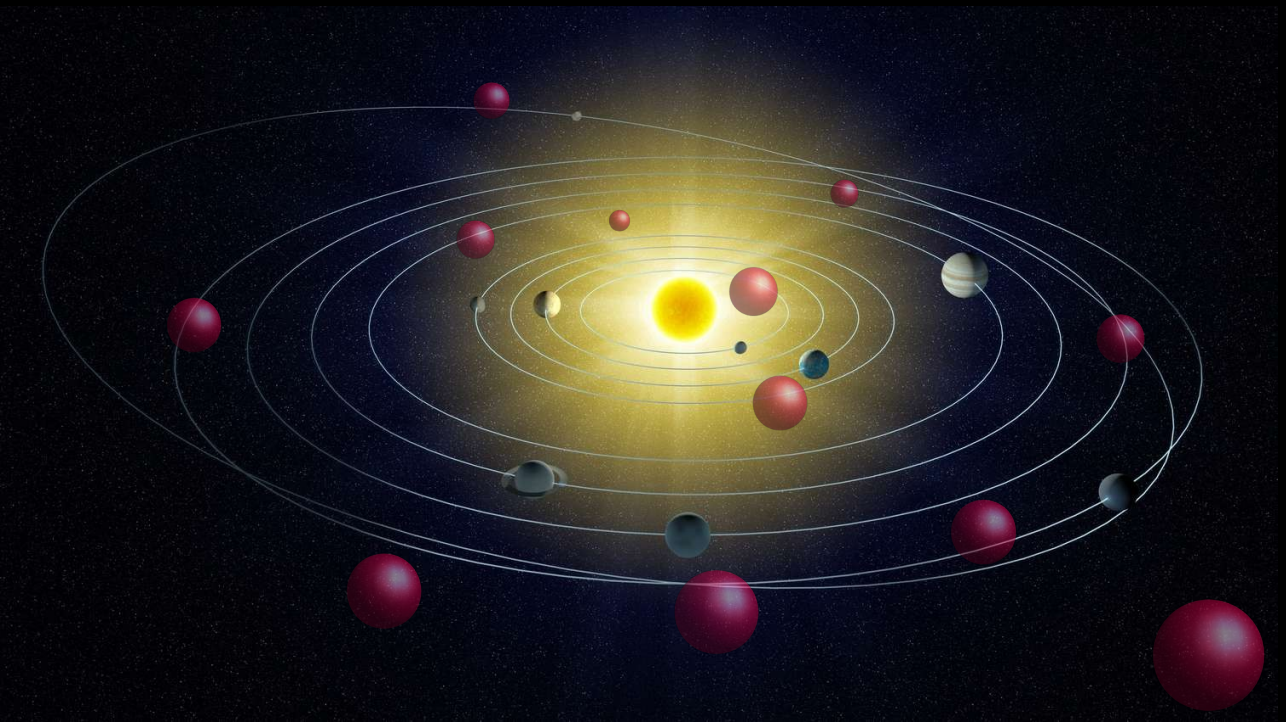
Axions in Seoul – Frontiers in Theory, Cosmology, and Experiment
with KimFest in Honor of Professor Jihn E. Kim

Jul 27 – 30, 2026 – Seoul National University

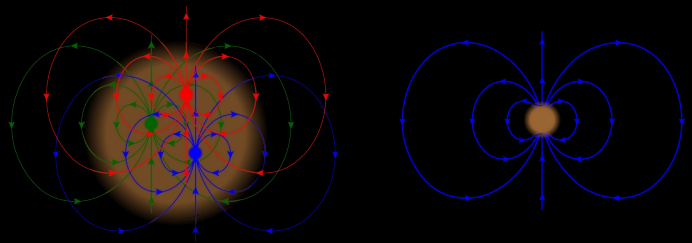
Post Inflationary Axion Cosmology



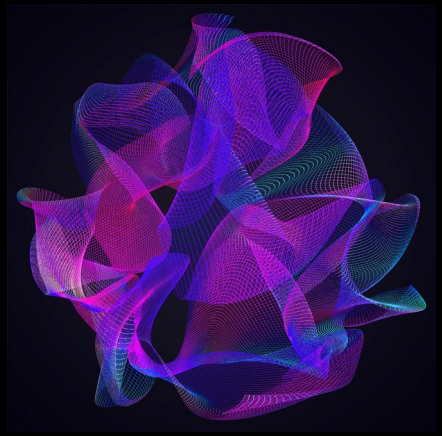
Giovanni Villadoro
ICTP

AXION (-LIKE) PARTICLE

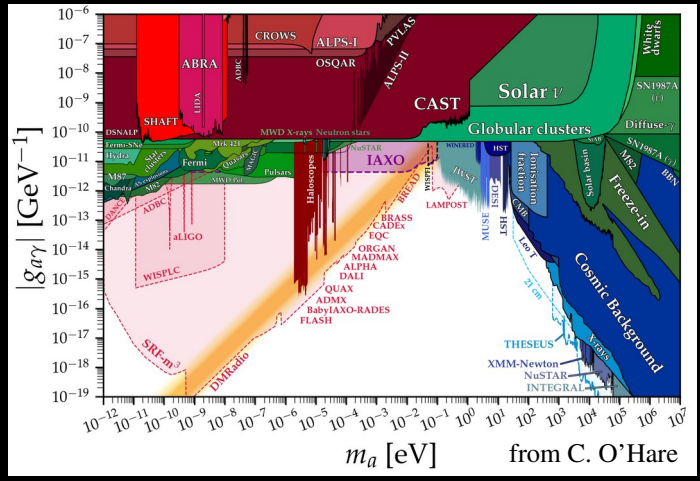
NEUTRON EDM



AXIVERSE



DARK MATTER



No tension between PQ-quality and Post-Inflationary Cosmology

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– PQ quality problem

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e.g. minimal KSVZ model w/ N=1

Petrossian-Byrne GV ‘25

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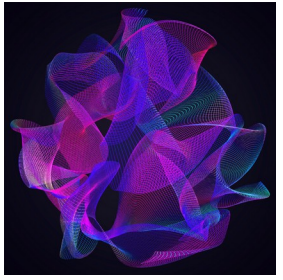
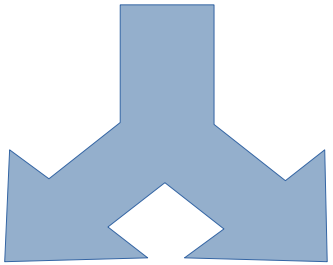
e.g. minimal KSVZ model w/ N=1

Petrossian-Byrne GV ‘25

– It may even be generic in the axiverse



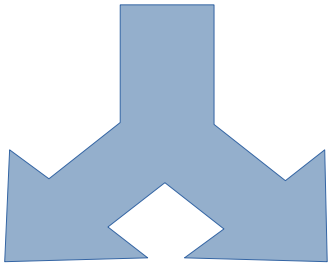
Relic Cold Axions



pre-inflation scenario

post-inflation scenario

Relic Cold Axions



$v_{PQ} \gtrsim \max(H_I, T_{\rm max})$

pre-inflation scenario

PQ-symmetric phase
not restored after inflation

for $v_{PQ} \sim H_I$
see e.g. Gorghetto, Hardy, Nicolaescu, Notari, Redi '24

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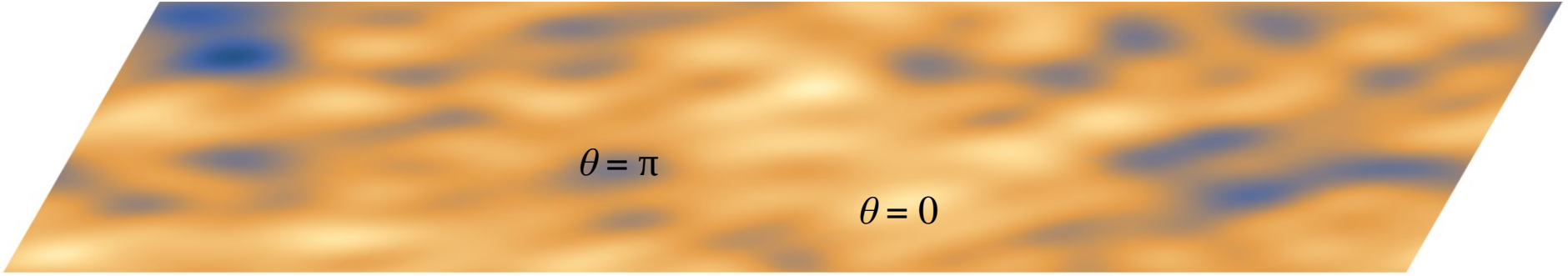
post-inflation scenario

PQ-symmetric phase
restored after inflation

Cosmic Evolution of Axions

pre-inflationary scenario



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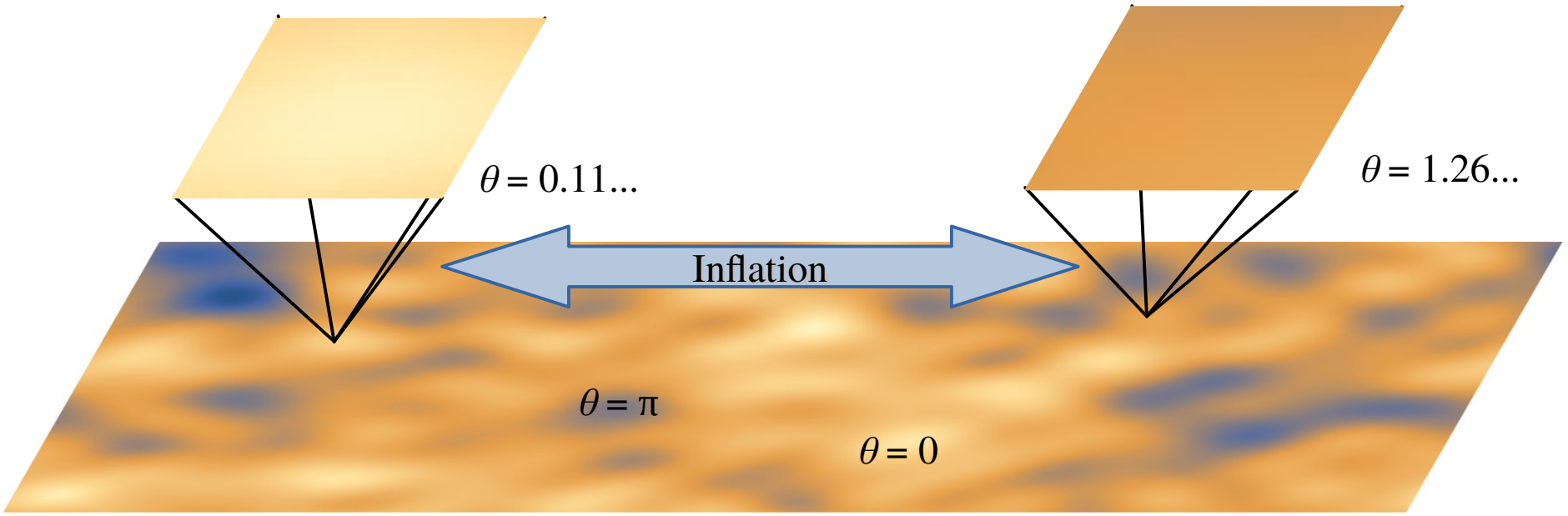

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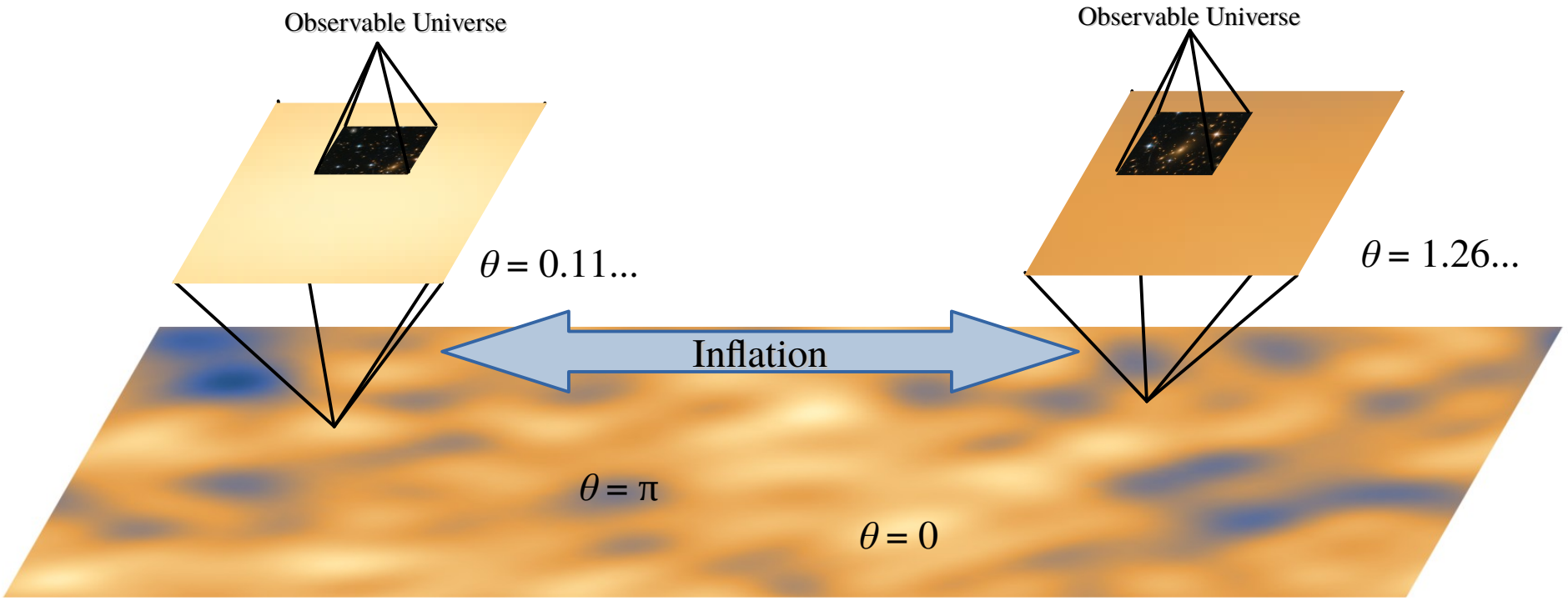
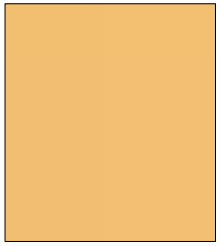


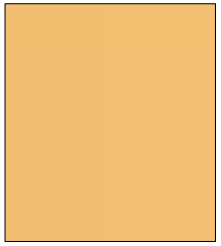
Misalignment mechanism



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

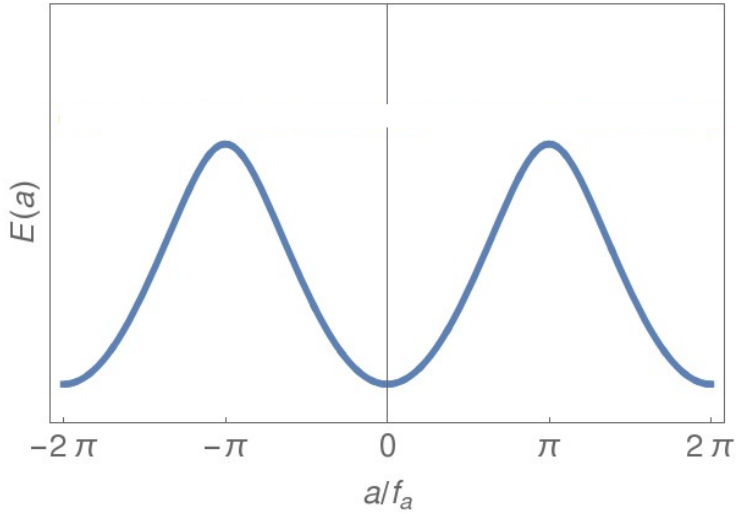
$$a(\vec{x}, t) \to a(t)$$

Misalignment mechanism



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

$a(\vec{x}, t) \to a(t)$ EOM: $\ddot{a} + 3H\dot{a} + V'(a) = 0$



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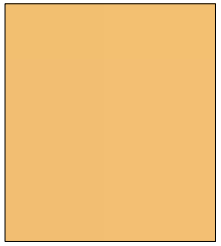

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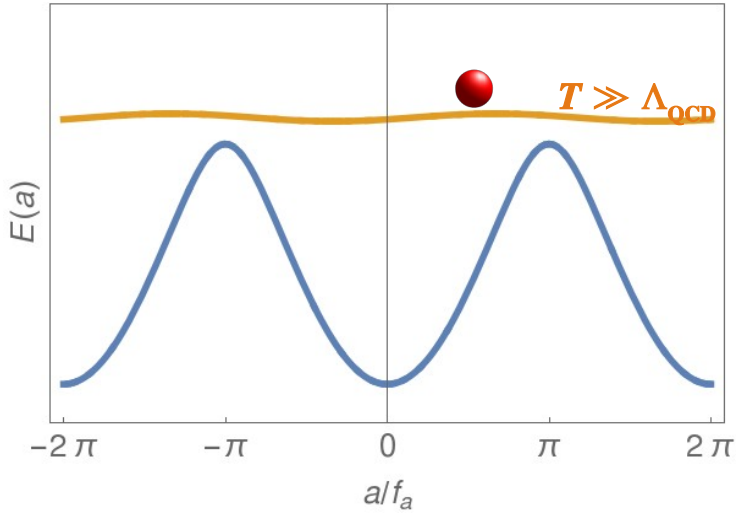
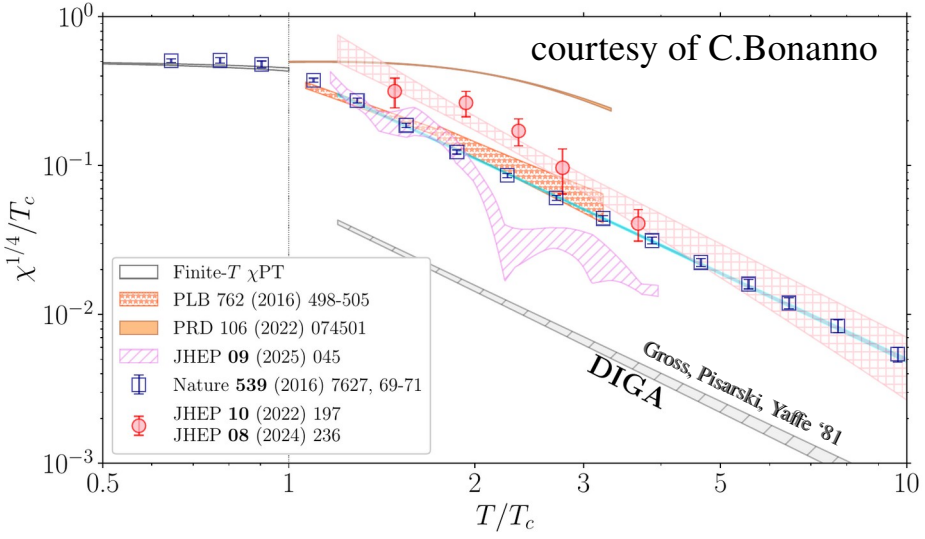


$V(a) \sim T^{-\alpha}$

$\alpha \approx 8$



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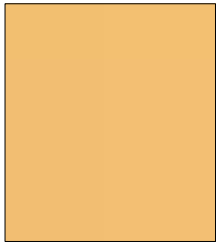

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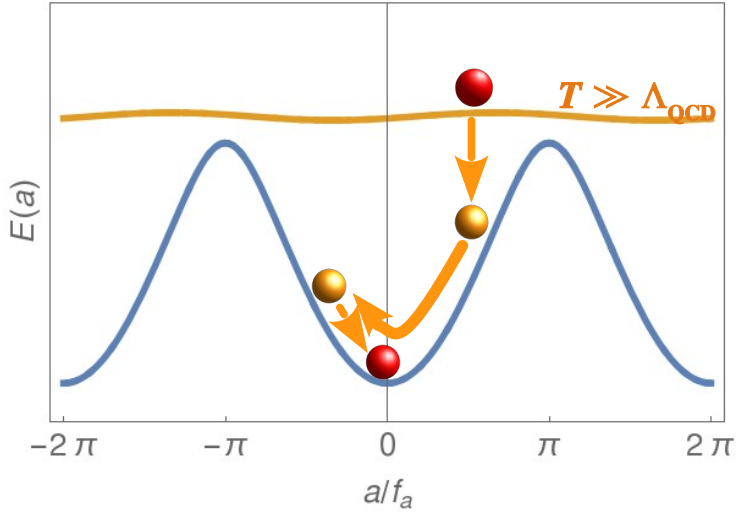

