Analogue holographic correspondence in optical metamaterials

D. V. Khveshchenko

UNC-Chapel Hill, Physics & Astronomy

GGI, Firenze, 14/04/15

Outline

- Holographic conjecture (broadly defined) and its status
- Emergent metrics and analogue gravity in optical metamaterials
- Metamaterial-based implementations of analogue holography
- Take-home messages

DVK

EPL, v.109, p.61001 (2015), (arXiv:1411.1693)

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EPL, v.104, p.47002 (2013), (arXiv:1305.6651);
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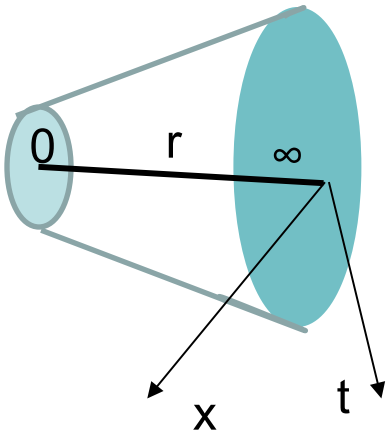
arXiv:1502.03375

Holographic correspondence:conjecture



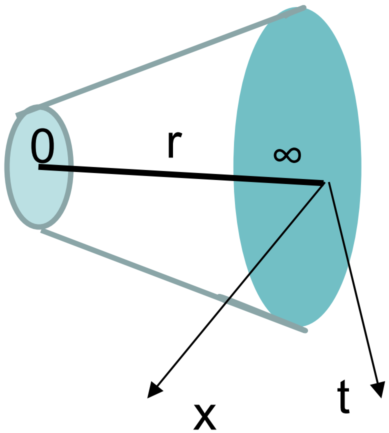
Holographic correspondence:conjecture

- Original ('AdS/CFT'):

  d=4 N=4 SYM <-> type-IIB superstrings (d=5 supergravity)

  (J.Maldacena; E.Witten, S.Gubser, I.Klebanov, A.Polyakov,…)

- SUSY,
- multi-component (N>>1),
- Lorentz and scale-invariant,
- boundary theory: very strongly interacting



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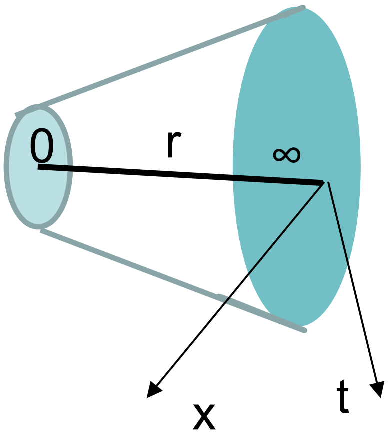

- Broadly defined (‘non-AdS/non-CFT’):

- non-SUSY,
- only a few components (N~1),
- Lorentz , scale, translationally, and/or rotationally non-invariant,
- boundary theory: only moderately interacting (T~U)

Holographic correspondence: evidence

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- Circumstantial:

black holes, quantum information, and Hawking radiation,
entanglement and tensor network states ('MERA'),
hydrodynamics of quark-gluon plasma, cold atomic gases,…

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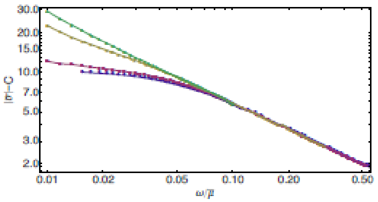
  Optical conductivity in cuprates (non-SUSY, N~1, T~U)



G,Horowitz and J.Santos, 1302.6586

$2 < \omega\tau < 8$

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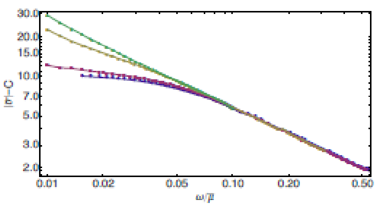

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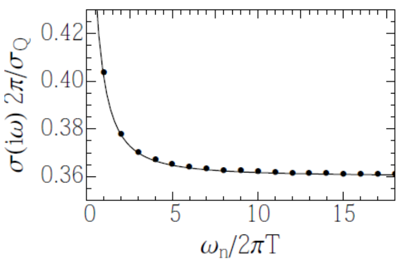
- (Almost) exact methods (MC):

  2d Bose-Hubbard model



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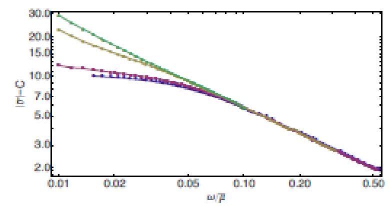

