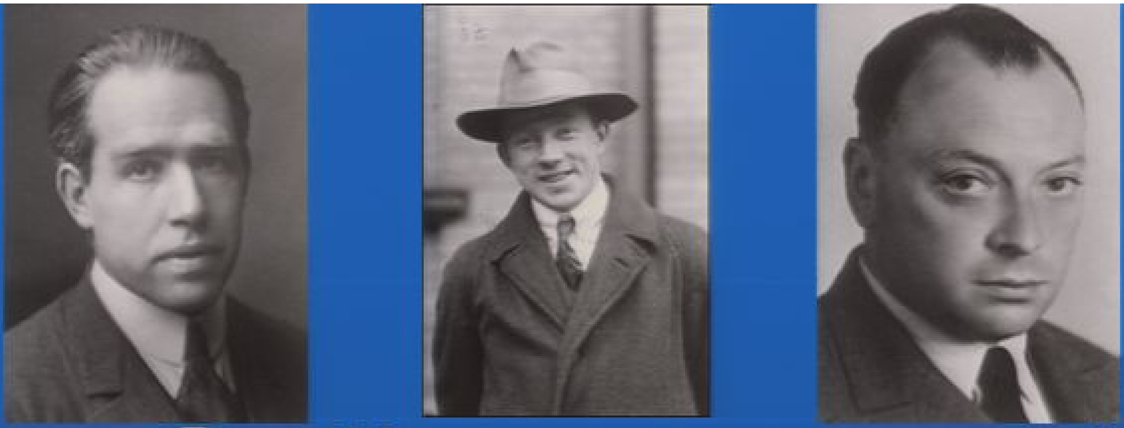
Title: Keynote Presentation - Cats, collapes and the nature of reality: What does quantum theory really mean?

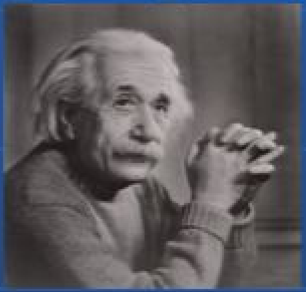
Date: Jul 14, 2006 11:00 AM

URL: http://pirsa.org/06070029

Abstract:



Cats, Collapses and the Nature of Reality



What does quantum theory really mean?

No Signal

VGA-1

No Signal

VGA-1

No Signal
VGA-1

No Signal

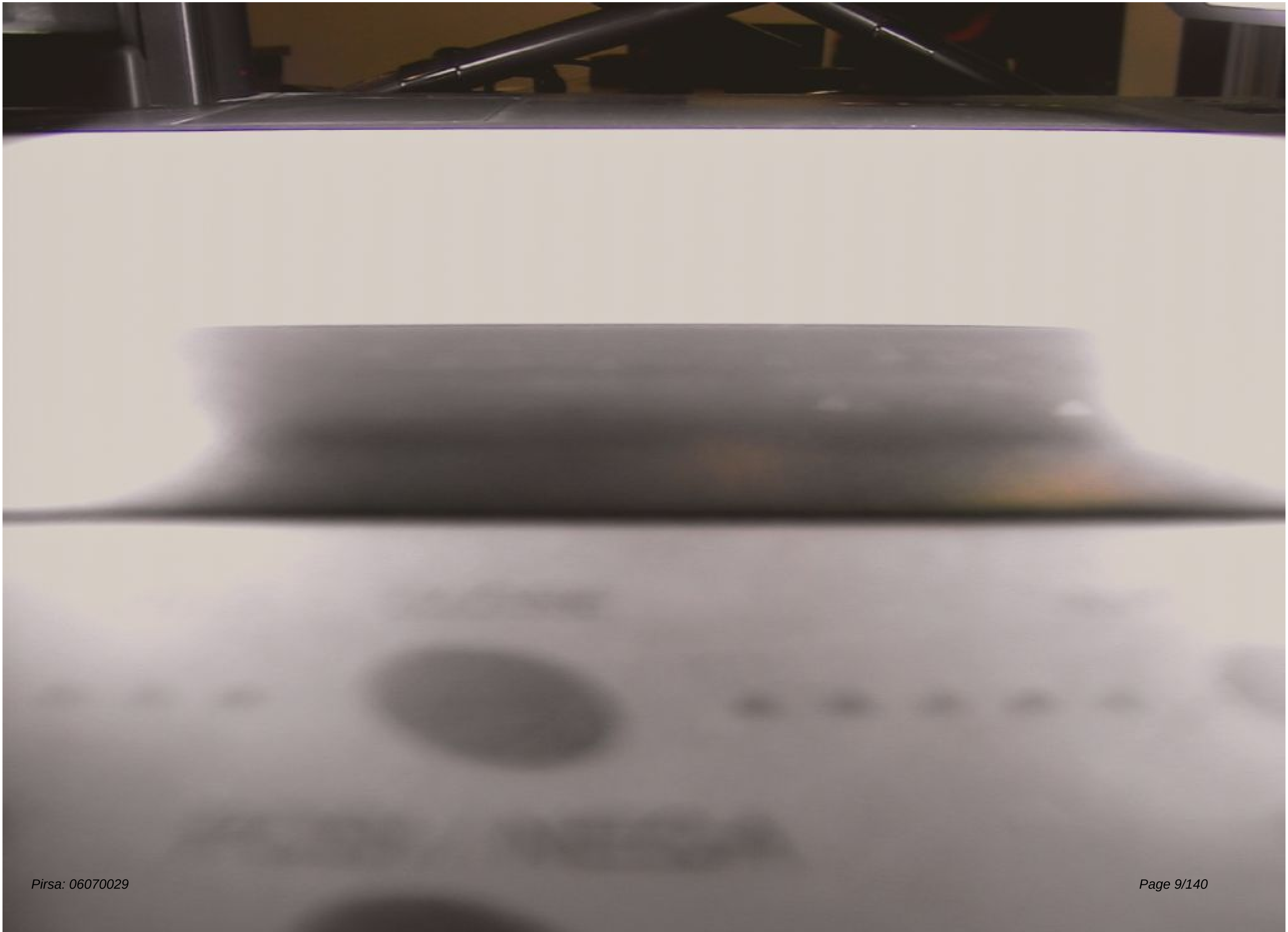
VGA-1

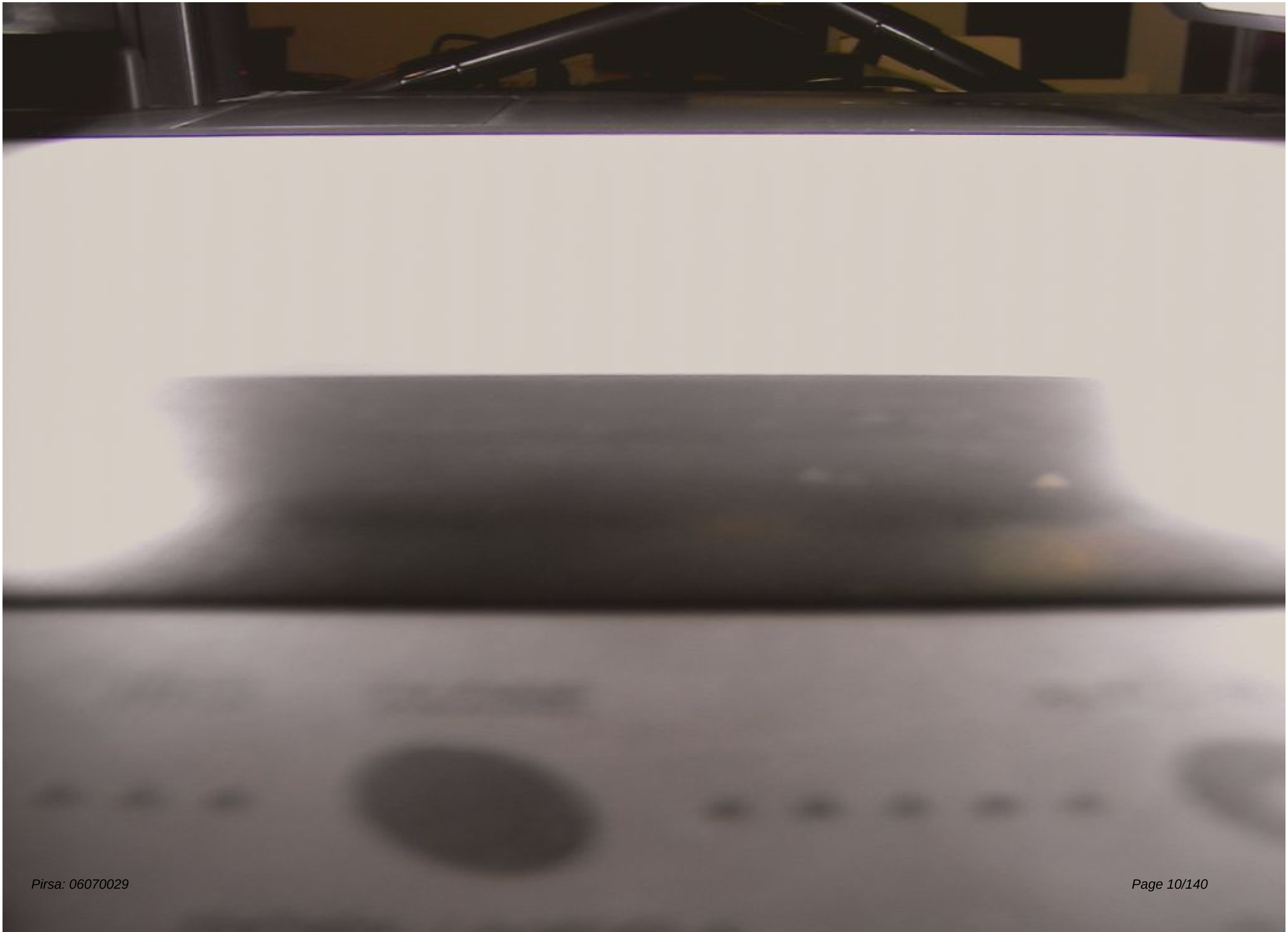
No Signal

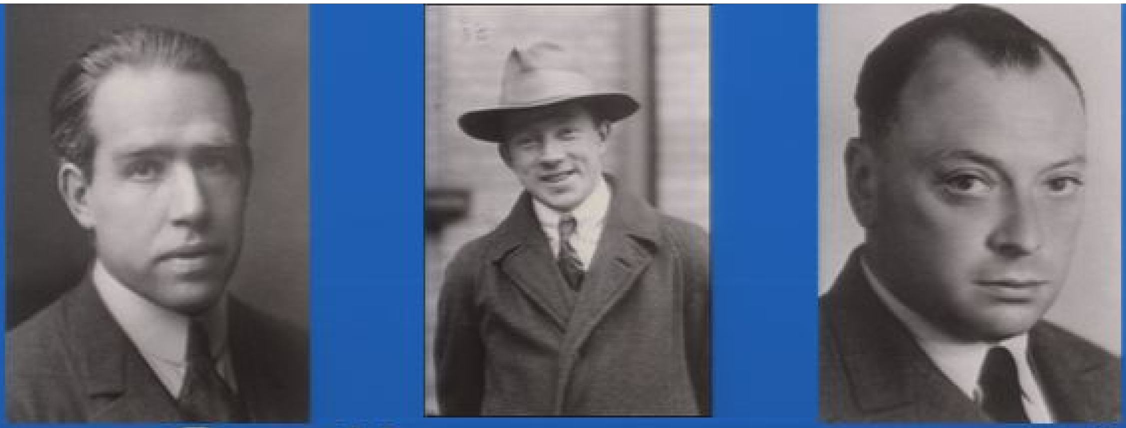
VGA-1

No Signal

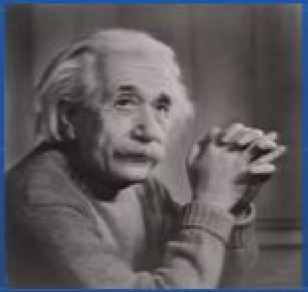
VGA-1



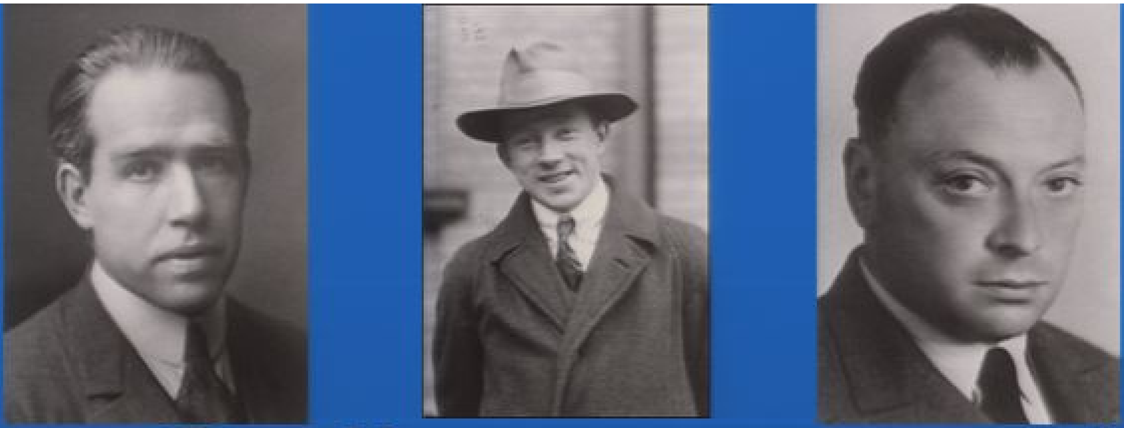




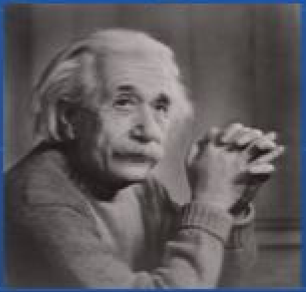
Cats, Collapses and the Nature of Reality



What does quantum theory really mean?



Cats, Collapses and the Nature of Reality



What does quantum theory really mean?

Einstein's reaction to quantum theory

Einstein spring 1927:

i) Quantum theory does not yield the classical behavior of macroscopic objects to a good approximation.
ii) Quantum theory leads to correlations among spatially separated objects that appear to violate action-by-contact principles.

Outline

- Classical Physics in Configuration Space
- Quantum Physics in Configuration Space
- The Measurement Problem
- Different Interpretations
- Conclusion

"*Never underestimate the pleasure of hearing something you already know!*"

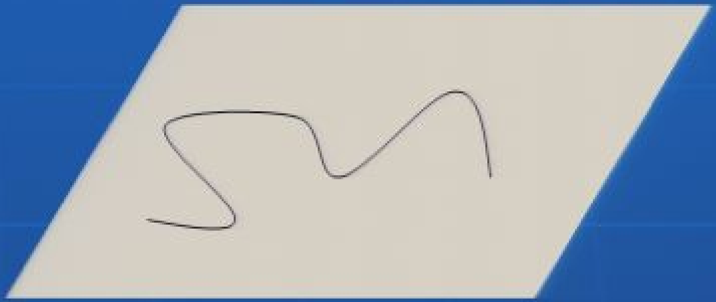
Enrico Fermi

Classical Physics

Configuration Space

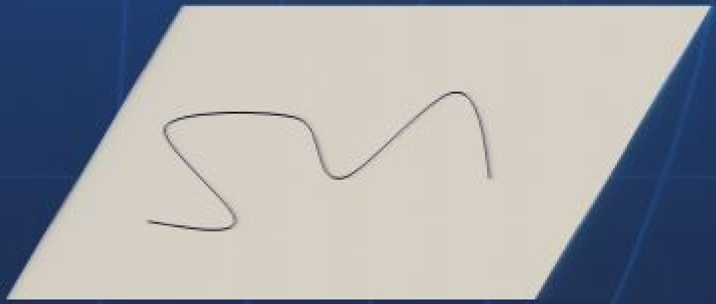
One Particle: $X=(x,y,z)$

3D



Two Particles: $X=((x_1,y_1,z_1),(x_2,y_2,z_2))$

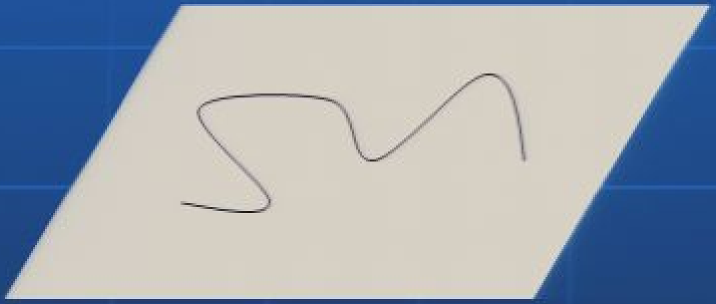
2×3D



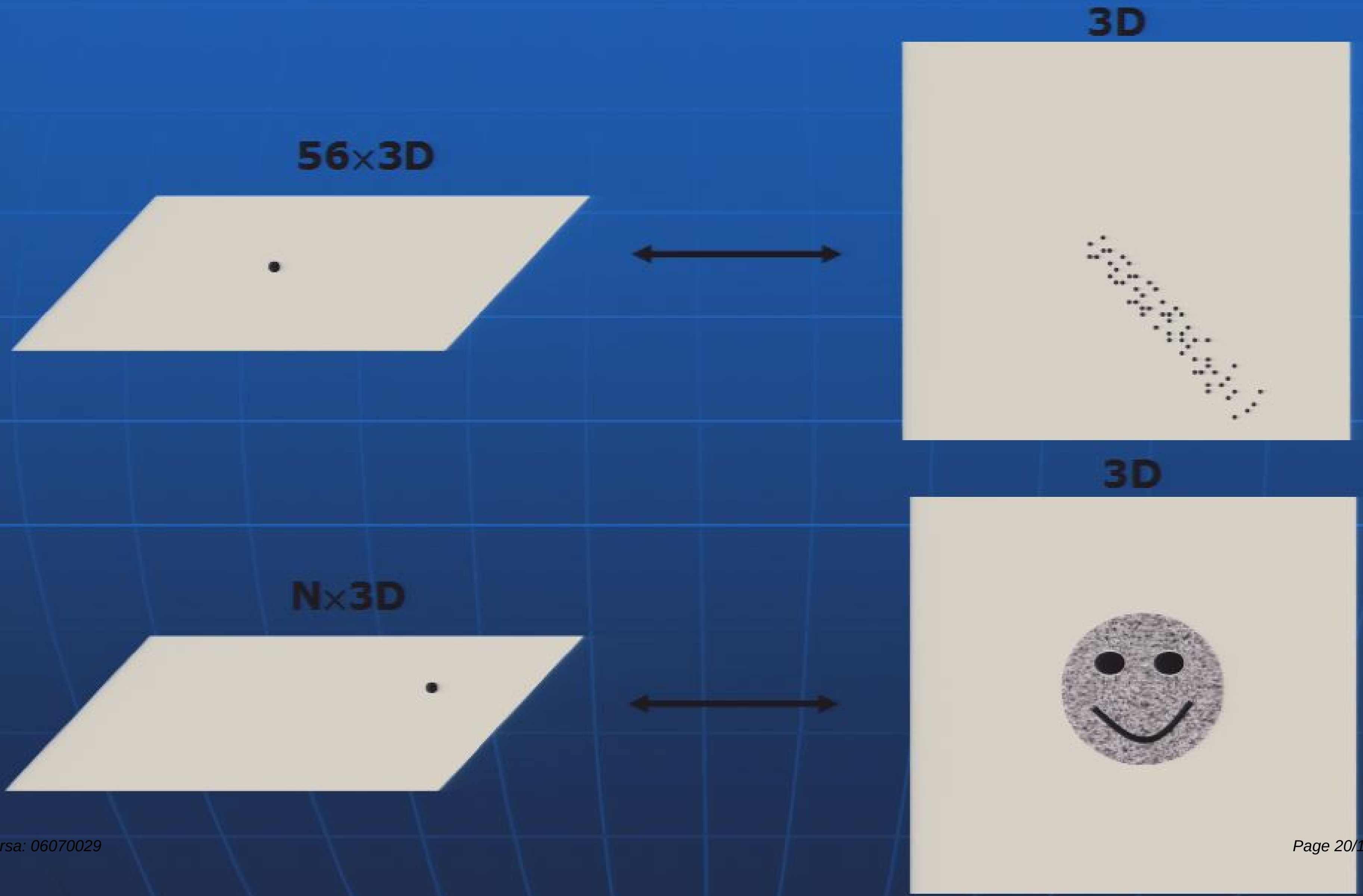
Configuration Space

N Particles: $X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N))$

N×3D



Correspondence to the Real World



56×3D

3D

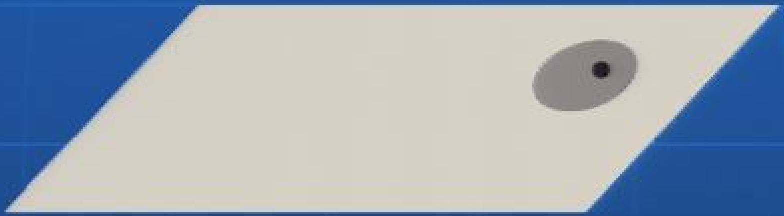
N×3D

3D

Short-Hand Notation

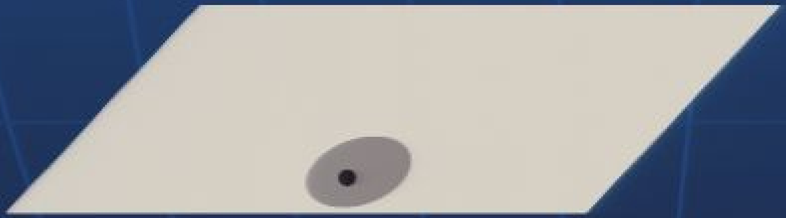
$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

$N\times 3D$



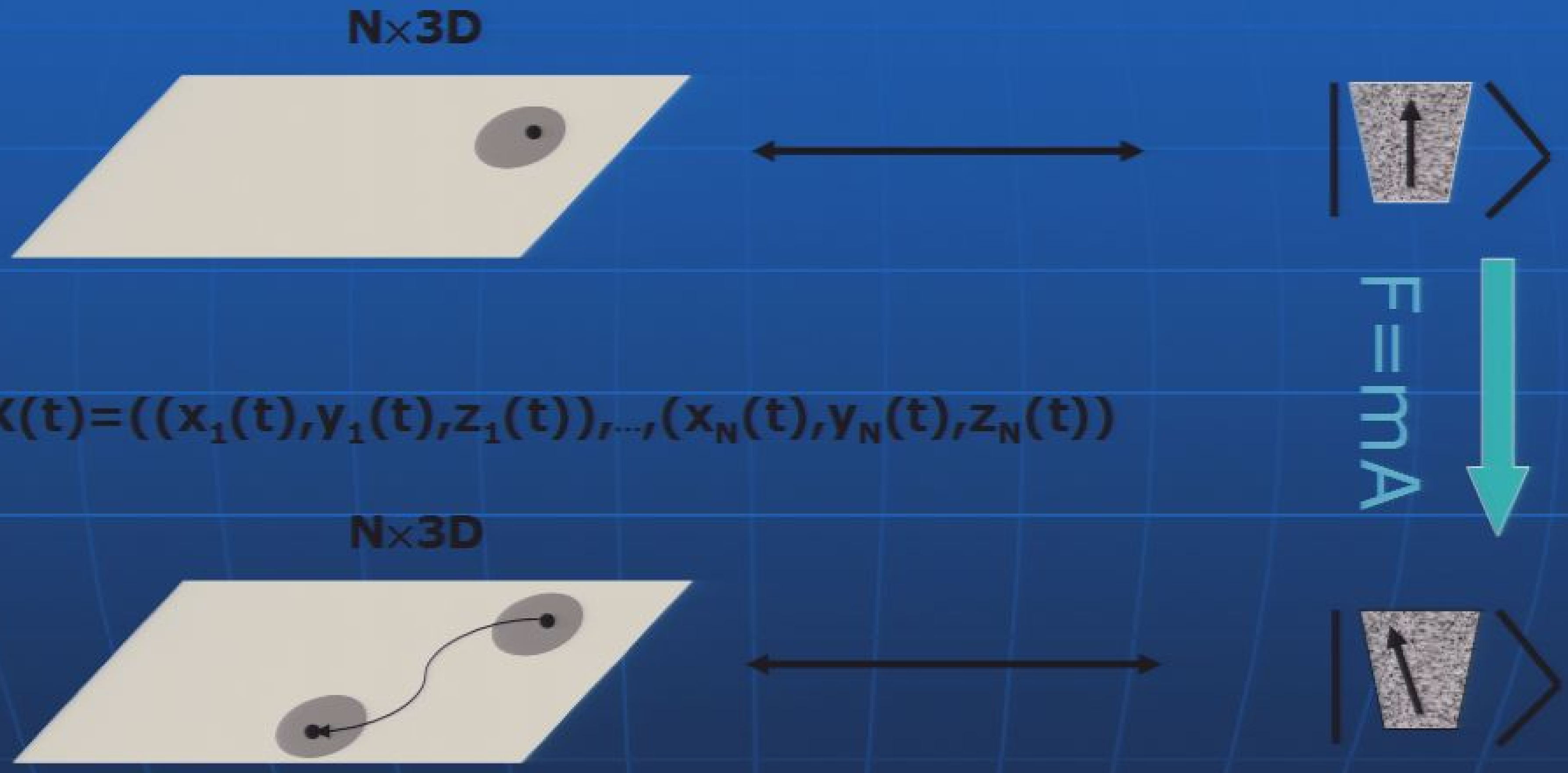
$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

$N\times 3D$



Evolution of the state X

$X(0)=((x_1(0),y_1(0),z_1(0)),\ldots,(x_N(0),y_N(0),z_N(0))$



$X(t)=((x_1(t),y_1(t),z_1(t)),\ldots,(x_N(t),y_N(t),z_N(t))$

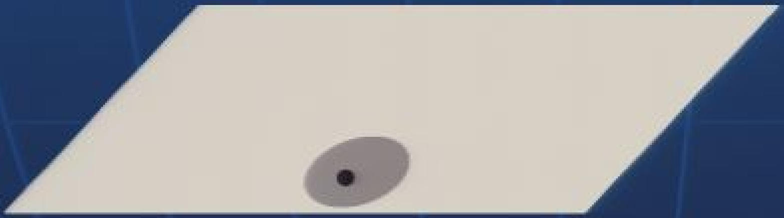
Short-Hand Notation

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

N×3D

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

N×3D



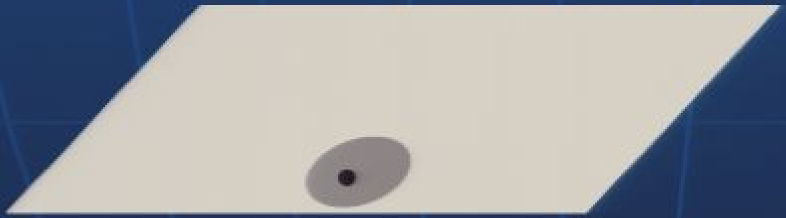
Short-Hand Notation

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

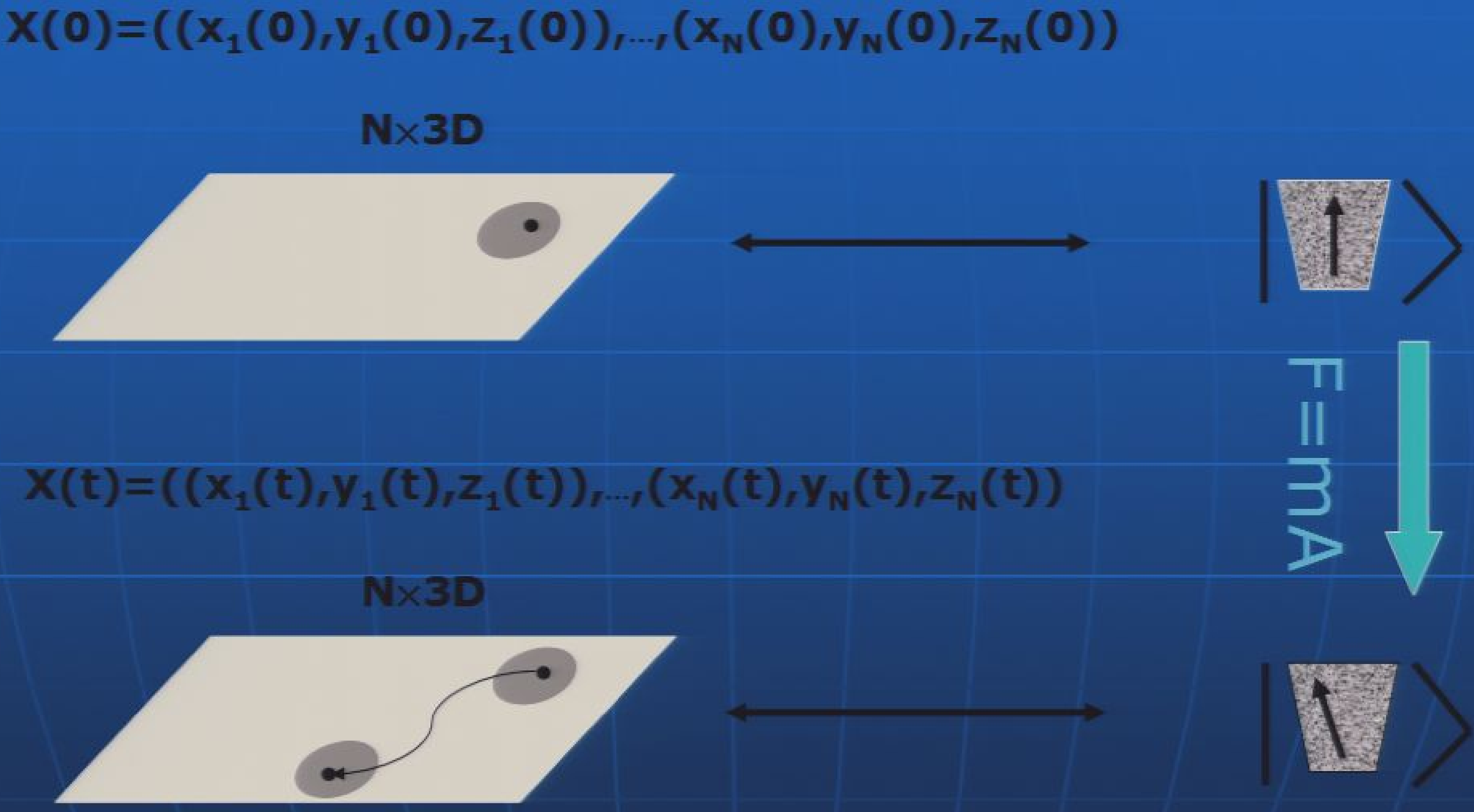
N×3D

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

N×3D



Evolution of the state X



$X(0)=((x_1(0),y_1(0),z_1(0)),\ldots,(x_N(0),y_N(0),z_N(0))$

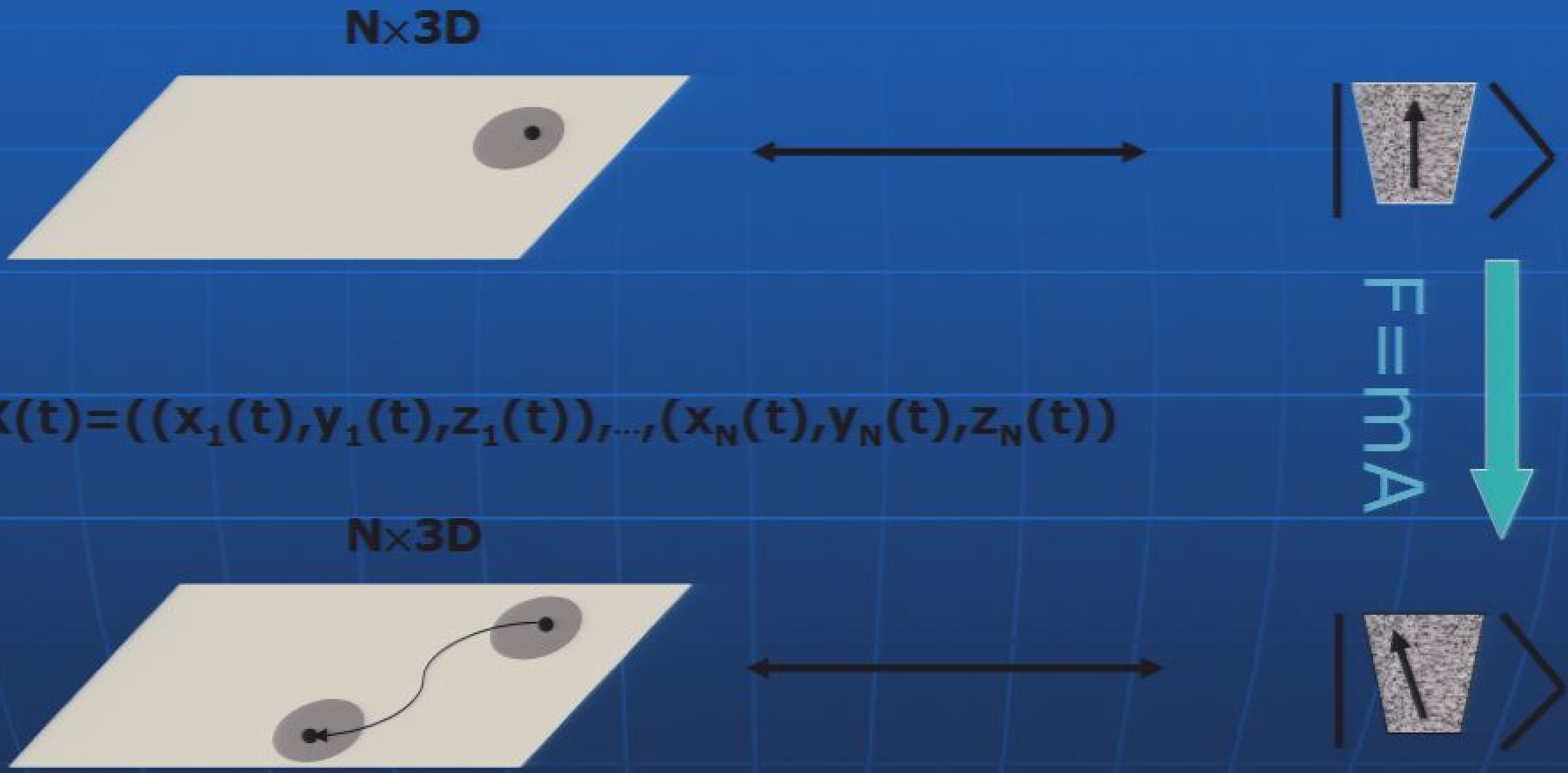
N×3D

$X(t)=((x_1(t),y_1(t),z_1(t)),\ldots,(x_N(t),y_N(t),z_N(t))$

N×3D

Quantum Theory

Evolution of the state X



$X(0)=((x_1(0),y_1(0),z_1(0)),\ldots,(x_N(0),y_N(0),z_N(0))$

N×3D

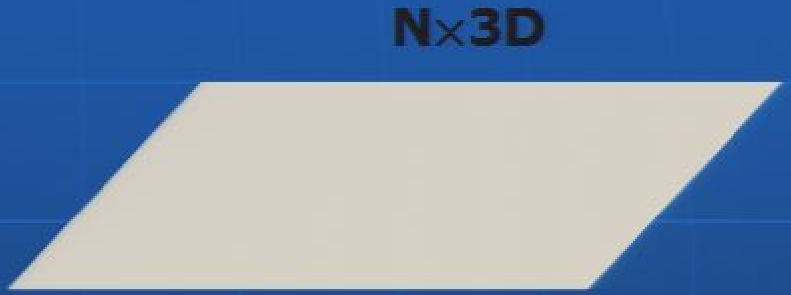
$X(t)=((x_1(t),y_1(t),z_1(t)),\ldots,(x_N(t),y_N(t),z_N(t))$

N×3D

Quantum Theory

Quantum Theory: what's different?

