A Case for Testing Quantum Mechanics

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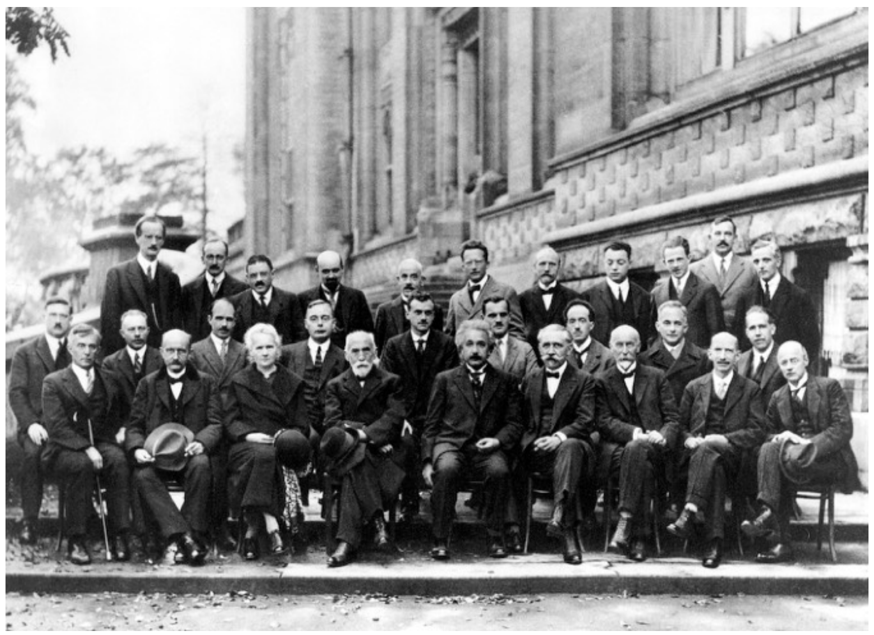
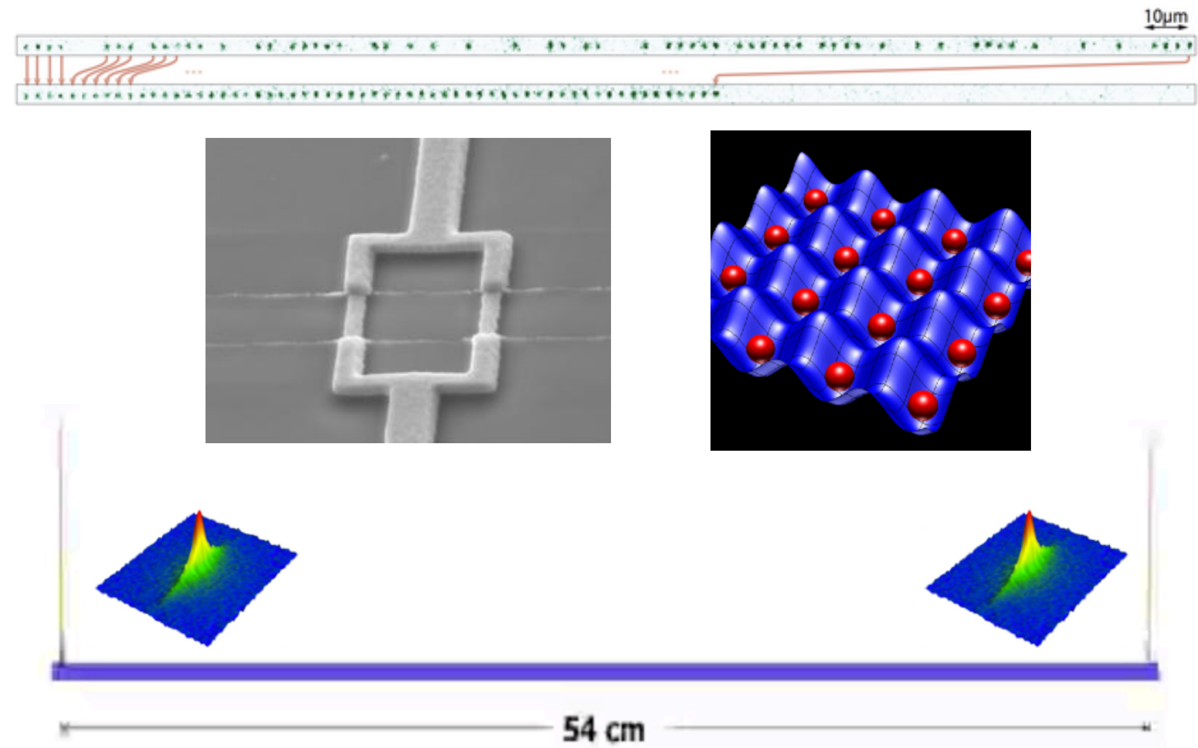
Modify Quantum Mechanics?

Why n(bergian)ot?



1927



2023

QM is the only known physical theory that is exactly linear

$$i\partial_t |\chi\rangle = \hat{H} |\chi\rangle$$

Modifying QM

non-linear: localized wave function talking to itself:

$$i\partial_t \psi = \hat{H}\psi + \hat{\mathscr{F}}(|\psi|)\psi$$

—> Different **“worlds” interact**

Non-unitary: definite to mixed states

$$\partial_t \hat{\rho} = -i\left[\hat{H}, \hat{\rho}\right] + \hat{L}\hat{\rho}\hat{L}^\dagger - \frac{1}{2}\left[\hat{L}^\dagger \hat{L}, \hat{\rho}\right]_+$$

—> **Decoherence** (different from b.g. fields?)

Physics to Modify?

Can we get rid of unsightly '**probability**'?

Bell's inequality, etc., rule out local hidden variables.

Ground state of Hydrogen:

If the electron has a definite position, there is an infinite degeneracy of states

Physics to Modify?

Can we get rid of **linearity**?

$$i\hbar \frac{\partial}{\partial t} |\psi\rangle = \hat{H} |\psi\rangle$$

de Broglie (1960) suggested QM is a linear approximation

“wave-function collapse” implies non-linearity

$$\hat{H} \rightarrow \hat{H}\left[|\psi\rangle, \langle\psi| \right]$$

Non-Linear Time Evolution

The Schrödinger Equation: position basis

$$i\hbar \frac{\partial}{\partial t}\psi(x) = H(\mathbf{x})\,\psi(x)$$

Weinberg's attempt (1989)

$$i\hbar \frac{\partial}{\partial t}\psi(x) = h(\psi^*, \psi)\,\psi(x)$$

Polchinski showed action at a distance with EPR pairs,
and suggested could be avoided (1990)

Needs to be local —> Quantum Field Theory

Quantum Field Theory

$$i\,\partial_t\,|\chi\rangle = \hat{H}\,|\chi\rangle$$

In the Schrödinger picture, the time evolution operator is still:

$$\hat{U} = e^{-i\hat{H}t}$$

with $\hat{H} = \int d^3x\ \hat{\mathscr{H}}(\mathbf{x})$ made up of field operators

Add state-dependent terms. Kibble first to explore this (1977)

QFT Examples

YUKAWA THEORY

$$\mathscr{H} \supset y\, \phi(\mathbf{x})\, \bar{\Psi}(\mathbf{x})\Psi(\mathbf{x})$$

Add non-linearity: $\mathscr{H} \supset y \left(\phi(\mathbf{x}) + \epsilon\langle\phi(\mathbf{x})\rangle\right) \bar{\Psi}(\mathbf{x})\Psi(\mathbf{x})$

$\langle\phi\rangle \equiv \langle\chi|\phi|\chi\rangle$

QED

$$\mathscr{L} \supset e\left(\frac{A_\mu + \epsilon_\gamma\langle A_\mu\rangle}{1+\epsilon_\gamma}\right)J^\mu$$

GRAVITY

$$g_{\mu\nu} \to \frac{g_{\mu\nu} + \epsilon_G\langle g_{\mu\nu}\rangle}{1+\epsilon_G}$$

Perturbatively, compute background source in the $\epsilon = 0$ theory

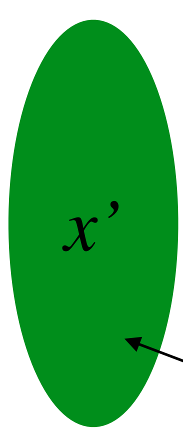
Non-Relativistic Limit — One Particle

$$\mathscr{L} \supset y(\phi + \epsilon\langle\chi|\phi|\chi\rangle)\bar{\Psi}\Psi$$

To get NR theory for fermions Ψ, compute $\langle\phi\rangle$.

