29/01/2026 MITP Youngst@rs Workshop

Phase transition during inflation

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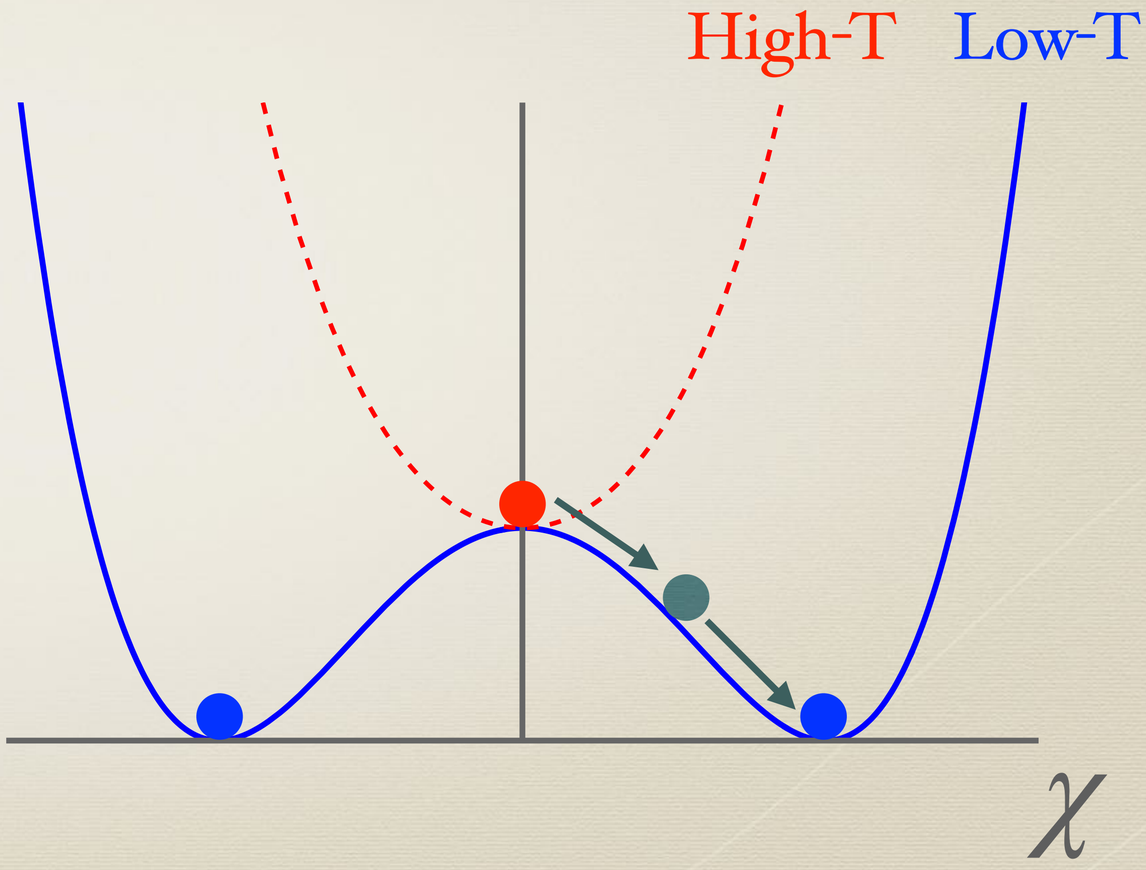
Outline

* Phase transition after inflation
* Phase transition during inflation
* Axion production
* Gravitational wave production
* Anisotropic gravitational waves

Thermal phase transition

$$y\chi\psi\bar{\psi}$$

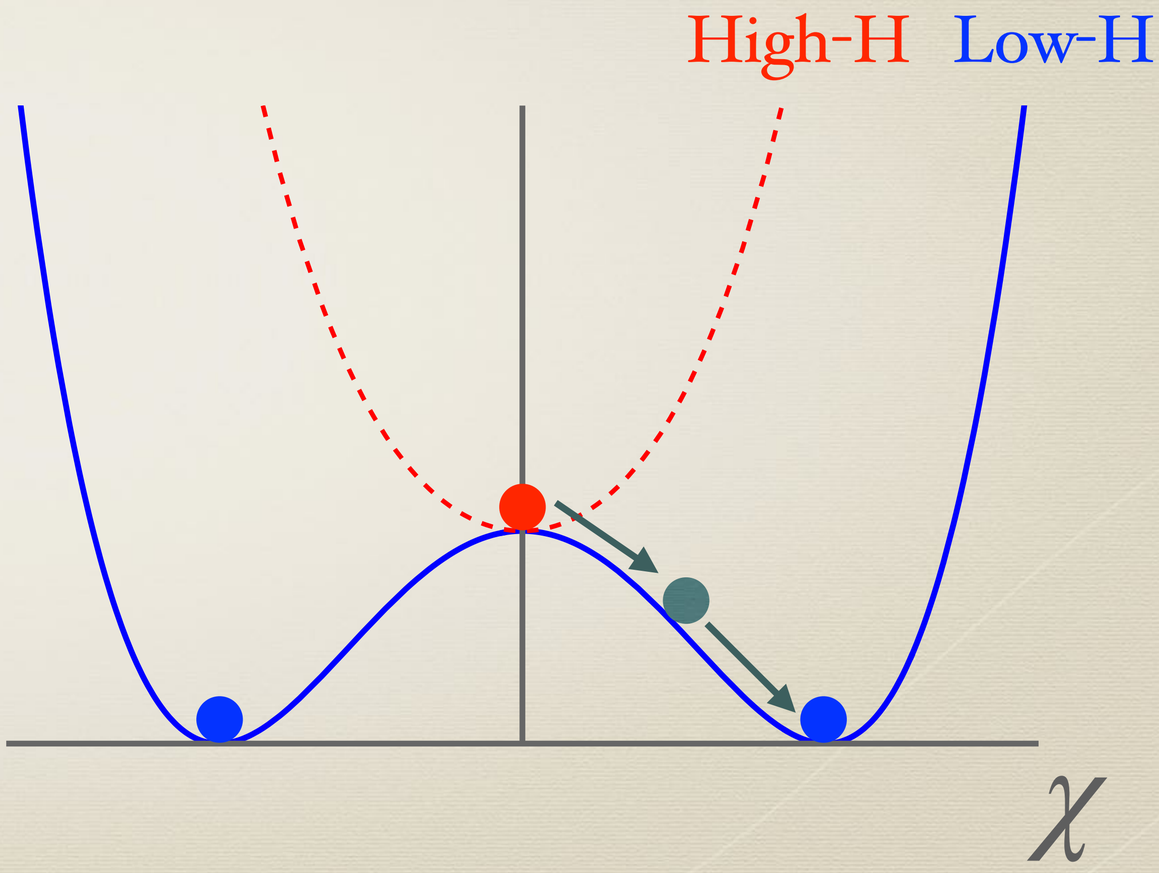
$$V = (-m^2 + y^2T^2)\chi^2 + \cdots$$



Phase transition by Hubble-induced mass

$$\chi^2 R + \frac{\chi^2}{M^2} V_{\rm inf}$$

$$V = (-m^2 + cH^2)\chi^2 + \cdots$$



Cosmological signals and roles

* Gravitational waves by first-order phase transition

  Talks by Musumeci, Moffett-Smith, Pieroni, Barni, Loladze, ...

* Matter-antimatter asymmetry by first-order phase transition

  Talks by Postma, Gent, Saha, ...

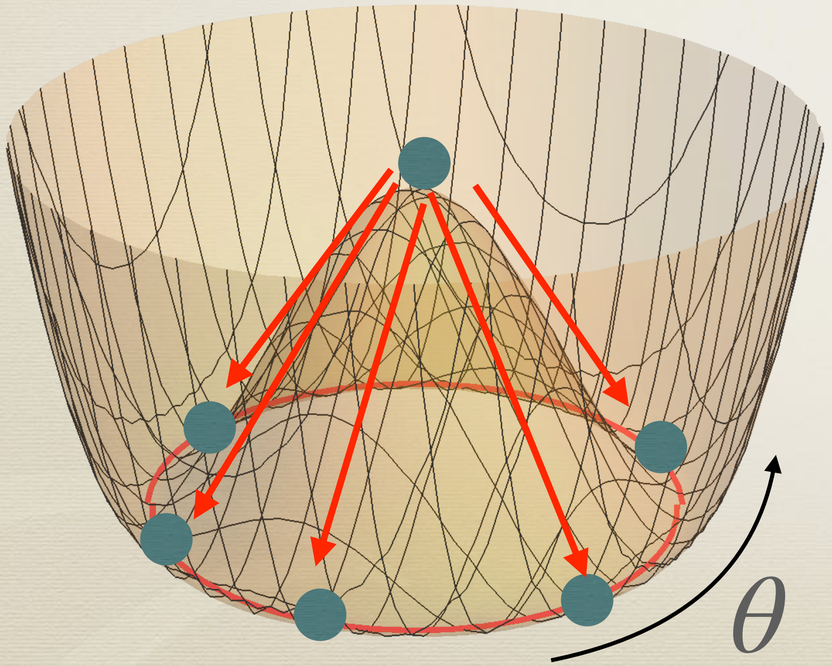
* Topological defects

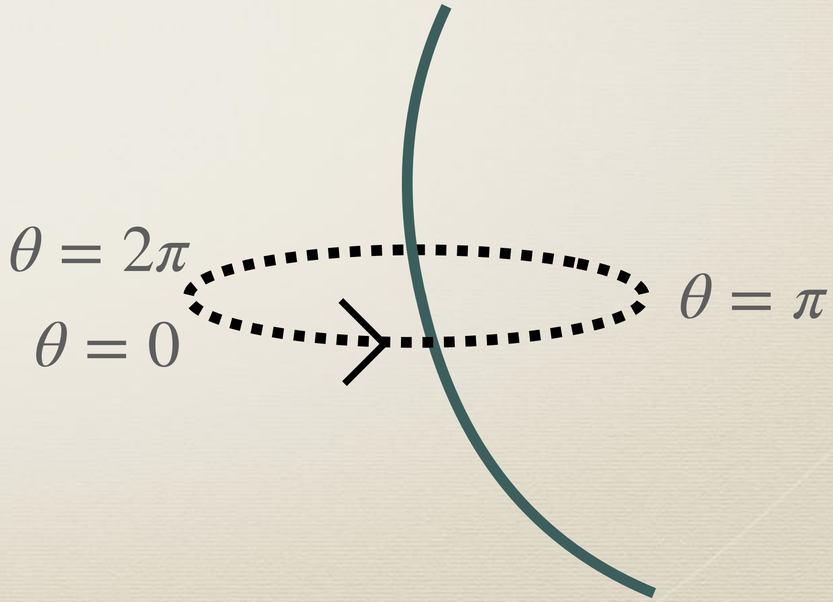
  Talks by Turner, ...

