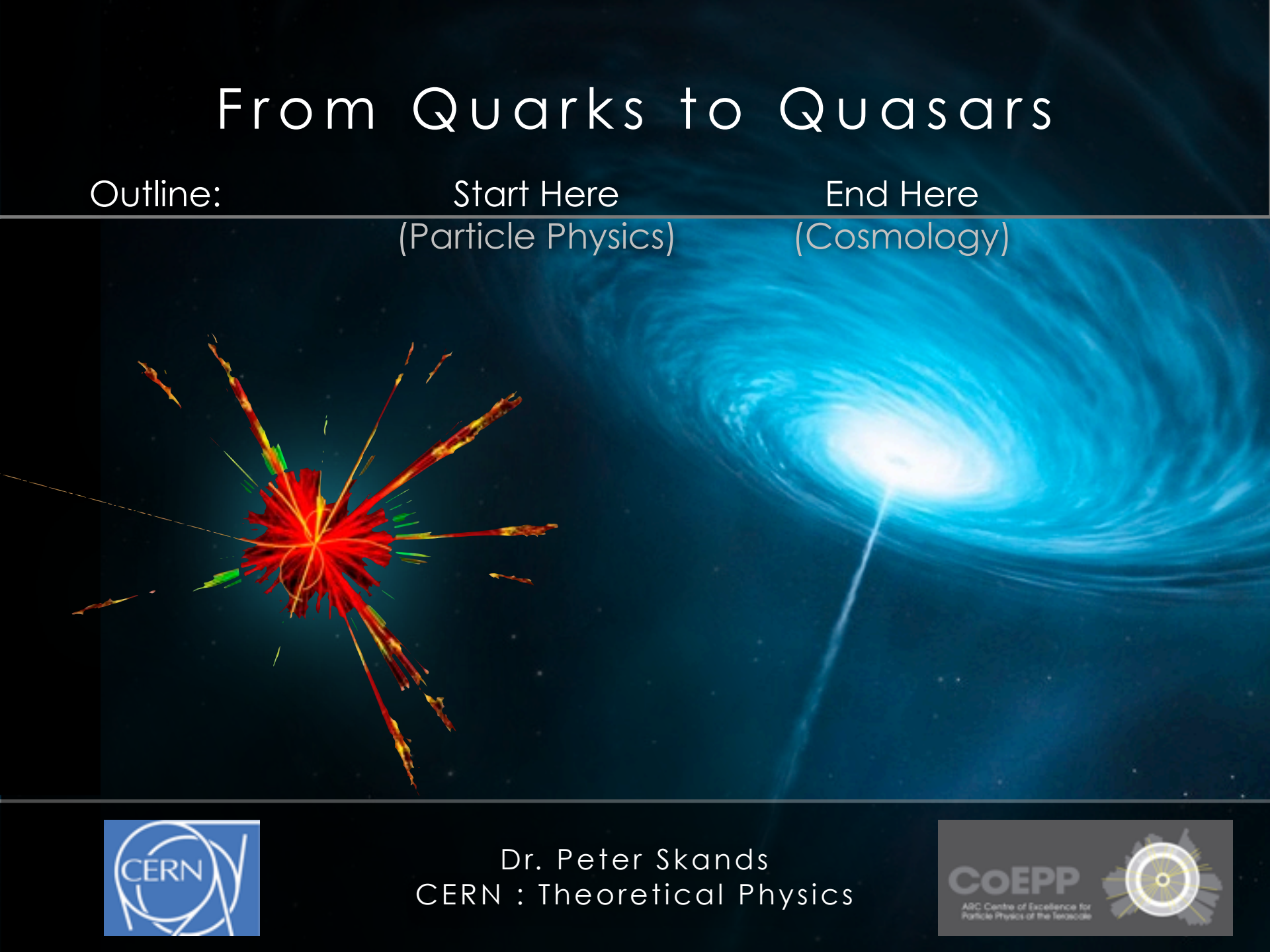
From Quarks to Quasars

Outline: Start Here (Particle Physics) End Here (Cosmology)

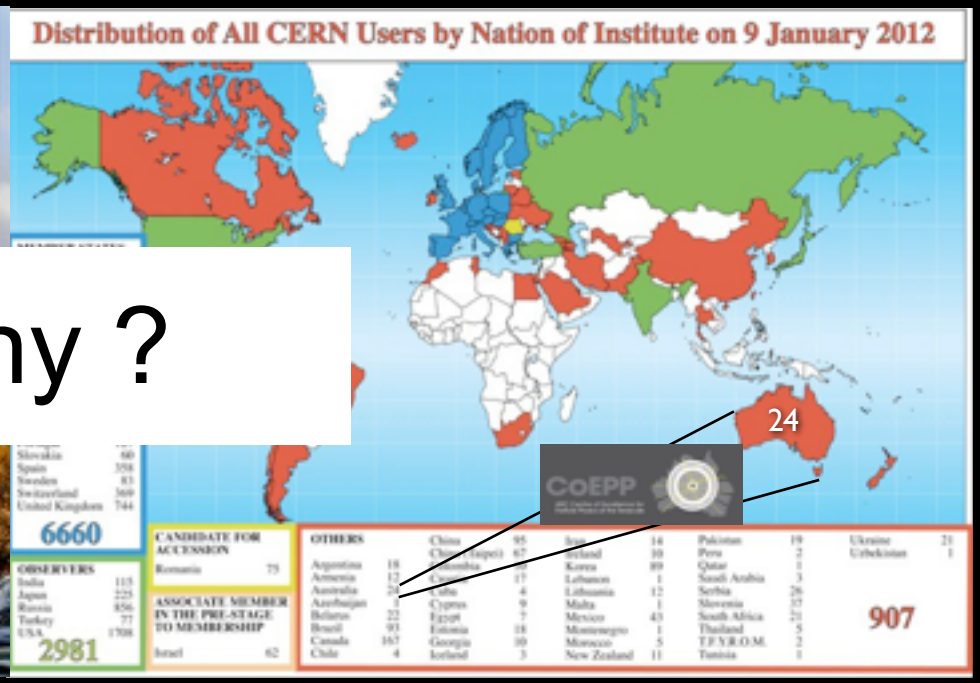


Dr. Peter Skands
CERN : Theoretical Physics

CERN : European Organization for Nuclear Research

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

Flags of CERN's Member States



Why ?

20 European Member States and around 60 other
countries collaborate in our scientific projects.
Yearly budget ~ 1 billion CHF ~ 1 billion A$

the building blocks of Life

The Carbon in our bodies

The Nitrogen

... were made in stars ...

