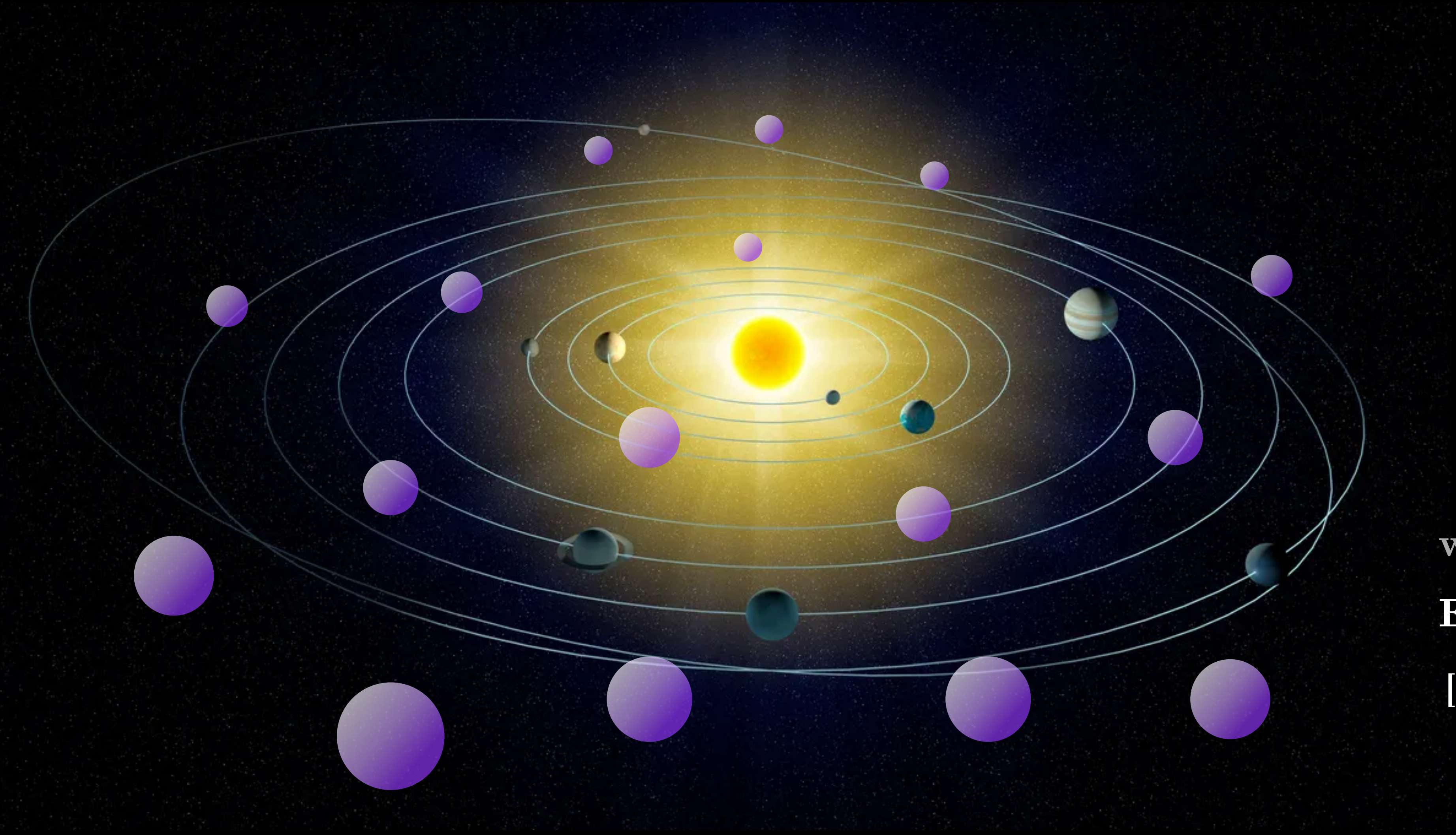
More Axion Stars from Strings

Marco Gorghetto



with

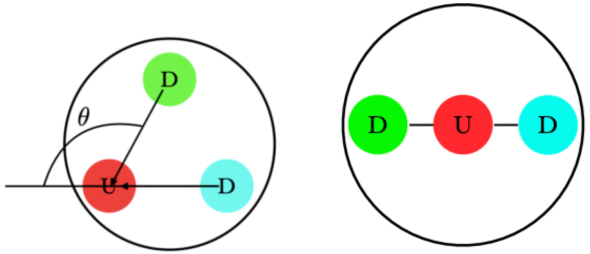
E. Hardy and G. Villadoro

[2405.19389]

QCD axion:

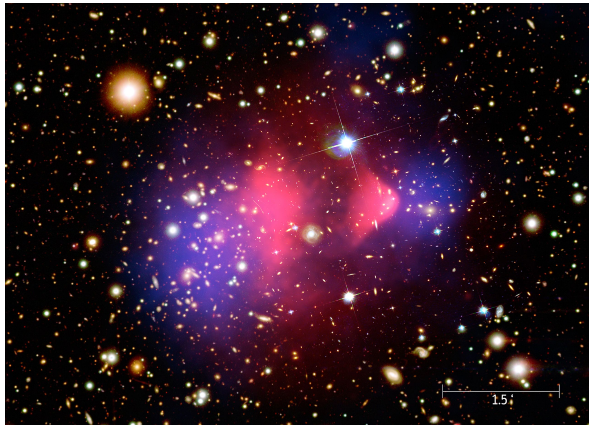
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \ldots \qquad \Rightarrow \qquad m = \frac{\chi_{\rm top}^{1/2}}{f_a} \simeq 0.57\,{\rm meV}\left(\frac{10^{10}\ {\rm GeV}}{f_a}\right)$$

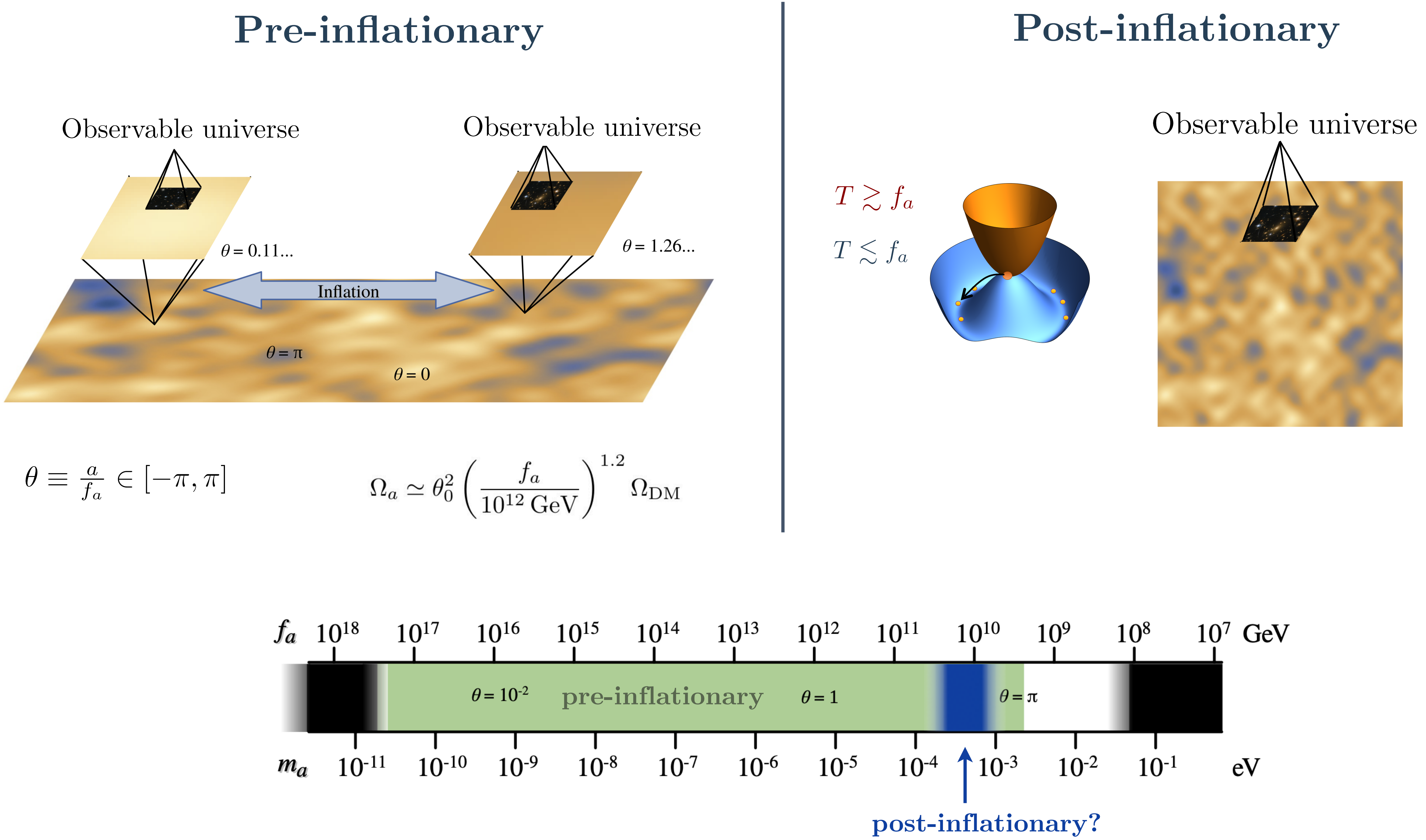
- Dynamically explains no neutron EdM



[picture from A. Hook]

- Contributes to all/part of the dark matter





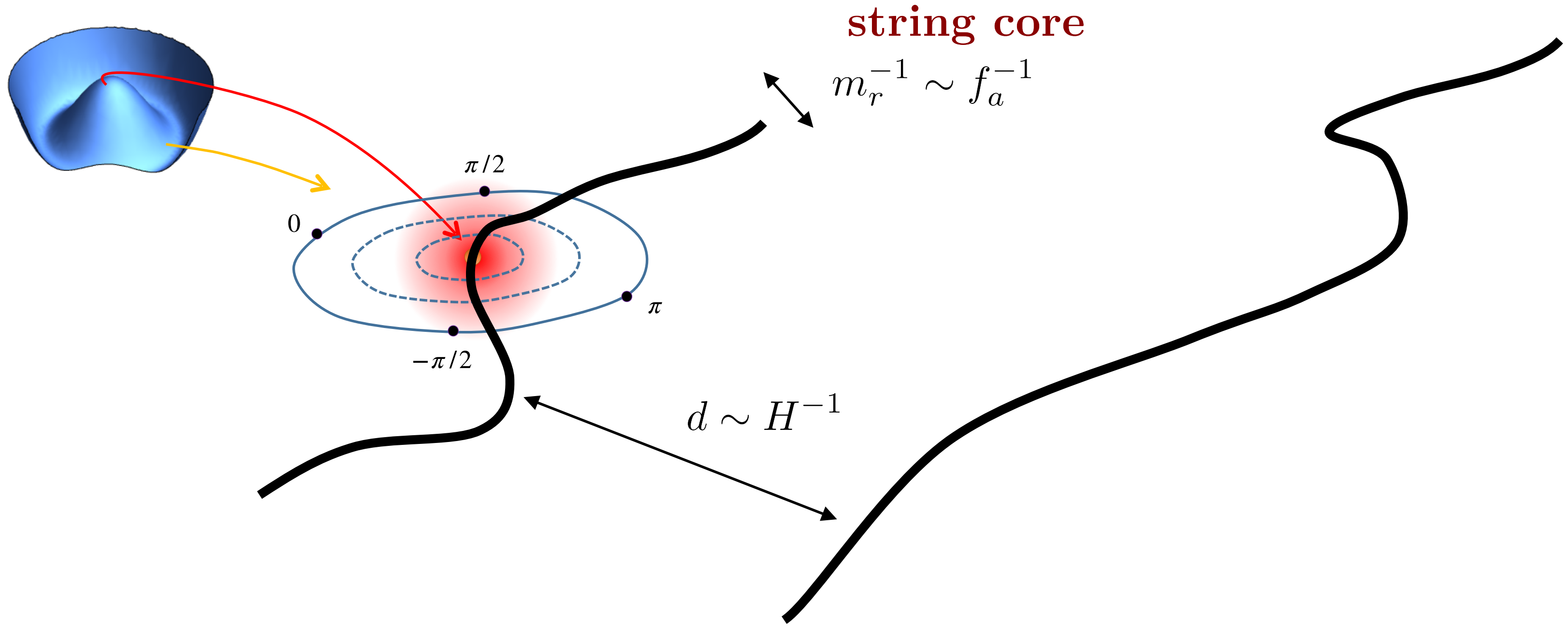
Pre-inflationary
Post-inflationary
Observable universe
Observable universe
Observable universe
θ = 0.11...
θ = 1.26...
Inflation
θ = π
θ = 0
$T \gtrsim f_a$
$T \lesssim f_a$
$\theta \equiv \frac{a}{f_a} \in [-\pi, \pi]$
$\Omega_a \simeq \theta_0^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.2} \Omega_{\mathrm{DM}}$
f_a 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} GeV
θ = 10^-2
pre-inflationary
θ = 1
θ = π
m_a 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} eV
post-inflationary?

