Title: Insights from background independent approaches to quantum gravity

Date: Sep 05, 2006 04:00 PM

URL: http://pirsa.org/06090023

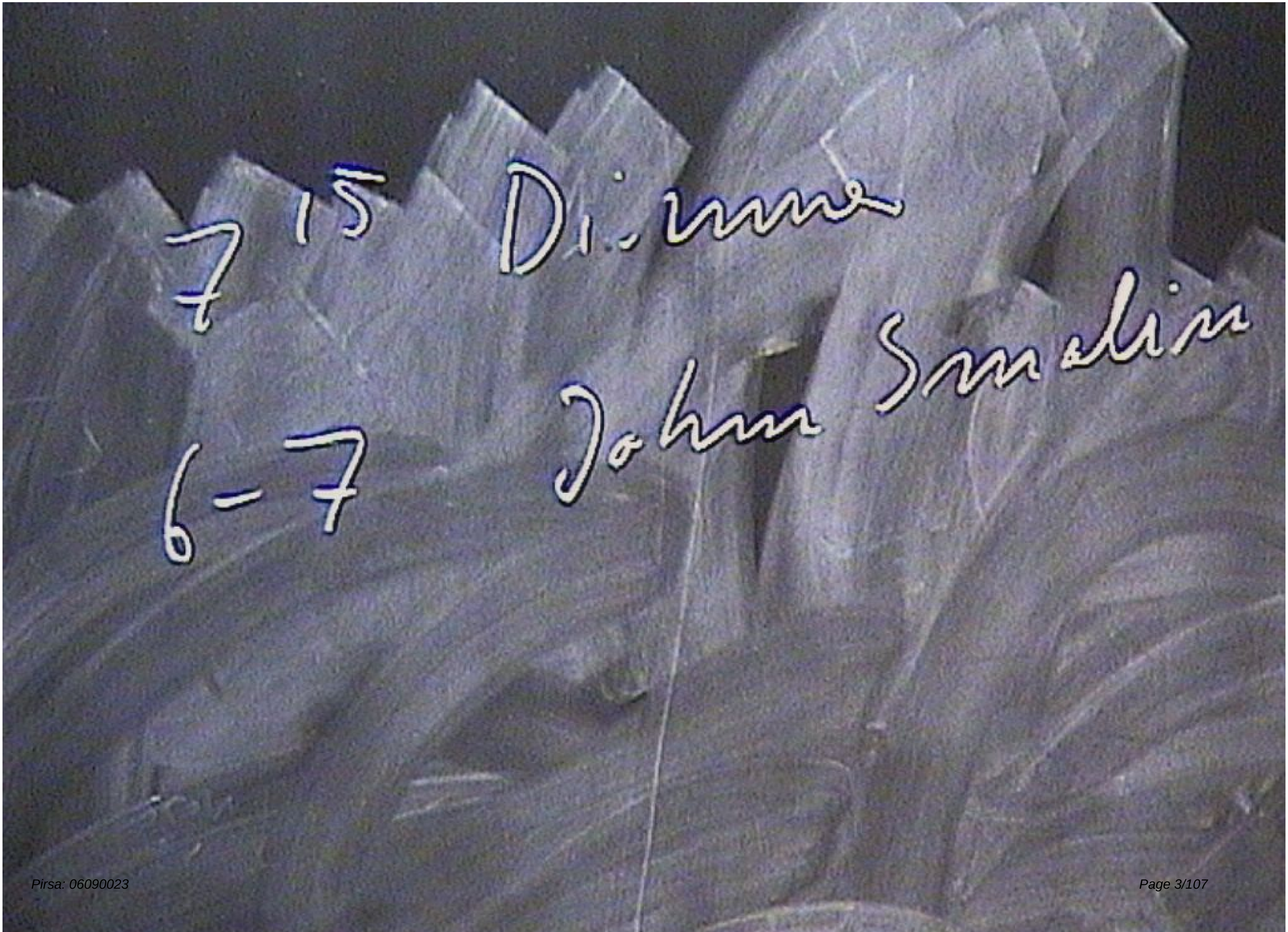
Abstract:

The invitation to this meeting asks:

The question of how to describe a natural ultraviolet cutoff in an expanding space-time is of significance in several respects. First, it concerns the fate of general covariance in the presence of a natural UV cutoff. Second, it concerns the continued generating of degrees of freedom through expansion, which carries with it the possibility of an associated generating of vacuum energy. Finally, through inflation, a natural ultraviolet cutoff may have left observable imprints in the CMB.

Do background independent approaches to quantum gravity have something to say about this question?

Comments by Thomas Thiemann, Fotini Markopoulou, Olaf Dreyer, ls


7 15 Dinner
6-7 John Smolin

The invitation to this meeting asks:

The question of how to describe a natural ultraviolet cutoff in an expanding space-time is of significance in several respects. First, it concerns the fate of general covariance in the presence of a natural UV cutoff. Second, it concerns the continued generating of degrees of freedom through expansion, which carries with it the possibility of an associated generating of vacuum energy. Finally, through inflation, a natural ultraviolet cutoff may have left observable imprints in the CMB.

Do background independent approaches to quantum gravity have something to say about this question?

Comments by Thomas Thiemann, Fotini Markopoulou, Olaf Dreyer, ls

Cosmology and disordered locality

F. Markopoulou, C. Prescod Weinstein, LS

1) Basics of LQG
2) Disordered locality
3) Possible cosmological implications
   (in progress)

Three principles:

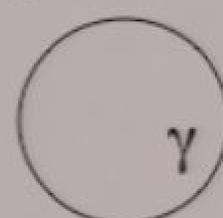
1) The Gauge principle: All forces are described by gauge fields

- Gauge fields: A_a valued in an algebra G
- Gravity: A_a valued in the lorentz group of SU(2) subgroup
- p form gauge fields
- Supergravity: Ψ_μ is a component of a connection.

2) Duality: equivalence of gauge and loopy (stringy) descriptions

observables of gauge degrees of freedom are non-local:
described by measuring parallel transport around loops

Wilson loop $T[\gamma, A] = \mathrm{Tr}\exp\int_\gamma A$



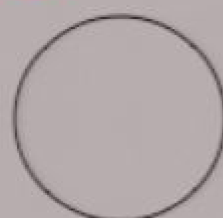
3) ***Diffeomorphism invariance and background independence***

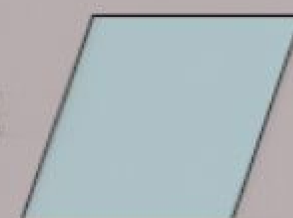
The gravitational field can be described as a gauge theory:

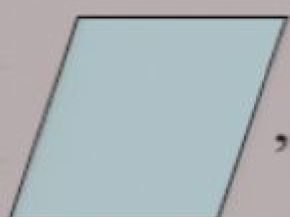
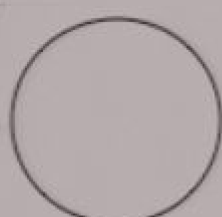
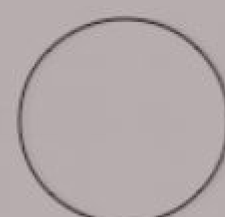
Spacetime connection	=	Gauge field	=	configuration variable
Spacetime metric	=	Electric field	=	momentum

•Quantum gauge fields can be described in terms of operators that correspond to Wilson loops and electric flux. These have a natural algebra that can be quantized:

The loop/surface algebra.

$T[\gamma,A] = \mathrm{Trexp} \int_\gamma A$ 

$E[S] = \int_S E$ 

[ , ] $= h\, G\, \mathrm{Int}$ 

The fundamental theorem: **Consider a background independent gauge theory, compact Lie group G on a spatial manifold Σ of dim >1. No metric!!** **(G=SU(2) for 3+1 gravity)**

There is a unique representation of the loop/surface algebra in which the Hilbert space carries a unitary rep of the diffeomorphism group of Σ, called H^{kin}.

Lewandowski, Okolo, Sahlmann, Thiemann+ Fleishhack (LOST theorem)

This means that there is a unique diffeomorphism invariant quantum quantum theory for each G and Σ.

The Hilbert space of diffeo invariant states, H, is a subspace of $\mathbf{H}^{kin*}$

Ashtekar: GR is a diffeomorphism invariant gauge theory!!

The dynamics of GR have been expressed in closed form in terms of finite operators and evolution amplitudes on H.

The fundamental theorem: **Consider a background independent gauge theory, compact Lie group G on a spatial manifold Σ of dim >1. No metric!!** **(G=SU(2) for 3+1 gravity)**

There is a unique representation of the loop/surface algebra in which the Hilbert space carries a unitary rep of the diffeomorphism group of Σ, called H^{kin}.

Lewandowski, Okolo, Sahlmann, Thiemann+ Fleishhack (LOST theorem)

This means that there is a unique diffeomorphism invariant quantum quantum theory for each G and Σ.

The Hilbert space of diffeo invariant states, H, is a subspace of $\mathbf{H}^{kin*}$

Ashtekar: GR is a diffeomorphism invariant gauge theory!!

The dynamics of GR have been expressed in closed form in terms of finite operaters and evolution amplitudes on H.

FINITE GEOMETRIC OBSERVABLES

R S

Let the spatial manifold, S have a boundary, B.

Some observables can be constructed via a regularization procedure that respects diffeomorphism invariance. These are ***finite*** and have ***discrete spectra:***

- Volume of Σ
- Area of the boundary of Σ
- Hamiltonian constraint

$$8\pi\gamma l_P^2\sqrt{j(j+1)}.$$

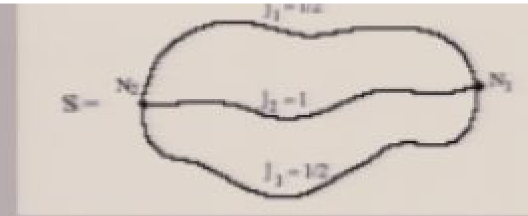
Area= $hG \, \Sigma_j \sqrt{j(j+1)}$

Volume= $l^3_{Pl} \, \Sigma_j \, v_j$

•Hence there is a smallest physical volume and area.

•Each spinnet state can be interpreted as a discrete quantum geometry with quantized volumes on nodes and areas on edges.

General structure: *causal spin network theories*

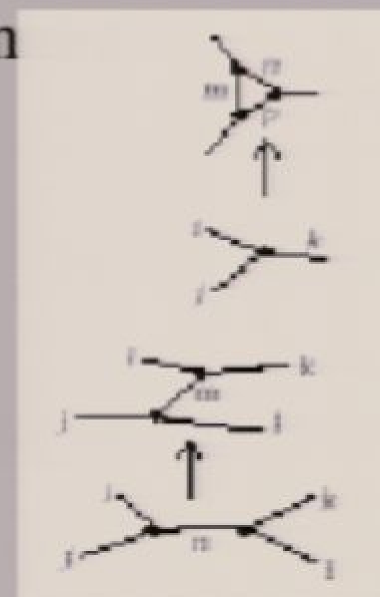


- Pick an algebra G

  Def: G-spin network is a graph Γ with edges labeled by representations of G and vertices labeled by invariants.

- Pick a differential manifold Σ.

  {Γ } an embedding of Γ in Σ, up to diffeomorphism



- Define a Hilbert space H:

  |{Γ }> Orthonormal basis element for each {Γ }

- Define a set of local moves and give each an amplitude

- A history is a sequence of moves from an in state to an out state

- Each history has a causal structure

Basic results:

1. *Diffeomorphsim invariance plus quantum theory leads to discreteness for geometry and matter and a uv cutoff.*

2. *The volume of space is represented by a positive Hermitian operator with a discrete spectrum.*

3. *The dynamics leads to transitions between states with different volumes.*

The problem of non-locality (F. Markopoulou, hep-th/0604120)

Two kinds of locality:

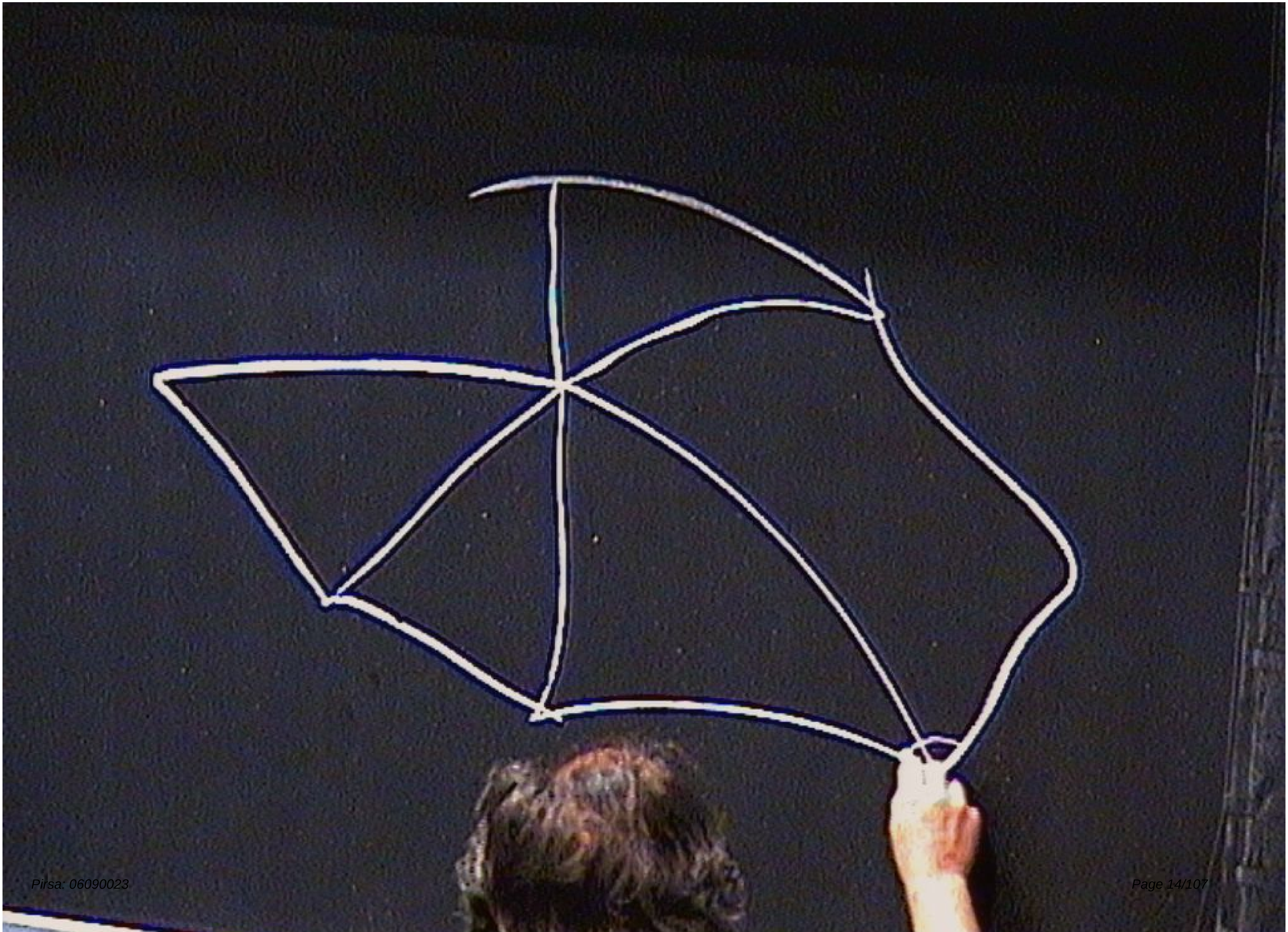
Microlocality: connectivity of a single spin net graph
causal structure of a single spin foam history.

