Waking up to the Quantum

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Outline

- A century of the Quantum
- Quantum in daily life
- From Certainty to Uncertainty?
- A new plus sign
- Helping to shape intuition

A century of the Quantum

A century of the Quantum

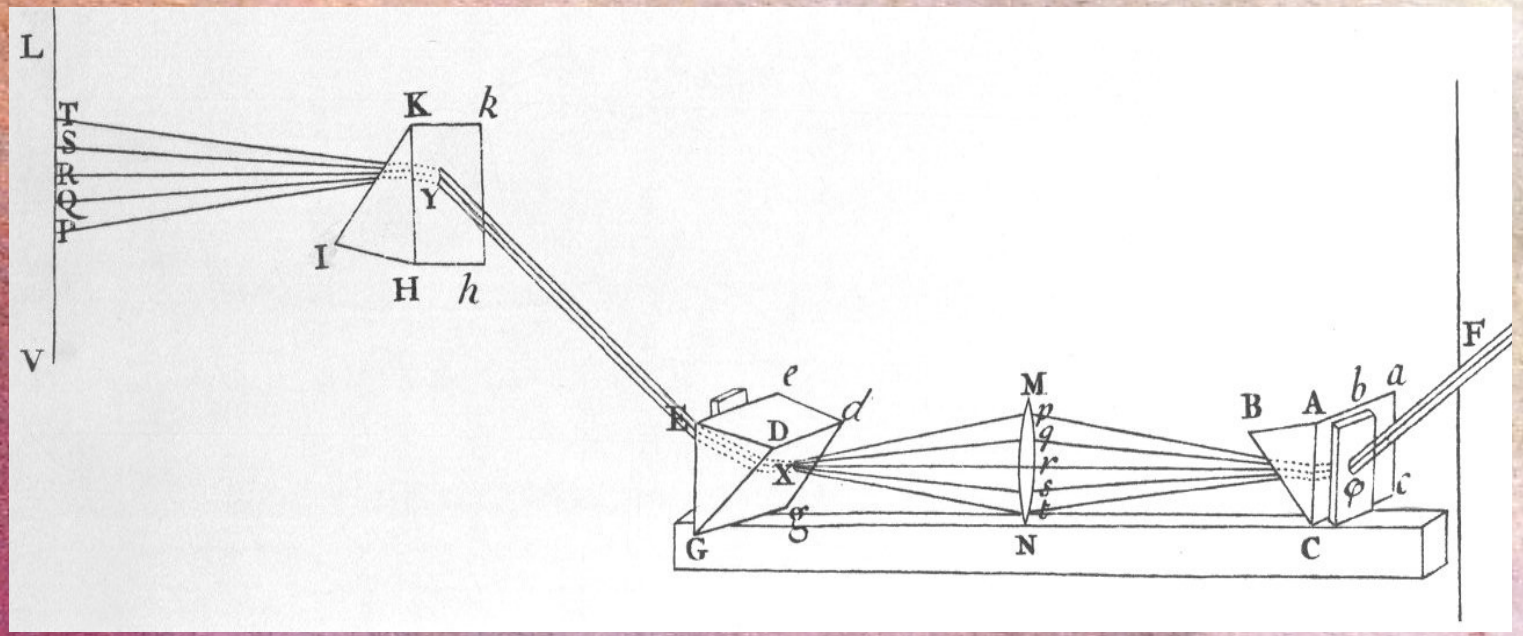
- **Mechanics**
- **Optics**
- **Thermodynamics**
- **Electricity and Magnetism**

Did we have the right to expect these to be related?

Is it a surprise that the Quantum principles which bring all of these together have to be a little perplexing?

Newton and the spectrum

- A theory called “Optiks”
- Mechanical model
  - Should it have been possible?



