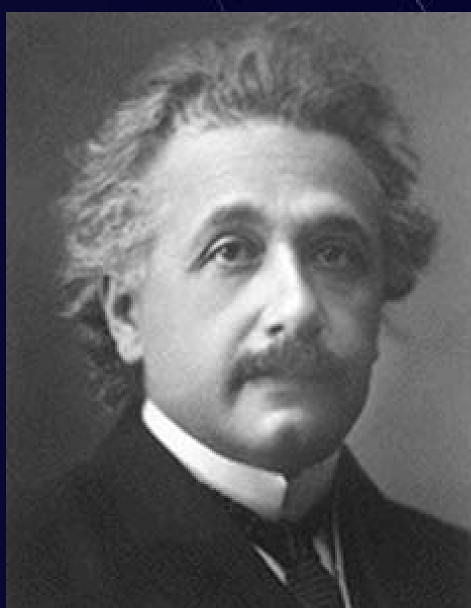
Einstein's Universe

UNIVERSITY of GLASGOW

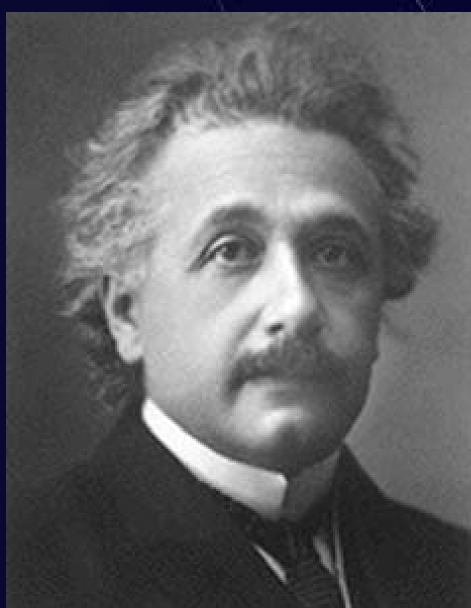


Dr Martin Hendry

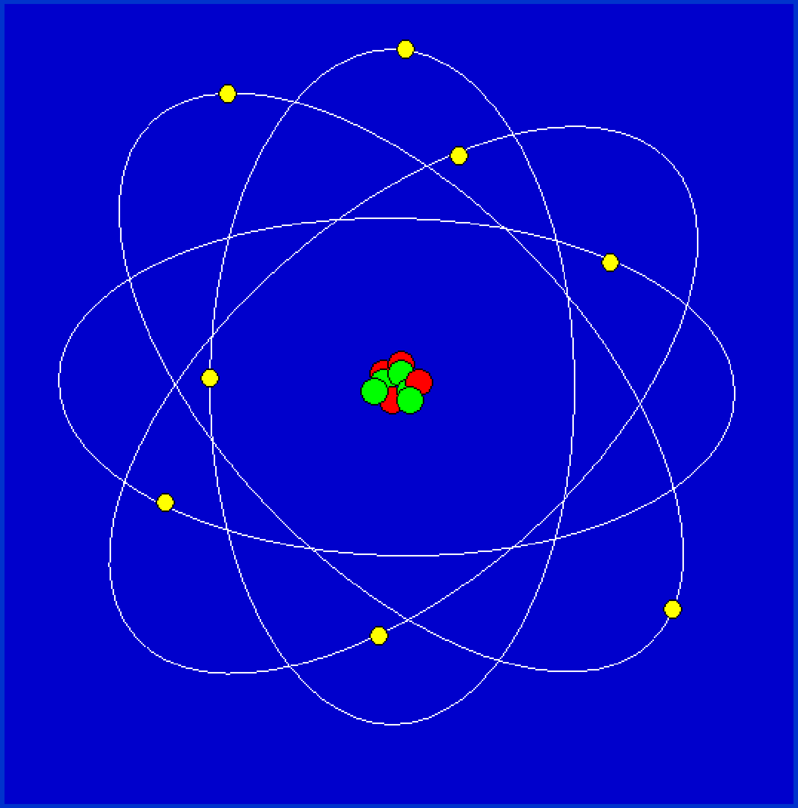
Dept of Physics and Astronomy
University of Glasgow, UK

Light in Lumps or Ripples?

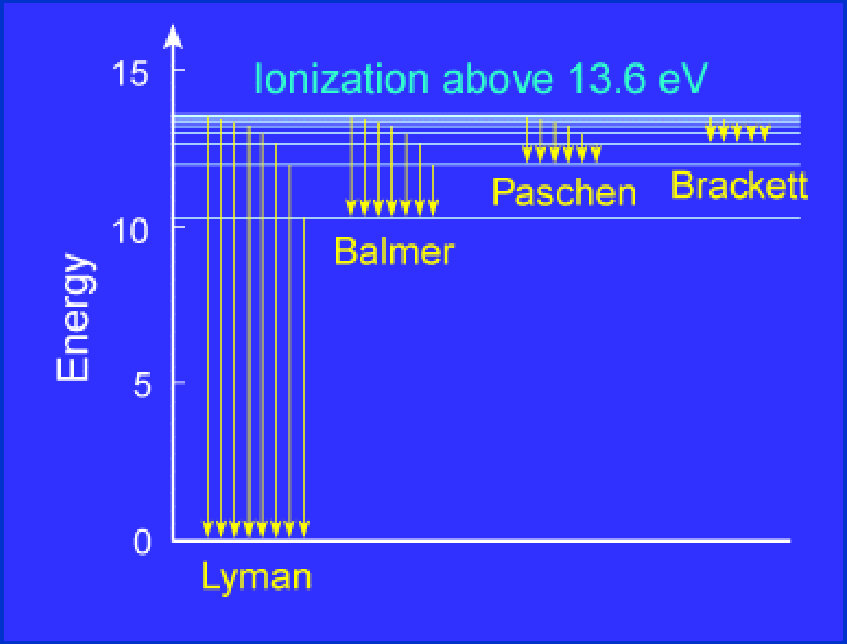
UNIVERSITY *of* GLASGOW

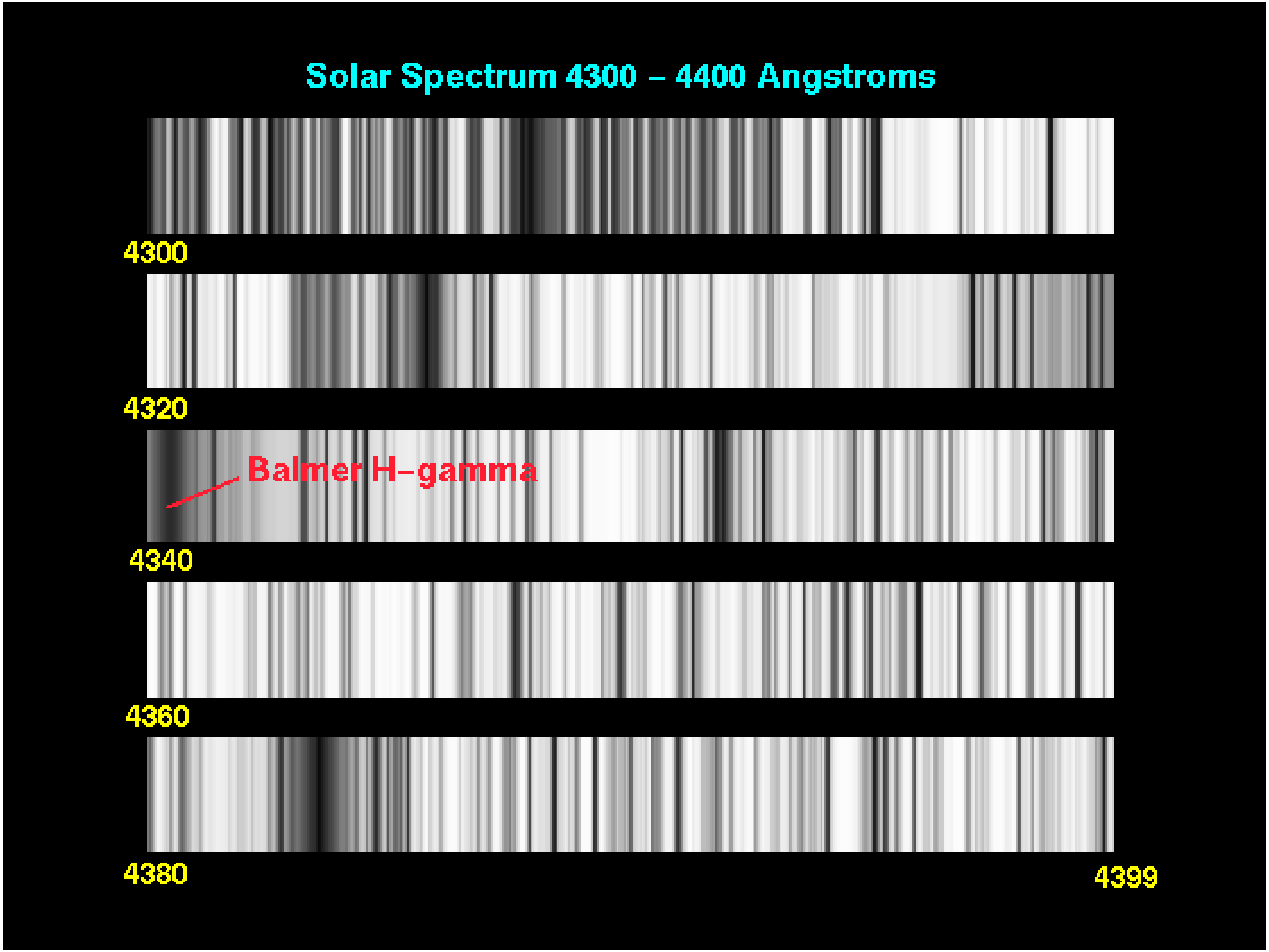


Einstein and the Quantum Revolution



The Bohr atom, 1913

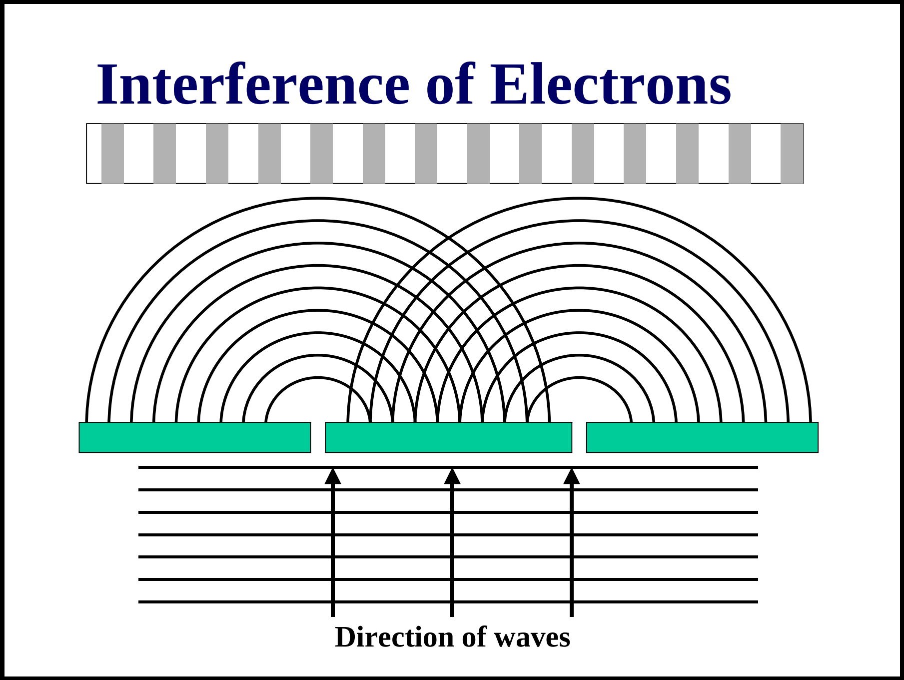



Solar Spectrum 4300 – 4400 Angstroms
4300
4320
Balmer H–gamma
4340
4360
4380
4399

Louis de Broglie, 1923

If light waves also behave like particles, why shouldn't electrons also behave like waves?