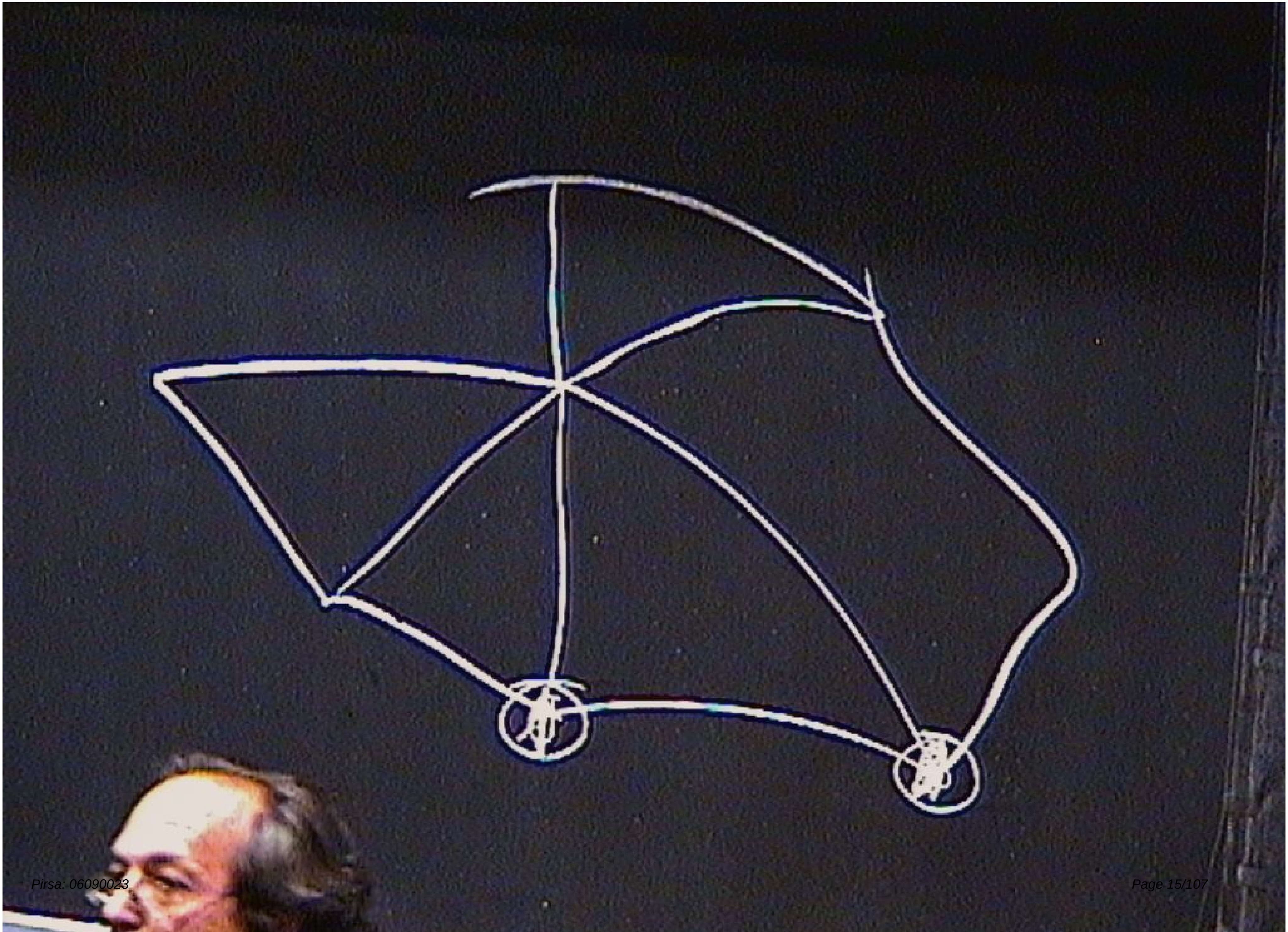
Macrolocality: nearby in the classical metric that emerges

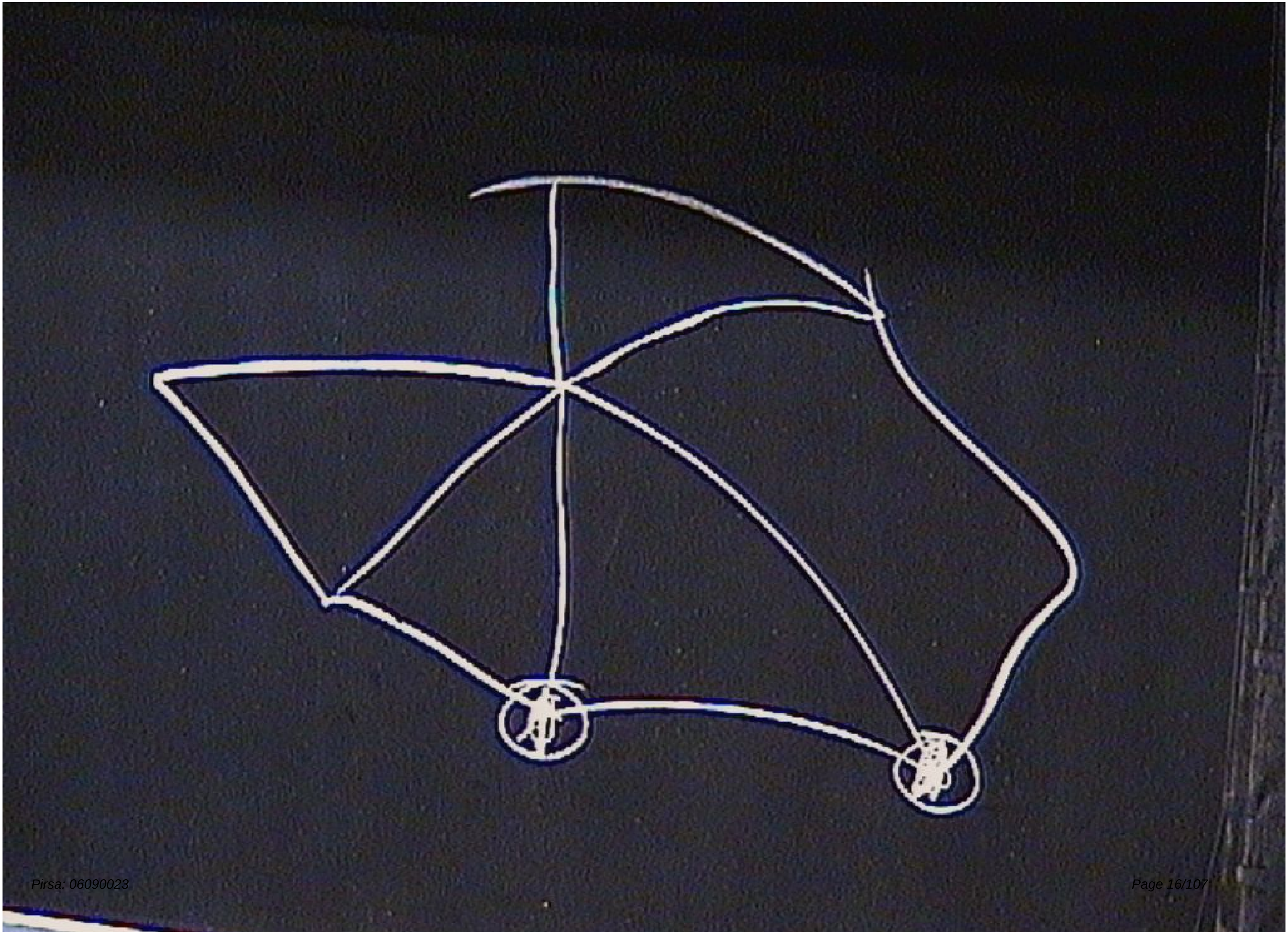
Issues: Semiclassical states may involve superpositions of large numbers of graphs. In addition being semiclassical is a coarse grained, low energy property.

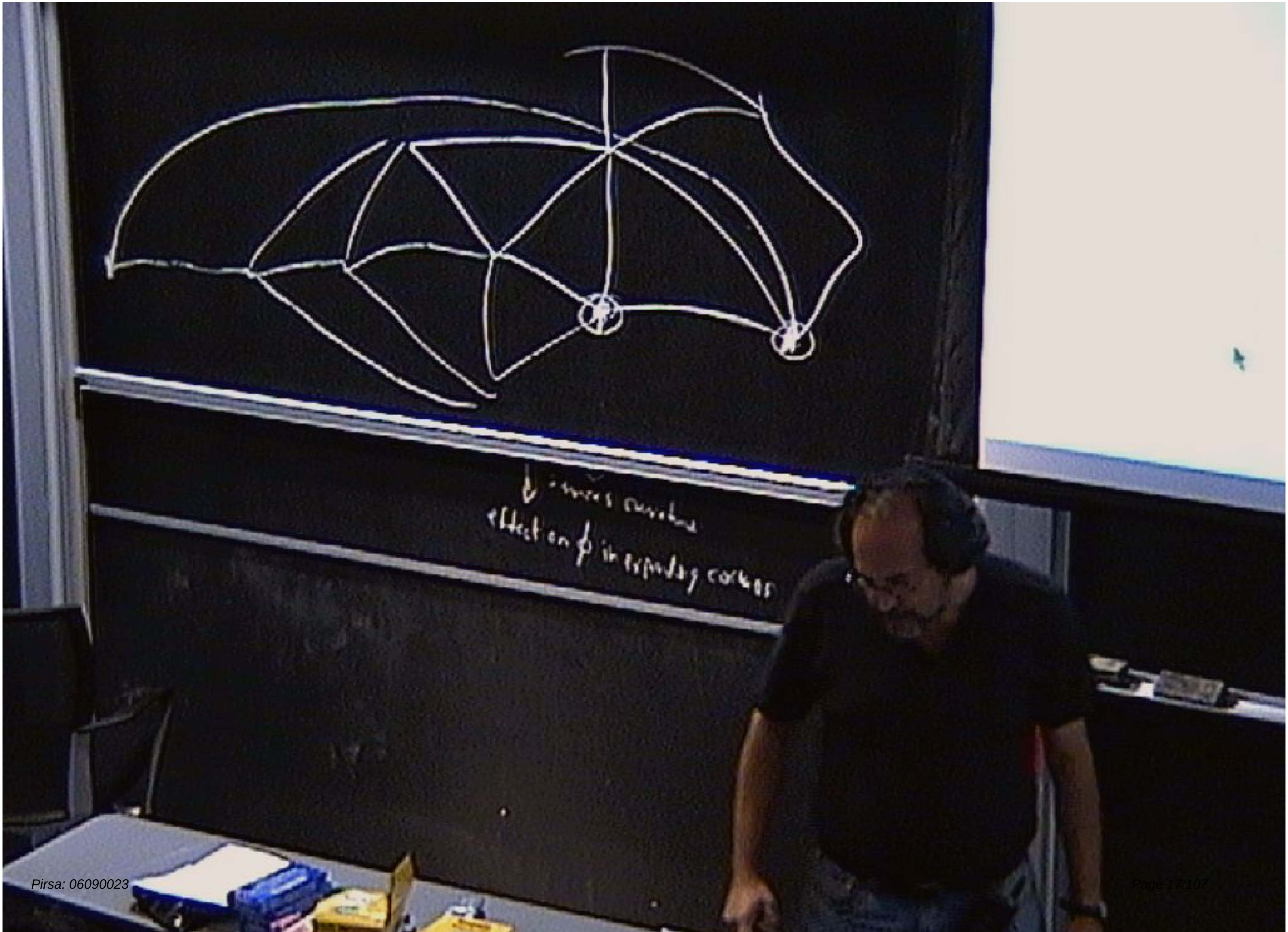
Could there not be mismatches between micro and macrolocality?

What if these are rare, but characterized by the cosmological rather than the Planck scale?



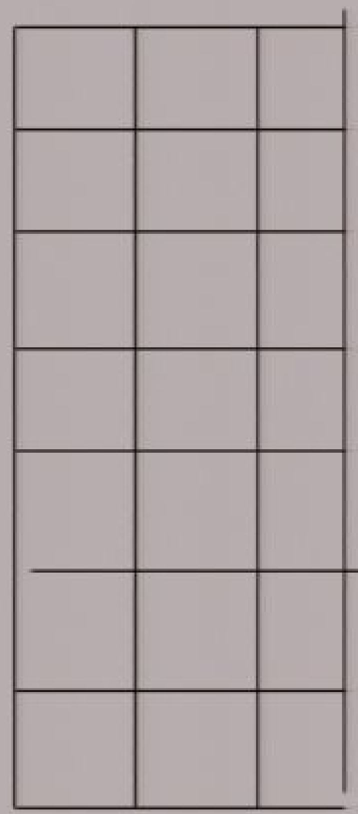






If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.



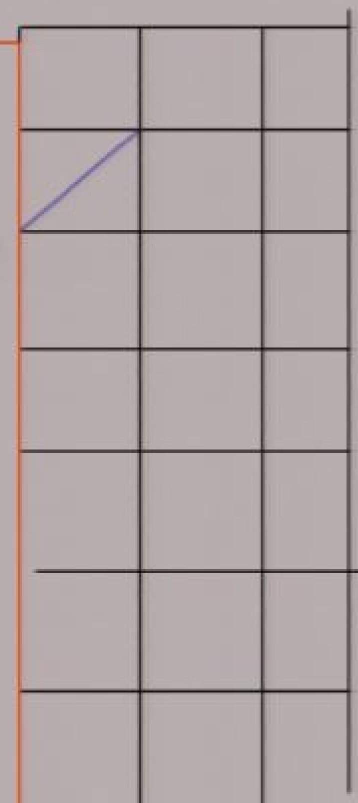
If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.

Lets add one more link randomly.

Does it conflict with the locality of the embedding?

d N ways that don't.



If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.

Lets add one more link randomly.

Does it conflict with the locality of the embedding?

d N ways that don't.

N^2 ways that do.

Thus, if the low energy definition of locality comes from a coarse graining of a combinatorial graph, it will be easily violated in fluctuations.

If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.

Lets add one more link randomly.

Does it conflict with the locality of the embedding?

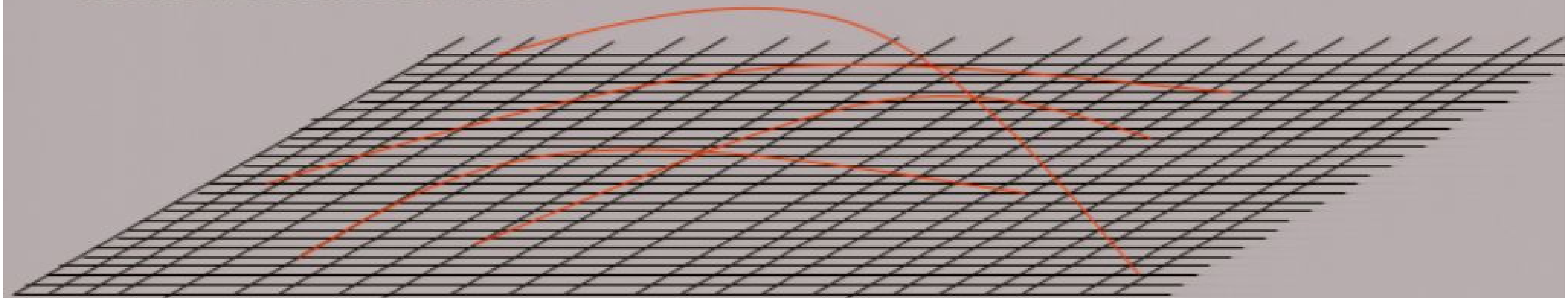
d N ways that don't.

N^2 ways that do.

Thus, if the low energy definition of locality comes from a coarse graining of a combinatorial graph, it will be easily violated in fluctuations.

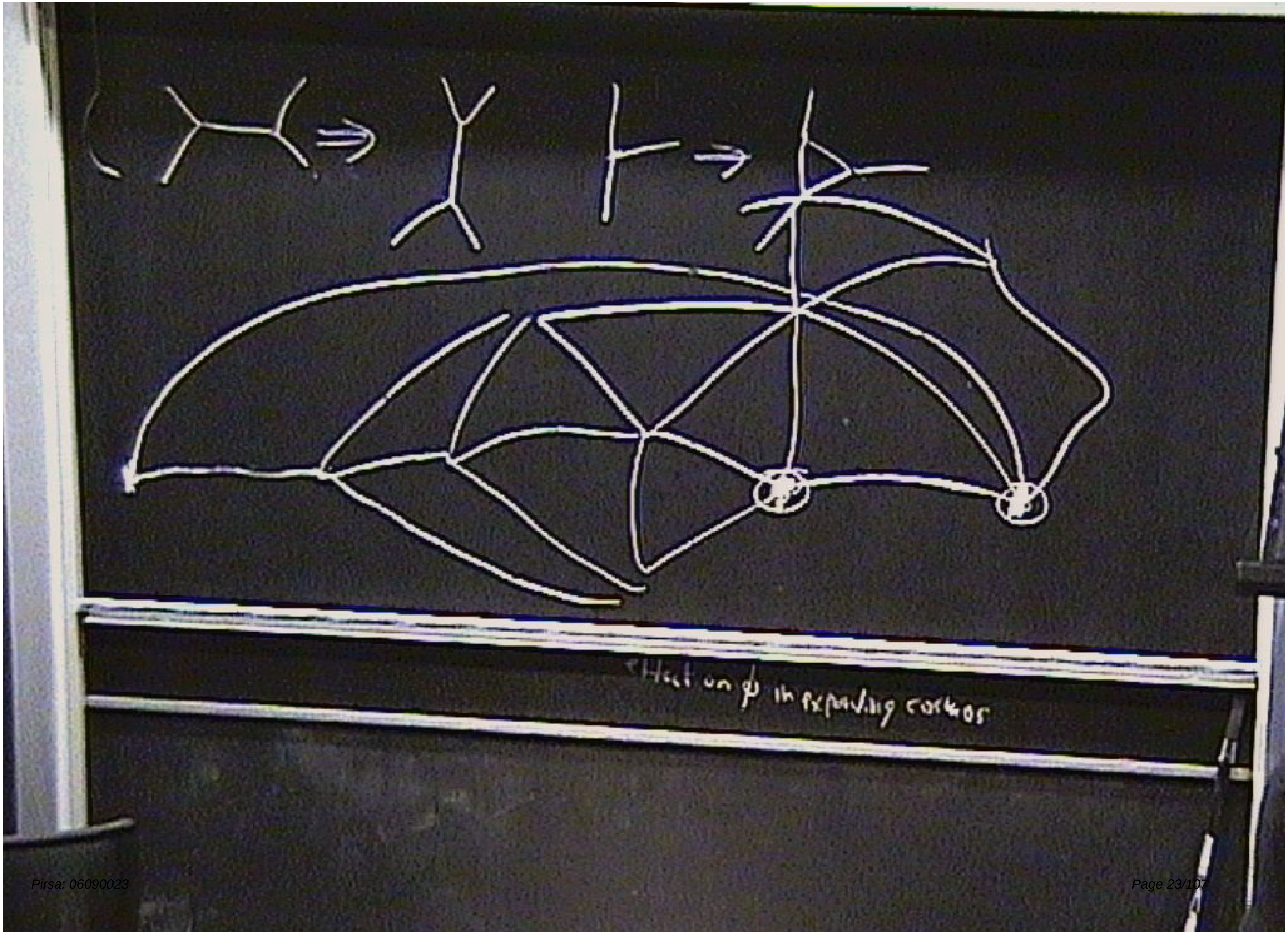
Might there then be dislocations or disordering of locality?

