

Exploring the Mysteries of Matter at Accelerators around the World

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A Cosmology Short Course for Museum & Planetarium Staff: The Dark Universe
Kavli Institute for Cosmological Physics, U. of Chicago, September 2010

Matter: What is it?

**The Fundamental Particles and their Interactions
How do they acquire Mass?**

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Different kinds of Matter:

Matter, Anti-Matter, Dark Matter ...

**The Mysteries of Matter ... and the New Theories to
explain them**

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Different kinds of Matter:

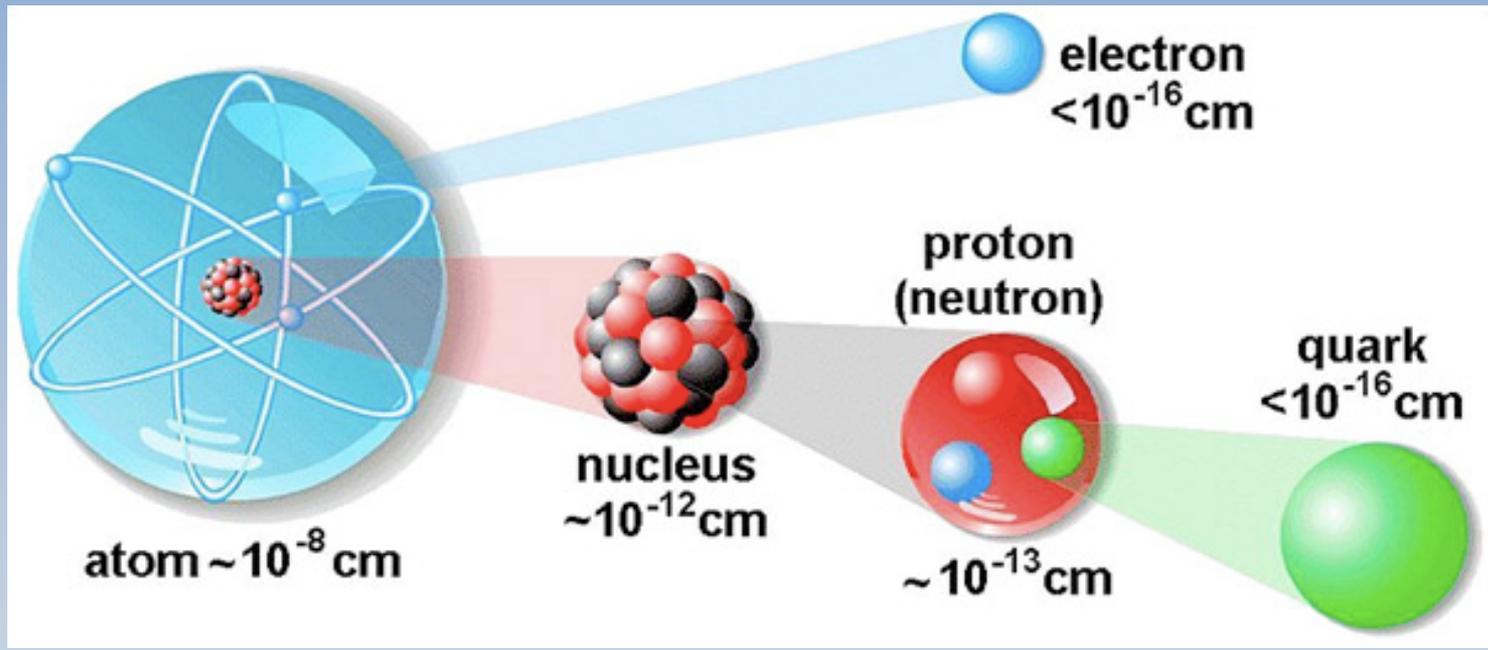
Matter, Anti-Matter, Dark Matter ...

**The Mysteries of Matter ... and the New Theories to
explain them**

Accelerators:

giant microscopes to study the smallest pieces of Matter

Matter: What is it?



