Title: Primordial Black Holes from Axion Domain Walls

Speakers: David Dunsky

Series: Particle Physics

Date: April 16, 2024 - 1:00 PM

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Abstract: Besides providing a possible explanation to the strong CP problem and dark matter, the QCD axion possesses a rich cosmology. For example, if PQ breaking occurs after inflation, then axion cosmic strings form. Near the QCD phase transition, every axion string become attached to a domain wall which pull on the strings and cause the string-wall network to decay. While every string becomes attached to a domain wall, it is possible, though rare, to form an enclosed domain wall that is not attached to any axion string. These enclosed domain walls collapse under their own self tension, compressing a large amount of energy into a small volume and thereby potentially forming a primordial black hole. In this talk, I will discuss the abundance of enclosed domain walls, their dynamics of collapse, the efficiency of black hole formation, and their relic abundance. For sufficiently large axion decay constants, there may be an observable gravitational lensing signal at future lensing telescopes, especially in models with axion-like-particles.

Zoom link

NYU | CCPP

Primordial Black Holes from Axion Walls

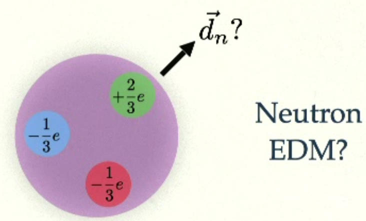
Particle Physics Seminar, Perimeter Institute

David Dunsky, Marius Kongsore

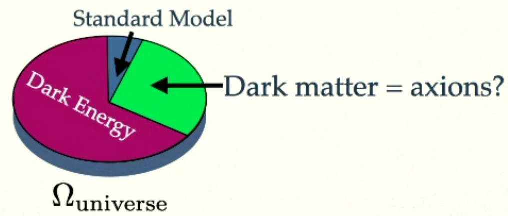
arXiv:2402.03426

Motivation and Key Idea

- Axion potential explanation for the strong CP problem



- Axion potential dark matter candidate



Motivation and Key Idea

- Standard cosmological picture (high reheat scenario):

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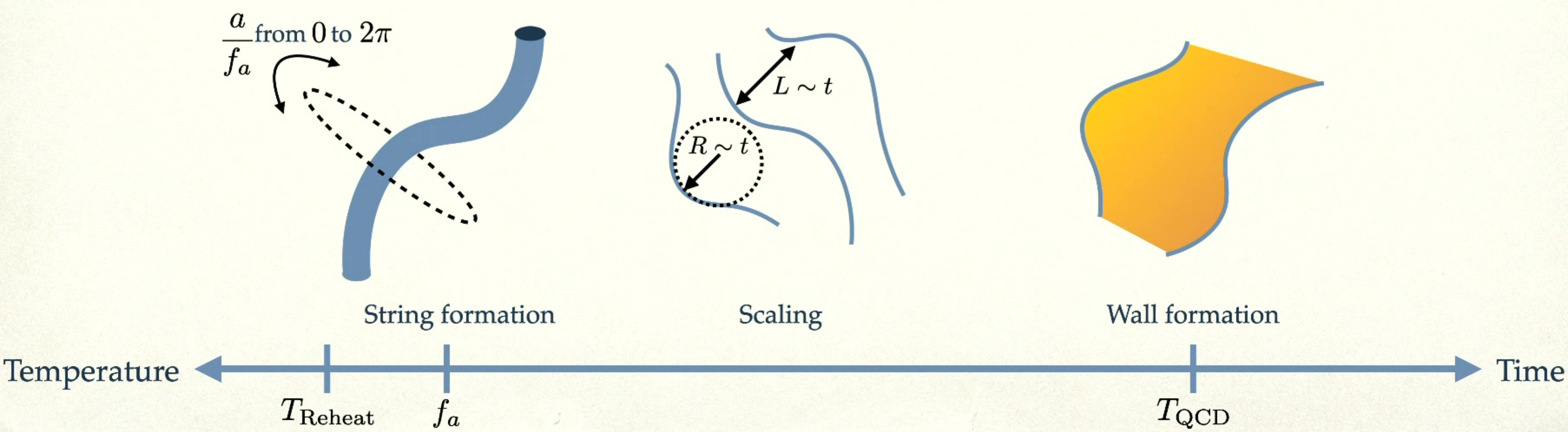
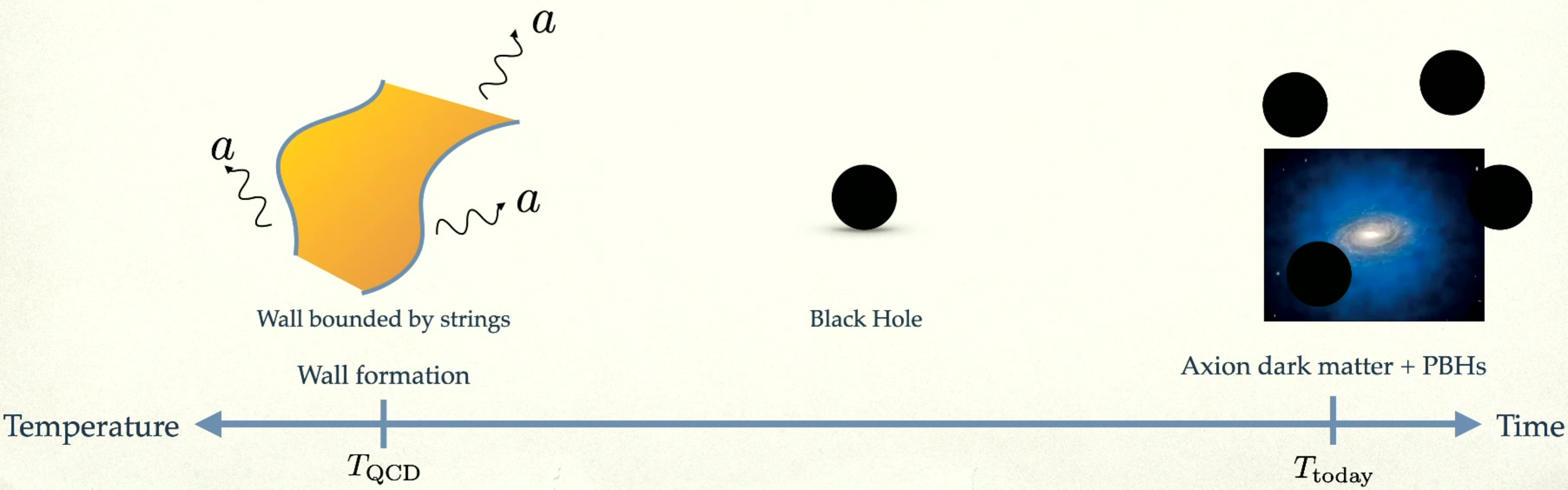


Motivation and Key Idea

- Rare, put possible to form enclosed domain walls
- Walls contract, potentially forming primordial black holes (PBHs)



Outline

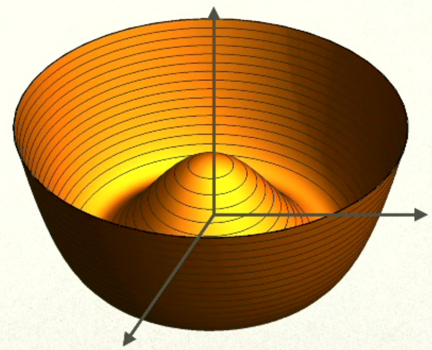
- Cosmology and formation of enclosed axion domain walls
- Enclosed wall dynamics
- Efficiency of PBH formation and relic abundance