Hypothesis: the low energy limit of QG is characterized by a small worlds network



Dislocations in locality are scale invariant up to the Hubble scale

Numerical studies of evolving spin networks by H. Finkel (hep-th/0601163) show that this is a generic outcome of evolution of random initial graphs by local moves.


effect on φ in expanding cosmos

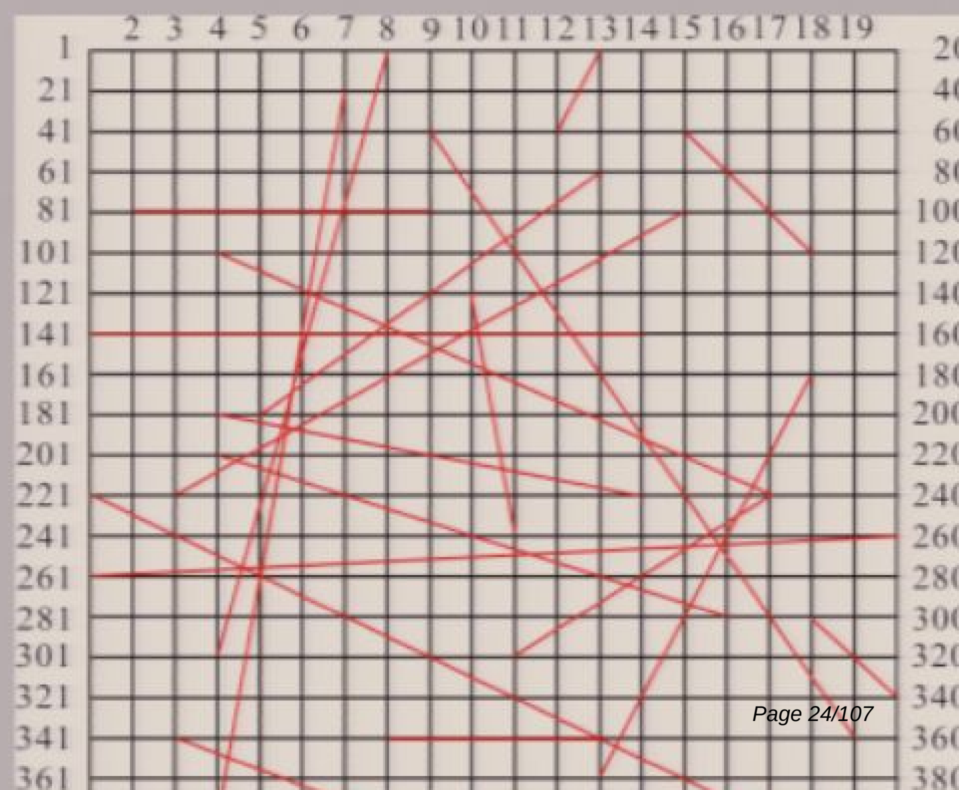
uppose the ground state is contaminated by a small proportion of ion-local links (locality defects)??

What is the effect of a small proportion of non-local edges n a regular lattice field theory?

f this room had a small proportion of non-local link, with no two iodes in the room connected, but instead connecting o nodes at cosmological distances, could we tell?

Yidun Wan studied the Ising nodel on a lattice contaminated by andom non-local links.

R=non-local links/local links
= 20/800=1/40



Cosmology with disordered locality: a simple model

- Start with standard flat FRW $ds^2 = -N^2 dt^2 + a^2(t) q^0_{ij} dx^i dx^j$

- Disorder locality by choosing a random distribution of pairs of points in the spatial manifold that are identified.

- Microscopically these are nodes in an underlying spin-network which are connected by a single link.

- P(x,y,a) is the probability that there is a non-local-connection between a point in a unit physical volume around x and a point in a unit physical volume around y, as a function of scale a.

- Scale invariant plus random implies $P(x,y,a) = N_{NL}(a) / V^2$

$$N_{NL} = \int_\Sigma d^3x \sqrt{q(x)} \int_\Sigma d^3y \sqrt{q(y)} P(x,y,a)$$

- $N_{NL}(a)$= the number of non-local links in a co-moving volume $V=a^3$

·We assume for the continuum approximation the following

annealing approximation: A random distribution of identified points with probability P(x,y,a) has the same effect on the energetics in the thermodynamic limit as a small non-local coupling between pairs of points of strength

$$\beta = P(x,y,a)/V^2$$

The action is the standard gravity + matter action plus non-local term.

$$S^{effective} = S^{local}(g_{ab}, \phi, \sigma) + S^{NL}(g_{ab}, T, \sigma)$$

σ refers to any degree of freedom with non-local couplings.
Microscopically:

$$S^{anti} = -\frac{\alpha}{l_{Pl}^2}\int dT \sum_{<mn>} \sigma_m \cdot \sigma_n$$

antiferromagnetic
Ansari-Markopoulou

The nearest neighbor interactions across a non-local link give a non-local term in the action:

$$S^{NL} = -\frac{\alpha}{l_{Pl}^2}\int dT \sum_{<mn>_{NL}} \sigma_m \cdot \sigma_n$$

In a continuum approximation this becomes

$$S^{NL} = l_{pl}\int d^3x dt \int d^y ds \sqrt{g(x,t)}\sqrt{g(y,s)}\sigma(x,t)\sigma(y,s)P[x,t;y,s]$$

P[x,t;y,s] is the probability density of identification between spacetime points. In a preferred slicing given by a T=constant

$$P[x,t;y,s] = \mathcal{P}[x,y;t]\delta[T(x,t) - T(y,s)](\frac{dT(x,t)}{[dt})^{-1}$$

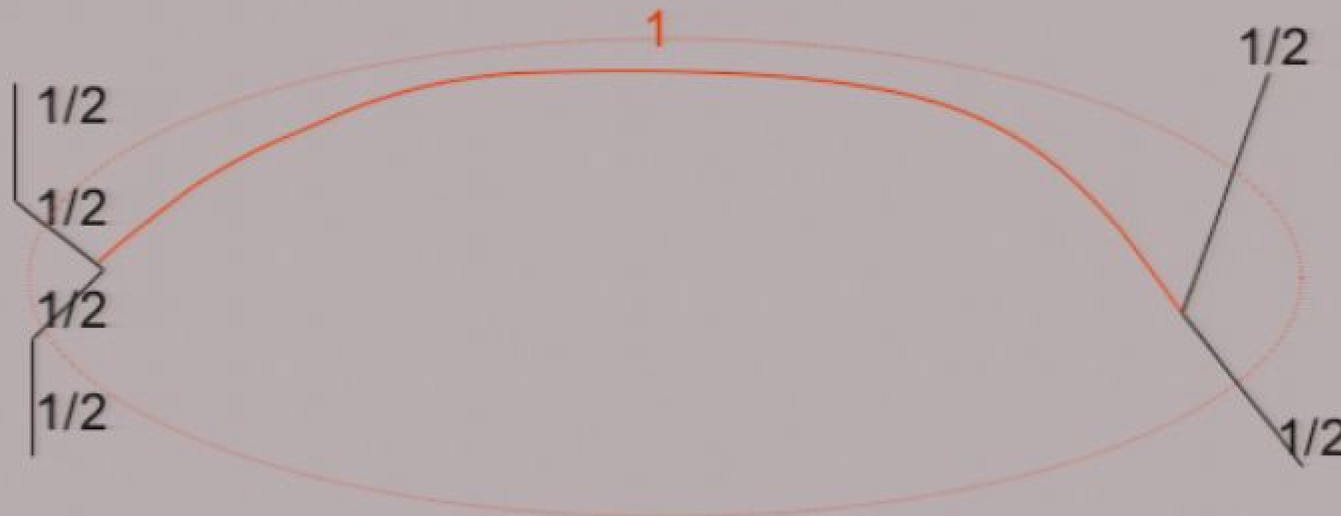
The evolution of $N_{NL}(a)$, the number of non-local connections.

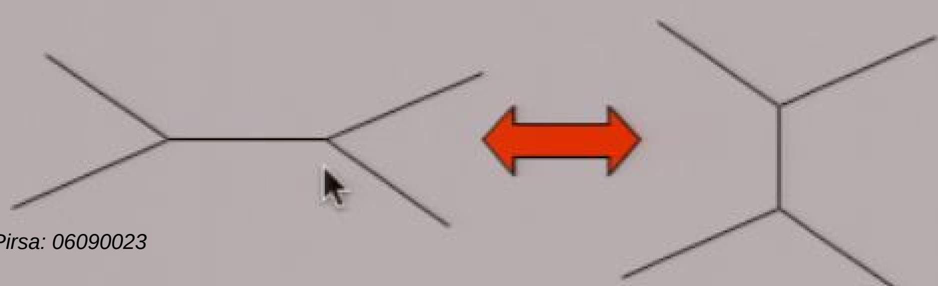
- There are microscopic processes by which non-local links split into two and processes in which pairs annihilate.

- We assume these come to equilibrium. This gives us the dependence of N_{NL} with scale factor a.

Exchange moves can increase the non-local edges.

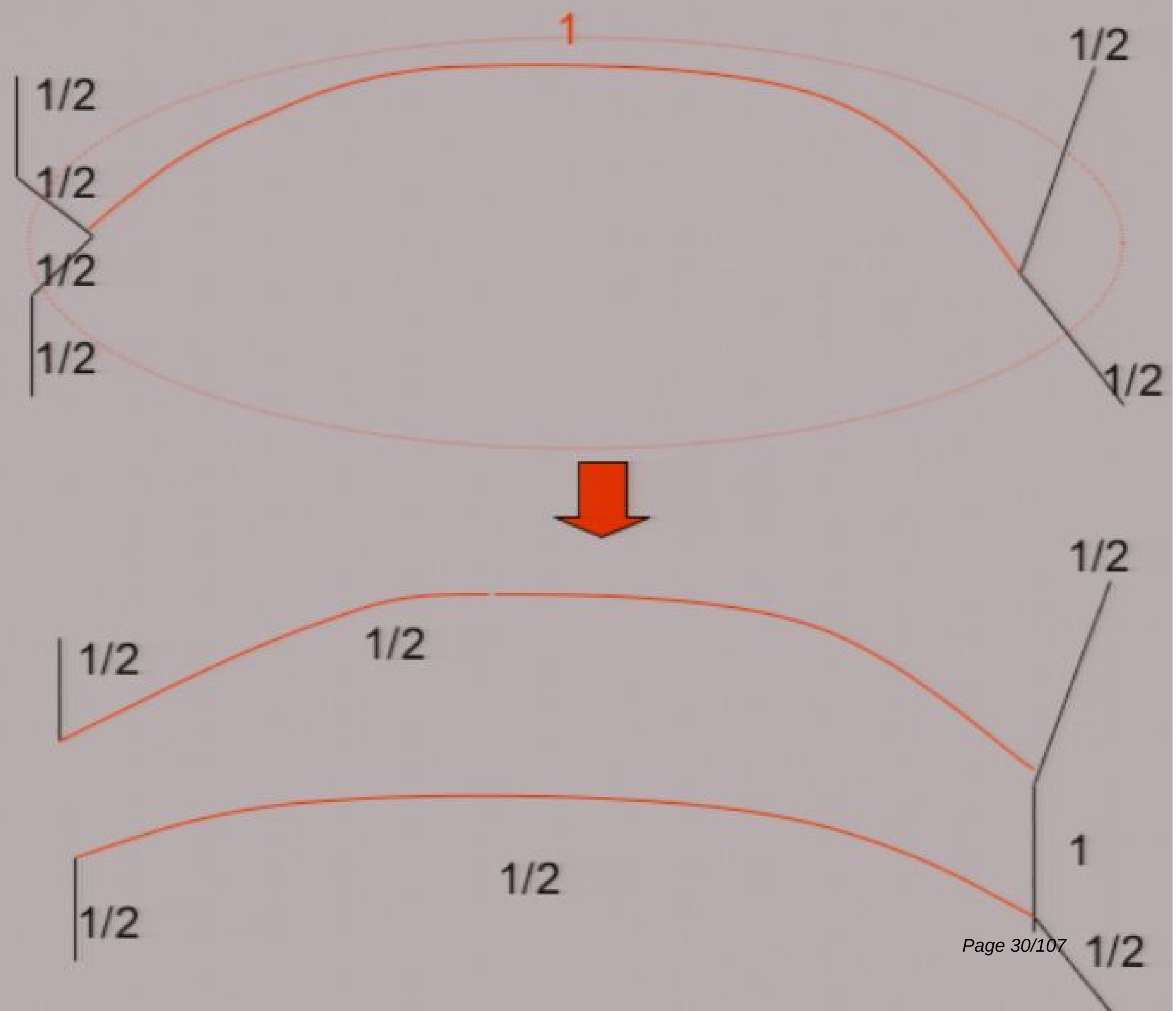
Perform a 2 to 2 move:





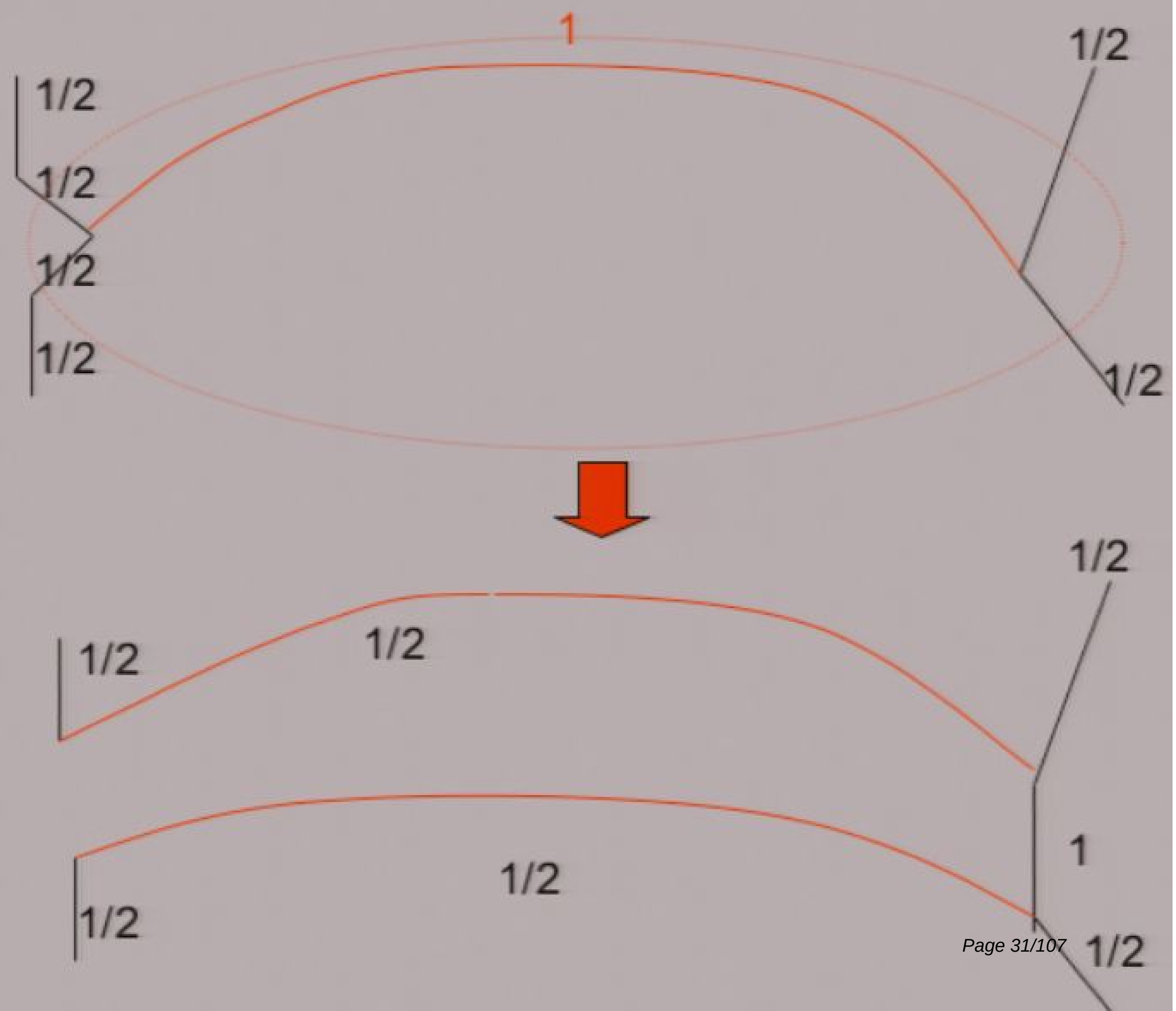
Exchange moves can increase the non-local edges.