Pilot Waves



Davisson & Germer;
Thomson & Reid, 1937

Making Quantum Mechanics Work

Werner Heisenberg

Erwin Schrödinger

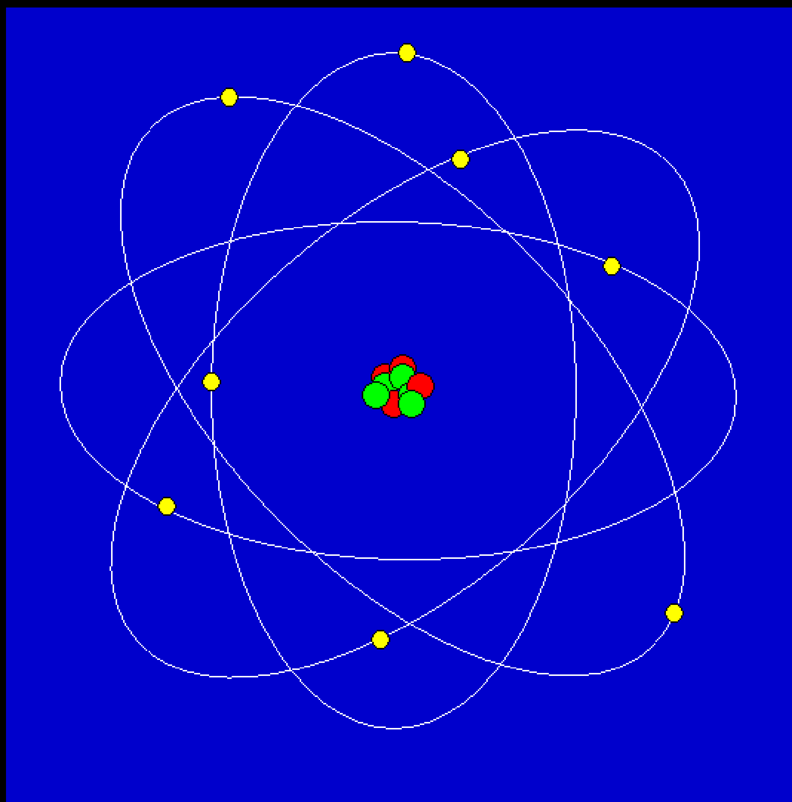
Max Born

Neils Bohr

Paul Dirac

Wolfgang Pauli

John von Neumann



All physical systems and events are inherently probabilistic, expressed by the **Wave Function**

when the quantum system is observed, the wave function **collapses**

Copenhagen Interpretation

All physical systems and events are inherently probabilistic, expressed by the **Wave Function**

Only

when the quantum system is observed, the wave function **collapses**

Copenhagen Interpretation

Heisenberg Uncertainty Principle

The precision of measurements in a quantum system is limited ***in principle***

Heisenberg Uncertainty Principle

The precision of measurements in a quantum system is limited ***in principle***

$$\Delta p \Delta x \sim \hbar$$

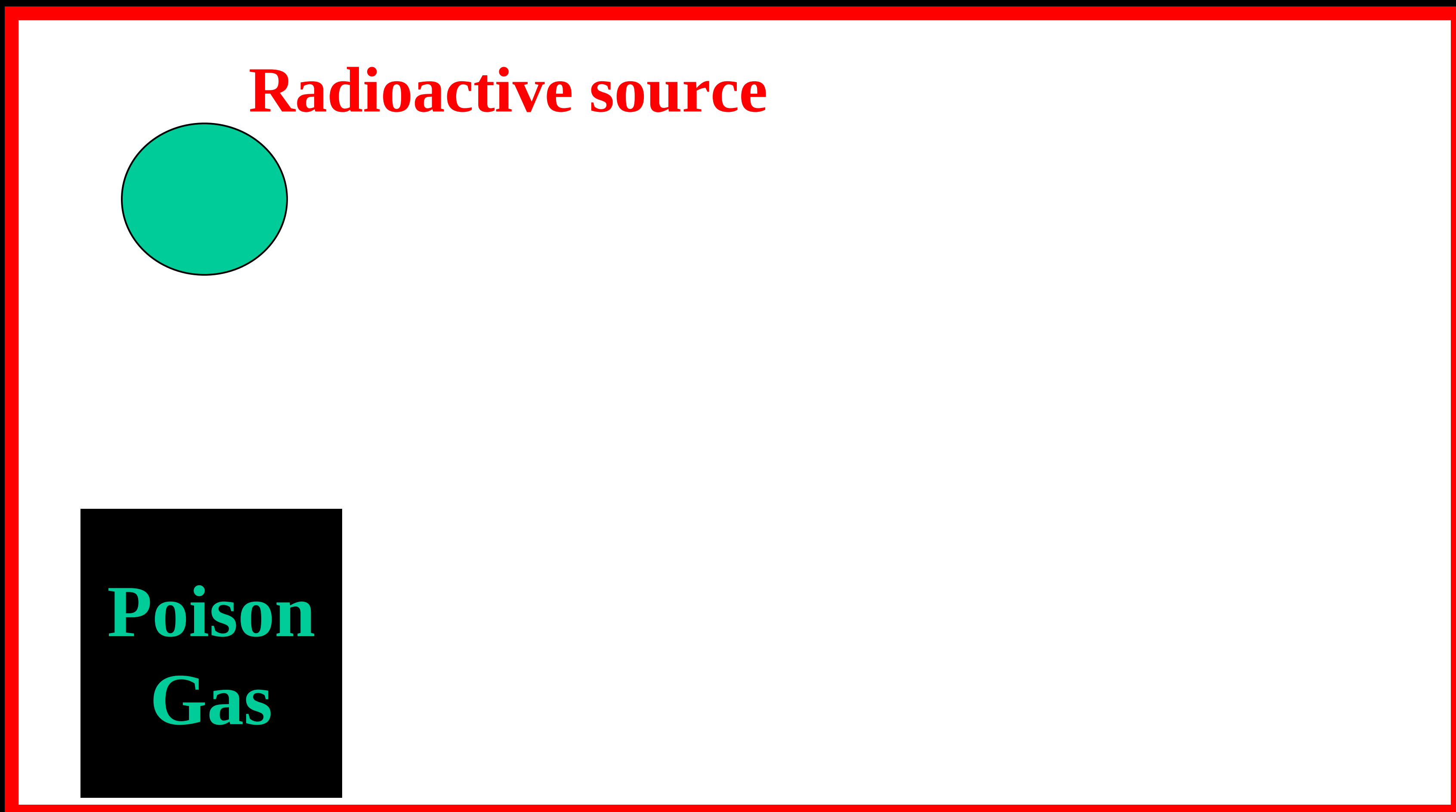
<u>*Heisenberg Uncertainty Principle*</u>

The precision of measurements in a quantum system is limited ***in principle***

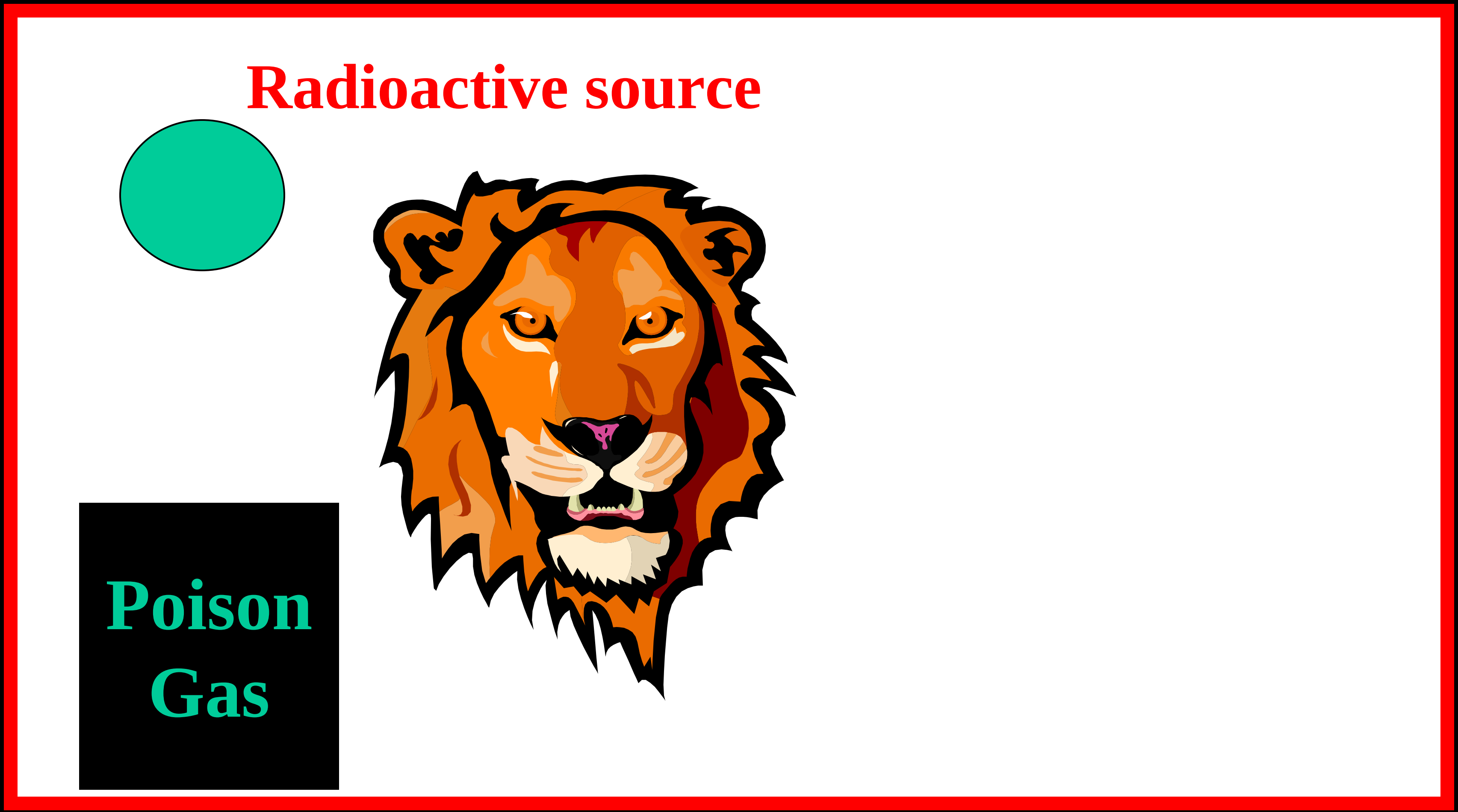
$$\Delta p \Delta x \sim \hbar$$

Position and momentum are *complementary* properties: the action of measurement determines which of the two properties the quantum system possesses

