Primordial Black Holes from Axion Walls

BSM @ 50 Years • ICISE

David Dunsky, Marius Kongsore

Work in progress

Motivation and Key Idea

- Standard cosmological picture (high reheat scenario):

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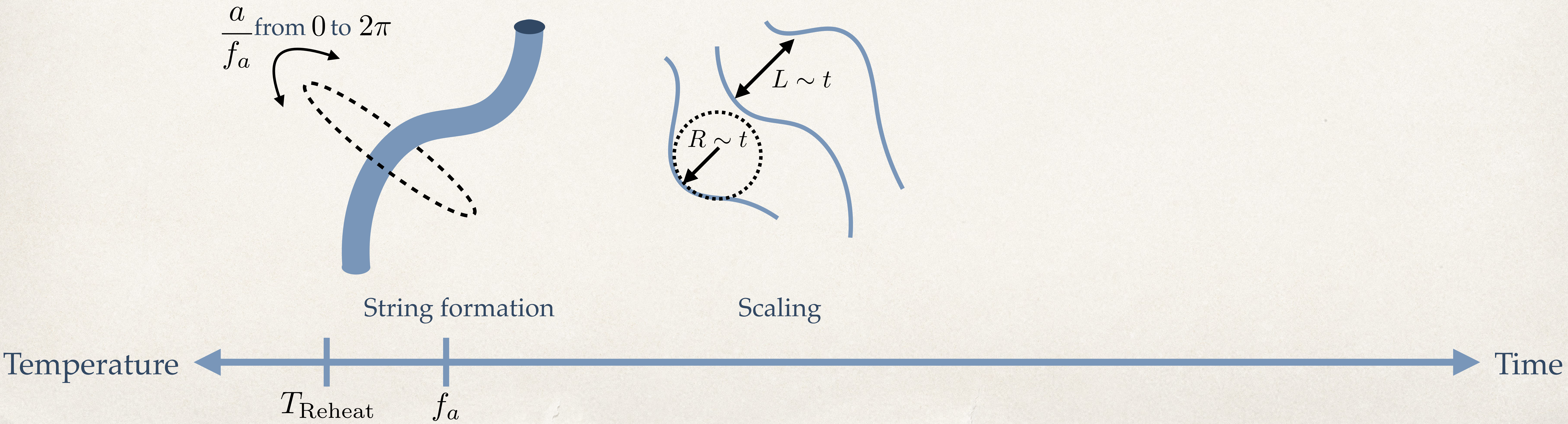

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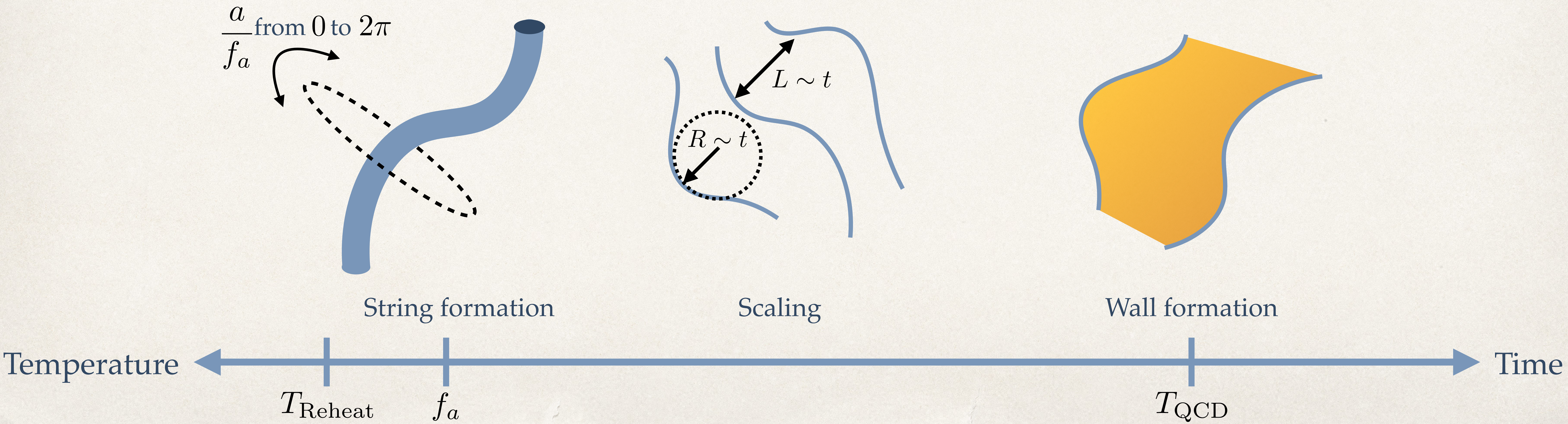

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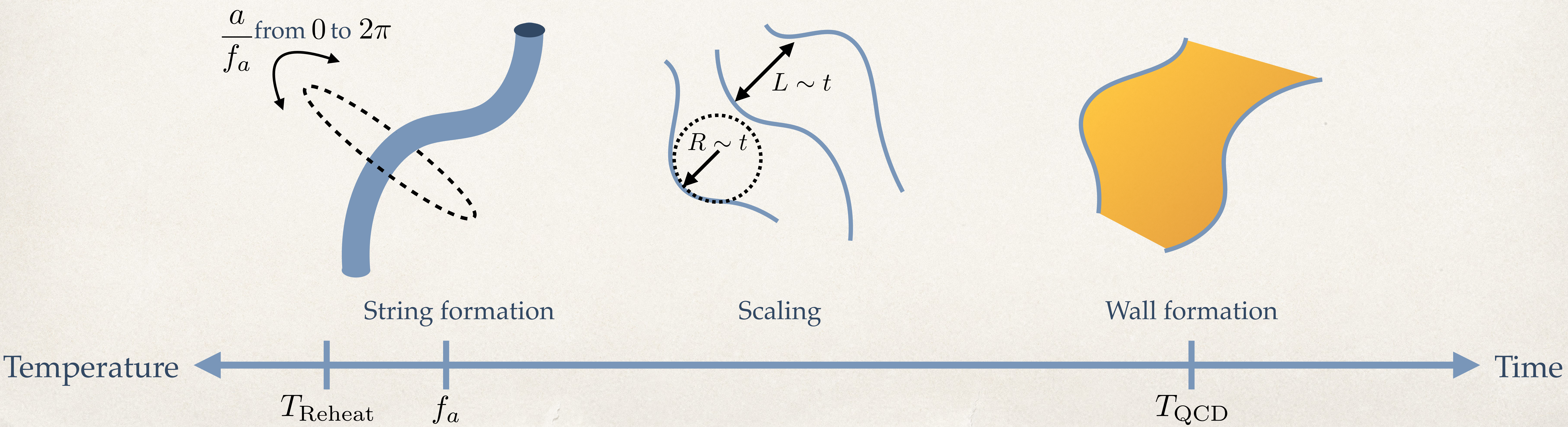

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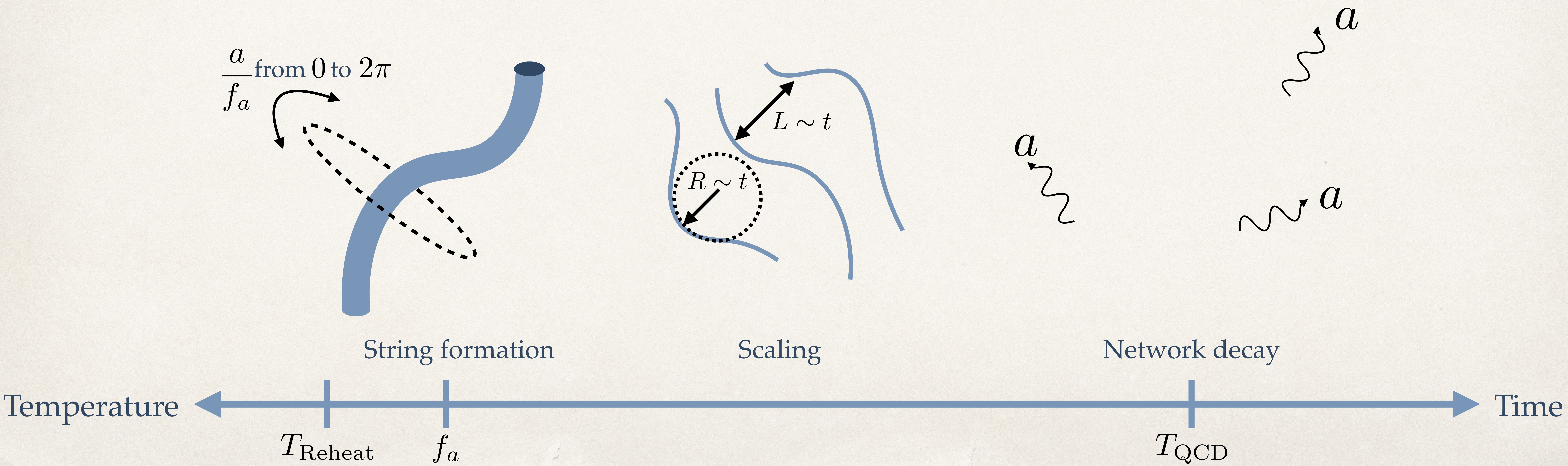

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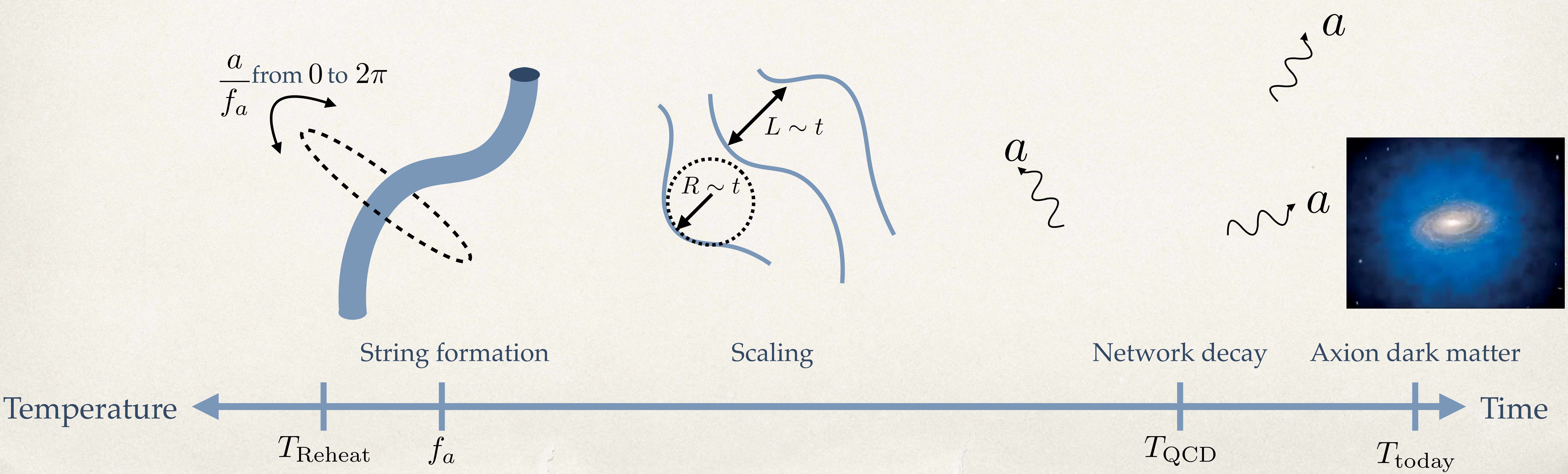

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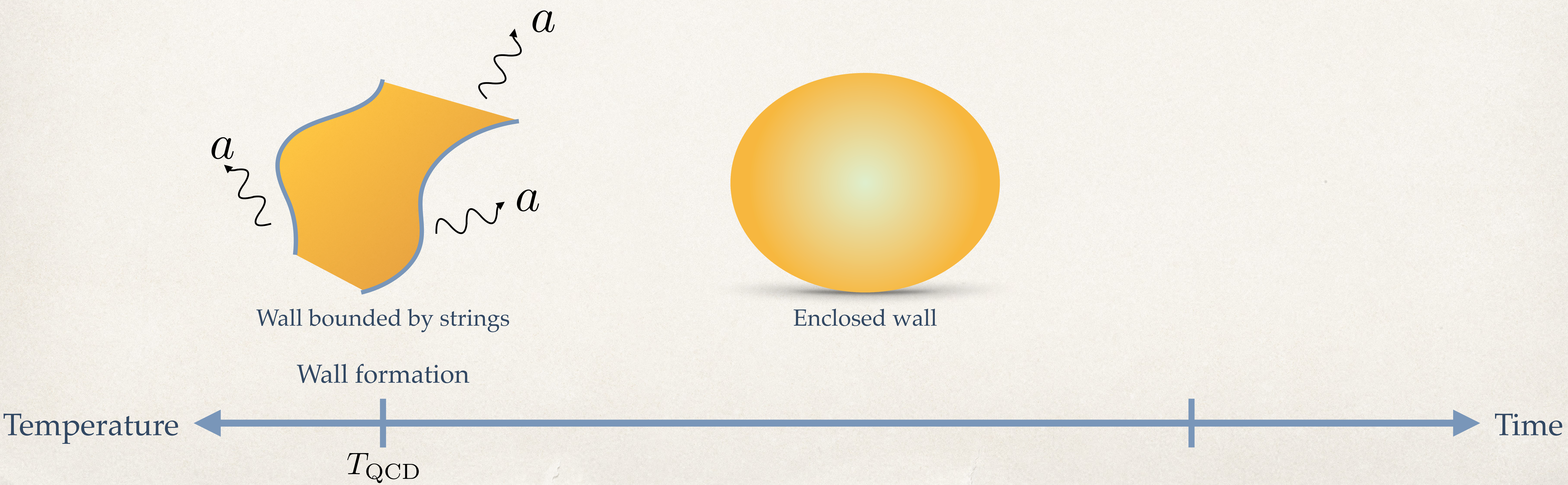

