Title: Preferred Global Slicing

Date: Jun 30, 2016 02:00 PM

URL: http://pirsa.org/16060119

Abstract:

Time in Cosmology (June 30th 2016)

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Preferred Global Slicing:
The case for fundamental global intrinsic time

Chopin Soo 許祖斌

Department of Physics,
Nat. Cheng Kung U, Taiwan

"*Talking about time without thinking about the universe is hopeless*"
-- Neil T.

"the 3rd approach":
"*our universe is one of a kind, explanation of time and cosmology should not be practiced as scaled up local physics;*
but how does cosmological time square with General Relativity?"
"causation is fundamental to Nature" -- Roberto M. U.

"*Need a theory of the whole universe as starting point* " -- Marina C.

"*Time is fundamental; the universe allows no and needs no external clock* "-- Lee S.

I DO agree with our organizers and hosts.

So let's "go the whole hog" :

The (ever-expanding) universe is the ultimate clock

$$i\hbar \frac{\partial \Psi}{\partial \ln V} = H_{\text{Phys.}} \Psi$$

Ψ = wave function of the universe

V= spatial volume of our universe (assumed spatially compact)

There is "conflict/tension" with 4-covariance in this "simple scheme".

However,

Quantum Gravity carries a message (one which Einstein's 4-covariant classical Gen. Rel. theory hides) ....

The conflict:

Existence of fundamental time is incompatible with 4-covariance of Einstein's theory

Those against (16votes) fundamental time have (all?) embraced 4-covariance.

But the majority (26votes) of fundamental time believers ("the fundamentalists") have not yet all declared themselves to be sceptics of 4-covariance and heretics (of Einstein's theory).

BATTELLE RENCONTRES

1967 LECTURES IN MATHEMATICS AND PHYSICS

EDITED BY

Cecile M. DeWitt
University of North Carolina at Chapel Hill

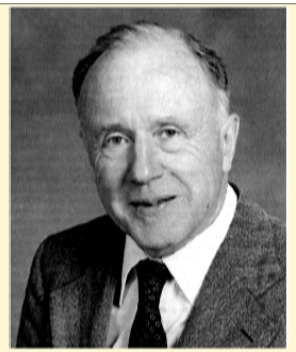
AND

John A. Wheeler
Princeton University

IX

Superspace and the Nature of Quantum Geometrodynamics

JOHN ARCHIBALD WHEELER



"Spacetime," a Concept of Limited Validity

There is no such thing as a 4-geometry in quantum geometrodynamics, and for a simple reason. No probability amplitude function $\psi({}^{(3)}\mathcal{G})$ can propagate through superspace as an indefinitely sharp wave packet ···

Quantum Gravity => the demise of 4-dimensional space-time

$$[q_{kl}(x), \pi^{ij}(x')] = (i\hbar)\tfrac{1}{2}(\delta^i_k\delta^j_l + \delta^i_l\delta^j_k)\delta(x - x')$$

BATTELLE RENCONTRES

1967 LECTURES IN MATHEMATICS AND PHYSICS

EDITED BY

Cecile M. DeWitt
University of North Carolina at Chapel Hill

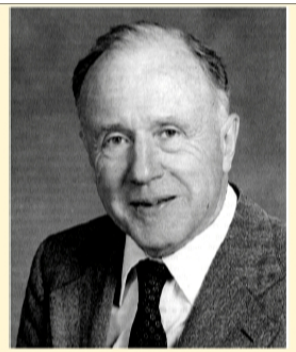
AND

John A. Wheeler
Princeton University

IX

Superspace and the Nature of Quantum Geometrodynamics

JOHN ARCHIBALD WHEELER

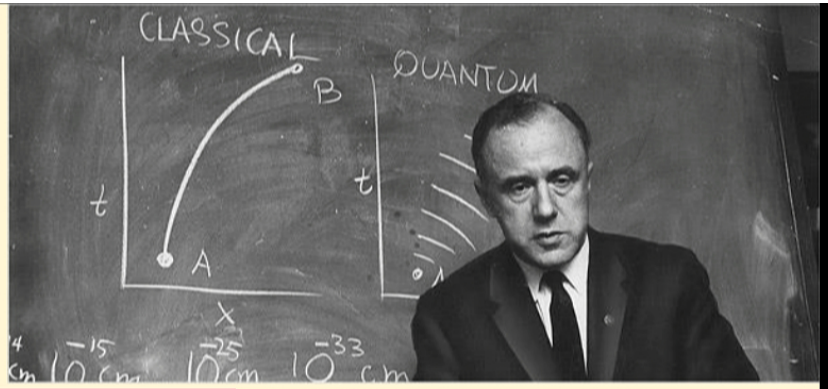


"Spacetime," a Concept of Limited Validity

There is no such thing as a 4-geometry in quantum geometrodynamics, and for a simple reason. No probability amplitude function $\psi({}^{(3)}\mathcal{G})$ can propagate through superspace as an indefinitely sharp wave packet ···

Quantum Gravity => the demise of 4-dimensional space-time

$$[q_{kl}(x), \pi^{ij}(x')] = (i\hbar)\tfrac{1}{2}(\delta^i_k\delta^j_l + \delta^i_l\delta^j_k)\delta(x - x')$$



IX

Superspace and the Nature of Quantum Geometrodynamics

JOHN ARCHIBALD WHEELER

BATTELLE RENCONT

1967 LECTURES IN MATHEMATICS AND

EDITED BY

Cecile M. DeWitt
University of North Carolina at Chapel Hill

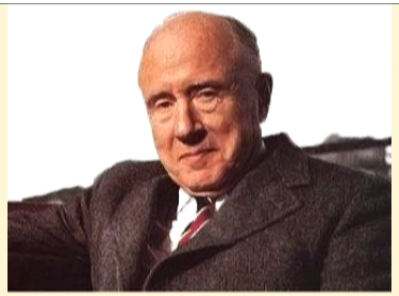
AND

John A. Wheeler
Princeton University

Three Dimensions, Not Four

Similarly in geometrodynamics: Here the dynamic object is not space-time. It is space. The geometrical configuration of space changes with time. But it is space, three-dimensional space, that does the changing. No surprise! In particle dynamics the dynamical object is not *x and t*, but only *x*. How to tell this to our friends in the world of mathematics? For so long they have heard us say that it was in default of the fourth dimension that Riemann could not have discovered general relativity. First there had to come special relativity and spacetime and the fourth dimension. Otherwise how could one have had any possibility to connect gravitation with the curvature of spacetime (Fig. 2)? This understood, how can physicists change their minds and "take back" one dimension? The answer is simple. A decade and more of work by Dirac, Bergmann, Schild, Pirani, Anderson, Higgs, Arnowitt, Deser, Misner, DeWitt, and others has taught us through many a hard knock that Einstein's geometrodynamics deals with the dynamics of geometry: of 3-geometry, not 4-geometry [1, 2].

3d Diffeo. Inv.



Wheeler: Three Dimensions, NOT Four!

A curved 4d space-time is a classical concept of limited applicability in Quantum Gravity.

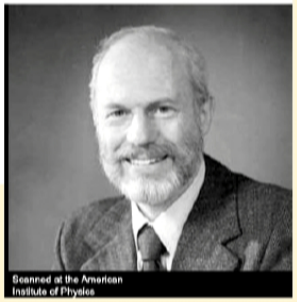
?=> `4-covariance' (symmetry of FOUR-dim. spacetime) cannot/need not be fundamental to Quantum Gravity!

... yet there is "that damn equation" (WdW eqn.)

