Towards a realistic holographic tensor network: From p-adic CFT to (minimal) CFT2

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Work (in progress) done in collaboration with :
p-adic stuff arXiv:2012.XXXXX, 21XX.YYYYY: Lin Chen, Xiong Liu, Jiaqi Lou

Levin-Wen models stuff arXiv:21YY.XXXXX (??) :
Ruoshui Wang, Xiangdong Zeng, Ce Shen

Overview

- Tensor network and AdS/CFT
  - Part I p-adic tensor network — Bending the BT tree
    - Method 1: RG flow
      (and emergent "Einstein equation")
    - Method 2: Wilson lines and p-adic black holes
  - Part II holographic network for more realistic CFTs ???
  - Outlook

Holographic entanglement and the tensor network

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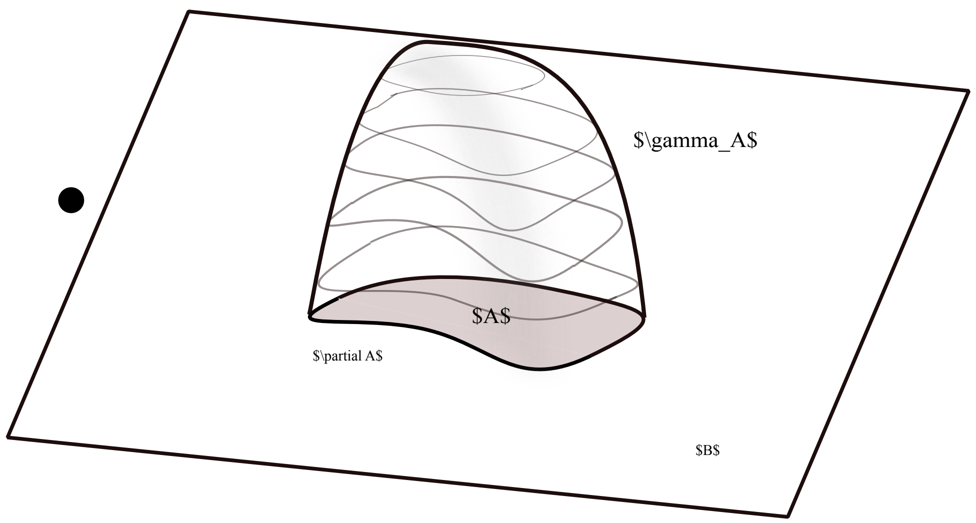
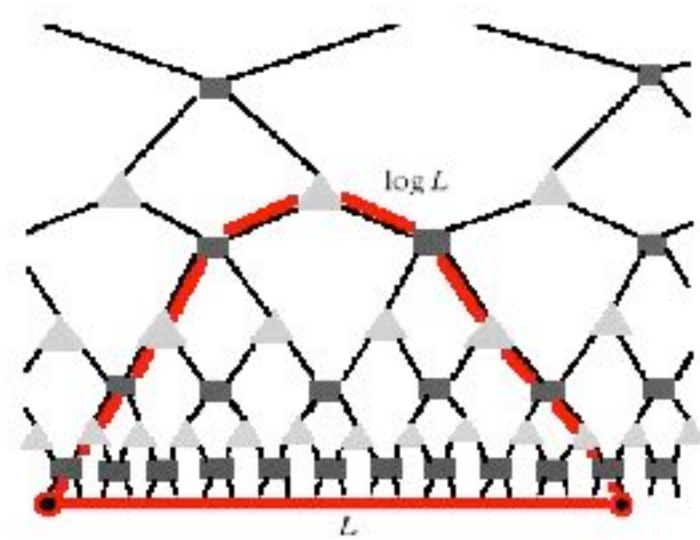


v.s.



$$S_{EE} = \frac{A}{4G}$$

$$S_{EE} \leq \mathcal{N} \log L$$

Picture courtesy Orus

- For MERA type networks, it recovers a Ryu-Takayanagi type entanglement entropy swingle

Part I : Bending the BT tree

One-page summary of p-adic CFT

CFT	p-adic CFT
$x \in \mathbb{R}$	$x \in \mathbb{Q}_p$
$x \to \frac{ax+b}{cx+d}$ $\left(\begin{array}{cc} a & b \\ c & d \end{array}\right) \in SL(2,\mathbb{R})$	$x \to \frac{ax+b}{cx+d}$ $\left(\begin{array}{cc} a & b \\ c & d \end{array}\right) \in PGL(2,\mathbb{Q}_p)$
$\mathcal{O}_i(x) \to \lvert\frac{ad-bc}{(cx+d)^2}\rvert^{-\Delta_i}$	$\mathcal{O}_i(x) \to \lvert\frac{ad-bc}{(cx+d)^2}\rvert_p^{-\Delta_i}$
$\mathcal{O}_i(x)\mathcal{O}_j(y) = \sum C_{ij}^k \lvert x-y\rvert^{\Delta_k-\Delta_i-\Delta_j}\mathcal{O}_k(y) + \text{descendents}$	$\mathcal{O}_i(x)\mathcal{O}_j(y) = \sum_k C_{ij}^k \lvert x-y\rvert_p^{\Delta_k-\Delta_i-\Delta_j}\mathcal{O}_k(y)$
$\langle\mathcal{O}_i(x)\mathcal{O}_j(y)\rangle = C_i\delta_{ij}\lvert x-y\rvert_p^{-2\Delta_i}$	$\langle\mathcal{O}_i(x)\mathcal{O}_j(y)\mathcal{O}(z)_k\rangle = \frac{C_iC_{jk}^i}{\lvert x-y\rvert_p^{\Delta_{ij}}\lvert x-z\rvert_p^{\Delta_{ik}}\lvert y-z\rvert^{\Delta_{jk}}}$

$$x = p^v\left(\sum_{m=0}^{\infty} a_m p^m\right)$$

$$|x|_p = p^{-v}$$

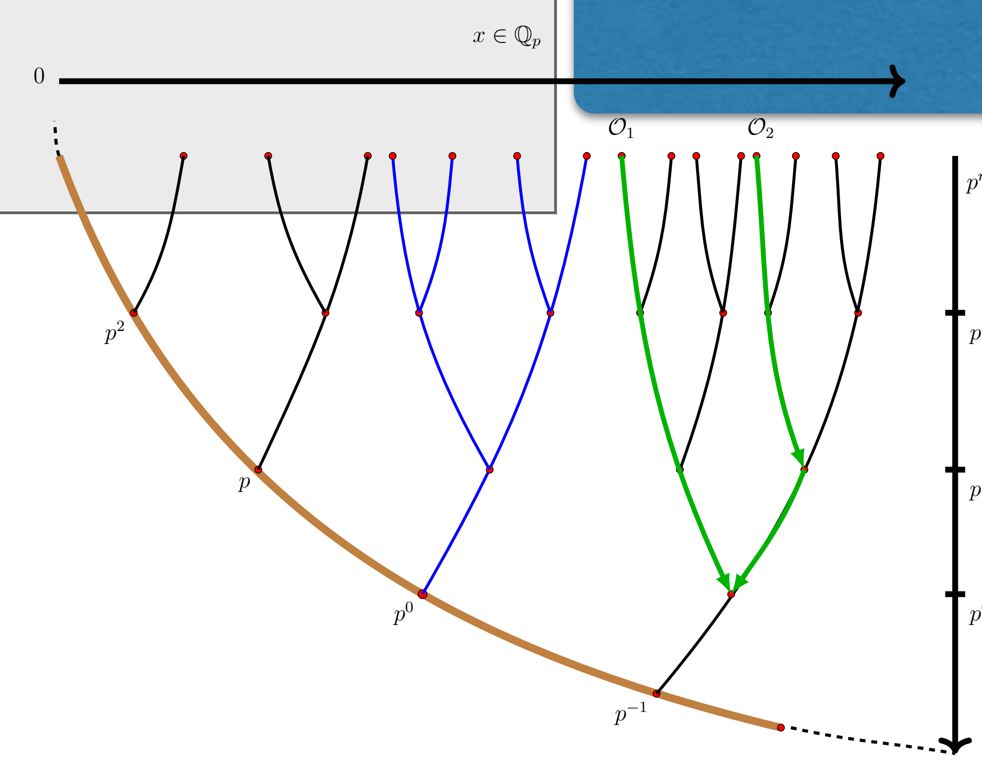
$$(x,y)_p = |x-y|_p$$

One line review of p-adic AdS/CFT:

Gubser et al. Commun.Math.Phys. 352 (2017) no.3, 1019-1059 ;
Heydeman, Matthew *et al.* Adv.Theor.Math.Phys. 22 (2018) 93-176

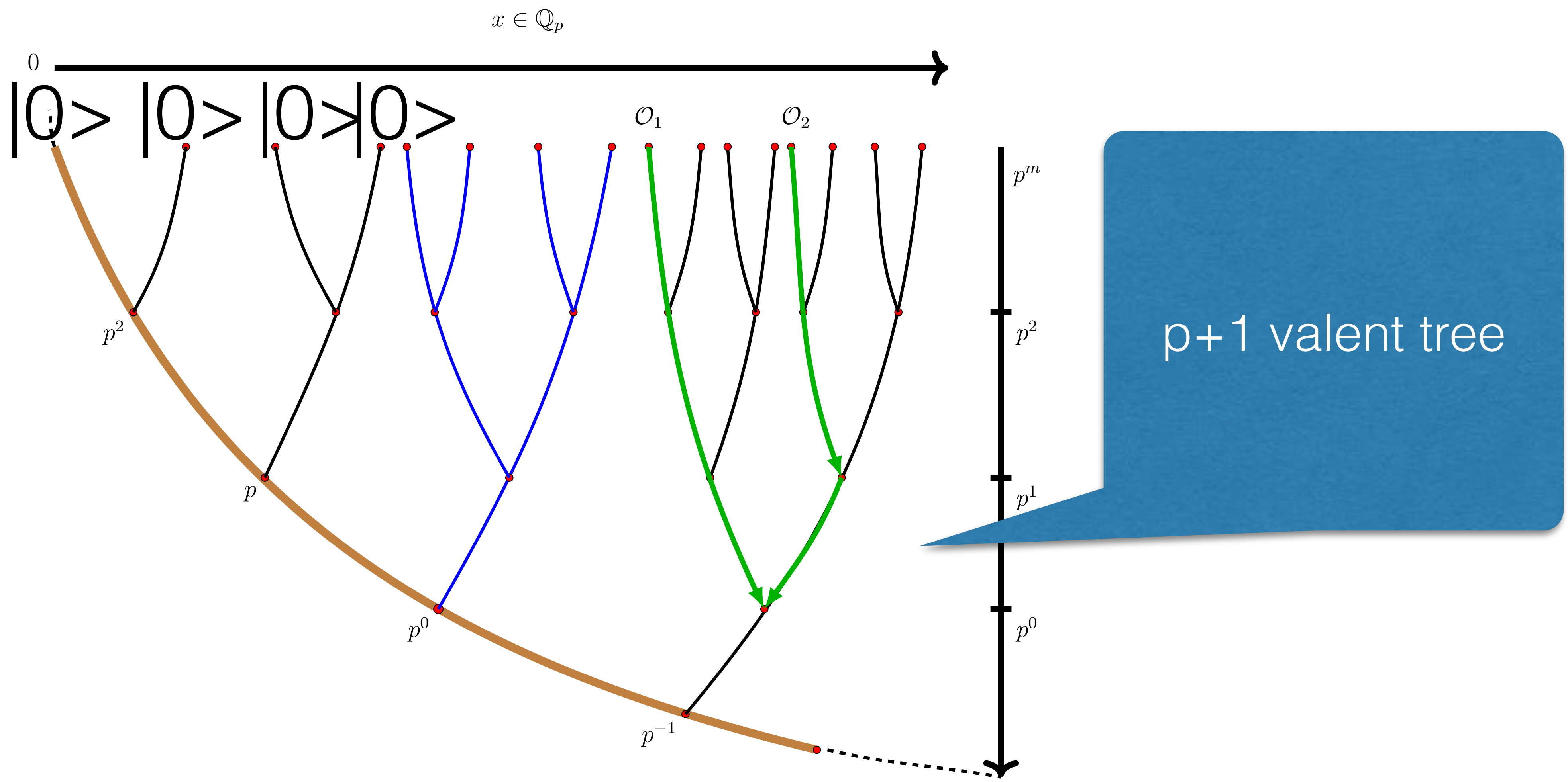
	upper half plane $\mathbb{H}$	Bruhat-Tits tree $\mathbb{H}_p$
Isometry group G	$\mathrm{SL}(2,\mathbb{R})$	$\mathrm{PGL}(2,\mathbb{Q}_p)$
Isotopy group K	$\mathrm{SO}(2,\mathbb{R})$	$\mathrm{PGL}(2,\mathbb{Z}_p)$
Boundary	$\mathbb{R}$	$\mathbb{Q}_p$
	$\mathbb{H} = \mathrm{SL}(2,\mathbb{R})/\mathrm{SO}(2,\mathbb{R}).$	$\mathbb{H}_p \equiv \frac{\mathrm{PGL}(2,\mathbb{Q}_p)}{\mathrm{PGL}(2,\mathbb{Z}_p)}$

The bulk is discrete.



Putting together the tensor network and the Bruhat-Tits tree: a proprosal for partition function and correlation functions

(tensor network of the partition function), HLY, Li, Melby-Thompson 2019



partition function

(C_{ij1} can be diagonalised)

Graph Laplacian

$$\Box\phi(v) = \sum_{u\sim v}(\phi(u) - \phi(v))$$

- consider $$G(v_1, v_2) = p^{-\Delta d(v_1,v_2)}$$
- p+1 = valancy of graph
- We have $$(\Box_{v_1} + m^2)G(v_1, v_2) = \mathcal{N}\delta_{v_1,v_2}$$

$$m^2 = -\frac{1}{\zeta_p(\Delta-1)\zeta(\Delta)}, \qquad \zeta_p(s) \equiv \frac{1}{1-p^{-s}}$$

Putting together the tensor network and the BT tree

the labels of the tensors are primaries of the CFT

p=2 $$G_{I_1 I_2 I_3} = p^{-\Delta_{I_1} - \Delta_{I_2} - \Delta_{I_3}} C_{I_1 I_2 I_3}$$

$$G_{I_1 I_2 I_3 \cdots I_{p+1}} = p^{-\Delta_{I_1} - \Delta_{I_2} - \Delta_{I_3} - \cdots \Delta_{I_{p+1}}} C_{I_1 I_2 I_3 \cdots I_{p+1}}$$

$$C_{I_1 \cdots I_n} = C_{I_1 I_2}^{J_1} C_{J_1 I_3}^{J_2} \cdots C_{J_{n-2} I_{n-1} I_n}$$

