(Anti)Matter of the Day

Pavel Nadolsky

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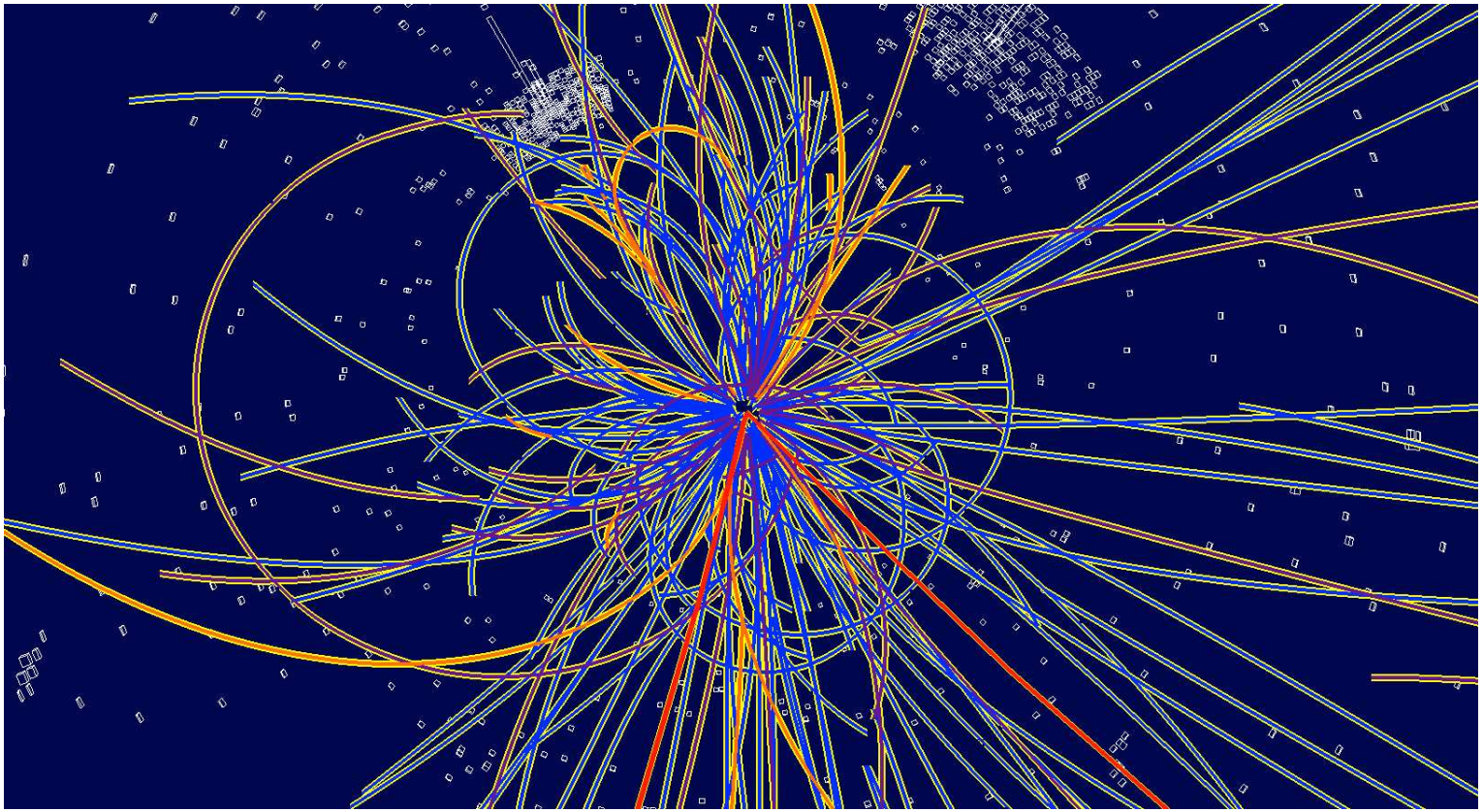
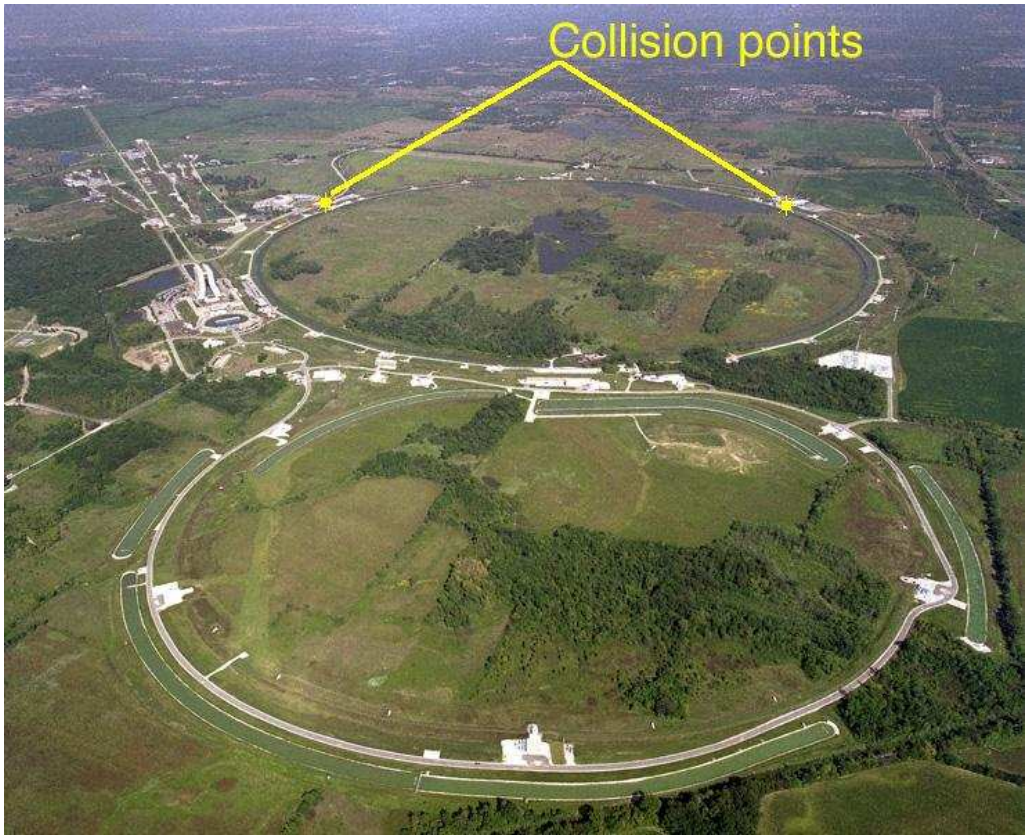
August 5, 2009

Awaiting for discoveries of unseen dimensions...



Particle physicists sizzle in anticipation of the most important leap in our field since the discovery of top quark in 1995

Awaiting for discoveries of unseen dimensions...



25 years since its commission, the Fermilab Tevatron collider near Chicago (with energy of 1 TeV per each beam) operates at the top of its performance; has an excellent chance to discover or rule out a long-sought Higgs particle predicted by the Standard Model

Awaiting for discoveries of unseen dimensions...

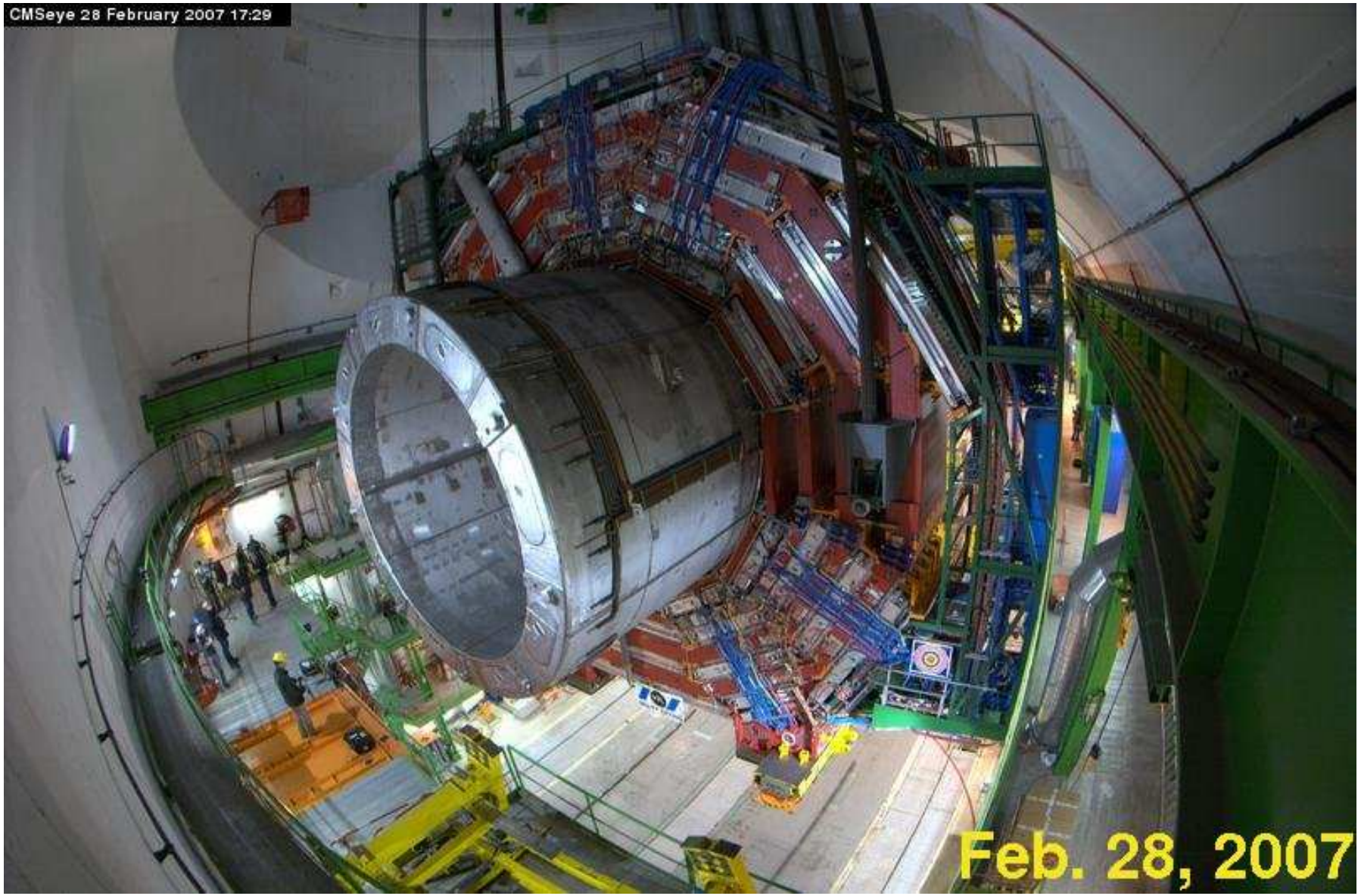
The Large Hadron Collider at CERN is an experiment of superlative scope; gets ready to produce the first set of data in November at energy 4-5 TeV per beam; will be eventually ramped up to 7 TeV

Awaiting for discoveries of unseen dimensions...