1 1/10.000 1/100.000 1/100.000.000

Electric charges

electron = -1

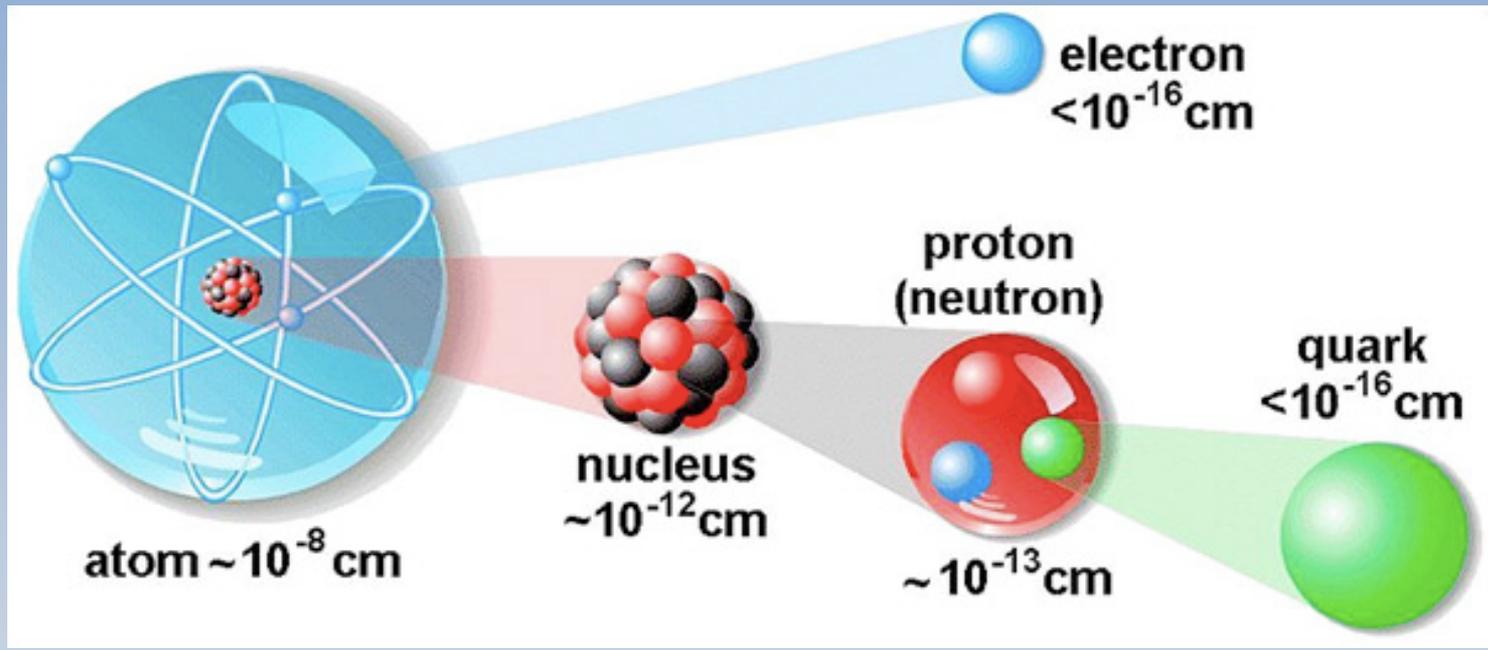
u-quark = 2/3

d-quark = -1/3

Proton

Neutron

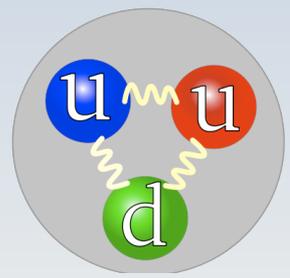
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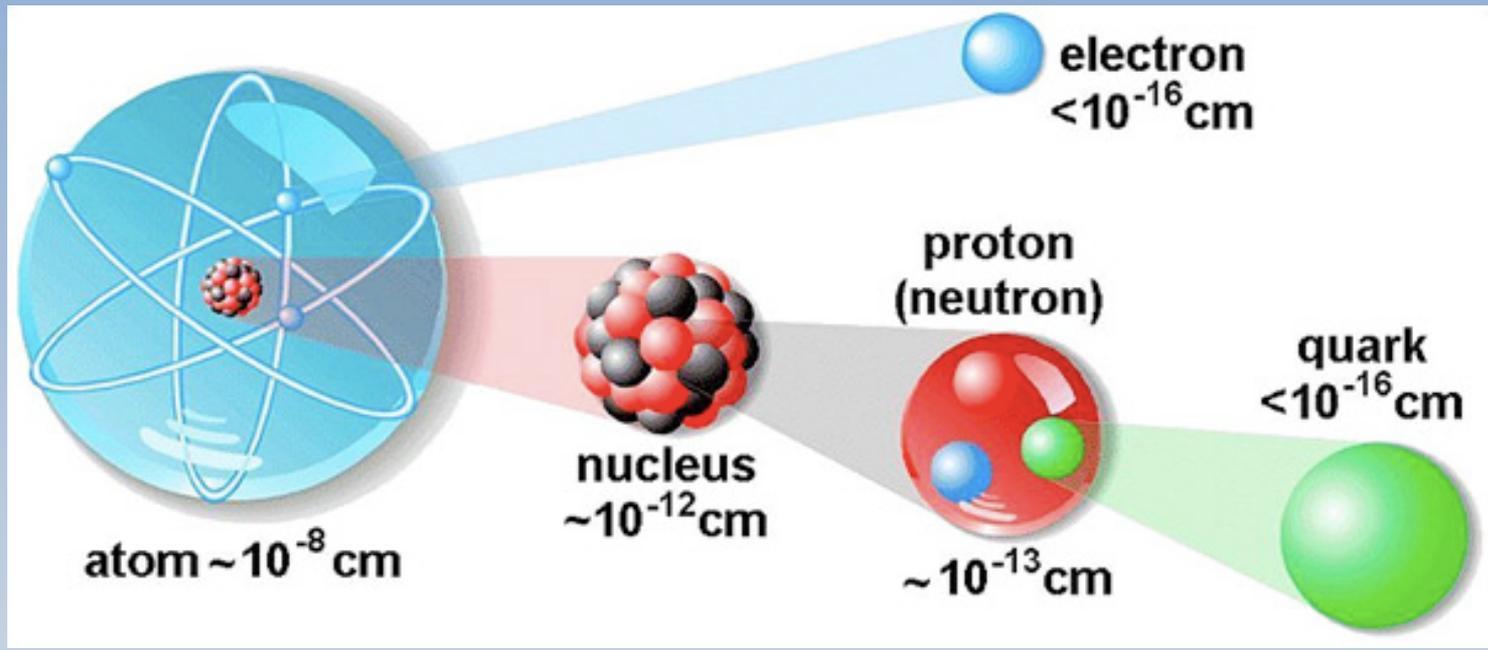
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Proton

Neutron

Matter: What is it?



