Title: Holographic phase transitions via thermally-assisted tunneling

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Collection/Series: Cosmological Frontiers in Fundamental Physics 2026

Subject: Cosmology

Date: April 28, 2026 - 6:40 PM

URL: https://pirsa.org/26040121

Abstract:

We construct the thermal bounce solution in holographic models that describes first-order phase transitions between the deconfined and confined phases in strongly-coupled gauge theories. This new, periodic Euclidean solution represents transitions that occur via thermally-assisted tunneling and interpolates between the O(4)-symmetric vacuum bubble at zero temperature and the high temperature O(3)-symmetric critical bubble associated with classical thermal fluctuations. The exact thermal bounce solution can be used to obtain the bounce action at low temperatures which allows for a more accurate determination of vacuum decay rates, significantly improving previous estimates in holographic models. In particular, provided the phase transition is sufficiently supercooled, new predictions are obtained for the gravitational wave signal strength for critical temperatures ranging from the TeV scale up to 10^{12} GeV, some of which are within reach of future gravitational wave detectors.

Holographic Phase Transition via thermally-assisted Tunneling

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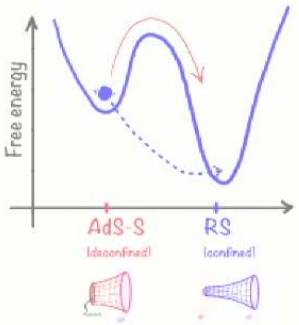

based on arXiv:2504.12437 with Tony Gherghetta & Andrey Shkerin

Cosmological Frontiers in Fundamental Physics 2026

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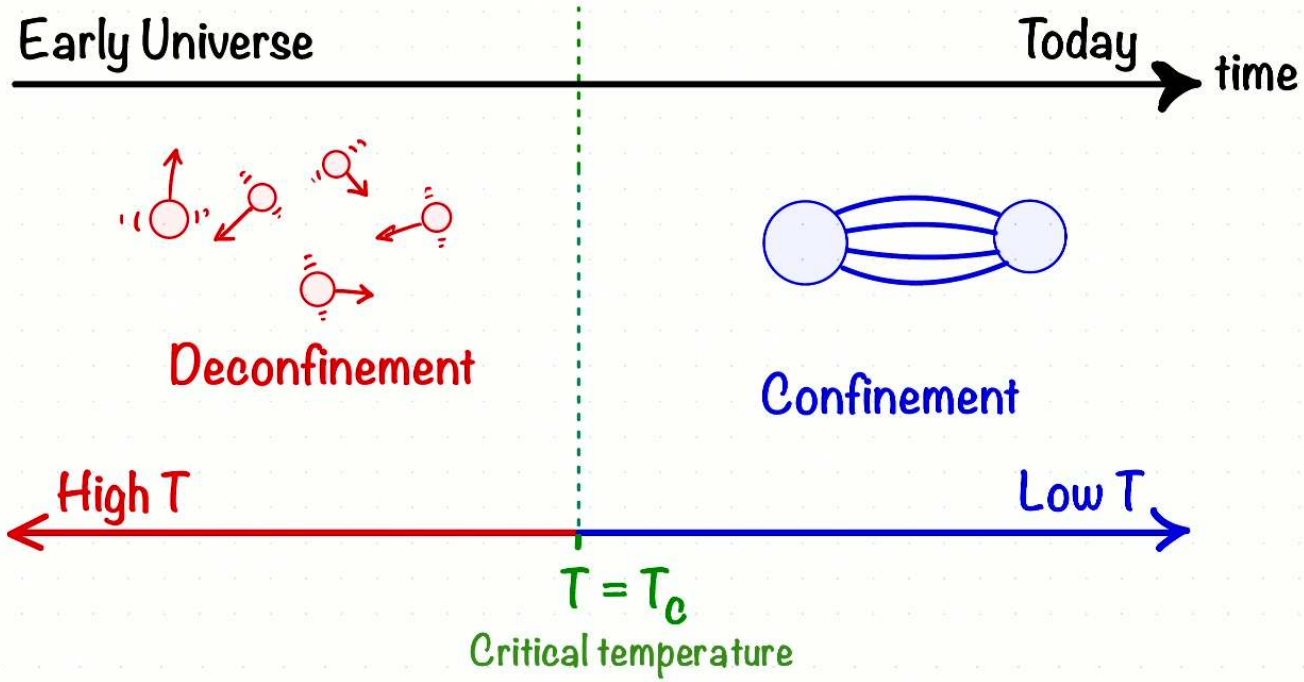
arXiv:2504.12437

