

# Anisotropic Weyl Anomalies and Lifshitz Holography

✿ Petr Hořava ✿

*Berkeley Center for Theoretical Physics*

2nd BCTP Summit at Lake Tahoe

Glenbrook, NV  
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# Outline

- I. Review of quantum gravity with anisotropic scaling
  - anisotropic Weyl symmetries & anomalies
  - detailed balance
- II. Lifshitz holography
  - Lifshitz spacetimes
  - anisotropic conformal infinity
  - IIa. Lifshitz holography in relativistic gravity
    - holographic renormalization, counterterms
    - anisotropic Weyl anomalies in detailed balance
    - detailed balance from recursions among holographic counterterms
  - IIb. Lifshitz holography in Lifshitz gravity
    - Lifshitz spacetime as a vacuum solution
    - general form of anisotropic Weyl anomalies with examples
    - general holographic Weyl anomalies from Lifshitz gravity
- III. Conclusions

## Some references

initial papers on gravity with anisotropic scaling:

..., arXiv:0812.4287, arXiv:0901.3775, ...

brief recent(ish) review:

arXiv:1101.1081 (GR 19 Proceedings).

focus of this talk:

work with Tom Griffin and Charles Melby-Thompson  
in arXiv:1112.5660, and to appear

I.

**Review: Gravity with anisotropic scaling**

# Gravity with anisotropic scaling

(also known as Hořava-Lifshitz gravity)

Field theory with anisotropic scaling ( $\mathbf{x} = \{x^i, i = 1, \dots, D\}$ ):

$$\mathbf{x} \rightarrow \lambda \mathbf{x}, \quad t \rightarrow \lambda^z t.$$

$z$ : dynamical critical exponent – characteristic of RG fixed point.

Many interesting examples:  $z = 1, 2, \dots, n, \dots$

fractions:  $3/2$  (KPZ surface growth in  $D = 1$ ),  $\dots, 1/n, \dots$

families with  $z$  varying continuously  $\dots$

Condensed matter, dynamical critical phenomena, quantum critical systems,  $\dots$

Goal: Extend to gravity, with propagating gravitons, formulated as a quantum field theory of the metric.

# Gravity with anisotropic scaling

(also known as Hořava-Lifshitz gravity)



Evgenii Mikhailovich Lifshitz (1915 – 1985)

## Example: Lifshitz scalar [Lifshitz, 1941]

Gaussian fixed point with  $z = 2$  anisotropic scaling:

$$S = S_K - S_V = \frac{1}{2} \int dt d^D \mathbf{x} \left\{ \dot{\Phi}^2 - (\Delta \Phi)^2 \right\},$$

( $\Delta$  is the spatial Laplacian).

Compare with the Euclidean field theory

$$W = -\frac{1}{2} \int d^d x (\partial \phi)^2.$$

Shift in the (lower) critical dimension:

$$[\phi] = \frac{d-2}{2}, \quad [\Phi] = \frac{D-2}{2}.$$



## Gravity at a Lifshitz point

**Spacetime structure:** Preferred foliation by leaves of constant time (avoids the “problem of time”).

**Fields:** Start with the spacetime metric in ADM decomposition: the spatial metric  $g_{ij}$ , the lapse function  $N$ , the shift vector  $N_i$ .

**Symmetries:** foliation-preserving diffeomorphisms,  $\text{Diff}(M, \mathcal{F})$ .

**Action:**  $S = S_K - S_V$ , with

$$S_K = \frac{1}{\kappa^2} \int dt d^D \mathbf{x} \sqrt{g} N (K_{ij} K^{ij} - \lambda K^2)$$

where  $K_{ij} = \frac{1}{N} (\dot{g}_{ij} - \nabla_i N_j - \nabla_j N_i)$  the extrinsic curvature,

$$\text{and } S_V = \frac{1}{\kappa_V^2} \int dt d^D \mathbf{x} \sqrt{g} N \mathcal{V}(R_{ijkl}, \nabla_i).$$

