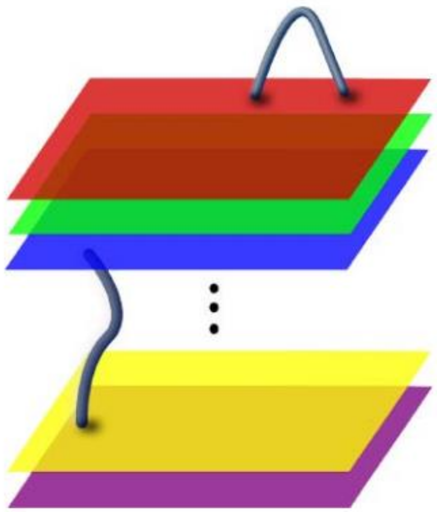

Black brane evaporation through D-brane bubble nucleation

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Based on **1910.06348** (with Carlos Hoyos and Niko Jokela) and **2106.13254**.

(See also 2109.13784 and 2110.14442 – with Fëanor Reuben Ares, Mark Hindmarsh, Carlos Hoyos, Niko Jokela – for more on bubble nucleation and holography!)

Outline

1) A brany black brane instability
2) Interlude: Bubbles!
3) Brane bubble nucleation

Black branes and D-branes

- Black brane solutions in SUGRA sourced by D-branes
- Near-horizon limit → holographic duality

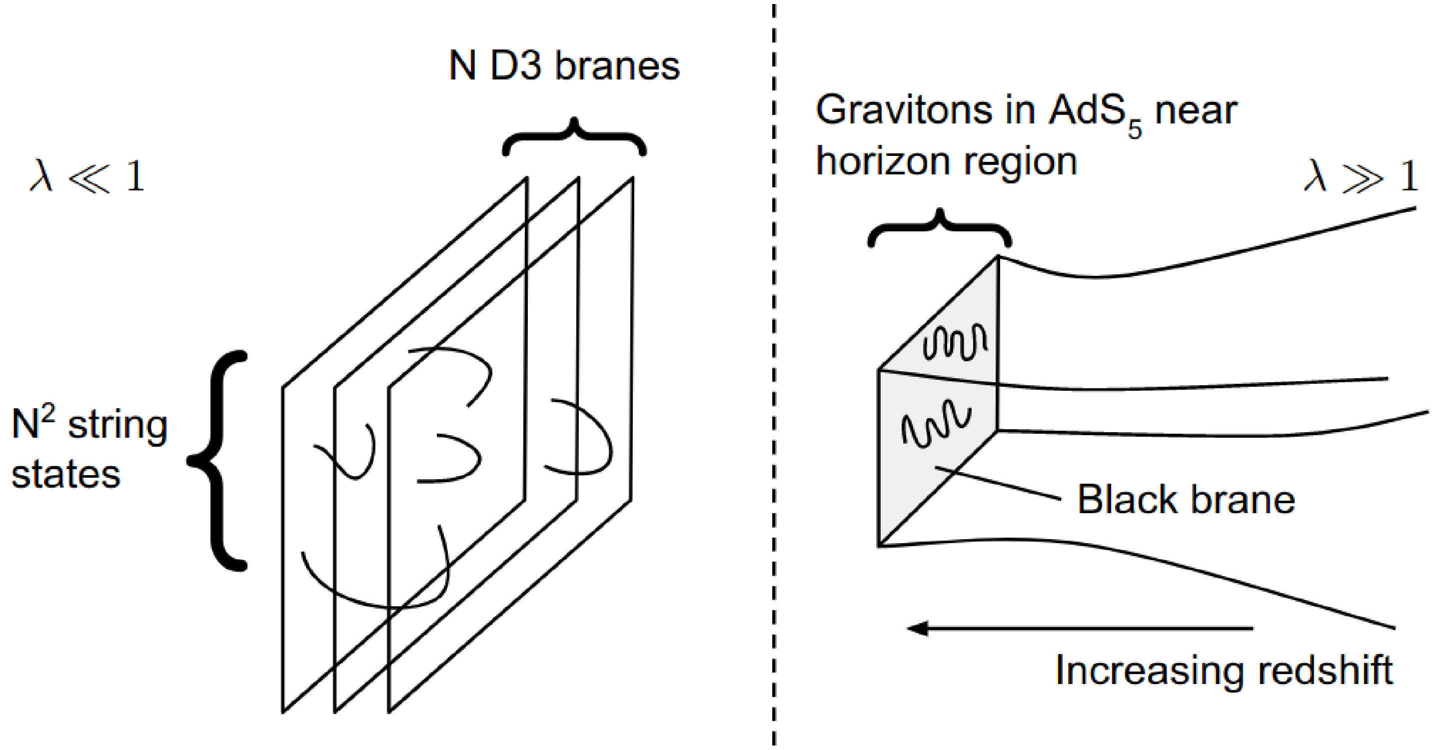


Fig. from Hartnoll et al. (2016)