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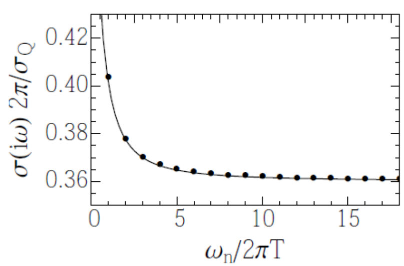

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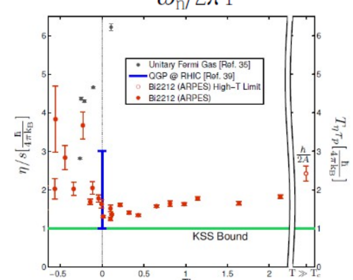
- Experiment:

  $\frac{\eta}{s}$ ratio from ARPES in cuprates



J.Rameau et al, 1409.5820

Holographic correspondence: outstanding questions

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- General:

DVK, arXiv:1404.7000

-What is the TRUE status of the (broadly defined) holographic conjecture?

-If it is indeed valid, then WHY?

- Do ALL strongly coupled systems have duals (or only a precious FEW)?

-How much SYMMETRY is enough and is LARGE N really necessary?

-Has the (non)AdS/(non)CFT dictionary been established in its FINAL form?

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-Do the boundary theories of the previously studied gravity duals have physical realizations among the known materials?

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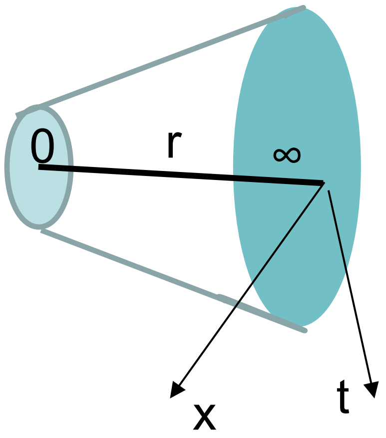
-Can anything at all be tested systematically in the lab?

Holographic correspondence: physical origin



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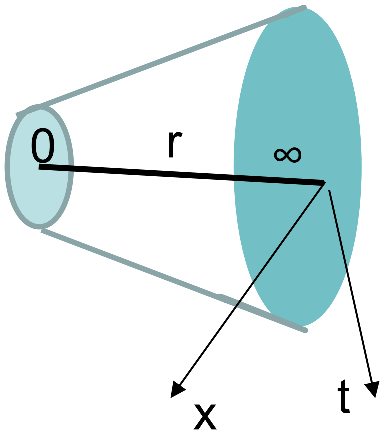
Dynamical renormalization (energy/length/information) scale

or a mere 'spectator' coordinate?



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Full fledged fluctuating (quantum) gravity in the bulk

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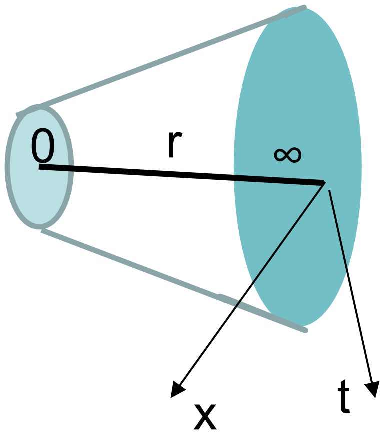

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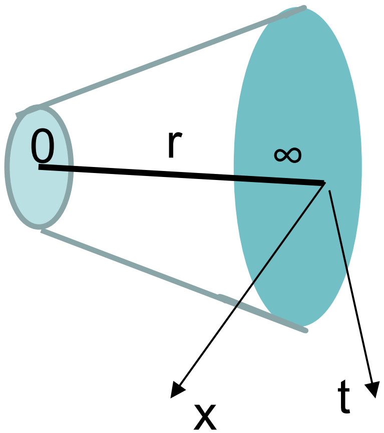

- Examples:

-   Thermodynamics of phase transitions (Fisher/Ruppeiner);
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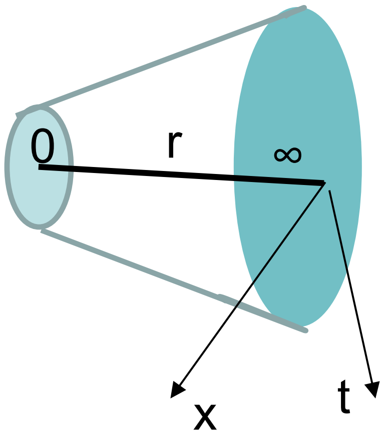

