Avoided Deconfinement in Randall-Sundrum Models

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Randall Sundrum (type I) Models

Randall & Sundrum: hep-ph/990522

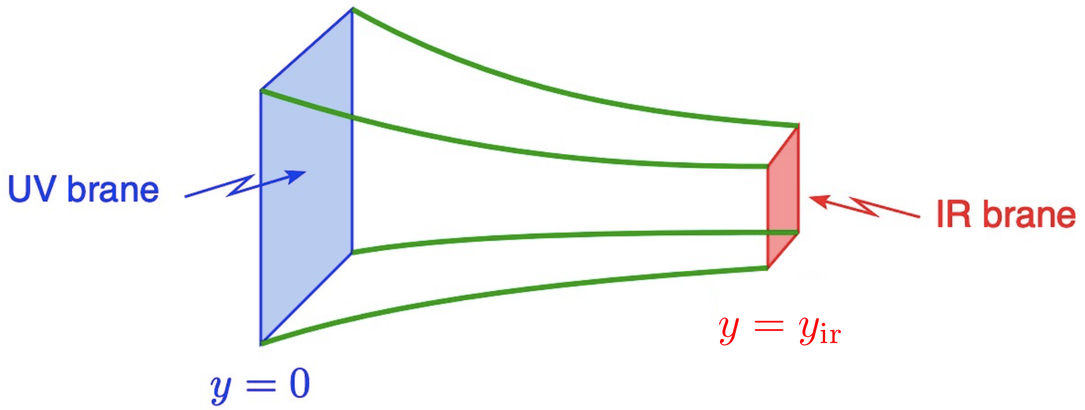
- Two branes (UV and IR) separated by region of AdS space
- Radion degree of freedom:

$$\mu(x) = ke^{-ky_{\mathrm{ir}}(x)}$$

- Solution to hierarchy problem through warping of scales:

$$\mathrm{TeV} \sim \langle \mu \rangle = ke^{-ky_{\mathrm{ir}}}$$

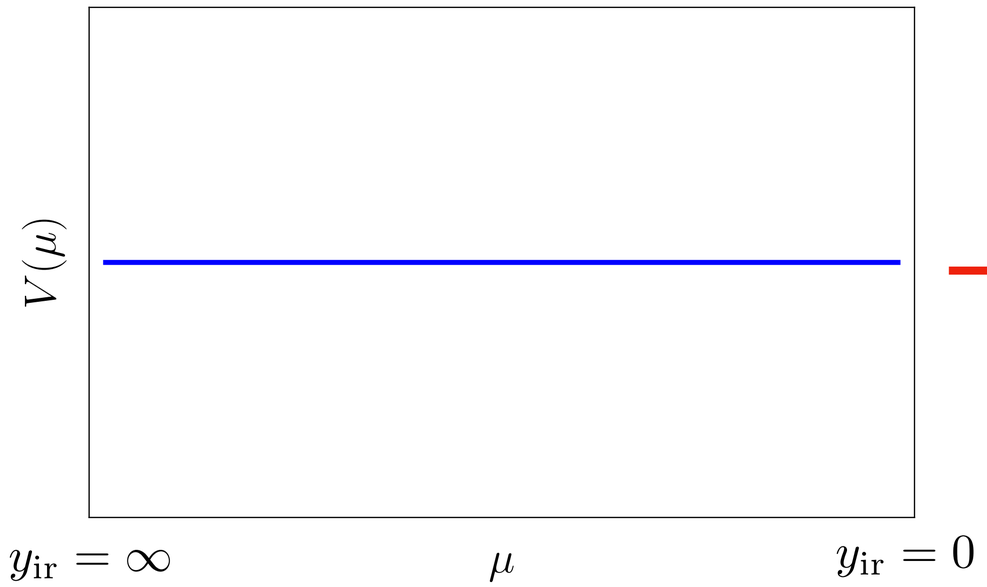
Diagram from Ponton: arxiv/1207.3827



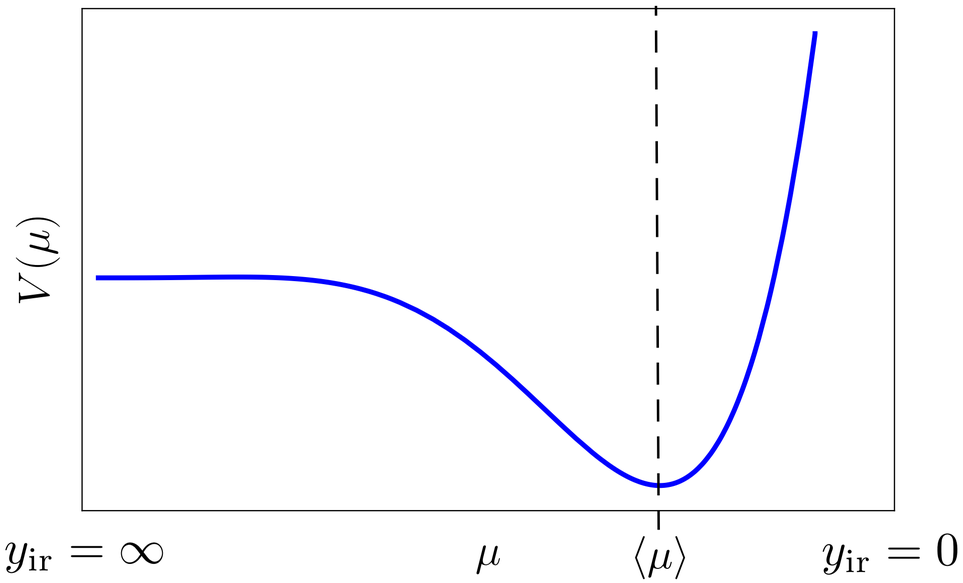
$$ds^2 = G_{AB}dx^A dx^B = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

Radion Potential RS model

Unstabilised RS



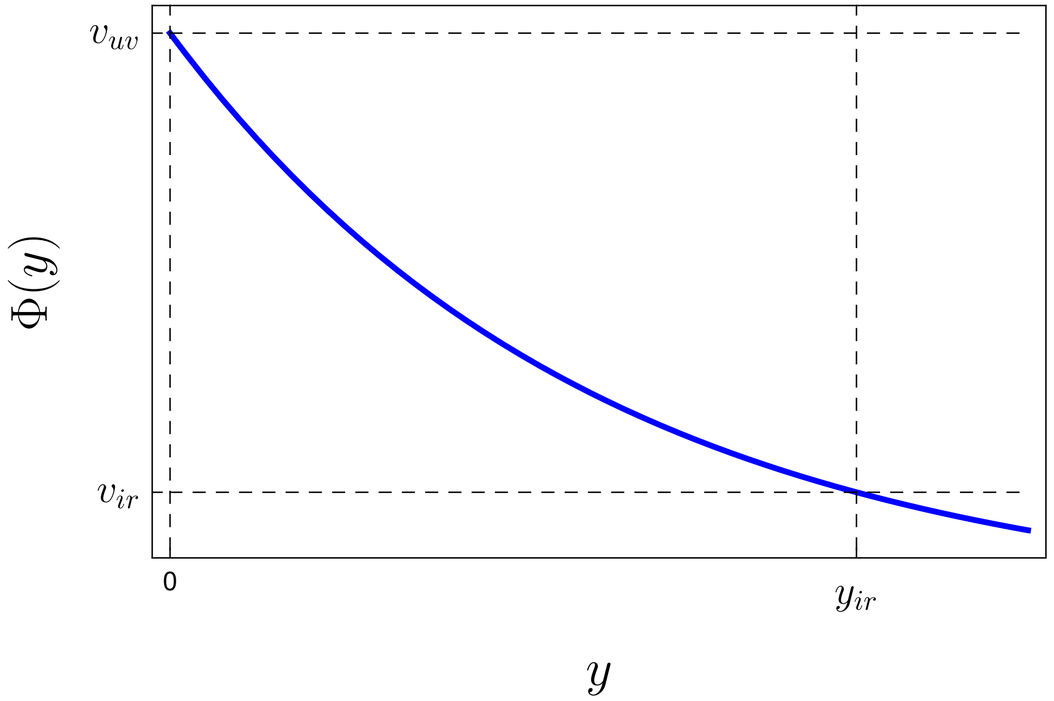
Stabilised RS



Goldberger Wise Stabilisation

Goldberger & Wise: hep-ph/9907447

- Add a scalar field Φ (the Goldberger Wise field) with:
  - 5d mass: $m_\Phi^2 = \epsilon k^3$
  - UV Boundary value: $\Phi(0) = v_{\rm uv}$
  - IR Boundary value: $\Phi(y_{\rm ir}) = v_{\rm ir}$



- Radion potential minimised for:

$$\langle \mu \rangle \sim k \left(\frac{v_{\rm ir}}{v_{\rm uv}} \right)^{1/\epsilon}$$