Outline

- Review of post-inflationary scenario
- Structure formation around matter-radiation equality and axion stars
- Dark matter substructure today

@ $T \simeq f_a$ (or $H \simeq f_a$)

Kibble mechanism $\Longrightarrow$ **Axion strings**



string tension

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

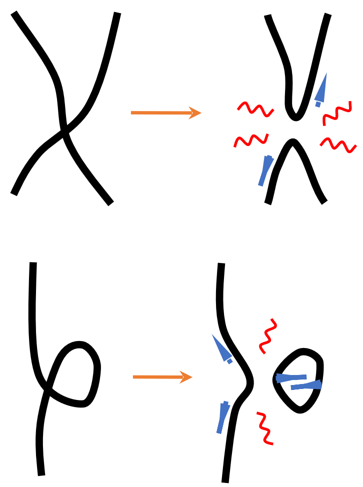
core — πf_a^2

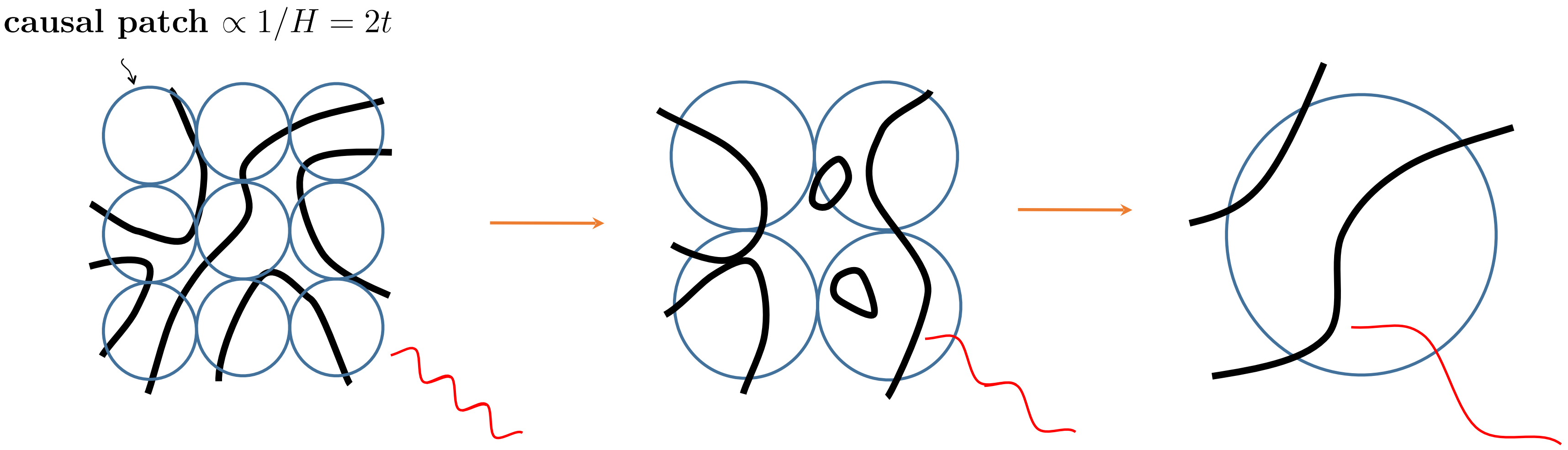
axion gradient — $\log \frac{d}{m_r^{-1}}$

