# Quantum Measurement and Why It's a Problem (And Some Solutions)

**Sean Carroll**
Johns Hopkins & Santa Fe Institute

Physics Today Webinar – Editor's Series
May 2023

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# James Hartle (1939-2023)

- Calculated the wave function of the universe (w/ Hawking)
- Formulated QM in terms of decoherent histories (w/ Gell-Mann)
- Tireless advocate for physics, young physicists, and clear thinking

## Textbook quantum mechanics

1. States are vectors in Hilbert space, $|\Psi\rangle \in \mathcal{H}$

2. Schrödinger's equation: $H|\Psi\rangle = i\partial_t|\Psi\rangle$

3. Measurements associated with an operator *A* give eigenvalues: $A|A_n\rangle = a_n|A_n\rangle$

4. Born Rule: probability of obtaining $a_n$ in a measurement is given by $|\langle A_n|\Psi\rangle|^2$

5. Collapse: after measurement, system is in state $|A_n\rangle$

# The Measurement Problem

- What exactly is a "measurement"?
- When precisely does a measurement occur?
- How quickly does it happen?
- What kinds of systems can perform measurements?
- Is there a threshold for inducing collapse?
- Is *consciousness* somehow involved?

Textbook quantum mechanics is <u>not sufficiently precise</u> to be taken seriously as a fundamental theory of nature.

**There is no quantum measurement problem**

*The idea that the collapse of a quantum state is a physical process stems from a misunderstanding of probability and the role it plays in quantum mechanics.*

N. David Mermin

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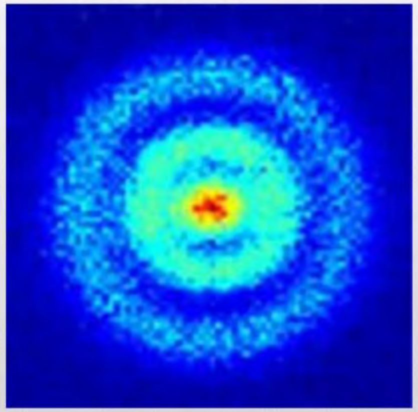
Perhaps you think you *know the answer* to the measurement problem, but there is nevertheless a problem.

If only because most people don't agree with you (for any given answer.)

## The Reality Problem

- What is the nature of the physical world?
- Does the wave function map onto reality, or is it just a tool for making predictions?
- Do we bring reality into existence by measurement?
- Are there physical degrees of freedom in addition to the wave function?

# The Copenhagen “Interpretation”: way more radical than we tend to admit



quantum ← → classical

Heisenberg Cut

# Thoughts on Copenhagen/Textbook QM

Albert Einstein: "The theory is apt to beguile us into error in our search for a uniform basis for physics, because, in my belief, it is an incomplete representation of real things."

Erwin Schrödinger: "I don't like it, and I'm sorry I ever had anything to do with it."

Hugh Everett: "A philosophical monstrosity..."

Karl Popper: "A mistaken and even vicious doctrine."

Doesn’t decoherence solve all this?

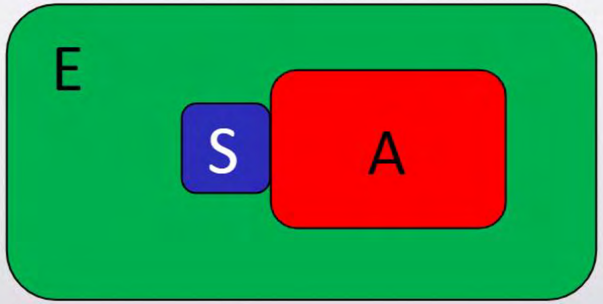
No.

