Towards testing beyond-quantum theories in particle physics

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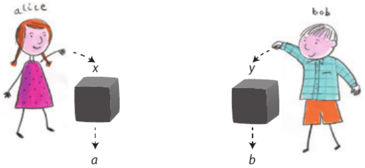
Oxford, 21 March 2023

Bell nonlocality – the **black box** approach

2 parties (Alice and Bob) — 2 **inputs** (x, y) — 2 **outputs** (a, b)

$$P(a, b \,|\, x, y)$$



[Sandu Popescu, *Nature Physics* 10, 264 (2014)]

The *experimental* (frequency) correlation function:

$$C_e(x, y) = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}}$$

Local hidden variables [Bell (1964) / Clauser, Horne, Shimony, Holt (1969)]

$$S_{\mathsf{LHV}} := C_{\mathsf{LHV}}(x, y) + C_{\mathsf{LHV}}(x, y') + C_{\mathsf{LHV}}(x', y) - C_{\mathsf{LHV}}(x', y') \leq 2$$

Quantum Mechanics [Cirelson (1980)]

$$S_{\mathsf{QM}} := C_{\mathsf{QM}}(x, y) + C_{\mathsf{QM}}(x, y') + C_{\mathsf{QM}}(x', y) - C_{\mathsf{QM}}(x', y') \leq 2\sqrt{2}$$

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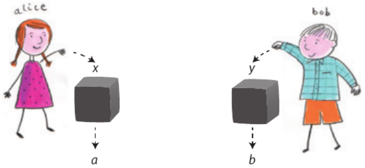

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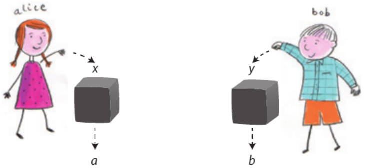

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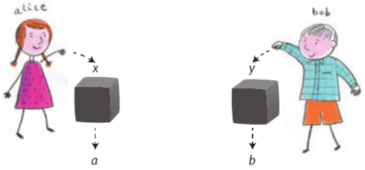

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Bell nonlocality — *beyond* quantum mechanics

$$S := C(x,y) + C(x,y') + C(x',y) - C(x',y')$$

Can we achieve $S = 4$?

- Alice and Bob can communicate,
- or their settings are pre-correlated.

But can we do it assuming:

- **no-signalling**: $\sum_b P(a,b\,|\,x,y) = \sum_b P(a,b\,|\,x,y')$, for all a,x,y,y',
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- **freedom of choice**: $P(x,y|\lambda) = P(x)\cdot P(y)$? Yes!

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b|x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\text{PR}} = 4.$$

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Beyond-quantum theories

1. Beyond-quantum correlations
   - No-signalling boxes
     [N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, S. Wehner, *Rev. Mod. Phys.* **86**, 419 (2014)]
   - 3-party monogamy violation

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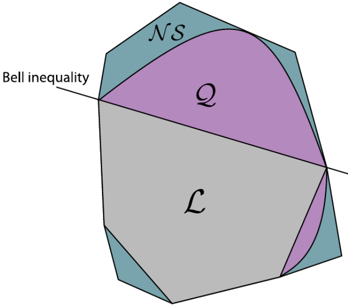

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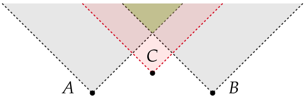

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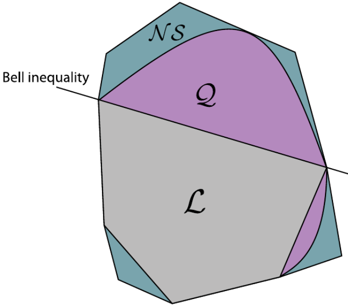

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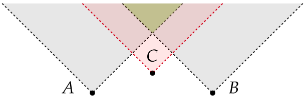

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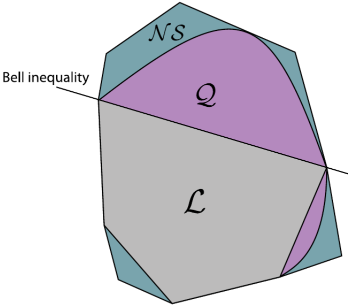

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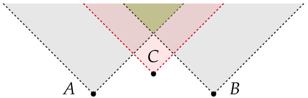