Perform a 2 to 2 move:



Exchange moves can increase the non-local edges.

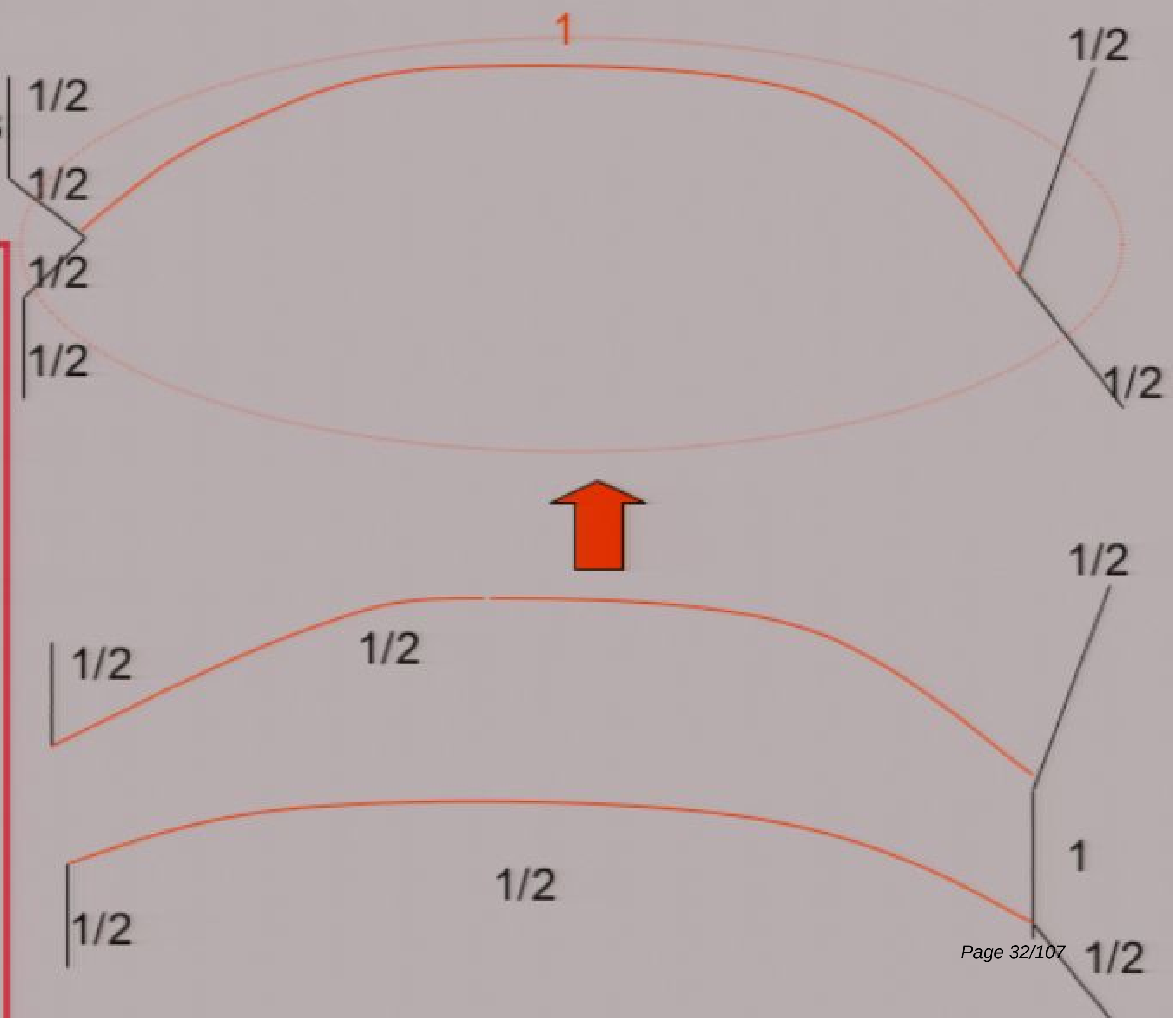
Perform a 2 to 2 move:



The two left and two right edges can now evolve away from each other, leading to two non-local edges.

Exchange moves that ***decrease*** the non-local edges.

This requires the inverse move on two non-local edges both of whose ends are coincident:



[T]he probability is the [p]robability that there are [a]re two non-local edges [t]hat coincide on each [e]nd times the probability [t]hat the move acts on [o]ne of them

$$= \beta N^2/V^3$$

$$dN/dt = \alpha N/V - \beta N^2/V^3$$

So there is a stable equilibrium when

$$N = (\alpha/\beta) V^2$$

This in turn implies the probabilities are time independent,

$$P(x,y,a) = N(a) / V^2 = (\alpha/\beta) = N_0/V_0$$

constant and metric independent.

Putting this back into our continuum approximation, we find a correction from the non-local interactions to the T^{ab}

$$T^{ab}(x,t) = \sqrt{g}^{-1}\frac{\delta S^{NL}}{\delta g_{ab}(x,t)} = -l_{pl} g^{ab}(x,t)\sigma(x,t)\int d^y ds \sqrt{g(y,s)}\sigma(x,t)\sigma(y,s)P[x,t;y,s]$$

Since P is metric independent we have

$$T^{ab} = g^{ab}V^{eff}$$

$$V^{eff}(x,t) = l_{pl}\frac{N_{NL}}{V}\sigma(x,t) <\sigma> = l_{pl}\frac{N_0 V}{V_0^2}\sigma(x,t) <\sigma>$$

A coarse grained field at each point has on average a tiny interaction with its averaged value:

$$<\sigma> = \int_{T=constant} d^3y\sqrt{q}\sigma(y,t)$$

If we expand in modes:

$$\sigma(x,T) = <\sigma>(T) + \sum_k (cos(k\cdot x)\sigma_k + c.c.)$$

We find a "quintessence model"

$$V_{NL}(<\sigma>) = \frac{M^2}{2} <\sigma>^2 (T)$$

$$M^2(T) = l_p \rho_{NL}$$

$$\rho_{NL} = \frac{N_{NL}}{V}$$

Estimating the number of non-local connections:

If σ is a gravitational degree of freedom: dimensionless, hence order unity

$$\frac{1}{R_{NL}^2} = V_{NL} = M^2(a) < \sigma >^2 (a)$$

$$\frac{1}{R_{NL}^2} = M^2(a) = l_{Pl}\rho_{NL}(a) = \frac{l_{Pl}N_{NL}}{a^3}$$

$$\Rightarrow \quad \boxed{N_{NL} = \frac{a}{l_{Pl}} = 10^{60}}$$

$$\rho_{NL} \approx \frac{10^{-120}}{l_{Pl}^3}$$

If σ is a matter degree of freedom, there is an extra G

$$\frac{1}{R_{NL}^2} = GV_{NL} = GM^2(a) < \sigma >^2 (a)$$

From naturality: $M(a) \approx < \sigma > (a)$

$$\Rightarrow \quad N_{NL}(a_{now}) \approx 10^{120}$$

$$\rho_{NL}(a_{now}) \approx \frac{10^{-60}}{l^3} \approx \frac{1}{fermi^3}$$

Spectrum of fluctuations from disordered locality

The non-local links give a non-local contribution to the two point function for a thermal bath of radiation:

$$D(x,y)_{NL} =< \frac{\delta\rho}{\rho}(x)\ \frac{\delta\rho}{\rho}(y) >= l_{Pl}^2 T^2 \sigma_U^2 \sum_{i=1}^{N} \delta^3(x,x_i)\delta^3(y,y_i)$$

Sum i is over non-local links

Prob. to jump across a NL link: $l_{Pl}^2 T^2$

Fluctuations in thermal spectrum: $\sigma_U^2 = \frac{<E^2> - <E>^2}{<E>^2} = \frac{T}{\rho V} = \frac{1}{VT^3}$

Fourier transform gives the power spectrum:

$$D(k)_{NL} = \int_V d^3x \int_V d^3y D(x,y)_{NL} e^{\imath k\cdot(x-y)} = \frac{A}{Vk^3}$$

$$A = 2\pi^2 l_{Pl}^2 T^2 N_{NL} \sigma_U^2$$

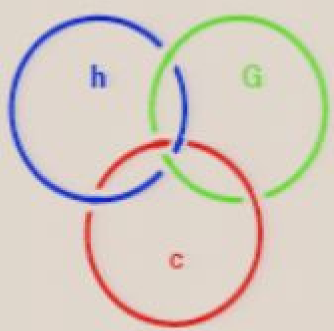
This is scale invariant because the distribution of non-local links is scale invariant.

Solving the Problem of Time
in GR and Cosmology

Thomas Thiemann[1,2]

[1] Albert Einstein Institut, [2] Perimeter Institute for Theoretical Physics

astro-ph/0607380



Contents

- The Puzzle
- Solution
- Future work

Contents

- The Puzzle
- Solution
- Future work

Contents

- The Puzzle
- Solution
- Future work

The Puzzle

GR is a gauge theory

- E.g. canonically described by phase space coordinates $q_{ab},\ P^{ab}$ on $M \cong R \times S$
- subject to spatial Diffeomorphism constraints

$$D(u) := \int_S d^3x\, u^a D_a, \quad D_a := -2\nabla_b P^{bc} q_{ca}$$

- and Hamiltonian constraints

$$C(N) := \int_S d^3x\, NC,$$

$$C = \frac{[q_{ac}q_{bd} - \frac{1}{2}q_{ab}q_{cd}]P^{ab}P^{cd}}{\sqrt{\det(q)}} - \sqrt{\det(q)}R^{(3)}[q]$$

The Puzzle

GR is a gauge theory

- E.g. canonically described by phase space coordinates $q_{ab},\ P^{ab}$ on $M \cong R \times S$
- subject to spatial Diffeomorphism constraints

$$D(u) := \int_S d^3x\, u^a D_a, \quad D_a := -2\nabla_b P^{bc} q_{ca}$$

- and Hamiltonian constraints

$$C(N) := \int_S d^3x\, NC,$$

$$C = \frac{[q_{ac}q_{bd} - \frac{1}{2}q_{ab}q_{cd}]P^{ab}P^{cd}}{\sqrt{\det(q)}} - \sqrt{\det(q)}R^{(3)}[q]$$

The Puzzle

GR is a gauge theory

- E.g. canonically described by phase space coordinates $q_{ab},\ P^{ab}$ on $M \cong R \times S$
- subject to spatial Diffeomorphism constraints

$$D(u) := \int_S d^3x\, u^a D_a,\quad D_a := -2\nabla_b P^{bc} q_{ca}$$

- and Hamiltonian constraints

$$C(N) := \int_S d^3x\, NC,$$

$$C = \frac{[q_{ac}q_{bd} - \frac{1}{2}q_{ab}q_{cd}]P^{ab}P^{cd}}{\sqrt{\det(q)}} - \sqrt{\det(q)}R^{(3)}[q]$$

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a}u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v, v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \ \forall \ u, N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\}, \ \ dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a}u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v.v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \ \forall \ u, N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\}, \ dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a} u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v.v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \ \forall \ u, N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\}, \ \ dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a} u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v.v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \;\forall\; u,\; N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\}, \quad dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a}u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v.v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \ \forall \ u, N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\}, \ \ dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Constraints generate diff(M)

- Define $v^\mu := Nn^\mu + X^\mu_{,a} u^a$
- Let $G(v) := D(u) + C(N)$ then

$$\{G(v), G(v')\}_{EOM} = G([v.v'])$$

- $\Rightarrow$ Constraints generate gauge transformations
- $\Rightarrow$ observable quantities must be gauge invariant

$$\{F, D(u)\} = \{F, C(N)\} = 0 \;\forall\; u,\; N$$

- $\Rightarrow$ "Equations of motion"

$$dq_{ab}/dt := \{G(v), q_{ab}\},\;\; dP^{ab}/dt := \{G(v), P^{ab}\}$$

- do not describe physical time evolution of observable quantities but reparametrisations of unphysical objects.

Why is it that the FRW eqns. describe the observed cosmic evolution?

- Hamiltonian constraint for k=0 FRW

$$C = -\frac{P^2}{12a} + (\Lambda + \rho_m)a^3$$

- Solve $da/dt = P =: \{a, C\}$ and resubstitute

$$3\frac{d^2a/dt^2}{a} = \Lambda - [\rho_m + 3p_m]$$

- These are gauge transformations of unobservables, otherwise we would have $\{a, C\} = 0$!!!
- What is going on?
- This is precisely the problem of time

Why is it that the FRW eqns. describe the observed cosmic evolution?

- Hamiltonian constraint for k=0 FRW

$$C = -\frac{P^2}{12a} + (\Lambda + \rho_m)a^3$$

- Solve $da/dt = P =: \{a, C\}$ and resubstitute

$$3\frac{d^2a/dt^2}{a} = \Lambda - [\rho_m + 3p_m]$$

- These are gauge transformations of unobservables, otherwise we would have $\{a, C\} = 0$!!!
- What is going on?
- This is precisely the problem of time

Why is it that the FRW eqns. describe the observed cosmic evolution?

- Hamiltonian constraint for k=0 FRW

$$C = -\frac{P^2}{12a} + (\Lambda + \rho_m)a^3$$

- Solve $da/dt = P =: \{a, C\}$ and resubstitute

$$3\frac{d^2a/dt^2}{a} = \Lambda - [\rho_m + 3p_m]$$

- These are gauge transformations of unobservables, otherwise we would have $\{a, C\} = 0$!!!
- What is going on?
- This is precisely the problem of time

Why is it that the FRW eqns. describe the observed cosmic evolution?

- Hamiltonian constraint for k=0 FRW

$$C = -\frac{P^2}{12a} + (\Lambda + \rho_m)a^3$$

- Solve $da/dt = P =: \{a, C\}$ and resubstitute

$$3\frac{d^2a/dt^2}{a} = \Lambda - [\rho_m + 3p_m]$$

- These are gauge transformations of unobservables, otherwise we would have $\{a, C\} = 0$!!!
- What is going on?
- This is precisely the problem of time

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q)$, $D := q^{ab} D_a D_b$, $C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4s^2 DQ}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x \, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x \, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \quad O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q)$, $D := q^{ab} D_a D_b$, $C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4 s^2 D Q}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x\, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x\, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \quad O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q)$, $D := q^{ab} D_a D_b$, $C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4s^2 DQ}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x\, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x\, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \quad O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q)$, $D := q^{ab} D_a D_b$, $C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4 s^2 D Q}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x\, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x\, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \;\; O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Specialisation to FRW

- Deviation parameter ($E = \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3\left(\frac{dO_a/d\tau}{O_a}\right)^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}]\left(1 + \frac{1}{x}\right)$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda\left(1 + \frac{4}{x}\right) - \frac{1}{2}\left\{[O_{\rho_m} + O_{\rho_{phantom}}]\left(1 - \frac{5}{x}\right) + 3[O_{p_m} + O_{p_{phantom}}]\left(1 + \frac{1}{x}\right)\right\}$$

- For suff. small s, deviation unobservable today but unavoidably predicts recollapse.

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q), \;\; D := q^{ab} D_a D_b, \;\; C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4 s^2 D Q}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x\, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x\, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \;\; O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Specialisation to FRW

- Deviation parameter ($E = \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3\left(\frac{dO_a/d\tau}{O_a}\right)^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}](1 + \frac{1}{x})$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda(1 + \frac{4}{x}) - \frac{1}{2}\left\{[O_{\rho_m} + O_{\rho_{phantom}}](1 - \frac{5}{x}) + 3[O_{p_m} + O_{p_{phantom}}](1 + \frac{1}{x})\right\}$$

- For suff. small s, deviation unobservable today but unavoidably predicts recollapse.

Specialisation to FRW

- Deviation parameter ($E = \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3\left(\frac{dO_a/d\tau}{O_a}\right)^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}](1 + \frac{1}{x})$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda(1 + \frac{4}{x}) - \frac{1}{2}\left\{[O_{\rho_m} + O_{\rho_{phantom}}](1 - \frac{5}{x}) + 3[O_{p_m} + O_{p_{phantom}}](1 + \frac{1}{x})\right\}$$

- For suff. small s, deviation unobservable today but unavoidably predicts recollapse.

Specialisation to FRW

- Deviation parameter (E $= \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3\left(\frac{dO_a/d\tau}{O_a}\right)^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}](1 + \frac{1}{x})$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda(1+\frac{4}{x}) - \frac{1}{2}\Big\{[O_{\rho_m} + O_{\rho_{phantom}}](1-\frac{5}{x}) + 3[O_{p_m} + O_{p_{phantom}}](1+\frac{1}{x})\Big\}$$

- For suff. small s, deviation unobservable today but unavoidably predicts recollapse.

Specialisation to FRW

- Deviation parameter ($E = \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3(\frac{dO_a/d\tau}{O_a})^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}](1 + \frac{1}{x})$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda(1 + \frac{4}{x}) - \frac{1}{2}\Big\{[O_{\rho_m} + O_{\rho_{phantom}}](1 - \frac{5}{x}) + 3[O_{p_m} + O_{p_{phantom}}](1 + \frac{1}{x})\Big\}$$

- For suff. small s, deviation unobservable today but unavoidably predicts recollapse.