Will depend on initial conditions and sources. At zeroth order, Ψ sources ϕ:

ψ wave function for single fermion Ψ

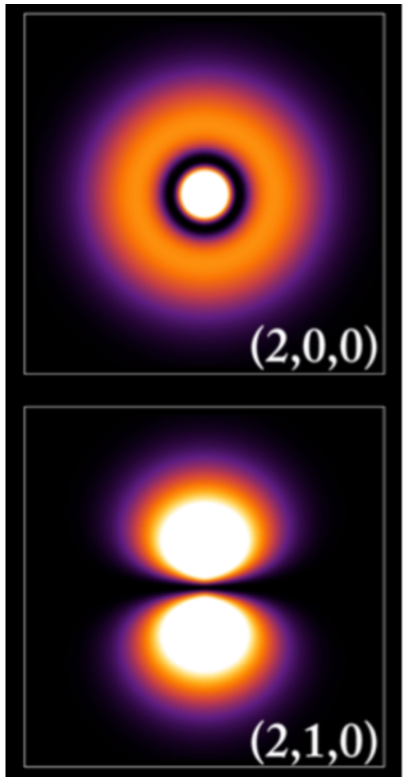


$$\langle\phi\rangle(x) \supset \int d^4x'\,|\psi(x')|^2\,G_R(x-x')$$

Charge density of Ψ

Causal Green's Function

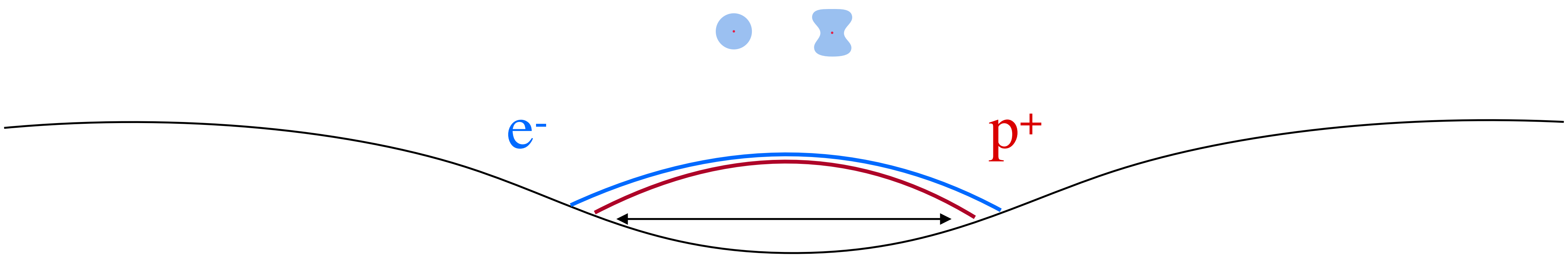
Constraints: Atomic Levels



What does this do to the Lamb Shift?

Say charged particles see their own w.f.:

$$i\,\frac{\partial}{\partial t}\psi(x) = H(\mathbf{x})\,\psi(x) + \epsilon_\gamma\,\alpha \int d^4x' \,|\,\psi(x')\,|^2\, G_R(x'-x)\,\psi(x)$$



Electron spread over the trap (micron) dilutes the electric field and thus the level splitting

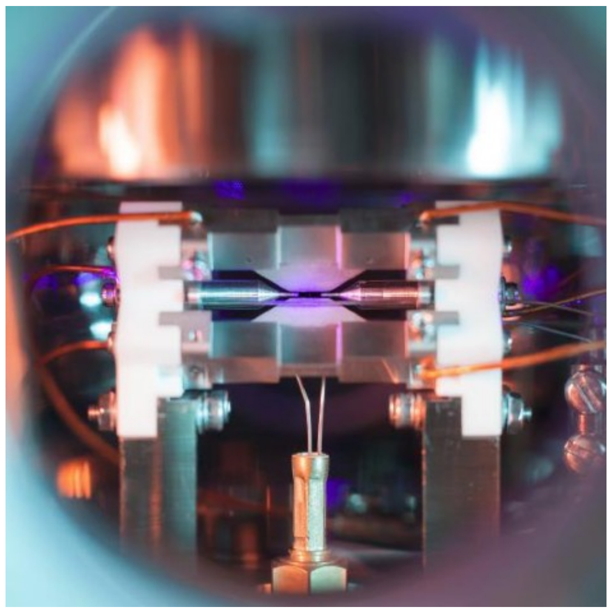
Proton's wave function also produces a field that nearly cancels the electron wave function.

Key — center of mass coordinate cannot be separated from relative coordinate due to locality.

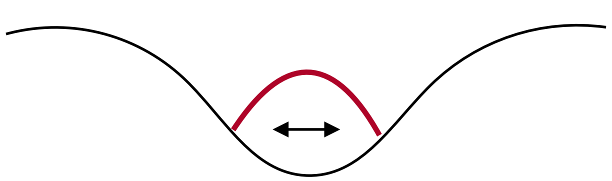
$$\epsilon_\gamma < 10^{-2}$$

Constraints

Leading Constraint



Ion Traps



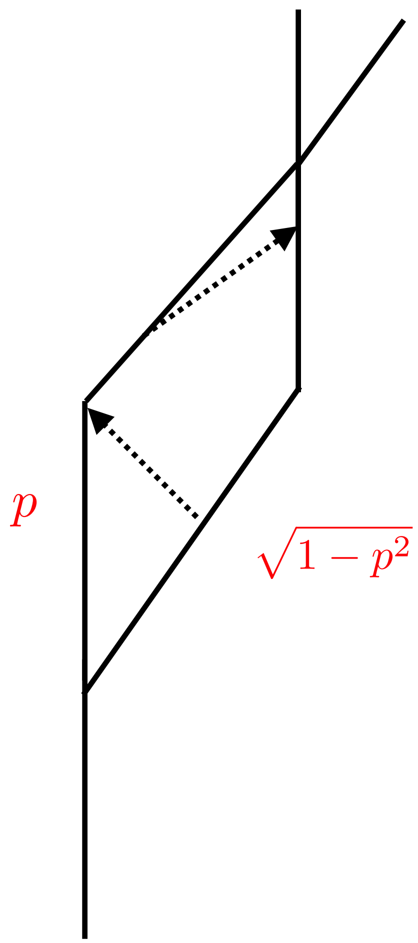
For $\varepsilon_\gamma > 0$ (repulsive interaction)

Too large a repulsion, can't trap ion $\varepsilon_\gamma < 10^{-5}$

No direct limit on $\varepsilon_\gamma < 0$ (attractive interaction)

Perhaps from mapping of ion in trap?

