Cool But Not (necessarily) Supercool:
RS Phase Transition

LR w/Rashmish Mishra

Outline

- Brief review RS and phase transition
  - Strong constraint on curvature (N in dual theory)
  - Supercooling in perturbative scenarios
  - Important for viability of RS
  - Important due to potential GW implications
  - Ideas to weaken constraint
  - Potential implications for gravity wave signal
- Recent work with Mishra:
  - I: Add self-interactions to GW field
    - Original scenario assumed only a mass term
  - II: Mimic KKLT/warped compactification
    - Phase transition driven by "shrinking circle"
    - Strong back-reaction on IR geometry
    - Black brane phase very different at low temperature
    - Potential implications for gravity wave signautre
- Conclude

Review: Phase Transition

Deconfined to Confined

High Temperature BB to RS

PhaseCreminelli, Nicolis, Rattazzi

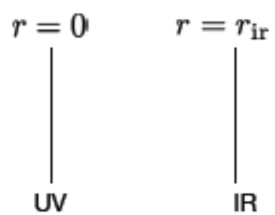
- Two solutions to EE at finite temperature with neg 5d cc

$\ell_{\text{AdS}} = 1$

RS

$$ds^2 = -\bar{e}^{2r}\mathrm{d}t^2 + \bar{e}^{2r}\mathrm{d}\vec{x}^2 + \mathrm{d}r^2$$

$$0 \leq r \leq r_{\text{ir}}$$



Confined

$\ell_{\text{AdS}} = 1$

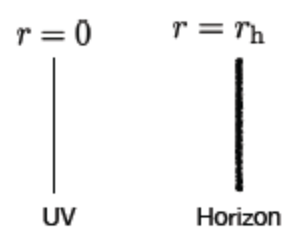
BB

$$ds^2 = -\bar{e}^{2r}\mathrm{d}t^2\left(1 - e^{4(r-r_h)}\right) + \bar{e}^{2r}\mathrm{d}\vec{x}^2 + \frac{\mathrm{d}r^2}{1 - e^{4(r-r_h)}}$$

$$0 \leq r \leq r_{\text{h}}$$

An approximate solution, exact in the limit of UV brane sent to boundary.

Temperature: $T = \frac{1}{\pi}e^{-r_h}$



Deconfined

w/o Stabilization, BB is Thermodynamically Preferred

Creminelli, Nicolis, Rattazzi

$$F_{BB} - F_{RS} = -2\pi^4 M_5^3 T^4$$

$\Delta F < 0$ at all temperatures.

Without additional ingredients, black brane always preferred
Would be no phase transition

With Stabilization

- Without stabilization phase transition never happens
  - Potential for radion is flate (in flat space)
- With stabilization, extra contribution from stabilizing potential
  - Calculate in 4d or 5d?
  - All calculations so far do a 4d calculation
- For perturbative consistency require a “light” radion
- Assumption is we can neglect KK modes
  - Turns out rate always suppressed with this assumption
  - Can still be phenomenologically viable
  - But constrained and supercooled
    - Can be strong constraint

(In our second model we inch toward a strongly coupled iR where KK modes should play a role)

With Stabilizing Scalar

χ: a 5D scalar with brane localized and bulk potential

$$S_\chi = \int d^5x\sqrt{g}\left(-\frac{1}{2}(\partial\chi)^2 - V_B(\chi)\right) - \sum_i \int d^4x\,\sqrt{g_i}\,V_i(\chi)$$

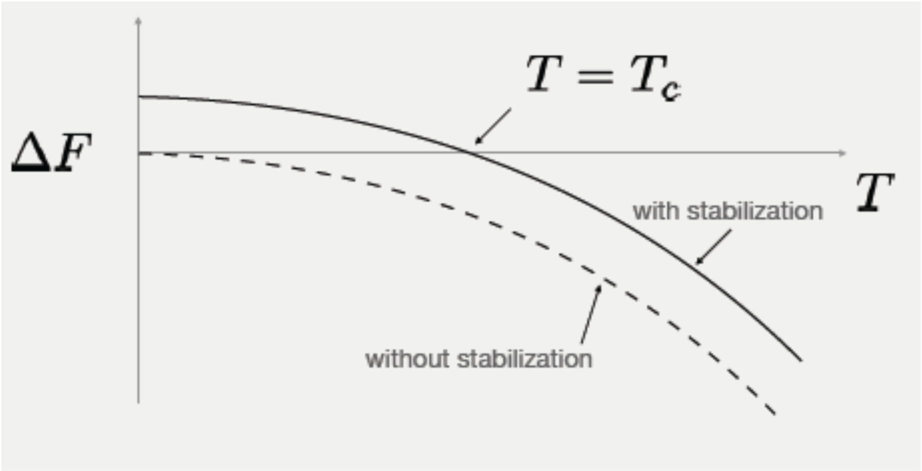
$\Delta F = 0$ at $T = T_c$

$T > T_c$: BB geometry (deconfined phase) favored.

$T < T_c$: RS geometry (confined phase) favored.

$$F_{RS} \approx V(\varphi_{\rm min}) + \mathcal{O}(T^4)\ ,\ V(\varphi_{\rm min}) < 0$$

$$F_{BB} - F_{RS} = -2\pi^4 M_5^3 T^4 - V(\varphi_{\rm min}) \equiv \quad 2\pi^4 M_5^3 (T_c^4 - T^4)$$



Tc depends on specific model

Simple Examples

A

$$V_B(\chi) = 2\epsilon\chi^2$$

$$\chi_{\mathrm{UV}} = v_{\mathrm{uv}}, \chi_{\mathrm{IR}} = v_{\mathrm{IR}},$$

$$V(\varphi) \sim \varphi^4 \left(1 - \left(\frac{\varphi}{\varphi_{\mathrm{min}}}\right)^{\epsilon}\right)^2 - \epsilon\varphi^4$$

$$T_c \sim \epsilon^{3/8}\varphi_{\mathrm{min}}$$

B

$$V_B(\chi) = 2\epsilon\chi^2$$

$$\chi_{\mathrm{UV}} = v_{\mathrm{uv}}, \chi'_{\mathrm{IR}} = -\alpha$$

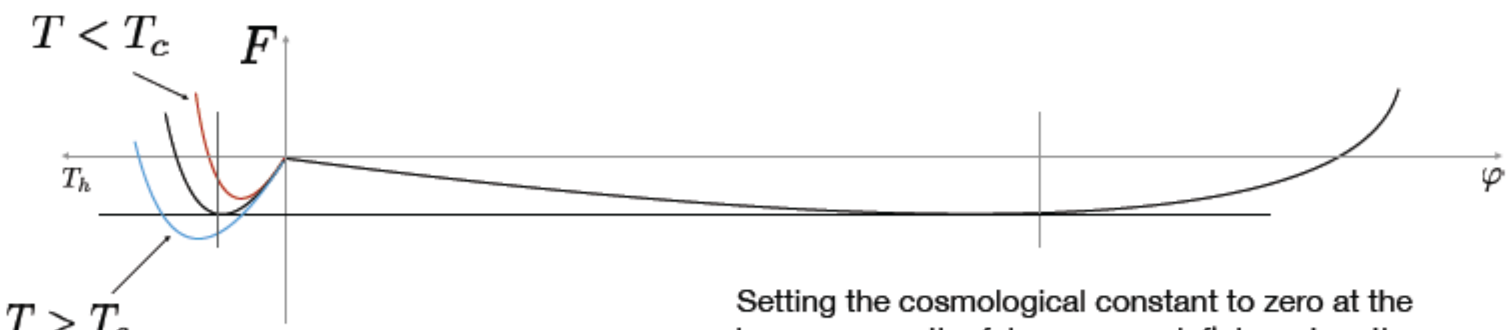
$$V(\varphi) \sim \varphi^4 \left(1 - \frac{1}{1+\epsilon/4}\left(\frac{\varphi}{\varphi_{\mathrm{min}}}\right)^{\epsilon}\right)$$

$$T_c \sim \epsilon^{1/4}\varphi_{\mathrm{min}}$$

- For validity of 4d EFT (neglect KK) modes ϵ must be small
- The critical temperature is below the minimum value of Φ

