Probing the reality of quantum states

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Outline

- The operational view (of physical theories)
- Physics or metaphysics?
    1. Quantum mechanics (QM) and hidden variable theories (HVT)
    2. Epistemic vs. ontic
    3. Previous work
- The main theorem
- The experiment and its interpretation
- Questions for the future

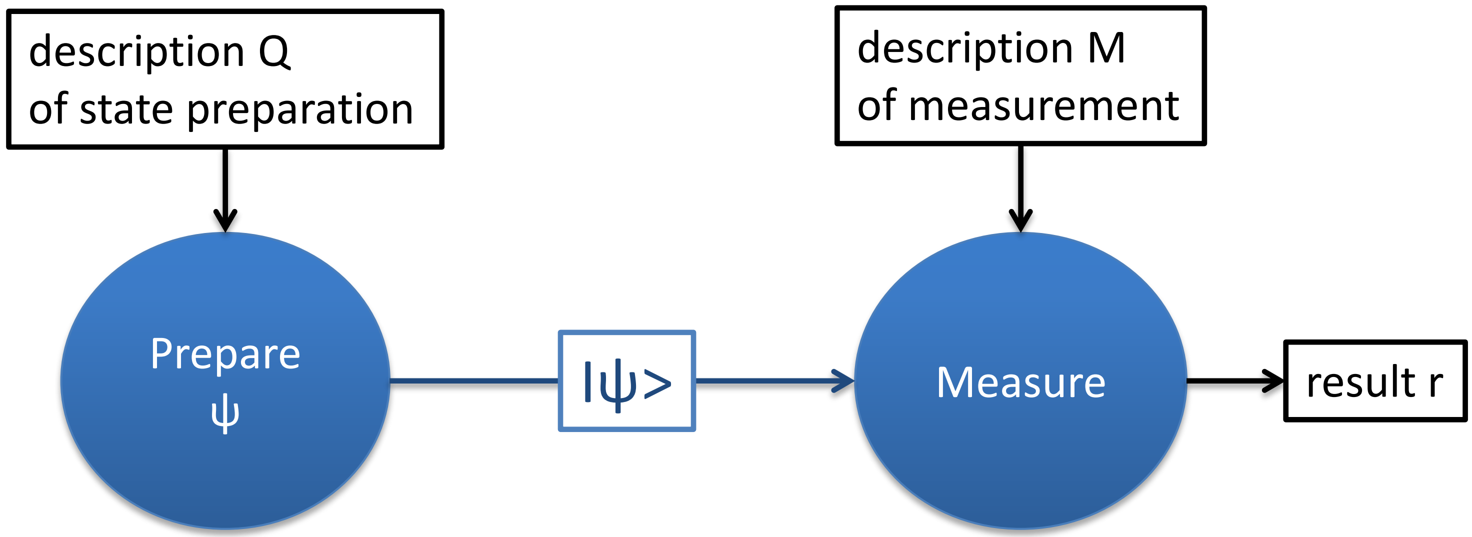
The operational view

- The primitives are 3 procedures: preparation, transformation and measurement.
- Must be specified in "classical language".
- The main problem of any theory is to calculate the transition probabilities: $P(r|M,T,Q)$
- M,T,Q are measurement, transformation and preparations and *r* is an outcome or effect.
- Quantum theory provides a recipe for calculating these probabilities. Are there any other?

States and effects

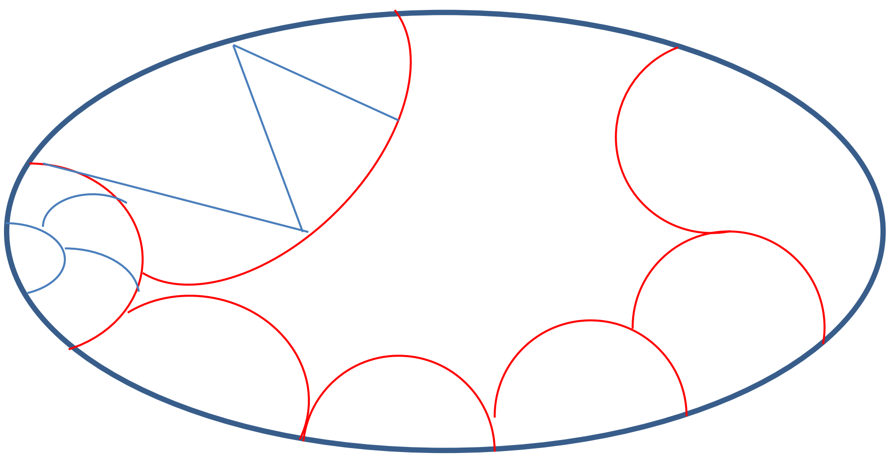
- Several preparations may give rise to the same distribution of outputs/results for any measurement (and transformation).
- They are considered equivalent.
- A state is an equivalence class of preparations. A theory partitions the set of preparations into disjoint subsets: the states.

