Title: Tensor network models of AdS/qCFT

Speakers: Jens Eisert

Collection: Tensor Networks: from Simulations to Holography III

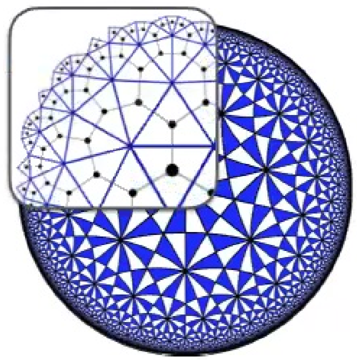
Date: November 16, 2020 - 1:00 PM

URL: http://pirsa.org/20110019

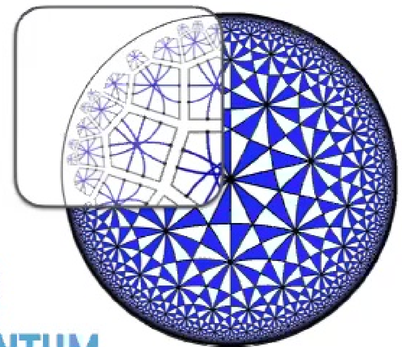
Abstract: "AdS/CFT endows gravity in anti-de Sitter (AdS) spacetime with a dual description in certain conformal field theories (CFTs) with matching symmetries. Tensor networks on regular discretizations of AdS space provide natural toy models of AdS/CFT, but break the continuous bulk symmetries. In this talk, we discuss several aspects of such toy models based on tensor networks. We show that this produces a quasiregular conformal field theory (qCFT) on the boundary and rigorously compute its symmetries, entanglement properties, and central charge bounds, applicable to a wide range of existing models. An explicit AdS/qCFT model with exact fractional central charges is given by holographic quantum error correcting codes based on Majorana dimers. These models also realize the strong disorder renormalization group, resulting in new connections between critical condensed-matter models, exact quantum error correction, and holography. If time allows, we will briefly review other recent group research on using tensor network models in quantum many-body physics including many-body localization and time crystals as well as in probabilistic modelling.

Based on arXiv:2004.04173, Phys. Rev. A 102, 042407 (2020), Phys. Rev. Research 1, 033079 (2019), Science Advances 5, eaaw0092 (2019)."

1. MATCHGATE TENSOR NETWORKS

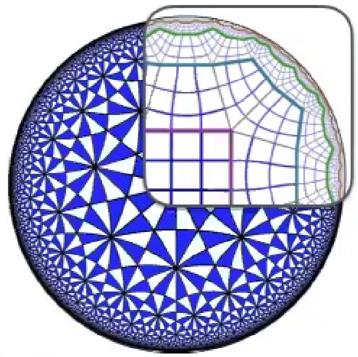


JAHN, GLUZA, PASTAWSKI, EISERT, SCIENCE ADVANCES 5, eaaw0092 (2019)



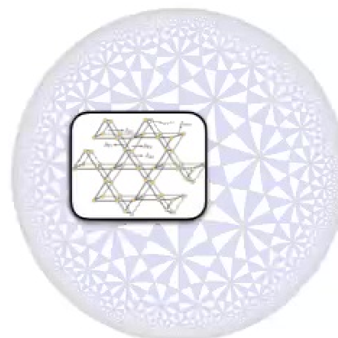
2. MAJORANA DIMERS AND HOLOGRAPHIC QUANTUM ERROR-CORRECTING CODES

JAHN, GLUZA, PASTAWSKI, EISERT, Phys Rev Research 1, 033079 (2019)



3. QUASI-PERIODIC CHAINS AND QCFT

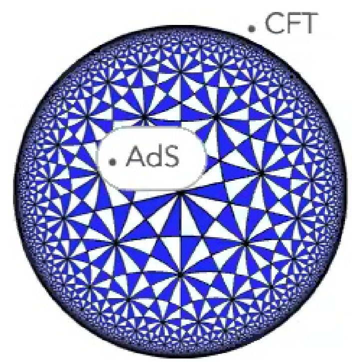
JAHN, ZIMBORAS, EISERT, Phys Rev A 102, 2407 (2020)
JAHN, ZIMBORAS, EISERT, arXiv:2004.04173
JAHN, GLUZA, VERHEUVEN, SINGH, EISERT, in preparation (2020)



4. OUTLOOK ON OTHER TENSOR NETWORK RESULTS

ADS/CFT CORRESPONDENCE

- Duality between Einstein gravity in $D+2$ Anti de Sitter spacetime and conformal field theory in $D+1$ dimensions



Maldacena, Avd Th Math Phys 2, 231 (1998)
Witten, Adv Theor Math Phys 2, 253 (1998)
van Raamsdonk, Gen Rel Grav 42, 2323 (2010)

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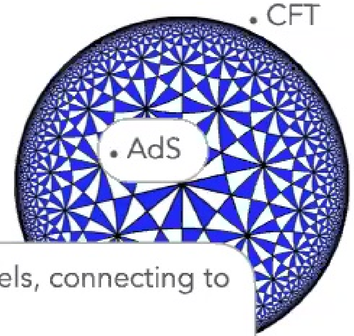
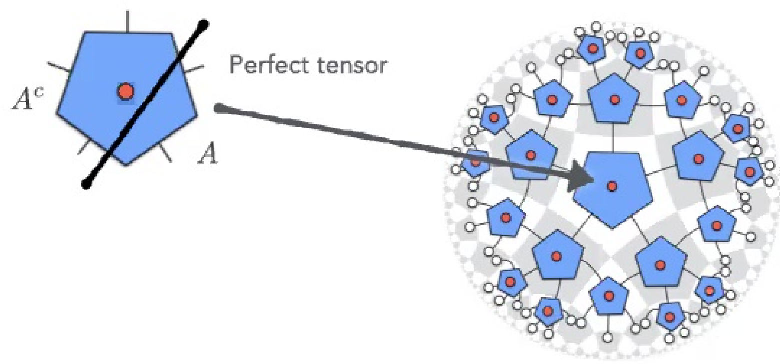
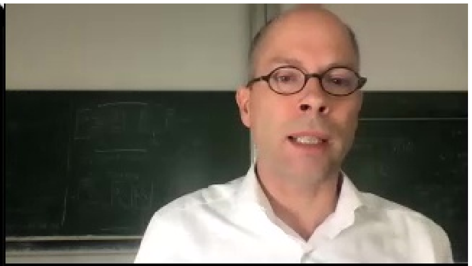


- **Tensor-network** based toy models, connecting to
  - condensed matter
  - quantum information

Maldacena, Avd Th Math Phys 2, 231 (1998)
Witten, Adv Theor Math Phys 2, 253 (1998)
van Raamsdonk, Gen Rel Grav 42, 2323 (2010)

- **Quantum error correction:** Holographic pentagon code





Pastawski, Yoshida, Harlow, Preskill, JHEP 2015, 149 (2015)
Helwig, Cui, Latorre, Riera, Lo, Phys Rev A 86, 052335 (2012)

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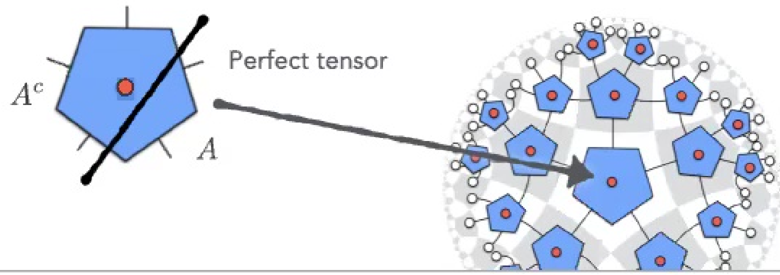
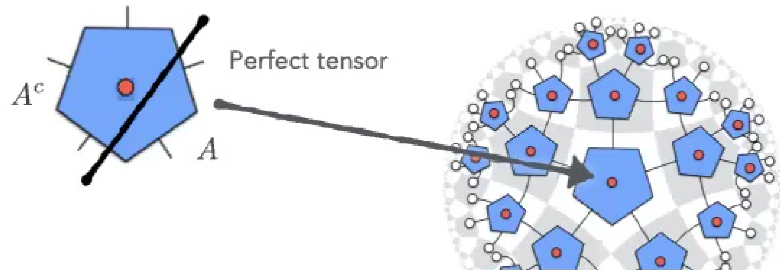


