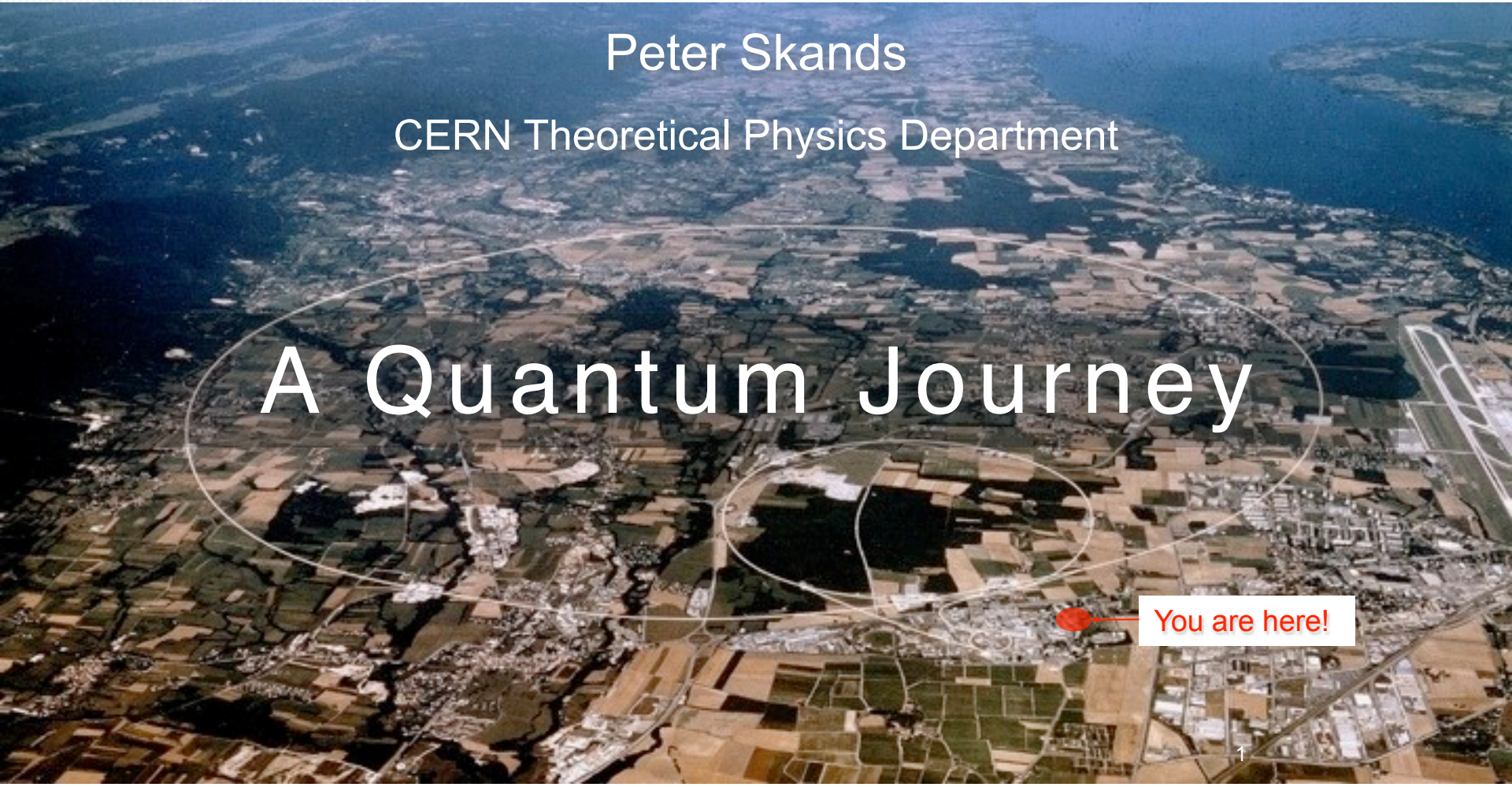
CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Peter Skands

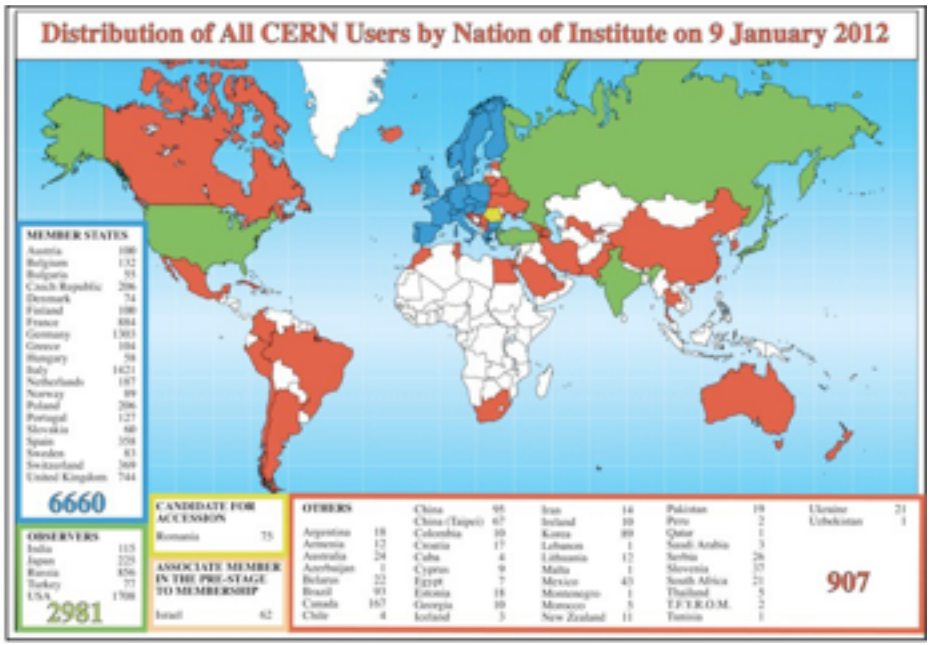
CERN Theoretical Physics Department

A Quantum Journey



Every day, around 10 000 scientists
from all over the world.

Flags of CERN's Member States

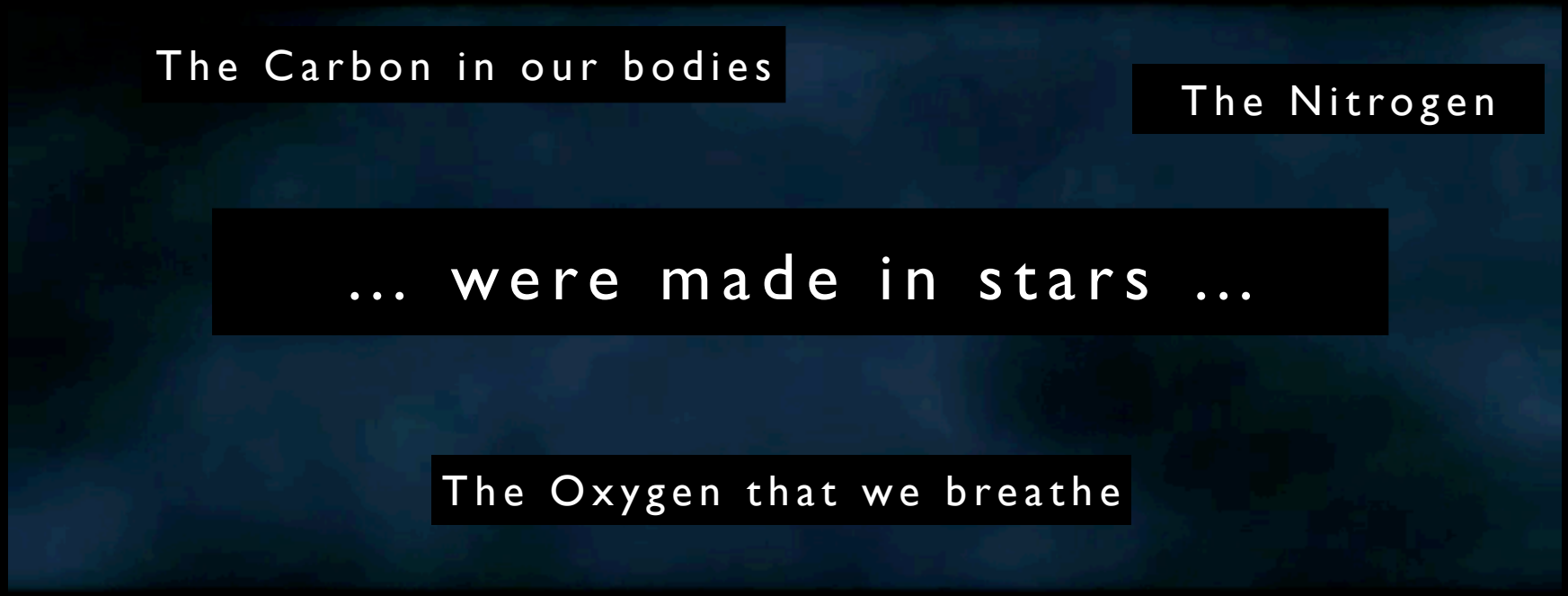


20 European Member States and around 60 other countries collaborate in our scientific projects.

Why ?

The Building Blocks of Life

The Building Blocks of Life



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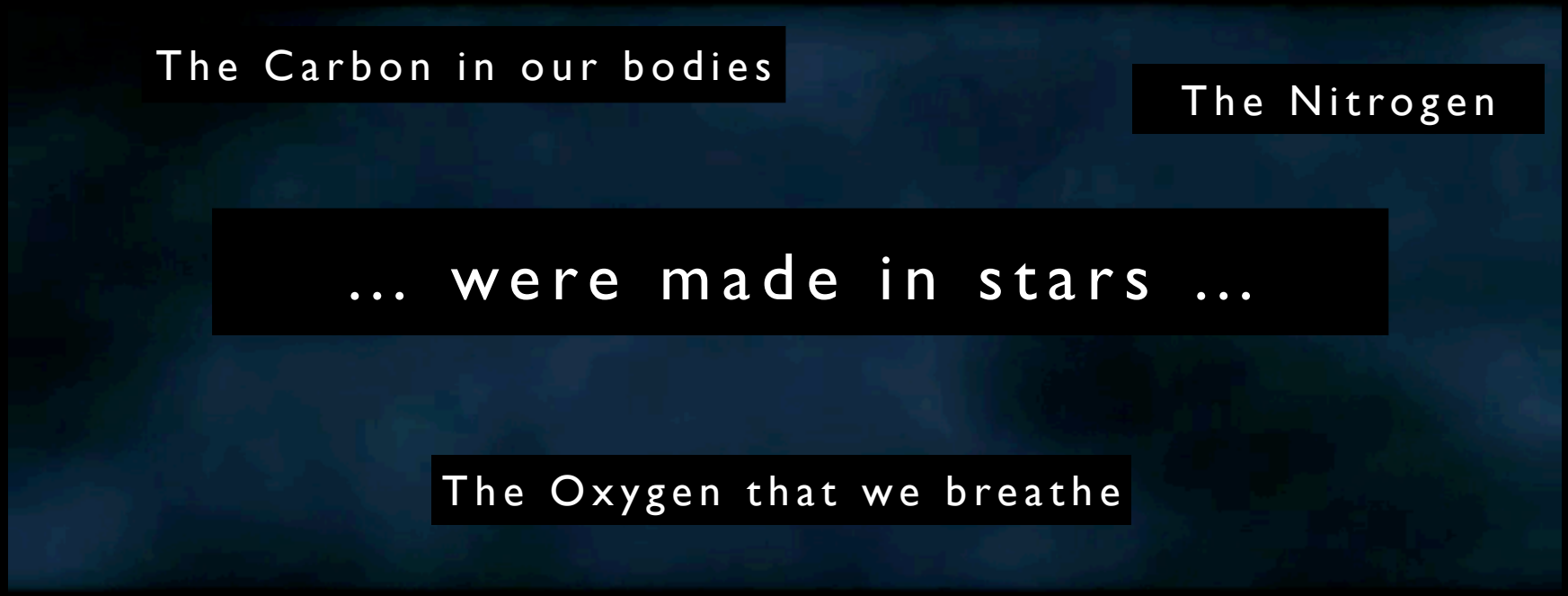

We are Children of Stardust

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D. Zindell: we are the **eyes** through which the universe beholds itself

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All I know for sure: Nature is a **Fantastic Work of Art**
Where did it come from? What is it? Where is it going?