The Oxygen that we breathe

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

the Tools of the trade

1. Accelerators : powerful machines to accelerate 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.

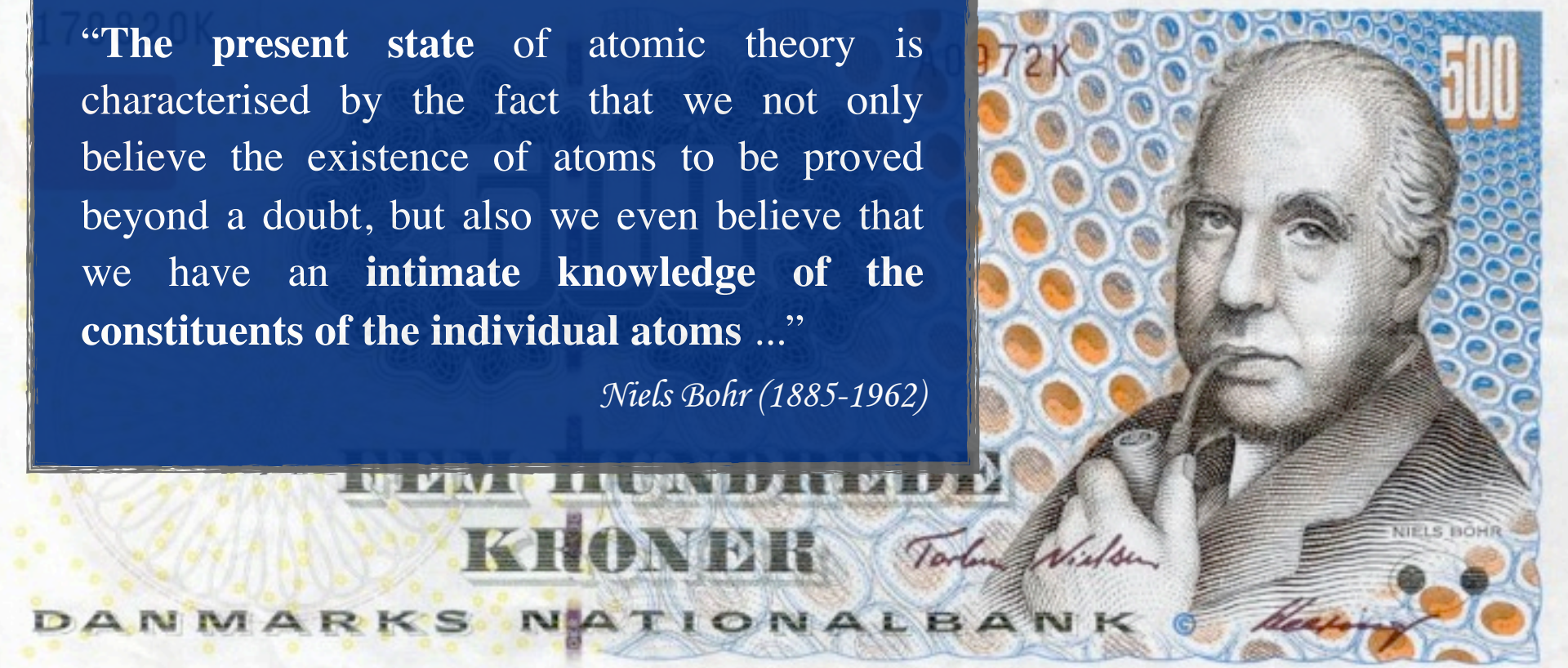
3. Computers : collecting, stocking, distributing and analyzing the enormous amounts of data produced by the detectors.

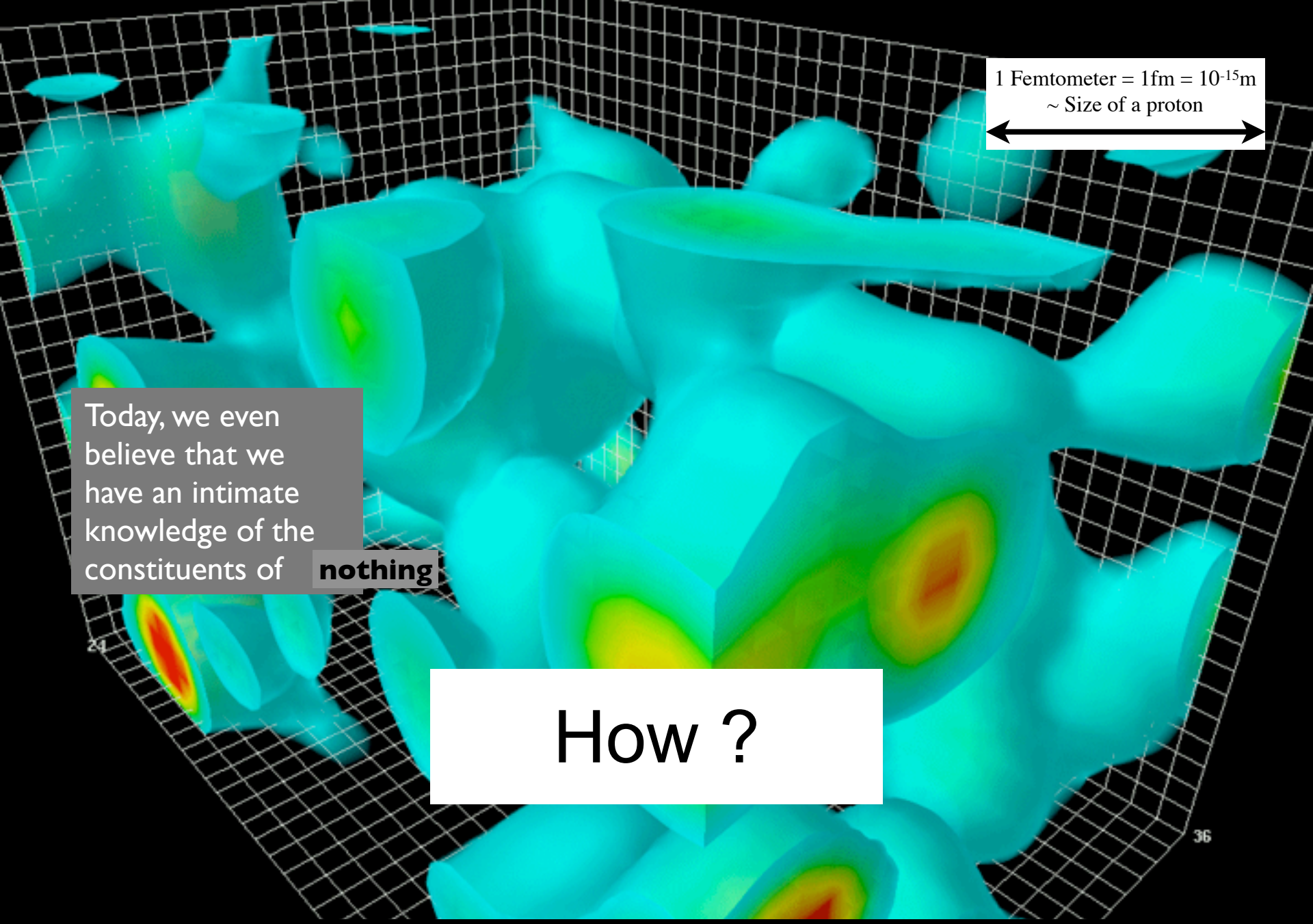
+ Theory

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)

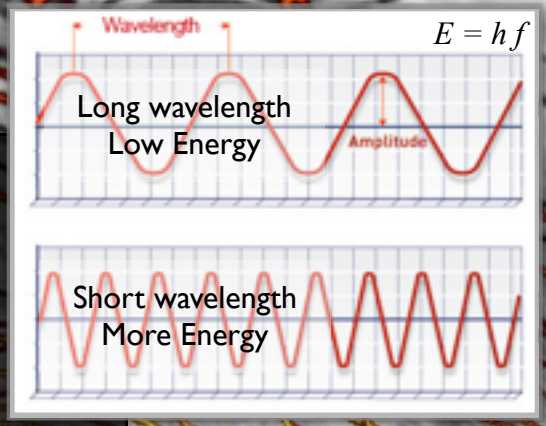




http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel

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

High Energy Physics



The true nature of the **strong nuclear force** is revealed at distances below about 10^{-15}m (= 10^{-6} nm)

