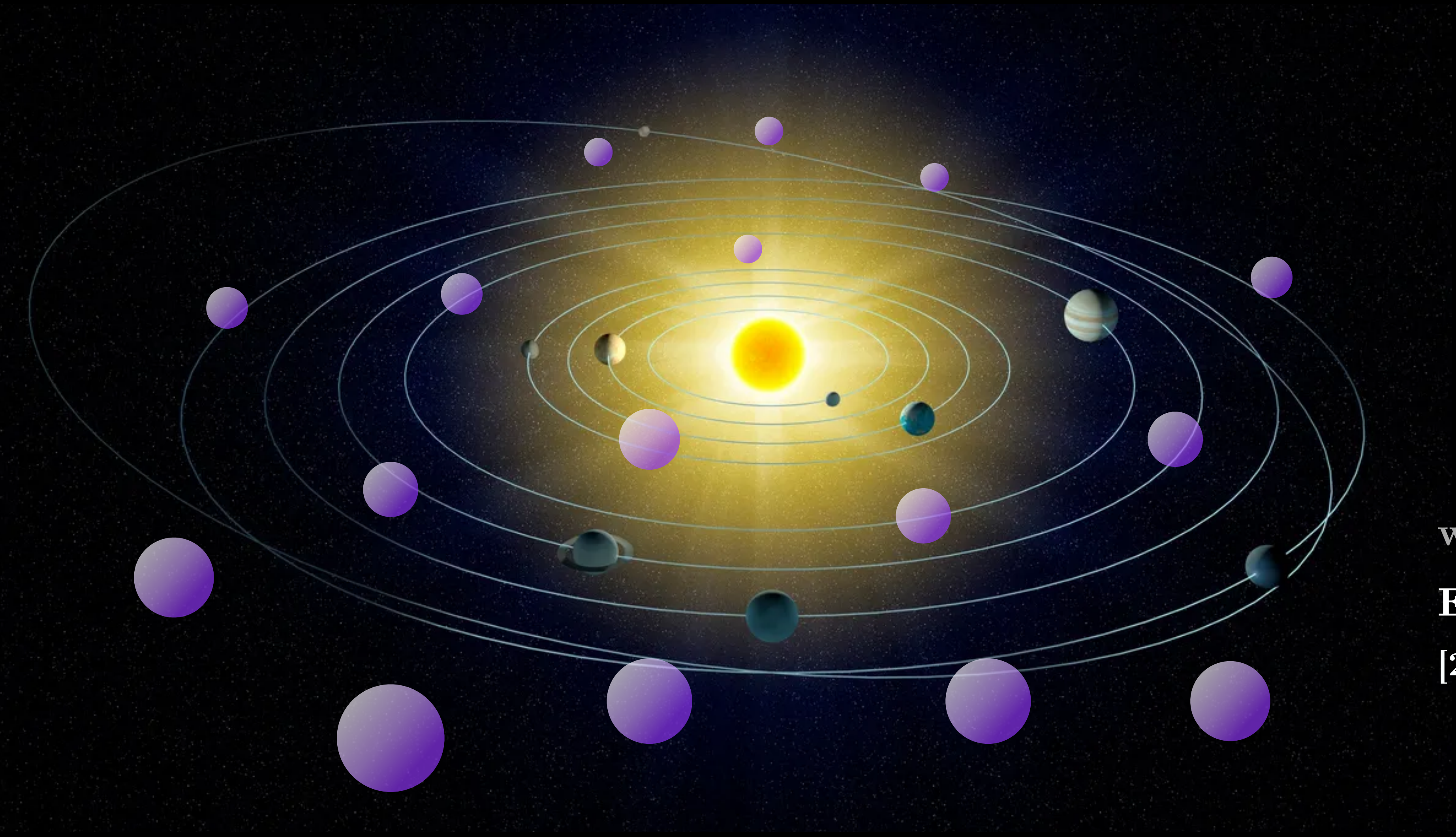
Axion strings, domain walls and miniclusters

Marco Gorghetto



with

E. Hardy and G. Villadoro

[2405.19389, 2007.04990]

Outline

1) Axions and the ‘post-inflationary’ scenario

→ the axion mass

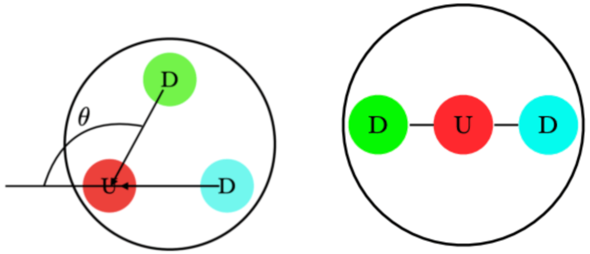
2) Structure formation and axion miniclusters/stars

QCD axion:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \ldots \quad \Rightarrow \quad m \simeq 0.57\,\mathrm{meV}\left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)$$

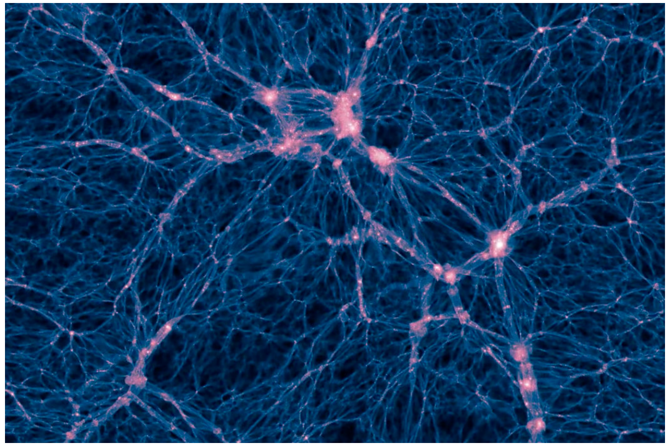
axion decay constant

- Dynamically explains no neutron EdM (strong CP problem)

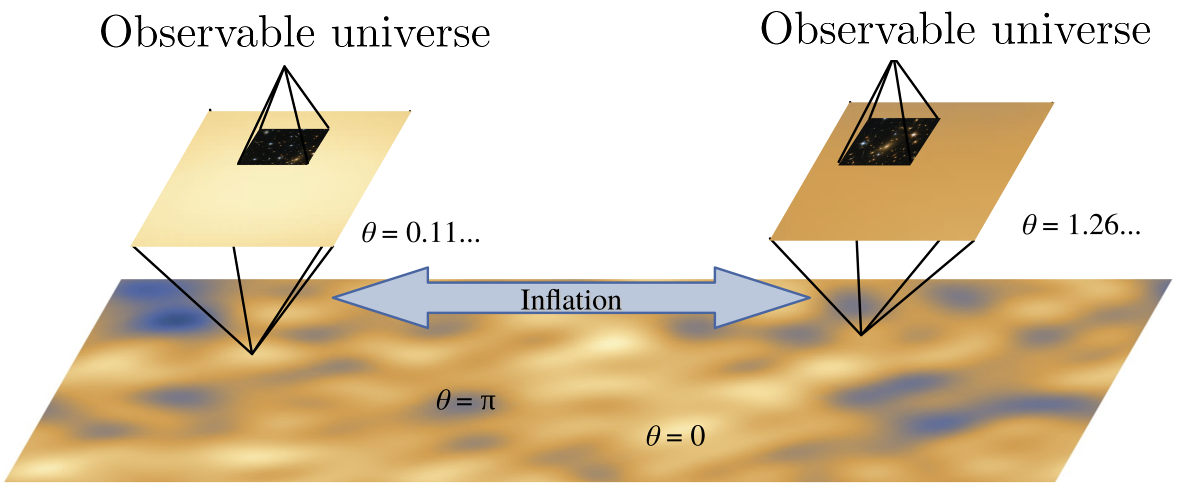


[picture from A. Hook]

- Makes up all/part of the dark matter



Pre-inflationary $(T_R \lesssim f_a)$

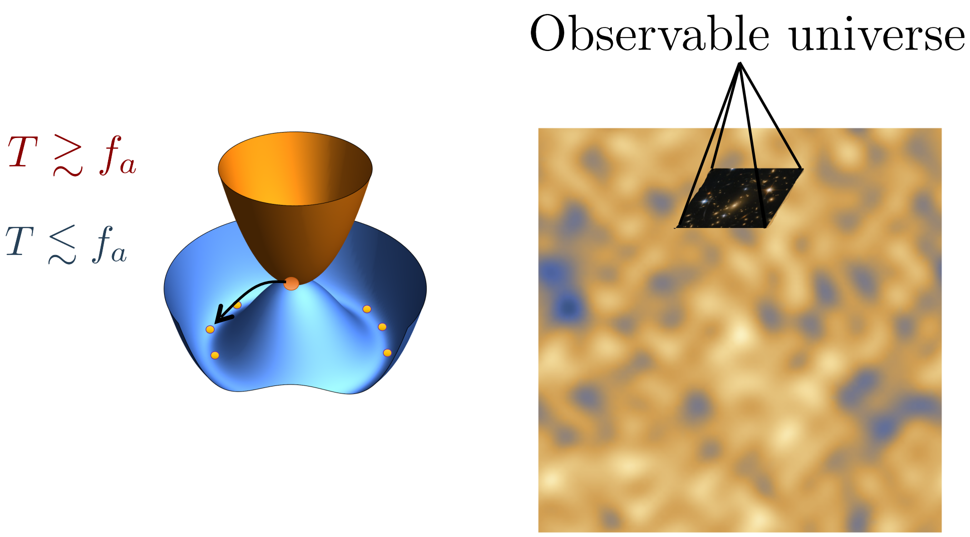


$\theta \equiv \frac{a}{f_a} \in [-\pi, \pi]$

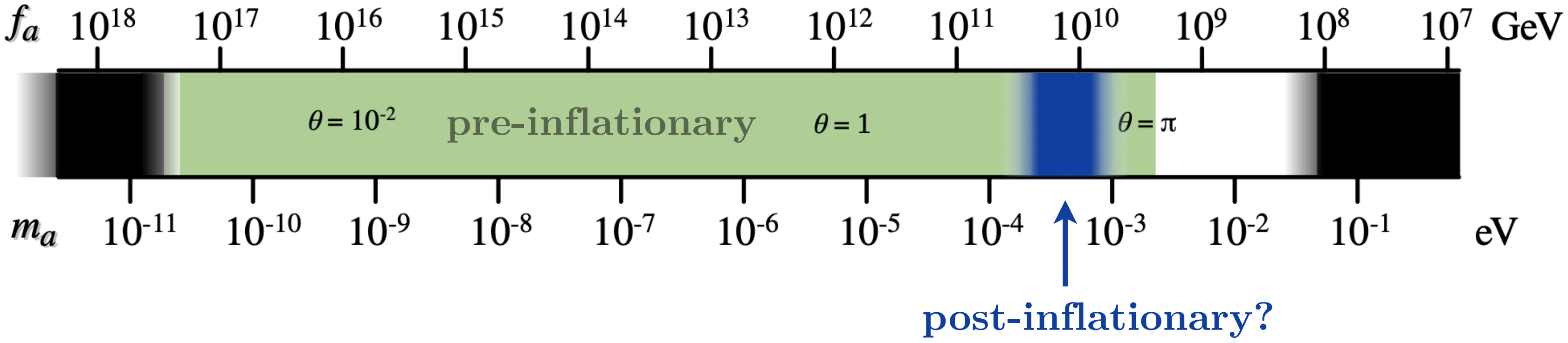
$$\Omega_a \simeq \theta_0^2 \left(\frac{f_a}{10^{12}\,\text{GeV}} \right)^{1.2} \Omega_{\text{DM}}$$

misalignment

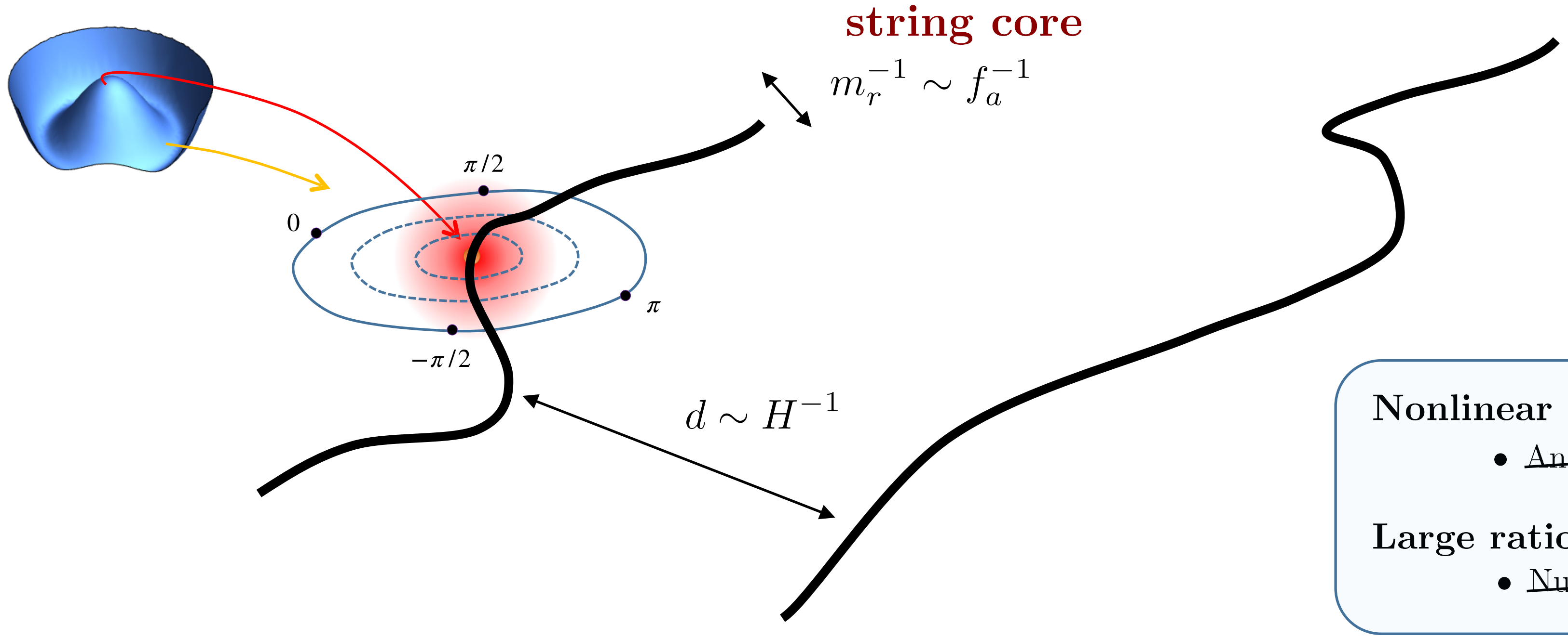
Post-inflationary $(T_R \gtrsim f_a)$



→ unique prediction for f_a (or m_a)