LHC attracts unprecedented public attention...

...in mass media

Compact Muon Solenoid as seen by BBC



...in mass media

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'It's like stepping on to a film set'

Construction of the Large Hadron Collidor, a giant underground particle accelerator, is reaching a major milestone as a key piece of machinery is lowered into the ground. BBC News Science Correspondent David Shukman reports from the scene.

It's like stepping onto the set of a James Bond film.

Or possibly something involving Austin Powers.

YB0 is the biggest and most impressive element of the CMS

Everything here is on a vast scale; billions of cables woven together, silicon sensors by the thousand, towering shapes of steel, impossibly

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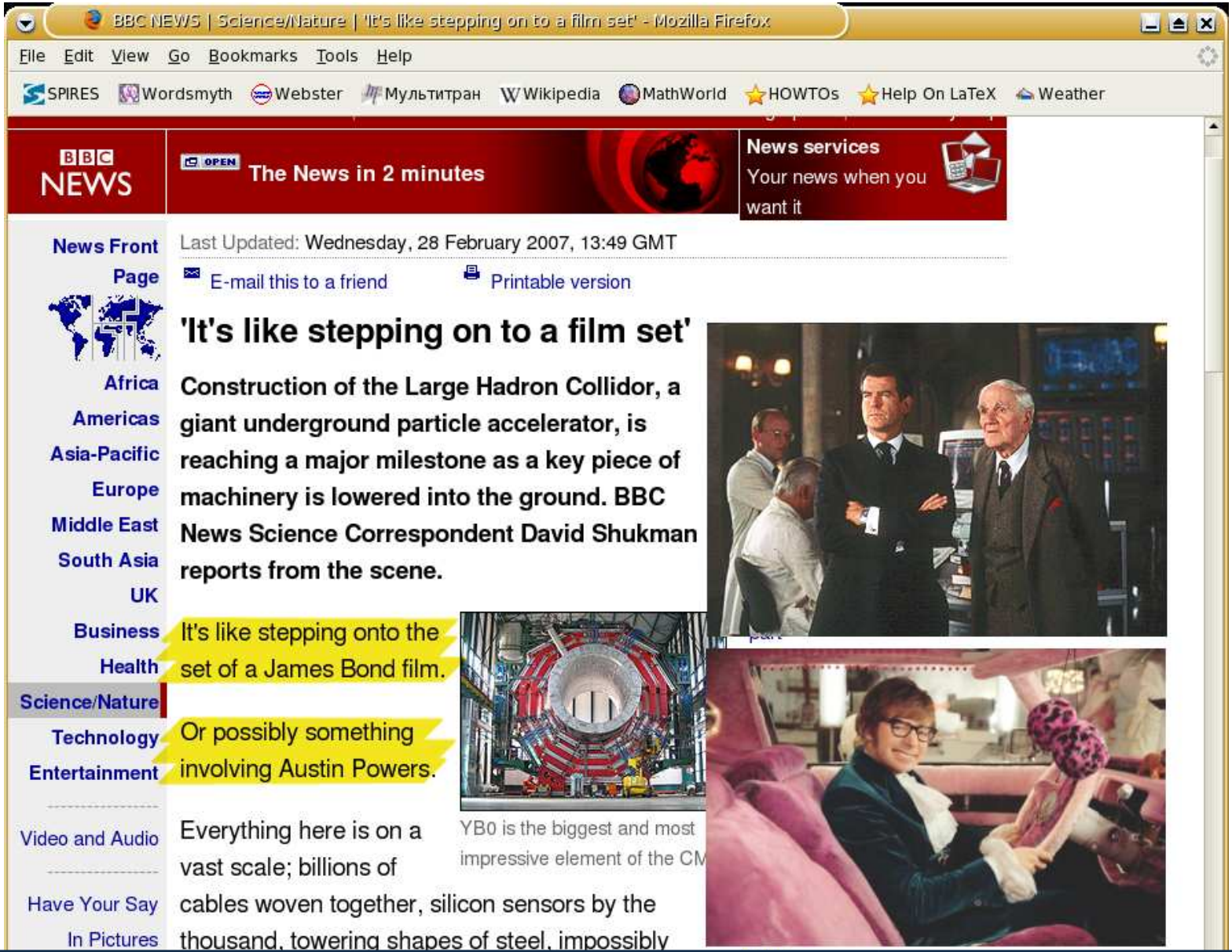
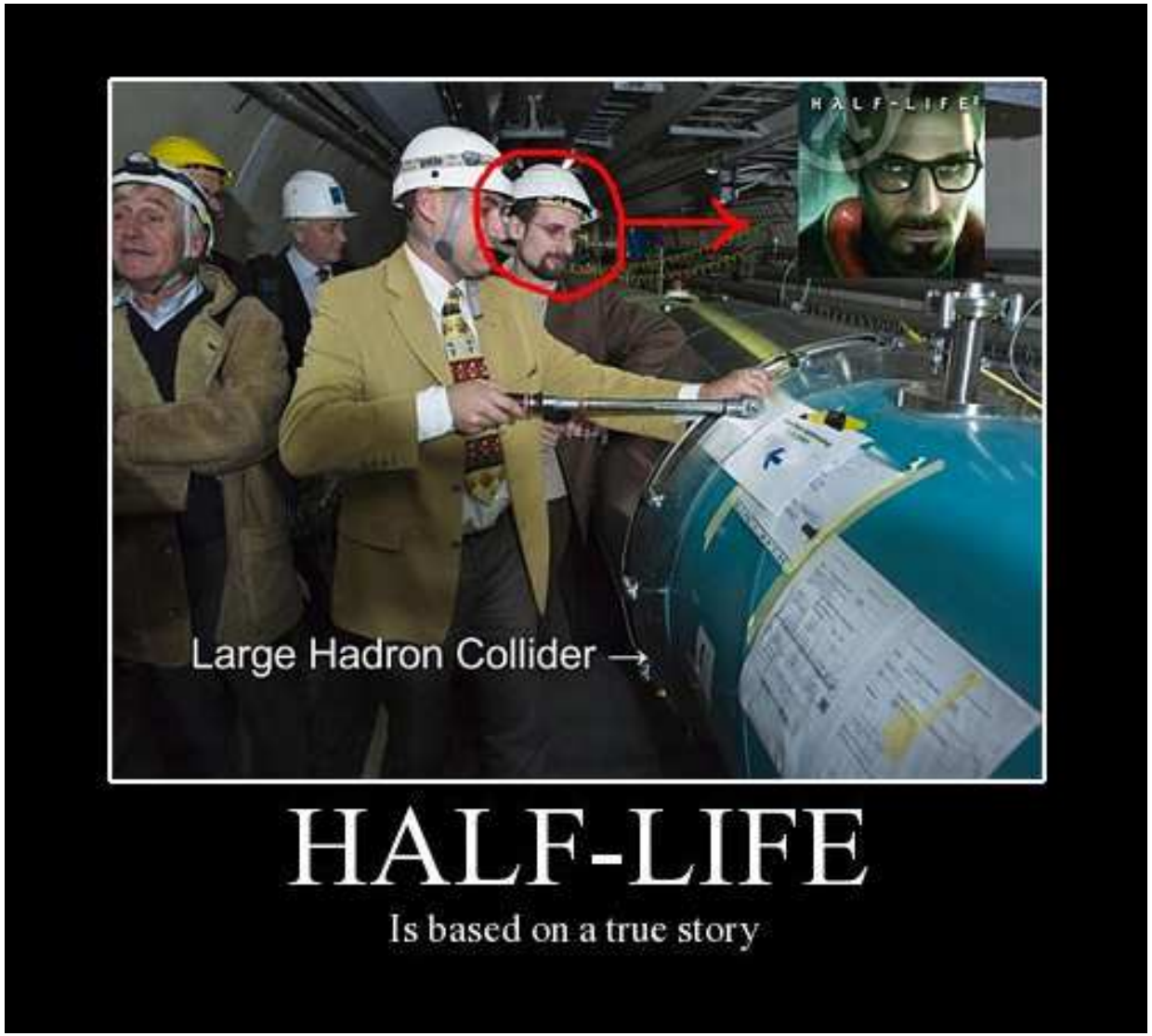


