Title: Emergence of noncontextuality under quantum darwinism

Speakers: Barbara Amaral

Collection: Foundations of Quantum Computational Advantage

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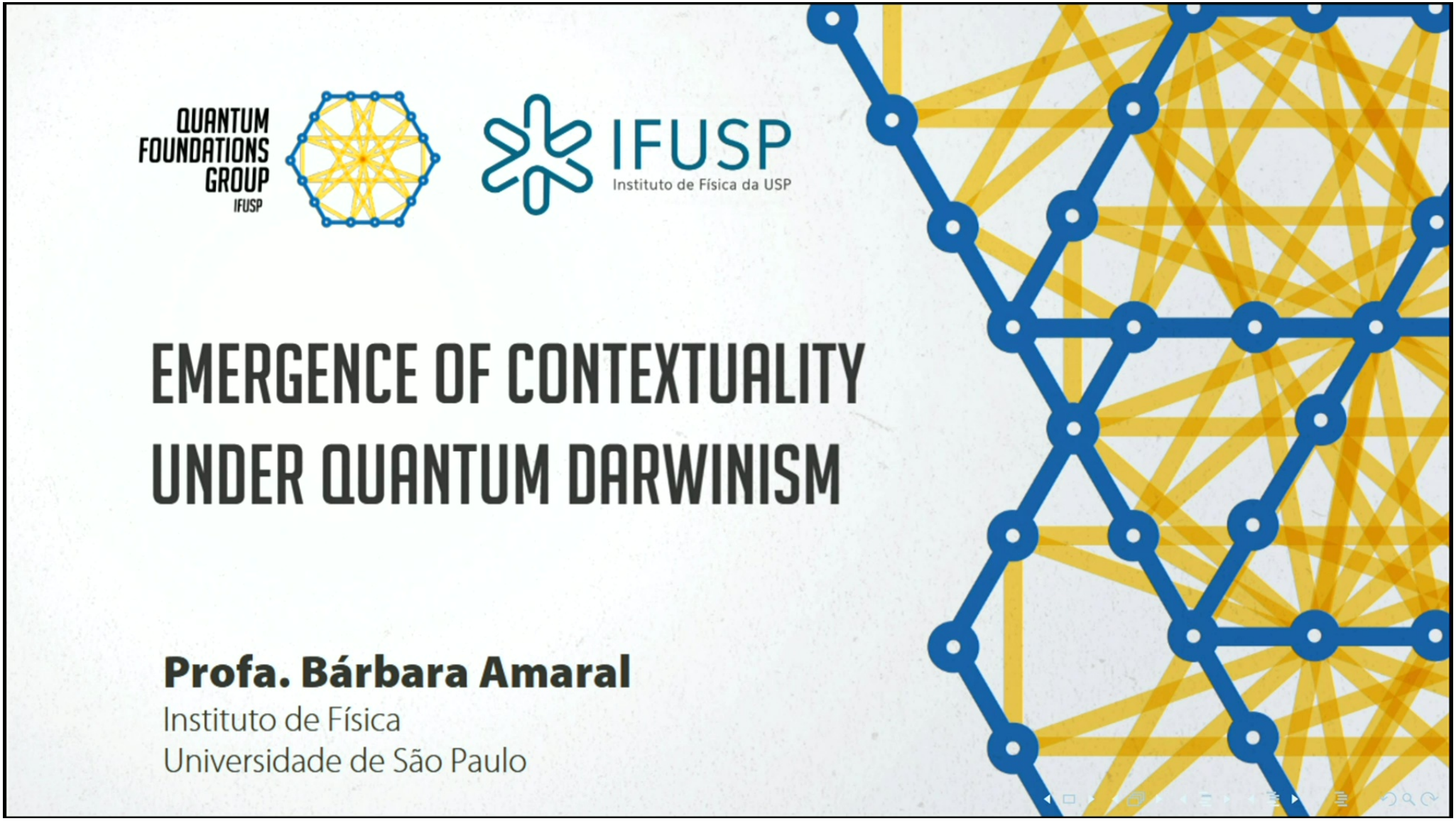
Abstract: Quantum Darwinism proposes that the proliferation of redundant information plays a major role in the emergence of objectivity out of the quantum world. Is this kind of objectivity necessarily classical? We show that if one takes Spekkens's notion of noncontextuality as the notion of classicality and the approach of Brandão, Piani, and Horodecki to quantum