Holographic Higgs Phases

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Work with...

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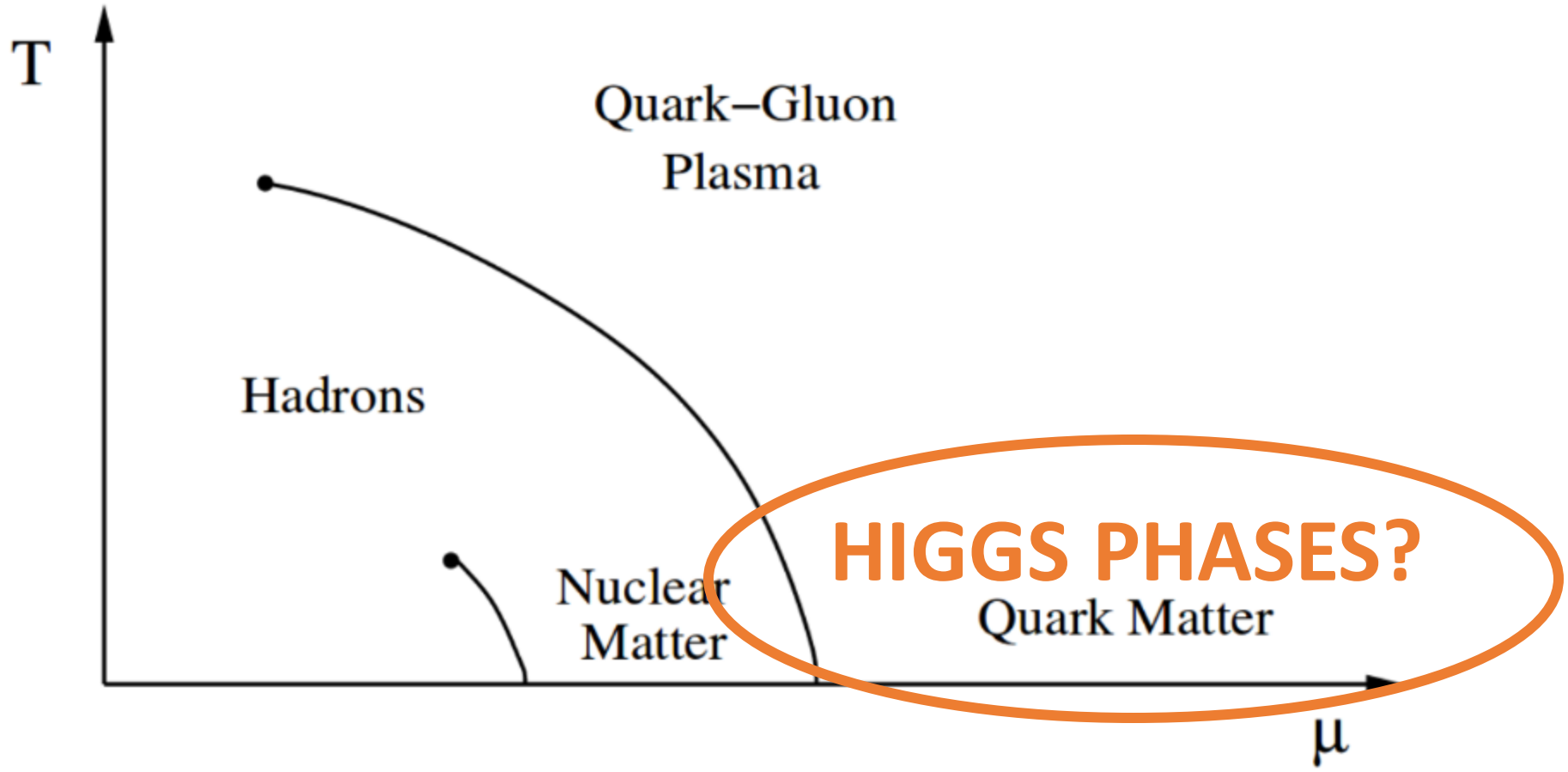
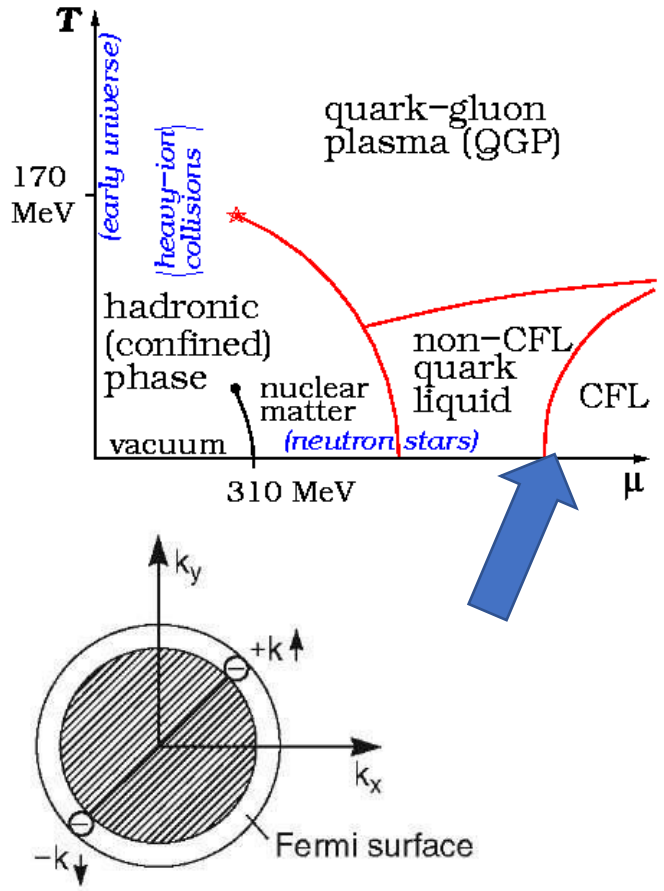
QCD phase diagram



Finite-density gauge theory and color superconductivity

Large density → QCD is under perturbative control!