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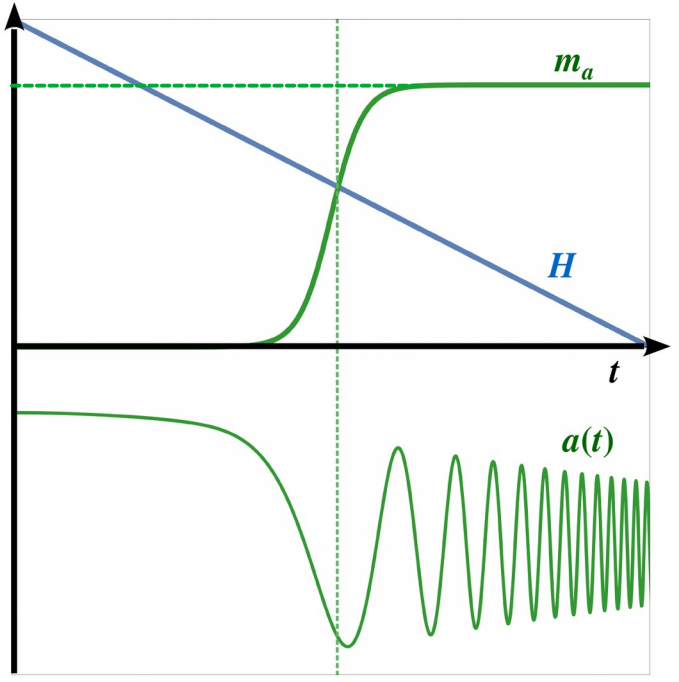

Misalignment mechanism

$$\Omega_a \simeq \Omega_{DM}\, \theta_0^2 \left[\frac{f_a}{10^{12}\ \mathrm{GeV}}\right]^{\frac{7}{6}} \qquad \theta_0 \lesssim 1$$

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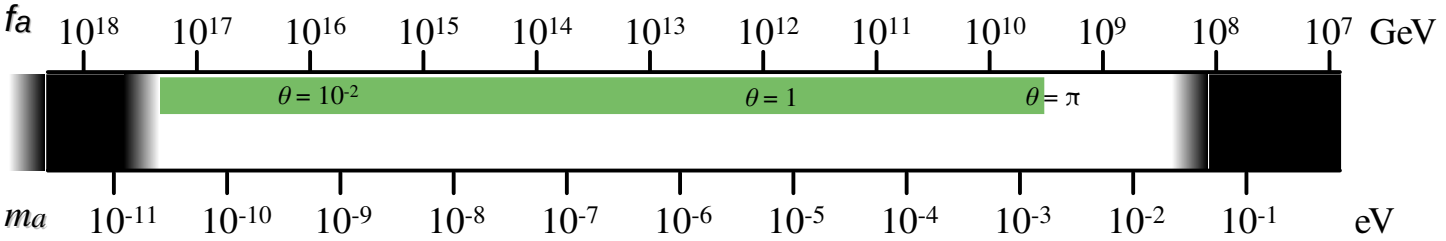

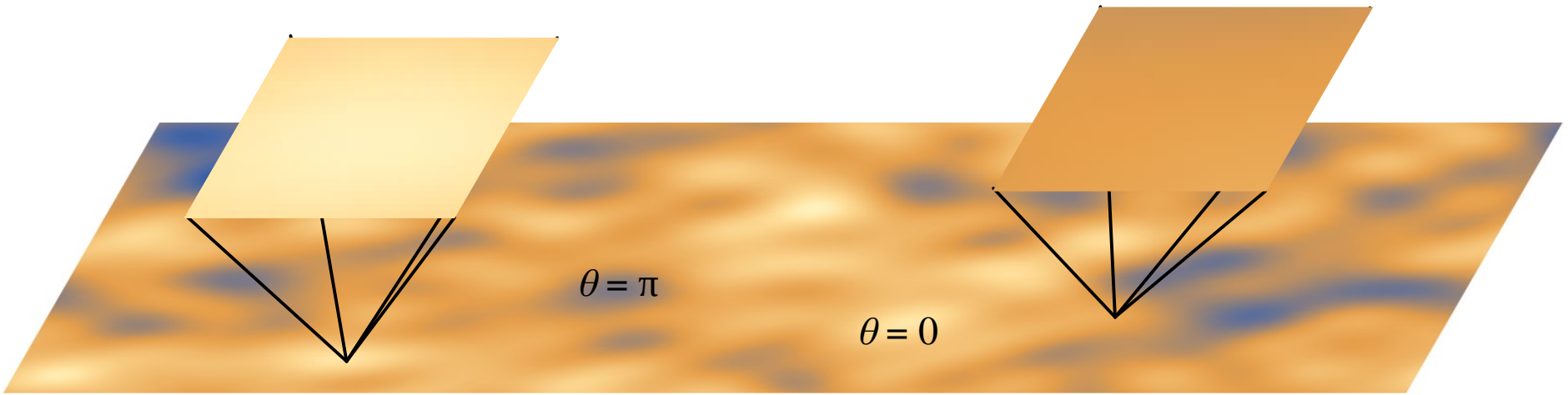

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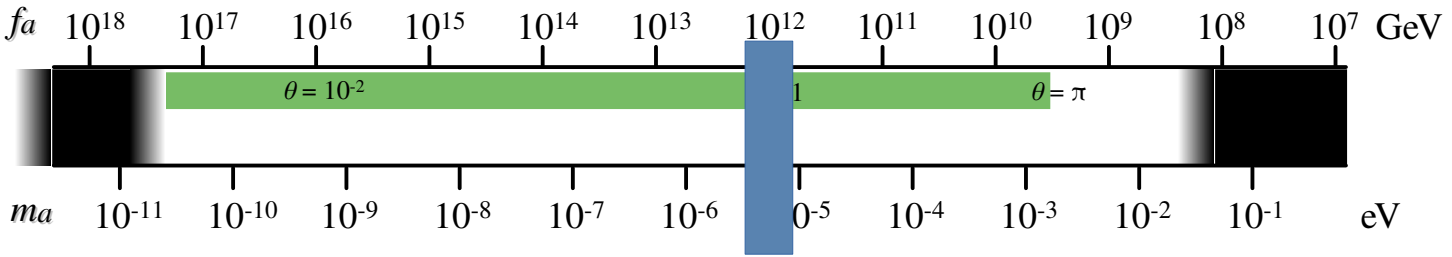
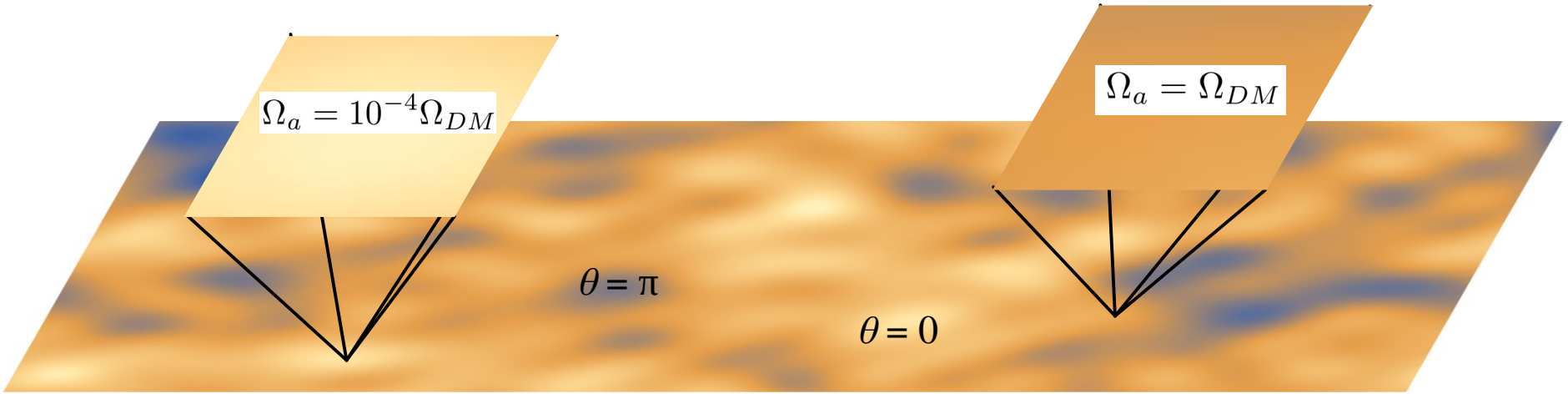


$$f_a = 10^{12}\ \mathrm{GeV}$$



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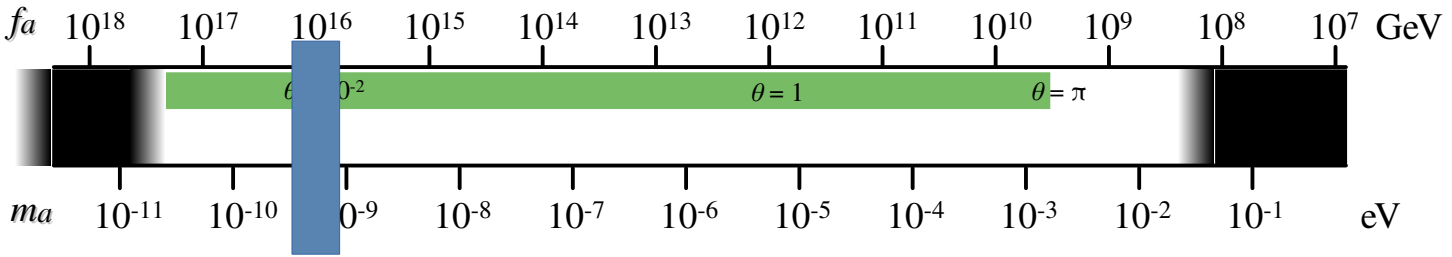

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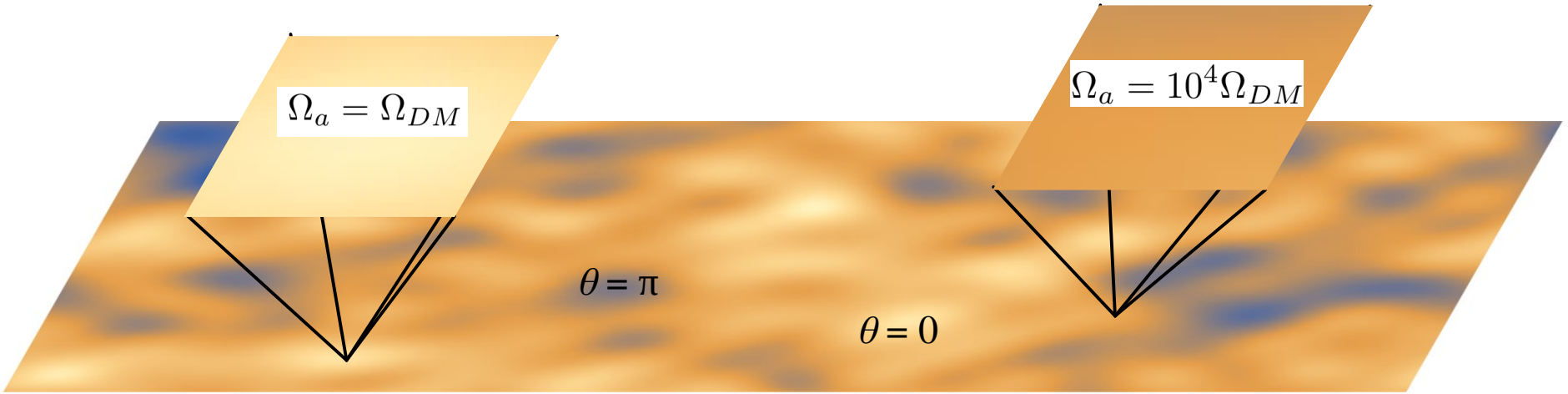

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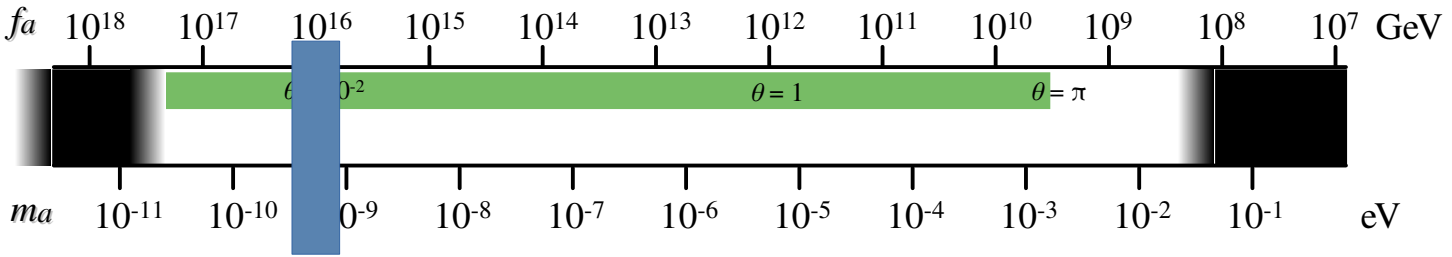

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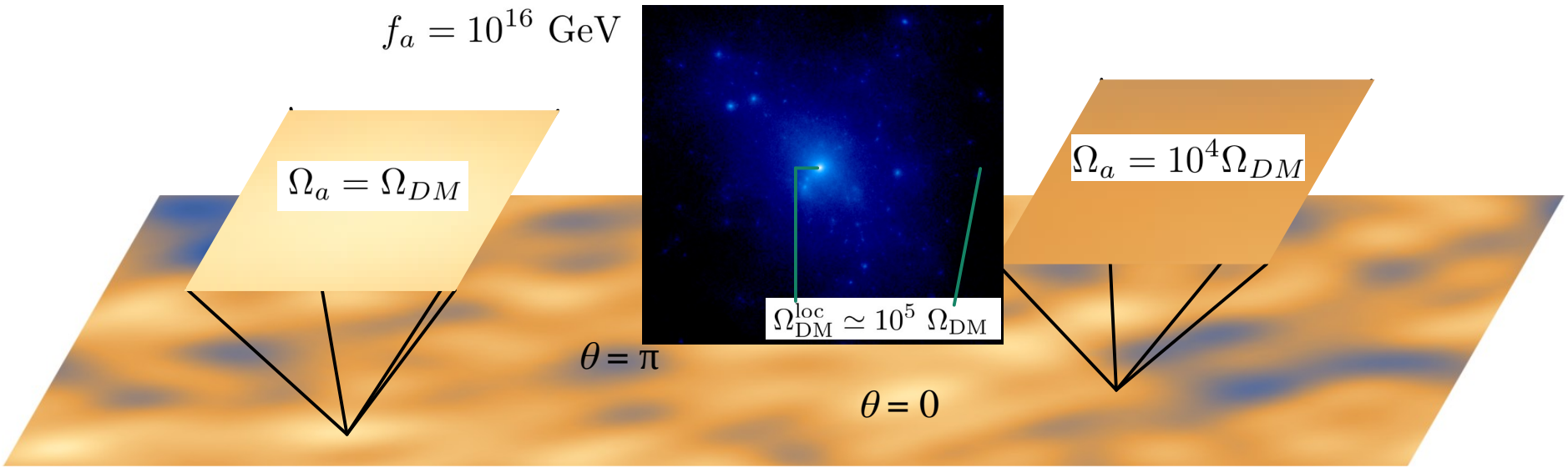

Misalignment mechanism for ALPs

(assuming m_a = const.)

$$\Omega_{\rm ALP} \simeq \Omega_{\rm DM}\theta_0^2 \left[\frac{m_a}{10^{-22}\ {\rm eV}}\right]^{\frac{1}{2}} \left[\frac{f_a}{10^{17}\ {\rm GeV}}\right]^2$$

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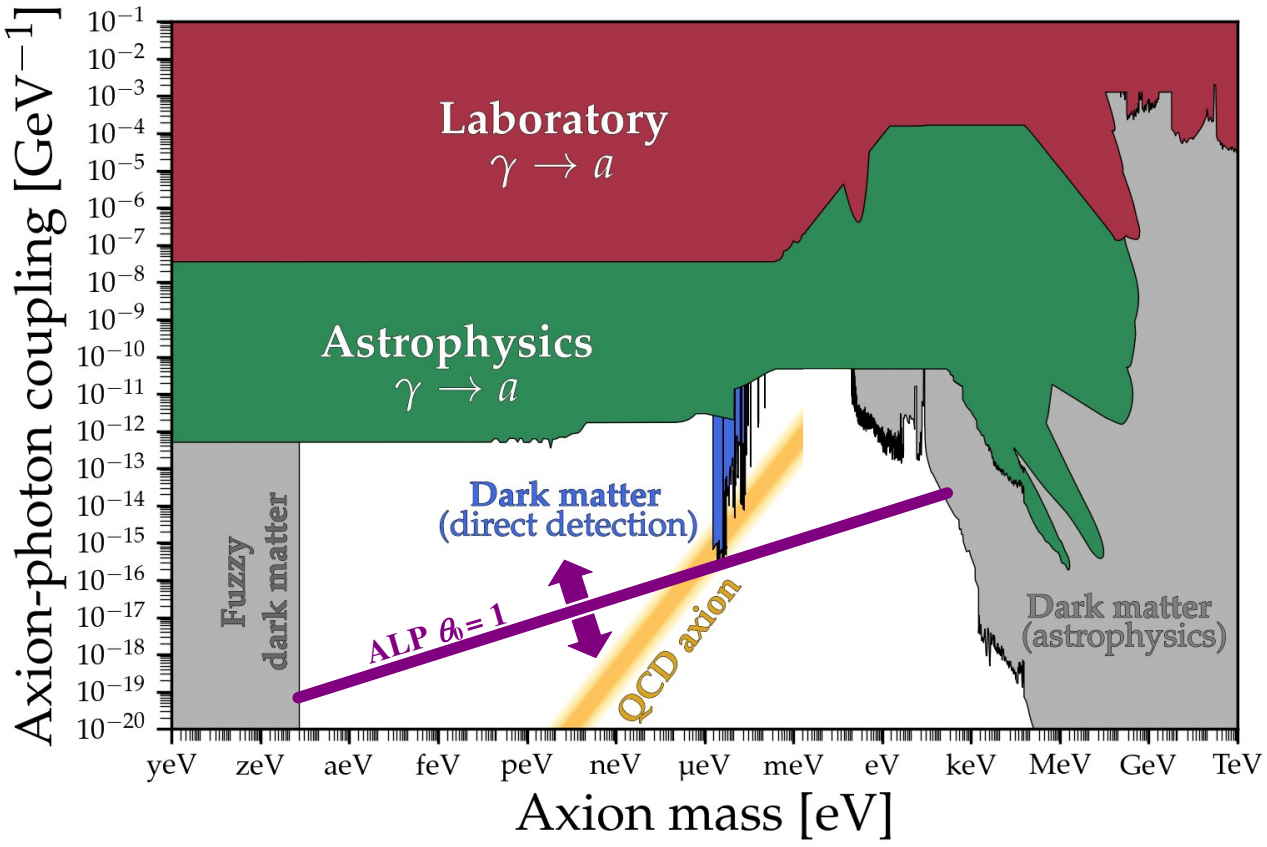
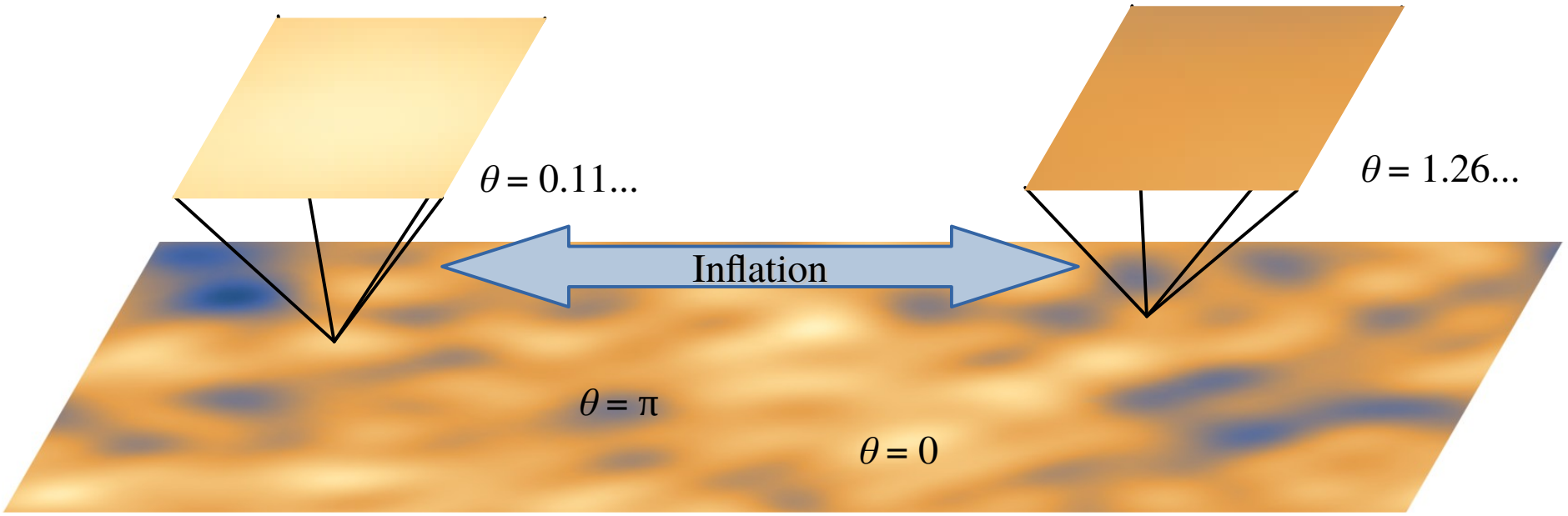
Fuzzy DM