$H \to T^2/M_p$

grows logarithmically in time

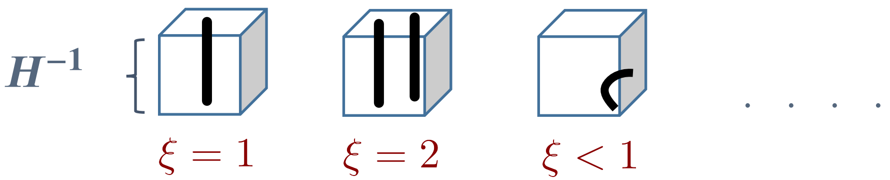
The Scaling Regime

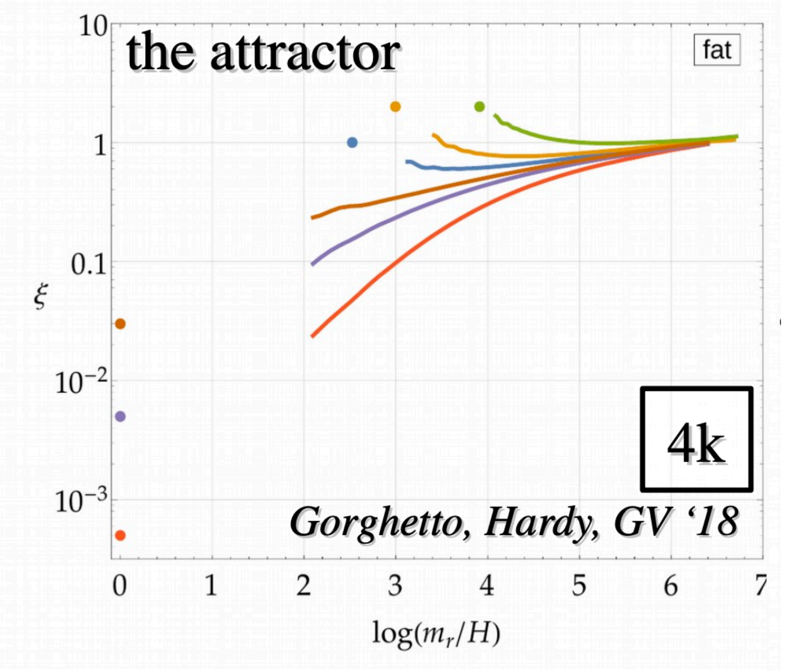


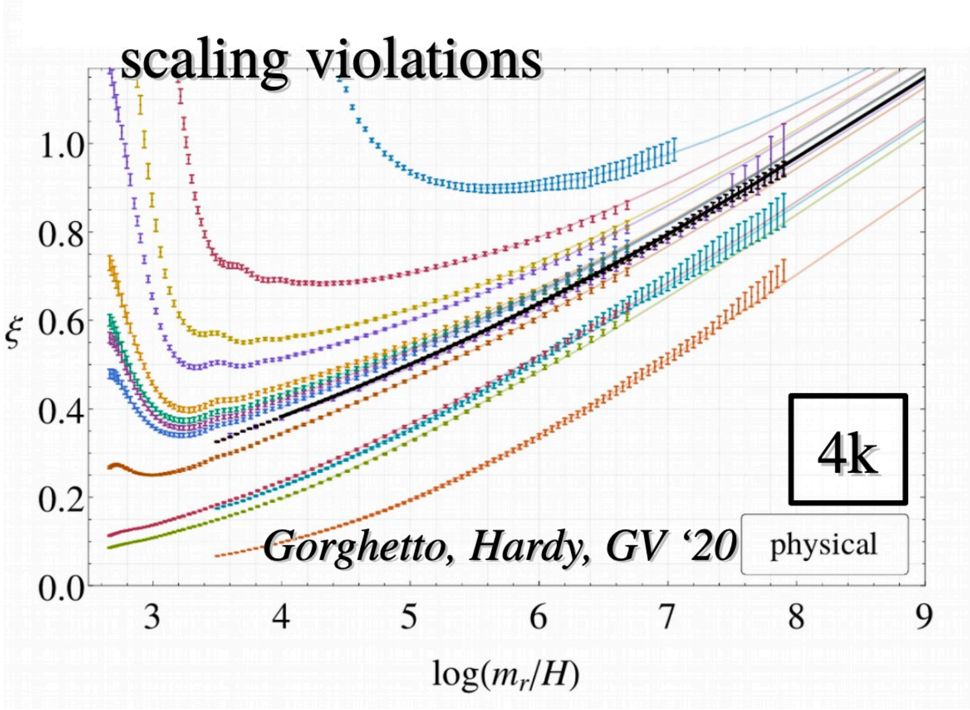


$$\rho_s = \frac{\xi \mu}{t^2}$$

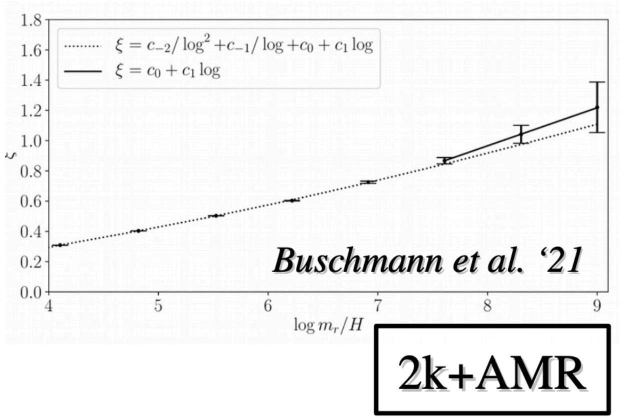
number of strings per Hubble patch

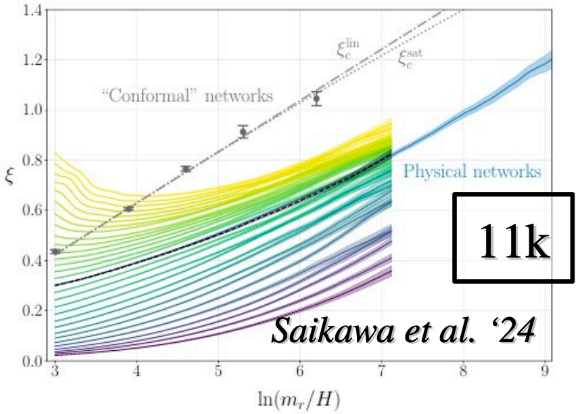


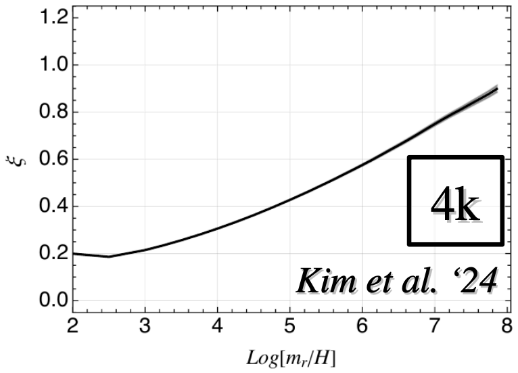




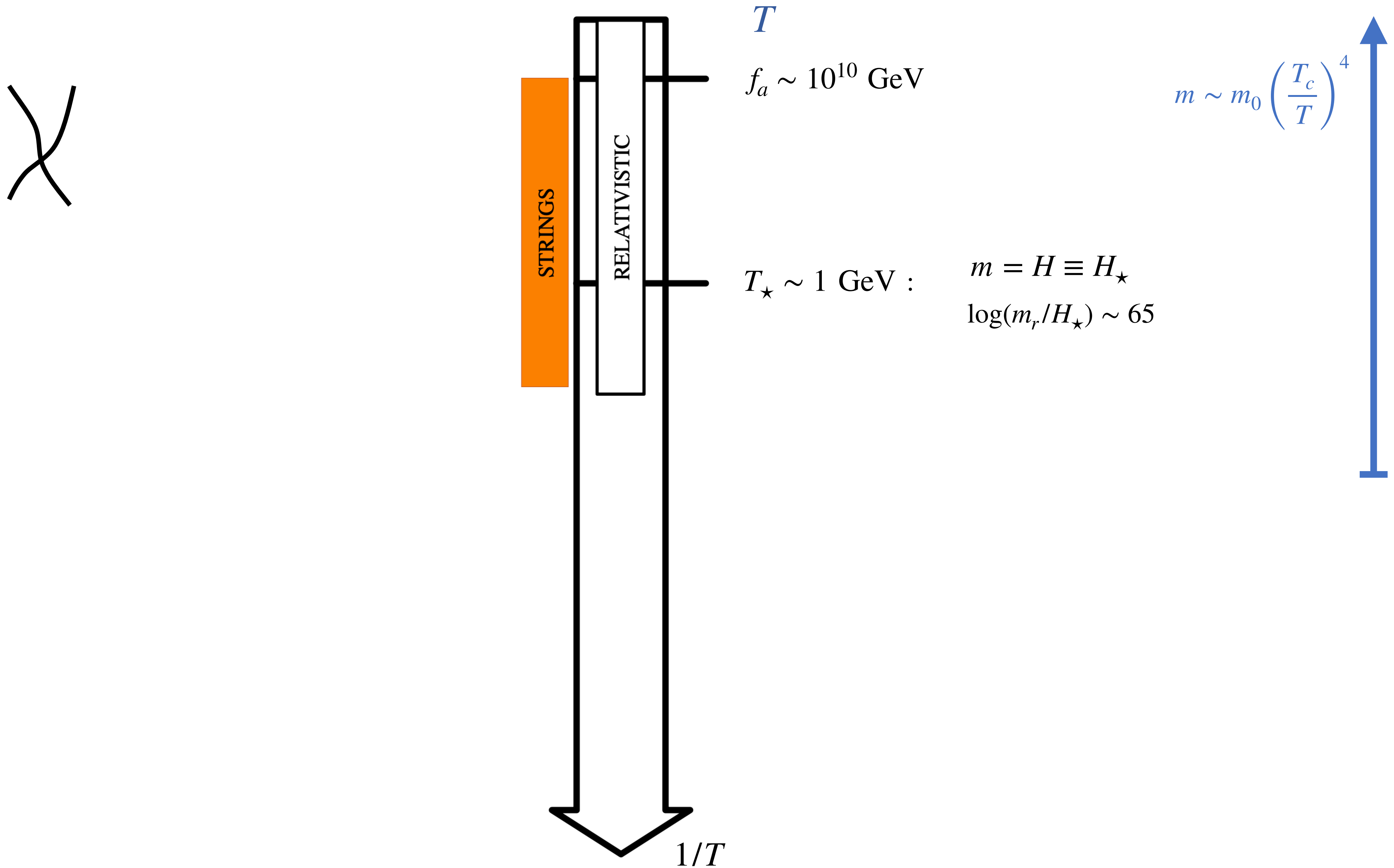
$$\xi \to \frac{\log(m_r/H)}{4 \div 5}$$







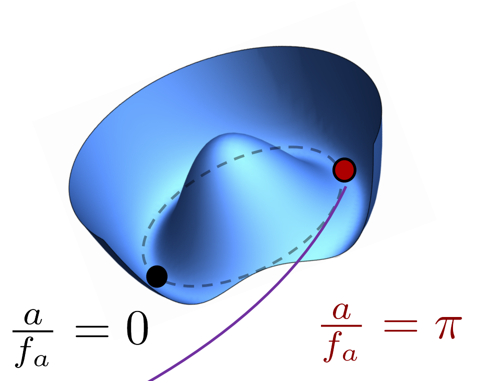
See also:
- Fleury, Moore '15
- Klaer, Moore '17, '19
- Kawasaki et al. '18
- Vaquero et al. '18
- Buschmann et al. '19

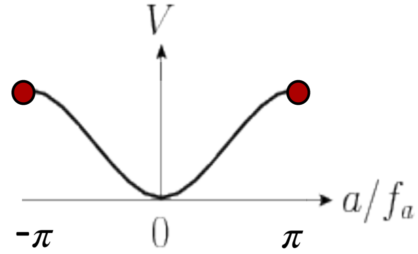


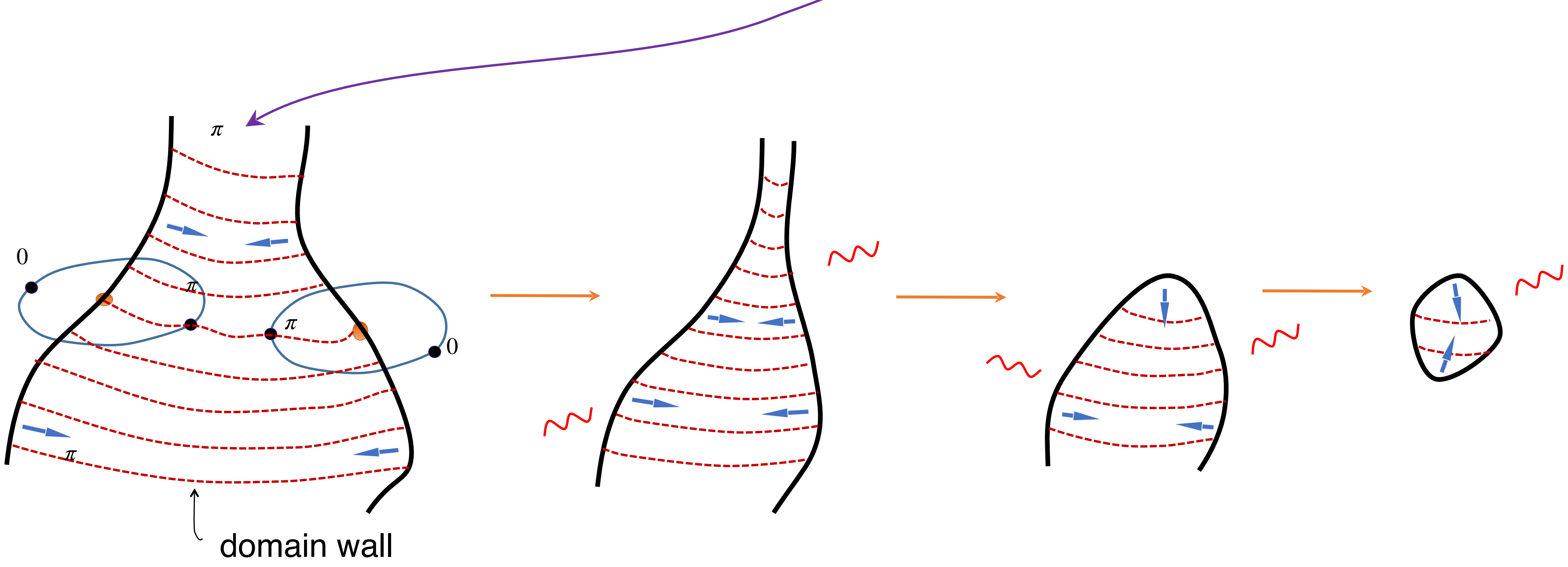
T
$f_a \sim 10^{10}$ GeV
$m \sim m_0 \left(\frac{T_c}{T}\right)^4$
STRINGS
RELATIVISTIC
$T_\star \sim 1$ GeV :
$m = H \equiv H_\star$
$\log(m_r/H_\star) \sim 65$
$1/T$

Domain Walls

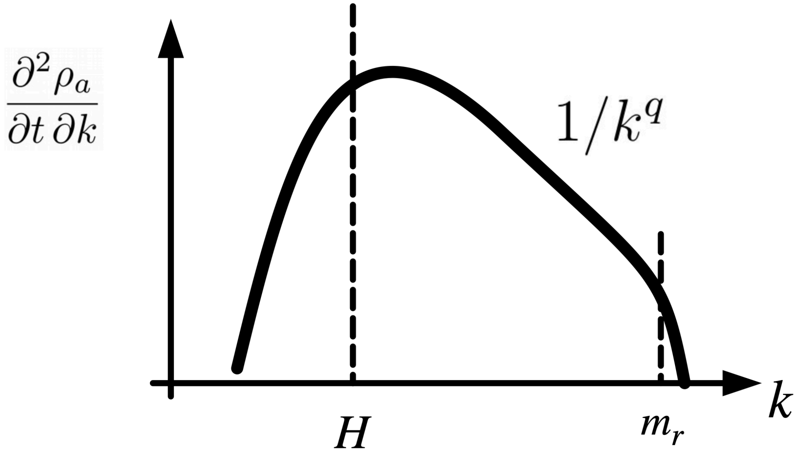
@ $T \simeq 1\,\text{GeV}$ $\quad (\; m = H \;)$







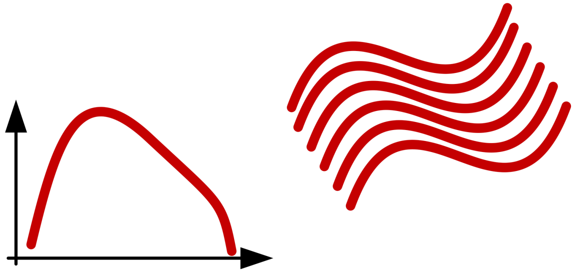
The Spectrum



$$n \sim \frac{\rho}{\langle k \rangle}$$

IR

$q > 1$

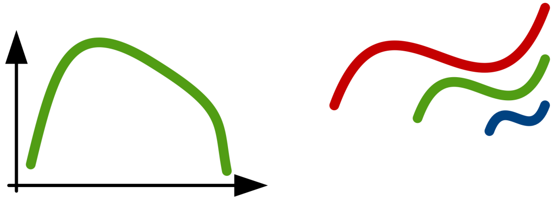


Davies, Shellard, ...

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

$\sim 10^3$

$q = 1$

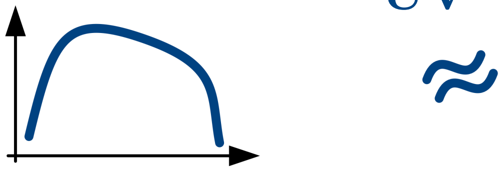


Sikivie, ...