Dark matter production, gravitational waves, ...

$U(1)$ and cosmic strings

Phase transition → Cosmic strings are produced





Scaling law

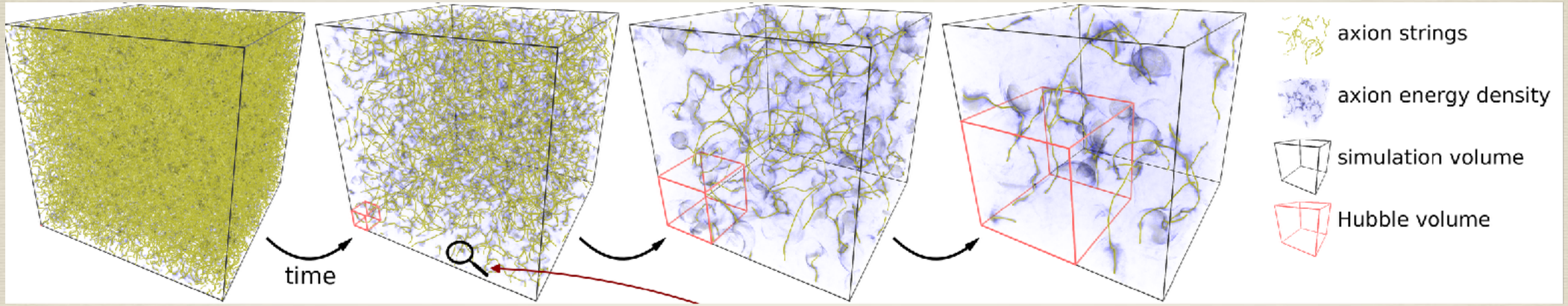


Figure from Bushmann et.al. (2021)

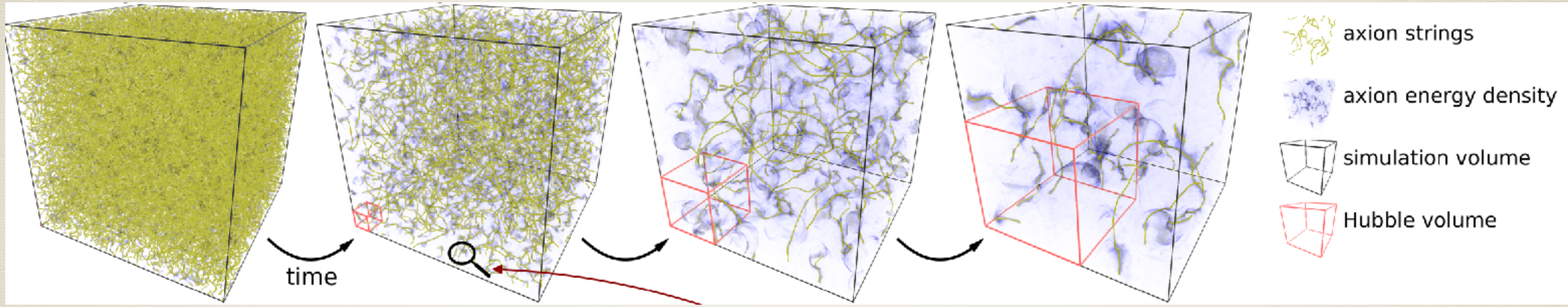
O(1) cosmic strings per horizon volume

Typical length of and distance between strings $\sim H^{-1}$

Where does the string energy go?

Global U(1) and NGB emission

With spontaneous breaking of global $U(1)$, a Nambu-Goldstone boson is predicted



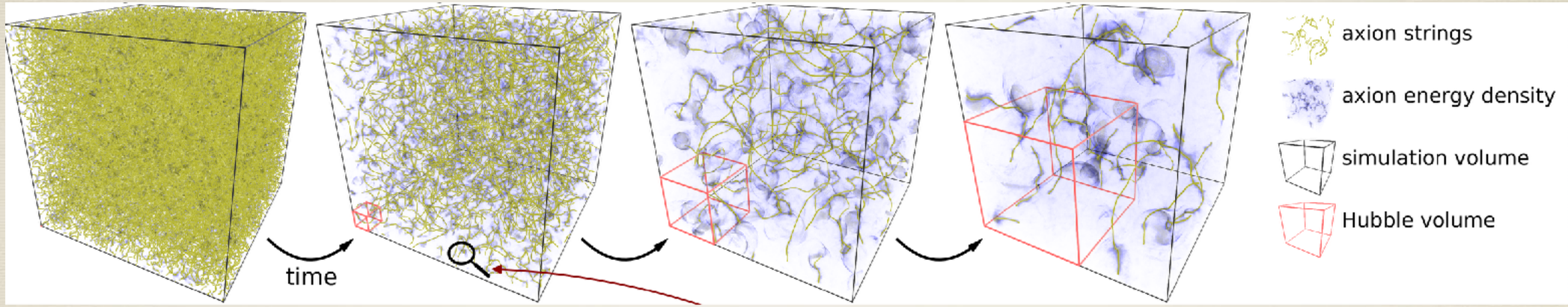
NGBs

For $U(1)_{PQ}$, which solves the strong CP problem, axion dark matter is produced

Davis (1986)

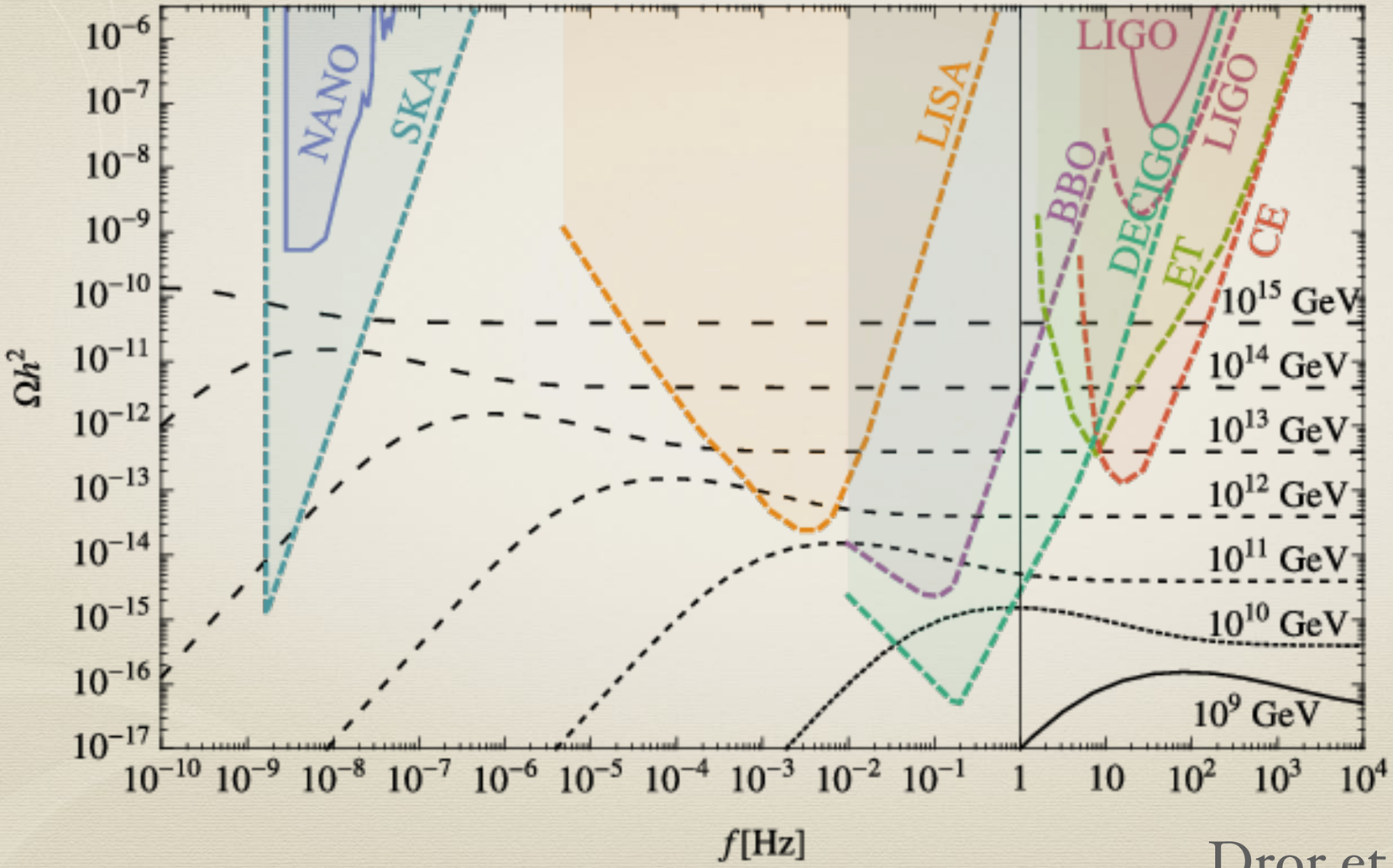
Gauged U(1) and GW emission

Would-be NGB is eaten by the gauge boson, mass $\gg$ (length scale)$^{-1}$



Gauge boson emission is suppressed. Mainly gravitational waves are emitted

Gauged U(1) and GW emission



symmetry-breaking scale

Dror et.al. (2019)

