



ψ -epistemic theories: The role of symmetry

Scott Aaronson,^{1,*} Adam Bouland,^{1,†} Lynn Chua,^{1,‡} and George Lowther^{2,§}

¹*Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139-4307, USA*

²*6 St Peter's Street, London, N1 8JG, United Kingdom*

(Received 22 July 2013; published 18 September 2013)

Formalizing an old desire of Einstein, “ ψ -epistemic theories” try to reproduce the predictions of quantum mechanics, while viewing quantum states as ordinary probability distributions over underlying objects called “ontic states.” Regardless of one’s philosophical views about such theories, the question arises of whether one can cleanly rule them out by proving no-go theorems analogous to the Bell inequality. In the 1960s, Kochen and Specker (who first studied these theories) constructed an elegant ψ -epistemic theory for Hilbert space dimension $d = 2$, but also showed that any deterministic ψ -epistemic theory must be “measurement contextual” in dimensions 3 and higher. Last year, the topic attracted renewed attention, when Pusey, Barrett, and Rudolph (PBR) showed that any ψ -epistemic theory must “behave badly under tensor product.” In this paper, we prove that even without the Kochen-Specker or PBR assumptions, there are no ψ -epistemic theories in dimensions $d \geq 3$ that satisfy two reasonable conditions: (1) symmetry under unitary transformations and (2) “maximum nontriviality” (meaning that the probability distributions corresponding to any two nonorthogonal states overlap). This no-go theorem holds if the ontic space is either the set of quantum states or the set of unitaries. The proof of this result, in the general case, uses some measure theory and differential geometry. On the other hand, we also show the surprising result that *without* the symmetry restriction, one can construct maximally nontrivial ψ -epistemic theories in every finite dimension d .

DOI: [10.1103/PhysRevA.88.032111](https://doi.org/10.1103/PhysRevA.88.032111)

PACS number(s): 03.65.Ta, 03.67.—a

I. INTRODUCTION

Debate has raged for almost a century about the interpretation of the quantum state. Although a quantum state evolves in a unitary and deterministic manner according to the Schrödinger equation, measurement is a probabilistic process in which the state is postulated to collapse to a single eigenstate. This is often viewed as an unnatural and poorly understood process.

ψ -epistemic theories have been proposed as alternatives to standard quantum mechanics. In these theories, a quantum state merely represents probabilistic information about a “real, underlying” physical state (called the *ontic state*). Perhaps not surprisingly, several no-go theorems have been proven that strongly constrain the ability of ψ -epistemic theories to reproduce the predictions of standard quantum mechanics. Most famously, the Bell inequality [1]—while not usually seen as a result about ψ -epistemic theories—showed that no such theory can account for the results of all possible measurements on an entangled state in a “factorizable” way (i.e., so that the ontic state has a separate component for each qubit and measurements of a given qubit only reveal information about that qubit’s component of the ontic state). Also, the Kochen-Specker theorem [2] showed that in Hilbert space dimensions $d \geq 3$, no ψ -epistemic theory can be both deterministic and “noncontextual” (meaning that whether an eigenstate ψ gets returned as a measurement outcome is independent of which *other* states are also in the measurement basis). More recently, the Pusey-Barrett-Rudolph (PBR) theorem [3] showed that

nontrivial ψ -epistemic theories are inconsistent, if the ontic distribution for a product state $|\psi\rangle \otimes |\phi\rangle$ is simply the tensor product of the ontic distribution for $|\psi\rangle$ with the ontic distribution for $|\phi\rangle$. Even more recently, papers by Maroney [4] and Leifer and Maroney [5] prove the impossibility of a “maximally ψ -epistemic theory,” in which the overlap of the ontic distributions for all nonorthogonal states fully accounts for the uncertainty in distinguishing them via measurements.

In this paper, we study what happens if one drops the Bell, Kochen-Specker, and PBR assumptions and merely asks for a ψ -epistemic theory in which the ontic distributions overlap for all nonorthogonal states. A ψ -epistemic theory is a particular type of ontological theory of quantum mechanics. Formally, an ontological theory in d dimensions specifies the following:

(1) a measurable space Λ , called the *ontic space* (the elements $\lambda \in \Lambda$ are then the ontic states);

(2) a function mapping each quantum state $|\psi\rangle \in H_d$ to a probability measure μ_ψ over Λ , where H_d is the Hilbert space in d dimensions;

(3) for each orthonormal measurement basis $M = \{\phi_1, \dots, \phi_d\}$, a set of d *response functions* $\{\xi_{k,M}(\lambda) \in [0, 1]\}$, which give the probability that an ontic state λ would produce a measurement outcome ϕ_k .

The response functions must satisfy the following two conditions:

$$\int_{\Lambda} \xi_{k,M}(\lambda) \mu_\psi(\lambda) d\lambda = |\langle \phi_k | \psi \rangle|^2, \quad (1)$$

$$\sum_{i=1}^d \xi_{i,M}(\lambda) = 1 \quad \forall \lambda, M. \quad (2)$$

Here Eq. (1) says that the ontological theory perfectly reproduces the predictions of quantum mechanics (i.e., the Born rule). Meanwhile, Eq. (2) says that the probabilities of the possible measurement outcomes must always sum to 1,

*aaronson@csail.mit.edu

†adam@csail.mit.edu

‡chualynn@mit.edu

§george.lowther@blueyonder.co.uk

even when ontic states are considered individually (rather than as elements of probability distributions). Note that Eqs. (1) and (2) are logically independent of each other.¹

The conditions above can easily be satisfied by setting $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$, the complex projective space consisting of unit vectors in H_d up to an arbitrary phase, and $\mu_\psi(\lambda) = \delta(\lambda - \psi)$, where δ is the Dirac delta function and $\xi_{k,M}(\lambda) = |\langle \phi_k | \lambda \rangle|^2$. However, that simply gives an uninteresting restatement of quantum mechanics, since the μ_ψ 's for different ψ 's have disjoint supports. An ontological theory in which the μ_ψ 's have disjoint supports is known as a ψ -ontic theory [6]. Let $\text{Supp}(\mu_\psi) \subseteq \Lambda$ be the support of μ_ψ . Then we call an ontological theory ψ -epistemic if there exist $\psi \neq \phi$ such that μ_ψ and μ_ϕ have total variation distance less than 1 [6], i.e.,

$$\frac{1}{2} \int_{\Lambda} |\mu_\psi(\lambda) - \mu_\phi(\lambda)| d\lambda < 1. \quad (3)$$

If μ_ψ and μ_ϕ have total variation distance less than 1, then we say that $|\psi\rangle$ and $|\phi\rangle$ have “nontrivial overlap.” Otherwise, we say they have “trivial overlap.” Note that it is possible for $|\psi\rangle$ and $|\phi\rangle$ to have trivial overlap even if μ_ψ and μ_ϕ have intersecting supports [this can happen if $\text{Supp}(\mu_\psi) \cap \text{Supp}(\mu_\phi)$ has measure 0].

Note also that if $|\psi\rangle$ and $|\phi\rangle$ are orthogonal, if we set $|\phi_1\rangle = |\psi\rangle$ and $|\phi_2\rangle = |\phi\rangle$, the conditions $|\langle \phi_1 | \psi \rangle| = |\langle \phi_2 | \phi \rangle| = 1$ and $|\langle \phi_2 | \psi \rangle| = |\langle \phi_1 | \phi \rangle| = 0$ imply that μ_ψ and μ_ϕ have trivial overlap. Hence, we call a theory *maximally nontrivial* if the overlap is *only* trivial for orthogonal states: that is, if all nonorthogonal states $|\psi\rangle, |\phi\rangle$ have nontrivial overlap.

In a maximally nontrivial theory, some of the uncertainty of quantum measurement is explained by the overlap between the distributions corresponding to nonorthogonal states. Recently, Maroney [4] and Leifer and Maroney [5] showed that it is impossible to have a “maximally ψ -epistemic theory” in which *all* of the uncertainty is explained by the overlap of distributions. Specifically, they require that, for all quantum states $|\psi\rangle, |\phi\rangle$,

$$\int_{\text{Supp}(\mu_\phi)} \mu_\psi(\lambda) d\lambda = |\langle \phi | \psi \rangle|^2. \quad (4)$$

Here we are asking for a much weaker condition, in which only *some* of the uncertainty in measurement statistics is explained by the overlap of distributions, and we do not impose any conditions on the amount of overlap.

Another property that we might like a ψ -epistemic theory to satisfy is *symmetry*. Namely, we call a ψ -epistemic theory *symmetric* if $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ and the probability distribution $\mu_\psi(\lambda)$ is symmetric under unitary transformations that fix $|\psi\rangle$, or equivalently, if μ_ψ is a function f_ψ only of the inner product² $|\langle \psi | \lambda \rangle|$. We stress that the function f_ψ is allowed to

¹Also, we call an ontological theory *deterministic* if the response functions take values only in $\{0,1\}$. The Kochen-Specker theorem then states that, in dimensions $d \geq 3$, any deterministic theory must have response functions that depend nontrivially on M .

²Note that in symmetric theories $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$, so we can think of each ontic state λ as corresponding to a quantum state $|\lambda\rangle$ in the original Hilbert space. This allows us to define quantities such as $|\langle \psi | \lambda \rangle|$.

be different for different ψ 's: Symmetry applies only to each μ_ψ individually. This makes our no-go theorem for symmetric theories stronger. If additionally μ_ψ is a *fixed* function f only of $|\langle \psi | \lambda \rangle|$, then we call the theory *strongly symmetric*. Note that, if a theory is strongly symmetric, then in order to apply a unitary U to a state $|\psi\rangle$, one can simply apply U to the ontic states. So strongly symmetric theories have a clear motivation: Namely, they allow us to keep the Schrödinger equation as the time evolution of our system.

A similar notion to symmetry was recently explored by Hardy [7] and Patra *et al.* [8]. Given a ψ -epistemic theory, it is natural to consider the action of unitaries on the ontic states $\lambda \in \Lambda$. Hardy and Patra *et al.* define such a theory to obey “ontic indifference” if for any unitary U such that $U|\psi\rangle = |\psi\rangle$, and any $\lambda \in \text{Supp}(\mu_\psi)$, we have $U\lambda = \lambda$. They then show that no ψ -epistemic theories satisfying ontic indifference exist in dimensions $d \geq 2$. Note that symmetric theories and even strongly symmetric theories need not obey ontic indifference, since unitaries can act nontrivially on ontic states in $\text{Supp}(\mu_\psi)$. So the result of Hardy and Patra *et al.* is incomparable with ours.

In dimension 2, there exists a strongly symmetric and maximally nontrivial theory found by Kochen and Specker [2]. In dimensions $d \geq 3$, Lewis *et al.* [9] found a nontrivial ψ -epistemic theory for all finite d . However, their theory is not symmetric and is far from being maximally nontrivial.