Darwinism, the answer to the above question is "'yes," if the environment encodes the proliferated information sufficiently well. Moreover, we propose a threshold on this encoding, above which one can unambiguously say that classical objectivity has emerged under quantum Darwinism.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EMERGENCE OF CONTEXTUALITY
UNDER QUANTUM DARWINISM
Profa. Bárbara Amaral
Instituto de Física
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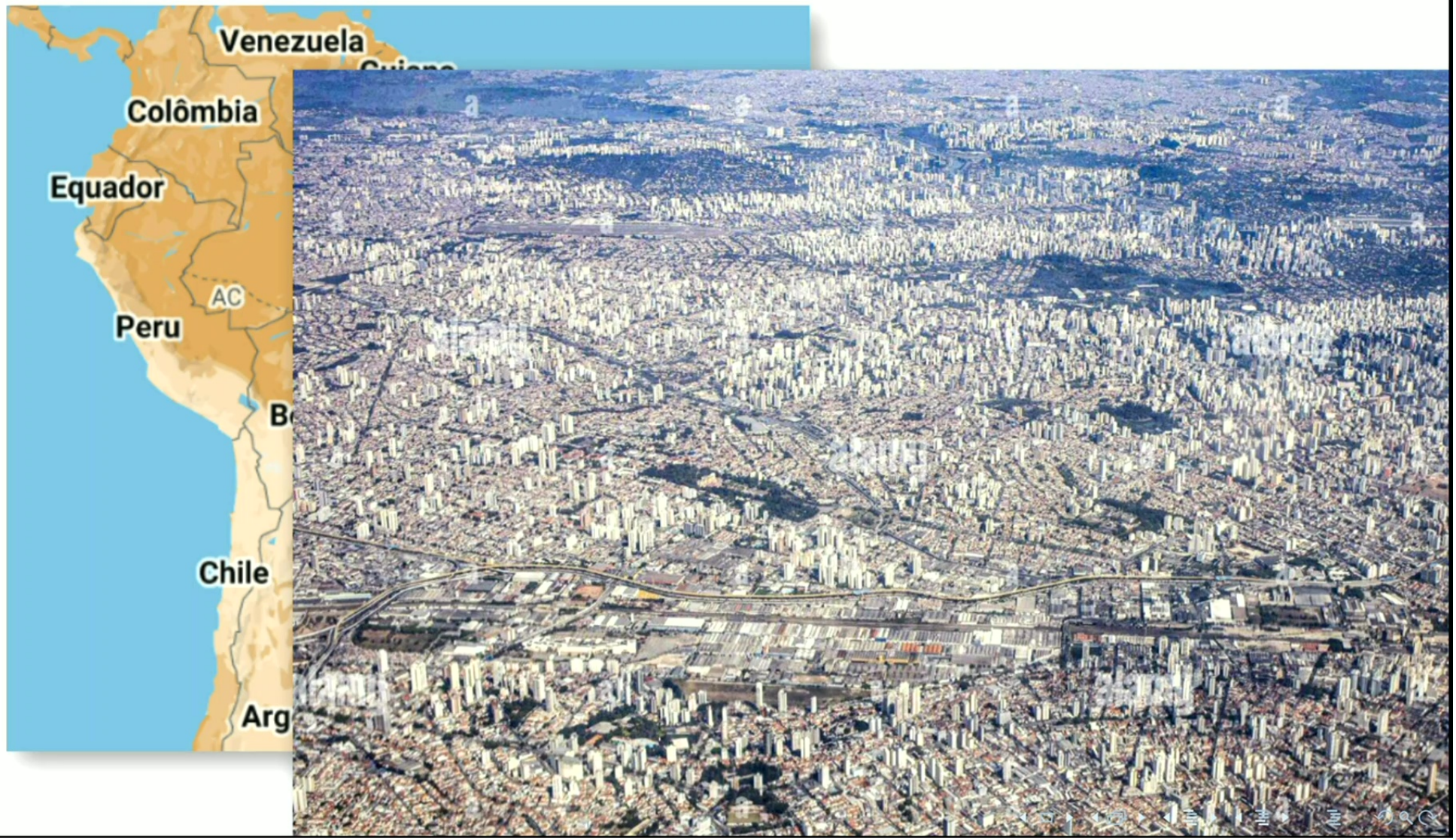
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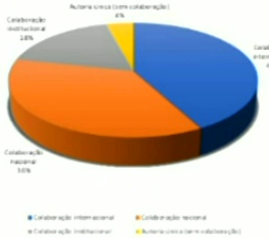

