

Title: Experimental Metaphysics

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Abstract:

Experimental Metaphysics



Rob Spekkens
PI day, 2014

Foundations of Quantum Theory

The background of the slide is a photograph of a classical building's interior, featuring several large, fluted columns supporting a high, vaulted ceiling. The lighting is dramatic, with strong shadows and highlights, suggesting an ancient or historical setting.

Provide an adequate interpretation

Explore nonclassical phenomena

Determine principles from which the quantum formalism may be derived

From thought experiments to real experiments

1935: Einstein-Podolsky-Rosen paper

1964: first Bell inequality, not robust to experimental error

1969: Clauser-Horne-Shimony-Holt paper, first Bell inequality robust to experimental error

1989: The polytope of local correlations (I. Pitowsky and others)

Theoretical developments

Experimental developments

1982: Aspect experiment testing the CHSH inequality

1998: Weihs *et al.* conduct expt that seals the locality loophole, but not the detector loophole

2001: Rowe *et al.* conduct expt that seals the detector loophole, but not the locality loophole

Near future: First loophole-free Bell experiment

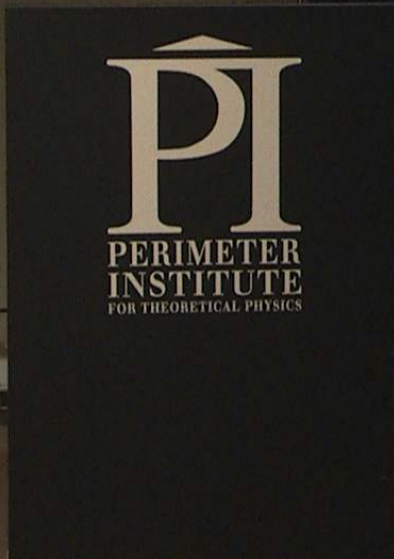
Why should we be interested in no-go theorems?

Foundational significance: Such no-go theorems constitute the **most precise and least subjective** statements about how quantum theory differs from its classical counterparts

Practical significance: If assumptions of a no-go theorem are classical principles, then it may imply impossibility of a classical simulation of certain quantum predictions.

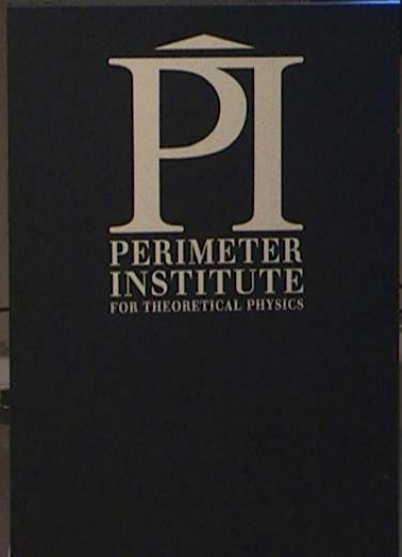
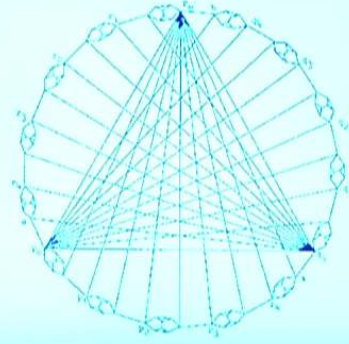
Nonclassicality is a resource

The Kochen-Specker theorem



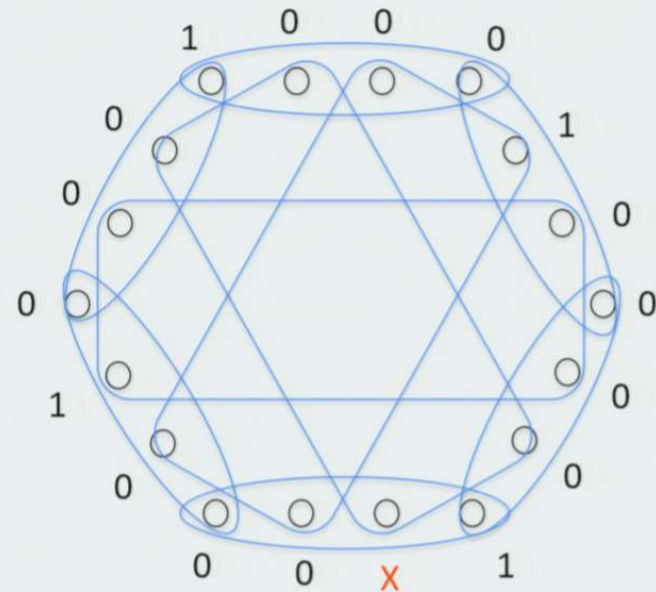
117 ray proof in 3d

Kochen and Specker, J. Math. Mech. 17, 59 (1967)



18 ray proof in 4d

Cabello, Estebaranz, Garcia-Alcaine, Phys. Lett. A 212, 183 (1996)



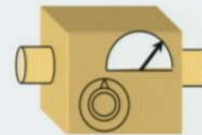
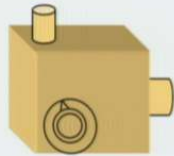
Can the Kochen-Specker theorem be tested experimentally?

“The whole notion of an experimental test of Kochen-Specker misses the point”

– N. David Mermin, 1998

But can't we identify the particular facts about nature that prohibit a noncontextual model?

