Emergence of classicality in macroscopic systems

Ravishankar Ramanathan
Tomasz Paterek
Alastair Kay
Pawel Kurzynski
Akihito Soeda
Dagomir Kaszlikowski

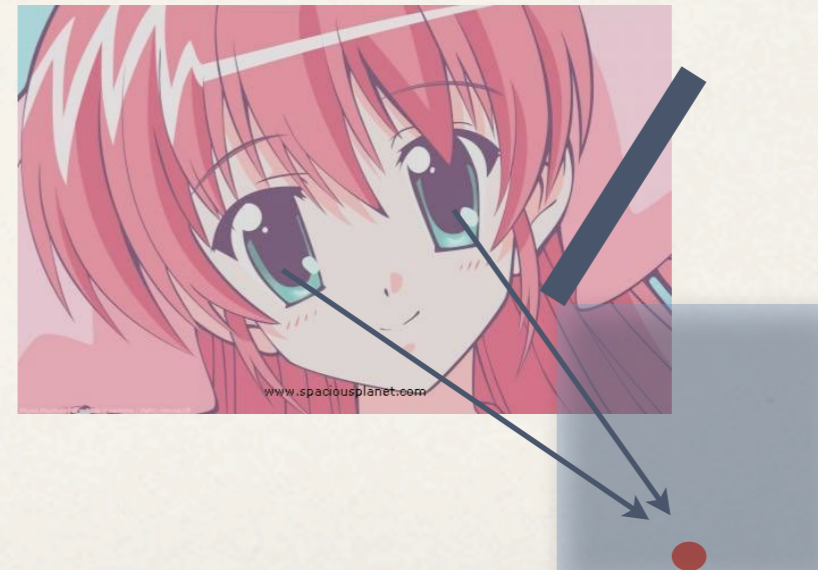This work was published in PRL and the Scientific American

Introduction

What makes quantum mechanics quantum?

Outcomes of measurement don't exist before measurement

What colour is a ball inside?

I see a red ball. Was it red before I looked?

Introduction

Lack of objective reality was demonstrated by

Bell, 1964

Kochen and Specker, 1967

Requires at least **two spin-1/2 particles**.
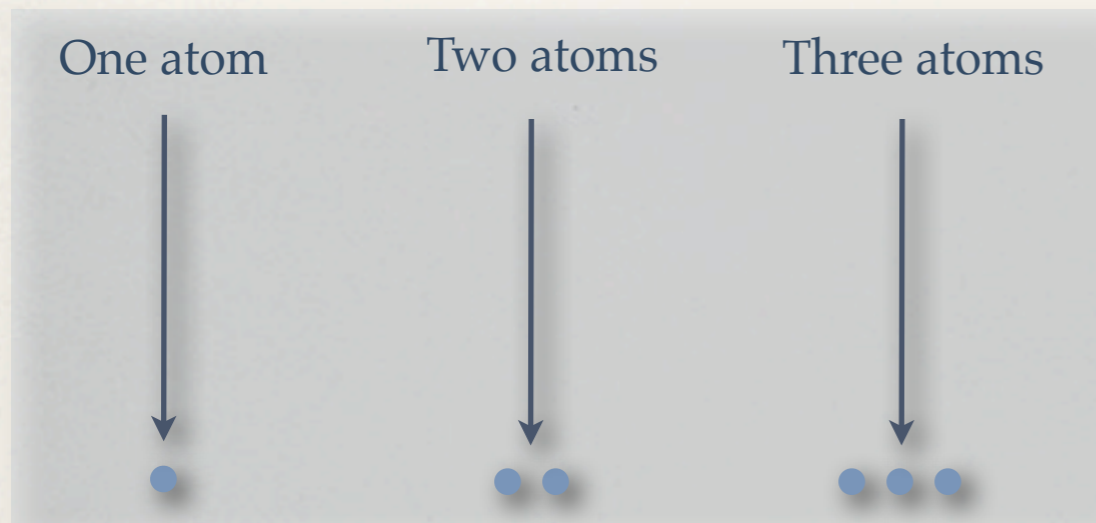
Requires only **one spin-1 particle**.

