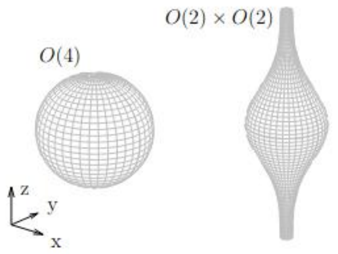
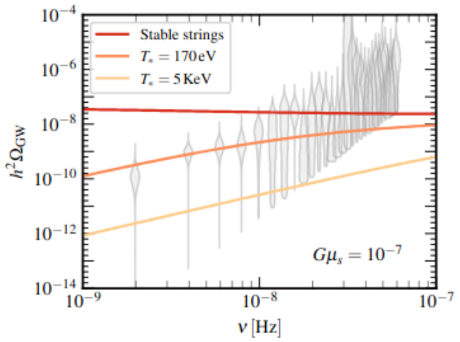
Phase transitions and topological defects

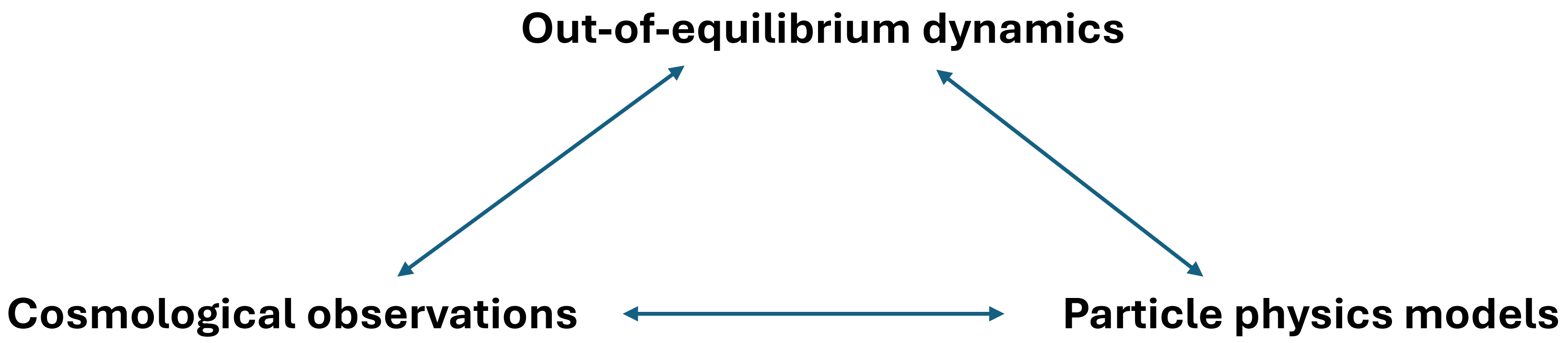
Aleksandr Chatrchyan

Based on arXiv:2510.27579
with Florian Niedermann and Phoebe Richman-Taylor





Main research theme



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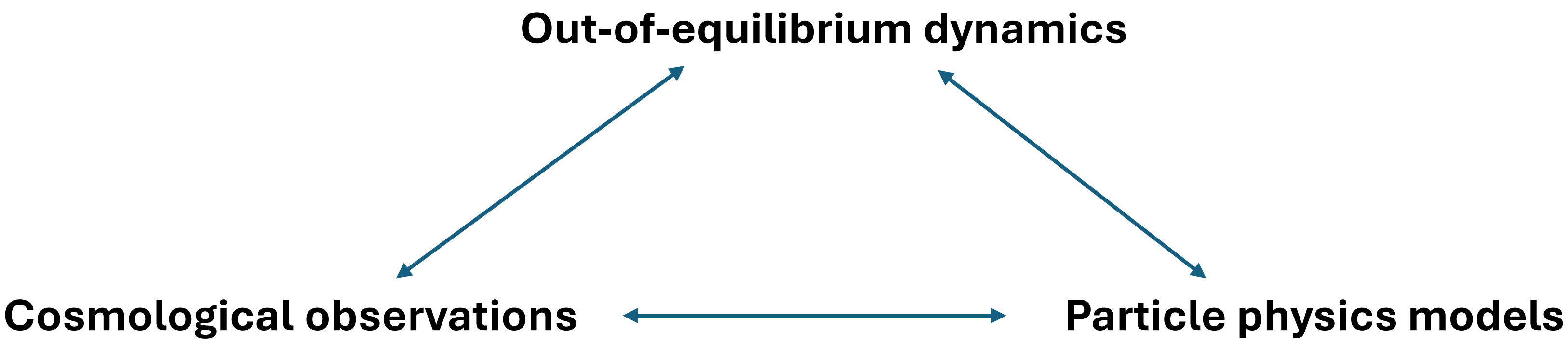
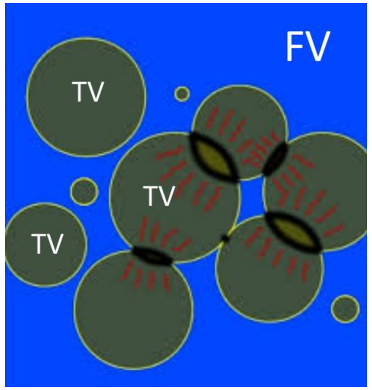