PHYSICAL REVIEW VOLUME 160, NUMBER 5 25 AUGUST 1967

Quantum Theory of Gravity. I. The Canonical Theory*

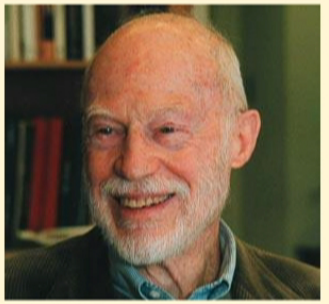
BRYCE S. DEWITT
Institute for Advanced Study, Princeton, New Jersey
and
Department of Physics, University of North Carolina, Chapel Hill, North Carolina†
(Received 25 July 1966; revised manuscript received 9 January 1967)



its metric the coefficient of the momenta in the Hamiltonian constraint. The geodesic incompletability of this manifold, owing to the existence of a frontier of infinite curvature, is demonstrated. The possibility is explored of relating this manifold to an infinite-dimensional manifold of 3-geometries, and of relating the structure of the latter manifold in turn to the dynamical behavior of space-time. The problem is approached through the WKB approximation and Hamilton-Jacobi theory. Einstein's equations are revealed as geodesic equations in the manifold of 3-geometries, modified by the presence of a "force term." The classical phenomenon of gravitational collapse shows that the force term is not powerful enough to prevent the trajectory of space-time from running into the frontier. The as-yet unresolved problem of determining when the collapse phenomenon represents a real barrier to the quantum-state functional is briefly discussed, and a boundary condition at the barrier is proposed. The state functional of a finite world can depend only on the 3-geometry of the hypersurface $x^0 = \text{constant}$. The label x^0 itself is irrelevant, and "time" must be determined intrinsically. A natural definition for the inner product of two such state functionals is introduced which, however, encounters difficulties with negative probabilities owing to the barrier boundary condition. In order to resolve these difficulties, a simplified model, the quantized Friedmann universe, is studied in detail. In order to obtain nonstatic wave functions which resemble a universe evolving, it is necessary to introduce a clock. In order that the combined wave functions of universe-*cum*-clock be normalizable, it turns

Suggestion:
DeWitt: Superspace metric has (- + + + + +) signature.
-ve mode: Intrinsic time $\zeta = [\det(q_{ij})(x)]^{1/4}$
But Wheeler-DeWitt-Equation and Hamilton-Jacobi Eq.
still 2nd order in "intrinsic time" (which is multi-fingered)

$$\left[-\frac{\delta^2}{\delta\zeta^2}+\frac{(32/3)}{\zeta^2}\bar{G}^{AB}\frac{\delta^2}{\delta\zeta^A\delta\zeta^B}+(3/32)\zeta^2\,{}^{(3)}R\right]$$
$$\times\Psi[{}^{(3)}\mathcal{G}]=0,$$



but, this intrinsic time $\zeta(x)$ is multi-fingered
(problematic for "time-ordering" of quantum evolution),
a tensor density, gauge-dependent, ...

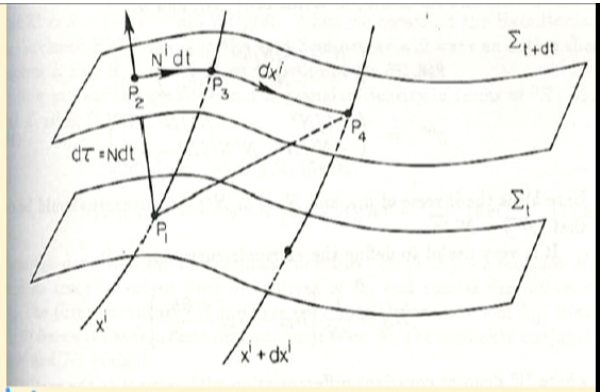
In V as intrinsic time is spatial diffeomorphism invariant
Global (not x-dependent multi-fingered)

Technical difficulties of 4-covariance:

Non-renormalizability.
Proposal: (P. Horava)
Give up 4d Diff. Invariance in favor of 3d Diff. Invariance for power-counting renormalizability

Essential conflict between 4-covariance and unitarity:
Tweaking potential terms (+ higher spatial derivatives)
$\Rightarrow$ changing the kinetic term (+ higher time derivatives)
Strategy: improve convergence by adding higher SPATIAL derivatives, without higher time derivatives

Role of constraints in Einstein's theory of GR:



On-shell (modulo constraints +EOM),
The constraints do generate 4d diffeomorphisms
Eventhough Dirac algebra is NOT algebra of 4d diffeomorphisms

$$\delta_{\vec{N}} q_{ab} = \{H_i[N^i], q_{ab}\}_{P.B.} = \mathcal{L}_{\vec{N}} q_{ab}$$
$$\delta_N q_{ab} = \{H[N], q_{ab}\}_{P.B.} = N q^{-\frac{1}{2}} (\pi q_{ab} - \pi_{ab})$$
$$[\,\text{modulo EOM}\,] = 2NK_{ab} = \mathcal{L}_{N\vec{n}} q_{ab}$$

$$\delta_{\vec{N}} \pi^{ab} = \{H_i[N^i], \pi^{ab}\}_{P.B.} = \mathcal{L}_{\vec{N}} \pi^{ab}$$

$$\delta_N \pi^{ab} = \{H[N], \pi^{ab}\}_{P.B.}$$
$$= q^{ab} \frac{N}{2} H - N\sqrt{q}(q^{ca} q^{db} - q^{cd} q^{ab}) R^{(4)}_{cd} + \mathcal{L}_{N\vec{n}} \pi^{ab}$$

$$ds^2 = -N^2 (cdt)^2 + q_{ij}(dx^i + N^i cdt)(dx^j + N^j cdt)$$

Paradigm Shift:

from 4-covariance
to
3-dimensional diffeomorphism invariance (3dDI)

$$i\hbar\frac{\partial\Psi}{\partial T}\;;=H_{\rm Phys.}\Psi$$

$$dT=\tfrac{2}{3}d\ln V \qquad \text{i.e.} \qquad T-T_o=\tfrac{2}{3}\ln(V/V_o)$$

$$[H_i(x),H_{\rm Phys.}]=0; \qquad H_i(x)\Psi=0$$

$$H_{\rm Phys}:=\int\frac{\bar{H}(x)}{\beta}d^3x;$$

And give up "that damn equation", the Hamiltonian constraint

How does this square with GR?

Q: What is the form of $H_{Phys.}$ that is "compatible" with Gen. Relativity?
(reproduces the EOMs of GR with the a posteriori value of N in GR)

Answer:

$$i\hbar\frac{\partial\Psi}{\partial T} = H_{\rm Phys}\Psi, \qquad H_{\rm Phys} := \int \frac{\bar{H}(x)}{\beta} d^3x;$$

$$\bar{H}[\bar{\pi}^{ij}, \bar{q}_{ij}, q] = \sqrt{\bar{G}_{ijkl}\bar{\pi}^{ij}\bar{\pi}^{kl} + V[\bar{q}_{ij}, q]} = \sqrt{\frac{1}{2}(\bar{q}_{ik}\bar{q}_{jl} + \bar{q}_{il}\bar{q}_{jk})\bar{\pi}^{ij}\bar{\pi}^{kl} + V[\bar{q}_{ij}, q]},$$

$$\beta^2 := \frac{1}{3(3\lambda - 1)}$$

Einstein's GR (in which $\lambda = 1$ and $V[\bar{q}_{ij}, q] = -\frac{q}{(2\kappa)^2}(R - 2\Lambda_{eff})$)

(fast forward)

Cont'd

$$i\hbar\frac{\partial\Psi}{\partial T} \; := \; H_{\rm Phys}\Psi, \qquad H_{\rm Phys} := \int \frac{\bar{H}(x)}{\beta} d^3x;$$