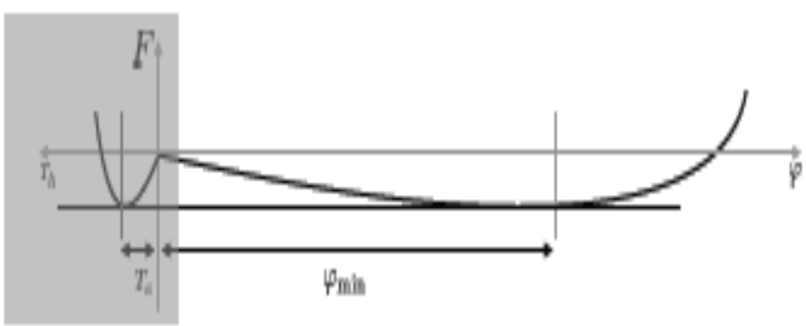
Dynamics Phase Transition

- First order!
- Can lead to visible GW signal



Setting the cosmological constant to zero at the true vacuum, the false vacuum inflates when the phase transition can take place (i.e. $T < T_c$)

- Assume bubble action dominated by radion



Phase transition completes when $\Gamma > H^4$, $H^2 \sim \rho_{\rm vac}/M_{\rm pl}^2$, $\rho_{\rm vac} \sim 2\pi^4 M_5^3 T_c^4$

Examples

$$V(\varphi) \sim \varphi^4 \left(1 - \left(\frac{\varphi}{\varphi_{\min}}\right)^{\epsilon}\right)^2 - \epsilon\varphi^4 \qquad S_3/T \approx 0.13 \frac{N^2}{\epsilon^{9/8}(v_{\rm ir}/N)^{3/2}} \frac{T_c/T}{(1-(T/T_c)^4)^2}$$

$$V(\varphi) \sim \varphi^4 \left(1 - \frac{1}{1+\epsilon/4}\left(\frac{\varphi}{\varphi_{\min}}\right)^{\epsilon}\right) \qquad S_3/T \approx 8 \frac{N^2}{(\epsilon\lambda)^{3/4}} \frac{T_c/T}{(1-(T/T_c)^4)^2}$$

General structure: $\Gamma \sim \exp\left(-\frac{N^2}{\delta} f(T/T_c)\right)$

- Small ϵ makes big bubble size
  - Associated with light radion, small EFT breaking
- Large N makes overall action too big
  - Associated with viable phenomenology, justifiable geometric interpretaiton
- f of order unity associated with thin wall approximation

Rate Generally Too Small

- Might not complete at all
- Or might complete only at very low temperature
- Either way, without modification puts bound on N and viability of RS
- (Note: small rate generally leads to big GW signal)

- How to avoid?
- Bigger ϵ (most solutions so far)
  - Leads to viable theories but still strong bound
- Smaller N
  - Smaller N in IR than UV; still have to accommodate phenomenology
- Use thick wall ? (dictated by theory)

- Are there solutions within "radion EFT"
- Are there solutions with perturbative reliability?

How generic are these results?

Are there motivated alternatives that improve situation?

- Increase δ (in previous models some power of ϵ)
  - IR contribution dominates instanton action so only need larger running in IR
    - Can get hierarchy due to small CFT breaking with small δ
    - But smaller bubble action due to bigger effective δ in IR
- One example by Csaki, Geller,Heller-Algazi, Ismail
  - Relevant Dilaton Stabilization
- Another by Agashe, Du, Ekterachian, Kumar, Sundrum
  - Transition between two CFTs
- More truly 5d calculation Gustafson, Hite, Hubisz, Sambasivam, Umuth-Jockey
- Our example (w/Mishra) similar in spirit to latter but more generic
  - We simply include an interaction term
  - Just cubic for simplicity but sufficiently general to illustrate point
  - Small contribution in UV when field small
  - Increases due to RG flor in IR

  End result can be Large IR CFT breaking

Our Model I:
Add Self-interactions in Bulk

$$V_B(\chi) = 2\epsilon_2\chi^2 + \frac{4}{3}\epsilon_3\chi^3$$

Choose $\epsilon_2 < 0, \epsilon_3 < 0$

to grow the deformation in the IR

$$V_{\rm uv} = \beta\left(\chi - v_{\rm uv}\right)^2, \beta \to \infty$$

$$V_{\rm ir}(\chi) = 2\alpha_{\rm ir}\chi$$

$$S = \int d^4x\sqrt{g}\left(-12M_5^3\left(\partial\varphi\right)^2 - V(\varphi)\right), \quad \varphi = e^{-r_{\rm ir}}$$

$$V(\varphi) = 24M_5^3\kappa^4\,\varphi^4\left(1 + \frac{a_2}{24M_5^3\kappa^4}\frac{\lambda\varphi^{\epsilon_2}}{1-\lambda\varphi^{\epsilon_2}} - \frac{a_3}{24M_5^3\kappa^4}\log(1-\lambda\varphi^{\epsilon_2})\right)$$

$$\lambda = \frac{v_{\rm uv}\epsilon_{32}}{1+v_{\rm uv}\epsilon_{32}}, \; \epsilon_{32} = \frac{\epsilon_3}{\epsilon_2}, \; a_2 = -\frac{1}{32}\epsilon_2\alpha_{\rm ir}^2 - \frac{\epsilon_2}{\epsilon_3}\alpha_{\rm ir} + 2\alpha_{\rm ir}, \; a_3 = \frac{1}{2}\frac{\epsilon_2}{\epsilon_3}\alpha_{\rm ir}$$