Cosmic Evolution of Axions

post-inflationary scenario



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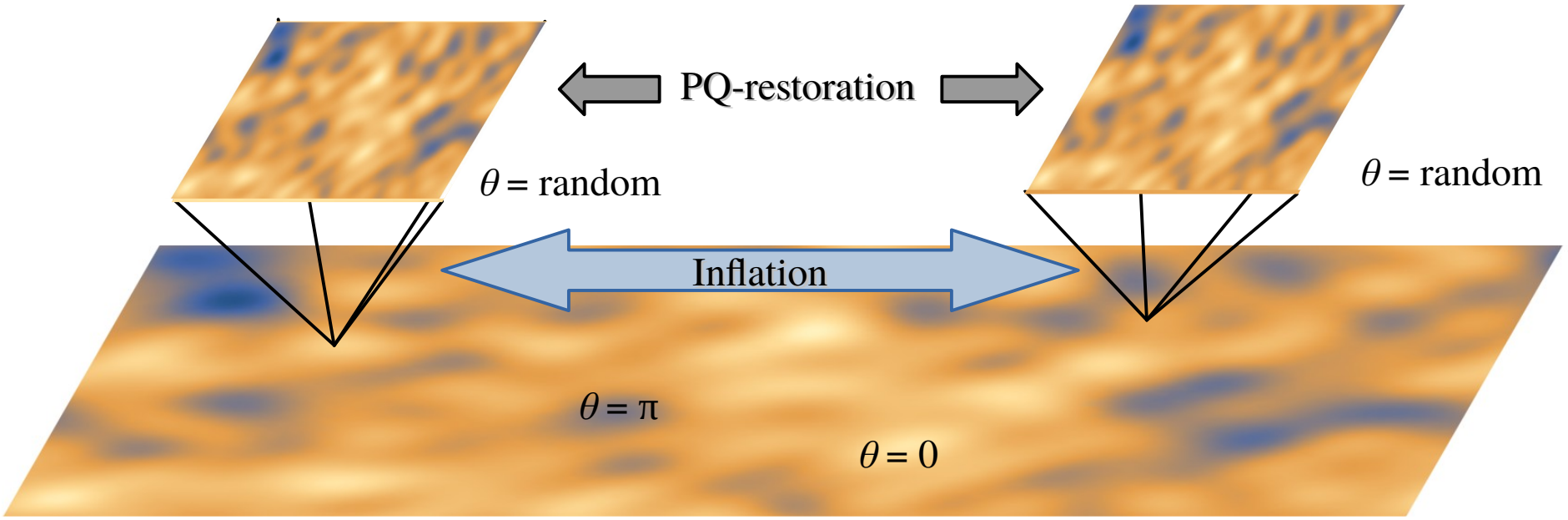

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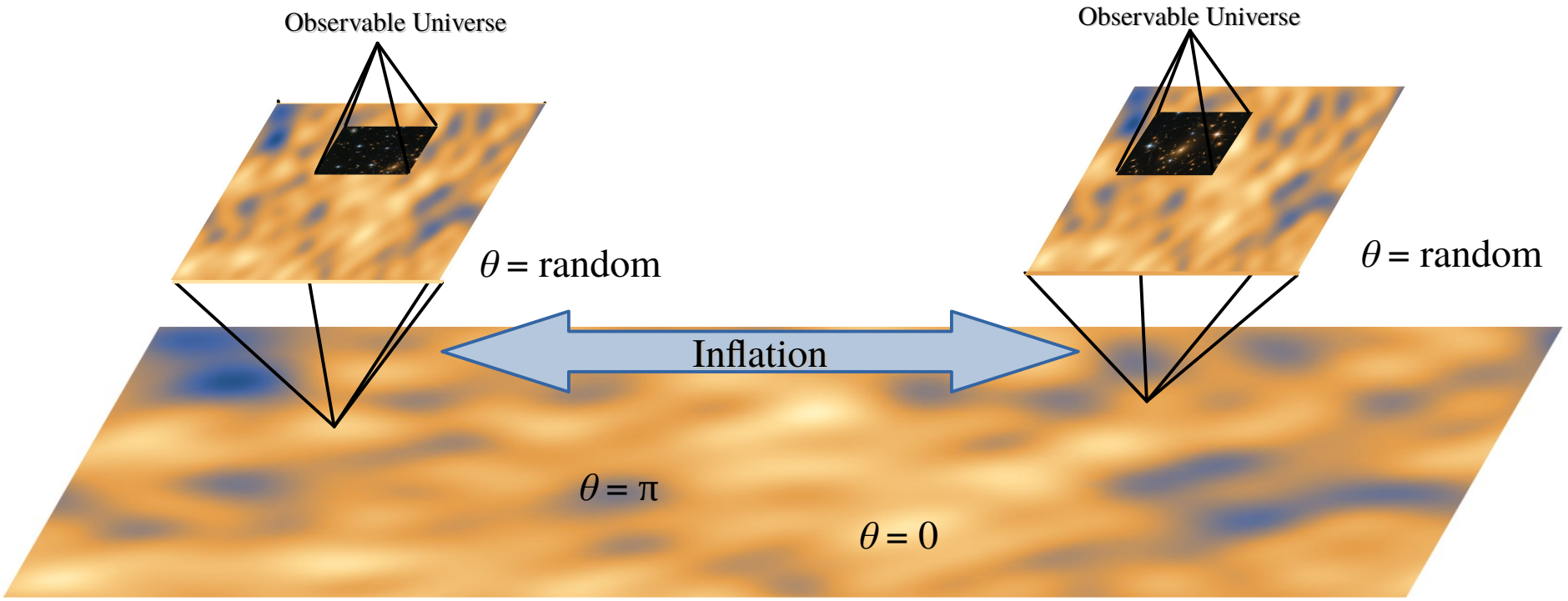
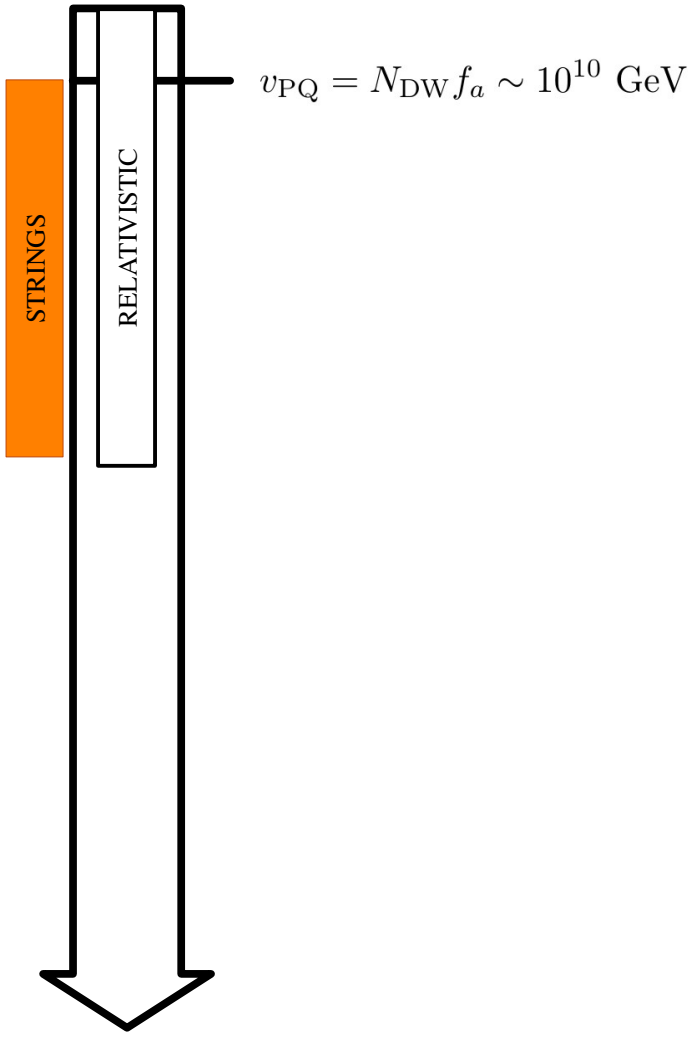
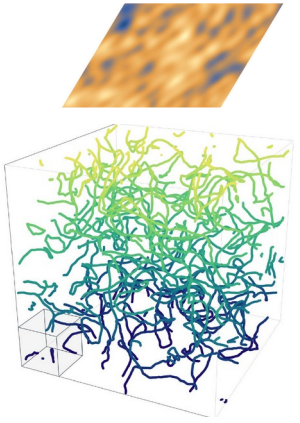


Post-inflationary cartoon:





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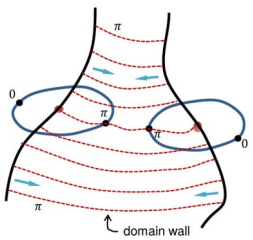

DOMAIN WALLS

STRINGS

RELATIVISTIC

$v_{\rm PQ} = N_{\rm DW} f_a \sim 10^{10}$ GeV

$T_\star \sim 1$ GeV : $\quad m = H$

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

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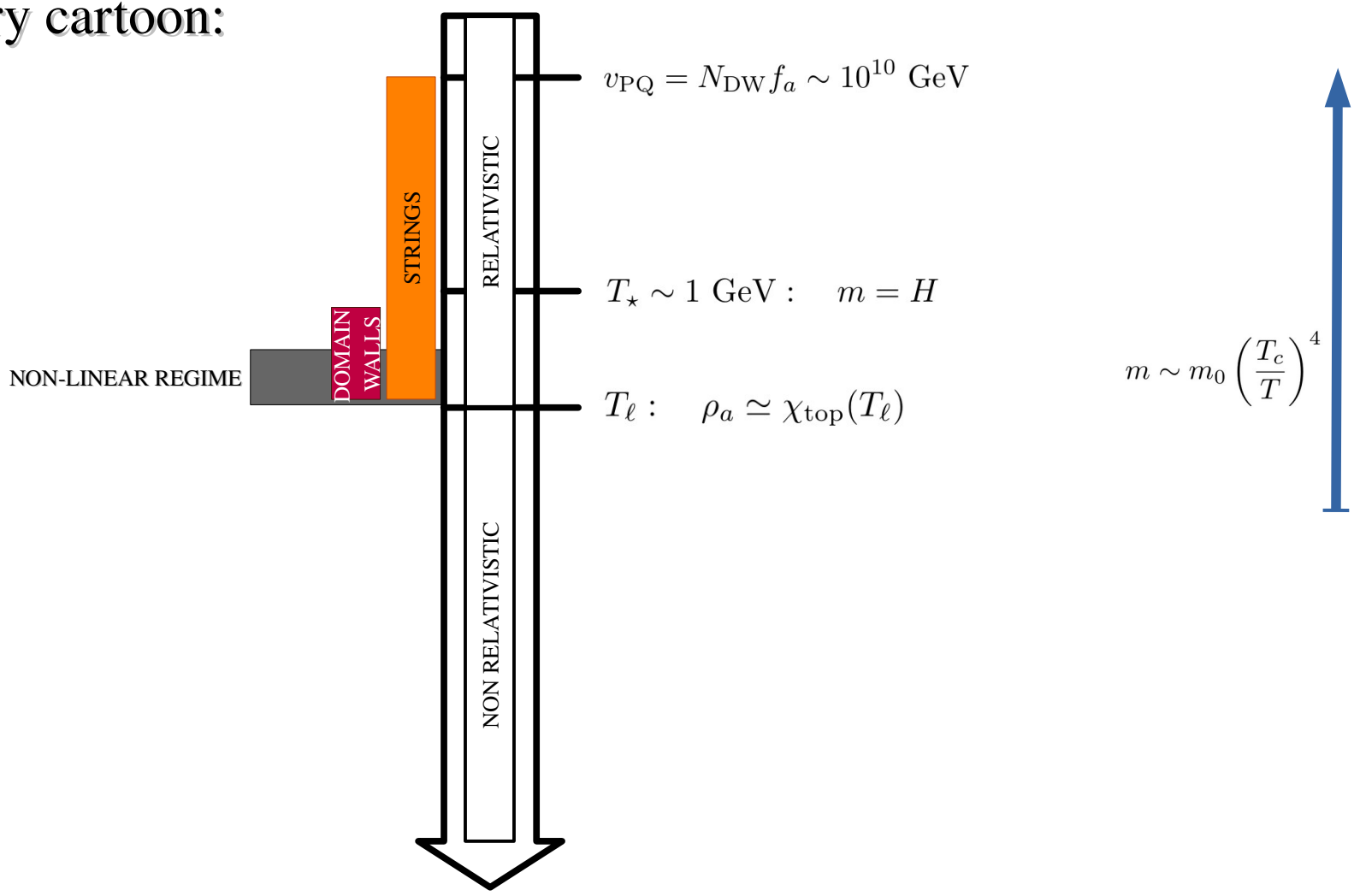

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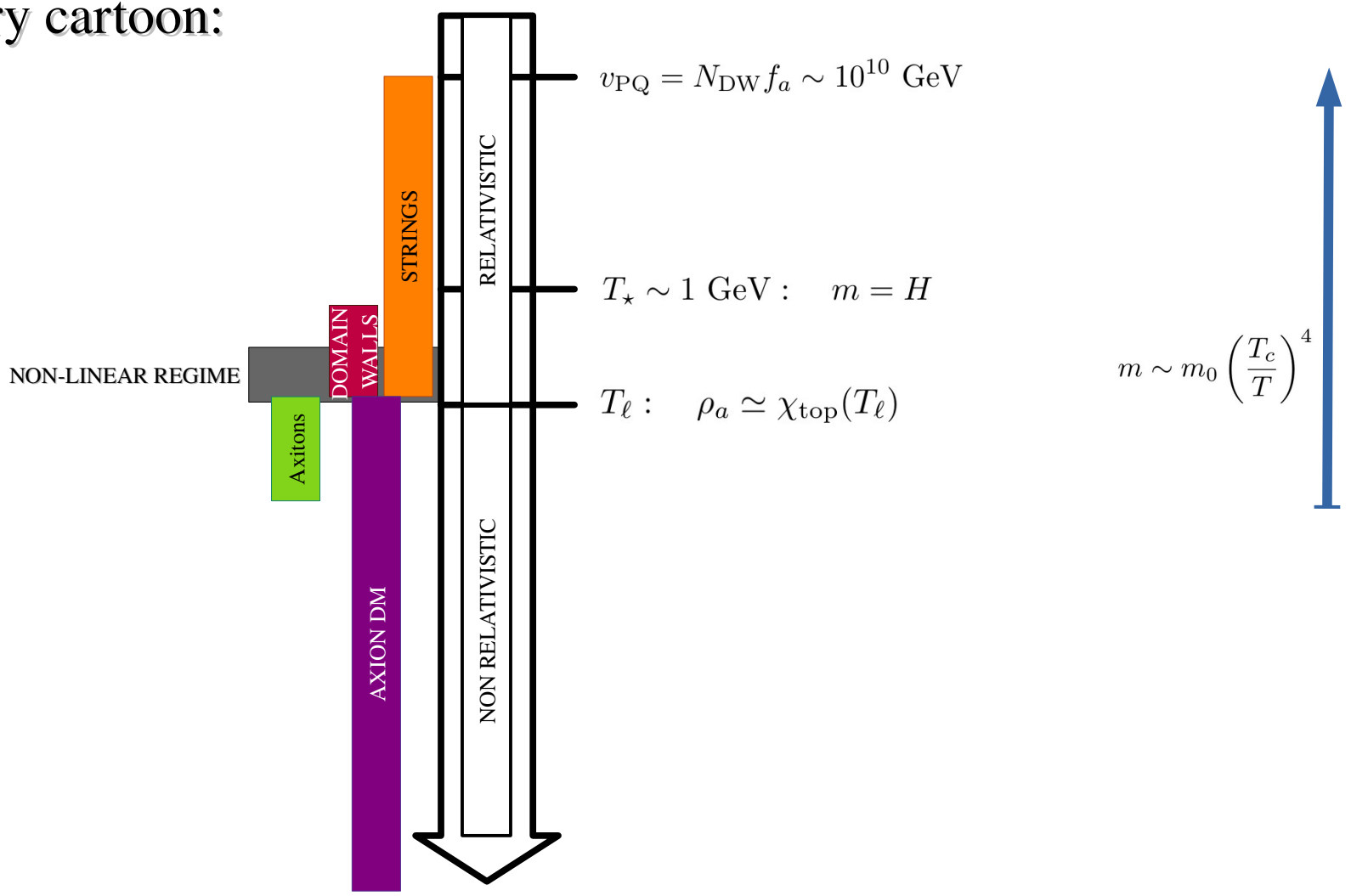

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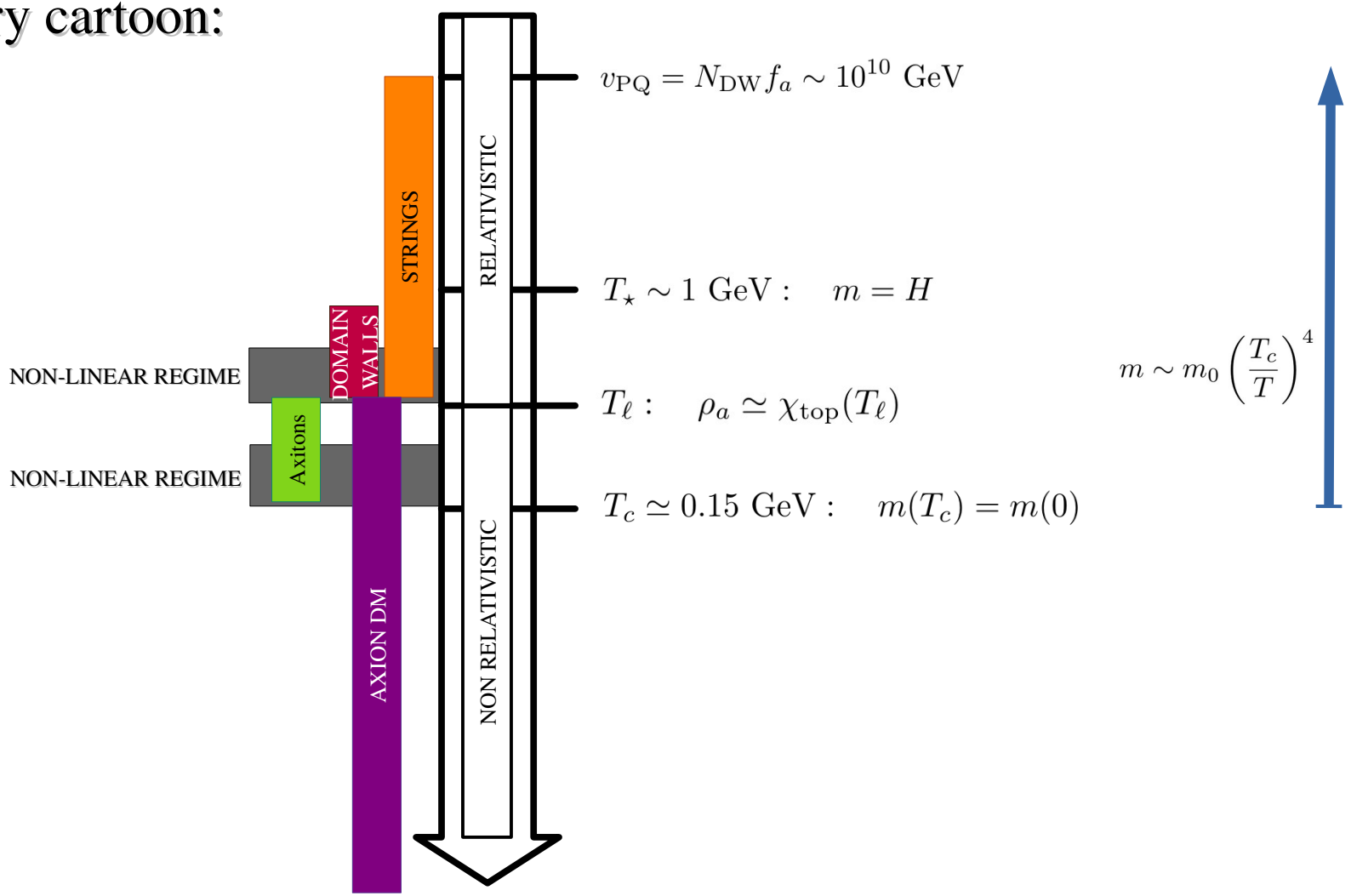