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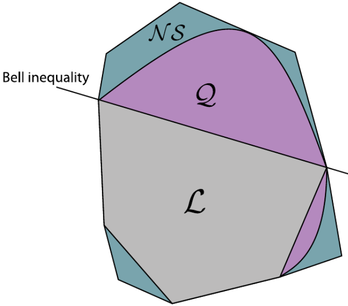

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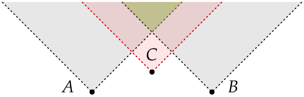

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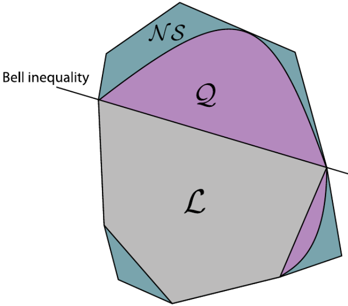

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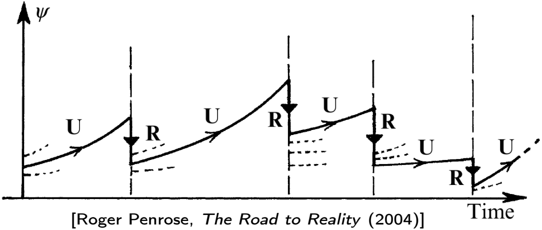
Purely operational 'theories' — model-independent approach

Objective collapse models



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- **nonlinearity** — modified Schrödinger equation
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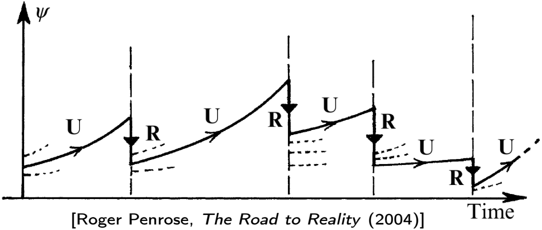

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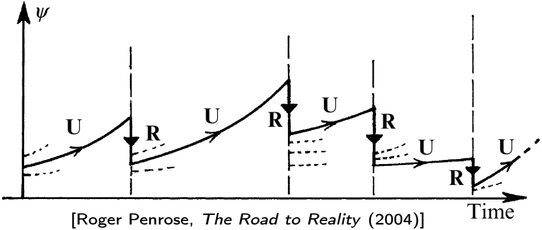

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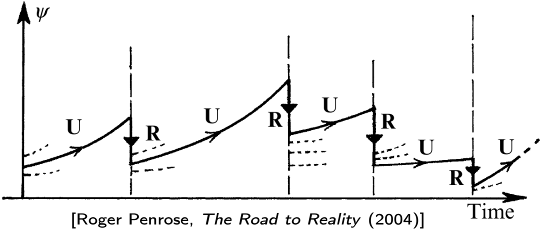

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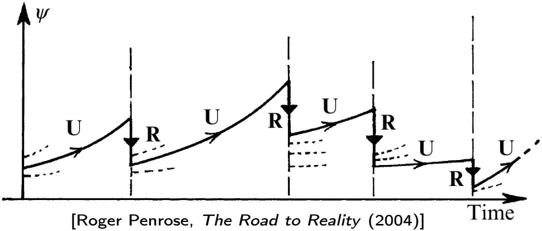

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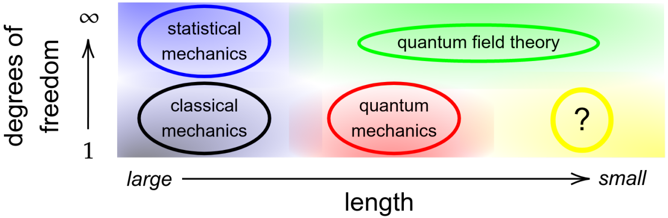
Collapse models involve deviations from unitarity and linearity.

Beyond-quantum physics?



- Is there a gap between QM and QFT?

$$C_{qs} = \{\langle\psi|A_a^x \otimes B_b^y|\psi\rangle\}, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B,$$
$$C_{qc} = \{\langle\psi|A_a^x B_b^y|\psi\rangle\}, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

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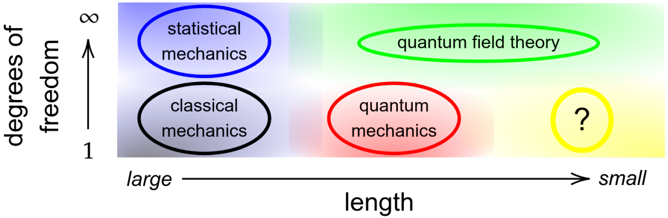