- Condensate formed of quarks near Fermi surface
- Breaking of gauge and global symmetries, a finite density Higgs mechanism



Higgs phases are important!

Transport!

Thermodynamics?

Higgsing in holography

At zero T, μ — easy to Higgs the theory!

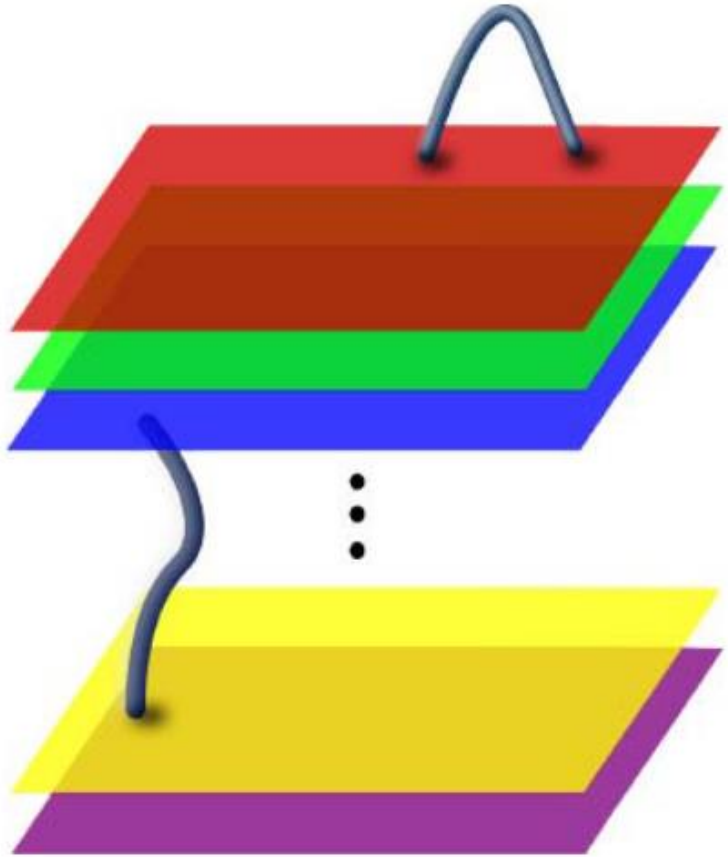
Canonical example: N D3 branes

N coincident branes → SU(N) gauge theory

BUT, **moduli space** (SUSY), can put branes anywhere at zero energy cost…

→ Separating the branes breaks gauge group
(*"Coulomb branch"*)

Can this happen spontaneously?



Coulomb vs. Higgs branch

N=4 SYM has only "Coulomb branch", SU(N) → $U(1)^{N-1}$

Add fundamentals → N=2, can have “qq”-condensates → Higgs branch

- More like QCD
- See e.g., Guralnik et al. (2004-05), Arean et al. (2007), Faedo et al. (2016)

Adding fundamentals → adding “flavor branes”

- Describing breaking of gauge group requires backreaction → hard!

In this talk, **no fundamentals**

- Easier, still theoretically interesting! (E.g., stability of N=4 at finite R-charge)
- *Perhaps* this can lead to insights useful for the Higgs branch, QCD…

Study in holography with **probe branes**

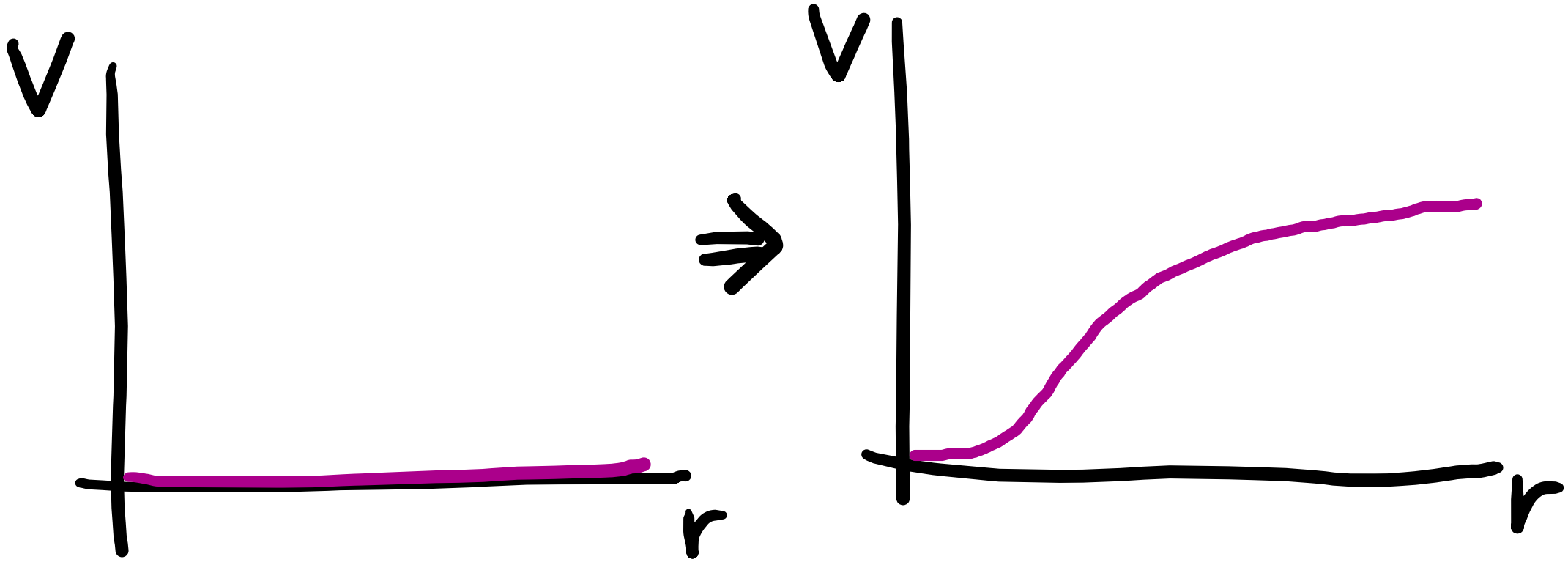
Start with classical geometry sourced by N branes

