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

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Last Lecture

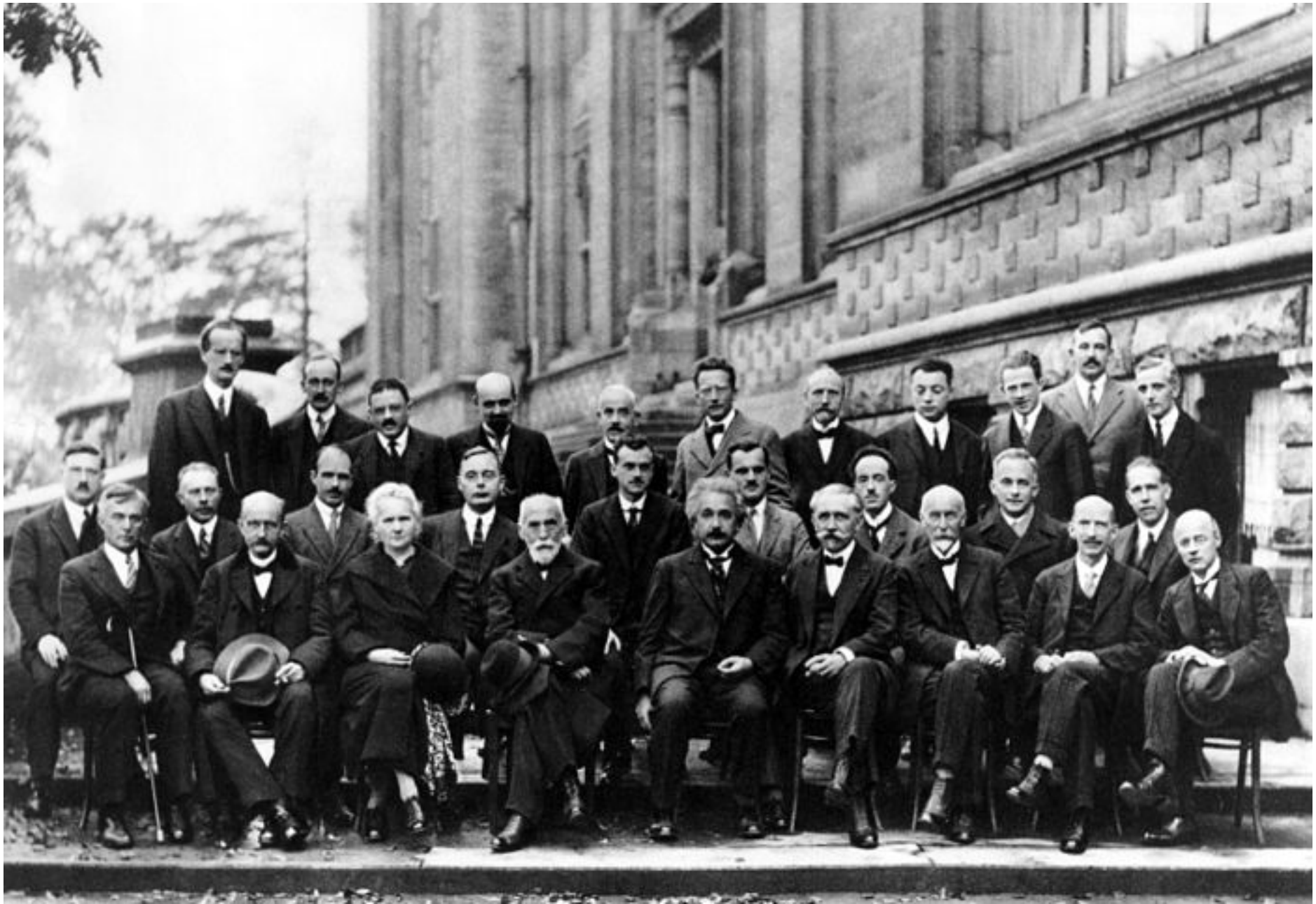
Newton's Dream: Direction of science

Turn of 20th Century: Dream in peril

20th Century Revolutions:

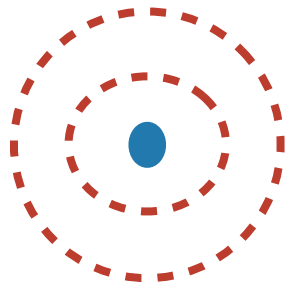
- Relativity
- Quantum Mechanics *(start here today)*

Quantum Mechanics



Quantum Mechanics

Picture of atom (circa 1911)



Electrons
- Negative charge
- ~all the space

Nucleus
- Positive charge
- ~all the mass

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 ?

Quantum Mechanics

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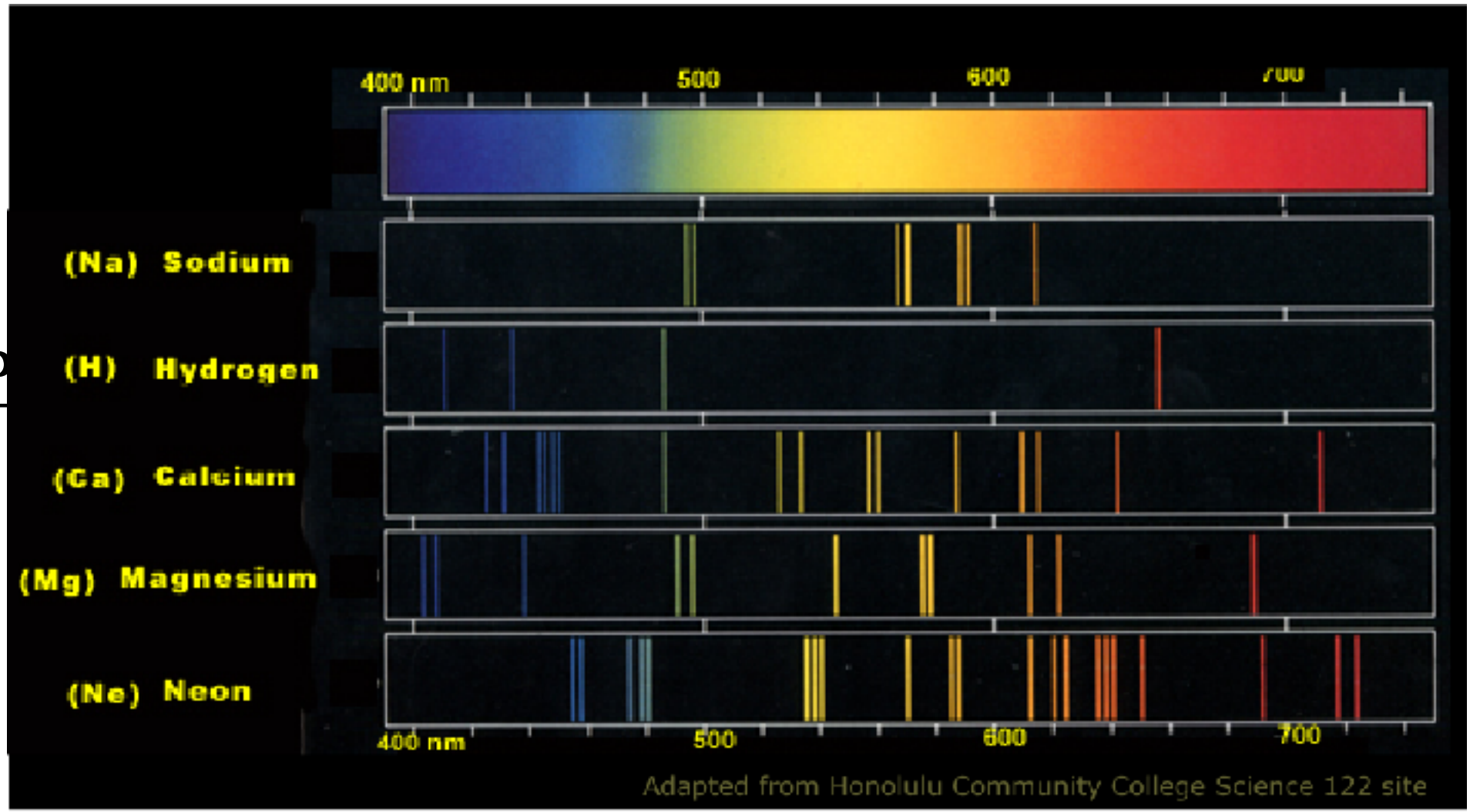

