A physically realist framework for quantum mechanics

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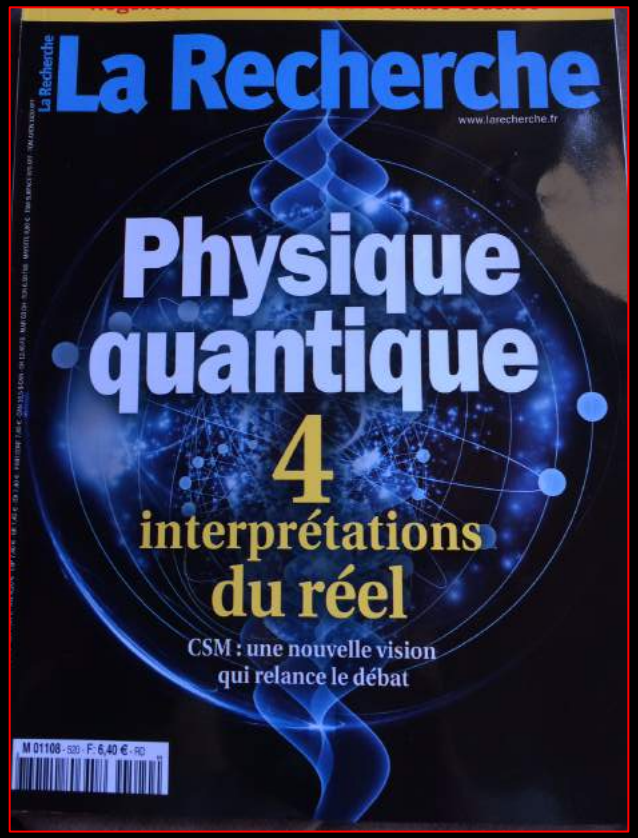
Collège de France, May 17, 2017

Manifeste pour un nouveau réalisme quantique

Un point de vue novateur propose de concilier l'existence d'une réalité indépendante de l'observateur avec l'importance du contexte expérimental.

Alexia Auffèves, physicienne, **Nayla Farouki,** philosophe, et **Philippe Grangier,** physicien



1 philosopher, 2 physicists, 1 motivation

- Introduce the « quantum stuff » with **words**, not maths
- *« Ontology first, formalism second! »*

A few words

Ontology Defines what exists [metaphysics, speculation]. Ontology is postulated
Epistemology Defines what can be known

Realism Statement that things exist, even if unobserved
State Mode of existence of a thing

Objectivity Statement that things have a state (even if even unobserved), and I can know it

Outline

- **Introduction: What is a physical state?**
  => *The « quantum problem »*

- Rebuilding a quantum ontology
- Revisiting quantumness
- Recovering the quantum formalism

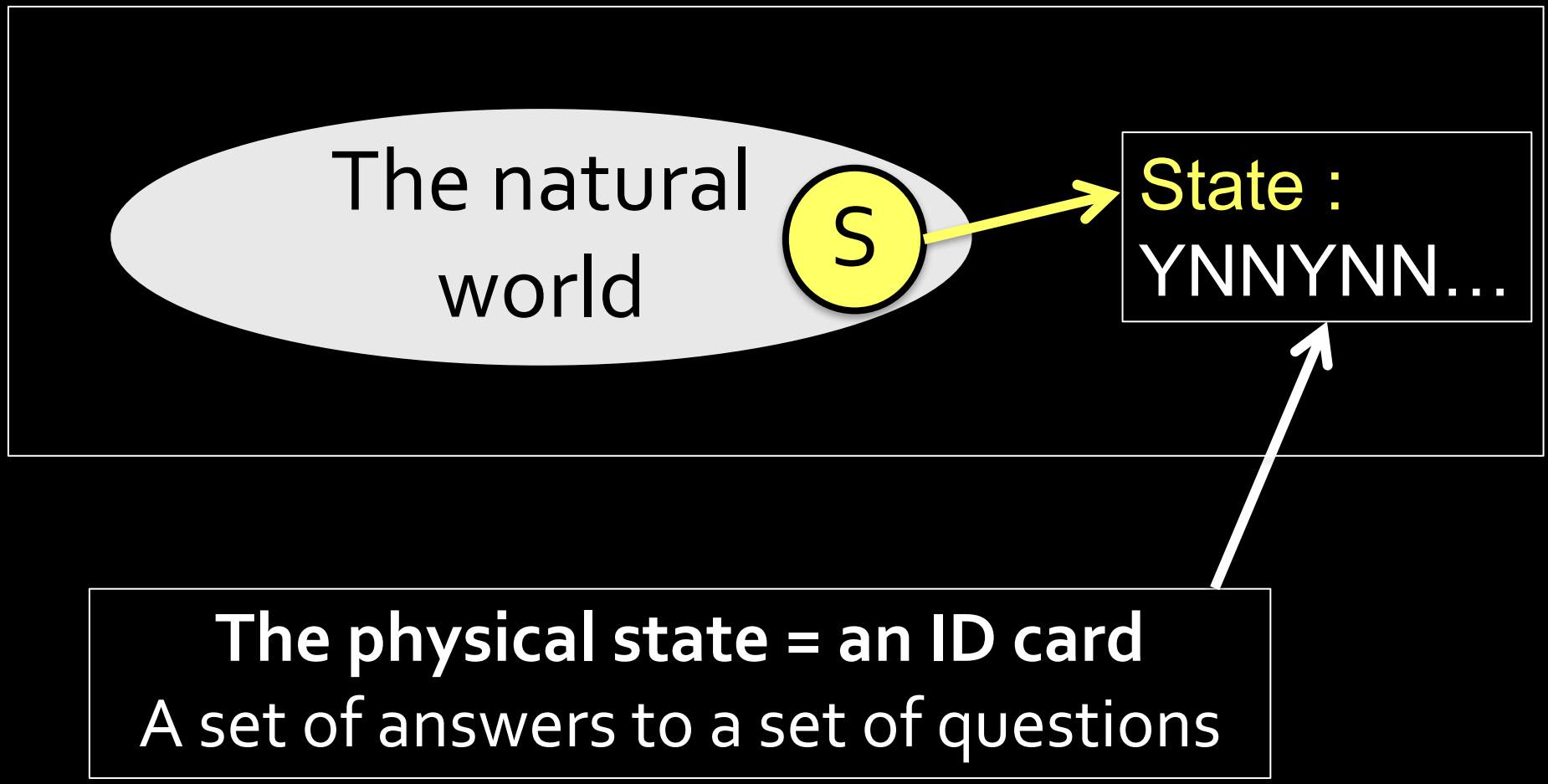
- Conclusions. Outlook.

What is a physical state *(in classical physics)*?

Statement of objectivity :

- There are systems = isolable entities of the natural world
- A system has a state (even if unobserved) and I can know it

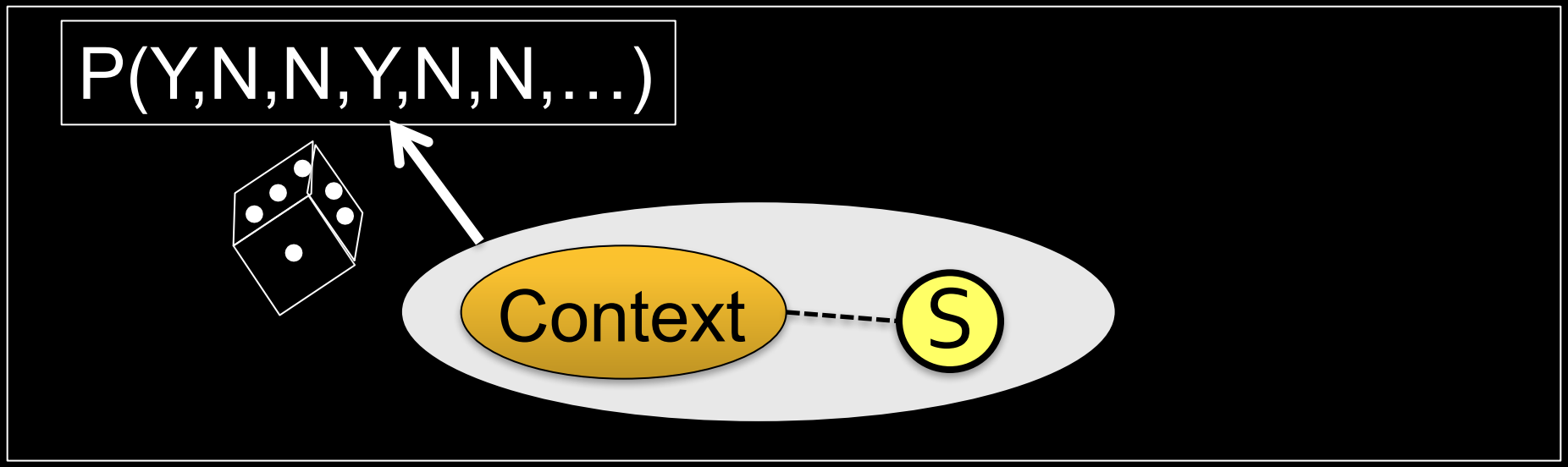
What is a physical state *(in classical physics)*?



The physical state = an ID card

A set of answers to a set of questions

What is a physical state *(in quantum physics)*?



Quantum systems are interfaced by an experimental context

- Access to the full ID card randomly perturbed
  - I cannot know the system state ☹
    - « Quantum problem »

« Realism » vs « anti-realism»

- The full physical state = the « classical state » exists, but is not accessible because of **practical reasons**
- **Quantum mechanics is not complete**
- Probabilities are due to ignorance of underlying reality

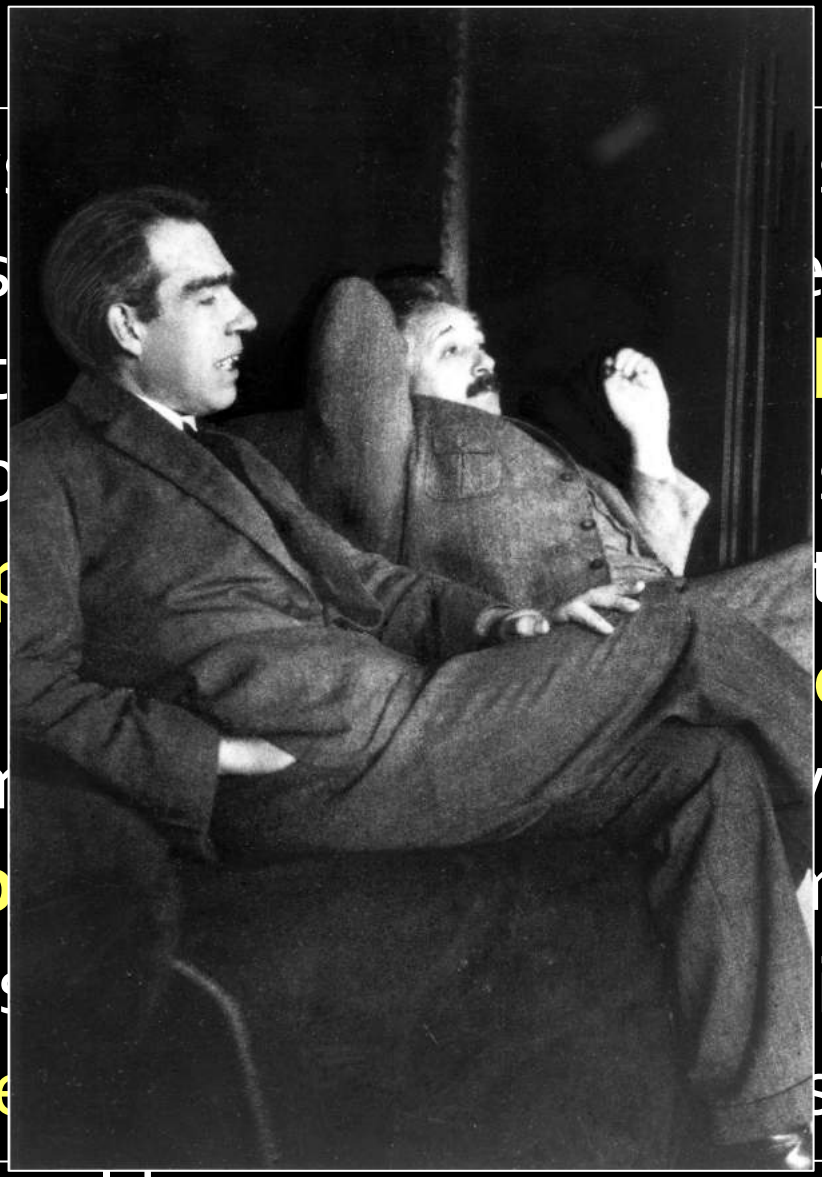
- The classical state is not accessible for **irreducible reasons**

$\Rightarrow$ The classical state does not exist

$\Rightarrow$ **QM is complete**

- The wave function is the ultimate description of the system's state

« Realism » vs « anti-realism»



- The full phy sical state is = the « class ssible for state » exist ble reasons not accessib sical state because of p t exist reasons omplete
- **Quantum m** e function is **is not comp** nate
- Probabilities ion of the to ignorance s state underlying reality

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

JOHN S. BELL†

Physics, *1*, 195-200 (1964).

- A.Aspect, P. Grangier et G. Roger, Phys. Rev. Lett. 47, 460 (1981)
- A.Aspect, P. Grangier et G. Roger, Phys. Rev. Lett. 49, 91 (1982)
- A. Aspect, J. Dalibard et G. Roger, Phys. Rev. Lett. 49, 1804 (1982)

Closing the Door on Einstein and Bohr's Quantum Debate

By closing two loopholes at once, three experimental tests of Bell's inequalities remove the last doubts that we should renounce local realism. They also open the door to new quantum information technologies.

by Alain Aspect*

- B. Hensen, et al, and R. Hanson, Nature 526, 682 (2015)
- M. Giustina, et al, and A. Zeilinger, Phys.Rev.Lett. 115, 250401 (2015)
- L. Shalm, et al, and S. Nam, Phys.Rev. Lett. 115, 250402 (2015)

What have we renounced to?

- Local realism
- Classical states

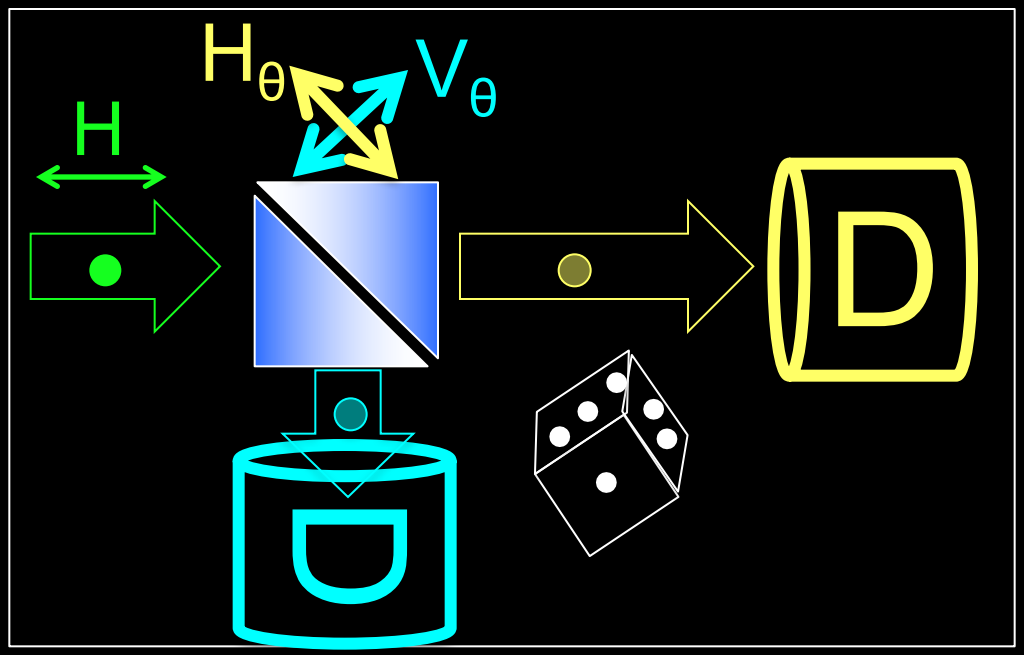
What are we getting accustomed to?

- Quantum states
- « Ordinary quantum ontology »

« Ordinary quantum ontology »

- Quantum system: A single photon
- Quantum state: The photon's polarization

- « Question »: Measurement in $\{H_\theta ; V_\theta\}$
- « Answer »: Random projection on H_θ or V_θ



The full « ID card » = The polarization for each θ angle has no physical meaning => **End of the classical state**

« Ordinary quantum ontology »

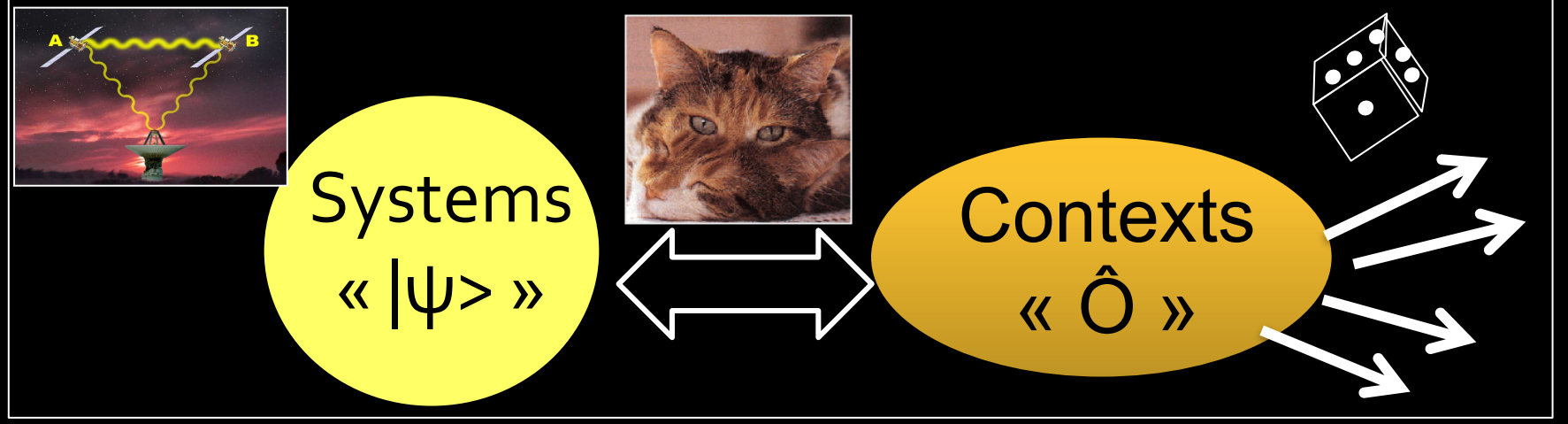
- Quantum system: A single photon
- Quantum state: The photon's polarization

Realism and objectivity look safe: The photon and its state exist, even if unobserved ☺

But…

- Measuring in the wrong basis irreversibly perturbs the state
- I cannot know the state of a single quantum system: « Hidden reality »
- **The quantum problem is still there** ☹

Ordinary discomfort zones



Quantum reality

- Hidden
- Weird :Superposition, Non-locality, spooky action…
- *Unitary evolution*

Classical contexts

- Quantum-classical boundary
- Randomness
- *Non-unitary evolution*

Outline

- Introduction: What is a physical state?
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- **Rebuilding a quantum ontology**
- Revisiting quantumness (with CSM)
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Our methodology

Knowing that

- Ontology is never demonstrated, but postulated
- Postulates can be based on intuitions
- Intuitions are based on **custom**

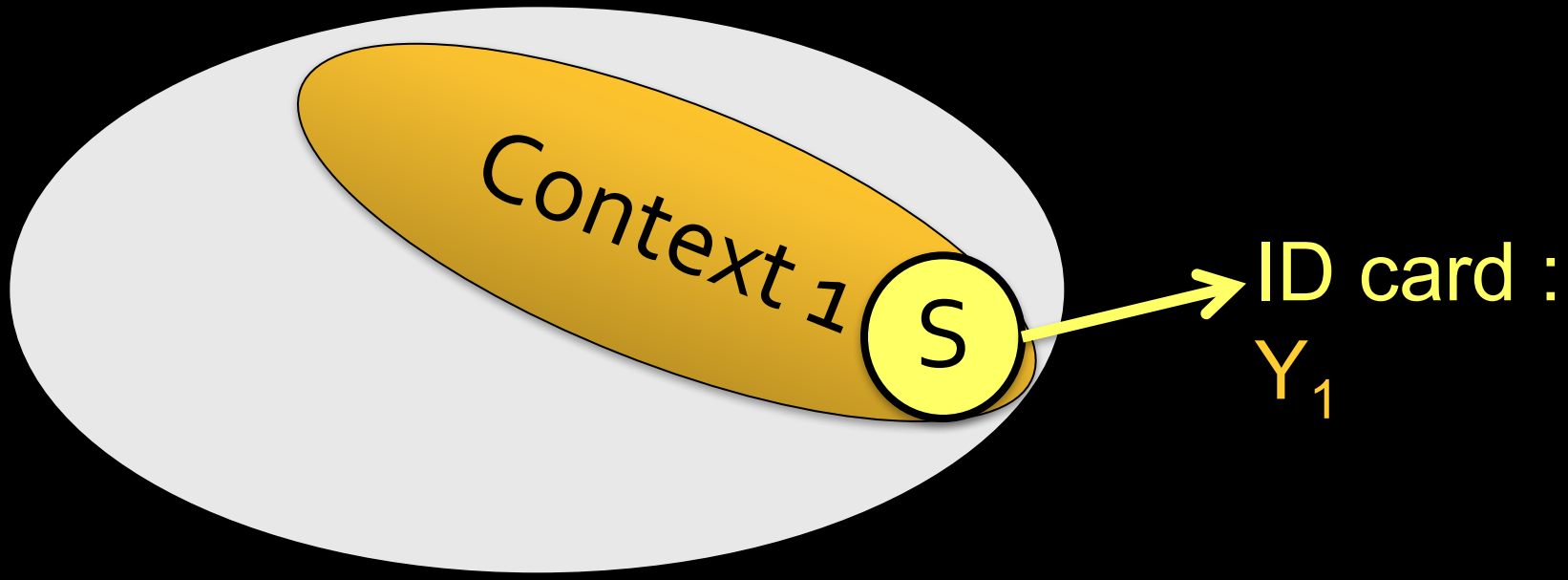
We shall

- Deconstruct classical intuitions
- Rebuild a new ontology of states, by induction from quantum phenomenology

Genealogy of a classical state

Operational approach :

- One builds a state by asking the system a set of questions and filling its ID card
- Each question is asked within a given context*