To "see" something that small: need high energies (wavelength inversely proportional to energy): kick an electron with 1 billion Volts = 1 Giga-electron-Volt (GeV)

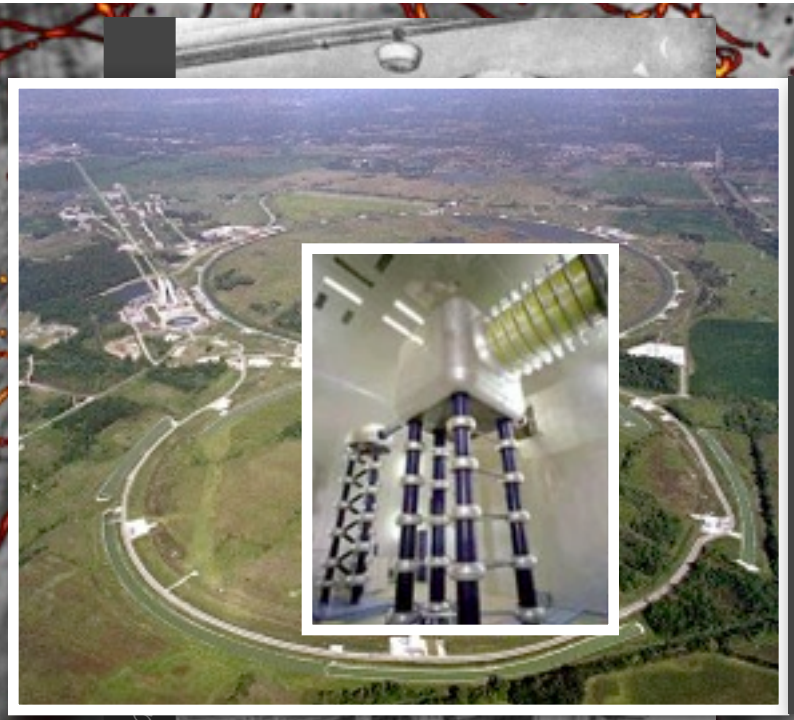
The energy of the Large Hadron Collider at CERN : 8 TeV

← "the Terascale" !

In computer simulations, we try to recreate the collisions happening in the LHC in as much detail as mother nature. The clarity of our vision of the **Terascale** depends on their accuracy. *You can help → LHC@home 2.0*

the real Accelerators

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



Fermi Laboratory, Chicago, USA, ca. 2000

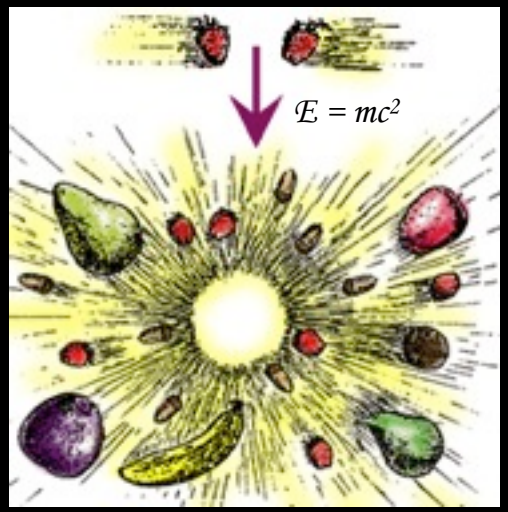
Modern van-de-Graaf

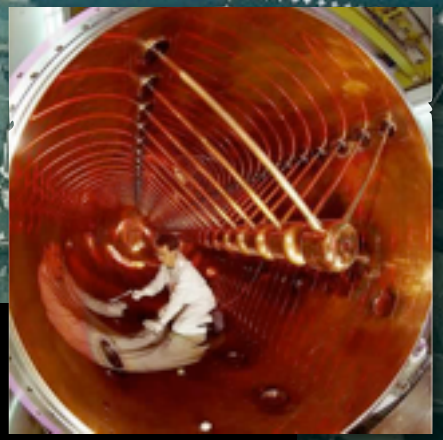
Early van-de-Graaf, ca 1937

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

Particle Accelerators

- The goal:





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

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
  - **Burning** Beryllium : 1.5

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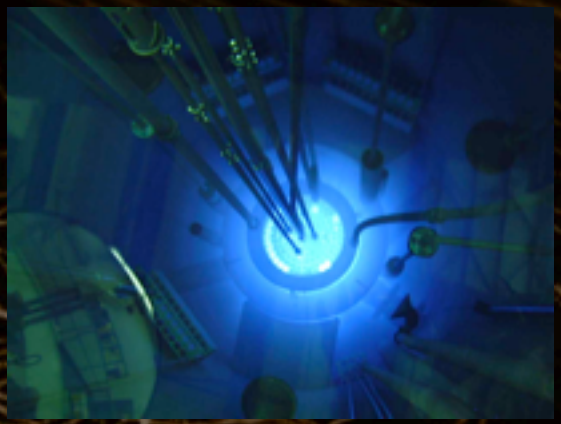
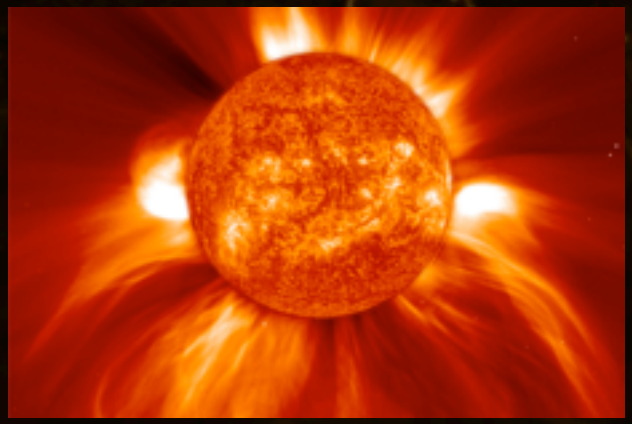
  - Uranium-235 **Fission** : 2 000 000
  - Deuterium-Tritium **Fusion** : 10 000 000