Experimental Tests



Interferometry - interaction between paths

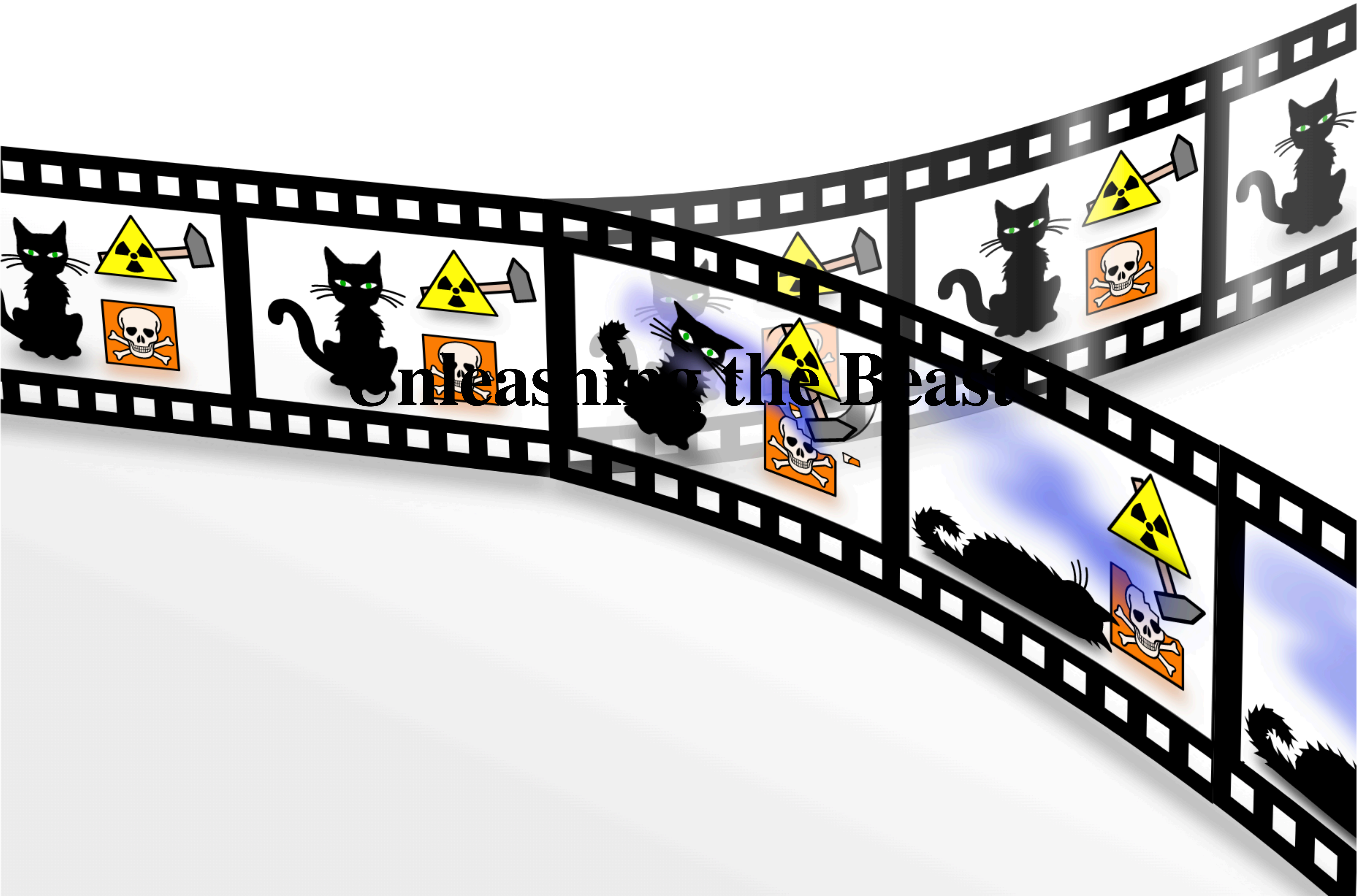
Take an ion - split its wave-function

Coulomb Field of one path interacts with the other path

Gives rise to phase shift that depends on the intensity p^2 of the split

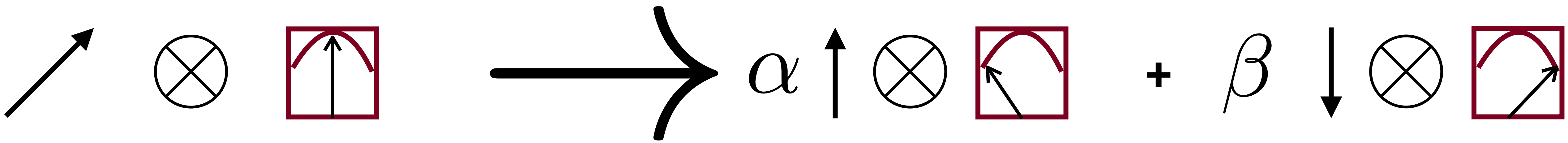
Use intensity dependence to combat systematics

Unleashing the Beast



Measurement in Quantum Mechanics

Time evolution with interaction between the system and measuring device



$|\chi\rangle$ $|A_0\rangle$ $|i\rangle \otimes |A_i\rangle$

$$|\chi\rangle \otimes |A_0\rangle \rightarrow \sum_i c_i |i\rangle \otimes |A_i\rangle$$

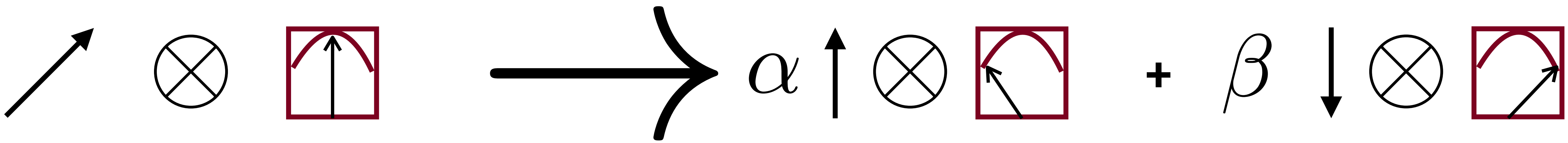
Prediction of Quantum Mechanics (“Many Worlds”)

Pick: $\langle A_j | A_i \rangle = \delta_{ij} \implies \rho_{|\Psi\rangle} = \sum_i c_i c_i^* |i\rangle\langle i|$

“Interpret” as direct sum of “worlds”

Measurement in Quantum Mechanics

Time evolution with interaction between the system and measuring device



$|\chi\rangle$ $\quad$ $|A_0\rangle$ $\quad$ $|i\rangle \otimes |A_i\rangle$

In linear QM, can pick orthogonal basis vectors just by knowing the interaction Hamiltonian

$$\langle A_j | A_i \rangle = \delta_{ij}$$

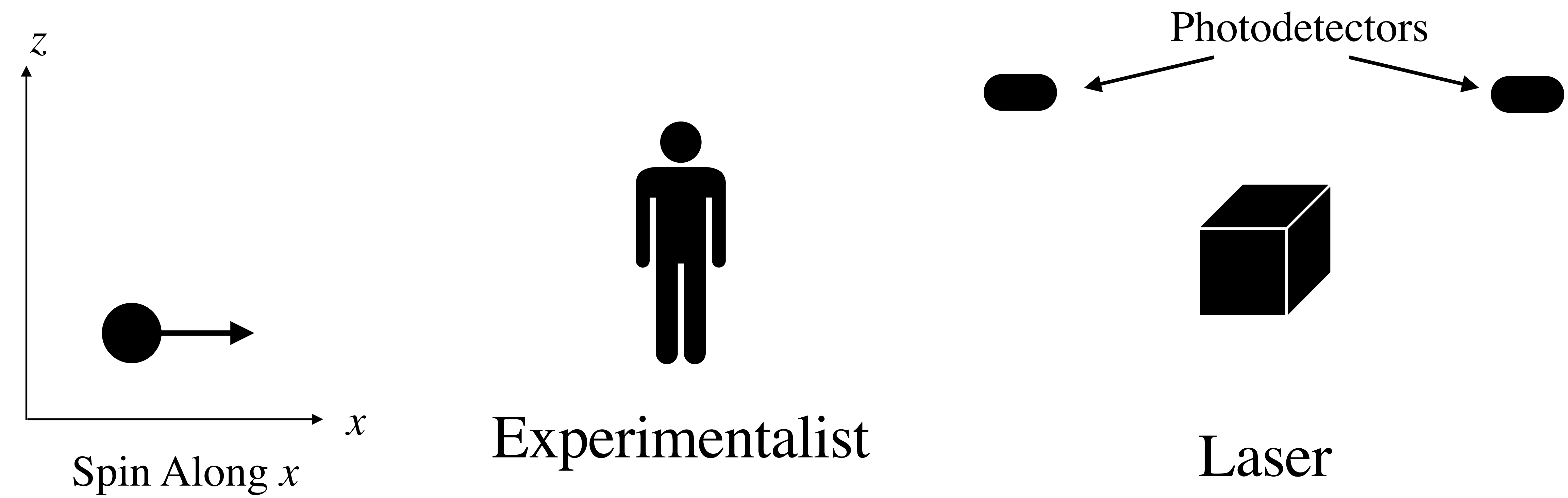
In non-linear QM, stationary states are generally **not** orthogonal —
the effective Hamiltonian depends on the initial state of the system