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

UV

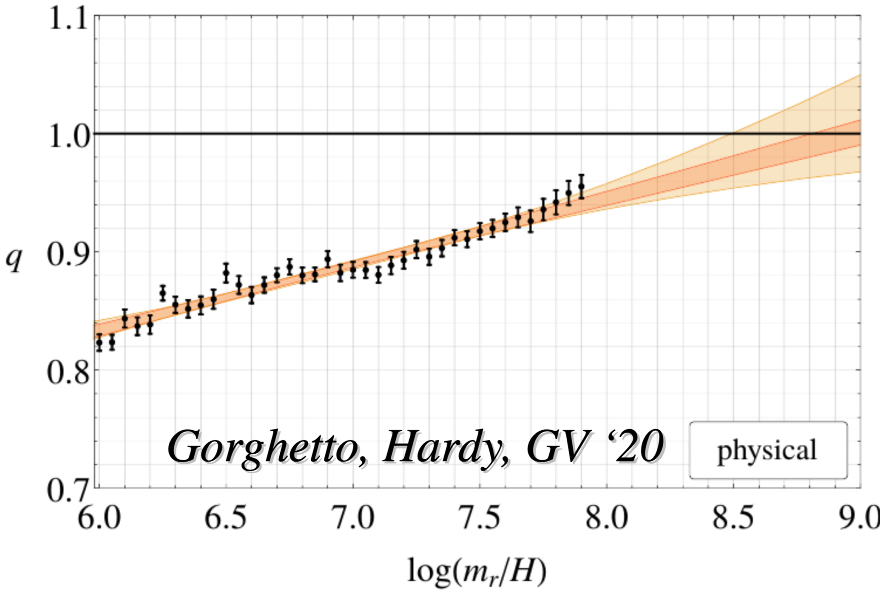
$q < 1$

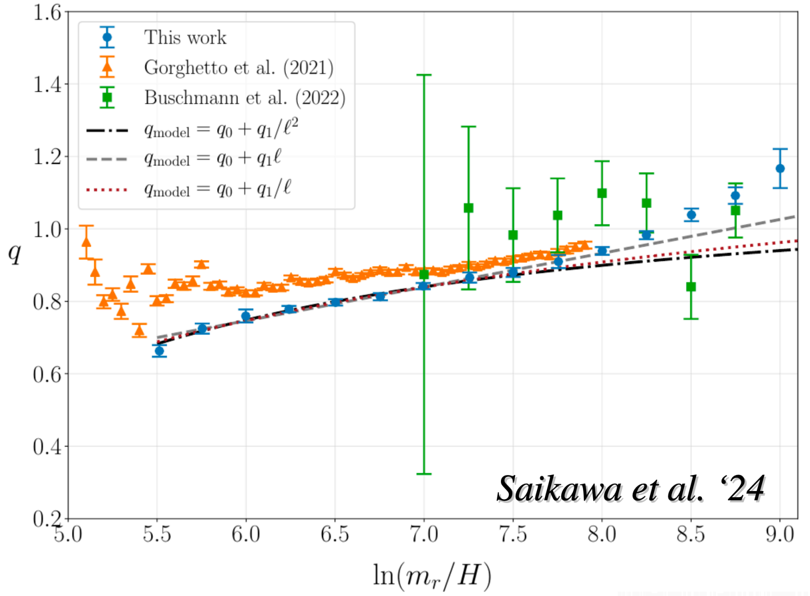


$$n \sim \frac{\rho}{H} \left(\frac{H}{m_r}\right)^{1-q} \sim n^{mis} \left(\frac{H}{m_r}\right)^{1-q}$$

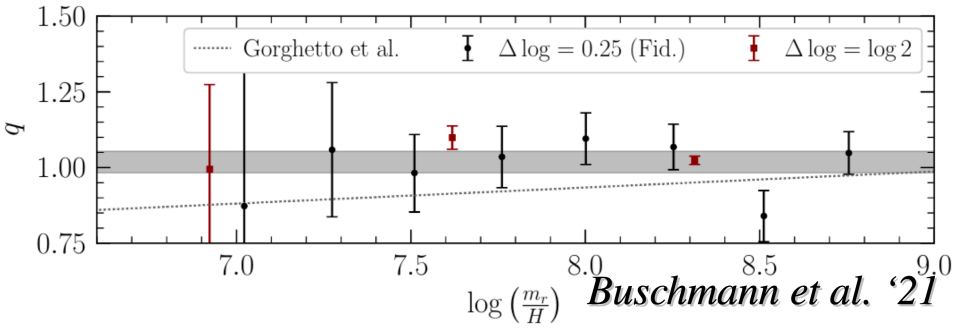
$\ll 1$

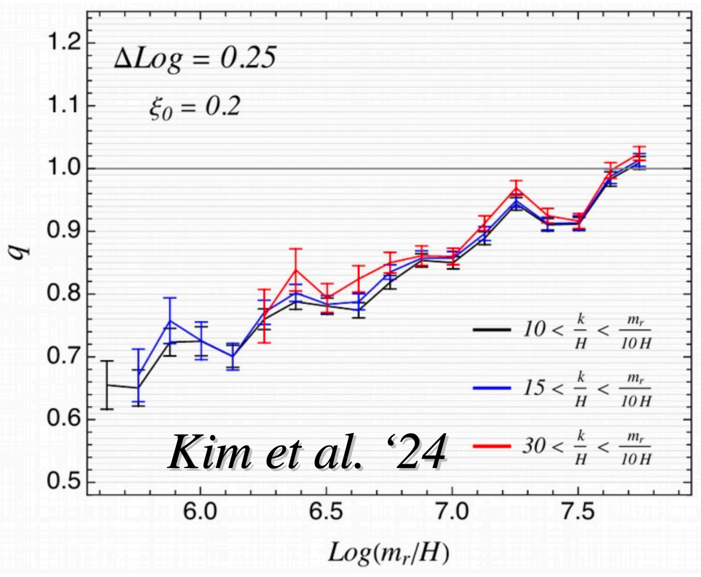
Spectral index





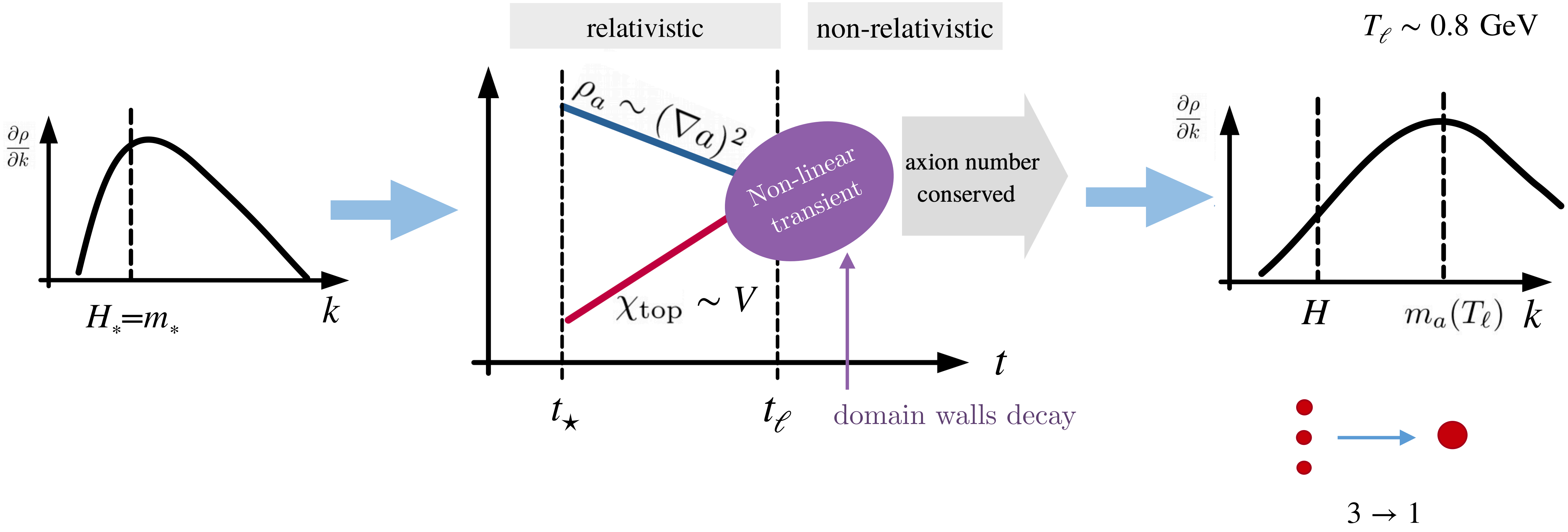
$q > 1?$





Effect of non-linearities (I)

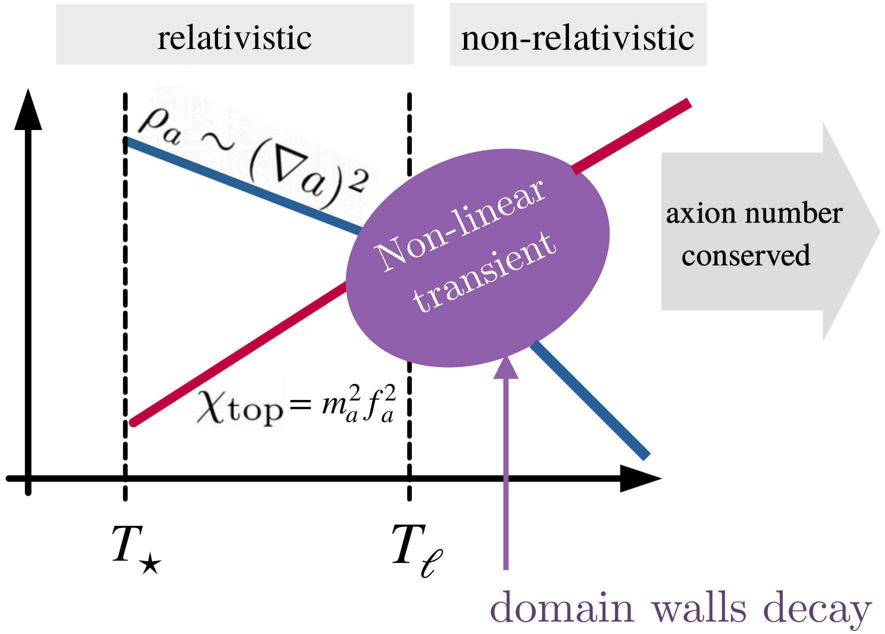
If $q \geq 1$: $\rho_a(t_\star) \gg \rho^{\text{mis}} \sim m_\star^2 f_a^2 = \chi_{\text{top}}(T_\star)$



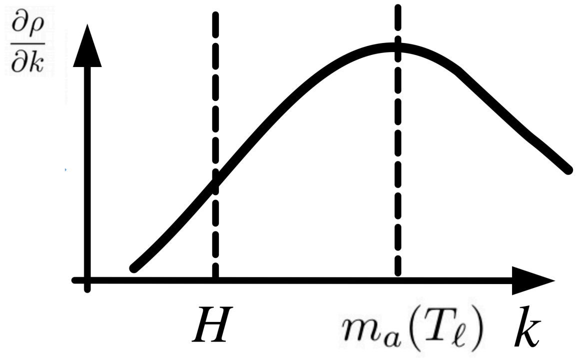
$f_a \simeq (1 \div 6) \cdot 10^{10}$ GeV $+$ DW?