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So… **‘Just do it!’ (HEP)** or **'Holographic WHAT?!’ (CMT)**

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- Fixed classical metric,
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Explains certain apparent holography-like features

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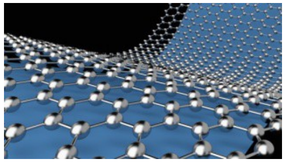

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- Desktop realizations:

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DVK, EPL v.104, p.47002 (2013)

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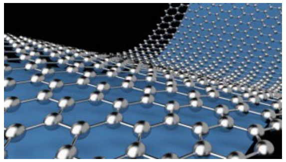

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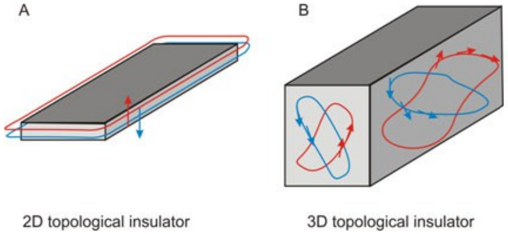
- Topological insulators/superconductors



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- Curved 3d space
- Fermi liquid on a 2d boundary is more robust than in 1d

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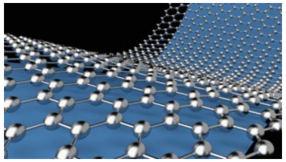

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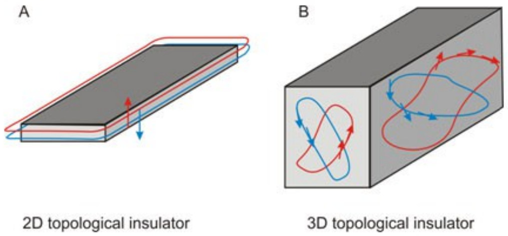

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- **Hyperbolic optical/IR metamaterials**

Metamaterials: analogue gravity

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- Artificial metric in electrically and/or magnetically active media

$$\gamma_{ij} = g_{ij}/|g_{\tau\tau}| = \epsilon_{ij}/det\hat{\epsilon} = \mu_{ij}/det\hat{\mu}$$

$$\epsilon_{ij} = \mu_{ij} = \sqrt{-\hat{g}}g_{ij}/|g_{\tau\tau}|$$

W.Lu et al,'10,
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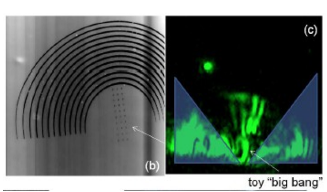
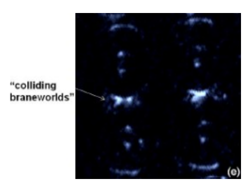
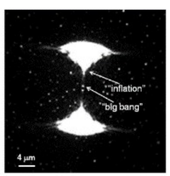
- Hyperbolic metamaterials

- Rindler and event horizons, black/white/worm-holes,
- inflation, Big Bang, Rip, and Crunch,
- metric signature transitions, end-of-time, multiverse,…







I.Smolyaninov et al,
1111.3300, 1201.5348

String holography meets its optical namesake: analogue correspondence in optical metamaterials

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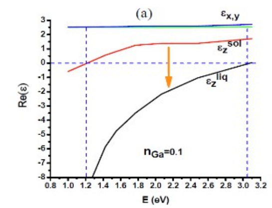
- Dispersion of extraordinary waves



$$\frac{\omega^2}{c^2}\vec{D}_\omega = \vec{\nabla}\times\vec{\nabla}\times\vec{E}_\omega \quad \text{and} \quad \vec{D}_\omega = \overleftrightarrow{\varepsilon}_\omega \vec{E}_\omega$$

$$\omega^2 = k_z^2/\epsilon_{xy} + k_{xy}^2/\epsilon_{zz}$$

I.Smolyaninov, E.Narimanov,'09…

$$ds^2 = -\epsilon_{xy}dz^2 - \epsilon_{zz}(dx^2 + dy^2)$$

$$\epsilon_{xy} > 0$$
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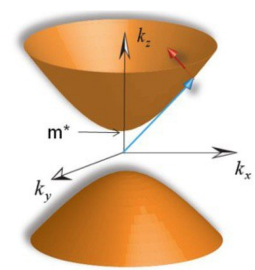

