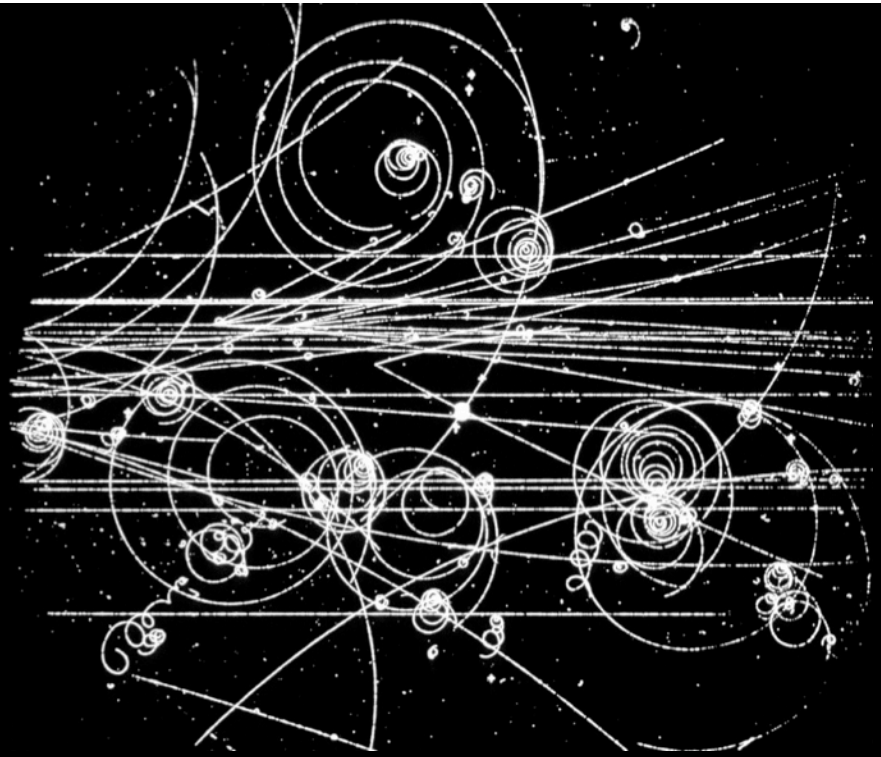
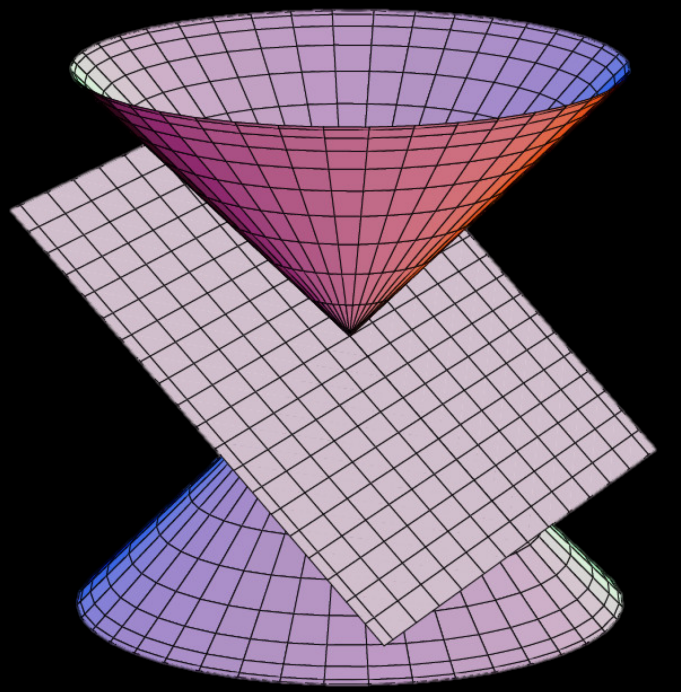




Modern Physics (Phys. IV): 2704

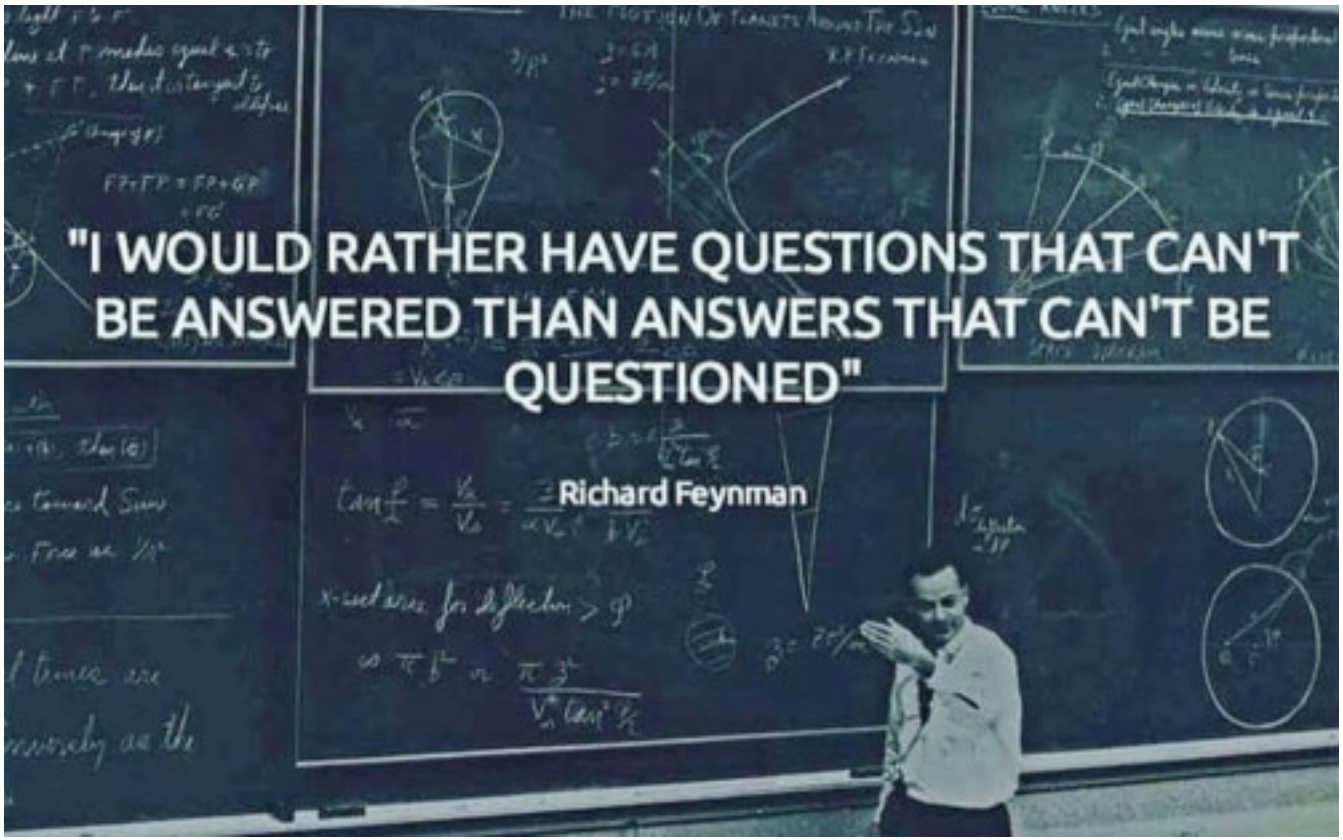
Professor Jasper Halekas
Van Allen 70
MWF 12:30-1:20 Lecture

Final Exam Details

- Final Exam is Ready
  - 10 questions
  - ~1/3 points on material on first midterm
  - ~1/3 points on material on second midterm
  - ~1/3 points on material since second midterm
  - Sample final and extra questions on last 1/3 posted
- You are allowed a calculator, and both sides of an 8.5x11 page for an equation sheet
- Final 7:30-9:30 am Friday 5/11 in Van 70 (this room)
  - Donuts on me!