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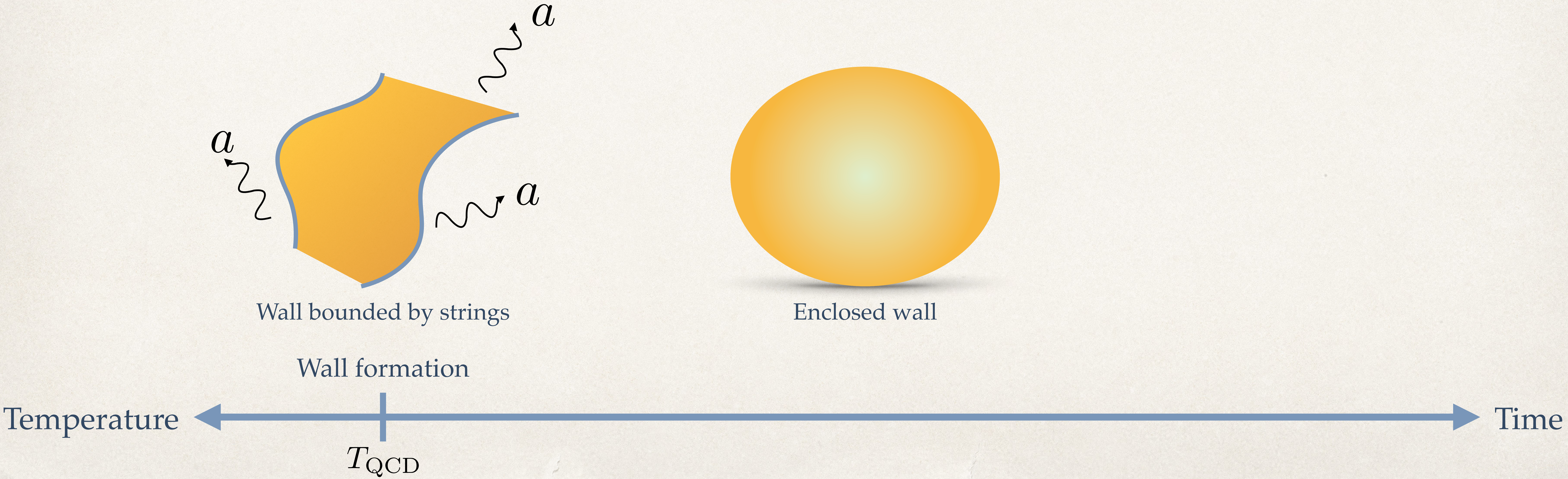

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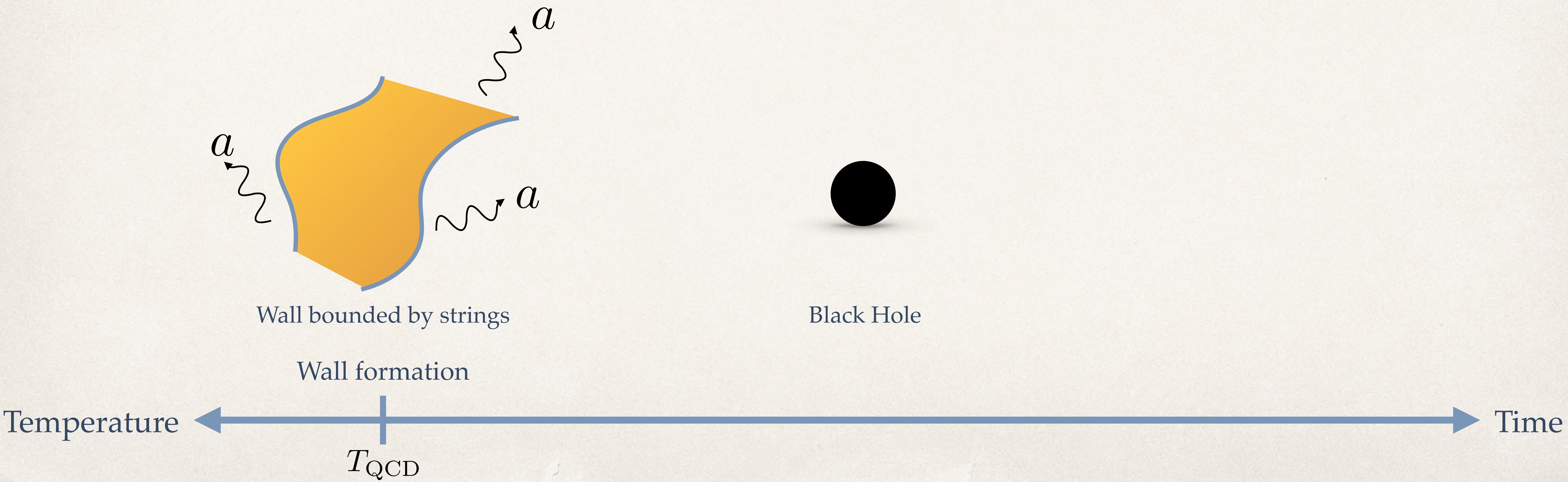

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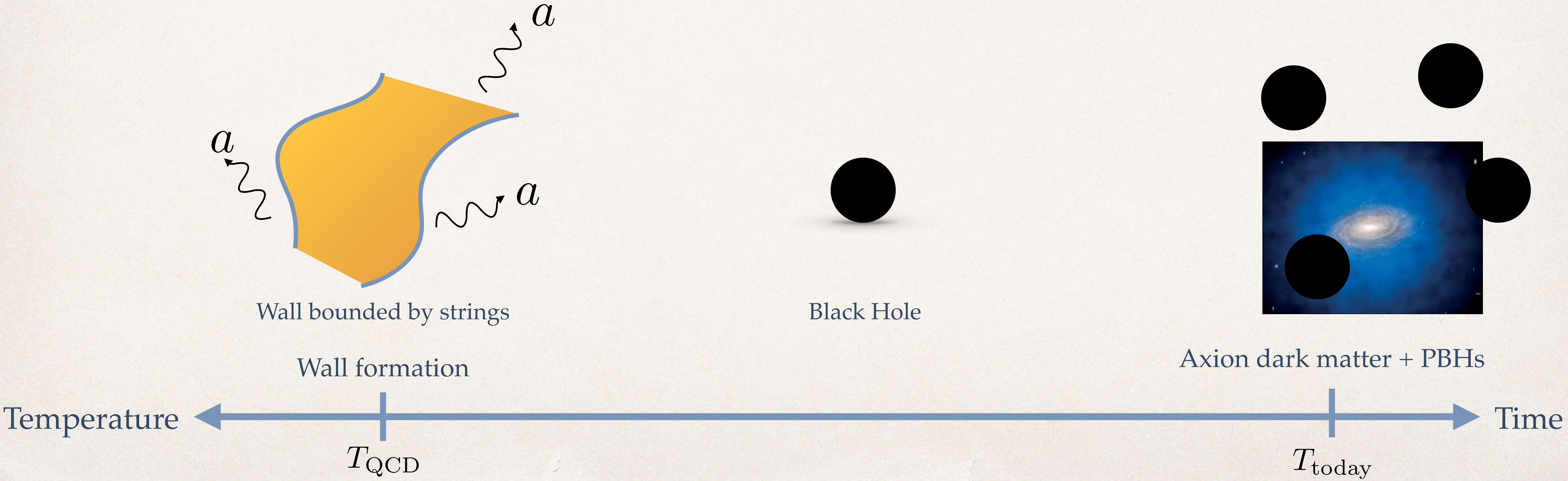

Outline

- Cosmology and formation of enclosed axion domain walls

- Enclosed wall dynamics

Dark Energy

- Efficiency of PBH formation and relic abundance

Cosmology and Formation of Enclosed Walls

Cosmology of Axion Defects

$$\mathcal{L}_{\rm UV} = |\partial_\mu \Phi|^2 - V_{\rm PQ}(\Phi)$$

- At high temperatures, Lagrangian respects $U(1)_{\rm PQ}$ symmetry
- Below scale f_a, $\langle \Phi \rangle \approx f_a e^{ia/f_a}$ from minimum of $V_{\rm PQ}$

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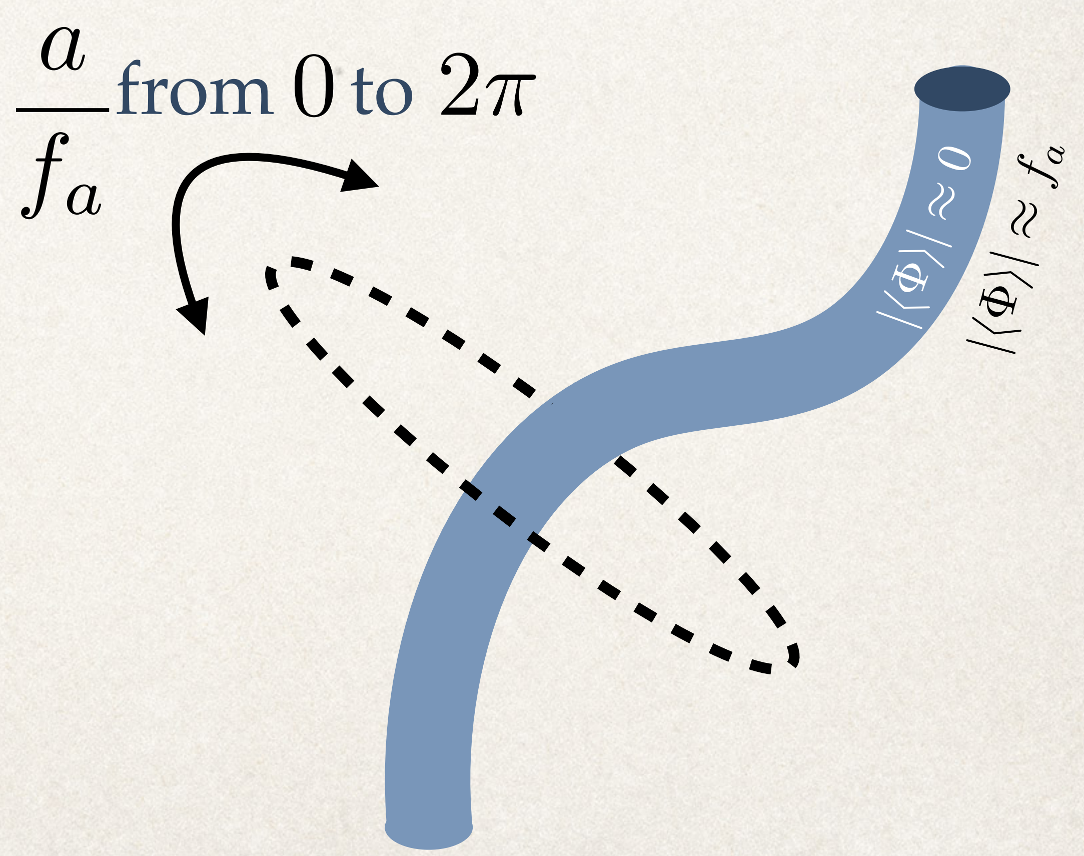
- Spontaneous breaking of $U(1)$ → cosmic strings

