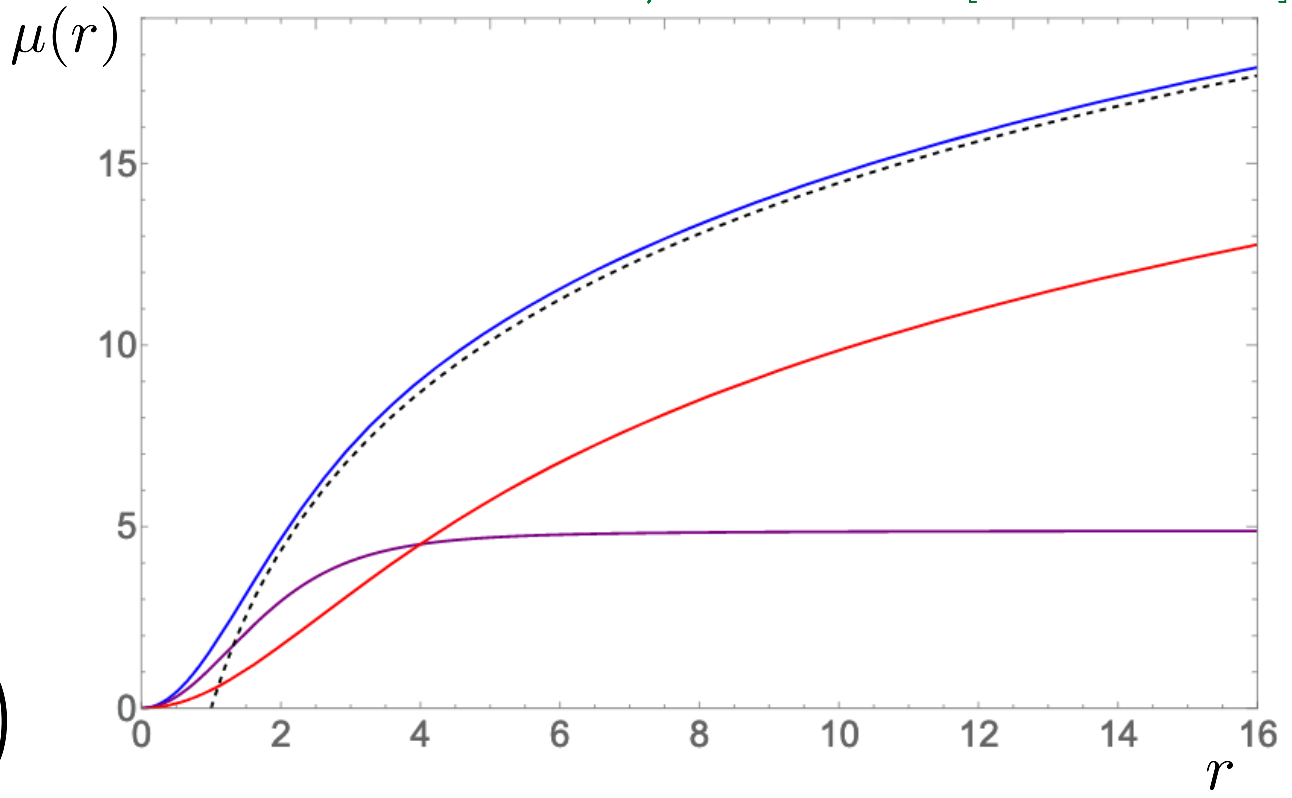
$$\mu(r) = \mu_0 + \int_\delta^R 2\pi r \left(\frac{f(r)}{r}\right)^2 dr$$

$$= \mu_0 + 2\pi f_a^2 \log\left(\frac{R}{\delta}\right) \begin{matrix}\text{IR} \\ \text{UV}\end{matrix}$$

For axion strings on cosmo scales:

$$\mu \approx 2\pi f_a^2 \log\left(\frac{m_s}{H}\right)$$

Drew, Shellard [1910.01718]



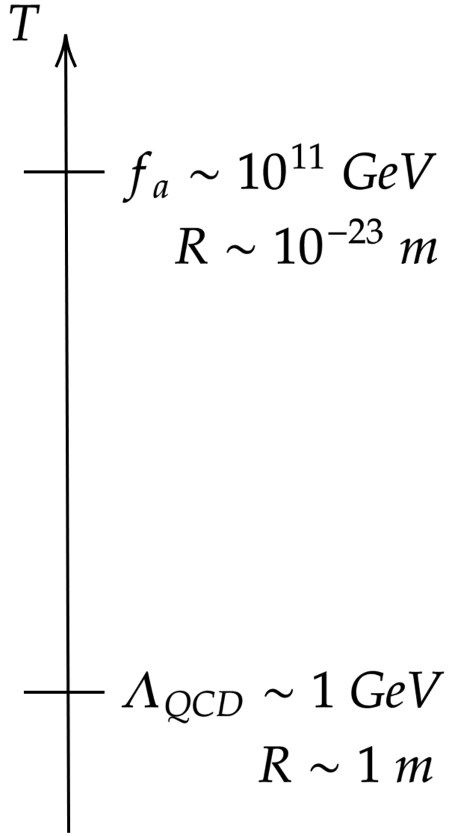
# Axion string networks

- Difficult to model a network of strings
- Scaling solution is ‘natural’ for local strings (one scale)
- Axion string properties should show log corrections
- Network density:

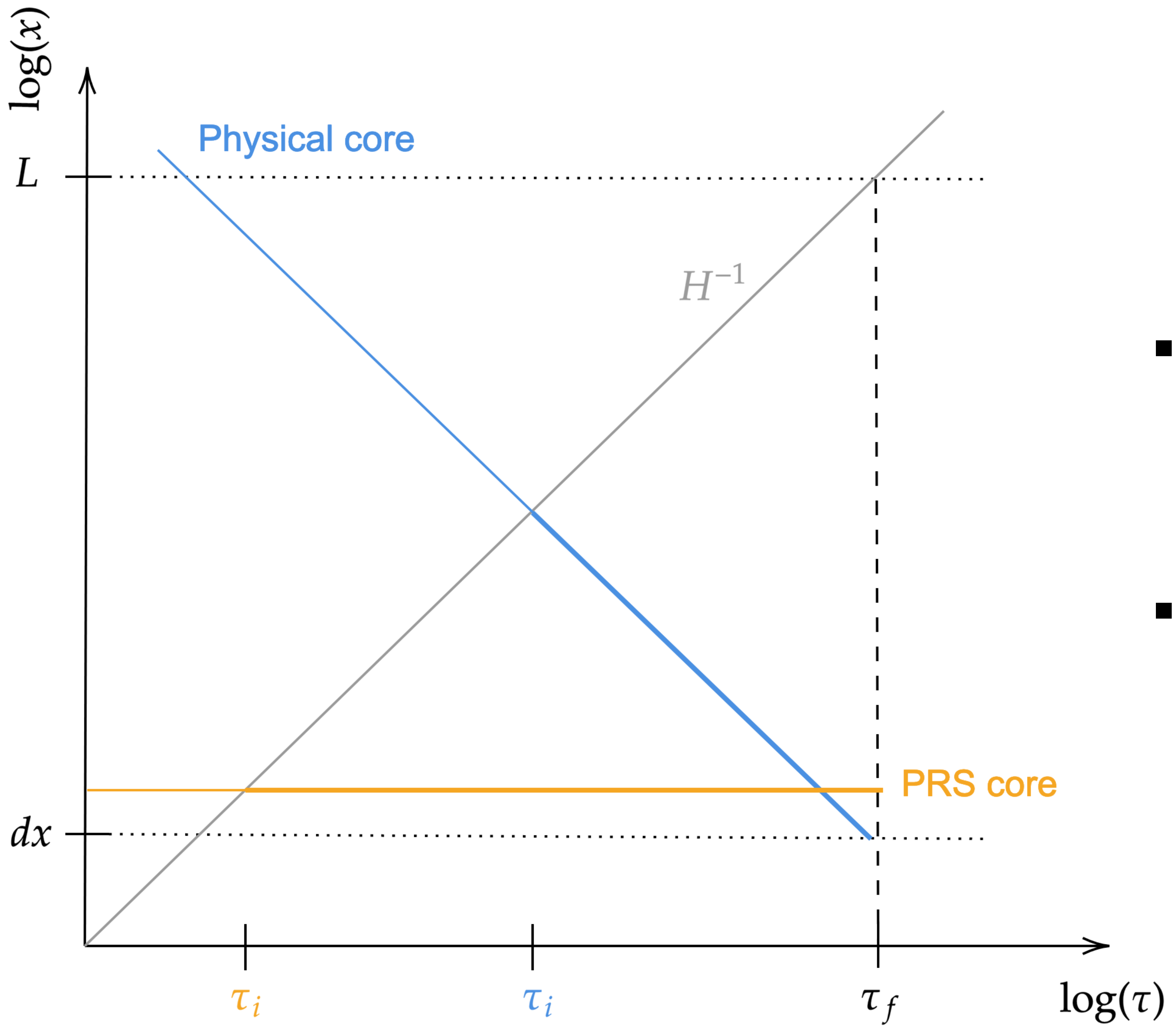
$$\rho_s \propto \xi(t) \qquad \xi(t) = \lim_{L\to\infty} \frac{\ell(t)t^2}{L^3}$$

- String network collapses at the QCD crossover
- Physical values unrealistic to simulate:

$$\log\left(\frac{m_s}{H_{QCD}}\right) \approx 70 \qquad vs. \qquad \log \sim 6$$



# Axion string simulations




Physical vs 'fat' simulations

- Keep physical core constant

$$m_s = \text{const.}$$

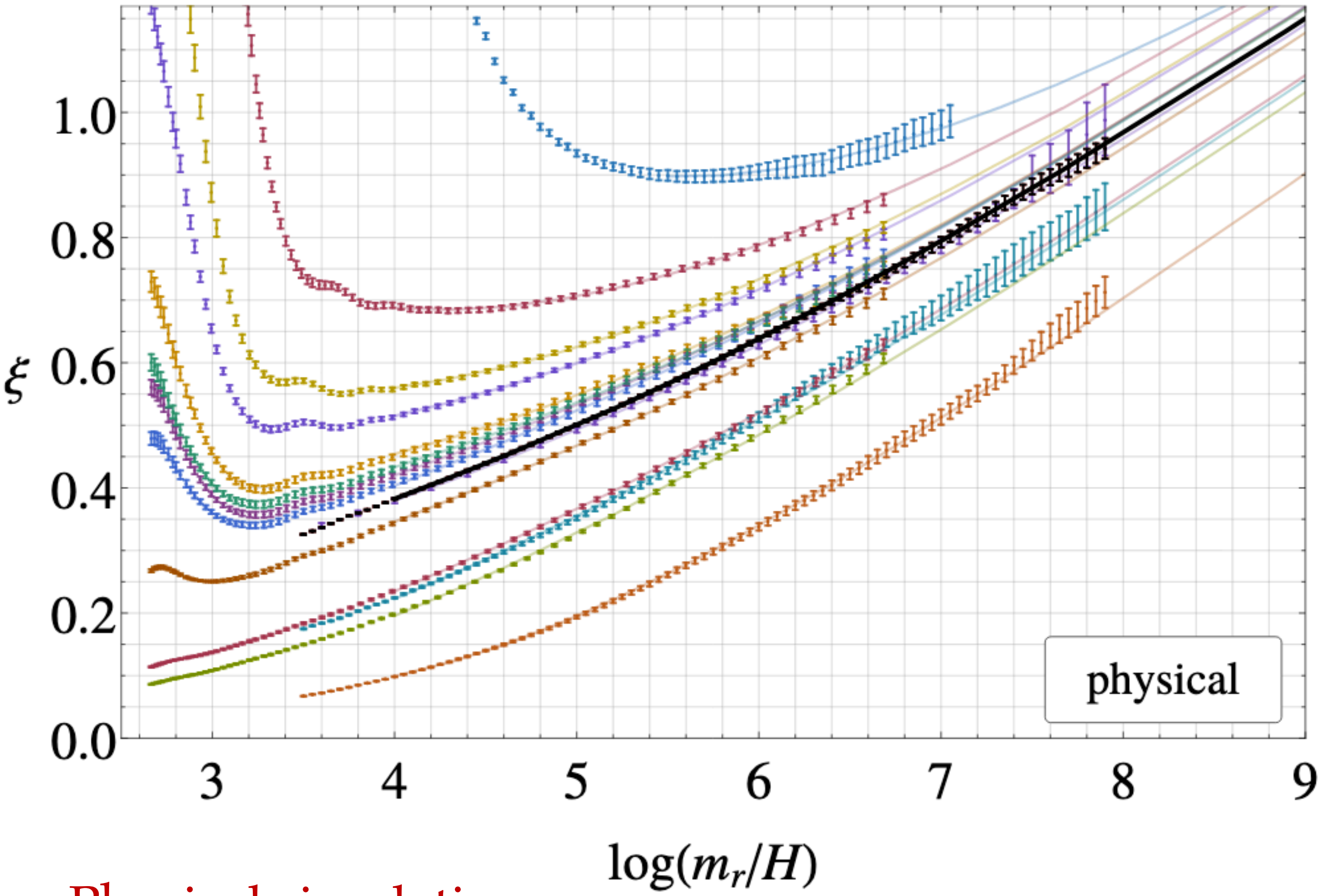
- Keep conformal core constant via PRS trick