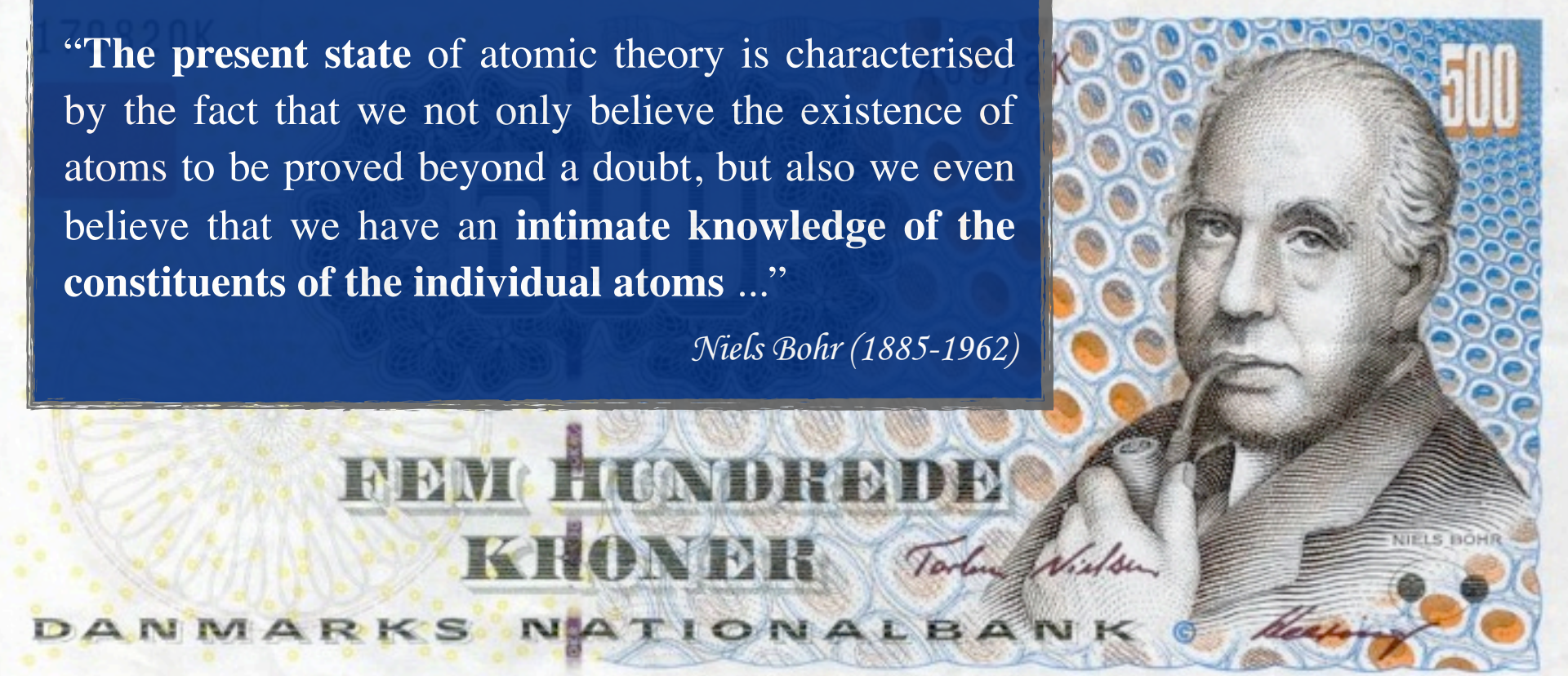
It inspires us to think beyond ourselves

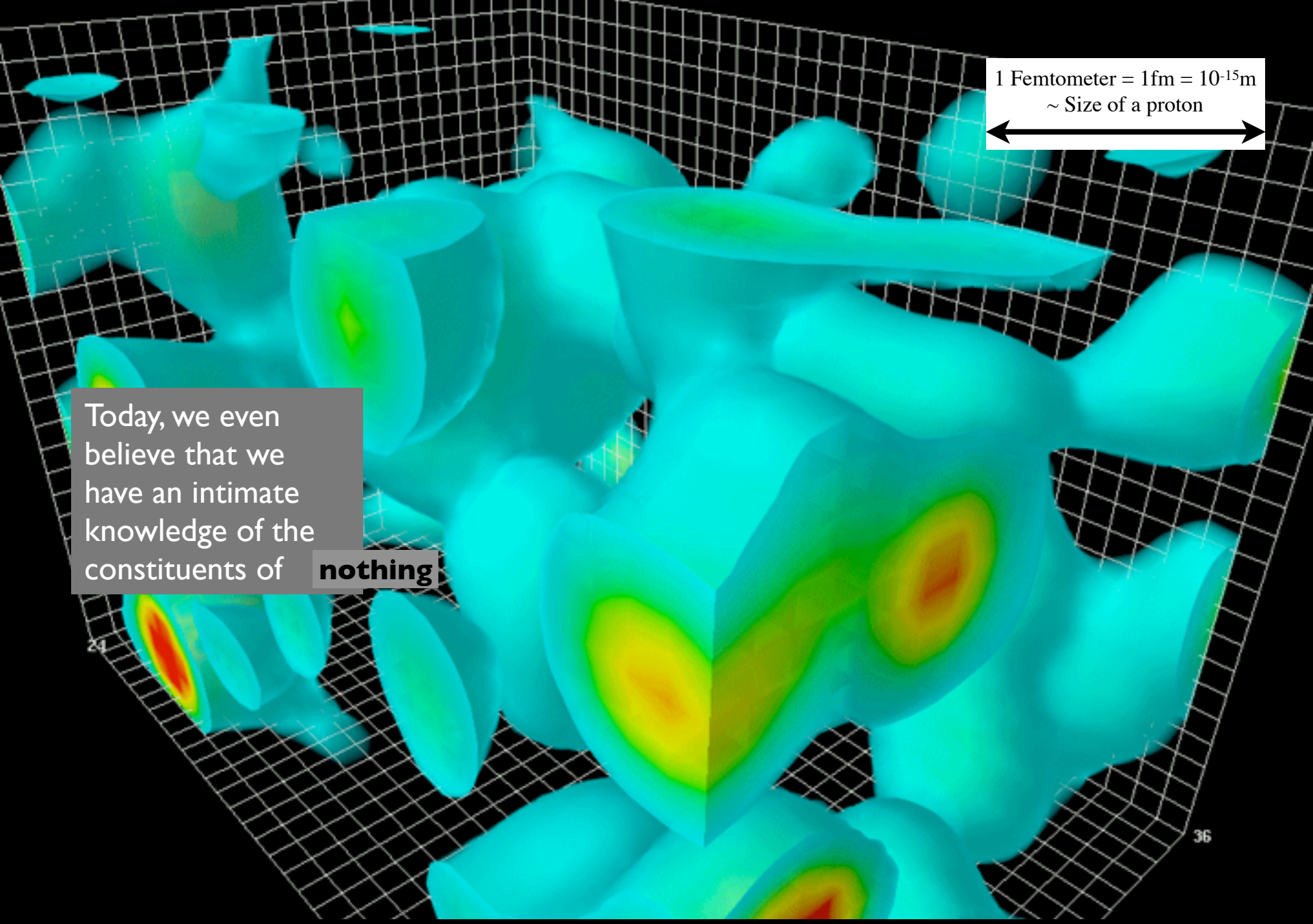
Atomic Theory

Stockholm, 1922

"**The present state** of atomic theory is characterised by the fact that we not only believe the existence of atoms to be proved beyond a doubt, but also we even believe that we have an **intimate knowledge of the constituents of the individual atoms** ..."

Niels Bohr (1885-1962)

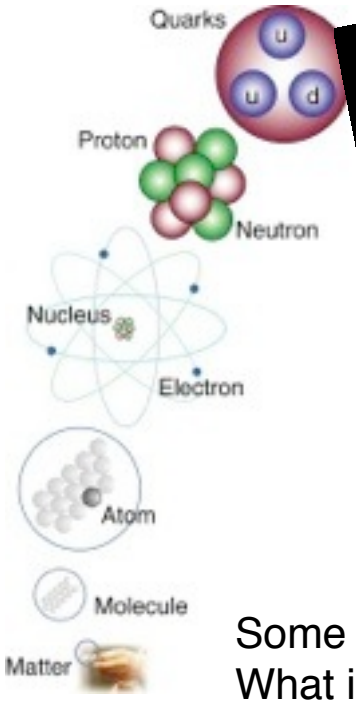


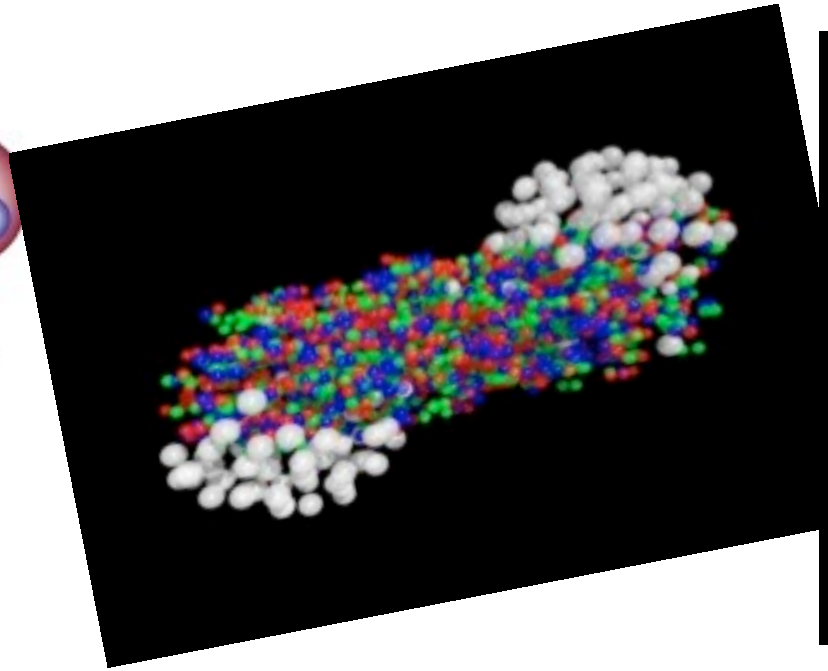


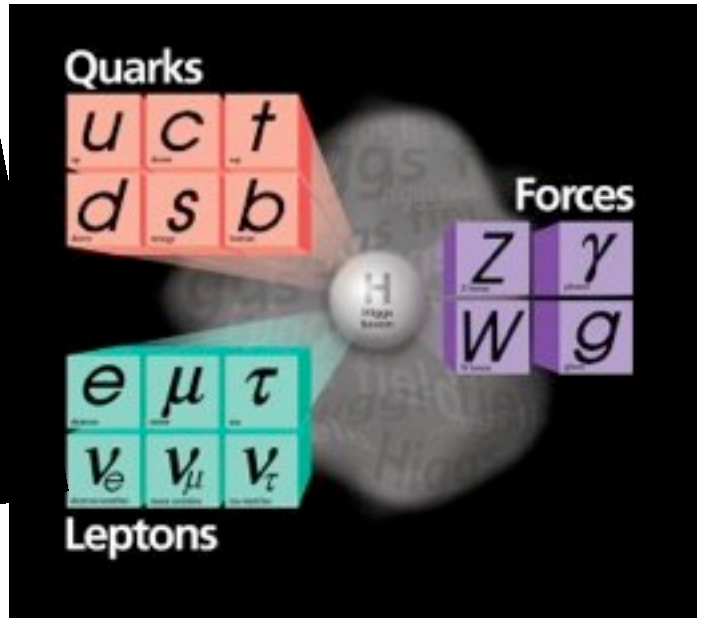
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel

Gluon action density: 2.4x2.4x3.6 fm, Supercomputer "Lattice simulation" from *D. B. Leinweber, hep-lat/0004025*

To advance our understanding of the Universe

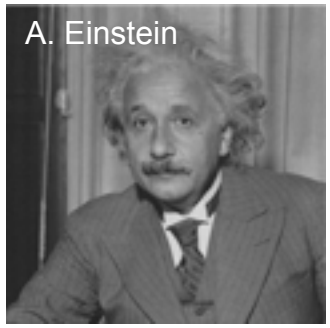






Some of the biggest unanswered questions today:
What is **mass**?
What is **96% of the Universe** made of?
What happened in the **first instants** of the Big Bang?
Why are there no **anti-matter** stars and galaxies?
Unexplored territories…new matter, new forces, new dimensions?

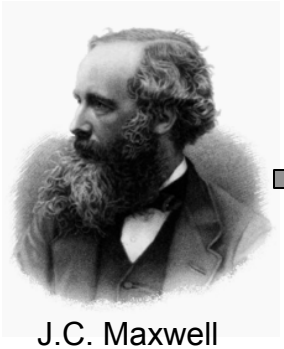
Fundamental research has always been a driving force for innovation



Relativity

100% SCIENCE

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!



