

Empty Space – or is it? Physics of the Vacuum

Mike Albrow, Fermilab

The vacuum is not nothing
no(such)thing

When we understand the vacuum,
we will understand all of *fundamental* physics



It sucks

Empty Space – or is it? Physics of the Vacuum

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Journey into space

Emptying a box

Magnetic and electric fields

The Higgs field and the Higgs boson

Gravity : Black holes & a Closed Universe

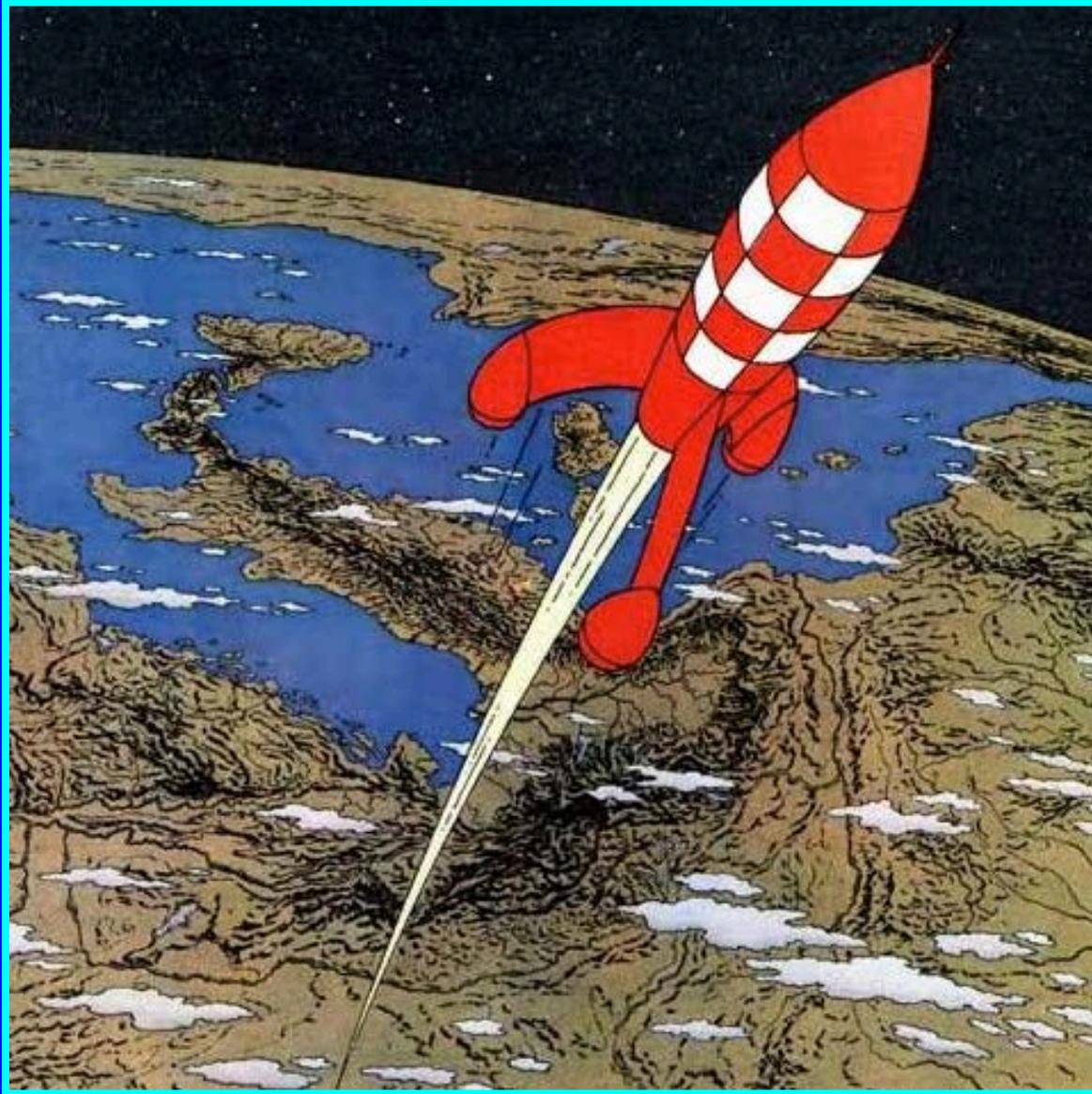
Dark energy and dark matter

----- Q -----

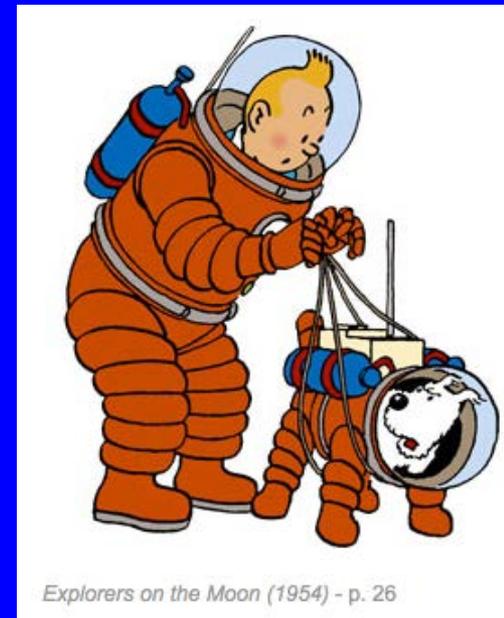
Is the vacuum unstable?

The smallest ever scales: frothy spacetime, extra dimensions?

Journey into Space



60 years ago!



The vacuum:

Much ado about nothing

..... Shakespeare

“Nature abhors a vacuum”

... Aristotle

Oh, really?

The vacuum contains all of
fundamental physics:
Space and time
Particles and forces
Mass and energy ...



Plato & Aristotle

Atoms are **nearly all** just electromagnetic fields

NUCLEUS is to **ATOM** as 1 mm is to 10 meters

Magnify an atom to
the size of a house:

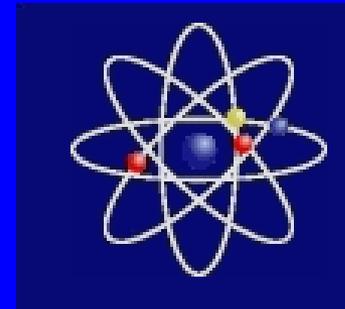
A real pub in Wales!



The nucleus is the
size of a pinhead in that house!

Size of electron orbits

Fraction of atom's volume that is "matter"
(nucleus + electrons) $\sim 0.000\ 000\ 000\ 000\ 001$



NO!

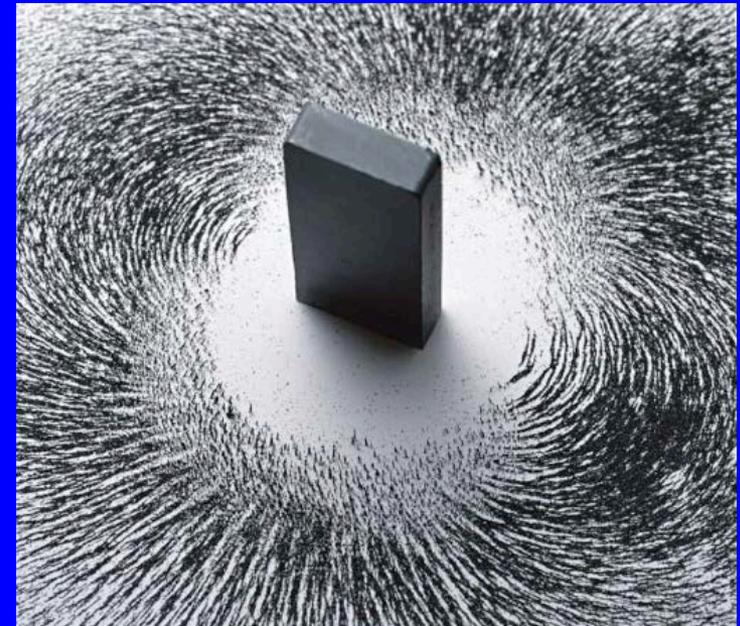
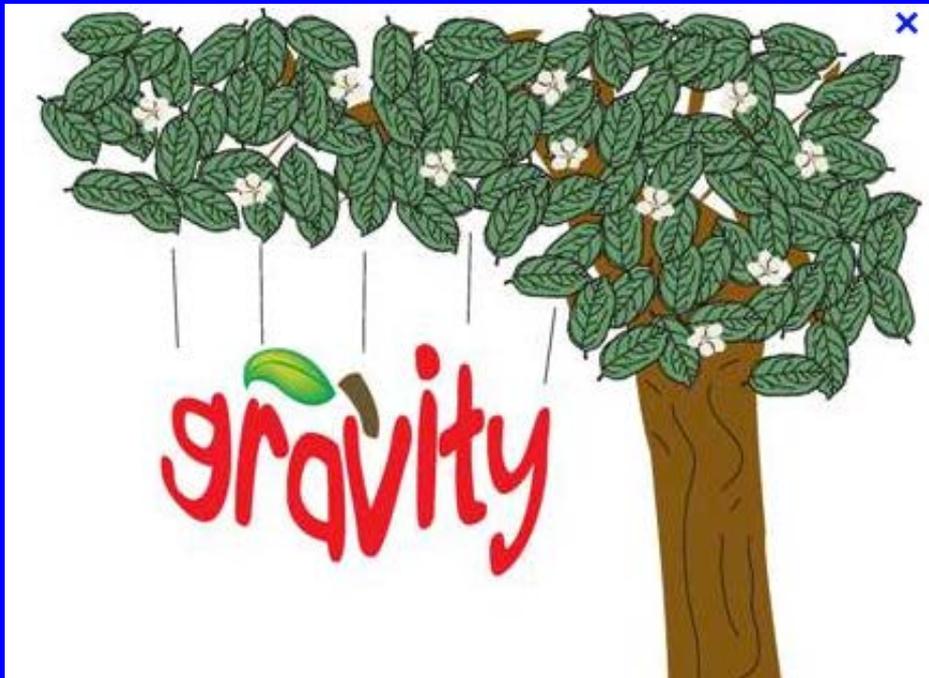
Fields you know:

Electricity and Magnetism

Gravity ...

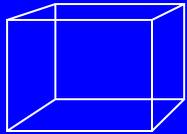
These fields vary from place to place
and from time to time.

Also they have a direction.