- Perfect tensor: Any bi-partite cut with $|A| \leq |A^c|$ is proportional to isometry

Pastawski, Yoshida, Harlow, Preskill, JHEP 2015, 149 (2015)
Helwig, Cui, Latorre, Riera, Lo, Phys Rev A 86, 052335 (2012)

- **Quantum error correction:** Holographic pentagon code



- **Perfect tensor:** Linear map from one spin to spins with is the **isometric encoding map of a quantum error-correcting code**
- $[[2n-1, 1, n]]$ quantum error correcting code
- Here, $2n-1=5$, "Pentagon code"

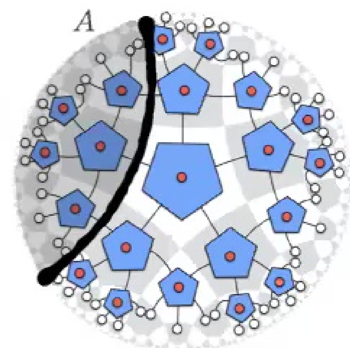
Pastawski, Yoshida, Harlow, Preskill, JHEP 2015, 149 (2015)
Helwig, Cui, Latorre, Riera, Lo, Phys Rev A 86, 052335 (2012)

- Entanglement entropy of a connected region of a boundary satisfies

$$S_A = |\gamma_A|$$

- γ_A minimal bulk geodesic
- Lattice version of Ryu-Takayanagi formula

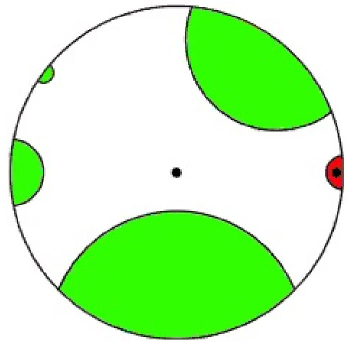
$$S_A = \frac{\text{Area}(\gamma_A)}{4G}$$



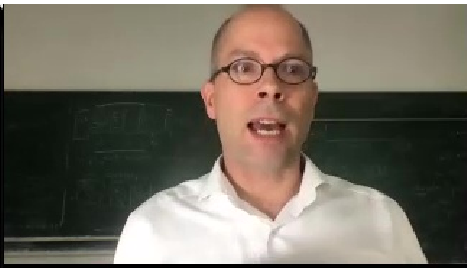
Pastawski, Yoshida, Harlow, Preskill, JHEP 2015, 149 (2015)
Ryu, Takayanagi, Phys Rev Lett 96, 181602 (2006)

"MODEL 1": PENTAGON CODES

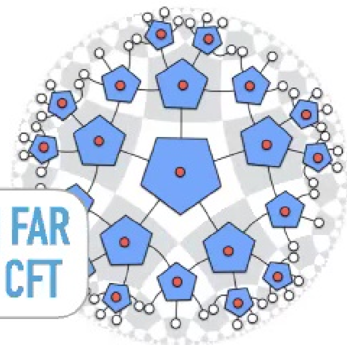
- Connection of **AdS-cft** to **holographic quantum error correction**



Almheiri, Dong, Harlow, JHEP 1504, 163 (2015)
Harris, McMahon, Brennen, Stace, Phys Rev A 98, 052301 (2018)



- Connection of **AdS-cft** to **holographic quantum error correction**

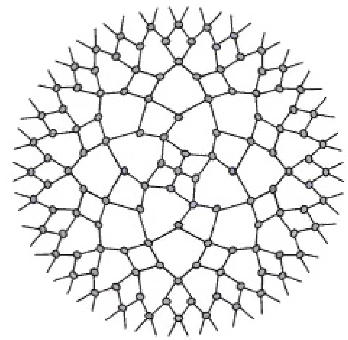


BUT, BOUNDARY STATE FAR FROM A REASONABLE CFT

Almheiri, Dong, Harlow, JHEP 1504, 163 (2015)
Harris, McMahon, Brennen, Stace, Phys Rev A 98, 052301 (2018)

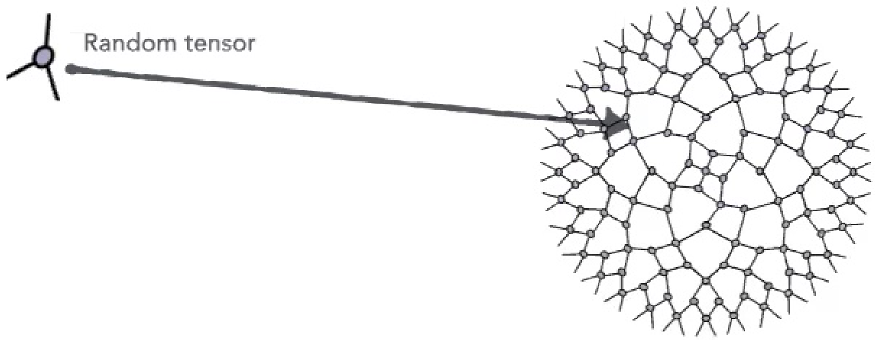
“MODEL 2”: MULTISCALE ENTANGLEMENT RENORMALIZATION (MERA)

- Tensor network consisting of **isometries** and **disentanglers**
- Approximates critical quantum states



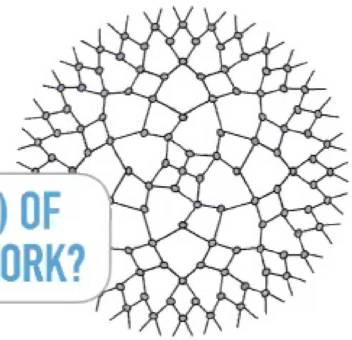
Vidal, Phys Rev Lett 101, 110501 (2008)
Evenbly, Vidal, Phys Rev B, 79, 144108 (2009)
Dawson, Eisert, Osborne, Phys Rev Lett 100, 130501 (2008)
Swingle, Phys Rev D 86, 065007 (2012)
Evenbly, White, Phys Rev Lett 116, 140403 (2016)
Haegeman, Swingle, Walter, Cotler, Evenbly, Scholz, Phys Rev X 8, 011003 (2018)

- Random isometric tensors are with high probability close to being perfect



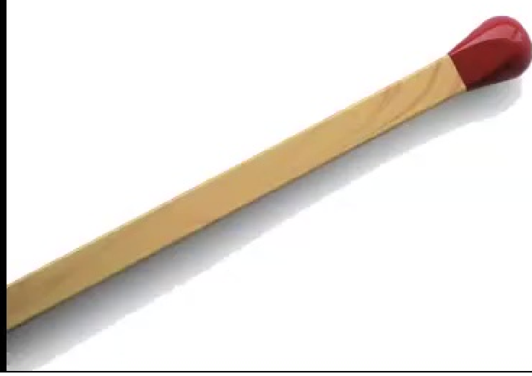
Hayden, Nezami, Qi, Thomas, Walter, Yang, JHEP 2016, 9 (2016)

CAN ONE EMBODY (ASPECTS) OF THEM IN A LARGER FRAMEWORK?



