Anisotropic states from smeared branes

Iberian Strings 2020
Santiago de Compostela

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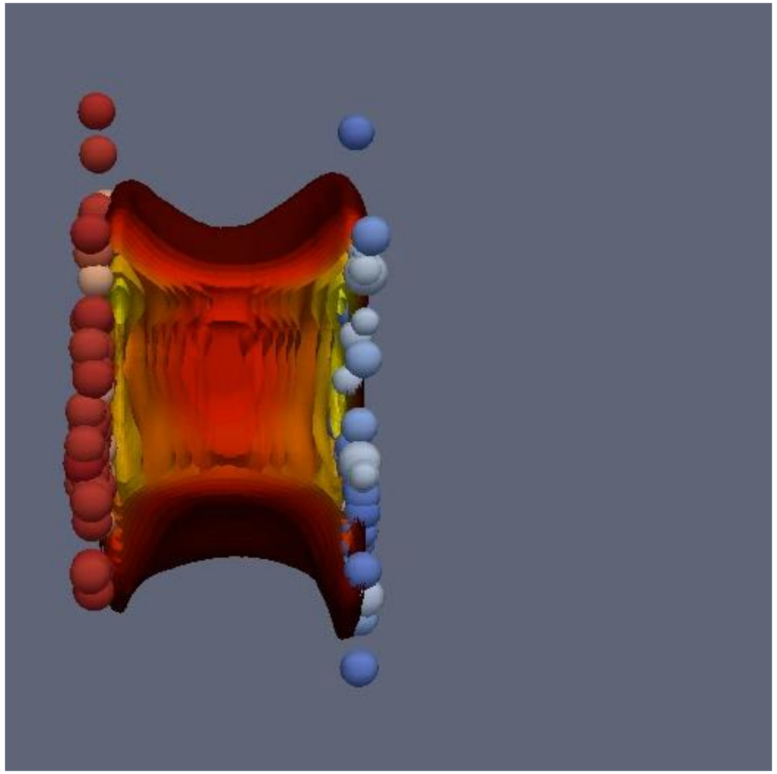
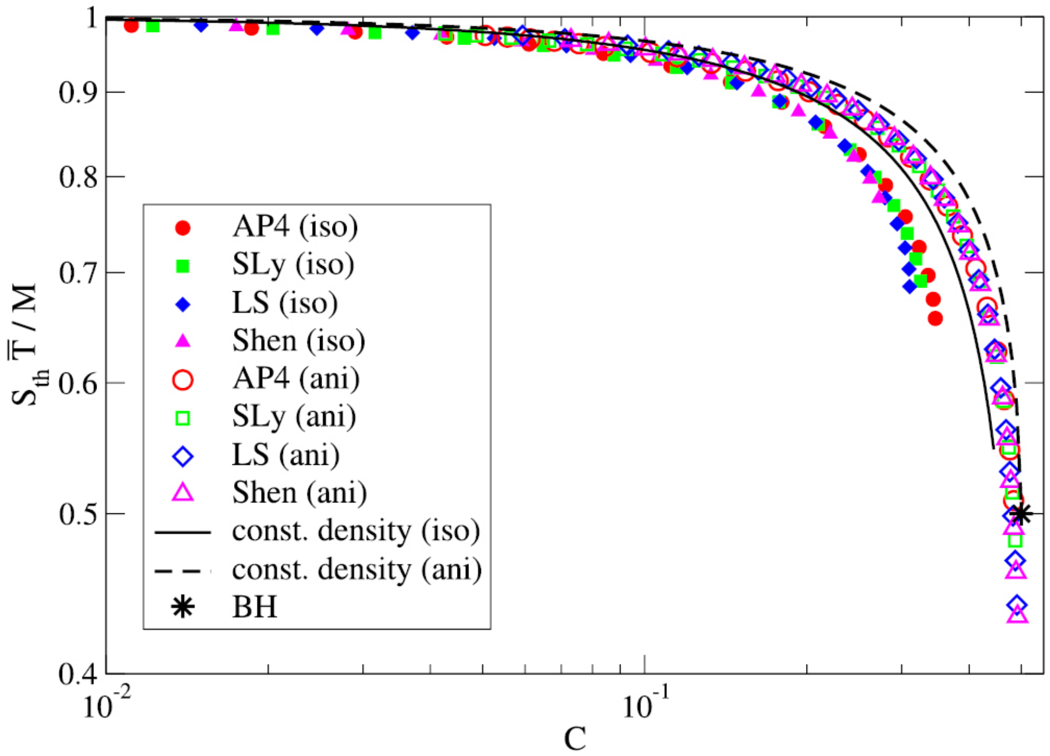
Anisotropic states

QCD

Heavy ion collisions



Neutron stars

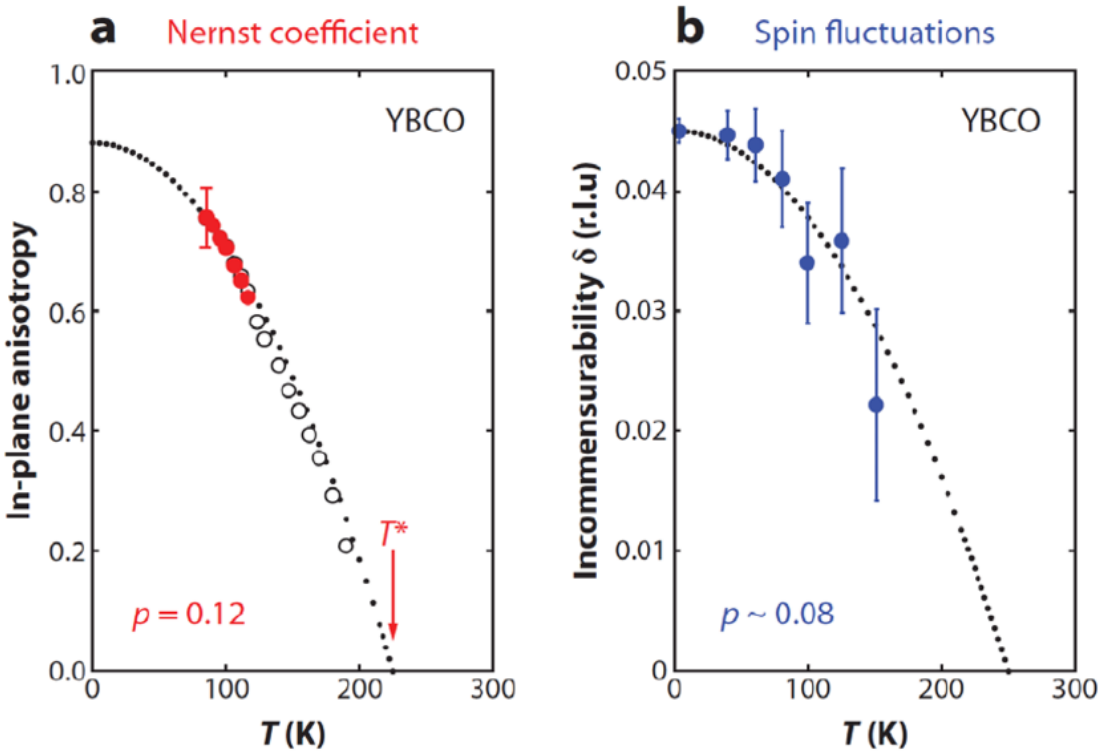


[Alexander, Yagi, Yunes '18]

