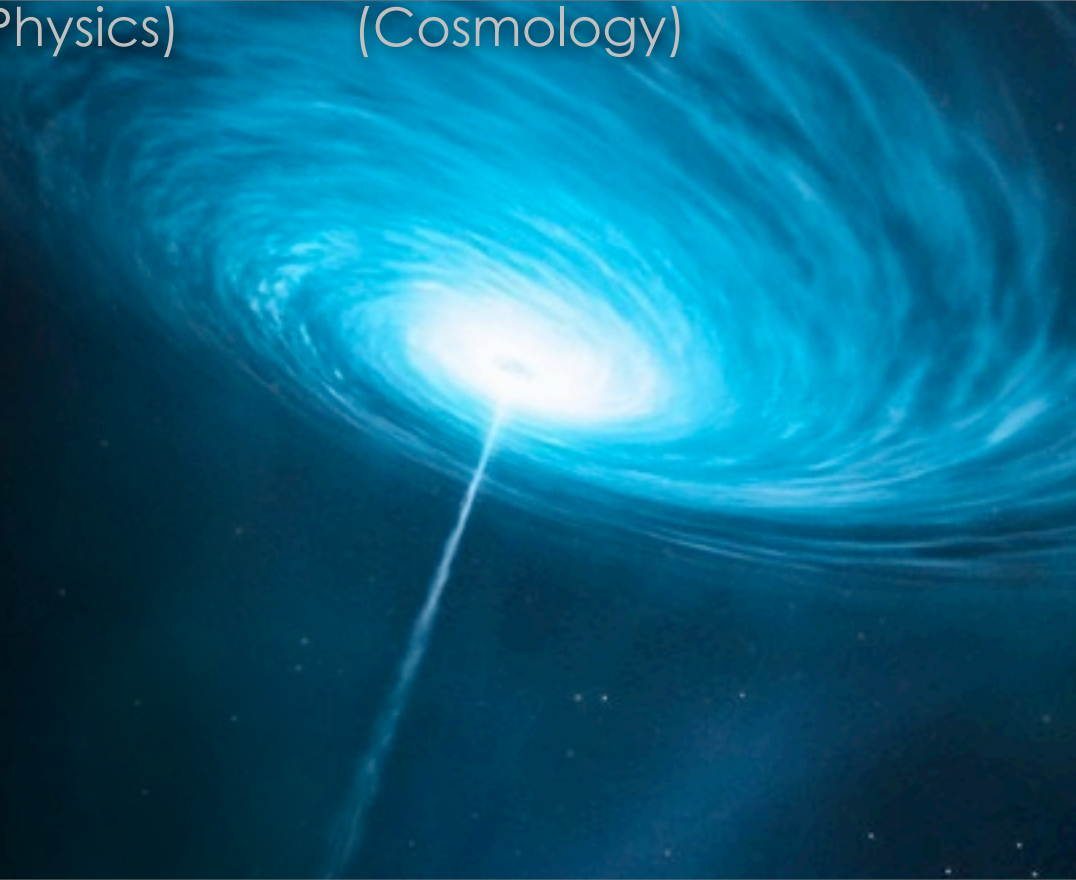
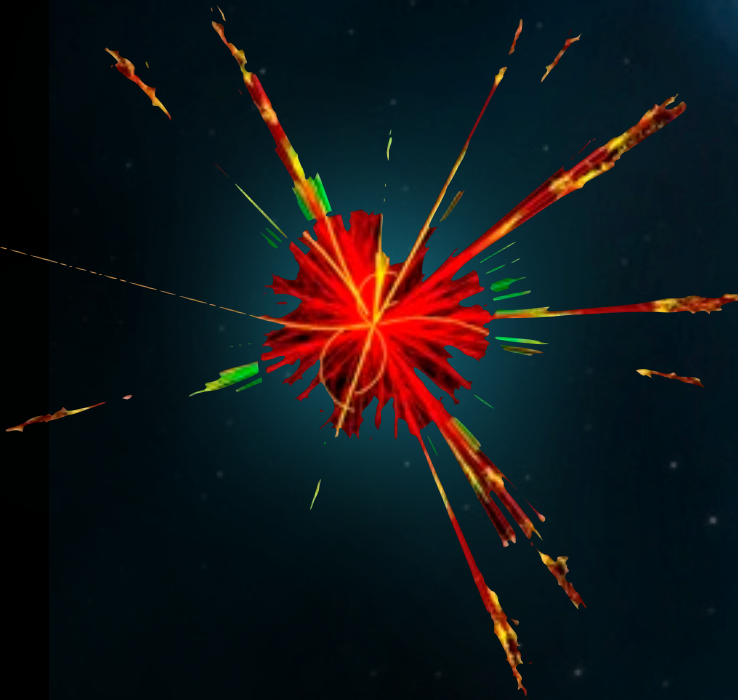


# From Quarks to Quasars

Outline:

Start Here  
(Particle Physics)

End Here  
(Cosmology)



Dr. Peter Skands  
CERN Theoretical Physics Dept



# Hvem er jeg?

Læste fysik-astronomi på KU  
(cand scient: 5 år)



→ Lunds Universitet:  
teoretisk fysik (PhD: 3 år)

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teoretisk fysik (PhD: 3 år)

→ Fermilab (Chicago)  
"Post Doc": 2 år  
"Scientist": 3 år

Nu: **CERN** ...