In pursuit of the perfect vacuum (recipe) :

Box of vacuum:



Matter (nuclei and electrons) take
 10^{-18} of volume! (in air)
 $1/1,000,000,000,000,000,000^{\text{th}}$



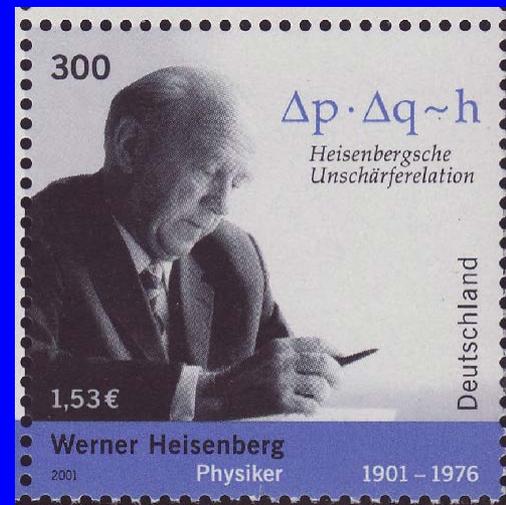
Even in copper: 5×10^{-15} ...of course its *full* of EM fields.

- 1) **Remove all the atoms** (nuclei and electrons and their electromagnetic fields)
- 2) **Cool down** to so close to $T = 0$ that thermal microwaves don't fit inside.
- 3) **Thick shield** (with no radioactivity) to shield out X-rays and γ -rays.
- 4) **Damn the neutrinos!** Invisible (until they interact). 100 billion/sec/little finger
- 5) Let the box **fall freely** in outer space : no gravitational fields.

Are we there yet?

Nice try, but no, for at least 2 reasons: Heisenberg and Higgs

WAY OUT HERE ?



Werner Heisenberg

How can we define the vacuum, if not the absence of any stuff?

Let's say: the lowest possible energy state

But Professor Heisenberg's Uncertainty Principle said that zero energy, really $E = 0$, does not make sense unless you have an infinite ∞ exposure time.

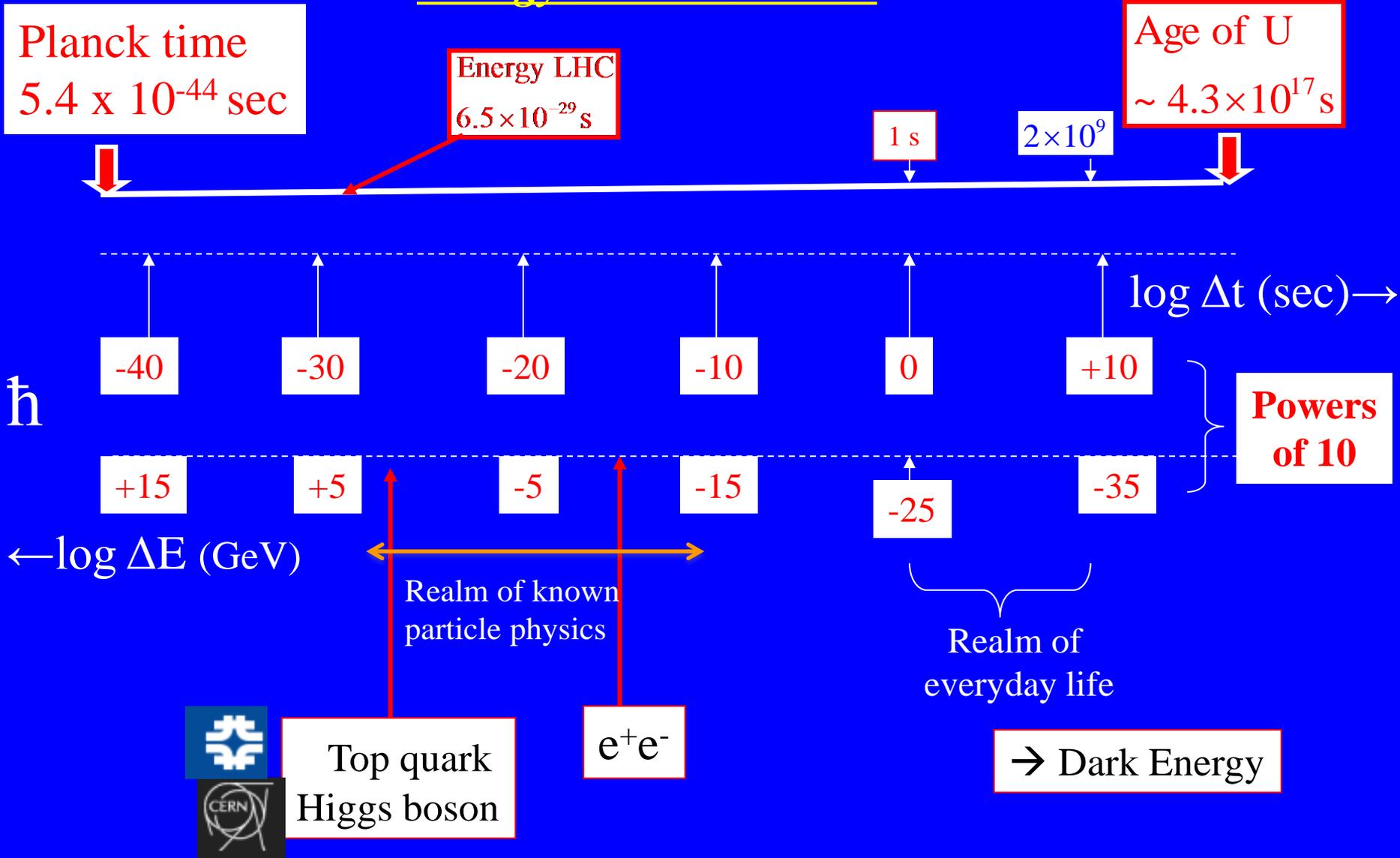


If you **antiblink**, short exposure, high energy fluctuations.



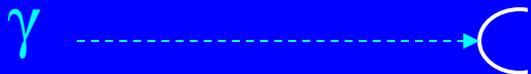
Δt is exposure

Energy and time scales

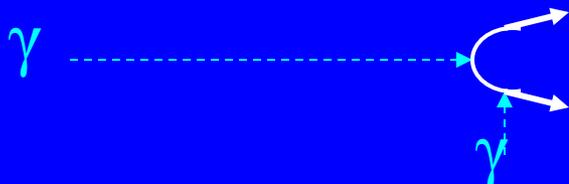
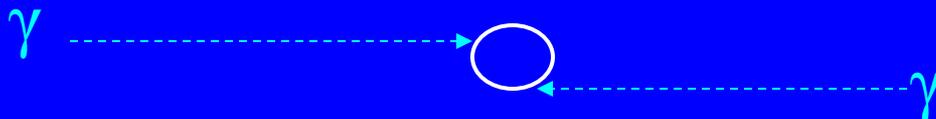


“The closer (and faster) you look, the more you see”

Exciting the vacuum with photons

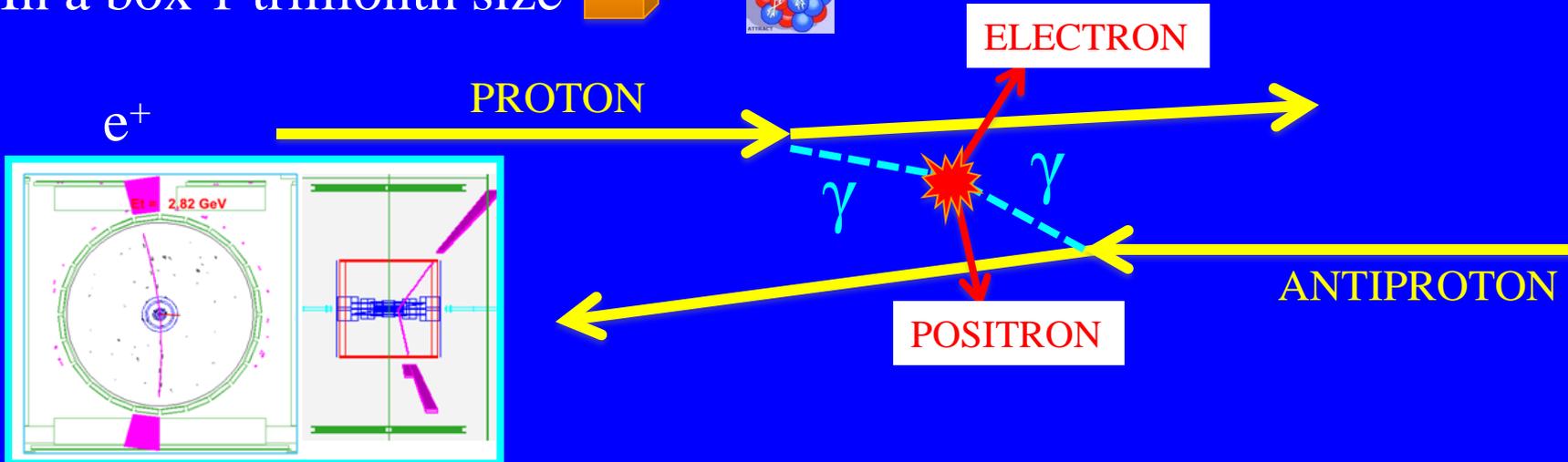


Doesn't work!
Energy and momentum conservation forbids it;
except for VERY short times
(evanescent)

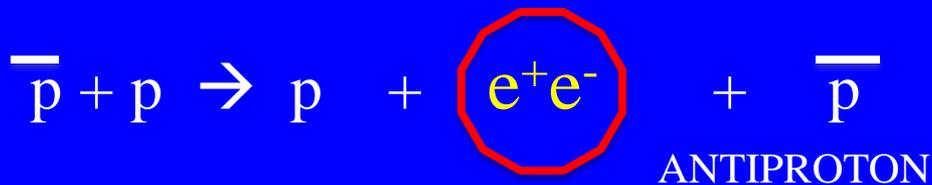


Does work!
Allowed by energy conservation
Energy injection promotes loop to reality.

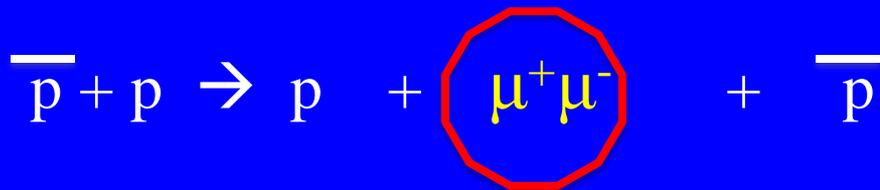
In a box 1 trillionth size 



Installing some special but small proton detectors in the Tevatron tunnel, 60 m from CDF, to discover new reactions:



and



Muon μ is heavy version of the electron. “Who ordered that”?
Exciting the vacuum with electromagnetic fields (aka photons)

More stuff in the box!

Mr Higgs et al.'s field

These were the key theorists who suggested a new “field”

Unlike gravity and electromagnetic fields:

Same everywhere and no direction, just a value

In a sense the vacuum IS this field : lowest possible energy state



Dr. Higgs said (an afterthought) that there should be a particle just as the photon is the particle of the electromagnetic field

Electrons in your little finger and electrons in an alien's little finger in another galaxy far far away have the same mass !!

Electrons can be created: e^- and e^+ (positron*) colliding massless photons (particles of light)!



If there's really "nothing", how could they possibly know what mass to have?

Something in outer space is in both places (and everywhere!)