J.C. Maxwell

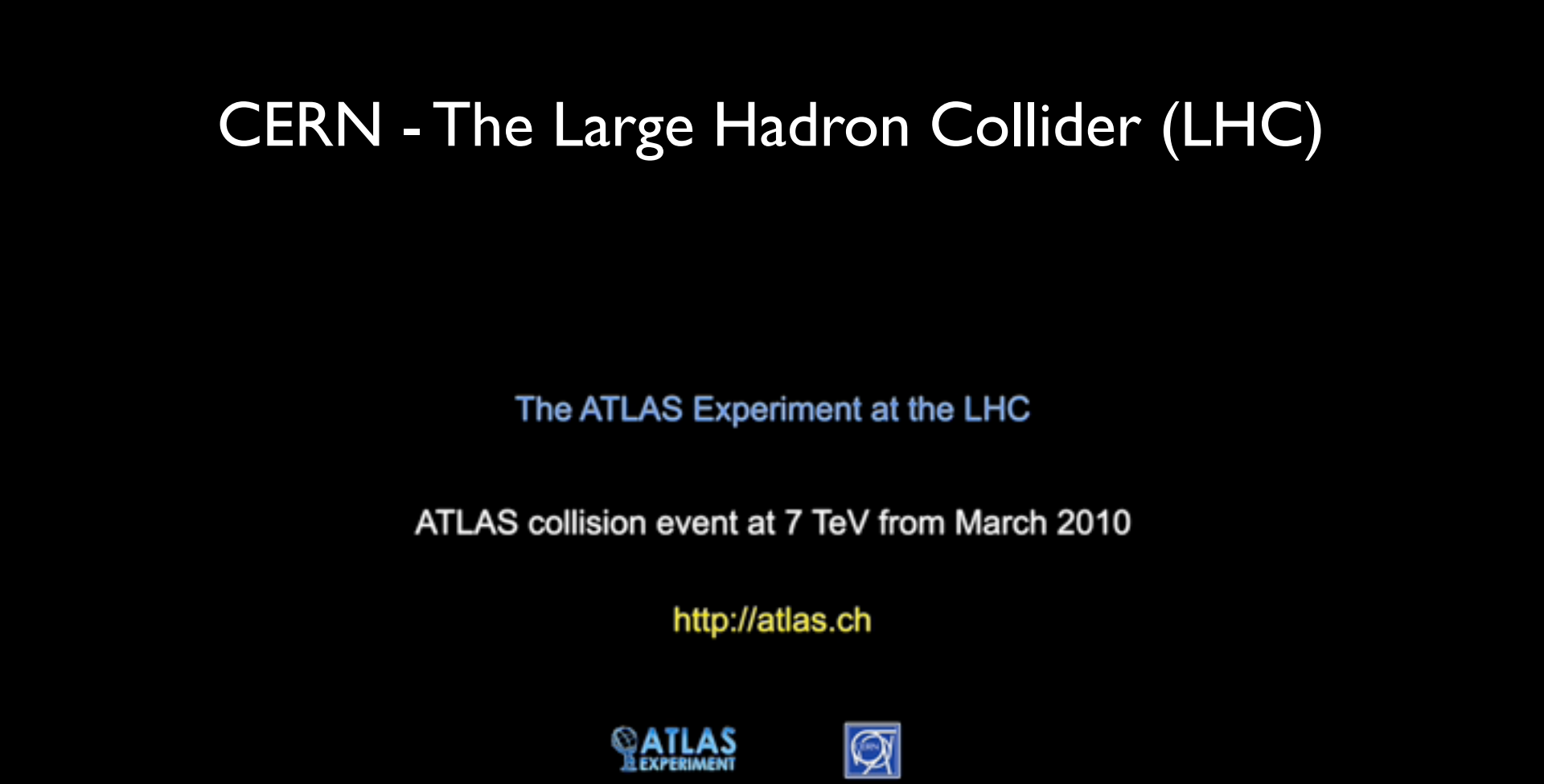
Electromagnetism

100% SCIENCE

Telephones use electromagnetic waves to communicate

How ?

CERN - The Large Hadron Collider (LHC)



LHC Collision at 7 TeV
ATLAS, March 2010

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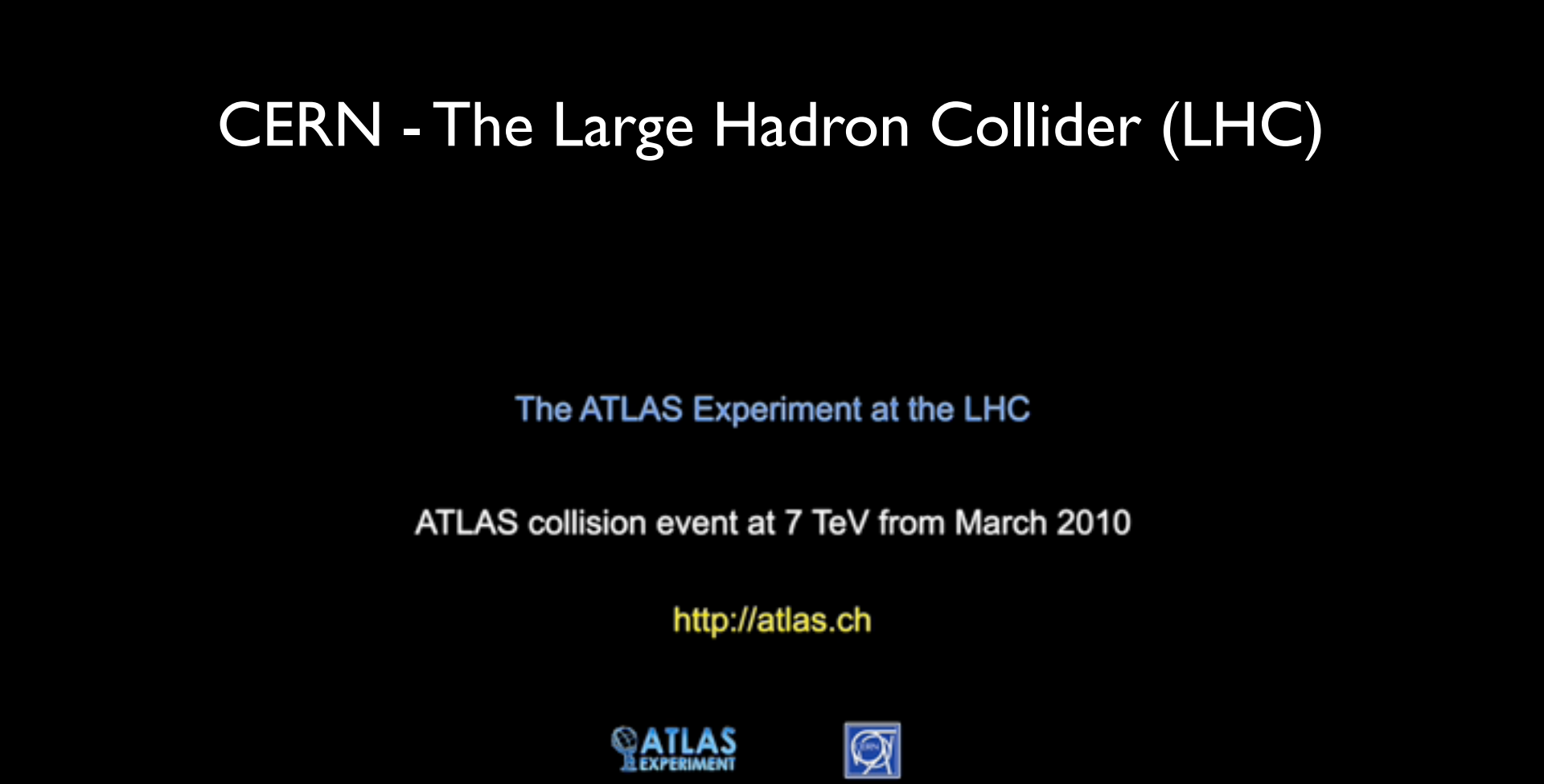

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The tools of the trade

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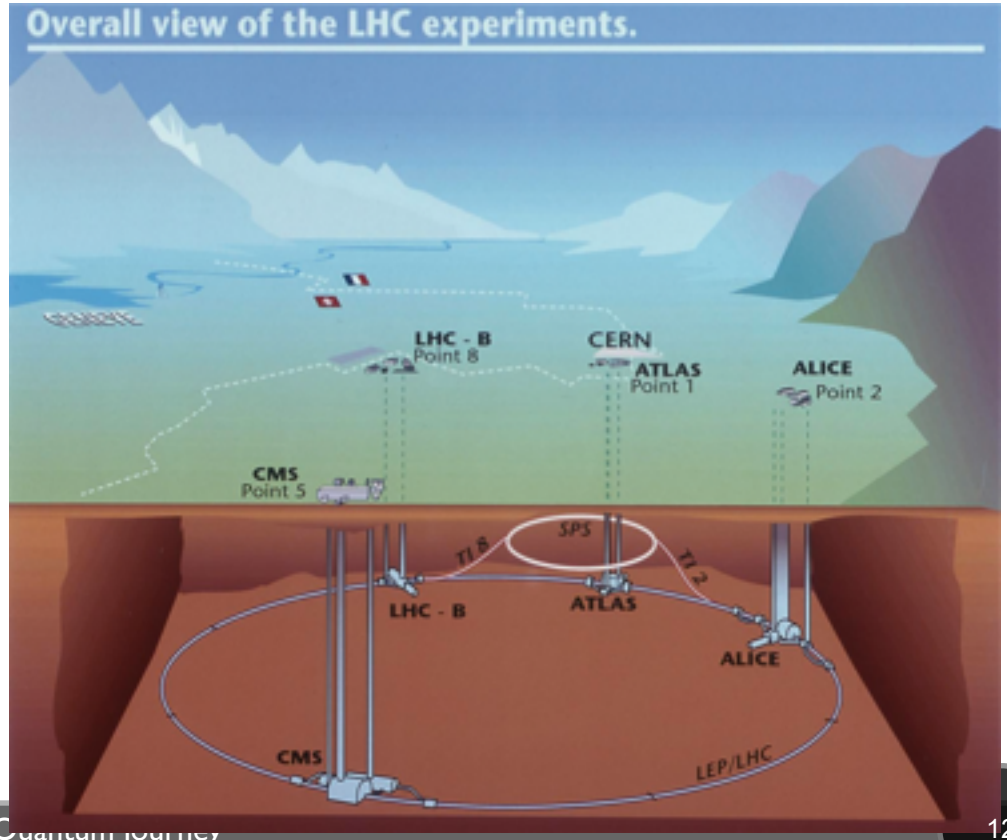
1. Accelerators : powerful machines capable of accelerating particles up to extremely high energies and bringing them into collision with other particles.



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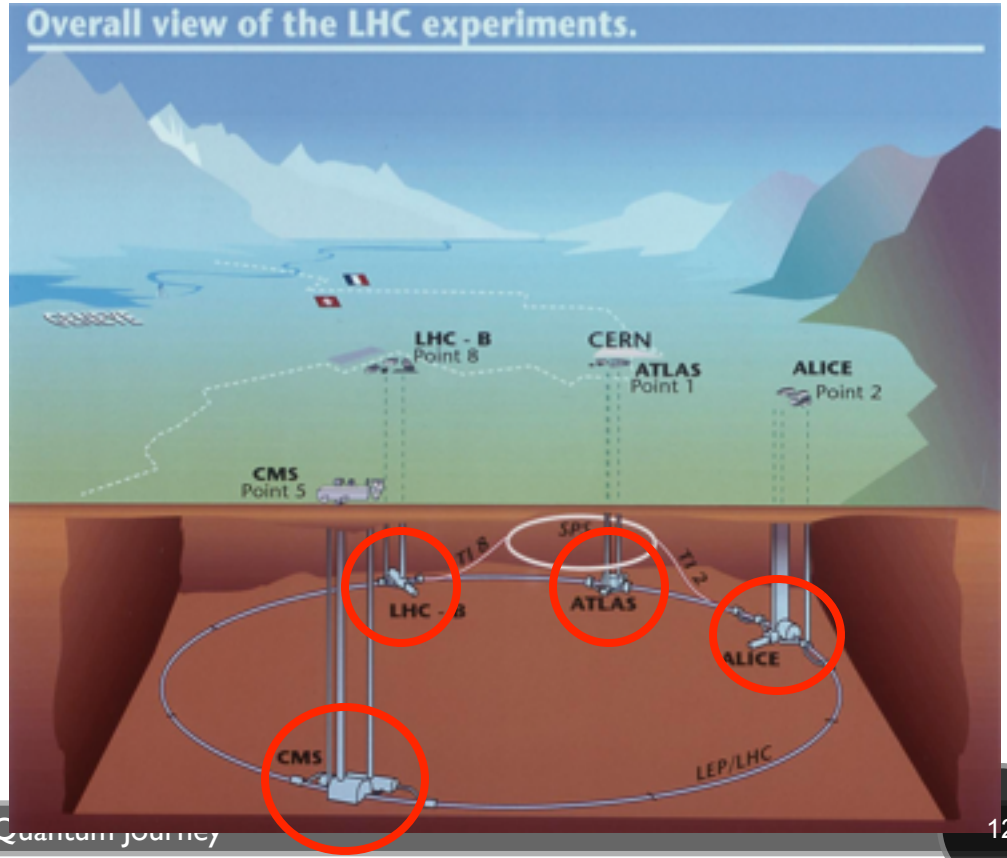
1. Accelerators : powerful machines capable of accelerating particles up to extremely high energies and bringing them into collision with other particles.

2. Detectors : gigantic instruments recording the particles spraying out from the collisions.



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1. Accelerators : powerful machines capable of accelerating particles up to extremely high energies and bringing them into collision with other particles.