## Projectable and nonprojectable theory

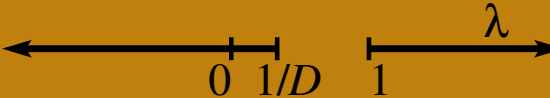
$N, N_i$  are the gauge fields for the  $\text{Diff}(M, \mathcal{F})$  symmetries generated by  $\delta t = f(t), \delta x^i = \xi^i(t, \mathbf{x})$ . Hence:

- (1) we can restrict  $N(t)$  to be a function of time only:  
**projectable theory.**
- (2) or, we allow  $N(t, \mathbf{x})$  to be a spacetime field. New terms, containing  $\nabla_i N/N$ , are then allowed in  $S$  by symmetries:  
**nonprojectable theory.**

**Spectrum:** Tensor graviton polarizations, plus an extra scalar graviton. Three options for the scalar: Live with it, gap it, or eliminate it by an extended gauge symmetry.

**Dispersion relation:** Nonrelativistic,  $\omega^2 \sim k^{2z}$ , around this Gaussian fixed point.

**Allowed range of  $\lambda$ :**



## Special case: Detailed balance

Sometimes, the potential term happens to be the square of EoM for some local action  $W$  in  $D$  dimensions:

This gives **theories in detailed balance**.

(Terminology borrowed from non-equilibrium stat-mech.)

Example: Lifshitz scalar satisfies the **detailed balance condition**,

$$(\Delta\Phi)^2 = \left( \frac{\delta W}{\delta\Phi} \right)^2, \quad \text{with } W = -\frac{1}{2} \int d^D \mathbf{x} (\partial\Phi)^2.$$

Simplest examples involving (projectable) gravity:

$$D = 2: \quad W = \int \sqrt{g} R \quad \rightarrow \quad \mathcal{V} = 0,$$

$$D = 3: \quad W = \int \omega_3(\Gamma) \quad \rightarrow \quad \mathcal{V} = C_{ij} C^{ij}.$$

(here  $\omega_3(\Gamma) = \Gamma \wedge d\Gamma + \frac{2}{3}\Gamma \wedge \Gamma \wedge \Gamma$ , and  $C_{ij}$  is the Cotton tensor.)

## RG flows

Assume  $z > 1$  UV fixed point. Relevant deformations trigger RG flow to lower values of  $z$ . **Example:** Lifshitz scalar.

$$S = \frac{1}{2} \int dt d^D \mathbf{x} \left\{ \dot{\Phi}^2 - (\Delta \Phi)^2 - \mu^2 \partial_i \Phi \partial_i \Phi - m^4 \Phi^2 \right\},$$

**Multicriticality.** New phases: modulated.

Similarly for gravity:

$$S = \frac{1}{\kappa^2} \int dt d^D \mathbf{x} \sqrt{g} N \left\{ K_{ij} K^{ij} - \lambda K^2 - \dots - \mu^{2z-2} R - M^{2z} \right\}.$$

Flows in IR to  $z = 1$  scaling. In the IR regime,  $S_V$  is dominated by the spatial part of Einstein-Hilbert.

(The  $z > 1$  Gaussian gravity fixed points also emerge in IR in condensed matter lattice models, [\[Cenke Xu & PH\]](#).)

## Anisotropic Weyl symmetries

Using a spacetime-dependent scaling factor  $\Omega(t, \mathbf{x}) = e^{\omega(t, \mathbf{x})}$ , define

$$g_{ij} \rightarrow \Omega^2 g_{ij}, \quad N_i \rightarrow \Omega^2 N_i, \quad N \rightarrow \Omega^z N.$$

Such **anisotropic Weyl transformations** are compatible with foliation-preserving diffeos:

$$\text{Weyl}_z(M, \mathcal{F}) \otimes \text{Diff}(M, \mathcal{F}).$$

Indeed,  $[\delta_\omega, \delta_{f, \xi^i}] = \delta_{f\dot{\omega} + \xi^i \partial_i \omega}$ .