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

- Redo class. cosmol. pert. theory in terms of invariants
  [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology:
  Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{H}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity

Specialisation to FRW

- Deviation parameter ($E = \pi$ const. of. motion)

$$x = \frac{E^2}{s^2 O_a(\tau)^6}$$

- Results in modified FRW eqns.

$$3(\frac{dO_a/d\tau}{O_a})^2 = [\Lambda + O_{\rho_m} + O_{\rho_{phantom}}](1 + \frac{1}{x})$$

-

$$3\frac{d^2O_a/d\tau^2}{O_a} = \Lambda(1 + \frac{4}{x}) - \frac{1}{2}\Big\{[O_{\rho_m} + O_{\rho_{phantom}}](1 - \frac{5}{x}) + 3[O_{p_m} + O_{p_{phantom}}](1 + \frac{1}{x})\Big\}$$

- For suff. small *s*, deviation unobservable today but unavoidably predicts recollapse.

Phantom Fields

Suggestion: Physical time evolution driven by unobservable matter component (physical clock)

- Phantom DBI action (Brown – Kuchař Deparam.)

$$S_{\text{phantom}} = s \int_M d^4X \sqrt{|\det(g)|} \sqrt{1 + g^{\mu\nu} [\nabla_\mu \Phi] [\nabla_\nu \Phi]}$$

- Let $Q = \det(q)$, $D := q^{ab} D_a D_b$, $C^{\text{total}} = \pi + H$ where

$$H(x) = \sqrt{C^2 - D - s^2 Q + \sqrt{[C^2 - D - s^2 Q]^2 - 4 s^2 D Q}}\,(x)$$

- Physical Hamiltonian (Dirac Obs.): $\mathbf{H} = \int_\sigma d^3x\, H(x)$
- Phys. time evol. (f: spat. diff. inv., $H_\tau = \int d^3x\, (\tau - \Phi) H$)

$$\frac{d}{d\tau} O_f(\tau) = \{\mathbf{H}, O_f(\tau)\}, \quad O_f(\tau) := \sum_{n=0}^{\infty} \frac{1}{n!} \{H_\tau, f\}_{(n)}$$

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

- Redo class. cosmol. pert. theory in terms of invariants
  [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology:
  Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{H}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

- Redo class. cosmol. pert. theory in terms of invariants
  [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology:
  Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{\mathbf{H}}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

- Redo class. cosmol. pert. theory in terms of invariants
  [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology:
  Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{\mathbf{H}}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

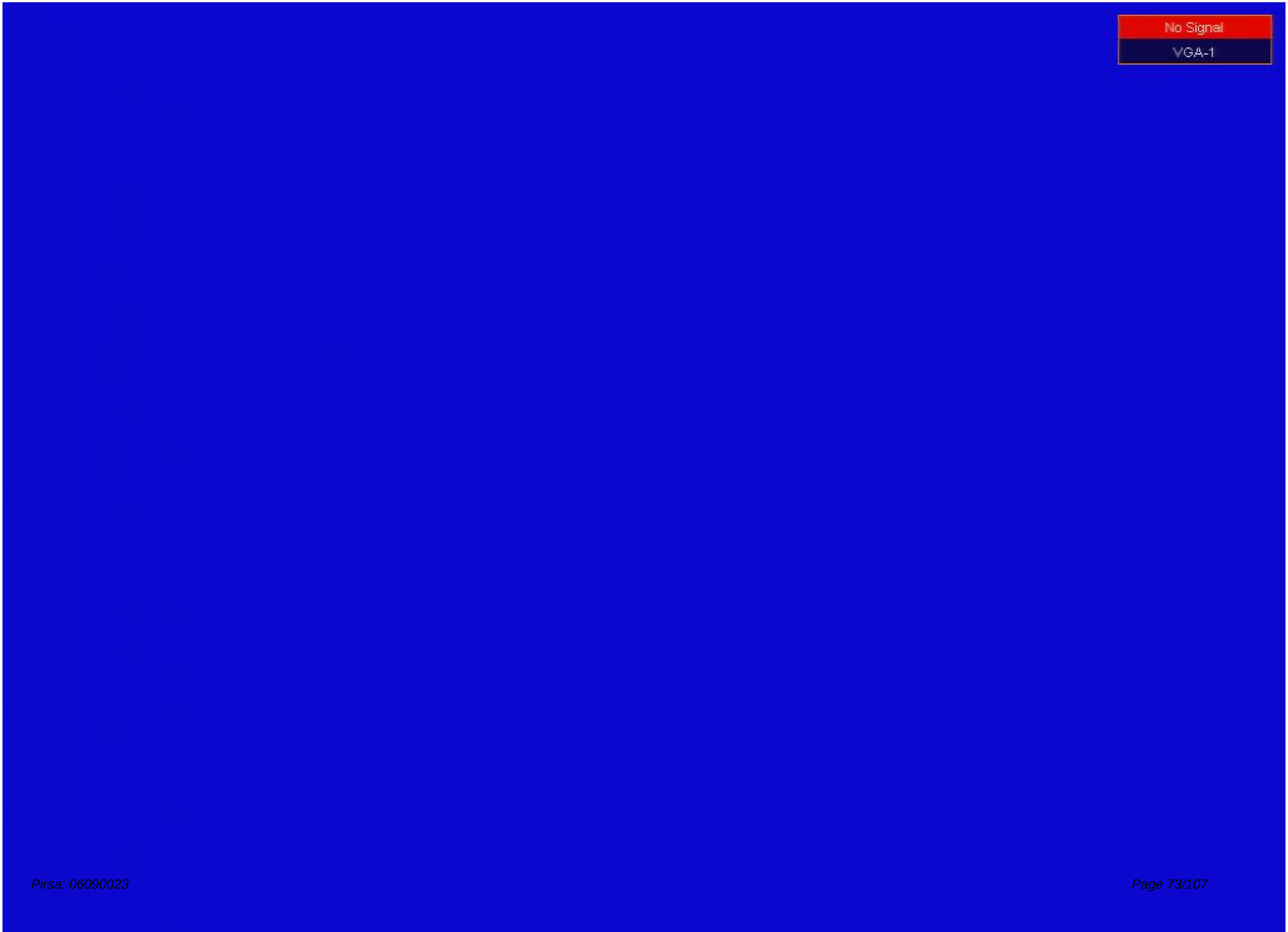
- Redo class. cosmol. pert. theory in terms of invariants [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology: Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{\mathbf{H}}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity

Invariant cosmological perturbation theory

Observable cosmological pert. to all orders!

[Giesel, Hofmann, T.T., Winkler 06-] (work in progress)

- Redo class. cosmol. pert. theory in terms of invariants
  [Mukhanov, Brandenberger, Feldmann 93]
- Solve vacuum problem in cosmology:
  Ground state = minimum energy eigenstate of physical Hamiltonian $\widehat{\mathbf{H}}$.
- No debate "at which time" to choose ground state since physical states are annihilated by Ham. constraint op.
- LQG model calculations already indicate resolution of initial singularity


No Signal
VGA-1

No Signal

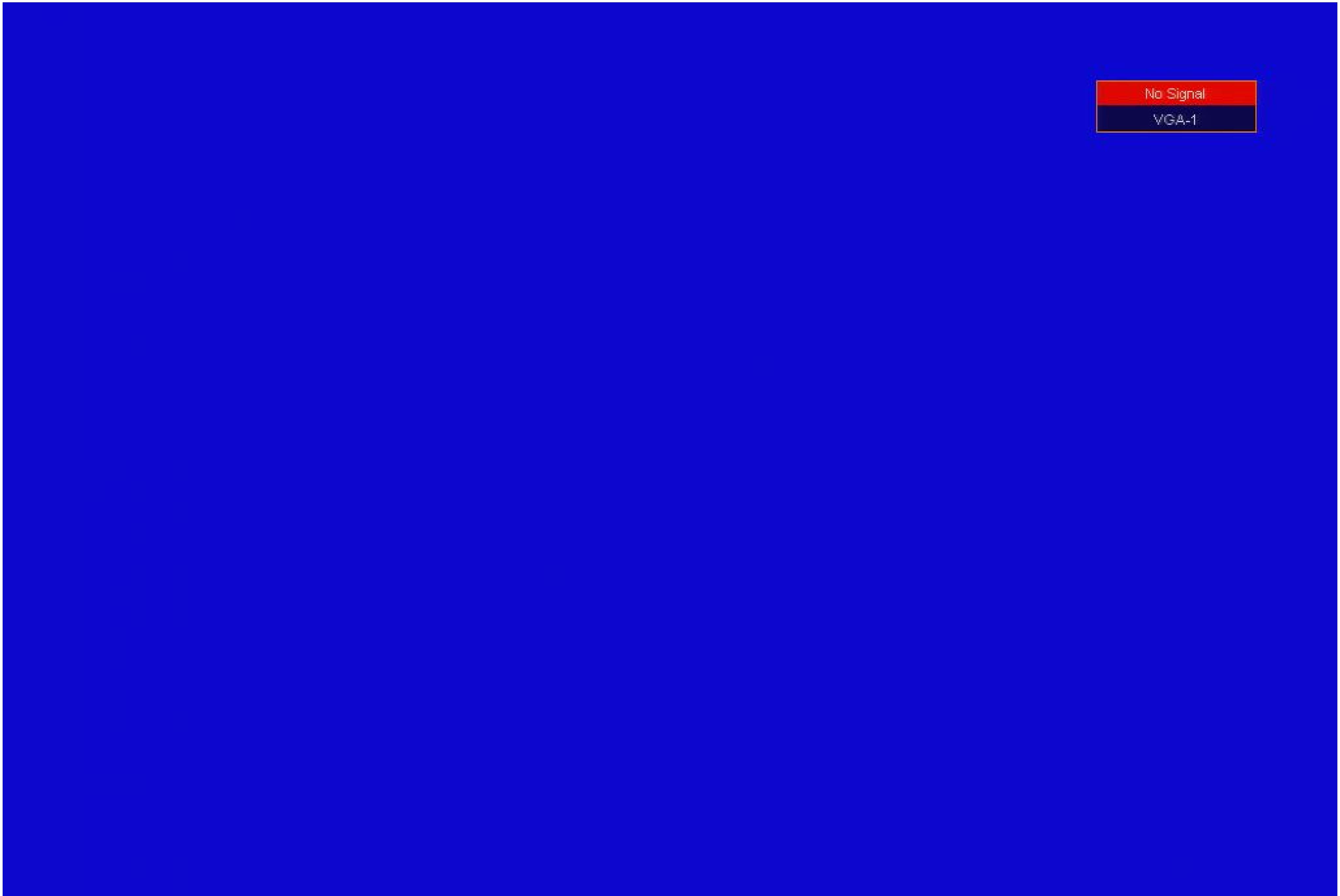
VGA-1

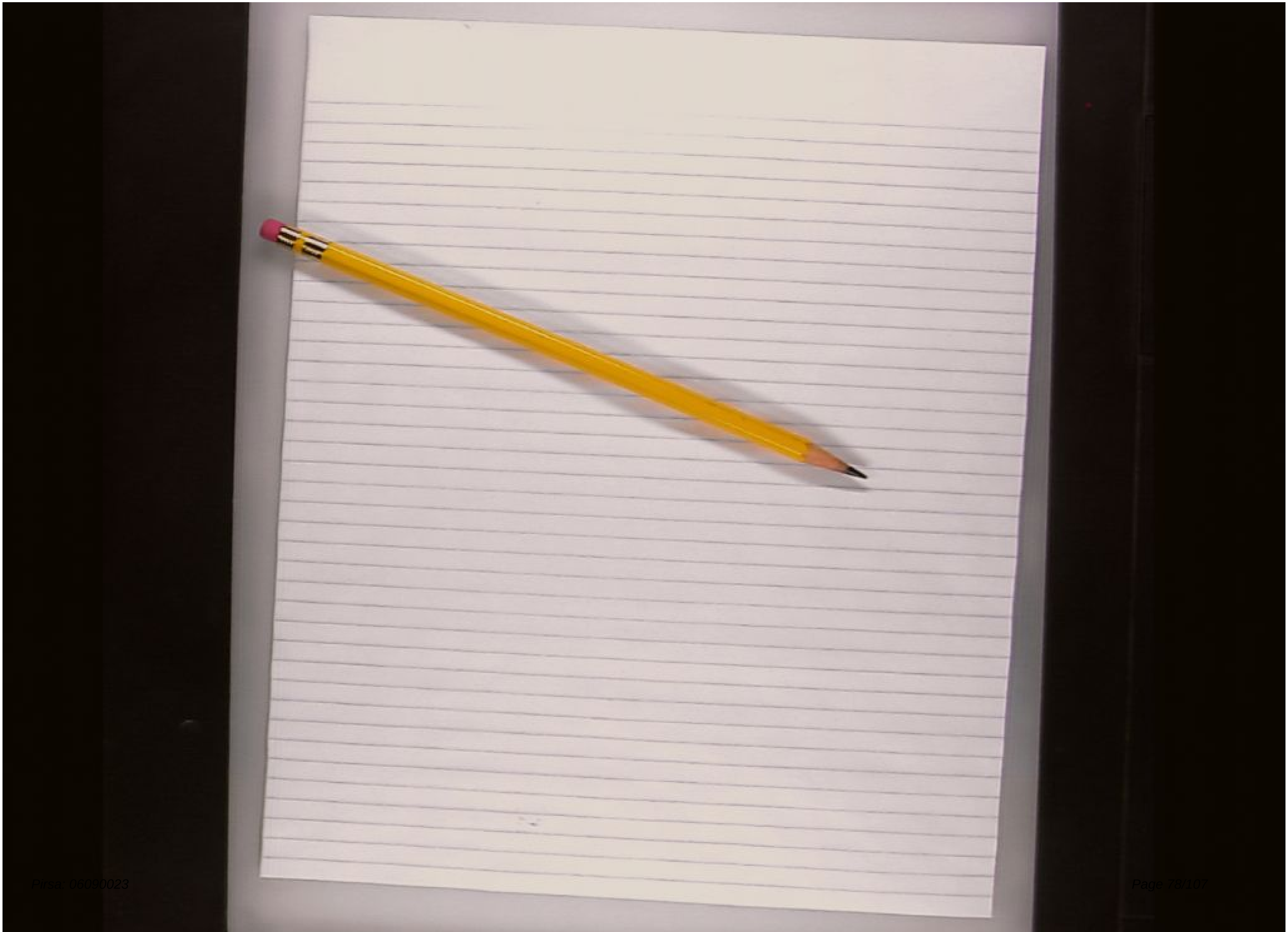
No Signal

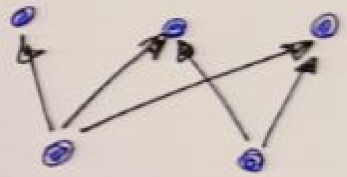
VGA-1

No Signal

VGA-1

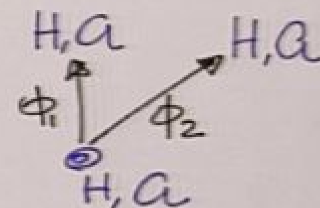

No Signal
VGA-1



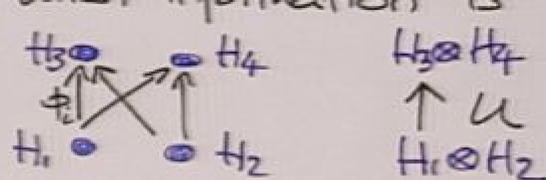


← LOCALLY FINITE region of spacetime [cf Foster, Sorkin]

Q: Can you promote to quantum systems and the arrows to quantum operations in a consistent way?



[1] Unitarity when information is conserved.



[2] Respect the causal links.

[3] Mathematically consistent (probab etc).

A : Yes.

E. Hawkins, FM, H. Sahlmann
hep-th/0311059

FM hep-th/9904009

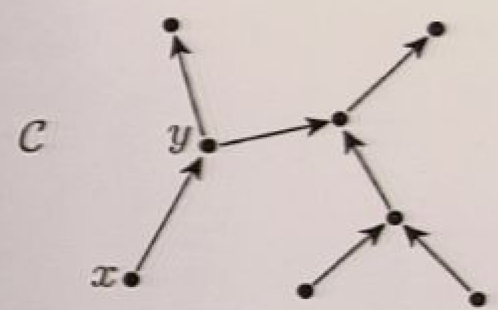
RF Blute, IT Ivanov & P. Panangaden
gr-qc/0111020,
gr-qc/0109053

B. Schumacher & MD Westmoreland

quant-ph/0604207

3

Definition: Quantum Causal History



Directed graph, no cycles.