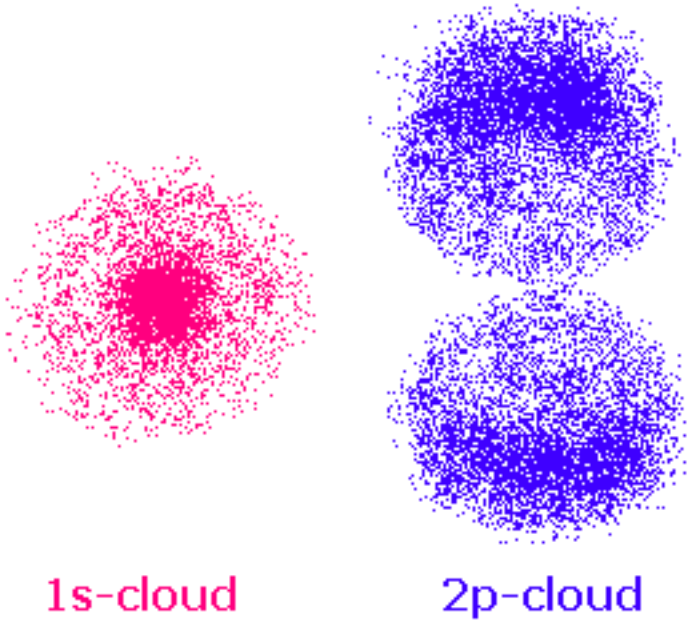
Physics is ridiculous

- Physics is also awesome!



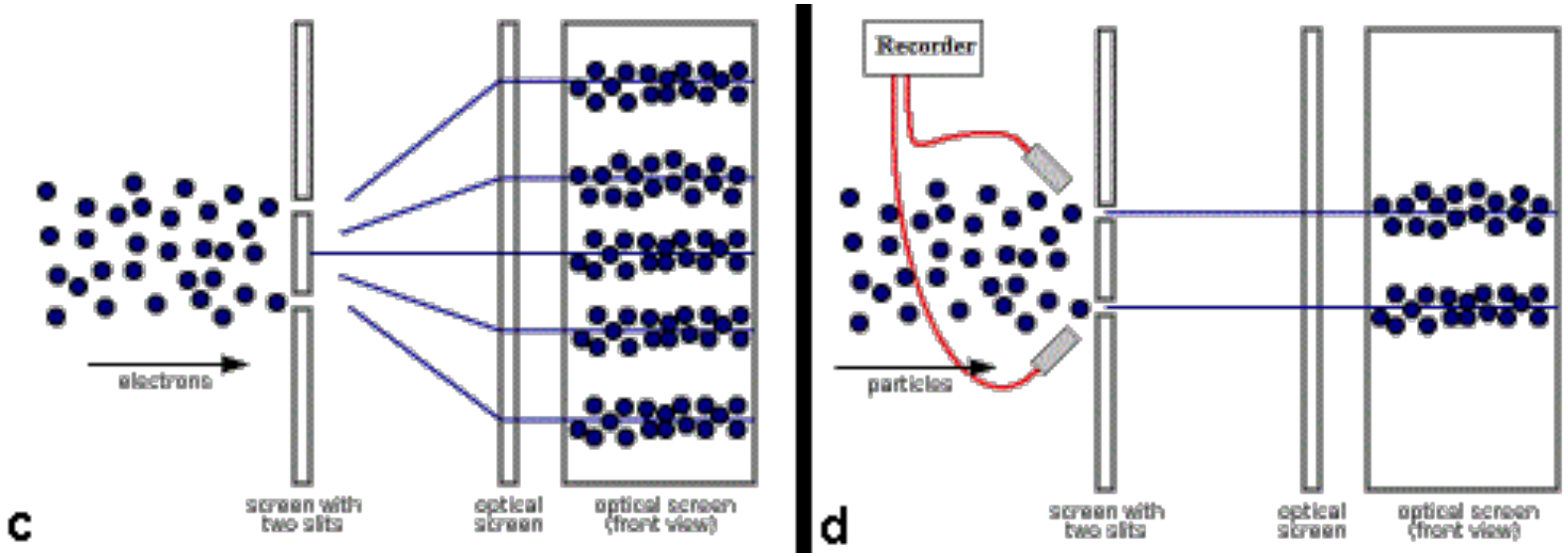
Some ludicrous things about QM

- The evolution of systems is probabilistic rather than deterministic
  - Schrödinger's equation describes a wave function, which when squared is a probability density
  - Einstein's knee-jerk response: "God does not play dice"



Some ludicrous things about QM

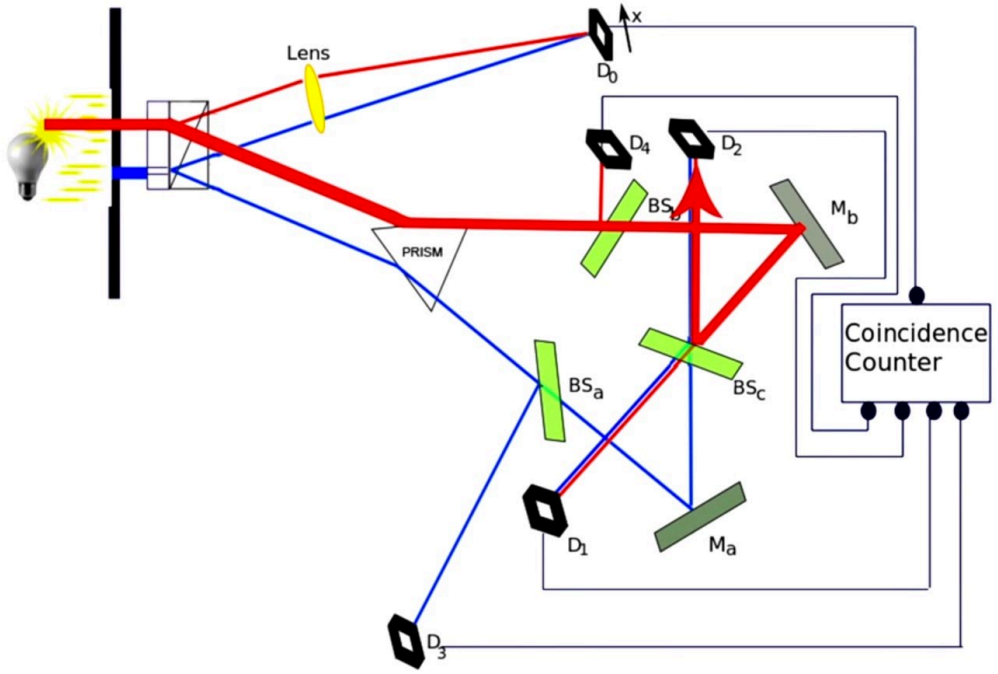
- Particles sometimes behave like particles and sometimes like waves



  - Not only that, they know when to behave like particles or waves based upon how you are observing them!