Phase transitions:

- Far-from-equilibrium dynamics (if first-order)
- Unique signatures, including gravitational waves
- Universality



Phase transitions and symmetries

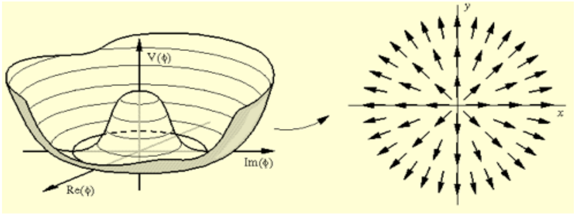
Symmetry breaking PTs

Examples

- Electroweak
- Quark-hadron
- At higher energies, possibly
  - Theories of grand unification
  - PQ symmetry for QCD axion

Topological defects can form

- Example: cosmic strings



Phase transitions and symmetries

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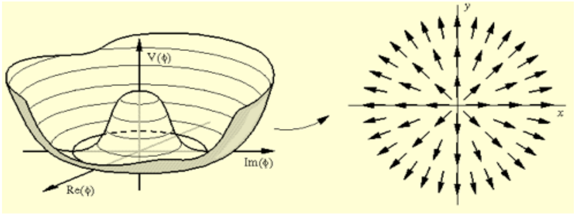

Symmetry restoring PTs

Less common, but possible
- Multi-field set-ups
- Increasing temperature during reheating

Topological defects can act as **catalyzers** for the transition

e.g. Steinhardt, 1981

- **This work**: string-induced transitions

Minimal set-up

- Complex scalar field with a U(1) symmetry

$$\mathcal{L}(\phi, A) = -[D_\mu \phi]^* [D_\mu \phi] - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

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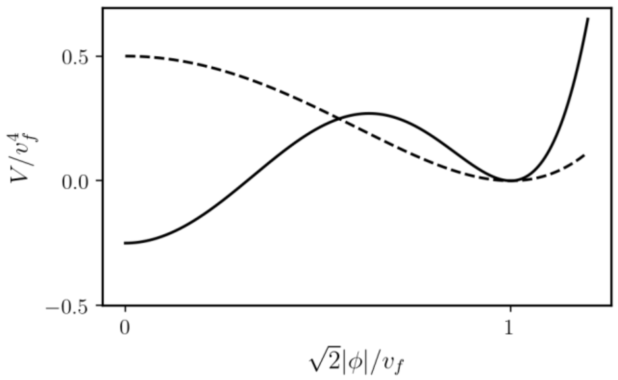
Potential with two local minima

- False vacuum at $\phi = v_f$
- True vacuum at $\phi = 0$

$$V(\phi) = V_1 + \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 + \lambda_6 (\phi^* \phi)^3$$



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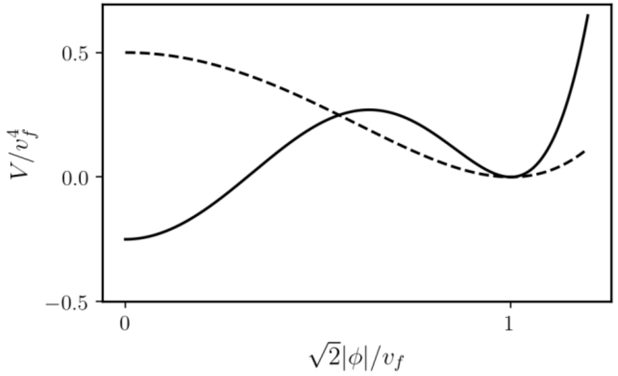
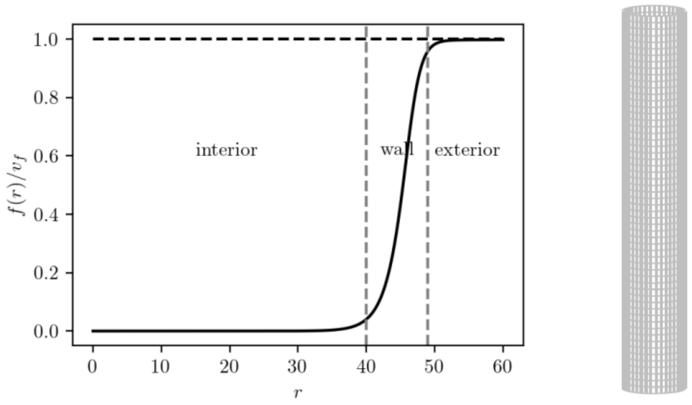