Good News: we still have the good old configuration space!

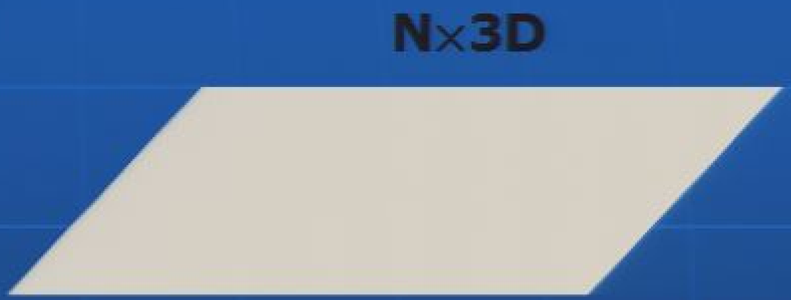


Bad News: a state is no longer represented by a point X in configuration space.

A state in quantum theory is represented by a complex function $\Psi(X)$ on configuration space, called the wave-function.

Quantum Theory: what's different?

Good News: we still have the good old configuration space!

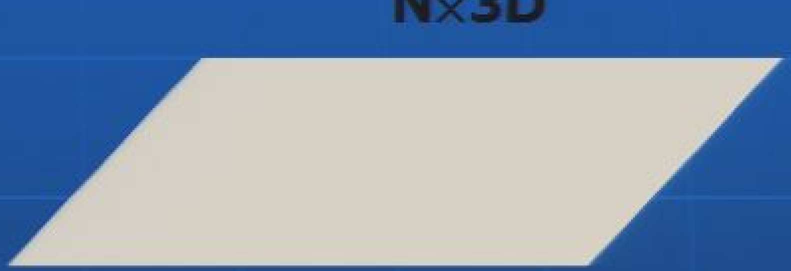


Bad News: a state is no longer represented by a point X in configuration space.

A state in quantum theory is represented by a complex function $\Psi(X)$ on configuration space, called the wave-function.

Quantum Theory: what's different?

Good News: we still have the good old configuration space!



Bad News: a state is no longer represented by a point X in configuration space.

A state in quantum theory is represented by a complex function $\Psi(X)$ on configuration space, called the wave-function.

The Wave-Function Ψ

$$\Psi((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N))$$

Wave-function: Give me a point X in configuration space and I'll give you a complex number: a+bi.

0.000+0.00i

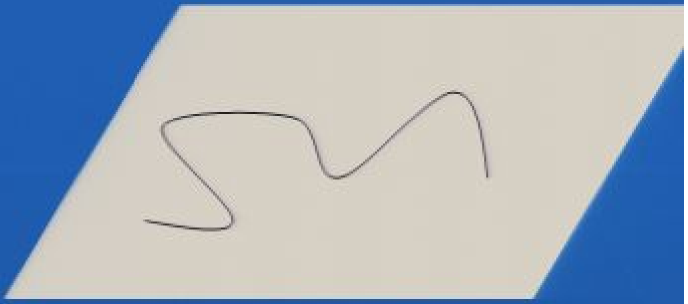
N×3 D

2.49834+4.458743i

3.452498+2.4389i

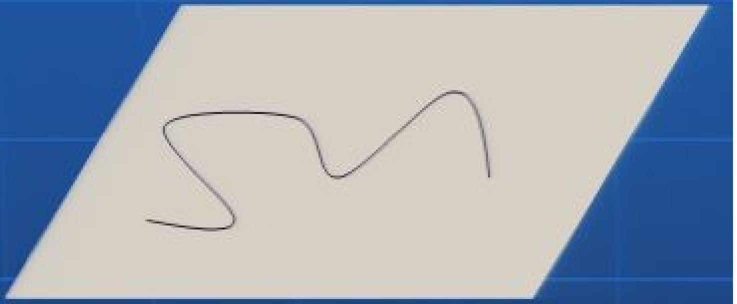
One Particle: $X=(x,y,z)$

$\Psi(x,y,z)$



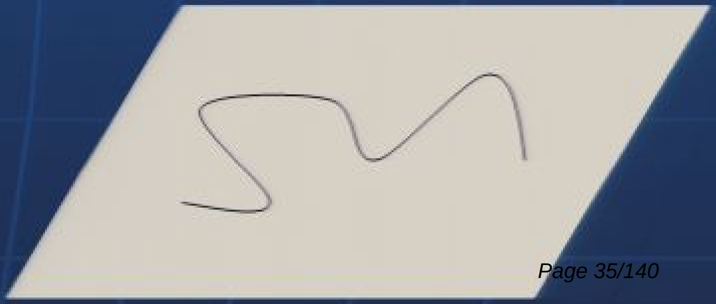
Two Particles: $X=((x_1,y_1,z_1),(x_2,y_2,z_2))$

$\Psi((x_1,y_1,z_1),(x_2,y_2,z_2))$



N Particles: $X=((x_1,y_1,z_1),(x_2,y_2,z_2),\dots,(x_N,y_N,z_N))$

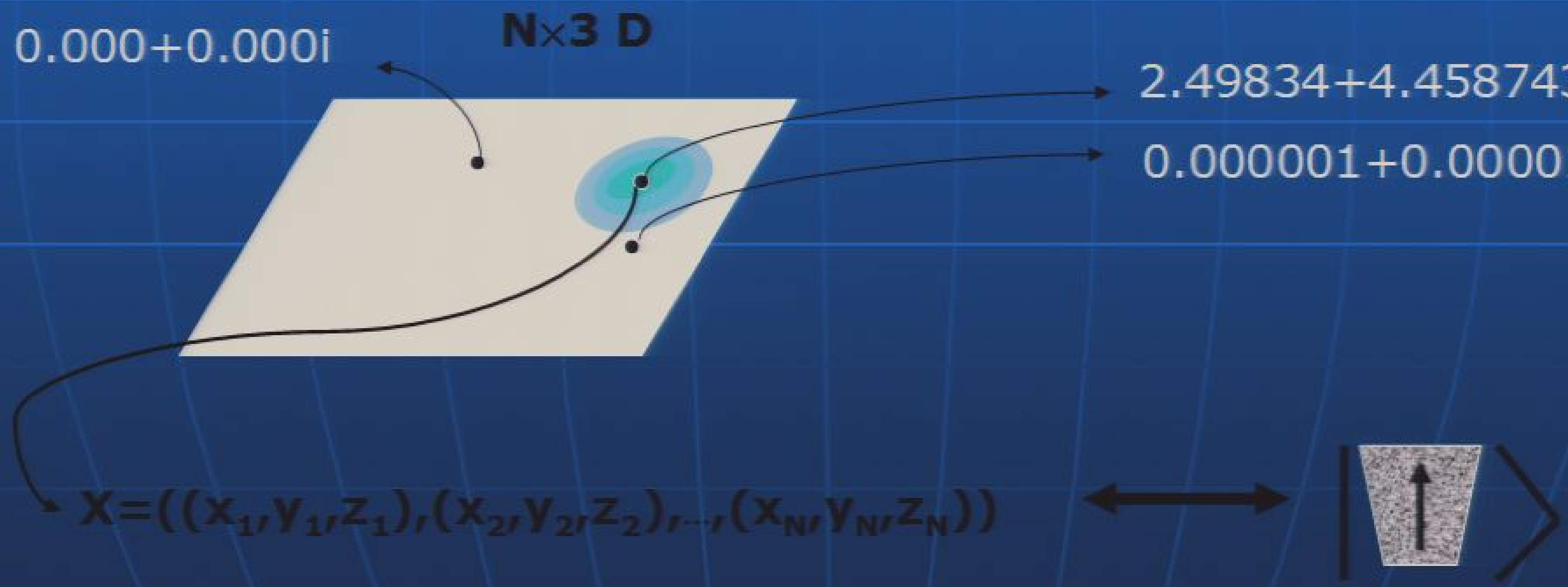
$\Psi((x_1,y_1,z_1),(x_2,y_2,z_2),\dots,(x_N,y_N,z_N))$



We are going to assume that quantum theory is fundamental and applies to everything, even macroscopic bodies and not just atoms and electrons.

Correspondence to Reality

Assume that we have a wave-function that is “peaked” around some point X in configuration space.



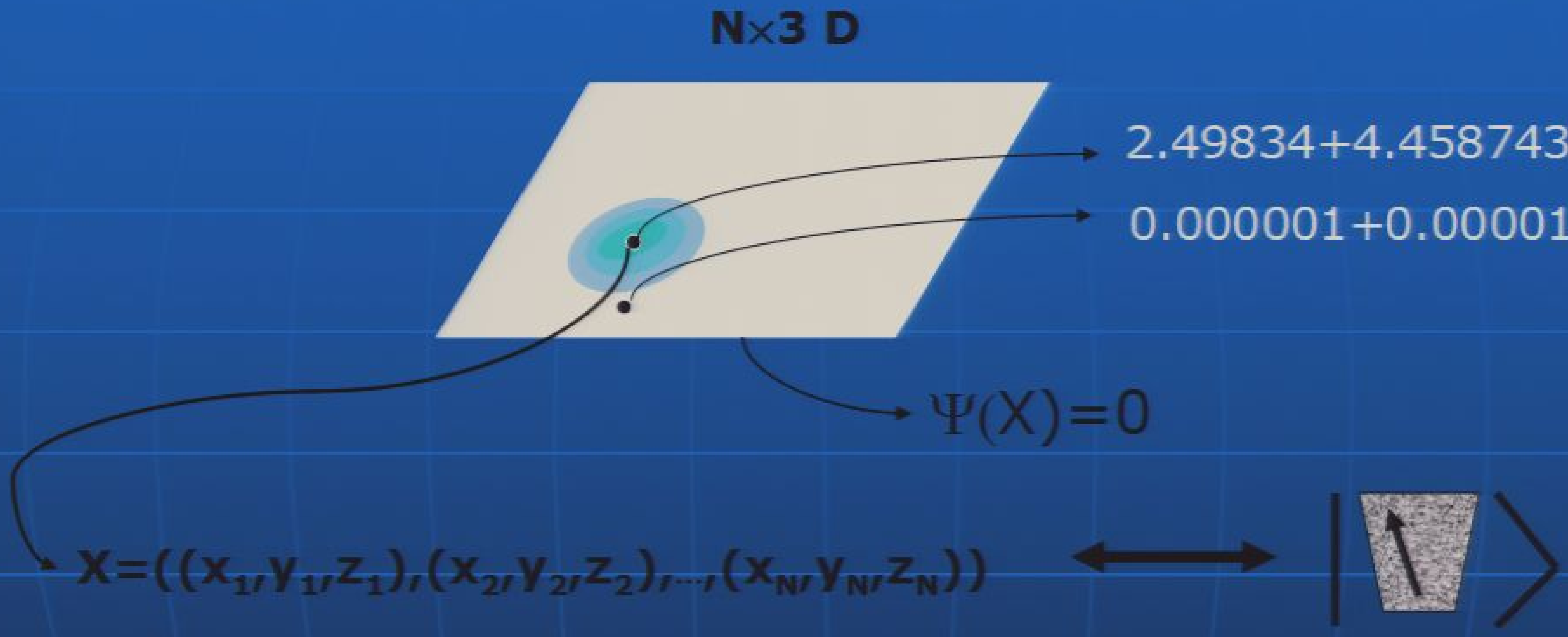
N×3 D

0.000+0.000i

2.49834+4.458743i

0.000001+0.00001i

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\dots,(x_N,y_N,z_N))$ ⟷



N×3 D

2.49834+4.458743i

0.000001+0.00001i

$\Psi(X)=0$

$$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\dots,(x_N,y_N,z_N))$$

Superposition Principle I

If Ψ_1 and Ψ_2 are possible quantum states then also

$$\alpha\Psi_1+\beta\Psi_2$$

is a possible quantum state.

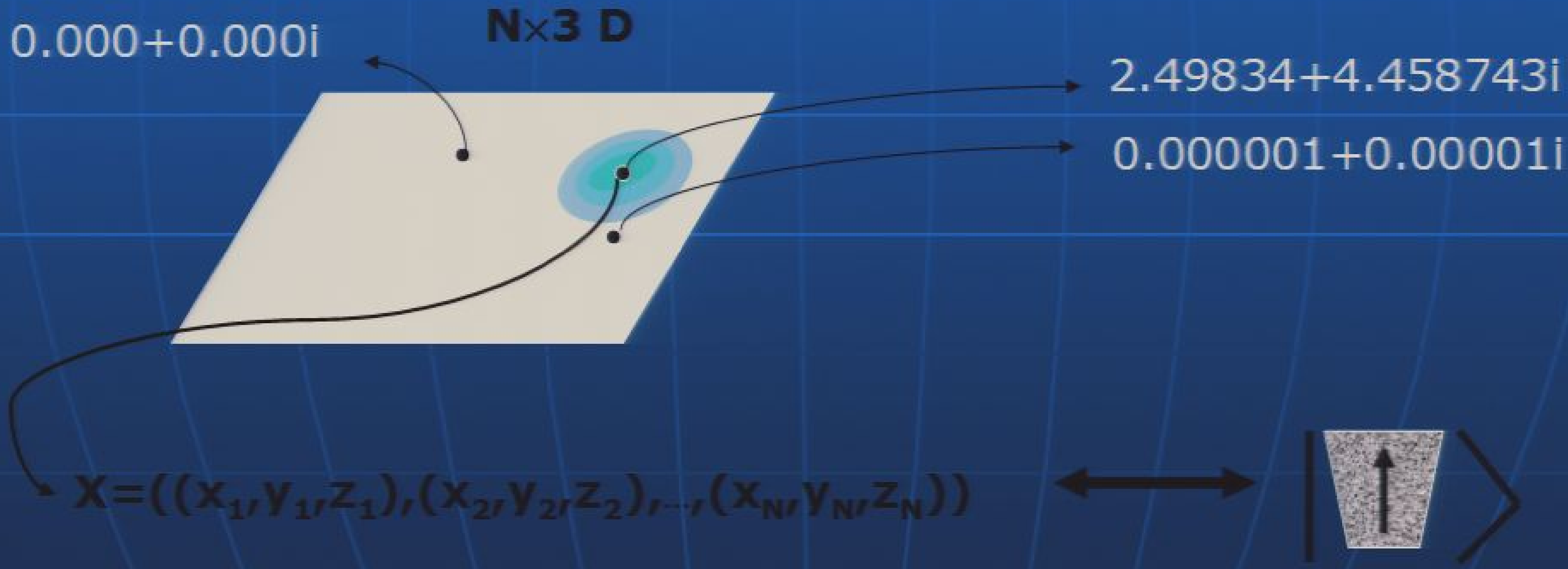
This is troubling…

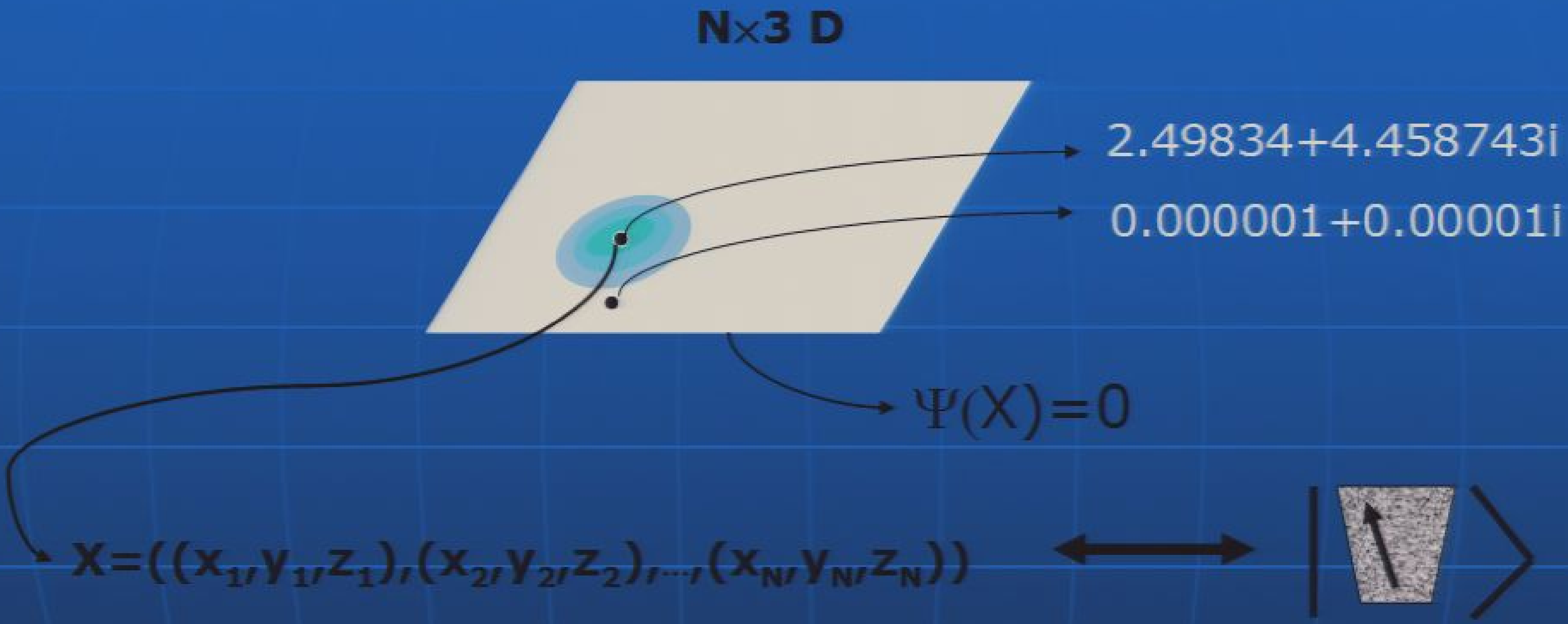
$\alpha\,|$  $\rangle + \beta\,|$  $\rangle$???

N×3 D

Correspondence to Reality

Assume that we have a wave-function that is "peaked" around some point X in configuration space.





N×3 D

2.49834+4.458743i

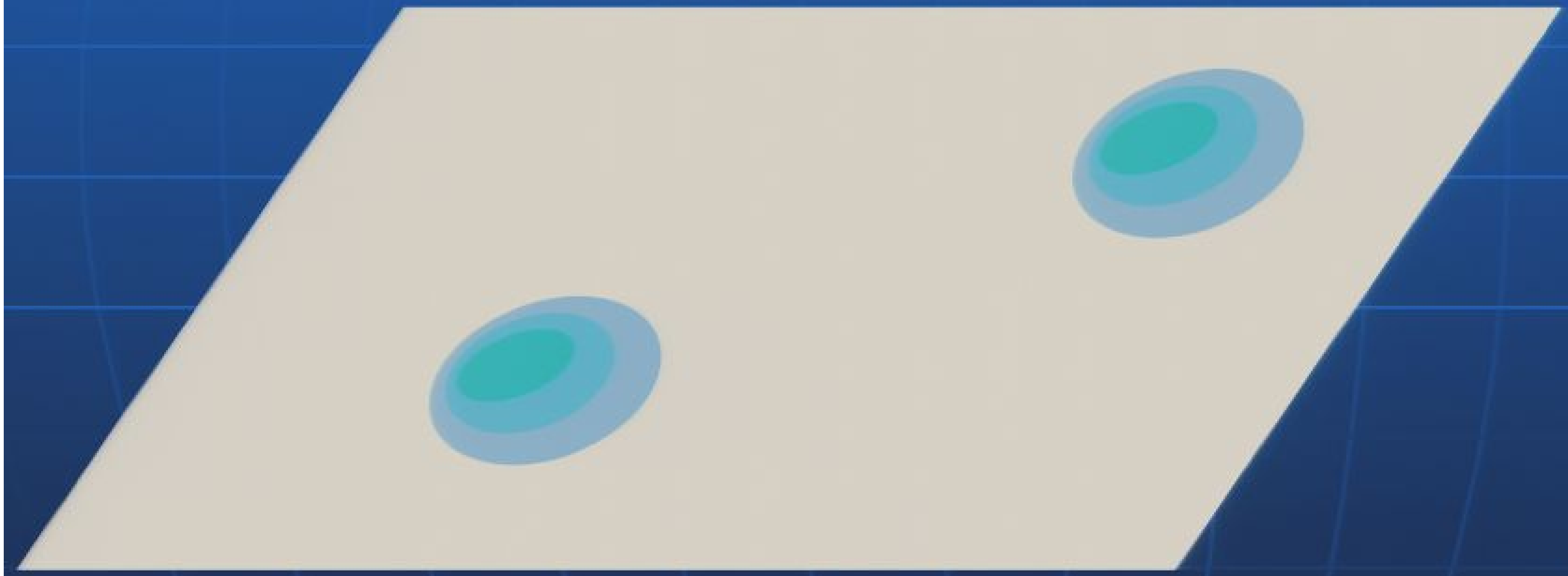
0.000001+0.00001i

$\Psi(X)=0$

$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\dots,(x_N,y_N,z_N))$ $\longleftrightarrow$

This is troubling…

$\alpha \Big|$  $\Big\rangle + \beta \Big|$  $\Big\rangle$???



N×3 D

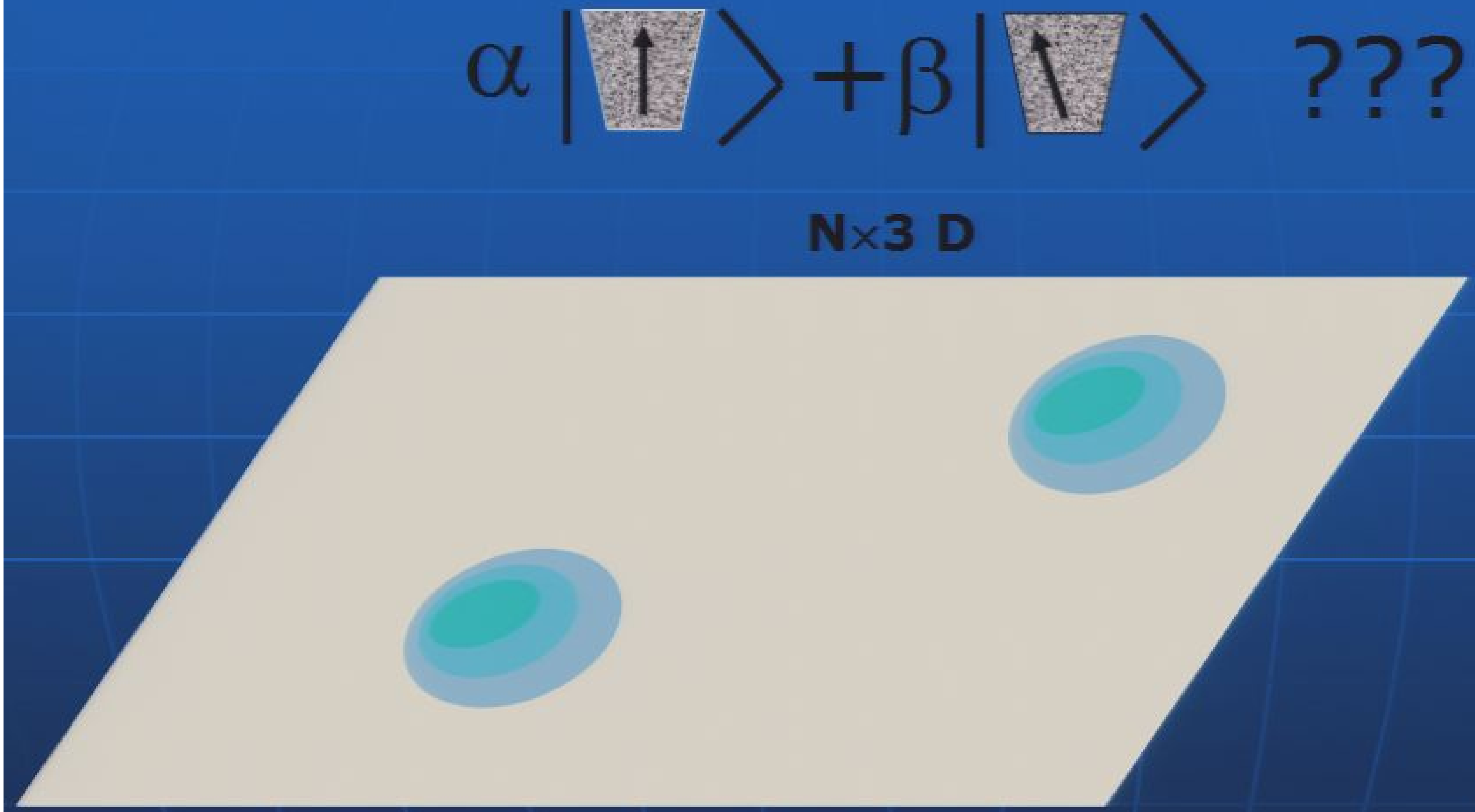
Maybe the laws of quantum theory will make it unlikely for these strange states to occur.

Perhaps if we start from a “peaked” state the state will (almost) never evolve into a state which is not “peaked”.

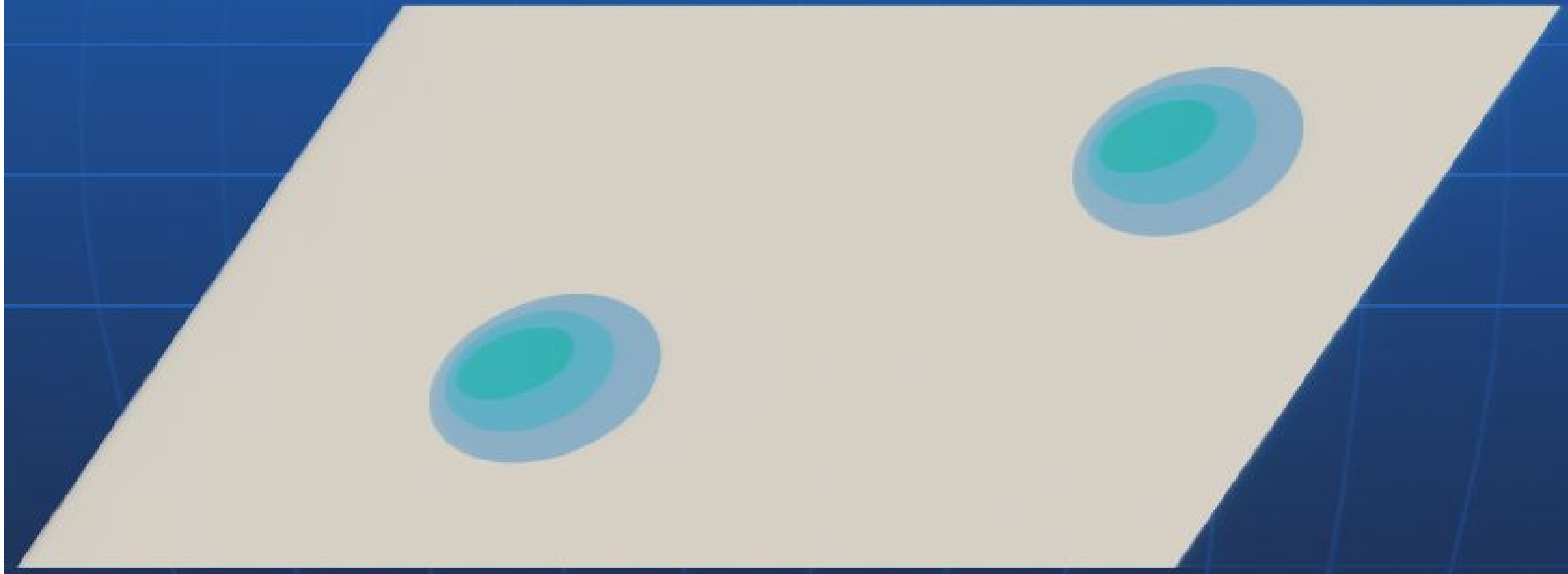
Perhaps quantum theory will only allow small objects (like electrons and atoms) to be in strange states of being “here and there” at the same time? After all that is what seems to happen in the two slit experiment, where the electron appears to be passing through both slits.

Let’s investigate!!!

This is troubling…



This is troubling…



Maybe the laws of quantum theory will make it unlikely for these strange states to occur.

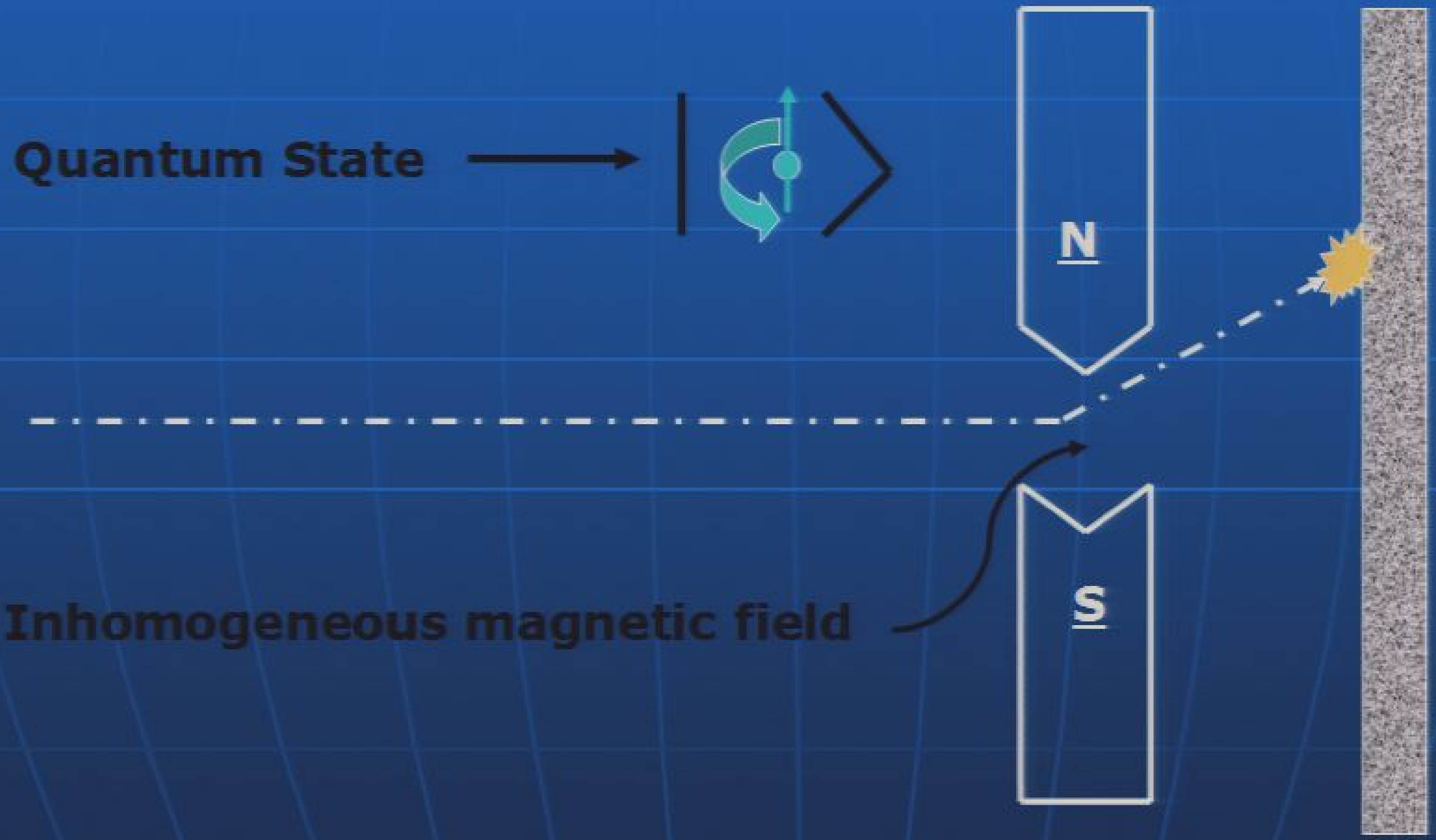
Perhaps if we start from a “peaked” state the state will (almost) never evolve into a state which is not “peaked”.