Take *one* out of N branes, move it around, compute energy as function of position → **effective potential**

With moduli space in vacuum, **flat** potential:

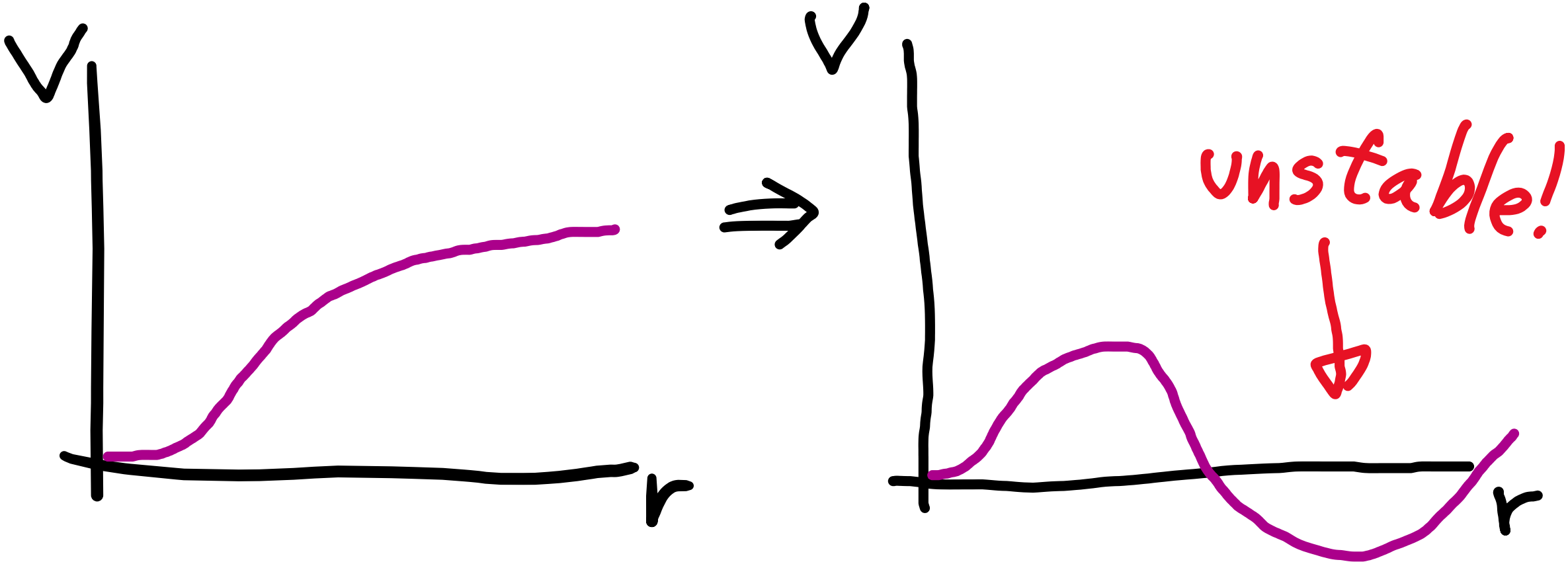
Turn on temperature…

Moduli space lifted → branes want to clump together



Turn on chemical potential…

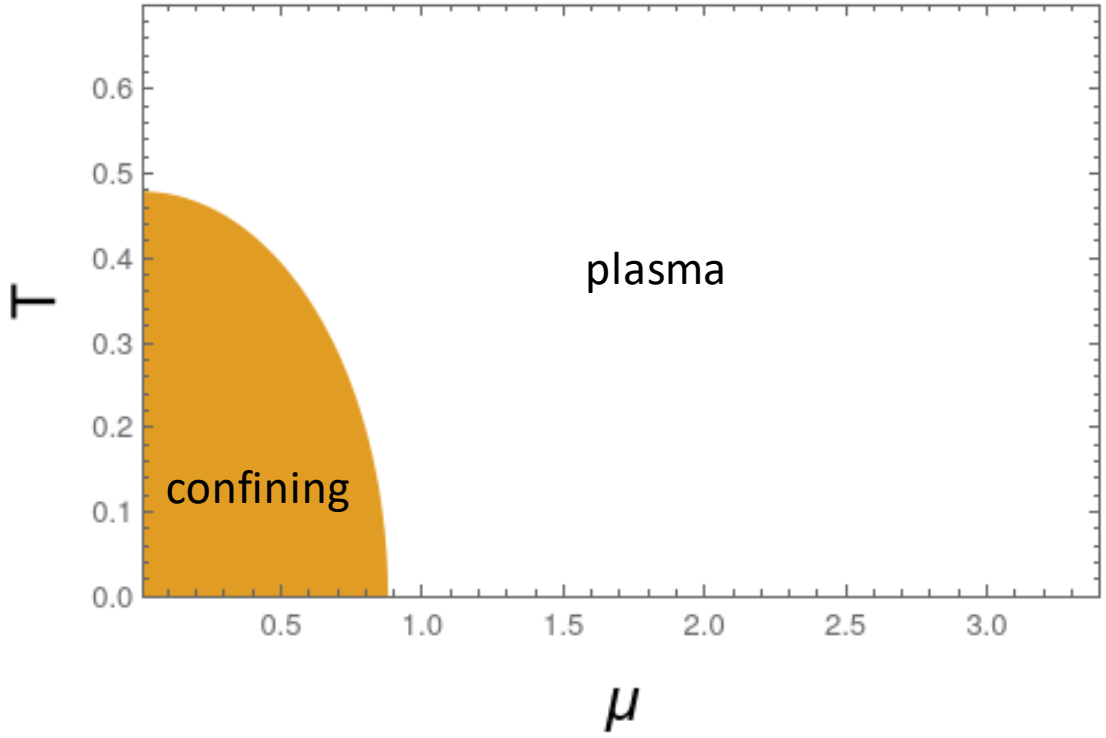
Can cause repulsion of D3 branes!



