How and Why to go Beyond the Discovery of the Higgs Boson

John Alison

University of Chicago

http://hep.uchicago.edu/~johnda/ComptonLectures.html

Last Lecture

Newton's Dream: Direction of science

Turn of 20th Century: Dream in peril

20th Century Revolutions:
- Relativity
- Quantum Mechanics

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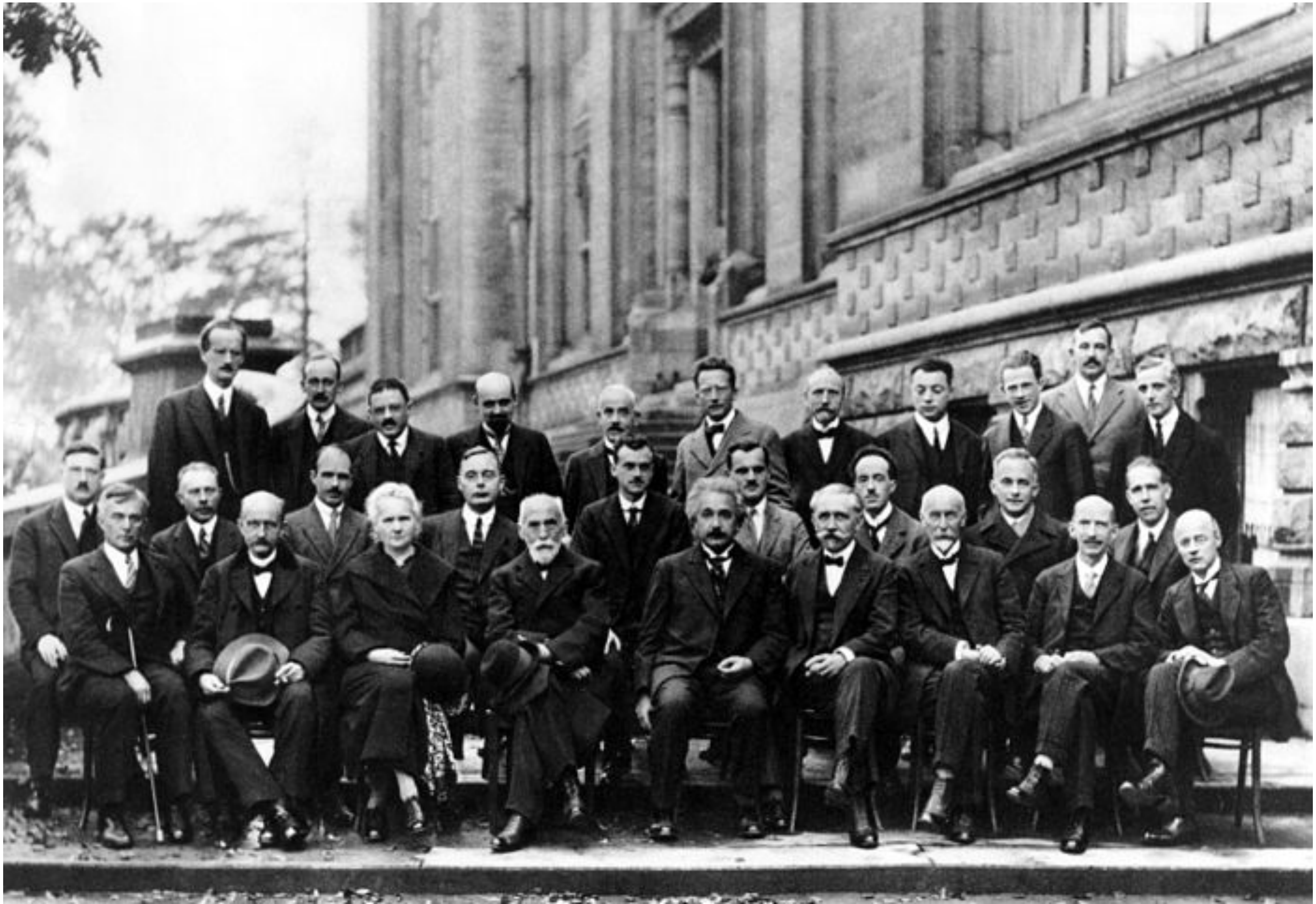
Newton's Dream: Direction of science

Turn of 20th Century: Dream in peril

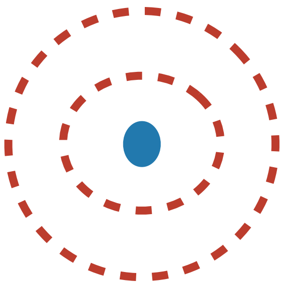
20th Century Revolutions:
- Relativity
- Quantum Mechanics *(start here today)*

Quantum Mechanics



Quantum Mechanics

Picture of atom (circa 1911)



Electrons
- Negative charge
- ~all the space

Nucleus
- Positive charge
- ~all the mass

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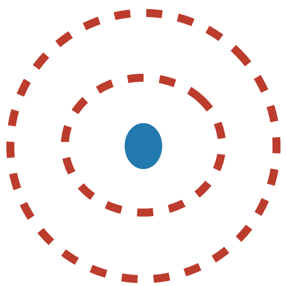

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Problems:

- Known physics predicts electrons should spiral in to nucleus.
  Why is matter stable ?
- Atoms absorb/emit energy (light) only at discrete values.
  Why not continuous, as predicted ?
- Wave-Particle duality: matter vs light
  Really two modes existence ? Which is fundamental ?

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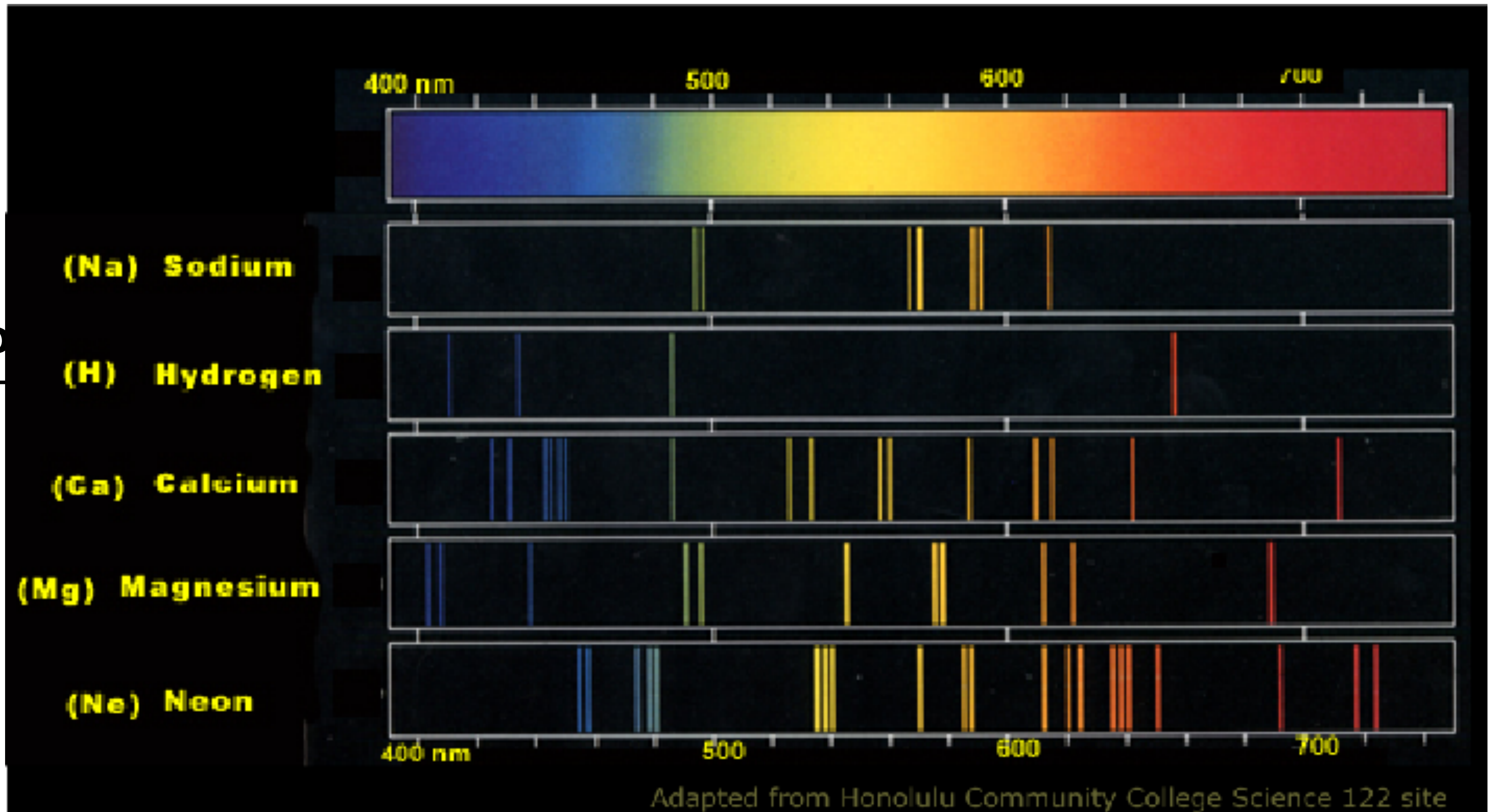

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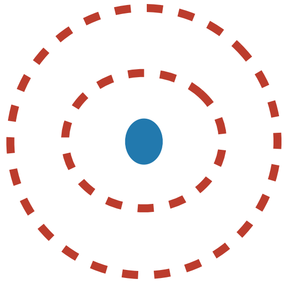

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<u>Long Period of Confusion</u>:
- Several ad-hoc competing ideas able to give partial answers
- Eventually unified to consistent theory
- Solution not modification of electric force or structure of atom
- Completely new framework for all physical processes

Quantum Mechanics

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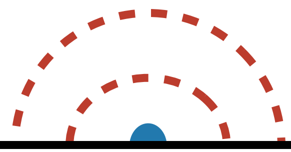


Electrons

Nucleus

Upshot:

Shouldn't talk about electron trajectories within an atom

Instead new mathematical concept "Amplitude" (ψ)

- ψ is the fundamental physics entity
- Describes everything there is to know about the electron

Quantum Mechanics gives prescription for how:

- Amplitudes evolve in time (behave like waves)
- To convert amplitudes to probabilities ($|\psi|^2$ = Prob)

Probabilities

Randomness in nature

ψ_μ

Exact same ψ_μ

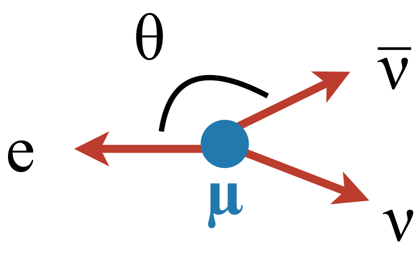
μ

μ

Probabilities

Randomness in nature

ψ_μ



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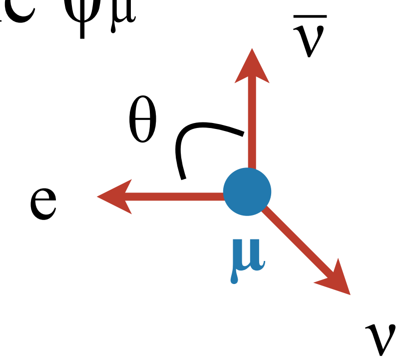
Exact same ψ_μ



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Probabilities

Randomness in nature

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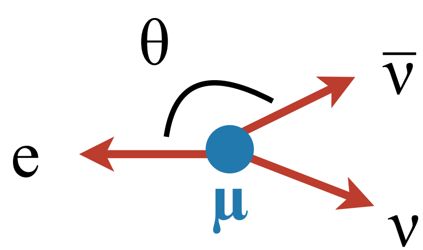

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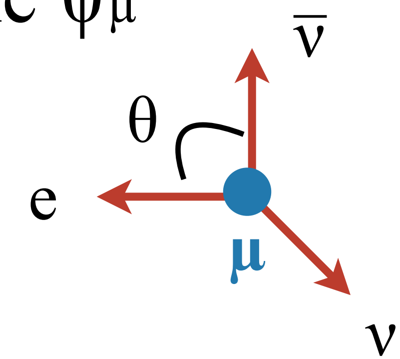

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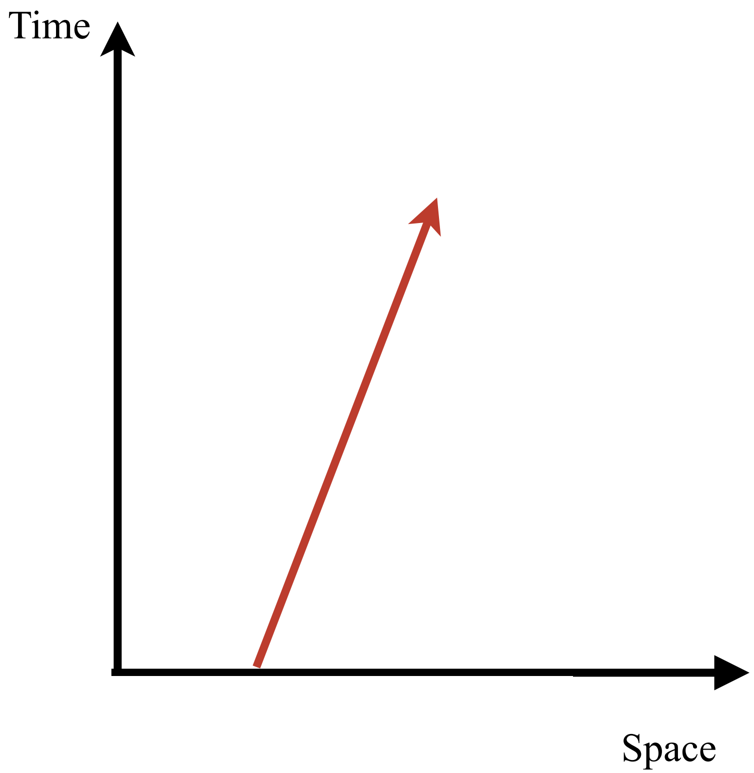
- QM cannot predict what will happen in any particular event (μ decay)
- QM can predict distributions (what happens on average)

Huge loss in predictivity !

