A QUANTUM-DIGITAL UNIVERSE: A QCA APPROACH TO FIELD THEORY

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Dipartimento di Fisica "A.Volta", Università di Pavia

Speakable in quantum mechanics: atomic, nuclear and subnuclear physics tests

ECT, Trento, 30 August 2011

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW A **84**, 012311 (2011)

Informational derivation of quantum theory

Giulio Chiribella*

Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Ontario, Canada N2L 2Y5†

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We derive quantum theory from purely informational principles. Five elementary axioms—causality, perfect distinguishability, ideal compression, local distinguishability, and pure conditioning—define a broad class of theories of information processing that can be regarded as standard. One postulate—purification—singles out quantum theory within this class.

DOI: 10.1103/PhysRevA.84.012311 PACS number(s): 03.67.Ac, 03.65.Ta

I. INTRODUCTION

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Continuing exploring *informationalism & operationalism* program

"It from Bit"

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Q-DIGITALIZATION PROGRAM

QCA AS A PLANCK-SCALE THEORY

PROBLEMS WITH QFT

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PROBLEMS WITH QFT

- renormalization

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QCA AS A PLANCK-SCALE THEORY

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PROBLEMS WITH QFT

- renormalization
- violation (?) of Einstein causality

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* space-time emergence from events
* *homogeneous* causal networks

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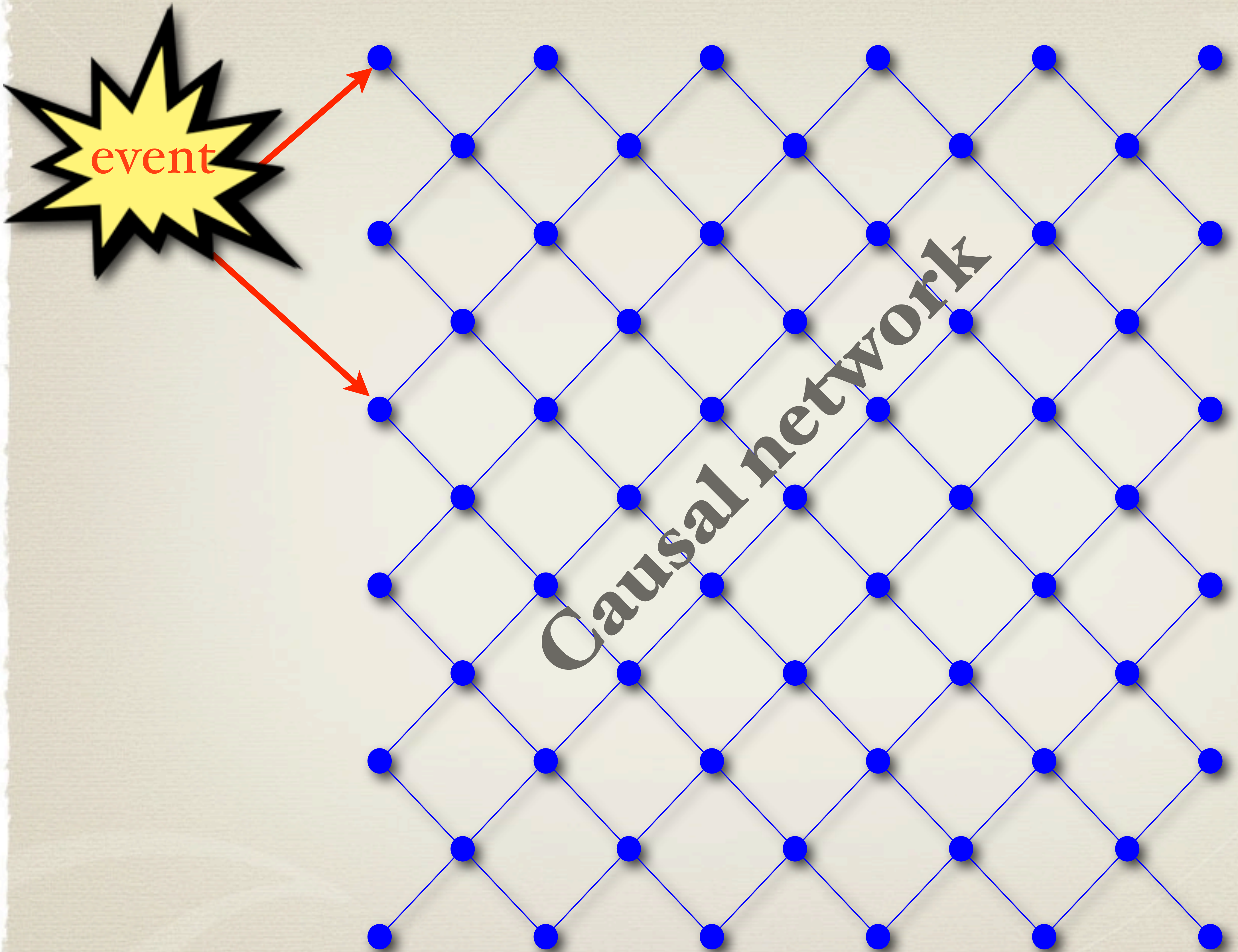
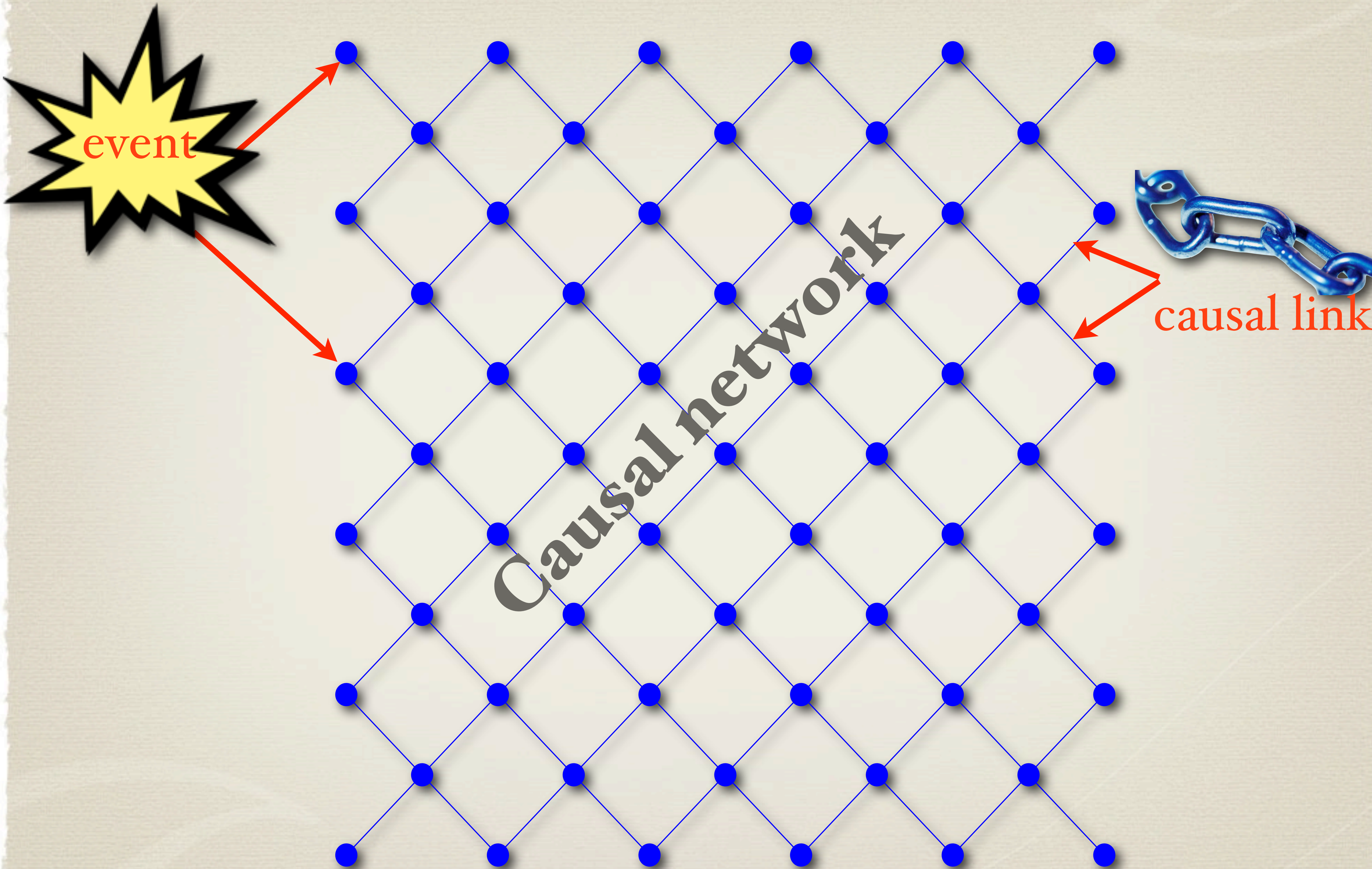
* dim. conundrum → *quantum*ness

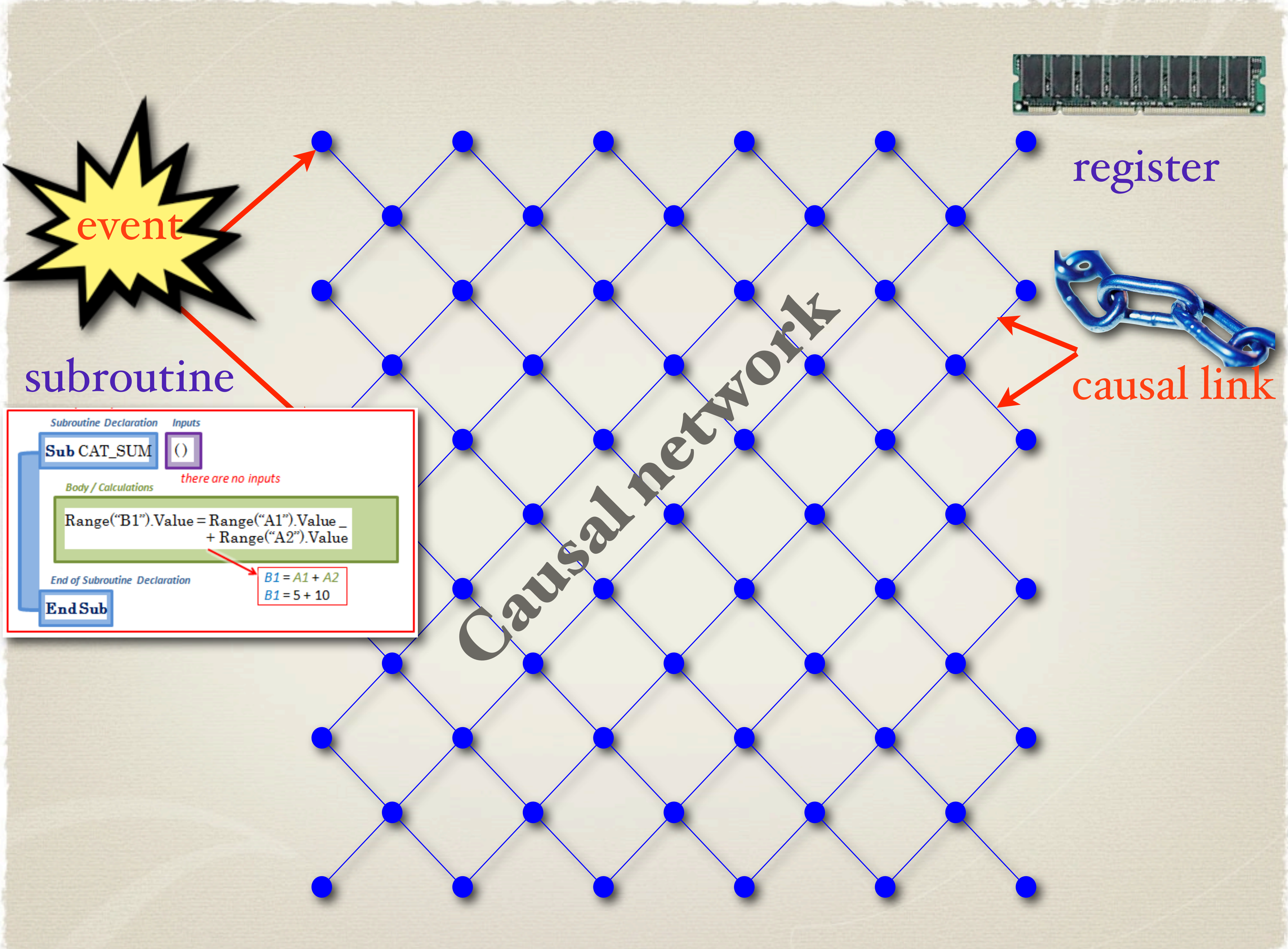
... AND MORE

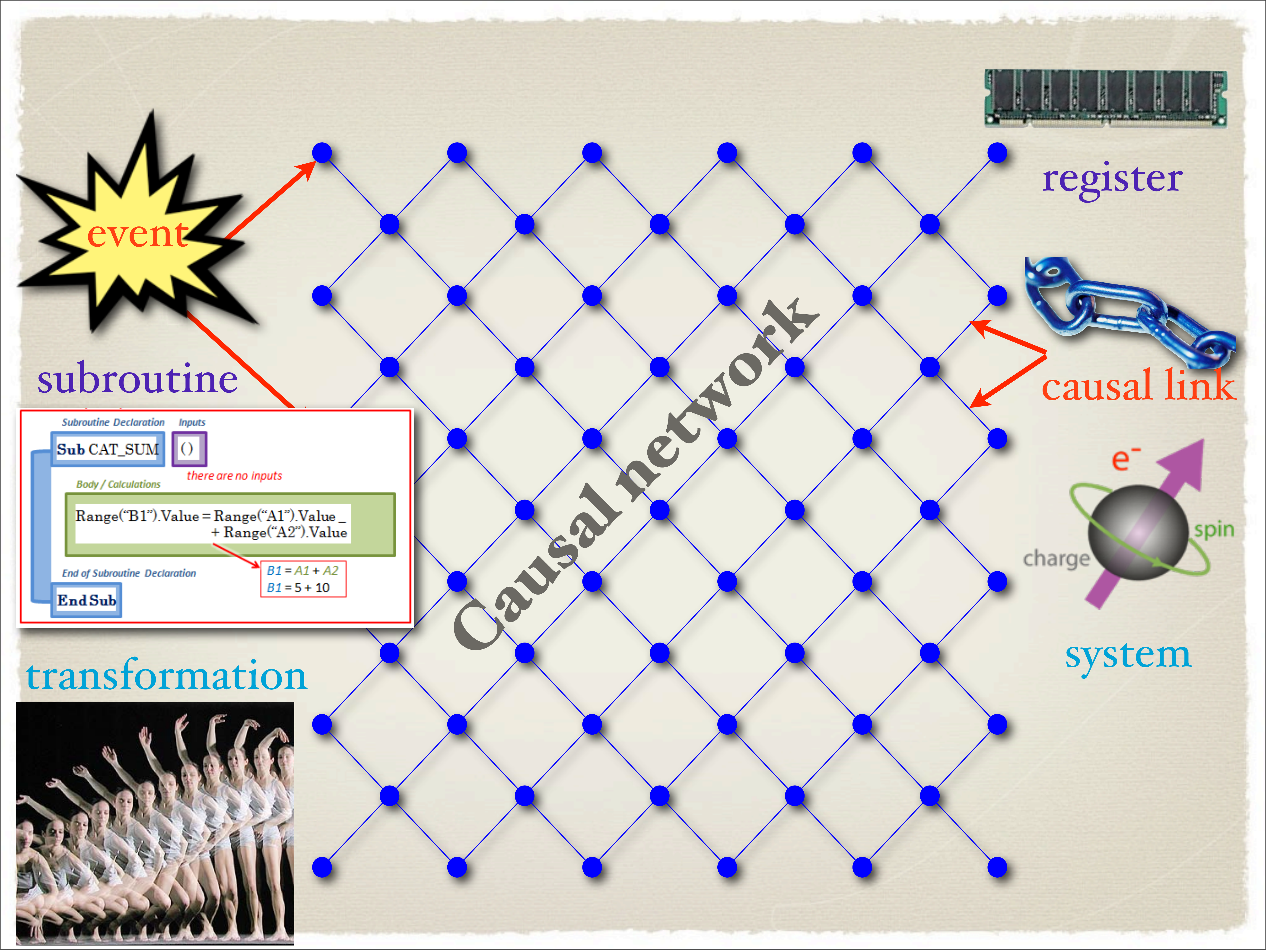
* quantization vs *classicalization*


Causal network


event
Causal network


event
Causal network
causal link


register
event
causal link
subroutine
Causal network
Subroutine Declaration
Inputs
Sub CAT_SUM
()
there are no inputs
Body / Calculations
Range("B1").Value = Range("A1").Value _
+ Range("A2").Value
B1 = A1 + A2
B1 = 5 + 10
End of Subroutine Declaration
End Sub



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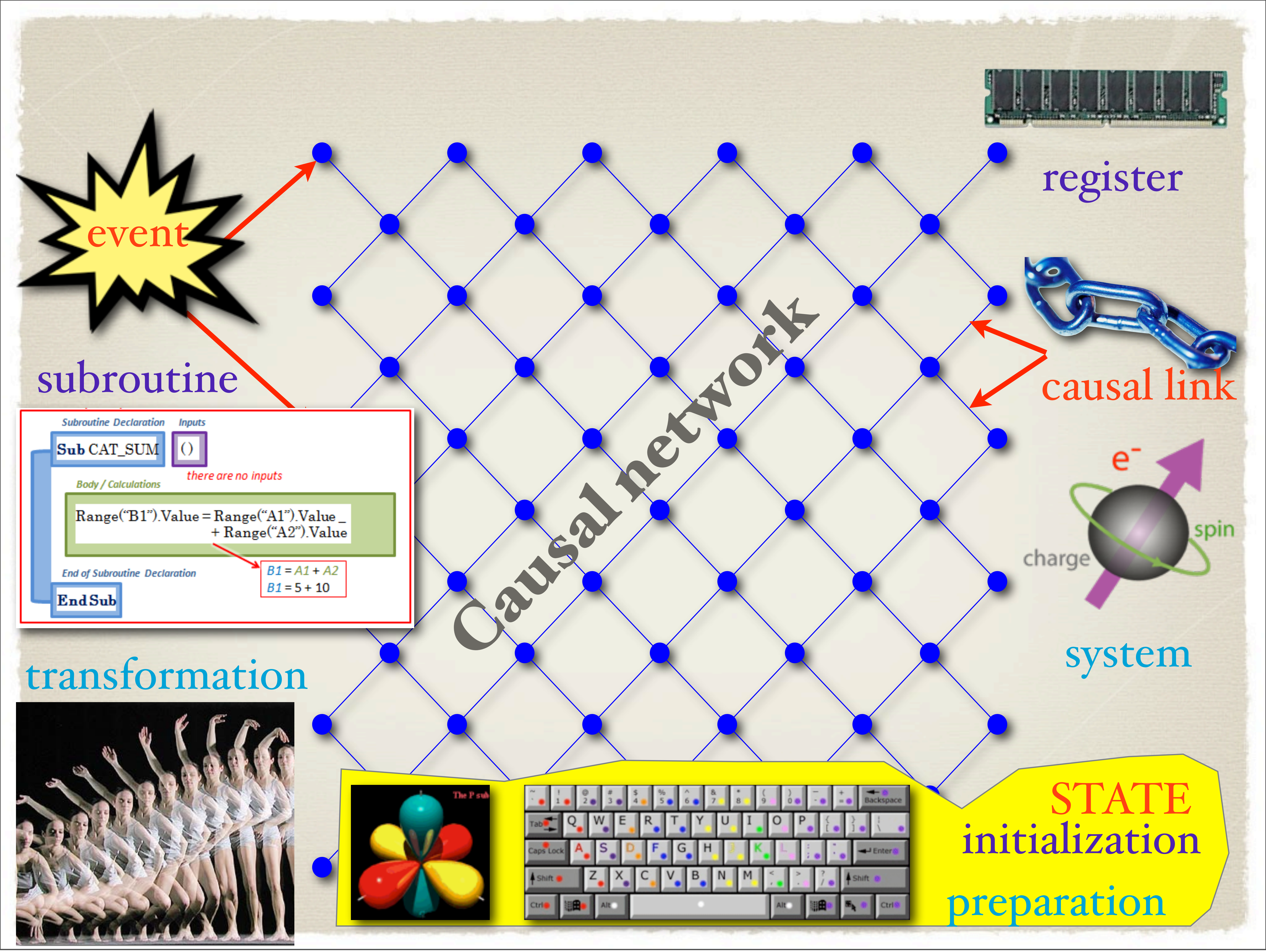
transformation
Causal network
register
causal link
e-
spin
charge
system



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e⁻
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system
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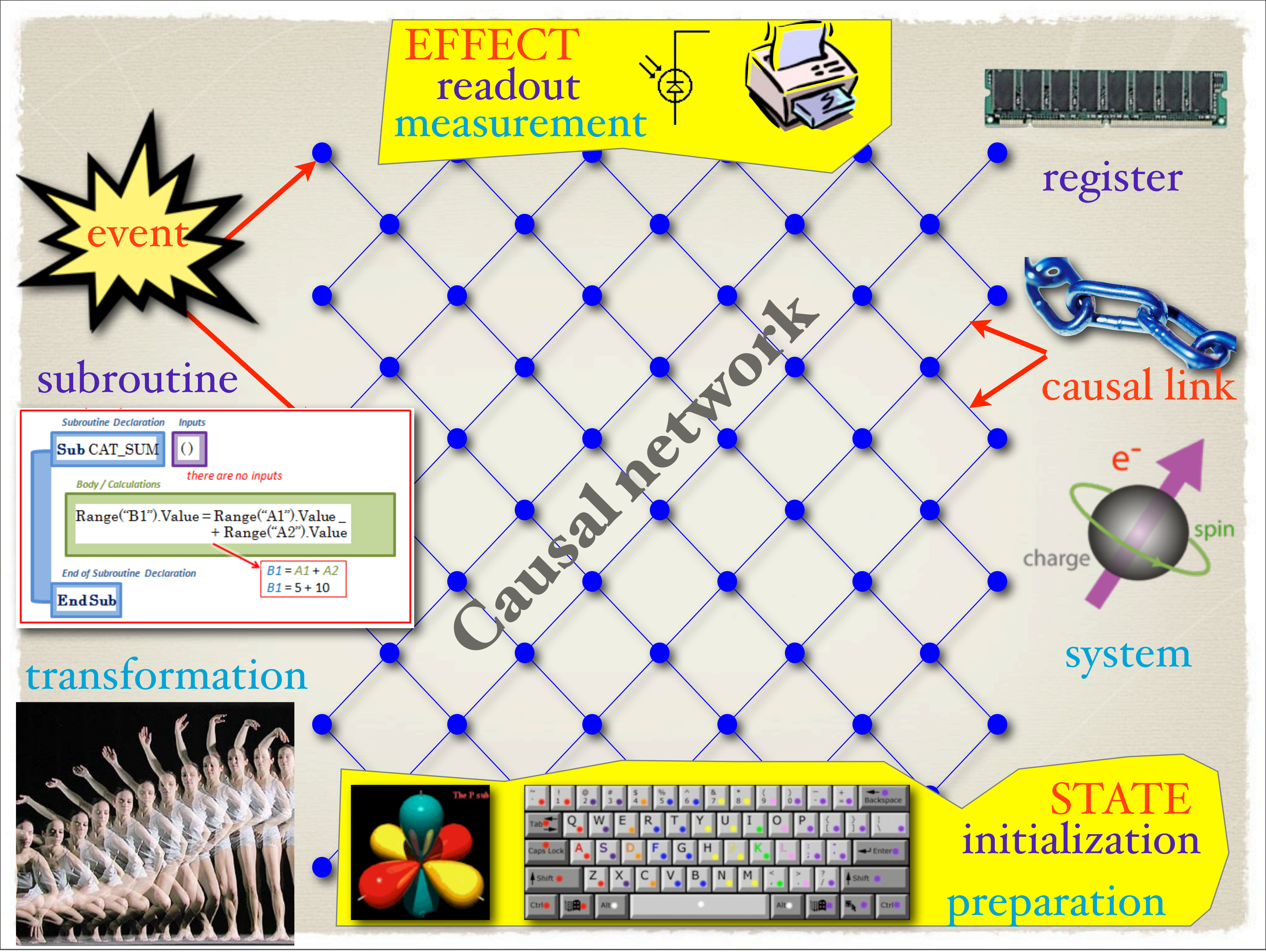
STATE
initialization
preparation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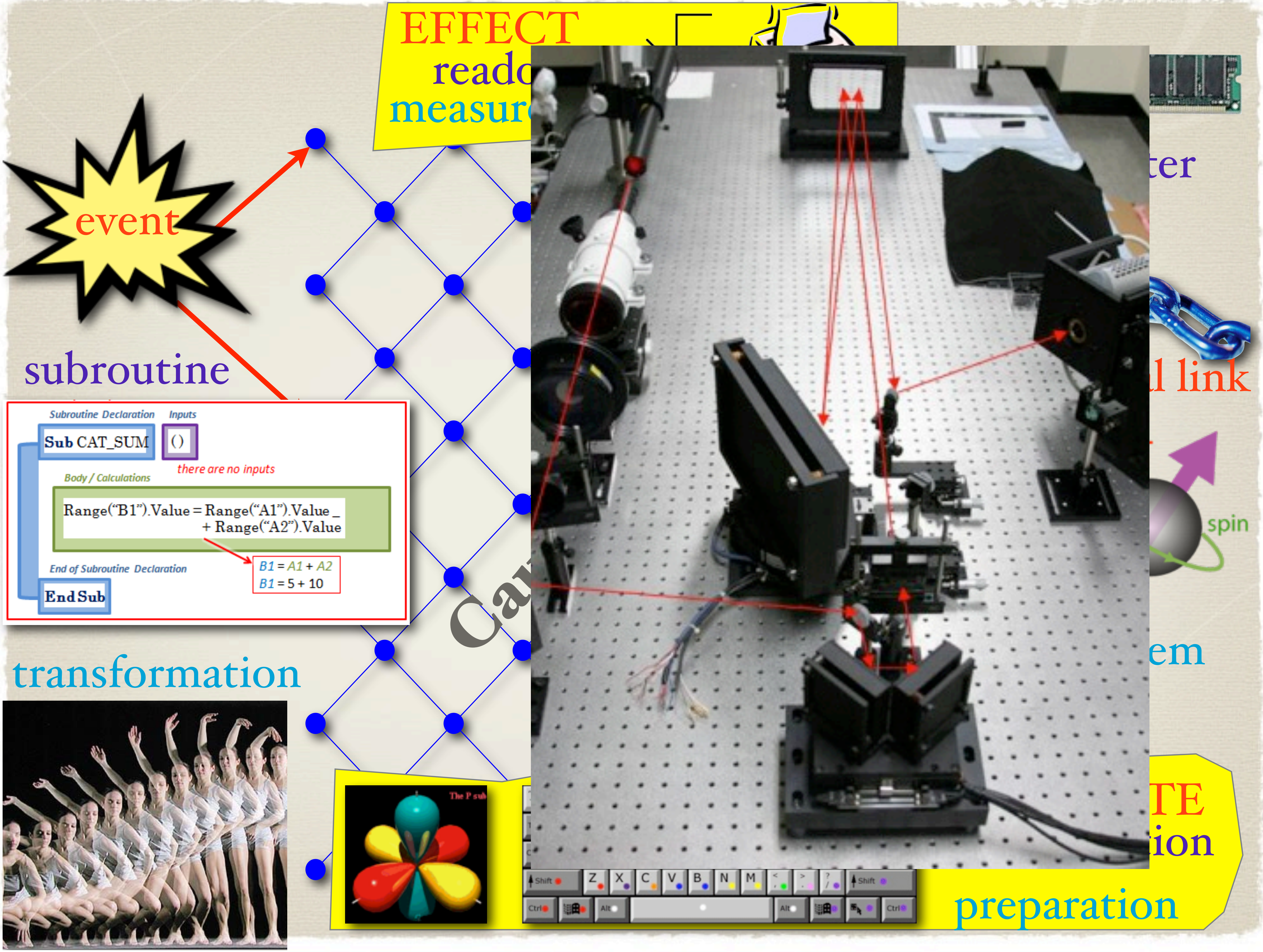
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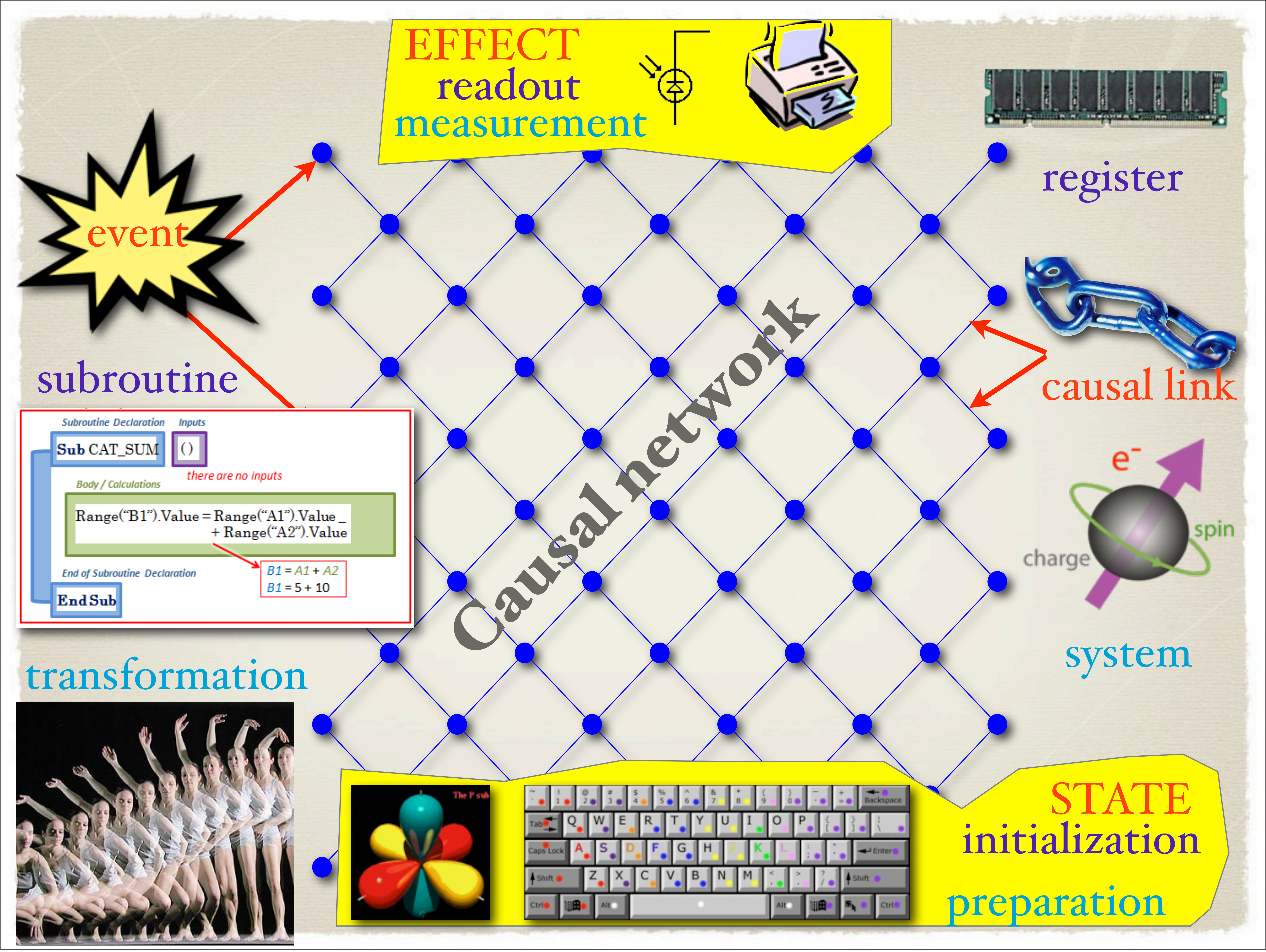
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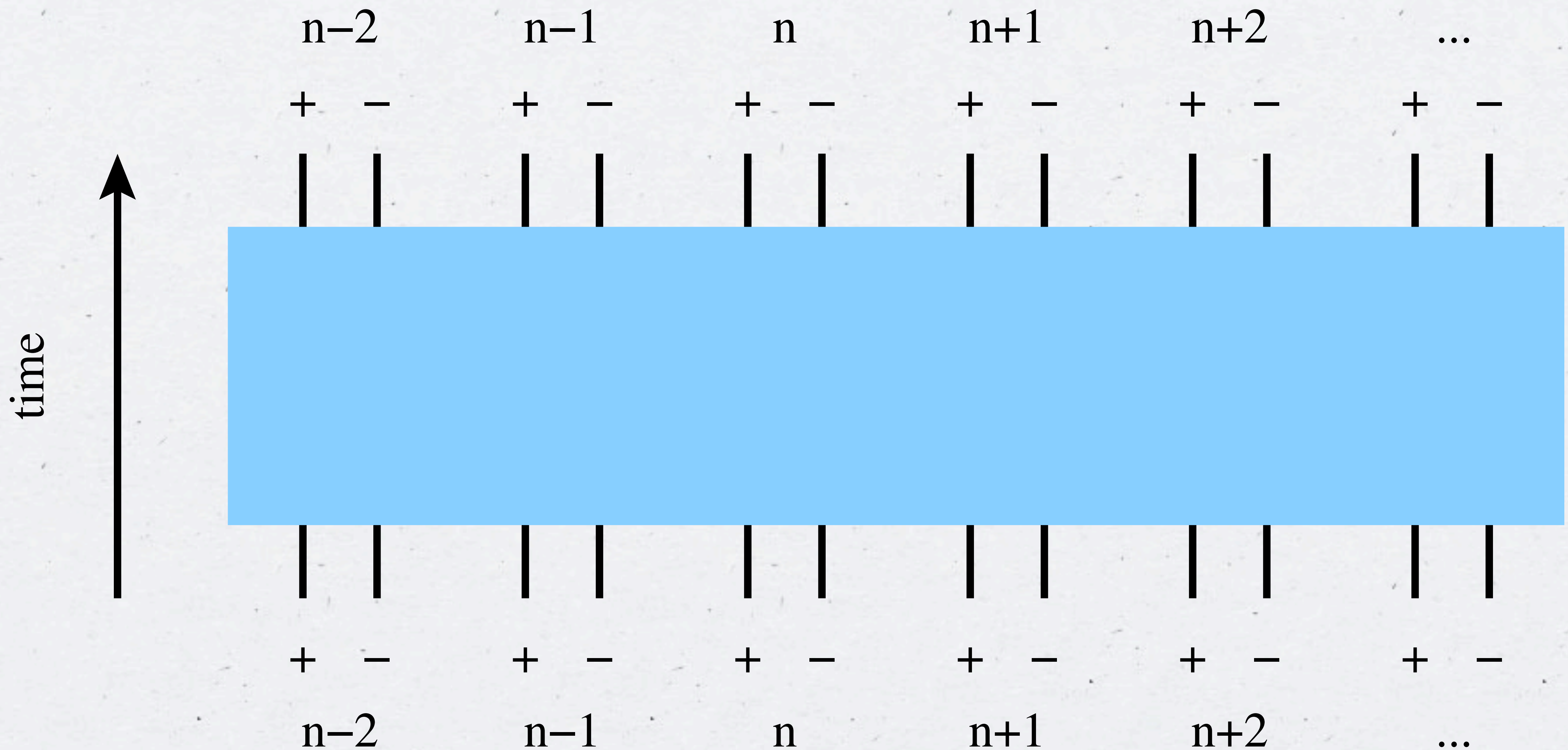
A QCA FIELD THEORY