Intrinsic properties - "Gunadharma"

- **Dalton and the atoms**
- **Colours, odours, fumes …**
  - **"Gunadharma"**
- **Should there be a Physics explanation?**
- **Eventually we understand chemical properties as resulting from dynamics (motion!) of electrons.**

A theory for the "caloric"

- **Heat "flows"**
  - **Is heat a substance?**
- **Count Rumford : kinetic energy of particles**
- **Carnot : Not all energy can be recovered**
- **Clausius : En-tropy vs. En-ergy**

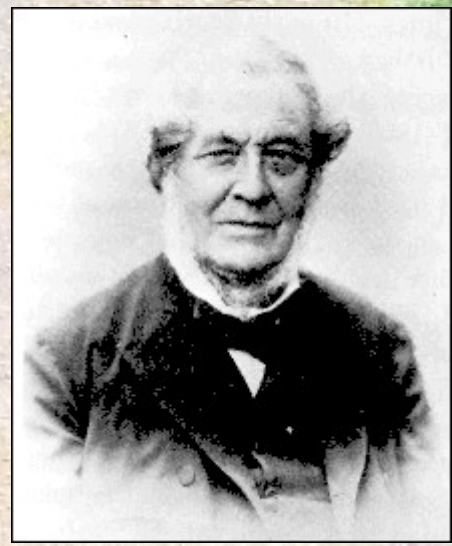
Boltzmann's grand synthesis

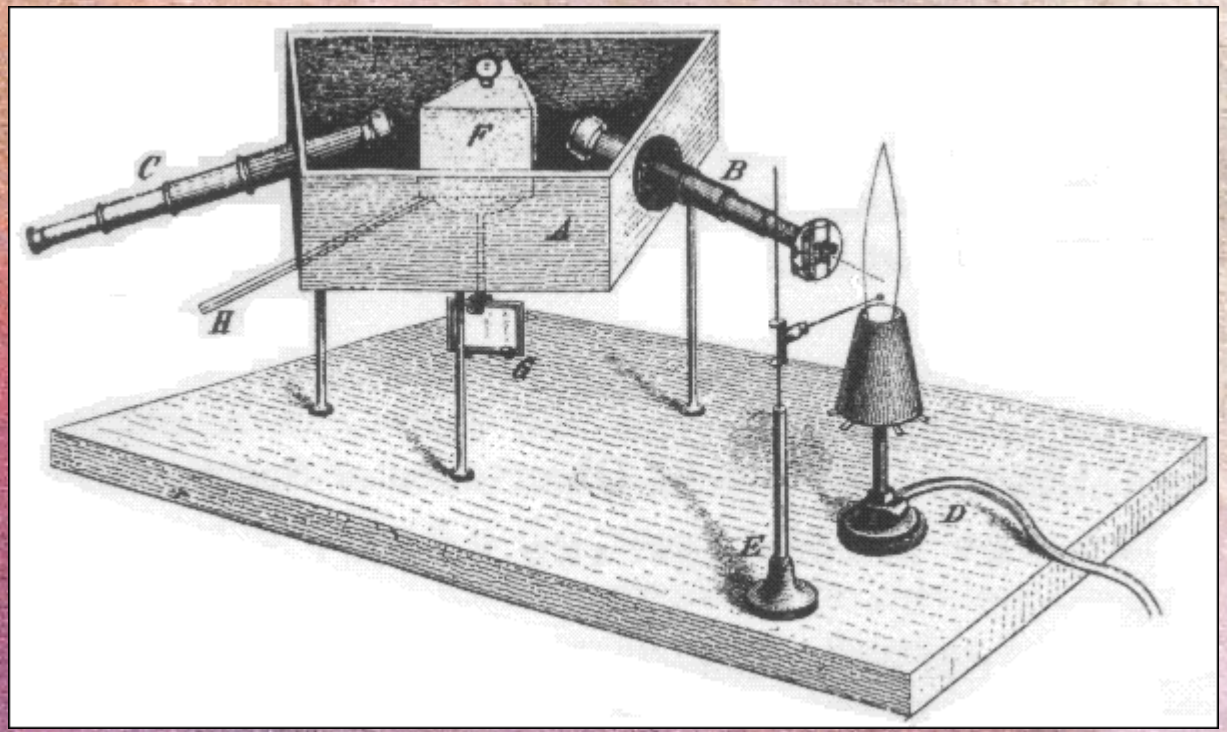
- **Boltzmann explains heat as motion of Dalton's atoms, relates entropy possible states of the atoms**