Uncertainty Principle

Classically (w/o QM)



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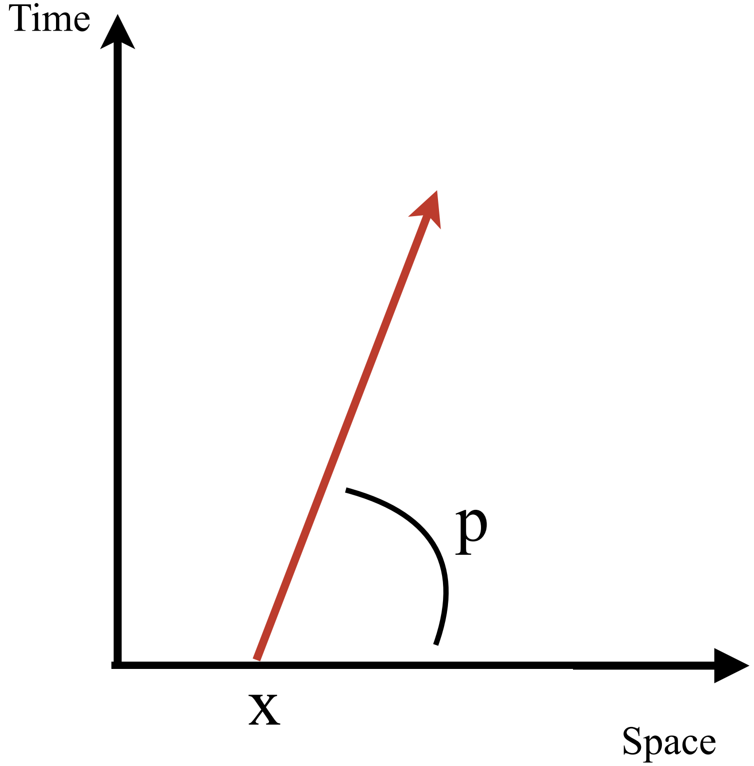
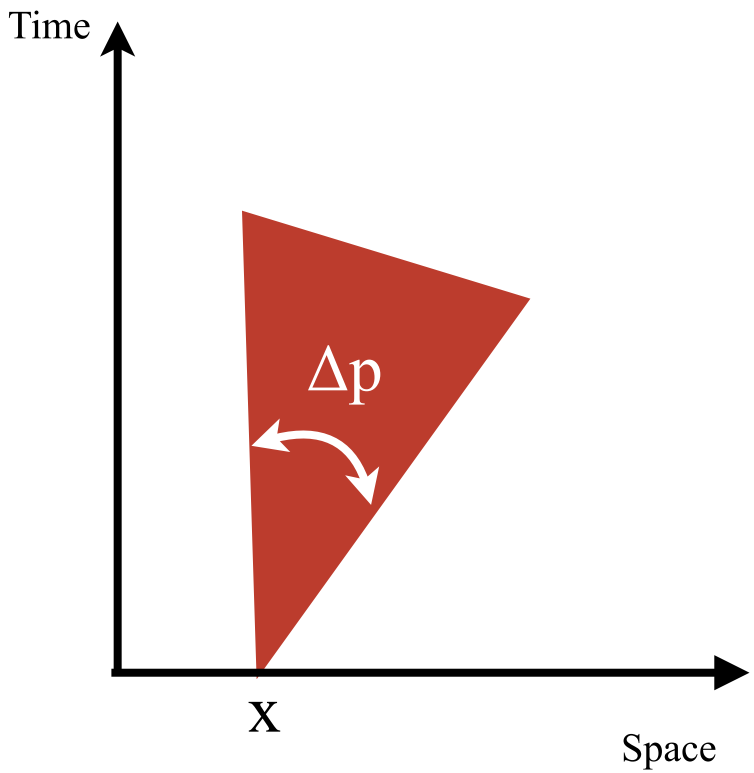


Uncertainty Principle

Quantum World



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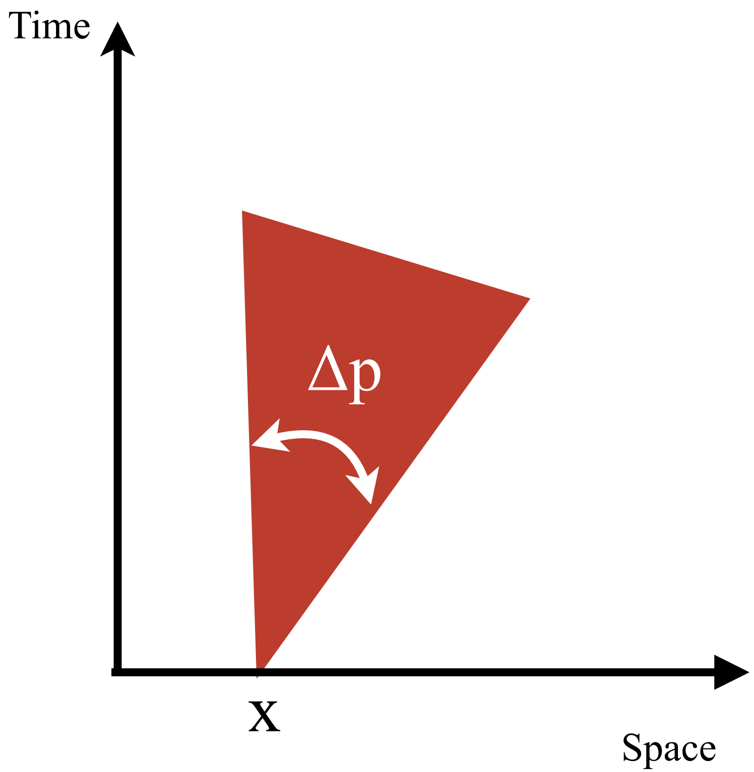

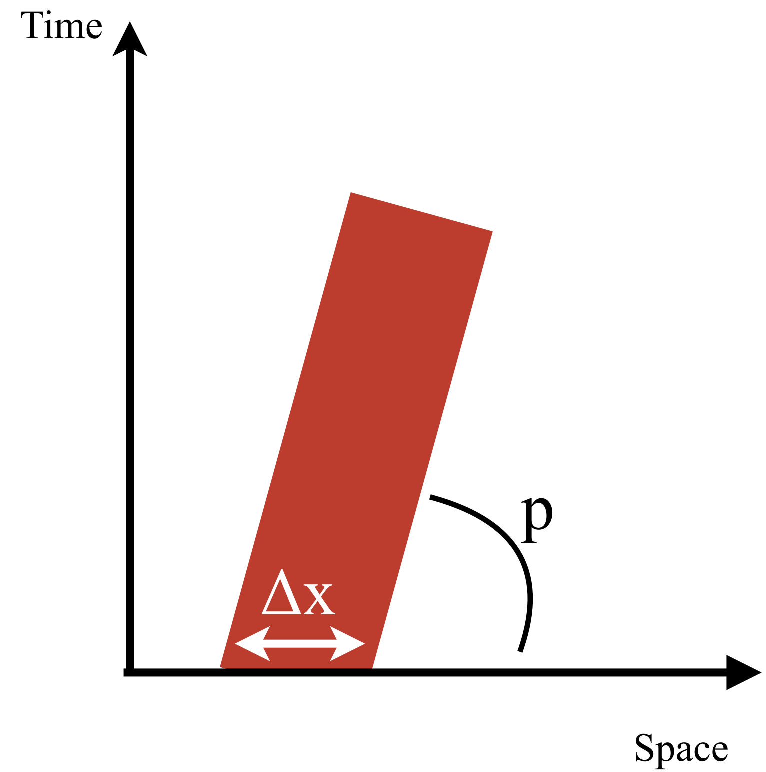

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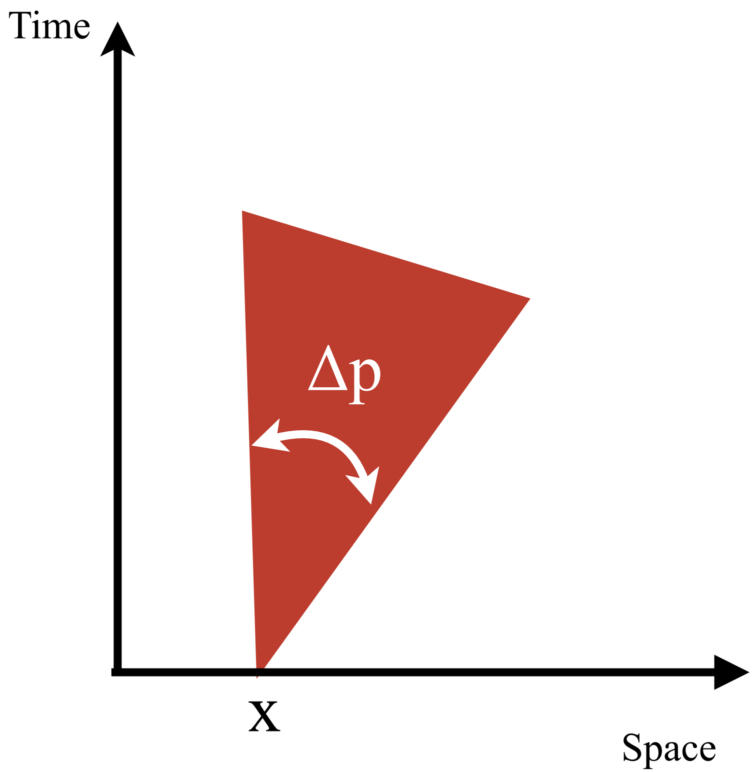
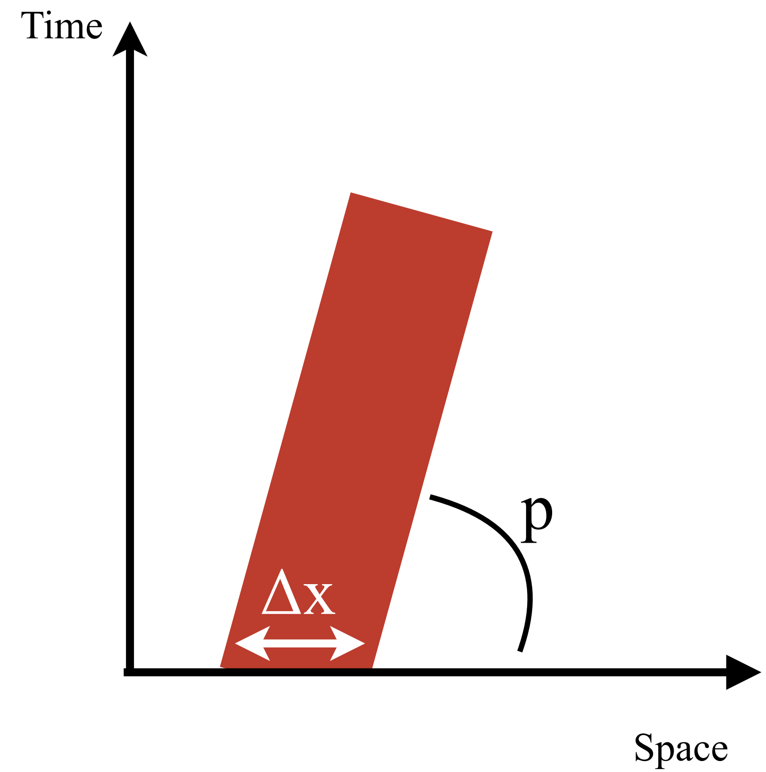
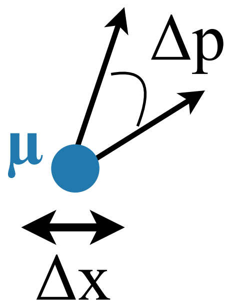