Not just electrons, but all (12 !) fundamental particles (quarks etc.)

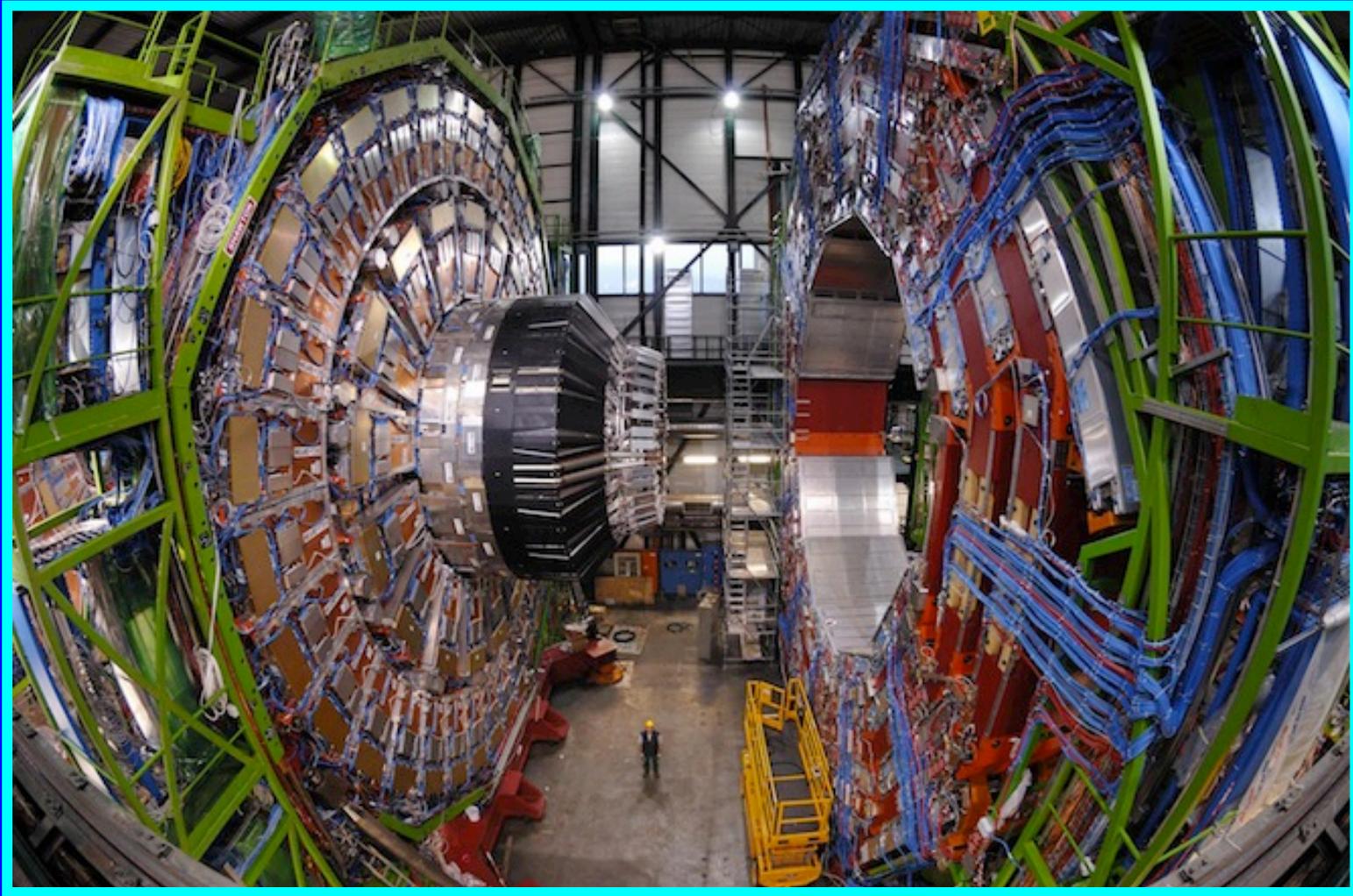


* PET = Positron (**antimatter**) Emission Tomography



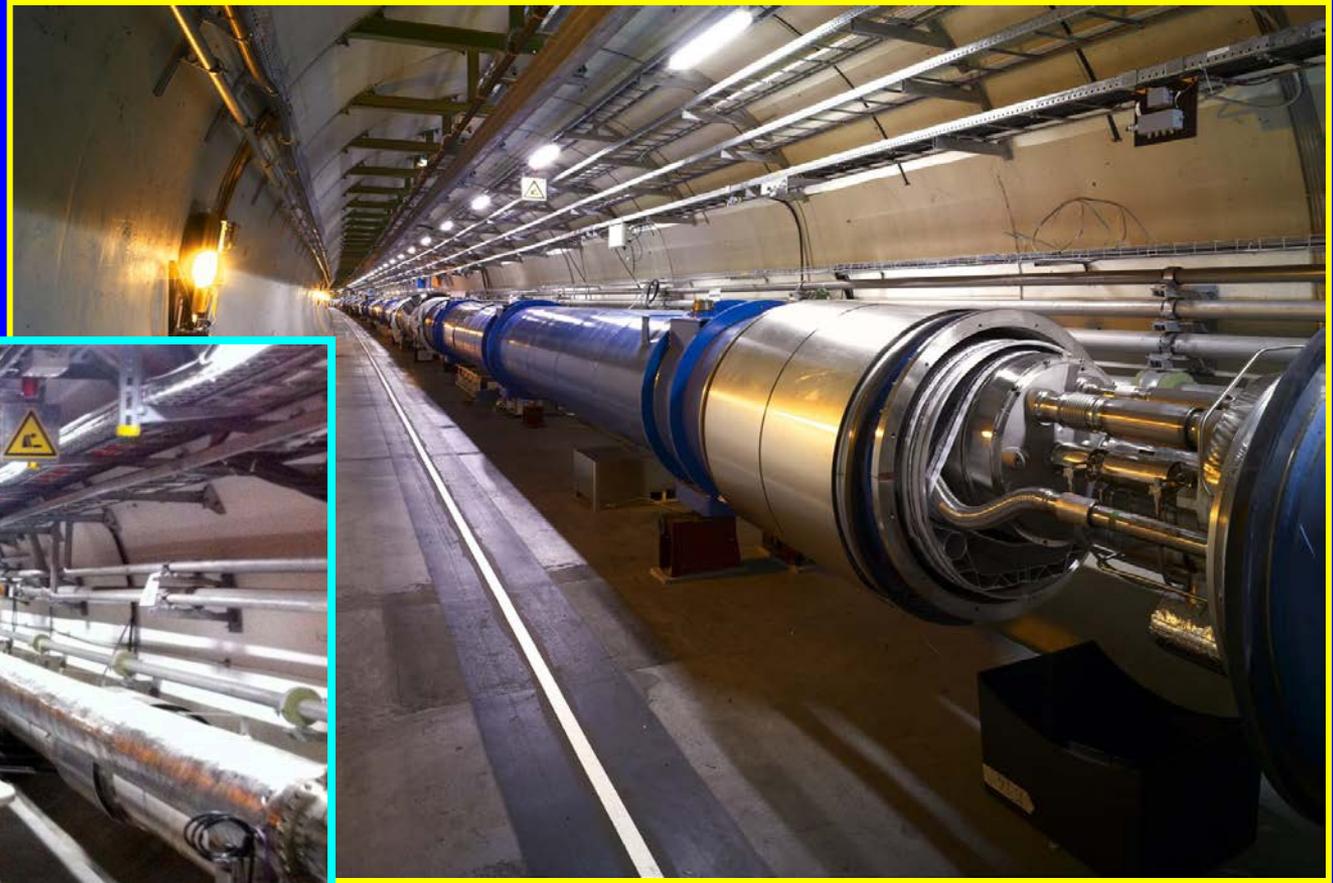
Dark Matter

The “Compact” Muon Spectrometer at CERN, Geneva (CH)
“My (+3000 colleagues) experiment” co-discovered the Higgs boson

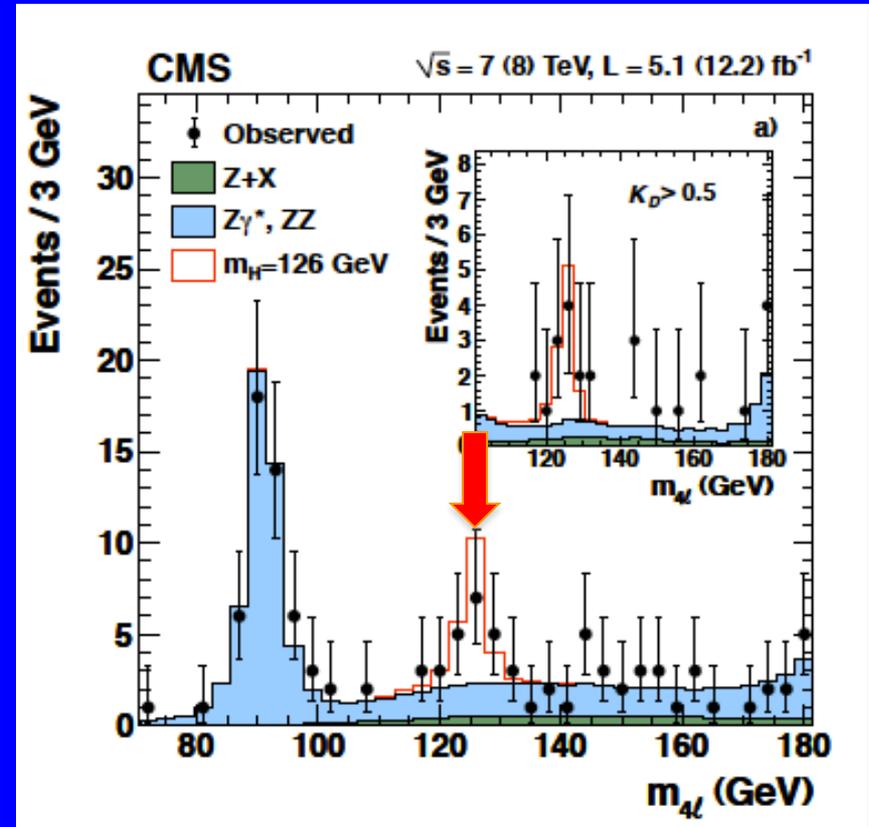
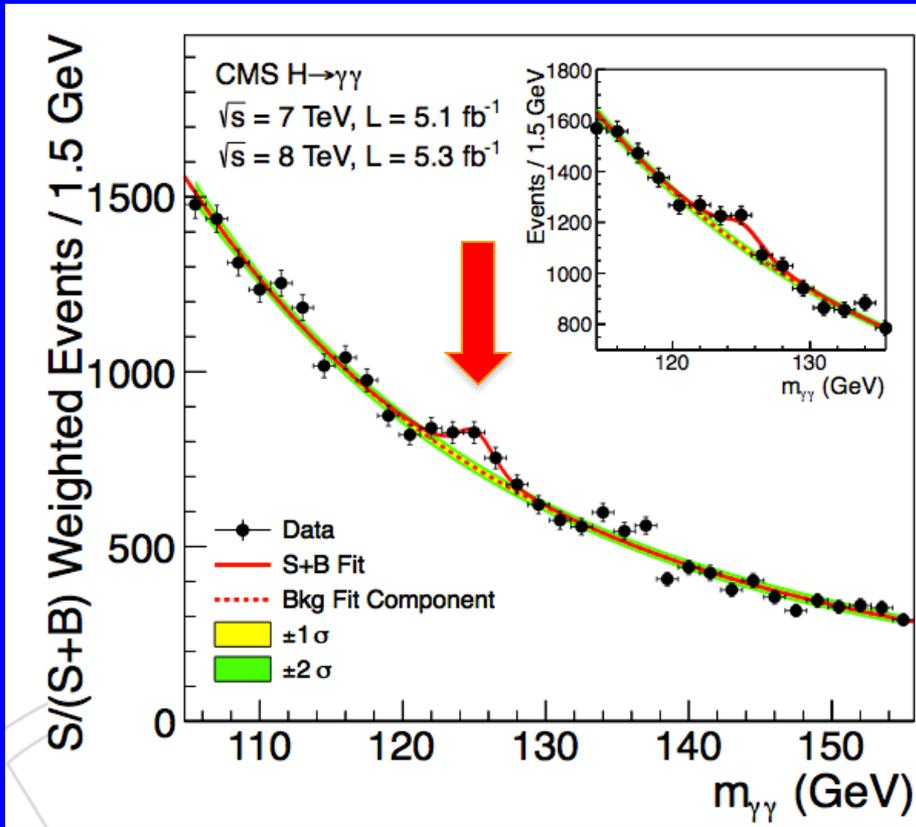