This provides the appropriate generalization of local “conformal transformations” to foliated spacetimes with anisotropic scaling.

Often, it is sufficient to have the preferred foliation and the anisotropic Weyl transformations defined only asymptotically, “near infinity.”

## Anisotropic Weyl anomalies

Consider an “anisotropic CFT” in  $D + 1$  dimensions, with dynamical exponent  $z$ .

Place it in a gravitational background. The theory may exhibit **anisotropic Weyl anomaly**:

$$\delta_\omega W_{\text{eff}} = \int dt d^D \mathbf{x} \sqrt{g} N \omega(t, \mathbf{x}) \mathcal{A}(t, \mathbf{x}).$$

What terms can appear in  $\mathcal{A}$ ? Question in BRST cohomology of  $\text{Weyl}_z(M, \mathcal{F})$ .

**Answer for  $D = 2, z = 2$ :** Assuming time reversal invariance, two independent anomaly terms (hence **two “central charges”**)

$$\mathcal{A} = c_K \left( K_{ij} K^{ij} - \frac{1}{2} K^2 \right) + c_V \left[ R - \left( \frac{\nabla N}{N} \right)^2 + \frac{\Delta N}{N} \right]^2.$$

## Conformal gravity at a Lifshitz point

For some fixed  $z$ , extend the gauge symmetry from  $\text{Diff}(M, \mathcal{F})$  to  $\text{Weyl}_z(M, \mathcal{F}) \ltimes \text{Diff}(M, \mathcal{F})$ .

Then:

- The kinetic term  $S_K$  will be invariant if  $z = D$  and  $\lambda = 1/D$ .
- The theory is automatically nonprojectable.
- The classical theory may be invariant, but the quantum theory generally expected to develop a Weyl anomaly.
- Choice: Theory may or may not satisfy detailed balance.

**Example:** Conformal  $z = 2$  gravity in  $D = 2$  with detailed balance,

$$S = S_K = \frac{1}{\kappa^2} \int dt d^2 \mathbf{x} \sqrt{g} N \left( K_{ij} K^{ij} - \frac{1}{2} K^2 \right).$$

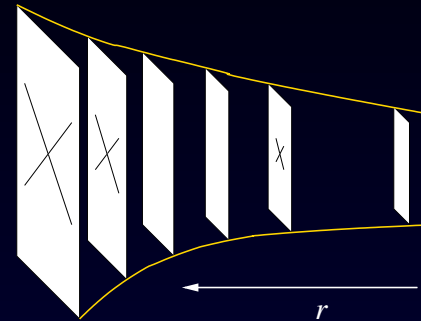
## II. Lifshitz holography



# Lifshitz holography

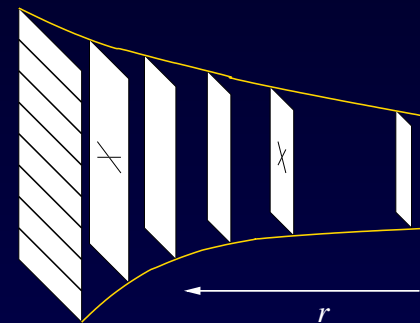
AdS: [Maldacena, 1997]

$$ds^2 = r^2(-dt^2 + d\mathbf{x}^2) + dr^2/r^2$$



Lifshitz: [Kachru et al, 2008]

$$ds^2 = -r^{2z}dt^2 + r^2d\mathbf{x}^2 + dr^2/r^2$$



Focus of this talk:

The role of HL gravity for Lifshitz spacetime.

## Which theory does this space solve?

Not Einstein equations in the vacuum . . .

Two options:

- (a) Keep theory relativistic, modify by inventing suitable matter; Lifshitz spacetime may be a solution when matter is excited.
- (b) Modify gravity; Lifshitz spacetime may be a vacuum solution.