$x \leq y$ related

$x \sim y$ unrelated

$x \mapsto H(x)$ finite dimensional

$(x \sim y) \mapsto H(x) \otimes H(y)$

$x \leq y \mapsto \phi : A[H(x)] \to A[H(y)]$

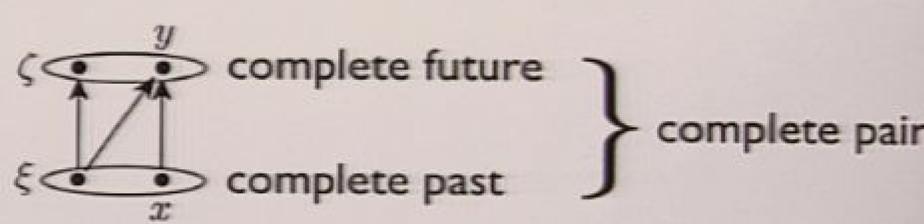
ϕ completely positive map

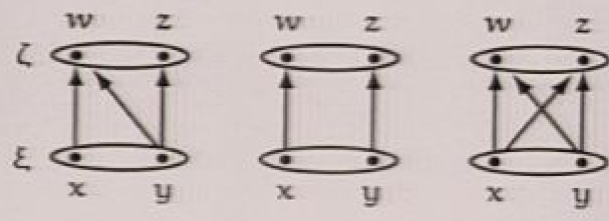
linear $\phi : \mathcal{B}(H_x) \to \mathcal{B}(H_y)$ such that

$id_k \otimes \phi : M_k \otimes \mathcal{B}(H_x) \to M_k \otimes \mathcal{B}(H_y)$

is positive for all $k \geq 1$ and trace-preserving.

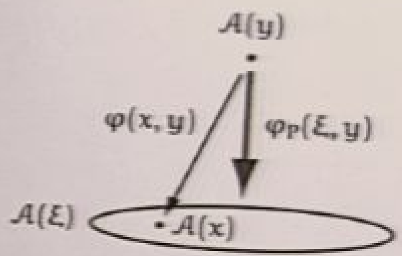
FM,
Hawkins, FM & Sahlmann


y
ζ
complete future
ξ
complete past
x
complete pair


w z
ζ
ξ
x y
w z
x y
w z
x y

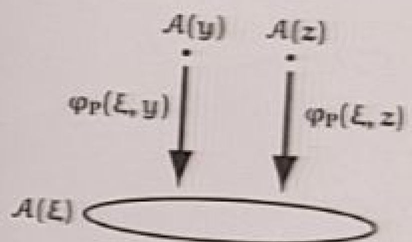
5

Axiom 1 (extension).



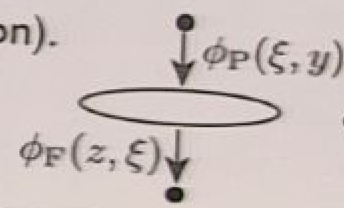
There exists $\phi_{\rm P}(\xi, y) : A(y) \to A(\xi)$ such that, for each $x \in \xi$, $\phi_{\rm P}|_{A(x)}$ is $\phi(x, y)$.

Axiom 2 (commutativity of unrelated elements).



The images of $\phi_{\rm P}(\xi, y)$ and $\phi_{\rm P}(\xi, z)$ in $A(\xi)$ commute.

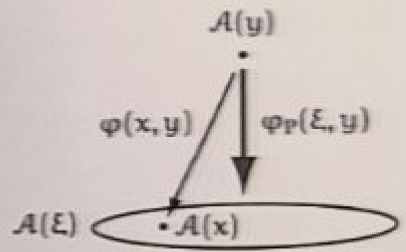
Axiom 3 (composition).



$$\phi(z, y) = \phi_{\rm F}(z, \xi) \circ \phi_{\rm P}(\xi, y)$$

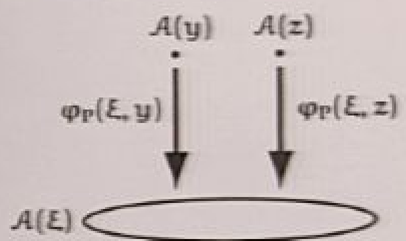
5

Axiom 1 (extension).



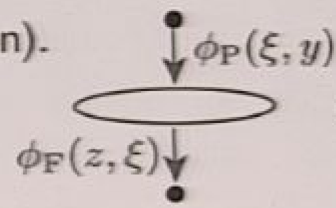
There exists $\phi_P(\xi,y) : A(y) \to A(\xi)$ such that, for each $x \in \xi$, $\phi_P|_{A(x)}$ is $\phi(x,y)$.

Axiom 2 (commutativity of unrelated elements).



The images of $\phi_P(\xi,y)$ and $\phi_P(\xi,z)$ in $A(\xi)$ commute.

Axiom 3 (composition).



$$\phi(z,y) = \phi_F(z,\xi) \circ \phi_P(\xi,y)$$

6

Unitary maps from completely positive maps

Theorem 2. *For any acausal sets $\xi, \zeta \subset \mathcal{C}$, if ζ is a complete future of ξ or ξ is a complete past of ζ then there exists a unique map*

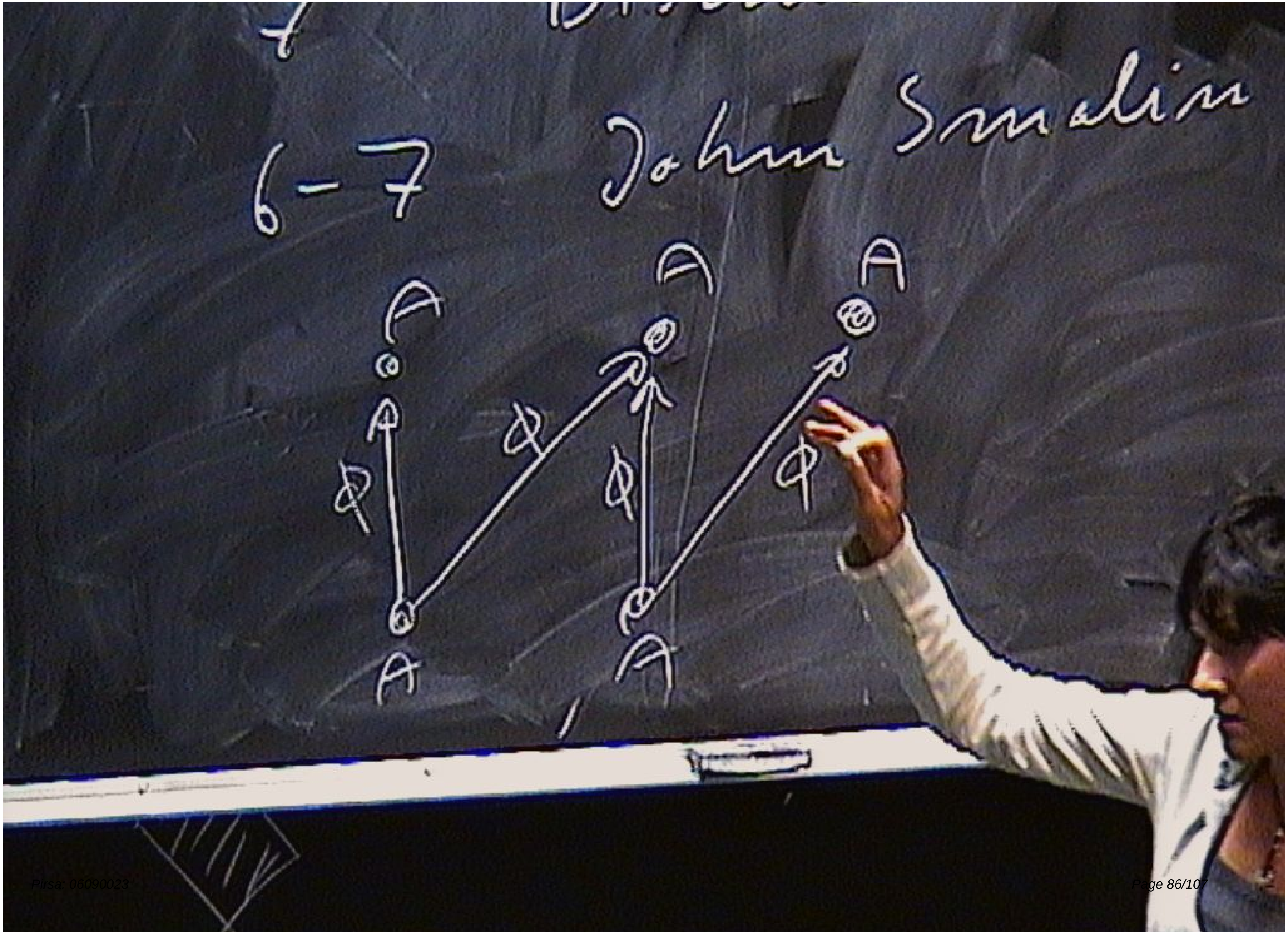
$$\varphi(\xi, \zeta) : \mathcal{A}(\zeta) \to \mathcal{A}(\xi)$$

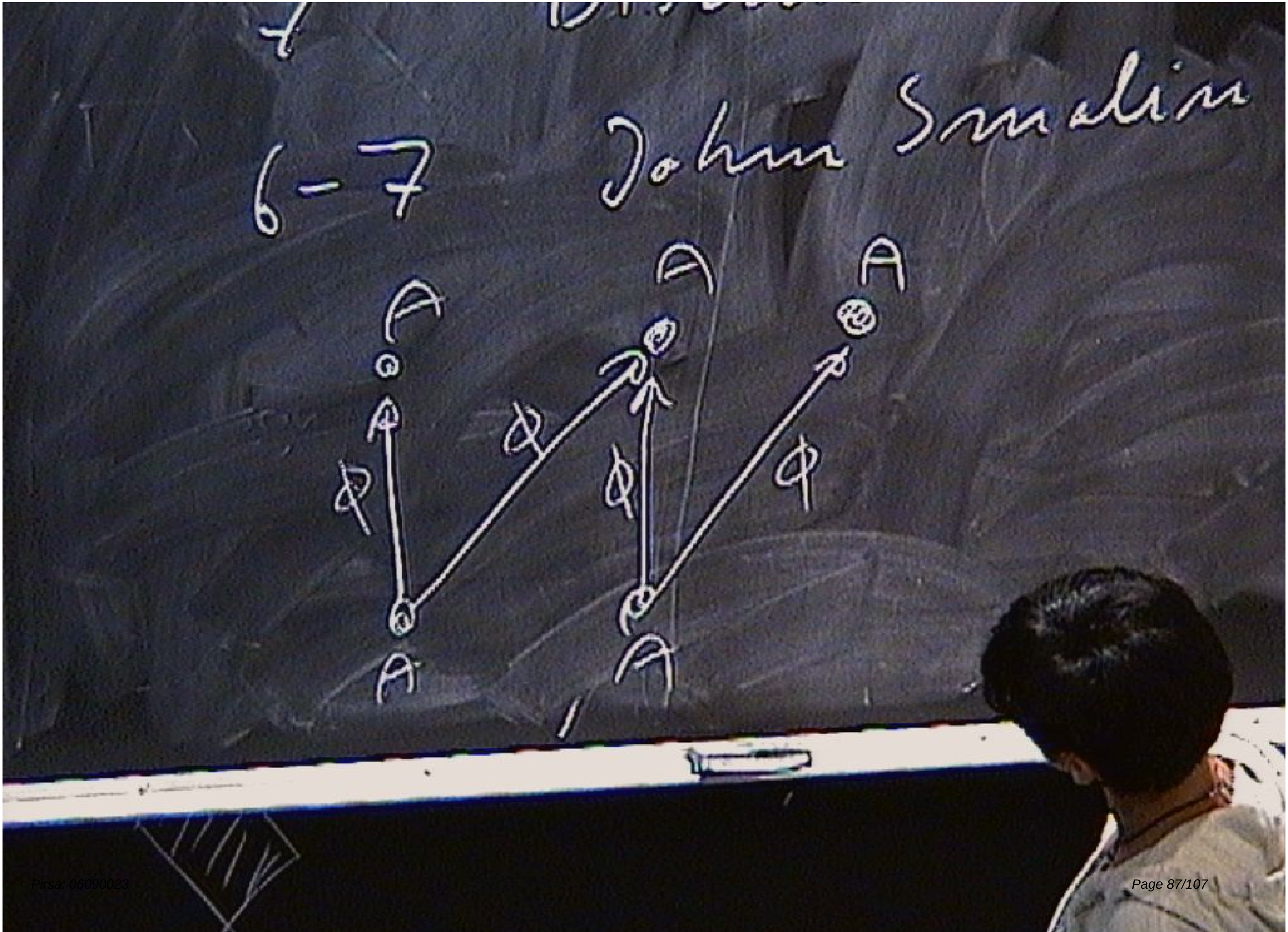
such that

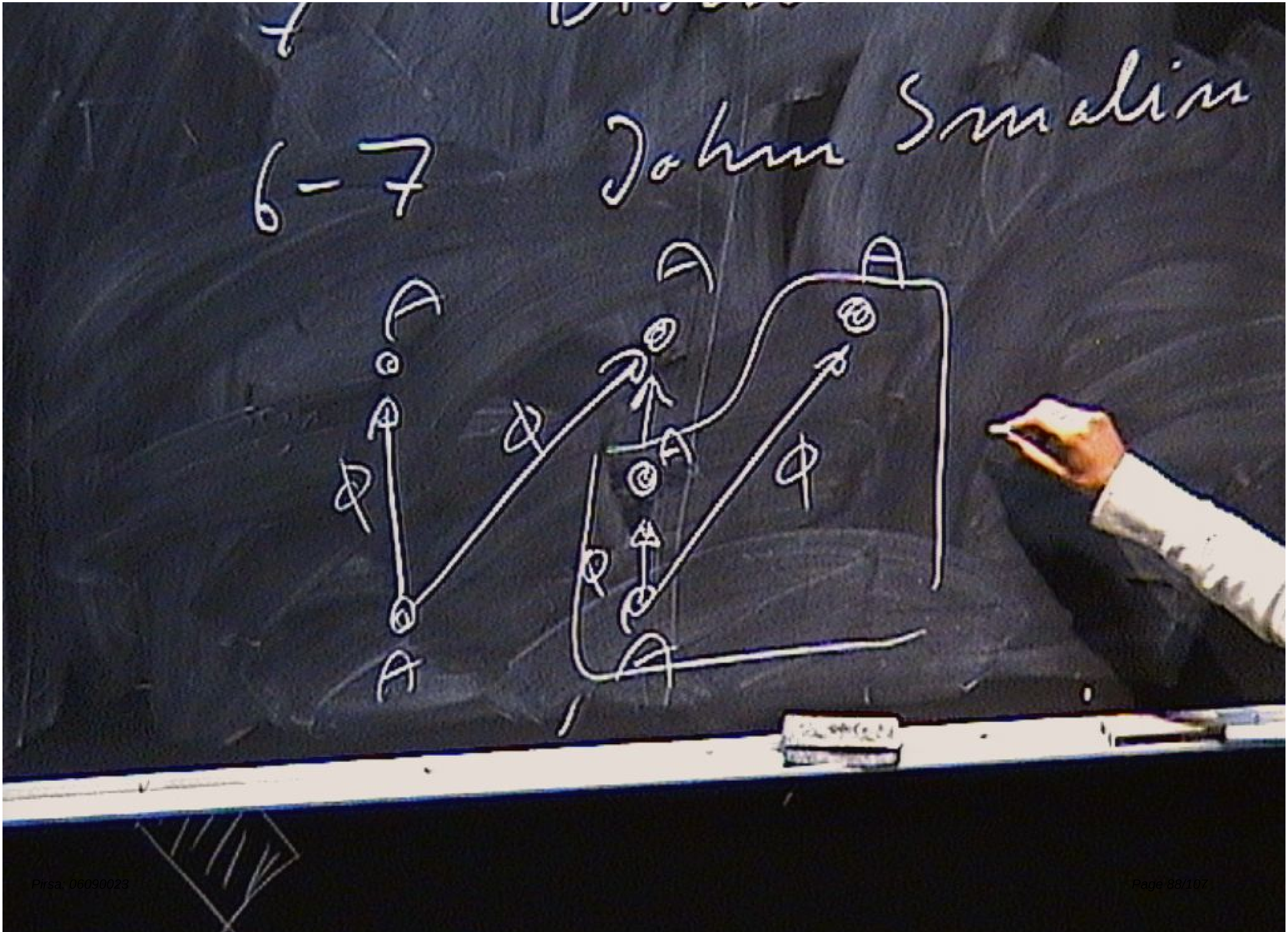
1. *For any $x \in \xi$ and $z \in \zeta$, the reduction of $\varphi(\xi, \zeta)$ to $\mathcal{A}(z) \to \mathcal{A}(x)$ is $\varphi(x, z)$.*
2. *If ξ is a complete past of ζ, then $\varphi(\xi, \zeta)$ is a homomorphism.*
3. *If ζ is a complete future of ξ, then $\varphi^\dagger(\xi, \zeta)$ is a homomorphism.*
4. *If $\xi \preceq \zeta$ is a complete pair, then $\varphi(\xi, \zeta)$ is an isomorphism.*
5. *If $\xi \preceq \upsilon \preceq \zeta$, then $\varphi(\xi, \upsilon) \circ \varphi(\upsilon, \zeta) = \varphi(\xi, \zeta)$.*