$$m_s(t) = m_s \frac{\tau_0}{\tau}$$

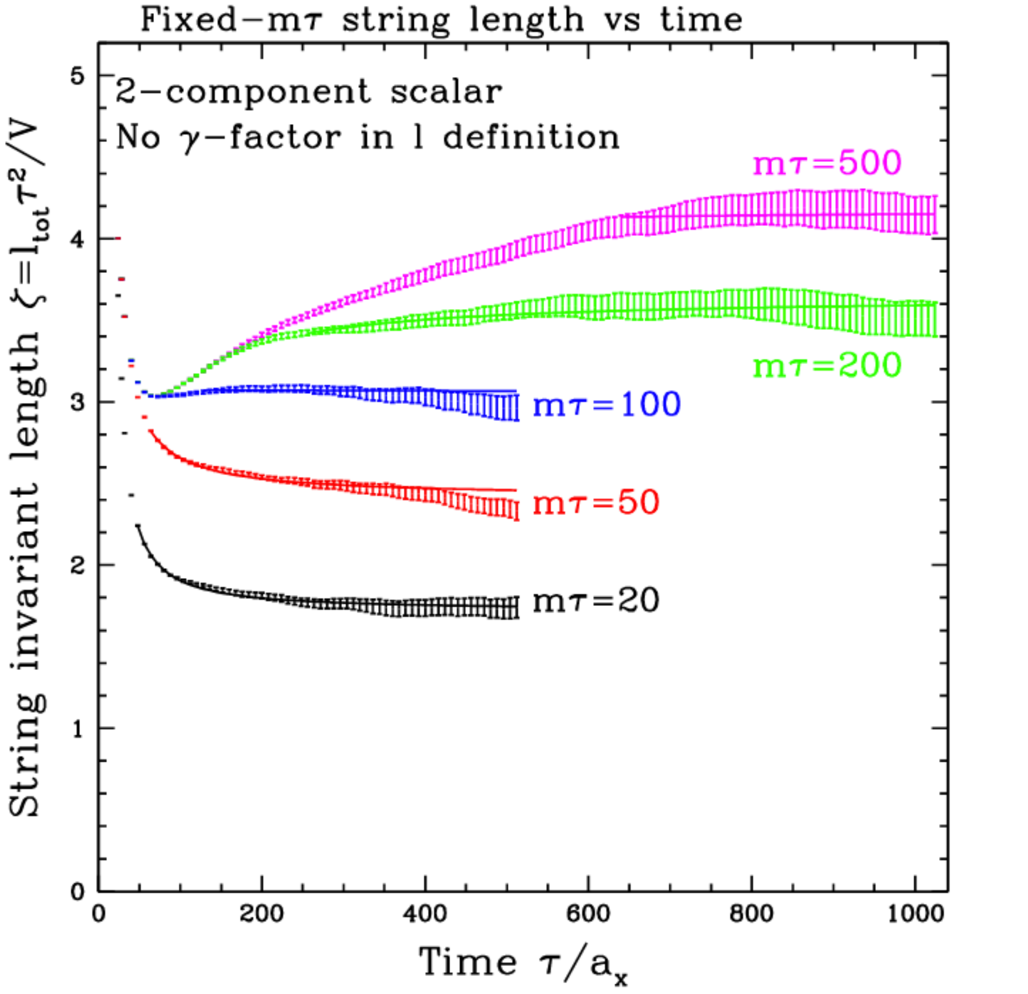
# Attractor vs scaling

Gorghetto et al. [2007.04990]

Klaer, Moore [1912.08058]