Bell approach is a special case of Kochen and Specker

Both confirmed experimentally: Bell by Aspect et. al. in 80's and KS by Zeilinger et. al. in 2011
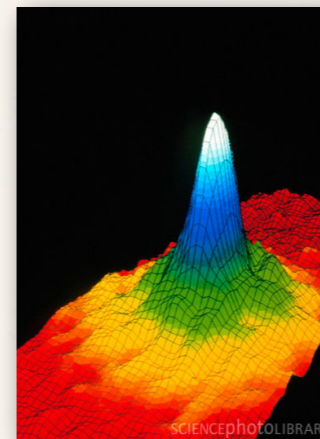
Introduction

One atom   Two atoms   Three atoms   ...   Million atoms   ...   Avogadro number of atoms

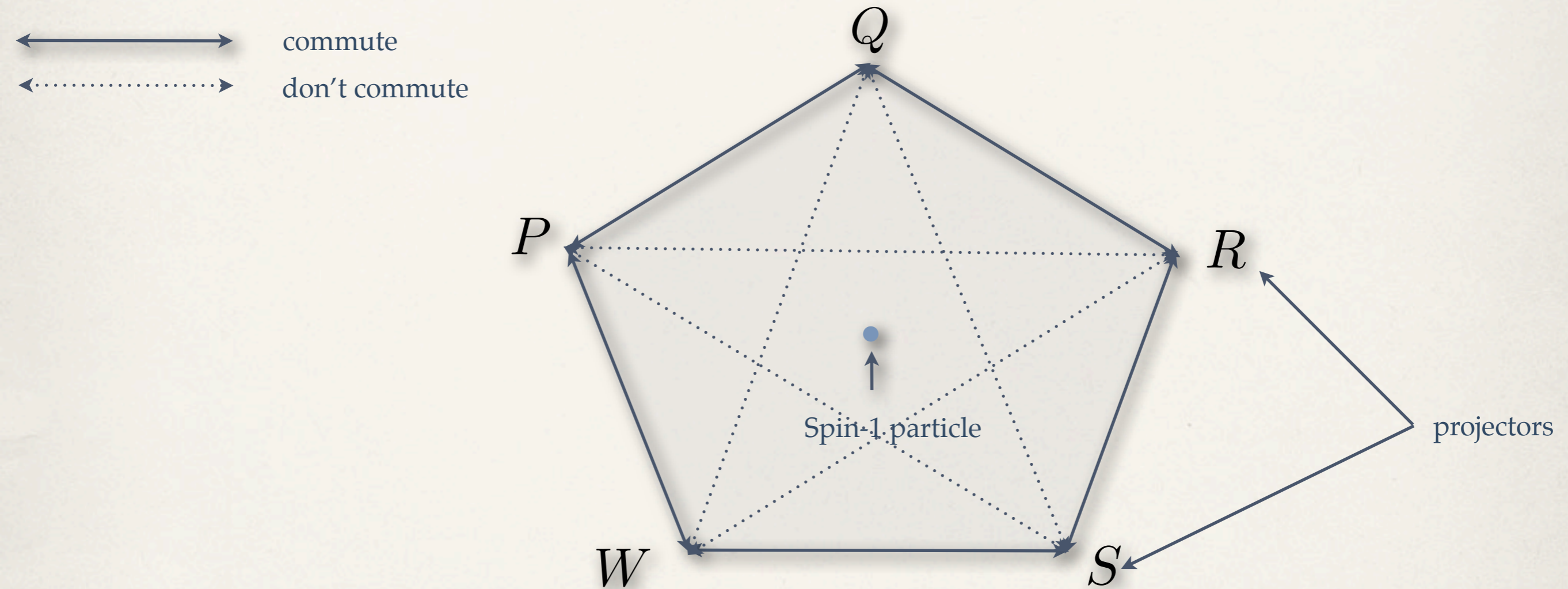Definitely quantum   Quantum?   Classical?