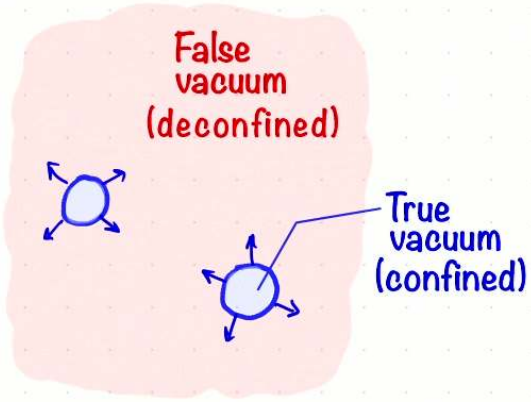
Phase Transition in Strongly-coupled Gauge theory

- Strongly coupled sector in BSM physics
- To address open problems:
  - Strong CP problem
  - Neutrino mass
  - Dark matter
- Composite -
  - axion
  - RH neutrino
  - Higgs



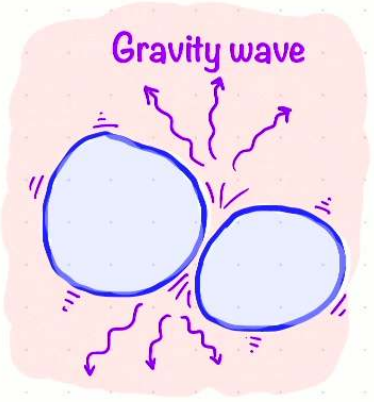