2. Detectors : gigantic instruments recording the particles spraying out from the collisions.

3. Computers : collecting, stocking, distributing and analysing the enormous amounts of data produced by the detectors.

LHC@home 2.0

Test4Theory - A Virtual Atom Smasher

http://lhcathome2.cern.ch/

Over 400 billion simulated collision events

Test4Theory

10,000 Volunteers wanted a virtual atom smasher (to help do high-energy theoretical-physics calculations)

Runs when computer is idle. Sleeps immediately when user is working.

Problem: Lots of different machine architectures

→ Use Virtualization (CernVM)

Provides standardized computing environment (in our case Scientific Linux) on *any* machine

Exact replica of our normal working environment → no worries

Sending Jobs and Retrieving output

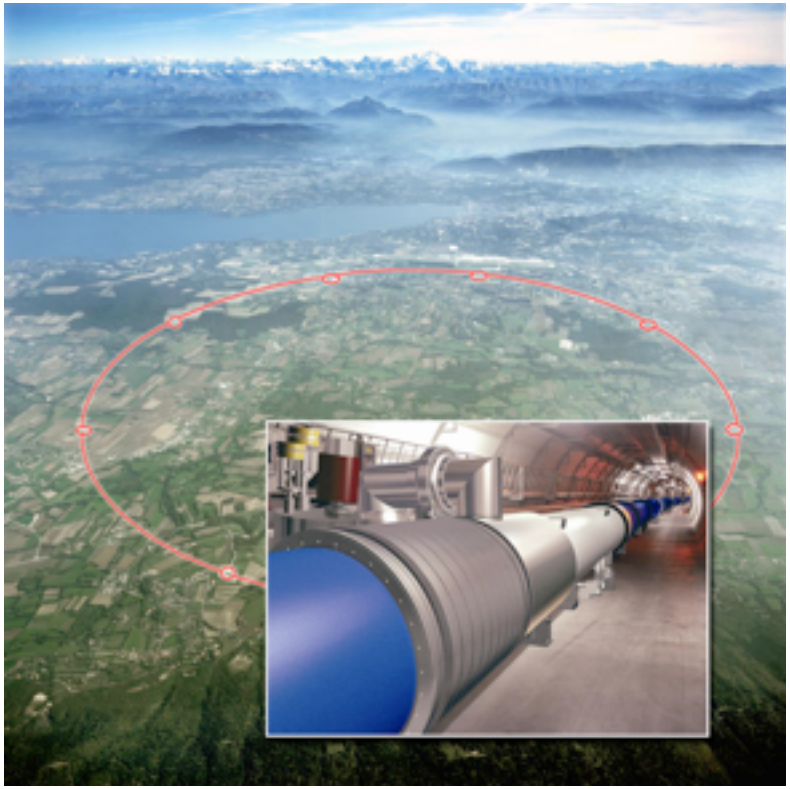
Using BOINC platform for volunteer clouds (but can also use other distributed computing resources)

http://lhcathome2.cern.ch/

Last 24 Hours: 2853 machines

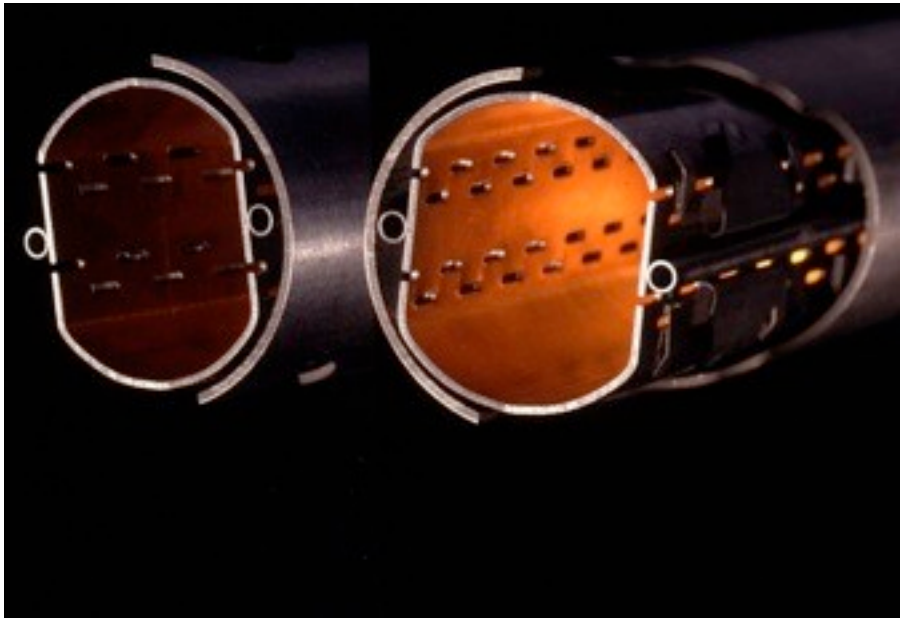
http://lhcathome2.cern.ch/

One of the fastest racetracks on the planet



Several thousand billion protons travel round the 27km ring over 11 000 times per second

The emptiest space in the solar system…

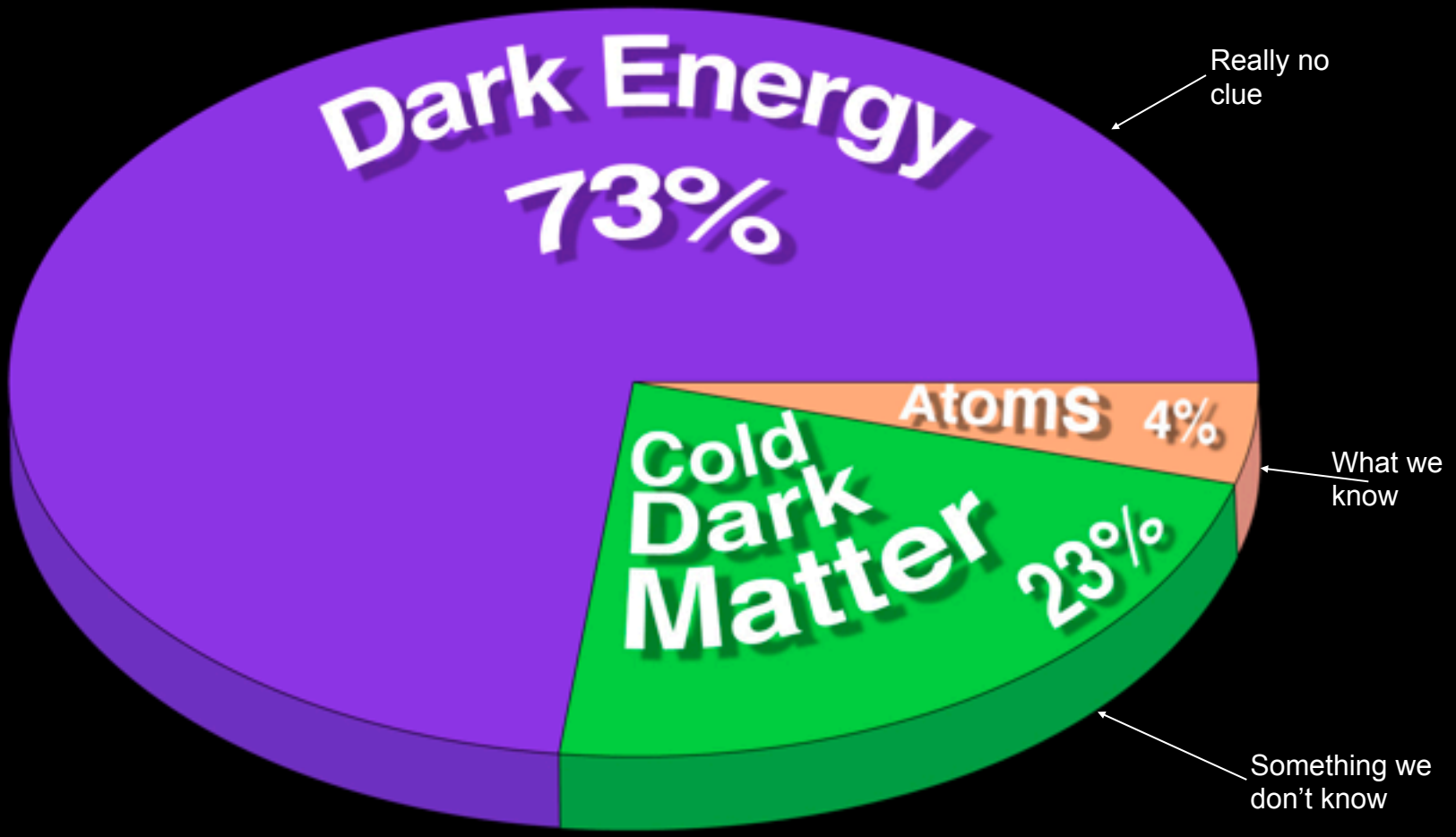


To accelerate protons to almost the speed of light, we need a vacuum similar to interplanetary space. The pressure in the beam-pipes of the LHC is about ten times lower than on the moon.

One of the coldest places in the Universe…

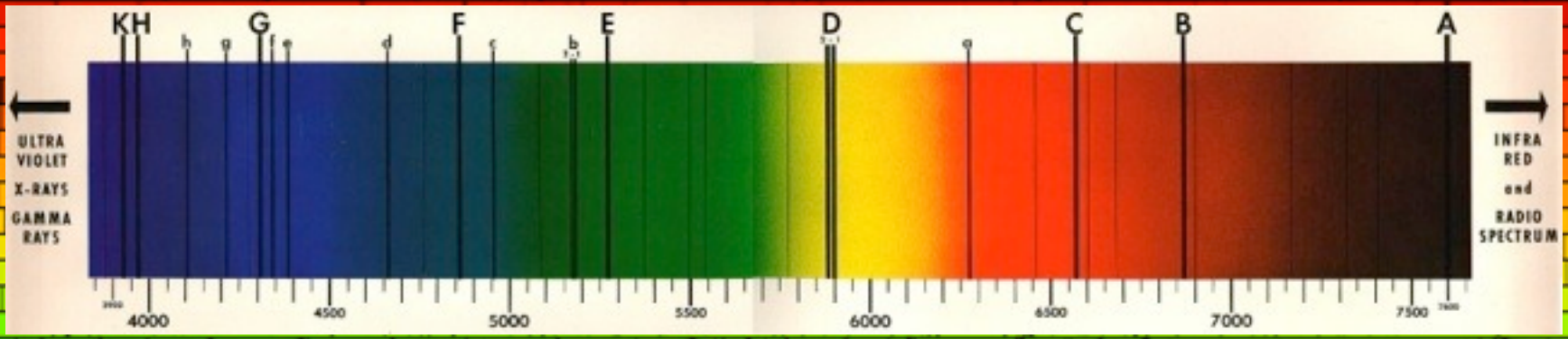
Temperature of Interstellar space: **-270 Celcius**, due to leftover light from the Big Bang, called the Cosmic Microwave Background (CMB) radiation

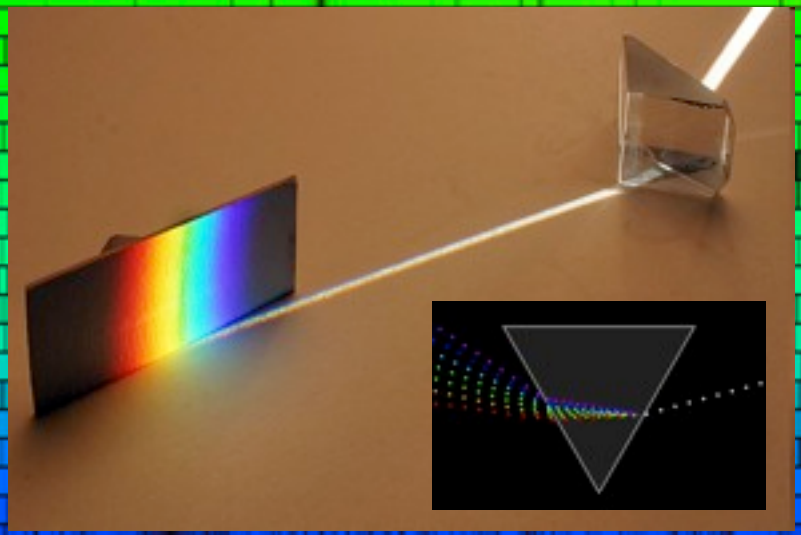
Temperature of the LHC: **-271.25 Celsius** (1.9 degrees above absolute zero)



What is the Universe made of ?

What is the Sun made of?