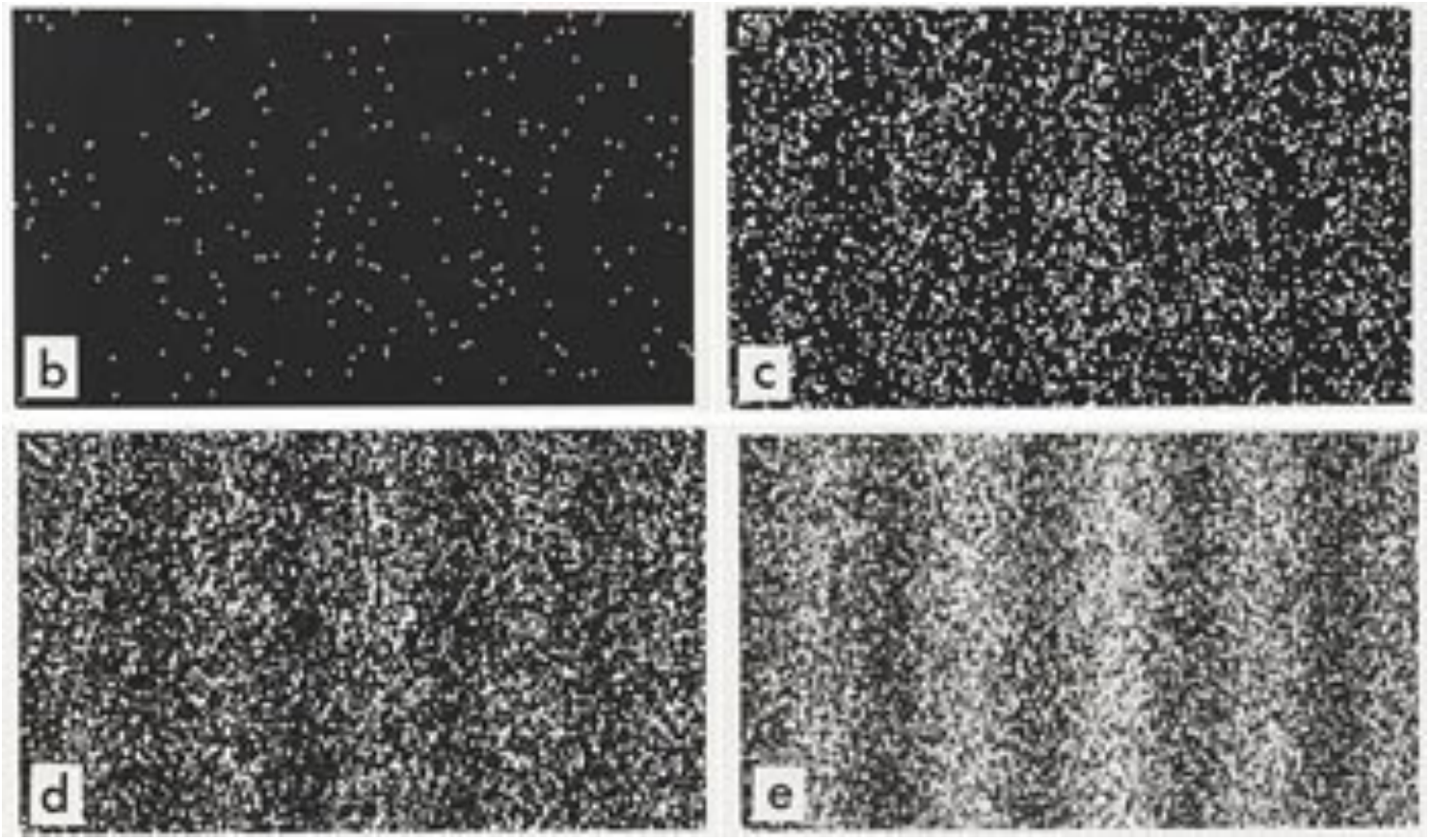
Delayed Choice Experiments

- "Quantum Eraser" experiments show that particles can be forced to behave like either particles or waves "after the fact" – retro-causality!

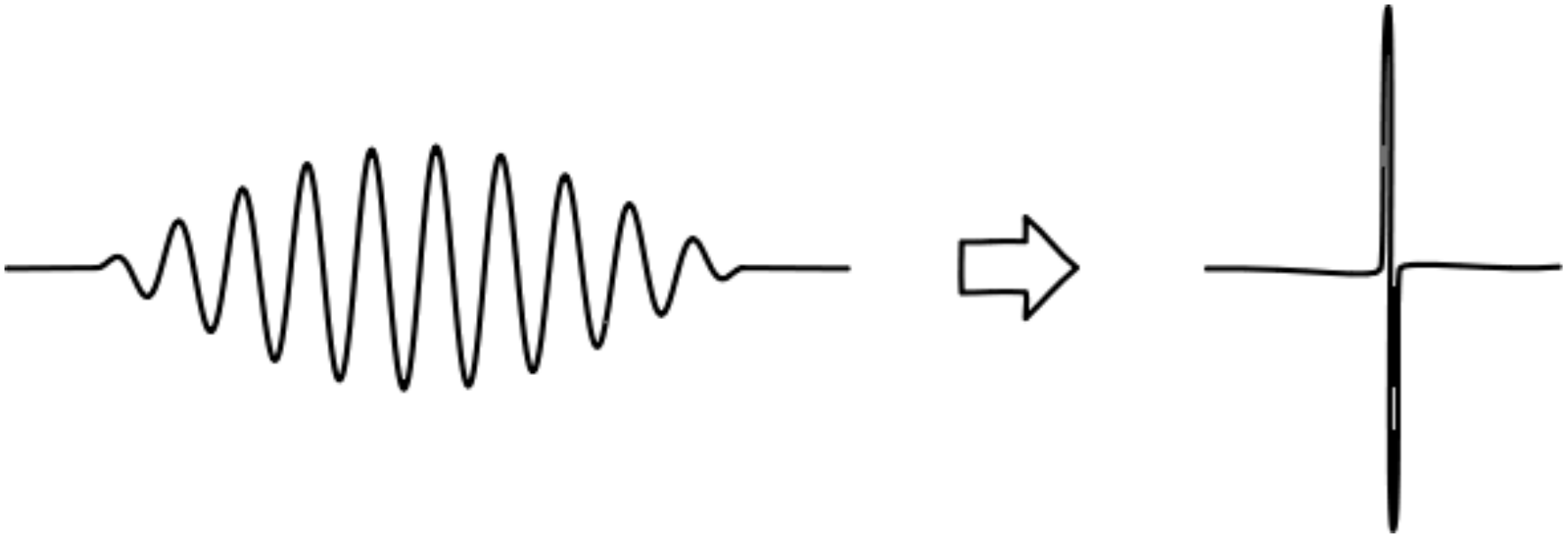


The Measurement Problem

- After it is observed, something described by a wave suddenly has a definite position – how does that happen?



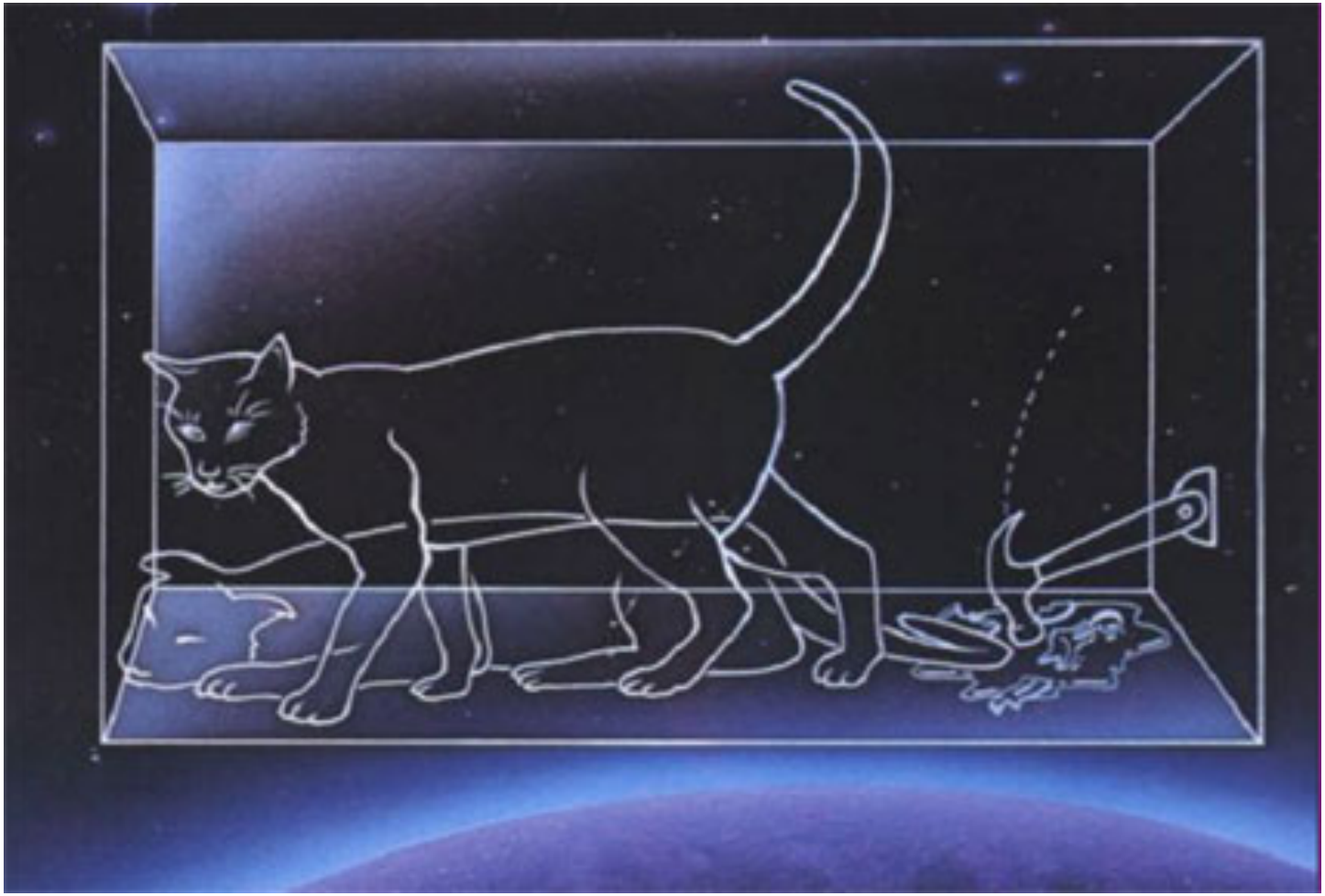
Collapse of the Wave Function



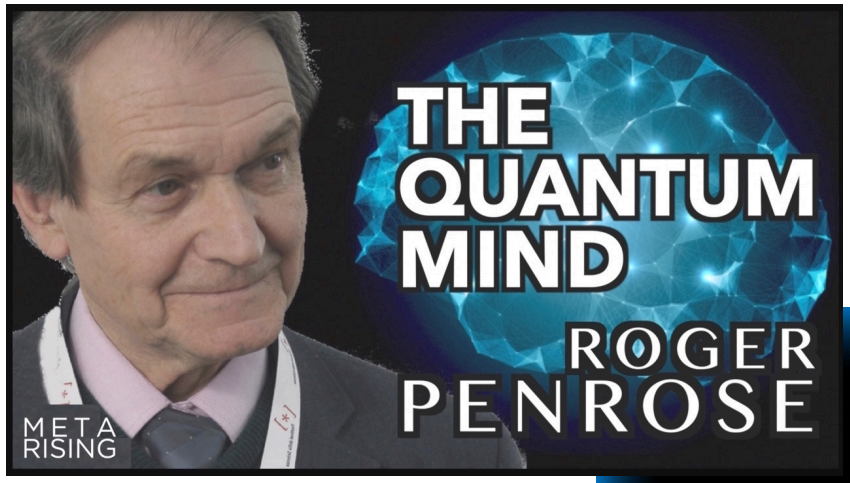
What is so special about the measurement/observation process?