12,500 tons, 80,000 crystals of lead-tungstate (98% metal yet transparent!)
700,000 electronic channels! In 1 sec writes “10,000 Encyclopaedia Britannicas”

The **Large Hadron Collider, LHC**: 27km of 2K superconducting magnets CERN Geneva Switzerland & France : All European countries, since 1950s



The key evidence: needle in millions of haystacks!



The Higgs boson can decay to two photons (gamma-rays) making 125 GeV peak

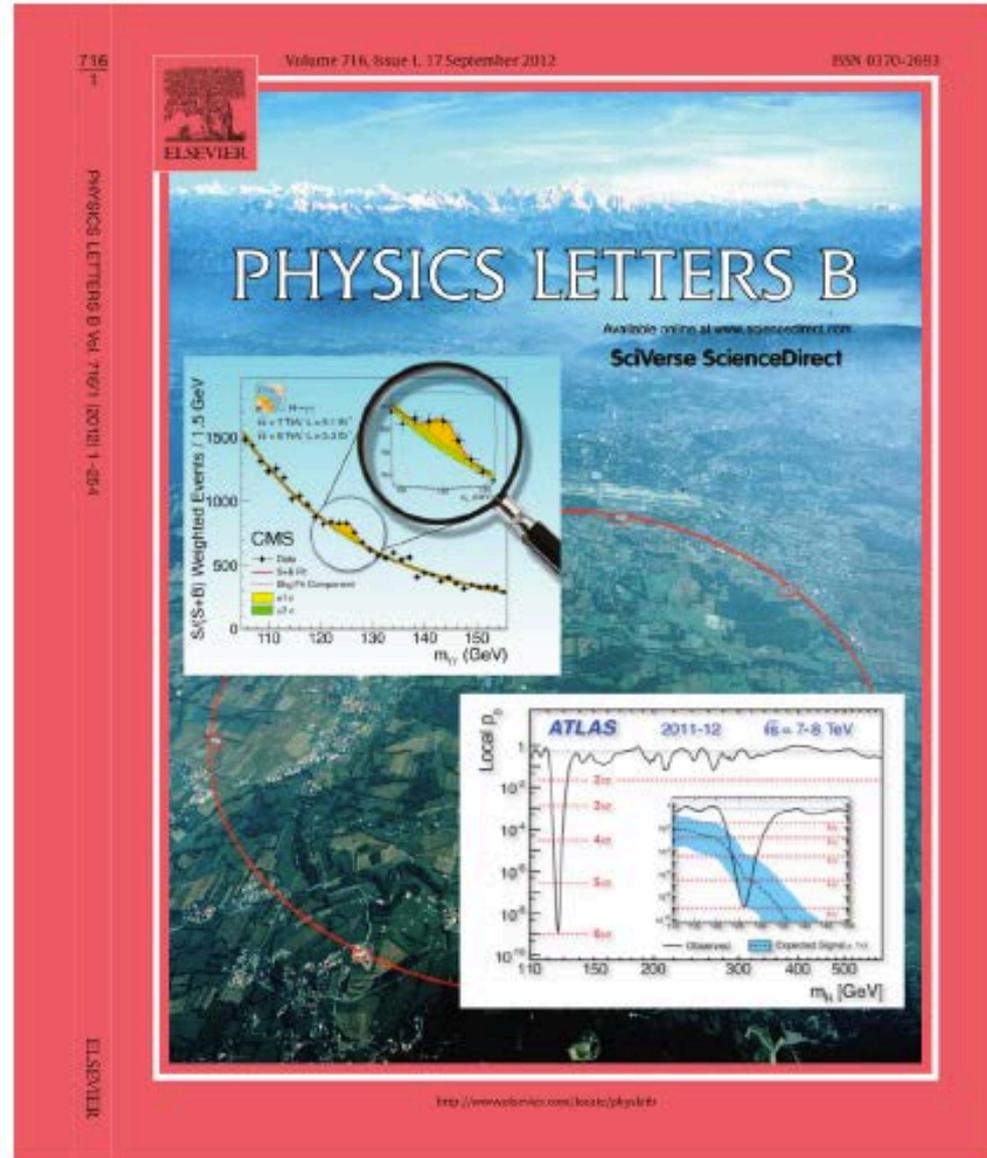
MASS →

The Higgs boson can decay to four electrons making a 125 GeV peak

Both big experiments (about 3000 physicists each!) saw it, agreed

July 4th 2012 at CERN and around the world

The discovery of a new mass resonance at LHC: $m \approx 125 - 126 \text{ GeV}$



The achievement is awesome!

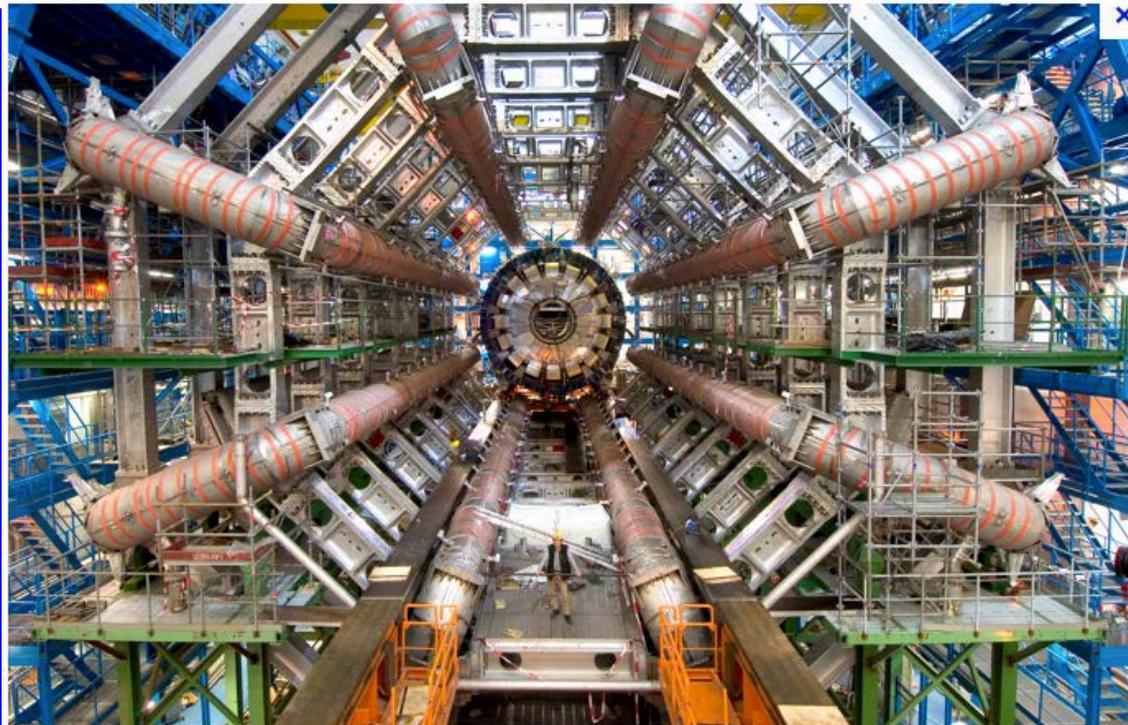
16 miles of accelerator:
sub-millimetre precision

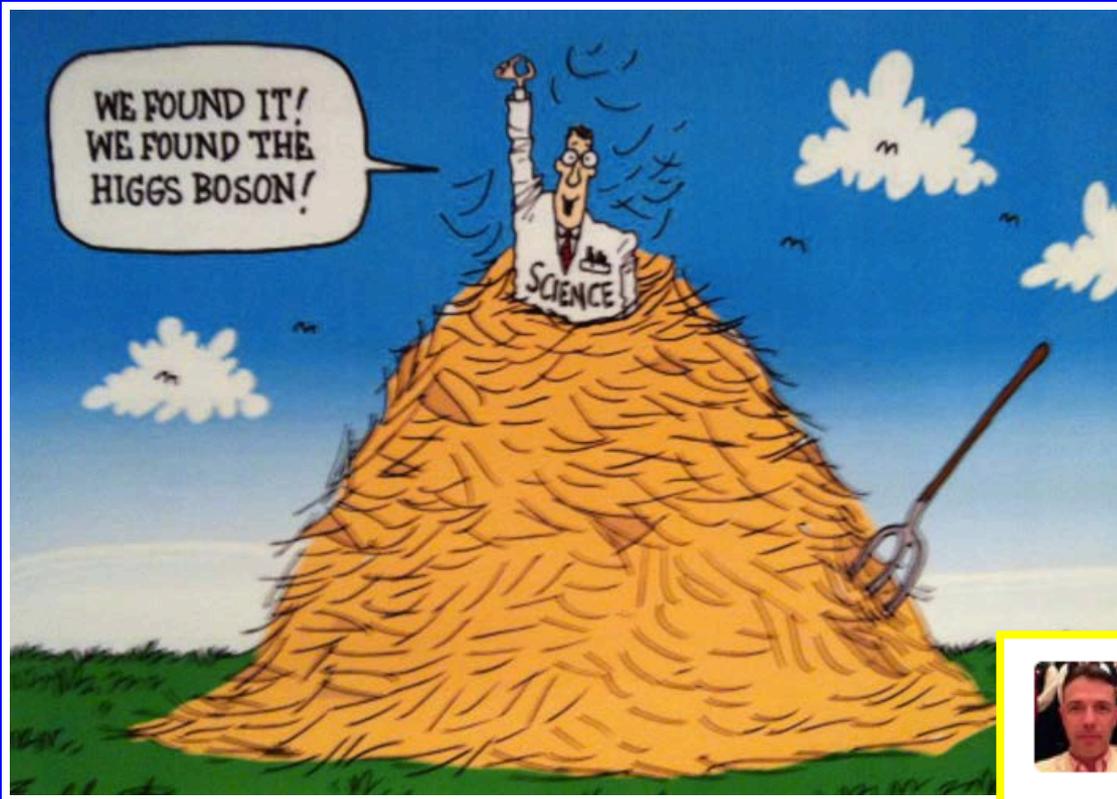
Two 5-storey high particle detectors
with about 3000 physicists each.