In Original Coordinate (approx) Solution

$$V_B(\chi) = 2\epsilon_2\chi^2 + \frac{4}{3}\epsilon_3\chi^3$$

$$V_{\rm uv} = \beta\left(\chi - v_{\rm uv}\right)^2, \beta \to \infty$$

$$V_{\rm ir}(\chi) = 2\alpha_{\rm ir}\chi$$

Choose $\epsilon_2 < 0, \epsilon_3 < 0$ to grow the deformation in the IR

Approximate solutions

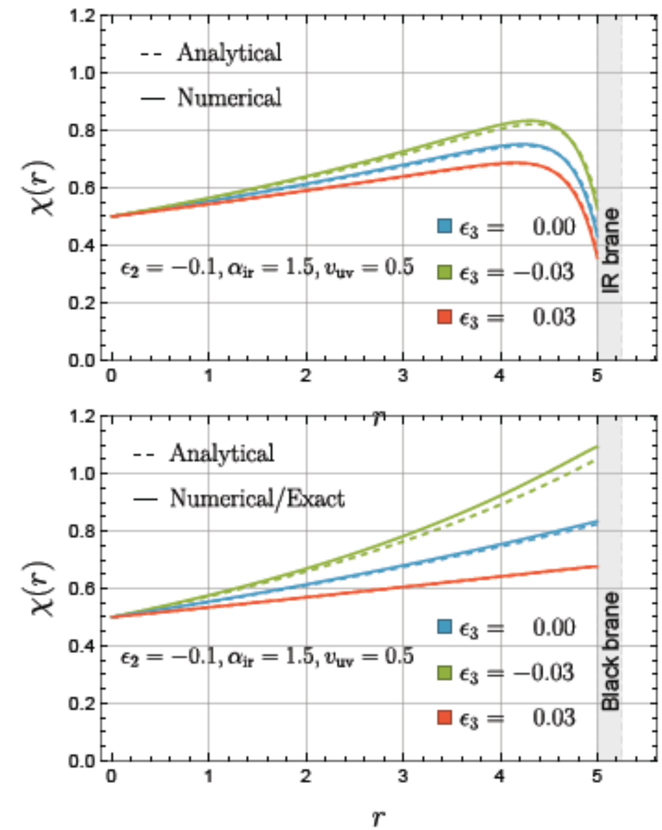
$|\epsilon_2| \ll 1, v_{\rm uv} \ll 1, r_{\rm ir} \gg 1, |\epsilon_2| r_{\rm ir} \lesssim 1, |\epsilon_3| r_{\rm ir} \lesssim 1$

$r_{\rm ir} \to r_h$ (for the BB solution)

$$\chi_{\rm RS}(r) = -\frac{\alpha_{\rm ir}}{4} e^{4(r-r_{\rm ir})} + \frac{v_{\rm uv} e^{-\epsilon_2 r}}{1 + v_{\rm uv}\epsilon_3\left(\frac{1-e^{-\epsilon_2 r}}{\epsilon_2}\right)}, \quad 0 \le r \le r_{\rm ir}$$

$$\chi_{\rm BB}(r) = \frac{v_{\rm uv} e^{-\epsilon_2 r}}{1 + v_{\rm uv}\epsilon_3\left(\frac{1-e^{-\epsilon_2 r}}{\epsilon_2}\right)}, \quad 0 \le r \le r_h$$

ϵ_3 is an additive effect to ϵ_2



Radion Potential

$$V(\varphi) = 24M_5^3\kappa^4\,\varphi^4\left(1 + \frac{a_2}{24M_5^3\kappa^4}\frac{\lambda\varphi^{\epsilon_2}}{1-\lambda\varphi^{\epsilon_2}} - \frac{a_3}{24M_5^3\kappa^4}\log(1-\lambda\varphi^{\epsilon_2})\right)$$

$$V(\varphi) = \varphi^4\left(b_0 + b_1\lambda\varphi^{\epsilon_2} + b_2\lambda^2\varphi^{2\epsilon_2} + b_3\lambda^3\varphi^{3\epsilon_2} + \cdots\right)$$

$$b_0 = 24M_5^3\kappa^4$$

$$b_1 = -v_{\rm uv}\left(\frac{1}{2}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-1},$$

$$b_2 = -v_{\rm uv}\left(\frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)\left(\frac{3}{4}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-2},$$

$$b_3 = -v_{\rm uv}\left(\frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^2\left(\frac{3}{4}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-2},$$

$$\vdots$$

$\epsilon_3 = 0$, only b_0, b_1 are non-zero.

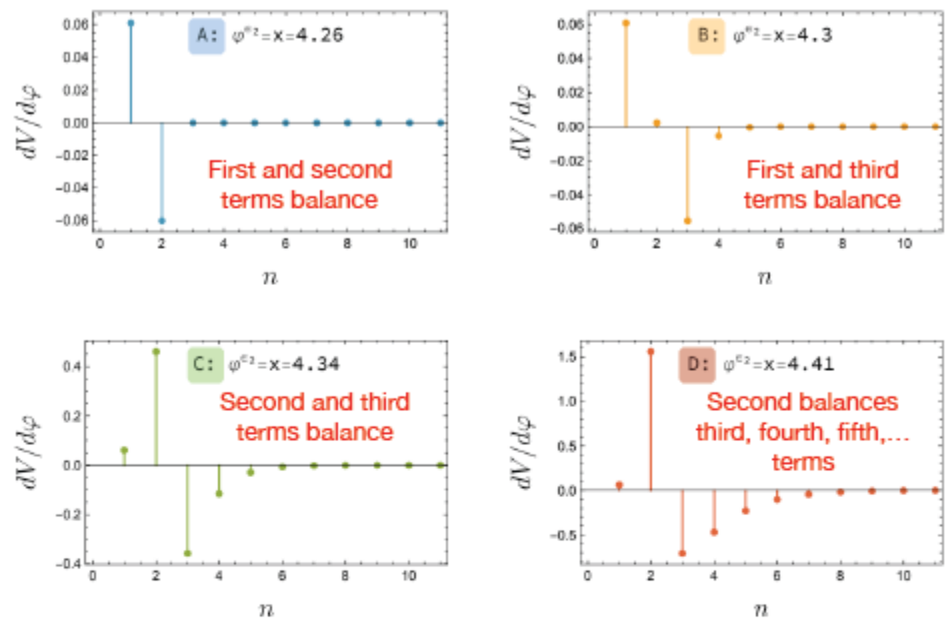
- When λ ~ ϵ, V ~ϵ

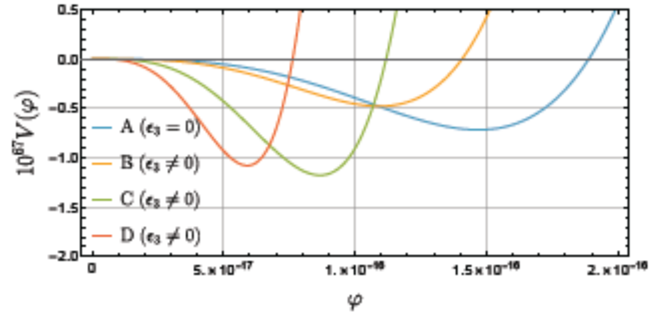
$\epsilon_3 \neq 0$: many terms.