Cosmology and Formation of Enclosed Walls

Cosmology of Axion Defects: Strings

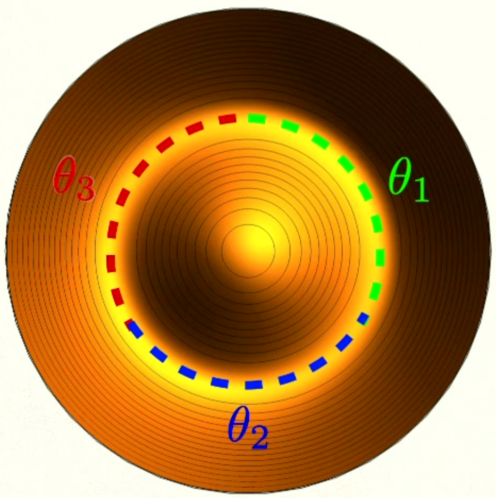
$$\mathcal{L}_{\rm UV} = |\partial_\mu \Phi|^2 - V_{\rm PQ}(\Phi)$$

- 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 $V_{\rm PQ}$



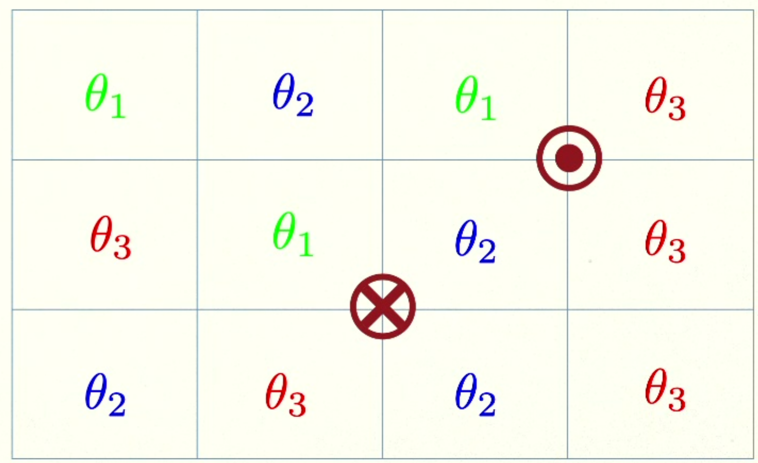
Cosmology of Axion Defects: Strings

$V_{\mathrm{PQ}}(\Phi)$



$$\langle \Phi \rangle \approx f_a e^{ia/f_a}$$

Spontaneous breaking of $U(1)$ symmetry



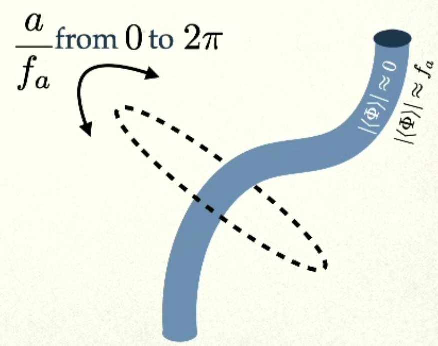
Sikivie, '83. See also Kibble '76 and Vachaspati & Vilenkin '84

Cosmology of Axion Defects: Strings

- Below scale f_a, $\langle\Phi\rangle \approx f_a e^{ia/f_a}$ from minimum of $V_{\rm PQ}$

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

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



String formation

Cosmology of Axion Defects: Strings

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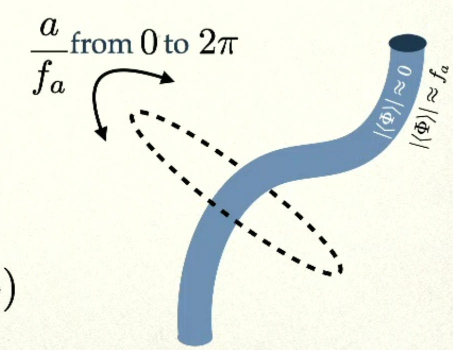
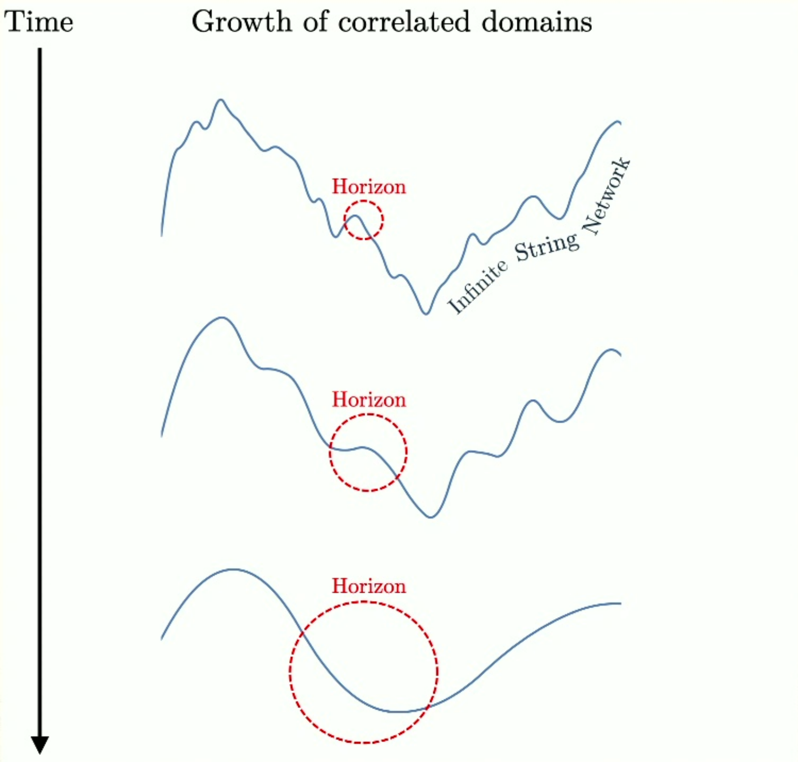


- Mass per unit length $\mu \approx V_{\rm PQ}(\Phi = 0)\delta_s^2 \sim f_a^4 \times f_a^{-2} \simeq \pi f_a^2 \ln(f_a\, L)$

String formation

Cosmology of Axion Defects: Strings



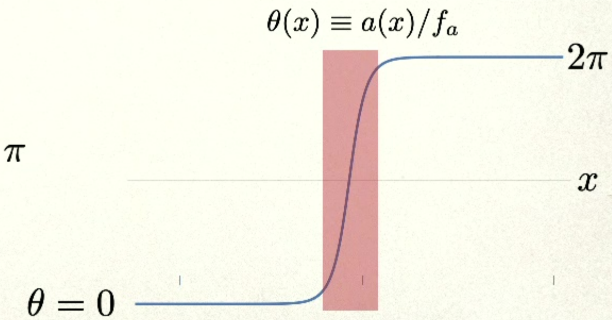
Cosmology of Axion Defects: Walls

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

- 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 $\theta \equiv a/f_a = \pi$



Domain Wall

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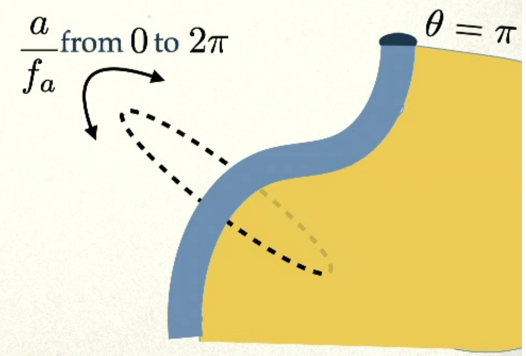