We need to apply Kochen-Specker and/or Bell to decide
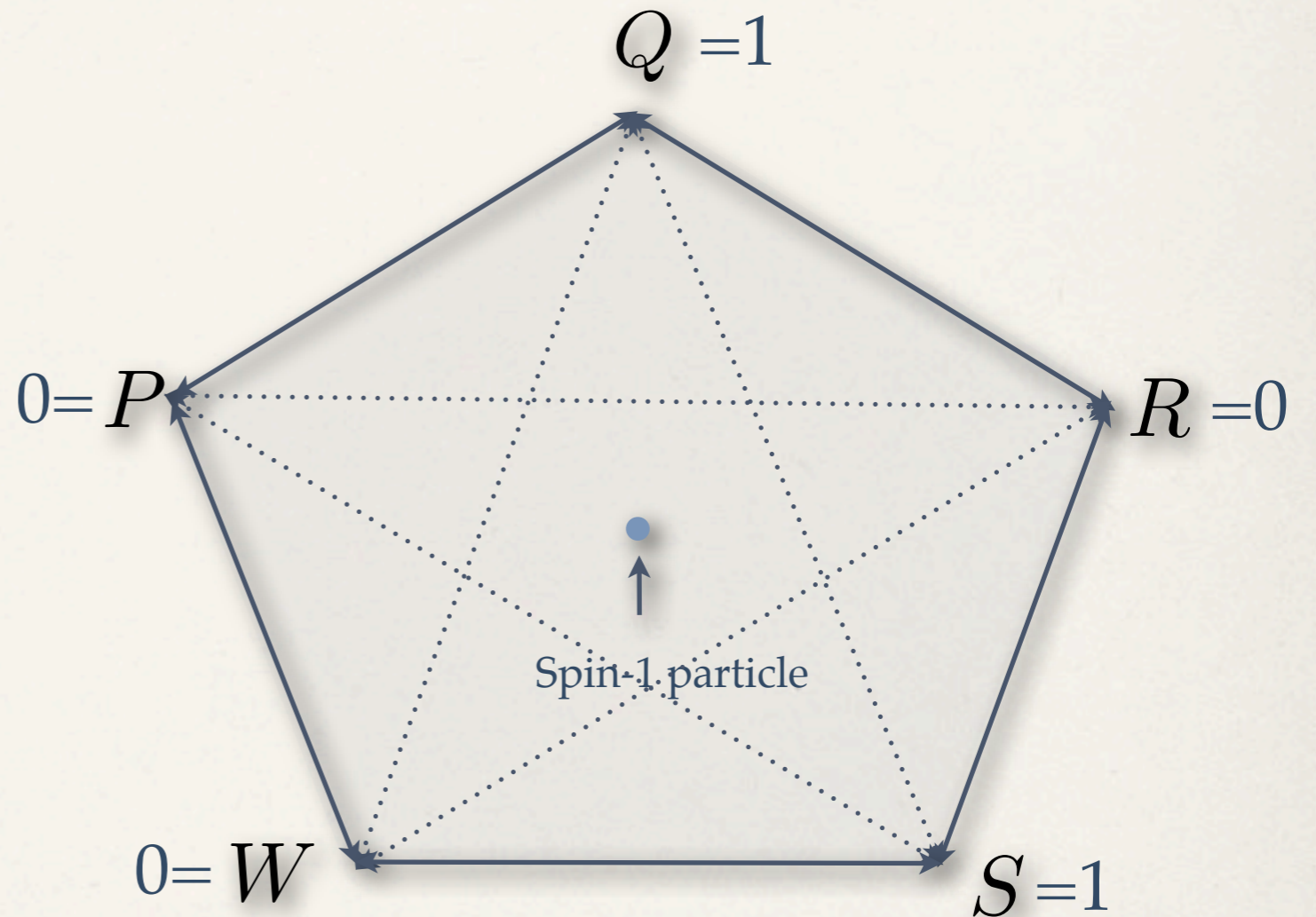
Kochen-Specker

Can I assign values to the outcomes of these measurements before they happened?