$$\Delta x \, \Delta p \geq h$$



Uncertainty Principle

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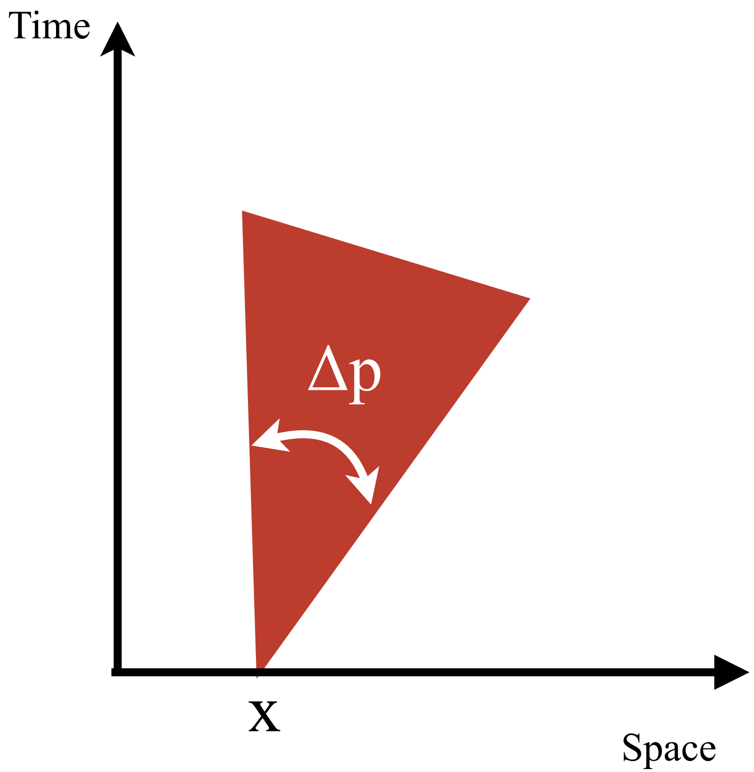
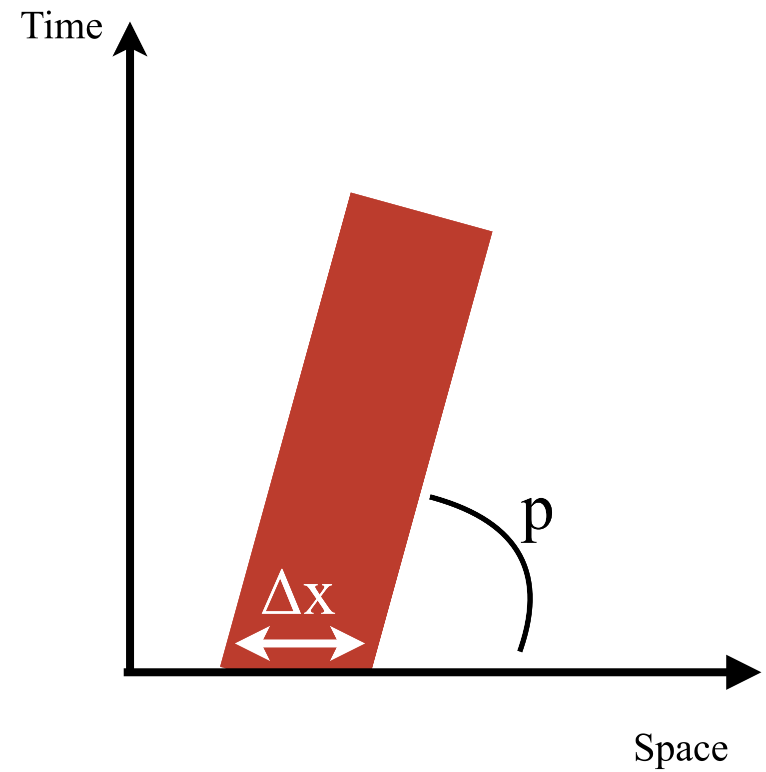
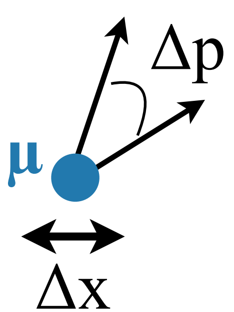




$$\Delta x \, \Delta p \geq h$$
$$\Delta E \, \Delta t \geq h$$



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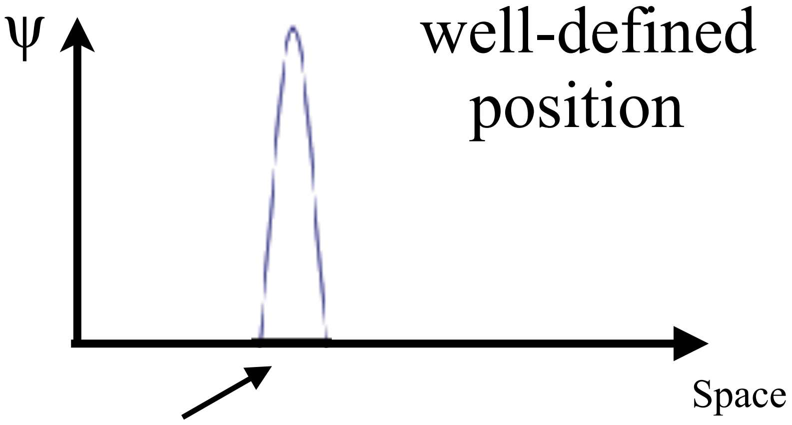
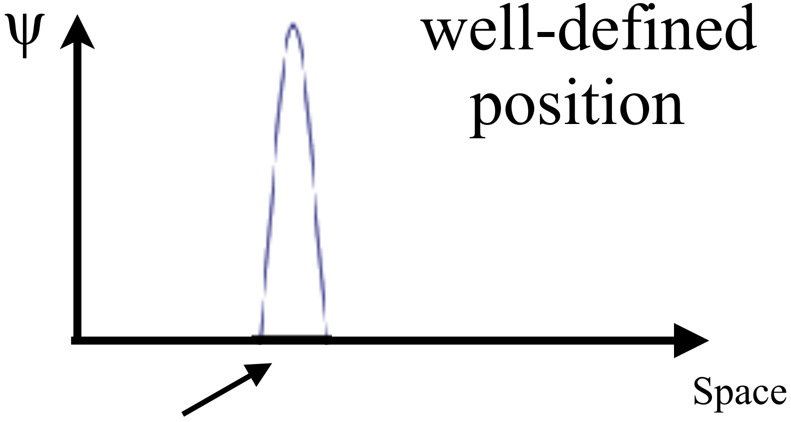


Position well-defined when probability (ψ^2) sharply peaked on one place

Uncertainty Principle

well-defined position



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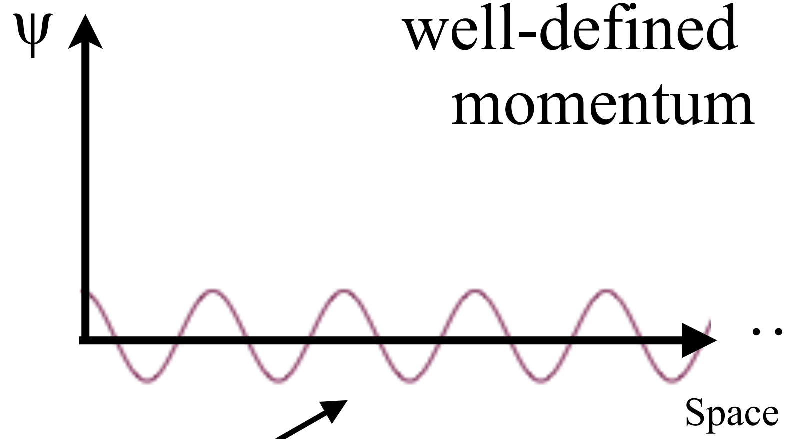
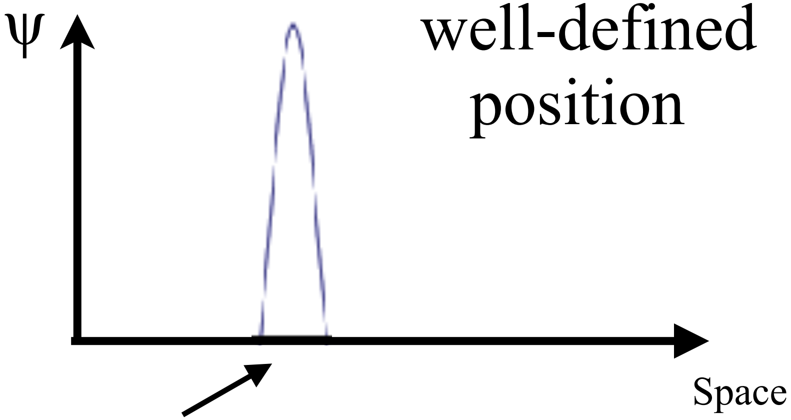
well-defined momentum



Momentum well-defined when uniform distance between peaks

Uncertainty Principle

well-defined position



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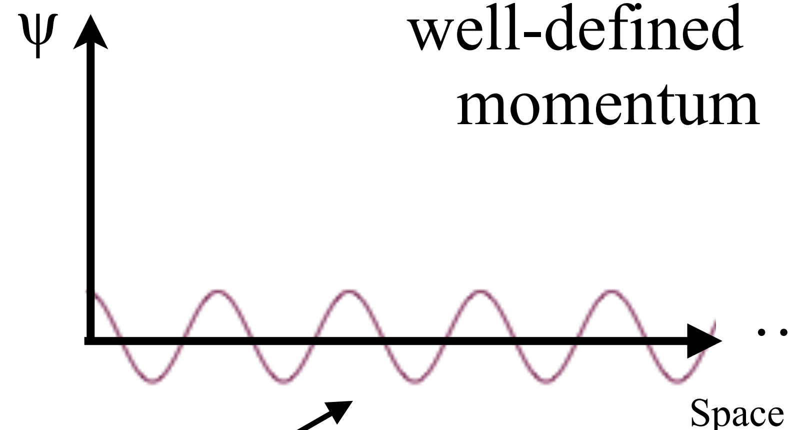

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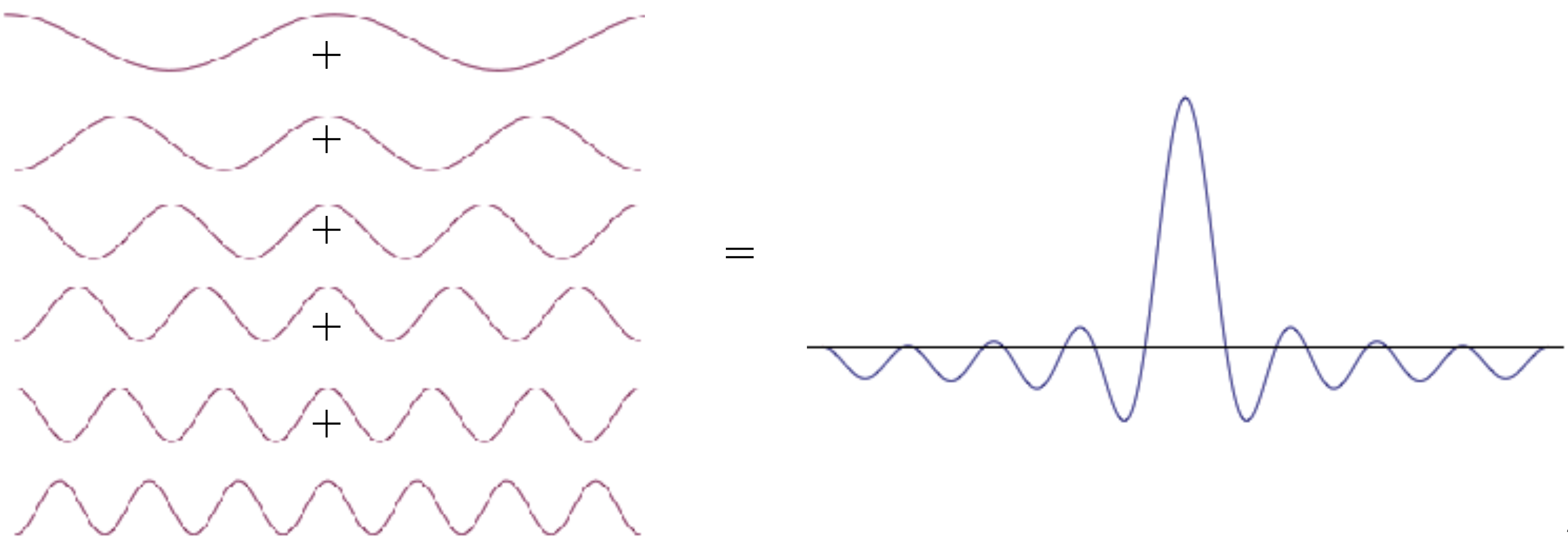

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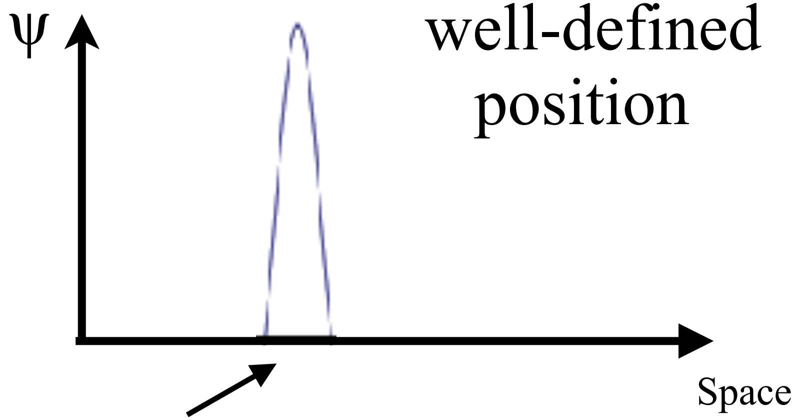