QUANTUM CELLULAR AUTOMATA



A QCA FIELD THEORY

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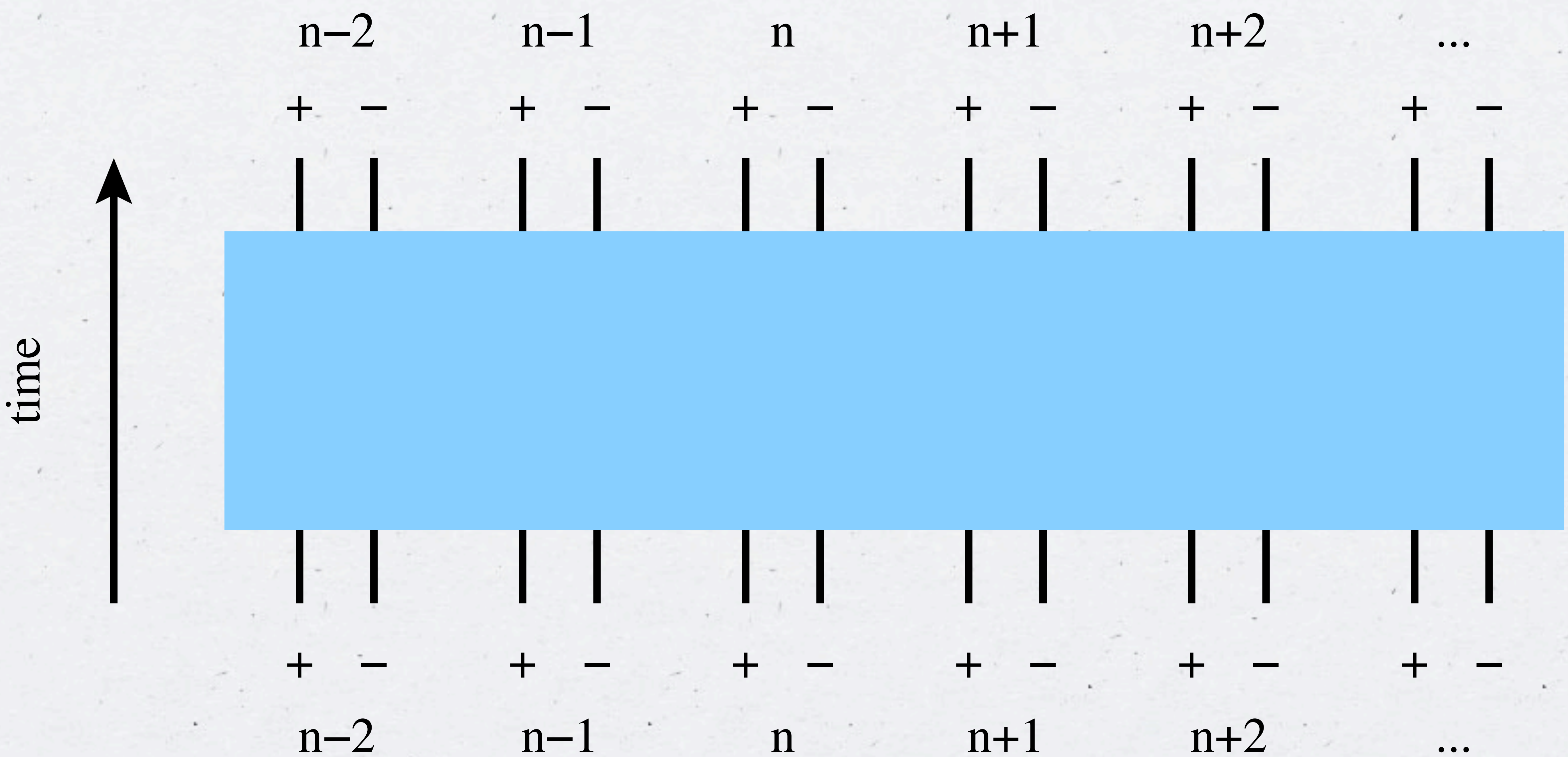
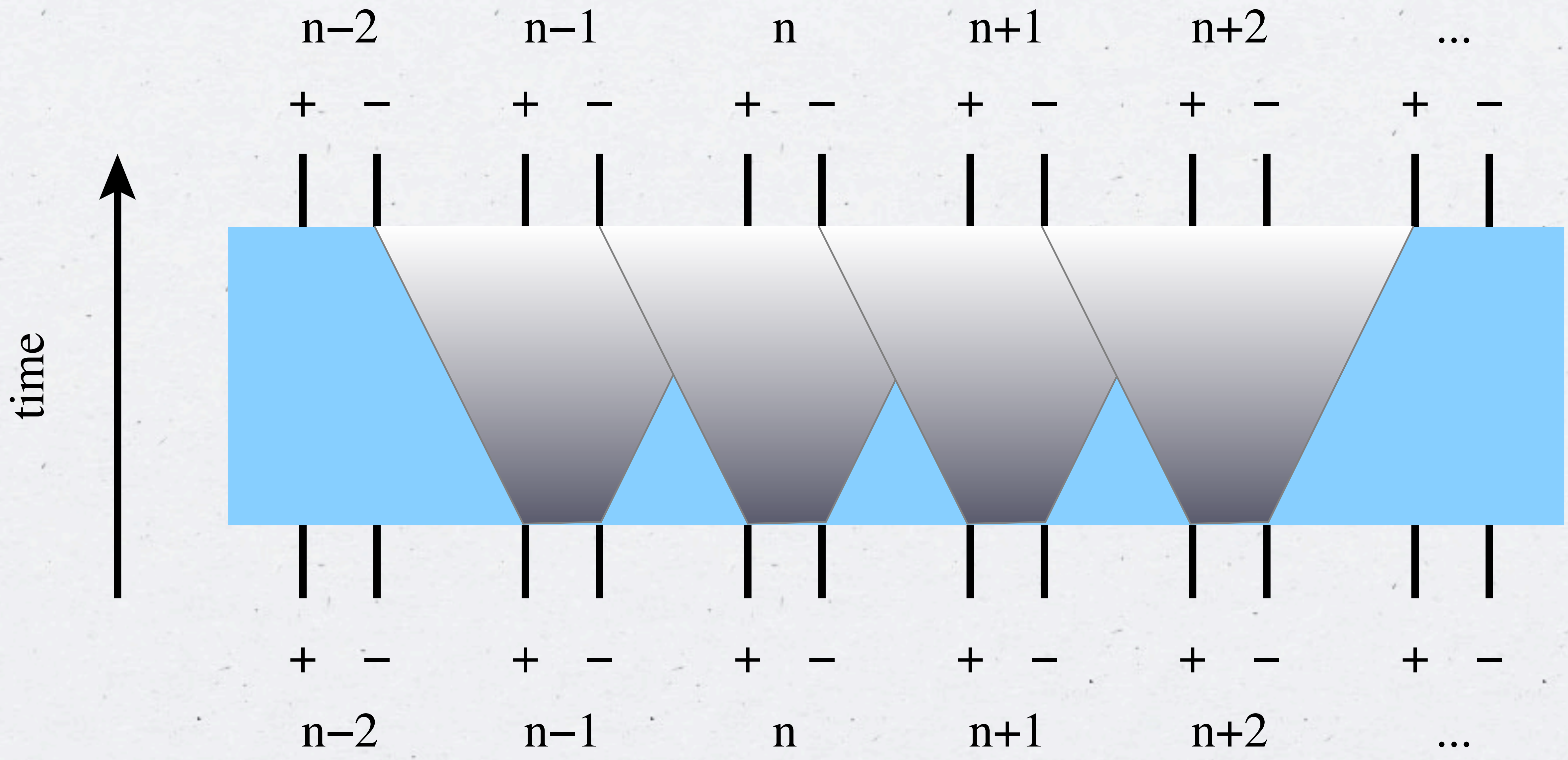


Translational invariance

A QCA FIELD THEORY

QUANTUM CELLULAR AUTOMATA

Locality of interactions



Translational invariance

A QCA FIELD THEORY

QUANTUM CELLULAR AUTOMATA

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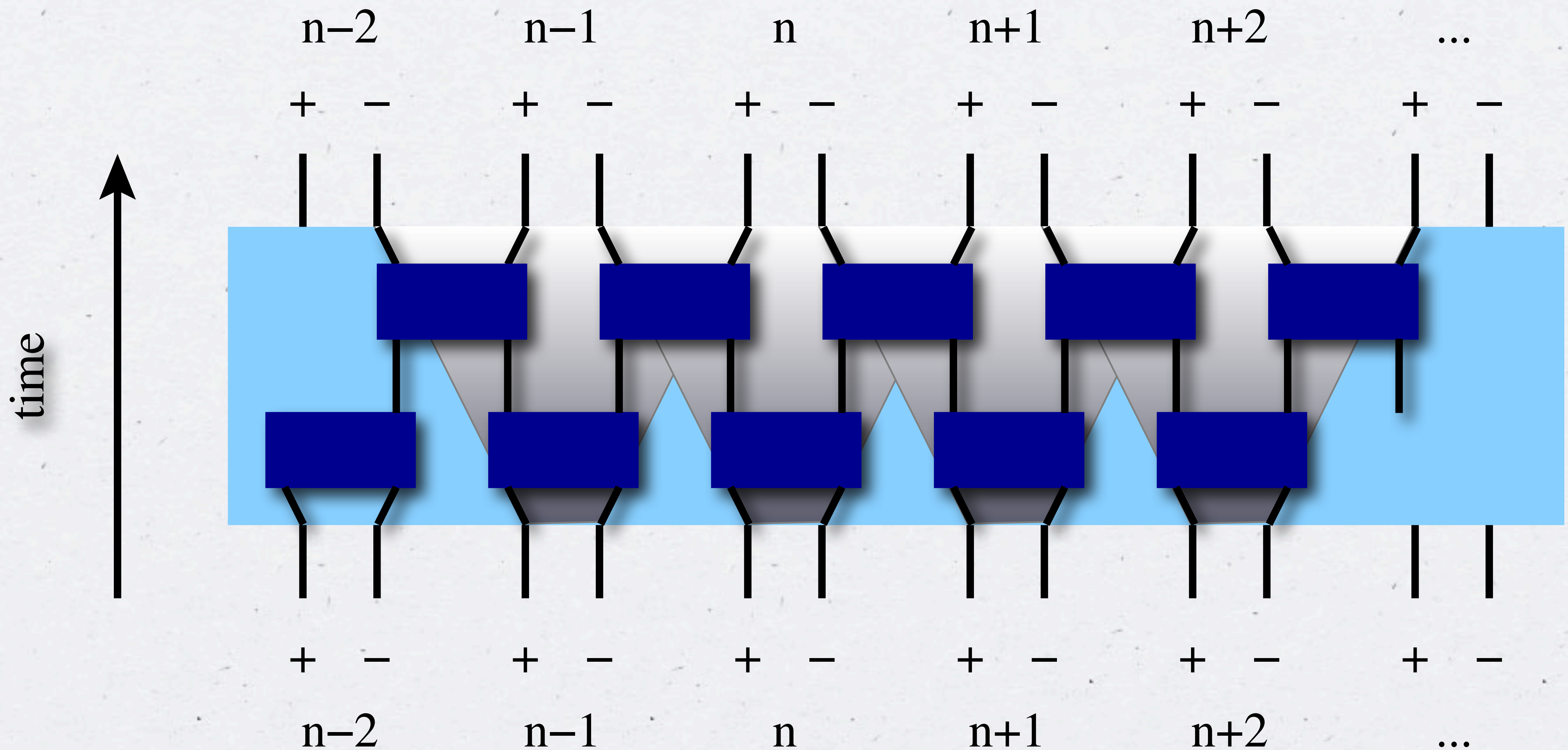
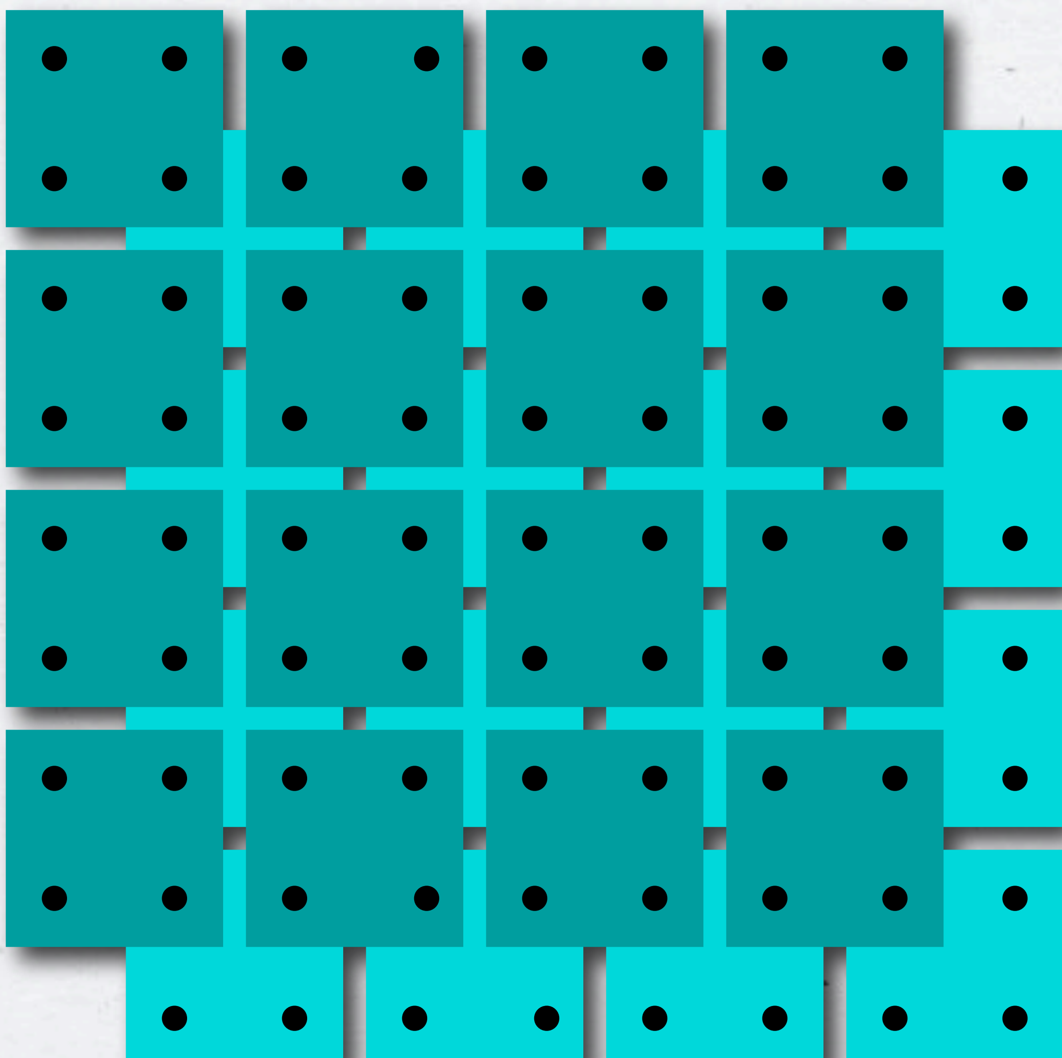


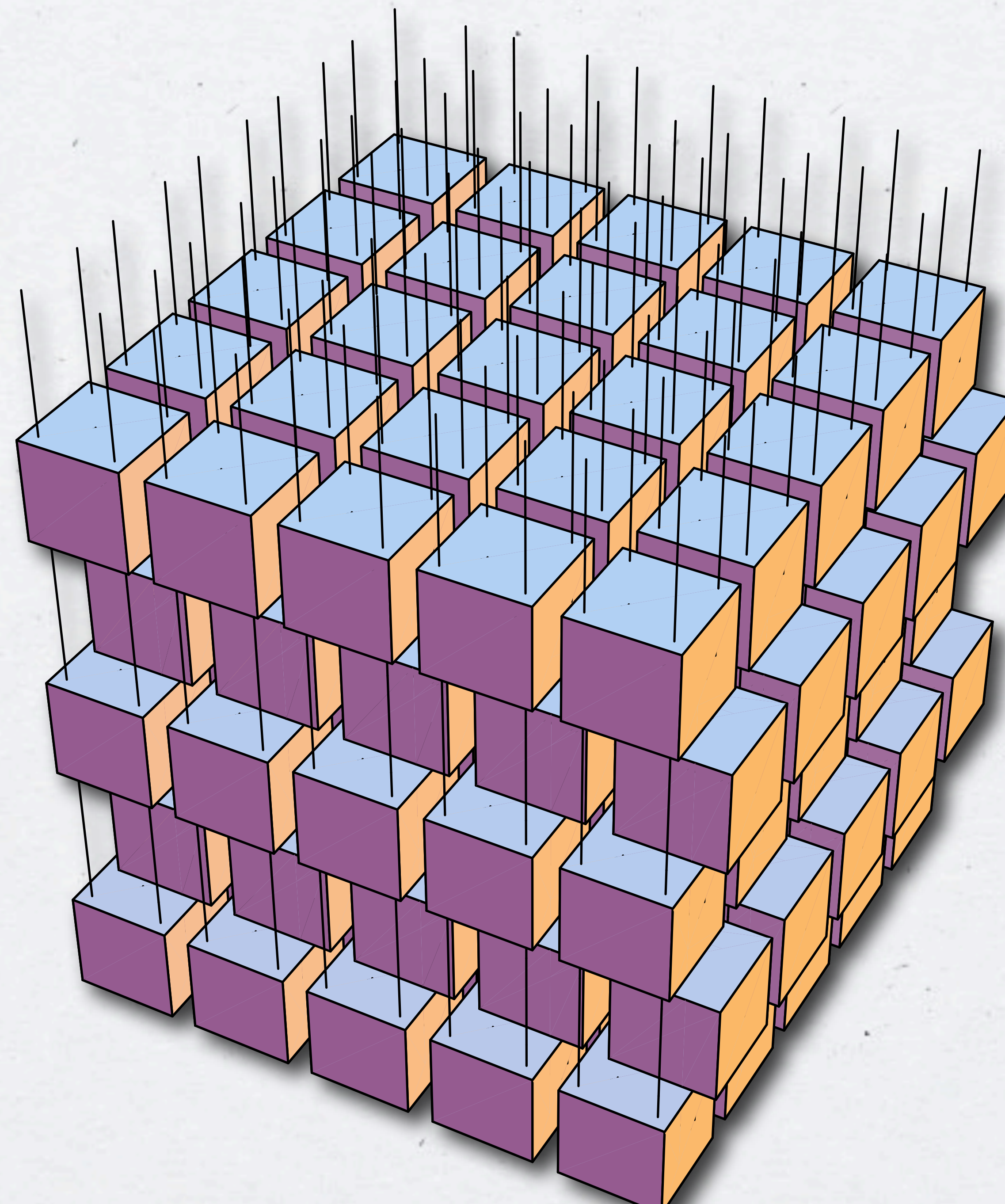
Translational invariance

Margolus scheme

A QCA FIELD THEORY

QUANTUM CELLULAR AUTOMATA





A QCA FIELD THEORY

TRANSLATIONAL INVARIANCE

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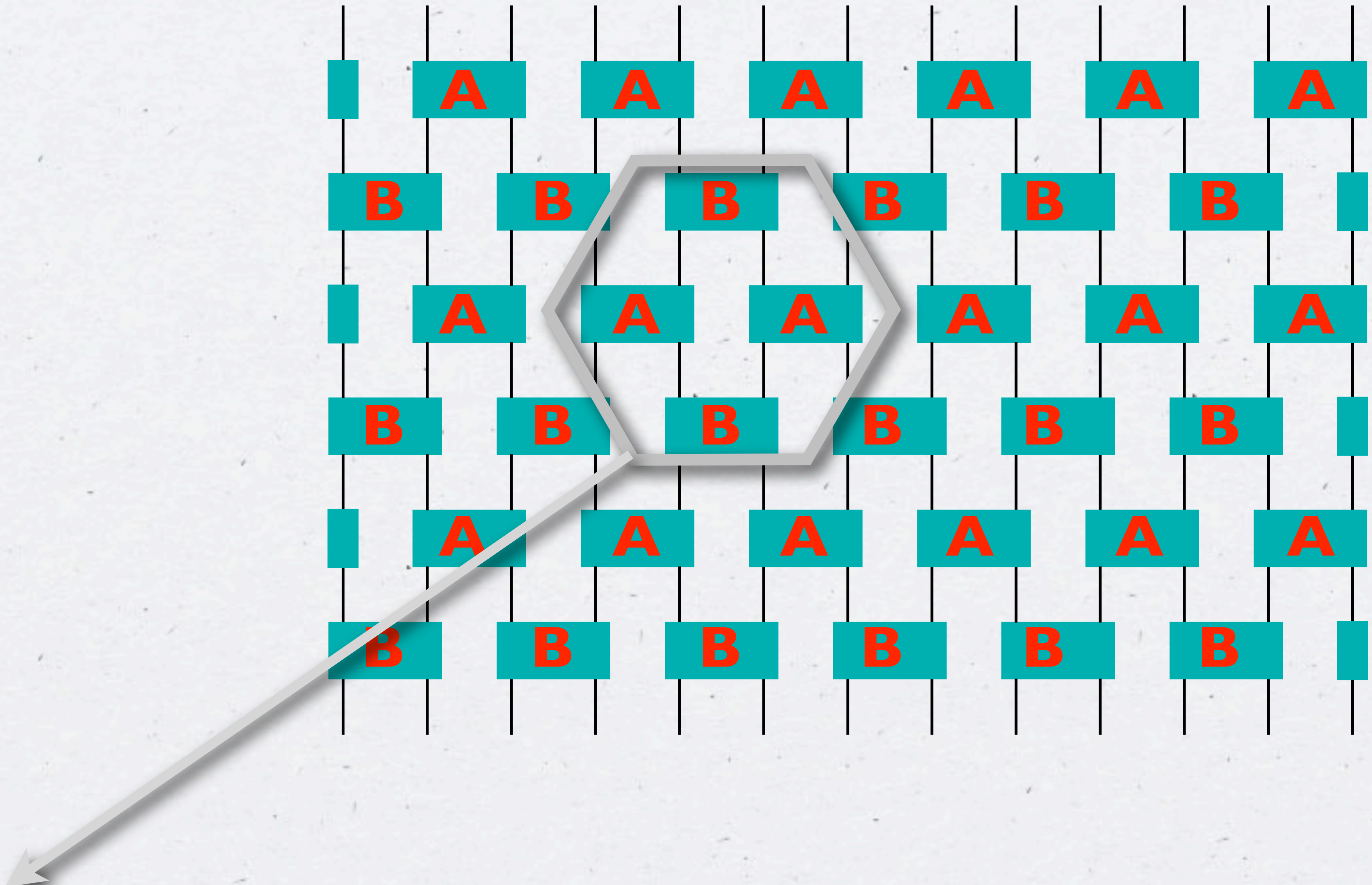


Physical law

CAUSAL NETWORKS

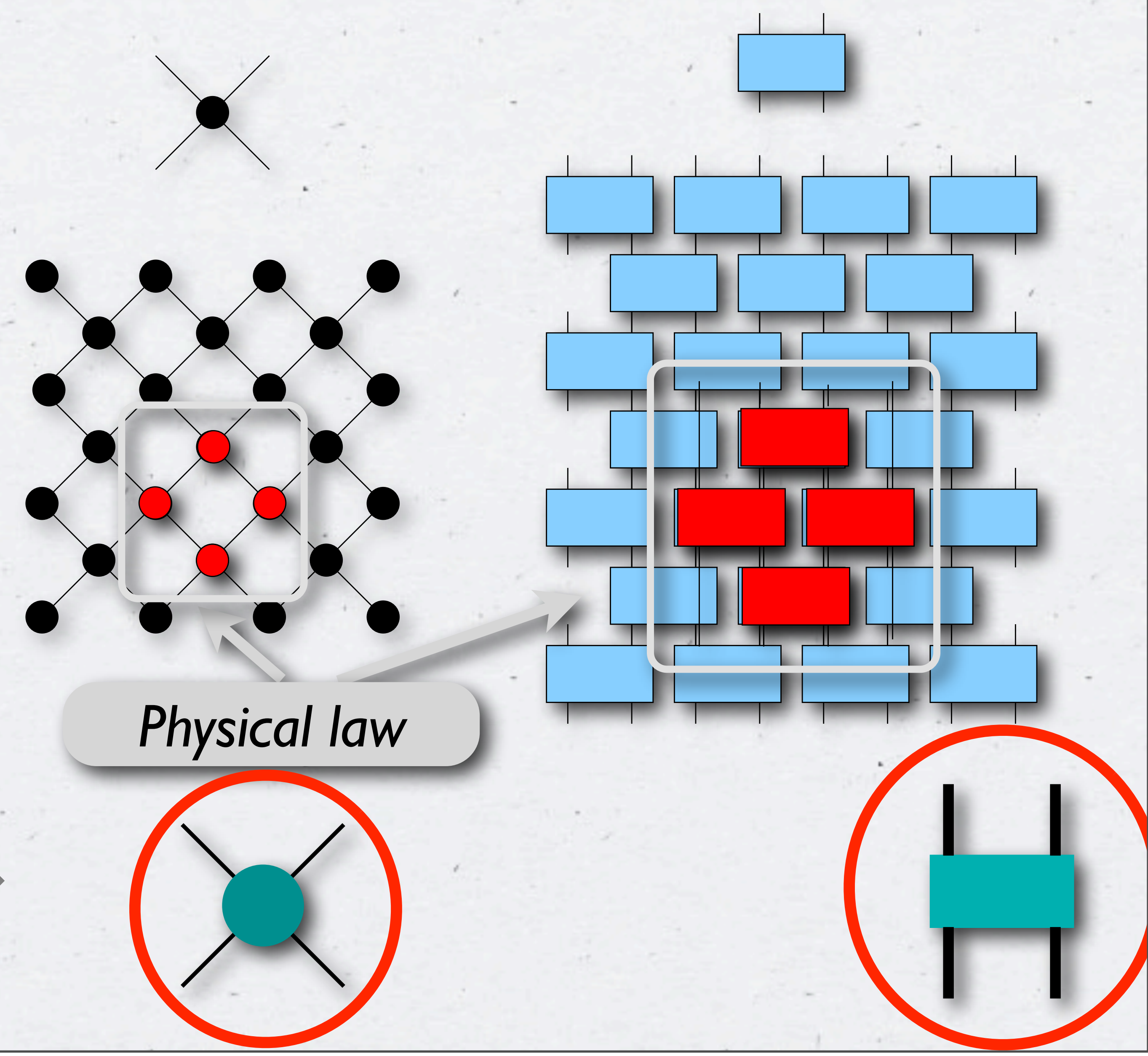
THE PHYSICAL LAW: UNDRESSING TOPOLOGY

- Homogeneous network topology

CAUSAL NETWORKS

THE PHYSICAL LAW: UNDRESSING TOPOLOGY

* Homogeneous network topology



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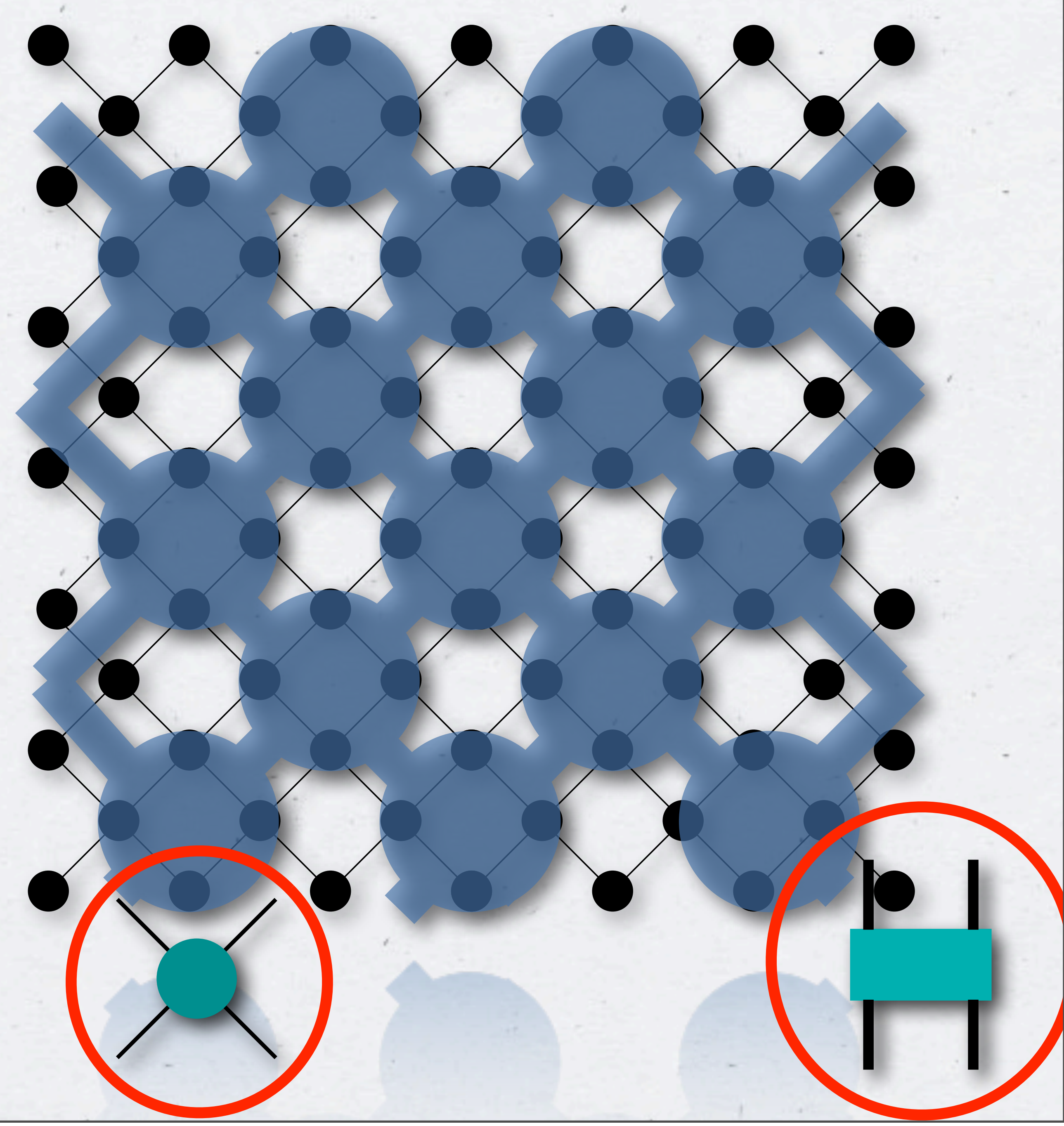

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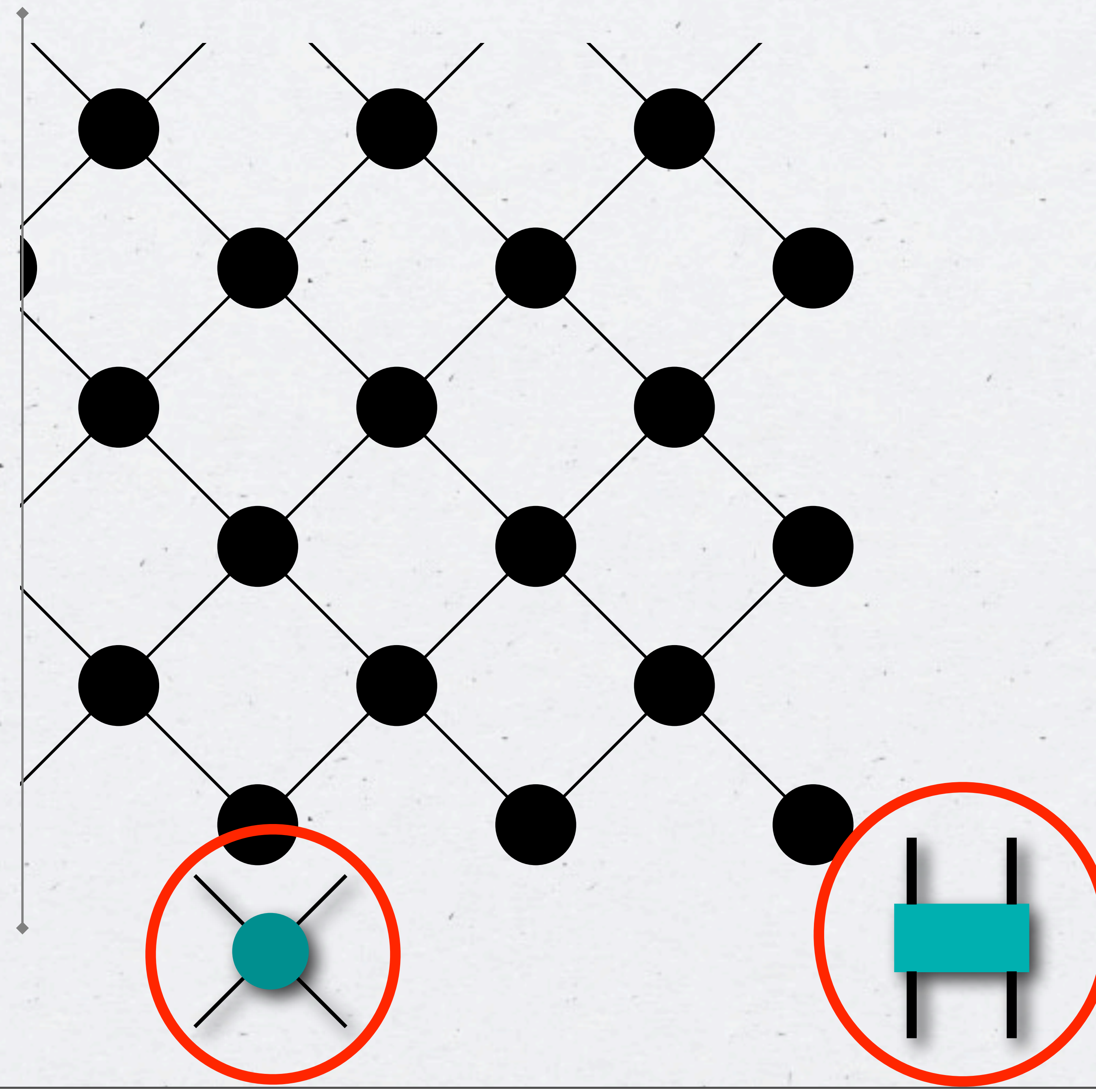
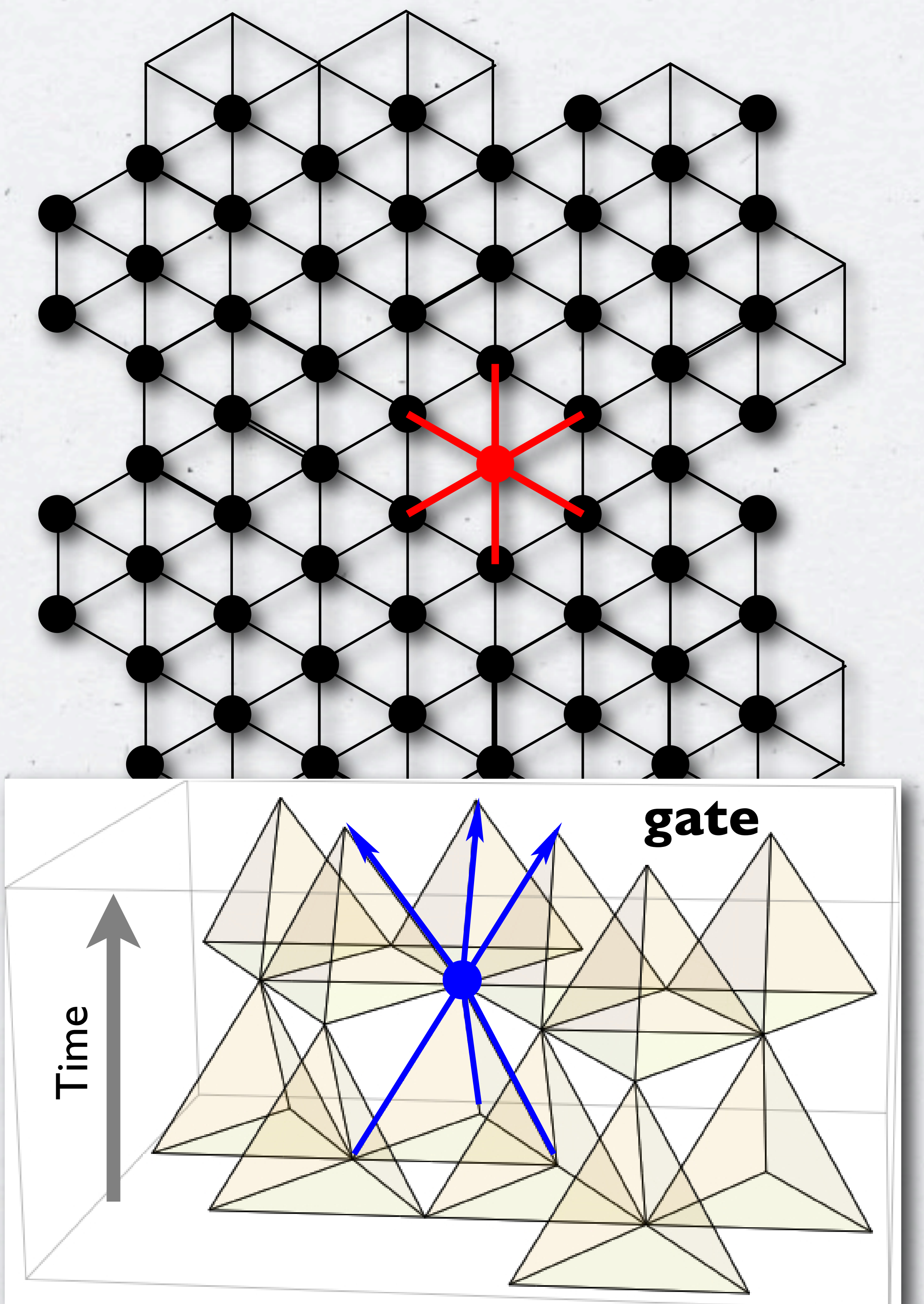