↑ Locus of points in physical space where $\langle \Phi \rangle = 0$



String formation

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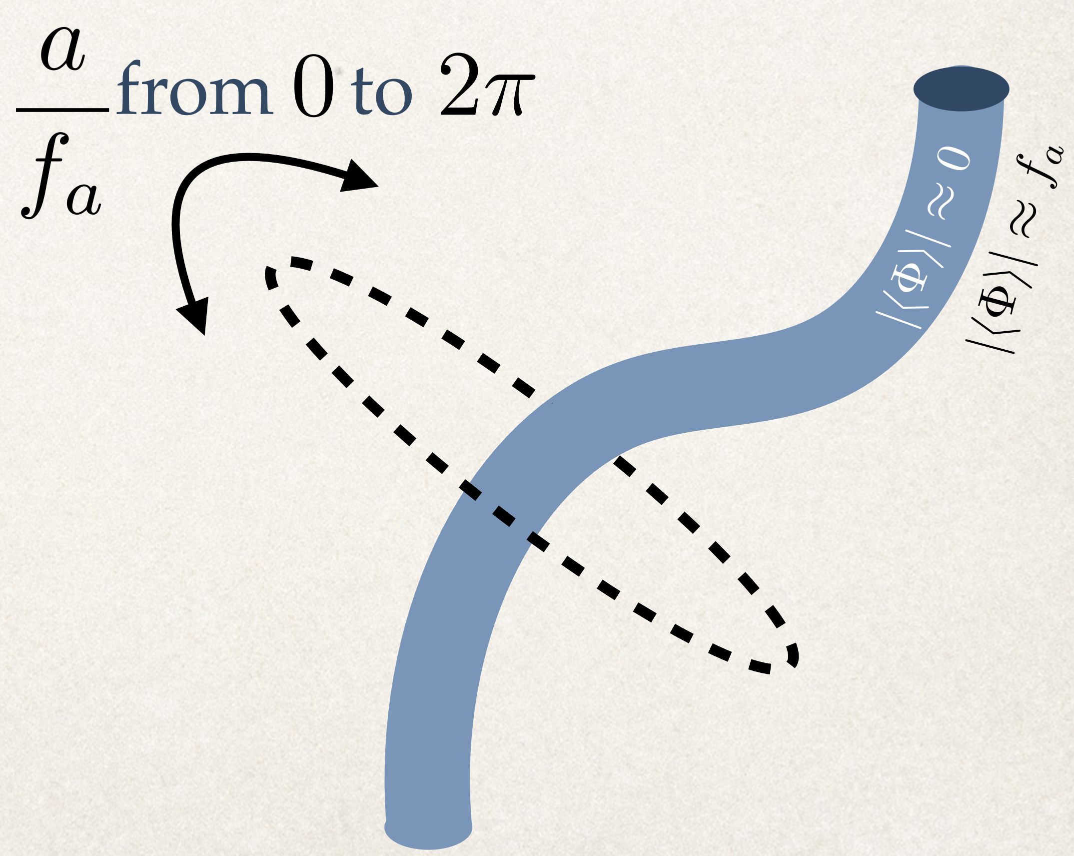
Locus of points in physical space where $\langle \Phi \rangle = 0$

- Mass per unit length $\mu \approx V_{\rm PQ}(\Phi = 0)\delta_s^2 \sim f_a^4 \times f_a^{-2} \simeq \pi f_a^2 \ln(f_a\, L)$



String formation

Cosmology of Axion Defects

$$\mathcal{L}_{\rm IR} = \frac{1}{2}\partial_\mu a\, \partial^\mu a - m_a^2(T) f_a^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

- Near $T_{\rm QCD}$, PQ breaking potential from strong dynamics

- Domain wall is field configuration that interpolates between the (unique) vacuum at $\theta \equiv a/f_a \;=\; 0$ back to 2π

Surface of points in physical space where $\theta \equiv a/f_a = \pi$

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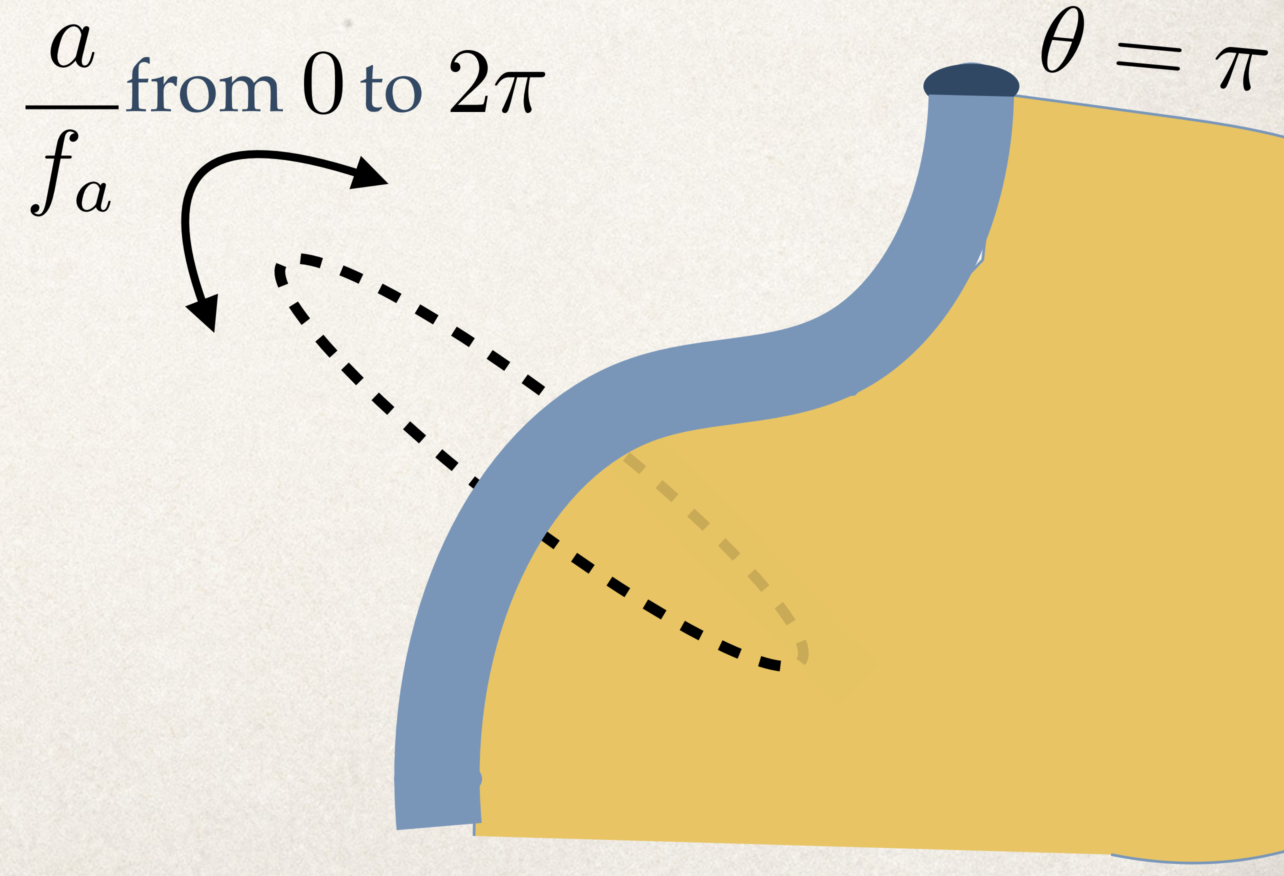

Wall formation

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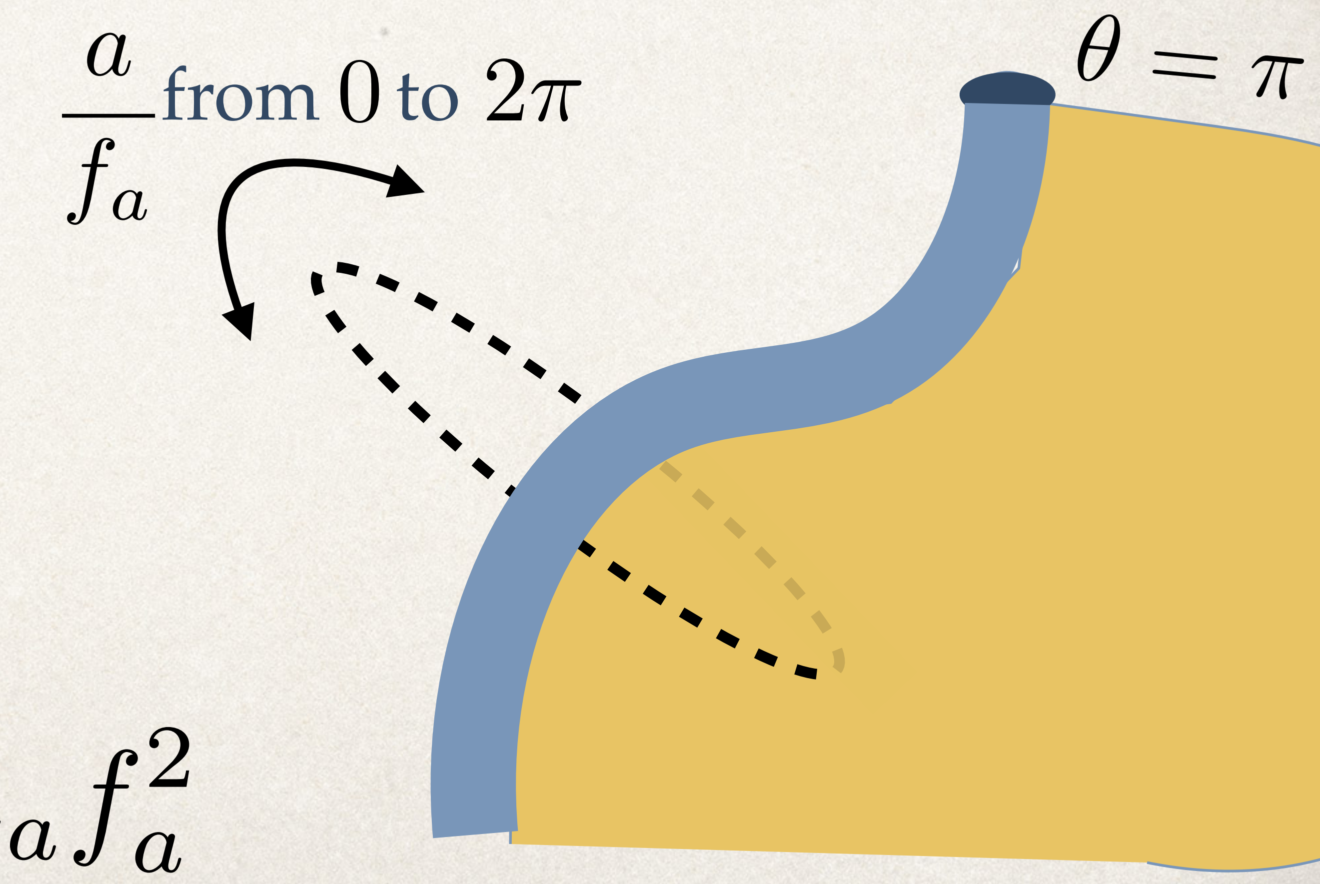
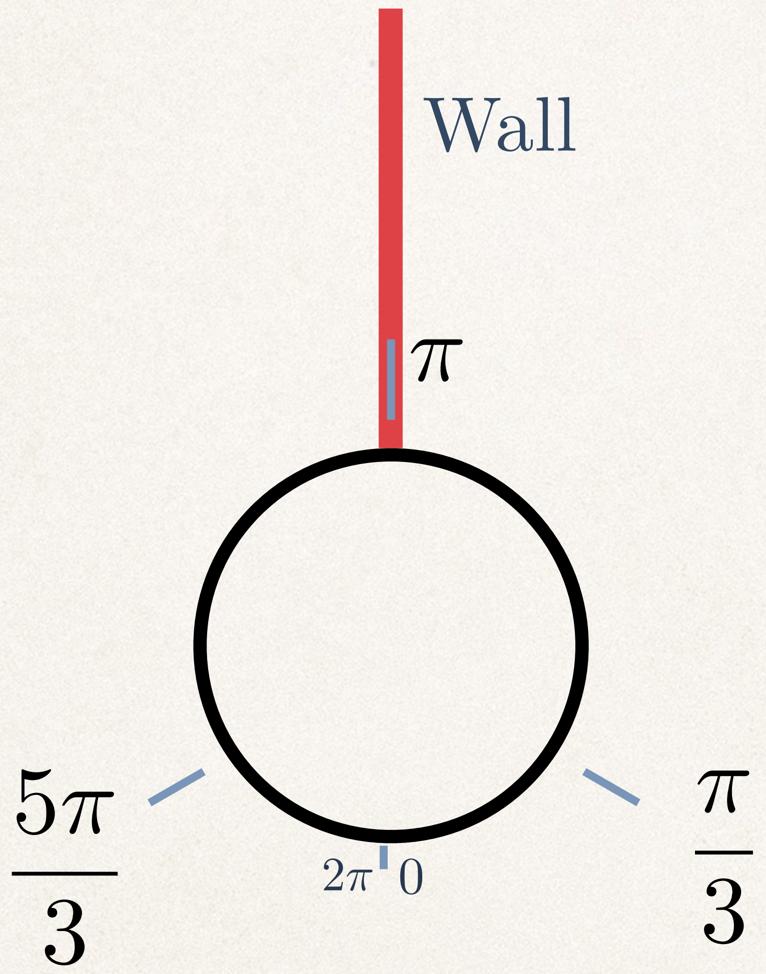


- Mass per unit area $\sigma \approx V_{\rm QCD}(\theta = \pi)\delta \sim m_a^2 f_a^2 \times m_a^{-1} \simeq 8 m_a f_a^2$

Wall formation

Abundance of Enclosed Walls



Axion string
(into the board)