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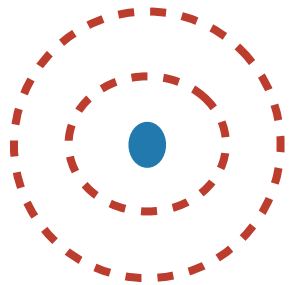

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Long Period of Confusion:

- 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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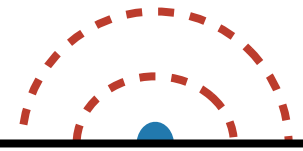


Electrons

Negative charge

Nucleus

Positive charge

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

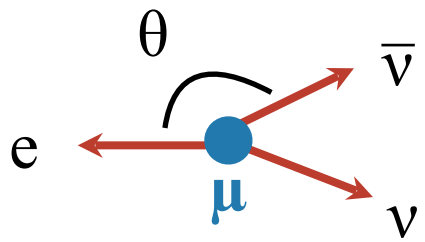
Quantum Mechanics gives prescription for how:

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

Probabilities

Randomness in nature

ψ_μ



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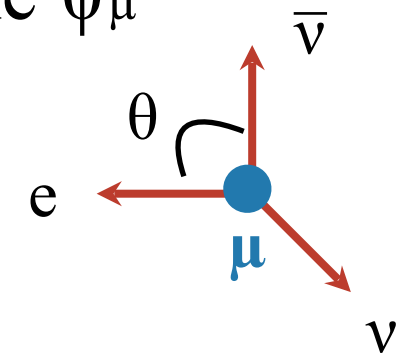
Exact same ψ_μ



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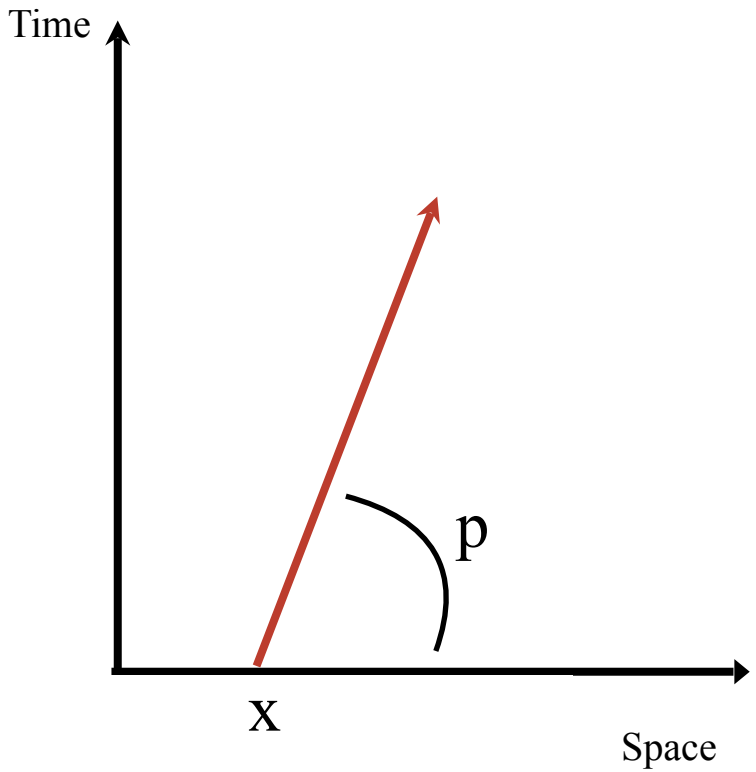
- QM cannot predict what will happen in any particular event (μ decay)
- QM can predict distributions (what happens on average)

Huge loss in predictivity !