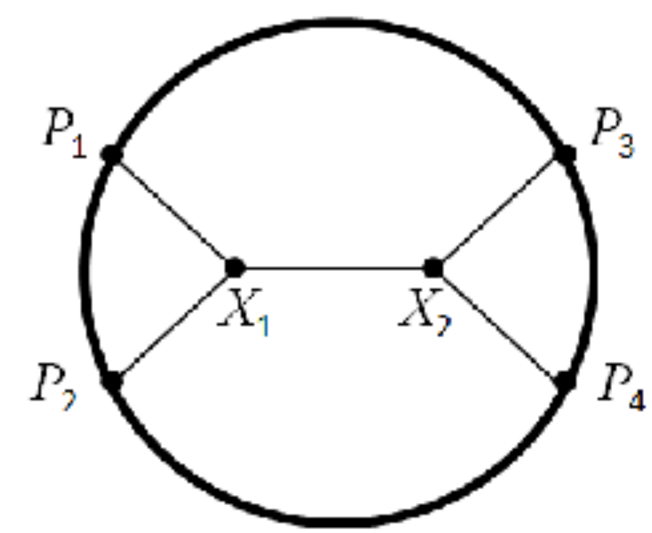
HKLL Relation/Witten Diagram

$$[\Box + m^2]K(x, z|y) = 0$$

$$\Delta = \frac{d}{2} \pm \sqrt{d^2/4 + m^2 L^2}$$

- HKLL relation :
- $\phi(x, z) = \int d^d y K(x, z|y)\mathcal{O}(y)$
-

Correlation function

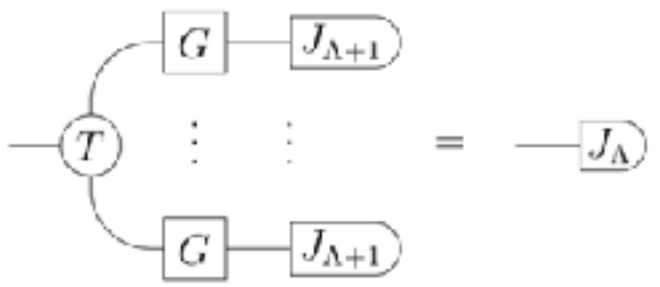


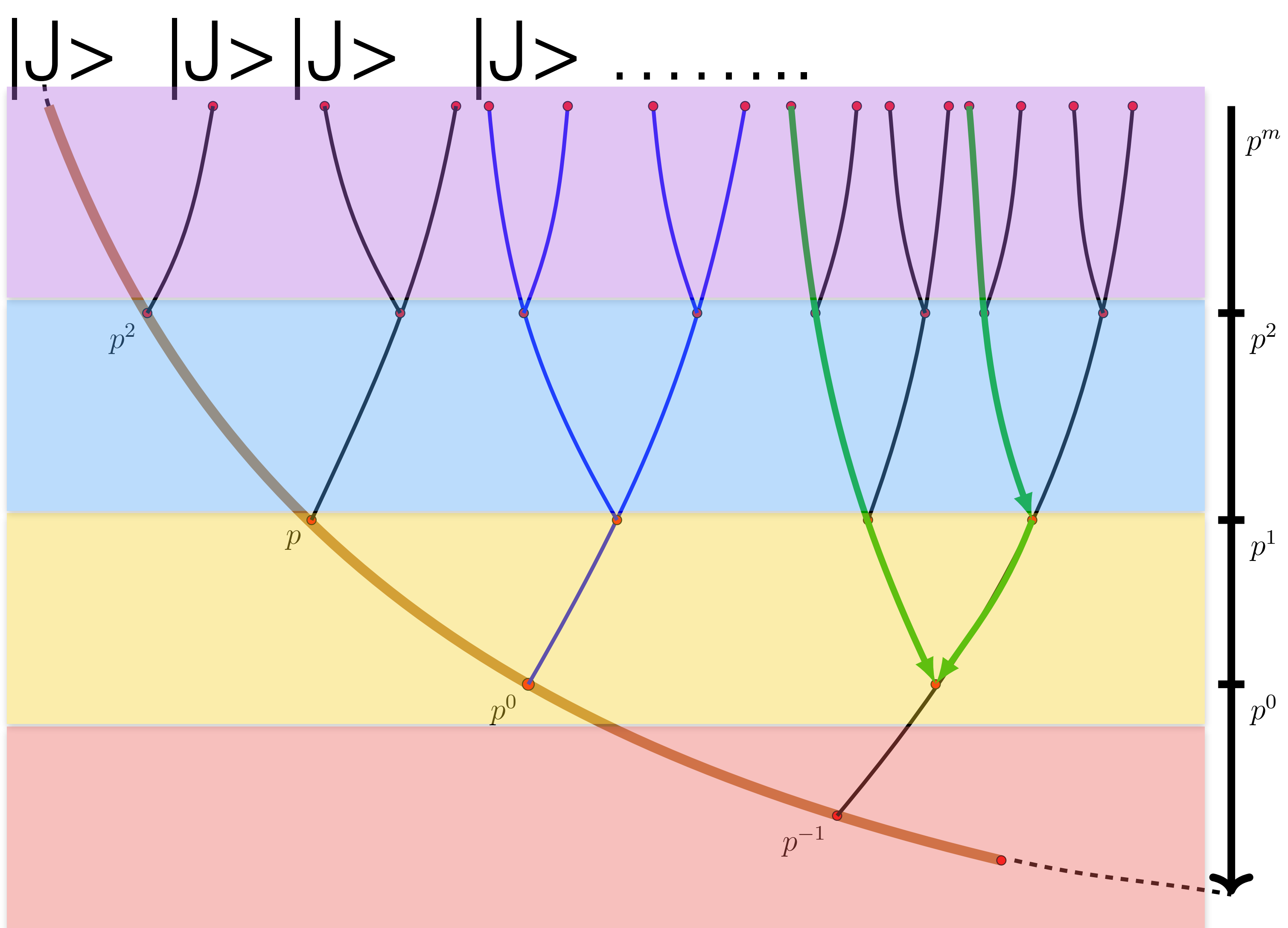
pic courtesy M. Paulos

P-adic RG flow

HLY, Li, Melby-Thompson 2019

Define RG flow $|J_n\rangle = |0\rangle + J_n^a|a\rangle$

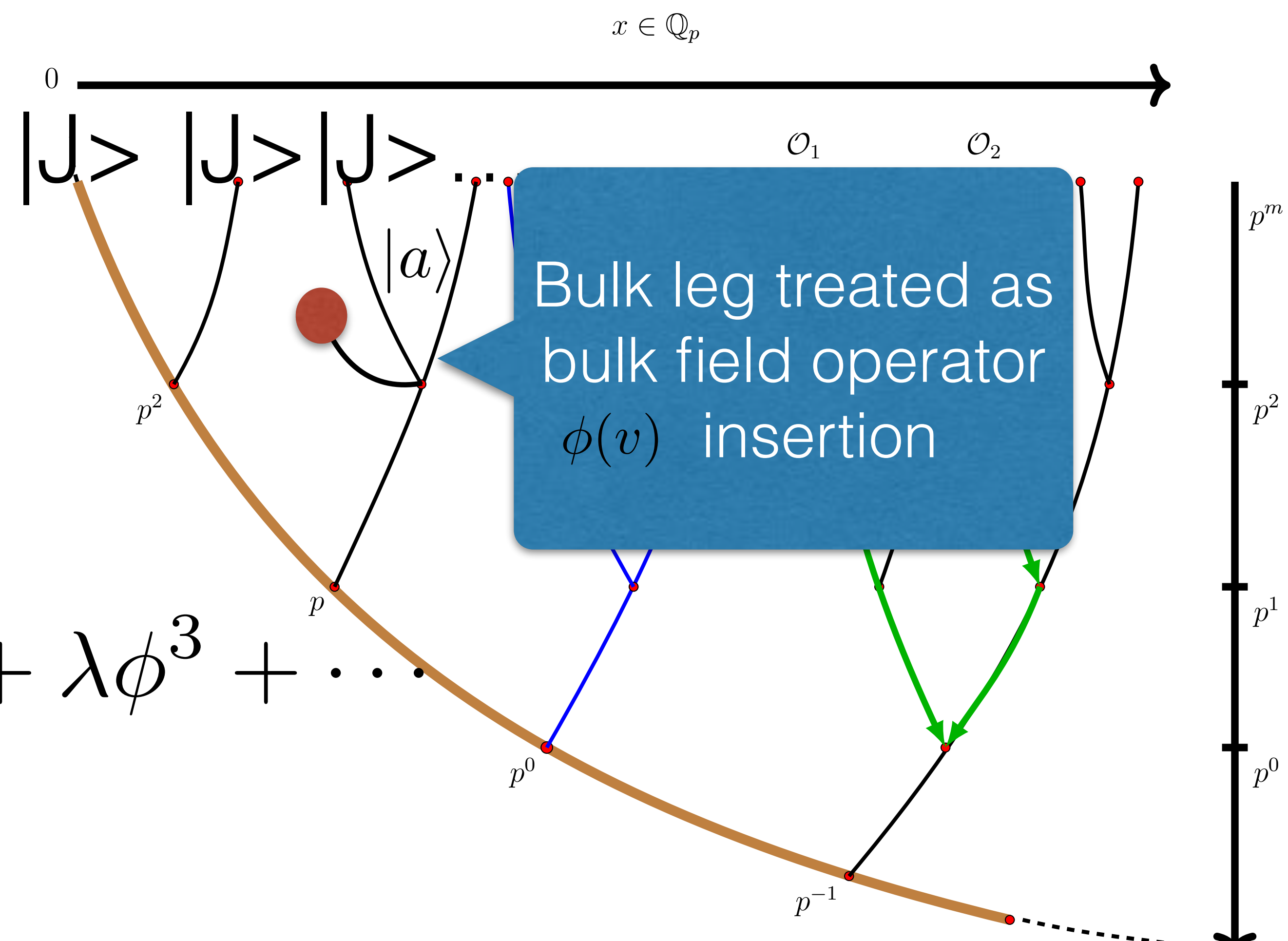




Is there some analogue of "Einstein Equation" that can describe this flow?

Recipe of Einstein equation (Some Guesses……)

1. Bulk expectation value of some scalar field. Compute stress tensor assuming the simplest possible kinetic term + possible interaction terms…



$$\partial\phi\partial\phi + m^2\phi^2 + \lambda\phi^3 + \cdots$$

$$\langle \phi_a(v) \rangle = \sum_{x_b, a} G^{\Delta_a}(x_b, v) J_a + \frac{1}{2} \sum_{a,b,c} \sum_{x_b, y_b, z} J_b J_c C_{abc} G^{\Delta_b}(x_b, z) G^{\Delta_c}(y_b, z) G^{\Delta_a}(z, v) + \mathcal{O}(J^3)$$

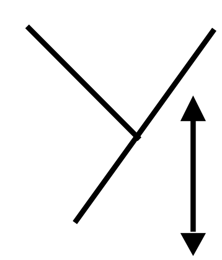
Recipe of Einstein equation (Some Guesses……)

2. A notion of distance on the links.

$$j_n \equiv 1 - \frac{|\langle J_{\Lambda-n}|J_{\Lambda-n-1}\rangle|^2}{\langle J_{\Lambda-n}|J_{\Lambda-n}\rangle\langle J_{\Lambda-n-1}|J_{\Lambda-n-1}\rangle}.$$

?

The overlap between the "renormalised boundary condition" with the next one is some kind of distance between two vertices? or some kind of angles between them = local curvature?



Recipe of Einstein equation (Some Guesses……)

2. A notion of distance on the links.

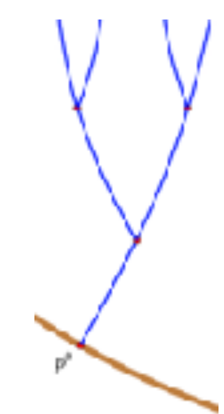
The overlap between the "renormalised boundary condition" with the next one is some kind of distance between two vertices? or some kind of angles between them = local curvature?

$$j_n = (\partial\phi)^2 + \lambda(\phi_{v_1} + \phi_{v_2})(\partial\phi)^2$$

$$\lambda = -C^{\epsilon}_{\epsilon\epsilon}\frac{(p-1)(2p^{2\Delta} + p^{\Delta+1} + p)}{(p^{\Delta}+1)(p^{3\Delta} - p^2)}$$

+ O(J^4)

$$\Box j_n \quad = \quad p(j_n - j_{n-1}) + (j_n - j_{n+1}).$$



$$\Box j_n = (-p^{2\Delta-1} - p^{2-2\Delta} + p + 1)(\partial\phi)^2 + C^{\epsilon}_{\epsilon\epsilon}C_0\phi^3_{v_1}$$