atom $\sim 10^{-8}$ cm

electron
 $< 10^{-16}$ cm

proton
(neutron)

quark
 $< 10^{-16}$ cm

nucleus
 $\sim 10^{-12}$ cm

$\sim 10^{-13}$ cm

1

1/10.000

1/100.000

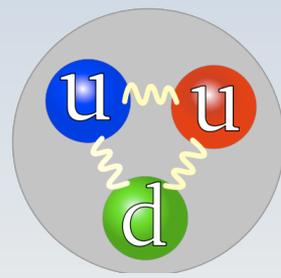
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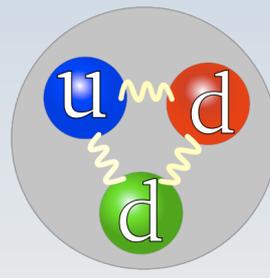
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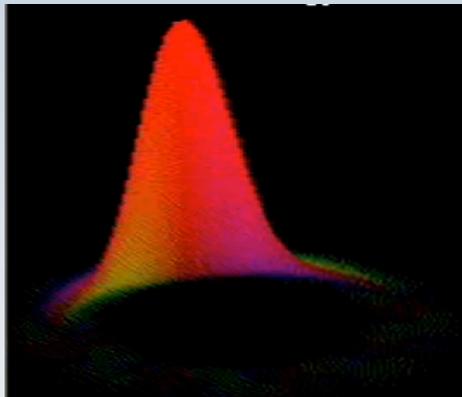
Neutron