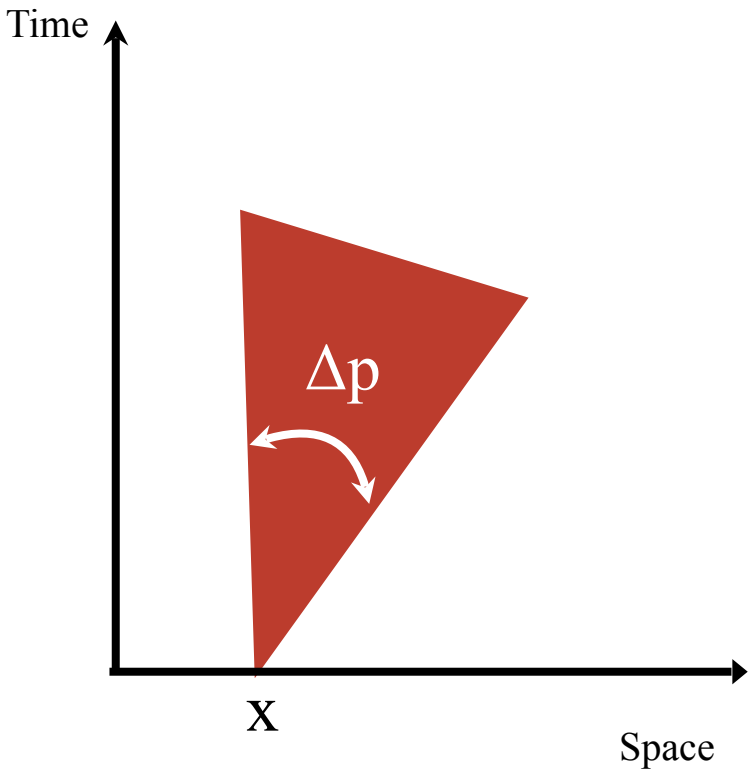
Uncertainty Principle

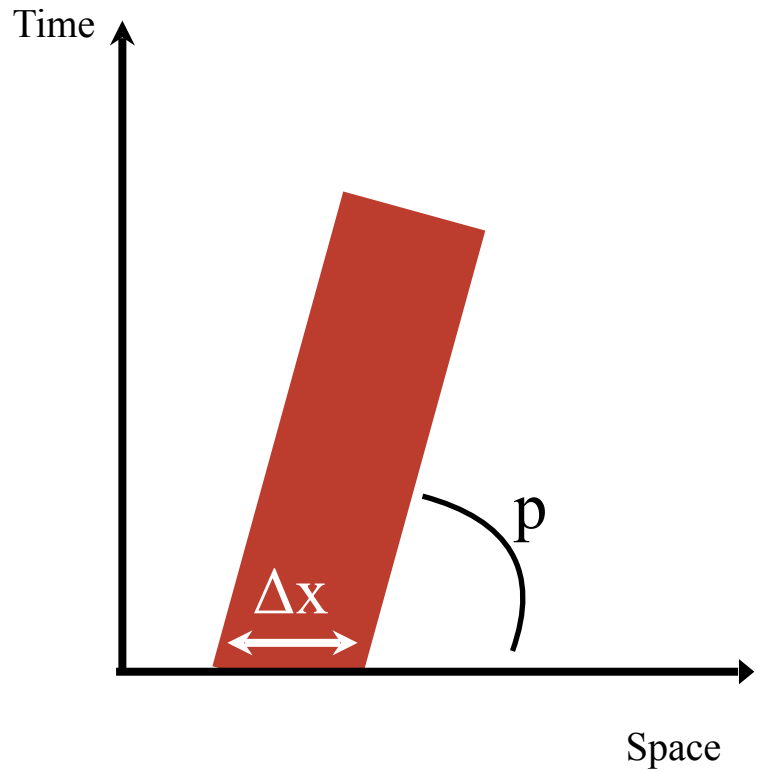
Classically (w/o QM)



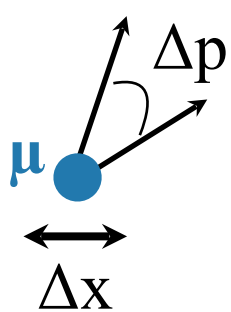
Uncertainty Principle

Quantum World





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



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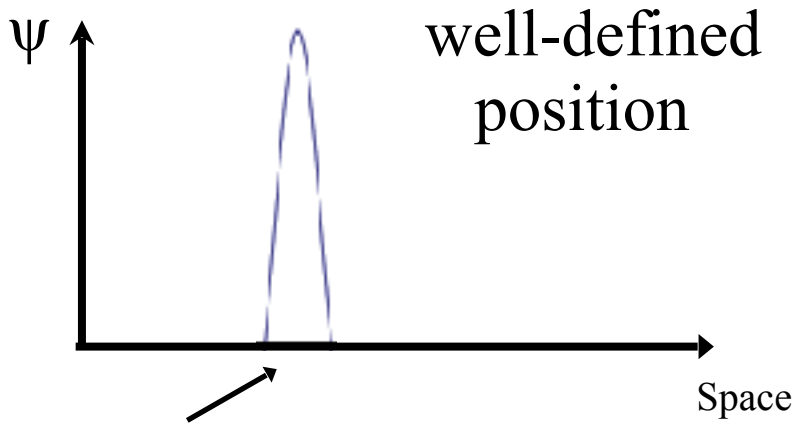
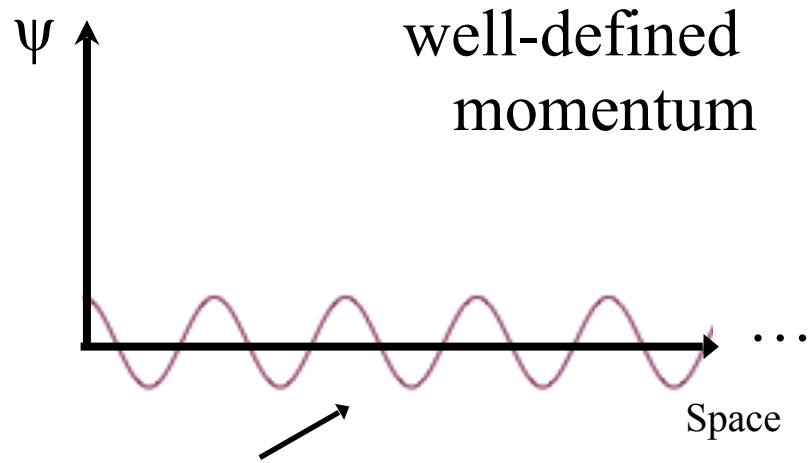
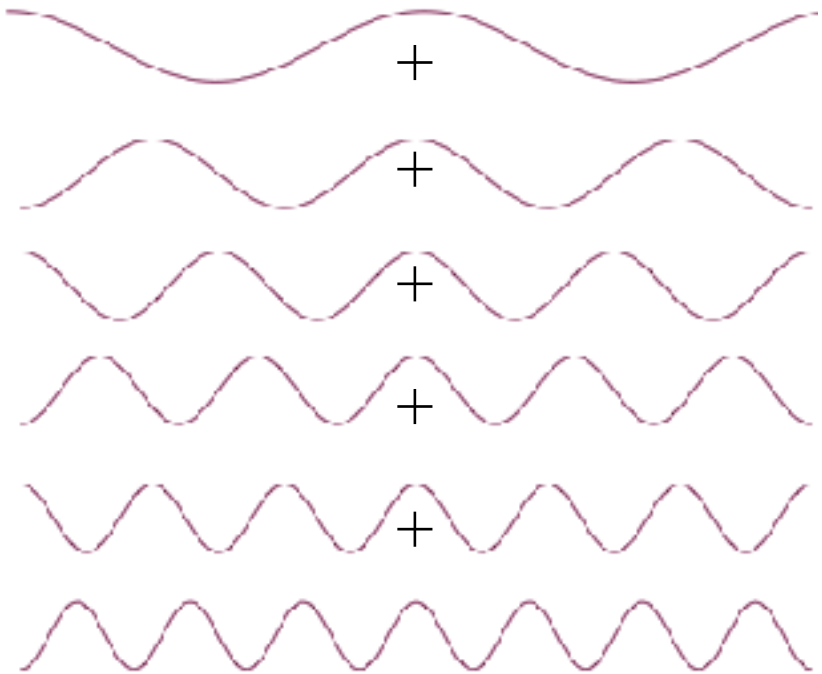


Position well-defined when
probability (ψ^2) sharply peaked on one place



Momentum well-defined when
uniform distance between peaks



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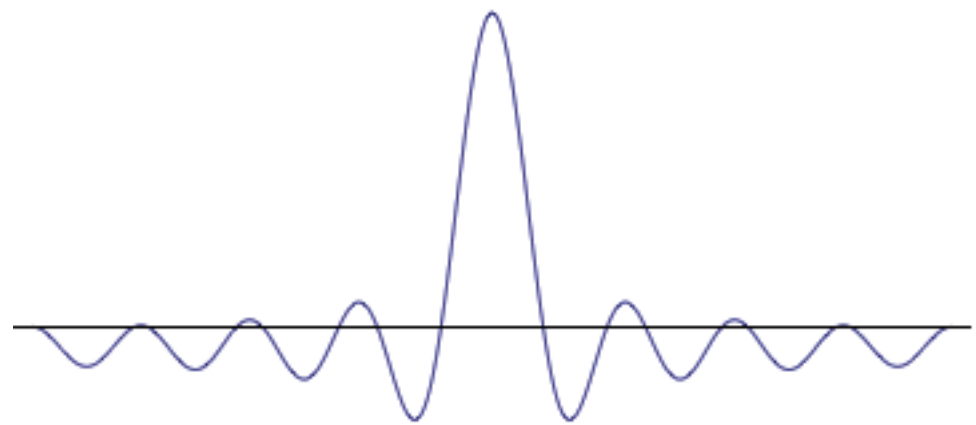