Is consciousness special?

Schrödinger's Cat



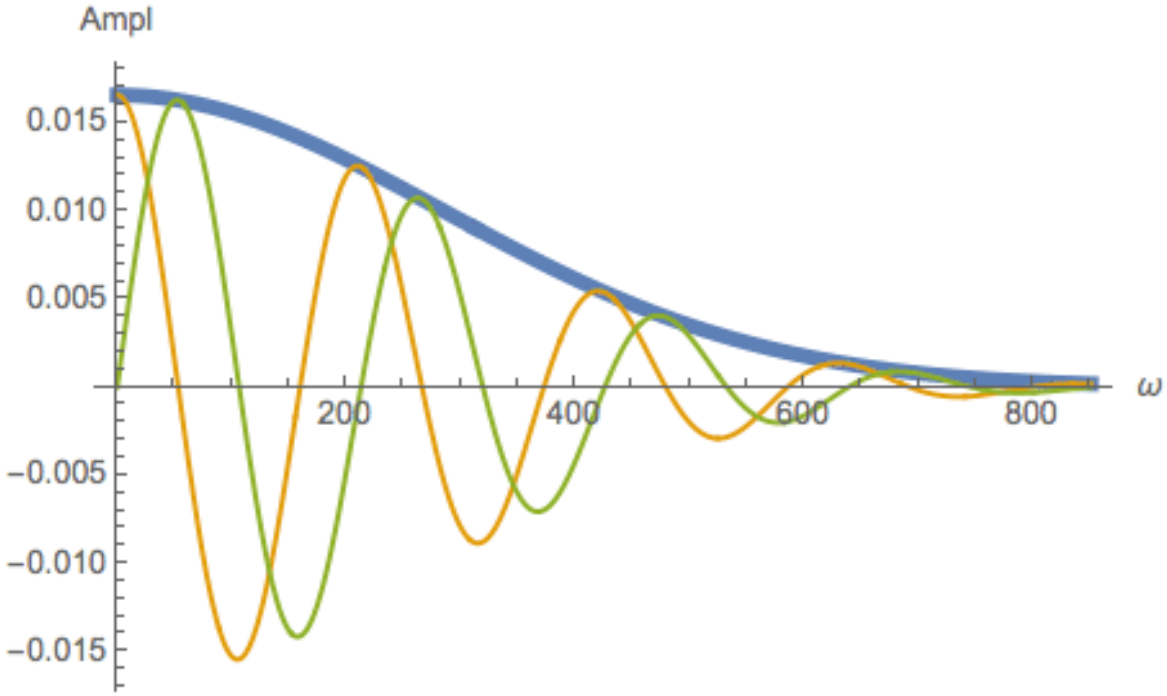
Consciousness and QM?



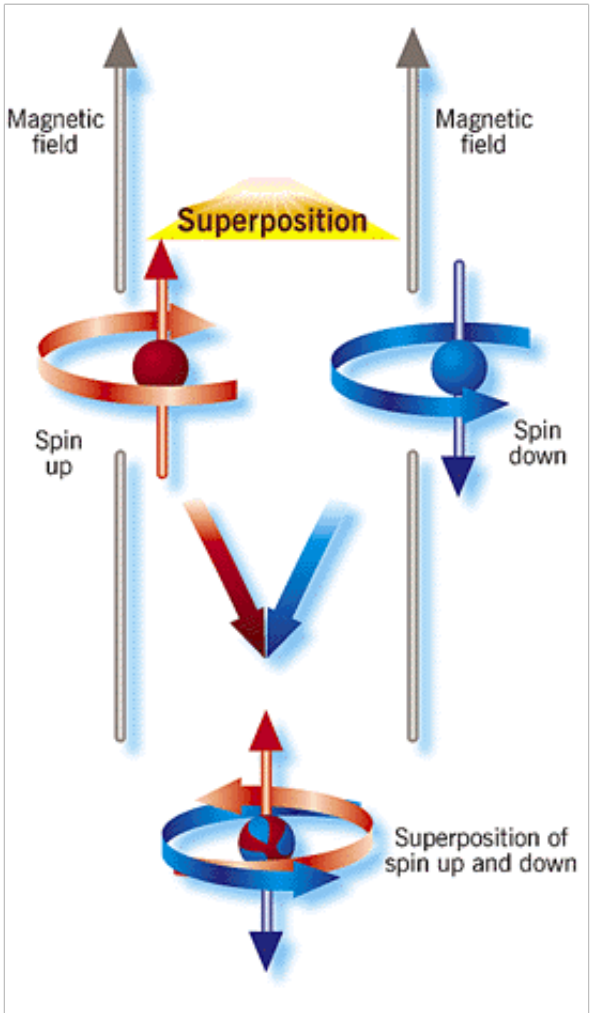
Even good scientists have silly ideas sometimes…

What the heck is a wave function anyway?

- If you can't actually observe the wave function itself, is it really a "real" thing?
  - Even the amplitude can only be "observed" with an ensemble of measurements, so is the amplitude even a "real" thing?