arXiv:2504.12437

$T > T_c$



$T = T_n < T_c$

Bubble nucleation

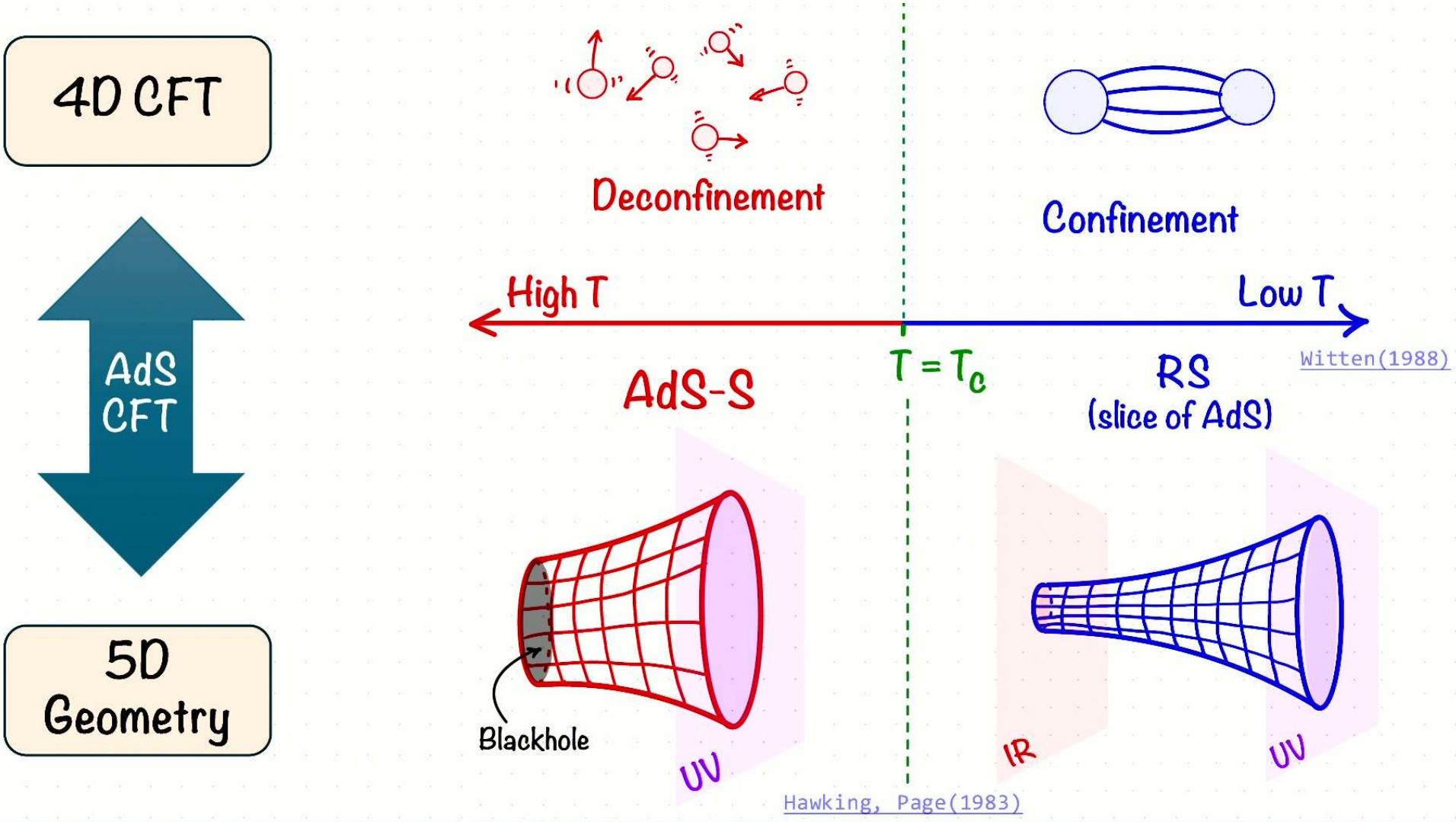


$T = T_* \simeq T_c$

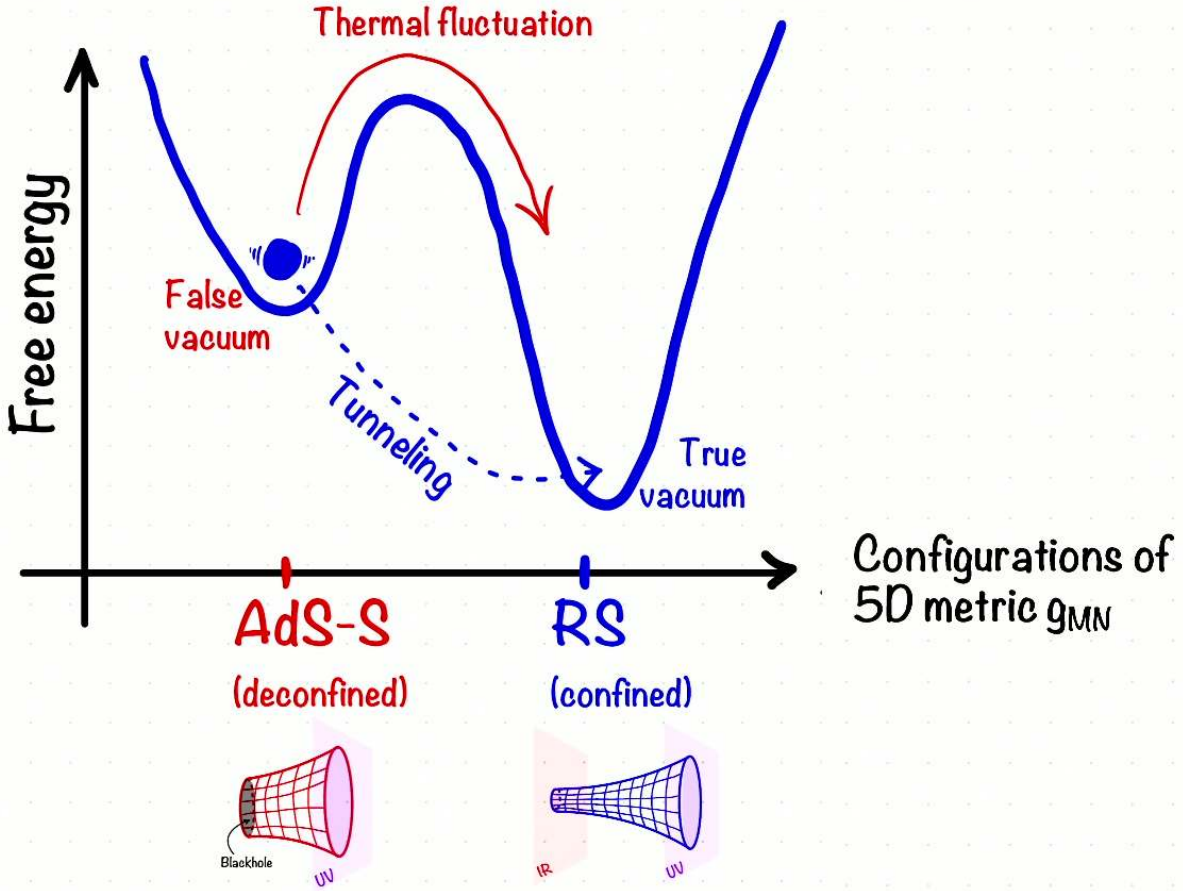
Bubble collision

Release of bubble wall energy

This work:
- dominant channel of bubble nucleation?
- thermally-assisted tunneling?