Example: D3-branes on the conifold

Put D3 stack at **conifold** singularity

Conifold: a cone with base space $T^{1,1}$, metric

$$ds^2_{T^{1,1}} = \frac{1}{6}\sum_{i=1}^{2}\left(d\theta_i^2 + \sin^2\theta_i d\phi_i^2\right) + \frac{1}{9}\left(d\psi + \cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2\right)^2$$

World volume gauge theory is the **Klebanov-Witten** gauge theory

- N=1 SU(N)xSU(N) gauge theory with matter in bifundamental rep.

Has "**baryonic" U(1)** conserved current

Example: D3-branes on the conifold

Herzog et al. (2009) found black brane solutions

- asymptotically $AdS_5 \times T^{1,1}$
- charged under the baryonic U(1)
- seemingly stable...

Dual to KW states at non-zero **temperature** and **chemical potential**

→ Interesting field theory applications!

(Finite density Higgs phases or "color superconductivity"...)

Looking for "brany" instabilities

Black brane solutions typically sourced by D-branes

Dynamics of single brane given by DBI + WZ action, e.g.

$$S_{D3} = -T_3 \int d^4\xi \sqrt{-\det g_4} + T_3 \int \hat{C}_4$$

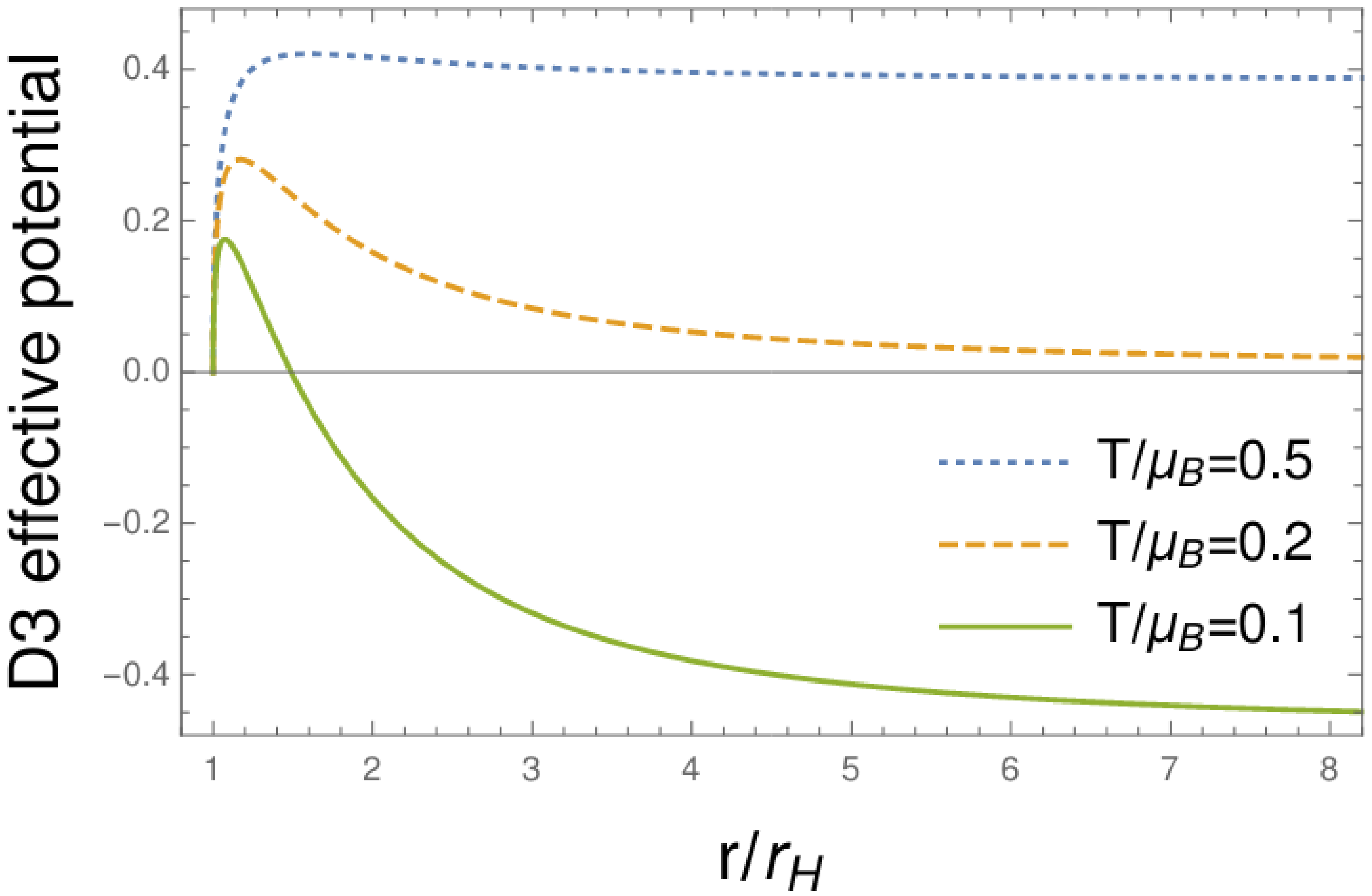
Can use it to derive **effective potential** V(r) for ***probe*** brane in given black brane background