Sikivie, '83. See also Kibble '76 and Vachaspati & Vilenkin '84

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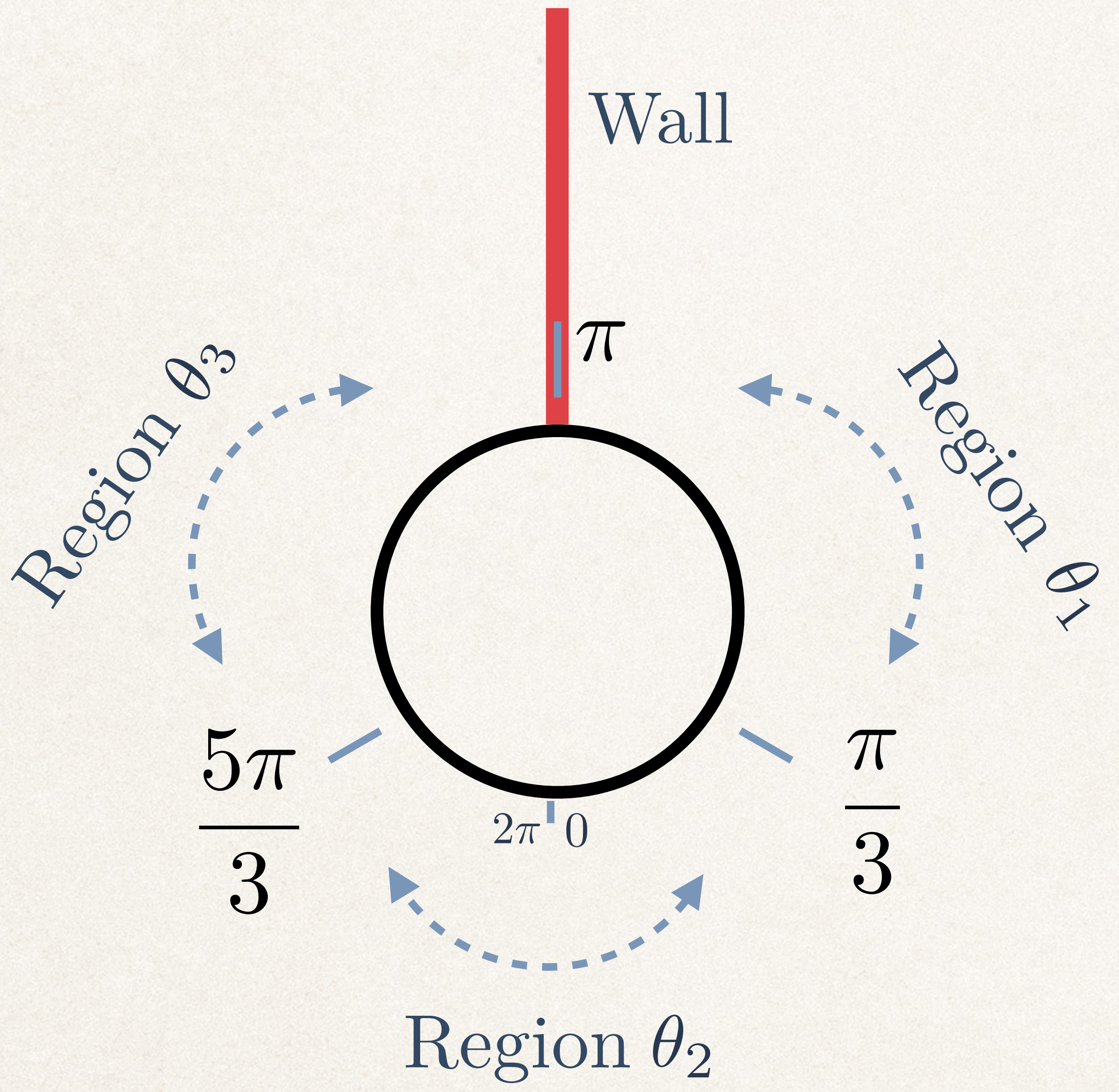

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θ_2	θ_1	θ_3	θ_1	θ_2	θ_3	θ_2	θ_2	θ_3	θ_2	θ_1
θ_2	θ_1	θ_2	θ_3	θ_3	θ_1	θ_3	θ_2	θ_1	θ_2	θ_2
θ_2	θ_2	θ_1	θ_2	θ_3	θ_3	θ_2	θ_3	θ_1	θ_3	θ_3
θ_3	θ_1	θ_2	θ_3	θ_1	θ_2	θ_2	θ_3	θ_3	θ_2	θ_1
θ_1	θ_2	θ_3	θ_1	θ_1	θ_2	θ_3	θ_1	θ_2	θ_1	θ_3
θ_2	θ_1	θ_2	θ_2	θ_1	θ_3	θ_3	θ_2	θ_3	θ_3	θ_3
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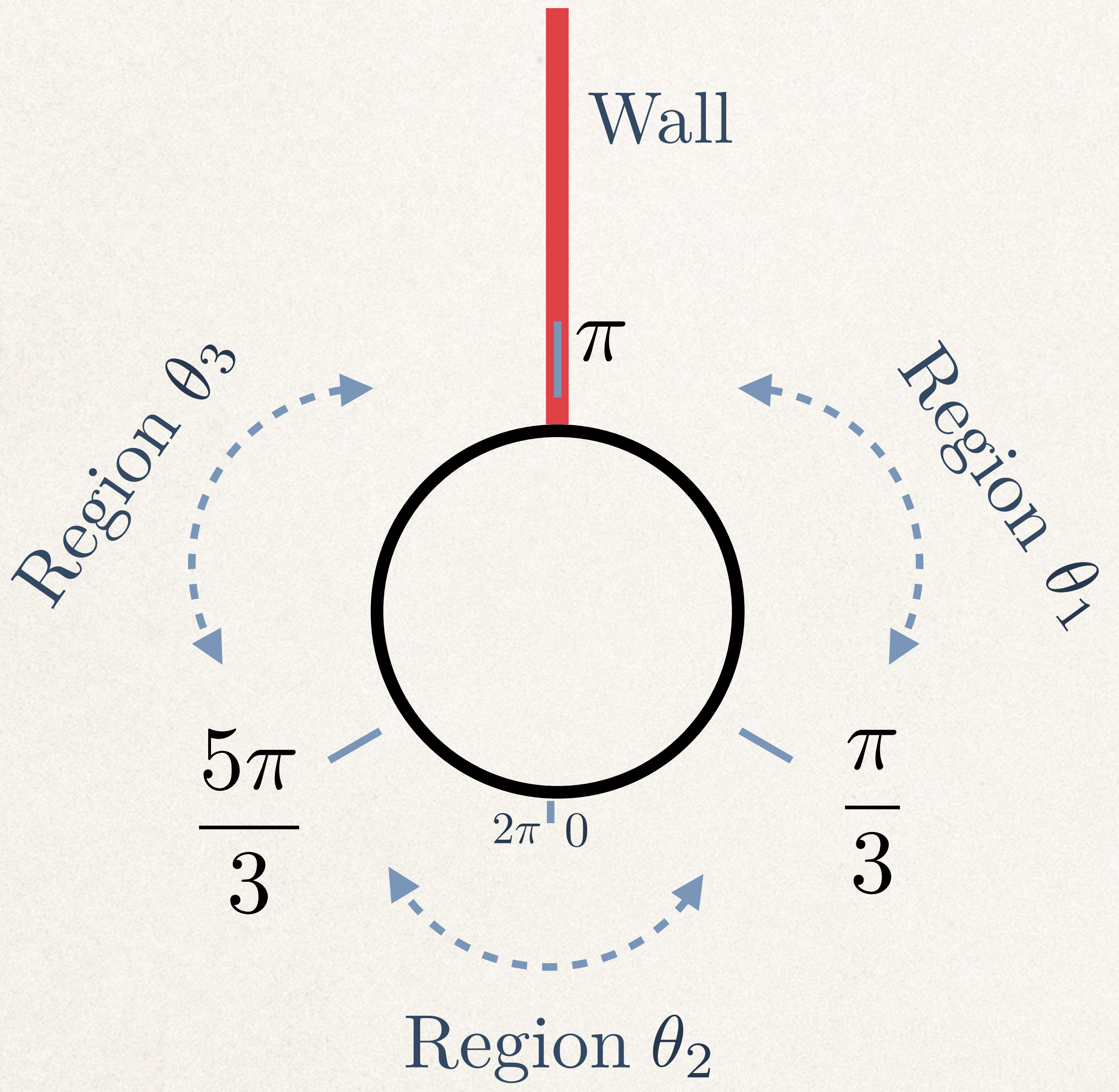

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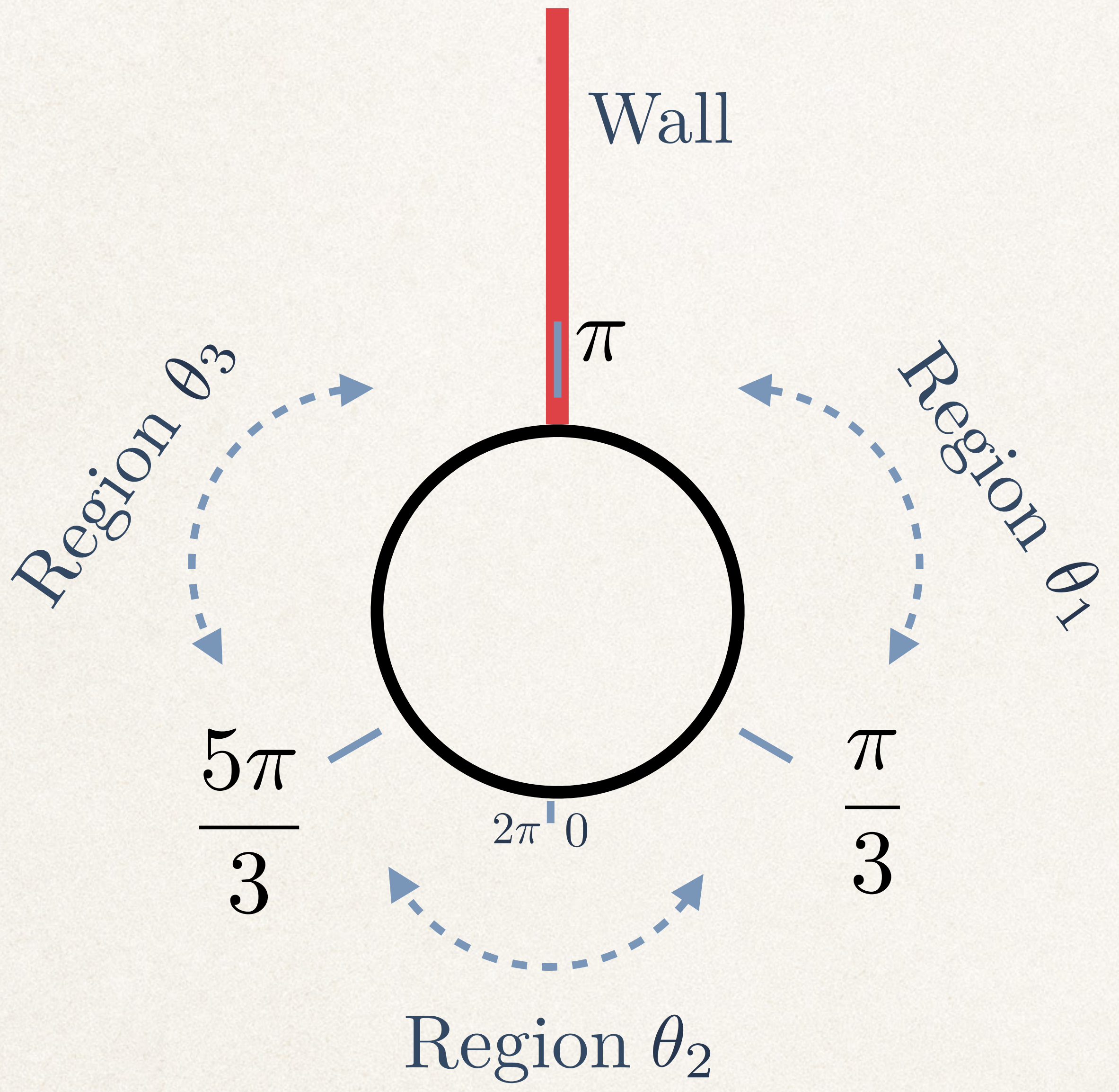