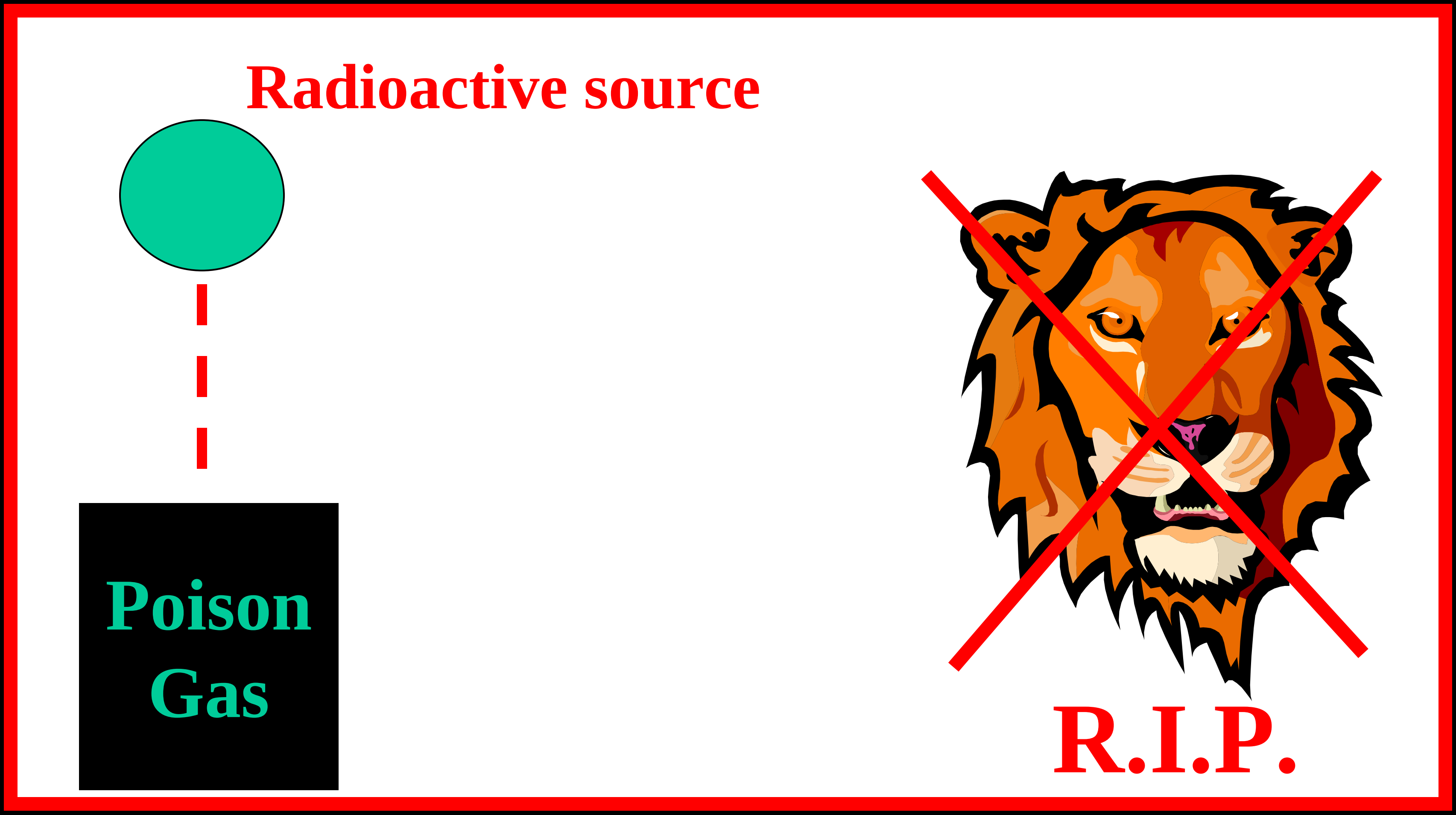
Schrödinger’s Cat



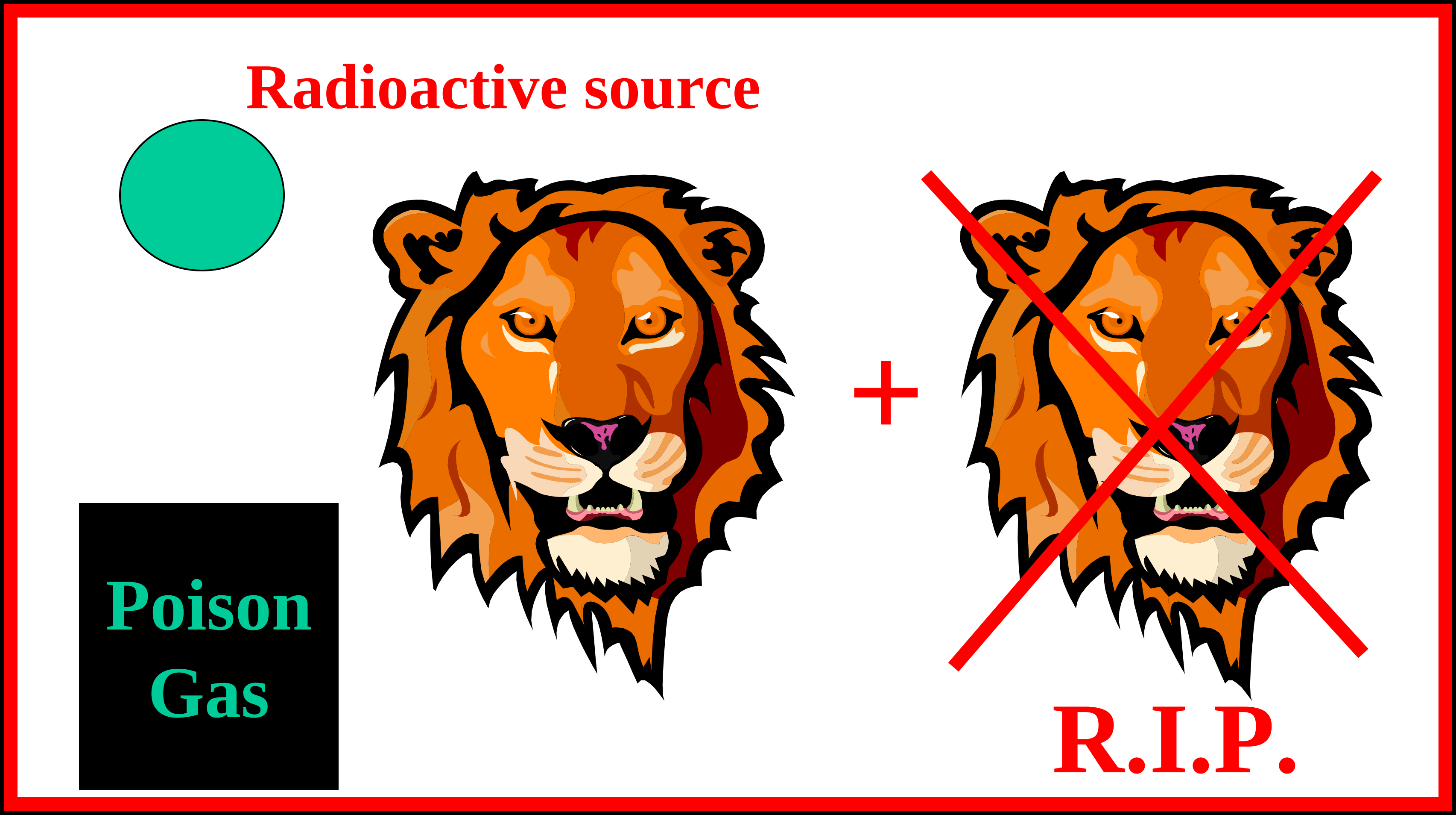
Schrödinger’s Cat



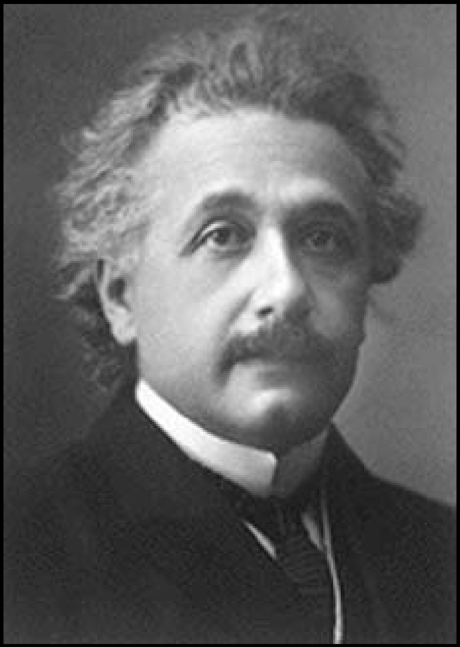
Schrödinger's Cat



Schrödinger’s Cat

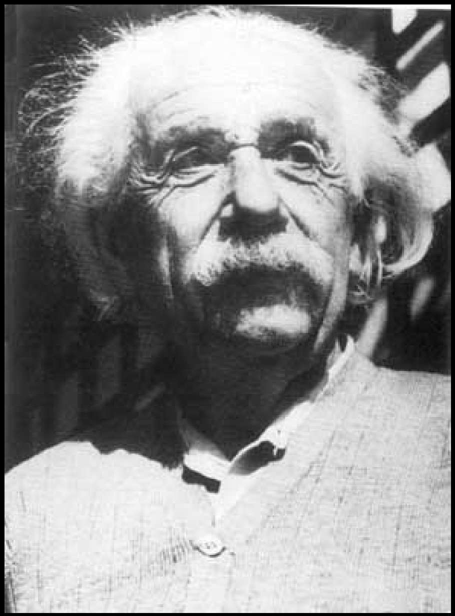


versus



Complementarity asserts that it is not just meaningless to talk about knowing simultaneously exact values of position and momentum; these quantities simply do not exist simultaneously.

versus

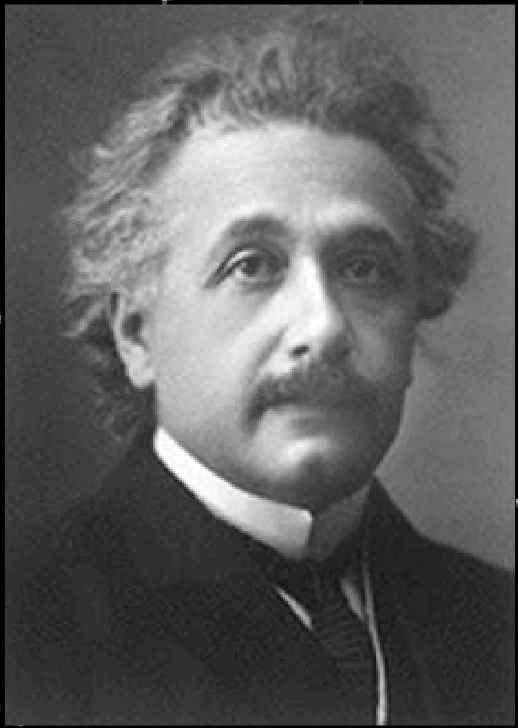


Complementarity asserts that it is not just meaningless to talk about knowing simultaneously exact values of position and momentum; these quantities simply do not exist simultaneously.

You believe in the God who plays dice, and I in complete law and order in a world which objectively exists

How are the outcomes chosen?

"God does not play dice"



Thought experiment, proposed by Einstein, Podolsky & Rosen (1935)

"Can quantum-mechanical description of physical reality be considered complete?"

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1.

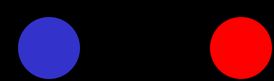
ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement. It is the second question that we wish to consider here, as applied to quantum mechanics.

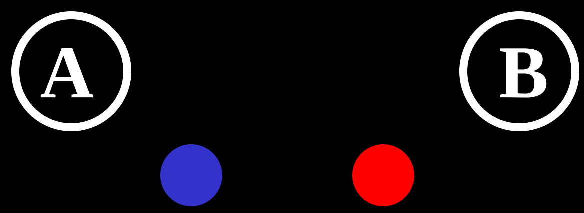
Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory*. We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of the physical reality.