Operational theories



Preparation

Measurement

P

M

These are defined as lists of **instructions**

Operational Quantum Mechanics



Preparation
 P

Measurement
 M

Density operator
 ρ

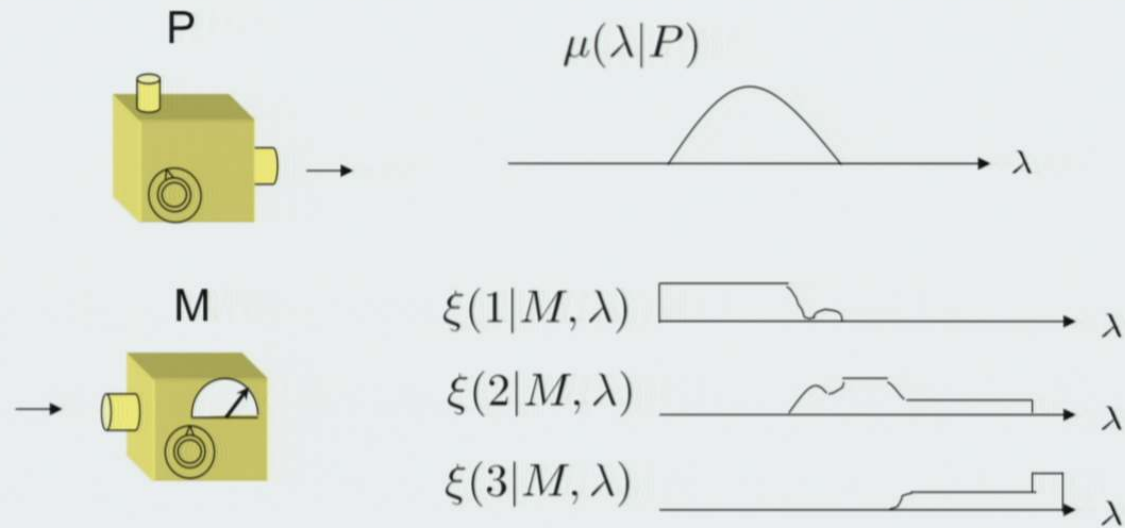
Positive operator-valued
measure (POVM)
 $\{E_k\}$

$$p(k|P, M) = \text{Tr}[E_k \rho]$$

Quantum theory

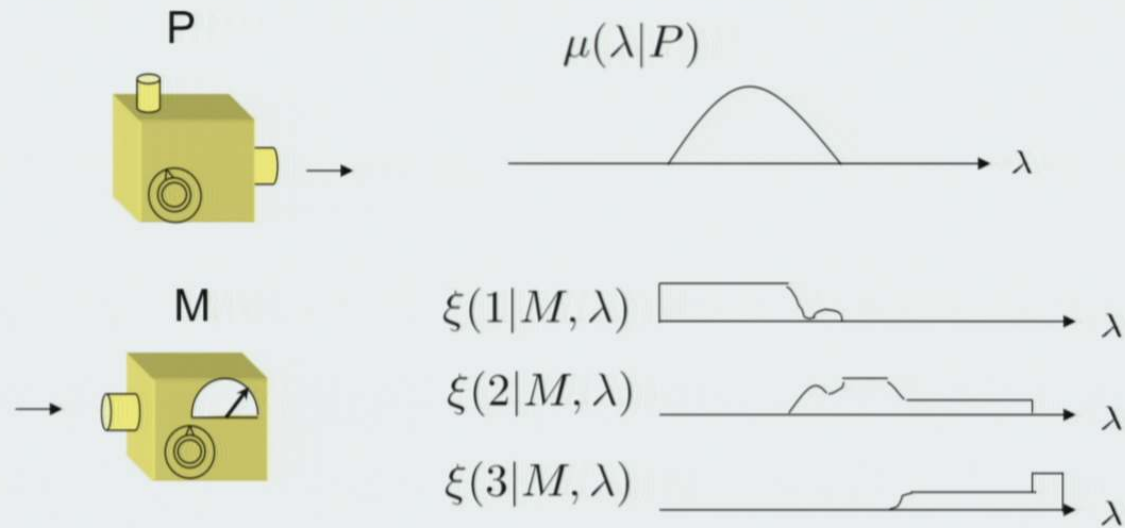


An ontological model of an operational theory



$$p(k|M, P) = \int d\lambda \xi(k|M, \lambda) \mu(\lambda|P)$$

An ontological model of an operational theory



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Prescription for Experimental Metaphysics

Make

assumptions about the ontological model

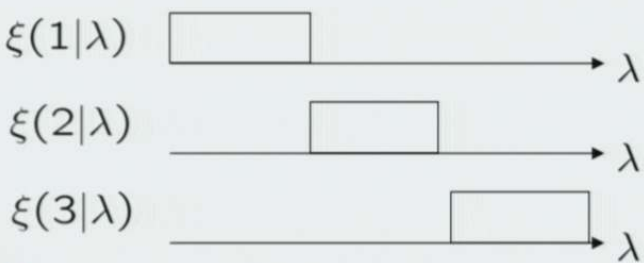
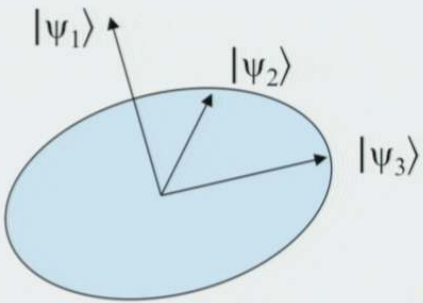
that have consequences for the operational statistics

Then

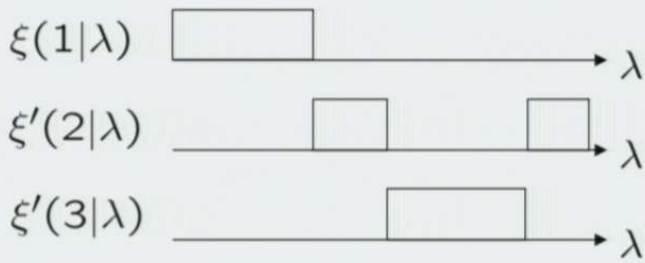
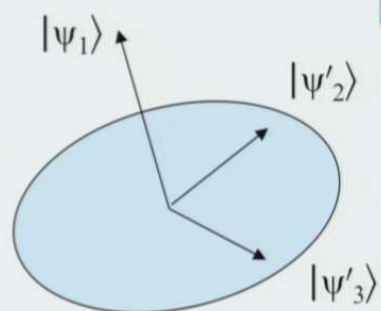
Experimentally probe aspects of the operational statistics