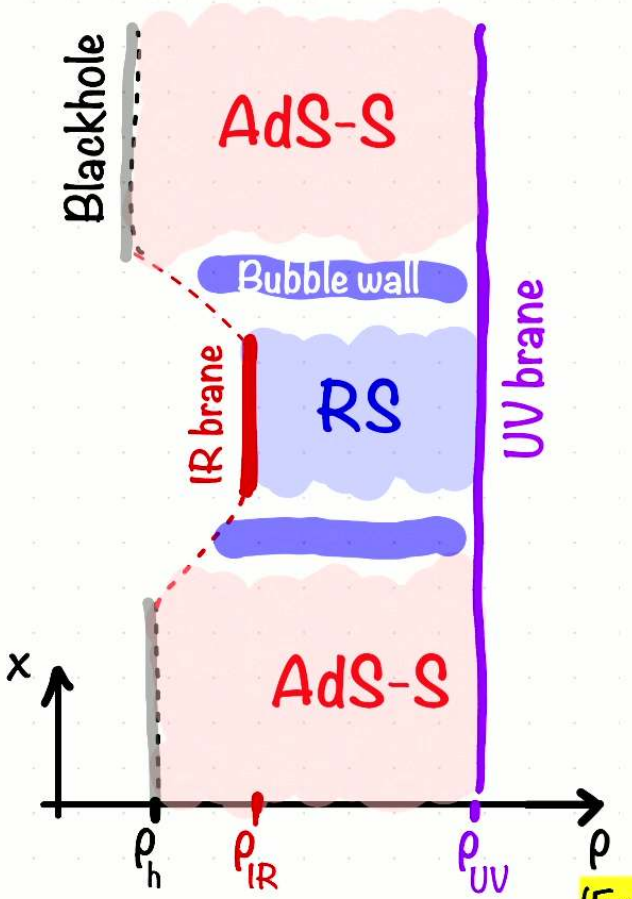

4D CFT
AdS
CFT
5D
Geometry
Deconfinement
Confinement
High T
Low T
T = Tc
AdS-S
RS
(slice of AdS)
Witten(1988)
Blackhole
UV
IR
UV
Hawking, Page(1983)

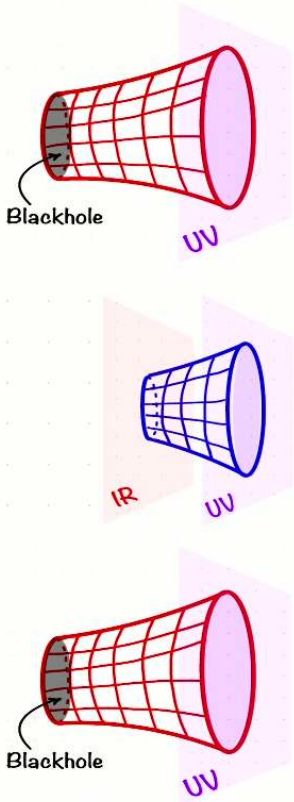
- Below T_c :


Thermal fluctuation
Free energy
False vacuum
Tunneling
True vacuum
Configurations of 5D metric g_{MN}
AdS-S
(deconfined)
RS
(confined)
Blackhole
UV
IR
UV