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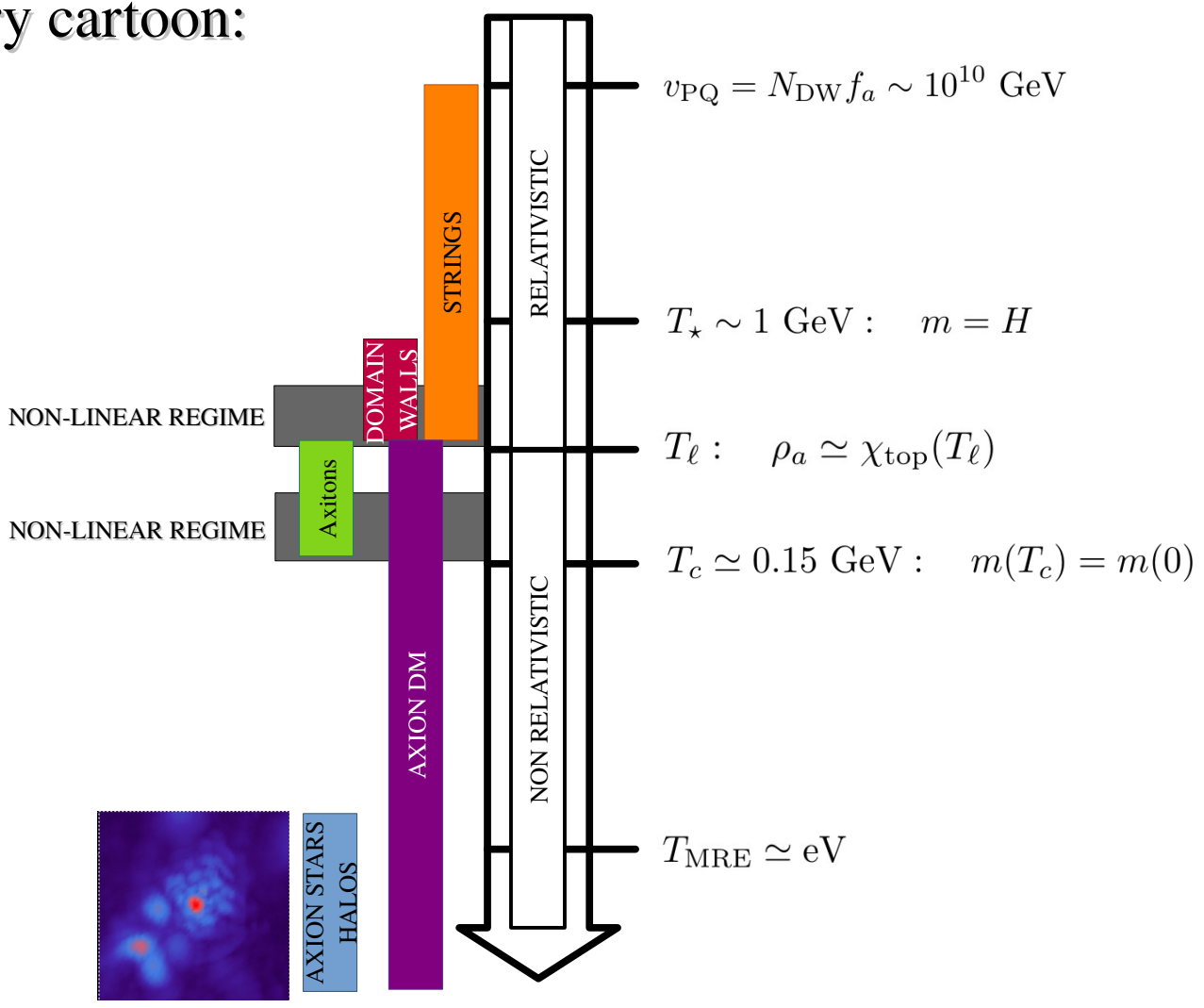
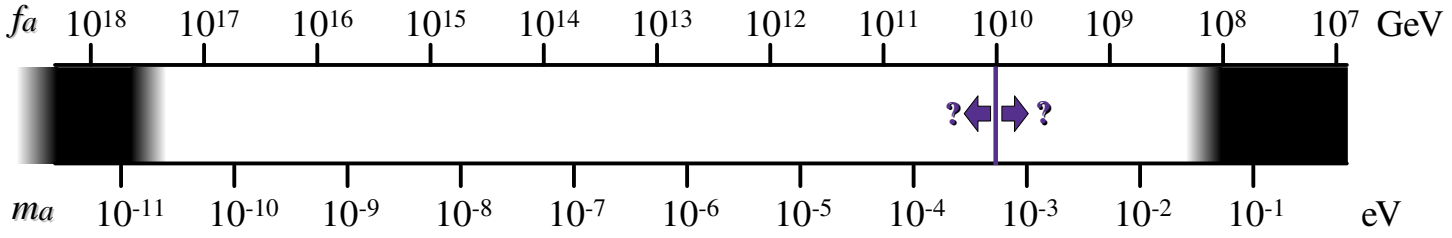


Goals:

1. Computation of the abundance

$$\Omega_a \simeq \left(\frac{f_a}{? \cdot 10^{10}\,\mathrm{GeV}} \right)^{1.2} \Omega_{\mathrm{DM}}$$



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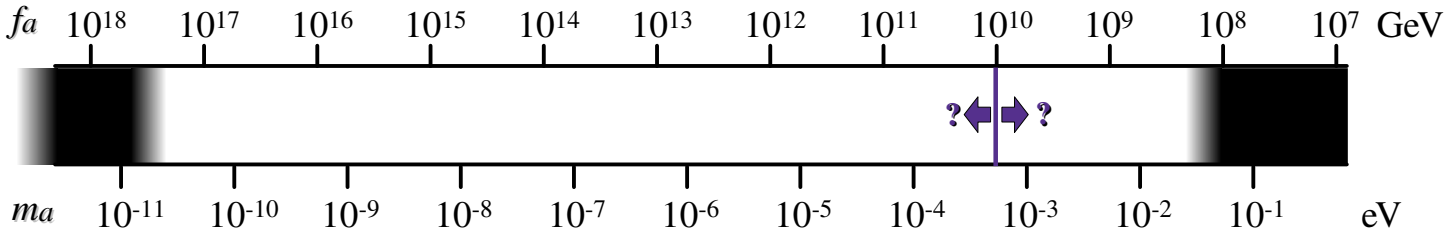
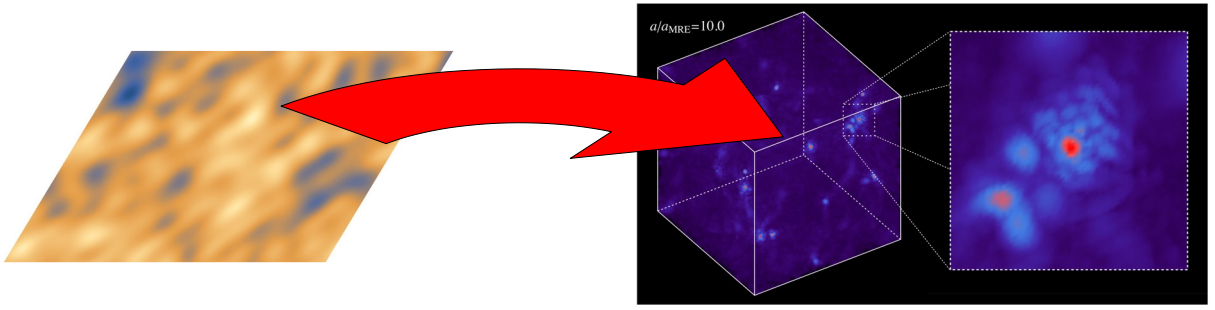
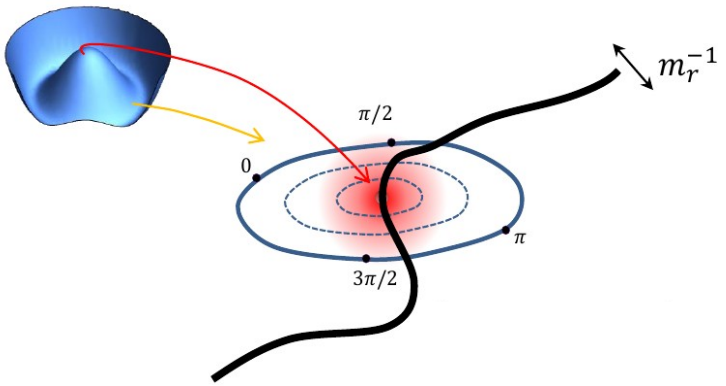


2. Characterization of small scale structures



Post-Inflation Scenario

@ $T \sim v_{PQ}$ (or $H \sim v_{PQ}$) Kibble mechanism $\rightarrow$ Axion Strings



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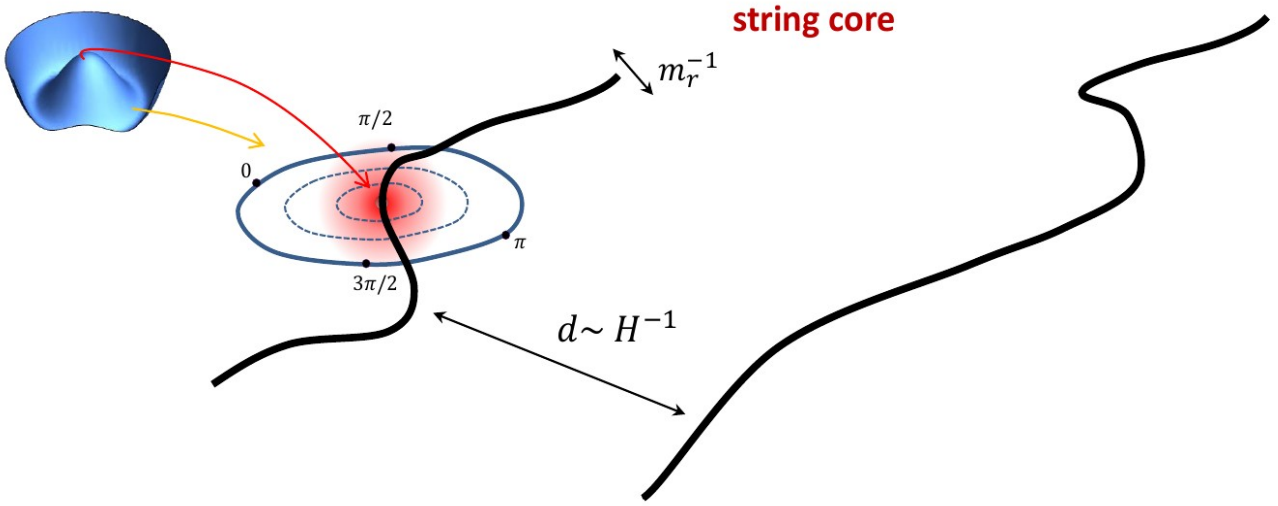

string tension $\mu = \dfrac{E}{L} = \pi v_{PQ}^2 \log(m_r \ell_{IR}) + \ldots$

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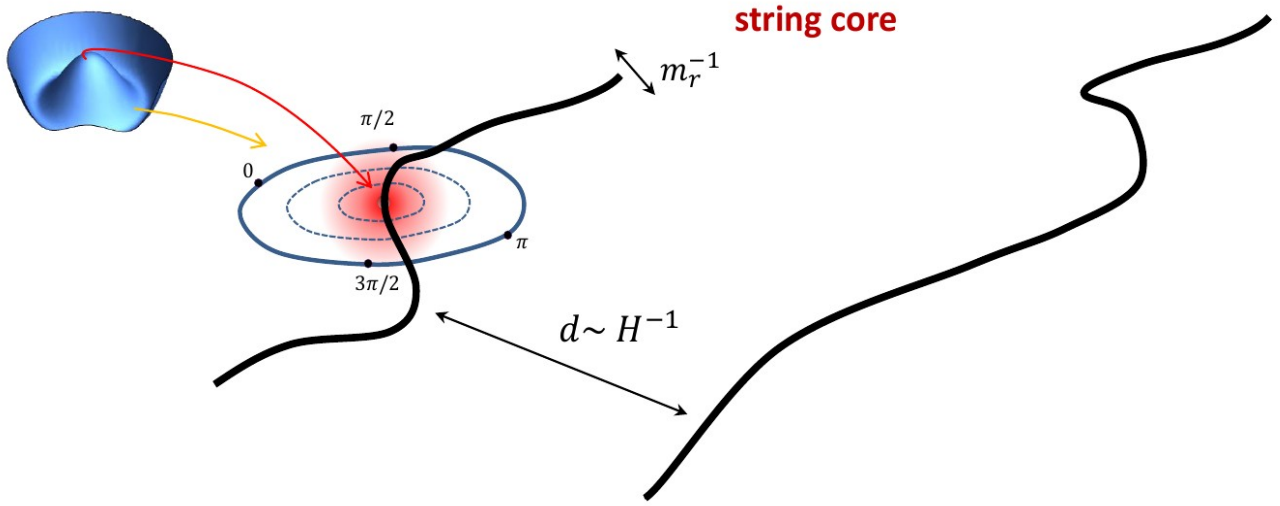

string tension $$\mu = \frac{E}{L} = \pi v_{PQ}^2 \log(m_r \ell_{IR}) \simeq \pi v_{PQ}^2 \log\left(\frac{m_r}{H}\right)$$

radial core

axion field

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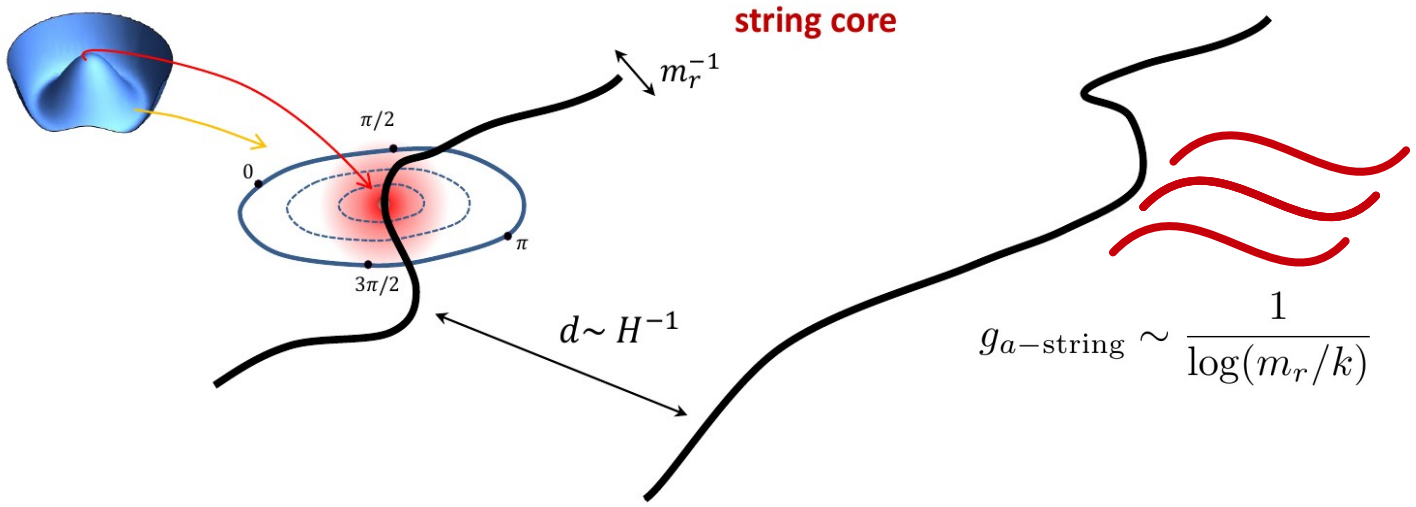

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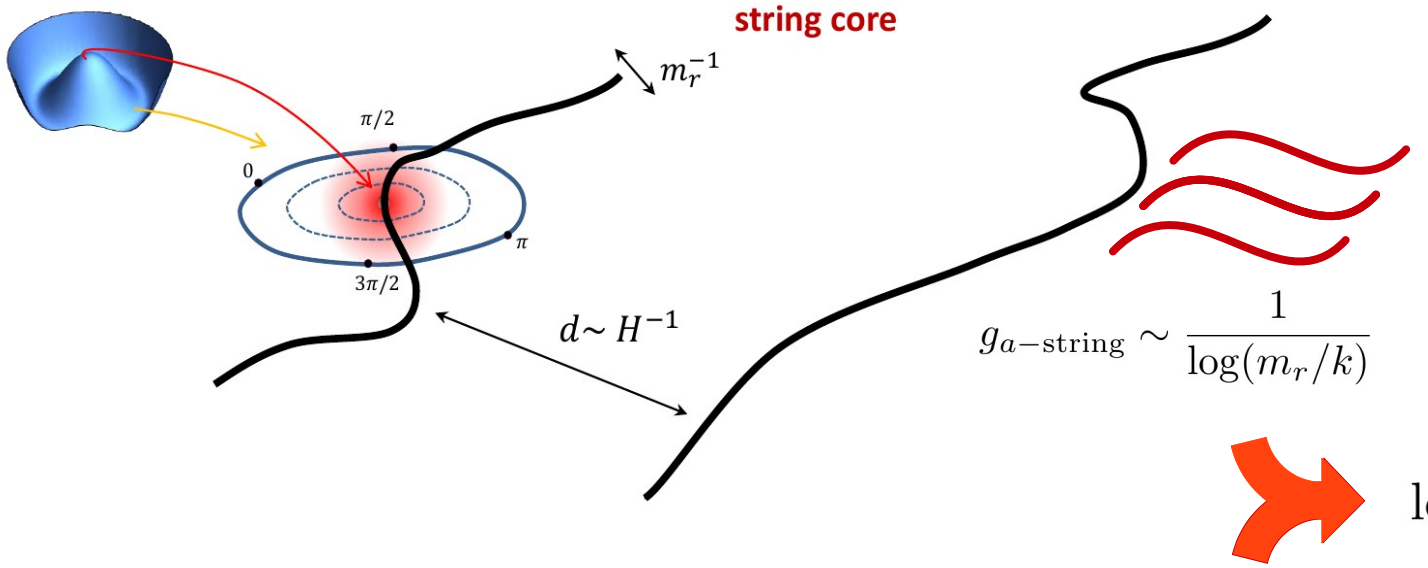