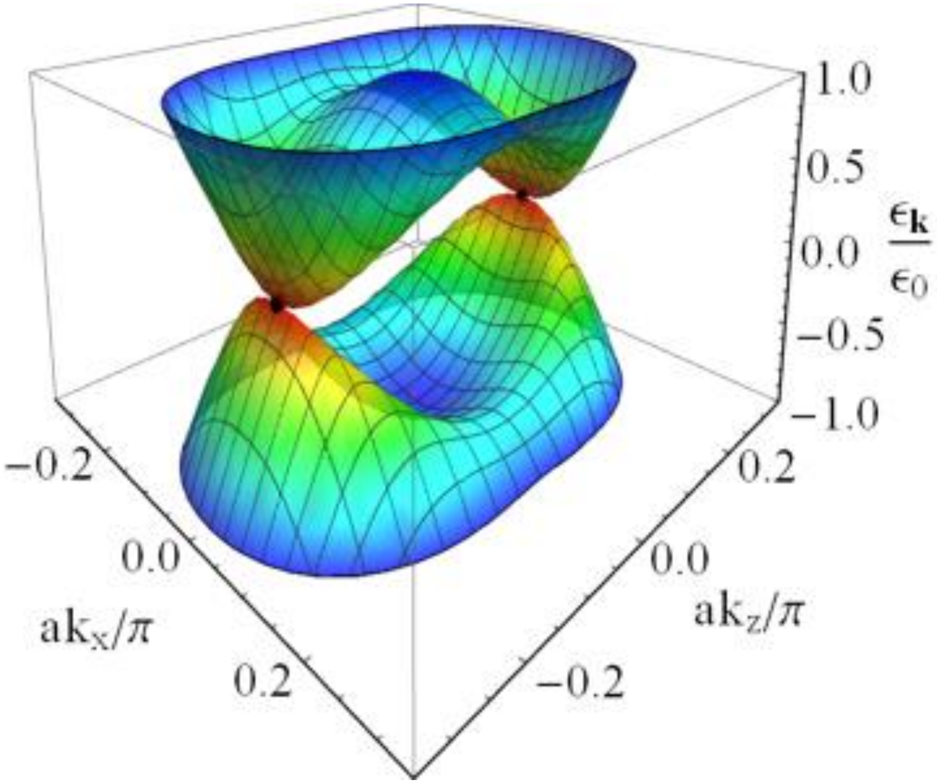
Anisotropic states

Strongly correlated electrons

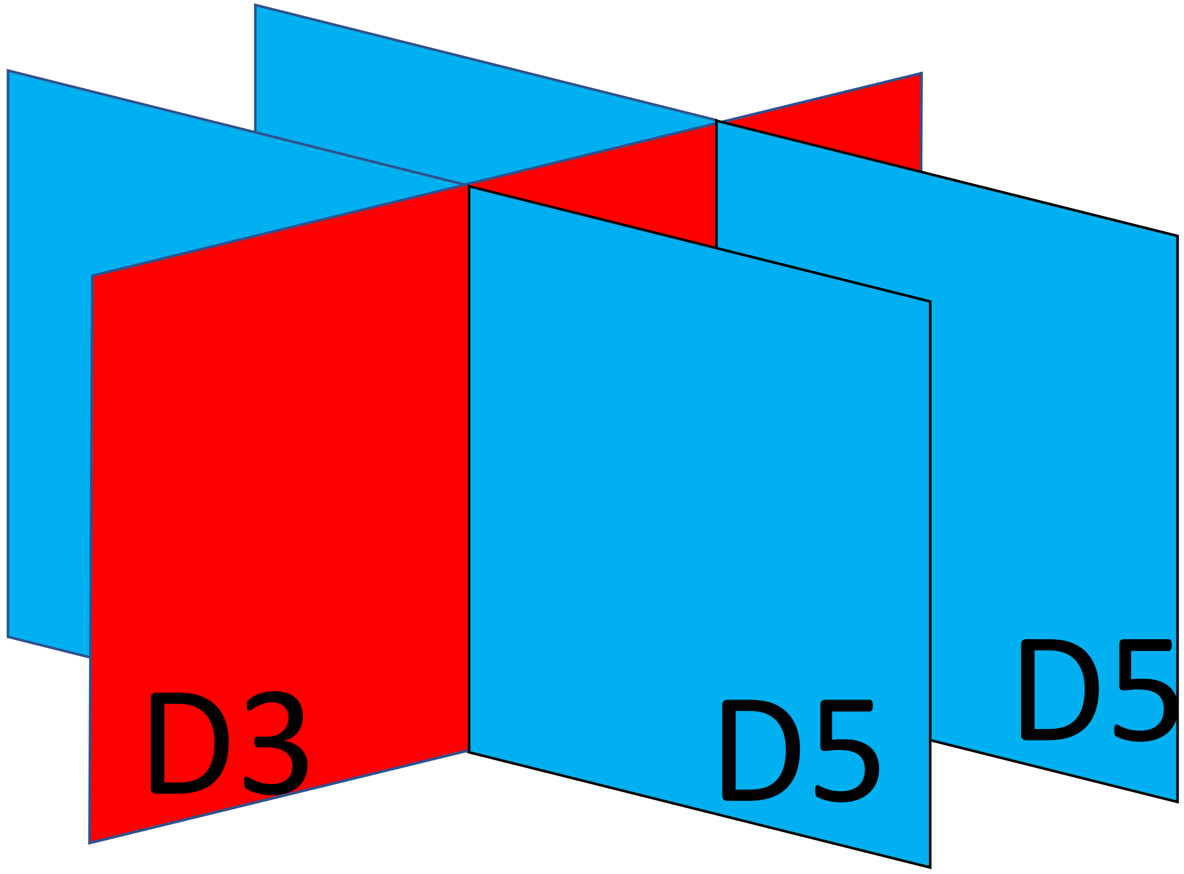
Cuprates, high Tc superconductors



Multi-Weyl semimetals



D-brane setup

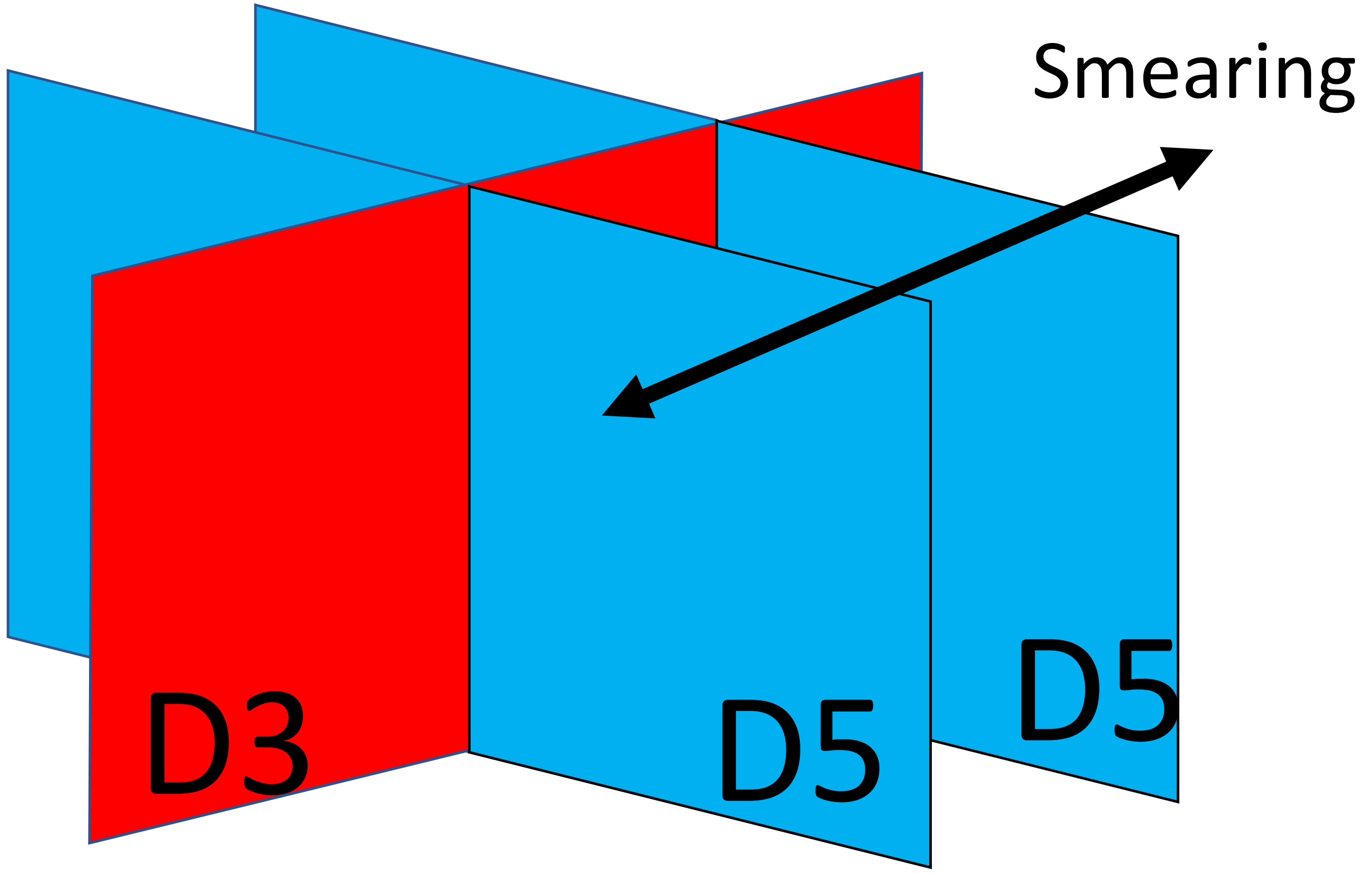


2+1 dimensional intersection

Supersymmetric

Defect CFT

D-brane setup



3+1 anisotropic theory

Supersymmetric

UV = D2 brane theory

[Penin, Ramallo, Zoakos ’17; Jokela, Penin, Ramallo, Zoakos ’19]

See Penin’s talk

Holographic dual

Type IIB SUGRA + 5-brane sources $dF_3 \neq 0$

Ten-dimensional metric

Anisotropy

$$
\begin{aligned}
ds^2_{10} &= h^{-\frac{1}{2}}\left[-(dx^0)^2+(dx^1)^2+(dx^2)^2+e^{-2\phi}(dx^3)^2\right] \\
&\quad + h^{\frac{1}{2}}\left[\zeta^2 e^{-2f}\,d\zeta^2+\zeta^2\,ds^2_{\mathbb{CP}^2}+e^{2f}(d\tau+A)^2\right],
\end{aligned}
$$

Squashing

SUSY solution determined by arbitrary 5-brane distribution $p(\zeta)$

Analytic solutions easily found!

Field theory interpretation

Dimensional reduction 10d → 5d $d(X * F_4) \neq 0$

$$F_4 = dC_3 \propto p(\zeta)$$

3-form potential -holo dual- to $\Delta = 3$ operator -Hodge dual- to axial current