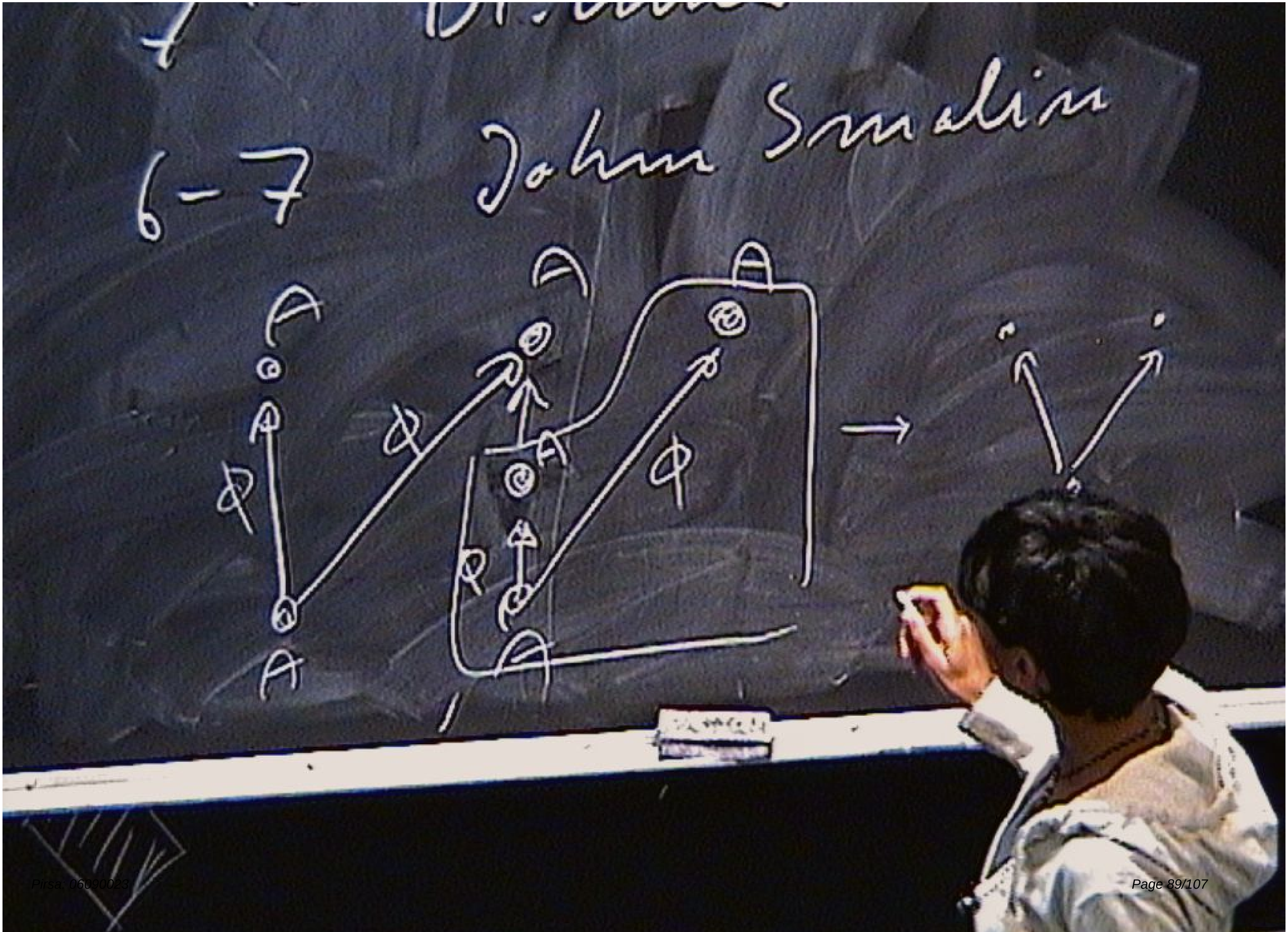
i.e., we can reconstruct unitary maps in the right places, *and*

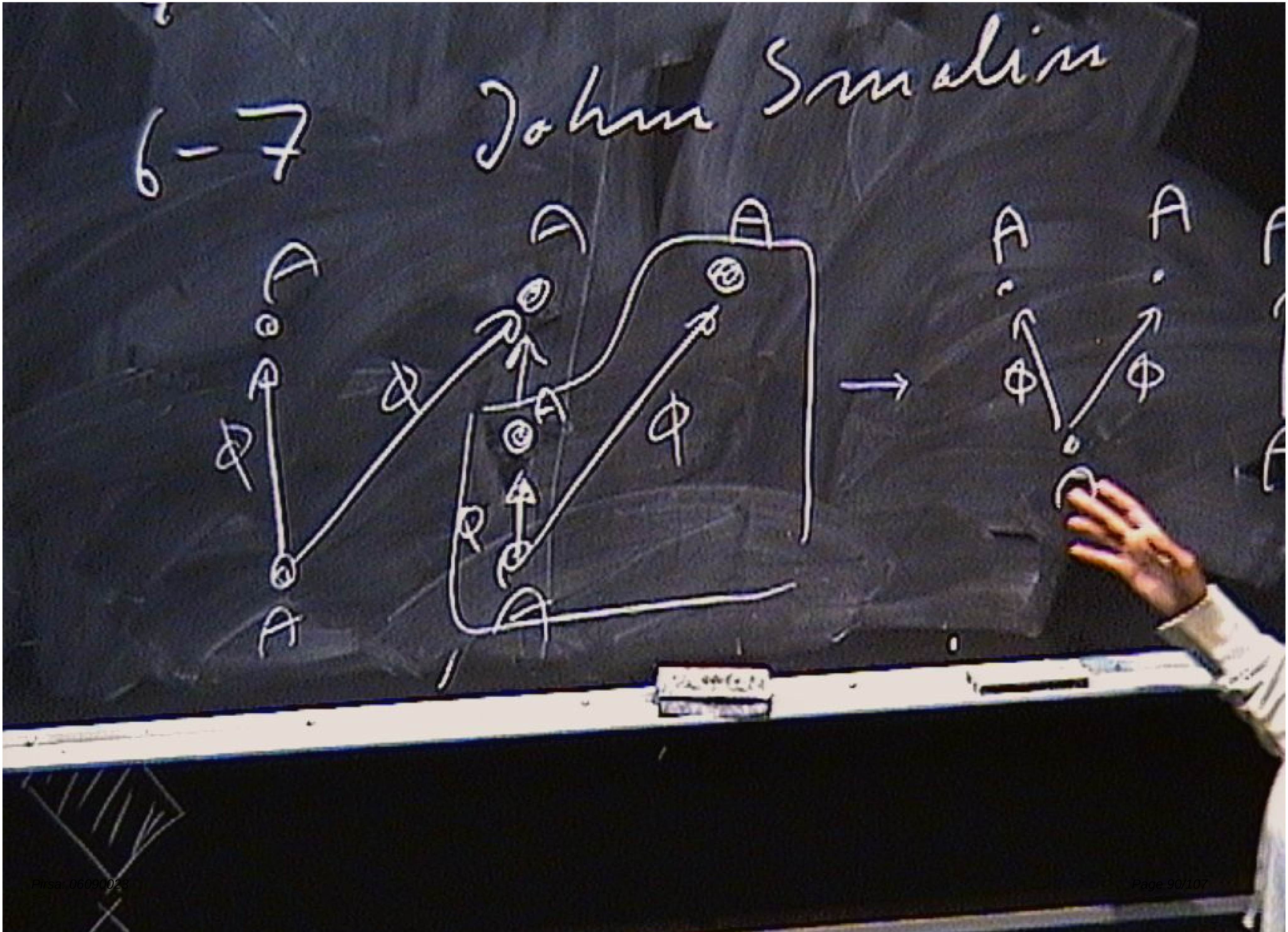
not every choice of unitary maps for complete pairs can be expressed in terms of CP maps (micro-causality).

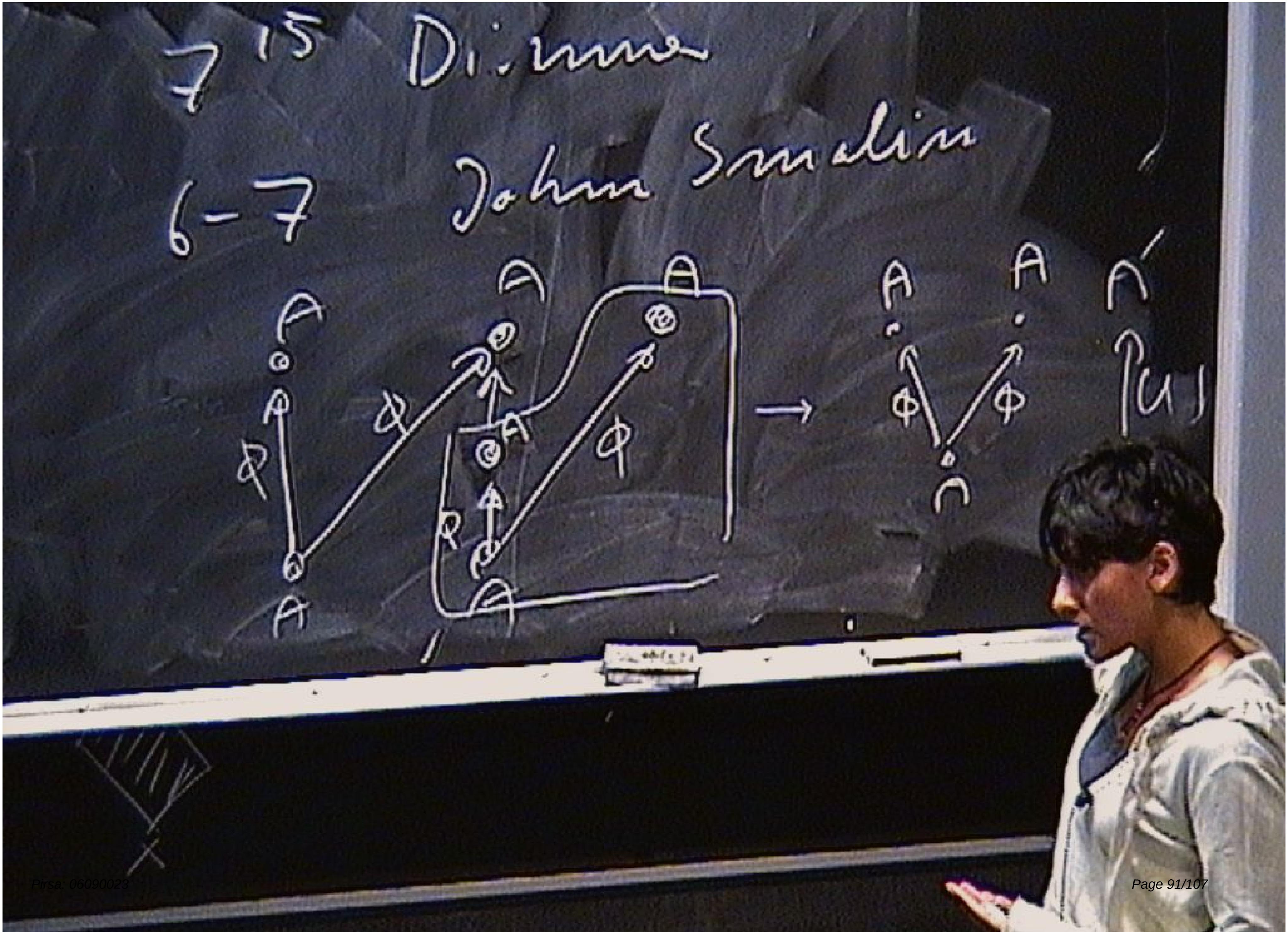

6-7
John Smolin
A
A
A
A
A
φ
φ
φ
φ


6-7
John Smolin
A
A
A
A
A

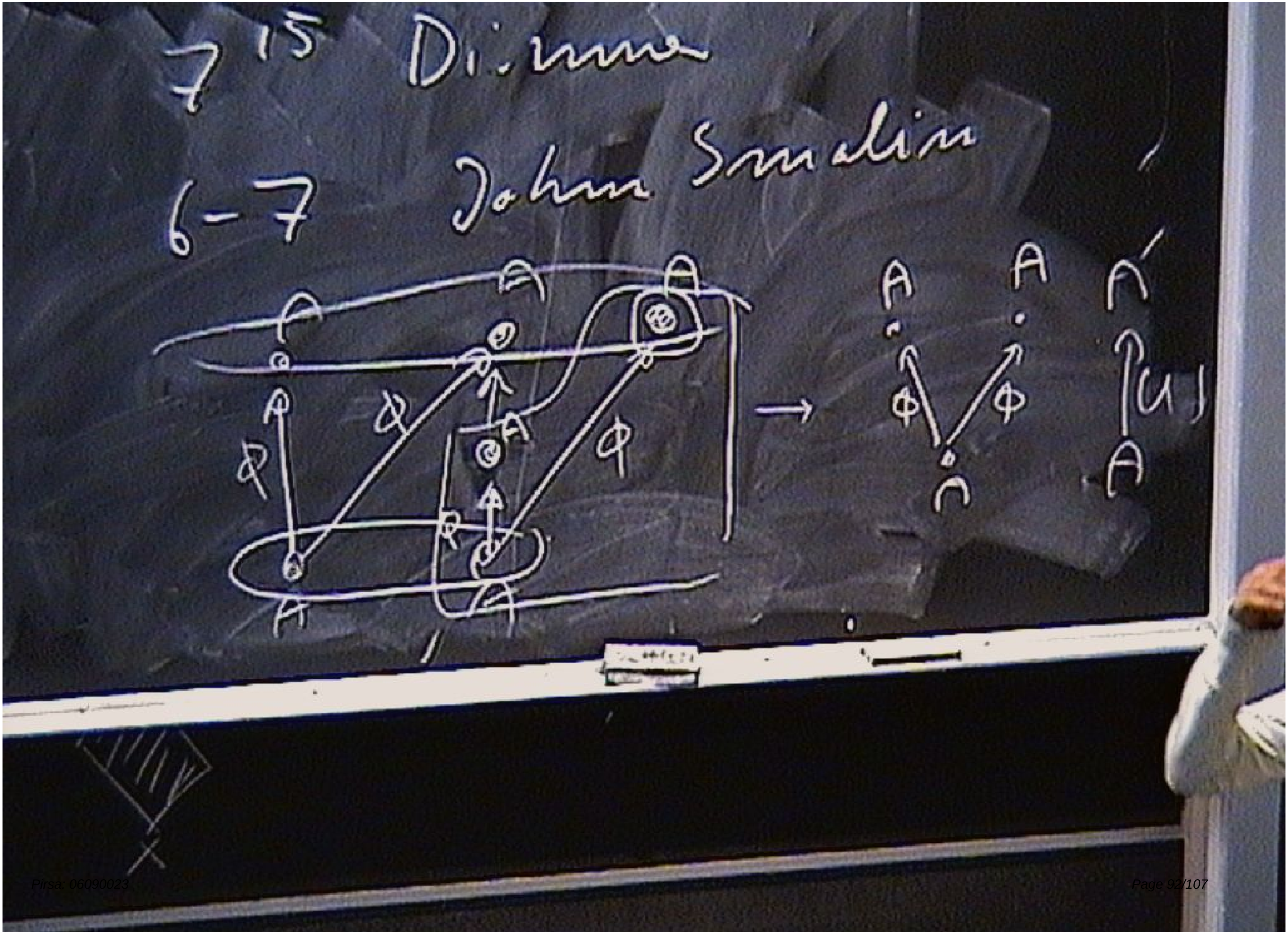

6-7
John Smolin


6-7
John Smolin


6-7
John Smolin
A
Φ



7 15 Dinner
6-7 John Smolin


7 15 Dinner
6-7 John Smolin

7

1. QCHs as discrete quantum field theory

Algebraic Quantum Field Theory:
Causal nets of algebras of local observables.

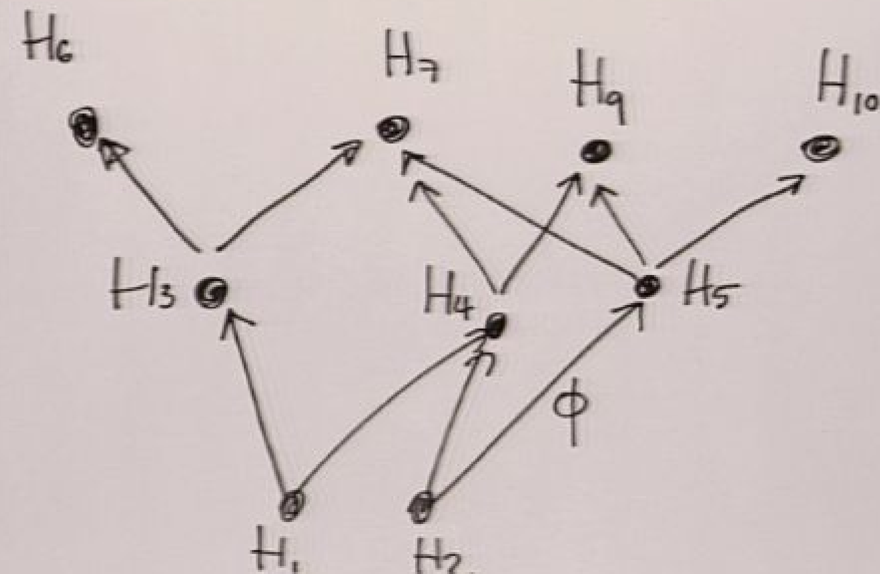
↓

causally complete region of fixed continuous spacetime ⟶ von Neumann algebra

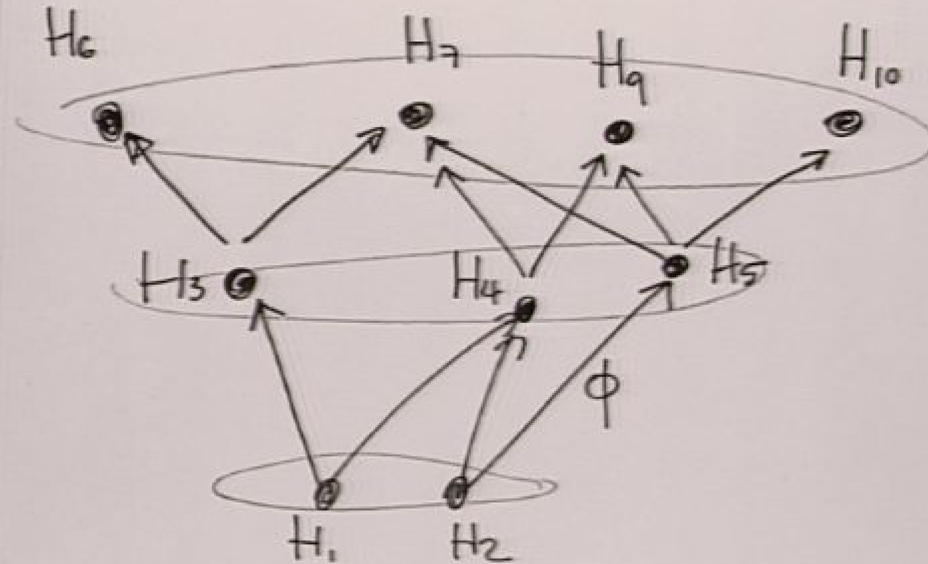
Quantum Causal Histories: Discrete version for fixed spacetime.