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radial core

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

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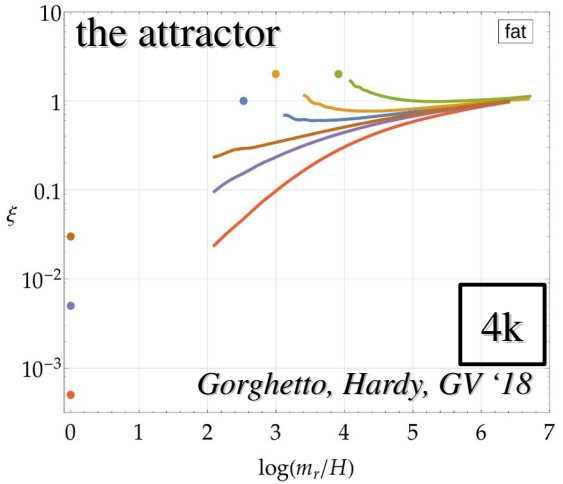

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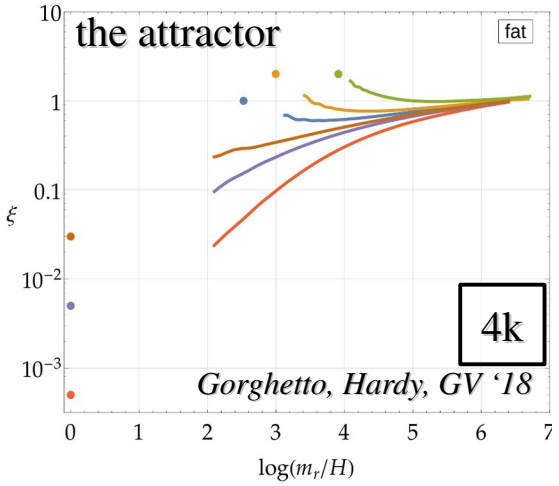

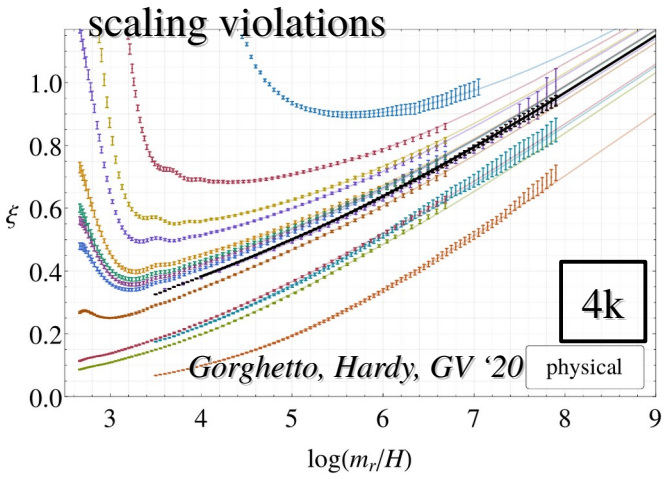

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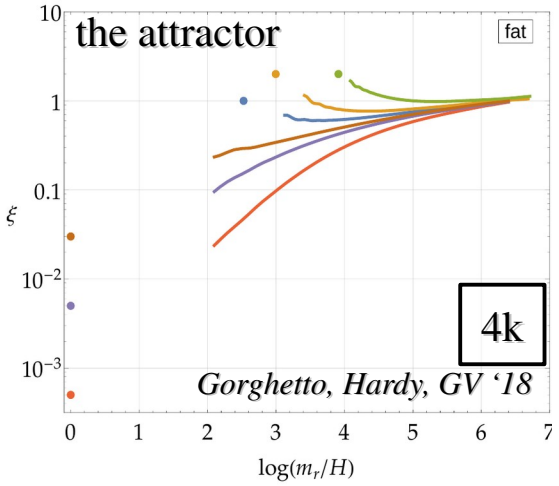

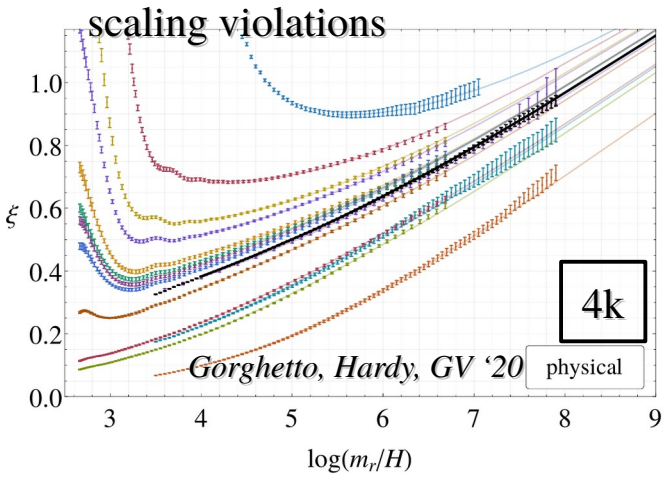

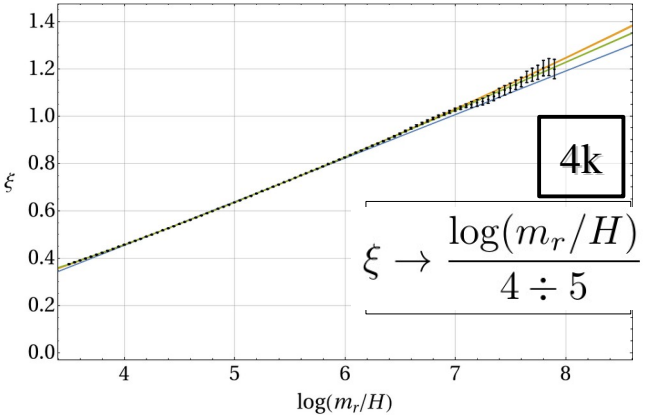

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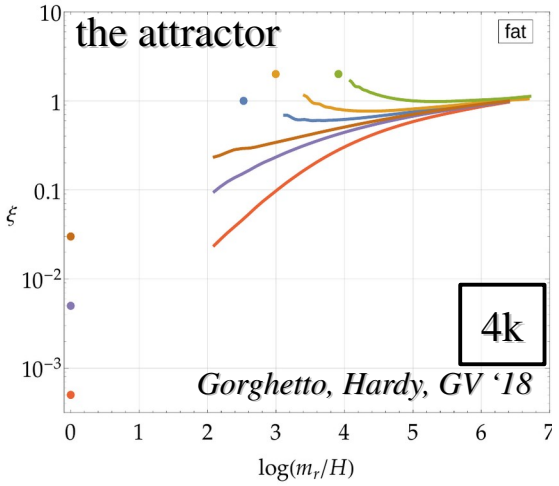

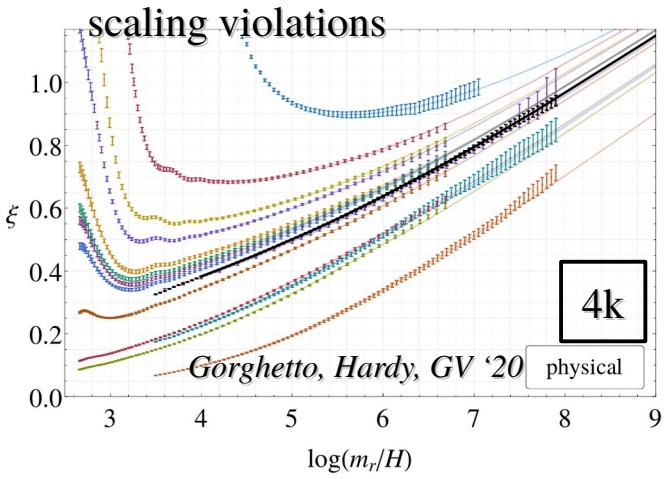

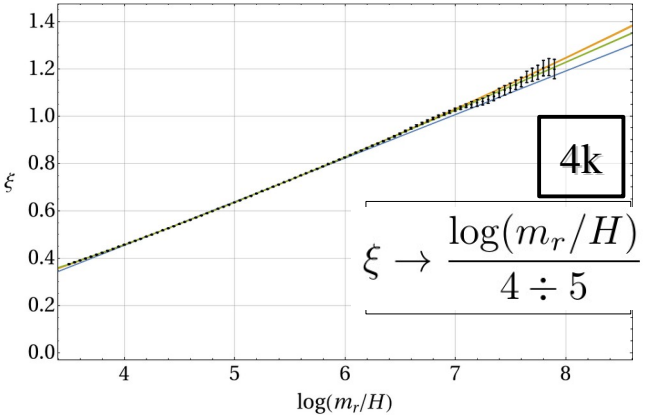

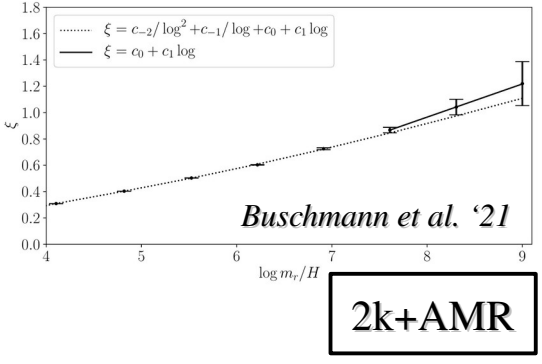

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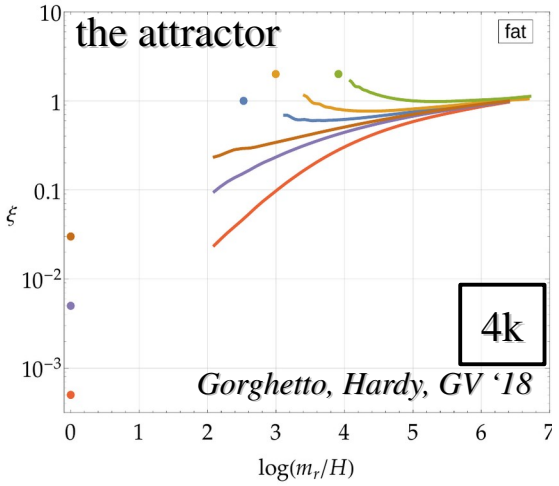

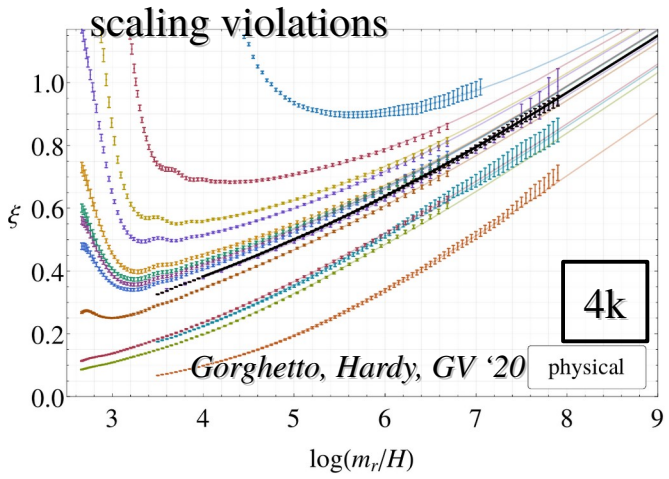

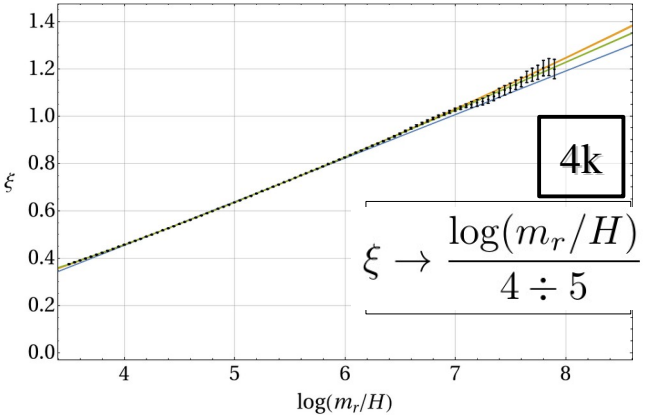

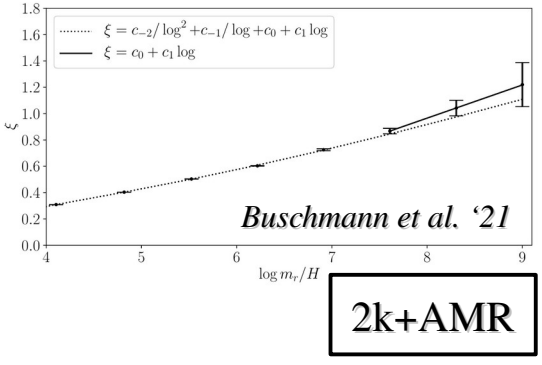

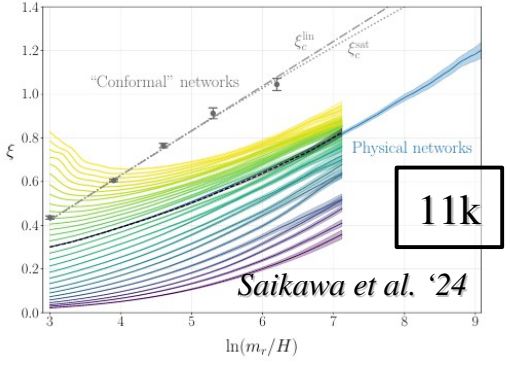

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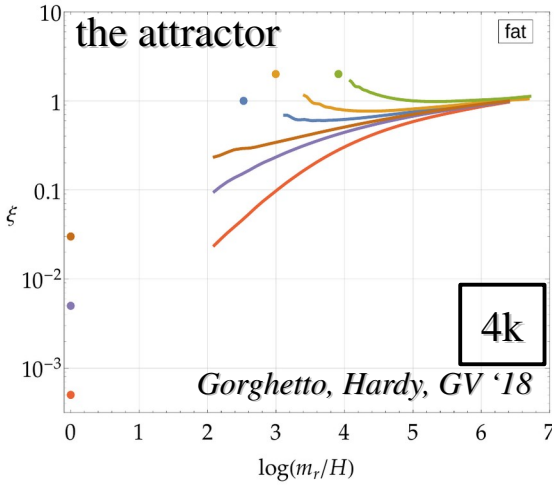
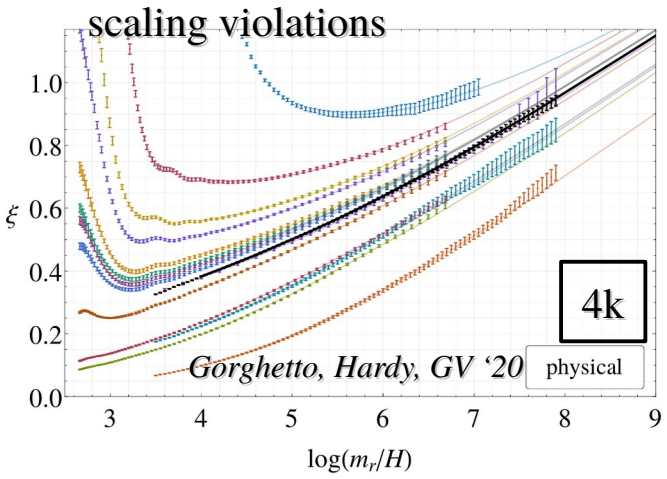
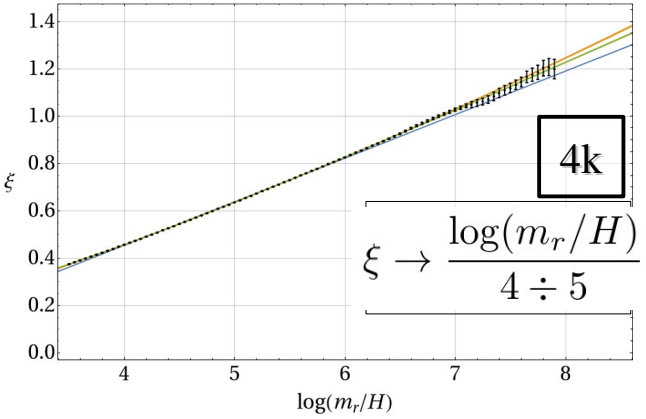
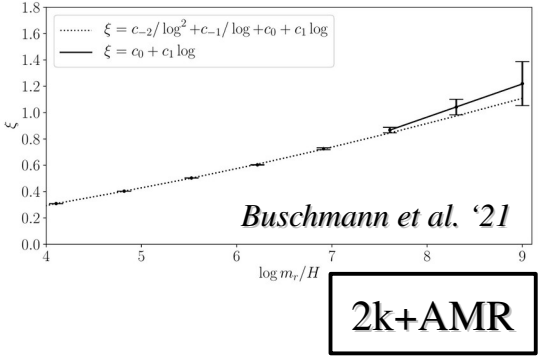
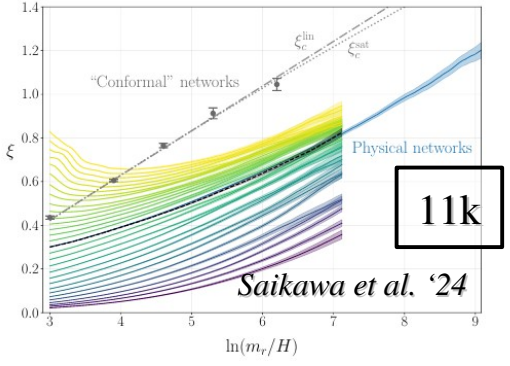
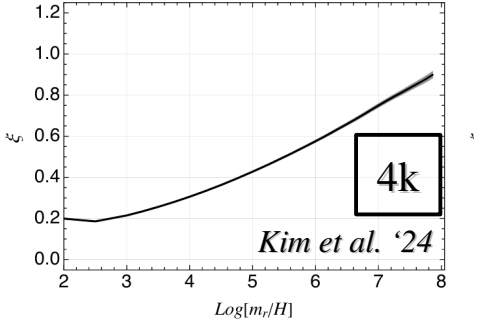










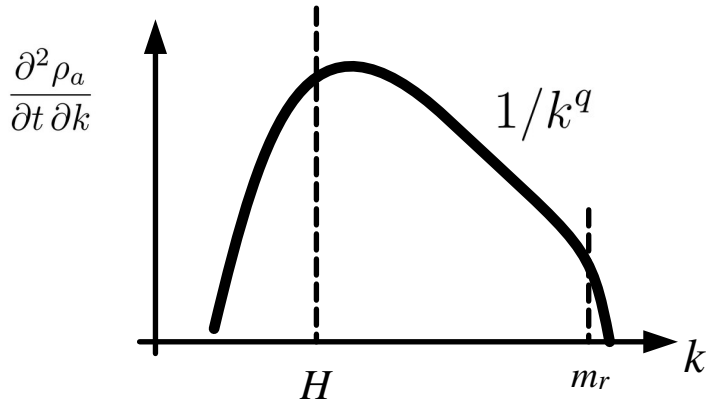


See also:

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

Axions from Strings

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



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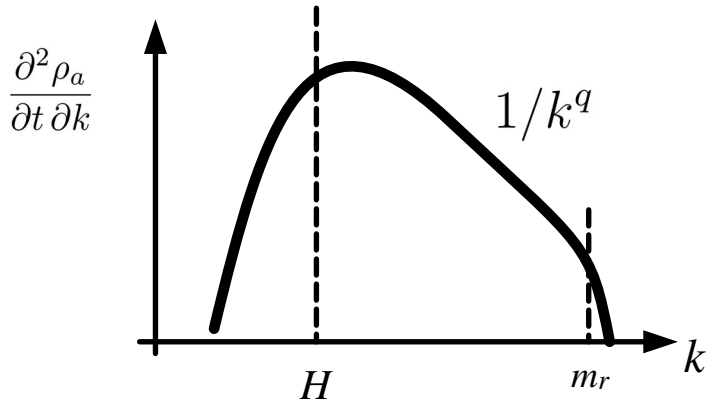

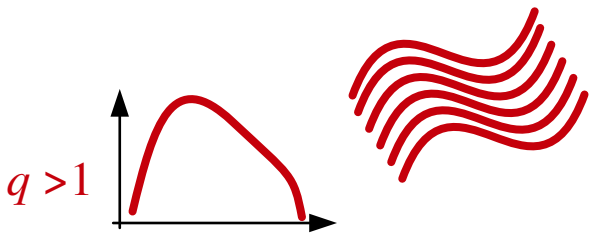

Davies, Shellard, ...