**Context: Around the system*

Genealogy of a classical state

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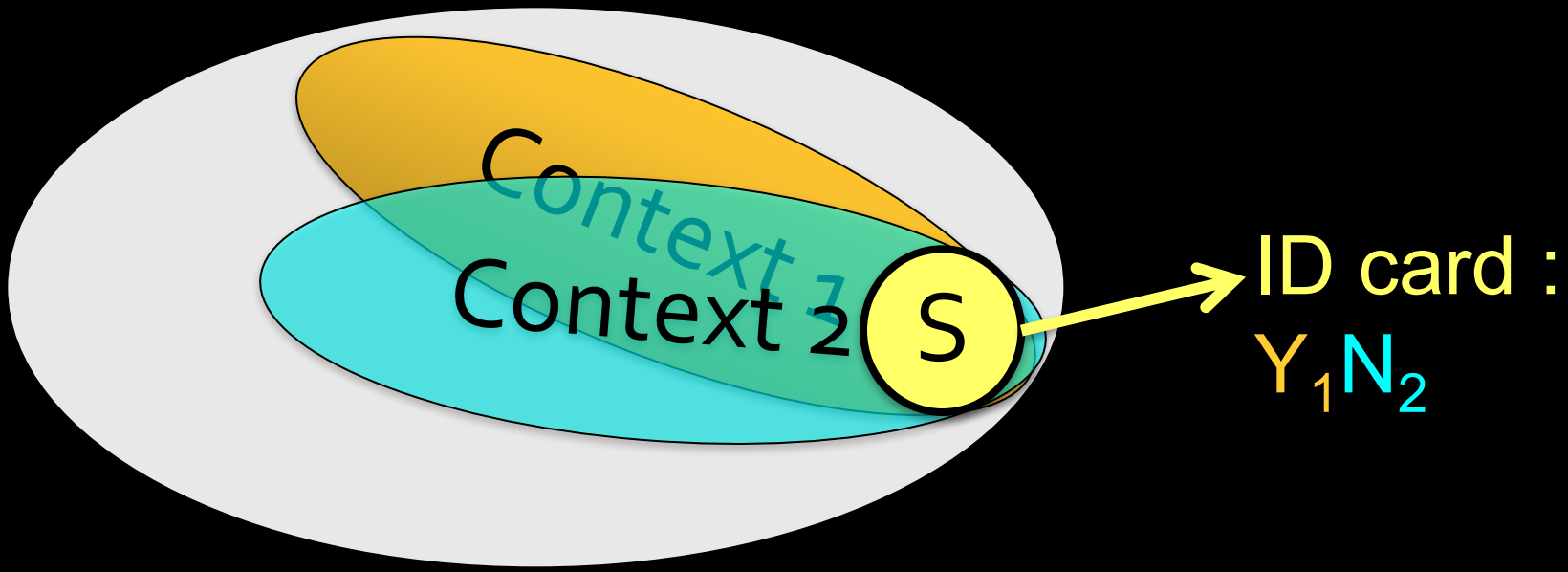

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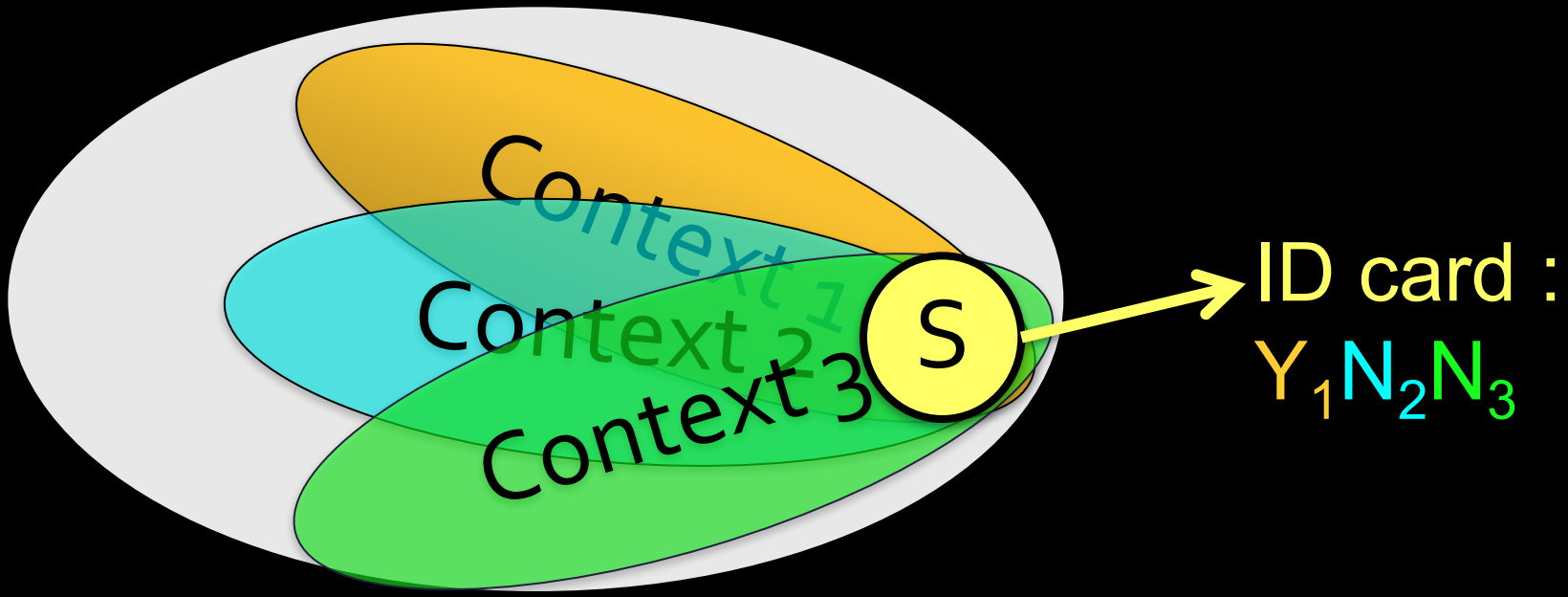
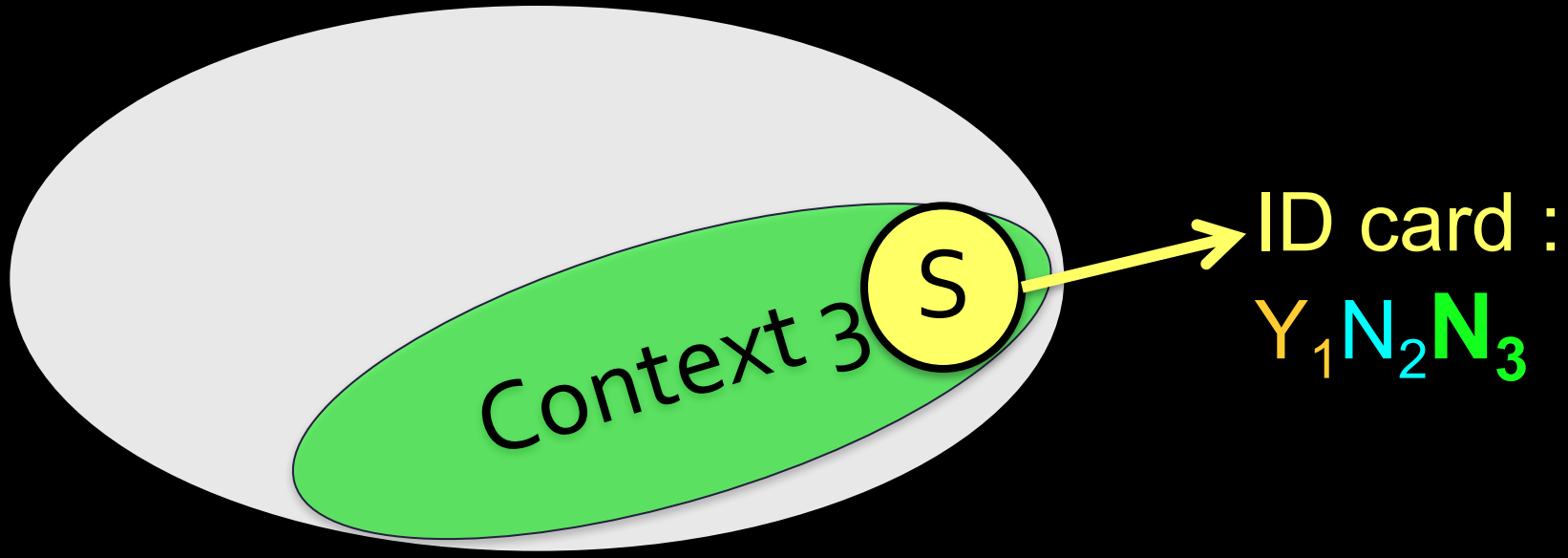


Genealogy of a classical state

Classical phenomenology
I can obtain repeatably the same answers to the same questions



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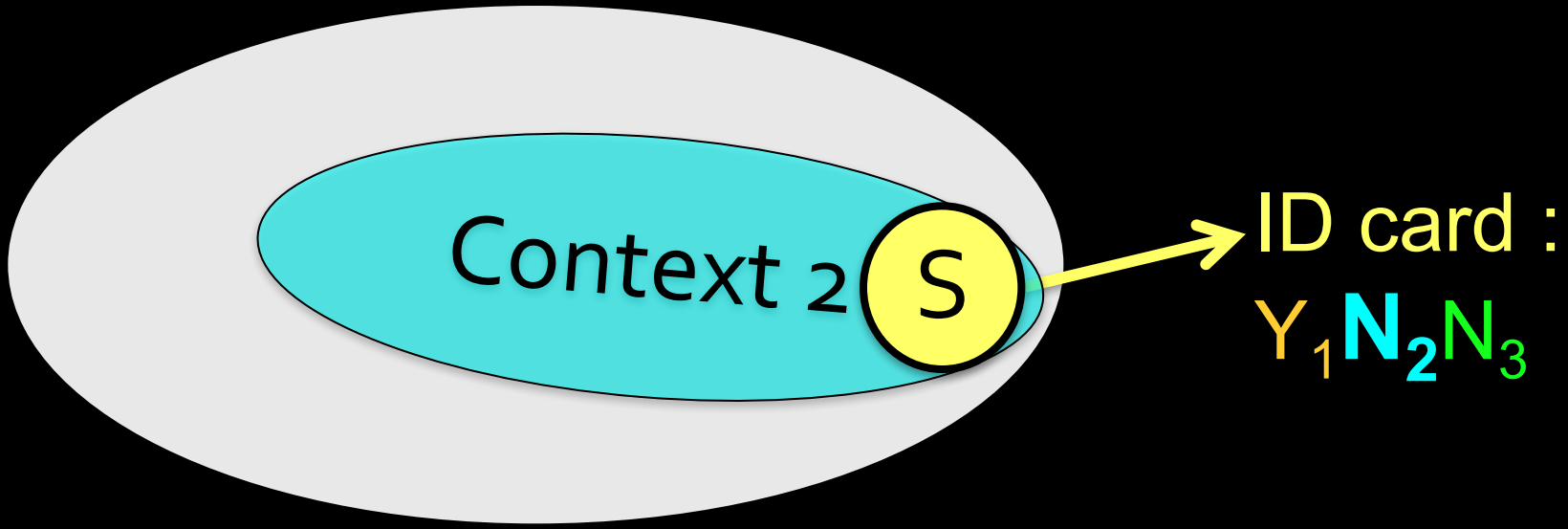
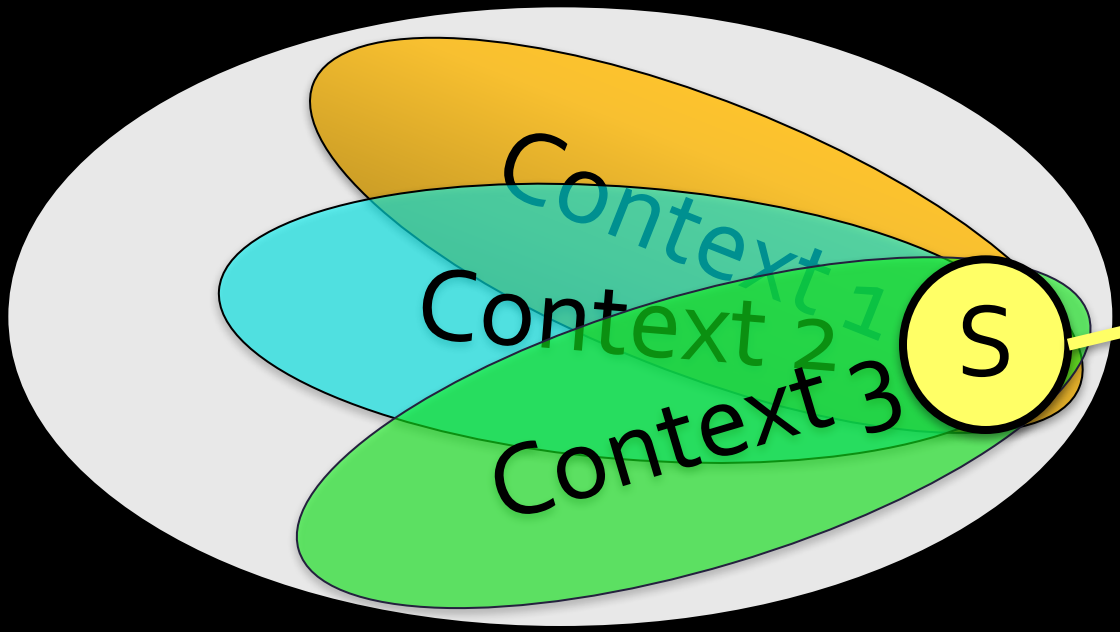
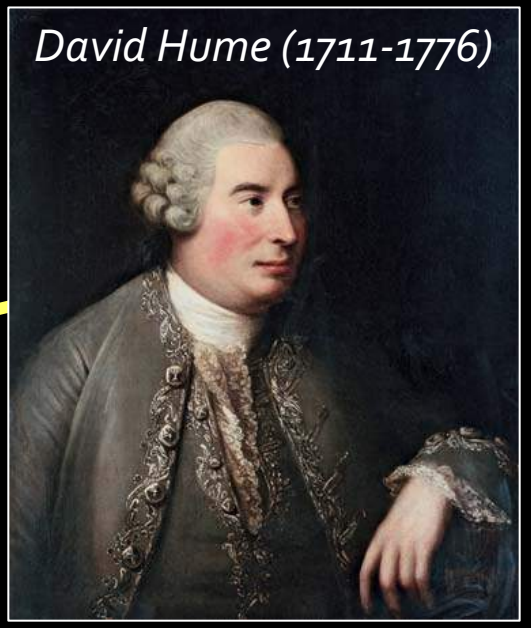


Genealogy of a classical state

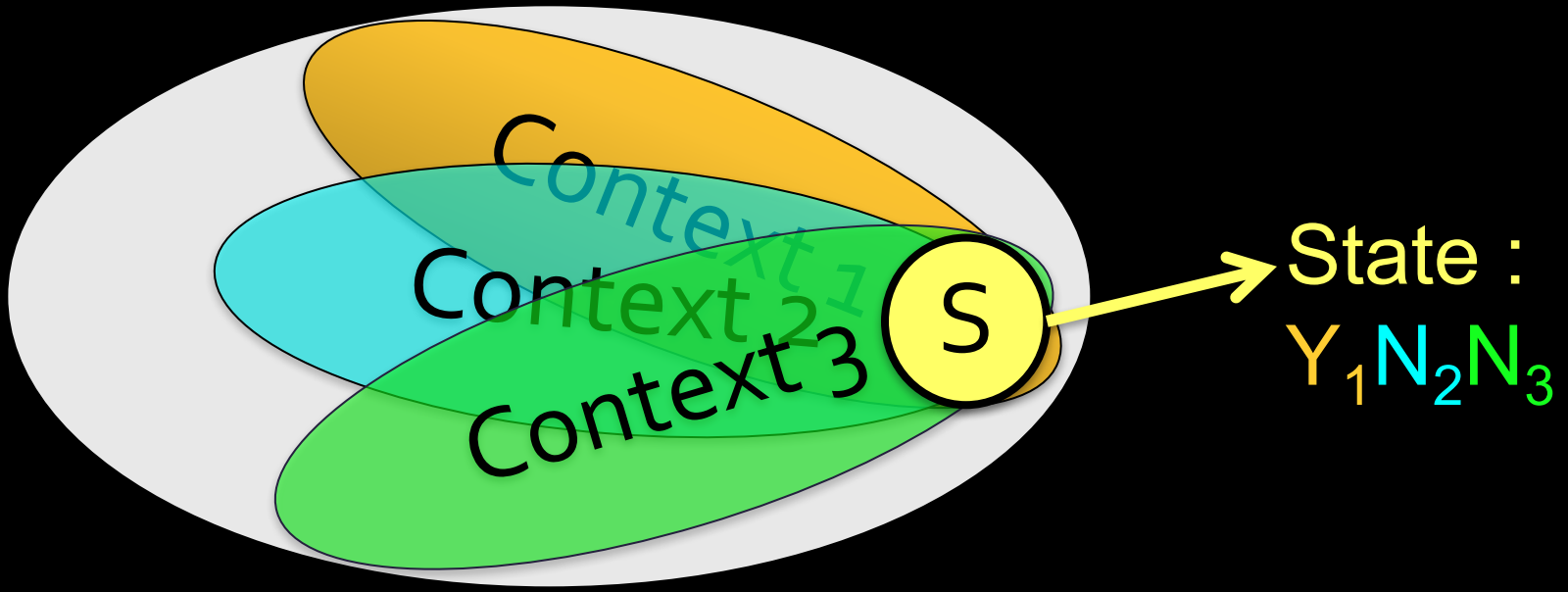
Repeatability -> Certainty (*Psychology*)
The ID card (*Operational*) -> State (*Ontology*)
One explains the repeatable answers by a permanent cause : the existence of a state





Genealogy of a classical state

In the classical world, the state does not depend on the ordering of the questions :
I can forget the contexts, (even forget the questions), and attribute the state to the system alone



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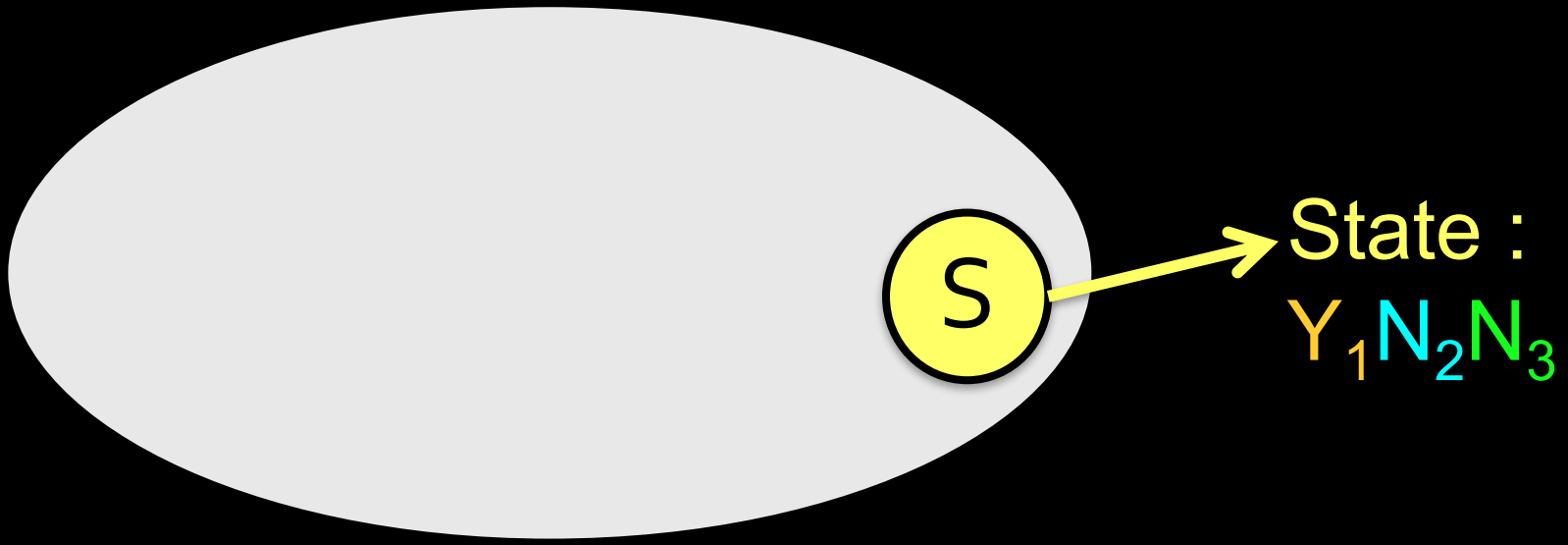
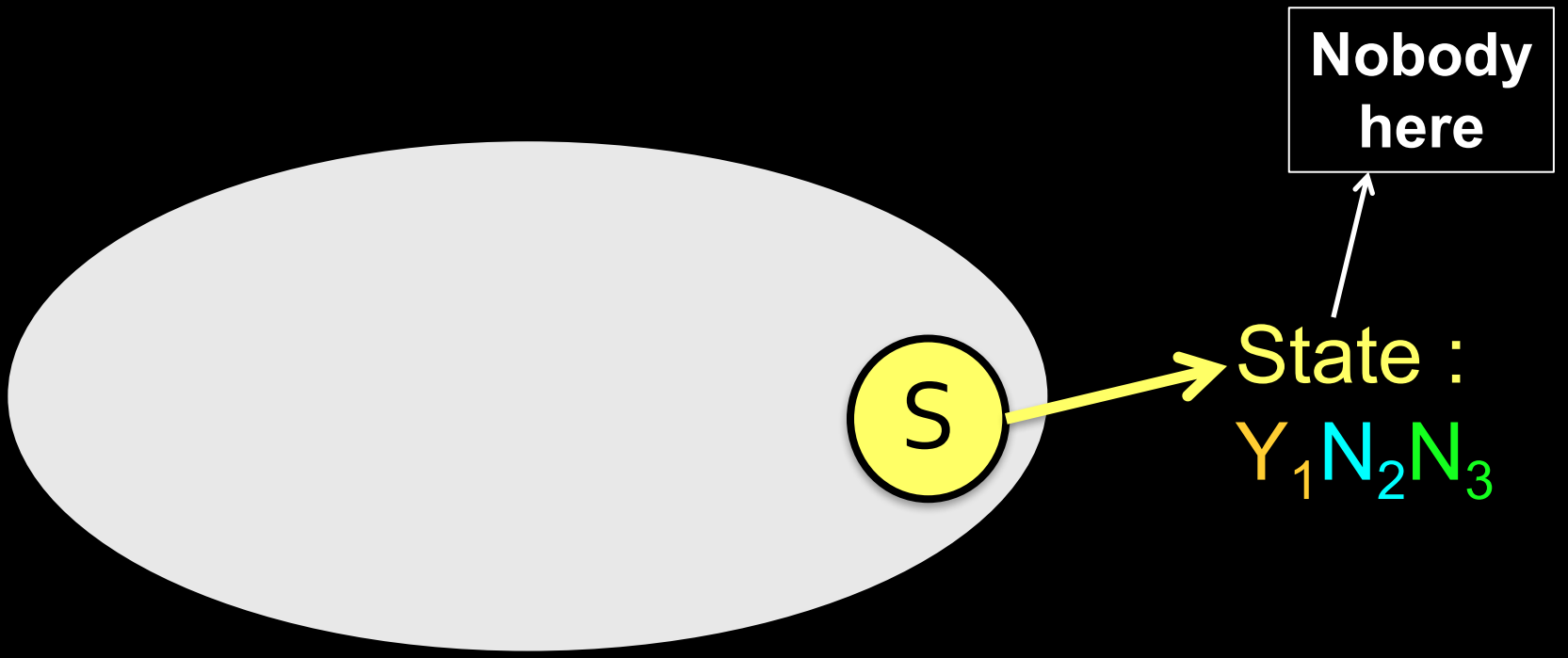


