Measurements on the Reality of the Wavefunction

quantum.info

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	ψ epistemic	ψ ontic
Anti-Realist	Copenhagen (Bohr) Neo-Copenhagen (QBism, Healey, Peres, Mermin, Zeilinger …)	
Scientific Realist	Einstein Ballentine (?) Spekkens Leifer	Dirac–von Neumann Many worlds Bohmian mechanics Spontaneous collapse Modal interpretations

Adapted from Matt Leifer

The ontological model framework

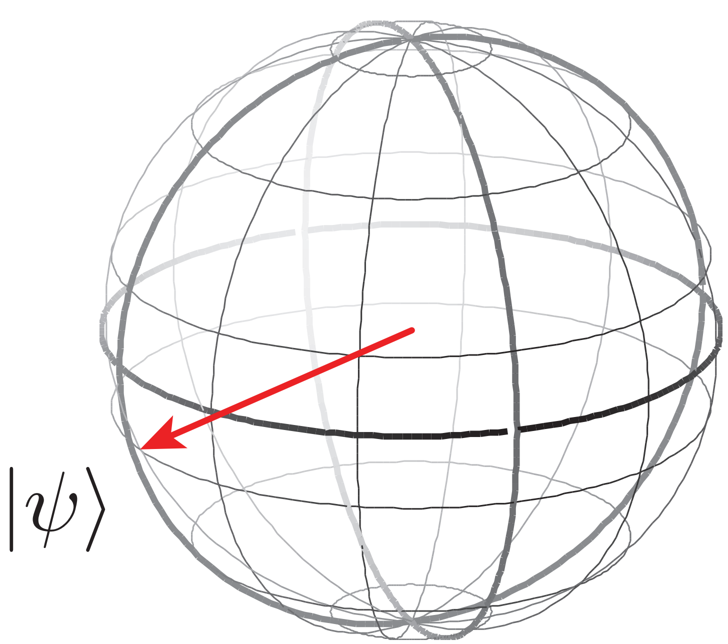
Ontological models *aka* hidden-variable models

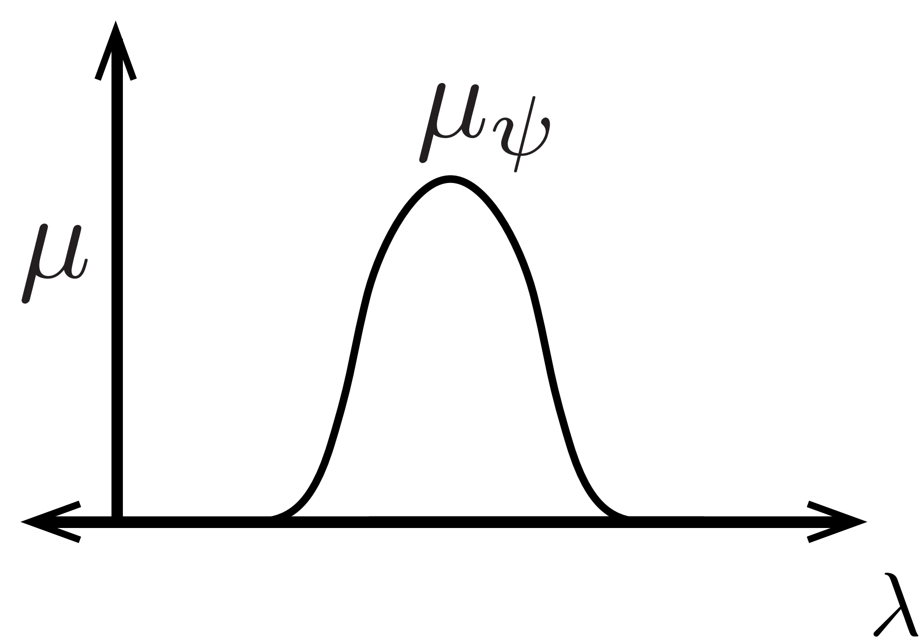
Λ : space of **ontic states** (analogous to phase space)

system has a value $\lambda \in \Lambda$ that specifies all its properties (like phase space points)

Prepare system in state $|\psi\rangle$ in the lab:

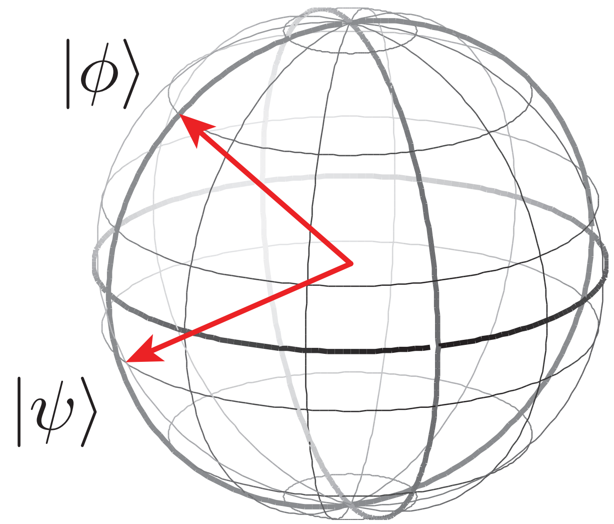
we actually prepare an ontic state λ that is sampled from a probability distribution $\mu_\psi(\lambda)$ — the **epistemic state**



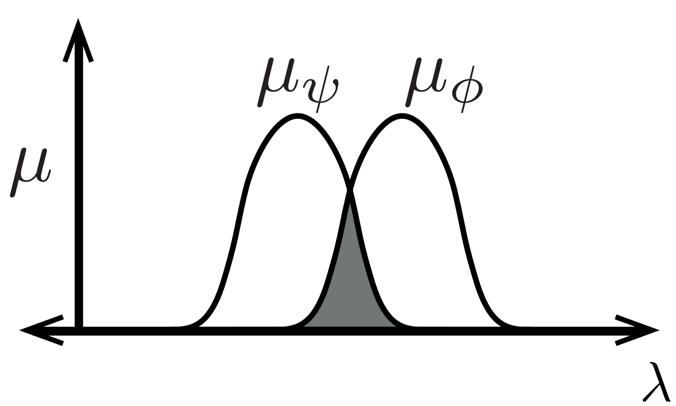


The ontological model framework

Two non-orthogonal states:

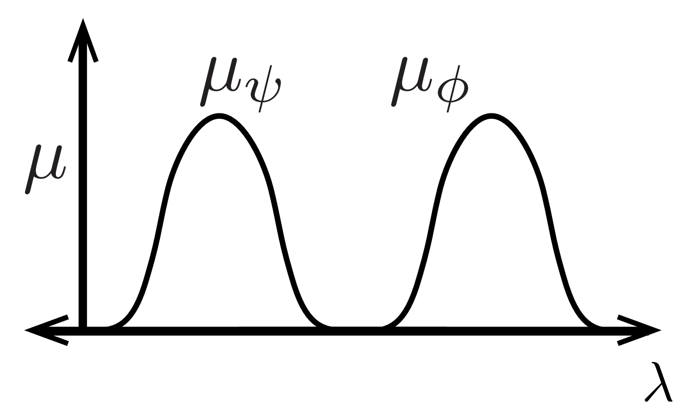


ψ-epistemic



ontic states compatible with more than one quantum state

ψ-ontic



quantum state uniquely determined by ontic state

Measurements on the reality of ψ

Ruling out ψ-epistemic models impossible without additional assumptions

Still possible to severely **constrain ψ-epistemic models**,
and bound the degree to which they explain quantum phenomena.

Barrett, Cavalcanti, Lal & Maroney
No ψ-epistemic model can fully explain the indistinguishability of quantum states
PRL **112**, 250403 (2014)

Leifer,
ψ-epistemic models are exponentially bad at explaining the distinguishability of quantum states
PRL **112**, 160404 (2014)

Branciard
ψ-epistemic models cannot explain the indistinguishability of quantum states
PRL **113**, 020409 (2014).

The limited distinguishability of non-orthogonal quantum states cannot be fully explained by ψ-epistemic models for systems of dimension >2

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The limited distinguishability of non-orthogonal quantum states cannot be fully explained by ψ-epistemic models for systems of dimension >2

Quantum States

Quantum trace distance:

$$\delta_Q(\psi,\phi) = \sqrt{1 - |\langle\psi|\phi\rangle|^2}$$

Quantum overlap:

$$\omega_Q(\psi,\phi) := 1 - \delta_Q(\psi,\phi)$$

Epistemic States

Classical trace distance:

$$\delta_C(p,q) := \frac{1}{2}\int |p(x) - q(x)| \, \mathrm{d}x$$

Classical overlap:

$$\begin{aligned}\omega_C(p,q) &:= 1 - \delta_C(p,q) \\ &= \int \min\{p(x), q(x)\} \, \mathrm{d}x\end{aligned}$$

For an ontological model to be **maximally ψ-epistemic**

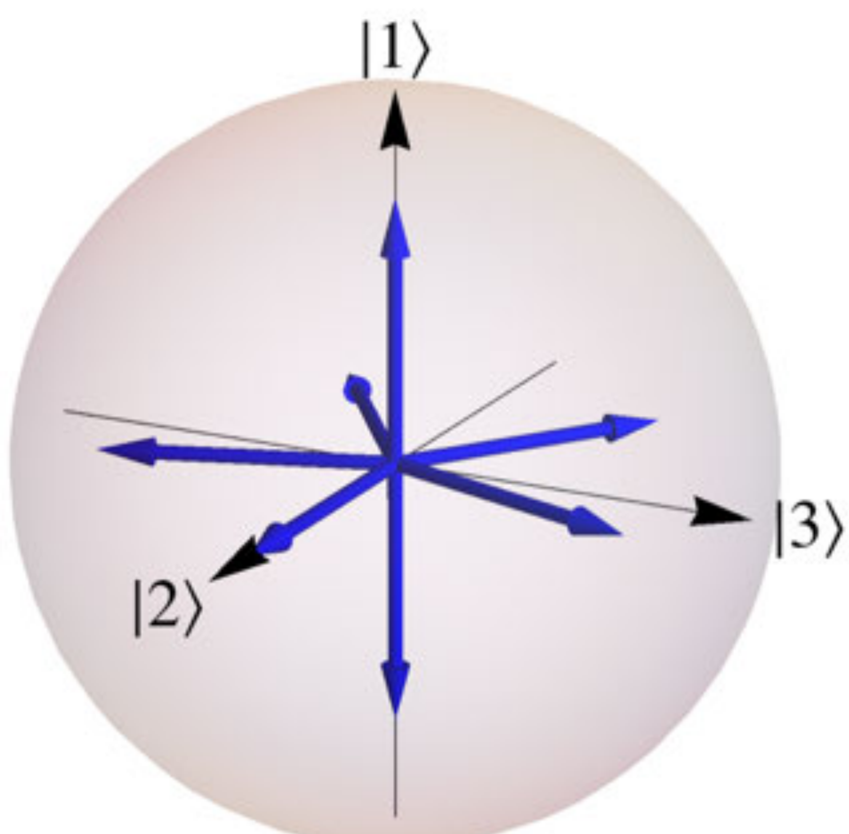
$$\omega_C(\mu_\psi, \mu_\phi) = \omega_Q(\psi,\phi) \quad \forall \psi, \phi$$

Measurements on the reality of ψ

$$\kappa(\psi,\phi) = \frac{\omega_{\mathrm{C}}(\mu_\psi,\mu_\phi)}{\omega_{\mathrm{Q}}(|\psi\rangle|\phi\rangle)}$$

κ<1 is incompatible with maximally ψ-epistemic models

Protocol: prepare a set of $n+1$ quantum states $\{|\psi_0\rangle, |\psi_1\rangle, \ldots, |\psi_n\rangle\}$



$$|\psi_0\rangle=|0\rangle=\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad |1\rangle=\begin{pmatrix}0\\1\\0\\0\end{pmatrix}$$

$$|2\rangle=\begin{pmatrix}0\\0\\1\\0\end{pmatrix} \quad |3\rangle=\begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

Projection onto subspace orthogonal to $|\psi_0\rangle=|0\rangle$

Ringbauer, Duffus, Branciard, Cavalcanti, White & Fedrizzi, Nature Physics 11, 249 (2015)