... in popular computer games

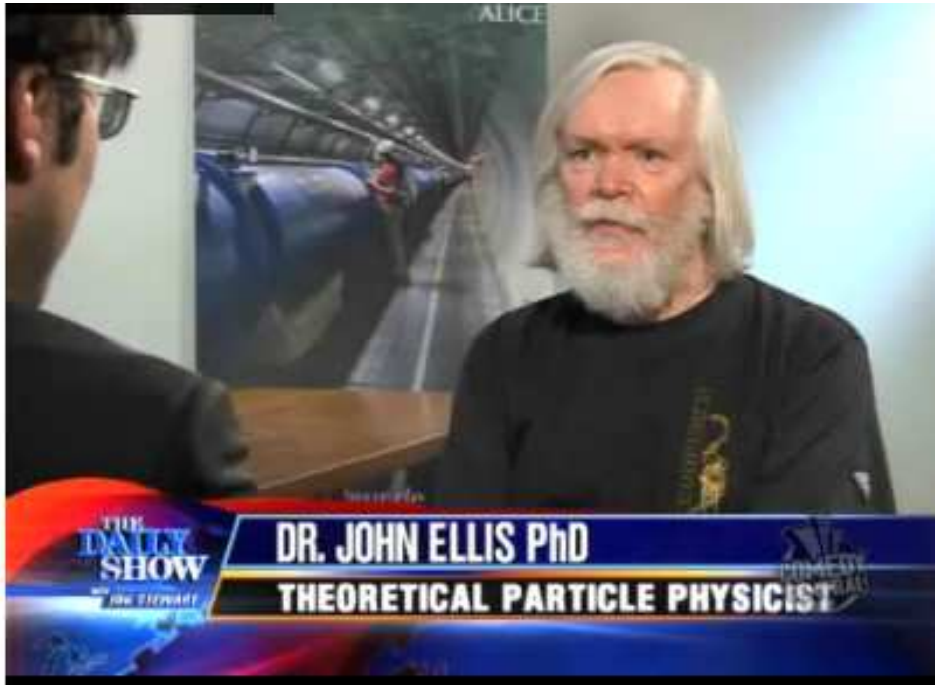


... in music

http://bit.ly/gWOc1

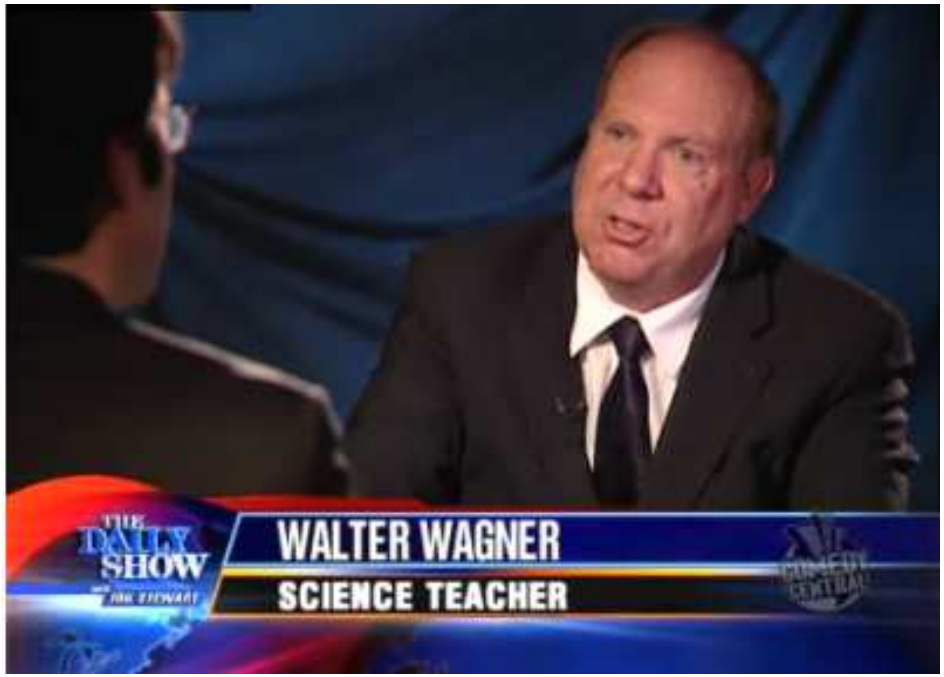
...in analytical shows

Jon Stewart: What is the chance that the LHC will destroy the Earth?



Head of the CERN Theory Division:

"The chance is absolutely zero percent"

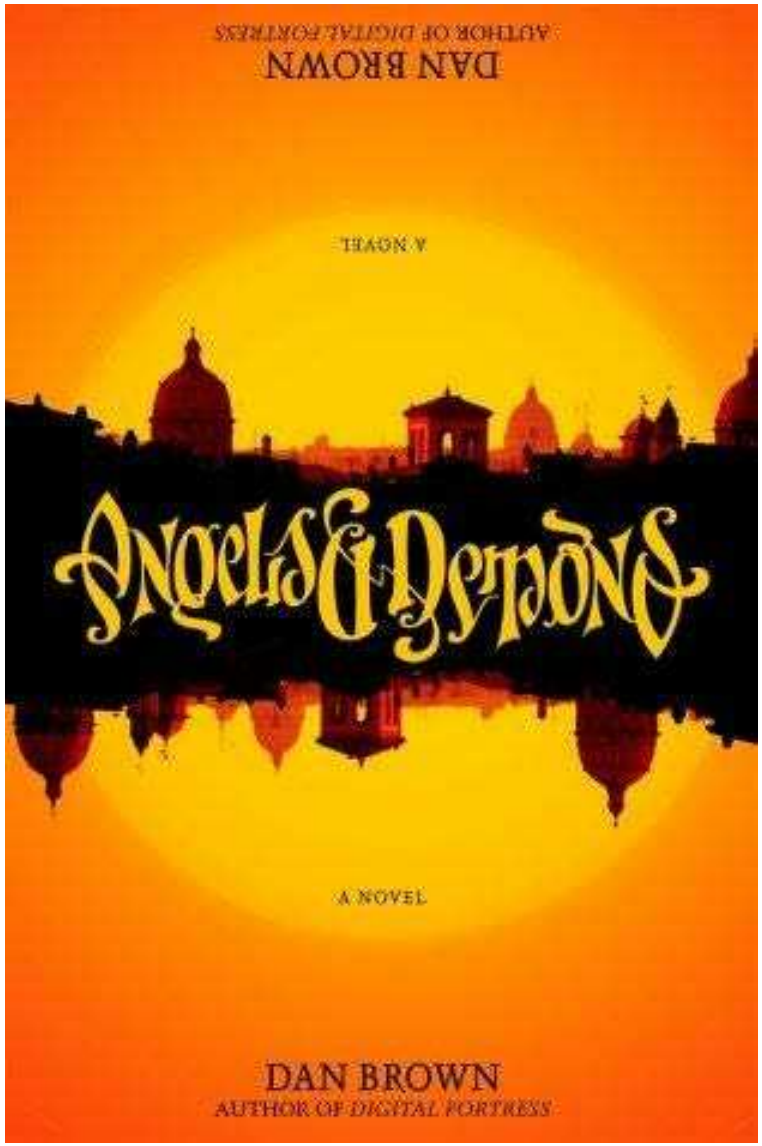


An author of a lawsuit against LHC:

"The chance is really 50:50: either it will happen, or it won't"

http://bit.ly/rZahR

Angels and Demons



A best-selling book by Dave Brown (2000) features the LHC

Angels and Demons

A movie starring Tom Hanks (May 2009) has a part filmed at the LHC

Angels and Demons

National Science Foundation, US Department of Energy, CERN, and Fermilab organized public lectures after the movie premiere about the science pursued at the LHC

PowerPoint template and video clips for the lecture are available at *http://uslhc.us/Angels_Demons/*

Angels and Demons: the plot

- Antimatter – a highly explosive substance – is stolen from the CERN's LHC and hidden in Vatican City
- Countdown to Vatican annihilation begins
- Race through Rome to avert death and destruction

CERN in the book and the movie

A top secret facility designed to reproduce Big Bang conditions

Real-life CERN

Near Geneva, Switzerland

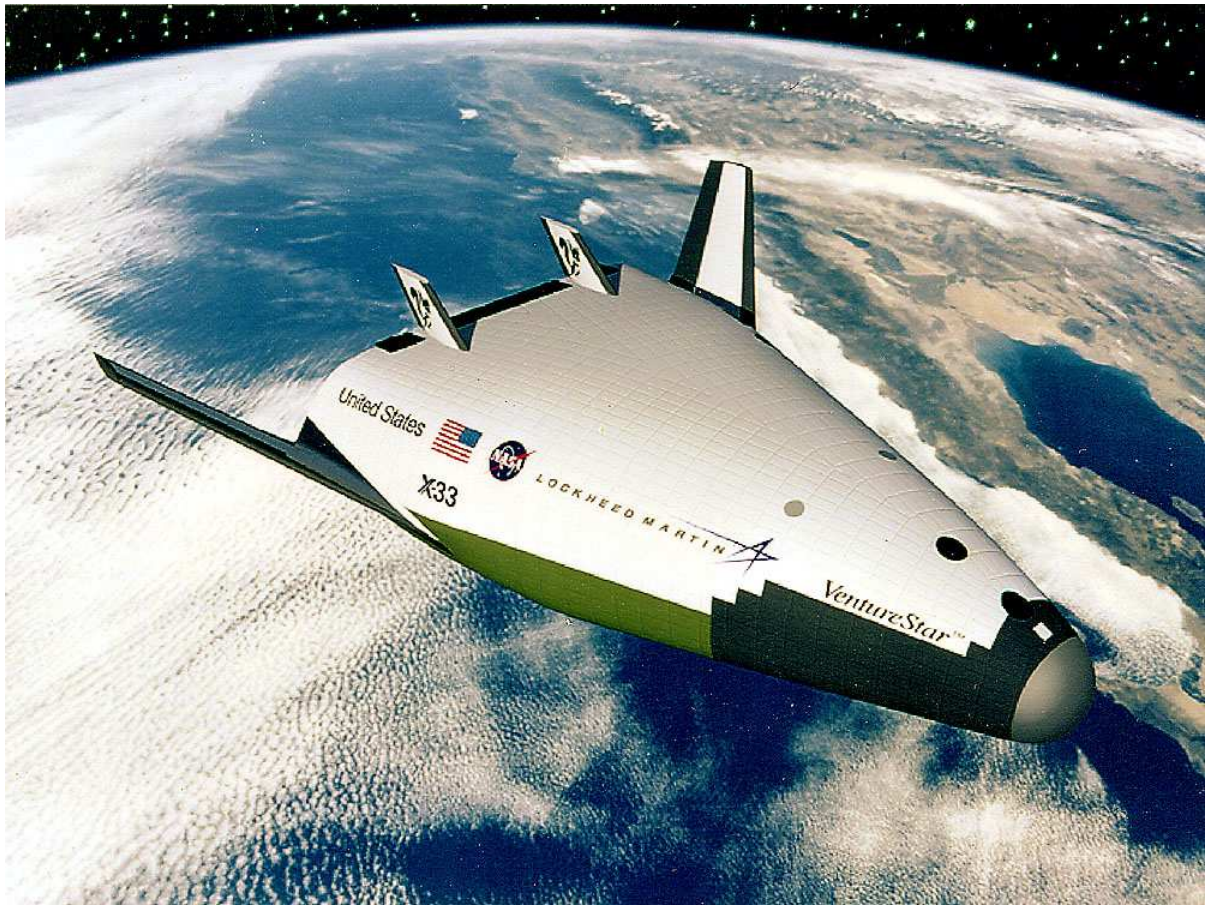
Not top secret

CERN

- European Laboratory for Particle Physics
- Founded in 1954
- 20 member countries
- More than 9,000 scientists
- Over 100 nationalities
- More than 1,000 from U.S. universities and labs

Amazing Things that real CERN does not have

A CERN-owned space plane to fly from US to Europe in 1 hour



Sorry, Bob, Ryszard, SMU postdocs and grad students participating in CERN ATLAS collaboration

A wind tunnel for parachute jumping during after-hours...