100 tons of superfluid He @ 2K

Unprecedented data handling:
100 Tb/sec out of the detectors

Tens of Petabytes data stored
and shared around the world.





Adam Rogers
@jetjocko

Yup. Higgs boson. Right where I left it.



Ed Casey
@edcasey



Whoa whoa whoa! We're cross-breeding hogs and bison now?

Thanks a lot Obamacare!



Steve Murray 
@NPsteve



"Are You There God Particle? It's Me, Average Person That Doesn't Understand You"

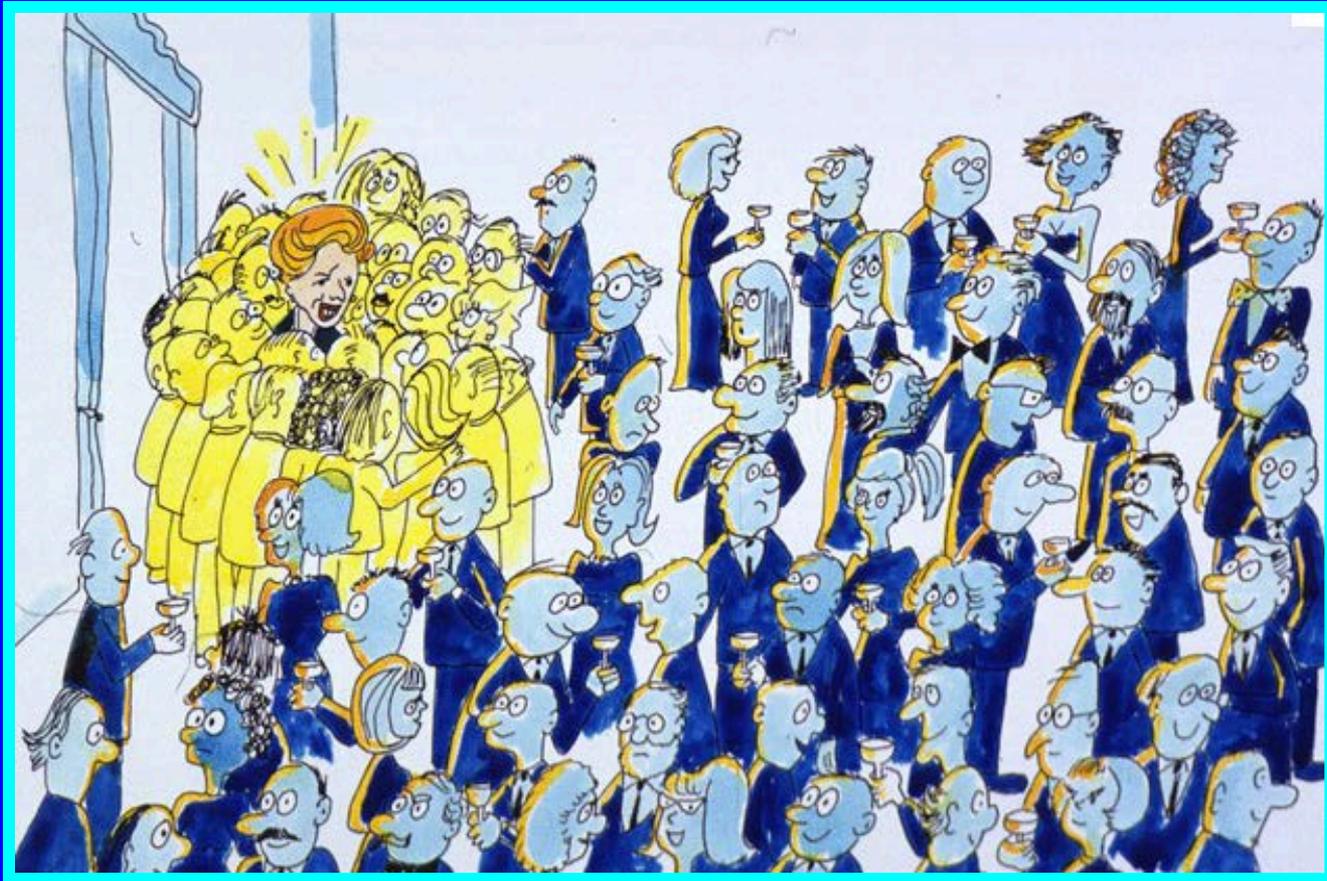


Ed Yong
@edyong209



A Higgs boson walks into a bar. The barman doesn't understand.

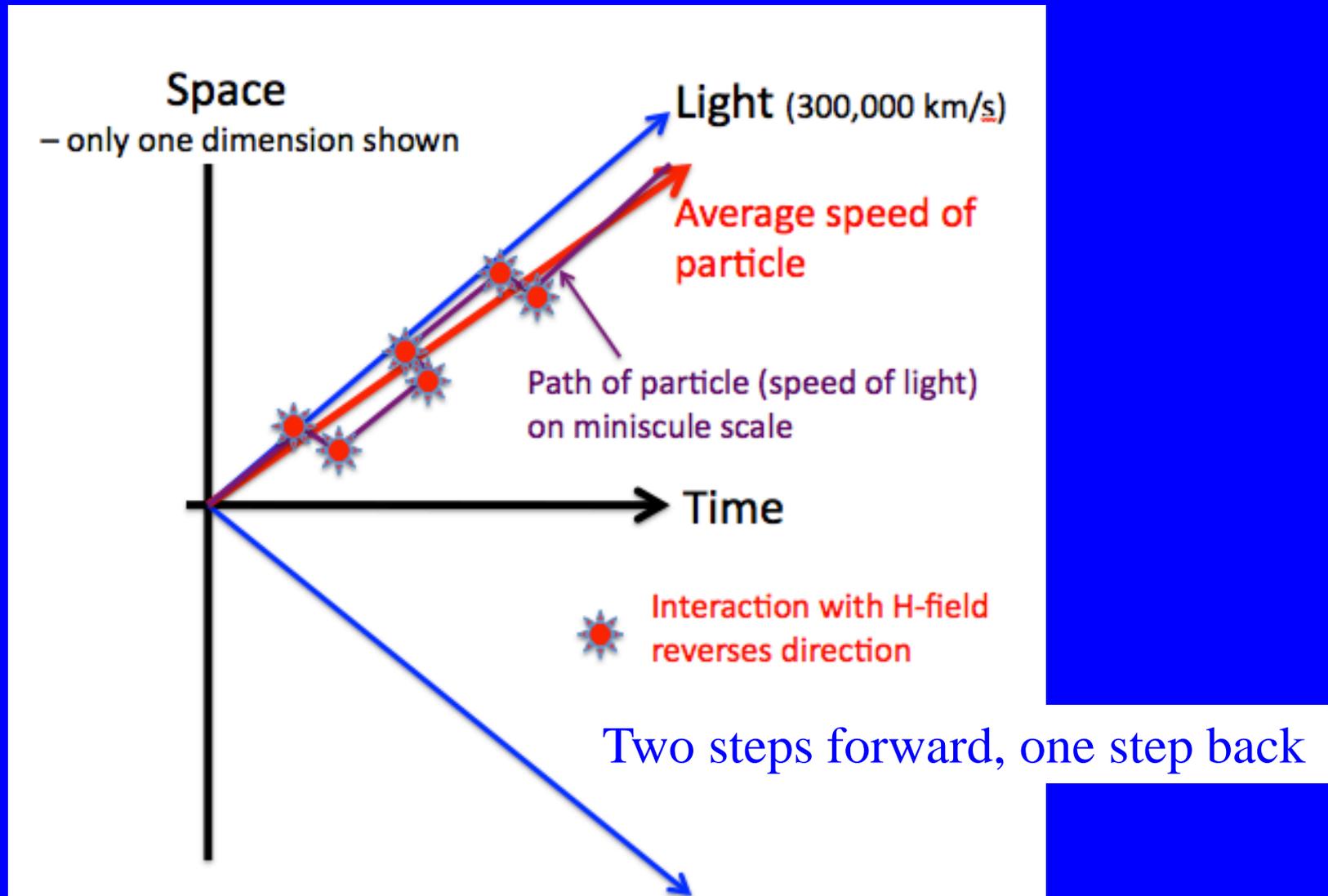
Conservative party (UK) cocktail party



The Iron Lady analogy (helped UK funding for LHC!)

This is not an analogy for the Higgs boson, but for the field.
The analogy for the Higgs boson is a rumor that moves across the room

Another analogy: particles zig-zag at light speed



Axes scale really ~ a trillion trillion trillion times smaller

Turn off the field : electrons zip at the speed of light, no atoms

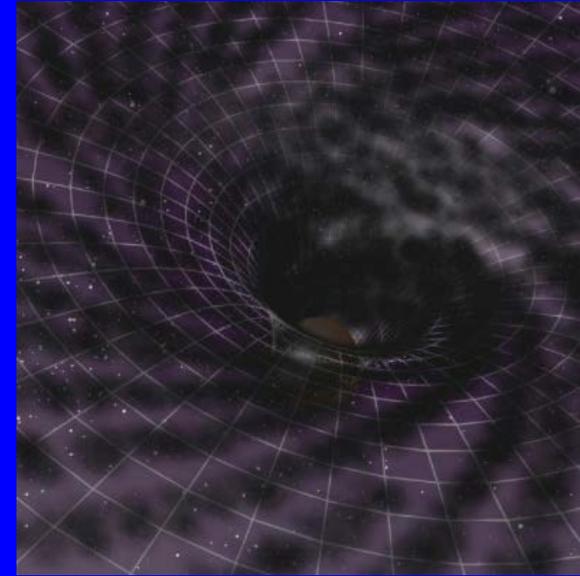
BLACK HOLES ... are out of sight!