Fonte: Scopus/Scival

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3. **Quantum Computing**: Exploring photonic processors, superconducting qubits, and quantum-inspired machine learning for groundbreaking computational capabilities.

My family tree

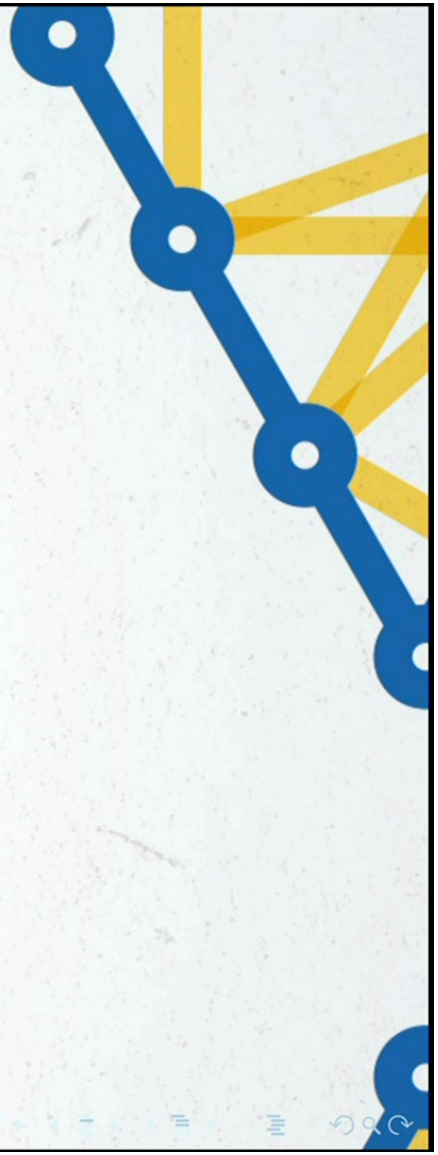
The problem

Our everyday experience is **classical**.

Noncontextuality is a **nonclassical** feature.

