Overview: from (many) qubits to space-time

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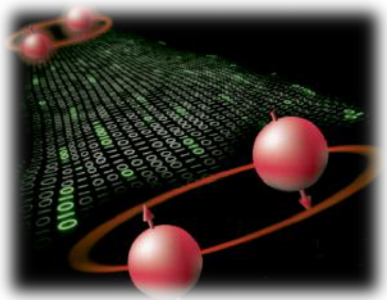
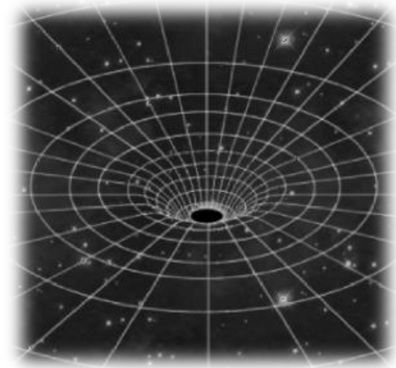
CERN, June 22 2016

c.f. talks by Latorre, Molina-Vilaplana, Pastawski, Wen, Maldacena

Motivation

Condensed Matter → *Quantum Information* →? *Space-time?*





(Objects that look like) space-times seem to emerge from the *entanglement structure* of quantum many-body states

(and we were not thinking about gravity at all...)

This talk: overview of some ideas along these lines

Outline

1) Review of TNs

2) PEPS and emergent Hamiltonians

3) Symmetric TNs and emergent spin networks

4) MERA and emergent AdS/CFT

5) Summary & open questions

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Entanglement obeys area-law

Entanglement → key resource in quantum information

teleportation, quantum algorithms,
quantum error correction, quantum cryptography…

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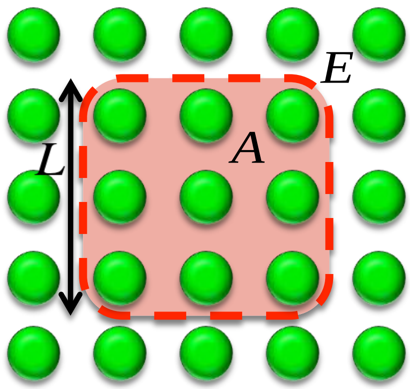
2d system



$$\rho_A = \mathrm{tr}_E\left(|\Psi\rangle\langle\Psi|\right)$$

Reduced density matrix of subsystem A

$$S(A) = -\mathrm{tr}\left(\rho_A \log \rho_A\right)$$

Entanglement entropy (von Neumann entropy)

For many ground states → $S(A) \sim L$

$(L > \xi)$

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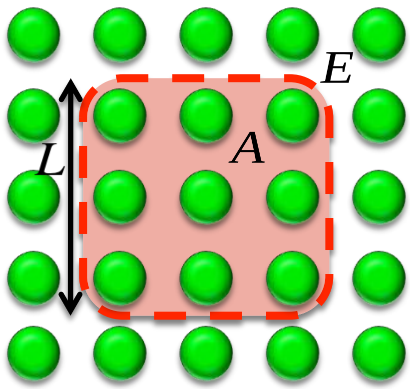

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$(L > \xi)$

In d dimensions

Generic state	$S(A) \sim L^d$ (volume)
Ground states of (most) local Hamiltonians	$S(A) \sim L^{d-1}$ (area)

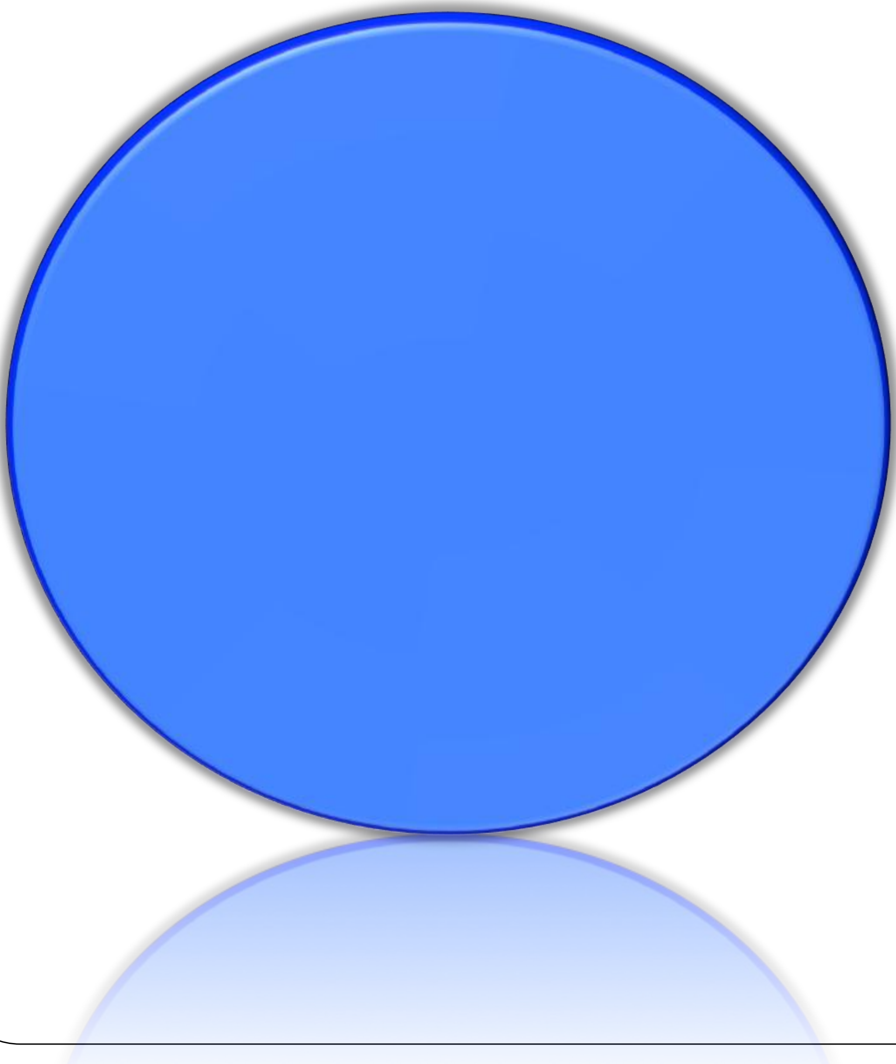
Srednicki, Plenio, Eisert, Dreißig, Cramer, Wolf…

Locality of interactions ⇔ area-law

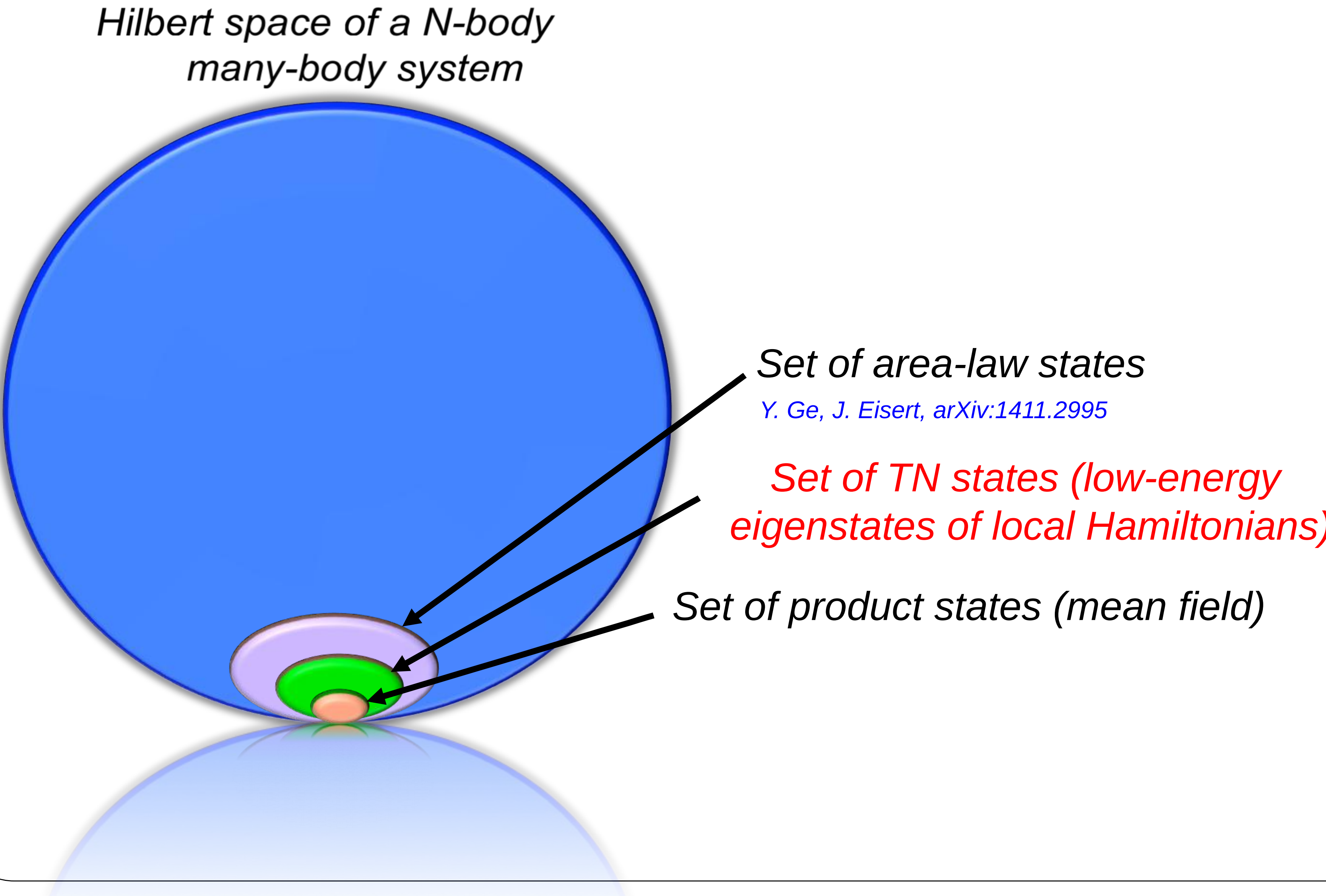
Many-body Hilbert space is far too large

Hilbert space is a convenient illusion

Hilbert space of a N-body many-body system



Hilbert space is a convenient illusion



Hilbert space is a convenient illusion

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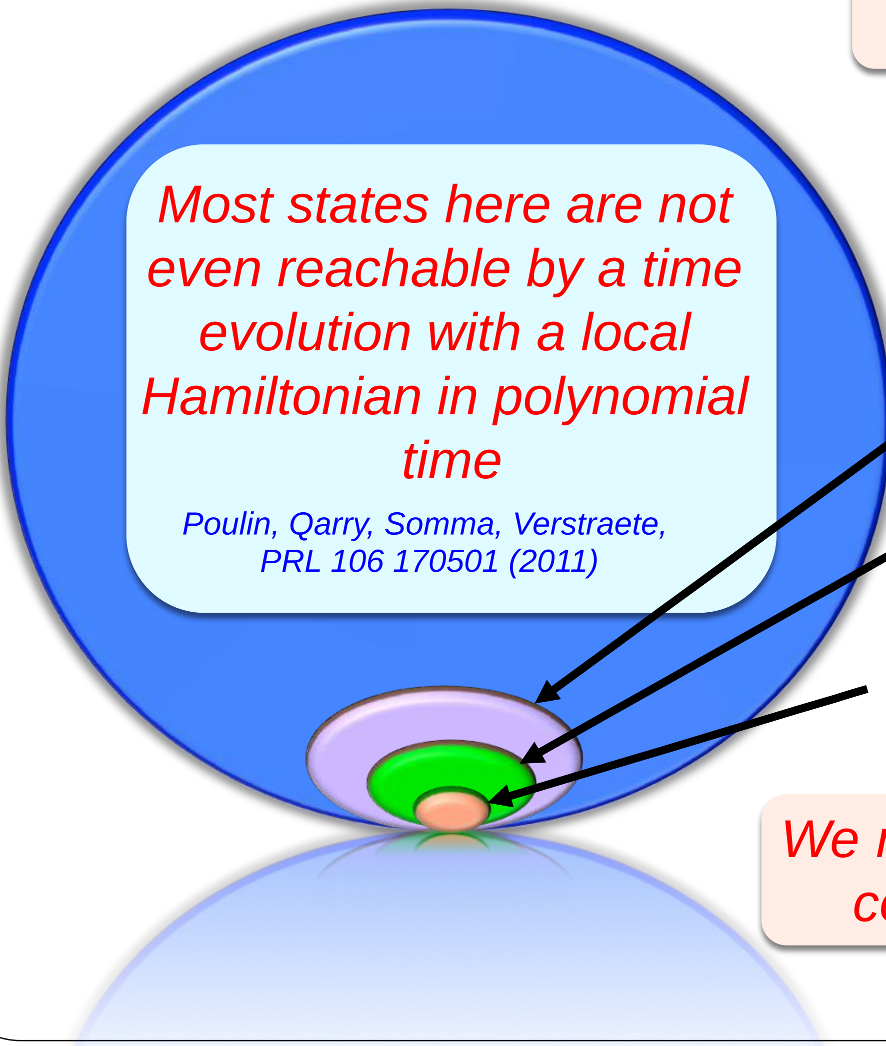

"Exploration" time ~ $O(10^{10^{23}})$ sec.

Compare to…

Age of the universe ~ $O(10^{17})$ sec.

Set of area-law states

Y. Ge, J. Eisert, arXiv:1411.2995

Set of TN states (low-energy eigenstates of local Hamiltonians)

Set of product states (mean field)

We need a language to target the relevant corner of quantum states directly

Tensor Networks

A new language

$$|\Psi\rangle = \sum_{i's} \Psi_{i_1 i_2 \ldots i_N} |i_1\rangle \otimes |i_2\rangle \otimes \cdots \otimes |i_N\rangle$$

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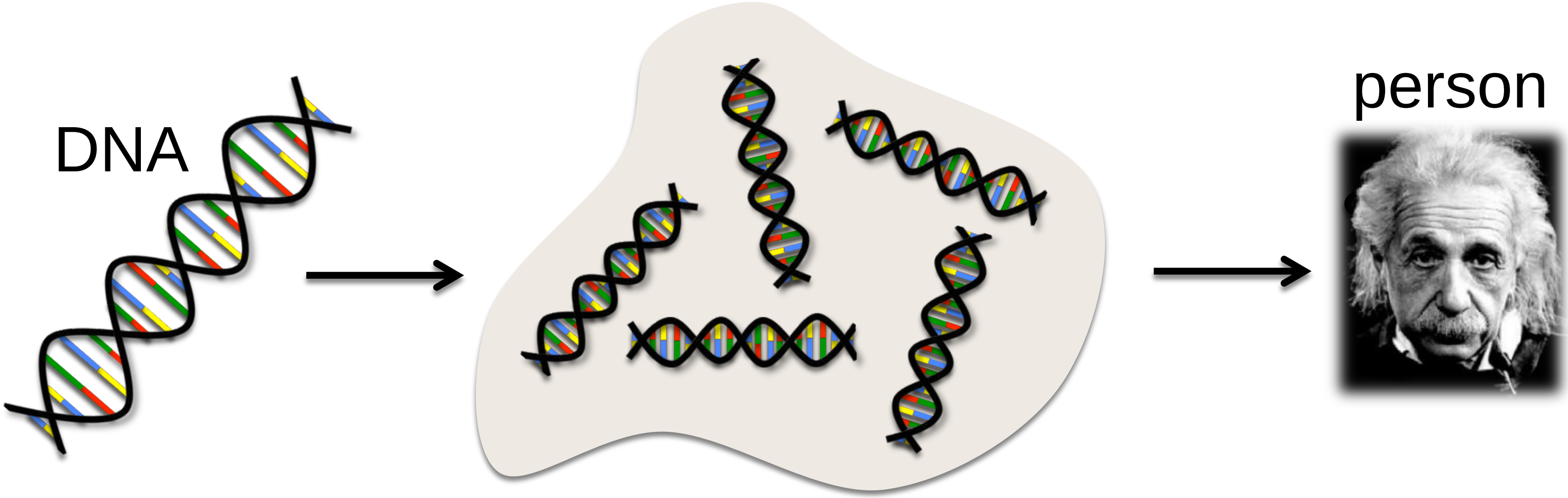

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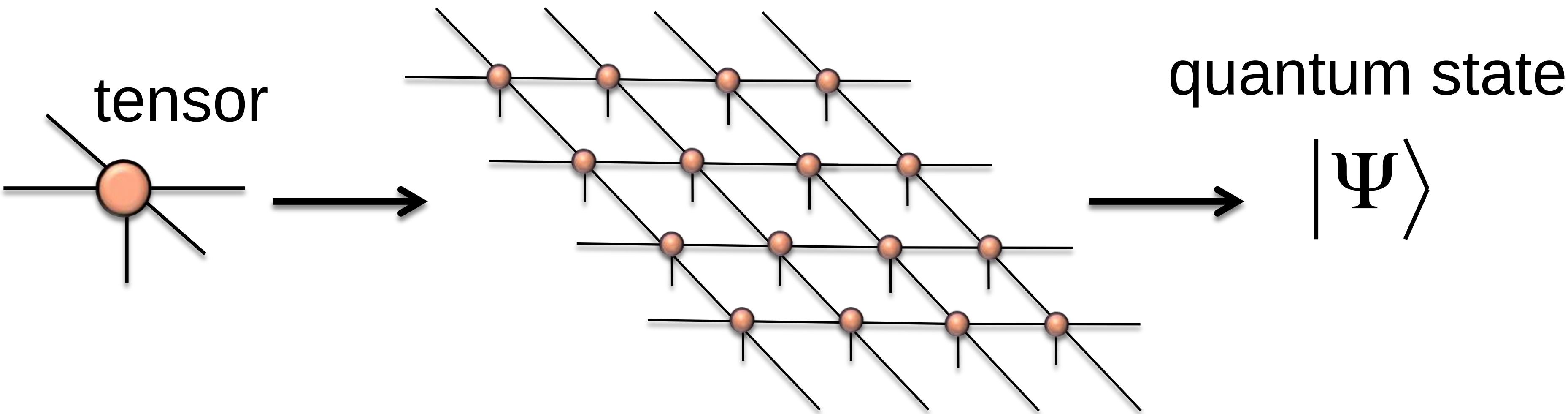

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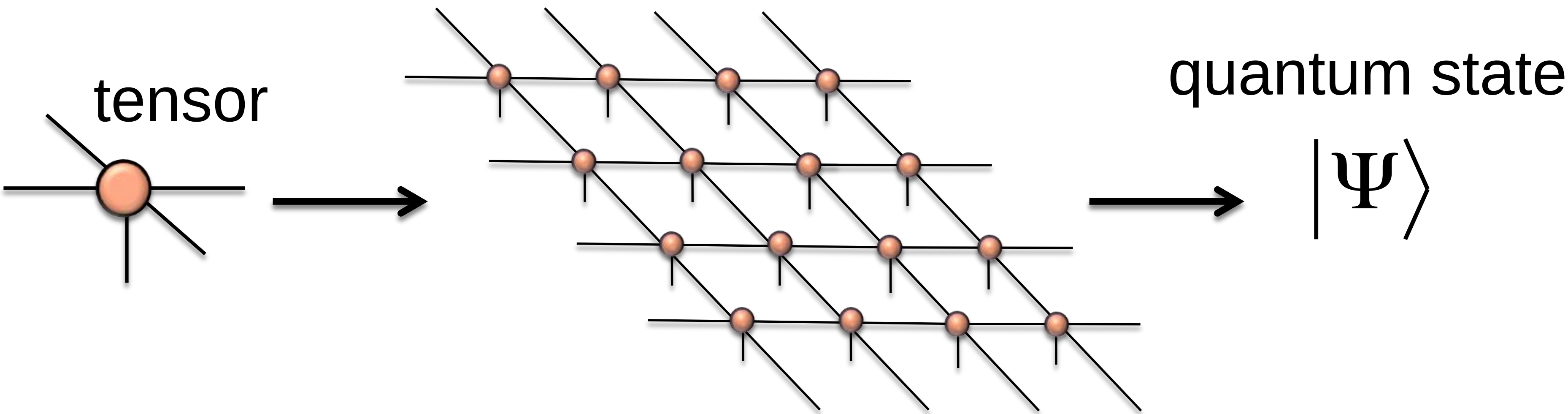
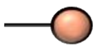


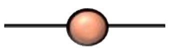
Tensors are local building blocks for the quantum state (like a DNA, or LEGO)

Tensor network diagrams

vector $\vec{v}$

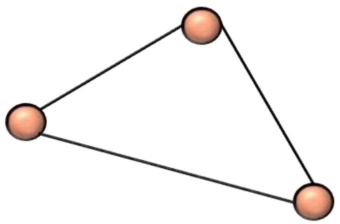


matrix A

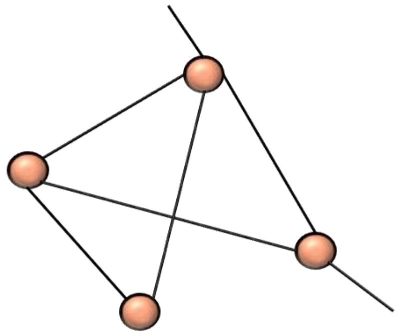


matrix product AB

trace of matrix product $\mathrm{tr}(ABC)$

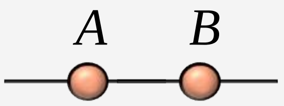


tensor contraction $f(A,B,C,D)$



Tensor Networks

*e.g. RO, Annals of Physics **349** (2014) 117–158*

$A \cdot B \rightarrow$ 

$$|\Psi\rangle = \sum_{i's} \Psi_{i_1 i_2 \ldots i_N} |i_1\rangle \otimes |i_2\rangle \otimes \cdots \otimes |i_N\rangle$$

p-level systems

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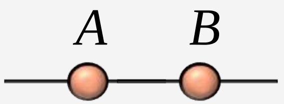
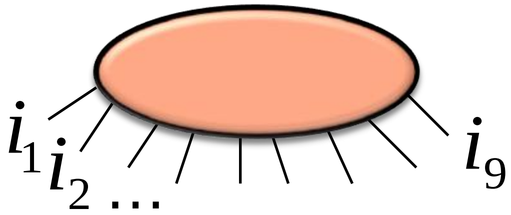
$A \cdot B \rightarrow$ 

$$|\Psi\rangle = \sum_{i's} \Psi_{i_1 i_2 \dots i_N} |i_1\rangle \otimes |i_2\rangle \otimes \cdots \otimes |i_N\rangle$$

p-level systems

$$\Psi_{i_1 i_2 i_3 i_4 i_5 i_6 i_7 i_8 i_9}$$



Tensor Networks

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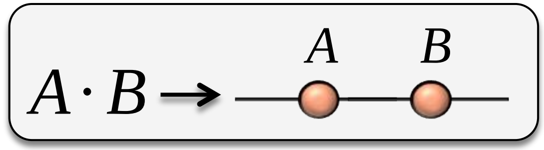

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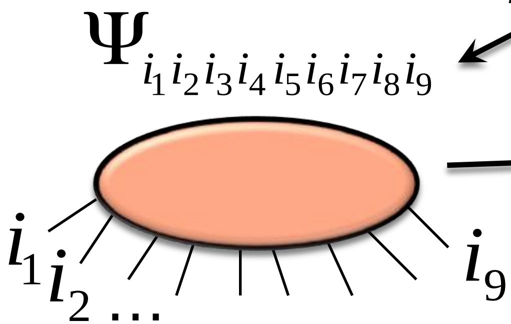
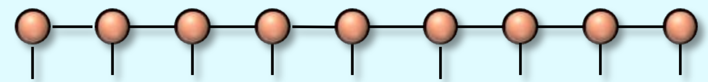


1d

Matrix Product States (MPS)



DMRG, PWFRG, TEBD…

Tensor Networks

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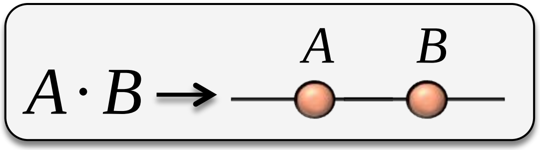

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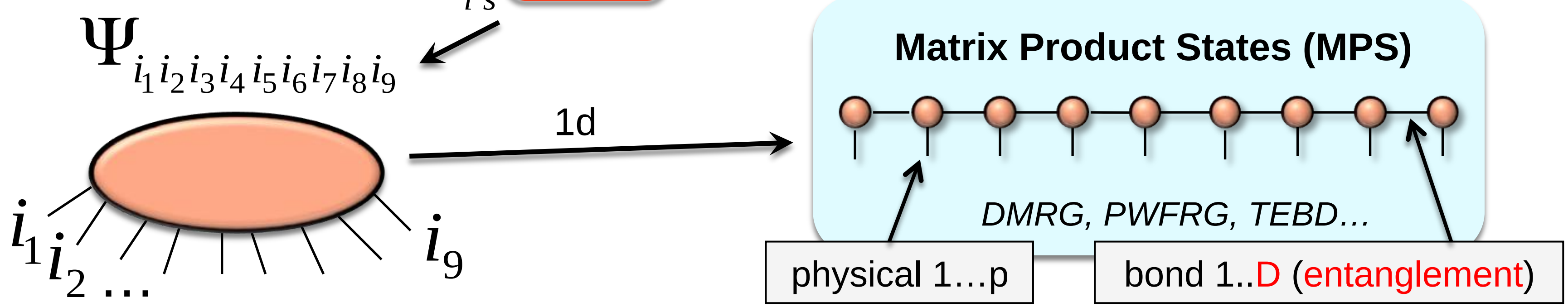

Tensor Networks

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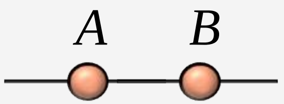
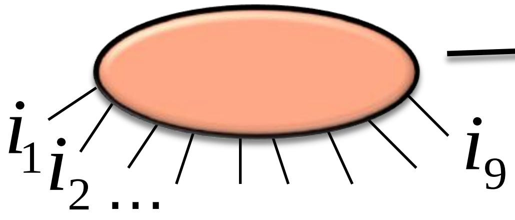
$A \cdot B \rightarrow$ 

$$|\Psi\rangle = \sum_{i's} \Psi_{i_1 i_2 \ldots i_N} |i_1\rangle \otimes |i_2\rangle \otimes \cdots \otimes |i_N\rangle$$

p-level systems

$\Psi_{i_1 i_2 i_3 i_4 i_5 i_6 i_7 i_8 i_9}$



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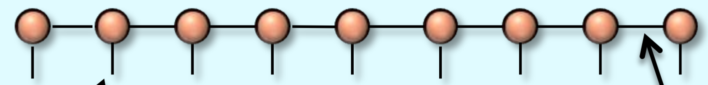


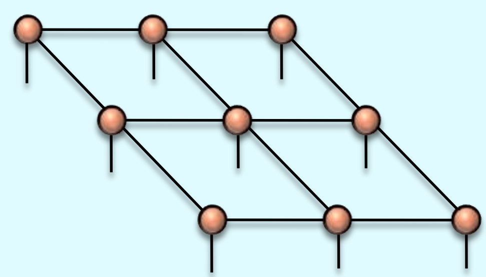
DMRG, PWFRG, TEBD…

physical 1…p

bond 1..D (entanglement)

2d, 3d...

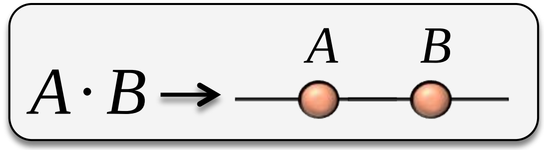
Projected Entangled Pair States (PEPS), Tensor Product States (TPS)



Tensor Product Variational Approach, PEPS & iPEPS algorithms, Tensor-Entanglement Renormalization, TRG/SRG/HOTRG/HOSRG…

Tensor Networks

e.g. RO, *Annals of Physics* **349** (2014) 117–158



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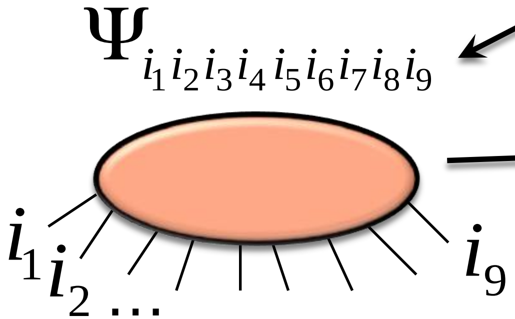
p-level systems

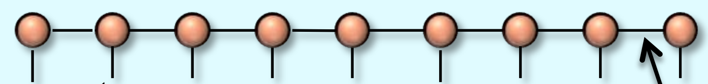


1d

2d, 3d...

