Title: Spacetime from bits

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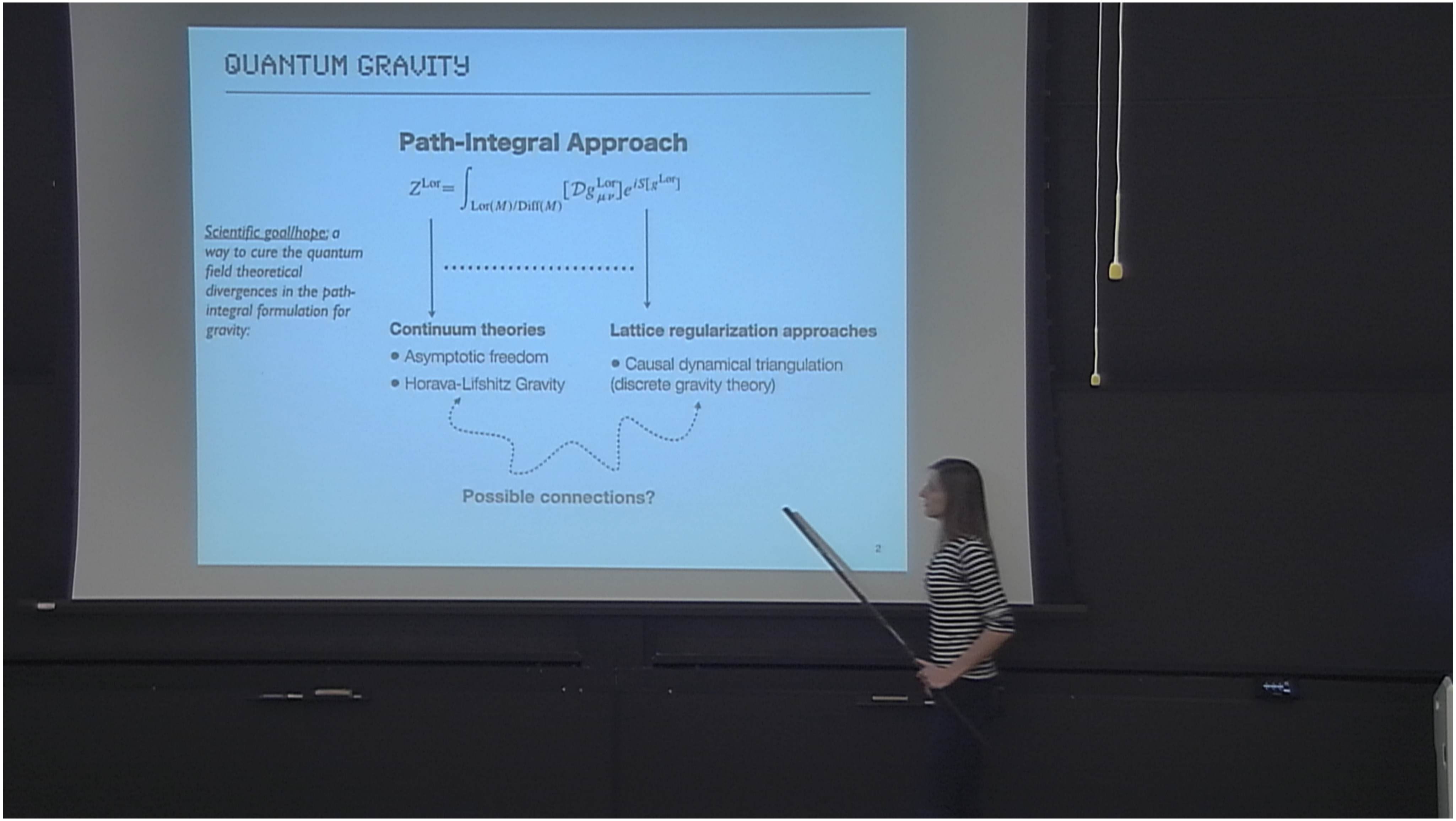
Abstract: <p>We present a new description of discrete space-time in 1+1 dimensions in terms of a set of elementary geometrical units that represent its independent classical degrees of freedom. This is achieved by means of a binary encoding that is ergodic in the class of space-time manifolds respecting coordinate invariance of general relativity. Space-time fluctuations can be represented in a classical lattice gas model whose Boltzmann weights are constructed with the discretized form of the Einstein-Hilbert action. Within this framework, it is possible to compute basic quantities such as the Ricci curvature tensor and the Einstein equations, and to evaluate the path integral of discrete gravity. The description as a lattice gas model also provides a novel way of quantization and, at the same time, to quantum simulation of fluctuating space-time.</p>


QUANTUM GRAVITY
Path-Integral Approach
$Z^{\mathrm{Lor}} = \int_{\mathrm{Lor}(M)/\mathrm{Diff}(M)} [\mathcal{D}g^{\mathrm{Lor}}_{\mu\nu}] e^{iS[g^{\mathrm{Lor}}]}$
Scientific goal/hope: a way to cure the quantum field theoretical divergences in the path-integral formulation for gravity:
Continuum theories
• Asymptotic freedom
• Horava-Lifshitz Gravity
Lattice regularization approaches
• Causal dynamical triangulation (discrete gravity theory)
Possible connections?
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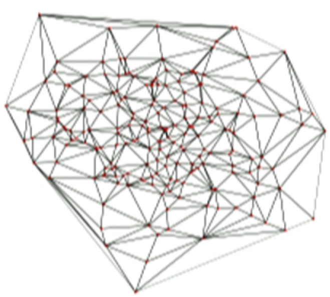
DISCRETE GRAVITY ➤ CAUSAL DYNAMICAL TRIANGULATION

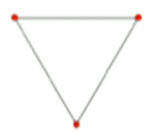
Discrete quantum gravity - idea:

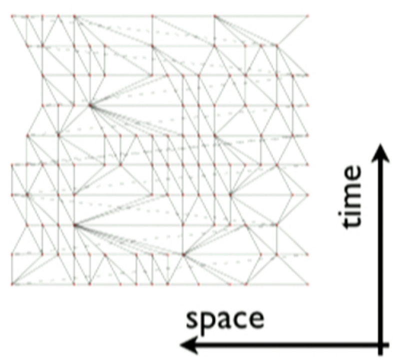
Lorentzian manifolds admit a **triangulation into a net of simplices** and spacetime curvature can be expressed in terms of simplectic analogues, e.g. deficit angles.

Causal dynamical triangulation:

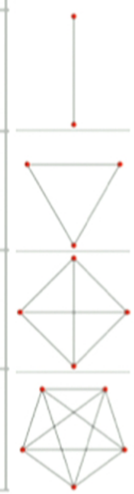
• **edge length** of "fundamental building blocks" (d+1 dimensional simplexes) are **fixed**;
• geometry emerges as the sum of all possible triangulations (modulo diffemorphsims) **obeying a global foliation** - e.g. in 1+1 dimensions:







0-simplex (point)	
1-simplex (line segment)	
2-simplex (triangle)	
3-simplex (tetrahedron)	
4-simplex (pentachoron)	



generalization of the notion of a triangle or tetrahedron to arbitrary dimension

3

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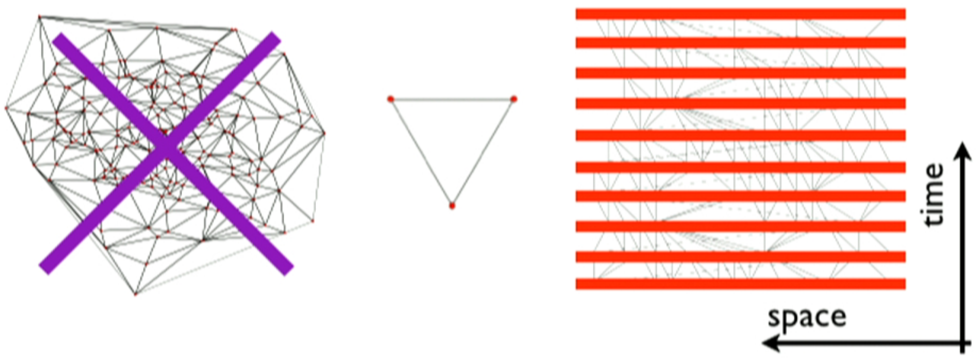