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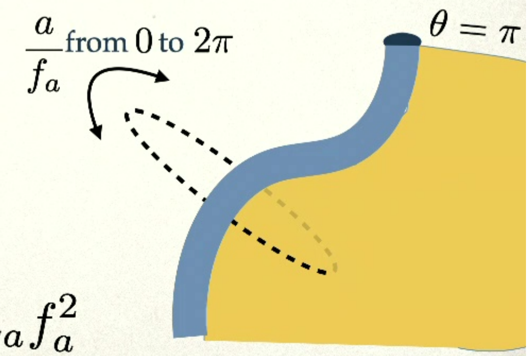
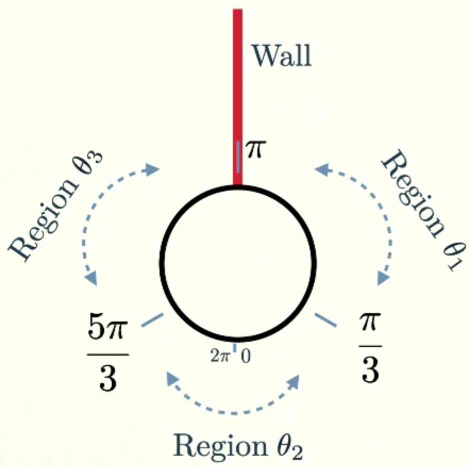


- Mass per unit area $\sigma \approx V_{\rm QCD}(\theta = \pi)\delta \sim m_a^2 f_a^2 \times m_a^{-1} \simeq 8 m_a f_a^2$

Wall formation

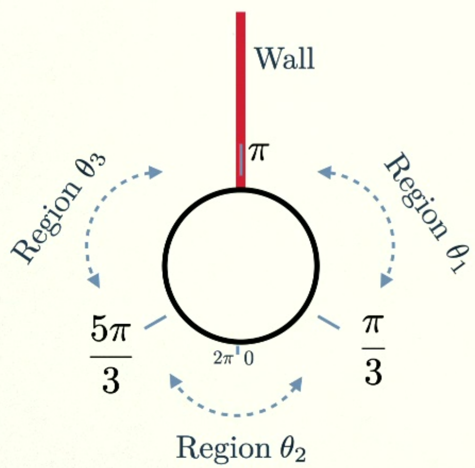
Abundance of Enclosed Walls



Axion string
(into the board)

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

Abundance of Enclosed Walls



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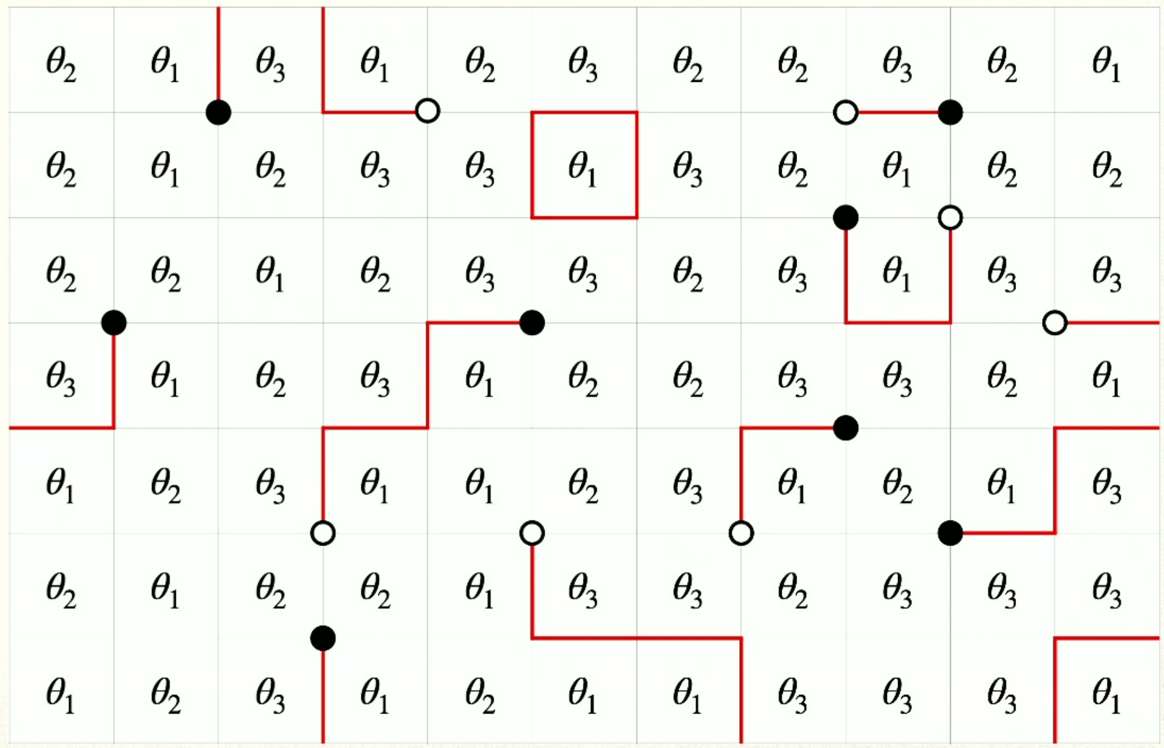

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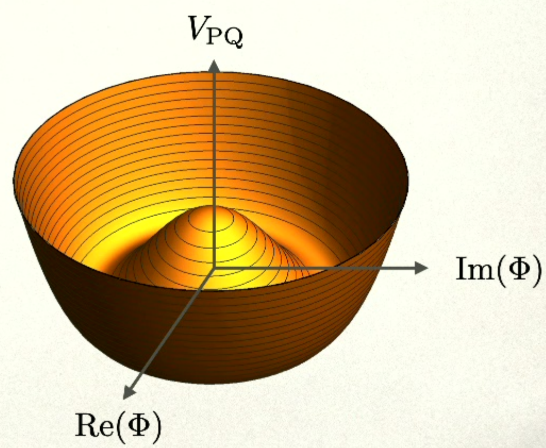

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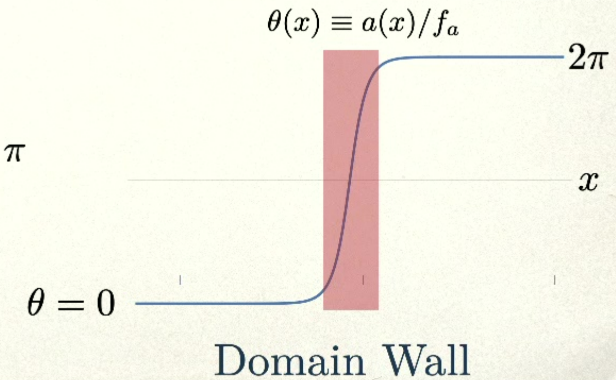

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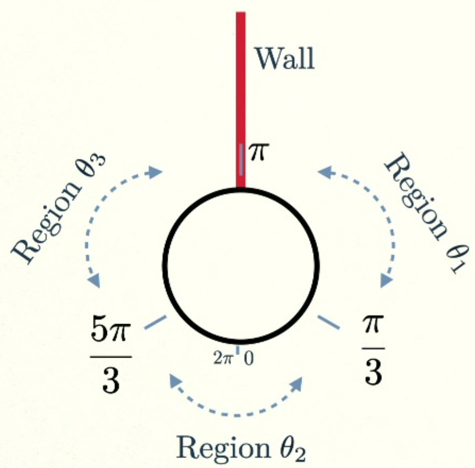