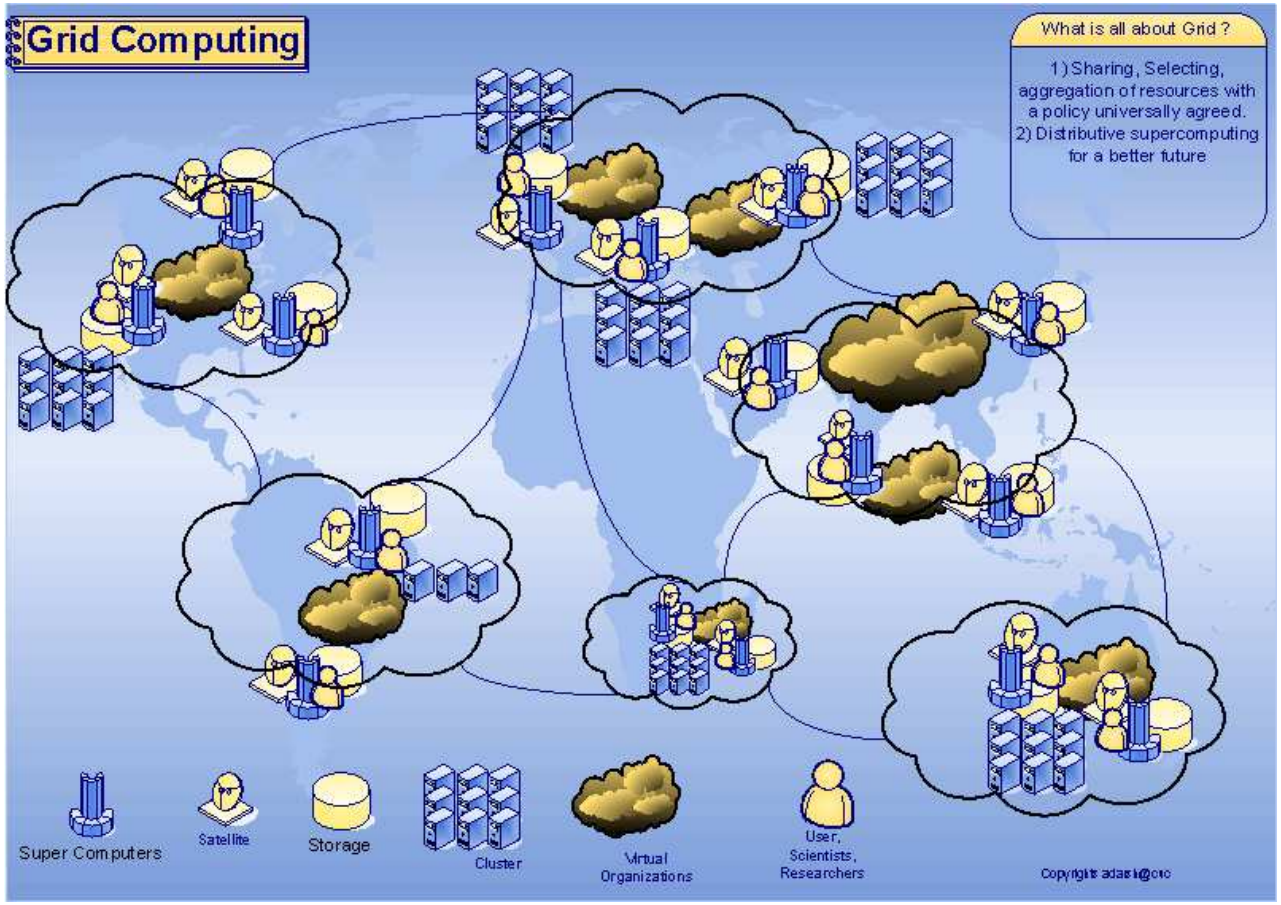
Amazing Things that real CERN does have

High-tech retina scanners to enable operation safety

Research in information technologies that resulted in invention of the Internet

Fred Olness (SMU) near the first WWW web server at CERN museum

The GRID – a computer network of new generation for distributed data processing



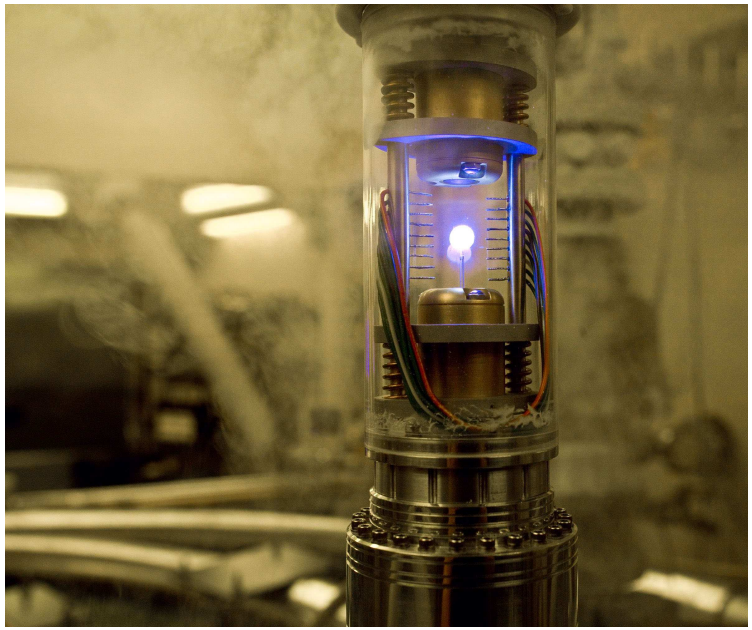
The Large Hadron Collider, the world's most powerful particle accelerator

- 16.8 miles around, 330 feet underground
- collisions of two proton beams, each with energy sufficient to pierce 100 feet of copper
- the energy stored in its superconducting magnets would equal that of an Airbus A380 flying at 450 miles an hour

Is there antimatter at CERN?

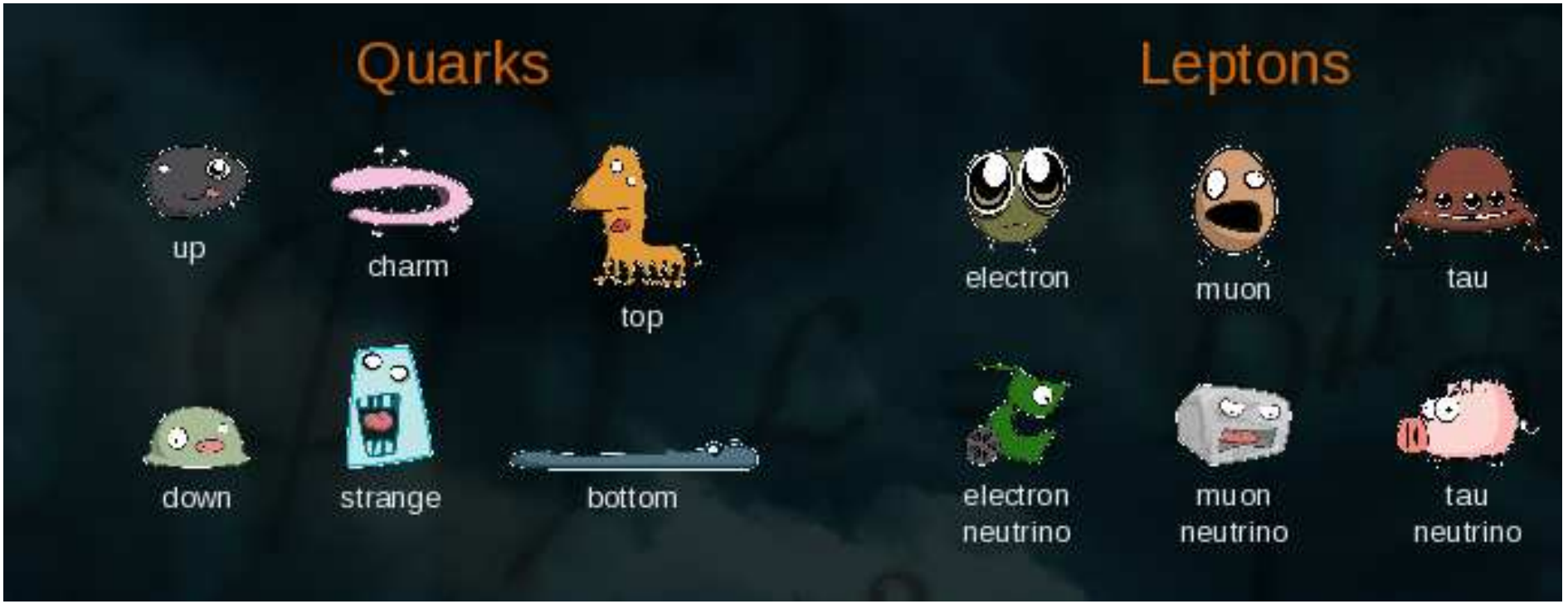
Antimatter

- It is real
- It is indeed produced at the Large Hadron Collider
- If enough of it, it could destroy Rome
- What is it?



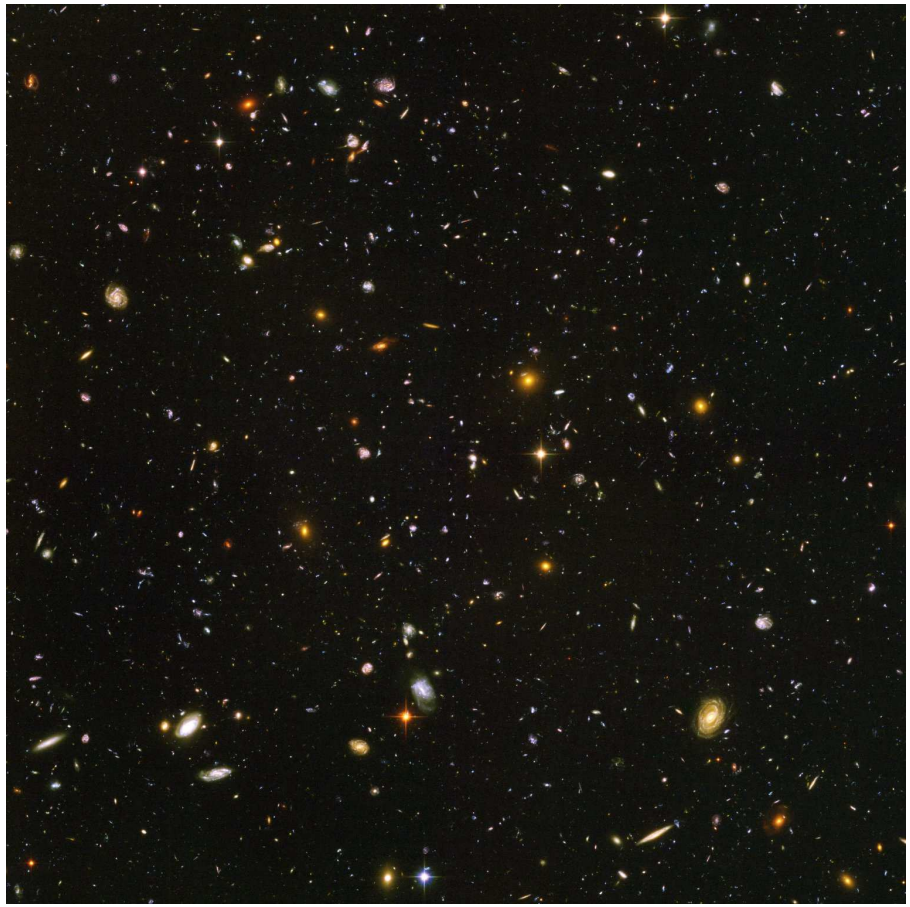
What is matter?

Massive particles in various combinations...