Physical simulation




Fixed tension simulation

# Axion radiation

- Energy spectrum of axions emitted by strings

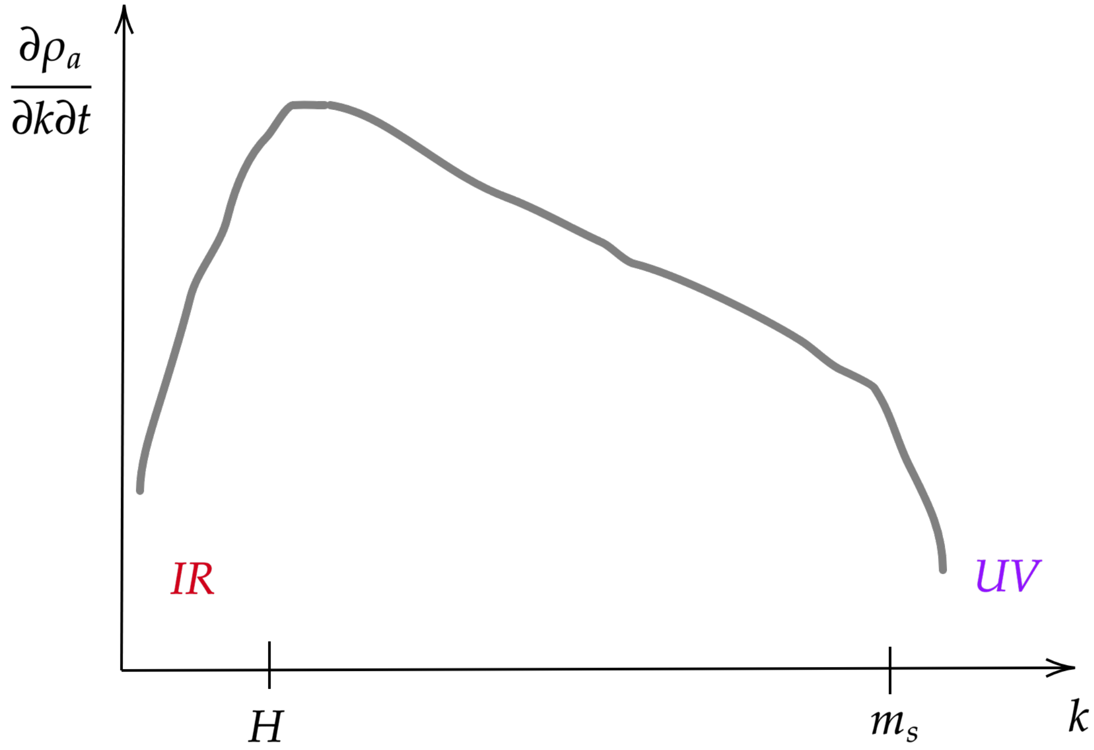
$$\frac{\partial \rho_a}{\partial k \partial t}$$

- Two scales imposing cutoffs in IR and UV

# Axion radiation

$$\frac{\partial \rho_a}{\partial k \partial t} \sim \frac{C}{k^q}$$

- Energy spectrum of axions emitted by strings
- Two scales imposing cutoffs in IR and UV
- Parametrize with a spectral index

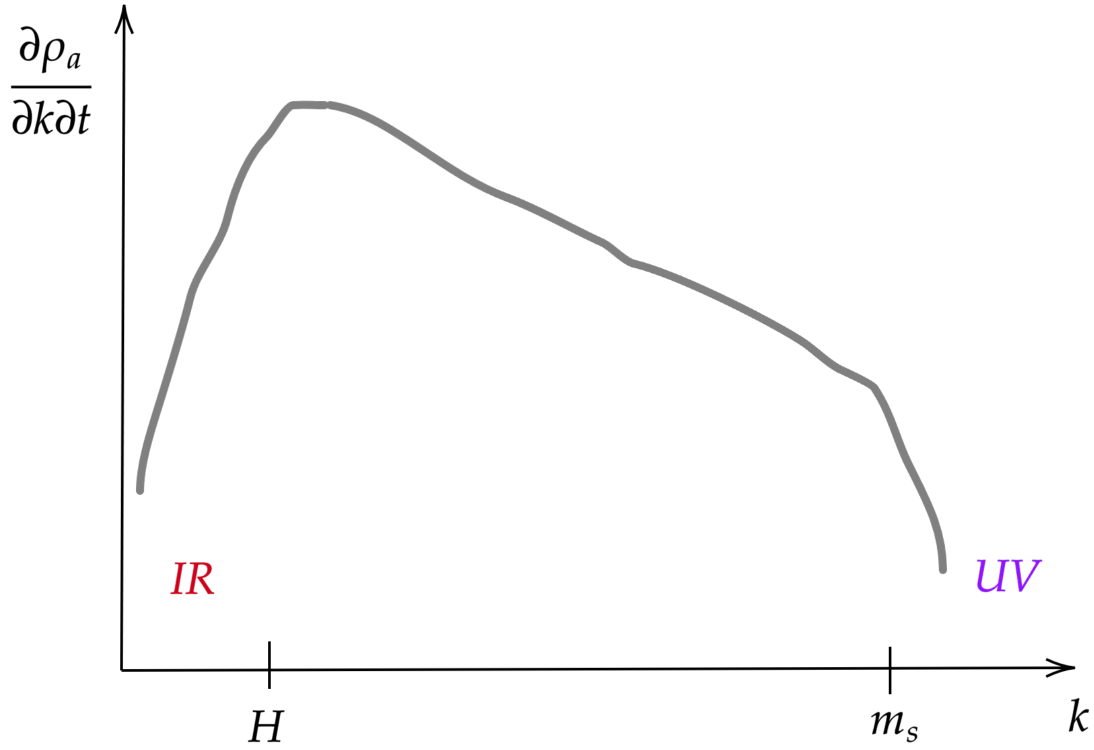


# Axion radiation

$$\frac{\partial \rho_a}{\partial k \partial t} \sim \frac{C}{k^q}$$

- Energy spectrum of axions emitted by strings
- Two scales imposing cutoffs in IR and UV
- Parametrize with a spectral index

$$n_a = \int \frac{dk}{\omega_k} \frac{\partial \rho_a}{\partial k} = \int dk \frac{C}{k^{q+1}}$$