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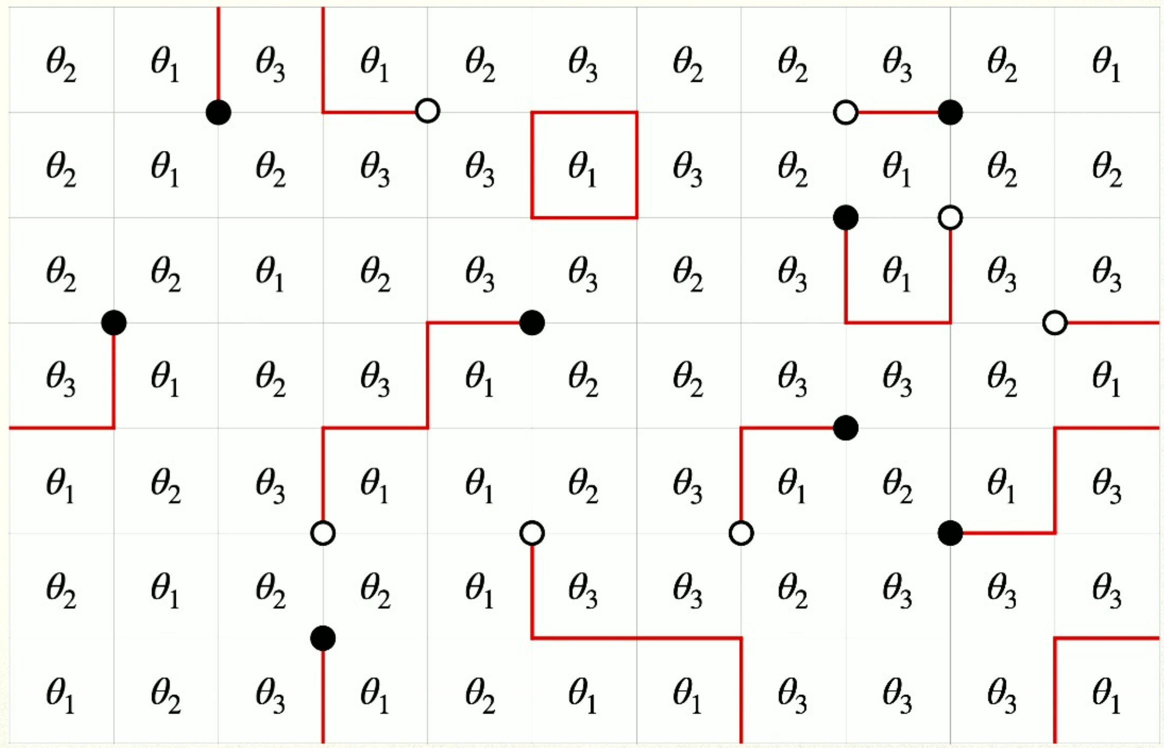

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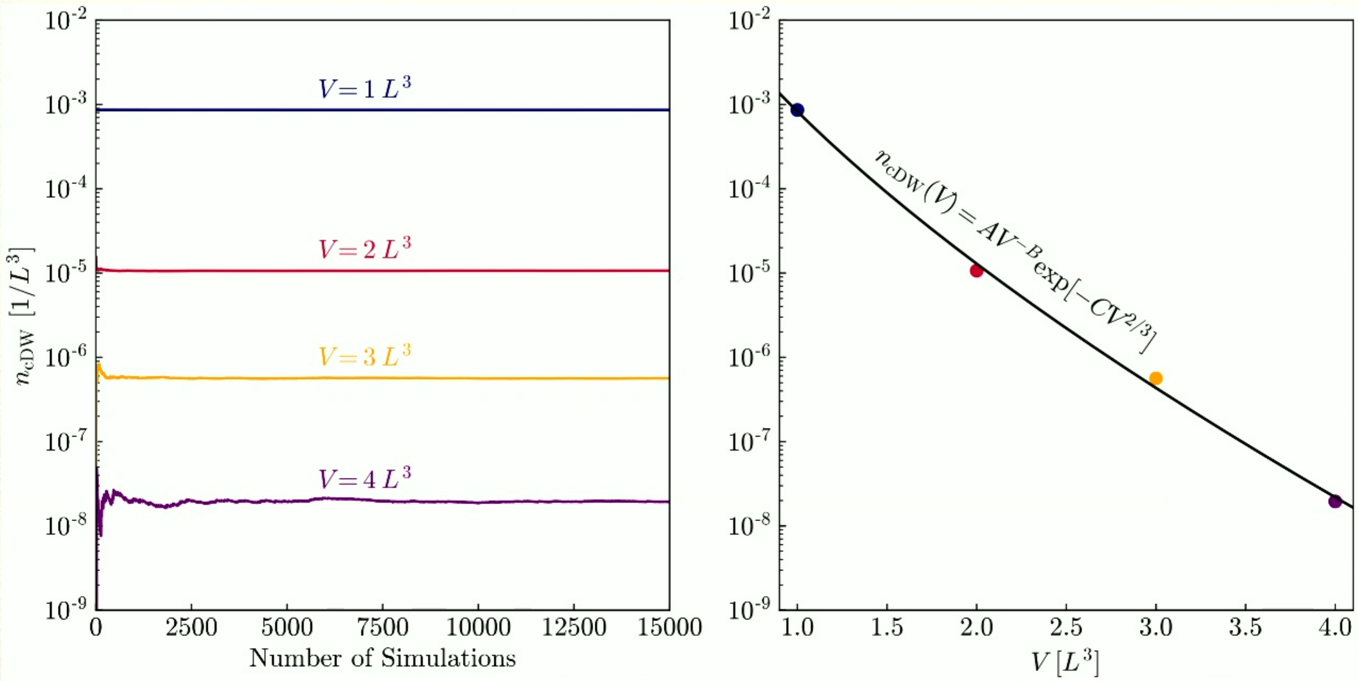


~1 enclosed wall
per 1000 correlation volumes
(~horizon)

Distribution of enclosed wall sizes
Can be larger than horizon

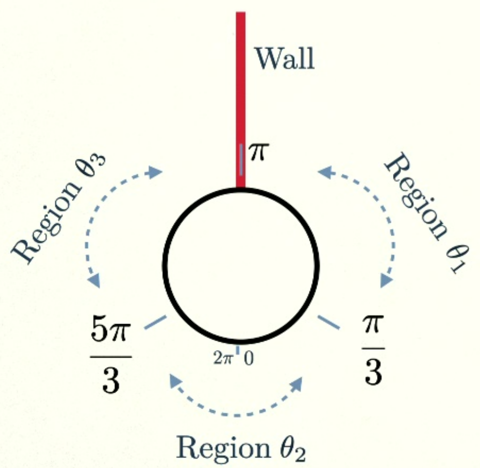
Abundance of Enclosed Walls

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

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



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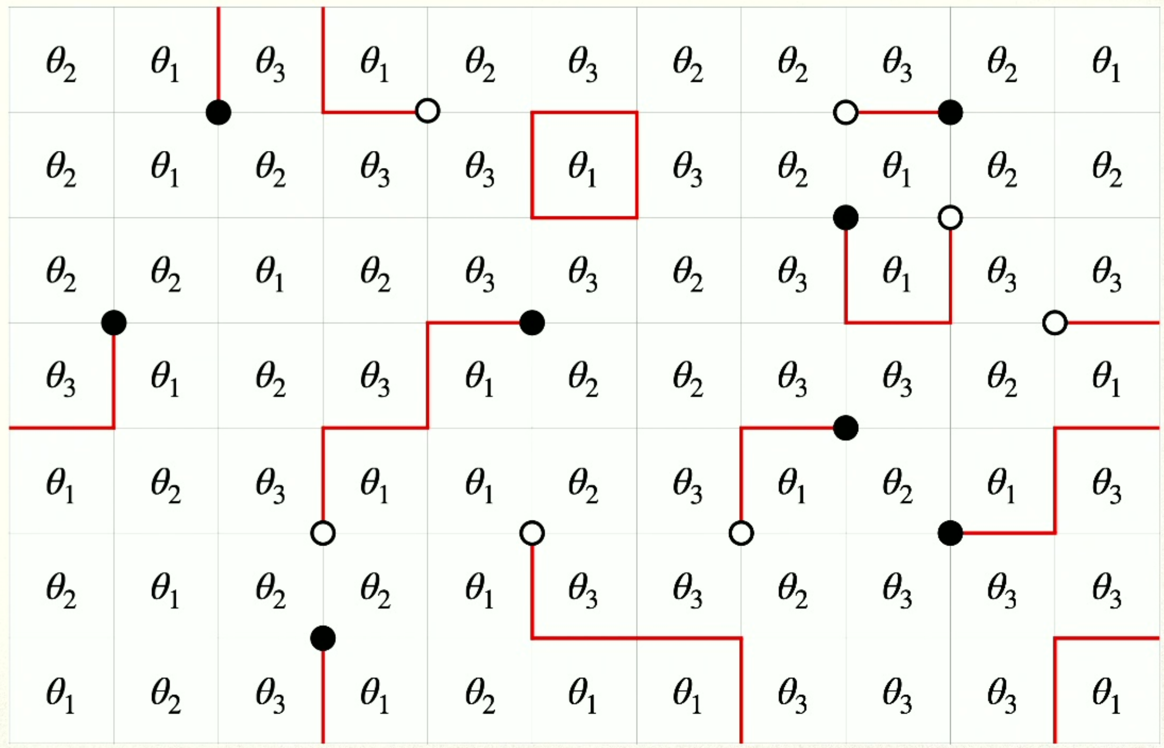