In this paper, we first give a construction of a maximally nontrivial ψ -epistemic theory for arbitrary d . Our theory builds on that of Lewis *et al.* [9] and was first constructed in a post on MathOverflow [10]. Unfortunately, this theory is rather unnatural and is not symmetric. We then prove that it is impossible to construct a maximally nontrivial theory that *is* symmetric for Hilbert space dimensions $d \geq 3$. Our proof makes extensive use of the notion of “deficiency” defined by Harrigan and Rudolph [11]. Furthermore, we extend this work to rule out a generalization of strongly symmetric theories with $\Lambda = U(d)$ rather than $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ in $d \geq 3$. Interestingly, none of our no-go results depend on the specific form of the Born rule, but rather only on the fact that the probability of obtaining outcome ϕ when measuring state ψ is zero when $\langle \psi | \phi \rangle = 0$. In short, if we want maximally nontrivial theories in three or more dimensions, then we either need an ontic space Λ other than $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ or $\Lambda = U(d)$, or else we need ontic distributions μ_ψ that “single out preferred directions in Hilbert space.”

II. NONSYMMETRIC, MAXIMALLY NONTRIVIAL THEORY

By considering $\Lambda = \mathbb{C}\mathbb{P}^{d-1} \times [0,1]$, Lewis *et al.* [9] found a deterministic ψ -epistemic theory for all finite d . They raised as an open problem whether a *maximally* nontrivial theory exists. In this section, we answer their question in the affirmative. Specifically, we first show that, for any two nonorthogonal states, we can construct a theory such that their probability distributions overlap. We then take a convex combination of such theories to obtain a maximally nontrivial theory.

Lemma 1. Given any two nonorthogonal quantum states $|a\rangle, |b\rangle$, there exists a ψ -epistemic theory $T(a,b) = (\Lambda, \mu, \xi)$ such that μ_a and μ_b have nontrivial overlap. Moreover, for

$T(a, b)$, there exists $\varepsilon > 0$ such that $\mu_{a'}$ and $\mu_{b'}$ have nontrivial overlap for all $|a'\rangle, |b'\rangle$ that satisfy

$$\|a - a'\|, \|b - b'\| < \varepsilon.$$

Proof. Our ontic state space will be $\Lambda = \mathbb{C}\mathbb{P}^{d-1} \times [0, 1]$. Given an orthonormal basis $M = \{\phi_1, \dots, \phi_d\}$, we first sort the ϕ_i 's in decreasing order of $\min(|\langle \phi_i | a \rangle|, |\langle \phi_i | b \rangle|)$. Then the outcome of measurement M on ontic state (λ, p) will be the smallest positive integer i such that

$$\begin{aligned} & |\langle \phi_1 | \lambda \rangle|^2 + \dots + |\langle \phi_{i-1} | \lambda \rangle|^2 \\ & \leq p \leq |\langle \phi_1 | \lambda \rangle|^2 + \dots + |\langle \phi_i | \lambda \rangle|^2. \end{aligned} \quad (5)$$

In other words, $\xi_{i,M}(|\lambda\rangle, p) = 1$ if i satisfies the above and no $j < i$ does and is 0 otherwise. If we assume that $\mu_\psi(|\lambda\rangle, p) = \delta(|\lambda\rangle - |\psi\rangle)$ for all $p \in [0, 1]$, then it can be verified that $T(a, b)$ is a valid ontological theory, albeit so far a ψ -ontic one.

We now claim that there exists an $\varepsilon > 0$ such that, for all orthonormal bases $M = \{\phi_1, \dots, \phi_d\}$, there exists an i such that $|\langle \phi_i | a \rangle| \geq \varepsilon$ and $|\langle \phi_i | b \rangle| \geq \varepsilon$. Indeed, by the triangle inequality, we can let $\varepsilon = |a|b|/d$, and $\varepsilon > 0$ since $|a|b| > 0$. This means that, for all measurements M and all $p \in [0, \varepsilon]$, the outcome is always $i = 1$ when M is applied to either of the ontic states $(|a\rangle, p)$ or $(|b\rangle, p)$.

Following Lewis *et al.* [9], we can “mix” the probability distributions μ_a and μ_b , or have them intersect in the region $p \in [0, \varepsilon]$, without affecting the Born rule statistics for any measurement. Explicitly, we can let

$$E_{a,b} = \{|a\rangle, |b\rangle\} \times [0, \varepsilon], \quad (6)$$

so that all $\lambda \in E_{a,b}$ give the same measurement outcome ϕ_1 for all measurements M . Then any probability assigned by μ_a or μ_b to states within $E_{a,b}$ can be redistributed over $E_{a,b}$ without changing the measurement statistics. Thus, we can define μ_a such that the weight it originally placed on $|a\rangle \times [0, \varepsilon]$ is now placed uniformly on $E_{a,b}$. More formally, we set

$$\mu_a(|\lambda\rangle, x) = \begin{cases} \delta(|\lambda\rangle - |a\rangle) & \text{if } x > \varepsilon, \\ \varepsilon \mu_{E_{a,b}}(|\lambda\rangle, x) & \text{if } x \leq \varepsilon, \end{cases} \quad (7)$$

where $\mu_{E_{a,b}}$ is the uniform distribution over $E_{a,b}$. We similarly define μ_b . This then yields a ψ -epistemic theory with nontrivial overlap between $|a\rangle$ and $|b\rangle$.

Furthermore, suppose we have $|a'\rangle, |b'\rangle$, such that $\|a - a'\|, \|b - b'\| < \frac{\varepsilon}{2}$. Then by continuity, we can similarly mix the distributions $\mu_{a'}$ and $\mu_{b'}$, or have them intersect each other in the region $p \in [0, \frac{\varepsilon}{2}]$, without affecting any measurement outcome. Note that the procedure of sorting the basis vectors of M might cause the measurement outcome to change discontinuously. However, this is not a problem since the procedure depends only on $|a\rangle$ and $|b\rangle$, which are fixed, and hence occurs uniformly for all $|a'\rangle$ and $|b'\rangle$ defined as above. ■

Lemma 1 implies that for any two nonorthogonal states $|a\rangle$ and $|b\rangle$, we can construct a theory where $\mu_{a'}$ and $\mu_{b'}$ have nontrivial overlap for all $\|a - a'\|, \|b - b'\| < \varepsilon$, for some $\varepsilon > 0$. To obtain a maximally nontrivial theory, such that any two nonorthogonal vectors have probability distributions that overlap, we take a convex combination of such ψ -epistemic theories.

Given two ψ -epistemic theories $T_1 = (\Lambda_1, \mu_1, \xi_1)$ and $T_2 = (\Lambda_2, \mu_2, \xi_2)$ and a constant $c \in (0, 1)$, we define the new theory $cT_1 + (1 - c)T_2 = (\Lambda_c, \mu_c, \xi_c)$ by setting $\Lambda_c = (\Lambda_1 \times \{1\}) \cup (\Lambda_2 \times \{2\})$ and $\mu_c = c\mu_1 + (1 - c)\mu_2$. For any $(\lambda, i) \in \Lambda_c$, we then define ξ_c to equal ξ_i on Λ_i .

The following is immediate from the definitions.

Lemma 2. $cT_1 + (1 - c)T_2$ is a ψ -epistemic theory. Furthermore, if T_1 mixes the probability distributions μ_a, μ_b of two states $|a\rangle$ and $|b\rangle$, and T_2 mixes $\mu_{a'}, \mu_{b'}$, then $cT_1 + (1 - c)T_2$ mixes both pairs of distributions, assuming $c \notin \{0, 1\}$.

Note that the ontic state space of a convex combination of theories contains a copy of each of the original ontic spaces Λ_1 and Λ_2 . If $\Lambda_1 = \Lambda_2$, it is natural to ask if we could get away with keeping only one copy of the ontic state space. Unfortunately, the answer, in general, is no. Suppose that we let $\Lambda_c = \Lambda_1 = \Lambda_2$, let $\mu_c = c\mu_1 + (1 - c)\mu_2$, and let $\xi_c = c\xi_1 + (1 - c)\xi_2$. Then the probability of measuring outcome i under measurement M and ontic distribution μ_{c_ψ} is

$$\int_{\Lambda} [c\xi_{1,M}(\lambda) + (1 - c)\xi_{2,M}(\lambda)][c\mu_1(\lambda) + (1 - c)\mu_2(\lambda)]d\lambda,$$

which will not, in general, reproduce the Born rule due to unwanted cross terms. This is why it is necessary to keep two copies of the ontic state space when taking a convex combination of theories.

Using Lemmas 1 and 2, we now construct a maximally nontrivial ψ -epistemic theory. Let $T(a, b)$ be the theory returned by Lemma 1 given $|a\rangle, |b\rangle \in H_d$. Also, for all positive integers n , let A_n be a $1/n$ -net for H_d , that is, a finite subset $A_n \subseteq H_d$ such that for all $|a\rangle \in H_d$, there exists $|a'\rangle \in A_n$ satisfying $\|a - a'\| < 1/n$. By making small perturbations, we can ensure that $\langle a|b\rangle \neq 0$ for all $|a\rangle, |b\rangle \in A_n$. Then our theory T is defined as follows:

$$T = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \left(\frac{1}{|A_n|^2} \sum_{a,b \in A_n} T(a, b) \right). \quad (8)$$

[Here, in place of $6/(\pi^2 n^2)$, we could have chosen any infinite sequence summing to unity.] This yields a maximally nontrivial theory, since it can be verified that μ_a and μ_b have nontrivial overlap for all nonorthogonal states $|a\rangle$ and $|b\rangle$. Note that the ontic space is now $\mathbb{C}\mathbb{P}^{d-1} \times [0, 1] \times \mathbb{N}$, which has the same cardinality as $\mathbb{C}\mathbb{P}^{d-1}$. It is thus possible to map this theory into a theory that uses $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ as its ontic space, using a bijection between the ontic spaces. However, it is clear that under such a bijection the theory becomes less symmetric: The quantum state $|a\rangle$ no longer has any association with the state $|a\rangle$ in the ontic space, and the measure is also very unnatural.

III. NONEXISTENCE OF SYMMETRIC, MAXIMALLY NONTRIVIAL THEORIES

We now turn to showing that it is impossible to construct a *symmetric* maximally nontrivial theory, in dimensions $d \geq 3$. Recall that a theory is called symmetric if

- (1) $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ and

(2) for any quantum state $|\psi\rangle$, the associated probability distribution μ_ψ is invariant under unitary transformations that preserve $|\psi\rangle$.

Specifically, if U is a unitary transformation such that $U|\psi\rangle = |\psi\rangle$, then we require that $\mu_{U\psi}(U\lambda) = \mu_\psi(\lambda)$. This implies that $\mu_\psi(\lambda)$ is a function only of $|\langle\psi|\lambda\rangle|^2$: That is,

$$\mu_\psi(\lambda) = f_\psi(|\langle\psi|\lambda\rangle|^2) \tag{9}$$

for some nonnegative function f_ψ . In other words, the probability measure μ_ψ associated with state ψ must be a measure ν_ψ on the unit interval which has been “stretched out” onto H_d over curves of constant $|\langle\psi|\lambda\rangle|^2$. If additionally we assume that for any U , $\mu_{U\psi}(U\lambda) = \mu_\psi(\lambda)$, or equivalently that $\mu_\psi(\lambda) = f(|\langle\psi|\lambda\rangle|^2)$ for some fixed non-negative function f , the theory is called strongly symmetric.