Superposition of States

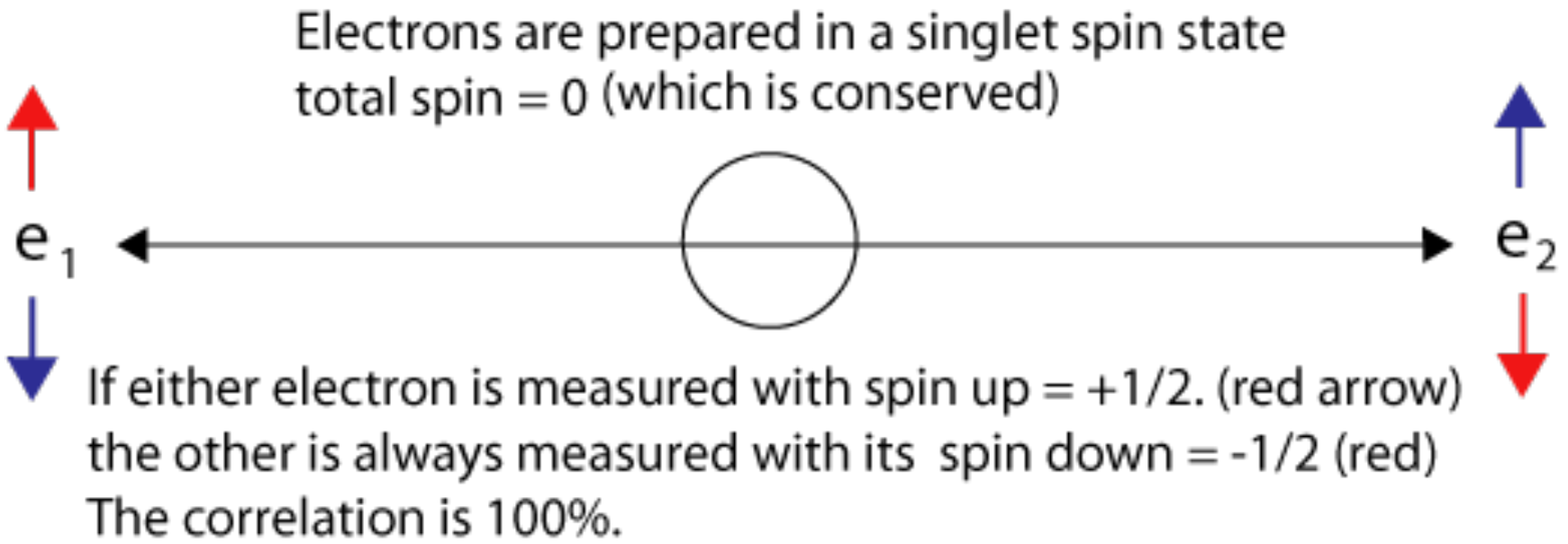


Superposition of two spin states

$$|\nearrow\rangle = a\,|\uparrow\rangle + b\,|\downarrow\rangle$$

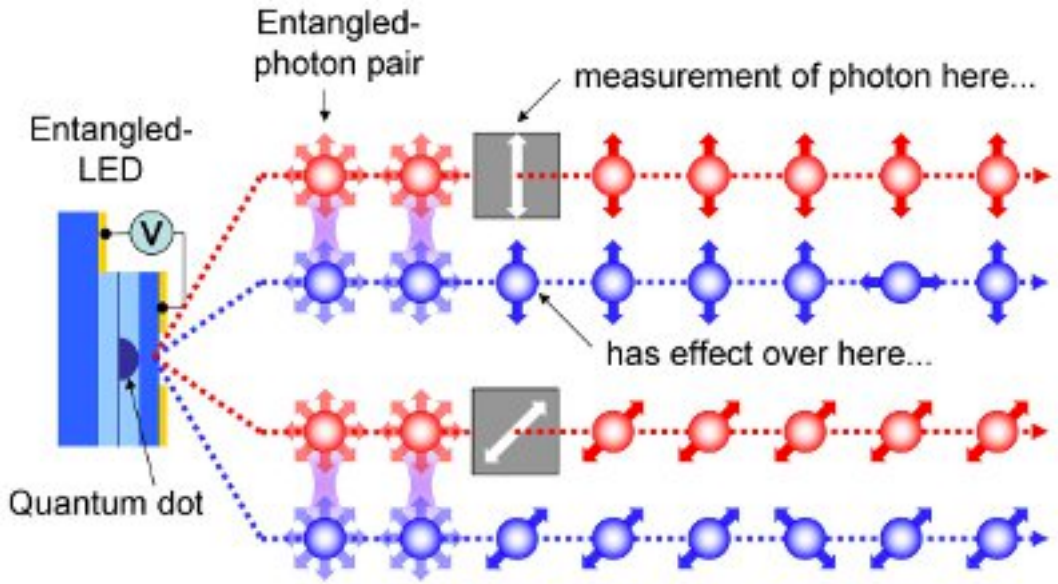
$$|a|^2 + |b|^2 = 1$$

Entangled States



Another ludicrous thing about QM

- Measurement in one location can affect particles in another – non-locality!
  - This appears to violate special relativity!



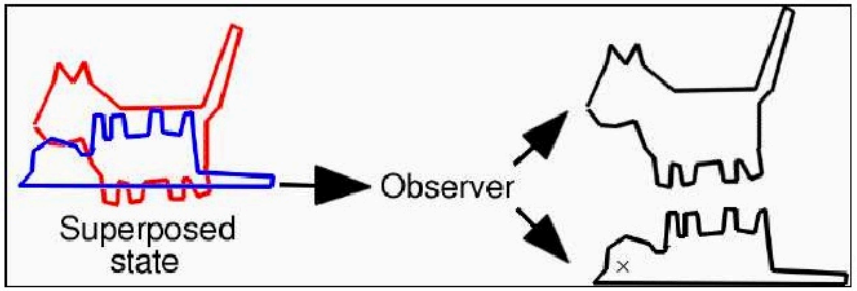
Interpretations of QM

Interpretation	Author(s)	Deterministic?	Wavefunction real?	Unique history?	Hidden variables?	Collapsing wavefunctions?	Observer role?	Local?	Counterfactual definiteness?
Ensemble interpretation	Max Born, 1926	Agnostic	No	Yes	Agnostic	No	None	No	No
Copenhagen interpretation	Niels Bohr, Werner Heisenberg, 1927	No	No[1]	Yes	No	Yes[2]	Causal	No	No
de Broglie–Bohm theory	Louis de Broglie, 1927, David Bohm, 1952	Yes	Yes[3]	Yes[4]	Yes	No	None	No	Yes
von Neumann interpretation	von Neumann, 1932, Wheeler, Wigner	No	Yes	Yes	No	Yes	Causal	No	No
Quantum logic	Garrett Birkhoff, 1936	Agnostic	Agnostic	Yes[5]	No	No	Interpretational[6]	Agnostic	No
Many-worlds interpretation	Hugh Everett, 1957	Yes	Yes	No	No	No	None	Yes	No
Popper's interpretation[42]	Karl Popper, 1957[43]	No	Yes	Yes	Yes	No	None	Yes	Yes[13]
Stochastic interpretation	Edward Nelson, 1966	No	No	Yes	No	No	None	No	No
Many-minds interpretation	H. Dieter Zeh, 1970	Yes	Yes	No	No	No	Interpretational[7]	Yes	No
Consistent histories	Robert B. Griffiths, 1984	Agnostic[8]	Agnostic[8]	No	No	No	Interpretational[6]	Yes	No
Objective collapse theories	Ghirardi–Rimini–Weber, 1986, Penrose interpretation, 1989	No	Yes	Yes	No	Yes	None	No	No
Transactional interpretation	John G. Cramer, 1986	No	Yes	Yes	No	Yes[9]	None	No	Yes[14]
Relational interpretation	Carlo Rovelli, 1994	No	No	Agnostic[10]	No	Yes[11]	Intrinsic[12]	Yes	No
Elementary Cycles	Donatello Dolce, 2009	Yes	Yes	Yes	No	Yes	Yes	No[15]	Yes

Copenhagen Interpretation

- Physical systems do not have definite properties prior to being measured, and QM can only predict probabilities that measurements will produce certain results.
- The act of measurement affects the system, causing the set of probabilities to reduce to only one possible value immediately after the measurement.

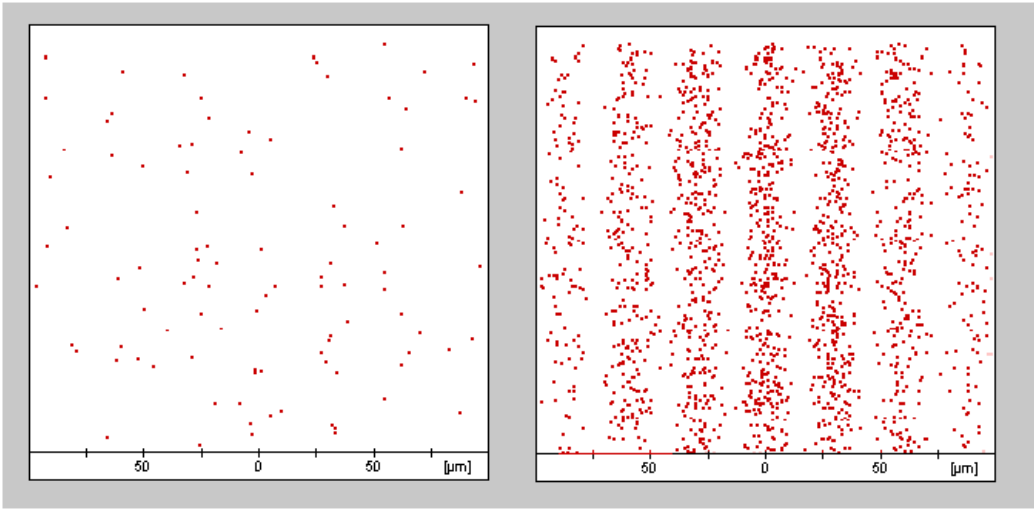
- Non-deterministic
- Non-local
- Causality somewhat sketchy
- Wavefunction not "real"



Quantum physics (in the Copenhagen interpretation) is non-deterministic and non-reversible!