Potential can be ~1 when Φ is large
Can't go all the way to nonperturbative
But lesson is clear

In more detail

$$V(\varphi) = 24M_5^3\kappa^4\,\varphi^4\left(1 + \frac{a_2}{24M_5^3\kappa^4}\frac{\lambda\varphi^{\epsilon_2}}{1-\lambda\varphi^{\epsilon_2}} - \frac{a_3}{24M_5^3\kappa^4}\log(1-\lambda\varphi^{\epsilon_2})\right)$$



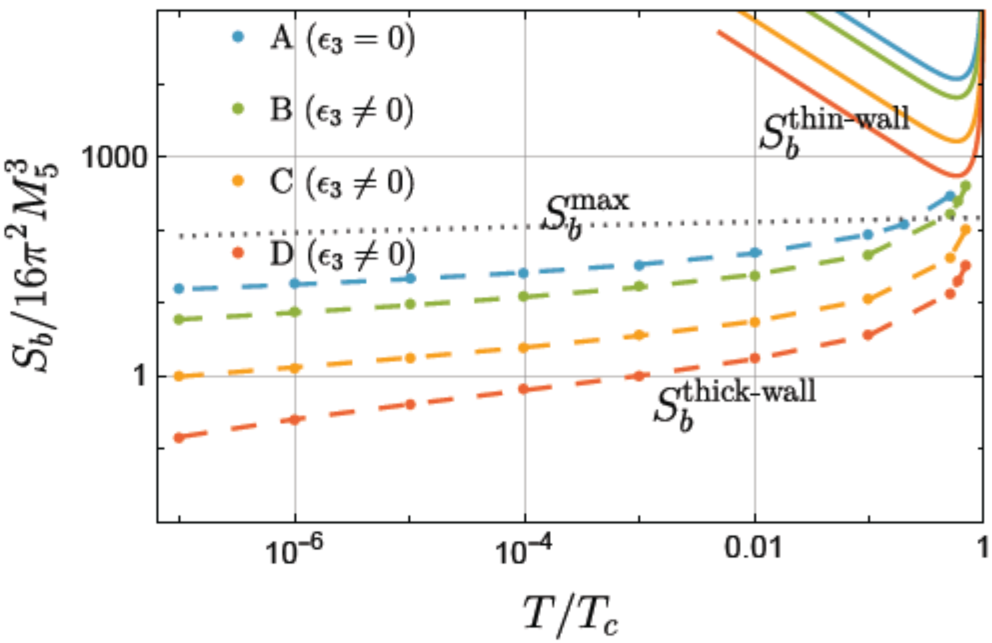


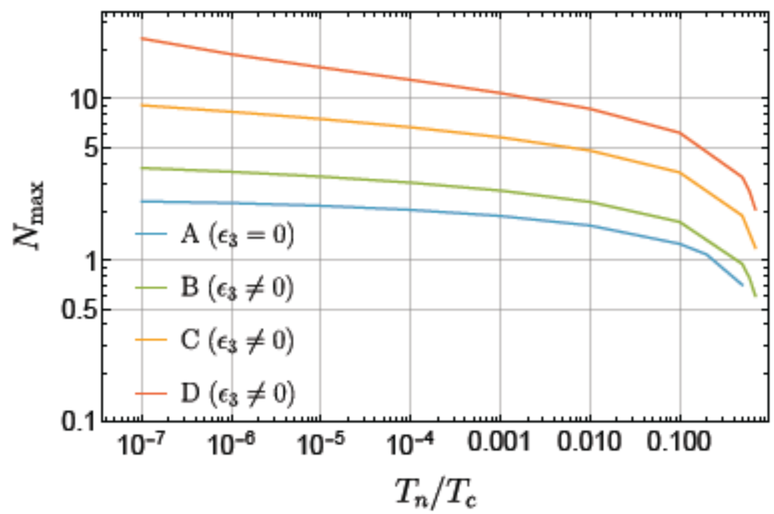
	κ	ϵ_2	ϵ_3	$\alpha_{\rm ir}$	$v_{\rm uv}$
A	$10^{-1/4}$	-1/25	0	1/10	1/14
B	$10^{-1/4}$	-1/25	-1/100	5/2	1/14
C	$10^{-1/4}$	-1/25	-1/90	5/2	1/5
D	$10^{-1/4}$	-1/25	-1/81	5/2	1/3

	$\varphi_{\rm min}\times 10^{16}$	$V''(\varphi_{\rm min})/\varphi_{\rm min}^2$
A	1.47	0.002
B	1.09	0.005
C	0.86	0.032
D	0.59	0.135

- Radion potential is deeper
  - here minimum shifts slightly but can also fix minimum to see same effect
- Point is this is more realistic model of strong IR breaking
- Different terms in radion potential can balance
- Not as suppressed: mimics truly strong CFT breaking in IR

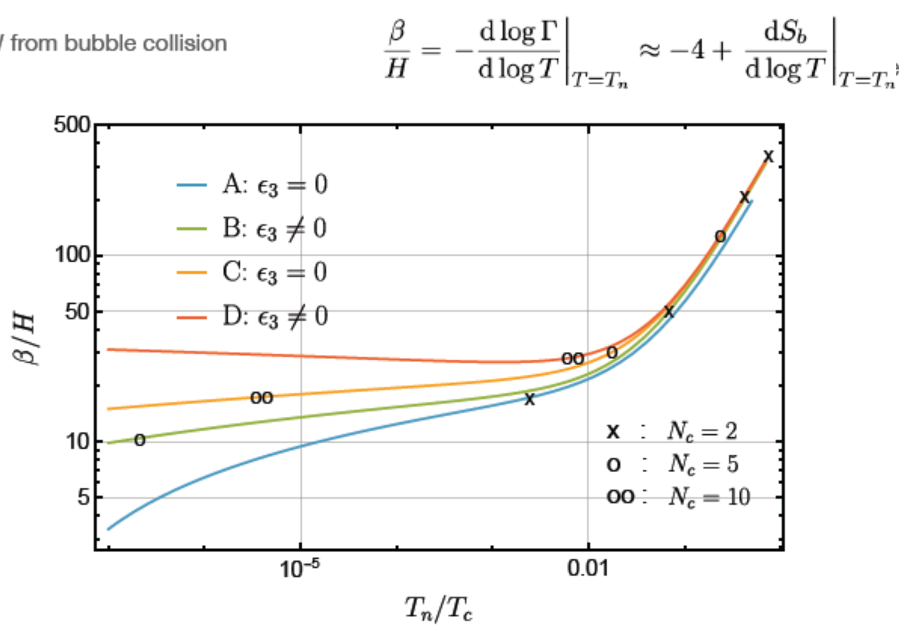
Resulting Reduction in Bounce Action And Less Restrictive Bound on N

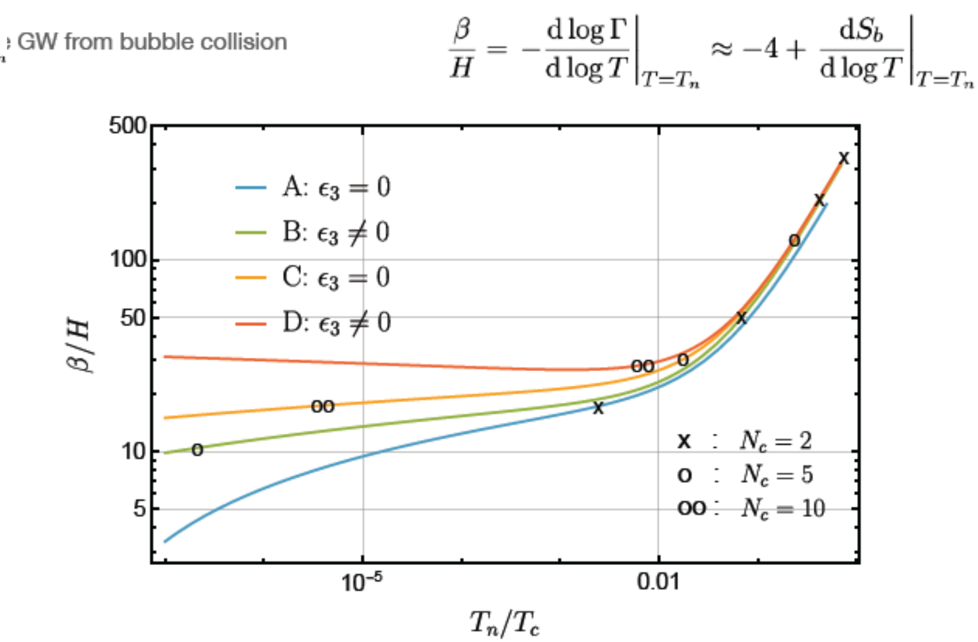




Important Consequence for GW

- Chief lesson is that less supercooling, less strongly first order
- Implies weaker GW signal