Humungous ones! 1,000,000,000 x mass of Sun
Centers of galaxies ... but less than 1% mass of galaxy

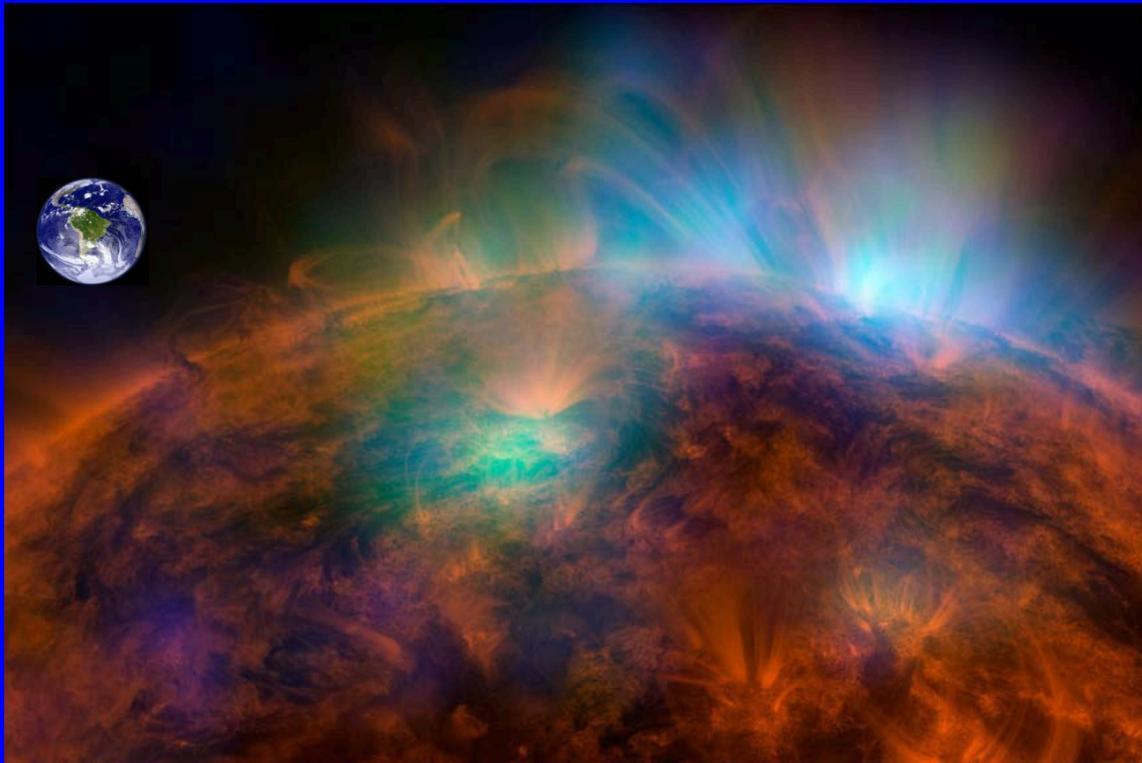


"Black holes have mass? ... I didn't even know they were catholic."

BLACK HOLES ... are out of sight!



Squeeze the Sun (here with X-ray eyes)

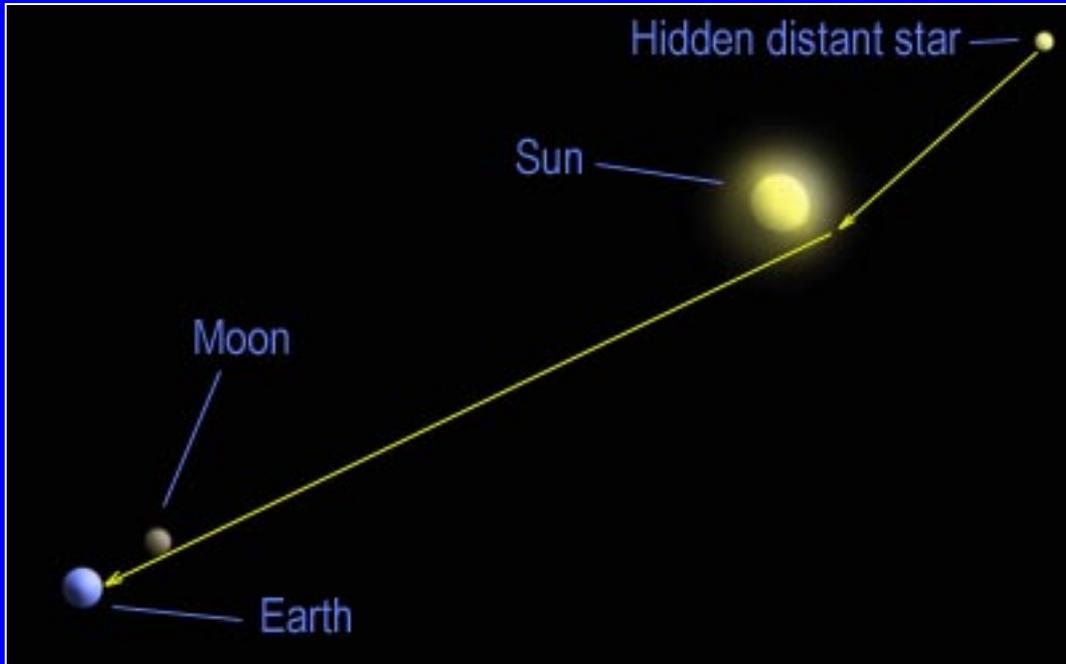


... down to Earth size ...
then 1000 x smaller
All nuclei squished together
“Neutron star” 10 km
10 billion tons in my box!

Keep squeezing → black hole
Smaller than my box!

May 29, 1919

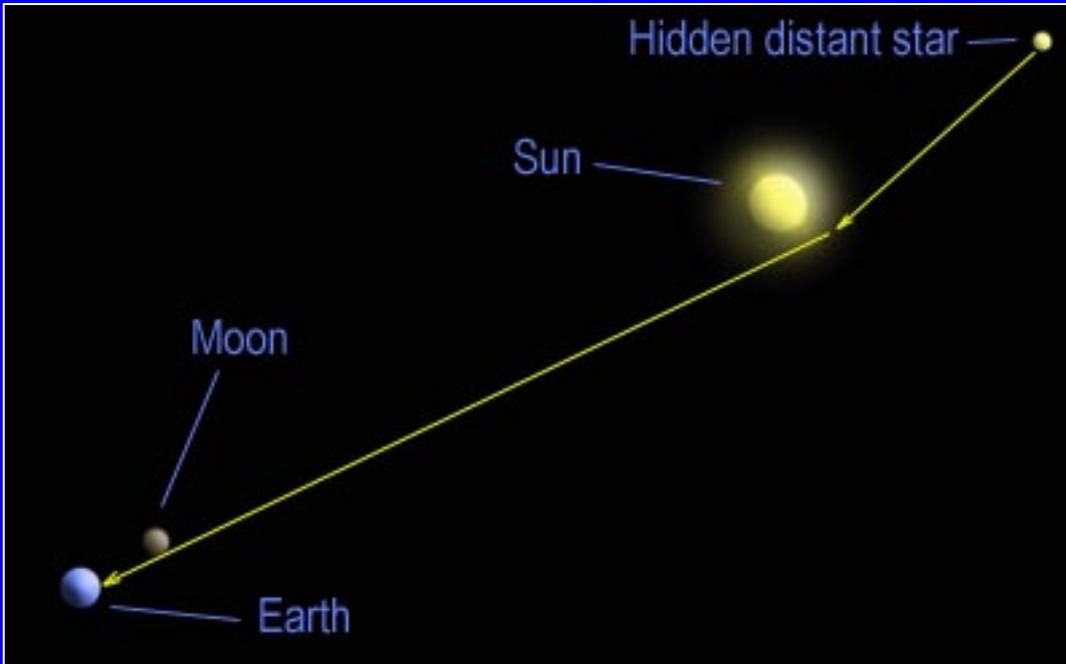
**The eclipse that proved Einstein right!
Space (spacetime) is bent by Sun's gravity!**



If spacetime flat

May 29, 1919

**The eclipse that proved Einstein right!
Space (spacetime) is bent by Sun's gravity!**

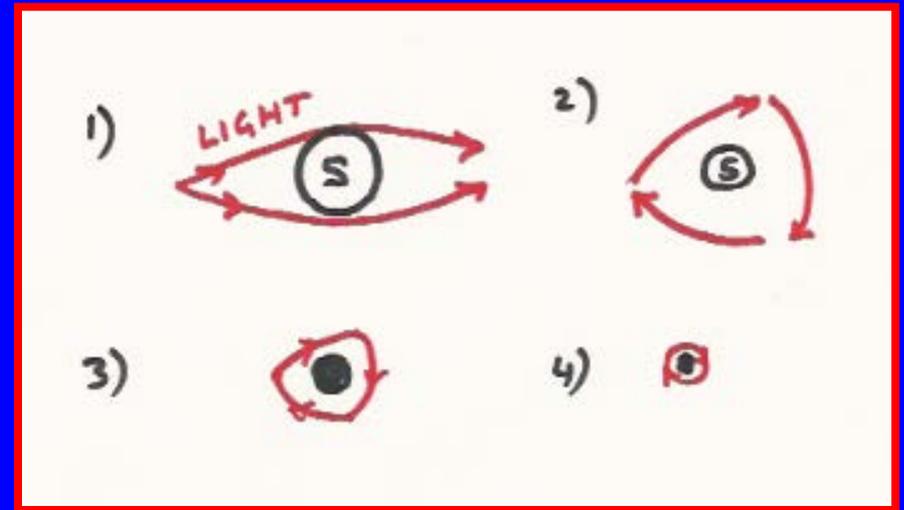


If spacetime bent

A far far away cluster of galaxies



Same Galaxy
See it twice!



Black hole when so crushed!

Dark Matter

There's something else very strange about the vacuum:
DARK ENERGY

Astronomers say something is making the Universe expand faster and faster!



"OK, so what's the speed of dark ?"