Find a contradiction

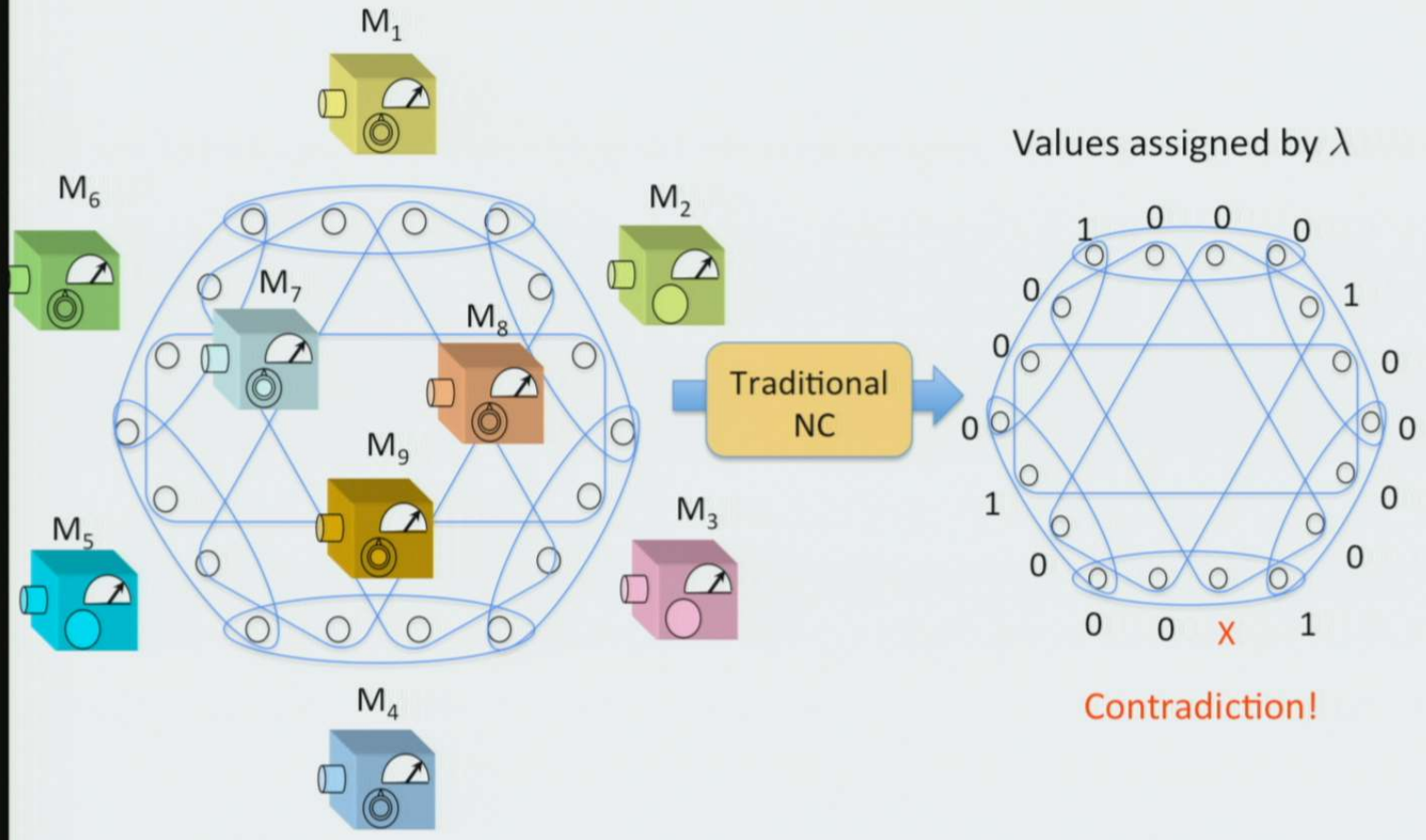
Traditional noncontextual model of quantum theory