In this section, we first prove several facts about symmetric, maximally nontrivial theories in general. Using these facts, we then show that no strongly symmetric, maximally nontrivial theory exists in dimension 3 or higher. Restricting to the strongly symmetric case will make the proof considerably easier. Later we show how to generalize to the “merely” symmetric case.

As mentioned earlier, Kochen and Specker proved that a strongly symmetric, maximally nontrivial ψ -epistemic theory exists in dimension $d = 2$ [2]. In their theory, which is illustrated in Fig. 1, the ontic space is $\Lambda = \mathbb{C}\mathbb{P}^1$, and the response functions for a given basis $M = \{\phi_1, \phi_2\}$ are

$$\xi_{1,M}(\lambda) = 1 \quad \text{if} \quad |\langle\lambda|\phi_1\rangle| \geq |\langle\lambda|\phi_2\rangle| \quad \text{or} \quad 0 \quad \text{otherwise,} \tag{10}$$

$$\xi_{2,M}(\lambda) = 1 \quad \text{if} \quad |\langle\lambda|\phi_2\rangle| \geq |\langle\lambda|\phi_1\rangle| \quad \text{or} \quad 0 \quad \text{otherwise.} \tag{11}$$

Hence, the response functions are deterministic and partition the ontic space. Intuitively, the result of a measurement on any ontic state is the state in the measurement basis to which it is closest. For any quantum state $|\psi\rangle \in H_2$, the probability

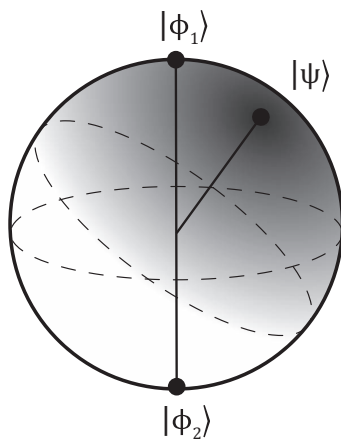


FIG. 1. Diagram of maximally nontrivial theory in $d = 2$ on the Bloch sphere. The shaded region corresponds to $\text{Supp}(\mu_\psi)$.

distribution over Λ is given by

$$\mu_\psi(\lambda) = \begin{cases} \frac{2}{\pi} (|\langle\lambda|\psi\rangle|^2 - \frac{1}{2}) & \text{if } |\langle\lambda|\psi\rangle|^2 > \frac{1}{2}, \\ 0 & \text{otherwise.} \end{cases}$$

It can readily be verified that this theory satisfies the conditions for a ψ -epistemic theory, and has the properties of being strongly symmetric and maximally nontrivial. It is also maximally ψ -epistemic in the sense described by Maroney [4] and Maroney and Leifer [5].

Given a measurement outcome ψ and a basis M containing ψ , we define the *nonzero set* $\text{Nonzero}(\xi_{\psi,M})$ to be the set of ontic states λ such that the response function $\xi_{\psi,M}(\lambda)$ gives a nonzero probability of returning ψ when M is applied:

$$\text{Nonzero}(\xi_{\psi,M}) = \{\lambda : \xi_{\psi,M}(\lambda) \neq 0\}. \tag{12}$$

Clearly in any ψ -epistemic theory, $\text{Supp}(\mu_\psi) \subseteq \text{Nonzero}(\xi_{\psi,M})$ for any measurement basis M that contains ψ , because the state $|\psi\rangle$ must return measurement outcome ψ with probability 1 for any such M . Harrigan and Rudolph [11] call a ψ -epistemic theory *deficient* if there exists a quantum state $|\psi\rangle$ and measurement basis M containing ψ such that

$$\text{Supp}(\mu_\psi) \subsetneq \text{Nonzero}(\xi_{\psi,M}). \tag{13}$$

In other words, a theory is deficient if there exists an ontic state λ such that λ has a nonzero probability of giving the measurement outcome corresponding to $|\psi\rangle$ for some M , even though $\lambda \notin \text{Supp}(\mu_\psi)$. This can be thought of as a “one-sided friendship” between $|\psi\rangle$ and λ .

It was first pointed out by Rudolph [12], and later shown by Harrigan and Rudolph [11], that theories in dimension $d \geq 3$ must be deficient. In this section, we prove that as a result of deficiency, it is impossible to have a symmetric, maximally nontrivial theory with $d \geq 3$. We derive a contradiction by showing that if the theory is maximally nontrivial, then there exist orthogonal states $|\psi\rangle, |\phi\rangle$ and a measurement basis M containing $|\psi\rangle$, such that if measurement M is performed on $|\phi\rangle$, then the outcome $|\psi\rangle$ is returned with nonzero probability, contradicting the laws of quantum mechanics.

We start with a few preliminary results on symmetric, maximally nontrivial theories. As stated previously, we know that μ_ψ is generated by stretching a probability measure ν_ψ on the unit interval over H_d along spheres of constant $|\langle\psi|\lambda\rangle|^2$. By the Lebesgue decomposition theorem, ν_ψ can be written uniquely as a sum of two measures $\nu_{\psi,C}$ and $\nu_{\psi,S}$, where $\nu_{\psi,C}$ is absolutely continuous with respect to the Lebesgue measure over the unit interval, and $\nu_{\psi,S}$ is singular with respect to that measure. Here when we say $\nu_{\psi,C}$ is “absolutely continuous” with respect to the Lebesgue measure, we mean that it assigns zero measure to any set of Lebesgue measure zero. When we say $\nu_{\psi,S}$ is “singular,” we mean that its support is confined to a set of Lebesgue measure zero. Similarly, μ_ψ can be decomposed into its absolutely continuous and singular parts $\mu_{\psi,C}$ and $\mu_{\psi,S}$, which are defined, respectively, from the components $\nu_{\psi,C}$ and $\nu_{\psi,S}$ of ν_ψ . By the Radon-Nikodym theorem, due to its absolute continuity $\nu_{\psi,C}$ has a probability density function $g_\psi(x)$ that is a function, not a pseudofunction or delta function. To simplify our analysis, first we show that it is only necessary to look at the absolutely continuous part of the distribution.

Lemma 3. For any distinct and nonorthogonal states $|\psi\rangle, |\phi\rangle$ in a symmetric, maximally nontrivial theory, $\mu_{\psi,C}$ and $\mu_{\phi,C}$ have nontrivial overlap.

Proof. Let S_a denote the set of states $\lambda \in \Lambda$ with $|\langle\lambda|\psi\rangle|^2 = a$. If $a = 1$, then S_a is a single point with zero μ_ϕ measure. For $0 < a < 1$, S_a is a $(2d - 3)$ -sphere centered about ψ , and for $a = 0$ it is a $(2d - 4)$ -dimensional manifold diffeomorphic to $\mathbb{C}\mathbb{P}^{d-1}$. In both of the latter cases, as ϕ, ψ are distinct nonorthogonal states, the distribution of $|\langle\lambda|\phi\rangle|^2$ for λ chosen uniformly on S_a is absolutely continuous with respect to the Lebesgue measure on $[0, 1]$. Therefore, the distribution of $|\langle\lambda|\phi\rangle|^2$ for $\lambda \in \Lambda$ chosen according to μ_ψ is absolutely continuous over $|\langle\lambda|\psi\rangle| < 1$.

By our symmetry condition, $\mu_{\phi,S}$ is the product of a singular measure on $[0, 1]$, denoted $\nu_{\phi,S}$, and the uniform measure on rings of constant $|\langle\phi|\lambda\rangle|^2$. Since drawing λ from μ_ψ induces an absolutely continuous measure on $|\langle\phi|\lambda\rangle|^2$, then in particular μ_ψ has probability zero of producing a state λ with $|\langle\phi|\lambda\rangle|^2 \in \text{Supp}(\nu_{\phi,S})$, because $\text{Supp}(\nu_{\phi,S})$ is a set of measure zero. This implies that μ_ψ has probability zero of producing a state $\lambda \in \text{Supp}(\mu_{\phi,S})$. Hence, there is zero overlap between μ_ψ and $\mu_{\phi,S}$. In particular, $\mu_{\psi,C}$ and $\mu_{\psi,S}$ have zero overlap with $\mu_{\phi,S}$. Similarly, $\mu_{\phi,C}$ and $\mu_{\phi,S}$ have zero overlap with $\mu_{\psi,S}$.

This shows that the overlap between $\mu_{\phi,C}$ and $\mu_{\psi,C}$ equals that between μ_ϕ and μ_ψ , which is nonzero for maximally nontrivial theories. ■

From now on, we assume μ_ψ is generated only from the absolutely continuous part $\nu_{\psi,C}$, so that μ_ψ has as probability density function $f_\psi(|\langle\psi|\lambda\rangle|^2)$ where f_ψ is a function, not a pseudofunction. We can do this without loss of generality, as our proof will not depend on the normalization of the probability distributions, and will only use facts about the absolutely continuous components of the measures.

Next, let the distance between two states ψ and ϕ be defined by their scaled radial distance (also called the *Fubini-Study metric*):

$$\|\psi - \phi\| = \frac{2}{\pi} \arccos(|\langle\psi|\phi\rangle|).$$

For any state $|\psi\rangle \in H_d$, with probability distribution $\mu_\psi(\lambda) = f_\psi(|\langle\psi|\lambda\rangle|^2)$, we define the *radius* of μ_ψ to be the distance between $|\psi\rangle$ and the furthest away state at which μ_ψ has substantial density:

$$r_\psi = \sup \left\{ r : \forall \delta > 0 \int_{\lambda: r-\delta < \|\psi-\lambda\| < r} \mu_\psi(\lambda) d\lambda > 0 \right\}. \quad (14)$$

Lemma 4. For a symmetric theory, given any two states $|\psi\rangle, |\phi\rangle$, we have $\|\psi - \phi\| \geq r_\psi + r_\phi$ if and only if $|\psi\rangle$ and $|\phi\rangle$ have trivial overlap.

Proof. Suppose that $\|\psi - \phi\| \geq r_\psi + r_\phi$ but $|\psi\rangle$ and $|\phi\rangle$ have nontrivial overlap. Then $\text{Supp}(\mu_\psi) \cap \text{Supp}(\mu_\phi)$ has nonzero measure, and for any λ in that set, the triangle inequality implies that $r_\psi + r_\phi \geq \|\psi - \lambda\| + \|\phi - \lambda\| \geq \|\psi - \phi\|$. Thus, r_ψ and r_ϕ satisfy $r_\psi + r_\phi = \|\psi - \phi\|$, which is a contradiction since $\|\psi - \lambda\| + \|\phi - \lambda\| = \|\psi - \phi\|$ only on a set of measure zero.