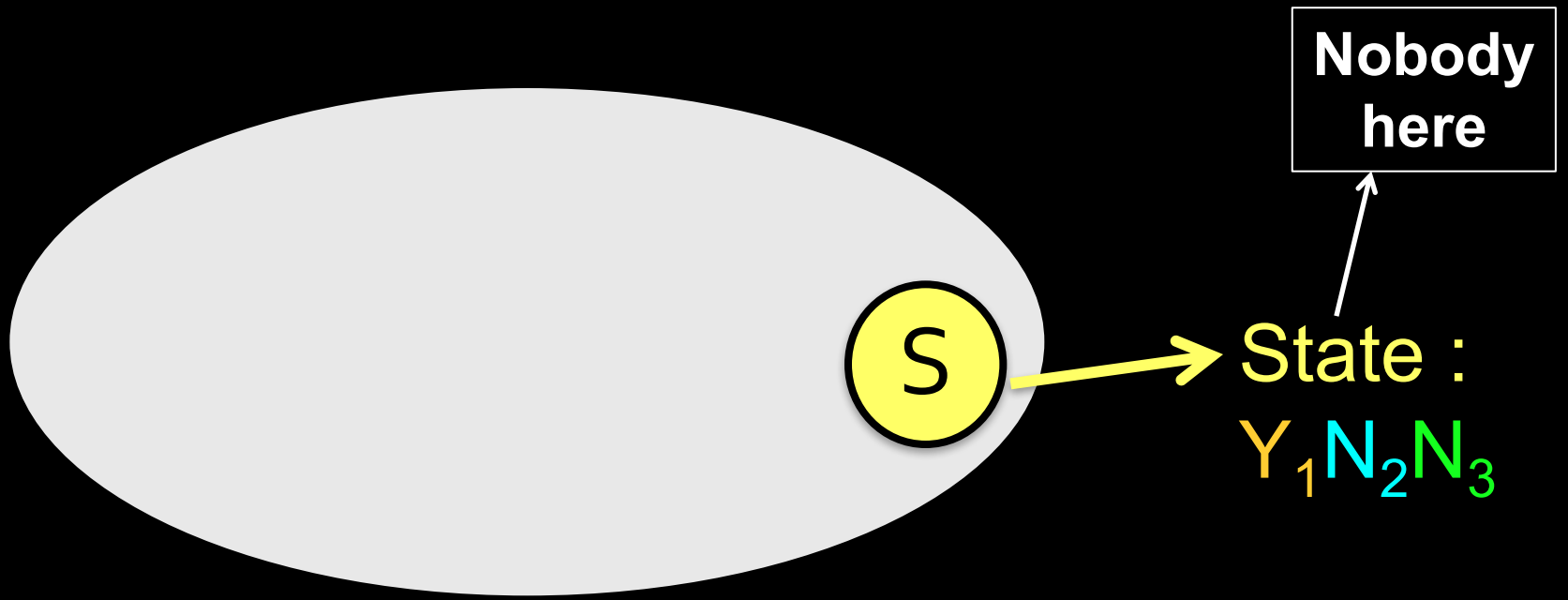
Genealogy of objectivity

This is usually considered the core of objectivity: the state of the system exists, even if unobserved



Genealogy of objectivity

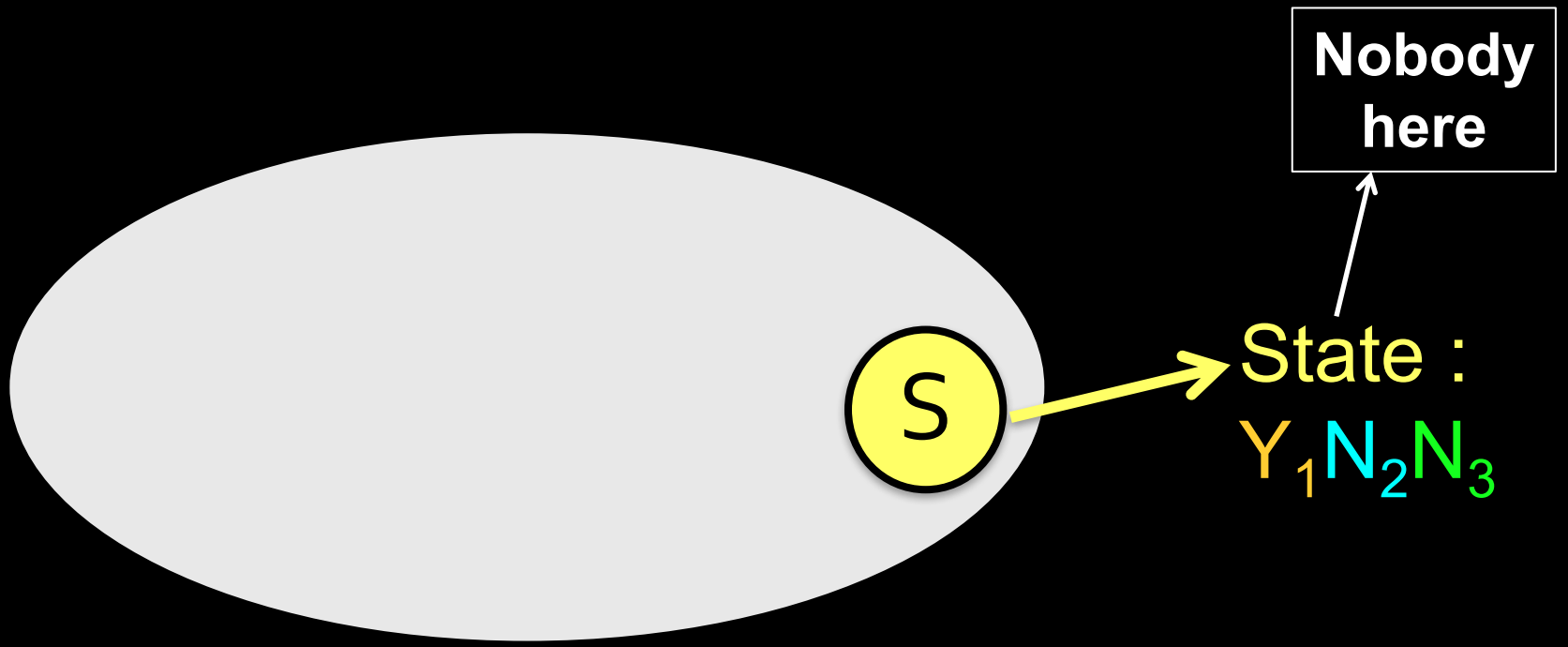
Our definition of objectivity = the existence of states *pertaining to the system alone*, derives from the classical phenomenology = **intuitions built in the classical world**



Genealogy of classical realism

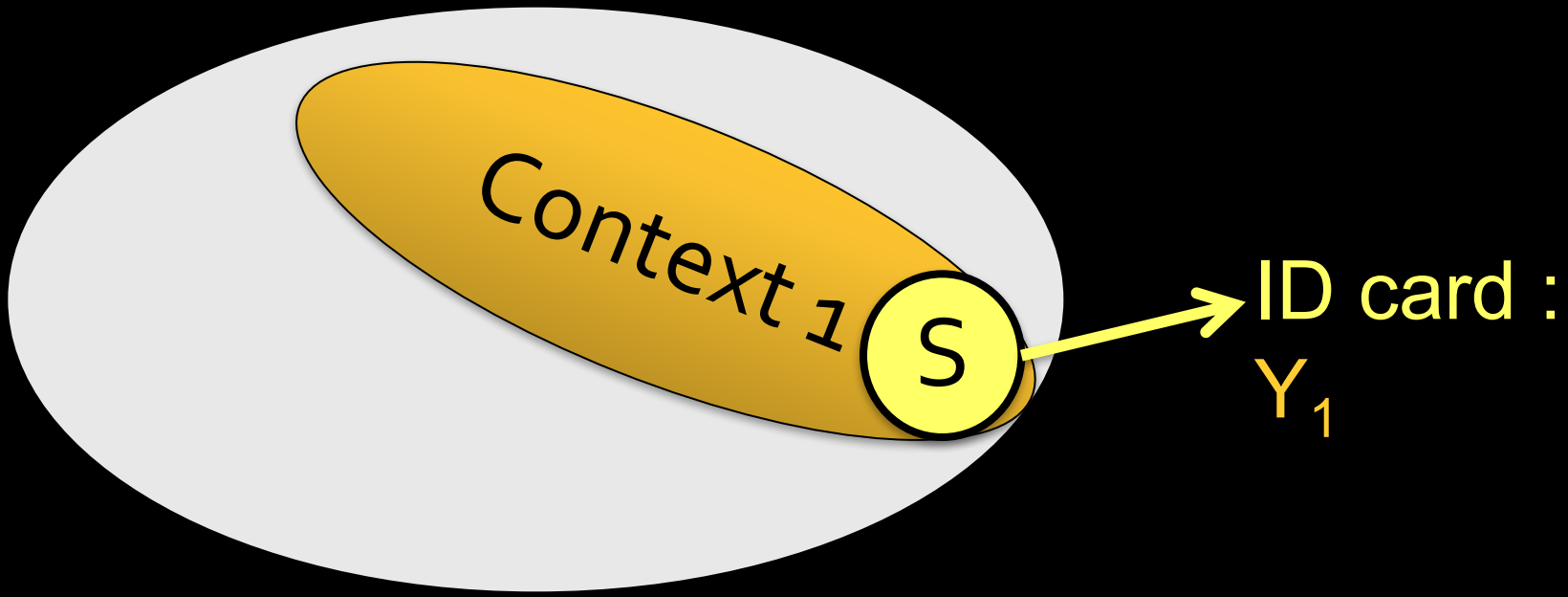
Our definition of objectivity derives from our classical experience

Such intuitions have deep roots: We perceive classical phenomena continuously, and for free



Quantum phenomenology

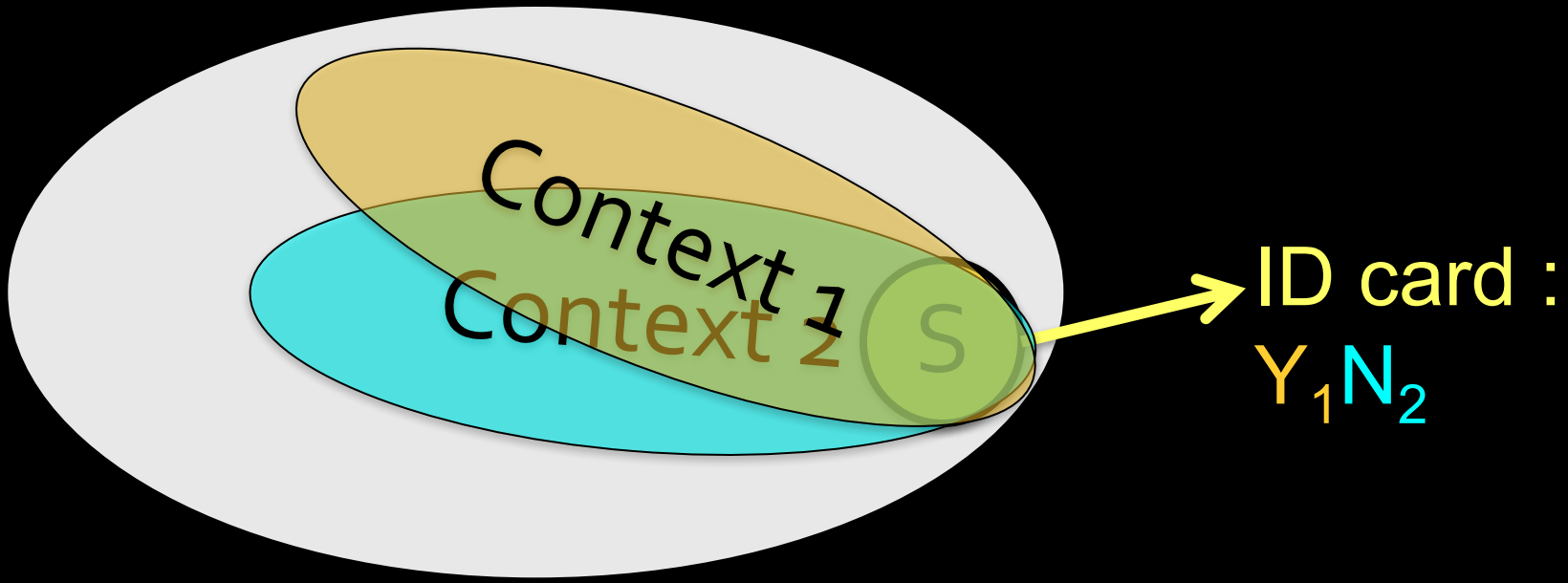
The ID card = the answers may depend on the ordering of the questions



Context = Measuring apparatus

Quantum phenomenology

The ID card = the answers may depend on the ordering of the questions



Quantum phenomenology

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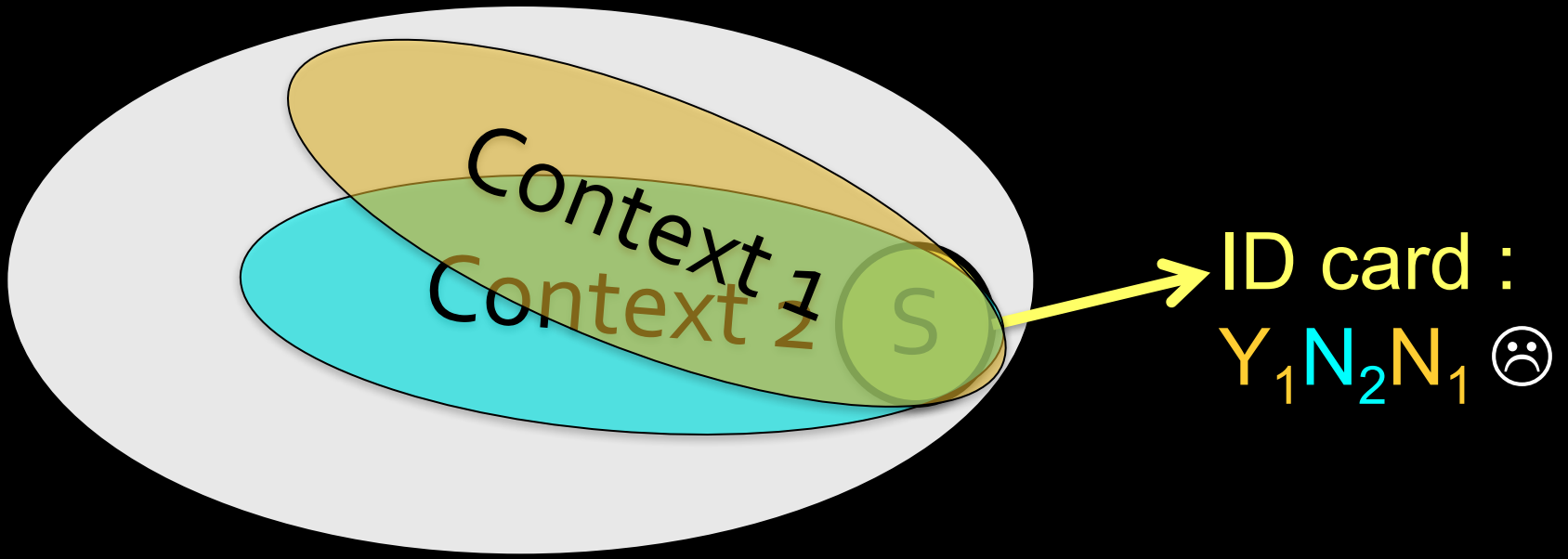
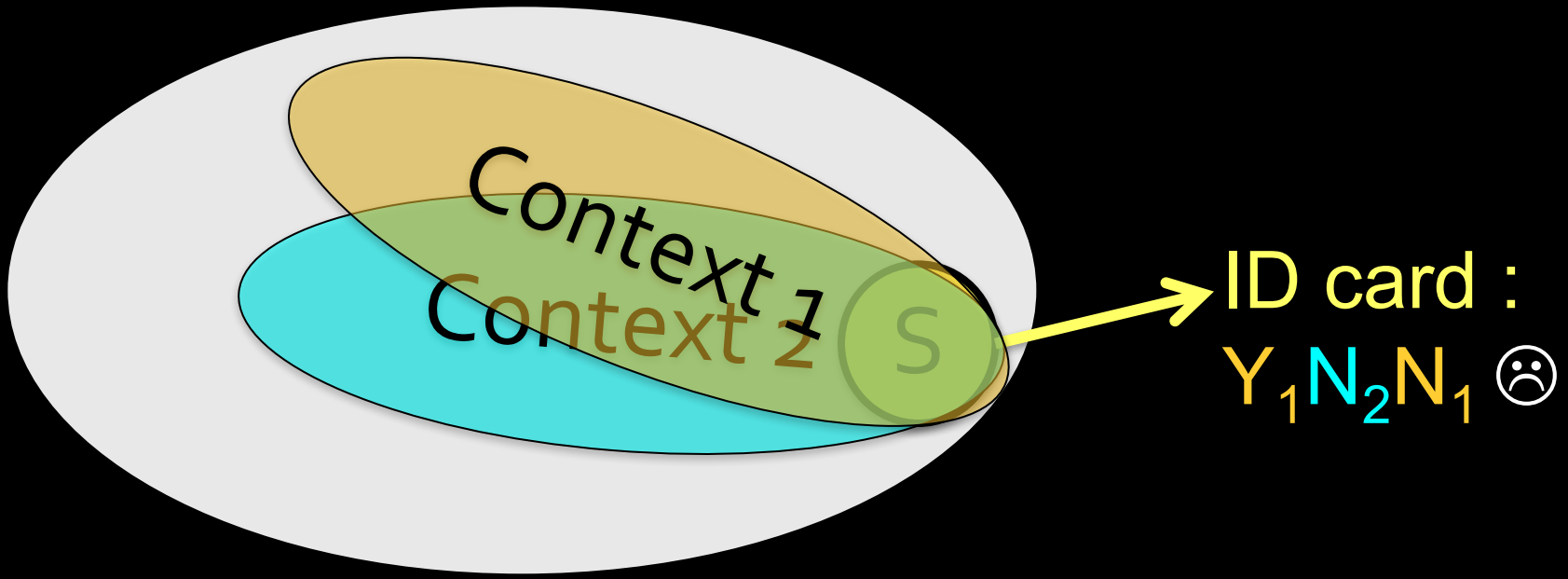


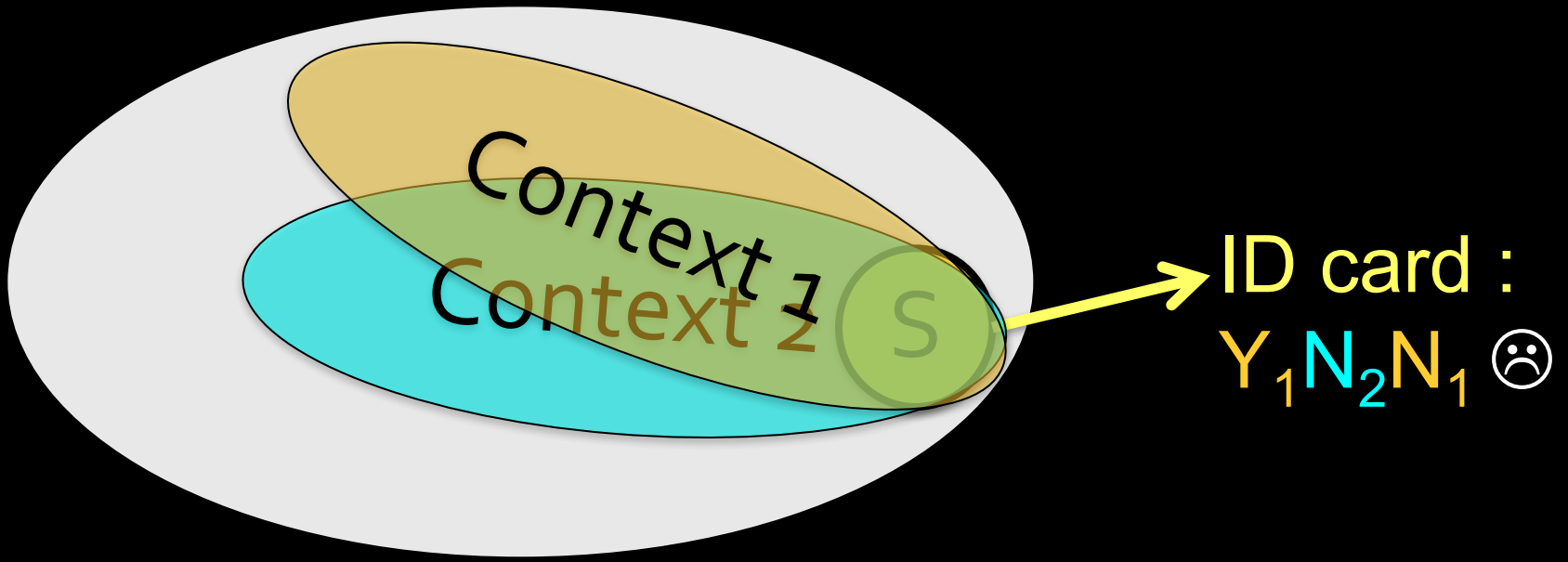
Option 1 : Ordinary realist

The state pertains to the system alone, the context perturbs the state



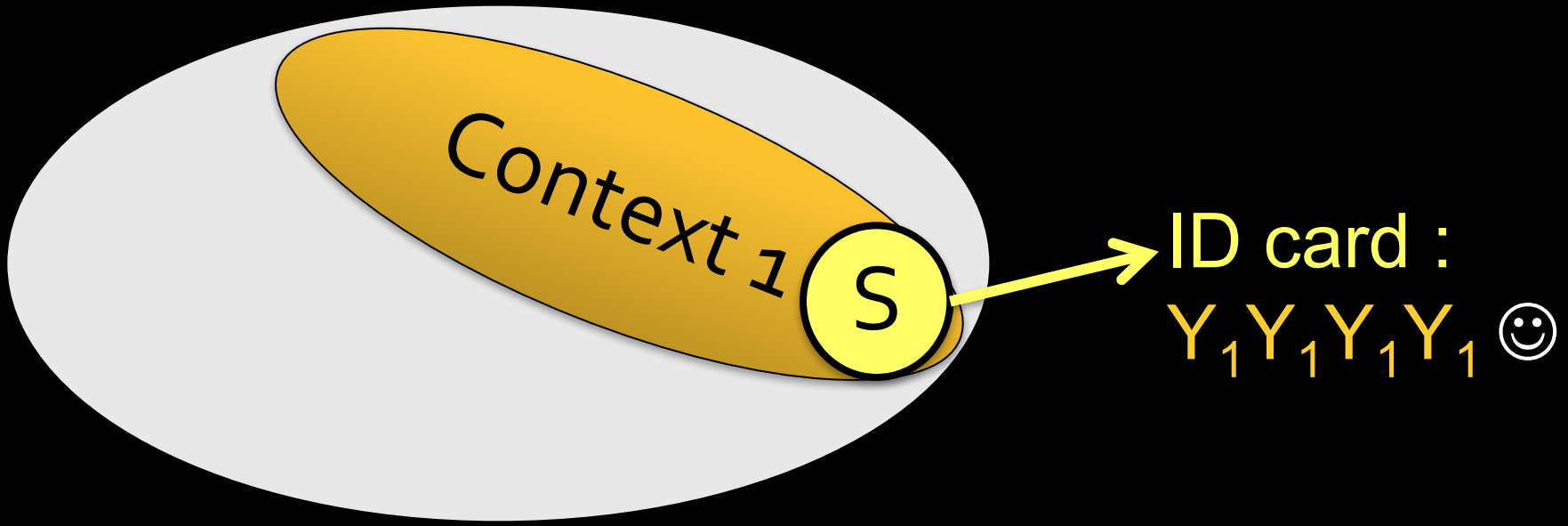
Option 2 : Anti-realist

There are no states, only preparations and measurements



Option 3 : New realist

« Certainty tracking » : one can obtain repeatably the same answer, **within the same context**
One can upgrade the ID card into a state, **within a given context**