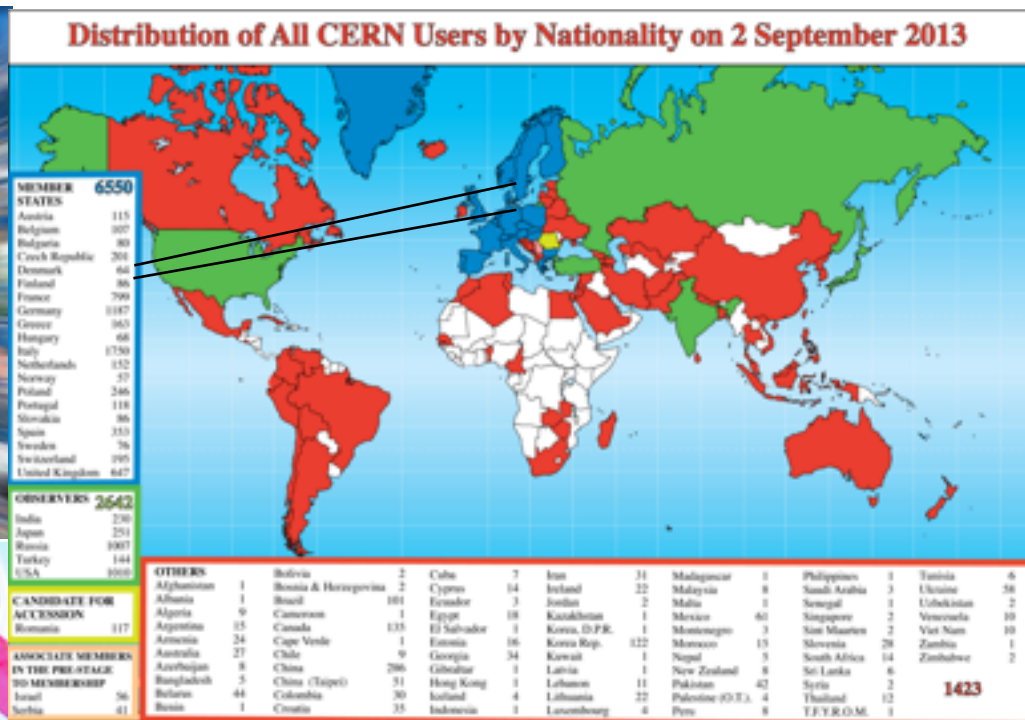




# CERN: European Organization for Nuclear Research

20 European Member States and around 60 other countries

~ 10 000 scientists work at CERN



Flags of CERN's Member States

Yearly budget ~ 1 billion CHF ~ 6 mia DKR



# What goes on at CERN

The ATLAS Experiment at the LHC

ATLAS collision event at 7 TeV from March 2010

<http://atlas.ch>



LHC Collision at 7 TeV  
ATLAS, March 2010

# Nutshell



Theory



Experiment

Adjust this

to agree with this

→ Science

# In Practice

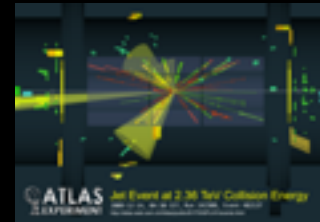


VINCIA



PYTHIA

...



Simulation Codes

Experimental Data

→ Simulated Particle Collisions

→ Published Data Points

signal to background  
May 12, 2013

## The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

By Glenn Roberts Jr.

[f](#) [t](#) [p](#) [in](#) [+](#) [-](#)

[PDF Download](#)

**Related *symmetry* content**

Breaking: Physicists, start your searches:

Think of it as a particle physics version of pop radio's "top 40" countdown: INSPIRE, a database of particle-physics publications, has released its [annual list](#) of most-cited articles.

Topping the charts in 2012 are articles about the Higgs boson, which made up about 20 percent of the list.

But the most-cited publication of 2012 is a [583-page manual](#) about PYTHIA, a program for simulating particle collisions and their byproducts.



# Min Forskning

## Teorien om den stærke kernekraft: Kvante-Chromodynamik (QCD)

Kvarker og Gluoner + Hadroner = bundne tilstande af kvarker (og antikvarker)

Mesoner (kvark-antikvark): pioner, kaoner,  $\rho$  mesoner, ...

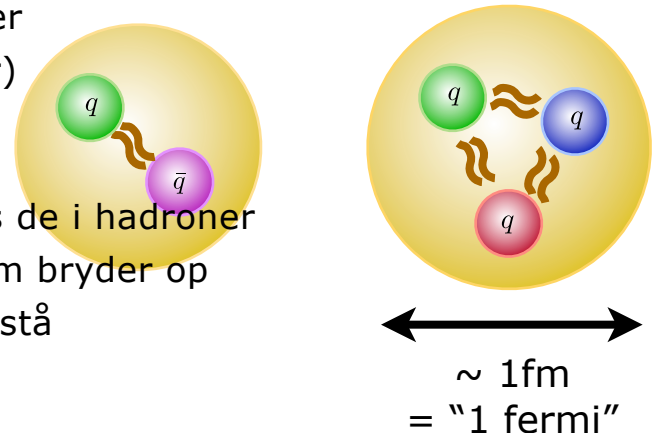
Baryoner (triple-kvark): protoner, neutroner, hyperoner, ...

## Bremsstrahlung

Når du sparker en kvark, stråler den gluoner  
(Jvf elektriske ladninger, der stråler fotoner)

## Hadronisering

Når kvarker og gluoner bliver 'kolde' bindes de i hadroner  
Der opstår 'gluon-streng' mellem dem, som bryder op  
Den process forsøger vi at modellere og forstå