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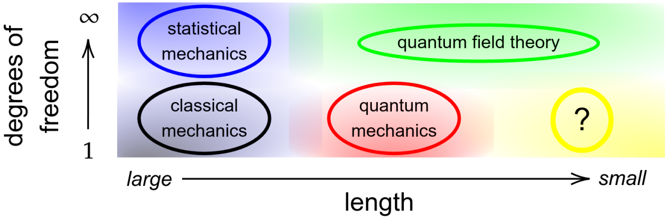

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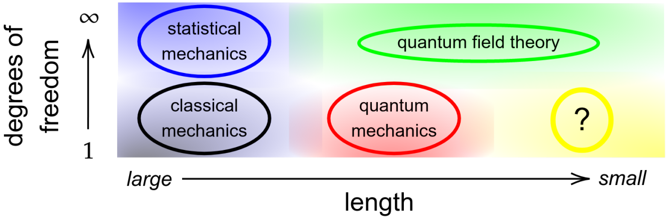

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- We regard a chosen physical system as a **Q-data box**, which can be probed with *quantum* information.
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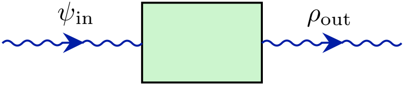

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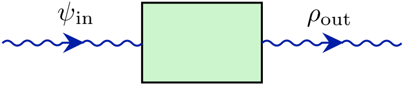

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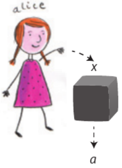
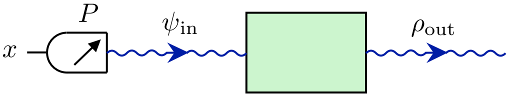


[Nat. Phys. **10**, 264 (2014)]



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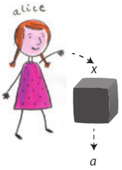

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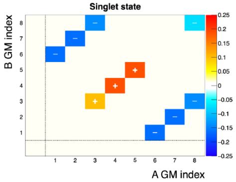

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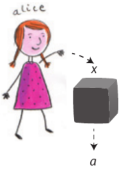

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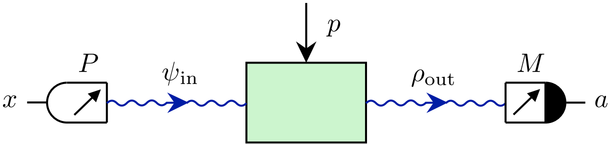

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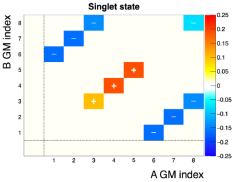

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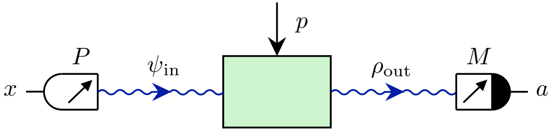

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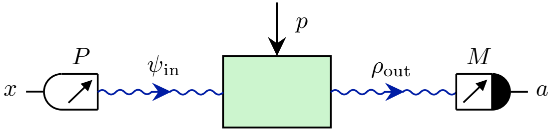

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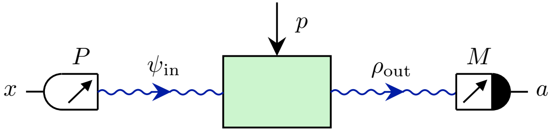

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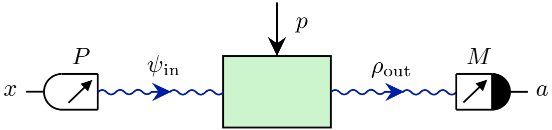

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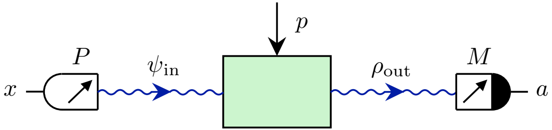

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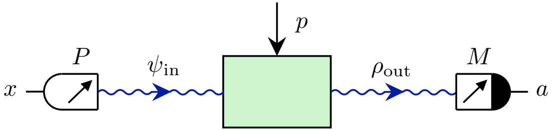

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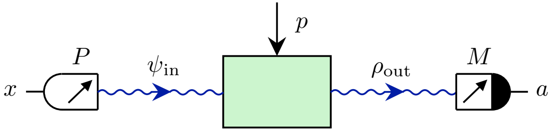