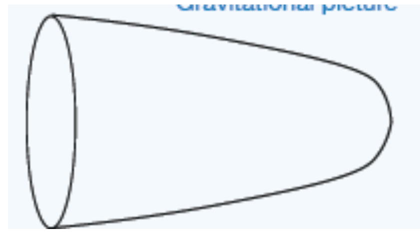




New
(and more radically different)
Model

Designed to mimic warped compactification

What Drives IR Brane?



- KKLT has a warped dimension
- Also five compact dimensions
- Warp factor essentially due to shrinking S_2 due to decreasing flux as we move to IR (dual)
- At some point it caps off
- Effectively reducing N (of SU(N))
  - Strong backreaction allows for nonperturbative regime so that no longer N^2 suppressed

Buchel wrote a "bestiary" of black hole phases

He found (even w/o a GW field) that phase transition will occur
His model effectively 5d RS-like theory with 7 additional scalars
We asked if we can get essence of result with a simplified model

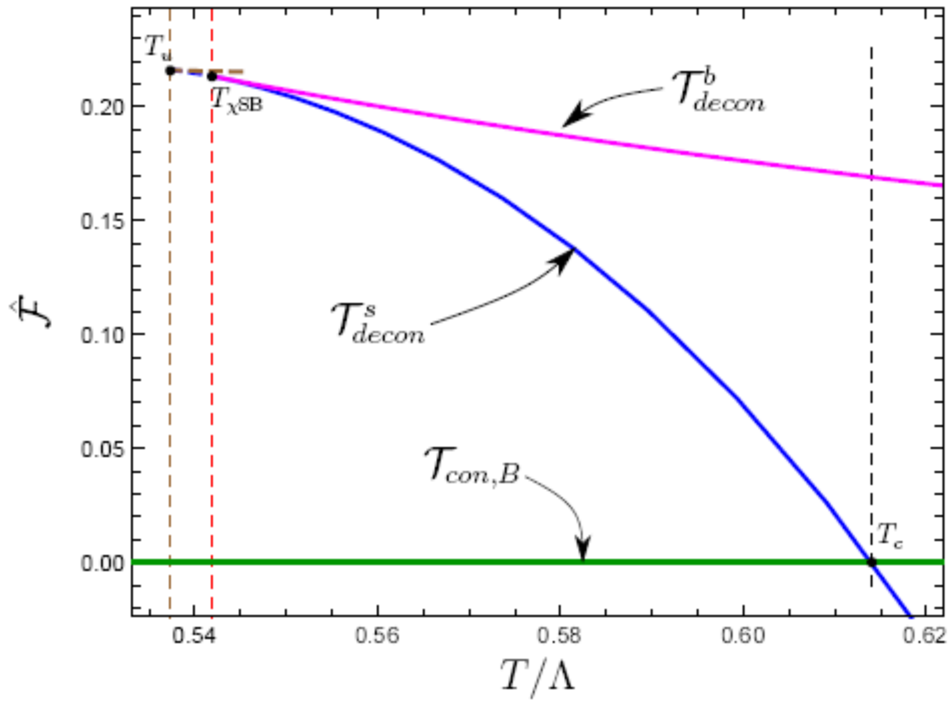


Figure 17: Phase diagram in the canonical ensemble at $\mu/\Lambda = 0$: the reduced free energy density $\hat{\mathcal{F}}$, see (6.1), versus the reduced temperature T/Λ for different states in the theory. Vertical dashed lines indicate critical temperatures T_c (black) for the confinement-deconfinement phase transition, $T_{\chi SB}$ (red) for the onset of the spontaneous chiral symmetry breaking, and T_u (brown) for the bifurcation point of the $\mathcal{T}^s_{decon}$ states with positive/negative specific heat.

Model II

Critically We Will Include Backreaction

$$S = S_{\rm GR} + S_{\phi} + S_{\rm bdy} \; ,$$

$$S_{\rm GR} = 2M_5^3 \int {\rm d}^5 x \sqrt{-g} \Big((1-\phi/\phi_c)^n \; R - 2\,(1-\phi/\phi_c)^m \; \Lambda \Big)$$

$$S_{\phi} = 2M_5^3 \int {\rm d}^5 x \sqrt{-g} \Big(- a(\partial\phi)^2 - v(\phi) \Big) \, . \qquad \ell_{\rm AdS} = 1$$

$$v(\phi) = 2\epsilon\phi^2, \epsilon < 0$$

- Number of "colors" changes as Ψ grows in IR
- Leading to small coefficient of 5d R in IR
- Note that Φ starts small so only after growing does coefficient have significant impact
- Can find less supercooling
- Significant change in IR to deconfined phase

Einstein Frame Action

After Weyl rescaling

$$S_\phi = 2M_5^3 \int \mathrm{d}^5x\sqrt{-g}\left(-\frac{1}{2}\,g^{MN}G(\phi)\,\partial_M\phi\,\partial_N\phi - V(\phi)\right)$$

$$G(\phi) = 2a\left(1-\frac{\phi}{\phi_c}\right)^{-n} + \frac{8n^2}{3\phi_c^2}\left(1-\frac{\phi}{\phi_c}\right)^{-2},$$

$$V(\phi) = 2\epsilon\phi^2\left(1-\frac{\phi}{\phi_c}\right)^{-\frac{5n}{3}} + 2\Lambda\left(1-\frac{\phi}{\phi_c}\right)^{-\frac{5n}{3}+m}$$

Choices to simplify the calculations

$m = 5n/3$: only cosmological constant survives for $\epsilon = 0$

$n = 2, a = 1$: simpler kinetic term

Canonically normalized field

$$S_\sigma = 2M_5^3 \int d^5x\sqrt{-g}\left(-\frac{1}{2}(\partial\sigma)^2 - V(\sigma)\right),\ \frac{\sigma}{\sigma_c} = -\log\left(1-\frac{\phi}{\phi_c}\right),\ \sigma_c = \left(\frac{32}{3\phi_c^2}+2\right)^{1/2}\phi_c$$

$$\phi = \phi_{\mathrm{uv}} \ll 1 \Rightarrow \sigma \to 0\,,\ \phi \to \phi_c \Rightarrow \sigma \to \infty$$