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

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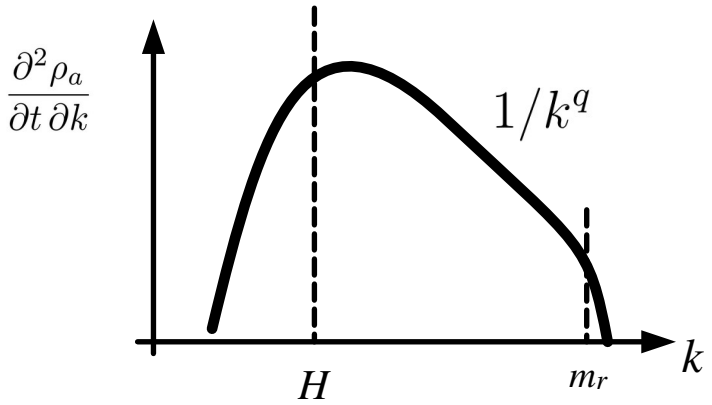

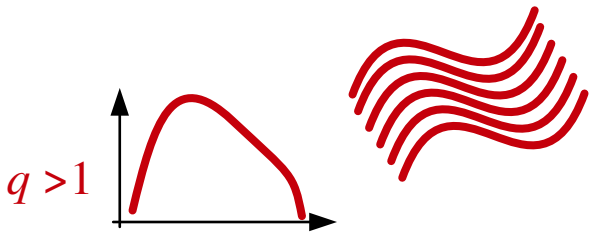

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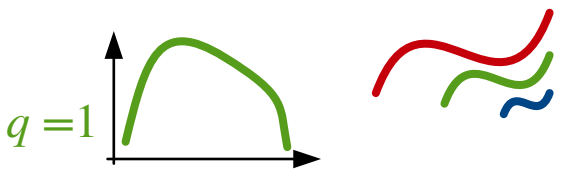

Sikivie, ...

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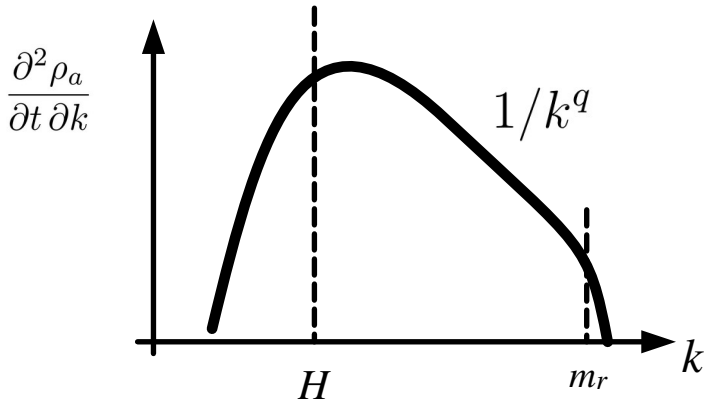

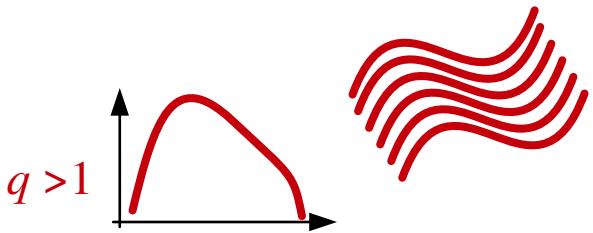

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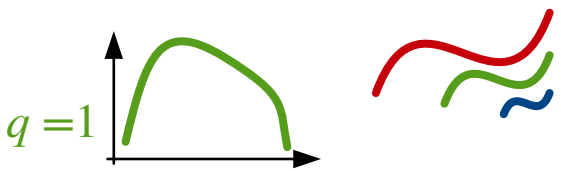

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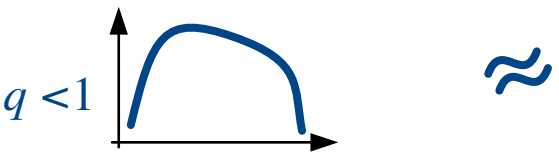
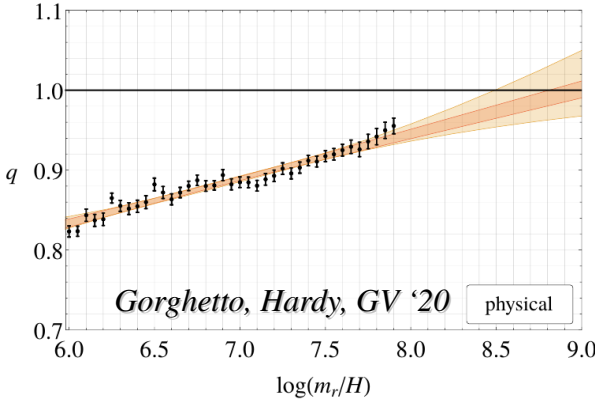


$$n \sim \frac{\rho}{H} \left(\frac{H}{m_r}\right)^{1-q} \sim n^{mis} \left(\frac{H}{m_r}\right)^{1-q}$$

Axions from Strings – spectral index



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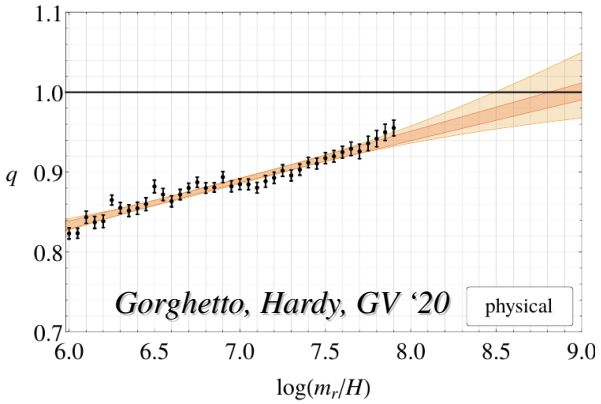

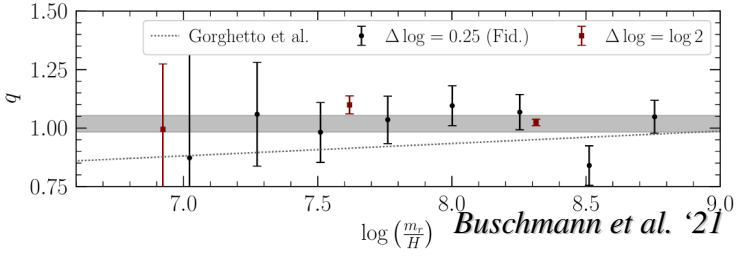

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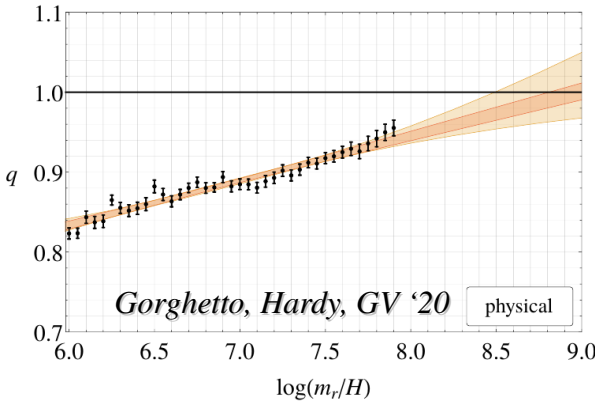

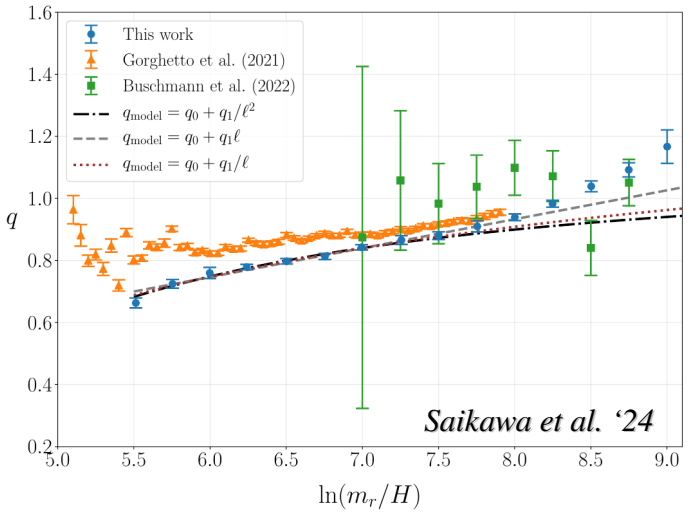

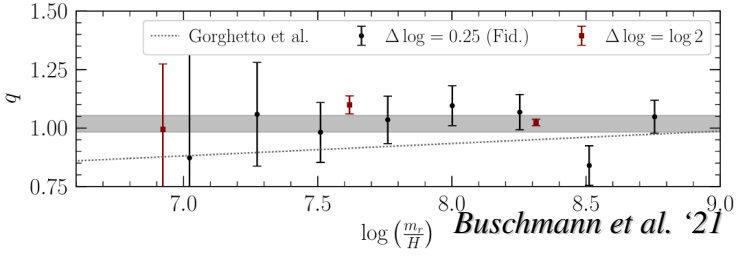

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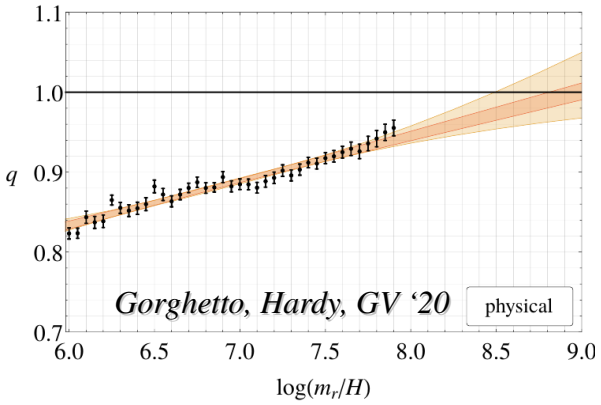

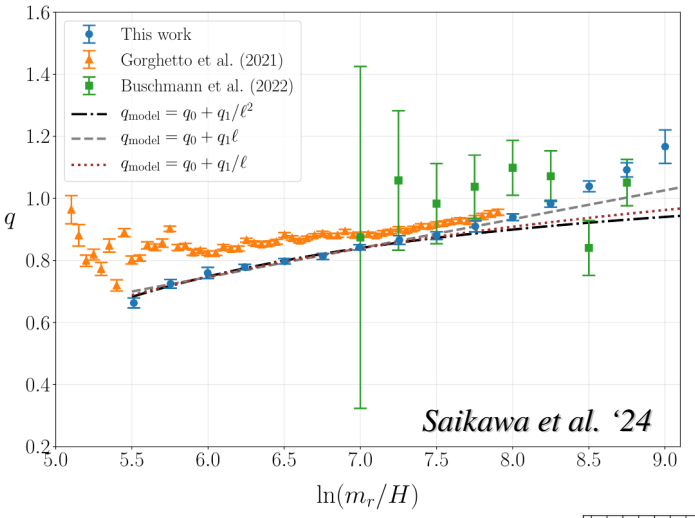

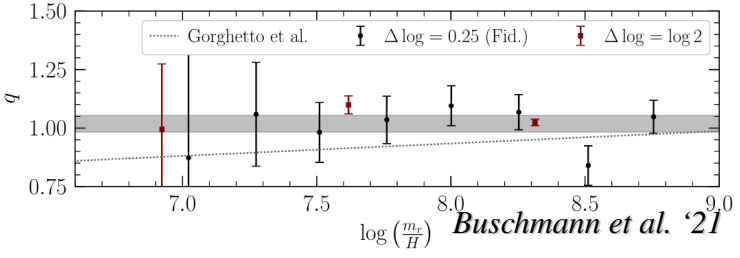

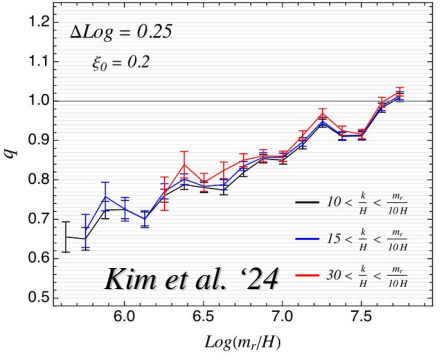

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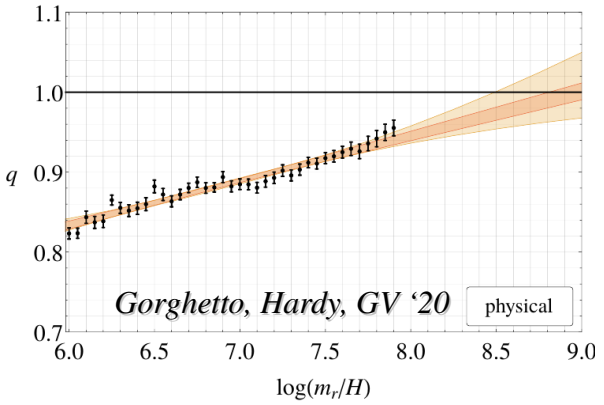

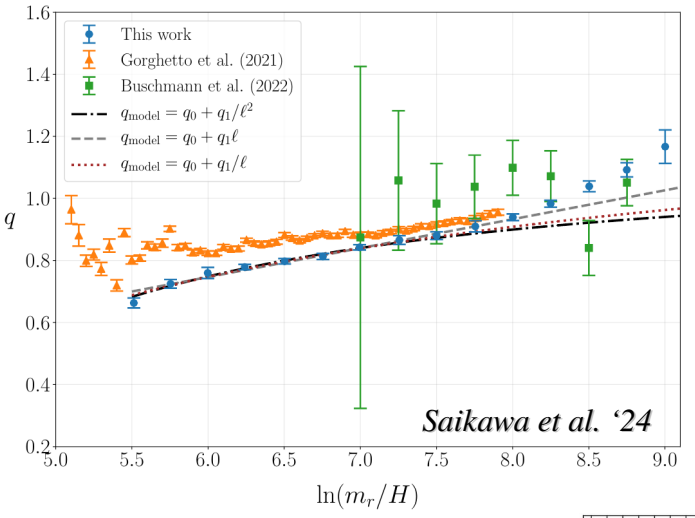

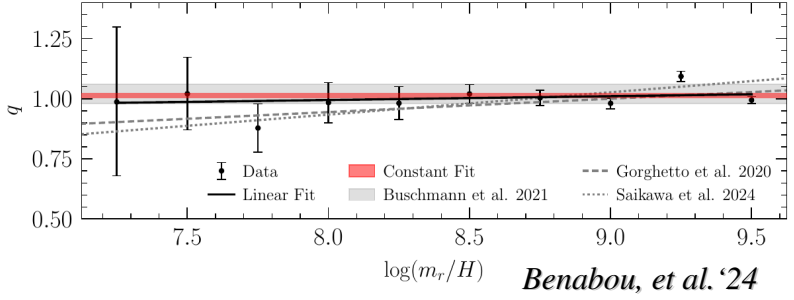

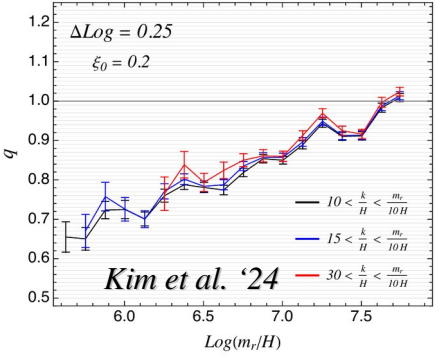

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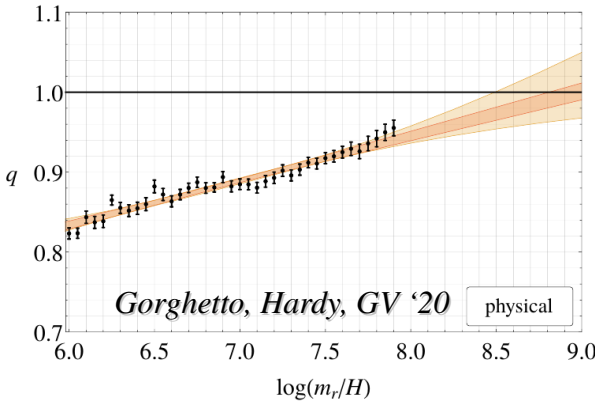
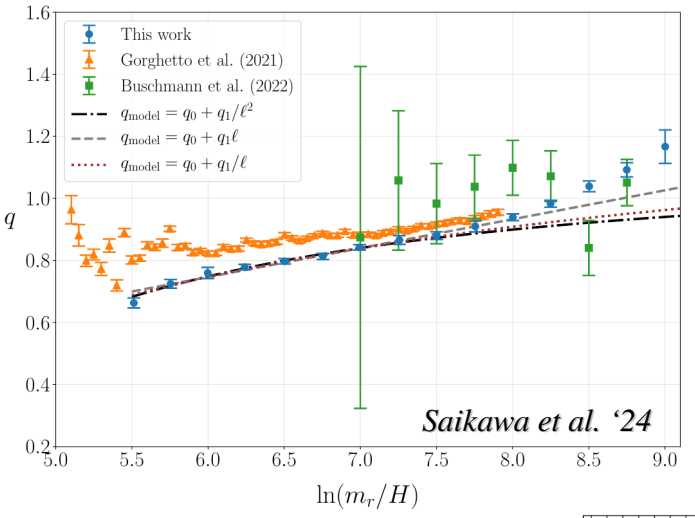
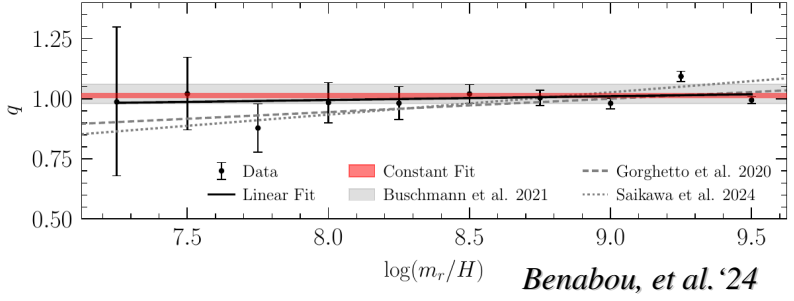
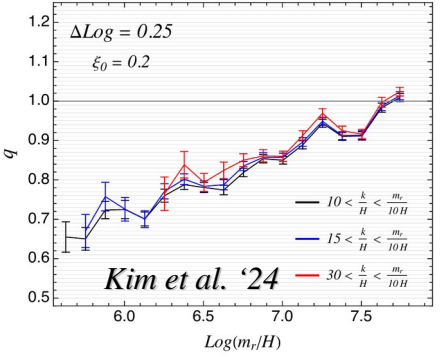




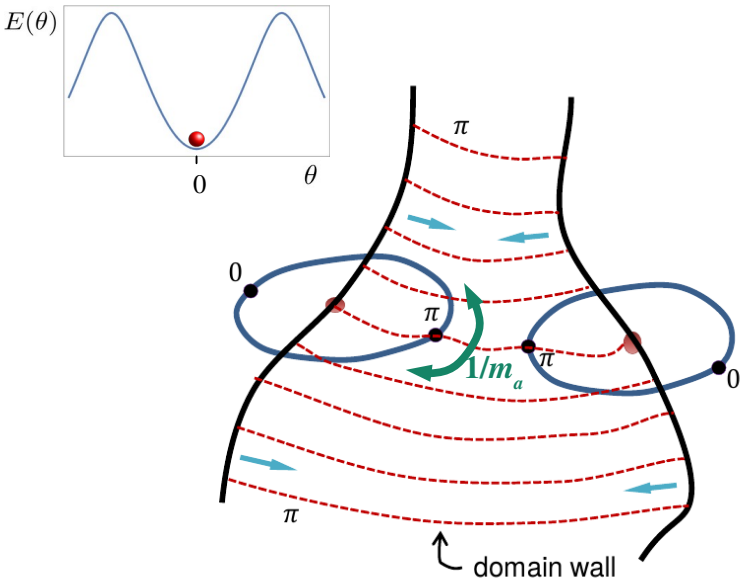
$q > 1$?