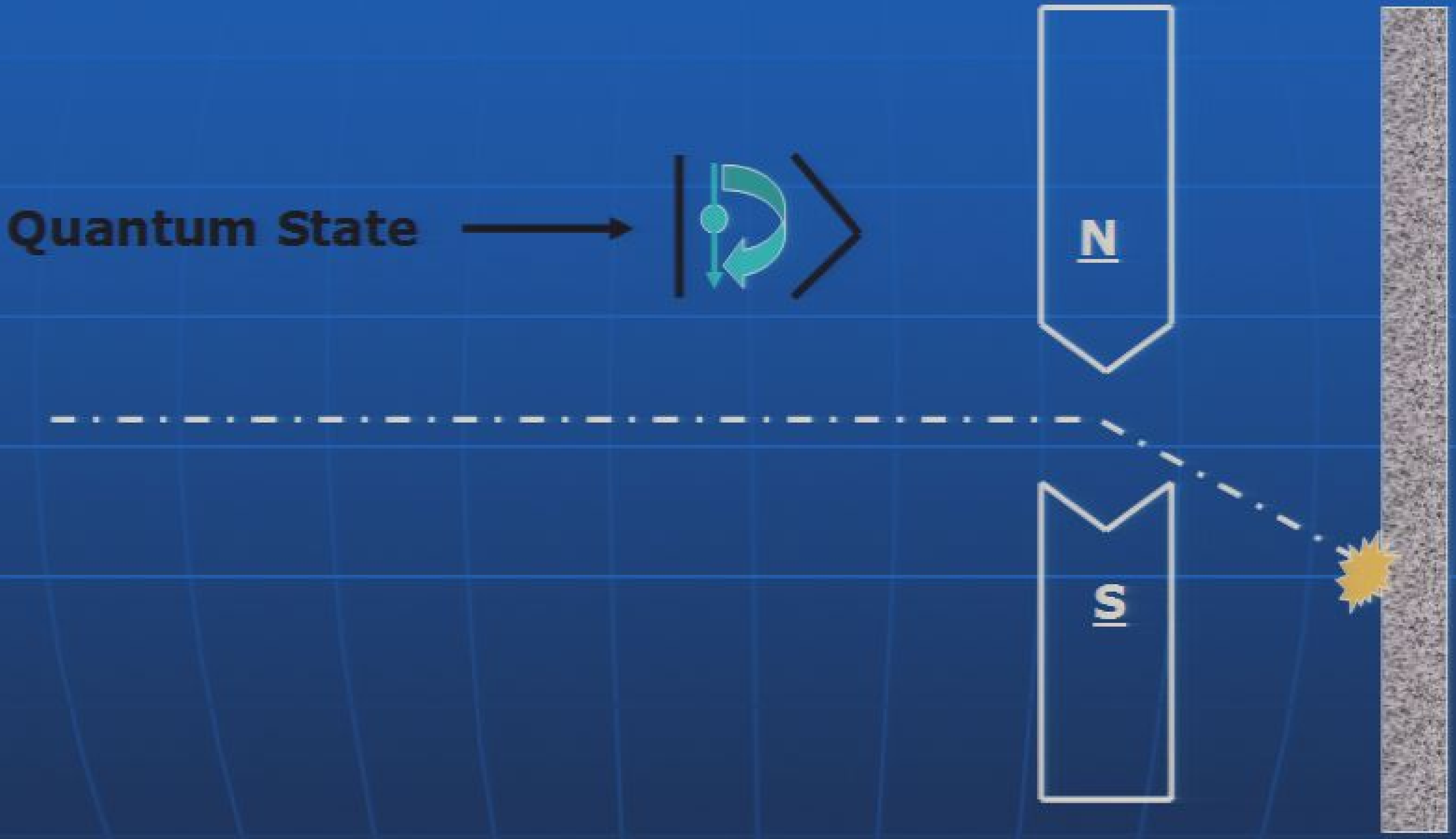
Perhaps quantum theory will only allow small objects (like electrons and atoms) to be in strange states of being “here and there” at the same time? After all that is what seems to happen in the two slit experiment, where the electron appears to be passing through both slits.

Let’s investigate!!!

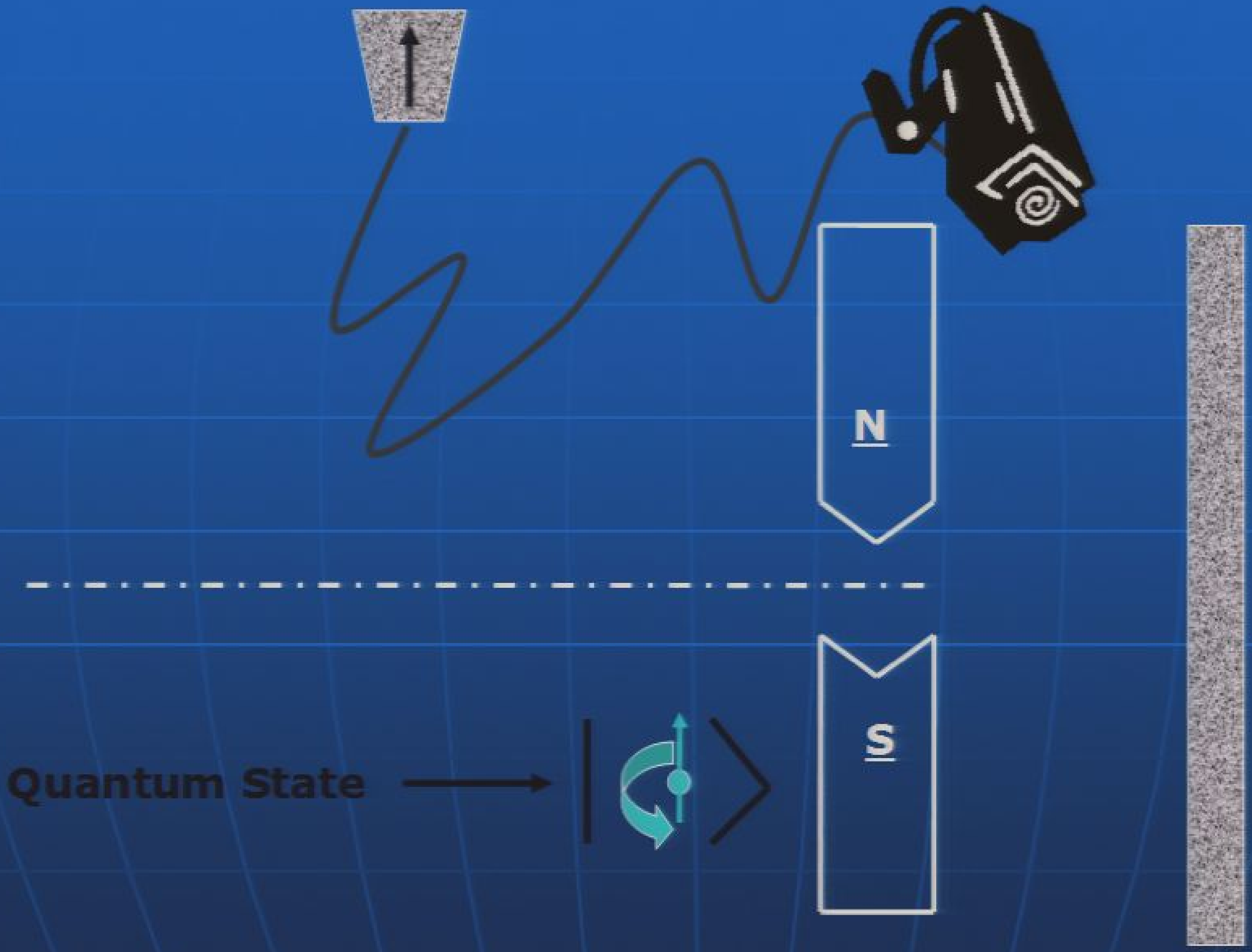
Quantum Measurement Theory

Example: measurement of spin

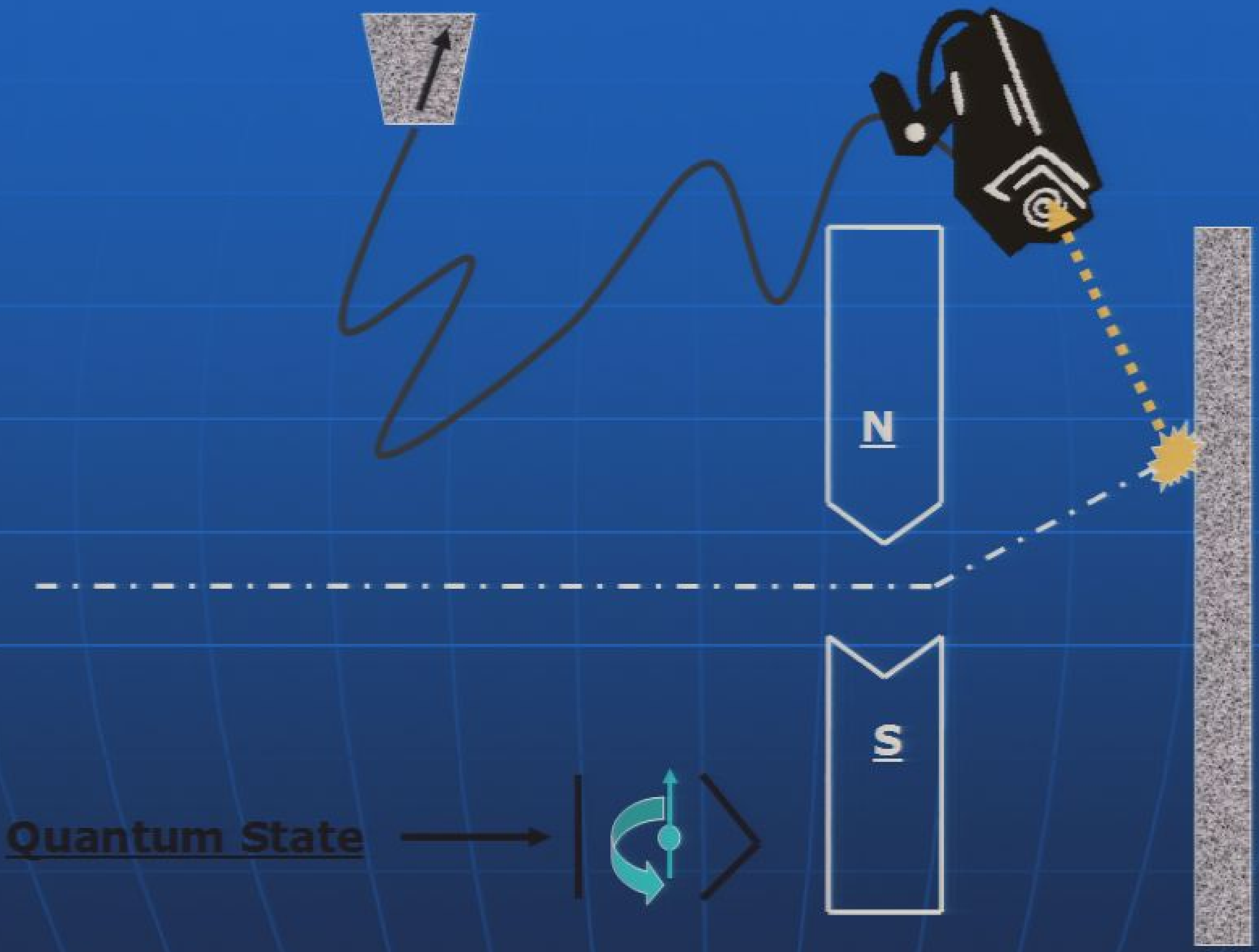




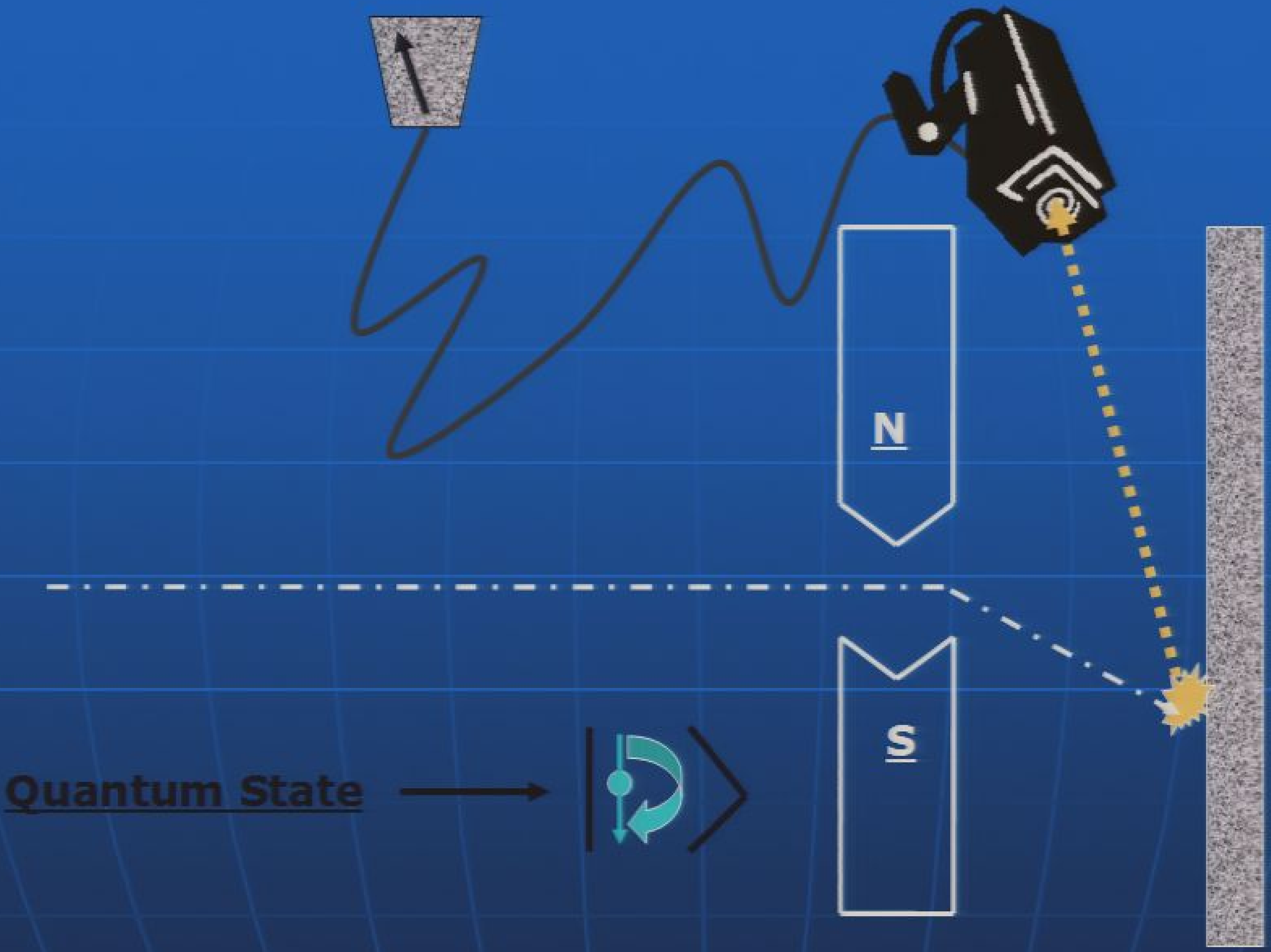
Quantum State



Quantum State →



Quantum State



Quantum State

Evolution of the quantum state

Ideal Experiment:

Superposition Principle II

If two quantum states evolve according to:

$$\Psi_1 \longrightarrow \Phi_1$$

$$\Psi_2 \longrightarrow \Phi_2$$

Then the super position $\alpha\Psi_1+\beta\Psi_2$ will evolve according to:

$$\alpha\Psi_1+\beta\Psi_2 \longrightarrow \alpha\Phi_1+\beta\Phi_2$$

The Measurement Problem

According to Superposition Principle I
the state

is a possible quantum state.
It is not a “strange” state since it is only the electron which is in a superposition of “spin up” and “spin down”.
In fact, this quantum state is routinely created in laboratories.

Superposition Principle II

If two quantum states evolve according to:

$$\Psi_1 \longrightarrow \Phi_1$$

$$\Psi_2 \longrightarrow \Phi_2$$

Then the super position $\alpha\Psi_1+\beta\Psi_2$ will evolve according to:

$$\alpha\Psi_1+\beta\Psi_2 \longrightarrow \alpha\Phi_1+\beta\Phi_2$$

The Measurement Problem

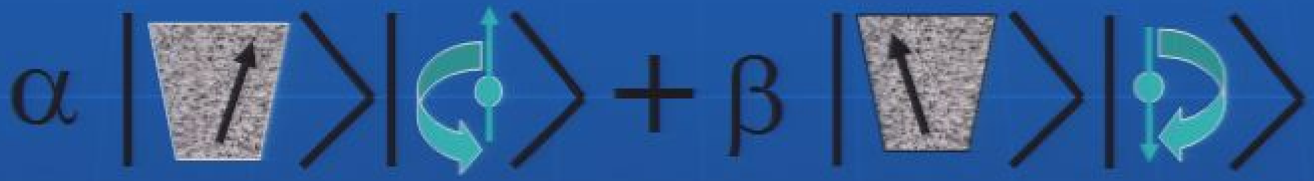
According to Superposition Principle I the state

is a possible quantum state.
It is not a "strange" state since it is only the electron which is in a superposition of "spin up" and "spin down".
In fact, this quantum state is routinely created in laboratories.

According to Superposition Principle II
the state has to evolve according to:

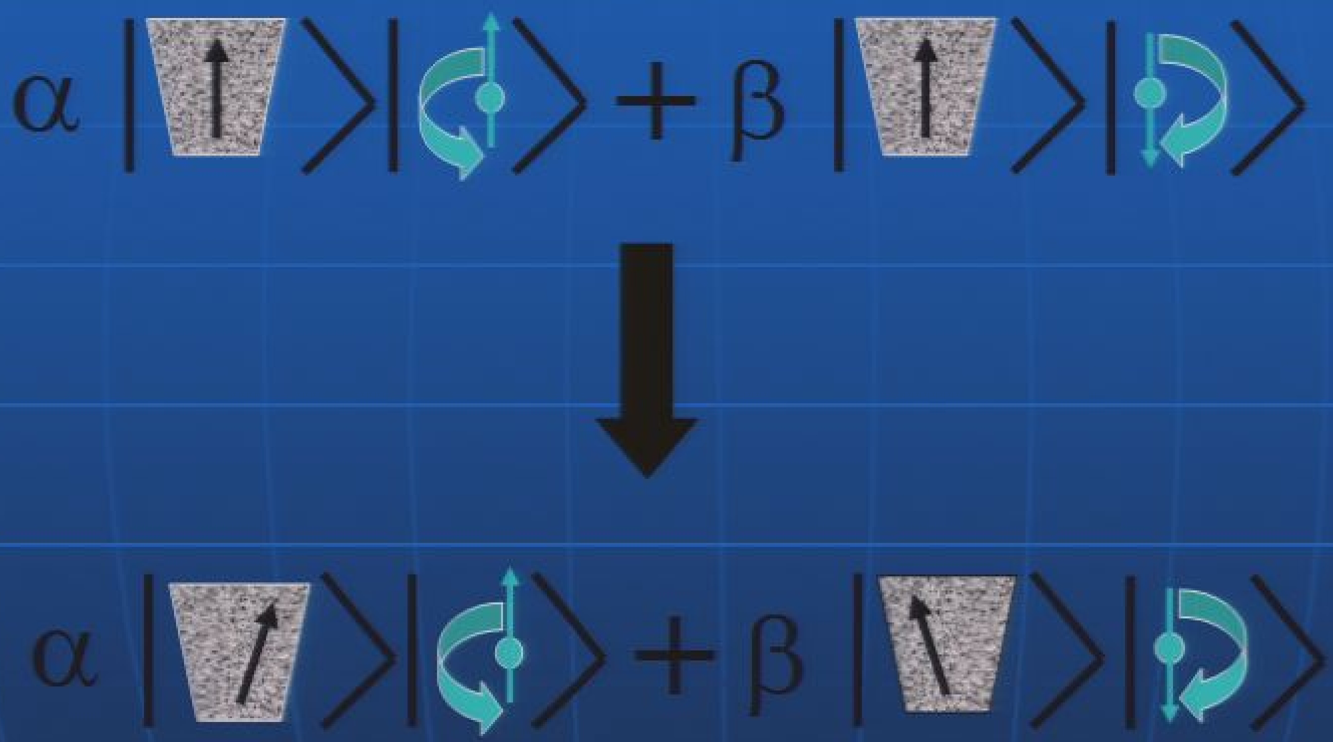
But now we are in trouble!

The state



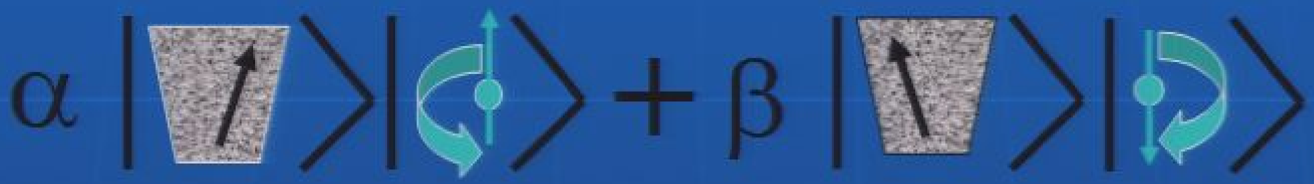
is a superposition of two macroscopically distinct states!

According to Superposition Principle II
the state has to evolve according to:



But now we are in trouble!

The state

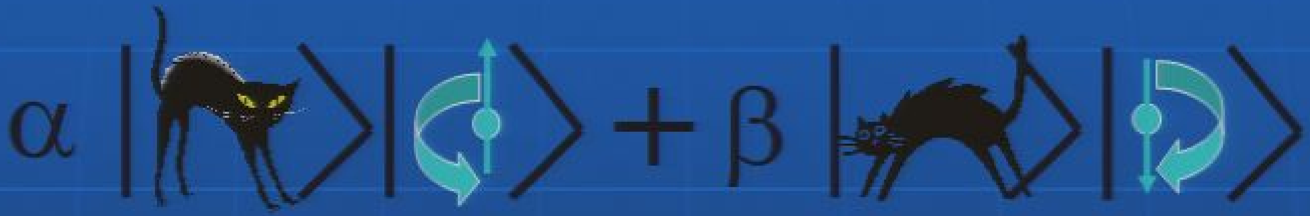


is a superposition of two macroscopically distinct states!

In a quantum experiment the state will in general evolve into a strange superposition of two macroscopically distinct states!

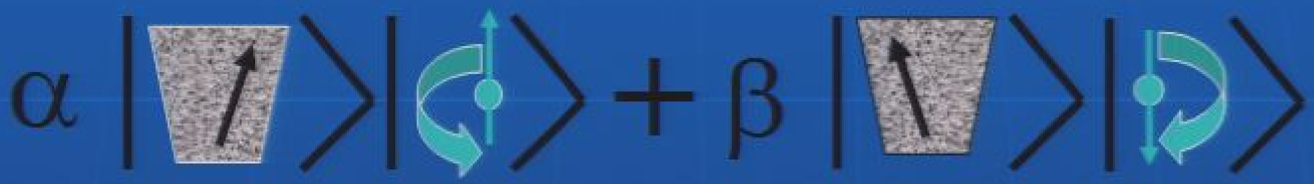
According to quantum theory it is not only electrons that can be here and there at the same time! Also macroscopic objects like the measurement equipment, … and human beings…

… or cats…



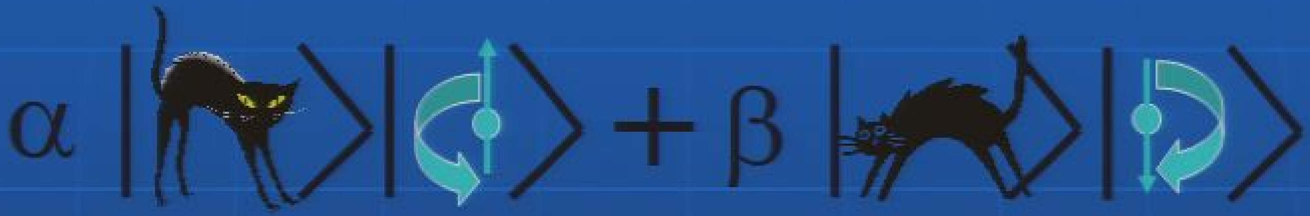
But now we are in trouble!

The state



is a superposition of two macroscopically distinct states!

… or cats…



Different Reactions

"Shut Up! and Calculate" Interpretation
Copenhagen Interpretation
Von Neumann-Dirac Collapse Interpretation
Many Worlds Interpretation
Quantum Information Interpretation
Hidden Variable Interpretation

Copenhagen Interpretation

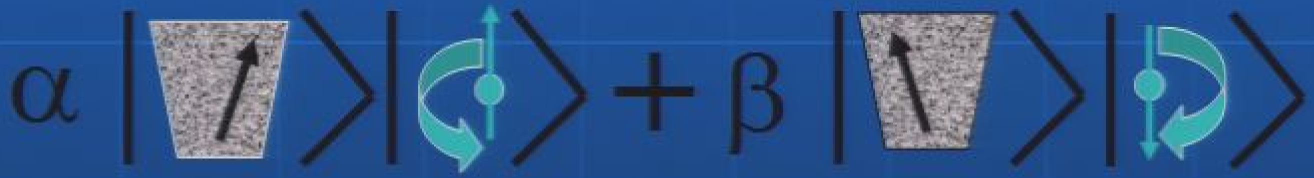
- The world should be divided into two parts: the quantum system one is measuring, and the classical apparatus that is doing the measuring
- The quantum system should be treated according to quantum theory
- The apparatus should be treated according to classical physics.
- The interaction between a quantum system and a classical system (i.e the measurement process) is regarded as unanalyzable. One cannot give a precise scientific description of what is going on in a measurement process.

Problems

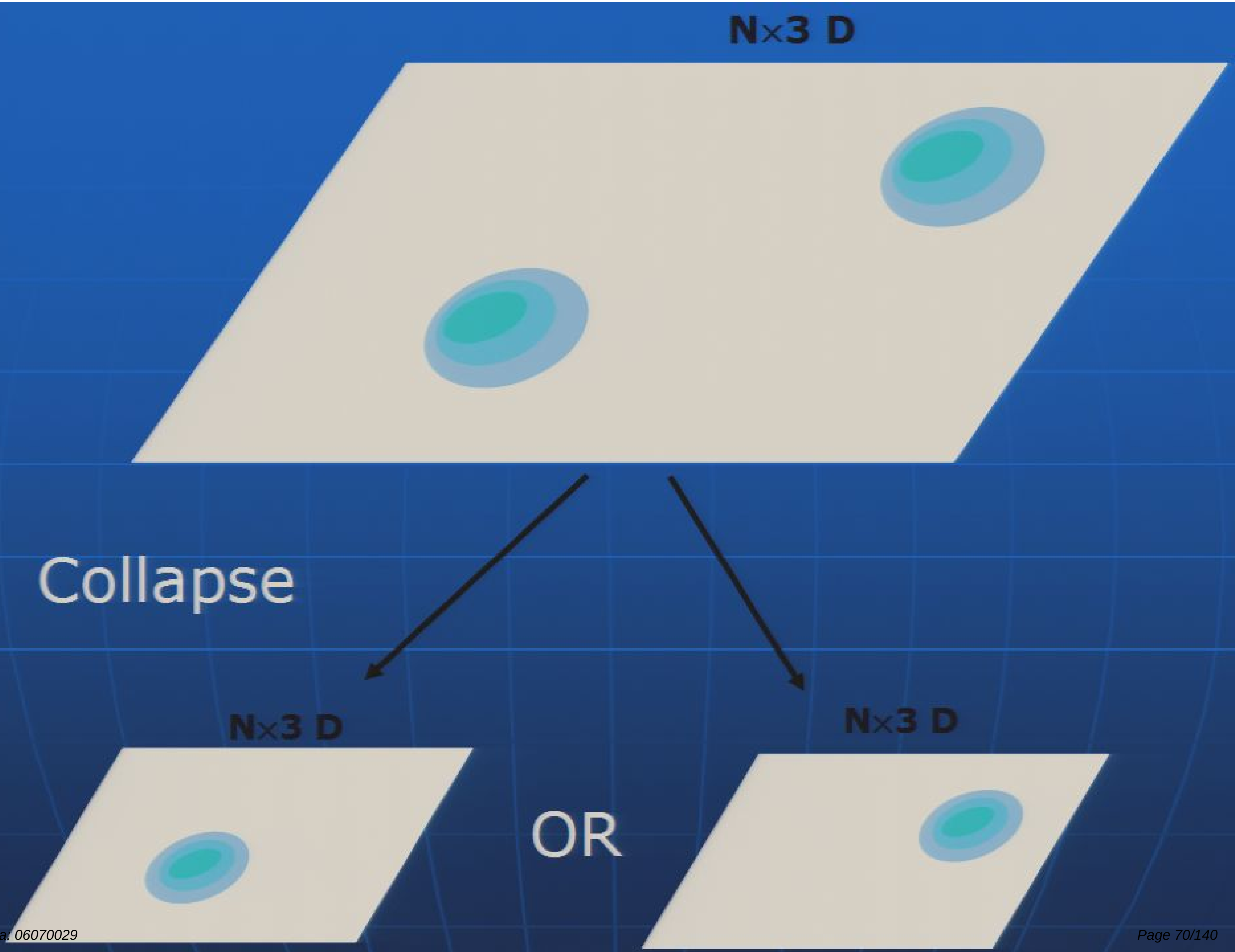
- How do I know what is a quantum system and what is a classical apparatus? A classical apparatus is made out of atoms! How many atoms do I need in order to be sure that it is a classical system?
- No satisfactory answer given by Bohr.
- And isn't it non-scientific to claim that it is scientifically impossible to analyze what happens during a measuring process?

Von Neumann & Dirac

- When macroscopic bodies are involved the wave-function



Collapses into



N×3 D

Collapse

N×3 D

OR

N×3 D

Problems

- If the wave-function collapses then when is this supposed to occur? How big must a “classical” apparatus be in order for a collapse to occur?
- And where are the mathematical equations that tell me EXACTLY how and when the wave-function collapses?

Collapse theories

- Pearle, Ghirardi, Rimini, Weber, modified quantum theory. Collapse is a physical process.
- Energy is not conserved.
- Fully relativistic collapse theories are difficult to make: infinite energy production per unit time!
- “Almost”-relativistic ones are possible to construct (Pearle).

Many Worlds

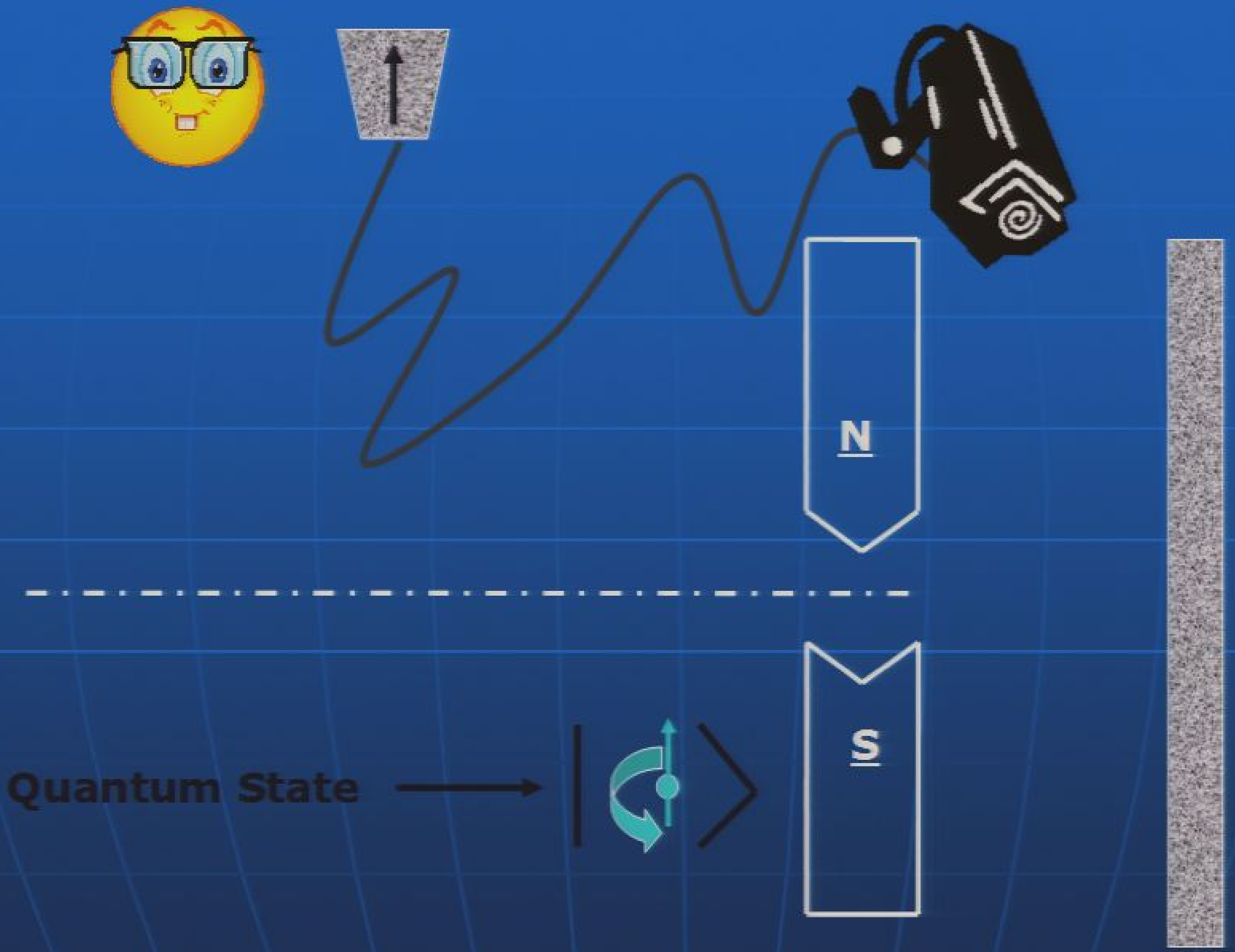
- Let’s take quantum theory REALLY seriously and fully accept these strange superpositions.