# Decoherence

Factorize Hilbert space into system x apparatus x environment:

$$\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_A \otimes \mathcal{H}_E$$

*S* = any quantum superposition
*A* = observable macroscopic device
*E* = microscopic, unknown d.f.s




ready state $$|\Psi\rangle = (|+\rangle_S + |-\rangle_S)|0\rangle_A|e_*\rangle_E$$

pre-measurement $$\rightarrow (|+\rangle_S|+\rangle_A + |-\rangle_S|-\rangle_A)|e_*\rangle_E$$

decoherence $$\rightarrow |+\rangle_S|+\rangle_A|e_+\rangle_E + |-\rangle_S|-\rangle_A|e_-\rangle_E$$

Trace over states of the apparatus and environment to get a density matrix for just the system:

$$\hat{\rho}_S = \mathrm{Tr}_{AE}|\Psi\rangle\langle\Psi| = \begin{pmatrix} p_1 & 0 & 0 & \dots \\ 0 & p_2 & 0 & \dots \\ 0 & 0 & p_3 & \dots \\ & \dots & & \end{pmatrix}$$

Eigenvalues obey axioms of probability:

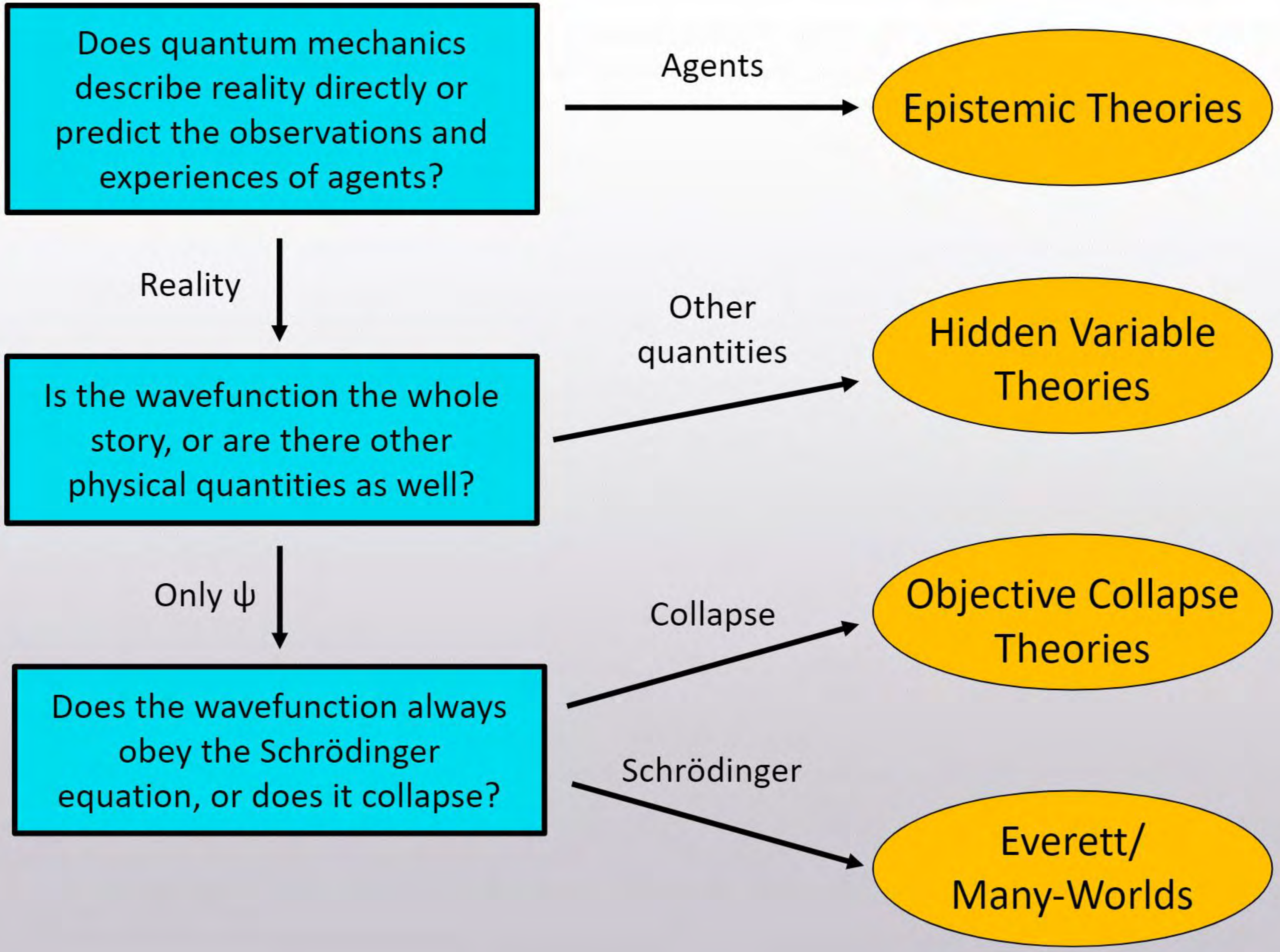
$$0 \leq p_i \leq 1 \,, \qquad \sum_i p_i = 1.$$

But you can't just say they *are* probabilities without taking a stance on the reality & measurement problems.

