Thermodynamics of IRFP* and Technicolor theories from gauge/gravity duality

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with

Kajantie arXiv:0912.4128 and
Kajantie,Tuominen work in progress

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*Infrared fixed point

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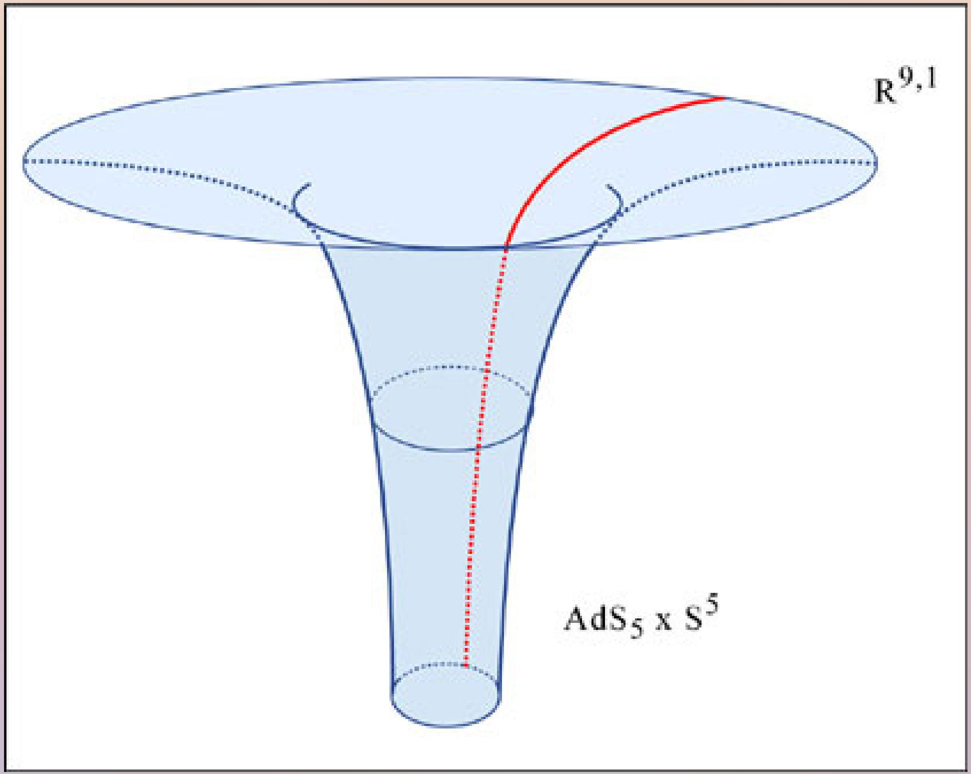
1. Motivation

- Study thermodynamics of field theories which have a strong coupling regime: QCD, IRFP, Technicolor...
- Strong coupling $\rightarrow$ perturbation theory does not work
- Methods: Lattice, gauge/gravity duality...

Aim of this talk

Introduce the 5D Einstein-Dilaton model and use it to calculate thermodynamics for various field theories.

2. Gauge/Gravity duality



Gauge/gravity duality or Holography

- Idea: pure gauge theory is dual to higher dimensional theory including gravity
- First realization by Maldacena, -97:

  - String theory on $AdS_5 \times S_5$ dual to d=4 SU(N) N=4 supersymmetric theory

Gravity

Gauge theory

- 't Hooft limit

$$\lambda = g^2 N_c \to \infty, \; N_c \to \infty$$

Classical gravity ⇄ **Strongly coupled quantum theory**

IHQCD: Improved Holographic QCD/SU(N). *Gursoy, Kiritsis, Mazzanti, Nitti...*

- Pure gravity in AdS is dual to a strongly coupled conformal field theory but realistic field theories have also a weak coupling regime and are non-conformal.
- In IHQCD these two aspects are introduced by extra scalar field

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R - \frac{12}{\mathcal{L}^2}\right) \longrightarrow S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R - \frac{4}{3}(\partial\Phi)^2 - V(\Phi)\right)$$

Arbitrary. Contains AdS constant

- Ansatz and identifications

$$ds^2 = b(r)^2\left[\frac{dr^2}{f(r)} - f(r)dt^2 + dx_m dx^m\right] \longrightarrow$$

$\Phi(r) \longrightarrow$

Energy scale $b(r)$

Coupling constant $\lambda(r) = e^{\Phi(r)}$

Vacuum $f(r) = 1$

Thermal state $f(r) \neq 1$

Equations/Potential fixing

- By the choice of the coupling constant and energy scale we have fixed the scheme we are working in
- Beta function:

$$\frac{d\lambda}{d\ln E} = \frac{d\lambda}{d\ln b} = \beta(\lambda)$$

- Einstein equations:

$$6\frac{b'^2}{b^2} - 3\frac{b''}{b} = \frac{4}{3}\frac{\lambda'^2}{\lambda^2} \qquad \frac{f''}{f'} + 3\frac{b'}{b} = 0 \qquad 6\frac{b'^2}{b^2} + 3\frac{b''}{b} + 3\frac{b'}{b}\frac{f'}{f} = \frac{b^2}{f}V(\lambda)$$

Dilaton potential is chosen so that it produces expected dynamics for dual theory.

For example: QCD must be asymptotically free at UV and confining at IR

QCD/SU(N) thermodynamics from IHQCD

Gursoy, Kiritsis, Mazzanti, Nitti (0903.2859), Panero (0907.3719)...

- Potential: $V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}\left[\log\left(1 + V_2\lambda^{4/3} + V_3\lambda^2\right)\right]^{1/2}\right\}$