Collapse theories

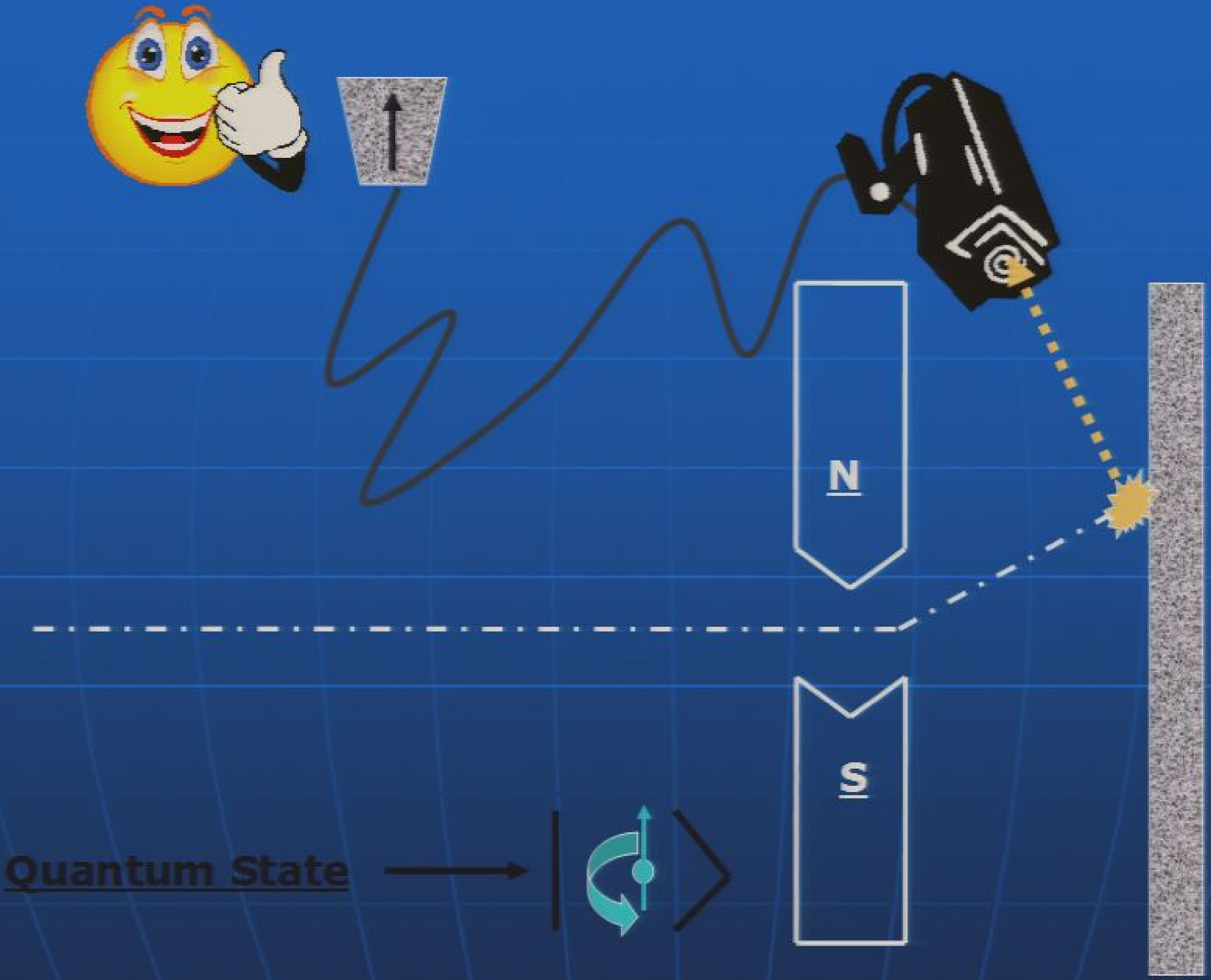
- Pearle, Ghirardi, Rimini, Weber, modified quantum theory. Collapse is a physical process.
- Energy is not conserved.
- Fully relativistic collapse theories are difficult to make: infinite energy production per unit time!
- “Almost”-relativistic ones are possible to construct (Pearle).

Many Worlds

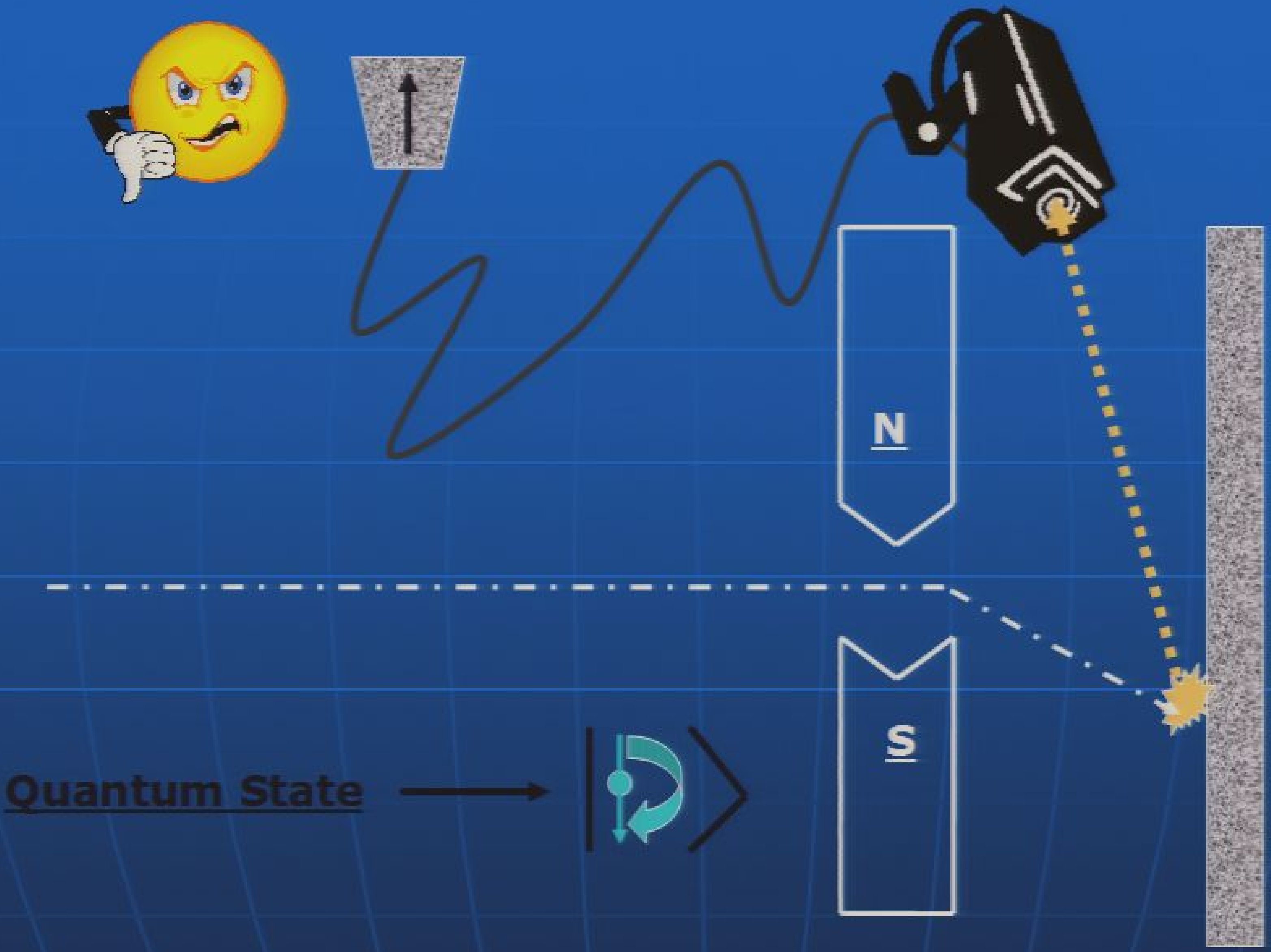
- Let's take quantum theory REALLY seriously and fully accept these strange superpositions.



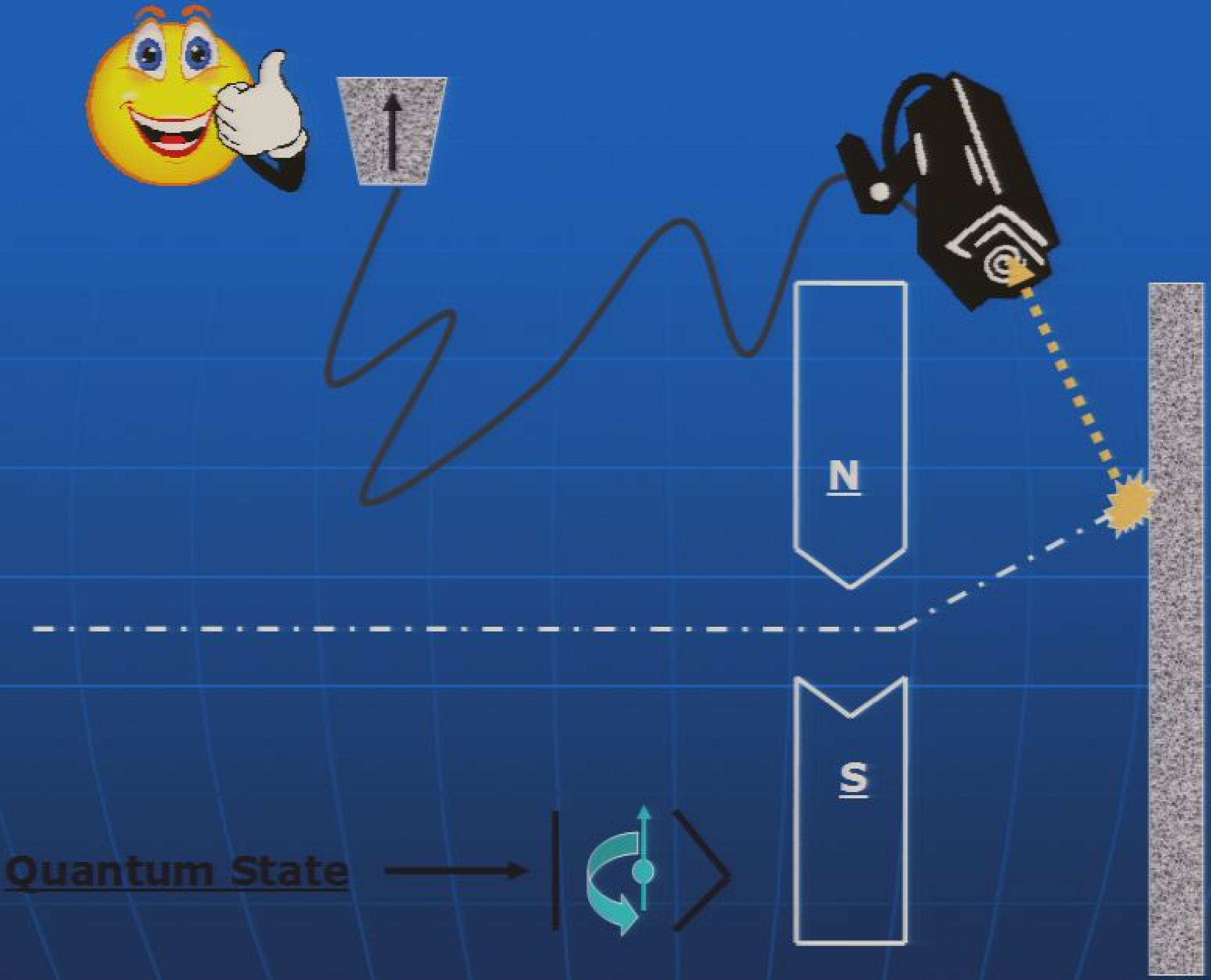
Quantum State



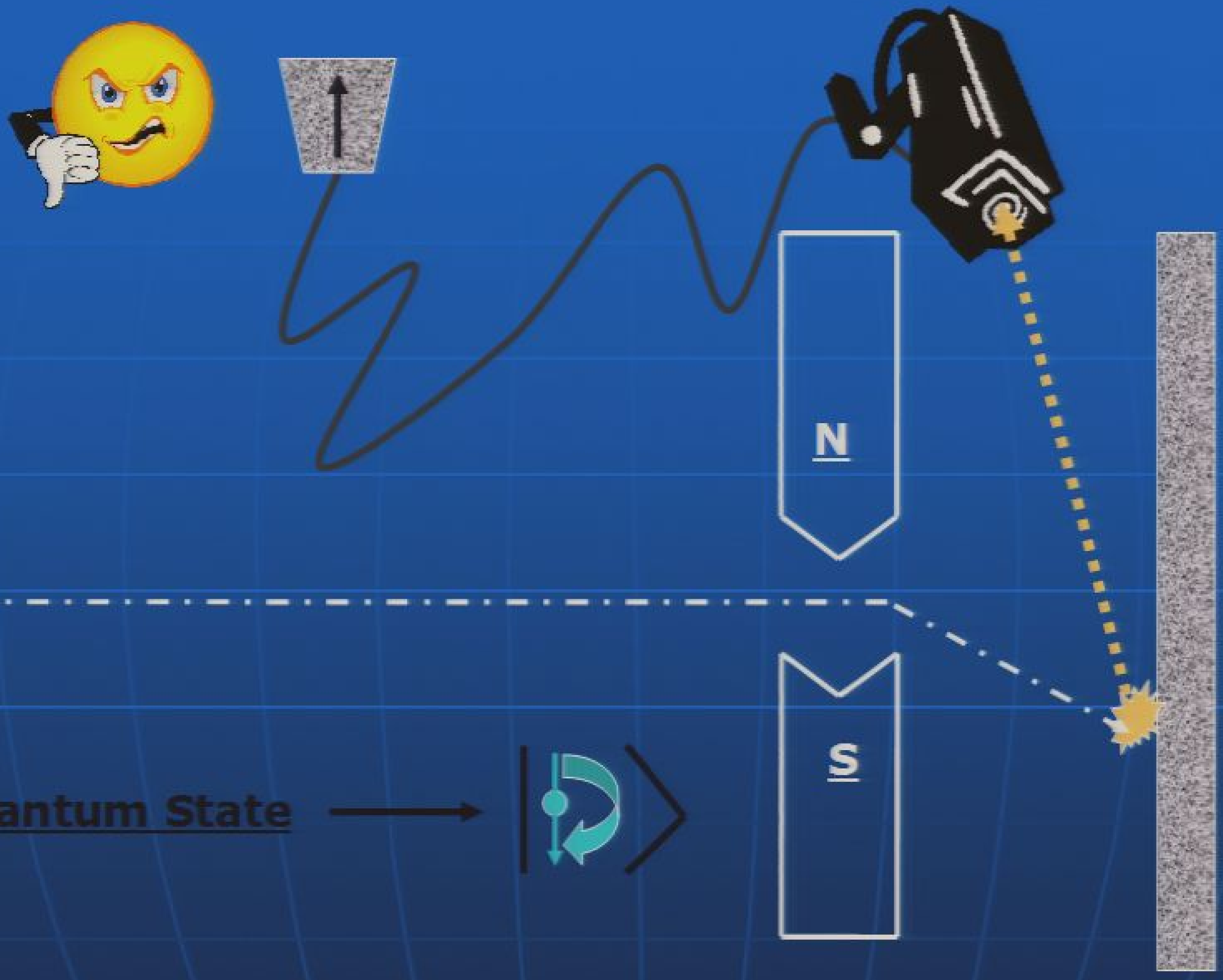
Quantum State



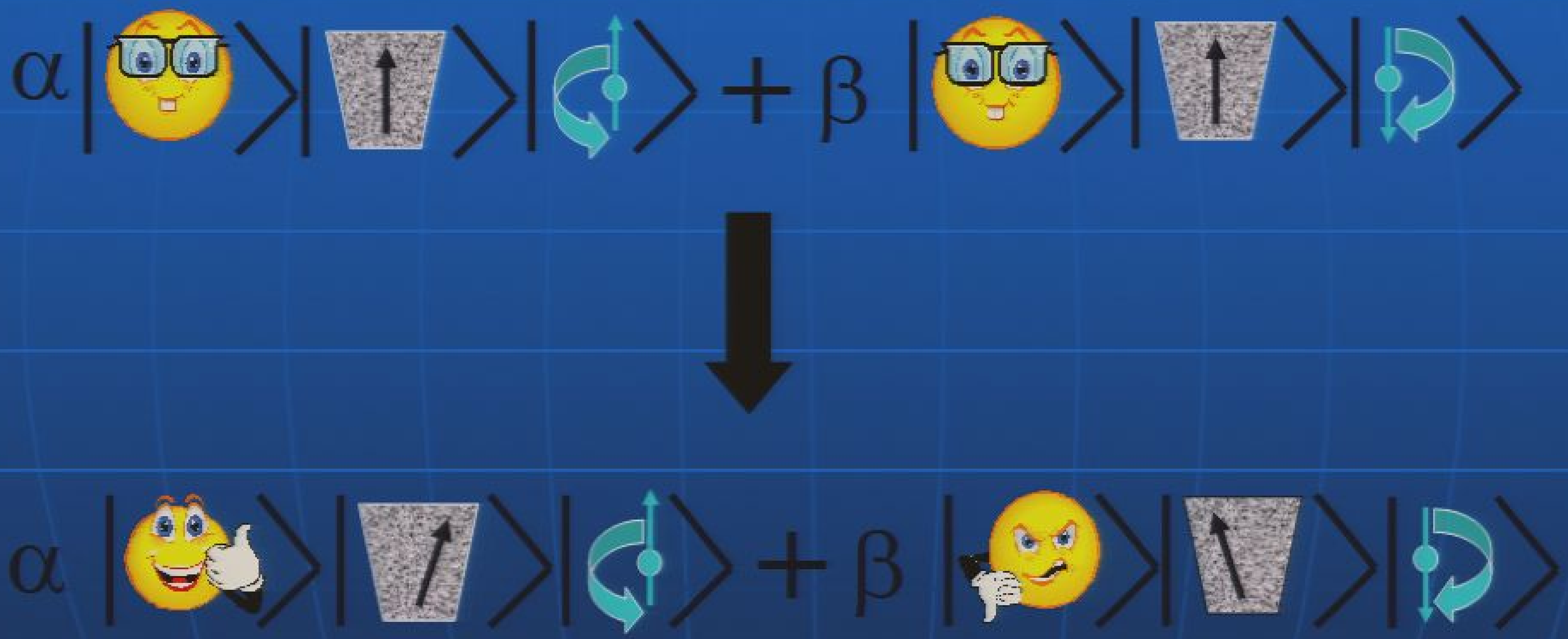
Quantum State →



Quantum State →

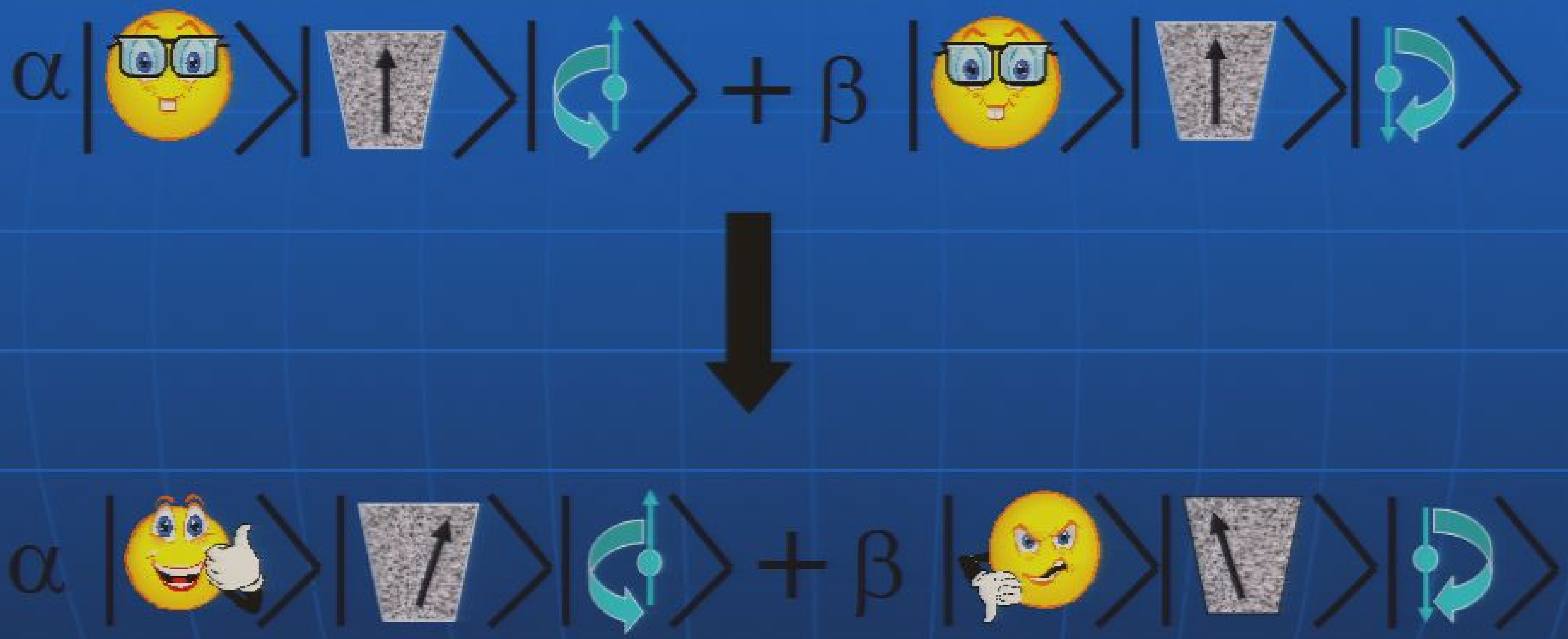


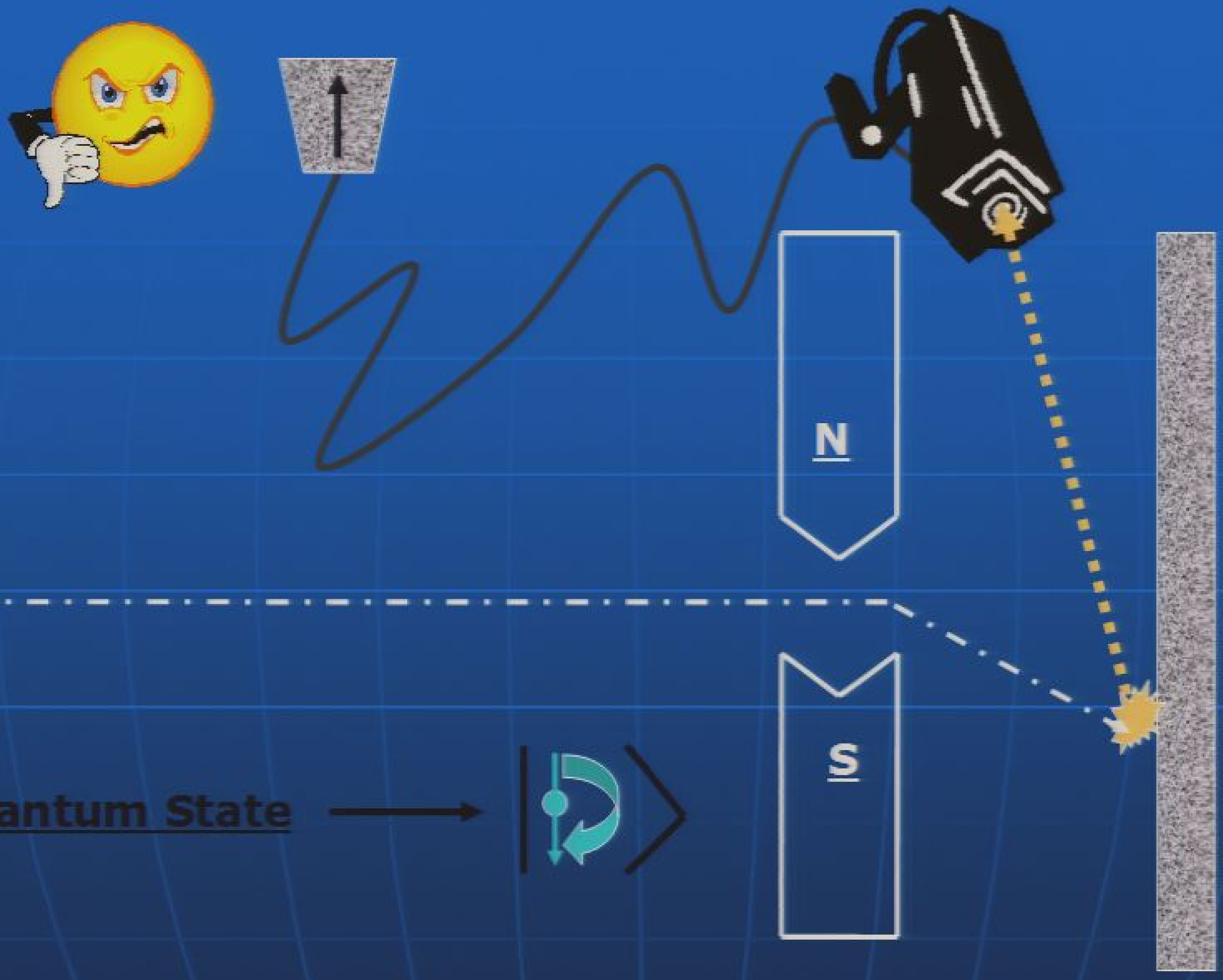
Quantum State →


α
+ β
α
+ β

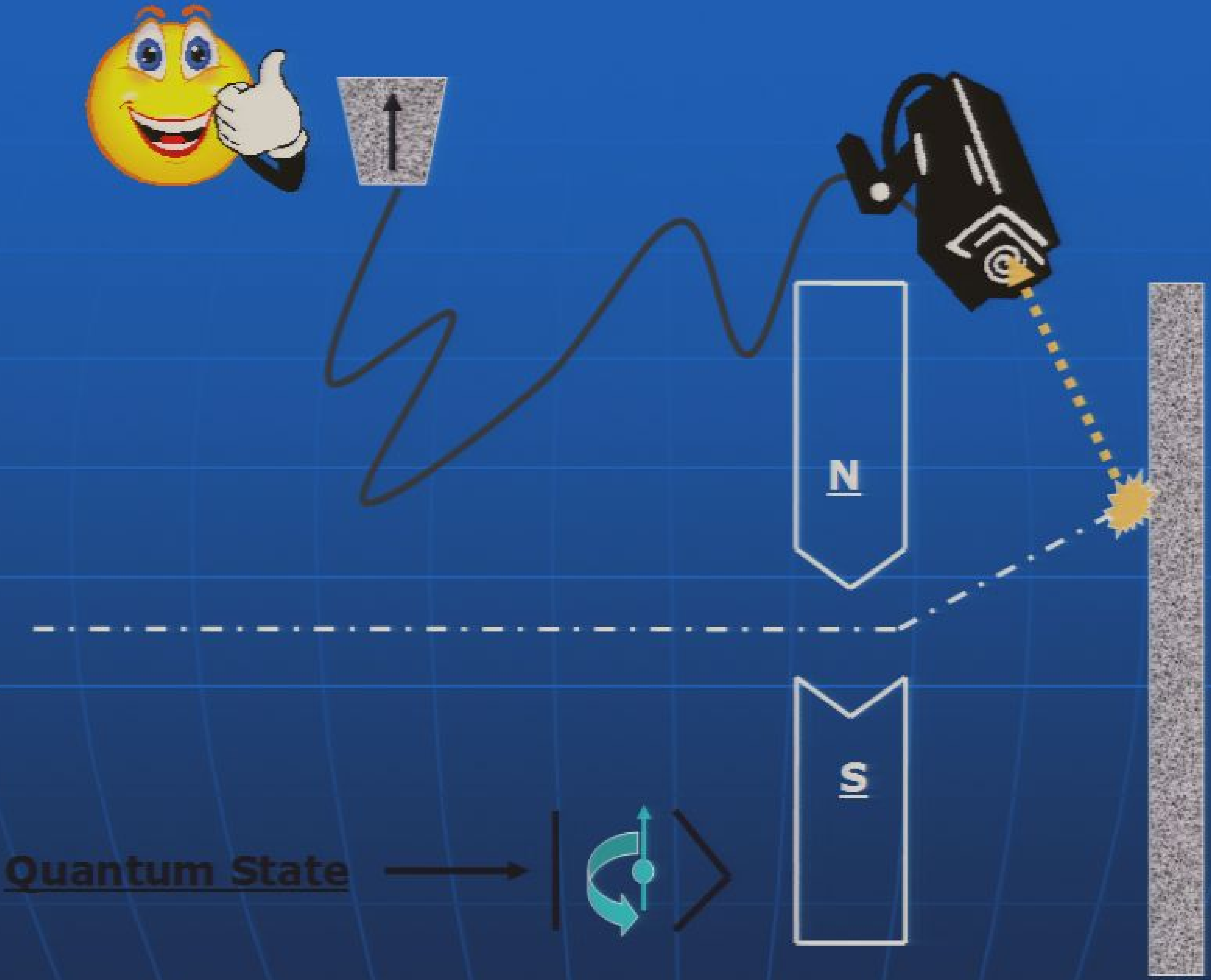
Problems

- Hard to understand why we see quantum statistics.
- Preferred basis problem: how can we identify the different worlds in the wave-function?
- We can never verify that these parallel worlds are really “out there”.