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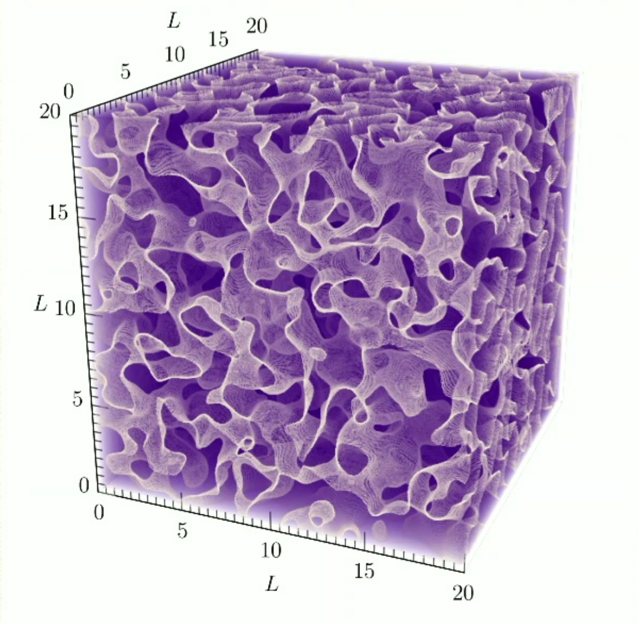
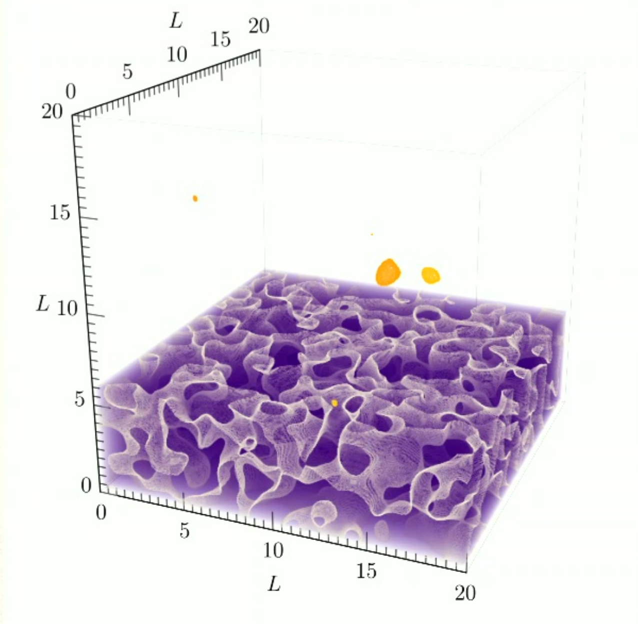


Surface of constant $\theta = \pi$



Enclosed walls

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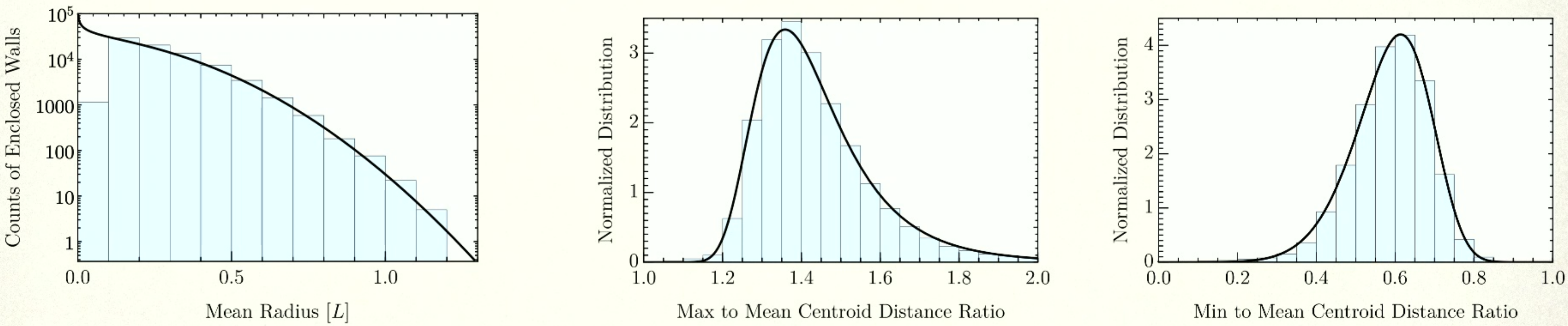


$$\frac{d \ln n_{\mathrm{c,DW}}}{dR} \propto -R^2$$

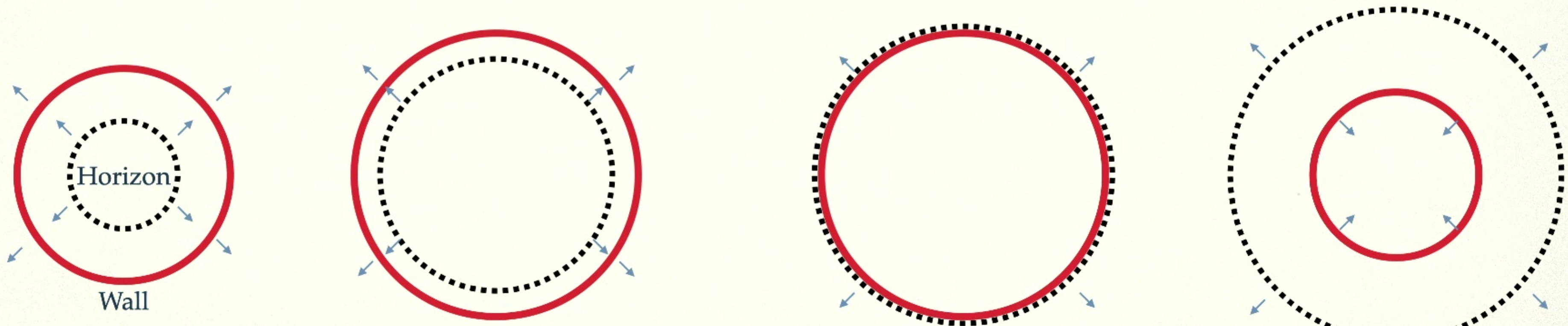
As expected from percolation theory

Walls not perfectly spherical!