$$C_3 \leftrightarrow tr\left(\bar{\lambda}\gamma^{\mu\nu\rho} H_a \lambda\right) \leftrightarrow i\epsilon^{\mu\nu\rho\sigma} tr\left(\bar{\lambda}\gamma_\sigma \gamma_5 H_a \lambda\right)$$

UV physics of 5-brane distribution

$$\zeta \longrightarrow \infty$$

$$p(\zeta) \sim p_0$$

Smearing of 2+1 intersection
(D2 branes)

Irrelevant deformation

$$tr\left(\bar{\lambda}\gamma_3 i\gamma_5 H_a \lambda\right)$$

$$p(\zeta) \sim \frac{1}{\zeta^3}$$

$AdS_5 \times S^5$
(color D3 branes)

Spontaneous symmetry breaking

Constrained from positive energy condition

IR physics of 5-brane distribution

$$\zeta \longrightarrow 0$$

$$p(\zeta) \sim \zeta^{\alpha}$$

$\alpha > 1$ Boomerang Flow: $AdS_5 \times S^5$ (same radius as UV)

[Donos, Gauntlett, Rosen, Sosa-Rodriguez '17]

$0 \leq \alpha < 1$ Lifshitz-type: $z = \frac{1}{n}$ $\alpha = (3n-1)/2$

$$ds_5^2 = \frac{\zeta^2}{R^2}\left[-(dx^0)^2 + (dx^1)^2 + (dx^2)^2 + (\mu\zeta)^{2(n-1)}(dx^3)^2\right] + \frac{R^2}{\zeta^2}d\zeta^2$$

$$2(n-1) = \frac{2}{z} - 2$$

Analytic solutions

5-brane distribution

$$\kappa\, p(\zeta) = \sqrt{W(\zeta)}\frac{(\kappa\zeta)^n}{\left(1+(\kappa\zeta)^m\right)^{\frac{n+3}{m}}} \qquad \begin{cases} n > 1, & \alpha = n \\ n < 1, & \alpha = \dfrac{3n-1}{2} \end{cases}$$