AdS/CFT interpretation of RS model

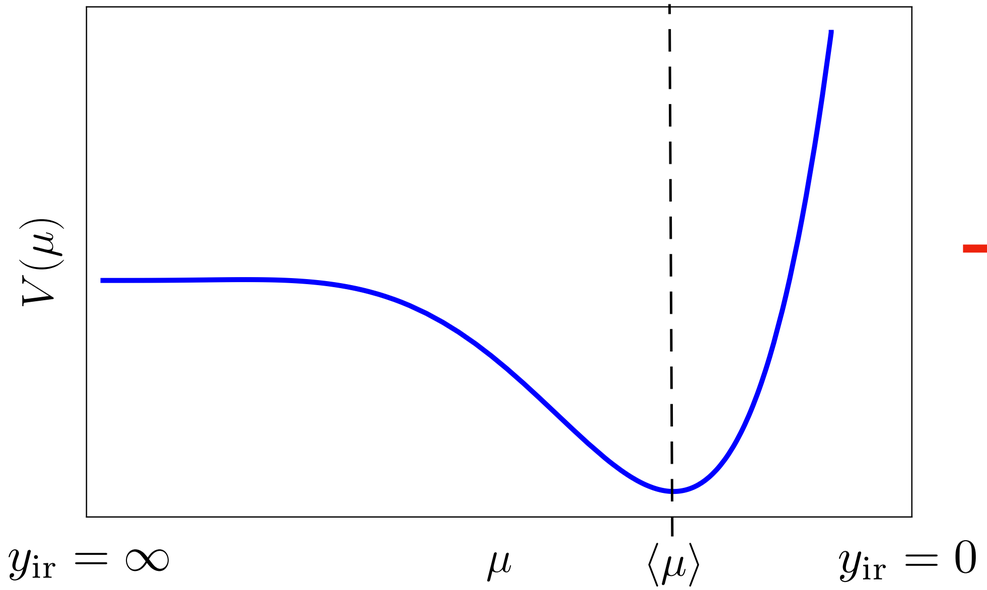
Rattazzi & Zaffaroni: hep-th/0012248; Arkani-Hamed, Porrati, & Randall: hep-th/0012148

RS Model	CFT
$N^2 = 16\pi^2 (M_5/k)^3 - 1$	Degrees of freedom = N^2
Weak gravity: $M_5/k \gg 1$	Large -N limit
ke^{-ky}	Renormalisation scale
GW Field profile	RG flow of marginal coupling
Radion vev	Confinement scale

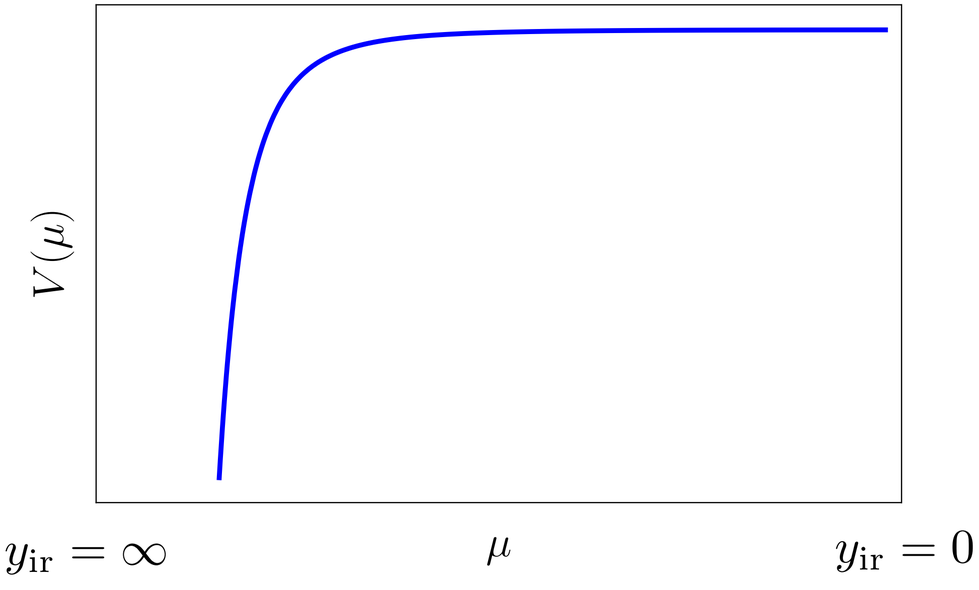
The RS model is dual to the confined phase of a strongly coupled CFT