No Guarantee: $\langle A_j | A_i \rangle = 0$

$$|\Psi\rangle \otimes |A_0\rangle \to \sum_i c_i |i\rangle \otimes |A_i\rangle + \epsilon \sum_{i,j} d_{i,j} |i\rangle \otimes |A_j\rangle$$

Measurement noise

Linear Quantum Mechanics



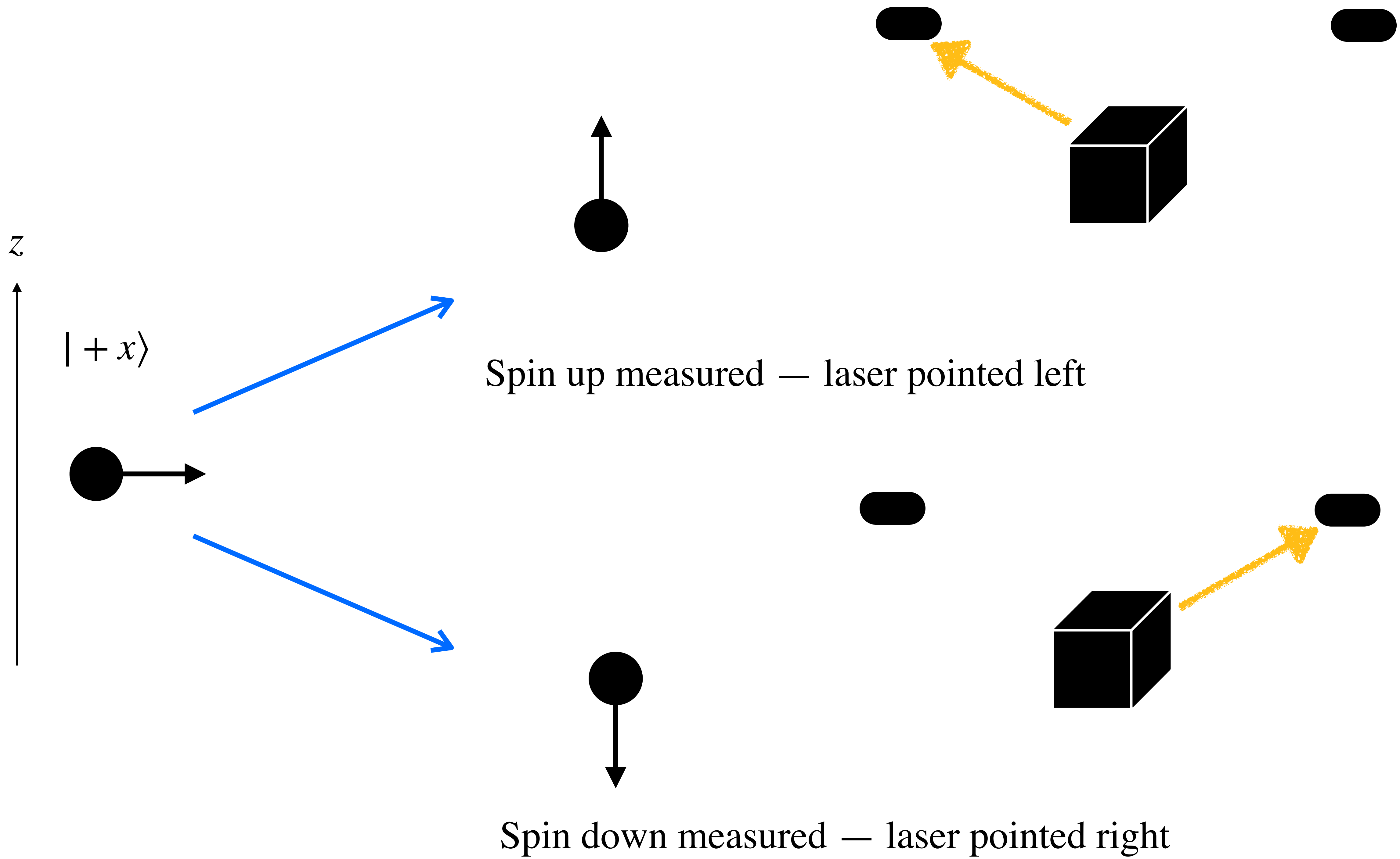
Initial State : $|\chi(0)\rangle$

Represents Full Quantum State (spin, experimentalist…)

Goal: Create Macroscopic Superposition

Method: Measure spin along z.
Depending upon outcome, send laser along different directions

Linear Quantum Mechanics

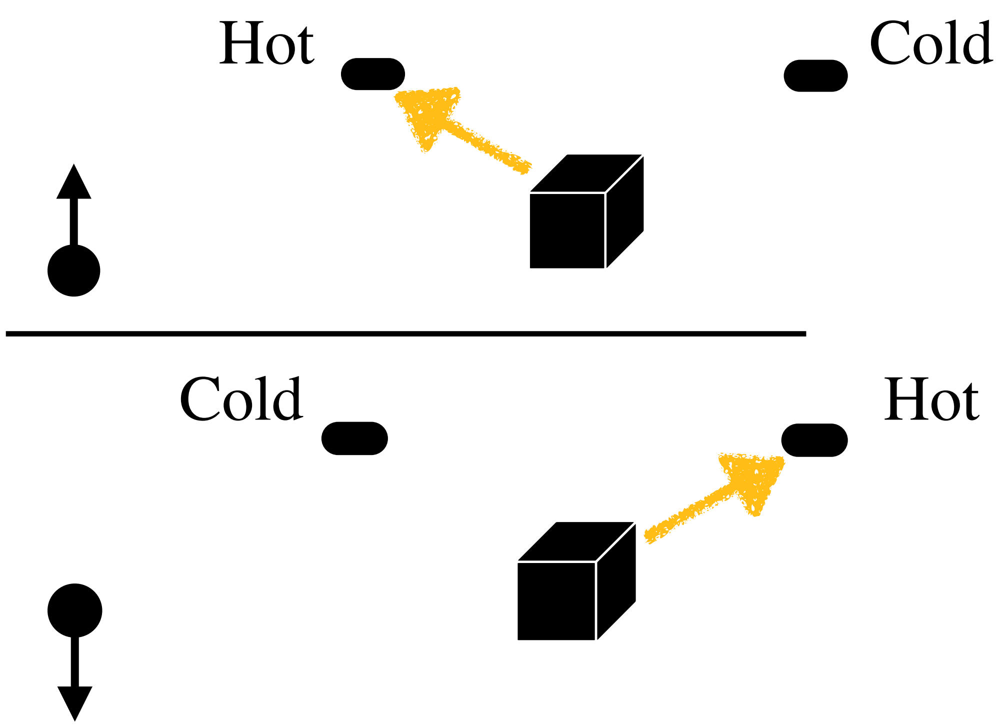


$$|\chi(t)\rangle = \frac{1}{\sqrt{2}}\left(|+z\rangle|L\rangle|Env_L\rangle + |-z\rangle|R\rangle|Env_R\rangle\right)$$

Linear Quantum Mechanics

Which photodetectors light up?

$$\mathscr{H} \supset eA_\mu J^\mu$$



Transition Matrix Elements

$$\langle +z | \langle L | \langle Env_L | A_\mu(x_L)\, J^\mu(x_L) | +z\rangle | L\rangle | Env_L\rangle \neq 0$$

$$\langle +z | \langle L | \langle Env_L | A_\mu(x_R)\, J^\mu(x_R) | +z\rangle | L\rangle | Env_L\rangle = 0$$