The elements of the physical reality cannot be determined by *a priori* philosophical considerations, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.* It seems to us that this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one

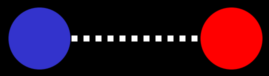
The Einstein Podolsky Rosen ‘Paradox’



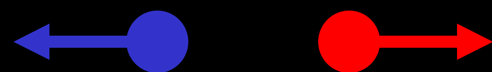
The Einstein Podolsky Rosen ‘Paradox’



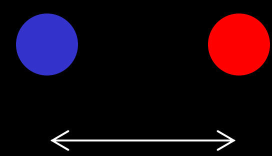
The Einstein Podolsky Rosen ‘Paradox’



The Einstein Podolsky Rosen ‘Paradox’

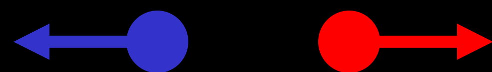


The Einstein Podolsky Rosen ‘Paradox’

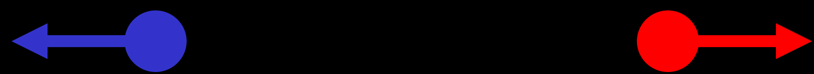


Can, in principle, measure precisely separation and **total** momentum before they fly apart

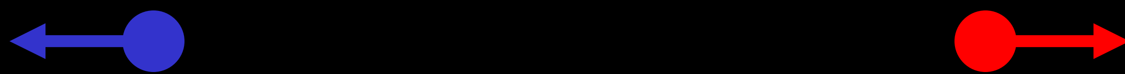
The Einstein Podolsky Rosen ‘Paradox’



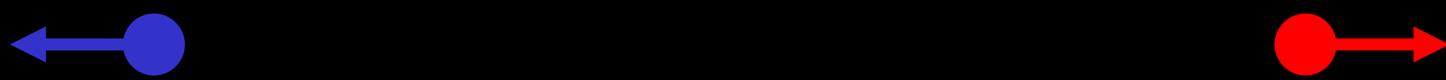
The Einstein Podolsky Rosen ‘Paradox’



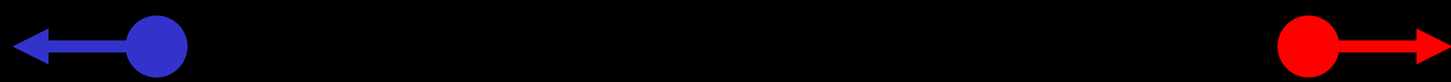
The Einstein Podolsky Rosen ‘Paradox’



The Einstein Podolsky Rosen ‘Paradox’

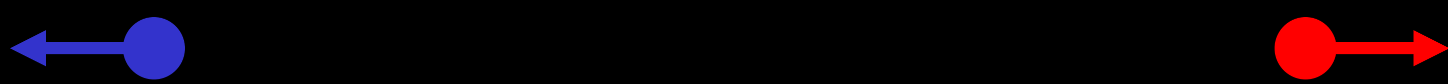


The Einstein Podolsky Rosen ‘Paradox’



Decide to measure
precisely the
momentum of A

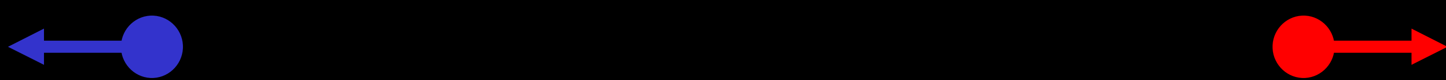
The Einstein Podolsky Rosen 'Paradox'



Decide to measure
precisely the
momentum of **A**

A assumes wave properties

The Einstein Podolsky Rosen ‘Paradox’



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A assumes wave properties

According to the Copenhagen Interpretation, B instantaneously assumes wave properties

The Einstein Podolsky Rosen ‘Paradox’

EPR regarded this prediction as unreasonable, as it violated causality.

The Einstein Podolsky Rosen 'Paradox'

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"[It] makes the reality of position and momentum in the second system depend upon the measurement carried out in the first system, which does not disturb the second system in any way. *No reasonable definition of reality could be expected to permit this.*"

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But this is exactly what **does** happen, in experiments carried out since the 1970s

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But this is exactly what **does** happen, in experiments carried out since the 1970s

Alain Aspect (1982) provided the final "proof"

III.5 ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

JOHN S. BELL†

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly non-local structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.

II. Formulation

With the example advocated by Bohm and Aharonov [6], the EPR argument is the following. Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins $\vec{\sigma}_1$ and $\vec{\sigma}_2$. If measurement of the component $\vec{\sigma}_1 \cdot \vec{a}$, where $\vec{a}$ is some unit vector, yields the value $+1$ then, according to quantum mechanics, measurement of $\vec{\sigma}_2 \cdot \vec{a}$ must yield the value -1 and vice versa. Now we make the hypothesis [2], and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other. Since we can predict in advance the result of measuring any chosen component of $\vec{\sigma}_2$, by previously measuring the same component of $\vec{\sigma}_1$, it follows that the result of any such measurement must actually be predetermined. Since the initial quantum mechanical wave function does *not* determine the result of an individual measurement, this predetermination implies the possibility of a more complete specification of the state.

Let this more complete specification be effected by means of parameters λ. It is a matter of indifference in the following whether λ denotes a single variable or a set, or even a set of functions, and whether the variables are discrete or continuous. However, we write as if λ were a single continuous parameter. The result A of measuring $\vec{\sigma}_1 \cdot \vec{a}$ is then determined by $\vec{a}$ and λ, and the result B of measuring $\vec{\sigma}_2 \cdot \vec{b}$ in the same instance is determined by $\vec{b}$ and λ, and

*Work supported in part by the U.S. Atomic Energy Commission

†On leave of absence from SLAC and CERN

Originally published in *Physics, 1*, 195-200 (1964).

Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,[a] and Gérard Roger
Institut d'Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

PACS numbers: 03.65.Bz, 35.80.+s

Bell's inequalities apply to any correlated measurement on two correlated systems. For instance, in the optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*,[1] a source emits pairs of photons (Fig. 1). Measurements of the correlations of linear polarizations are performed on two photons belonging to the same pair. For pairs emitted in suitable states, the correlations are strong. To account for these correlations, Bell[2] considered theories which invoke common properties of both members of the

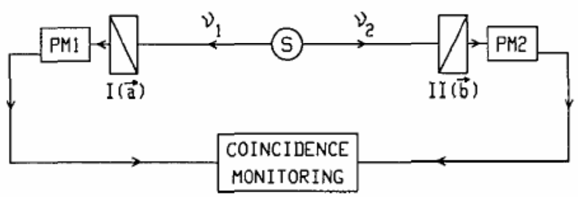
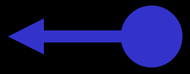
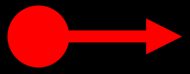


FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

The Einstein Podolsky Rosen ‘Paradox’





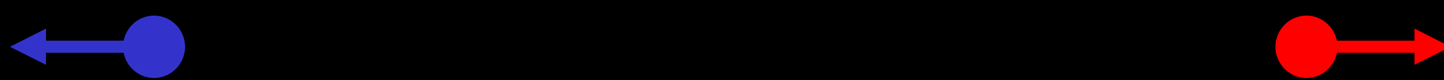
Decide to measure precisely the momentum of A

A assumes wave properties

According to the Copenhagen Interpretation, B instantaneously assumes wave properties

The Einstein Podolsky Rosen ‘Paradox’

Could the existence of the wave-measuring apparatus at **A** *influence the wave function of the whole system, so that* **B** *somehow ‘knows’ before they separate that it is going to ‘be’ a wave?…..*



Decide to measure precisely the momentum of **A**

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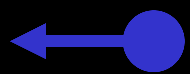
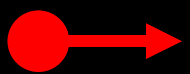
The Einstein Podolsky Rosen 'Paradox'

In Aspect's experiment, the decision to measure either the wave or particle properties of **A** *is taken only* **after** *they have separated (and so are causally disconnected in classical theories).*





Decide to measure precisely the momentum of **A**

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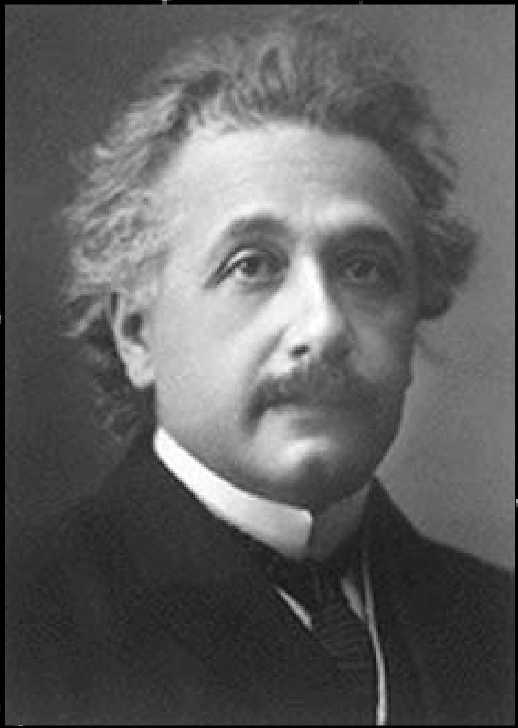
How are the outcomes chosen?

"God does not play dice"



EPR experiment proves conclusively that he does!

Light is *both* lumps and ripples – but not at the same time!

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Which aspect is ‘real’ is determined (only) when light interacts with matter

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(Could quantum reality depend on the intervention of a conscious observer?...)

Light is *both* lumps and ripples –
but not at the same time!

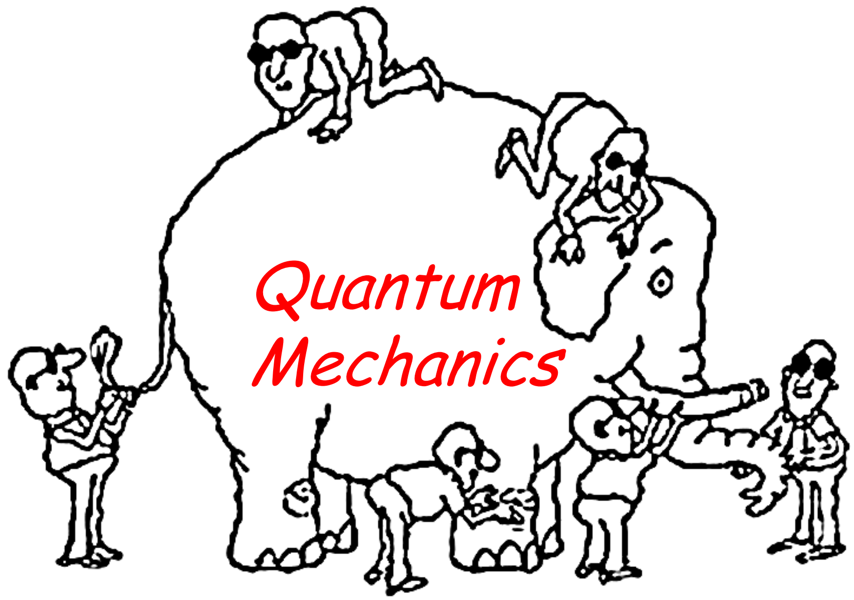
Which aspect is ‘real’ is determined (only) when light interacts with matter

(Could quantum reality depend on the intervention of a conscious observer?...)