RS model at High Temperature

Stabilised RS at low temperature



RS at high temperature



Confinement Phase Transition

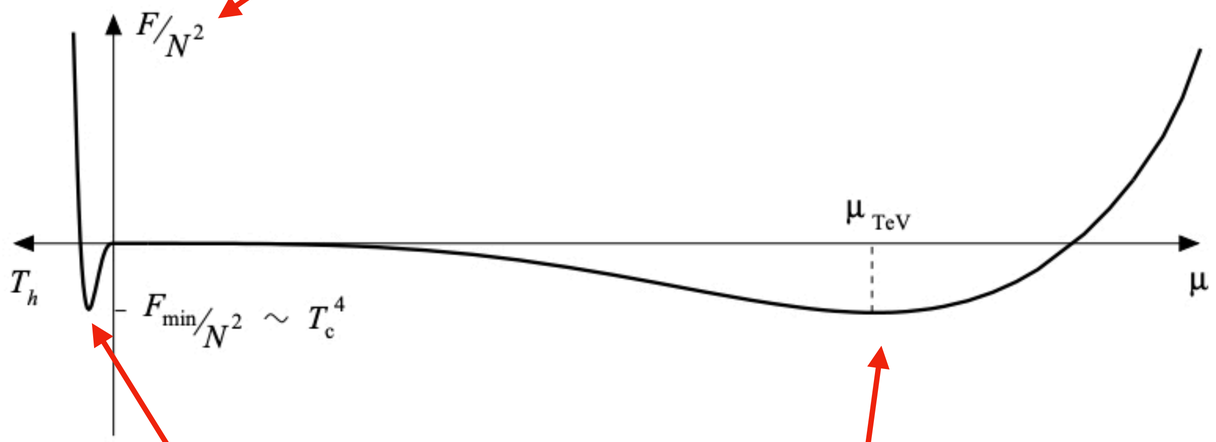
Creminelli, Nicolis & Rattazzi: hep-th/0107141, Witten: hep-th/9803131

- Deconfined phase described by AdS-Schwarzschild solution
- Confinement phase transition is 1st order — rate is determined by tunnelling from false to true vacuum
- Tunneling rate is exponentially suppressed:

$$\Gamma \propto e^{-N^4 \epsilon^{-3/2}} \qquad \Gamma \propto e^{-N^{7/2} \epsilon^{-9/8}}$$

Potential height scales with N^2

Diagram from arxiv/hep-th/0107141



Horizon position in deconfined phase

Radion vev in RS/confined phase

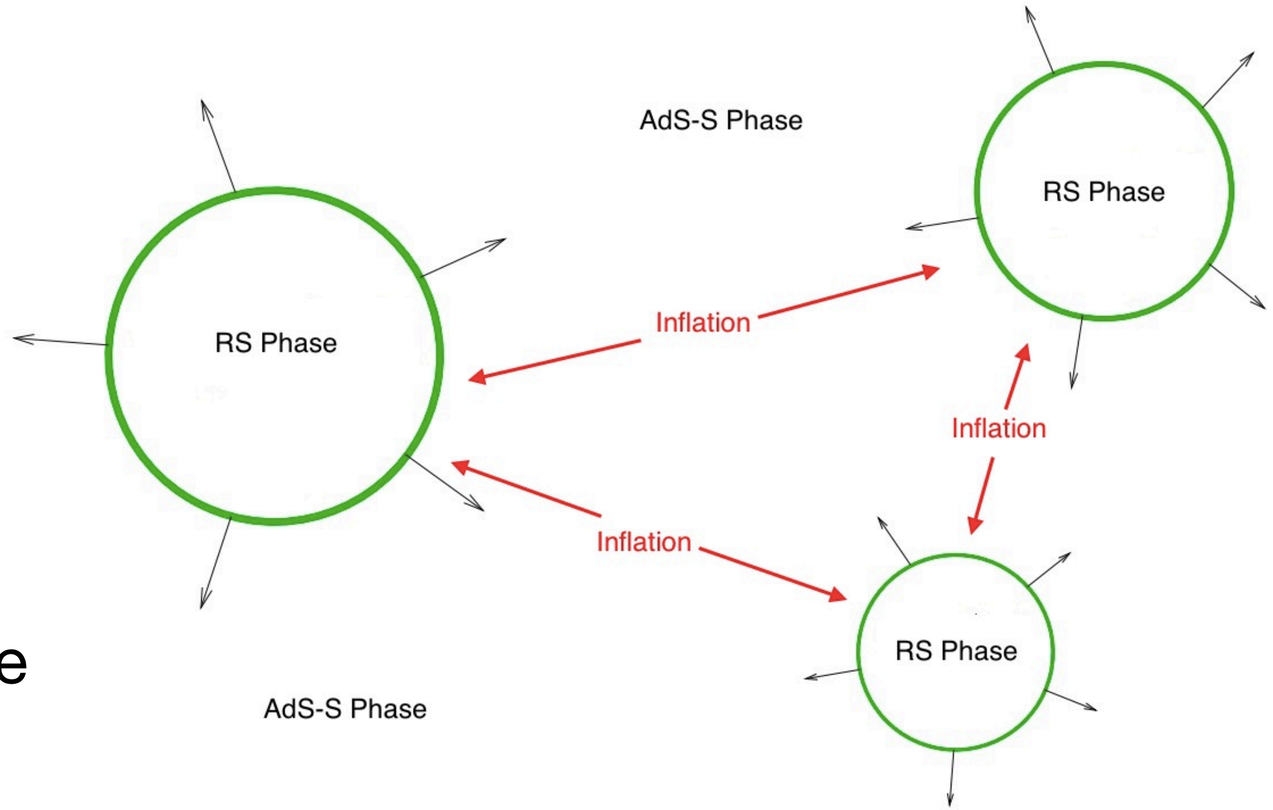
Cosmological Problems

Creminelli, Nicolis & Rattazzi: hep-th/0107141; Guth & Weinberg: Nucl. Phys. B. B212, 1983