Scalar Potential

$$S_\sigma = 2M_5^3 \int d^5x\sqrt{-g}\left(-\frac{1}{2}(\partial\sigma)^2 - V(\sigma)\right)$$

$$V(\sigma) = 2\Lambda + 2\,\widetilde{\epsilon}\,\sigma_c^2\, e^{\frac{10}{3}\frac{\sigma}{\sigma_c}}\left(1 - e^{-\sigma/\sigma_c}\right)^2$$

$$\widetilde{\epsilon} = \epsilon(\phi_c/\sigma_c)^2$$

$$V(\sigma) \underset{\sigma \ll \sigma_c}{=} 2\Lambda + 2\tilde{\epsilon}\sigma^2 + \frac{14}{3}\frac{\tilde{\epsilon}}{\sigma_c}\sigma^3 + \frac{101}{18}\frac{\tilde{\epsilon}}{\sigma_c^2}\sigma^4 + \cdots$$

$$V(\sigma) \underset{\sigma \gg \sigma_c}{=} 2\tilde{\epsilon}\sigma_c^2 e^{\frac{10}{3}\frac{\sigma}{\sigma_c}}$$

BB Metric

Without back reaction: $ds^2 = \rho^2 \left(1 - \frac{\rho_h^4}{\rho^4}\right) dt_E^2 + \frac{d\rho^2}{\rho^2 \left(1 - \frac{\rho_h^4}{\rho^4}\right)} + \rho^2 \, dx^2 \,, \quad \rho_h \le \rho \le \rho_{\text{uv}}$

Metric ansatz: $ds^2 = a^2(\rho)\rho^2 \left(1 - \frac{\rho_h^4}{\rho^4}\right) dt_E^2 + \frac{b^2(\rho) d\rho^2}{\rho^2 \left(1 - \frac{\rho_h^4}{\rho^4}\right)} + c^2(\rho)\rho^2 \, dx^2$

Define ρ such that $c(\rho) = 1$

Define $\xi \equiv \frac{\rho^4 - \rho_h^4}{\rho_{\text{uv}}^4 - \rho_h^4}$

UV brane: $\xi = 1$

Horizon: $\xi = 0$

$\alpha = \frac{\rho_h^4}{\rho_{\text{uv}}^4 - \rho_h^4} \approx \rho_h^4/\rho_{\text{uv}}^4 \ll 1$

$$ds^2 = a^2(\xi)\, \xi \, dt_E^2 + \frac{b^2(\xi)}{\xi} d\xi^2 + \sqrt{\xi + \alpha}\, dx^2$$

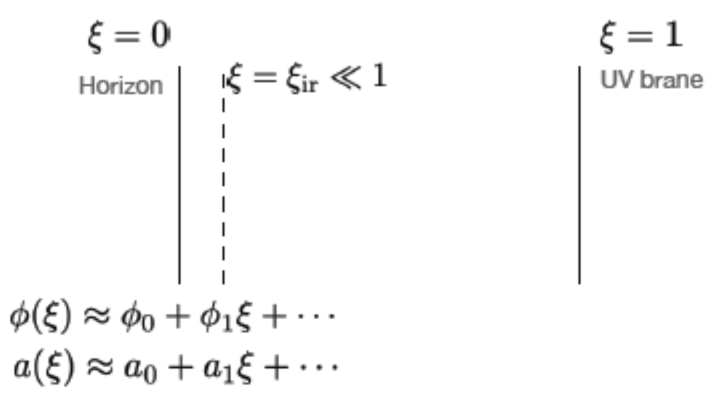
Solve for $a(\xi), b(\xi), \phi(\xi)$.

$$a(\xi) \underset{\text{no b.r.}}{=} \frac{1}{(\xi + \alpha)^{1/4}} \,,$$

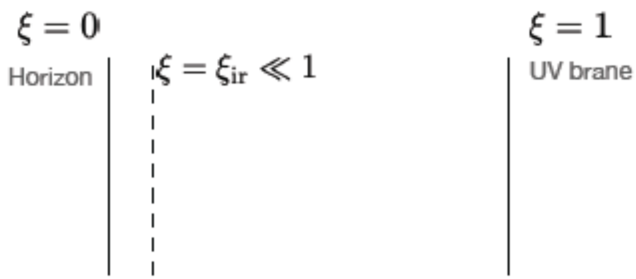
$$b(\xi) \underset{\text{no b.r.}}{=} \frac{1}{4\,(\xi + \alpha)^{1/2}} \,.$$

Need Boundary Conditions

- Challenge is UV values specified
- IR requires smoothness of metric
  - Do IR expansion
  - Relate derivative to values
- Can then find UV values that yield consistent solutions



Solving



$$\phi(\xi) \approx \phi_0 + \phi_1 \xi + \cdots$$
$$a(\xi) \approx a_0 + a_1 \xi + \cdots$$

$$a_1(a_0, \phi_0) = \frac{a_0}{32\alpha}\left(\frac{3}{G(\phi_0)}\left(\frac{V'(\phi_0)}{V(\phi_0)}\right)^2 - 8\right)$$
$$\phi_1(a_0, \phi_0) = -\frac{3}{4\alpha}\frac{1}{G(\phi_0)}\frac{V'(\phi_0)}{V(\phi_0)}$$

Fix: ϕ_{uv}, a_{uv}

Choose: ϕ'_{uv}, a'_{uv}

Solve: $1 \geq \xi \geq \xi_{ir} \ll 1$

Calculate: $\phi_{ir}, \phi'_{ir}, a_{ir}, a'_{ir}$

Check: $a'_{ir} = a_1(\phi_{ir}, a_{ir})$, $\phi'_{ir} = \phi_1(\phi_{ir}, a_{ir})$

Solutions

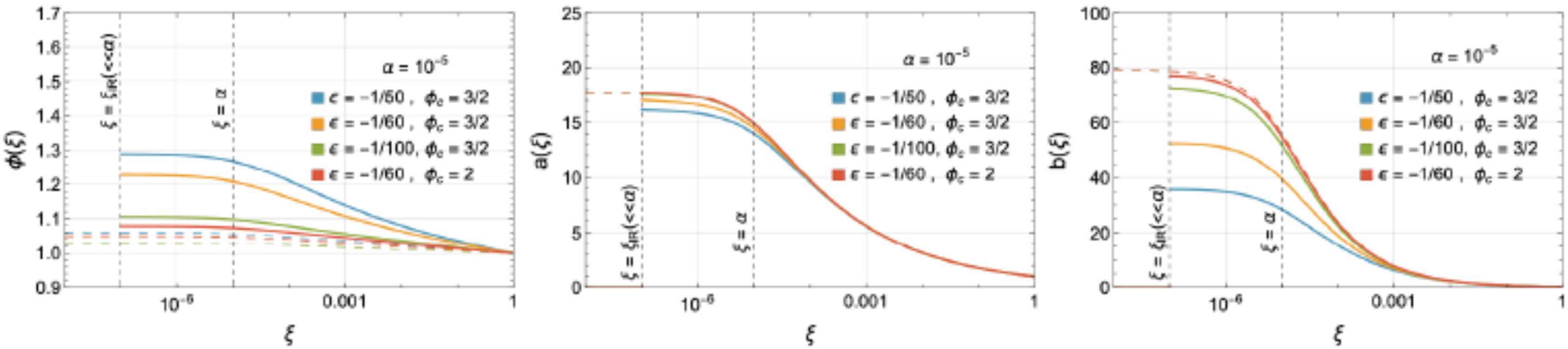
$$\phi_{\rm uv} = 1, \xi_{\rm ir}/\alpha = 10^{-2}.$$