$@\, T \simeq f_a$ Kibble mechanism $\Longrightarrow$ **Axion strings**



Nonlinear dynamics:

- ~~Analytical approach~~ ☹

Large ratio of scales:

- ~~Numerical approach~~ ☹

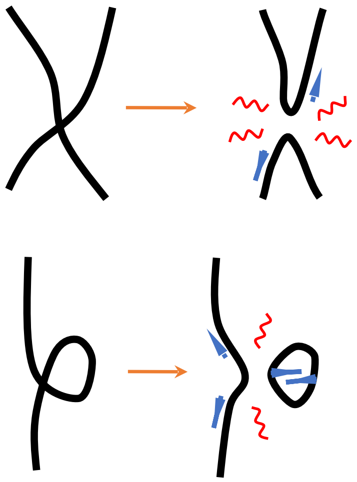
string tension

$$\mu = \frac{E}{L} \sim \underbrace{\pi f_a^2}_{\text{core}} \underbrace{\log \frac{d}{m_r^{-1}}}_{\text{axion gradient}} \sim \pi f_a^2 \log \frac{m_r}{H}$$

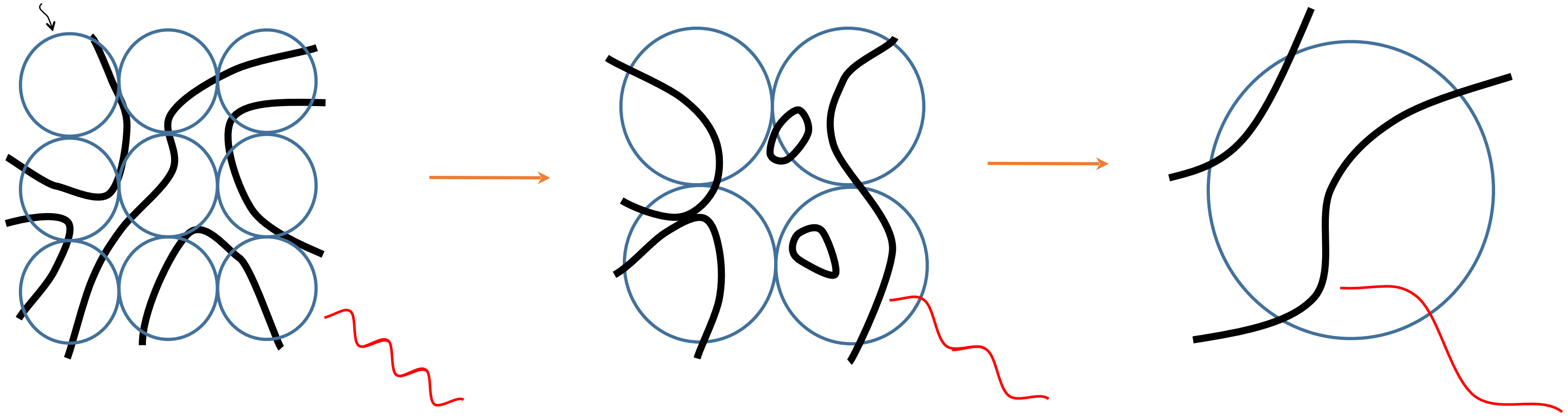
$H \to T^2/M_p$

grows logarithmically in time

The Scaling Regime

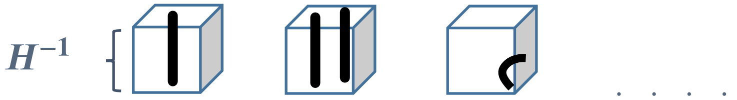


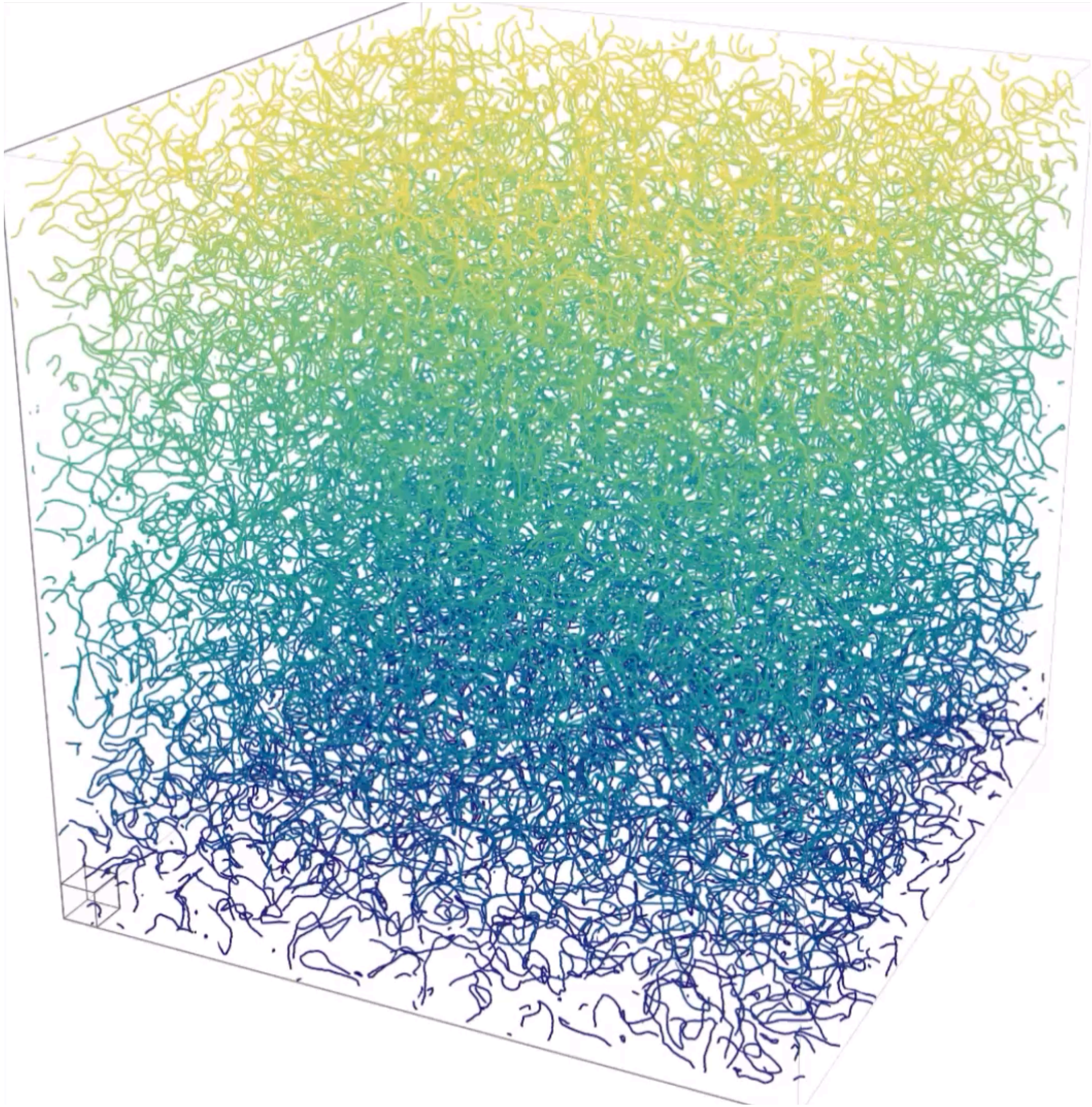
causal patch $\propto 1/H = 2t$



rate of energy loss: $\Gamma \simeq \frac{\xi \mu}{t^3}$

number of strings
per Hubble patch



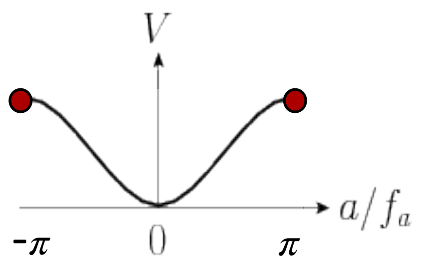


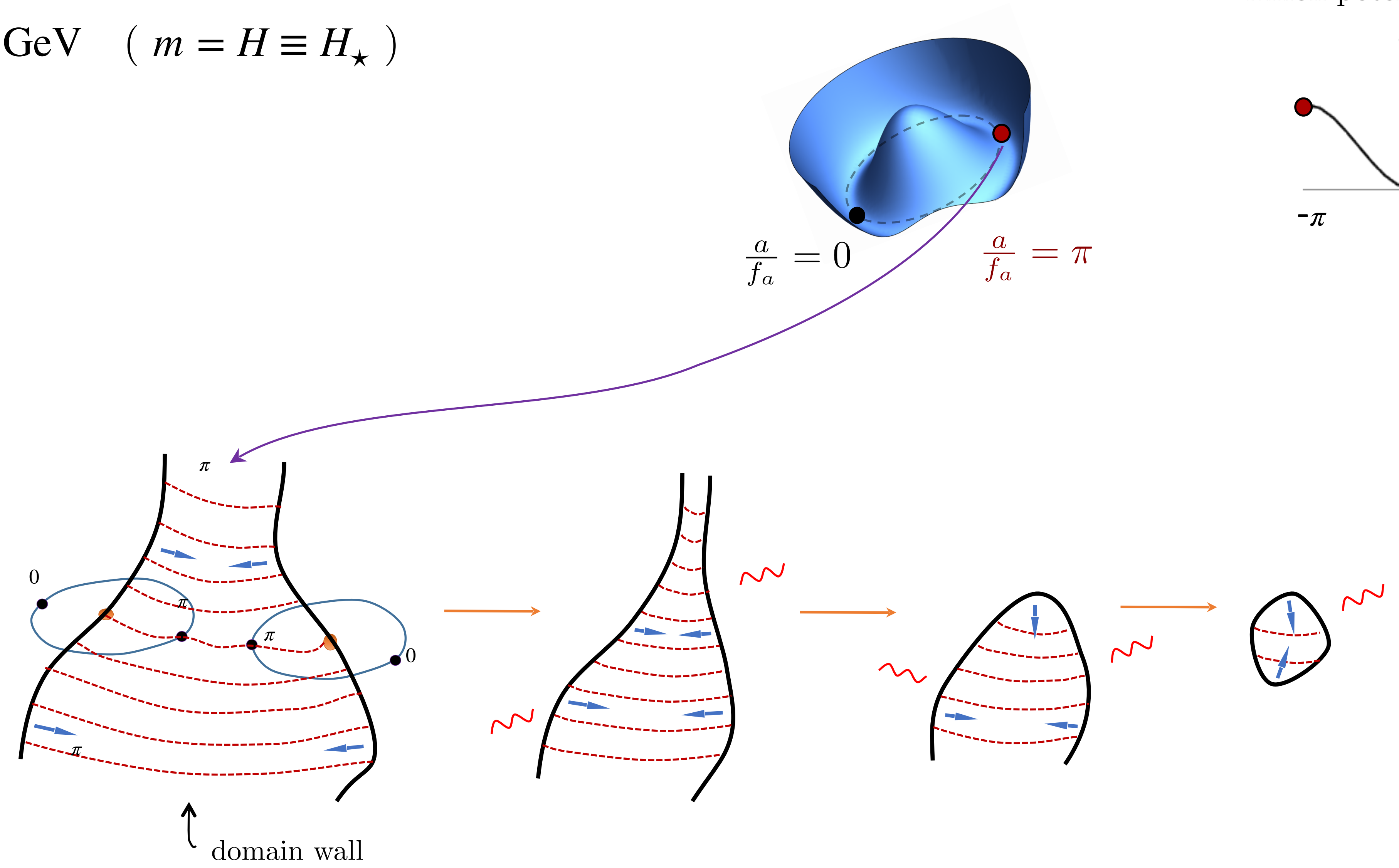
Axion Domain Walls

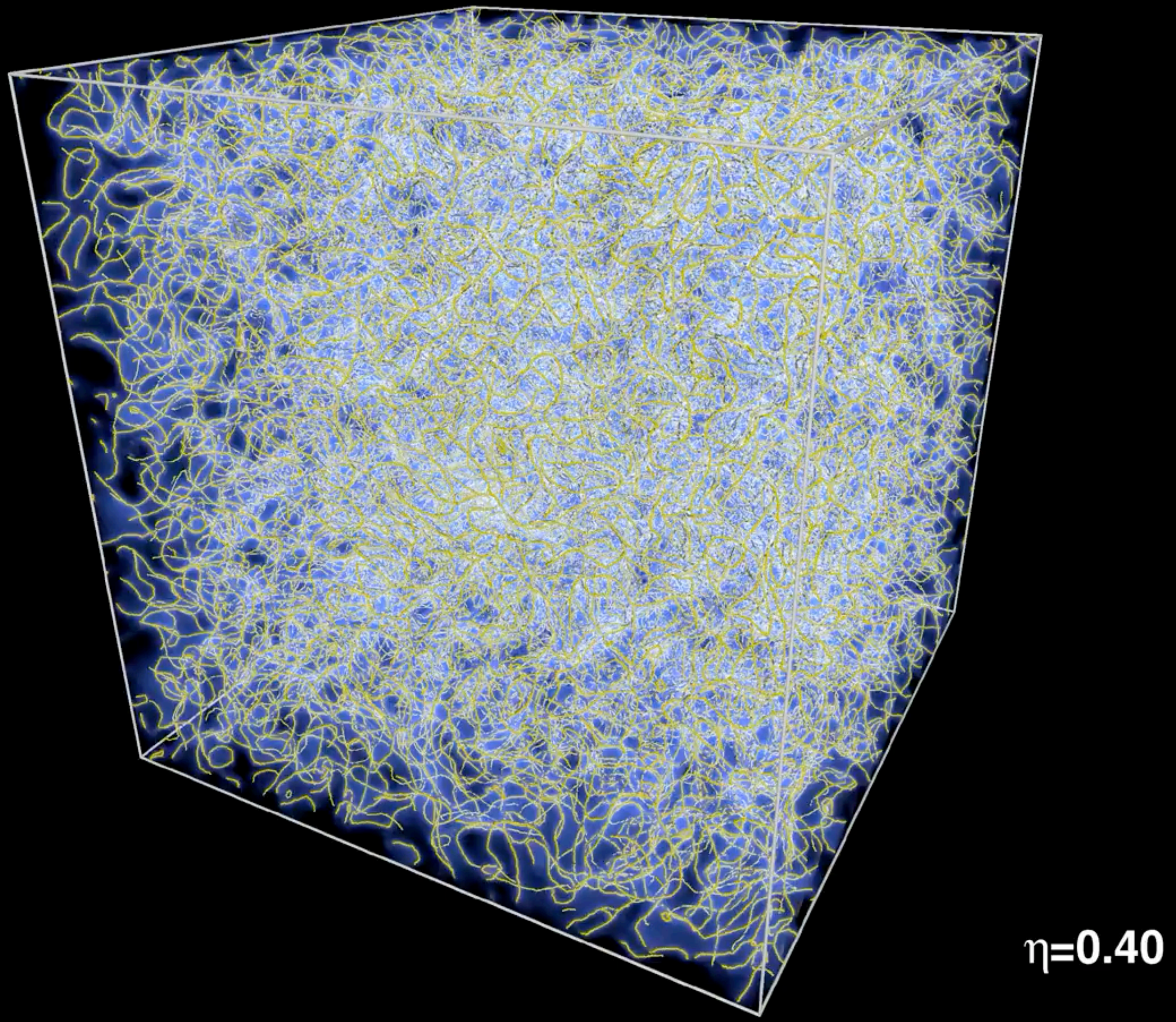