We will see that in **both** cases, ideas of anisotropic gravity play a central role.

**Ila.**  
**Lifshitz holography in relativistic gravity**

## Relativistic holography for Lifshitz space

Various matter sources possible, one of the simplest/most popular is a massive vector: [Taylor]

$$S = \frac{1}{16\pi G_N} \int dt d^D \mathbf{x} dr \sqrt{-G} (\mathcal{R} - 2\Lambda) + \frac{1}{8\pi G_N} \int dt d^D \mathbf{x} \sqrt{-g} \mathcal{K} - \frac{1}{4} \int dt d^D \mathbf{x} dr \sqrt{-G} (F_{\mu\nu} F^{\mu\nu} + 2m^2 A_\mu A^\mu).$$

To get Lifshitz with given  $z$  as solution, one must take

$$\Lambda = \frac{1}{2} [z^2 + (D-1)z + D^2], \quad m^2 = Dz, \quad \langle A_t \rangle = \frac{2(z-1)}{z}.$$

Also, various string/M-theory embeddings now exist.

[Balasubramanian, Narayan; Gauntlett et al; . . . ]

## Anisotropic conformal infinity

Even if we embed Lifshitz space into relativistic gravity with matter, we need anisotropic scaling to define properly the asymptotic structure near “infinity”.

**Conformal infinity** [Penrose]: Rescale the bulk metric on  $\mathcal{M}$

$$g_{\mu\nu} \rightarrow \tilde{g}_{\mu\nu} \equiv \Omega(t, \mathbf{x}, r)g_{\mu\nu},$$

so that  $\tilde{g}_{\mu\nu}$  now extends “past infinity” of  $\mathcal{M}$ . Then take  $\overline{\mathcal{M}}$ . For Lifshitz spacetimes with  $z > 1$ : **Conformal infinity is a line!** (This contradicts holographic expectations).

**Anisotropic conformal infinity** [PH & C. Melby-Thompson, 2009]: For asymptotically foliated spacetimes, use anisotropic Weyl transformations instead. **Anisotropic conformal infinity of Lifshitz spacetime is of codimension one, with a preferred nonrelativistic foliation.** (As expected from holography.)

# Holographic renormalization

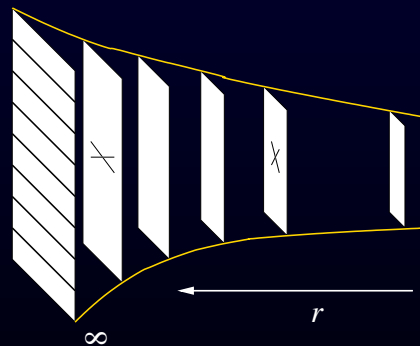
Holographic correspondence:

$$\mathcal{Z}_{\text{bulk}}[\Phi|_{\partial\mathcal{M}} = \Phi_0] = \left\langle \exp \left( \int_{\partial\mathcal{M}} \Phi_0 \mathcal{O} \right) \right\rangle_{\text{CFT}}.$$

In the classical gravity limit, this implies

$$W_{\text{eff}}[\Phi_0] = -S_{\text{on-shell}}[\Phi_0]_{\text{gravity}}.$$

The action diverges, requires (holographic) **regularization and renormalization**:



# Holographic renormalization

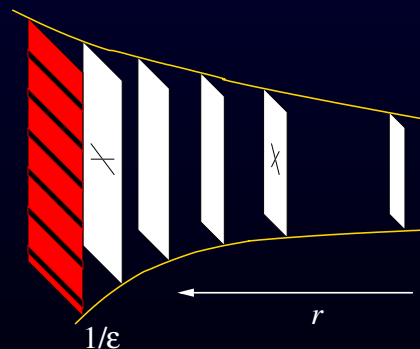
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## Counterterms: Hamilton-Jacobi theory

[de Boer, Verlinde, Verlinde; Skenderis et al; Ross & Saremi; . . .]