Quantum states are ‘entangled’: they can influence each other instantaneously, even when separated by great distances

"Those who are not shocked when they first come across quantum theory cannot possibly have understood it"

The Blind Men and the Quantum: Adding Vision to the Quantum World



John G. Cramer

Dept. of Physics, Univ. of Washington

Seattle, Washington, 98195

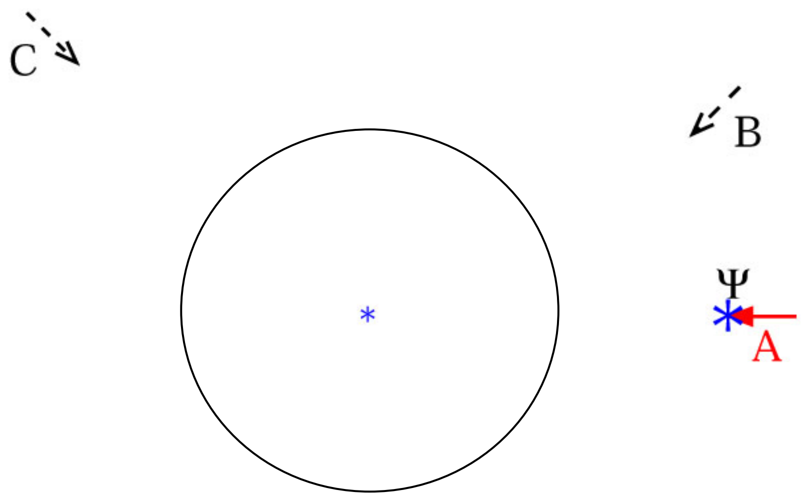
1st Hal Clement Memorial Lecture

Boskone 41, Boston, MA, February 15, 2004

Three Quantum Paradoxes

Paradox 1 (non-locality): Einstein's Bubble

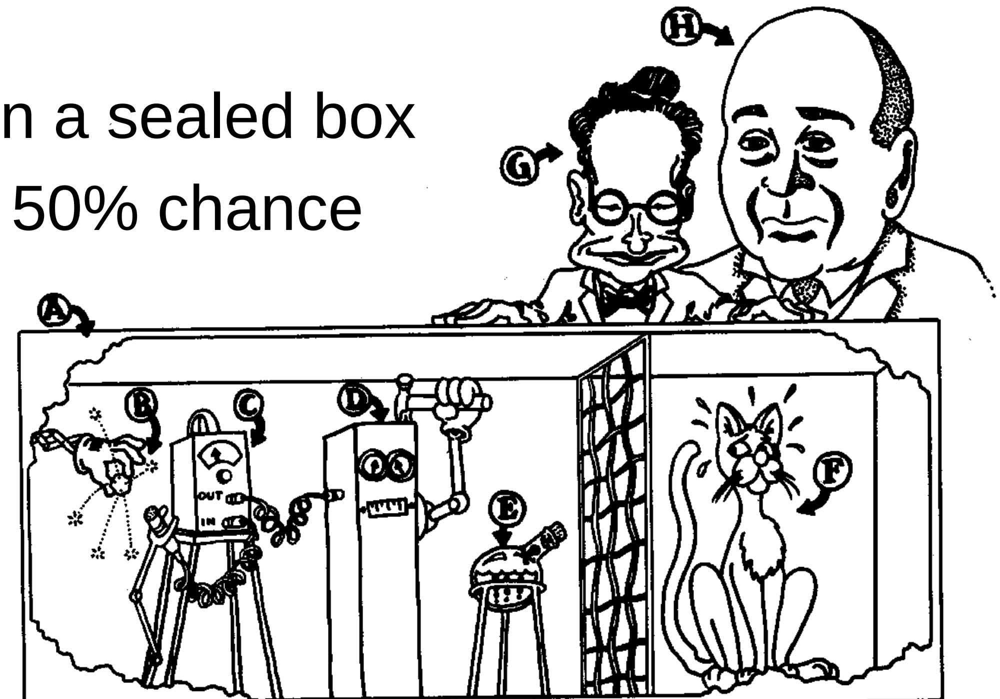
Situation: A photon is emitted from an isotropic source. Its spherical wave function Ψ expands like an inflating bubble. It reaches a detector, and the Ψ bubble "pops" and disappears.



Question (Albert Einstein):

If a photon is detected at Detector A, how does the photon's wave function Ψ at the location of Detectors B & C *know* that it should vanish?

Paradox 2 (Ψ collapse): Schrödinger's Cat



(William R. Warren, Jr., © 1985, reproduced with permission.)

Experiment: A cat is placed in a sealed box containing a device that has a 50% chance of killing the cat.

Question: What is the wave function of the cat just before the box is opened?

$$\left(\Psi = \tfrac{1}{\sqrt{2}}\text{dead} + \tfrac{1}{\sqrt{2}}\text{alive ?}\right)$$

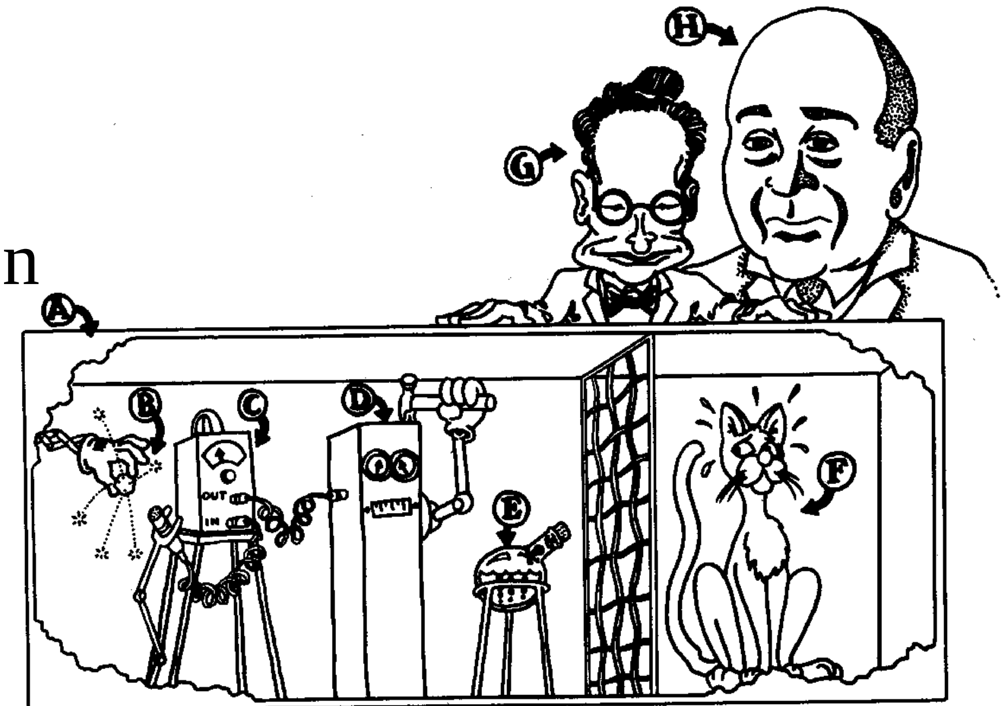
When does the wave function collapse?....

Paradox 2 (Ψ collapse): Schrödinger's Cat

The question is, ***when*** and ***how*** does the wave function collapse.

•What event collapses it?

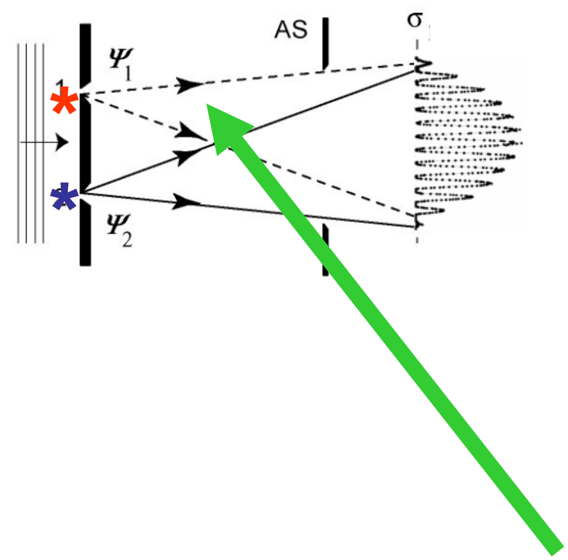
•How does the collapse spread to remote locations?



(William R. Warren, Jr., © 1985, reproduced with permission.)

Paradox 3 (wave vs. particle): Wheeler's Delayed Choice

A source emits one photon.
Its wave function passes through slits 1 and 2, making interference beyond the slits.
The observer can choose to either:



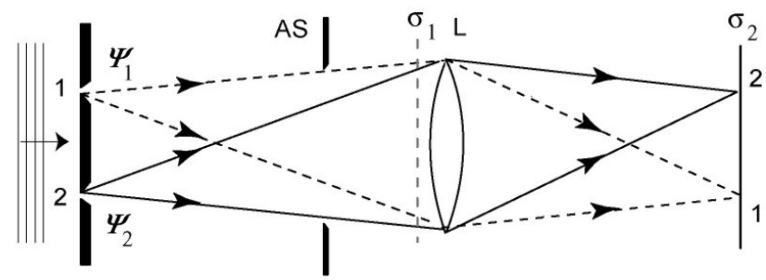
(a) measure the interference pattern at plane σ_1, requiring that the photon travels ***through both slits***.

or

(b) measure at plane σ_2 which slit image it appears in, indicating that it has passed ***only through slit 2***.

The observer waits until after the photon has passed the slits to decide which measurement to do.

Paradox 3 (wave vs. particle): Wheeler's Delayed Choice

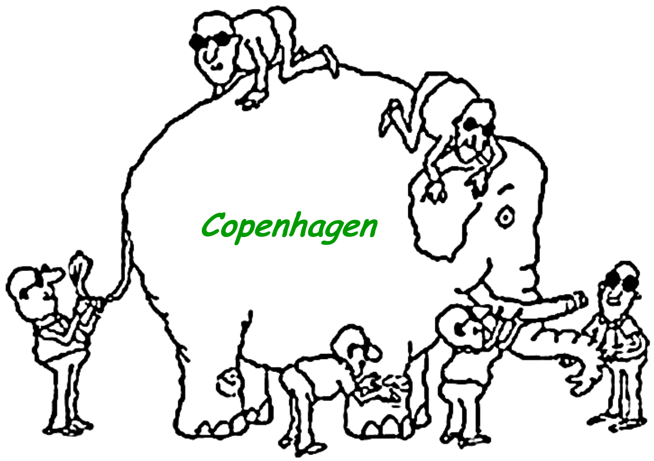


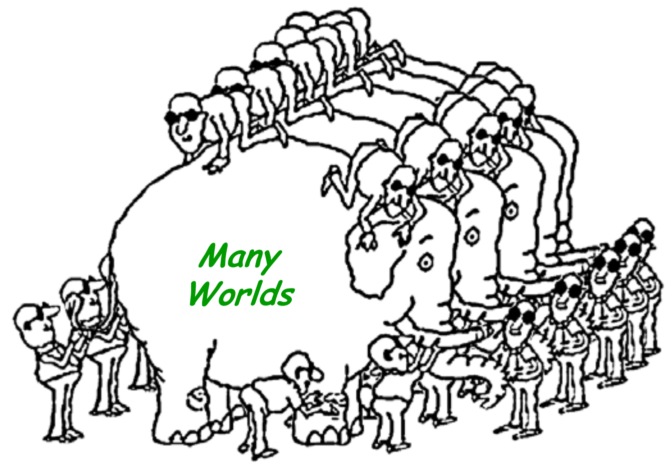
Thus, the photon does not decide if it is a particle or a wave until ***after*** it passes the slits, even though a particle must pass through only one slit and a wave must pass through both slits.