Quantum Theory



$P(r|M,\psi)$=Born Rule

- The quantum state parameterizes an equivalence of preparation.
- So does any other theory of physical processes.
- Example: thermodynamic state vs. microstate.



Operational definition of reality

- We can now define the nature of states in one theory with respect to another.
- *Quantum states are real in the more complete "hidden variable" model if its states are completely contained in a quantum state.*
- This implies if two preparations can be distinguished by QM then it is also true in the HVT.

- …at the 1984 Santa Fe Workshop…more than one was heard to say “The experimental evidence now forces us to believe that atoms are not real.”

E. T. Jaynes, *Clearing up mysteries*

- Let us get real.
- There is set Λ of *ontic states*.
- They are the “real” states of individual system.
- Corresponding to each preparation Q there is a prob. density

$$P(\lambda|Q), \lambda \in \Lambda$$

- There is prob. density for the outcomes r of measurement M in the ontic states: $P(r|M, \lambda)$

The touchstone

- QM is the only theory of microsystems (and larger) that we have. So we can test.

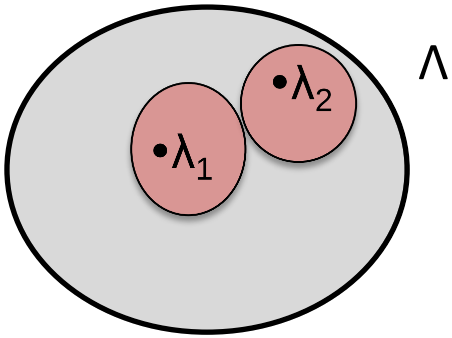
$$\int_{\Lambda} P(r|M,\lambda)P(\lambda|Q)\mathrm{d}\lambda = P(r|M,\psi_Q)$$

Or the discrete version

$$\sum P(r|M,\lambda)P(\lambda|Q) = P(r|M,\psi_Q)$$

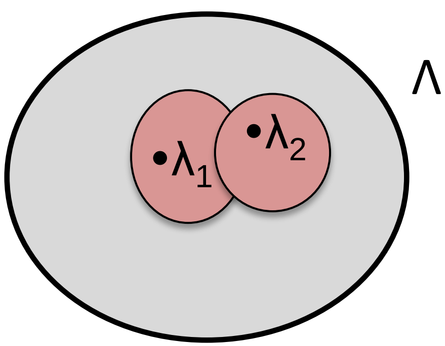
ψ-ontic vs. ψ-epistemic

- ψ-ontic (real!)



$$\forall Q_1, Q_2 \quad P(\lambda|Q_1)P(\lambda|Q_2) = 0 \text{ for } \psi_{Q_1} \neq \psi_{Q_2}$$