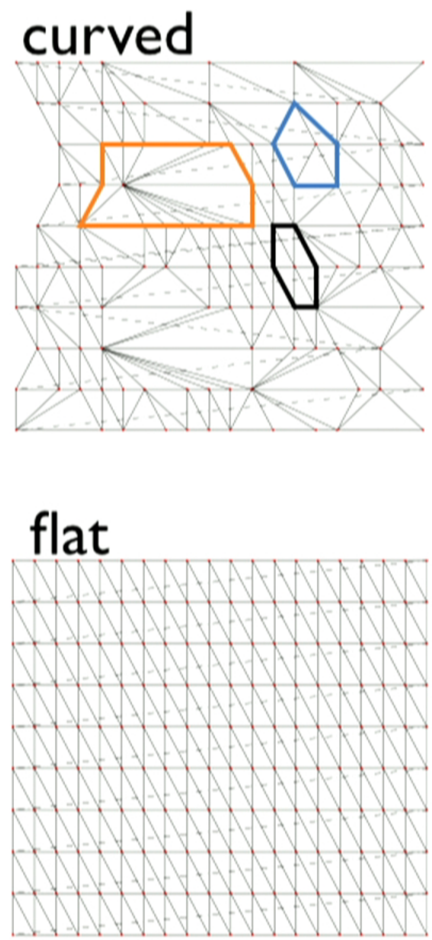

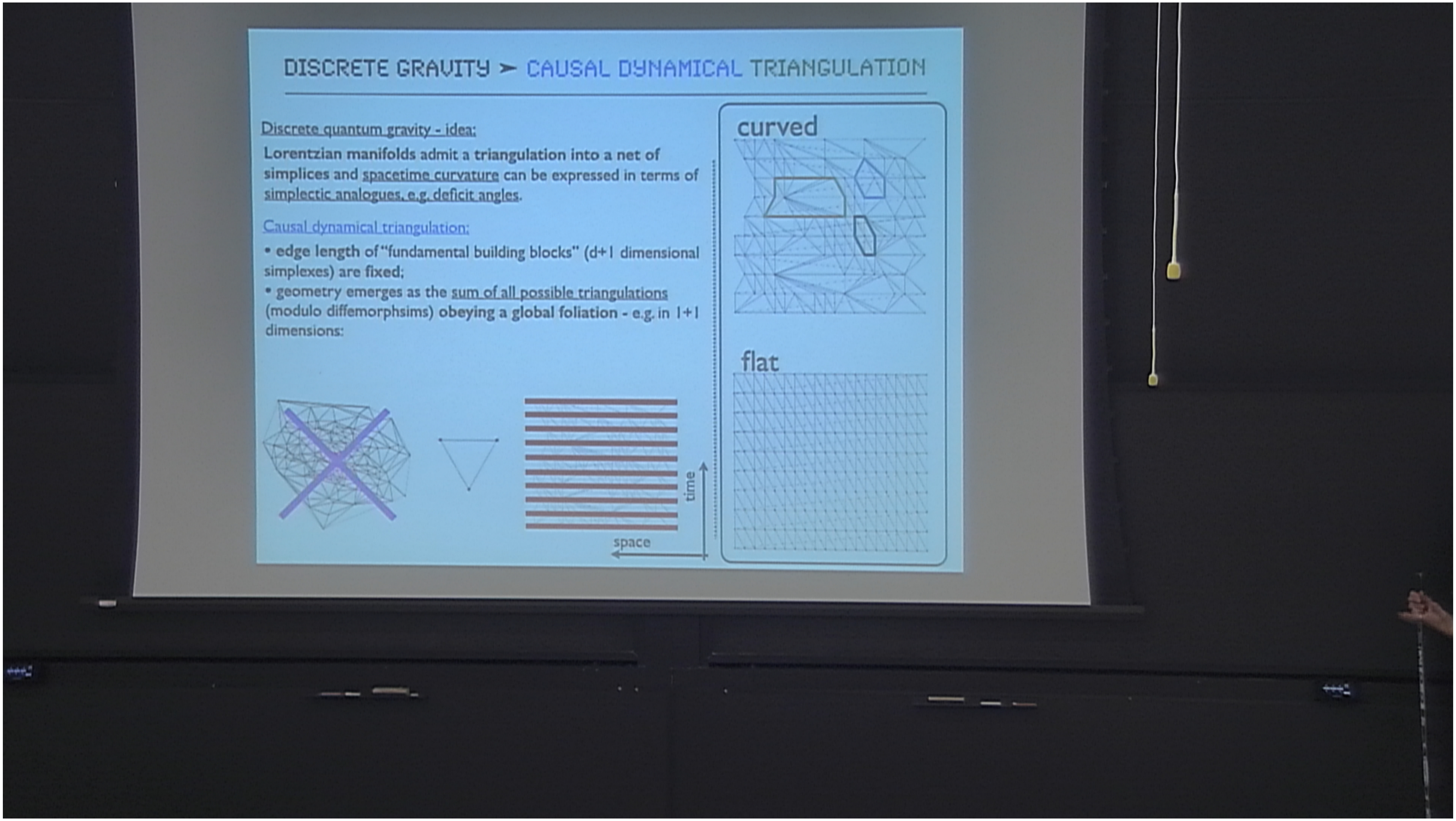
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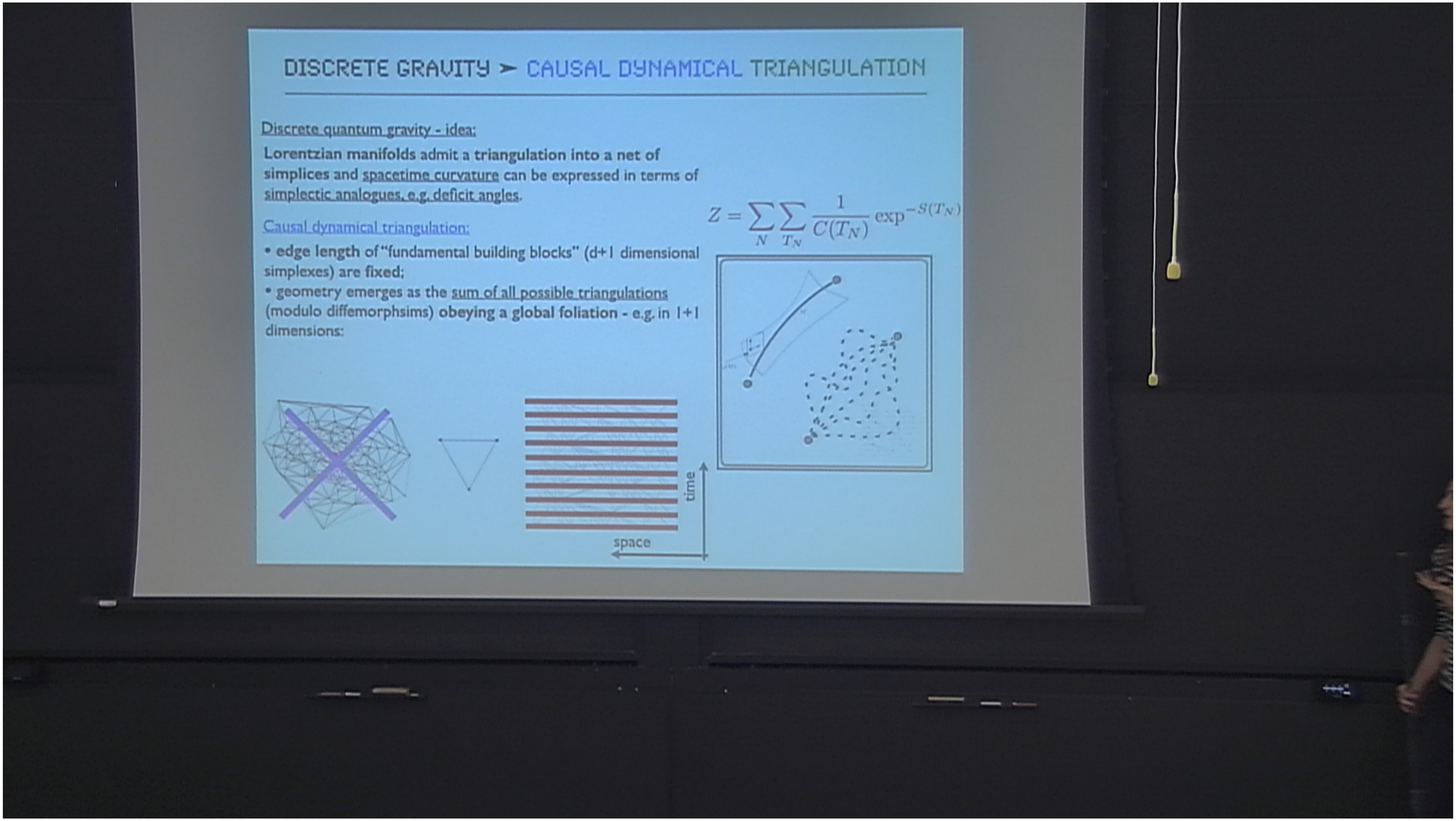
time
space
curved
flat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$Z = \sum_N \sum_{T_N} \frac{1}{C(T_N)} \exp^{-S(T_N)}$
time
space