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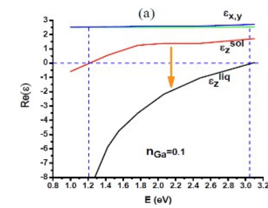
- Attainable 2+1 geometries

$$ds^2 = \frac{d\tau^2}{u^{2\alpha}} + R^2\frac{du^2}{u^{2\beta}} + \frac{dx^2}{u^{2\gamma}}$$

$$ds^2 = u^{2\theta/d}\left(\frac{d\tau^2}{u^{2\zeta}} + \frac{L^2du^2 + d\mathrm{x}^2}{u^2}\right)$$

$$\zeta = \frac{1-\beta+\alpha}{1-\beta+\gamma}, \quad \theta = \frac{1-\beta}{1-\beta+\gamma}$$

Hyperscaling-violation metrics



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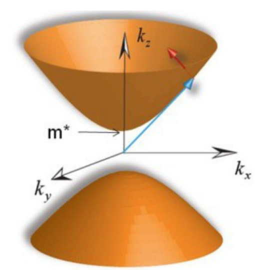
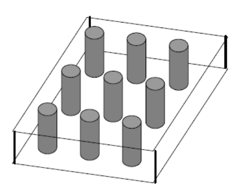
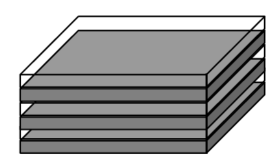
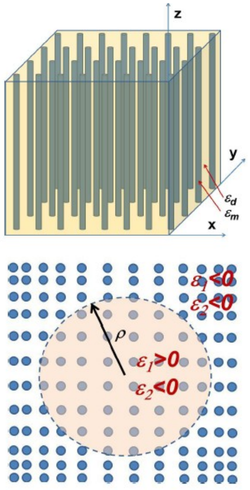






n(x,y) n(z)

Axially-symmetric setup



n(x,y) - density
of the m-component

Axially-symmetric setup

- Radially-dependent density of the metallic component

$$ds^2 = -\epsilon_{xy} dz^2 - \epsilon_{zz}(dx^2 + dy^2)$$

$$g_{\tau\tau} = -\epsilon_{xy}, \quad g_{rr} = g_{\phi\phi}/r^2 = -\epsilon_{zz}$$

$$\epsilon_{zz}(r) = \epsilon_m n + \epsilon_d(1-n)$$

$$\epsilon_{xy}(r) = \epsilon_d \frac{\epsilon_m(1+n) + \epsilon_d(1-n)}{\epsilon_m(1-n) + \epsilon_d(1+n)}$$

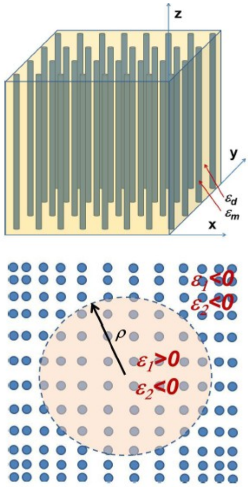
Zeros/poles:

$$n_1 = (\epsilon_m + \epsilon_d)/(\epsilon_d - \epsilon_m)$$

$$n_2 = \epsilon_d/(\epsilon_d - \epsilon_m)$$

$$\epsilon_d > 0$$

$$\epsilon_m < 0$$



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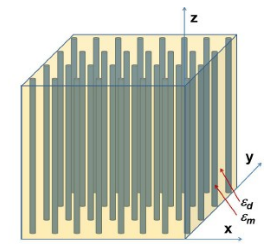

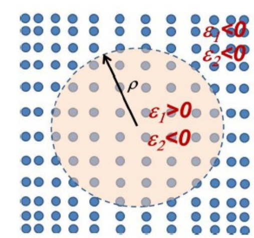

$$\epsilon_d > 0$$

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- Mimicking the metric

$$ds^2 = \frac{d\tau^2}{u^{2\alpha}} + R^2 \frac{du^2}{u^{2\beta}} + \frac{dx^2}{u^{2\gamma}}$$

$$n(r) = 1/3 + c(R/r)^{2\alpha}$$

$$\beta = 2 - \alpha \qquad \gamma = 1 - \alpha$$

$$u = R/r$$

$$x = R\phi$$

$$c \ll 1$$

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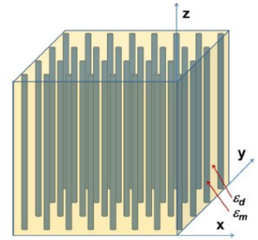