Jahn, Gluza, Pastawski, Eisert, Science Adv 5, eaaw0092 (2019)
Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

1. MATCHGATE TENSOR NETWORKS



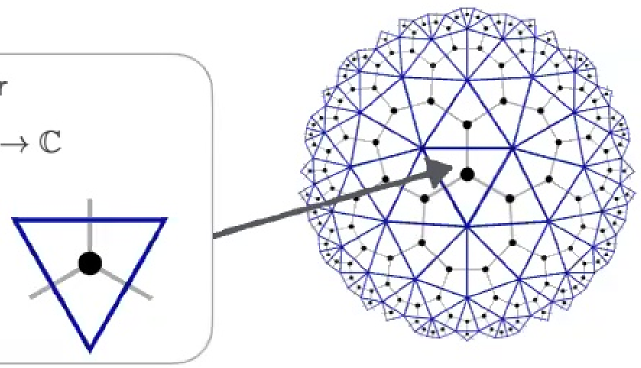
MATCHGATE TENSOR NETWORKS

- Choose some some tiling of the plane

- Matchgate tensor

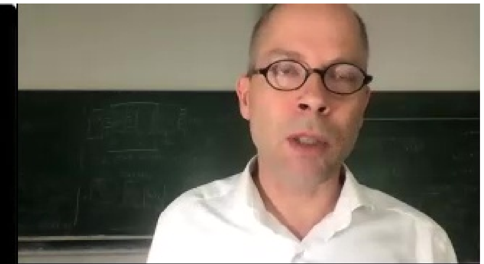
  $T_v : \{0,1\}^{\times r} \to \mathbb{C}$

  per vertex $v \in V$



- Boundary state obtained by tensor contraction $|\psi\rangle = \sum_{j \in \{0,1\}^{\times L}} \mathcal{T}(j)\,|j\rangle$

Bravyi, Cont Math 482, 179 (2009)
Jahn, Gluza, Pastawski, Eisert, Science Adv 5, eaaw0092 (2019)



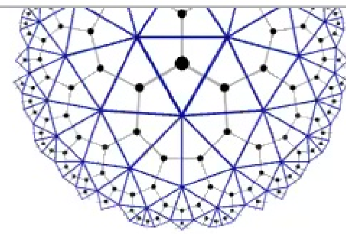
MATCHGATE TENSOR NETWORKS

- **Matchgate tensors:** Consider a rank-r tensor $T(x)$ with inputs $x \in \{0,1\}^{\times r}$, $T(x)$ is a matchgate if there exists an antisymmetric matrix $A \in \mathbb{C}^{r \times r}$ and a reference index $z \in \{0,1\}^r$ such that

$$T(x) = \mathrm{Pf}(A_{|x\mathrm{XOR}z})T(z)$$

where $\mathrm{Pf}(A)$ is the Pfaffian of A and $A_{|x}$ is the submatrix of A acting on the subspace supported by x

Cai, Choudhary, Lu, CCC07, IEEE Conference (2007)



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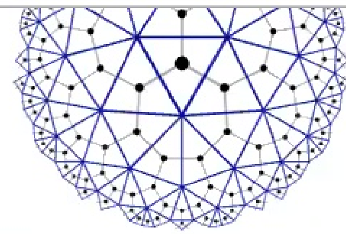

- Generic even matchgate with $\bar{z} = 0$ has

$$\Phi_T(\theta) = T(\overline{0}) \exp\left(\frac{1}{2} \sum_{j,k=1}^{r} A_{j,k} \theta_j \theta_k \right)$$

with generating matrix A

Bravyi, Cont Math 482, 179 (2009)
Jahn, Gluza, Pastawski, Eisert, Science Adv 5, eaaw0092 (2019)

MATCHGATE TENSOR NETWORKS

- **Observation:** The contraction requires $O(L^2 N)$ steps for L boundary sites and N contracted tensors

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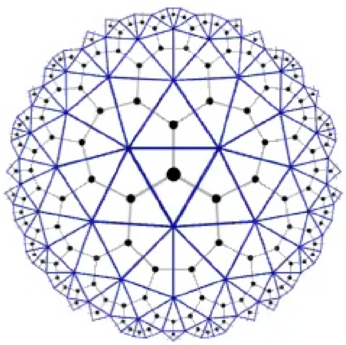
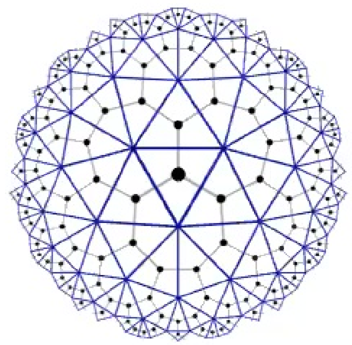


Bravyi, Cont Math 482, 179 (2009)
Jahn, Gluza, Pastawski, Eisert, Science Adv 5, eaaw0092 (2019)

MATCHGATE TENSOR NETWORKS

Place generating matrices on some tiling



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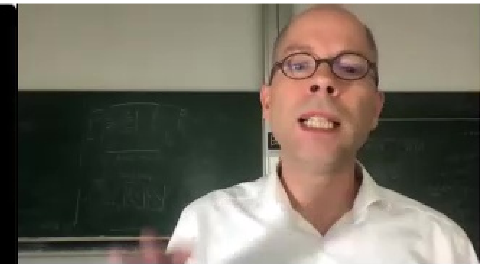
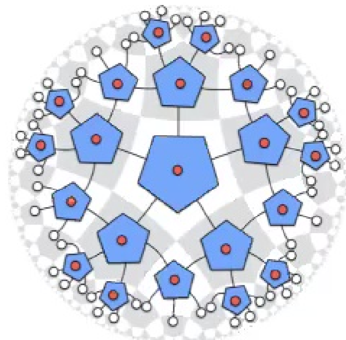
Jahn, Gluza, Pastawski, Eisert, Science Adv 5, eaaw0092 (2019)



- **Observation:** The holographic pentagon code with computational basis input in the bulk yields a matchgate tensor network



- Gives rise to stabilizer code $\langle S_j \rangle_{j=1}^{5}$, e.g.,

$$S_1 = \sigma^x \otimes \sigma^z \otimes \sigma^z \otimes \sigma^x \otimes \mathbb{1}_2 = \mathrm{i} m_7 m_2$$
$$S_2 = \mathbb{1}_2 \otimes \sigma^x \otimes \sigma^z \otimes \sigma^z \otimes \sigma^x = \mathrm{i} m_9 m_4$$