The axion potential becomes important

$$@\, T \simeq 1\,\mathrm{GeV} \quad (\ m = H \equiv H_\star\ )$$

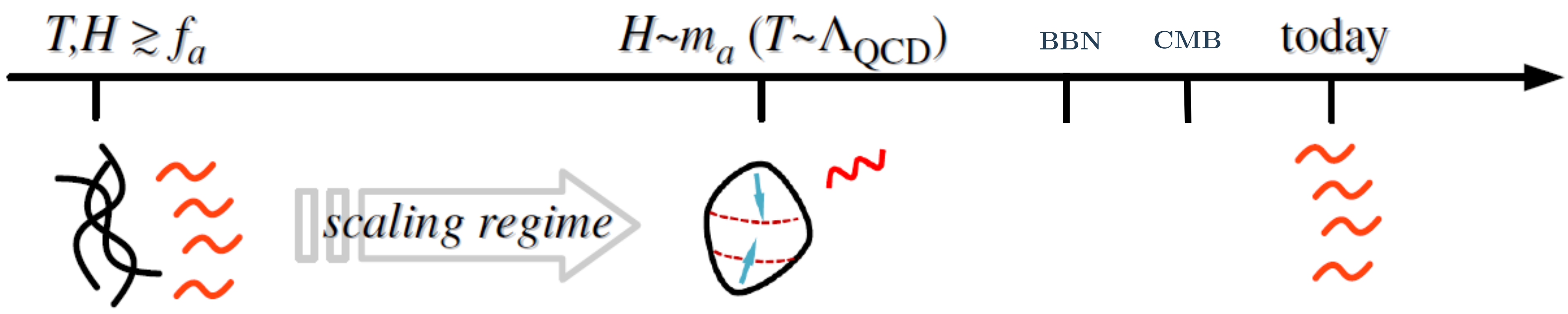
Axion potential from QCD:







by Malte Buschmann



$\log(m_r/H)$ $\sim \mathbf{1 \div 15}$ $\sim \mathbf{70}$

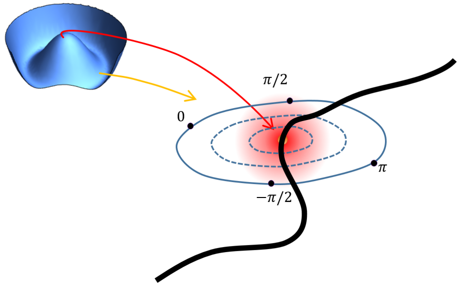
strings form

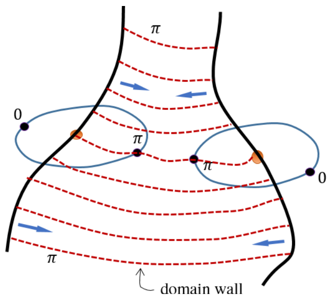
domain walls form and annihilate

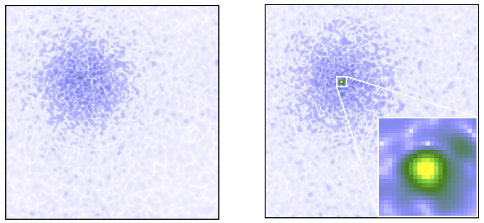
relic axions

strings **domain walls**

axion stars
miniclusters

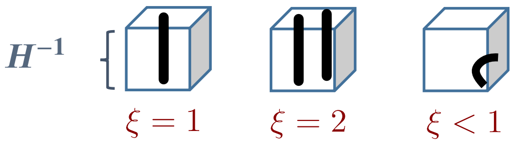


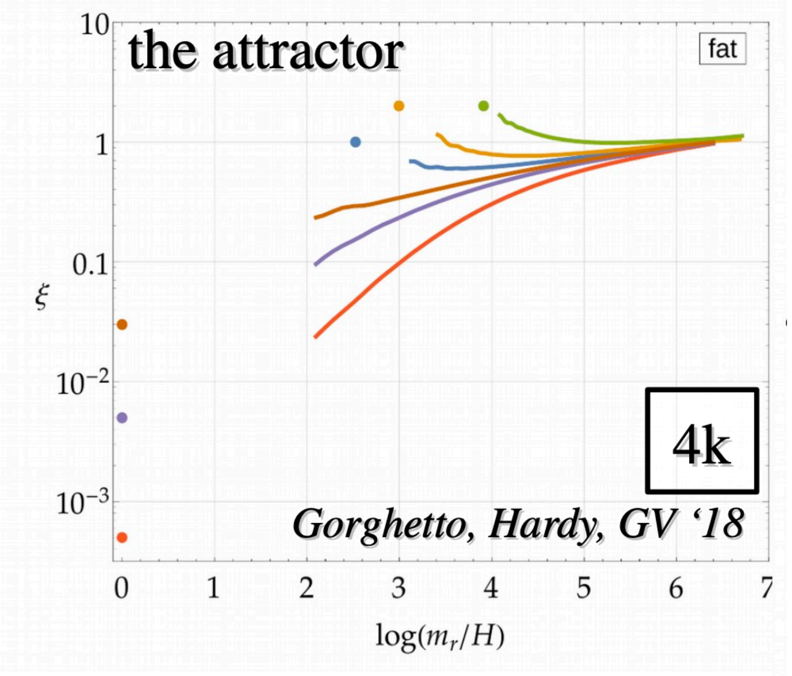


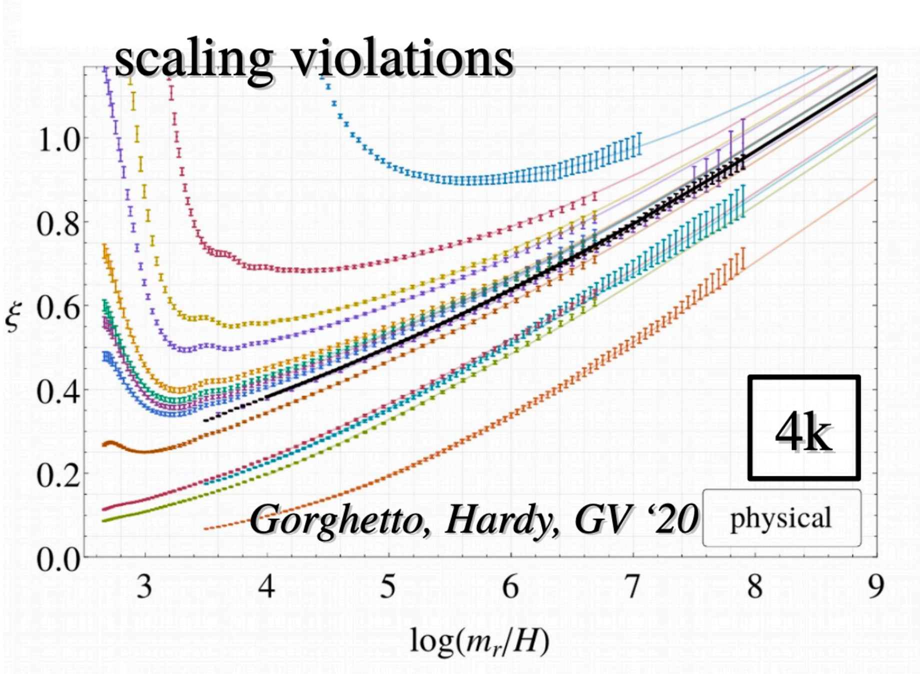


Levkov et al.
[from 1804.05857]

The number of strings



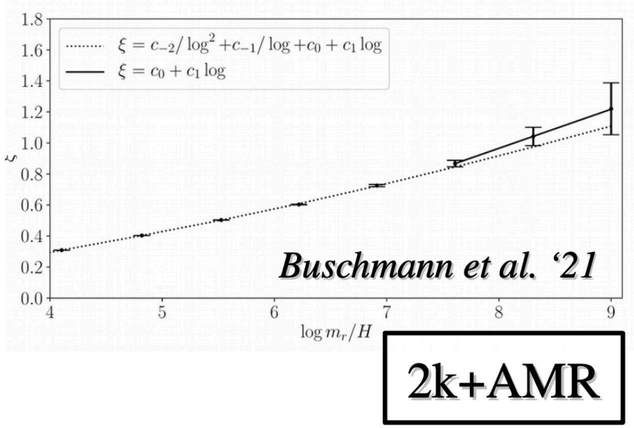


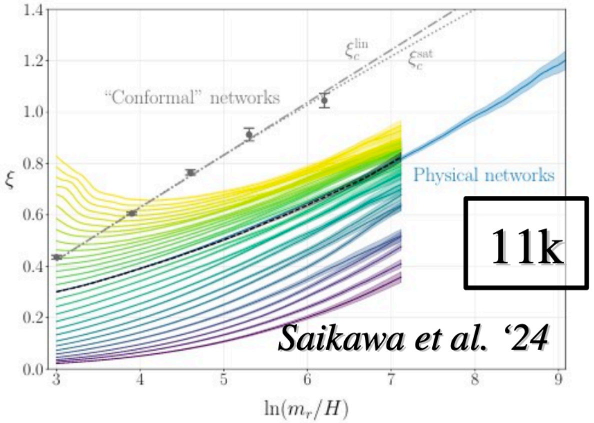


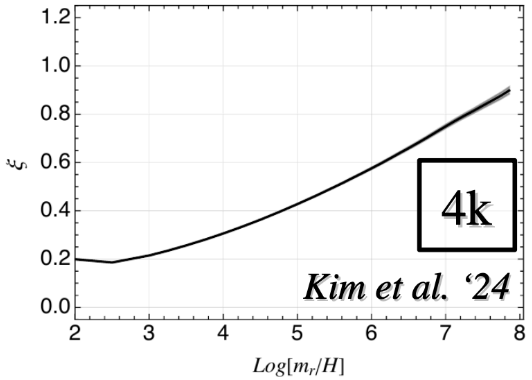
$$\xi \to \frac{\log(m_r/H)}{4 \div 5}$$