Correct UV asymptotics

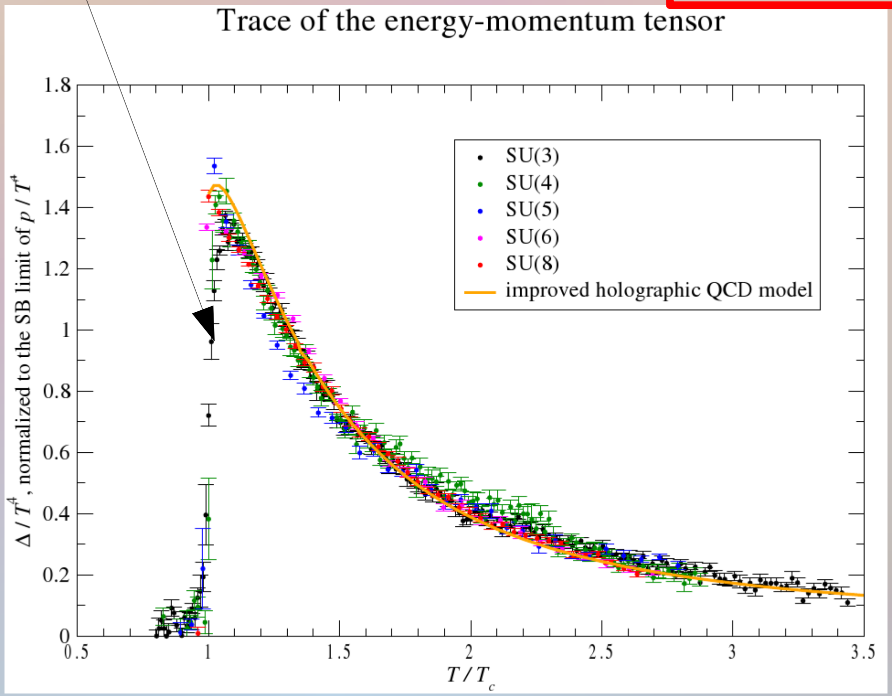
Confining + linear glue ball spectra

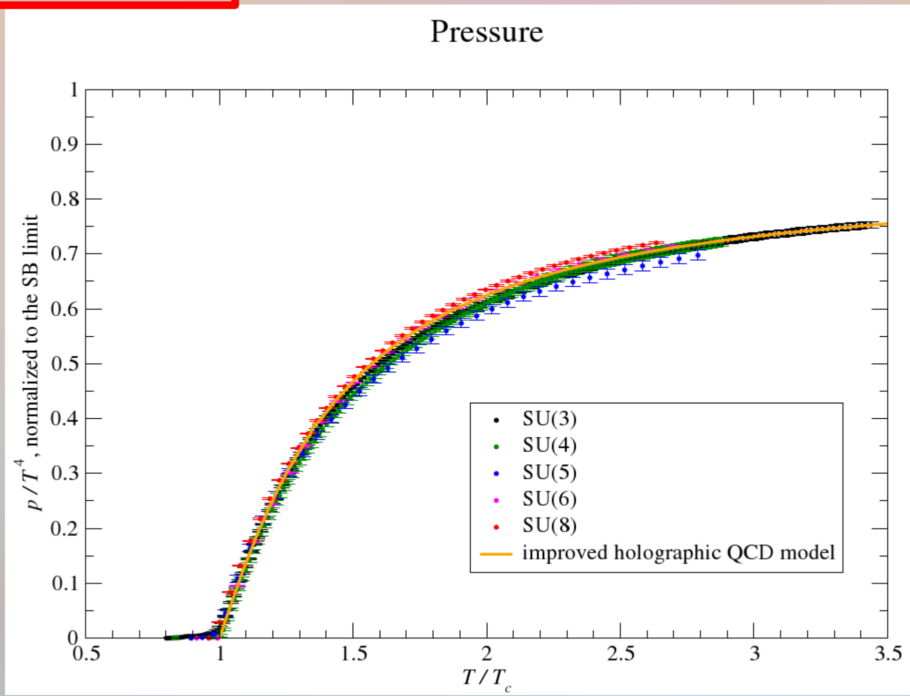
Fitted to data

$V_1 = 14 \qquad V_3 = 170$

First order transition

Very good agreement





3. Theories with Infrared Fixed Point

Banks-Zaks

- Definition: $\beta(\lambda_{fp}) = 0$

  -Scheme independent: $\lambda(\lambda^\star_{fp}) = \lambda_{fp}$

$$\frac{d\lambda}{d\ln E} = \beta(\lambda) \;\Rightarrow\; \beta^\star(\lambda^\star) = \left(\frac{d\lambda(\lambda^\star)}{d\lambda^\star}\right)^{-1} \beta(\lambda(\lambda^\star))$$

Beta function slope still depends on scheme!

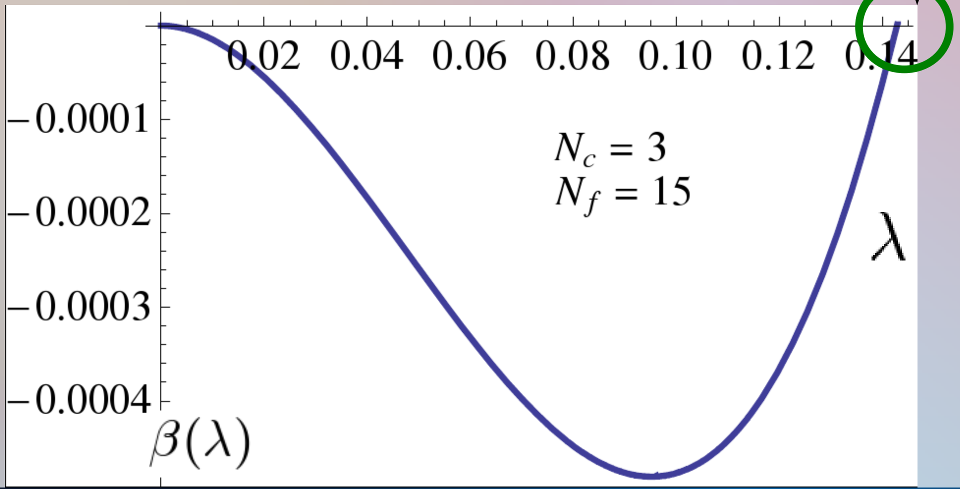
Perturbative FP $\rightarrow$ in the weak coupling regime

- QCD with large number of flavors: *Banks-Zaks('82)* fixed point

$$\beta(\lambda) = -b_0(N_c, N_f)\lambda^2 - b_1(N_c, N_f)\lambda^3$$

$$\lambda_{fp} = -\frac{b_1(N_c, N_f)}{b_0(N_c, N_f)} > 0$$

$$N_c = 3,\; N_f \geq 9$$



Non-pertubative fixed point

- In supersymmetric QCD the beta function can be calculated exactly. *Novikov-Shifman-Vainshtein-Zakharov*
- There has been a proposal for the exact beta function for non-supersymmetric theories. *Ryttov, Sannino...*

Generally these take a form

$$\beta(\lambda) = -2\beta_0\lambda^2 \frac{(1-v\lambda)}{1-j\lambda}$$

- Search for theories with IRFP is a hot topic in lattice field theory. *Catterall-Giedt-Sannino-Schneible 0807.0792, Hietanen-Rummukainen-Tuominen 0904.0864, Del Debbio-Lucini-Patella-Pica-Rago 0907.3896*

WARNING!

- Fermions are crucial for IRFP and TC theories
- Adding effects of the flavor to gauge/gravity duality is non-trivial. *Karch, Katz, Erdmenger, Meyer, O'Bannon, Ammon, Kiritsis, Kerner*
- We assume that 5D Einstein-Dilaton model can be used also with theories where flavor is important and that flavor affects only the form of the dilaton potential

$$V(\lambda) \longrightarrow$$

QCD, infrared fixed point, Technicolor

WARNING!