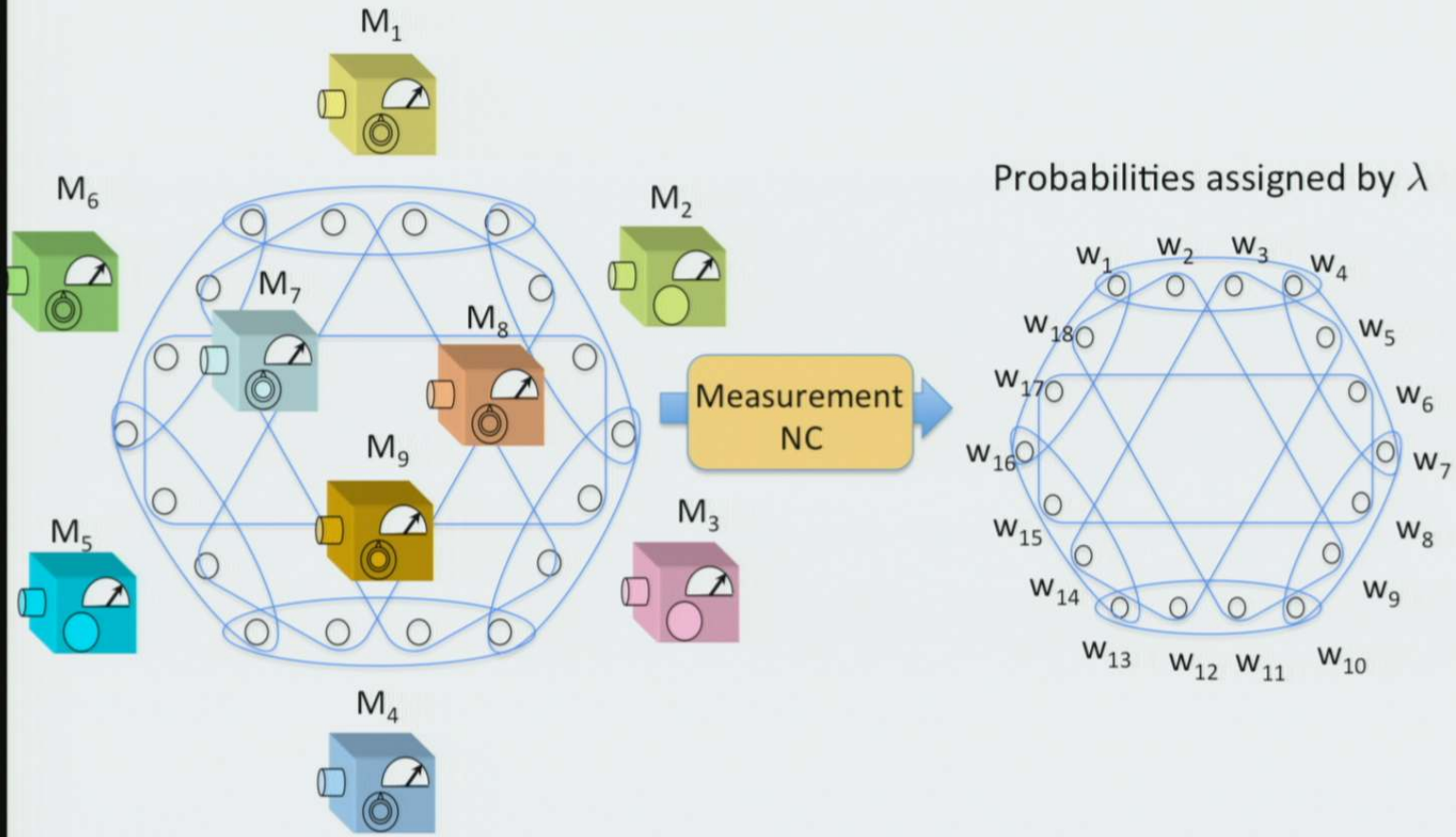
Traditional NC



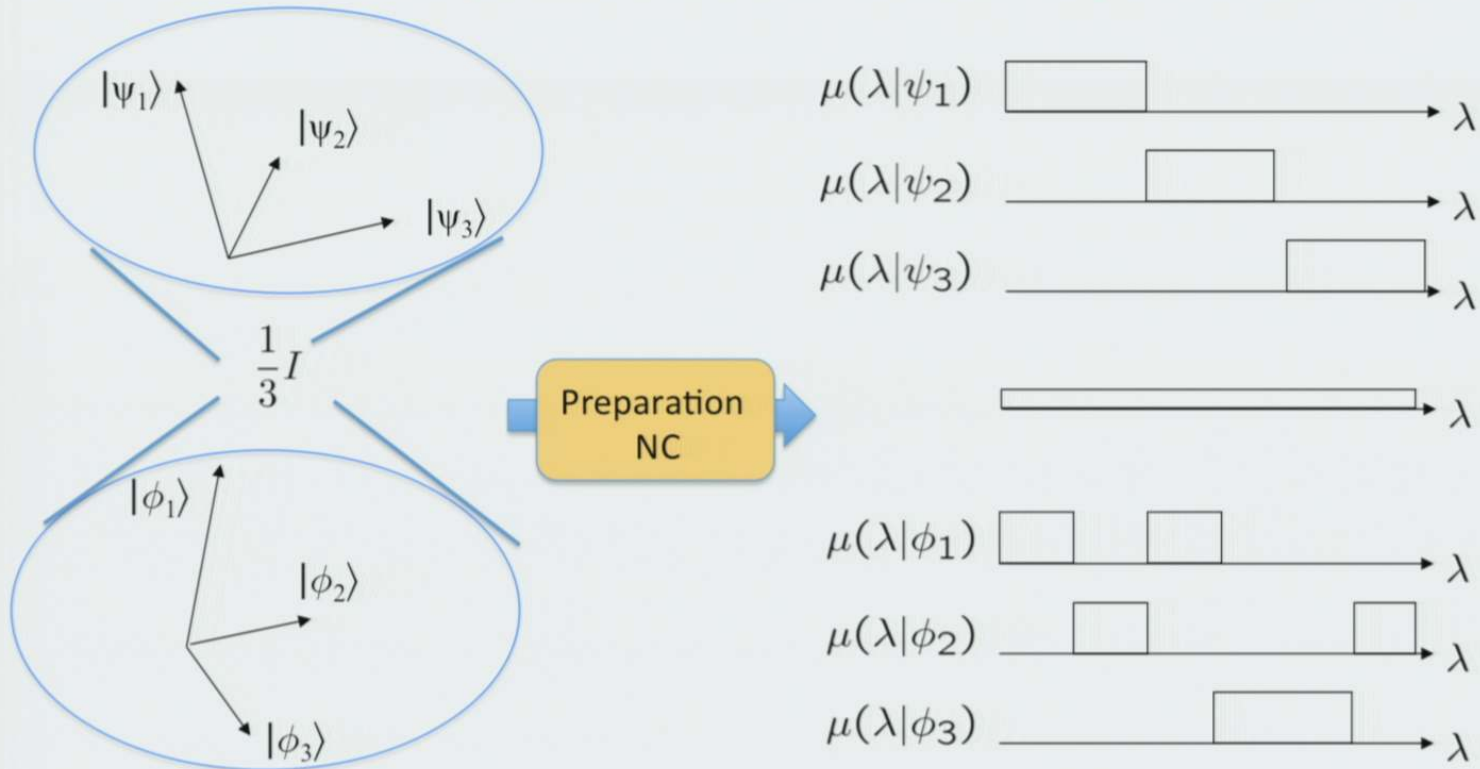
$\forall P : p(X = 4|M_1, P) = p(X = 1|M_2, P)$
 $\forall P : p(X = 4|M_2, P) = p(X = 1|M_3, P)$
 ...