There are plausible solutions.

We just don’t agree on which one.

We’ve moved beyond talking about “interpretations,”
and onto comparing true scientific theories.


Does quantum mechanics describe reality directly or predict the observations and experiences of agents?
Agents
Epistemic Theories
Reality
Is the wavefunction the whole story, or are there other physical quantities as well?
Other quantities
Hidden Variable Theories
Only ψ
Does the wavefunction always obey the Schrödinger equation, or does it collapse?
Collapse
Objective Collapse Theories
Schrödinger
Everett/ Many-Worlds

## Epistemic Theories (Copenhagen, QBism...)

Don't talk about "reality"; talk about agents, their experiences, and their states of knowledge.

Qbism: the wave function of a system might be different for different observers. Subjective.

No worries about spooky action at a distance.

Big worries for what the universe is. Are "agents" and "experiences" part of fundamental physics?

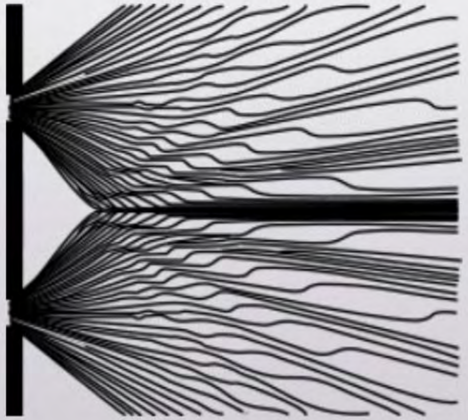
A truly radical departure for what science is.

# Hidden-Variable Theories

Louis de Broglie; David Bohm.

Wave function and additional particle degrees of freedom.
(Waves interfere; particles get observed.)

“Pilot wave”: wave function guides motion of particles, but is unaffected by them.



Explicitly nonlocal dynamics.

Very hard to reconcile with quantum field theory.

# The Nobel Prize in Physics 2022

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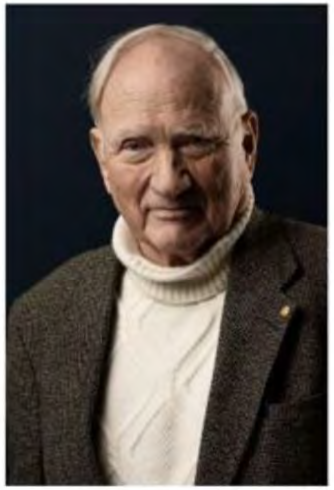
Alain Aspect

Prize share: 1/3



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John F. Clauser

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Anton Zeilinger

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First Nobel in foundations of QM since Max Born, 1954

For a long time, the question was whether the correlation was because the particles in an entangled pair contained hidden variables, instructions that tell them which result they should give in an experiment. In the 1960s, John Stewart Bell developed the mathematical inequality that is named after him. This states that if there are hidden variables, the correlation between the results of a large number of measurements will never exceed a certain value. However, quantum mechanics predicts that a certain type of experiment will violate Bell's inequality, thus resulting in a stronger correlation than would otherwise be possible.

# Bell's Theorem

Local realist theories cannot reproduce the predictions of quantum entanglement (under certain plausible-seeming assumptions).

"As a professional theoretical physicist, I like the Bohm theory because it is sharp mathematics. I have there a model of the world in sharp mathematical terms that has this non-local feature."

# History

1927, Solvay: de Broglie describes his theory, Pauli terrorizes him into giving up.

1932: John von Neumann's QM book includes a theorem saying hidden variables can't work.

1935: Greta Hermann points out that von Neumann's assumptions are easy to violate. She is ignored.