+ O(J^4)

$$C_0 \quad = \quad (p-1)p^{-6\Delta-2}\left(p-p^{\Delta}\right)^2\left(p^{\Delta}+p\right)$$

$$\frac{\left(p^{8\Delta} + p^{9\Delta} + (p+1)p^{\Delta+5} + p^{2\Delta+5} - p^{3\Delta+3} - (2p+1)p^{4\Delta+3} - 2(p+1)p^{5\Delta+2} + 2p^{7\Delta+1} + p^6\right)}{\left(p^{\Delta}+1\right)\left(p^{3\Delta}-p^2\right)}$$

Recipe of Einstein equation (Some Guesses……)

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$$j_n = (\partial\phi)^2 + \lambda(\phi_{v_1} + \phi_{v_2})(\partial\phi)^2$$

$$\Box j_n = (-p^{2\Delta-1} - p^{2-2\Delta} + p + 1)(\partial\phi)^2 + C^{\epsilon}_{\epsilon\epsilon} C_0 \phi^3_{v_1}$$

+ O(J^4)

$$S = \sum_{\langle xy\rangle}(\kappa_{xy} - 2\Lambda) + \sum_{\langle xy\rangle}\frac{J_{xy}}{2}(\phi_x - \phi_y)^2 + \sum_x \frac{m^2}{2}\phi_x^2\,,$$

$$\kappa_{xy} + 2\frac{q-1}{q+1} = -\frac{q-3}{2(q+1)^2}\Box j_{xy} + O(j^2)\,.$$

$$\frac{1}{2(q+1)}\Box j_{xy} + O(j^2)\,,$$

Gubser, Heydeman, Jepsen, Marcolli, Parikh, Saberi, Stoica, Trundy

Another way of deforming away from "pure AdS" — A view from "*p-adic Chern-Simons theory*"

The p-adic tensor network is a Wilson line network with gauge group PGL(2,Qp).

LYH, Li, Melby-Thompson 2018

Construct global gauge potential :

Take reference point $f_0^t = (1, 0), \qquad g_0^t = (0, 1)$

$$g(x) = \Gamma_p^{i_1} \Gamma_p^{i_2} \cdots \Gamma_p^{i_{d(P,x)}}$$

$$\langle\langle \vec{f}, \vec{g} \rangle\rangle_v = \langle\langle \begin{pmatrix} p^n \\ 0 \end{pmatrix}, \begin{pmatrix} x^{(n)} \\ 1 \end{pmatrix} \rangle\rangle \quad \longleftrightarrow \quad \mathfrak{g}(v) = \begin{pmatrix} p^n & x^{(n)} \\ 0 & 1 \end{pmatrix}$$

$$W(x \to y) = g(x) g(y)^{-1}$$

$$\left[\prod_{i=1}^{3} \langle \Delta_i | \right] \hat{\mathfrak{W}}_{\Delta_i}(v_a \to v_i) | \mathcal{S} \rangle$$

We deform the p-adic connection getting help from the pure AdS case

$$A = \begin{pmatrix} -\frac{1}{2}d\rho & e^{\rho}dz \\ \frac{4G}{l}L(z)e^{-\rho}dz & \frac{1}{2}d\rho \end{pmatrix}.$$

- In Qp, the Lie algebra of the matrix group is not very well defined —
  because infinitesimal stuff (in terms of p-adic norm) exponentiated could lead to a divergent p-adic norm.