A century of the Quantum

Heavens on the Earth

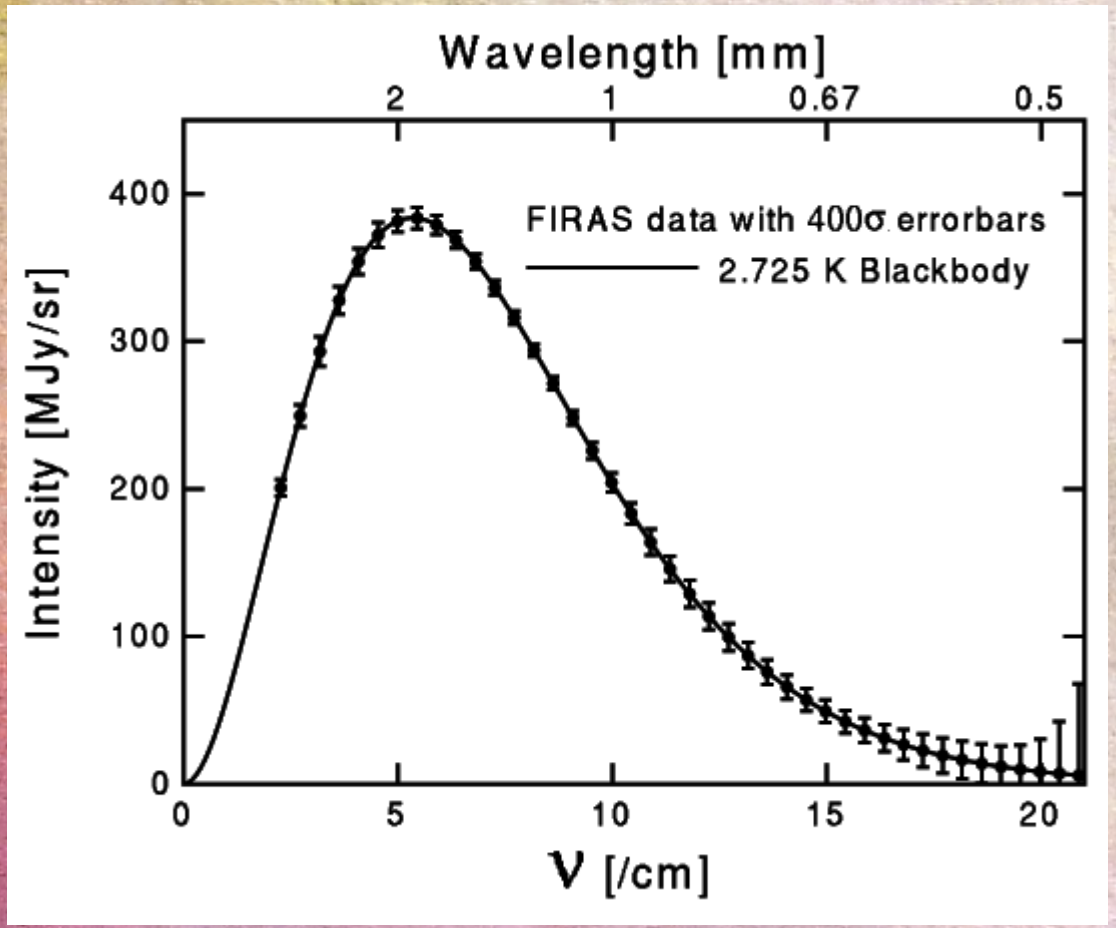
Kirchhoff and Bunsen





A century of the Quantum

Blackbody radiation : A “gas of light”



Kirchhoff's challenge

Kirchhoff's challenge

… was not really solved till 1924

- **Quantization was proposed by Planck in 1900**
- **Photons were proposed by Einstein in 1905**
- **But a full derivation from Statistical Mechanics of photons was given by S N Bose in 1924**

… more to come later

Einstein receiving the Planck Medal of the Prussian Academy at the hands of Planck

Foundation of a grand synthesis

To summarise, Quantum physics provided the fundamental tenets bringing a vast variety of apparently unrelated phenomena to be explained by two basic forms of dynamics :

1. **Kinetic energy of quanta**
2. **Configurational (potential) energy of quanta**

Therefore let us return to a tracing the history of a few key concepts of dynamics

The Quantum in Daily life

Before we move on let us highlight this synthesis provided by the quantum. It is *not* something grudgingly revealing its queer behaviour only under a scanner – it is around us, in daily life.

Wake up to :Quantum in Daily life

- **Valency : chemistry; biochemistry**
- **Color … (shielding in atoms and approximate equality of light frequencies; evolution of vision)**
- **Solids : no solidity without Exclusion Principle**
- **Magnetism : spin**
- **White Dwarfs : super-atoms strung in the sky**

From “Certainty” to “Uncertainty”? (No!)