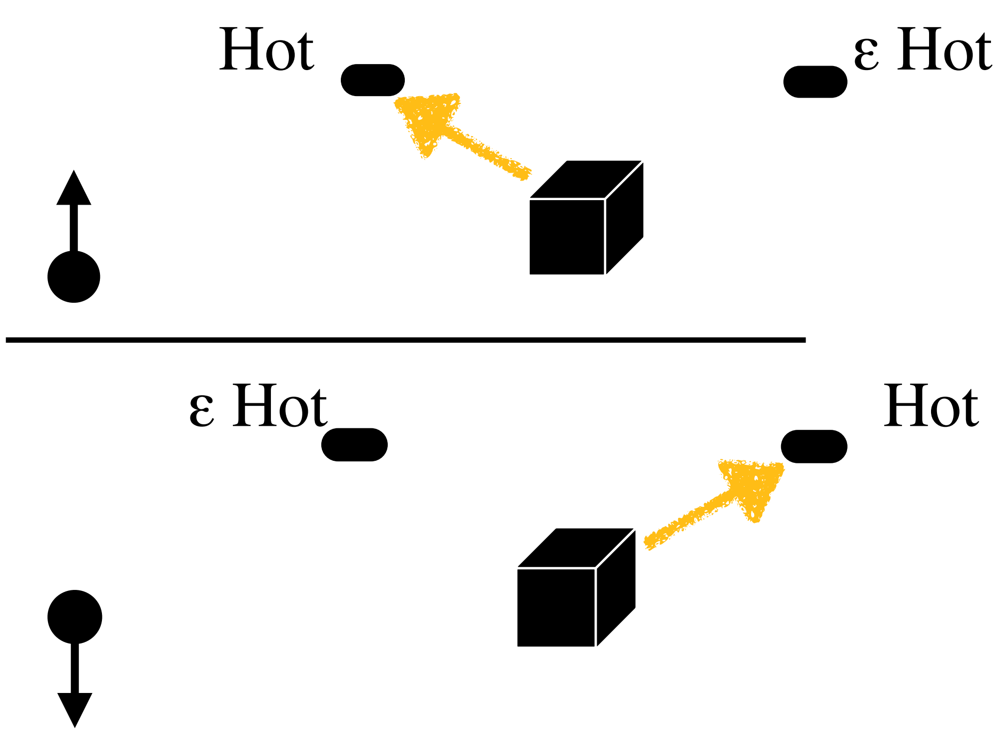
$$\langle L | A_\mu(x_R) | L\rangle = 0$$

$$|\chi(t)\rangle = \frac{1}{\sqrt{2}}\left(| +z\rangle | L\rangle | Env_L\rangle + | -z\rangle | R\rangle | Env_R\rangle \right)$$

Non-Linear Quantum Mechanics

Which photodetectors light up?

$$\mathscr{H} \supset eA_\mu J^\mu + e\varepsilon\langle A_\mu\rangle J^\mu$$



Transition Matrix Elements

$$\langle +z|\langle L|\langle Env_L|\langle A_\mu(x_L)\rangle J^\mu(x_L)|+z\rangle|L\rangle|Env_L\rangle \neq 0$$

$$\langle +z|\langle L|\langle Env_L|\langle A_\mu(x_R)\rangle J^\mu(x_R)|+z\rangle|L\rangle|Env_L\rangle \neq 0$$

$$\downarrow$$

$$\langle\chi|A_\mu(x_L)|\chi\rangle \neq 0\,,\ \langle\chi|A_\mu(x_R)|\chi\rangle \neq 0$$

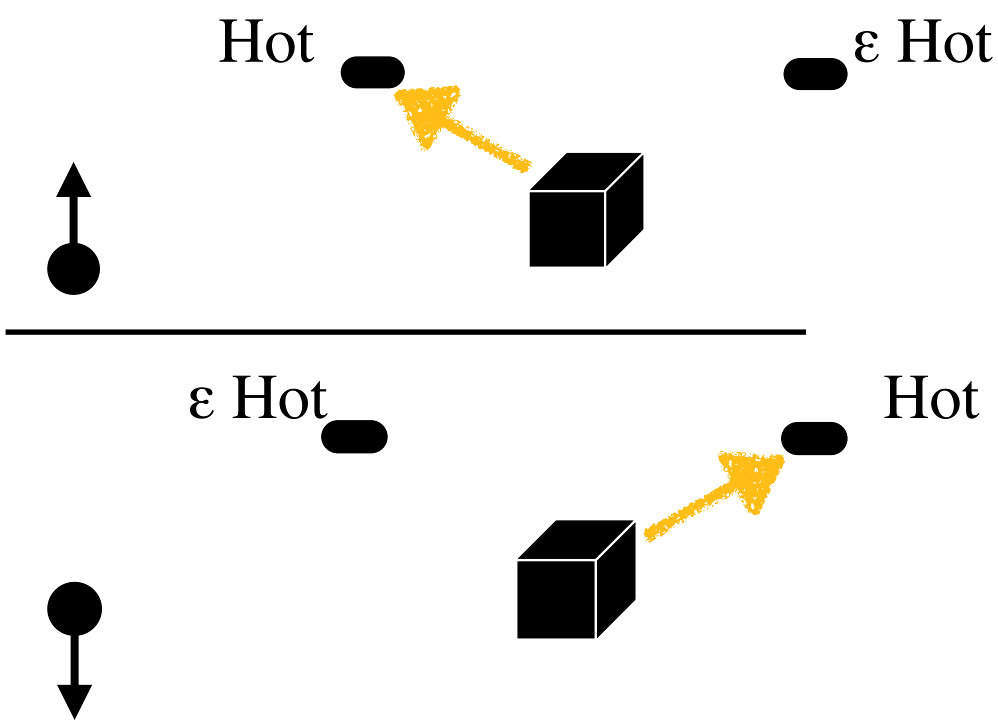
Communication between "worlds"

Non-linearity visible despite Environmental De-coherence!
Polchinski: "Everett Phone"

Quantum Pollution

Delicate Non-Linearity

O performs the laser experiment on October 24th
- discovers non-linear quantum mechanics!



$$|\chi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle|O_L\rangle + |R\rangle|O_R\rangle\right)$$

Now O wants to repeat experiment

Suppose $|O_U\rangle$ decides to run experiment at 9am on Oct 26
But $|O_D\rangle$ runs experiment on 9am on Nov 3rd

State just after 9am on Oct 26

$$|\chi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle|O_L\rangle\frac{|L'\rangle|O_L'\rangle + |R'\rangle|O_D'\rangle}{\sqrt{2}} + |R\rangle|O_R\rangle\right)$$

Delicate Non-Linearity

State after 9am on Oct 26

$$|\chi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle |O_L\rangle \frac{|L'\rangle |O'_L\rangle + |R'\rangle |O'_D\rangle}{\sqrt{2}} + |R\rangle |O_R\rangle \right)$$

Compare with State on Oct 24

$$|\chi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle |O_L\rangle + |R\rangle |O_R\rangle \right)$$

$$\langle L | \langle O_L | \langle L' | \langle O'_L | \langle A_\mu(x_R)\rangle\, J^\mu(x_R) | \chi(t = \text{Oct } 26)\rangle = \frac{1}{2}\langle L | \langle O_L | \langle A_\mu(x_R)\rangle\, J^\mu(x_R) | \chi(t = \text{Oct } 24)\rangle$$

Effect is 1/2 of prior effect!

But, full effect if O_U and O_D perform experiment at same time!

Quantum Pollution: Without adequate care, superpositions may diverge wildly, preventing exploitability. Not automatic - but need careful protocols!

But hasn't there already been dilution?

What part of the wave function…

$$|\chi\rangle = \alpha|\mathrm{Us}\rangle + \beta|\mathrm{Them}\rangle$$

$$\mathscr{H} \supset eA_\mu J^\mu + e\varepsilon\langle A_\mu\rangle J^\mu$$

$$|\chi\rangle = \alpha|\mathrm{Us}\rangle + \beta|\mathrm{Them}\rangle \to \langle\chi|A_\mu|\chi\rangle = |\alpha|^2\langle\mathrm{U}|A_\mu|\mathrm{U}\rangle + |\beta|^2\langle\mathrm{T}|A_\mu|\mathrm{T}\rangle$$

$$\langle\chi|A_\mu|\chi\rangle \to |\alpha|^2\langle\mathrm{U}|A_\mu|\mathrm{U}\rangle$$

For $\alpha \ll \beta$, the wave function is dominated by something *we* are not a part of.