Kochen-Specker

$$Prob(p, q, r, s, w)$$

$$Prob(p = 1 \& q = 1) = 0$$

$$\langle P \rangle_{cl} = \sum_{p=0}^{1} p\,Prob(p)$$

$$\langle P \rangle_{cl} + \langle Q \rangle_{cl} + \langle R \rangle_{cl} + \langle S \rangle_{cl} + \langle W \rangle_{cl} \leq 2$$
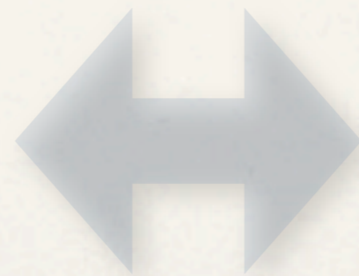
Klyachko inequality

Kochen-Specker

Quantum mechanics violates Klyachko

$$\langle P \rangle_{qm} + \langle Q \rangle_{qm} + \langle R \rangle_{qm} + \langle S \rangle_{qm} + \langle W \rangle_{qm} = \sqrt{5}$$

This means that

results of measurements depend on the context in which they are measured or they simply don't exist ⬌ $Prob(p, q, r, s, w)$ doesn't exist

Kochen-Specker

Interesting remark

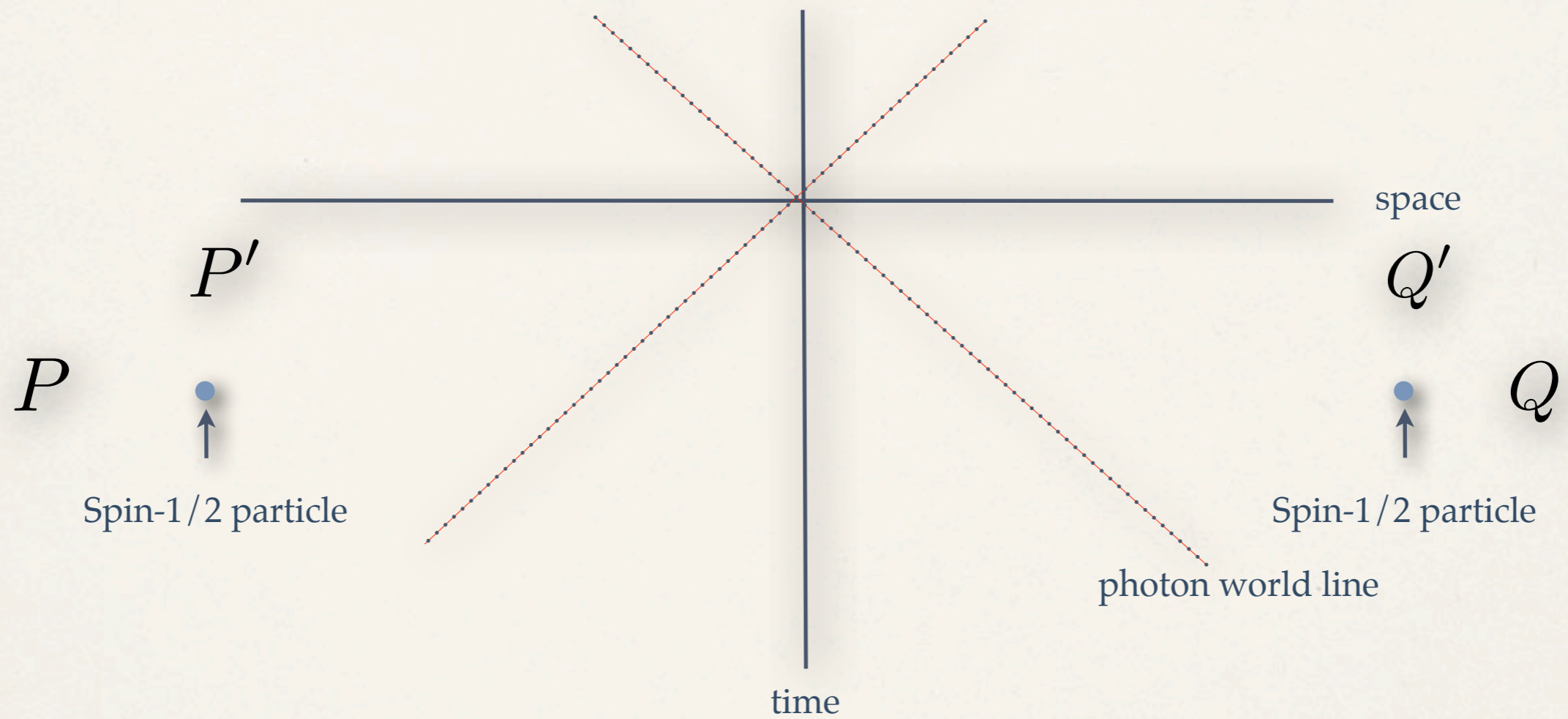All projectors don't commute $Prob(p, q, r, s, w) = Prob(p)Prob(q)Prob(r)Prob(s)Prob(w)$