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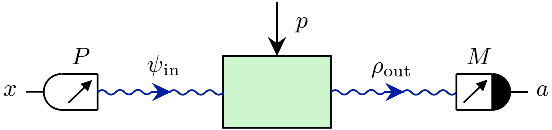

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- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
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$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle \psi_{\text{in}}^{(1)} | \psi_{\text{in}}^{(2)} \rangle\right|^2}\right).$$

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- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle\psi_{\text{in}}^{(1)}|\psi_{\text{in}}^{(2)}\rangle\right|^2}\right) .$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

Towards experimental quantum process tomography

Main idea:

1. Prepare a 'quantum-programmed' particle carrying ψ_{in}, e.g. electron's spin or photon's polarization.
2. Scatter it on a nucleonic target.
3. Perform projective measurements on the outgoing projectiles.
4. Reconstruct the output state ρ_{out}.

Challenges:

- Need to prepare the quantum state of GeV particles $\rightsquigarrow$ polarized beams
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- Need to measure spin/polarization of *individual* projectiles $\rightsquigarrow$???

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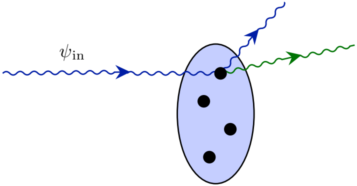

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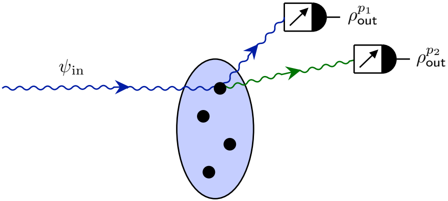

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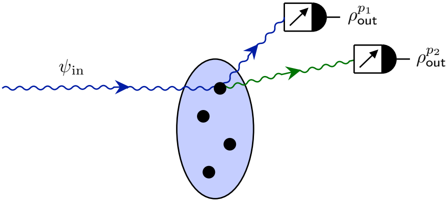

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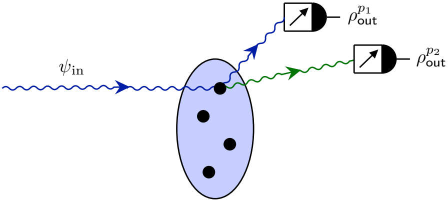

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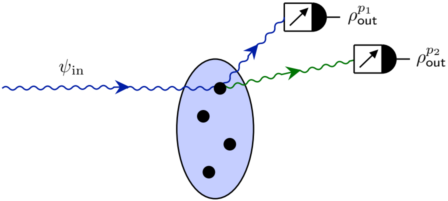

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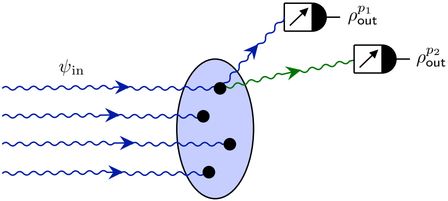

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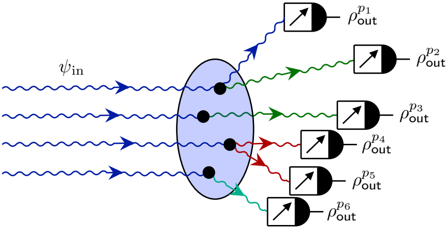

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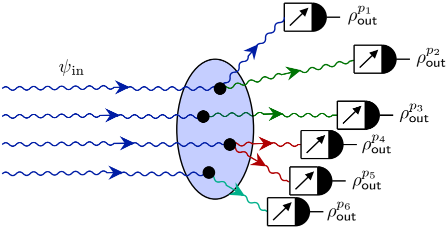

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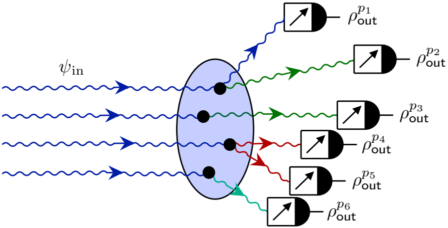

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Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000

Take-home messages:

- Quantum mechanics can be probed from an **'outside' perspective**.
- Whenever we are doing a Bell-type test, we are testing QM against *both* local hidden variables and **beyond-quantum correlations**.
- Need for **quantum process tomography**:
  - Understanding quantum dynamics at subnuclear scales.
  - Seeking deviations from unitarity and linearity.

Thank you for your attention!

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