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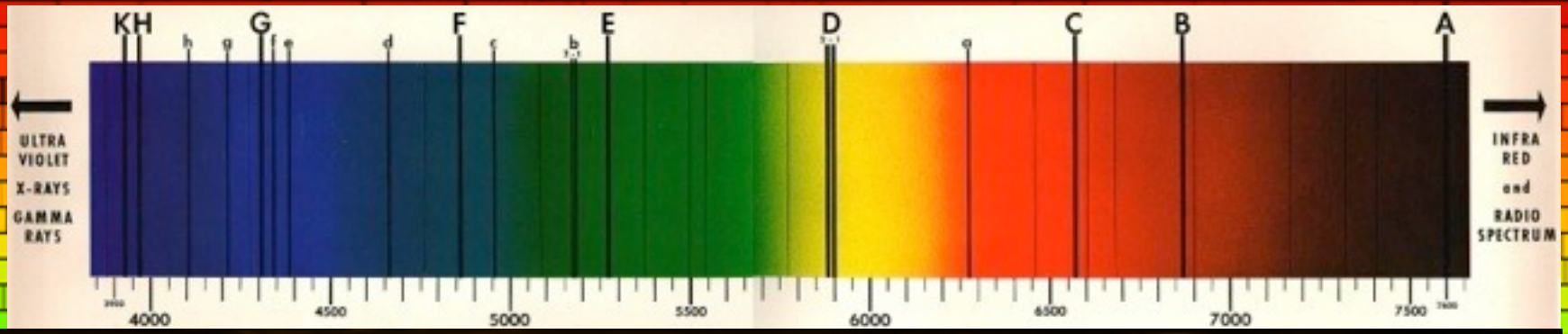
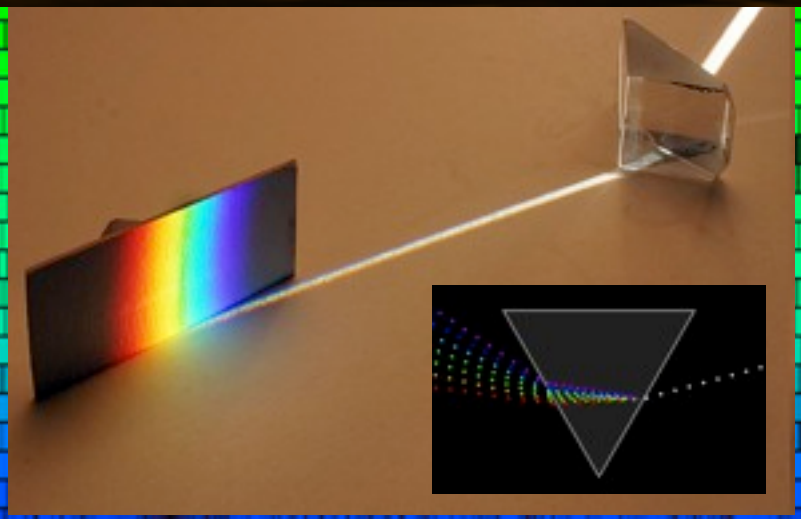


- William H. Wollaston (1802): 7 mysterious holes in the rainbow …

Wollaston (1766-1828)



George III (1738-1820)

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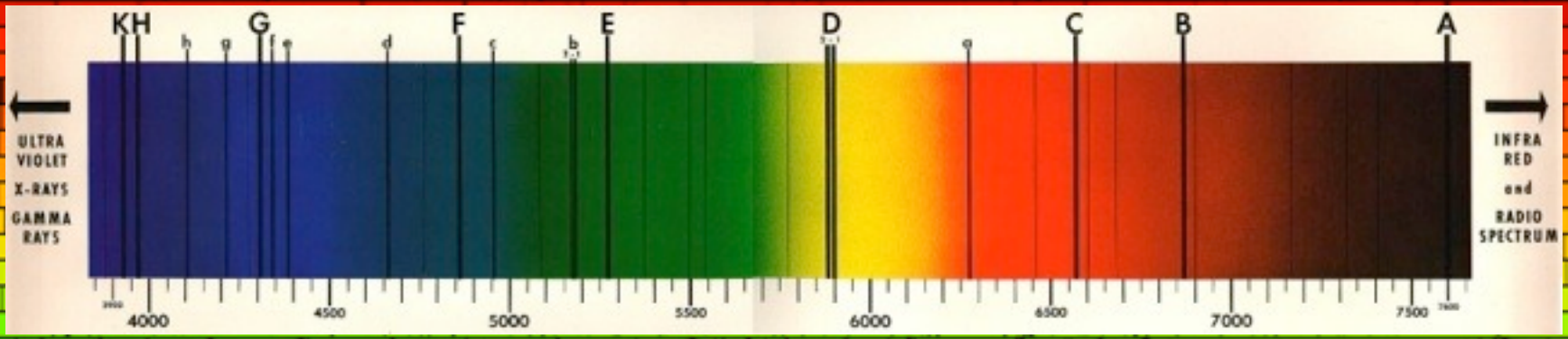
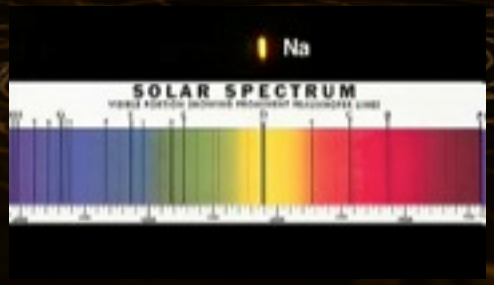


- Joseph von Fraunhofer (1821): 500 lines …
  - Is the Sun made of salt? [NaCl]
- The eclipse of 1868: Sun = Helios
- The birth of Spectroscopy
  - A rainbow bridge to touch the stars!
- 1895: star stuff on Earth



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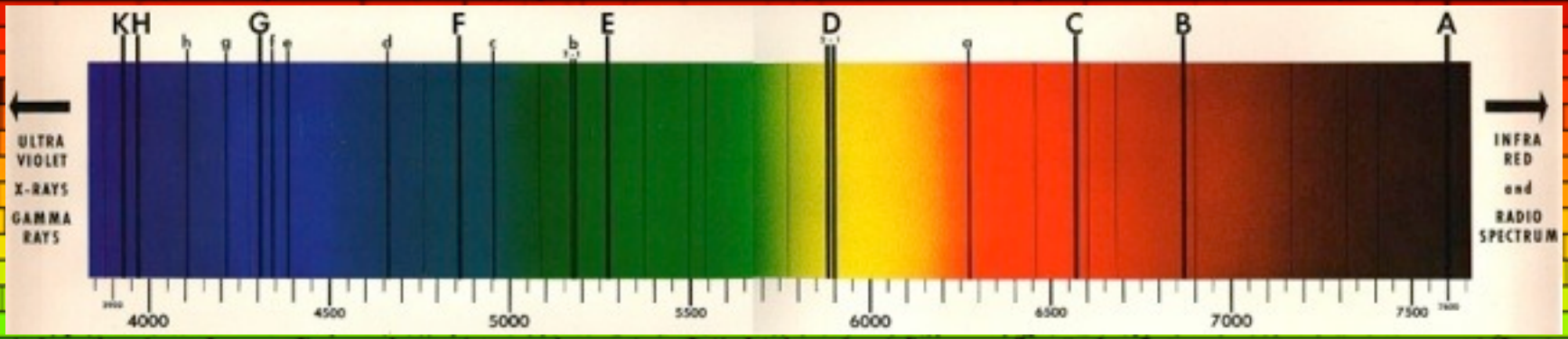

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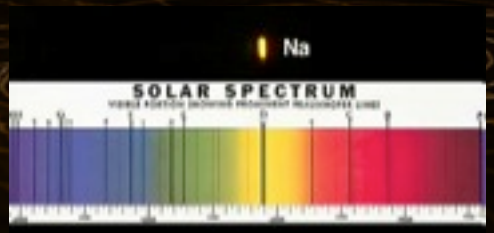

Next time you see one of those orange street lamps, think back to 1821

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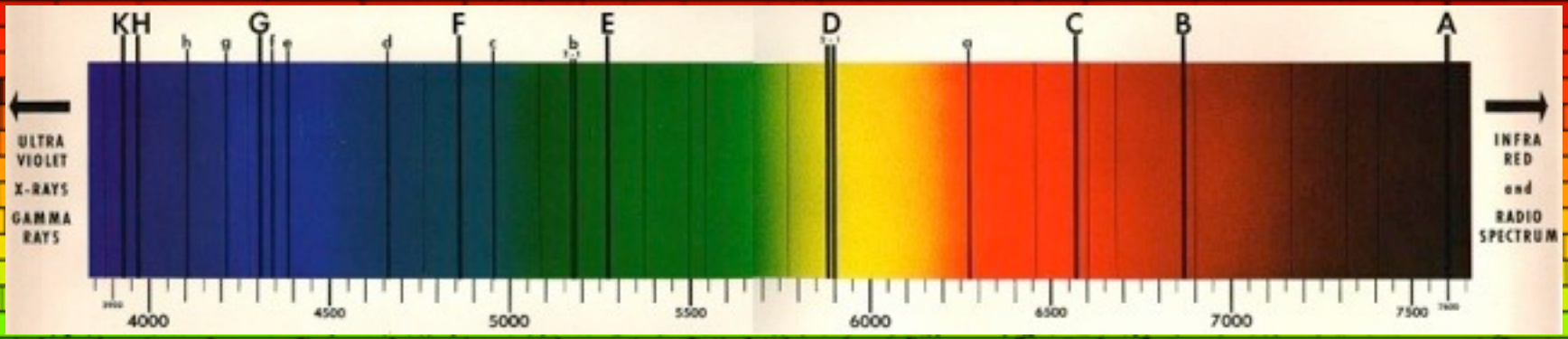

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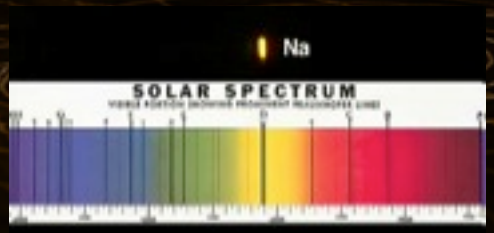

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1895: The X Rays

"The Academy awarded the Nobel Prize in Physics to Wilhelm Conrad Röntgen … for the discovery with which his name is linked for all time: the discovery of the so-called Röntgen rays or, as he himself called them, X-rays. These are, as we know, a new form of energy and have received the name "rays" on account of their property of propagating themselves in straight lines as light does. The actual constitution of this radiation of energy is still unknown."

Presentation speech, first Nobel prize, Stockholm, 1901

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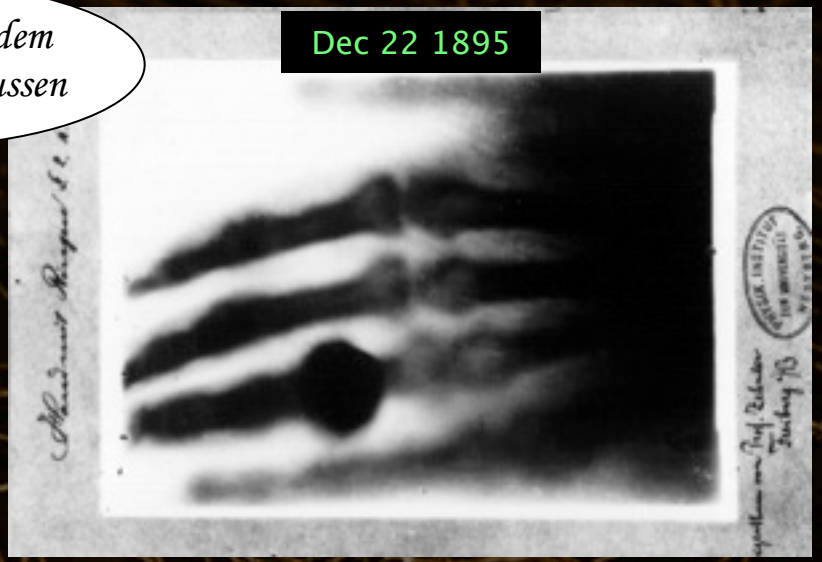

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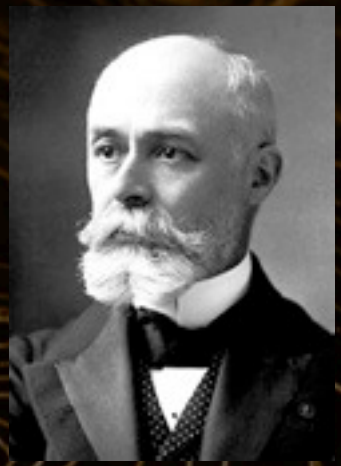
Radio Activity

- Becquerel's salts
  - Is there a relation between Röntgen's vacuum-tube induced phosphorescence and natural phosphorescence?



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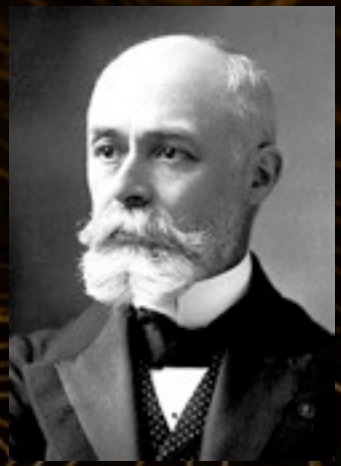

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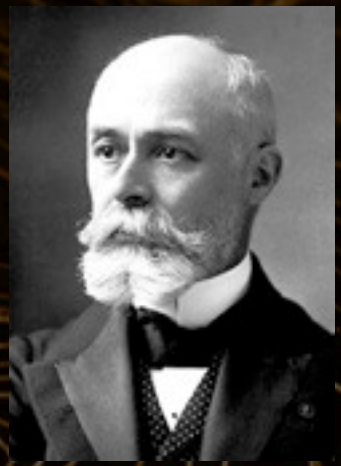

- Pierre and Marie: call it "radioactivity"
- Two hypotheses
  1. An unknown sort of radiation fills all of space. The radioactive elements are the ones that are able to transform this radiation to observable forms

Radio Activity

PS : Eve Curie's "Madame Curie" is a must read.