Case A: IR domination

$$q > 1$$

Soft axions, large number density

Case B: UV domination

$$q < 1$$

Hard axions, small number density

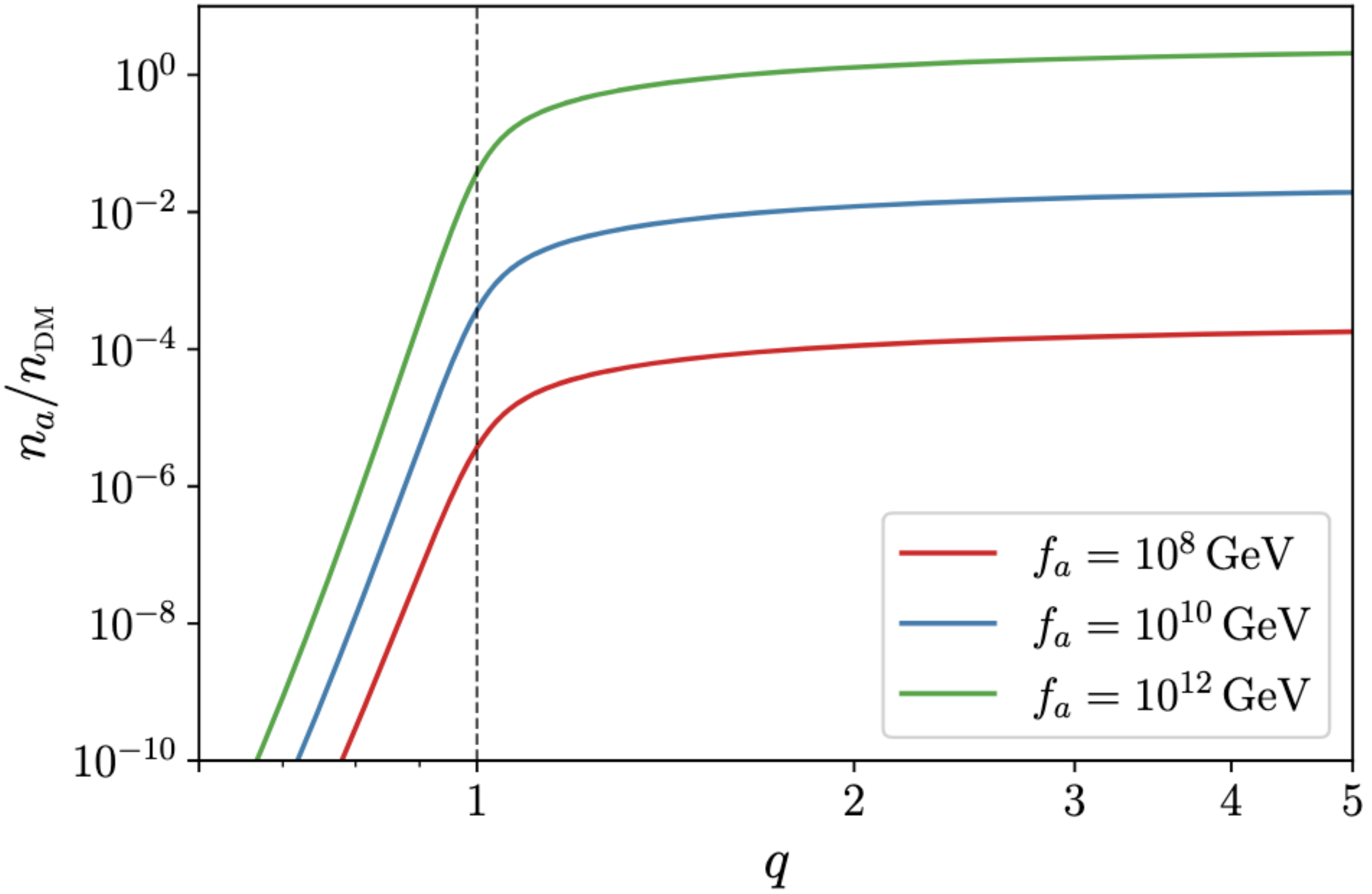
Dine et al. [2012.13065]

- Expect a logarithmic growth on the spectral index

$$q = q(\log)$$

- Most of DM axions are produced at last Hubble time

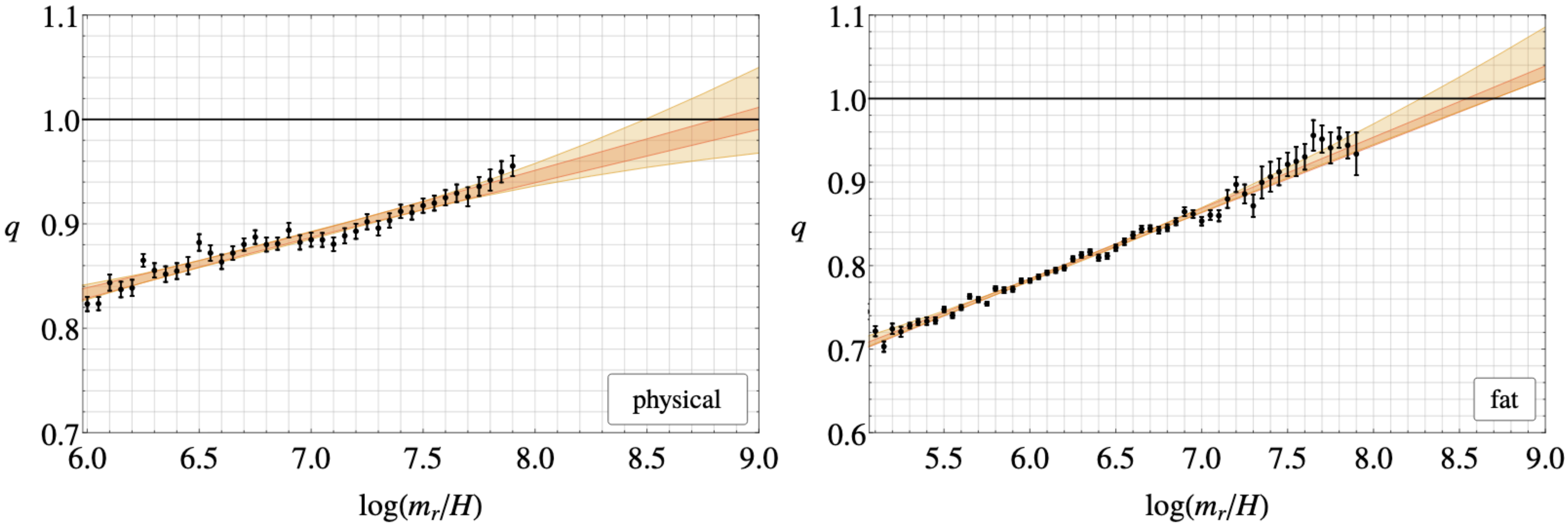
- Spectral index at QCDPT determines number density of DM axions