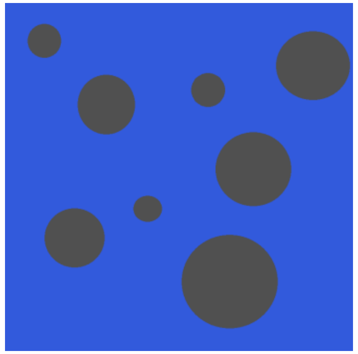
Supports "metastable" cosmic strings

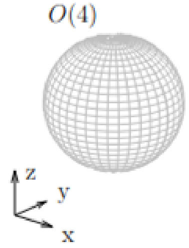
$$\phi(x) = \frac{f(r)}{\sqrt{2}} e^{i\theta n} \qquad r = \sqrt{x^2 + y^2} \qquad f(r \to \infty) = v_f$$



Competing decay channels

Nucleation of **spherical** bubbles in the **bulk**





Gravitational waves radiated during bubble collisions

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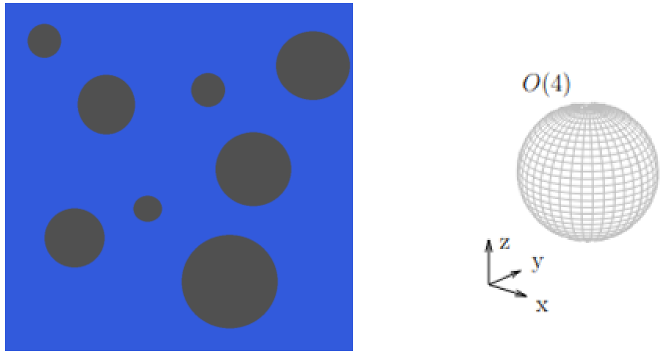
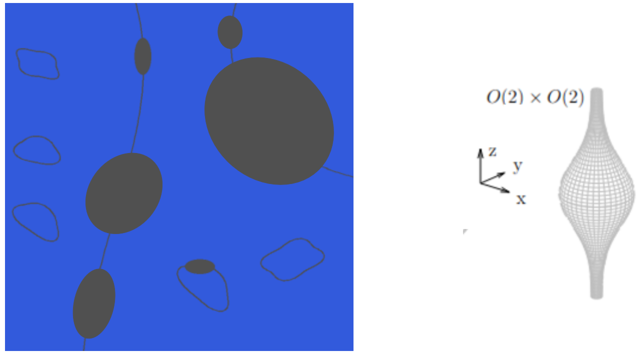


Gravitational waves radiated during bubble collisions

Nucleation of **elongated** bubbles **on top of strings**



Reduced bounce symmetry **in the presence of a string**

$$\underbrace{O(4)}_{\rho} \xrightarrow[\text{string}]{} \underbrace{O(2)}_{\varrho} \times \underbrace{O(2)}_{r} \qquad \varrho = \sqrt{z^2 + \tau^2}$$

Gravitational waves radiated from

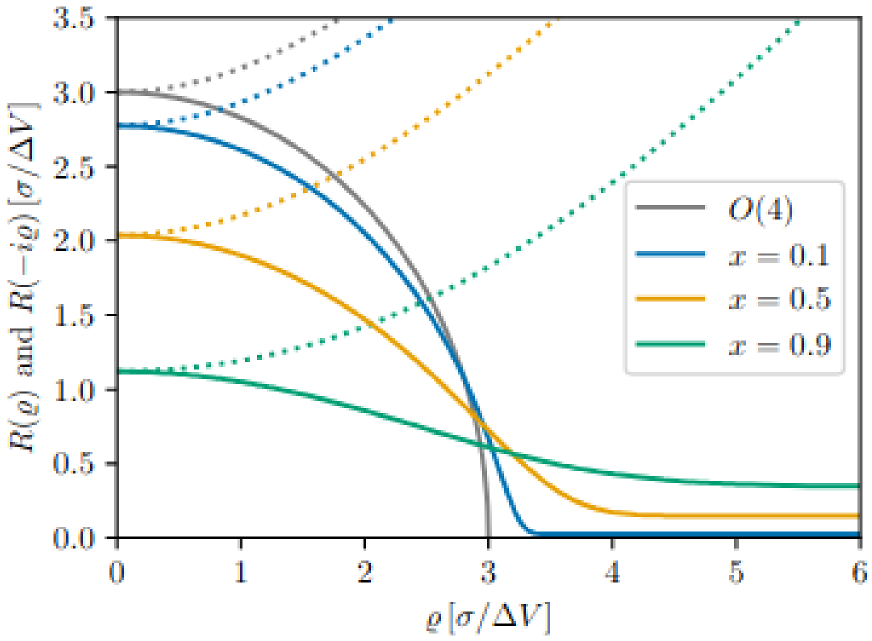
- bubble collisions,
- individual bubbles,
- metastable string network