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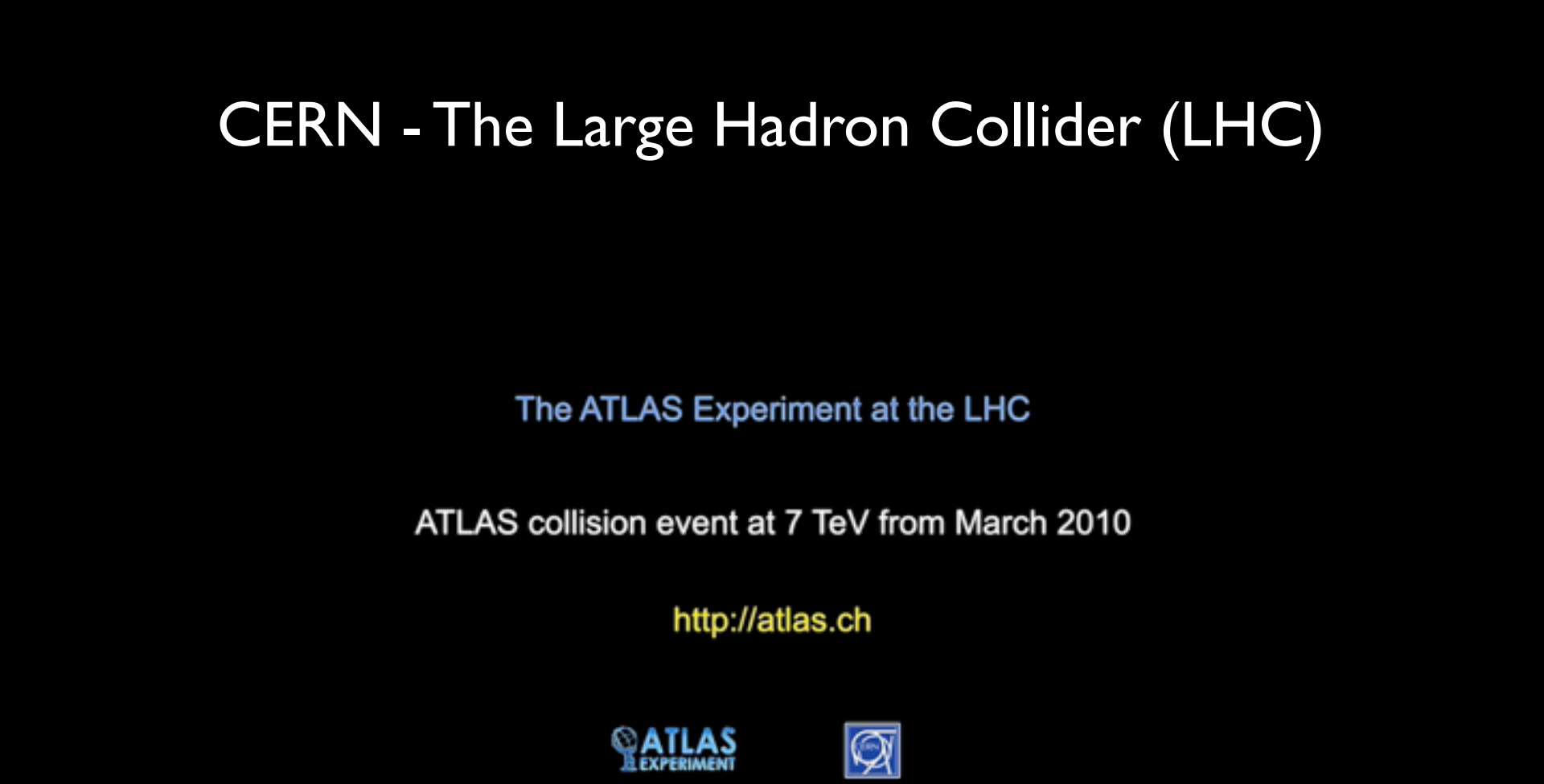
  - **Tevatron** collisions : 2 000 000 000 000
  - **LHC** collisions: 8 000 000 000 000

- 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 …"

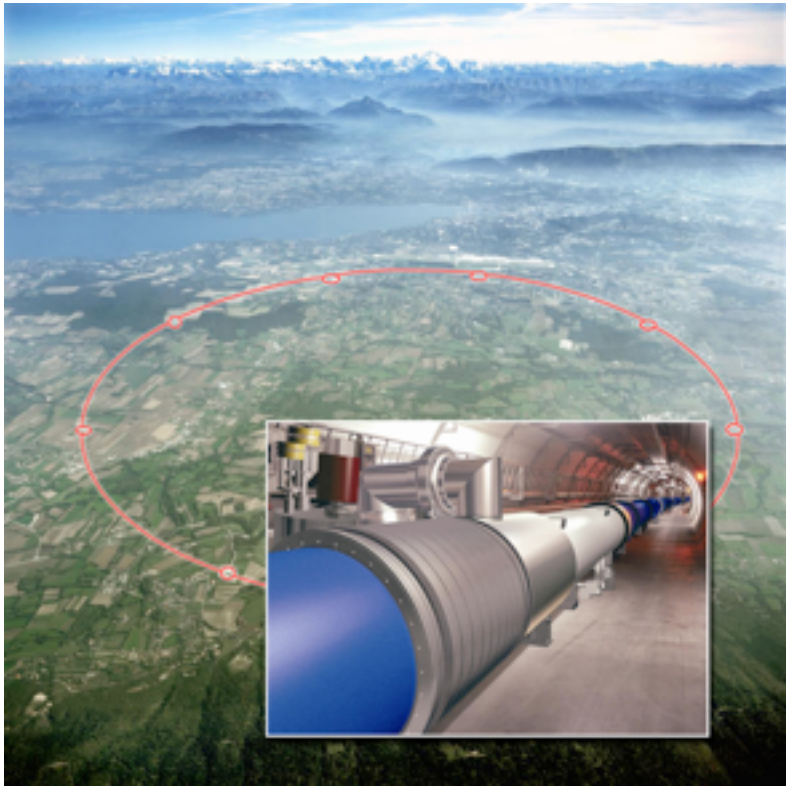
Dave Vandermeulen, antimatter expert, Fermilab

CERN - The Large Hadron Collider (LHC)



LHC Collision at 7 TeV
ATLAS, March 2010

One of the fastest racetracks on the planet



LHC Beam Energy:

$E = 3500\ \text{GeV} = 5.6\times10^{-7}\ \text{J}$

Proton Mass:

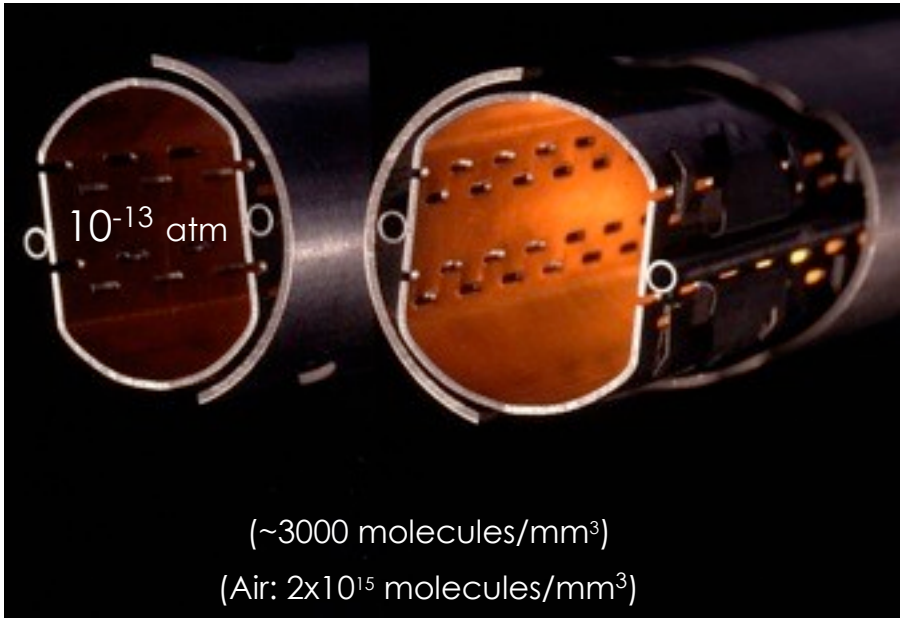
$m = 1.7\times10^{-27}\ \text{kg}$

$\gamma = E/(mc^2) \sim 3600$

$\beta = v/c \sim 0.9999999$

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)

→ Fundamental Science

July 4th 2012:

"Higgs-like" particle seen at CERN

(+ over 500 other published physics papers from LHC so far)

What is "Mass"?