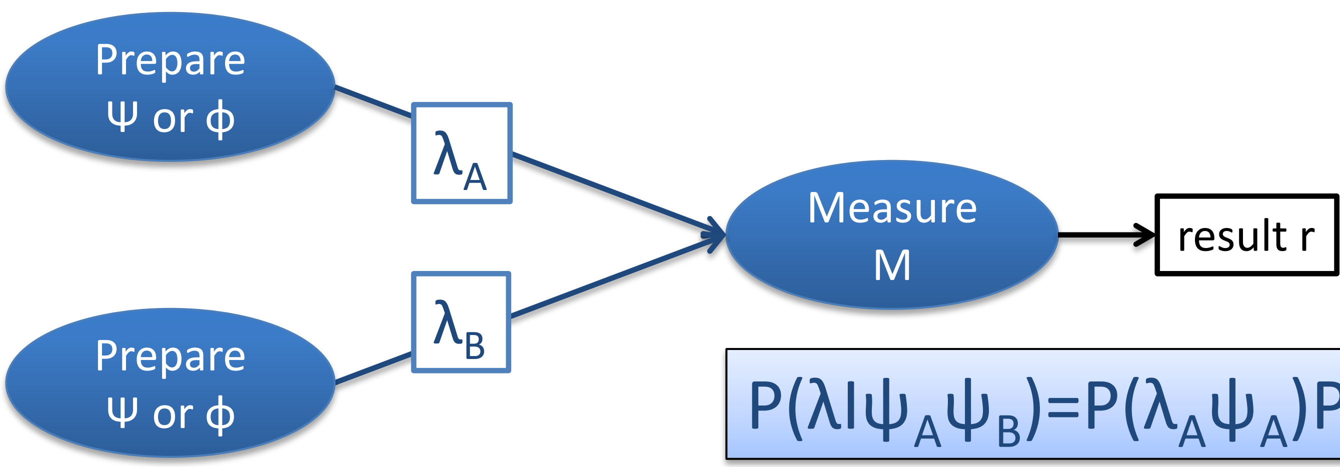
- ψ-epistemic



$$\exists Q_1, Q_2 \quad P(\lambda|Q_1)P(\lambda|Q_2) > 0 \text{ for } \psi_{Q_1} \neq \psi_{Q_2}$$

Ψ-Epistemic Models : Prior Work

- Einstein, Bell, Kochen and Specker, Spekkens….
- In any finite dimension d, there exist non trivial ψ-epistemic models (LBJR12)
- Assuming <u>preparation independence</u>, Epistemic models are incompatible with quantum mechanics (PBR12)



$$P(\lambda | \psi_A \psi_B) = P(\lambda_A \psi_A) P(\lambda_B \psi_B)$$

See ColbeckRenner11&12, Hardy12 for other no go theorems.

Continuous epistemic models (Informal)

- Continuity Assumption:

For fixed λ, P(λIψ) depends continuously on ψ

(except perhaps at some isolated points)

  - Not true for ψ-ontic models
  - Natural for ψ-epsitemic models

- Continuous ψ-epistemic models are incompatible with quantum theory

Continuous epistemic models

CONTINUITY ASSUMPTION

- Fix ψ
- For all Φ such that $|\langle\Phi|\Psi\rangle|^2 \geq 1-\delta$

There exists λ such that $P(\lambda|\text{ Prepare }\Psi) > 0$ *and* $P(\lambda|\text{ Prepare }\Phi) > 0$

NO GO THEOREM

- Fix dimension d
- Continuity assumption incompatible with quantum mechanics if $\delta \geq 1/(d-1)$

Continuity Assumption:

- Fix ψ
- For all Φ such that $|\langle\Phi|\Psi\rangle| \geq 1-\delta$

There exists λ such that $P(\lambda|\text{Prepare } \Phi)>0$

NO GO THEOREM

- Fix dimension d
- Continuity assumption incompatible with quantum mechanics if $\delta \geq 1/(d-1)$

PROOF:

- Consider quantum states $$\Psi_k = \frac{\sum_{j\neq k} |j>}{\sqrt{d-1}}$$

- all Ψ_k at distance $1/(d-1)$ from each other
- Measure in Computational Basis:

$P(k|\Psi_k)=0$ for all k

- Continuous Epistemic Models:
  - By continuity there exists λ such that
    - $P(\lambda|\Psi_k)>0$ for all k
    - Definition: $\omega(\lambda)=\min_k P(\lambda|\Psi_k)$

➔ Contradiction:

$$0 = \Sigma_k P(k|\Psi_k) = \Sigma_k \Sigma_\lambda P(k|\lambda)\, P(\lambda|\Psi_k) \geq \Sigma_\lambda \Sigma_k P(k|\lambda)\omega(\lambda) = \Sigma_\lambda \omega(\lambda) > 0$$

Overcoming the dimension bound

From single systems to composite. Ontic state is a function of (λ_1, λ_2)

- Weak separability: If $P(\lambda_1|\psi_{Q_1})P(\lambda_2|\psi_{Q_2}) > 0$ then $P(\lambda_1, \lambda_2|\psi_{Q_1} \otimes \psi_{Q_2}) > 0$ <u>for independently prepared systems.</u>

No-go *theorem: there is no continuous epistemic model that is consistent with quantum theory.*