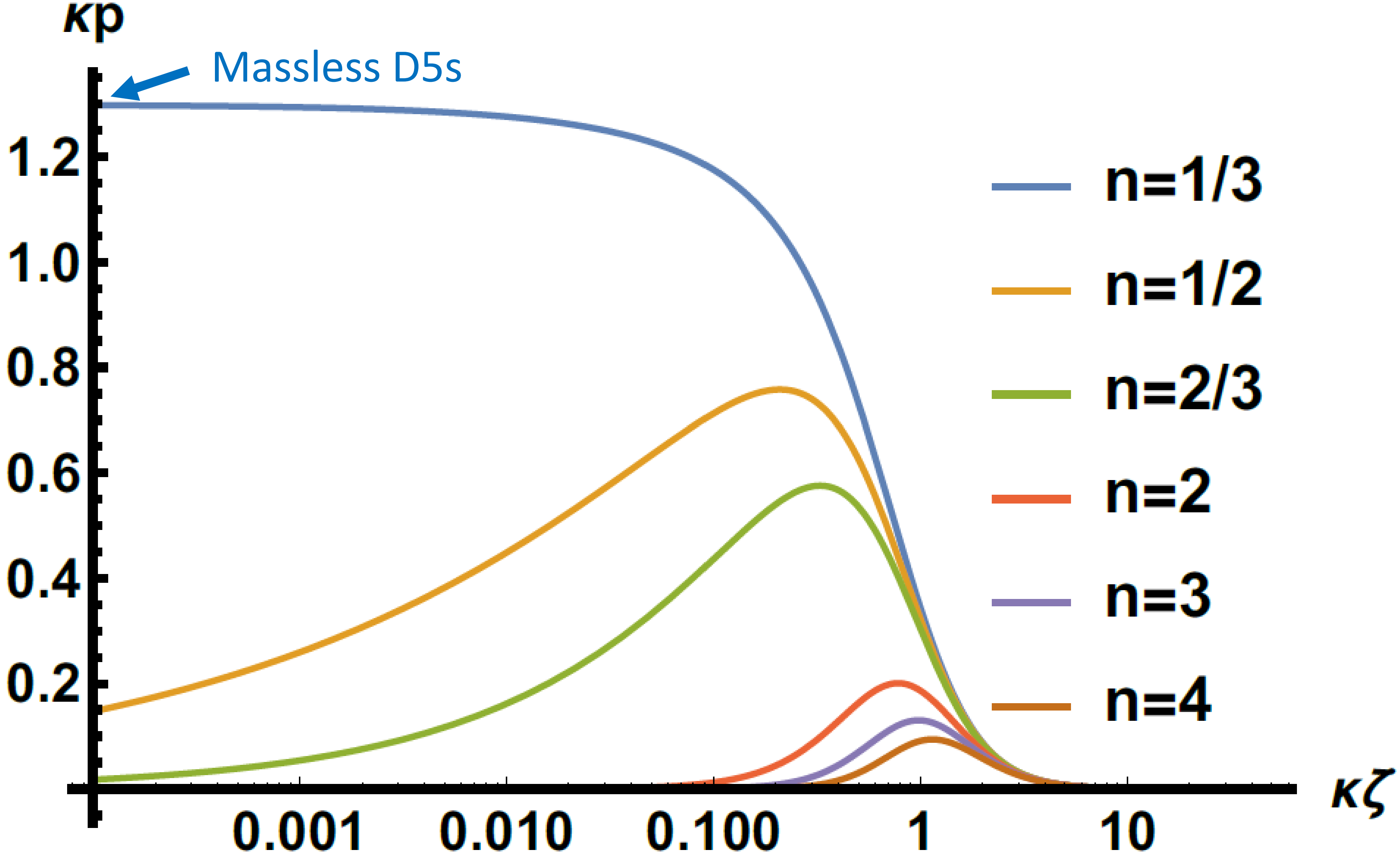
Master equation

$$\frac{d}{d\zeta}\left(\zeta\,\frac{dW}{d\zeta}\right) + 6\,\frac{dW}{d\zeta} = -\frac{6\,Q_f\,p(\zeta)}{\zeta^2\sqrt{W}}$$

Master function

$$W(\zeta) \;=\; 1 + Q_f\left[\frac{1}{4(\kappa\,\zeta)^4}F\left(\frac{4}{m},\frac{3+n}{m};\frac{4+m}{m};-(\kappa\,\zeta)^{-m}\right) + \frac{(\kappa\,\zeta)^{n-1}}{5+n}F\left(\frac{5+n}{m},\frac{3+n}{m};\frac{5+m+n}{m};-(\kappa\,\zeta)^{m}\right)\right]$$

Analytic solutions



Anisotropy along the RG flow

$$\frac{1}{z_{eff}(\zeta)} \equiv 1 + \zeta \frac{d}{d\zeta} \log \sqrt{\left| \frac{g_{x^3 x^3}}{g_{x^0 x^0}} \right|}$$