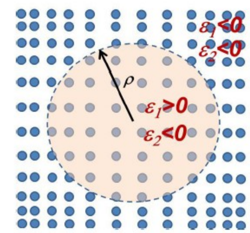

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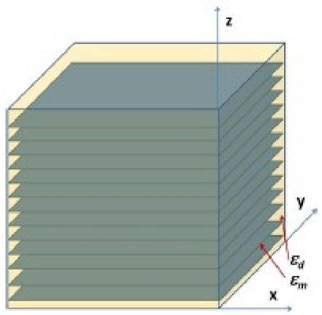
- HV geometry: $\theta, z \to \infty \quad \theta/\zeta = (\alpha-1)/(2\alpha-1)$ $\quad \gamma = 0, \ \alpha = \beta = 1 \qquad AdS_2 \times R$

Layered setup



n(z)

Layered setup

- z-dependent density of the metallic component

$$ds^2 = -\epsilon_{xy} dz^2 - \epsilon_{zz}(dx^2 + dy^2)$$

$$g_{\tau\tau} = -\epsilon_{xy}, \quad g_{rr} = g_{\phi\phi}/r^2 = -\epsilon_{zz}$$

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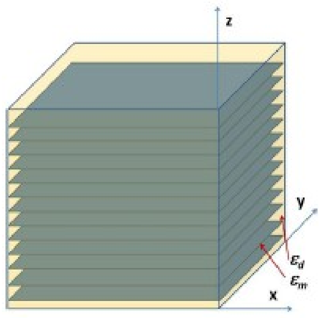
$$\epsilon_{xy}(z) = \epsilon_m n + \epsilon_d (1-n)$$



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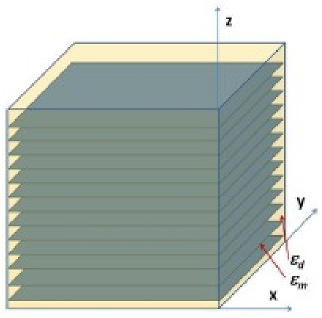

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$$\alpha = -\beta = \gamma.$$

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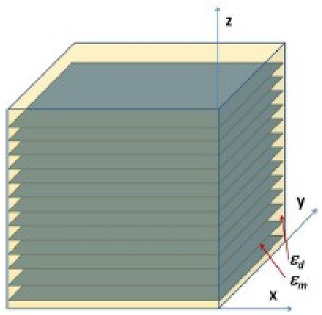

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- HV geometry: $\zeta = 1 \quad \theta = (1+\alpha)/(1+2\alpha)$ $\quad \alpha = -1 \quad AdS_3$

Boundary propagator

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- WKB solutions $\psi_{\pm}(r,\omega,k) \sim \frac{1}{V^{1/4}(r)} e^{\mp \int_r^R dr' \sqrt{V}(r')}$ $mR \gg 1$
- Asymptotic behavior of the propagator $G_{\omega}(\tau, x) \sim \exp[-S(\tau, x)]$
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- Axially-symmetrical: $S(\tau,0) \sim \tau^{\theta/\zeta}$, $\quad 0 < \theta/\zeta = (\alpha-1)/(2\alpha-1) < 1/2$ $\qquad S(\tau,0) \sim \ln\tau$, $\quad S(0,x) \sim x$ $\qquad \alpha = 1$

Prospective 'boundary dual': fluctuating 2d membrane

- Fluctuating elastic membrane:

  (coupled in- and out-of-plane modes)

$$F = \int d^d\mathbf{x}[\frac{\kappa}{2}(\nabla^2 h)^2 + \mu v_{\alpha\beta}^2 + \frac{\lambda}{2} v_{\alpha\alpha}^2]$$

$$v_{\alpha\beta} = \partial_\alpha \xi_\beta + \partial_\beta \xi_\alpha + \partial_\alpha h \partial_\beta h$$

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2d membrane crumpling transition:

$$\eta_c \sim 1$$

$$S_{boundary} = \frac{1}{2\nu} \int d^2\mathbf{k} \mathbf{k}^{2+\theta/\zeta} |\phi_\mathbf{k}|^2 \qquad \nu \sim L^{1-\theta/\zeta_\omega}$$

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- Practical realizations: Co nanoparticles in kerosene, PMMA on gold, $InGaAs$ (m) / $AlGaAs/GaAs$ (d) ,…

Conclusions

- The holographic conjecture still remains to be verified, especially in its broadly generalized 'non-CFT/non-AdS' form.
- The bottom-up approach can be prone to confusing the genuine ‘bona fide’ holography with some apparent ‘analogue’ one.
- In every specific case, the physical nature of the latter can be elucidated without invoking any new physical principles.
- In optical metamaterials, the simulated (pseudo)holographic behavior can be systematically studied with such established experimental techniques as holographic and speckle interferometry, as well as the other optical field correlation probes.