Note

- For IRFP and TC duals the underlying field theory is unspecified and thermodynamic properties are calculated using the dilaton potential which produces typical beta functions.
- Dilaton potential contains free parameters which have to be restricted by the choice of underlying theory

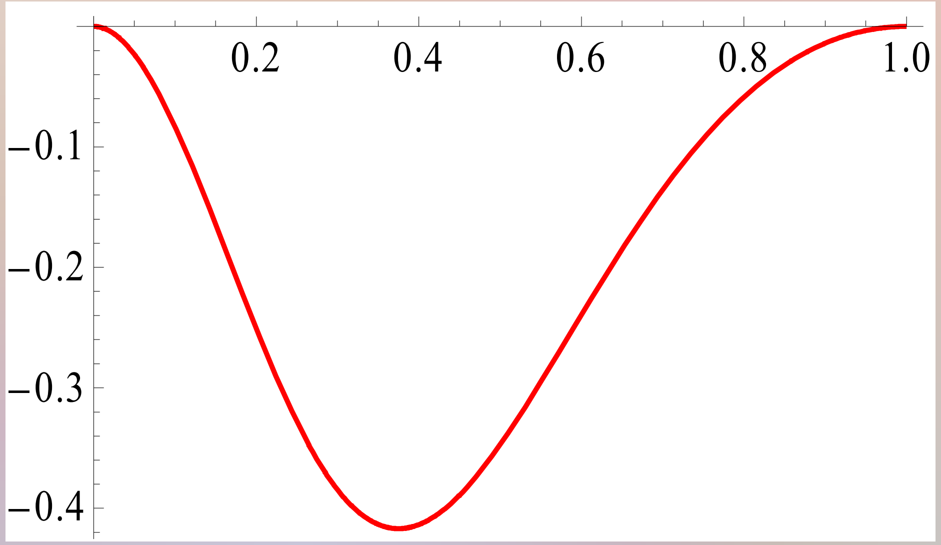
Holographic IRFP: thermodynamics

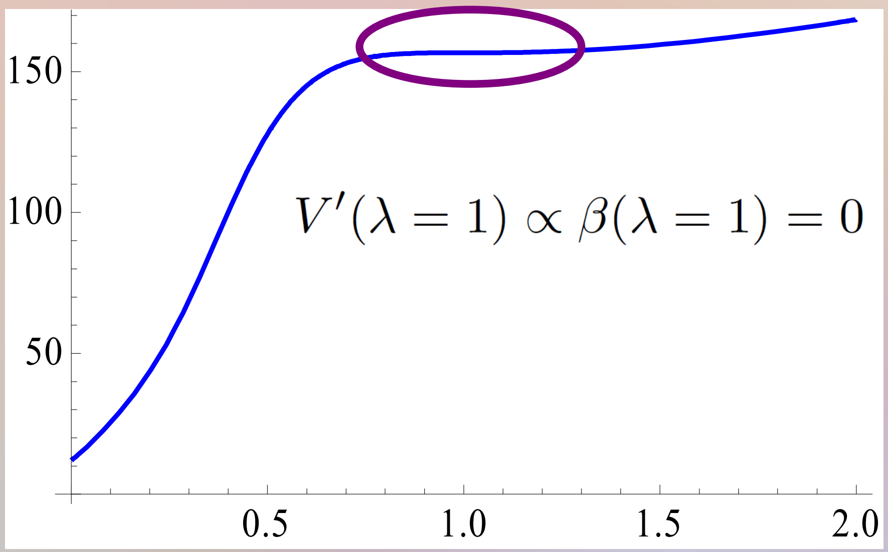
Alanen, Kajantie, Tuominen...