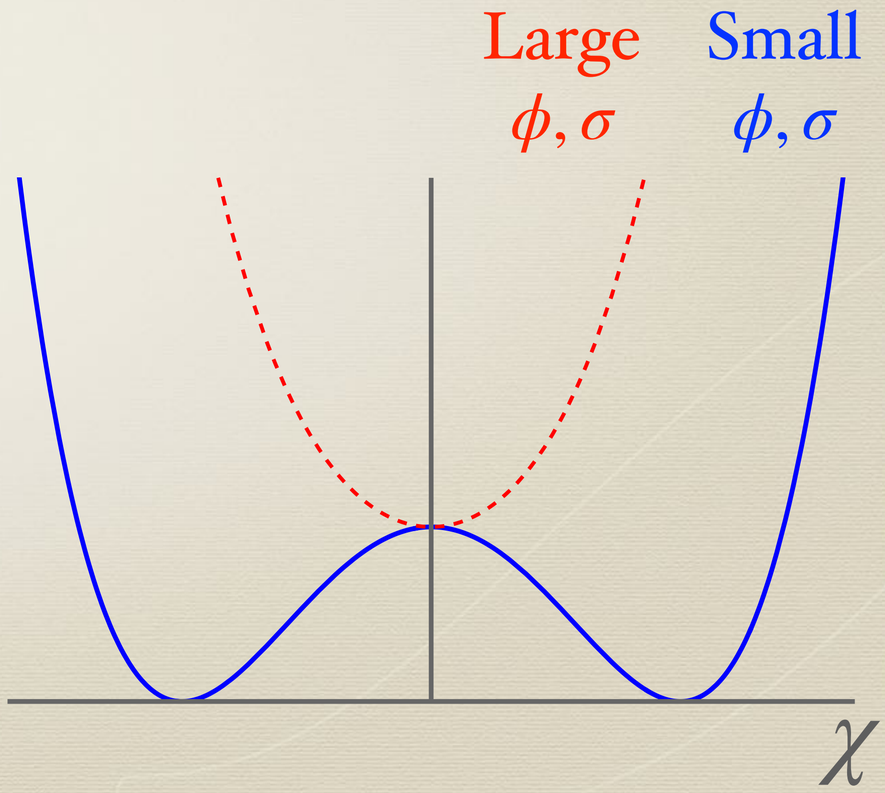
Outline

* Phase transition after inflation
* Phase transition during inflation 
* Axion production
* Gravitational wave production
* Anisotropic gravitational waves

Known possibilities

Thermal phase transition during observable inflation seems unlikely,
since the bath, even if it exists, is quickly red-shifted away

* Slow-rolling inflaton field ϕ $\quad V = \lambda\phi^2\chi^2$
* Slow-rolling spectator field σ $\quad V = \lambda\sigma^2\chi^2$



Similar to hybrid inflation,
but χ's energy density is negligible

Inflaton-triggered phase transition

$$V = (-m_\chi^2 + \lambda\phi^2)\chi^2 + \cdots$$

Can the field value of the inflaton change appreciably during inflation?

Ex. New inflation $\quad V(\phi) = V_0 - \frac{3}{2}\kappa H_{\rm inf}^2\phi^2 + \cdots \qquad \kappa \simeq 0.02$

$$\Rightarrow \quad \phi \simeq \phi_i \times \exp(N_e\kappa)$$

The inflation field value changes by $O(1)$ factor during observable inflation

Need a coincidence $m_\chi^2 \sim \lambda\phi_i^2$, but phase transition is possible

Spectator-triggered phase transition

Bao and KH (2026)

$$V = (-m_\chi^2 + \lambda\sigma^2)\chi^2 + \cdots$$

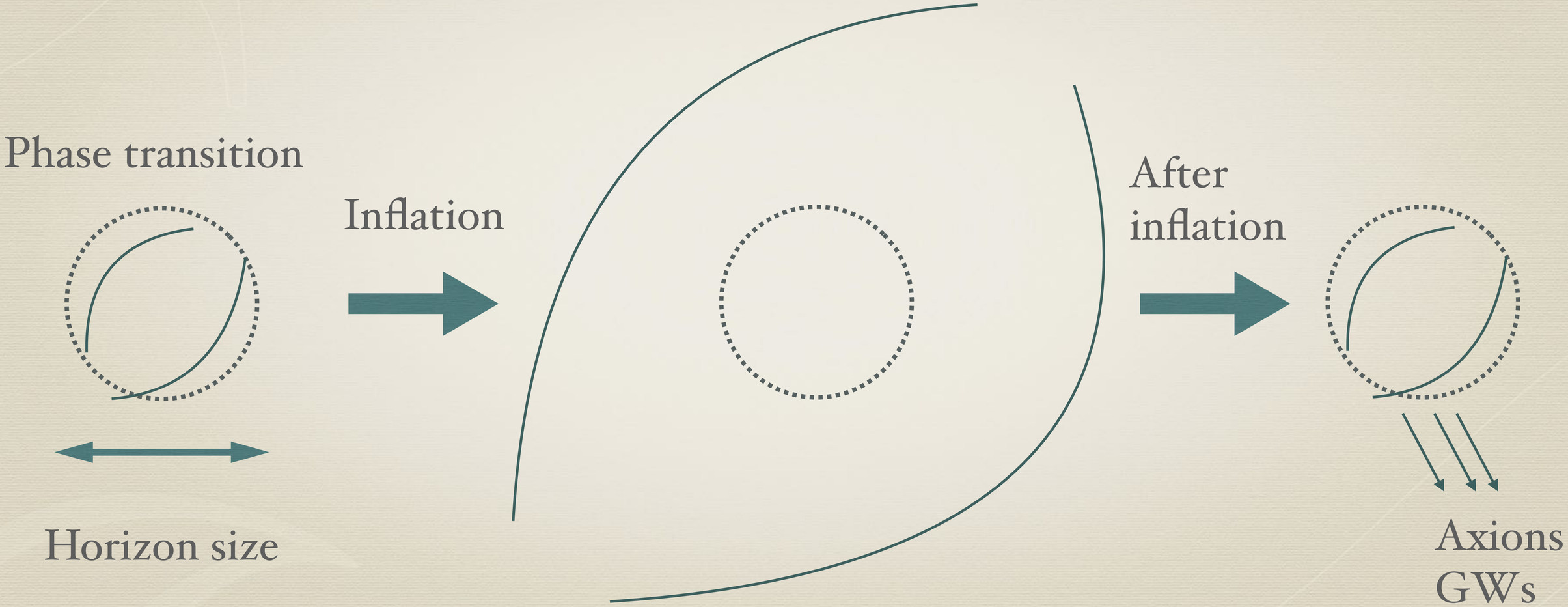
$$V(\sigma) = \frac{3}{2}\kappa H_{\rm inf}^2\sigma^2 + \cdots$$

$$\sigma \simeq \phi_i \times \exp(-N_e\kappa)$$

The spectator field value can change by much more than $O(1)$ factor during inflation

Phase transition is possible without coincidence

Inflated topological defects



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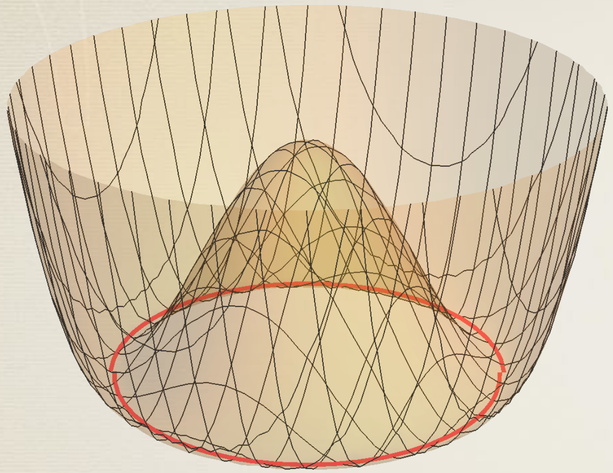
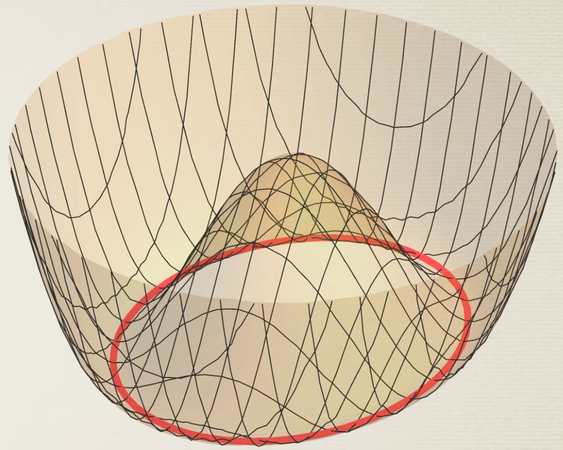
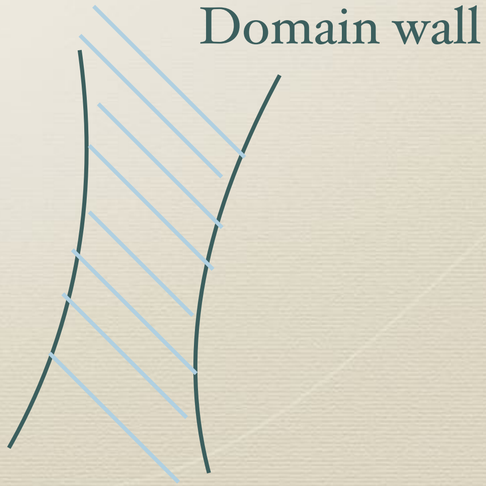
Axion emission



QCD dynamics



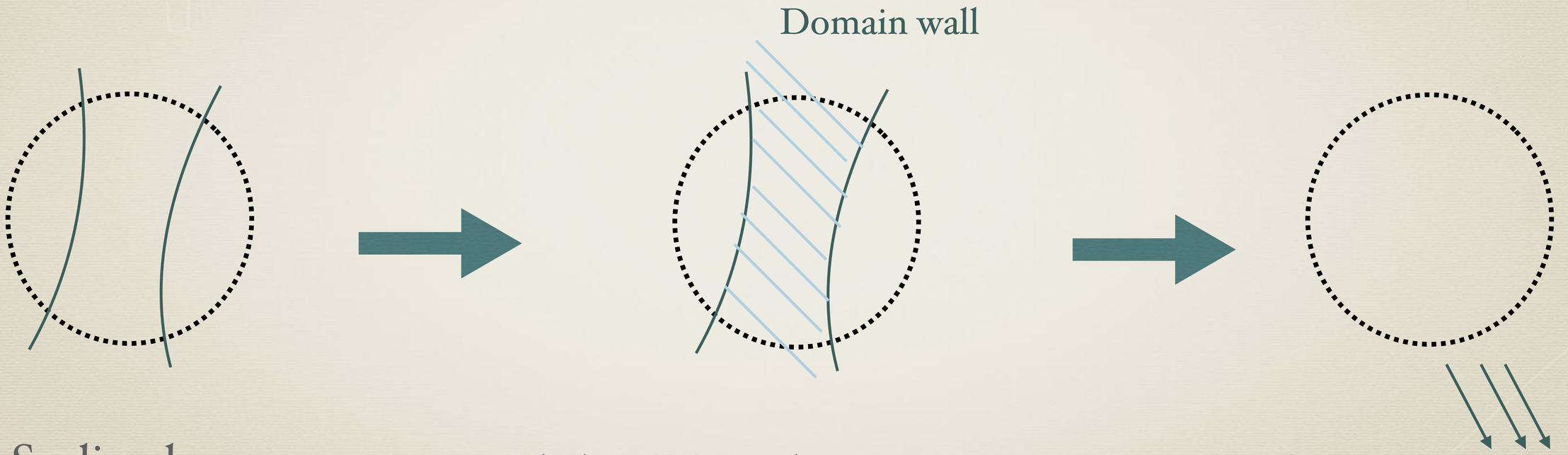


Domain wall

Axion emission

Davis (1986)