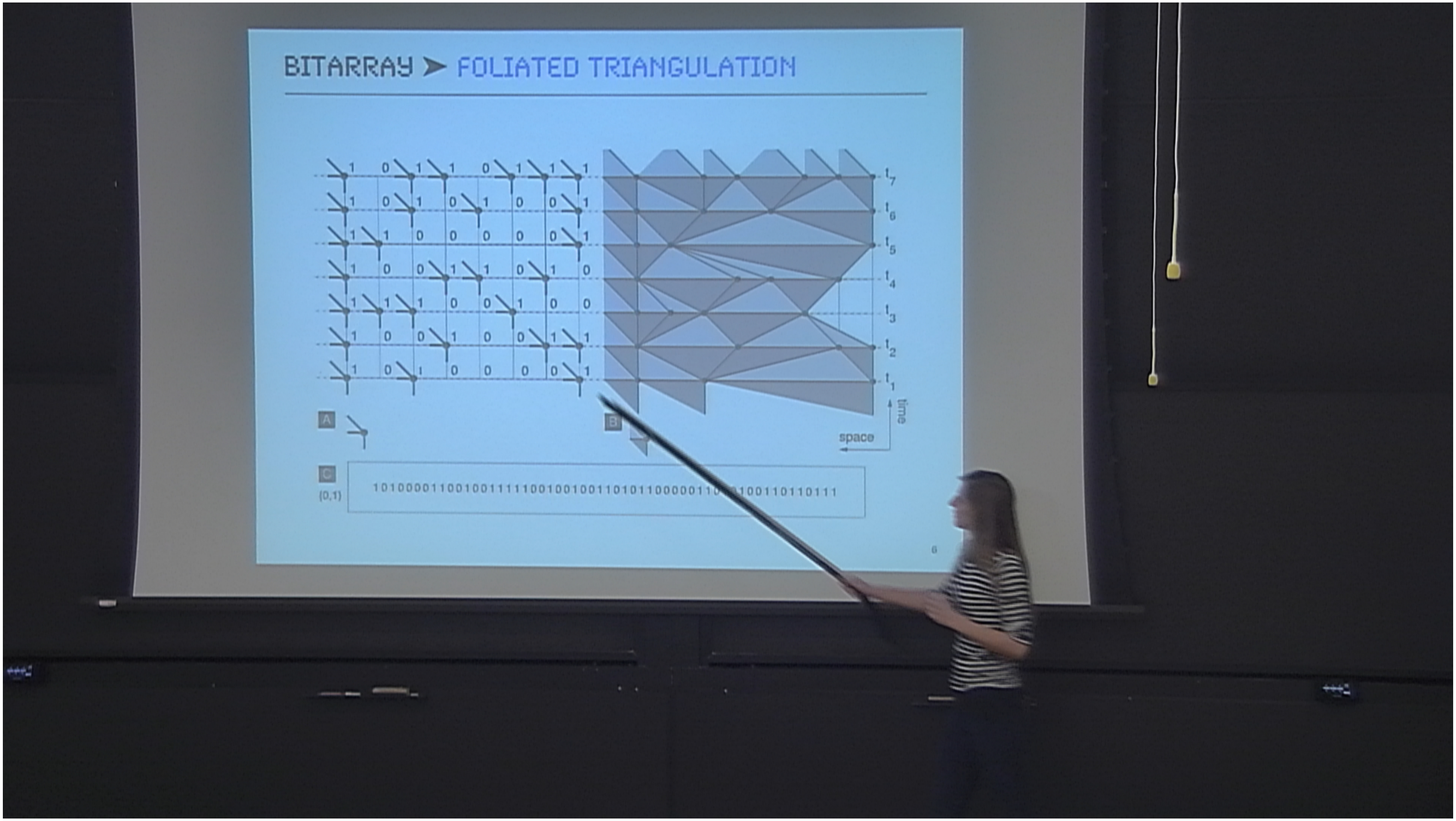
THE BASIC IDEA

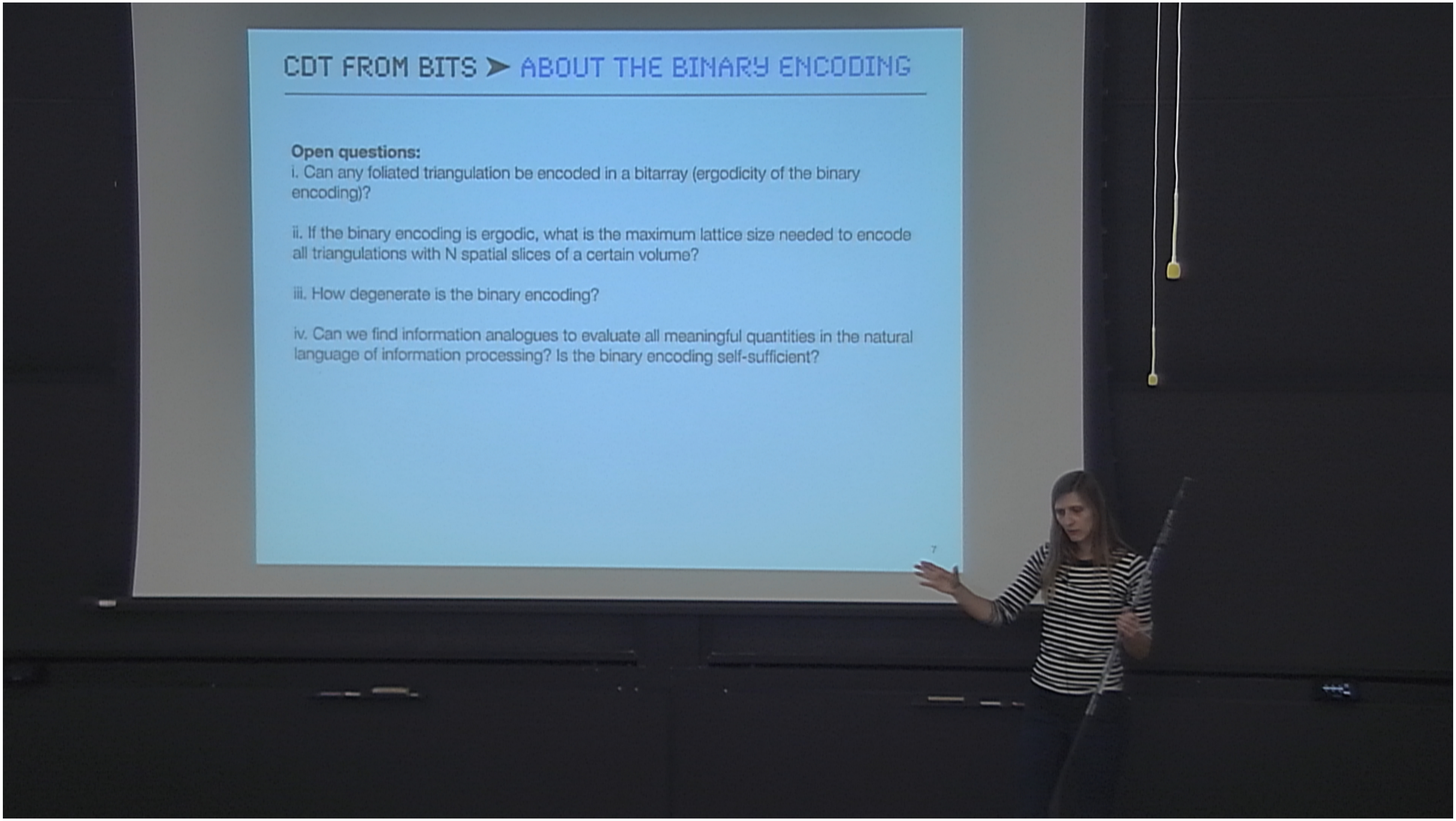
A line of thought:

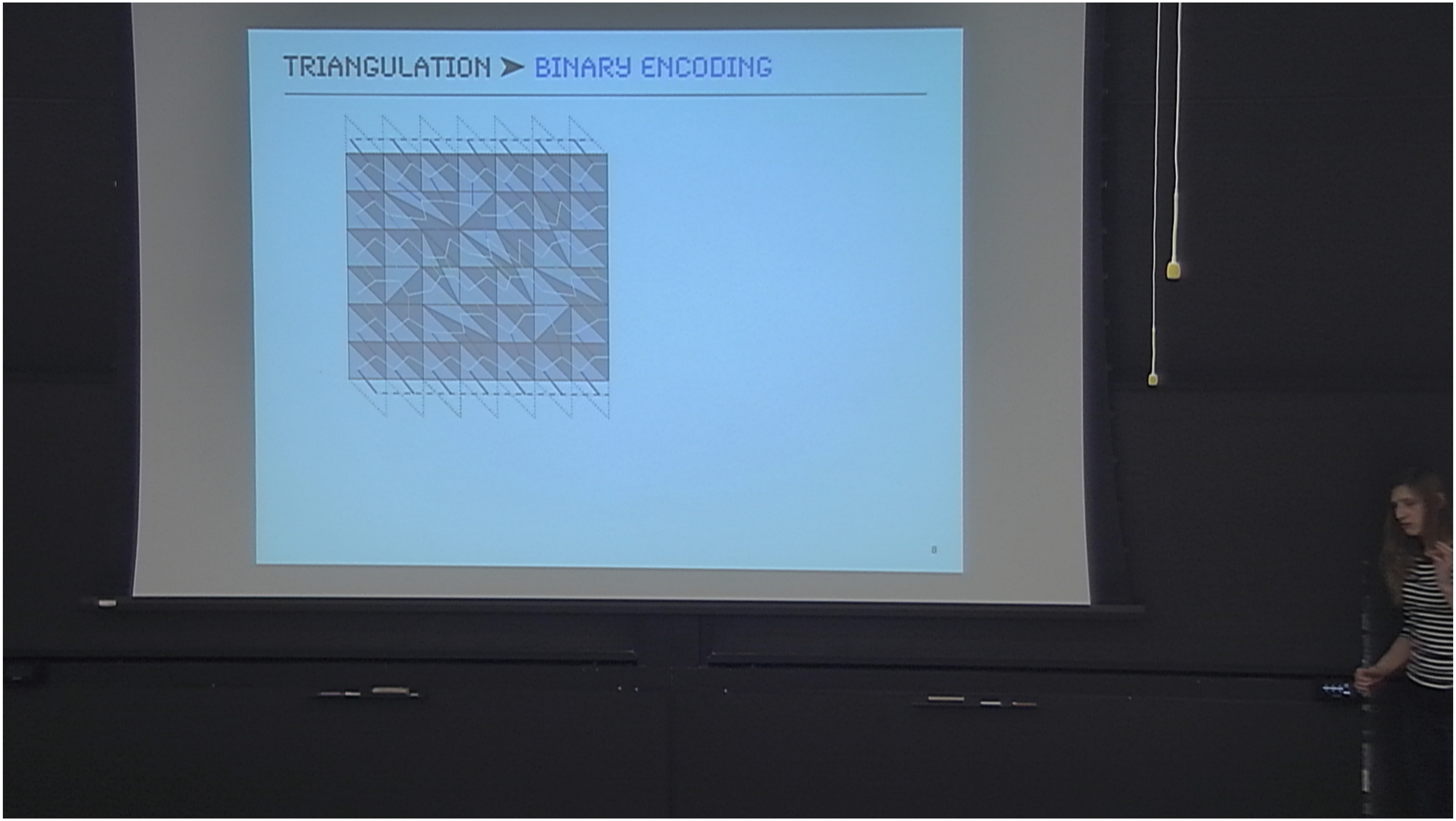
i. CDT is a sufficiently simple — at least in 1+1 dimensions — approach of quantum gravity, such that one would be allowed to look for analogue systems.

ii. These analogue systems are only useful if they give us some deeper (or different insights) into CDT, and/or relate CDT to physical systems.