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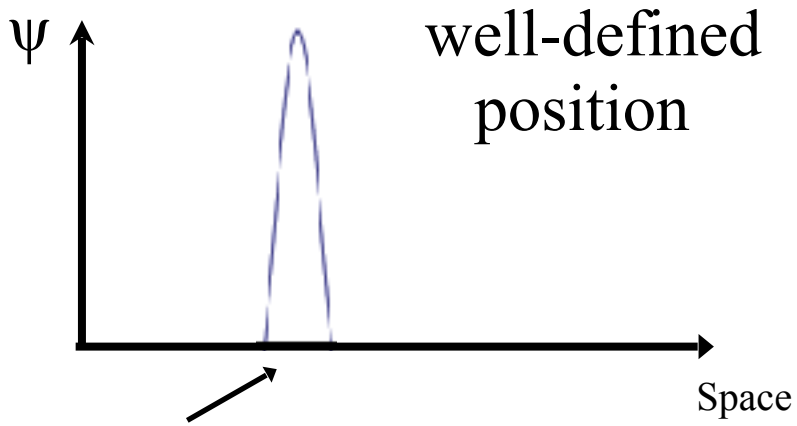

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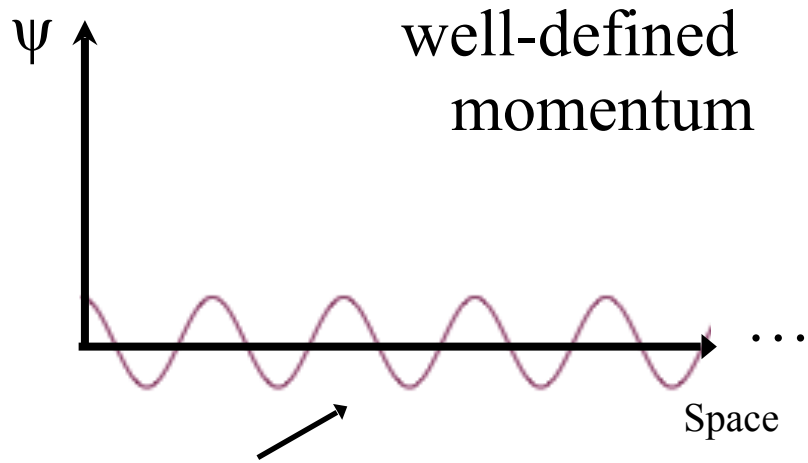
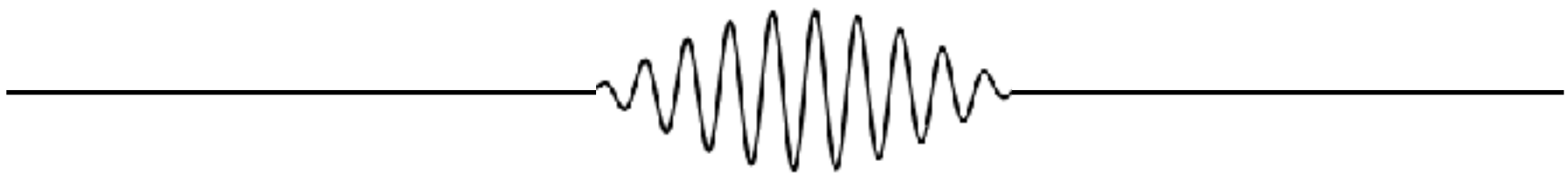


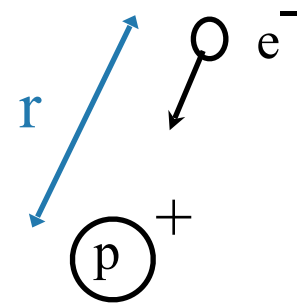
Momentum well-defined when
uniform distance between peaks

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

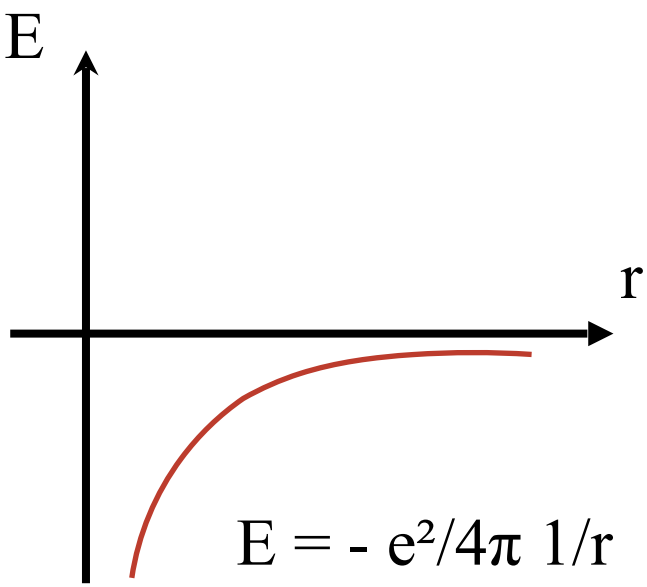


Stability of Matter

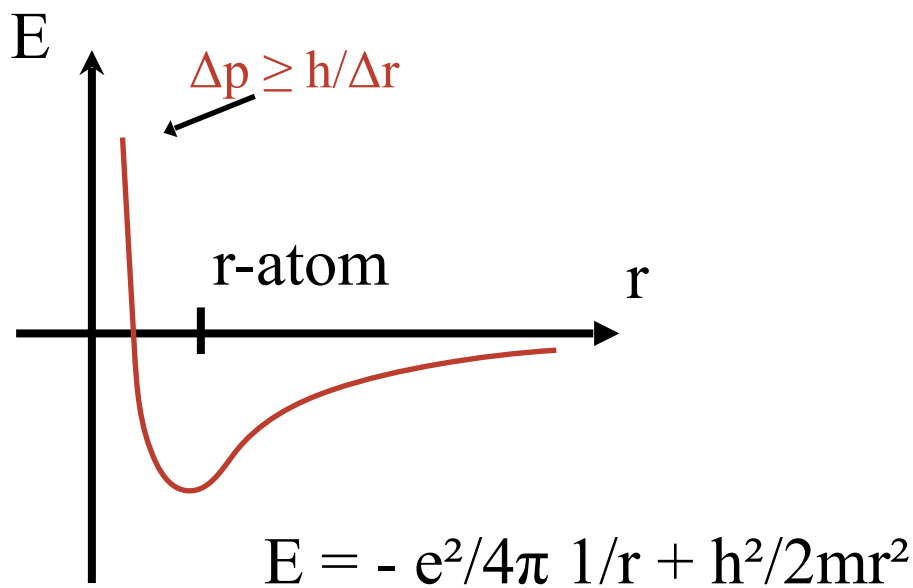
Atom:



Classically (w/o QM)