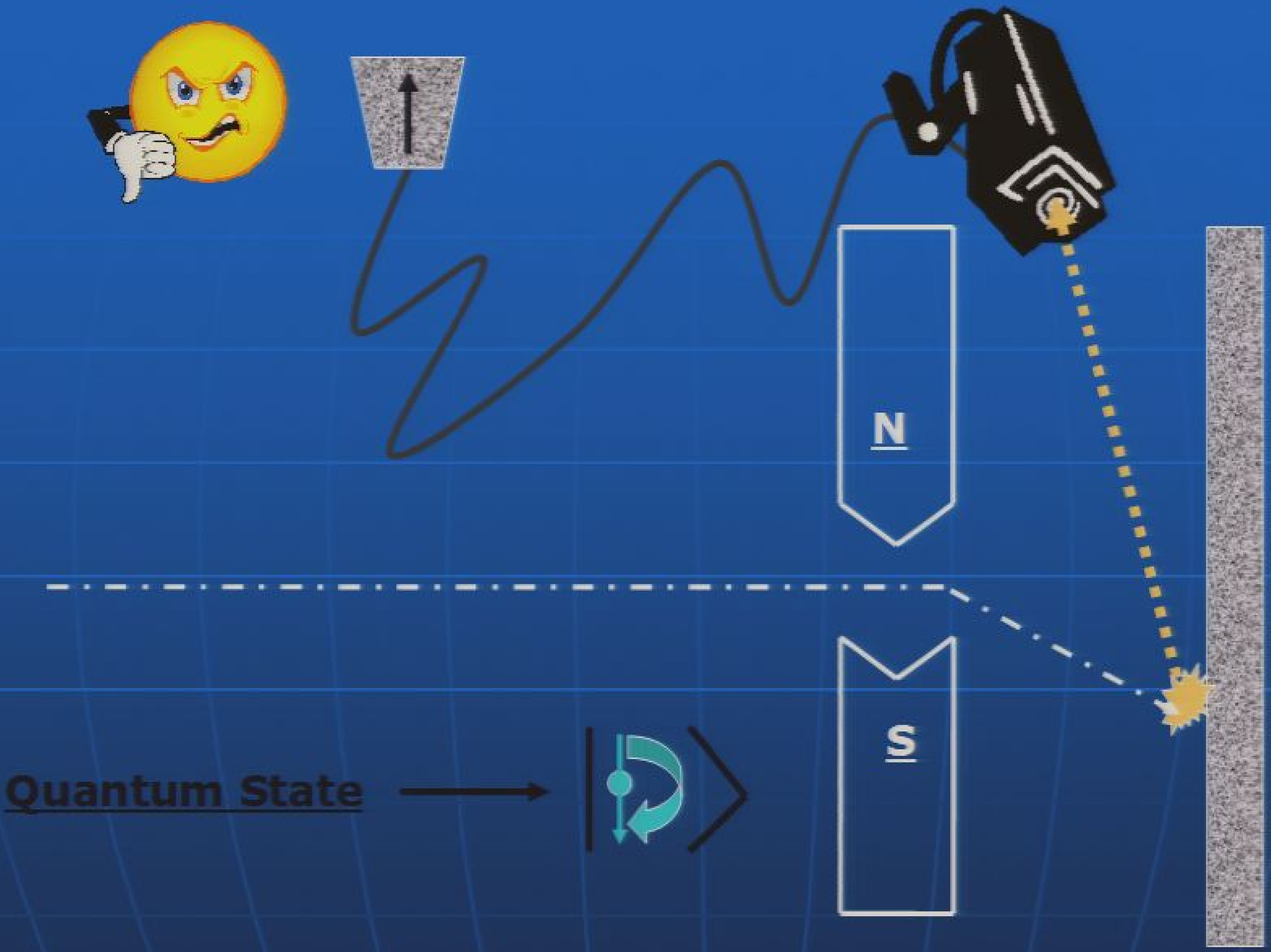

α
+ β
α
+ β



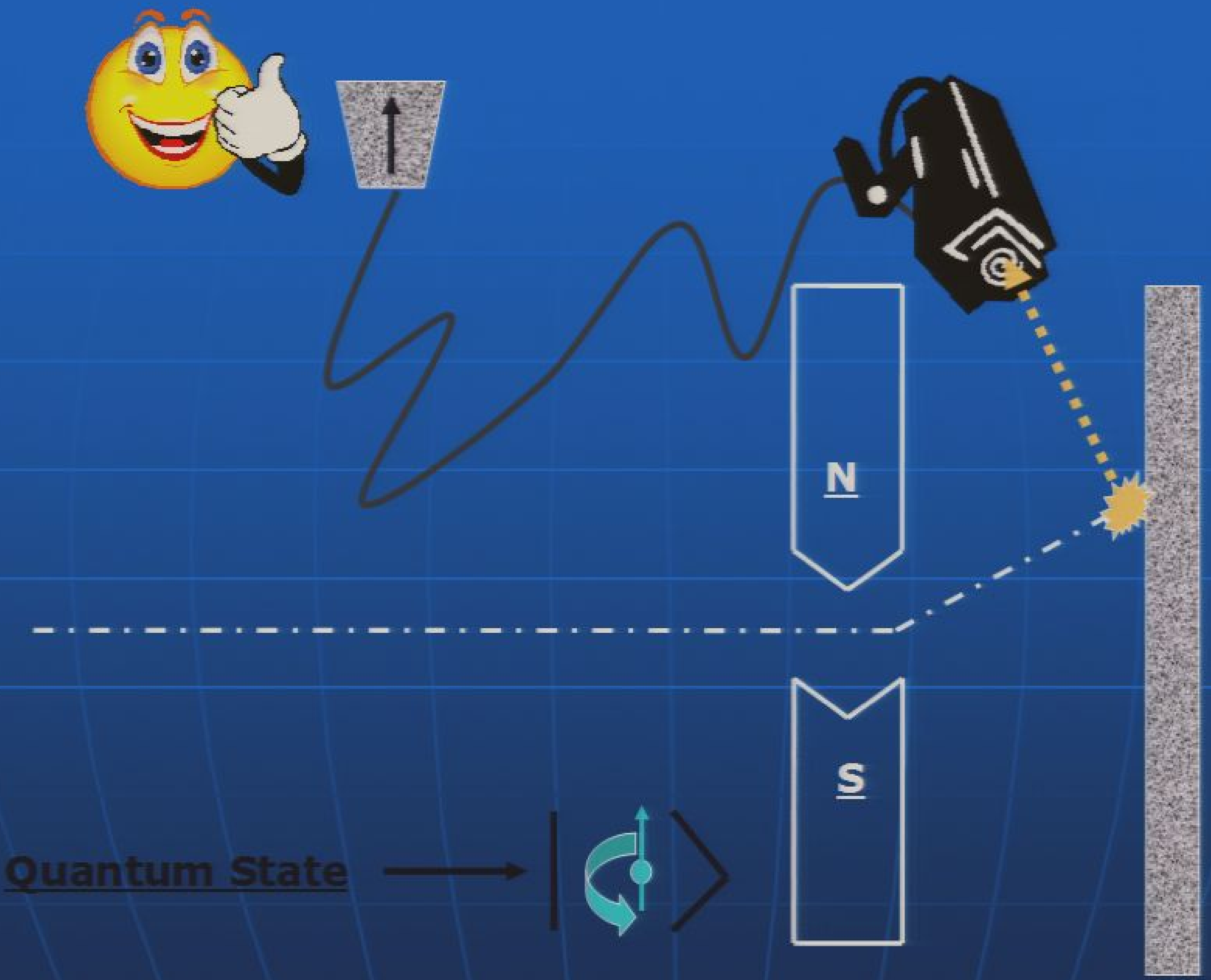
Quantum State →



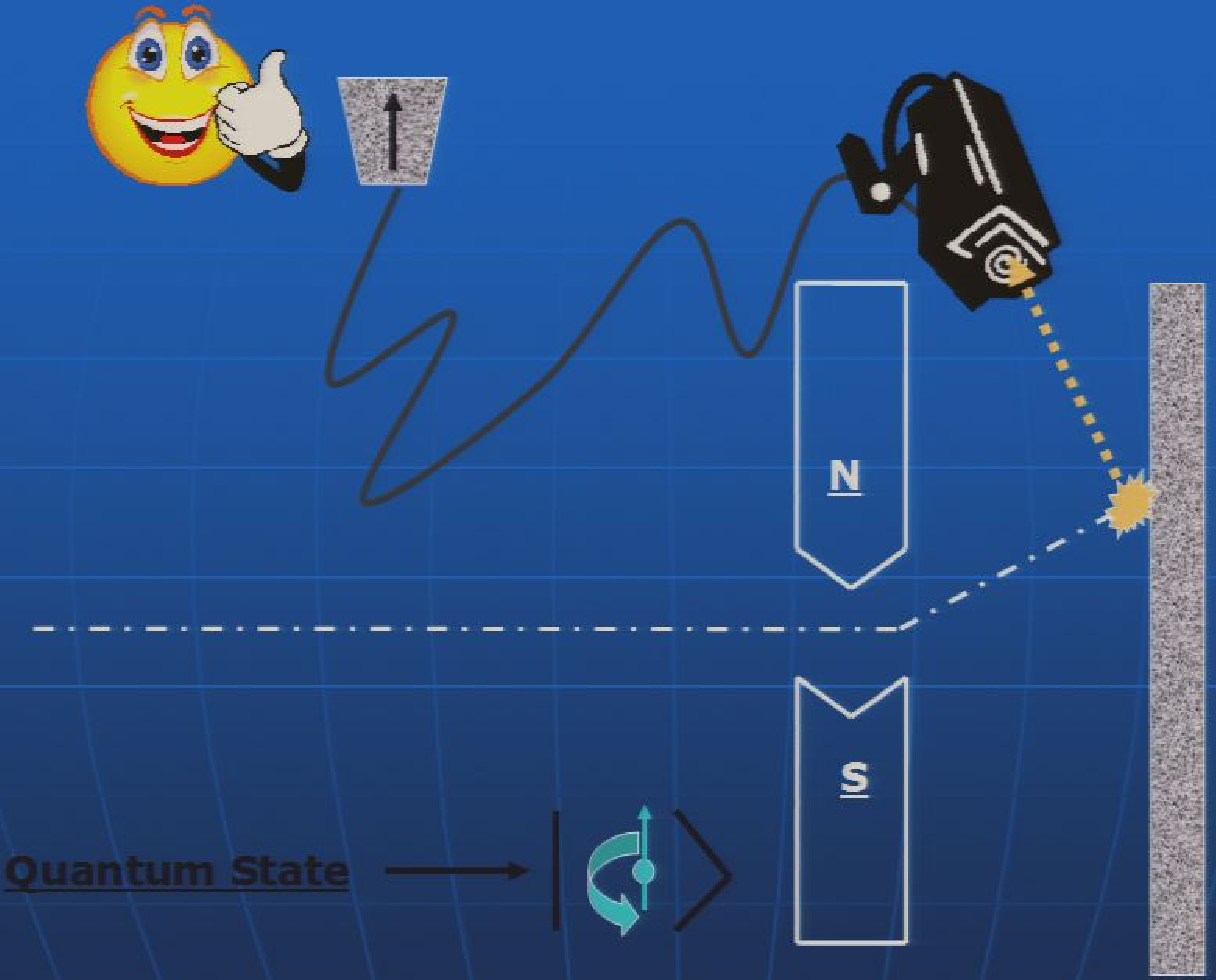
Quantum State



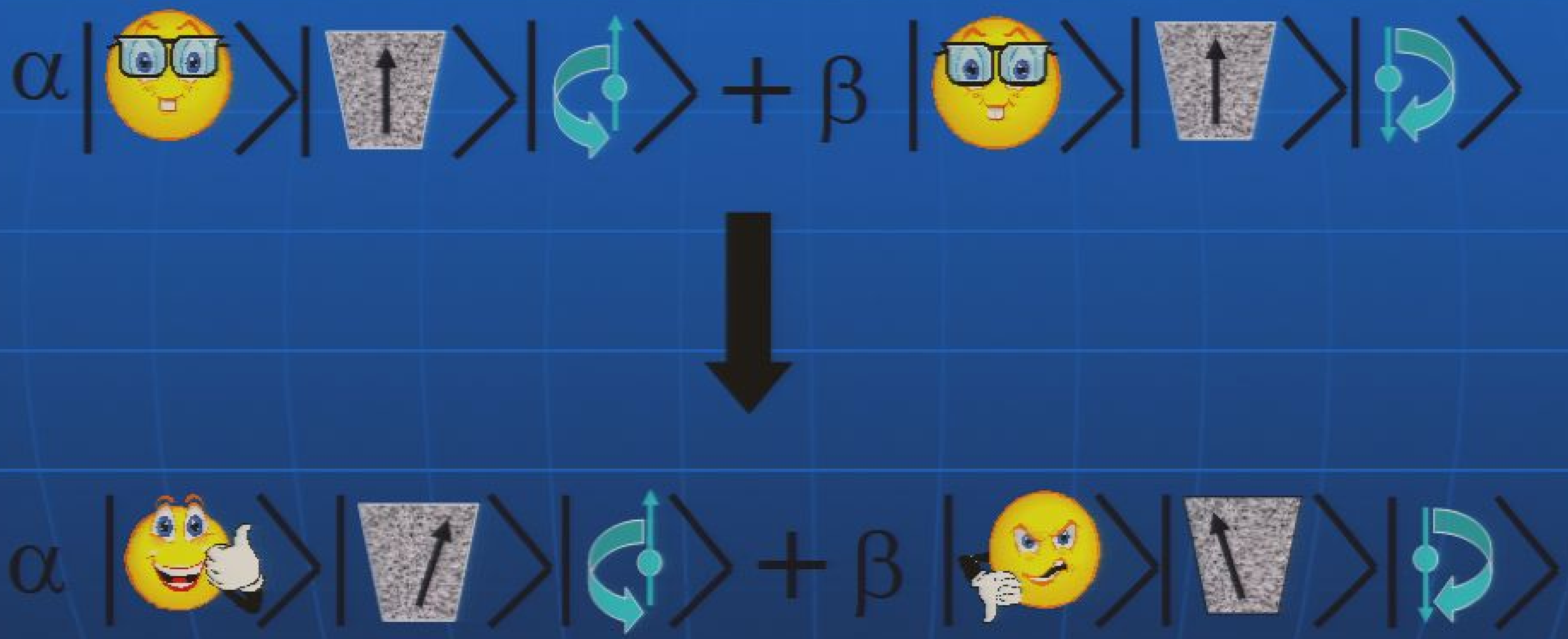
Quantum State



Quantum State →

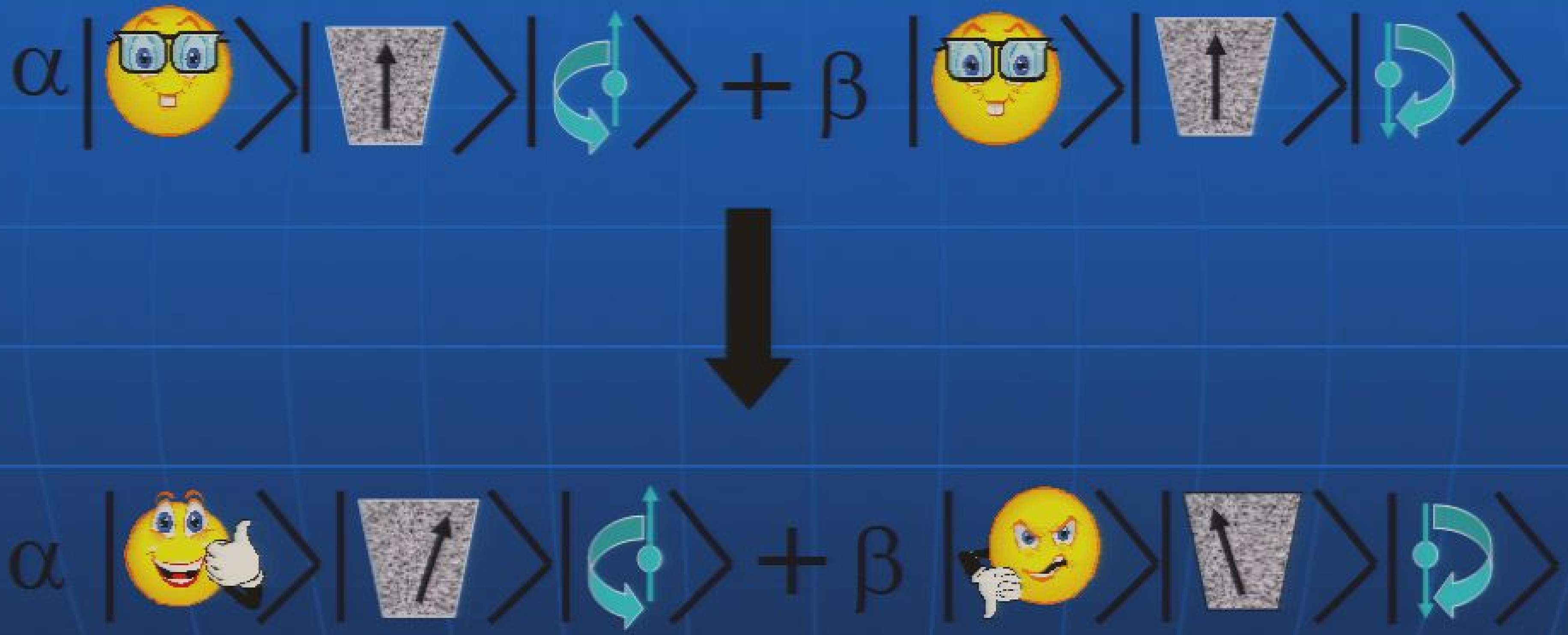


Quantum State


α
+ β
α
+ β

Problems

- Hard to understand why we see quantum statistics.
- Preferred basis problem: how can we identify the different worlds in the wave-function?
- We can never verify that these parallel worlds are really “out there”.


α
+ β
α
+ β

Problems

- Hard to understand why we see quantum statistics.
- Preferred basis problem: how can we identify the different worlds in the wave-function?
- We can never verify that these parallel worlds are really “out there”.

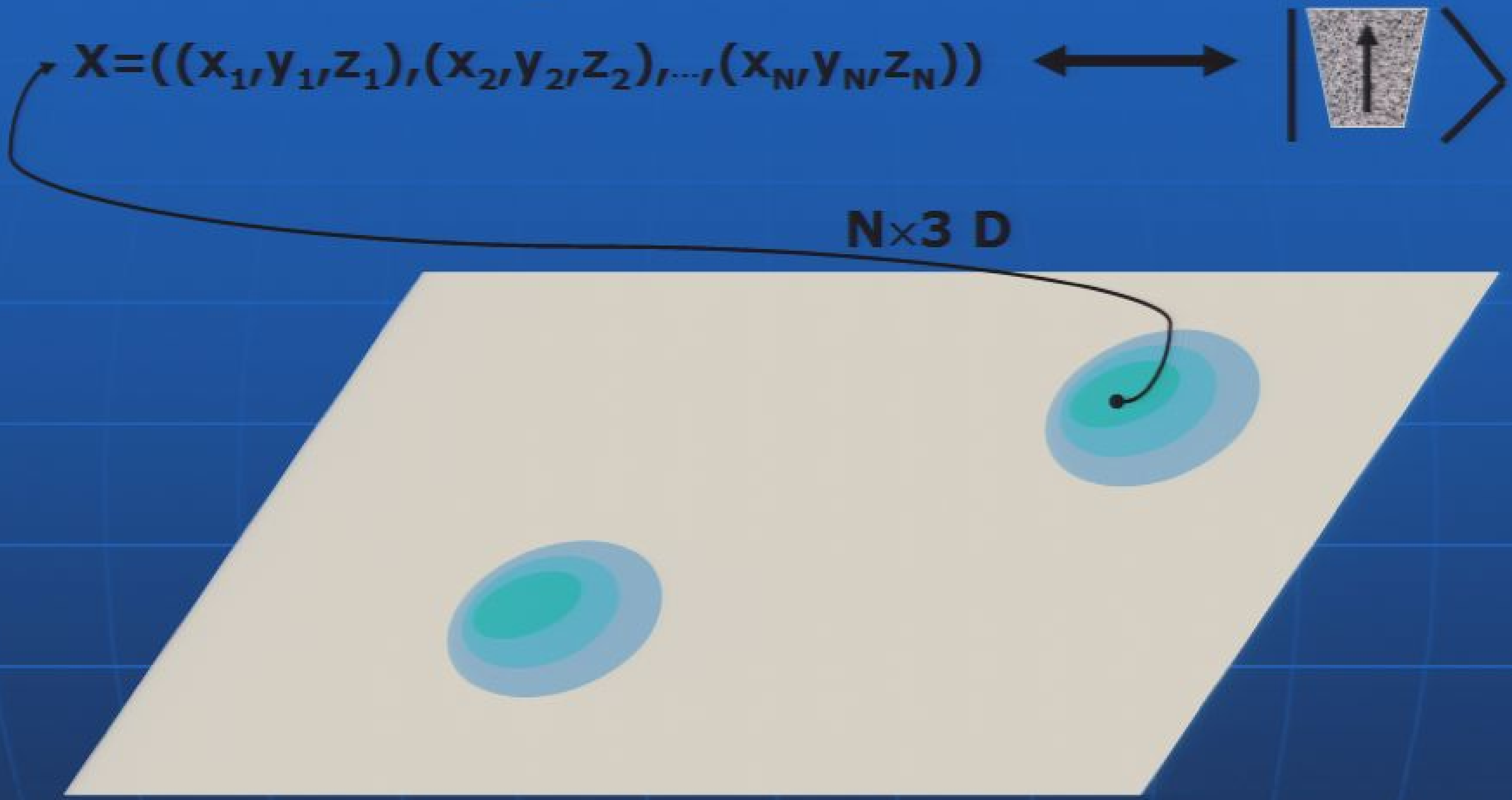
It’s all about information!

- The wave-function does not describe actual reality, but only the knowledge of an ideal observer.
- When an observer obtains information about the system he updates the quantum state.

Problems

- Knowledge about what? Knowledge about the outcome of an experiment?
- Ok, but if you are claiming to say something precise here you better specify exactly what you mean by an "an experiment". Is it perhaps the interaction between a classical apparatus and a quantum system?
- We again run into the same problem we had with the Copenhagen interpretation.

deBroglie-Bohm theory



$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

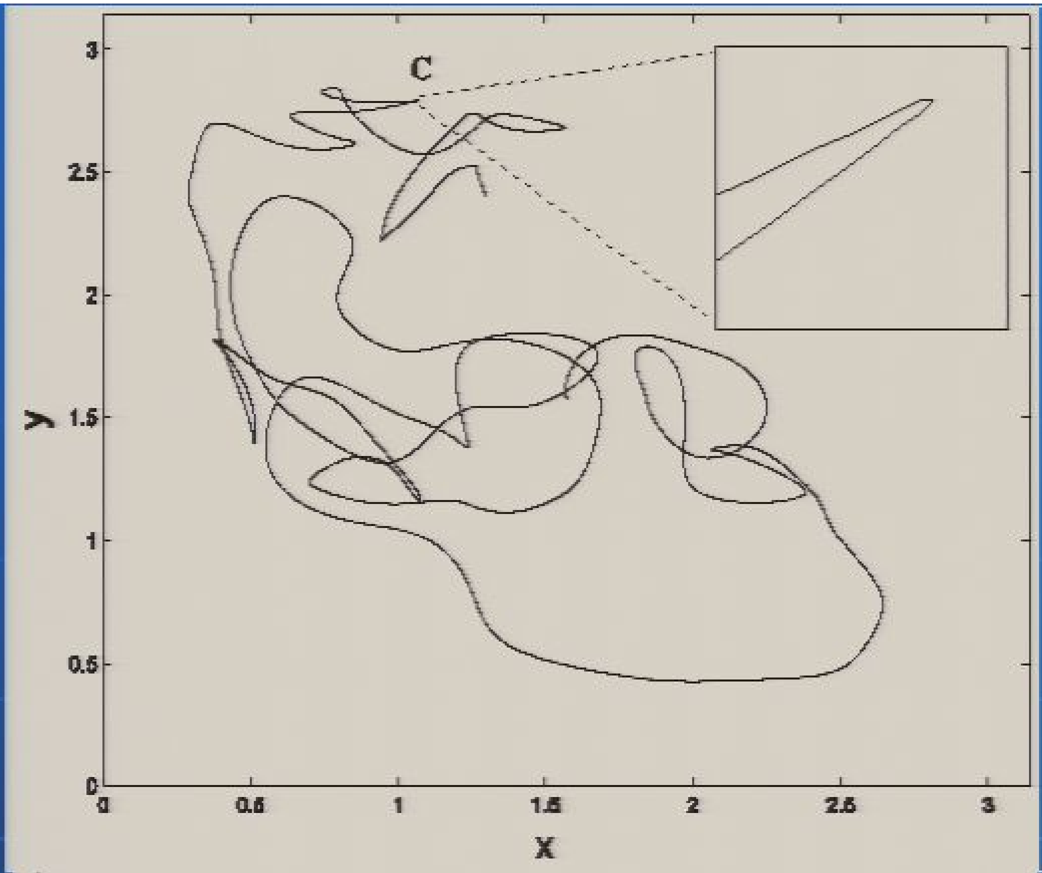
A system is described by $(\Psi(x),X(t))$.

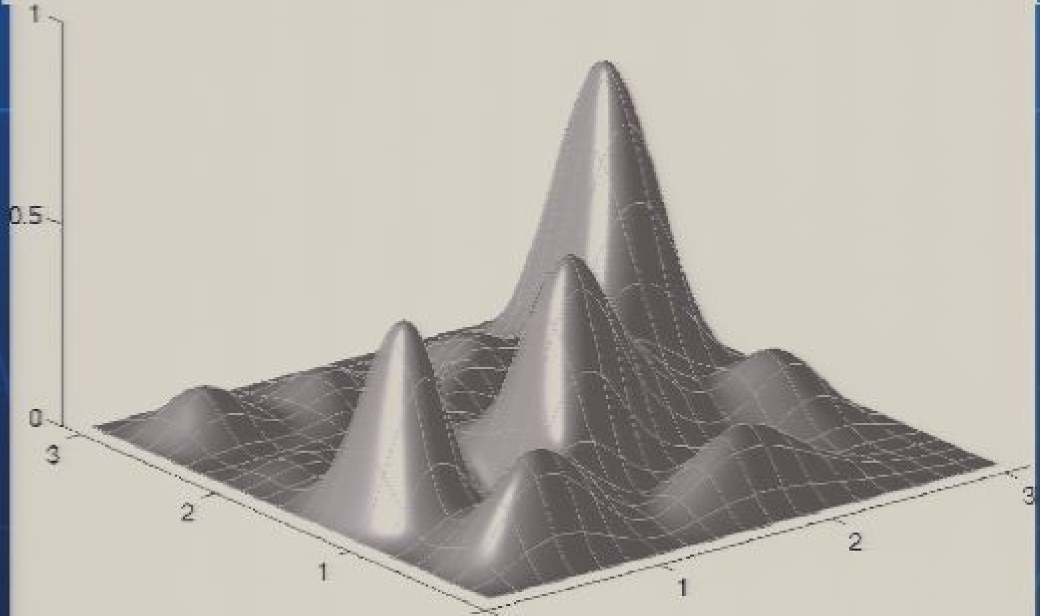
Dynamics

In classical theory X evolves according to Newtons laws F=mA.

In deBroglie-Bohm theory X evolves according to the non-classical equations

$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$


C
y
0
0.5
1
1.5
2
2.5
3
x
0
0.5
1
1.5
2
2.5
3

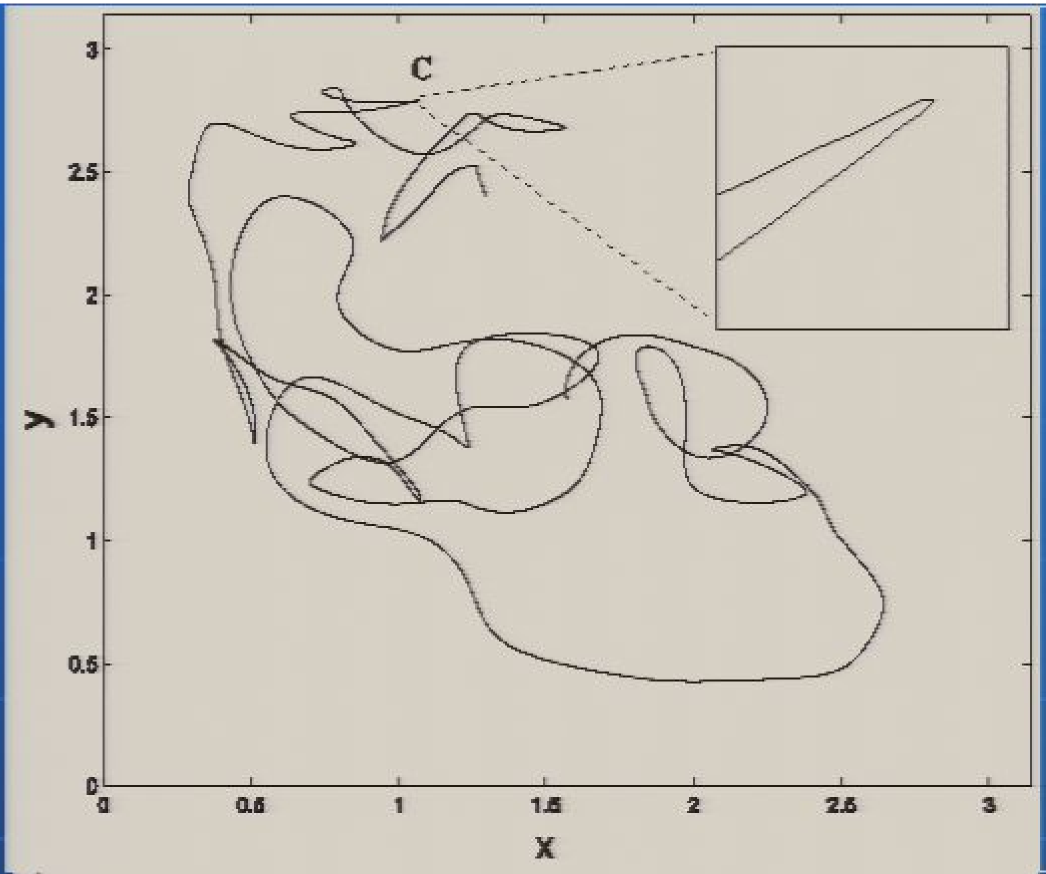

1
0.5
0
3
2
1
3
2
1

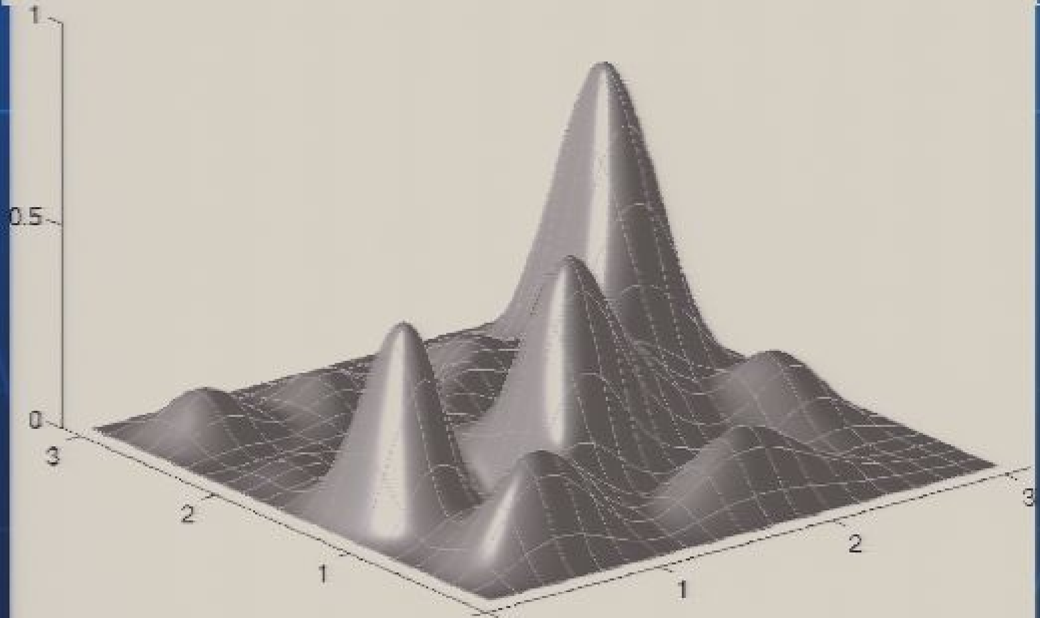
Dynamics

In classical theory X evolves according to Newtons laws F=mA.

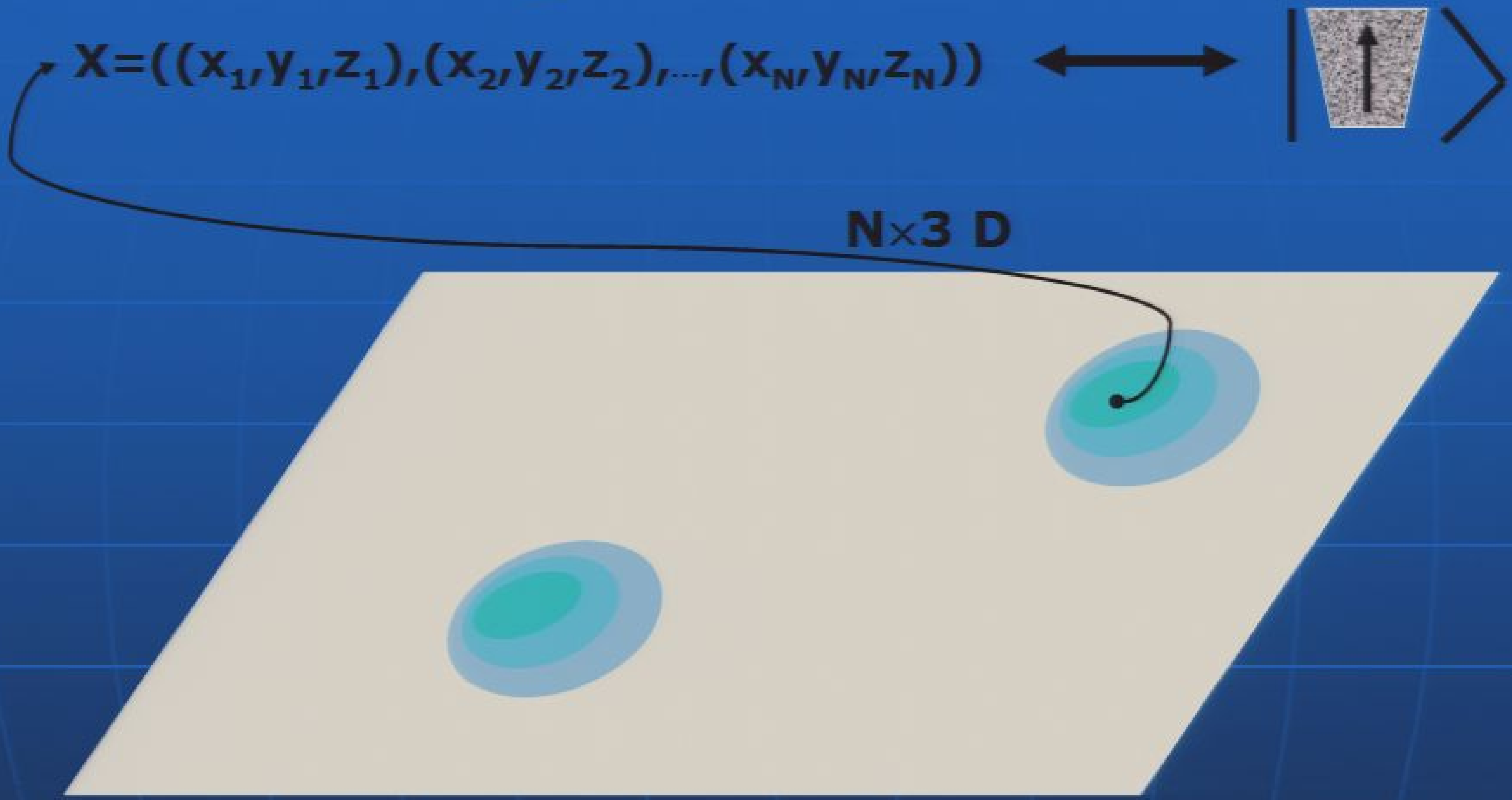
In deBroglie-Bohm theory X evolves according to the non-classical equations

$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$


C
y
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
X


1
0.5
0
3
2
1
3
2
1

deBroglie-Bohm theory



$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow$

A system is described by (Ψ(x),X(t)).