- Supercooling leads to long period of inflation
- Requiring phase transition finish leads to:

$$N \lesssim 3.7$$

- Modifications can relax bounds, but don't change qualitative picture



Kaplan, Schuster & Toro: hep-ph/0609012,
Hassainan, March-Russell & Schvellinger: hep-th/0708.2060
Agashe et. al.: hep-ph/1910.06238, hep-ph/2010.04083

Outline

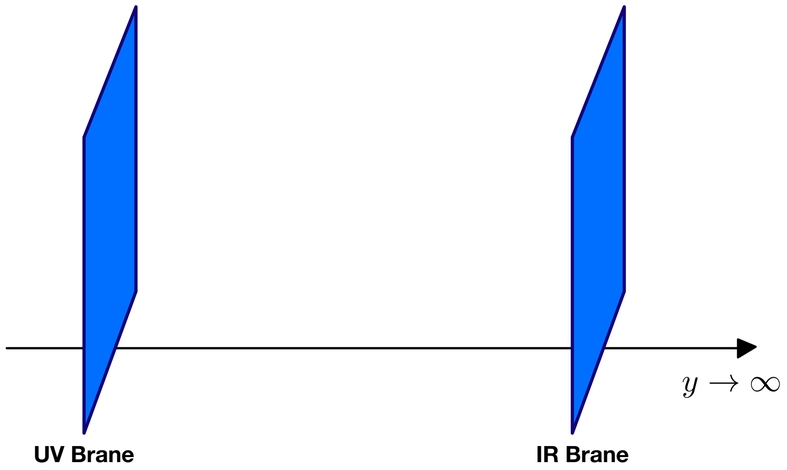
RS is a model for:

- Confinement and strong coupling above the TeV scale
- Spontaneously broken conformal symmetry
- Solutions to hierarchy problem

Problem:

- Confined phase unstable at high temperature
- Confinement phase transition is strongly suppressed, early universe cosmology is not viable