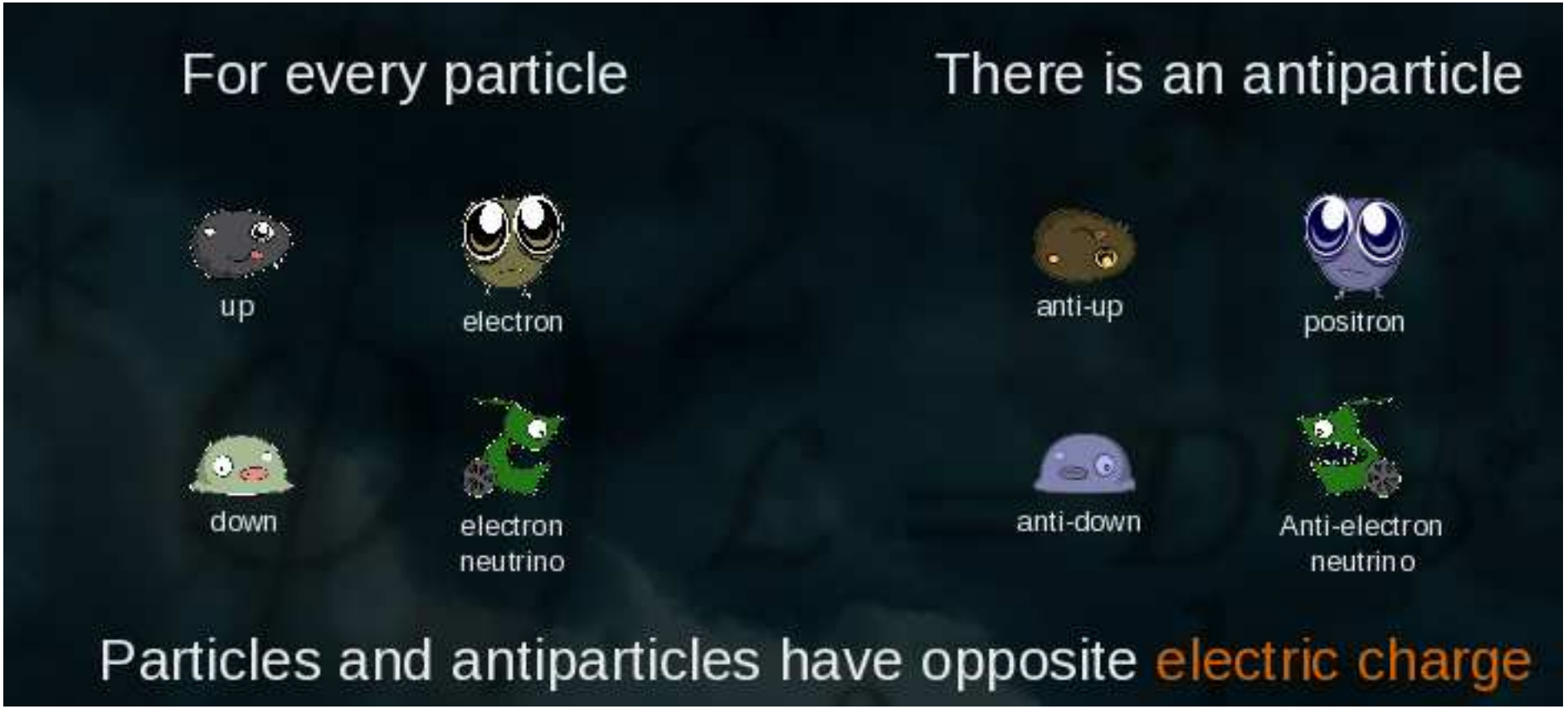
... plus carriers of forces (photons, weak bosons, gluons, and gravitons)

What is matter?



Visible objects in the Universe are built of matter particles

Where does antimatter fit?



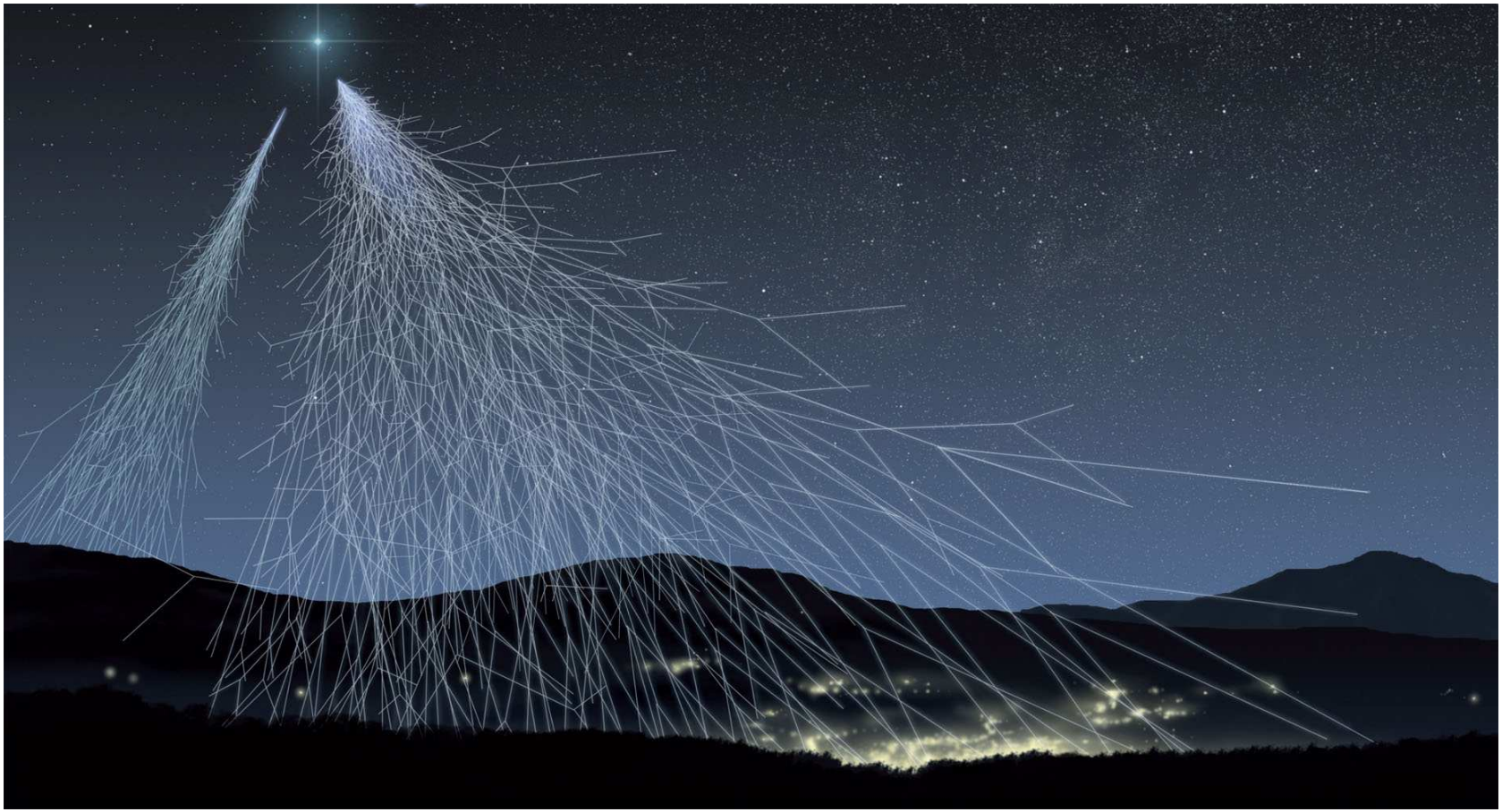
Can we make antimatter?

We can, and we do

In particle accelerators

Can we make antimatter?

Nature can, too



Matter vs. antimatter

Anti-Tom Hanks

would look very much like

Tom Hanks

Matter vs. antimatter

Anti-Tom Hanks

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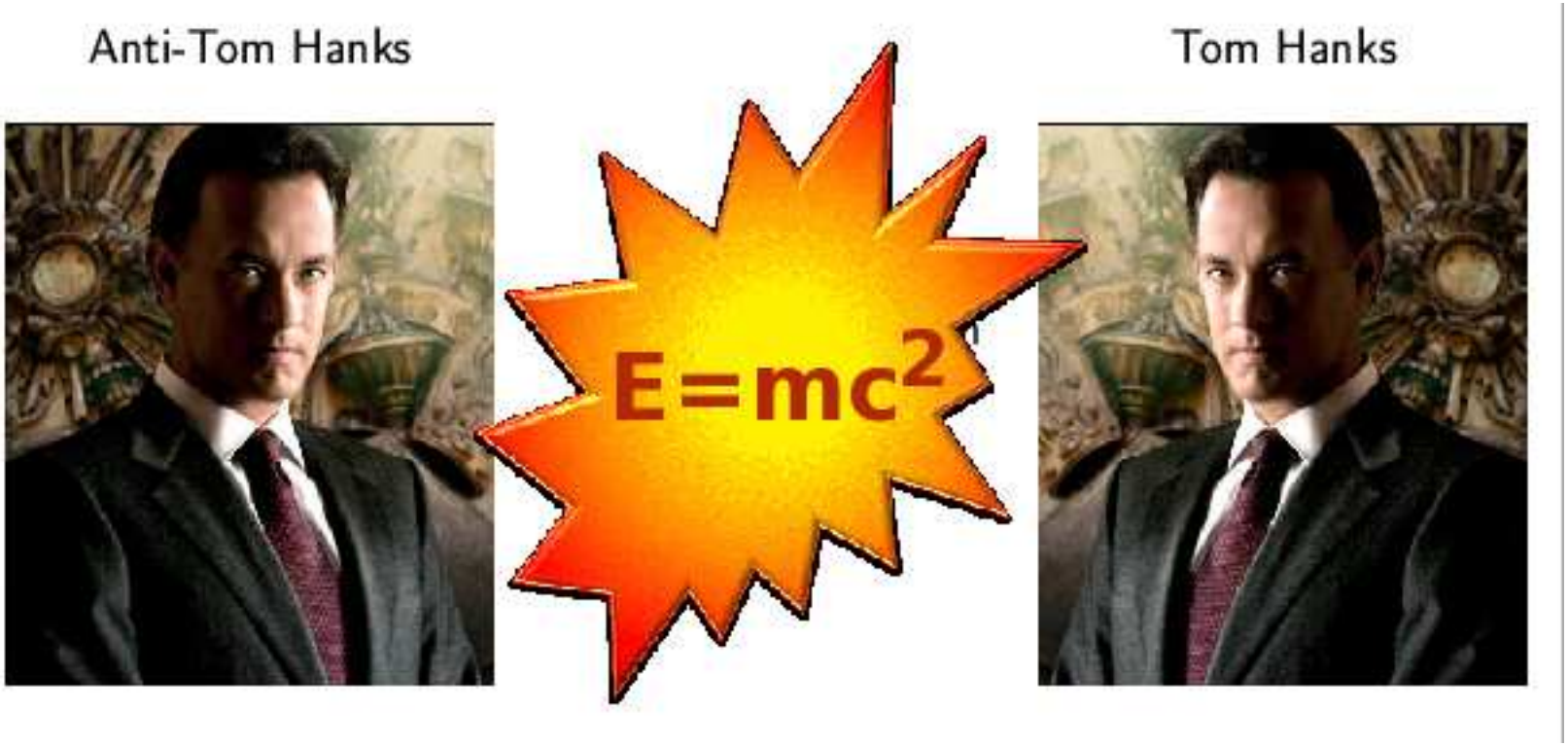
... but were they to meet...

Matter vs. antimatter



... but were they to meet...