- Calculate <u>dilaton potential</u> from a given beta function

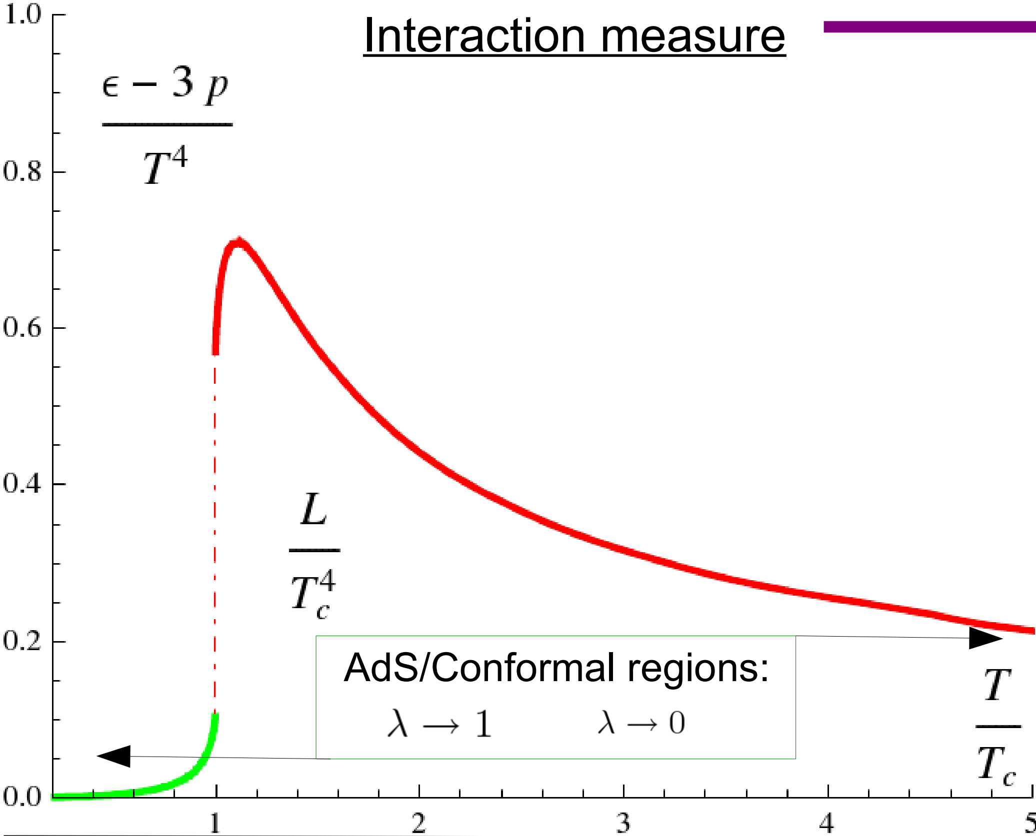
Can be calculated exactly

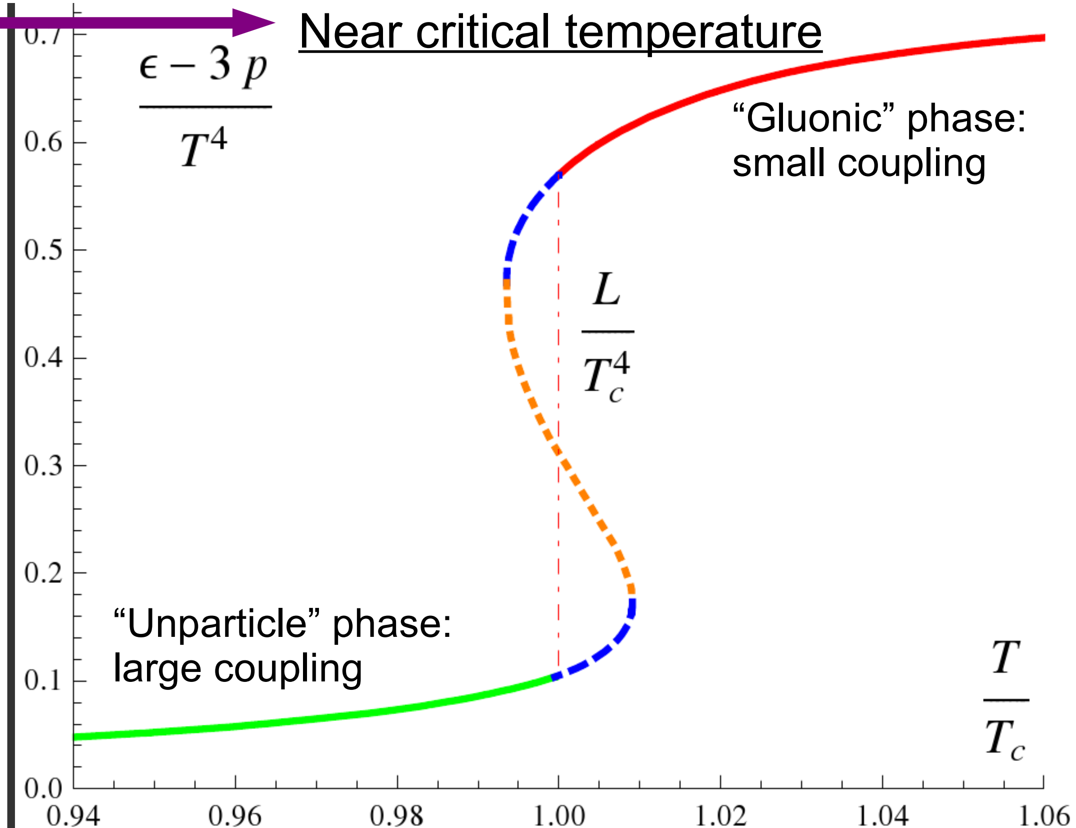
$$\beta(\lambda) = -c\lambda^2 \frac{(1-\lambda)^2}{1+a\lambda^3} \xrightarrow{f(r)=1} V(\lambda) = \frac{12}{\mathcal{L}^2} e^{-\frac{8}{9}\int d\lambda \frac{\beta(\lambda)}{\lambda^2}} \left[1 - \left(\frac{\beta(\lambda)}{3\lambda}\right)^2\right]$$

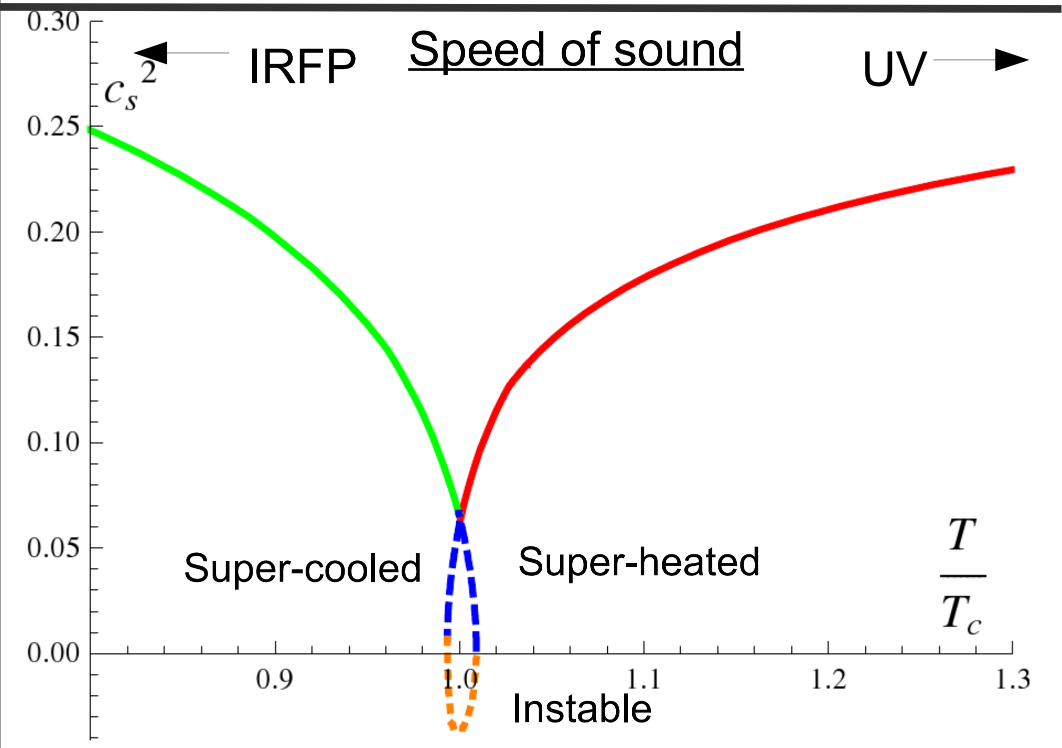




- Search black hole solutions with $f(r) \neq 1$ $\rightarrow$ **<u>Thermodynamics</u>**