Apparently the measurement choice determines whether the photon is a particle or a wave ***retroactively***!

Three Interpretations of Quantum Mechanics

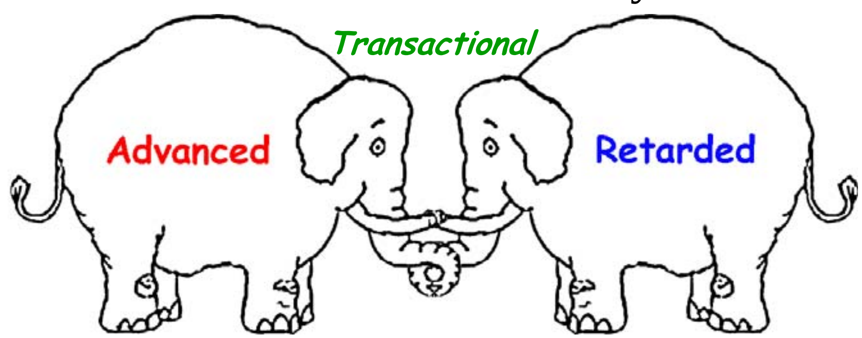
Summary of QM Interpretations



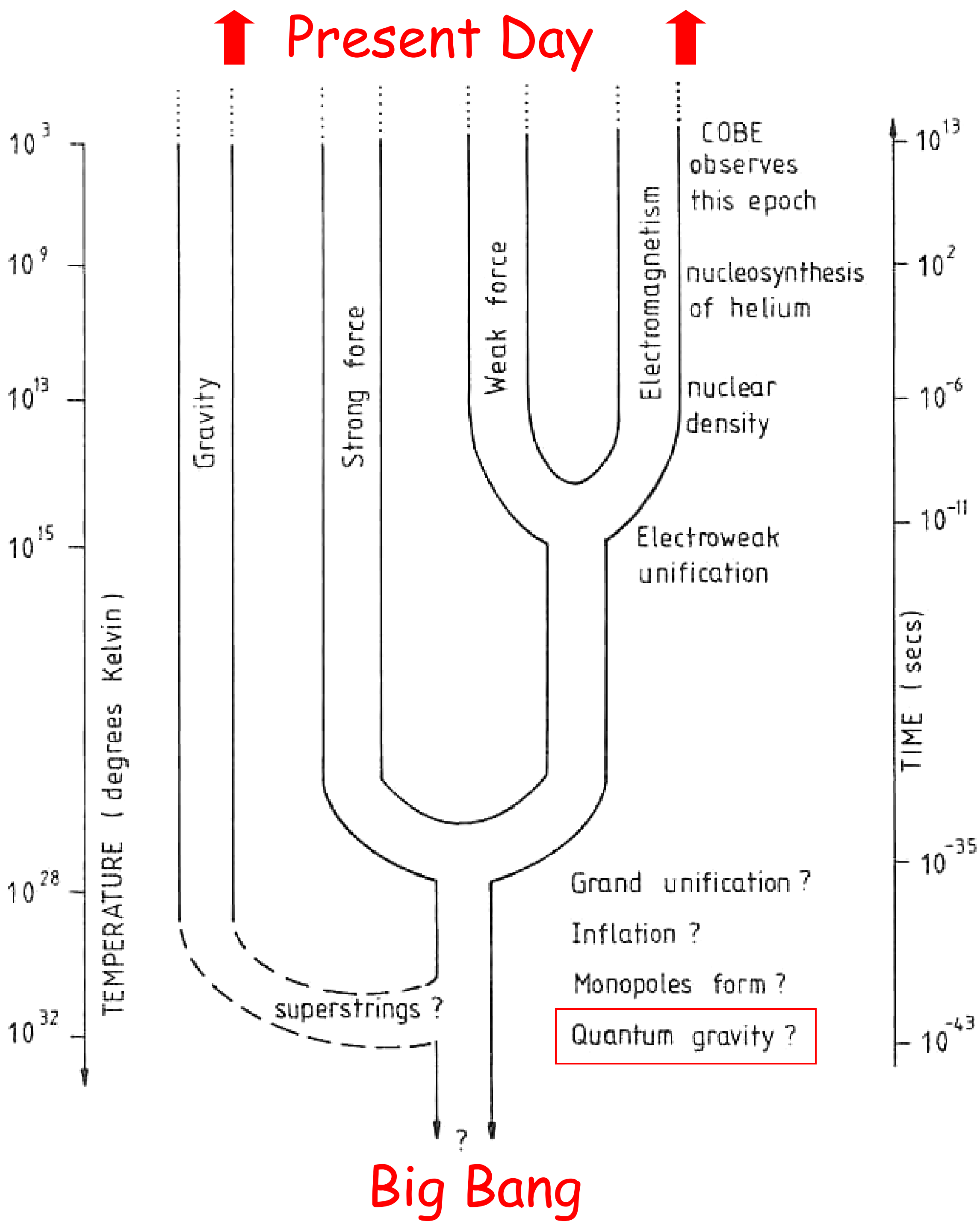


Uses "observer knowledge" to explain wave function collapse and non-locality. Advises "don't-ask/don't tell" about reality.

Uses "world-splitting" to explain wave function collapse. Has problems with non-locality. Useful in quantum computing.



Uses "advanced-retarded handshake" to explain wave function collapse and non-locality. Provides a way of "visualizing" quantum events.

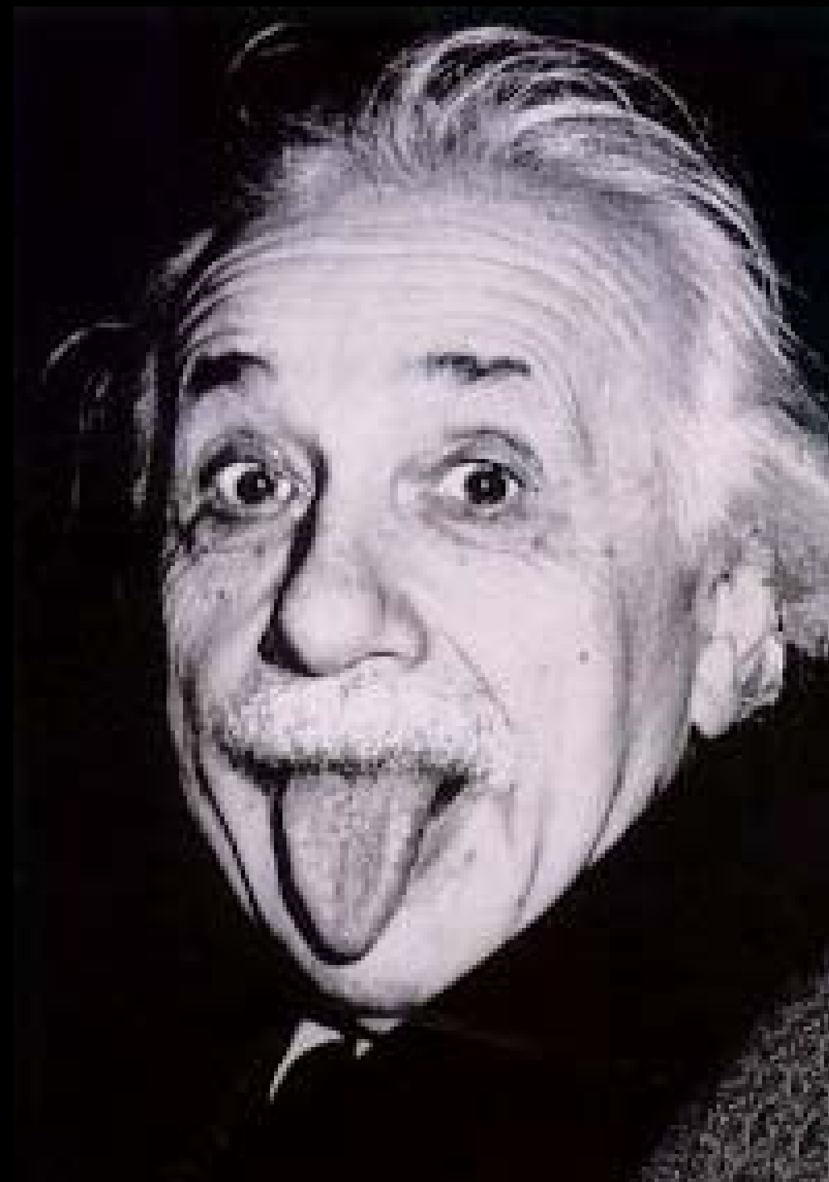


Present Day
Gravity
Strong force
Weak force
Electromagnetism
COBE observes this epoch
nucleosynthesis of helium
nuclear density
Electroweak unification
Grand unification ?
Inflation ?
Monopoles form ?
Quantum gravity ?
superstrings ?
?
TEMPERATURE (degrees Kelvin)
10^3
10^9
10^{13}
10^{15}
10^{28}
10^{32}
TIME (secs)
10^{13}
10^2
10^{-6}
10^{-11}
10^{-35}
10^{-43}
Big Bang

Grand Unification Theories

"The generalisation of the theory of gravitation has occupied me unceasingly since 1916"

Einstein, 1952



Bekenstein Entropy

In 1971 Jacob Bekenstein drew an important analogy:

Area of the event horizon behaves like the <u>thermodynamic entropy</u> of a Black Hole

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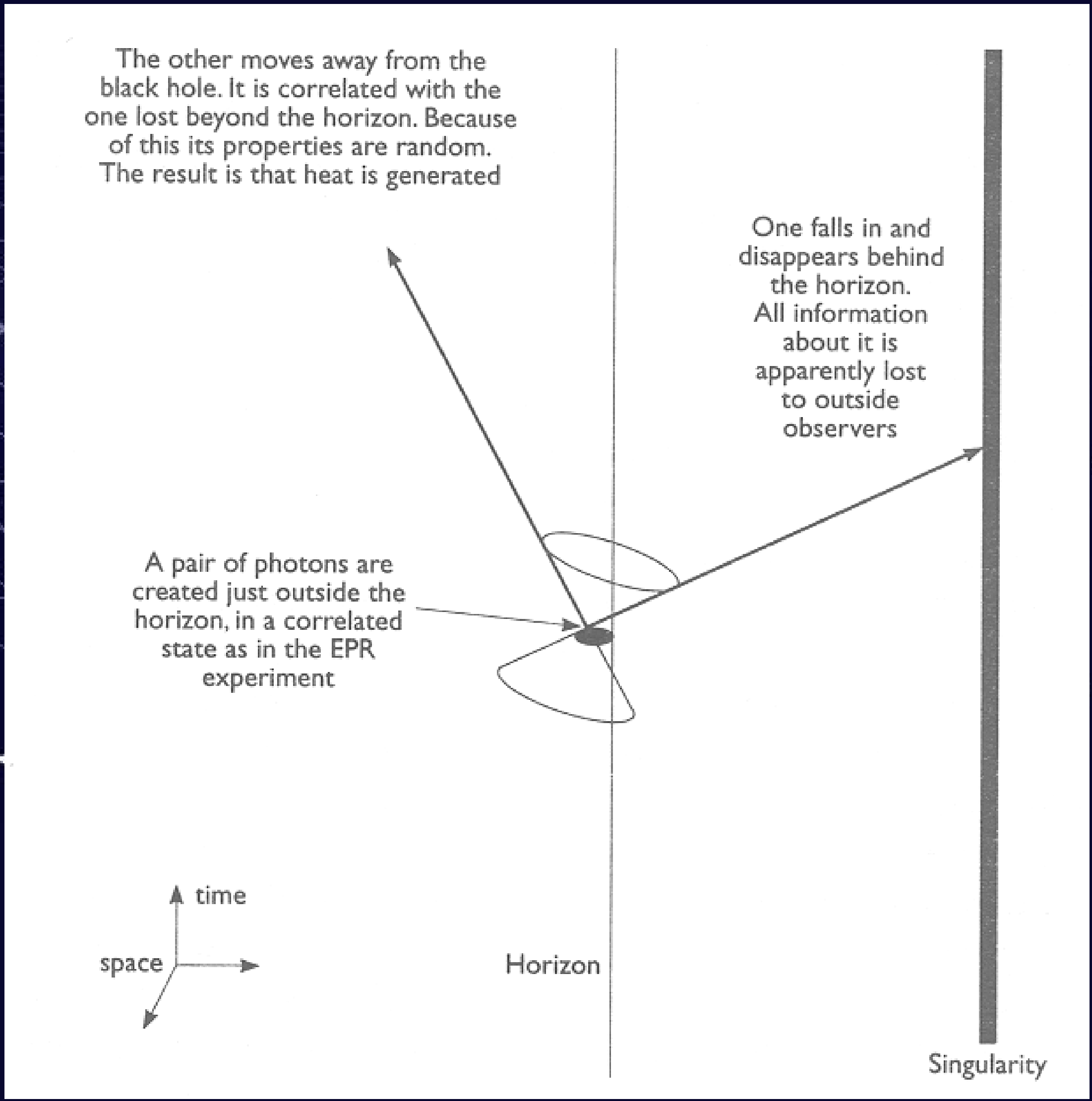
Area of the event horizon behaves like the thermodynamic entropy of a Black Hole