Stephen Wright

Dark Energy

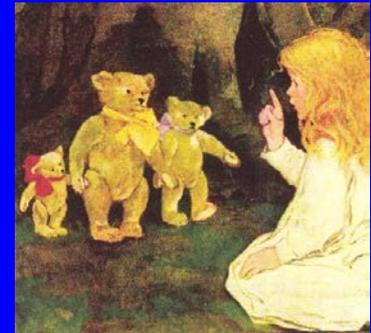
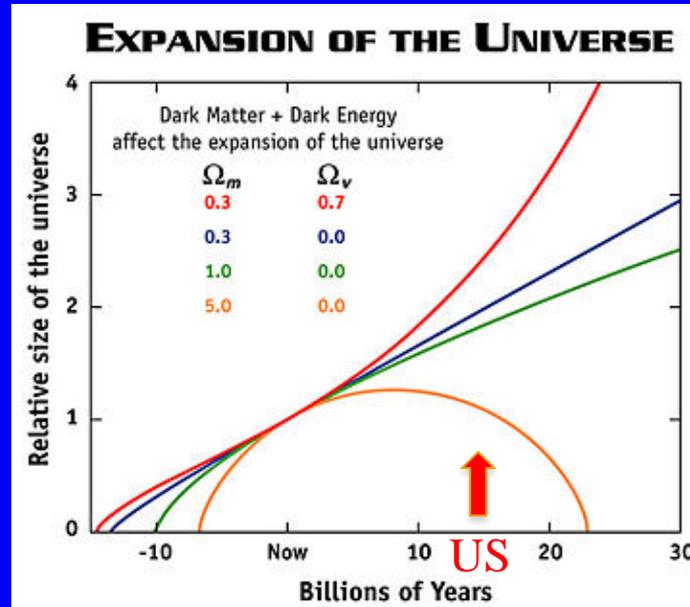
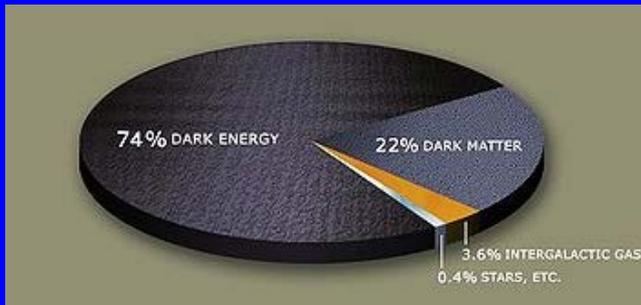
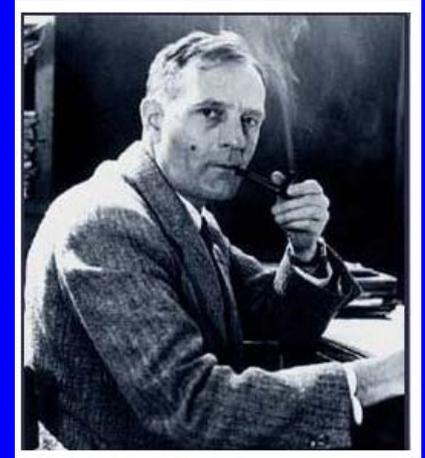
The Universe seems to be expanding faster and faster!

An extremely low density component of the vacuum.

Einstein had a term “cosmological constant” to allow a static universe (1917)

Hubble (1929): Universe expanding! Damn, drop it!

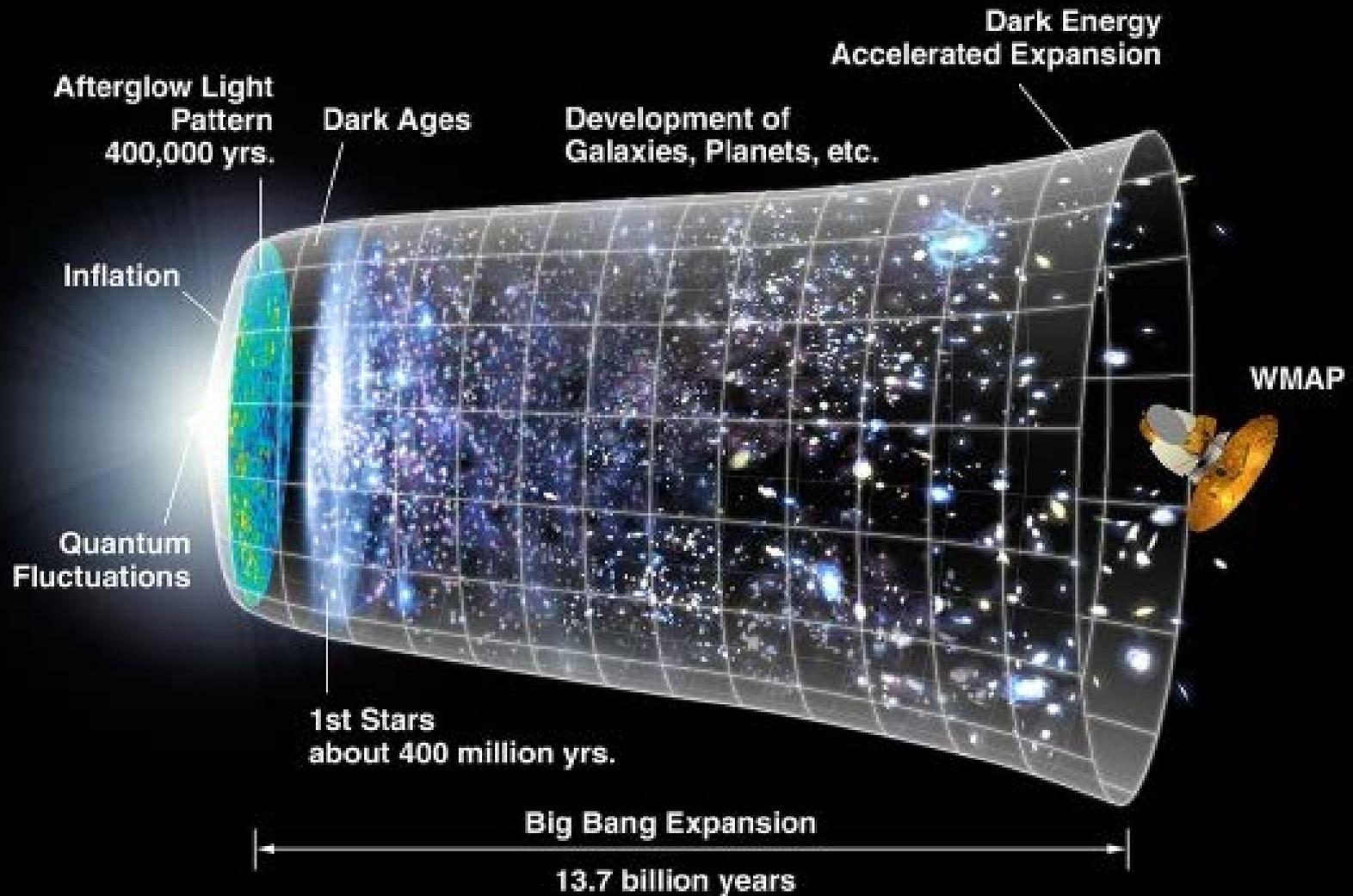
(1998-2000) Expansion accelerating! Damn, bring it back!



Goldilocks effect

What is it?

Purely schematic history of the universe!



Some property of the vacuum seems to be making the expansion go faster and faster !! **For EVER ??** Maybe not. **We have no idea! Or many ideas**

ZOOM IN ALL THE WAY – “PLANCK BOX”

Space seems smooth (so does time)

All the way down?

In a box 1 “Planck length” in size in 1 “Planck time”

Energy fluctuation (Heisenberg’s principle) → Planck mass

This would be a black hole!

Space itself gets “frothy”, unsmooth, full of (worm)holes

On larger scale if more than 3 dimensions of space “extra-dim”

Tightly curled up. (straw) Some theories have $3 + 8 = 11$ +time

The Higgs boson was the last missing piece of our *Standard Model*
of particles and interactions.

It closes a chapter but not the **Book of Nature**. Maybe only Chapter 1 ?

Finding it leads to the rejection of many wrong theoretical blind alleys.
That's SCIENCE

My personal belief / faith / hope :
There will be questions to answer
as long as humans are here to ask them

Why **3** matter families?

Why **3** space dimensions?
Are there more? 10,11?

Does **H(125)** decay as predicted?
Hopefully not!

What is **DARK MATTER**?
Other particles? SuperSymmetry?

Is our **UNIVERSE** just one
among trillions?

How do **neutrinos** work?

12 matter particles

What happened to all the **ANTIMATTER**?
different masses? Calculate?

What is **DARK ENERGY**?
Why is the Universe accelerating?

Do the **strong** and **electro-weak** forces unify?

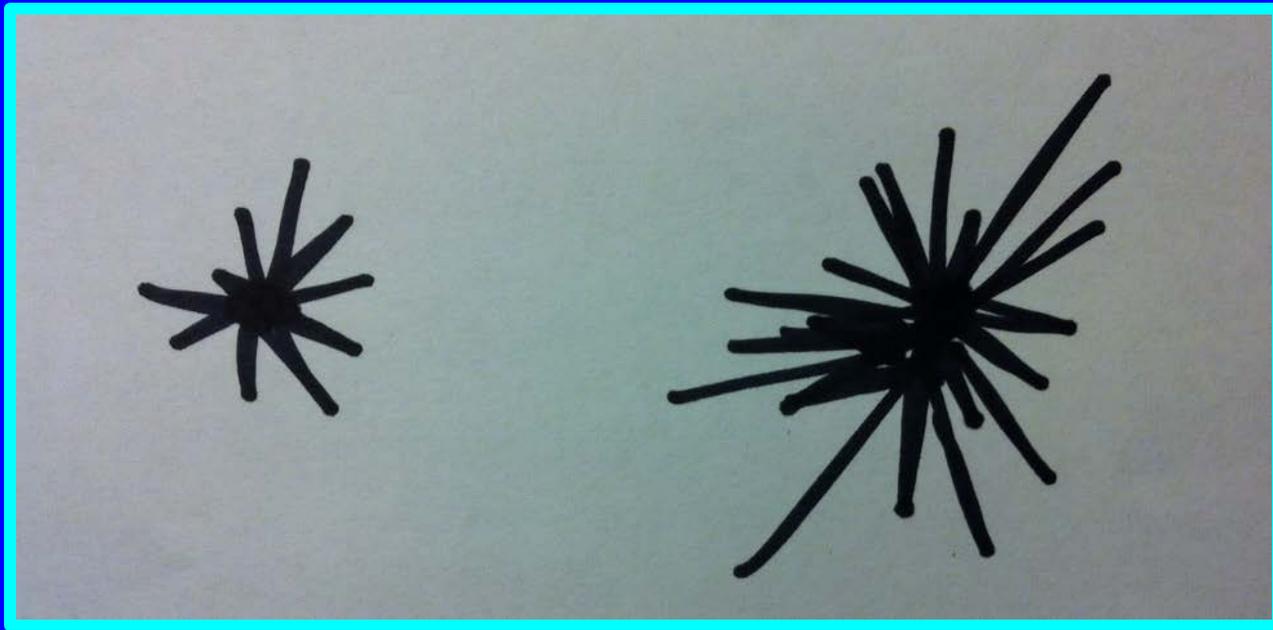
What will happen in **DEEP TIME**?
 10^{20} years? 10^{100} years?

THANK YOU

BACK UPS →

What about a particle “at rest” ?