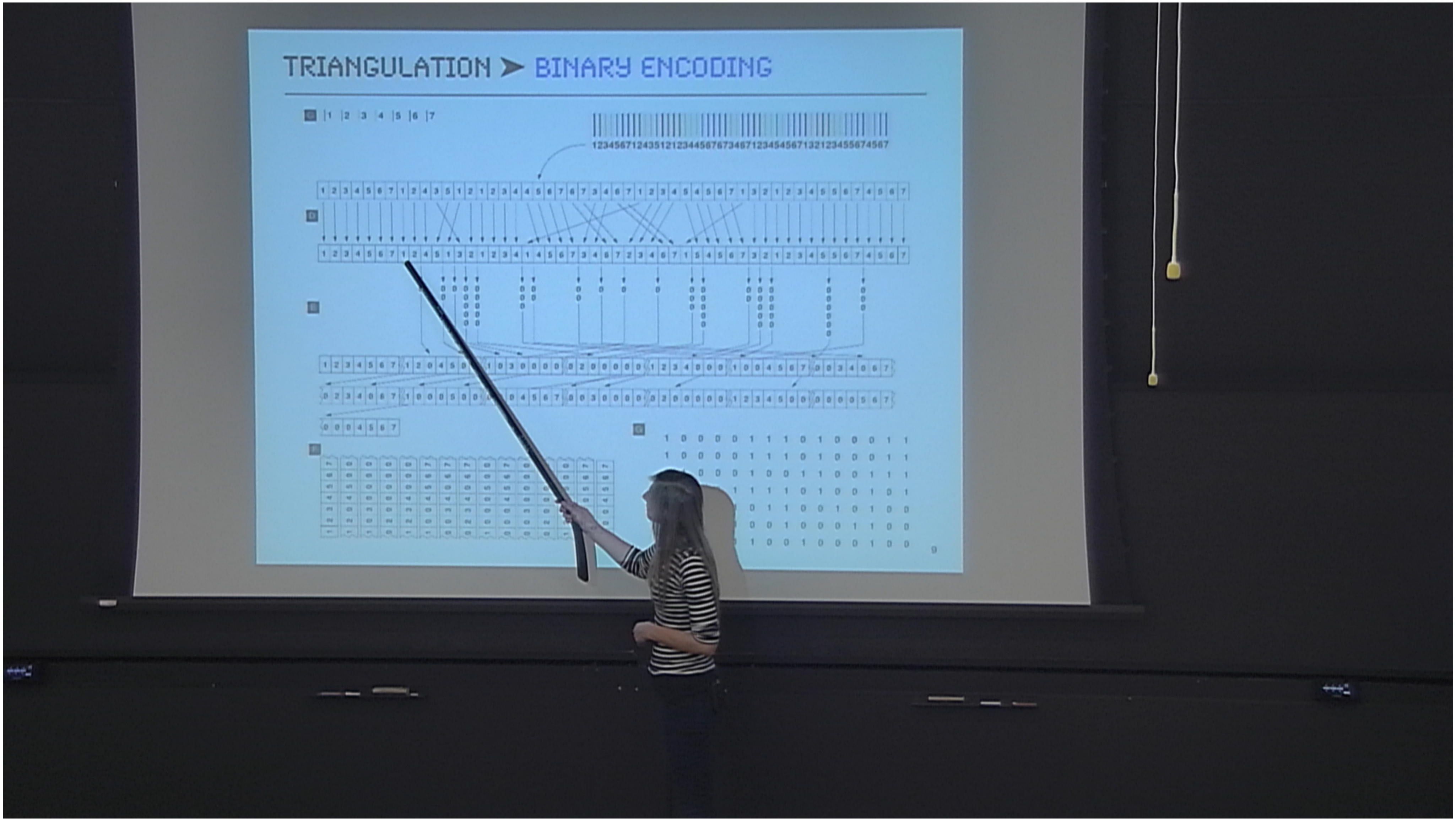
iii. I will show that it is possible to identify such an analogy, BUT there is a problem associated to CDT and quantum gravity more general, which becomes apparent when looking for applications of our findings…


BITARRAY ➤ FOLIATED TRIANGULATION
A
B
C
(0,1)
space
time


CDT FROM BITS ➤ ABOUT THE BINARY ENCODING
Open questions:
i. Can any foliated triangulation be encoded in a bitarray (ergodicity of the binary encoding)?
ii. If the binary encoding is ergodic, what is the maximum lattice size needed to encode all triangulations with N spatial slices of a certain volume?
iii. How degenerate is the binary encoding?
iv. Can we find information analogues to evaluate all meaningful quantities in the natural language of information processing? Is the binary encoding self-sufficient?