Scale-invariant

Matrix Product States (MPS)

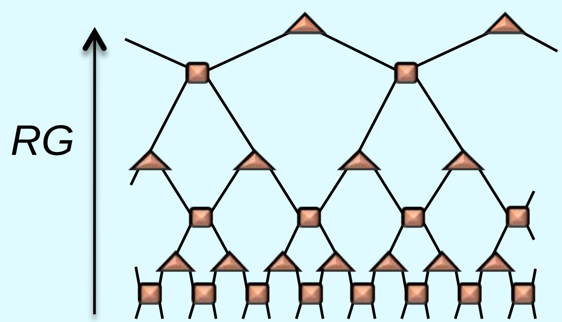


DMRG, PWFRG, TEBD…

physical 1…p

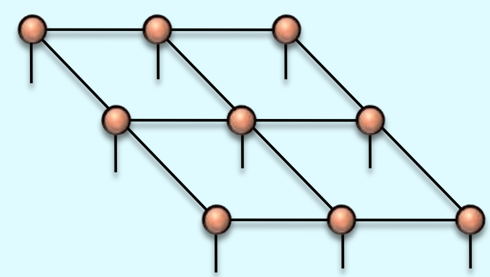
bond 1..D (entanglement)

Multiscale Entanglement Renormalization Ansatz (MERA)



AdS/CFT, Entanglement Renormalization

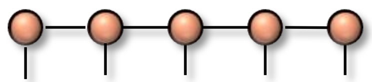
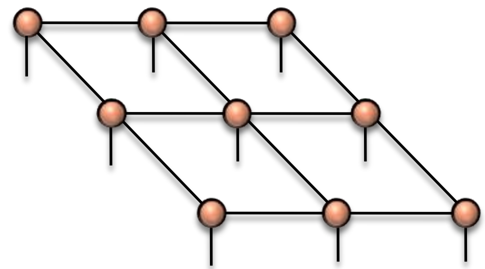
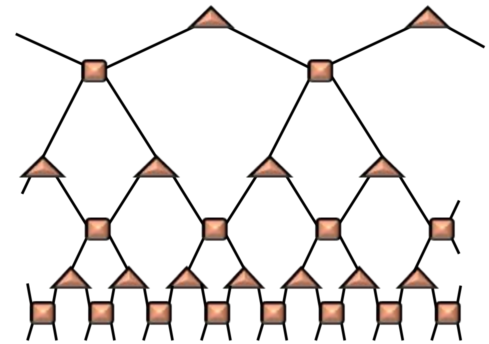
Projected Entangled Pair States (PEPS), Tensor Product States (TPS)



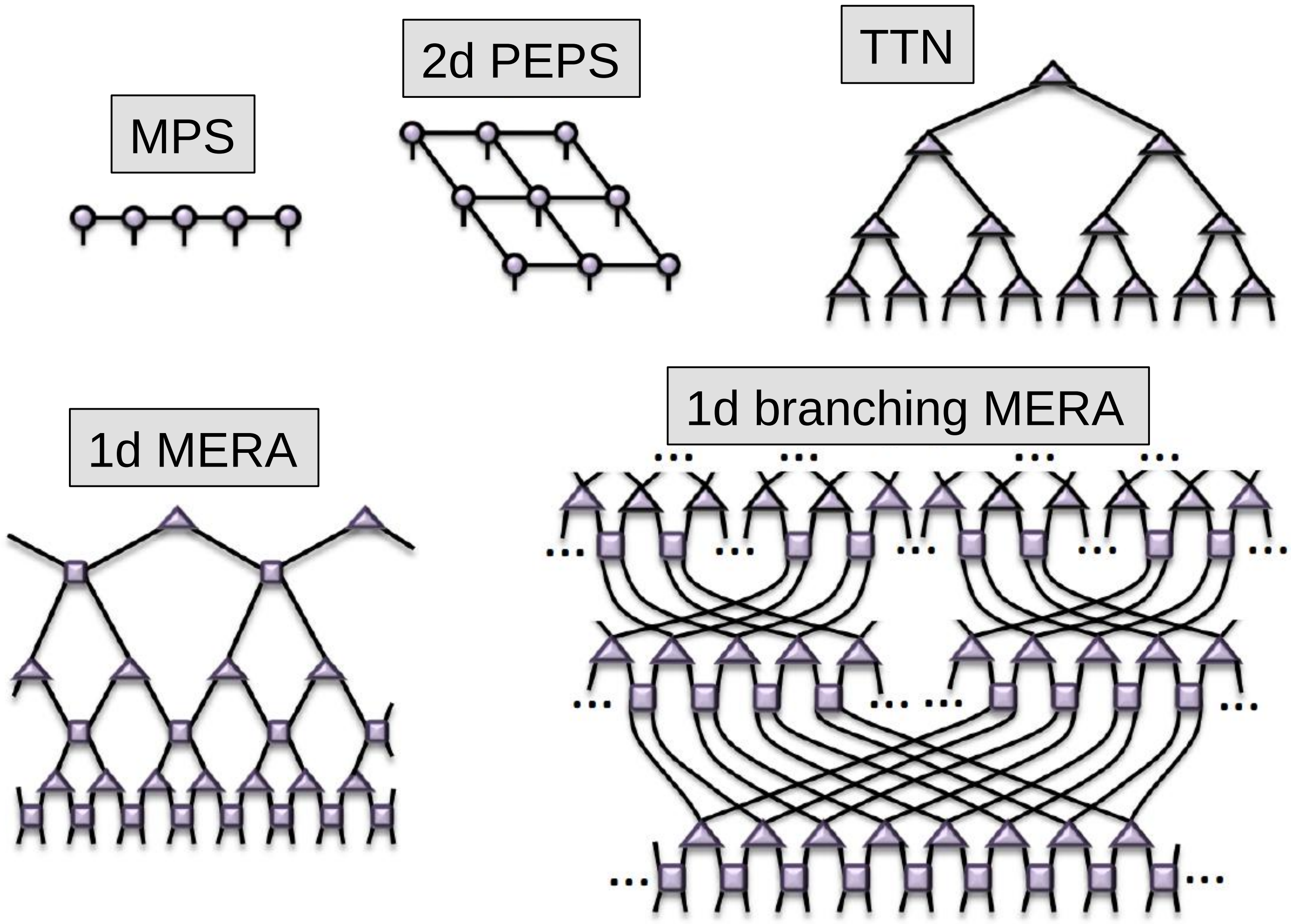
Tensor Product Variational Approach, PEPS & iPEPS algorithms, Tensor-Entanglement Renormalization, TRG/SRG/HOTRG/HOSRG…

Efficient O(poly(N)), satisfy area-law, low-energy eigenstates of local Hamiltonians

Comparison

	MPS in 1d 	*PEPS in 2d* 	*MERA in 1d* 
Ent. entropy	$S(L)=O(1)$	$S(L)=O(L)$	$S(L)=O(\log L)$
Exact contraction	efficient	inefficient	efficient
Corr. length	finite	finite & infinite	finite & infinite
To/from	1d Ham.	2d Ham.	1d Ham.
Tensors	arbitrary	arbitrary	constrained

Increasing complexity...



Exact in many cases
Variational ansatz for numerical simulations (e.g. DMRG)

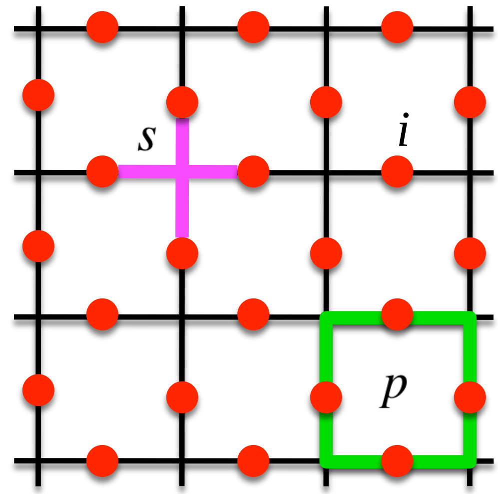
Exact example 1: Kitaev's Toric Code

Kitaev, 1997

$$H = -J\sum_s A_s - J\sum_p B_p$$

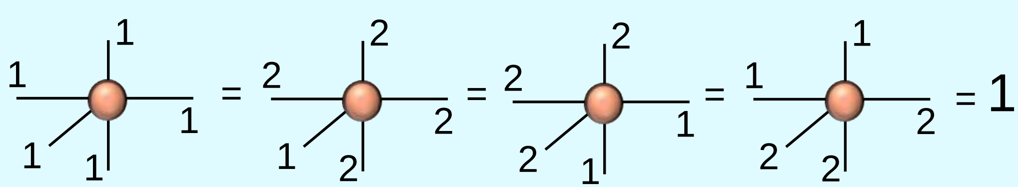
$$A_s = \prod_{i\in s}\sigma_i^x$$ *star operator*

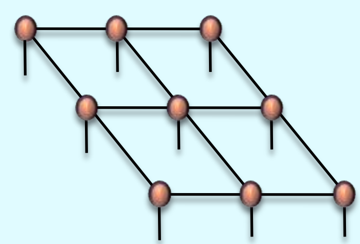
$$B_p = \prod_{i\in p}\sigma_i^z$$ *plaquette operator*



Simplest known model with "topological order"

Ground state (and in fact all eigenstates) are PEPS with D=2





And another tensor rotated 90˚

Exact example 2: Kitaev's honeycomb model

A. Kitaev, Annals of Physics 321, 2-111 (2006)

P. Schmoll, RO, arXiv:1605.04315

Bogoliubov modes

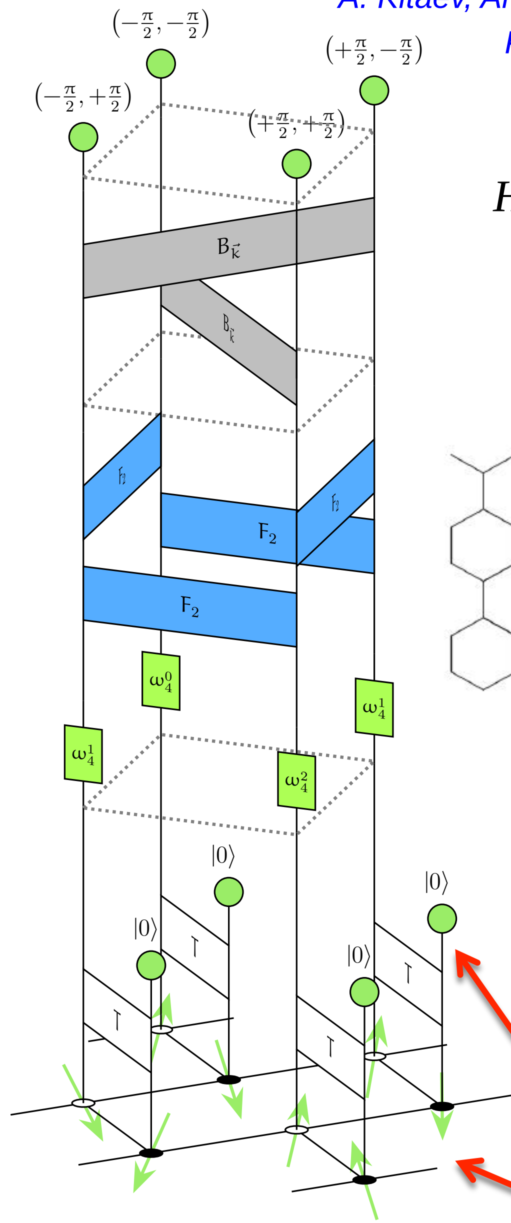
Bogoliubov transformation

Dirac momentum modes

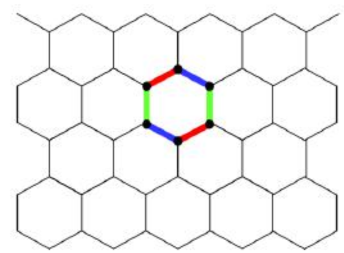
Fermionic Fourier transformation

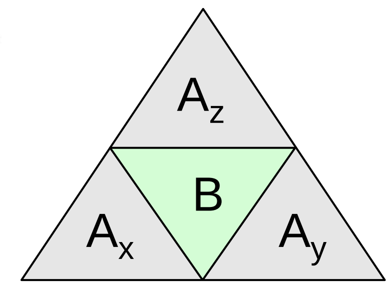
Dirac real-space modes

Majorana braidings + Jordan-Wigner



$$H = -J_x \sum_{x-links} \sigma_j^x \sigma_k^x - J_y \sum_{y-links} \sigma_j^y \sigma_k^y - J_z \sum_{z-links} \sigma_j^z \sigma_k^z$$





Abelian and non-abelian, chiral and non-chiral topological phases

Vortex modes

Spins on the honeycomb

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JG|U

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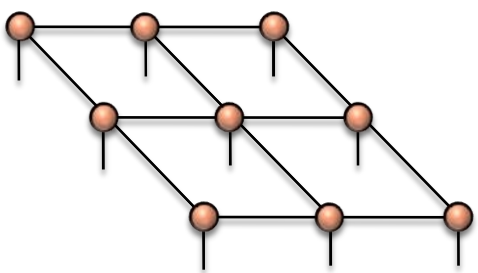
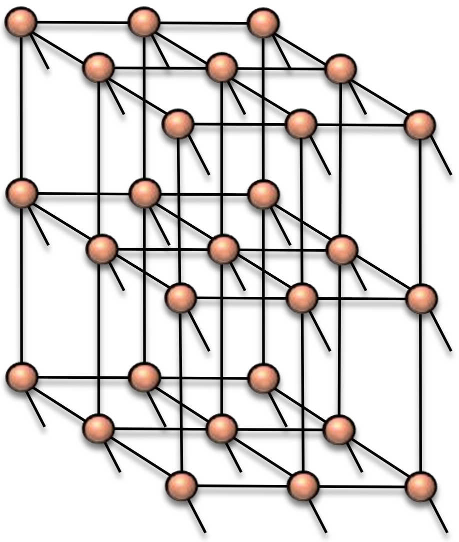
Projected Entangled Pair States (PEPS)

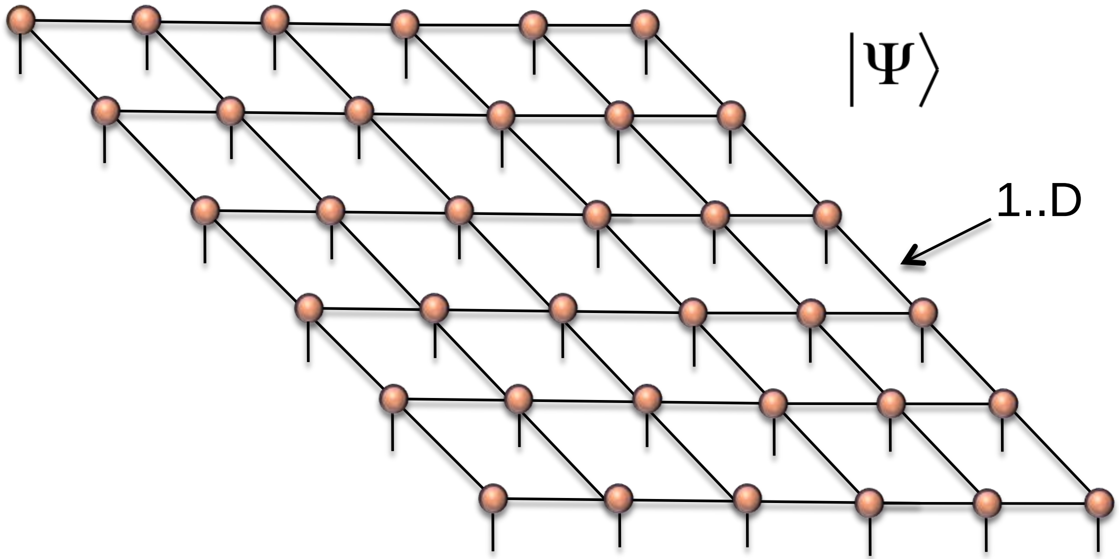


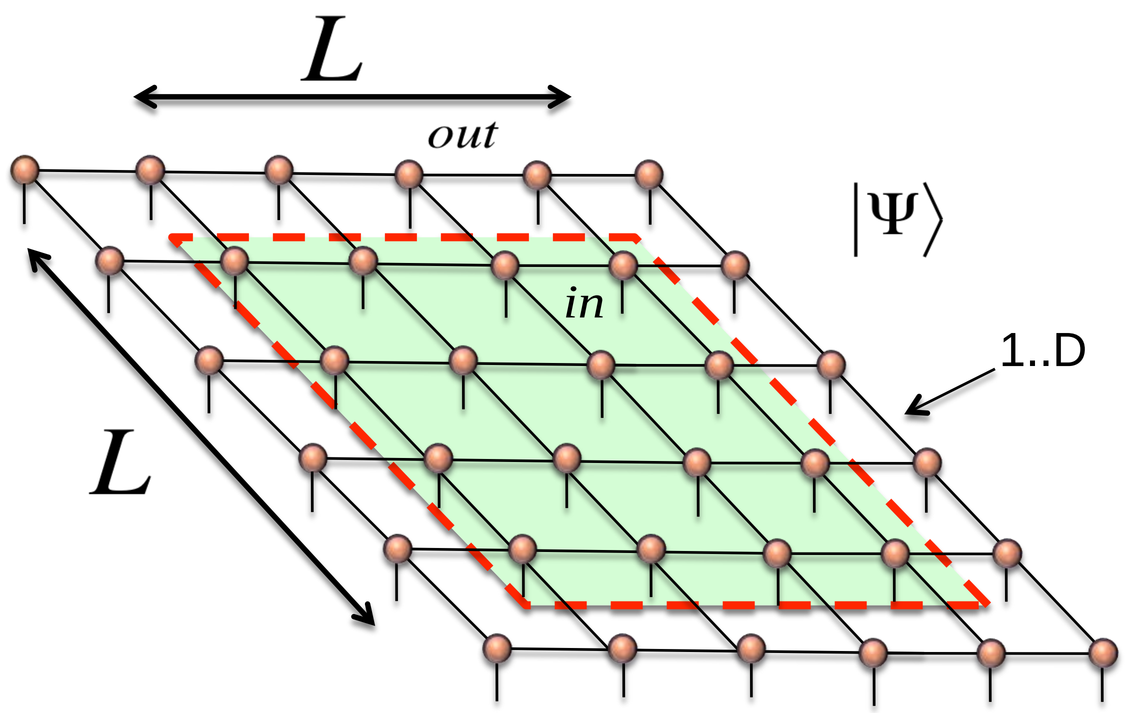
2d systems



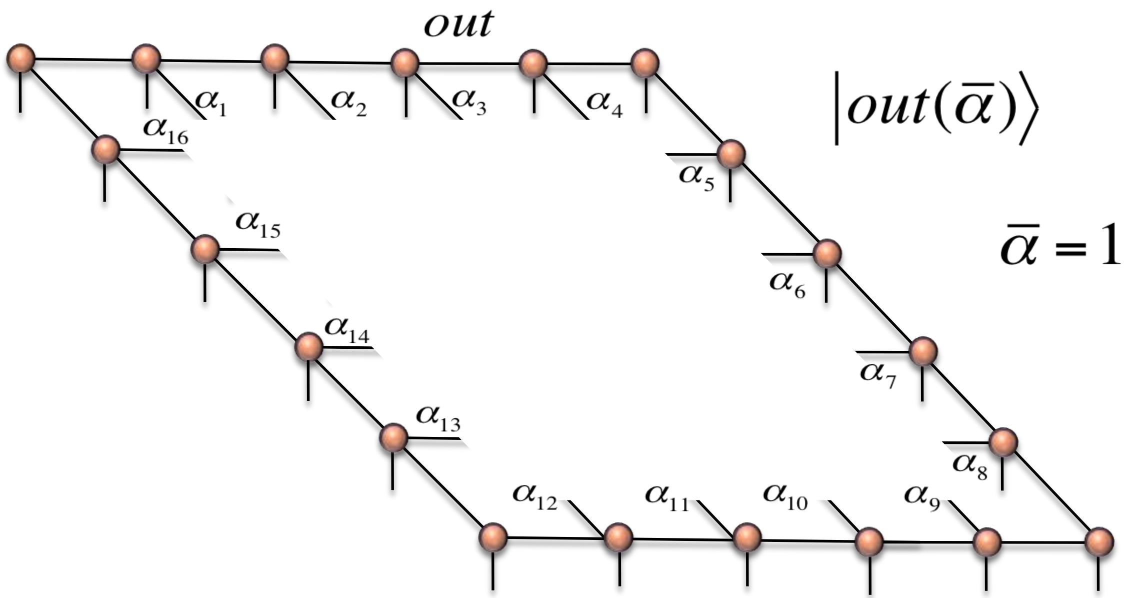
3d systems

PEPS obey 2d area-law


$|\Psi\rangle$
1..D

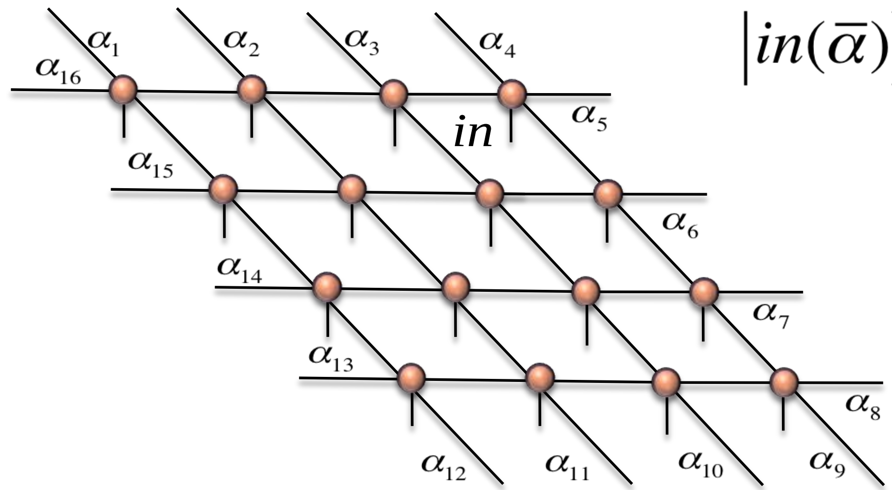


L
out
$|\Psi\rangle$
in
1..D
L



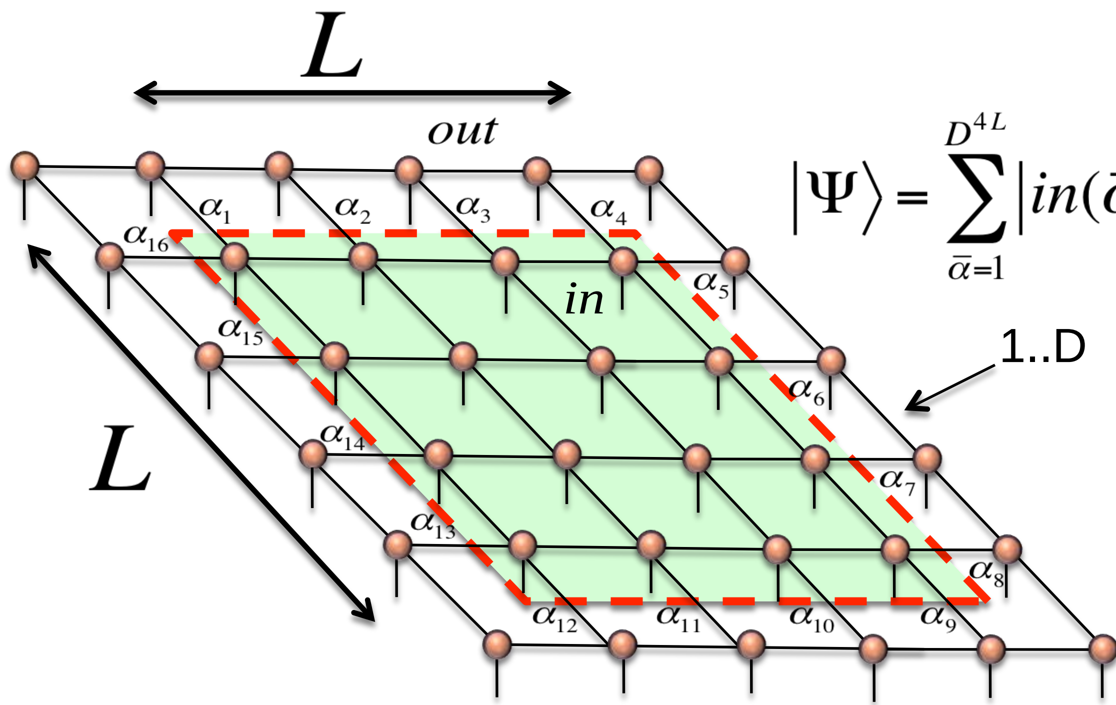
$$|out(\bar{\alpha})\rangle$$

$$\bar{\alpha} = 1, 2, \ldots, D^{4L}$$



$$|in(\bar{\alpha})\rangle$$

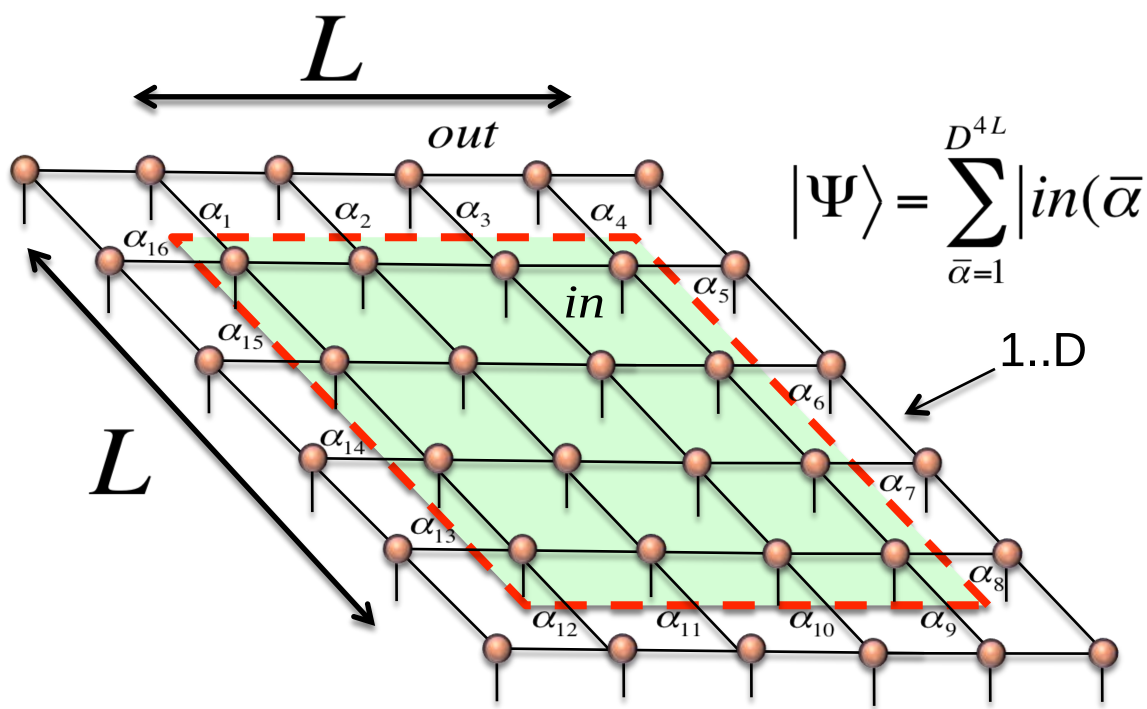
$$\bar{\alpha} = 1, 2, \ldots, D^{4L}$$



$$|\Psi\rangle = \sum_{\bar{\alpha}=1}^{D^{4L}} |in(\bar{\alpha})\rangle |out(\bar{\alpha})\rangle$$

$$\rho_{in} = \mathrm{tr}_{out}\left(|\Psi\rangle\langle\Psi|\right) = \sum_{\bar{\alpha},\bar{\alpha}'} X_{\bar{\alpha},\bar{\alpha}'} |in(\bar{\alpha})\rangle\langle in(\bar{\alpha}')| \qquad X_{\bar{\alpha},\bar{\alpha}'} = \langle out(\bar{\alpha}')|out(\bar{\alpha})\rangle$$

$$rank(\rho_{in}) \le D^{4L} \qquad S(L) = -\mathrm{tr}\left(\rho_{in} \log \rho_{in}\right) \le \log(D)4L$$



$$|\Psi\rangle = \sum_{\bar{\alpha}=1}^{D^{4L}} |in(\bar{\alpha})\rangle |out(\bar{\alpha})\rangle$$

$$\rho_{in} = \mathrm{tr}_{out}\left(|\Psi\rangle\langle\Psi|\right) = \sum_{\bar{\alpha},\bar{\alpha}'} X_{\bar{\alpha},\bar{\alpha}'} |in(\bar{\alpha})\rangle\langle in(\bar{\alpha}')| \qquad X_{\bar{\alpha},\bar{\alpha}'} = \langle out(\bar{\alpha}')|out(\bar{\alpha})\rangle$$