- Also the BT tree is discrete, and so the shortest Wilson lines should at least connect two nearest neighbours on the tree.
- Let us formally exponentiate the AdS result

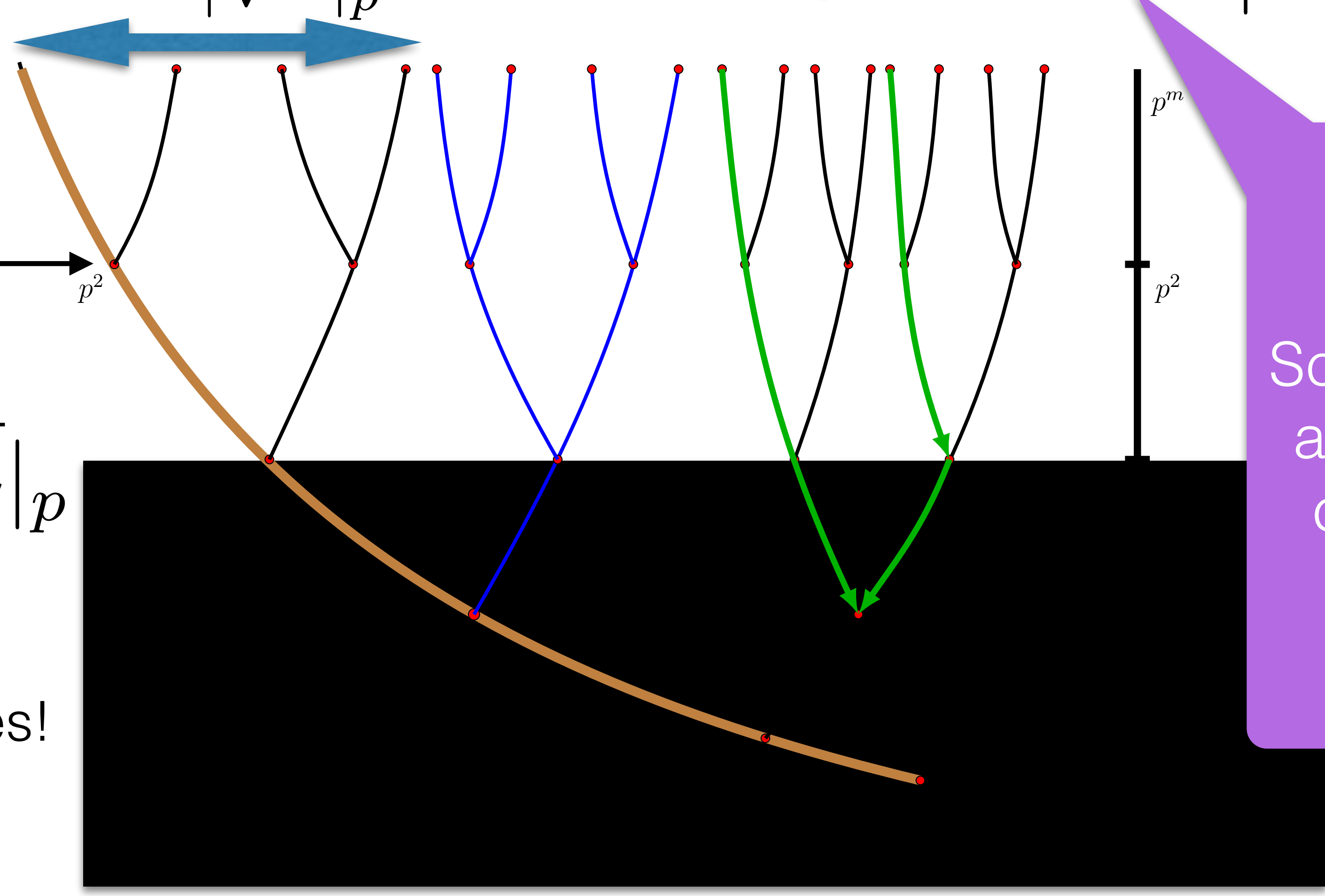
$$\begin{aligned} \mathfrak{W}(v_1 \to v_2) &= P\exp\left(\int_{v_1}^{v_2} A_\mu(\xi)d\xi^\mu\right) \\ &= P\exp\left(\int_{z_1}^{z_2} A_z(\rho_1, z)dz\right) \cdot P\exp\left(\int_{\rho_1}^{\rho_2} A_\rho(\rho, z_2)d\rho\right). \end{aligned}$$

$$\mathfrak{W}(v_1 \to v_2) = \begin{pmatrix} e^{-\mathrm{d}\rho}\cosh\left(\frac{\mathrm{d}z\sqrt{L}}{\sqrt{k}}\right) & \frac{e^{\rho_1}\sqrt{k}\sinh\left(\frac{\mathrm{d}z\sqrt{L}}{\sqrt{k}}\right)}{\sqrt{L}} \\ \frac{e^{-\rho_2}\sqrt{L}\sinh\left(\frac{\mathrm{d}z\sqrt{L}}{\sqrt{k}}\right)}{\sqrt{k}} & \cosh\left(\frac{\mathrm{d}z\sqrt{L}}{\sqrt{k}}\right) \end{pmatrix} e^{\mathrm{d}\rho/2},$$

We deform the p-adic connection getting help from the pure AdS case

To ensure that the exponential has finite p-adic norm, we have $|dx|_p < \frac{1}{|\sqrt{L}|_p}$

Periodicity emerges: $\beta = \frac{1}{|\sqrt{L}|_p}$? $S \sim |\sqrt{L}|_p$



Locally the tenors take exactly the same value as before.

$r \leq |\sqrt{L}|_p$

When the bound is violated, the Wilson line expectation value vanishes! There is effectively a horizon (?!)

Scales in the same way as number of vertices cut by the "*horizon*".

Part II : Towards a Holographic network for more realistic CFTs

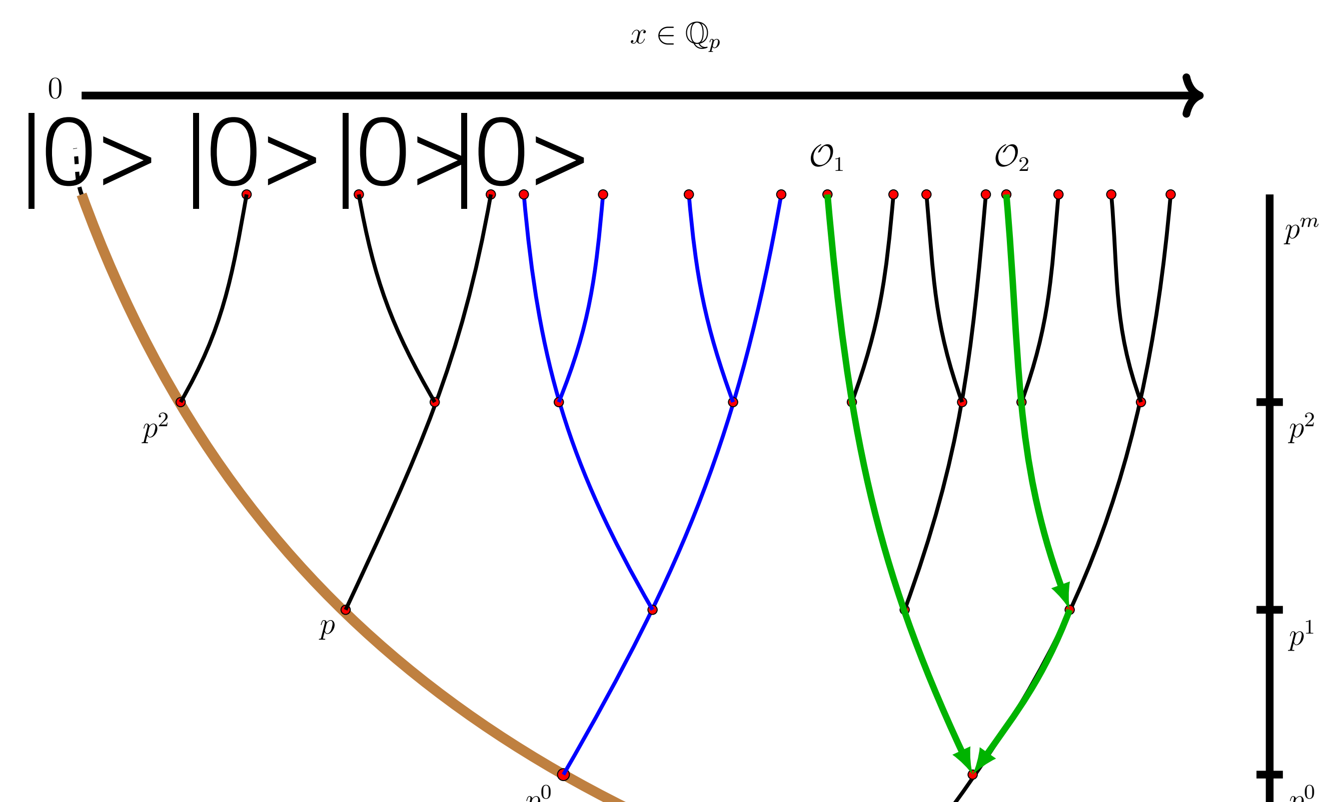
Part II -Towards building a holographic network describing realistic CFTs??