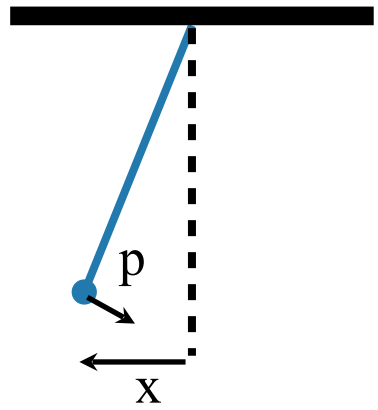
Quantum World



Electron will sit directly on nucleus

Atoms are stable w/finite size

Minimum Energy



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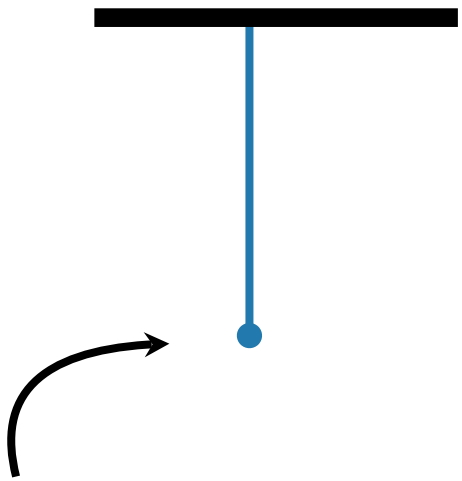
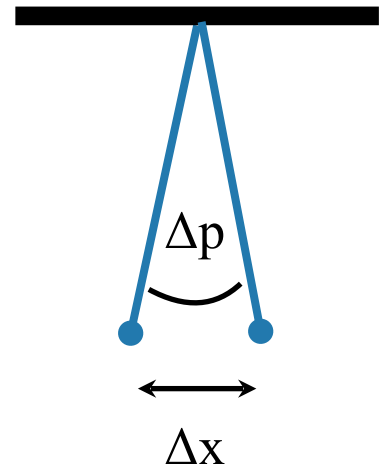


Lowest possible energy is 0.
Not moving and at lowest point.

Quantum World



Cannot be both at lowest point
and not moving.
Minimum non-zero energy: E~hω

Wave vs Particles

Everything is a *quantum* particle !

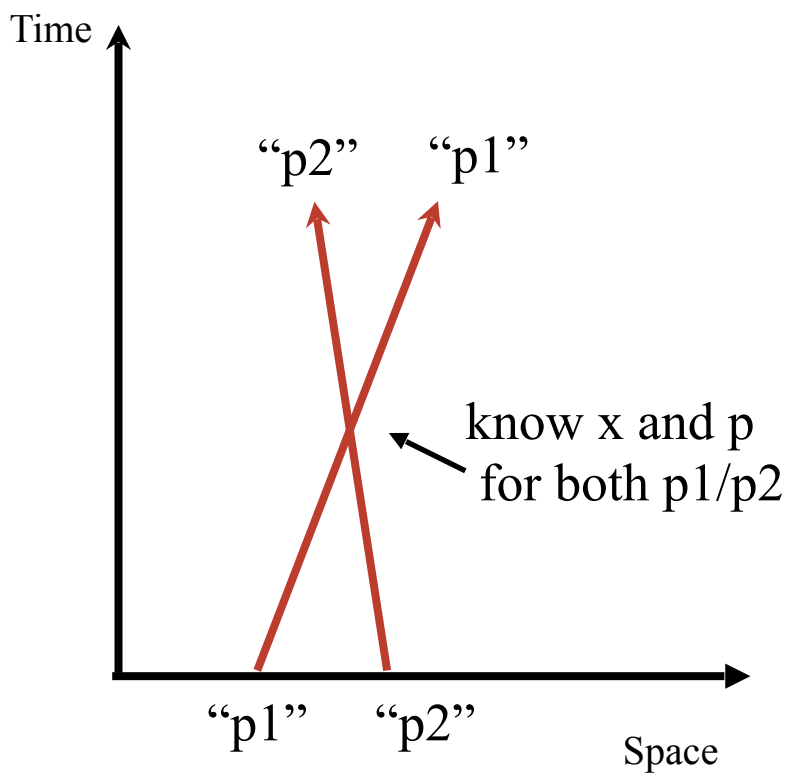
Particles have definite values of:

- momentum and mass
- spin: *(0, 1/2, 1, ... × h)*
- other properties: e.g: charge

Wave vs Particles

Everything is a *quantum* particle !

Classically



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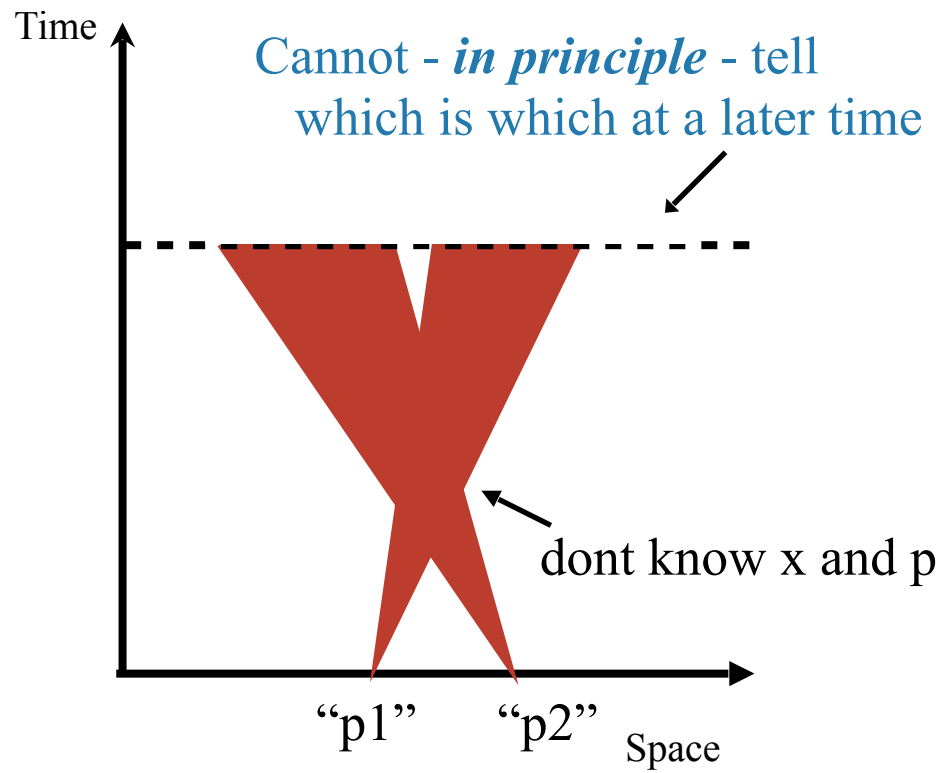


Can not follow trajectories of quantum particles

Treated identical particles must be treated as indistinguishable

Wave vs Particles

Everything is a *quantum* particle !