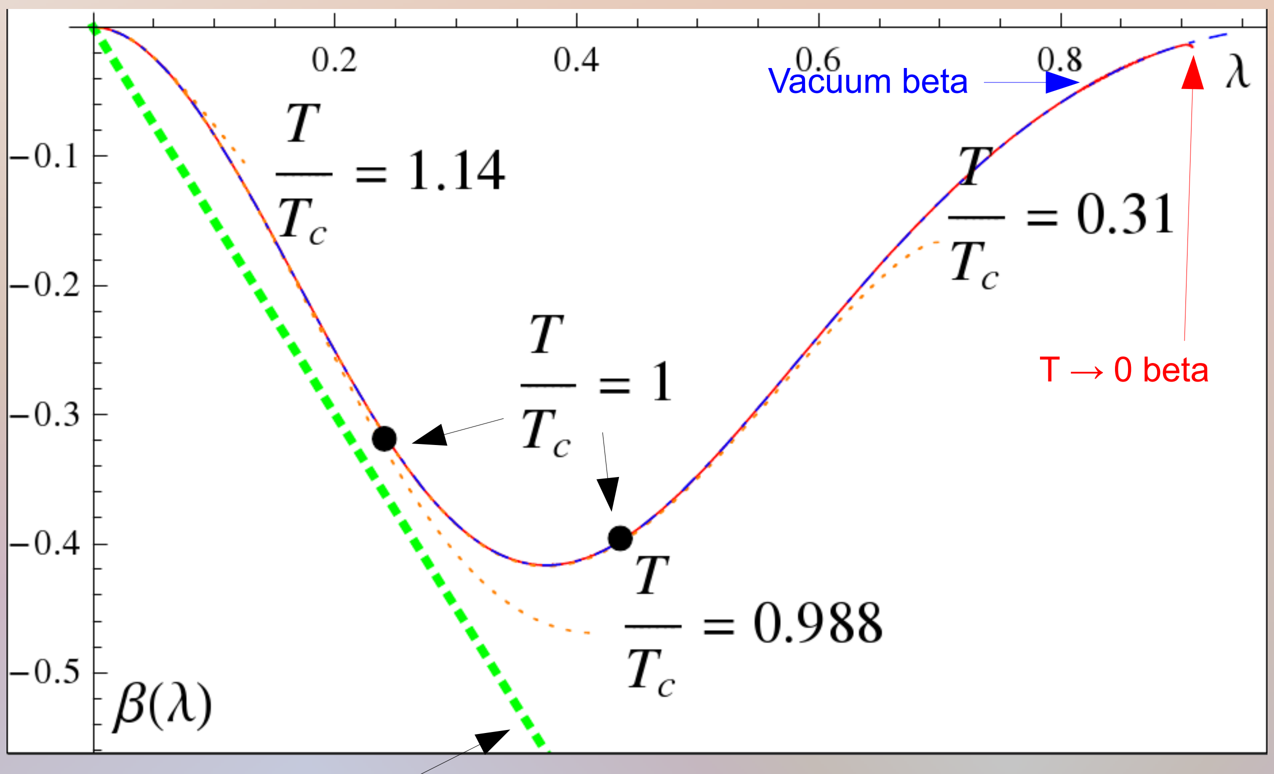






- QCD-like interaction measure
- First order phase transition between two asymptotically conformal phases: gluonic → unparticle $\epsilon - 3p \to 0 \qquad p = \frac{g_{eff}}{90}\pi^2 T^4$
- Super-heated/cooled phases: thermodynamically unfavored
- Unstable: speed of sound squared is negative
- Not confining/deconfining transition! BH phase always dominates. BH → BH transition.

Beta function



"confining line"

$$\beta(\lambda) = -\frac{3}{2}\lambda$$

- Asymptotically free at UV
- First order phase transition
- Infrared fixed point
- "Thermal" beta function

4. Walking Technicolor

Walking Technicolor

Weinberg, Susskind, Eichten, Lane, Sannino...

- TC idea: add new <u>strongly coupled theory</u> to EW scale which produces masses for weakly interacting bosons by chiral condensate

VEV for Higgs $250 GeV$

$$\langle\phi\rangle^3 = v^3 \sim \Lambda^3_{EWSB}$$

→

Techniquark condensate

$$\langle\overline{Q}_i Q_i\rangle \propto \Lambda^3_{TC} \sim \Lambda^3_{EWSB}$$

Similar to QCD chiral condensate

$$\langle\overline{\psi}_i\psi_i\rangle \propto \Lambda^3_{QCD}$$

- ETC idea: masses for SM-fermions

Yukawa interaction

$$\phi\overline{\psi}\psi$$

→

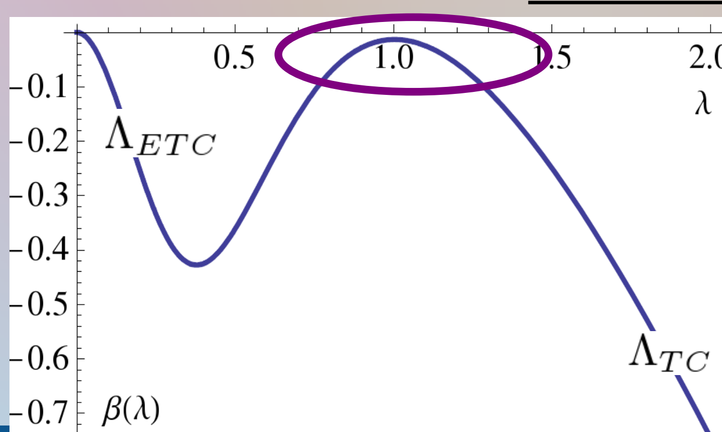
Interactions with techniquarks

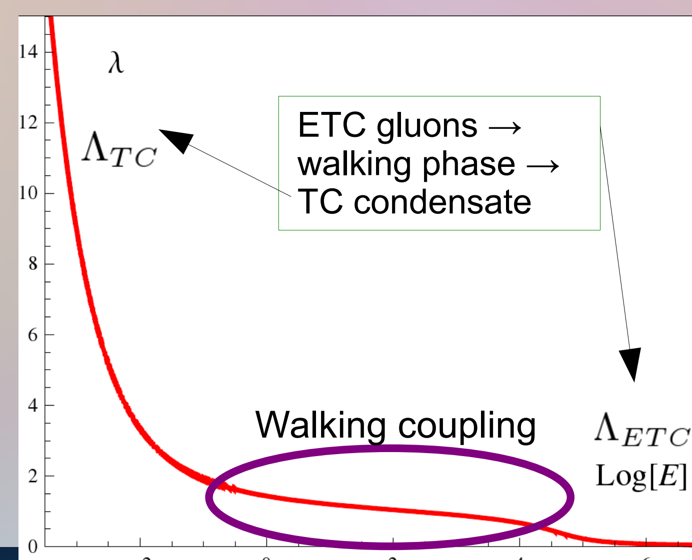
$$\frac{\bar{Q}Q\overline{\psi}\psi}{\Lambda^2_{ETC}} \qquad \frac{\Lambda_{TC}}{\Lambda_{ETC}} \lesssim 10^{-3}$$