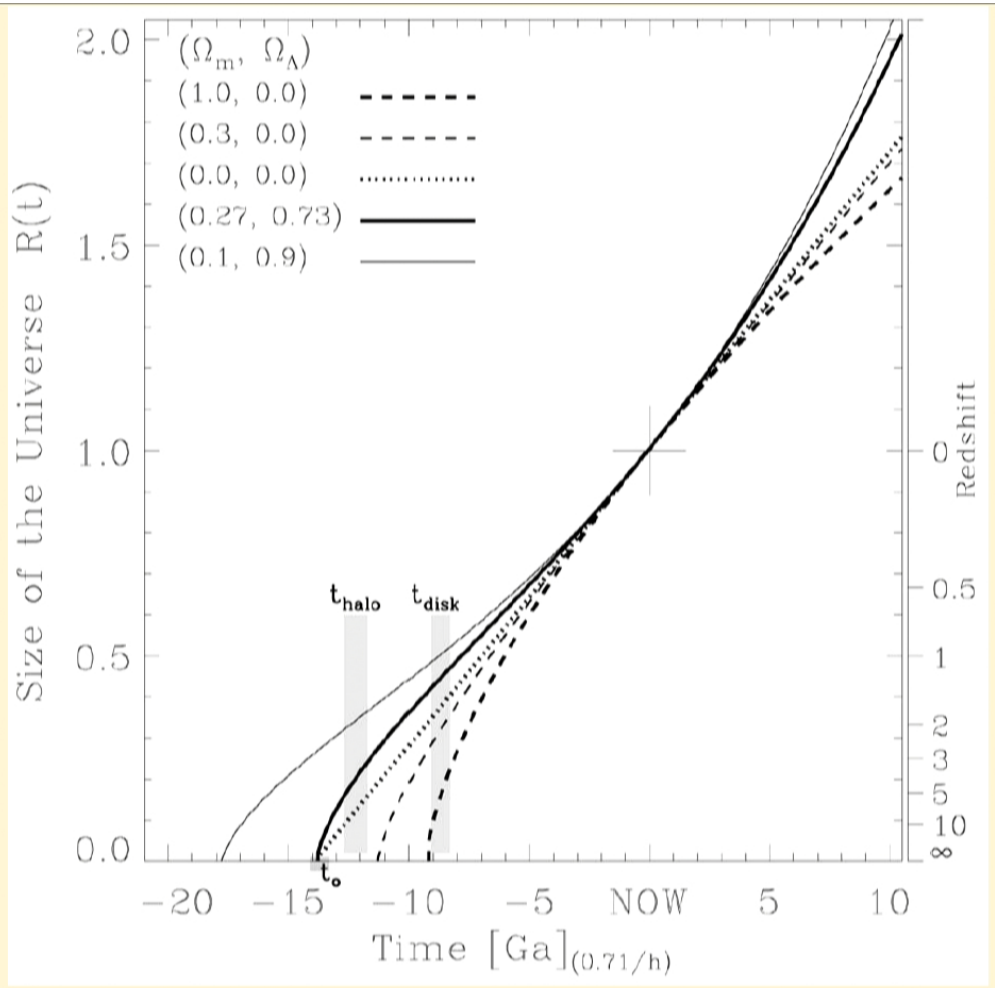
$$dT = \tfrac{2}{3} d\ln V \qquad \text{i.e.} \qquad T - T_o = \tfrac{2}{3}\ln(V/V_o)$$

dT ~ change in logarithm of spatial volume of the universe

1)This is exact in the FULL theory and NOT mini-superspace or FRW model

2)Barring conclusive evidence to the contrary, observationally, our Universe has always increased in size and lnV ~TimeT
(perhaps this is a signal that the "fundamentalists" got it right)

3)In FRW models, time interval between then (a) and now (a_0) is
$\Delta \ln V = 3\ln(a_0/a)$; $a_0/a = (1 + z)$; z = redshift


$(\Omega_m, \Omega_\Lambda)$
(1.0, 0.0)
(0.3, 0.0)
(0.0, 0.0)
(0.27, 0.73)
(0.1, 0.9)
Size of the Universe R(t)
2.0
1.5
1.0
0.5
0.0
t_{halo}
t_{disk}
t_o
−20
−15
−10
−5
NOW
5
10
Time [Ga]$_{(0.71/h)}$
Redshift
0
0.5
1
2
3
5
10
∞

Cont'd

$$i\hbar\frac{\partial\Psi}{\partial T} \; := \; H_{\rm Phys}\Psi, \qquad H_{\rm Phys} := \int \frac{\bar{H}(x)}{\beta} d^3x;$$

$$dT = \tfrac{2}{3} d\ln V \qquad \text{i.e.} \qquad T - T_o = \tfrac{2}{3}\ln(V/V_o)$$

dT ~ change in logarithm of spatial volume of the universe

1)This is exact in the FULL theory and NOT mini-superspace or FRW model

2)Barring conclusive evidence to the contrary, observationally, our Universe has always increased in size and lnV ~TimeT
(perhaps this is a signal that the "fundamentalists" got it right)

3)In FRW models, time interval between then (a) and now (a_0) is
$\Delta \ln V = 3\ln(a_0/a)$; $a_0/a = (1 + z)$; z = redshift

Cont'd

$$i\hbar\frac{\partial\Psi}{\partial T} \; := \; H_{\rm Phys}\Psi, \qquad H_{\rm Phys} := \int \frac{\bar{H}(x)}{\beta} d^3x;$$

$$dT = \tfrac{2}{3} d\ln V \qquad \text{i.e.} \qquad T - T_o = \tfrac{2}{3}\ln(V/V_o)$$

dT ~ change in logarithm of spatial volume of the universe

1)This is exact in the FULL theory and NOT mini-superspace or FRW model

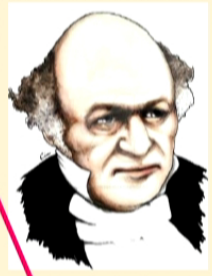
2)Barring conclusive evidence to the contrary, observationally, our Universe has always increased in size and lnV ~TimeT
(perhaps this is a signal that the "fundamentalists" got it right)

3)In FRW models, time interval between then (a) and now (a_0) is
$\Delta \ln V = 3\ln(a_0/a)$; $a_0/a = (1 + z)$; z = redshift

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

quantum & classical: same t

from one (Schrodinger Eq.) comes MANY (Classical EOMs)



through

Hamilton-Jacobi Equation

$$\frac{\partial S}{\partial t} + H\left(q_1, \ldots, q_s; \frac{\partial S}{\partial q_1}, \ldots, \frac{\partial S}{\partial q_s}; t\right) = 0.$$

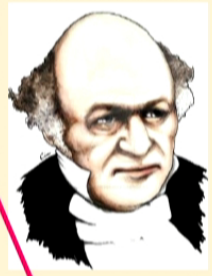
$S(q_1, \ldots q_s; \alpha_1, \ldots, \alpha_s, C)$

*In principle, time-dependent Hamiltonian is ALLOWED

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

quantum & classical: same t

from one (Schrodinger Eq.) comes MANY (Classical EOMs)



through

Hamilton-Jacobi Equation

$$\frac{\partial S}{\partial t} + H\left(q_1, \ldots, q_s; \frac{\partial S}{\partial q_1}, \ldots, \frac{\partial S}{\partial q_s}; t\right) = 0.$$