Particles have definite values of:

- momentum and mass
- spin: *(0, 1/2, 1, ... × h)*
- 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 $\psi(p1,p2) = \pm \psi(p2,p1)$

Two fundamental types of particles:

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

"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)

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 know to size of an atom:
$\Delta v \sim 10^{-26}$ mph ($\Delta p / m$)

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)

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**

May 13th: **The Discovery of**

May 20th: **Experimental Ch**

May 27th: **Memorial Day: N**

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:

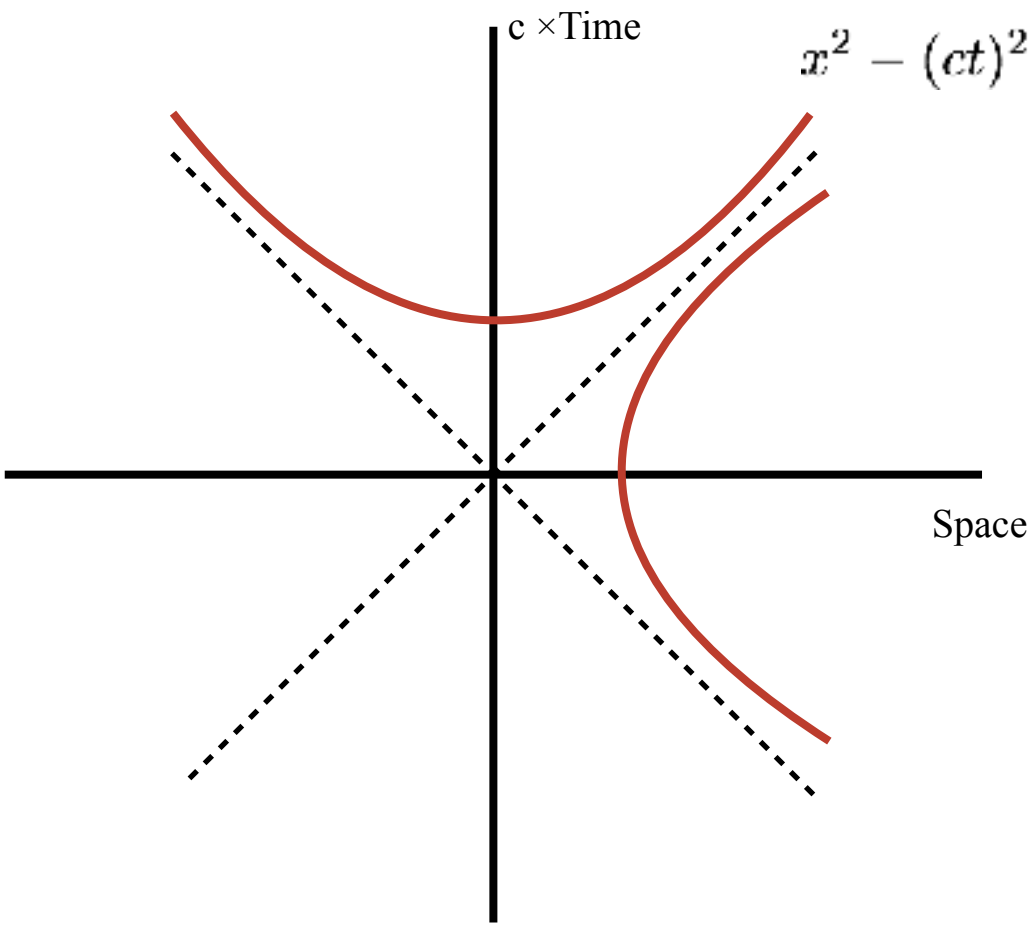
Combining Relativity and Quantum Mechanics

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.

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)

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

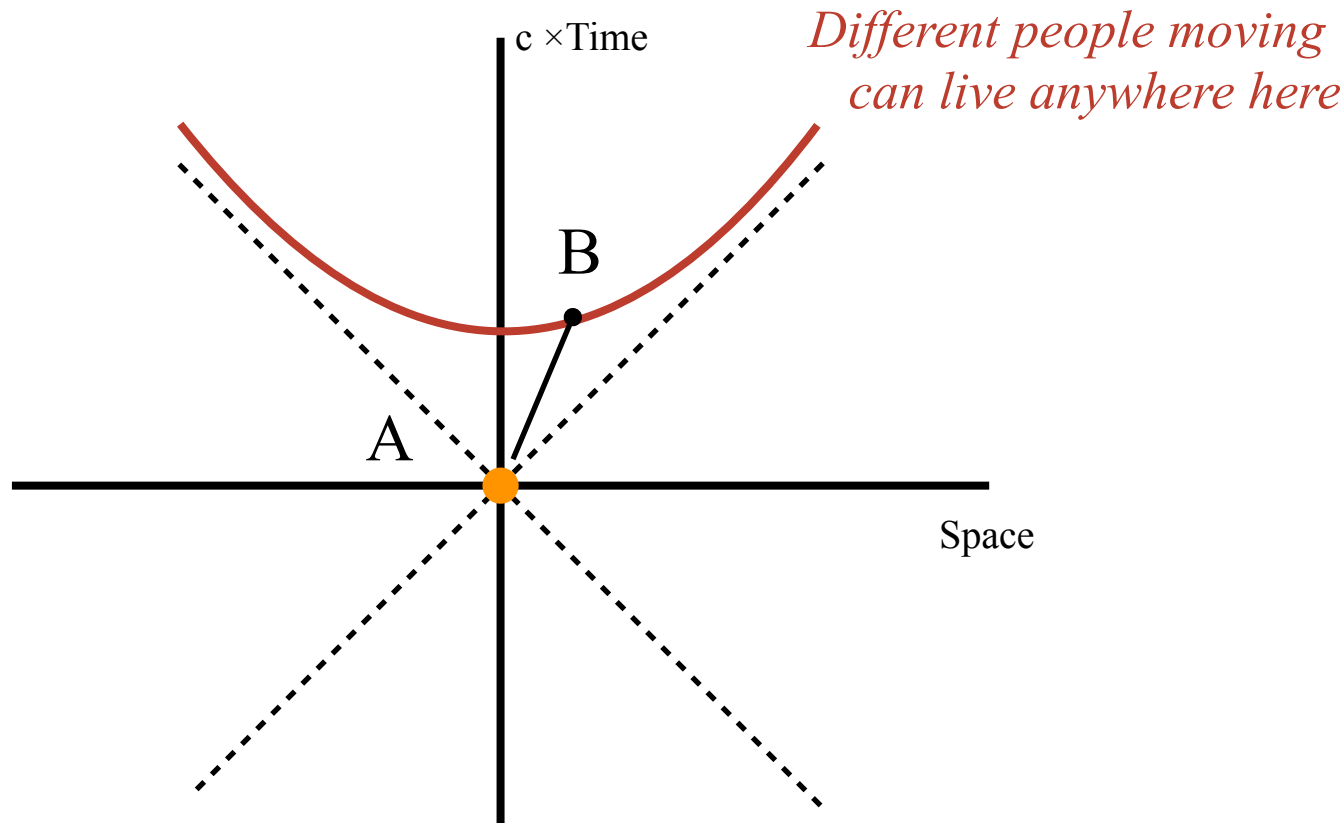
What happens next can only depend of what happened before
(Does not depend on something that hasn't happened yet !)

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

Causality basic prerequisite to science !