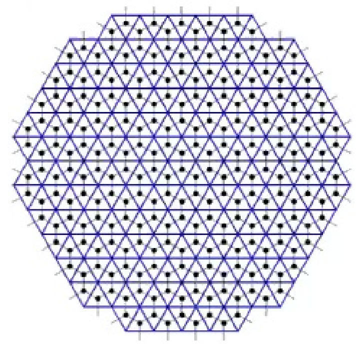
expressed in Majoranas

Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

REGULAR TILINGS AND BULK CURVATURE

- $\{3,6\}$ flat tiling

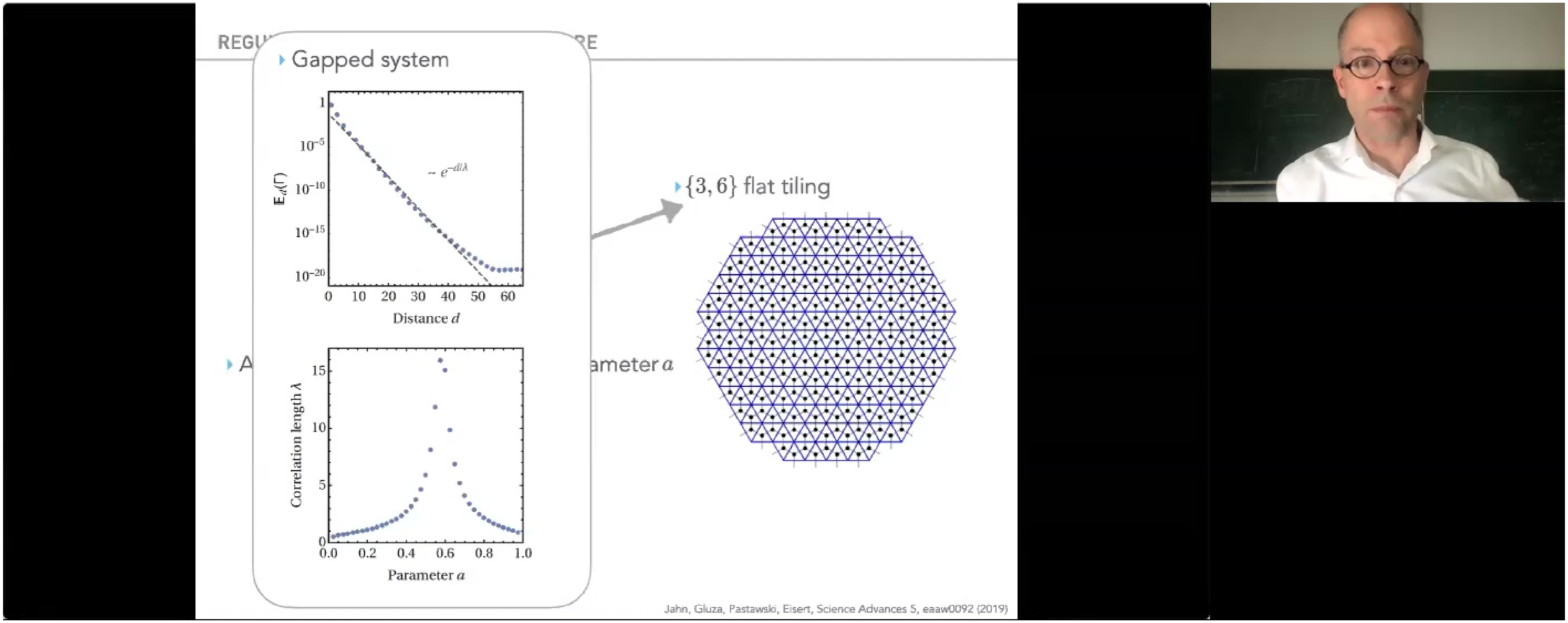
Schläfli symbol



- Anti-symmetric matrix A, single parameter a

$$A = \begin{pmatrix} 0 & a & a \\ -a & 0 & a \\ -a & -a & 0 \end{pmatrix}$$

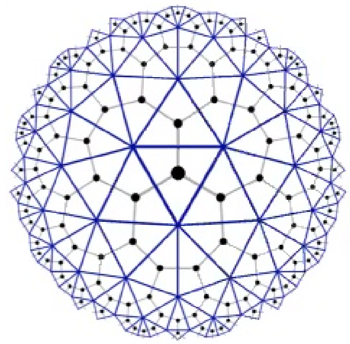
Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)



REGU
RE
Gapped system
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
$\mathrm{E}_d(\Gamma)$
$\sim e^{-d/\lambda}$
0 10 20 30 40 50 60
Distance d
15
10
5
0
Correlation length λ
0.0 0.2 0.4 0.6 0.8 1.0
Parameter a
A
ameter a
$\{3,6\}$ flat tiling
Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

REGULAR TILINGS AND BULK CURVATURE

- $\{3, k\}$, $k > 6$, hyperbolic tiling



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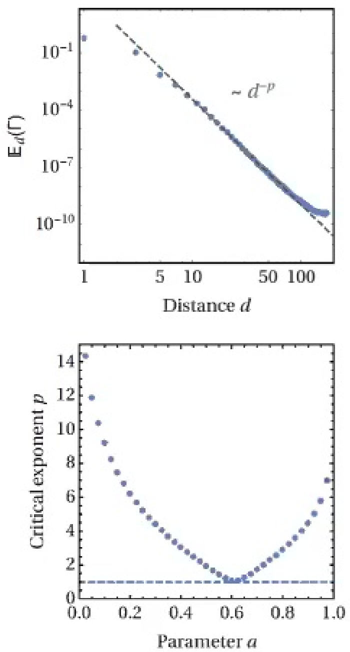
Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

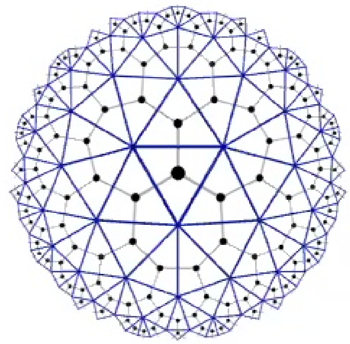
REGU… …RE

- $\{3,7\}$ critical system



- A … ameter a

- $\{3,k\}$, $k>6$, hyperbolic tiling



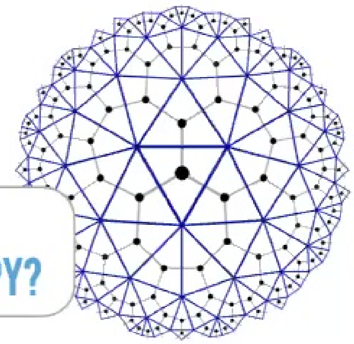
- For $a \approx 0.61$, critical Ising theory

$$H = \mathrm{i}\left(\sum_{i=1}^{N-1} m_i m_{i+1} + m_1 m_N\right)$$

Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

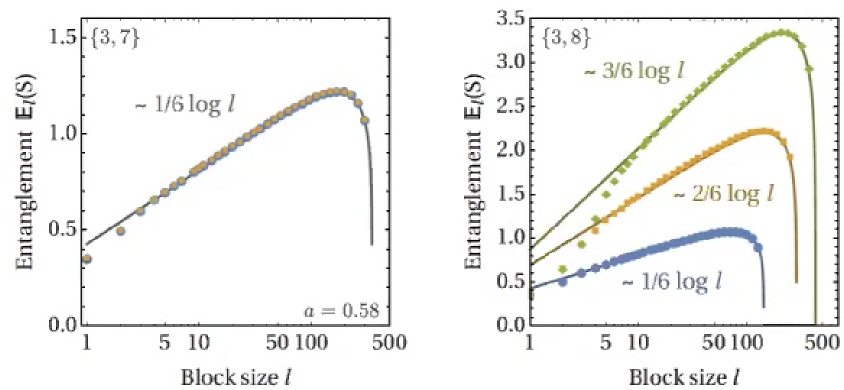
ENTANGLEMENT ENTROPY OF CFTS

- $\{3,k\}$, $k > 6$, hyperbolic tiling



HOW ABOUT THE ENTANGLEMENT ENTROPY?

Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

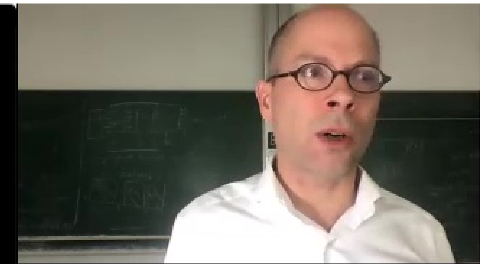


Tiling with higher bond dimensions χ (144, 288, 432 Majorana fermions for $\chi = 2, 4, 8$, respectively)

- CFT entanglement entropy of a block

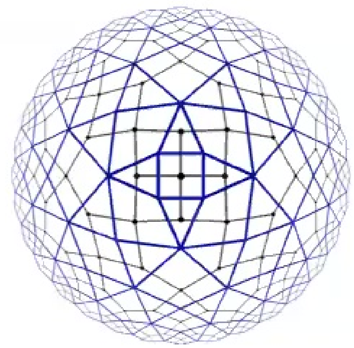
$$S_\ell = \frac{c}{3} \ln\left(\frac{L}{\pi\epsilon} \sin\frac{\pi\ell}{L}\right) \simeq \frac{c}{3} \ln\frac{\ell}{\epsilon} + O\left((\ell/L)^2\right)$$

Holzhey, Larsen, Wilczek, Nucl Phys B 424, 443 (1994)
Calabrese, Cardy, J Stat Mech 0406, 06002 (2004)
Eisert, Cramer, Plenio, Rev Mod Phys 82, 277 (2010)



MERA AND MATCHGATE CIRCUITS

MERA?



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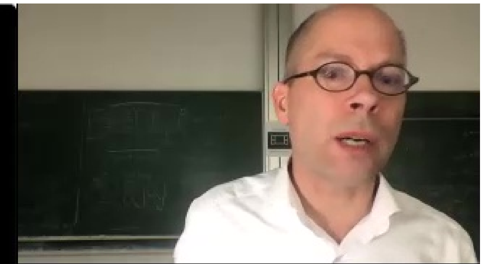
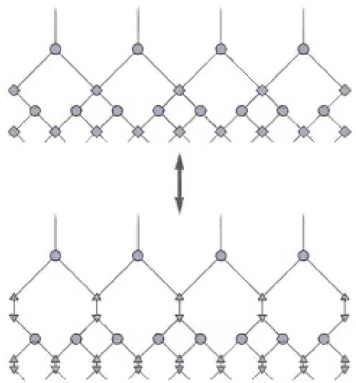
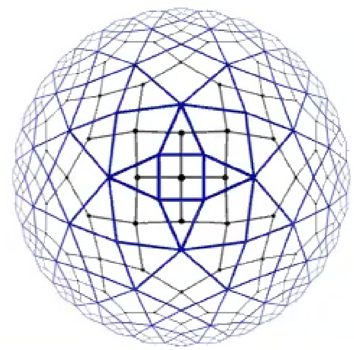


- Tiling with 3-and 4-leg **MERA tensor network**
- At $L = 256$, for $a = 0.566$, $b = 0.443$, $c = 0.363$, relative energy density error to continuum solution is about $\epsilon = 0.0002$