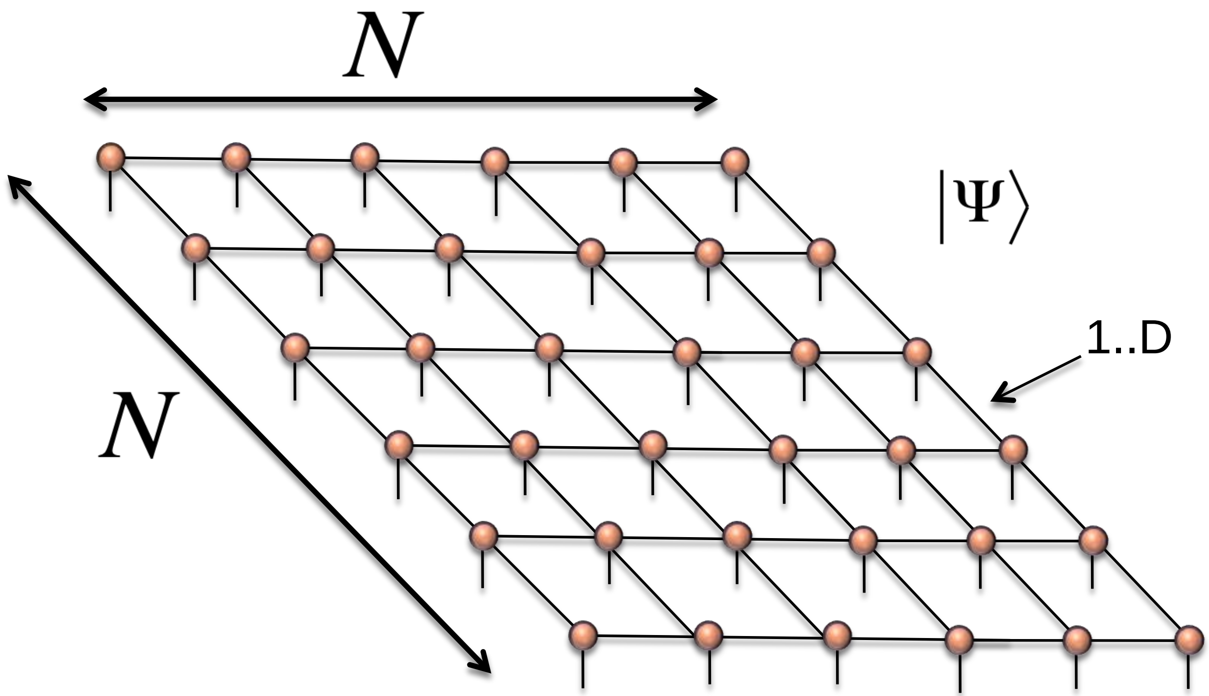
$$rank(\rho_{in}) \leq D^{4L} \qquad S(L) = -\mathrm{tr}\left(\rho_{in}\log\rho_{in}\right) \leq \log(D)\,4L$$

prefactor

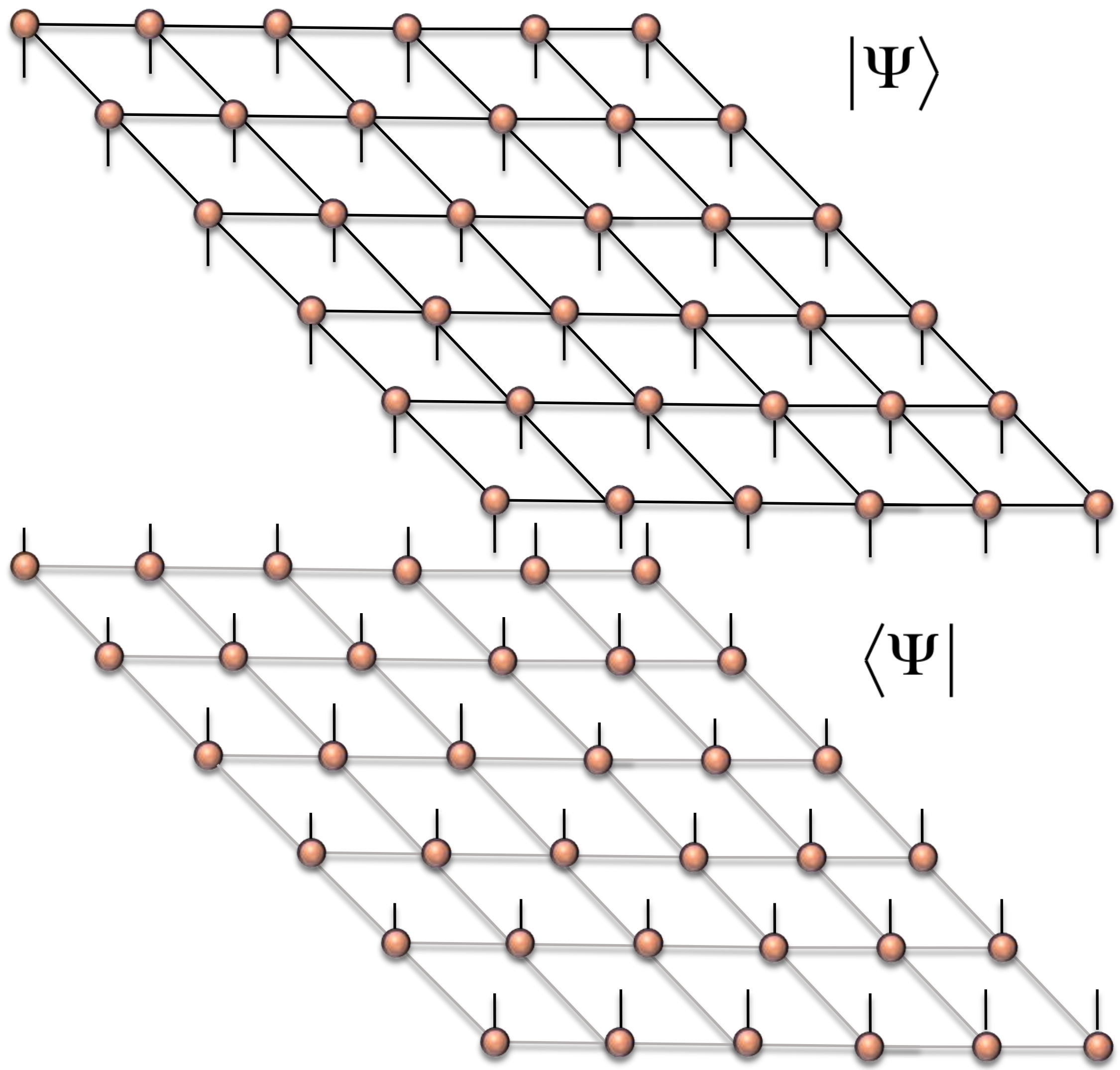
size of the boundary

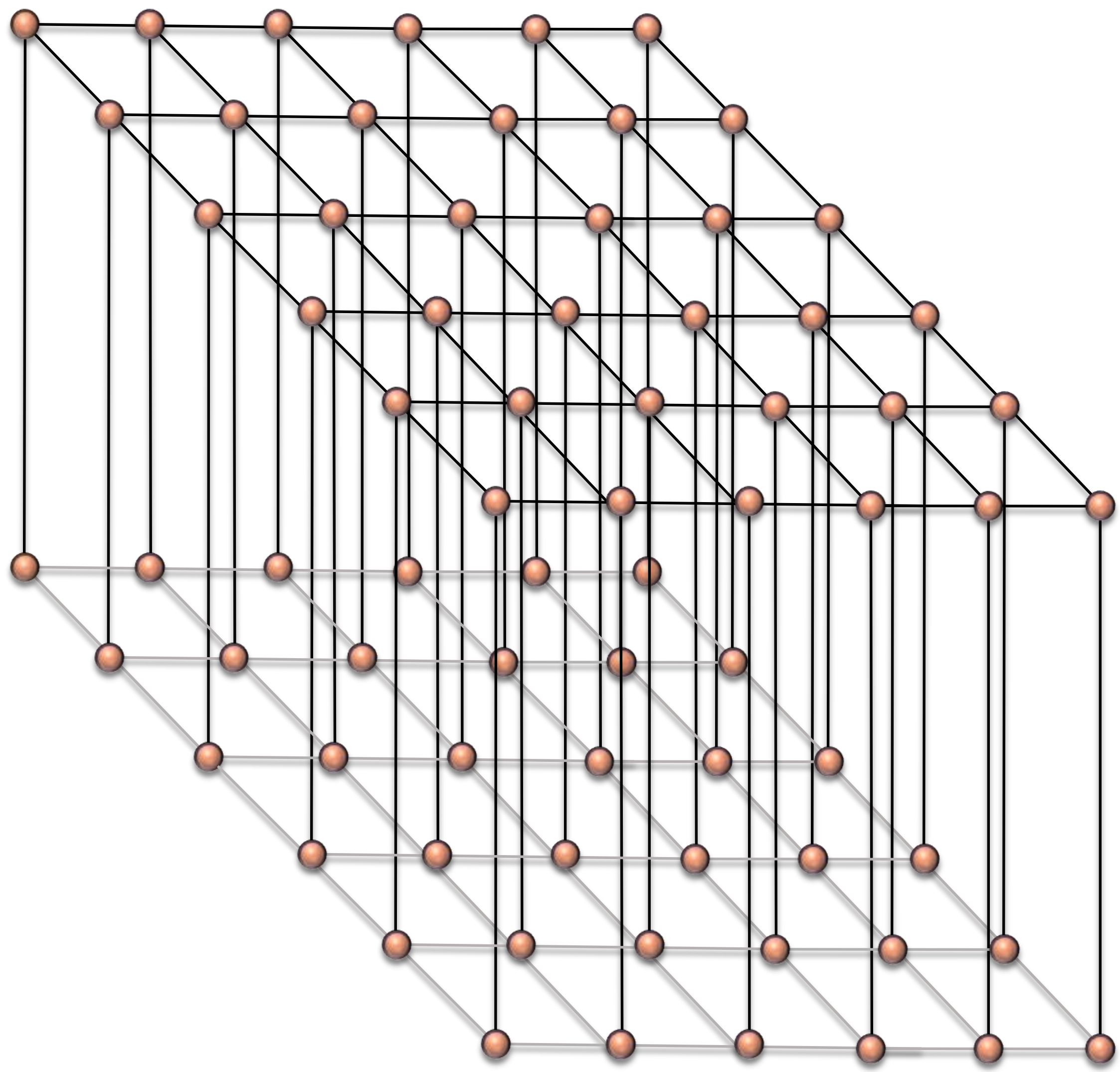
PEPS & Entanglement Hamiltonians

e.g. I. Cirac et al, PRB 83, 245134 (2011), N. Schuch et al, PRL 111, 090501 (2013)

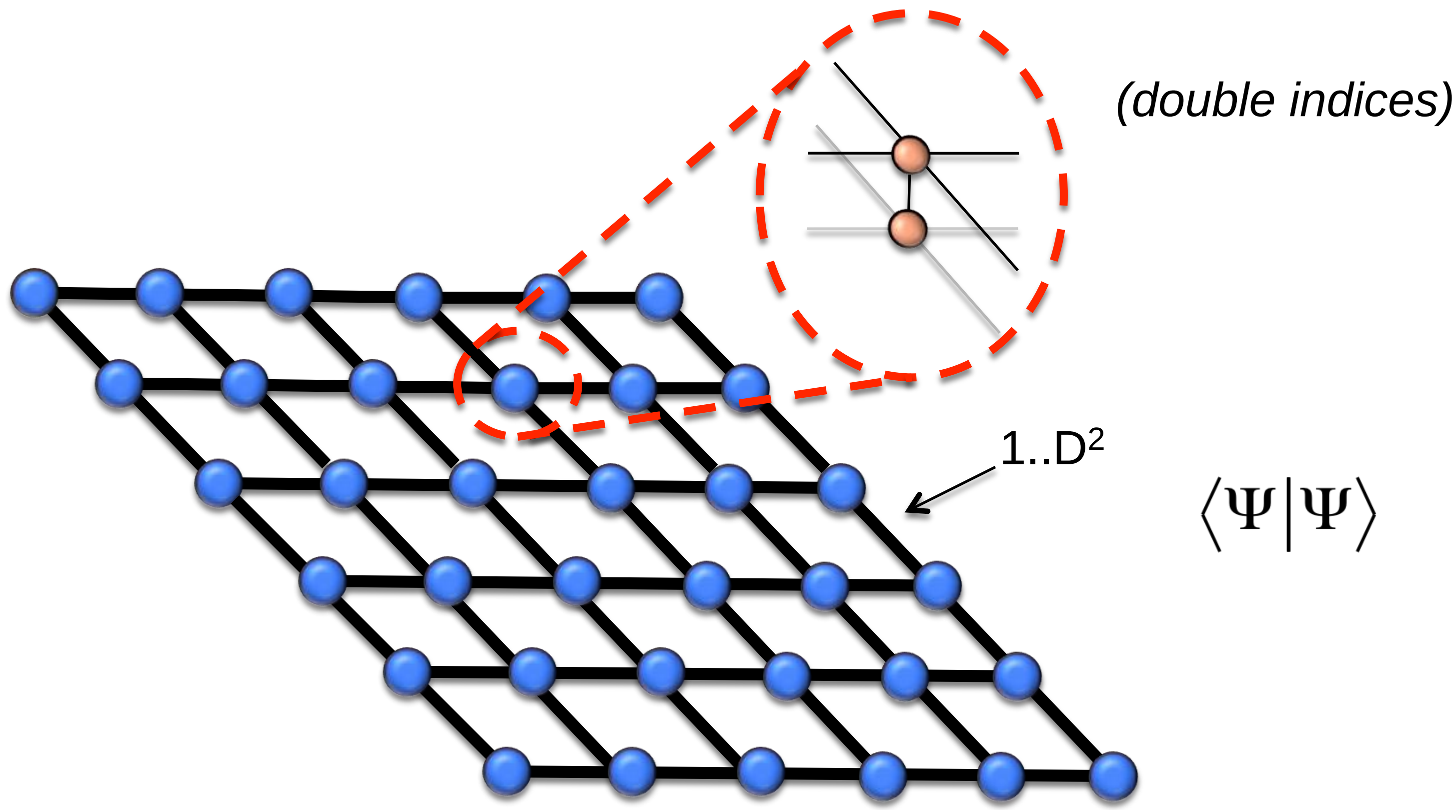


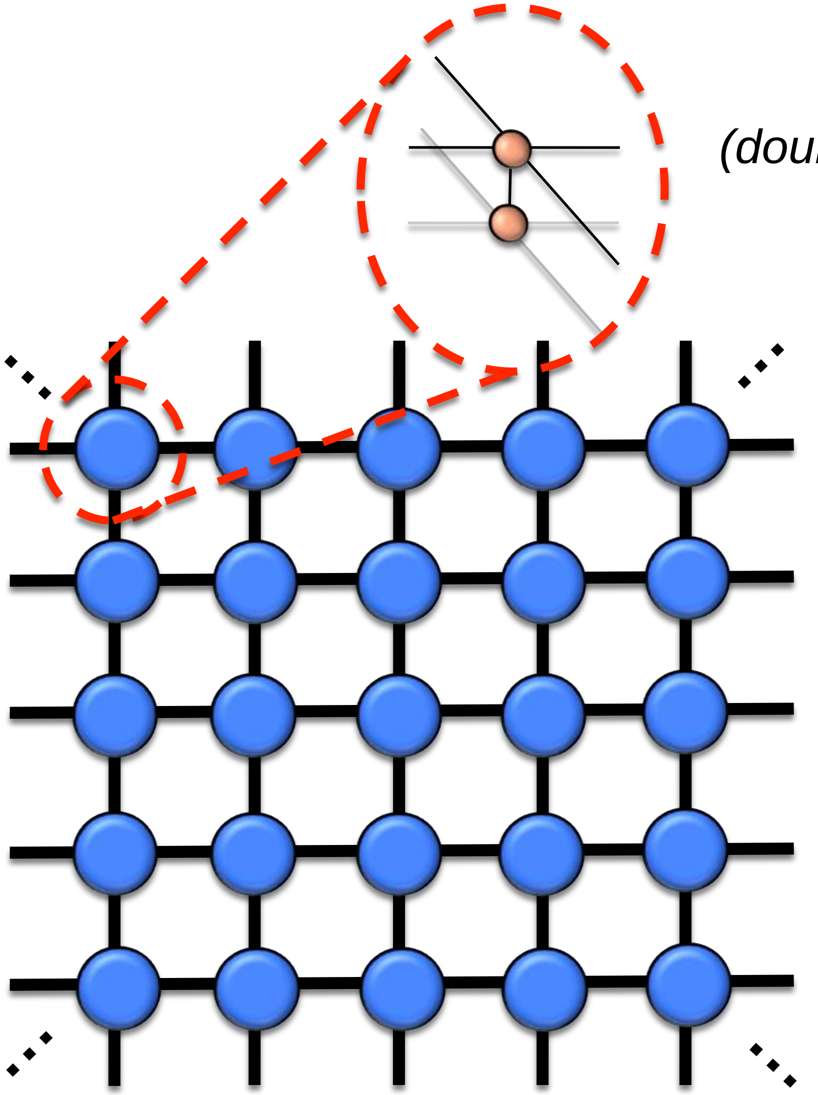
N
$|\Psi\rangle$
1..D
N


$|\Psi\rangle$
$\langle\Psi|$

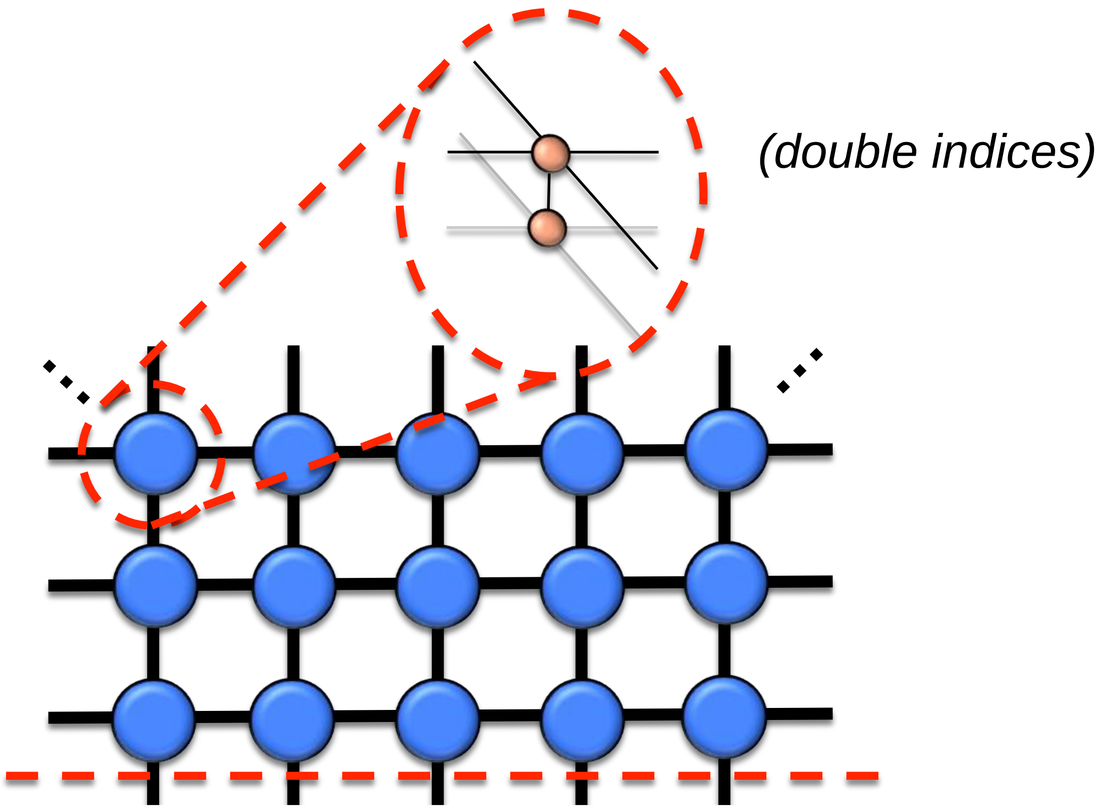


$$\langle \Psi | \Psi \rangle$$


(double indices)
1..D²
$\langle \Psi | \Psi \rangle$

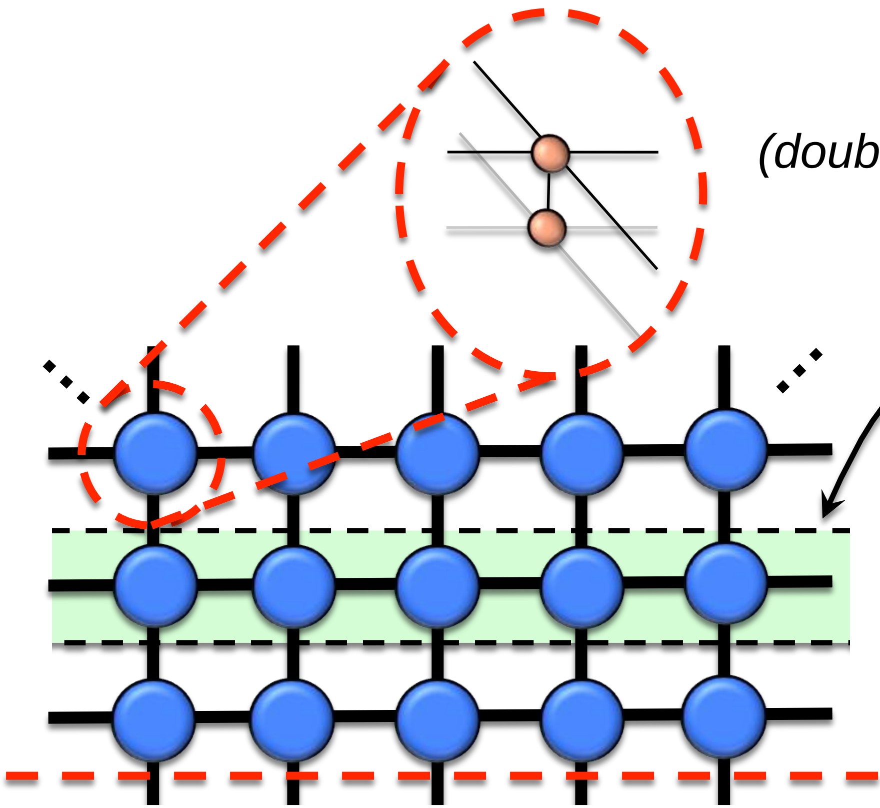


(double indices)



Boundary

How is physics described here?

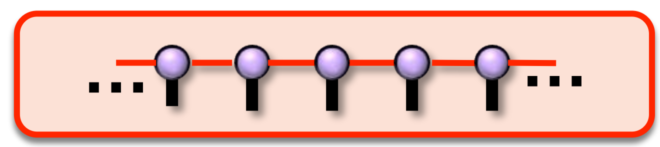


(double indices)

1-dim transfer matrix:

dominant eigenvector?

Can be approximated using infinite MPS

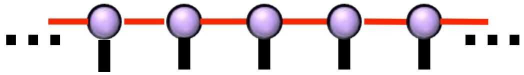


iTEBD, iDMRG, PWFRG, etc

Boundary

How is physics described here?

Emergent Hamiltonians



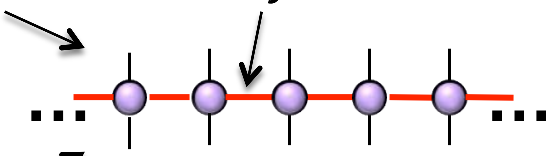
Remember it has double indices…

Emergent Hamiltonians

Virtual indices of bra

1…D

Boundary virtual index 1... χ



Virtual indices of ket

1…D

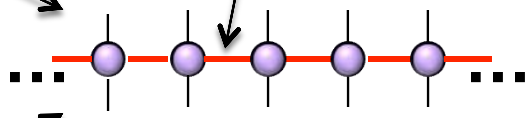
It is also hermitian and positive by construction (up to finite- χ effects)

Emergent Hamiltonians

Virtual indices of bra 1…D

Boundary virtual index 1... χ

Virtual indices of ket 1…D



||

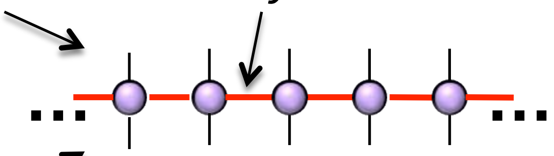
$$\rho = \exp(-H_E)$$

1d Entanglement Hamiltonian

It is also hermitian and positive by construction (up to finite-χ effects)

Who is H_E ???

Emergent Hamiltonians



It is also hermitian and positive by construction (up to finite-χ effects)

||

1d Entanglement Hamiltonian

$$\rho = \exp(-H_E)$$

Who is H_E ???

Bulk	Correspondence	Boundary
Gapped 2d systems, trivial phase		1d Hamiltonian, short-range
Critical 2d systems		1d Hamiltonian, long-range
Gapped 2d systems, topological order	➡	Completely non-local (projector)
Chiral topological order, gapless		(1+1)d Conformal field theory

RO, M. Mambrini, D. Poilblanc, work in progress

Particles and energies from Hamiltonians, and Hamiltonians from networks of entanglement + bulk-boundary correspondence

Outline

1) Review of TNs

2) PEPS and emergent Hamiltonians

3) Symmetric TNs and emergent spin networks

4) MERA and emergent AdS/CFT

5) Summary & open questions

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1) Review of TNs

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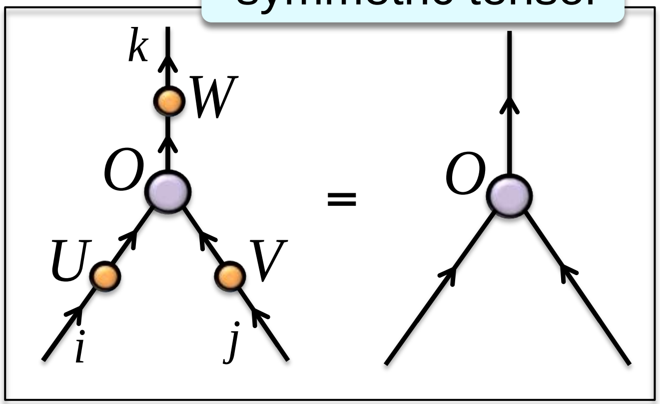
Symmetric tensors and Schur's lemma

e.g., S. Singh, R. N. C. Pfeifer, G. Vidal, PRA 82, 050301 (2010)

symmetric tensor



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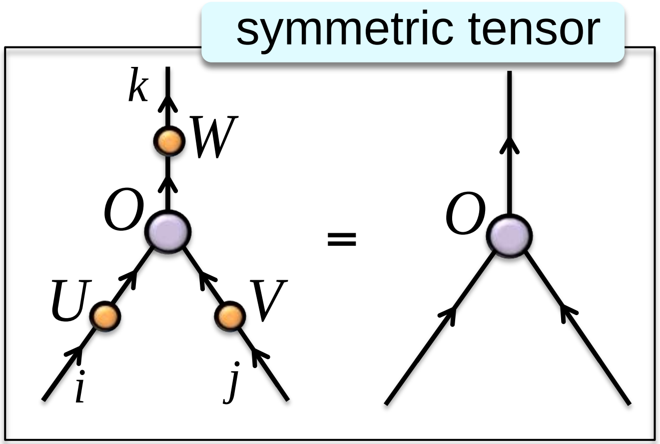
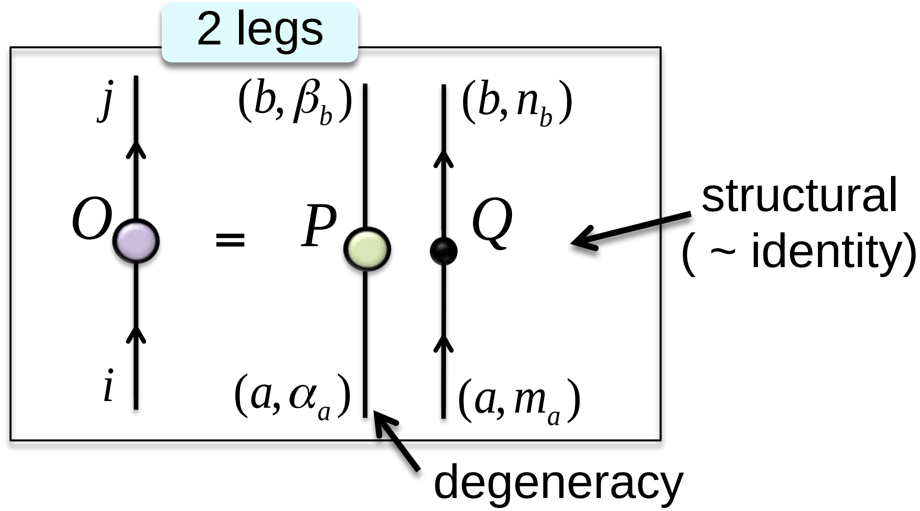
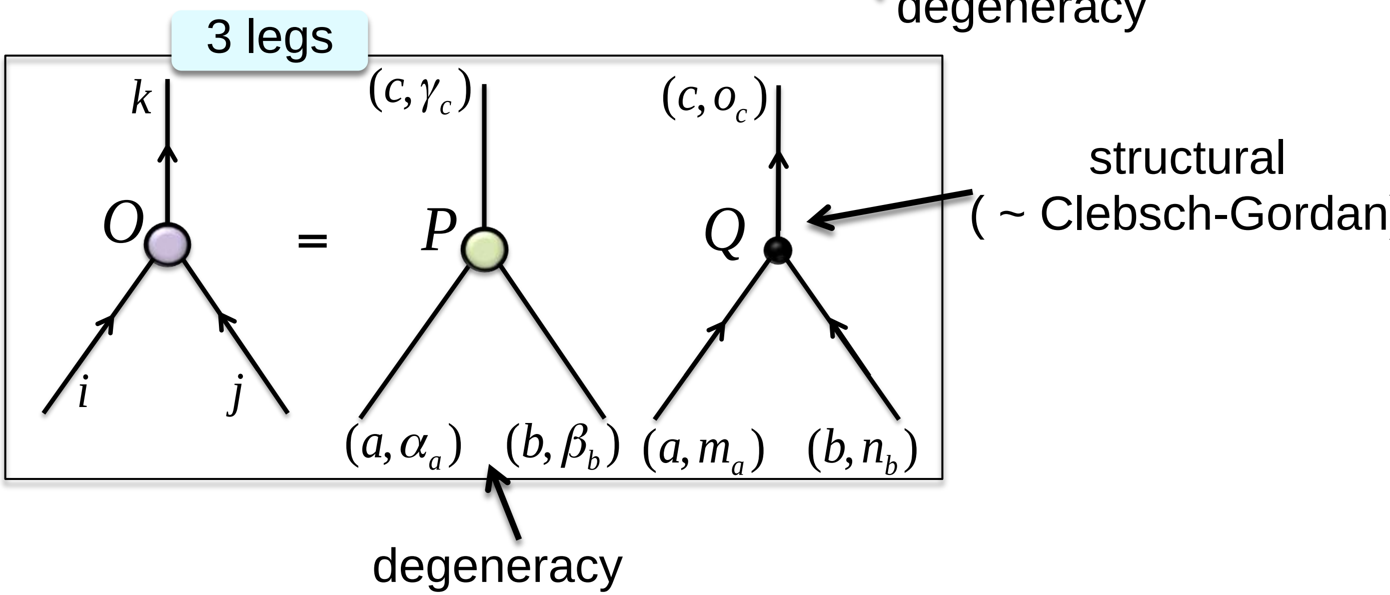


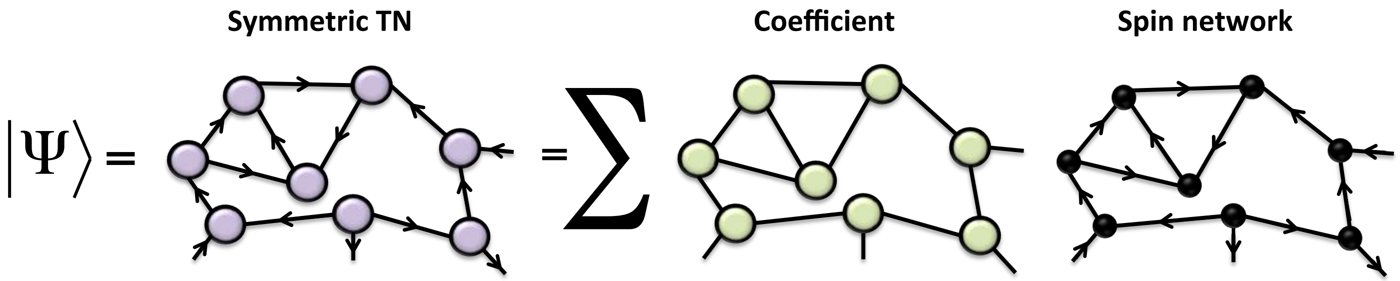




Structural part depends only on the group properties (intertwiners)