All projectors commute $Prob(p, q, r, s, w) =$ given by quantum mechanics

KS argument requires both commutativity and non-commutativity!

Food for thought: does $[X, P] = i$ alone imply quantum behaviour?

Bell

P'

P

Q'

Q

space

Spin-1/2 particle
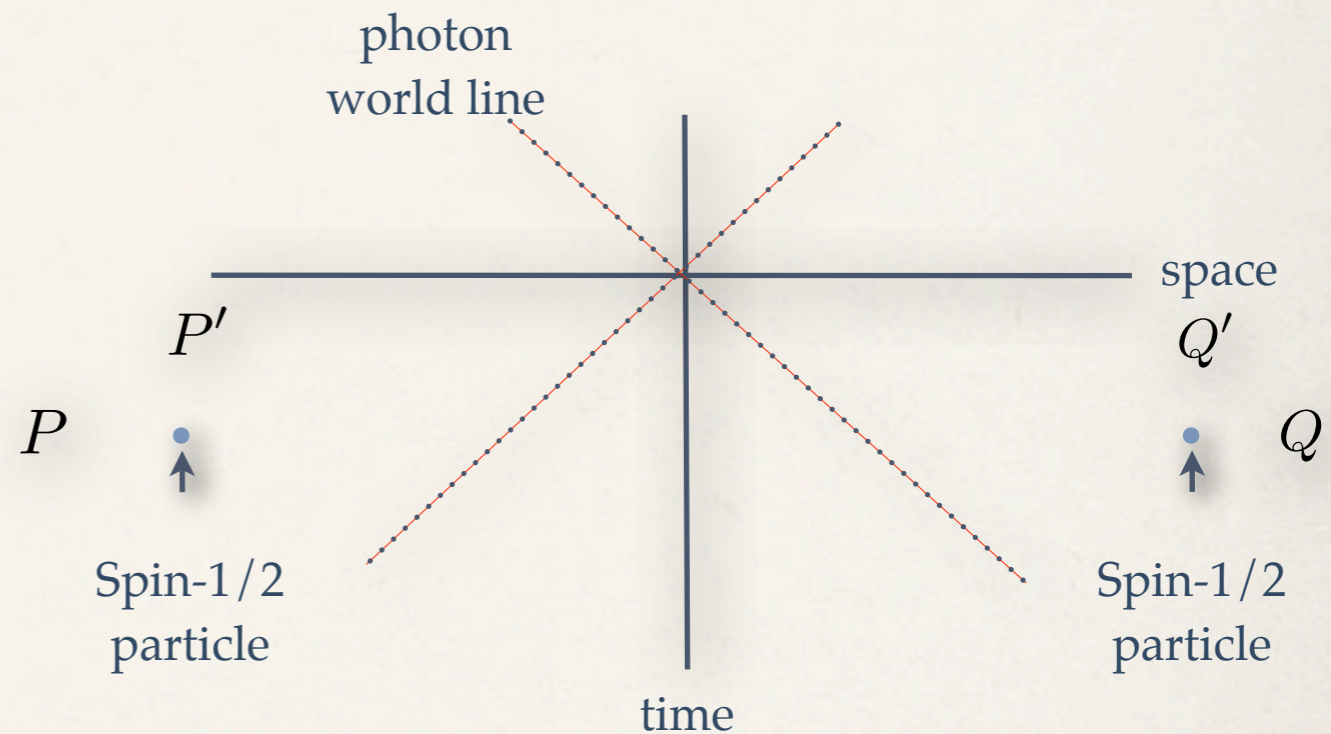
Spin-1/2 particle

photon world line

time

Can I assign values to the outcomes of these measurements before they happened?

Bell

$$Prob(p, p', q, q')$$

$$\langle P \otimes Q \rangle_{cl} = \sum_{p,q=0}^{1} pq Prob(p, q)$$

photon
world line

space
Q'

P'

P

Q

Spin-1/2
particle

Spin-1/2
particle

time