TRIANGULATION ➤ BINARY ENCODING
8


TRIANGULATION ➤ BINARY ENCODING
(i) pair-wise commutations of the kind
$[\dots,\psi_i,\psi_j,\dots] \sim [\dots,\psi_j,\psi_i,\dots]$,
where $|\psi_i - \psi_j| \geq 2$,
e.g. [2132232] ~ [2312232] ≁ [3212232];
(ii) cyclic permutations of the kind
$[\psi_1,\psi_2\dots,\psi_F] \sim [\psi_2,\dots,\psi_F,\psi_1]$,
e.g. [2312232] ~ [3122322];
(iii) mirror operations of the kind
$[\psi_1,\psi_2\dots,\psi_F] \sim [\psi_F,\dots,\psi_2,\psi_1]$,
e.g. [2312232] ~ [2322132].
t_7
t_6
t_5
t_4
t_3
t_2
t_1
|1 |2 |3 |4 |5 |6 |7
8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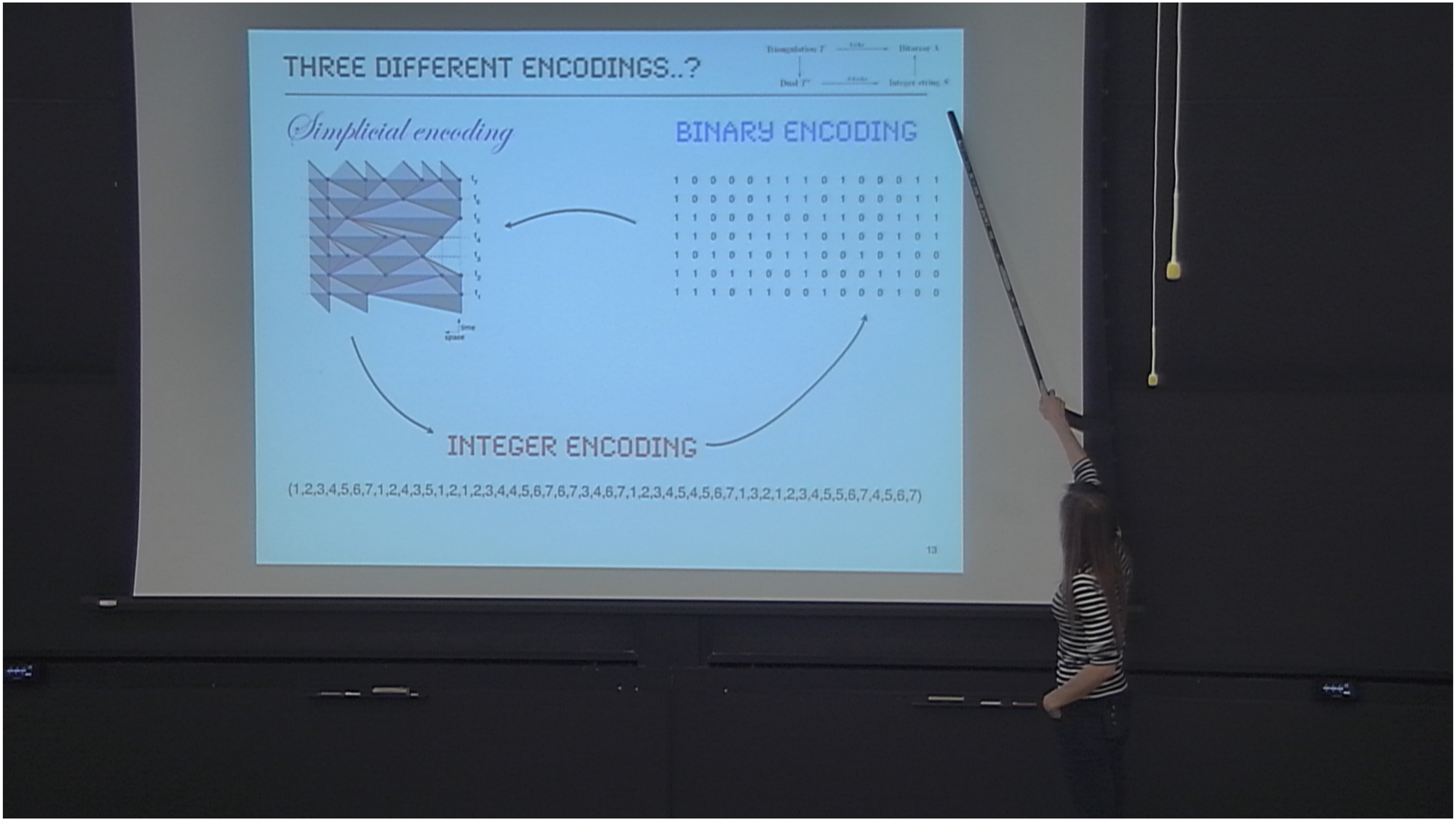
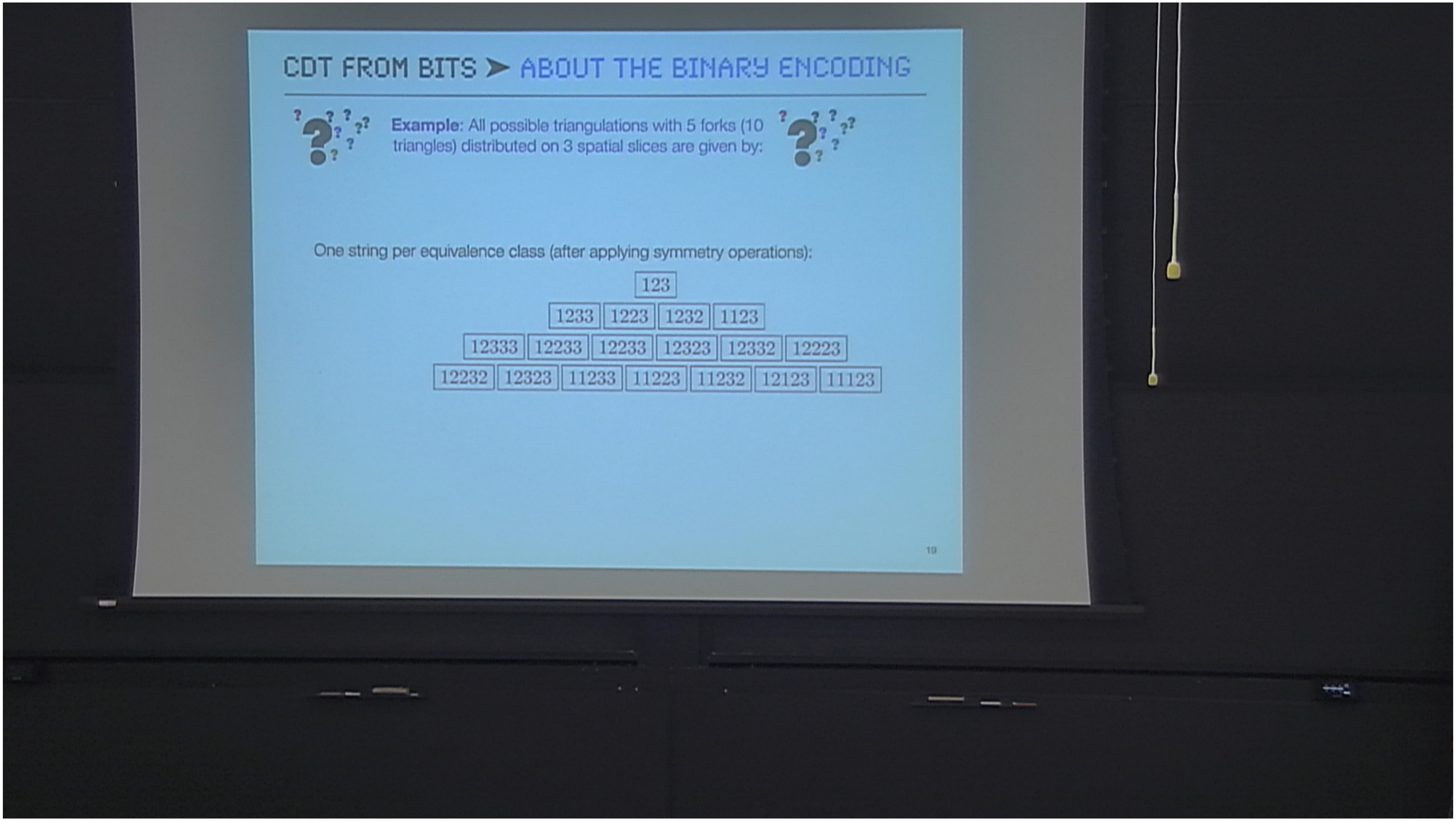
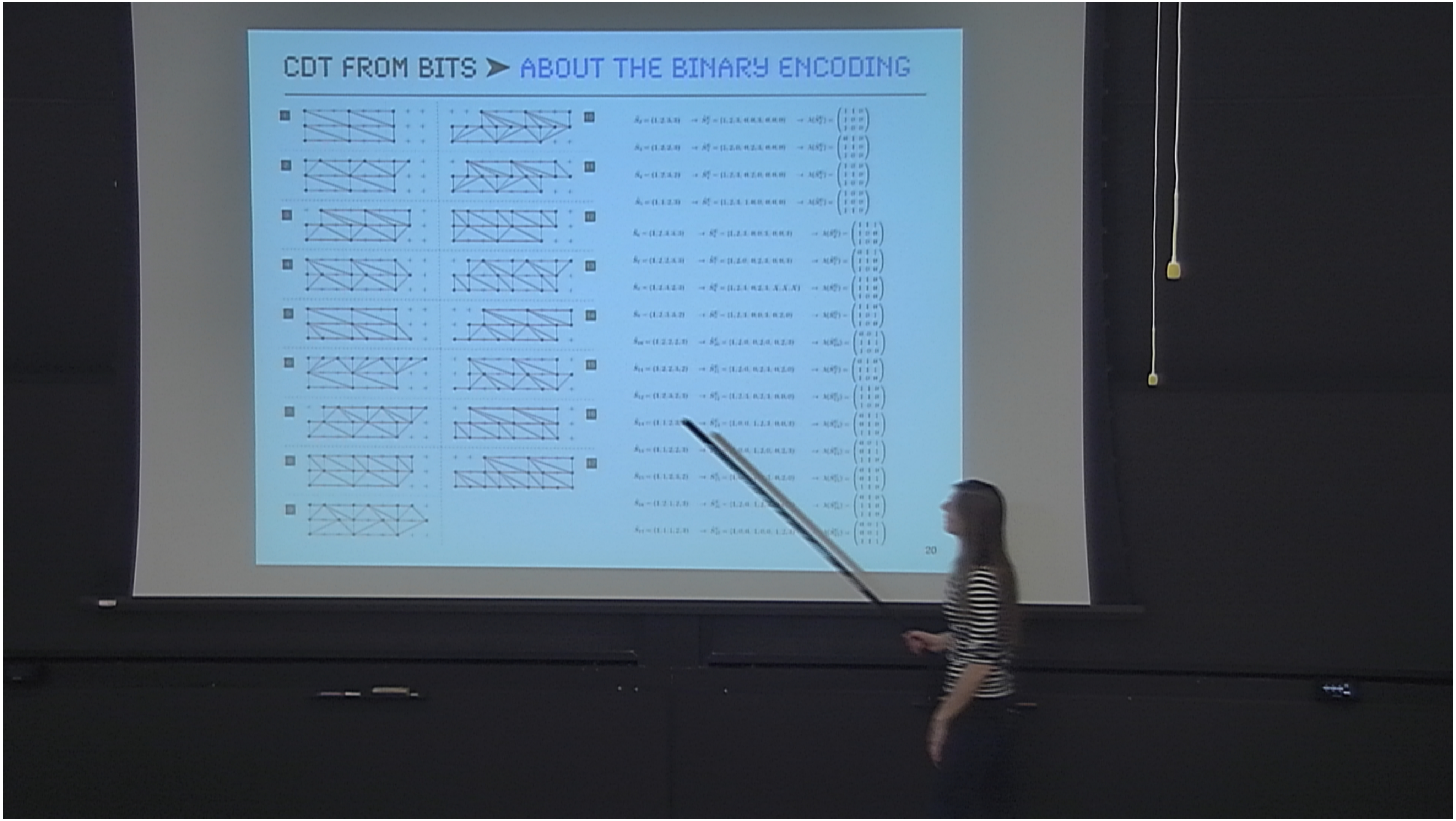
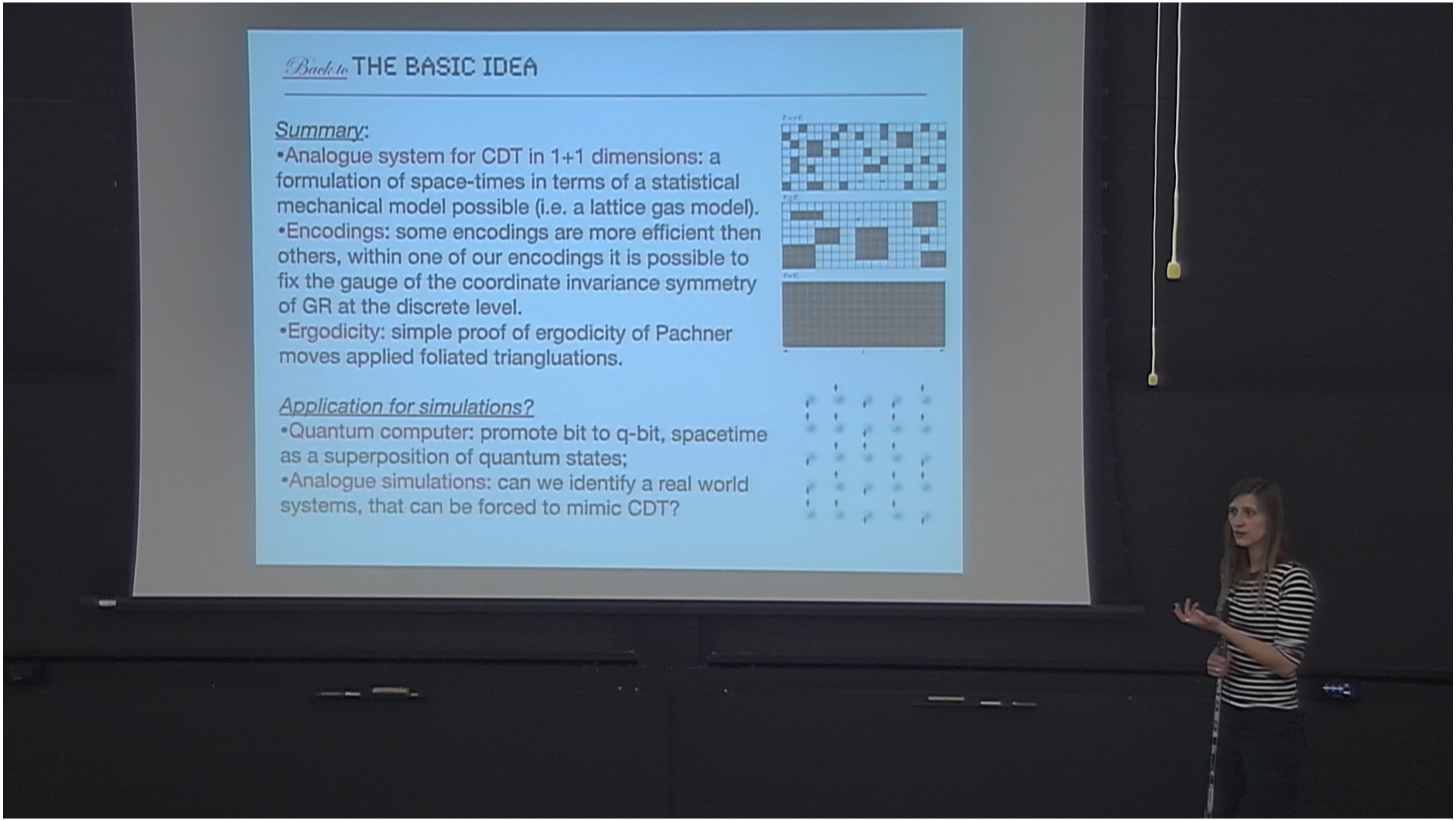