Dynamics

In classical theory X evolves according to Newtons laws F=mA.

In deBroglie-Bohm theory X evolves according to the non-classical equations

$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$

Good News

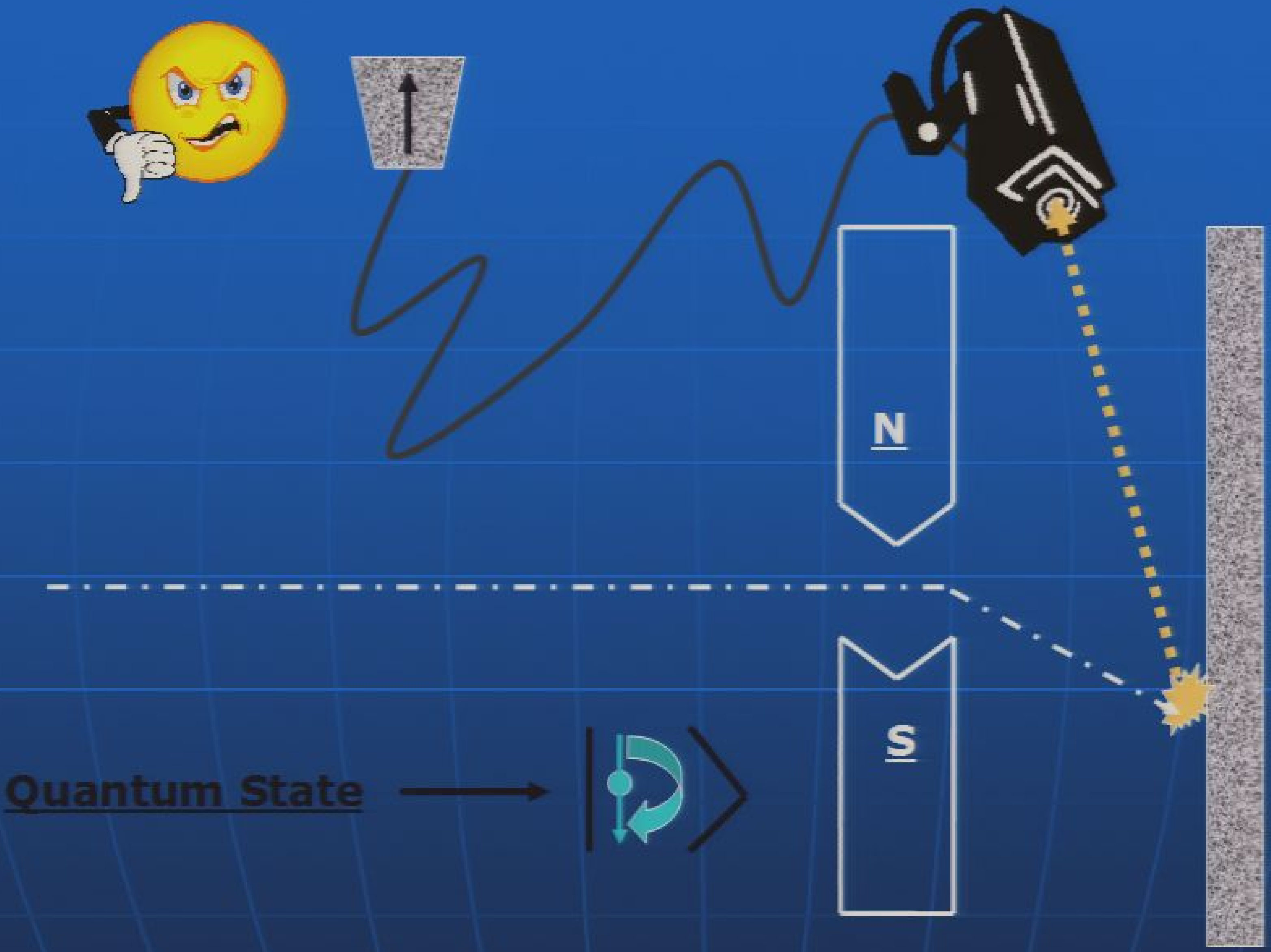
The theory is completely well defined, even deterministic, reproduces all the predictions of quantum theory (also also relativistic quantum theory) and the superposition principle is still valid.

dBB is a much richer theory with quantum theory emerging only in quantum equilibrium.

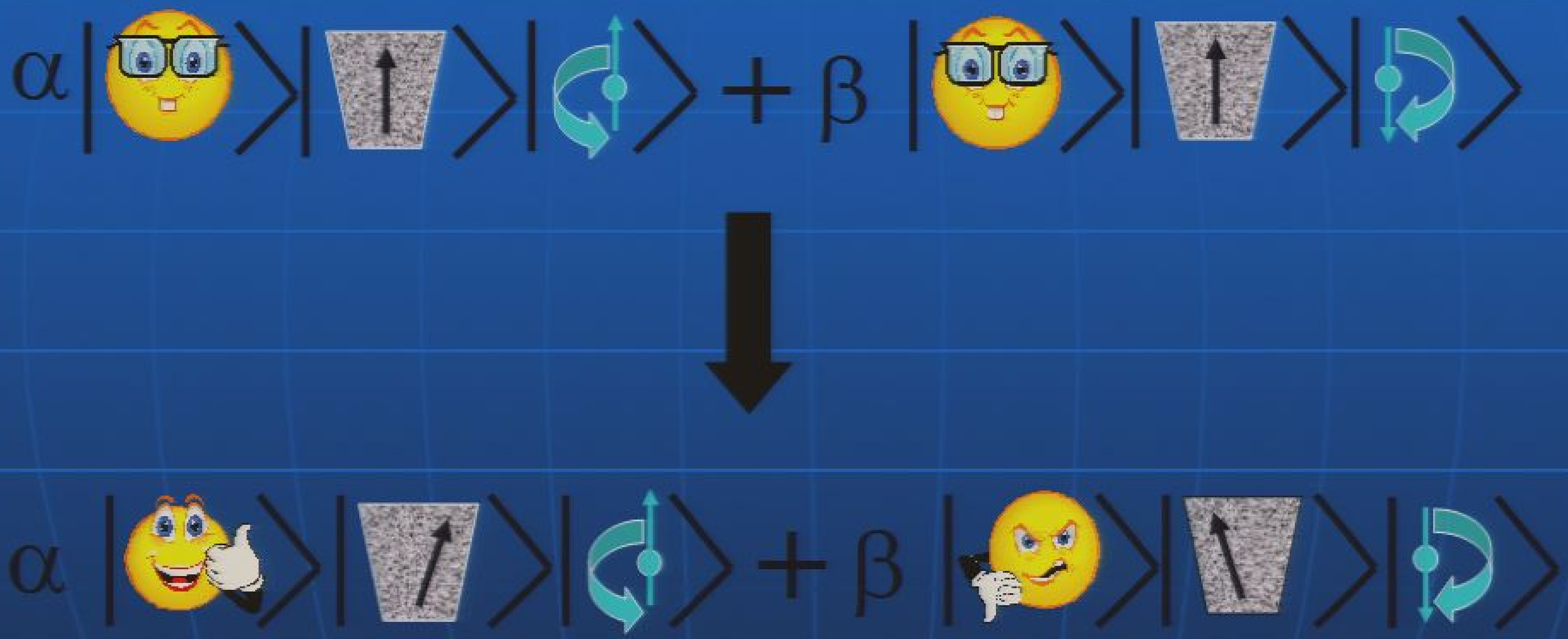
Explains the quantum statistics as a feature of quantum equilibrium.

Problems

- The universe according to this theory seems rather strange. There are two things that make up the world i) the particles in 3D space ii) the wave-function that “lives” in 3N D configuration space.
- The wave-function is fundamentally unobservable. The world we see is represented by the configuration X(t) just as in Newtonian physics.
- Empty wave problem.



Quantum State →


α
+ β
α
+ β

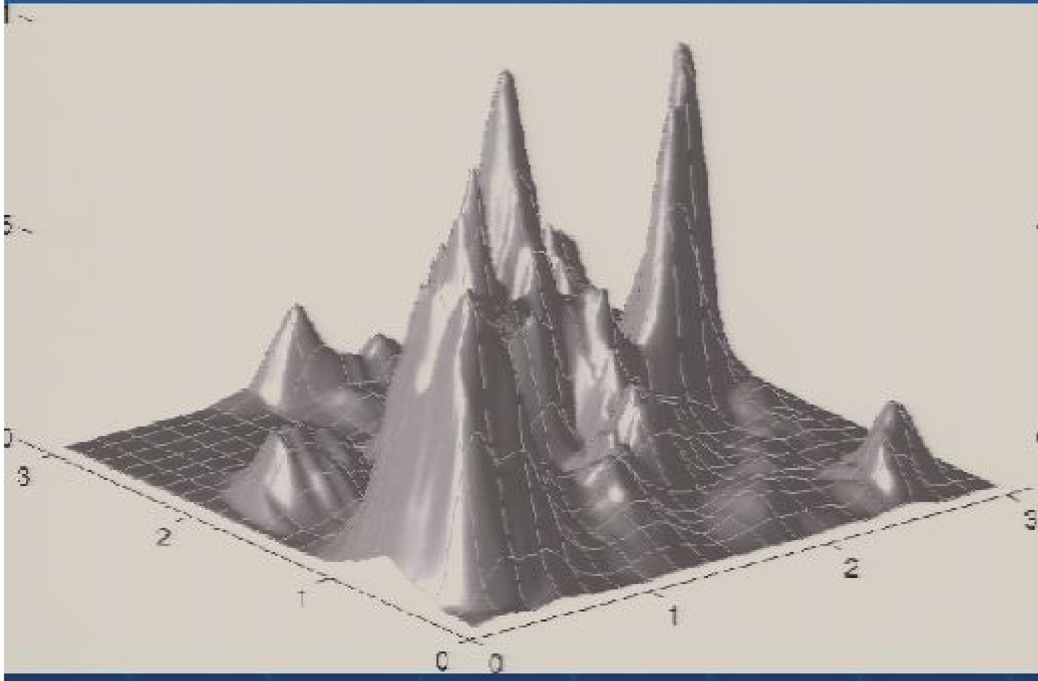
It’s all about information!

- The wave-function does not describe actual reality, but only the knowledge of an ideal observer.
- When an observer obtains information about the system he updates the quantum state.

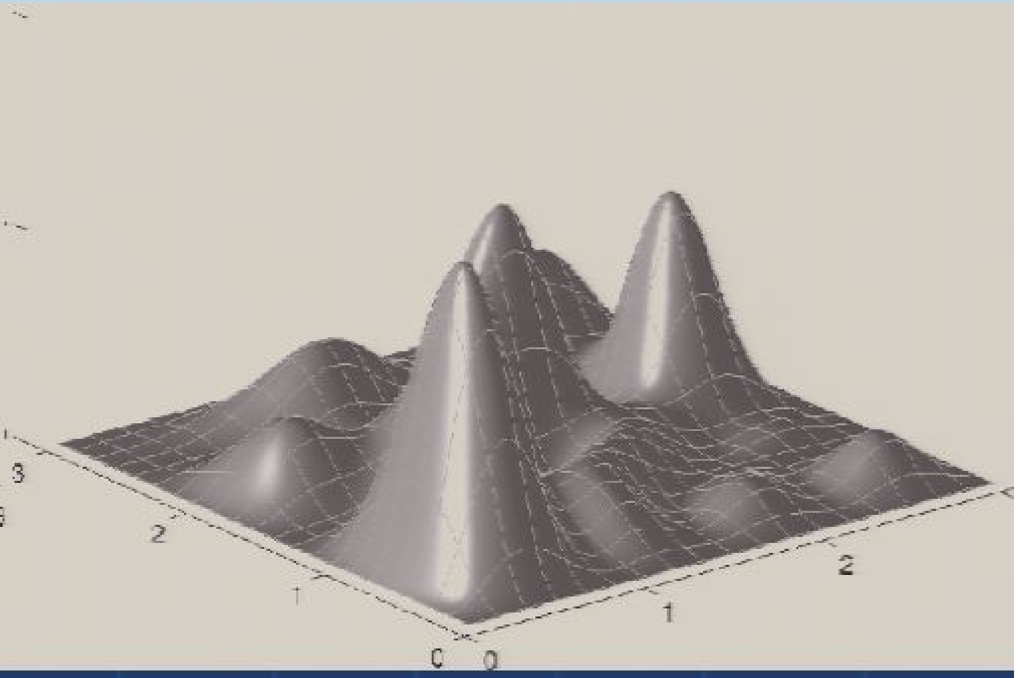
Problems

- Knowledge about what? Knowledge about the outcome of an experiment?
- Ok, but if you are claiming to say something precise here you better specify exactly what you mean by an "an experiment". Is it perhaps the interaction between a classical apparatus and a quantum system?
- We again run into the same problem we had with the Copenhagen interpretation.

P(x,y) at t=2π



$|\psi(x,y)|^2$ at t=2π



End of slide show, click to exit.

Problems

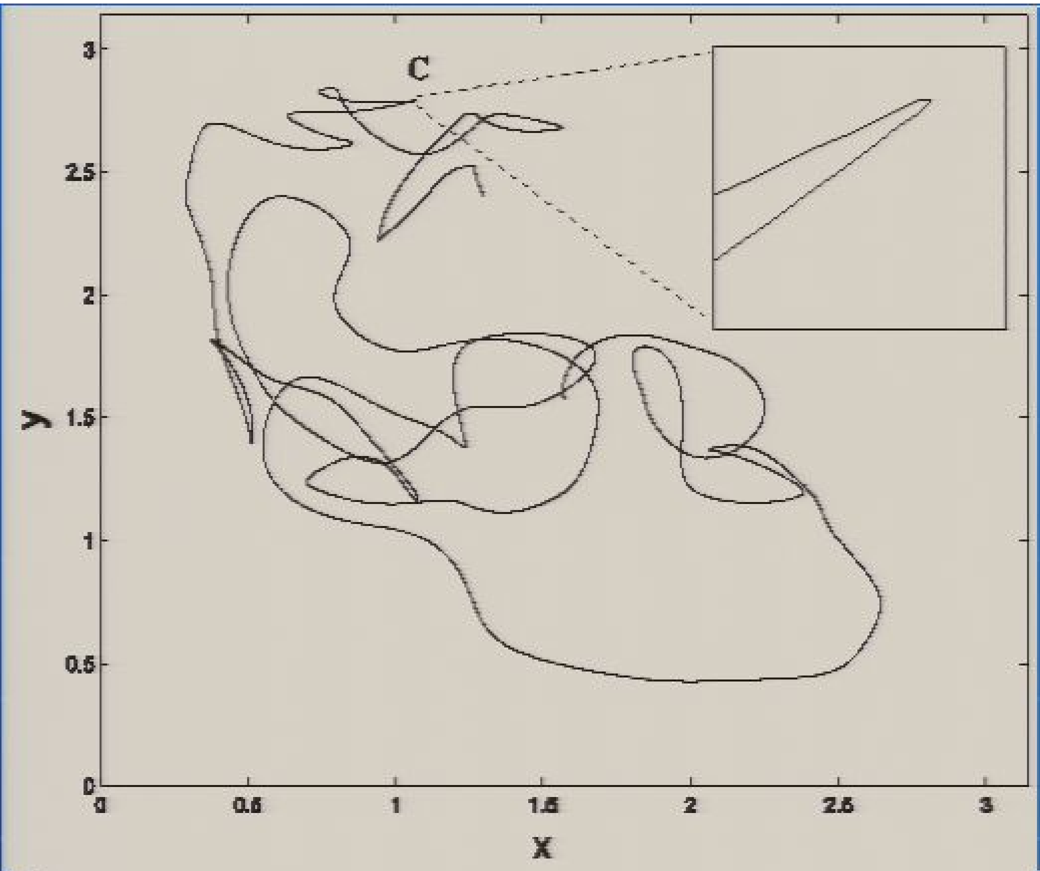
- The universe according to this theory seems rather strange. There are two things that make up the world i) the particles in 3D space ii) the wave-function that "lives" in 3N D configuration space.
- The wave-function is fundamentally unobservable. The world we see is represented by the configuration X(t) just as in Newtonian physics.
- Empty wave problem.

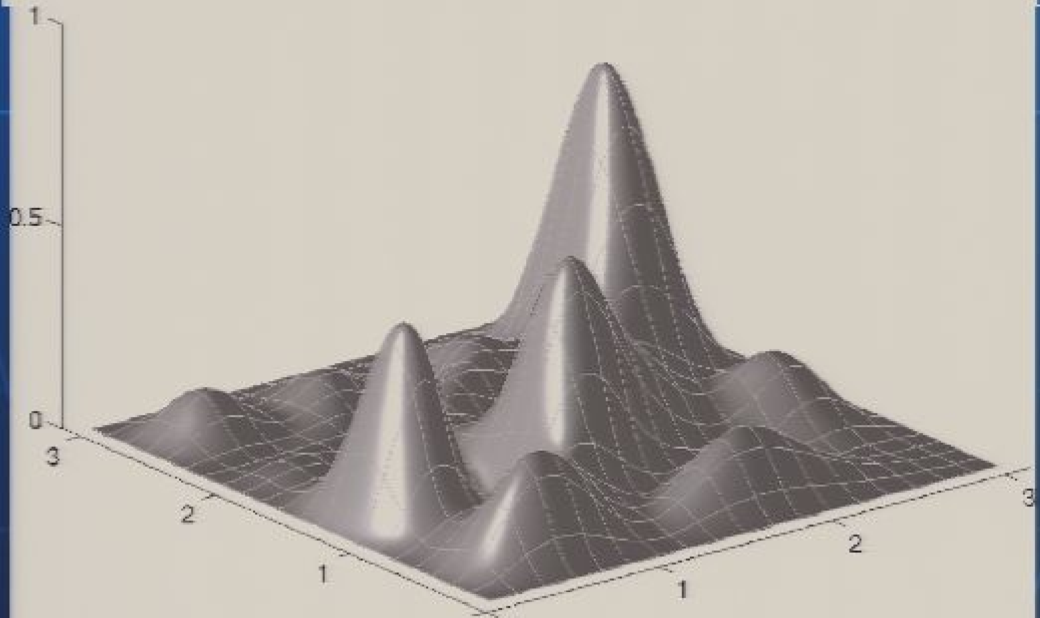
Good News

The theory is completely well defined, even deterministic, reproduces all the predictions of quantum theory (also also relativistic quantum theory) and the superposition principle is still valid.

dBB is a much richer theory with quantum theory emerging only in quantum equilibrium.

Explains the quantum statistics as a feature of quantum equilibrium.


C
y
x
0
0.5
1
1.5
2
2.5
3
0
0.5
1
1.5
2
2.5
3


1
0.5
0
3
2
1
1
2
3

Good News

The theory is completely well defined, even deterministic, reproduces all the predictions of quantum theory (also also relativistic quantum theory) and the superposition principle is still valid.

dBB is a much richer theory with quantum theory emerging only in quantum equilibrium.

Explains the quantum statistics as a feature of quantum equilibrium.

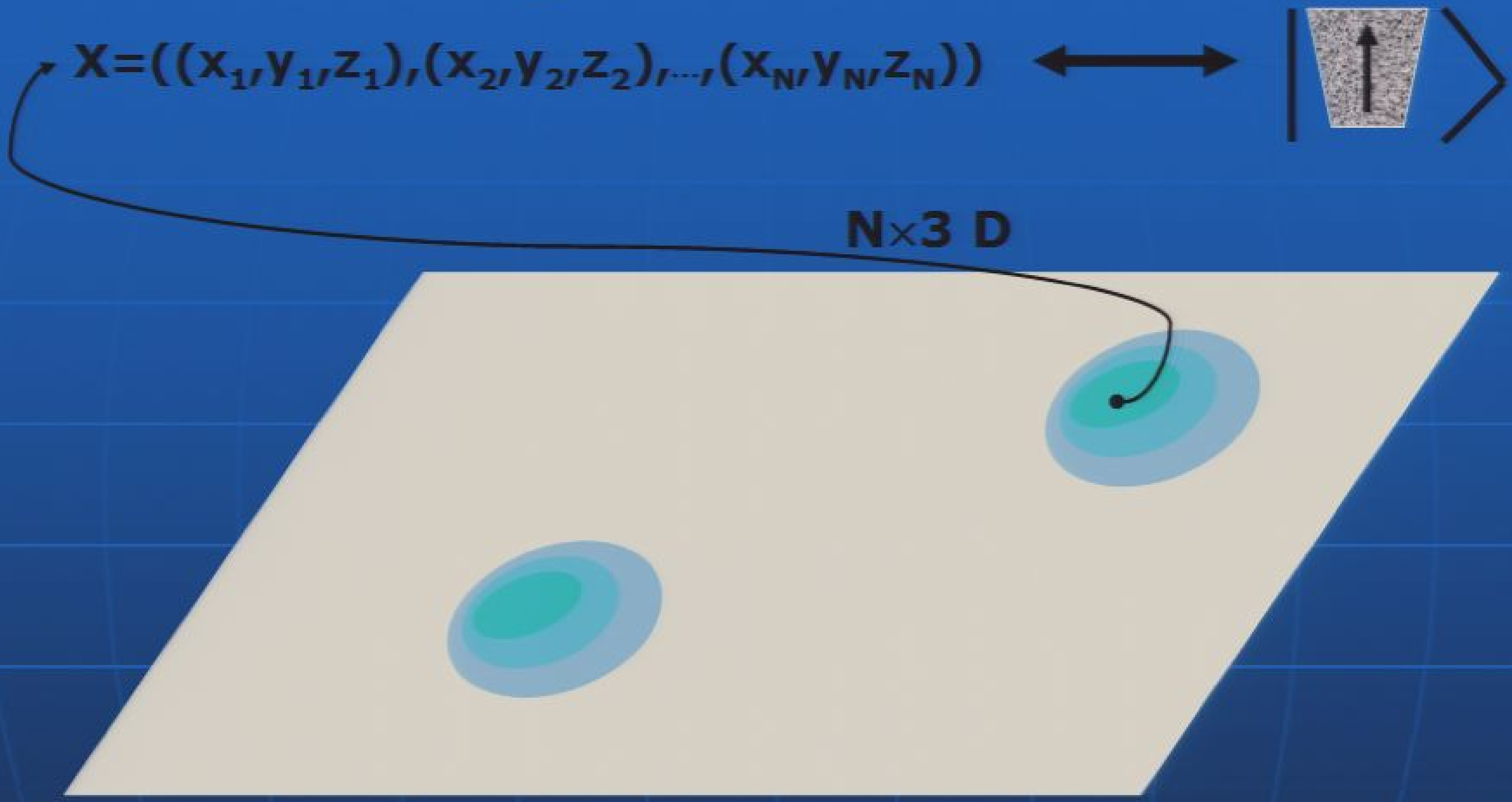
Dynamics

In classical theory X evolves according to Newtons laws F=mA.

In deBroglie-Bohm theory X evolves according to the non-classical equations

$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$

deBroglie-Bohm theory



$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N)) \longleftrightarrow \left|\uparrow\right\rangle$

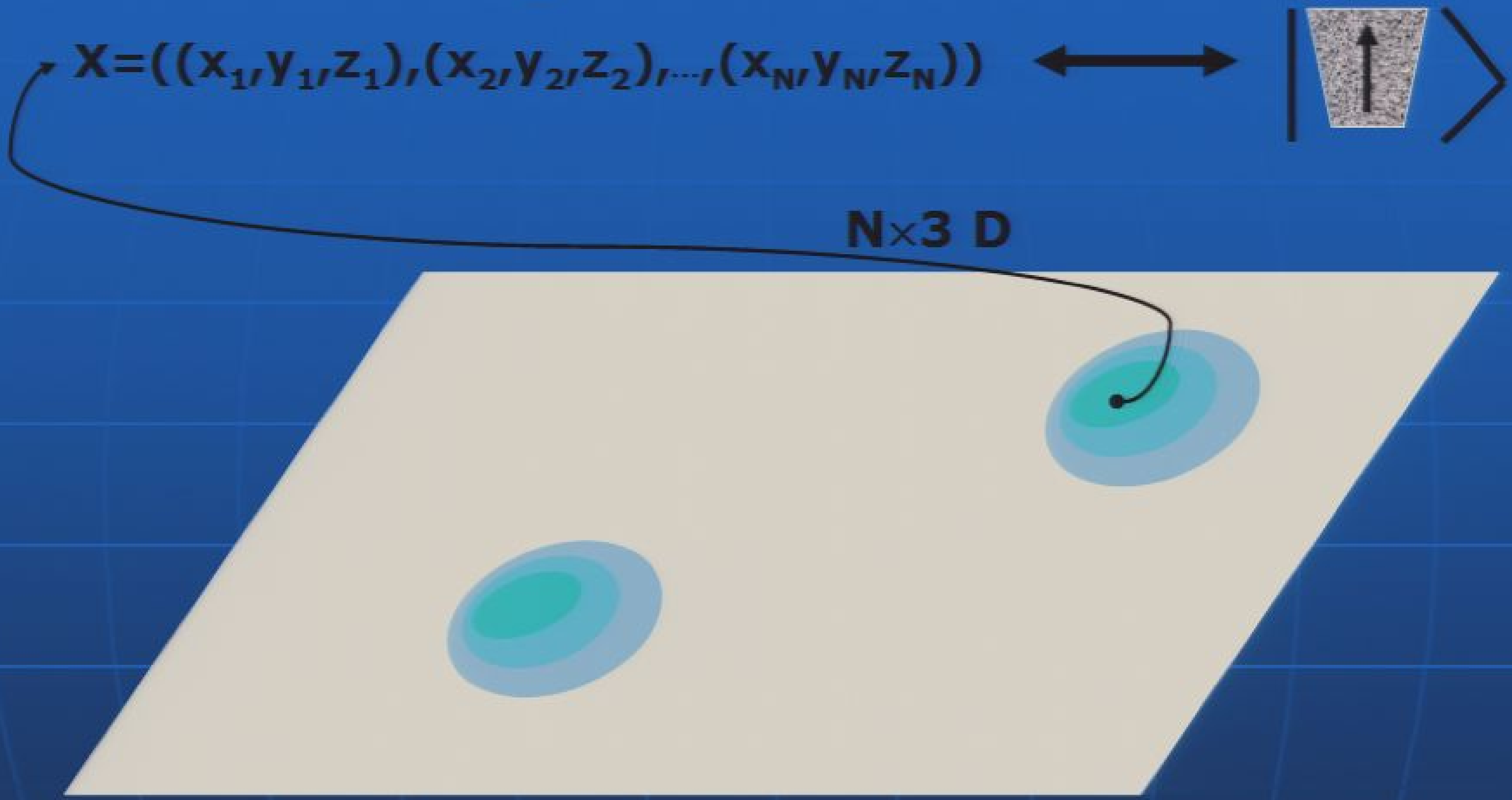
N×3 D

A system is described by $(\Psi(x),X(t))$.

It’s all about information!

- The wave-function does not describe actual reality, but only the knowledge of an ideal observer.
- When an observer obtains information about the system he updates the quantum state.

deBroglie-Bohm theory



$X=((x_1,y_1,z_1),(x_2,y_2,z_2),\ldots,(x_N,y_N,z_N))$

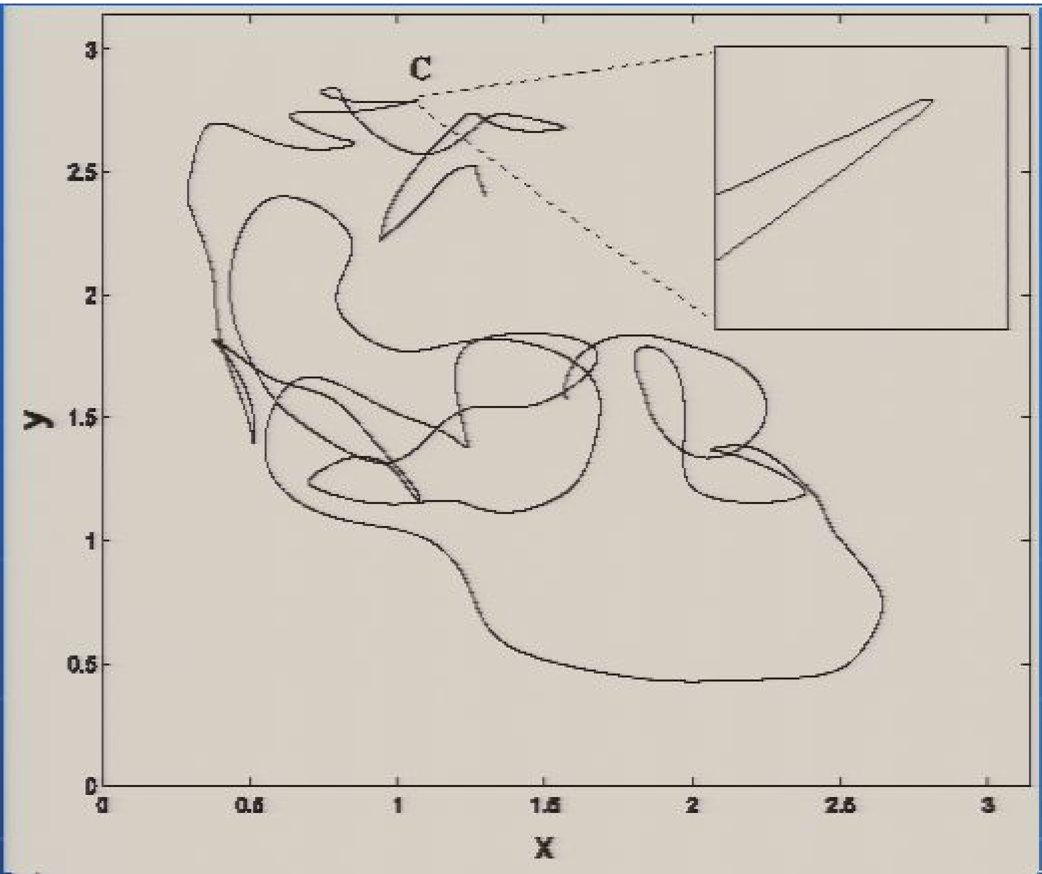
A system is described by $(\Psi(x),X(t))$.

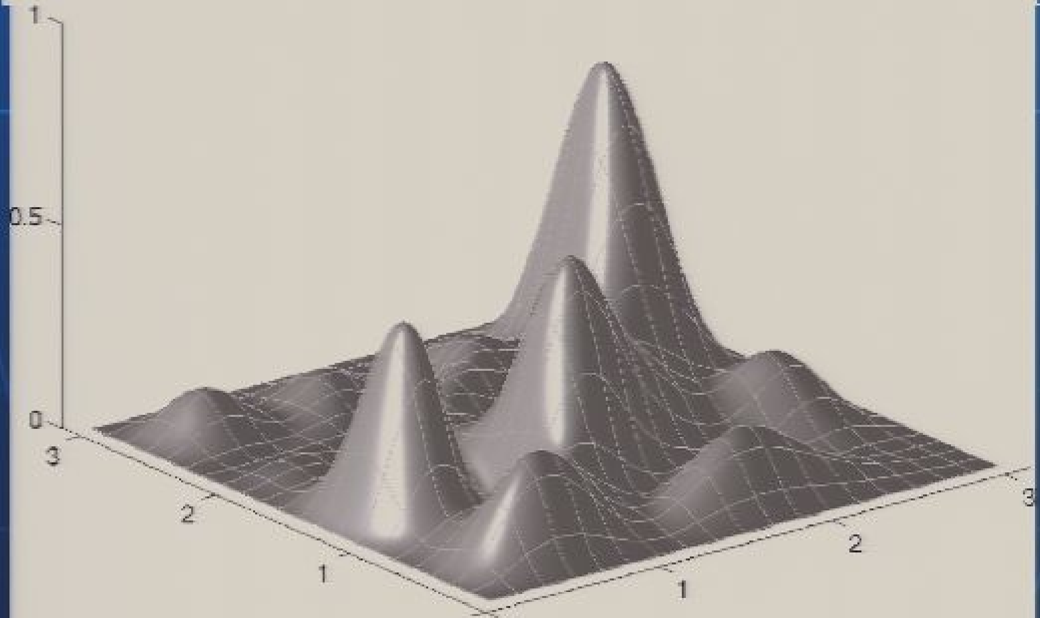
Dynamics

In classical theory X evolves according to Newtons laws F=mA.