Postulate 1 : C-S-M

- In quantum physics, the « quantum state » pertains both to the system AND the context
- To differenciate it from a classical state (which does not depend on any context), we further call the quantum state a **modality**
- **C-S-M ontology «Context-System-Modality»**

Auffèves and Grangier, Foundations of Physics 46:121–137 (2016)

Postulate 1 : C-S-M

- Whithin a given context, modalities are mutually exclusive
- Two modalities pertaining to two different contexts are not necessarily exclusive : they can be incompatible
- A given modality can pertain to more than one context (Extra-contextuality of modalities)

Example

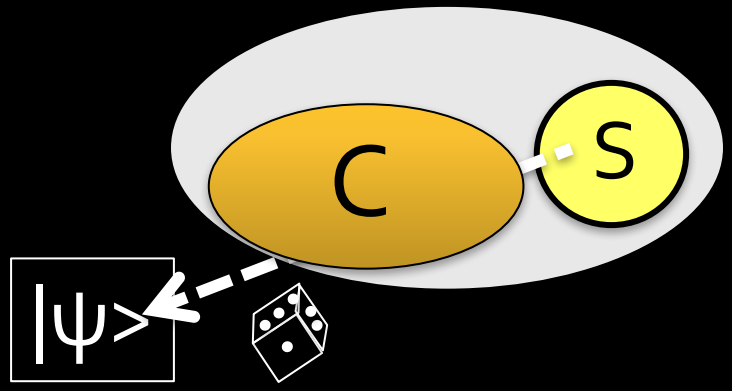
- System : A single photon
- Context : A PBS with neutral axes {H,V}.
- Modality : « transmitted » or « reflected »

- A photon has no state by itself. A photon + polarizer has, and it is a modality.
- The modality is objective, but contextual
- There are no coherent superpositions of states. There are modalities in other contexts *(*$|H\rangle+|V\rangle = |H_{45}\rangle$*)*

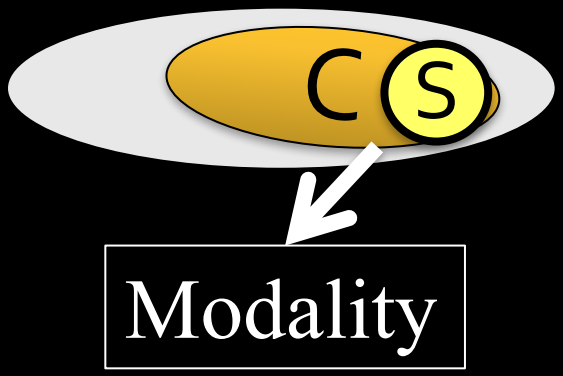
From ordinary quantum ontology to CSM

Ordinary quantum ontology

- Non-contextual states
- Exist even unobserved
- Hidden and weird



CSM



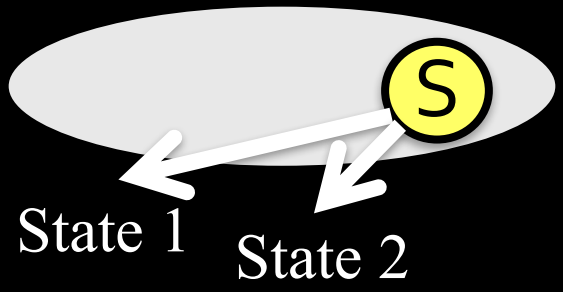
- States-phenomena
- Actual and certain
- Exist even unobserved
- Contextual objectivity

Grangier, P., EJP 23(3), 331 (2002)

Grangier, P., Int. J. Quantum Inf. 3(1), 17–22 (2005)

Impact on ontology *vs* epistemology

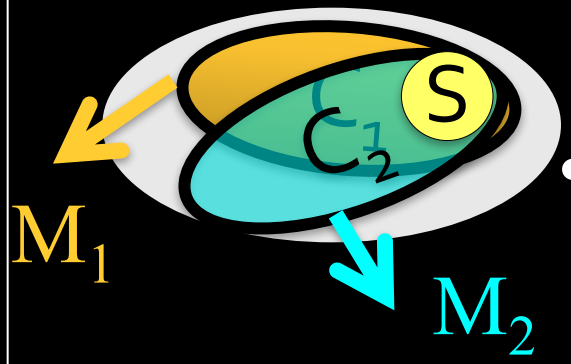
Classical realism



- The thing is what exists « below » the states [*Ontology*]
- A state pertains to the thing only [*Epistemology*]

Ontology and epistemology have the same object

CSM

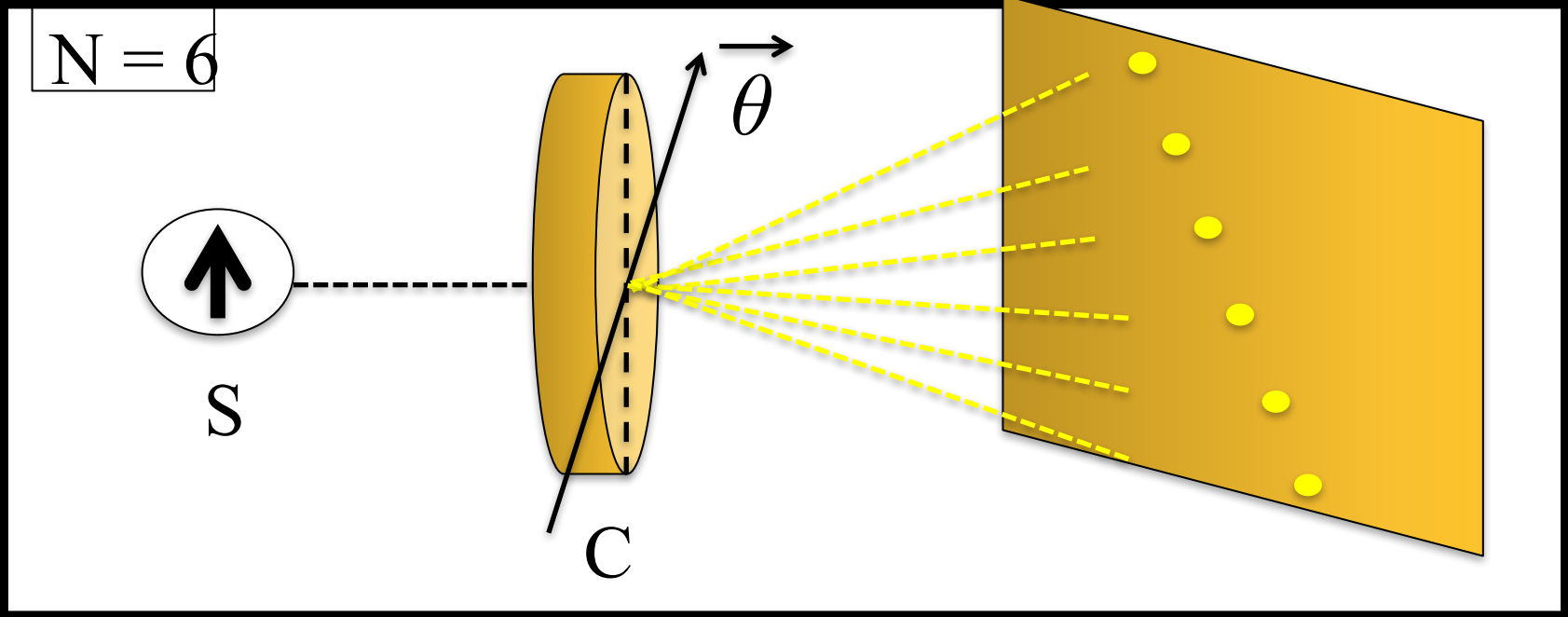


- The system is what exists below the modalities [*Ontology*]
- A modality pertains to the system and a context [*Epistemology]*

Ontology and epistemology have different objects

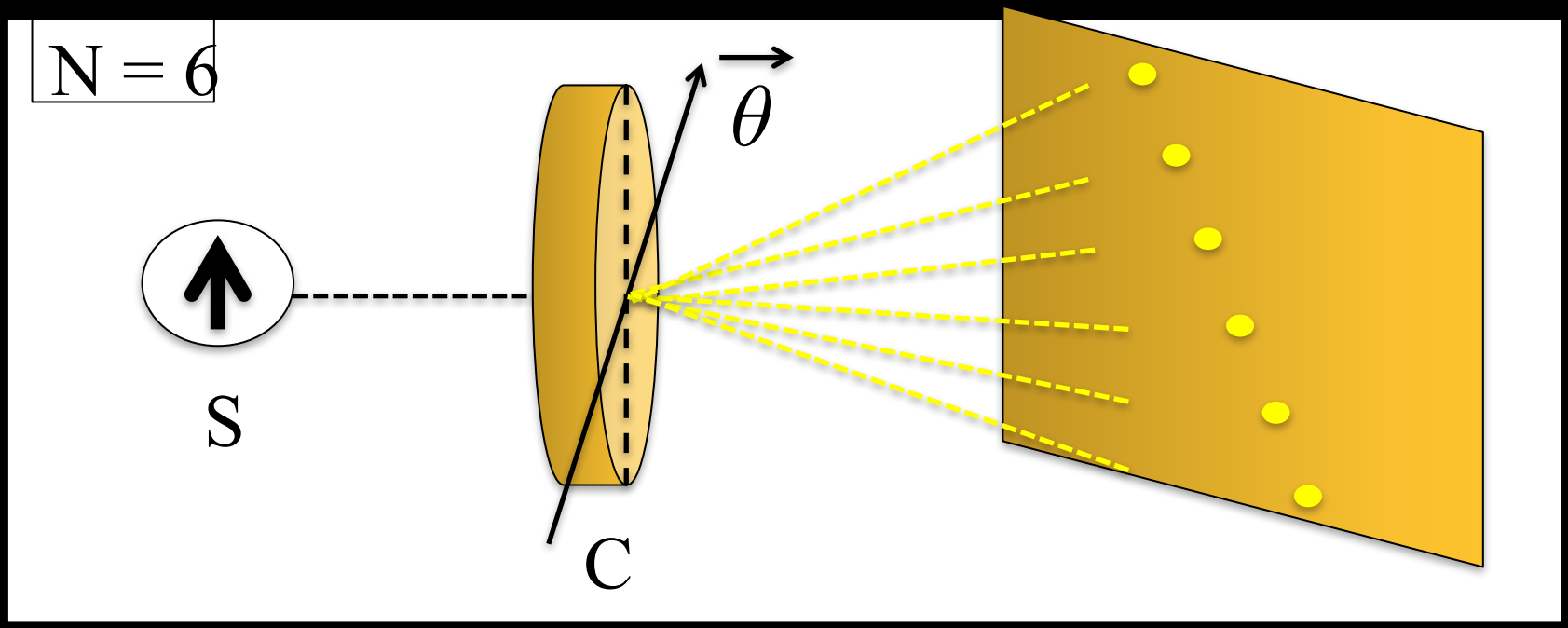
Postulate 2 : Quantization

A system is characterized by a fixed, discrete number N of exclusive modalities.
N is independant of the context.



Postulate 3 : Continuity

A context is **classical** = Its state does not depend on another context, and is described by a continuous parameter θ.



Summary

Postulate 1 (Contextuality): Modalities pertain to a system and a context

Postulate 2 (Quantization): A system is characterized by a fixed number N of exclusive modalities.

Postulate 3 (Continuity): A context is classical, its state is described by a continuous parameter θ.

Ontological postulates induced from the quantum phenomenology

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- Introduction: What is a physical state?
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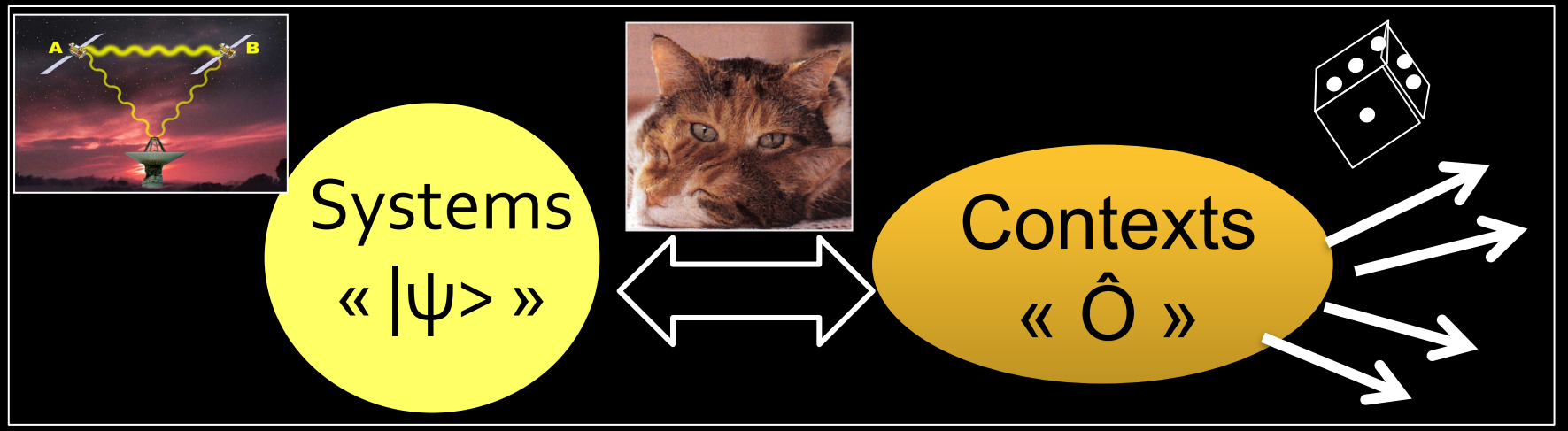
Back to ordinary discomfort zones



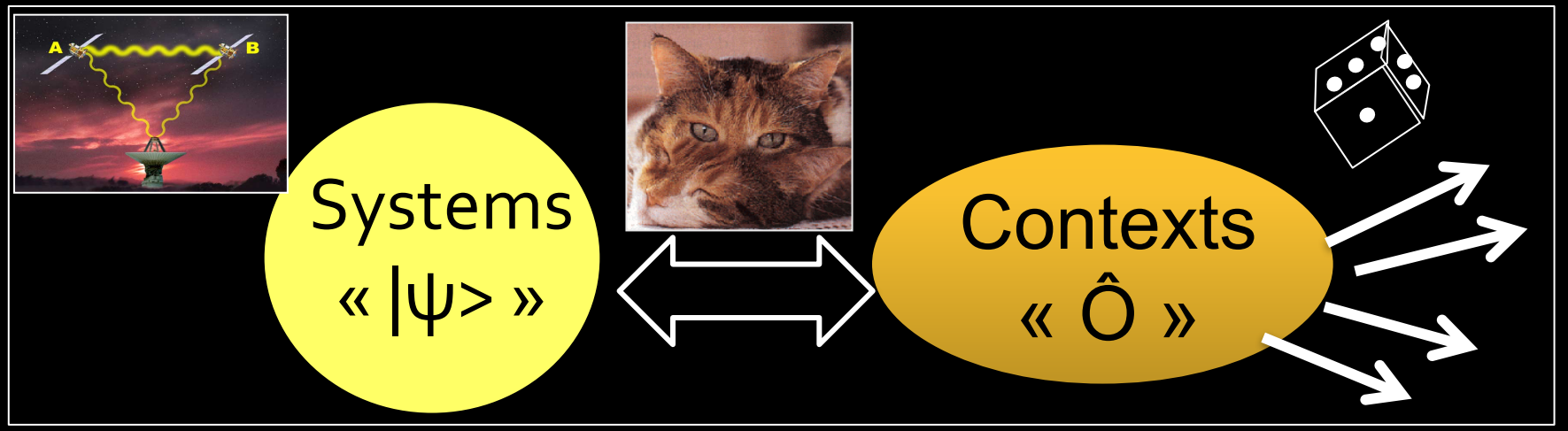
Quantum reality

- Hidden ✔
- Superpositions ✔
- Non-locality, spooky action
- *Unitary evolution*

Classical contexts

- Quantum-classical boundary
- Randomness
- *Non-unitary evolution*

Back to ordinary discomfort zones



Quantum reality

- Hidden ✔
- Superpositions ✔
- **Non-locality, spooky action ?**
- *Unitary evolution*

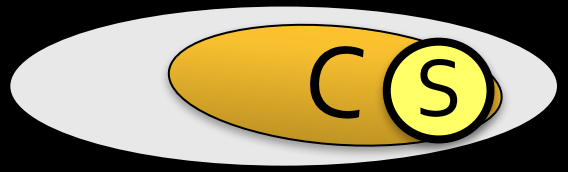
Classical contexts

- **Quantum-classical boundary?**
- **Randomness ?**
- *Non-unitary evolution*

From classical to quantum states

Universality of contextuality

- States always show up in a given context
- Reality is always contextual



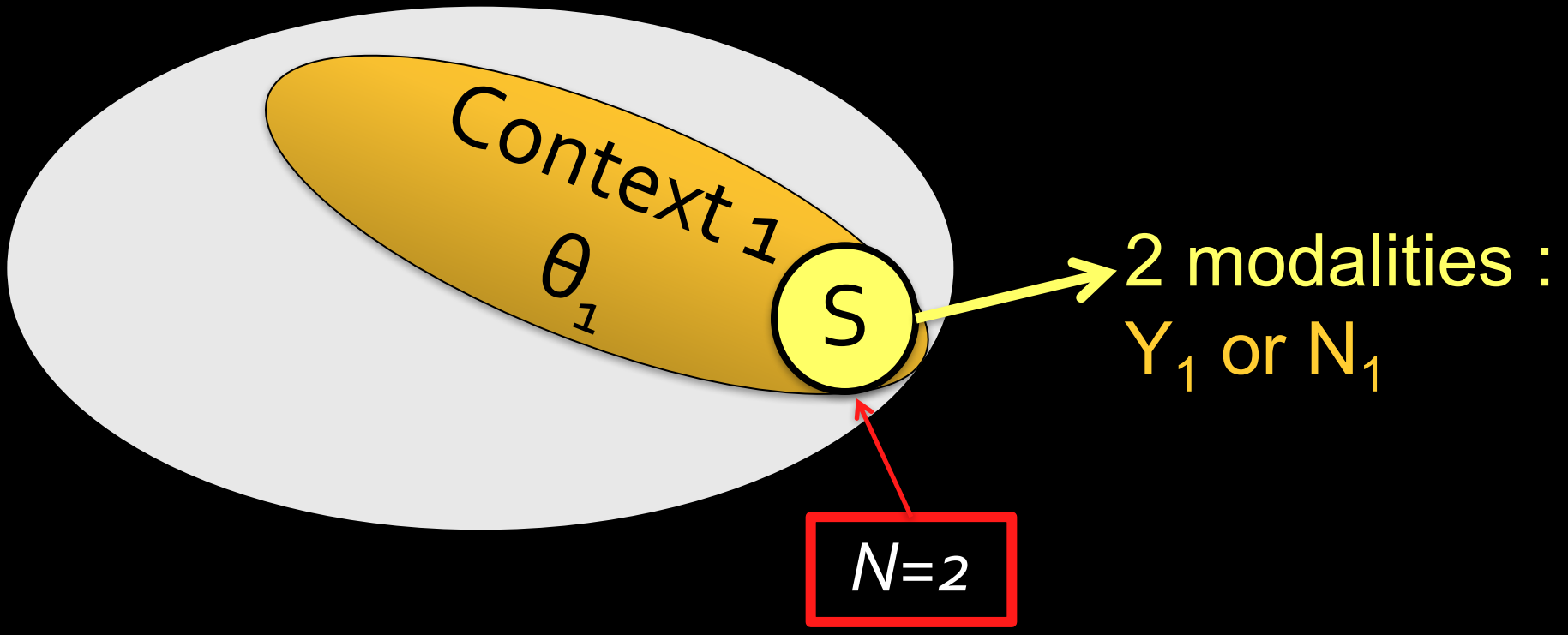
Classical reality
Contexts are there, but can be forgotten
« Soft » contextuality