Example: N=4 SYM on S^3 with finite R-charge

Dual gravity solutions:

1. Spinning black brane (near horizon $AdS_5 \times S^5$ with angular momentum on S^5) – deconfined plasma
2. "Thermal AdS" – confinement



Probe D3 in spinning black brane background

OH, Hoyos, Jokela (2020), Yamada (2008)

Start from standard DBI+WZ action…

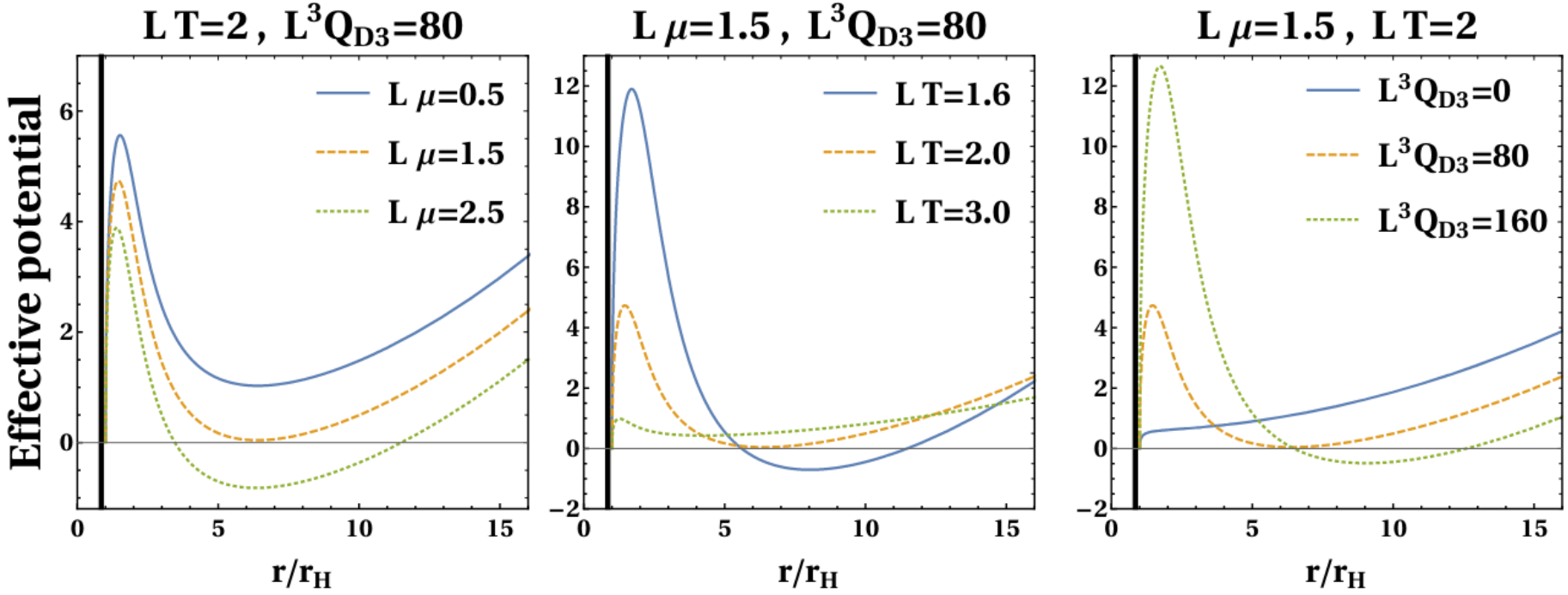
Probe brane **dragged along with background** – has conserved angular momentum and energy

Legendre transform to replace angular velocity with angular momentum → effective 5D Lagrangian...

$$\mathcal{L}^J_{D3} = -2\pi^2 T_3 \dot{\mathcal{T}} \left\{ -(C_4)_t - \frac{J_C}{L} A_t + \sqrt{-\left(\mathcal{Z}^6 + \frac{J_C^2}{L^2}\right)\left(g_{tt} + g_{zz}\mathcal{Z}'^2\right)} \right\}$$

Probe D3 in spinning black brane background

...and effective potential:



(Similar results in Klebanov-Witten “conifold” theory at non-zero baryon charge!)

Aside: Brane nucleation

OH (PRD 2022)

Potential barrier between horizon and global minimum → brane must tunnel through barrier!