Causality in Relativity

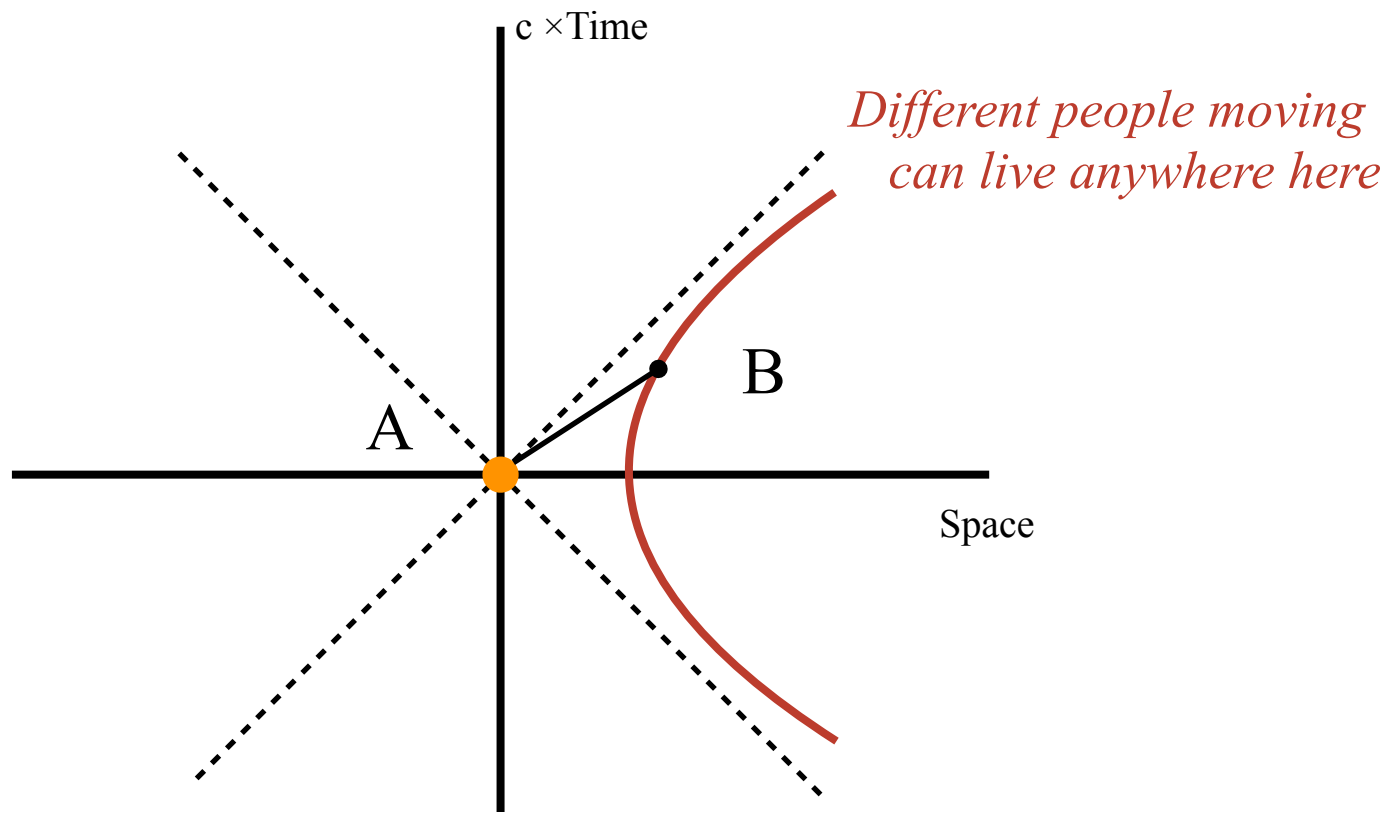
Cant send signals faster than maximum speed



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

Causality in Relativity

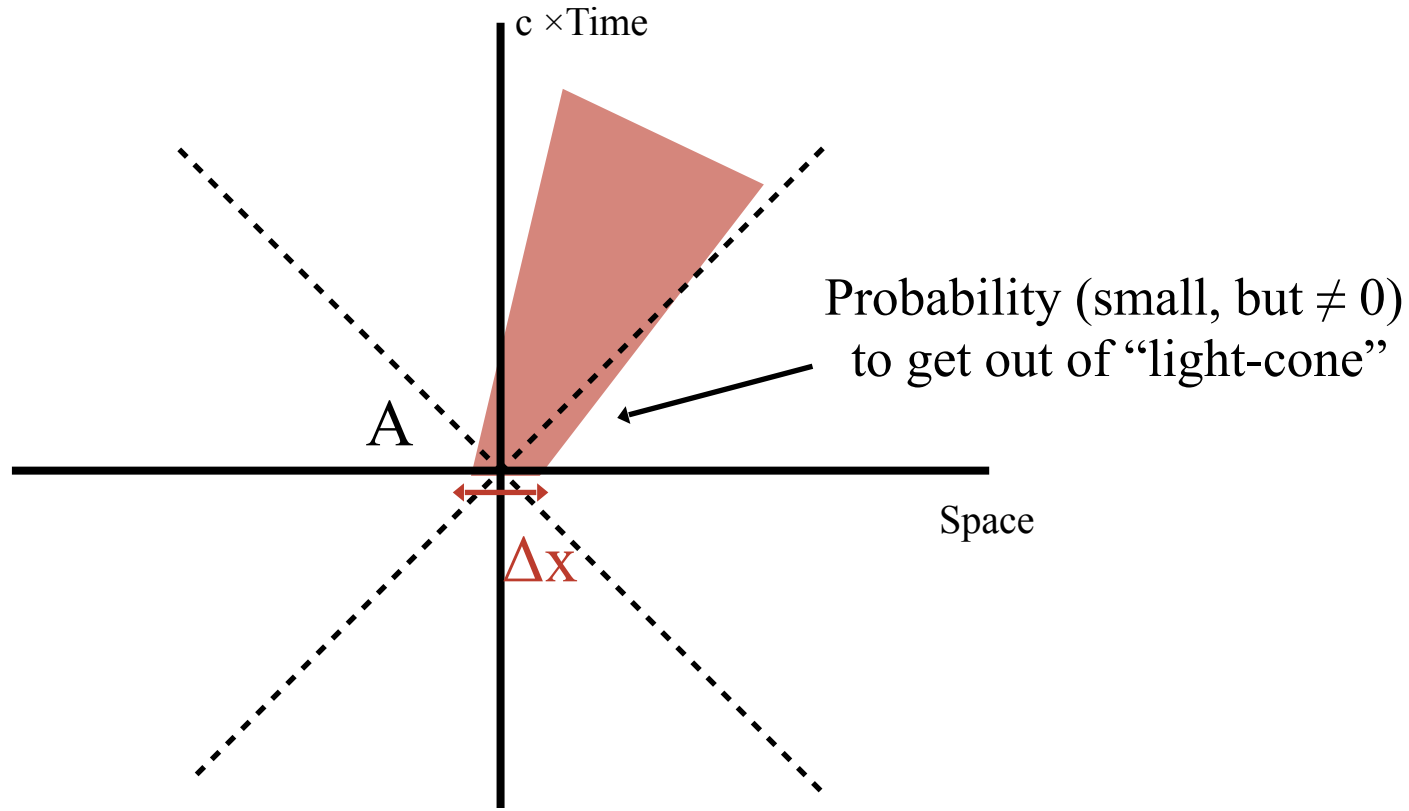
If you could go faster than c, things go wrong