A: $\epsilon = -1/50,\ \phi_c = 3/2\,.$

B: $\epsilon = -1/60,\ \phi_c = 3/2\,.$

C: $\epsilon = -1/100,\ \phi_c = 3/2\,.$

D: $\epsilon = -1/60,\ \phi_c = 2\,.$



- a, b smaller when backreaction
- Φ growth larger for larger ϵ smaller Φ_c
- Saturates at α
- Smaller α yields bigger growth in Φ

Can Now Evaluate Thermodynamic Quantities

Regularity in the (t_E, ξ) plane, near $\xi = 0$ fixes the temperature

$$\frac{T}{\rho_{\rm uv}} = \lim_{\xi \to 0} \frac{1}{(1+\alpha)^{1/4}} \frac{a(\xi)}{4\pi b(\xi)}$$

Entropy from the Bekenstein-Hawking formula

$$s = \frac{S}{\mathrm{Vol}_3} = \frac{\mathcal{A}_{\rm horizon}}{4G_N} \frac{1}{\mathrm{Vol}_3}$$

$$s = 8\pi M_5^3 \frac{\alpha^{3/4}}{(1+\alpha)^{3/4}} \rho_{\rm uv}^3$$

$s = s(T)$

or

$T = T(s)$

Free energy from the thermodynamic relation

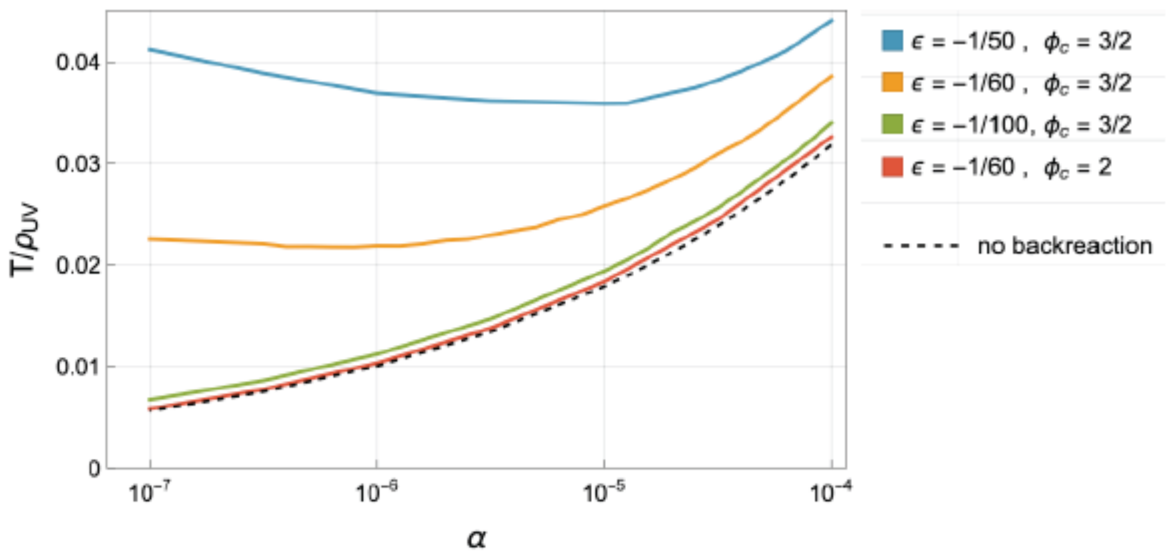
$$s = -\partial_T f$$

$$f(T) - f_0 = -\int_{s_0}^{s} \mathrm{d}s \, \frac{\mathrm{d}T}{\mathrm{d}s} s$$

- Everything in terms of calculable finite quantities

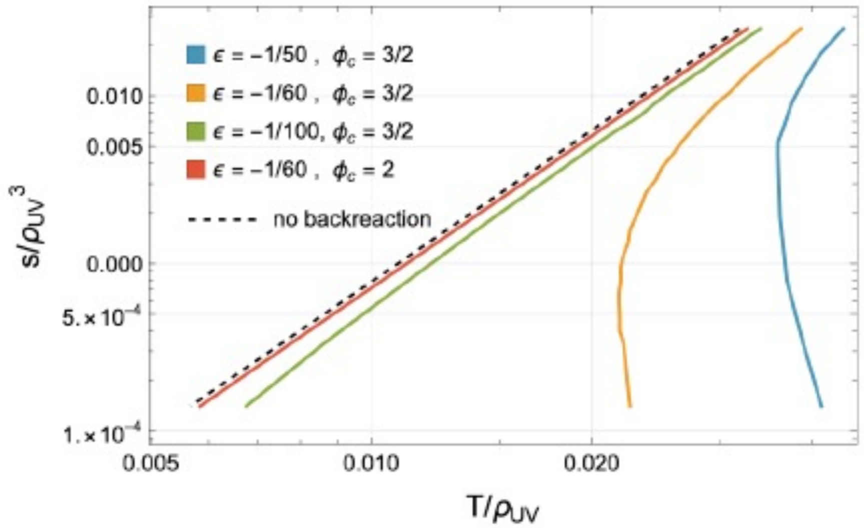
Big Finding: Minimum Temperature!

When large enough backreaction



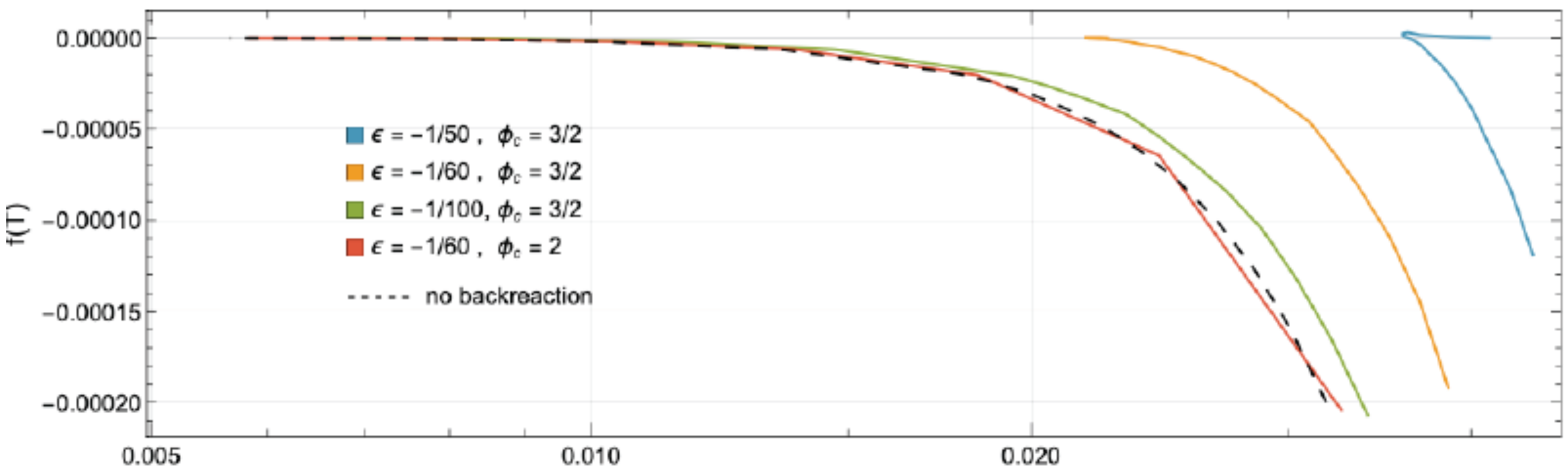
- Only when large back-reaction
  - Potential grows comparable to 5d cc
- This has been seen in RS, global AdS, etc