Looking for "brany" instabilities

1. In *pure* $AdS_5 \times T^{1,1}$: **Flat potential** (SUSY moduli space), branes can sit anywhere.
2. Turning on *temperature* → potential monotonically increasing away from horizon – D-branes drawn to black brane – moduli space lifted
3. Adding *charge* adds repulsive force **pushing brane towards boundary**

If global minimum of effective potential is away from horizon, system can lower its energy by ***nucleating*** branes there!

Probe D3 in our black brane solutions



Unstable below critical value of T/μ.

Interlude – Bubbles!

Barrier penetration & bubble nucleation

- Decay of ***false vacuum*** mediated by "fluctuations" (quantum or thermal)
- Studied by Callan, Coleman (1977), at non-zero temperature by Linde
- Transition mediated by Euclidean bubble solution (the "bounce")
- Nucleation rate ~ e^{-S}

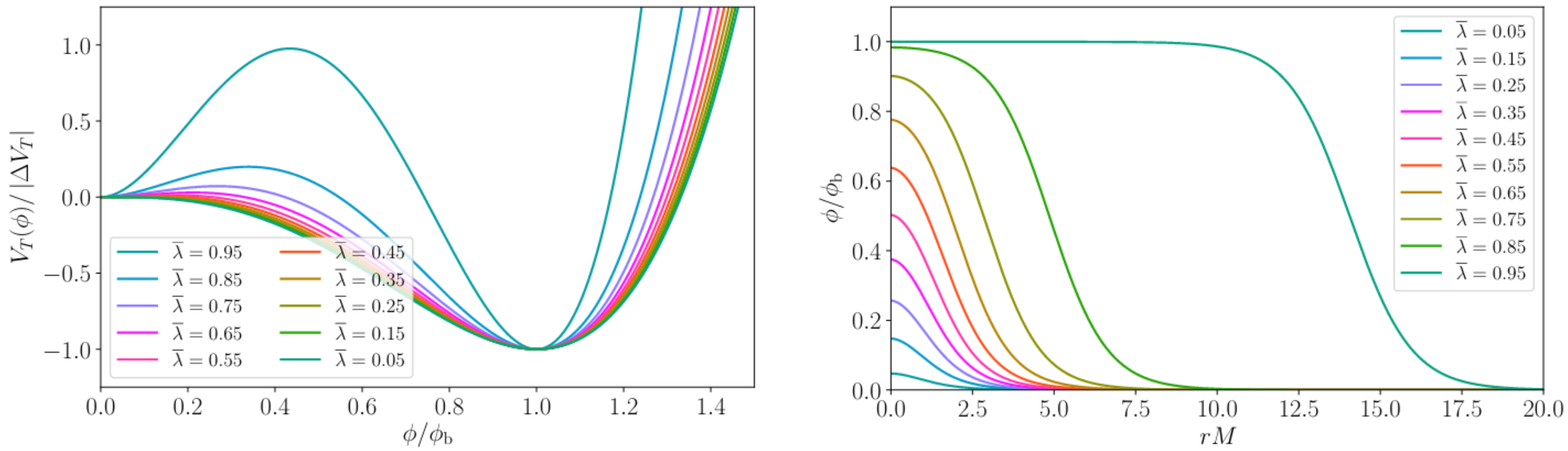
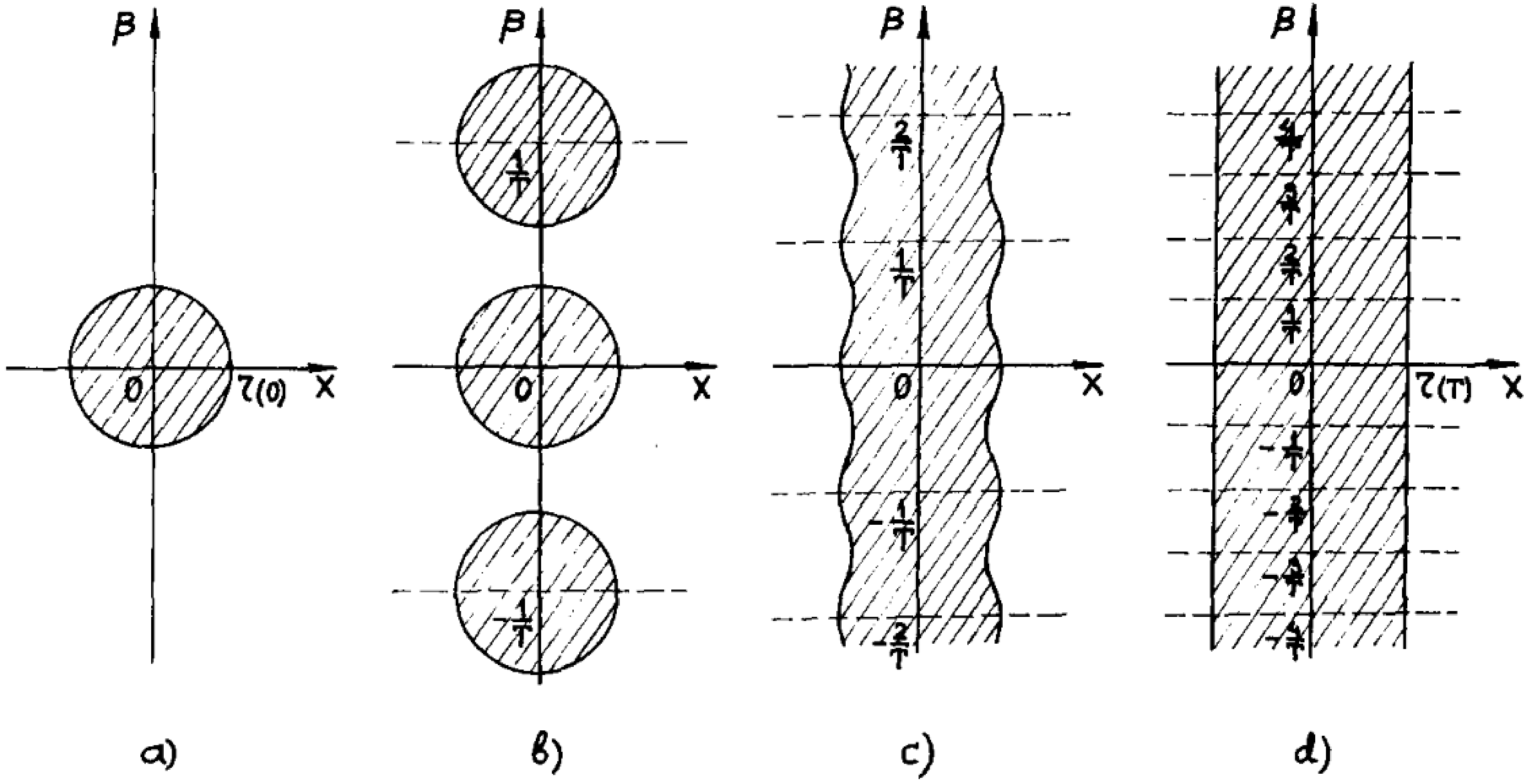


Figure from Hindmarsh et al. (2021)

At non-zero temperature, consider Euclidean periodic time direction! Linde (1980)



Back to our black branes!