Emergent spin networks

e.g., S. Singh, R. N. C. Pfeifer, G. Vidal, PRA 82, 050301 (2010)



Emergent spin networks

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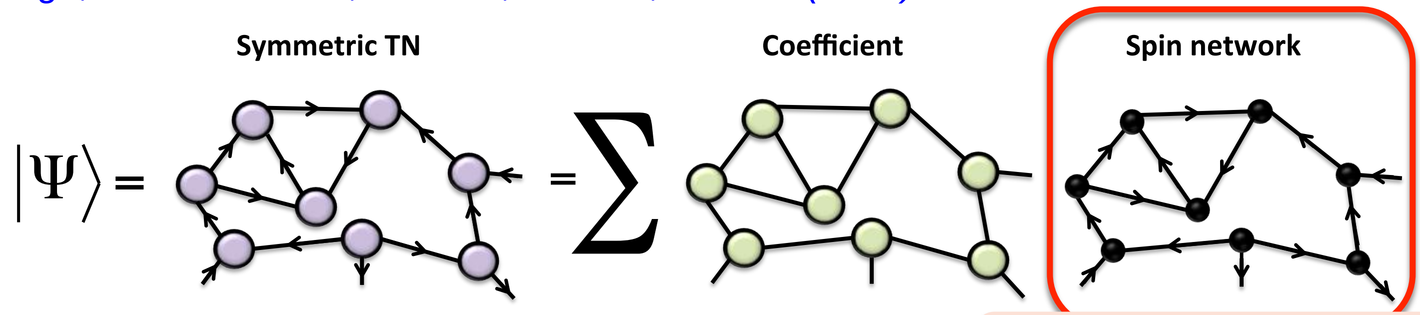
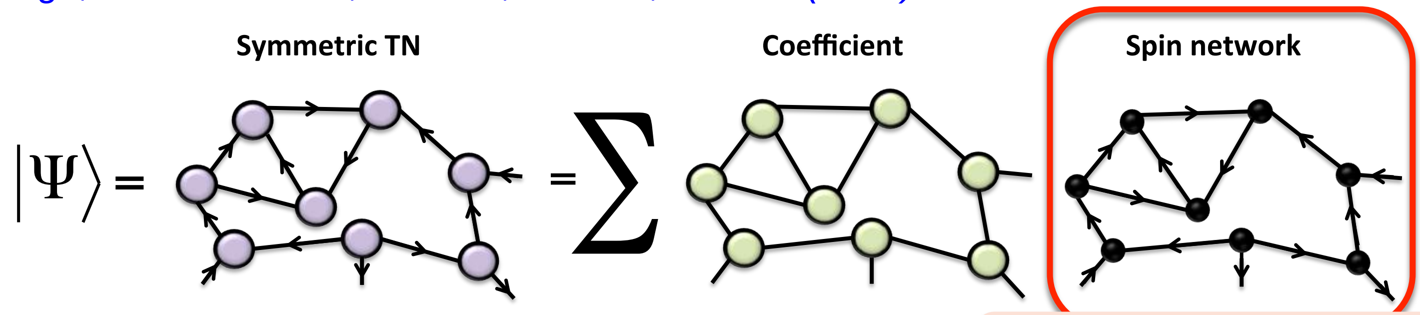


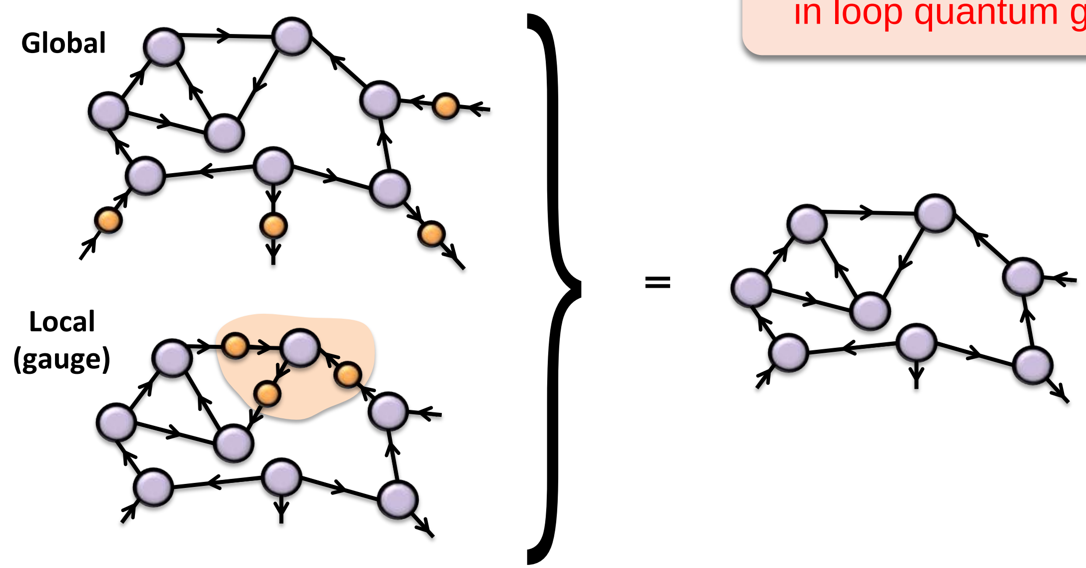
States of quantum geometry in loop quantum gravity...

Emergent spin networks

e.g., S. Singh, R. N. C. Pfeifer, G. Vidal, PRA 82, 050301 (2010)



States of quantum geometry in loop quantum gravity...



Global and gauge symmetries are handled naturally

Outline

1) Review of TNs

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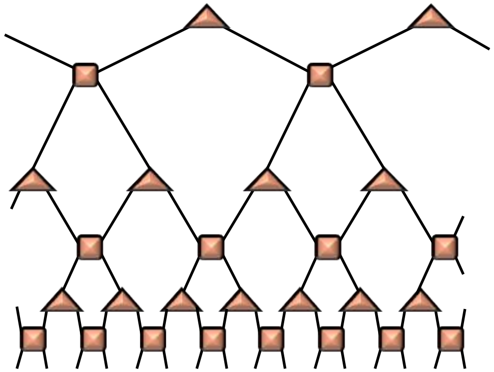
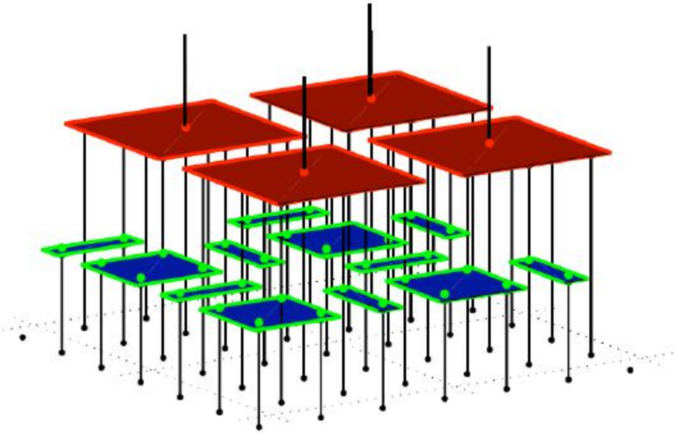
Multiscale Entanglement Renormalization Ansatz (MERA)

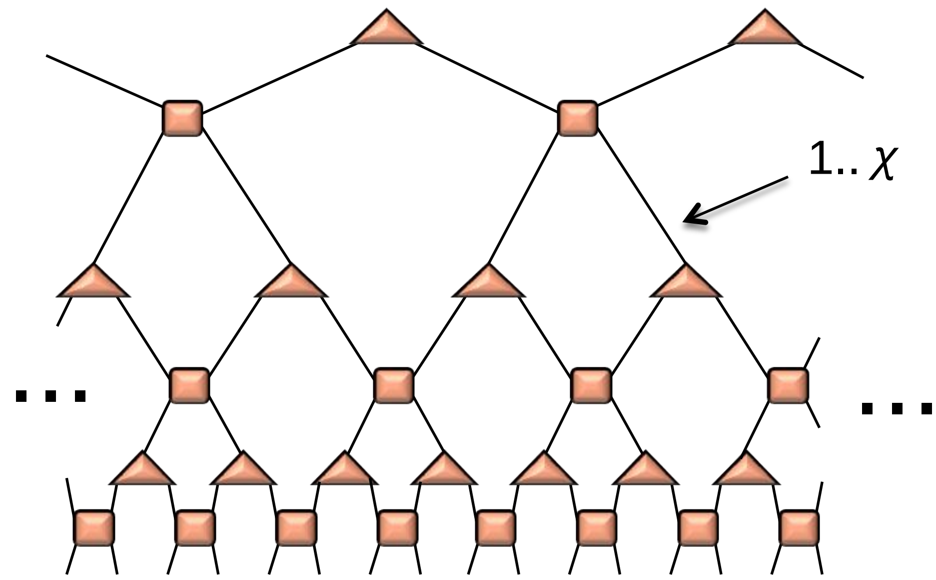


1d systems

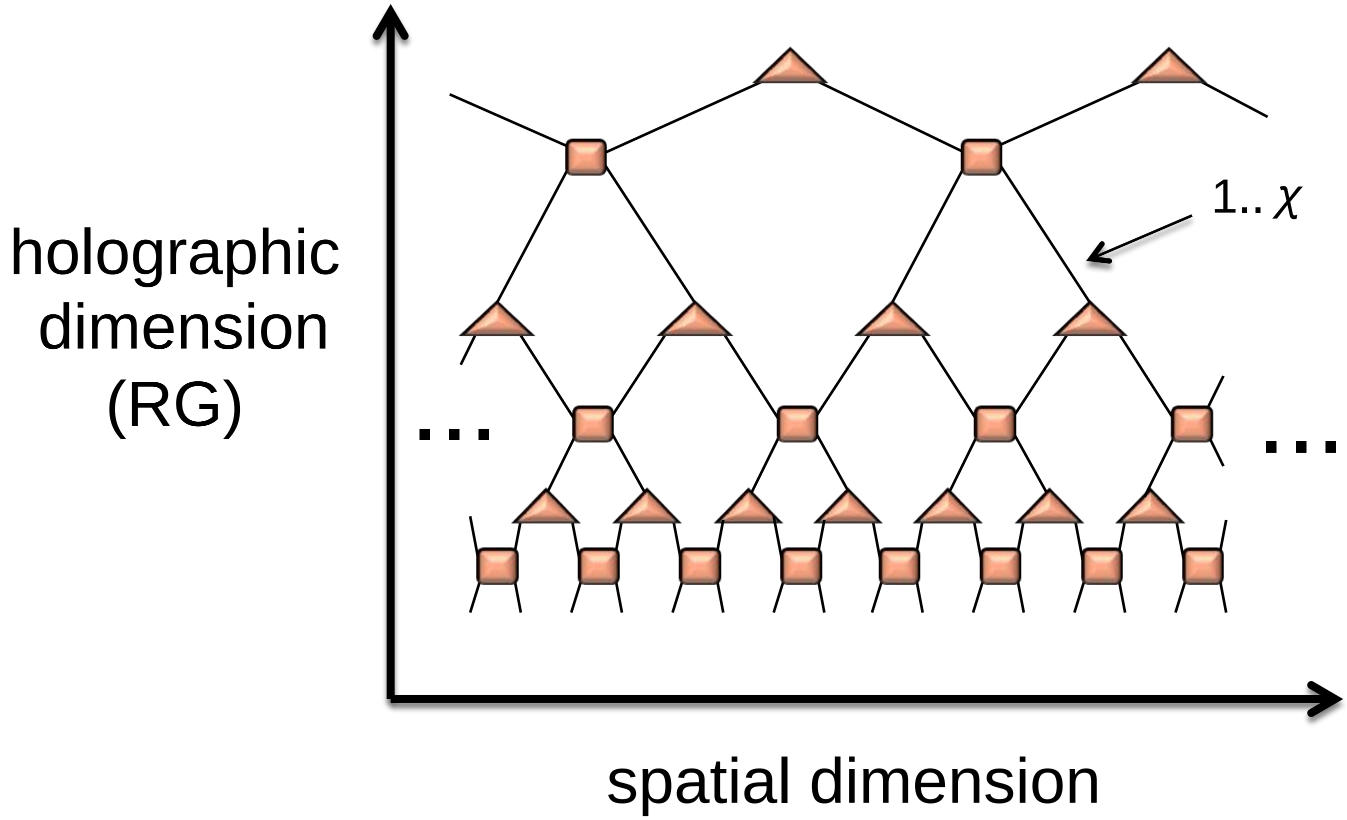


2d systems

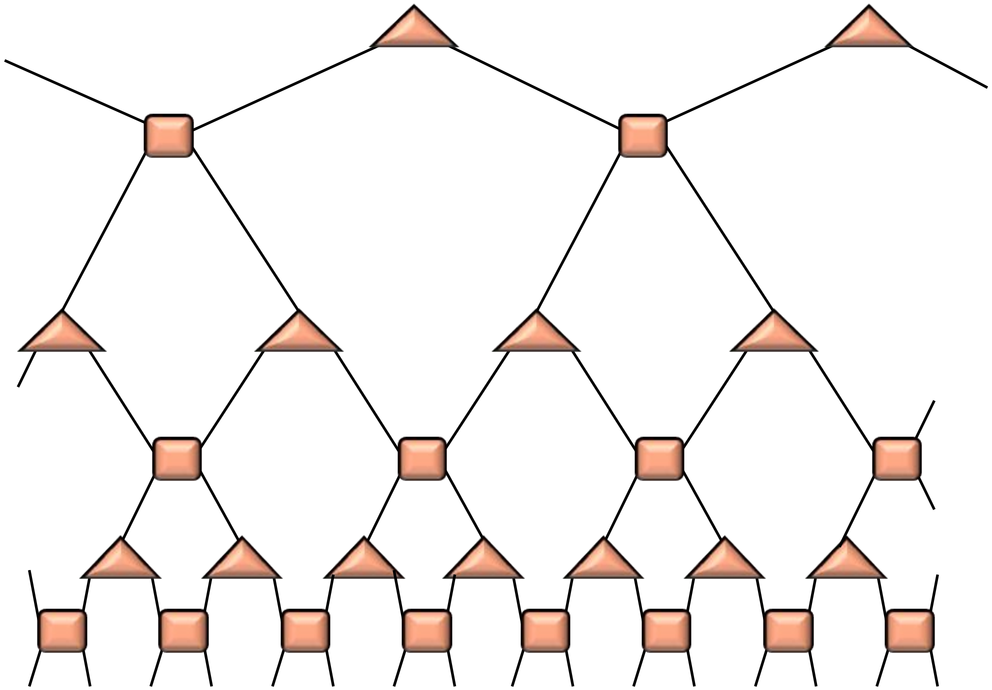
1d MERA

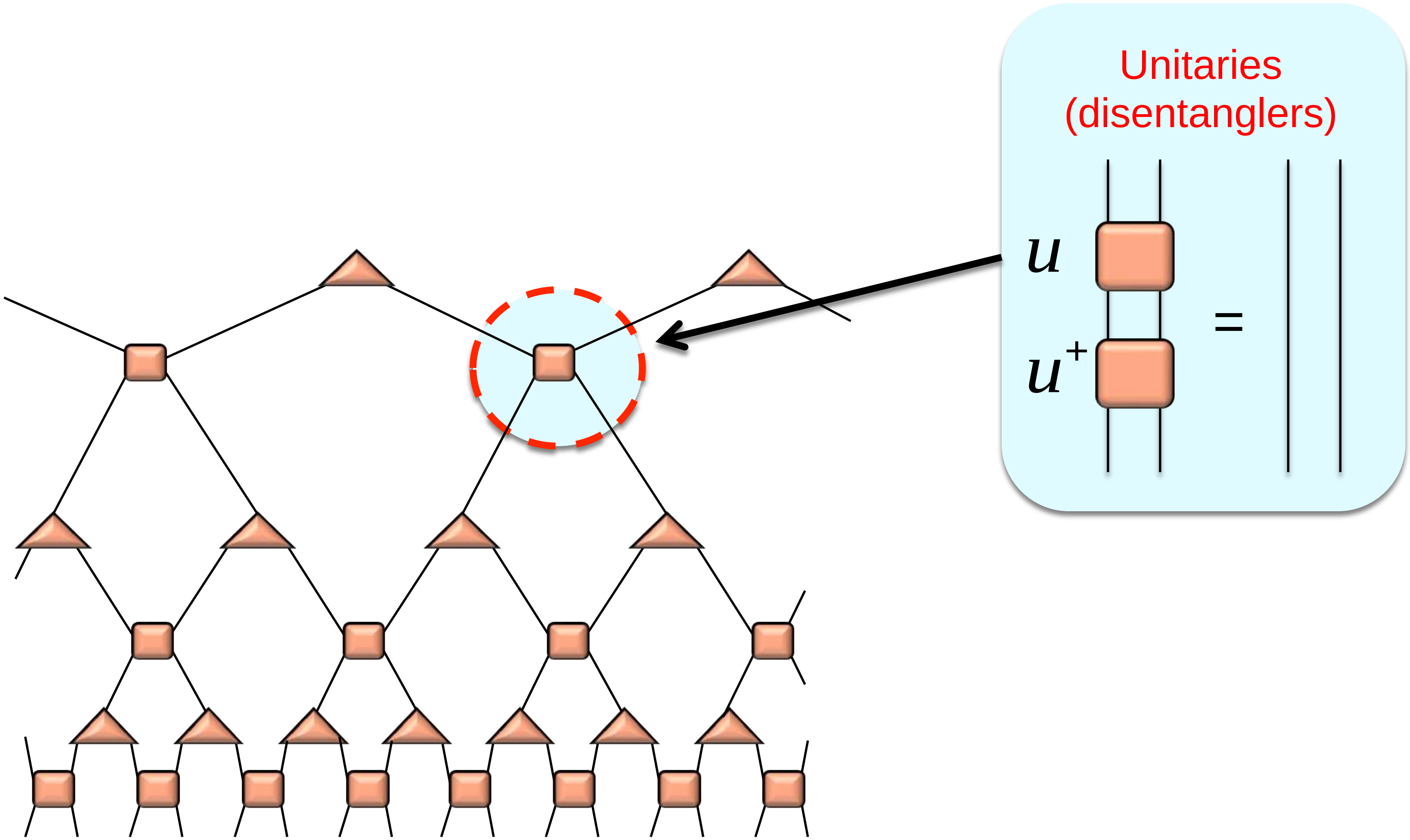


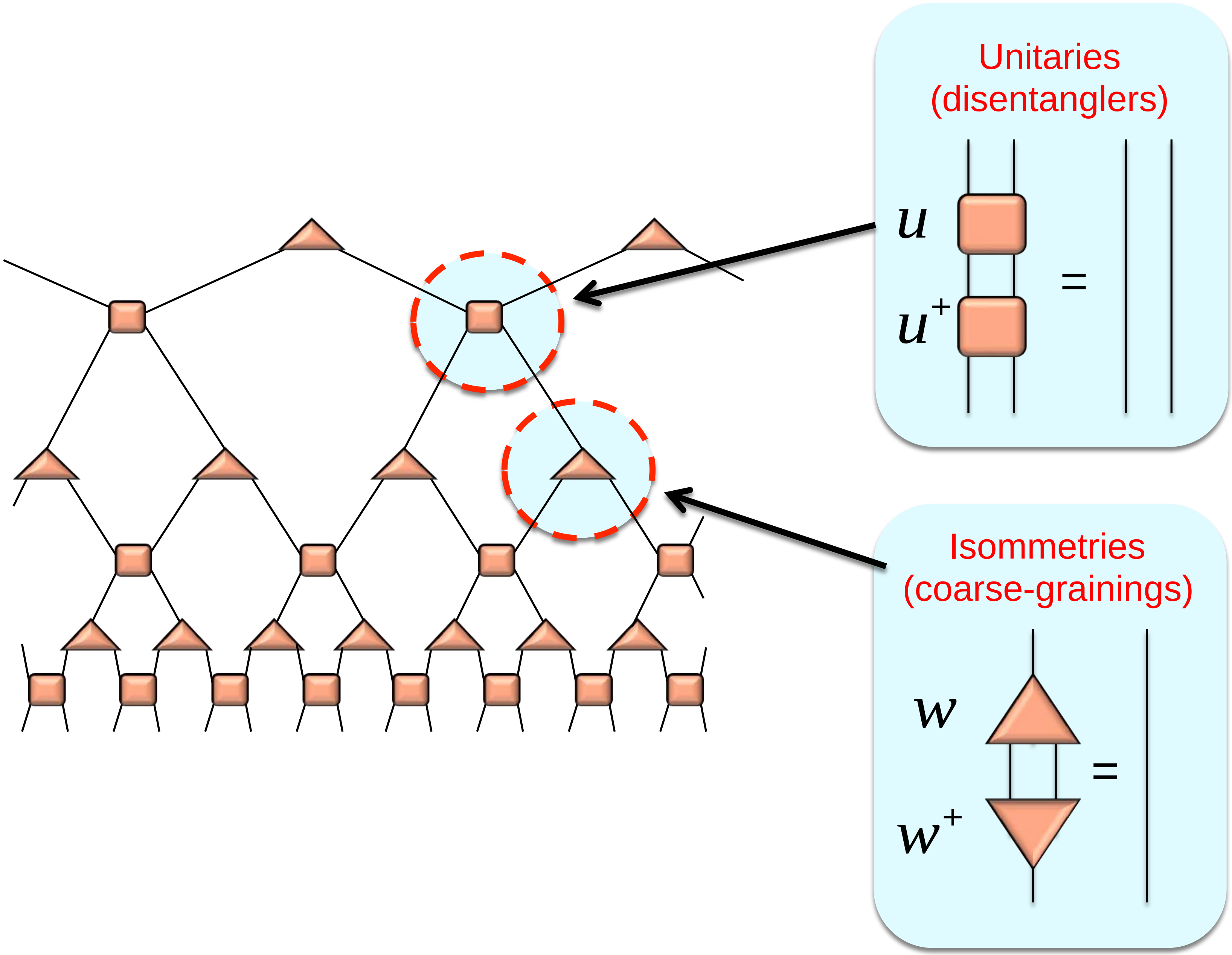
1d MERA



Tensors obey constraints

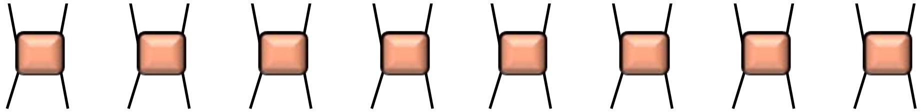



Unitaries
(disentanglers)
u
u^+
=


Unitaries
(disentanglers)
u
u+
=
Isommetries
(coarse-grainings)
w
w+
=

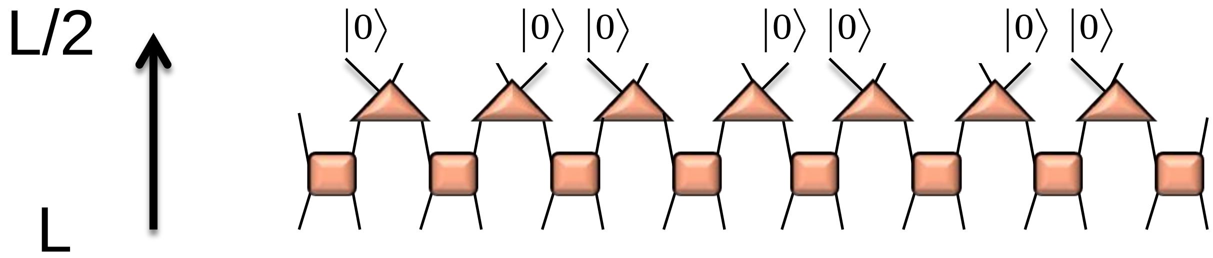
Reason:

entanglement is built locally
at all length scales



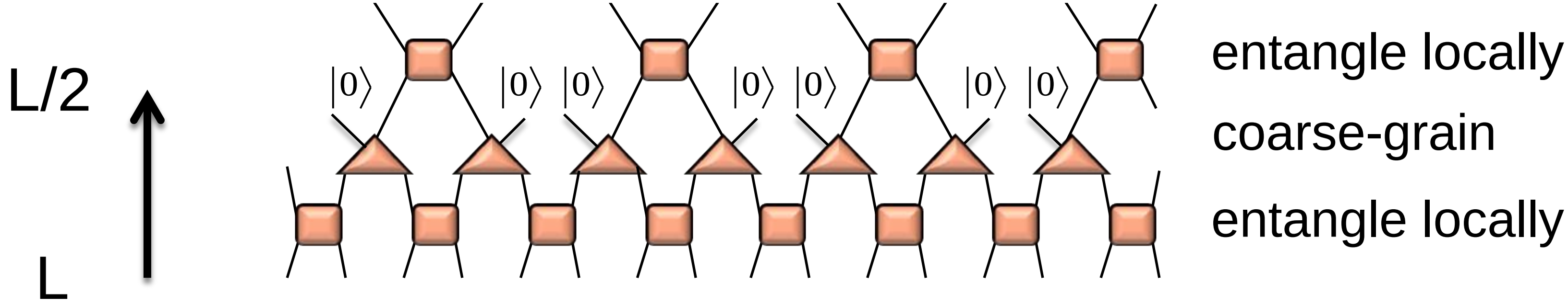
entangle locally

L

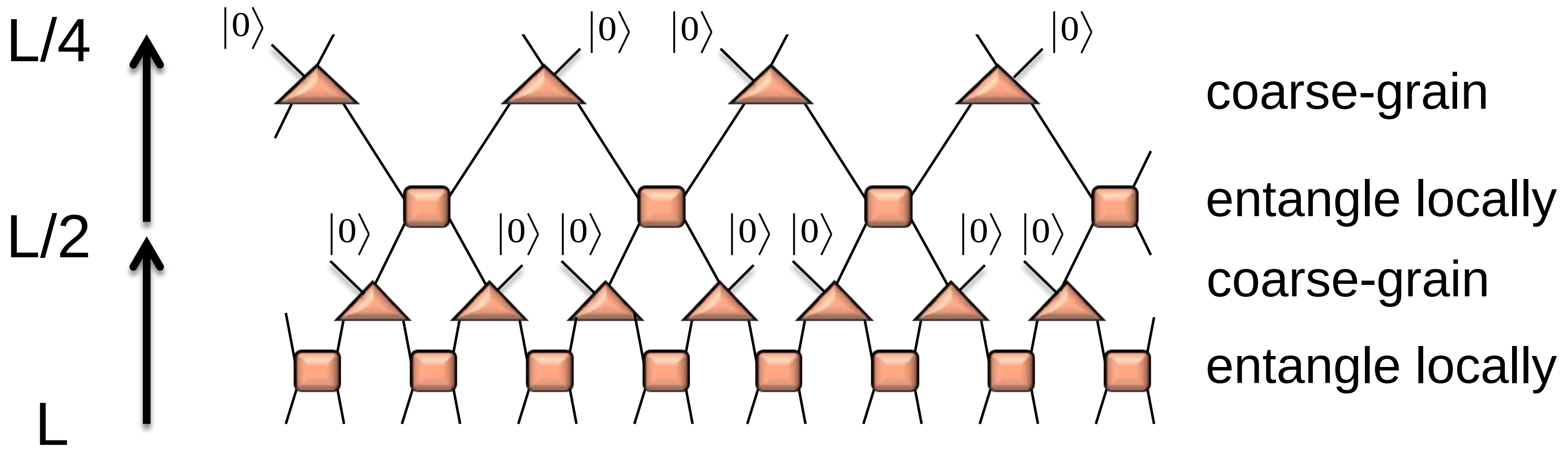


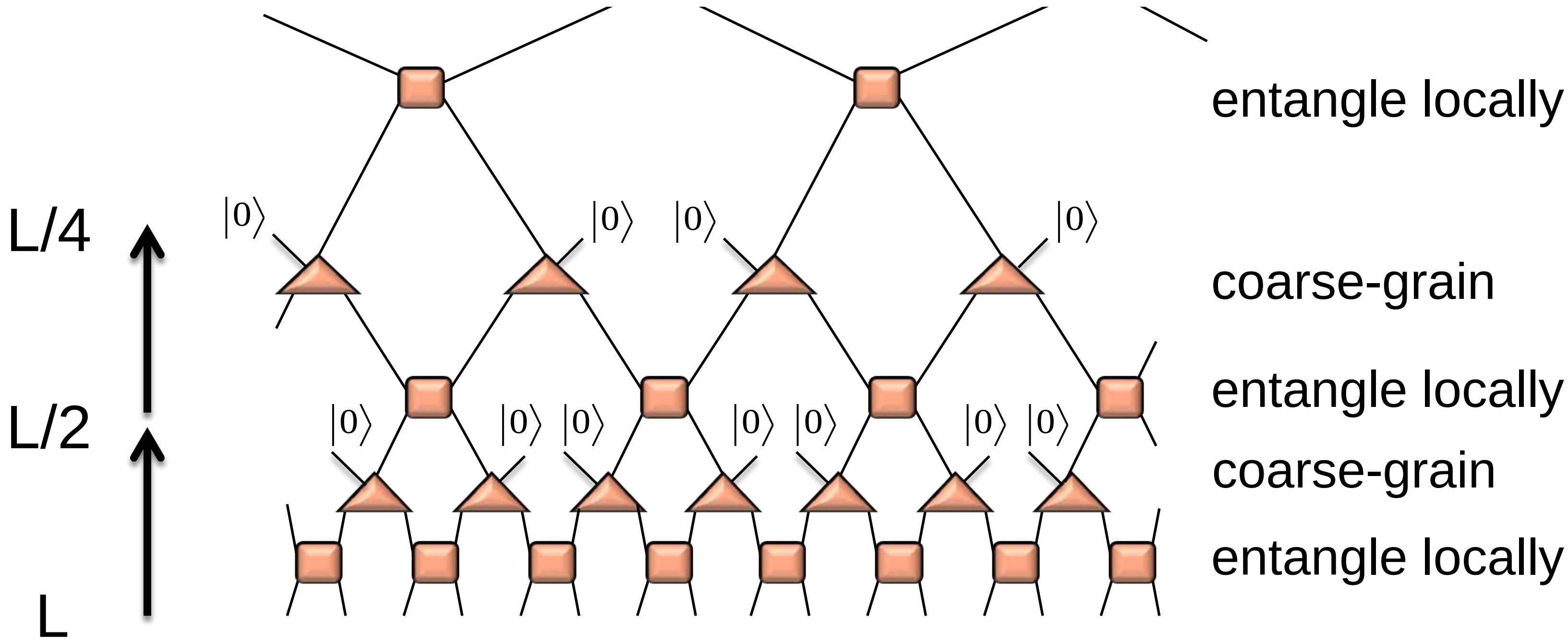
coarse-grain

entangle locally

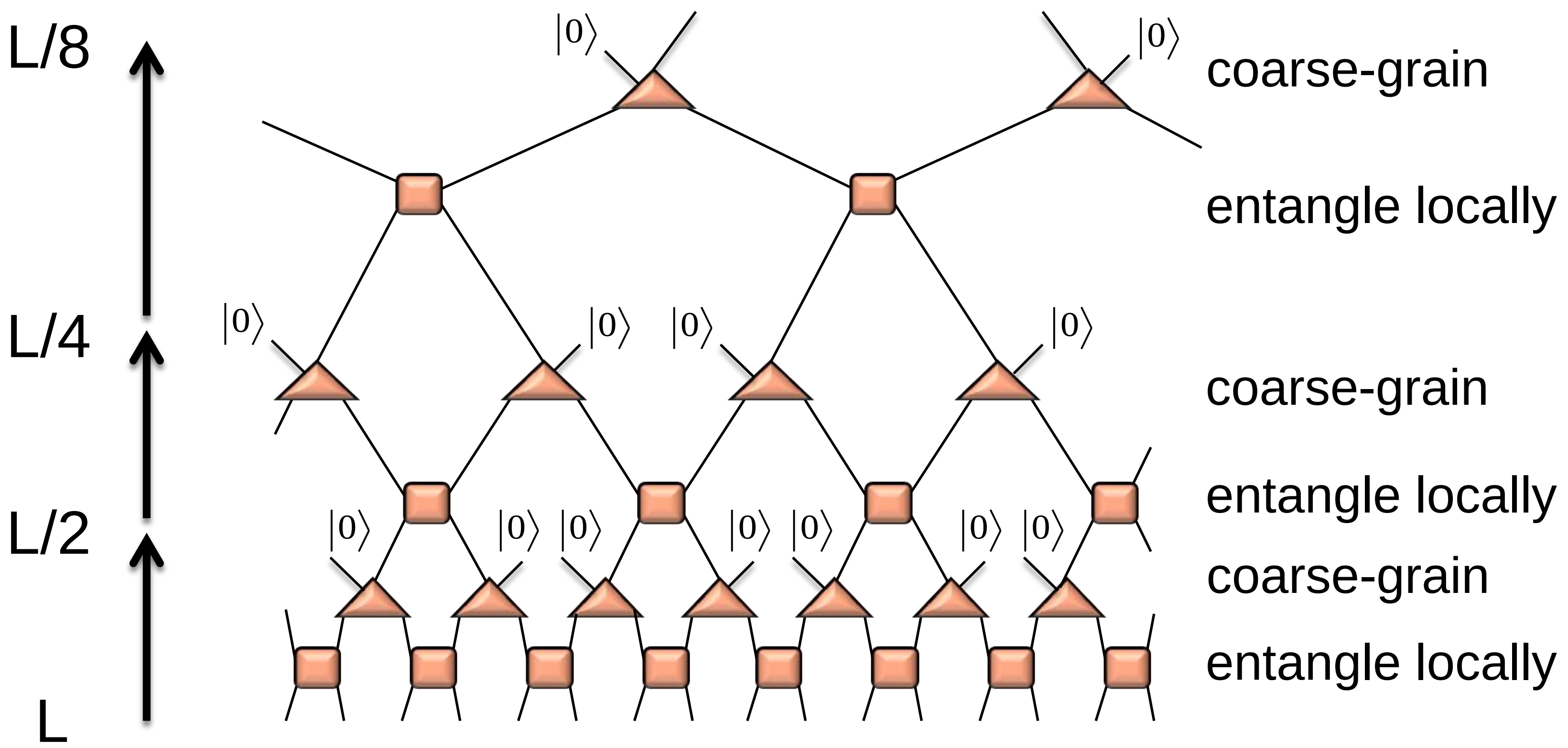


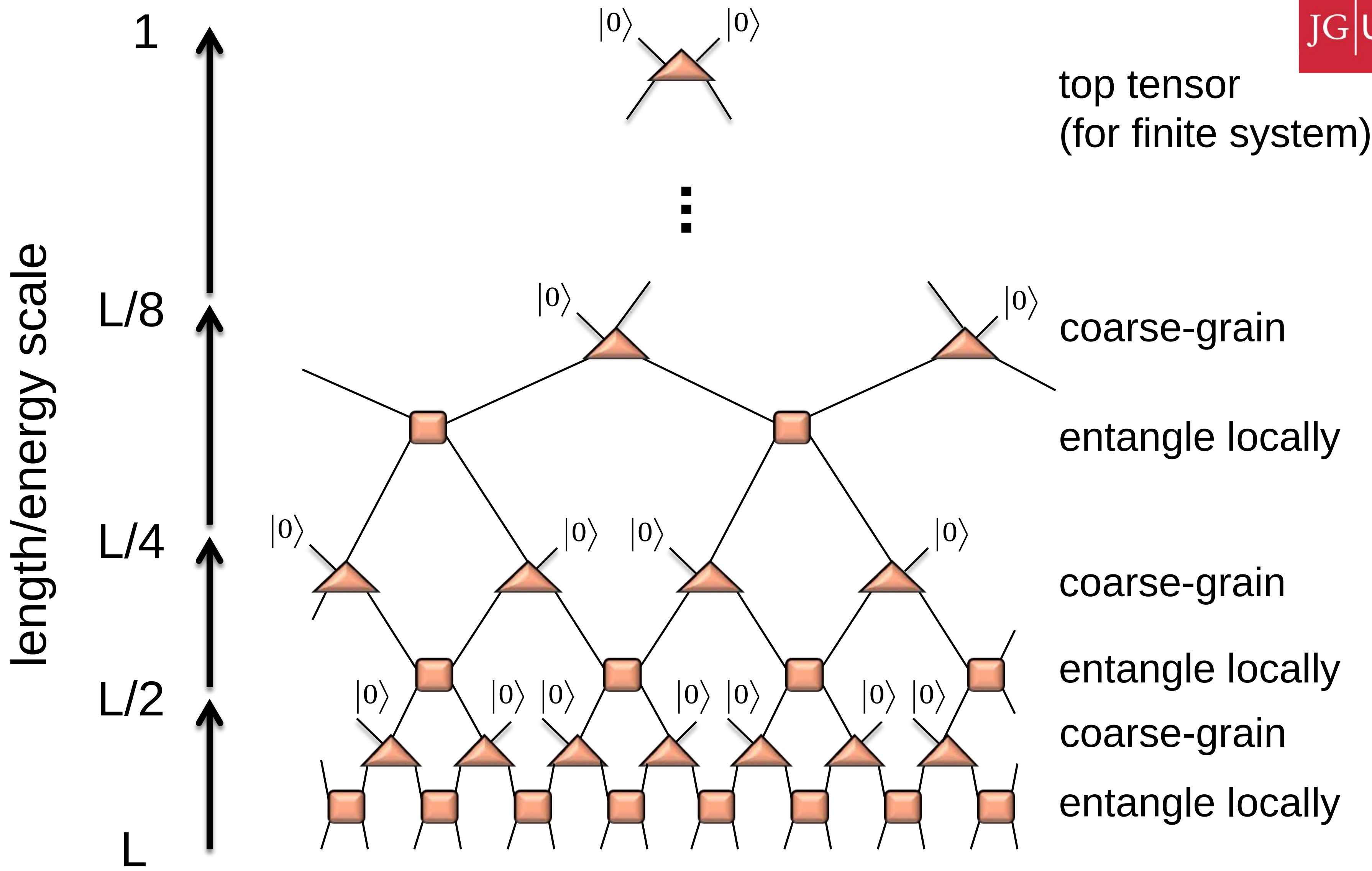
L/2
L
|0⟩
entangle locally
coarse-grain
entangle locally


L/4
L/2
L
|0⟩
coarse-grain
entangle locally
coarse-grain
entangle locally

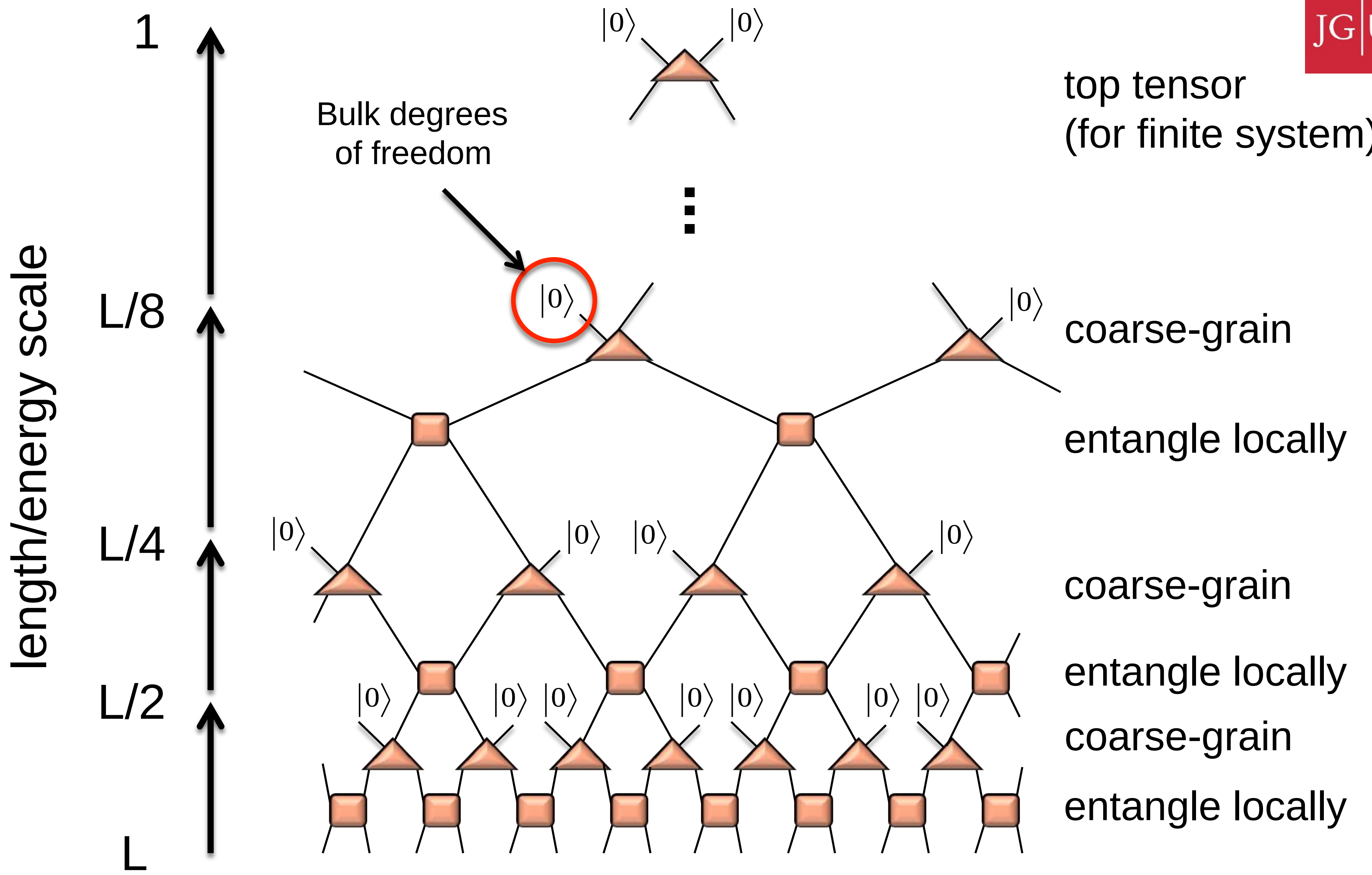


L/4
L/2
L
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
|0⟩
entangle locally
coarse-grain
entangle locally
coarse-grain
entangle locally


L/8
L/4
L/2
L
|0⟩
coarse-grain
entangle locally
coarse-grain
entangle locally
coarse-grain
entangle locally

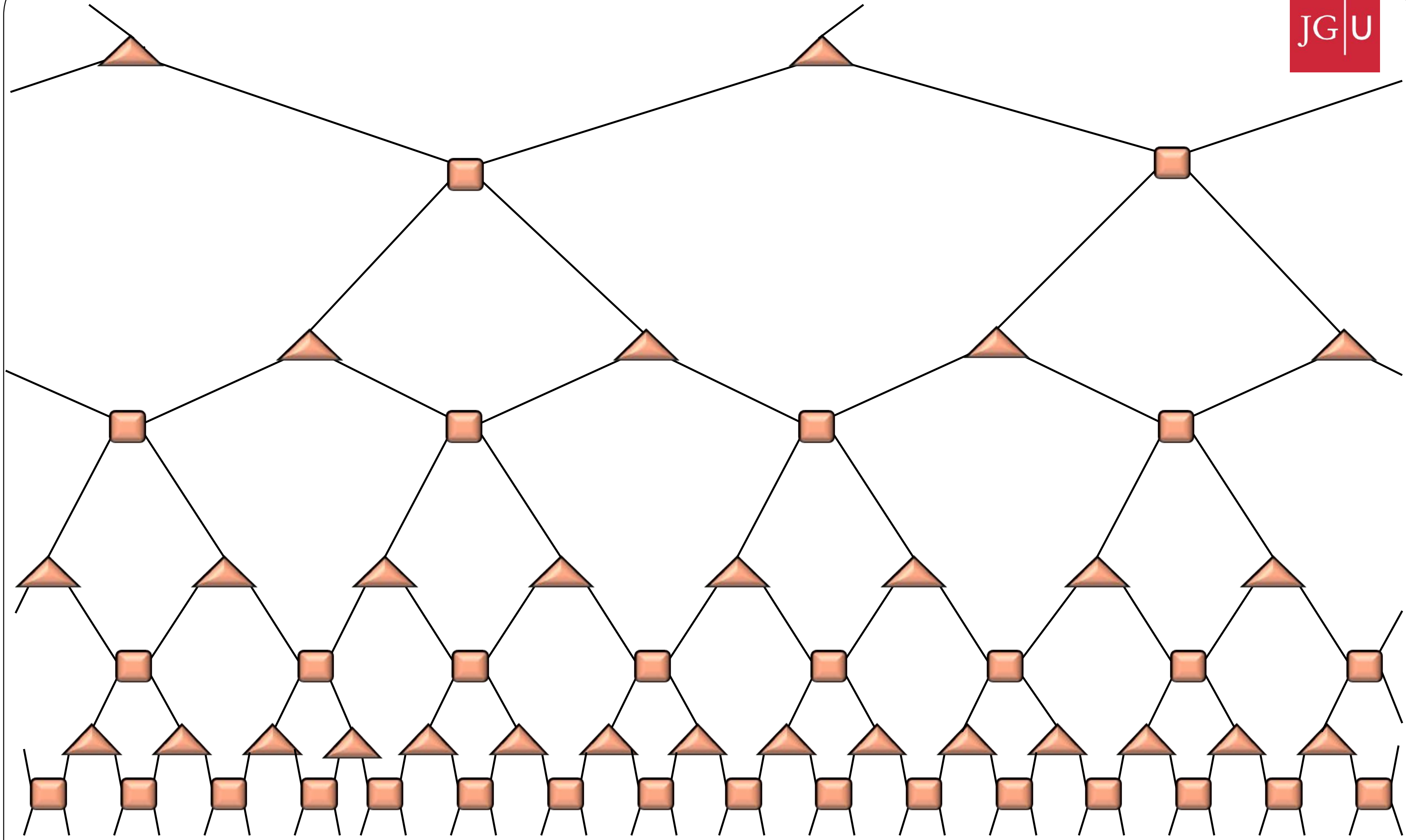


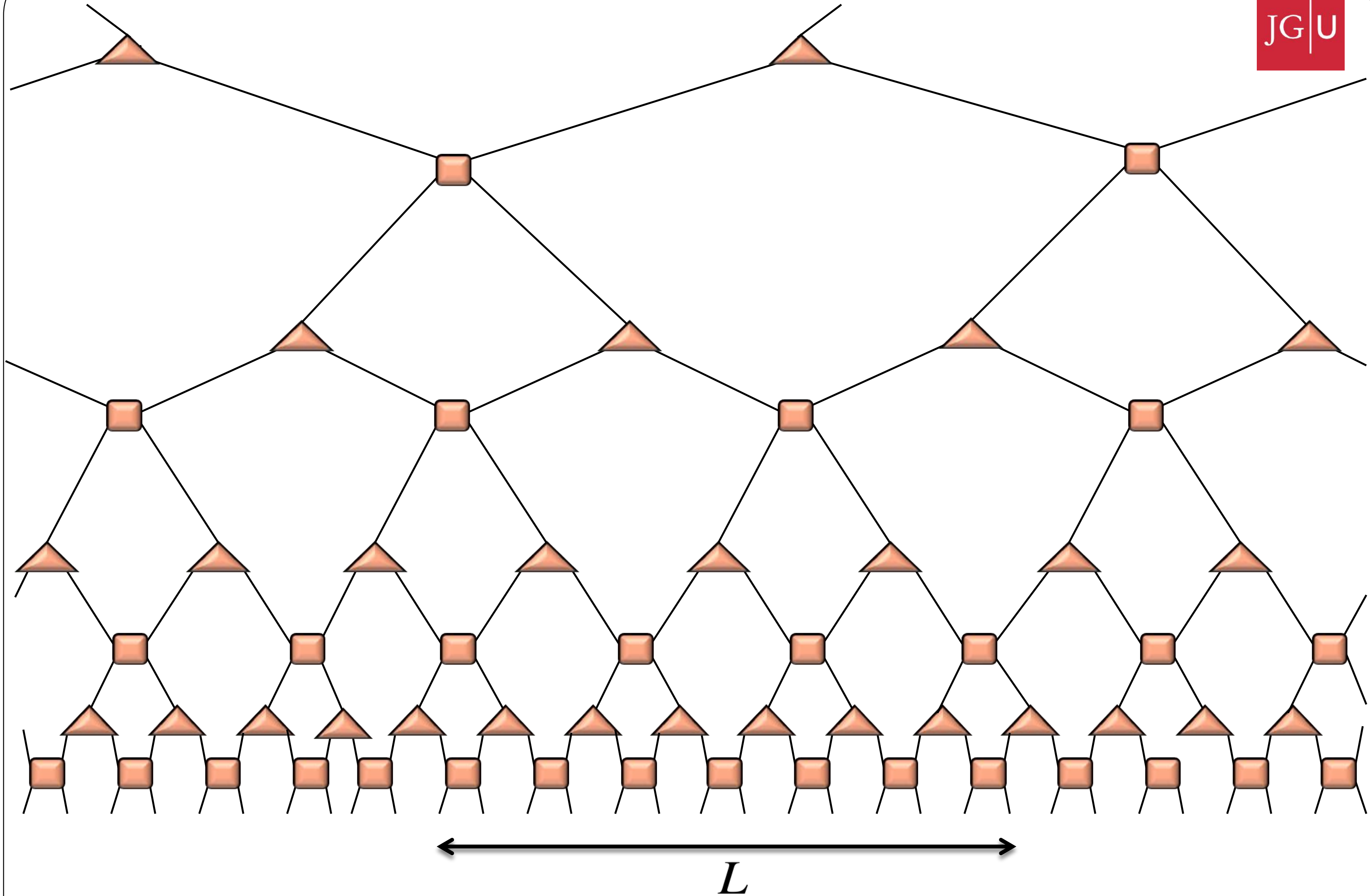
Extra dimension defines an RG flow: Entanglement Renormalization

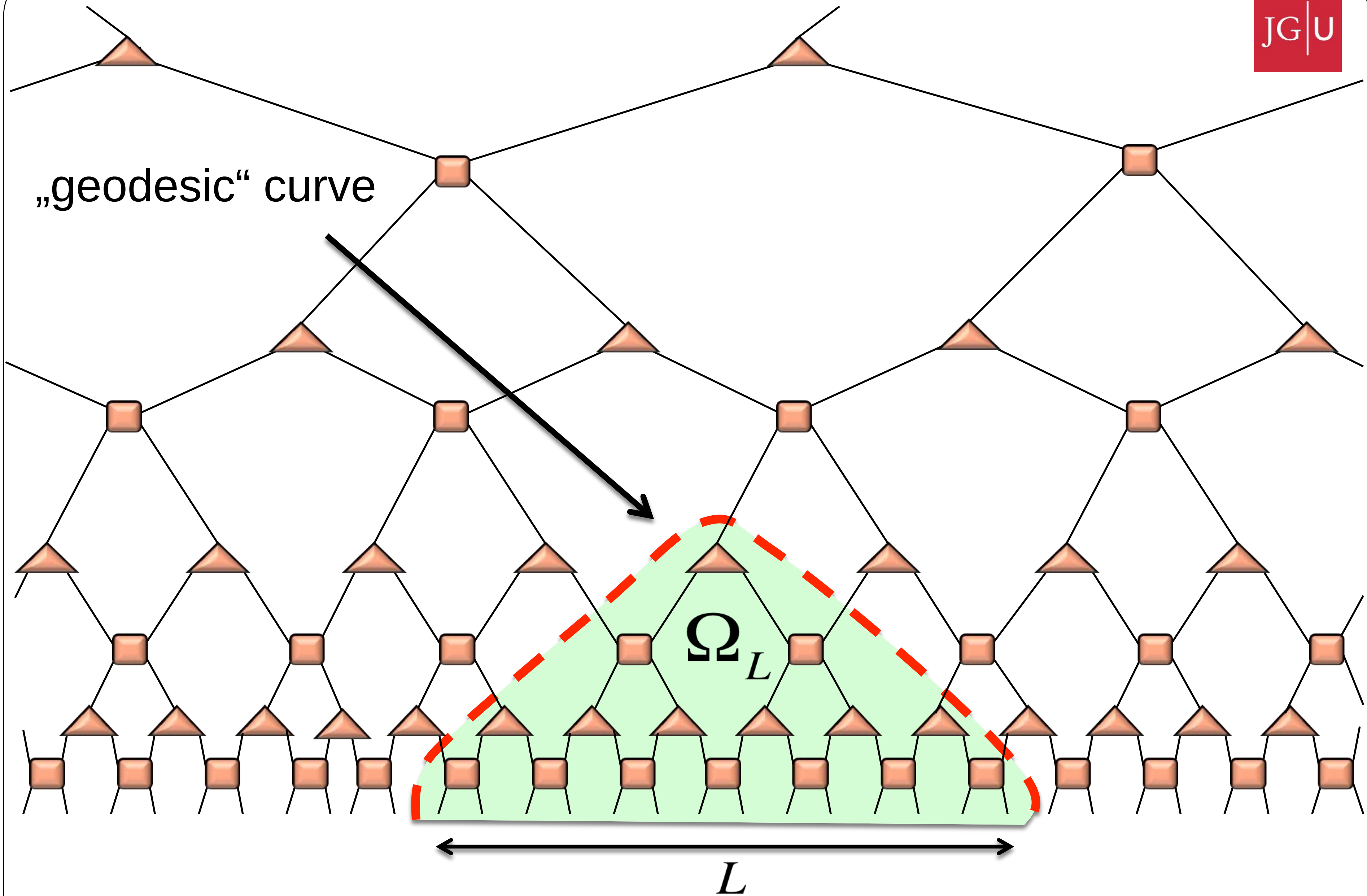


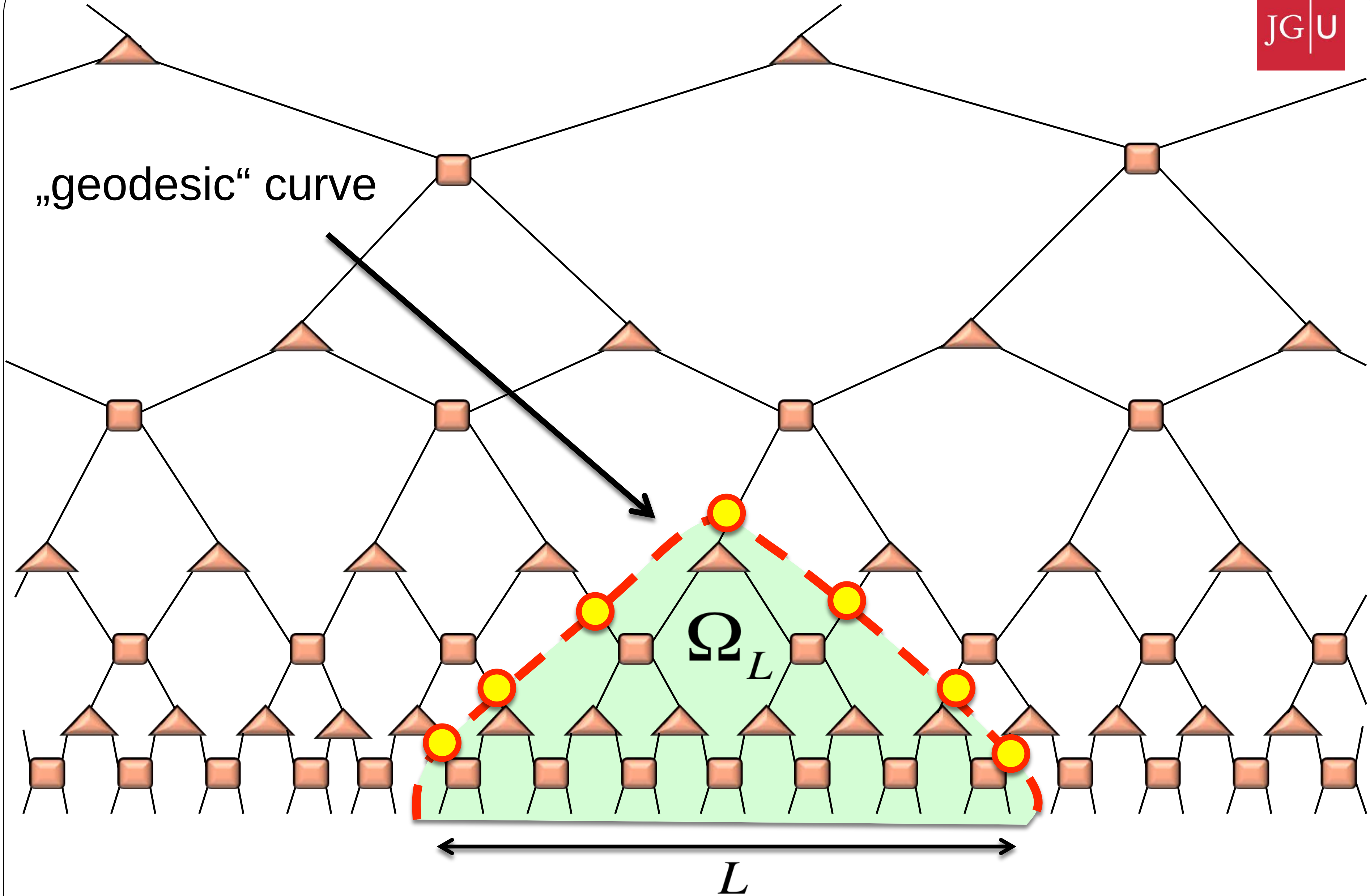
Extra dimension defines an RG flow: Entanglement Renormalization

Entropy of 1d MERA

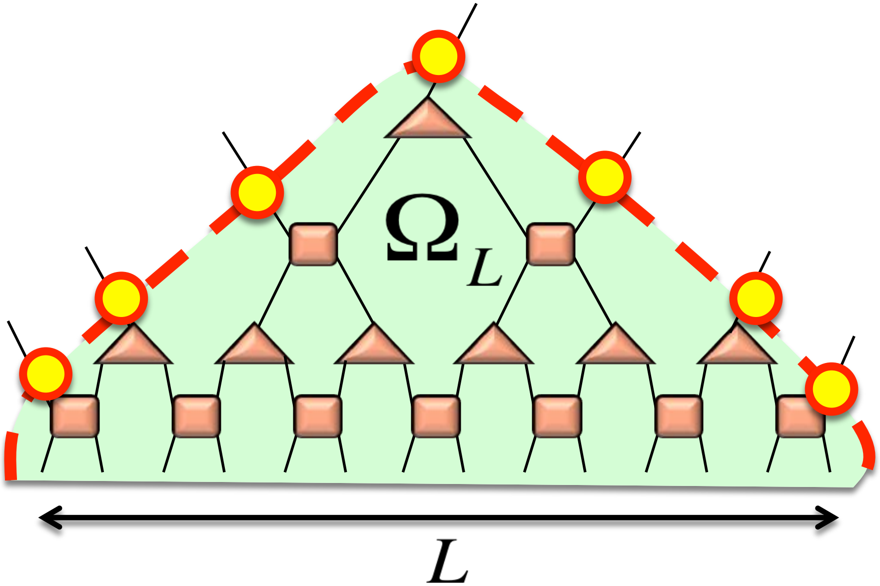



L

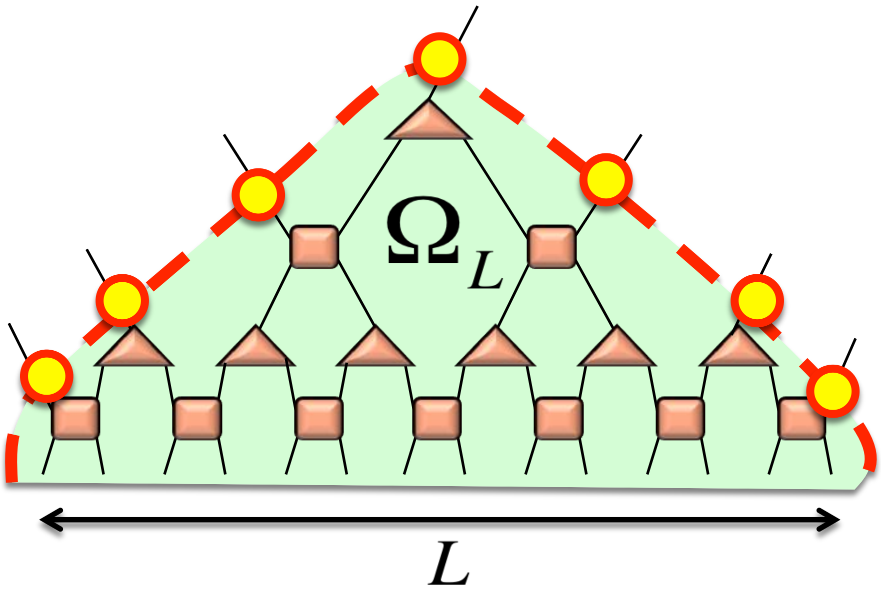

„geodesic“ curve
Ω_L
L



Entanglement as boundary in holographic geometry: $S(L) \leq \log(\chi)\left|\partial\Omega_L\right|$