CAUSAL NETWORKS

GRAPH DIMENSION

* Homogeneous network topology

* *Space-time dimension:* graph-dimension = d+1

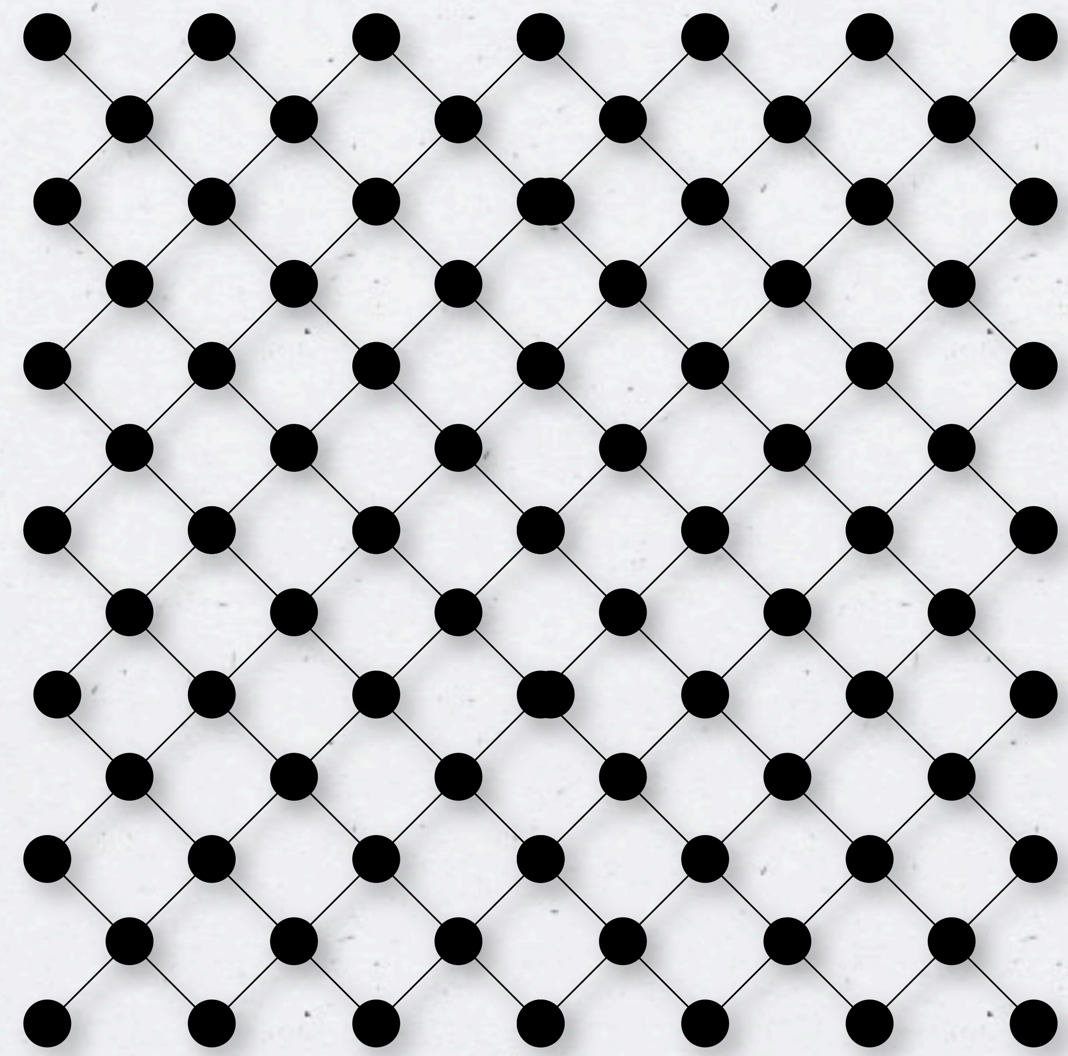


CAUSAL NETWORKS

FEW POSSIBLE LATTICES

- Homogeneous network topology
- graph-dimension = d+1

few possible causal networks



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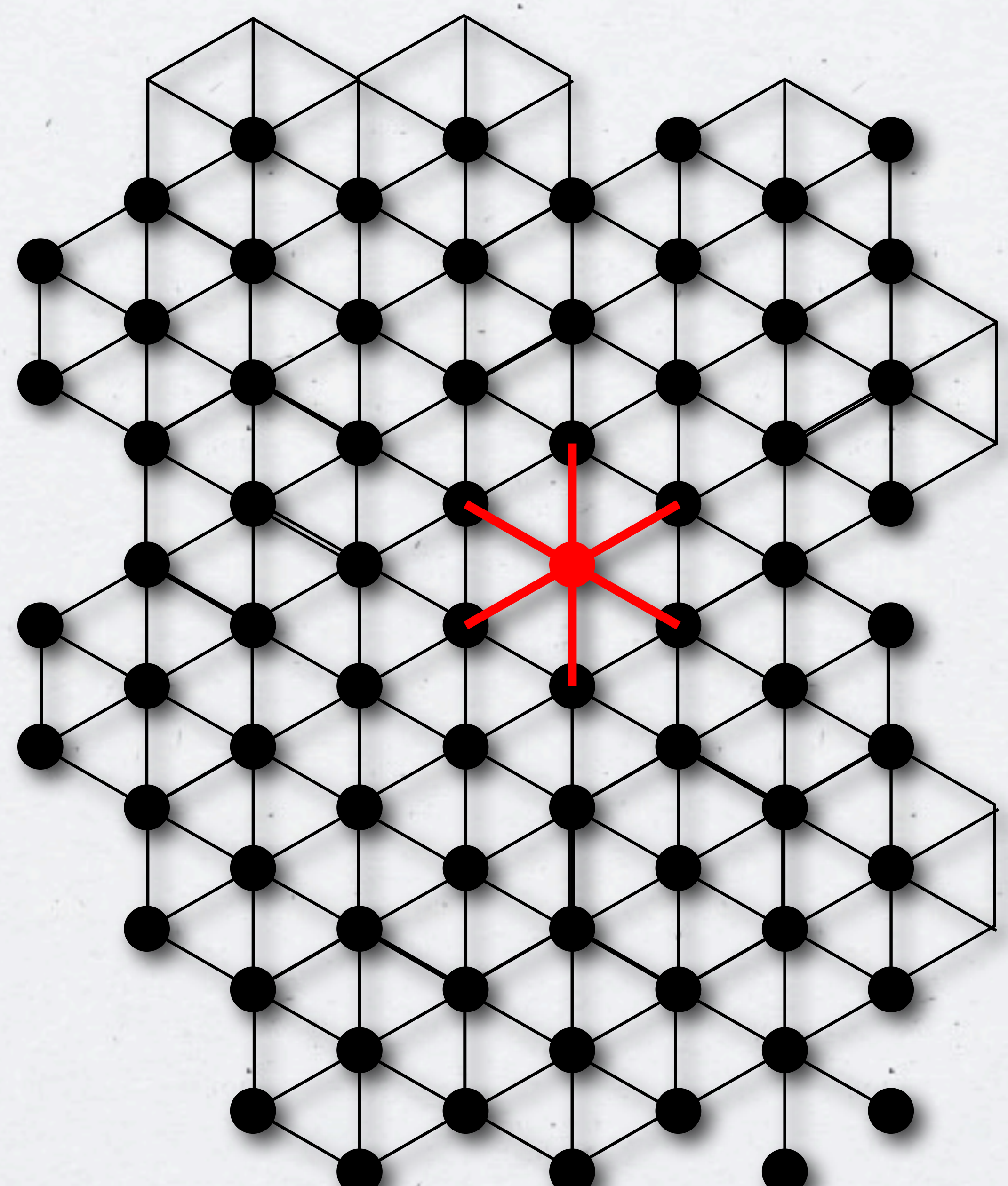

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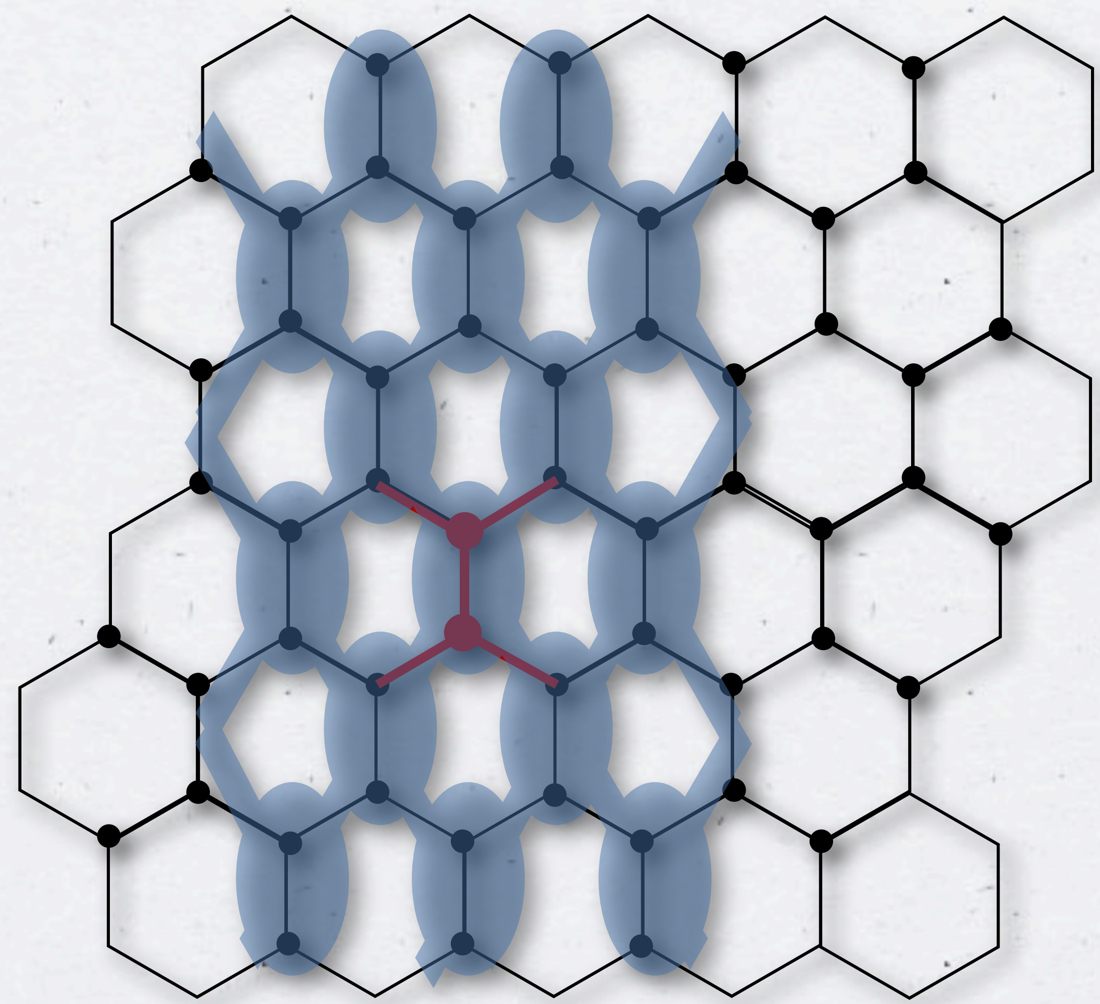
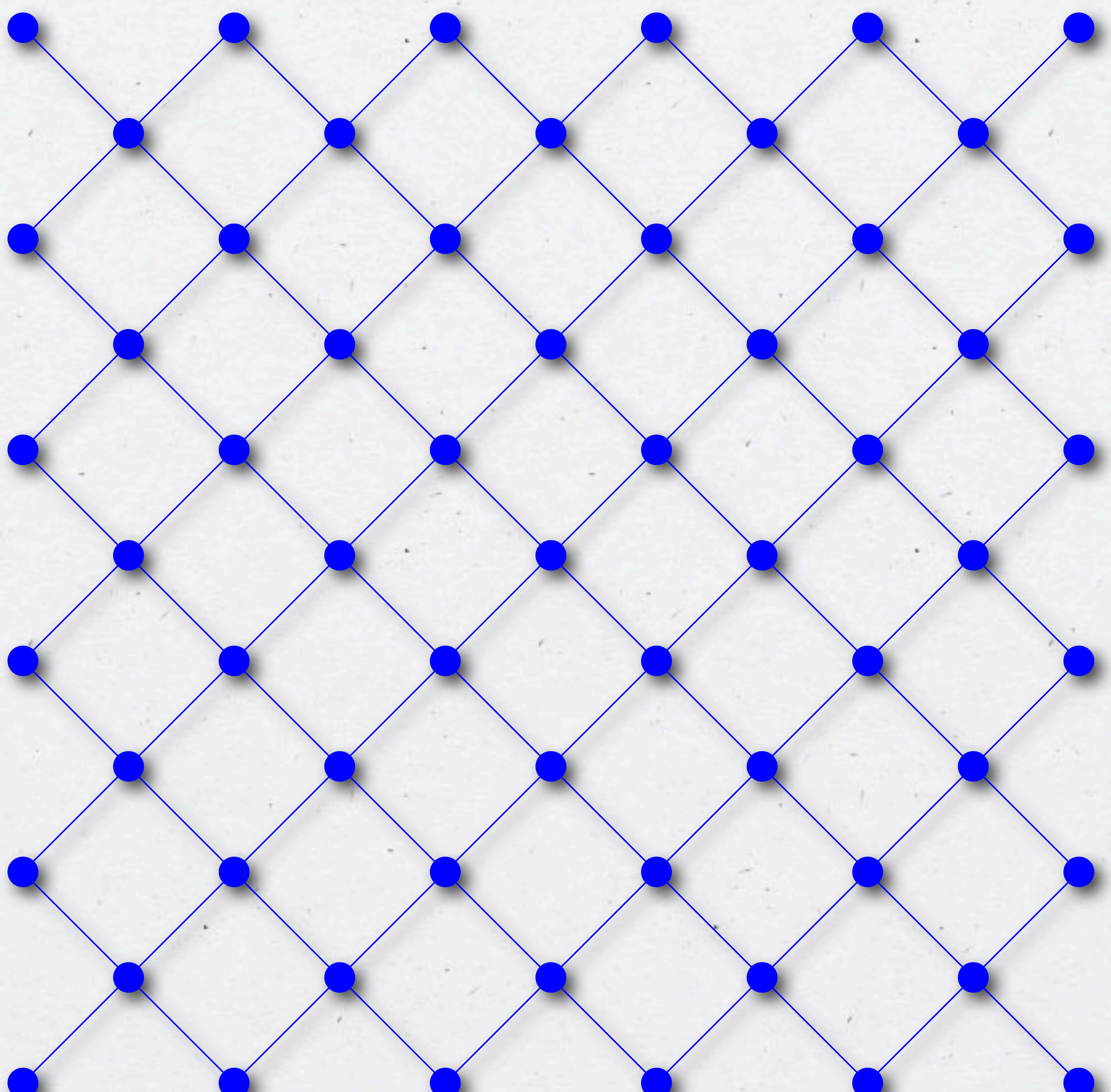


EMERGENCE OF SPACE-TIME FROM CN

CAUSAL DEPENDENCE



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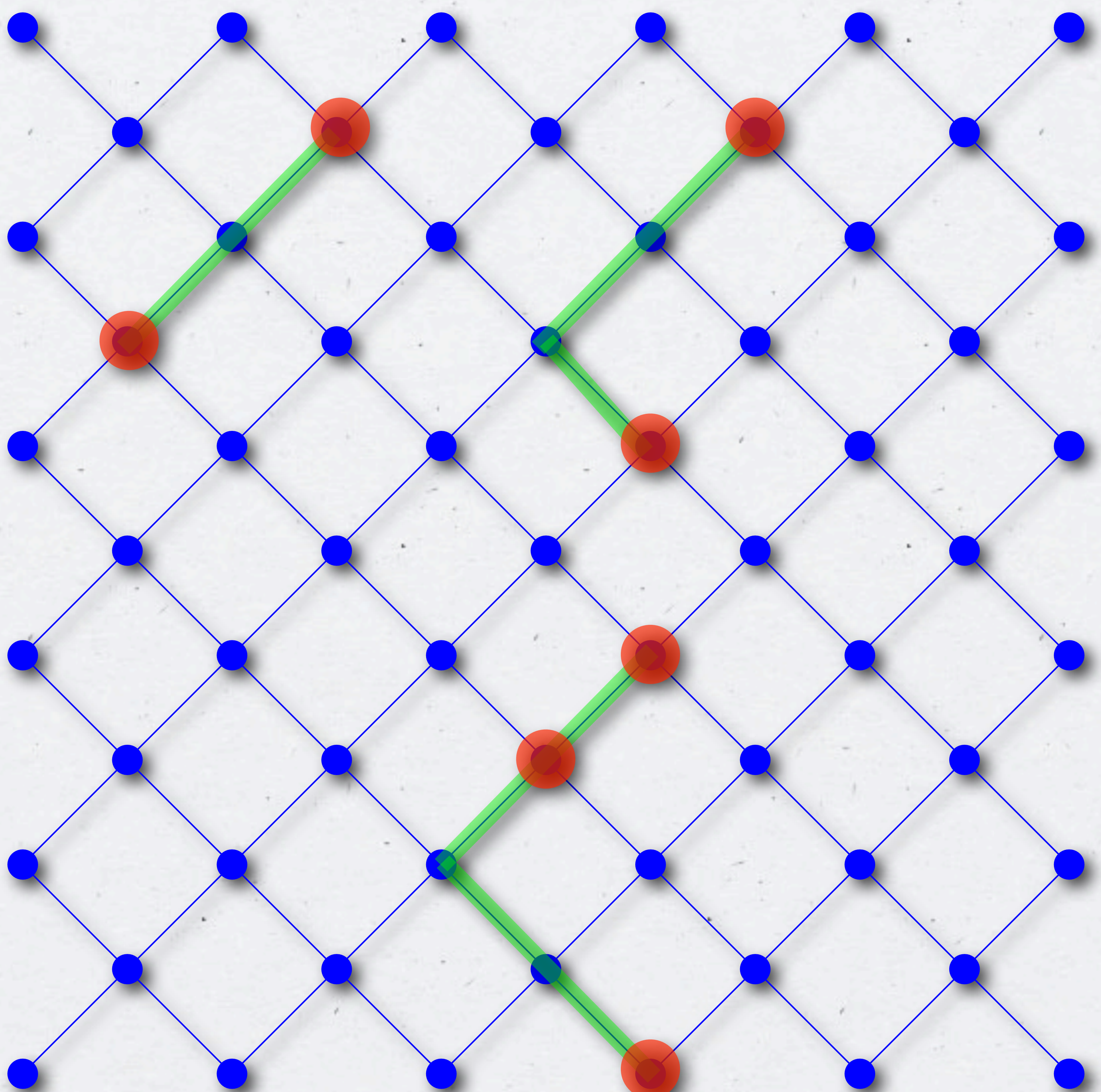
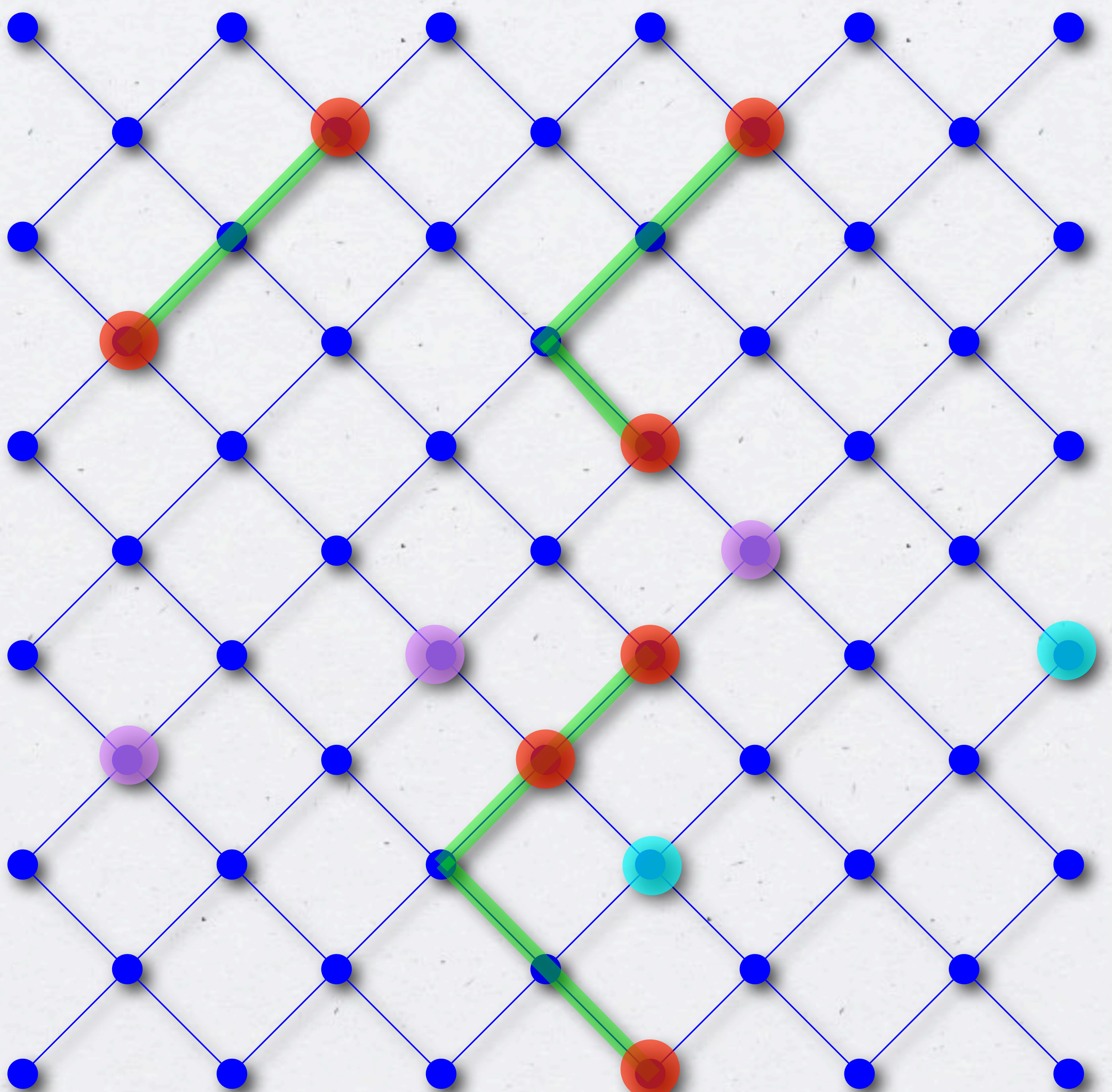


Causally dependent events

EMERGENCE OF SPACE-TIME FROM CN

CAUSAL DEPENDENCE



Causally dependent events

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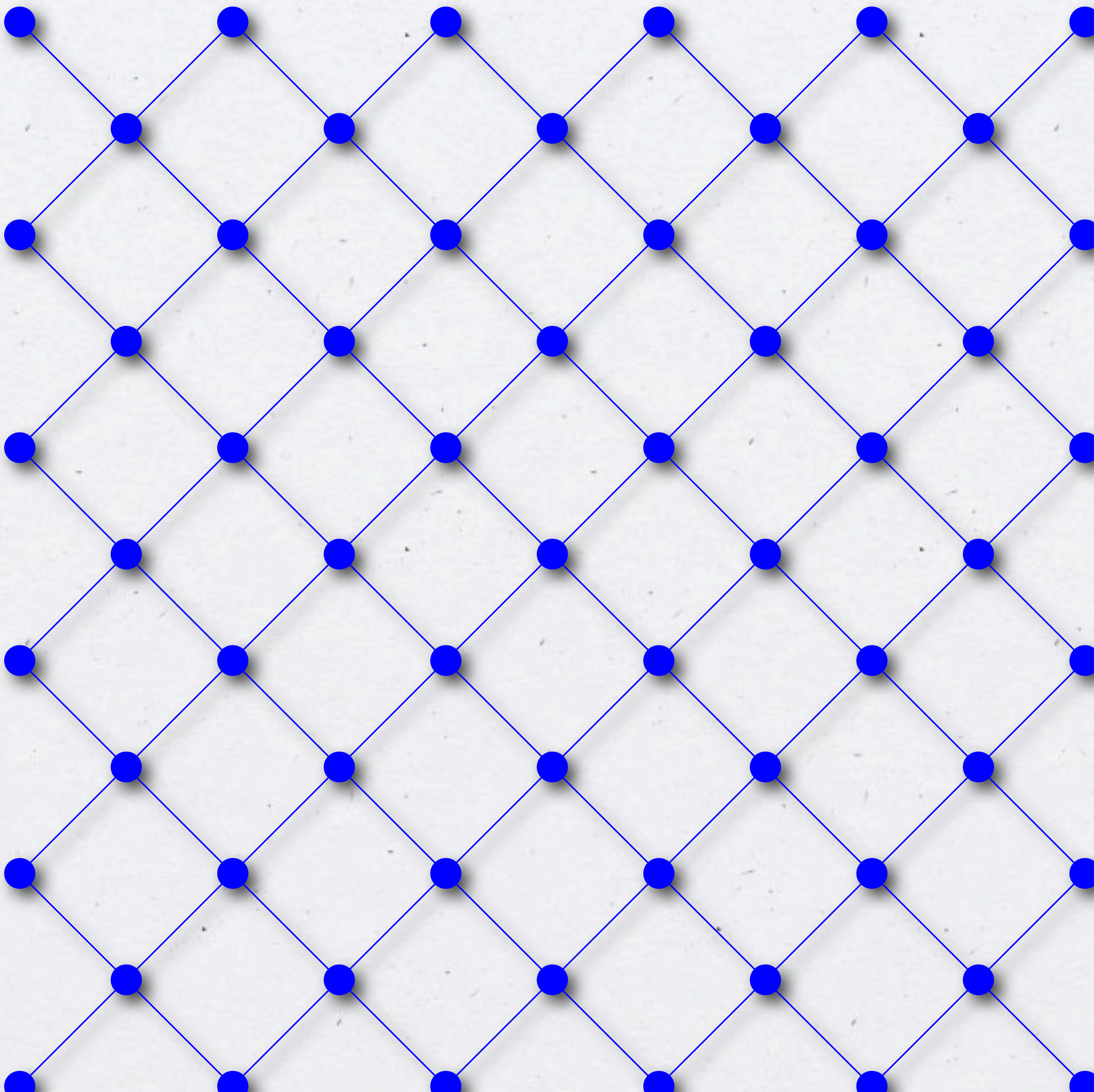
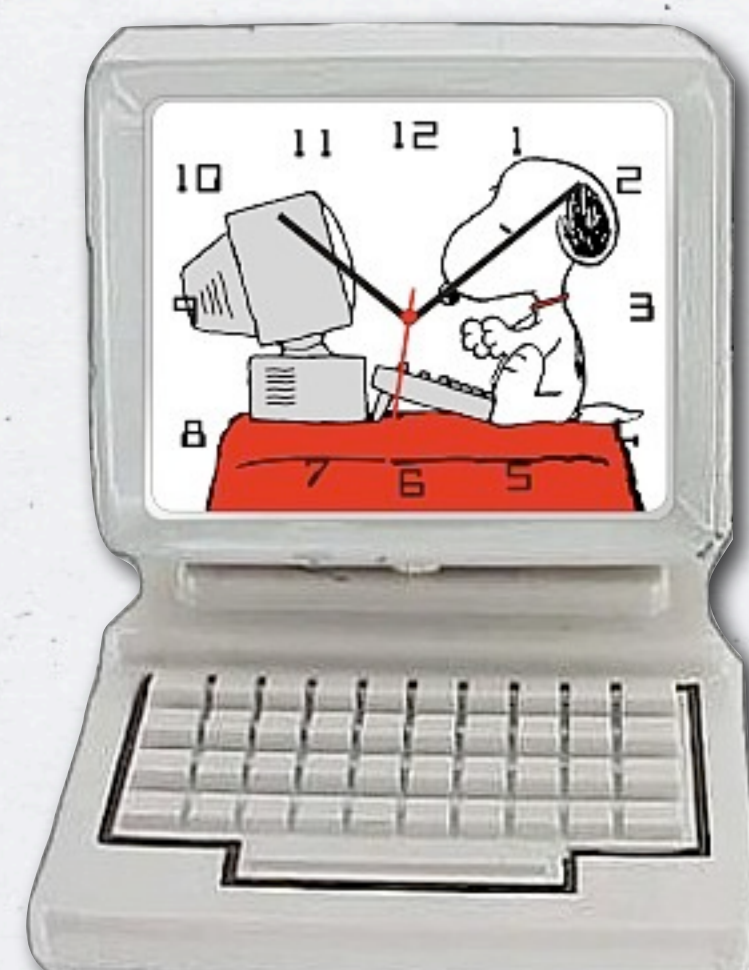
EMERGENCE OF SPACE-TIME FROM CN

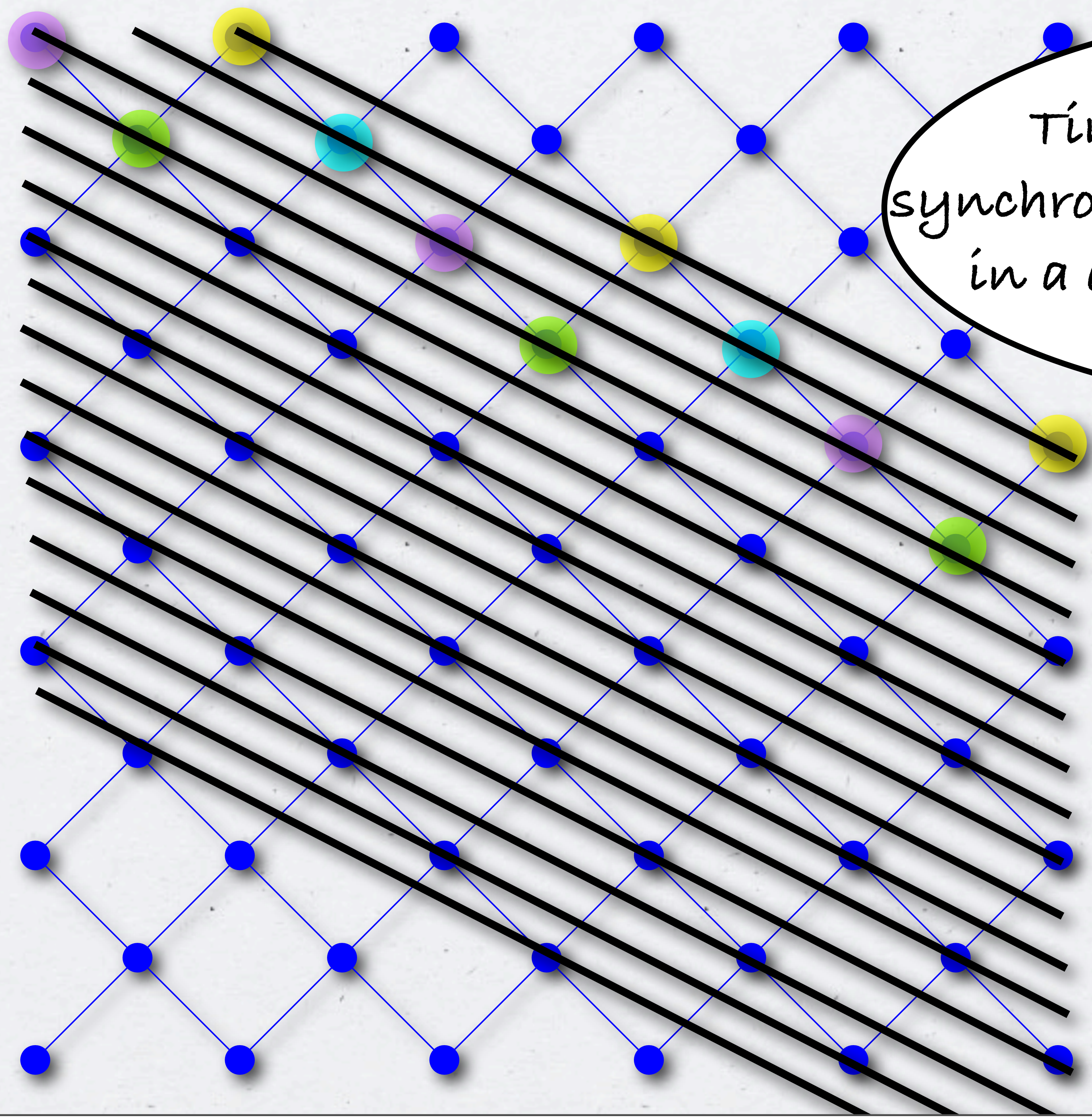
FOLIATION: TIME AS A COMPUTER CLOCK

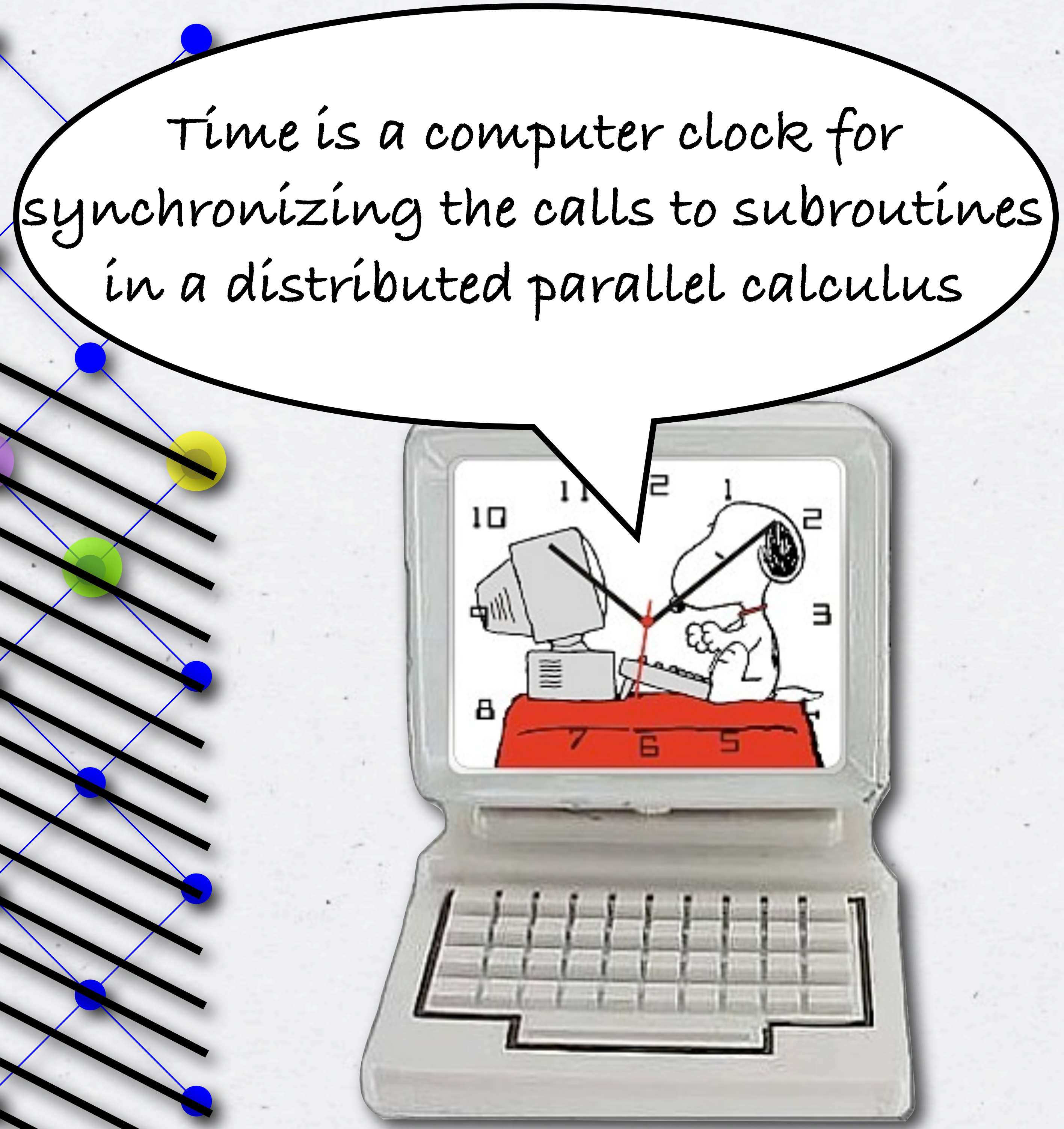




EMERGENCE OF SPACE-TIME FROM CN

THE COMPUTATIONAL TOMONAGA-SCHWINGER





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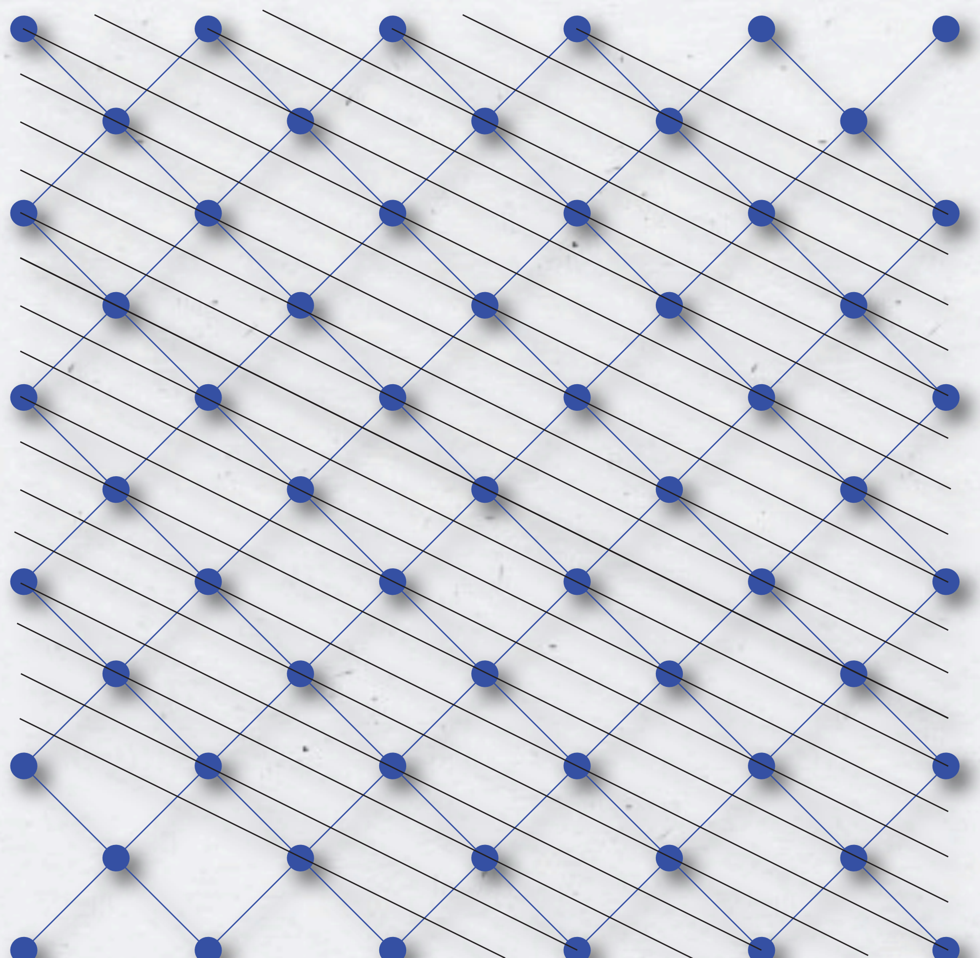
BOOSTED FRAME



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THE COMPUTATIONAL TOMONAGA-SCHWINGER