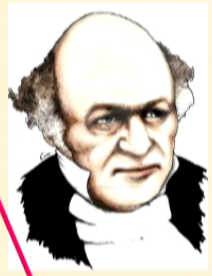
$S(q_1, \ldots q_s; \alpha_1, \ldots, \alpha_s, C)$

*In principle, time-dependent Hamiltonian is ALLOWED

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

quantum & classical: same t

from one (Schrodinger Eq.) comes MANY (Classical EOMs)



through

Hamilton-Jacobi Equation

$$\frac{\partial S}{\partial t} + H\left(q_1, \ldots, q_s; \frac{\partial S}{\partial q_1}, \ldots, \frac{\partial S}{\partial q_s}; t\right) = 0.$$

$S(q_1, \ldots q_s; \alpha_1, \ldots, \alpha_s, C)$

*In principle, time-dependent Hamiltonian is ALLOWED

Upshot of paradigm shift:

1)Gauge-invariant (3dDI) time evolution and time-ordering

2) allows tweaking/modification of the potential V without getting into inconsistencies with closure of the constraint algebra, and yet capture the "same dynamics" in the limit when the potential is that of Einstein's GR

3)The Hamiltonian is actually T-DEPENDENT
=> time asymmetry, non-time-reversal-invariant;
also different terms dominate at different eras of T
(different physics kicks in at different times

$\Rightarrow$ as if there are "different laws at different times")

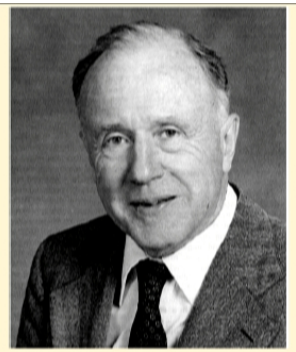
"Hard symmetry breaking"

1)Time Ordering

IX

Superspace and the Nature of Quantum Geometrodynamics

JOHN ARCHIBALD WHEELER



however, the facts are clear. The ${}^{(3)}\mathcal{G}$'s that occur with significant probability amplitude do not fit and cannot be fitted into any single ${}^{(4)}\mathcal{G}$. That "magic structure" of classical geometrodynamics simply does not exist. Without that building plan to organize the ${}^{(3)}\mathcal{G}$'s of significance into a definite relationship, one to another, even the "time ordering of events" is a notion devoid of all meaning.

These considerations reveal that the concepts of spacetime and time itself are not primary but secondary ideas in the structure of physical theory. These concepts are valid in the classical approximation. However, they have neither meaning nor application under circumstances when quantum-geometrodynamical effects become important. Then one has to forgo that view of nature in which every event, past, present, or future, occupies its preordained position in a grand catalog called "spacetime." There is no spacetime, there is no time, there is no before, there is no after. The question what happens "next" is without meaning.

1)Is there a temporal ordering which is invariant under all the symmetries of the theory?
2) Multi-fingered time leads to path-dependent non-integrability (path vs time-ordering)
3) Is there "causality" with H=0 ?

The alternative: 3dDI theory

Q:What replaces the "time-ordering of events " which underpins causality?

A:Time-ordered development (evolution) of quantum states

(the physical quantum state is the fundamental gauge-invariant entity that can be ordered in 3dDI cosmological time

c.f. Minkowski QFT invariant under Lorentz isometry)

$$i\hbar\frac{\partial\Psi}{\partial T}\ ; = H_{\rm Phys.}\Psi$$

$$[H_i(x), H_{\rm Phys.}] = 0; \qquad H_i(x)\Psi = 0$$

$$|\Psi(T)\rangle = U(T, T_o)|\Psi(T_o)\rangle$$

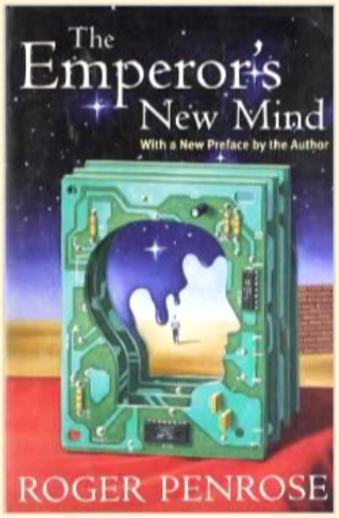
$$U(T, T_0) := \mathcal{T}\exp\left[-\tfrac{i}{\hbar}\int_{T_0}^{T}\mathcal{H}_{phys}(T')\delta T'\right]$$

Dyson series

$$= I - \frac{i}{\hbar}\int_{T_o}^{T} dT_1\mathcal{H}_{Phys}(T_1) + (\frac{i}{\hbar})^2\int_{T_o}^{T} dT_2\int_{T_o}^{T_2} dT_1\mathcal{H}_{Phys}(T_2)\mathcal{H}_{Phys}(T_1) + ...$$
$$+ (\frac{-i}{\hbar})^n\int_{T_o}^{T} dT_n\int_{T_o}^{T_n} dT_{n-1}...\int_{T_o}^{T_2} dT_1\mathcal{H}_{Phys}(T_n)\mathcal{H}_{Phys}(T_{n-1})...\mathcal{H}_{Phys}(T_1) + ...$$

"Placing cosmic history in a single line" --Roberto M. U.

Wave function of the universe: our shared history, present, and future



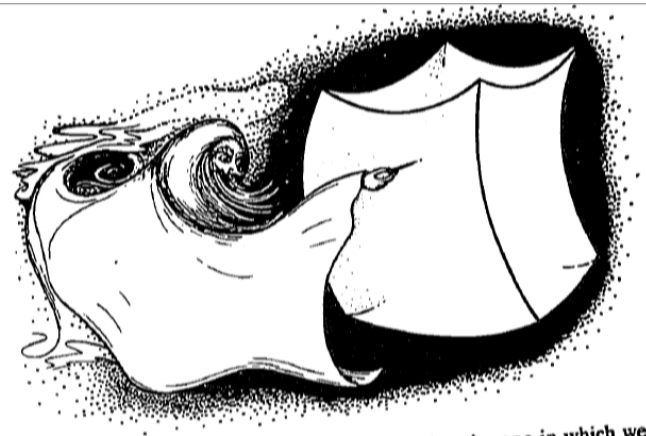
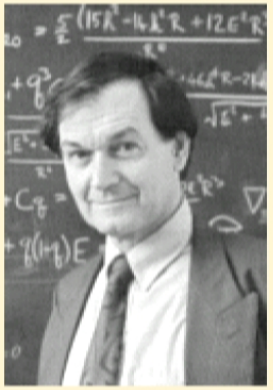
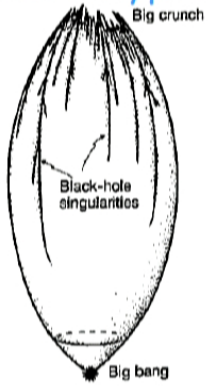


Fig. 7.19. In order to produce a universe resembling the one in which we live, the Creator would have to aim for an absurdly tiny volume of the phase space of possible universes—about $1/10^{10^{123}}$ of the entire volume, for the situation under consideration. (The pin, and the spot aimed for, are not drawn to scale!)



27.13 Our extraordinarily special Big Bang

Weyl Curvature Hypothesis



10^{80} baryons in our universe

Black hole Bekenstein-Hawking Entropy

$S_{BH} = [A/(4l^2_p)]k_B$

Entropy of (BH dominated) Universe

$S=10^{123}\ k_B$ =>

No of states:

$\Omega = e^{10^{123}}$

Fig. 7.17. The entire history of a closed universe which starts from a uniform low-entropy big bang, with **WEYL** = 0 and ends with a high-entropy big crunch—representing the congealing of many black holes—with **WEYL** $\to \infty$.