The bounce in the thin-wall limit

- Euclidean action (global string) takes the form

$$S_E = 2\pi \int \varrho \, d\varrho \Big[-\underbrace{\pi R^2(\varrho)\Delta V}_{\text{interior}} + \underbrace{2\pi\, R(\varrho)\sigma\, \gamma^{-1}(\varrho)}_{\text{wall}} + \underbrace{\pi\, n^2 v_f^2 \ln\Big(\frac{R_{\max}}{R(\varrho)}\Big)}_{\text{exterior}} \Big]$$

- The bounce can be found numerically (using shooting) and describes 1d tunneling.

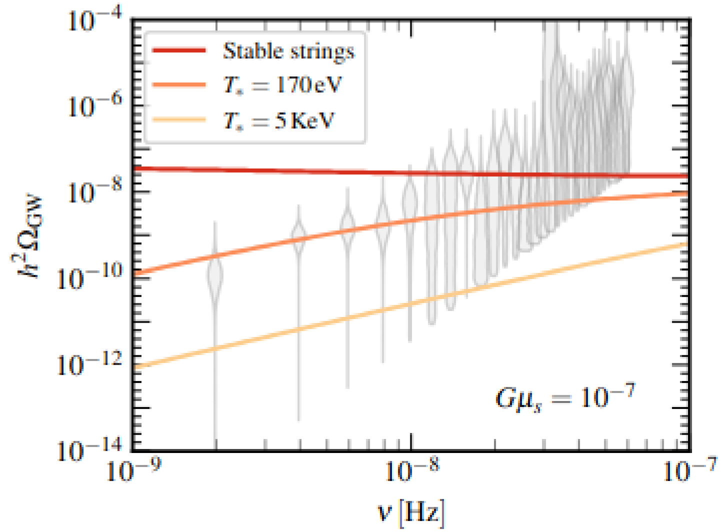


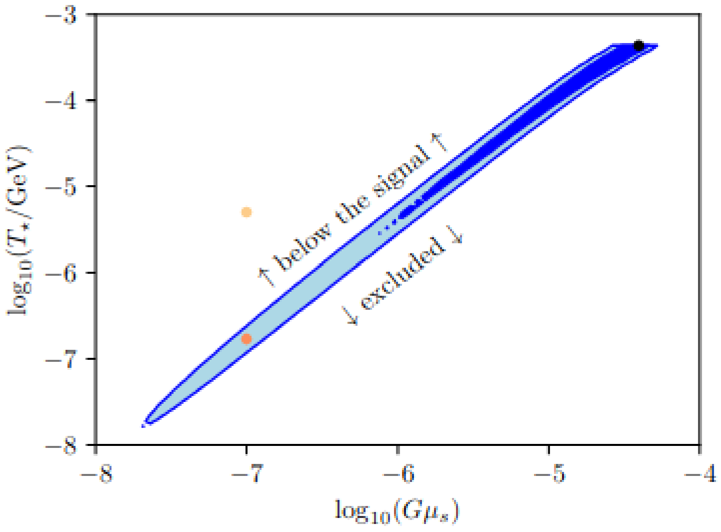
Decaying (metastable) string network and the NANOGrav signal

Metastable cosmic strings provide a **better fit** to the NANOGrav 15-year data compared to stable strings.

Weaker bounds on the string tension

Connection to **a post-BBN** phase transition.





Late time transitions and the Hubble tension

Direct (local) measurements

$$H_0 = 73.04 \pm 1.04 \ \mathrm{km\ s^{-1} Mpc^{-1}}$$

Riess et. al. 2022

Indirect measurements (based on ΛCDM):

$$H_0 = 67.36 \pm 0.54 \ \mathrm{km\, s^{-1} Mpc^{-1}}$$

Aghanim et. al. 2018

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Riess et. al. 2022	Aghanim et. al. 2018

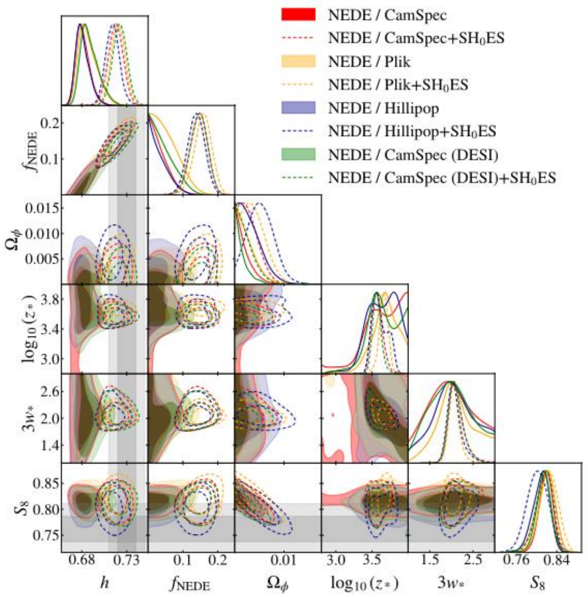
- Latent heat from the phase transition can alleviate the tension by lowering the sound horizon in the CMB
  - New early dark energy

Niedermann, Sloth 2021

$$r_s = \int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)}$$

sound speed

redshift of recombination



2408.14537

Thank you for your attention!