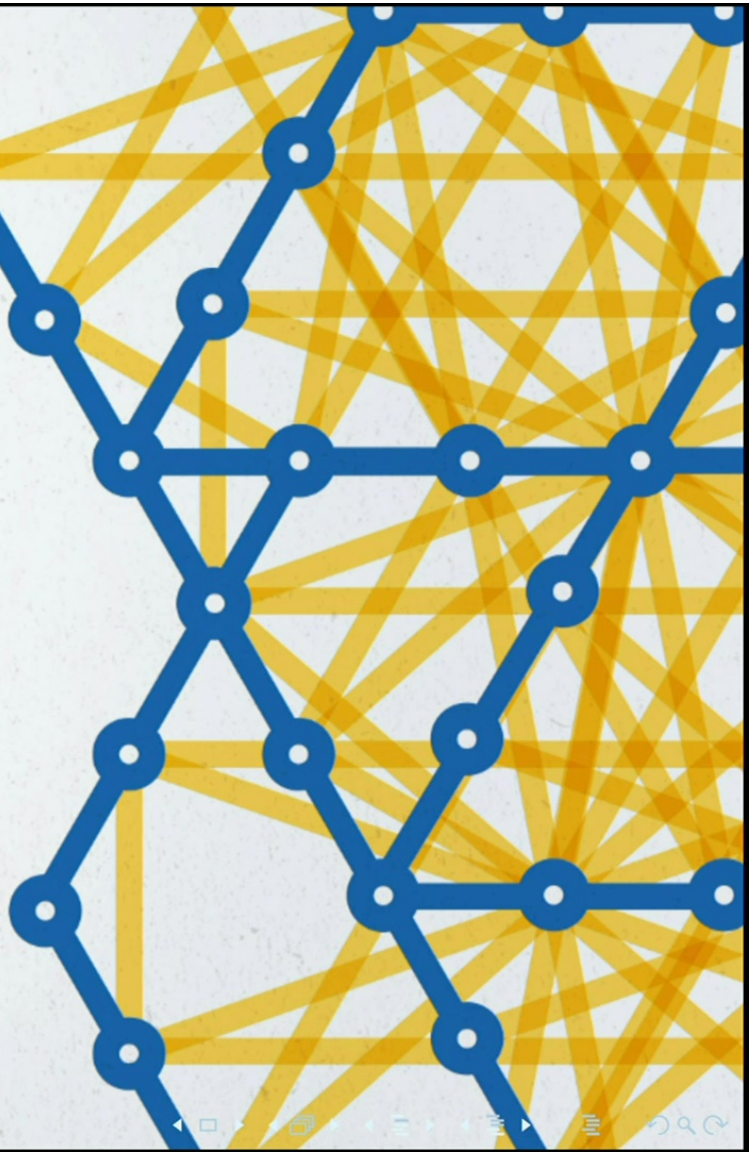
The problem

Classical limits must kill contextuality!



QUANTUM DARWINISM

F. Brandão, M. Piani, P. Horodecki, Nat. Comm. 6 7908 (2015).



Example

Example

$$|00\rangle \mapsto |00\rangle$$
$$|10\rangle \mapsto |11\rangle$$

$$\alpha|00\rangle + \beta|10\rangle \to \alpha|00\rangle + \beta|11\rangle$$

Measurement on system B: 0 with probability $|\alpha|^2$, 1 with probability $|\beta|^2$.

Example

$$|000...00\rangle \mapsto |00...00\rangle$$

$$|10...00\rangle \mapsto |11...11\rangle$$

$$\alpha|000...00\rangle + \beta|10...00\rangle \to \alpha|00...00\rangle + \beta|11..11\rangle$$

Measurement on systems *Bs*: 00...0 with probability $|\alpha|^2$, 11...1 with probability $|\beta|^2$.

Example

$$|00\rangle \mapsto |00\rangle$$

$$|10\rangle \mapsto |1+\rangle$$

$$\alpha|00\rangle + \beta|10\rangle \to \alpha|00\rangle + \beta|1+\rangle$$

Measurement on system B: not full information about Z_A.

Example

$$|00...0\rangle \mapsto |00...0\rangle$$

$$|10...0\rangle \mapsto |1+..+\rangle$$

$$\alpha|00...0\rangle + \beta|10...0\rangle \to \alpha|00...0\rangle + \beta|1+...+\rangle$$

Measurement on system B: not full information about Z_A.
Different Bobs do not necessarily agree.

Environment as a witness dynamics

$\Phi : \mathcal{D}(\mathcal{H}_A) \to \mathcal{D}(\mathcal{H}_{\mathcal{E}})$

$S_t \subset \{1, ..., N\}$ set of labels describing t portions of the environment $\mathcal{E}$.