Angels & Demons & antimatter

- Rome is threatened by $\frac{1}{4}$ gram of antimatter
- Annihilation of $\frac{1}{4}$ g matter + $\frac{1}{4}$ g antimatter = 10 kilotons of TNT
  - compute it using $E = mc^2$
  - 1 ton of TNT releases $4.2 \cdot 10^9$ J
- More than enough to destroy the Vatican

Can antimatter be an energy source?

Efficiency parameters for fuel materials

- Efficiency of energy extraction (EEE)

$$\text{EEE} = \frac{\text{energy returned}}{\text{mass} \cdot c^2}$$

- Efficiency of energy production (EROEI = Energy returned on energy invested)

$$\text{EROEI} = \frac{\text{energy returned}}{\text{energy invested}}$$

Extraction of 1 barrel of mid-Eastern oil consumes the equivalent of $1/30$ oil barrel of energy. $\Rightarrow$ EROEI for mid-Eastern oil is 30

Economically viable fuels have EROEI> 1

Comparison of fuel materials

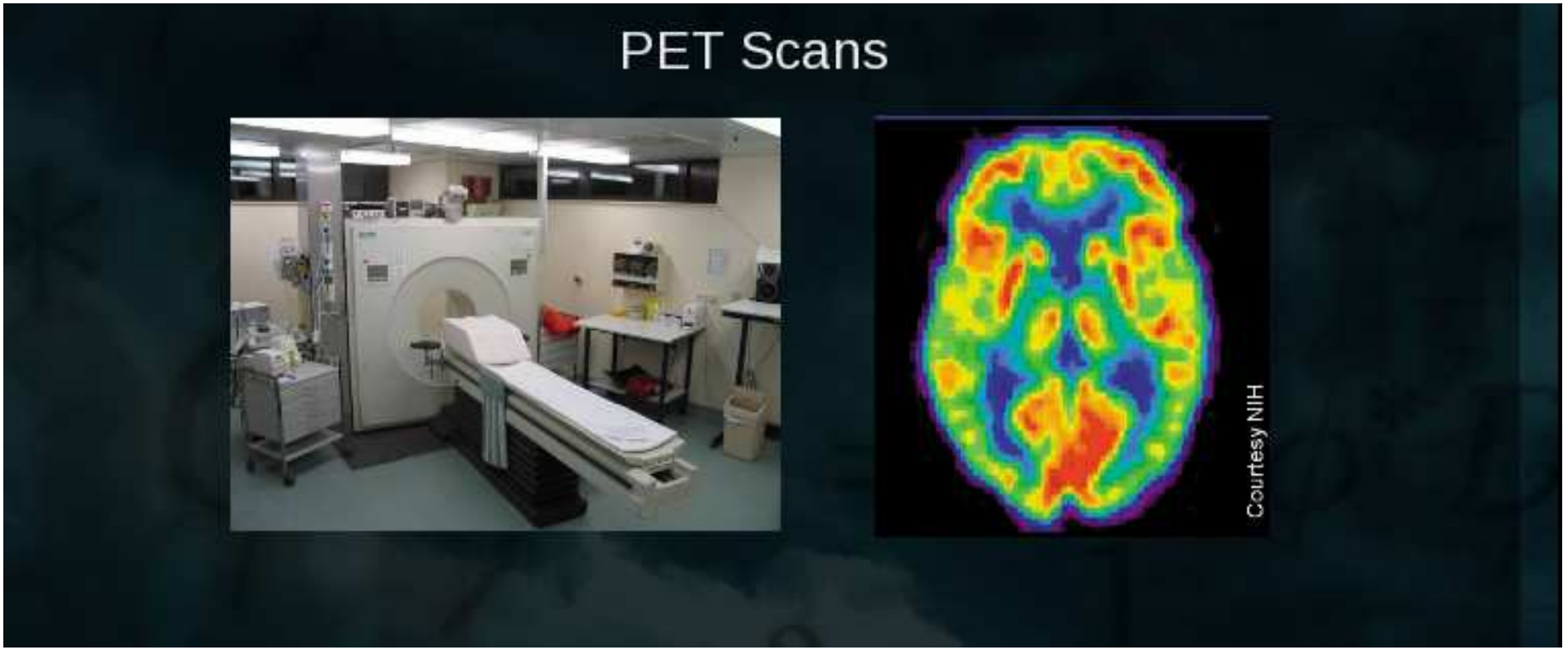
Material	EEE	EROEI
Oil	$\frac{1}{1{,}000{,}000{,}000}$	**100 (1940's); < 30 (now); < 5 (by 2030)**
Tar sands, shale oil		1.5-4
Hydro power		45
Coal		~ 25
Nuclear	$\frac{1}{1{,}000}$	5-20 (depending on assumptions)
Wind		4-10
Solar		5
Antimatter	**1**	$\frac{1}{1{,}000{,}000{,}000}$

Can antimatter be an energy source?

- No. Anti-matter can release lots of energy...but it takes lots of energy to make
  - 62.5 trillion USD to produce 1 gram
- Humanity produces very, very, very little anti-matter
  - Fermilab creates $2 \cdot 10^{-9}$g of antiprotons per year; will take 109 million years to make $1/4$ gram

We're safe!

Antimatter can be used for



Antimatter can be used for

solving some of the biggest mysteries in science

- What is the origin of physical laws?
- Why do we have mass?
- Why is the visible Universe made mostly of matter? Where did antimatter go?
- What is “dark matter” and “dark energy”?

Physical laws as symmetries

- In particle physics, physical laws are often viewed as fundamental symmetries of nature

Symmetry

- Latin *symmetria*, from Greek "like measure"

1. balanced proportions
2. invariance; independence of the object from certain variations of parameters

Symmetries can be exact or approximate

Physical laws as symmetries

- Any physical law reflects some symmetry (invariance) of the physical system
- Examples
  - Physical laws do not change with time (are invariant under translations in time) $\Leftrightarrow$ conservation of energy
  - Physical laws are the same at any point in space (are invariant under translations in space) $\Leftrightarrow$ conservation of momentum
- Other physical symmetries exist, responsible for conservation of angular momentum, existence of physical forces, etc.

Symmetry= Ability to predict

In the real picture, Symmetry is wonderfully broken

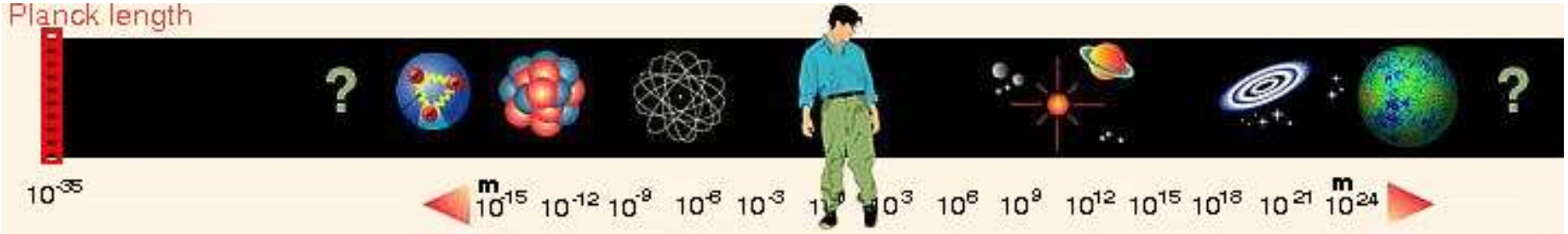
Piero della Francesca: Polittico della Misericordia

From the talk by L. Maiani (CERN)

Our universe is a strange place...

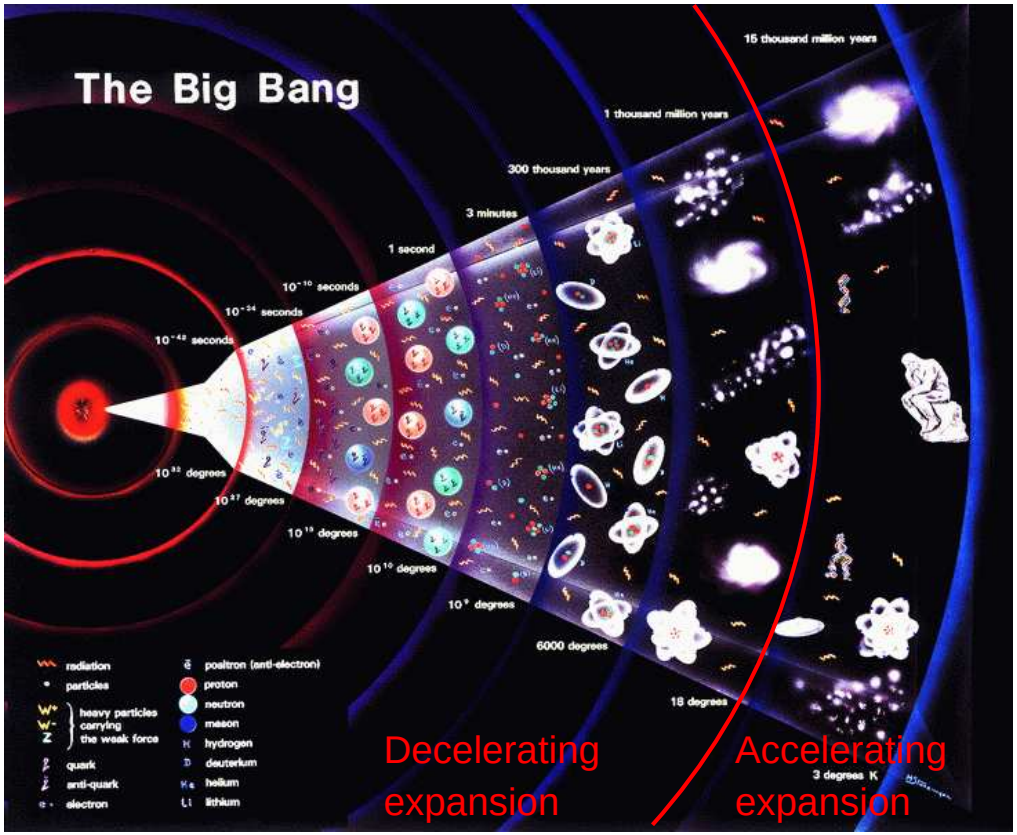
...a mixture of a few omnipresent symmetries and their numerous violations

- The visible universe
- is large, but finite in size
  - contains objects that are larger or smaller than our everyday world by many orders of magnitude
  - momentum conservation is an extremely accurate, but nonetheless approximate, symmetry