Quantization of modalities

Quantum reality
Contexts are needed to define a state
« Hard » contextuality

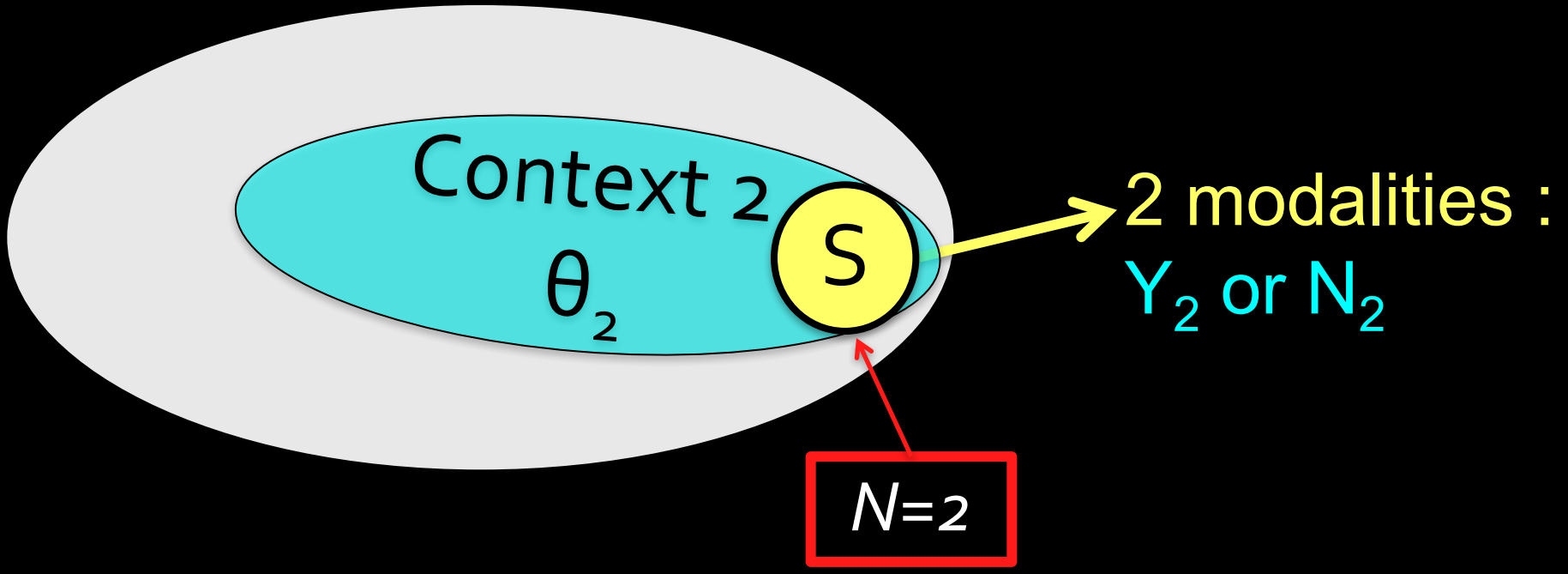
Proof: building a modality

- Ask questions to the system to define its ID card
- **Context 1 :** 2 repeatable answers => 2 exclusive modalities



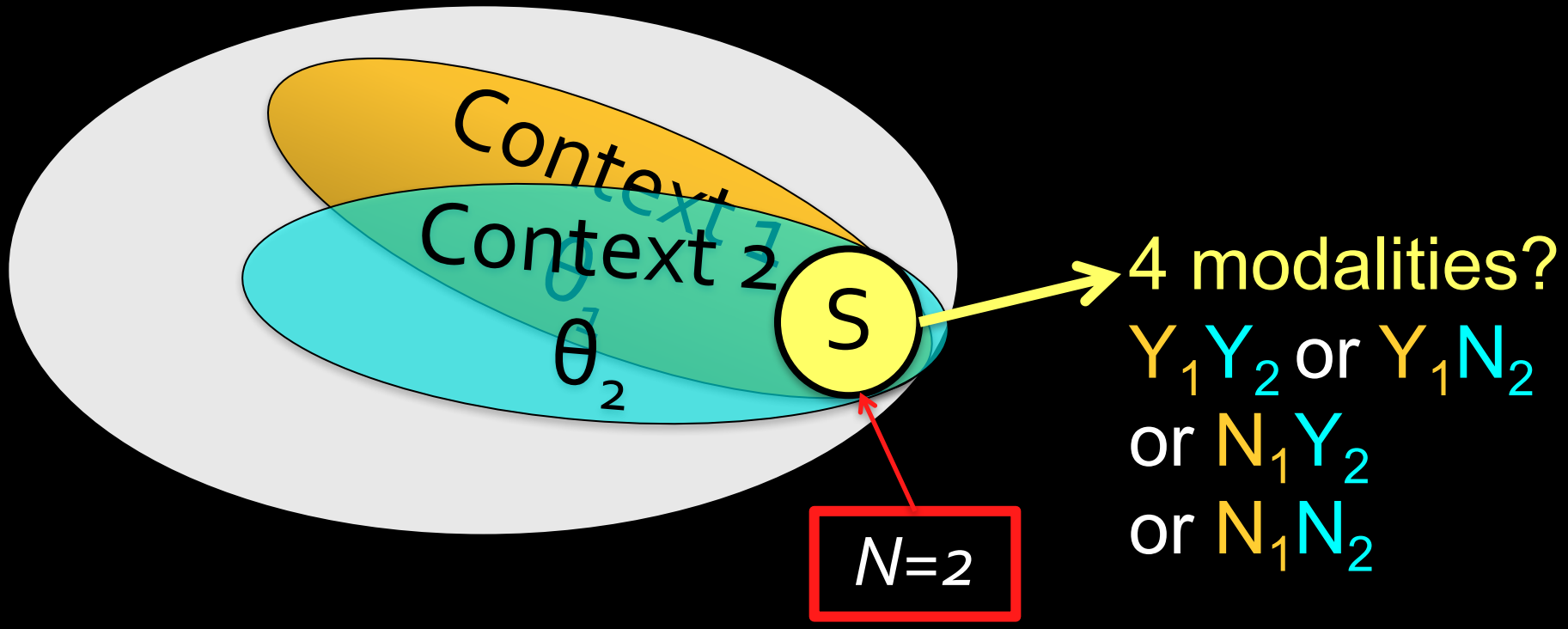
Proof: building a modality

- Ask questions to the system to define its ID card
- **Context 2 :** 2 repeatable answers => 2 exclusive modalities



Proof: building a modality

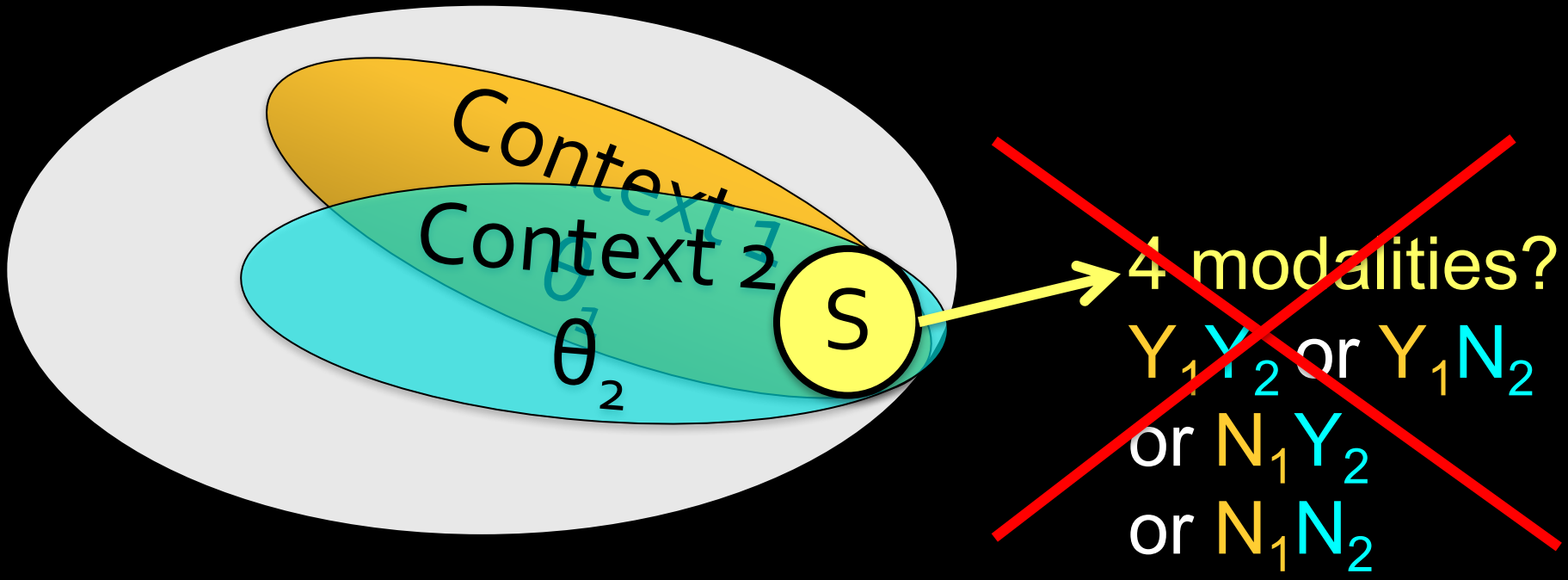
Back to Context 1 : **Can I predict the answers with certainty?**



Proof: building a modality

The answers cannot be predicted, otherwise there would be 4 exclusive modalities

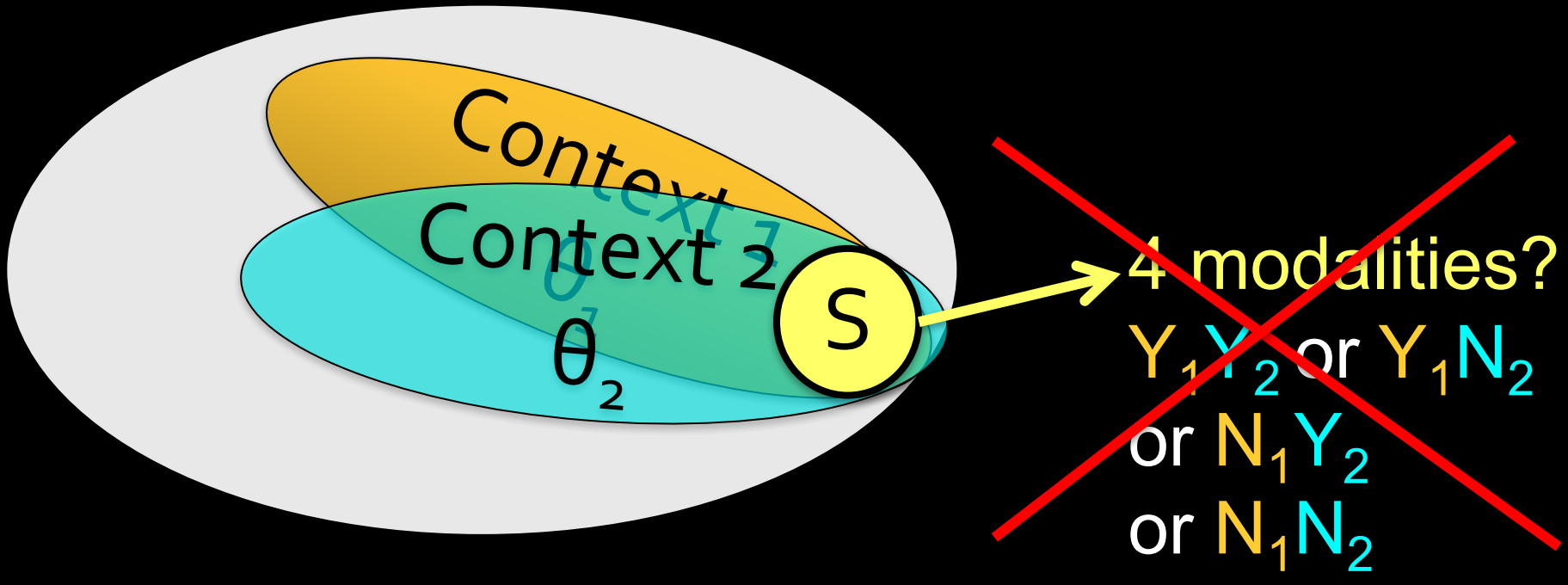
=> Violation of the quantization postulate



Proof: building a modality

Contextuality + Quantization postulate

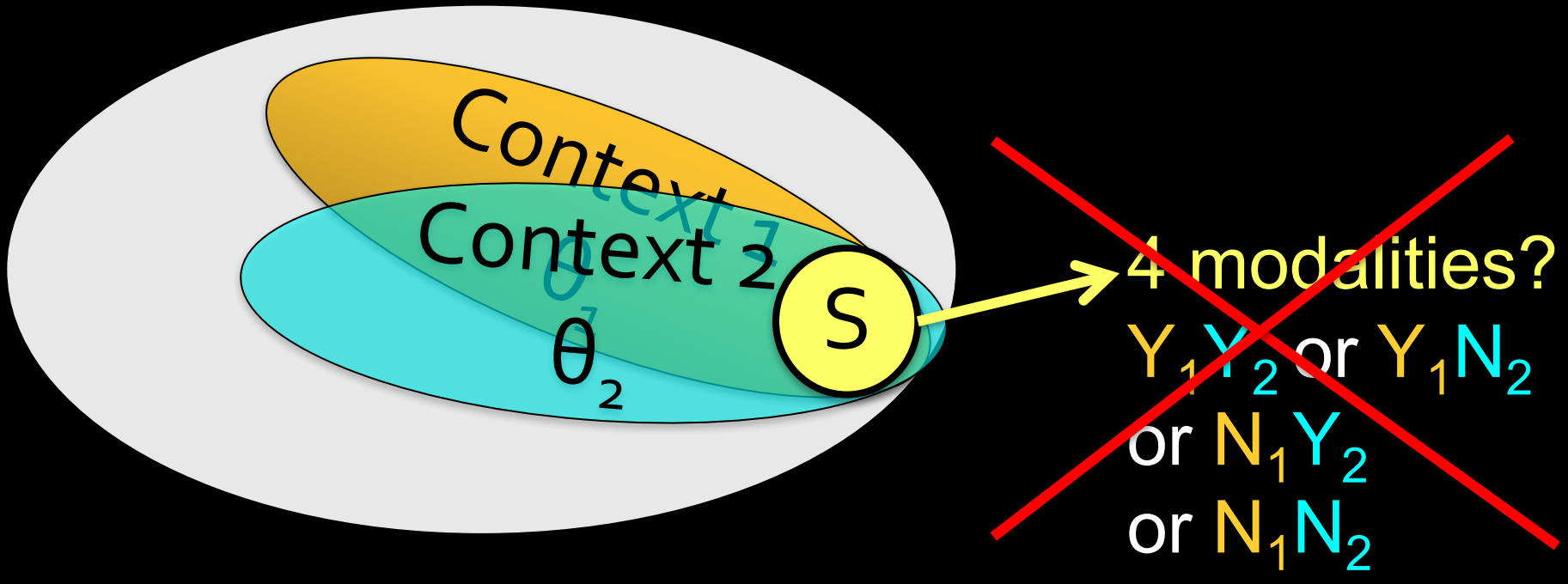
- « Hard contextuality »
- Non commutation of the questions



Proof: building a modality

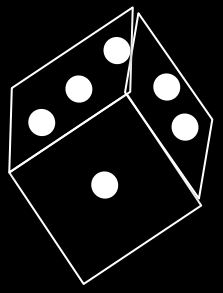
Contextuality + Quantization postulate

- Unpredictable answers
- Quantum randomness



Proof: building a modality

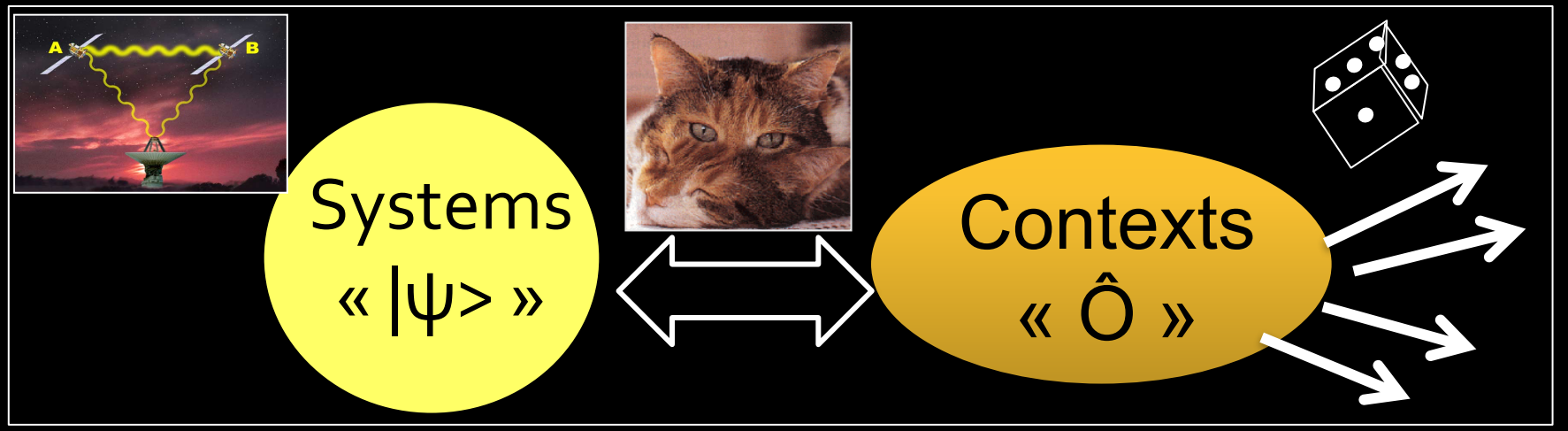
Contextuality + Quantization
Less predictable answers than possible questions



- Non-commutation
- Hard contextuality
- Unpredictable answers
- Quantum randomness

Core quantum features

Back to ordinary discomfort zones



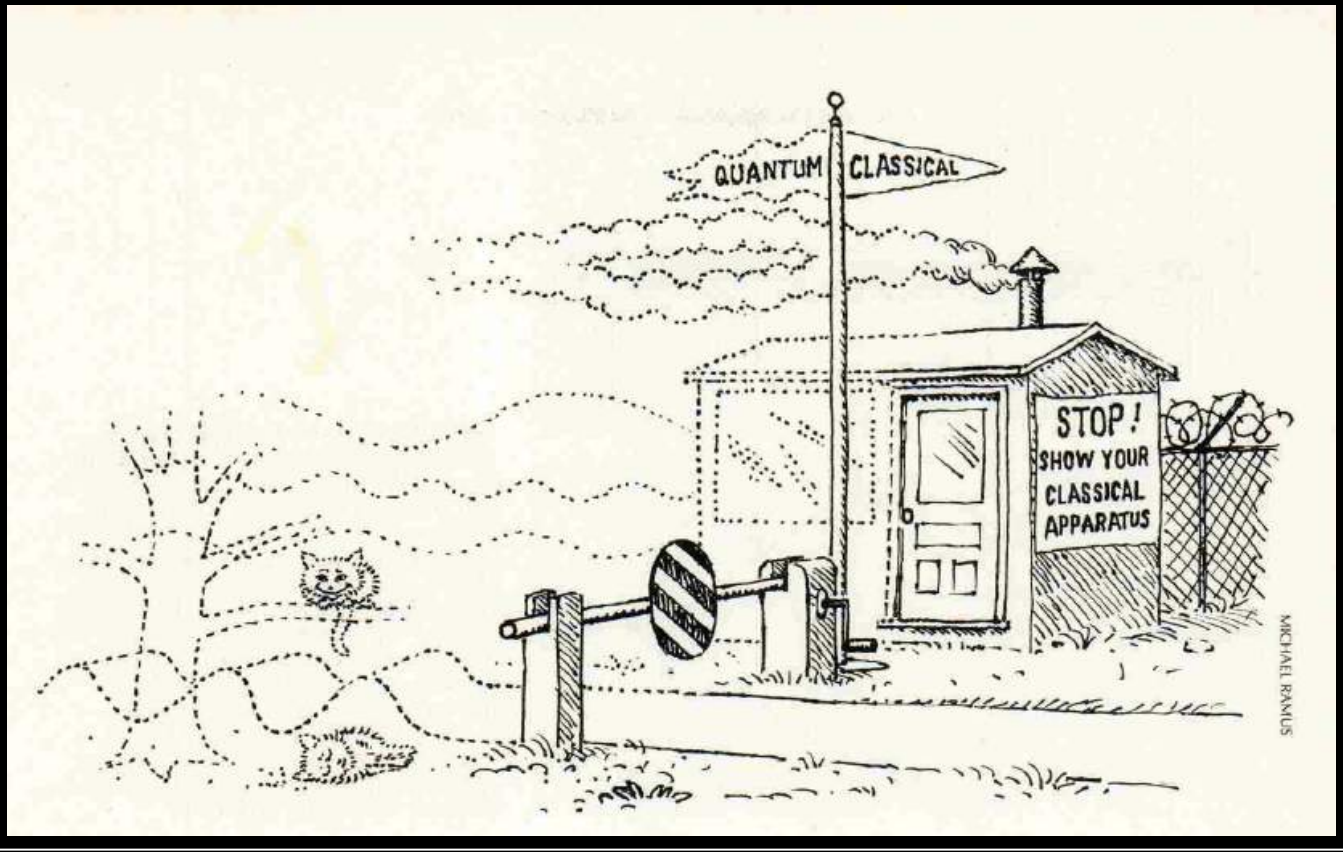
Quantum reality

- Hidden ✔
- Superpositions ✔
- Non-locality, spooky action
- *Unitary evolution*