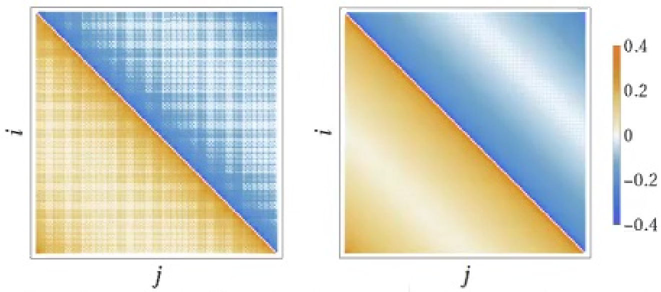




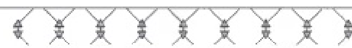
Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

MERA AND MATCHGATE CIRCUITS

- Tiling with 3-and 4-leg **MERA tensor network**



Entries of the fermionic correlation matrix as a function of distance, left for$\{3, 7\}$ bulk tiling with 252 Majorana fermions, right for MERA with 256 sites



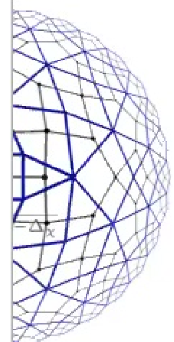
Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

EXTRACTING CRITICAL DATA

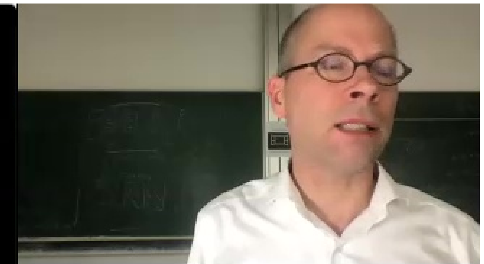
- Ising theory at criticality described by a 1+1-dimensional CFT

Parameter	Exact	$\{3,6\}$ bulk	$\{3,7\}$ bulk	mMERA	Wavelets
ϵ_0	-0.6366	-0.6139	-0.5617	-0.6365	-0.6211
c	0.5000	0.5006	0.5018	0.4958	0.4957
$\Delta_\psi, \Delta_{\bar{\psi}}$	0.5000	0.4948	0.4951	0.5023	0.5000
Δ_ϵ	1.0000	0.9856	1.0121	1.0027	1.0000
Δ_σ	0.1250	0.1403	0.1368	0.1417	0.1402
$C_{\sigma,\sigma,\epsilon}$	0.5000	0.5470	0.5336	0.5156	0.4584

TABLE I. Table of *conformal data* for the regular $\{3,6\}$ and $\{3,7\}$ bulk tilings as well as the mMERA, compared to the exact results and the wavelet MERA [16]. Listed are the ground-state energy density ϵ_0, central charge c, scaling dimensions Δ_ϕ of the fields $\phi = \psi, \bar{\psi}, \epsilon, \sigma$, and the structure constant $C_{\sigma,\sigma,\epsilon}$



Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)



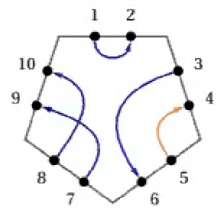
EXTRACTING CRITICAL DATA

SO WITH FEW PARAMETERS, ONE ARRIVES AT ALMOST TRANSLATIONALLY INVARIANT STATES AND CAN EXTRACT A WIDE RANGE OF CRITICAL DATA

Jahn, Gluza, Pastawski, Eisert, Science Advances 5, eaaw0092 (2019)

2. GETTING MORE SERIOUS ON QUANTUM ERROR CORRECTION

- For holographic stabilizer codes such as pentagon code develop picture of **paired Majorana dimers**



$$\Gamma_{i,j} = \begin{cases} -1 & \text{for an arrow } i \to j \\ 1 & \text{for an arrow } j \to i \\ 0 & \text{if no arrow connects } i \text{ and } j \end{cases}$$

Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

HOLOGRAPHIC MAJORANA DIMER MODELS OF QUANTUM ERROR CORRECTION

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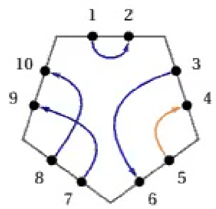

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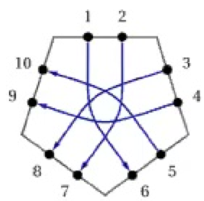
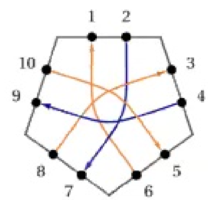
- Pentagon code logical states spanned by basis states $\bar{0}$ and $\bar{1}$

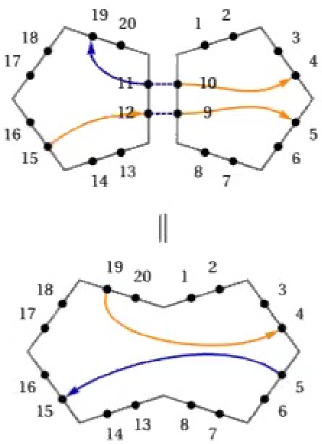
$|\bar{0}\rangle_5 =$ 

$|\bar{1}\rangle_5 =$ 

Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

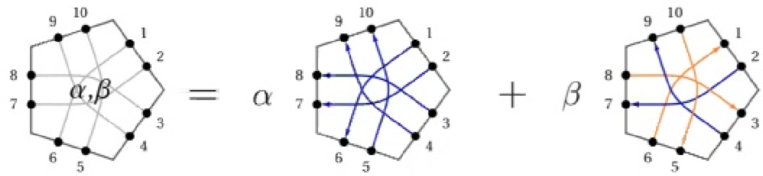
HOLOGRAPHIC MAJORANA DIMER MODELS OF QUANTUM ERROR CORRECTION

- Diagrammatic contraction rules amenable to analytical analysis
- "Fusing" of dimers along edges



Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

HOLOGRAPHIC MAJORANA DIMER MODELS OF QUANTUM ERROR CORRECTION

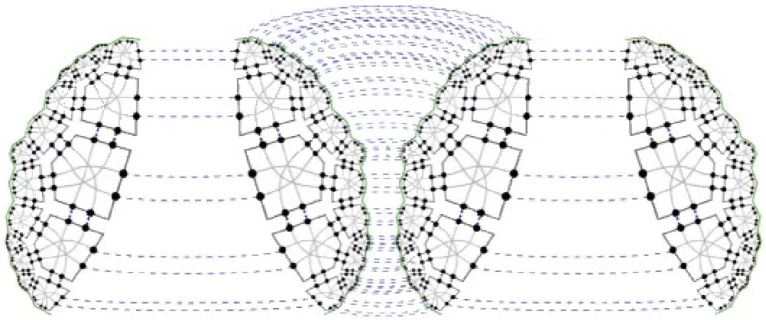


- **Theorem:** Computational basis state vectors of the bulk are dual to Majorana dimer states on the boundary
- Can compute second moments of **non-Gaussian states** arising in **quantum error correcting codes** etc

Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

HOLOGRAPHIC MAJORANA DIMER MODELS OF QUANTUM ERROR CORRECTION

$$\rho_A^2 = 2^{2N_{C,w}}$$



- **Theorem:** Can compute Renyi entropies

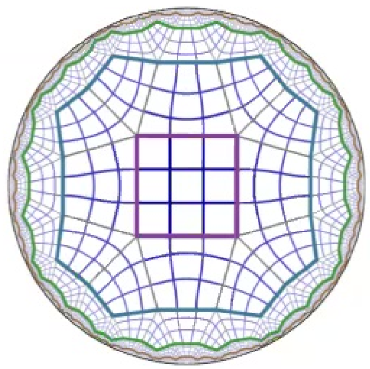
Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