$$\langle P \otimes Q \rangle_{cl} + \langle P \otimes Q' \rangle_{cl}) + \langle P' \otimes Q \rangle_{cl} - \langle P' \otimes Q' \rangle_{cl} \leq \langle P \rangle_{cl} + \langle Q \rangle_{cl}$$

Bell inequality

Bell

Quantum mechanics violates Bell

This means that

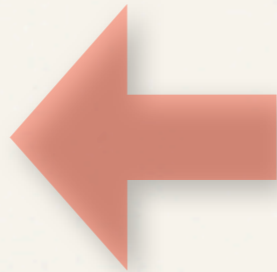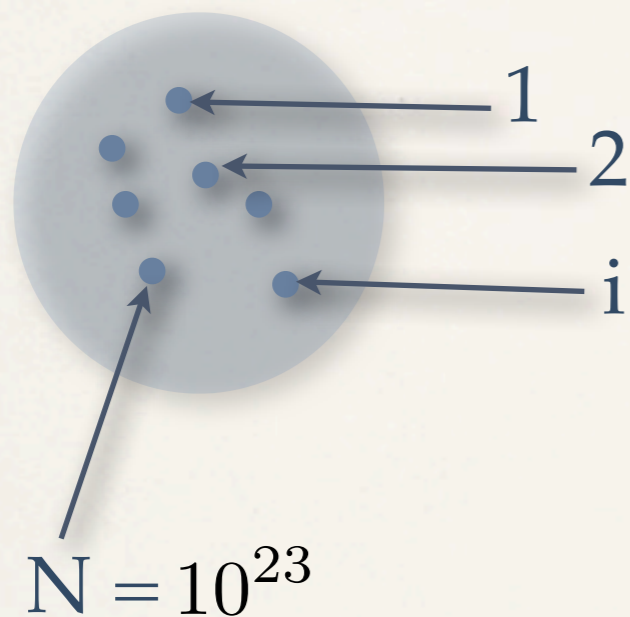results of measurements depend on the context in which they are measured or they simply don't exist ⟷ $Prob(p, p', q, q')$ doesn't exist

Essential remark: context imposed by locality

Macroscopic measurements

1

2

i

What can you measure on this?