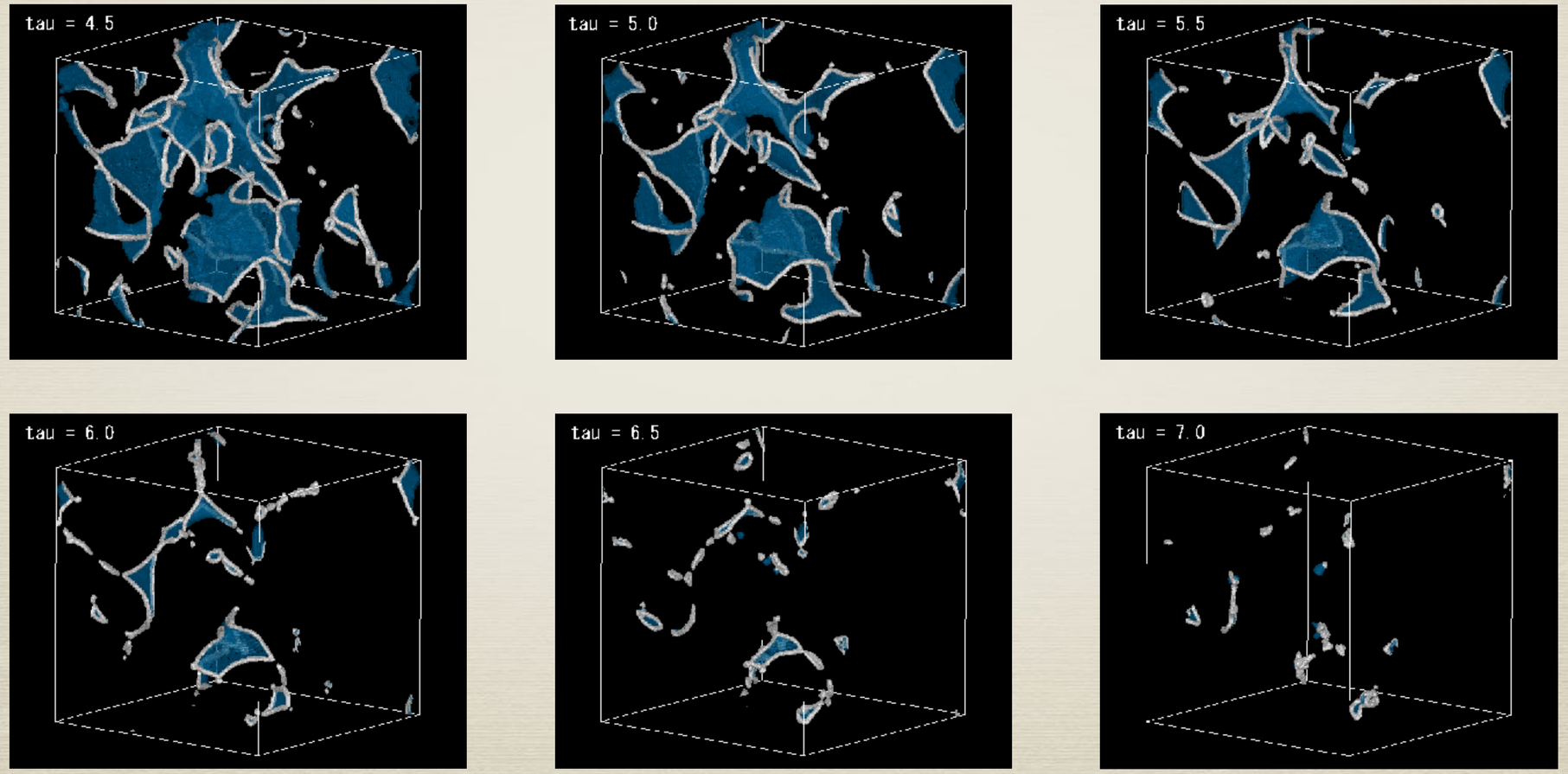
For phase transition after inflation,



$$m_a \sim H$$

Axion emission

String-domain wall networks decay when $m_a(T) \sim H$

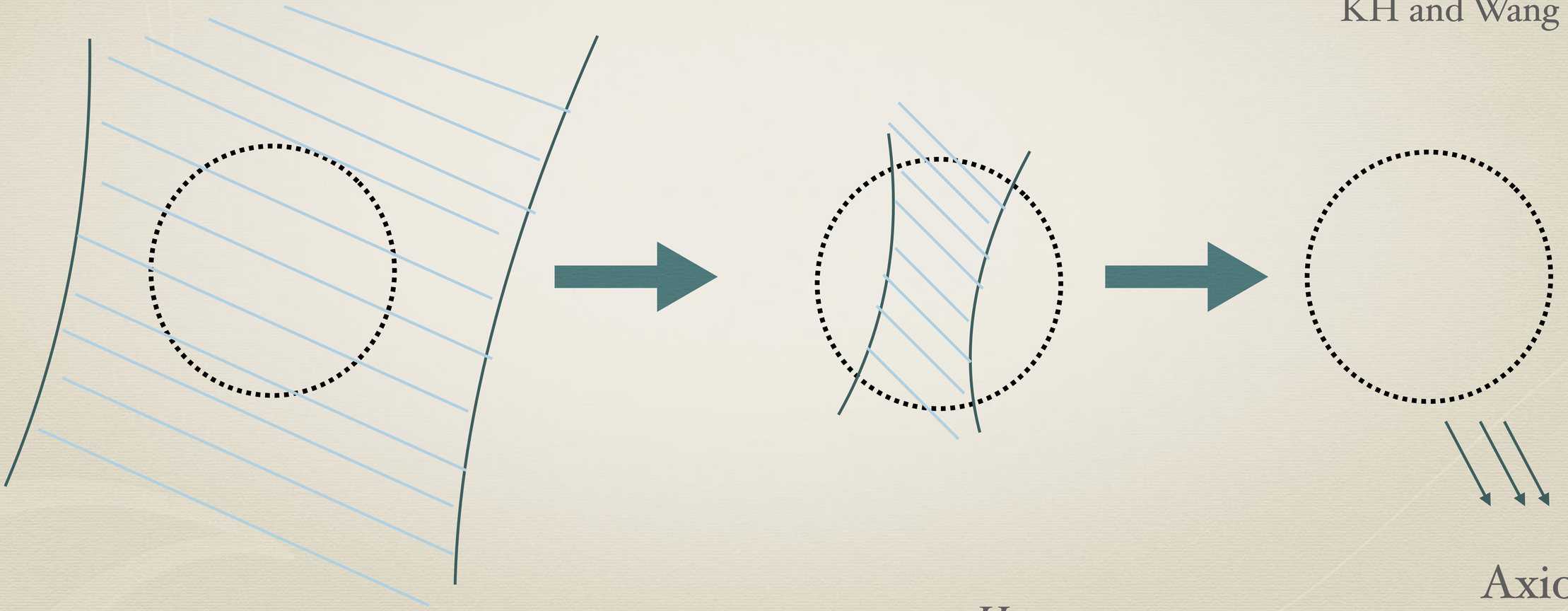


Figures from Hiramatsu et.al. (2012)

Enhanced axion abundance

Baratella, Pomarol and Rompineve (2018)
Redi and Tesi (2022)
KH and Wang (2022)

For phase transition during inflation,



$m_a \sim H$

$m_a \gg H$

Enhanced axion abundance

* Phase transition after inflation

$$\frac{\rho_a}{\rho_{\rm DM}} \sim \left(\frac{f_a}{10^{11}\ {\rm GeV}}\right)^{1.19}$$

e.g. Gorghetto, Hardy, and Villadoro (2021)
Bushmann et.al. (2021)

* Phase transition during inflation

$$\frac{\rho_a}{\rho_{\rm DM}} \sim \frac{f_a}{10^{9}\ {\rm GeV}} \frac{10\ {\rm MeV}}{T_{\rm re}}$$

$T_{\rm re}$: the temperature of the reentry

Baratella, Pomarol and Rompineve (2018)
Redi and Tesi (2022)
KH and Wang (2022)