$\simeq 15$

$@ \log = 70$



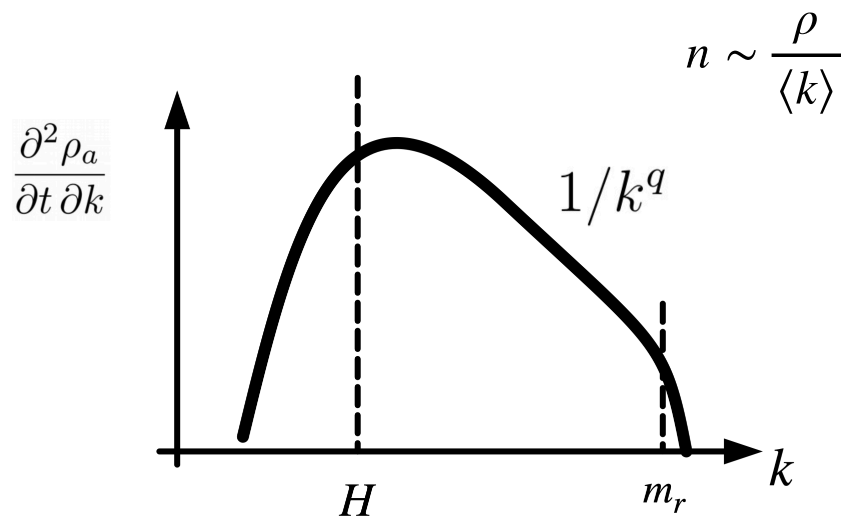


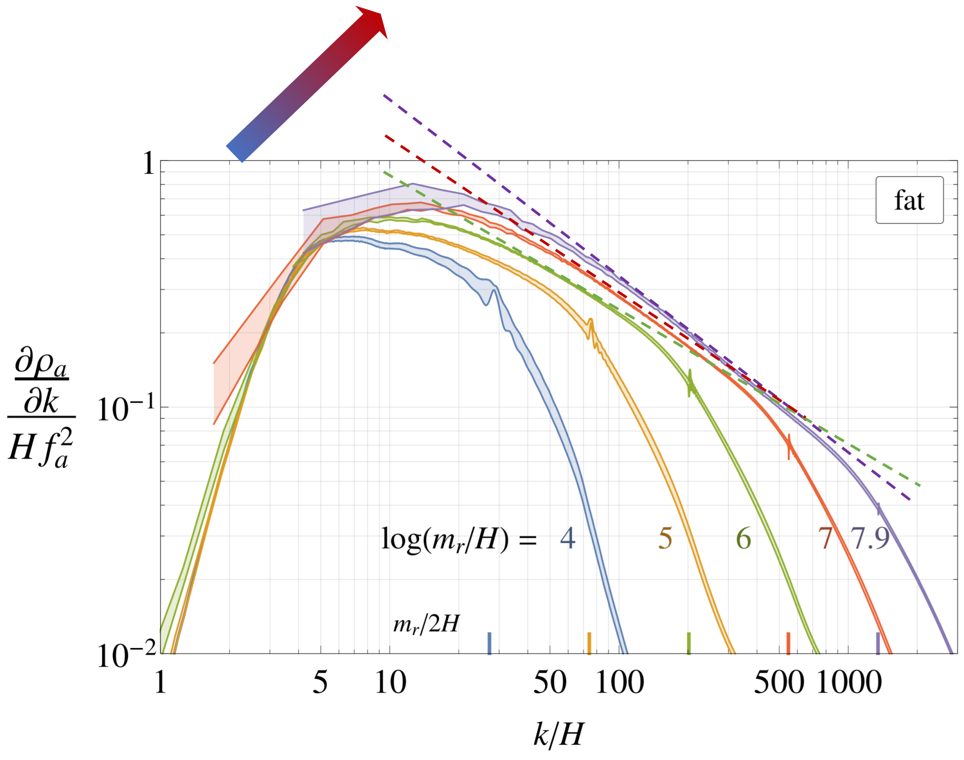


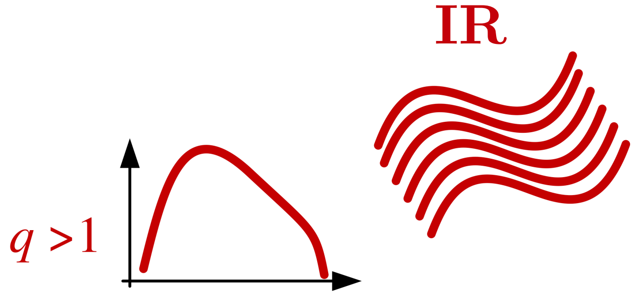
See also:

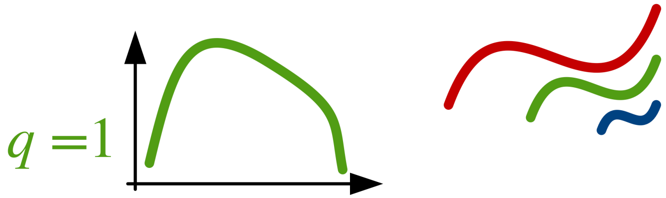
- Fleury, Moore '15
- Klaer, Moore '17, '19
- Kawasaki et al. '18
- Vaquero et al. '18
- Buschmann et al. '19

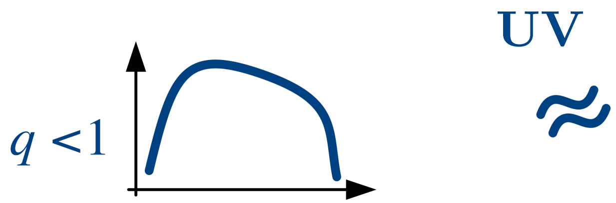
The energy spectrum











Davies, Shellard, ...

$$n \sim \frac{\rho}{H} \sim \xi \log f^2 H \sim \boxed{\xi \log} n^{mis}$$

$\sim 10^3$

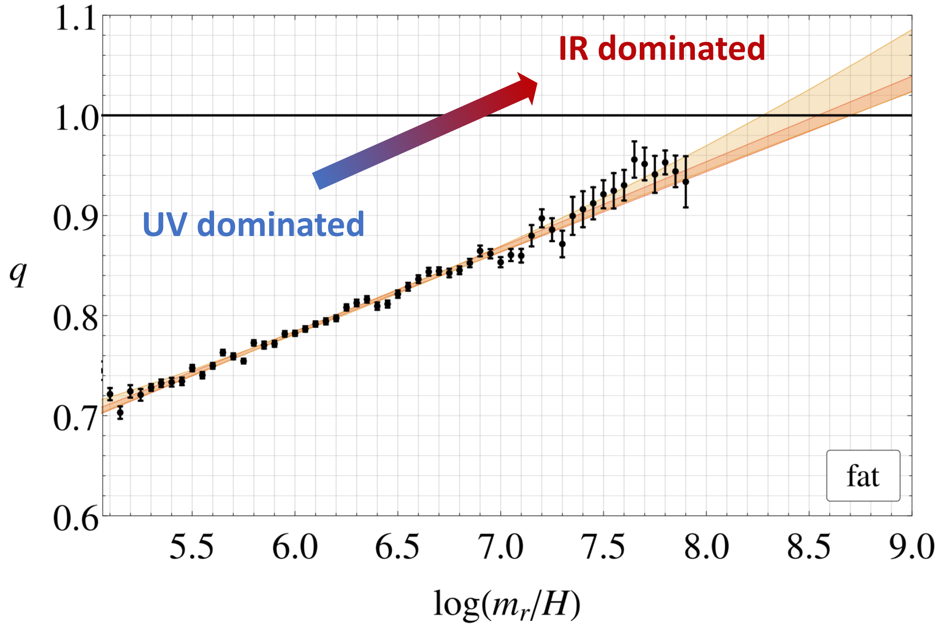
Sikivie, ...

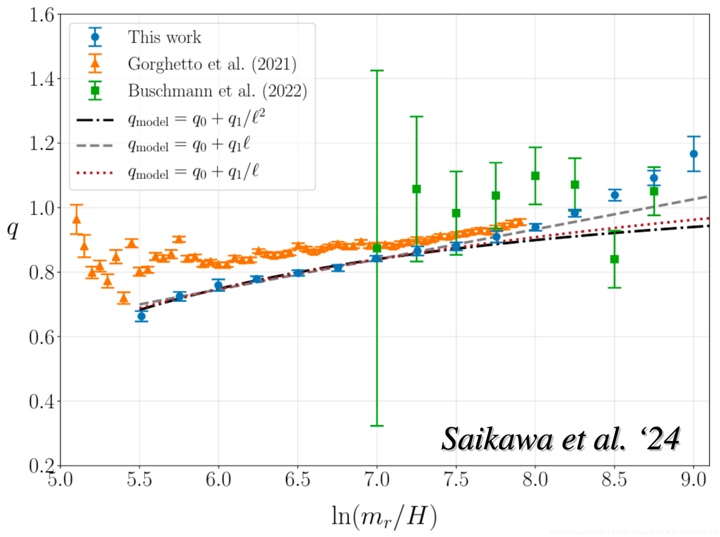
$$n \sim \frac{\rho}{H \log} \sim \xi f^2 H \sim \boxed{\xi} n^{mis}$$

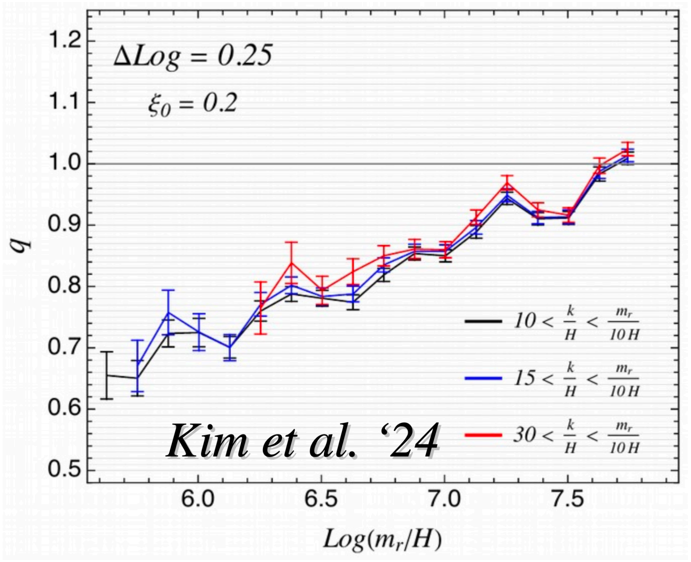
$$n \sim \frac{\rho}{H}\left(\frac{H}{m_r}\right)^{1-q} \sim n^{mis} \boxed{\left(\frac{H}{m_r}\right)^{1-q}}$$