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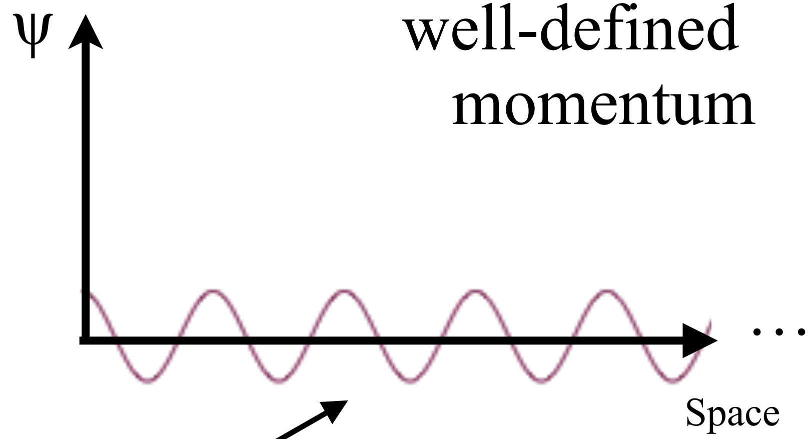
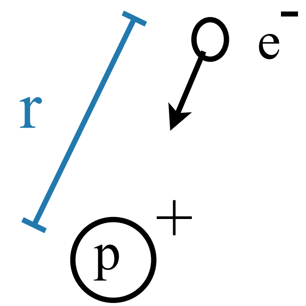


Momentum well-defined when uniform distance between peaks

Reasonably well-defined position **and**
Reasonably well defined momentum

Stability of Matter

Atom:



Stability of Matter

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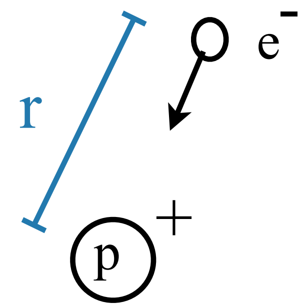
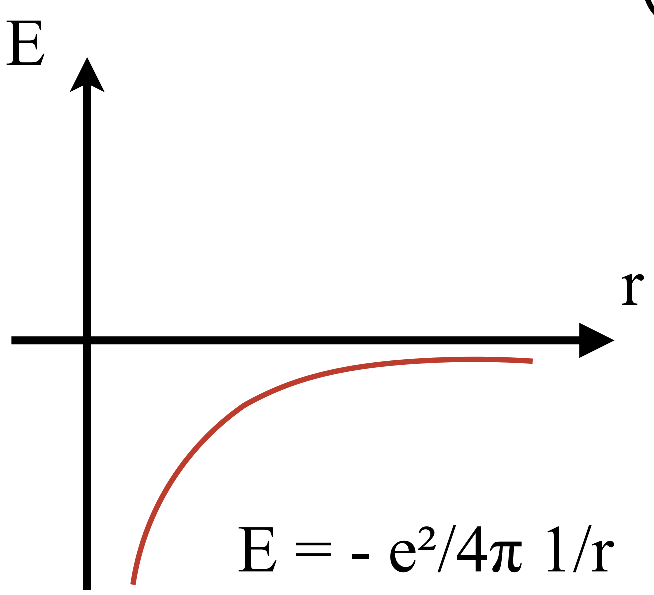


Classically (w/o QM)



Electron will sit directly on nucleus

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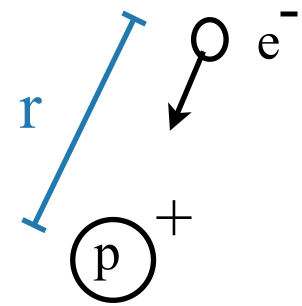

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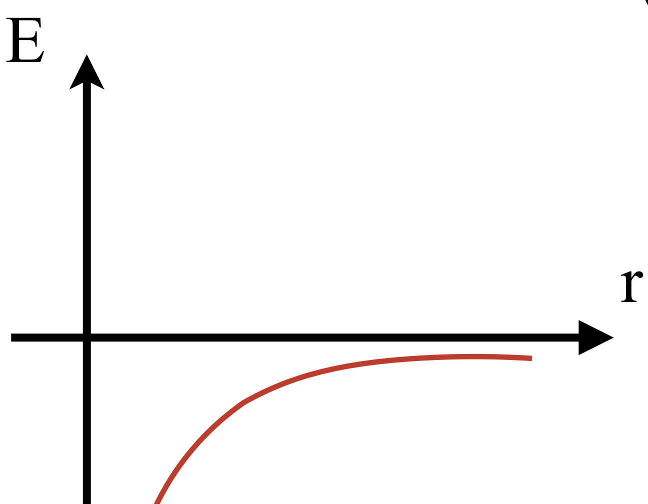
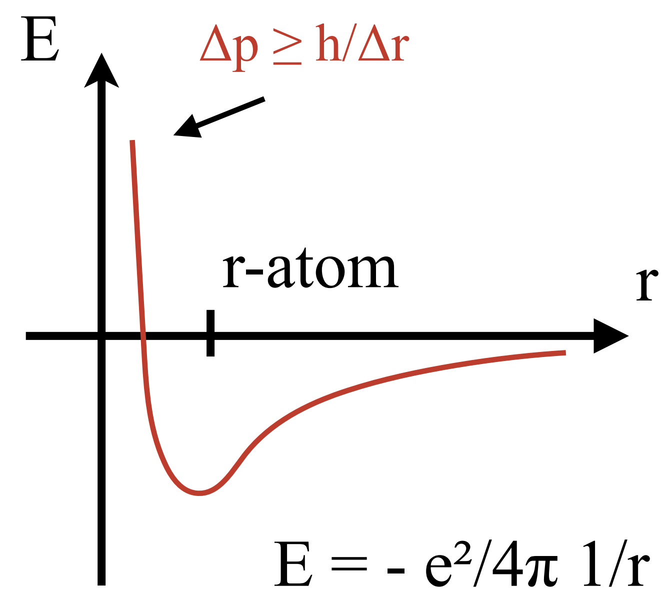


$E = - e^2/4\pi \; 1/r$

Electron will sit directly on nucleus

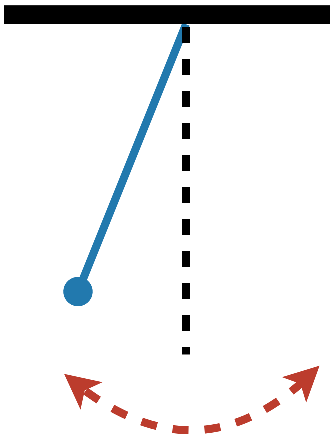
Quantum World



$E = - e^2/4\pi \; 1/r + h^2/2mr^2$

Atoms are stable w/finite size

Minimum Energy



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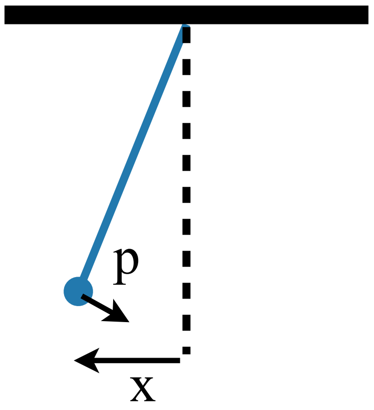

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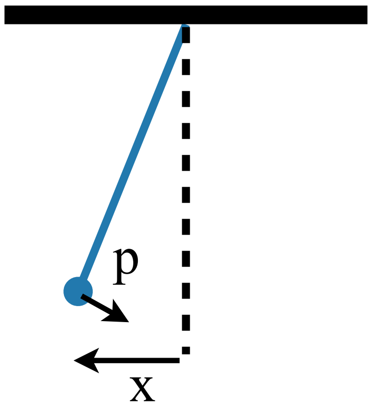

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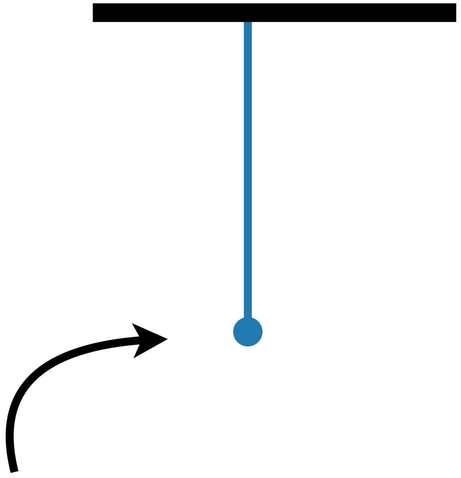
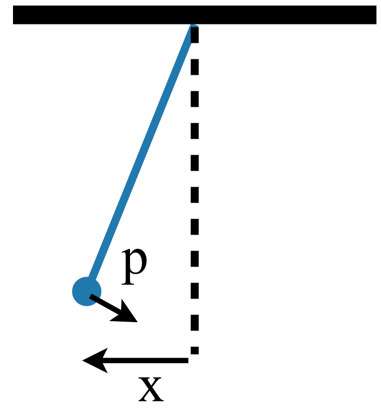


Lowest possible energy is 0.
Not moving and at lowest point.

Minimum Energy



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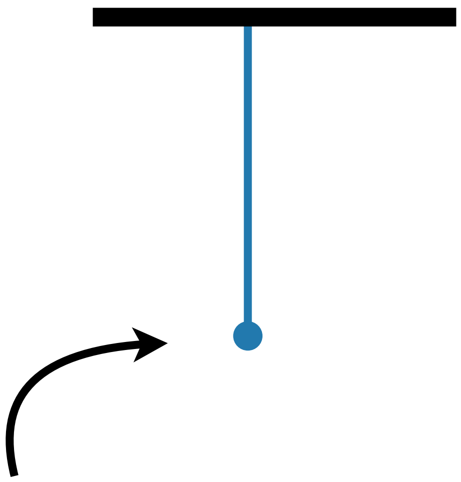

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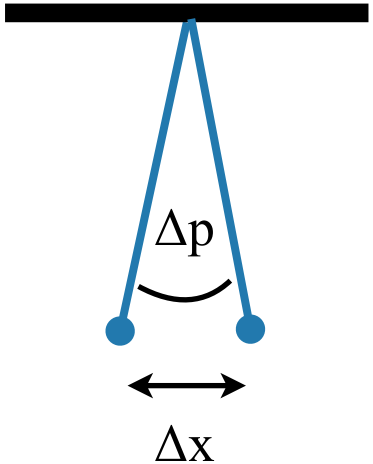

Cannot be both at lowest point and not moving.
Minimum non-zero energy: $E \sim h\omega$

Wave vs Particles

Everything is a *quantum* particle !

Particles have definite values of:

- mass
- spin: *(0, 1/2, 1, ...* $\times$ *h)*
- other properties: e.g: charge

Wave vs Particles

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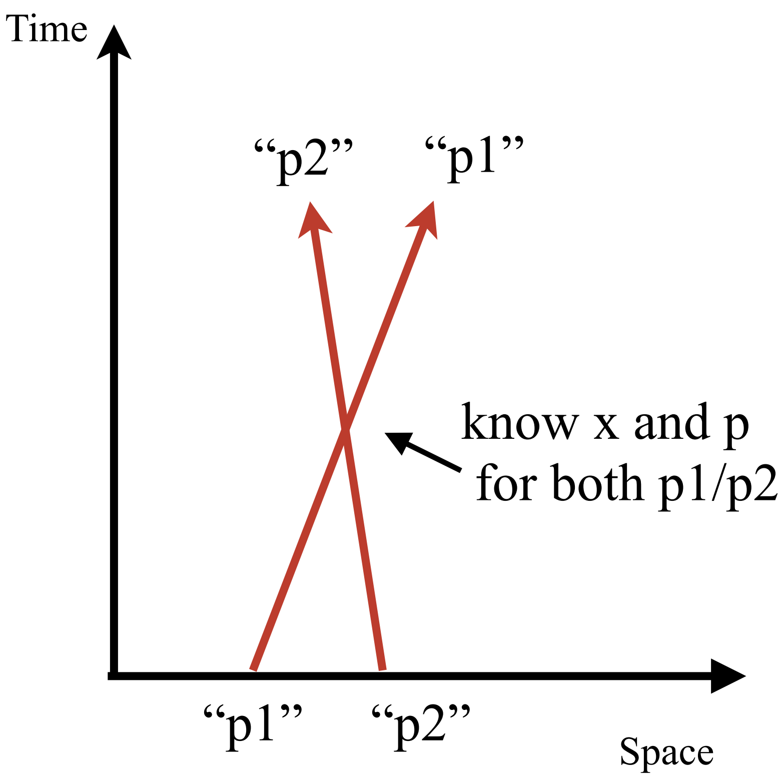
Classically