1950: Bohm writes a QM textbook, quoting von Neumann. Einstein points out the loopholes to him.

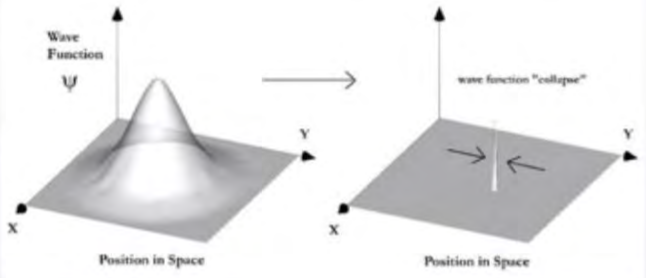
1952: Bohm publishes his hidden-variable theory.

Oppenheimer: "If we cannot disprove Bohm, we must agree to ignore him."

1964: John Bell, inspired by Bohm, proves need for non-locality.

# Objective Collapse Theories

Ghirardi-Rimini-Weber (GRW, 1986): particle wave functions truly collapse, randomly (~ 1/300,000,000 years)




Continuous Spontaneous Localization: ongoing maintenance of macroscopic spatial coherence

Penrose: wave functions collapse when components are gravitationally different from each other

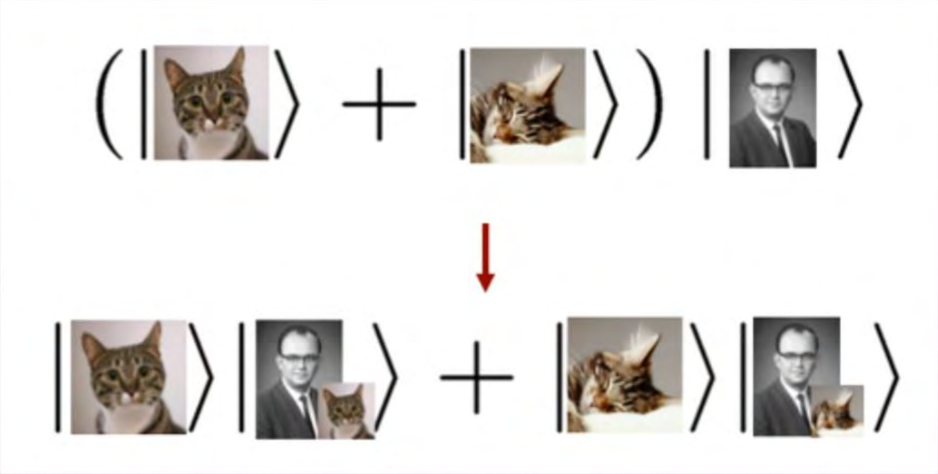
Upshot: macroscopic systems always look pretty classical, so “measurement” is trivial

Seems a little ad hoc to most working physicists; also hard to reconcile with QFT

# Many-Worlds

The wave function represents reality, and always obeys the Schrödinger equation. (That's it.)

Trick: post-decoherence, branches evolve as separate worlds, and should be treated as such.



In this theory, measurement is indeed just decoherence.

# Notes on Many-Worlds

- The simplest theory. (Wave function + Schrödinger.)
- The worlds are not put in. They were always there in Hilbert space. Schrödinger evolution makes them real.
- Completely deterministic, reversible.
- Where does probability come from? Honest question!
- Self-locating uncertainty: immediately after branching you don’t know which branch you are on.
- Why does the world look at all classical (space, stuff...)?