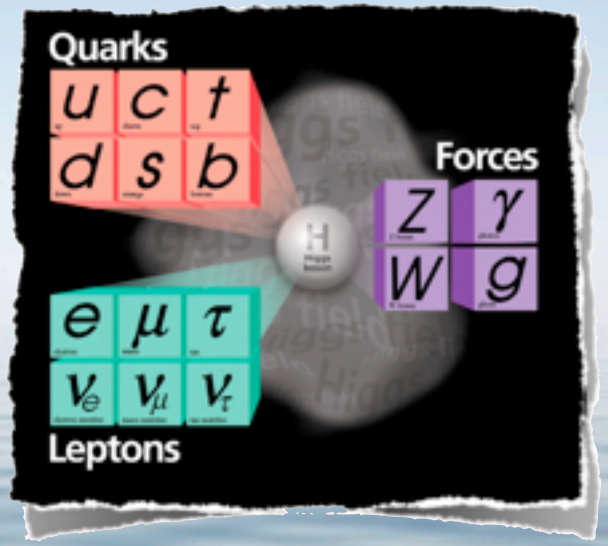
- Consider a 'field' distributed evenly across the Universe, of uniform strength
- Suppose that different particles experience this 'field' as being more or less transparent
  - To a photon (light), the field is completely "translucent"
  - But an electron (or a proton), will interact with it
- Suppose that this field condenses around the particles which couple to it, causing an increased energy density around those particles. Looks like mass ($E=mc^2$).
- We call this field the "H" (or Higgs) Field
- If correct, it should be possible to create waves in the Higgs field itself (though that may require a lot of energy)

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
- Made out of **pure 'Higgs' stuff**, in particle form this wave is known as the 'Higgs particle' or 'Higgs boson'
- This particle would quickly dissolve (decay) into other particles, but should be **detectable** via its decay products
- The **discovery** of a particle consistent with these properties was announced at CERN on July 4, 2012
- The coming years will see a huge activity trying to determine all the **quantum properties** of this new "H particle"

the Last Piece of the puzzle?

Atoms
Neutrinos
Exotic matter
Antimatter



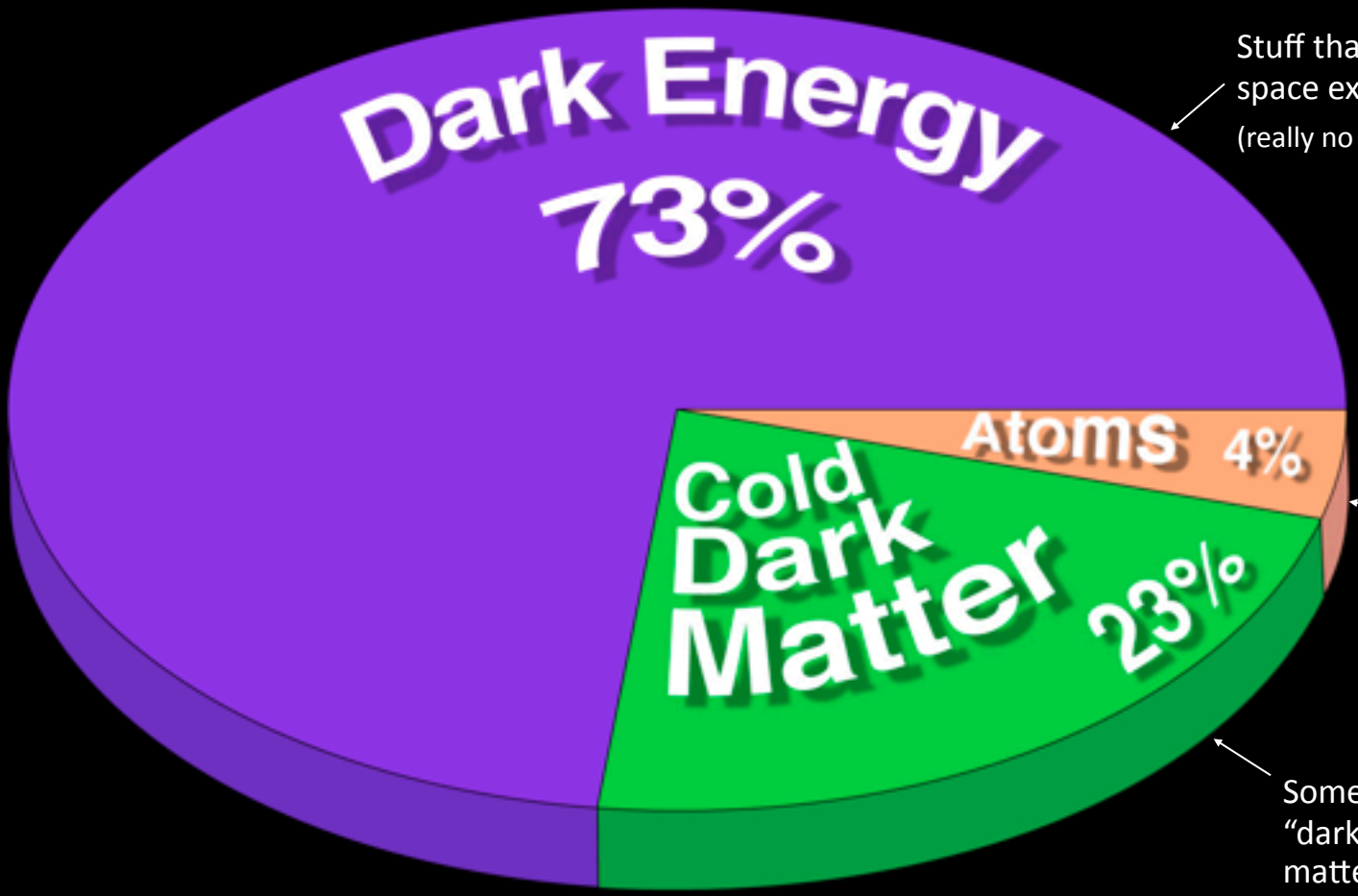
Electromagnetism
The nuclear forces
+ Gravity (Einstein)

+ Mass

Or is there something beyond?