Classical contexts

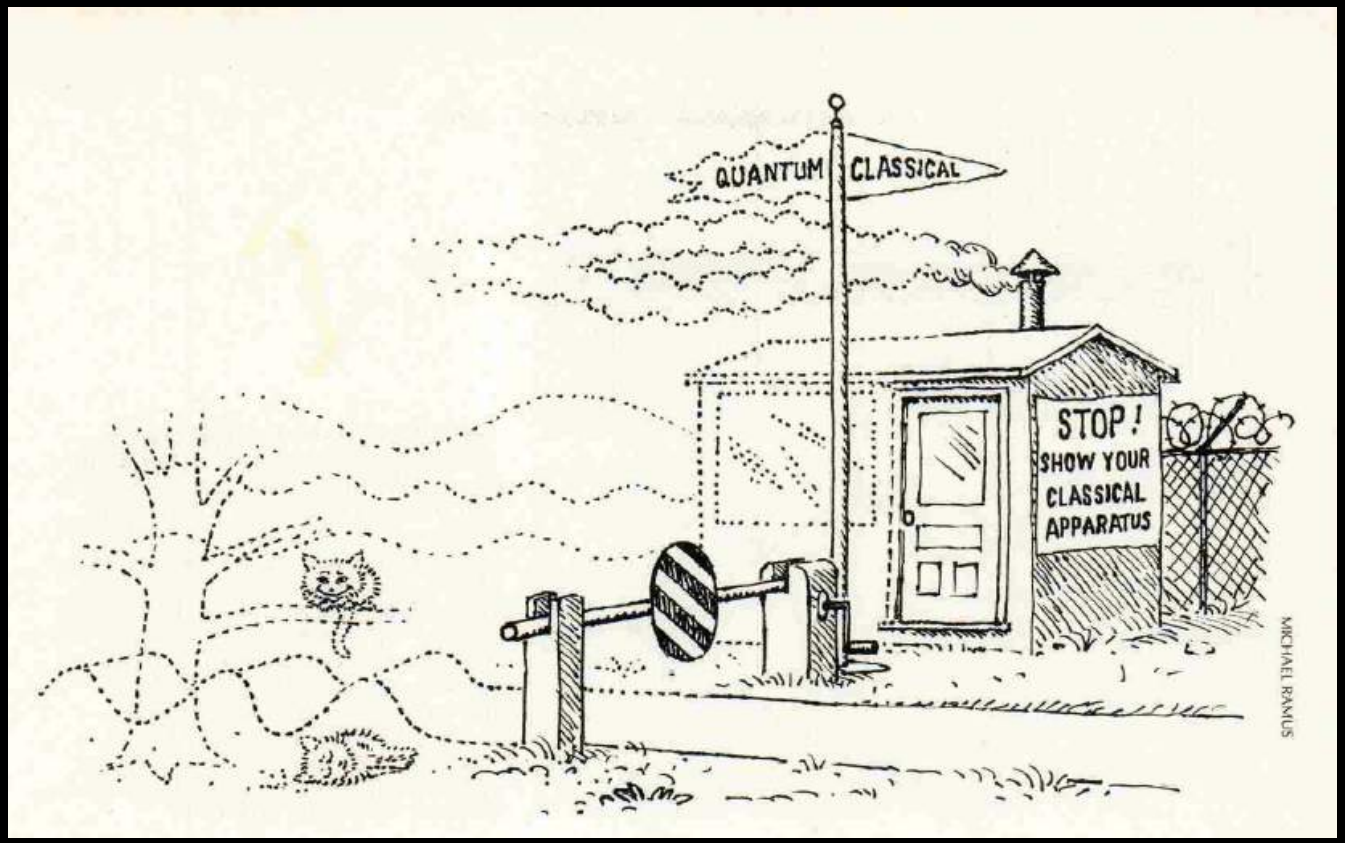
- **Quantum-classical boundary?**
- Randomness ✔
- *Non-unitary evolution*

Revisiting the quantum-classical boundary



- *Decoherence and the transition from quantum to classical, Zurek 1991*
- *Decoherence, einselection and the quantum origins of the classical, Zurek 2003*

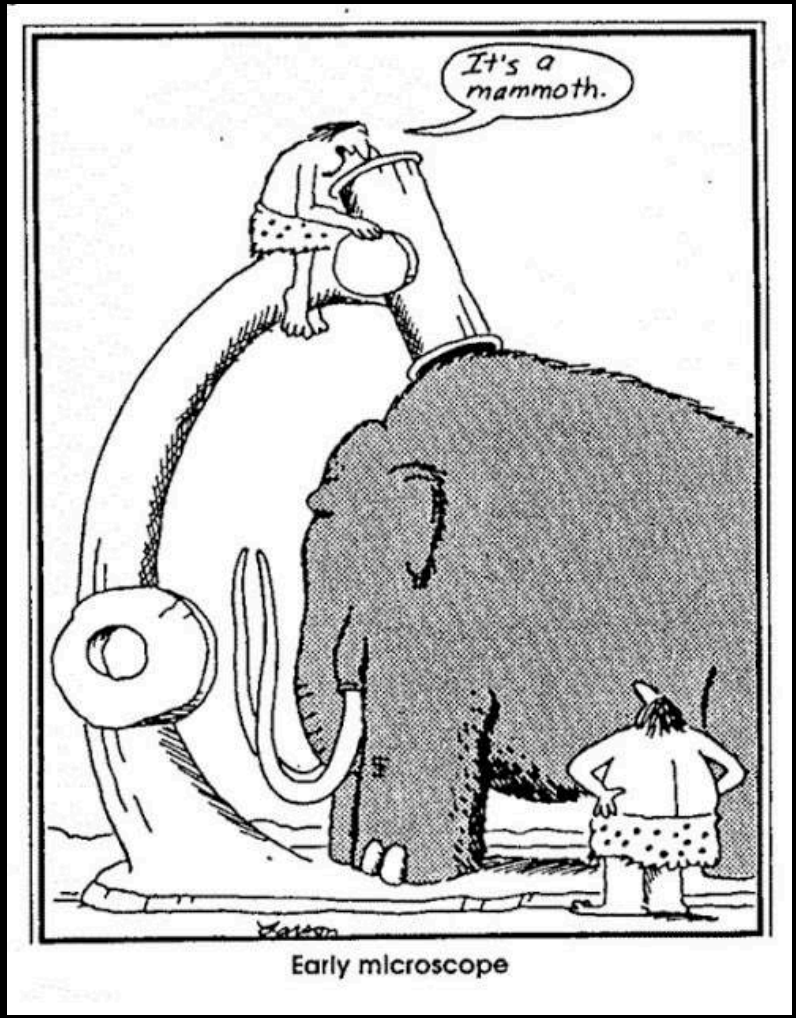
Revisiting the quantum-classical boundary



- Emergence of the classical (Bottom-up approach)
- Starting point: Hilbert space
- Final point: End of the measurement postulate

CSM and the classical-quantum boundary

- Classical context (θ)
- System
- N quantized modalities

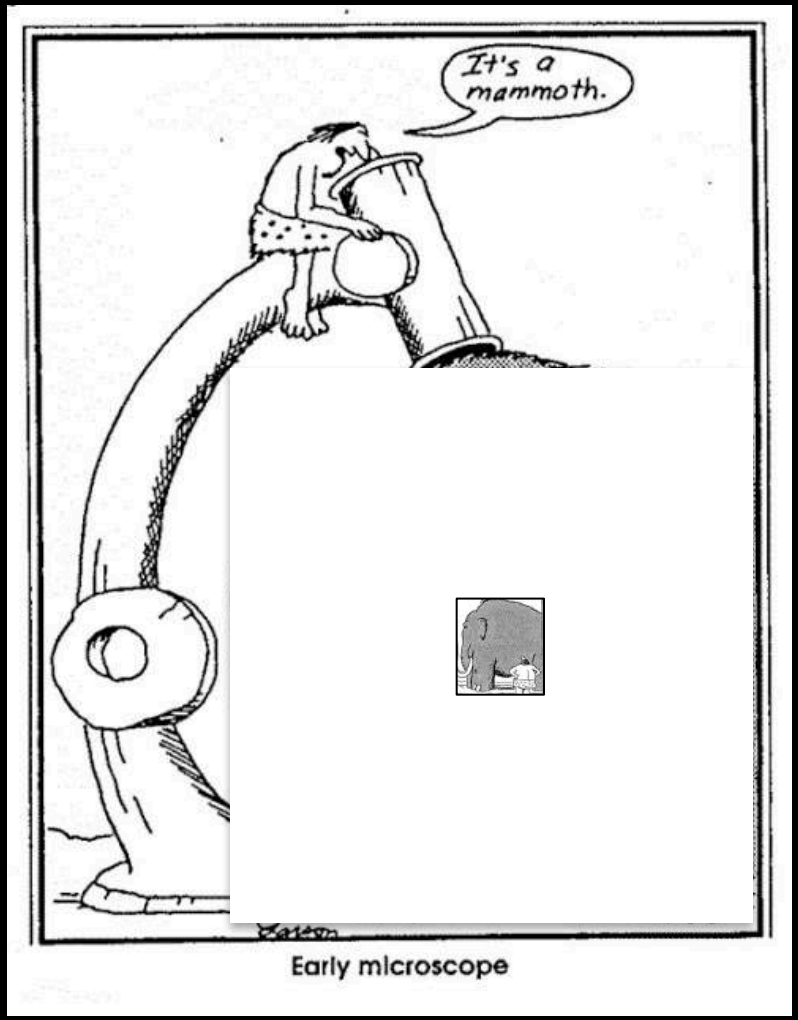


CSM and the classical-quantum boundary

- Classical context (θ)
- System
- N quantized modalities

There are quantum effects, because:

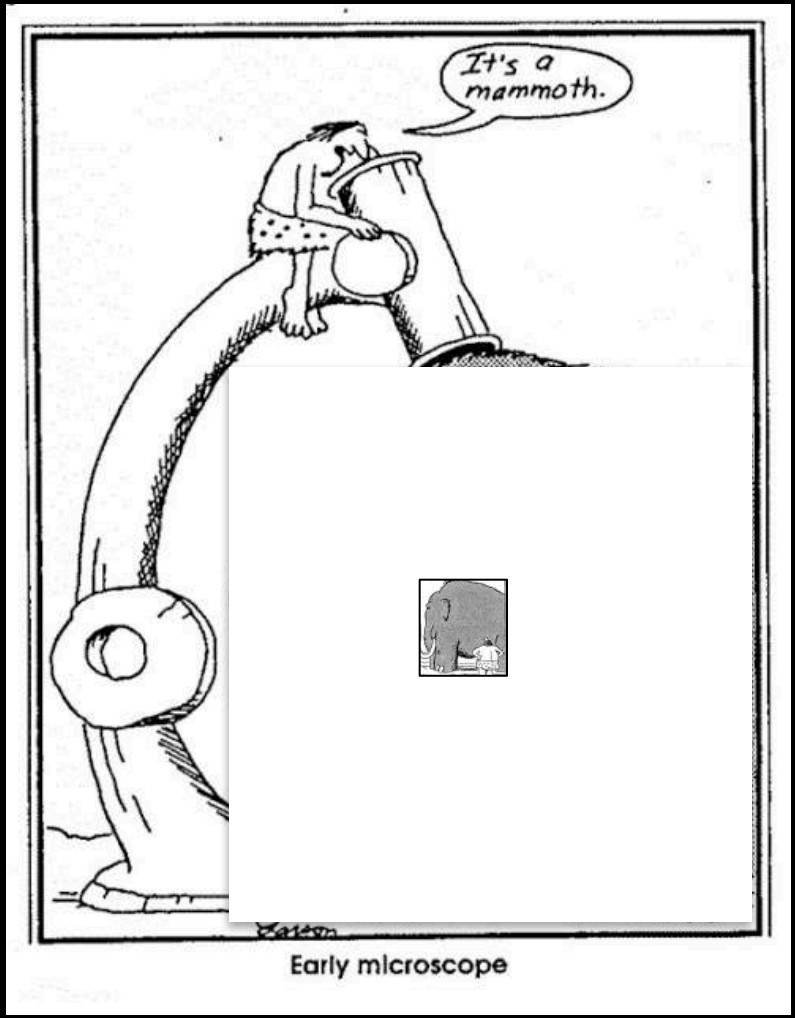
- There are less predictable answers (N) than questions (θ)
- Need for a system **and** a context



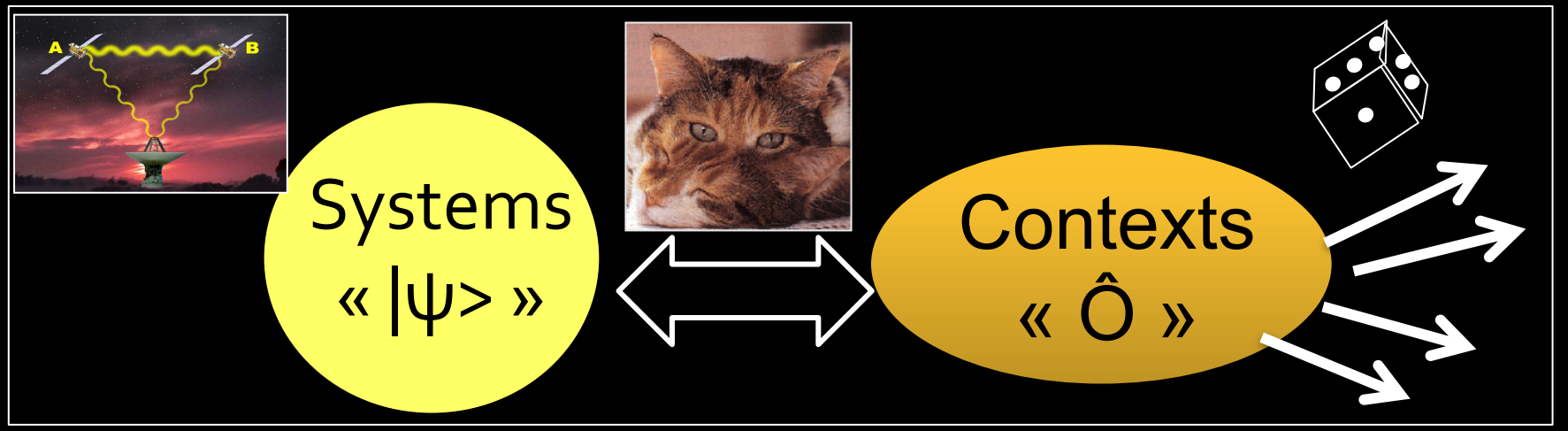
CSM and the classical-quantum boundary

Top-down approach

- The context is always already there
- The system will never « swallow the context »
- No emergence of the classical (from the quantum)



Back to ordinary discomfort zones



Quantum reality

- Hidden ✔
- Superpositions ✔
- **Non-locality, spooky action ?**
- *Unitary evolution*

Classical contexts

- Quantum-classical boundary ✔
- Randomness ✔
- *Non-unitary evolution*

Spooky action and non-locality

Alice

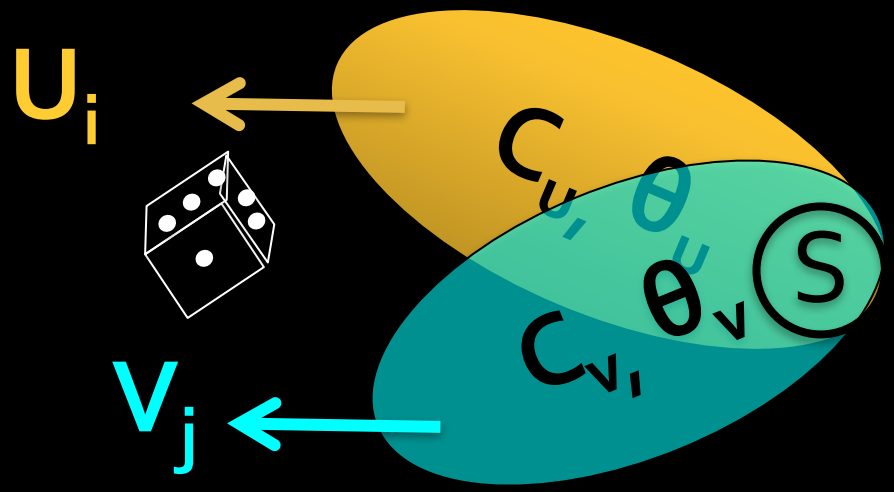
Bob

Ordinary quantum ontology:

- Alice and Bob share an EPR pair of photons
- Alice's measurement => Wave packet reduction
- Simultaneous projection on $|H_A\rangle$ and $|V_B\rangle$
- « Spooky action »

CSM and wave packet reduction

« Coherent superposition » => A modality in another context

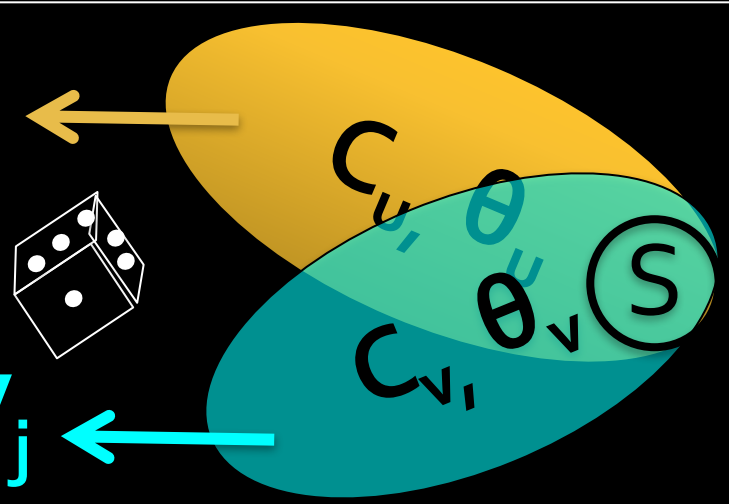


« Wave packet reduction » => Random change of modality when the context is changed

The CSM view on EPR

U_i =EPR state
C_u = global context

V_j =factorized state
C_v = local contexts



1. « Alice's measurement » = Change of context = Random change of modality
2. After the measurement: the context is at Alice's, and the system is at Bob's

The CSM view on EPR

Alice

EPR source

Bob

- **Non-locality = A consequence of the bipartite nature of reality**
- **No spooky action**

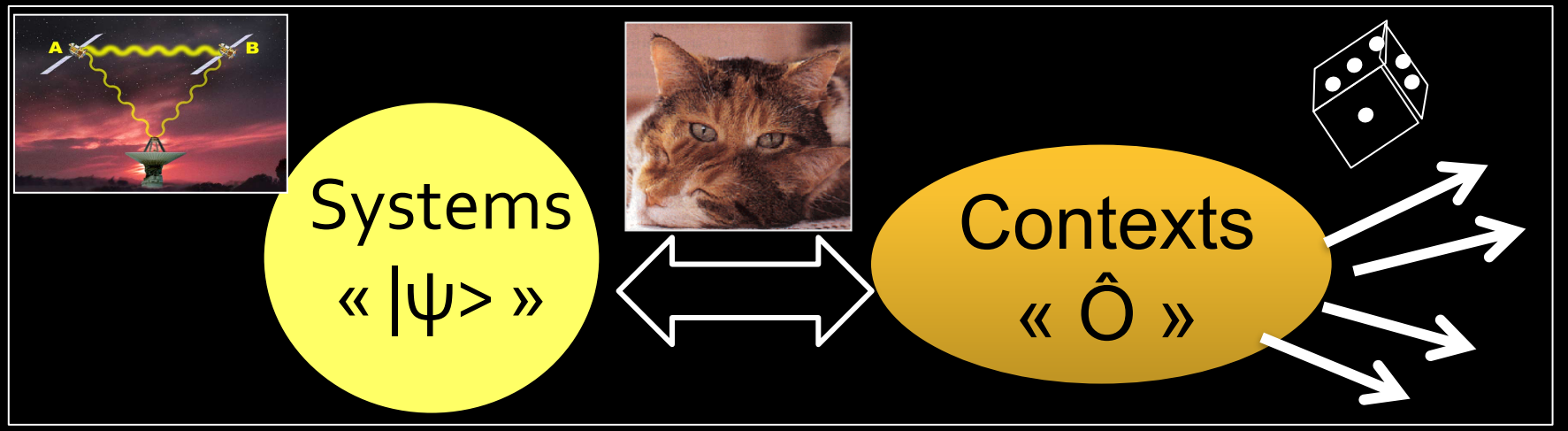
Outline

- Introduction: What is a physical state?
  => *The « quantum problem »*

- Rebuilding a quantum ontology
- Revisiting quantumness
- **Recovering the quantum formalism**

- Conclusions. Outlook.