$N = 10^{23}$

Macroscopic = impossible to address individual particles

Examples: pressure, magnetization, temperature

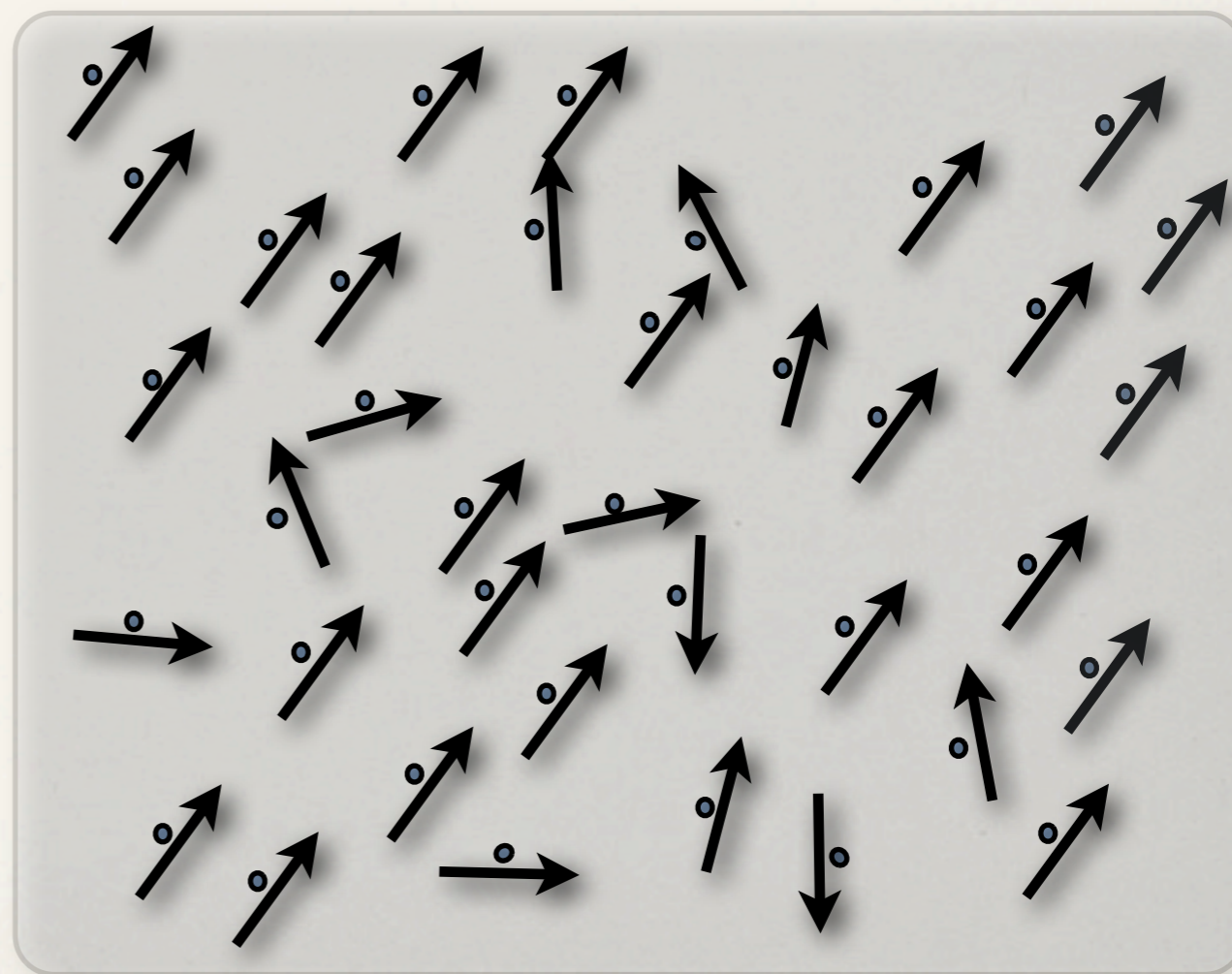$$O_1 = \sum_{i=1}^{N} A_i$$

Macroscopic Kochen-Specker

Is this system classical?

Can one violate Klyachko type inequality

To do this we need context

Large system of spins

Macroscopic Kochen-Specker

We go to the lab and measure magnetization in some directions

Mathematically we measure a set of projectors
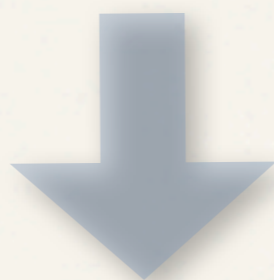
$$P_{\vec{n}}(m)$$