Entanglement as boundary in holographic geometry: $S(L) \le \log(\chi)\left|\partial\Omega_L\right|$



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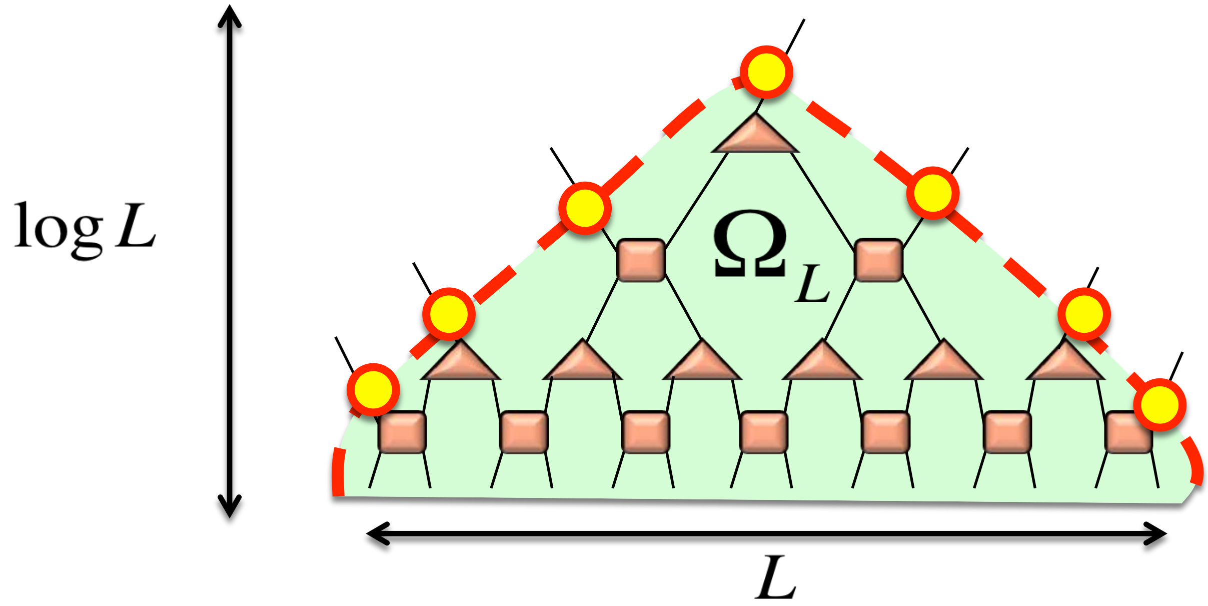
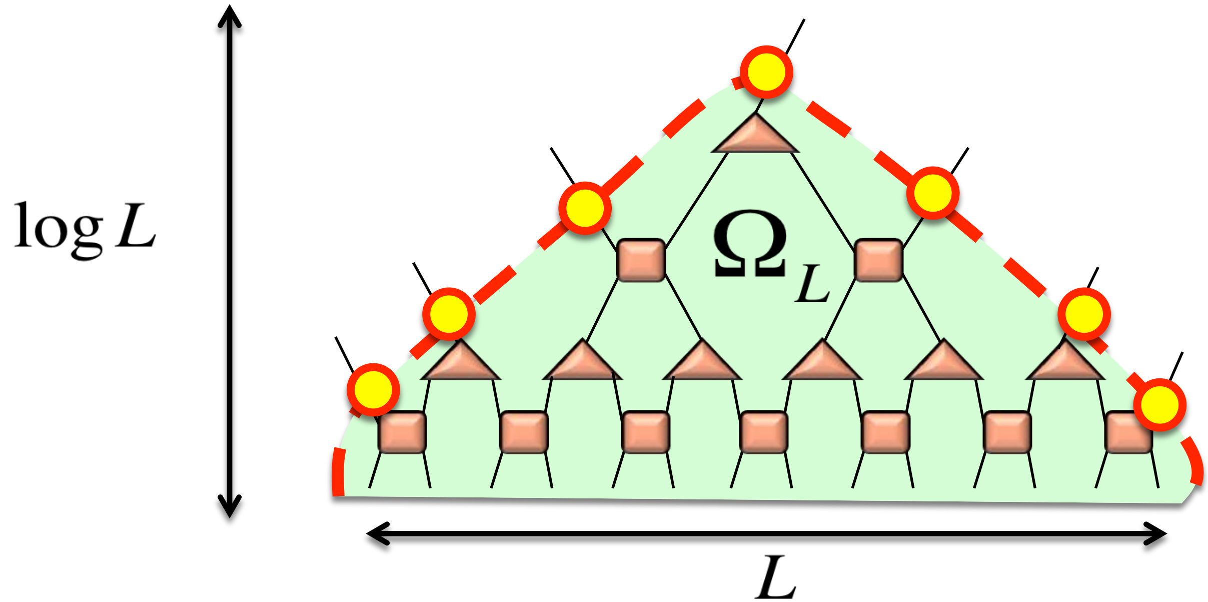


Entanglement as boundary in holographic geometry: $S(L) \leq \log(\chi)\left|\partial\Omega_L\right|$



Entanglement as boundary in holographic geometry: $S(L) \leq \log(\chi)\left|\partial\Omega_L\right|$

Constant contribution at every layer

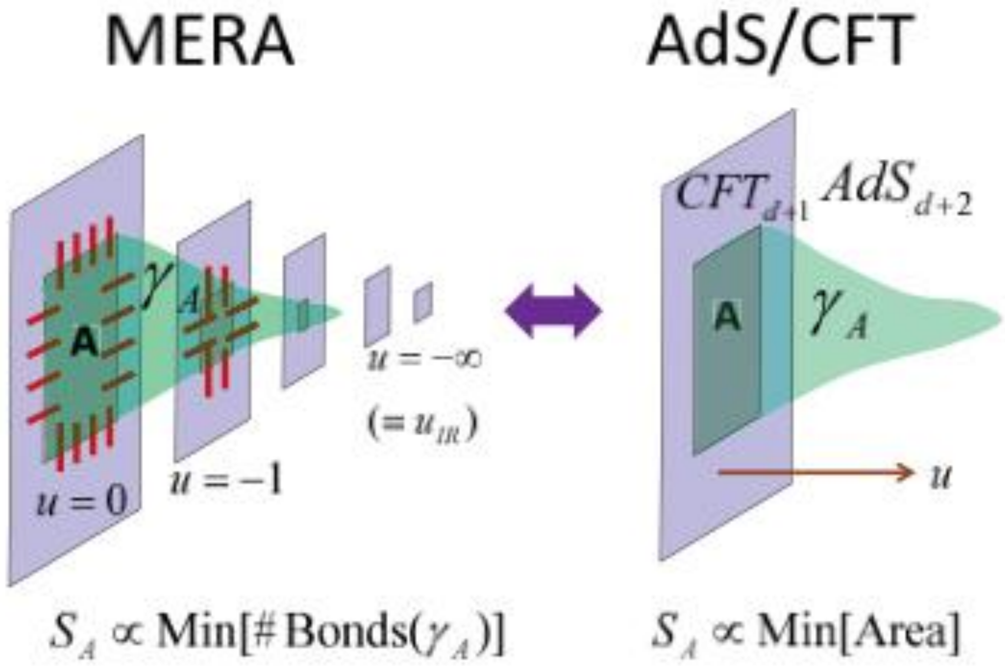
1d MERA can produce logarithmic violations to the area-law: $S(L) \approx \log L$

(like 1d critical systems!)

MERA & AdS/CFT

e.g. B. Swingle, PRD 86, 065007 (2012), G. Evenbly, G. Vidal, JSTAT 145:891-918 (2011)

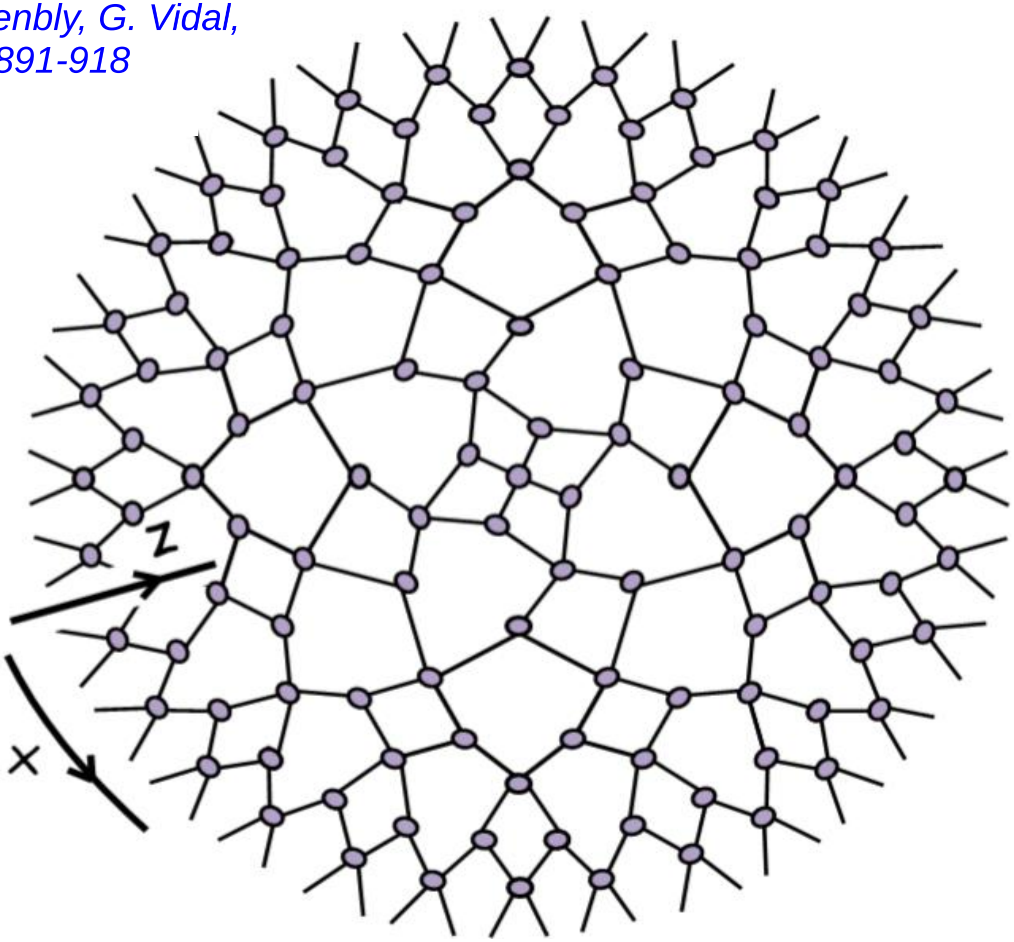
Emergent space-time



Picture from M. Nozaki, S. Ryu, T. Takayanagi, JHEP10(2012)193

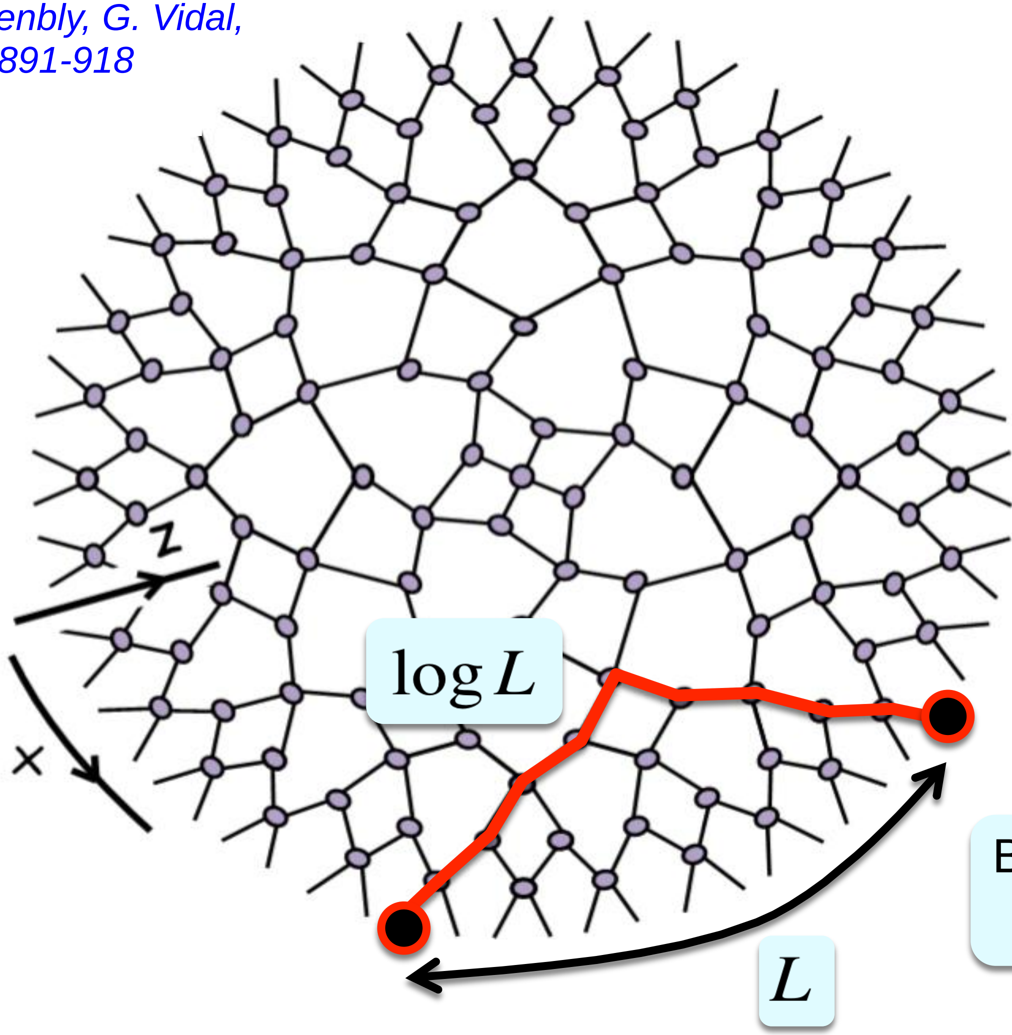
MERA entropy ~ Ryu-Takayanagi prescription

Picture from G. Evenbly, G. Vidal,
(2011) JSTAT 145:891-918



(time slice)

Picture from G. Evenbly, G. Vidal, (2011) JSTAT 145:891-918

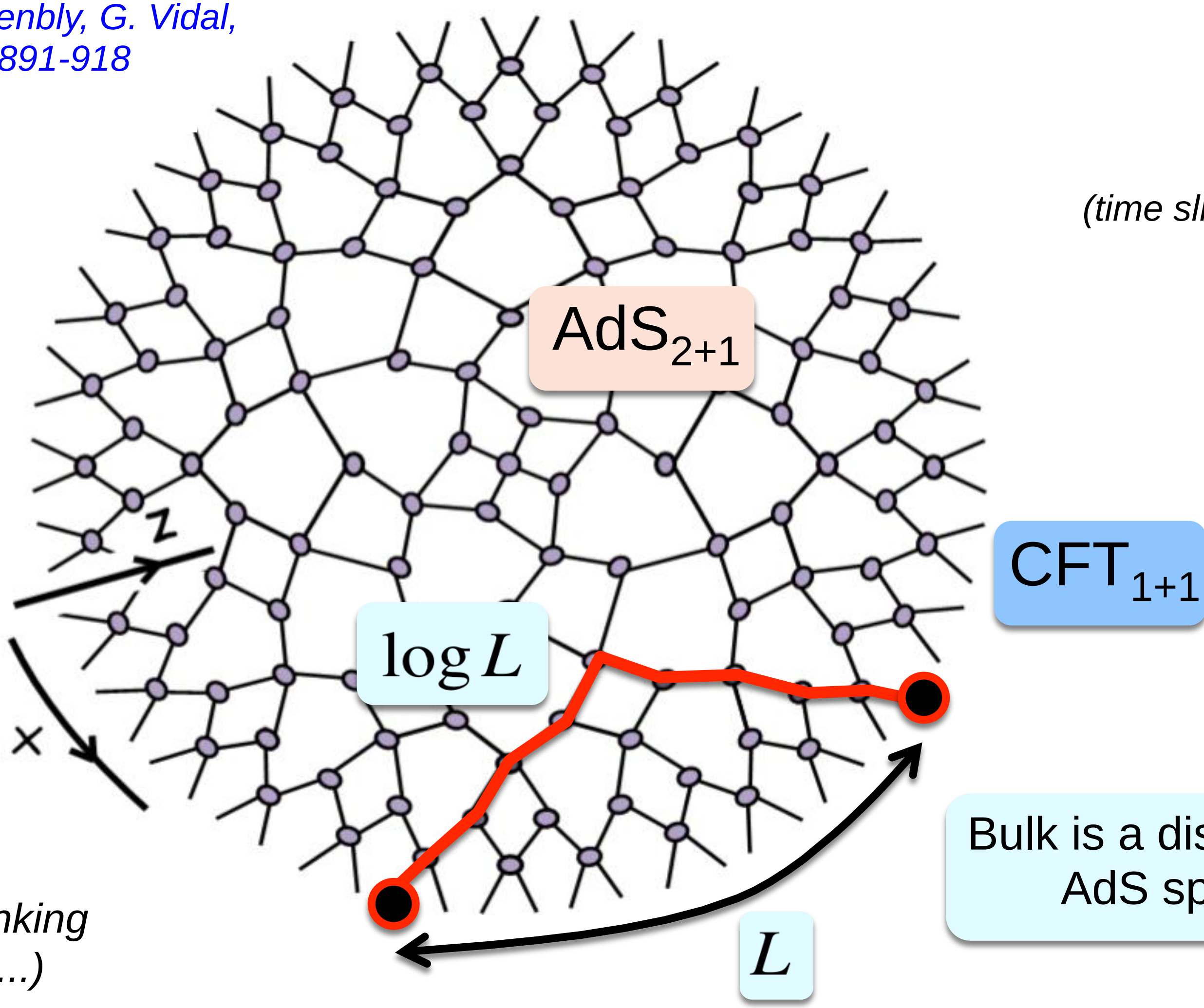


(time slice)

Bulk is a discretized AdS space

Picture from G. Evenbly, G. Vidal, (2011) JSTAT 145:891-918

(time slice)

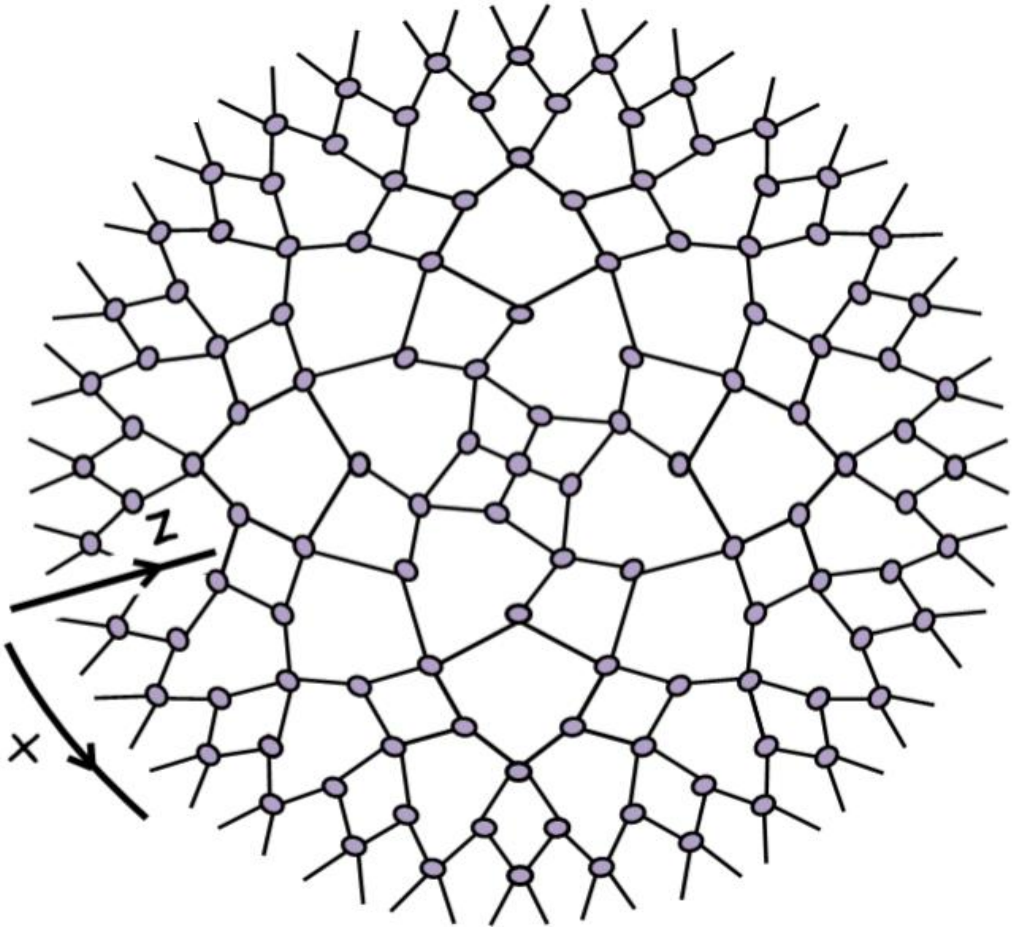


Bulk is a discretized AdS space

(and we were not thinking about gravity at all...)

For a scale-invariant MERA, the tensors of a critical model with a CFT limit correspond to a „gravitational“ description in a discretized AdS space:
„lattice“ realization of AdS/CFT correspondence

Let‘s now play
some jazz...



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Let‘s now play
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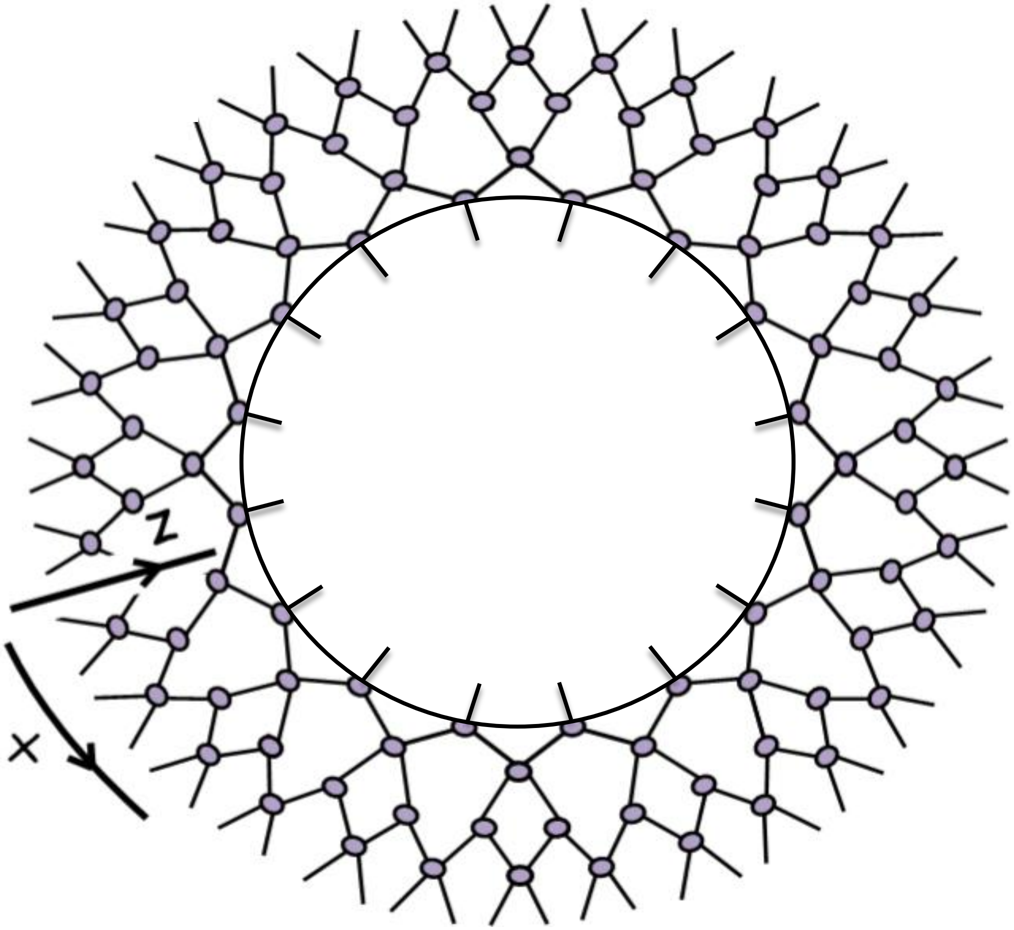
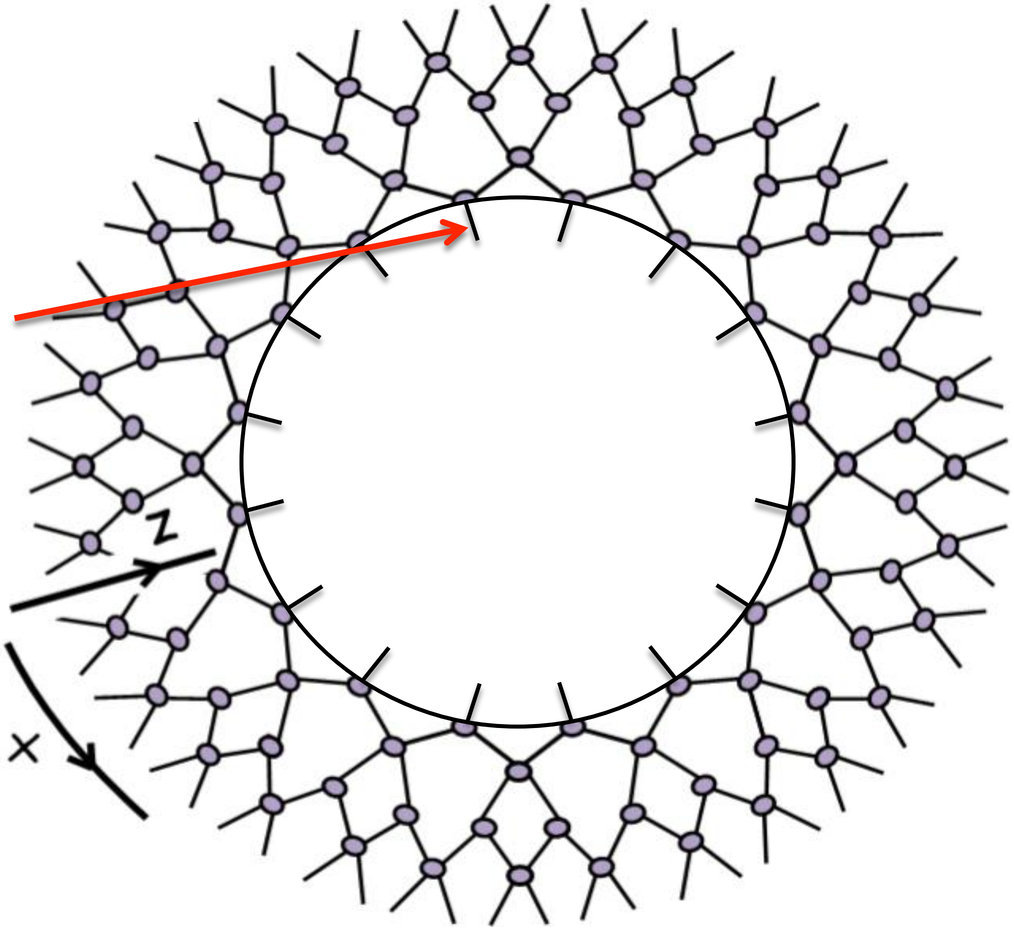


(time slice)

Finite correlation length (gapped systems) = finite number of layers

Let‘s now play
some jazz...

Product state =
trivial fixed point

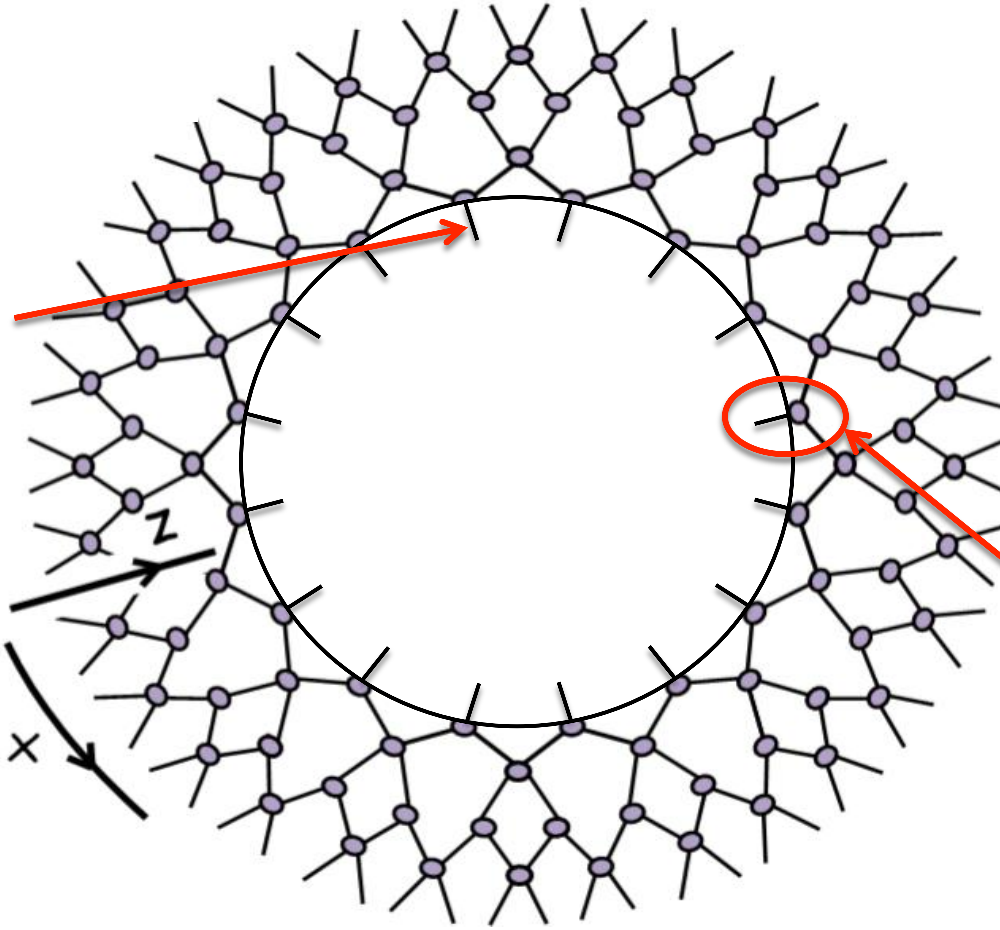


(time slice)

Finite correlation length (gapped systems) = finite number of layers

Let‘s now play some jazz...