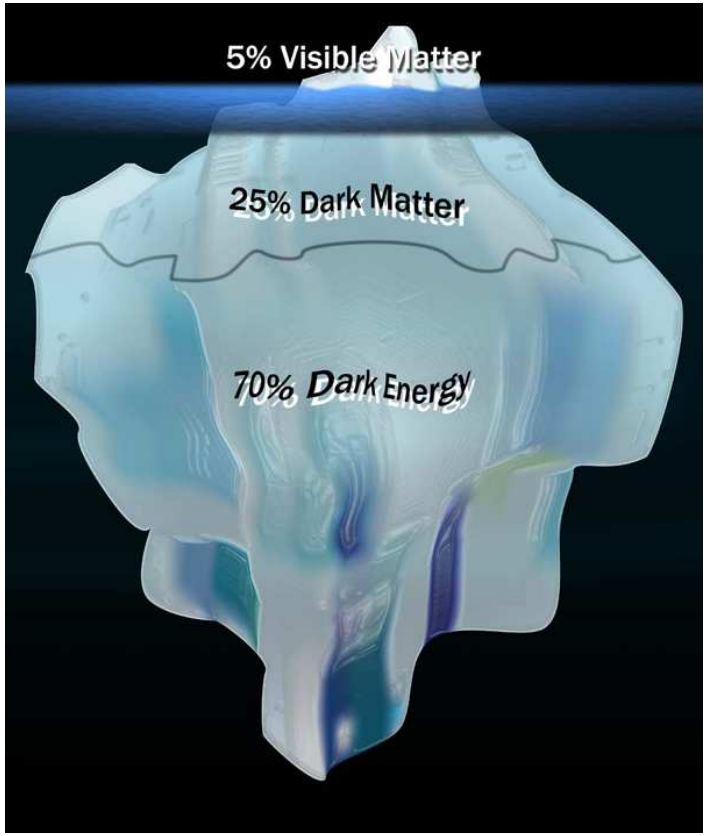
Historical timeline of the Universe

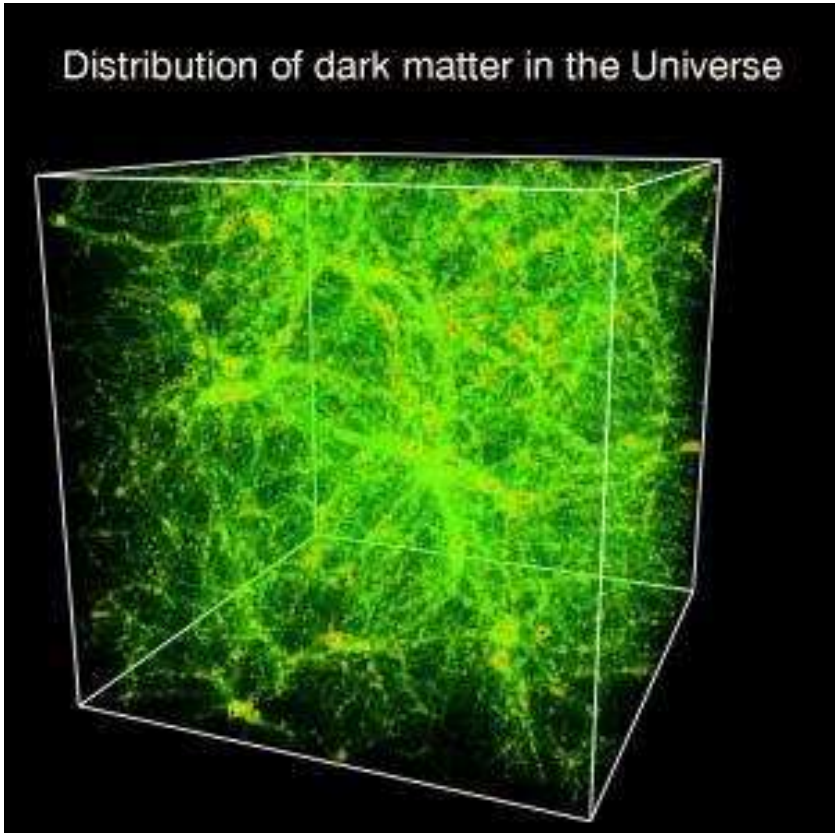
- The visible universe came into existence 14 billion years ago in the Big Bang; expands since then at variable rate



- energy conservation is also a very accurate, but still approximate, symmetry

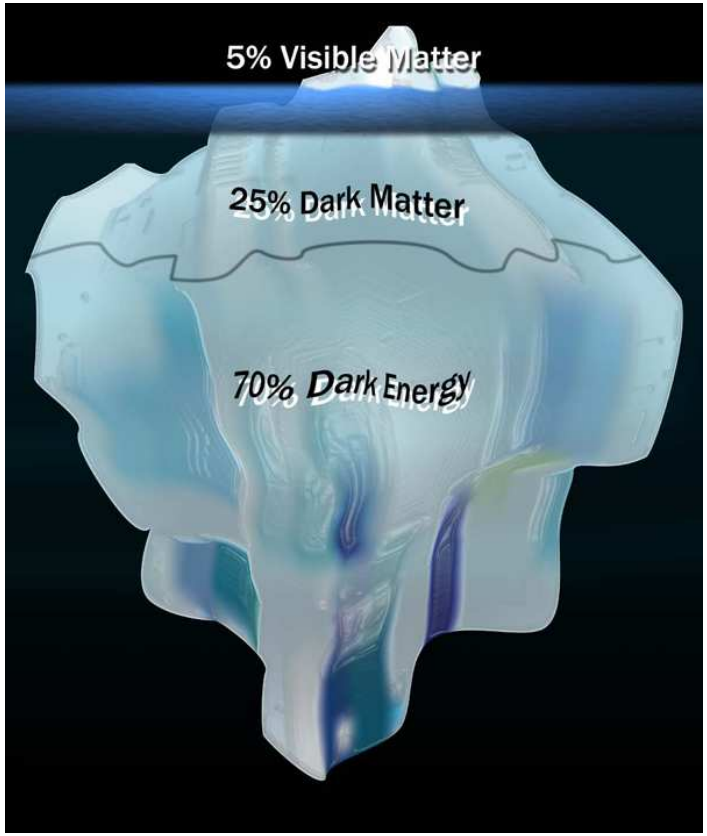
Mass (energy) composition of the universe

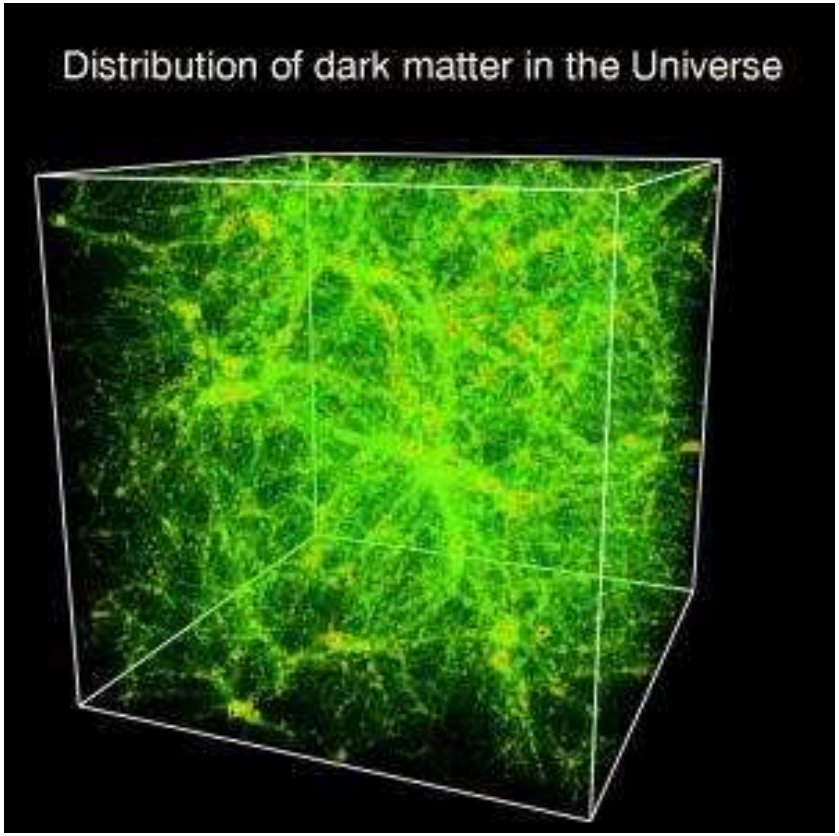




- 95% of matter exists in "empty space" voids in unknown forms
- Mysterious "dark energy" is needed to explain the accelerated expansion of the universe

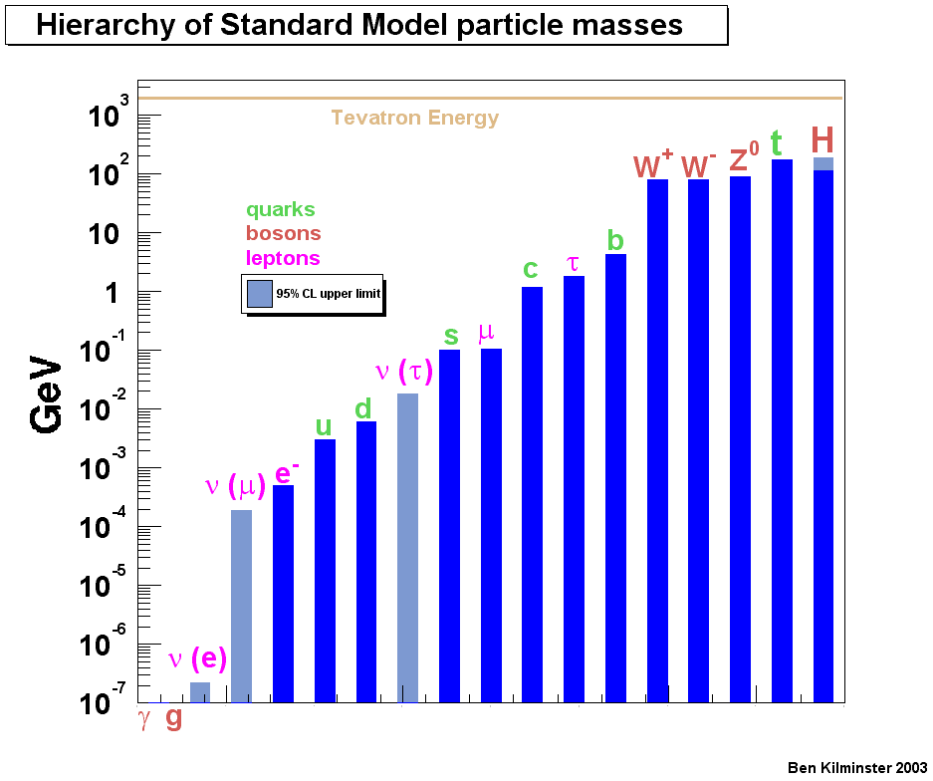
Mass (energy) composition of the universe