# Is any of this testable?

1. In comparison to what?

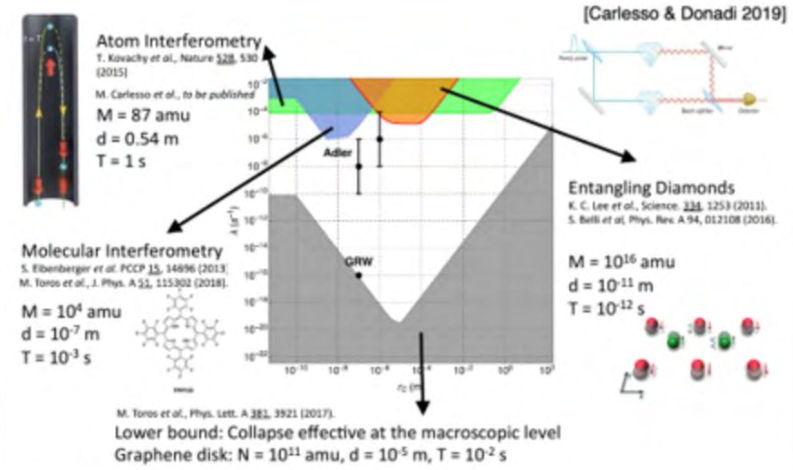



**Fig. 1.** Exclusion plots for the CSL parameters from interferometric experiments with respect to the GRW's and Adler's theoretically proposed values Ghirardi *et al.* (1986);