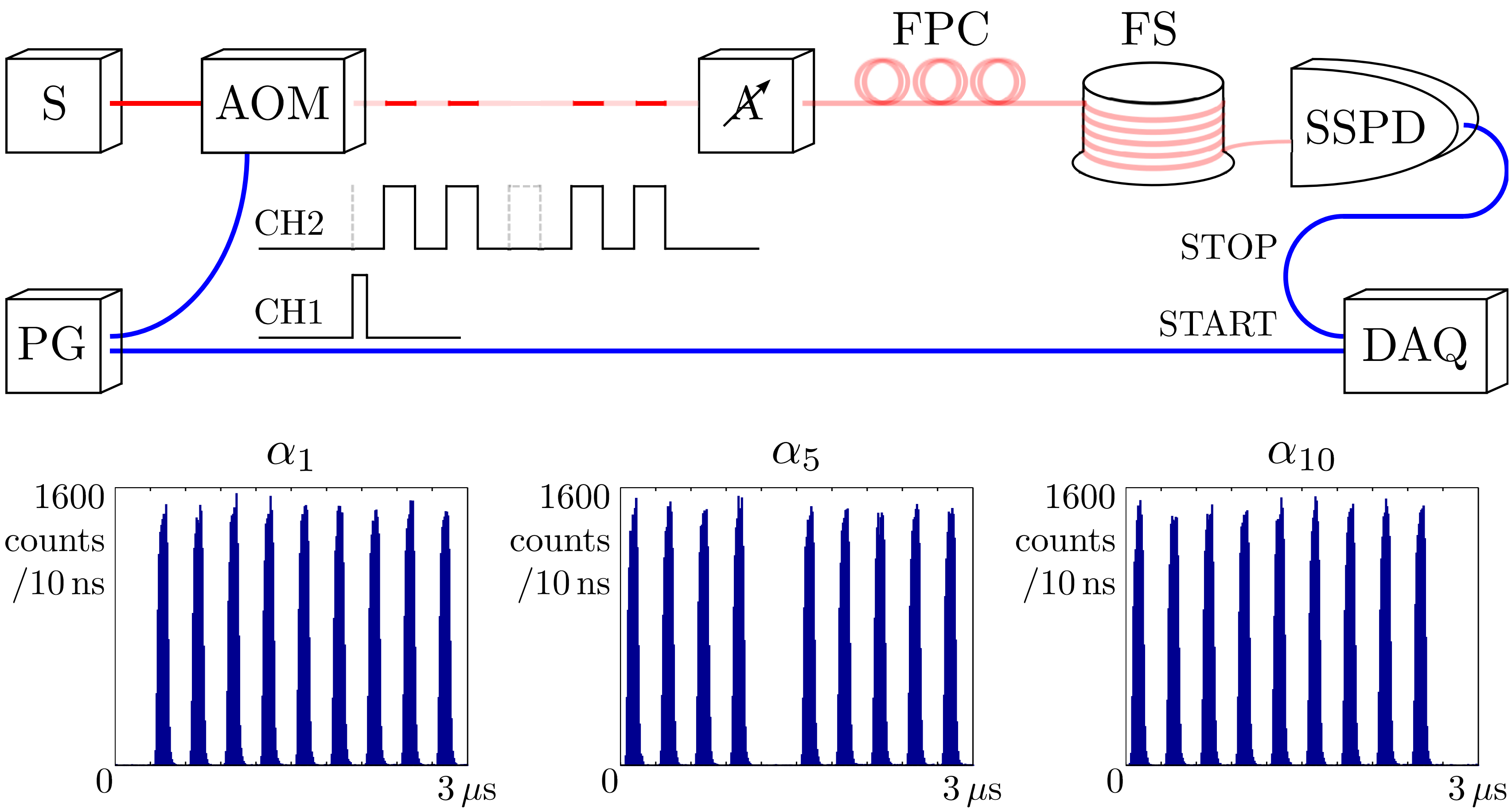
The alternatives

1. There are no epistemic HVT.
2. Quantum theory is not quite correct.
3. One of our assumptions must be discarded.

Experimental Test of Epistemic Models

Aim: produce $\Psi_k = \Sigma_{j \neq k} |j\rangle$

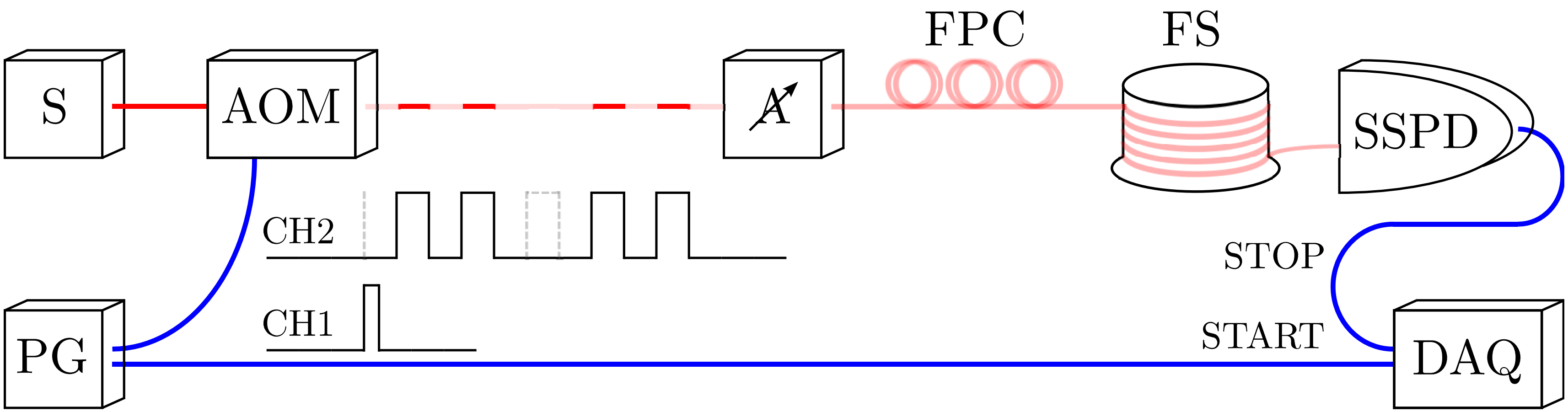
Method: Attenuated coherent states in multiple time bins



Experimental Test of Epistemic Models

Aim: produce $\Psi_k = N \sum_{j \neq k} |j\rangle$