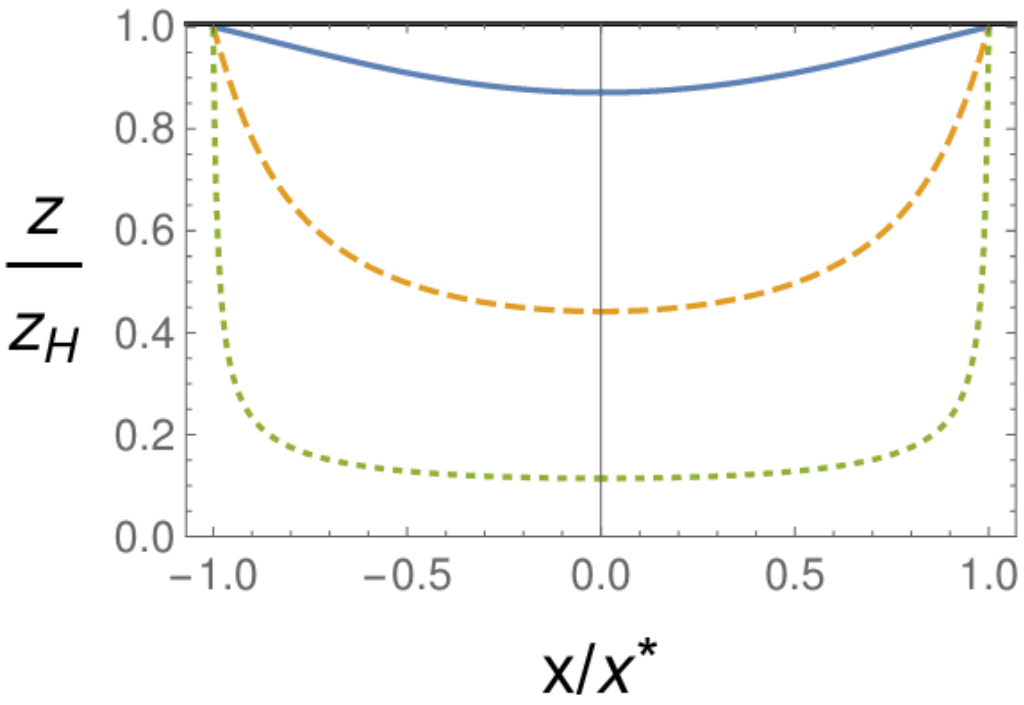
Study (still in probe limit) by allowing the brane to ***move*** and to ***bend*** in the field theory directions

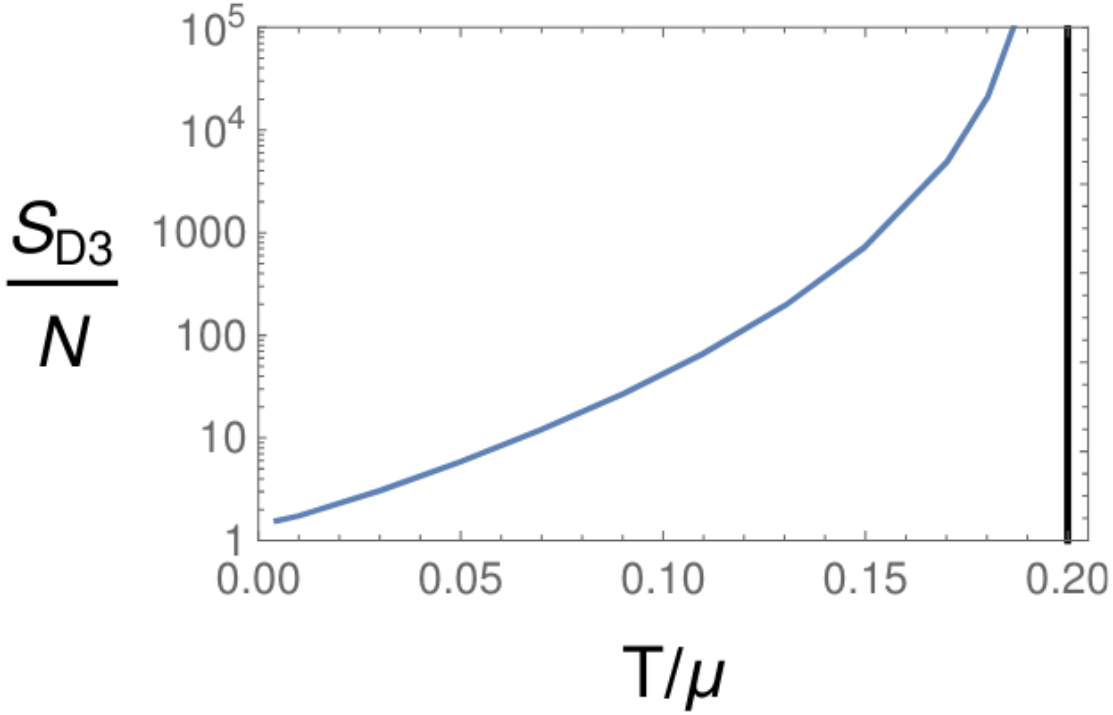
→ Ansatz $R = R(t, x_i)$ → (more general) ***effective action:***

$$S_{D3} \sim -T_3 \int dt\, d\vec{x} \sqrt{a(R) - b(R)(\partial_t R)^2 + c(R)(\partial_i R)^2} - C_4^{(t)}(R) + \cdots$$

Results: Brane nucleation!

Look for high-temperature $O(3) \times O(2)$-symmetric solutions ***"bubbling off"*** the horizon; $R = R(\rho)$…





(Results shown for KW conifold theory)

Next steps:

1. Include backreaction → find stable endstate
2. Abstract away general features → lessons for QCD modelling??

→ Bottom-up model with ~*color branes*~

Bottom-up color brane model

5D gravity theory with a 2-form and a 5-form field strength:

$$S = \int \left(R - \Lambda + F_2^2 + G_5^2 \right) + S_{brane}$$

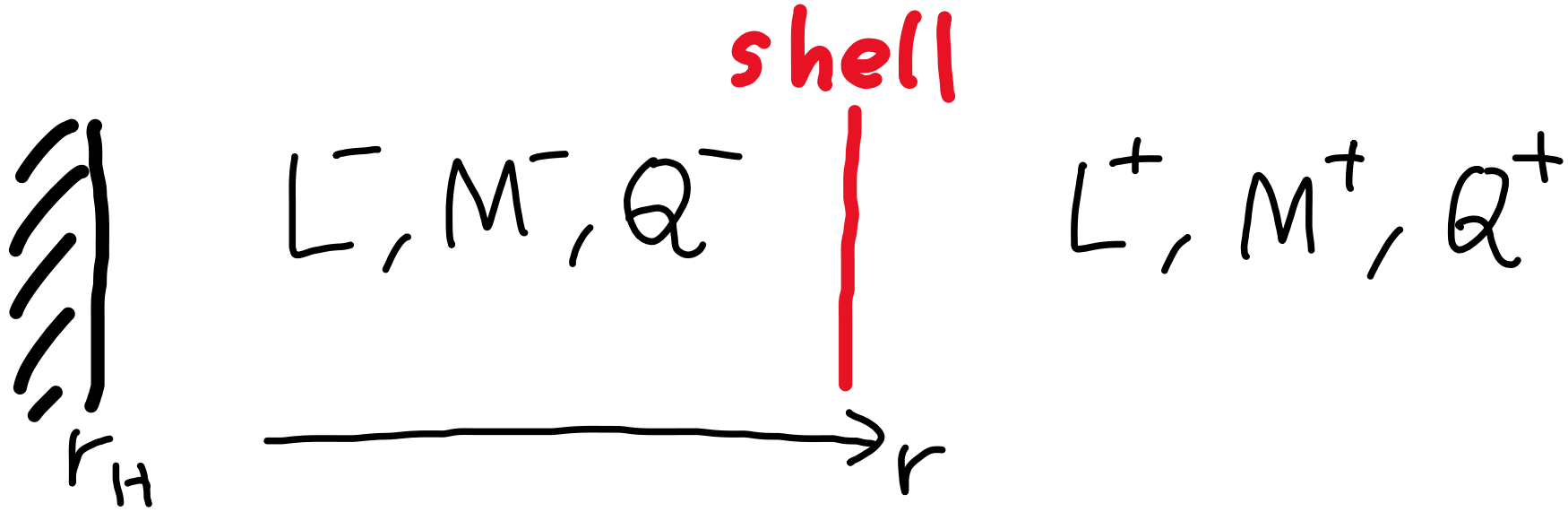
Include 3-branes, which source 4-form and 1-form potentials:

$$S_{brane} = DBI_{5D} + WZ_{5D} + \int A_\mu J^\mu$$

- 5-form in 5D proportional to volume form; gives positive contribution to CC
- 3-branes act as domain walls, across them CC changes (cf. Brown-Teitelboim)

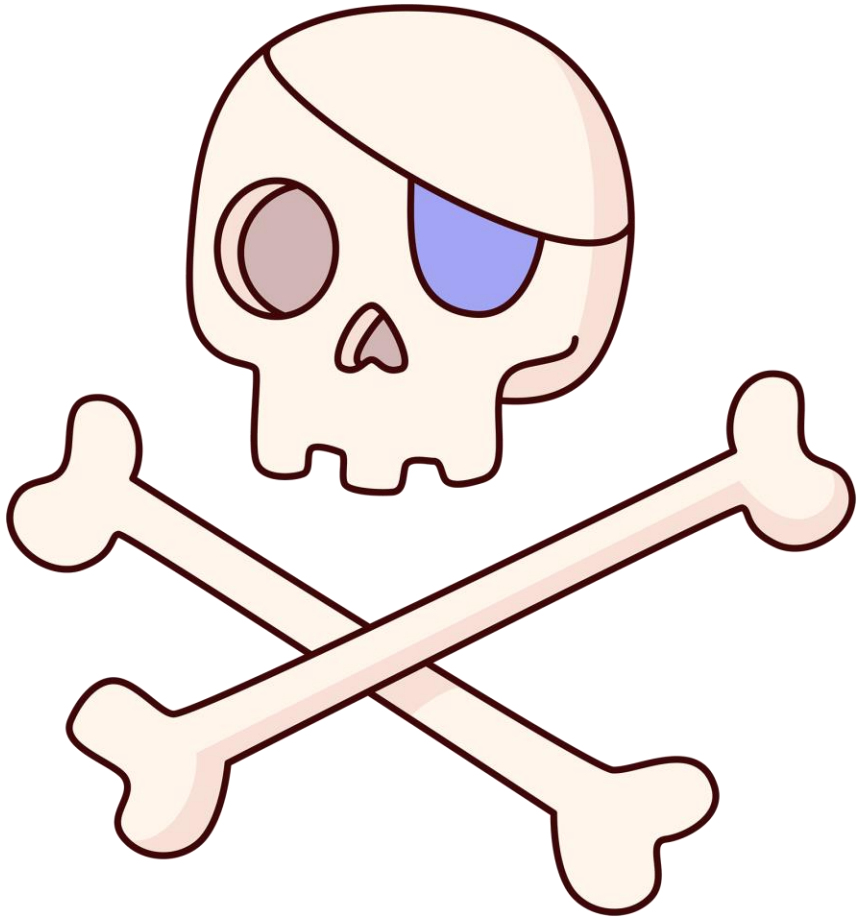
How to include backreaction?