What is motion?

- **Location (position)**
- **Locomotion (movement)**

Motion is the simplest form of "change". Unlike complicated transformations of entities, here something merely changes location.

An intellectual struggle

Motion from ancient times and variety of secular and religious philosophical systems posed a problem.

- **Zeno's paradox – conflict of observation and logic**
- **Aristotalian conception proposed that sustained motion required a "motive force"**

An intellectual struggle

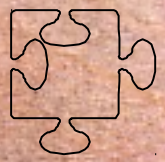
Nagarjuna in *Madhyamika Karika :*

- ***Does "motion" have reality independent of that which moves?***
- ***Does the space through which motion occurs exist befor ethat motion occurs?***
- ***Can the notion of "state of rest" (no motion) be valid if its modification (motion) has not occurred?***

A theological critique

We may take several attitudes to this

A profound idea



A confounding puzzle

To be passed over in silence

Yawn … I am sleepy

But an intellectual struggle it has been

Galileo cuts the Gordian Knot

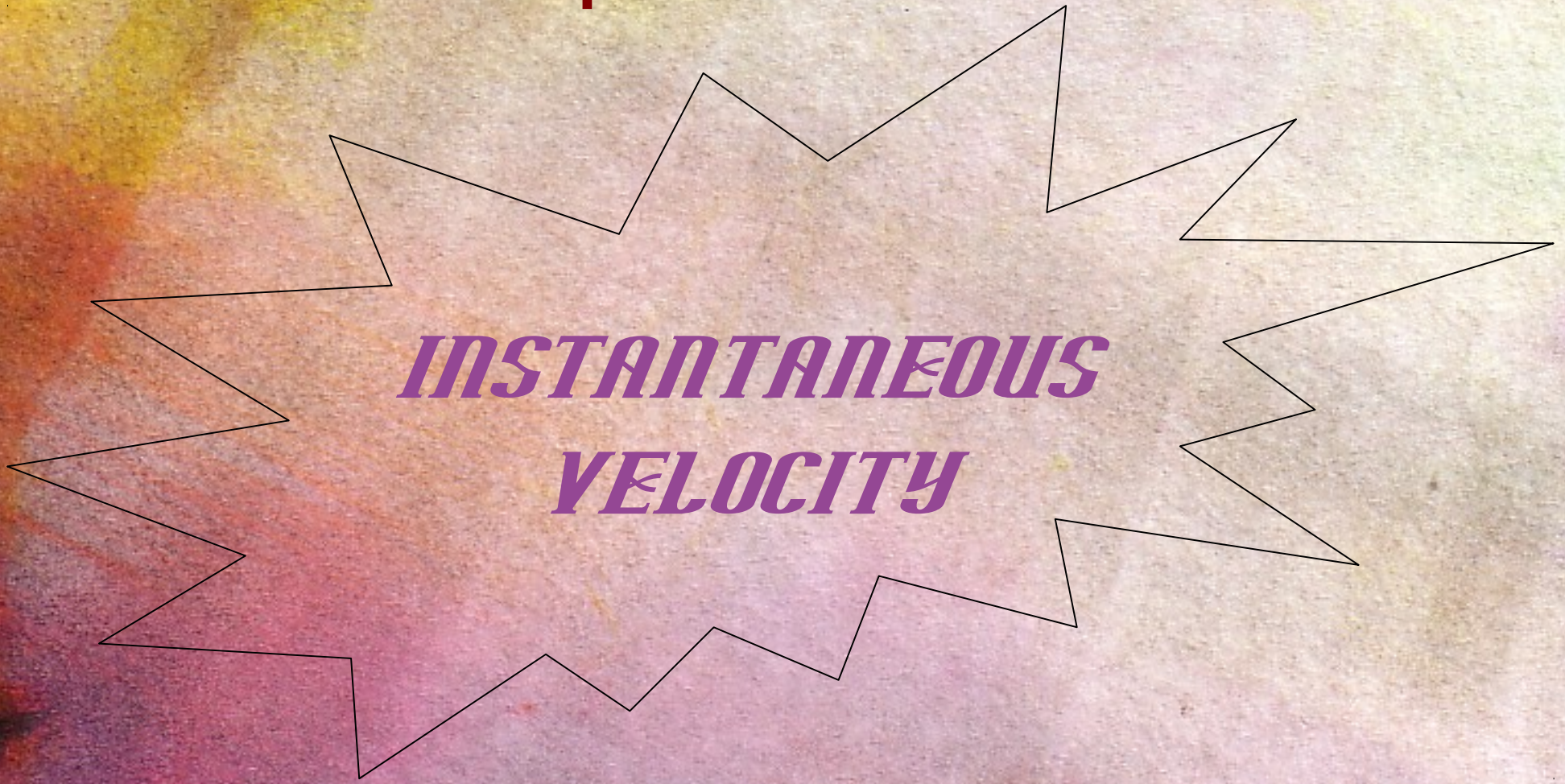
- **Perform empirical observation**
  - **“Tower of Pisa experiment”**
- **Proposes thought experiments in lieu of actual empirical experiment**
  - **The chess players inside a moving ship**
  - **The ball rolling onto a plane offering *progressively* less friction**