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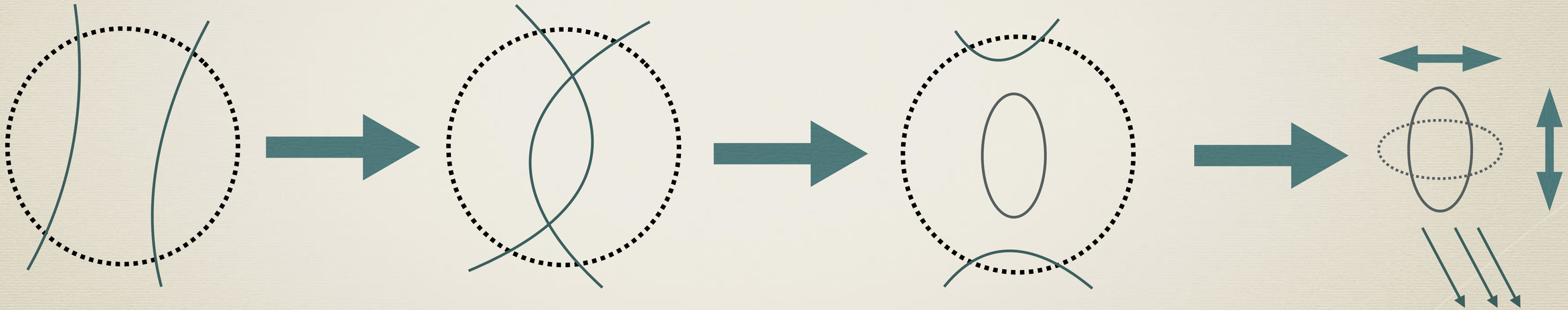
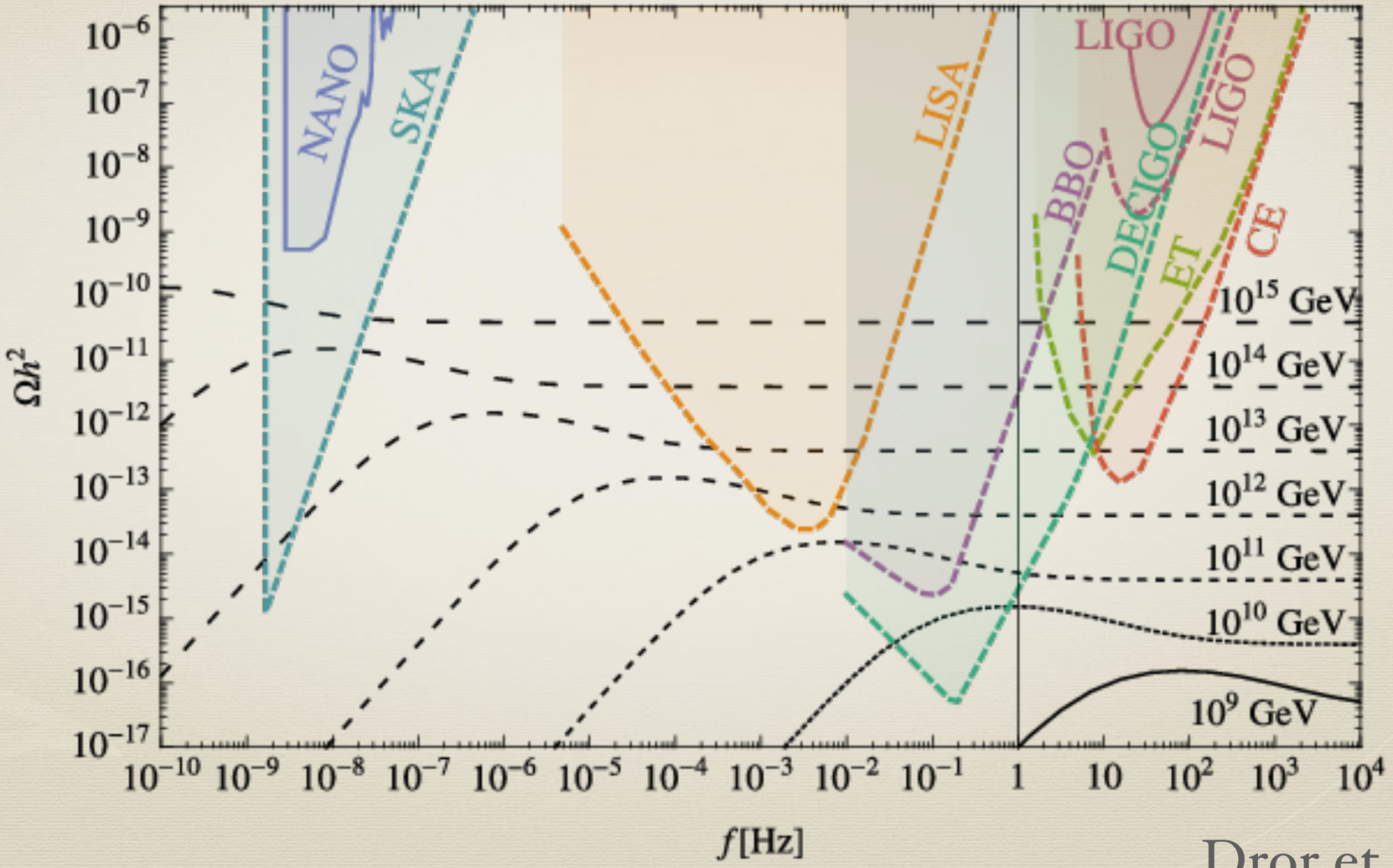
Gravitational wave

For phase transition after inflation,

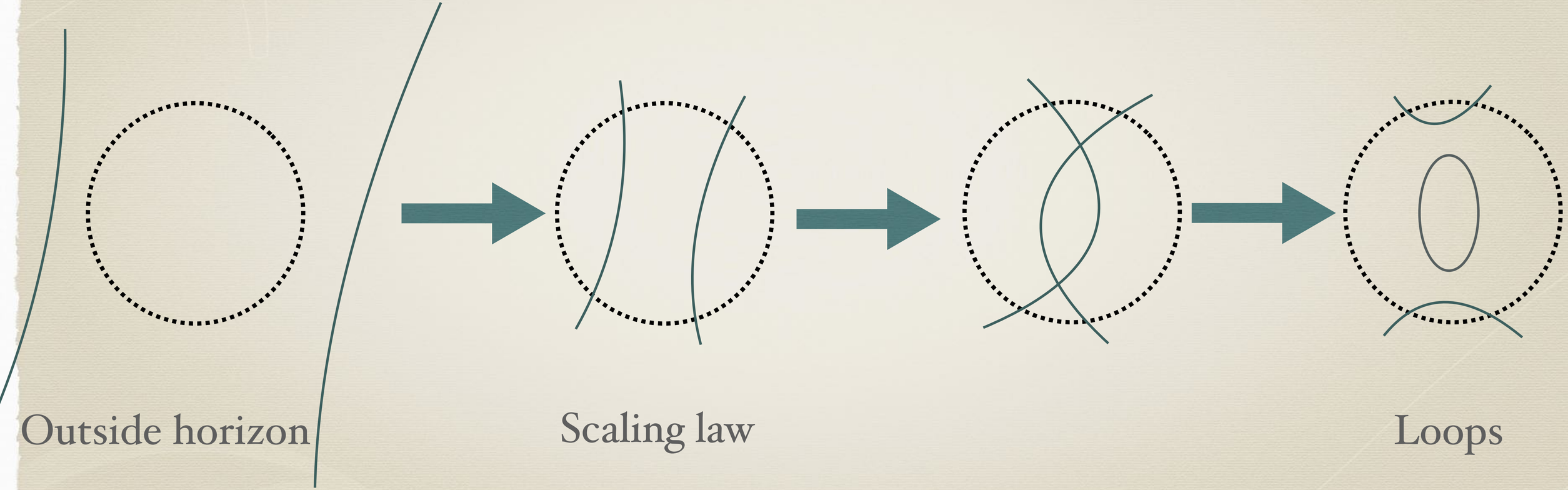




Dror et.al. (2019)