Some lessons learned…

- The tensor network describing the partition function rather than the wavefunction preserve more isometries allowing more quantitative manipulations.

- Our partition function takes the form of a “strange correlator”

You, Bi, Rasmussen, Slagle, Xu 2013



Minimal models and Levin Wen models

1. Tensor Categories can be used to construct Hamiltonians of CFT minimal models
Feiguin, Trebst, Ludwig, Troyes, Kitaev, Wang, Freedman PRL 2007;

2. The partition functions of minimal models can be thought of as imposing boundary conditions on a corresponding topological model defined using these tensor categorical data
Aaesen, Fendley, Mong J. Phys. A; Math. Theor. 2016; 2020 ;

3. There is a strange correlator representation of these CFT partition functions — the overlap between a direct product state and a Levin - Wen wavefunction
Bal, Williamson, Vanhove, Bultinck, Haegeman, Verstraete PRL 2018;
Lootens, Vanhove, Verstraete PRL 2019

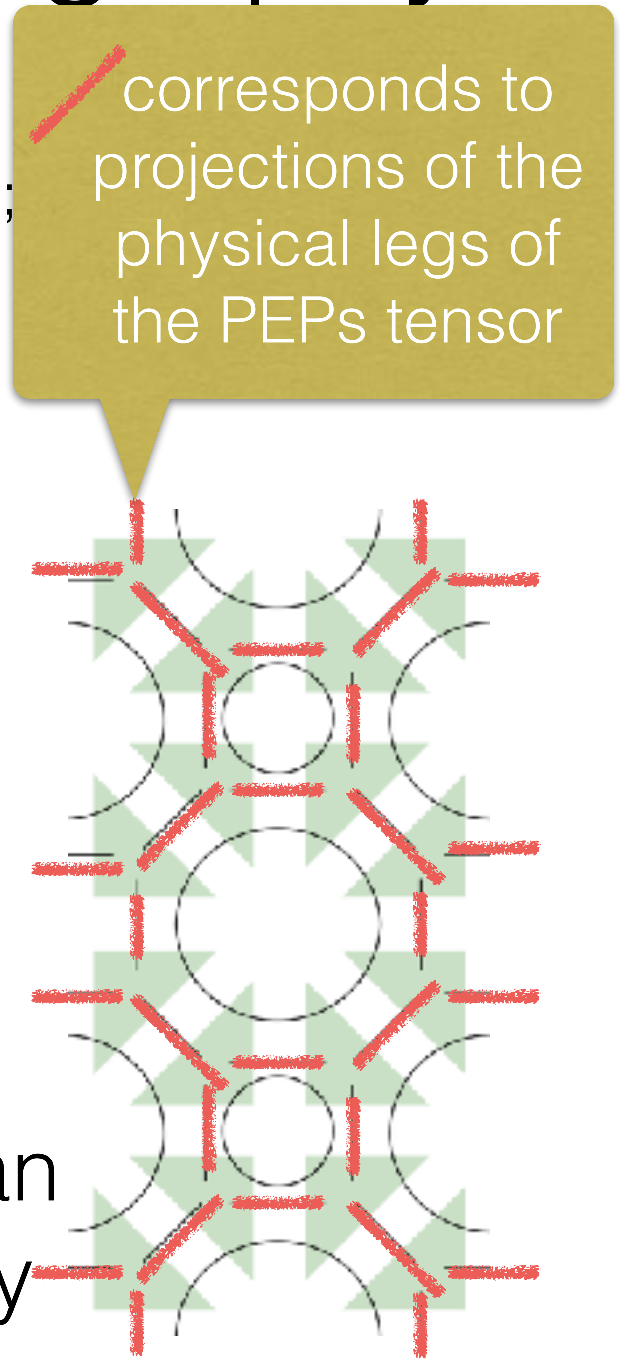
There are beautiful tensor network (PEPs) construction

Minimal models and Levin Wen models — and holography

- PEPS representation of Levin-Wen models
  Gu, Levin, Swingle, Wen PRB 2009; Buershaper, Aguado, Vidal PRB 2009;
  (More recently — the form we follow closely , is presented in
  Bultinck, Marien, williamson, Sahinoglu, Haegeman, Verstraete Annals of physics 2017; Williamson, Bultinck, Verstraete 2017)

- The idea of Levin-Wen PEPs tensor network may recover some form of holography was discussed.
  Luo, Lake, Wu PRB 2017

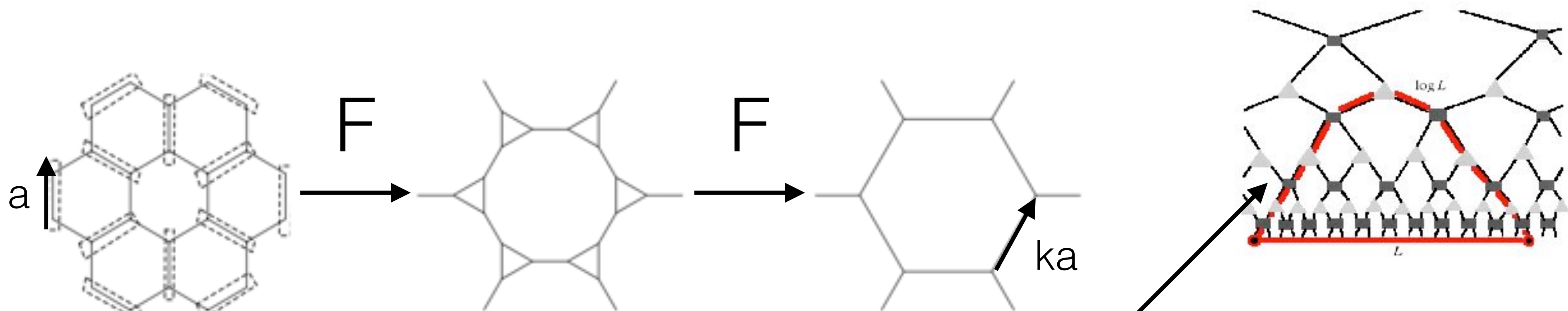
- The Levin Wen wavefunction being topological, can be transformed using Alexandre moves to arbitrary triangulations. — the strange correlator can be coarse grained by repeated use of these moves of the Levin- Wen wavefunction



$$\langle \Omega_N | \Psi_a^{LW} \rangle$$

Minimal models and Levin Wen models — and holography

$|\Omega_N\rangle = \prod_i$



$\langle \Omega_N | \Psi_a^{LW} \rangle$ $\qquad$ $\langle \Omega_N | FF | \Psi_{ka}^{LW} \rangle = \langle \Omega_{N-1} | \Psi_{ka}^{LW} \rangle$

In previous works, this is used to assist usual procedure of tensor network renormalisation.