## "Monte Carlo event generators"

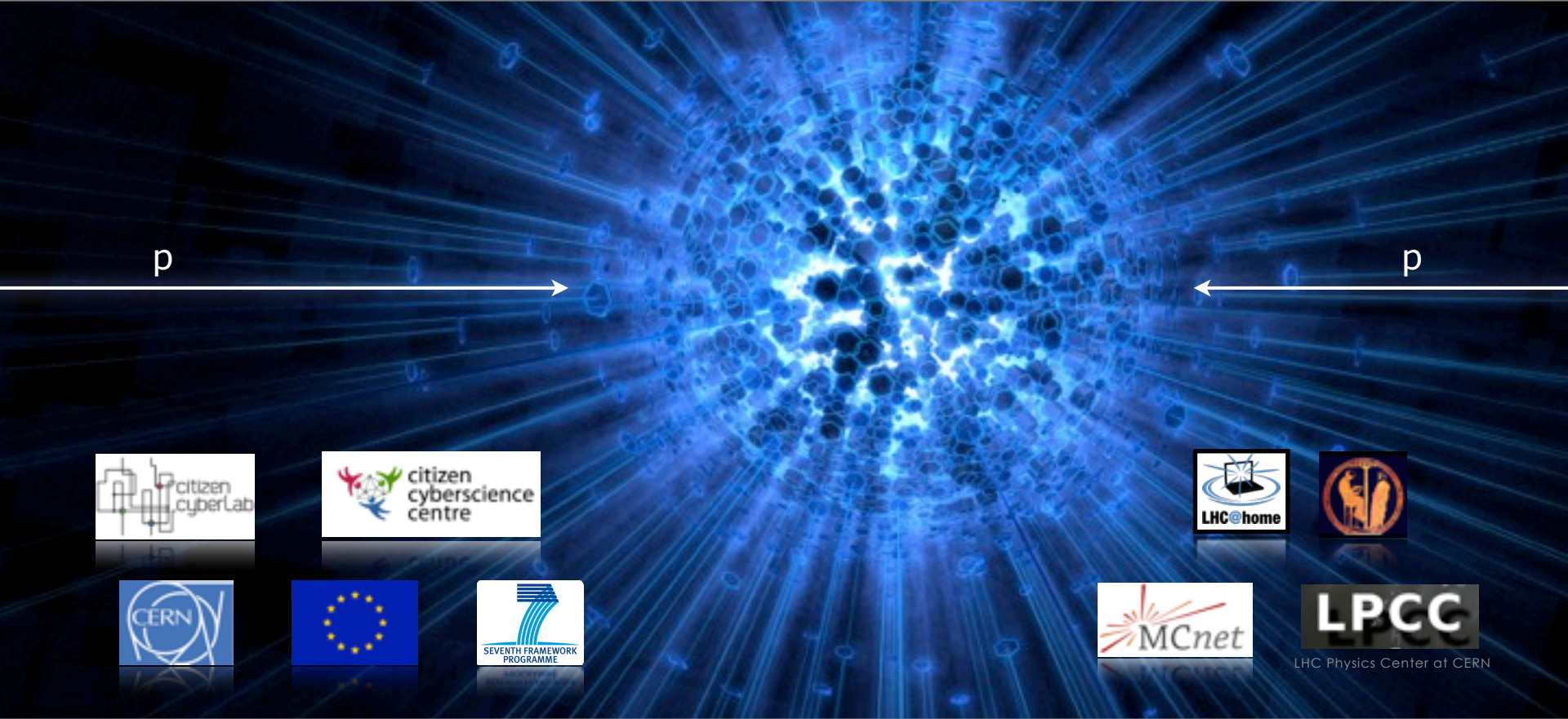
- Kvante-sandsynligheder → tilfældige tal
- tilfældige begivenheder, som i eksperimentet ~ en 'virtuel accelerator'
  - Used by experiments to give "theory predictions", to compare with data
  - Used to design and optimize detectors and analysis strategies
  - Used by theorists to explore new solutions, new ideas, new physics

Not a computer scientist. But the numerical calculations I (want to) do require a lot of power → distributed computing: farms / GRID / clouds.



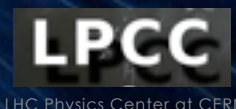
# LHC@home 2.0

Test4Theory - A Virtual Atom Smasher



p

p



Over 1000 billion simulated collision events

# Test4Theory - LHC@home

<http://lhathome.cern.ch/test4theory>

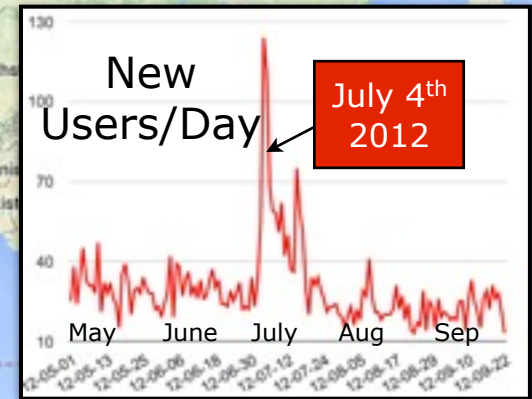
LHC@home 2.0 Test4Theory volunteers' machines seen since Sun Nov 17 2013 14:00:00 GMT+1100 (EST) (2804 machines overall)

The LHC@home 2.0 project [Test4Theory](#) allows users to participate in [running simulations of high-energy particle physics](#) using their home computers.

The results are submitted to a [database](#) which is used as a common resource by both experimental and theoretical scientists working on the [Large Hadron Collider](#) at CERN.

## New: *Citizen Cyberlab* (funds from EU)

Develop an app that lets citizen scientists learn about, interact with, and optimize **high-energy physics simulations**, by comparing them to real data



# Why ?



# 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



# 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)*





1 Femtometer = 1fm =  $10^{-15}$ m  
~ Size of a proton

# How ?

Today, we even believe that we have an intimate knowledge of the constituents of **nothing**



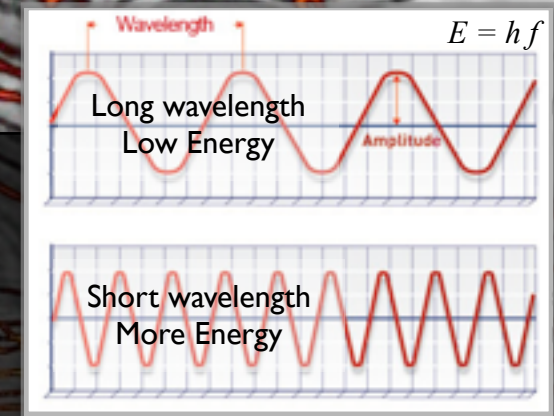
# High Energy Physics

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

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

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](#)