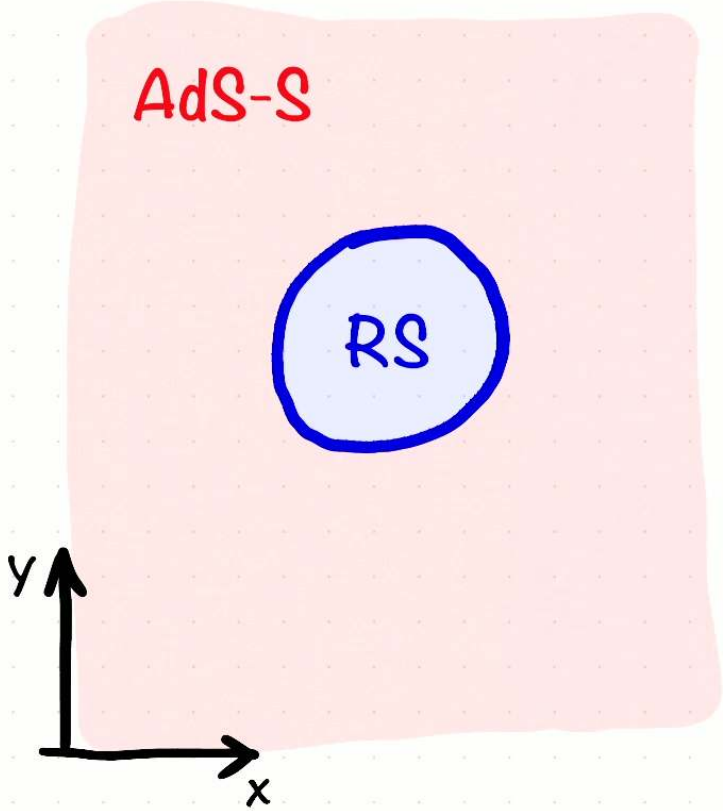
Bubble nucleation in 5D

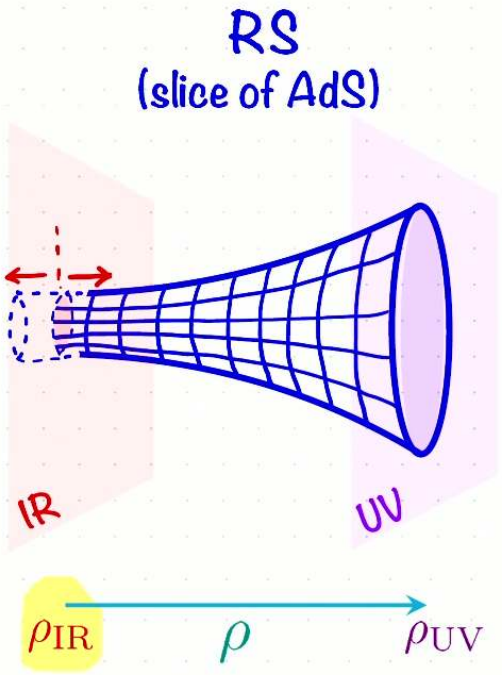
Creminelli, Nicolis, Rattazzi(2002)





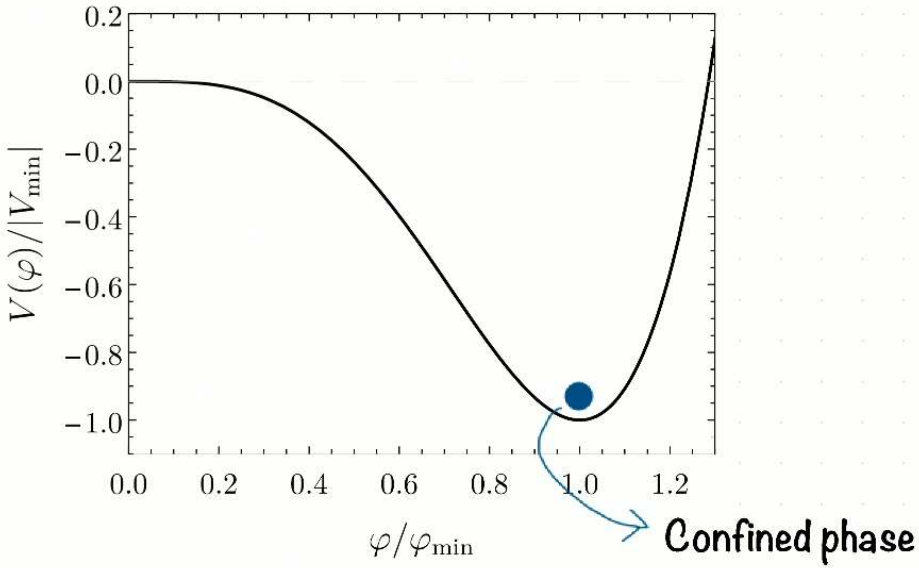
(Extra dimension)