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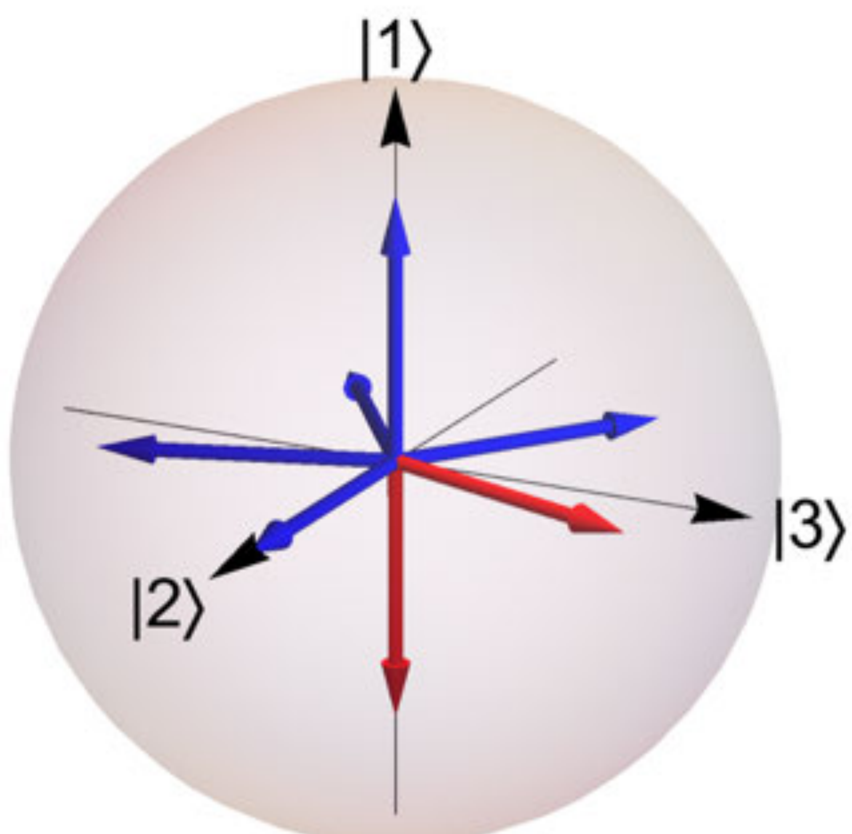
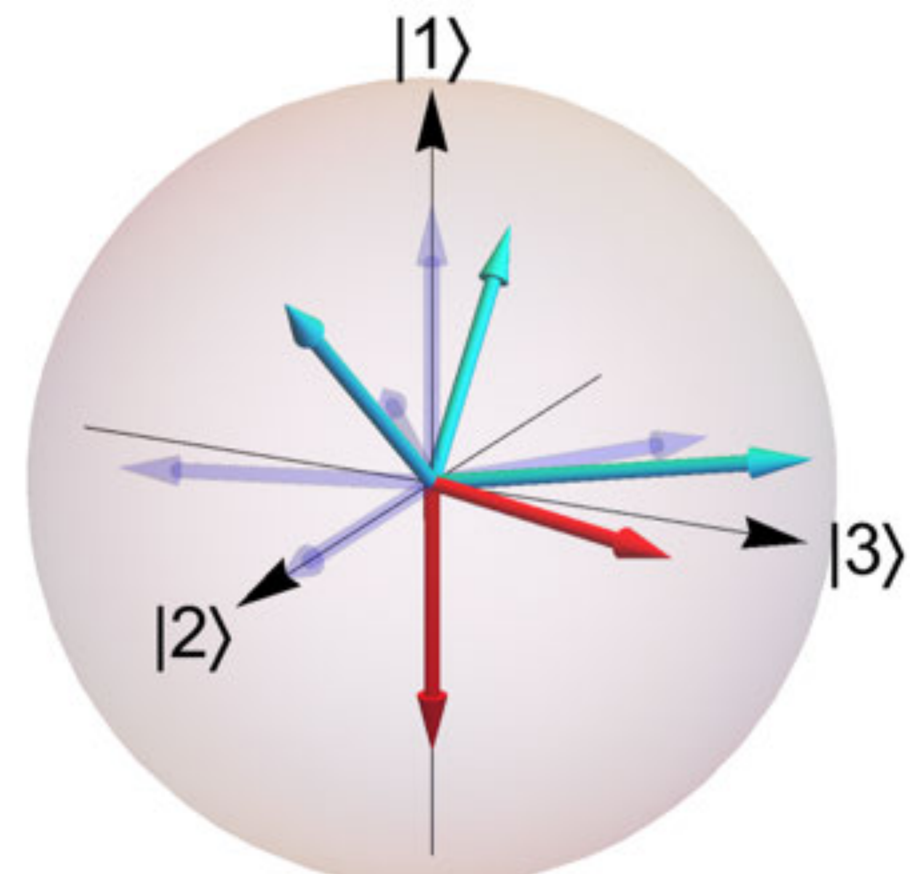
Protocol: prepare a set of $n+1$ quantum states $\{|\psi_0\rangle, |\psi_1\rangle, \ldots, |\psi_n\rangle\}$

for each triplet of states $\{|\psi_0\rangle, |\psi_{j_1}\rangle, |\psi_{j_2}\rangle\}$ perform a measurement $M_{j_1 j_2}$ with three outcomes (m_0, m_1, m_2)