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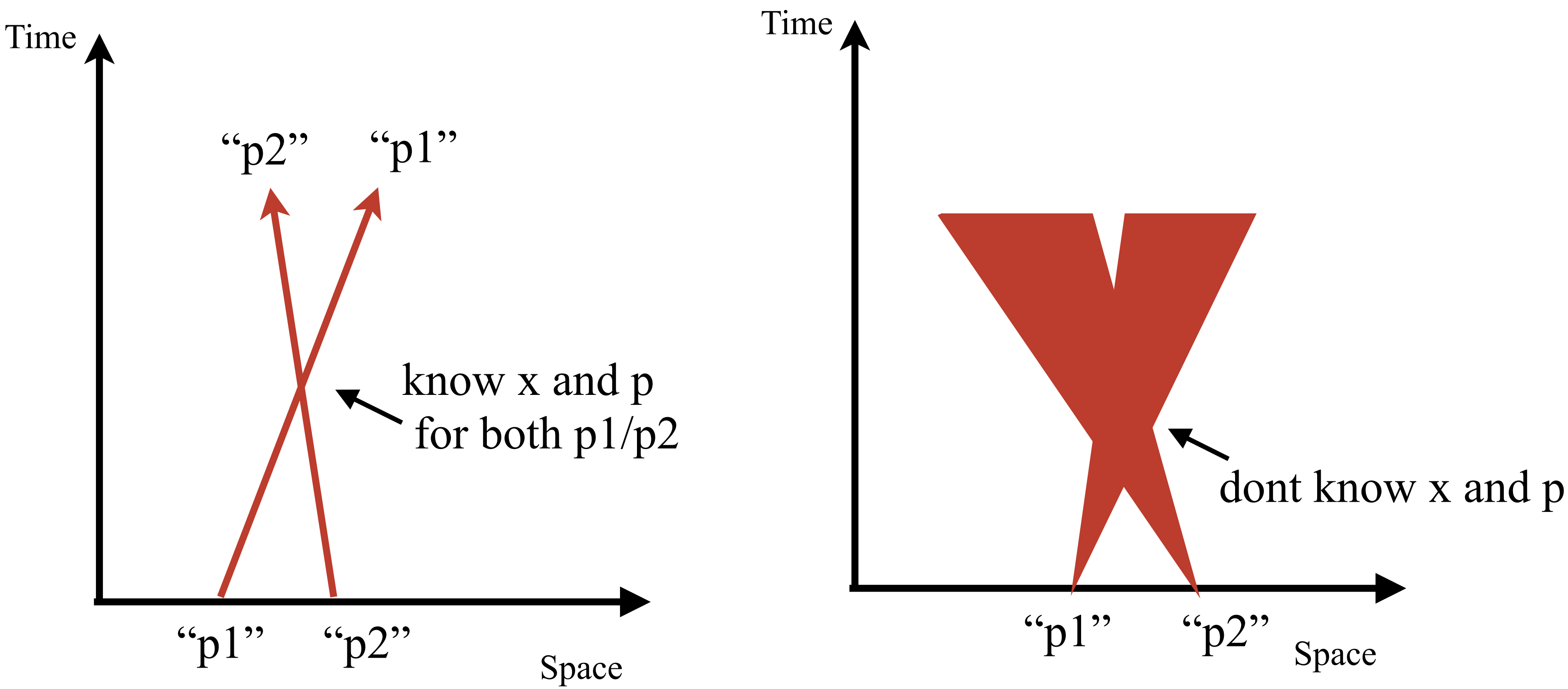

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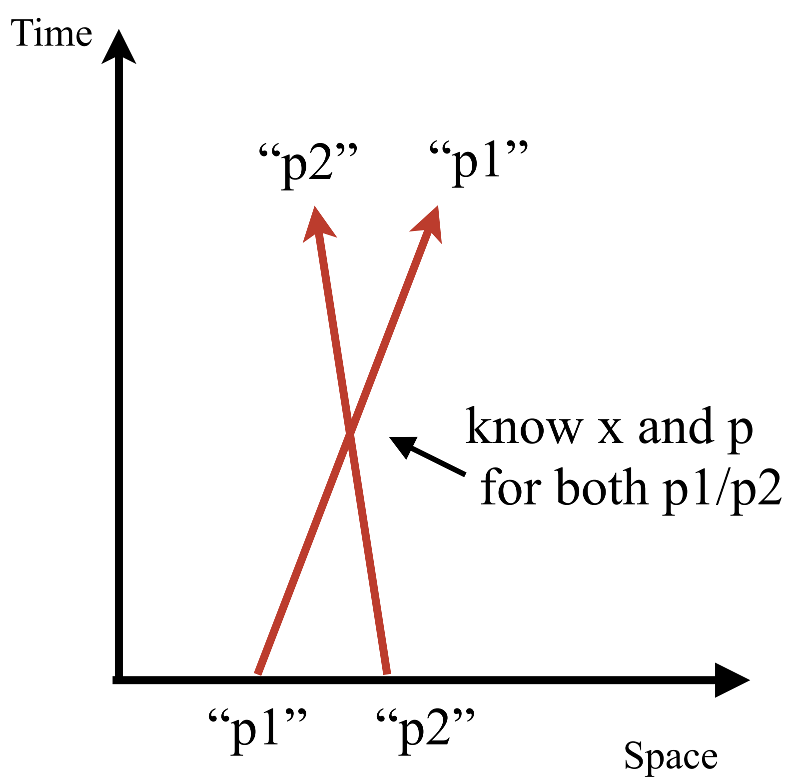

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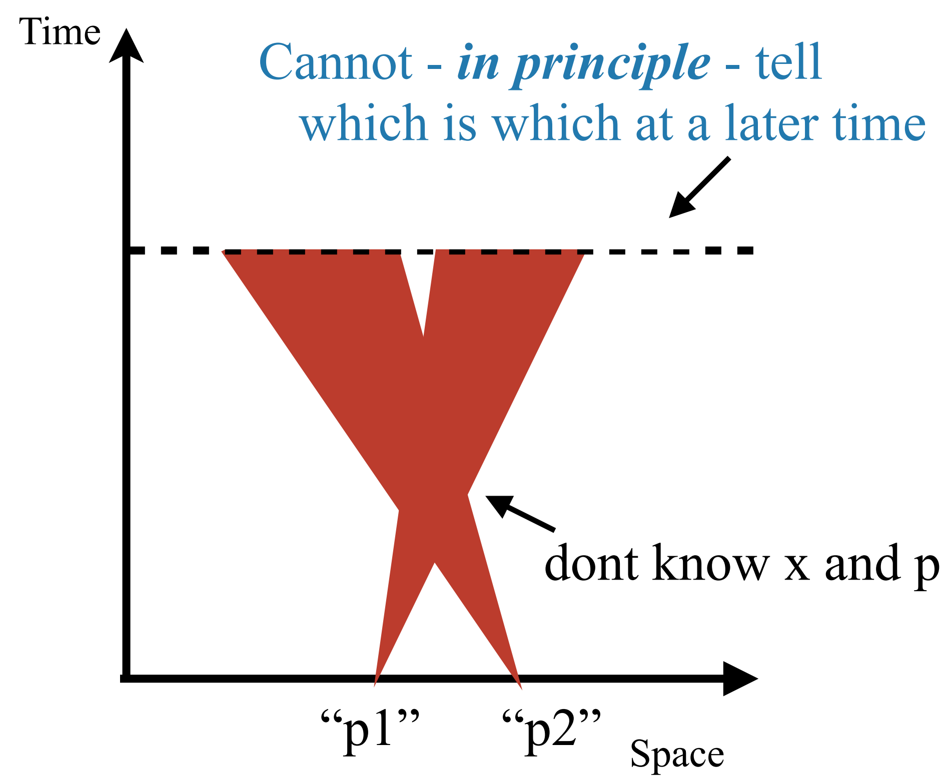

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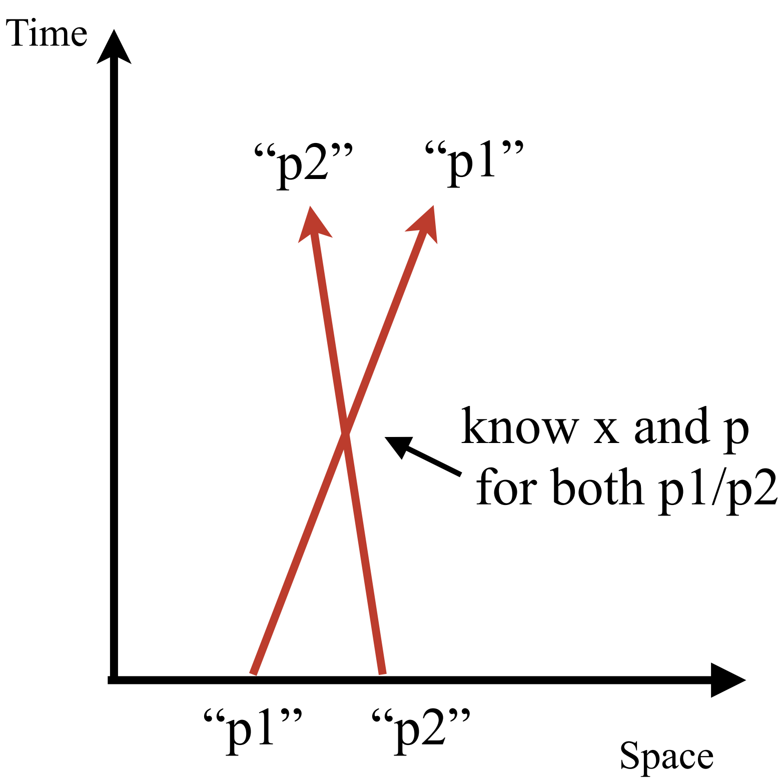

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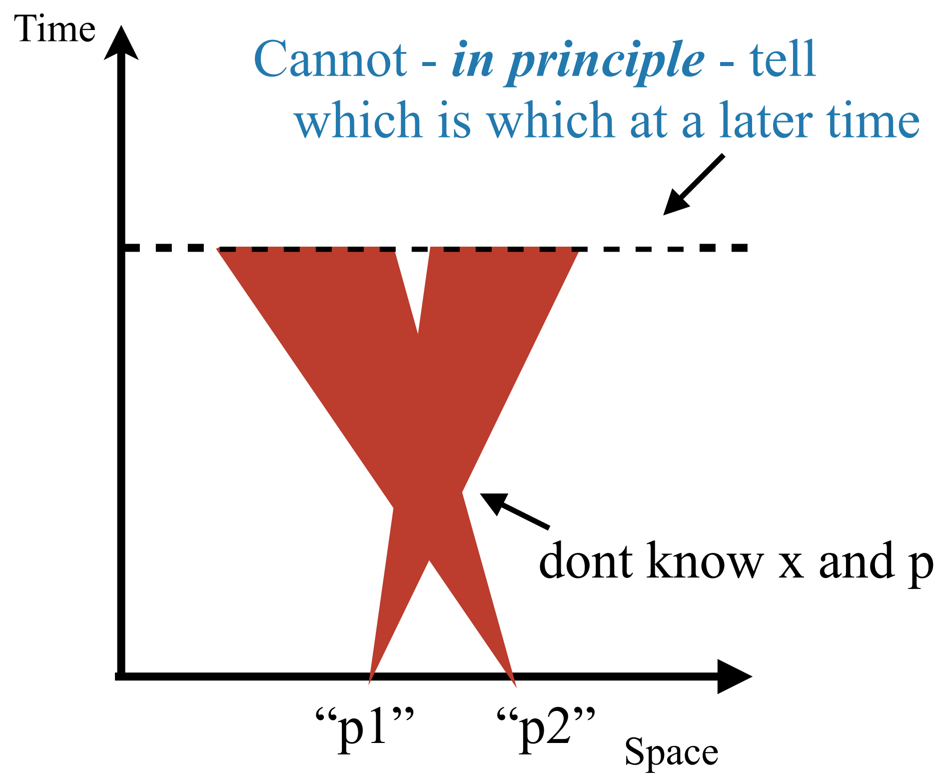

Can not follow trajectories of quantum particles
Treated identical particles must be treated as indistinguishable

Wave vs Particles

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- other properties: e.g: charge

Identical Particles Indistinguishable: Cannot trace trajectories

- Physics depends on $|\psi|^2$
- $|\psi(p1, p2)|^2 = |\psi(p2, p1)|^2$ or $\psi(p1,p2) = \pm\, \psi(p2,p1)$

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Two fundamental types of particles:

"Fermions" $\psi(p1,p2) = -\, \psi(p2,p1)$
"Bosons" $\psi(p1,p2) = +\, \psi(p2,p1)$

Wave vs Particles

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"Bosons" $\psi(p1,p2) = +\, \psi(p2,p1)$

Big collections of Fermions act like classical particles

Big collections of Bosons act like classical waves

Why don’t we not notice these strange effects?

Relativity: c is a big number (~0.5 billion mph)

Quantum Mechanics: h is a small number $\sim 5\times 10^{-34}$ J s

Why don't we not notice these strange effects?