Method: Attenuated coherent states in multiple time bins



<u>Technical specifications:</u>

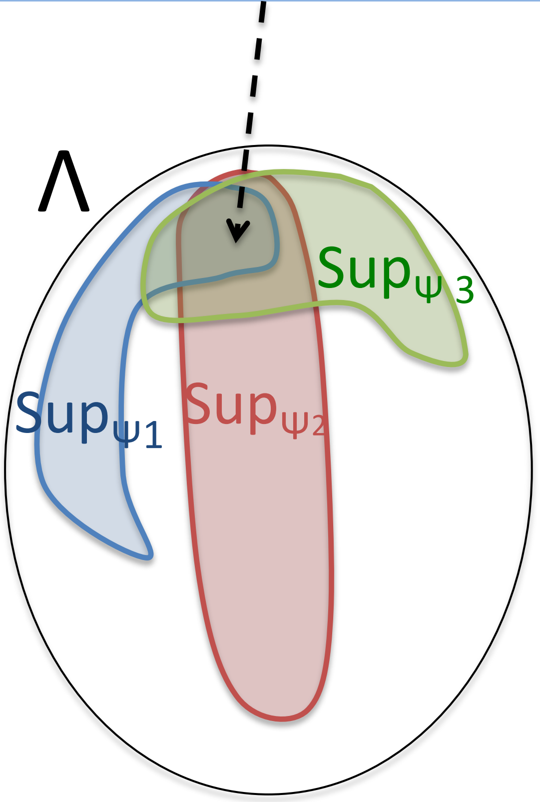
- S: 1550nm cw laser with coherence time 160µs
- AOM: extinction ratio: 50dB CW & 40dB pulsed. 25ns rise/fall time.
- Pulses: 100ns long separated by 200ns
- # pulses: 3 to 80 (total pulse train duration = 0.9µs to 24µs)
- Mean photon number in pulse train: <n>=0.2
- FS=5km fiber spool
- SSPD: 4% efficiency; 3Hz dark count rate

!!!
Interpretation:
Detection loophole
!!!