LESSON

MATCHGATE TENSOR NETWORKS PROVIDE VERSATILE FRAMEWORK, ALLOWING FOR NEW INSIGHTS INTO HOLOGRAPHIC CODES

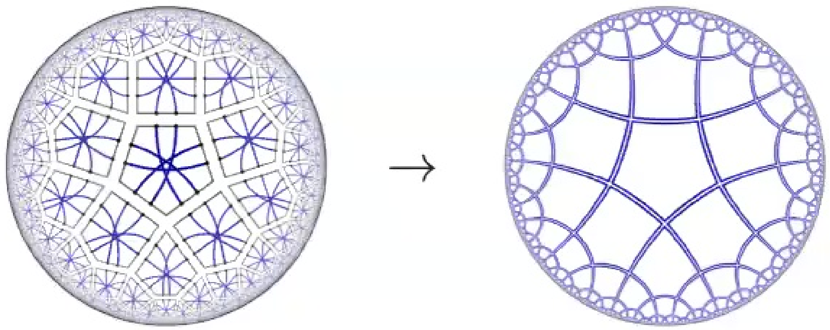
Jahn, Gluza, Pastawski, Eisert, Phys Rev Research 1, 033079 (2019)

3. QUASI-PERIODIC CHAINS AND QCFTS



GEODESIC STRUCTURE OF DIMERS

- $\{4,5\}$dual of the $\{5,4\}$Pentagon code, captured in terms of Majorana dimers
- New picture of **holographic QEC**: Geodesic structure of dimers



Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)
Compare Boyle, Dickens, Flicker, arXiv:1805.02665

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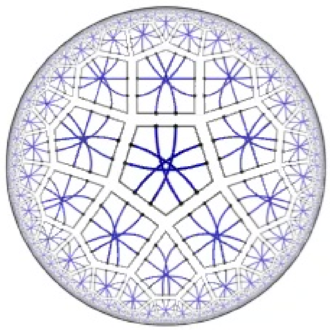
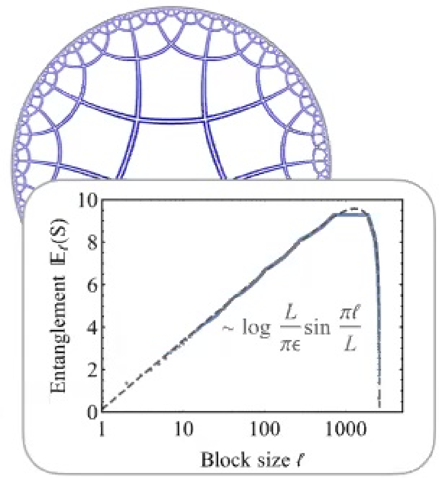


$\rightarrow$



- On average, the pentagon code has a CFT-like log entanglement scaling with

$$c \approx 4.74$$

Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)
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EFFECTIVE FRACTIONAL CENTRAL CHARGES

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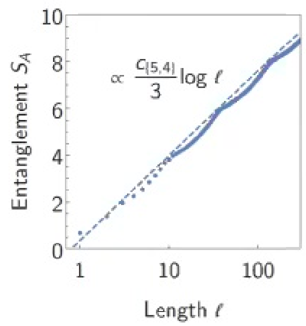
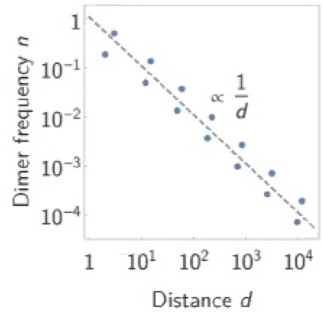
- New picture of **holographic QEC**: Geodesic structure of dimers

Entanglement entropy



Logarithmic growth

Correlations decay



CFT-like falloff

Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)
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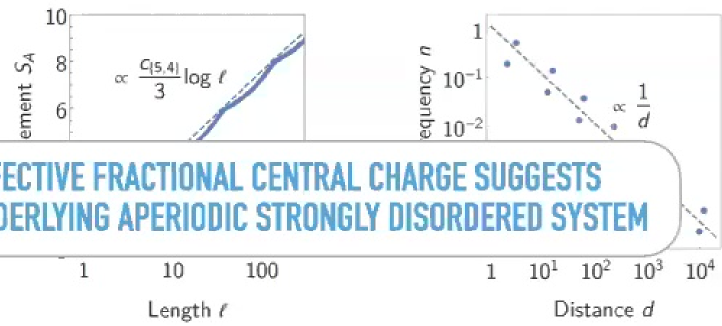
Entanglement entropy | **Correlations decay**



EFFECTIVE FRACTIONAL CENTRAL CHARGE SUGGESTS UNDERLYING APERIODIC STRONGLY DISORDERED SYSTEM

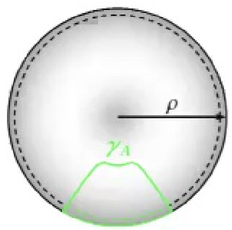
Logarithmic growth | **CFT-like falloff**

Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)
Compare Boyle, Dickens, Flicker, arXiv:1805.02665

ADS GEOMETRY AND CENTRAL CHARGES

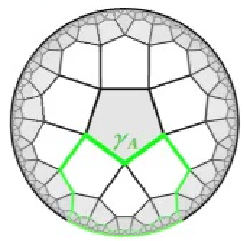
- $\{4,5\}$dual of the $\{5,4\}$Pentagon code, captured in terms of Majorana dimers
- Time-slice of anti-de Sitter spacetime projected onto the Poincare disk

- **Continuum**



$$|\gamma_A| \sim 2\alpha \log |A|$$
$$\Rightarrow c = \frac{2\alpha}{3G}$$

- **Discrete**

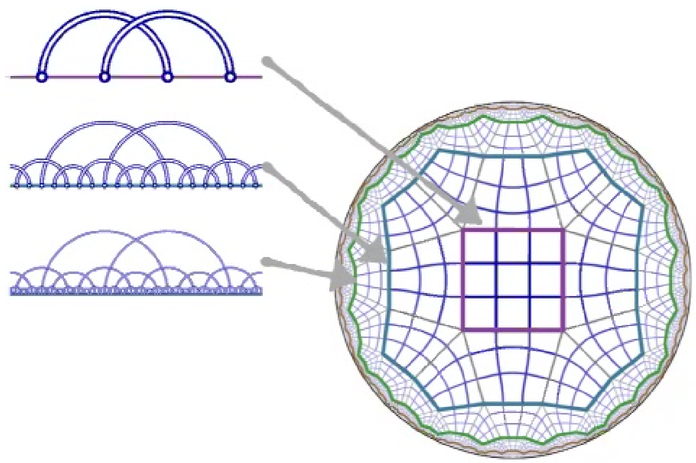


Scaling between $|\gamma_A|$and $|A|$ tiling independent

Ryu, Takayanagi, Phys Rev Lett 96, 181602 (2006)
Brown, Henneaux, Comm Math Phys 104 2 (1986)

INFLATION RULES AND QUASI-REGULAR STRUCTURES

- $\{4,5\}$dual of the $\{5,4\}$Pentagon code, captured in terms of Majorana dimers



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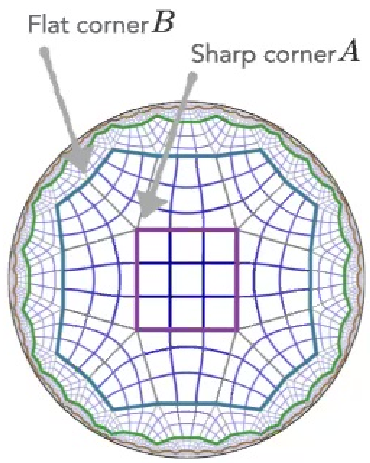
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

- $\{4,5\}$dual of the $\{5,4\}$Pentagon code, captured in terms of Majorana dimers