Ensemble Interpretation

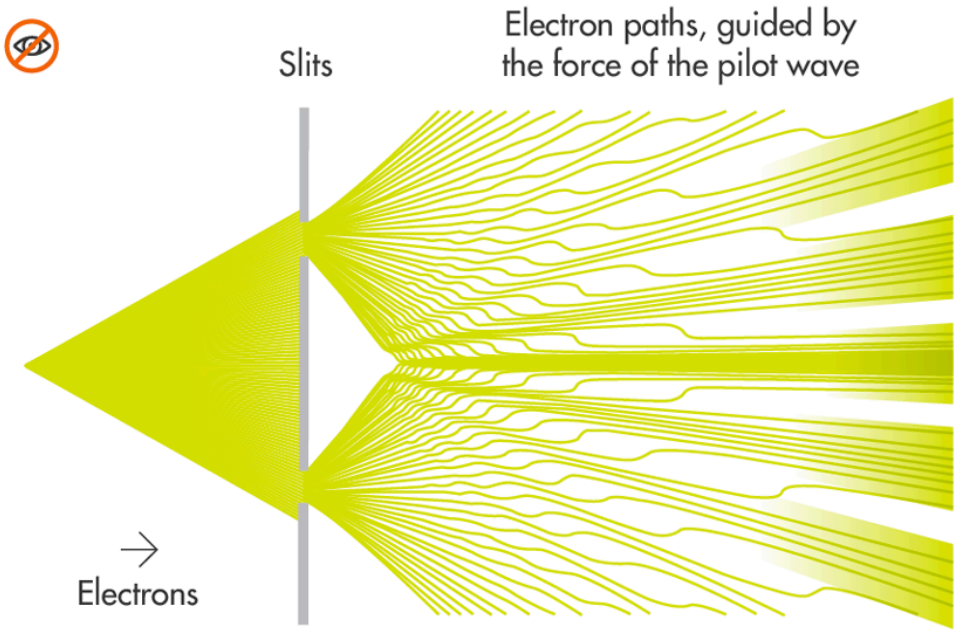
- The wave function is purely probabilistic and only has meaning for a large number of particles
  - Deterministic?
  - Non-local



  - Hard time dealing with single particles!

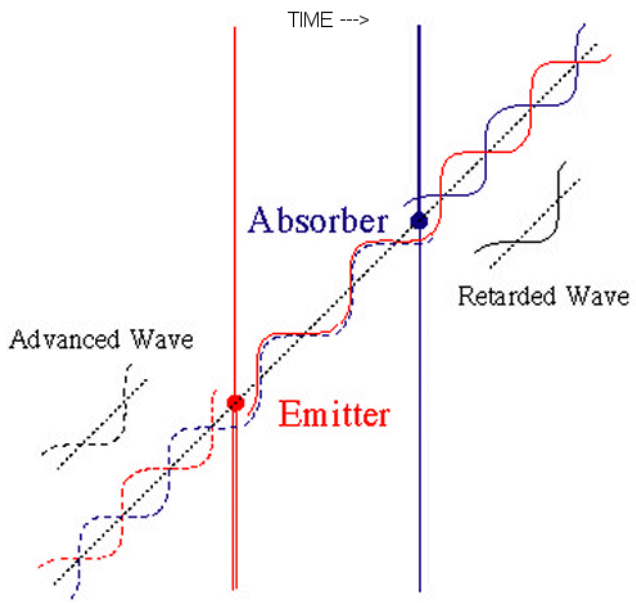
Pilot Wave (Hidden-Variable) Interpretation

- Every particle is a physical point object, but is accompanied by a "pilot wave" that guides its motion.
- Deterministic
- Non-local
- Wave function "real"



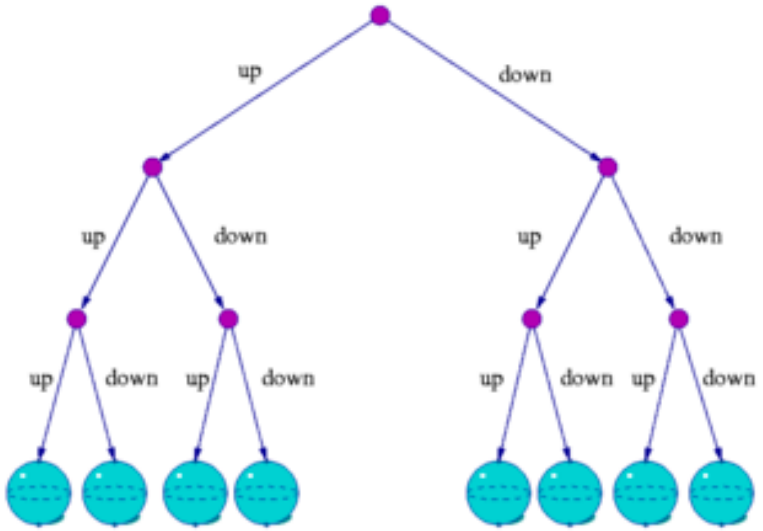
Transactional Interpretation

- Solutions to Schrödinger equation propagate both forward and backward in time, and exchange energy and momentum when interacting
  - Non-deterministic
  - Non-local
  - Non-causal
  - Wave function "real"



Many-Worlds Interpretation

- Every quantum outcome is realized – the universe splits at each branch point
- Deterministic and local!
- Wave function is "real"

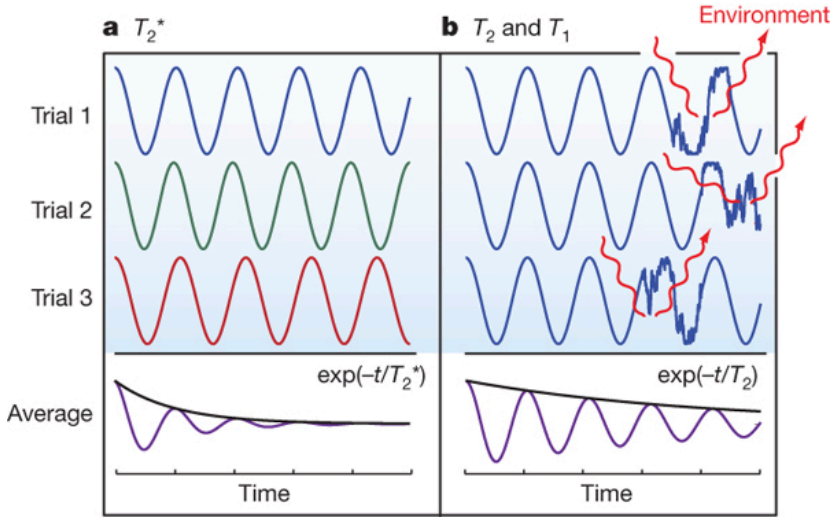


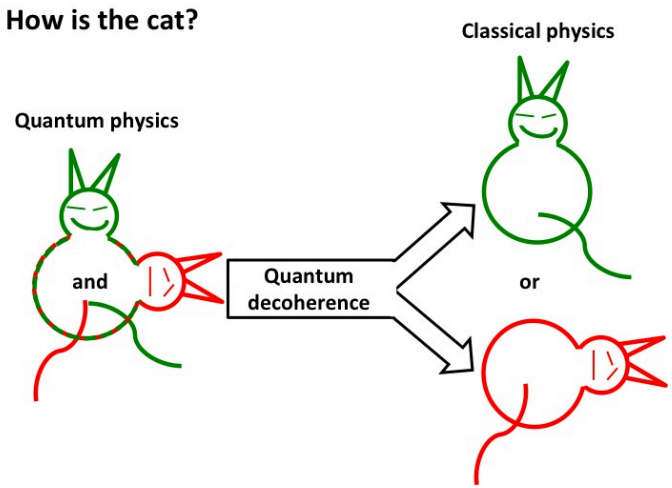
A widespread point of view

- It works – just calculate!

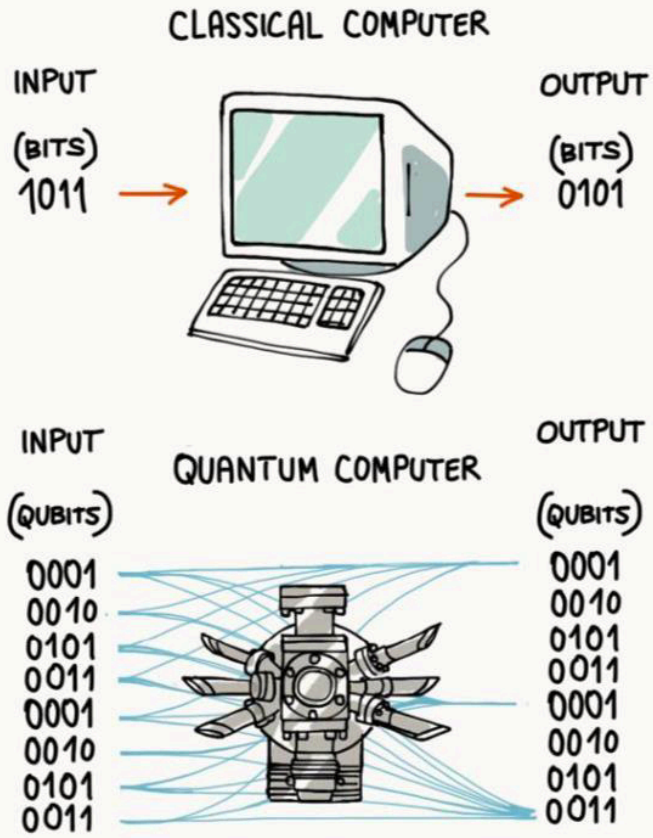
A modern view of wave function collapse

- Wave functions collapse through "decoherence"
  - The wave function of the object and the wave function of the external world (the "observer") become entangled