Now suppose that $\|\psi - \phi\| < r_\psi + r_\phi$. Consider λ_{int} , an ontic state which lies at the intersection of rings of radii r_ψ and r_ϕ about ψ and ϕ , respectively. In other words $\|\psi - \lambda_{\text{int}}\| = r_\psi$

and $\|\phi - \lambda_{\text{int}}\| = r_\phi$. Such a λ_{int} exists because $\|\psi - \phi\| < r_\psi + r_\phi$. Then in the neighborhood of λ_{int} , we claim that μ_ψ and μ_ϕ have nontrivial overlap.

To show this, we define a set B of positive measure, on which μ_ψ and μ_ϕ are “equivalent” to the Lebesgue measure, in the sense that if $S \subseteq B$ has positive Lebesgue measure, then S has positive measure under both μ_ψ and μ_ϕ . This implies that ψ and ϕ have nontrivial overlap on B .

By the symmetry condition, each μ_ψ is a product measure between a measure ν_ψ on $[0, 1]$ and a uniform measure on surfaces of constant $|\langle\psi|\lambda\rangle|$. Let u and v be the normal vectors to surfaces of constant $|\langle\psi|\lambda\rangle|$ and $|\langle\phi|\lambda\rangle|$ at $|\lambda_{\text{int}}\rangle$, respectively. Note that u (v) is equal to the tangent vector to the geodesic running from ψ (ϕ) to λ_{int} evaluated at λ_{int} . Since $\|\psi - \phi\| < r_\psi + r_\phi$, these are distinct geodesics, so u and v are linearly independent.

Since $\mathbb{C}\mathbb{P}^{d-1}$ is a smooth Riemannian manifold, u and v form a local coordinate system in the ε neighborhood of $|\alpha\rangle$, which we denote $N_\varepsilon(|\alpha\rangle)$. If we associate coordinates x_1, x_2 with u and v , the integral over $N_\varepsilon(|\alpha\rangle)$ can be parameterized as

$$\int g(x_1, x_2, y_1, \dots, y_{2d-4}) dx_1 dx_2 dy_1, \dots, dy_{2d-4}.$$

Here g is the square root of the metric, which is strictly positive in the neighborhood of $|\lambda_{\text{int}}\rangle$. Also, dx_i is the Lebesgue integral over the coordinate x_i , and the y_i are coordinates corresponding to the remaining $2d - 4$ dimensions of the space.

Now consider the set

$$B = N_\varepsilon(|\alpha\rangle) \cap \text{Supp}(\mu_\psi) \cap \text{Supp}(\mu_\phi).$$

Trivially, μ_ψ and μ_ϕ are equivalent to the Lebesgue measure on B . Note that $\text{Supp}(\mu_\psi)$ is a union of surfaces S_1 of constant $|\langle\lambda|\psi\rangle|$ which are perpendicular to u at α . If ε is sufficiently small these surfaces have negligible curvature, so they look like orthogonal hyperplanes in the x_1 coordinate system. Let ε_1 be the Lebesgue measure on $\text{Supp}(\mu_\psi) \cap B$. Let S_2 and ε_2 be defined similarly for ϕ . If the surfaces S_1, S_2 had zero curvature, the Lebesgue measure of B would simply be the product of the measures $\varepsilon_1 \varepsilon_2$, since x_1 and x_2 are orthogonal coordinates. Since the surfaces have slight curvature, and the coordinates x_i are not truly orthogonal, the above calculation has to be changed slightly. Specifically, for sufficiently small ε the Lebesgue measure of B can be approximated by $g \varepsilon_1 \varepsilon_2$, where g is the square root of the metric at λ_{int} . This quantity is strictly positive since each $\varepsilon_i > 0$ by the definition of r , the metric g is strictly positive, and μ_ψ and μ_ϕ are absolutely continuous with respect to the Lebesgue measure. Hence, B has positive Lebesgue measure. ■

Corollary 1. If $|\psi\rangle$ and $|\phi\rangle$ are orthogonal, then $r_\psi + r_\phi \leq 1$.

Proof. If $\langle\psi|\phi\rangle = 0$, then $\|\psi - \phi\| = 1$. Since any orthogonal $|\psi\rangle$ and $|\phi\rangle$ have trivial overlap, Lemma 4 implies that $r_\psi + r_\phi \leq 1$. ■

Lemma 5. Given any maximally nontrivial and symmetric theory in $d \geq 3$, for any state $|\psi\rangle \in H_d$, we have $r_\psi = \frac{1}{2}$.

Proof. We first show that $r_\psi \leq \frac{1}{2}$ for all $|\psi\rangle \in H_d$, which we illustrate on the left side of Fig. 2 for the case where $d = 3$. Suppose there exists $|\psi\rangle$ such that $r_\psi = \frac{1}{2} + \varepsilon$ for some $\varepsilon > 0$.

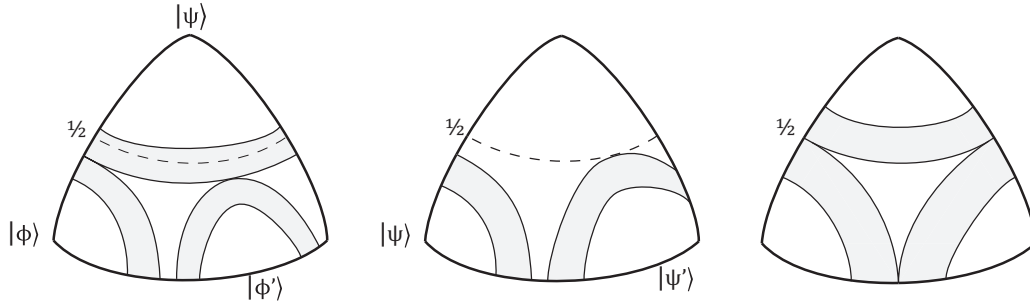


FIG. 2. From left to right are pictorial representations of the proof that $r_\psi \leq \frac{1}{2}$ in dimension 3, the proof that $r_\psi = \frac{1}{2}$, and the form of the μ_ψ 's that we ultimately deduce (with $r_\psi = \frac{1}{2}$ for all $|\psi\rangle \in H_d$). The shaded regions are the supports of the respective probability distributions.

From Corollary 1, for all $|\phi\rangle$ orthogonal to $|\psi\rangle$, we have $r_\phi \leq \frac{1}{2} - \varepsilon$. In dimension $d \geq 3$, there exist nonorthogonal states $|\phi\rangle, |\phi'\rangle$ such that $\langle\psi|\phi\rangle = \langle\psi|\phi'\rangle = 0$ and $|\phi\rangle \neq |\phi'\rangle$. Then $r_\phi + r_{\phi'} \leq 1 - 2\varepsilon$. If we choose $|\phi\rangle, |\phi'\rangle$ such that $1 - 2\varepsilon < \|\phi - \phi'\| < 1$, then from Lemma 4, we have that μ_ϕ and $\mu_{\phi'}$ have trivial overlap even though $\langle\phi|\phi'\rangle \neq 0$. This contradicts the theory being maximally nontrivial.

We now show that $r_\psi \geq \frac{1}{2}$ for all $|\psi\rangle \in H_d$, as illustrated in the center of Fig. 2. Suppose there exists $|\psi\rangle$ such that $r_\psi = \frac{1}{2} - \varepsilon$ for some $\varepsilon > 0$. Since $r_{\psi'} \leq \frac{1}{2}$ for all $|\psi'\rangle \in H_d$, thus, $r_\psi + r_{\psi'} \leq 1 - \varepsilon$. If we choose $|\psi\rangle, |\psi'\rangle$ such that $1 - \varepsilon < \|\psi - \psi'\| < 1$, then μ_ψ and $\mu_{\psi'}$ have trivial overlap from Lemma 4 even though $\langle\psi|\psi'\rangle \neq 0$. This again contradicts maximum nontriviality. ■

This immediately implies the following.

Corollary 2. In dimensions $d \geq 3$, a symmetric ψ -epistemic theory is maximally nontrivial if and only if for any state $|\psi\rangle$ and for all $\delta > 0$ the measure μ_ψ integrated over the following region is nonzero:

$$\{\lambda : \frac{1}{2} \leq |\langle\psi|\lambda\rangle|^2 \leq \frac{1}{2} + \delta\}. \quad (15)$$

Moreover, $\text{Supp}(\mu_\psi)$ has measure zero on the set of λ such that $|\langle\psi|\lambda\rangle|^2 < \frac{1}{2}$.

Proof. By Lemma 5, for any state $|\psi\rangle$ we have $r_\psi = \frac{1}{2}$. By rewriting the distance between states in terms of their inner product, the corollary follows from the definition of r_ψ in Eq. (14). ■

In Lemma 5, we showed that the radius r_ψ of every state ψ in a maximally nontrivial symmetric theory is $\frac{1}{2}$. We now use this to show that a certain set of ontic states is deficient. Recall that we say a set S is deficient for measurement M if S is not in $\text{Supp}(\mu_{\phi_i})$ for any $\phi_i \in M$.

Corollary 3. Given any symmetric, maximally nontrivial ψ -epistemic theory in $d \geq 3$, for any measurement basis $M = \{\phi_i\}_{i=1}^d$, the region

$$R_M = \{\lambda : |\langle\phi_i|\lambda\rangle|^2 < \frac{1}{2}, i = 1, \dots, d\}$$

is deficient except on a set of measure zero. (Note that, by elementary geometry, R_M has positive measure if and only if $d \geq 3$.)

Proof. By Corollary 2, for all $i = 1, \dots, d$, the set $\text{Supp}(\mu_{\phi_i})$ must have measure zero over the region R_M . However, Eq. (2) implies that any $\lambda \in R_M$ must be in $\text{Nonzero}(\xi_{i,M})$ for some i

even if it is not in $\text{Supp}(\mu_{\phi_i})$. This means that R_M is deficient except possibly on a set of measure zero. ■

In general, deficiency occurs in any theory in $d \geq 3$ even without the symmetry assumption, as proved by Harrigan and Rudolph [11] using the Kochen-Specker theorem [2]. In Corollary 3, we showed that symmetry implies a specific type of deficiency.

To show that no strongly symmetric, maximally nontrivial theory exists, we first prove two simple results for ψ -epistemic theories in general. These results will help us to derive a contradiction for strongly symmetric, maximally nontrivial theories.

Lemma 6. Given any two orthogonal states $|\phi\rangle$ and $|\psi\rangle$, the set $\text{Supp}(\mu_\phi) \cap \text{Nonzero}(\xi_{\psi,M})$ has measure zero for all measurements M that contain ψ .