Back to ordinary discomfort zones



Quantum reality

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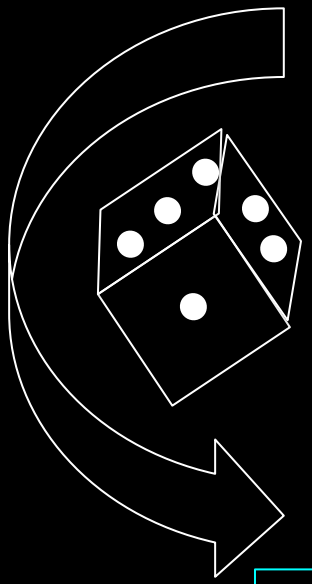
Classical contexts

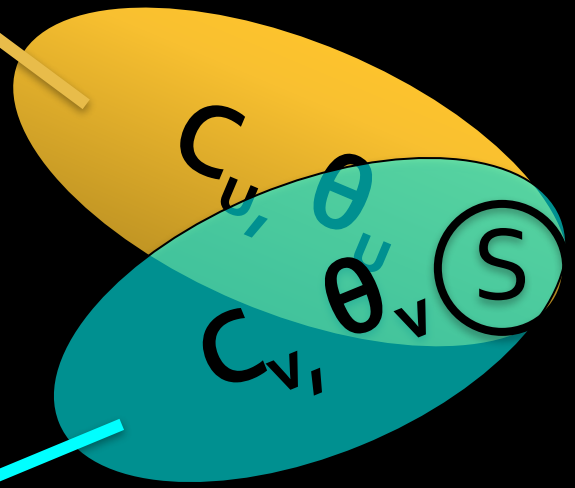
- Quantum-classical boundary ✔
- Randomness ✔
- *Non-unitary evolution*

The fundamental quantum event

N modalities $\{u_i\}$



Random change of modality when the context is changed



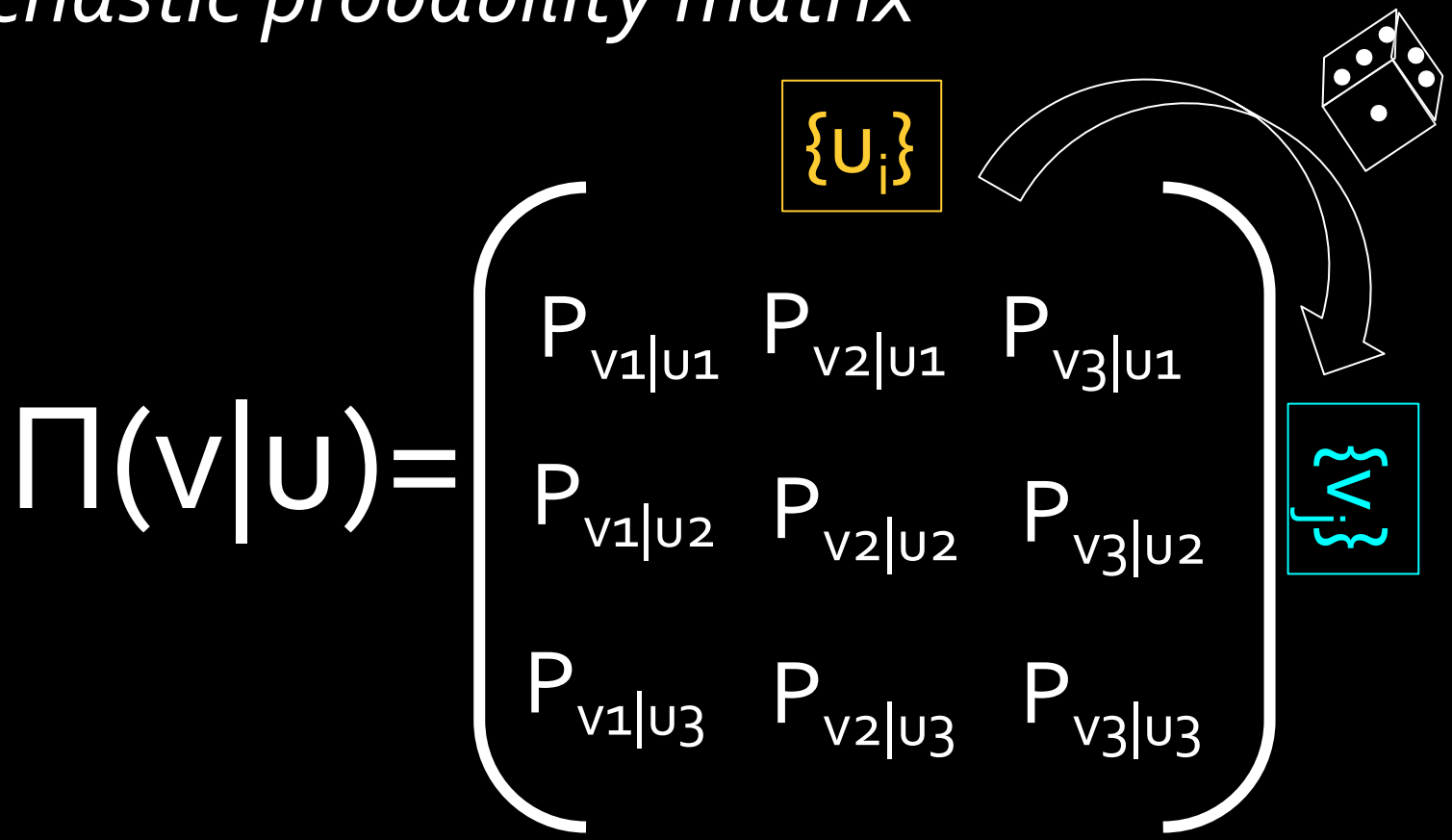
N modalities $\{v_j\}$

Goal of the theory: Describe the event

Auffèves and Grangier, Scientific Reports 43365 (2017)

The fundamental mathematical object

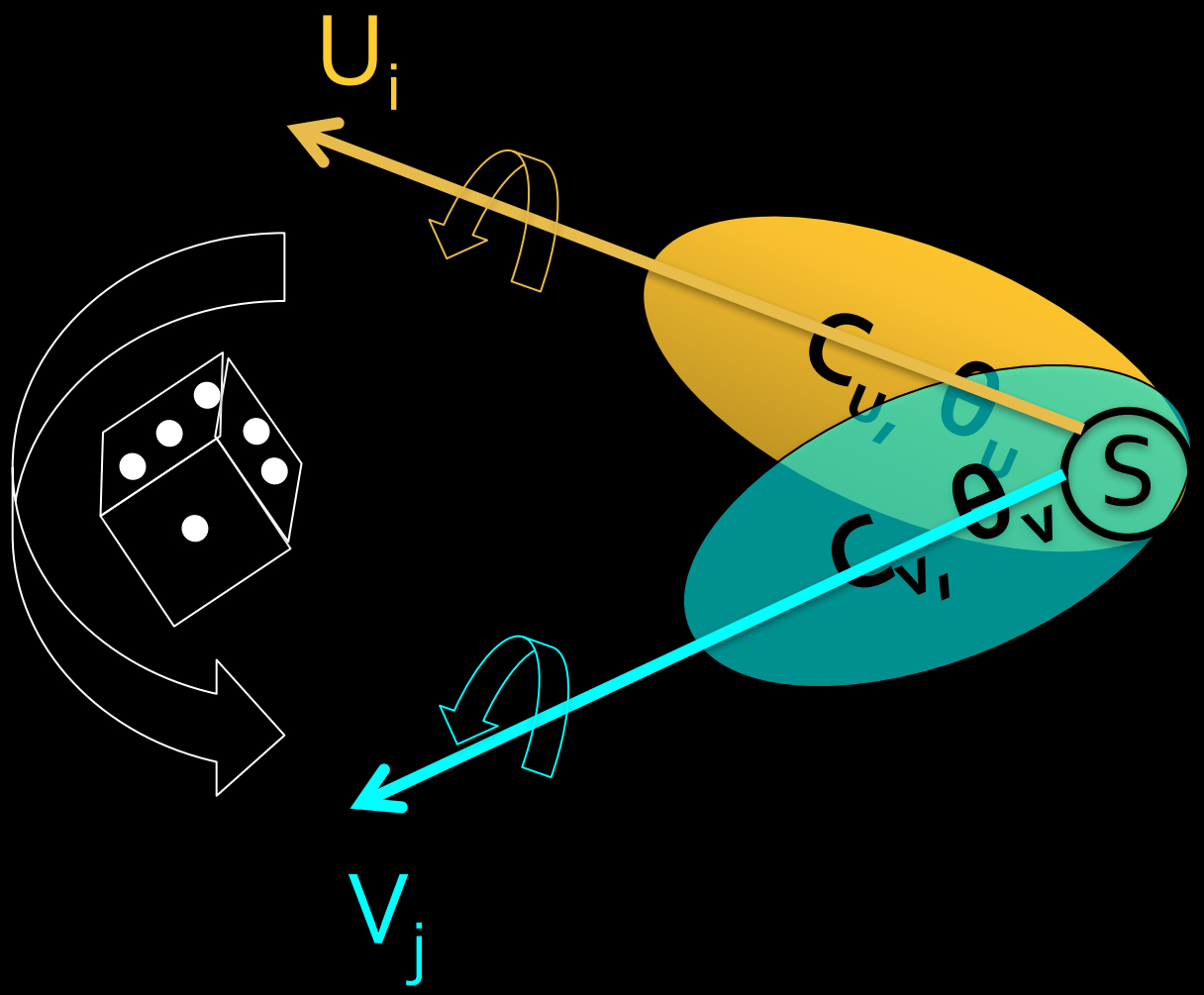
Stochastic probability matrix



Goal of the theory: Model Π(v|u)

Extra-contextuality of modalities

$P_{vj|ui}$ solely depends on U_i and V_j

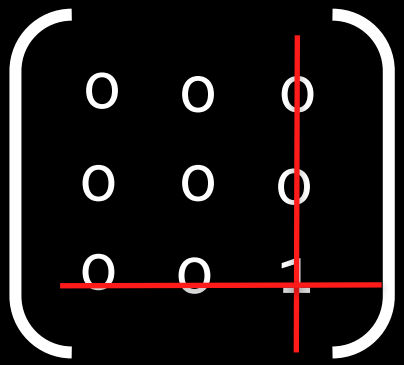


Step 1: Rewrite Π

$$\Pi(v|u) = \begin{pmatrix} P_{v1|u1} & P_{v2|u1} & P_{v3|u1} \\ P_{v1|u2} & P_{v2|u2} & P_{v3|u2} \\ P_{v1|u3} & P_{v2|u3} & P_{v3|u3} \end{pmatrix}$$

- $P_{vj|ui} = \mathrm{Tr}[P_i \Sigma^{+} P_j \Sigma]$
- $\Sigma = [P_{vj|ui}{}^{1/2} \exp(i\phi_{vj|ui})]$
- $\phi_{vj|ui}$ arbitrary phases

$P_k =$



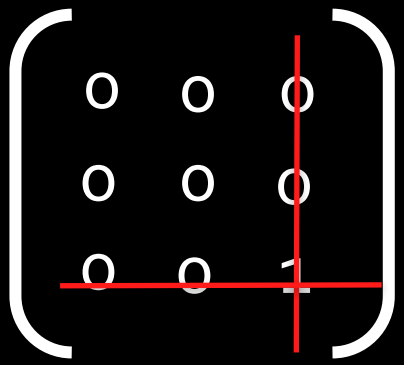
Goal: put constraints on these phases

Step 1: Rewrite Π

$$\Pi(v|u) = \begin{pmatrix} P_{v1|u1} & P_{v2|u1} & P_{v3|u1} \\ P_{v1|u2} & P_{v2|u2} & P_{v3|u2} \\ P_{v1|u3} & P_{v2|u3} & P_{v3|u3} \end{pmatrix}$$

- $P_{vj|ui} = Tr[P_i \Sigma^{+} P_j \Sigma]$
- $\Sigma = [P_{vj|ui}^{1/2} \exp(i\phi_{vj|ui})]$

$P_k =$



- $\Sigma (C_u, C_v)$
- Contexts pertain to a continuous group
- $\Sigma = 1$ if no change of context
- $\Sigma \to 1$ if $C_v \to C_u$

Step 1: Rewrite Π

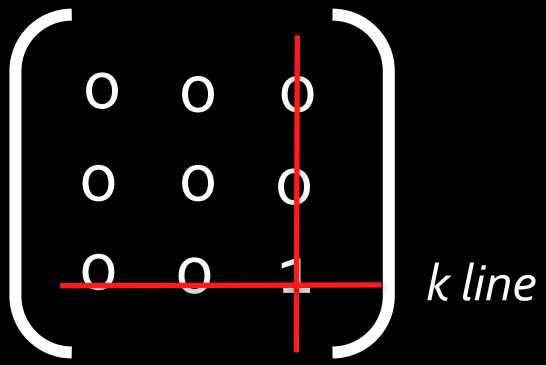
$$\Pi(v|u) = \begin{pmatrix} P_{v1|u1} & P_{v2|u1} & P_{v3|u1} \\ P_{v1|u2} & P_{v2|u2} & P_{v3|u2} \\ P_{v1|u3} & P_{v2|u3} & P_{v3|u3} \end{pmatrix}$$

$P_{vj|ui} = Tr[P_i \Sigma^+ P_j \Sigma]$

⇩ *Singular values decomposition*

- $\mathbf{P_{vj|ui} = Tr[P'_i R P''_j R]}$
- $\{P'_i\}$; $\{P''_j\}$ projectors
- R real diagonal positive

$P_k =$



$\Sigma = URV^+$, $\Sigma^+ = VRU^+$

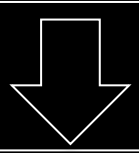
$P' = UPU^+$, $P'' = VPV^+$

U, V unitaries

Step 2: Call ontology for help

$P_{vj|ui} = Tr[P'_i R P''_j R]$
Depends on C_u and C_v

Identity for stochastic matrices



$P_{vj|ui} = Tr[P'_i R P''_j R]$

- **R, P'_i, P''_j depend on U_i and V_j only**
- R, P'_i, P''_j invariant when

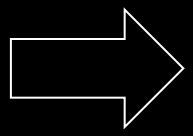
$C_u \rightarrow C_u'$ and $C_v \rightarrow C_v'$ **keeping U_i and V_j unchanged**

Extra-contextuality of modalities

Step 3: Chase the contradiction

Wanted: $R(U_i, V_j)$

- $Tr[R^2 P'_k]=N$
- $Tr[R^2]=N$
- For each k



$Tr[(R^2-1)P'_k]=0$

N linear equations

$D=Det\,[|U_{m,n}|^2]$

Either R=1, or D=0

- Suppose $R(C_u, C_v) \neq 1 \Rightarrow D(C_u, C_v)=0$
- $C_u \rightarrow C'_u$; $C_v \rightarrow C'_v \Rightarrow D \neq 0 \Rightarrow R(C'_u, C'_v)=1$
- R depends on the whole contexts

ABSURD => R=1

Step 4: Unitary matrices

$P_{vj|ui} = Tr[P_i \Sigma^{+} P_j \Sigma]$

$\Sigma = [P_{vj|ui}^{1/2} \exp(i\phi_{vj|ui})]$

$\Sigma = URV^{+}$, $\Sigma^{+} = VRU^{+}$

U,V unitaries

$R=1 \Rightarrow \Sigma = \Sigma^{+} = \Sigma^{-1}$

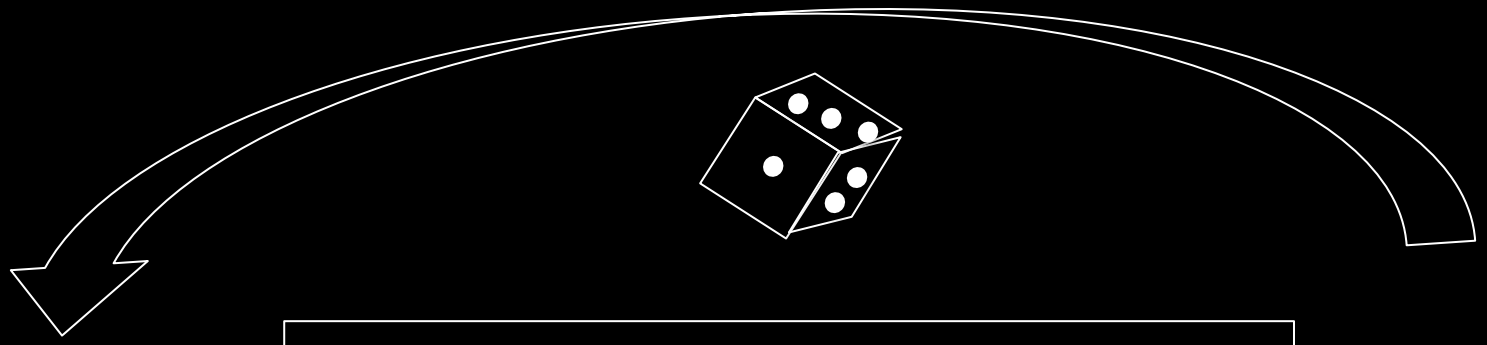
Real matrices?

Continuity of contexts

Continuous path relating identity and permutation

Σ = complex, unitary matrix

And finally: Usual quantum formalism



- $P_{vj|ui} = \mathrm{Tr}[P_i \Sigma_{v|u}{}^{+} P_j \Sigma_{v|u}]$
- $P_{vj|ui} = \mathrm{Tr}[\Sigma_{v|u} P_i \Sigma_{v|u}{}^{+} P_j]$

V_j

U_i

- U_i, V_j = Rays in a Hilbert space
- Change of context = $\Sigma_{v|u}$ unitary
- Probabilities follow Born's rule

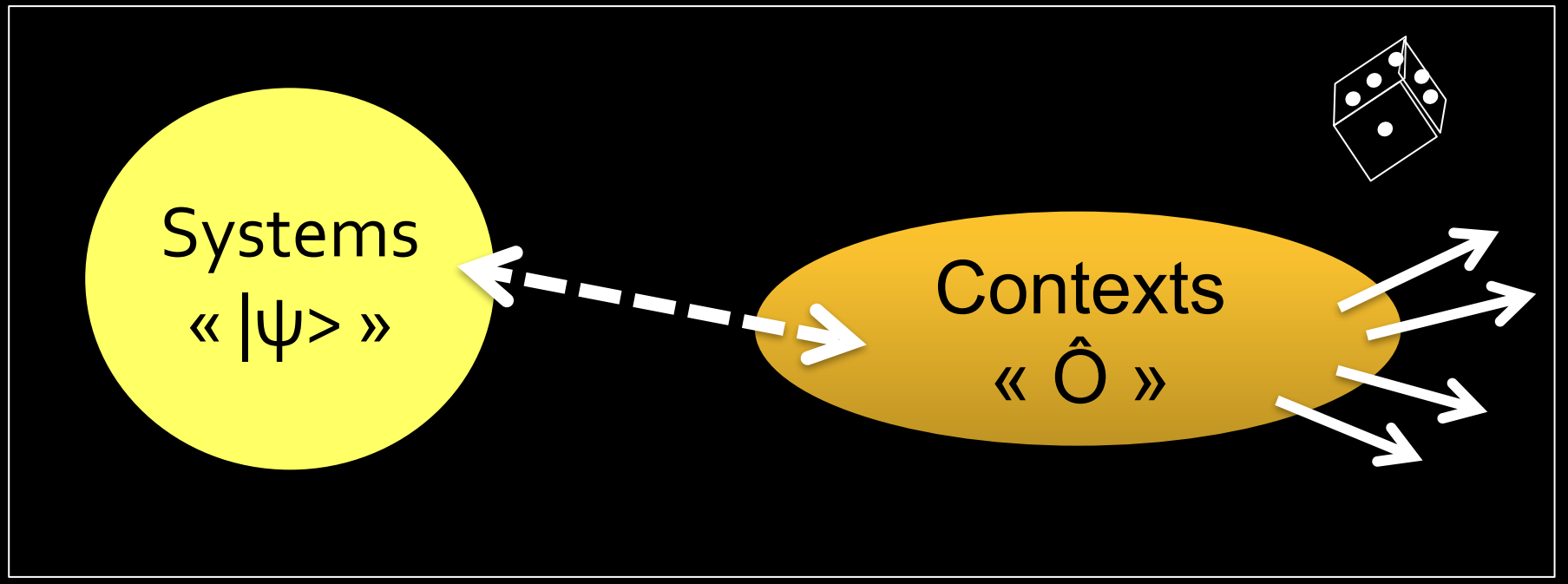
Outline

- Introduction: What is a physical state?
  => *The « quantum problem »*

- Rebuilding a quantum ontology
- From classical to quantum
- Recovering the quantum formalism