Generalize the probe computation

Allow the brane to ***move*** and to ***bend*** in the field theory directions

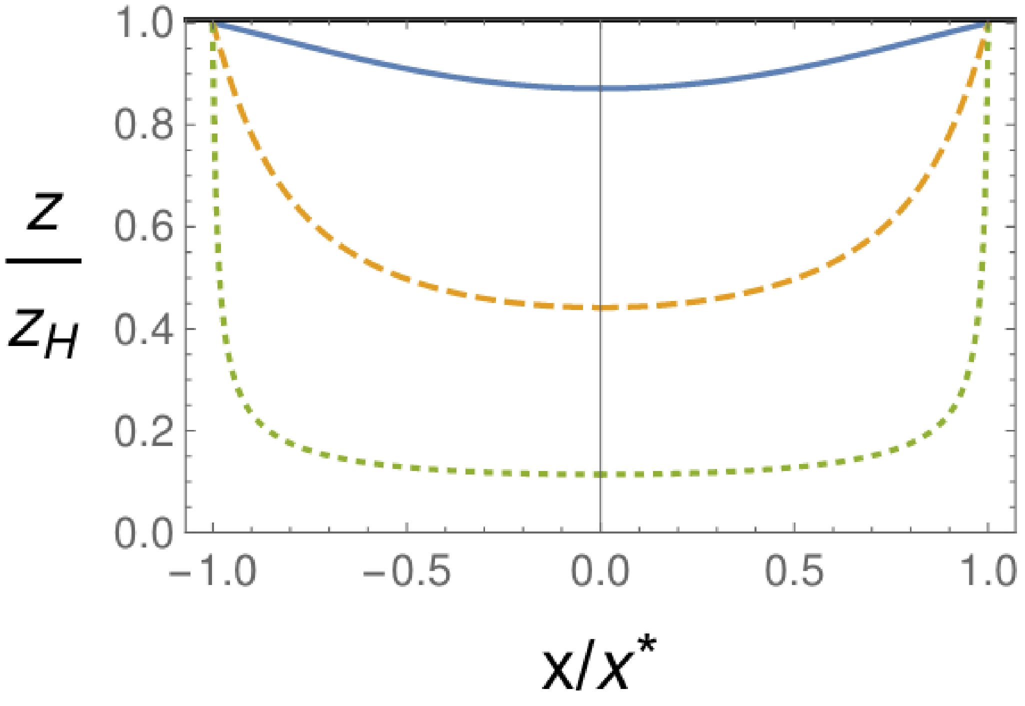
Ansatz $R=R(t,x_i)$

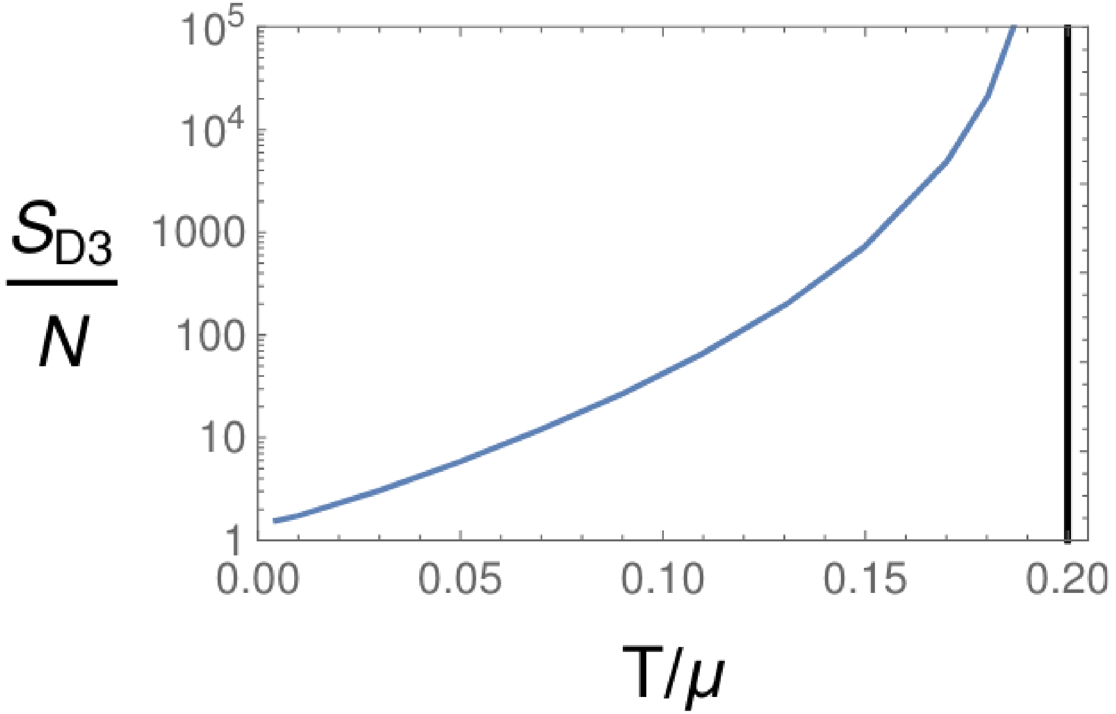
Resulting ***effective action:***

$$S_{D3} = -\frac{27N}{32\pi^2}\int dt\, d\vec{x} \left\{ R^3 e^{-\frac{1}{2}w(R)-\frac{10}{3}\chi(R)} \sqrt{g(R) - \frac{e^{w(R)}}{g(R)}\dot{R}^2 + \frac{1}{R^2}\sum_i (\partial_i R)^2} - a_4(R) \right\}$$

Results: Nucleation!

Look for high-temperature O(3)xO(2)-symmetric solutions: R=R(ρ)





After nucleation: Expansion

Bubbles are accelerated outwards by pressure difference

→ in vacuum, asymptotes towards speed of light