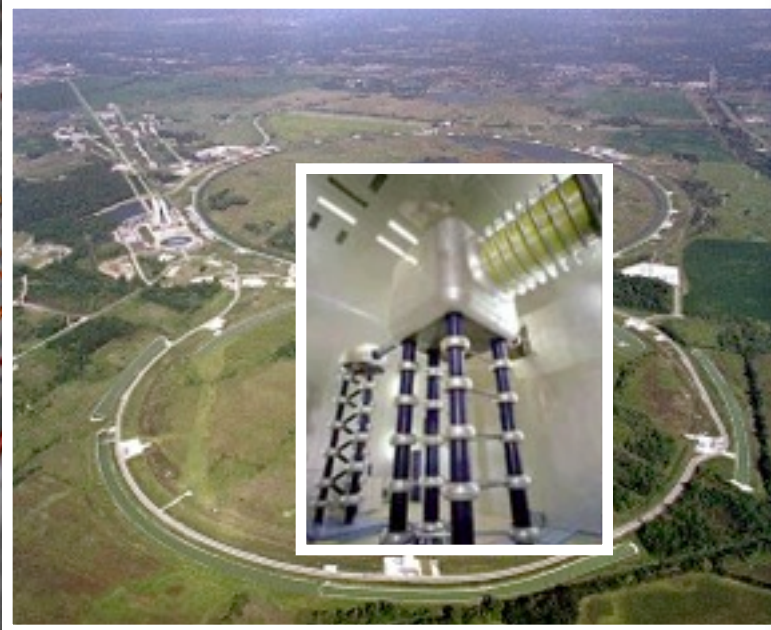


← “the Terascale” !



# the real Accelerators

- 1932: Cockcroft & Walton built a system that could fire protons, like bullets, into metal targets:  $p + \text{LiF} \rightarrow \text{Be}, \text{He}, \text{O}, \dots$



*Fermi Laboratory, Chicago, USA,  
ca. 2000*



*Modern van-de-Graaf*

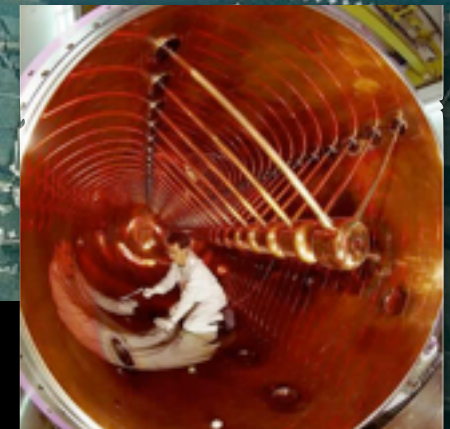
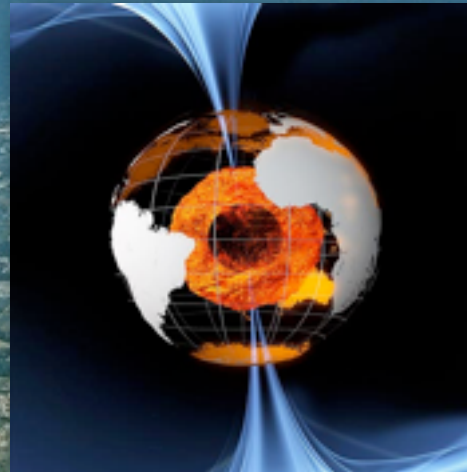
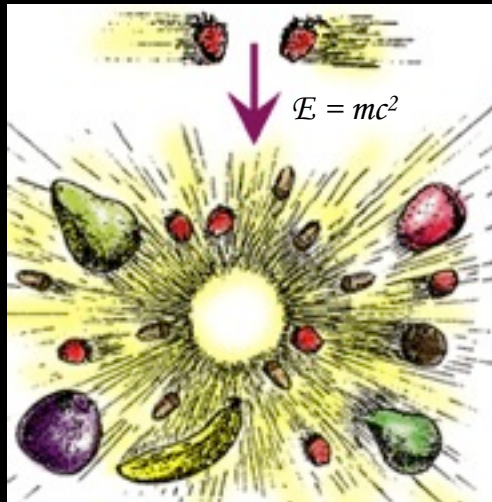
*Early van-de-Graaf, ca 1937*

(Nobel 1951) “Transmutation of atomic nuclei by artificially **accelerated** atomic particles”



# Particle Accelerators

> The goal:



- ❑ Accelerators are 'optical' systems, with
  - ❑ Light  $\rightarrow$  charged particles
  - ❑ Lenses  $\rightarrow$  magnets
  - ❑ Wave length shortening  $\rightarrow$  particle acceleration



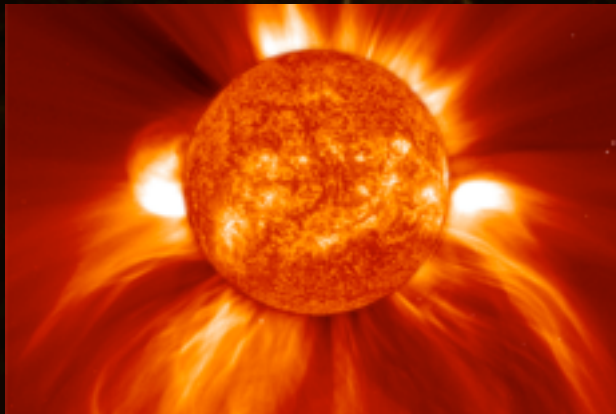
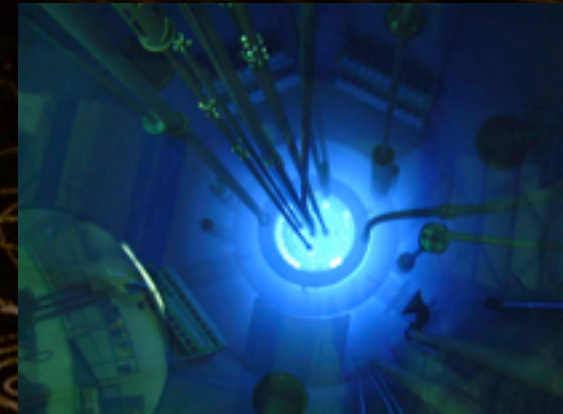
# So what is “High” Energy ?