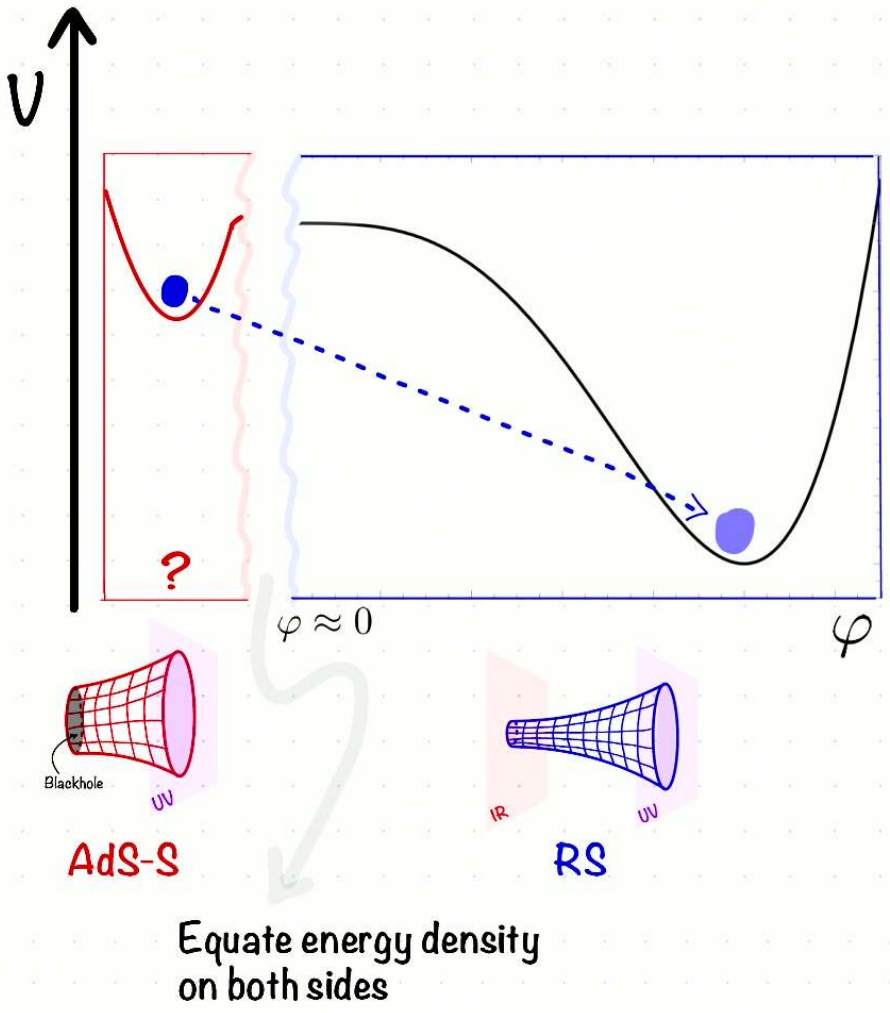


- 4D effective action for the radion $\varphi\,(t, \vec{x})$:

$$S_\varphi \sim \int d^4x\sqrt{g}\left(-\frac{1}{2}(\partial\varphi)^2 - V(\varphi)\right)$$



- Make $\rho_{\rm IR}$ dynamical $\Rightarrow$ radion $\varphi\,(t, \vec{x})$
- $\varphi\,(t, \vec{x})$ ~ location of IR brane along the extra dimension



Equate energy density on both sides

- Euclidean equation of motion of $\varphi(\tau, r)$

$$\partial_\tau^2 \varphi + \partial_r^2 \varphi + \frac{2}{r}\partial_r \varphi - V'(\varphi) = 0 \,.$$

- Regularity at the origin:

$$\partial_r \varphi|_{r=0} = 0 \,.$$

- $1/T$ periodic in Euclidean time τ

- Equate energy density on both sides :

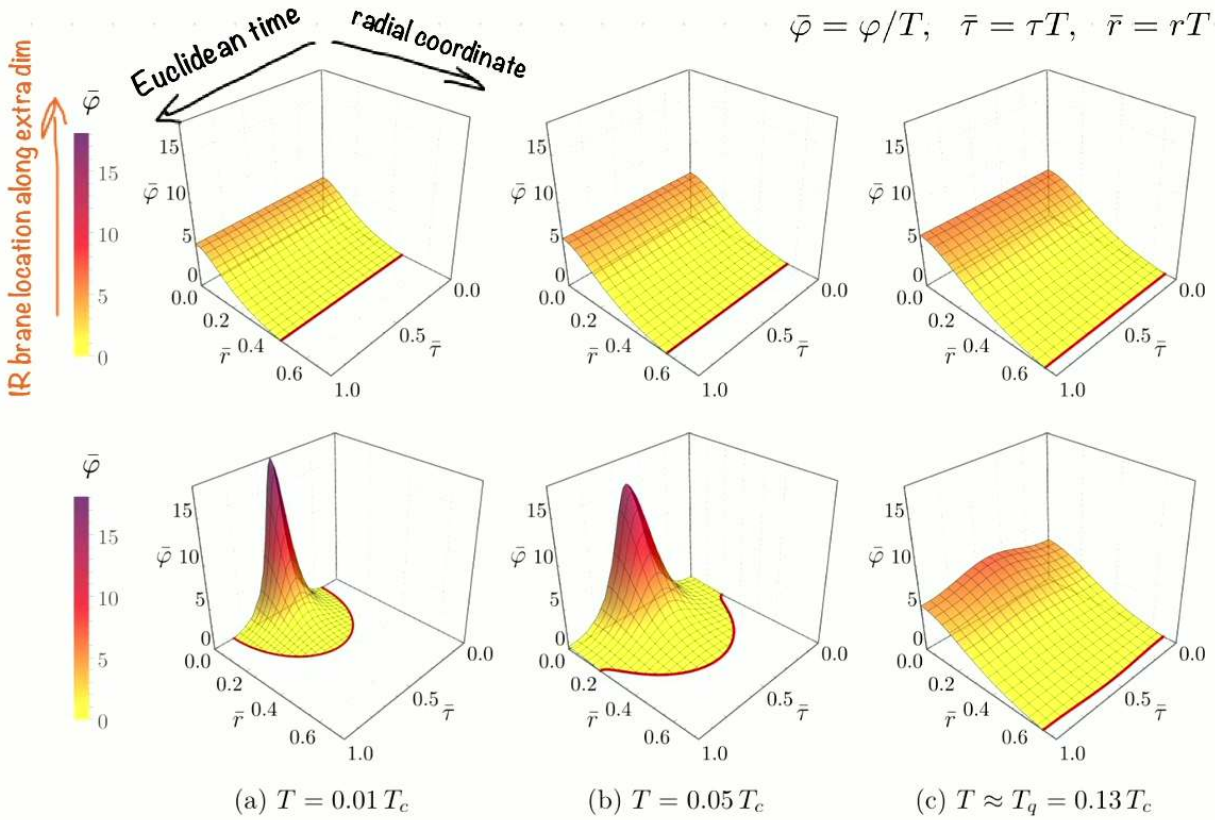
$$\left[(\partial_\tau \varphi)^2 + (\partial_r \varphi)^2\right]_{\varphi \approx 0} = \frac{\pi^4}{6} T^4 \,.$$