- 2. "This leads to the supposition that the transformation is more far-reaching than the ordinary chemical transformations, that the existence of the atom is even at stake, and that one is in the presence of a transformation of the elements."

Pierre Curie, Stockholm, 1905

- Helium production + existence of Radium → the alchemists were right!
- Radium becomes more expensive than gold and diamonds

The Radium Girls

- Radium is a million times more radio-active than Uranium
- 1917-1926: was used in a wide variety of applications,
  - e.g., luminous paint for military watches and instruments
  - Factory girls were encouraged to point the brushes with their lips
  - For fun, they painted their nails, teeth, and even their faces …

United States Radium Corporation factory, Orange, New Jersey, Ca. 1917

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- The body treats Radium like Calcium → stored in the bones
- The right of individual workers to sue for damages from corporations due to labor abuse was established as a result of the Radium Girls case.

The Fruit of Knowledge

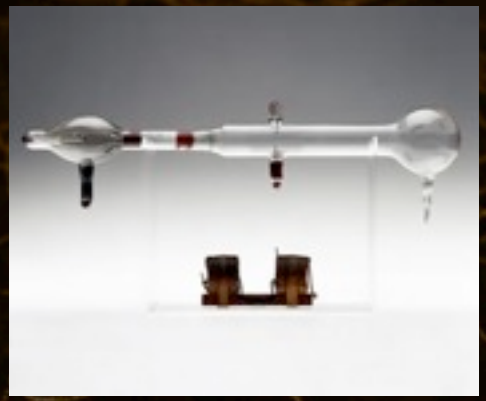
It can even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from knowing the secrets of Nature, whether it is ready to profit from it or whether this knowledge will not be harmful for it.

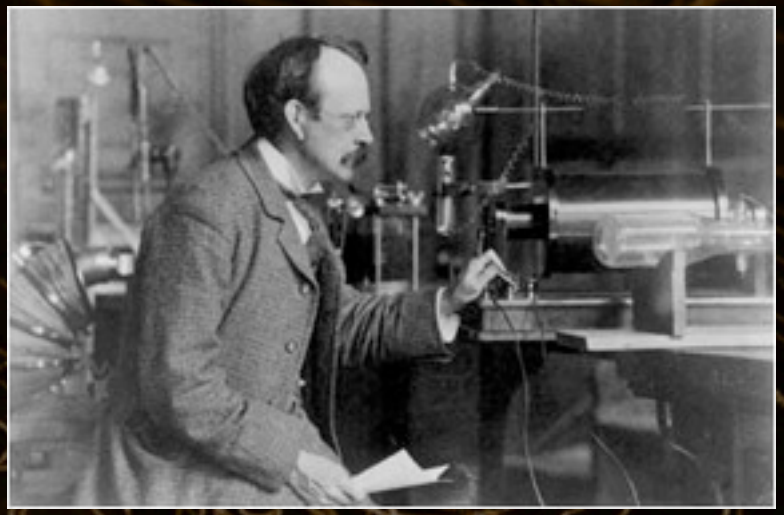
The example of the discoveries of Nobel is characteristic, as powerful explosives have enabled man to do wonderful work. They are also a terrible means of destruction in the hands of great criminals who are leading the peoples towards war.

I am one of those who believe with Nobel that mankind will derive more good than harm from the new discoveries.

Pierre Curie, Stockholm, 1905

Splitting the Atom





J.J. Thomson, 1897

"Thus the atom is not the ultimate limit to the subdivision of matter; we may go further … the corpuscles appear to form a part of all kinds of matter … it seems natural therefore to regard it as one of the bricks of which atoms are built up."

The Photon

- Einstein (1905): Light is quantized!
  - **Photo-Electric Effect:**

Shine light (X-rays) on atoms

→ Kick out electrons

  - → direct proof of the existence of "light quanta" = photons

Problems turned to proof:

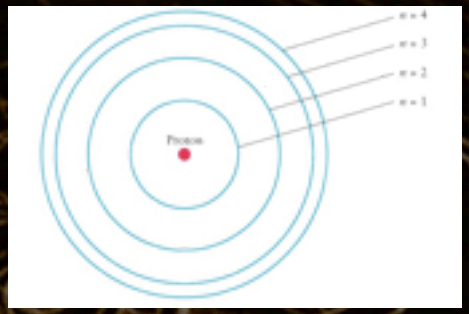
1. Variation of light intensity ➔ variation of electron numbers
2. Variation of light frequency ➔ variation of electron energy

Wollaston's explanation

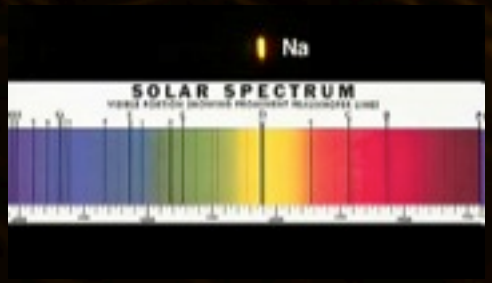
- Atom + quantum hypothesis → Niels Bohr (1913): "There exist fundamentally only separate stationary states in the atoms"

Planck's constant

- $E_2 - E_1 = h\,\nu = E_{photon}$



- Applied to kitchen salt and sunlight, Wollaston's rainbow, now 100 years old, was finally explained



- But what a strange explanation …

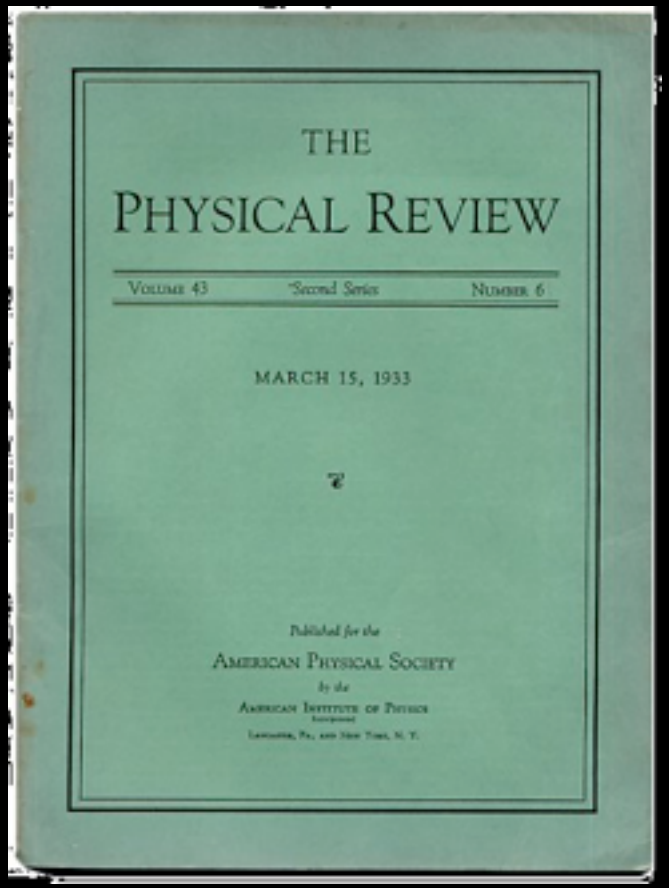
The Language of Atoms

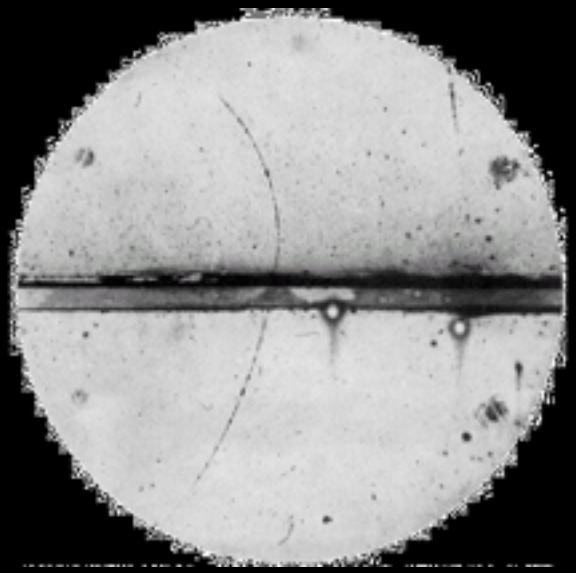
Niels Bohr (1885-1962)

- Correspondence
  - From quantum mechanics, the classical laws must be obtained in the limit of large quantum numbers or small h
- Complementarity
  - Mutually exclusive descriptions must be accepted. An experiment can show particle-like properties of matter, or wave-like ones, but not both at the same time.

Antimatter

- Dirac's relativistic wave equation with "spin" → E^2 = …





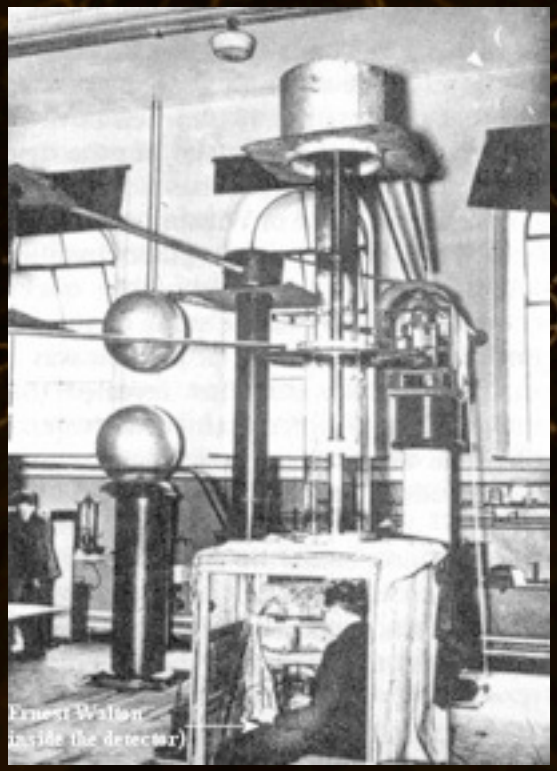
Carl Anderson (1905-1991)

"On August 2, 1932 … the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence […] of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron"

C. Anderson, "The positive electron", Phys. Rev. 43 (1933) p.491

The World Seen by Accelerators

- 1932: Cockroft & Walton built a system that could fire protons, like bullets, into metal targets: p + LiF → Be, He, O, …



Cavendish laboratory, ca. 1932

(1951): "Transmutation of atomic nuclei by artificially accelerated atomic particles"

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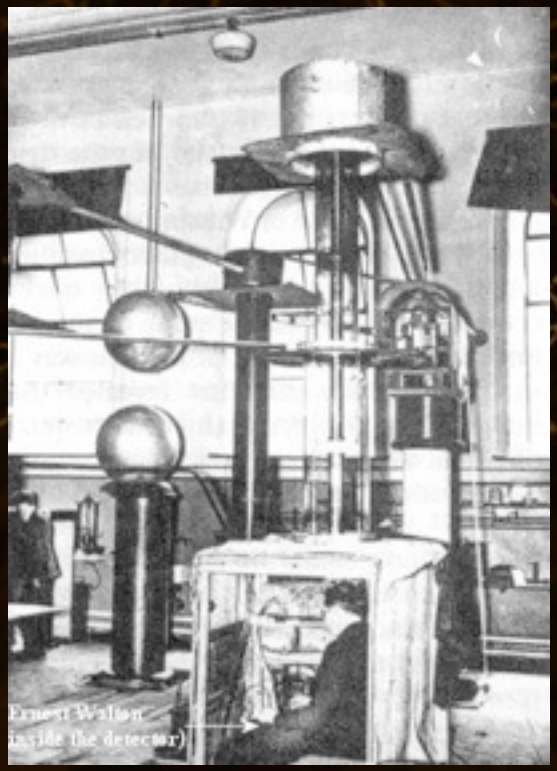