- Large top-quark mass → TC must **<u>"walk"</u>**

Coupling almost independent of the scale E

$$\frac{d\lambda}{d\ln E} = \beta(\lambda) \approx 0$$





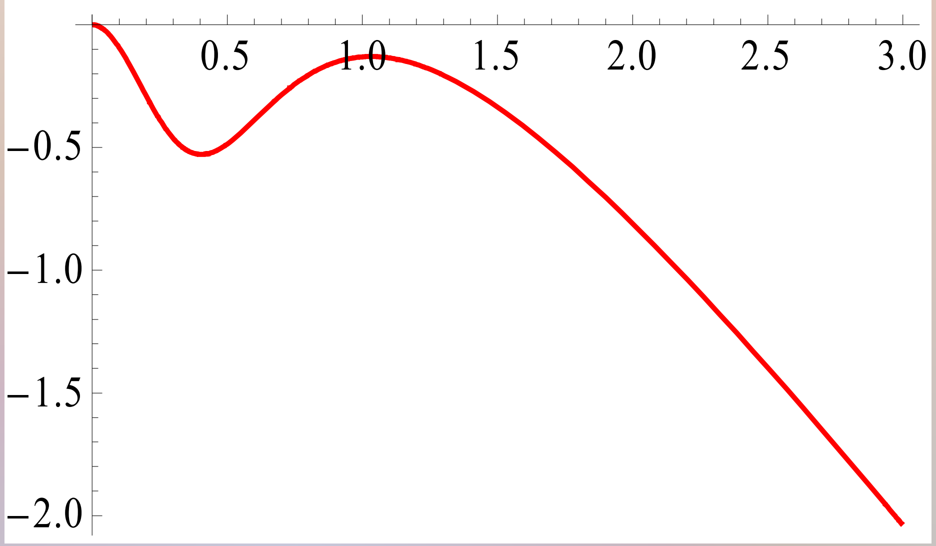
Holographic Walking TC: thermodynamics

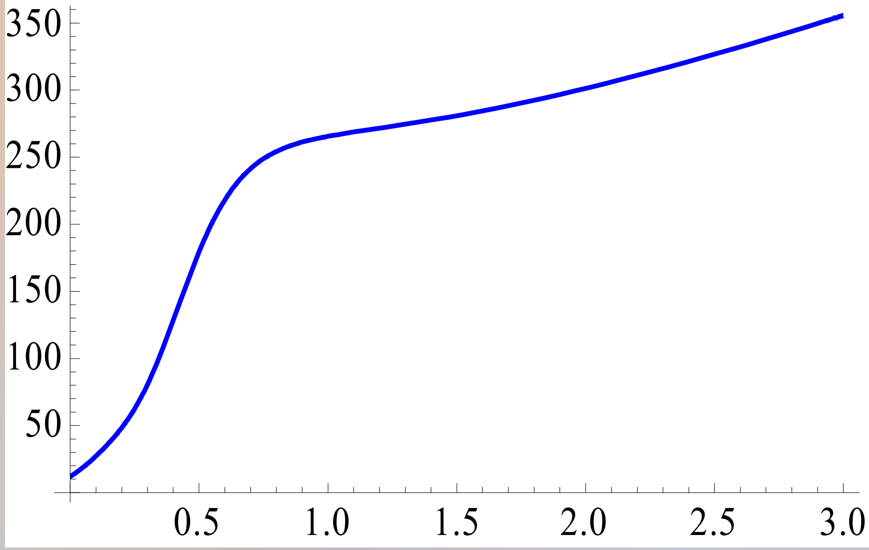
Alanen, Kajantie, Tuominen...

Walking beta → Walking potential (exact) → Walking + confining potential

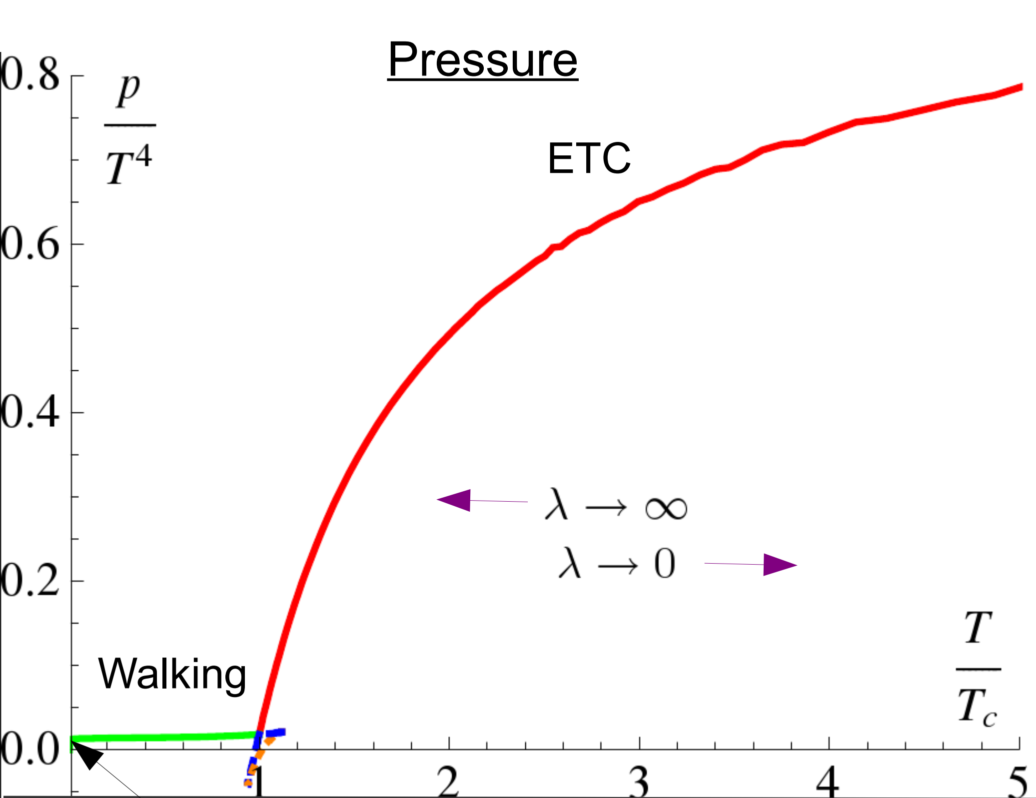
$$\beta_0(\lambda) = -c\lambda^2 \frac{[(1-\lambda)^2 + e]}{1 + a\lambda^3} \longrightarrow V_0(\lambda) \longrightarrow V(\lambda) = V_0(\lambda)\left[1 + \frac{e}{10}\sqrt{\log(1+\lambda^4)}\right]$$