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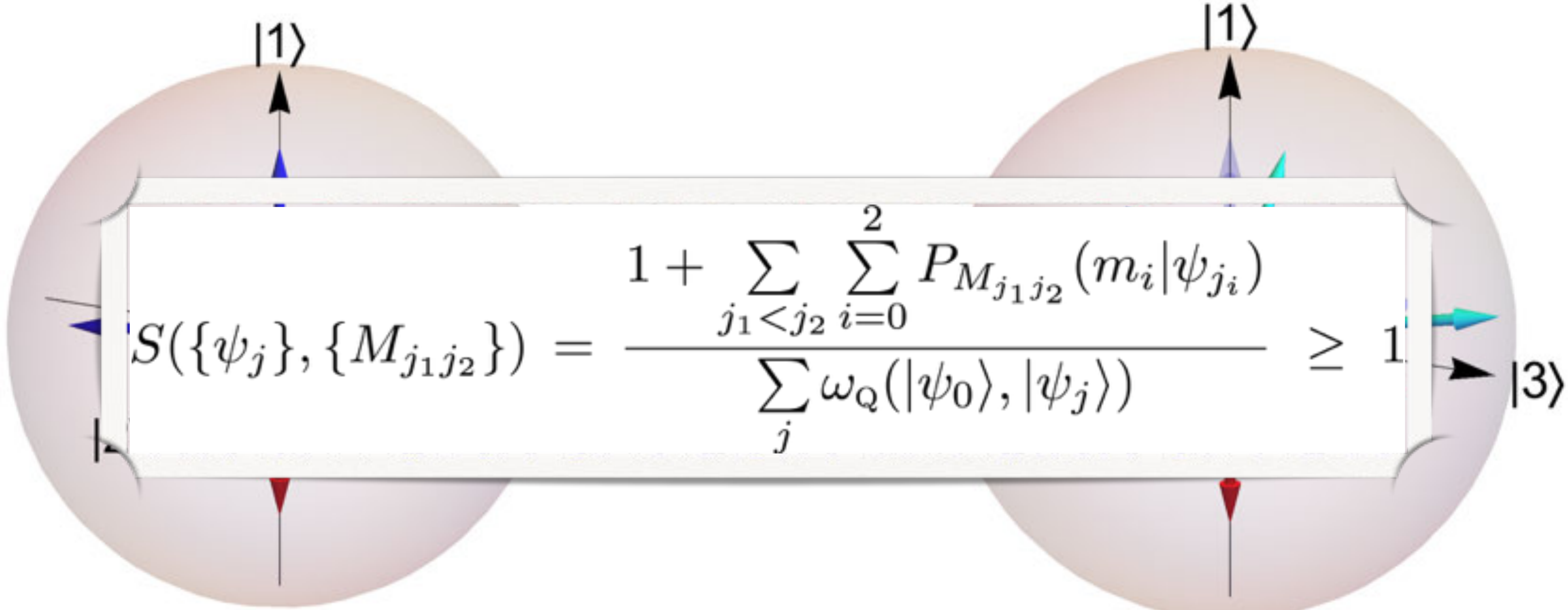
probability for outcome m_i is $P_{M_{j_1 j_2}}(m_i|\psi_{j_i})$,



$$S(\{\psi_j\}, \{M_{j_1 j_2}\}) = \frac{1 + \sum_{j_1<j_2} \sum_{i=0}^{2} P_{M_{j_1 j_2}}(m_i|\psi_{j_i})}{\sum_j \omega_Q(|\psi_0\rangle, |\psi_j\rangle)} \geq 1$$

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Measurements on the reality of ψ

Upper bound on classical overlap

$$S(\{\psi_j\},\{M_{j_1 j_2}\}) = \frac{1 + \sum_{j_1<j_2} \sum_{i=0}^{2} P_{M_{j_1 j_2}}(m_i|\psi_{j_i})}{\sum_j \omega_{\mathrm{Q}}(|\psi_0\rangle, |\psi_j\rangle)} \geq 1$$

Quantum overlap

S is an upper bound on how much indistinguishability can be explained by overlapping probability distributions

$S \geq 1$ for maximally **ψ**-epistemic models

In principle, for $d \geq 4$, $S \rightarrow 0$ as number of states, n, increases

BUT as n increases, number of measurements increases quadratically

Ringbauer, Duffus, Branciard, Cavalcanti, White & Fedrizzi, Nature Physics 11, 249 (2015)

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Upper bound on classical overlap

$$S(\{\psi_j\},\{M_{j_1 j_2}\}) = \frac{1 + \sum_{j_1<j_2}\sum_{i=0}^{2} P_{M_{j_1 j_2}}(m_i|\psi_{j_i})}{\sum_j \omega_Q(|\psi_0\rangle, |\psi_j\rangle)} \geq 1$$

Quantum overlap

S is … d by

Requires d > 2

Error per measurement < 0.003

S≥1 for maximally ψ-epistemic models

In principle, for d≥4, S→0 as number of states, n, increases

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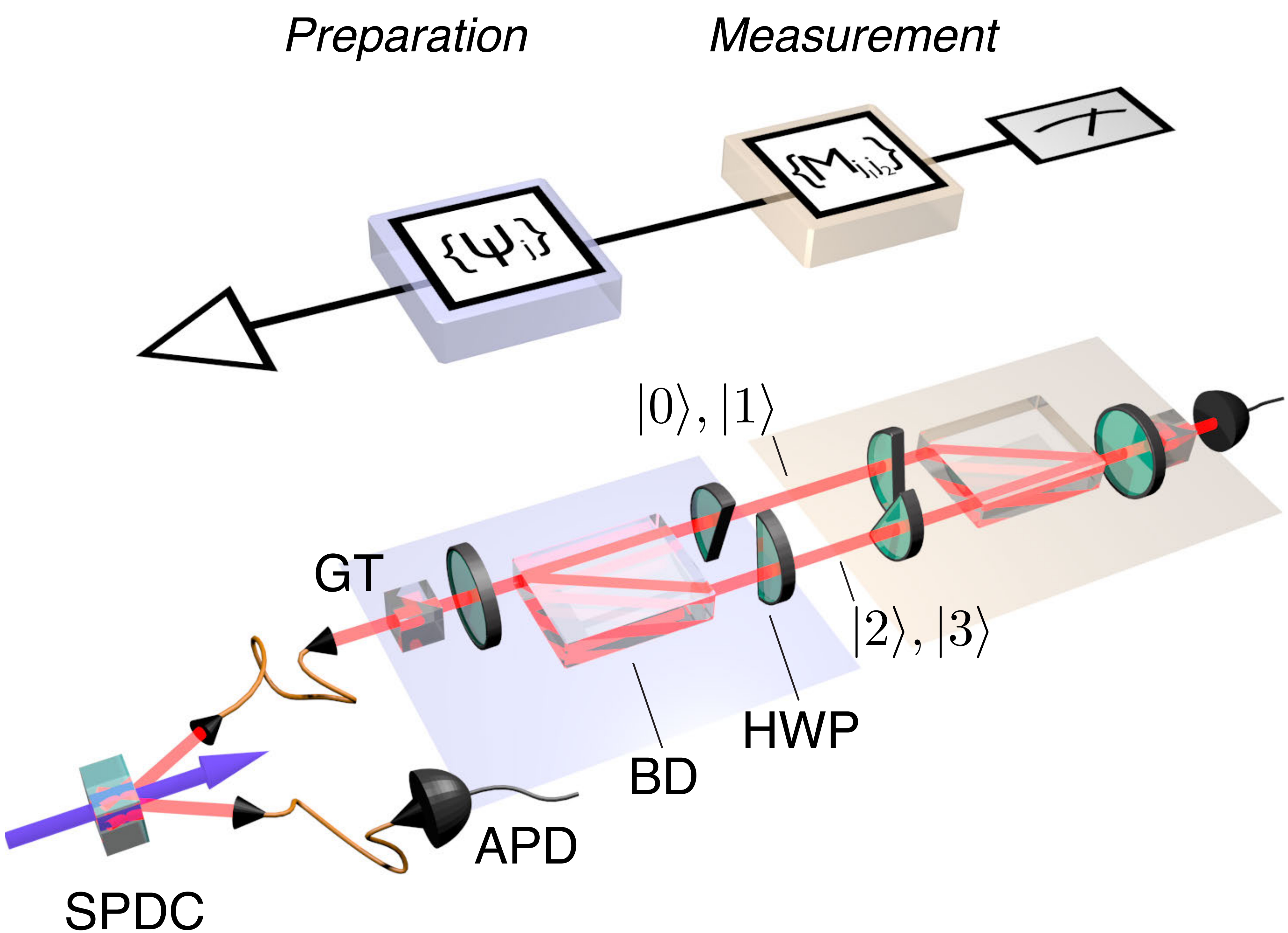