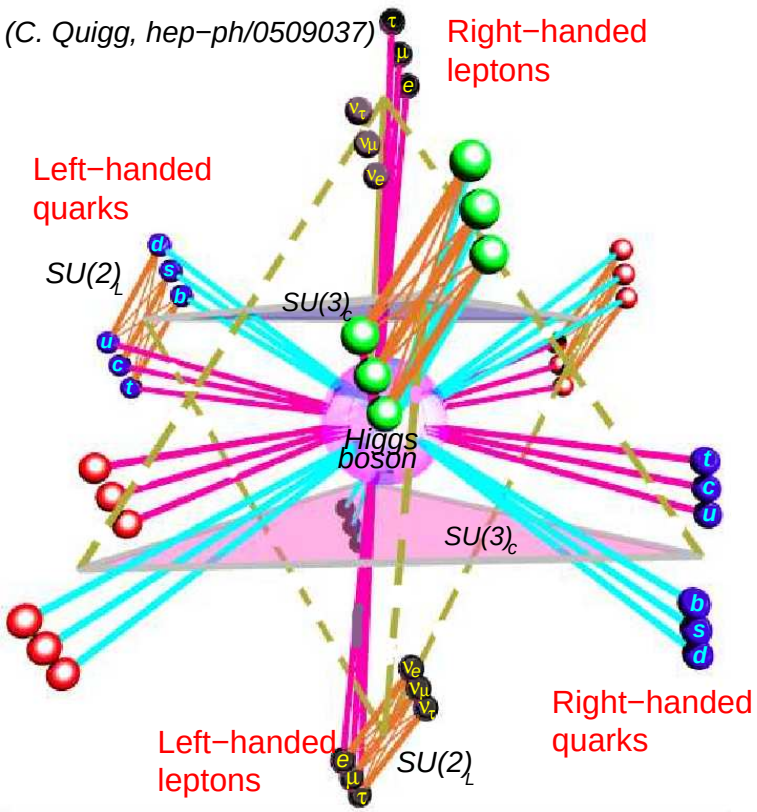
- Cosmological questions can be answered by studying space-time at the tiniest distances $\Rightarrow$ particle colliders!

Particle zoo



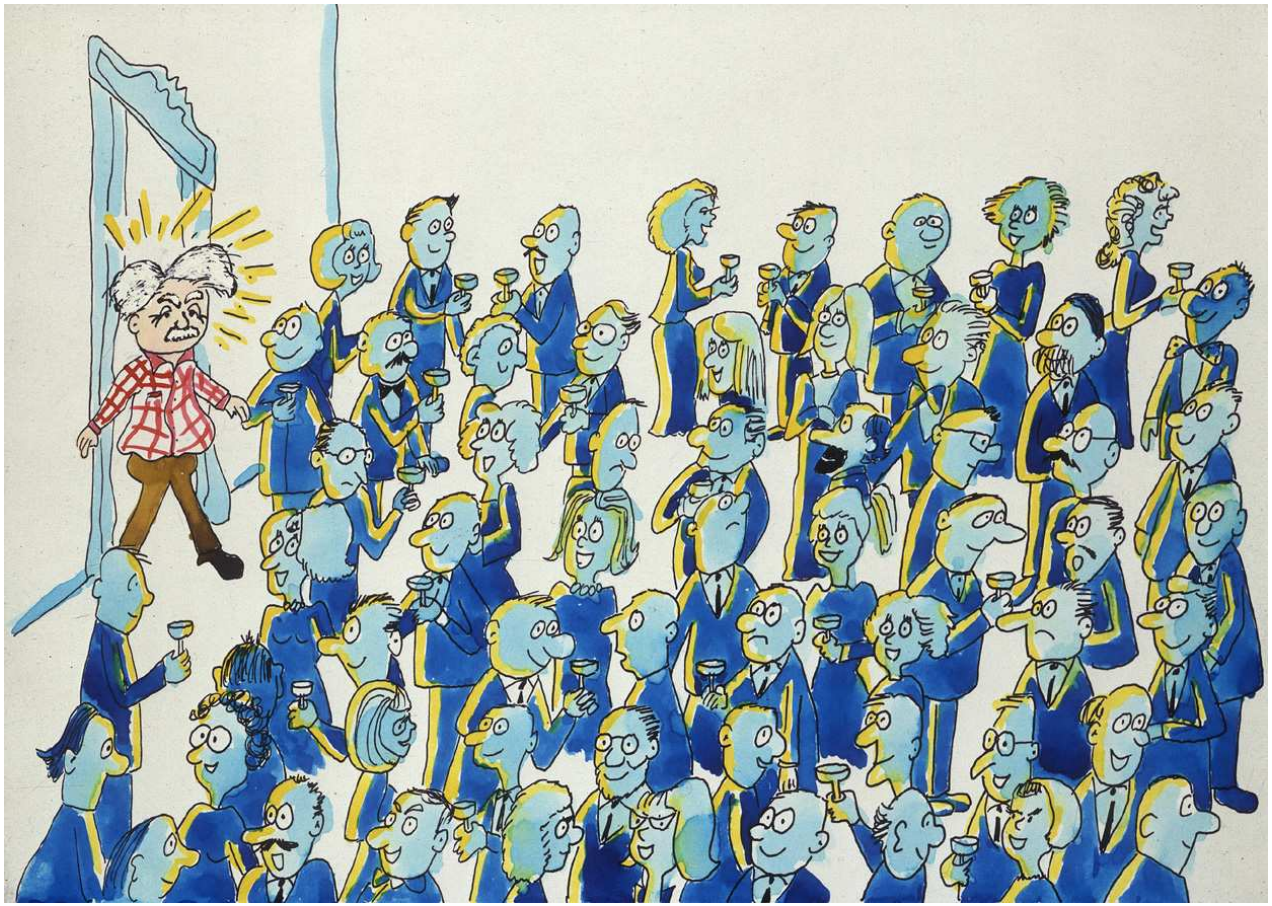
- Standard Model depends on many parameters, which appear to be arranged in random order
- For example, particle masses span 9 orders of magnitude (why?)

Profound symmetries of the Standard Model



- Nonetheless, particles are related in the Standard Model through very good symmetries between their interactions
- One also expects to find a new Higgs field that
  - breaks the symmetry between electromagnetic and weak interactions
  - **dynamically** generates masses of SM particles
- By all estimates, the LHC energy is sufficient to produce Higgs particles or their equivalents

A cartoon of Higgs mechanism

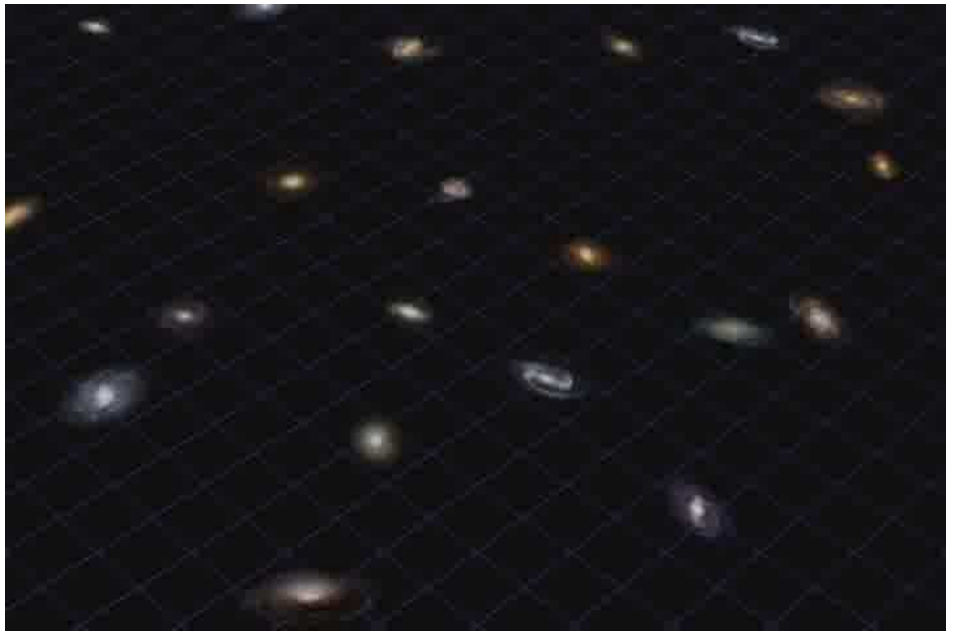


The basic idea of Higgs mechanism

- Interaction with environment creates additional inertia in the motion (=mass)
- Particle interactions obtain their masses from interactions with the surrounding Higgs field

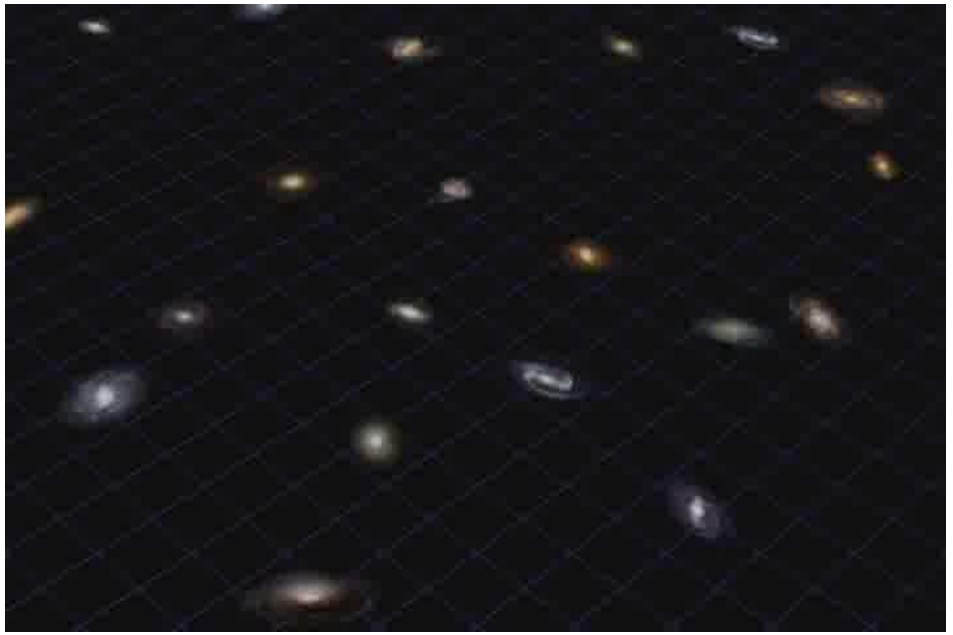
Mystery of antimatter

- We exist because there is almost no antimatter around
- But particle theory suggests that Big Bang created equal numbers of particles and antiparticles 14 billion years ago
- Where did antimatter go?



Mystery of antimatter

- Antimatter can be greatly depleted since Big Bang given that
  - Universe expands
  - particles behave slightly differently than antiparticles (CP-symmetry violation)
  - matter undergoes nonperturbative "baryon-number-violating" interactions soon after Big Bang



The exact mechanism is still unknown

What can the LHC reveal?

- Mechanism of electroweak symmetry breaking
- Origin of particle masses
  - observe the Higgs particle; or several types of Higgs particles
- New fundamental symmetries: supersymmetry
- Non-trivial structure of space-time at small distances (additional spatial dimensions)
- Nature of dark matter
- Mechanism for suppression of antimatter
- and much more!