Product state = trivial fixed point



(time slice)

If arbitrary, then we can have non-trivial thermal states.

If isommetry, then all information is encoded in the network of correlations and

$$\rho_{in} = I$$

Finite correlation length (gapped systems) = finite number of layers

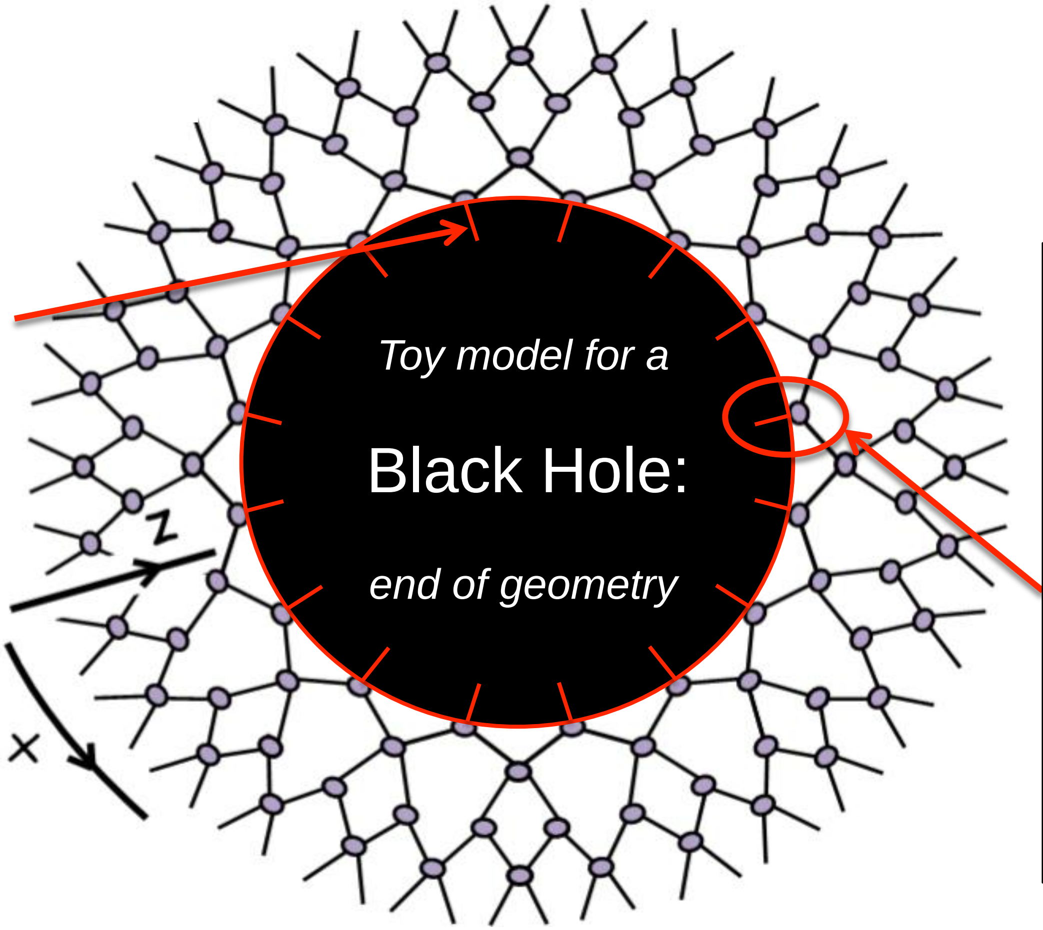
$$\rho_{in} = tr_{out}\left(|\Psi\rangle\langle\Psi|\right)$$

$$\rho_{out} = tr_{in}\left(|\Psi\rangle\langle\Psi|\right)$$

*Same **thermal** spectrum (entanglement Hamiltonian) finite temperature, scale invariance broken*

Let‘s now play some jazz...

Product state = trivial fixed point



(time slice)

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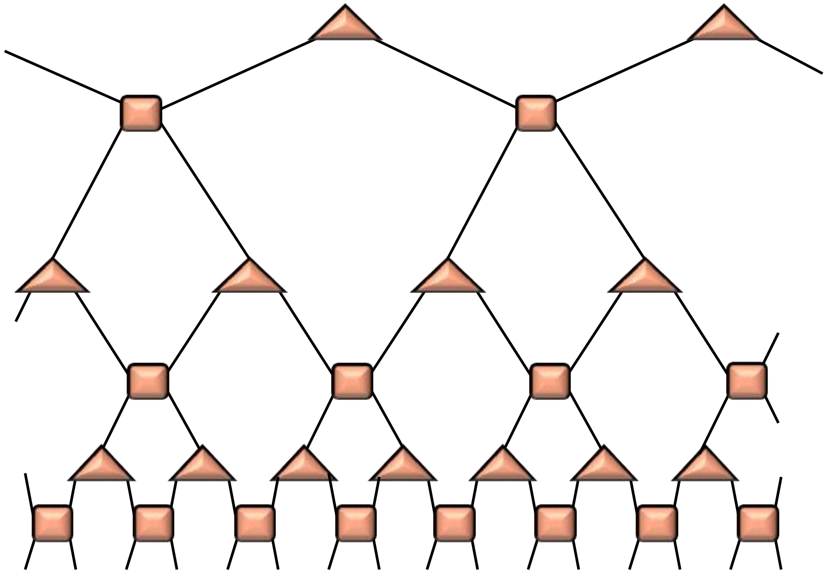
$$\rho_{in} = I$$

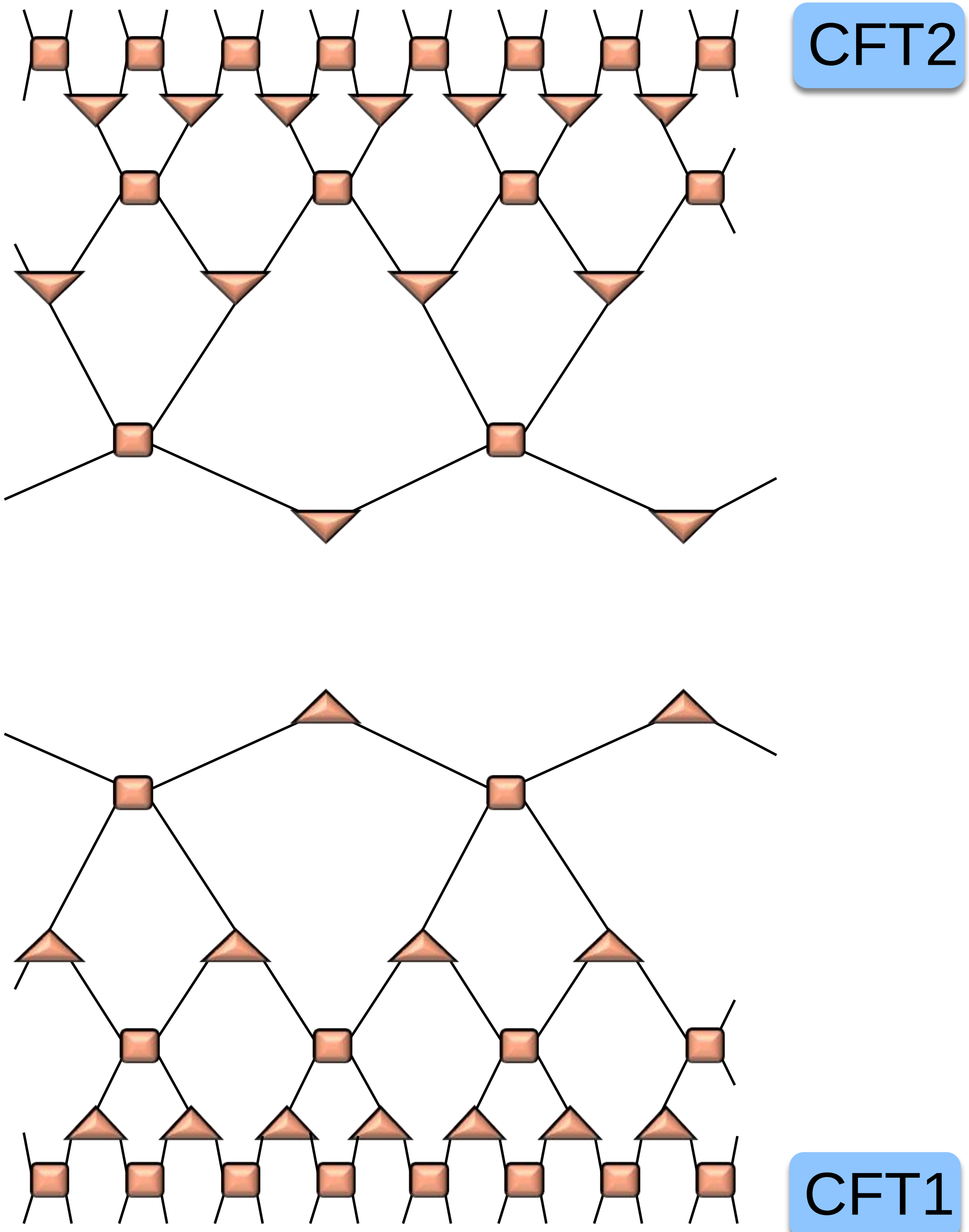
Finite correlation length (gapped systems) = finite number of layers

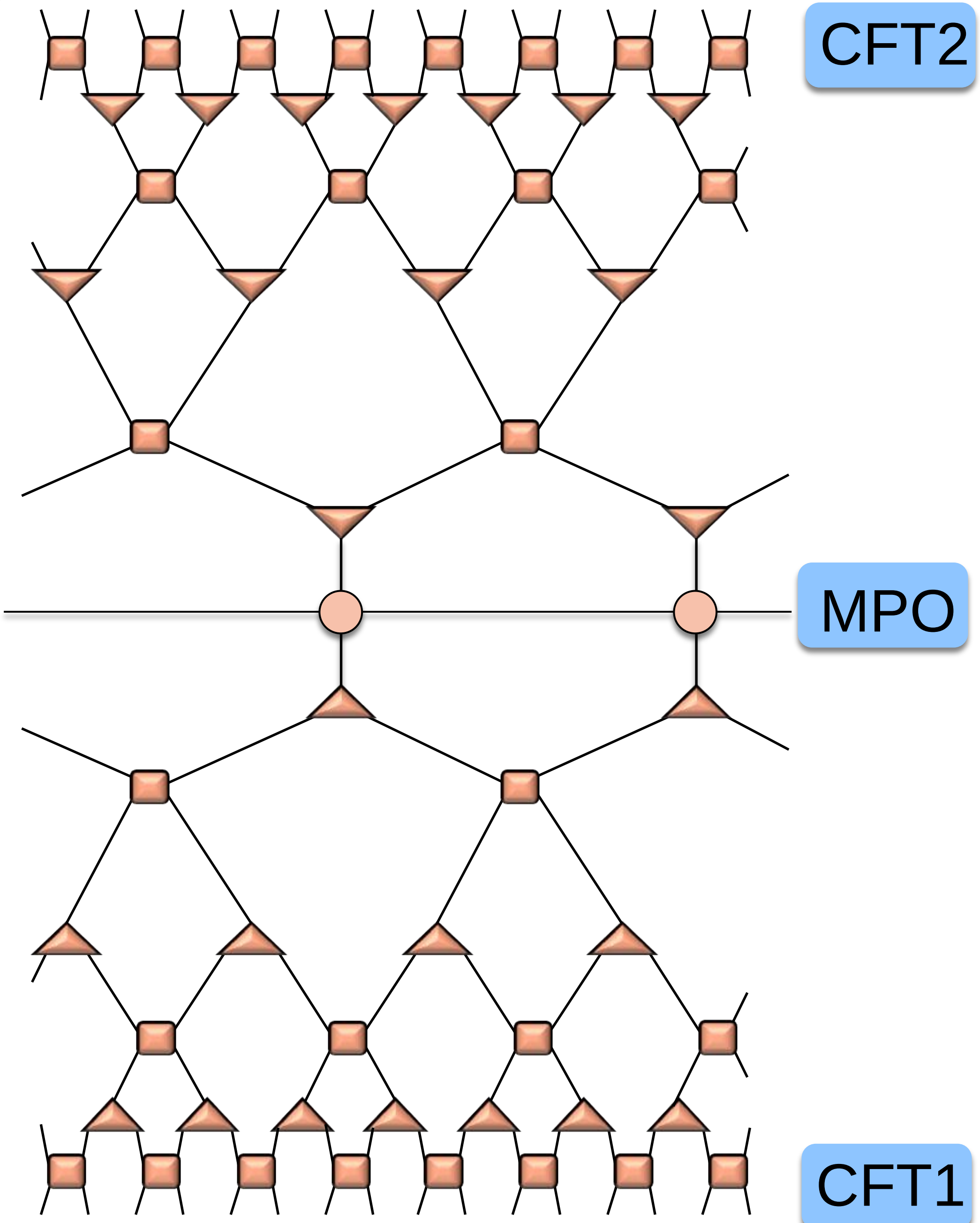
$$\left.\begin{aligned}\rho_{in} &= tr_{out}\left(|\Psi\rangle\langle\Psi|\right)\\ \rho_{out} &= tr_{in}\left(|\Psi\rangle\langle\Psi|\right)\end{aligned}\right\}$$

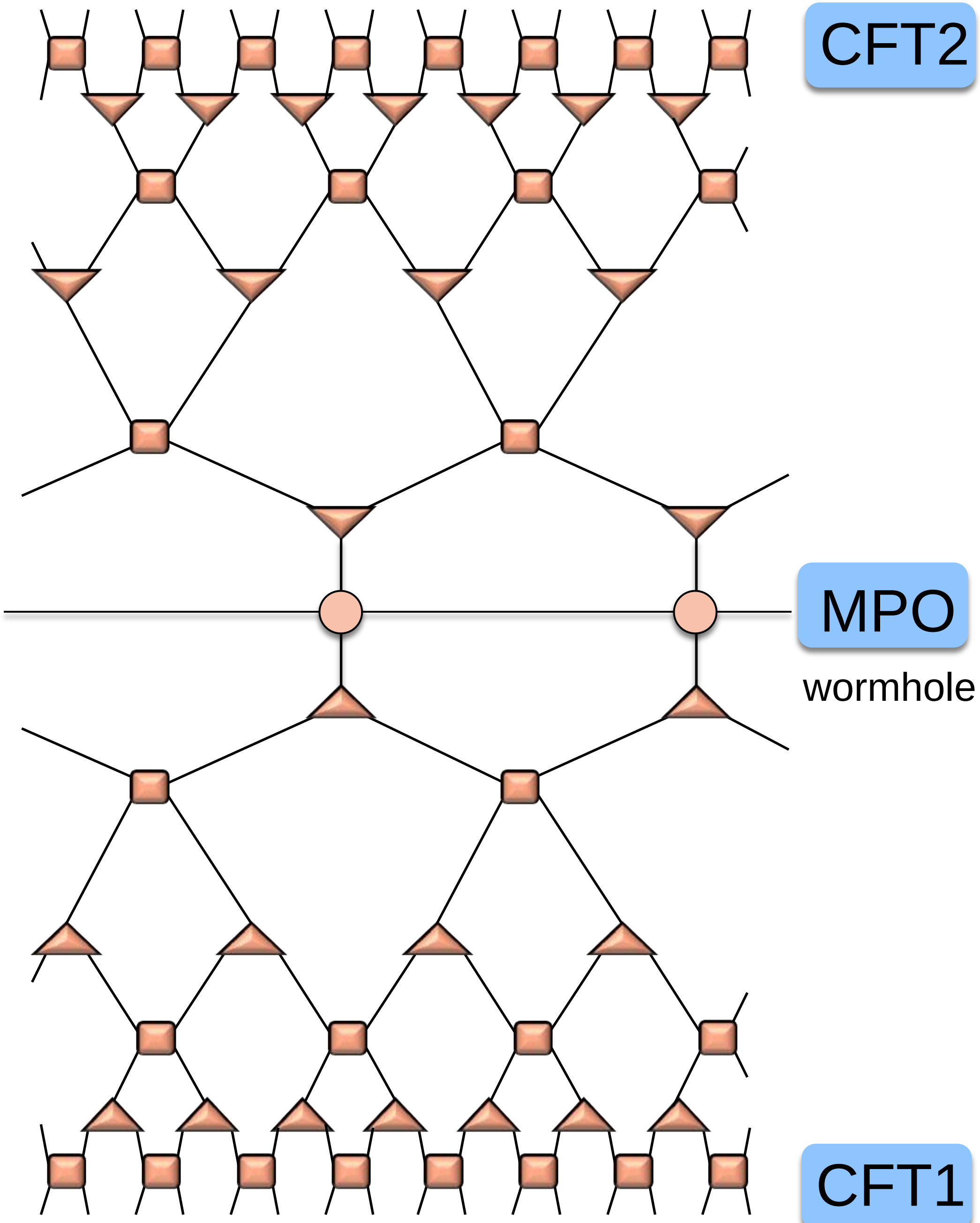
Same ***thermal*** *spectrum (entanglement Hamiltonian)*
finite temperature, scale invariance broken



CFT1


CFT2
CFT1


CFT2
MPO
CFT1

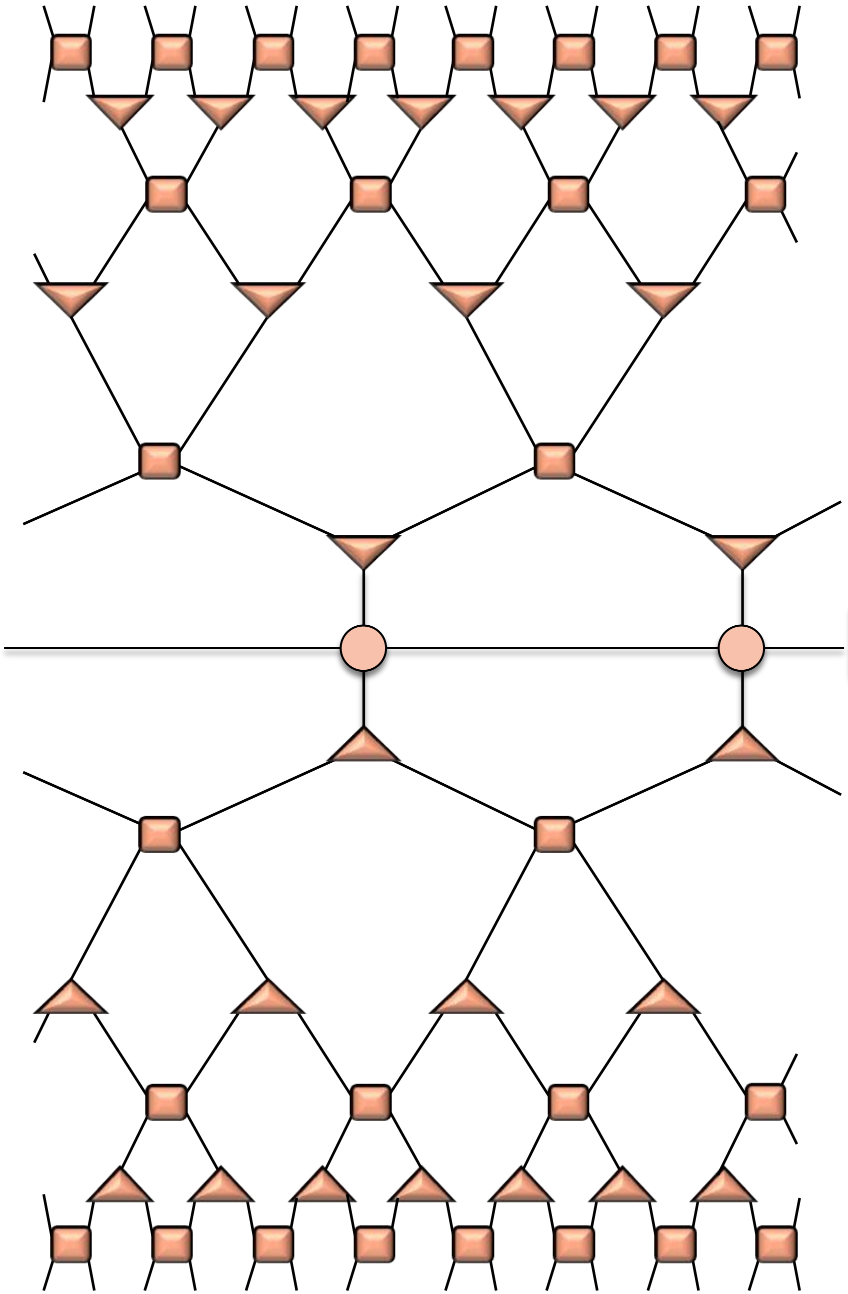


e.g., T. Hartman, J. Maldacena, JHEP05(2013)014

Thermofield double state

Eternal AdS black-hole

$$|TFD\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\beta E_n/2} |n\rangle_1 |n\rangle_2$$



CFT2

MPO

wormhole

CFT1

e.g., T. Hartman, J. Maldacena, JHEP05(2013)014

Thermofield double state

Eternal AdS black-hole

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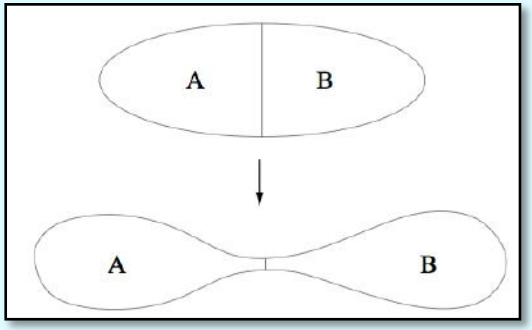
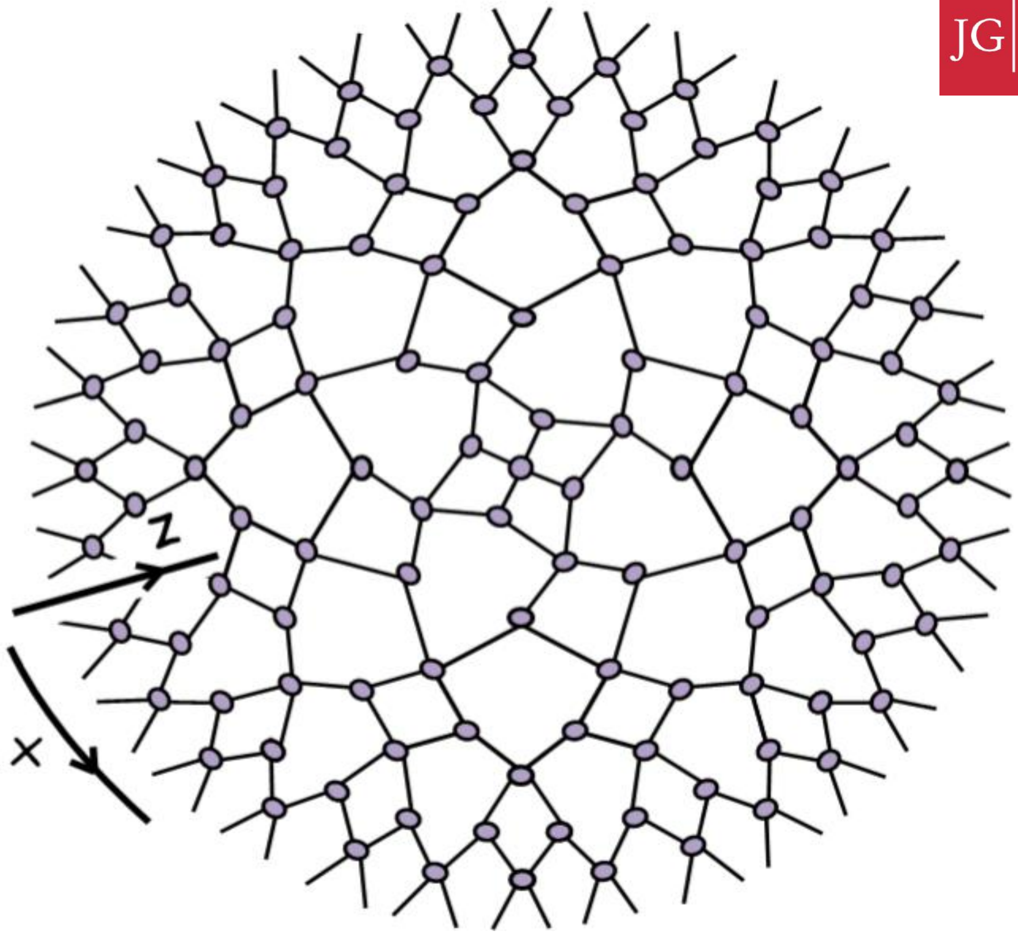
Entanglement connects upper and lower spacetimes



M. Van Raamsdonk, arXiv:0907.2939

ER=EPR, Maldacena & Susskind

MERA



cMERA

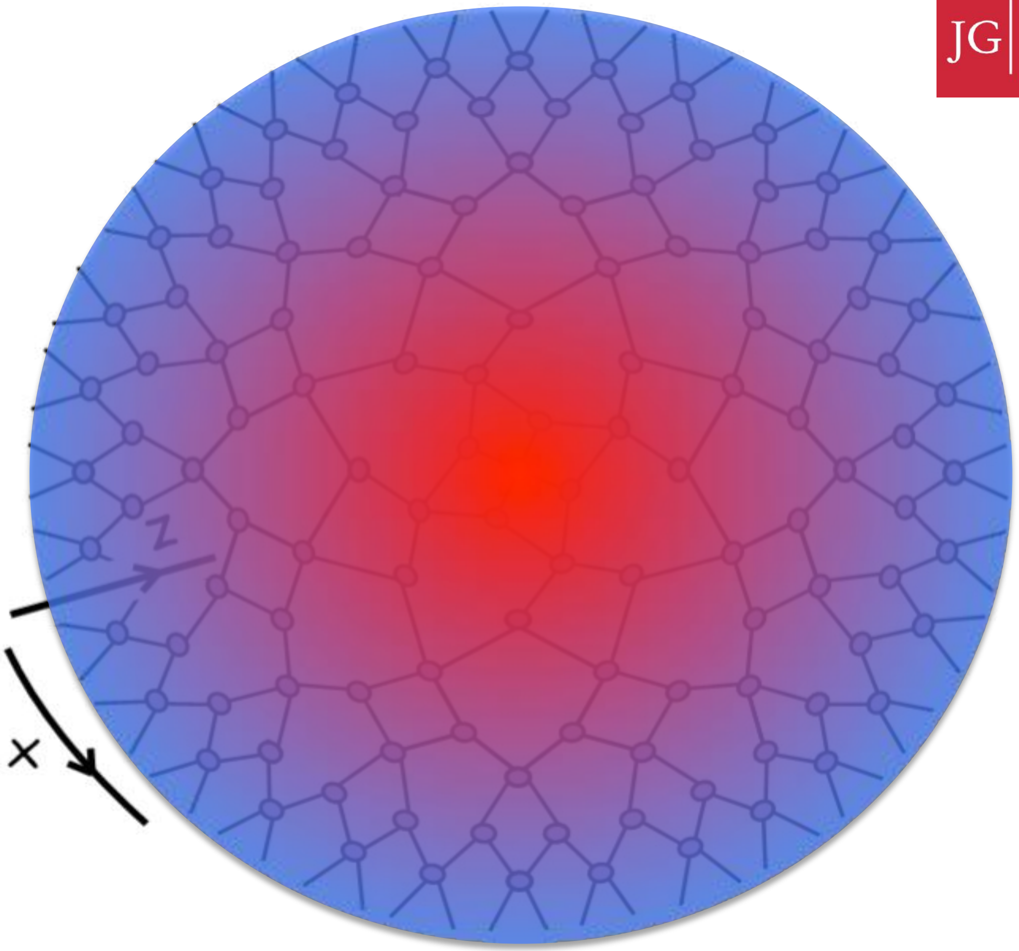
(continuum)

$$|\psi\rangle = Pe^{-i\int_{u2}^{u1}\left(K(u)+L\right)du}|\Omega\rangle$$

J. Haegeman et al,
Phys. Rev. Lett. 110, 100402 (2013)

$K(u)$ Disentangler generator

L Isommetry generator



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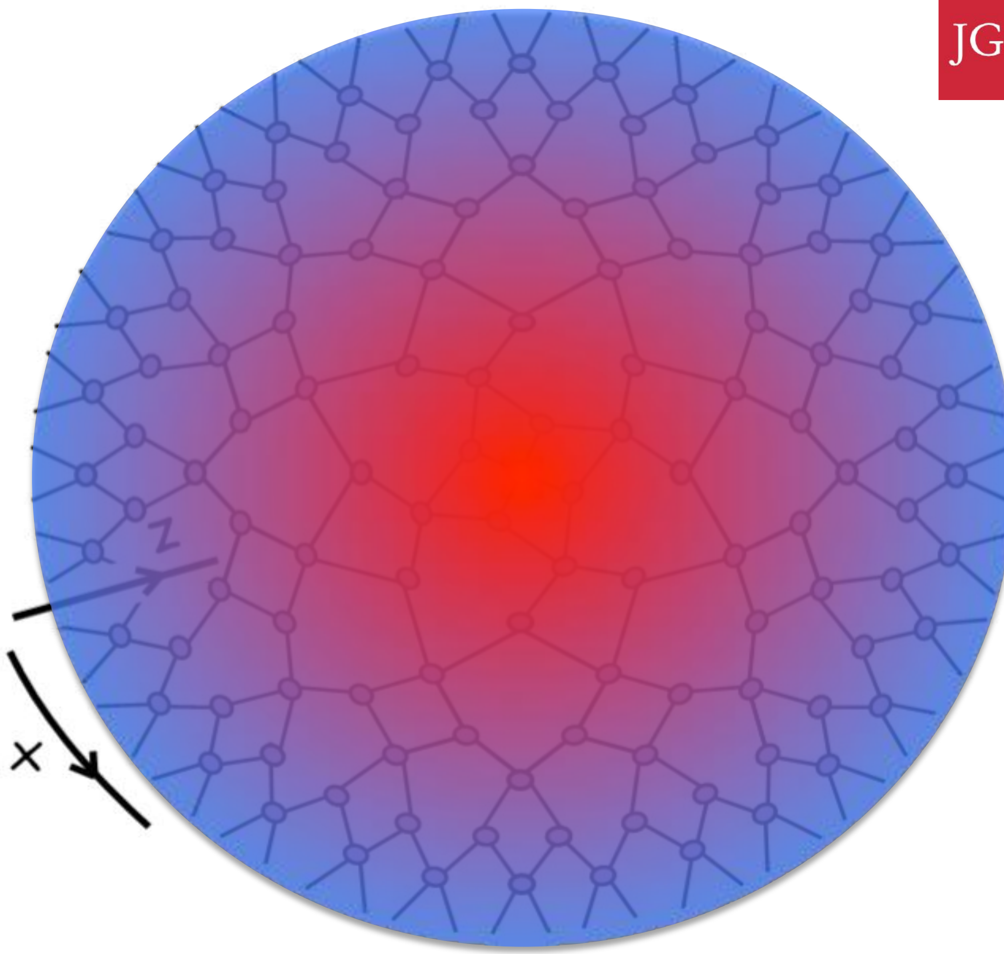

$$g_{uu}(u)du^2 = \mathcal{N}^{-1}\left(1 - \left|\langle\Psi(u)|e^{iL\cdot du}|\Psi(u+du)\rangle\right|^2\right)$$