- Solve the equation of motion:

$$\partial_\tau^2\varphi + \partial_r^2\varphi + \frac{2}{r}\partial_r\varphi - V'(\varphi) = 0$$

- under the boundary conditions:

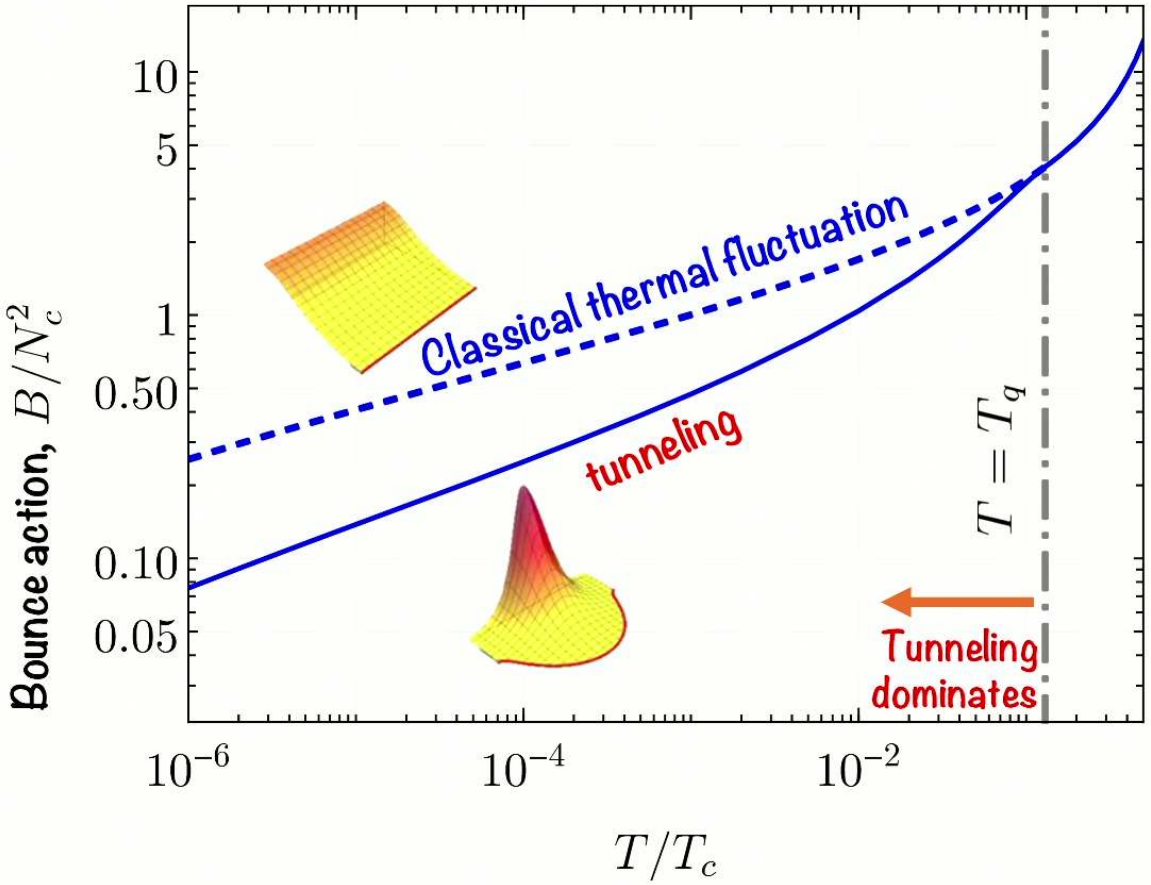
$$\begin{cases} \partial_r\varphi|_{r=0} = 0\,. \\ \varphi(\tau, r) = \varphi(\tau + 1/T, r) \\ \left[(\partial_\tau\varphi)^2 + (\partial_r\varphi)^2\right]_{\varphi\approx 0} = \dfrac{\pi^4}{6}T^4\,. \end{cases}$$



(a) $T = 0.01\,T_c$ (b) $T = 0.05\,T_c$ (c) $T \approx T_q = 0.13\,T_c$

- τ–independent solution (O(3) symmetric) ⇒ classical thermal fluctuation (top row)
- τ–dependent solution ⇒ quantum tunneling (bottom row)
- At very low temperature ⇒ O(4) symmetric