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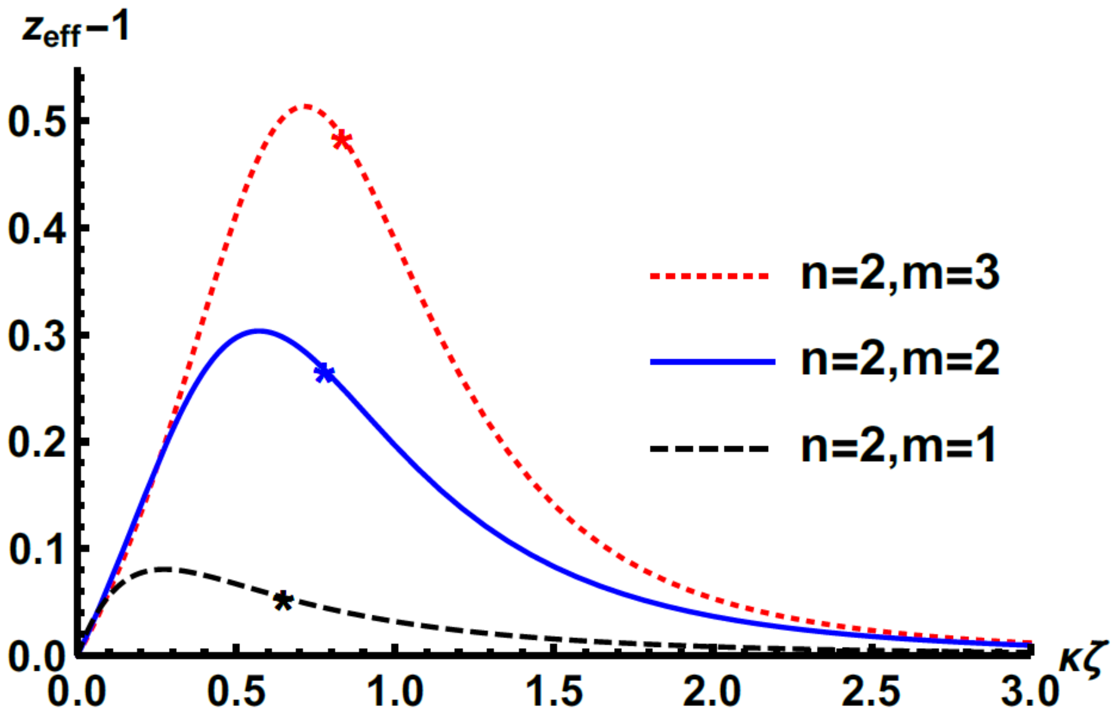
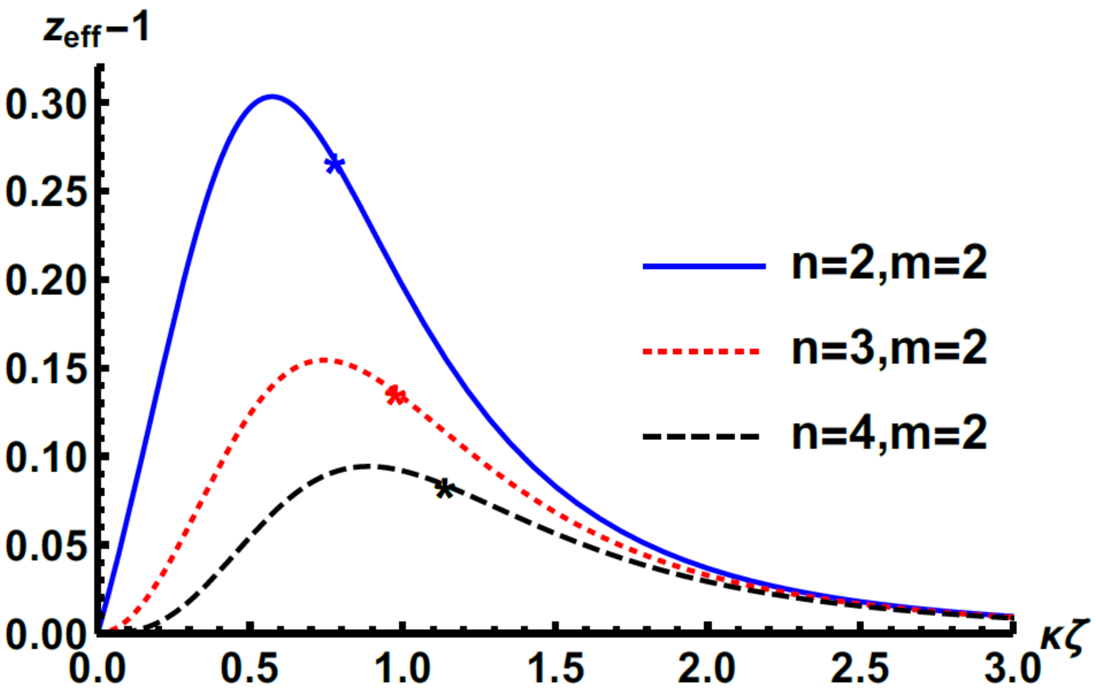
Boomerang flows





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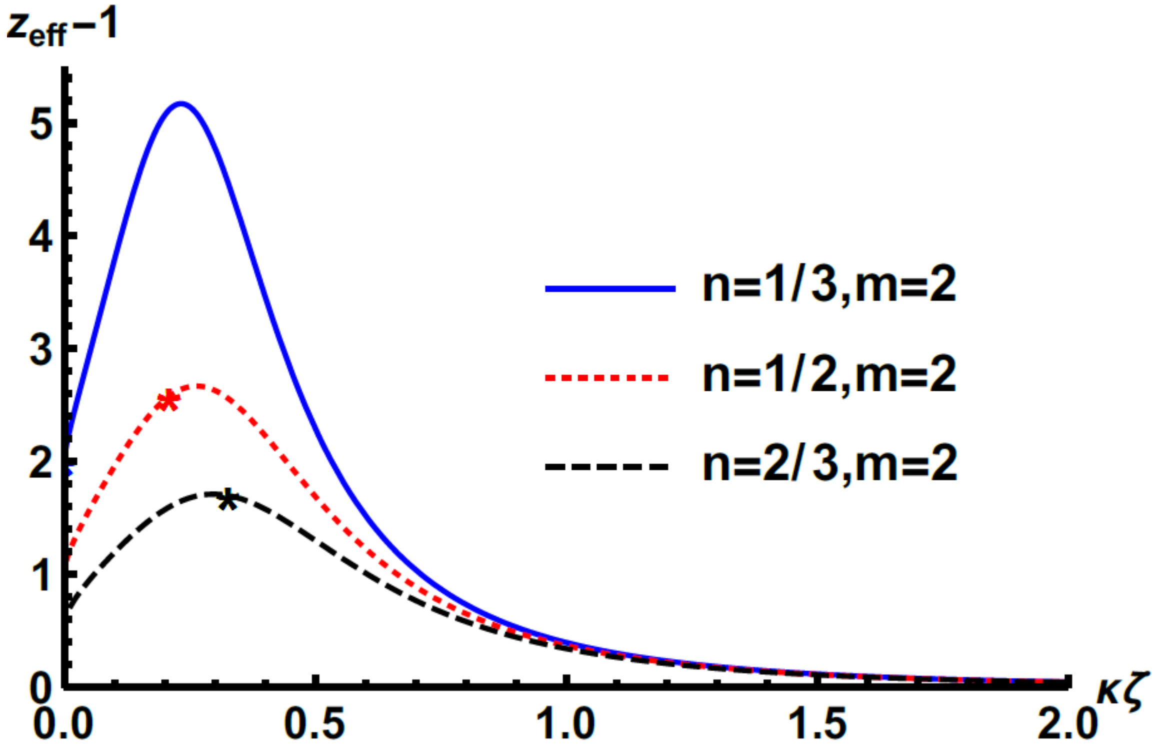
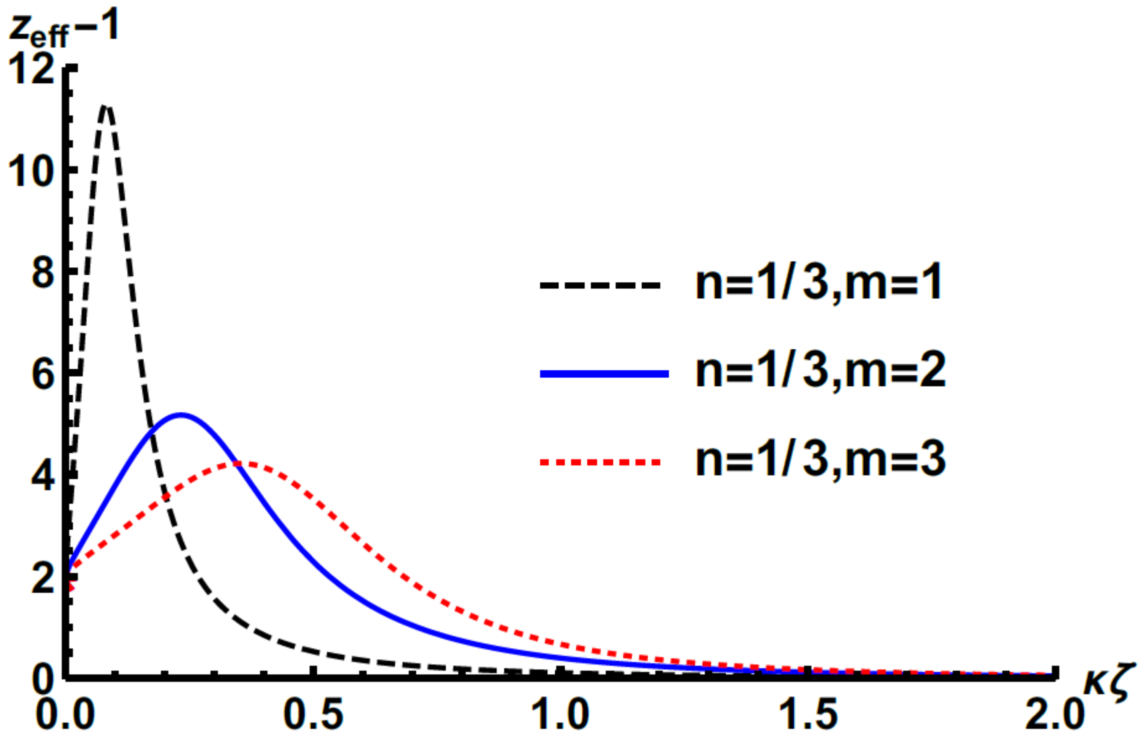
Lifshitz flows