Measures the density of strength of disentanglers.
Compatible with AdS metric

M. Nozaki, S. Ryu, T. Takayanagi, JHEP10(2012)193

curvature ~ change of entanglement at every length scale

Outline

1) Review of TNs

2) PEPS and emergent Hamiltonians

3) Symmetric TNs and emergent spin networks

4) MERA and emergent AdS/CFT

5) Summary & open questions

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5) Summary & open questions

Summary: “it from qubit”

Many-body entanglement (QM, non-relativistic)

Summary: “it from qubit”

Many-body entanglement (QM, non-relativistic)

↓

Tensor networks

Summary: “it from qubit”

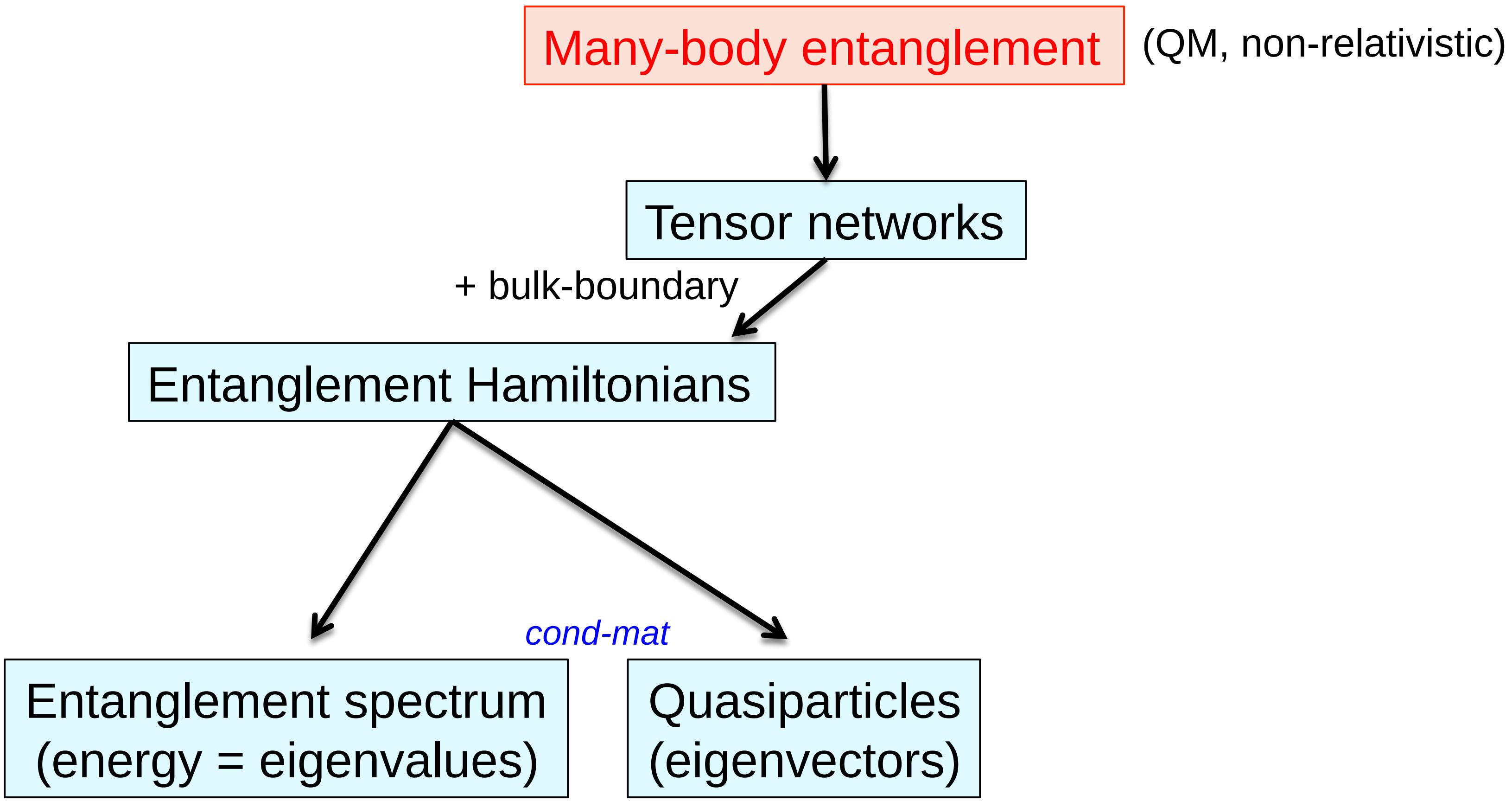
Many-body entanglement (QM, non-relativistic)

Tensor networks

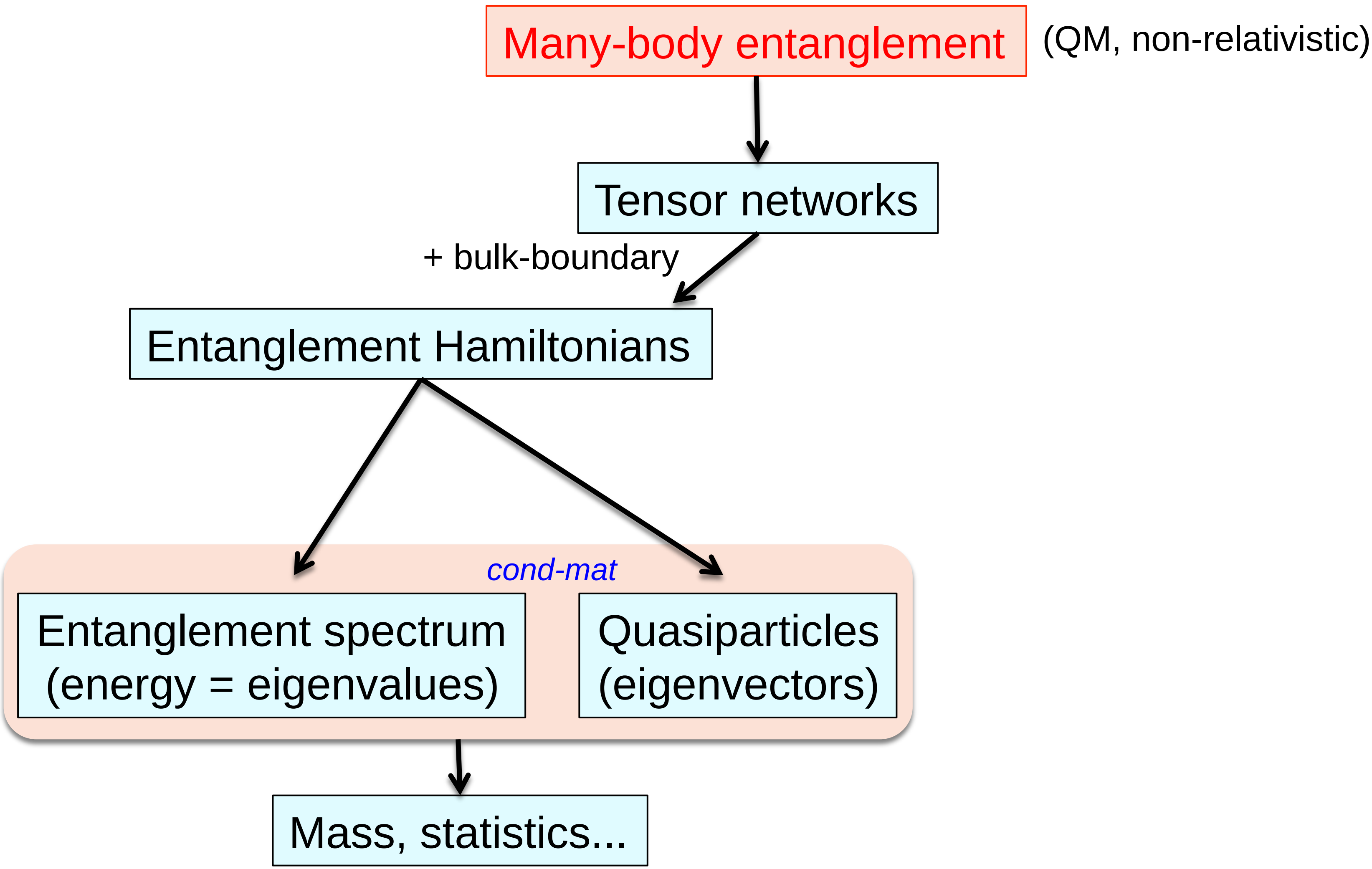
+ bulk-boundary

Entanglement Hamiltonians

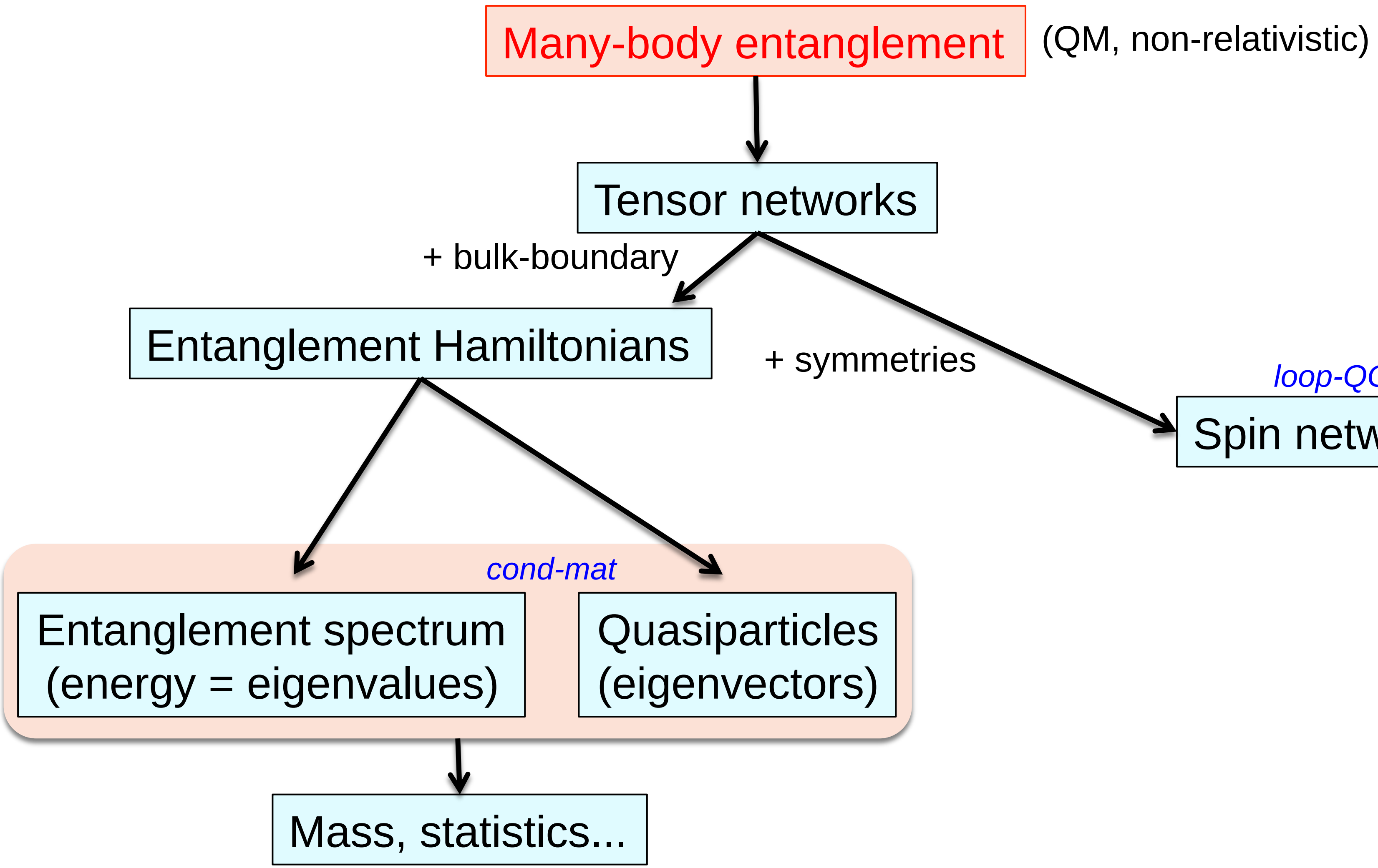
Summary: “it from qubit”



Summary: “it from qubit”



Summary: “it from qubit”



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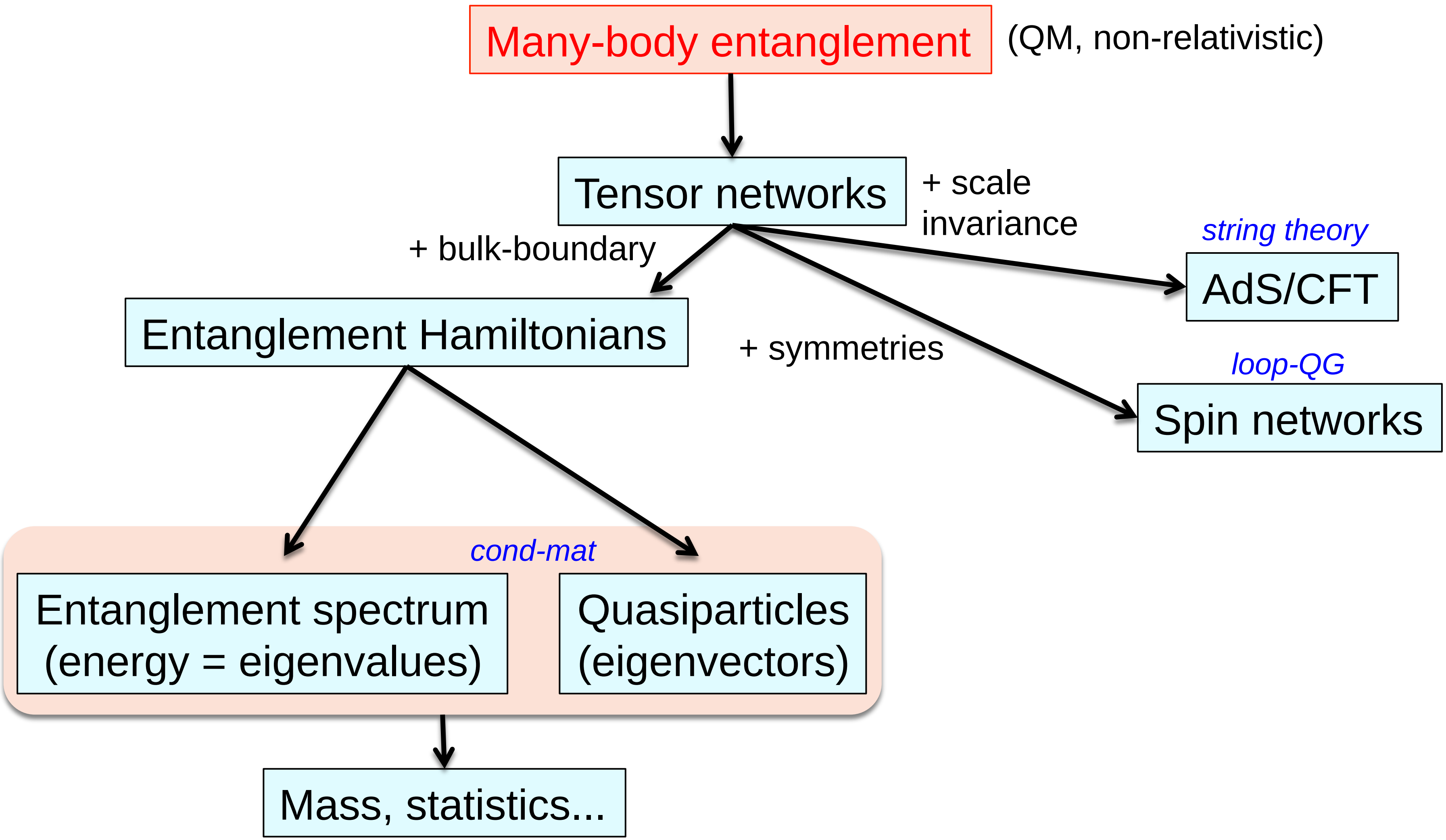

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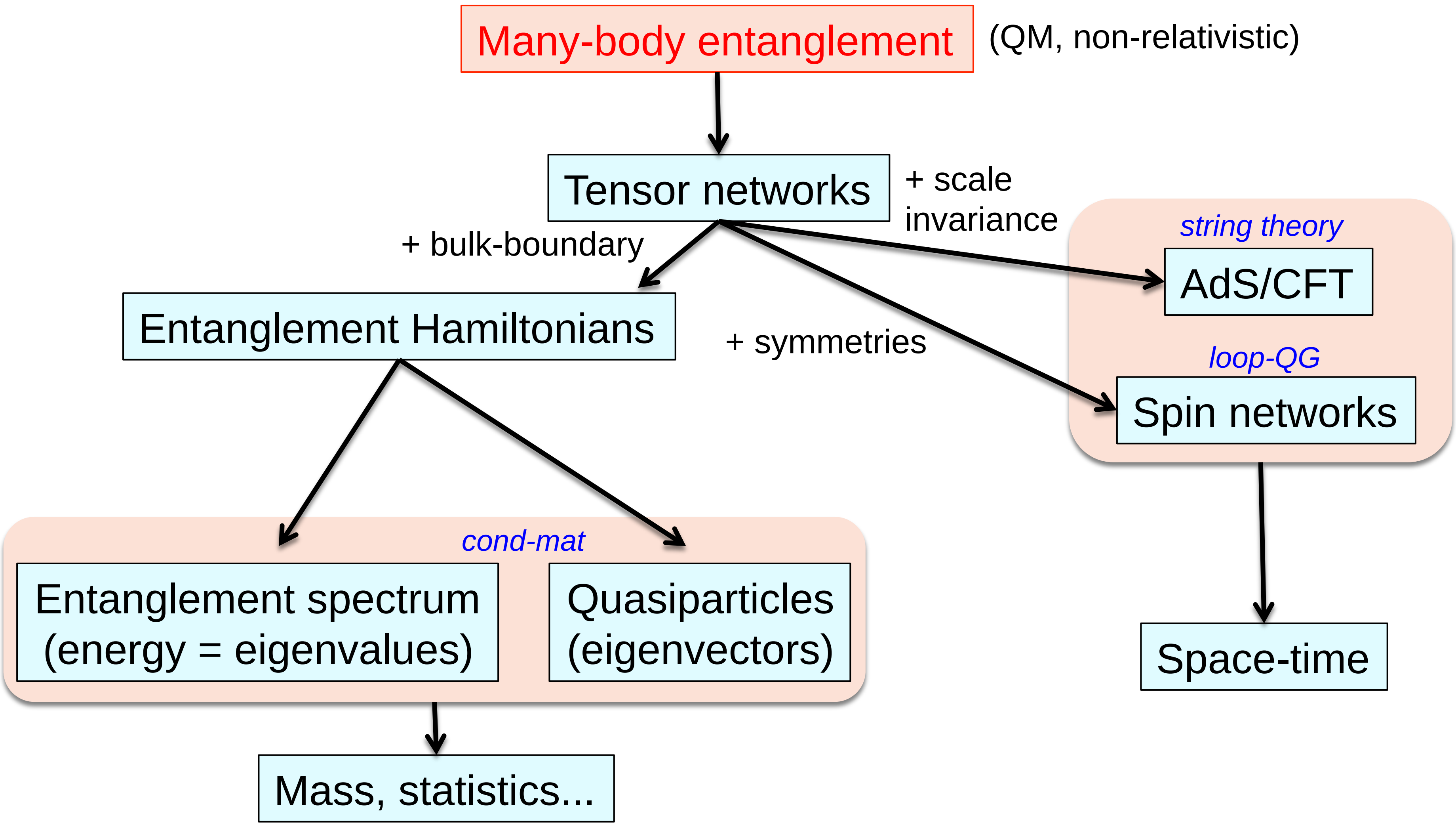
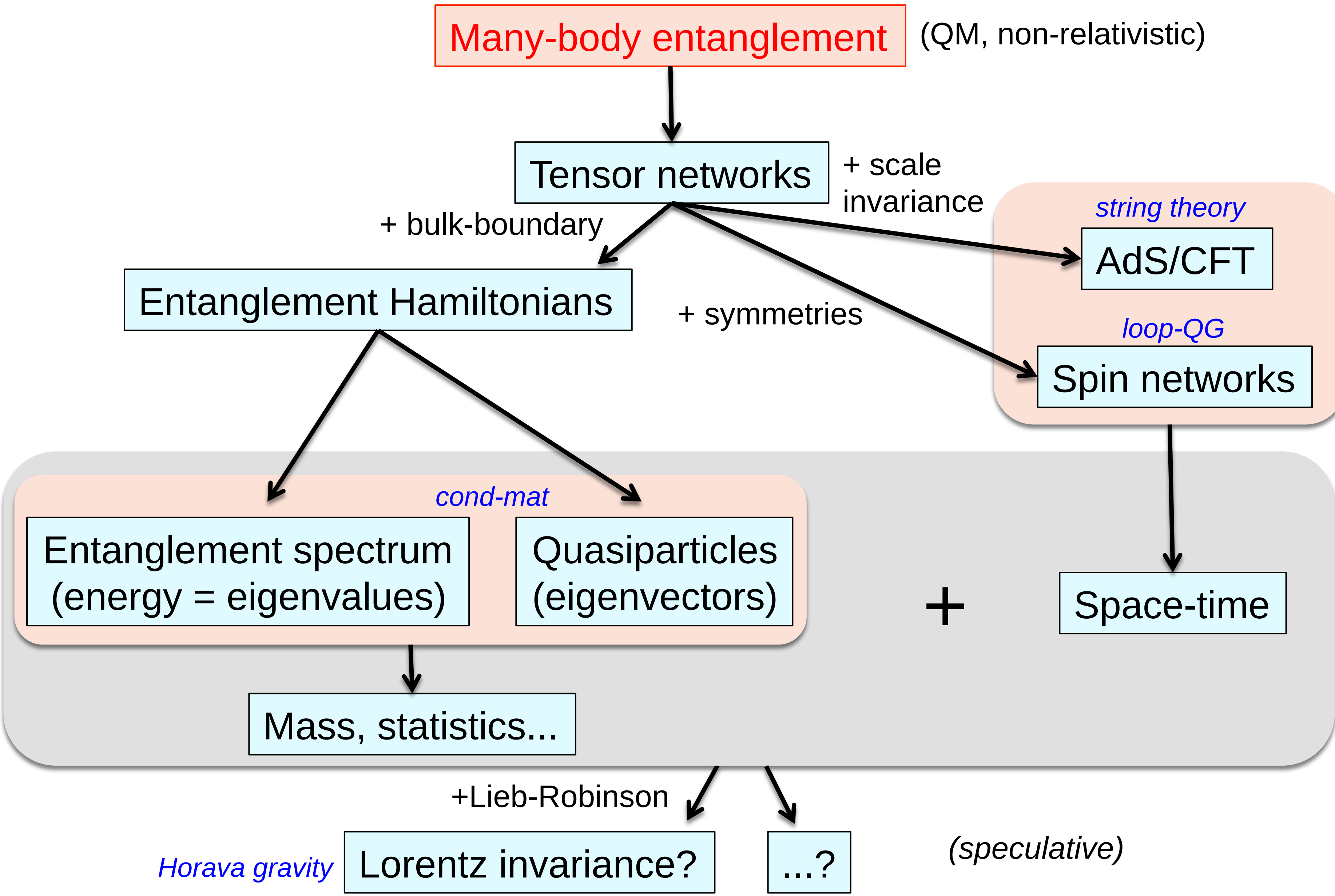


Summary: “it from qubit”



Other developments

JG|U

- Exact holographic mapping
  X.-Liang Qi, arXiv:1309.6282

- AdS/CFT as Quantum Error-Correcting Code
  A. Almheiri, X. Dong, D. Harlow, JHEP 1504:163 (2015)

- Holographic Quantum Error Correcting Codes
  F. Pastawski, B. Yoshida, D. Harlow, J. Preskill, JHEP 06 149 (2015)
  J. I. Latorre, G. Sierra, arXiv:1502.06618

- Einstein's equations from Entanglement Entropy
  T. Faulkner, M. Guica, T. Hartman, R. C. Myers, M van Raamsdonk, JHEP 03 051 (2013); B. Swingle, M. van Raamsdonk, arXiv:1405.2933

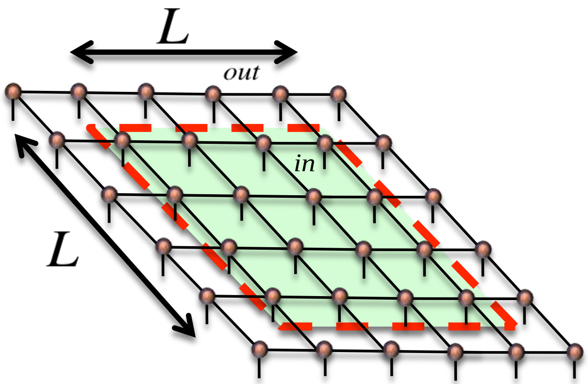
- ...

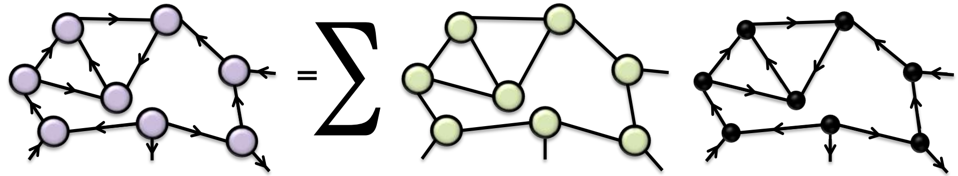
Some cross-over open questions

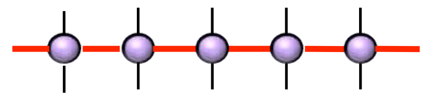
- cMERA, wavelets, and AdS/CFT?
- Superpositions of TTNs? Linear optics?

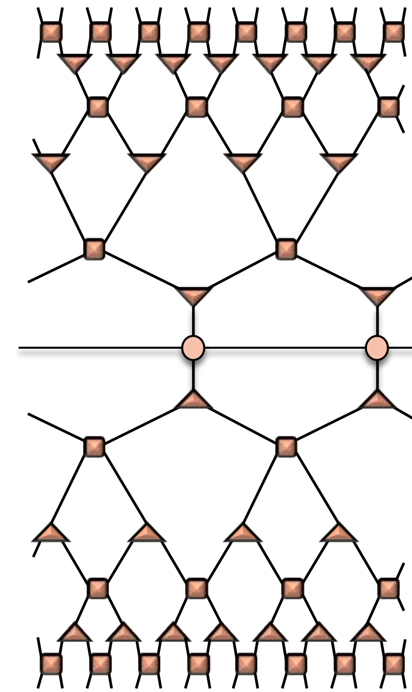
C. Papadopoulos, RO work in progress

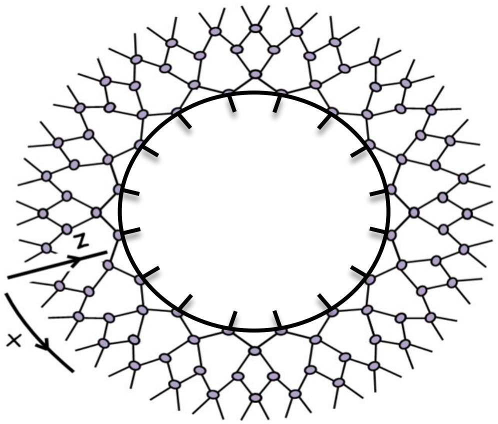
- Consistent AdS/TN? What about other correspondences?
- TN structure of, e.g., N=4 SYM? (Type-IIB on $AdS_5 \times S^5$) Can one derive string theory from entanglement? *c.f. talk by J. Molina-Vilaplana*
- Non-classical gravity from „exotic" TNs? (topological order & D-branes, TNs with symmetries...)
- Holographic multipartite entanglement? Holographic mixed-state entanglement? *D. Pang, RO, work in progress*
- „Gravitational" interpretation of branching MERA?
- Numerical simulations of gravity with TN methods?
- „entanglement renormalization" ⟷ „holographic renormalization"?
- Lorentz invariance from Lieb-Robinson bounds?
- ...











Thank you!