- **Inflation rules:**

  $A \mapsto ABA$
  $B \mapsto ABABA$



Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
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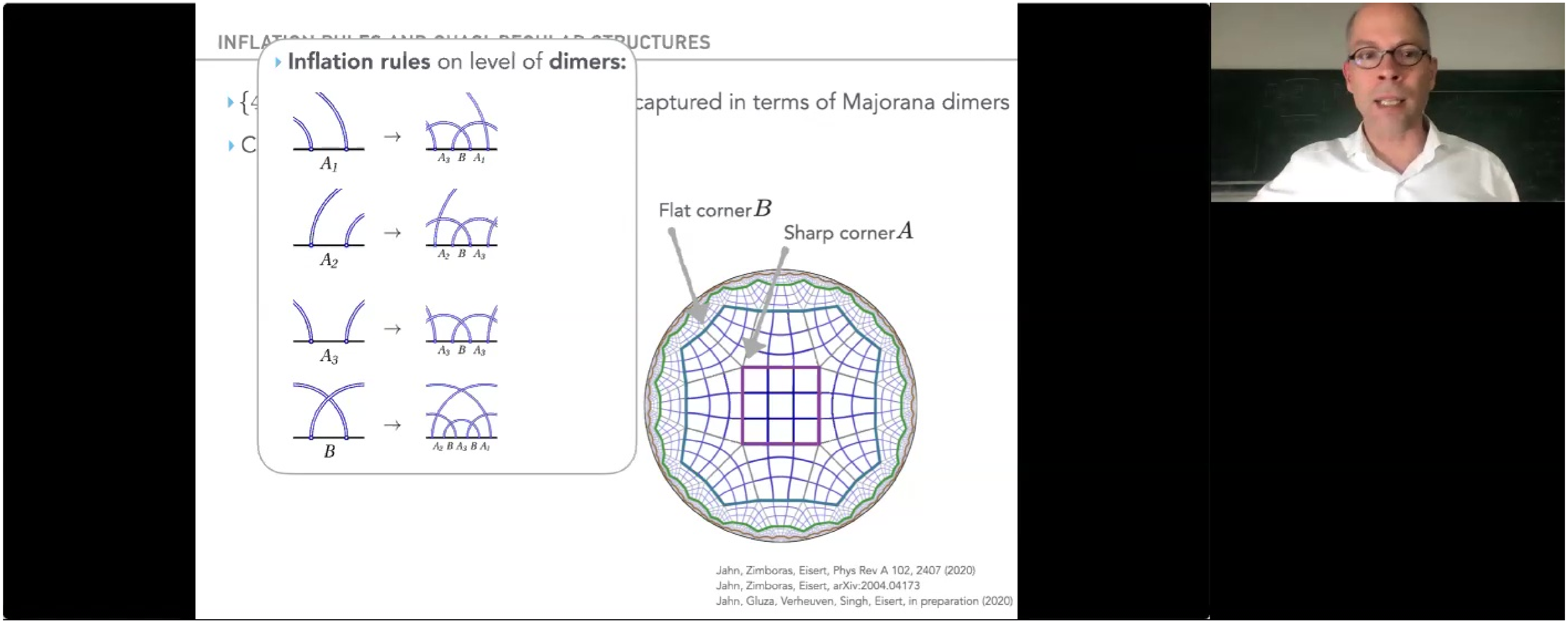
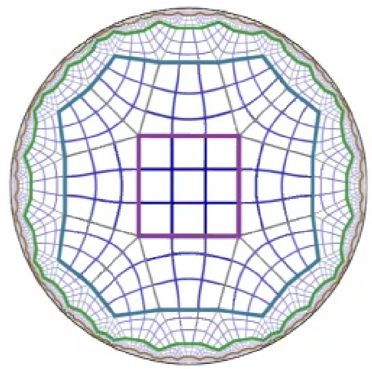

INFL
UCTURES
Inflation rules on level of dimers:
A_1 → A_3 B A_1
A_2 → A_2 B A_3
A_3 → A_3 B A_3
B → A_2 B A_3 B A_1
captured in terms of Majorana dimers
Flat corner B
Sharp corner A
Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

INFLATION RULES AND QUASI-REGULAR STRUCTURES

- Gives rise to **quasi-periodic chain** on the boundary
- Can find rigorous expressions for entanglement entropies, following a machinery of strong disorder renormalization group approaches
  Igloi, Juhasz, Zimboras, Europhys Lett 79, 37001 (2007)



Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
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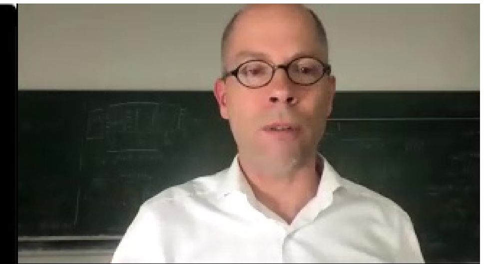


INFLATION RULES AND QUASI-REGULAR STRUCTURES

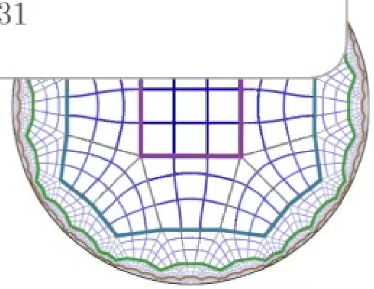
- Gives rise to **quasi-periodic chain** on the boundary

- **Theorem:** The asymptotic entanglement entropy is given by*

$$S_A = n_c \frac{(1+\sqrt{3})\log 2}{2\log(2+\sqrt{3})} \log\frac{\ell}{\epsilon}$$

- Comparing with cft formula

$$c_{\{4,5\}} = \frac{3(1+\sqrt{3})\log 2}{\log(2+\sqrt{3})} \approx 4.31$$



*ϵ effective lattice spacing, n_c number of cuts

Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

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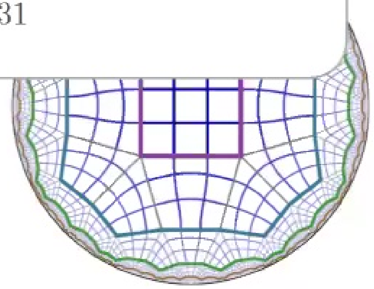


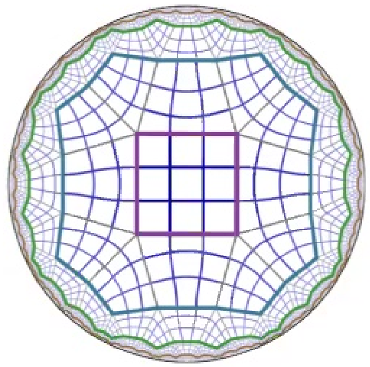
  - $\{4,k\}$ tiling gives rise to

$$c_{\{4,k\}} = \frac{3(6-k+\sqrt{8-6k+k^2})\log 2}{\log(k-3+\sqrt{8-6k+k^2})}$$

*ϵ effective lattice spacing, n_c number of cuts

Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

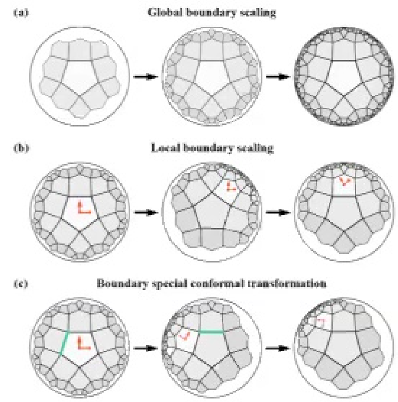
Quasiregular CFT (qCFT) as a discretized quantum field theory invariant under discrete global and local scaling transformations, exhibiting approximate translation invariance



Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

- **Quasiregular CFT (qCFT)** as a discretized quantum field theory invariant under discrete global and local scaling transformations, exhibiting approximate translation invariance

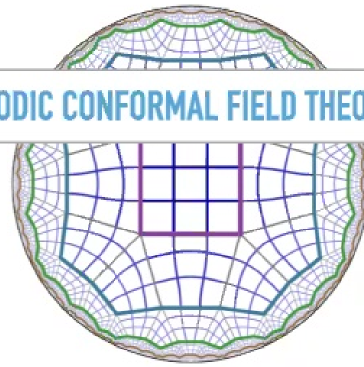
- **Conformal transformations** up to quasi-regular symmetry
  - Global scale transformations
  - Translations
  - Local scale transformations
  - (Inversions)
  - Special conformal transformations
- Subgroup of conformal transformations
- Realized by Pentagon code



Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

QUASI-REGULAR CFTS

LESSON: MAJORANA DIMERS GIVE RISE TO QUASI-PERIODIC CHAINS THE ENTROPY OF WHICH CORRESPONDS TO TUNEABLE (NON-INTEGER) CENTRAL CHARGES



CAN BE SEEN AS QUASI-PERIODIC CONFORMAL FIELD THEORY

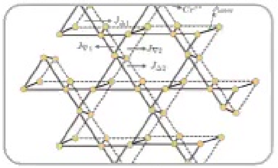
Jahn, Zimboras, Eisert, Phys Rev A 102, 2407 (2020)
Jahn, Zimboras, Eisert, arXiv:2004.04173
Jahn, Gluza, Verheuven, Singh, Eisert, in preparation (2020)