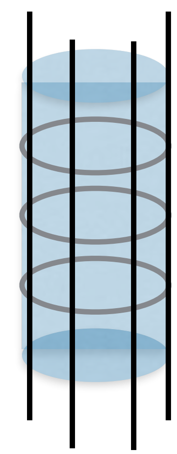
Evenbly, Vidal PRL 2014; Bal, Williamson, Vanhove, Bultinck, Haegeman, Verstraete PRL 2018; Lootens, Vanhove, Verstraete PRL 2019

Here, we make the (perhaps obvious ;P) observation that $\langle \Omega_N | FFF \cdots$ looks like Euclidean AdS3. Isn't it in fact an analytic holographic tensor network !

Minimal models and Levin Wen models — and holography

Operator Insertion:

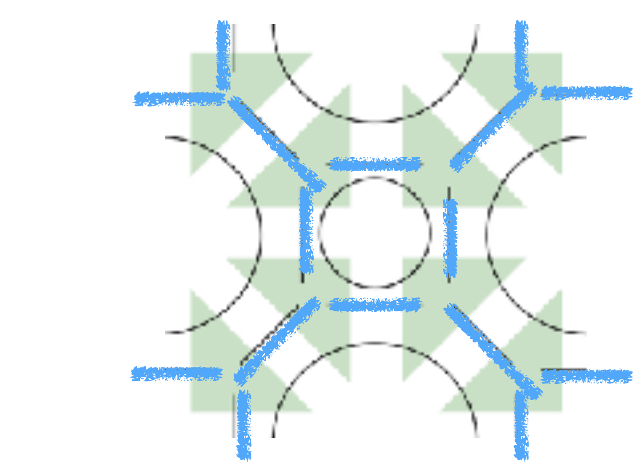
They are eigenstates
of a cylinder



Boundary conditions vs operator insertion.

A different boundary projection

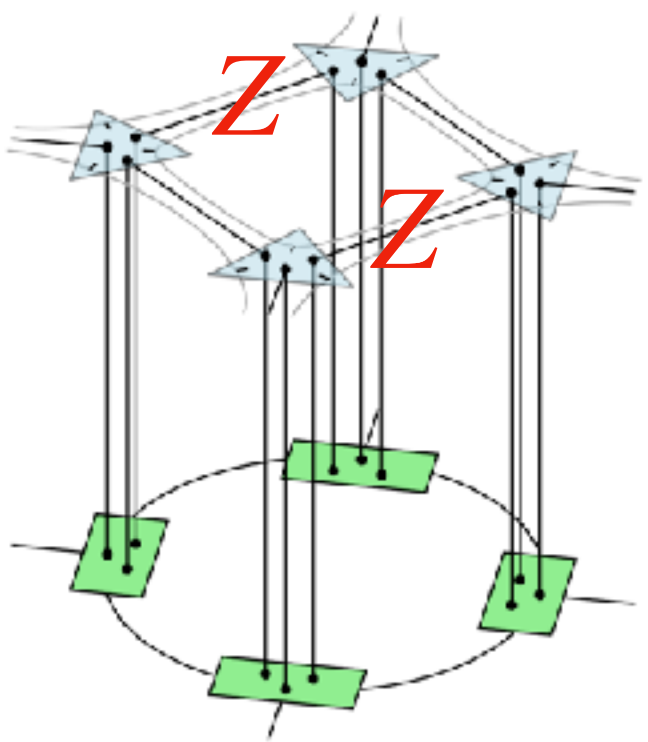
We check in the
case of the Ising the primaries
can be obtained from
changing the boundary
conditions of the Levin-Wen
PEPs tensor network



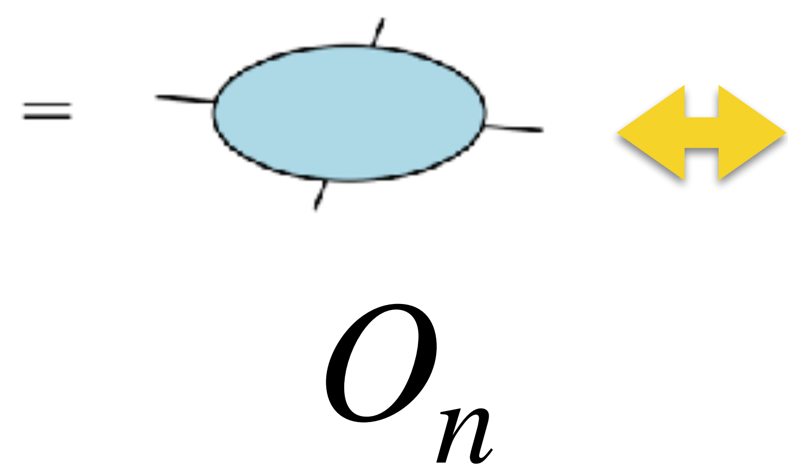
Looks like a direct analogue of the p-adic tensor network?

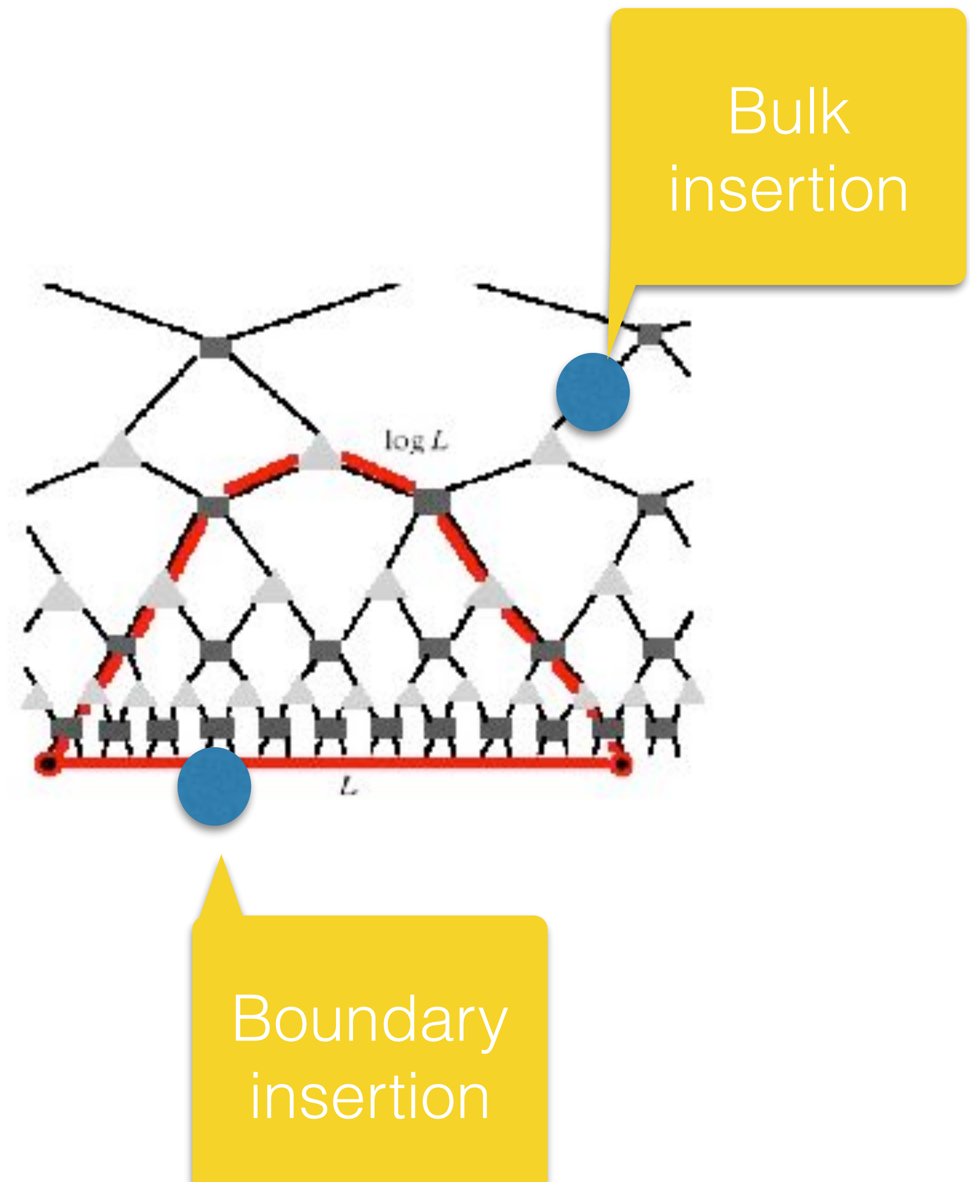
Minimal models and Levin Wen models — and holography