Dynamics of Enclosed Walls

Stretching with Hubble Expansion

- Superhorizon walls initially stretch with expansion



Formation	Stretching	Horizon re-entry	Collapse
$R_0 = \alpha t_0$	$R(t) = R_0 \frac{a(t)}{a(t_0)}$	$R(t_{\mathrm{RE}}) \approx \begin{cases} \alpha R_0 & \mathrm{RD} \\ \alpha^2 R_0 & \mathrm{MD} \end{cases}$	$t_c \approx t_{\mathrm{RE}} + R_{\mathrm{RE}}/c$

Collapse after Horizon Re-entry

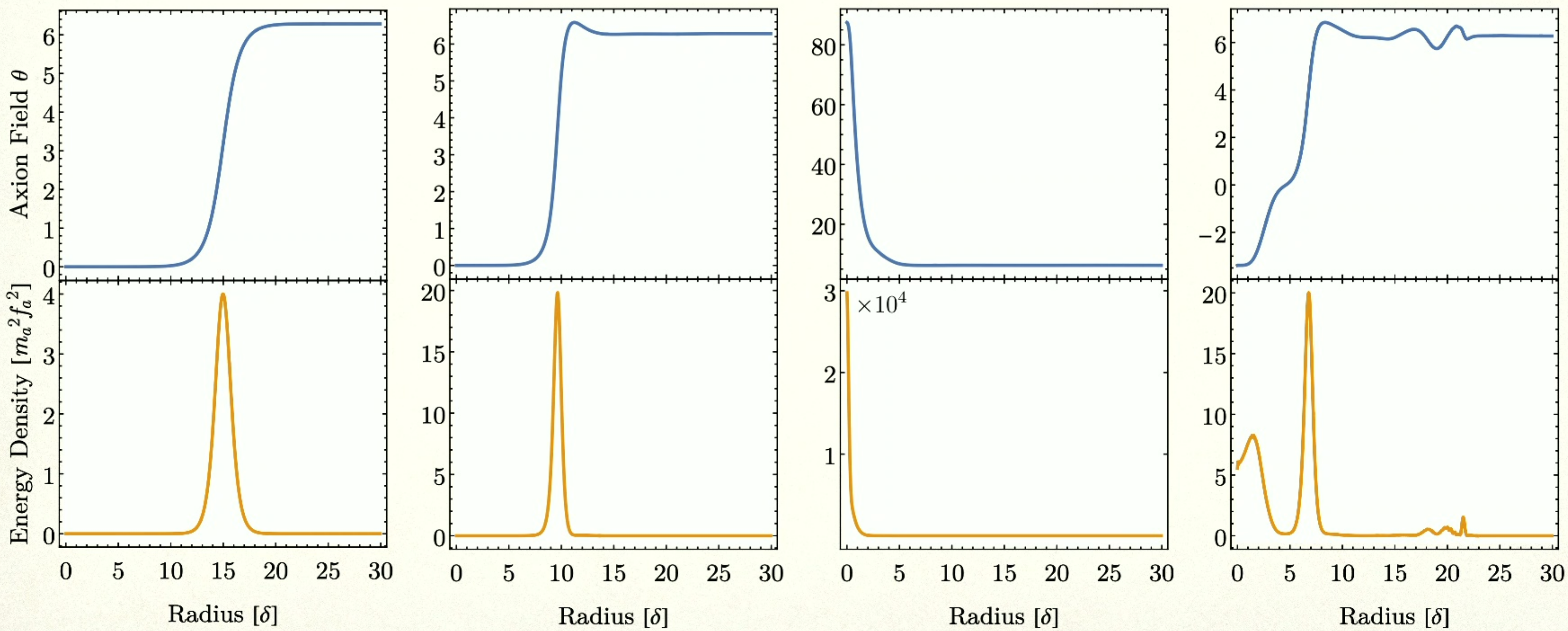
- **Expectation:** $4\pi\sigma R_{\rm RE}^2 = \gamma 4\pi\sigma R^2 \rightarrow (R_{\rm RE}/R)^2 = \gamma$
  (Nambu-Goto, thin wall limit)

- **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
  Widrow '89

Spongebob

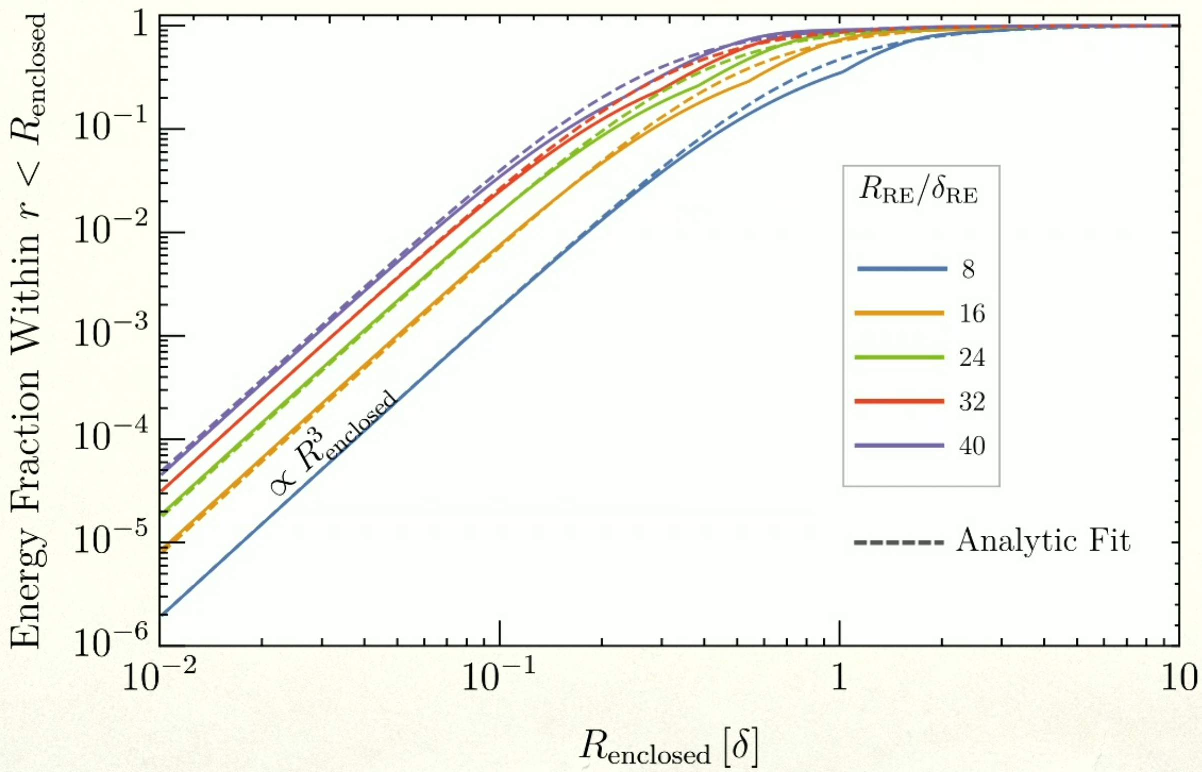
Collapse after Horizon Re-entry



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

Widrow '89

Max Energy Fraction Enclosed



$\propto R^3$

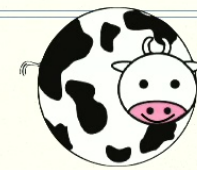
Arises from constant energy density at small radii

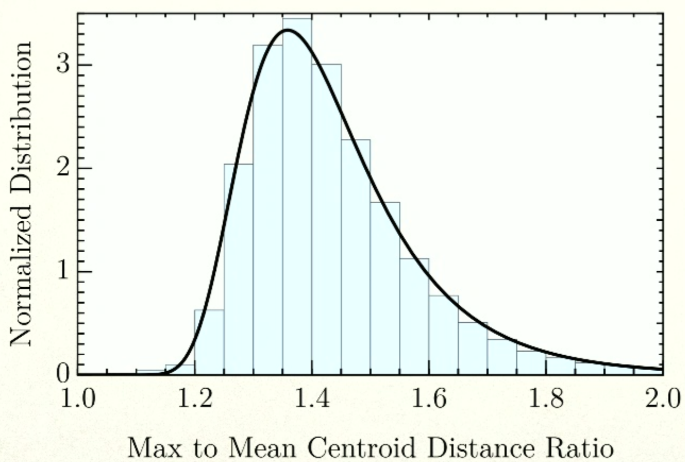
$$\propto \delta_{\min}^3 \approx \left[\delta_{\mathrm{RE}}\left(\frac{\delta_{\mathrm{RE}}}{R_{\mathrm{RE}}}\right)^{2/3}\right]^3$$