Newton formalises

- **The limit process (progressive improvement of Galileo's thought experiment)**
- **At home with Zeno's paradox – infinite series can have finite answers**

Newton formalises

A key concept we accept and also make our students accept is



Newton formalises

- **Nagarjuna could well have questioned :**

Can something be at a place and also be moving?

Newton formalises

Can we be sure that the limit process is valid?

Are we overdoing Galileo's gedanken experiment?

A “koti kasharpan” question of phenomenology, not of logic!!!!

"Uncertainty" sets in

- We use Euclidean conception of idealised point as location
- We use Newtonian concept of instantaneous velocity
- Now we expect both to be workable simultaneously

Origins of "Uncertainty relation"

- **Heisenberg formulated matrix mechanics in 1925**
- **Schroedinger incorporated de Broglie's idea and formulated wave mechanics**

Origins of "Uncertainty relation"

- It seemed there was a contradiction and Heisenberg found waves "irritating"
- His attempt at reconciling the two gave rise to uncertainty principle
  - Wave nature corresponded to non-commutativity

Predictable and unpredictable

- **Recall however that QM is a predictive theory**
- **Both matrix mechanics and wave mechanics give *first order differential equation* in time**
  - **Matrix mechanics for observables**
  - **Wave mechanics for for states**
- **Dirac did the best he could … a vector space (Hilbert space)… not "waves"**

Predictable and unpredictable

- **Born soon revealed what was probabilistic**
- **Evolution of states predictable**
- **Outcome of observations probabilistic**
  - **No *hidden* variables!!**
  - **Not observer dependent either !!!**
- **Double slit experiment, Stern-Gerlach experiment … delayed choice; tunnelling**
  - **All mind boggling but not defying objectivity or autonomous nature of QM**

Poor wording

- **Random sample from the internet :**

Summary: Lessons from Heisenberg

- The idea of a perfectly predictable universe cannot be true
- There is no such thing as an ideal, objective observer