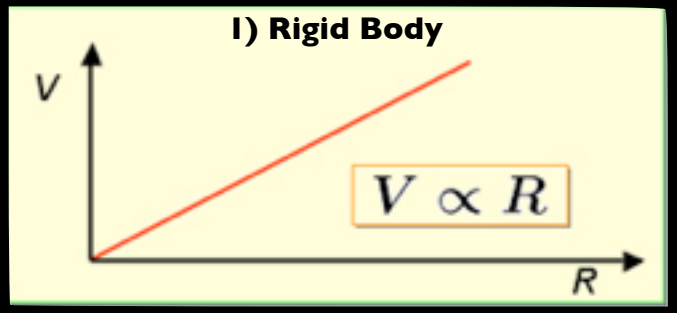
Like: Quantum Gravity? Higgs Origins? Grand Unification? Extra Dimensions? …

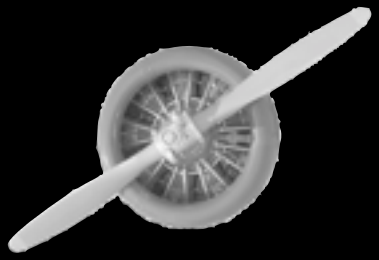
The Dark side of the Universe

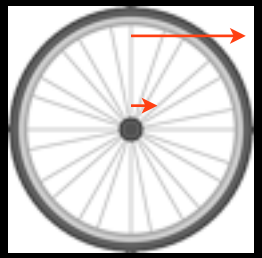


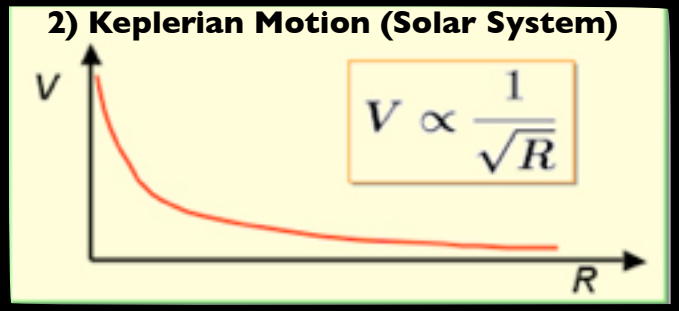
Dark Matter: 23%

Rotation Curves

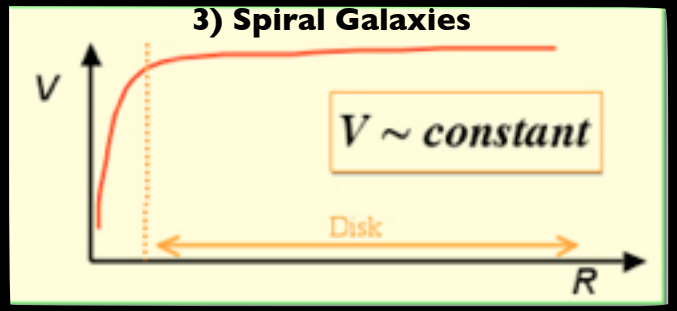


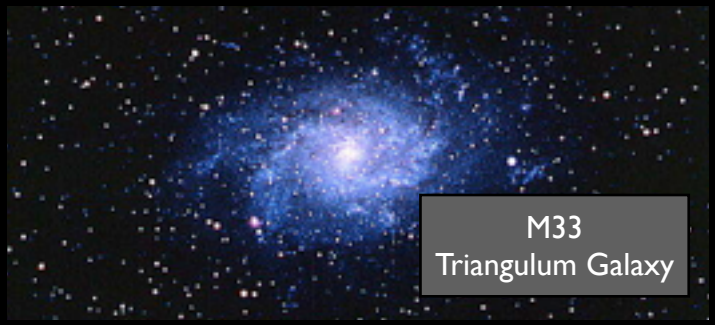




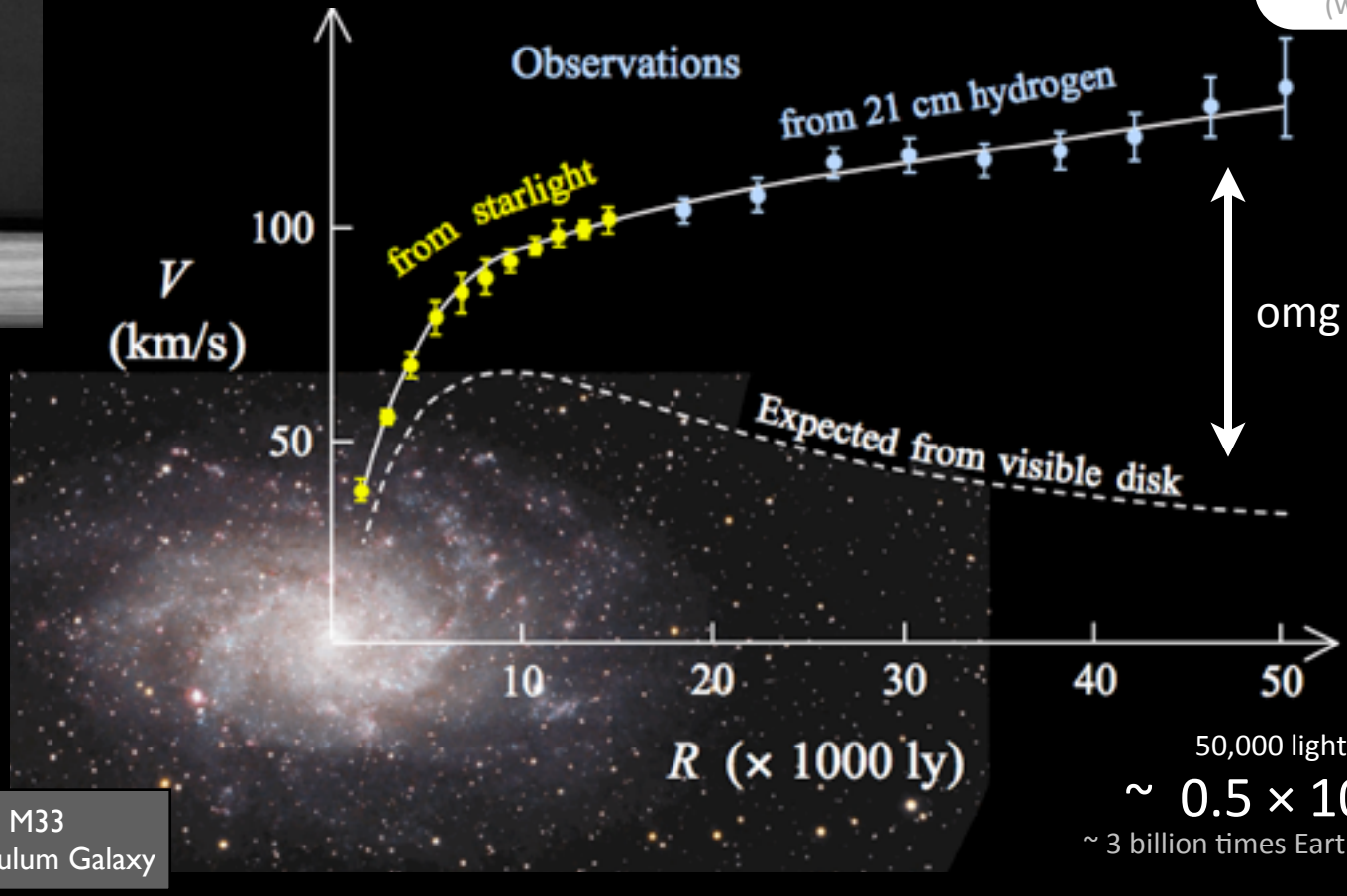


Mercury: 48 km/s Earth: 30 km/s Neptune: 5 km/s

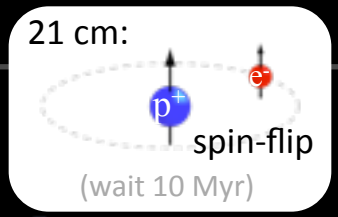




Rotation Curves of Galaxies
(and of Galaxy Clusters)