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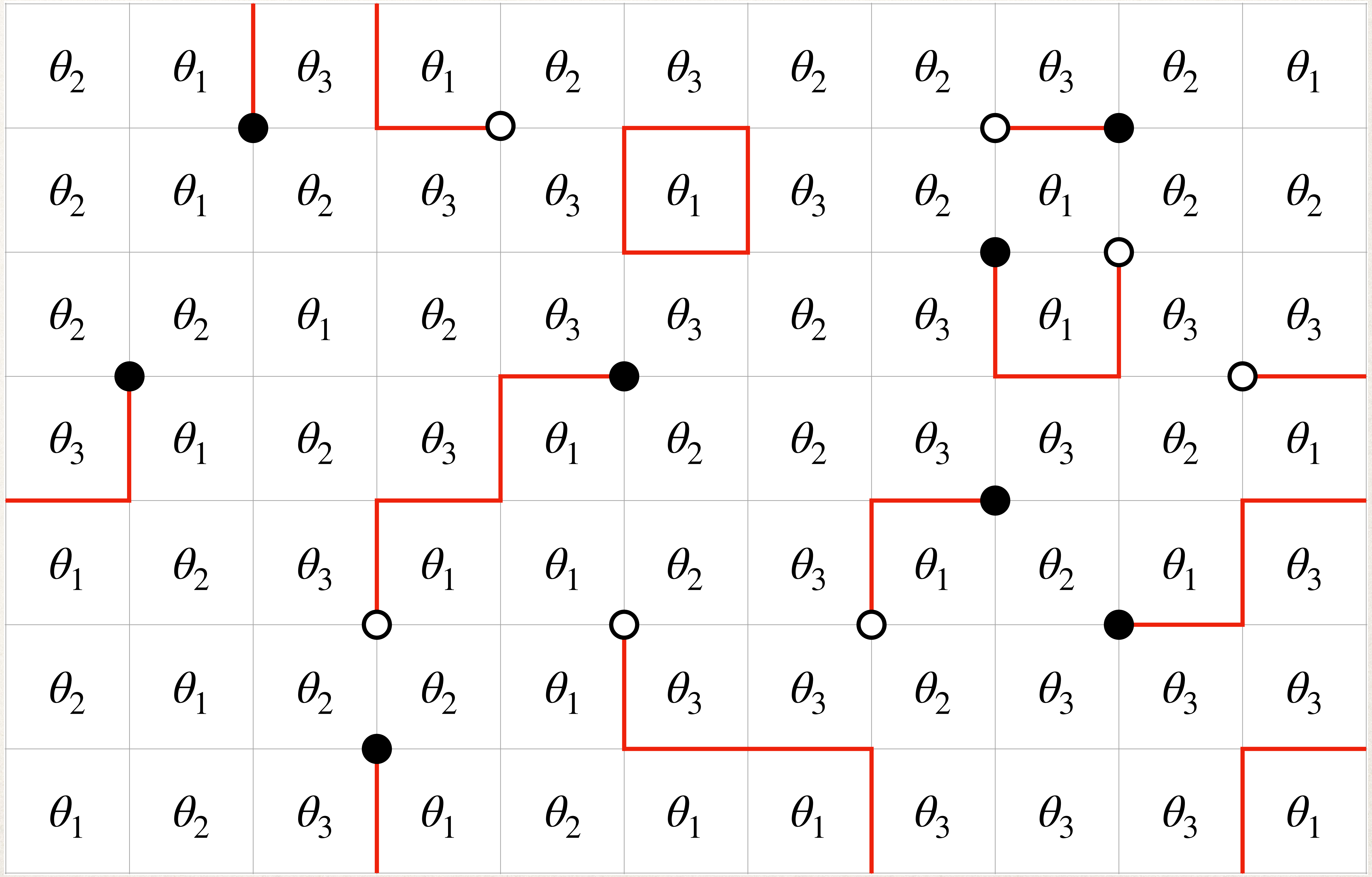

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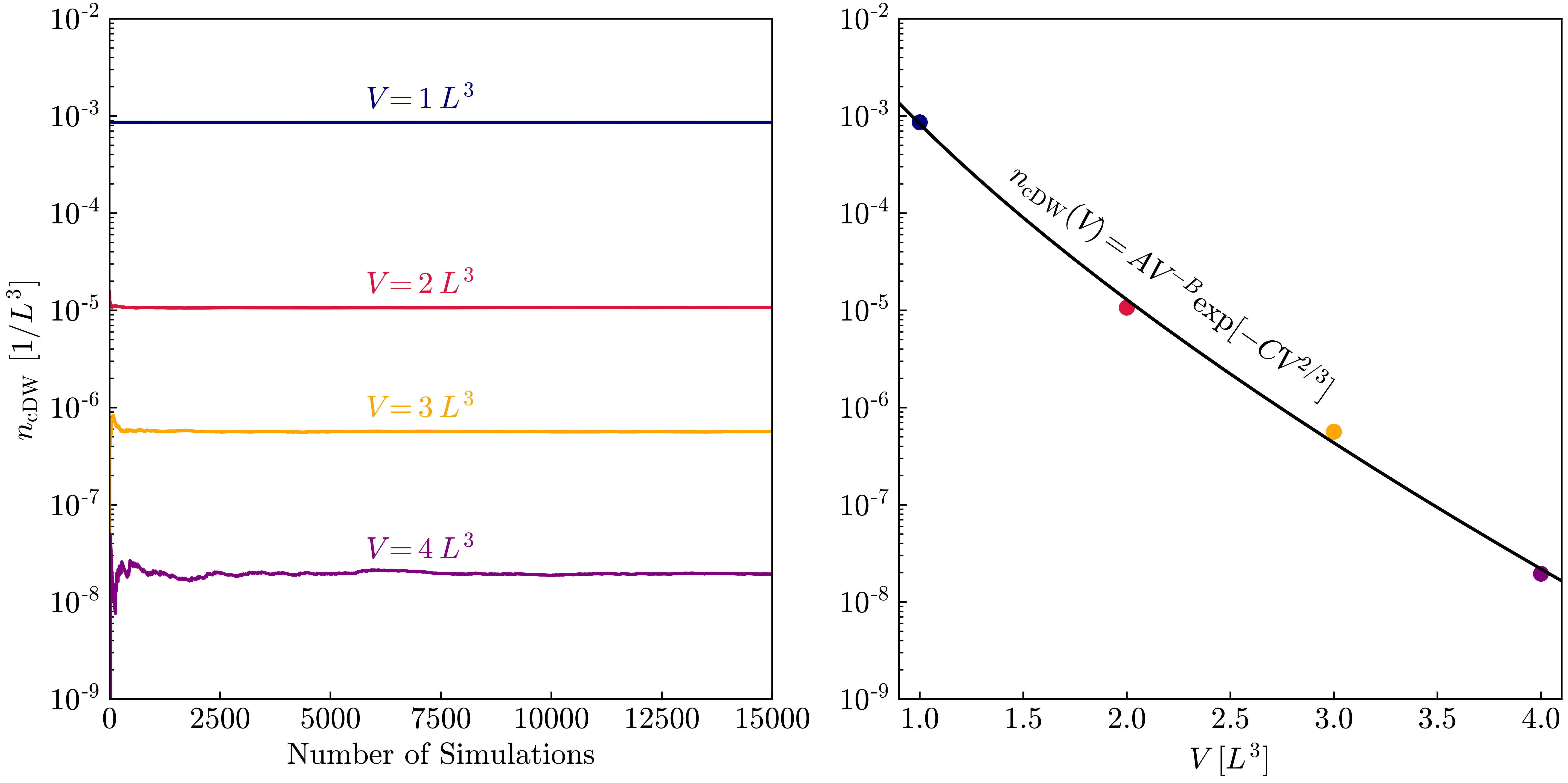

~1 enclosed wall
per 1000 correlation volumes
(~horizon)

Distribution of enclosed wall sizes
Can be larger than horizon

Abundance of Enclosed Walls

- Method of Sikivie essentially $$\mathrm{Corr}(\theta(\mathbf{x_1}), \theta(\mathbf{x_2})) = \begin{cases} 1 & |\mathbf{x}_1 - \mathbf{x}_2| < L \\ 0 & |\mathbf{x}_1 - \mathbf{x}_2| > L \end{cases}$$

Abundance of Enclosed Walls

- Continuum random field $\mathrm{Corr}(\theta(\mathbf{x_1}), \theta(\mathbf{x_2})) = \exp\left(-\frac{|\mathbf{x}_1 - \mathbf{x}_2|^2}{L^2}\right)$

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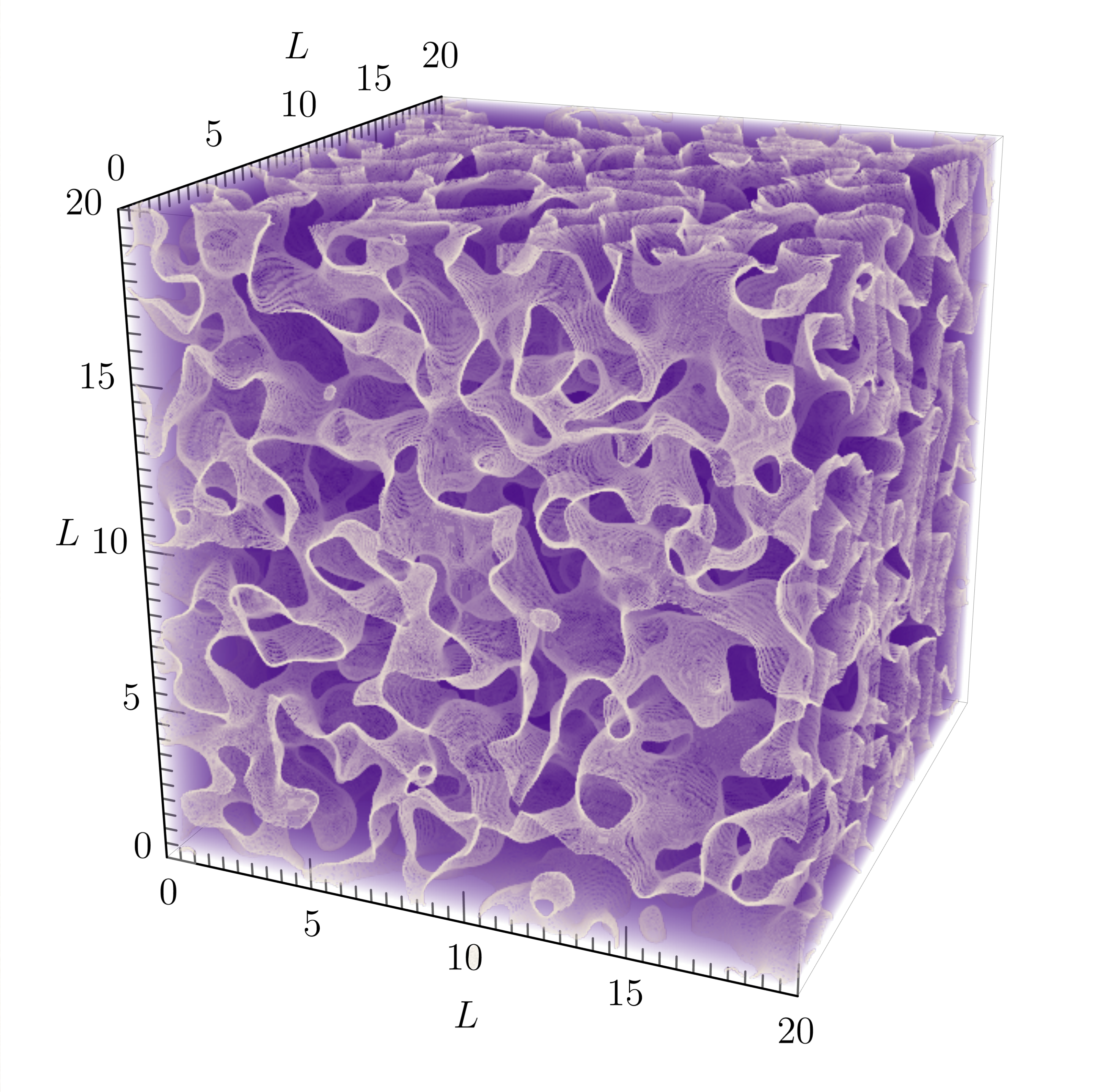