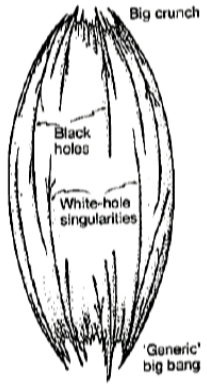


Fig. 7.18. If the constraint **WEYL** = 0 is removed, then we have a high-entropy big bang also, with **WEYL** $\to \infty$ there. Such a universe would be riddled with white holes, and there would be no second law of thermodynamics, in gross contradiction with experience.

$10^{10^{123}}$ (our extraordinarily special Big Bang)
>> 10^{700} (game of GO (19X19)!)
>> 10^{120} (cosmological constant problem)

Failure of Einstein's theory to
naturally account for extraordinarily special initial condition.

Can 3dDI theory fare better?

Modifications to the theory

Einstein's GR (in which $\lambda = 1$ and $V[\bar{q}_{ij}, q] = -\frac{q}{(2\kappa)^2}(R - 2\Lambda_{eff})$)

$$\bar{H}(\bar{\pi}^{ij}, \bar{q}_{ij}, q) = \sqrt{\bar{G}_{ijkl}\bar{\pi}^{ij}\bar{\pi}^{kl} + V(\bar{q}_{ij}, q)}$$

$$V = \tilde{W}^i{}_j\tilde{W}^j{}_i + \gamma\tilde{W}^i{}_i\tilde{W}^j{}_j \qquad \gamma > -\frac{1}{3}$$

$$\tilde{W}^i_j = \sqrt{q}(\Lambda + a'R)\delta^i{}_j + b'\sqrt{q}R^i{}_j + g'\tilde{C}^i{}_j$$

$$= \sqrt{q}(\Lambda + a'q^{-\frac{1}{3}}\bar{R})\delta^i{}_j + b'\sqrt{q}q^{-\frac{1}{3}}\bar{R}^i{}_j + g'\bar{\tilde{C}}^i{}_j + (\text{terms involving } \partial_i \ln q)$$

dimensionless coupling constant

$\bar{\tilde{C}}^i{}_j = \tilde{C}^i{}_j$ with q-independent Cotton York tensor density

C^{ij} = Cotton-York tensor

$$\bar{R}_{ij} = R_{ij} - \tfrac{1}{6}\nabla_i\partial_j \ln q - \tfrac{1}{6}\bar{q}_{ij}\bar{q}^{kl}\nabla_k\partial_l \ln q + \tfrac{1}{36}(\partial_i \ln q)(\partial_j \ln q) - \tfrac{1}{36}\bar{q}_{ij}\bar{q}^{kl}(\partial_k \ln q)(\partial_l \ln q)$$

$$\ln[\tfrac{q(x,T)}{q(x,T_{\rm now})}] = 3(T - T_{\rm now})$$

Initial and & final Hamiltonian of the Universe:

with

$$\begin{aligned}\tilde{W}^i_j &= \hbar[\sqrt{q}(\Lambda' + a'R)\delta^i_j + b'\sqrt{q}\bar{R}^i_j + g\tilde{C}^i_j] \\ &= \hbar[\sqrt{q}(\Lambda' + a'q^{-\frac{1}{3}}\bar{R})\delta^i_j + b'\sqrt{q}q^{-\frac{1}{3}}\bar{\bar{R}}^i_j + g\tilde{C}^i_j] + \partial_i \ln q \ \ terms\end{aligned}$$

where the $\bar{R}$, $\bar{\bar{R}}^i_j$ and the Cotton York tensor $\tilde{C}^i_j$ terms are q independent; $\gamma > -\frac{1}{3}$ and

$$\bar{\tilde{C}}^i{}_j = \tilde{C}^i{}_j$$

$$\begin{aligned}\tilde{W}^i{}_j &\mapsto \tilde{C}^i{}_j \text{ for } T - T_{\rm now} \to -\infty, V/V_{\rm now} \to 0 \\ \tilde{W}^i{}_j &\mapsto \Lambda\delta^i{}_j \text{ for } T - T_{\rm now} \to \infty, V/V_{\rm now} \to \infty\end{aligned}$$

⇒ Potential in Hamiltonian is dominated by Cotton-York (C-Y) term at early times and cosmological constant term at late times (CY-> R-> Λ dominance as the universe expands)

⇒ C-Y dominance at early times

⇒ lowest energy configuration corresponds to 3d conformally flat space with vanishing extrinsic curvature

⇒ compatible with Robertson-Walker initial configuration (satisfies Penrose's Weyl Curvature Hypothesis)

3) Arrow of Time (expansion of our universe) coincides with increasing entropy:

The Hamiltonian depends EXPLICITLY on T, and is NOT T-reversal invariant!

(T ~ ln V , so $T \to -T \Leftrightarrow V \to 1/V$)

But unitarity of evolution $U(T, T_0)$ is preserved as long as Hamiltonian is Hermitian, albeit time-dependent.

our universe started out from "low entropy" RW Big Bang

- $W_T = \frac{g}{4}\int \tilde{\tilde{\epsilon}}^{ijk}(\bar{\bar{\Gamma}}^l_{im}\partial_j\bar{\Gamma}^m_{kl} + \frac{2}{3}\bar{\Gamma}^l_{im}\bar{\Gamma}^m_{jn}\bar{\Gamma}^n_{kl})\,d^3x + b\int\sqrt{q}Rd^3x$
- $\hat{Q}^i_j = e^{W_T}\hat{\bar{\pi}}^i_j e^{-W_T} = \frac{\hbar}{i}\bar{E}^i_{j(mn)}[\frac{\delta}{\delta\bar{q}_{mn}} - \frac{\delta W_T}{\delta\bar{q}_{mn}}] = \frac{\hbar}{i}\bar{E}^i_{j(mn)}\frac{\delta}{\delta\bar{q}_{mn}} + ib\hbar\sqrt{q}\bar{R}^i_j + ig\hbar\tilde{C}^i_j$

$$\bar{H} = \sqrt{\hat{Q}^{\dagger i}_j\hat{Q}^j_i} = \sqrt{\hat{\bar{\pi}}^{\dagger j}_i\hat{\bar{\pi}}^i_j + \hbar^2(g\tilde{C}^i_j + b\sqrt{q}\bar{R}^i_j)(g\tilde{C}^j_i + b\sqrt{q}\bar{R}^j_i) + [\hat{\bar{\pi}}^i_j, ib\hbar\sqrt{q}\bar{R}^j_i]}$$

- $\because [\hat{\bar{\pi}}^i_j, ib\sqrt{q}\hbar\bar{R}^j_i] = -\frac{5}{12}b\hbar^2\delta(0)\sqrt{q}(5R - \frac{9}{\epsilon})$ incorporates the E-H term, means the simple Hamitlonian density, $\sqrt{\hat{Q}^{\dagger i}_j\hat{Q}^j_i}$ already contains Einstein's GR with Λ
- $\bar{R}^i_j$ and the C-Y tensor appear in the higher-curvature/derivative combination $(g\tilde{C}^j_i + a\sqrt{q}\bar{R}^j_i)(g\tilde{C}^i_j + a\sqrt{q}\bar{R}^i_j)$, these 'non-GR' terms are absent in FRW cosm. also in const. curv. slicings of PG soln. of BHs $\Rightarrow$ C-Y preponderance at early times, Einstein's GR dominates at low curv. and long wavelengths in a theory in which '4d sym. is not a fundamental property of the physical world'

Dirac's words


DON'T POKE THE BEAR

DON'T POKE THE BEAR

Problem

- Classical GR is invariant under (active) space-time diffeomorphisms.