M33
Triangulum Galaxy



50,000 light years

~ 0.5×10^{18} km

~ 3 billion times Earth-Sun distance

Something unknown is making galaxies spin like crazy

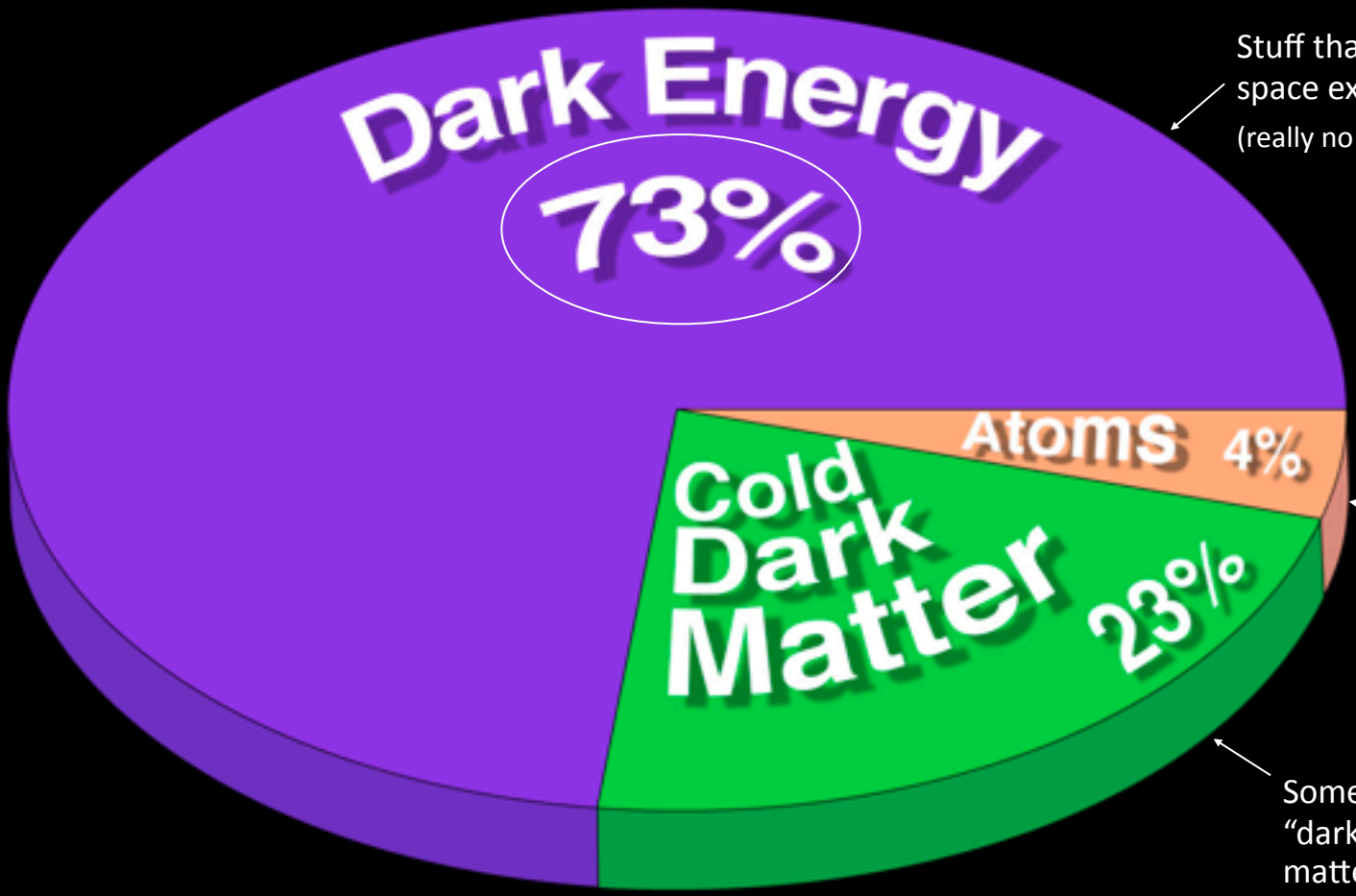
When Galaxies Collide

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

But we still don't know what "it" is
Maybe we can make it in the LHC ?
Or "see" it in space or on Earth?
Stay tuned…

Astrophysical Journal 648 L109-L113 (2006)

The Dark side of the Universe: 2

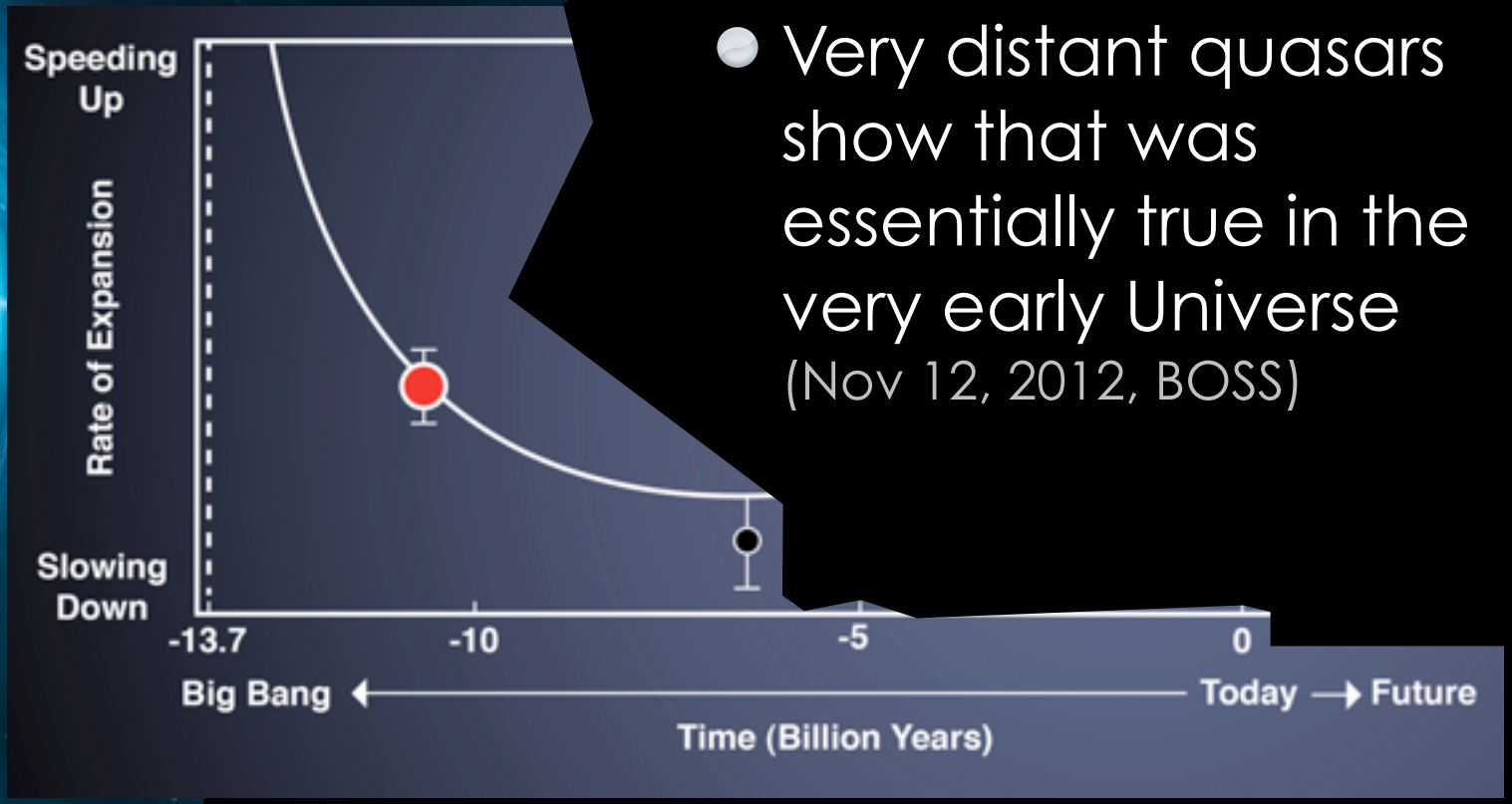


Quasars

- Extremely far away → appear point-like ("Quasi-Stellar" → Quasar)
- The most luminous objects in the Universe → we can see them even when they're very, very far away (~ 10 billion light years) …
- … when the Universe was younger