Axion Domain Walls

@ $T \sim$ GeV ↔ $m_a \sim H$



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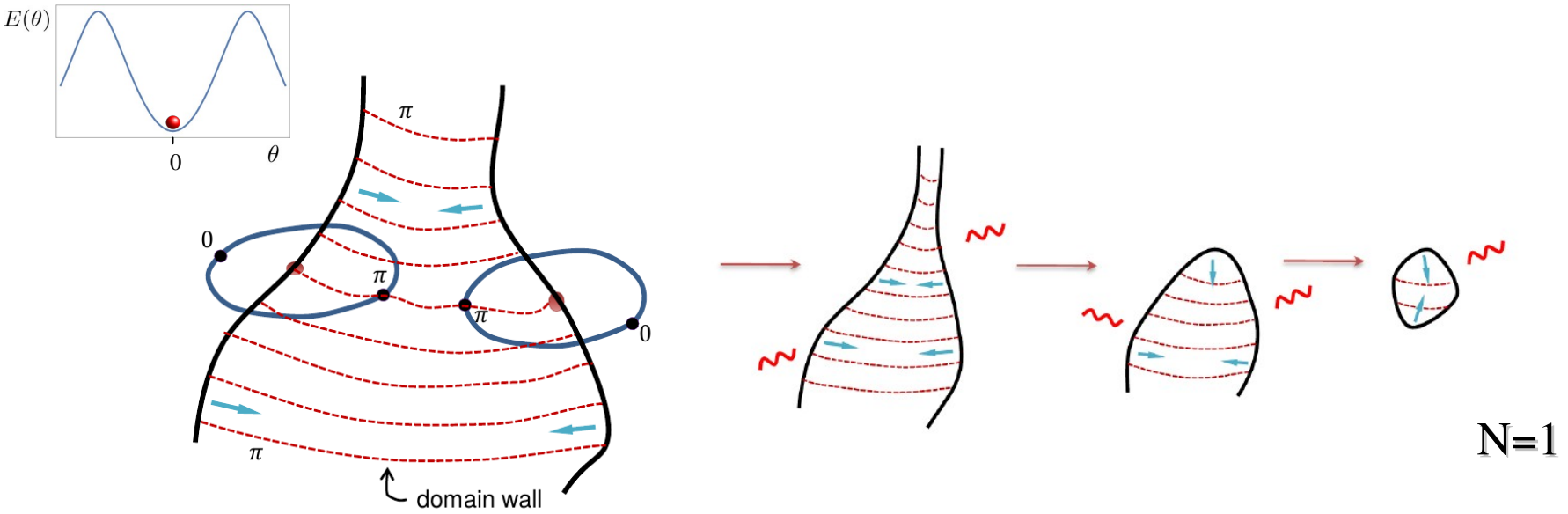

Non-linear regime:

$$\text{if } q \geq 1: \quad \rho_a(t_\star) \gg \rho^{\text{mis}} \sim \chi_{\text{top}}(T_\star)$$

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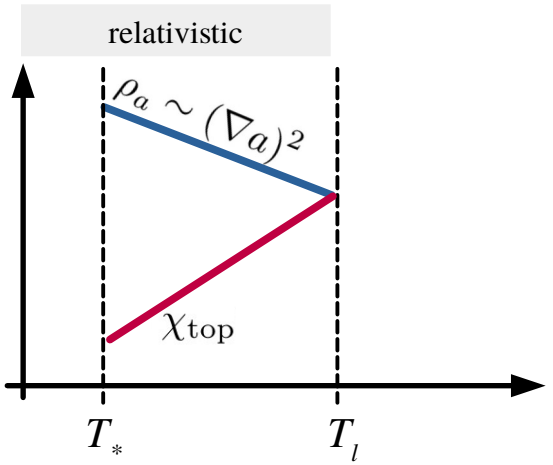

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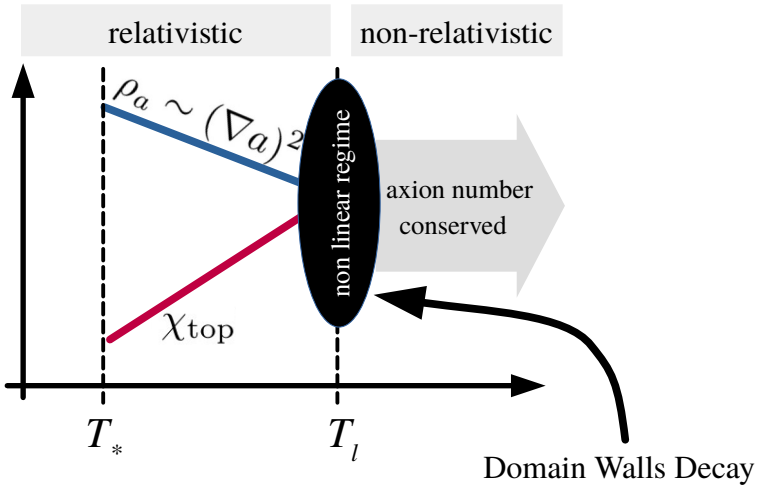

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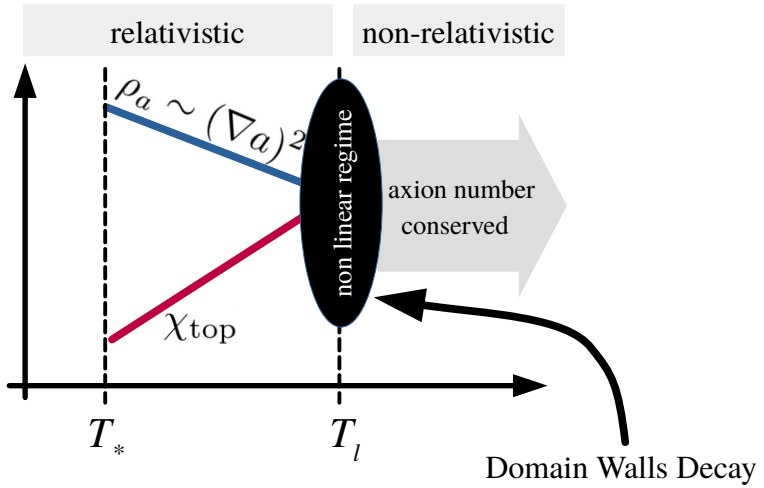

$$n_a^{q>1} \propto \xi \log \cdot n_a^{mis} \;\rightarrow\; \sqrt{\xi \log} \cdot n_a^{mis}$$

Gorghetto, Hardy, GV '20

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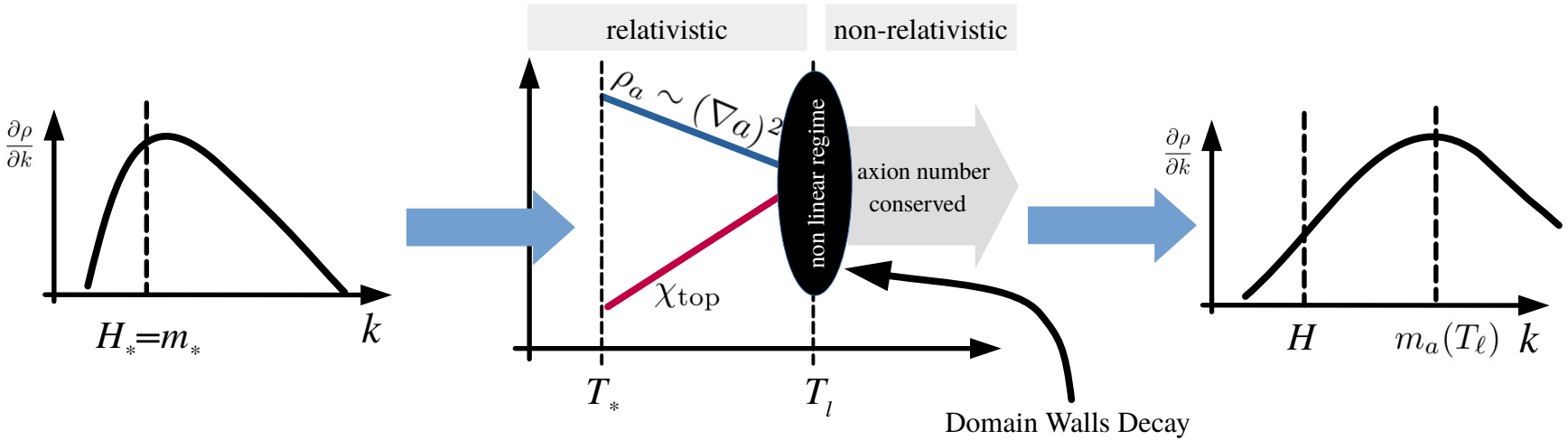

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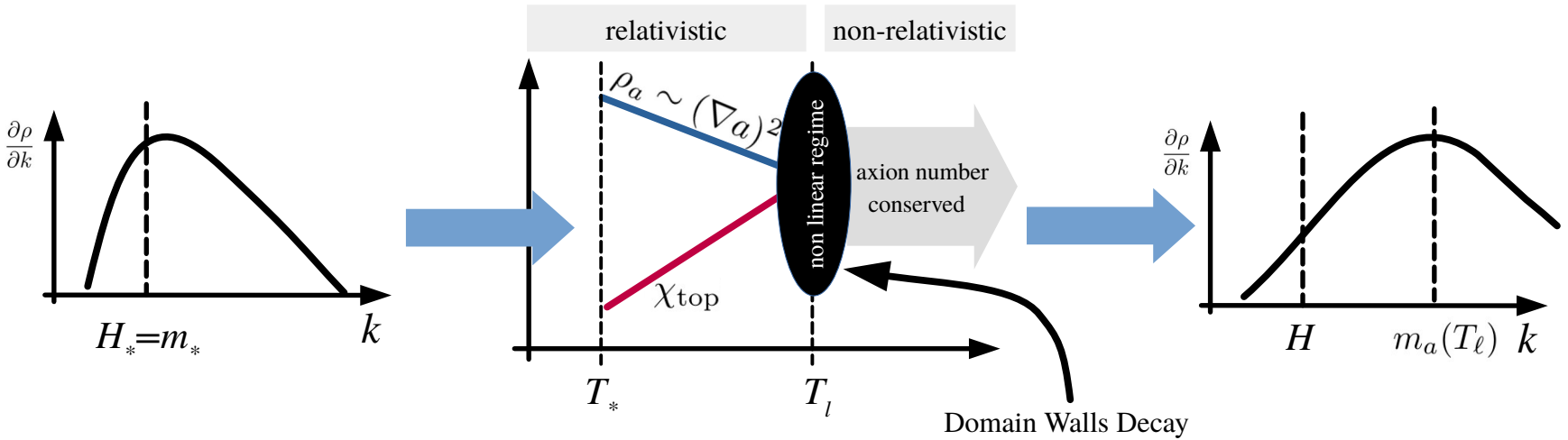
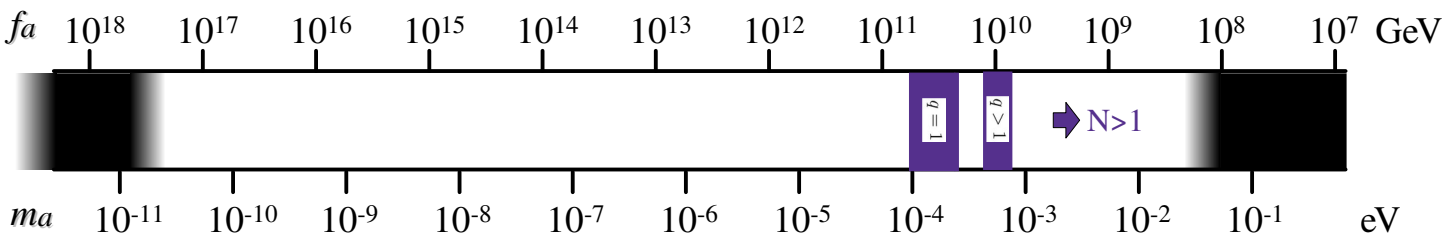
Gorghetto, Hardy, GV '20

Non-linear regime:

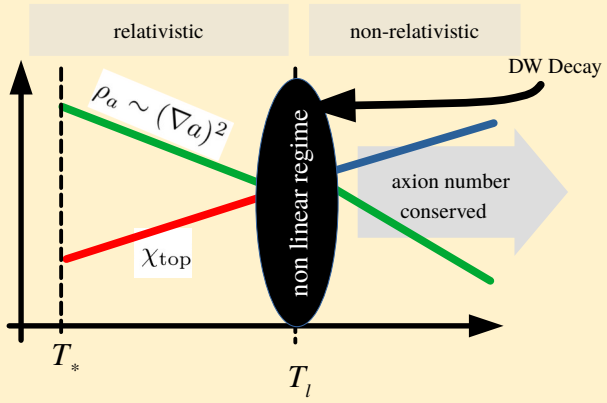
$$\text{if } q \geq 1: \quad \rho_a(t_\star) \gg \rho^{\text{mis}} \sim \chi_{\text{top}}(T_\star)$$

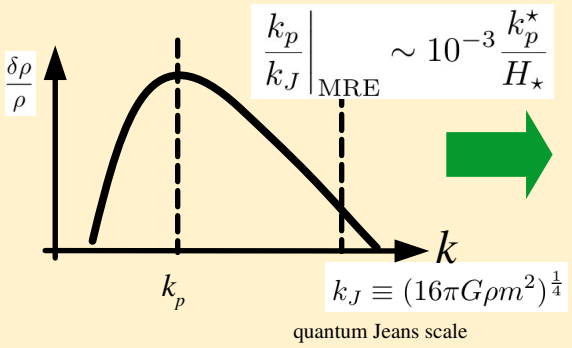


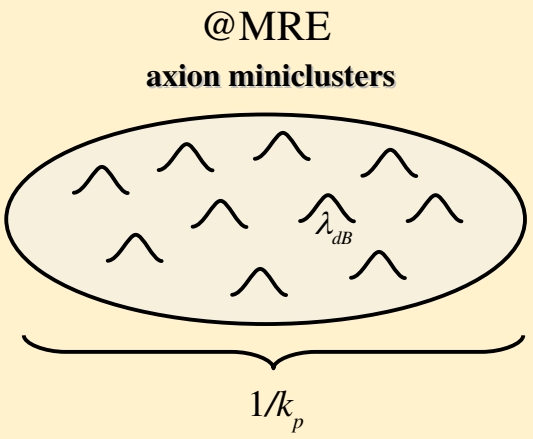


What happens after DW decay?

standard lore

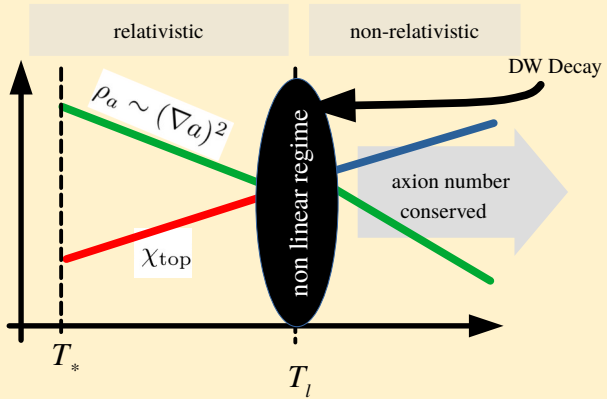


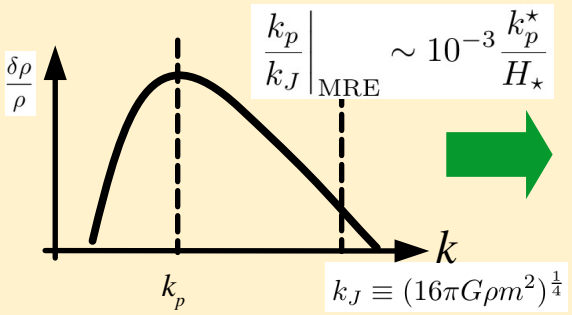


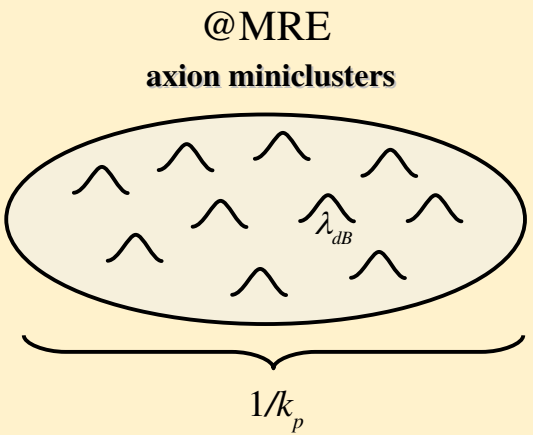


What happens after DW decay?