A concrete realization

- Two coupled scalars

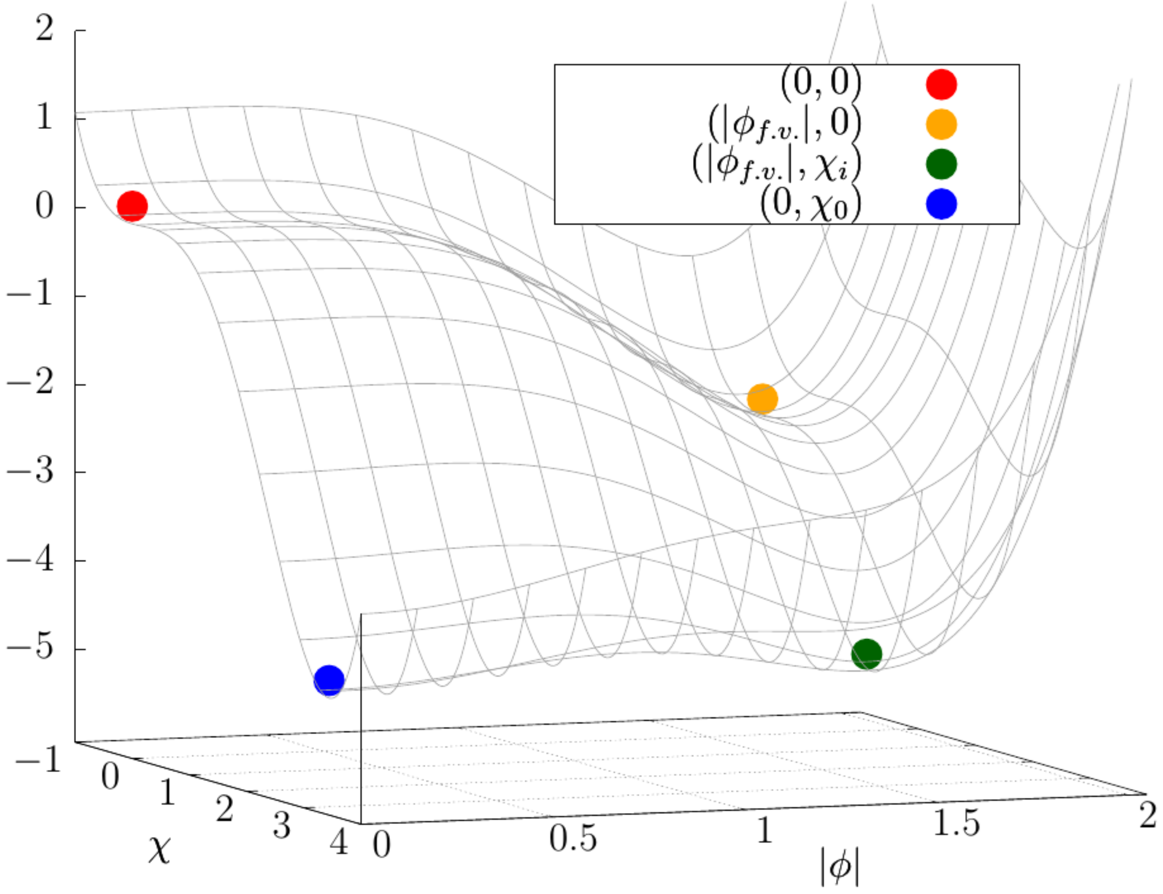
$$V(\phi,\chi) = V_\phi(\phi) + V_\chi(\chi) + V_{\text{int}}(\phi,\chi)$$

$$V_\chi(\chi) = \frac{m^2}{2}\chi^2 - \frac{\lambda_3}{3}\chi^3 + \frac{\lambda_\chi}{4}\chi^4 ,$$

$$V_\phi(\phi) = -\mu^2|\phi|^2 - \lambda|\phi|^4 + \lambda_6|\phi|^6 .$$

$$V_{\text{int}}(\phi,\chi) = (\xi\,\chi^2 - \eta\,\chi)|\phi|^2 ,$$

$$\begin{array}{ccc} (0,0) & \xrightarrow{\text{strings form}} & (|\phi_{\text{f.v.}}|, 0) \\ \not\downarrow \text{blocked} & & \downarrow \text{roll-over} \\ (0,\chi_0) & \xleftarrow{\text{string-induced decay}} & (|\phi_{\text{f.v.}}|, \chi_i) \end{array}$$