BUT our bubbles are interacting with a charged plasma (in the dual gauge theory)
→ leads to **friction!**

On the gravity side, this is due to interaction with **horizon**

Leads to **late-time steady-state solution**

Late-time steady-state solution

Can approximate wall as planar

Make steady-state ansatz: $$X(t, r) = vt + \xi(r)$$

- Similar to "drag force" computations (Herzog et al. hep-th/0605158 and Gubser hep-th/0605182).
- See also Bigazzi et al. 2104.12817.

Conserved **momentum current** gives differential equation for $\xi(r)$

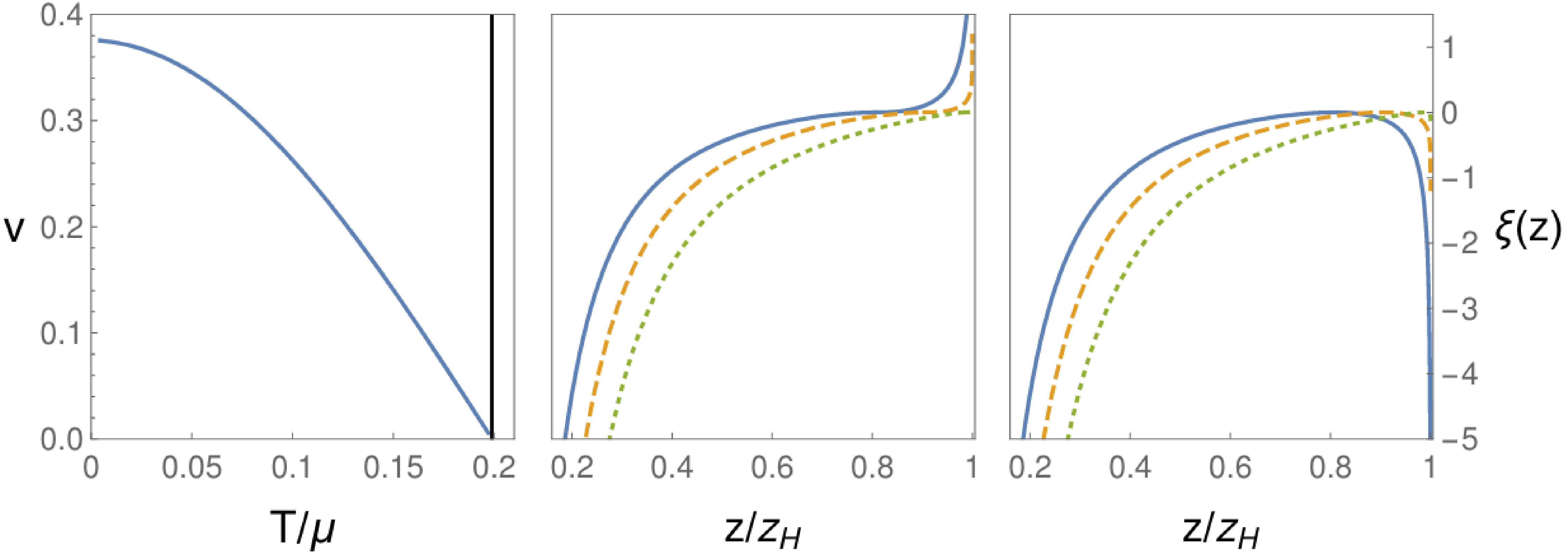
Late-time steady-state solution

Conservation of momentum current gives differential equation for ξ(r):