Problem

- Classical GR is invariant under (active) space-time diffeomorphisms.
- Problem: how do you find an (anomaly free) representation of these diffeomorphisms in the quantum theory?

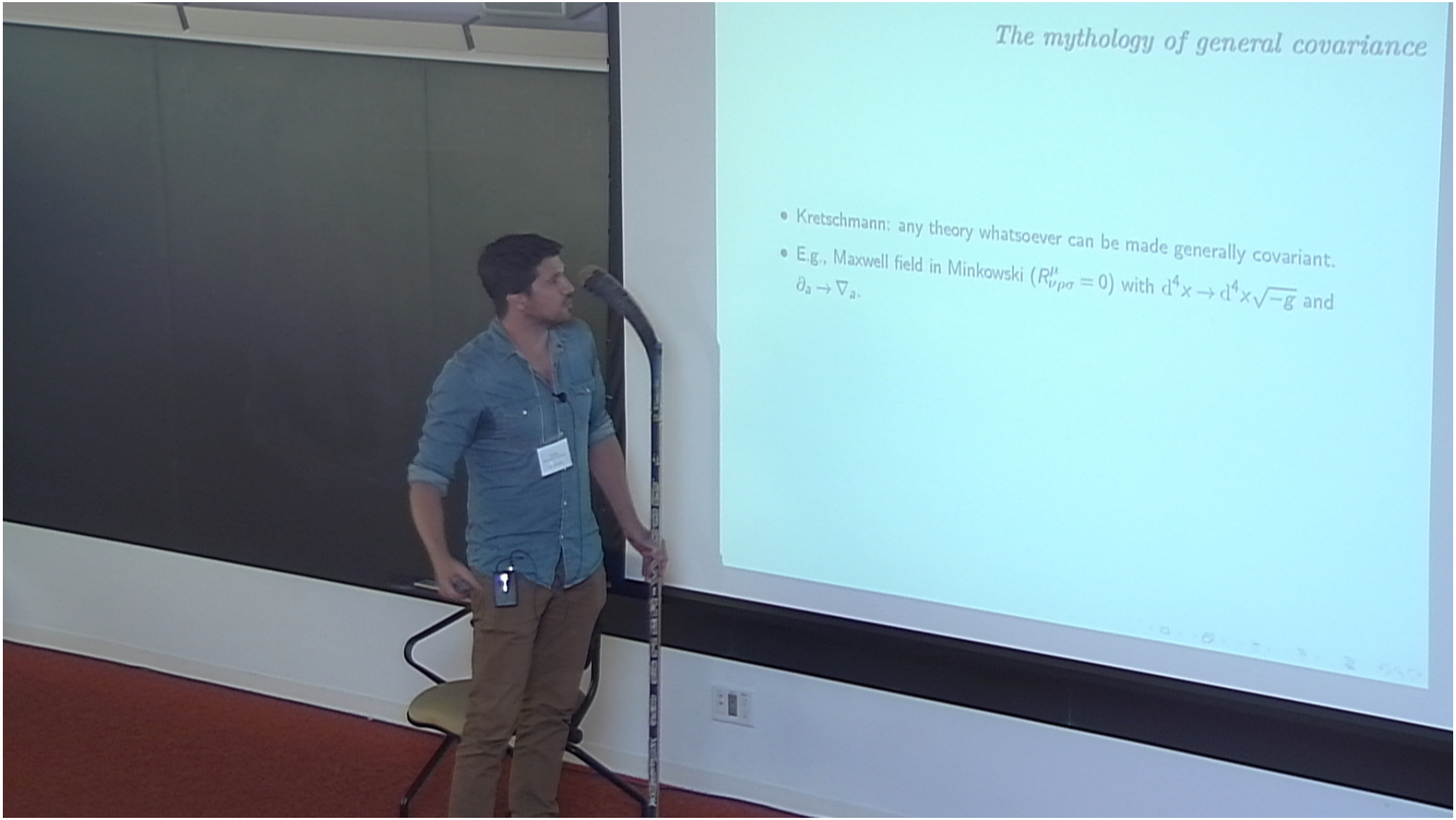
Problem

- Classical GR is invariant under (active) space-time diffeomorphisms.
- Problem: how do you find an (anomaly free) representation of these diffeomorphisms in the quantum theory?

> 50+ years of research has yielded no general consensus towards the resolution of this problem.

The mythology of general covariance

- Kretschmann: any theory whatsoever can be made generally covariant.


The mythology of general covariance
• Kretschmann: any theory whatsoever can be made generally covariant.
• E.g., Maxwell field in Minkowski ($R^{\mu}_{\nu\rho\sigma} = 0$) with $\mathrm{d}^4x \to \mathrm{d}^4x\sqrt{-g}$ and $\partial_a \to \nabla_a$.

The mythology of general covariance

- Kretschmann: any theory whatsoever can be made generally covariant.
- E.g., Maxwell field in Minkowski ($R^{\mu}_{\nu\rho\sigma} = 0$) with $\mathrm{d}^4x \to \mathrm{d}^4x\sqrt{-g}$ and $\partial_a \to \nabla_a$.

The mythology of general covariance

- Kretschmann: any theory whatsoever can be made generally covariant.
- E.g., Maxwell field in Minkowski ($R^{\mu}_{\nu\rho\sigma} = 0$) with $\mathrm{d}^4x \to \mathrm{d}^4x\sqrt{-g}$ and $\partial_a \to \nabla_a$.
- Why?Coordinate assignments are arbitrary labels for real things. They are inferences we make based on arbitrary conventions.

The mythology of general covariance

- Kretschmann: any theory whatsoever can be made generally covariant.
- E.g., Maxwell field in Minkowski ($R^{\mu}_{\nu\rho\sigma} = 0$) with $\mathrm{d}^4x \to \mathrm{d}^4x\sqrt{-g}$ and $\partial_a \to \nabla_a$.
- Why?Coordinate assignments are arbitrary labels for real things. They are inferences we make based on arbitrary conventions.

$\therefore$ the "(Holy) Spirit of General Covariance" is a red herring!

The Principle of Relativity

What was Einstein's "beautiful" insight?

The Principle of Relativity

What was Einstein's "beautiful" insight?

- What we need: to define inertial structure (i.e., what is a force and an acceleration.
- Requirement: no particular choice should be privileged *a priori*.

The Principle of Relativity

What was Einstein's "beautiful" insight?

- What we need: to define inertial structure (i.e., what is a force and an acceleration.
- Requirement: no particular choice should be privileged *a priori*.

How?

- Inertial structure = time-like geodesics.
- Varying over all metrics means varying over all possible inertial structures.
- $\therefore$ no particular choice is preferred.

The Principle of Relativity

What was Einstein's "beautiful" insight?

- What we need: to define inertial structure (i.e., what is a force and an acceleration.
- Requirement: no particular choice should be privileged *a priori*.

How?

- Inertial structure = time-like geodesics.
- Varying over all metrics means varying over all possible inertial structures.
- $\therefore$ no particular choice is preferred.

Preferred Slicing I

Fixing an arbitrary set of labels does not privilege an inertial frame.

Preferred Slicing II

Quantization of any gauge theory requires some form of gauge fixing and some gauge fixings are better than others!

Preferred Slicing II

Quantization of any gauge theory requires some form of gauge fixing and some gauge fixings are better than others!

$\Rightarrow$ What do you really lose when you quantize in a particular set of coordinates?

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms.