($q > 1$, $q = 1$)

After DW decay: the standard lore



$m_a(T) \gg k_p$ axions become non-relativistic



$$m \sim m_0 \left(\frac{T_c}{T} \right)^4$$

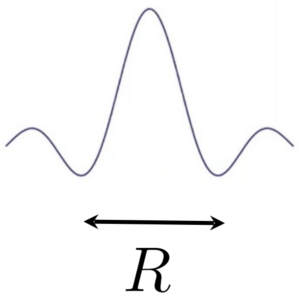
$$V(a) \simeq \frac{1}{2} m^2 a^2$$ axions become free

$\Longrightarrow$ the field redshifts like CDM until MRE

@ MRE, fluctuations $\delta\rho/\rho \sim 1$ gravitationally collapse in objects of size $\sim 1/k_p$

Gravitational collapse *vs* Jeans scale

overdensity ρ



spatial size of the overdensity

R

$\longleftrightarrow$

de Broglie wavelength of the particles
in the resulting clump

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

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

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

$\downarrow$

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

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

$R > \lambda_J \quad \leftrightarrow \quad k < k_J \quad \Longrightarrow$ fluctuations unaffected and behave like CDM

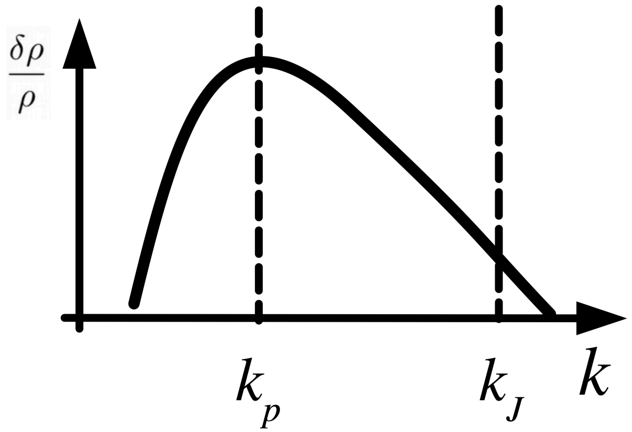
$R < \lambda_J \quad \leftrightarrow \quad k > k_J \quad \Longrightarrow$ fluctuations oscillate and quantum pressure prevents collapsing

After DW decay: the standard lore

quantum Jeans scale

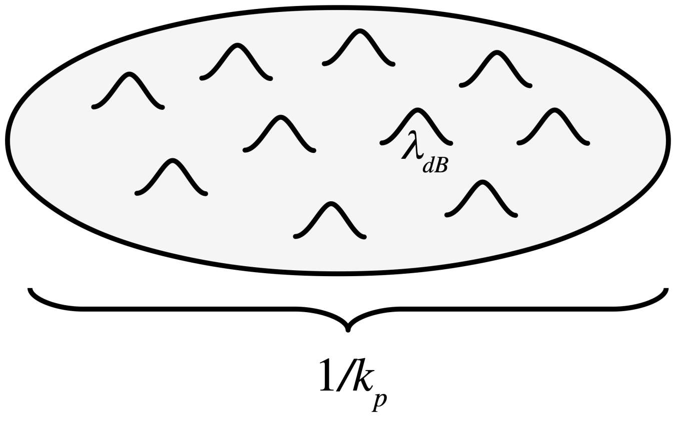
$k_J \equiv (16\pi G\rho m^2)^{\frac{1}{4}}$

@MRE



axion minicluster

$\lambda_{\rm dB} \ll 1/k_p$



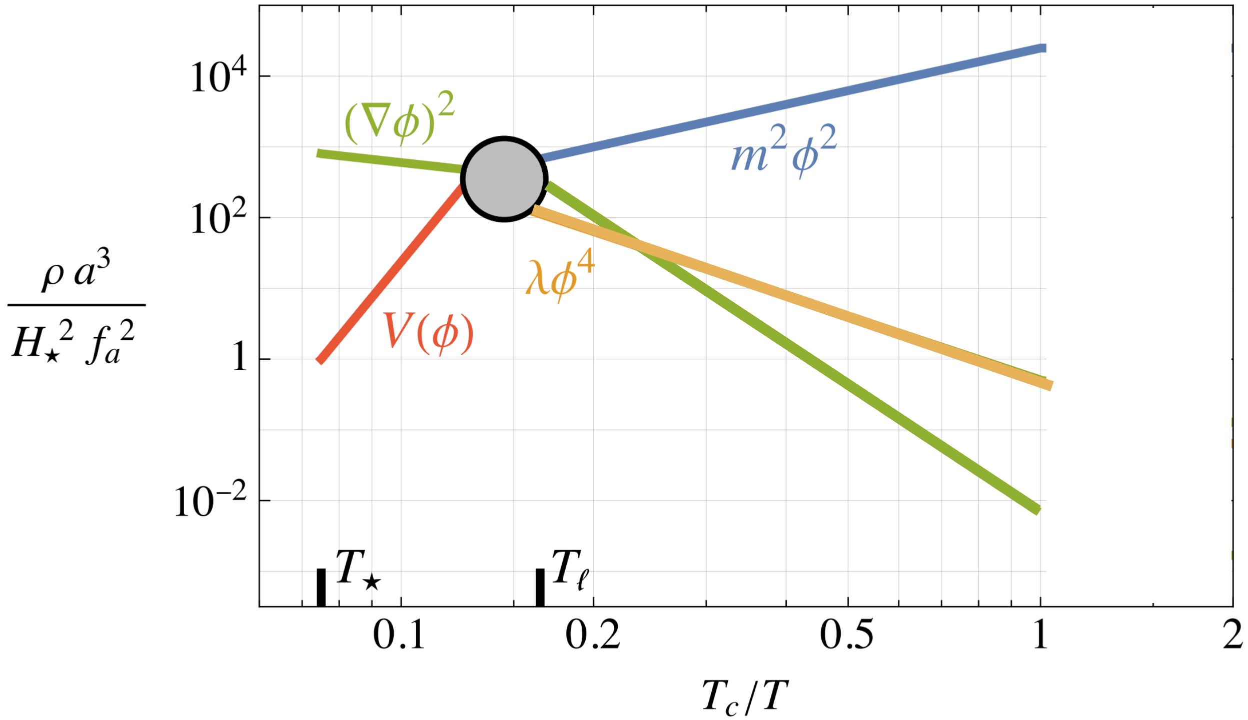
$$\left.\frac{k_p}{k_J}\right|_{\rm MRE} \simeq \left(\frac{f_a}{M_p}\right)^{1/3} \frac{k_{p\star}}{H_\star} \sim 10^{-3}\, \frac{k_{p\star}}{H_\star}$$

Naive because:

1) @ $t = t_\ell$: $k_p \to m(T_\ell)$

2) for $t_\ell < t < t_c$: extra blue shift due to the self-interactions

However: effect of non-linearities (II)



$\rho \sim \dot\phi^2 + m^2\phi^2 +$

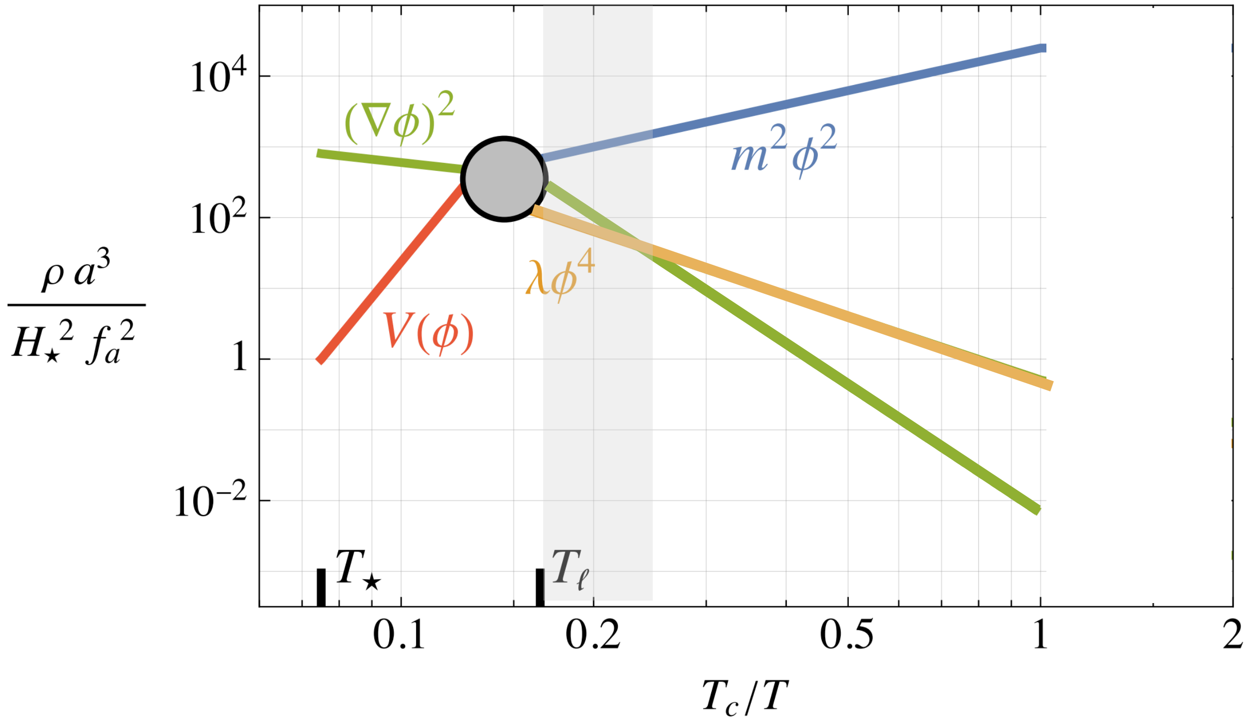
$(\nabla\phi)^2 \; + \; \lambda\phi^4$

$\phi \sim \psi e^{-imt}$

$T_c \sim 0.15\,\text{GeV}$

$$\left(i\partial_t + \frac{\nabla^2}{2m} - \xcancel{m\Phi} + \frac{\lambda|\psi|^2}{8a^3 m_0 m^2}\right)\psi = 0$$

However: effect of non-linearities (II)



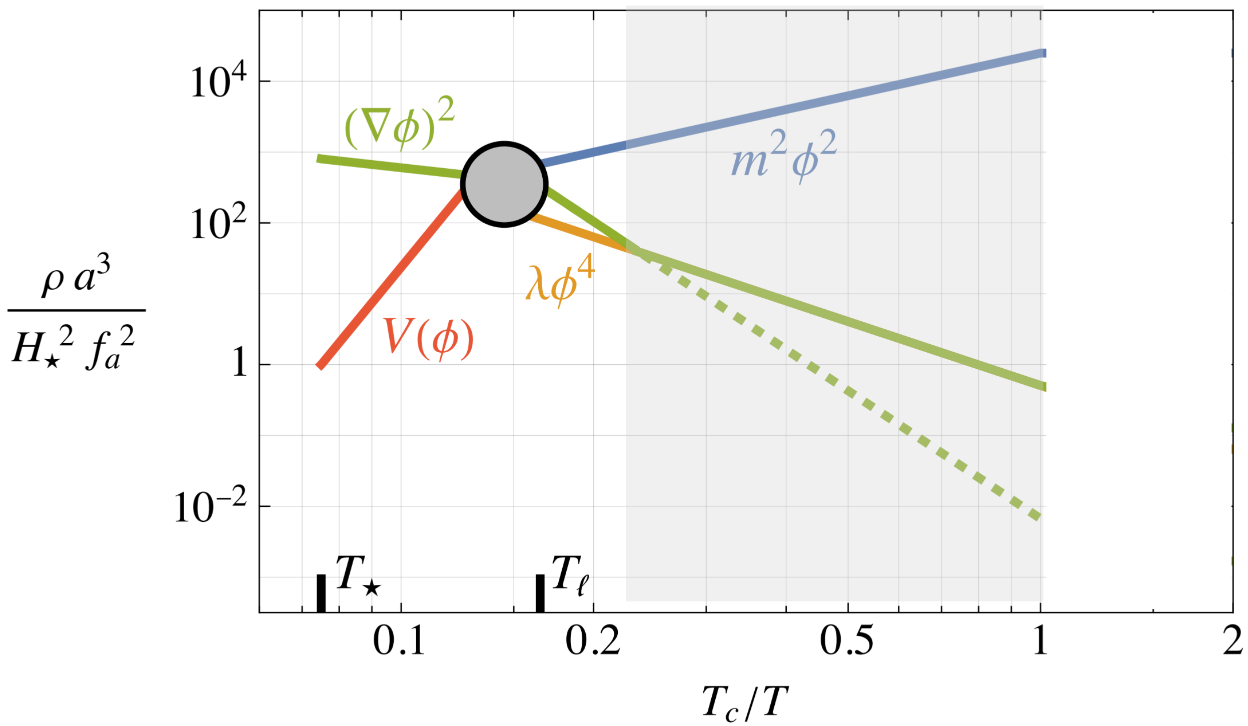
$$\rho \sim \dot{\phi}^2 + m^2\phi^2 + (\nabla\phi)^2 + \lambda\phi^4$$

grows

$$\left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi + \frac{\lambda|\psi|^2}{8a^3 m_0 m^2}\right)\psi = 0$$