Proof. Suppose to the contrary that $\text{Supp}(\mu_\phi) \cap \text{Nonzero}(\xi_{\psi,M})$ has positive measure for some measurement M containing ψ . Then by definition, if the state $|\phi\rangle$ is measured using M , the outcome corresponding to $|\psi\rangle$ is returned with nonzero probability. However, since $|\langle\psi|\phi\rangle|^2 = 0$, this contradicts the Born rule [Eq. (1)]. ■

Lemma 7. For any $\alpha \in \Lambda$, let $B_\varepsilon(\alpha) = \{\lambda : \|\lambda - \alpha\| < \varepsilon\}$ be an ε ball around α for some $\varepsilon > 0$. Given a measurement basis $M = \{\phi_i\}_{i=1}^d$, there exists some j such that

$$\int_{B_\varepsilon(\alpha)} \xi_{j,M}(\lambda) d\lambda > 0. \quad (16)$$

Proof. For any such $\alpha \in \Lambda$ the following holds:

$$\int_{B_\varepsilon(\alpha)} \sum_{i=1}^d \xi_{i,M}(\lambda) d\lambda = \int_{B_\varepsilon(\alpha)} 1 d\lambda > 0.$$

This then implies that there exists some j such that

$$\int_{B_\varepsilon(\alpha)} \xi_{j,M}(\lambda) d\lambda > 0. \quad \blacksquare$$

Using these two results, we can now prove that in dimension $d \geq 3$, there exists no strongly symmetric, maximally nontrivial ψ -epistemic theory.

Theorem 1. There exists no strongly symmetric, maximally nontrivial ψ -epistemic theory in dimension $d \geq 3$.

Proof. Suppose we have a symmetric, maximally nontrivial theory in dimension $d \geq 3$, and we fix a measurement basis $M = \{\phi_i\}_{i=1}^d$. From Corollary 3, there exists a deficiency

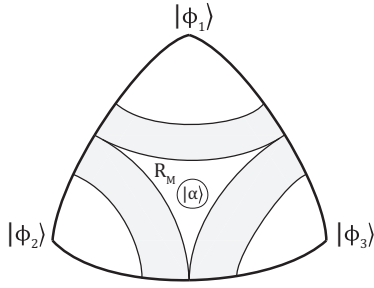


FIG. 3. Pictorial representation of the deficiency region for $d = 3$. The shaded regions are the supports of the respective probability measures, and the middle unshaded region R_M is deficient.

region given by

$$R_M = \left\{ \lambda : |\langle \phi_i | \lambda \rangle|^2 < \frac{1}{2}, i = 1, \dots, d \right\},$$

perhaps minus a set of measure zero. This is illustrated in Fig. 3 for the case where $d = 3$.

Consider $|\alpha\rangle = \frac{1}{\sqrt{d}}(|\phi_1\rangle + \dots + |\phi_d\rangle)$, which is contained in the deficiency region. Given $\varepsilon > 0$, let $B_\varepsilon(\alpha) = \{\lambda : \|\lambda - \alpha\| < \varepsilon\}$ be the ε ball around $|\alpha\rangle$. We choose ε such that $B_\varepsilon(\alpha)$ is contained in R_M . From Lemma 7, there exists some j such that $B := B_\varepsilon(\alpha) \cap \text{Nonzero}(\xi_{j,M})$ has nonzero measure. Without loss of generality, we assume that $j = 1$.

Let ν be the measure obtained by averaging μ_ψ over all states $|\psi\rangle$ orthogonal to $|\phi_1\rangle$, and let A be the set of all λ such that $|\langle \phi_1 | \lambda \rangle|^2 < \frac{1}{2}$. Since the theory is strongly symmetric, ν must be a function only of $|\langle \phi_1 | \lambda \rangle|^2$. Moreover, each of the measures μ_ψ assigns positive measure to the region of states λ such that $|\langle \psi | \lambda \rangle|^2$ is close to $\frac{1}{2}$; hence, the averaged measure ν assigns positive measure to every open subset of A , and therefore in particular to B . This contradicts Lemma 6, which implies that each of the averaged measures μ_ψ must assign zero measure to $\text{Nonzero}(\xi_{1,M})$ and hence B . ■

A. Proof of generalized no-go theorem

We now generalize our proof of Theorem 1 to the “merely” symmetric case, where the probability distributions μ_ψ can vary with ψ . First note that our previous proof does not immediately carry over. Since the probability distributions can vary as ψ changes, it is possible that the distributions for states orthogonal to ϕ_1 might be able to “evade” the set B in the proof of Theorem 1, which returns answer ϕ_1 under measurement M , while maintaining some density near their outer radii.

To see how this might occur, consider the following one-dimensional example: Let $\Lambda = \mathbb{R}$ be the real line. Construct $B \subseteq [0, 1]$ to be a “fat Cantor set” on $[0, 1]$ as follows. Initially set $B = [0, 1]$. In step 1, remove the middle $1/4$ of this interval so that $B = [0, \frac{3}{8}] \cup [\frac{5}{8}, 1]$. At the i th step, remove the middle $\frac{1}{2^{2i}}$ of each of the 2^i remaining intervals. Continue indefinitely. The resulting set B is called a “fat Cantor set” because it is nowhere dense (so contains no intervals), yet has positive Lebesgue measure on $[0, 1]$.

For each point $x \in \mathbb{R}$, let μ_x be the uniform distribution on $[x - 1, x + 1]$ with B removed. Then μ_x is absolutely continuous with respect to the Lebesgue measure for all $x \in \mathbb{R}$, and furthermore has positive measure on $[1 + x - \varepsilon, 1 + x]$

for all $\varepsilon > 0$. However, despite the fact that B has positive measure, the distributions μ_x never intersect B . The worry is that our distributions in $\mathbb{C}\mathbb{P}^{d-1}$ could likewise evade the set B in our proof, foiling our contradiction. This worry is related to a variant of the Kakeya/Besicovitch problem, as we discuss in Sec. IV.

We can extend Theorem 1 without solving a Kakeya-like problem, but to do so we need a result about the differential geometry of $\mathbb{C}\mathbb{P}^{d-1}$. Interestingly, we use the fact that we are working in a complex Hilbert space; we believe the proof could be adapted to a real Hilbert space, but it would be much less convenient.

Discussing the differential geometry of $\mathbb{C}\mathbb{P}^{d-1}$ is easiest if we first pick a gauge for $\mathbb{C}\mathbb{P}^{d-1}$, that is, if we pick a representative from each equivalence class of vectors which differ only by a global phase. We use the following gauge: Let $|\alpha\rangle = \frac{1}{\sqrt{d}}(|\phi_1\rangle + \dots + |\phi_d\rangle)$. For each equivalence class, we pick a representative u such that $\langle \alpha | u \rangle$ is real and positive. This uniquely identifies representatives for all equivalence classes of states, except those orthogonal to α . Moreover, this way of choosing a gauge is continuous and smooth near α ; more precisely, equivalence classes which are close to one another have representatives which are also close to one another. This allows us to integrate over the manifold near α using these representatives. Using this gauge, we now prove the following.

Lemma 8. Let M be a measurement basis $\{\phi_i\}$, let $|\alpha\rangle$ be defined as above, and let $d \geq 3$. Then there exist d vectors u_1, \dots, u_d in $\mathbb{C}\mathbb{P}^{d-1}$ such that

- (i) $\langle u_i | \phi_i \rangle = 0$ for all i ;
- (ii) $\langle u_i | \alpha \rangle = \frac{1}{\sqrt{2}}$ for all i ;

(iii) the tangent vectors t_i to the geodesics from u_i to α are linearly independent at α when the tangent space is viewed as a real vector space.

Proof. Let $a = \sqrt{\frac{d}{2(d-1)^2}}$ and $b = \sqrt{\frac{d-2}{4(d-1)}}$. Then we define u_1, \dots, u_{d-2} as follows:

$$u_i = \left(\sum_{j \neq i} a |\phi_j\rangle \right) + ib |\phi_{i+1}\rangle - ib |\phi_{i+2}\rangle.$$

For the last two vectors, we set

$$u_{d-1} = \left(\sum_{j \neq d-1} a |\phi_j\rangle \right) + ib |\phi_d\rangle - ib |\phi_1\rangle,$$

$$u_d = \left(\sum_{j \neq d} a |\phi_j\rangle \right) + b |\phi_1\rangle - b |\phi_2\rangle.$$

Note that the coefficients in u_d are all real, unlike for the other $d - 1$ vectors. It is straightforward to verify that $\langle u_i | \phi_i \rangle = 0$ and $\langle u_i | \alpha \rangle = \frac{1}{\sqrt{2}}$ for all i . Furthermore, we can compute the tangent vectors t_i as follows. The geodesics from $|u_i\rangle$ to $|\alpha\rangle$ in the Fubini-Study metric can be parameterized by

$$\gamma(t) = \cos(t)|v_i\rangle + \sin(t)|\alpha\rangle,$$

where v_i is the normalized component of u_i orthogonal to α , that is $v_i = k(u_i - \langle \alpha | u_i \rangle \alpha)$ for some real normalization constant k . These geodesics lie entirely within our choice of

gauge. Therefore, t_i is the projection of $\gamma'(t)|_{t=\pi/2}$ onto the plane orthogonal to α , which is

$$t_i = u_i - \langle \alpha | u_i \rangle \alpha.$$

Since t_i is in the tangent space, its normalization is irrelevant. Also, since our gauge is fixed, there is no ambiguity involving the global phase of u_i or t_i .

We now verify that the t_i 's are linearly independent. Suppose that $c_1 t_1 + \dots + c_d t_d = 0$, with c_i real. Note that $\langle \alpha | u_i \rangle \alpha$ has all real coefficients, so a coefficient of t_i is imaginary if and only if the corresponding coefficient of u_i is imaginary. Since $c_1 t_1 + \dots + c_d t_d = 0$, in particular the imaginary terms in $|\phi_i\rangle$ must sum to zero for all i . For $i = 3 \dots d$, only the terms $c_{i-2} t_{i-2}$ and $c_{i-1} t_{i-1}$ contain imaginary multiples of $|\phi_i\rangle$. Hence, this constraint implies $c_{i-2} = c_{i-1}$. Additionally, $c_1 t_1$ is the only term containing an imaginary multiple of $|\phi_2\rangle$, so we must have $c_1 = 0$. Therefore, $c_1 = c_2 = \dots = c_{d-2} = 0$. Since $c_{d-1} t_{d-1}$ is the only term containing an imaginary multiple of $|\phi_1\rangle$, we must have $c_{d-1} = 0$, and hence $c_d = 0$ as well. Therefore, the t_i 's are linearly independent. ■

Note that in a real Hilbert space, the analogous statement to Lemma 8 is false because the dimension of the tangent space at α is only $d - 1$. In a complex Hilbert space the dimension of the tangent space is $2d - 2$, so the tangent space can contain d linearly independent vectors assuming $d \geq 2$.

We now show that Lemma 8 implies the existence of a set B of positive measure, on which every μ_{u_i} is “equivalent” to the Lebesgue measure, in the sense that if $S \subseteq B$ has positive Lebesgue measure, then S has positive measure under each μ_{u_i} .

Lemma 9. Let u_i and $|\alpha\rangle$ be as defined in Lemma 8. Then there exists a set B in the neighborhood of $|\alpha\rangle$, of positive Lebesgue measure, such that the μ_{u_i} are equivalent to the Lebesgue measure on B .