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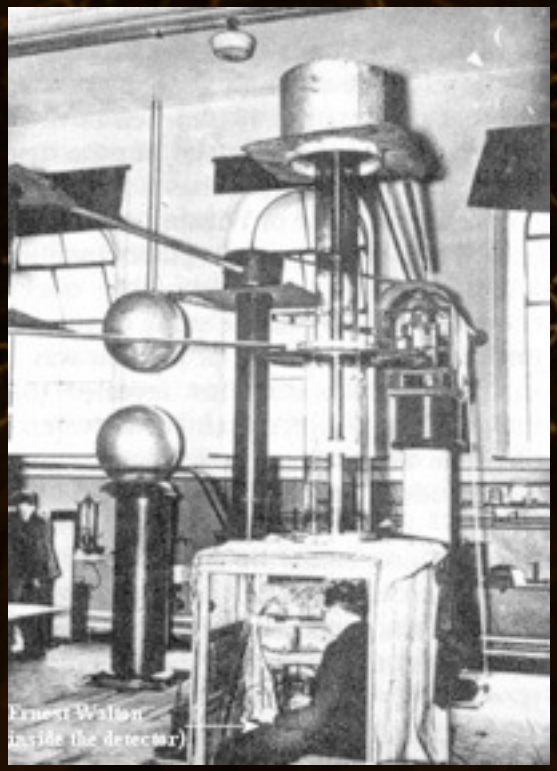

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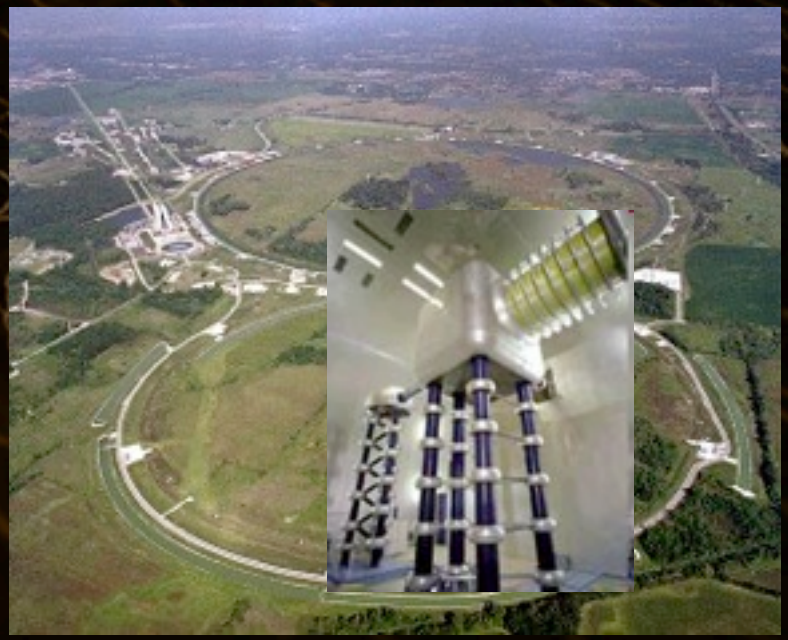

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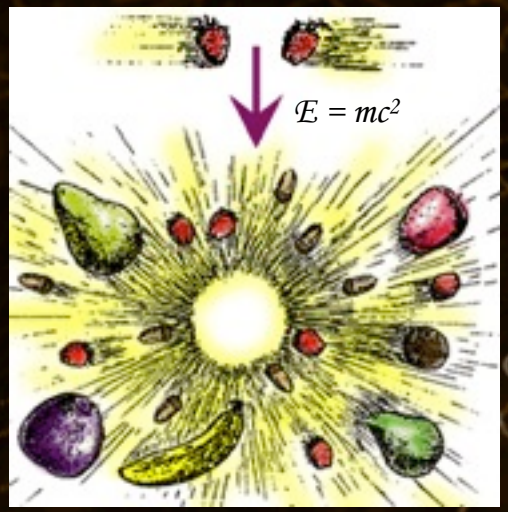
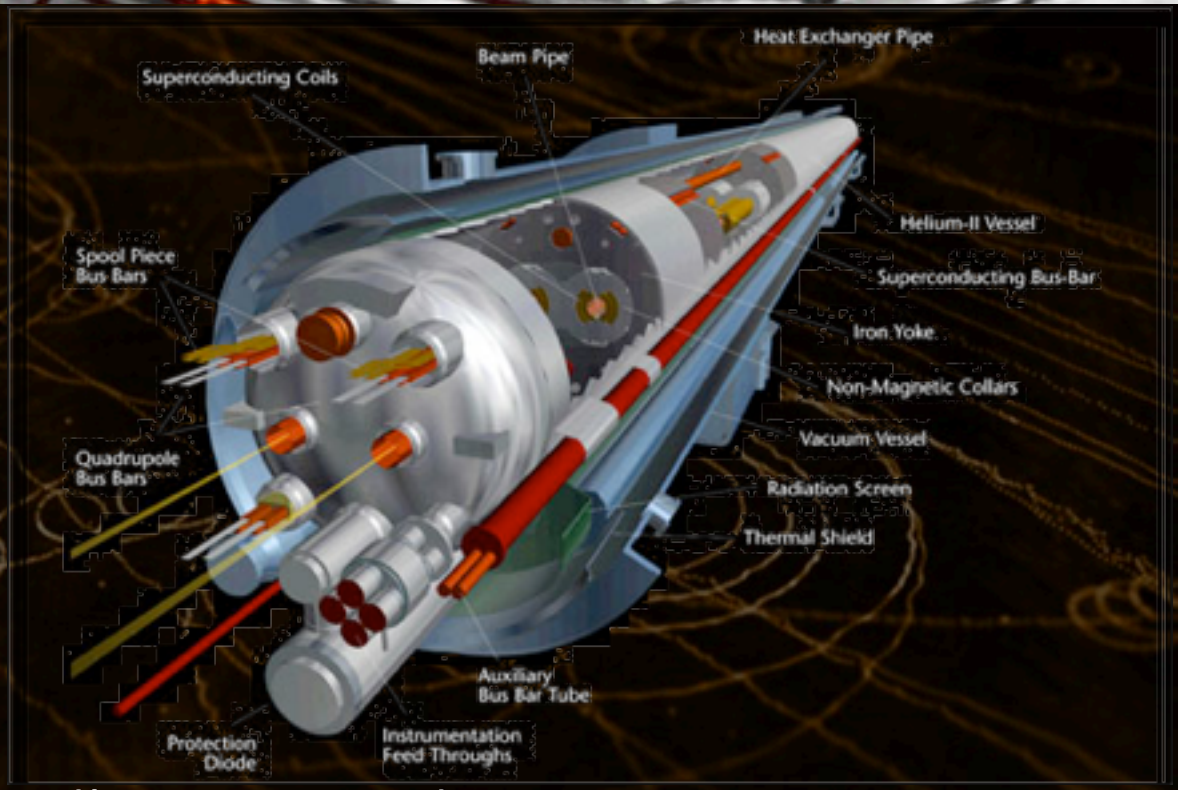
Particle Accelerators

- The goal:





- Accelerators are 'optical' systems, with
  - Light → charged particles
  - Wave length shortening → particle acceleration
  - Lenses → magnets

So what is "High" Energy ?

- Relative to combustion of 1 kg of octane molecules (gasoline) :
  - 100m **Waterfall** : 0.000 025
  - **Burning** wood : 0.3
  - **Burning** sugar (metabolism) : 0.5
  - **Burning** ethanol or coal : 0.75
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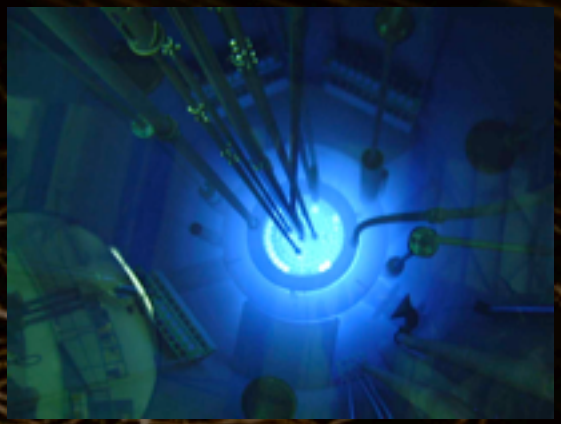

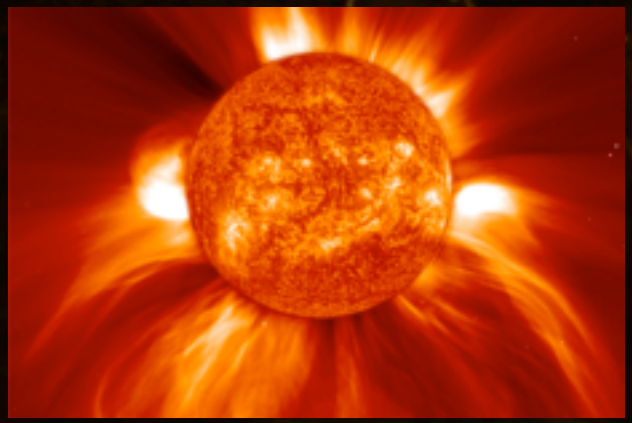

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  - **Tevatron** collisions : 2 000 000 000 000
  - **LHC** collisions: 8 000 000 000 000

- Still, Dan Brown exaggerated a bit in "Angels & Demons" …
  - "If all of the antimatter ever produced at Fermilab had been collected, we would have a couple of nanogrammes …"

Dave Vandermeulen, antimatter expert, Fermilab

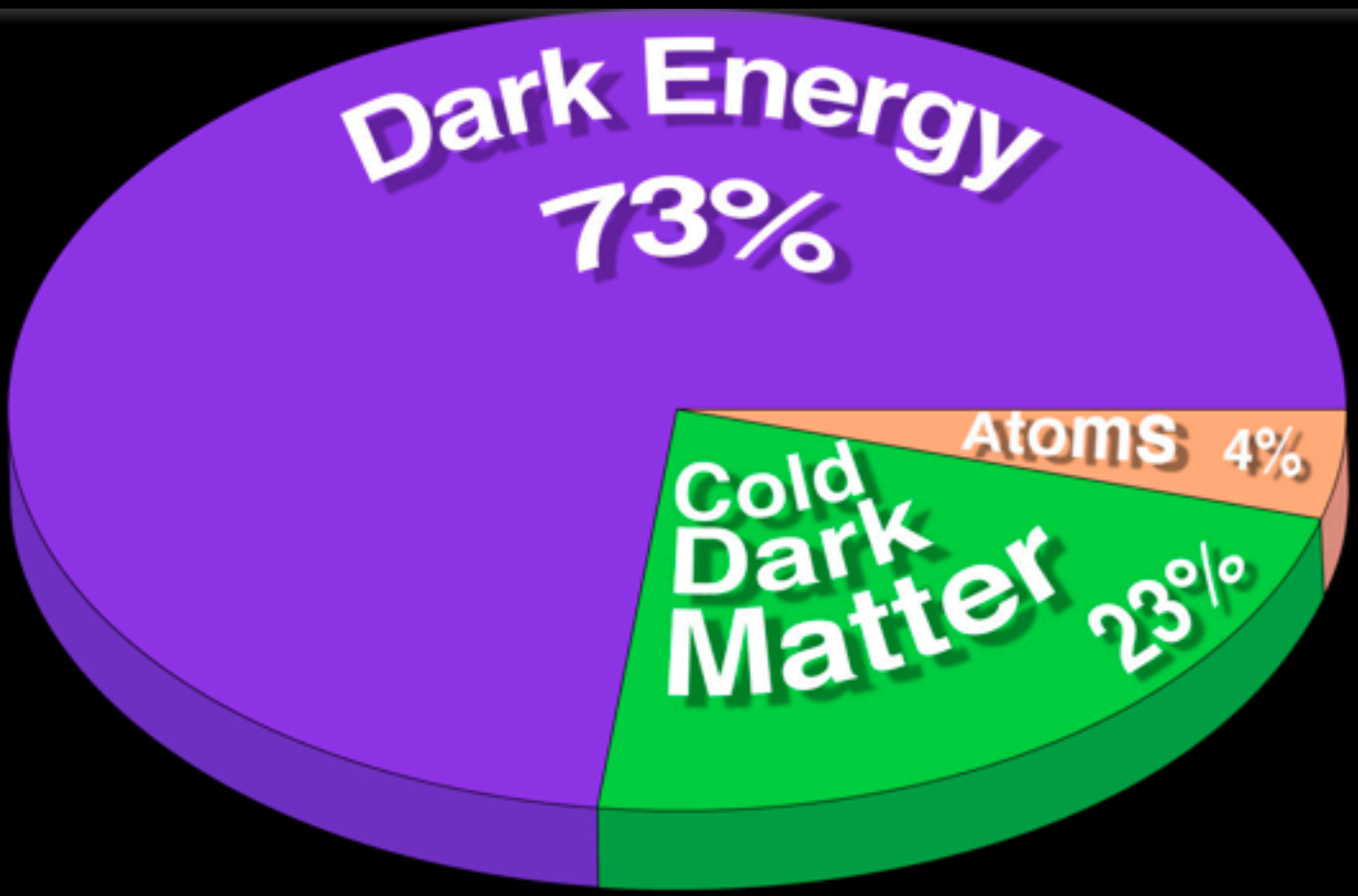
What is "Mass"?