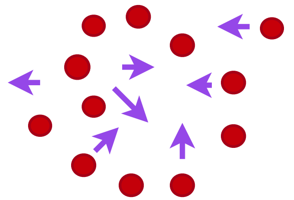
perturbation

However: effect of non-linearities (II)



$$\rho \sim \dot\phi^2 + m^2\phi^2 + (\nabla\phi)^2 + \lambda\phi^4$$

λ grows



$$\left(i\partial_t + \frac{\nabla^2}{2m} - \cancel{m\Phi} + \frac{\lambda|\psi|^2}{8a^3 m_0 m^2}\right)\psi = 0$$

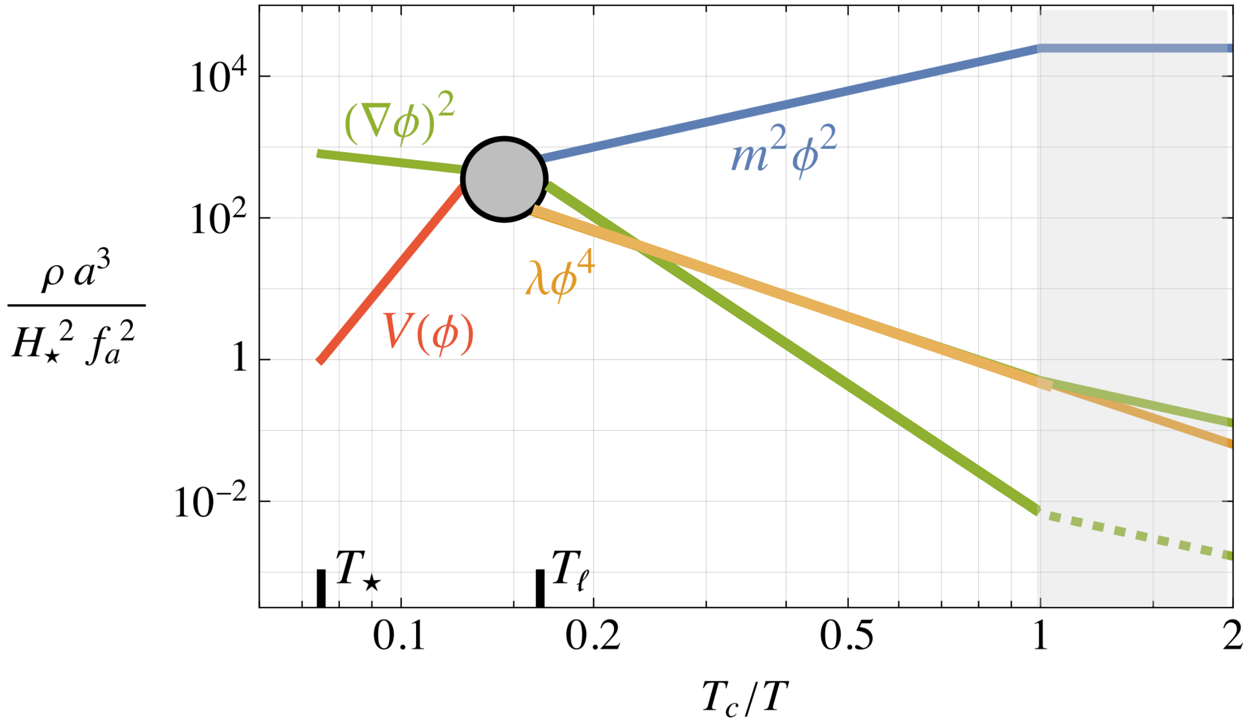
same order as the others

$$k_p \to k_v = \sqrt{\lambda\langle\phi^2\rangle} \simeq \sqrt{\rho}/f_a$$

$$(\nabla\phi)^2 \sim \lambda\phi^4$$

$$\tau_v = 8m/(\lambda\phi^2)$$

However: effect of non-linearities (II)

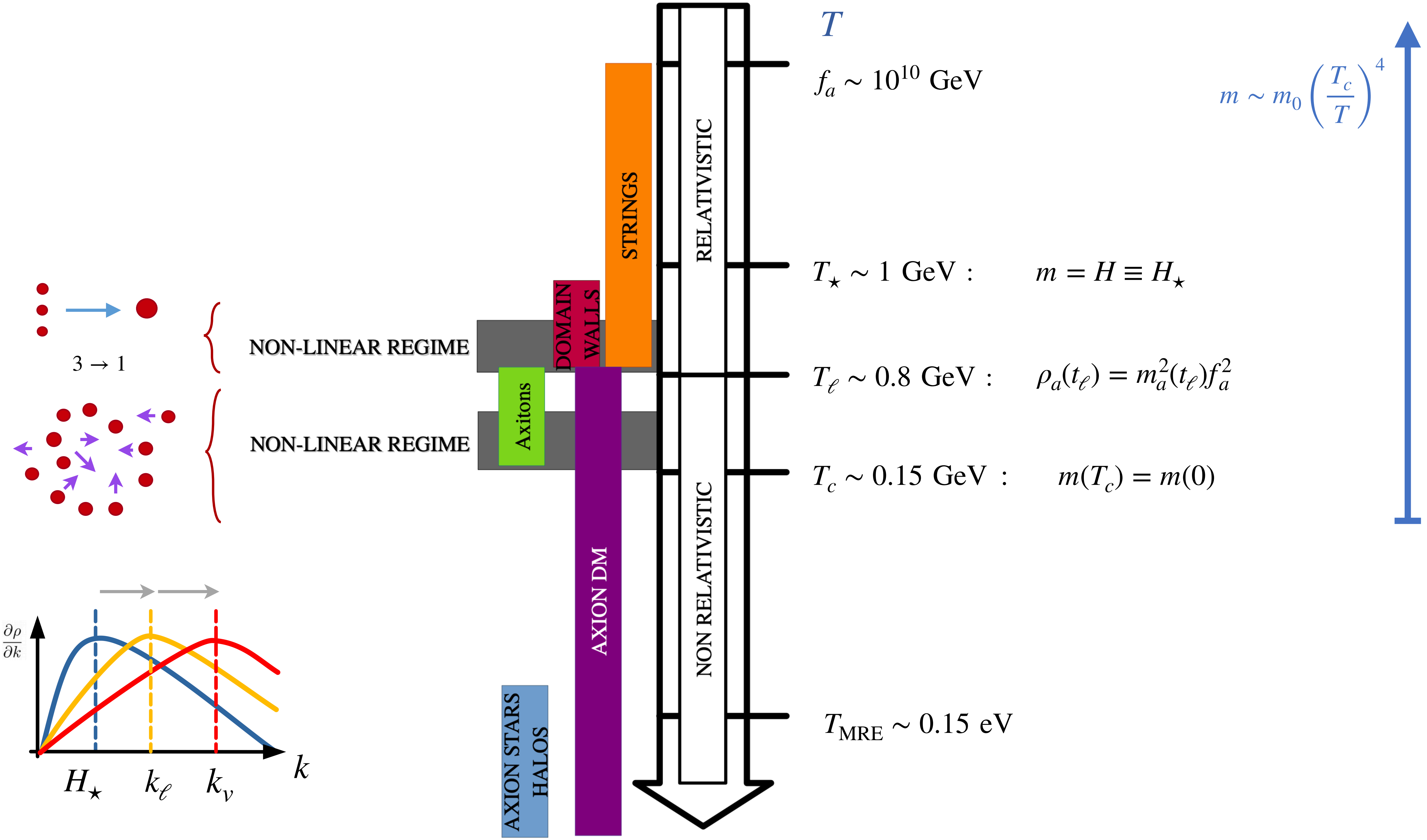


$$\rho \sim \dot{\phi}^2 + m^2\phi^2 + (\nabla\phi)^2 + \lambda\phi^4$$

λ → constant

$$\left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi + \frac{\lambda|\psi|^2}{8a^3 m_0 m^2}\right)\psi = 0$$

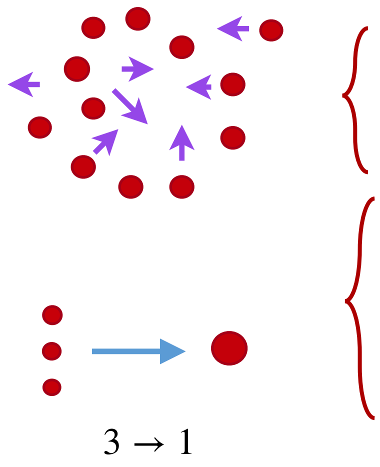
↓ perturbation



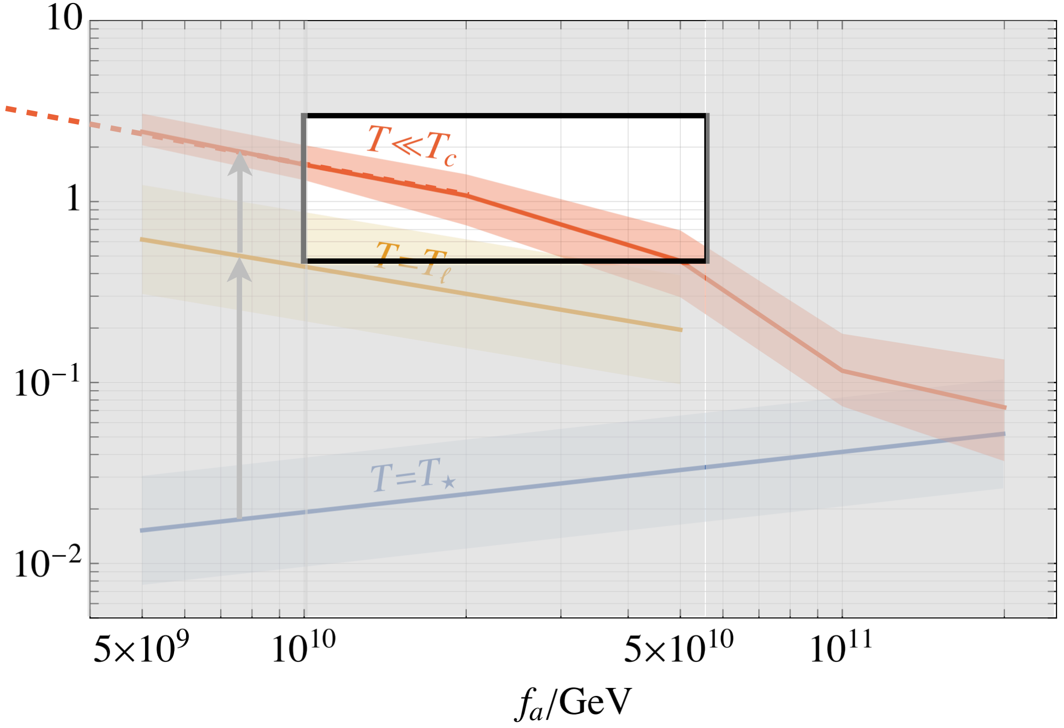
T
$f_a \sim 10^{10}$ GeV
$m \sim m_0 \left(\frac{T_c}{T}\right)^4$
STRINGS
RELATIVISTIC
$T_\star \sim 1$ GeV : $m = H \equiv H_\star$
DOMAIN WALLS
NON-LINEAR REGIME
$3 \to 1$
$T_\ell \sim 0.8$ GeV : $\rho_a(t_\ell) = m_a^2(t_\ell) f_a^2$
Axitons
NON-LINEAR REGIME
$T_c \sim 0.15$ GeV : $m(T_c) = m(0)$
AXION DM
NON RELATIVISTIC
$\frac{\partial \rho}{\partial k}$
k
$H_\star$
k_ℓ
k_v
$T_{\rm MRE} \sim 0.15$ eV
AXION STARS HALOS