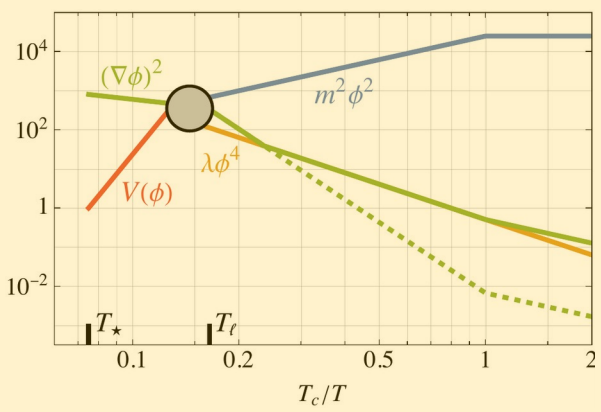
standard lore

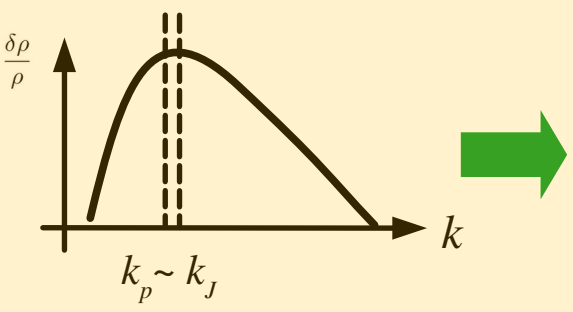


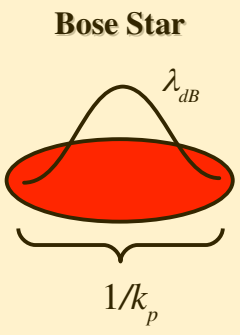




corrected description

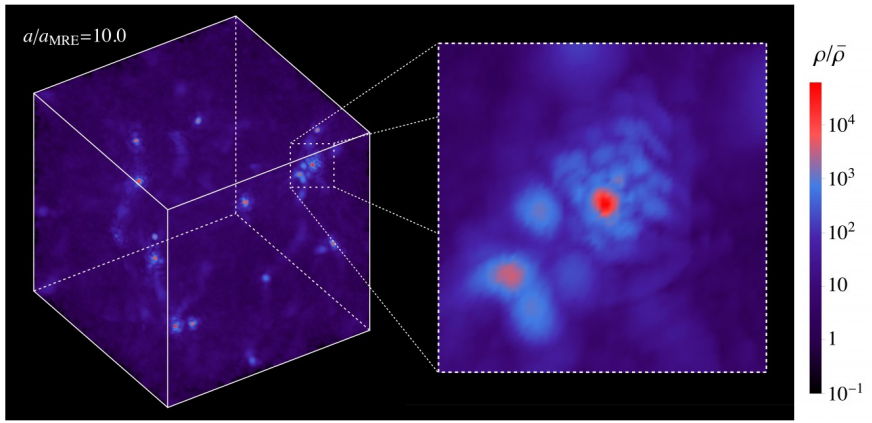




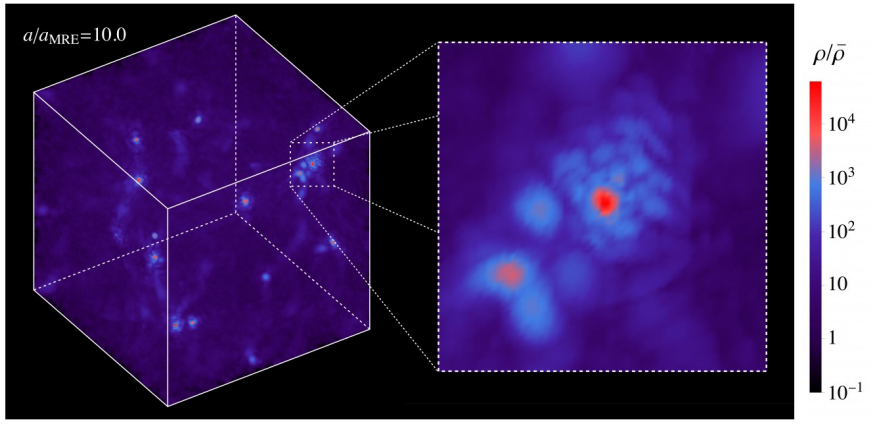


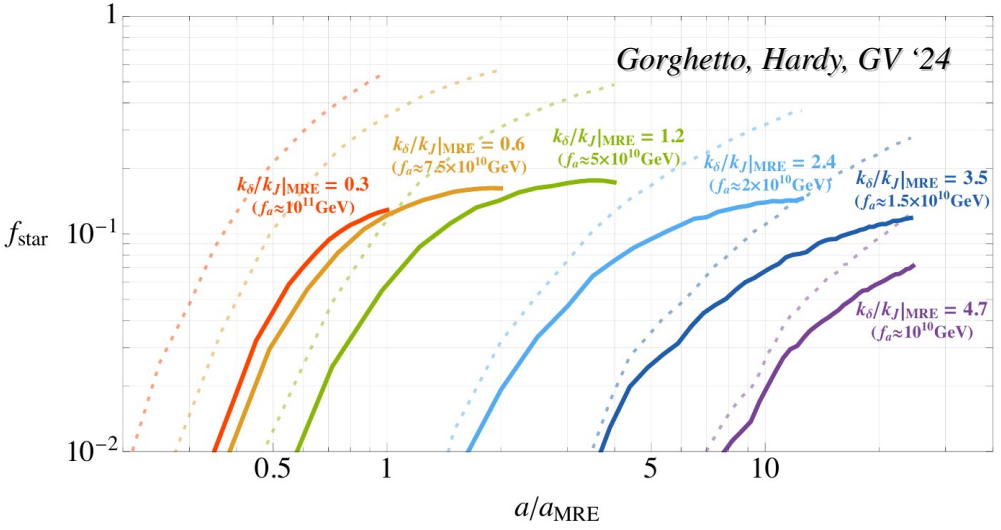
Gorghetto, Hardy, GV '24

Axion Stars: from simulations

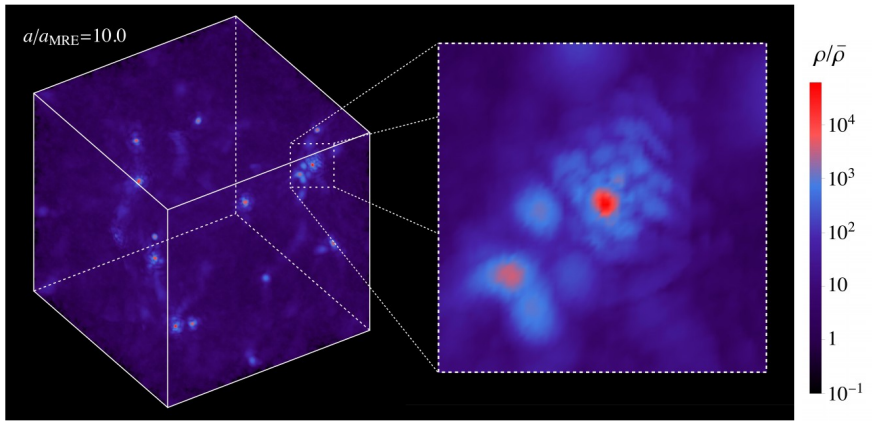


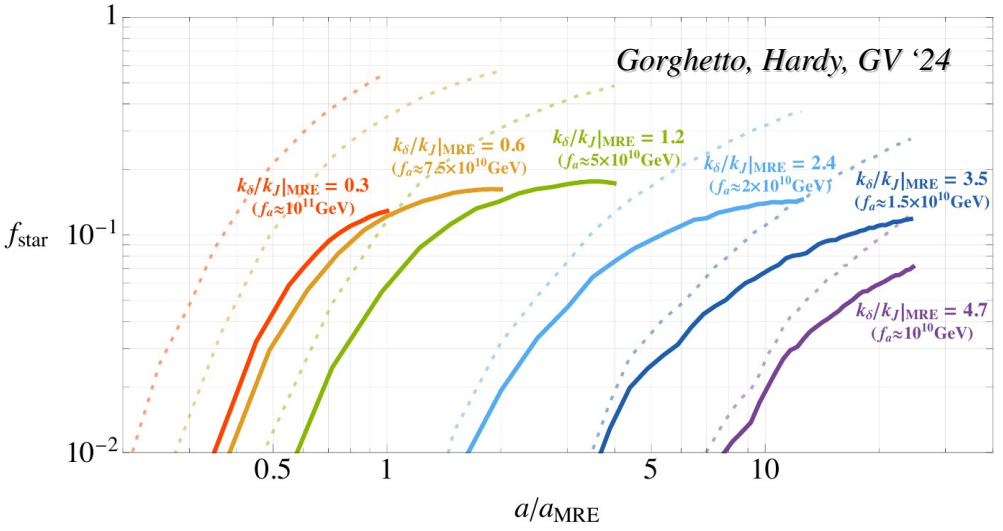
Axion Stars: from simulations

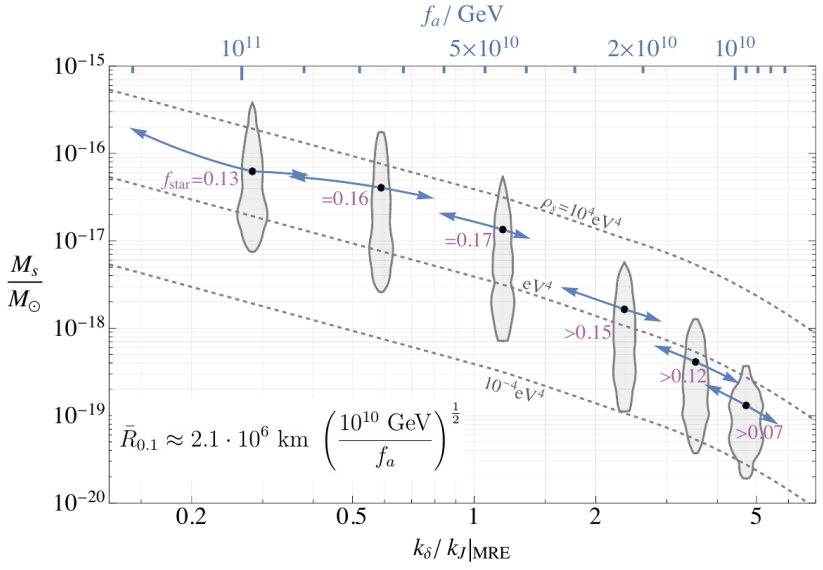




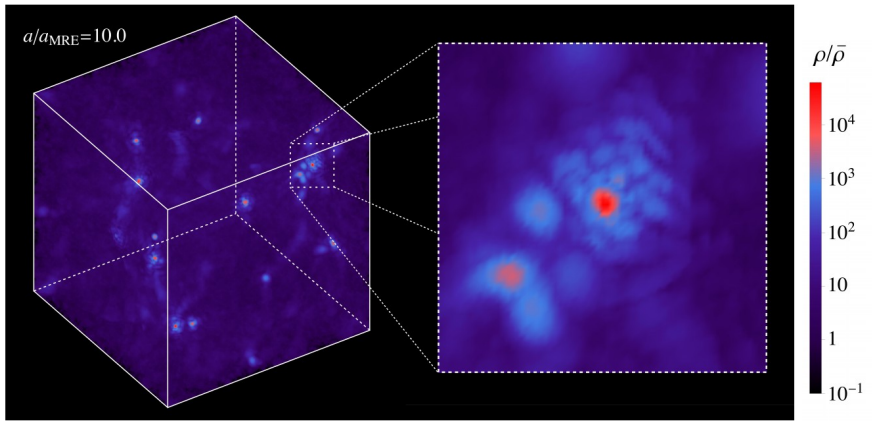
Axion Stars: from simulations

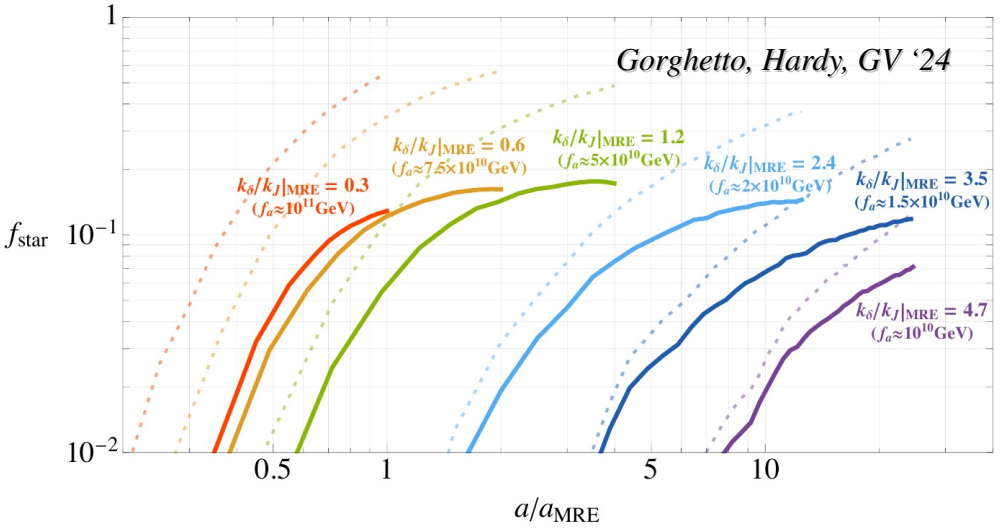


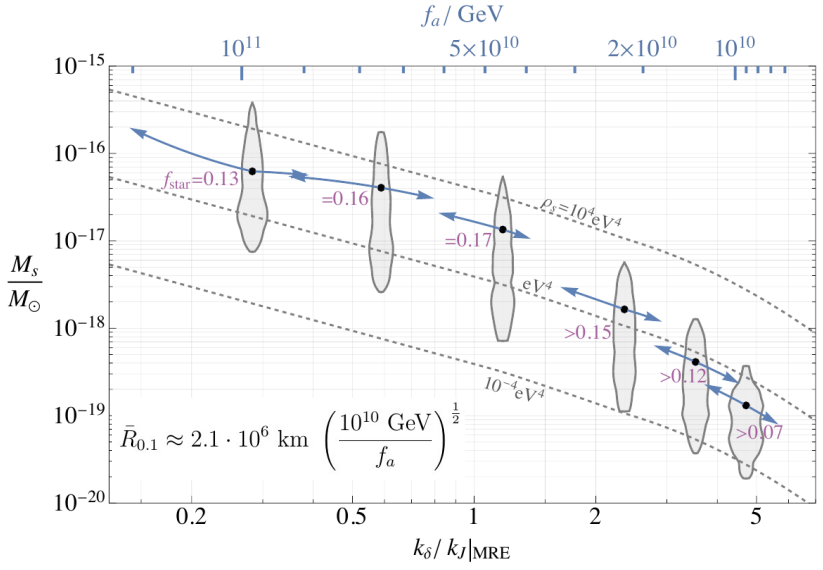


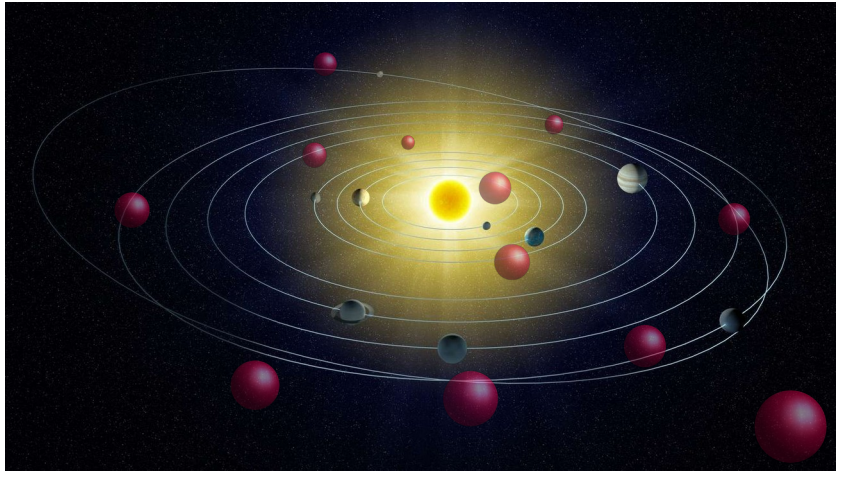


Axion Stars: from simulations



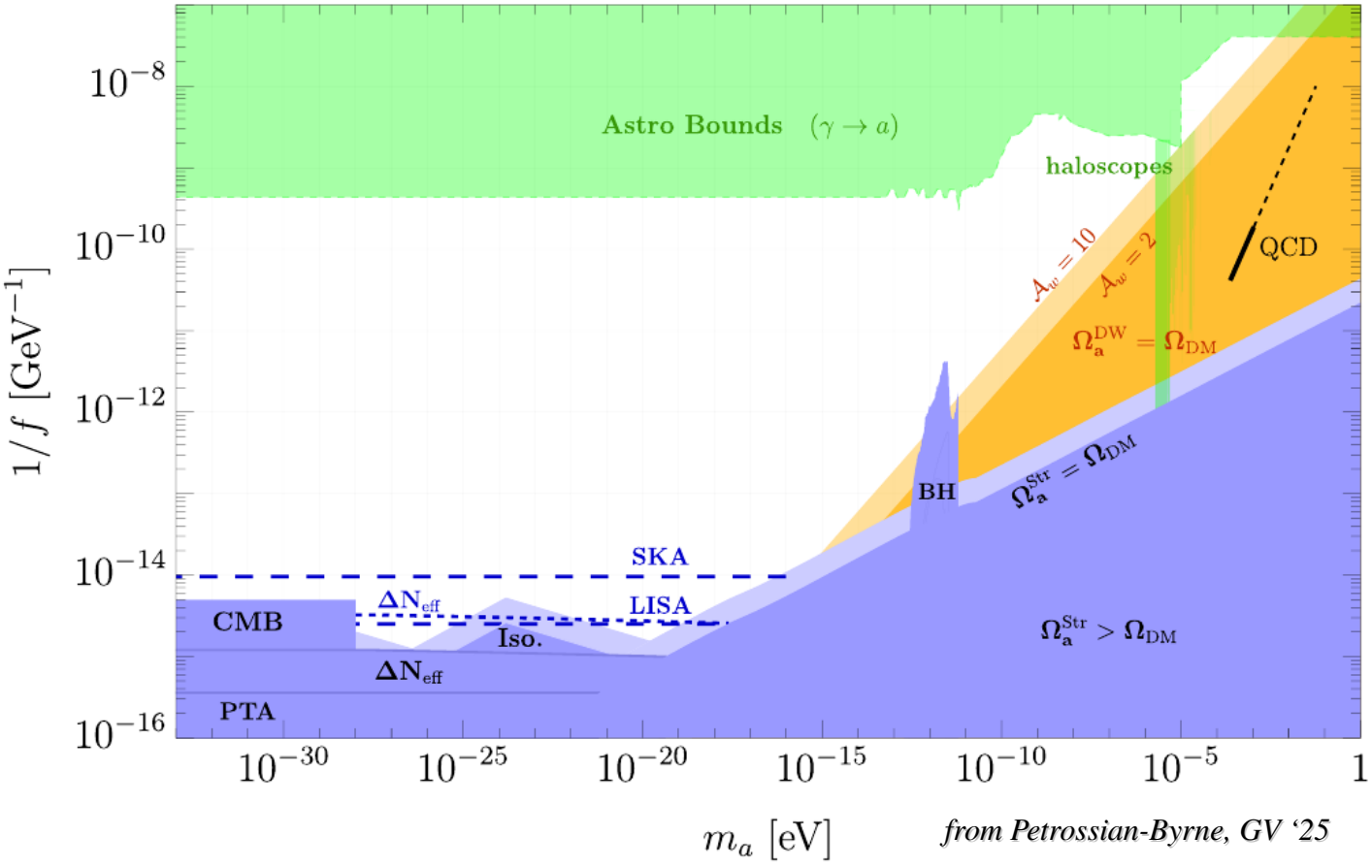






Post-Inflationary ALP landscape

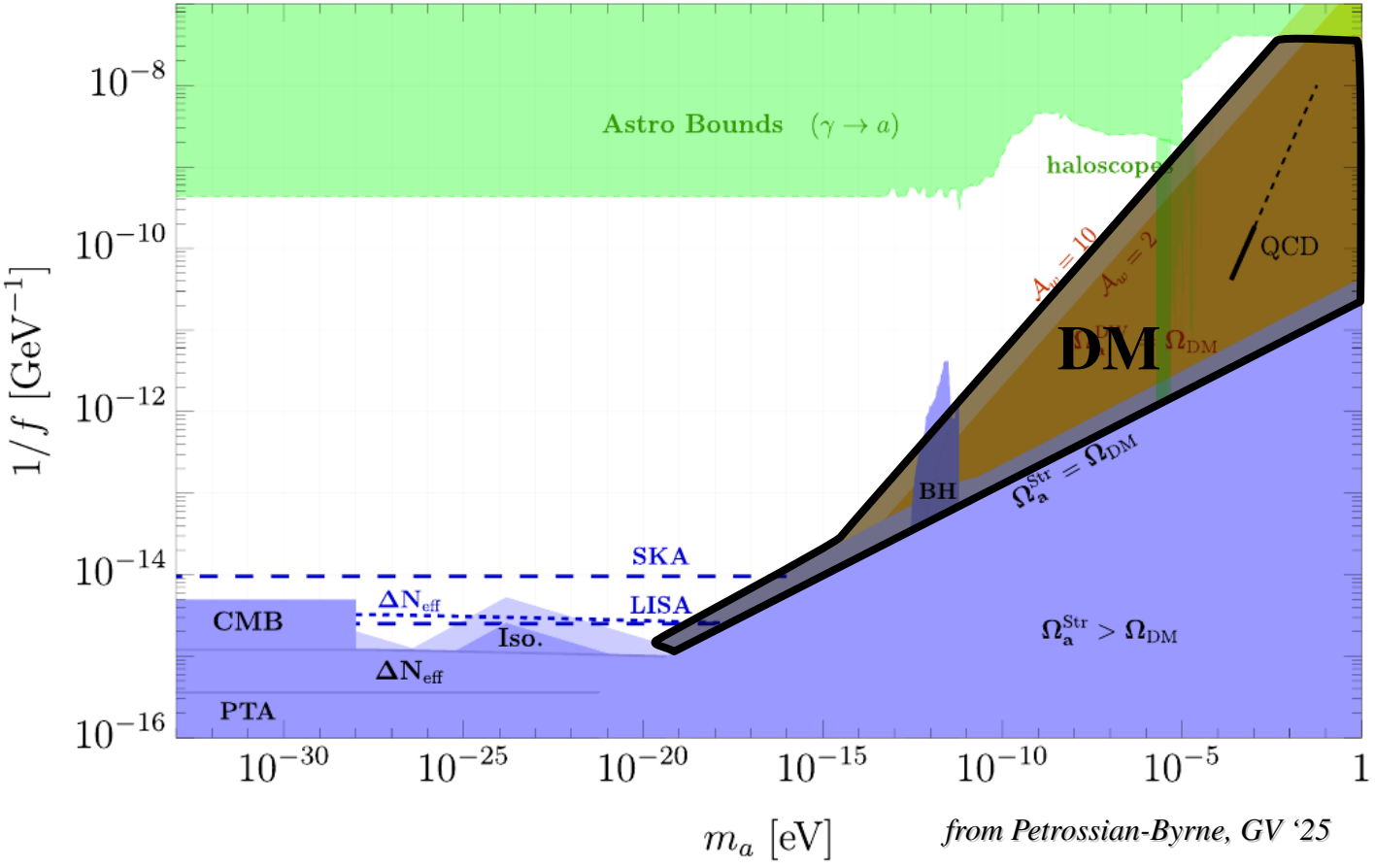
see e.g. Gorghetto, Hardy, Nicolaescu '21
Gorghetto, Hardy '22



from Petrossian-Byrne, GV '25

Post-Inflationary ALP landscape

see e.g. Gorghetto, Hardy, Nicolaescu '21
Gorghetto, Hardy '22



from Petrossian-Byrne, GV '25

Future Prospects from next gen. simulations (w/ AMR) :

– reduce/understand systematics

– scaling/extrapolation (q >= 1 ?)

– understanding dynamics behind scaling properties

– string+DW regime (N>1 ?)

– late time evolutions of axion stars / mini-halos

Extensions:

– scaling w/ Non-minimal core (axiverse)

– mixed global/local strings

– superconducting strings

– friction effects

– ...