Surface of constant $\theta = \pi$

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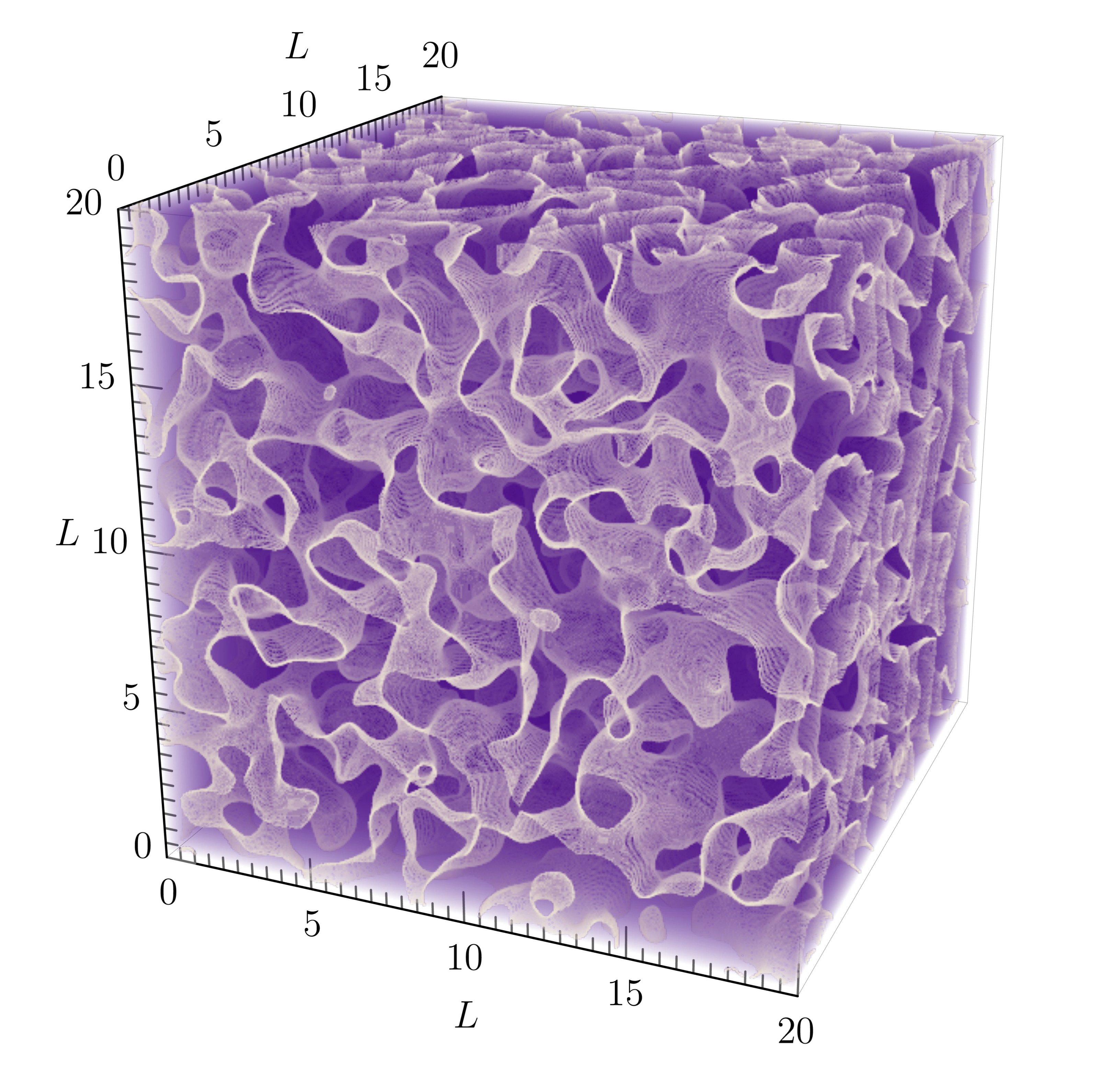

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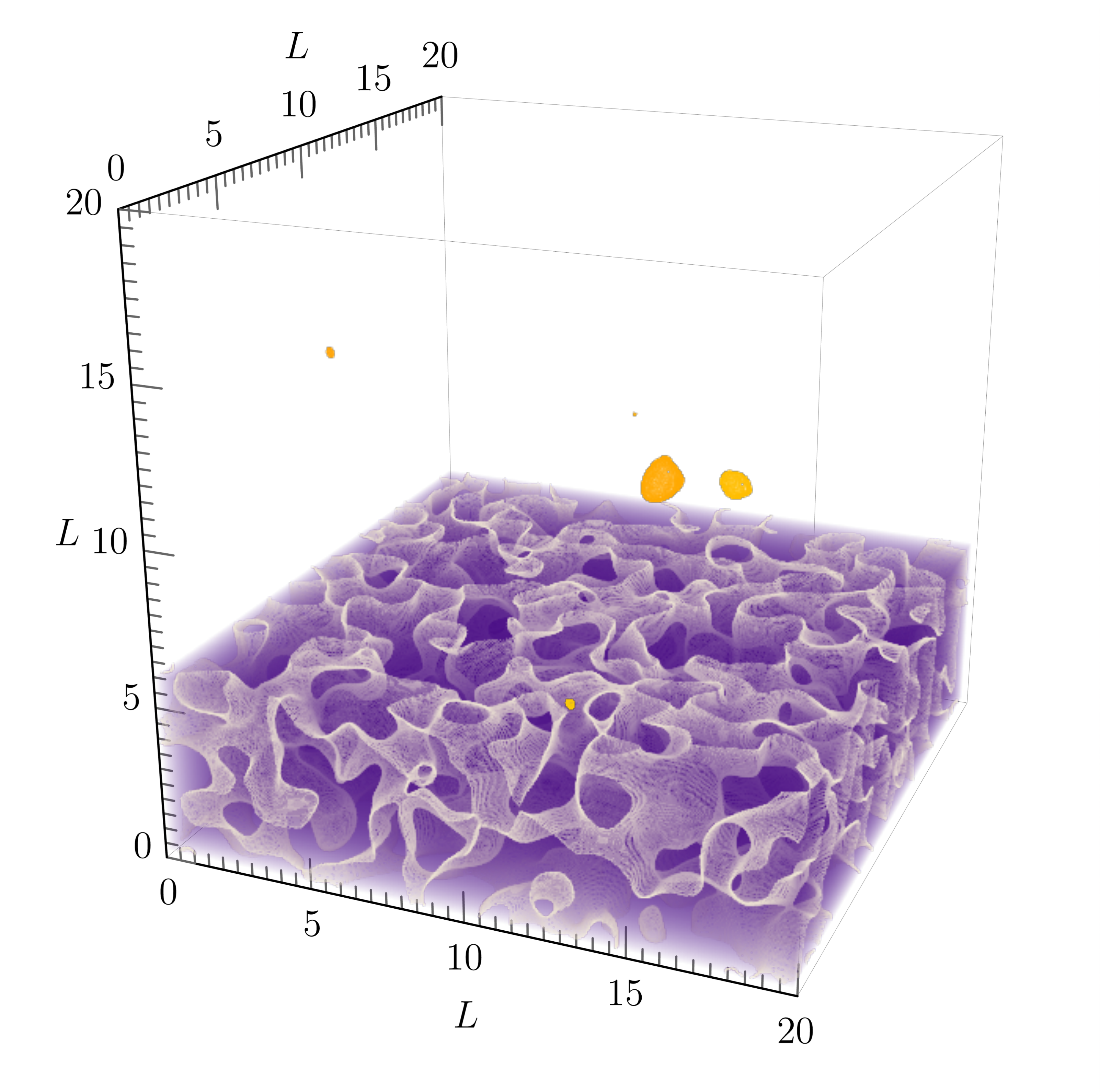

Enclosed walls

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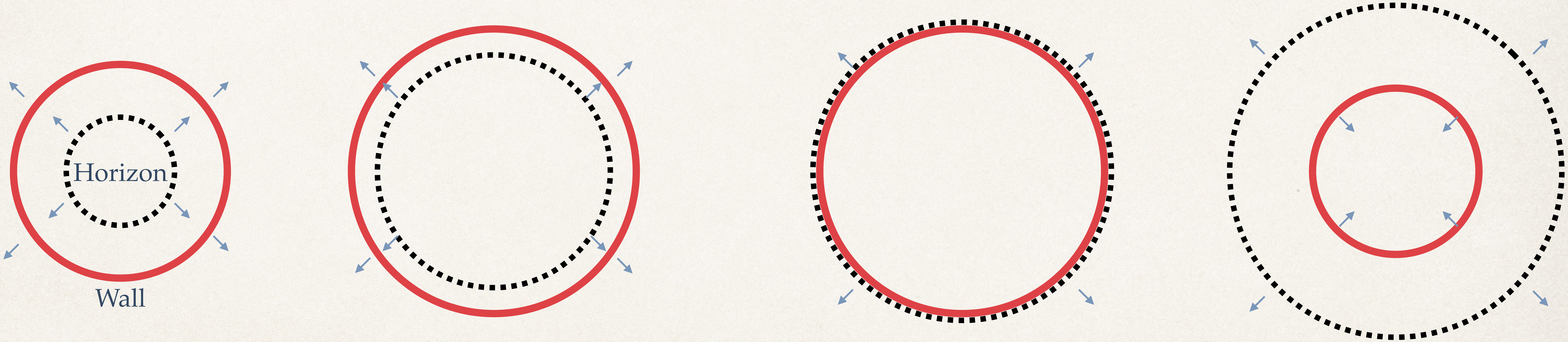
Dynamics of Enclosed Walls

Stretching with Hubble Expansion

- Superhorizon walls initially stretch with expansion



$$R_0 = \alpha t_0$$

Formation

$$R(t) = R_0 \frac{a(t)}{a(t_0)}$$

Stretching

$$R(t_{\rm RE}) \approx \begin{cases} \alpha R_0 & \text{RD} \\ \alpha^2 R_0 & \text{MD} \end{cases}$$

Horizon re-entry

$$t_c \approx t_{\rm RE} + R_{\rm RE}/c$$

Collapse

Collapse after Horizon Re-entry

- Expectation: $4\pi\sigma R_{\rm RE}^2 = \gamma 4\pi\sigma R^2 \to (R_{\rm RE}/R)^2 = \gamma$
  (Nambu-Goto)

Spongebob

Collapse after Horizon Re-entry

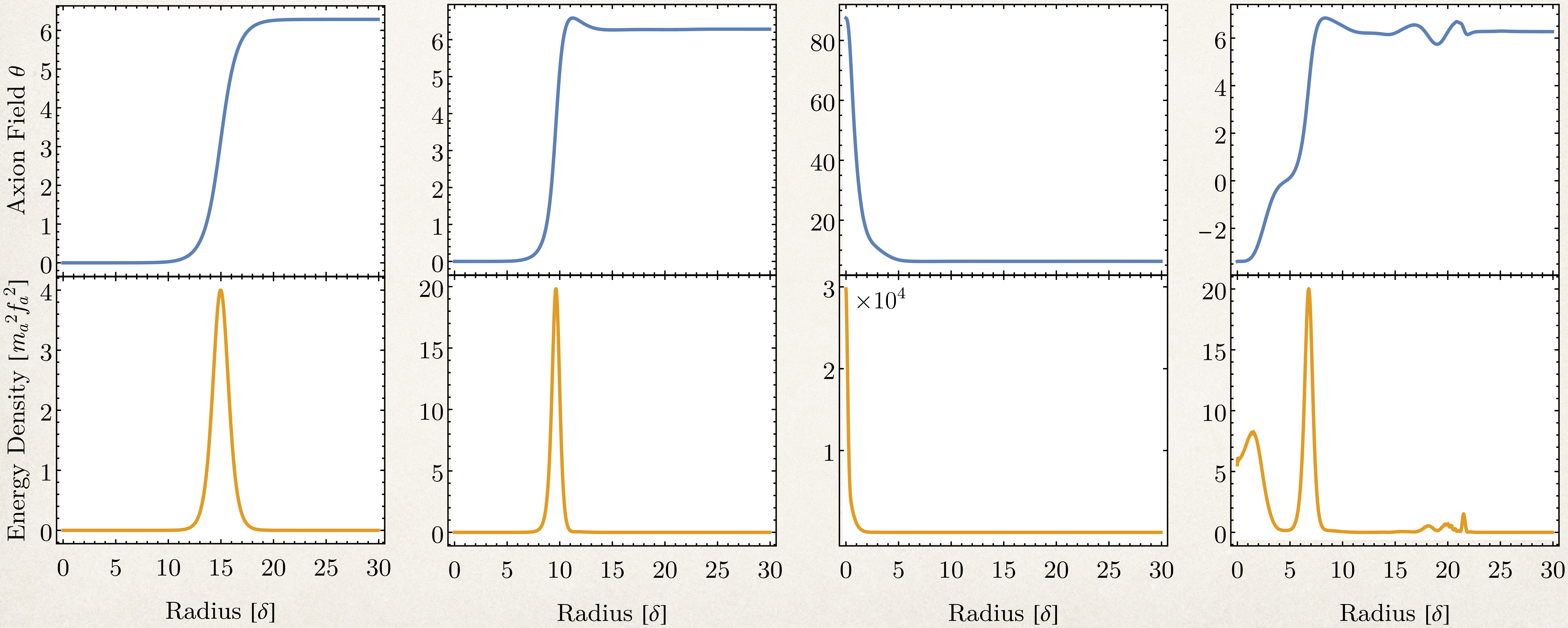
- Expectation: $4\pi\sigma R_{\rm RE}^2 = \gamma 4\pi\sigma R^2 \rightarrow (R_{\rm RE}/R)^2 = \gamma$
  (Nambu-Goto)

- Reality: $(\partial_t^2 - \nabla^2)a(x) + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$

  (Euler-Lagrange Equation)
  Necessary to capture thick wall effects and axion radiation