$$\xi'(r) = \pm \frac{P^r + a_4(r)}{g(r)} \sqrt{\frac{e^{w(r)} v^2 - g(r)/r^2}{[P^r + a_4(r)]^2 - r^6 e^{-w(r) - \frac{20}{3}\chi(r)} g(r)}}$$

1. We expect the brane to asymptote (in center of bubble) to "true vacuum" at AdS boundary → fixes momentum current
2. Denominator inside square root now crosses zero at finite radius. To get ***real*** solution, must **fix speed v** such that numerator crosses zero at same radius.
3. Can then integrate ODE (numerically)

Results: Late-time expansion!



Takeaways

Certain black brane solutions can have "stringy/brany" instabilities

Brane nucleation instabilities allow black branes to evaporate by emitting D-branes

→ Interesting field theory dual; finite-density Higgsing of gauge group

→ Information paradox???

→ Weak gravity conjecture: Extremal black brane shouldn't be stable

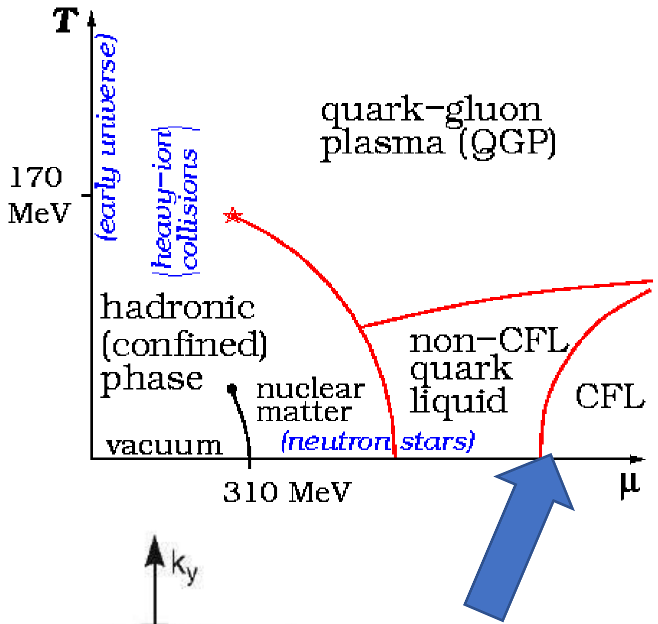
Happens through D-branes **"bubbling off"** the horizon

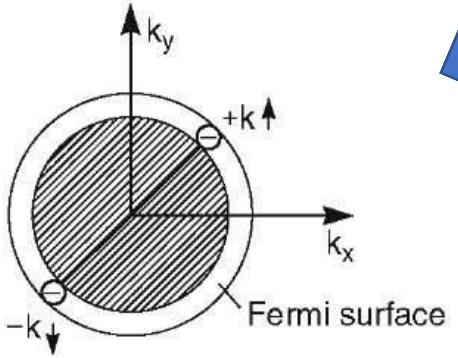
Can be studied in probe limit → nucleation rate, terminal bubble velocity, etc.

Extra slides...

Finite-density gauge theory and color superconductivity

- At **large density** and low temperatures
  - QCD under perturbative control!
- Condensate formed of quarks near Fermi surface
- Breaking of gauge (and global) symmetries, finite density Higgs mechanism
- If our nucleating branes could find (meta)stable minimum at finite radius --> holographic realization of "color superconductor"





Probe D5 on the conifold

- D5 wrapped on S^2 at finite radius acts as domain wall changing rank of **one of the gauge groups**
- Can have quantized **worldvolume flux** on wrapped S^2. This gives D3 charge to D5 ("dissolves" D3's in D5)
- Large enough flux gives instability in same region as for probe D3
- ...BUT minimum now at finite radius!