In deBroglie-Bohm theory X evolves according to the non-classical equations

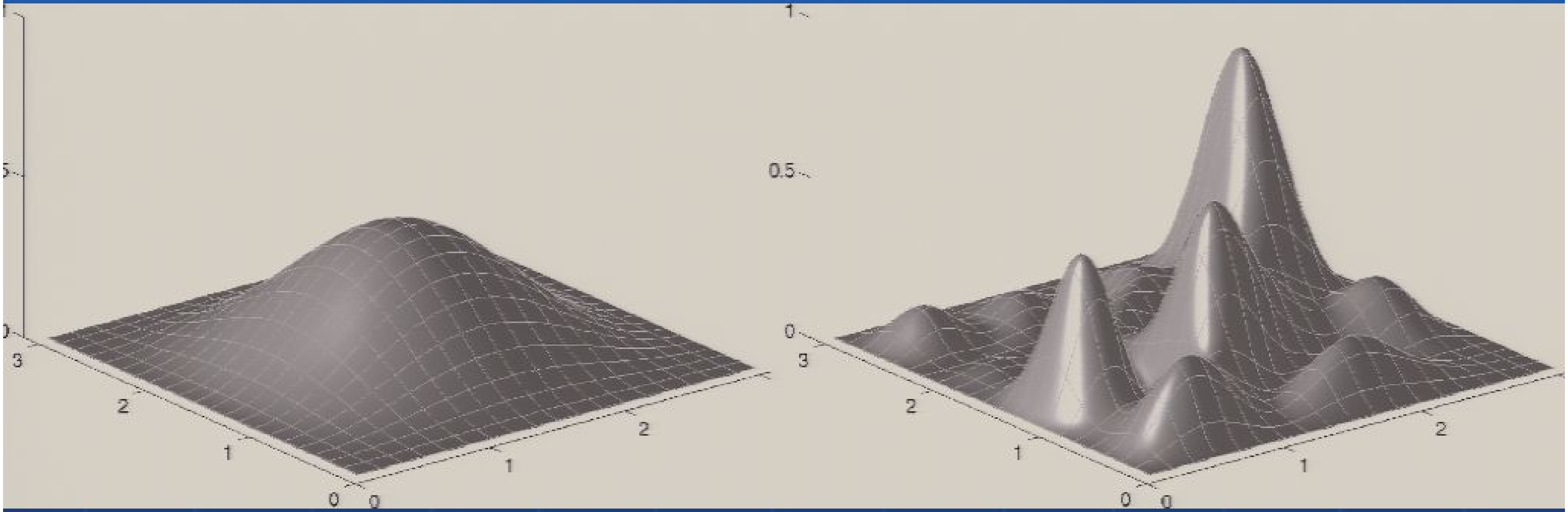
$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$


C
y
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
x


1
0.5
0
3
2
1
3
2
1

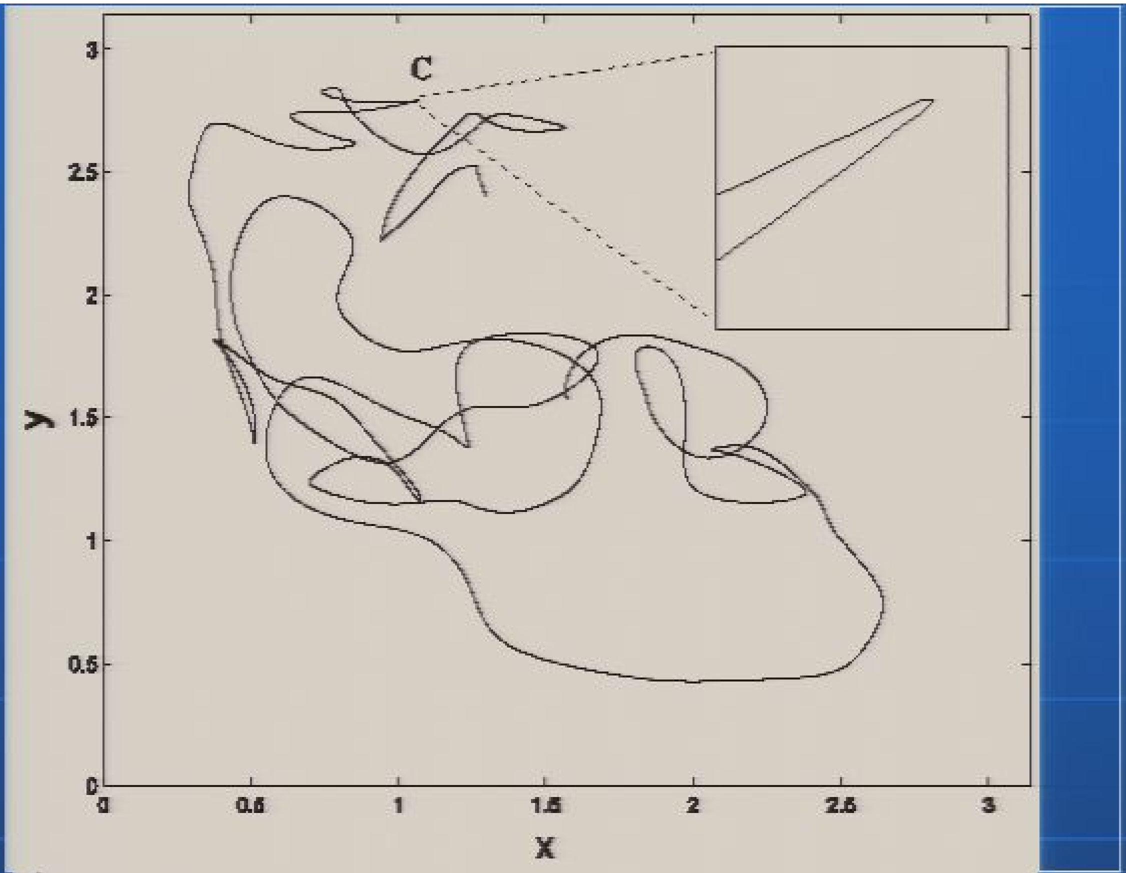
P(x,y) at t=0

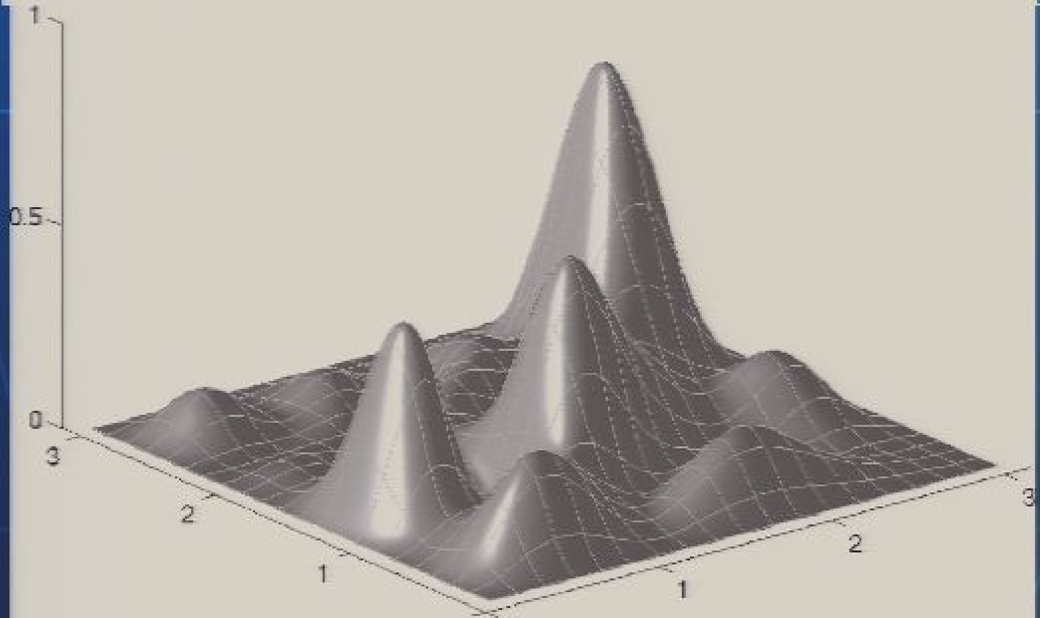
$|\psi(x,y)|^2$ at t=0



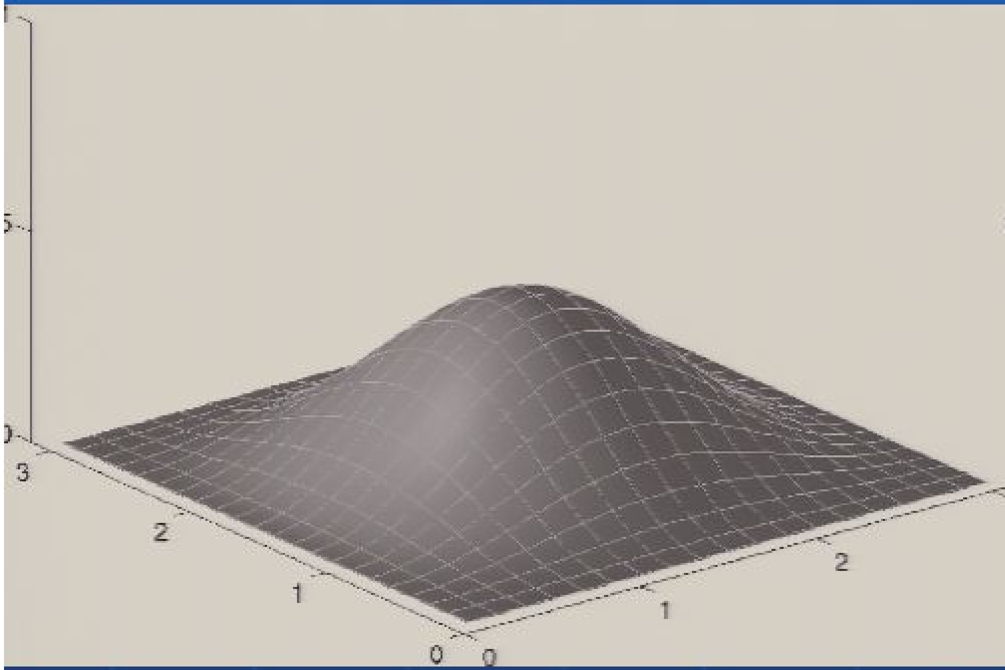
Good News

- The theory is completely well defined, even deterministic, reproduces all the predictions of quantum theory (also also relativistic quantum theory) and the superposition principle is still valid.
- dBB is a much richer theory with quantum theory emerging only in quantum equilibrium.
- Explains the quantum statistics as a feature of quantum equilibrium.