Spongebob

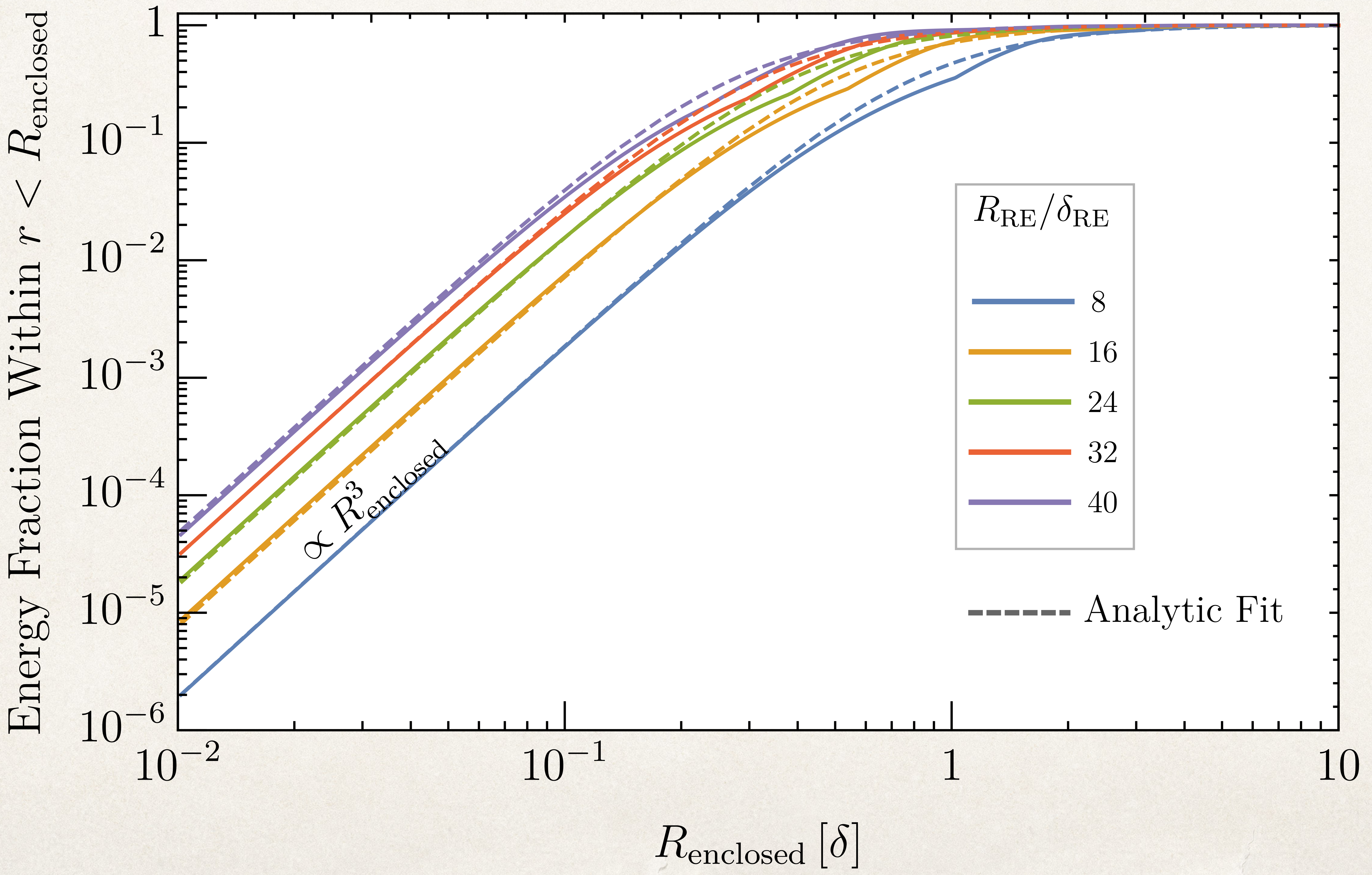
Collapse after Horizon Re-entry



Initial wall profile → Lorentz contraction → Thin-wall breakdown → Collapse → Strong axion emission

Widrow '89

Max Energy Fraction Enclosed



$\propto R^3$

Arises from constant energy density at small radii

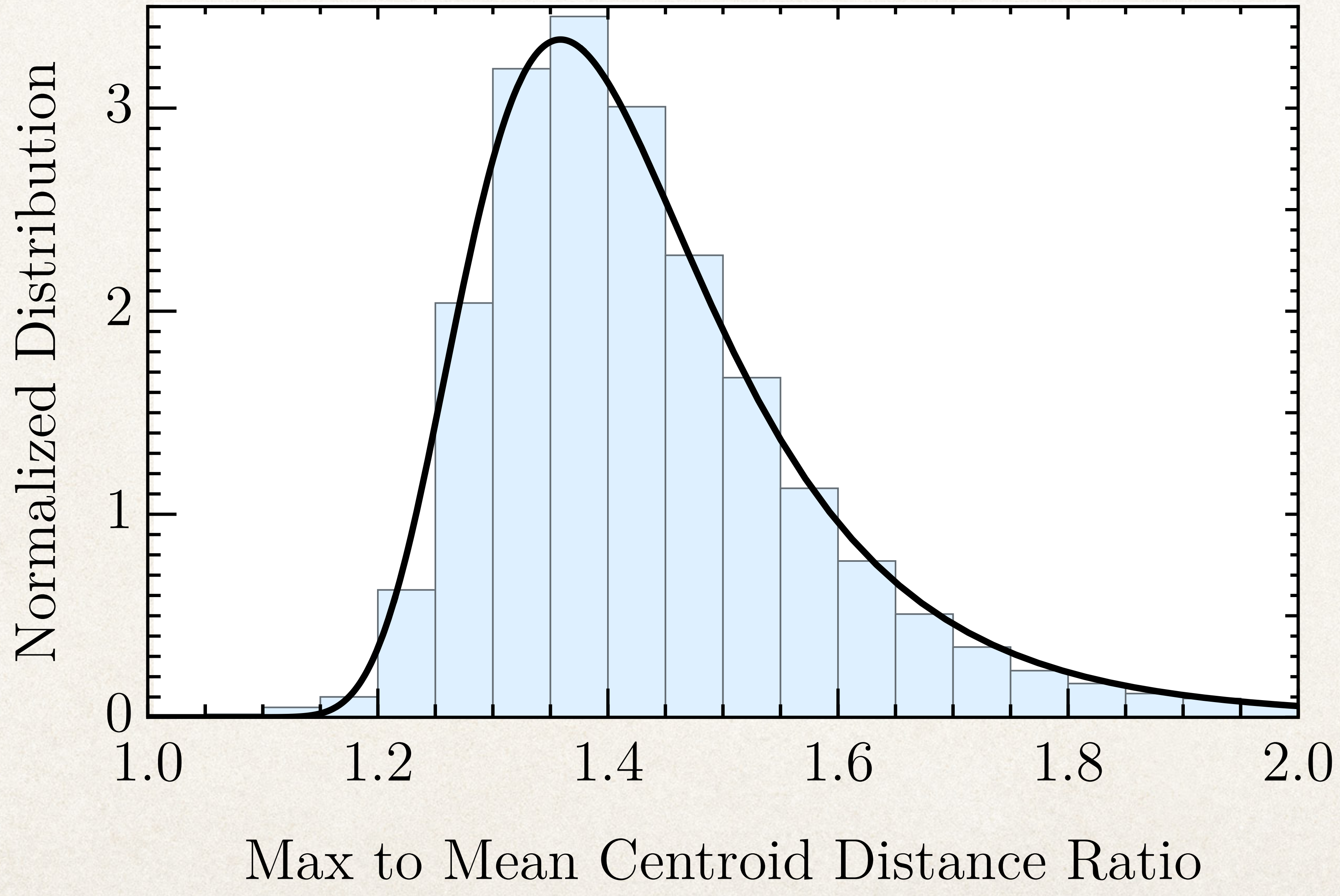
$$\propto \delta^3_{\text{min}} \approx \left[\delta_{\text{RE}}\left(\frac{\delta_{\text{RE}}}{R_{\text{RE}}}\right)^{2/3}\right]^3$$

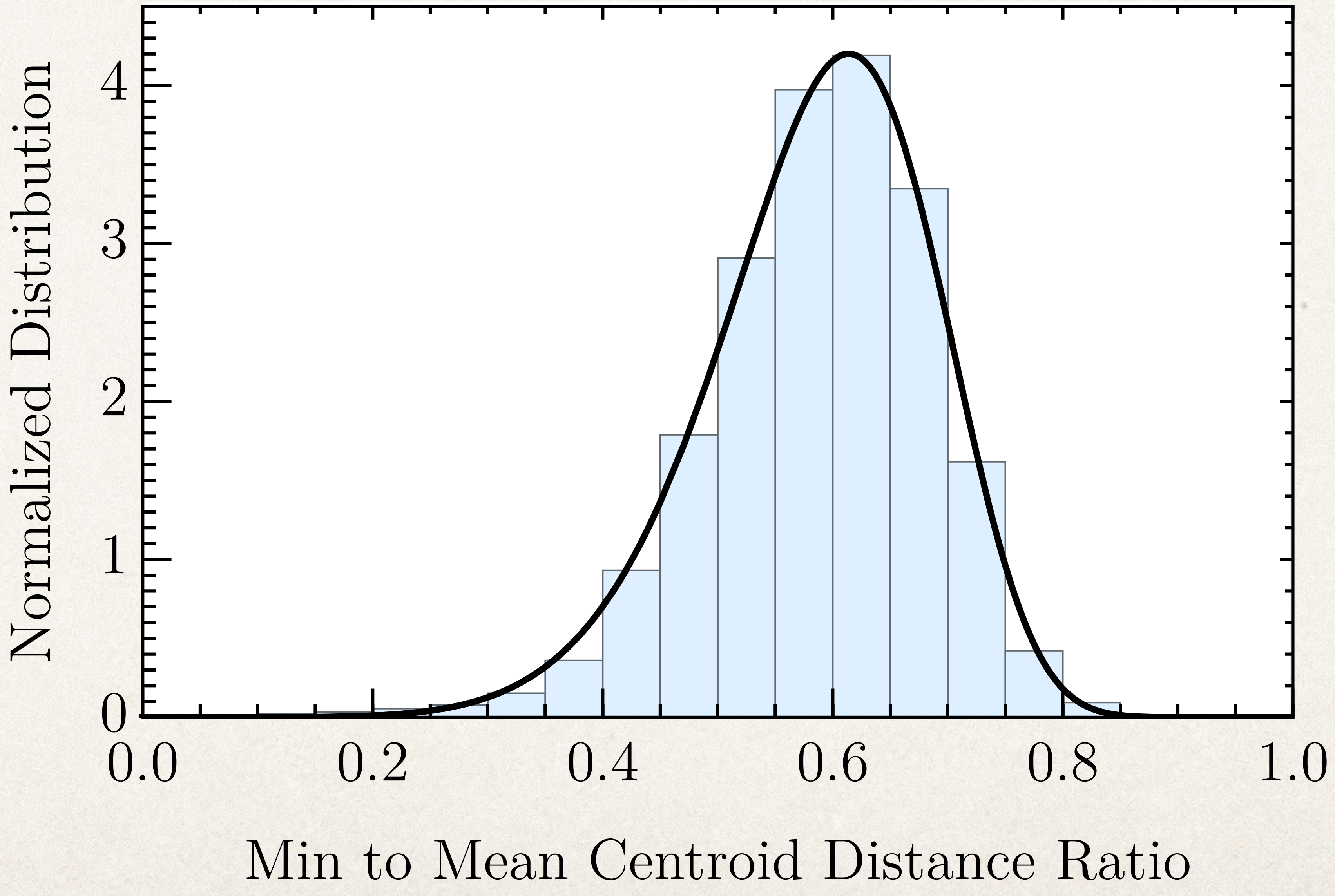
Arises from minimum (Lorentz contracted) wall thickness

Aspherical Walls

- Been making the spherical ~~cow~~ wall approximation so far

- Realistic walls not perfectly spherical





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- Largest scale asphericities are most important:

1. Hubble damping of scales $R \lesssim t$
2. Small scale asphericities damped, large ones most important*

Widrow '89, Garriga & Vilenkin '91

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Widrow '83, Garriga & Vilenkin '91

- Model as ellipsoid

Efficiency of PBH Formation and Relic Abundance

Factors Affecting PBH Abundance

Parameter	Effect on PBH Formation
f_a	Larger f_a increases wall mass and reduces Schwarzchild radius
δ	Smaller δ improves compressibility of wall, making it easier to fit in Schwarzschild radius
$\alpha \equiv R_0/t_0$	Larger α increases wall mass due to increased size (including growth during expansion). Provides more time for axion mass to turn on, and thinner (Lorentz-contracted) wall thickness. But lower abundance if PBH forms.

- How to relate all parameters to calculate PBH abundance?