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)

Worries

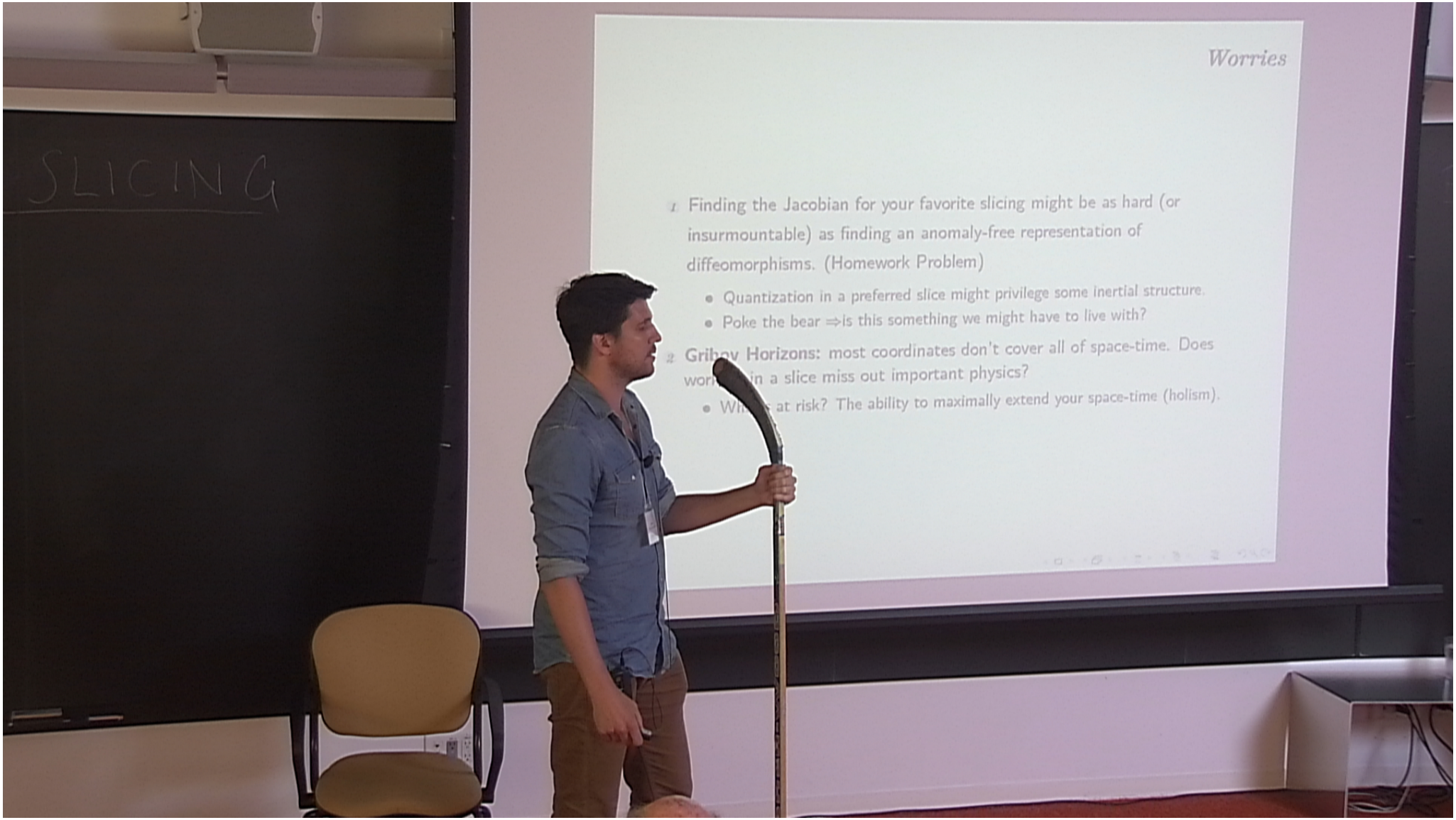
1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
   - Quantization in a preferred slice might privilege some inertial structure.
   - Poke the bear $\Rightarrow$

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
   - Quantization in a preferred slice might privilege some inertial structure.
   - Poke the bear $\Rightarrow$is this something we might have to live with?

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
   - Quantization in a preferred slice might privilege some inertial structure.
   - Poke the bear $\Rightarrow$is this something we might have to live with?
2. **Gribov Horizons:** most coordinates don't cover all of space-time. Does working in a slice miss out important physics?
   - What's at risk? The ability to maximally extend your space-time (holism).


SLICING
Worries
1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
• Quantization in a preferred slice might privilege some inertial structure.
• Poke the bear ⇒is this something we might have to live with?
2. Gribov Horizons: most coordinates don't cover all of space-time. Does work in a slice miss out important physics?
• What's at risk? The ability to maximally extend your space-time (holism).

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
   - Quantization in a preferred slice might privilege some inertial structure.
   - Poke the bear $\Rightarrow$is this something we might have to live with?
2. **Gribov Horizons:** most coordinates don't cover all of space-time. Does working in a slice miss out important physics?
   - What's at risk? The ability to maximally extend your space-time (holism).

Worries

1. Finding the Jacobian for your favorite slicing might be as hard (or insurmountable) as finding an anomaly-free representation of diffeomorphisms. (Homework Problem)
   - Quantization in a preferred slice might privilege some inertial structure.
   - Poke the bear ⇒is this something we might have to live with?
2. **Gribov Horizons:** most coordinates don't cover all of space-time. Does working in a slice miss out important physics?
   - What's at risk? The ability to maximally extend your space-time (holism).

⇒ this problem is not unique to gravity!! (Unavoidable in Yang–Mills.)

Response I: Shape Dynamics

- One option is to change your fundamental ontology $\Rightarrow$ replace maximal extension of space-time with maximal extension of your new ontology (e.g., new phase space).

Response I: Shape Dynamics

- One option is to change your fundamental ontology $\Rightarrow$ replace maximal extension of space-time with maximal extension of your new ontology (e.g., new phase space).

Response I: Shape Dynamics

- One option is to change your fundamental ontology $\Rightarrow$ replace maximal extension of space-time with maximal extension of your new ontology (e.g., new phase space).
- Use new symmetry principle to fix coordinates. (I.e., trade symmetries.)
- Shape Dynamics: there exists a choice of simultaneity under which the degrees of freedom are invariant under spatial conformal transformations.