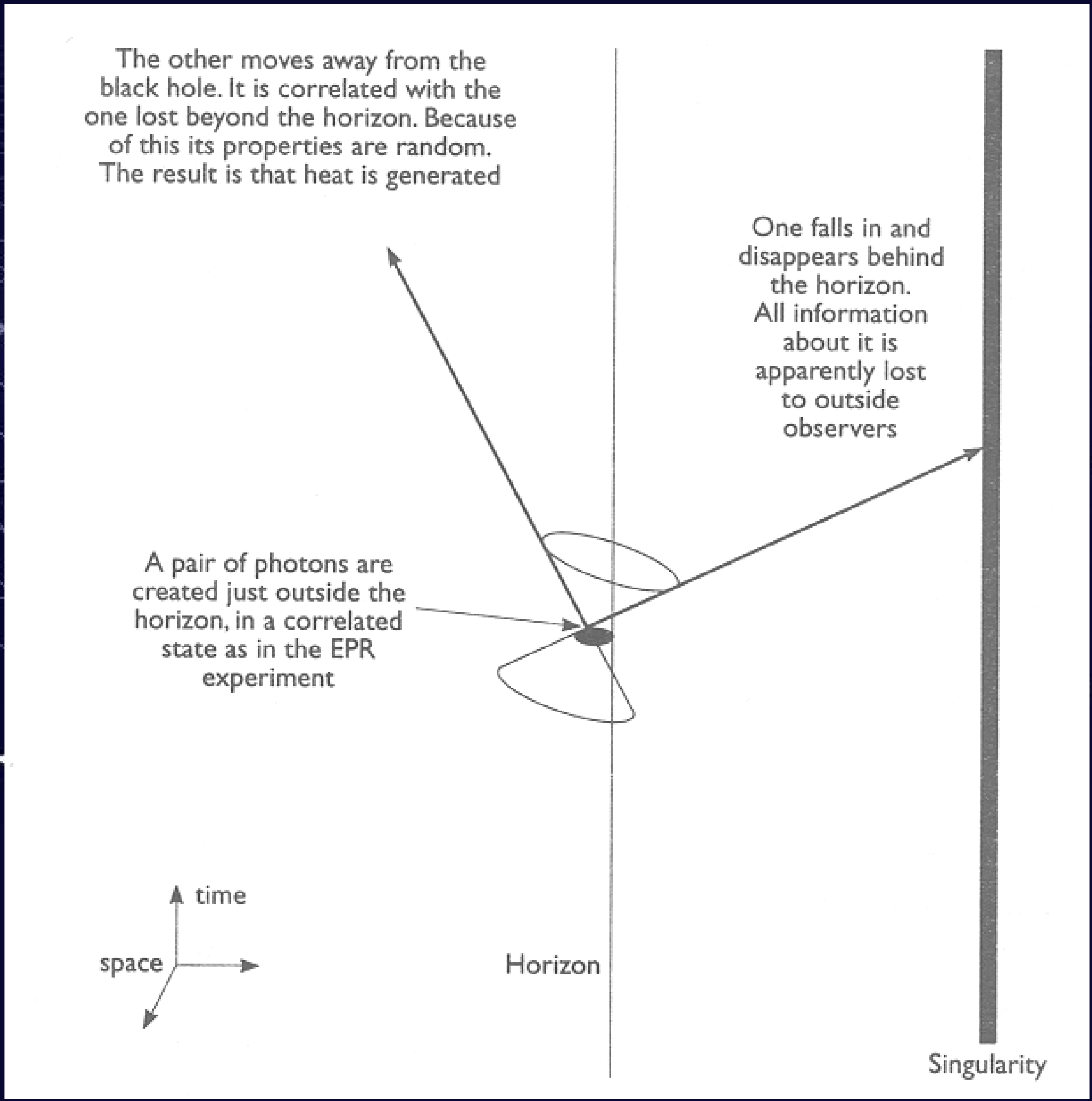
But a thermodynamical system also has a temperature

How hot is a Black Hole?...

By studying them as quantum objects, Stephen Hawking showed that Black Holes radiate

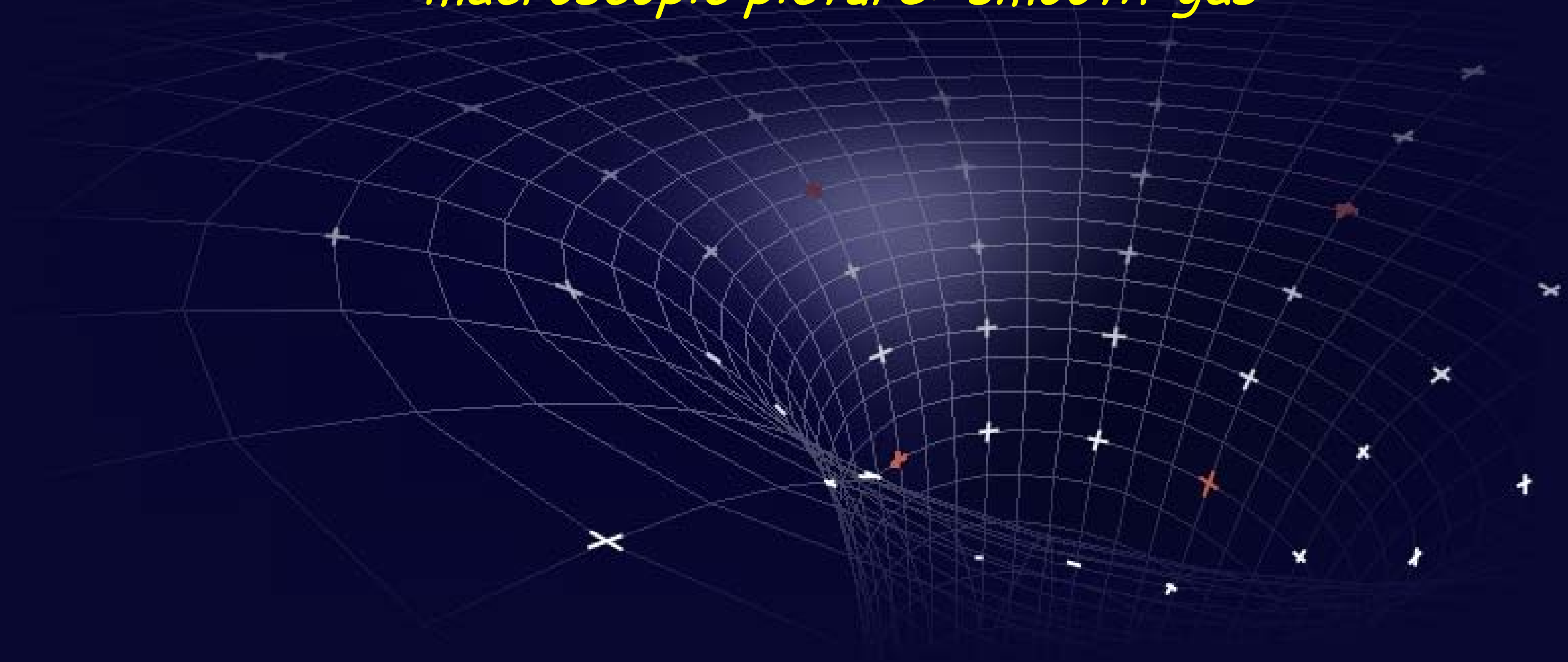


This completed the link between Black Holes and thermodynamics



Quantised spacetime

- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas



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- Entropy measures our information about the motions of individual atoms
- Does Bekenstein Entropy indicate a quantum interpretation of spacetime?

Theories of Quantum Gravity

Currently two popular candidates:-

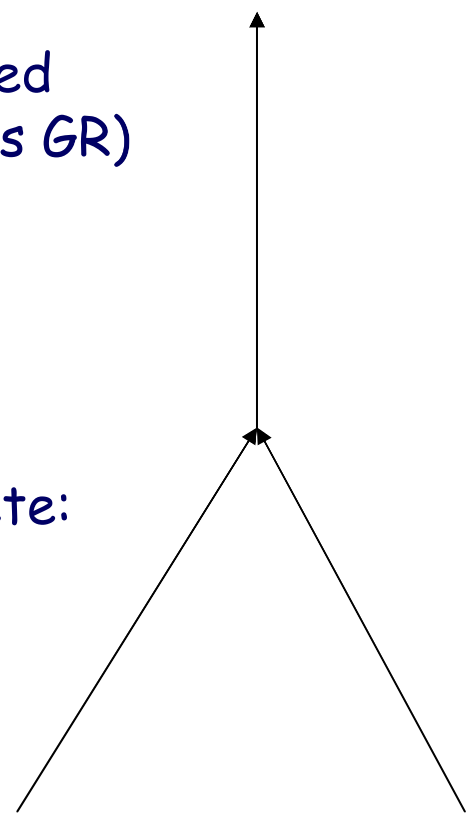
- String theory
- Loop quantum gravity

Both have strengths and weaknesses

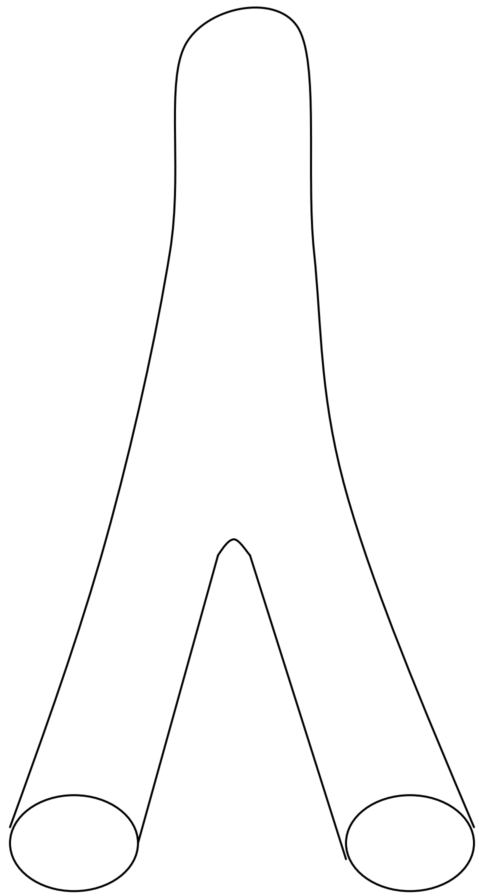
String Theory

- Point particles replaced by string loops
- Avoids 'infinities'
- BUT defined on fixed background (violates GR)
- No unique theory (e.g. *Membranes* in higher dimensions)
- Spacetime is discrete:

$$\Delta x \sim \frac{\hbar}{\Delta p} + C\Delta p$$



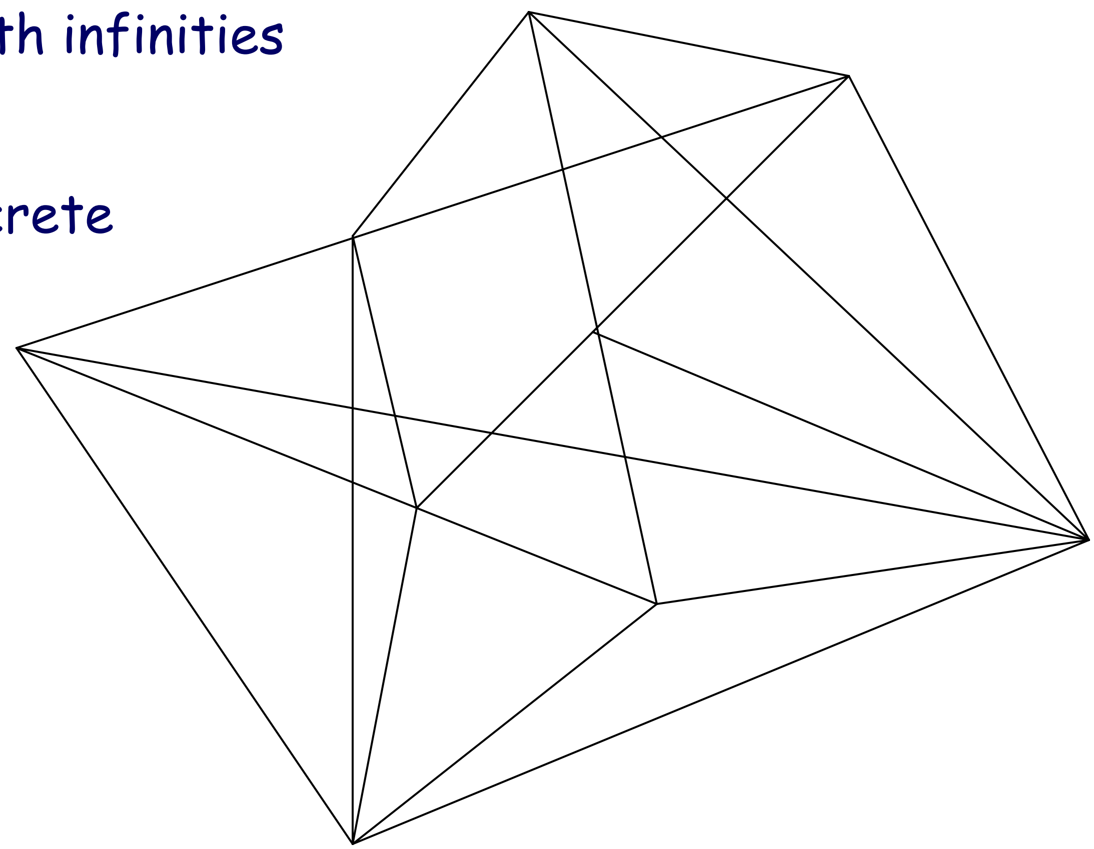
Particle representation



String representation

Loop Quantum Gravity

- Network of relations between events
- Quantum correlations built in
- BUT problems with infinities (gravitons)
- Spacetime is discrete

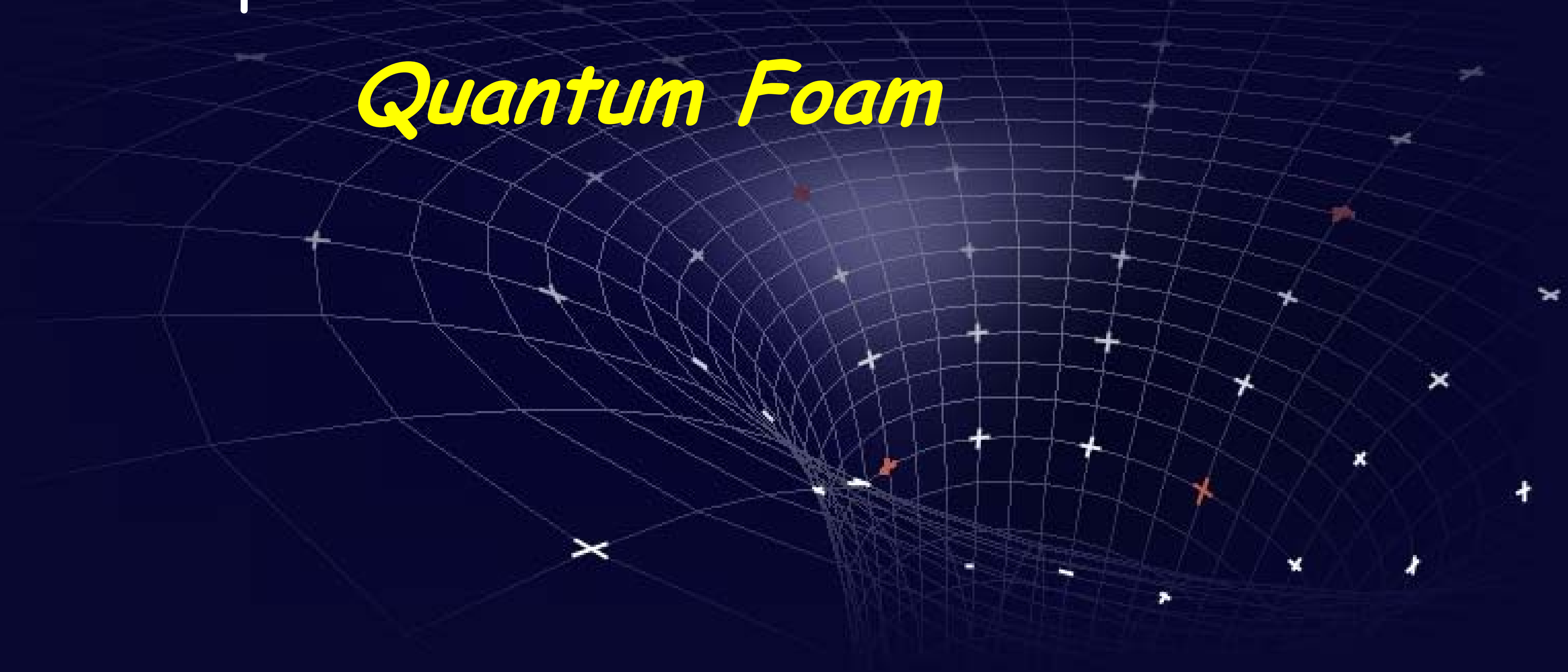


Quantum loop network

Three roads to same result:-

Spacetime comes in discrete chunks

Quantum Foam



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Holographic principle:-

Three roads are different manifestations of same quantum gravity theory

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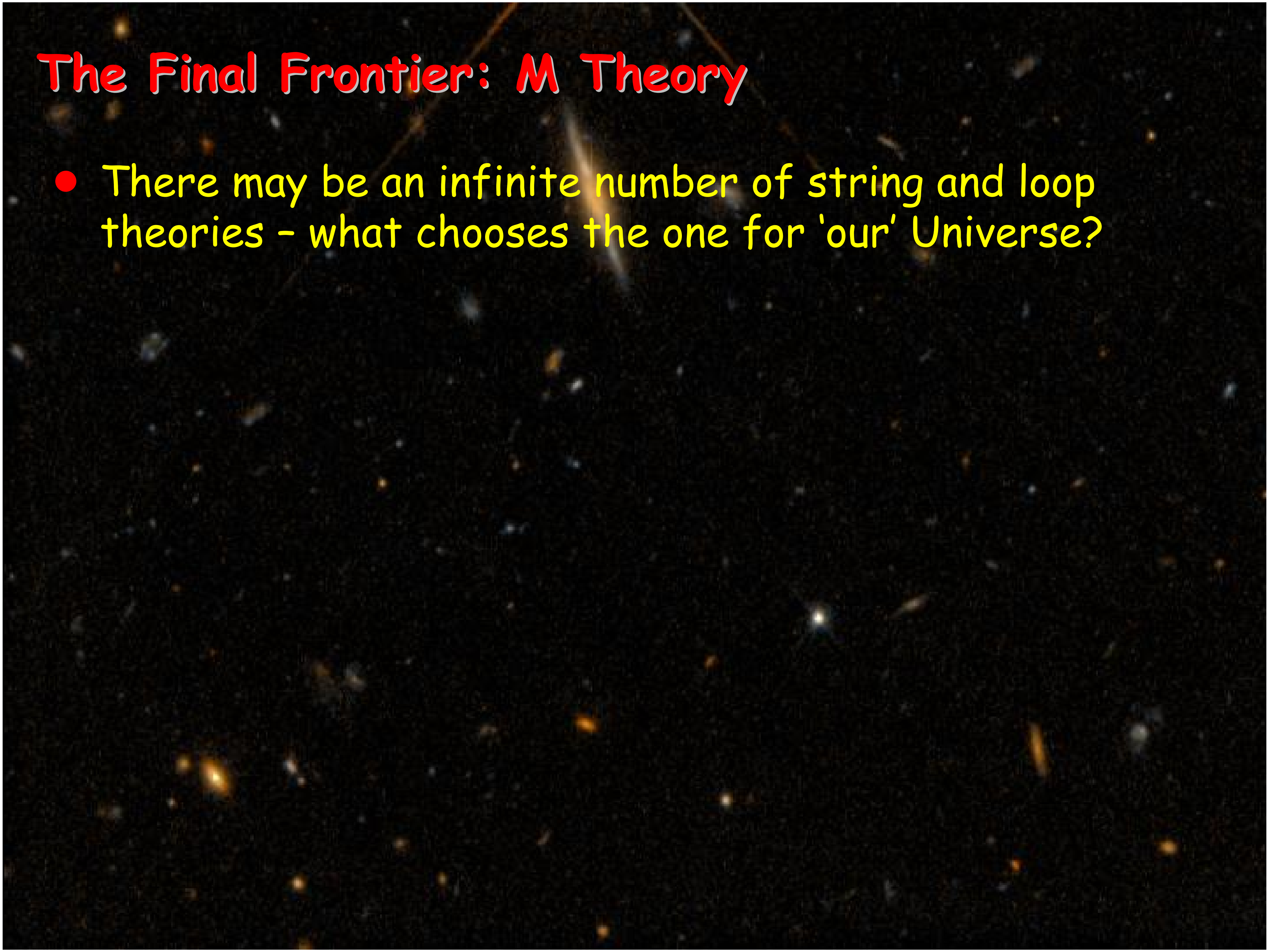
Analogous to Galileo and Kepler

The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?



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  - o why do we live in a (3+1)-D Universe?
  - o why is the Universe so large and old?
  - o why does spacetime look smooth on large scales?

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Watch this space!