Conditions for PBH Formation

- From simulations of collapse, computed $f \equiv \frac{E(R_{\rm encl})}{E(\infty)}$

where the total energy is $E(\infty) = 4\pi\sigma R_{\rm RE}^2$ $\sigma = 8 m_a f_a^2 = 8\delta^{-1} f_a^2$

(Wall tension)

- Demand $R_{\rm encl} < R_{\rm schw} = 2GE(R_{\rm encl}) = 2GE(\infty) f$

- Solve for minimum $R_{\rm RE}/\delta_{\rm RE}$ to compress enough energy into Schwarzschild radius

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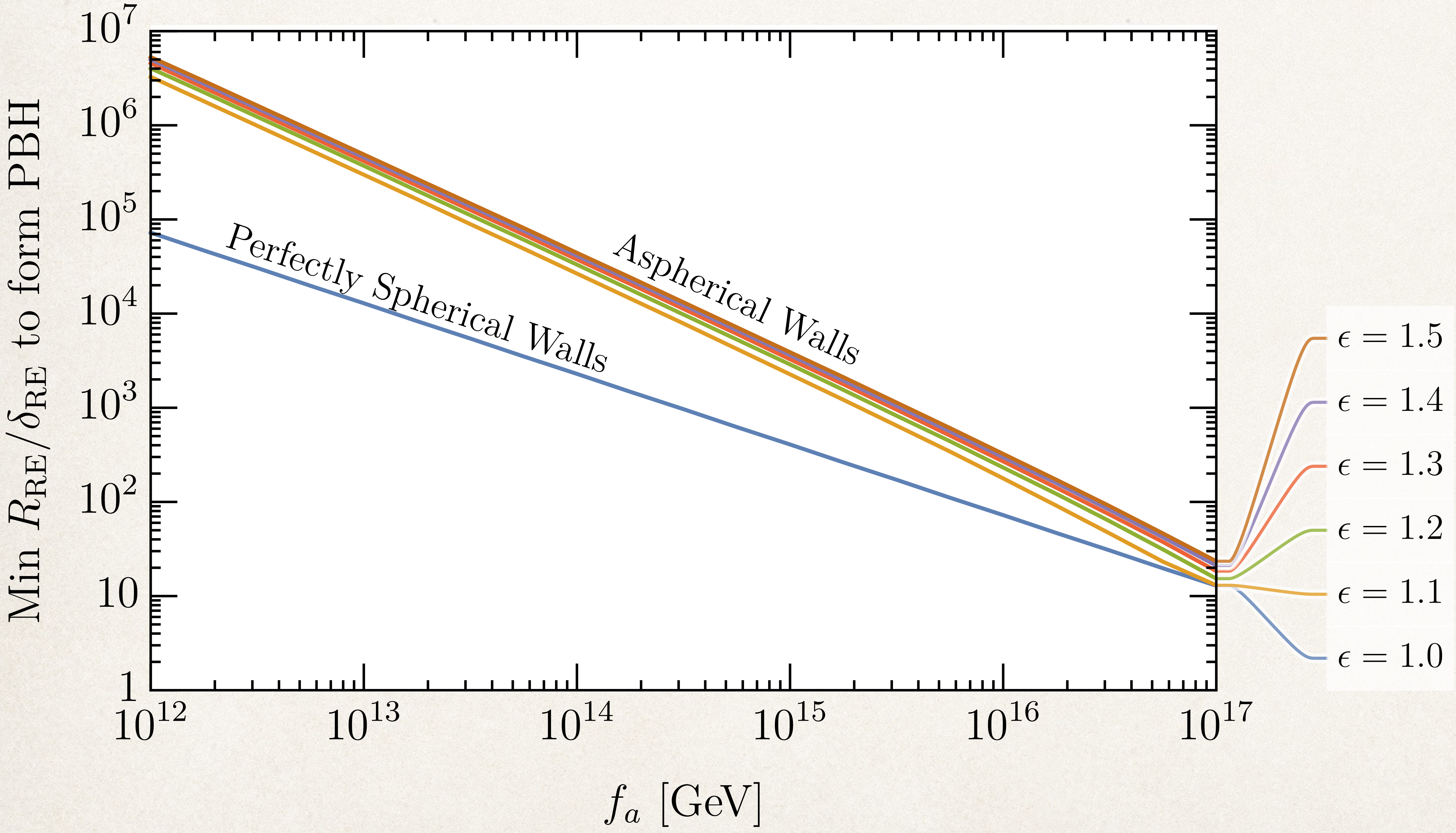

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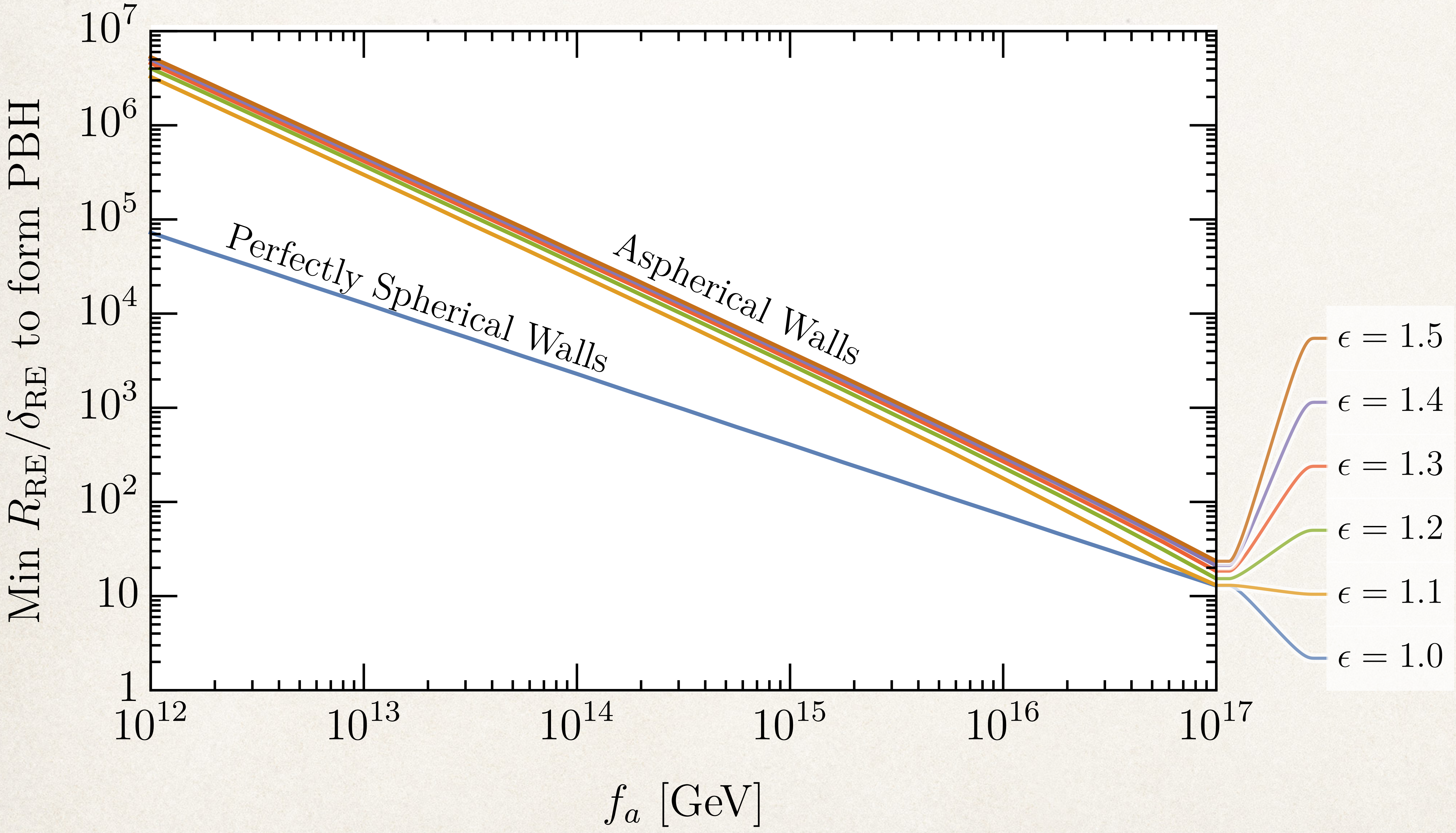


Increase in wall tension from temperature dependent axion mass

Superhorizon stretching

Initial enclosed wall properties

Relate to cosmology by

$$\frac{\delta_{\mathrm{RE}}}{R_{\mathrm{RE}}} = \frac{\delta_0}{R_0}\frac{R_0}{R_{\mathrm{RE}}}\frac{\delta_{\mathrm{RE}}}{\delta_0}$$

$$= \left(\frac{1}{m_a(t_0)\alpha t_0}\right)\left(\frac{a(t_0)}{a(t_{\mathrm{RE}})}\right)\left(\frac{m_a(t_0)}{m_a(t_{\mathrm{RE}})}\right)$$

Relic Abundance

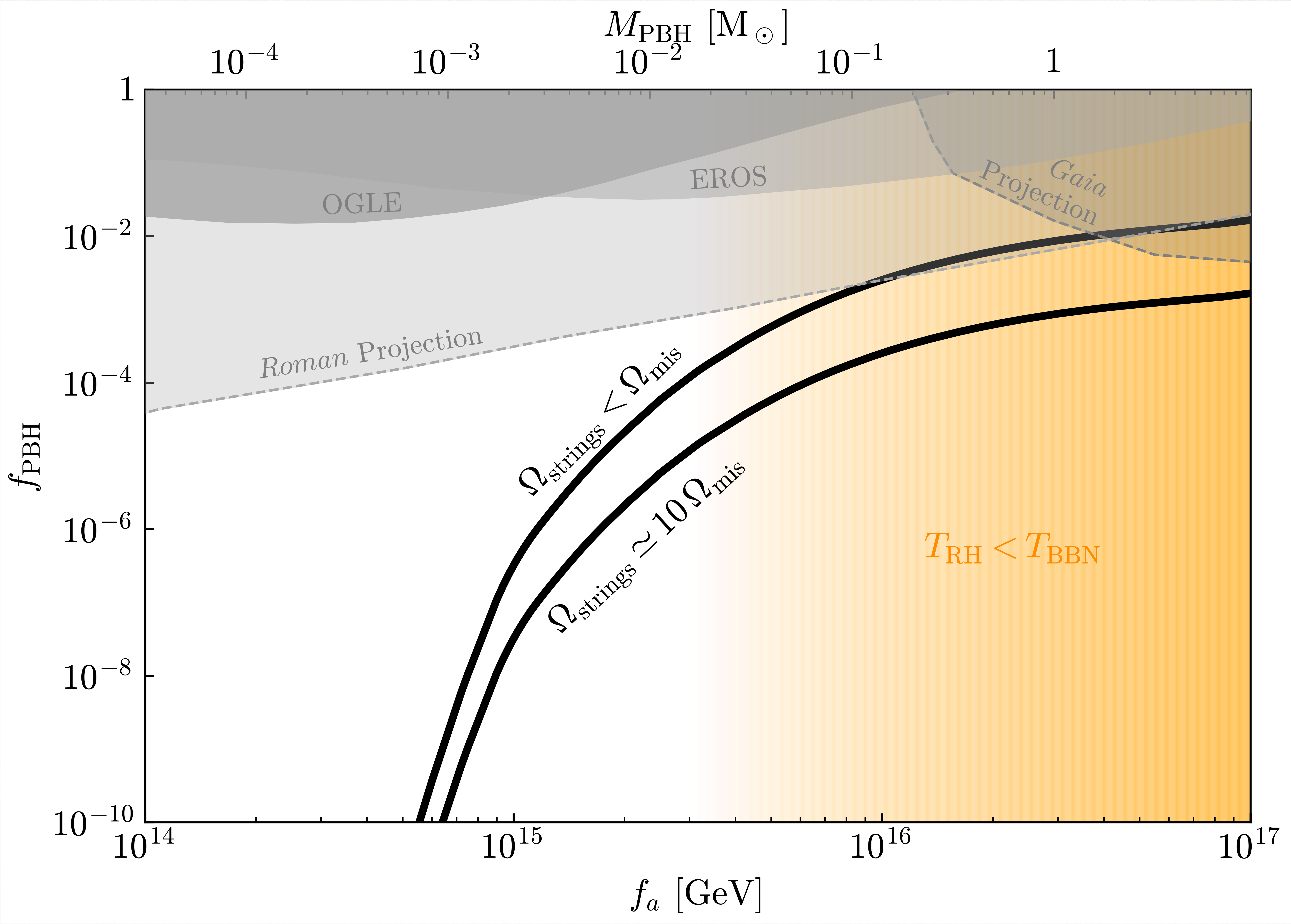
$$\rho_{\rm BH} = M_{\rm PBH} n_{\rm PBH}$$

$$M_{\rm PBH} \approx 4\pi R_{\rm RE}^2 \sigma$$

$$\sigma \simeq 8 m_a(t_c) f_a^2$$

$$n_{\rm PBH} = n_{\rm encl}(R_0) \left(\frac{a(t_0)}{a(t)}\right)^3$$

$$\times \Theta(R_{\rm RE}/\delta_{\rm RE} - \text{ Min } R_{\rm RE}/\delta_{\rm RE})$$



Conclusions

- Axion cosmology can generate PBHs, abundance largest for large f_a
- Preliminary, but lensing signal appears slightly out of reach of next generation Roman space telescope *DeRocco et al '23*
- Formalism translates simply to ALPs too
- Most excited to apply to GUT variations of this mechanism (Pati-Salam Left-Right models). Particularly interesting due to (potential) gap near $(10^{-17} - 10^{-11})M_\odot$ where PBHs (may) be all of dark matter *Carr & Kuhnel '22*