2. Yes, absolutely. We can look for objective collapse.

3. We don't know whether Everett & Bohm are distinguishable because we haven't tried very hard.

4. If they turn out not to be, thinking within one or another paradigm can still affect future progress.

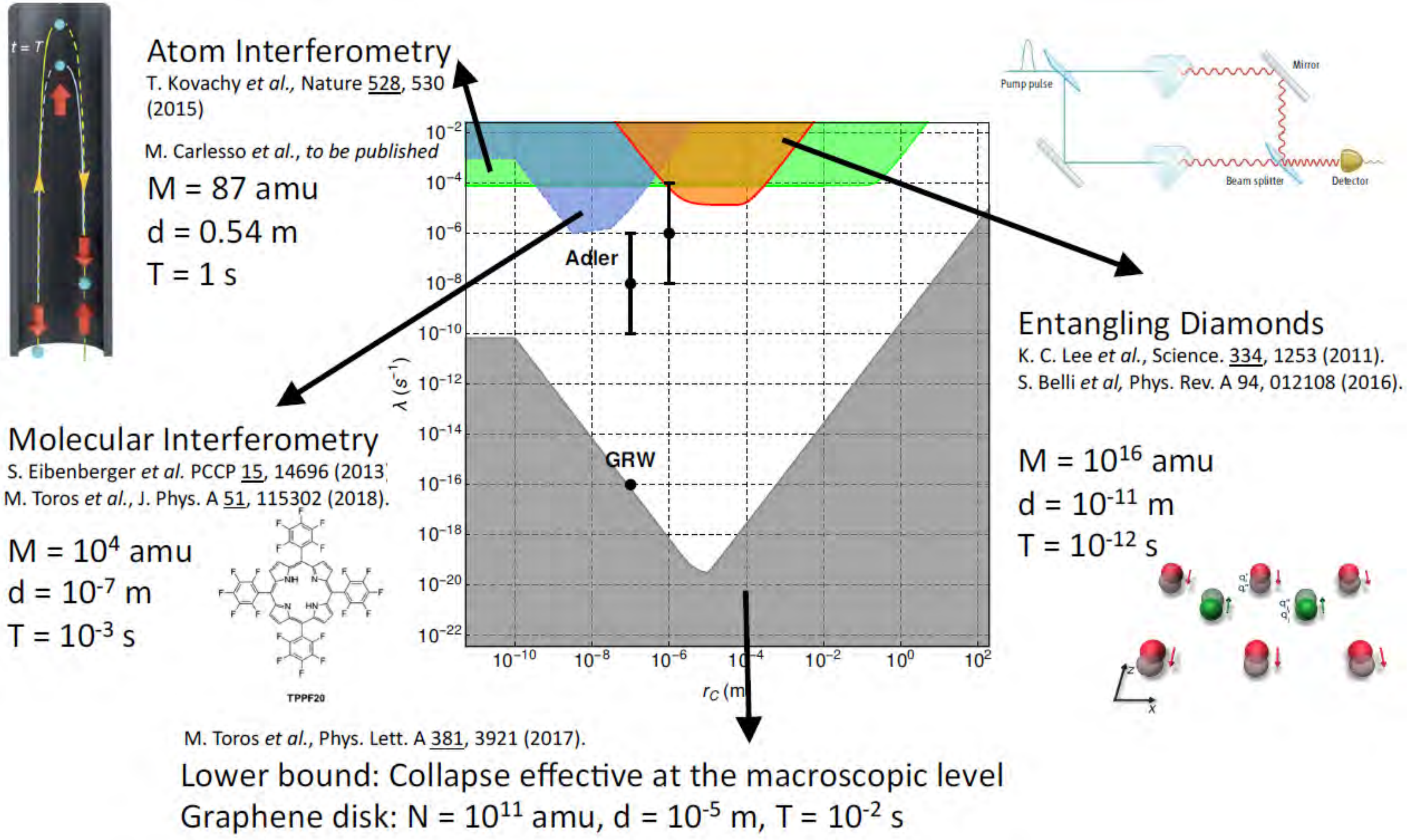



**Fig. 1.** Exclusion plots for the CSL parameters from interferometric experiments with respect to the GRW's and Adler's theoretically proposed values Ghirardi *et al.* (1986); Adler (2007): molecular interferometry Eibenberger *et al.* (2013); Toroš *et al.* (2017) (blue area), atom interferometry Kovachy *et al.* (2015a) (green area) and experiment with entangled diamonds Lee *et al.* (2011); Belli *et al.* (2016) (orange area). We report with the grey area the region excluded from theoretical arguments Toroš *et al.* (2017). $M$, $d$ and $T$ refer respectively to the mass, the superposition distance involved and the time of each experiment.

M. Carlesso and S. Donadi,

*Collapse Models: Main Properties and the State of Art of the Experimental Tests*, in

*Advances in Open Systems and Fundamental Tests of Quantum Mechanics: Proceedings of the 684. WE-Heraeus-Seminar,*

*Bad Honnef, Germany, 2–5 December 2018* (Springer, 2019),

pp. 1–13, Fig. 1.
https://arxiv.org/abs/1907.12460

*(Expanded slide is on next page)*


## Atom Interferometry

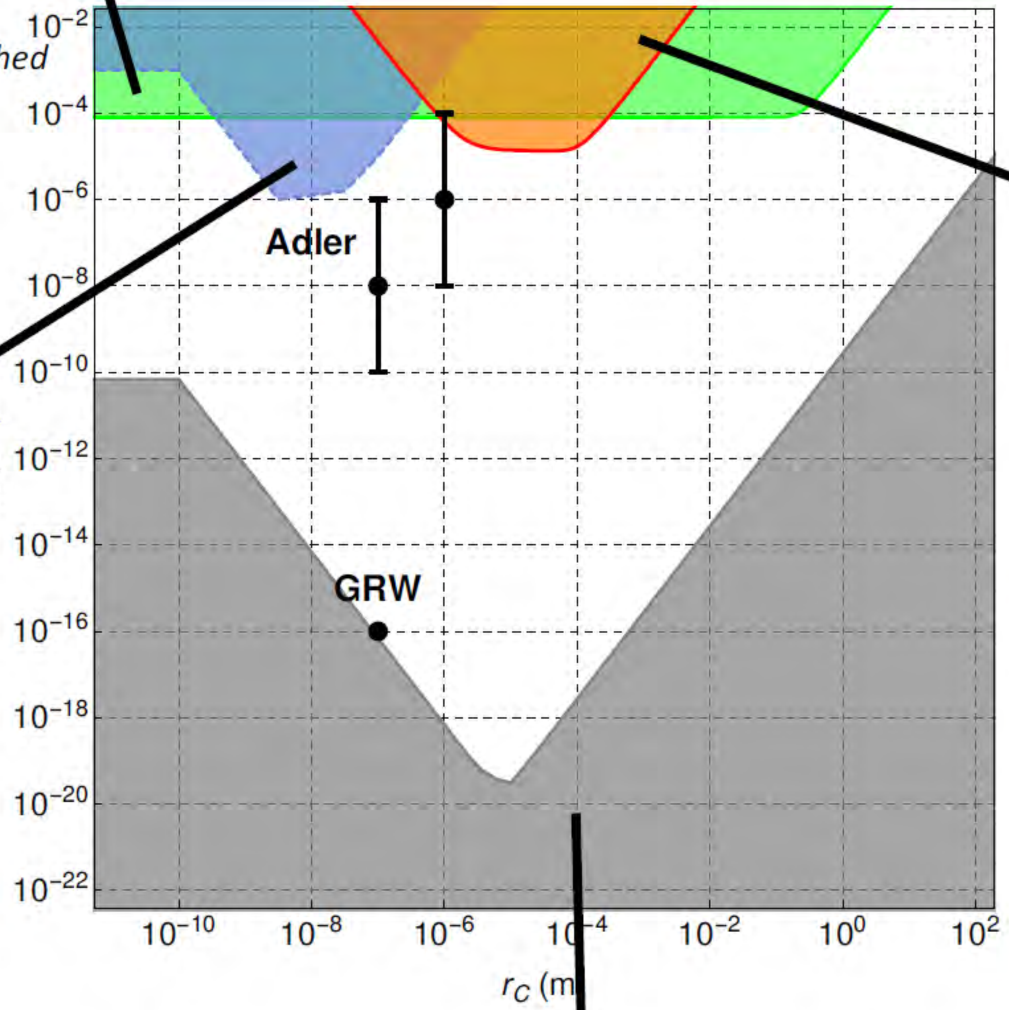
T. Kovachy *et al.*, Nature 528, 530 (2015)