Relativity: c is a big number (~0.5 billion mph)

If I move at 500 mph for 80 years: Gain ~1 millisecond

Quantum Mechanics: h is a small number $\sim 5\times 10^{-34}$ J s

If my position is known to size of an atom:
Δv ~ 10^-26 mph (Δp /m)

Revolution & Newton's Dream

Particular nature of revolution in Physics.
- Previous theories where not rejected.
  - Seen as approximation in certain context
- Progress brings greater unification (Loss in predictivity)

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Concepts thought different, faces of same thing:

Relativity:

- Space and time
- Energy and Mass (also momentum)
- Electricity and Magnetism
- (Gravity shown to be result of warping of space time)

Quantum Mechanics:

- Waves and Particles
- Chemistry and Physics

Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: ***Mission Barely Possible: QM + SR***

April 15th: **The Standard Model**

April 22nd: **Importance of the Higgs**

April 29th: **Guest Lecture**

May 6th: **The Cannon and the Camera**

May 13th: **The Discovery of the Higgs Boson**

May 20th: **Experimental Challenges**

May 27th: **Memorial Day: No Lecture**

June 3rd: **Going beyond the Higgs: What comes next ?**

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May 27th: **Memorial Day:**

June 3rd: **Going beyond th**

Sources:

- **Nima Arkani-Hamed**
- **Steven Weinberg**
- …

I will keep this list up to date as we go along.

Today's Lecture

Mission Barely Possible:

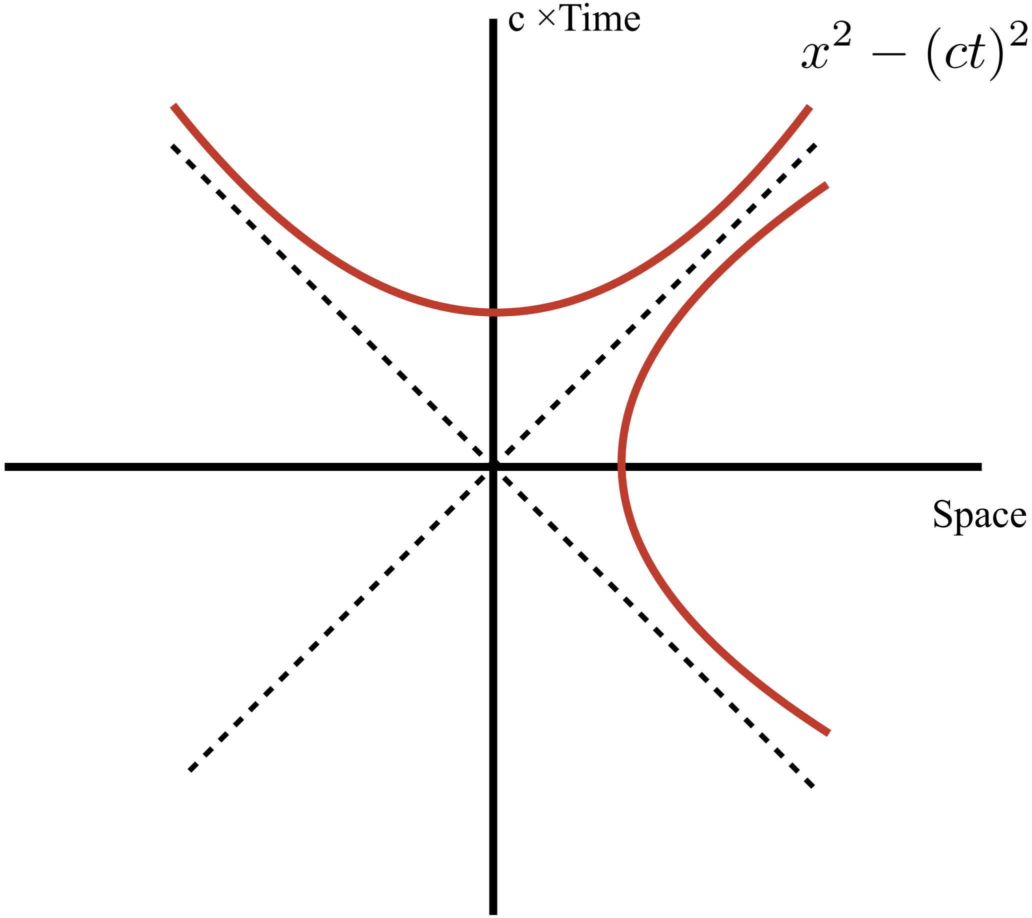
Combining Relativity and Quantum Mechanics

Reminder:

20th Century Revolutions

Reminder: Relativity

Space-time



Mass increases with speed !

Closely associated to this:

$$E = mc^2$$

$$E^2 = p^2c^2 + m^2c^4$$

Reminder: Quantum Mechanics

New mathematical concept "Amplitude" (ψ)

Prescription for how:

- Amplitudes evolve ***in time*** (behave like waves)
- To convert amplitudes to probabilities ($|\psi|^2$ = Prob)

Determinism gone. Only predict probabilities.

$\Delta x\, \Delta p \geq h$

$\Delta E\, \Delta t \geq h$

Minimum non-zero energy: $E \sim h\omega$

Particles: Fermions/Bosons

Spin quantized units of 1/2 h

Combining Relativity & QM

First 25 years of the 20th century two revolutions.
85 years since then, were all about putting these together.

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Looks to be impossible: Basic languages are different

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QM: Time special (fundamental) role. Specify ψ at one time.
Prescription for how to evolve to later times,

Combining Relativity & QM

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85 years since then, were all about putting these together.

Looks to be impossible: Basic languages are different

QM: Time special (fundamental) role. Specify ψ at one time. Prescription for how to evolve to later times,

Relativity: Time is not special! (can mix space and time by moving)

Combining Relativity & QM

First 25 years of the 20th century two revolutions.
85 years since then, were all about putting these together.

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Relativity: Time is not special! (can mix space and time by moving)

Turns out (just barely) possible: ***Quantum Field Theory***

- Basic framework for how the world works.
- Dramatically restricts what a theory can possibly look like

Consequences of Union

Anti-particles must exist

- Shocking / Unexpected
- Doubled everything in universe
- Makes the vacuum interesting

Key role of Spin:

- Relation between spin and particle type
- Dramatically limits types of particles can have

Major constraints on types of interactions allowed

- Only certain interaction will ever be important
- Always be a finite number of parameters that matter

Causality

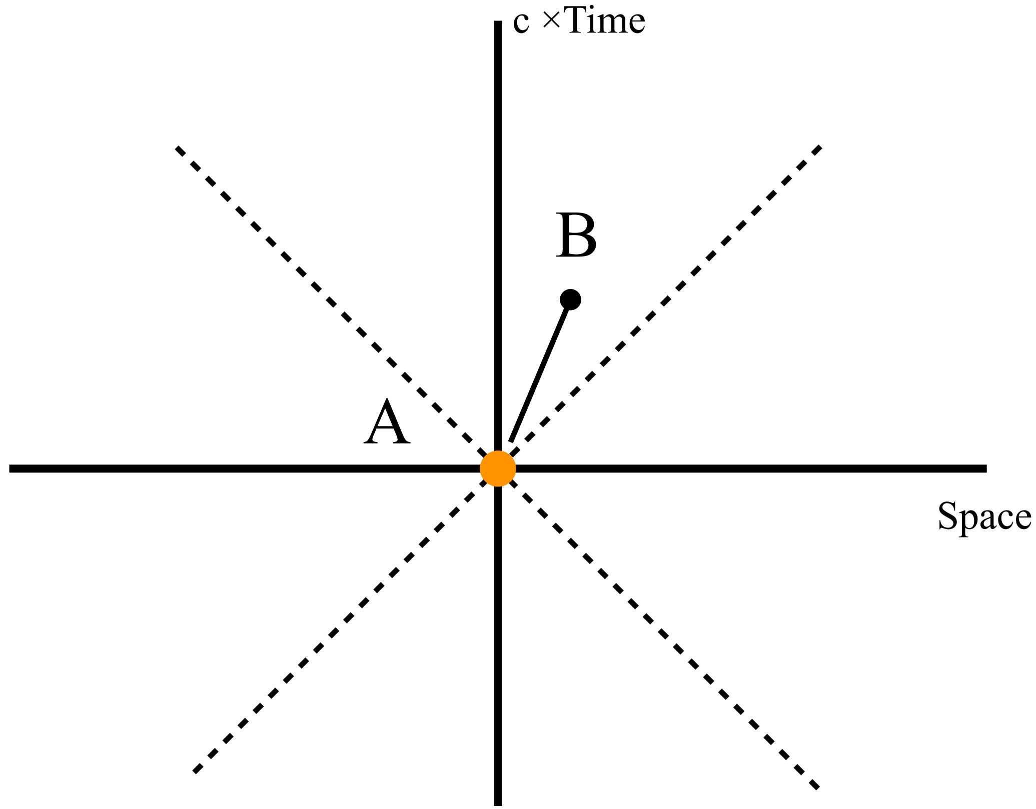
What happens next can only depend of what happened before
(Does not depend on something that hasn't happened yet !)

If someone dies from a gun shot, the gun must be shot first.

Causality basic prerequisite to science !

Causality in Relativity

Cant send signals faster than maximum speed



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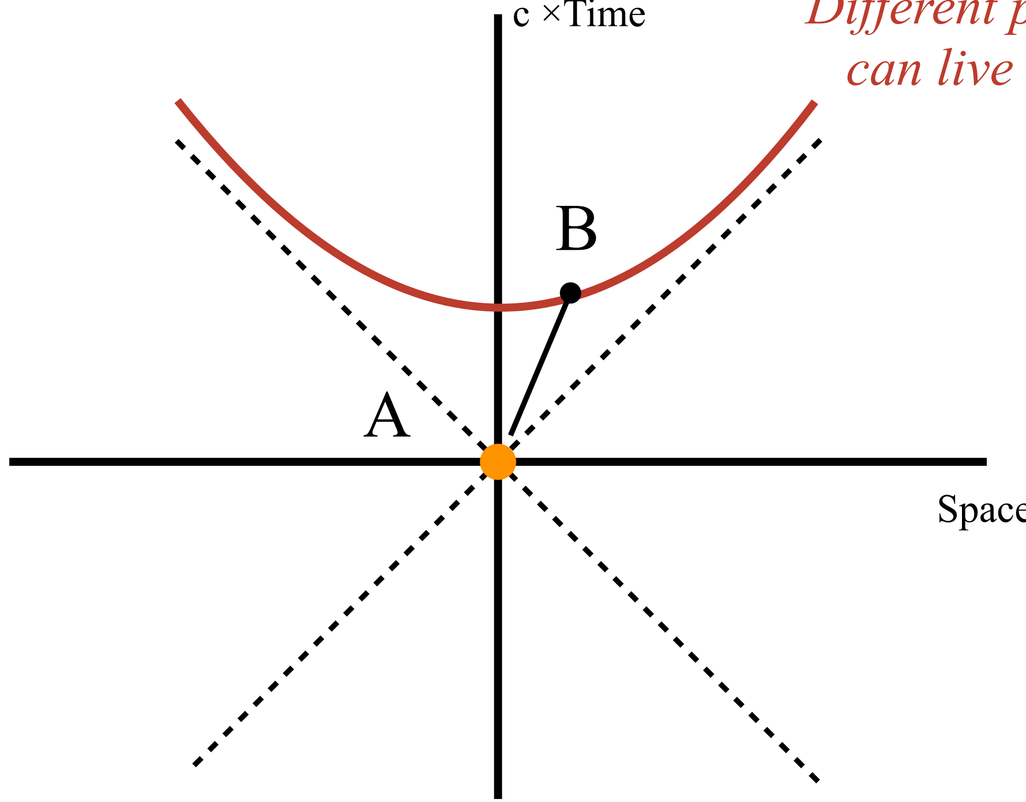
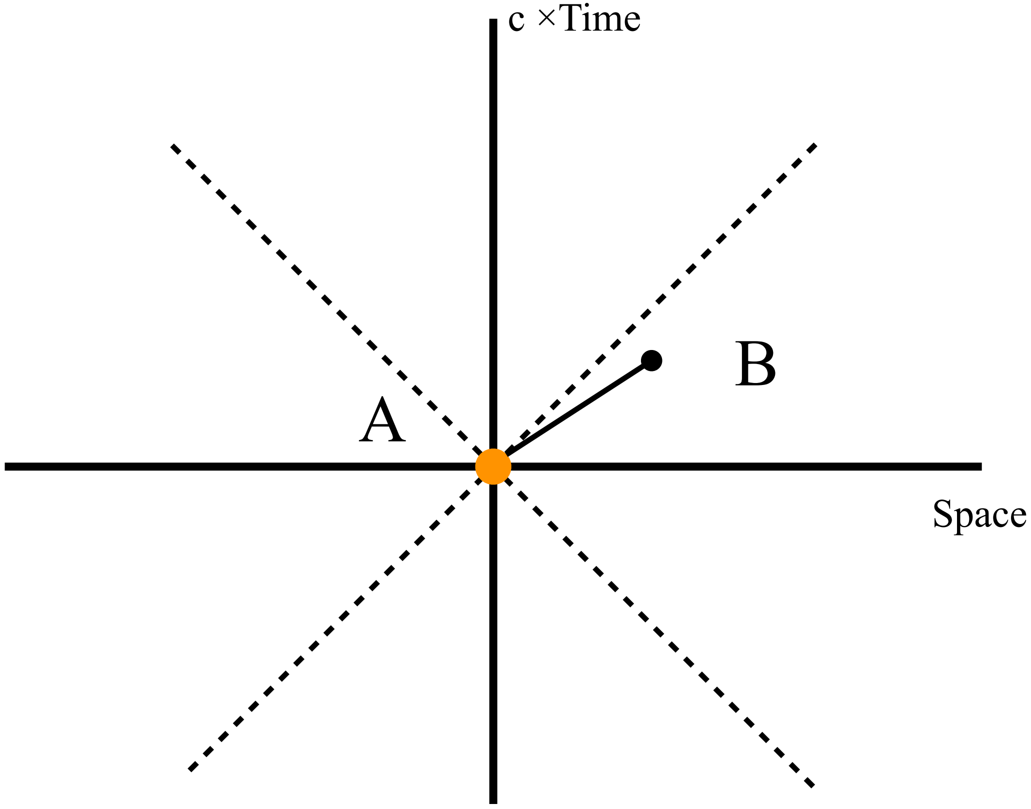