Assume 3-branes *localize* around specific radius → form a thin shell, with **simple, sourceless geometries** inside and outside



- Use **Israel junction conditions** to glue together inside & outside
- Shell 4D stress tensor is pure cosmological constant; take value to correspond to "critical brane" (matching with top-down probe result)

Warning: Preliminary results

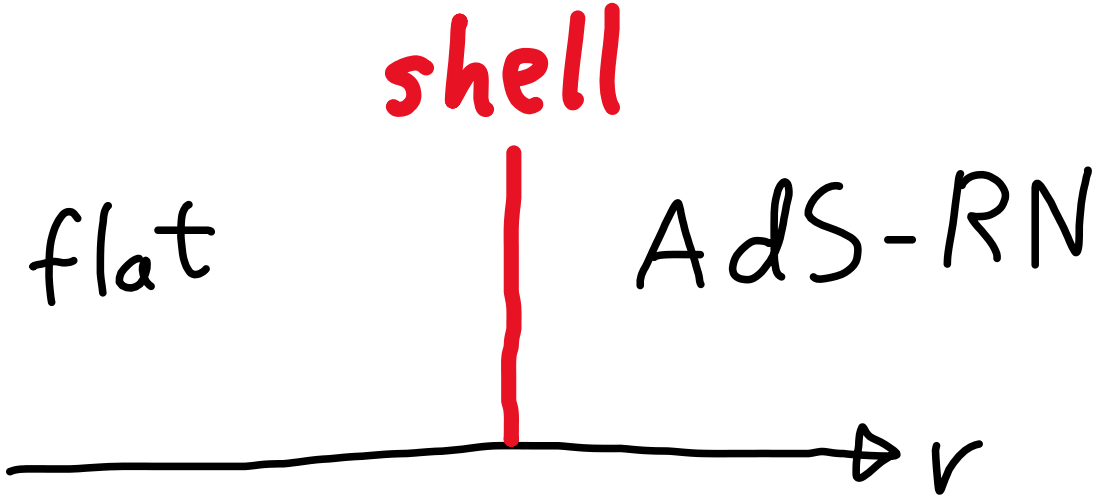


Thin shell solutions

Further assumption: **ALL** branes nucleate → inside is flat!

Three parameters in bulk:

- total mass M
- total charge Q
- radial position of shell R



Junction conditions on metric give two independent equations

→ one-parameter family of **static shell solutions**

Thin shell solutions – Thermodynamics

Charge density, stress tensor – similar to standard black hole solutions

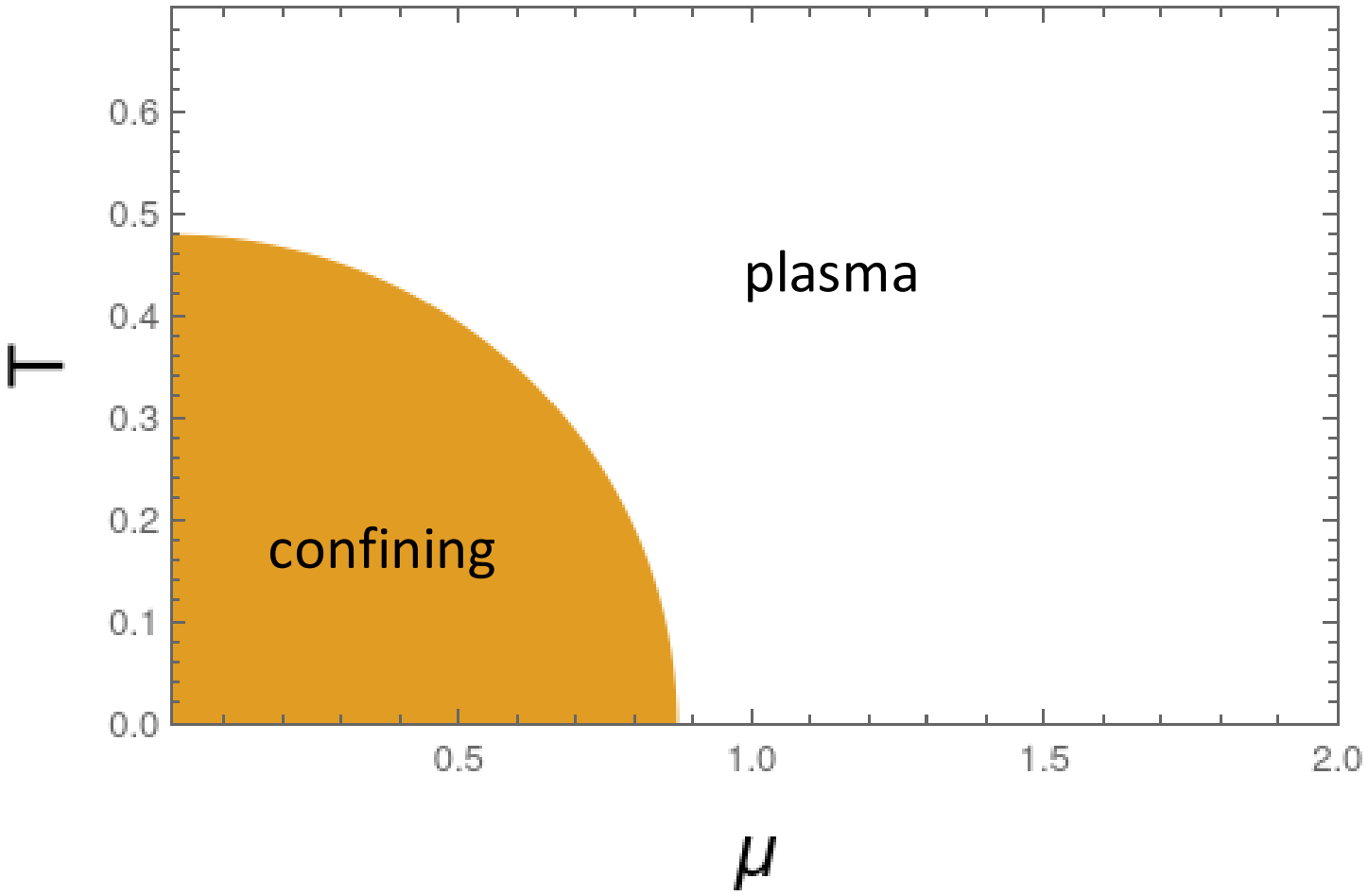
No horizon! Entropy zero at leading order, temperature arbitrary