Quasars

- Gravity slows down expansion of Universe
- Very distant quasars show that was essentially true in the very early Universe (Nov 12, 2012, BOSS)



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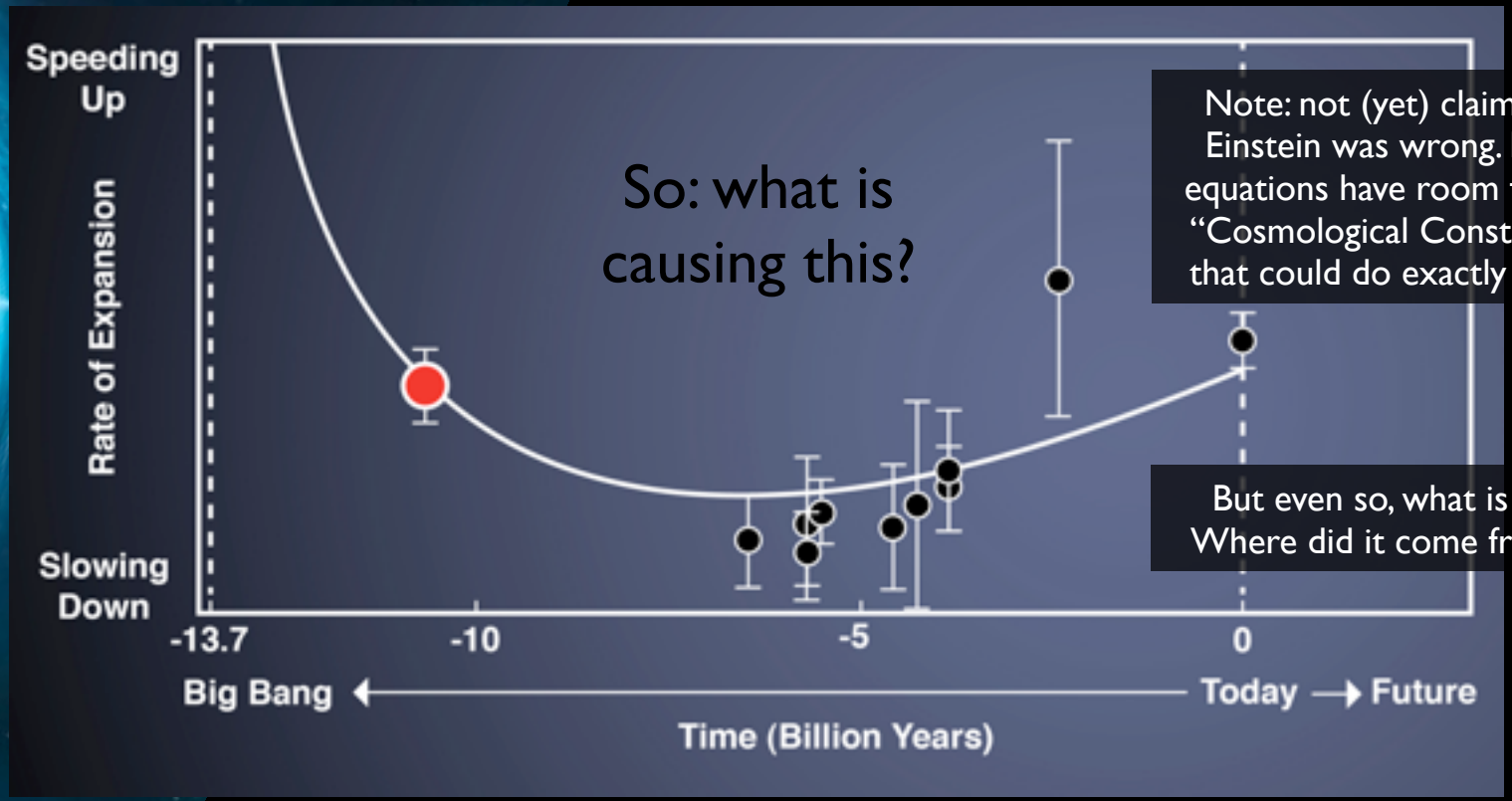


Questions (for you?)

- What are Dark Matter and Dark Energy? Are they new "stuff" that obeys known laws, or are they new laws unto themselves? Or both?
- How well can ***you*** solve Quantum Field Theory? Without assuming things that aren't true? At infinite orders? At strong coupling?
- Is 4 dimensions all there is? If more, how do they look? Is holography relevant?
- Where did the Higgs potential come from? How is it stable? What determines how particles couple to it?
- Why does normal matter have heavier 'exotic' cousins? I.e., the other quarks and leptons. Do they play a role in some grander pattern?
- Why are there 4 fundamental forces? Are there more? Or are they really one?
- Why is there a bit more matter than antimatter around? (e.g., us)
- Also, what *is* quantum gravity?
- Ideas are not enough. ***How to test! How to calculate!***

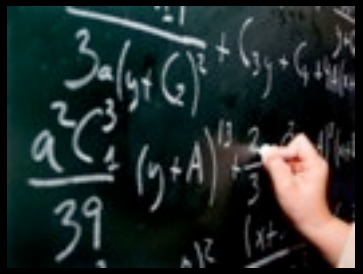
LHC@home 2.0

Test4Theory - A Virtual Atom Smasher

http://lhcathome2.cern.ch/

Over 500 billion simulated collision events

Nutshell



Theory

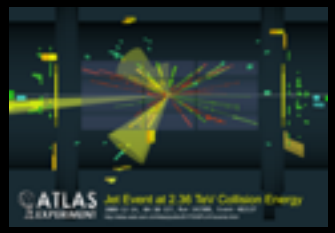
Experiment

Adjust this to agree with this

→ Science

In Practice

. . .

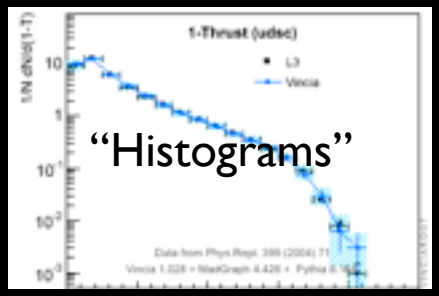


Simulation Codes

→ Simulated Particle Collisions

Experimental Data

→ Published Data Points



Last 24 Hours: 2853 machines

http://lhcathome2.cern.ch/