Local exploitability $\epsilon \to |\alpha|^2\epsilon$ determined by initial conditions
Dramatic difference from linear QM

Classical World?

$|U(t)\rangle = |$  $\rangle + \delta|\blacksquare\rangle$ **Or** $|U(t)\rangle = \delta|$  $\rangle + |\blacksquare\rangle$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

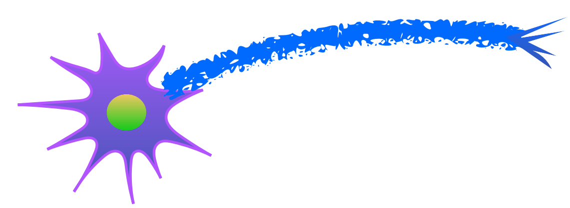
$\Delta x \sim 100\text{nm}$

Changing classical evolution of a system requires coherent motion of N atoms

Probability that N atoms coherently move in some way: p^N

With p ~ O(1) scattering probability

What about the weather?
What about my brain??



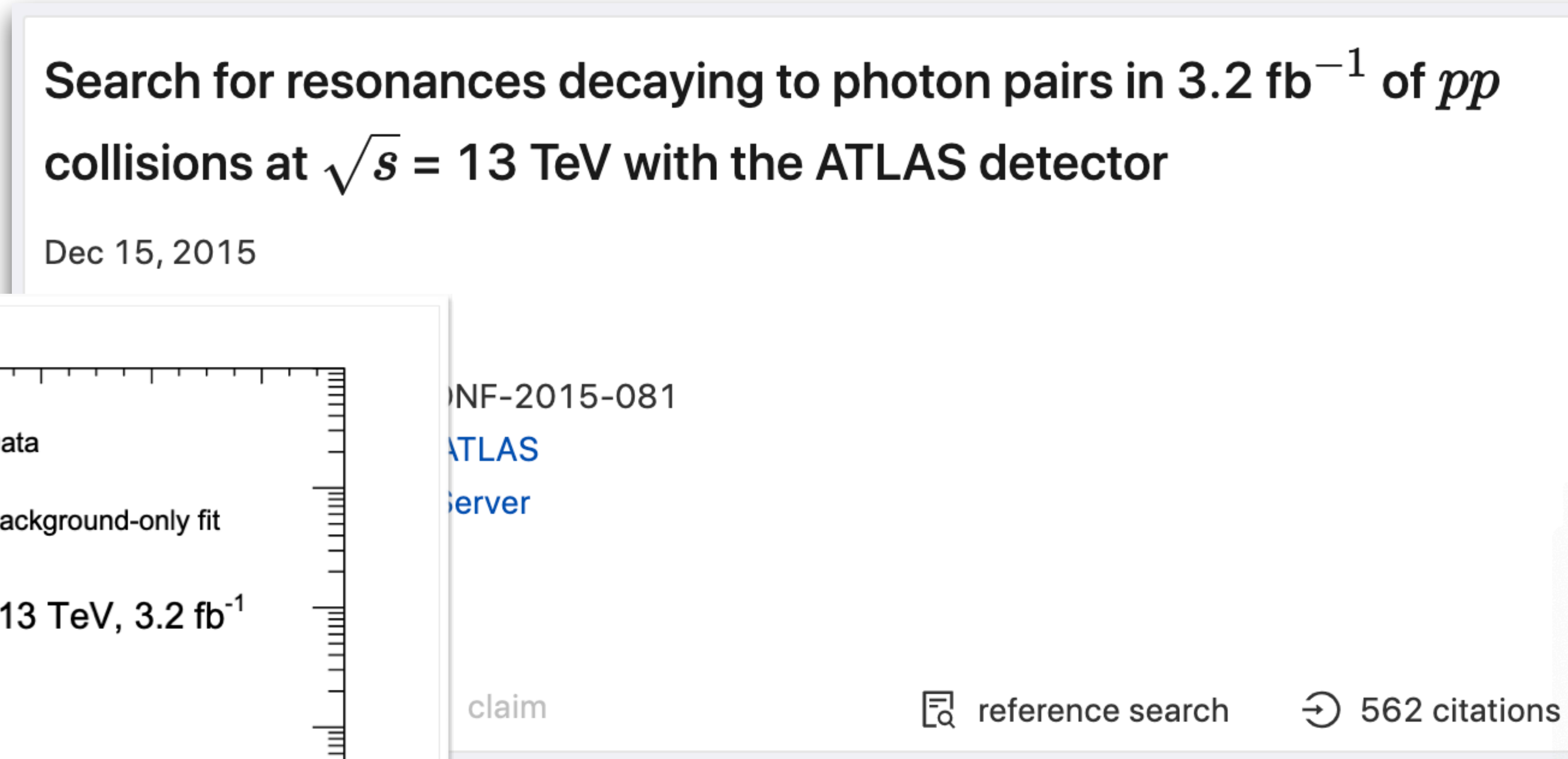
100's + ions to get one neuron to fire

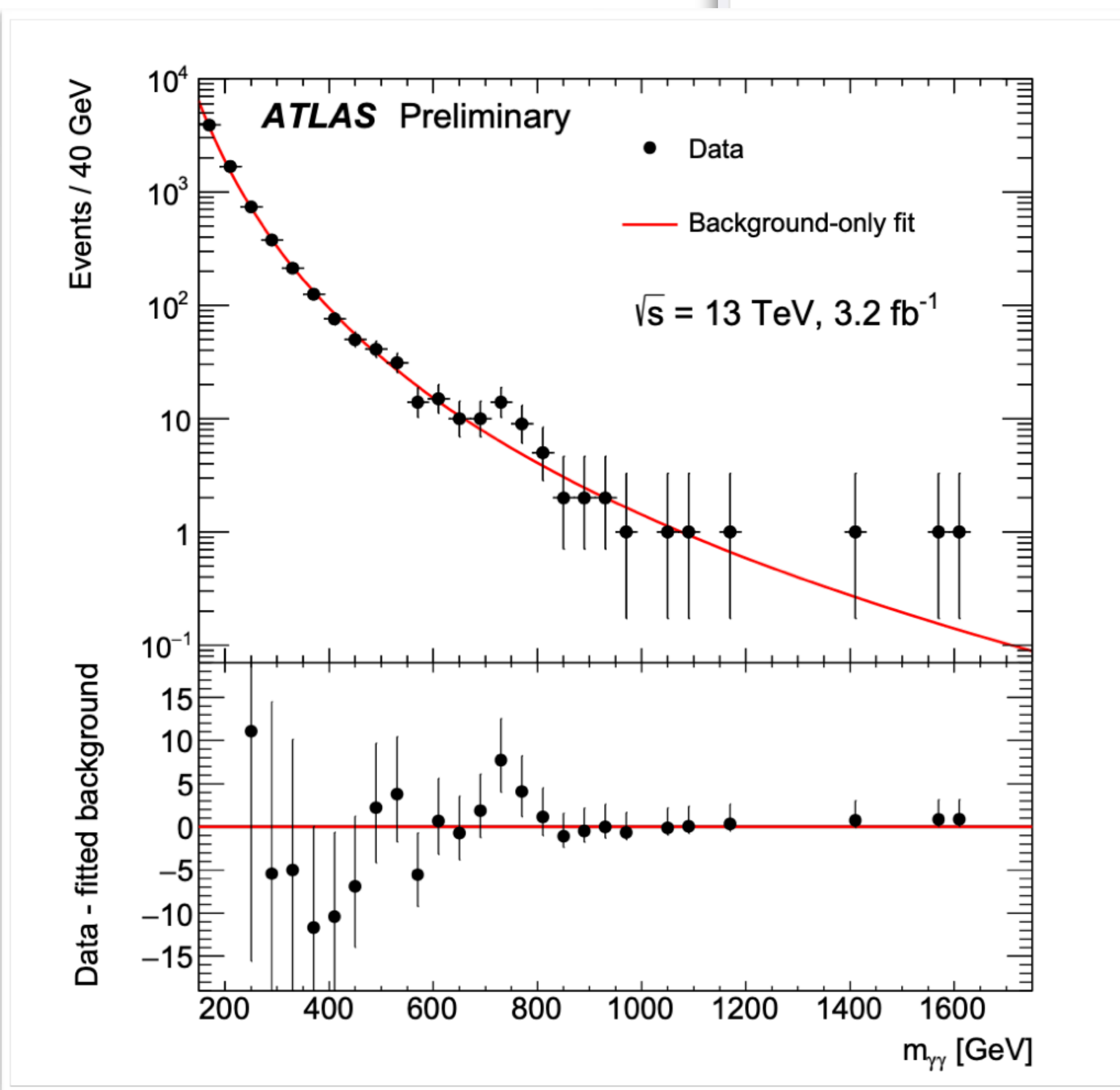
$|U(t)\rangle = |$  $\rangle + \delta|\blacksquare\rangle$ Reasonable

Quantum Amplifiers are Hard!