EW$_t$-dynamics for the subset $B_{S_t} := \{B_j\}_{j \in S_t}$

$$\Phi^{B_{S_t}} := \mathrm{Tr}_{\mathcal{E} \setminus B_{S_t}} \circ \Phi.$$

BPH

If $N \gg t$, then there exists a POVM $\{\tilde{E}_k\}$ acting on $\mathcal{D}(\mathcal{H}_A)$ such that, for most choices of S_t,

$$\Phi^{BS_t}(\rho^A) \approx \sum_k \mathrm{Tr}[\tilde{E}_k \rho^A] \sigma_k^{BSt},$$

where $\sigma_k^{BS_t} \in \mathcal{D}(\bigotimes_{j \in S_t} \mathcal{H}_{B_j})$ and $\{\tilde{E}_k\}_k$ is independent of B_{S_t}.

$$\Phi^{BS_t}(\rho^A) \approx \sum_k \mathrm{Tr}[\tilde{E}_k \rho^A] \sigma_k^{BS_t}$$

This tells us that EWt-dynamics already leads to emergence of some objectivity: objectivity of observables.

Example

$$\rho_B = \mathrm{Tr}[|0\rangle\langle 0|\rho^A]|00\ldots0\rangle\langle 00\ldots0| + \mathrm{Tr}[|1\rangle\langle 1|\rho^A]| + +$$

$$\Phi^{B_j}(\rho^A) \approx \sum_k \mathrm{Tr}[\tilde{E}_k \rho^A] \sigma_k^{B_j}$$

Quantum Darwinism: $\sigma_k^{B_j}$ encode well the information about label k.

$$\Phi^{B_j}(\rho^A) \approx \sum_k \mathrm{Tr}[\tilde{E}_k \rho^A] \sigma_k^{B_j}$$

Quantum Darwinism: $\sigma_k^{B_j}$ are sufficiently distinguishable.

Darwinism process with distinguishability η

QD_η is said to occur if for all B_j,

$$\min_{\rho^A} p_{\mathrm{guess}}[(\tilde{p}_k, \sigma_k^{B_j})] \geq \eta.$$

Example

$$\rho_B = \mathrm{Tr}[|0\rangle\langle 0|\rho^A]|00\ldots0\rangle\langle 00\ldots0| + \mathrm{Tr}[|1\rangle\langle 1|\rho^A]|11\ldots$$

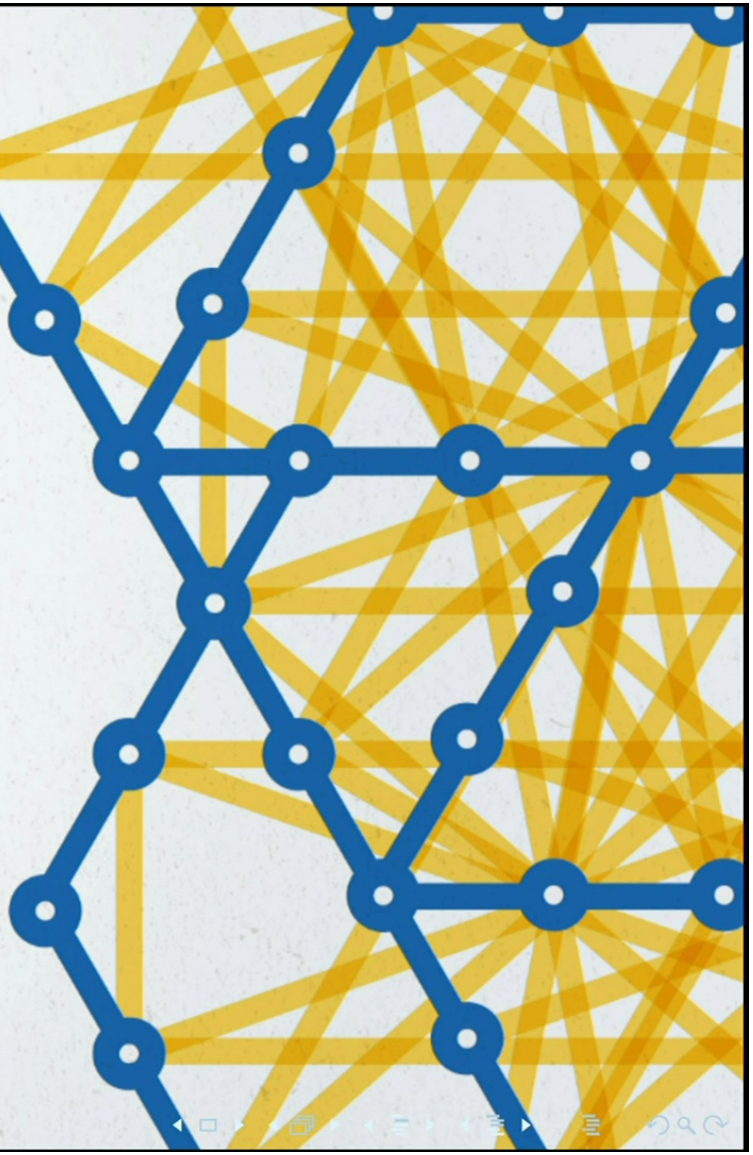
$$\underbrace{\text{EWt-dynamics} + \text{good enough encoding}}_{\text{QD}_\eta}$$