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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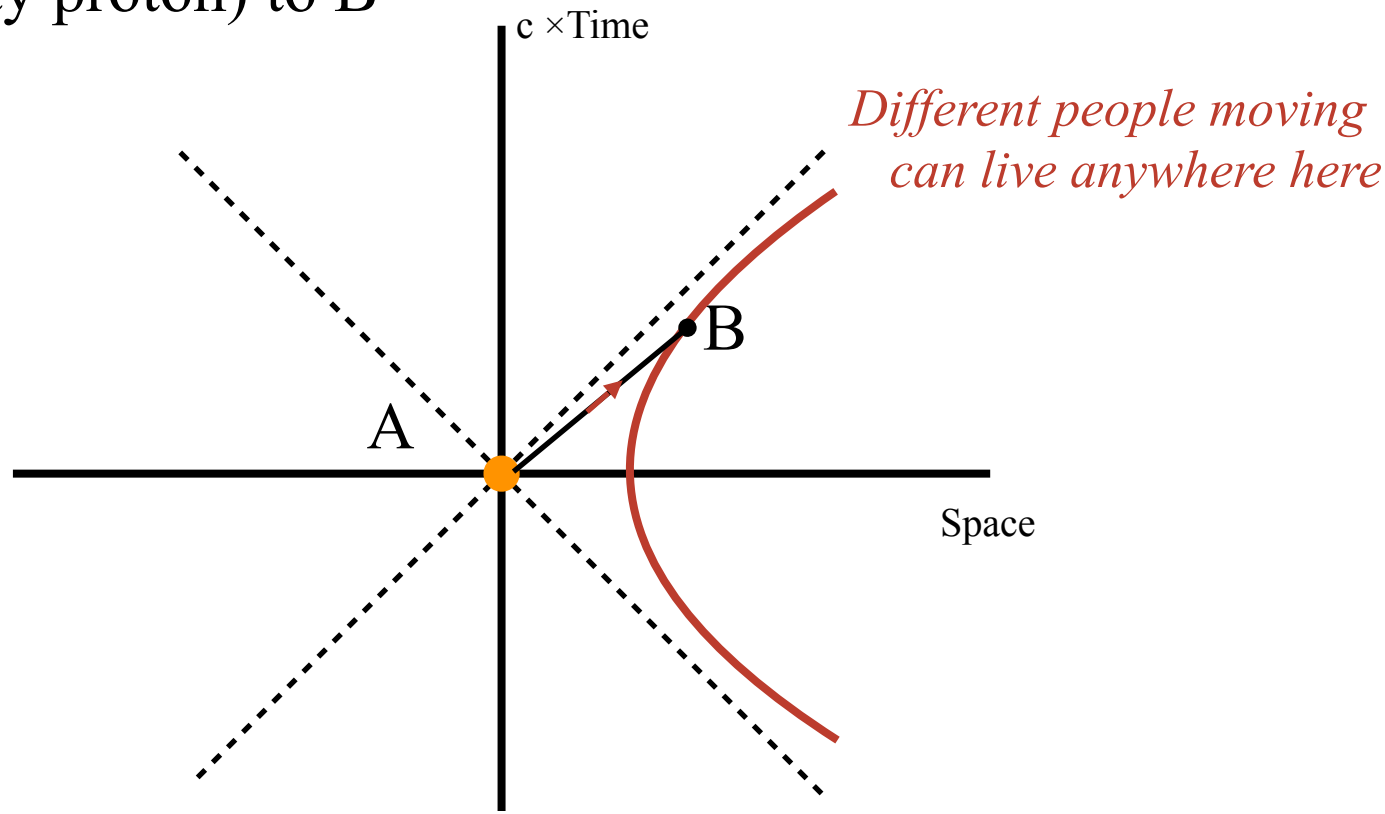
A shoots particle (say proton) to B



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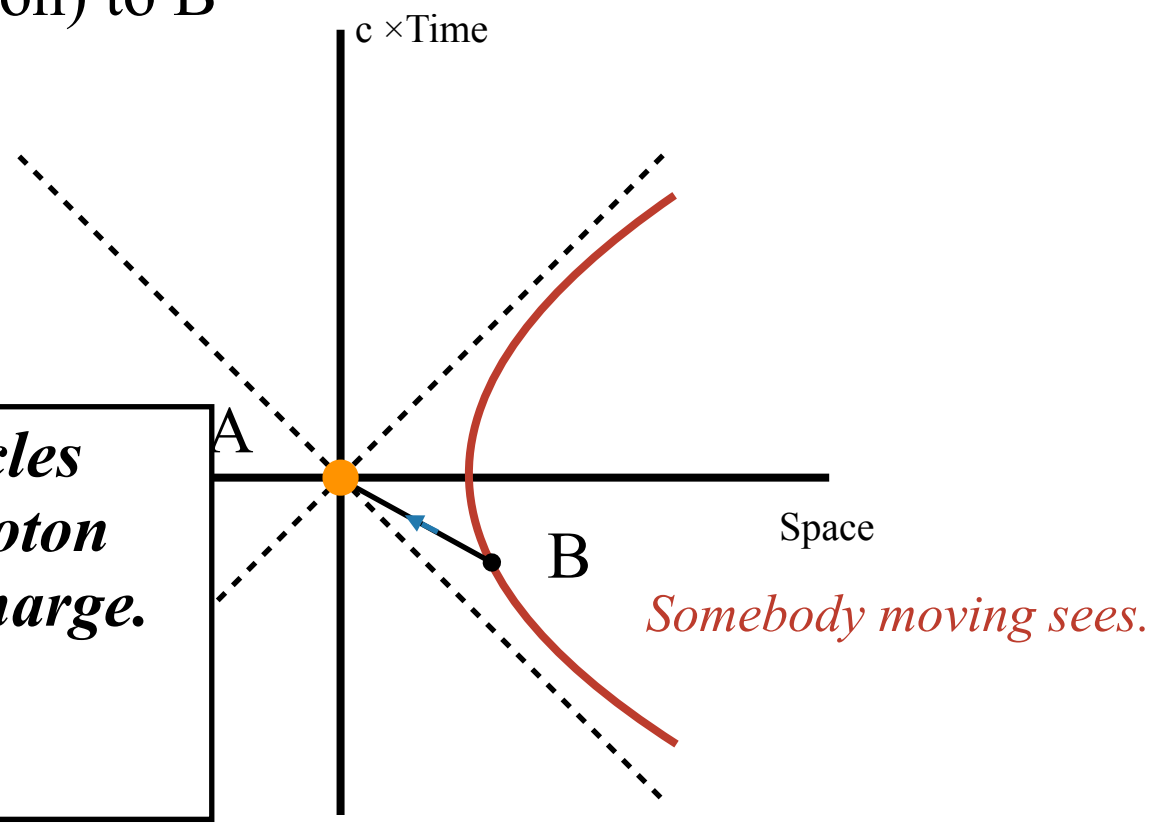

There must exist particles that are identical to proton except with opposite charge.

Anti-particles !

Problem, looks like current is going backwards in time from A to B
Way out, if interpret this as B sending something to A
But B has to send something with opposite charge. *(know A lost charge)*

Has an Impact on *Nothing*

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

Nothing special…until try to check small regions

Before QM:

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

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 $\Delta E \sim 2m_e c^2$

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

QM + R: Forced to talk spin *(Something special w/massless particles)*
Integer spin = Bosons / Half-integer = Fermions
Can only have: 0 1/2 1 3/2 2

Interactions

QM: Any conceivable interaction possible

QM + R: Charge is conserved
Only finite number of specific interactions allowed :

bosons
fermions