- **Conclusions. Outlooks.**

Back to ordinary quantum ontology



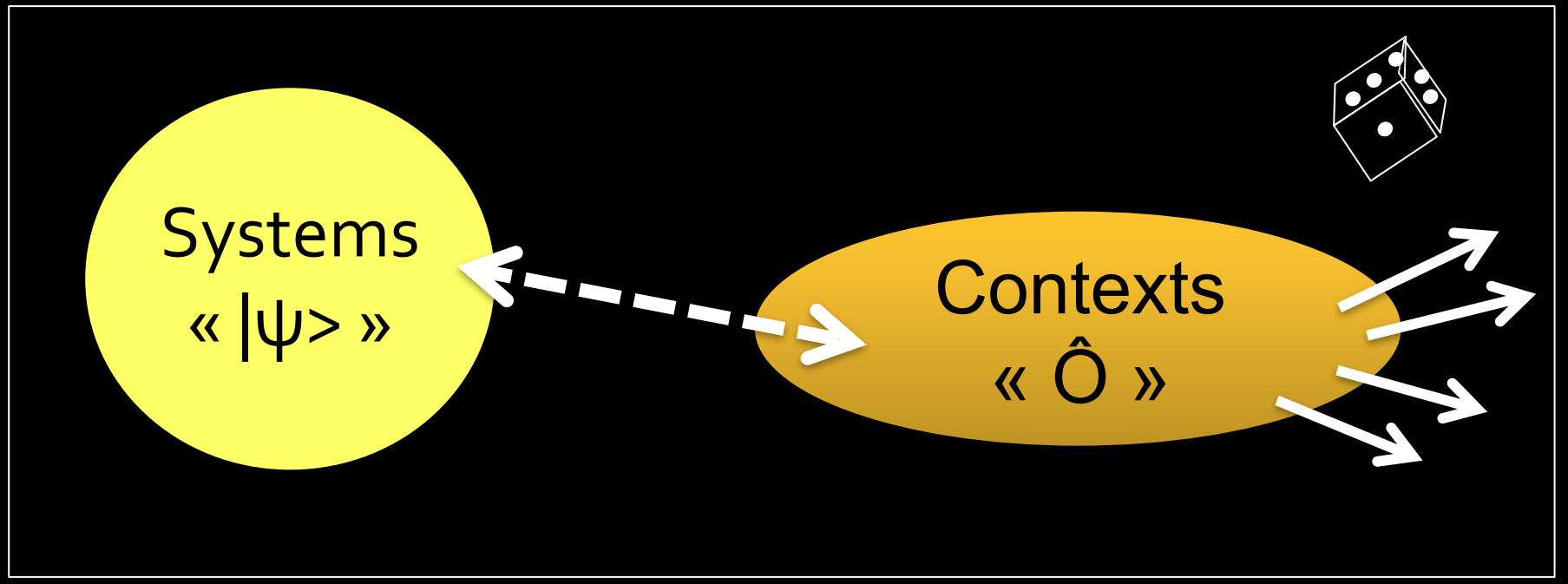
Quantum reality

- Superpositions
- Unitary + deterministic

Classical contexts

- Quantum-classical boundary?
- Non-unitary + Random

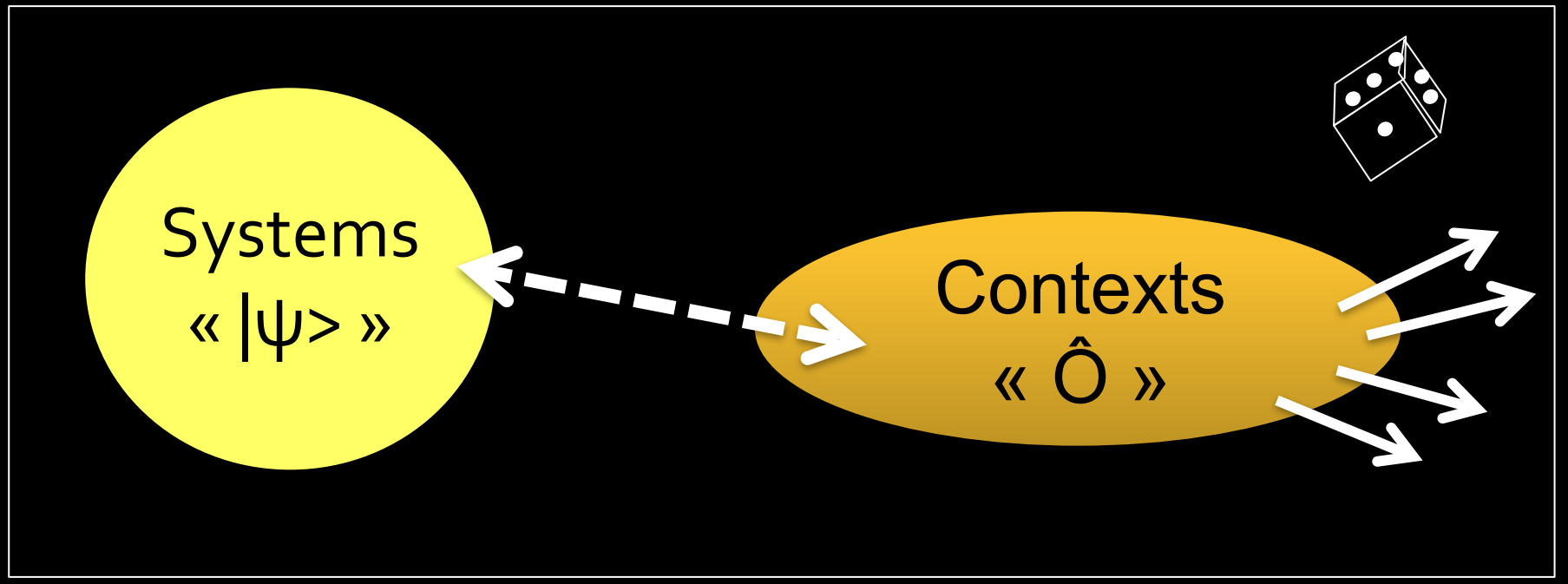
Back to ordinary quantum ontology



First source of intuition: Classical realism

States « ψ » pertain to systems alone

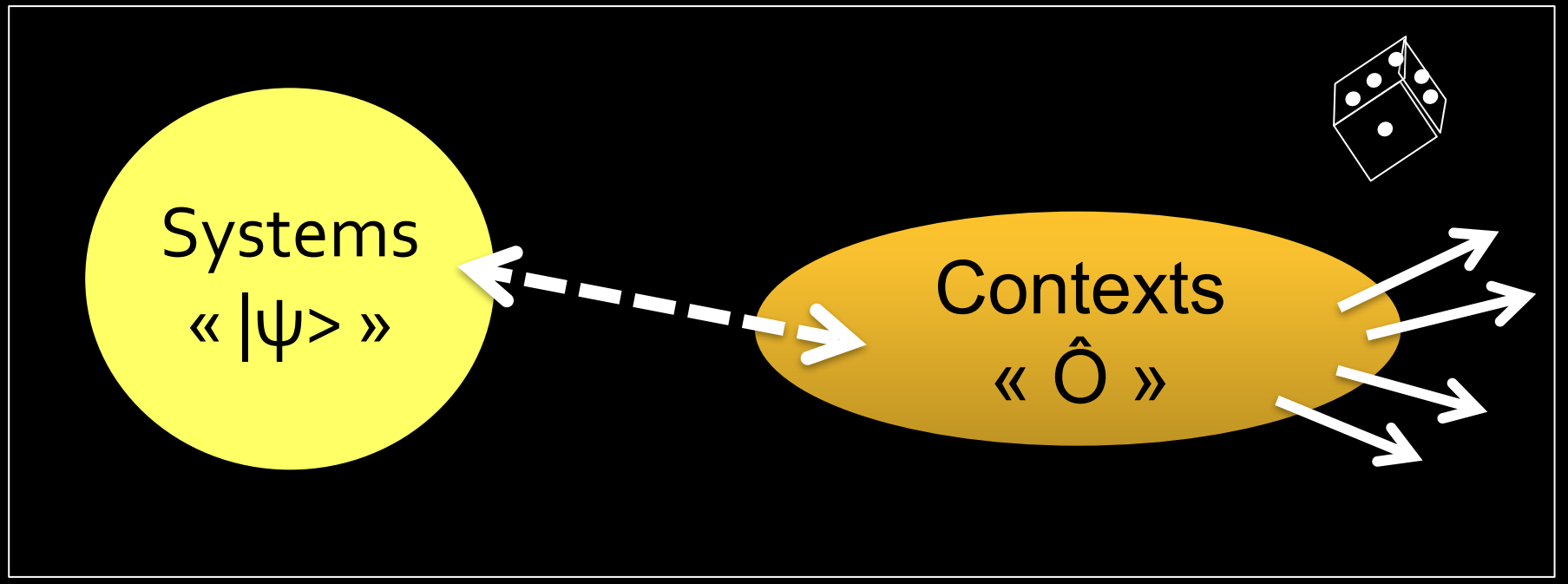
Back to ordinary quantum ontology



Second source of intuition: Statistical physics

- Reality is hidden, below
- The classical emerges from the quantum

Back to ordinary quantum ontology



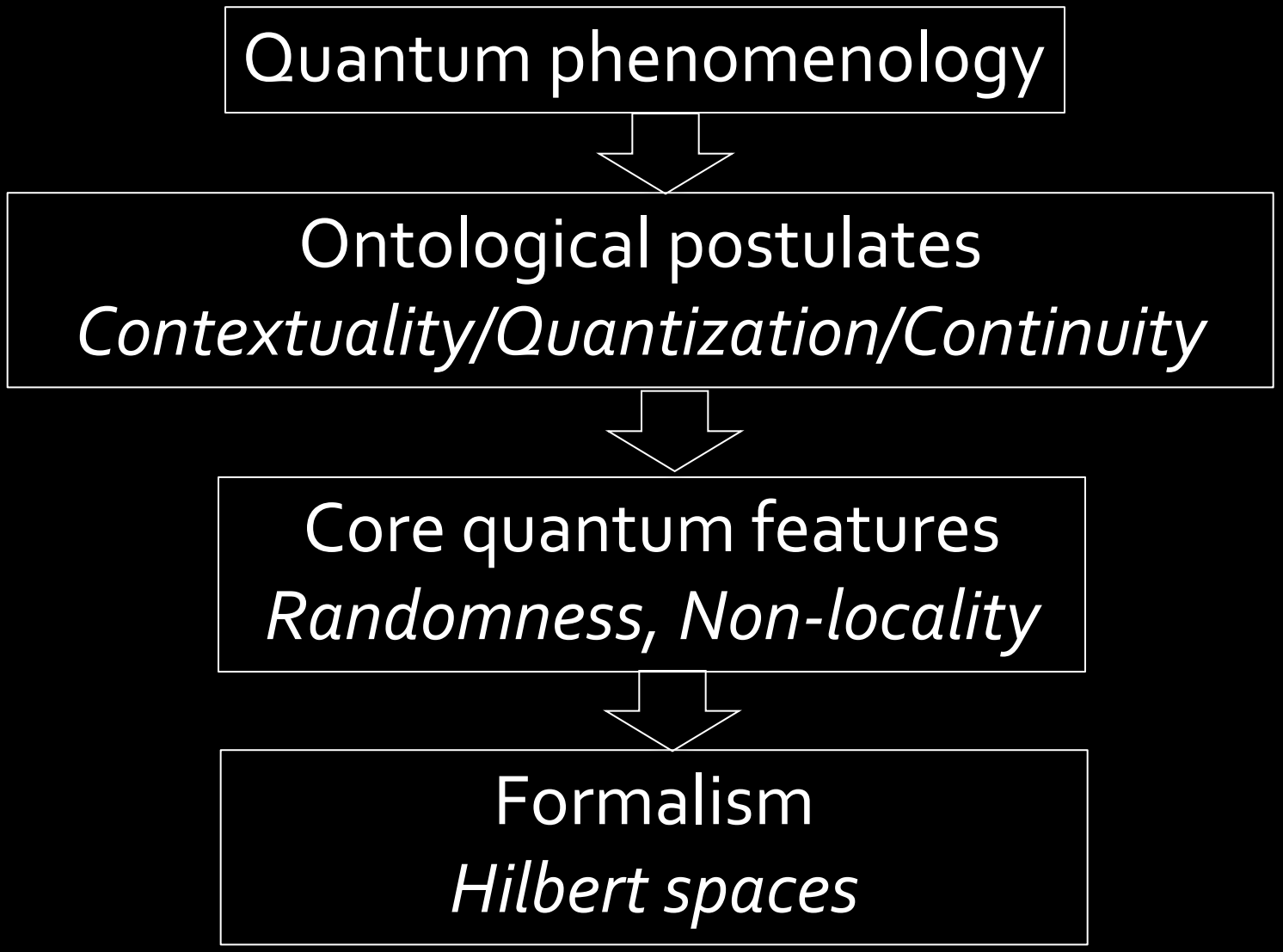
Third source of intuition: Formalism

- Quantum mechanics starts with maths
- Formalism = **the** reality we get accustomed to

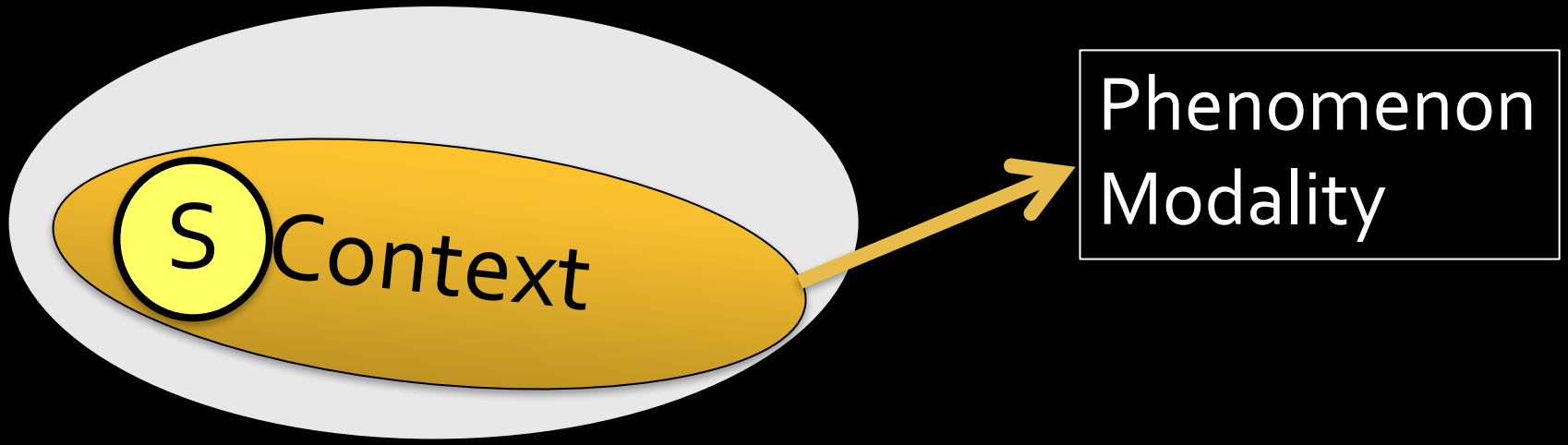
C-S-M: Inversion of norms

1. Ontology *vs* formalism
2. Phenomena *vs* « ψ »
3. Non-unitarity *vs* unitarity
4. Quantization *vs* interferences
5. Classical *vs* quantum
6. Randomness *vs* determinism

Ontology first, formalism second



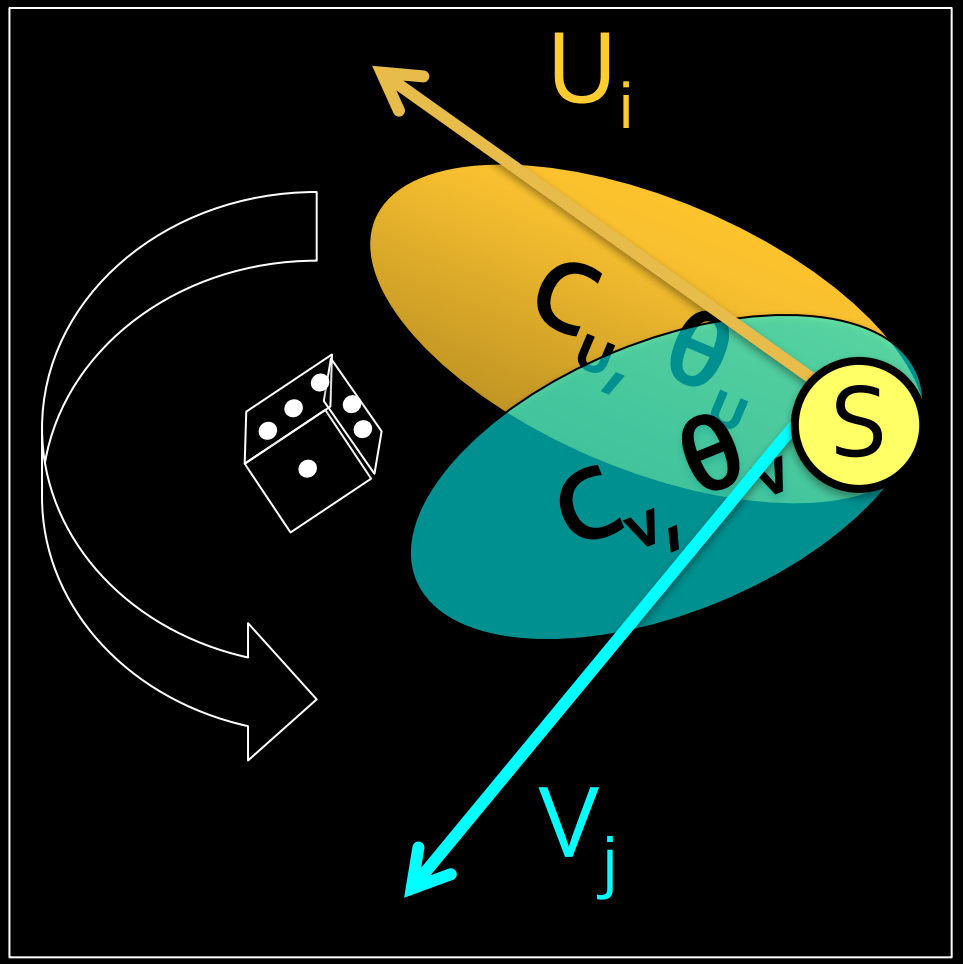
Phenomena first, « ψ » second



- The CSM approach of reality is based on certainty and actuality
- What is real is the modality-phenomenon.
- Ψ is a potentiality

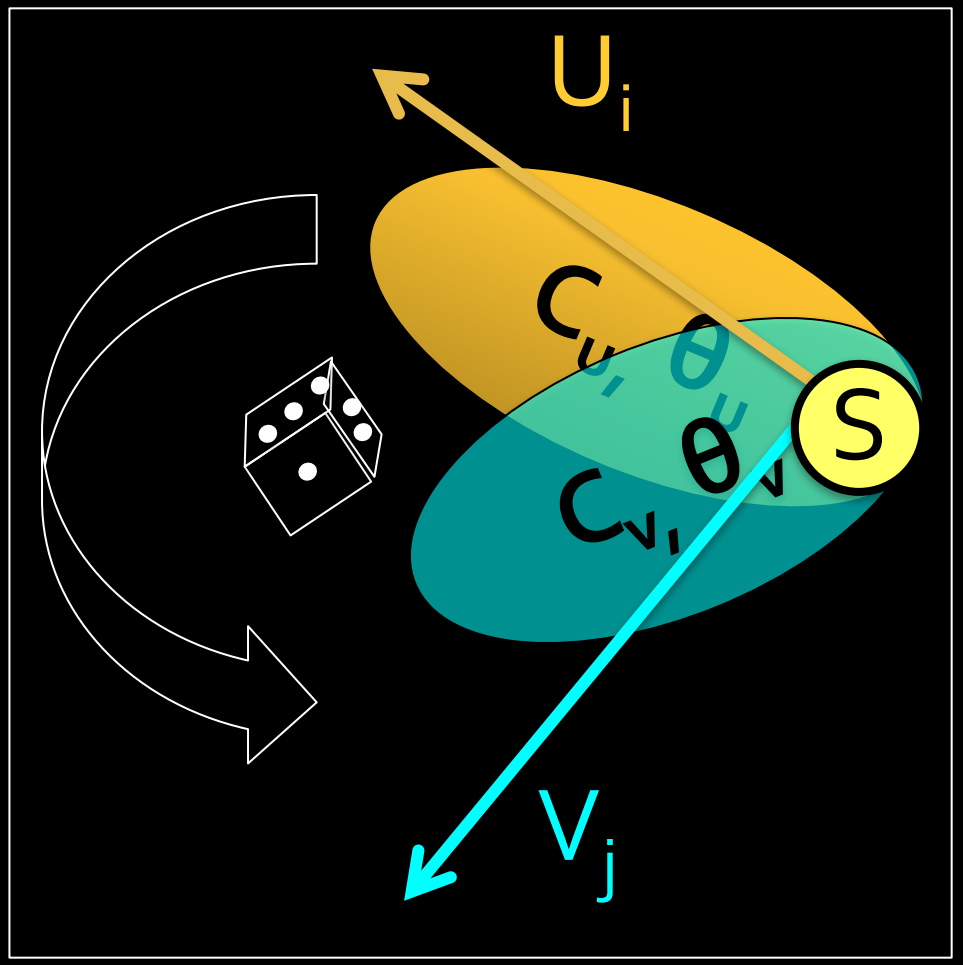
Non-unitarity first, unitarity second

- Fundamental quantum event = the change of probability (Non-unitary)
- Unitary transformations describe the change of context



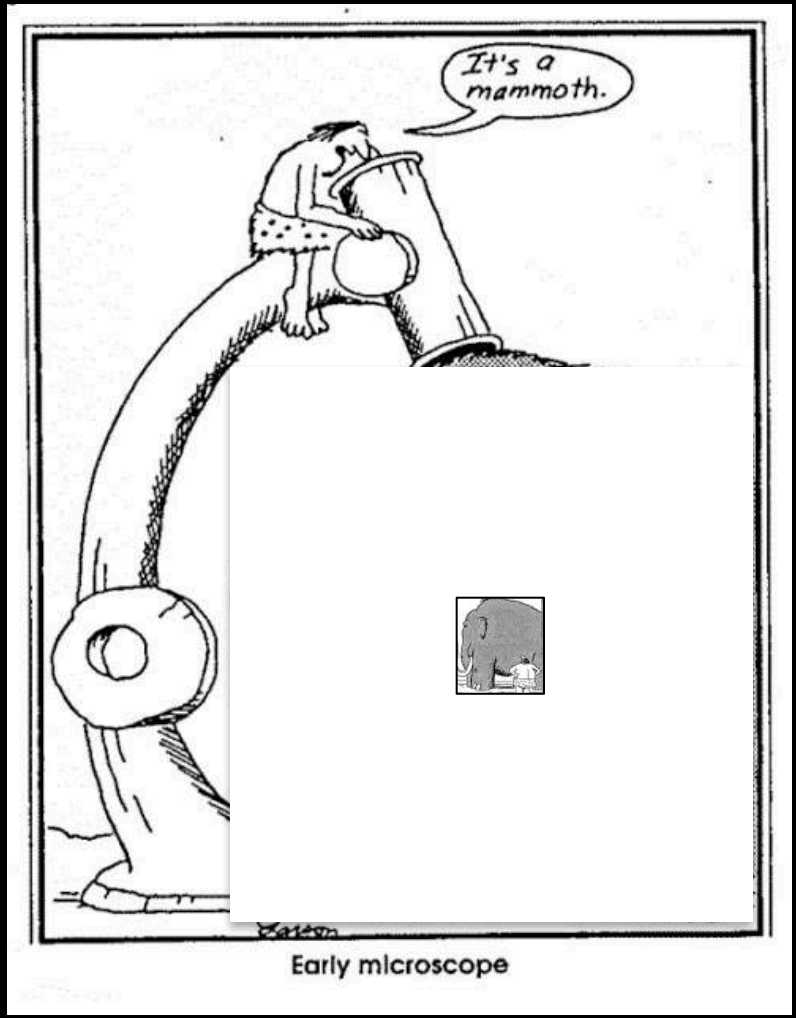
Quantization first, interferences second

- The random change of modality is due to quantization
- To describe context changes, unitary matrices are needed => complex numbers => interferences



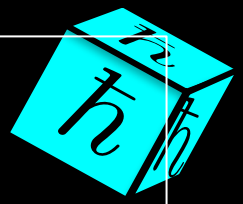
Classical first, quantum second

- Quantum effects pop up, because there are less repeatable answers (N) than possible questions (θ)
- Top-down approach
- The basis: the classical



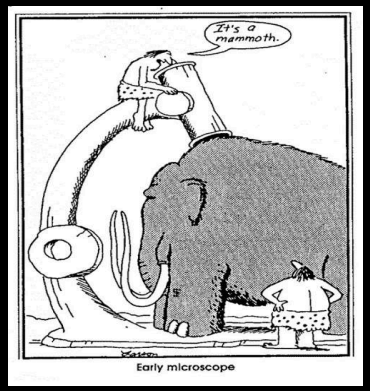
Randomness first, determinism second

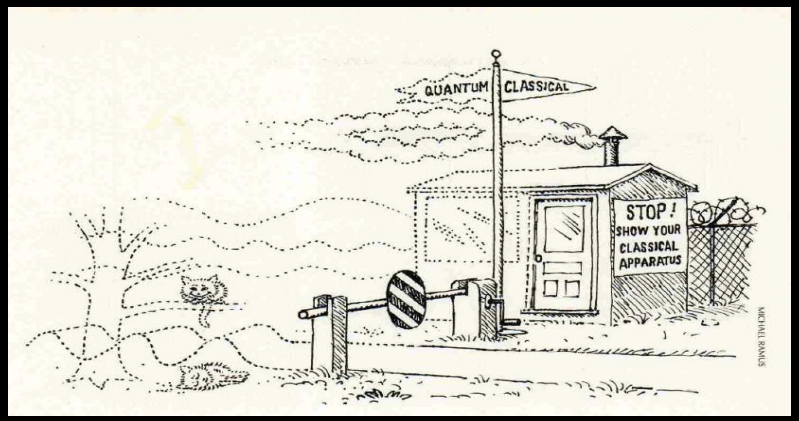
- Epistemological randomness
- Information loss due to coarse-graining
- Bottom up approach
- From microscopic to macroscopic



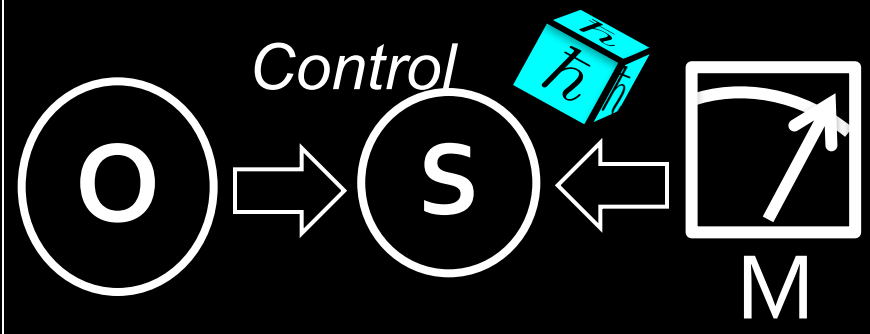
- Ontological randomness
- Unpredictability due to quantization
- Top down approach
- From macroscopic to microscopic

Some outlooks





Get CSM out of the lab!
Context -> *Environment*



Rebuild quantum thermodynamics on quantum randomness

Rethink epistemology vs ontology, given contextual objectivity