Gravitational wave

For phase transition before inflation,

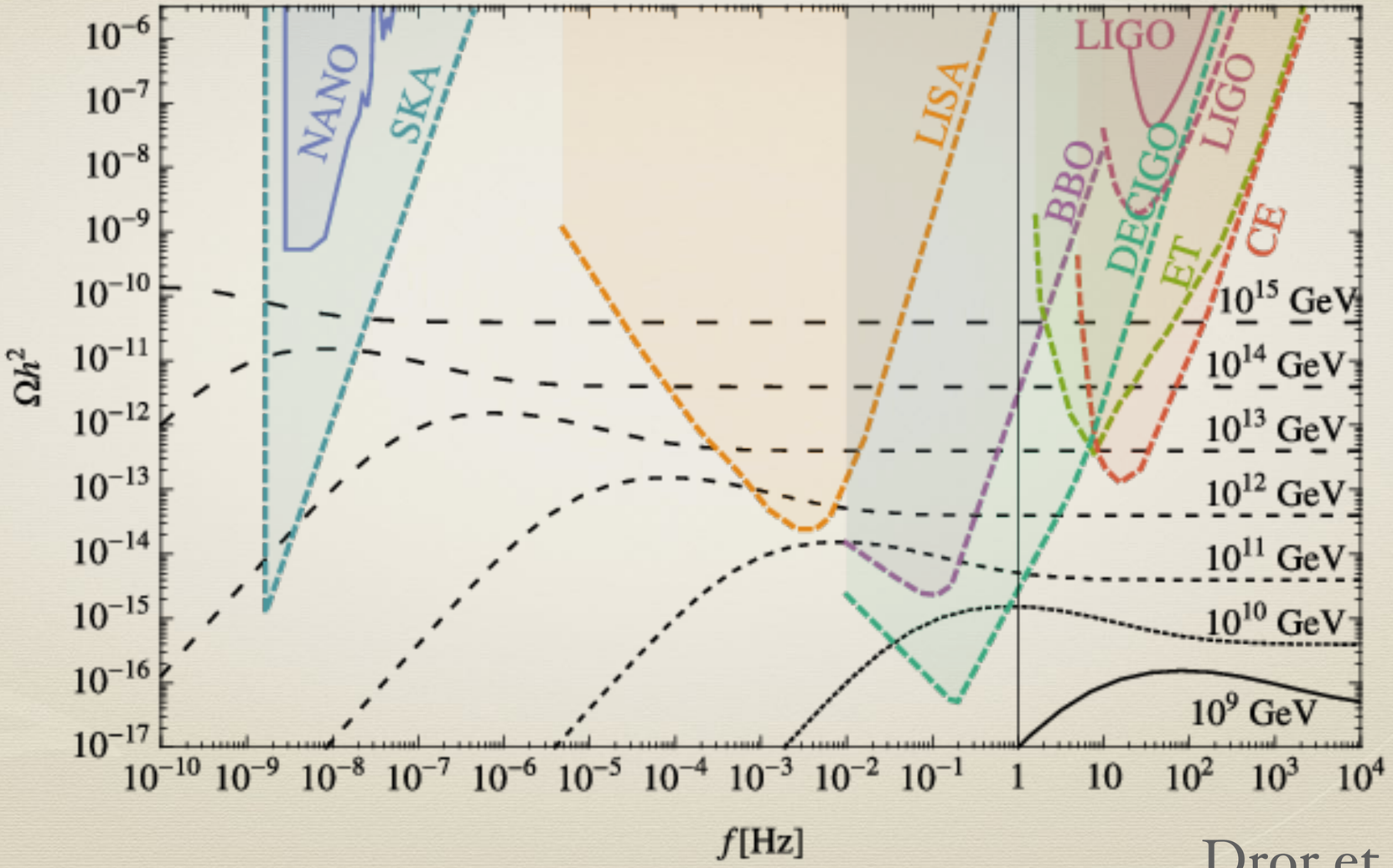


Outside horizon

Scaling law

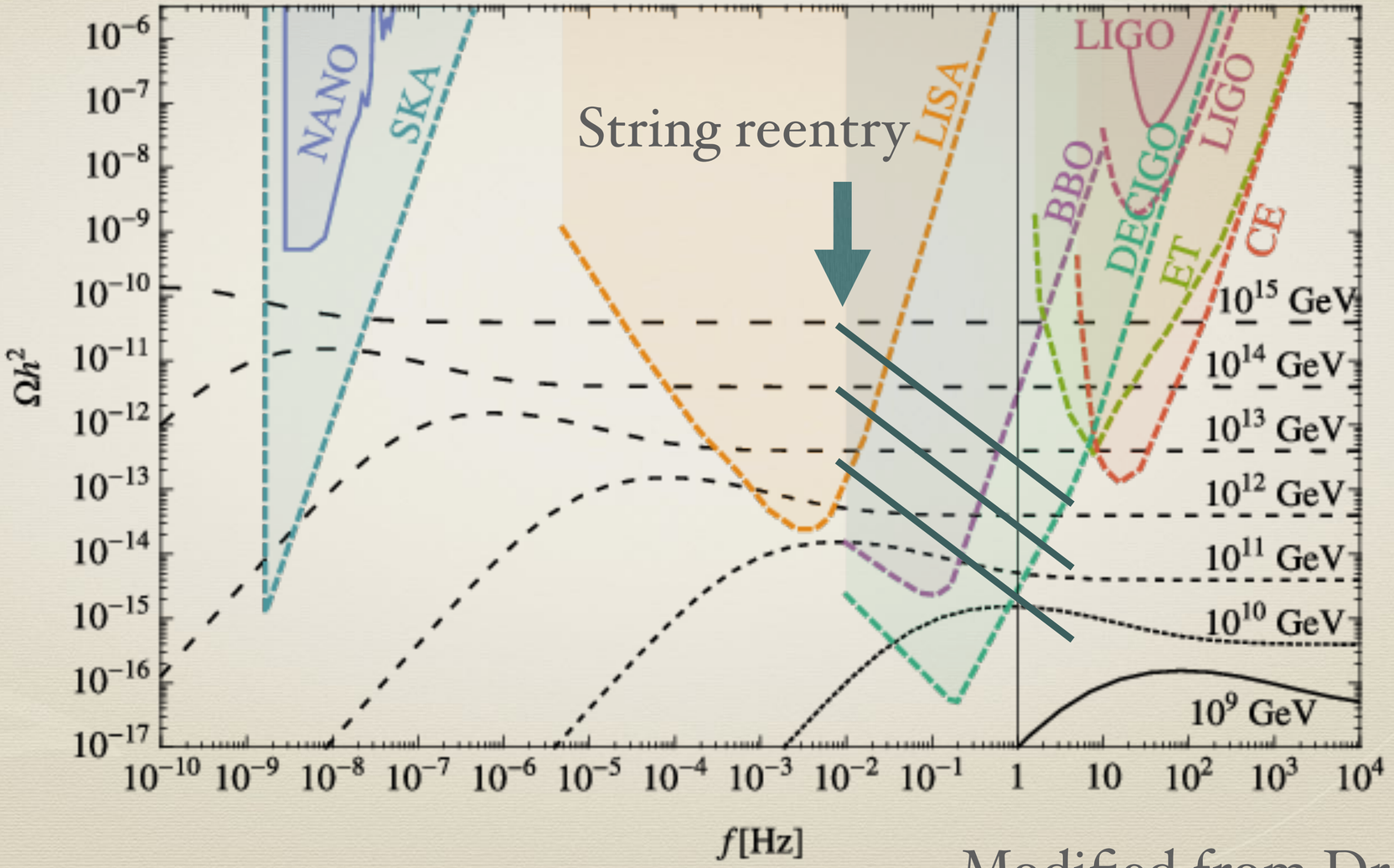
Loops

Gravitational waves are not produced at earlier time



Dror et.al. (2019)

Guedes, Avelino and Sousa (2018)
Cui, Lewicki and Morrissey (2019)



Modified from Dror et.al. (2019)

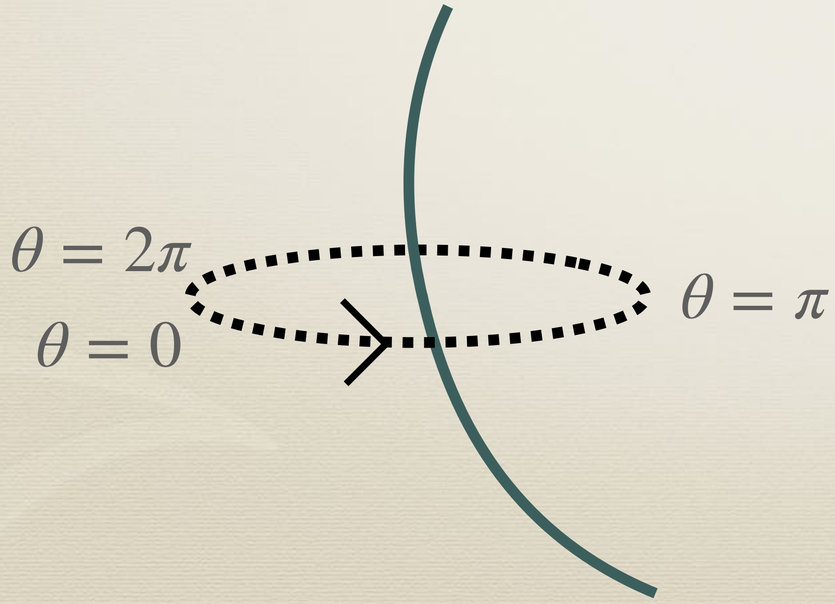
Two phase transitions

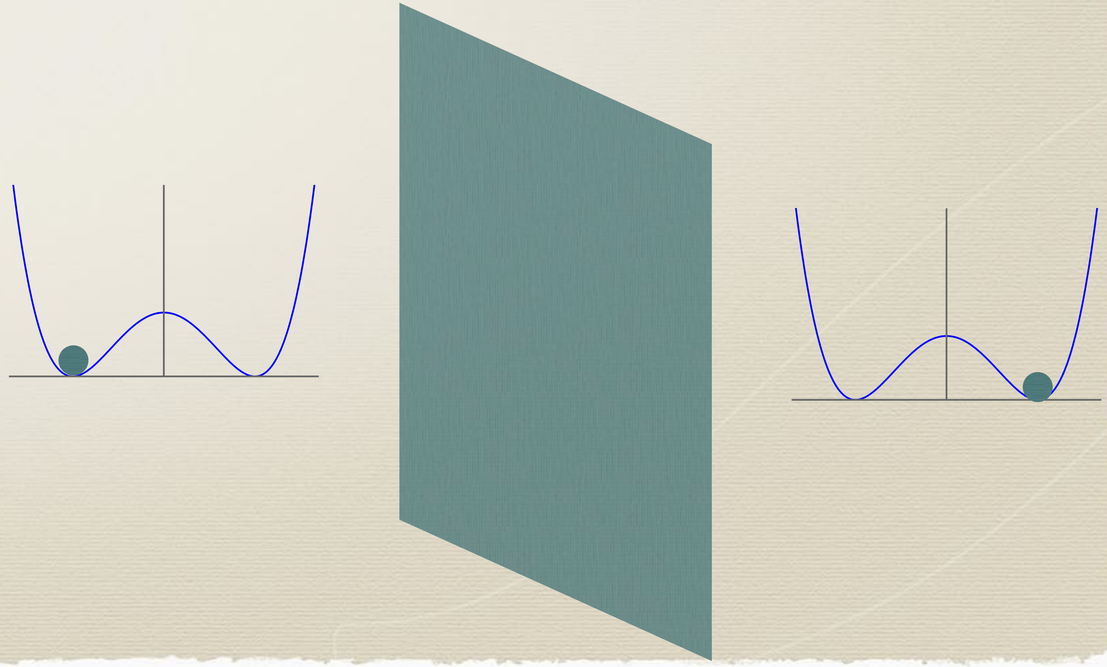
Ex.

$U(1)$ → during inflation → Z_2 → after inflation → none

cosmic strings

domain walls





Two phase transitions

Ex.