Gauge potential continuous at shell, can affect chemical potential

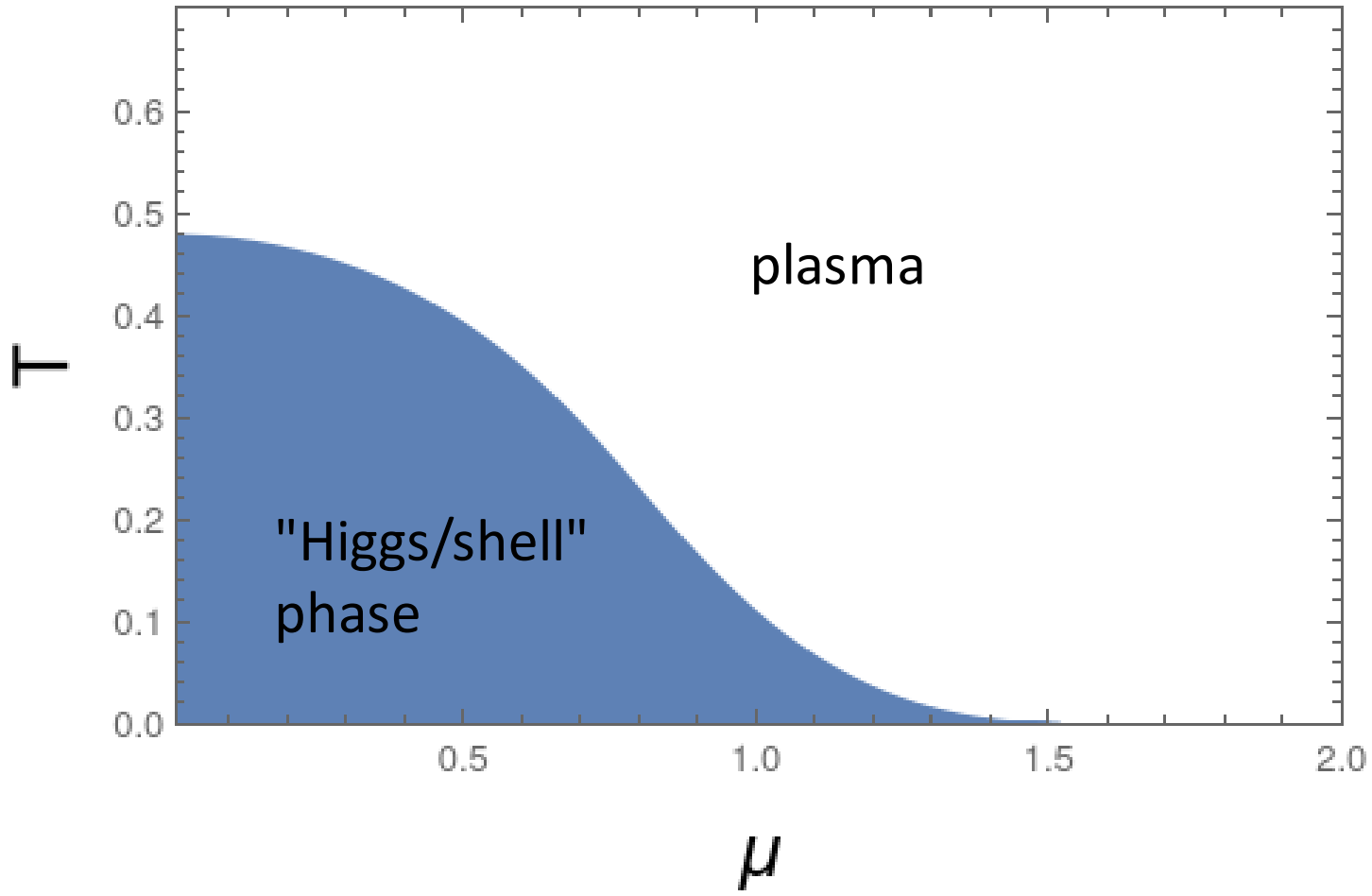
First law shown to hold for static solutions → *non-trivial check*

Free energy computed as $F = E - TS - \mu Q$, compare with standard AdS-RN and confined solutions.

Phase diagram: no branes



Phase diagram: with branes



Confining geometry (and some more) replaced by new brane shell solution!

Interpreting the new phase

- Similar to vacuum N=4 SYM solution of Kraus-Larsen-Trivedi (1999)
  → Spherical shell of branes with flat space inside
  → SU(N) broken to $U(1)^{N-1}$
- No horizon, but **non-trivial thermodynamics** at leading order in 1/N
- Phase transition 1st order in general, but "smoothened" at points
- Outer geometry has **naked singularity** (cf. Evans-Hockings 2002)
  → “Resolved” by shell
- Classification from loop operators (following Rozali et al. 2012)
  → Wilson loop Coulombic
  → 't Hooft loop: area law

Work in progress…

Allow for more general interior geometries, brane distributions

- Partial nucleation → smooth(er) transition between plasma/Higgs phase/confinement?

Study properties of solutions

- Stability, thermodynamics, transport, …

Embed in top-down

- N=4 SYM, “conifold" theories, ...
- Interesting theoretically (ground state of N=4 SYM at finite R-charge chemical potential)
- Lessons for (QCD) modelbuilding??

What to **TAKE AWAY?**

- Higgs phases are **generic** in gauge theories, for example QCD at non-zero density
- Important for transport, maybe also thermodynamics
  → *may* affect neutron star physics

- Realized in holography through "color branes" nucleating in bulk
- Can be incorporated in **generic bottom-up models** by adding dynamical 3-branes
  → useful for modelbuilding?