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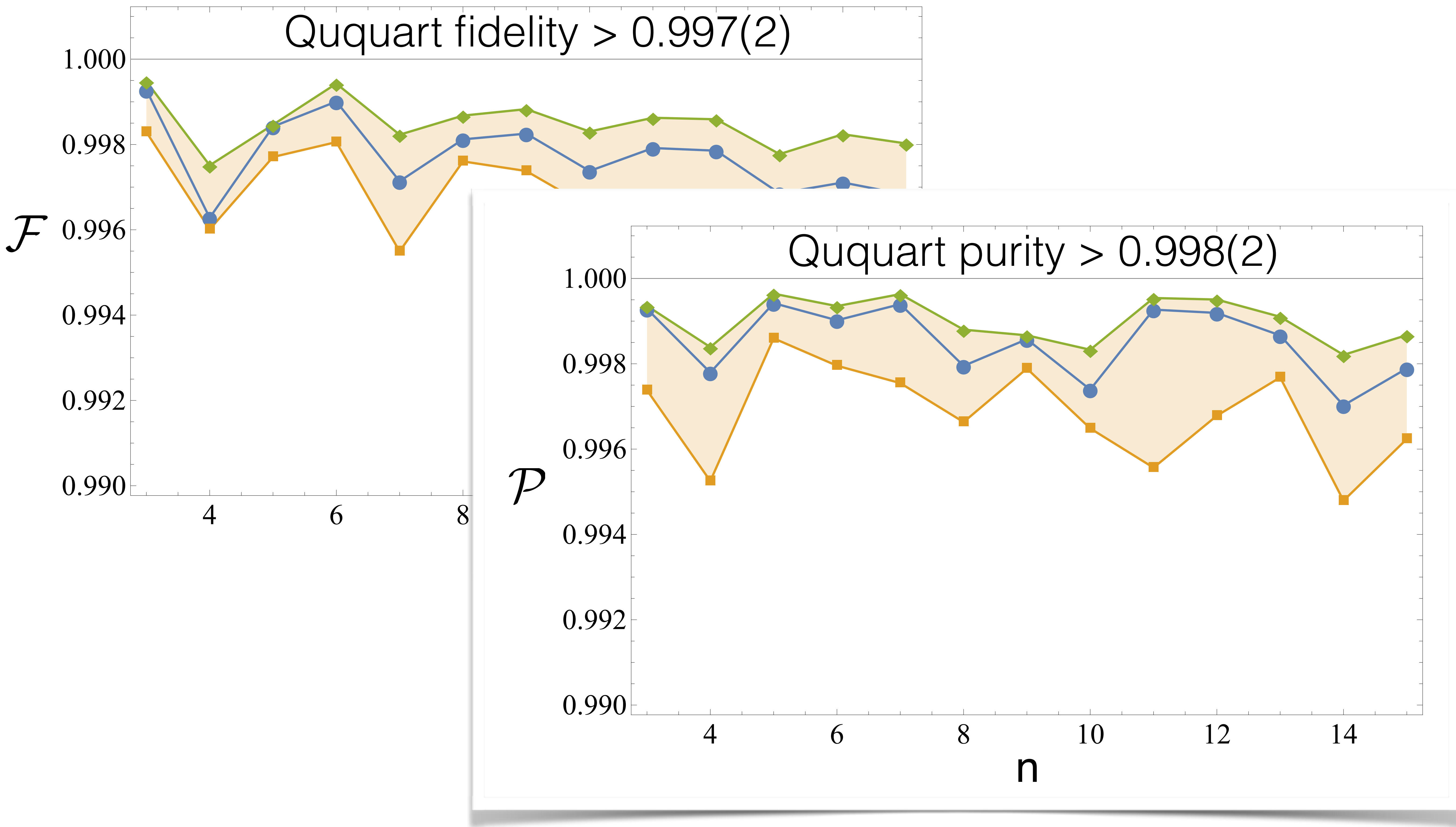
Know your stuff