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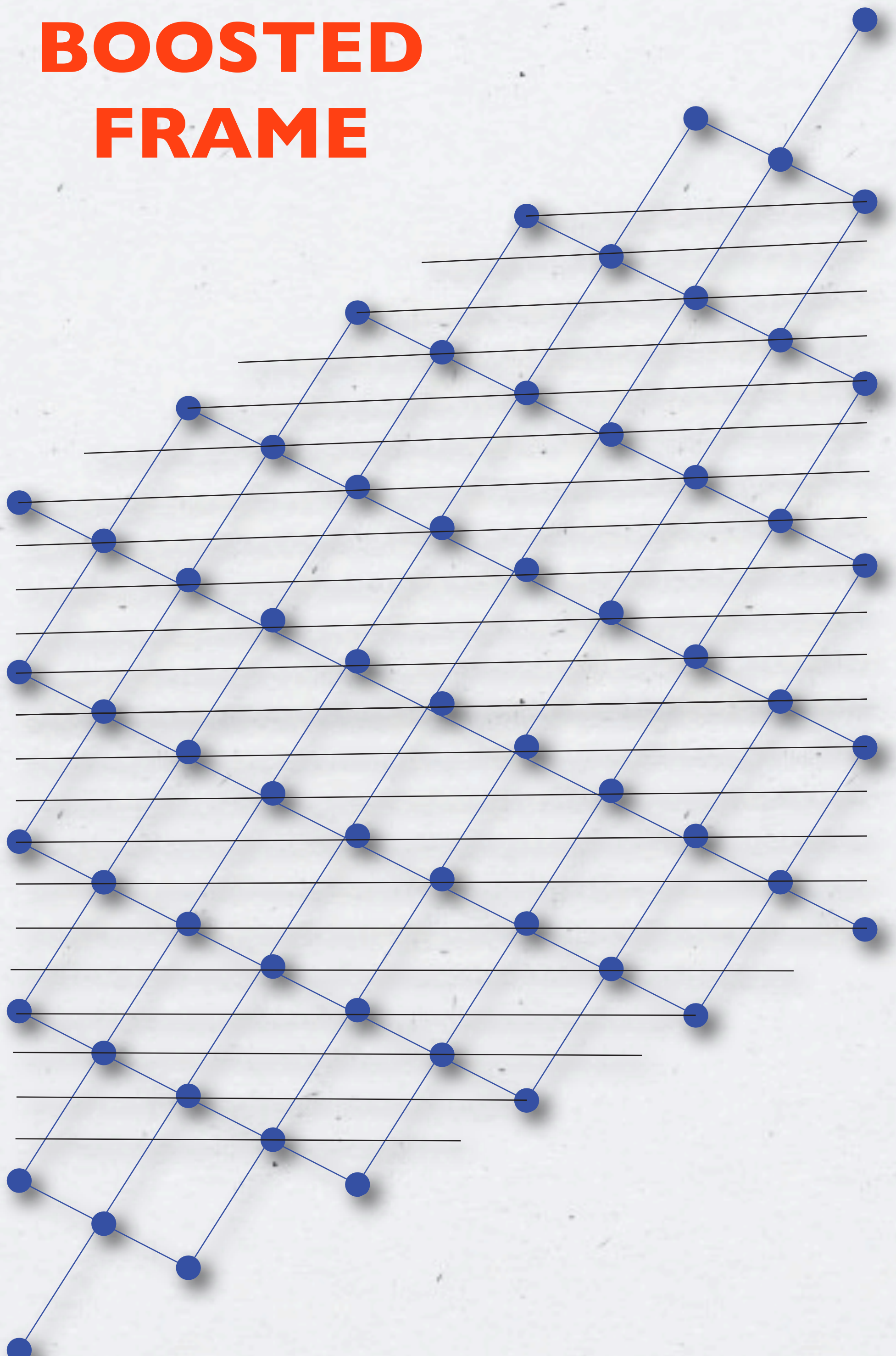

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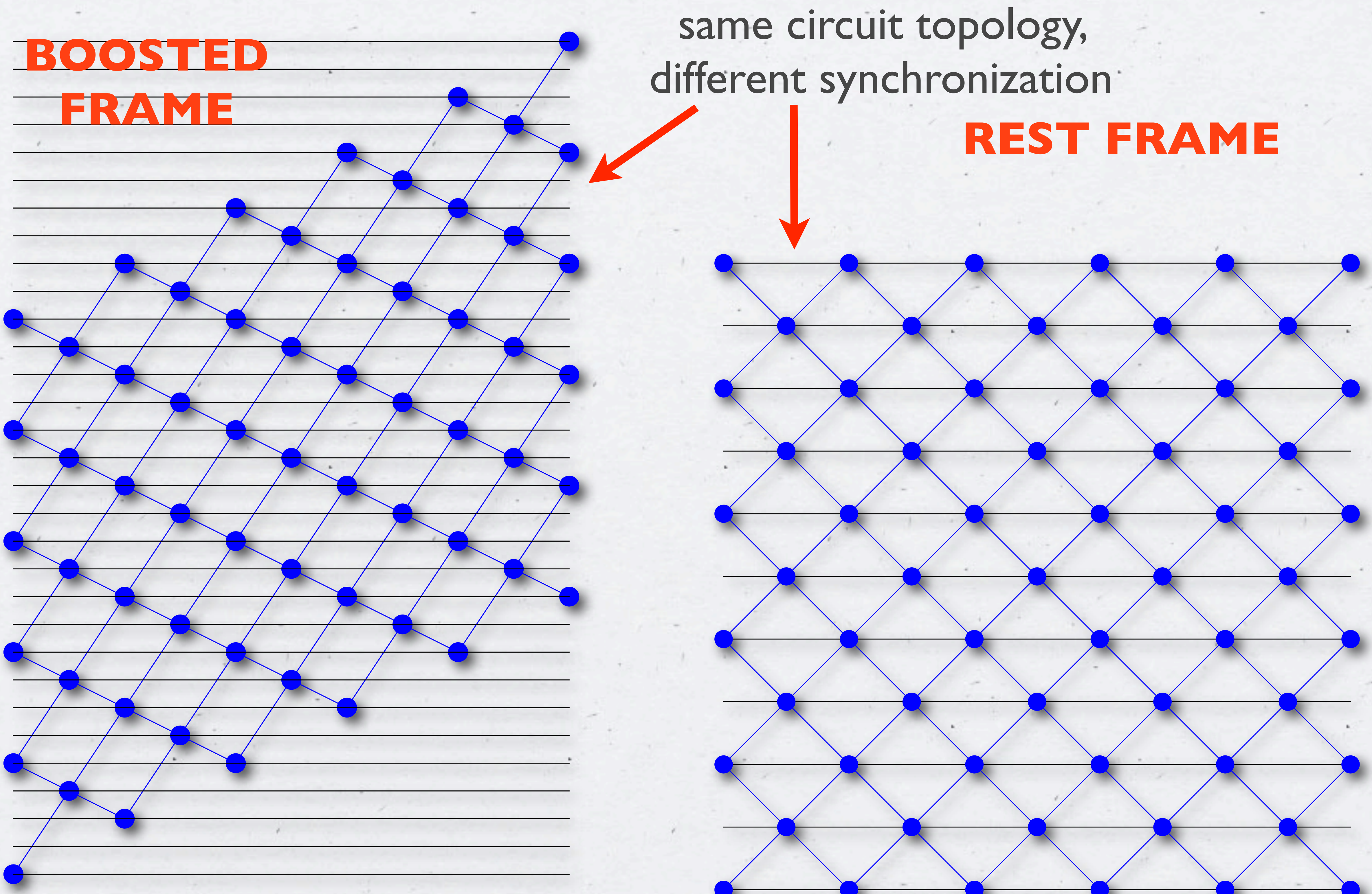

EMERGENCE OF SPACE-TIME FROM CN

TIME-DILATION AND SPACE-CONTRACTION

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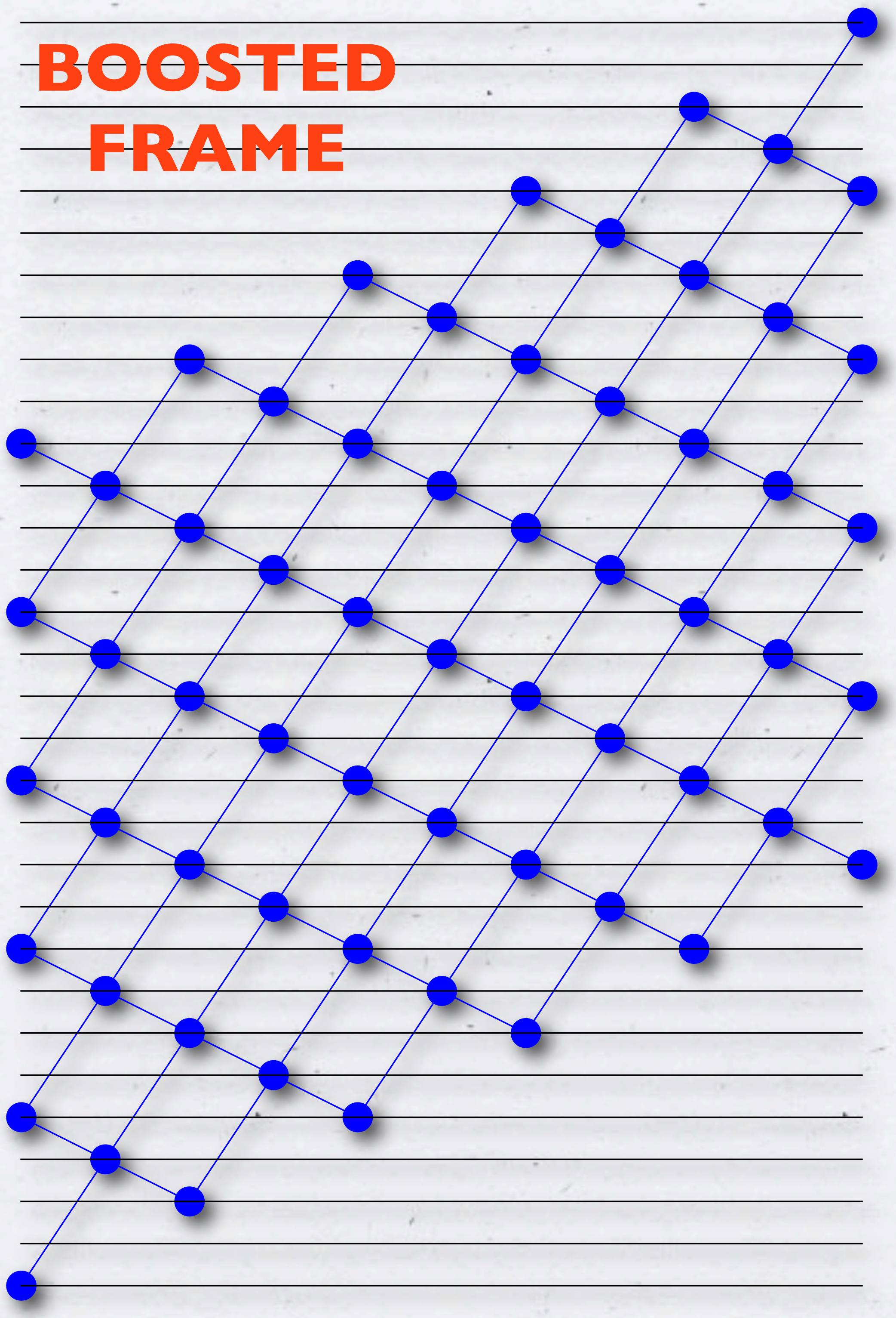

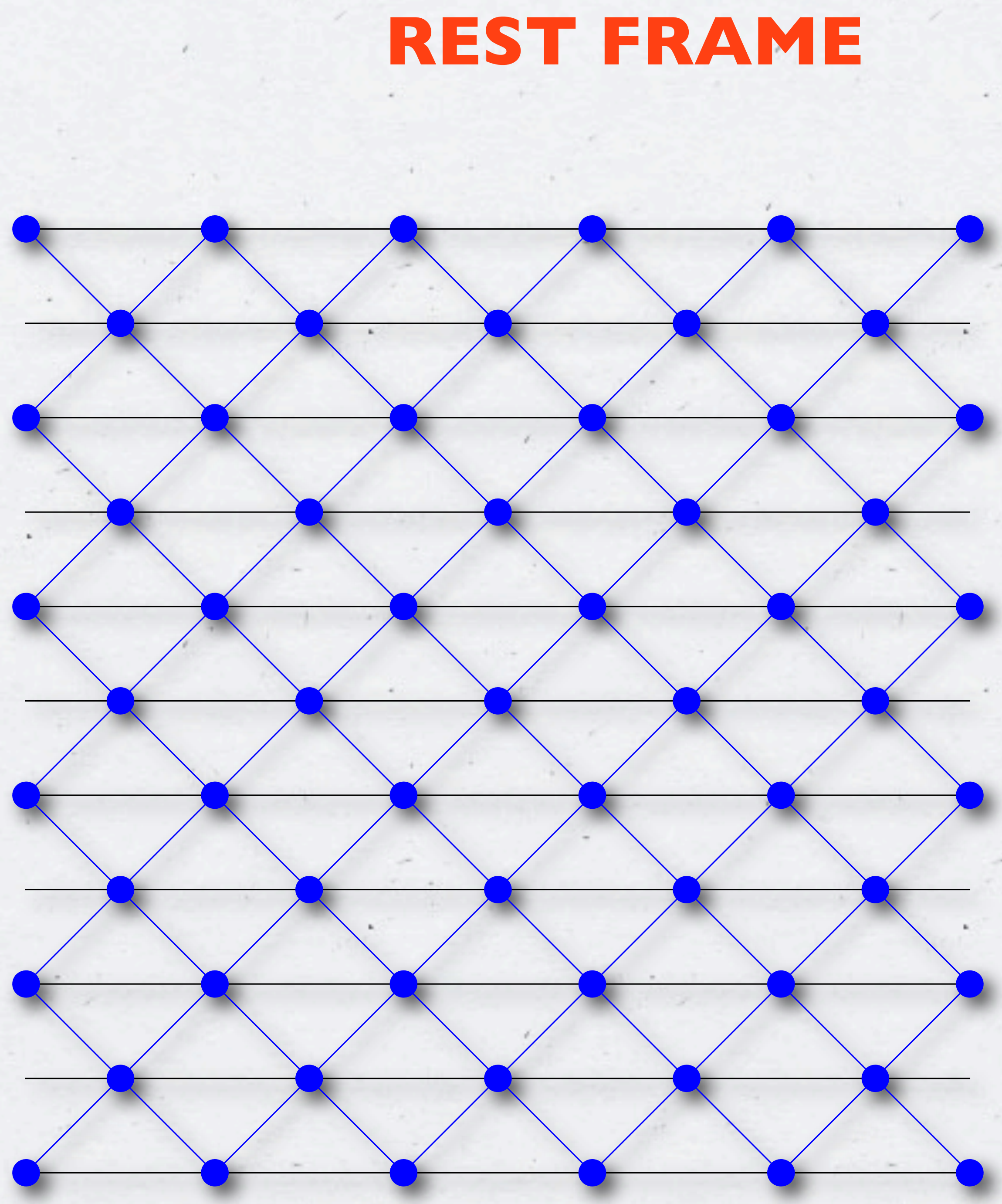

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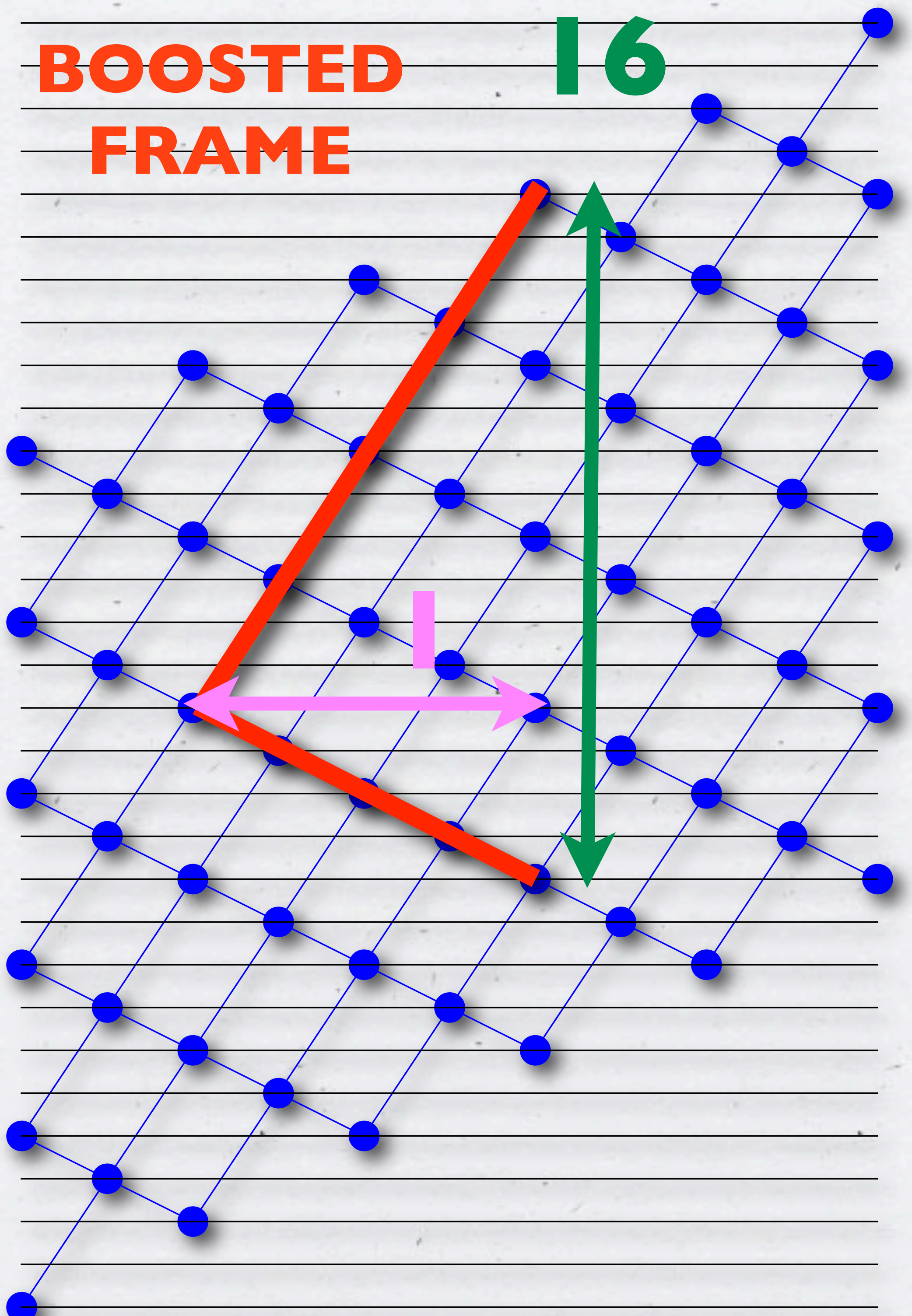
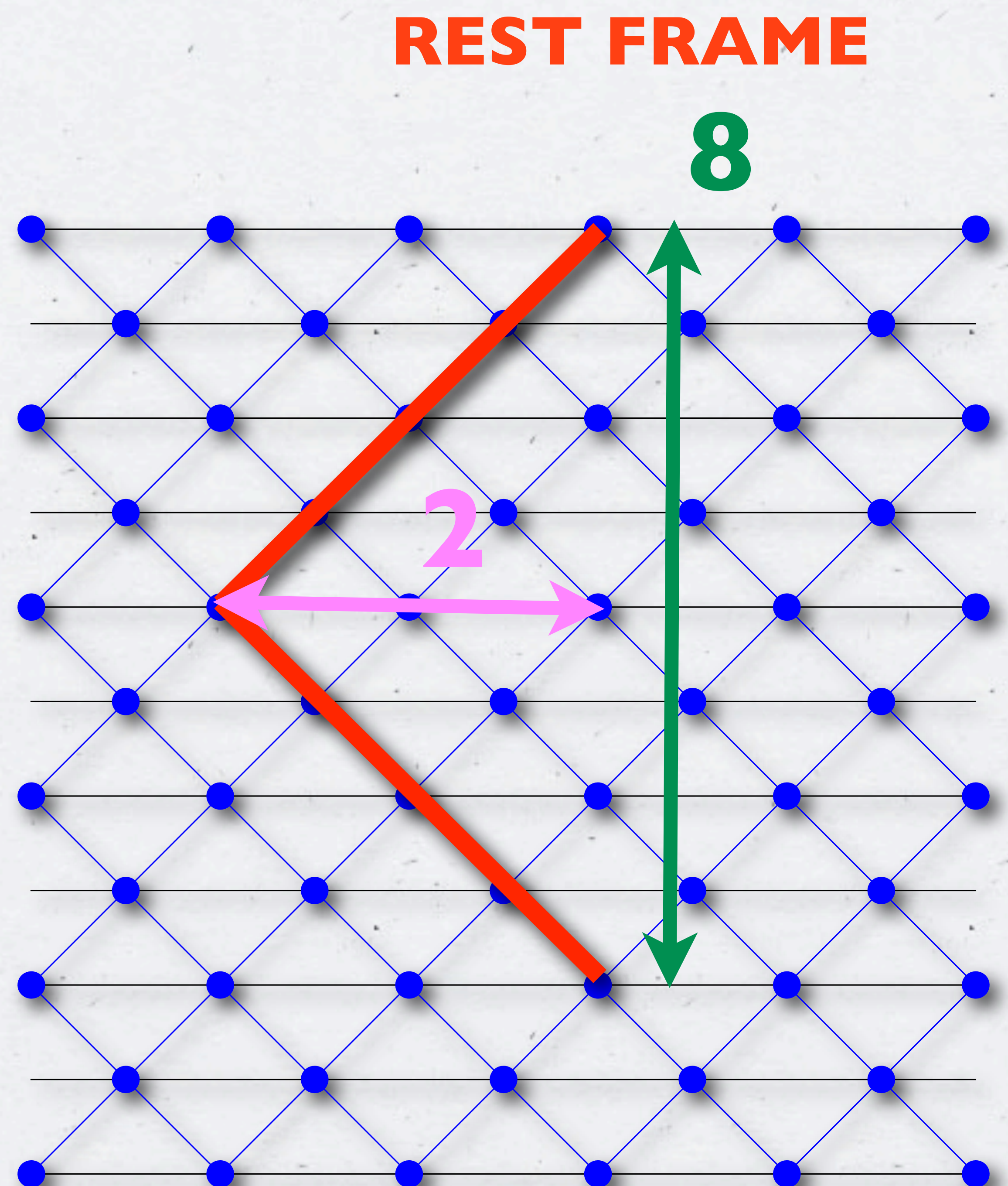
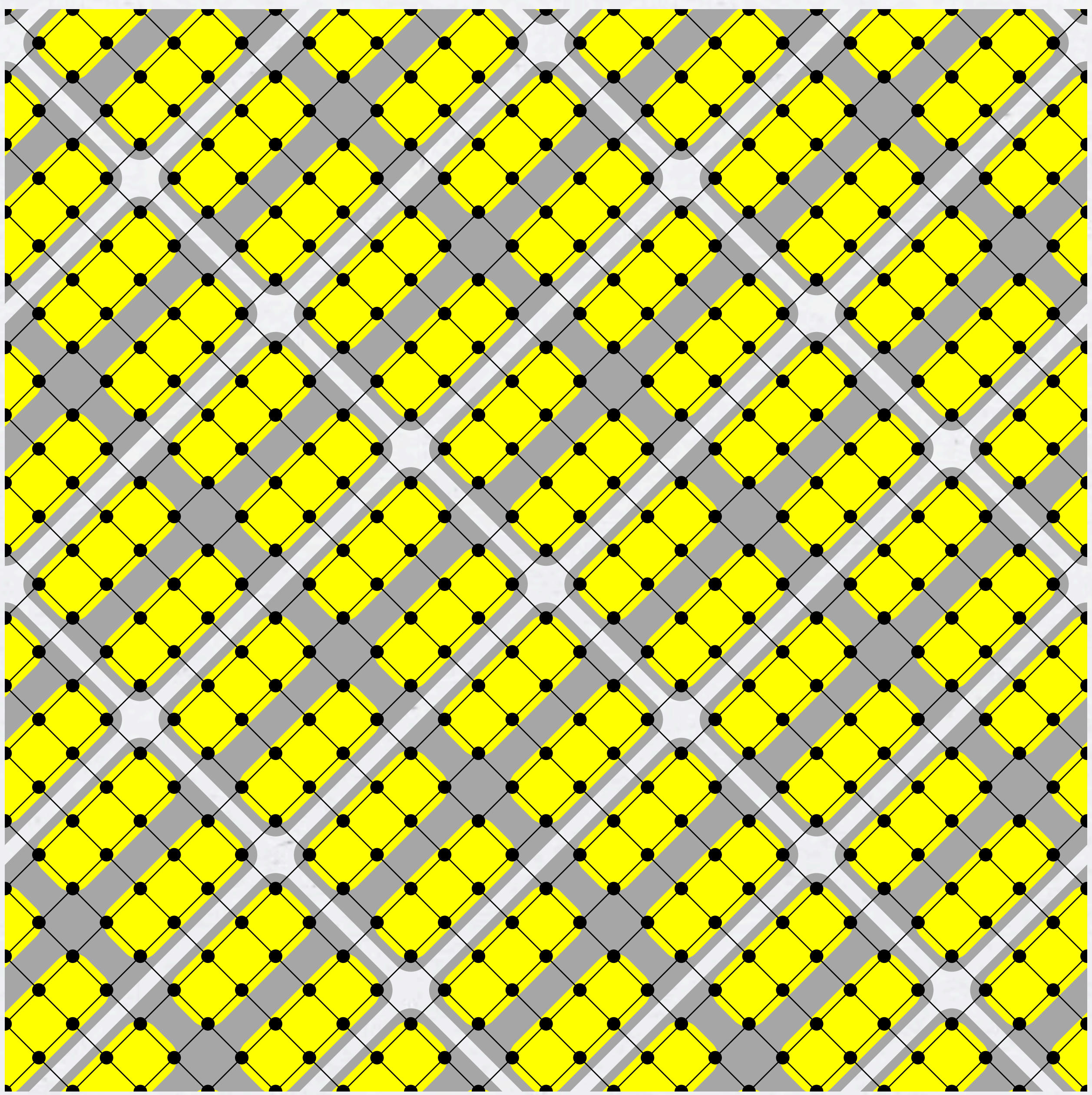




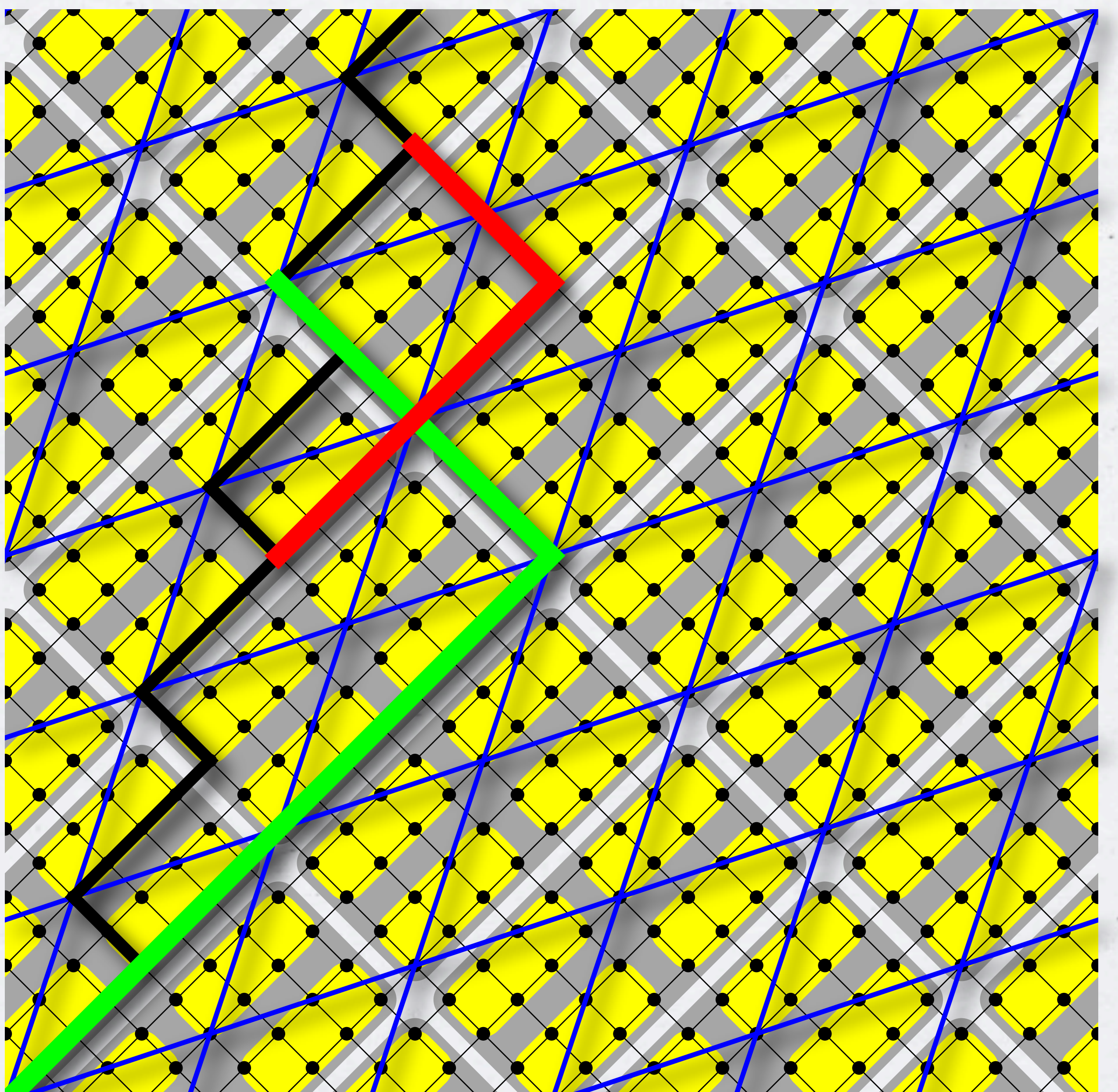
EMERGENCE OF SPACE-TIME FROM CN

CONSTRUCTION OF THE COORDINATE SYSTEM



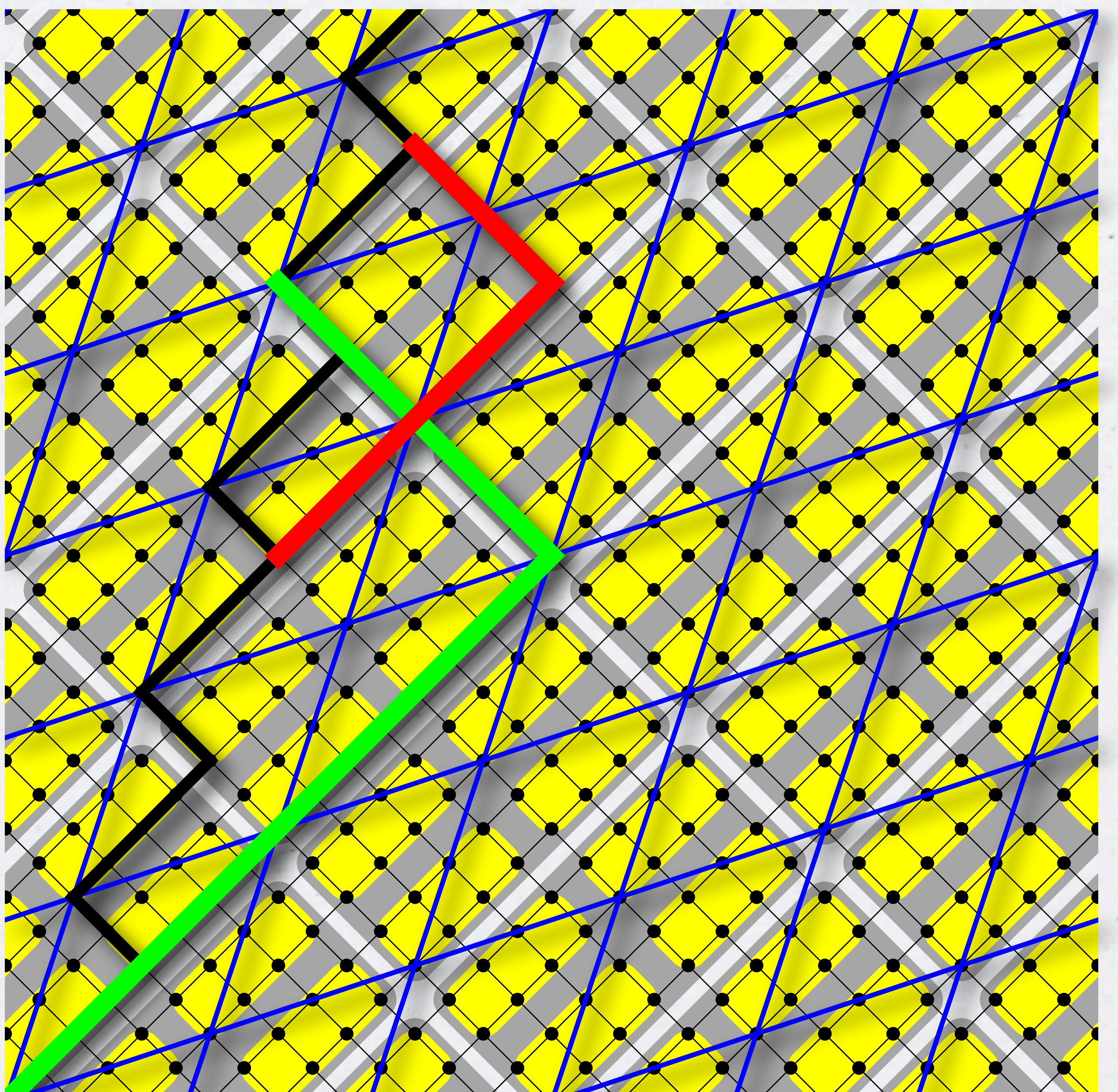
EMERGENCE OF SPACE-TIME FROM CN

CONSTRUCTION OF THE COORDINATE SYSTEM



EMERGENCE OF SPACE-TIME FROM CN

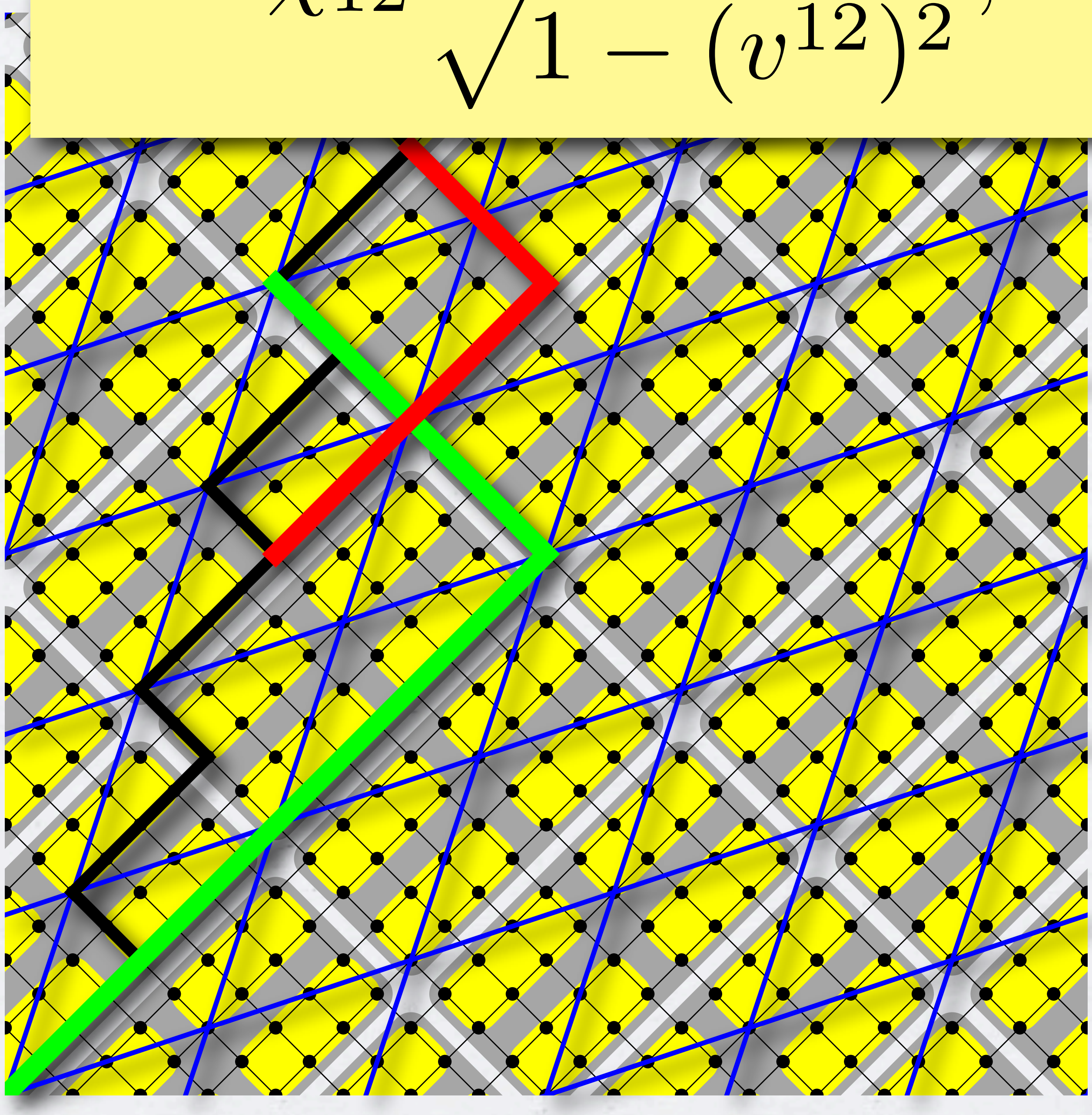
DIGITAL LORENTZ TRANSFORMATIONS



EMERGENCE OF SPACE-TIME FROM CN

DIGITAL LORENTZ TRANSFORMATIONS

$$t^1 = \chi_{12} \frac{t^2 + v^{12} s^2}{\sqrt{1-(v^{12})^2}}, \qquad s^1 = \chi_{12} \frac{s^2 + v^{12} t^2}{\sqrt{1-(v^{12})^2}},$$