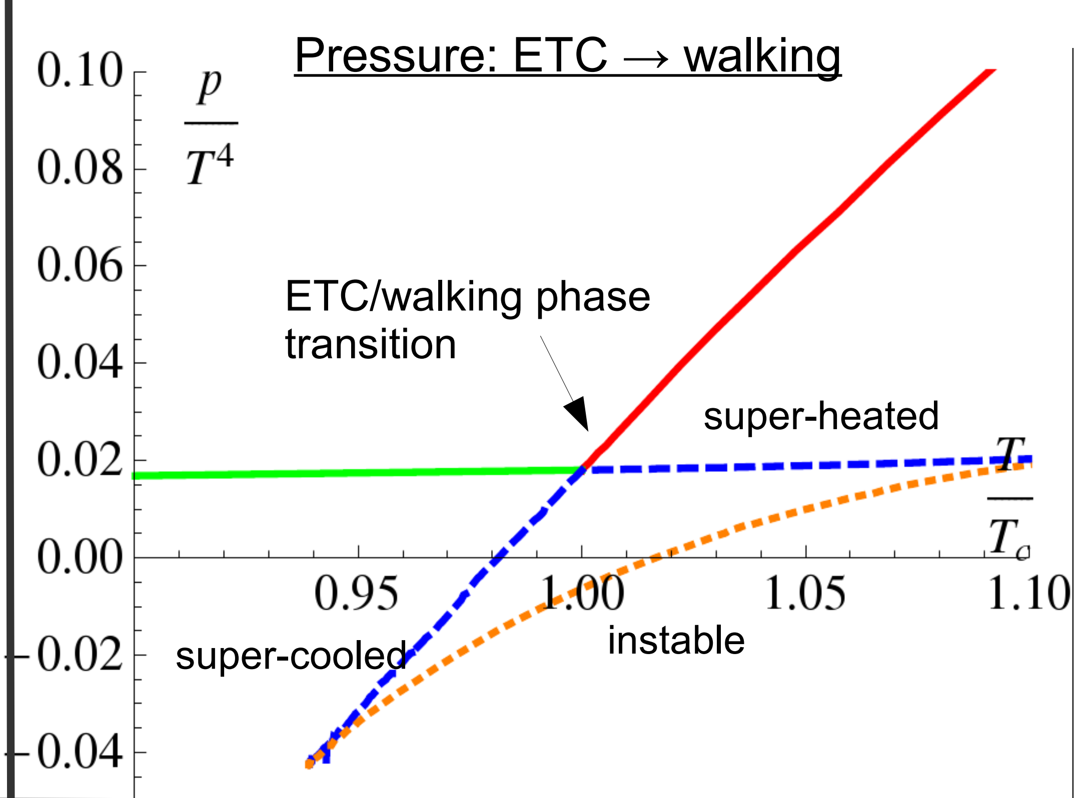
$\longrightarrow \beta(\lambda)$ Not known exactly