Compare action : thermal fluctuation VS tunneling



nucleation rate,

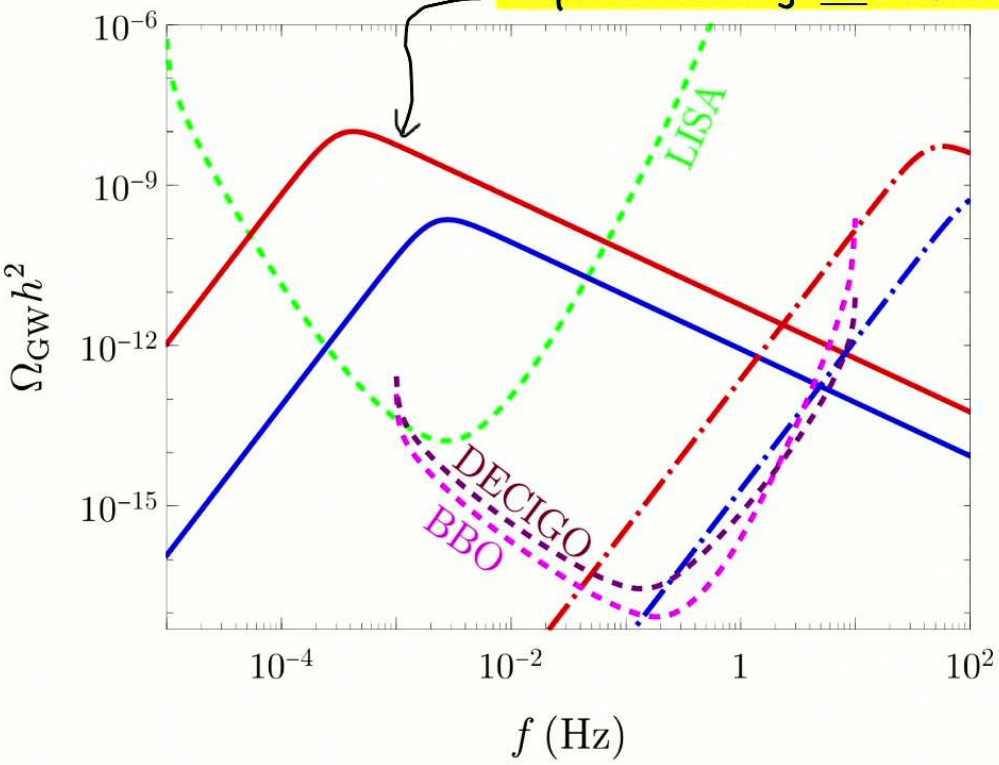
$$\Gamma(T) = A(T)\mathrm{e}^{-B(T)}$$

T_q ⇒ Classical-to-quantum transition temperature

$N_c \to$ No. of colors of the gauge theory

Gravitational Wave Signal – Dominated by Tunneling

Requires tunneling. No bubble nucleation from O(3) symm. solution



No. of colors, radion mass squared (in units of KK scale)

N_c, m_φ^2

6 , 0.1 — $T_c = \text{TeV}$

6 , 0.9 — $T_c = \text{TeV}$

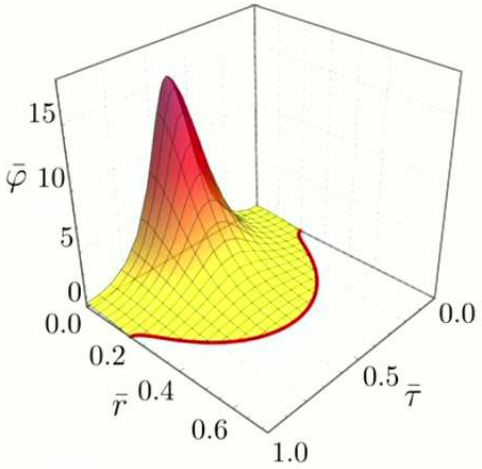
3 , 0.1 — $T_c = 10^8\text{GeV}$

6 , 0.9 — $T_c = 10^8\text{GeV}$

Fig: The abundance of the stochastic GWs as a function of frequency due to collisions of bubbles nucleated via thermal tunneling.

Summary

- Previously known limits: the higher temperature $O(3)$ critical bubble, and the zero-temperature limit: $O(4)$ vacuum bubble
- Found a new τ-dependent thermal bounce describing thermally assisted tunneling
- Connects the known $O(3)$ and $O(4)$ symmetric solutions



- Potentially observable gravitational-wave signals for deconfinement-confinement phase transition in BSM physics
- Next Step: the full 5D solution – a gravitational instanton interpolating between the two geometries?