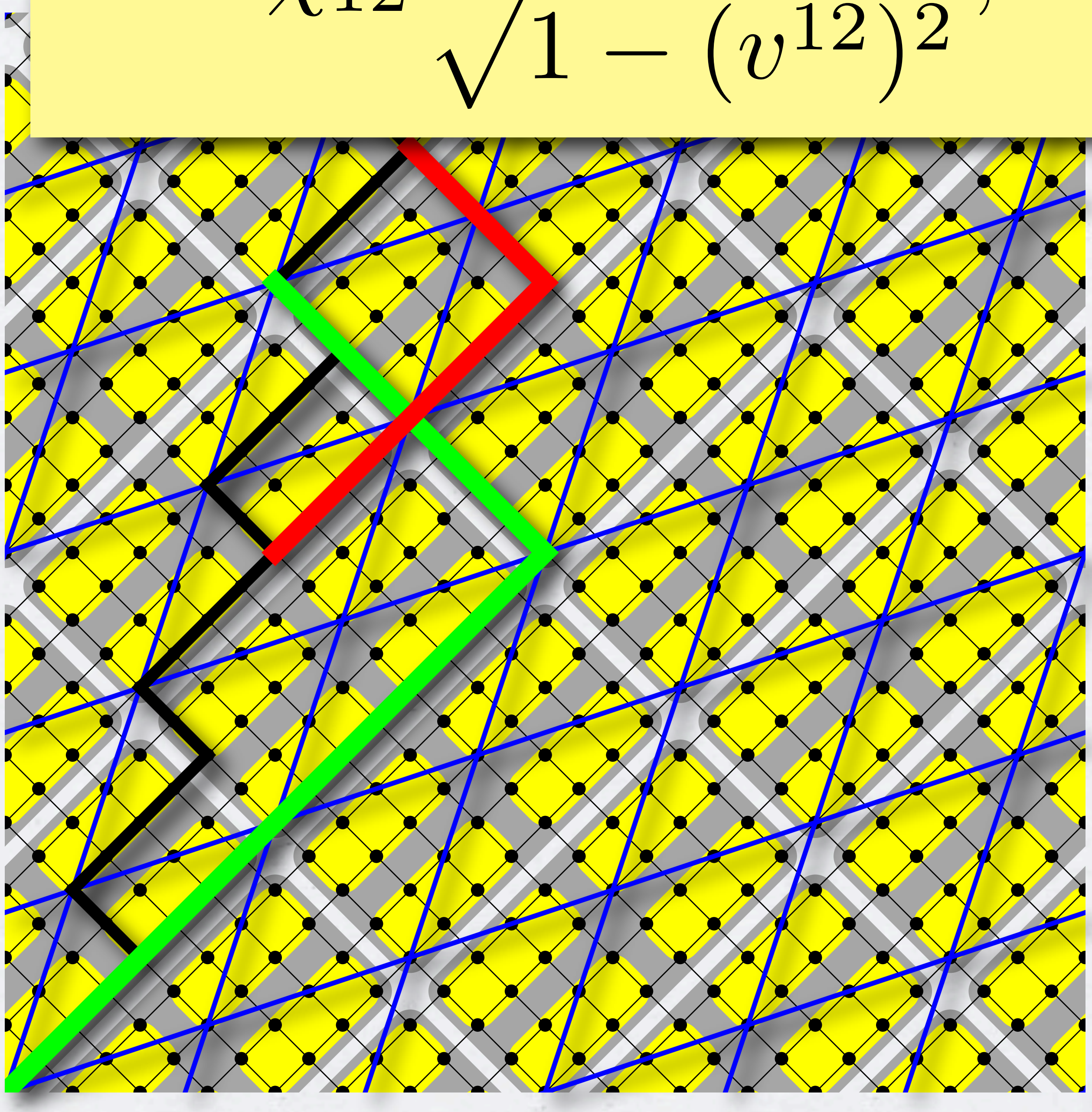
$$\chi_{12} := \sqrt{\alpha^{12}\beta^{12}}$$

$$v_{13} = \frac{v_{12} + v_{23}}{1 + v_{12} v_{23}}$$

EMERGENCE OF SPACE-TIME FROM CN

DIGITAL LORENTZ TRANSFORMATIONS

$$t^1 = \chi_{12} \frac{t^2 + v^{12} s^2}{\sqrt{1-(v^{12})^2}}, \qquad s^1 = \chi_{12} \frac{s^2 + v^{12} t^2}{\sqrt{1-(v^{12})^2}},$$



$$\chi_{12} := \sqrt{\alpha^{12}\beta^{12}}$$

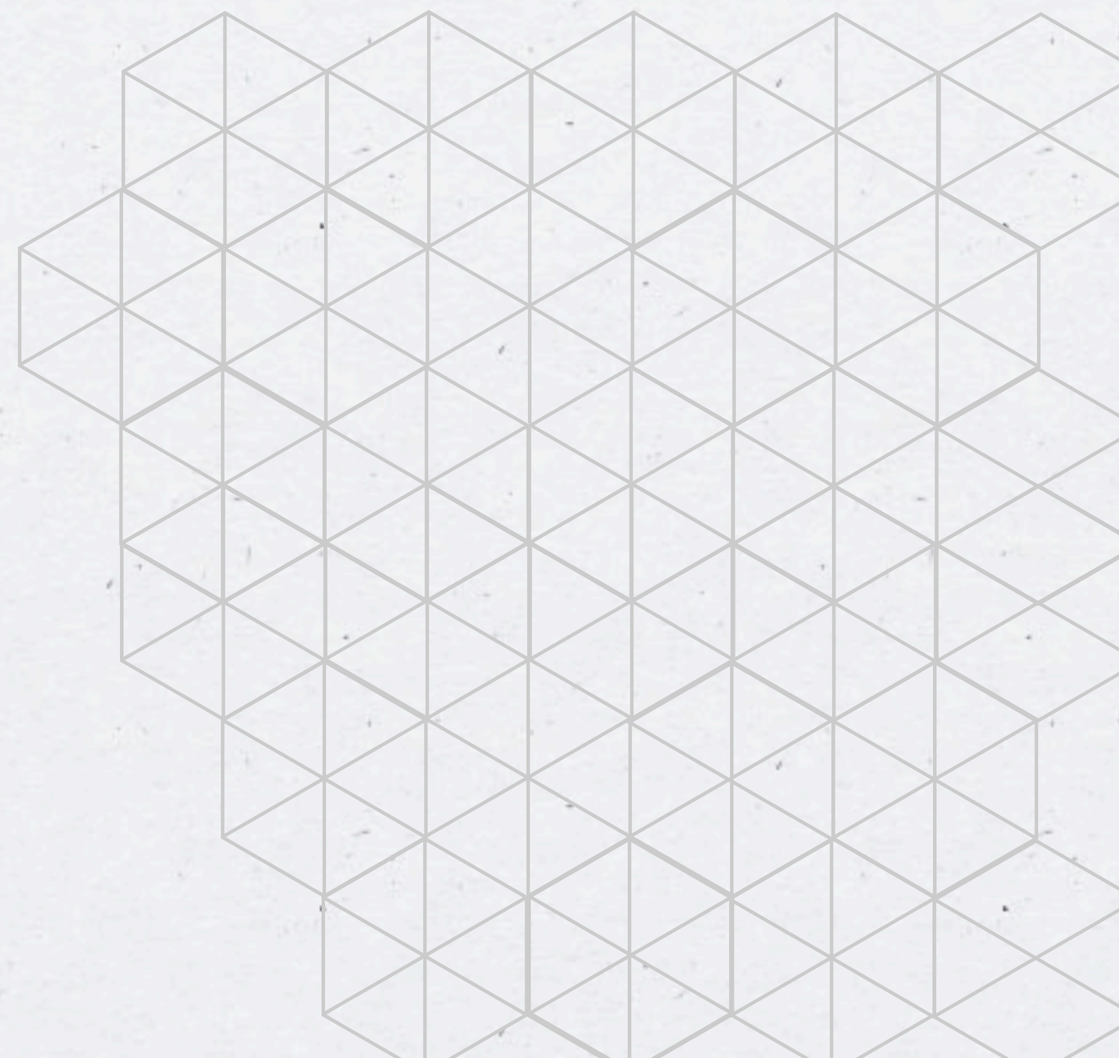
$$\frac{1}{2}(\alpha^{12} + \beta^{12})$$

$$v_{13} = \frac{v_{12} + v_{23}}{1 + v_{12} v_{23}}$$

EMERGENCE OF SPACE-TIME FROM CN

DIMENSIONAL CONUNDRUM

- Anisotropy of max-speed of information (no-digital-go theorem by Tobias Fritz)



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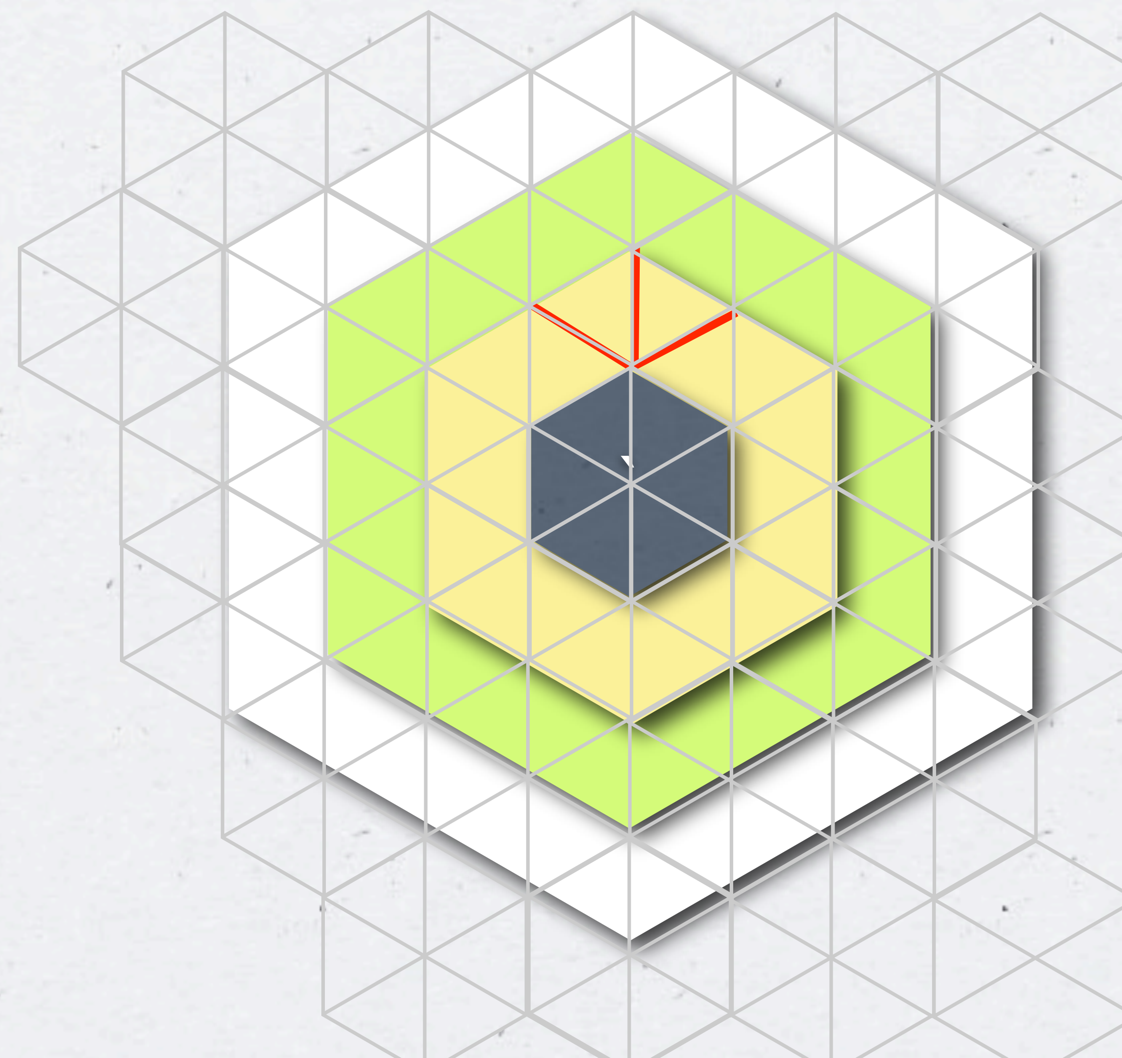

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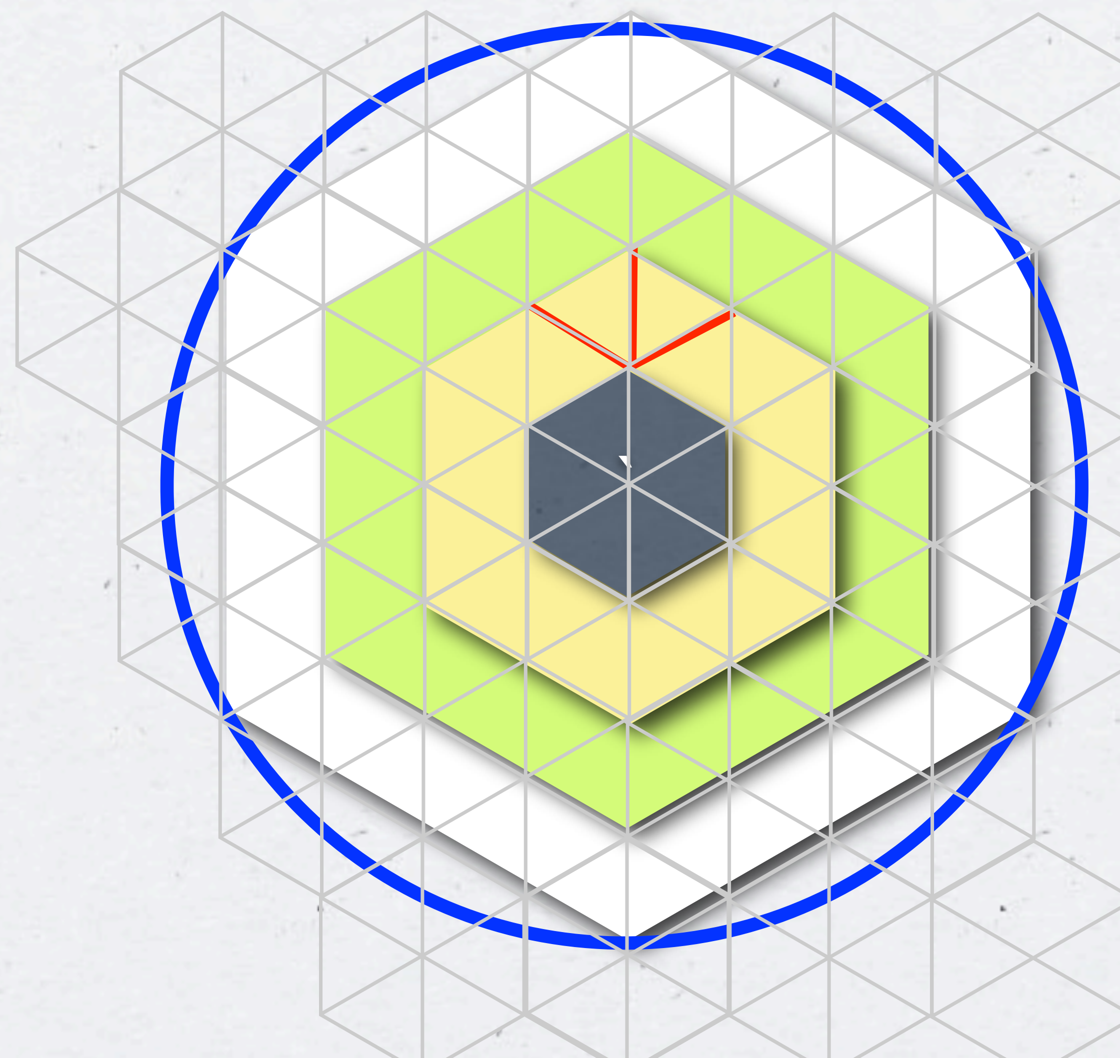

EMERGENCE OF SPACE-TIME FROM CN

DIMENSIONAL CONUNDRUM

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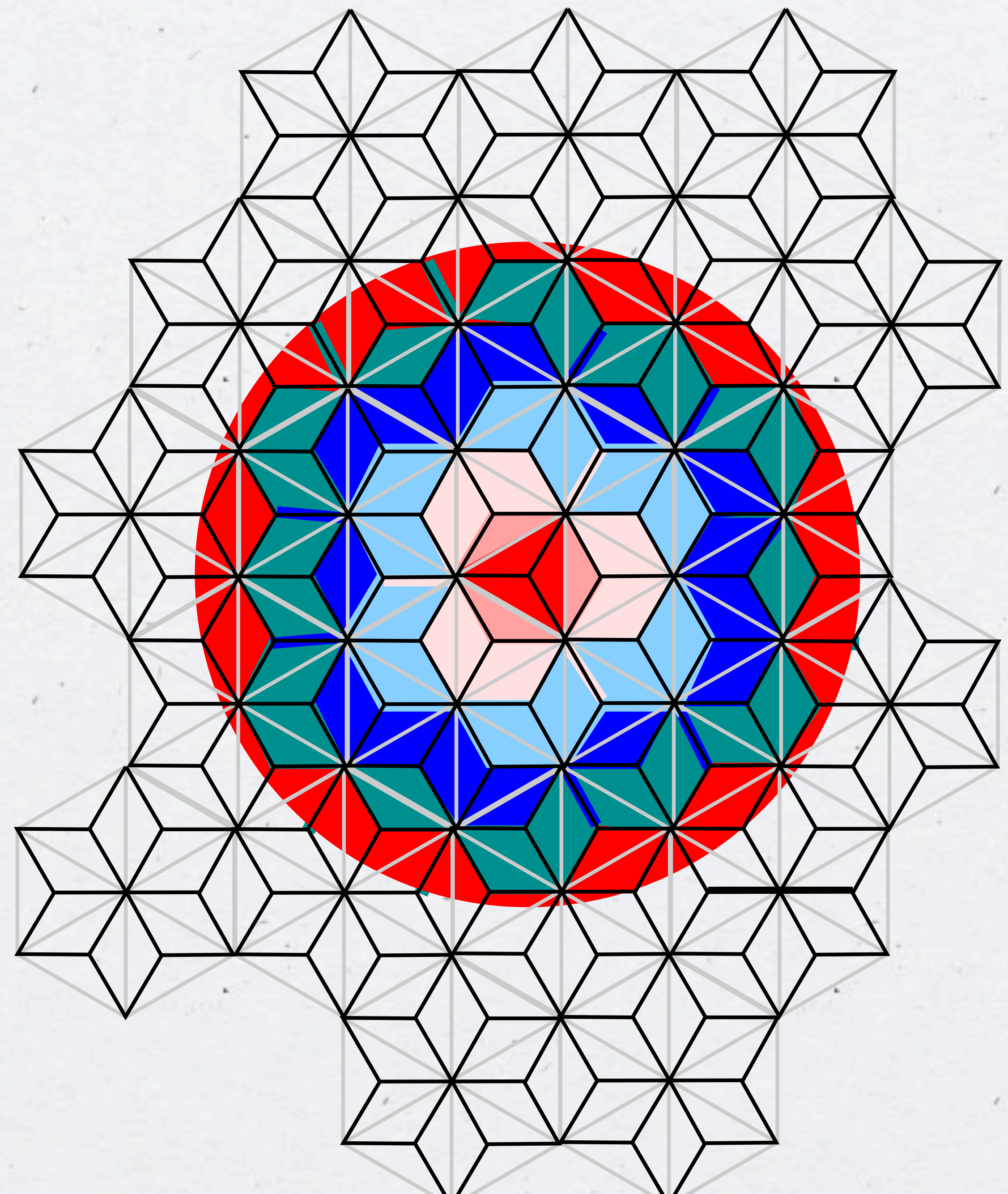

EMERGENCE OF SPACE-TIME FROM CN

DIMENSIONAL CONUNDRUM

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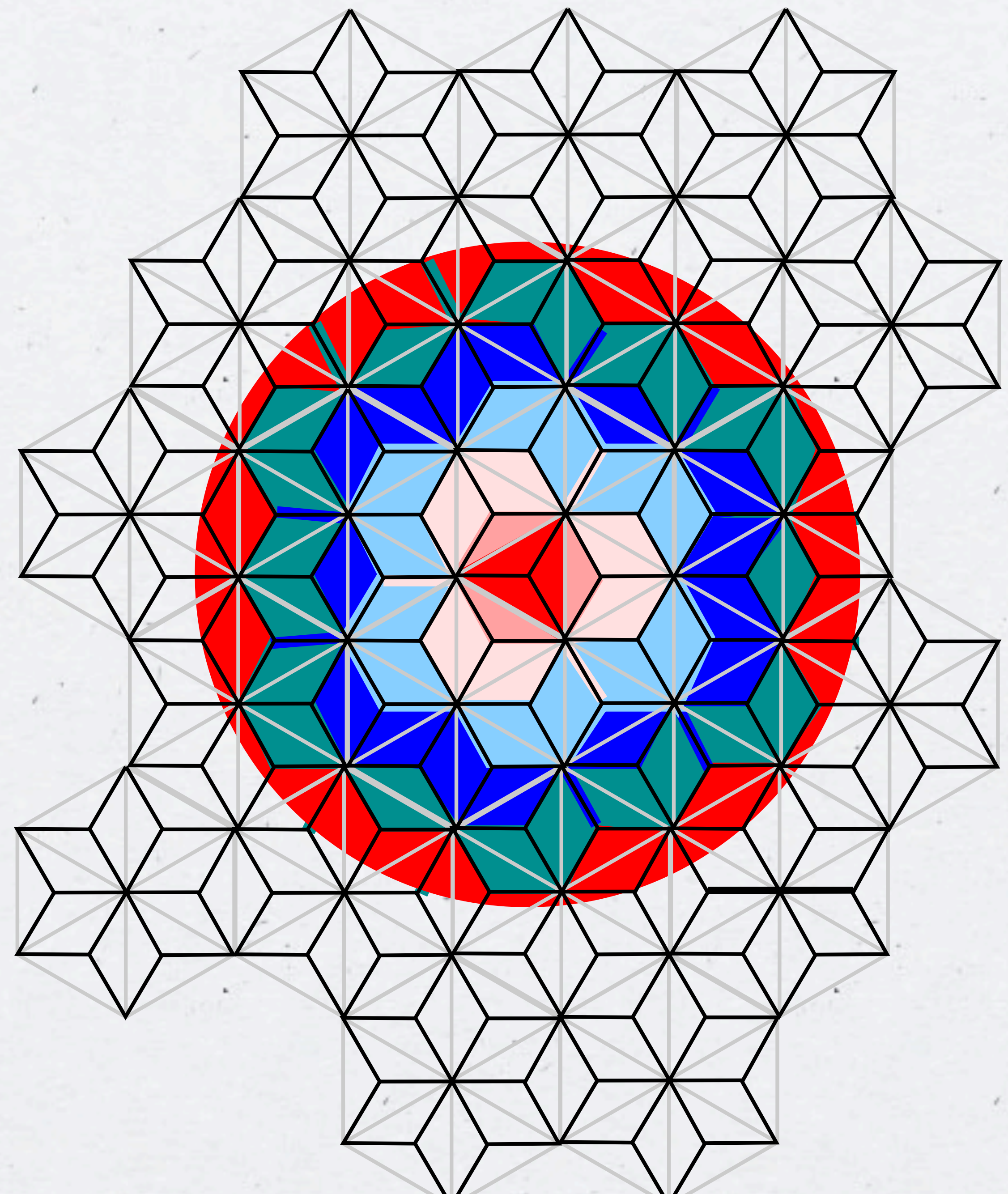
* Anisotropy of max-speed of information (no-digital-go theorem by Tobias Fritz)

Possible solution:

quantum nature of the CN!



INFORMATION FLOW IN 1+1:
LORENTZ COVARIANCE IS A BONUS!

THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUATION (1+1 dimensions)

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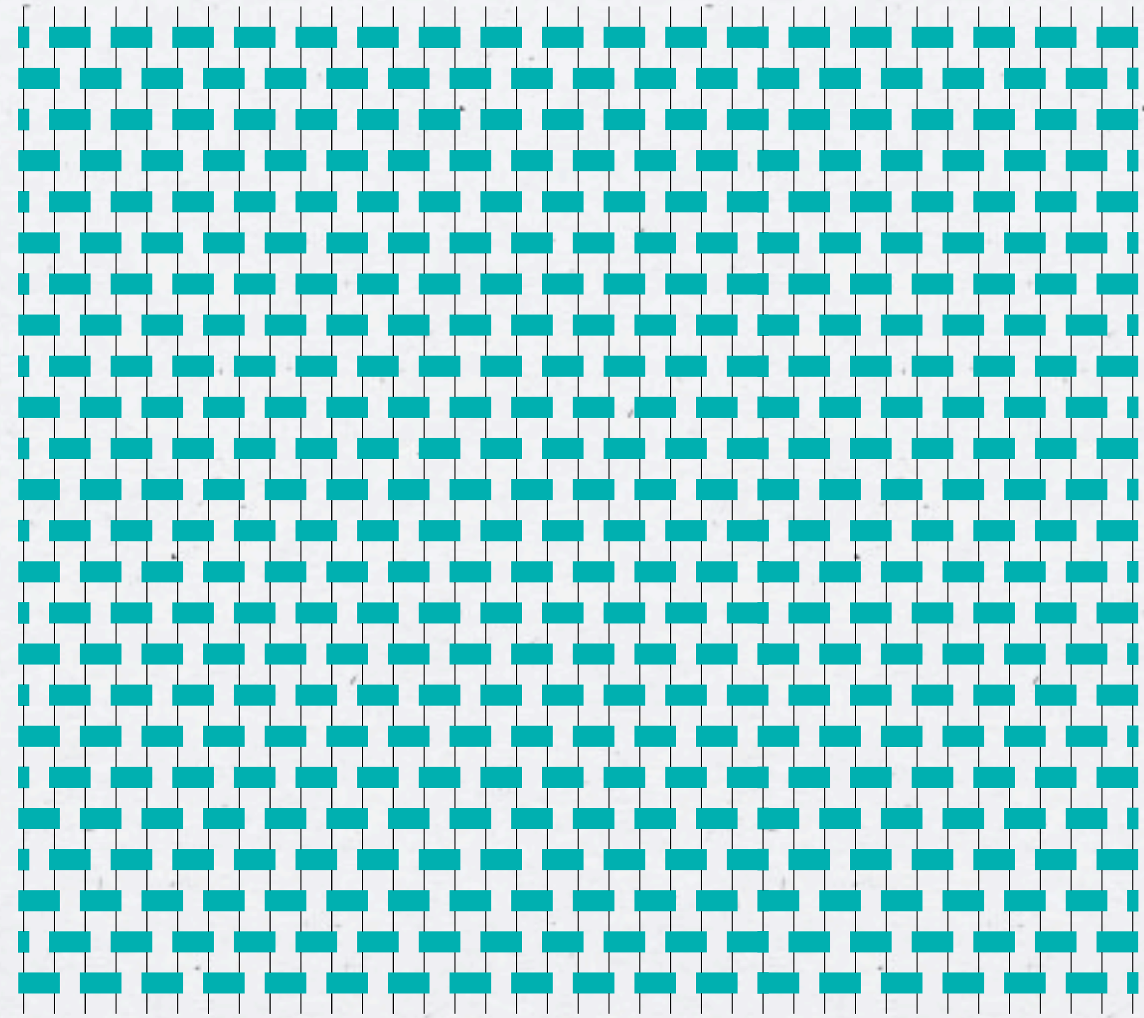

THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUATION (1+1 dimensions)

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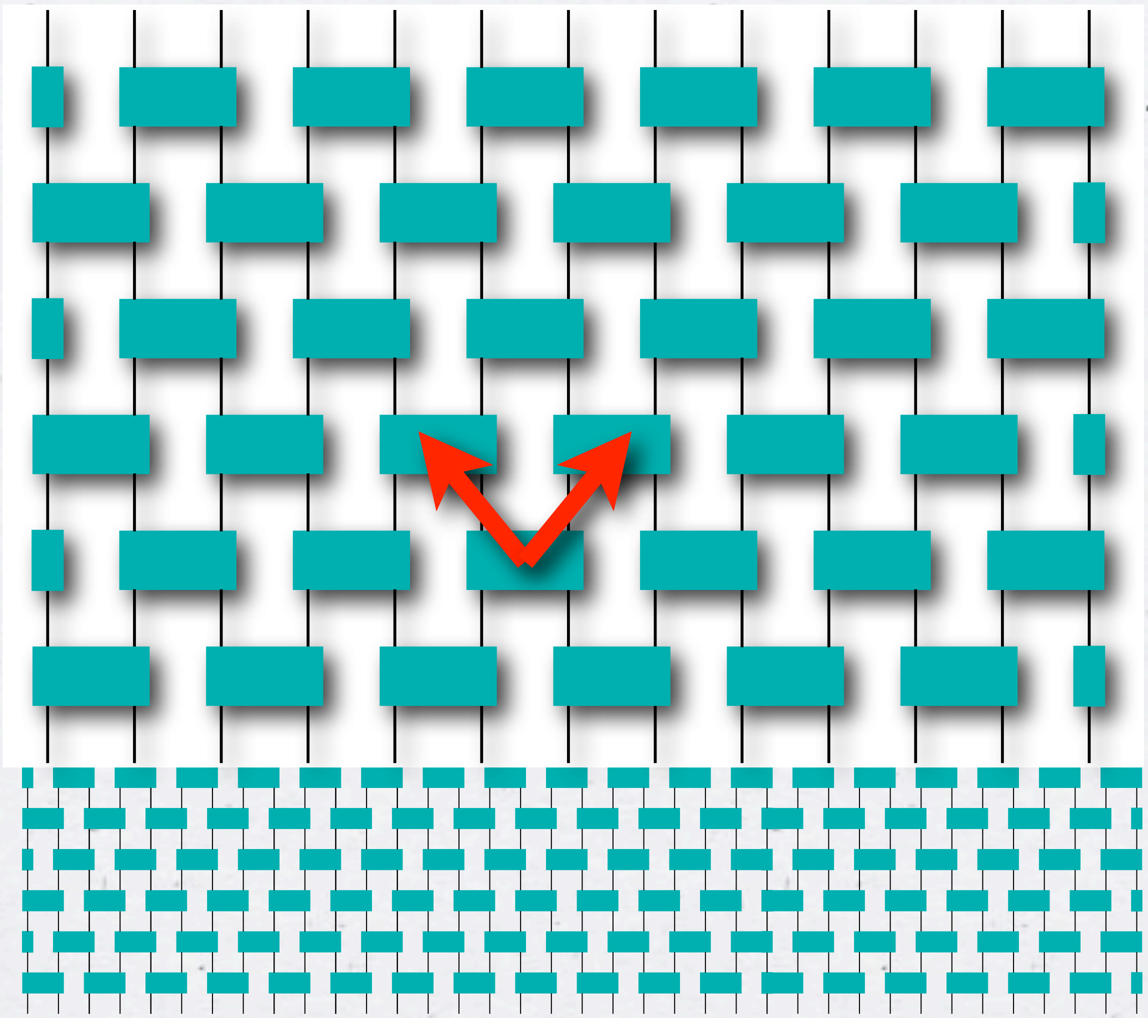
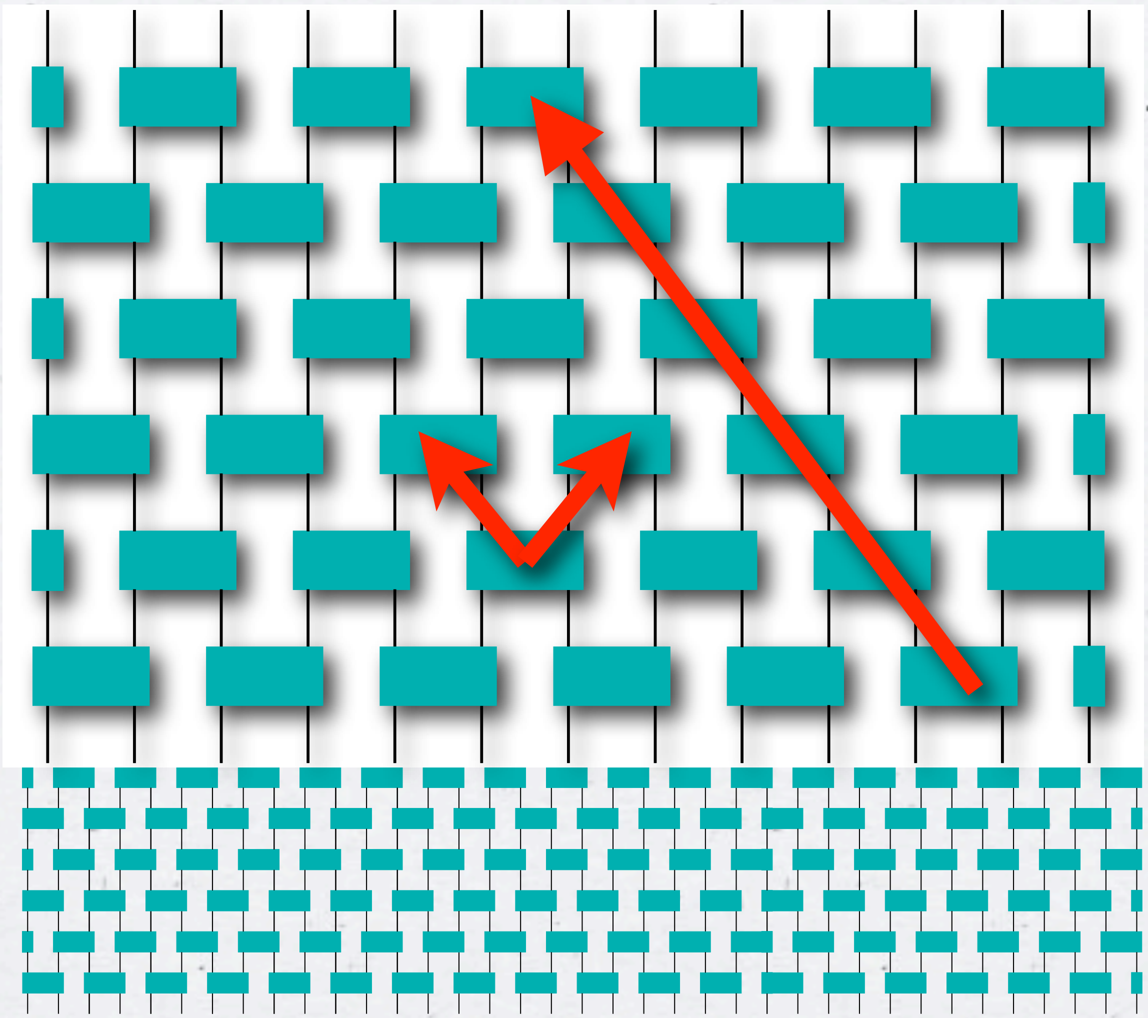
Information can flow only in two directions



THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUATION (1+1 dimensions)

Information can flow only in two directions
and at fixed direction only at max speed

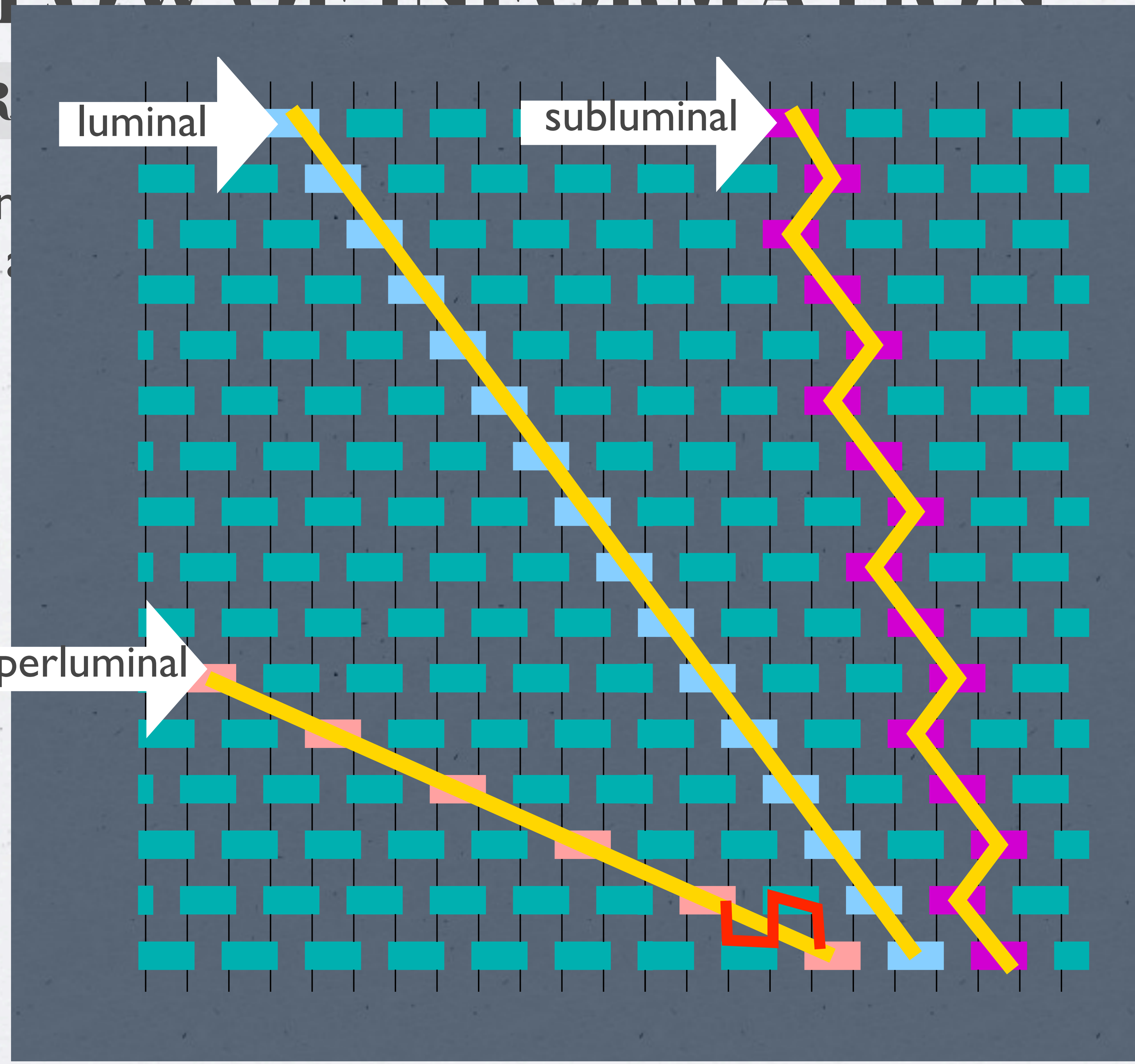


THE FREE FLOW OF INFORMATION

i.e. the DIR

★ ★ ★ ★

Information can flow only ir
and at fixed direction only a



THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUATION (1+1 dimensions)