- 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





# So what is “High” Energy ?

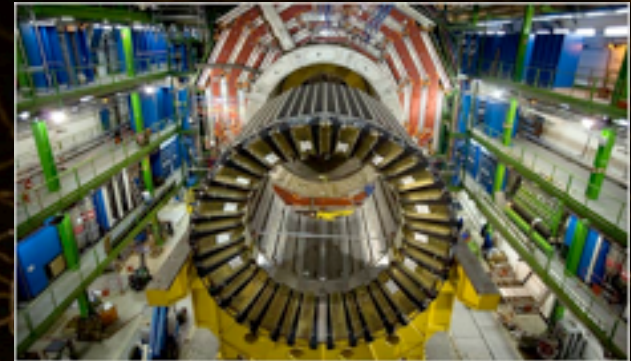
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  - Matter-Antimatter **Annihilation** : 2 000 000 000





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  - Matter-Antimatter **Annihilation** : 2 000 000 000
  - **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*

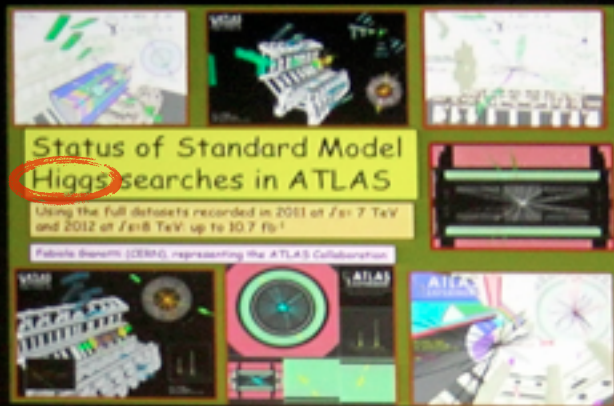
# → Fundamental Science



**ICHEP2012**  
Melbourne

**36th International Conference  
on High Energy Physics**

4 – 11 July 2012  
Melbourne Convention and Exhibition Centre



**Status of Standard Model  
Higgs searches in ATLAS**

Using the full datasets recorded in 2011 at  $\sqrt{s} = 7$  TeV  
and 2012 at  $\sqrt{s} = 8$  TeV, up to  $30.7 \text{ fb}^{-1}$