$\Rightarrow$ Bobs are likely to agree!

$$\underbrace{\text{EWt-dynamics} + \text{good enough encoding}}_{\text{QD}_\eta}$$

$$\Rightarrow \text{Objectivity of outcomes!}$$

GENERALIZED CONTEXTUALITY



R. W. Spekkens, Physical Review A 71, 052108 (2005).

Operational theory

- A list $\mathcal{P}$ of preparations;
- A list $\mathcal{M}$ of measurements, and a set of effects $\{b|M\}_b$ for each measurement M in $\mathcal{M}$;
- A rule to compute probabilities

$$p(k|b, M).$$

Equivalences

- Preparations P_1 and P_2 are equivalent if $p(b|M, P_1) = p(b|M, P_2)$.
- Effects $b_1|M_1$ and $b_2|M_2$ are equivalent if $p(b_1|M_1, P) = p(b_2|M_2, P)$.

Ontological model

- Measurable space (Λ, Σ).
- $P \mapsto \mu_P$ measure over (Λ, Σ).
- $(b|M) \mapsto \xi_M(b|\cdot)$, $\xi_M(b|\lambda) \geq 0$, $\sum_b \xi_M(b|\lambda) = 1$.

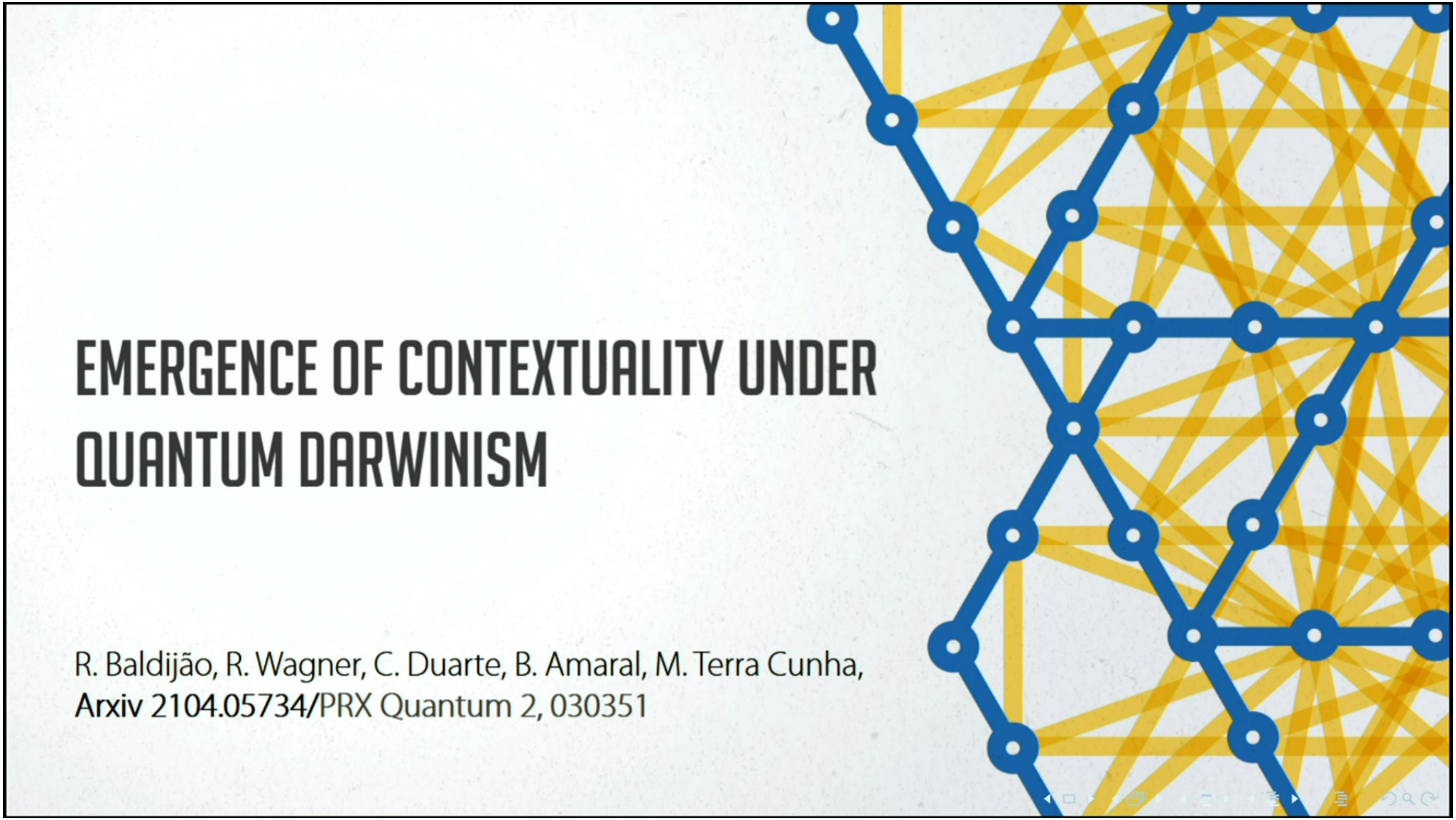
Ontological model