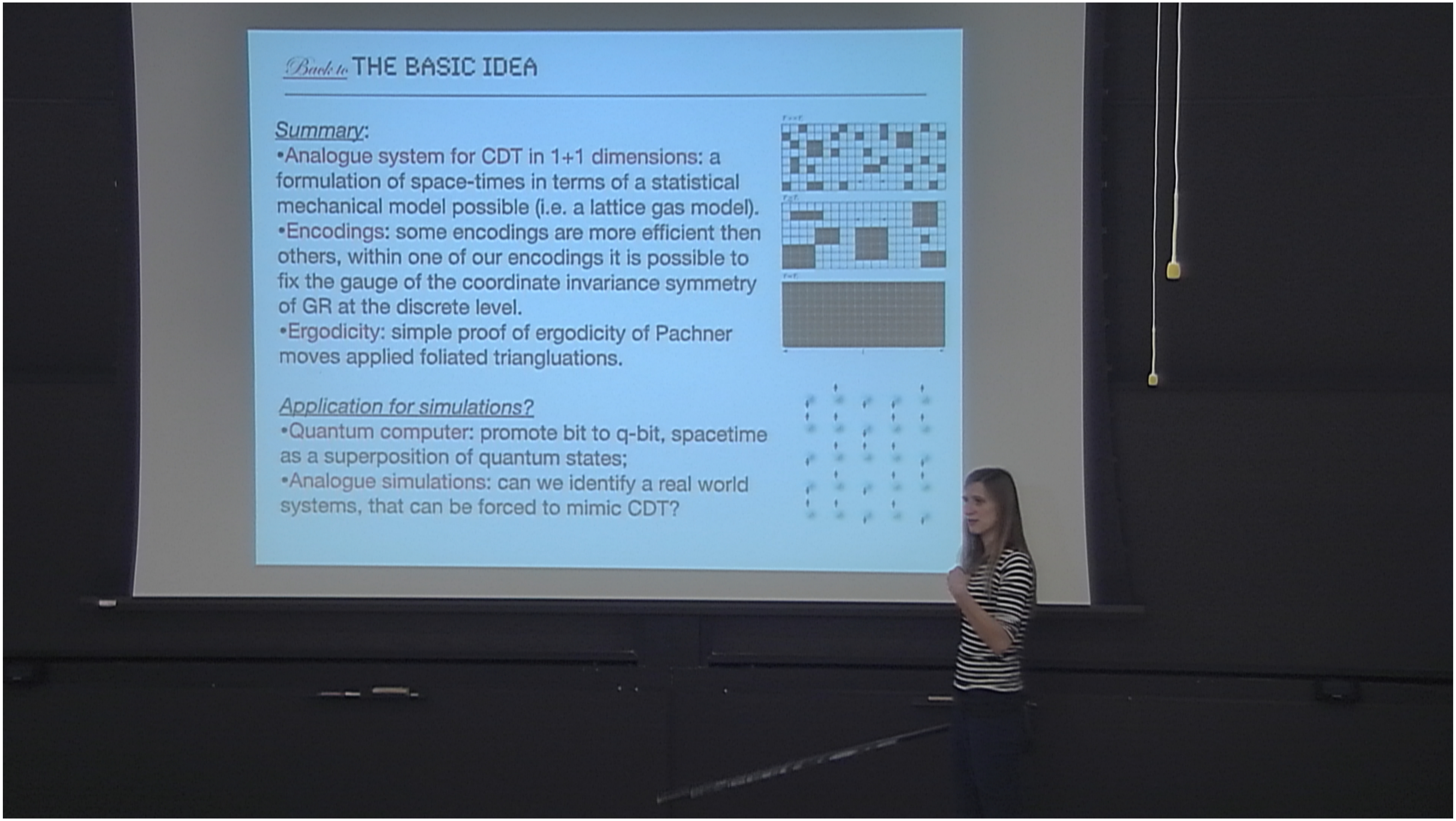
THREE DIFFERENT ENCODINGS..?
Simplicial encoding
BINARY ENCODING
1 0 0 0 0 1 1 1 0 1 0 0 0 1 1
1 0 0 0 0 1 1 1 0 1 0 0 0 1 1
1 1 0 0 0 1 0 0 1 1 0 0 1 1 1
1 1 0 0 1 1 1 1 0 1 0 0 1 0 1
1 0 1 0 1 0 1 1 0 0 1 0 1 0 0
1 1 0 1 1 0 0 1 0 0 0 1 1 0 0
1 1 1 0 1 1 0 0 1 0 0 0 1 0 0
time
space
INTEGER ENCODING
(1,2,3,4,5,6,7,1,2,4,3,5,1,2,1,2,3,4,4,5,6,7,6,7,3,4,6,7,1,2,3,4,5,4,5,6,7,1,3,2,1,2,3,4,5,5,6,7,4,5,6,7)
13