$\forall P : p(4|M_1, P) = p(1|M_2, P)$
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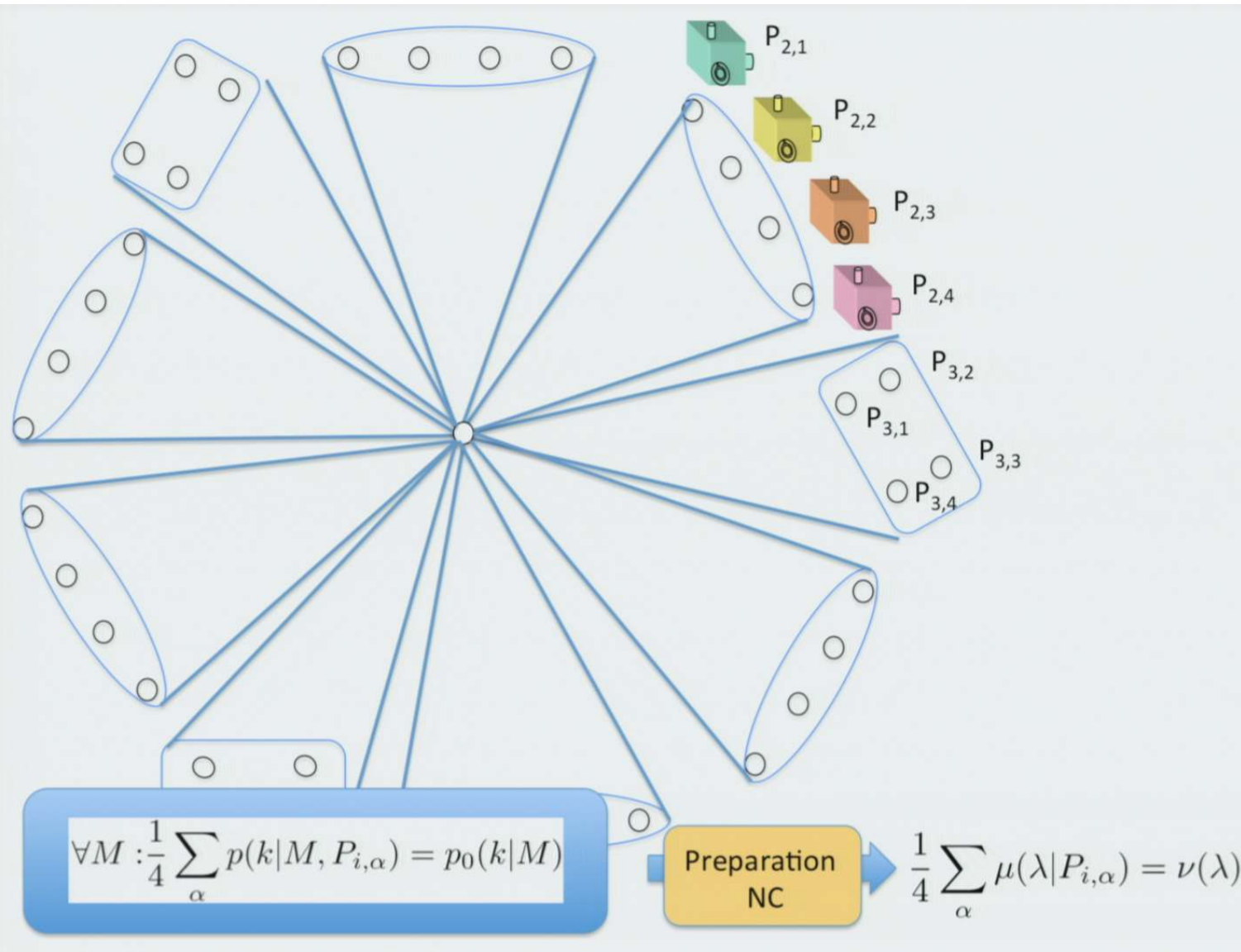


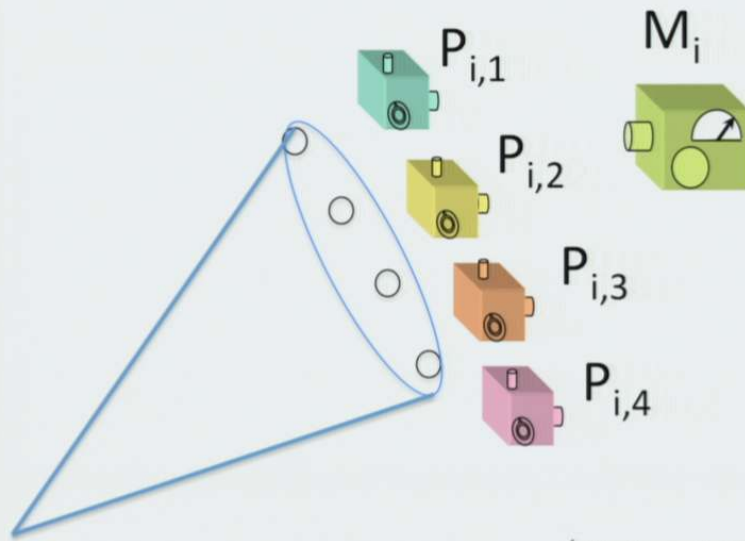
Preparation Noncontextuality



$$\begin{aligned} & \frac{1}{3}|\psi_1\rangle\langle\psi_1| + \frac{1}{3}|\psi_2\rangle\langle\psi_2| + \frac{1}{3}|\psi_3\rangle\langle\psi_3| \\ &= \frac{1}{3}|\phi_1\rangle\langle\phi_1| + \frac{1}{3}|\phi_2\rangle\langle\phi_2| + \frac{1}{3}|\phi_3\rangle\langle\phi_3| \end{aligned}$$

$$\begin{aligned} & \frac{1}{3}\mu(\lambda|\psi_1) + \frac{1}{3}\mu(\lambda|\psi_2) + \frac{1}{3}\mu(\lambda|\psi_3) \\ &= \frac{1}{3}\mu(\lambda|\phi_1) + \frac{1}{3}\mu(\lambda|\phi_2) + \frac{1}{3}\mu(\lambda|\phi_3) \end{aligned}$$