On-shell action  $S[g_{ij}, N_i, N; \dots]$ , as a functional of boundary fields, satisfies HJ equation in radial evolution.

In gravity, this means  $\mathcal{H}_r \left( \pi_{\alpha\beta} = \frac{\delta S}{\delta g_{\alpha\beta}} \right) = 0$   
(plus supermomentum constraints).

Parametrize  $S[g_{ij}, N_i, N] = \frac{1}{16\pi G_N} \int dt d^D \mathbf{x} \sqrt{g} N \mathcal{L}$ .

Note:  $\mathcal{L}$  is divergent, expand asymptotically as

$$\mathcal{L} = \dots + \frac{\mathcal{L}^{(4)}}{\varepsilon^4} + \frac{\mathcal{L}^{(2)}}{\varepsilon^2} + \tilde{\mathcal{L}}^{(0)} \log \varepsilon + \mathcal{L}^{(0)} + \mathcal{O}(\varepsilon^2).$$

Plug into HJ equation, which gives a recursive relation among counterterms.



## Counterterms for $z = 2$ in $D = 2$ : Conformal Lifshitz gravity

Holographic recursion relations for counterterms can be solved for general  $D$  and  $z$ , at least in principle.

In the first nontrivial conformal case,  $D = 2$  and  $z = 2$ , they give:

$$\mathcal{L}^{(4)} = 6, \quad \mathcal{L}^{(2)} = \frac{1}{2}R + \frac{1}{4} \left( \frac{\nabla N}{N} \right)^2, \quad \tilde{\mathcal{L}}^{(0)} = K_{ij}K^{ij} - \frac{1}{2}K^2.$$

The recursion relations imply  $\delta_D \mathcal{L}^{(0)} \sim \tilde{\mathcal{L}}^{(0)}$ .

Since  $\mathcal{L}^{(0)}$  is the renormalized action, and  $\delta_D$  (=the radial evolution operator) is the anisotropic Weyl rescaling,  $\tilde{\mathcal{L}}^{(0)}$  gives the anisotropic Weyl anomaly.

This anomaly takes the form of  $z = 2$  conformal Lifshitz gravity action in detailed balance, at the anisotropic boundary.

## Holographic anomaly in detailed balance

Note that of the two possible central charges, **only  $c_K$  is generated in this holographic theory.**

What distinguishes  $c_K$  from  $c_V$ ? **The  $c_K$  anomaly satisfies the detailed balance condition.**

This was further verified for bulk gravity coupled to scalars  $X^I$ . In addition to the kinetic piece,

$$\frac{1}{\kappa^2} \int dt d^2\mathbf{x} \sqrt{g} N \left( K_{ij} K^{ij} - \frac{1}{2} K^2 \right) + \frac{1}{2} \int dt d^2\mathbf{x} \frac{\sqrt{g}}{N} \left( \dot{X}^I - N^i \partial_i X^I \right)^2,$$

**the anomaly now develops also a potential part,**

$$\int dt d^2\mathbf{x} \sqrt{g} N \left\{ (\Delta X^I)^2 + \frac{\kappa^2}{2} T_{ij}(X) T^{ij}(X) \right\}.$$

This is in detailed balance, with  $W = \frac{1}{2} \int d^2\mathbf{x} \sqrt{g} \partial_i X^I \partial^i X^I$ .

## Field-theory examples with $z = 2$ , $D = 2$

Lifshitz scalar field in gravitational background:

$$S = \frac{1}{2} \int dt d^2\mathbf{x} \sqrt{g} \left\{ \frac{1}{N} \left( \dot{\Phi} - N^i \nabla_i \Phi \right)^2 - N (\Delta \Phi)^2 \right\}.$$

Classically anisotropically Weyl invariant with  $z = 2$ ,  $\delta\Phi = 0$ .