c-functions

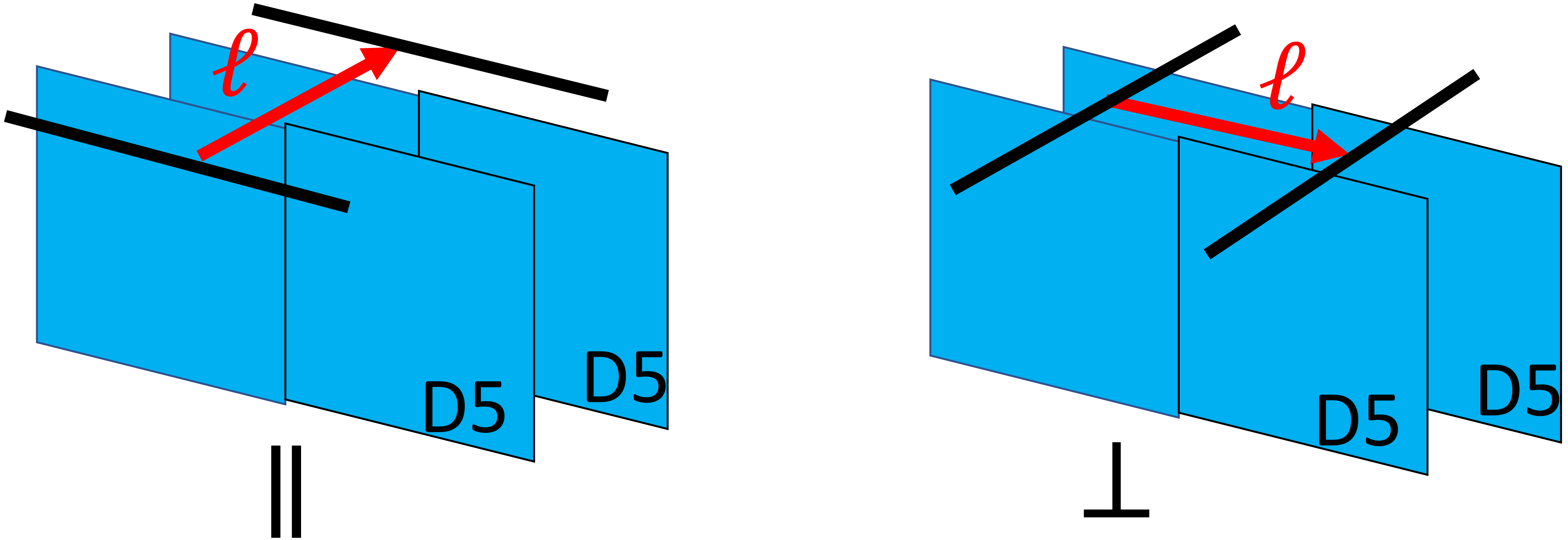
- c-functions that are monotonic along the RG flow are exist for unitary QFTs in 2,3 and 4 dimensions
- Heuristically, they are identified with the decreasing number of degrees of freedom as the RG Flow evolves from UV to IR, in the Wilsonian approach
- Proofs of monotoniticity asume Lorentz invariance, without it monotonic c-functions may not exist
- There have been attempts to define monotonic c-functions for theories with holographic duals in the absence of Lorentz invariance [Liu, Zhao '12; Cremonini, Dong '13; Chu, Giataganas '19; Ghasemi, Parvizi '19]

(do not apply to our case, 5d vs 10d)

c-functions from entanglement entropy of a strip

[Myers, Sinha '10]

$$c_{\parallel}(\ell) = \frac{1}{V_2} C_{\parallel}(\ell) \frac{\partial S_{EE}^{\parallel}}{\partial \ell} \ , \ c_{\perp}(\ell) = \frac{1}{V_2} C_{\perp}(\ell) \frac{\partial S_{EE}^{\perp}}{\partial \ell}$$