All moving observers agree that A happens before B
Can say safely say: "A causes B"

Causality in Relativity

If you could go faster than c, things go wrong



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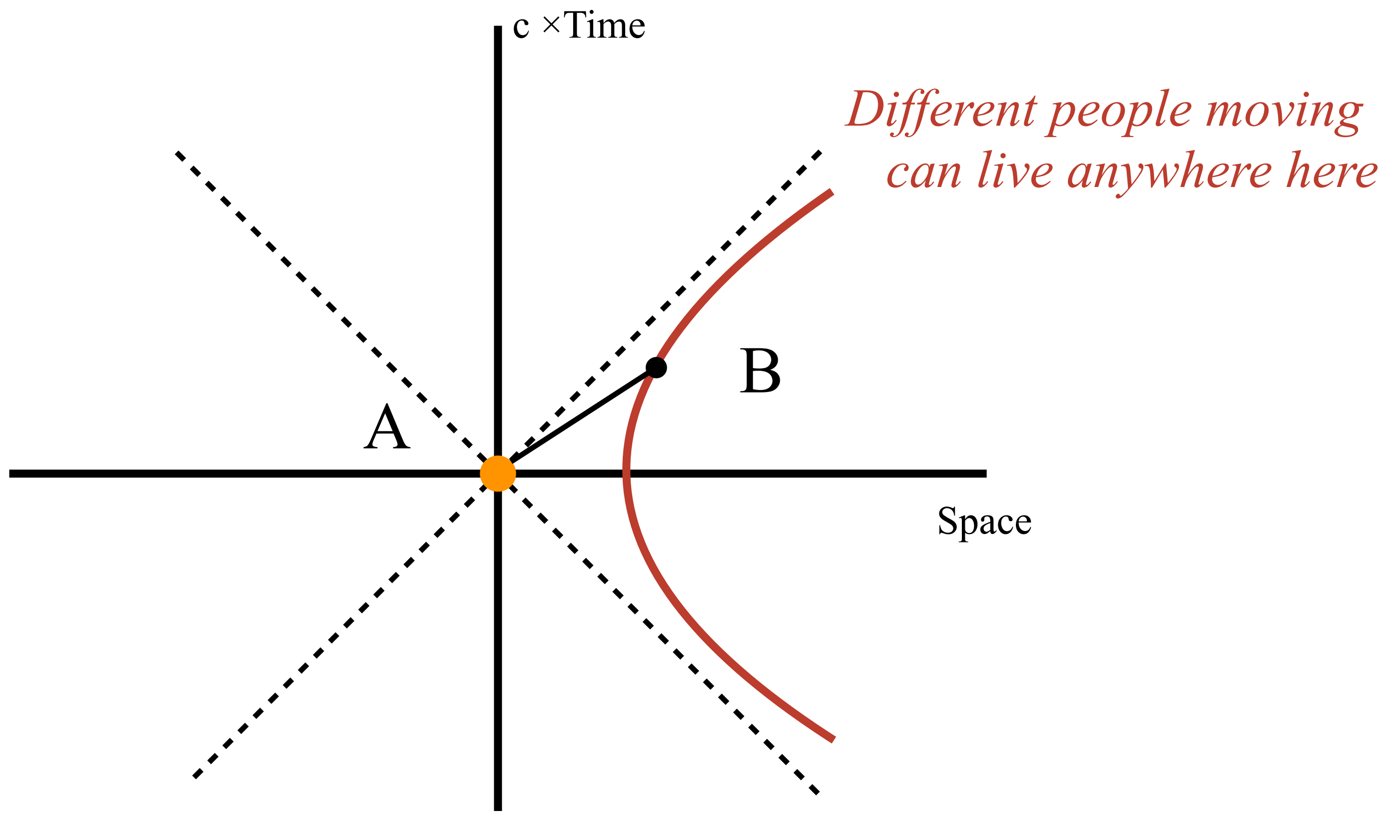
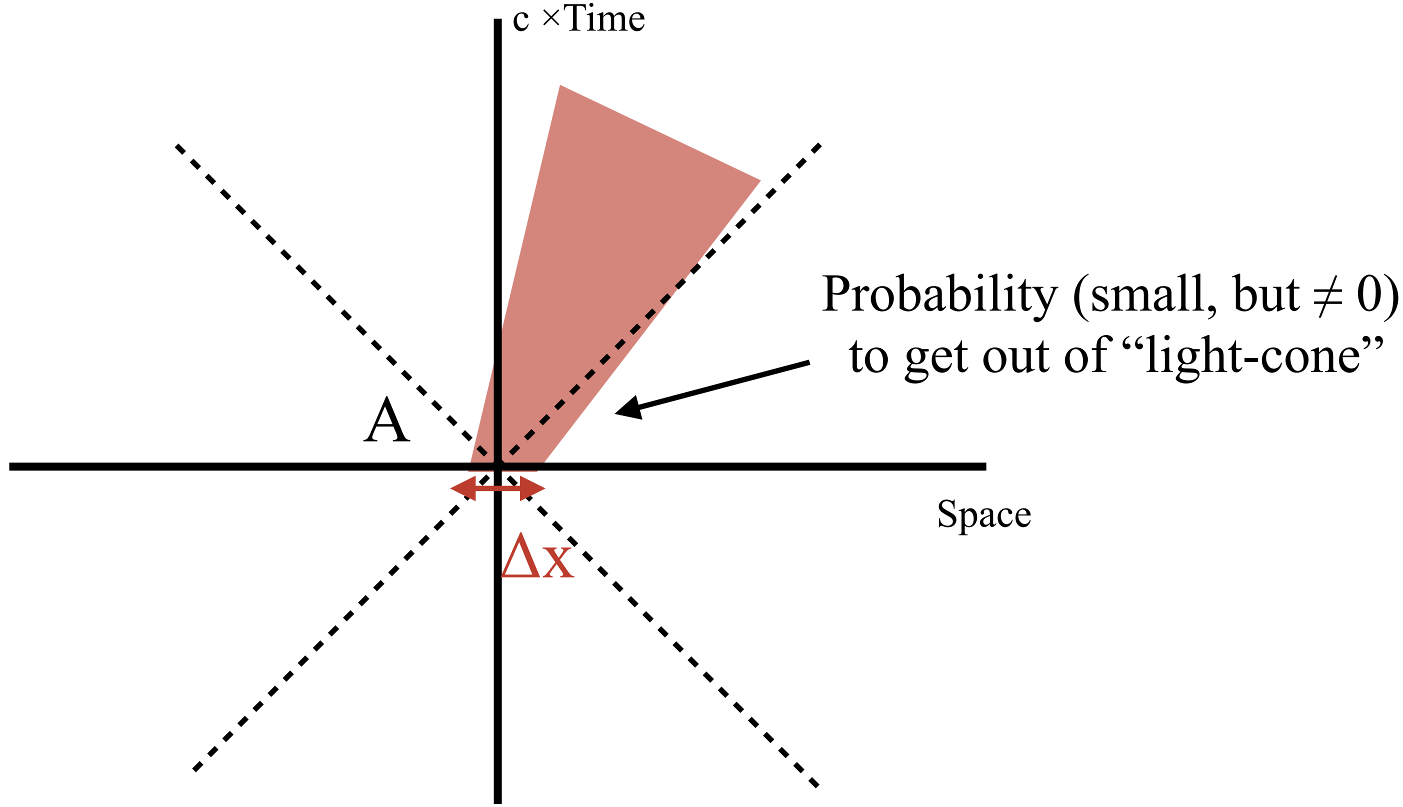


Depending about how you move, disagree about what comes first.
Causality is violated. *Bullet hits B before A pulls trigger.*

Causality in Relativistic QM

w/QM always some non-zero probability of getting out.



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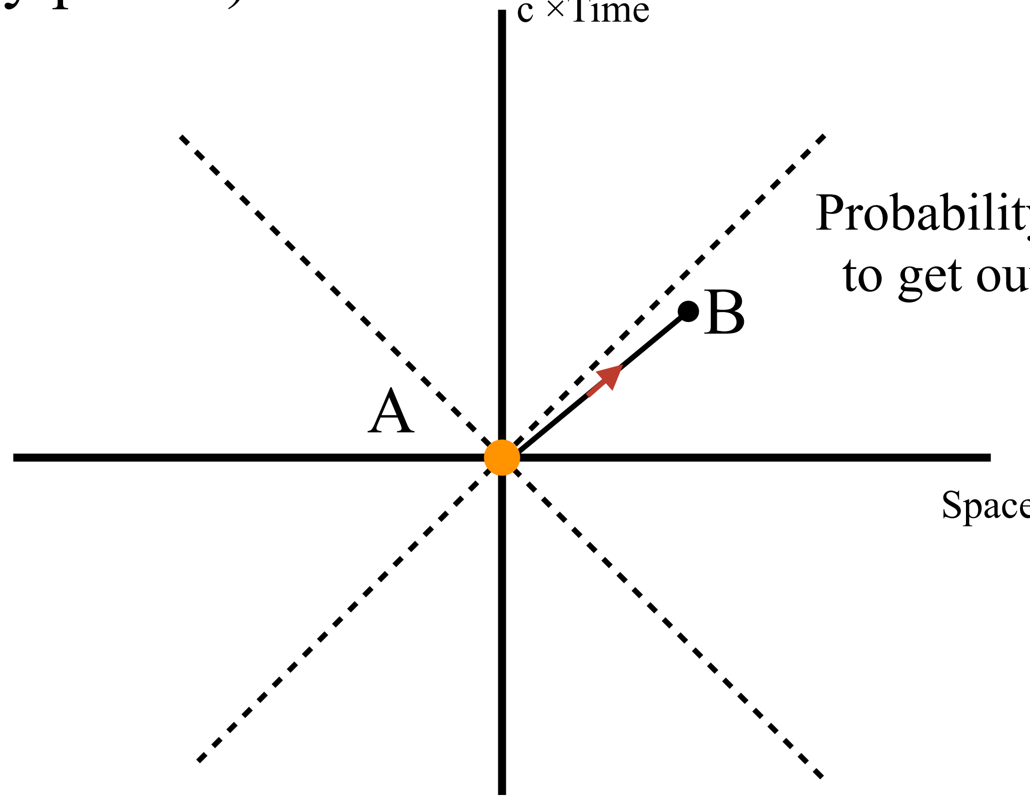

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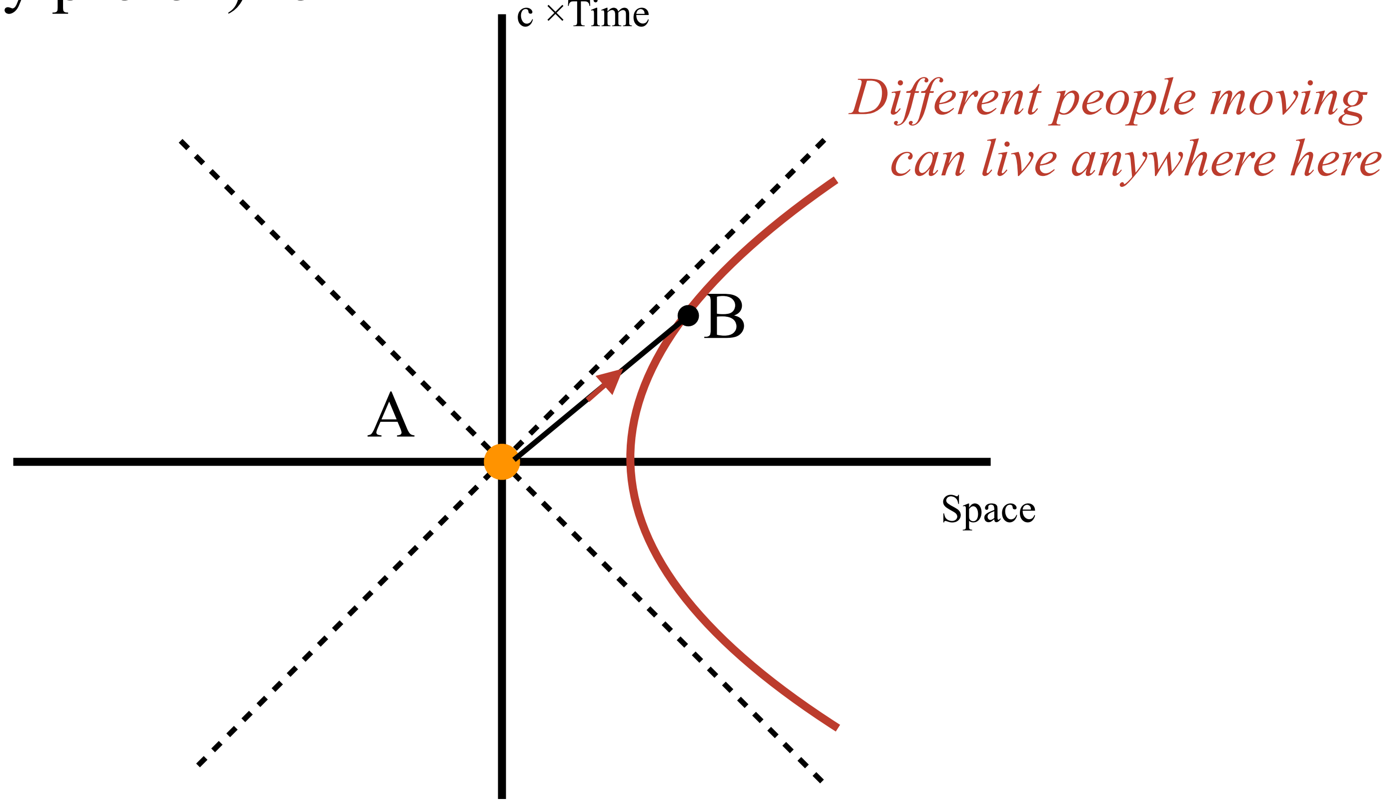