- Measurable space (Λ, Σ).
- $P \mapsto \mu_P$ measure over (Λ, Σ).
- $(b|M) \mapsto \xi_M(b|\cdot)$, $\xi_M(b|\lambda) \geq 0$, $\sum_b \xi_M(b|\lambda) = 1$.
- $p(b|M, P) = \sum_\lambda \mu_P(\lambda)\xi_M(b|\lambda)$.

Noncontextual ontological models

$$P_1 \sim P_2 \Rightarrow \mu_{P_1} = \mu_{P_2}$$

$$(b_1|M_1) \sim (b_2|M_2) \Rightarrow \xi_{M_1}(b_1|\lambda) = \xi_{M_2}(b_2|\lambda)$$


EMERGENCE OF CONTEXTUALITY UNDER
QUANTUM DARWINISM
R. Baldijão, R. Wagner, C. Duarte, B. Amaral, M. Terra Cunha,
Arxiv 2104.05734/PRX Quantum 2, 030351

Lemma 1

If $\{\sigma_k^{B_j}\}_k$ form an affinely independent set, there exists a noncontextual ontological model for the distribution about A available to B_j.

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If $\{\sigma_k^{B_j}\}_k$ form an affinely independent set, there exists a noncontextual ontological model for the distribution about A available to B_j.