# Case $q > 1$

1. Evidence of running in the spectral index, linear extrapolation could give reasonable result

Gorghetto et al. [2007.04990]




2. Axion strings approach the 'thin string' limit (Nambu-Goto strings) Agreement with recent work by Drew and Shellard [1910.01718]

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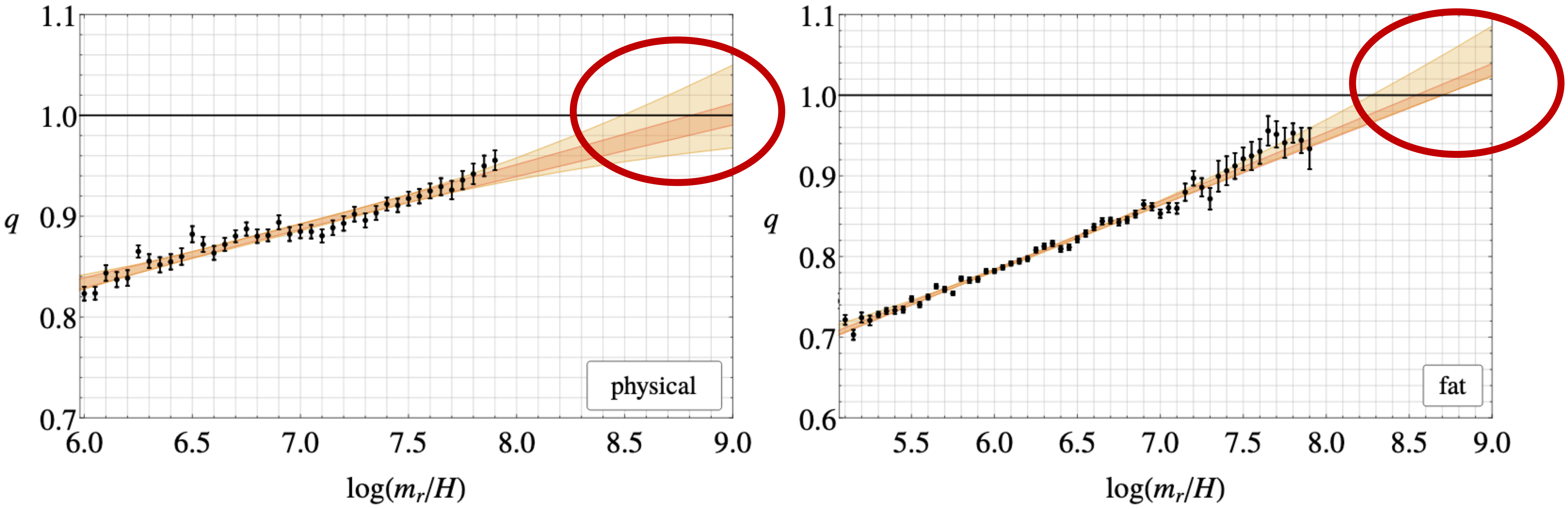
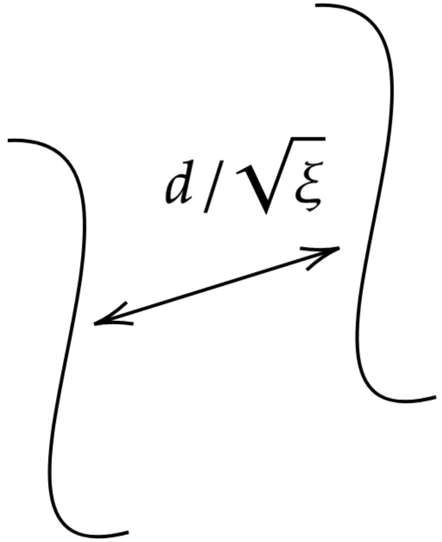



2. Axion strings approach the 'thin string' limit (Nambu-Goto strings)
   Agreement with recent work by Drew and Shellard [1910.01718]

# Case $q \lesssim 1$

- String tension is IR divergent and requires careful definition
- Enhancement in string density does not necessarily lead to enhanced axion number density
- IR cutoff suppresses low momentum axions
- Numerical evidence for circular strings with $q \approx 1$
- Only field simulations of string network is reliable

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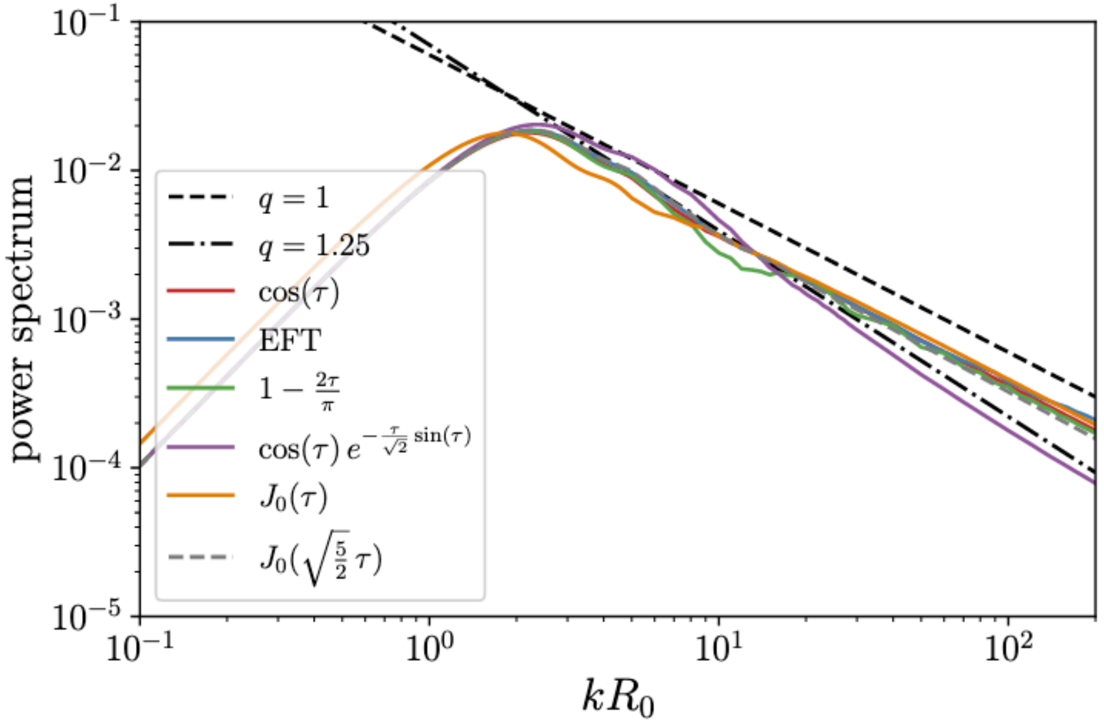