$\ll 1$

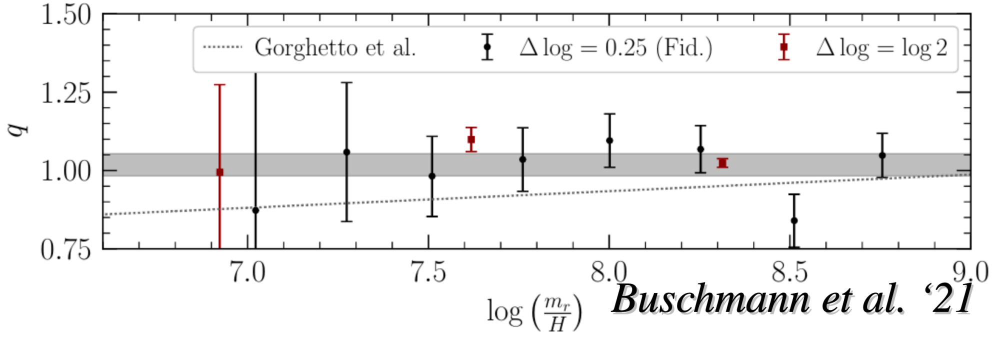
The spectral index







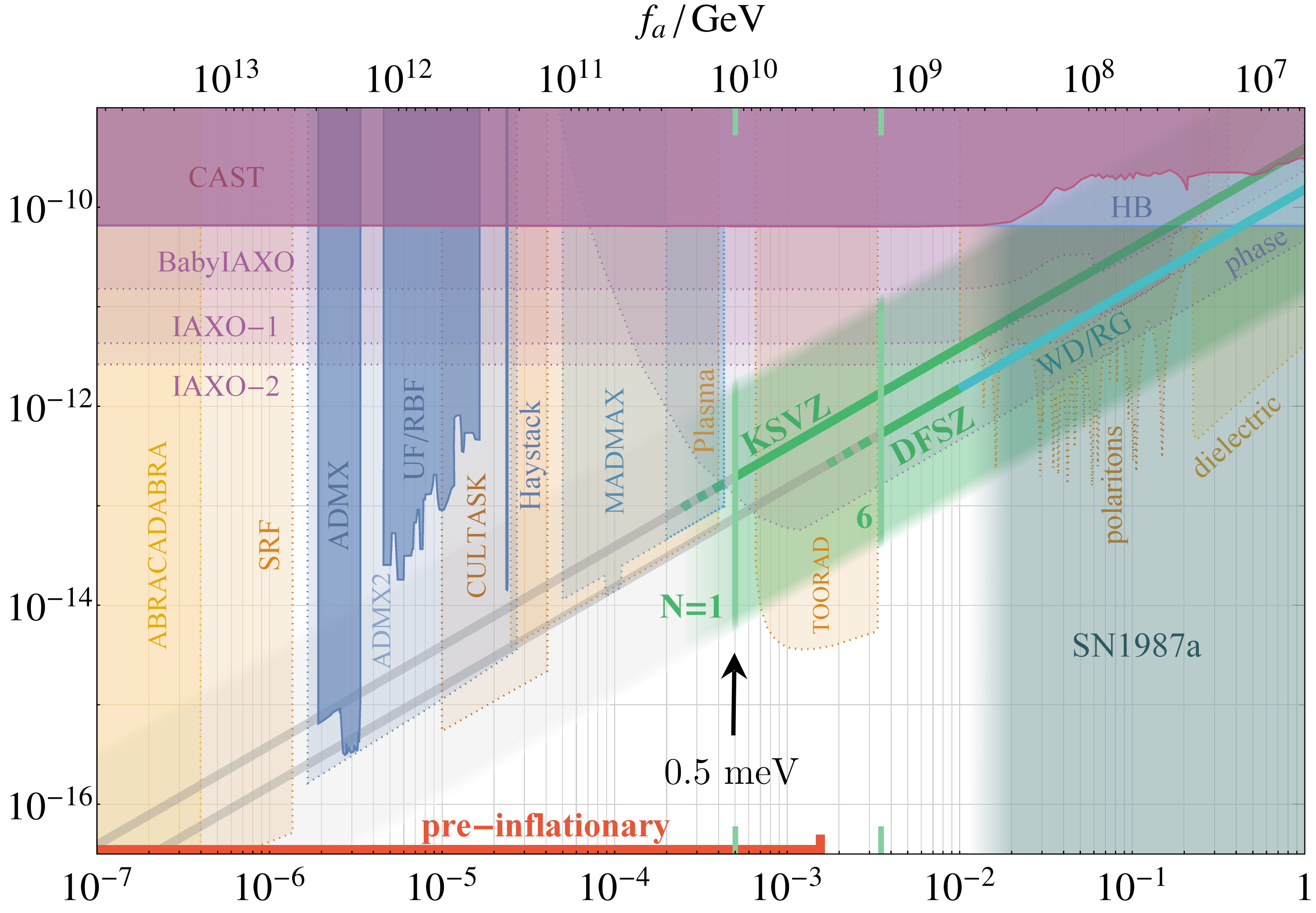
$q \simeq 1?$



Evolution of q → log → 70 $q > 1$

$$f_a \simeq (\overset{q>1}{1} \div \overset{q=1}{6}) \cdot 10^{10}\ \text{GeV} \quad + \text{DW?}$$

$m_a \simeq 0.5 \div 0.1\ \text{meV}$



$q \simeq 1$ $q > 1$

$f_a \lesssim 10^{10}$ GeV from DM overproduction

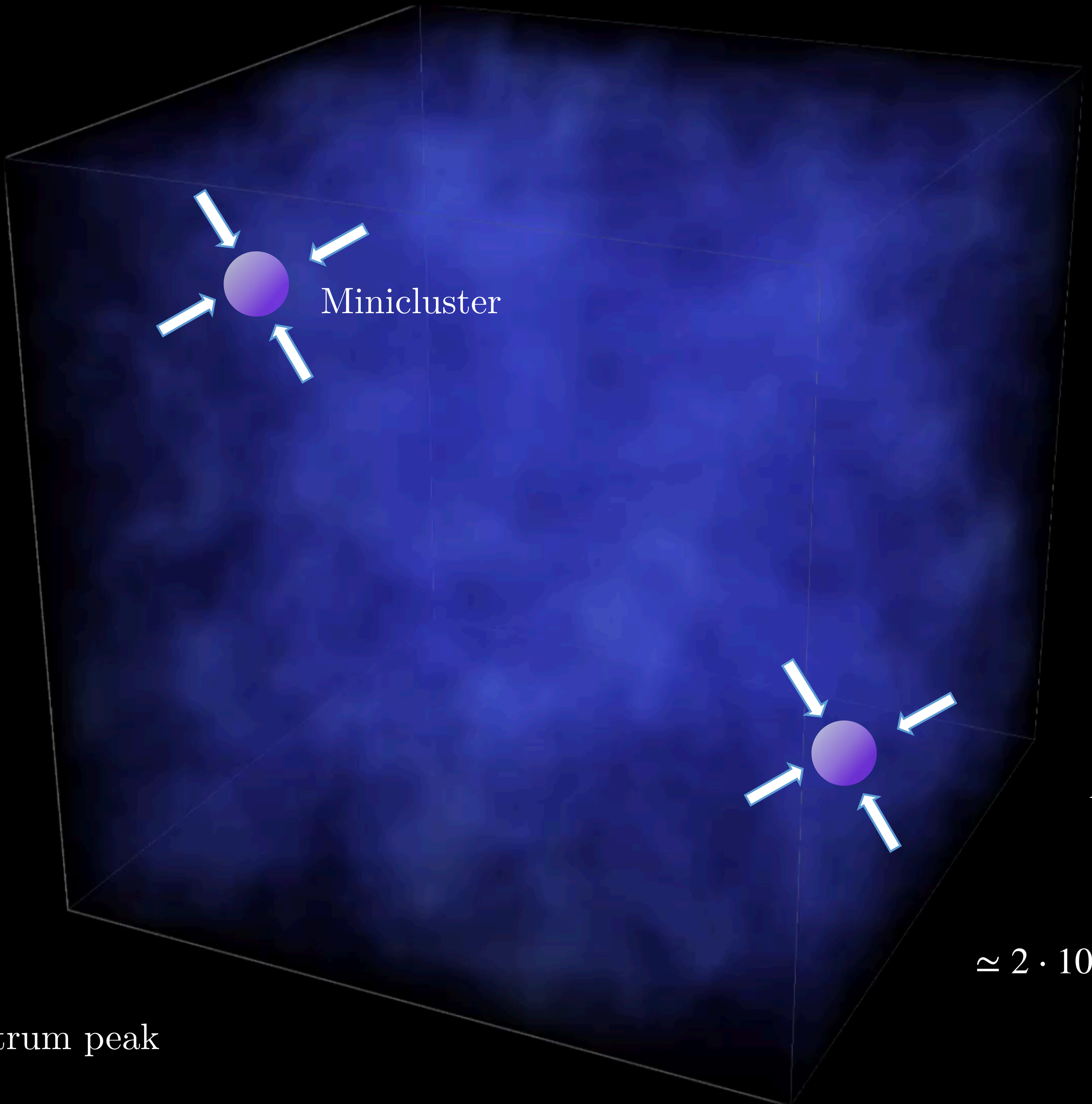
$\simeq$ if domain wall contribution negligible

$m_a \gtrsim 0.5$ meV

Formation of structures

after wall decay, $T \ll \Lambda_{\rm QCD}$

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$



$\sim H_\star^{-1}$

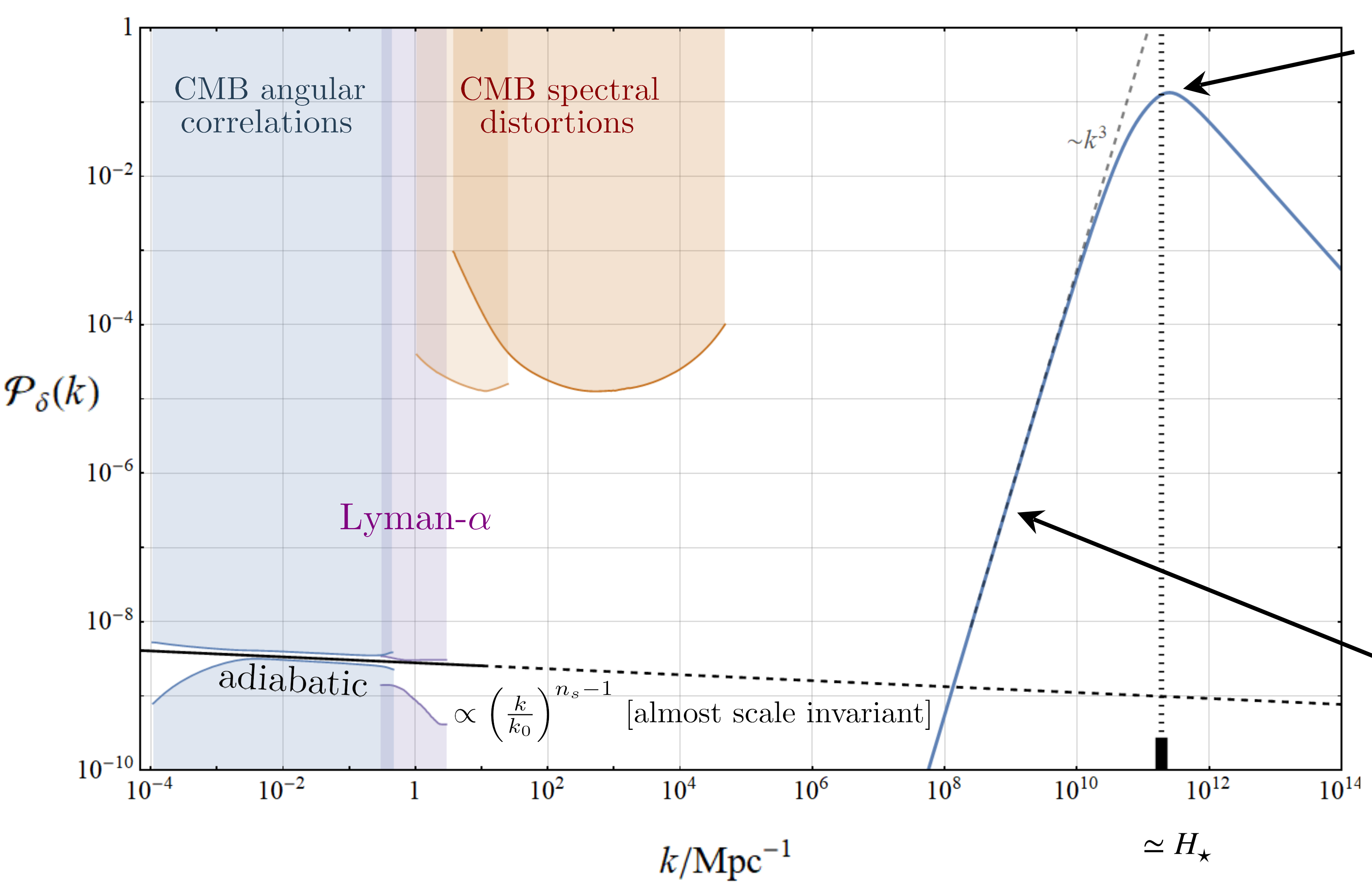
$\sim k_p^{-1}$ spectrum peak

$$M_C \simeq \frac{4\pi}{3}\bar{\rho}\left(\frac{\pi}{H_\star}\right)^3$$

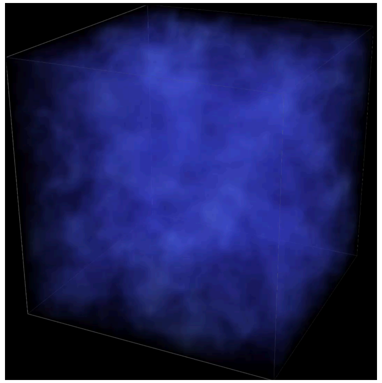
$$\simeq 2 \cdot 10^{-12} M_\odot \left(\frac{0.1\,\mathrm{meV}}{m_a}\right)^{1/2}$$

(naive)

Axion dark matter over-density power spectrum



Order-one fluctuations produced by string and domain walls (isocurvature)