Proof. Consider

$$B = N_\varepsilon(|\alpha\rangle) \cap \text{Supp}(\mu_{u_1}) \cap \text{Supp}(\mu_{u_2}) \cap \dots \cap \text{Supp}(\mu_{u_d}),$$

where $N_\varepsilon(|\alpha\rangle)$ denotes the ε neighborhood of α . For sufficiently small ε , one can show that B has the desired properties using the same techniques as in the proof of Lemma 4. ■

From these two lemmas, the proof of our main theorem follows, since the orthogonality of each u_i to ϕ_i (together with the Born rule) implies that the set B cannot give any outcome with positive probability under the measurement $M = \{\phi_i\}$. However, each element in B must give *some* outcome under measurement.

Theorem 2. There exists no symmetric, maximally nontrivial ψ -epistemic theory in dimension $d \geq 3$.

Proof. By Lemmas 8 and 9, there is a measurement basis $M = \{\phi_1, \dots, \phi_d\}$ and vectors u_1, \dots, u_d such that each u_i is orthogonal to ϕ_i .

Furthermore, there is a set B of positive measure such that each μ_{u_i} is equivalent to the Lebesgue measure on B . Therefore, by the Born rule, for each i we must have

$$\int_B \mu_{u_i}(\lambda) \xi_{i,M}(\lambda) d\lambda = 0.$$

Since each μ_{u_i} is equivalent to the Lebesgue measure on B , this implies

$$\int_B \xi_{i,M}(\lambda) d\lambda = 0.$$

However, also, since $\sum_i \xi_{i,M}(\lambda) = 1$ for each state λ , we have that

$$\sum_i \int_B \xi_{i,M}(\lambda) d\lambda = \int_B d\lambda > 0,$$

which is a contradiction. ■

B. Extending the proof to $\Lambda = U(d)$

We now rule out a generalization of strongly symmetric, maximally nontrivial theories with a larger ontic space, namely $\Lambda = U(d)$.

Recall that a theory is strongly symmetric if $\Lambda = \mathbb{C}\mathbb{P}^{d-1}$ and $\mu_{U\psi}(U\lambda) = \mu_\psi(\lambda)$ for all unitaries U . A theory is (weakly) symmetric if $\mu_{U\psi}(U\lambda) = \mu_\psi(\lambda)$ only for those U such that $U\psi = \psi$.

We can generalize the definition of strong symmetry to any ontic space Λ on which the unitary group has an action. We define a theory to be strongly symmetric with ontic space Λ and action $a : U(d) \times \Lambda \rightarrow \Lambda$ if $\mu_{U\psi}(a(U,\lambda)) = \mu_\psi(\lambda)$ for all unitaries U . In other words, for all U and ψ , the following two distributions on λ are identical: Draw λ from $\mu_{U\psi}$, or draw λ' from μ_ψ and then set $\lambda = a(U,\lambda')$. Strongly symmetric theories admit a natural dynamics, since applying a unitary to a quantum state is equivalent to applying the unitary to the ontic states via the action a .

A natural choice of Λ in this context is $U(d)$, the symmetry group of the d -dimensional Hilbert space. The unitary group $U(d)$ has a natural action on itself by left multiplication. We now show that there are no strongly symmetric, maximally nontrivial theories with $\Lambda = U(d)$ and with the action $a(U,\lambda) = U\lambda$ given by left multiplication.

Our proof proceeds similarly to the proof above. Assume there exists a strongly symmetric, maximally nontrivial theory with $\Lambda = U(d)$. We find a set of quantum states $\{\Psi_1, \Psi_2, \Psi_3\}$, such that the μ_{Ψ_j} have nontrivial joint overlap, by which we mean that $\text{Supp}(\Psi_1) \cap \text{Supp}(\Psi_2) \cap \text{Supp}(\Psi_3)$ has positive measure. We then create an orthonormal basis $\{e_1, \dots, e_d\}$ such that for all i , there exists a j such that $\langle e_i | \Psi_j \rangle = 0$. Therefore, if measured in the basis $\{e_i\}$, the ontic states in S cannot give output e_i for any i by the Born rule, which contradicts the fact that they must give some outcome under measurement.

To show this, we first need to characterize strongly symmetric theories with $\Lambda = U(d)$. We now show that the probability distributions μ_ψ of any strongly symmetric theory are fully characterized by some probability measure ν on $\mathbb{C}\mathbb{P}^{d-1}$. In the following, we denote ontic states $M, N \in U(d)$ with Latin characters and quantum states $\lambda, \psi, \phi \in \mathbb{C}\mathbb{P}^{d-1}$ with Greek characters.

Lemma 10. Let $\pi = (\Lambda, \mu, \xi)$ be a strongly symmetric theory with $\Lambda = U(d)$ and with action a given by left multiplication. Then there exists a probability measure ν on $\mathbb{C}\mathbb{P}^{d-1}$ which fully characterizes the probability distributions μ_ψ for all ψ . In particular, to draw a sample M from μ_ψ , one

can first draw $\lambda \in \mathbb{C}\mathbb{P}^{d-1}$ from ν , and then draw M uniformly (according to the Haar measure) such that $M^\dagger\psi = \lambda$.

Proof. Suppose we draw M from μ_ψ . Let ν_ψ be the distribution on $\mathbb{C}\mathbb{P}^{d-1}$ induced by $M^\dagger\psi$.

Suppose that $U\psi = \psi$ for some unitary U . Then by symmetry, μ_ψ must be invariant under applying U . Note that if $M^\dagger\psi = \lambda$, then $(UM)^\dagger\psi = M^\dagger U^\dagger\psi = M^\dagger\psi = \lambda$ as well.

Let $\mu_{\psi,\lambda}$ be the measure over M 's obtained by starting from μ_ψ and then conditioning on $M^\dagger\psi = \lambda$. By the above observation, if μ_ψ is invariant under every such U , then $\mu_{\psi,\lambda}$ must also be invariant under U for every λ . In particular, this implies that $\mu_{\psi,\lambda}$ must be the uniform (Haar) measure on matrices M such that $M^\dagger\psi = \lambda$. Therefore, to draw a sample M from μ_ψ , one can first draw λ from ν_ψ , and then draw M uniformly (according to the Haar measure) such that $M^\dagger\psi = \lambda$.

Now suppose that $U\psi = \phi$. Let M be drawn from μ_ϕ and N be drawn from μ_ψ . By strong symmetry, the distribution of UN is the same as the distribution of M . However, we also know that $(UN)^\dagger\phi = N^\dagger U^\dagger\phi = N^\dagger\psi$. Hence, the induced distribution of $(UN)^\dagger\phi$ is the same as the induced distribution of $N^\dagger\psi$. However, by strong symmetry the former distribution is ν_ϕ , and the latter distribution is ν_ψ . Hence, $\nu_\psi = \nu_\phi = \nu$ for all ϕ and ψ as desired. ■

By the Lebesgue decomposition theorem, ν can be uniquely decomposed as $\nu = \nu_S + \nu_C$, where ν_C is absolutely continuous with respect to the Lebesgue measure on $\mathbb{C}\mathbb{P}^{d-1}$, and ν_S is singular with respect to the Lebesgue measure on $\mathbb{C}\mathbb{P}^{d-1}$. As in the previous section, we now show that maximum nontriviality implies that ν_C has positive total measure, and we restrict our attention to ν_C in future parts.

Lemma 11. In any maximally nontrivial, strongly symmetric theory with $\Lambda = U(d)$ and action a given by left multiplication, ν_C has positive total measure.

Proof. By Lemma 10, if M is drawn from μ_ψ , then M^\dagger maps ψ to a state λ chosen from ν and maps ϕ uniformly at random to a state λ' with inner product $|\langle\psi|\phi\rangle| = |\langle\lambda|\lambda'\rangle|$. Likewise, if N is drawn from μ_ϕ , then N^\dagger maps ϕ to a state λ' chosen from ν and maps ψ uniformly at random to a state λ with inner product $|\langle\psi|\phi\rangle| = |\langle\lambda|\lambda'\rangle|$.

By maximum nontriviality, μ_ψ and μ_ϕ have nontrivial overlap for any nonorthogonal ψ and ϕ . Let $S = \text{Supp}(\nu)$. Since μ_ψ and μ_ϕ have nontrivial overlap for all nonorthogonal ψ and ϕ , we must have that for all $r \in (0, 1]$, if λ is chosen according to ν and λ' is chosen uniformly such that $|\langle\lambda|\lambda'\rangle| = r$, then $\lambda' \in S$ with positive probability. In particular, there must exist some $\lambda \in S$ such that, if r is chosen uniformly at random in $(0, 1)$ and λ' is chosen uniformly at random such that $|\langle\lambda|\lambda'\rangle| = r$, then $\lambda' \in S$ with positive probability. This immediately implies that S has positive Lebesgue measure, since the Lebesgue measure of S can be expressed as the integral of the indicator for $\lambda' \in S$ over $\mathbb{C}\mathbb{P}^{d-1}$, which can be written in polar coordinates centered about λ . The integral is positive by the preceding observation. Hence, $S = \text{Supp}(\nu)$ has positive Lebesgue measure and ν_C has positive total measure. ■

As before, we now assume that $\nu = \nu_C$; i.e., we discard the singular part of ν . We can do this without loss of generality since our contradiction does not rely on the normalization of ν .

Next we show that it is easy to find states $\{\Psi_1, \Psi_2, \Psi_3\}$ such that the μ_{Ψ_i} have nontrivial joint overlap; i.e., the intersection of their supports is a set of positive measure. The proof makes

crucial use of the Lebesgue density theorem. The Lebesgue density theorem says that for any set S of positive measure, for almost every point in S , the density of S at that point is 1. More formally, the density of S at point x , denoted $d_x(S)$, is defined as

$$d_x(S) = \lim_{\epsilon \rightarrow 0^+} \frac{\mu(B_\epsilon(x) \cap S)}{\mu(B_\epsilon(x))},$$

where μ is the Lebesgue measure and $B_\epsilon(x)$ is the ϵ -ball centered at x . The Lebesgue density theorem says that for any measurable set S , the set $T = \{x \in S : d_x(S) = 1\} \subseteq S$ differs from S by at most a set of measure zero. In particular T has the same measure as S . The points $x \in S$ such that $d_x(S) = 1$ are called the Lebesgue density points of S .

Lemma 12. For any strongly symmetric theory with $\Lambda = U(d)$, there exists a set $T \subseteq \mathbb{C}\mathbb{P}^{d-1}$ such that

- (1) T has positive measure;
- (2) if $M^\dagger\psi \in T$ then M is a Lebesgue density point of $\text{Supp}(\mu_\psi)$;
- (3) if μ_ψ and μ_ϕ have nontrivial overlap, then there exists M such that $M^\dagger\psi \in T$ and $M^\dagger\phi \in T$;
- (4) for any three states Ψ_1, Ψ_2, Ψ_3 such that there exists M with $M^\dagger\Psi_i \in T$ for each $i = 1, 2, 3$, the intersection $\text{Supp}(\mu_{\Psi_1}) \cap \text{Supp}(\mu_{\Psi_2}) \cap \text{Supp}(\mu_{\Psi_3})$ has positive measure.