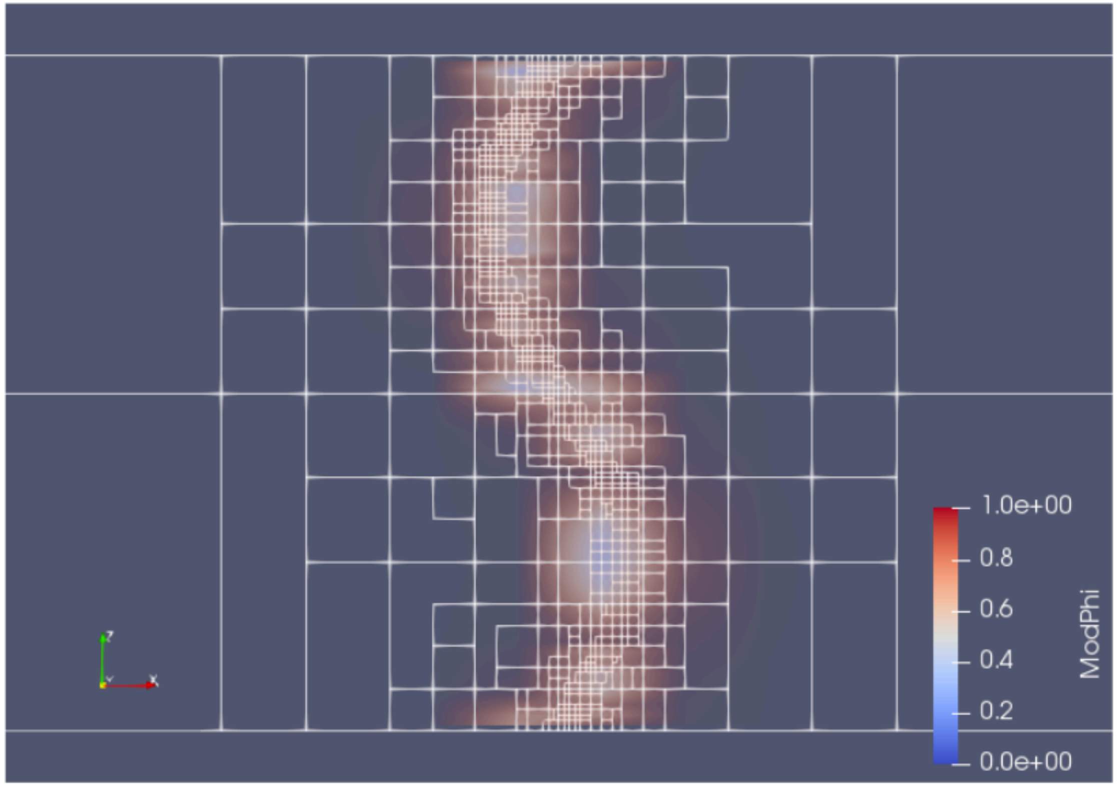
# How to extend simulation range?

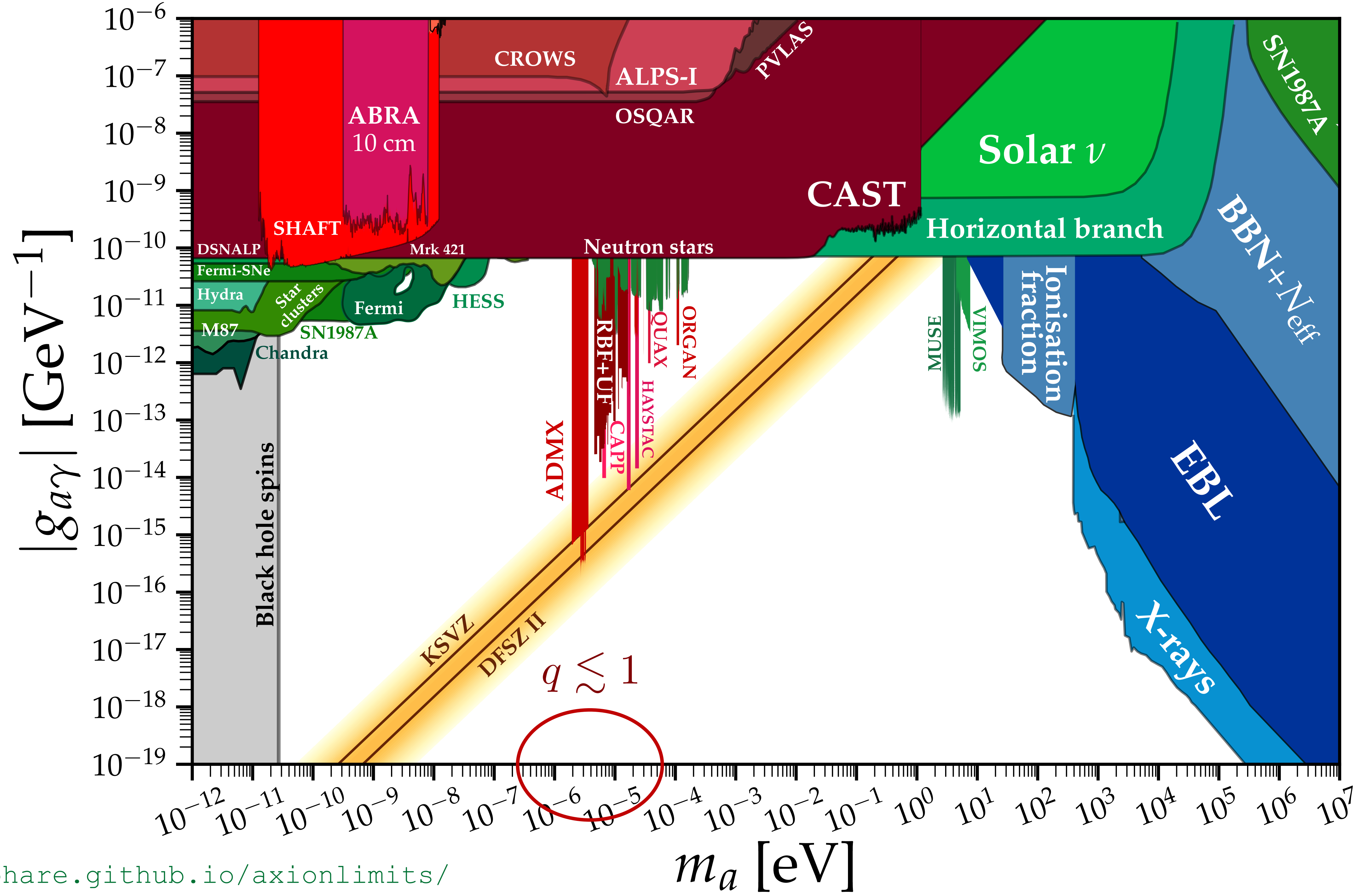
- Adaptive mesh refinement (AMR) might be the answer
- Adaptive space step