Quantum state tomography



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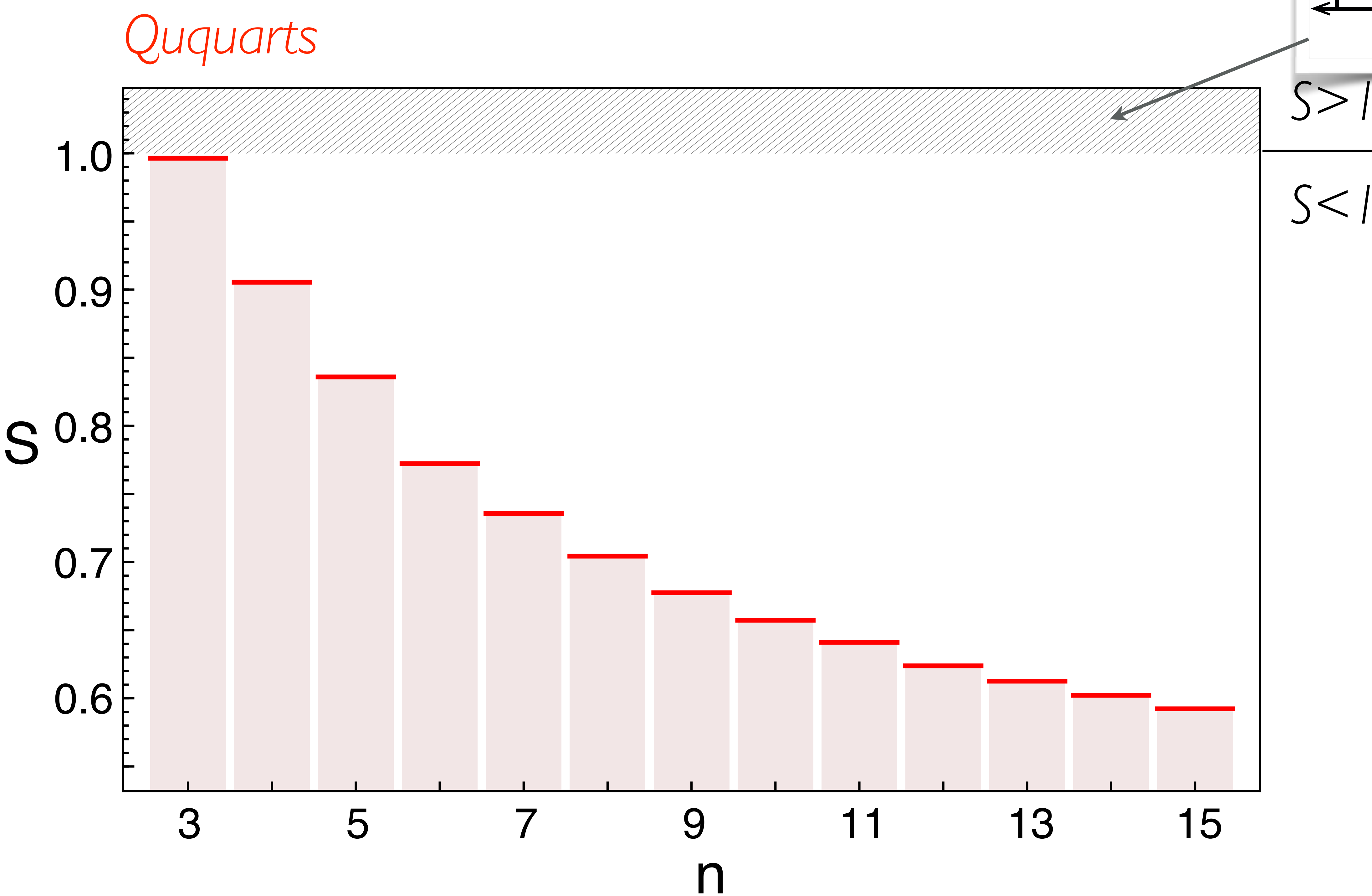

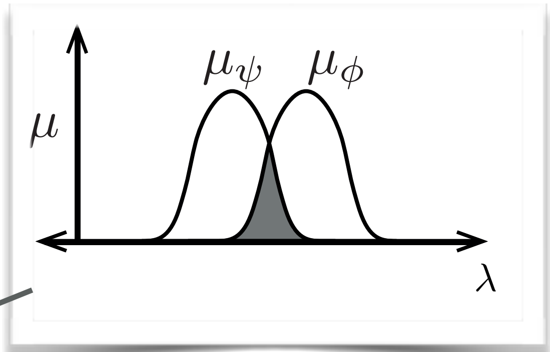

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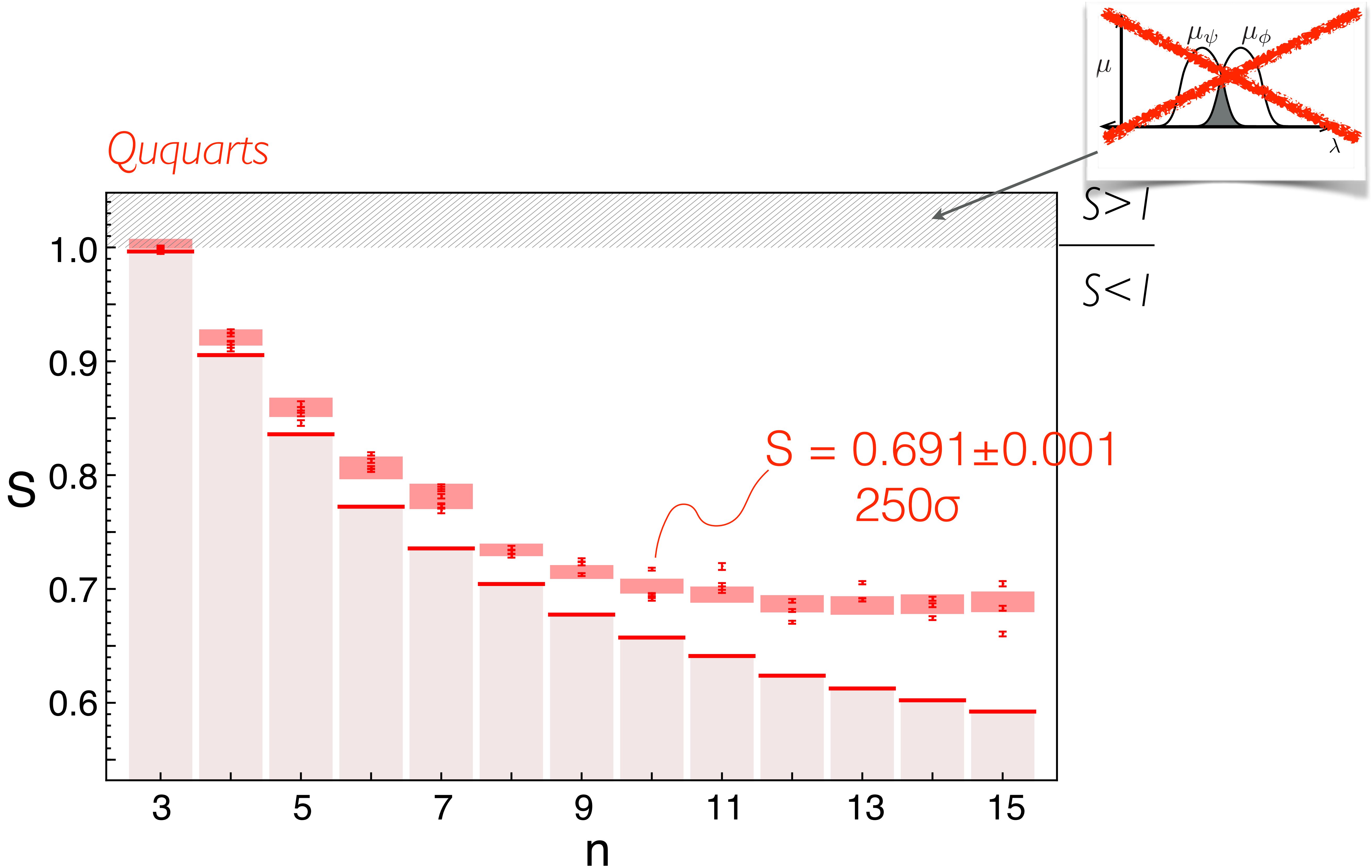