Entropy not Single Valued



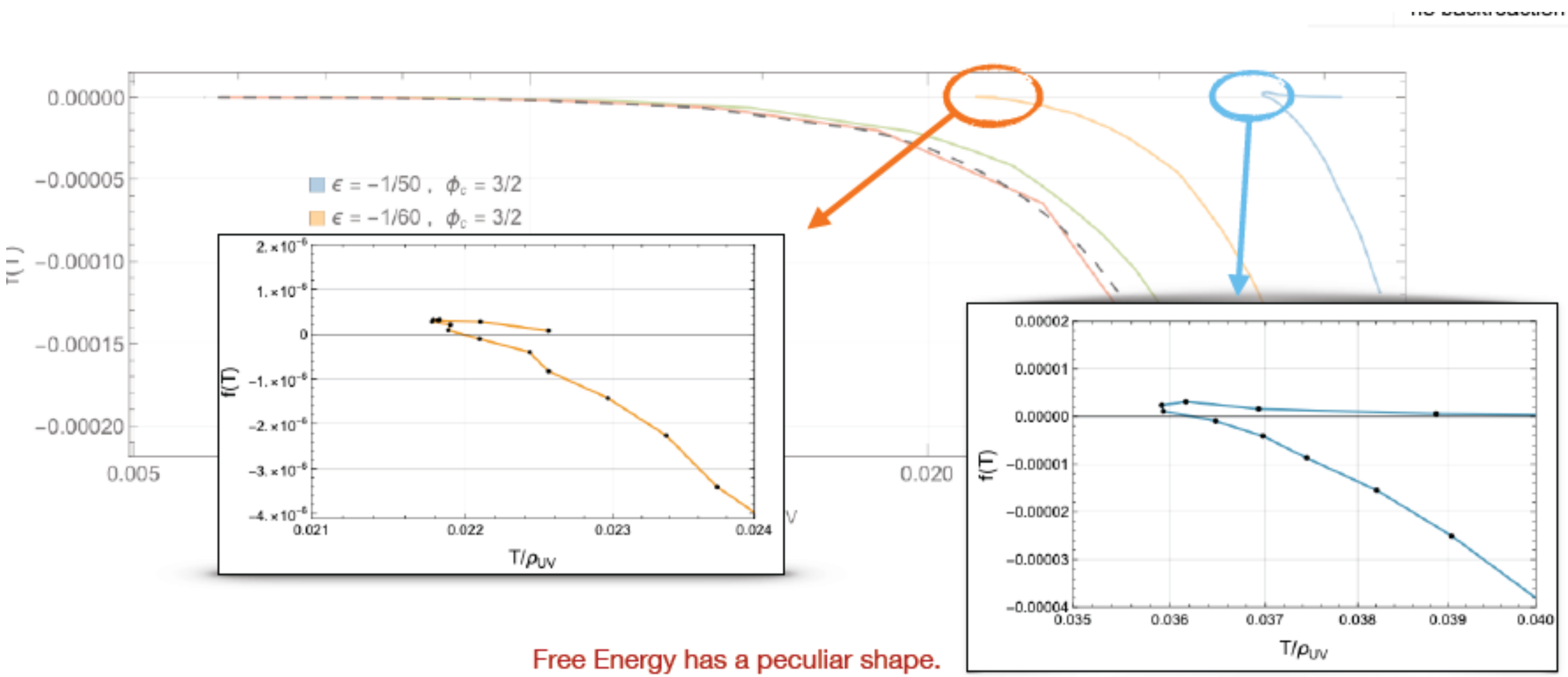
- Same temperature but different entropies

Free Energy Also Not Single-Valued



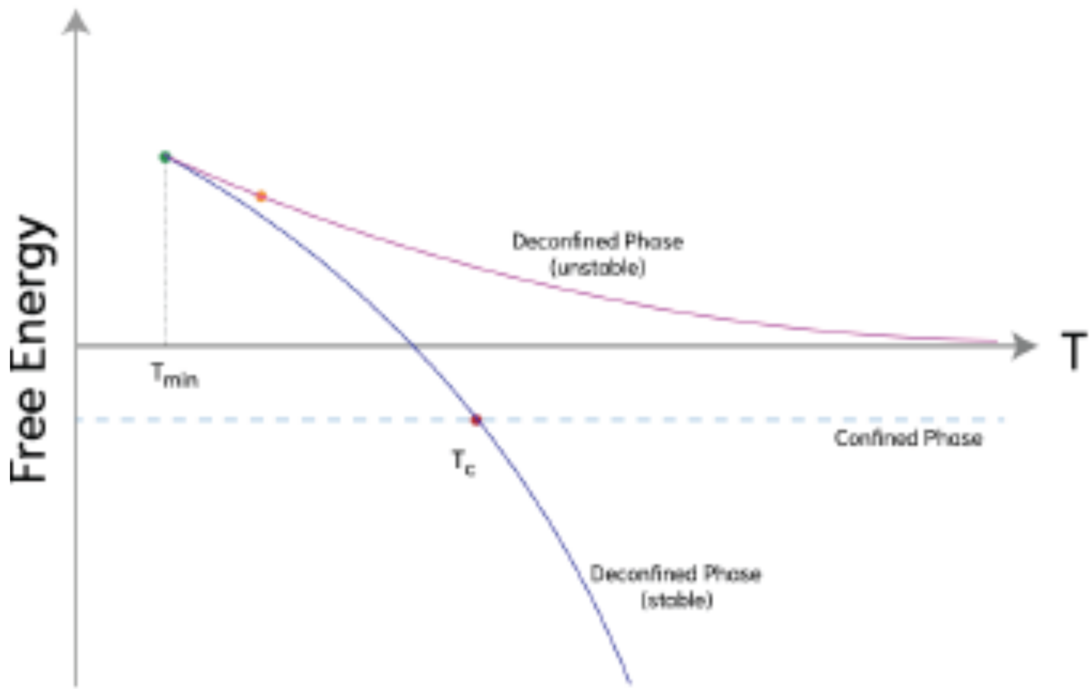
- This is important for phase structure

Focus on Strongly Back-Reacted Cases



Free Energy has a peculiar shape.

Back-Reacted Phase Diagram



- RS is preferred stable phase at low temperature
- There might be a spinoidal phase transition in GW signal (or some other sign of instability)

Consequences and Generality?

- This was a specific model but reason to think can be generic
  - Featured in examples
  - Extra contribution from scalar field can significantly modify metric when no longer in perturbative regime
- Important Consequences

  Not necessarily first order phase transition

  Not necessarily supercooling
- Can be other GW signals

  RS might be less constrained

  Really a 5d analysis necessary

Conclusions

- RS Cosmology subtle
  - Seems to depend fairly strongly on model

  Can have GW signatures and supercooling

  But connected

    Models with less supercooling associated with less strong GW signal

  We explored one perturbative model where constraints weaked

  And one ultimately nonperturbative model where it will be very interesting to see GW consequences

  Story old, but not over!