$$\Delta x \sqrt{(\nabla \phi_1)^2 + (\nabla \phi_2)^2} > |\phi_{\rm thr}|$$

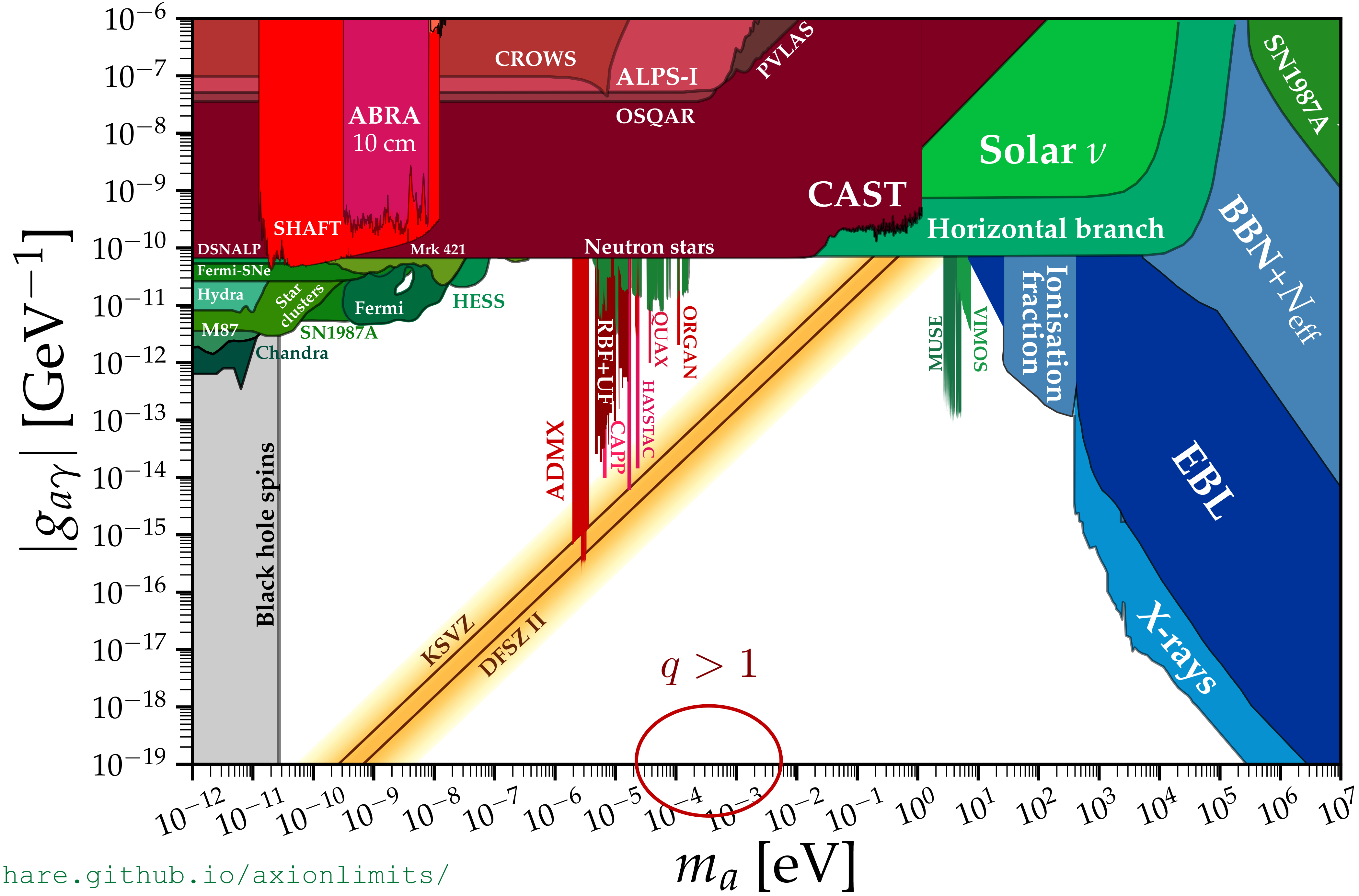
- Reach up to $log \approx 14$
- Drew and Shellard implemented for a single string
- *Extend to axion string network*

Drew, Shellard [1910.01718]






cajohare.github.io/axionlimits/

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Thank you!