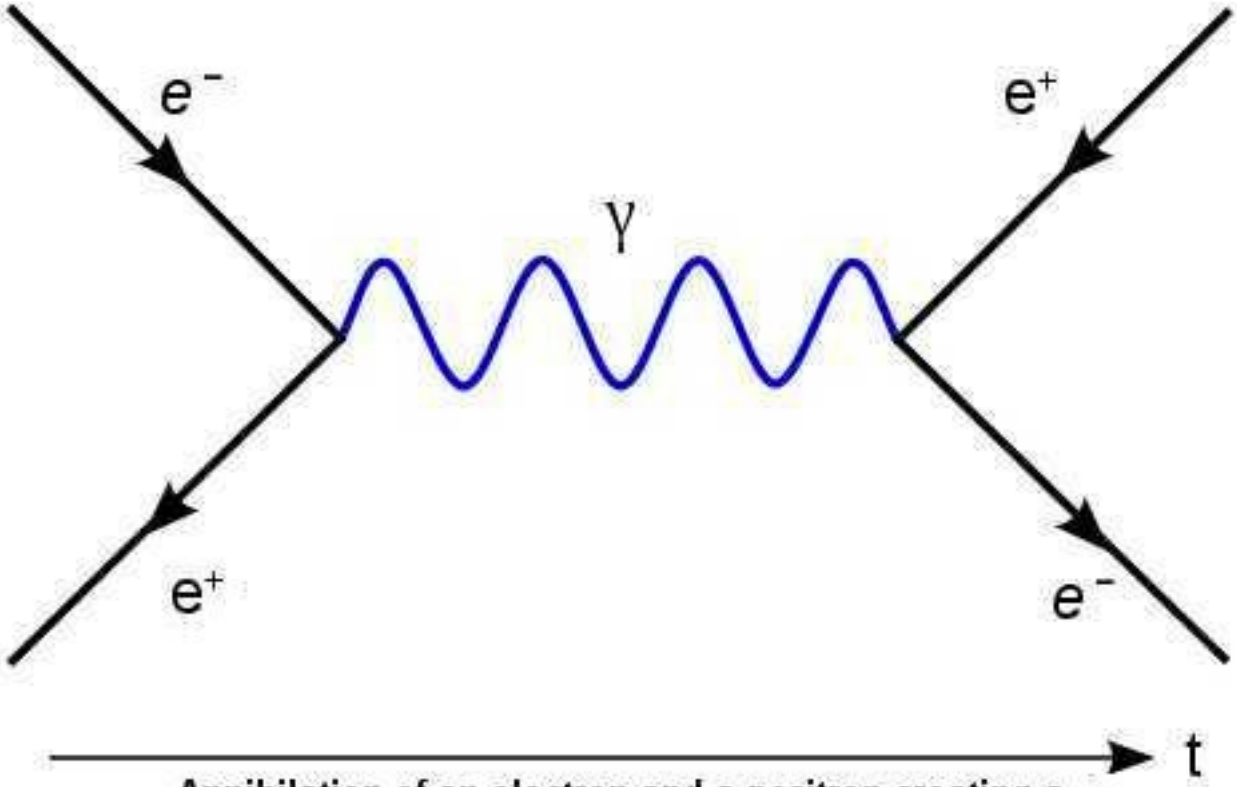
Quantum Computing?



- A QUANTUM SYSTEM REPLACES CLASSICAL BITS WITH QUANTUM QUBITS
- QUBITS FOLLOW THE SUPERPOSITION PRINCIPLE AND CAN EXIST AS "0" AND "1" AT THE SAME TIME
- USING QUBITS INSTEAD OF BITS, WITH A SINGLE IMPUT ONE COULD PROCESS ALL THE POSSIBLE COMBINATIONS OF "0" AND "1"'S IN A STRING AT THE SAME TIME
- QUANTUM ALGORITMS USING THIS ABILITY COULD SOLVE CERTAIN TYPES OF PROBLEMS MUCH, MUCH FASTER THAN ANY CLASSICAL COMPUTER