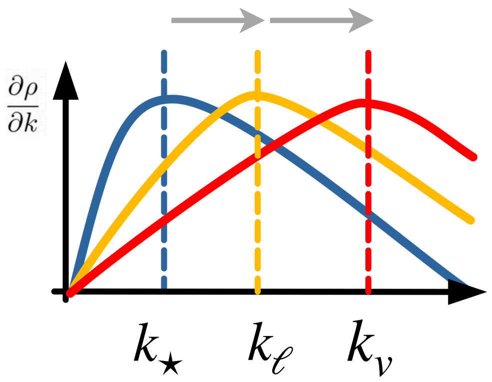
The remarkable coincidence

$$\left.\frac{k_p}{k_J}\right|_{\mathrm{MRE}} \simeq 0.4 \left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)^{1/2}$$



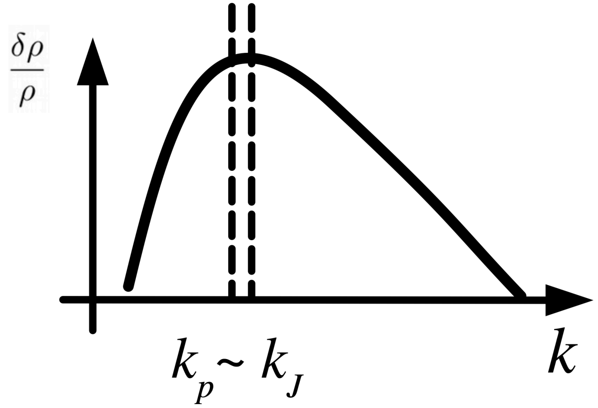
$\frac{k_p}{k_J}|_{\mathrm{MRE}}$

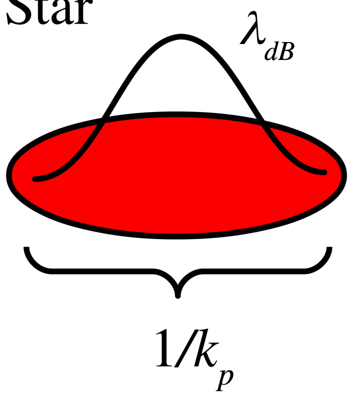




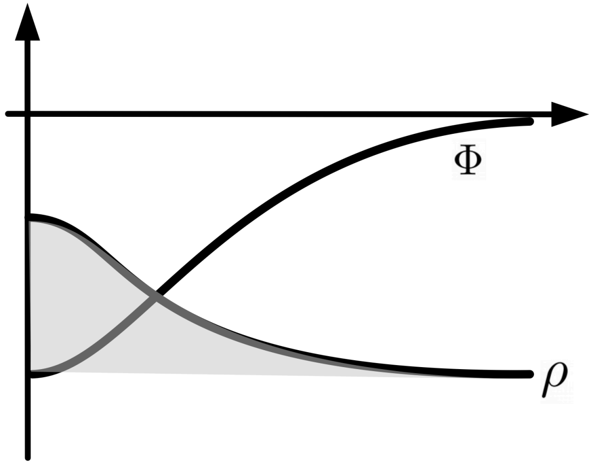
$$k_p \to k_v = \sqrt{\lambda\langle\phi^2\rangle} \simeq \sqrt{\rho}/f_a$$

Axion stars:





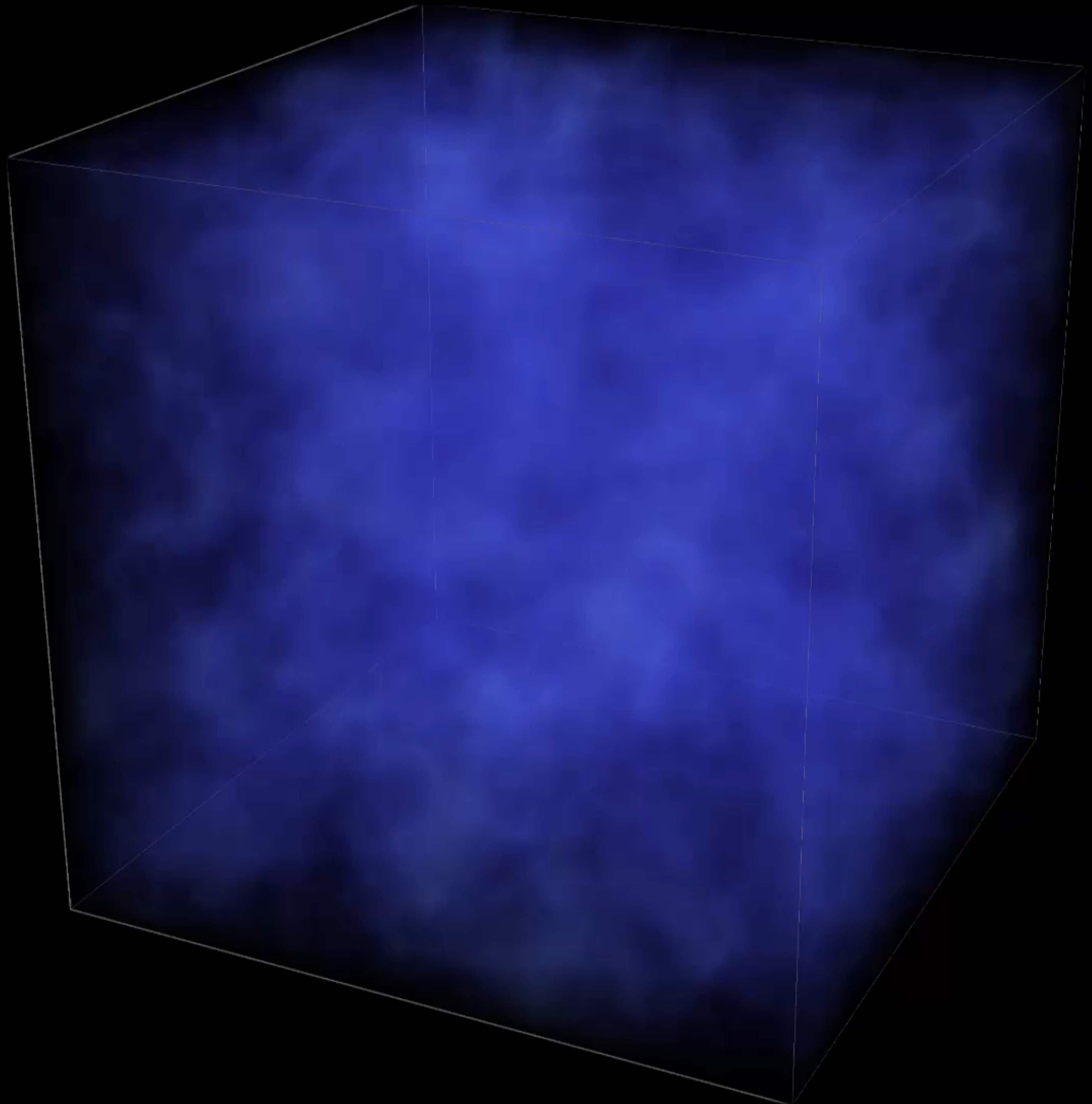
$$\begin{cases} \dot{\psi} + \frac{\nabla^2}{2m}\psi + m\Phi\psi = 0 \\ \nabla^2\Phi = 4\pi G|\psi|^2 \end{cases} \rightarrow \begin{cases} \nabla^2\sqrt{\rho} = 2m^2\Phi\sqrt{\rho} \\ \nabla^2\Phi = 4\pi G\rho \end{cases} \qquad \rho = |\psi|^2$$



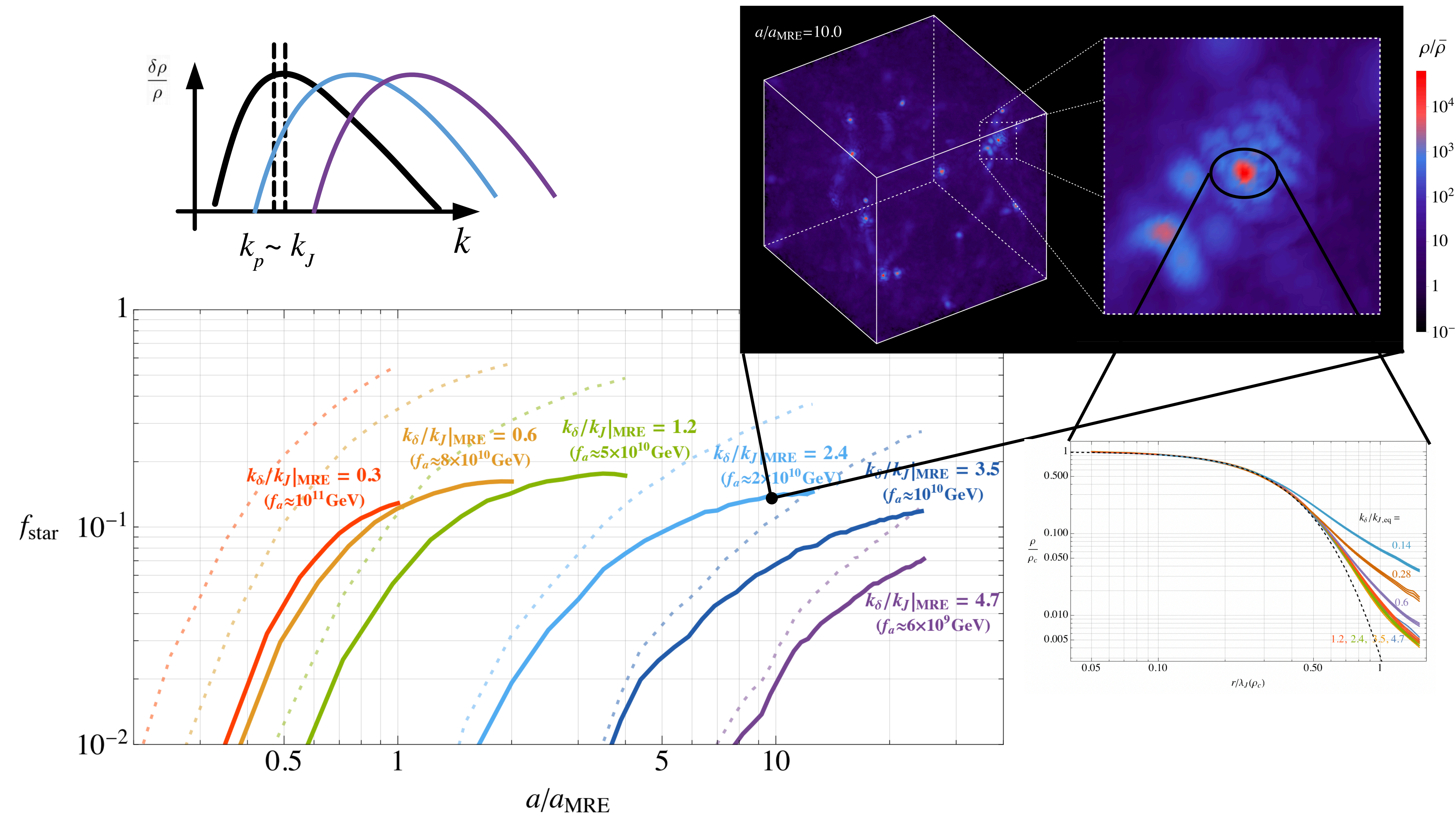
$$\frac{1}{2}mv^2 \sim \frac{GM_s m}{R_s}$$