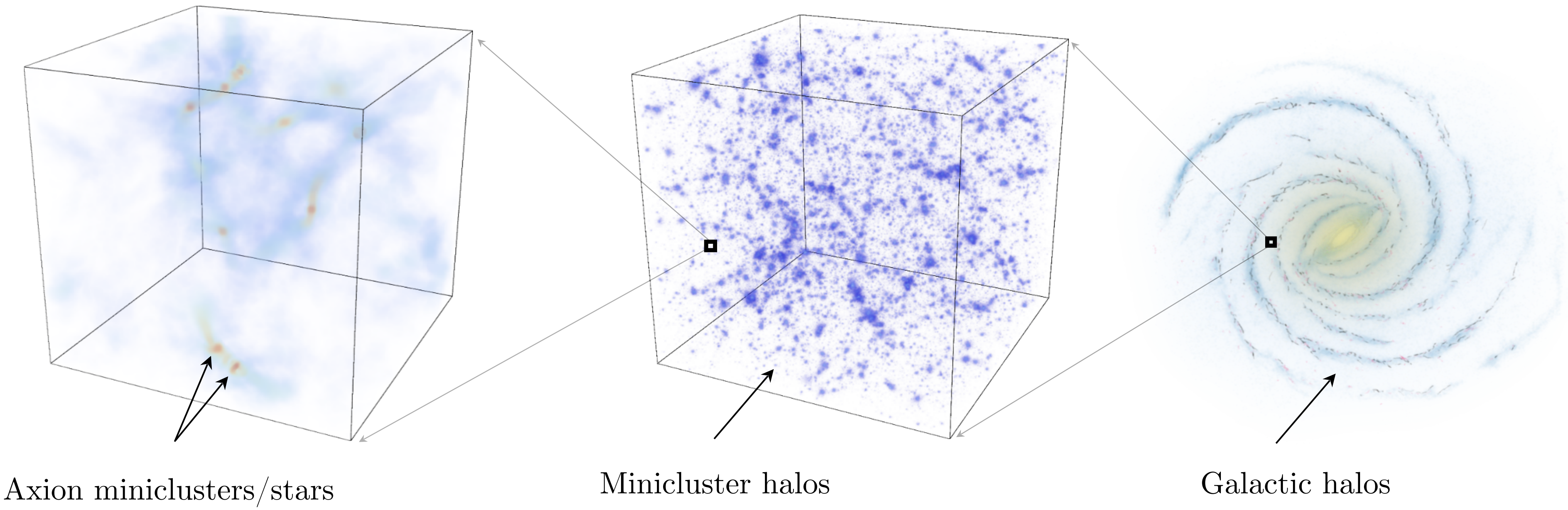


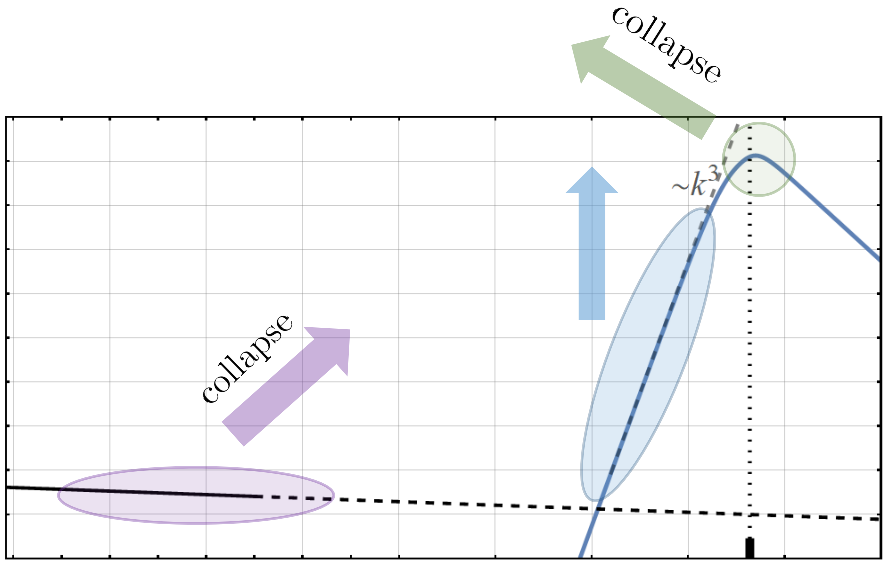
Uncertain!

White-noise tail

Uncertain!

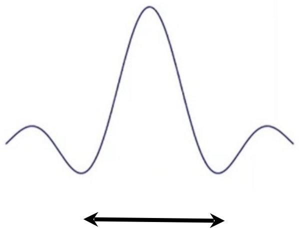
Overview of the dynamics





Gravitational collapse *vs* quantum Jeans scale

overdensity ρ



R

spatial size of the overdensity

R

$\longleftrightarrow$

de Broglie wavelength of the particles in the resulting clump

$$\frac{1}{mv}$$

$$\simeq \frac{1}{m(\frac{GM}{R})^{1/2}} \simeq \frac{1}{R(4\pi G\rho m^2)^{1/2}}$$

$M \to 4\pi\rho R^3/3$

$\downarrow$

$$R_{\rm crit} \simeq \lambda_J \simeq (16\pi G\rho m^2)^{-1/4}$$

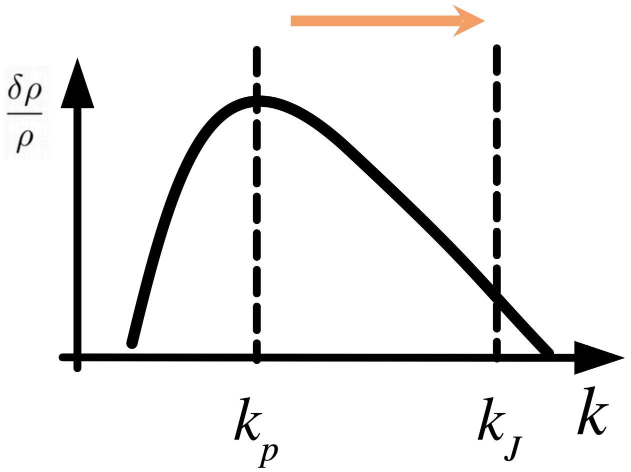
quantum Jeans length $\lambda_J = 2\pi/k_J$ $\equiv$ smallest scale an overdensity can have before wave effects (quantum pressure) have to be considered

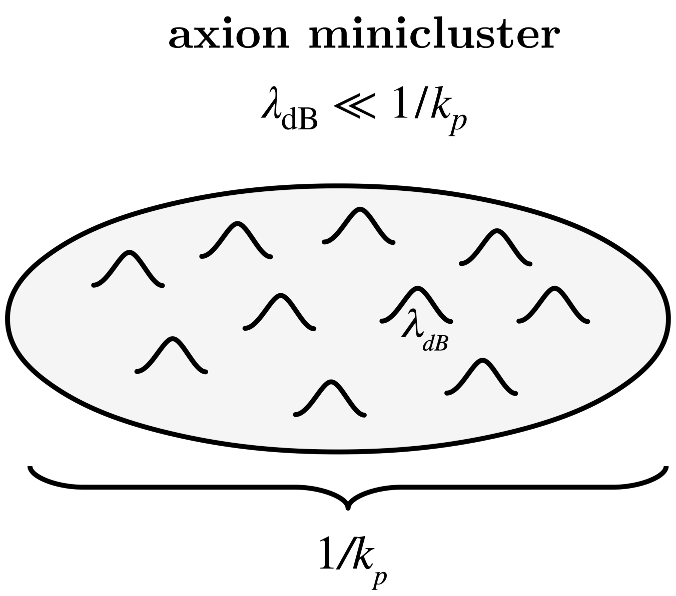
The standard lore after DW decay

quantum Jeans scale

$k_J \equiv (16\pi G\rho m^2)^{\frac{1}{4}}$

@MRE

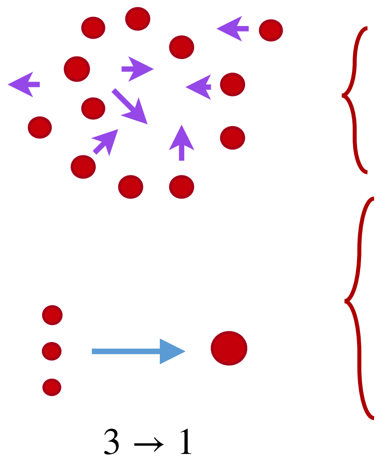


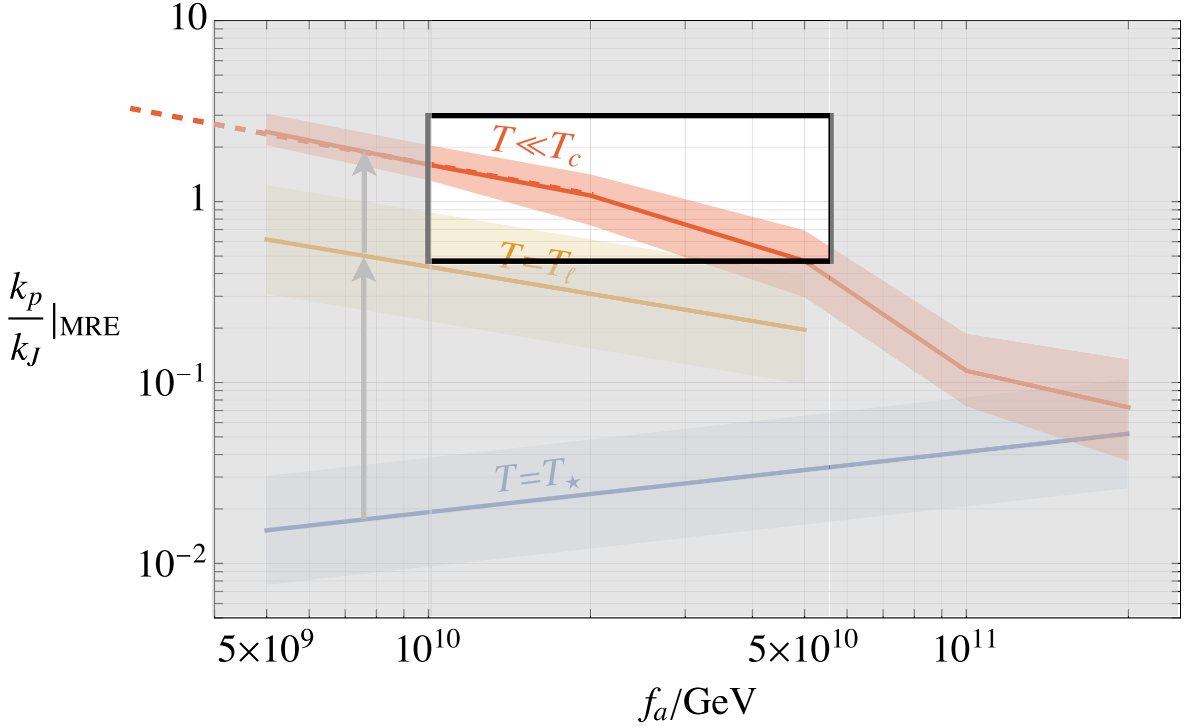


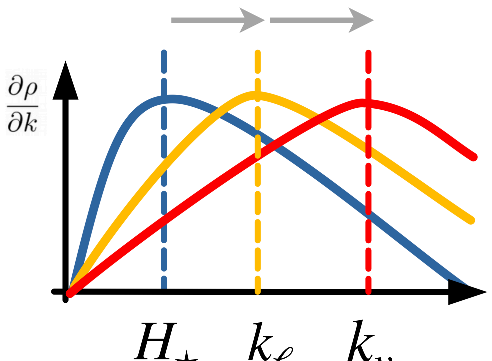
$$\left.\frac{k_p}{k_J}\right|_{\mathrm{MRE}} \simeq \left(\frac{f_a}{M_p}\right)^{1/3} \frac{k_{p\star}}{H_\star} \sim 10^{-3}\,\frac{k_{p\star}}{H_\star}$$

Naive because k_p increases due to the self-interactions and becomes of order k_J