$U(1)$ → during inflation → Z_2 → after inflation → none

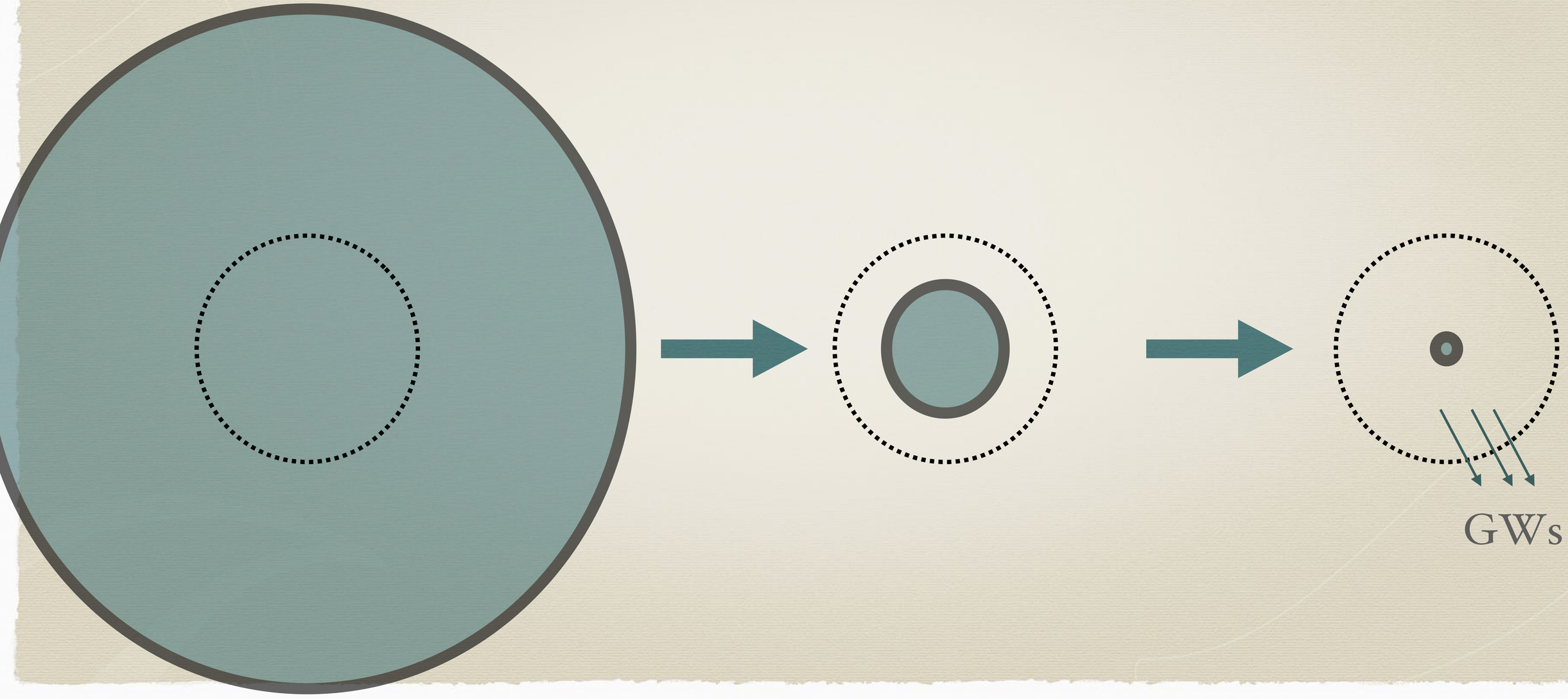
cosmic strings

domain walls

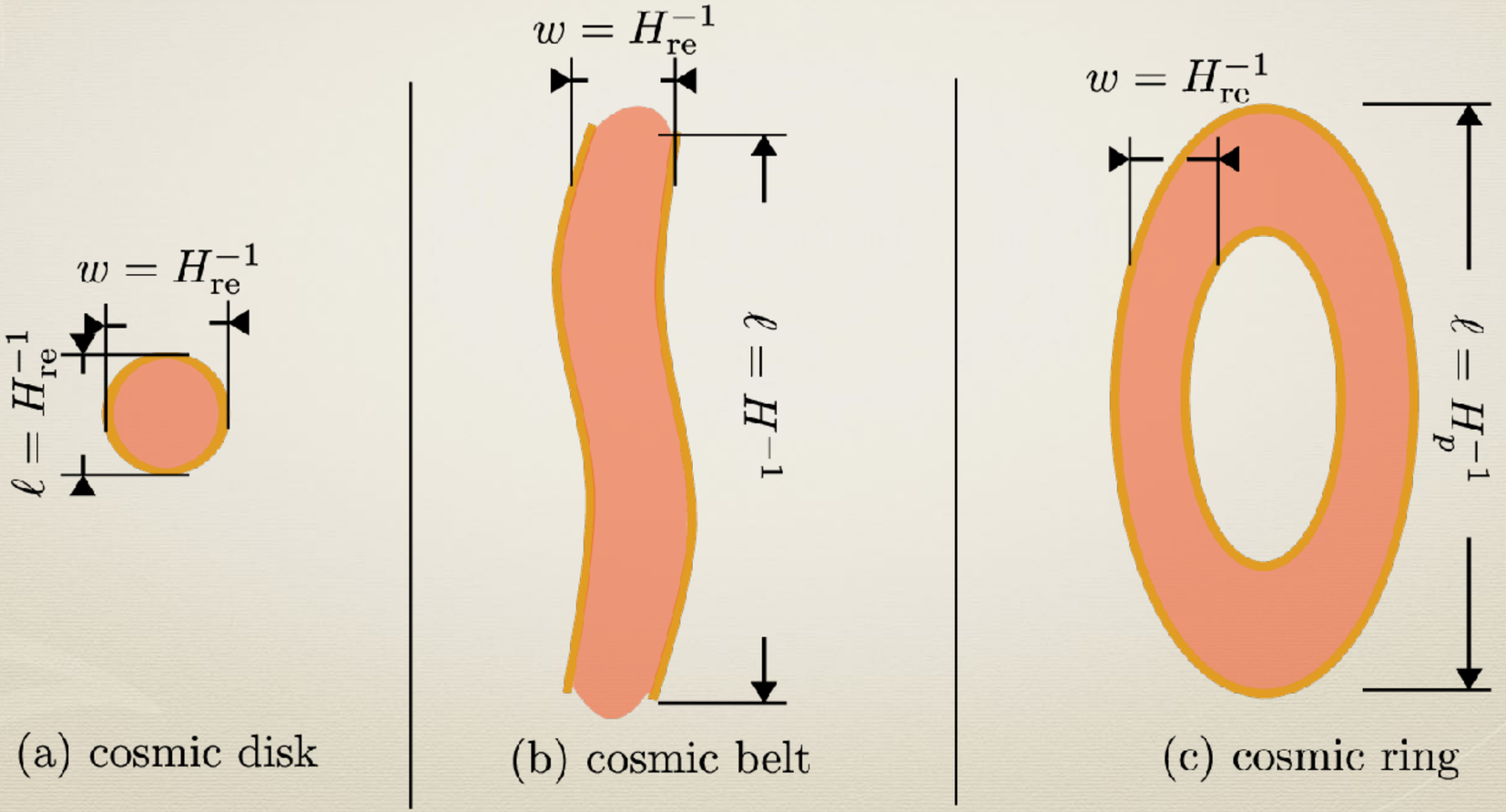
The whole symmetry breaking pattern is $U(1)$ → none

The only stable topological defects are strings. Domain walls should be unstable once cosmic strings are involved.

Walls bound by strings



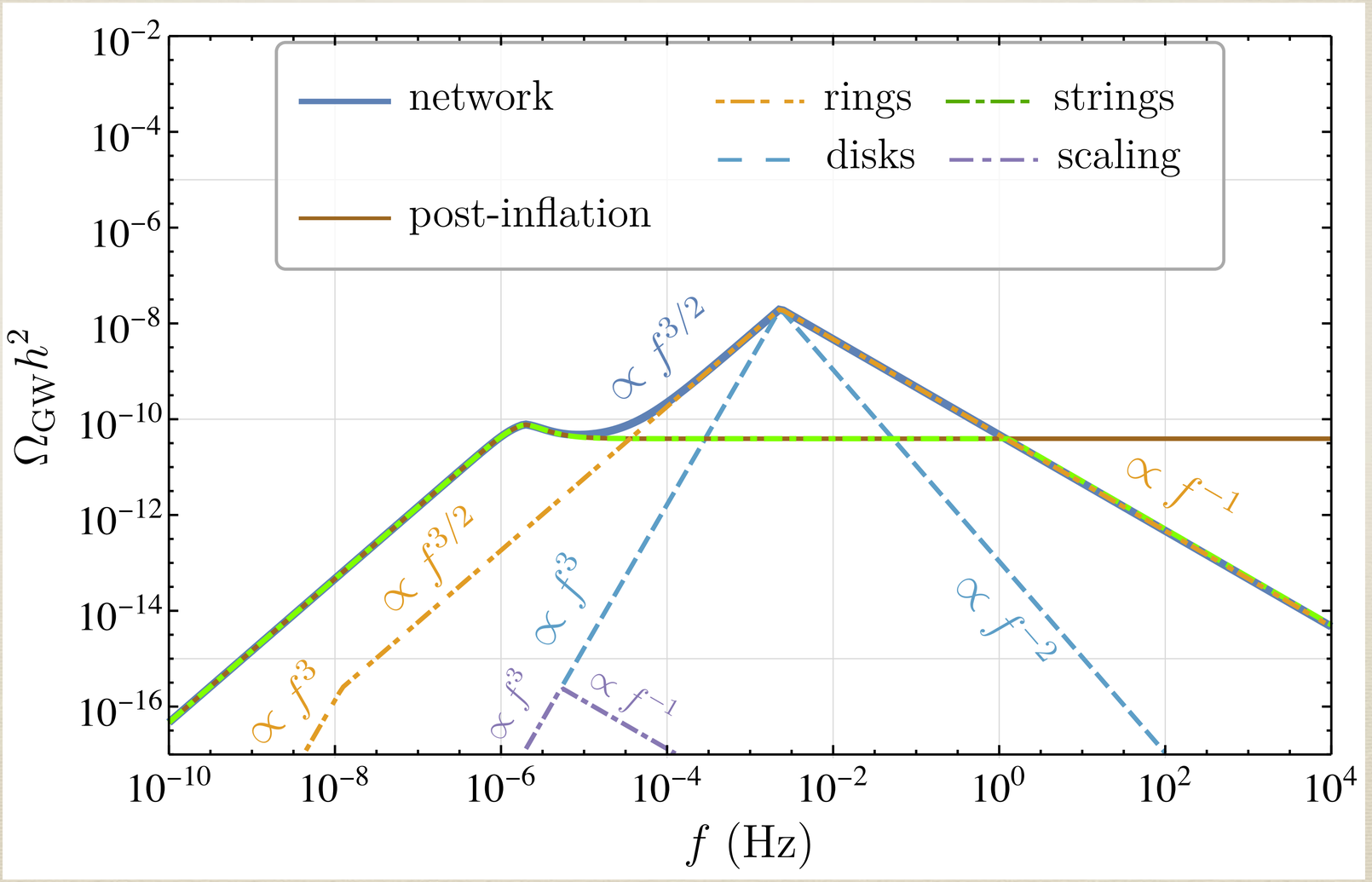
Defects



(a) cosmic disk (b) cosmic belt (c) cosmic ring

GW spectrum

Bao, KH and Wang (2026)