Measure predictability for M_i and $P_{i,\alpha}$

$$\eta(M_i, P_{i,\alpha}) \equiv \max_X p(X | M_i, P_{i,\alpha})$$

Calculate the average predictability

$$R \equiv \frac{1}{9} \sum_i \frac{1}{4} \sum_{\alpha} \eta(M_i, P_{i,\alpha})$$

But: $\eta(M, P) \leq \int d\lambda \eta(M, \lambda) \mu(\lambda|P)$

$$R \equiv \frac{1}{9} \sum_i \frac{1}{4} \sum_{\alpha} \eta(M_i, P_{i,\alpha})$$

$$R \leq \int d\lambda \left(\frac{1}{9} \sum_i \eta(M_i, \lambda) \left[\frac{1}{4} \sum_{\alpha} \mu(\lambda|P_{i,\alpha}) \right] \right)$$

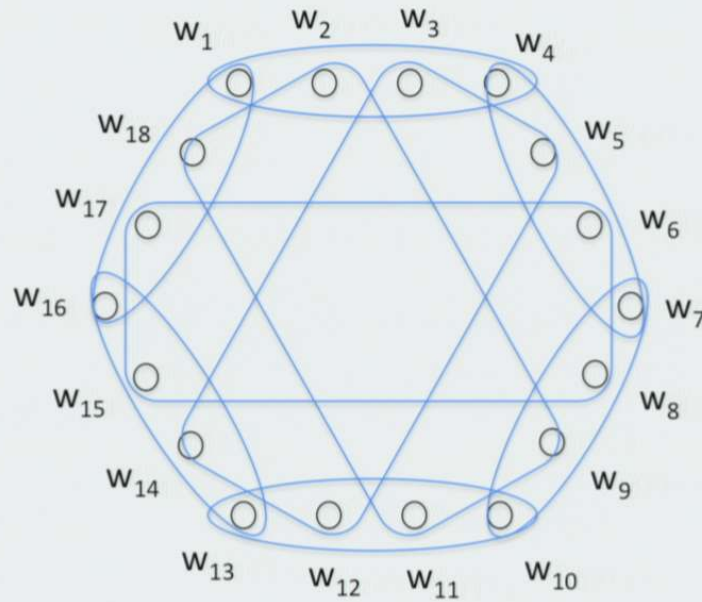
$$\forall M : \frac{1}{4} \sum_{\alpha} p(k|M, P_{i,\alpha}) = p_0(k|M)$$

Preparation
NC

$$R \leq \int d\lambda \left[\frac{1}{9} \sum_i \eta(M_i, \lambda) \right] \nu(\lambda)$$

$$R \leq \max_{\lambda} \left[\frac{1}{9} \sum_i \eta(M_i, \lambda) \right]$$

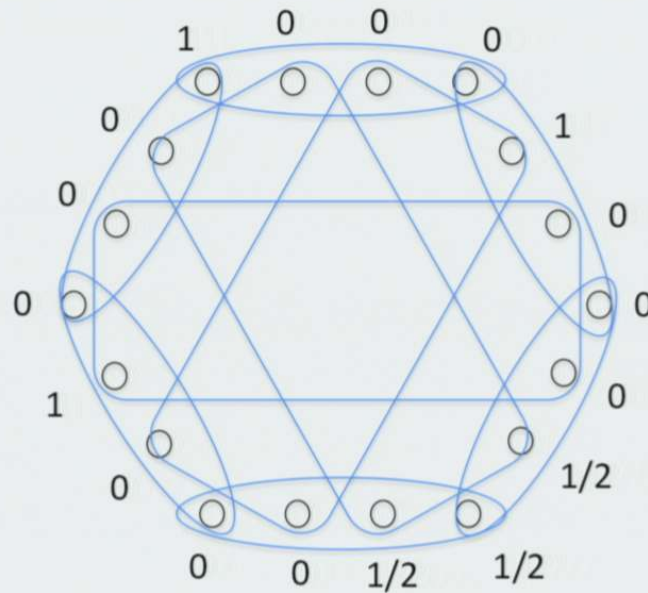
$$R \leq \max_{\lambda} \left[\frac{1}{9} \sum_i \eta(M_i, \lambda) \right]$$



The solutions form a 9-dimensional polytope with 146 vertices

(For more on these polytopes, talk to Tobias Fritz)