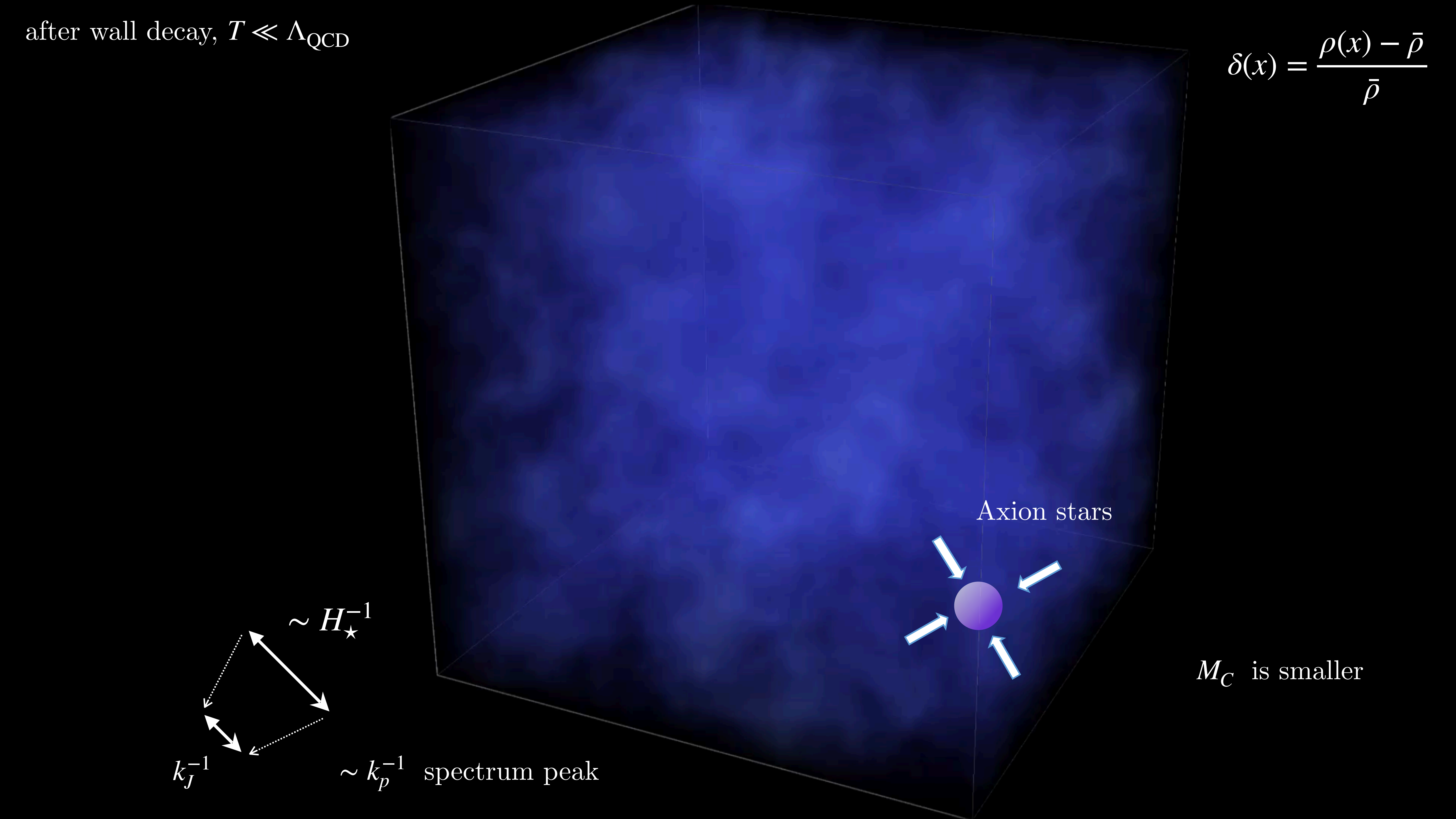
The remarkable coincidence





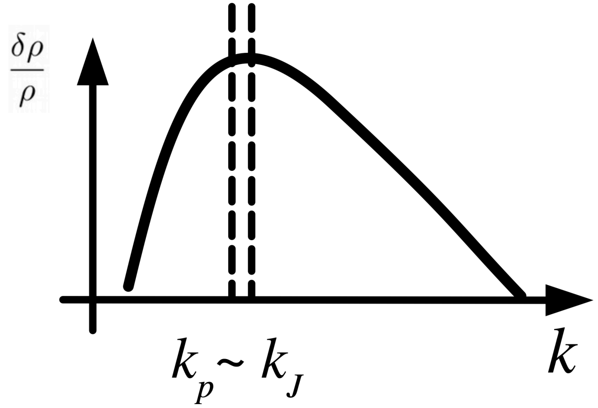


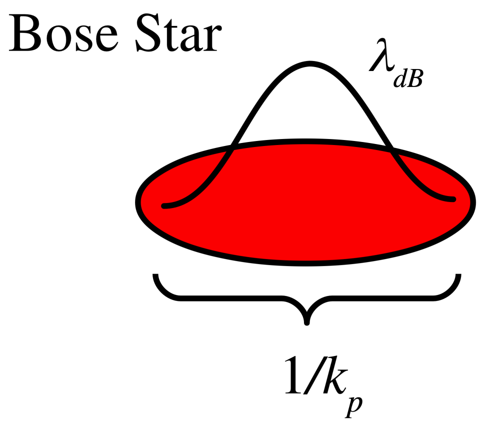
[MG, Hardy, Villadoro, 2405.19389]



after wall decay, $T \ll \Lambda_{QCD}$
$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$
Axion stars
M_C is smaller
$\sim H_\star^{-1}$
k_J^{-1}
$\sim k_p^{-1}$ spectrum peak

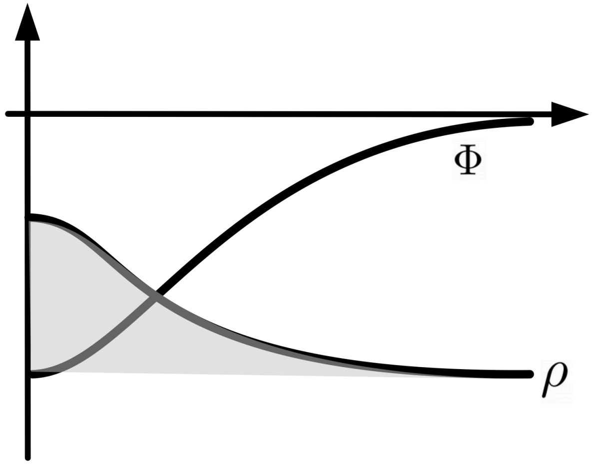
Axion stars:



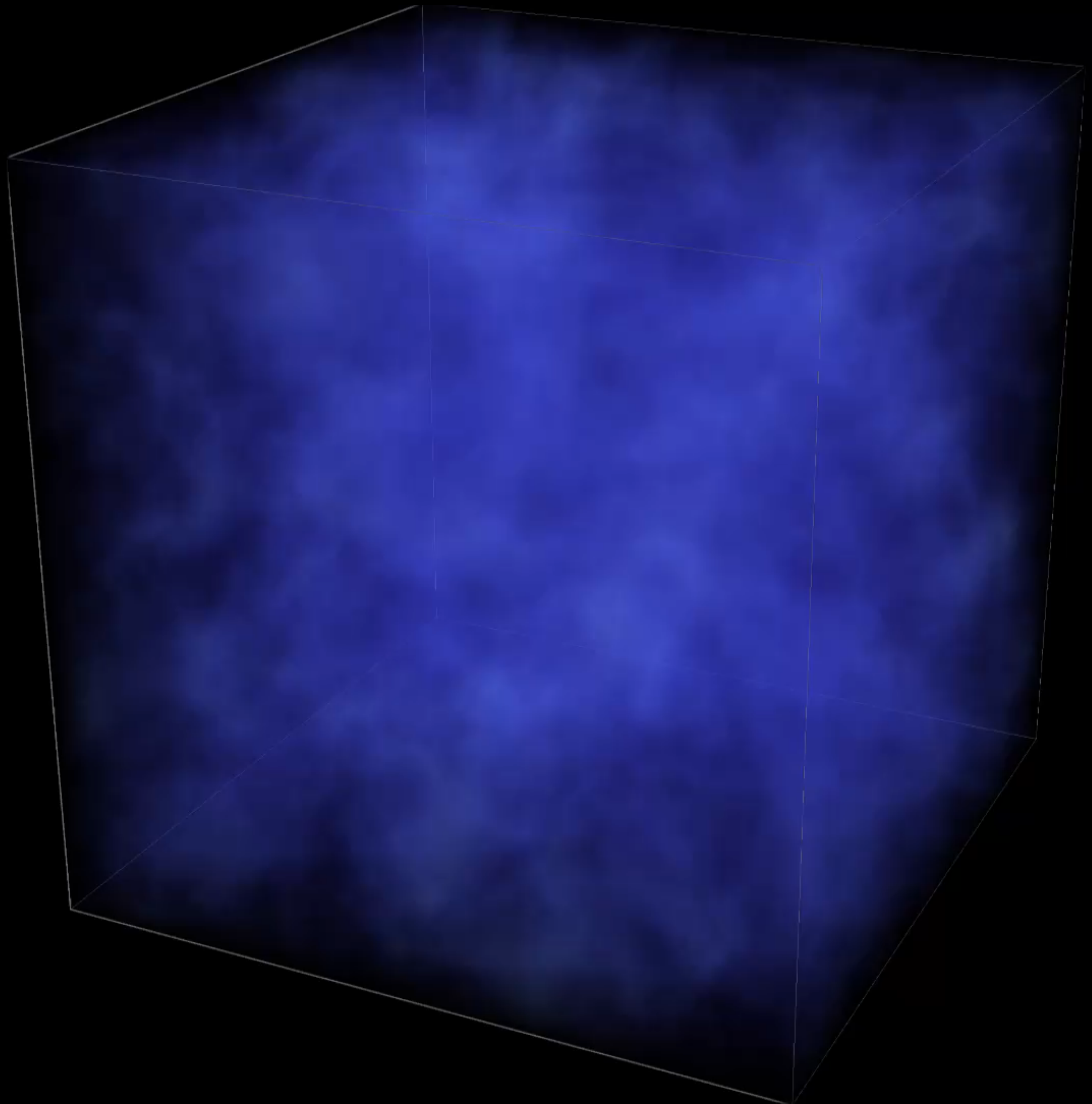


$$\begin{cases} \dot{\psi} + \frac{\nabla^2}{2m}\psi + m\Phi\psi = 0 \\ \nabla^2\Phi = 4\pi G|\psi|^2 \end{cases} \rightarrow \begin{cases} \nabla^2\sqrt{\rho} = 2m^2\Phi\sqrt{\rho} \\ \nabla^2\Phi = 4\pi G\rho \end{cases}$$