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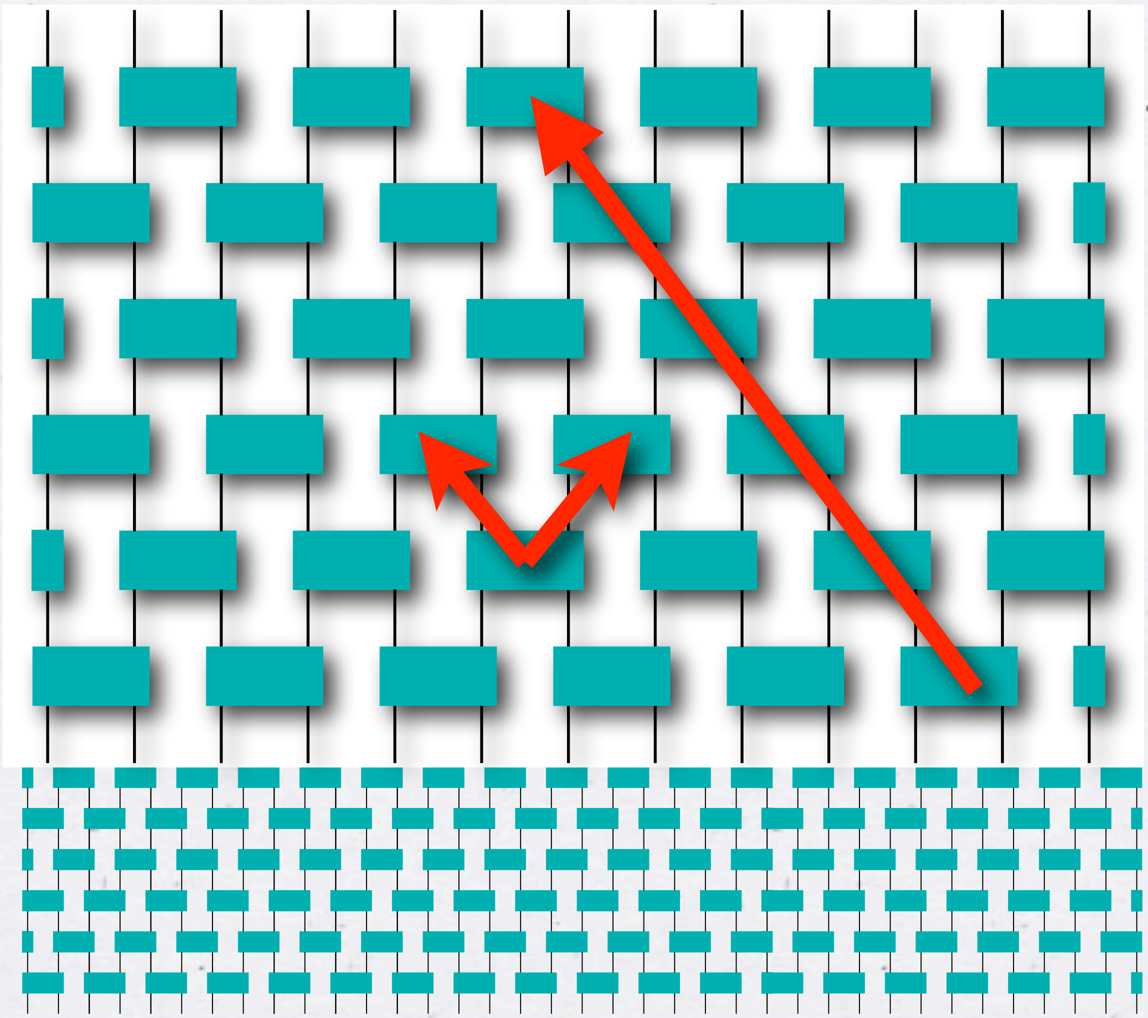

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i.e. the DIRAC EQUATION (1+1 dimensions)

★ ★ ★ ★ ★ ★ ★ ★

Information can flow only in two directions
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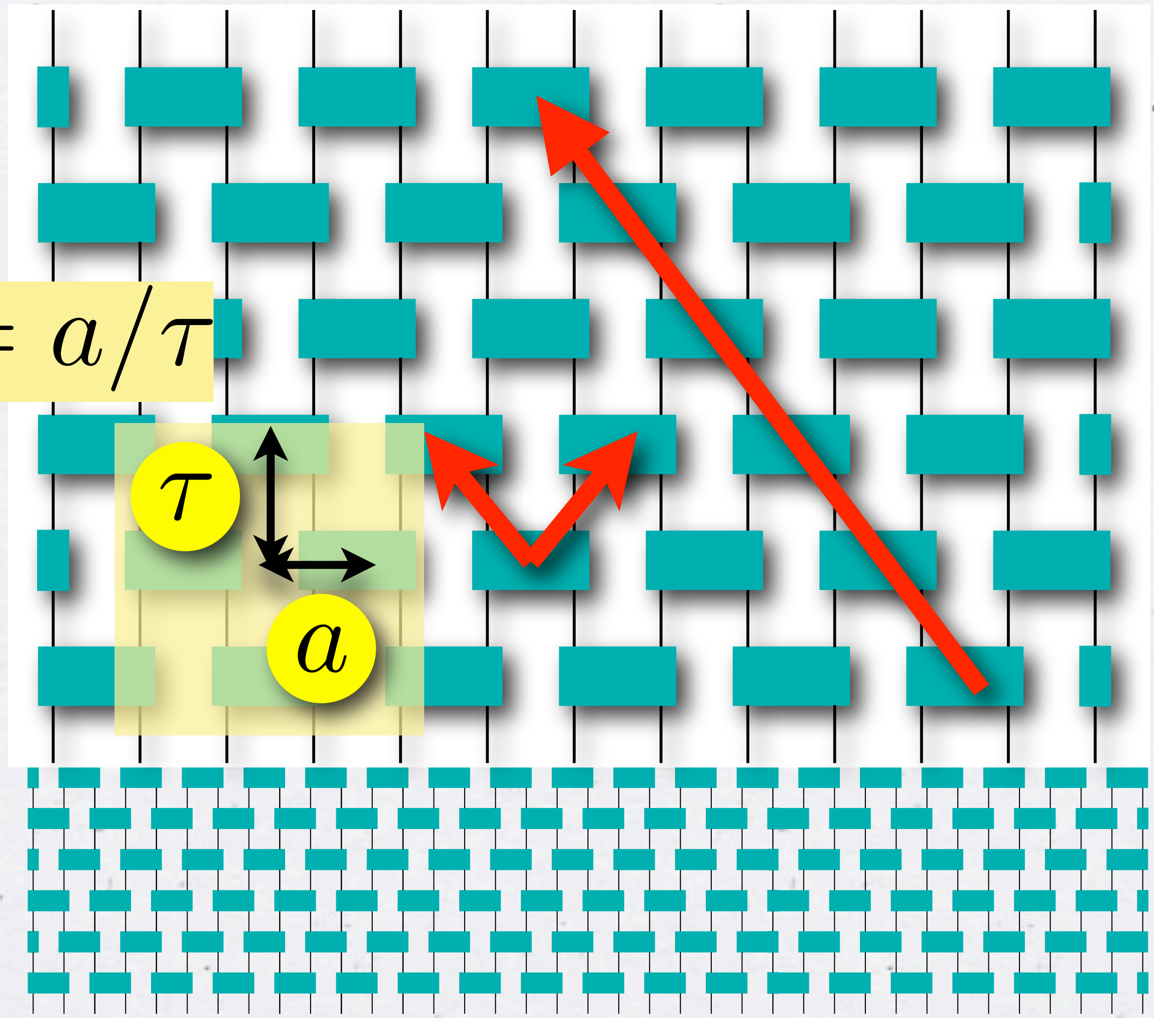
$c = a/\tau$



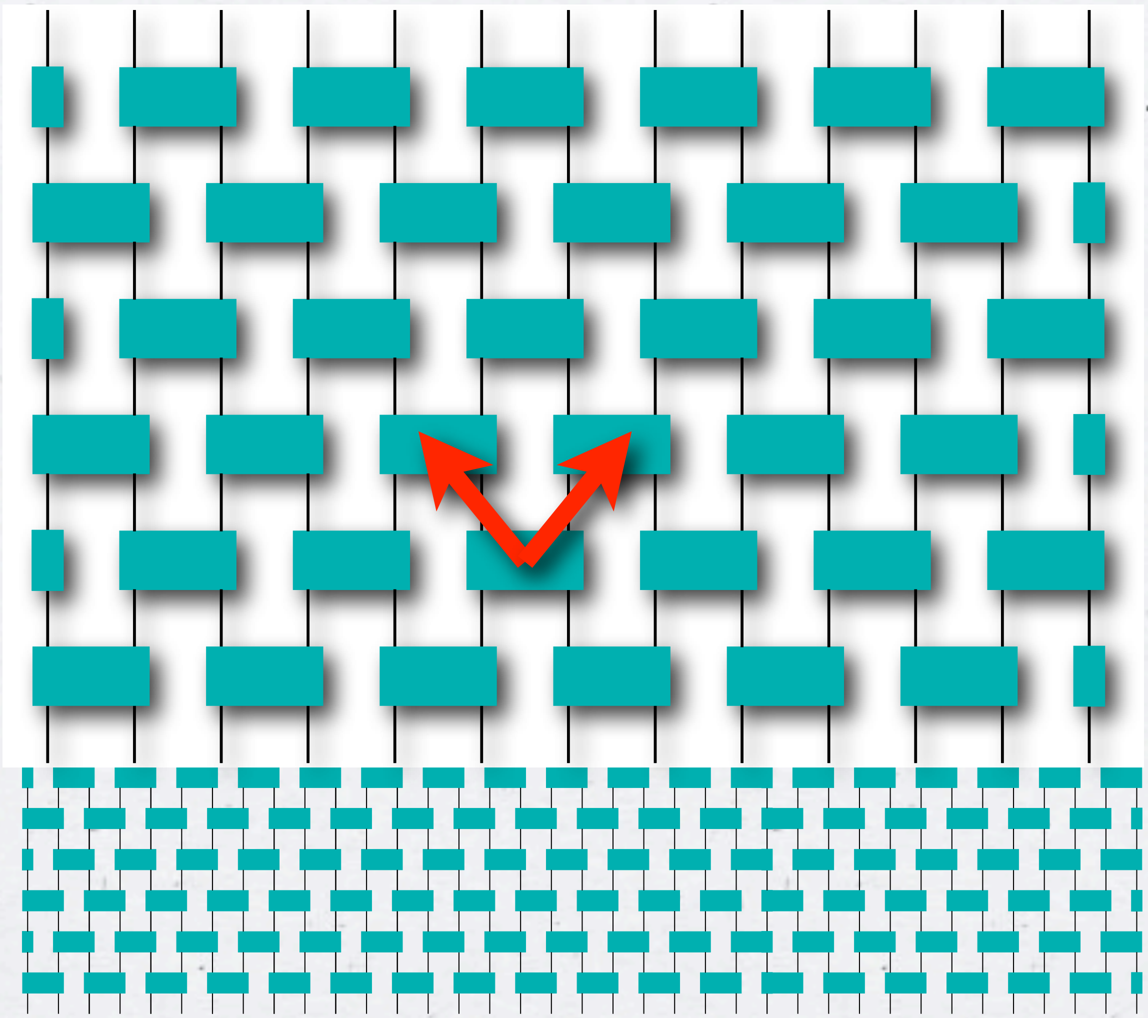
THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUATION (1+1 dimensions)

★ ★ ★ ★ ★ ★ ★ ★

Information can flow only in two directions and at fixed direction only at max speed

$$\widehat{\partial}_t \begin{bmatrix}\phi^+\\ \phi^-\end{bmatrix} = \begin{bmatrix} c\widehat{\partial}_x & 0 \\ 0 & -c\widehat{\partial}_x\end{bmatrix}\begin{bmatrix}\phi^+\\ \phi^-\end{bmatrix}$$



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i.e. the DIRAC EQUATION (1+1 dimensions)

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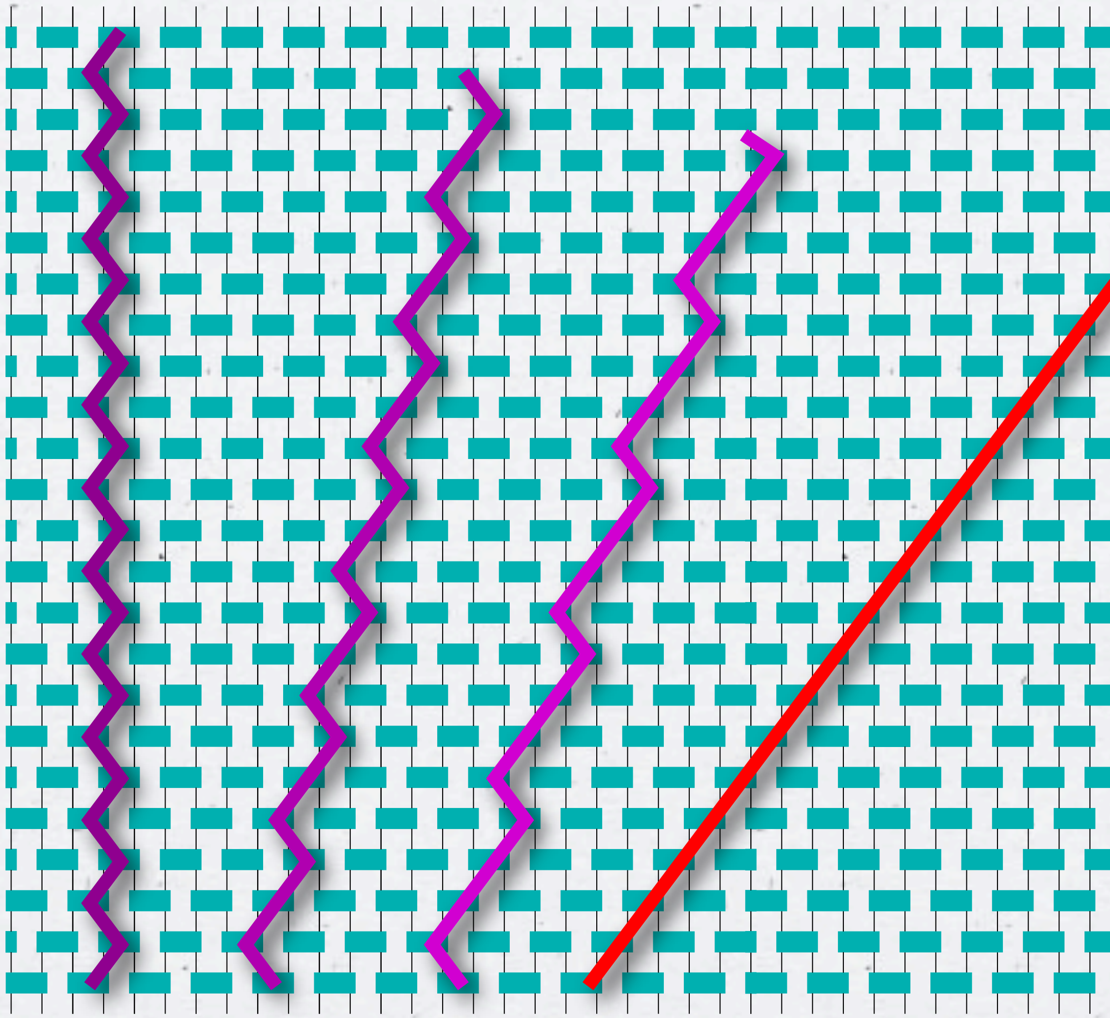
Slower speed = periodic change of direction



THE FREE FLOW OF INFORMATION

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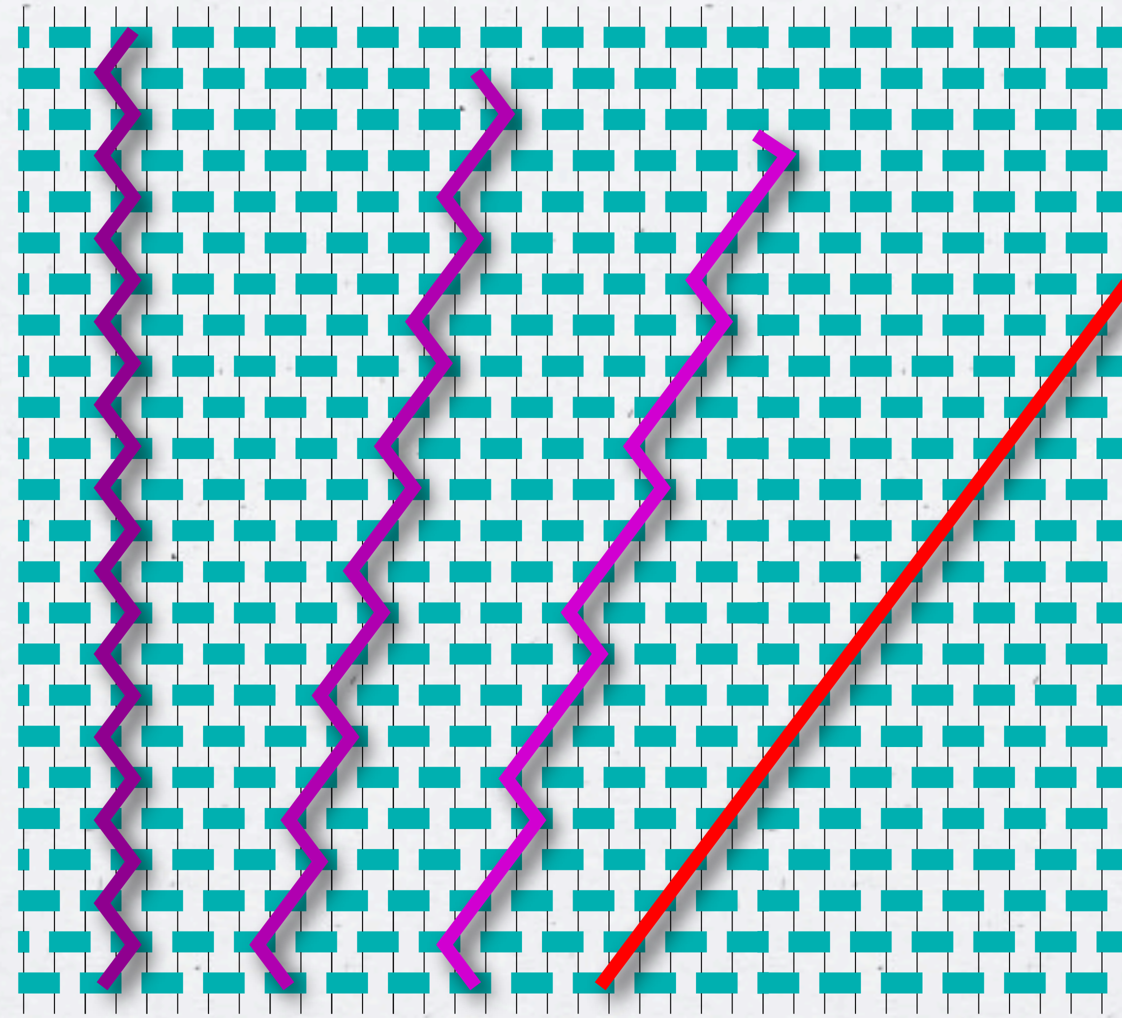
★ ★ ★ ★ ★ ★ ★ ★

Information can flow only in two directions and at fixed direction only at max speed

$$\widehat{\partial}_t \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix} = \begin{bmatrix} c\widehat{\partial}_x & 0 \\ 0 & -c\widehat{\partial}_x \end{bmatrix} \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix}$$

Slower speed = periodic change of direction



coupling between ϕ^+ and ϕ^- by an imaginary constant

$$\boxed{\widehat{\partial}_t \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix} = \begin{bmatrix} c\widehat{\partial}_x & -i\omega \\ -i\omega & -c\widehat{\partial}_x \end{bmatrix} \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix}}$$

(spinless) ***Dirac equation!***

No need of imposing relativistic invariance!

THE FREE FLOW OF INFORMATION

i.e. **the DIRAC EQUA**

★ ★ ★ ★

Information can flow only in two direc
and at fixed direction only at max spe

$$\widehat{\partial}_t \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix} = \begin{bmatrix} c\widehat{\partial}_x & 0 \\ 0 & -c\widehat{\partial}_x \end{bmatrix} \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix}$$

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coupling between ϕ^+ and ϕ^- by
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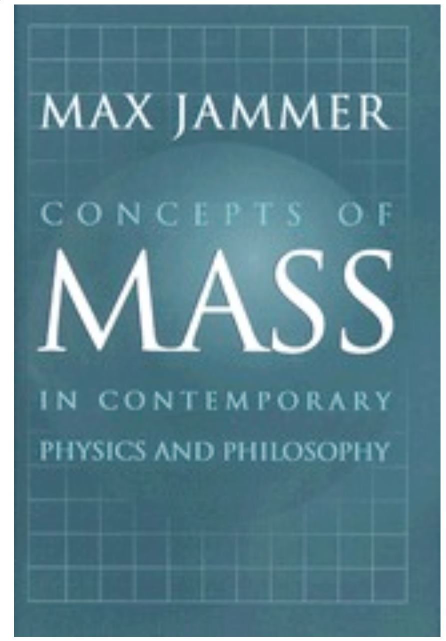
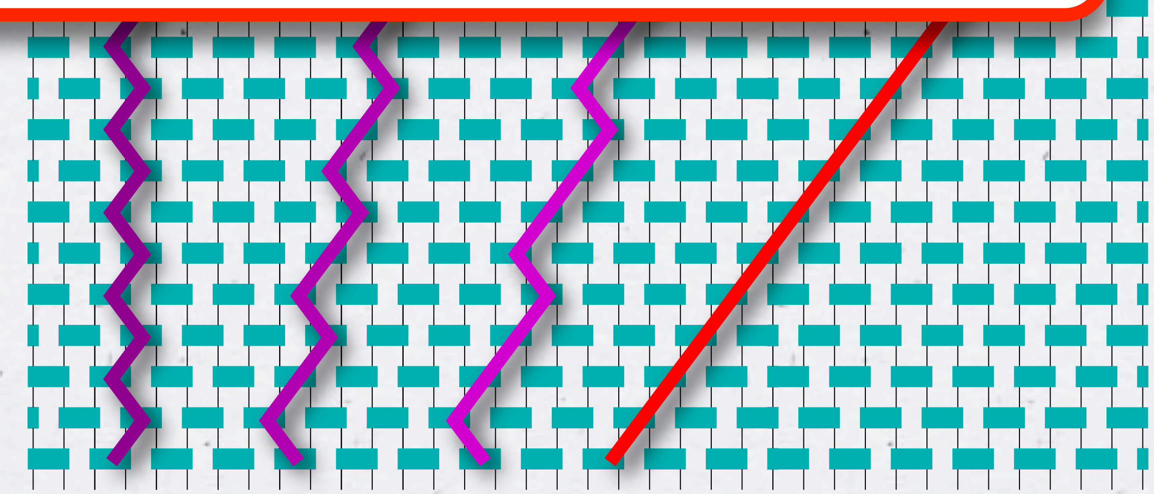


... a kinematical definition of inertial mass ...



(spinless) ***Dirac equation!***

No need of imposing
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THE FREE FLOW OF INFORMATION

i.e. the DIRAC EQUA

★ ★ ★ ★

Information can flow only in two direc
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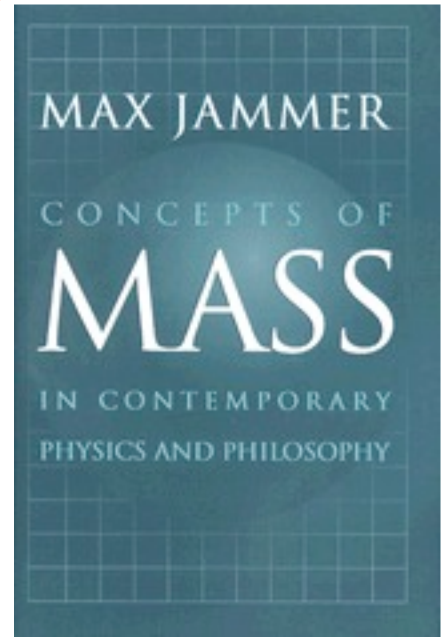
$$\widehat{\partial}_t \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix} = \begin{bmatrix} c\widehat{\partial}_x & 0 \\ 0 & -c\widehat{\partial}_x \end{bmatrix} \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix}$$

Slower speed = periodic change of direction



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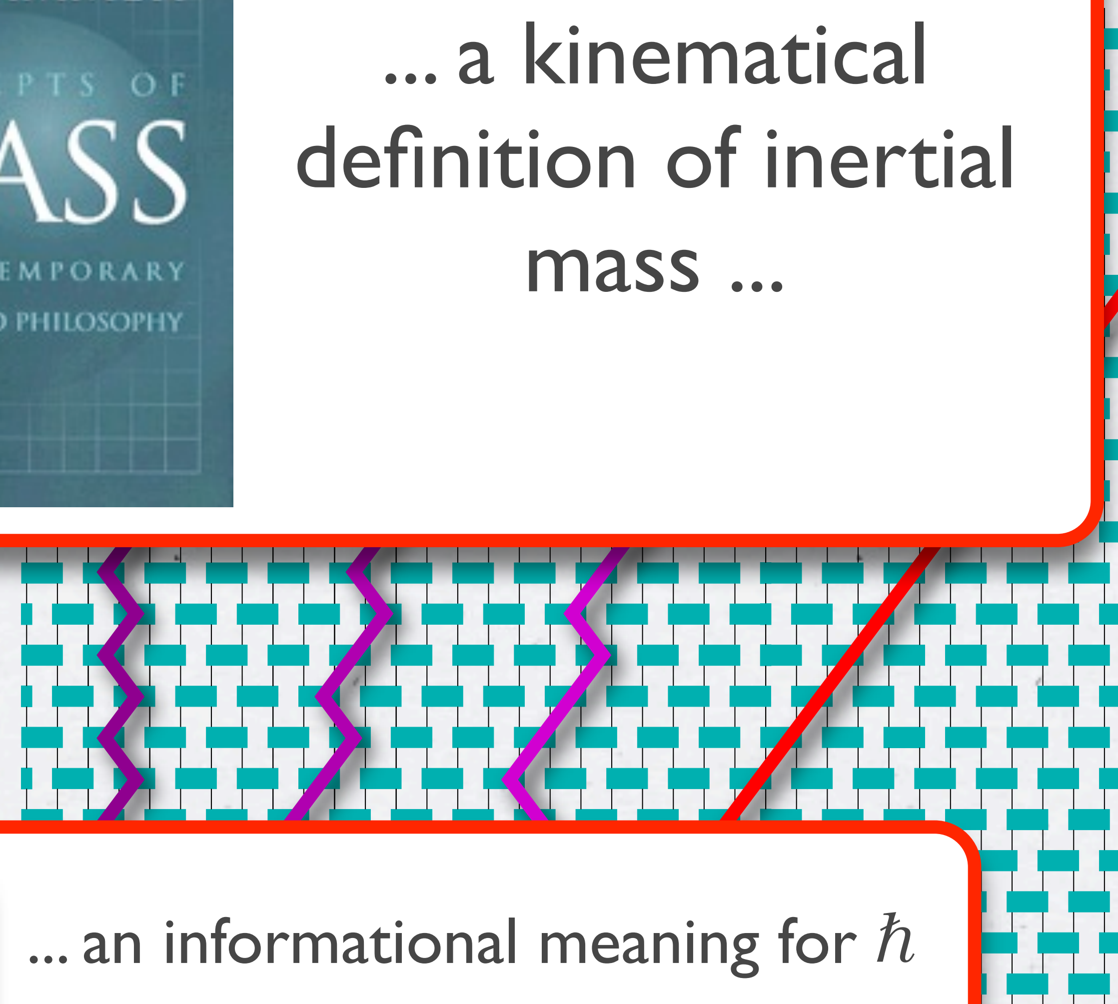


coupling b
an im

$$\lambda = \frac{\hbar}{mc}$$

Compton wavelenght

m	mass in Kg
ω	mass (informational) in s^{-1}

... an informational meaning for $\hbar$

(conversion info-mass - kg-mass)

$$m = \frac{1}{c^2}\hbar\omega$$

n!

$$\widehat{\partial}_t \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix}$$

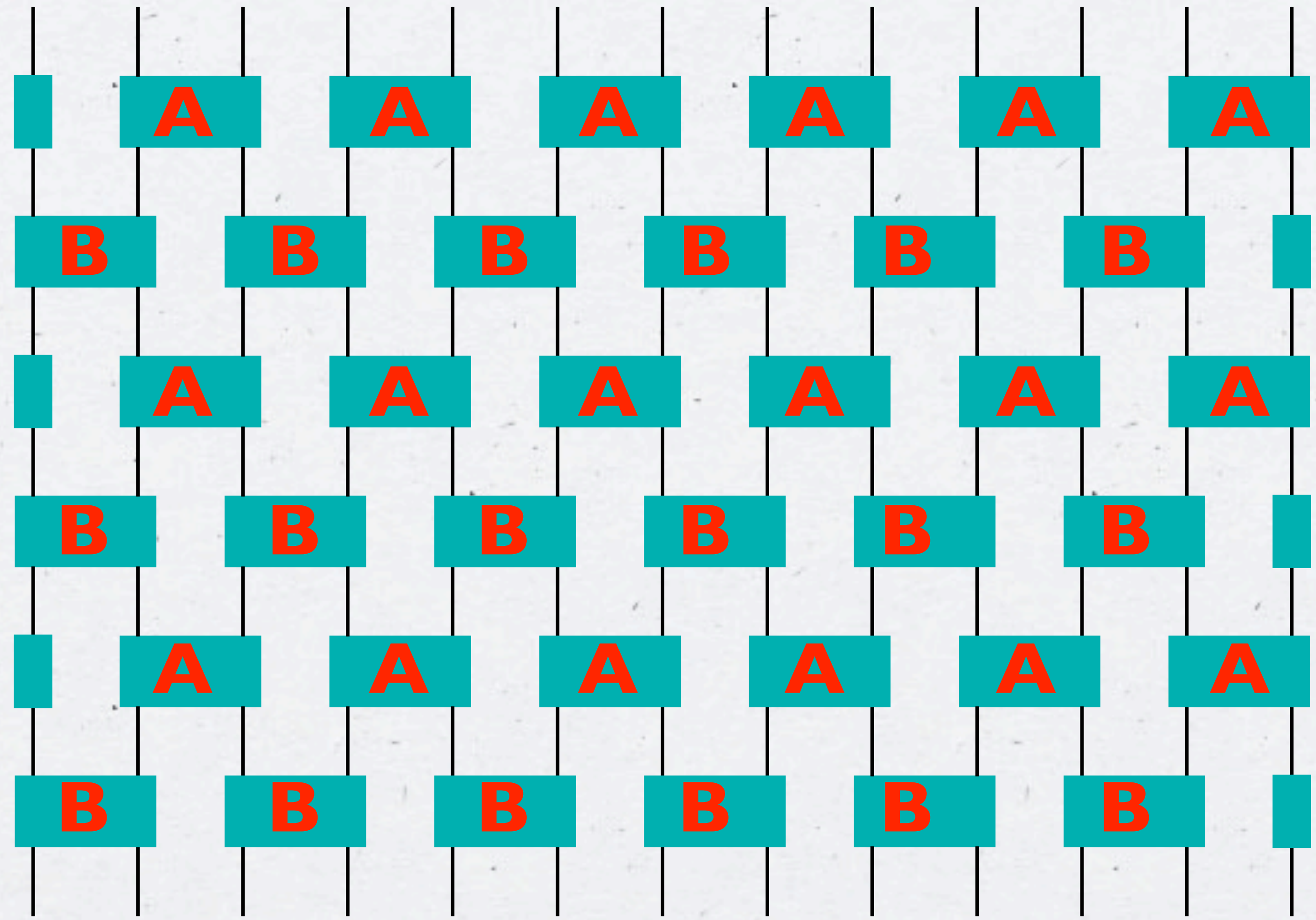
relativistic invariance!

FREE INFORMATION FLOW

DIRAC EQUATION

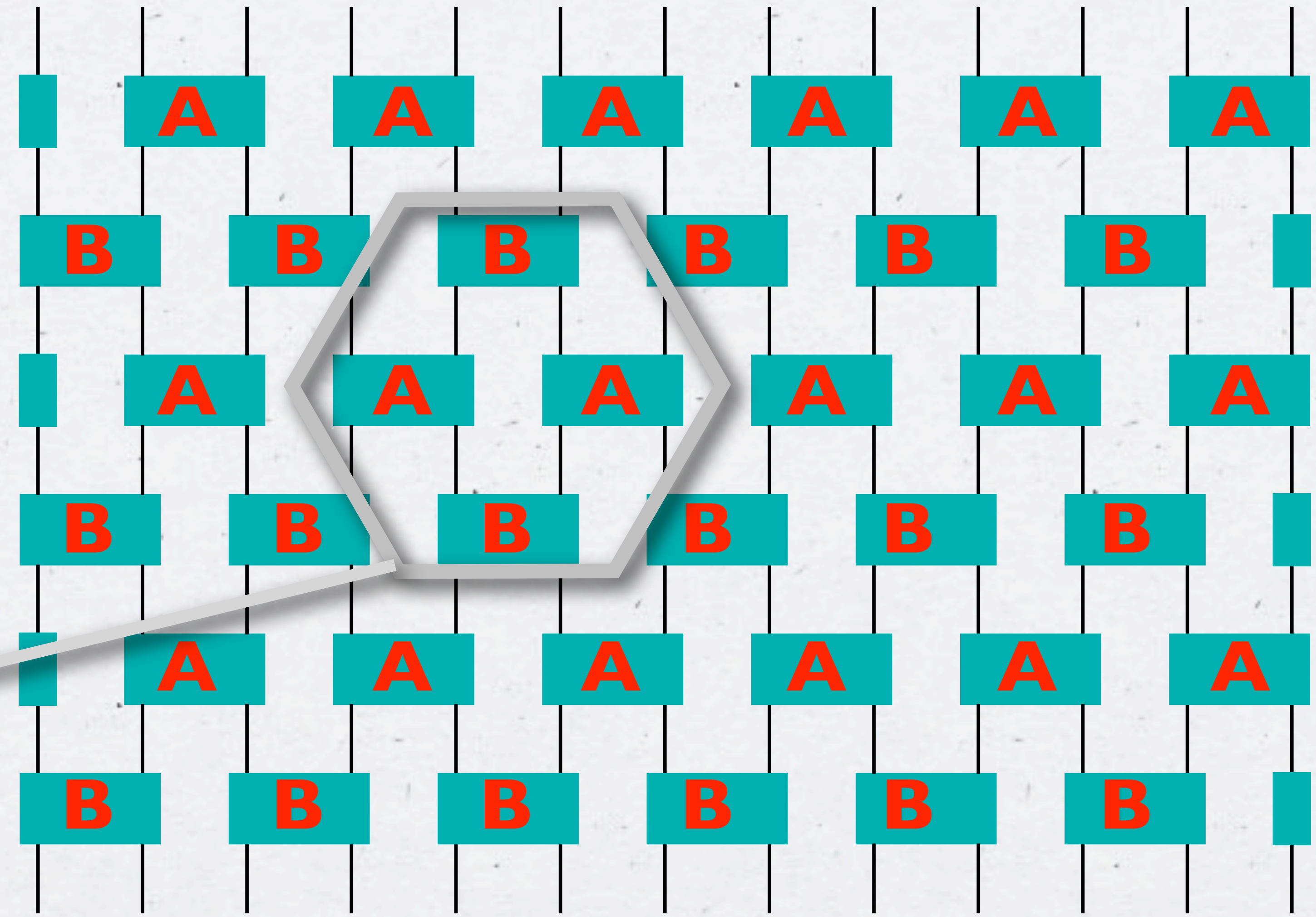
★ ★ ★ ★ ★ ★ ★ ★

spin: circuit "undressing"



FREE INFORMATION FLOW

DIRAC EQUATION



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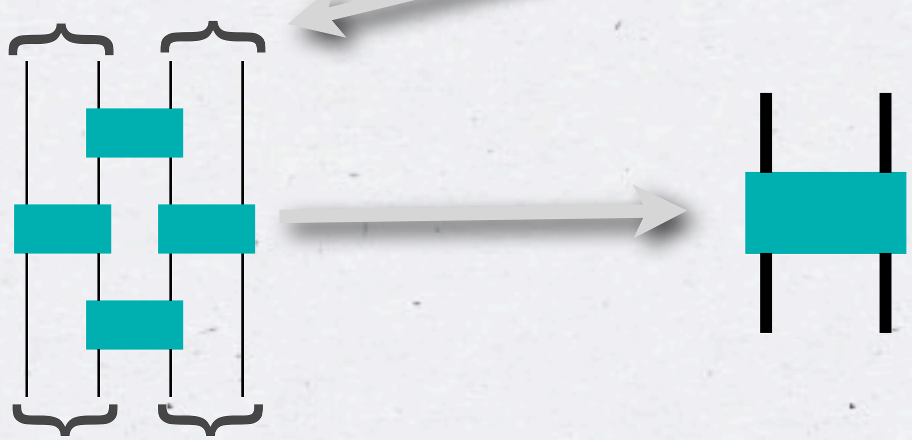