Bulk operator insertion:



Picture courtesy Verstraete et al 2019

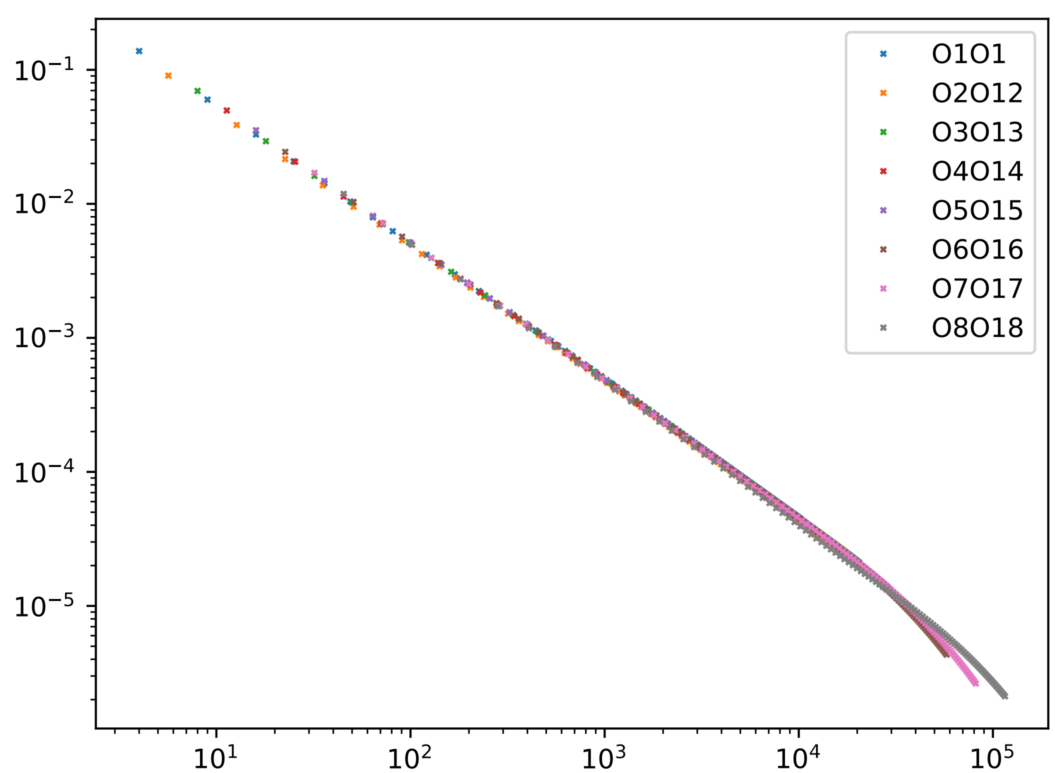




Minimal models and Levin Wen models — and holography

Preliminary result for a bulk boundary propagator:

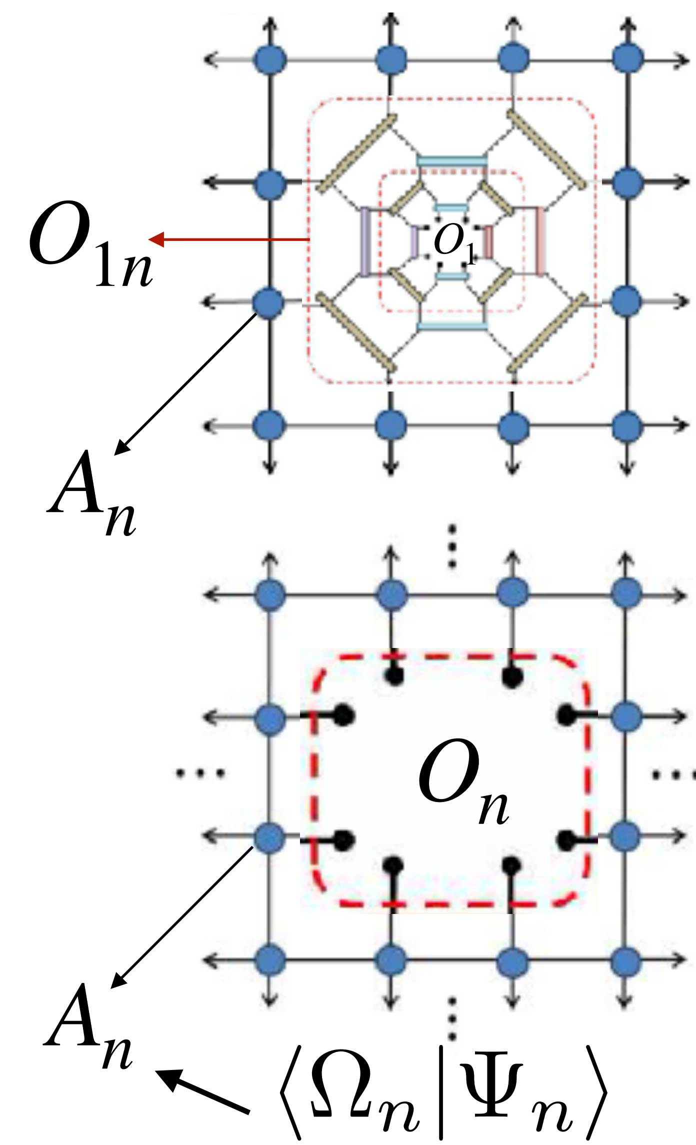
$< O_1 O_{1n} > \quad vs. \quad z_n x_n^2$



$$< O_n O_{1n} > \sim \left(\frac{z_n}{x_1^2 + z_n^2}\right)^{\Delta} = \left(\frac{1}{z_n(x_n^2+1)}\right)^{\Delta} \qquad x_1 = z_n x_n, \quad z_n = \left(\sqrt{2}\right)^{n-1}$$

er.. looks like the bulk insertion didn't recover the right descendants, but only the primary! — this should be an issue of correctly dealing with sub-AdS locality in the network .

Picture courtesy Vidal et al 2014



Bar, Can, Carroll, Chatwin-Davies, Hunter-Jones, Pollack, Remmen, 2015

Outlook

- Our result is some discretised realisation of Sung-Sik's new paper. arXiv:2009.11880

- It is suggested that the path-integral of a d-dimensional field theory can be thought of as the overlap of two wave functions in d+1 dimensions.

$$Z = \langle \mathbb{I} | S \rangle$$

- The identity being a state invariant under RG, so that one could evolve the bra with RG flow operator H, but then group it with S that leads to flow of the couplings — this is
very close in spirit to the strange correlator holographic network that we studied here.

Outlook

- Quantitative control of descendants which could allow control of sub-AdS locality and gravitational excitations (?)
  You, Milsted, Vidal 2018, 2020; You, Vidal 2020

- Generalization to higher dimensions, and Categorical symmetry
  Verstraete et al ; Gaiotto, Kulp 20;
  Kong, Zheng 2017; Ji, Wen 2019; Kong, Lan, Wen, Zhang, Zheng 2020 …..

Thank you very much!