Proof. Let $S = \text{Supp}(\nu)$ and let $S'_\psi = \text{Supp}(\mu_\psi)$. Note that S and S'_ψ have positive measure by Lemma 11. Let T'_ψ be the set of Lebesgue density points of S_ψ . Let $T = \{M^\dagger\psi : M \in T'_\psi\}$.

First note that the definition of T is independent of our choice of ψ . Indeed, by strong symmetry, if $U\psi = \phi$, then $UT'_\psi = T'_\phi$, where the notation US denotes the set $\{Us : s \in S\}$. Therefore,

$$\begin{aligned} T &= \{M^\dagger\psi : M \in T'_\psi\} = \{(UM)^\dagger U\psi : M \in T'_\psi\} \\ &= \{M^\dagger\phi : M \in T'_\phi\}. \end{aligned}$$

Second, note that $T \subseteq S$ since $T'_\psi \subseteq S'_\psi$. Furthermore, since T'_ψ differs from S'_ψ only by a set of measure zero, T differs from S only by a set of measure zero as well. Hence, T has positive measure, which proves property (1).

Also, T precisely characterizes T'_ψ , in the sense that $M \in T'_\psi$ if and only if $M^\dagger\psi \in T$. The “if” direction follows directly from the definition, while the “only if” direction follows from the fact that once $M^\dagger\psi$ is fixed, the distribution of M under μ_ψ is uniform over the remaining degrees of freedom by Lemma 10. This proves property (2).

Next suppose that μ_ψ and μ_ϕ have nontrivial overlap, i.e., $\text{Supp}(\mu_\psi) \cap \text{Supp}(\mu_\phi)$ has positive measure. Then by Lemma 10, the set $\{M : M^\dagger\psi \in S \text{ and } M^\dagger\phi \in S\}$ has positive measure as well. Since T differs from S only by a set of measure zero, this implies that $\{M : M^\dagger\psi \in T \text{ and } M^\dagger\phi \in T\}$ has positive measure also. Hence, there exists an M such that $M^\dagger\psi \in T$ and $M^\dagger\phi \in T$. This proves property (3).

Finally suppose that for three states Ψ_1, Ψ_2, Ψ_3 there exists an M with $M^\dagger\Psi_i \in T$ for each $i = 1, 2, 3$. By property (2) we know that M is a Lebesgue density point of $\text{Supp}(\mu_{\Psi_i})$ for each i . Suppose that we perturb M by a small amount $\epsilon > 0$ uniformly at random to obtain a new matrix N . More formally, choose N according to the Haar measure on $B_\epsilon(M)$. Since M is a Lebesgue density point of $\text{Supp}(\mu_{\Psi_i})$, by choosing small enough ϵ , the density of $\text{Supp}(\mu_{\Psi_i})$ in $B_\epsilon(M)$ can be made

arbitrarily close to 1. Therefore, by choosing ϵ small enough, we can ensure that for each i , the probability that $N^\dagger \Psi_i \in T$ is at least (say) 0.99.

The events $N^\dagger \Psi_i \in T$ are not necessarily independent, but by the union bound the probability that $N^\dagger \Psi_i \in T$ for all $i = 1, 2, 3$ is at least 0.97. Hence, N will be in $\text{Supp}(\mu_{\Psi_1}) \cap \text{Supp}(\mu_{\Psi_2}) \cap \text{Supp}(\mu_{\Psi_3})$ with positive probability. This implies that $\text{Supp}(\mu_{\Psi_1}) \cap \text{Supp}(\mu_{\Psi_2}) \cap \text{Supp}(\mu_{\Psi_3})$ has positive Lebesgue measure, and hence the μ_{Ψ_i} have nontrivial joint overlap, which proves property (4). ■

Now we show that if Ψ_1 , Ψ_2 , and Ψ_3 are chosen appropriately, then there exists an orthonormal basis $\{e_1, \dots, e_d\}$ such that for all i , there exists a j such that $\langle e_i | \psi_j \rangle = 0$. In particular such a basis exists if Ψ_1 and Ψ_2 are “nearly orthogonal” and Ψ_3 is not coplanar with Ψ_1 and Ψ_2 .

Lemma 13. Let u_1 and u_2 be orthonormal vectors, and let Ψ_3 be a state that is not coplanar with u_1 and u_2 . In particular, assume that $|\langle \Psi_3 | u_1 \rangle|^2 + |\langle \Psi_3 | u_2 \rangle|^2 \leq k$ for some fixed $k < 1$. Then there exists a $k' > 0$ (depending on k) such that if $\Psi_1 = u_1$ and Ψ_2 is in the u_1, u_2 plane such that $0 < |\langle \Psi_1 | \Psi_2 \rangle| < k'$, then there exists an orthonormal basis $\{e_1, \dots, e_d\}$ such that for all $i = 1 \dots d$ there exists $j \in \{1, 2, 3\}$ such that $\langle e_i | \psi_j \rangle = 0$.

Proof. Set $\Psi_1 = u_1$. Without loss of generality, we can set

$$\Psi_2 = \frac{au_1 + u_2}{\sqrt{|a|^2 + 1}}$$

for some complex parameter a which we have yet to specify. By the Gram-Schmidt process, there exists a vector u_3 , and complex coefficients b, c , such that

$$\Psi_3 = \frac{bu_1 + cu_2 + u_3}{\sqrt{|b|^2 + |c|^2 + 1}},$$

where $\{u_1, u_2, u_3\}$ is an orthonormal basis for the subspace spanned by Ψ_1 , Ψ_2 , and Ψ_3 . Note that the statement $|\langle \Psi_3 | u_1 \rangle|^2 + |\langle \Psi_3 | u_2 \rangle|^2 \leq k$ implies that $b, c \leq f(k)$ for some function f of k .

Now consider the following three (non-normalized) vectors, parameterized by $x \in \mathbb{C}$:

$$\begin{aligned} e_1 &= xu_2 + u_3, \\ e_2 &= u_1 - a^*u_2 + a^*x^*u_3, \\ e_3 &= a(1 + x^*x)u_1 + u_2 - x^*u_3. \end{aligned}$$

By construction the e_i 's are orthogonal to one another, e_1 is orthogonal to Ψ_1 , and e_2 is orthogonal to Ψ_2 . We would like to have

$$\langle e_3 | \Psi_3 \rangle = ba^*(1 + |x|^2) + c - x = 0$$

as well. If either $a = 0$ or $b = 0$, we can achieve this by simply setting $x = c$, so assume a and b are nonzero. Also, let $w = \frac{ba^*}{|ba^*|}$, which has norm 1. Then setting $\langle e_3 | \Psi_3 \rangle = 0$ is equivalent to setting

$$|ba^*|(1 + |x|^2) + cw - xw = 0.$$

Setting $xw = p + iq$ for real p, q gives

$$\begin{aligned} |ba^*|(1 + p^2 + q^2) + \text{Re}(cw) - p &= 0, \\ \text{Im}(cw) - q &= 0. \end{aligned}$$

Plugging the value of q from the second equation into the first gives a quadratic in p ,

$$|ba^*|p^2 - p + |ba^*|[1 + \text{Im}(cw)^2] + \text{Re}(cw) = 0.$$

This has a real solution in p if and only if

$$1 - 4|ba^*|\{|ba^*|[1 + \text{Im}(cw)^2] + \text{Re}(cw)\} \geq 0.$$

Note that b, c are bounded above by $f(k)$ as noted above. By making Ψ_1 nearly orthogonal to Ψ_2 , we can choose a arbitrarily close to zero. This makes the left-hand side of the inequality arbitrarily close to 1, so the inequality will hold. Hence, we can solve for x and find an e_3 that is orthogonal to Ψ_3 . Therefore, if $|\langle \Psi_1 | \Psi_2 \rangle| < k'$ for some k' which depends on k , then the desired orthonormal basis exists.

This gives a basis e_1, e_2, e_3 for the subspace spanned by Ψ_1, Ψ_2 , and Ψ_3 such that $\langle e_i | \Psi_i \rangle = 0$ for each $i = 1, 2, 3$. If the dimension of the space d is more than 3, any extension of this basis to e_1, \dots, e_d has the property that for all $i = 1, \dots, d$, there exists a $j \in \{1, 2, 3\}$ such that $\langle e_i | \psi_j \rangle = 0$. ■

Our no-go theorem follows from the above observations.

Theorem 3. There are no strongly symmetric, maximally nontrivial ψ -epistemic theories with $\Lambda = U(d)$ in dimension $d \geq 3$.

Proof. Suppose a strongly symmetric, maximally nontrivial theory exists with $\Lambda = U(d)$ in dimension $d \geq 3$. We find three states Ψ_1, Ψ_2 , and Ψ_3 with the following two properties.

- (A) $\mu_{\Psi_1}, \mu_{\Psi_2}$, and μ_{Ψ_3} have nontrivial joint overlap and
- (B) there exists an orthonormal basis e_1, \dots, e_d such that for all $i = 1, \dots, d$, there exists a $j \in \{1, 2, 3\}$ such that $\langle e_i | \psi_j \rangle = 0$.

The contradiction follows as in the proof of Theorem 2. Consider making a measurement in the basis e_1, \dots, e_d . Let $S = \text{Supp}(\mu_{\Psi_1}) \cap \text{Supp}(\mu_{\Psi_2}) \cap \text{Supp}(\mu_{\Psi_3})$, and consider ontic states $M \in S$. Note that $M \in \text{Supp}(\mu_{\Psi_j})$, and that for each $j = 1, 2, 3$ and each e_i , there exists a $j \in \{1, 2, 3\}$ such that $\langle e_i | \Psi_j \rangle = 0$. So by the Born rule, for each i at most a set of measure zero of $M \in S$ can return answer e_i with positive probability. Since each $M \in S$ gives some outcome e_i under measurement, S must have measure zero. However, S has positive measure by property (A), which is a contradiction.

Using Lemma 12, one can show that for all nonorthogonal states Ψ_1 and Ψ_2 , there exists a state Ψ_3 not coplanar with Ψ_1 and Ψ_2 such that the states have property (A).³ By Lemma 13, if Ψ_1 and Ψ_2 are “nearly orthogonal,” and Ψ_3 is not coplanar with Ψ_1 and Ψ_2 , then the states have property (B). These two facts nearly suffice to guarantee the existence of three states with properties (A) and (B), but they fall short. The reason is that the degree to which Ψ_1 and Ψ_2 must be “nearly orthogonal” depends on the choice of Ψ_3 . Although for every Ψ_1 and Ψ_2 there exists a noncoplanar Ψ_3 which has property (A),

³Indeed, by Lemma 12 there exists a set T with the four properties defined in the lemma. Given Ψ_1 and Ψ_2 which are nonorthogonal, by property 3 of T there exists an M such that $M^\dagger \Psi_1 \in T$ and $M^\dagger \Psi_2 \in T$. Since T has positive measure by property 1, there exists a Ψ_3 not coplanar with Ψ_1 and Ψ_2 such that $M^\dagger \Psi_3 \in T$ as well. These three states have nontrivial joint overlap by property 4 of T .

the choice of Ψ_3 could depend arbitrarily on Ψ_1 and Ψ_2 , so in particular could be such that property (B) is not satisfied.