Quantum Weyl anomaly: [de Boer et al., also us]

Calculated using  $\zeta$ -function regularization,

$$c_K \neq 0, \quad c_V = 0.$$

Only one non-zero central charge; anomalies in detailed balance!

## Detailed balance from holographic recursion

Why in the world should the holographic Weyl anomaly satisfy detailed balance?

**Answer:** This follows from the holographic recursion relation among the counterterms!

Indeed, the HJ equation – expanded order by order in the conformal dimension – implies that

$$\tilde{\mathcal{L}}^{(0)} \sim \left( \frac{\delta \mathcal{L}^{(2)}}{\delta g_{\alpha\beta}} \right)^2.$$

This is precisely the condition of detailed balance, with the quadratic counterterm  $\mathcal{L}^{(2)}$  playing the role of  $W$ !

## Holographic recursions for other $D, z$

Do they lead to detailed balance, or a generalization thereof?

$AdS_5/CFT_4$ : Counterterms known [Maldacena, . . . ]:

roughly, 
$$\frac{\text{const}}{\varepsilon^4} + \frac{S_{\text{EH}}}{\varepsilon^2} + S_{\text{conf}} \log \varepsilon.$$

Holographic recursion predicts

$$S_{\text{conf}} = \int \frac{\delta S_{\text{EH}}}{\delta g_{\mu\nu}} \mathcal{G}_{\mu\nu\sigma\rho} \frac{\delta S_{\text{EH}}}{\delta g_{\sigma\rho}};$$

this is indeed true!

Lifshitz with  $3 + 1$  boundary and  $z = 3$ : Counterterms not fully known yet, but recursion predicts a more complex relation: log counterterm given in terms of variations of  $S^{(2)}$  and  $S^{(4)}$  (work in progress).

## More QFT examples with $z = 2, D = 2$

We saw that the minimal Lifshitz scalar has one central charge  $c_K \neq 0$  but the other one  $c_V = 0$ .

Are there theories with both independent central charges?

(if not, then we don't need to look for their holographic description . . .)

## More QFT examples with $z = 2, D = 2$

We saw that the minimal Lifshitz scalar has one central charge  $c_K \neq 0$  but the other one  $c_V = 0$ .

Are there theories with both independent central charges?

(if not, then we don't need to look for their holographic description . . .)

Indeed, the answer is yes:

$$S = \frac{1}{2} \int dt d^2\mathbf{x} \sqrt{g} \left\{ \frac{1}{N} \left( \dot{\Phi} - N^i \nabla_i \Phi \right)^2 - N (\Delta \Phi)^2 \right\} \\ + \gamma \int dt d^2\mathbf{x} \sqrt{g} N \left[ R - \left( \frac{\nabla N}{N} \right)^2 + \frac{\Delta N}{N} \right]^2 \Phi^2.$$

Now that we know that theories with independent  $c_K, c_V$  exist, what is the holographic dual of  $c_V$ ?

## Holography with the general anomaly?

- The simplest relativistic system does not work.
- If looking for a more complicated relativistic model:  
Need to relax the holographic recursion between counterterms,

$$\tilde{\mathcal{L}}^{(0)} \neq \left( \frac{\delta \mathcal{L}^{(2)}}{\delta g_{\alpha\beta}} \right)^2 .$$

- But: it turns out that Lifshitz gravity works, in the vacuum!

**Disclaimer:** That does not imply that one cannot do this with relativistic gravity coupled to matter; indeed, the boundary between relativistic and nonrelativistic is somewhat fuzzy.)



**IIb.**  
**Lifshitz holography with Lifshitz gravity**

## Lifshitz gravity for Lifshitz holography

Requires nonprojectable theory (because we anticipate anisotropic Weyl transformations on the codimension-one boundary, hence  $N$  near boundary must depend on spacetime).

Lifshitz spacetime now foliated not just asymptotically, but everywhere (in the bulk). A single, codimension-one foliation by leaves of constant  $t$  (multiple & nested foliations also possible, not studied here).