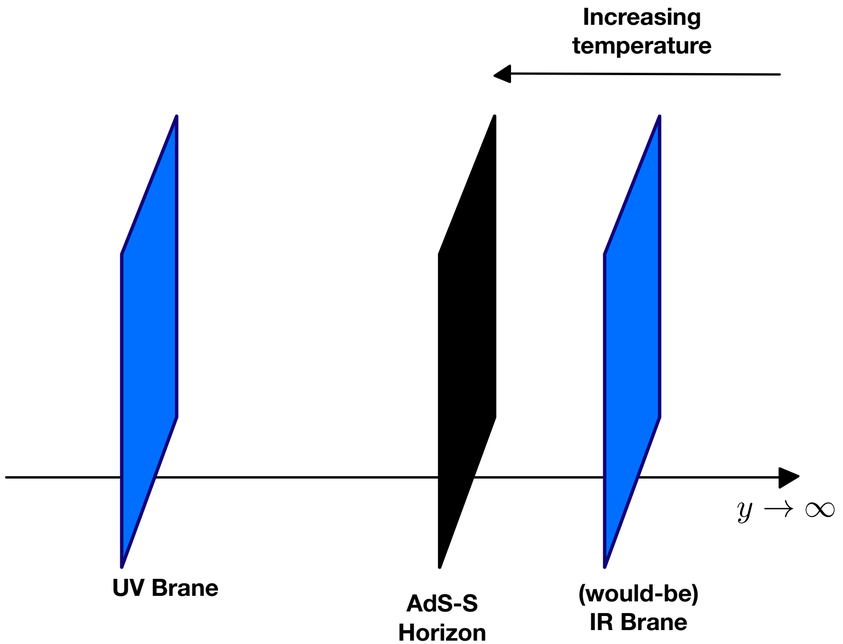
Avoided Deconfinement

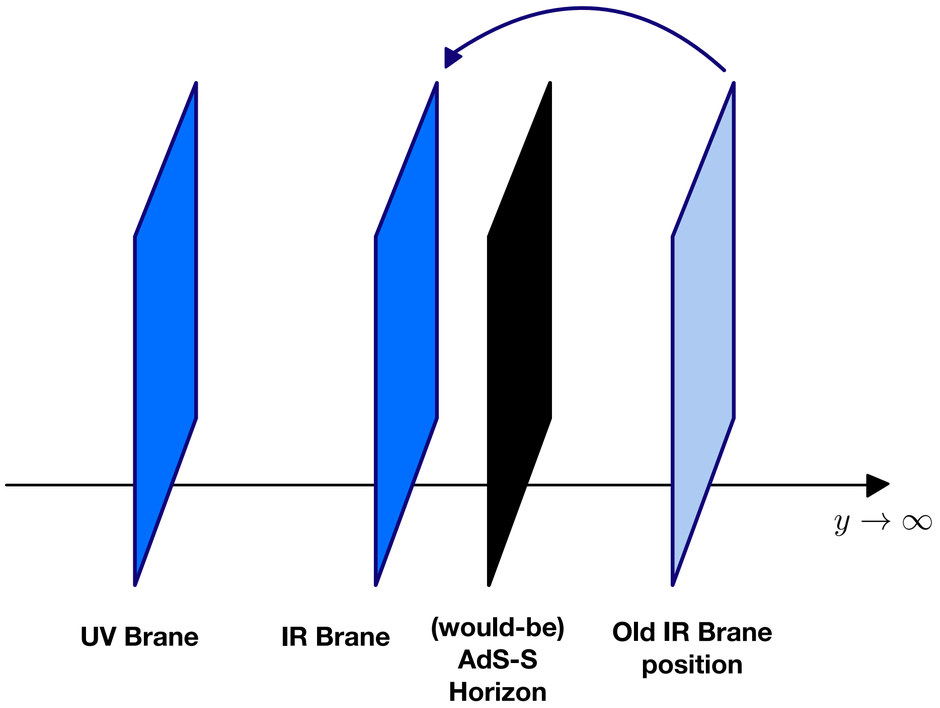


Zero Temperature solution

RS Model at high temperature

AD Model at high temperature





Avoided Deconfinement

- Aim is to modify stabilisation mechanism so confined phase is (meta)stable at high temperature
- Achieve this by having the GW field value on the IR brane increase with temperature
- IR brane then moves with temperature to avoid collapsing into black hole
- Model similar to models of symmetry non restoration, e.g.:

Weinberg: Phys. Rev. D 9, 3357 (1974)
Meade & Ramani: arxiv/1807.07578
Baldes & Servant: arxiv/1807.08770
Glioti, Rattazzi & Vecchi: arxiv/1811.11740

Modified Stabilisation

- Want boundary condition of GW field to satisfy:

$$\Phi^2(y_{\rm ir}) = v_{\rm ir}^2 + bT^2, \qquad b > 0$$

- One model which leads to this is (for ϕ a vector of N_s scalar fields):

$$V_{\rm ir} = \frac{\lambda_1}{4}\left(\Phi^2 - v_{\rm ir}^2\right)^2 + \frac{m_\phi^2}{2}\phi^\dagger\phi + \frac{\lambda_2}{4}(\phi^\dagger\phi)^2 + \frac{\lambda_3}{2}(\phi^\dagger\phi)\Phi^2$$

- Which leads to b.c. on the IR brane:

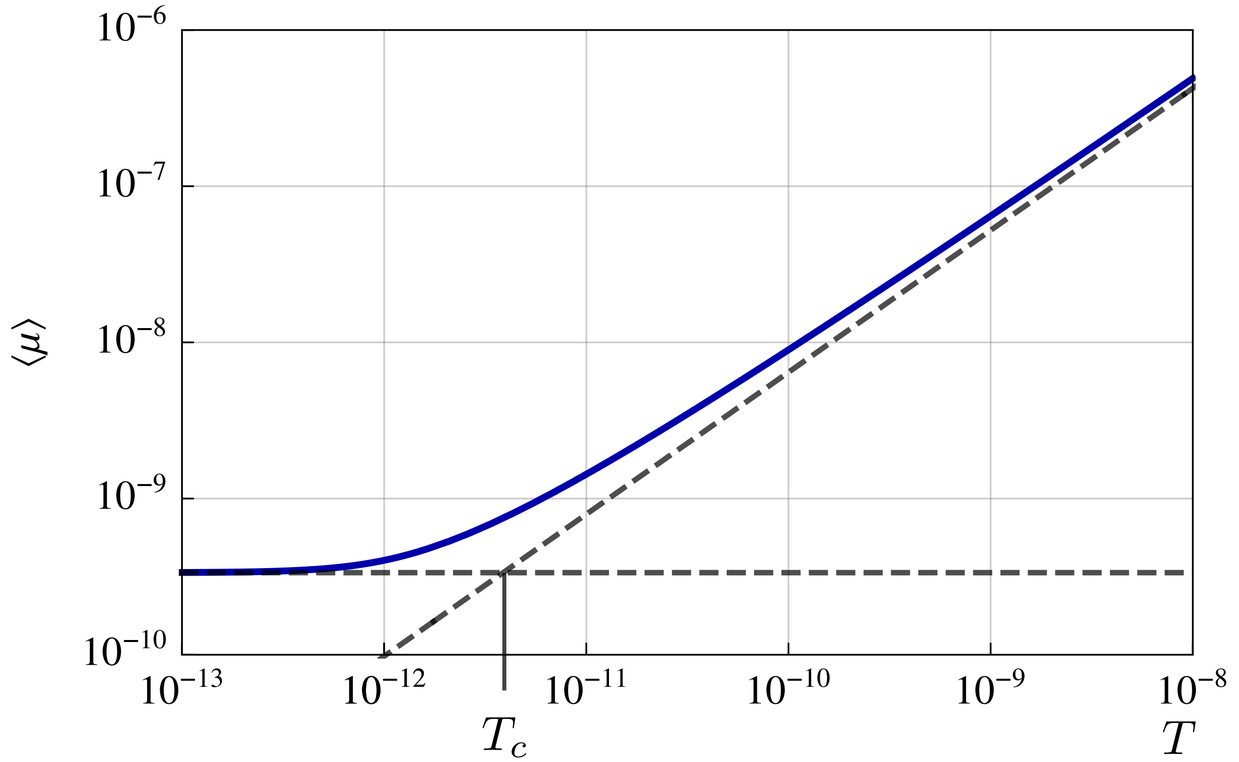
$$\Phi^2(y_{\rm ir}) = v_{\rm ir}^2 - \frac{\lambda_3}{\lambda_1}\frac{N_s}{3}T^2 e^{2ky_{\rm ir}}$$