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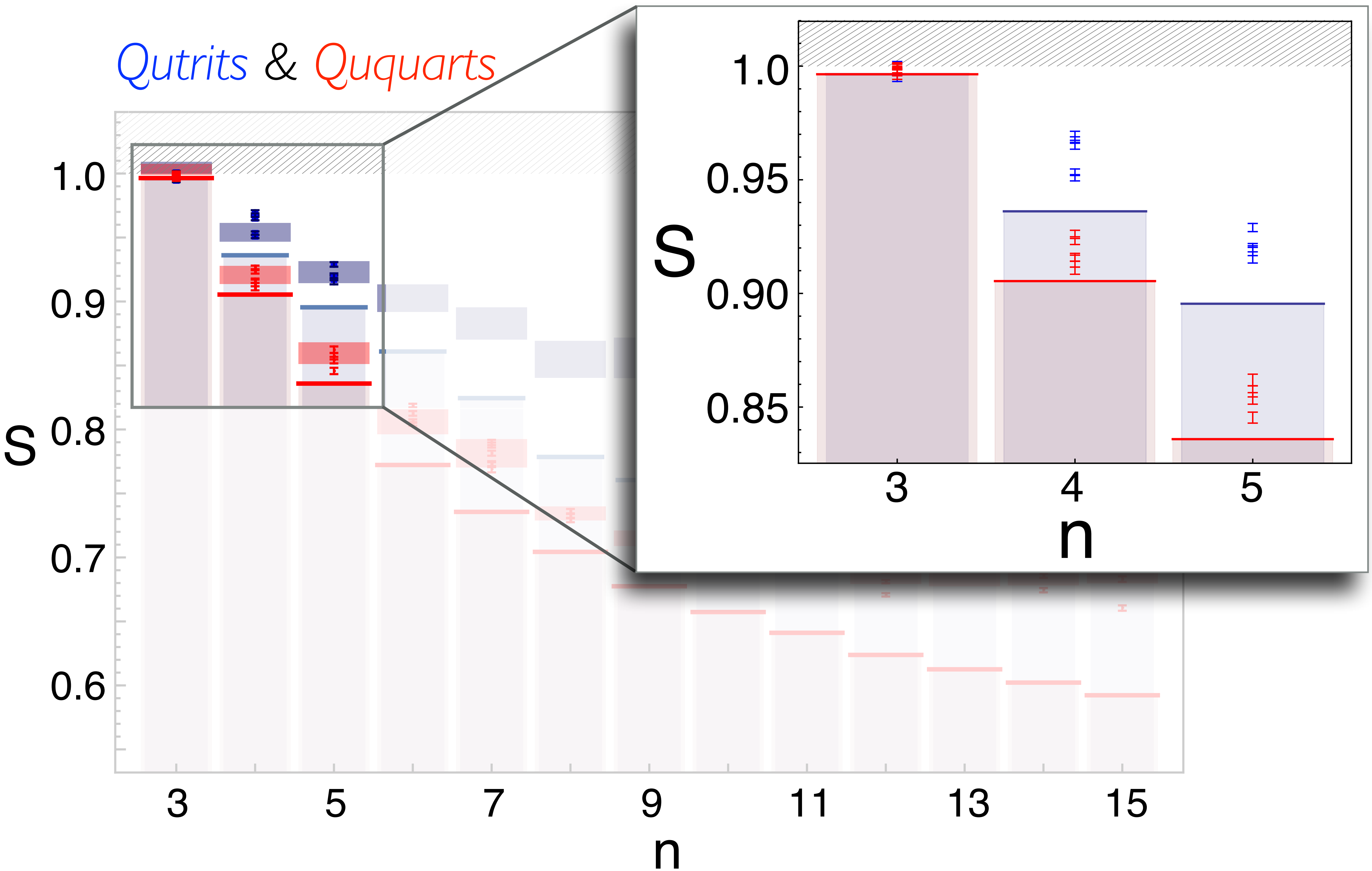

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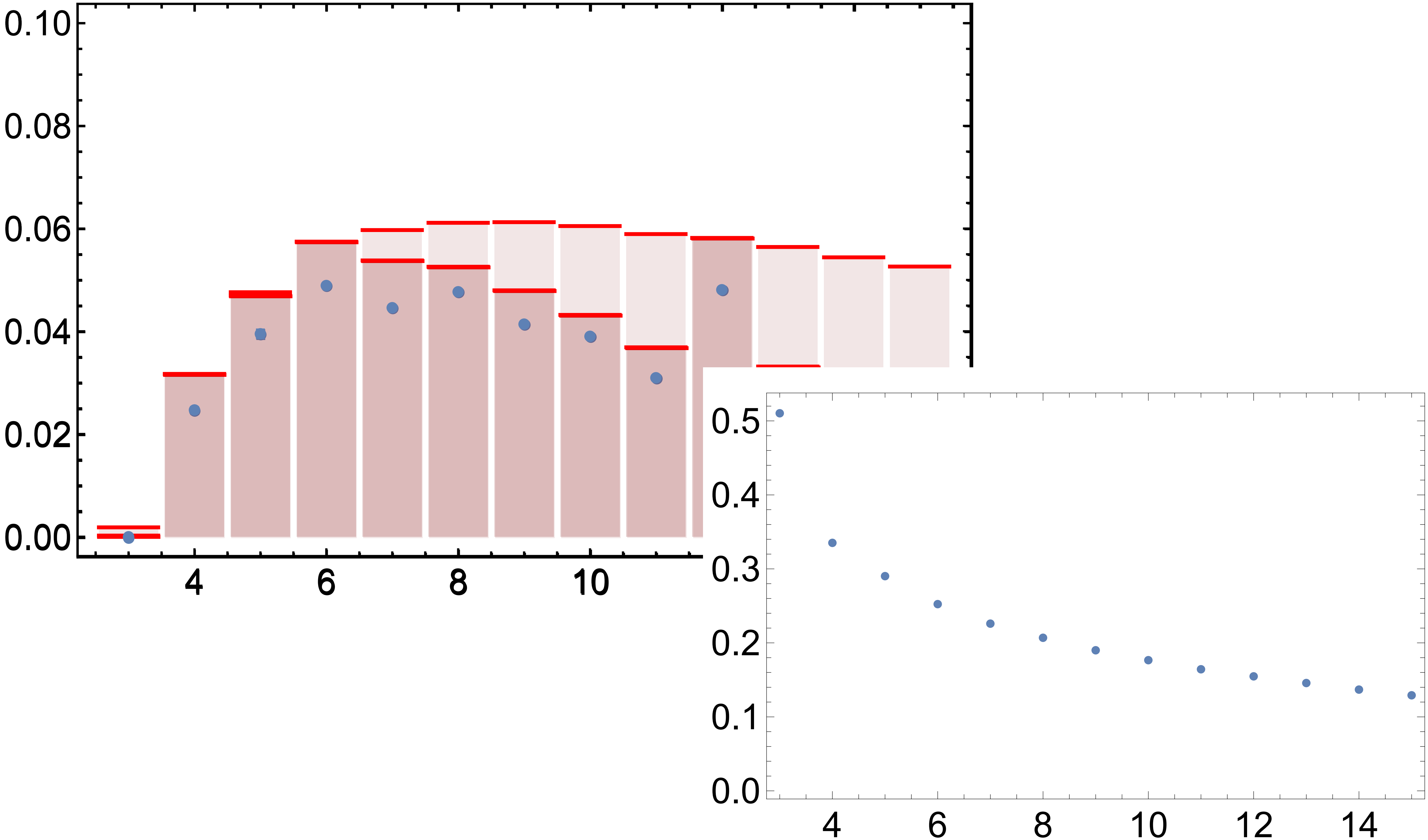
Overlap Deficit