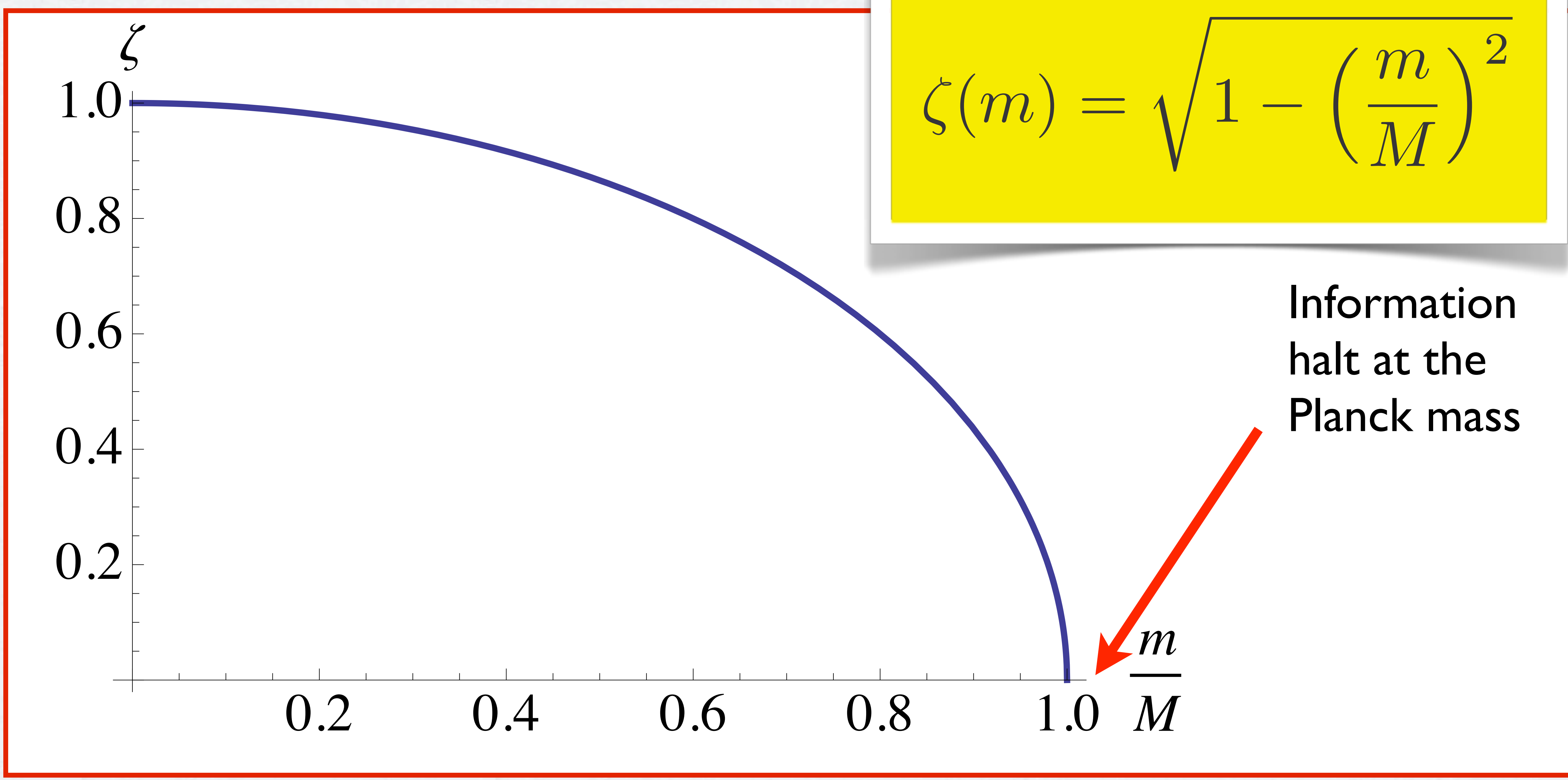
THE NETWORK BECOMES QUANTUM: QCA

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

The coupling between left and right fields leads to a renormalization of the field speed due to unitariety.

$$c \to \zeta c, \quad \zeta = \zeta(m)$$

$$\zeta(m) = \sqrt{1 - \left(\frac{m}{M}\right)^2}$$



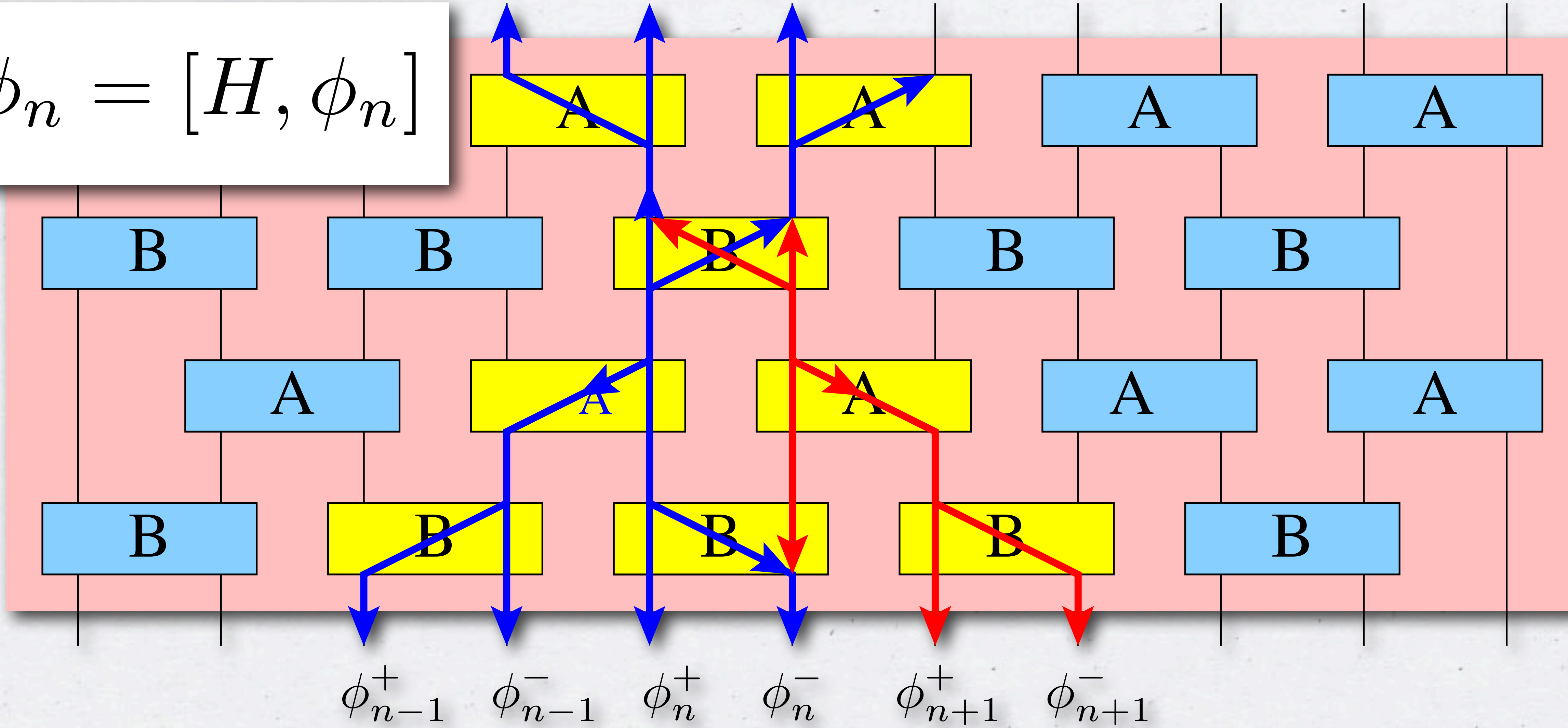
Information halt at the Planck mass

PHYSICS EMERGING FROM THE COMPUTATION

EMERGENT HAMILTONIAN

Dirac in 1+1 d

$$i\widehat{\partial}_t \phi_n = [H, \phi_n]$$



$$H = -\sum_n \phi_n^\dagger \mathrm{H}_{\mathrm{loc}} \phi_n$$

$$\mathrm{H}_{\mathrm{loc}} = \frac{i}{2k\tau}(U_f - U_b^\dagger)$$

Hermiticity is a consequence of the universality of the physical law.

FIELDS REPLACED BY QUBITS

Jordan-Wigner construction

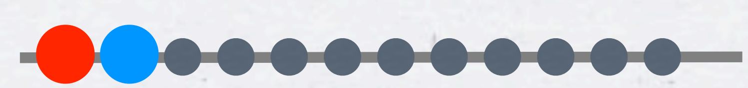
$$\gamma_n := \sigma_n^+ \prod_{l=-\infty}^{n-1} \sigma_k^z \qquad [\gamma_n, \gamma_m] = 0, \; [\gamma_n^\dagger, \gamma_m] = \delta_{mn}$$

FIELDS REPLACED BY QUBITS

Jordan-Wigner construction

$$\gamma_n := \sigma_n^+ \prod_{l=-\infty}^{n-1} \sigma_k^z \qquad [\gamma_n, \gamma_m] = 0,\ [\gamma_n^\dagger, \gamma_m] = \delta_{mn}$$

$$\gamma_n^\dagger \gamma_{n-1} := \sigma_n^+ \sigma_{n-1}^-$$



FIELDS REPLACED BY QUBITS

Jordan-Wigner construction

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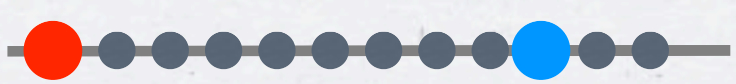


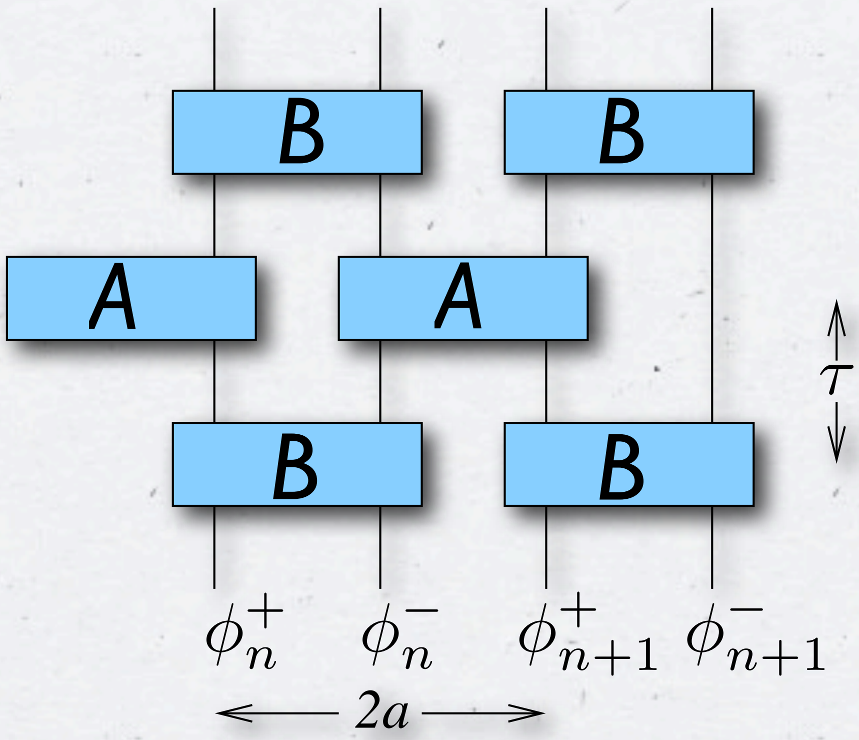
$$\gamma_n^\dagger \gamma_{n-k-1} := \sigma_n^+ \sigma_{n-1}^z \ldots \sigma_{n-k}^z \sigma_{n-k-1}^-$$

FIELDS REPLACED BY QUBITS

Dirac in 1+1 d

$$A = \exp\left\{ i\theta \left[\phi_n^{+\dagger} \phi_{n-1}^- + \phi_{n-1}^{-\dagger} \phi_n^+ \right] \right\}$$
$$B = \exp\left\{ i\tfrac{\pi}{2} \left[\phi_n^{+\dagger} \phi_n^- + \phi_n^{-\dagger} \phi_n^+ \right] \right\}$$

Fields are eliminated!



Commuting	Anticommuting
Harmonic oscillator	*Jordan-Wigner*
$[a_l, a_k^\dagger] = \delta_{lk}$	$\phi_n^+ = \sigma_{2n}^- \prod_{k=-\infty}^{n-1} \sigma_{2k+1}^z \sigma_{2k}^z$
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$

$$A = \exp\left[-i\theta \left(\sigma_{2n-1}^- \sigma_{2n}^+ + \sigma_{2n-1}^+ \sigma_{2n}^- \right) \right]$$
$$B = \exp\left[-i\tfrac{\pi}{2} \left(\sigma_{2n}^+ \sigma_{2n+1}^- + \sigma_{2n}^- \sigma_{2n+1}^+ \right) \right]$$

Gates act on local qubits only!

FIELDS REPLACED BY QUBITS

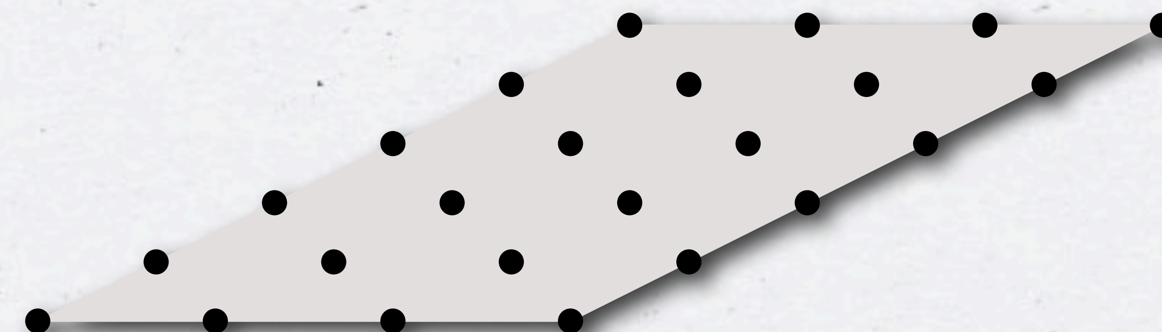
Dirac in > 1+1 d!!

- Jordan-Wigner transformation for $d+1>2$

FIELDS REPLACED BY QUBITS

Dirac in > 1+1 d!!

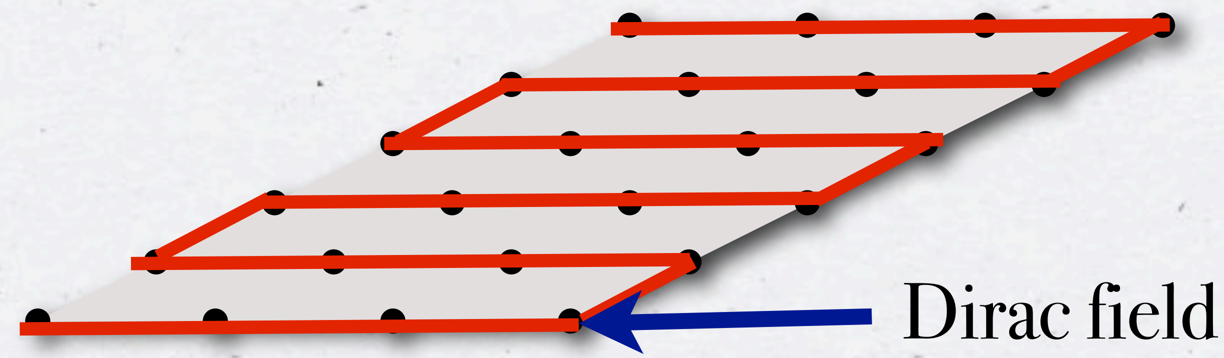
- Jordan-Wigner transformation for d+1>2



FIELDS REPLACED BY QUBITS

Dirac in > 1+1 d!!

* Jordan-Wigner transformation for d+1>2

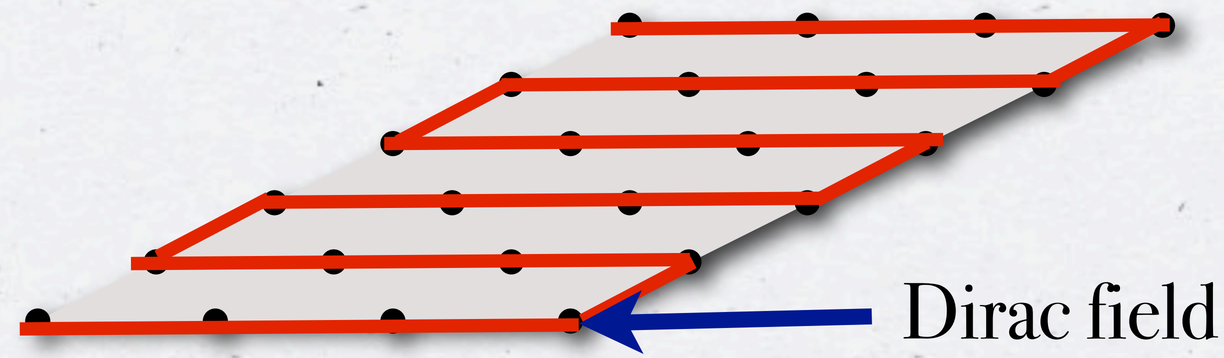


FIELDS REPLACED BY QUBITS

Dirac in > 1+1 d!!

- Jordan-Wigner transformation for d+1>2

- Possible solution: add a Majorana field!



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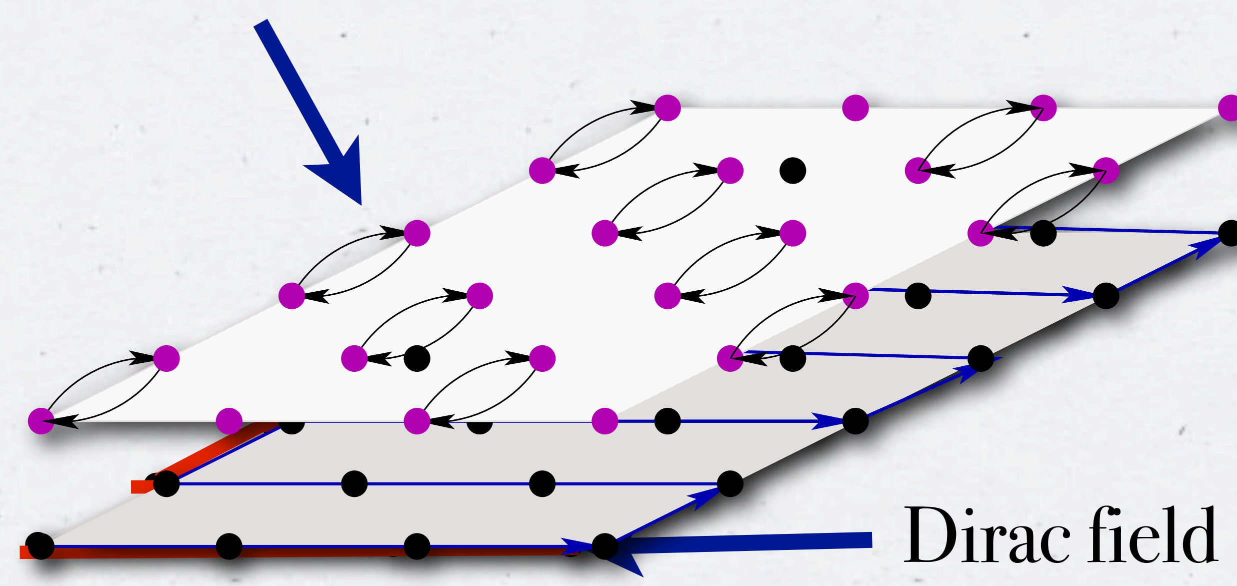


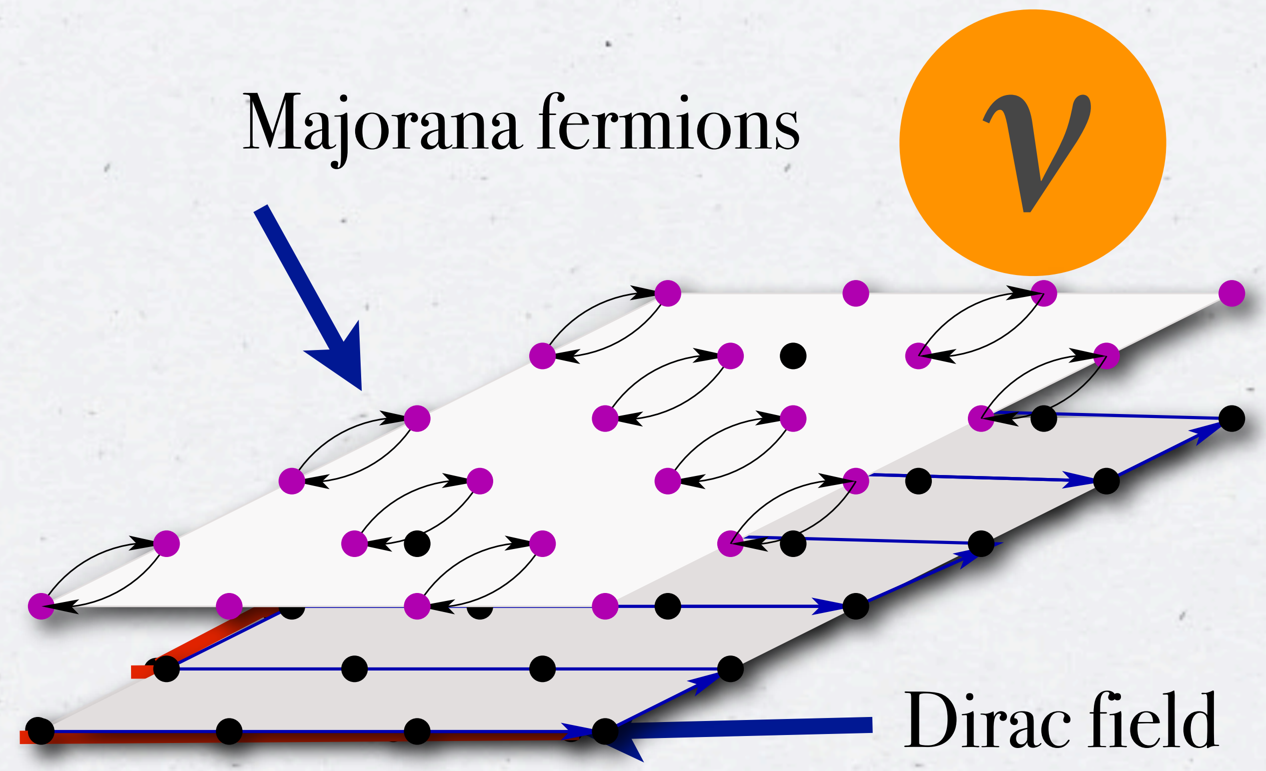
Verstraete and Cirac, J. Stat. Mech. **9** 12 (2005)

fields	qubits
$\gamma^\dagger_{k,l}\gamma_{k,l+1} + \gamma^\dagger_{k,l+1}\gamma_{k,l}$	$(\sigma^x_{k,l}\sigma^x_{k,l+1} + \sigma^y_{k,l}\sigma^y_{k,l+1})(-)^{l+1}\tilde{\sigma}^x_{k,l}\tilde{\sigma}^y_{k,l+1}$
$\gamma^\dagger_{k,l}\gamma_{k+1,l} + \gamma^\dagger_{k+1,l}\gamma_{k,l}$	$(\sigma^x_{k,l}\sigma^x_{k+1,l} + \sigma^y_{k,l}\sigma^y_{k+1,l})\tilde{\sigma}^z_{k,l}$

FIELDS REPLACED BY QUBITS

Dirac in > 1+1 d!!

- Jordan-Wigner transformation for d+1>2
- Possible solution: add a Majorana field!



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$\gamma^{\dagger}_{k,l}\gamma_{k+1,l}+\gamma^{\dagger}_{k+1,l}\gamma_{k,l}$	$(\sigma^{x}_{k,l}\sigma^{x}_{k+1,l}+\sigma^{y}_{k,l}\sigma^{y}_{k+1,l})\tilde{\sigma}^{z}_{k,l}$

EMERGENCE OF SPACE-TIME FROM CN

HIGHER-DIMENSION CONUNDRUM

★ ★ ★ ★ ★ ★ ★ ★

PHYSICAL REVIEW D VOLUME 49, NUMBER 12 15 JUNE 1994

Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata

Iwo Bialynicki-Birula
*Centrum Fizyki Teoretycznej, Polska Akademia Nauk, Lotników 32/46, 02-668 Warsaw, Poland**
and Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,
Robert-Mayer-Strasse 8-10, Frankfurt am Main, Germany
(Received 27 September 1993; revised manuscript received 27 December 1993)

Very simple unitary cellular automata on a
time evolution of the wave functions for spinn
value of the wave function at a given site dep
discretized evolution is also unitary and preserv
is studied in detail, and it is shown that ever
under some natural assumptions, leads in the co
histories is evaluated and is shown to reprodu
Generalizations to include massive particles (D
higher-spin particles are also described.

PACS number(s): 03.65.Pm, 02.70.−c, 11.15.Ha

II. WEYL EQUATION ON A LATTICE

I shall start with a lattice description of the wave equation for a massless spin-1/2 particle and extend it later to massive particles and to higher spins. In my quantum cellular automaton the two-component wave function $\phi(i,j,k,t)$ is defined on a cubic lattice and it is updated at each time increment Δt according to the local algorithm

$$\begin{aligned}\phi(i,j,k,t+\Delta t) = {} & W_{+++}\phi(i+1,j+1,k+1,t)\\ & +W_{++-}\phi(i+1,j+1,k-1,t)+\cdots\\ & +W_{---}\phi(i-1,j-1,k-1,t), \qquad (1)\end{aligned}$$

EMERGENCE OF SPACE-TIME FROM CN

HIGHER-DIMENSION CONUNDRUM

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*Centrum Fizyki Teoretycznej, Polska Akademia Nauk, Lotników 32/46, 02-668 Warsaw, Poland**
and Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,
Robert-Mayer-Strasse 8-10, Frankfurt am Main, Germany
(Received 27 September 1993; revised manuscript received 27 December 1993)

Very simple unitary cellular automata on a
time evolution of the wave functions for spinn
value of the wave function at a given site dep
discretized evolution is also unitary and preserv
is studied in detail, and it is shown that ever

generic evolution operator U_Δ introduced before. The exact evolution operator in the continuum limit is recovered from the Lie-Trotter product formula (cf., for example, Ref. [39]), when $N = t/\Delta t$ tends to infinity,

$$\lim_{N\to\infty}[\exp(a\sigma_x\partial_x)\exp(a\sigma_y\partial_y)\exp(a\sigma_z\partial_z)]^N$$
$$= \exp(c\,\boldsymbol{\sigma}\cdot\nabla\,\Delta t). \quad (18)$$

II. WEYL EQUATION ON A LATTICE

I shall start with a lattice description of the wave equa-
assless spin-1/2 particle and extend it later
particles and to higher spins. In my quan-
automaton the two-component wave func-
, t) is defined on a cubic lattice and it is up-
ch time increment Δt according to the local

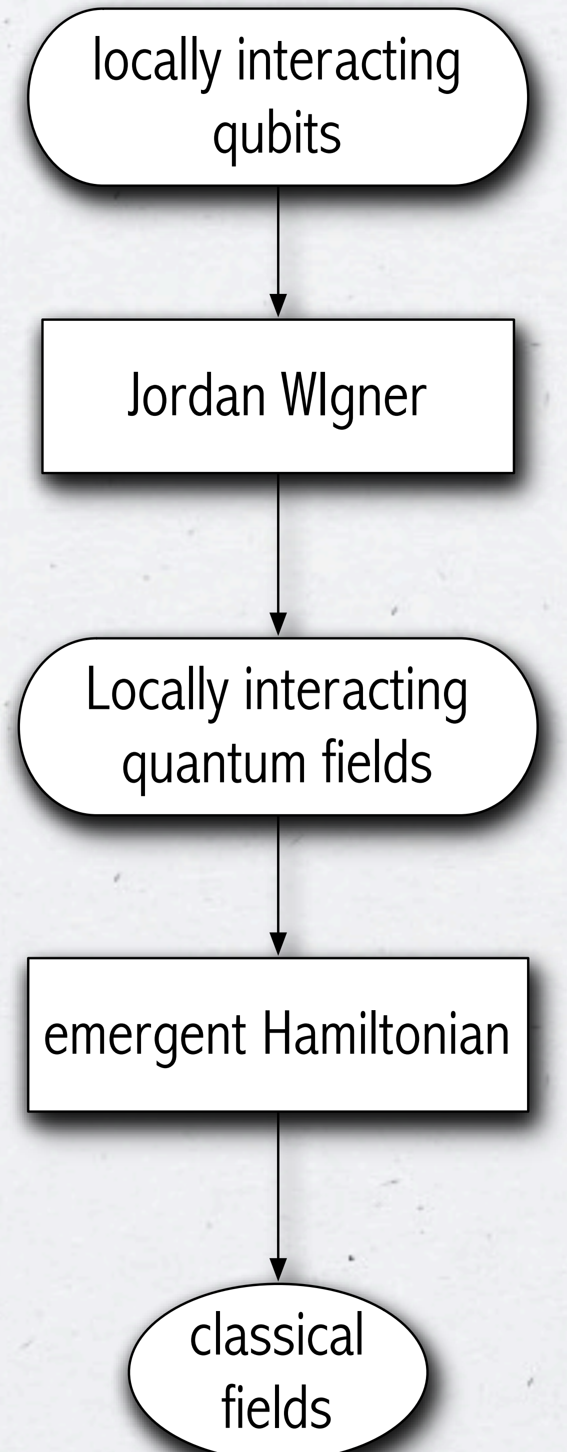
$$\Delta t) = W_{+++}\phi(i+1,j+1,k+1,t)$$
$$+W_{++-}\phi(i+1,j+1,k-1,t)+\cdots$$
$$+W_{---}\phi(i-1,j-1,k-1,t), \quad (1)$$