CDT FROM BITS ➤ ABOUT THE BINARY ENCODING
Example: All possible triangulations with 5 forks (10 triangles) distributed on 3 spatial slices are given by:
One string per equivalence class (after applying symmetry operations):
123
1233 1223 1232 1123
12333 12233 12233 12323 12332 12223
12232 12323 11233 11223 11232 12123 11123
19



CDT FROM BITS ➤ ABOUT THE BINARY ENCODING
20


Back to THE BASIC IDEA
Summary:
•Analogue system for CDT in 1+1 dimensions: a formulation of space-times in terms of a statistical mechanical model possible (i.e. a lattice gas model).
•Encodings: some encodings are more efficient then others, within one of our encodings it is possible to fix the gauge of the coordinate invariance symmetry of GR at the discrete level.
•Ergodicity: simple proof of ergodicity of Pachner moves applied foliated triangluations.
Application for simulations?
•Quantum computer: promote bit to q-bit, spacetime as a superposition of quantum states;
•Analogue simulations: can we identify a real world systems, that can be forced to mimic CDT?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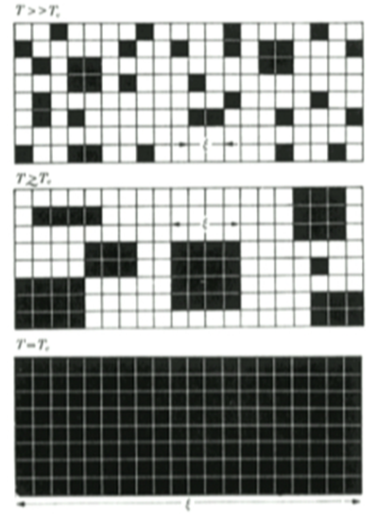

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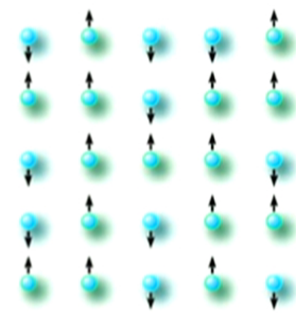

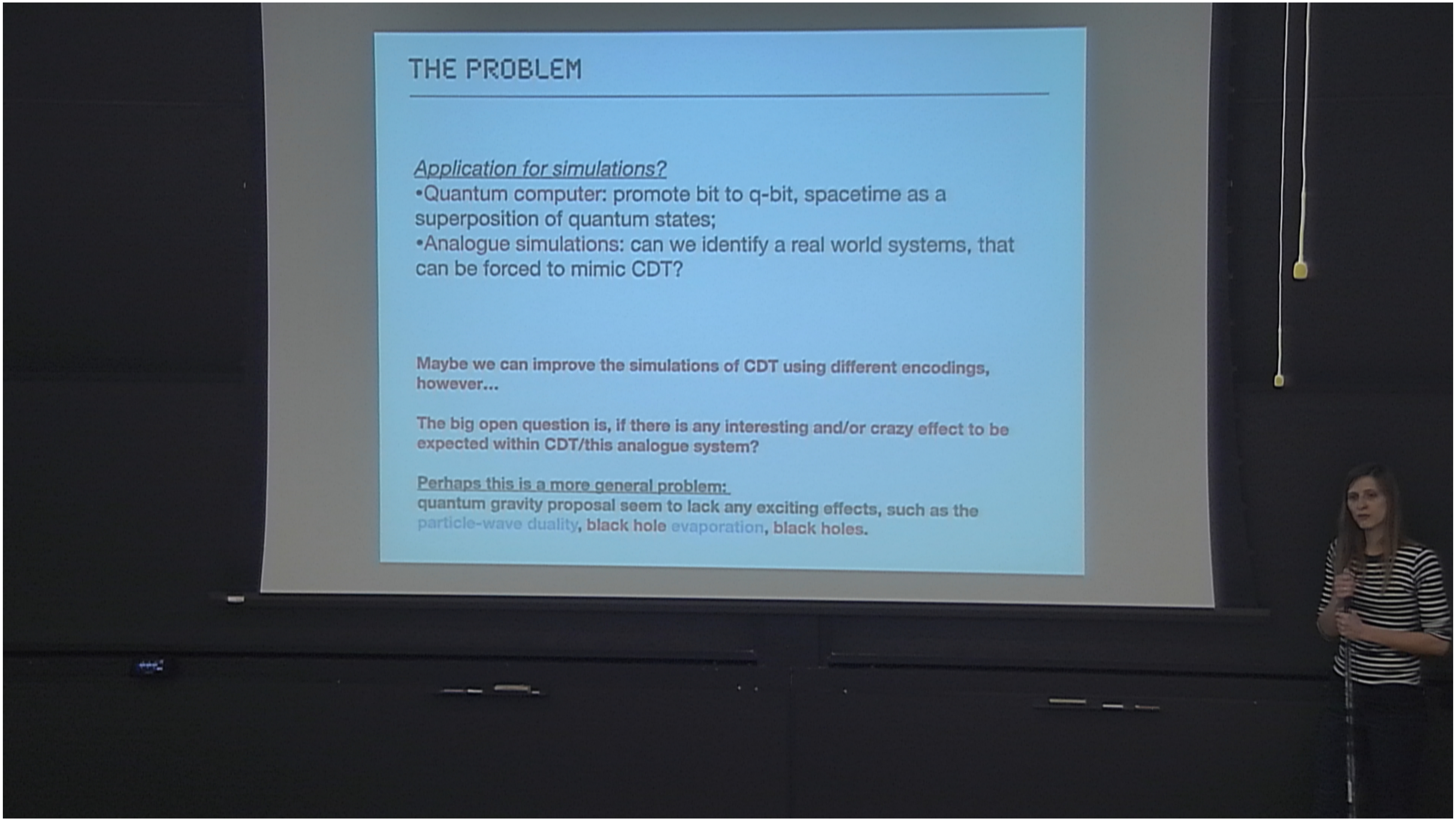
THE PROBLEM
Application for simulations?
•Quantum computer: promote bit to q-bit, spacetime as a superposition of quantum states;
•Analogue simulations: can we identify a real world systems, that can be forced to mimic CDT?
Maybe we can improve the simulations of CDT using different encodings, however...
The big open question is, if there is any interesting and/or crazy effect to be expected within CDT/this analogue system?
Perhaps this is a more general problem:
quantum gravity proposal seem to lack any exciting effects, such as the particle-wave duality, black hole evaporation, black holes.