High Temperature Behaviour

- Radion stabilised at high temperatures:

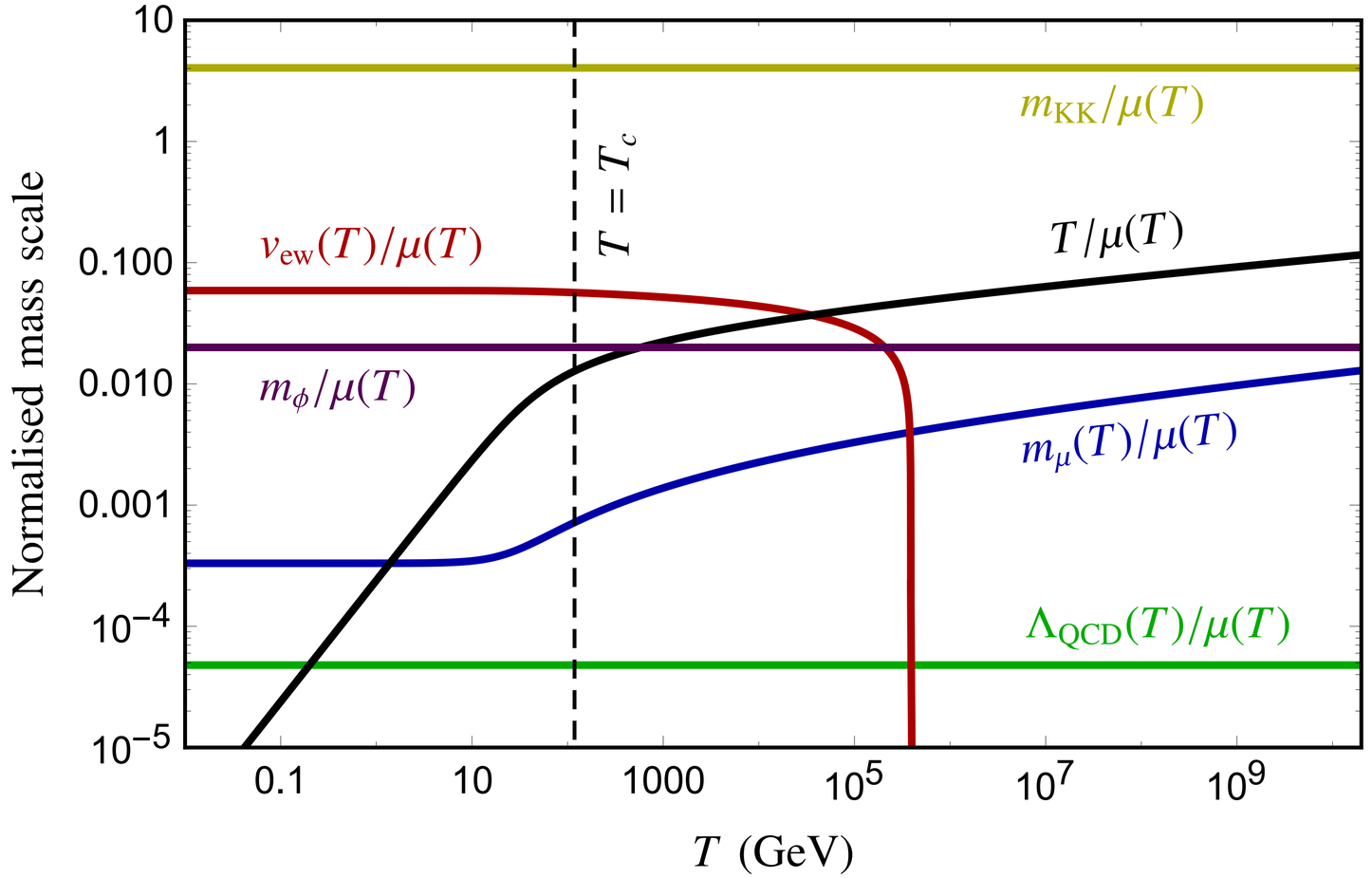
$$\mu = ke^{-ky_{\rm ir}} \propto T^{\frac{1}{1+\epsilon}}$$