With no Higgs field it zips off at the speed of light, but the H-field keeps kicking it back. A heavier particle (muon) interacts more strongly and it stays “small”. A light particle (electron) interacts more weakly:



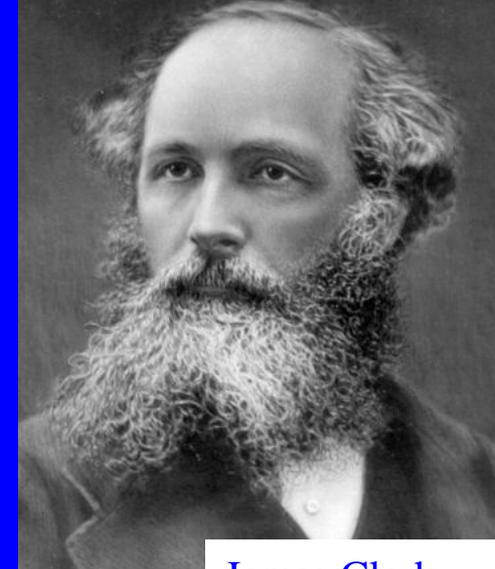
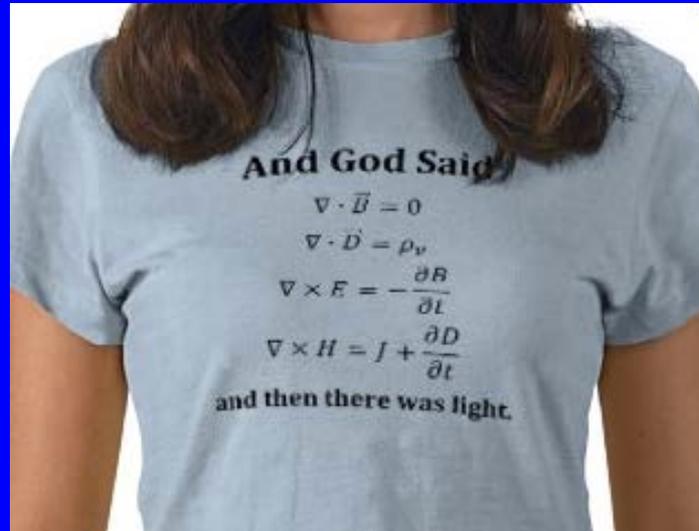
Muon (μ)

Electron (e)

Note: these diagrams are magnified gzillions of times!



Michael Faraday



James Clerk Maxwell



ELECTRICITY

Maxwell combined the equations and out popped a speed. He put in the numbers and out came 186,000 m/sec! Light! One theory, electromagnetic waves:

Radio, microwaves, heat, light, X-rays, gamma rays

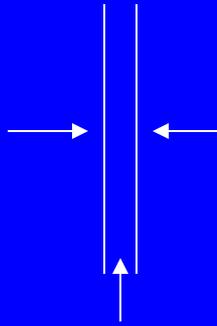
MAGNETISM

UNIFY!

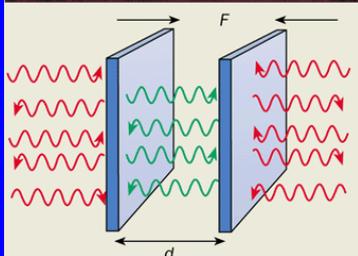
Light!
Photons!



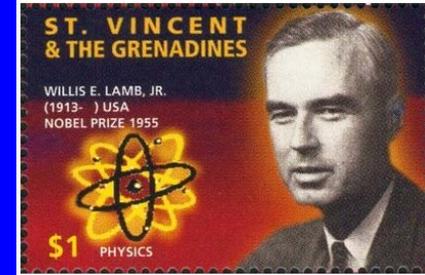
Casimir force:



Long wavelength
EM vacuum modes
excluded:
plates attract

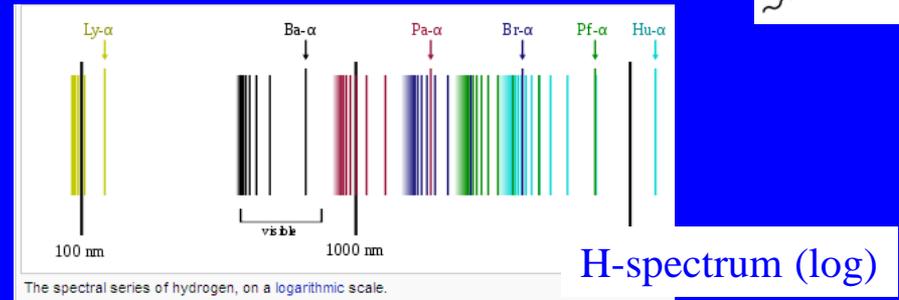
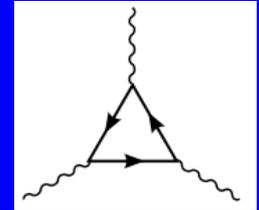


Lamb shift:

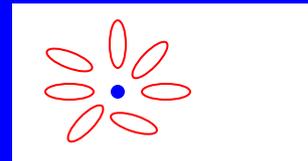


Virtual e^+e^- vacuum fluctuations
Virtual photons
Shift levels \rightarrow microwave

QED

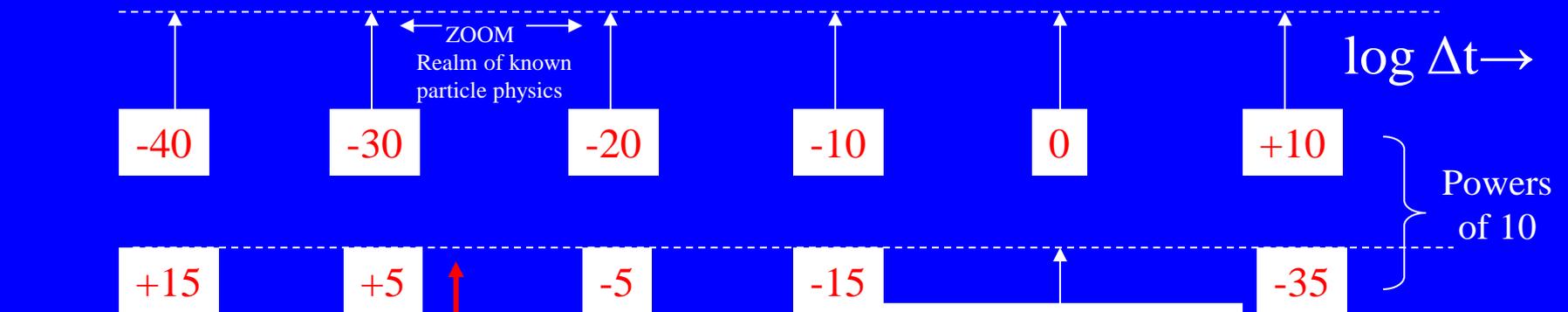
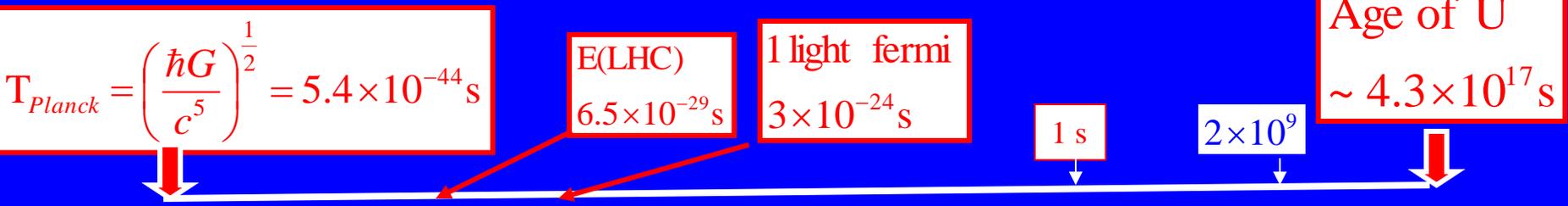


Running of α_s, α_{em} : vacuum polarization



Vacuum is teeming with EM fluctuations

Energy and time scales



$\leftarrow \log \Delta E \text{ (GeV)}$

$\hbar = 6.6 \times 10^{-25} \text{ GeV}$

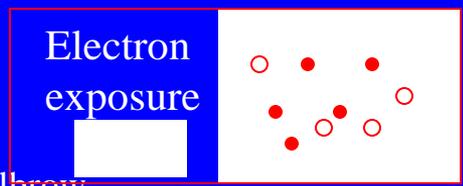
Realm of everyday life

GUT Scale X, Y, Z ?
H?

\rightarrow Dark Energy?

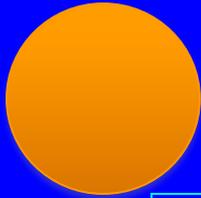
MONOPOLE LOOPS?

Axion condensate?



Symmetries: the basis of physics

Sphere: rotate it any way ... the same



Emmy Noether:



Most brilliant mathematician
Could not get a university post
Had to lecture under professor's name



Orientation of experiment does not matter (if no external fields)
Physics the same in any place → momentum conservation
Physics the same at any time → Energy conservation

But matter –antimatter symmetry is broken! We are all matter.

WHY?

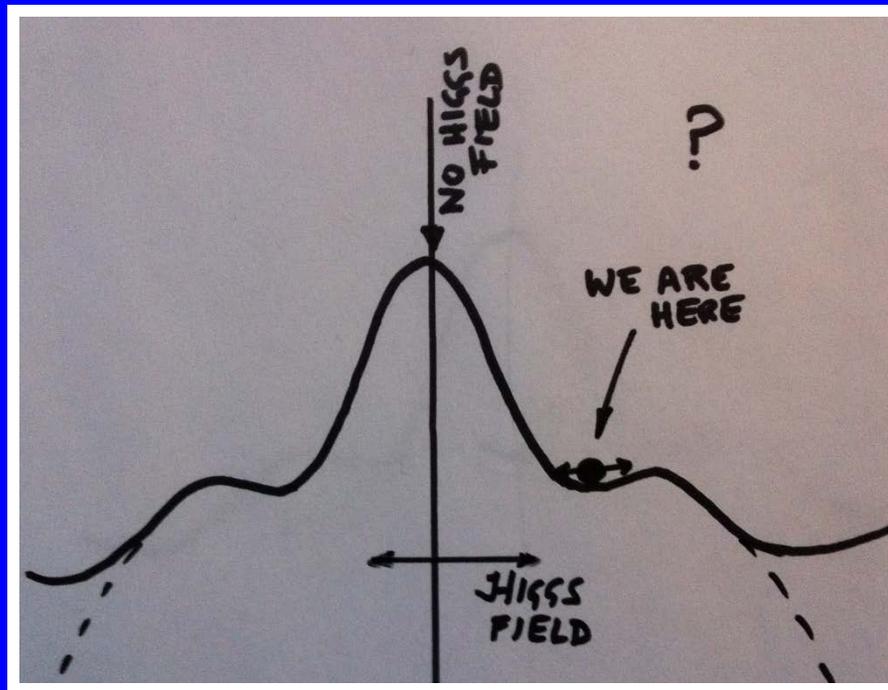
Some theorists say:

If the Higgs boson were much lighter than about 125 GeV

The vacuum would be unstable!

Like clean pure water below freezing, drop in an ice crystal and

WHOOSH! all ice



Unless new physics is there at higher energies.

But then maybe not. It didn't happen yet in the whole Universe!