Fabiola Gianotti (CERN), representing the ATLAS Collaboration

Fabiola Gianotti  
Spokeswoman of ATLAS

CERN Main Amphitheatre

**July 4<sup>th</sup> 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)

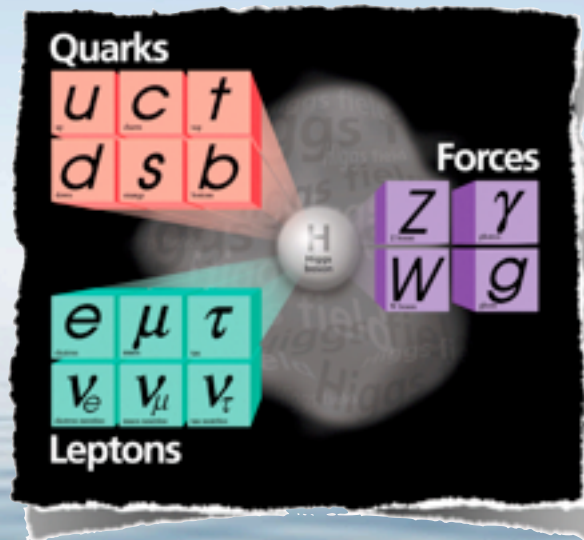


# The Higgs Particle

- 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



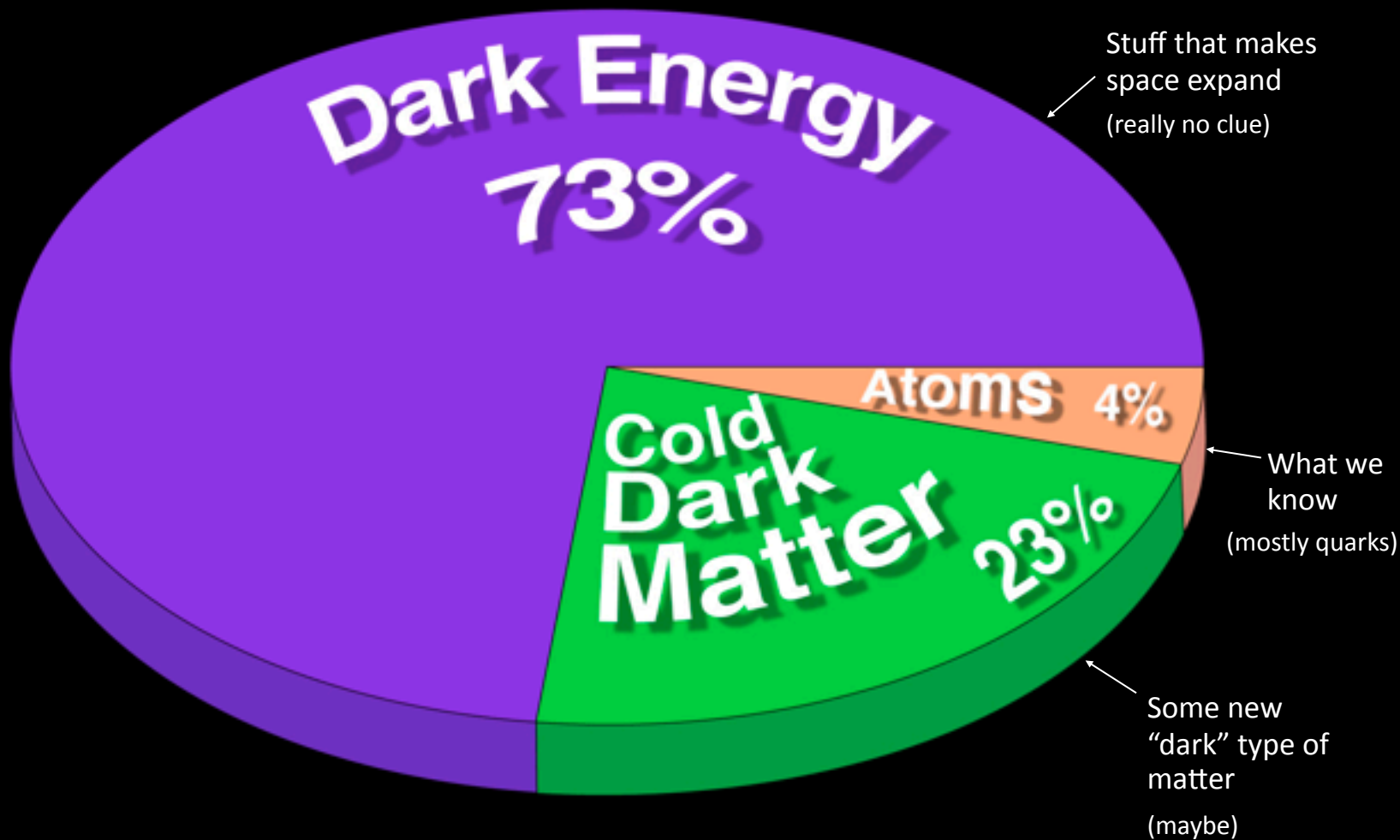
Electromagnetism  
The nuclear forces  
+ Gravity (Einstein)

+ Mass

## Or is there something beyond?

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

# The Dark side of the Universe

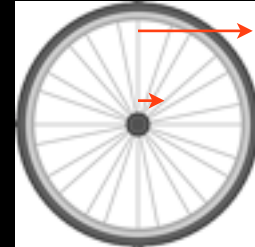
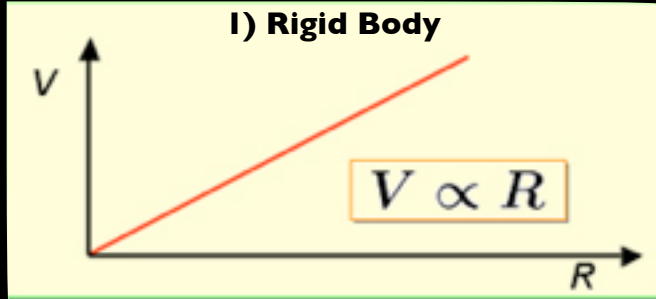




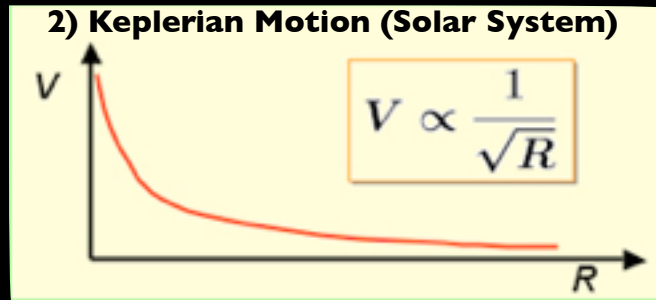
# Dark Matter: 23%

## Rotation Curves

### 1) Rigid Body



### 2) Keplerian Motion (Solar System)

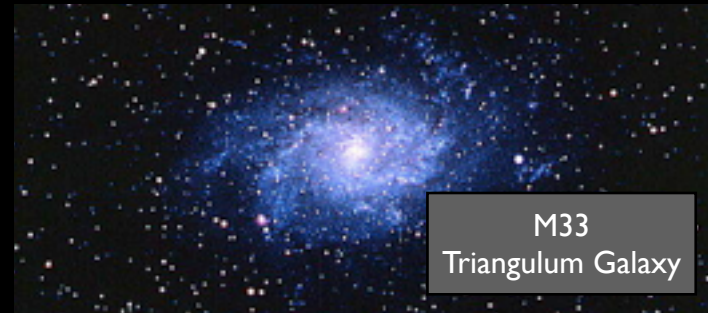
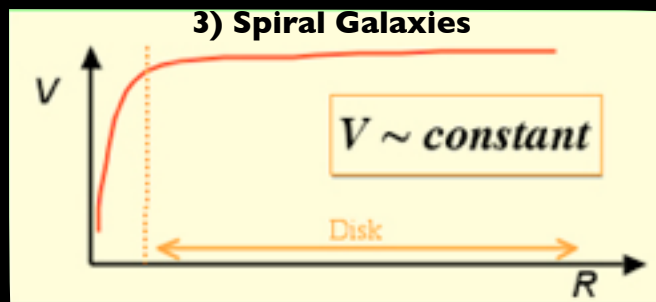