- Consider an ether 'field' distributed evenly across the Universe, of uniform strength
- Suppose that different particles experience this field as being more or less transparent, i.e. that different particles couple to it with different strength
  - To a photon, it's completely "translucent"
  - But an electron (or a proton), will interact with it
- Suppose that the nature of the interaction is such that the ether 'condenses' around particles which couple to it, causing an increased energy density around the particle
- We call this field the "H" (or Higgs) Field

The Higgs Particle

- If correct, the Higgs mechanism makes one spectacular prediction: it should be possible to excite a wave in the Higgs field itself, an ether wave
- This wave would quickly dissolve (decay) into massive particles, but should be detectable via its decay products
- Made out of pure 'Higgs' ether, in particle form this wave is known as the 'Higgs particle' or 'Higgs boson'
- The discovery of a particle consistent with these properties was announced at CERN on July 4, 2012
- The coming months (and years) will see a huge activity trying to determine all the (quantum) properties of this new "H" particle

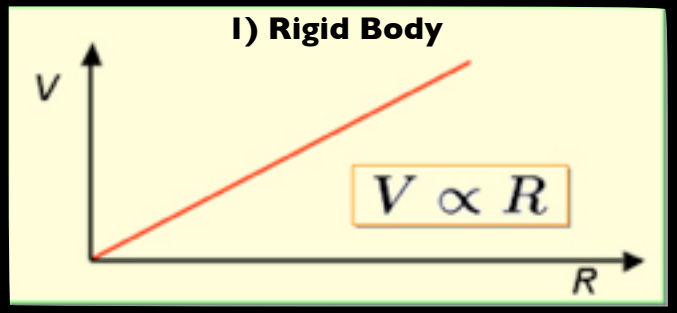
The Dark Side of the Universe

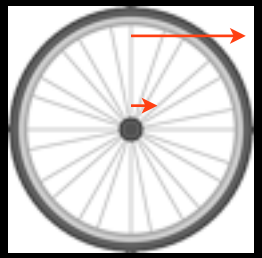


What is "Dark Matter" ?

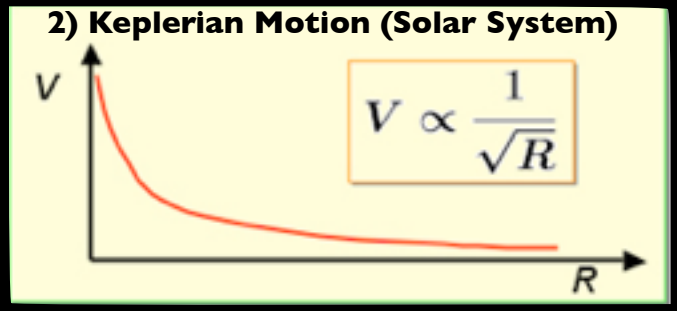
Rotation Curves

1) Rigid Body



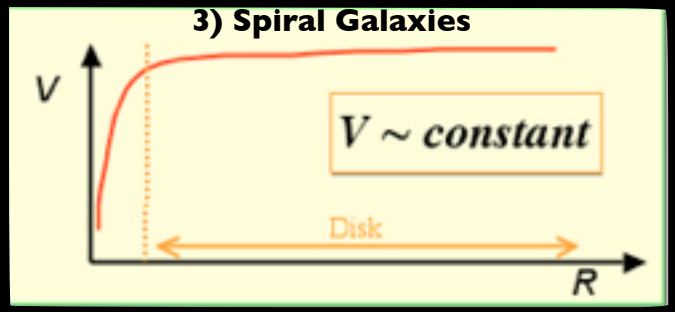


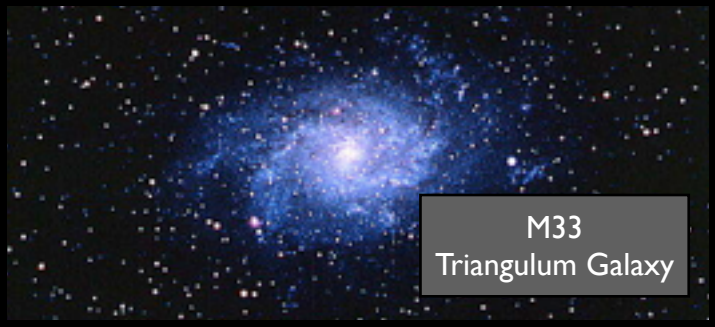
2) Keplerian Motion (Solar System)



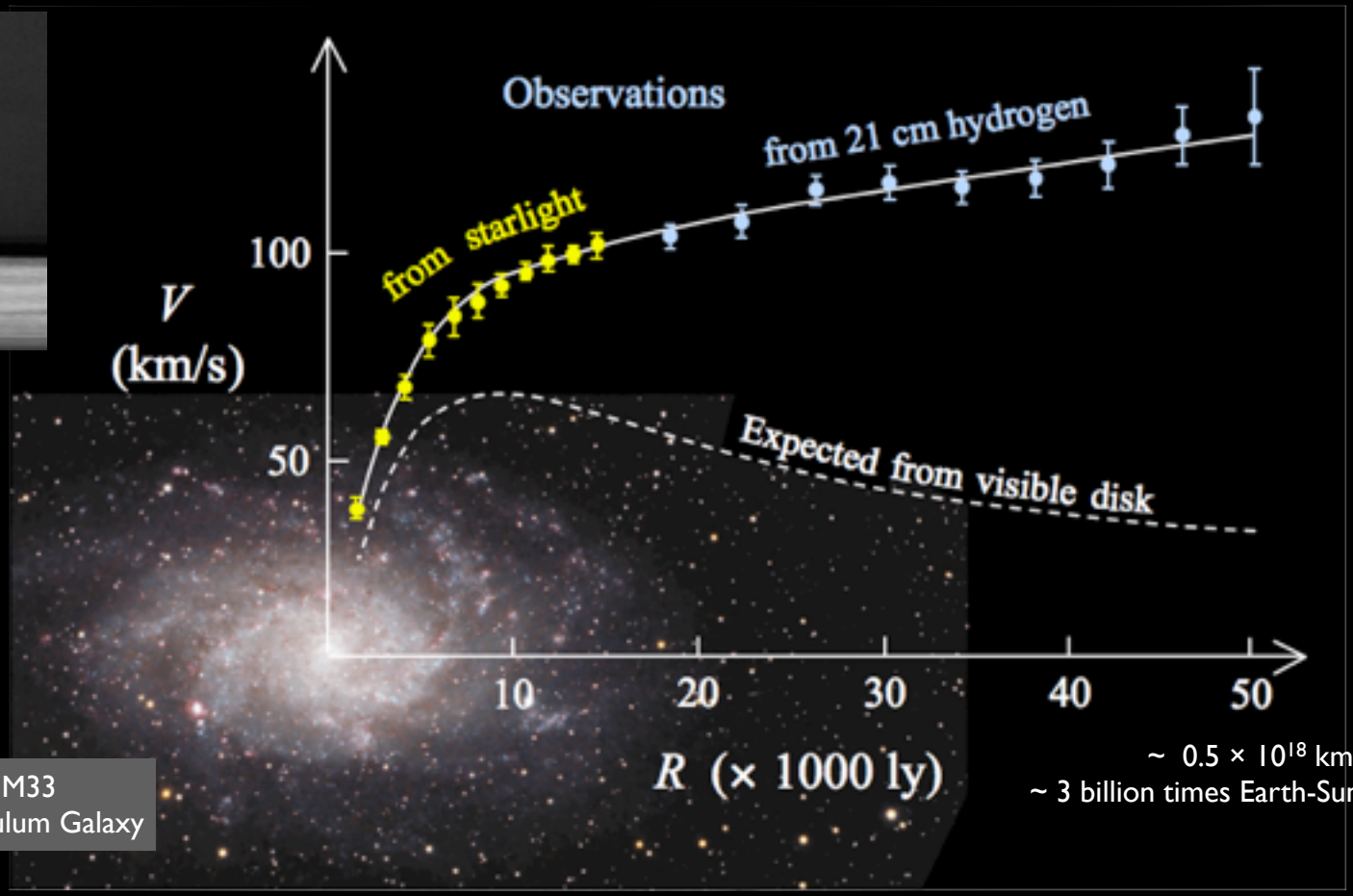
Mercury: 48 km/s Earth: 30 km/s Neptune: 5 km/s

3) Spiral Galaxies





Rotation Curves of Galaxies
(and of Galaxy Clusters)



M33
Triangulum Galaxy

~ 0.5×10^{18} km
~ 3 billion times Earth-Sun distance

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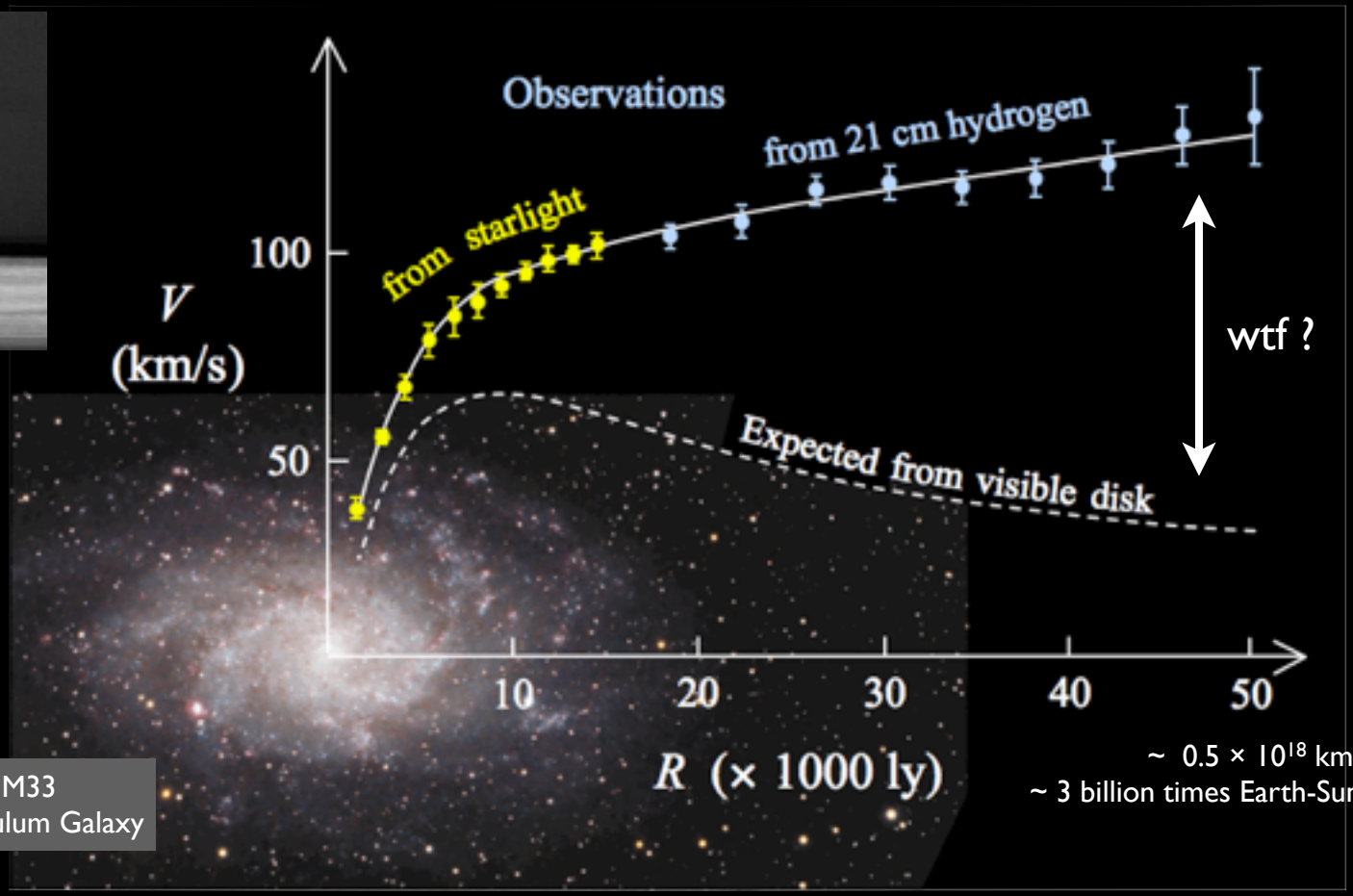

Something unknown is making galaxies spin like crazy

When Galaxies Collide

- August 2006: Clowe et al.: "A direct empirical proof of the existence of dark matter"

Astrophysical Journal 648 L109-L113 (2006)

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But we still don't know what "it" is
Maybe we can make it in the LHC?

Astrophysical Journal 648 L109-L113 (2006)

LHC : The Undiscovered Country

- **Open-minded "model building":**

Matter

There could be new fundamental matter

"Fundamental" matter might be composite

Force

There could be new fundamental forces

Known forces might not be fundamental

Spacetime

What is gravity, at the fundamental level?

There could be new laws of space and time

Known laws might break down

There could be extra dimensions

P. Hein,

Poet and friend of Niels Bohr

We glibly talk
of nature's laws
But do things have
a natural cause?

Black earth turned into
yellow crocus
Is undiluted
hocus-pocus