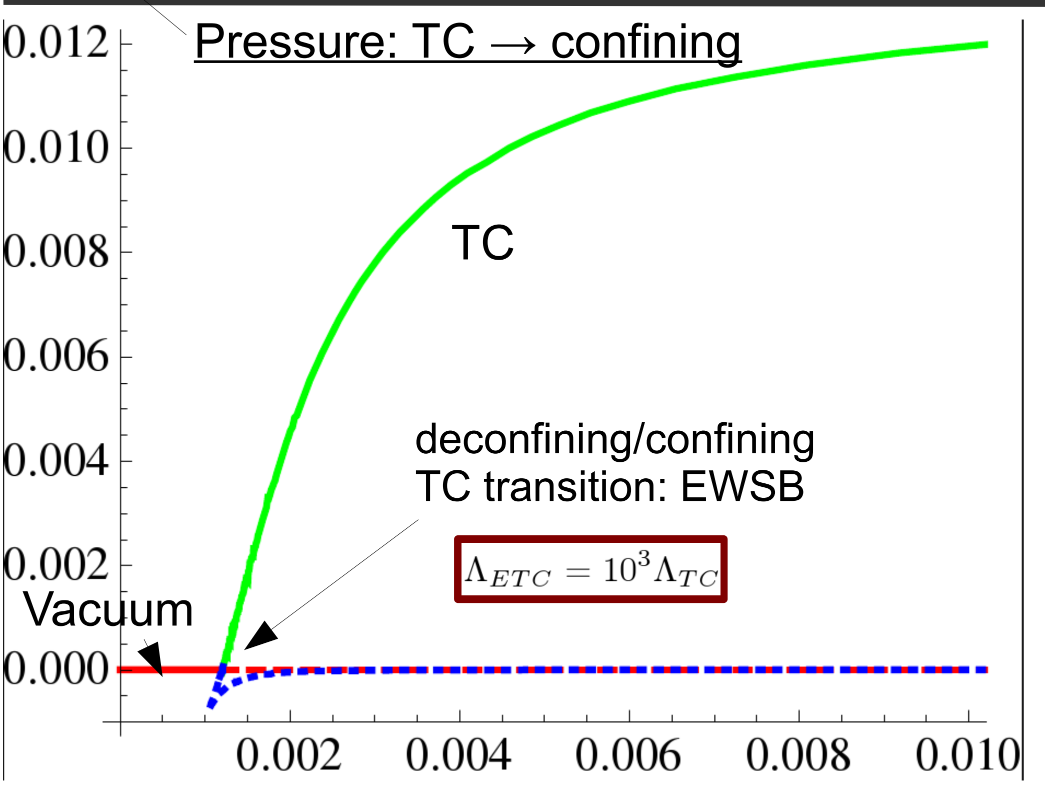




- Search black hole solutions with $f(r) \neq 1$ → **Thermodynamics**



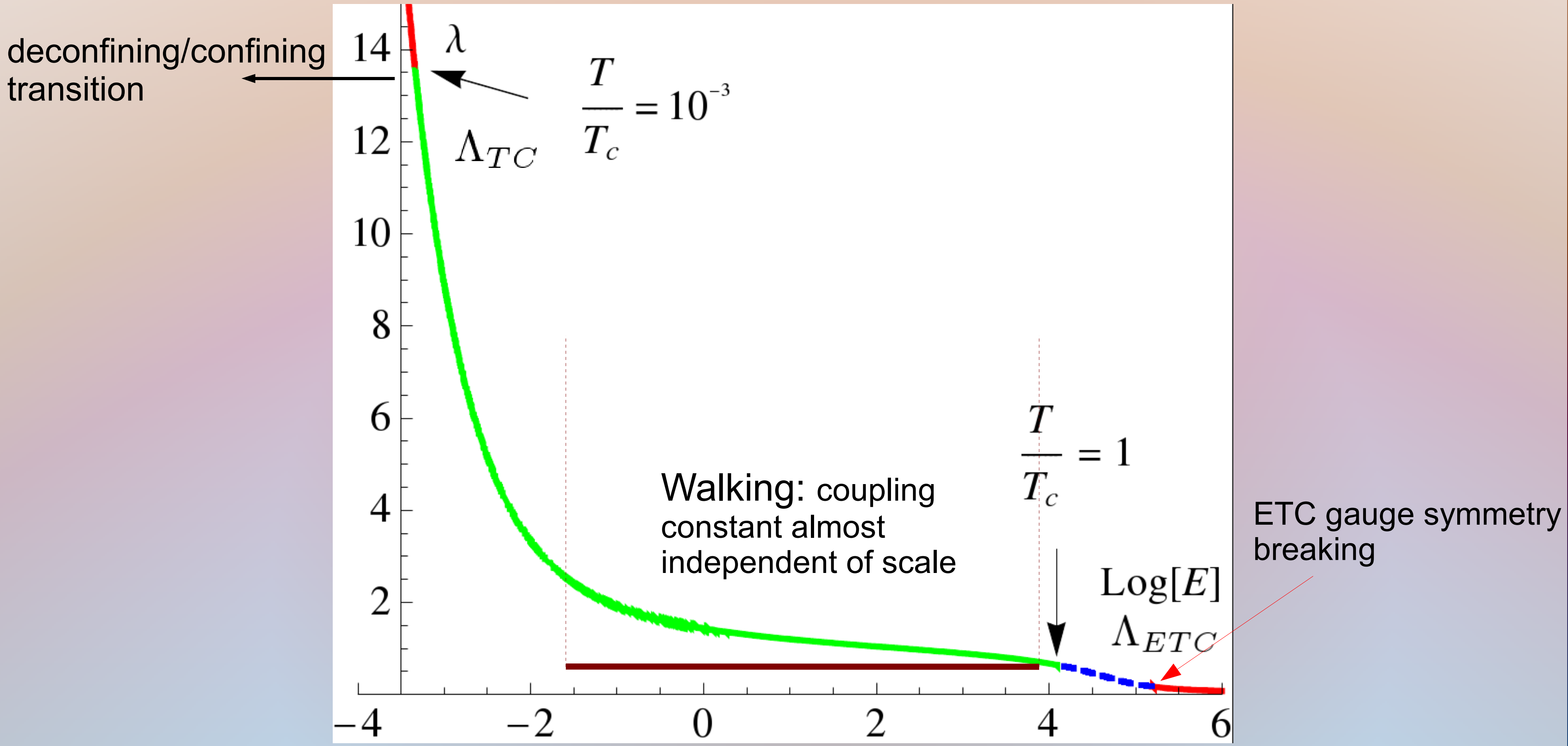




- **Two first order transitions**
- ETC at UV: technigluons + technifermions.
- Transition from ETC → walking region: Massive technigluons.
- Transition from walking → confining TC: Technifermions form bound states. EWSB.

Coupling/Energy

This dilaton potential really produces walking behavior for the coupling



Beta function

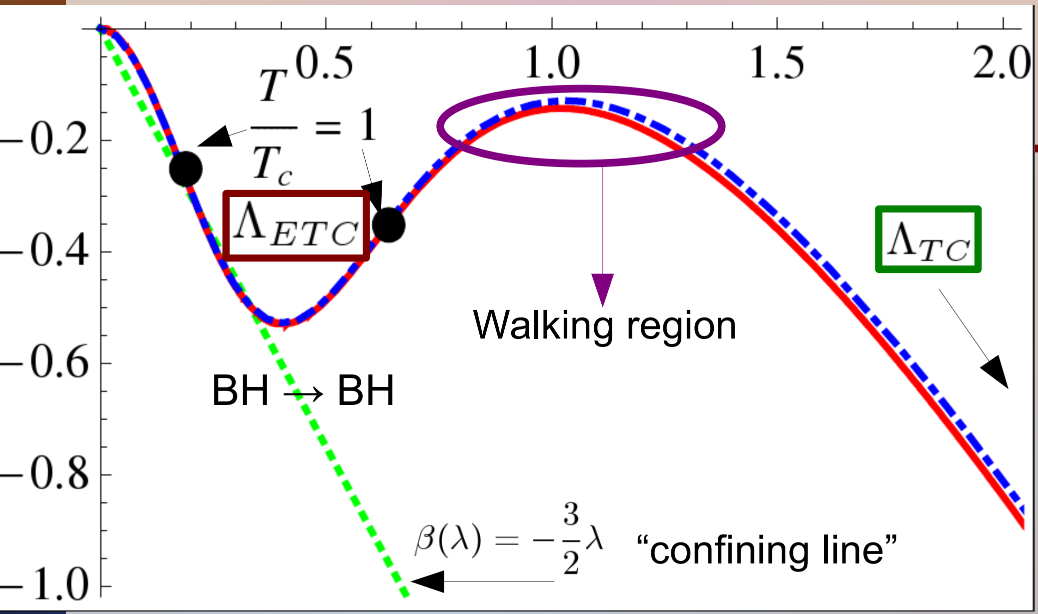
Walking potential

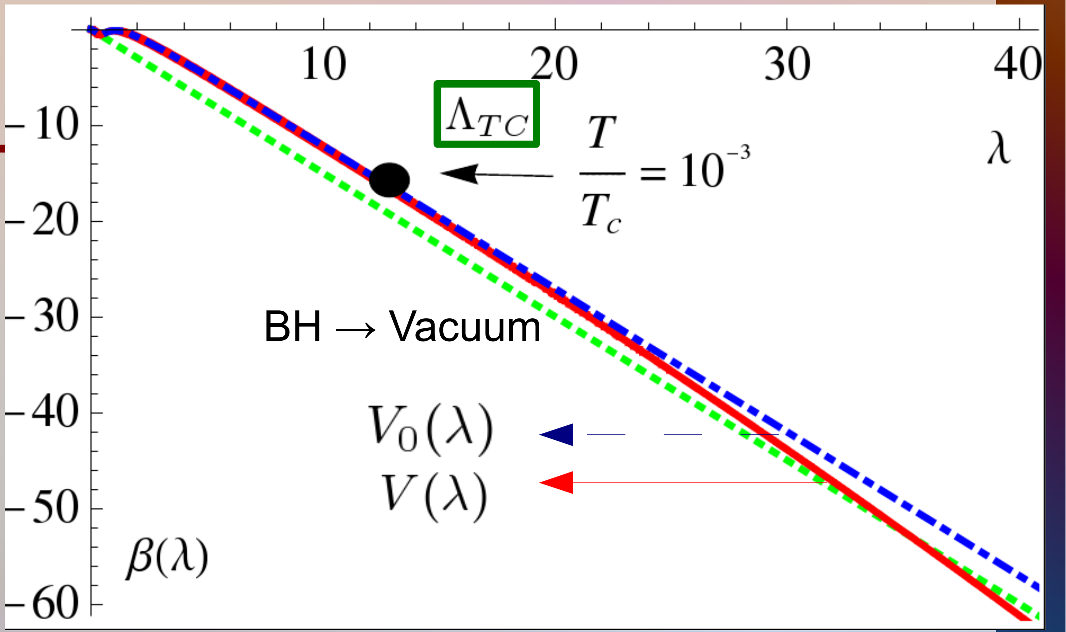
$$\beta_0(\lambda) = -c\lambda^2 \frac{[(1-\lambda)^2 + e]}{1 + a\lambda^3} \longleftrightarrow V_0(\lambda)$$

Walking + confining potential

$$V(\lambda) = V_0(\lambda)\left[1 + \frac{e}{10}\sqrt{\log(1+\lambda^4)}\right] \longrightarrow \beta(\lambda)$$

Log term is introduced to get beta function to cut “confining line” at IR $\beta(\lambda) = -\frac{3}{2}\lambda$





5. Conclusions

- We have presented a scheme for converting a beta function of a gauge theory to its thermodynamics via gauge/gravity duality
- The scheme is a phenomenological bottom-up one; real effect of the fermions?
- Many further topics for study:
  - Scanning over parameters, different betas/potentials, case of several couplings, transport coefficients, mass spectra...