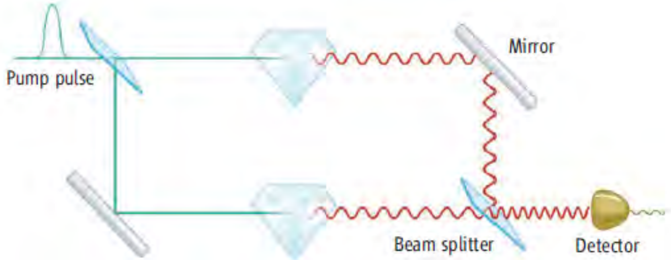
M. Carlesso *et al.*, *to be published*

M = 87 amu

d = 0.54 m

T = 1 s




## Entangling Diamonds

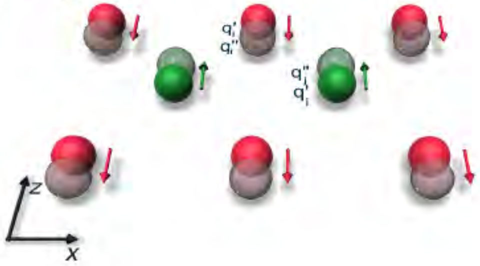
K. C. Lee *et al.*, Science. 334, 1253 (2011).

S. Belli *et al*, Phys. Rev. A 94, 012108 (2016).

M = $10^{16}$ amu

d = $10^{-11}$ m

T = $10^{-12}$ s




## Molecular Interferometry

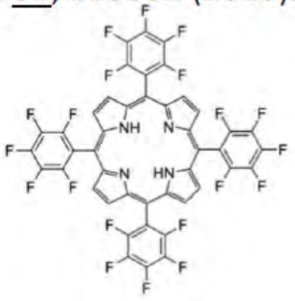
S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M. Toros *et al.*, J. Phys. A 51, 115302 (2018).

M = $10^4$ amu

d = $10^{-7}$ m

T = $10^{-3}$ s



TPPF20

M. Toros *et al.*, Phys. Lett. A 381, 3921 (2017).

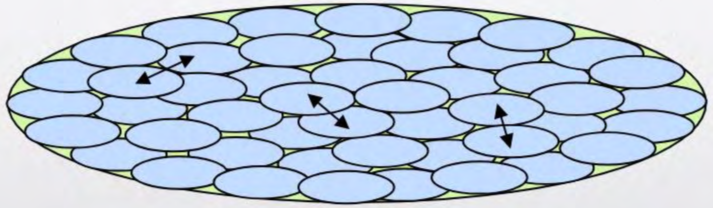
Lower bound: Collapse effective at the macroscopic level

Graphene disk: N = $10^{11}$ amu, d = $10^{-5}$ m, T = $10^{-2}$ s

# Putting foundational theories to work: deriving space from Hilbert space

In quantum field theory, Hilbert space is the product of subspaces representing degrees of freedom associated with spatial locations.

$$\mathcal{H} = \bigotimes_a \mathcal{H}_a$$



In this decomposition, interactions are local – degrees of freedom interact directly with neighbors, not with far-away locations.