At low energies, just as in GR:

- Anisotropic gravity will be dominated by  $z = 1$  terms.
- We neglect the small corrections due to all other higher-derivative terms, including the  $z > 1$  terms in  $S_V$ .

## Low-energy effective theory

The low-energy action will be similar to Einstein-Hilbert, with several important differences:

$$S = \frac{1}{\kappa^2} \int dt d^D \mathbf{x} dr \sqrt{G} N (K_{ab} K^{ab} - \lambda K^2) \\ + \frac{1}{\kappa^2} \int dt d^D \mathbf{x} dr \sqrt{G} N \left[ R - 2\Lambda - \frac{\alpha^2}{2} \left( \frac{\nabla_a N}{N} \right)^2 \right].$$

We have two additional low-energy couplings compared to GR:  $\lambda$  and  $\alpha$ .

Roughly, one will be fixed by choosing  $z$  for the vacuum, the other is free to give the missing central charge in the anomaly.

## Lifshitz as the vacuum solution

Require now that the Lifshitz spacetime with chosen value of  $z$  is a solution of the vacuum EoM.

This determines the cosmological constant (essentially, by our choice of scale),

$$2\Lambda = -D(D + 1) - (z - 1)(z + 2D),$$

and fixes one of the two new couplings,

$$\alpha^2 = \frac{2(z - 1)}{z},$$

leaving  $\lambda$  undetermined. Note: This relation implies  $\alpha^2 \leq 2$ , a relation known in nonprojectable HL gravity

[Blas,Pujolàs,Sibiryakov]

## Scalar gravitons & anisotropic BF bound

Although no extra matter field introduced, the scalar graviton plays the role of an extra propagating DoF.

One can ask for the scaling dimensions  $\Delta_+$  and  $\Delta_-$  associated with the asymptotic behavior of the bulk scalar graviton:

$$\Delta_{\pm} = \frac{z + D}{2} \left\{ 1 \pm \sqrt{1 + \frac{4(1 - \lambda)D}{(1 - \lambda)(z + D)^2}} \right\}.$$

The requirement that  $\Delta_{\pm}$  be real gives interesting constraints on  $\lambda$ ,

$$\lambda \geq 1 \quad \text{or} \quad \lambda \leq \frac{(z - D)^2 + 4D}{(z + D)^2}.$$

In the special case of  $z = D$ , the latter gives  $\lambda \leq 1/D$ ,

and opens up a BF-like window:  $\frac{1}{D+1} \leq \lambda \leq \frac{1}{D}$ .

## Holographic recursion in HL gravity

Again, use Hamilton-Jacobi equation. Logic is identical to the relativistic case.

The new low-energy terms modify the recursion relations just enough to avoid the detailed balance condition for  $\tilde{\mathcal{L}}^{(0)}$ .

Both  $c_K$  and  $c_V$  are now independently produced in holographic renormalization.

Hence, HL gravity with anisotropic scaling is the natural arena for nonrelativistic holography and AdS/CFT correspondence.

# III. Conclusions

# Conclusions

- Gravity with anisotropic scaling is finding multiple use in holography for nonrelativistic QFTs.
- Even when the bulk theory is relativistic, anisotropic Weyl symmetry is crucial for the proper definition of conformal infinity of spacetime, and in the treatment of asymptotic expansions for holographic renormalization.
- Anisotropic Weyl symmetries can be anomalous. For  $z = 2$  in  $D = 2$ , there are two independent central charges. Both can be independently realized in families of consistent QFTs.
- The minimal relativistic model of Lifshitz holography does not yield the most general form of anisotropic Weyl anomaly: Only one of the central charges is nonzero.
- Lifshitz spacetimes also solve vacuum EoM of nonprojectable HL gravity. This construction yields the most general form of the holographic anisotropic Weyl anomaly.
- HL gravity is the natural arena for nonrelativistic holography.