direction
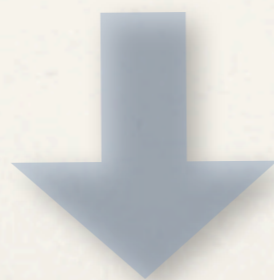
value of magnetization

Macroscopic Kochen-Specker

We showed that for any directions and values of magnetization
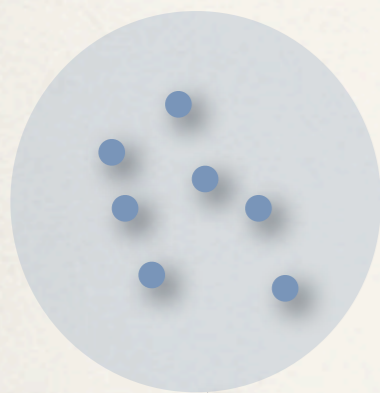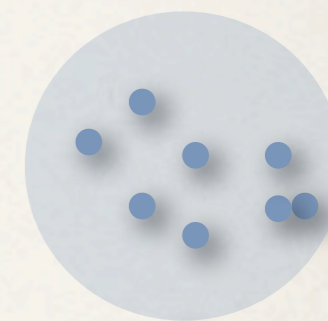
$$[P_{\vec{n}}(m), P_{\vec{n}'}(m')] \neq 0$$

No context

Impossible to decide if the system is classical or not!!

Macroscopic Bell

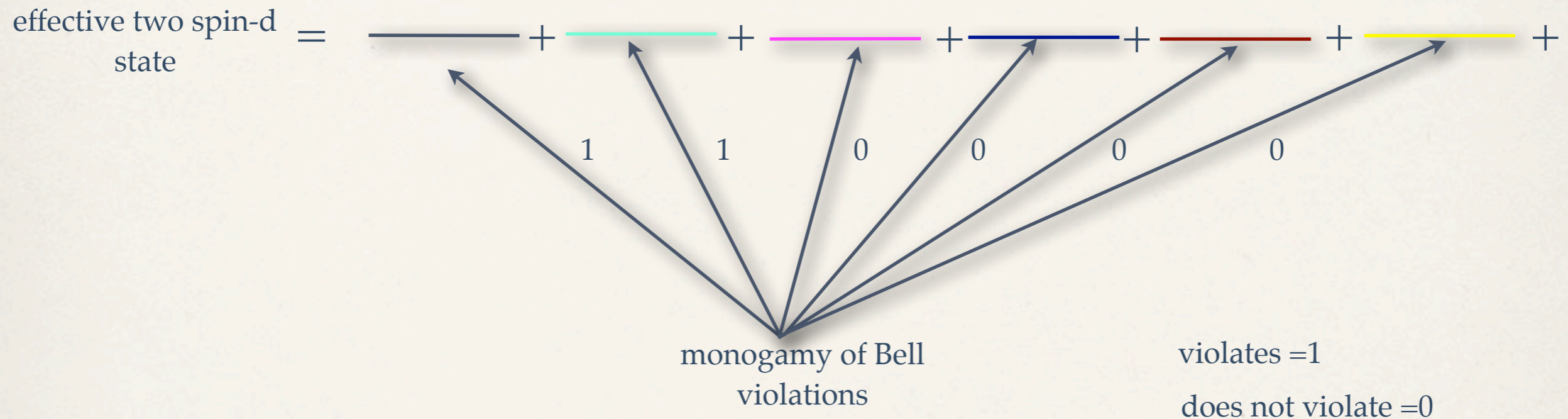Can this system violate Bell inequality?

Avogadro number
of spin-d particles

Avogadro number
of spin-d particles

Macroscopic Bell

$M_A(\vec{n})$

$M_B(\vec{m})$

effectively

Macroscopic Bell

effective two spin-d state $=$ ——— $+$ ——— $+$ ——— $+$ ——— $+$ ——— $+$ ——— $+$

1   1   0   0   0   0

monogamy of Bell violations

violates =1

does not violate =0

It can be shown that in the end there is no violation!

Macroscopic correlations are classical

The meaning of it all

?