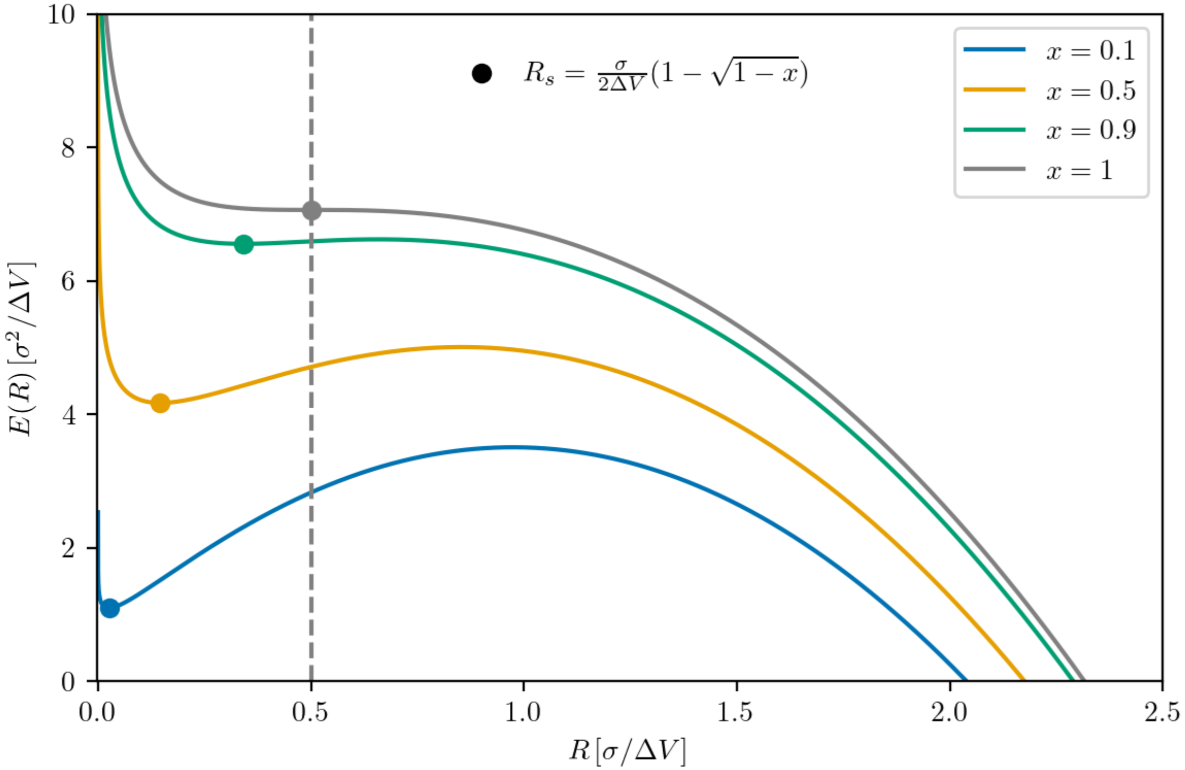


Global string in the thin-wall limit

- String radius can be found by minimizing its energy per length

$$\frac{E(R)}{L} = -\underbrace{\pi R^2 \Delta V}_{\text{interior}} + \underbrace{2\pi R\sigma}_{\text{wall}} + \underbrace{\pi\, n^2 v_f^2 \ln\left(\frac{R_{\max}}{R}\right)}_{\text{exterior}}$$

Lee et. al., 2013



- Metastable strings exist for $0 < x < 1$

- where $R_s = \dfrac{\sigma}{2\Delta V}(1 - \sqrt{1-x})$

$$x = \frac{2n^2 v_f^2 \Delta V}{\sigma^2}$$

Homogeneous vs string-induced vacuum decay

- The bounce is a classical solution in Euclidean time, with appropriate boundary conditions.