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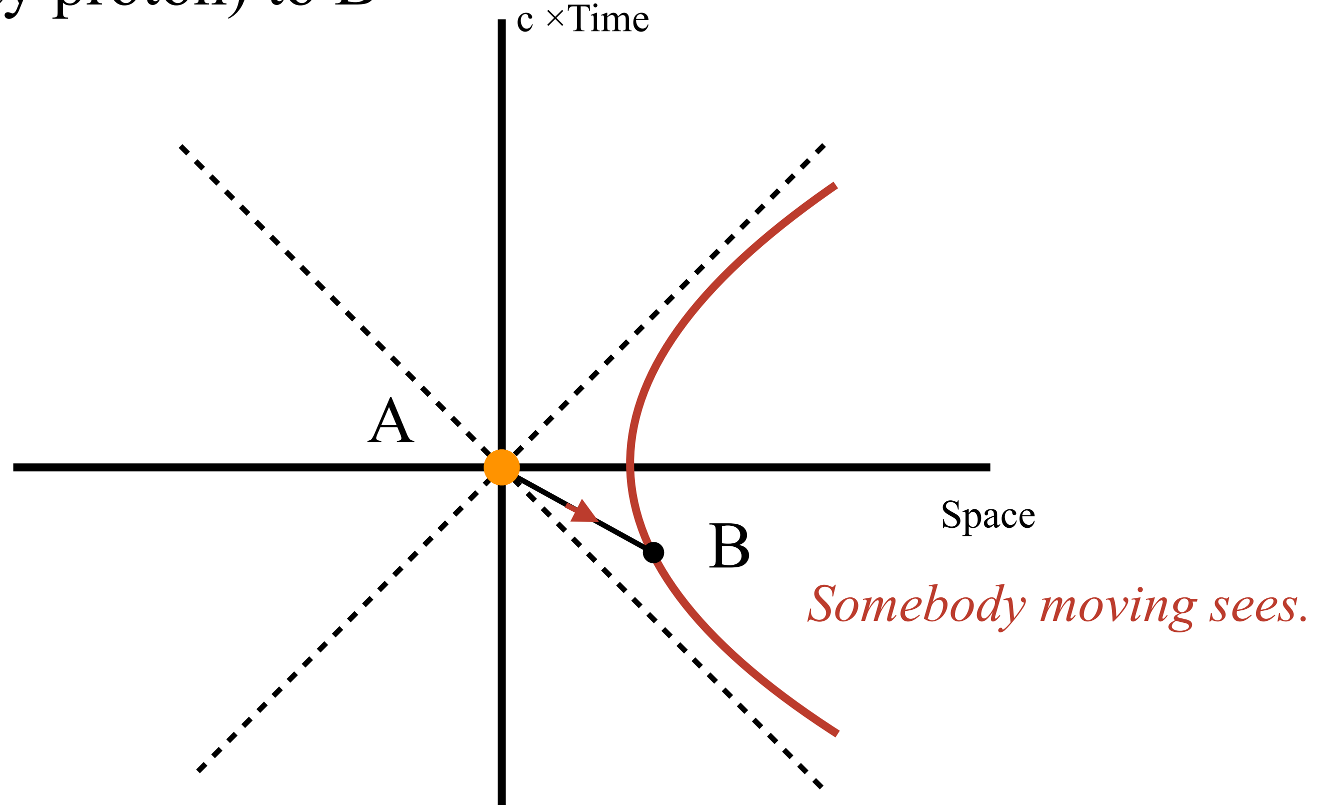

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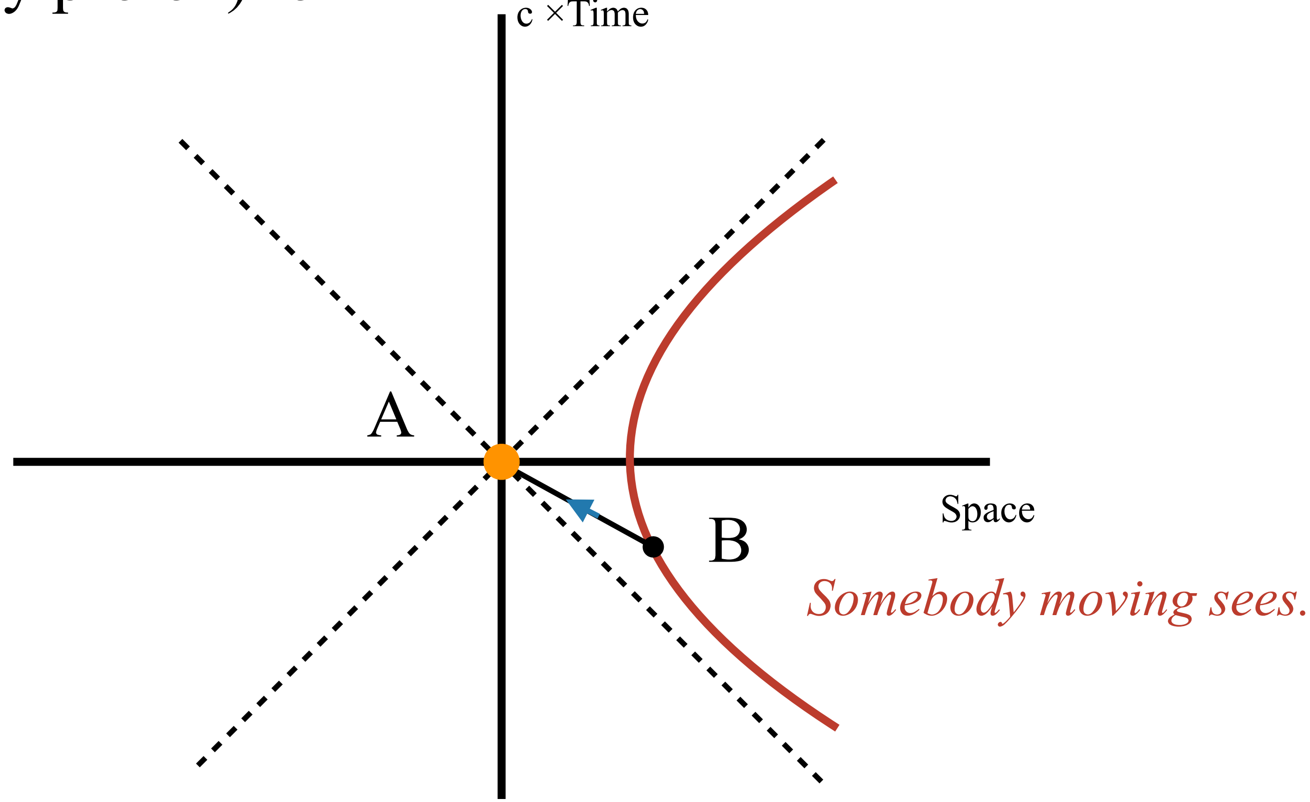

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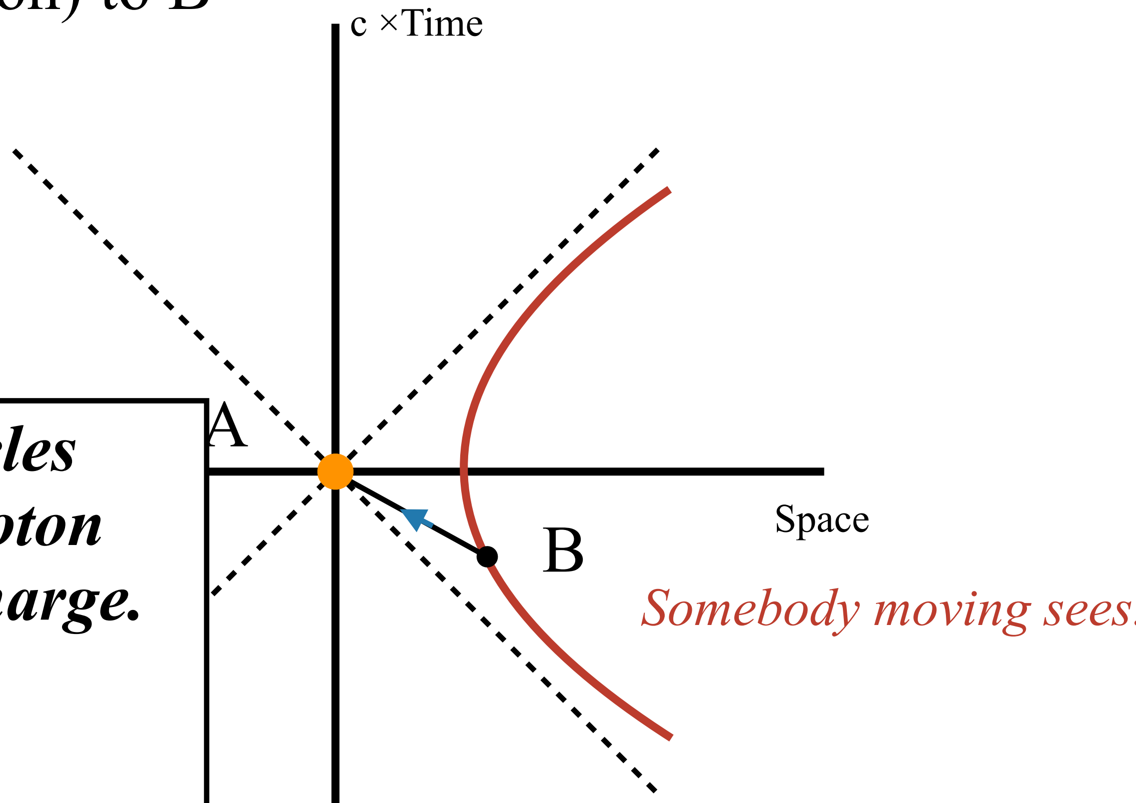

There must exist particles that are identical to proton except with opposite charge.

Anti-particles !

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What does it take to study empty space *("the vacuum")* ?

Nothing special…until try to check small regions

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Before QM:

Build tiny robots. (Get tiny robots to build tinier robots, who ..)

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With QM:

At small distances, uncertainty principle kicks in

Need large Δp (or equivalently large ΔE)

Smaller and smaller distances, need higher and higher energies

Empty Space Interesting

When eventually get to small enough distances to need $\Delta E \sim 2m_ec^2$

Nothing prevents creation of particle - anti-particle pair
- Everything is conserved (energy/charge/…)
- Some probability for this to happen

Completely changes our picture of the vacuum
- Simple act of looking at the creates something
- No sense in which the vacuum is empty

Often here accelerator as worlds most powerful microscopes

Looking at the vacuum

Other Implications Combining R & QM

Spin

QM: Could accommodate spin
Any 1/2 integer value allowed

Interactions

QM: Any conceivable interaction possible

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QM + R: Forced to talk spin *(Something special w/massless particles)*
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Local (no more action at a distance)
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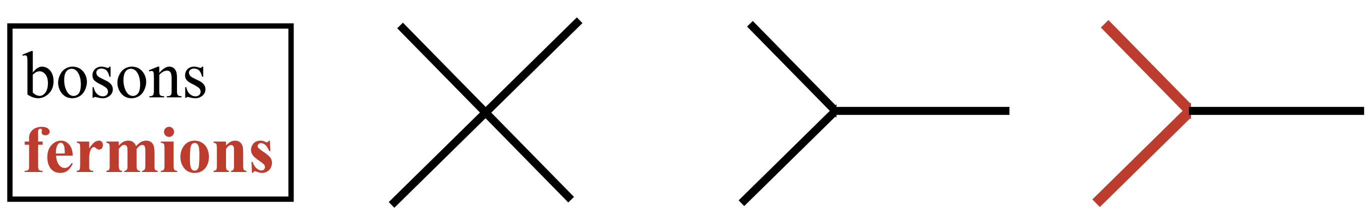

Other Implications Combining R & QM

This is the basic framework for any possible theory
Talk next time about what the world is made of

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