- Confined phase metastable at high temperatures
- Have critical temperature T_c above which radion vev starts to vary



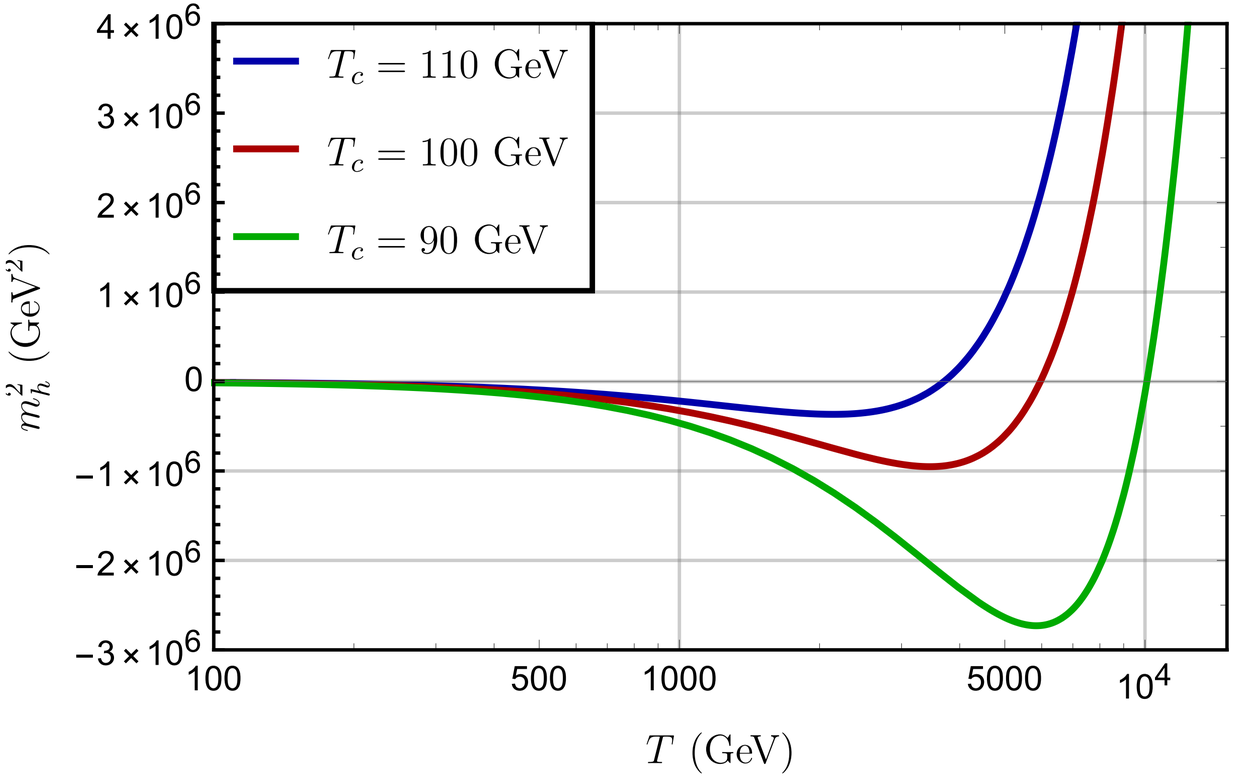
SM Mass Scales

- QCD scale, electroweak vev scale with radion, leading to behaviour: $\frac{T}{\Lambda} \propto T^{\frac{\epsilon}{1+\epsilon}}$



Early Universe Cosmology

- Electroweak phase transition can be at significantly higher temperature
- Modified freeze-out mechanisms for particles heavier than T_c
- UV and IR sectors in contact in the very early universe - possible implications for baryogenesis



Conclusion

- RS models are a way to study confinement in strongly coupled gauge theories
- Confinement phase transition is exponentially suppressed by N^2, leads to strong bounds on N
- Proposed solutions in literature relax this bound somewhat but don’t change qualitative behaviour
- Avoided deconfinement resolves problem by stabilising the confined phase at high temperature
- Modified cosmology at high temperature - possible implications for baryogenesis