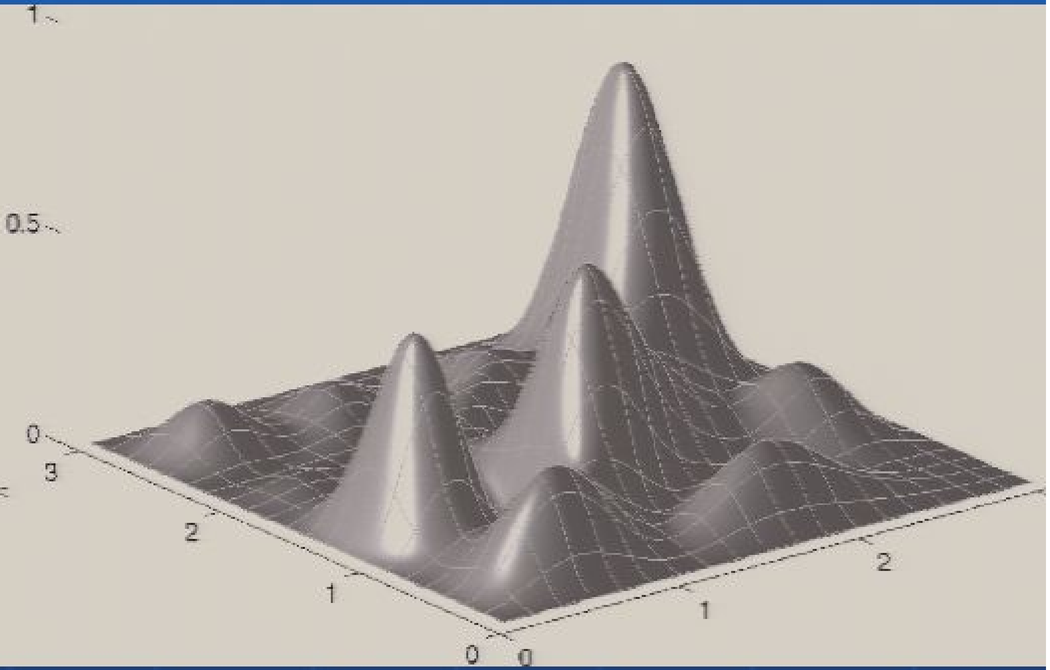

C
y
x
0
0.5
1
1.5
2
2.5
3


1
0.5
0
3
2
1
3
2
1

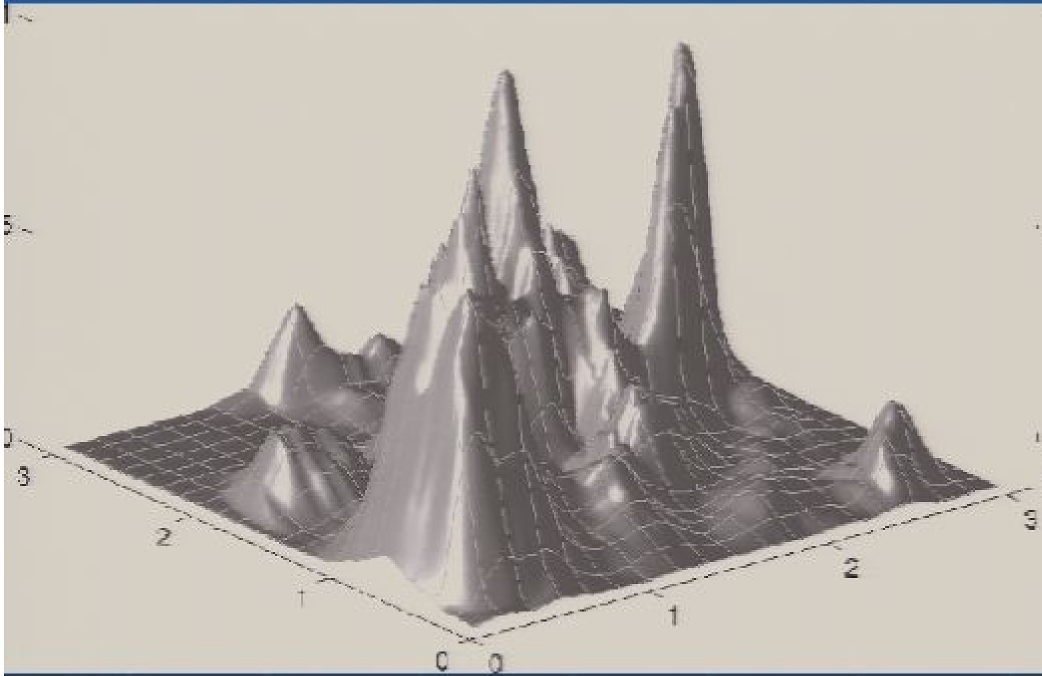
P(x,y) at t=0



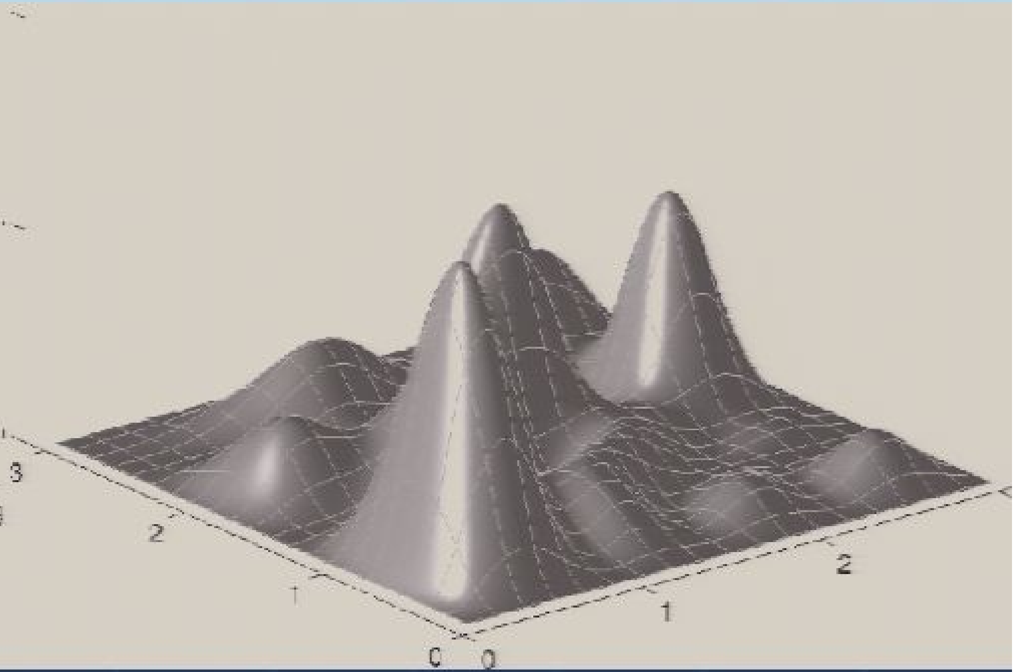
$|\psi(x,y)|^2$ at t=0



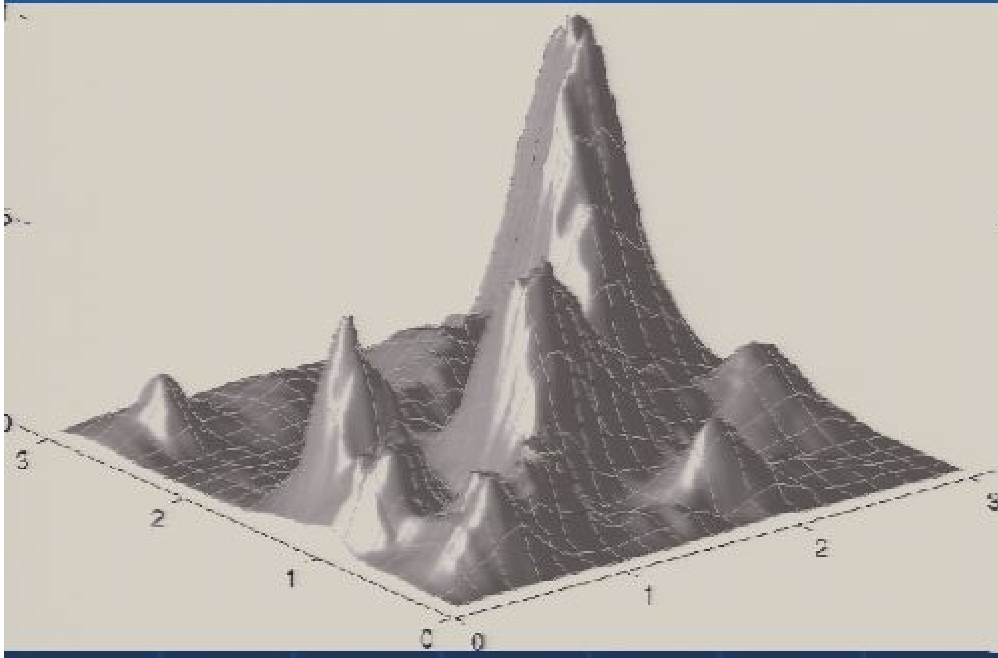
P(x,y) at t=2π



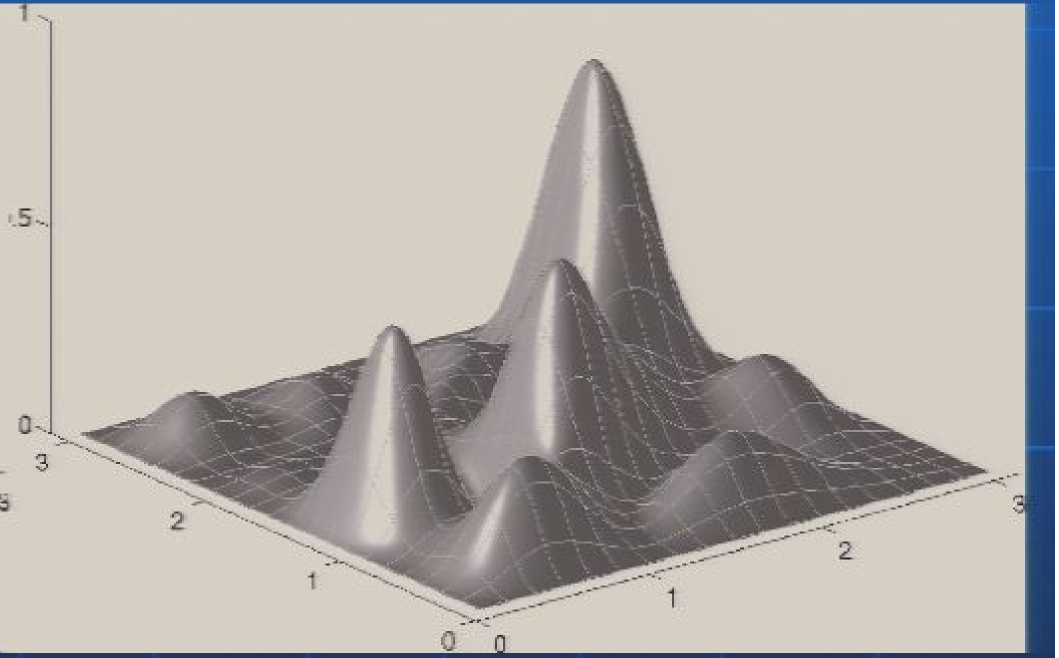
|ψ(x,y)|² at t=2π



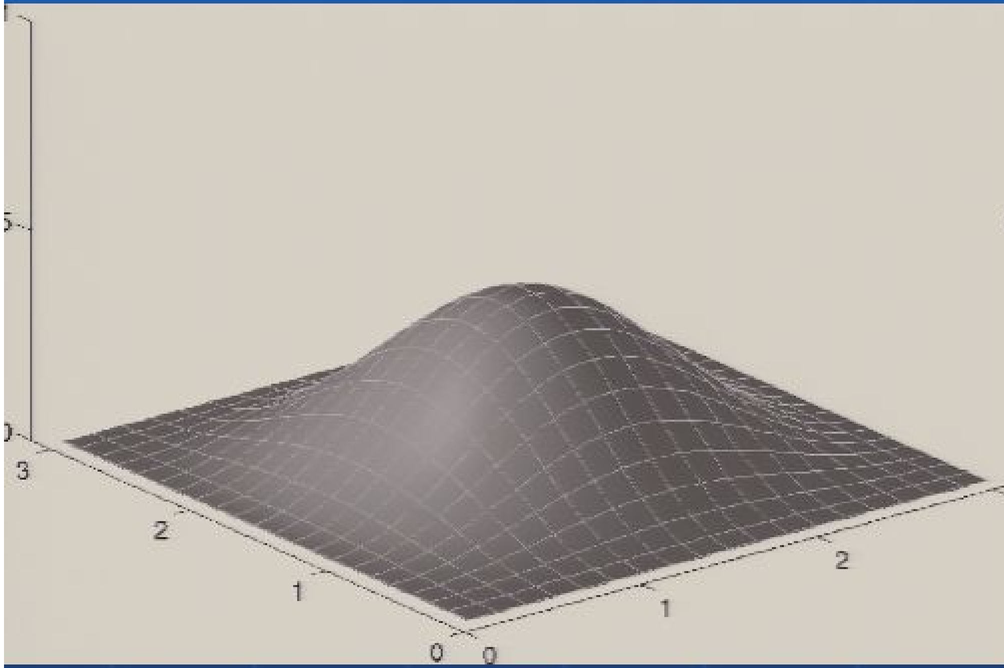
$P(x,y)$ at $t=4\pi$



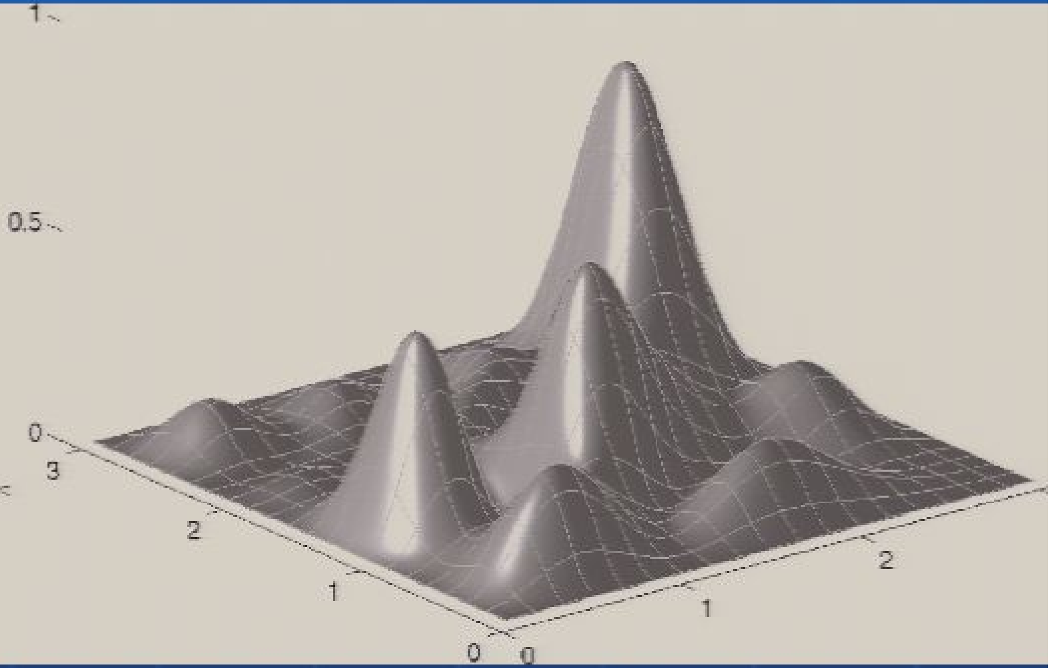
$|\psi(x,y)|^2$ at $t=4\pi$



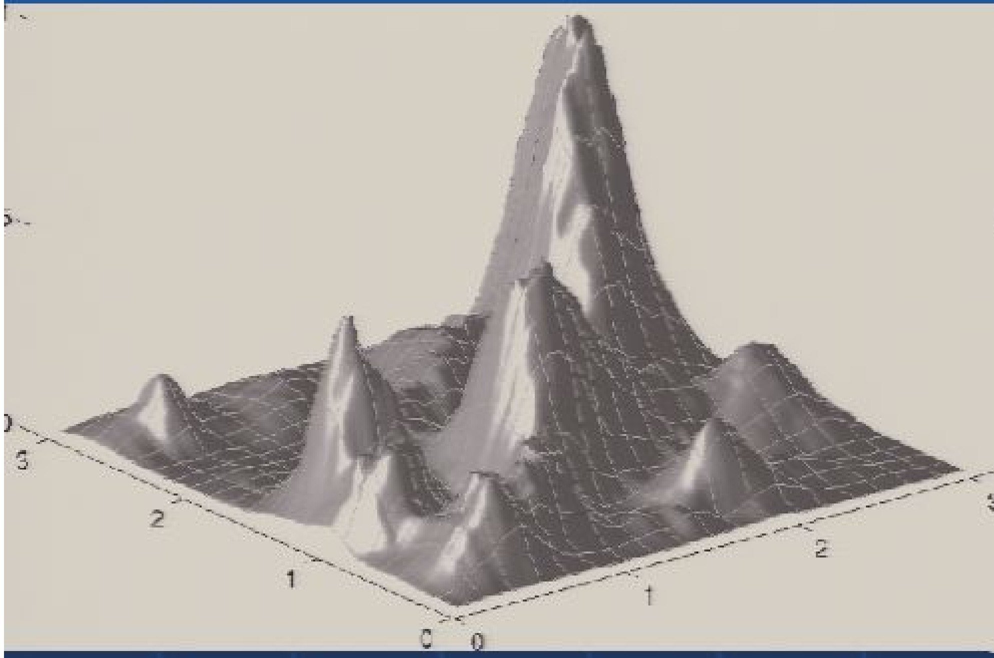
P(x,y) at t=0



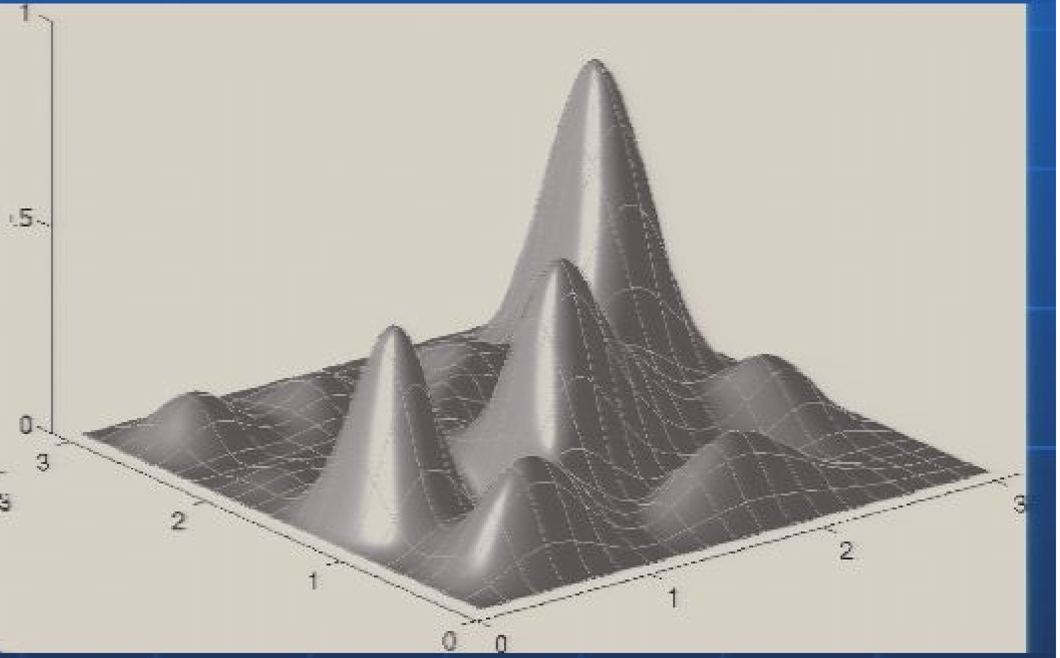
$|\psi(x,y)|^2$ at t=0



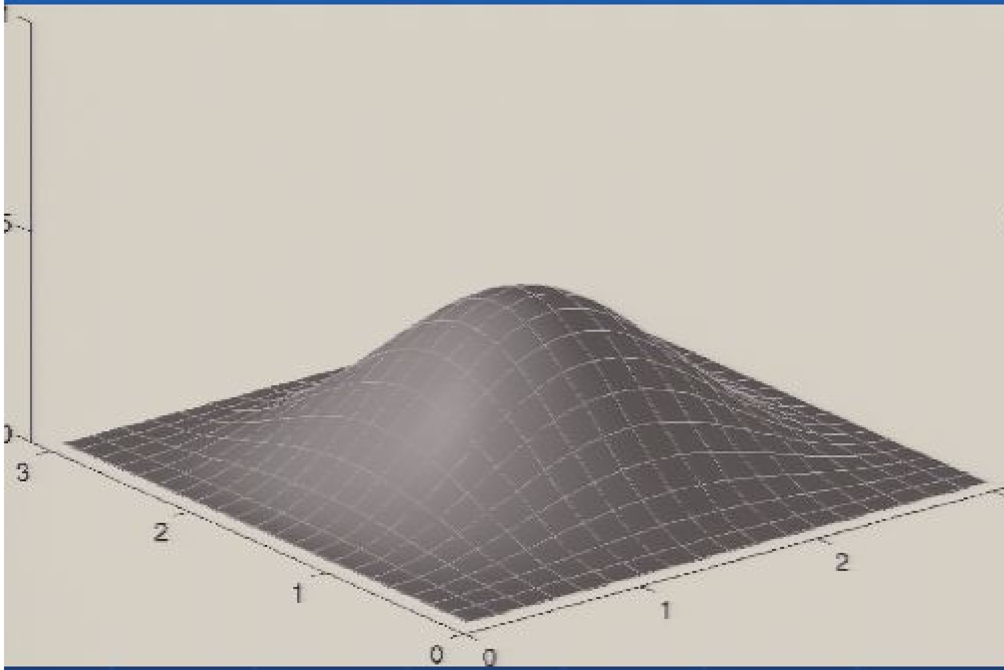
P(x,y) at $t=4\pi$



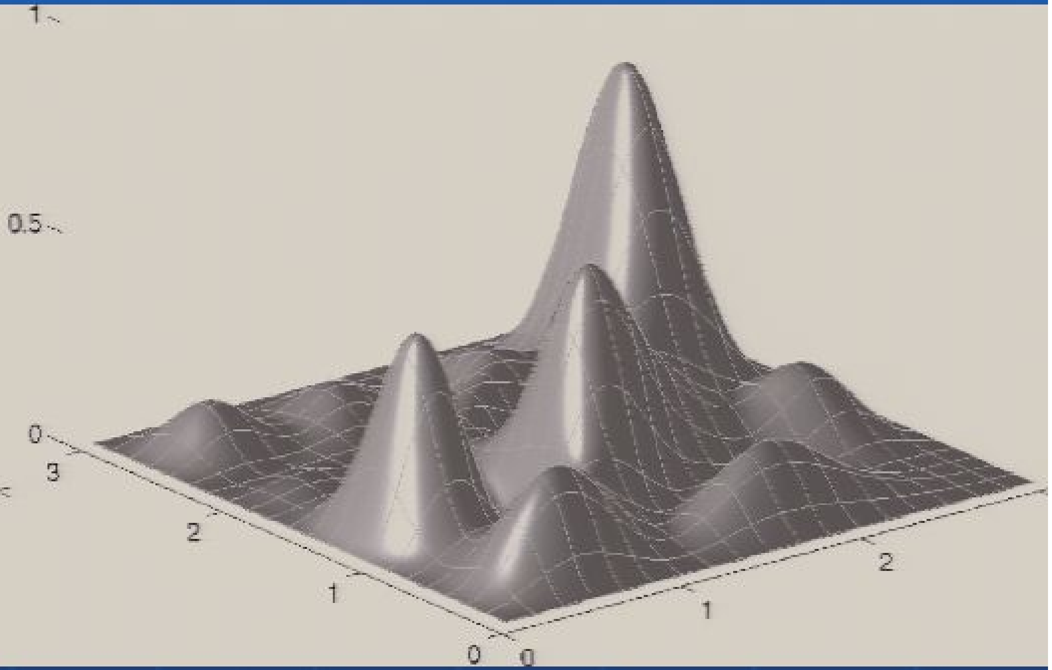
$|\psi(x,y)|^2$ at $t=4\pi$



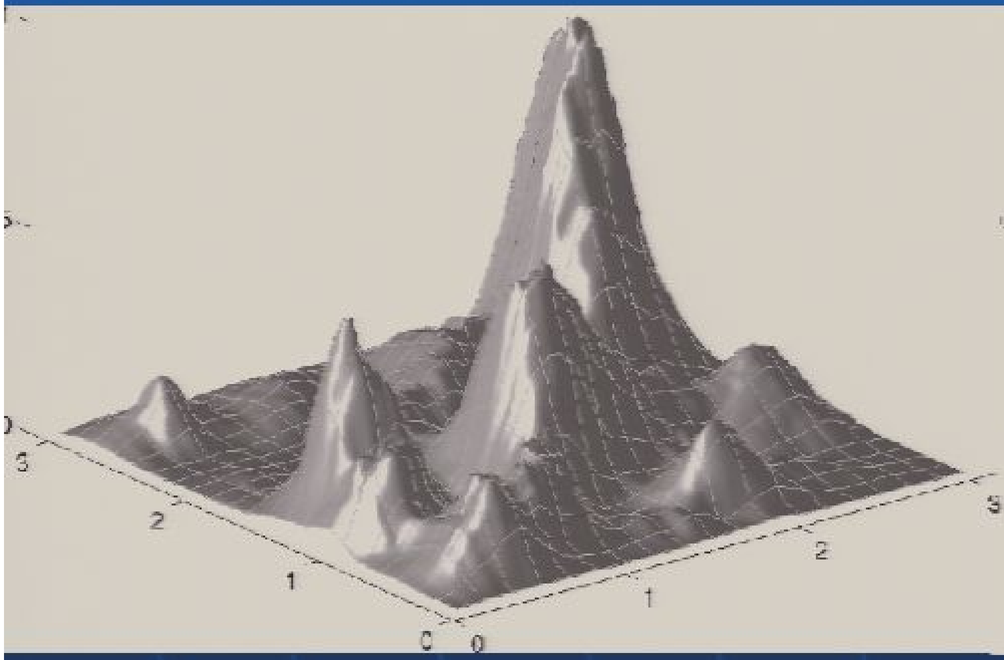
P(x,y) at t=0



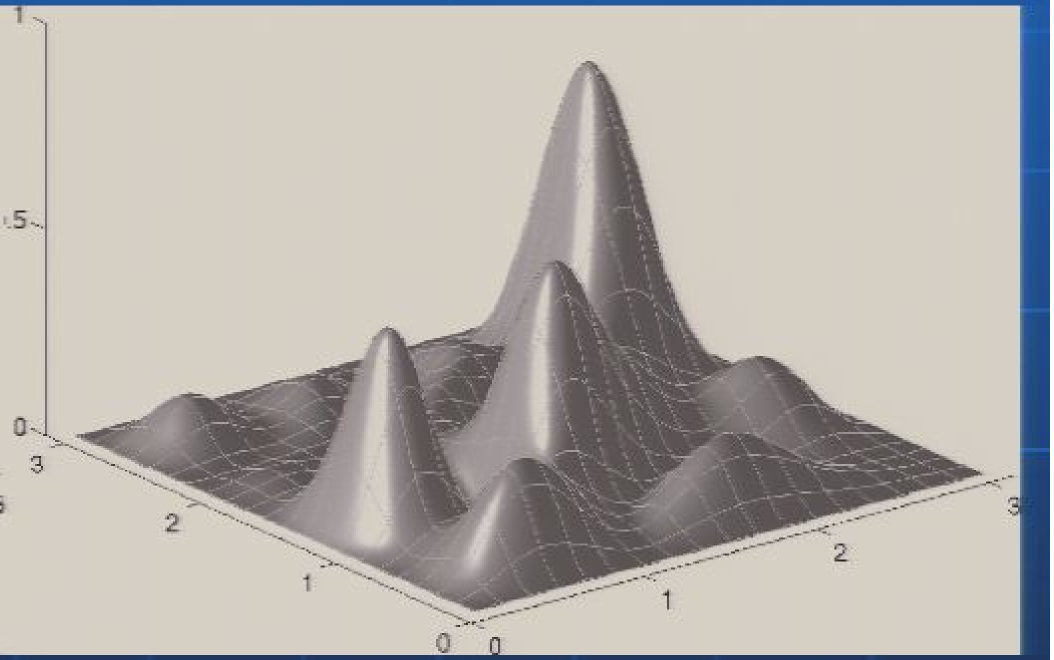
$|\psi(x,y)|^2$ at t=0



P(x,y) at t=4π

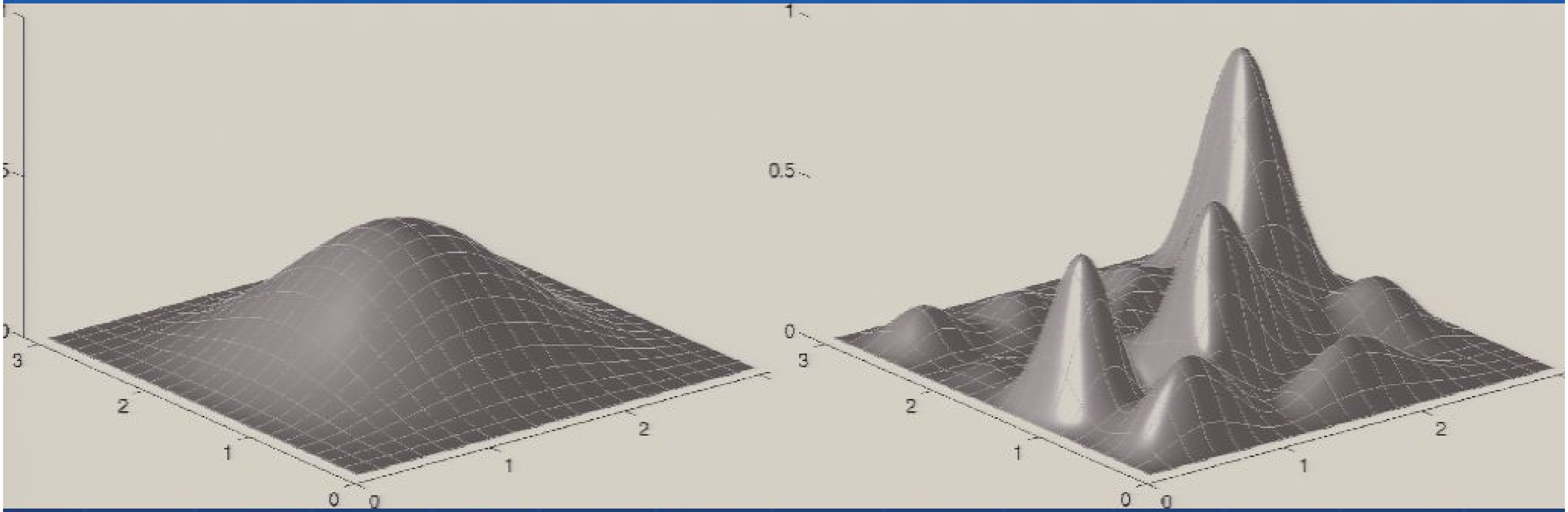


|ψ(x,y)|² at t=4π

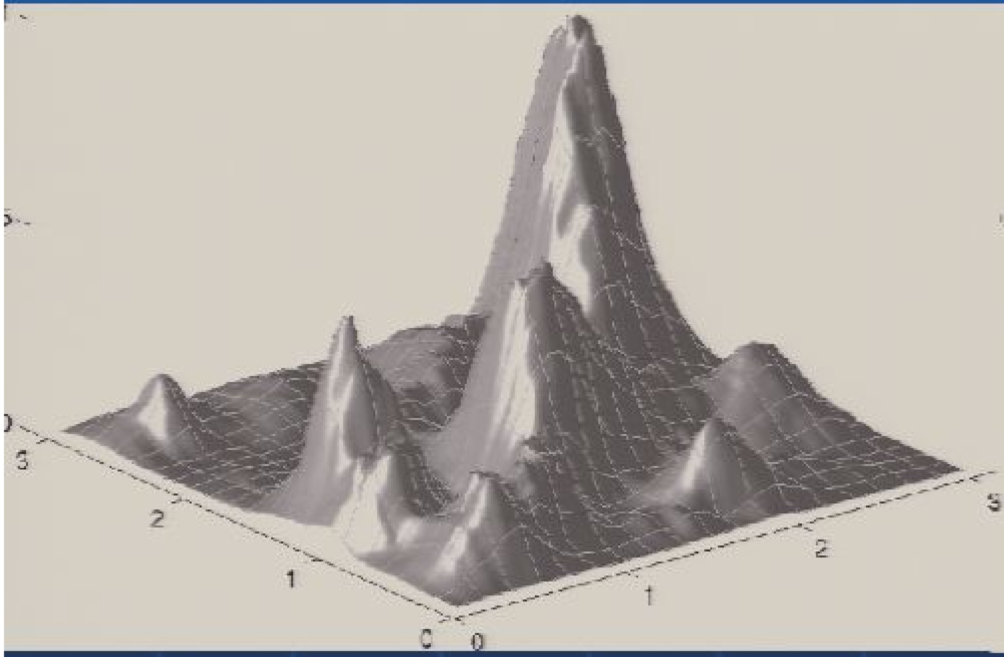


P(x,y) at t=0

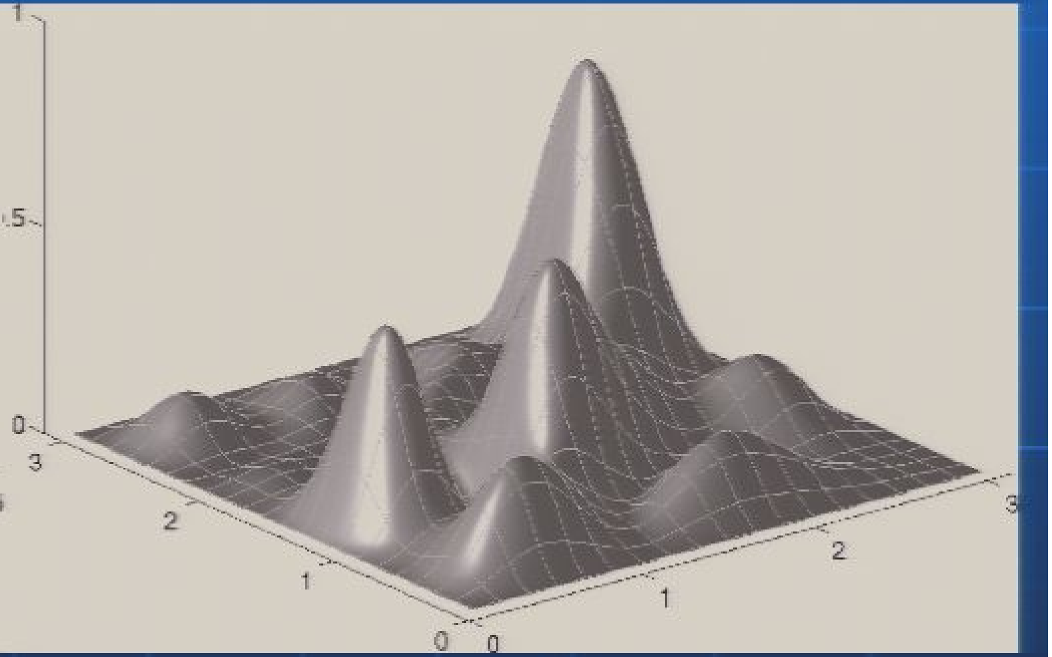
$|\psi(x,y)|^2$ at t=0



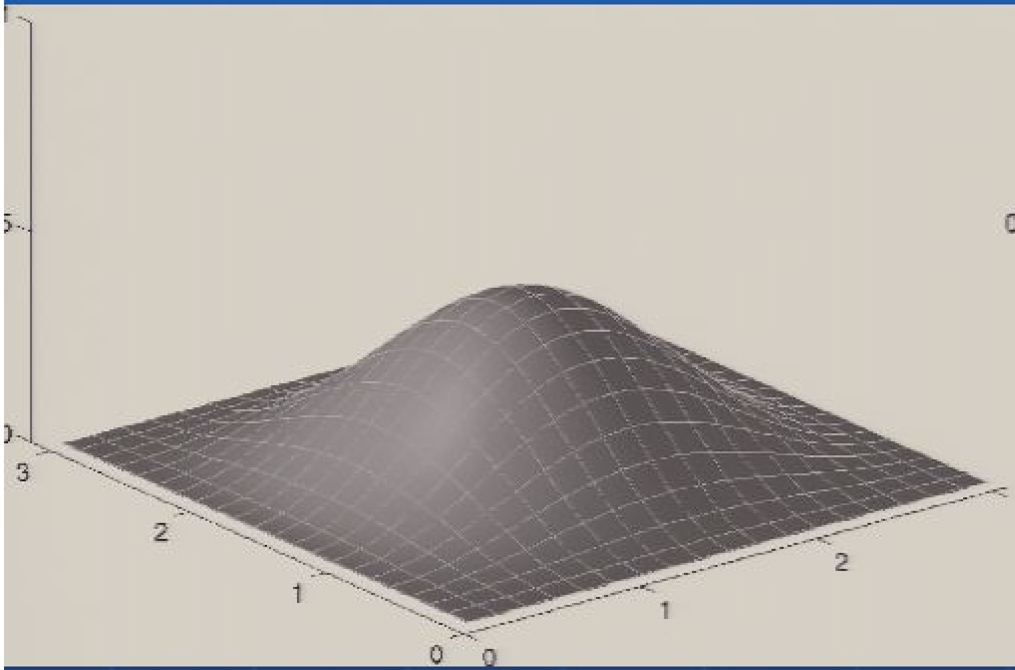
P(x,y) at t=4π



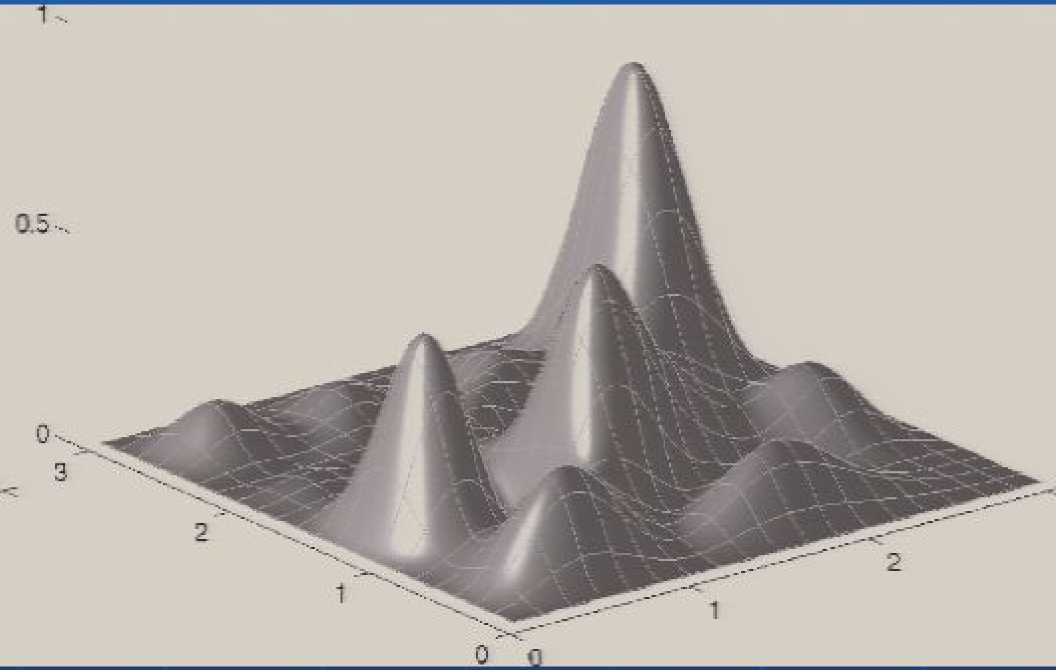
|ψ(x,y)|² at t=4π



$P(x,y)$ at $t=0$

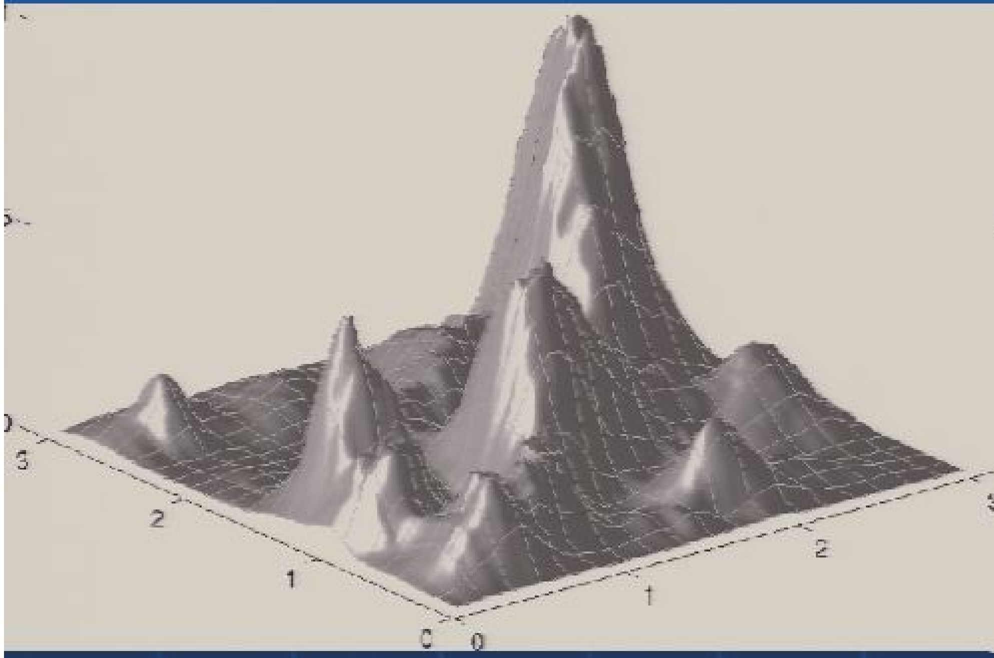


$|\psi(x,y)|^2$ at $t=0$

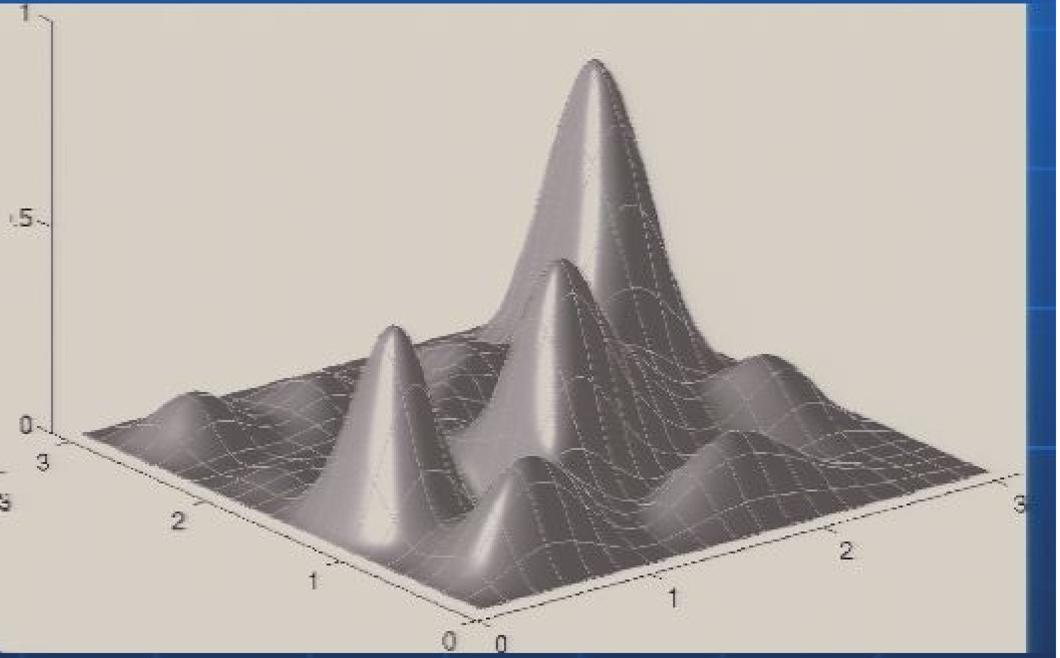


End of slide show, click to exit.

P(x,y) at t=4π



|ψ(x,y)|² at t=4π

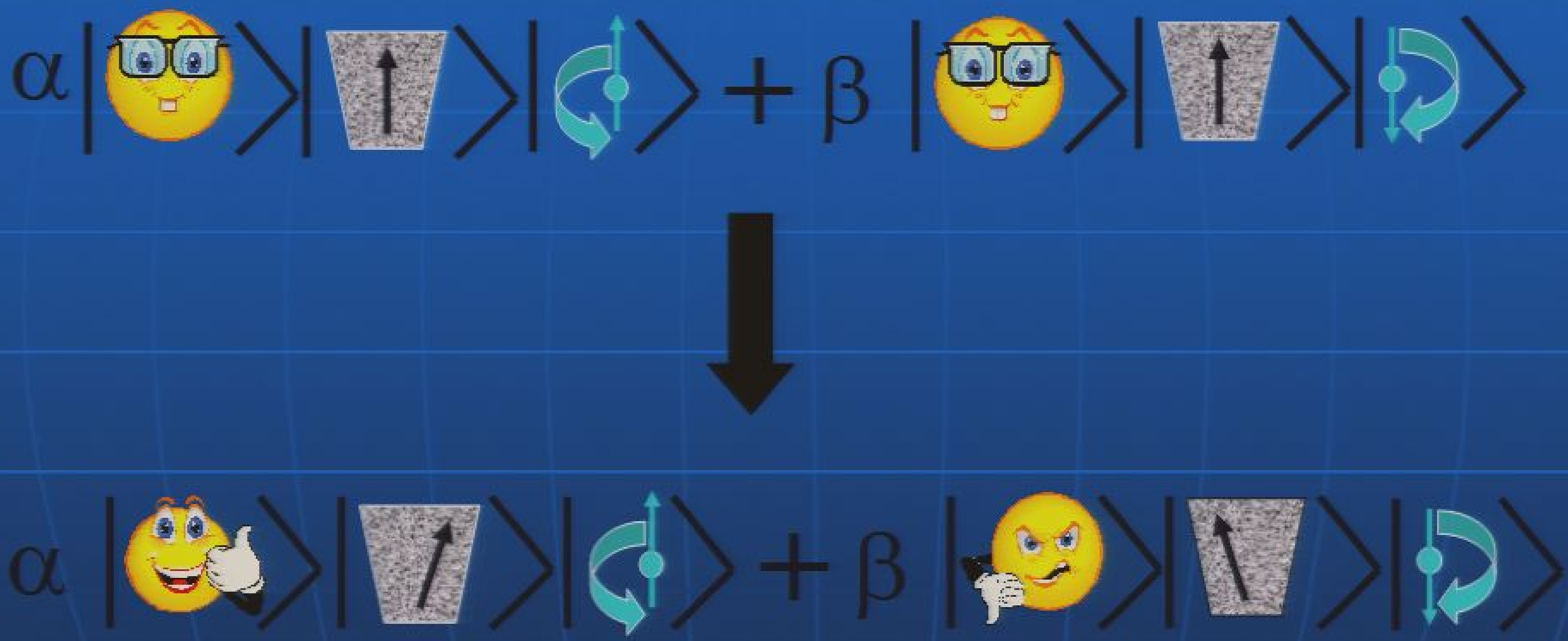


Dynamics

In classical theory X evolves according to Newtons laws F=mA.

In deBroglie-Bohm theory X evolves according to the non-classical equations

$$m\frac{dX}{dt} = \mathrm{Im}(\frac{\nabla\Psi}{\Psi})$$

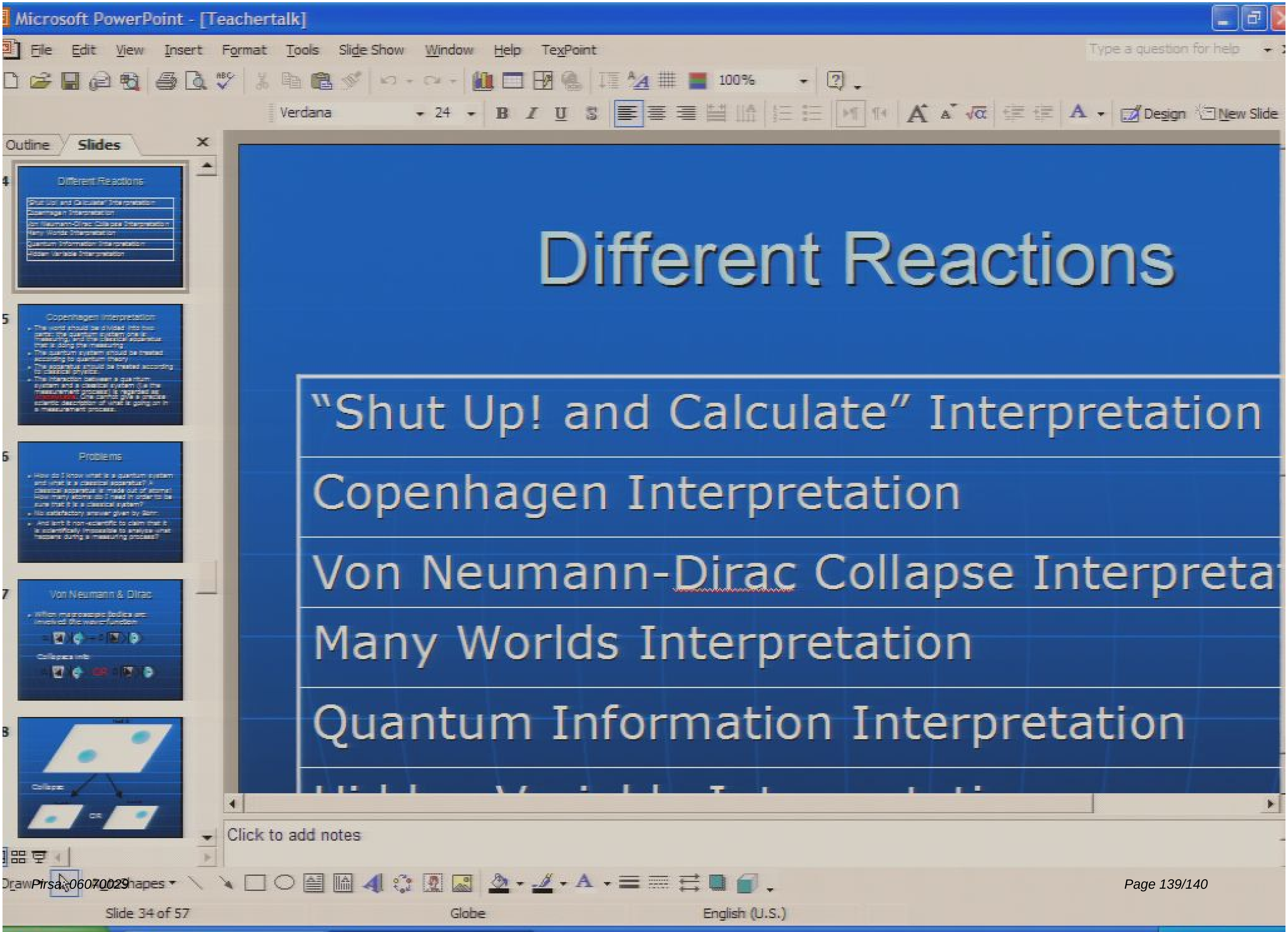

α
+ β
α
+ β

Problems

- If the wave-function collapses then when is this supposed to occur? How big must a “classical” apparatus be in order for a collapse to occur?
- And where are the mathematical equations that tell me EXACTLY how and when the wave-function collapses?

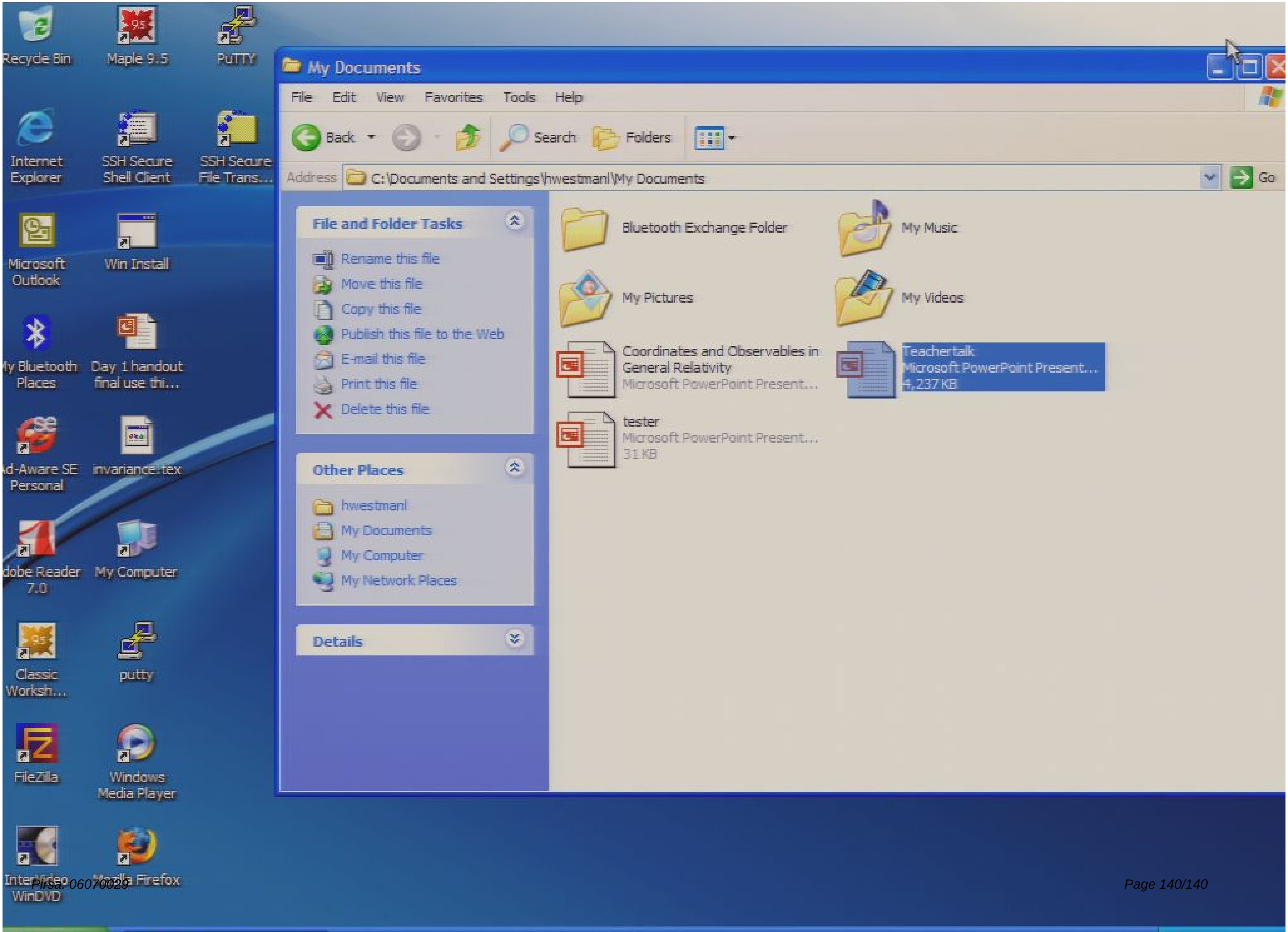
Different Reactions

- "Shut Up! and Calculate" Interpretation
- Copenhagen Interpretation
- Von Neumann-Dirac Collapse Interpretation
- Many Worlds Interpretation
- Quantum Information Interpretation
- Hidden Variable Interpretation



Different Reactions

- "Shut Up! and Calculate" Interpretation
- Copenhagen Interpretation
- Von Neumann-Dirac Collapse Interpreta
- Many Worlds Interpretation
- Quantum Information Interpretation



Address: C:\Documents and Settings\hwestmanl\My Documents