$A(x)$ in $x \mapsto A(x)$ means matter degrees of freedom on x

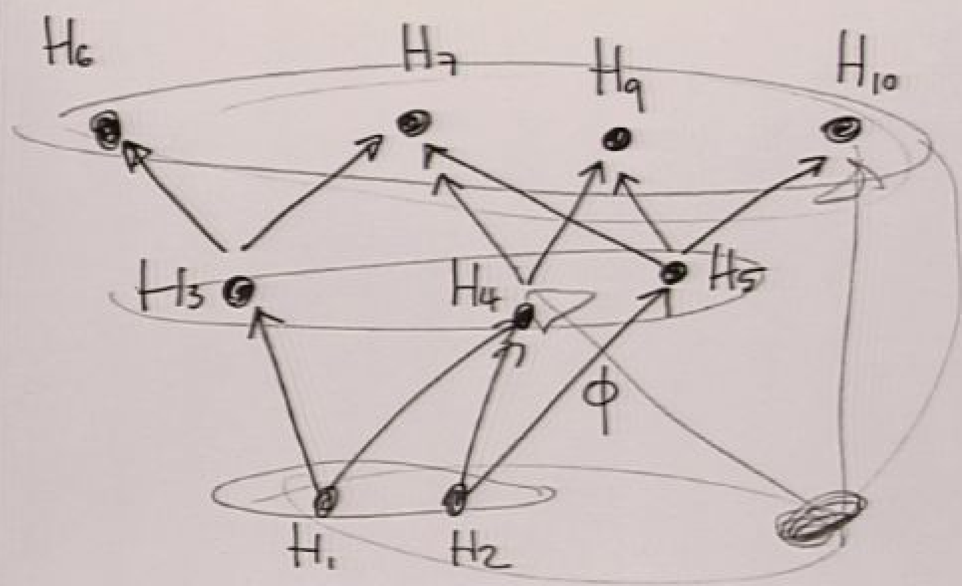
Can use to address unitarity issues in discrete expanding space.
It is of interest to extend to infinite-dimensional algebras on locally finite graph.



$$H_1 \otimes H_2 \xrightarrow{\Phi} H_3 \otimes H_4 \otimes H_5$$



$$H_1 \otimes H_2 \xrightarrow{\Phi} H_3 \otimes H_4 \otimes H_5$$



$$H_1 \otimes H_2 \xrightarrow{\Phi} H_3 \otimes H_4 \otimes H_5$$

7

1. QCHs as discrete quantum field theory

Algebraic Quantum Field Theory:
Causal nets of algebras of local observables.

↓

causally complete region of fixed continuous spacetime $\longrightarrow$ von Neumann algebra

Quantum Causal Histories: Discrete version for fixed spacetime.
$A(x)$ in $x \mapsto A(x)$ means matter degrees of freedom on x

Can use to address unitarity issues in discrete expanding space.
It is of interest to extend to infinite-dimensional algebras on locally finite graph.

What I *really* think:

They say:

"If there is a cutoff in the dofs in the universe, as it expands, the dofs / modes must increase."

Obvious hidden assumption:

The fundamental dofs the cutoff refers to are spatial geometry.

The problem belongs to the semiclassical approximation & it is not fundamental.

Background Independence & the Cosmological Constant Problem

O. Dreyer

I. Background Independence

II. The cosmological constant problem

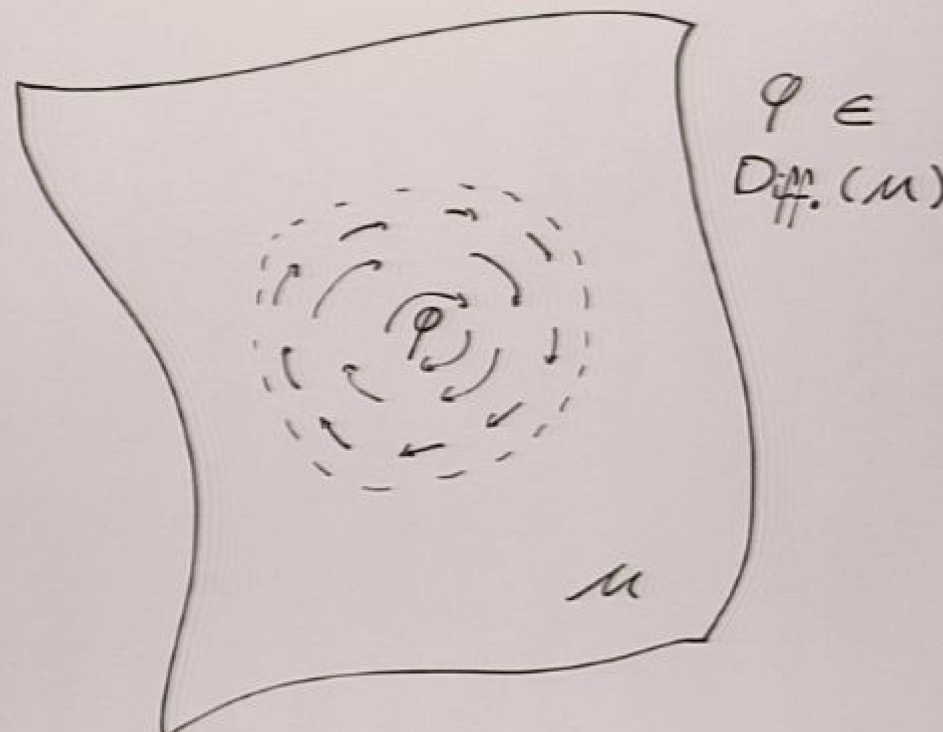
III. A new look

IV. Outlook

hep-th/0409048

I. Background Independence

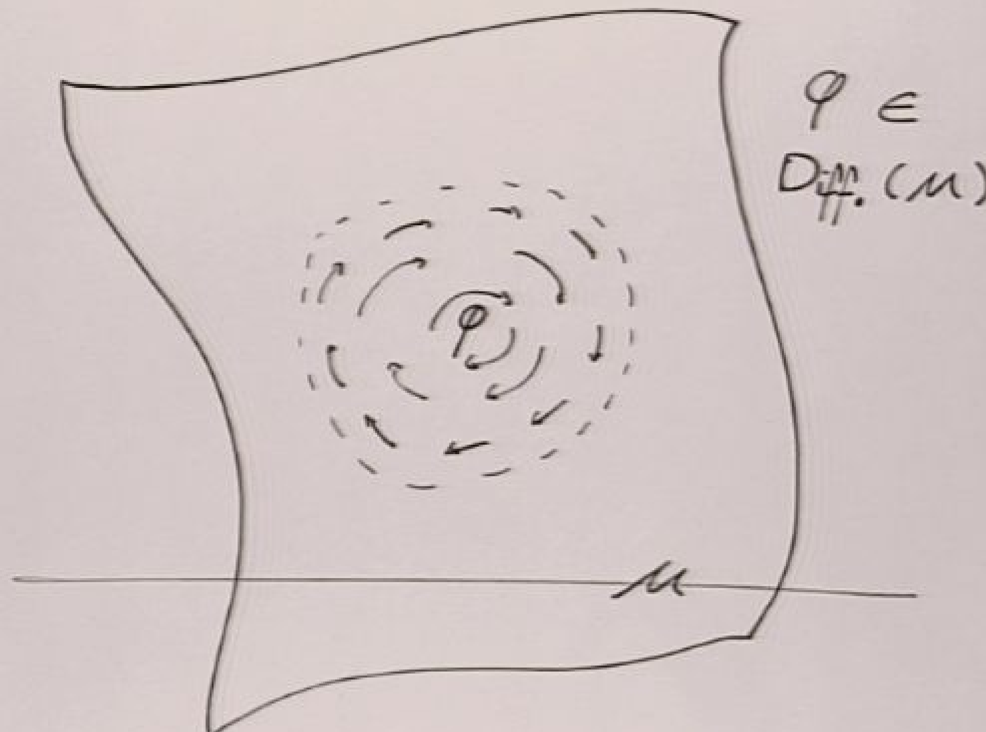
The hole argument



How can GR be predictive ?

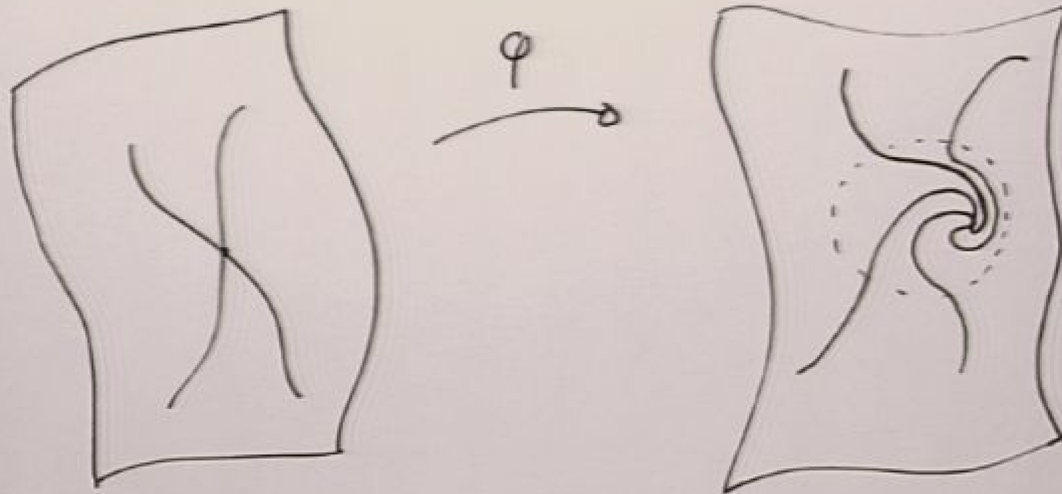
I. Background Independence

The hole argument



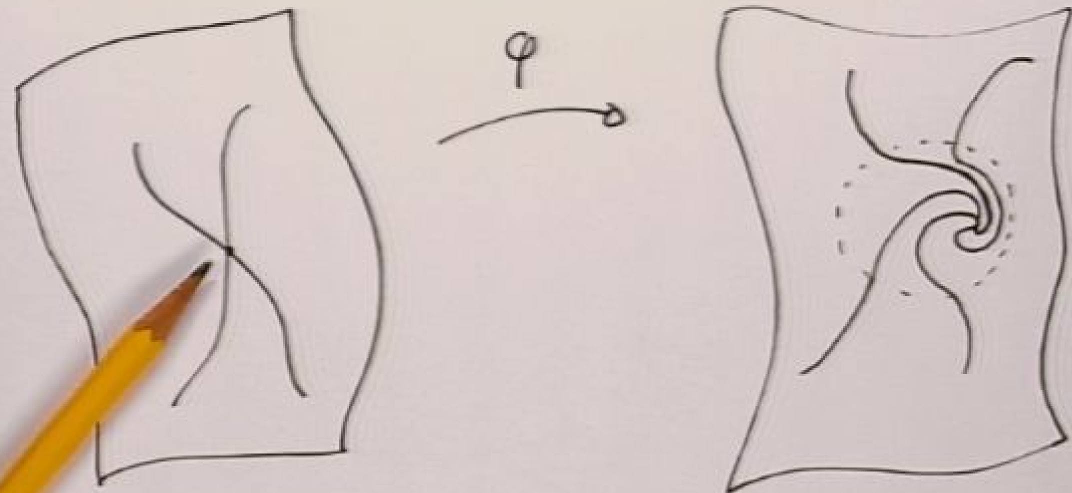
How can GR be predictive ?

Ia. Background Independence



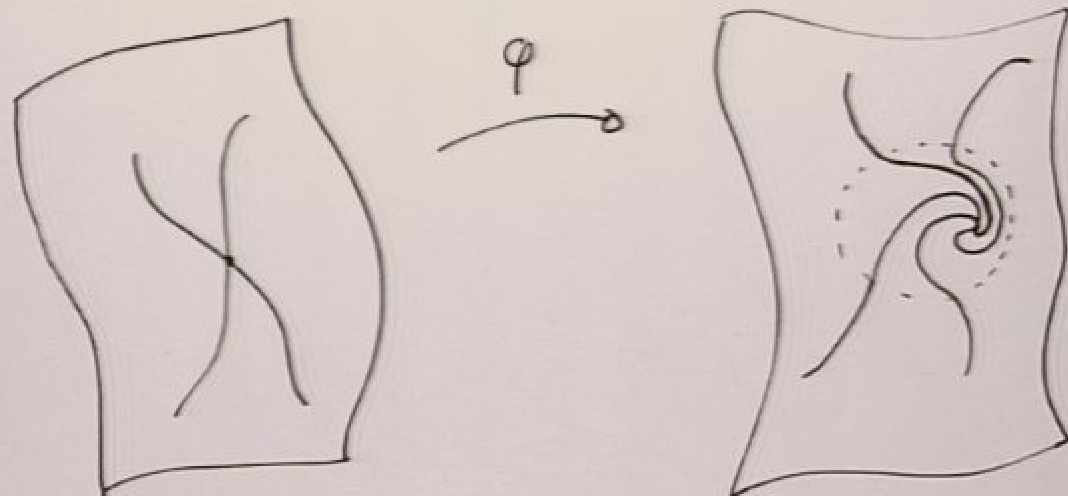
Points $\hat{=}$ What happens at those points

Ia. Background Independence



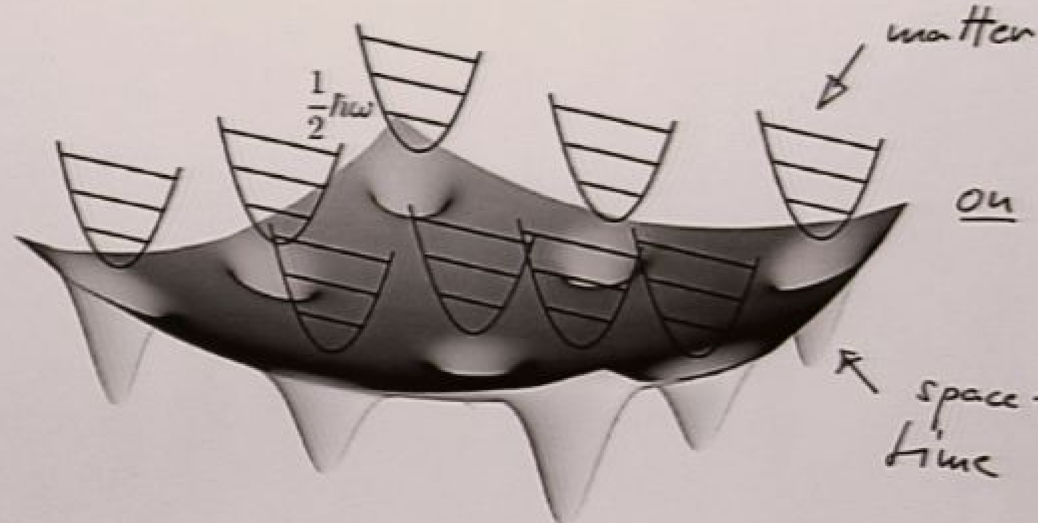
Points ≙ What happens at those points

Ia. Background Independence



Points $\hat{=}$ What happens at those points

II. The Cosmological Constant Problem



$$\int^{\omega_p} \hbar\omega \; \omega^2 d\omega \sim \hbar\omega_p^4$$

123 orders of magnitude off

III. A new look

Origin of the problem:

We think of matter as being <u>on</u> spacetime.

This is <u>not</u> background independent.

The cosmological constant problem arises because we are not sufficiently background independent.

IV. Outlook

- Why is λ small and not zero?

  Maybe: Use argument from causal sets. Replace $\sqrt{N}$ uncertainty with quantum uncertainty.
  (Ahmed et all., PRD 69, 103523 (2004))

- Size of the Hilbert space of the system and the geometry of space are not related.