Mercury: 48 km/s

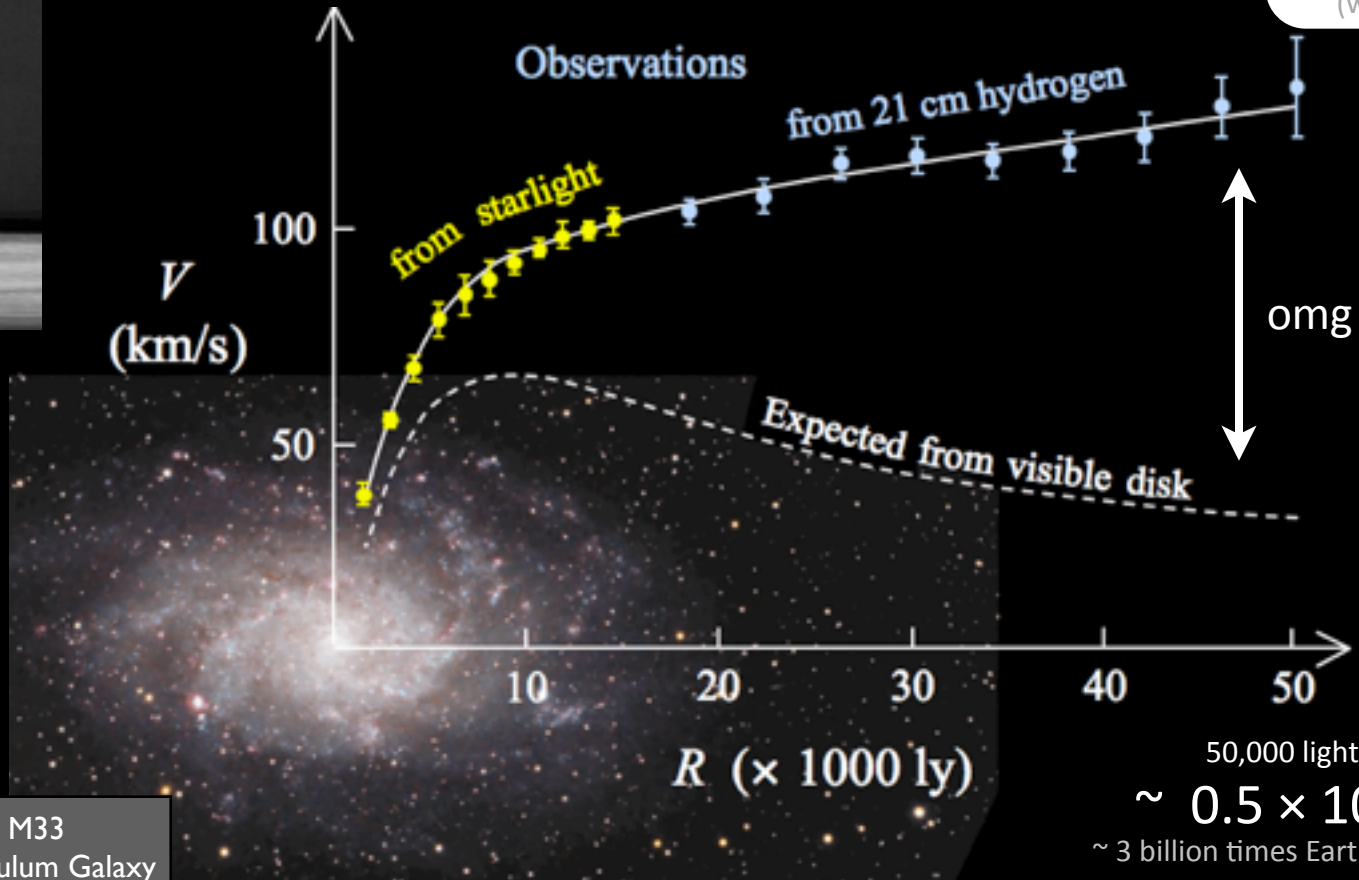
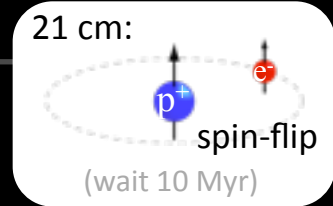
Earth: 30 km/s