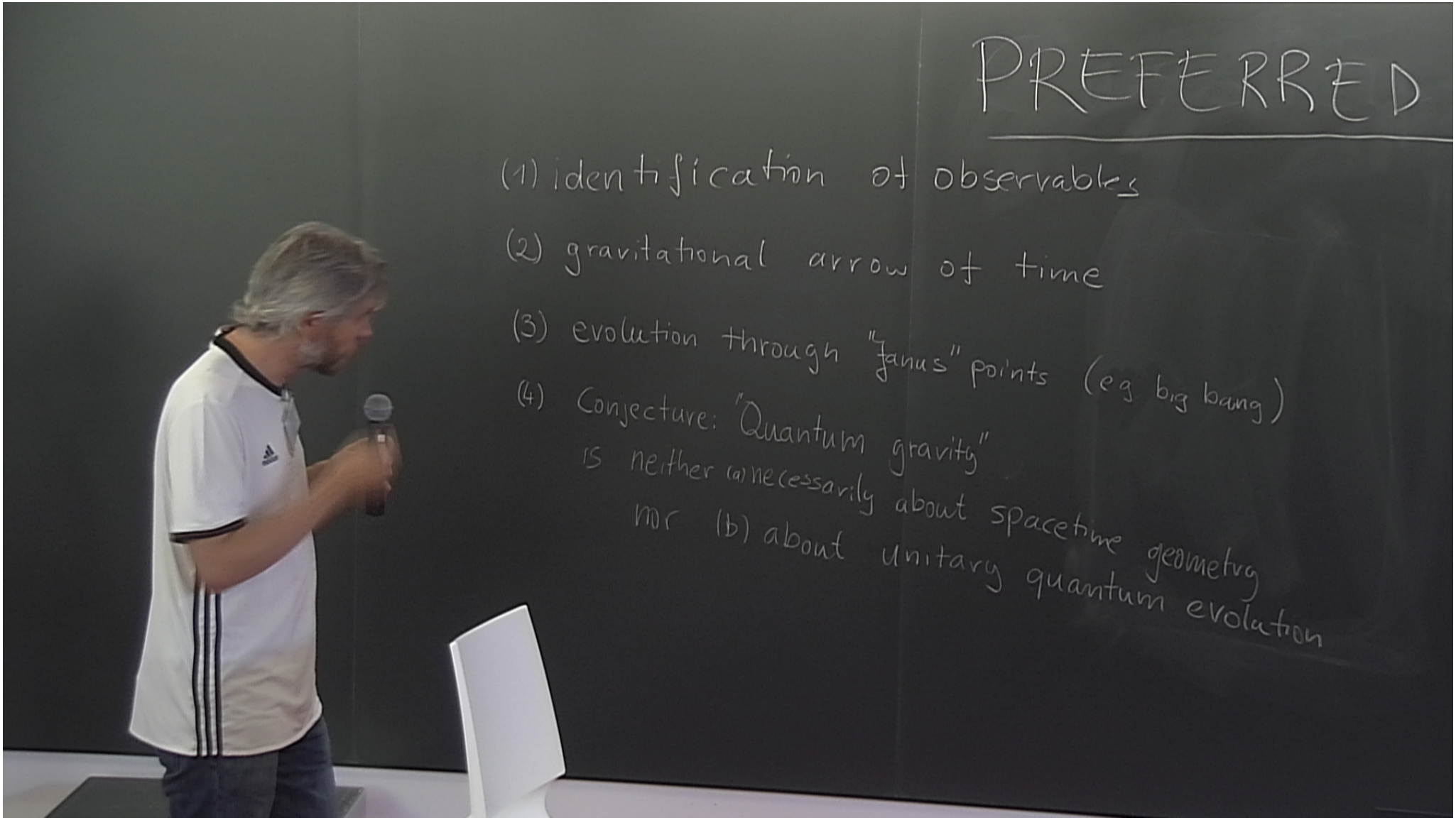
Response I: Shape Dynamics

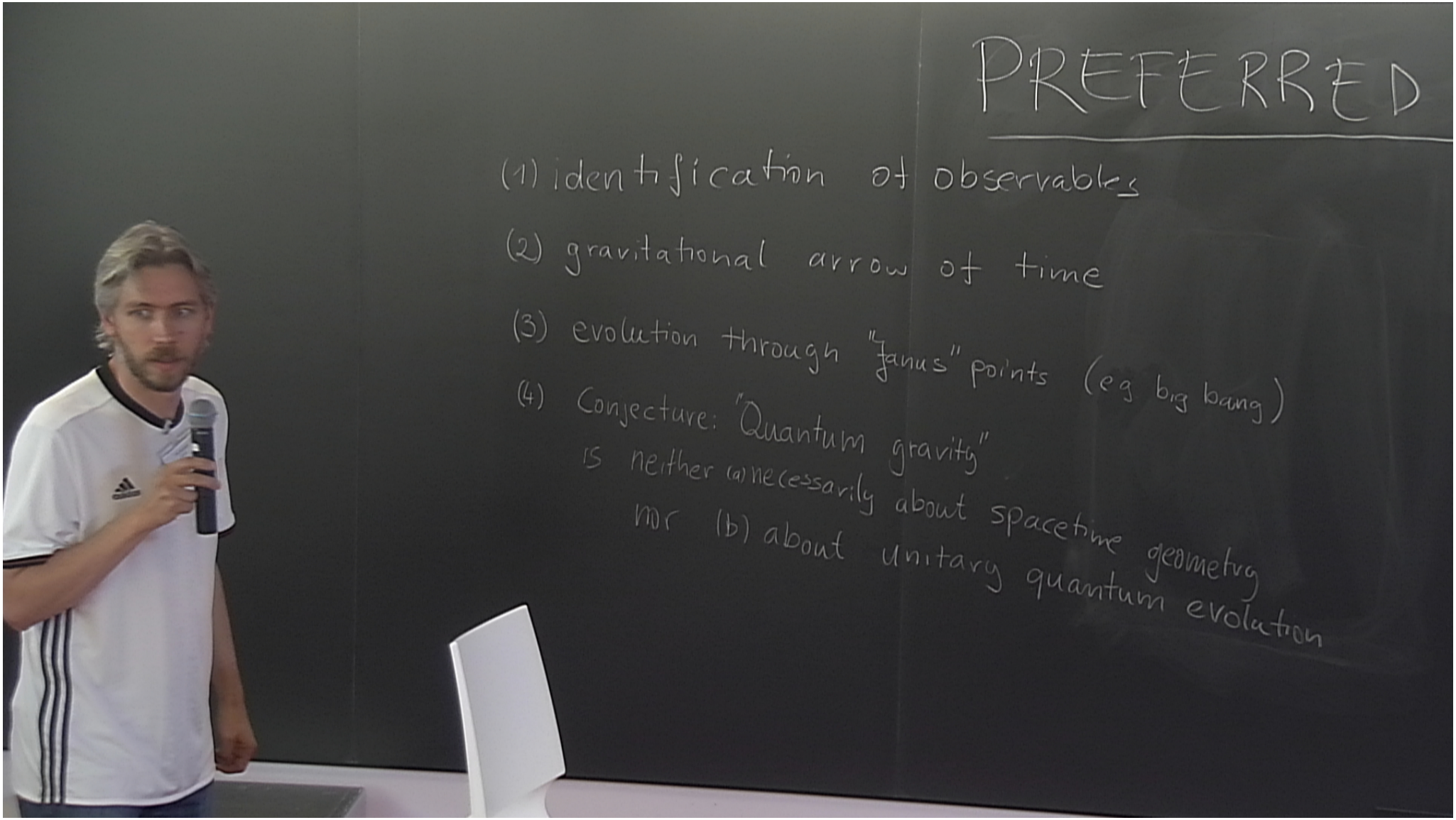
- One option is to change your fundamental ontology $\Rightarrow$ replace maximal extension of space-time with maximal extension of your new ontology (e.g., new phase space).
- Use new symmetry principle to fix coordinates. (I.e., trade symmetries.)
- Shape Dynamics: there exists a choice of simultaneity under which the degrees of freedom are invariant under spatial conformal transformations.
- Use this notion of simultaneity to define your new ontology (i.e., evolving conformal spatial geometry) and new notion of holism.
- Quantize in this slicing.

Response II: Epistemic Wave-function

If you think about quantum probabilities as a result of a local observer's limited epistemic access to the true state of the universe, and the evolution of the wave-function as an updating of knowledge about this state, then you don't need a holistic picture of the world. [arXiv:1606.07265]

Thank You!


PREFERRED
(1) identification of observables
(2) gravitational arrow of time
(3) evolution through "Janus" points (eg big bang)
(4) Conjecture: "Quantum gravity"
is neither (a) necessarily about spacetime geometry
nor (b) about unitary quantum evolution


PREFERRED
(1) identification of observables
(2) gravitational arrow of time
(3) evolution through "Janus" points (eg big bang)
(4) Conjecture: "Quantum gravity"
is neither (a) necessarily about spacetime geometry
nor (b) about unitary quantum evolution