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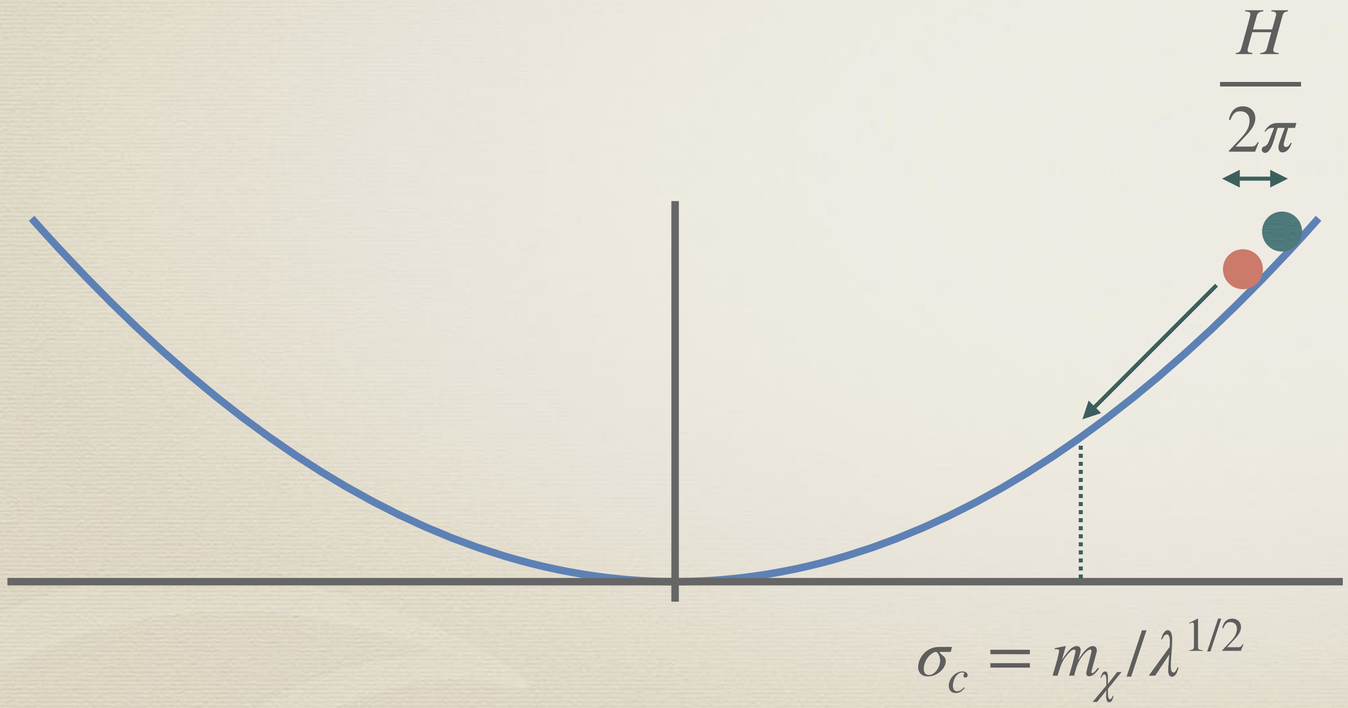
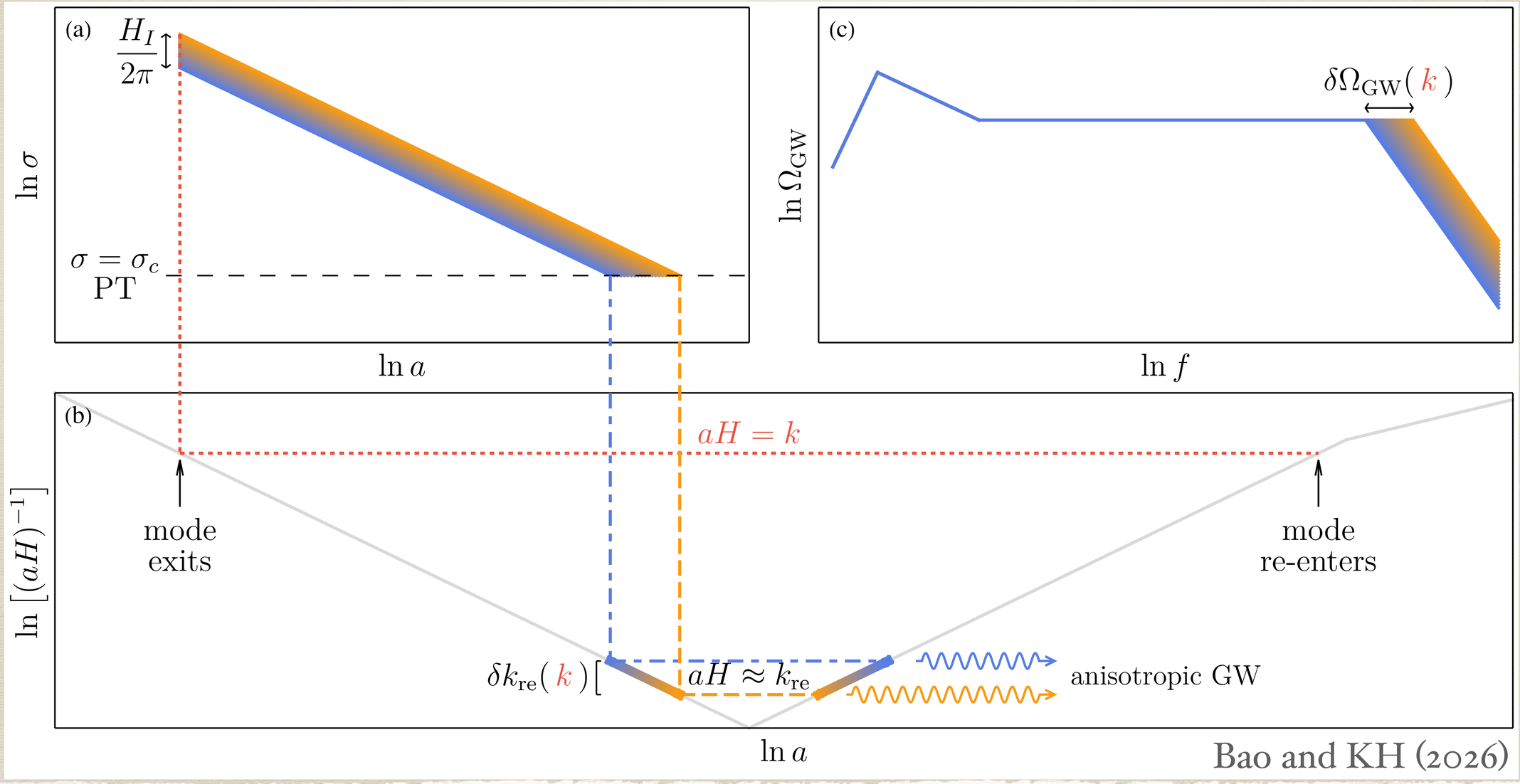
Spectator-triggered phase transition

$$V = (-m_\chi^2 + \lambda\sigma^2)\chi^2 + \cdots$$



The timing phase transition modulates

Ex. Gauged cosmic strings



Bao and KH (2026)

Largest possible GW anisotropy

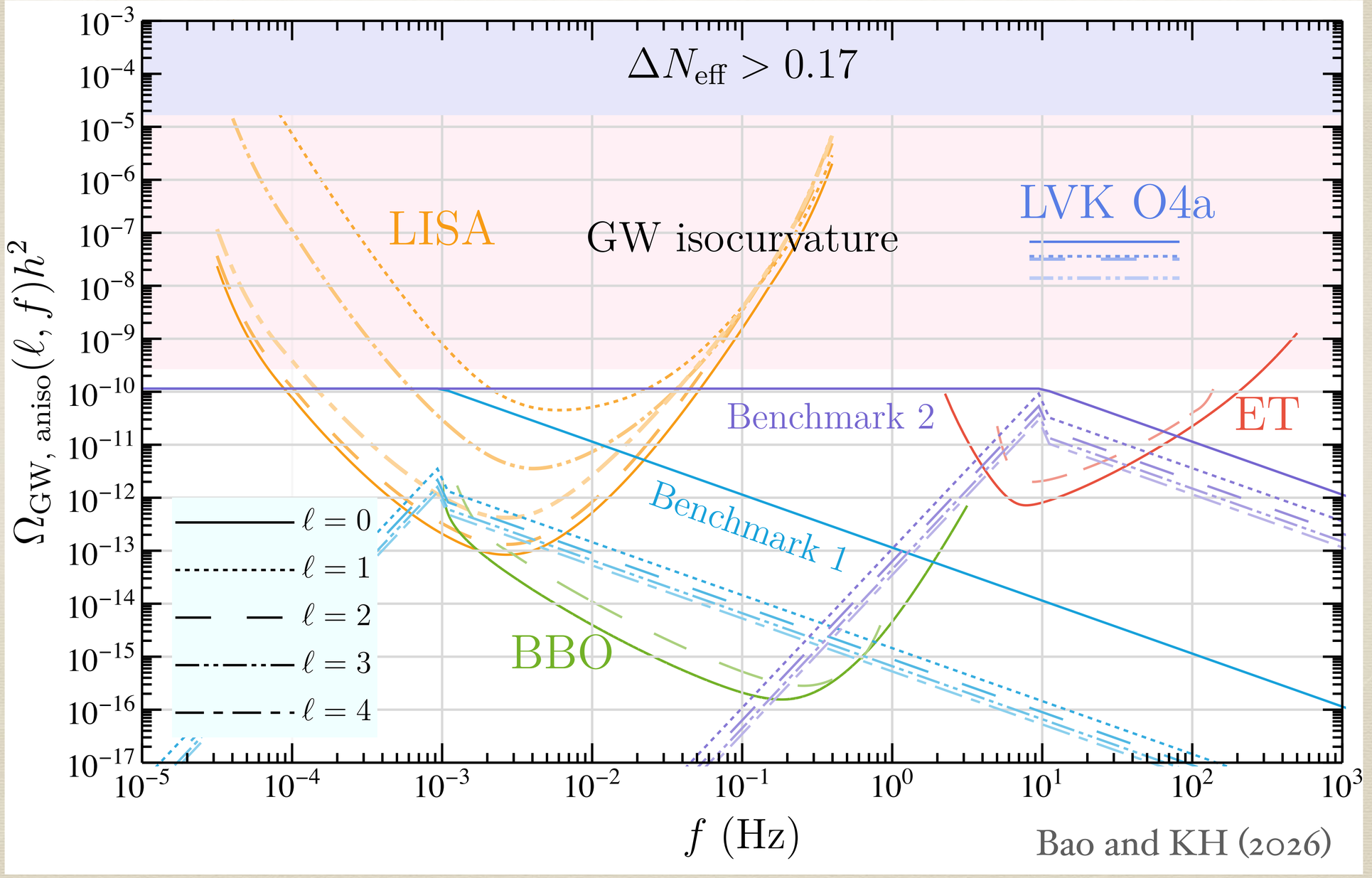
In this setup, all of the energy of the strings go to GWs

The only source of CMB-scale cosmic perturbations are anisotropic GWs

$$\delta\Omega_{\rm GW}h^2 < 2.8\times10^{-10}$$

from Planck 2018

Other mechanisms are subject to stronger constraints
because the source of the GWs dominantly decays into the SM bath


$\Delta N_{\rm eff} > 0.17$
LISA
GW isocurvature
LVK O4a
Benchmark 2
ET
Benchmark 1
BBO
$\ell = 0$
$\ell = 1$
$\ell = 2$
$\ell = 3$
$\ell = 4$
$\Omega_{\rm GW,\,aniso}(\ell, f)h^2$
f (Hz)
Bao and KH (2026)

Summary

* Phase transition during inflation has phenomenological applications
* Triggered by a slow-rolling spectator field, resultant signals can be anisotropic
* Other applications? Possible connection with cosmology/particle-physics puzzles?