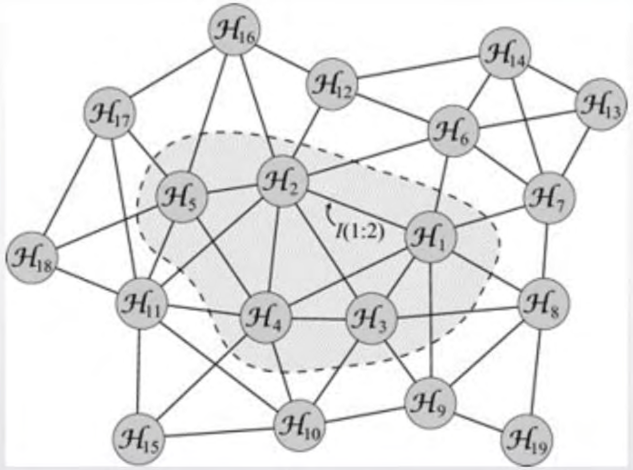
Can we <u>derive</u> locality from the spectrum of the Hamiltonian?

Cotler, Penington, and Renard, 2017: yes.

- Most Hamiltonians have <u>no</u> local factorization.
- When it exists, locality is (mostly) <u>unique</u>.

[Cotler et al. 2017]

# Why Is There Gravity?




Holography: Entropy of a region is proportional to the Area of its boundary.

What if we define emergent “area” in terms of entanglement entropy?

Entanglement

$$\delta\mathcal{A} \propto \delta S$$

Geometry

$$G_{\mu\nu}$$

Energy

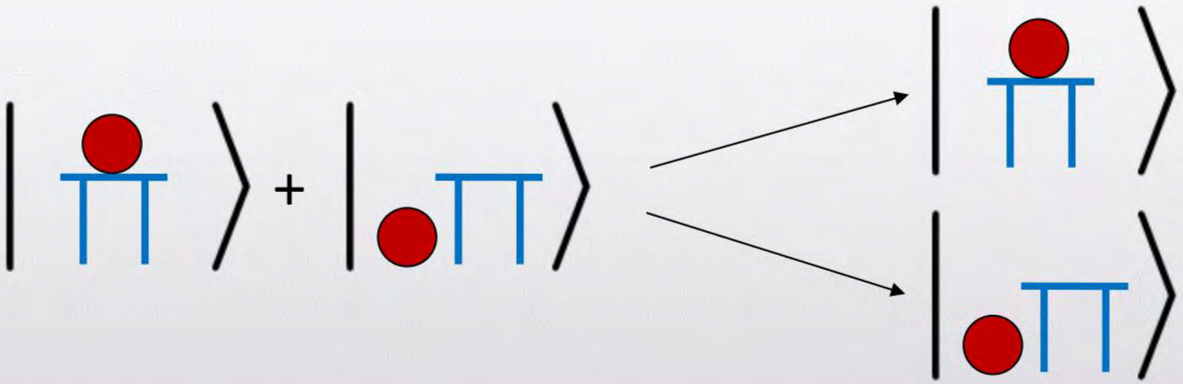
$$T_{\mu\nu}$$

Geometry that emerges from entanglement is naturally dynamical, and naturally obeys the weak-field Einstein equation.

[Cao, Carroll & Mikhalakis 2016; Cao & Carroll 2018; cf. Jacobson 1995, 2015]

# Why Does Energy Appear to Be Conserved?

Energy defined as $E_\psi \equiv \langle\psi|\widehat{H}|\psi\rangle$ is constant in the overall wave function, but will fluctuate over time as seen by any observer.



Macroscopic superpositions of very different energies will decohere and branch extremely rapidly.

→ Each branch evolves to a superposition of states with almost-equal energies, which therefore appear constant.

[Carroll & Lodman, 2021]

# Conclusions

- Textbook quantum mechanics is wildly successful at accounting for experiments, but falls well short of the precision needed for a fundamental theory.
- We can do better, but many physicists seem uninterested.
- We might already have the correct answer to the measurement/reality problems, but we don’t agree on what it is, so the problem remains.
- Thinking about these issues can drive progress on other well-known problems in physics.
- Physicists should care about reality.