- **Have no prejudiced expectations, find no disappointment!**

Why quanta are not particles

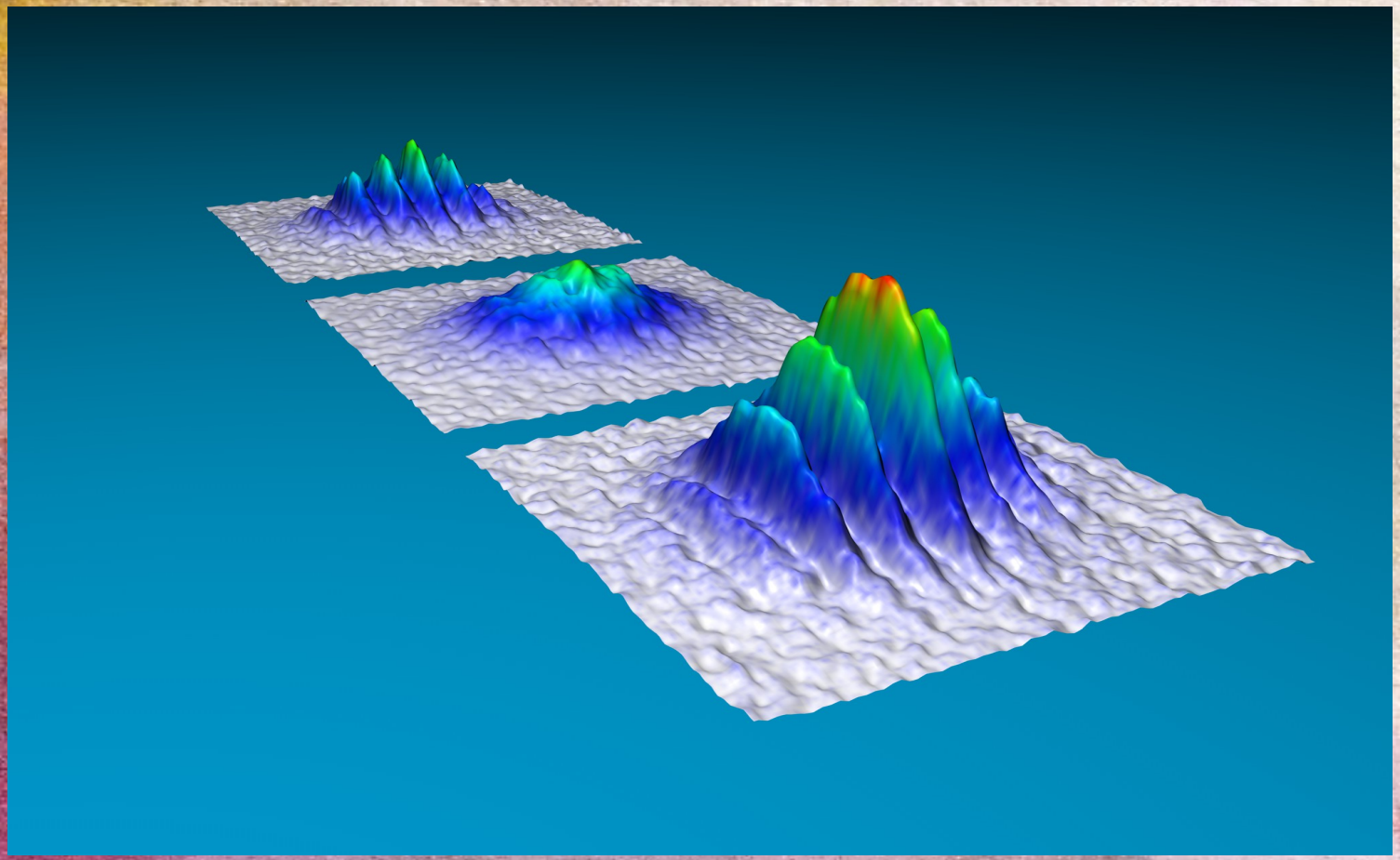
- Many body QM postponed and separated from single variable QM
- But only in many body systems does QM come really to life
- Bosons and Fermions
  - Exclusion principle
- Some of the peculiarities of single particle QM may well have to do with conserved charge carried by the electron

Satyendra Nath Bose

Why quanta are not particles

"Entaglement"...

- **… in nature or of our conceptions?**



A new plus sign in Physics

A new plus sign

- **Dirac amphasises that**
  1. **Revelation of Planck's constant for the first time tells you where the large ends and the small begins – sets the scale**
  2. **QM reveals a new fundamental principle absent in the classical world**

The Principle of Linear Superposition

A new plus sign

- The fact is there are no “waves” of probability amplitude
- An amazing fact of QM is that states of different momenta can be superposed to obtain a new permissible state
  - Existence of *h* associates a length scale with a momentum (de Broglie)
  - Use of Fourier series as for classical waves gives a strong analogy to wave phenomenon
- Convenience yes, paradox, no

Number operator

- **Number of quanta is an observable in QM**
- **A strong principle like charge conservation enforces superposition among states only of a definite number**
- **But not all systems have conserved charges**
  - **Photons, phonons, Majorana fermions ...**

Not so new a plus sign!

- **The work of Sudarshan on coherent states (Nobel to Glauber 2005) clarified that the observed states of radiation are actually fully Quntum**
  - **There are no order *h* corrections to these states**
- **When an engineer adds the values of electric fields due to two sources, he is using the Quantum superposition principle**

Quantum Mechanics in daily life

Shaping the intuition

Shaping the intuition

- From superconductivity to high temperature superconductivity
- SQUID, Graphene, Quantum dots ...
- Quantum information storage and transmission
- Majorana-like quasi-particles in “topological” insulators

Quantum on our table top

Thank You !