Natural Quantum Dilution

The ’750 GeV’ resonance!





Have we been diluting our wave function on Earth for the past 100 years?

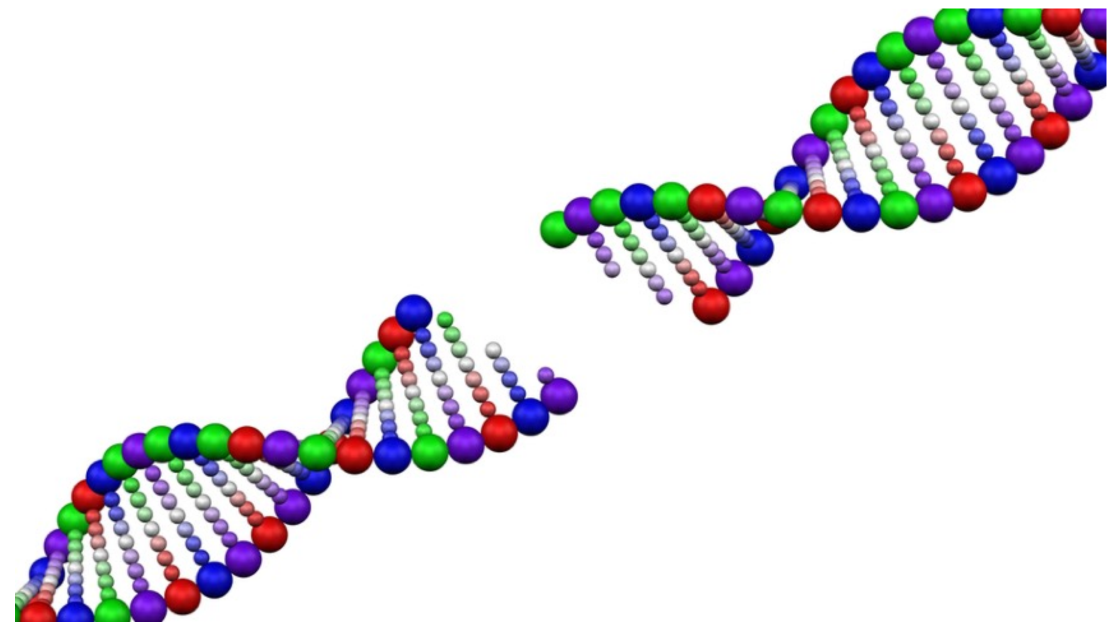
Evolutionary Dilution?

Is N ~ O(few) for evolution?

Maybe for RNA/DNA?

RNA formation?

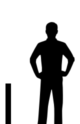
Is Evolution a quantum amplifier?!?



$|U(t=0)\rangle =$ 

$|U(t)\rangle = |$  $\rangle(|$  $\rangle + |\text{No life}\rangle + \ldots)$

$|U(t=0)\rangle =$ 

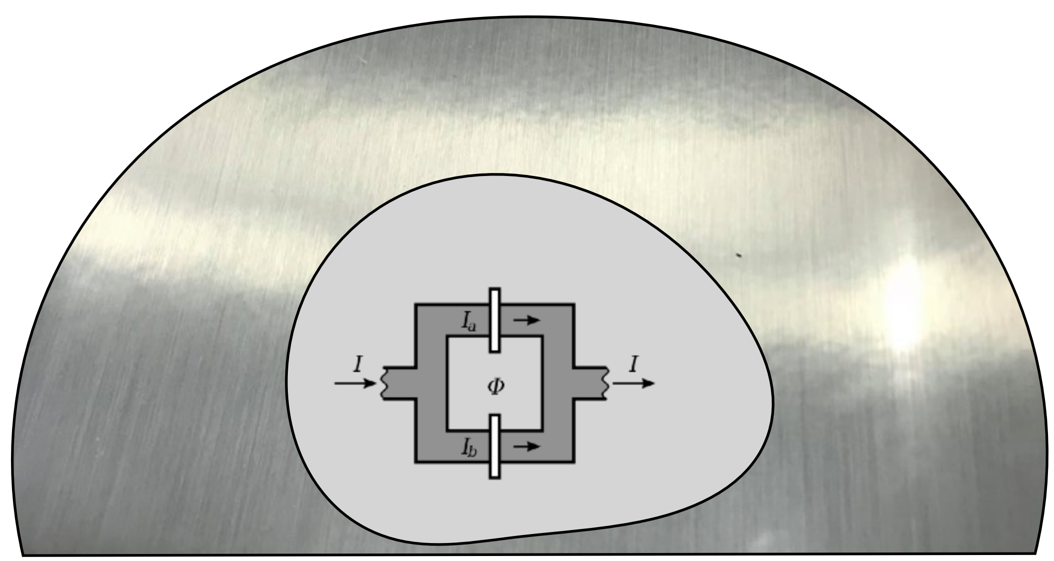
$|U(t)\rangle = |$  $\rangle(|$  $\rangle + |$  $\rangle + \ldots)$

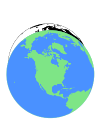
Tests for a Quantum-Diluted Earth

Look for coherent fields turned on in all parts of the wavefunction:
The magnetic field of the Earth!

$$eJ^{\mu}(A_{\mu} + \epsilon_{\gamma}\langle A_{\mu}\rangle)$$

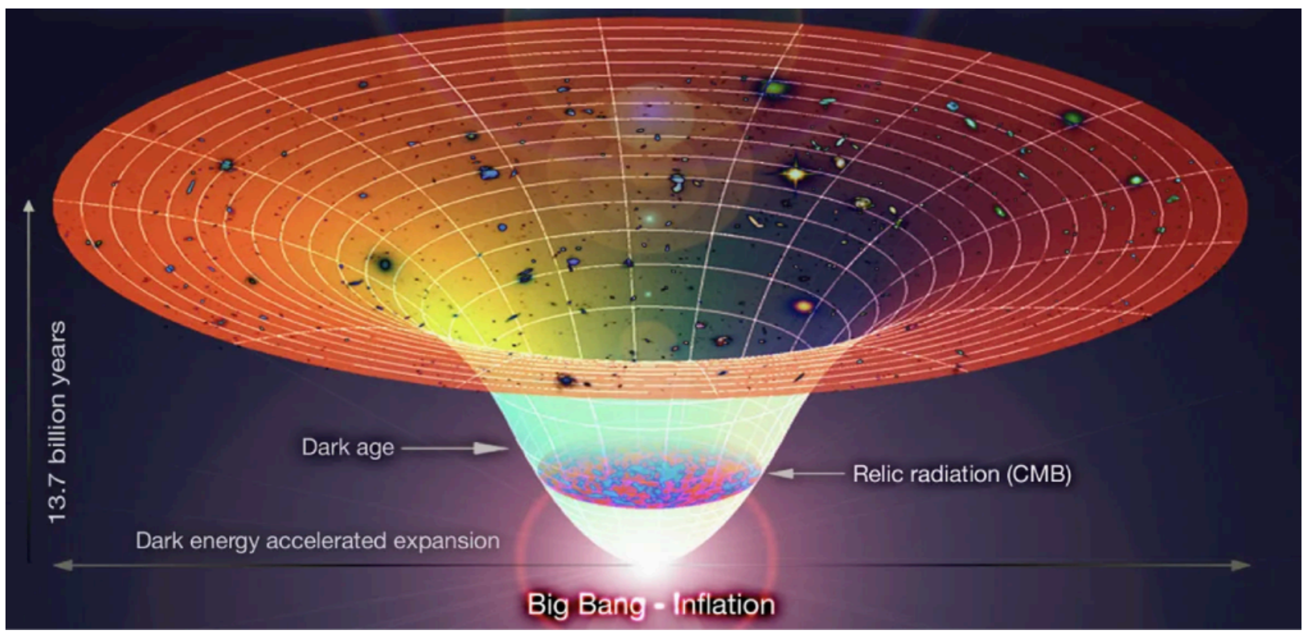
Remove an ancient magnetic source in our part of the wave function and measure the field in that region.