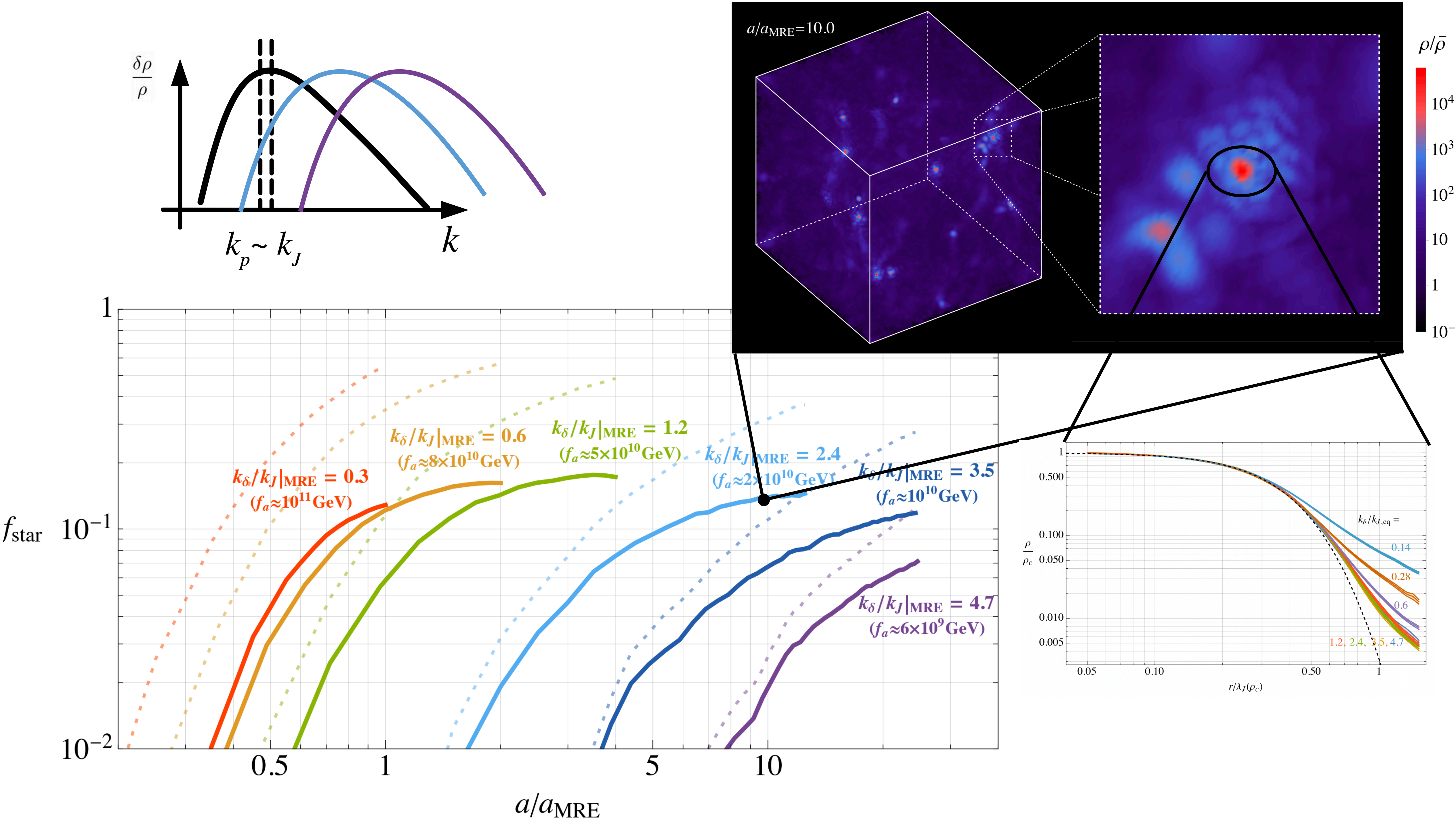
$$\rho = |\psi|^2$$



$$M_s R_s \sim \frac{1}{Gm^2}$$

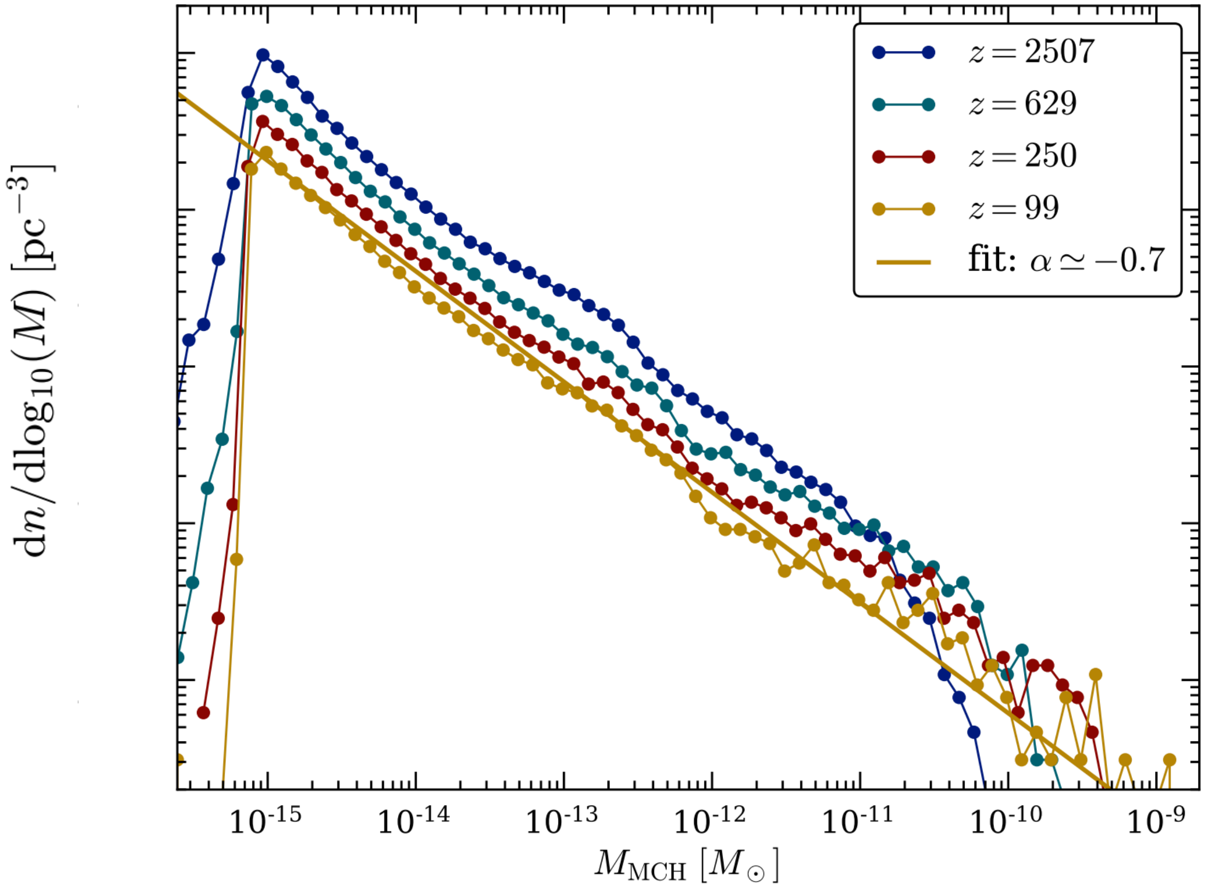


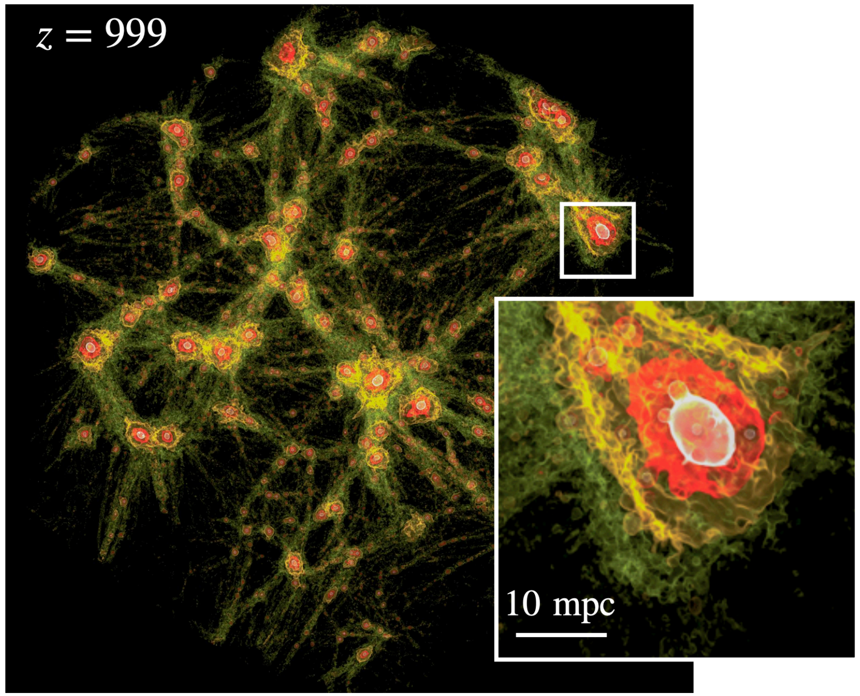
$$0.5 < \frac{a}{a_{\rm eq}} < 7$$



$\frac{\delta\rho}{\rho}$
$k_p \sim k_J$
k
$a/a_{\rm MRE}$=10.0
$\rho/\bar{\rho}$
10^4
10^3
10^2
10
1
$f_{\rm star}$
$k_\delta/k_J|_{\rm MRE}$ = 0.3 ($f_a \approx 10^{11}$GeV)
$k_\delta/k_J|_{\rm MRE}$ = 0.6 ($f_a \approx 8\times10^{10}$GeV)
$k_\delta/k_J|_{\rm MRE}$ = 1.2 ($f_a \approx 5\times10^{10}$GeV)
$k_\delta/k_J|_{\rm MRE}$ = 2.4 ($f_a \approx 2\times10^{10}$GeV)
$k_\delta/k_J|_{\rm MRE}$ = 3.5 ($f_a \approx 10^{10}$GeV)
$k_\delta/k_J|_{\rm MRE}$ = 4.7 ($f_a \approx 6\times10^{9}$GeV)
$a/a_{\rm MRE}$
ρ/ρ_c
$r/\lambda_J(\rho_c)$
$k_\delta/k_{J,\rm eq}$ =
0.14
0.28
0.6
1.2, 2.4, 3.5, 4.7

Minicluster halos mass distribution



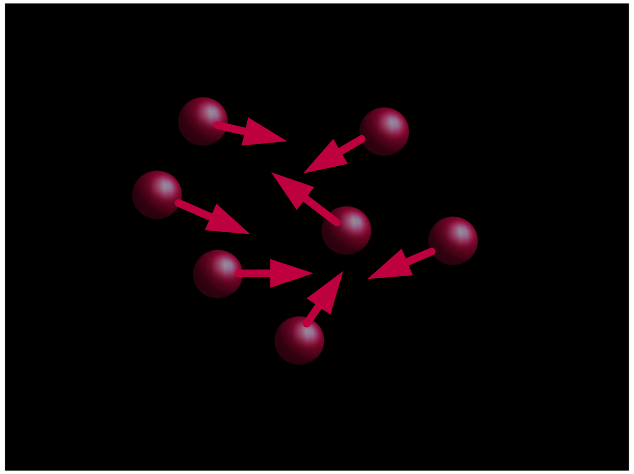


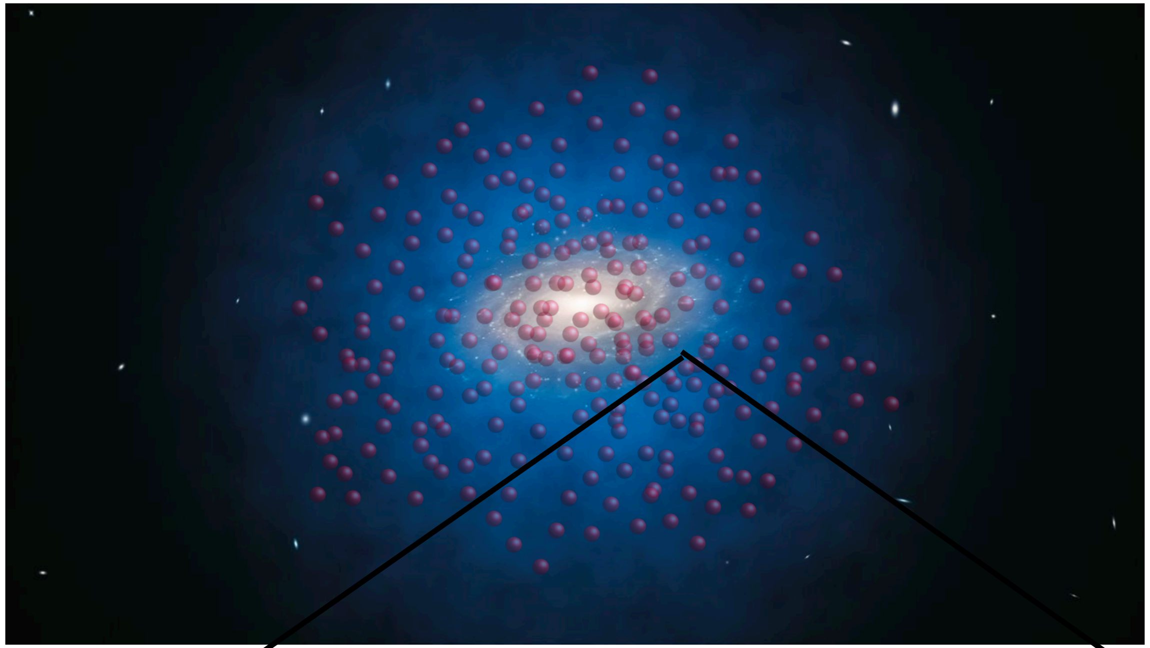
[Eggemeier, 22']

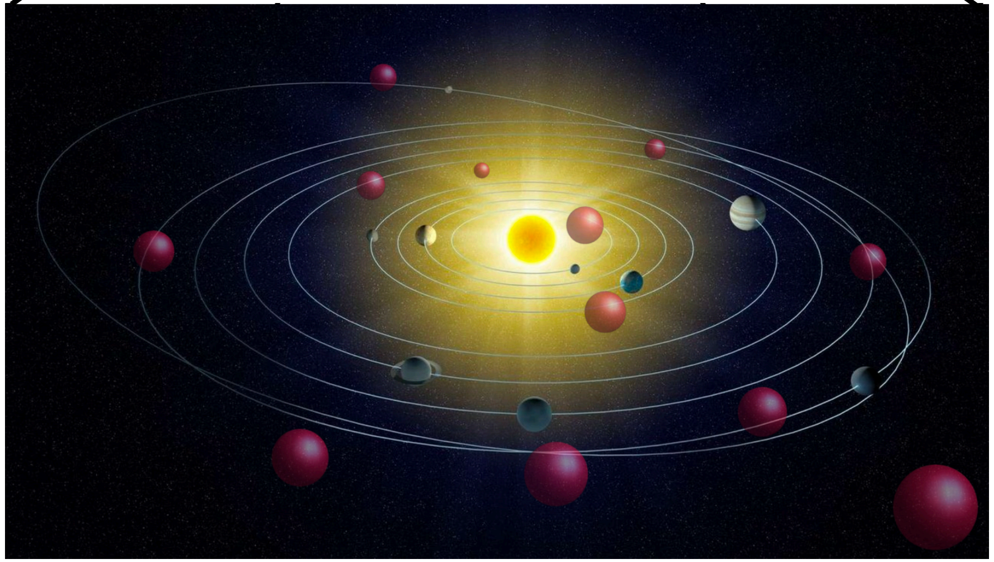
N-body simulations from initial conditions from string-wall decay at log $\simeq 7$

[Eggemeier et al, 19', 22']

Axion stars (after MRE):







e.g. for $\begin{cases} M_s = 10^{-19} M_\odot \\ f_a = 10^{10}\ \text{GeV} \\ f_s = 0.1 \end{cases} \rightarrow \begin{cases} n_s^{-1/3} = 1.4 \cdot 10^8\,\text{km} \\ \tau_\oplus = 5\ \text{yrs} \\ \Delta t \simeq 8\ \text{hrs} \end{cases}$

Axion "minivoids" [Eggemeier 22, O'Hare 22]

Conclusions

- Post-inflationary abundance still **uncertain**, despite progress

$$f_a \lesssim 10^{10}\,\mathrm{GeV} \quad \text{or} \quad m_a \gtrsim 0.5\,\mathrm{meV} \quad \text{from dark matter over-production}$$

- **Axion star** formation enhanced at MRE,
  but power spectrum after string-wall decay still uncertain

- Potential new observational opportunities

Thanks!