Boomerang flows

$$C_{\parallel} = C_{\perp} \equiv \beta_4 \ell^3$$

Average c-function

$$\bar{c} = (c_{\parallel} c_{\perp}^2)^{1/3}$$

Lifshitz flows

UV scaling
$\ell \longrightarrow 0$

$$C_{\parallel}(\ell) \simeq C_{\perp}(\ell) \simeq \beta_4 \ell^3$$

IR scaling
$\ell \longrightarrow \infty$

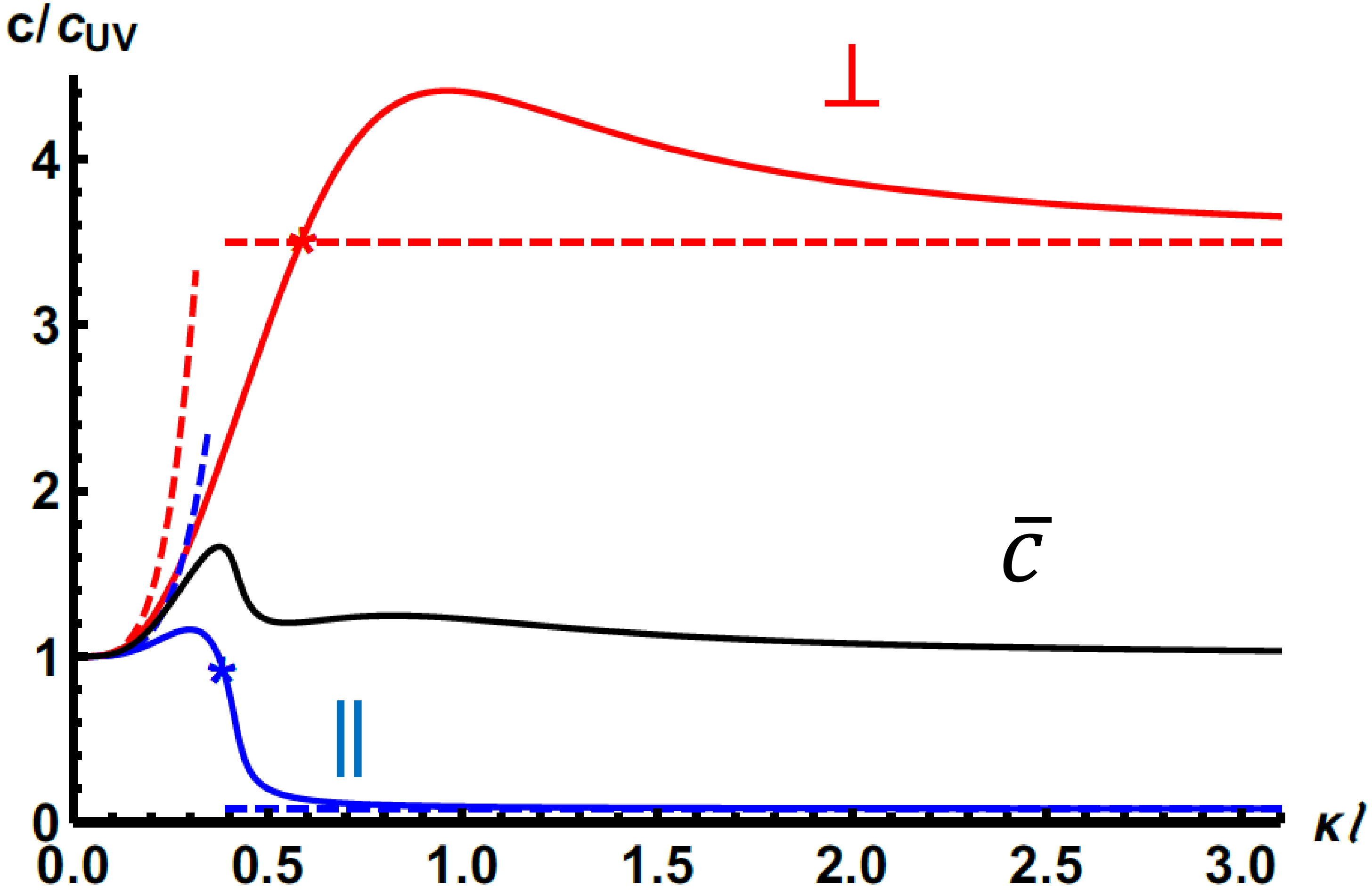
$$C_{\parallel}(\ell) \simeq \beta_{d_{\parallel}+2} \ell_0^3 \left(\frac{\ell}{\ell_0}\right)^{1+\frac{2}{n}} \quad , \quad C_{\perp}(\ell) \simeq \beta_{d_{\perp}+2} \ell_0^3 \left(\frac{\ell}{\ell_0}\right)^{n+2}$$

$$\frac{2}{n} = d_{\parallel} > d_{UV} = 2 > d_{\perp} = n+1$$

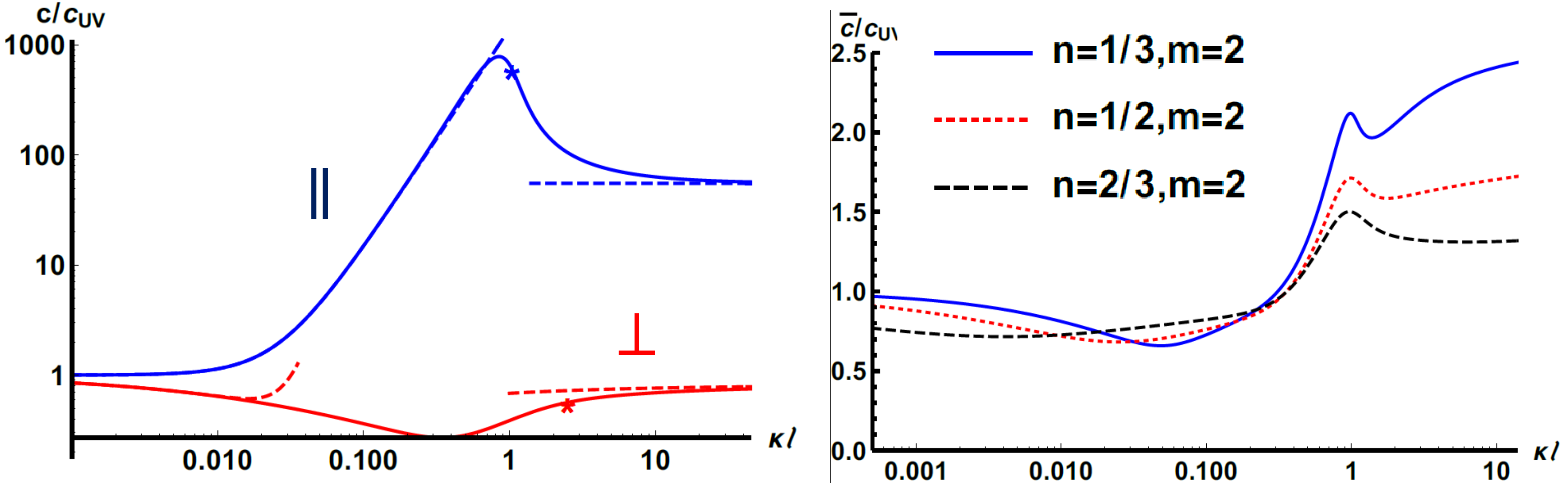
Average c-function

$$\bar{c} = \left(c_{\parallel}^{n} c_{\perp}^2\right)^{\frac{1}{n+2}}$$

Boomerang flows



Lifshitz flows



c-function from null congruences

[Alvarez, Gomez '98; Sahakian '99]