$|U(t)\rangle = |$  $\rangle(\alpha\,|\text{missing magnetic material}\,\rangle + \beta\,|\text{magnetic material}\rangle)$

Cosmological Quantum Amplifier: Inflation

Standard cosmic inflation:
rapidly places quantum state in a homogenous and isotropic state
(Bunch-Davies Vacuum)



Homogeneous state becomes massive superposition of statistically similar Universes!

$$|\chi\rangle = \sum_i c_i |U_i\rangle, \; c_i \sim e^{-N}$$

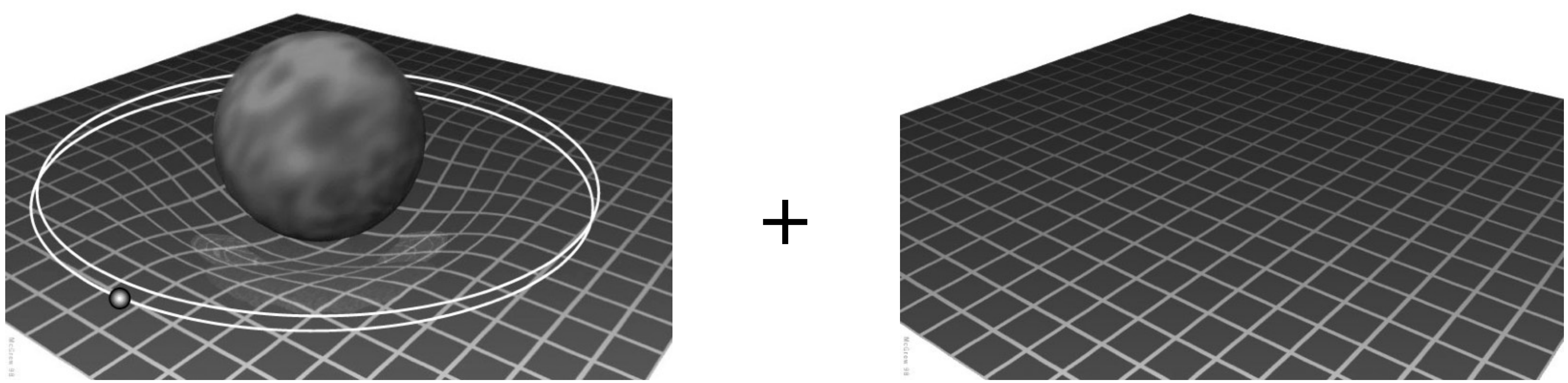
Most of the Universe: The space-time point where the Earth is located is in intergalactic space!

Tests for a Quantum-Diluted Universe(!)

Look for coherent fields turned on in all parts of the wavefunction:
The magnetic field of the Earth!

$$T^{\mu\nu}(g_{\mu\nu} + \epsilon_G \langle g_{\mu\nu} \rangle) + \cdots$$

Objects in our part of the wave function will produce different gravitational fields than the average

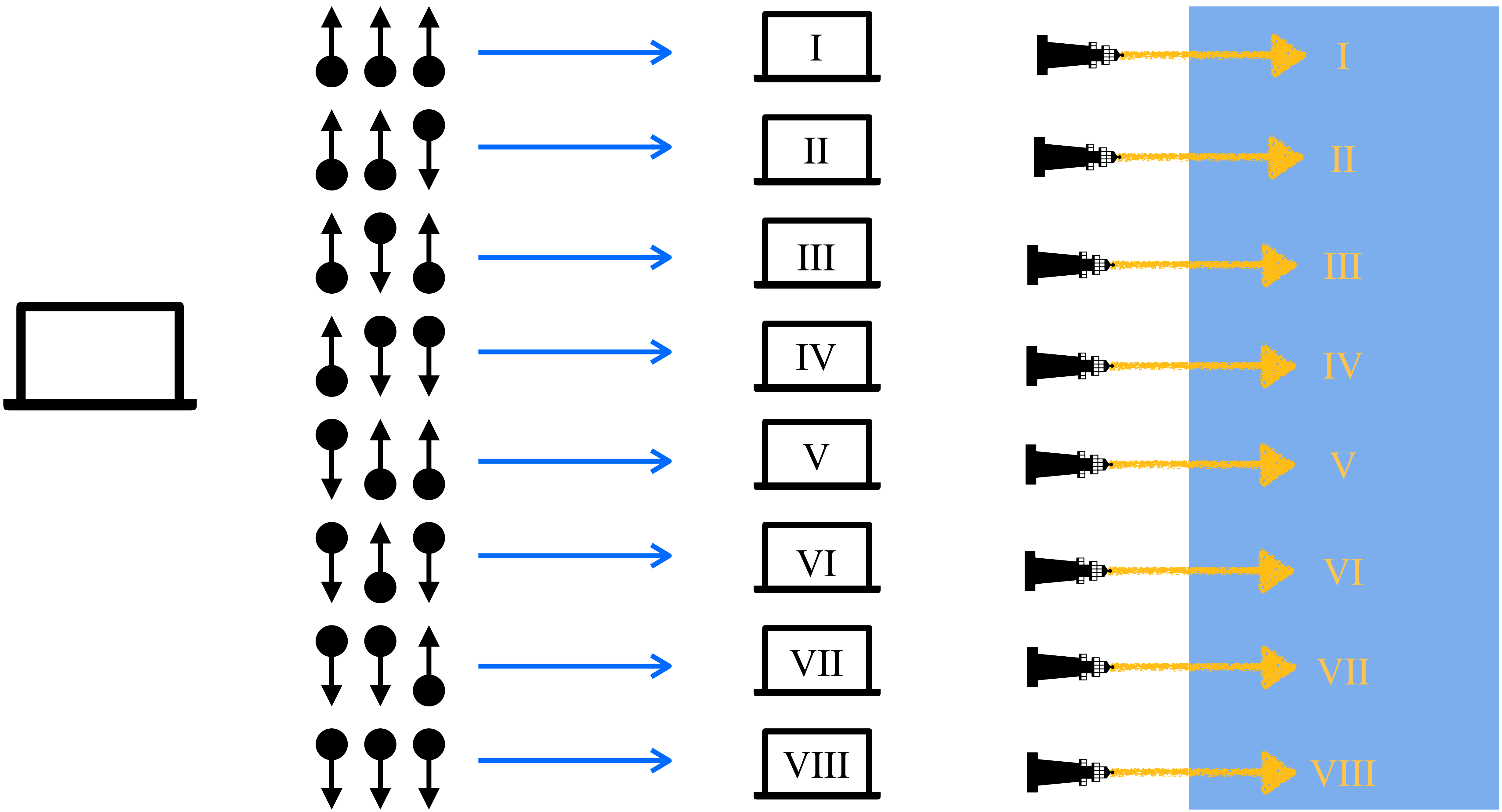


Implications

If we have a Classical Universe

Macroscopic superpositions can be produced at will.

Parallelize any computation:



Quantum Computing!

Conclusions

There are consistent ways to explore deviations from QM

Locality makes many past tests insensitive — **new probes required**

NL effects can be experimentally tested by amplifying quantum measurements

Quantum amplification in the history of the universe could suppress local non-linearities

If locally diluted, non-zero fields across the wave function could be detected (ancient magnetic/gravitational fields, cosmological metric)

If NLQM is locally accessible, it will radically change what we can do technologically

Thank you!