QM and Special Relativity

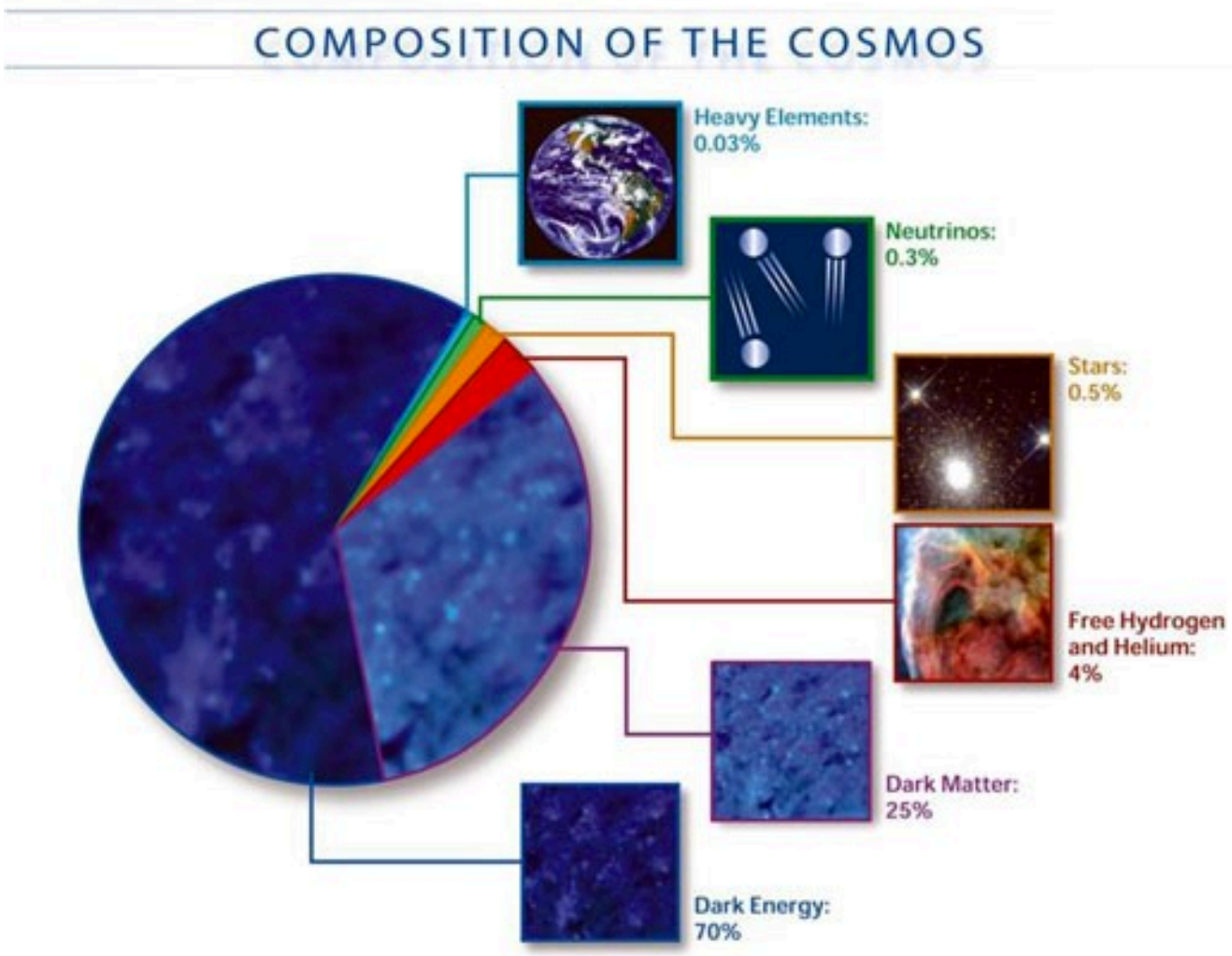
QED = Quantum ElectroDynamics



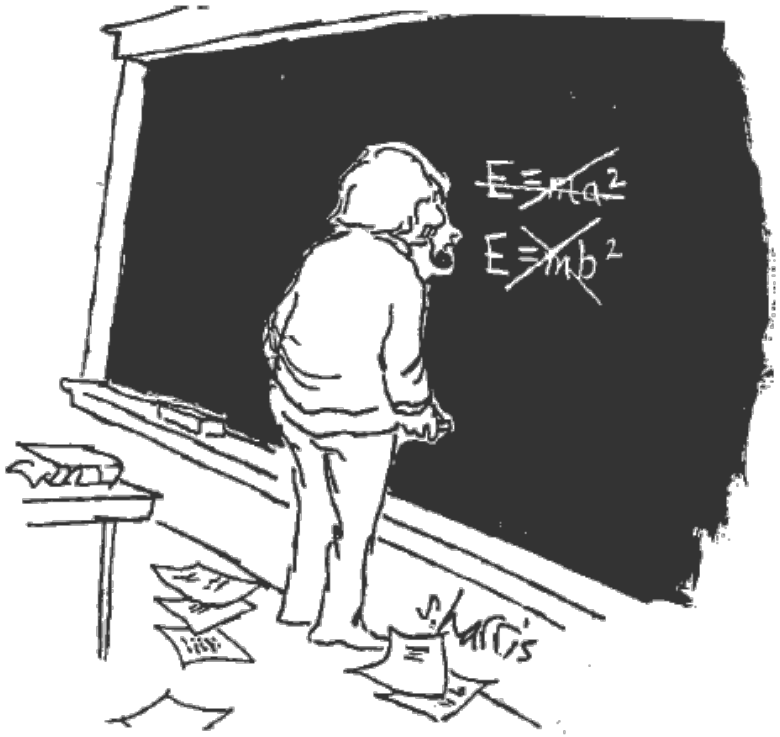
Annihilation of an electron and a positron creating a photon which decays into a new electron positron pair

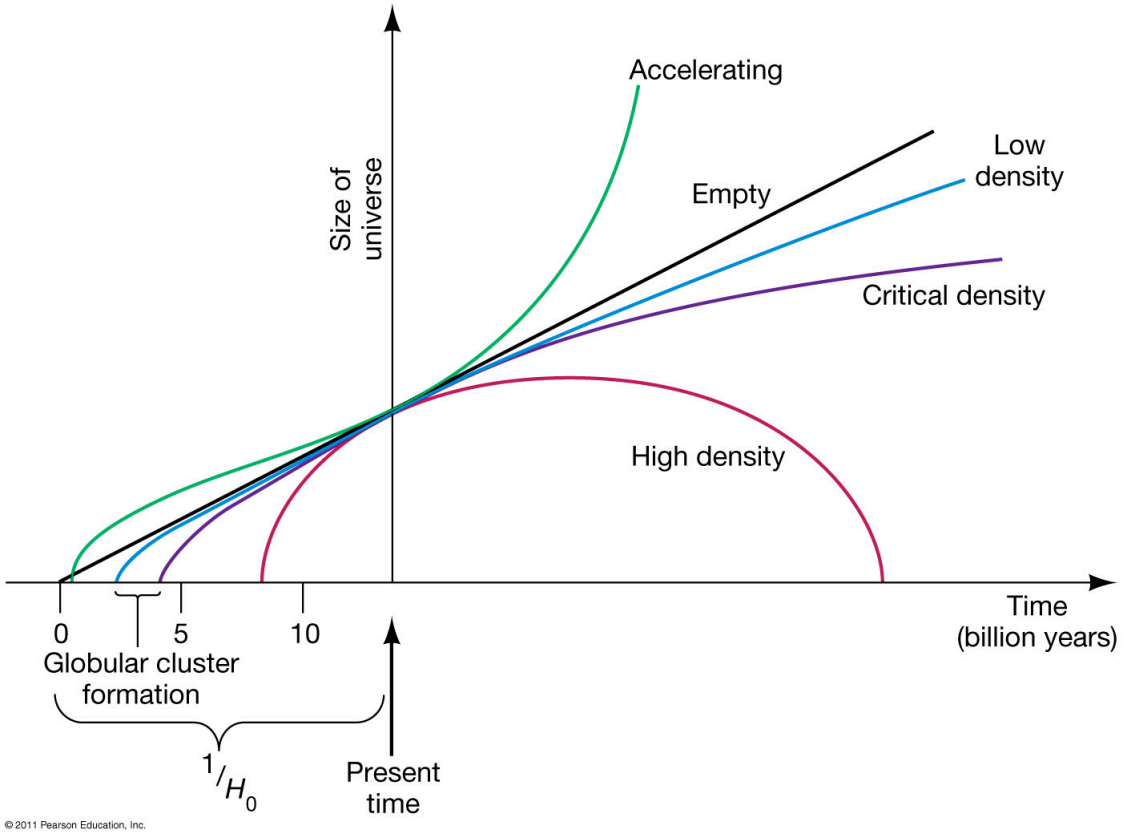
QM and General Relativity = Quantum Gravity

What is the Universe?

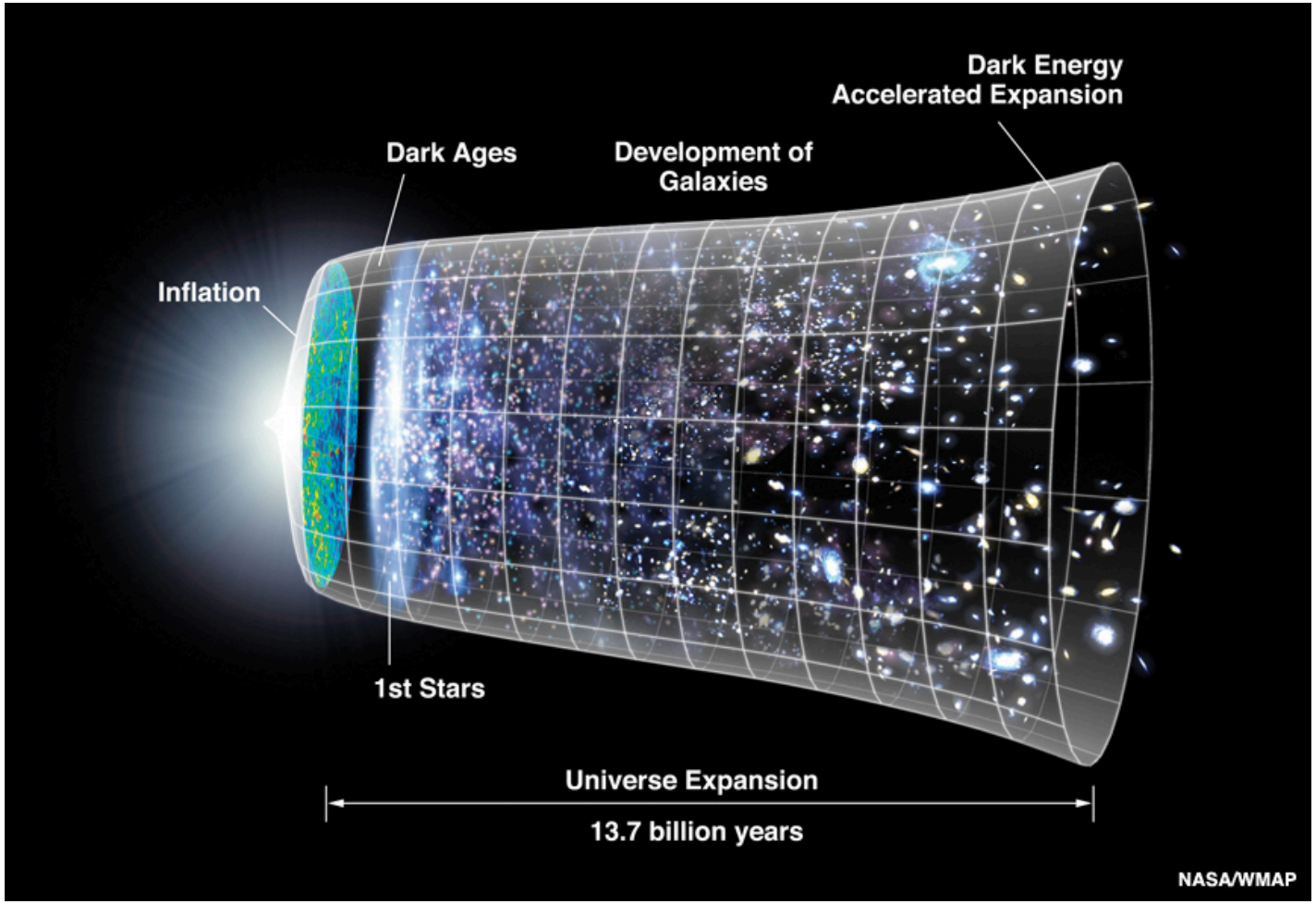


Dark Energy


E=mc²
E=mb²


Accelerating
Low density
Empty
Critical density
High density
Size of universe
Time (billion years)
0
5
10
Globular cluster formation
1/H0
Present time
© 2011 Pearson Education, Inc.

Cosmic Evolution



We have no idea!