To fix this, we consider an infinite sequence of quantum states ψ_n and ϕ_n of decreasing inner product. For each n , there exists a χ_n that shares property (A) with ψ_n and ϕ_n . Since $\mathbb{C}\mathbb{P}^{d-1}$ is compact, even though the χ_n 's might "wander" in $\mathbb{C}\mathbb{P}^{d-1}$, by passing to a subsequence we can assume they converge to fixed state χ , which we show can be chosen to be noncoplanar with ψ_n and ϕ_n for large n . This allows us to "nail down" the choice of χ_n so that we can apply Lemma 13 to $\Psi_1 = \psi_n$, $\Psi_2 = \phi_n$, and $\Psi_3 = \chi_n$.

More precisely, by Lemma 12, there exists a set T with the following properties:

- (1) T has positive measure;
- (2) If $M^\dagger \psi \in T$ then M is a Lebesgue density point of $\text{Supp}(\mu_\psi)$;
- (3) If μ_ψ and μ_ϕ have nontrivial overlap, then there exists an M such that $M^\dagger \psi \in T$ and $M^\dagger \phi \in T$;
- (4) For any three states Ψ_1, Ψ_2, Ψ_3 such that there exists an M with $M^\dagger \Psi_i \in T$ for each $i = 1, 2, 3$, the intersection $\text{Supp}(\mu_{\Psi_1}) \cap \text{Supp}(\mu_{\Psi_2}) \cap \text{Supp}(\mu_{\Psi_3})$ has positive measure.

Consider a sequence of quantum states ψ_n, ϕ_n such that $\psi_n \rightarrow \psi$ and $\phi_n \rightarrow \phi$ for orthogonal states ψ and ϕ as $n \rightarrow \infty$, but $|\langle \psi_n | \phi_n \rangle| > 0$ for all $n \in \mathbb{N}$. For each n , by maximum nontriviality μ_{ψ_n} and μ_{ϕ_n} have nontrivial overlap, and there exists an M_n such that $M_n^\dagger \psi_n \in T$ and $M_n^\dagger \phi_n \in T$ by property (3) of T .

Let $\tilde{\psi}_n = M_n^\dagger \psi_n$, and let $\tilde{\phi}_n = M_n^\dagger \phi_n$. By construction $\tilde{\psi}_n, \tilde{\phi}_n \in T$. These form sequences in $\mathbb{C}\mathbb{P}^{d-1}$. Since $\mathbb{C}\mathbb{P}^{d-1}$ is compact, there exists a subsequence of the $\tilde{\psi}_n$'s which approaches some $\tilde{\psi}$ as $n \rightarrow \infty$. Therefore, by passing to a subsequence, there exists $\tilde{\psi}$ and $\tilde{\phi}$ such that $\tilde{\psi}_n \rightarrow \tilde{\psi}$ and $\tilde{\phi}_n \rightarrow \tilde{\phi}$ as $n \rightarrow \infty$.

Since T has positive measure by property (1), there exists a $\tilde{\chi} \in T$ that is not coplanar with $\tilde{\psi}$ and $\tilde{\phi}$. Fix such a $\tilde{\chi}$, and let $\chi_n = M_n \tilde{\chi}$. Passing to a subsequence again, we have that $\chi_n \rightarrow \chi$ for some state χ . Note χ is not coplanar with ψ and ϕ , since the M_n^\dagger 's preserve inner products. Also note that for each n , we have $M_n^\dagger \psi_n, M_n^\dagger \phi_n, M_n^\dagger \chi_n \in T$. So by property 4 of T , the measures $\mu_{\psi_n}, \mu_{\phi_n}$, and μ_{χ_n} have property (A) (nontrivial joint overlap) for each n .

Now as $n \rightarrow \infty$, we have that $|\langle \psi_n | \phi_n \rangle| \rightarrow 0$, and yet at the same time $\chi_n \rightarrow \chi$ for some fixed state χ which is not coplanar with ψ and ϕ . Hence, for sufficiently large n , if $e_{1,n}$ and $e_{2,n}$ span the ψ_n, ϕ_n plane, then we will have $|\langle e_{1,n} | \chi_n \rangle|^2 + |\langle e_{2,n} | \chi_n \rangle|^2 \leq k$ for some $k < 1$. By Lemma 13, there exists a k' such that if $|\langle \psi_n | \phi_n \rangle| < k'$, then property (B) holds for ψ_n, ϕ_n , and χ_n . For sufficiently large n , we have $|\langle \psi_n | \phi_n \rangle| < k'$, since $|\langle \psi_n | \phi_n \rangle| \rightarrow 0$, and hence property (B) holds for these states.

Putting this together, we can find a value of n such that the three states $\Psi_1 = \psi_n$, $\Psi_2 = \phi_n$, and $\Psi_3 = \chi_n$ have both properties (A) and (B). The contradiction follows as noted above. ■

IV. CONCLUSIONS AND OPEN PROBLEMS

In this paper, we gave a construction of a maximally nontrivial theory in arbitrary finite dimensions. However, the

theory we constructed is not symmetric and is rather unnatural. We then proved that symmetric, maximally nontrivial ψ -epistemic theories do not exist in dimensions $d \geq 3$ (in contrast to the $d = 2$ case, where the Kochen-Specker theory provides an example). Our impossibility proof made heavy use of the symmetry assumption. As for the assumption $d \geq 3$, we used that in two places: first and most importantly to get a nonempty deficiency region (in Corollary 3) and, second, to prove that $r_\psi = \frac{1}{2}$ in Lemma 5.

It might be possible to relax our symmetry assumption and obtain no-go theorems for different ontic spaces, since deficiency holds for any ψ -epistemic theory in $d \geq 3$ even without a symmetry assumption. As shown above, we can generalize our no-go theorem to rule out strongly symmetric maximally nontrivial theories with $\Lambda = U(d)$. It would be particularly interesting to know whether (merely) symmetric theories exist in $\Lambda = U(d)$, or in any ontic spaces Λ that are larger than $\mathbb{C}\mathbb{P}^{d-1}$, but that are still acted on by the d -dimensional unitary group.

Also, in our proof, we did not use the specific form of the Born rule, only the fact that projection of $|\psi\rangle$ onto $|\phi\rangle$ must occur with probability 0 if $\langle \psi | \phi \rangle = 0$. Additional properties of the Born rule might place further constraints on ψ -epistemic theories.

Interestingly, trying to generalize the proof of Theorem 1 directly to obtain a proof of Theorem 2 gives rise to a variant of the Kakeya/Besicovitch problem. Recall that to prove Theorem 1, we showed that ontic states in a set B in the neighborhood of α returned value j under measurement, and yet the average measure of states orthogonal to j had nontrivial support on B . Now if the measures $\mu_\psi = f_\psi(|\langle \psi | \lambda \rangle|^2)$ vary with ψ , it remains open whether the measures of states orthogonal to j must have support on B , or if instead it is possible for them to "evade" B to avoid contradicting the Born rule.

Placing this problem in the plane rather than in $\mathbb{C}\mathbb{P}^{d-1}$, we obtain a clean Kakeya-like problem as follows. Let S be a subset of \mathbb{R}^2 with the following property. For all $x \in \mathbb{R}^2$ and $\varepsilon > 0$, S contains a set of circles, centered at x , that has positive Lebesgue measure within the annulus $\{y : |y - x| \in [1 - \varepsilon, 1]\}$. Can the complement of S have positive Lebesgue measure? This question has been discussed on MathOverflow [13] but remains open.

Here are some additional open problems.

(i) An obvious problem is whether symmetric (and nontrivial (but not necessarily *maximally* nontrivial) theories exist in dimensions $d \geq 3$.

(ii) How does the size of the deficiency region scale as the dimension d increases?

(iii) In the maximally nontrivial theory we constructed, the overlap between any two nonorthogonal states $|\psi\rangle, |\phi\rangle$ is vanishingly small: like $(\varepsilon/d)^{O(d)}$ as a function of the dimension d and inner product $\varepsilon = |\langle \psi | \phi \rangle|$. Is it possible to construct a theory with substantially higher overlaps – say, $(\varepsilon/d)^{O(1)}$? (Note that if $d \geq 3$, then the result of Leifer and Maroney [5] says that the overlap cannot achieve its "maximum" value of ε^2 .)

(iv) Can we construct ψ -epistemic theories with the property that an ontic state λ , in the support of an ontic distribution μ_ψ , can *never* be used to recover the quantum state ψ uniquely? (This question was previously asked

by Leifer and Maroney [5], as well as by Montina on MathOverflow [10].)

(v) What can be said about the case of infinite-dimensional Hilbert spaces?

ACKNOWLEDGMENTS

We thank Andrew Drucker for discussions about the measure-theoretic aspects of this paper and Matt Leifer and Terry Rudolph for discussions about ψ -epistemic theories in general. We also thank Terence Tao, Sean Eberhard, Ramiro de

la Vega, Scott Carnahan, and Alberto Montina for discussions on MathOverflow. S.A. was supported by the National Science Foundation under Grant No. 0844626 and by an NSF STC grant, a TIBCO Chair, a Sloan Fellowship, and an Alan T. Waterman Award. A.B. was supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1122374 and by the Center for Science of Information (CSoI), an NSF Science and Technology Center, under Grant Agreement No. CCF-0939370. L.C. was supported by the MIT Summer Program for Undergraduate Research.

-
- [1] J. S. Bell, *Physics* **1**, 195 (1964).
 - [2] S. Kochen and E. P. Specker, *J. Math. Mech.* **17**, 59 (1967).
 - [3] M. F. Pusey, J. Barrett, and T. Rudolph, *Nat. Phys.* **8**, 476 (2012).
 - [4] O. J. E. Maroney, [arXiv:1207.6906](https://arxiv.org/abs/1207.6906).
 - [5] M. S. Leifer and O. J. E. Maroney, *Phys. Rev. Lett.* **110**, 120401 (2013).
 - [6] N. Harrigan and R. W. Spekkens, *Found. Phys.* **40**, 125 (2010).
 - [7] L. Hardy, *Int. J. Mod. Phys. B* **27**, 1345012 (2013).
 - [8] M. K. Patra, S. Pironio, and S. Massar, *Phys. Rev. Lett.* **111**, 090402 (2013).
 - [9] P. G. Lewis, D. Jennings, J. Barrett, and T. Rudolph, *Phys. Rev. Lett.* **109**, 150404 (2012).
 - [10] <http://mathoverflow.net/questions/95537/psi-epistemic-theories-in-3-or-more-dimensions>.
 - [11] N. Harrigan and T. Rudolph, [arXiv:0709.4266](https://arxiv.org/abs/0709.4266).
 - [12] T. Rudolph, [arXiv:quant-ph/0608120](https://arxiv.org/abs/quant-ph/0608120).
 - [13] <http://mathoverflow.net/questions/108507/a-kekeya-like-problem-must-a-union-of-annuli-fill-the-plane>.