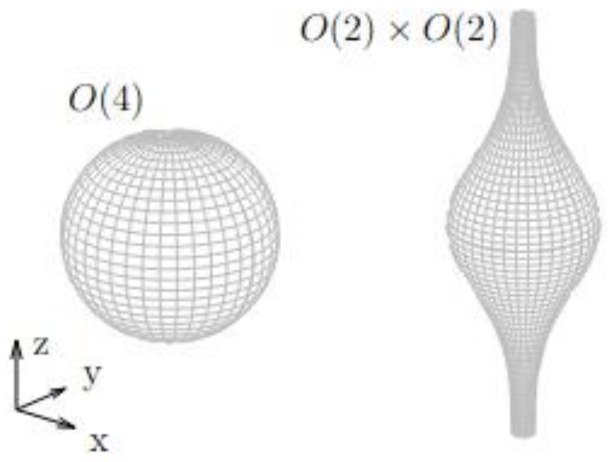
- **In the absence of strings**, eom admit an O(4)-symmetric bounce $\phi_{\rm b}(\rho)$

$$\rho = \sqrt{x^2 + y^2 + z^2 + \tau^2}$$

- Reduced bounce symmetry **in the presence of a string**

$$\underbrace{O(4)}_{\rho} \xrightarrow[\text{string}]{} \underbrace{O(2)}_{\varrho} \times \underbrace{O(2)}_{r}$$

$$\varrho = \sqrt{z^2 + \tau^2} \qquad r = \sqrt{x^2 + y^2}$$

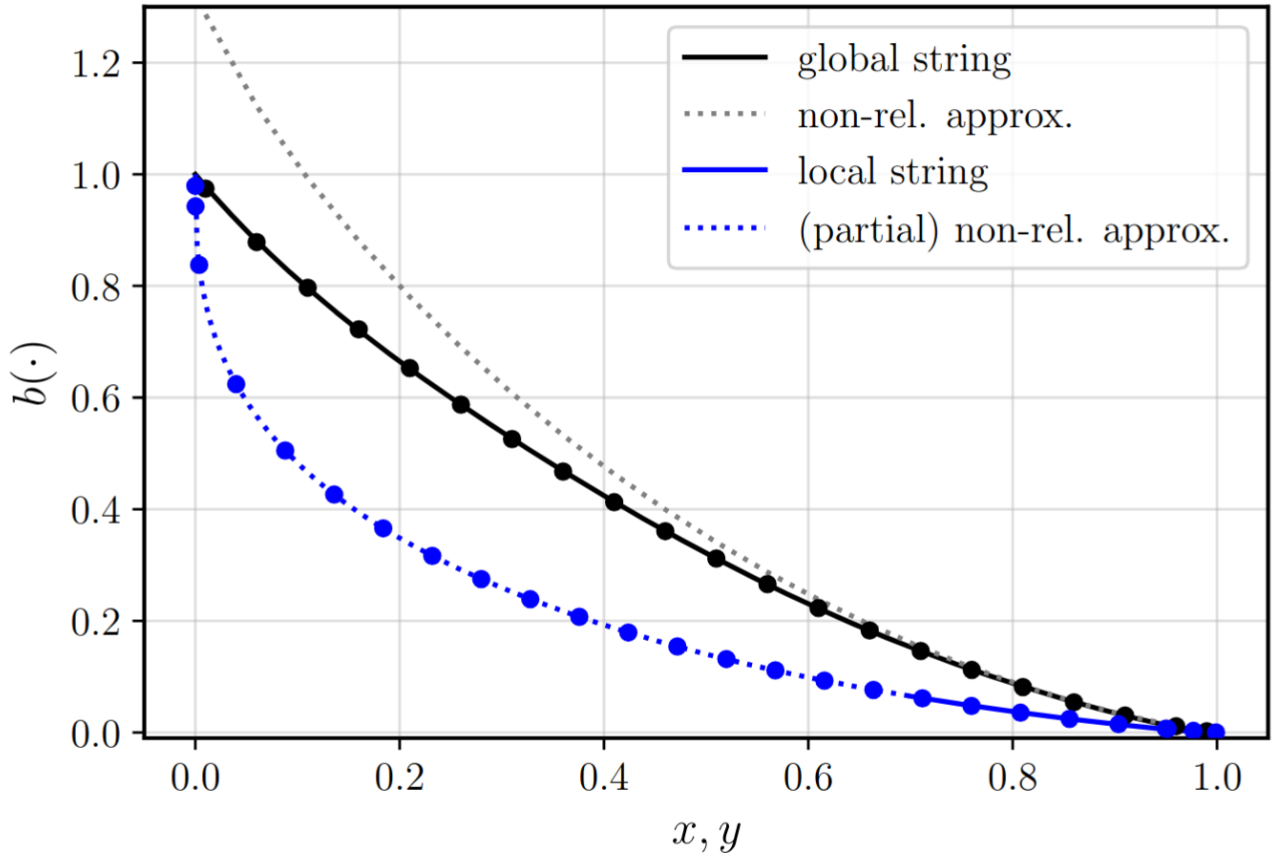


Dasgupta, 1997

The bounce action

The bounce action determines the leading contribution to the false vacuum decay rate

$$b = B/B_0 \qquad B = S_E[\phi_{\rm b}] - S_E[\phi_{\rm f.v.}]\,, \qquad \Gamma \propto e^{-B}$$