$$\delta_\omega = \min[\omega_{\mathrm{Q}}](1 - S)$$



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Scientific Realist	~~Einstein~~ ~~Ballentine (?)~~ ~~Spekkens~~ ~~Leifer~~	Dirac–von Neumann Many worlds Bohmian mechanics Spontaneous collapse Modal interpretations

Adapted from Matt Leifer

There is still room for improvement

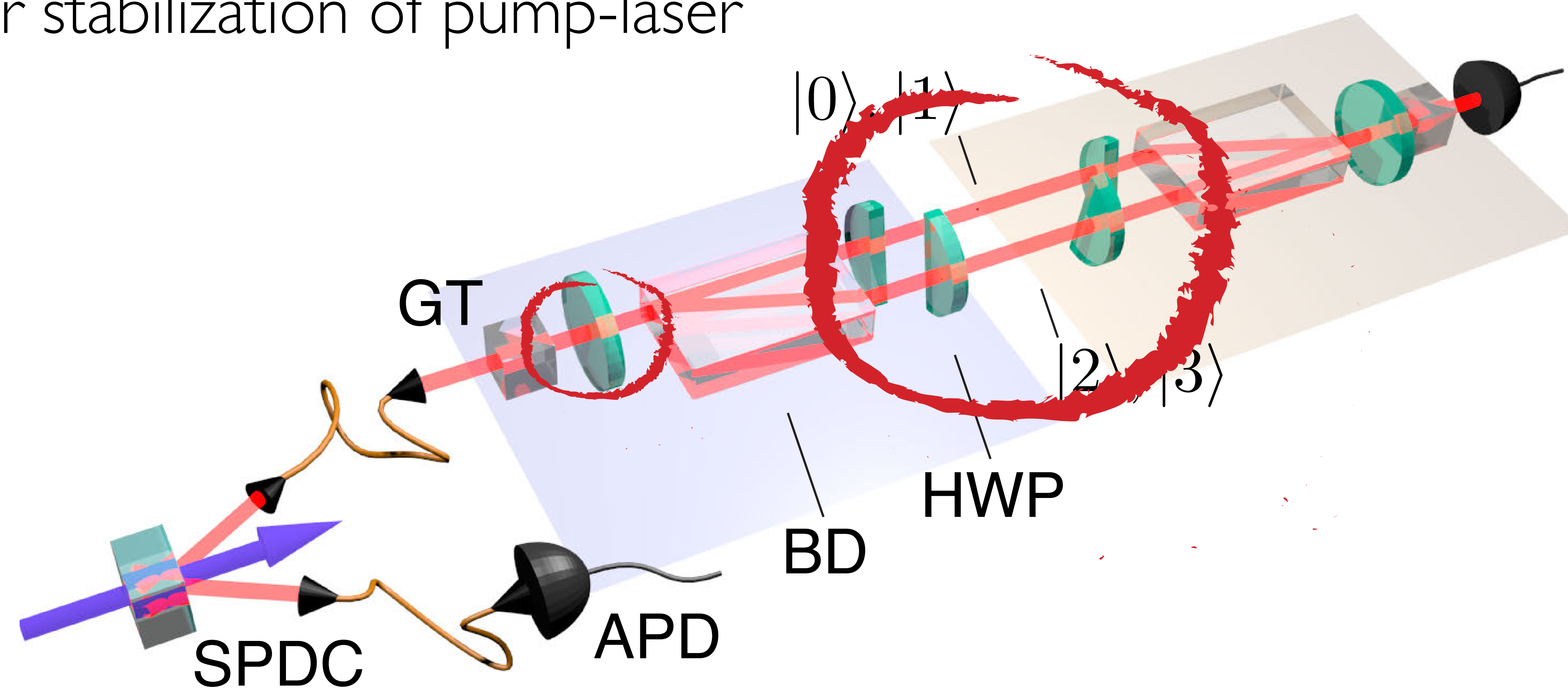
High-accuracy waveplates (λ/500 or better)

More stable optical mounts; more precise phase control

Better shielding or active locking of interferometer

Explore full state space

Better stabilization of pump-laser



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Implications

Ruled out maximally ψ-epistemic models for systems of dimension >2

Excluded non-maximal models with $S > 0.691 \pm 0.001$

> Realist ψ-epistemic models fail to fully explain quantum indistinguishability.

Without giving up the notion of objective reality we must:

- Accept the ontic interpretation of the wavefunction
- Consider more exotic ontologies

Ringbauer, Duffus, Branciard, Cavalcanti, White & Fedrizzi, Nature Physics 11, 249 (2015)