$$k^\mu \nabla_\mu k^\nu = 0$$

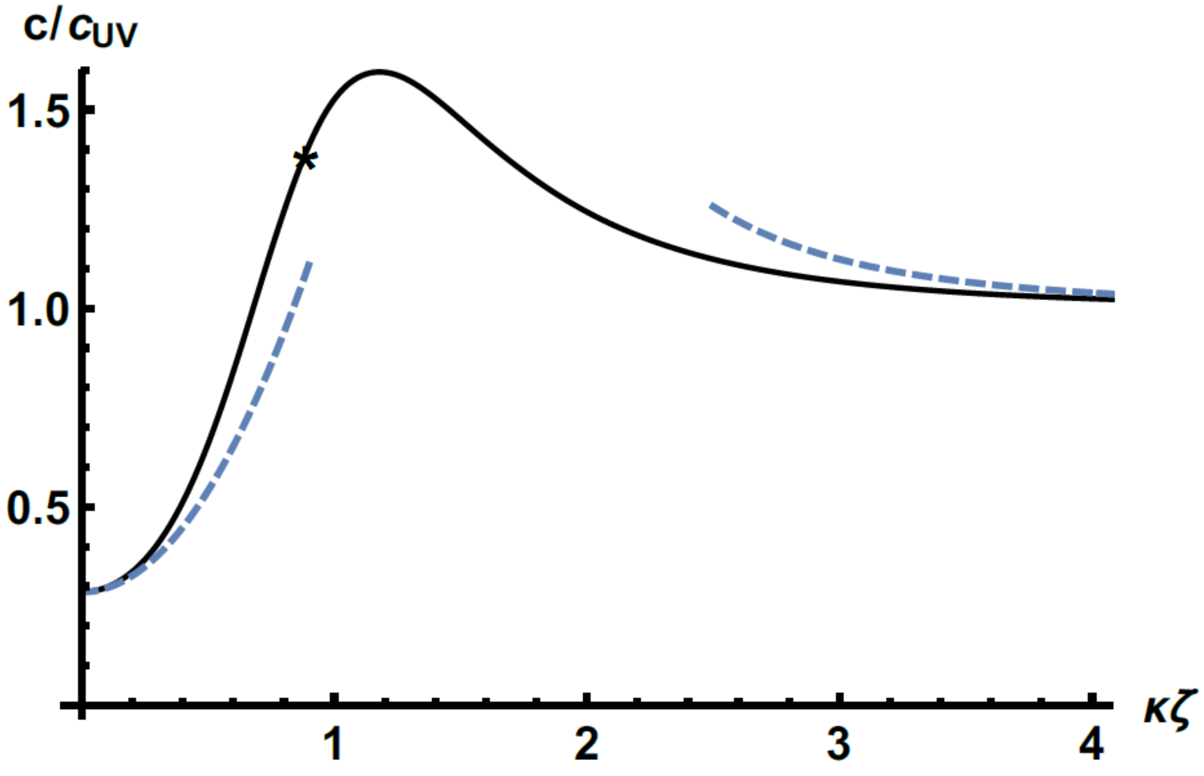
$$\theta = \nabla_\mu k^\mu$$

$$c(\zeta) \sim \frac{1}{\sqrt{h}\,\theta^3}$$

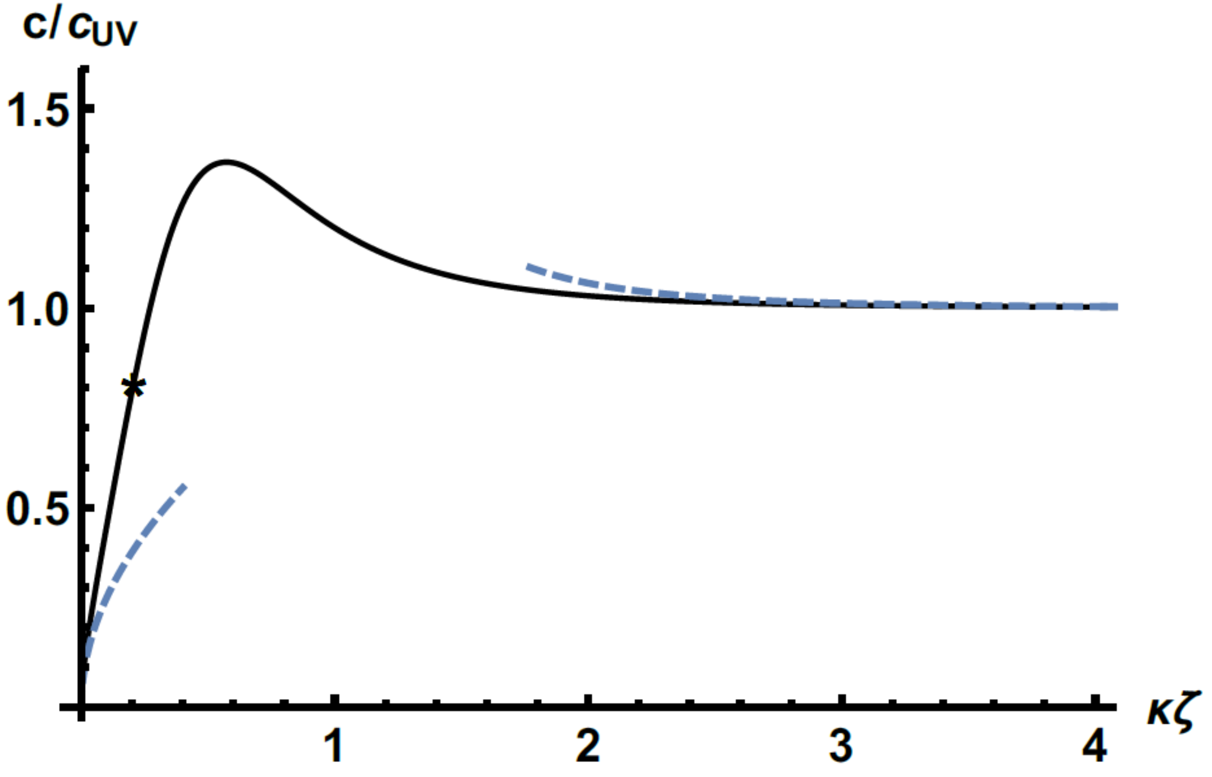
h induced metric

c-function from null congruences

Boomerang flow



Lifshitz flow



Outlook

- Wilson loops and other extended objects
- Flavor branes: anisotropic EoS at finite density [Gran, Jokela, Musso, Ramallo, Tornsö '19]
- Source for axial current: conexion to holographic Weyl semimetals?
- Finite temperature and transport

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Thank you!