$$R \leq \max_{\lambda} \left[\frac{1}{9} \sum_i \eta(M_i, \lambda) \right]$$

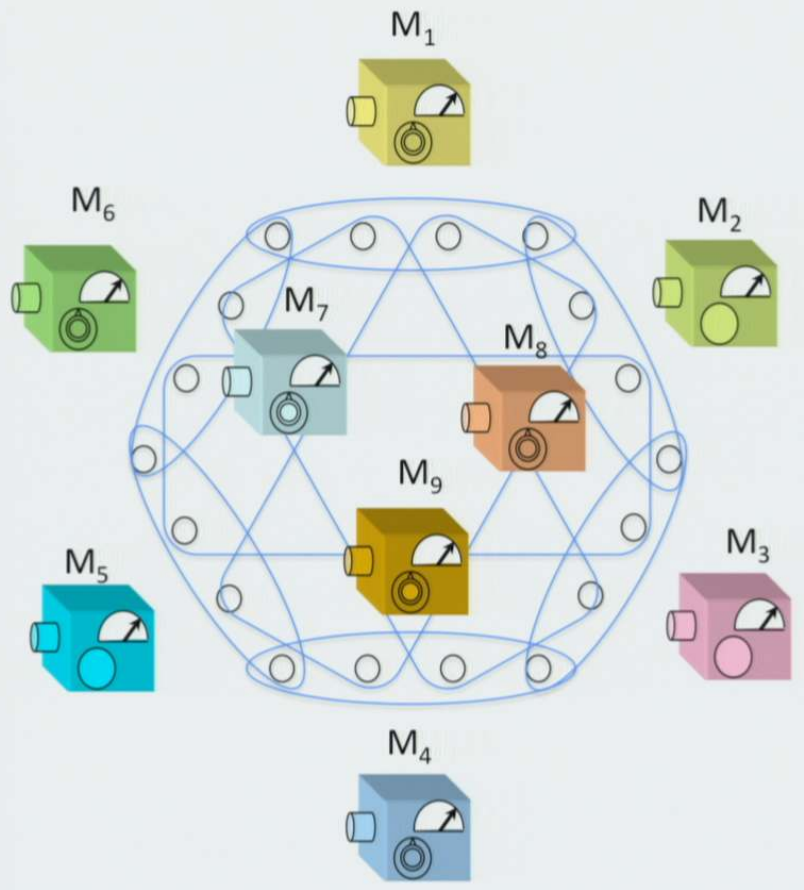


$$\begin{aligned} & \max_{\lambda} \left[\frac{1}{9} \sum_i \eta(M_i, \lambda) \right] \\ &= \frac{1}{9} \left(6 \cdot 1 + 3 \cdot \frac{1}{2} \right) \\ &= \frac{5}{6} \end{aligned}$$

$$R \leq \frac{5}{6}$$

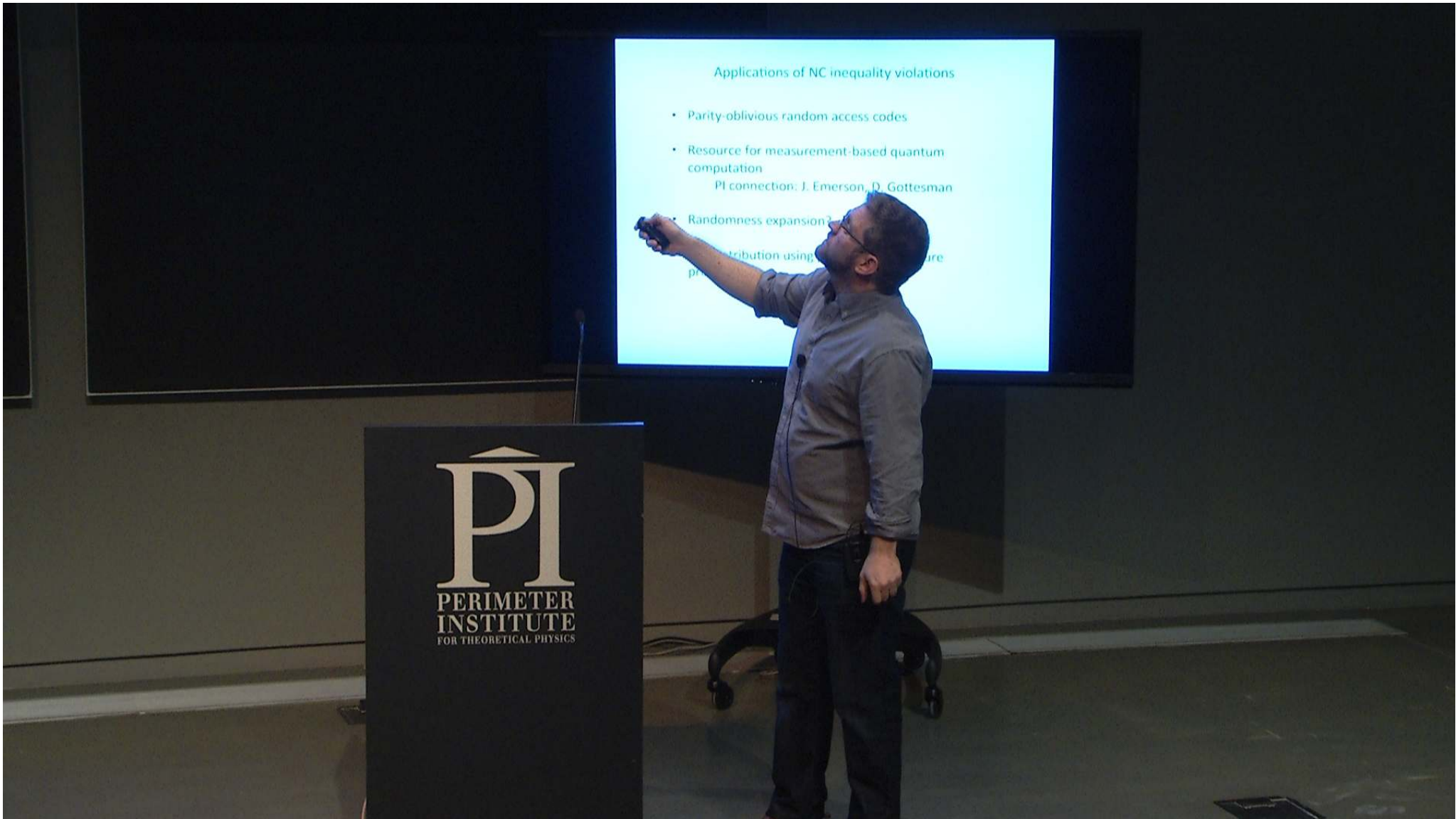
A Noncontextuality
Inequality

$\forall P : p(4|M_1, P) = p(1|M_2, P)$
 $\forall P : p(4|M_2, P) = p(1|M_3, P)$
...