This holds true for any measurement $\{F_b^{B_j}\}$ implemented by Bob B_j.

Lemma 2

There exists a bound $\hat{P}$ such that, if

$$p_{\text{guess}}[(\tilde{p}_k, \sigma_k^{B_j})] > \hat{P} \ \forall \ \rho^A,$$

the set of states $\{\sigma_k^{B_j}\}_k$ must be affinely independent.

Main result

Suppose the conditions for QD_η are met with $\eta > \hat{P}$. Then, each Bob can construct a noncontextual ontological model for the respective scenario.

Main result

$$\eta > \hat{P} \Rightarrow \text{affine independence}$$

$$\text{affine independence} \Rightarrow \text{noncontextuality}$$

Summary

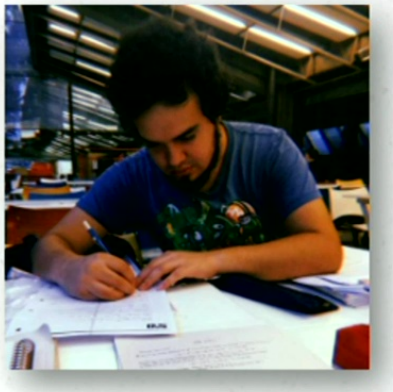
- Noncontextuality generically emerges out of quantum Darwinism in infinite environments;
- It can emerge even if Darwinism fails (EW+affine independence are enough);
- Objectivity emerging from Darwinism can be considered classical;
- In finite environments, contextuality is strongly constrained;

Next

- Do other classical limits allow for emergence of noncontextuality?
- Relation to non-Markovianity?
- Explore particular cases in many-body systems.

QUANTUM DARWINISM IN MANY-BODY QUANTUM SYSTEMS

Felipe Barreto



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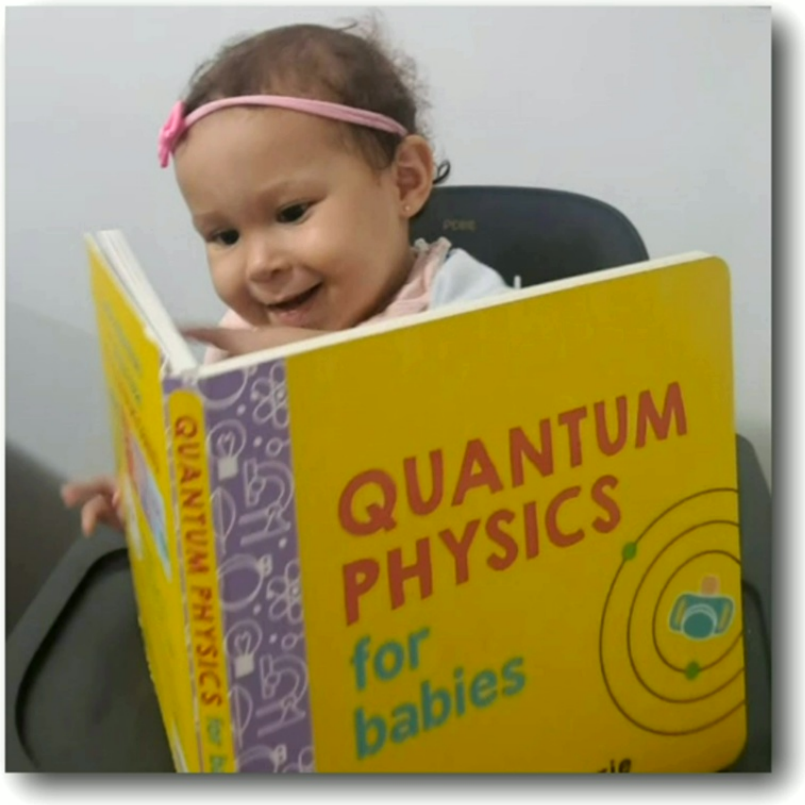
FAÇA CIÊNCIA COMO UMA GAROTA!



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