For global strings

$$x = \frac{2n^2 v_f^2 \Delta V}{\sigma^2}$$

For local strings

$$y = \left(\frac{8}{3}\right)^3 \frac{n^2 \Delta V^3}{g^2 \sigma^4}$$

Efficiency of the string-induced decay channel

- Including also the **prefactor**, we find that the string-induced decay channel dominates over the homogeneous one if

$$0.4 \lesssim x \leq 1\,, \quad \text{and} \quad 0.1 \lesssim y \leq 1$$

This follows by comparing the **percolation times**,

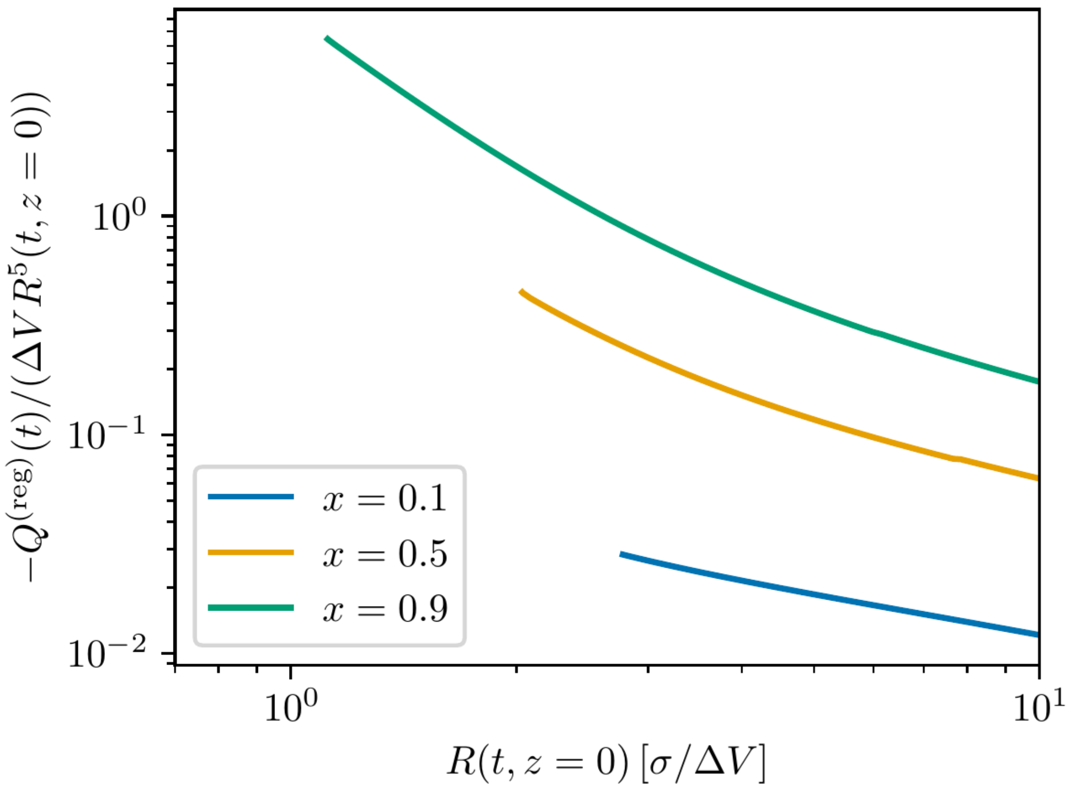
$$H^4 \sim \frac{\Gamma}{V}$$

and assuming approximately **one Hubble-sized string per Hubble patch**.

GWs from bubble collisions vs nonspherical bubbles

- Peak frequency of GWs is set by inverse duration of the transition: $\nu_\star \sim \beta$

- Quadrupole moment:
- Bubble collisions: $Q(R) \sim R^5 \times \Delta V$
- Nonspherical bubbles: computed from our numerical solutions



Even initially very nonspherical, the bubbles become **more spherical** as they expand

Gravitational wave spectrum from the string network

- Stable (local) strings network in the scaling regime:

$$\Omega_{\mathrm{GW},0}(\nu) = G\mu_s^2 \frac{1}{\rho_0} \sum_k \Gamma^{(k)} \left(\frac{2k}{\nu}\right) \int_{t_{\mathrm{SSB}}}^{t_0} dt \left(\frac{a(t)}{a_0}\right)^5 n_{\mathrm{loop}}\left(\frac{2k}{\nu}\frac{a(t)}{a_0}, t\right)$$

where $n_{\mathrm{loop}}(l,t)$ is the number density of string loops

e.g. Servant et al, 2019

- Metastable strings:
  - No loops after the transition, $n_{\mathrm{loop}}(l,t) = 0 \text{ for } t > t_\star.$
  - GW spectrum suppressed at small frequencies