FIELDS REPLACED BY QUBITS

CLASSICALIZATION vs QUANTIZATION

FIELDS REPLACED BY QUBITS

CLASSICALIZATION vs QUANTIZATION



FIELDS REPLACED BY QUBITS

CLASSICALIZATION vs QUANTIZATION

★ ★ ★ ★ ★ ★ ★ ★

locally interacting qubits

↓

Jordan WIgner

↓

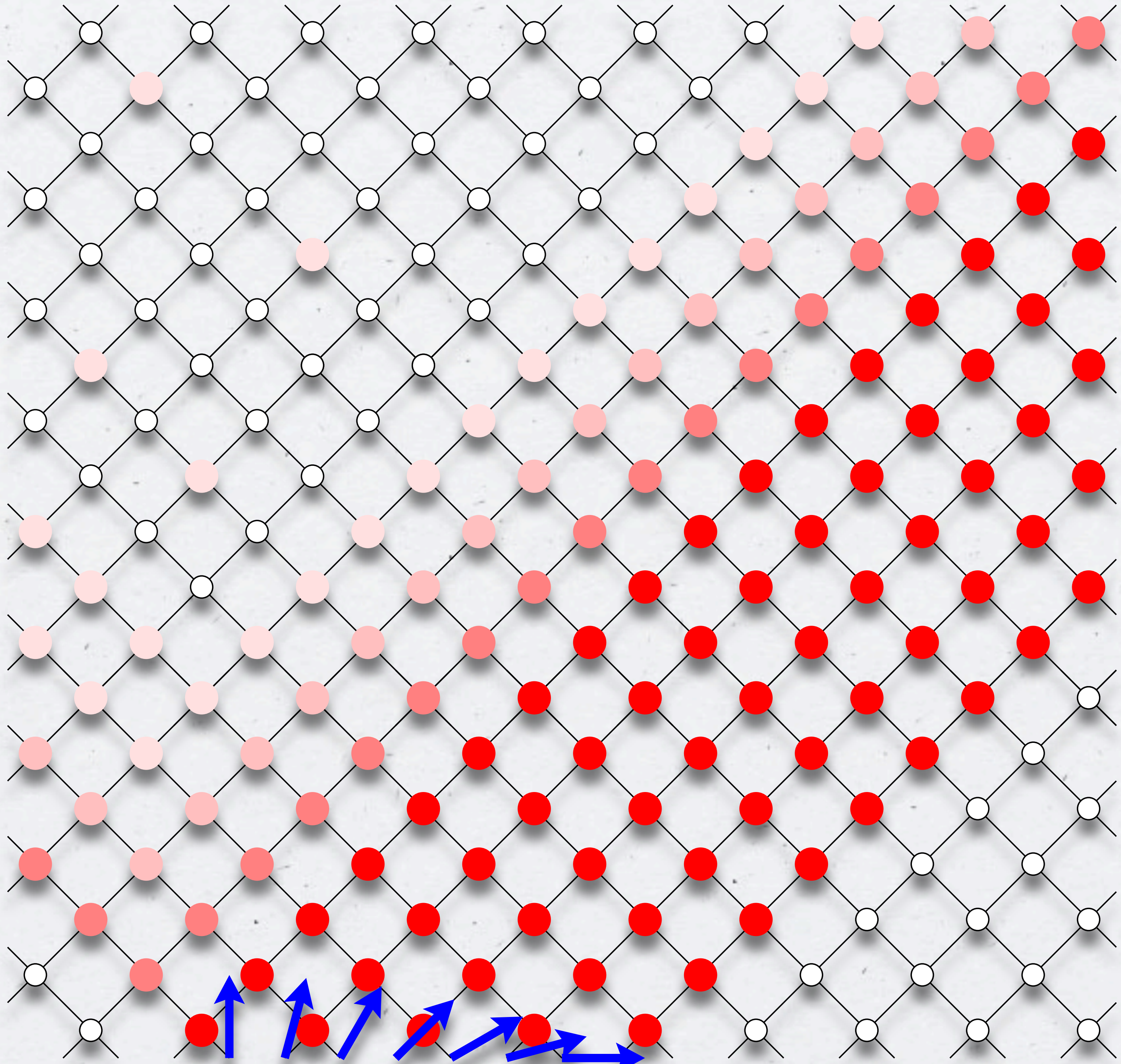
Locally interacting quantum fields

↓

emergent Hamiltonian

↓

classical fields



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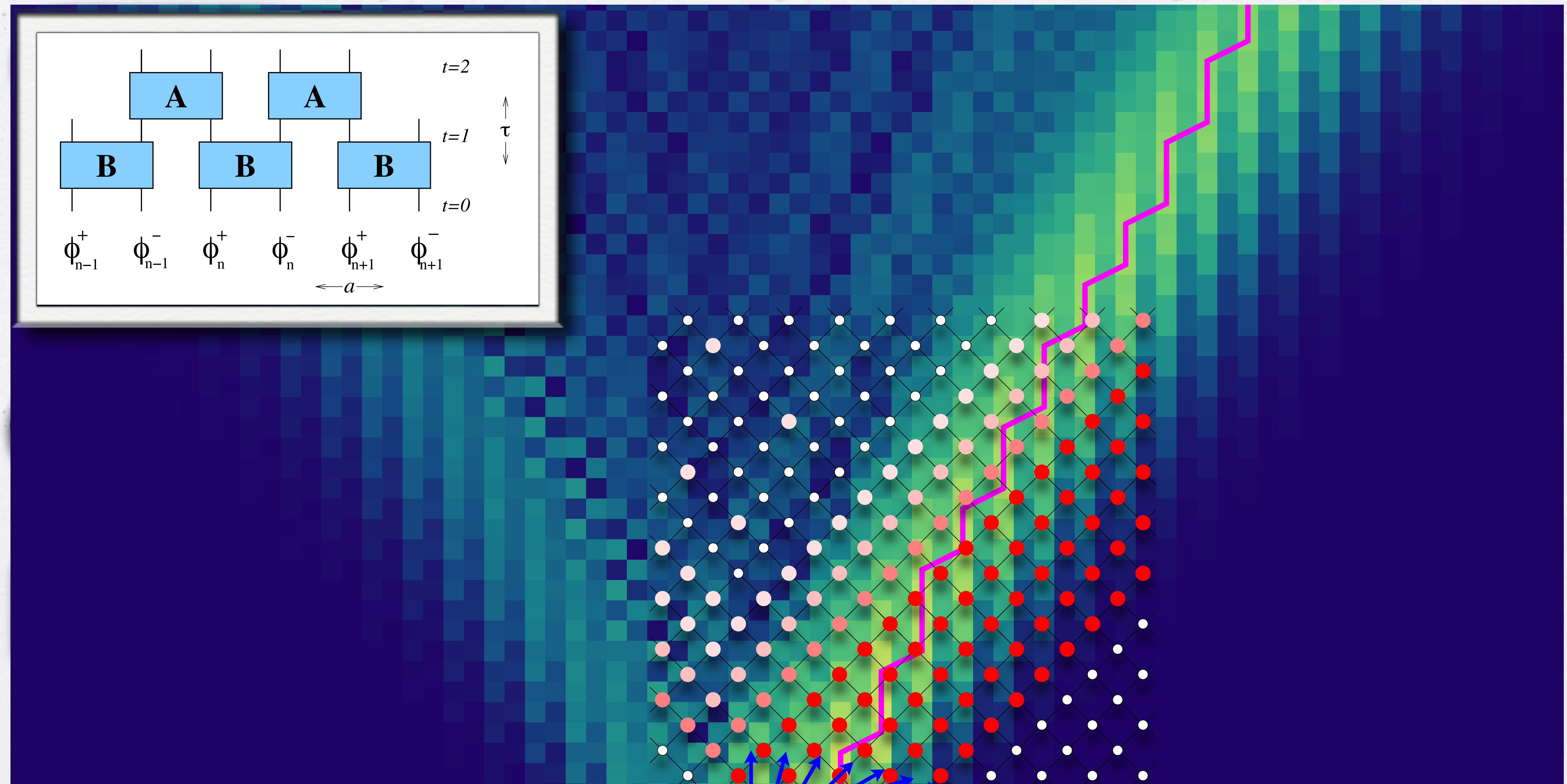
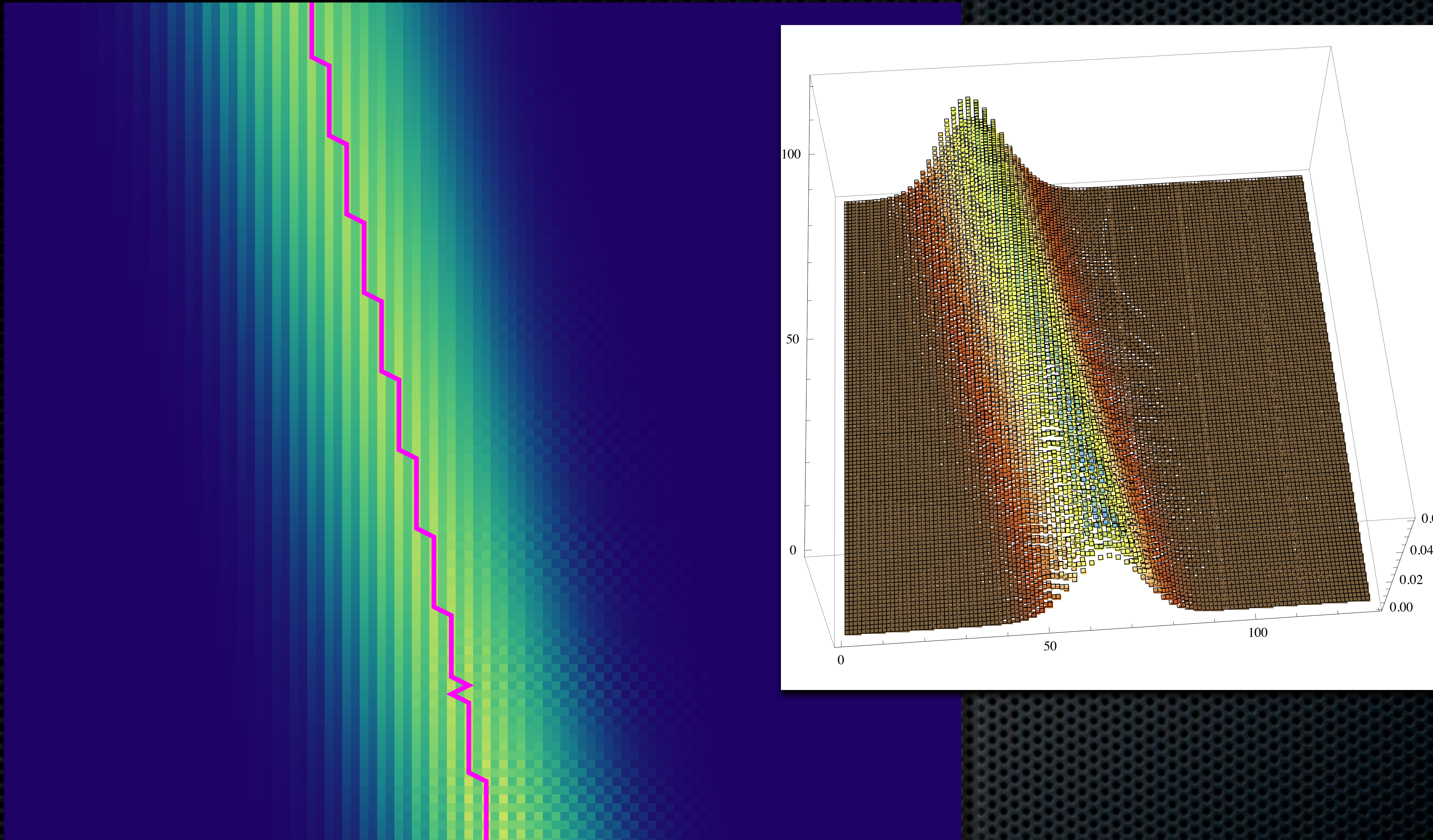
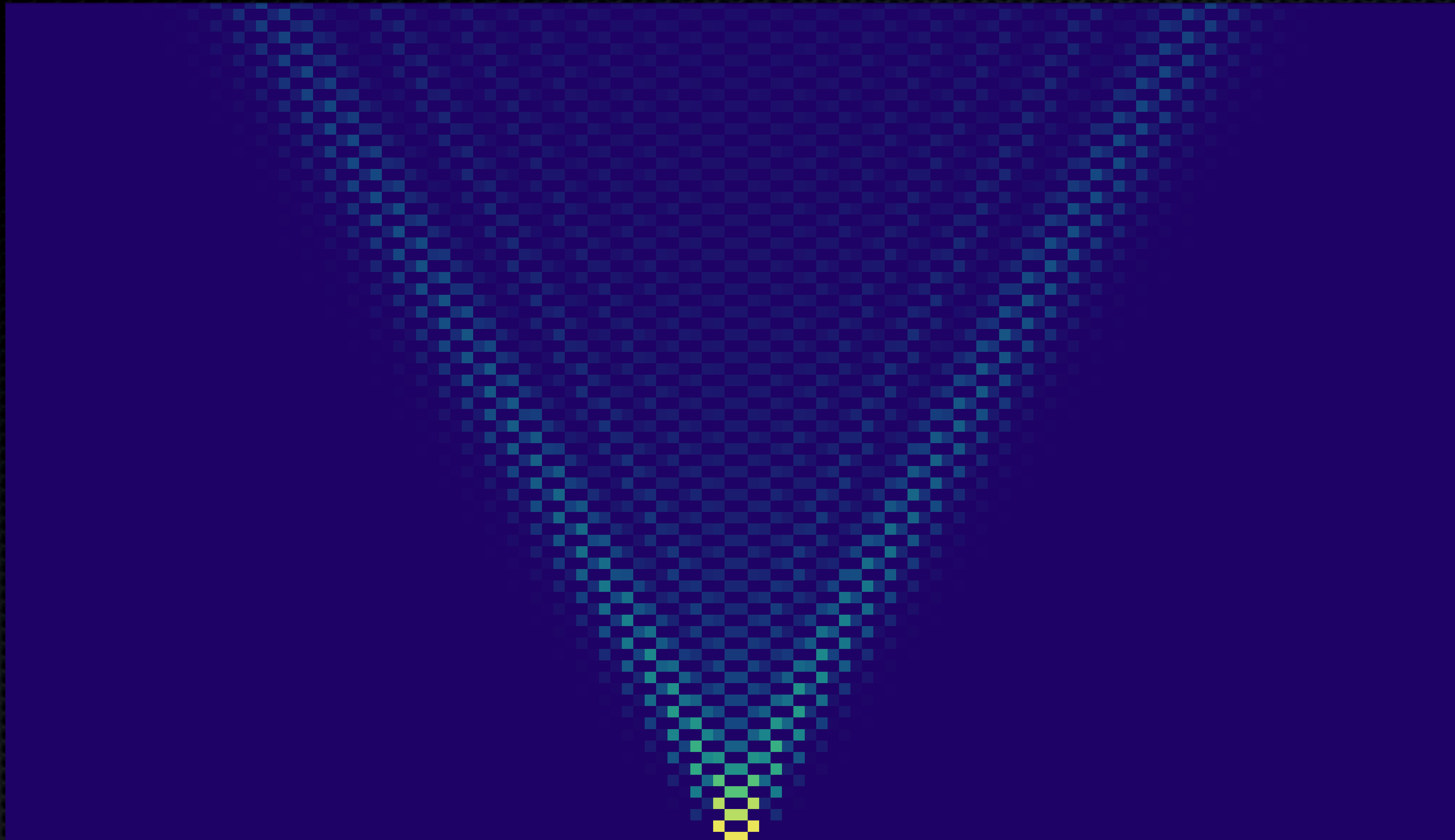


fields



Dirac QCA: First Quantization

Single particle state



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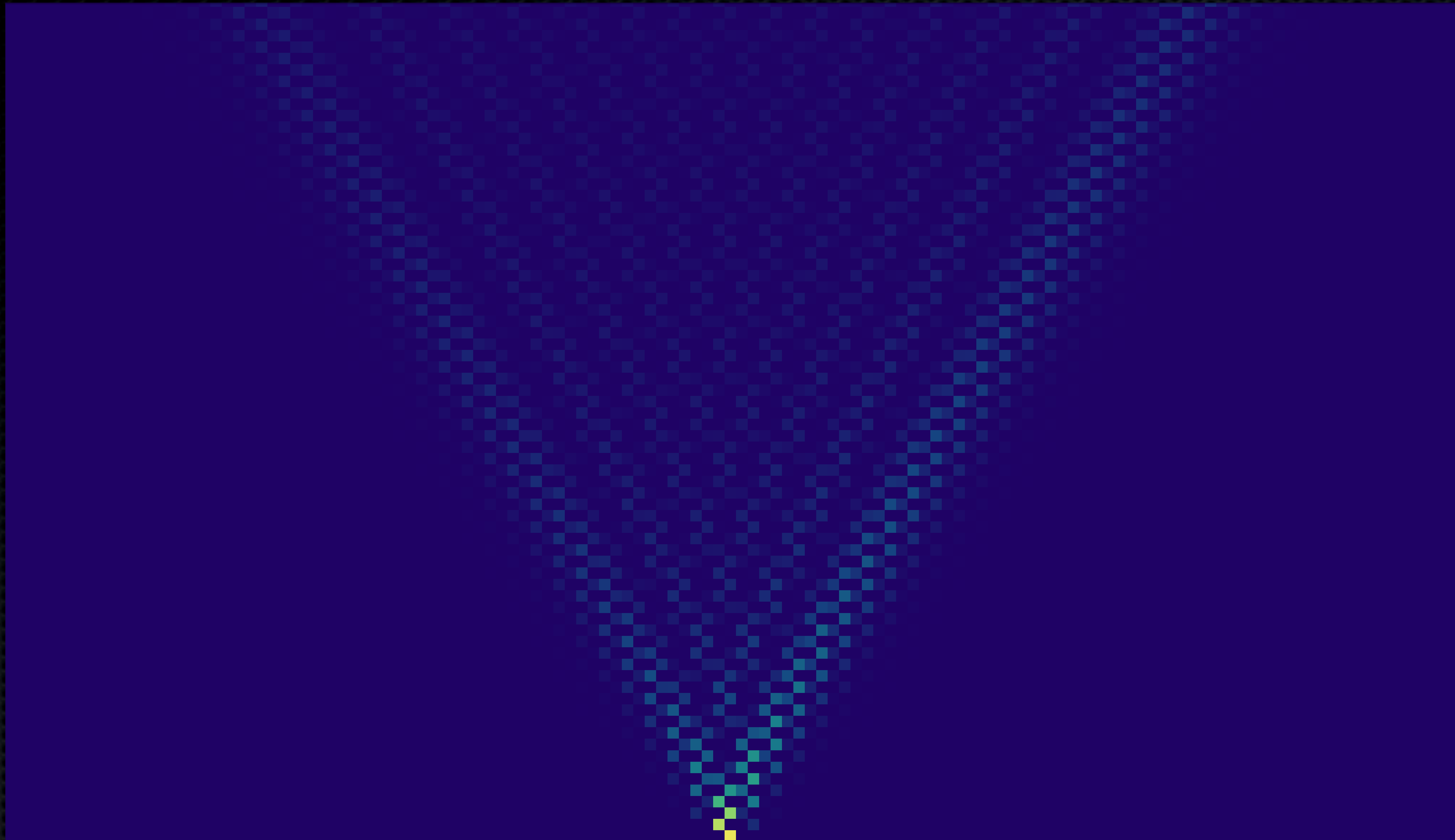

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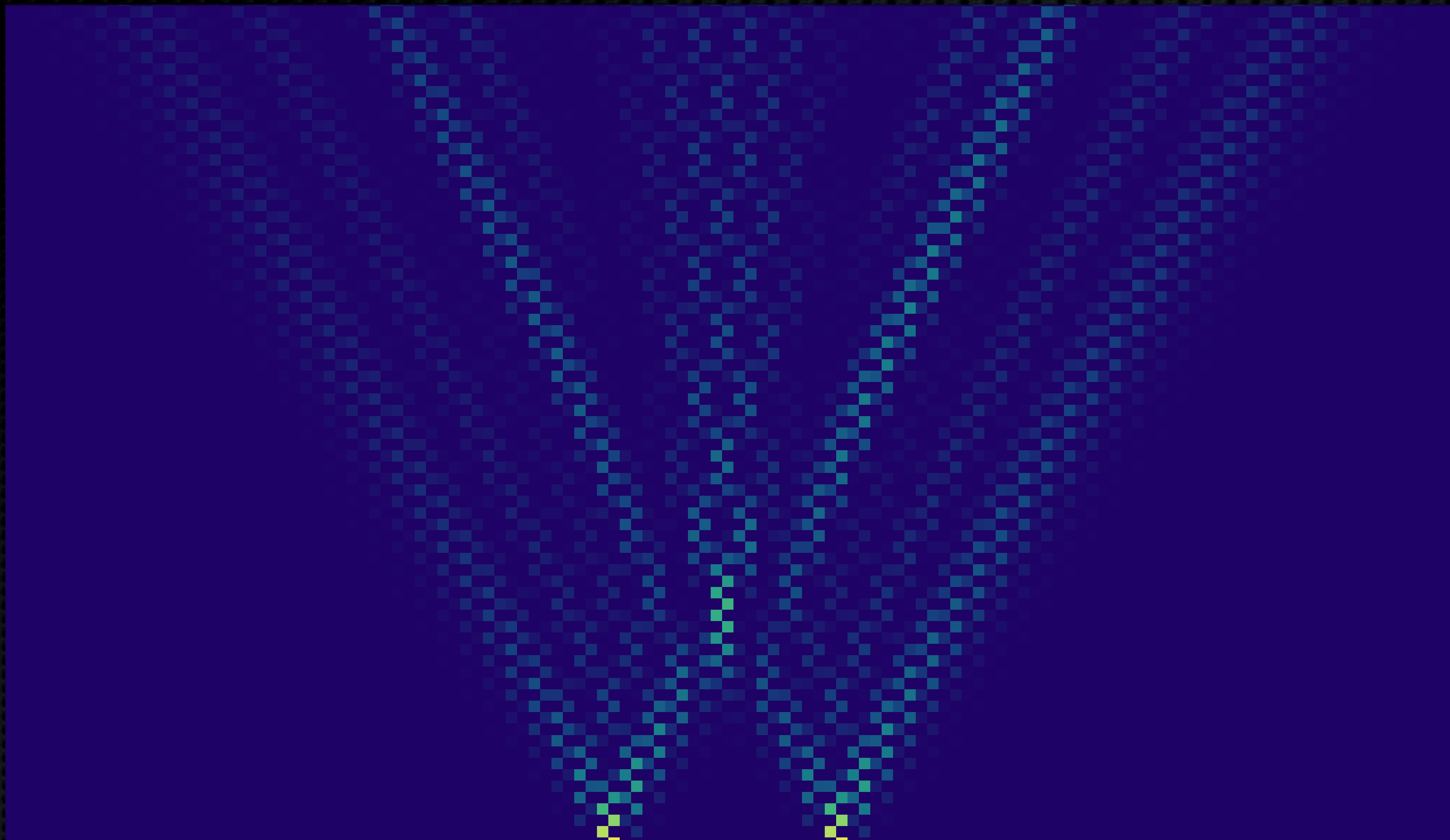

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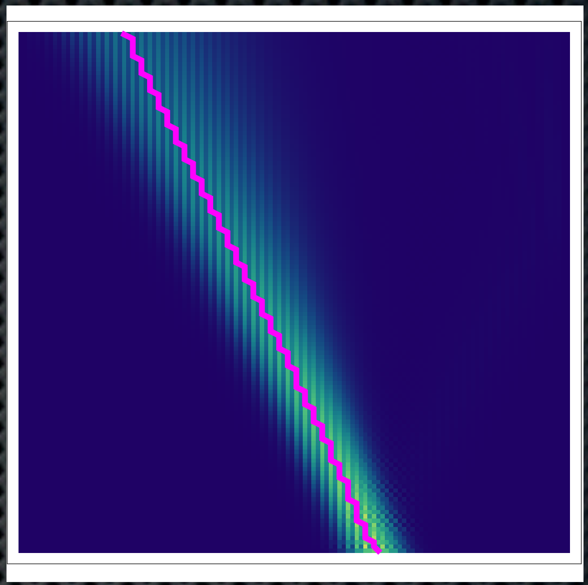
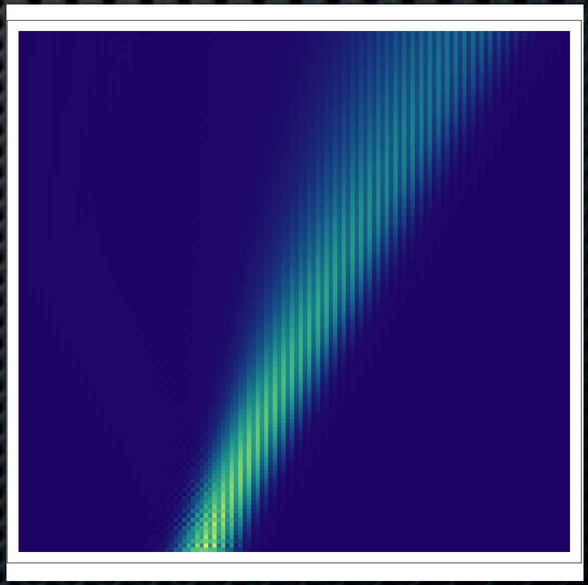
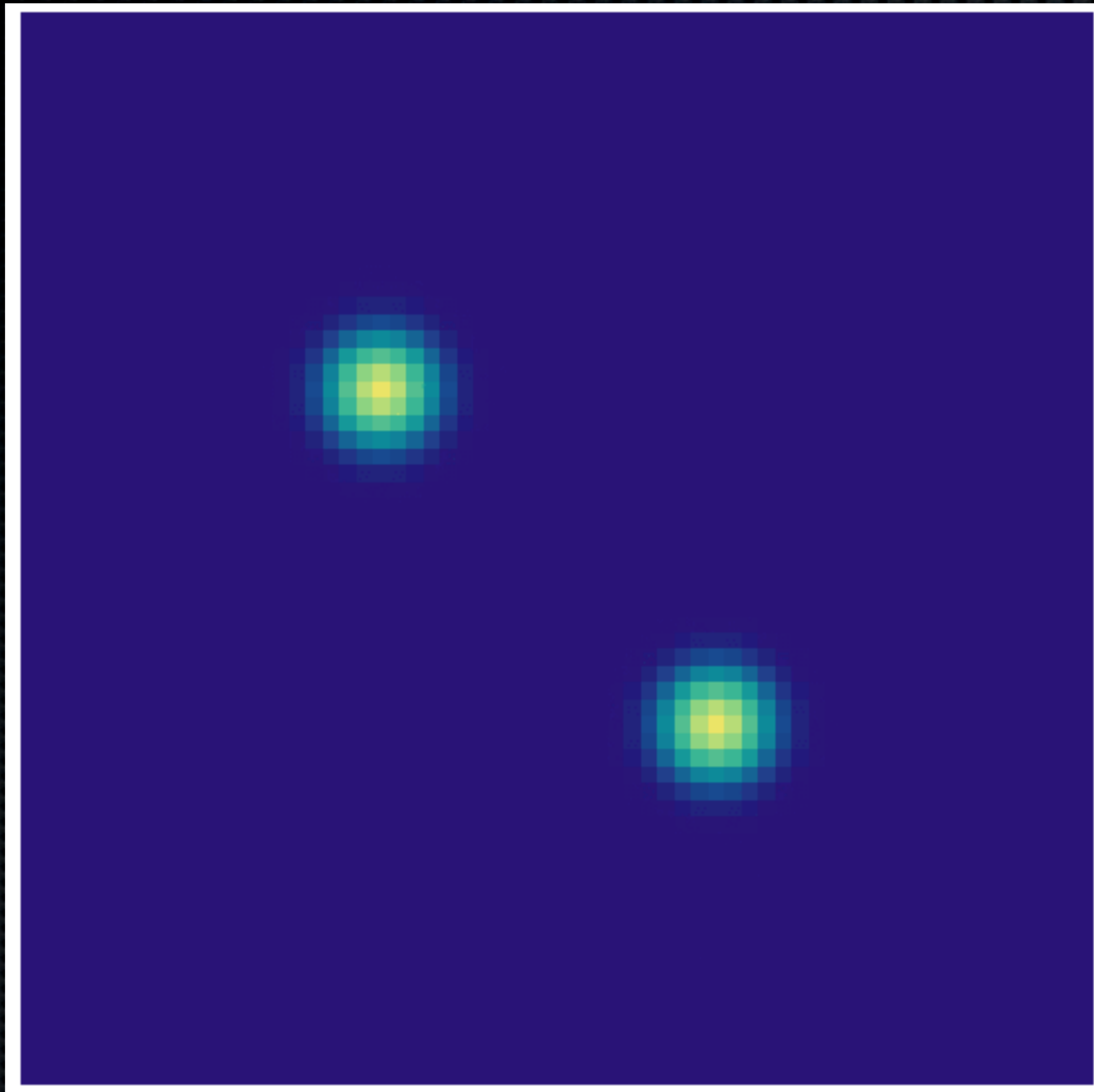
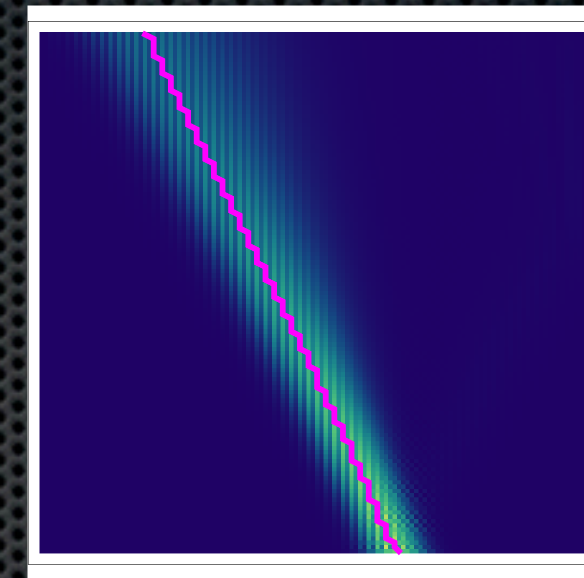
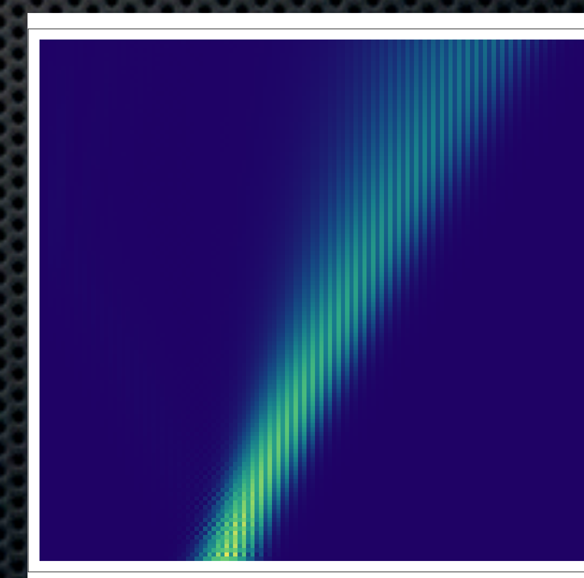




First Quantization: two-particle states







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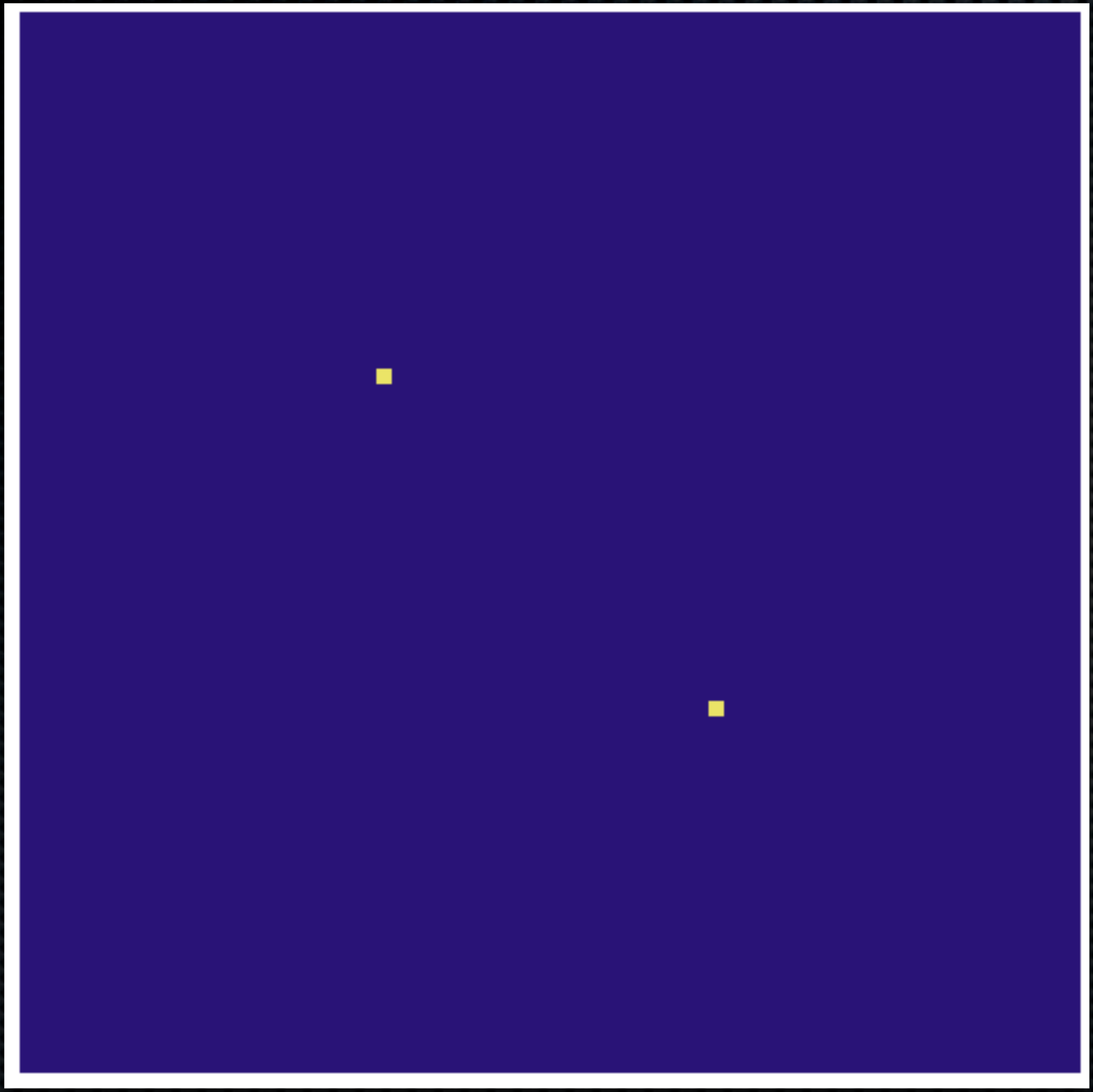
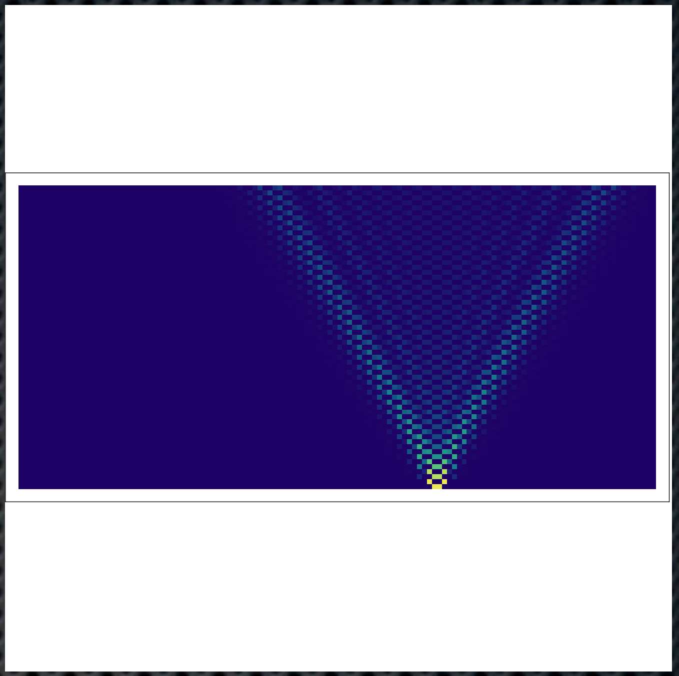
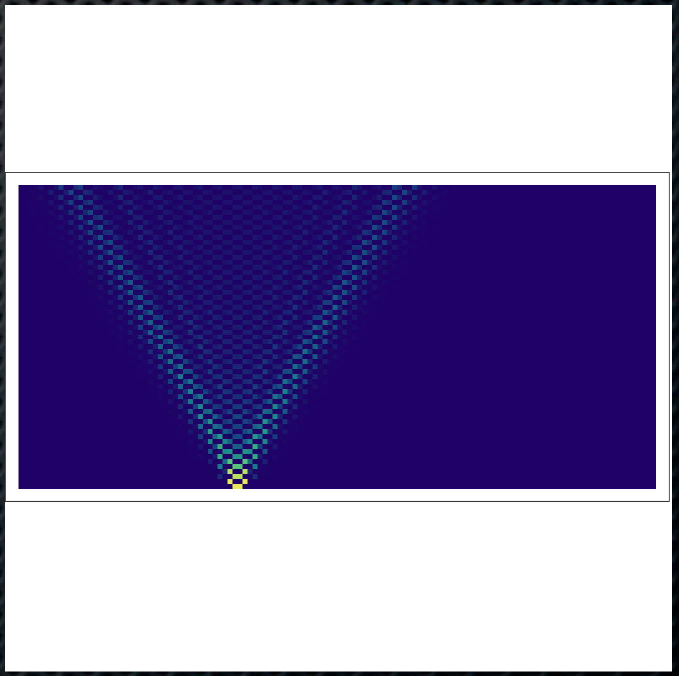




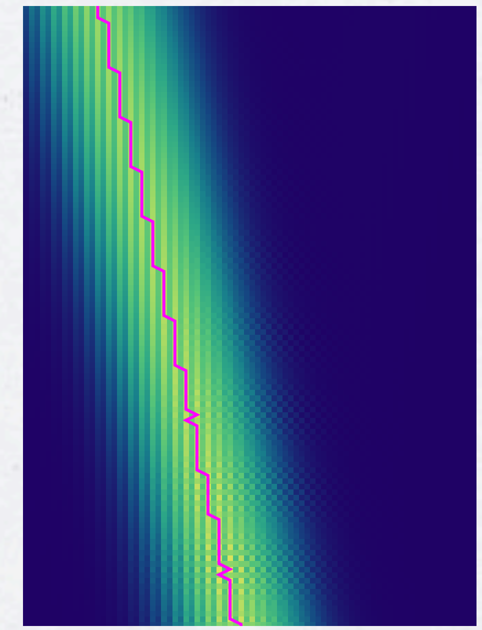


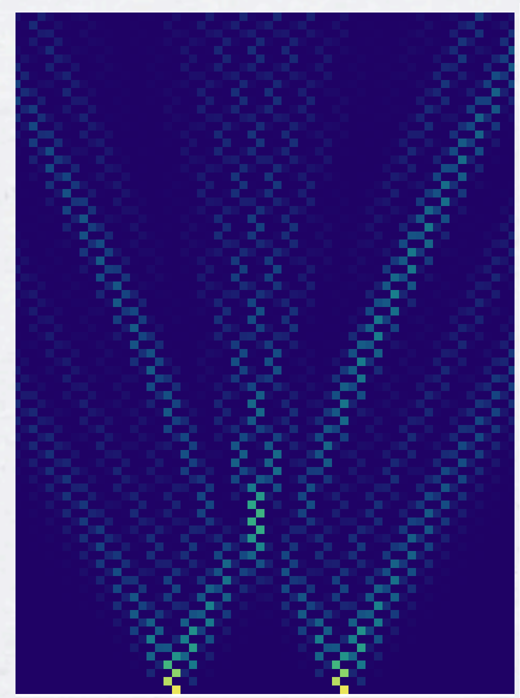
First Quantization: two-particle states

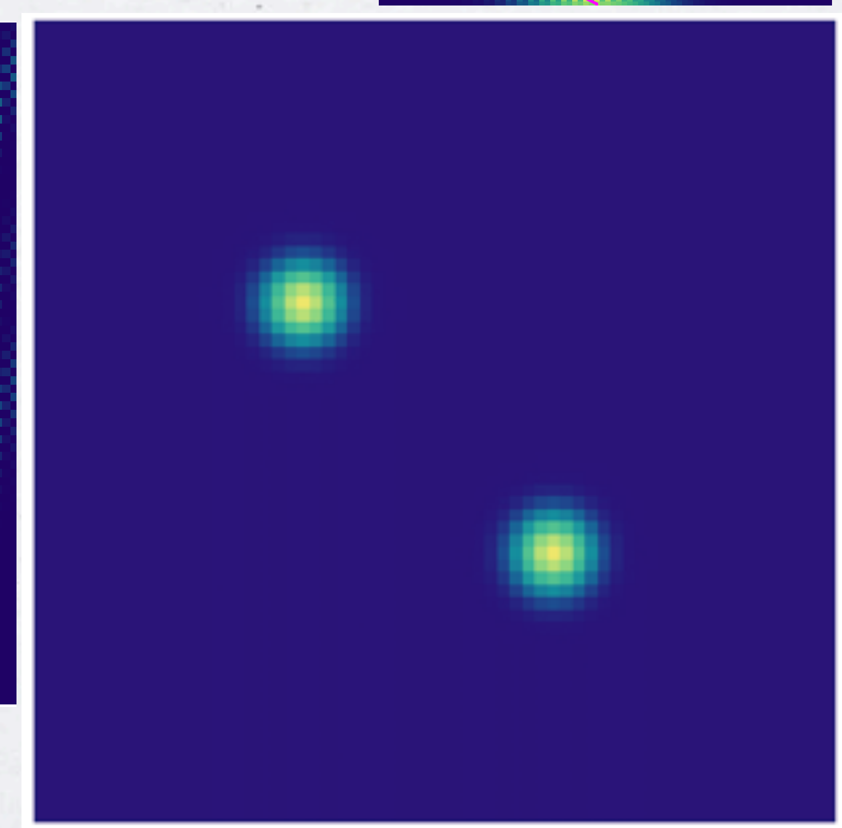
IS REALITY QUANTUM-DIGITAL?

SOME INTERESTING POINTS FOR DISCUSSION

- Emergent physics:
  - Minkowski space-time
  - Hamiltonian
  - inertial mass
  - Planck constant
  - classical mechanics
  - quantization/dequantization
  - gravitation...
- Violations:
  - Lorentz covariance,
  - dispersion relations ...







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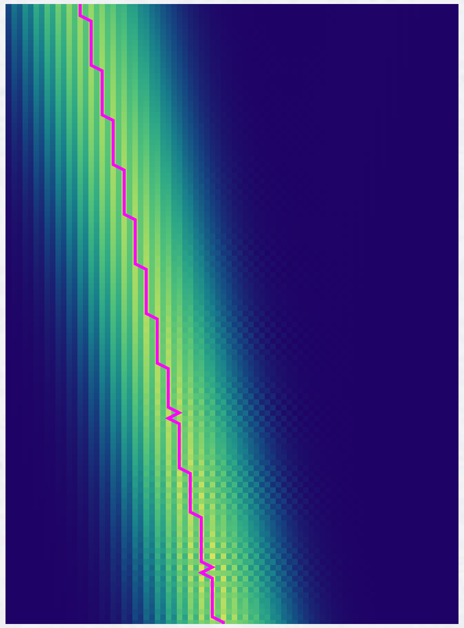

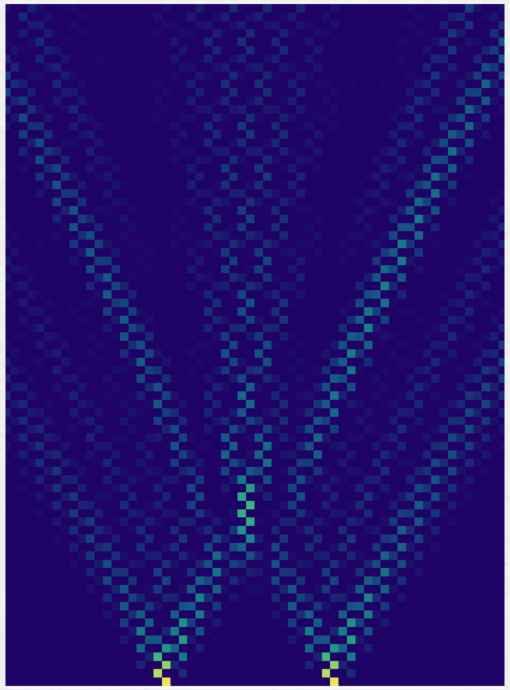

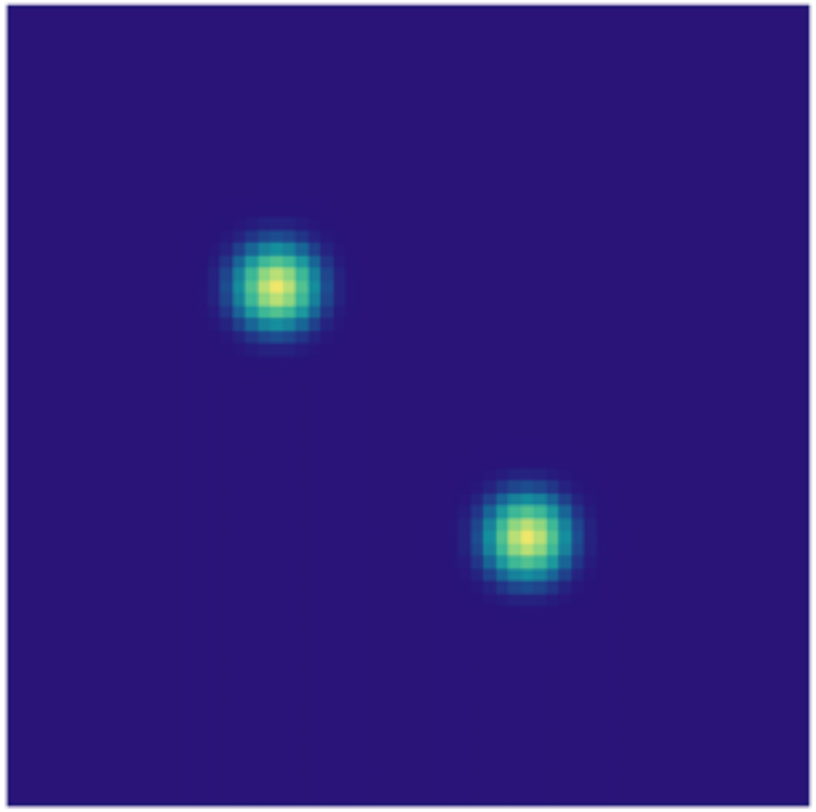

THANK YOU!