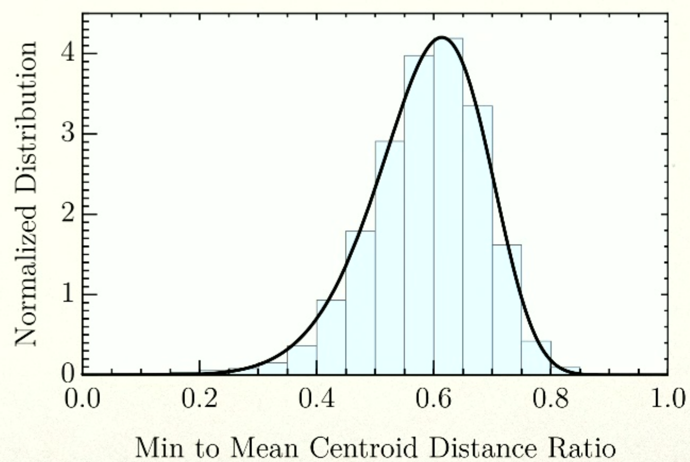
Arises from minimum (Lorentz contracted) wall thickness

Aspherical Walls

- Been making the spherical ~~cow~~ wall approximation so far
- Realistic walls not perfectly spherical







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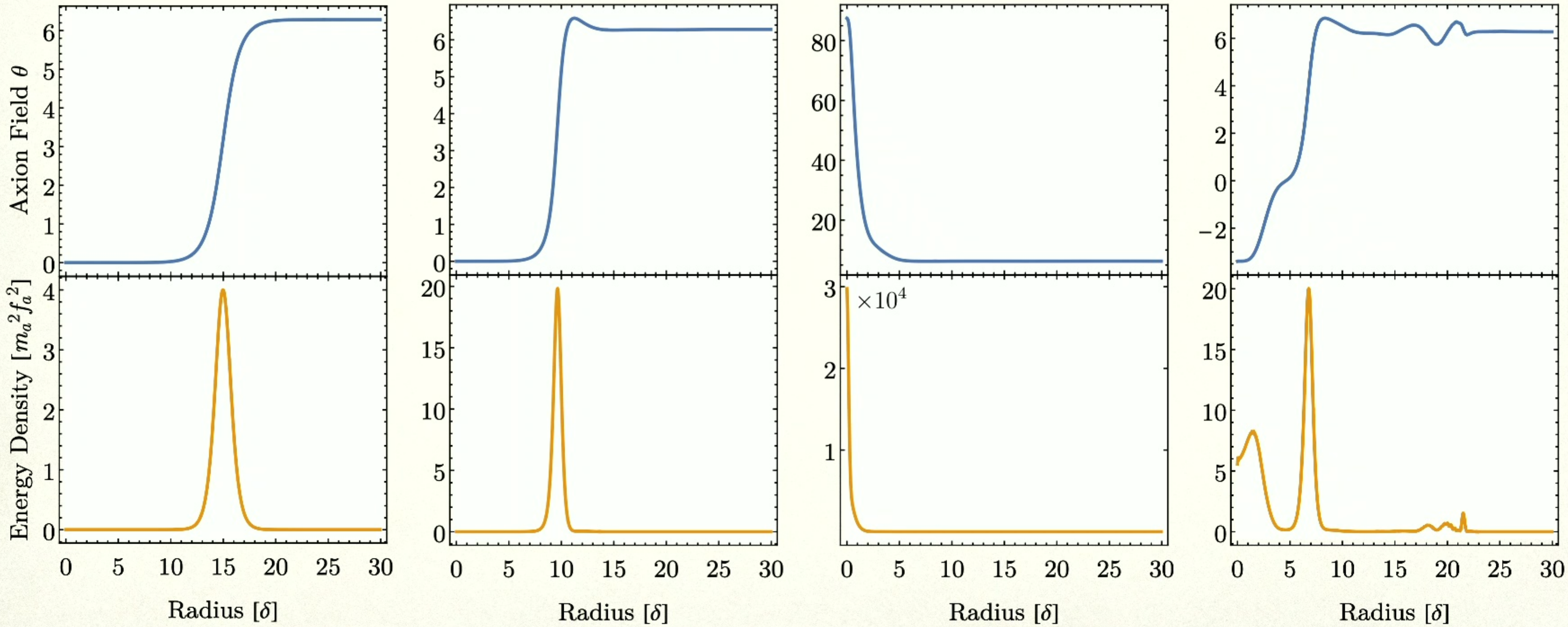

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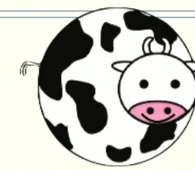


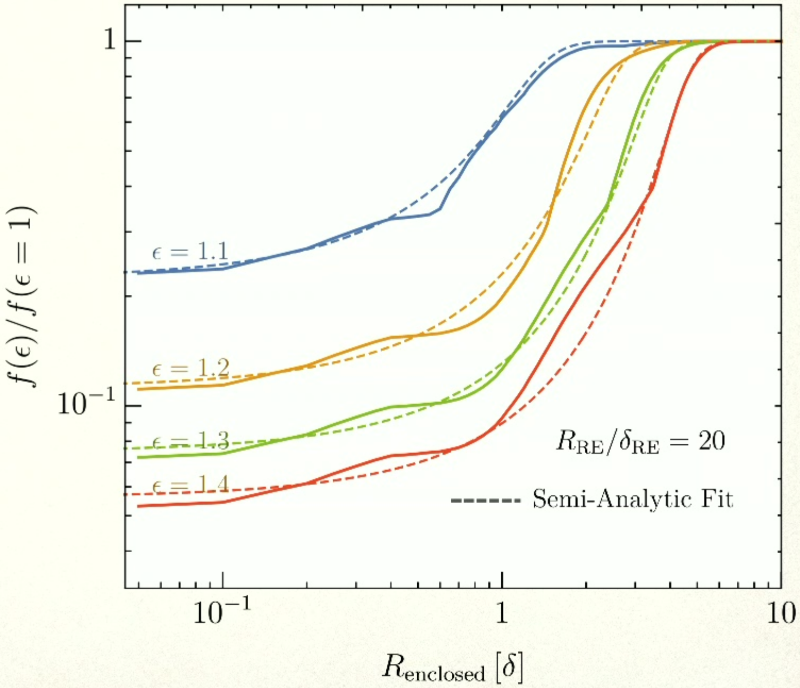
- Been making the spherical ~~cow~~ wall approximation so far
- Realistic walls not perfectly spherical
- Largest scale asphericities are most important:

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

Widrow '89, Garriga & Vilenkin '91

Aspherical Walls

- Asphericities grow most near final stage of collapse
- "Break radius" increases with larger $R_{\mathrm{RE}}/\delta_{\mathrm{RE}}$ and ϵ
- Combine semi-analytic result from simulations with initial wall apsheriticies and distribution of sizes to see if PBHs can form