Interpretation: Detection Loophole
Need « Fair Sampling Assumption »

- Recall: key of no go theorem was existence of common epistemic state λ

If this intersection is non empty, then incompatiblity with quantum mechanics



Interpretation: Detection Loophole

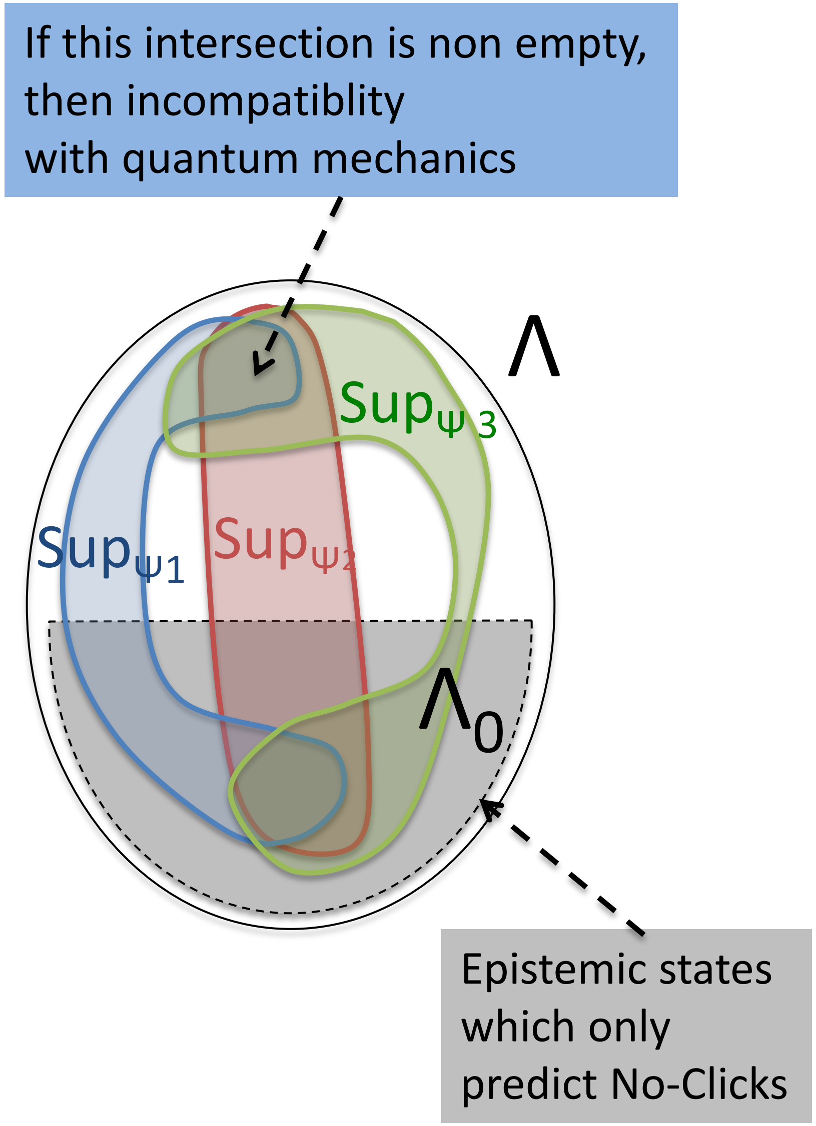
- Definitions:
  - $\omega_{Clk}(\lambda)=\min_k P(\lambda I \Psi_k \& Clk)$
  - Continuous Epistemic models with detection efficiency:

  $\omega_{Clk}(\lambda)$ not identically 0

- Mathematical identity:

$\varepsilon_{exp} = \Sigma_k P(k \mid \Psi_k \& Clk)$
$\geq \Sigma_\lambda \omega_{Clk}(\lambda)$

The experiment puts an upper bound on $\Sigma_\lambda \omega_{Clk}(\lambda) \leq 10^{-3}$



- The main issues are: existence of vacuum and two or more photon states.
- Use a relativized metric and estimate the low probabilities of higher Fock states.
- Use photon number superselection rule.
- Detection efficiency and dark counts.
- Condition everything on the “click” event.
- Use a gedanken alternative.
- Fluctuations in the input coherent state.
- Continuity takes care of this!

The third alternative: how “natural” are our assumptions?

- Continuity: discontinuous models lack aesthetic appeal!?
- We can replace continuity with measurability.

$P(\lambda|\psi_Q)$ has support whose probability > 0 (in the quantum state space) with respect to a continuous measure (e.g. Haar measure)

Without this the effect of “epistimicity” will be lost in any system with a bit of continuous noise.

Some questions for the futre

- General HVT with no-signalling constraints.
- Security analysis (of protocols)
- Improved experiments (closing the loopholes, single photons, entangled pairs)
- Epistemic HVTs with some locality assumptions in the presence of noise.
- Power of superbeings with access and control over hidden variable states.
- Are we resigned to the fact hidden variables will stay hidden from us?