$$R_s \sim \frac{1}{mv} \sim 1/k_J$$

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

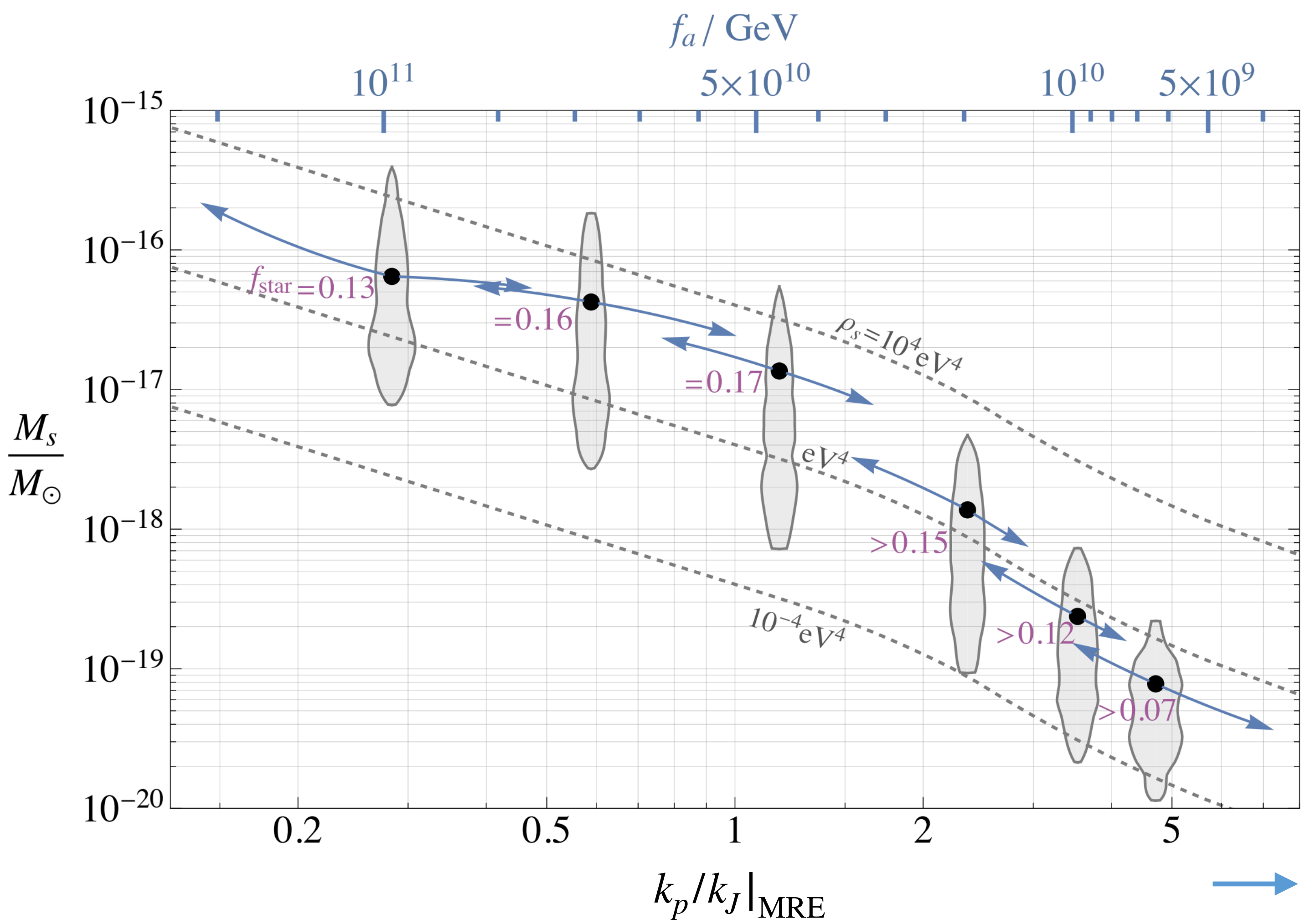


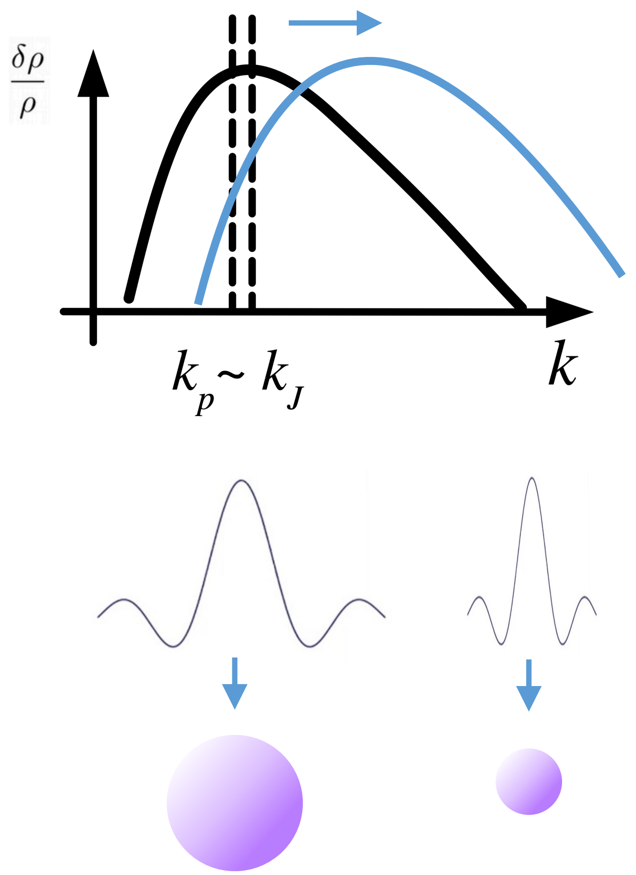
$$0.5 < \frac{a}{a_{\mathrm{eq}}} < 7$$



δρ/ρ
k_p ~ k_J
k
a/a_MRE=10.0
ρ/ρ̄
10^4
10^3
10^2
10
1
f_star
1
10^-1
10^-2
0.5
1
5
10
a/a_MRE
k_δ/k_J|MRE = 0.3 (f_a≈10^11 GeV)
k_δ/k_J|MRE = 0.6 (f_a≈8×10^10 GeV)
k_δ/k_J|MRE = 1.2 (f_a≈5×10^10 GeV)
k_δ/k_J|MRE = 2.4 (f_a≈2×10^10 GeV)
k_δ/k_J|MRE = 3.5 (f_a≈10^10 GeV)
k_δ/k_J|MRE = 4.7 (f_a≈6×10^9 GeV)
ρ/ρ_c
1
0.500
0.100
0.050
0.010
0.005
k_δ/k_J,eq =
0.14
0.28
0.6
1.2, 2.4, 3.5, 4.7
0.05
0.10
0.50
1
r/λ_J(ρ_c)

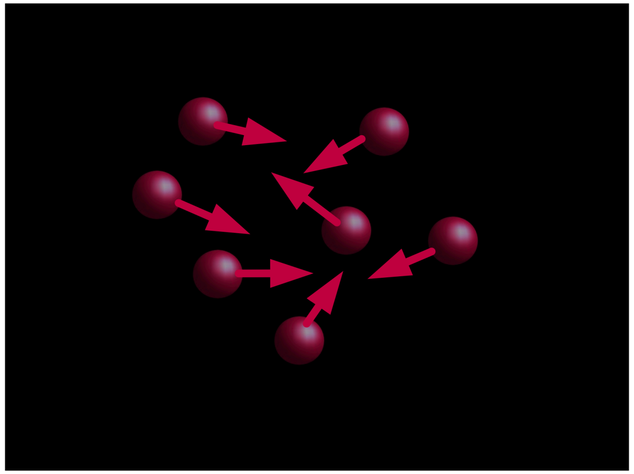
Axion stars properties:

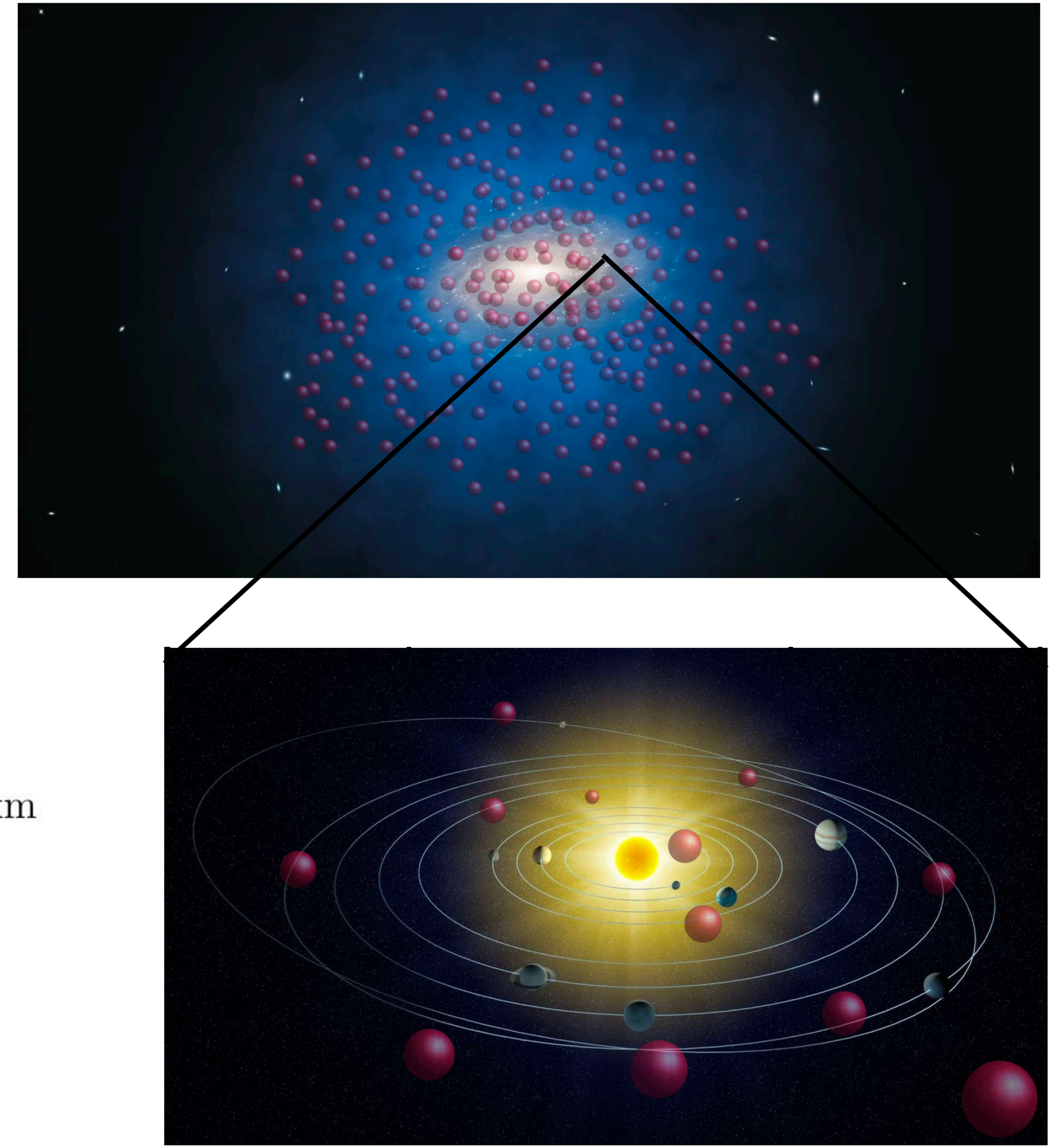




$$\bar{R}_{0.1} \approx 2.1 \cdot 10^6 \text{ km} \left(\frac{10^{10}\text{ GeV}}{f_a}\right)^{\frac{1}{2}} \qquad v_a \approx \text{mm/s}$$

Axion stars (after MRE):





e.g. for

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

Conclusions

- Post-inflationary abundance still **uncertain** (despite progress)

- **Important** non-linear dynamics after strings-wall decay

- **Axion star** formation enhanced at MRE

- Potential new observational opportunities