Neptune: 5 km/s

### 3) Spiral Galaxies



# Rotation Curves of Galaxies (and of Galaxy Clusters)



M33  
Triangulum Galaxy

Something unknown is making galaxies spin like crazy



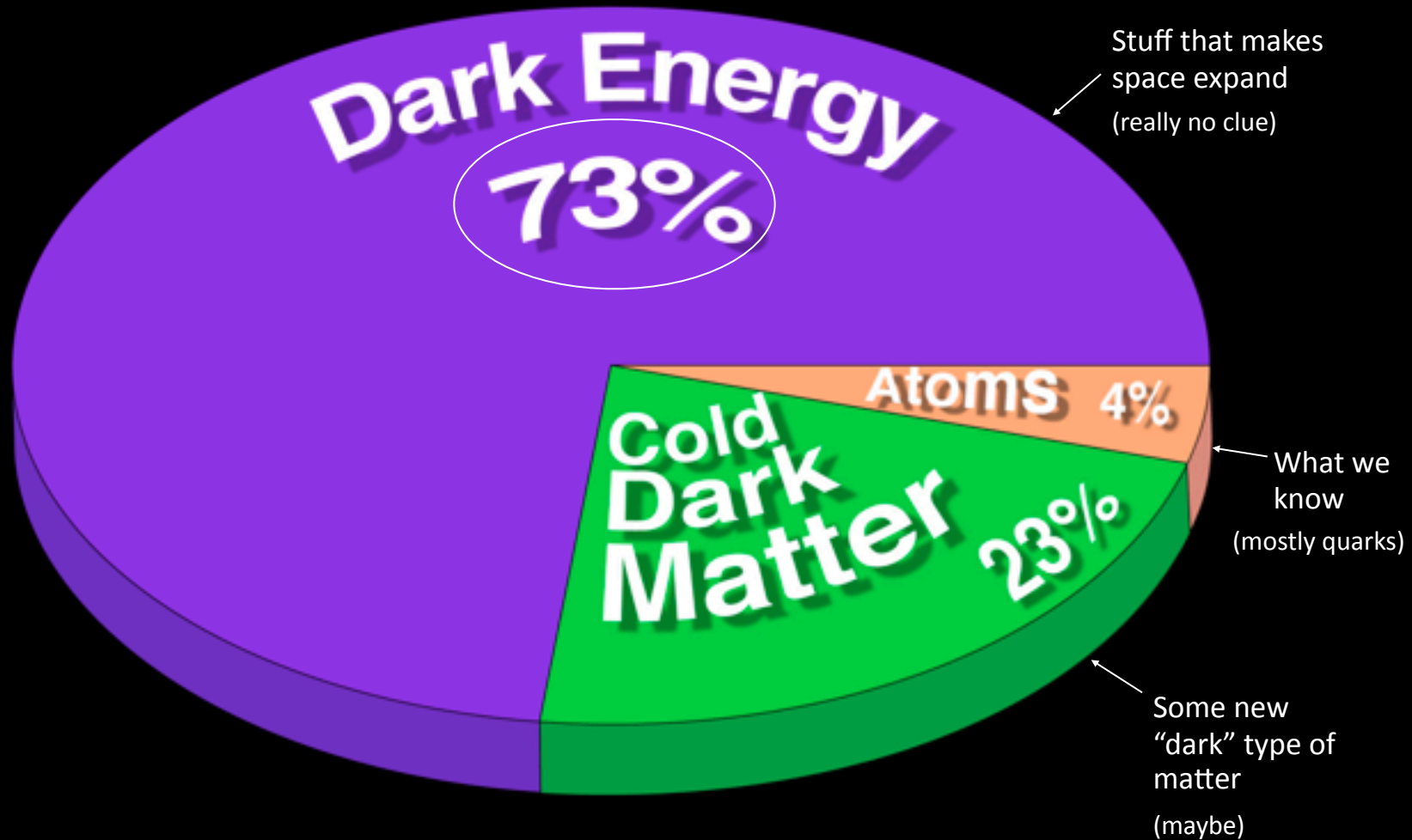
# When Galaxies Collide

- 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



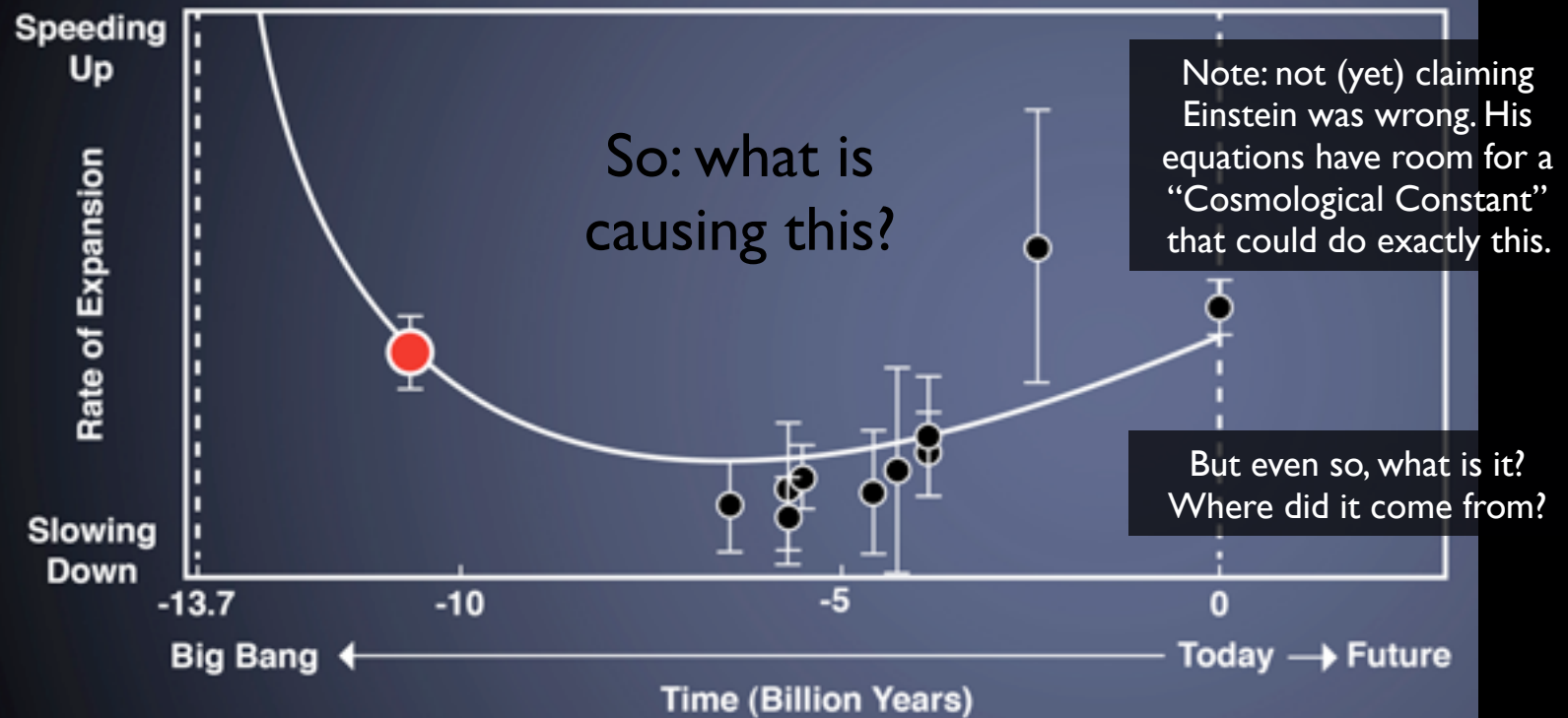
# Quasars

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



# Quasars

- Gravity slows down expansion of Universe



# 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? Fluctuations within fluctuations within fluctuations within fluctuations ...
- 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? Is it fundamental? Are there more Higgs fields?
- 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 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? Superstrings? Or something else?
- Ideas are not enough. ***How to test! How to calculate!***