Applications of NC inequality violations

- Parity-oblivious random access codes
- Resource for measurement-based quantum computation
PI connection: J. Emerson, D. Gottesman
- Randomness expansion?
- Key distribution using prepare and measure protocol?



Applications of NC inequality violations

- Parity-oblivious random access codes
- Resource for measurement-based quantum computation
PI connection: J. Emerson, D. Gottesman
- Randomness expansion?
distribution using ...

Quantum theory

Operational theories
that **satisfy all**
noncontextuality
inequalities

Operational theories
that **violate some**
noncontextuality
inequality

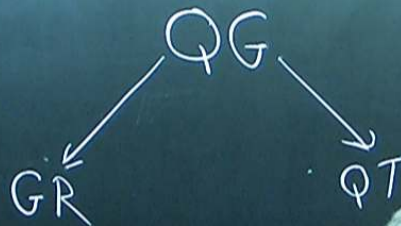


The challenge of indefinite causal structure.



cancel
rad

The challenge of indefinite causal structure.



conservative

deterministic

for general

radical.

dynamical

prob.

of indefinite causal structure.



intrinsic
al.c.s.
fixed background
c.s.
inherently prob.
indefiniteness.

need a framework
for general probability



re causal structure.

T

ed background
C.S.

erthly probs.
finiteness.

need a framework
for general probabilistic
theories that can accommodate
indefinite C.S.

formalism locality

re causal structure.

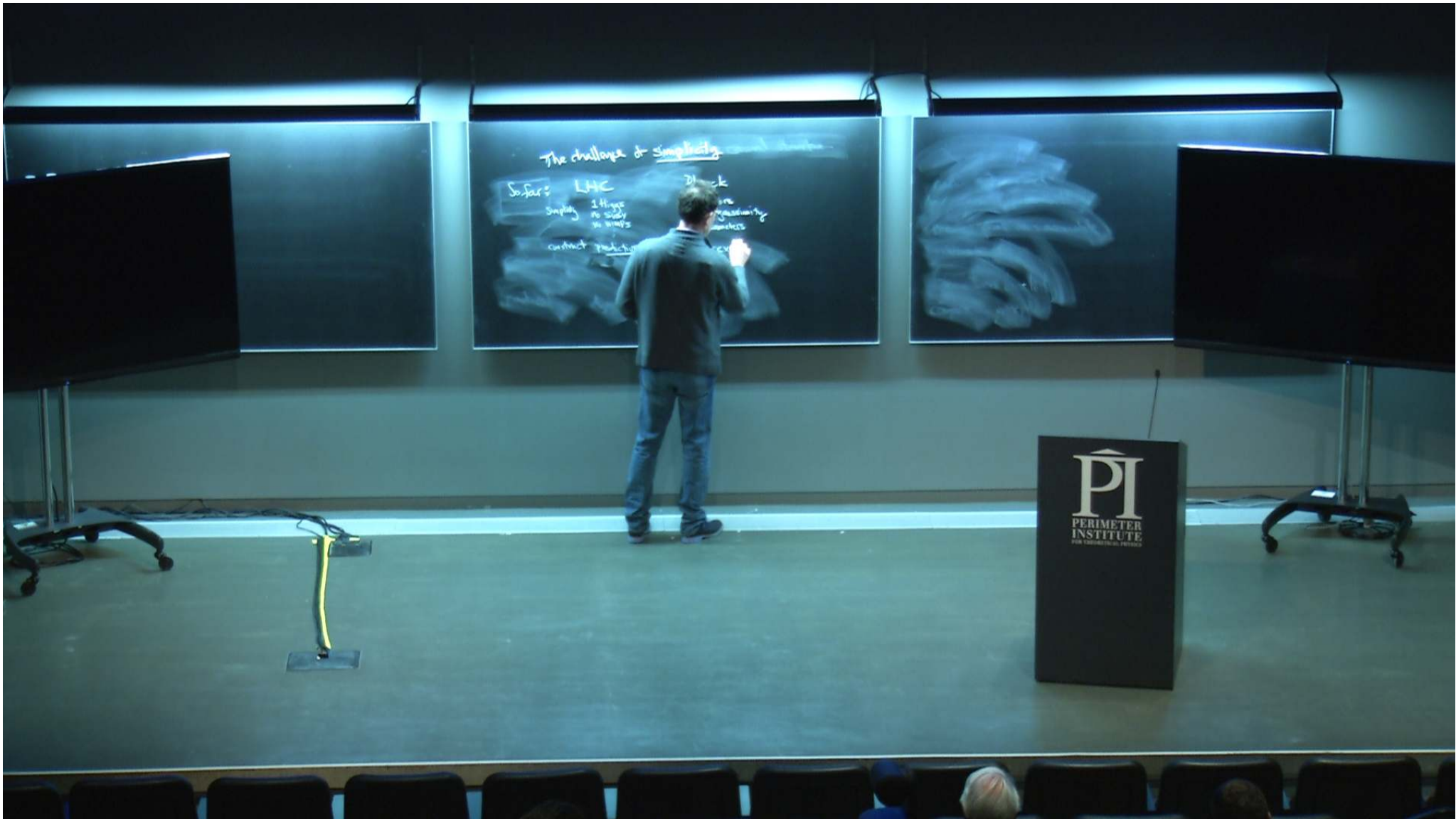
T

ed background
C.S.

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formation locality,
composition principle.



The challenge of simplicity ~~causal structure~~

So far:

LHC

Planck

Simplicity

1 Higgs
no SUSY
no WIMPs
⋮

no tensors
no non-gaussianity
2 parameters

construct predictive theories that explain simplicity

The challenge of simplicity

So far:

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clues