Conditions for PBH Formation

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

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

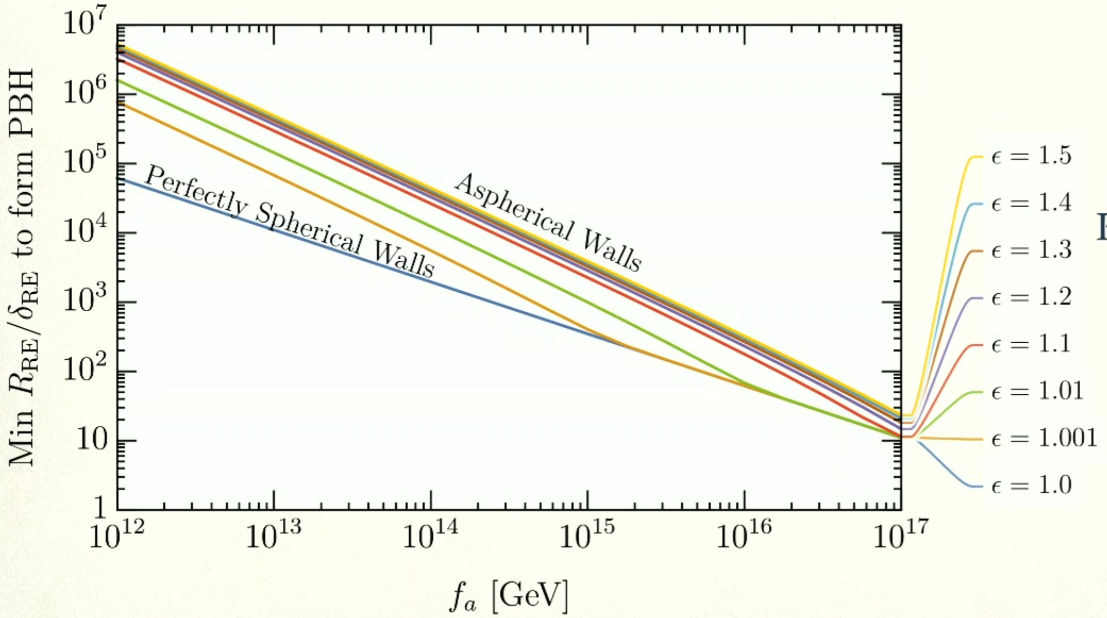
  (Wall tension)

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

$$\downarrow$$

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

Conditions for PBH Formation



Increase in wall tension from temperature dependent axion mass

Superhorizon stretching

Initial enclosed wall properties

Relate to cosmology by

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

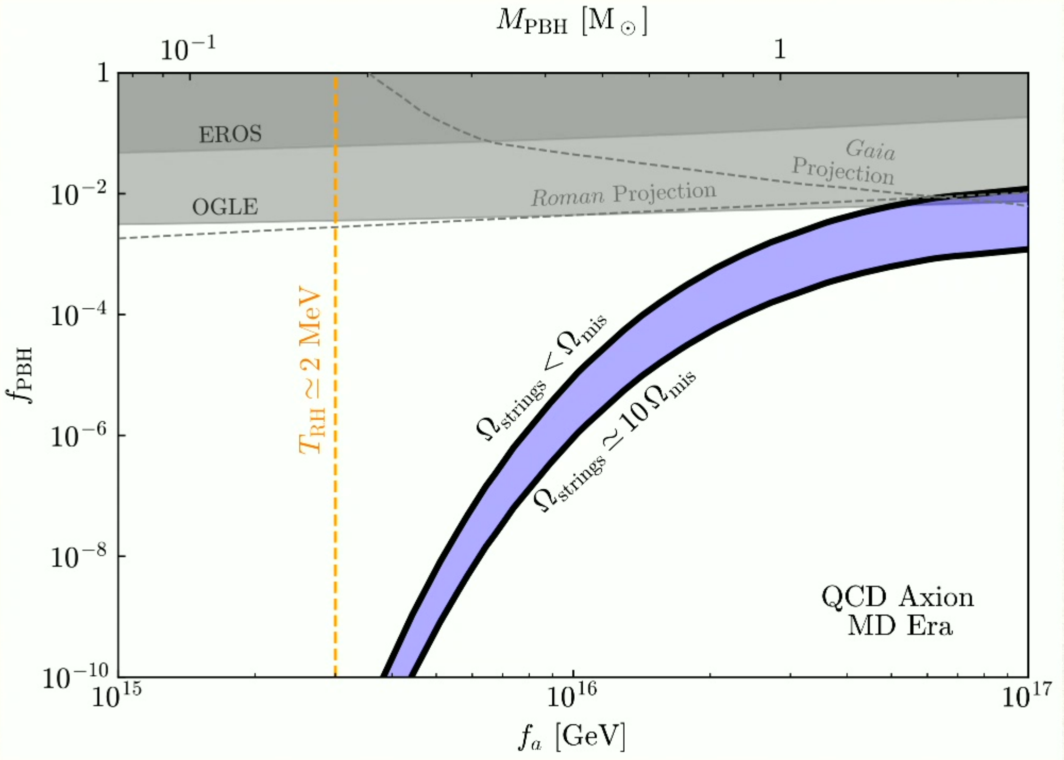
$$= \left(\frac{1}{m_a(t_0)\alpha t_0}\right)\left(\frac{a(t_0)}{a(t_{\rm RE})}\right)\left(\frac{m_a(t_0)}{m_a(t_{\rm RE})}\right)$$

Relic Abundance

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

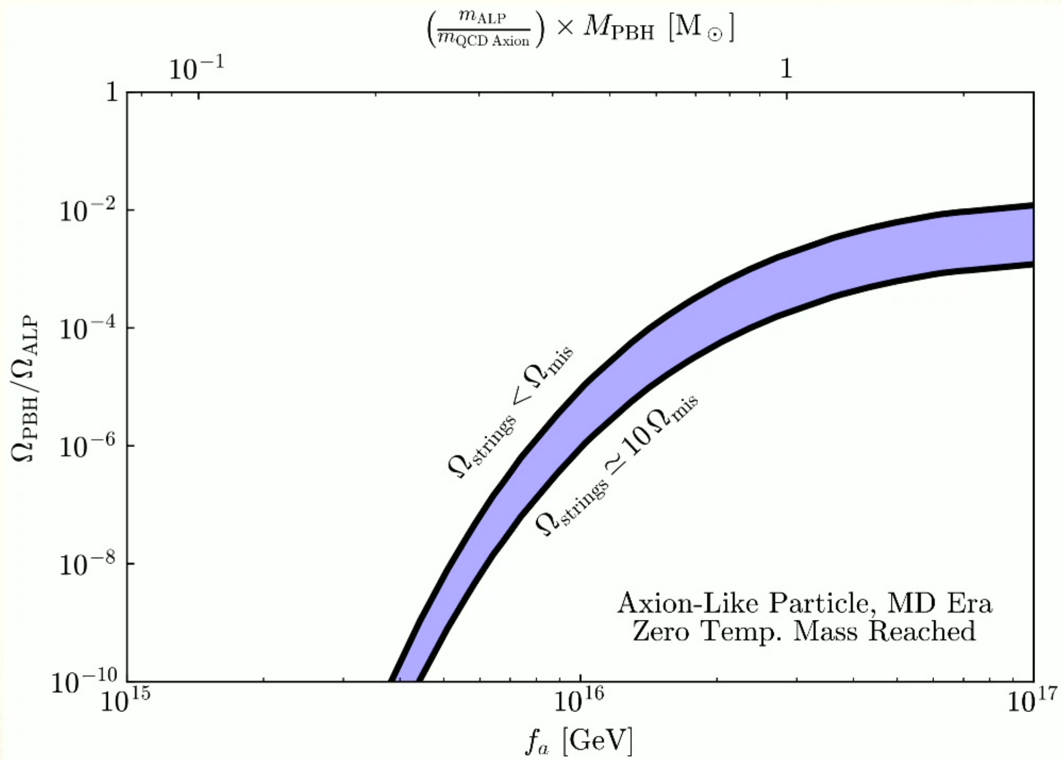
$$M_{\rm PBH} \approx 4\pi R_{\rm RE}^2 \sigma$$
$$\sigma \simeq 8 m_a(t_c) f_a^2$$

$$n_{\rm PBH} = n_{\rm encl}(R_0) \left(\frac{a(t_0)}{a(t)}\right)^3$$
$$\times \Theta(R_{\rm RE}/\delta_{\rm RE} - \ {\rm Min}\ R_{\rm RE}/\delta_{\rm RE})$$
$$\times P(\text{Not colliding})$$



ADD ALPS more comments

- Formalism for PBH formation applies to axion-like-particles too
- PBH conditions depend *only* on $R_{\rm RE}/\delta_{\rm RE}$ (and ϵ), so ALP mass drops out
- PBH mass depends on $m_{\rm ALP}$



Conclusions

- Axion cosmology can generate PBHs, abundance largest for large f_a
- For QCD axion, lensing signal appears 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*

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