4. OUTLOOK: OTHER RECENT WORK ON TENSOR NETWORKS

TENSOR NETWORKS FOR REAL SYSTEMS

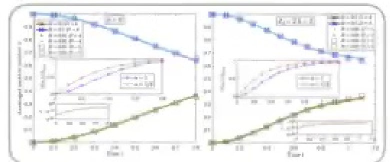
- Tensor networks for **real condensed matter systems and materials**

Tensor network investigation of the double layer **Kagome compound** $Ca_{10}Cr_7O_{28}$



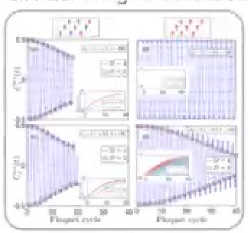
Kshetrimayum, Balz, Lake, Eisert, Ann Phys 421, 168292 (2020)

Time evolution of **many-body localized systems** in two spatial dimensions



Kshetrimayum, Goihl, Eisert, arXiv:1910.11359

Quantum time crystals with programmable disorder in higher dimensions



Kshetrimayum, Goihl, Kennes, Eisert, arXiv:2004.07267
Kshetrimayum, Kennes, Eisert, Phys Rev B 102, 195116 (2020)

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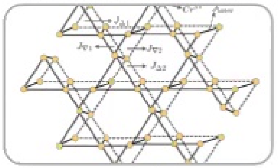

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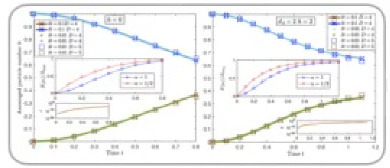

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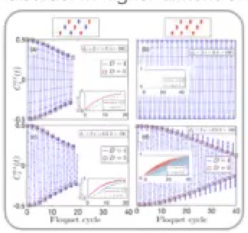
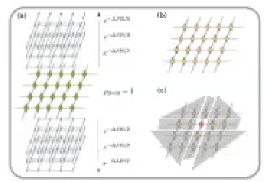


Kshetrimayum, Goihl, Kennes, Eisert, arXiv:2004.07267
Kshetrimayum, Kennes, Eisert, Phys Rev B 102, 195116 (2020)

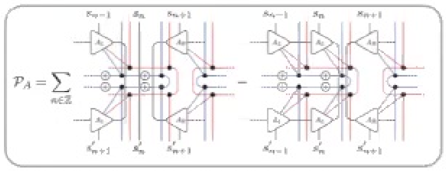
A tensor network annealing algorithm for two-dimensional **thermal states**



Kshetrimayum, Rizzi, Eisert, Orus, Phys Rev Lett 122, 070502 (2019)

NEW CONTRACTION SCHEMES FOR PEPS

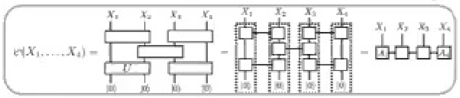
Efficient variational contraction of two-dimensional tensor networks with a **non-trivial unit cell**



Nietner, Vanhecke, Verstraete, Eisert, Vanderstraeten, Quantum 4, 328 (2020)

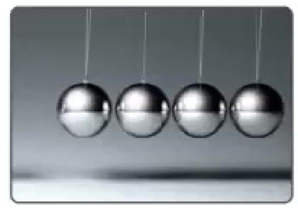
TENSOR NETWORKS IN MACHINE LEARNING

Expressive power of tensor-network factorizations for **probabilistic modeling**, with applications from hidden Markov models to **quantum machine learning**



Glasser, Sweke, Pancotti, Eisert, Cirac, NeurIPS 2019

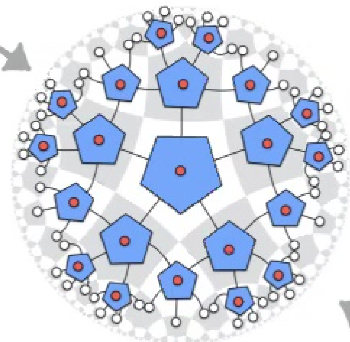
Tensor network approaches for **learning non-linear dynamical laws**



Goessmann, Goette, Roth, Sweke, Kutyniok, Eisert, arXiv:2002.12388, NeurIPS 2020

SUMMARY

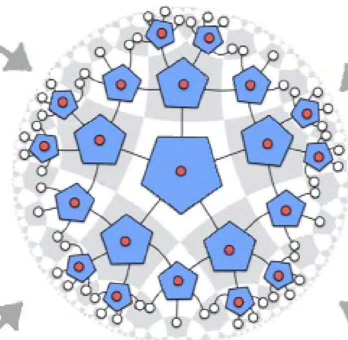
Interesting endeavor to think of tensor network models capturing holographic aspects



Quasi-regular CFTs

SUMMARY

Interesting endeavor to think of tensor network models capturing **holographic** aspects

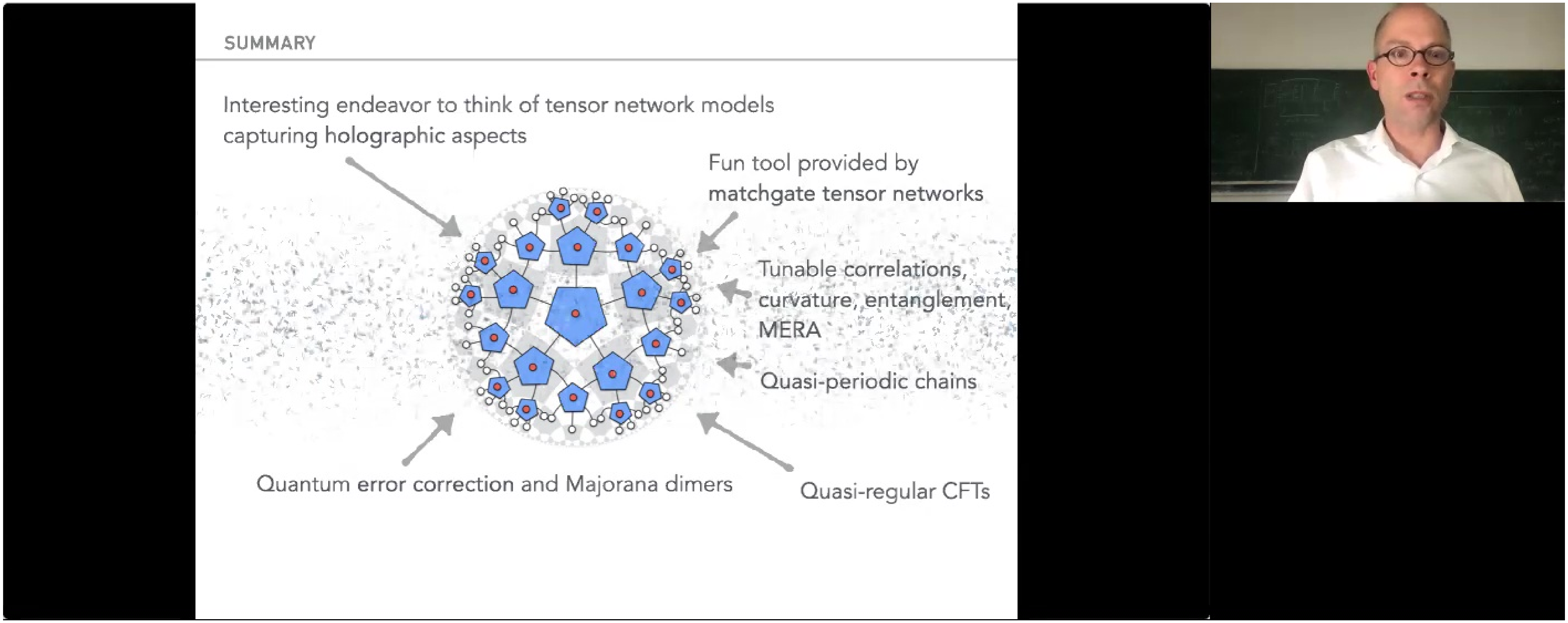


Fun tool provided by **matchgate tensor networks**

Tunable correlations, curvature, entanglement, MERA

Quantum error correction and Majorana dimers

Quasi-regular CFTs


SUMMARY
Interesting endeavor to think of tensor network models capturing holographic aspects
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THANKS FOR YOUR ATTENTION

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