What holds matter together?

Two forces that we experience everyday

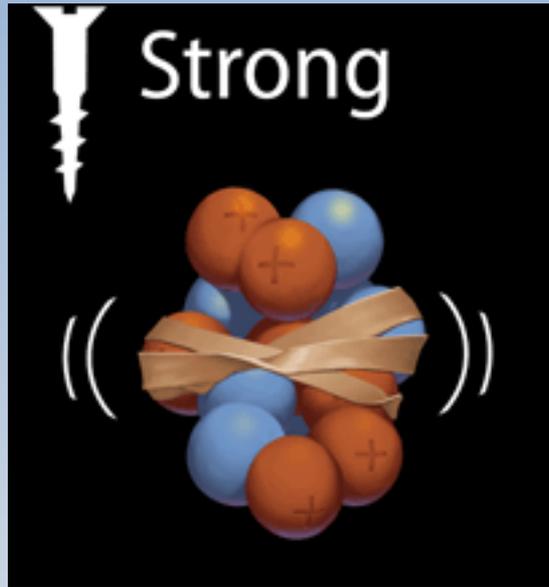
Force	Strength	Carrier	Physical effect
Electromagnetic	.001	Photon	Light, electricity
Gravity	10^{-38}	Graviton?	Gravitation

Molecules, Rocks, Creatures are held together by the tentacles of powerful electric forces and magnetic fields inside the atoms



Atoms governed by
the laws of quantum mechanics

Two forces we do not observe everyday but are essential to our life



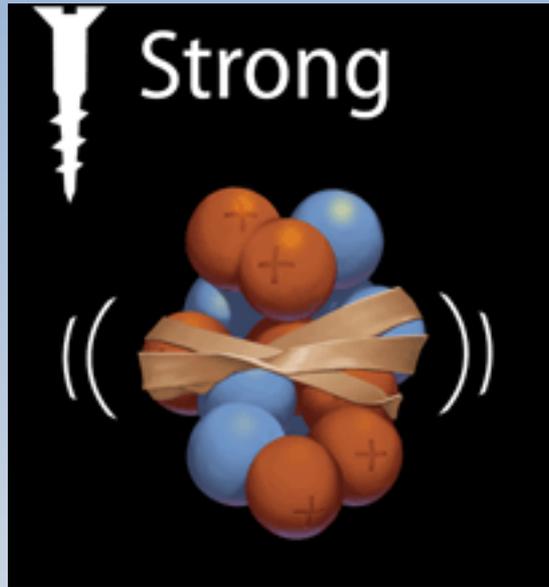
Binds together proton and
neutron to form nuclei



Explains nuclear fusion in the Sun!
and ultimately, **Sunlight**



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Force	Strength	Carrier	Physical effect
Strong nuclear	1	Gluons	Binds nuclei
Weak nuclear	.00001	Z^0, W^+, W^-	Radioactivity

The Standard Model Zoo of Sub-atomic Particles

- Heavier copies of those which make up ordinary atoms
- Particles which are the mediators of sub-atomic forces

		THREE GENERATIONS OF MATTER			CHARGE:	
		I	II	III		
MATTER CONSTITUENTS: FERMIONS	QUARKS	2.75 UP	1300 CHARM	178000 TOP	$\leftarrow \frac{2}{3}$	91188 Z^0
		6 DOWN	110 STRANGE	4500 BOTTOM	$\leftarrow -\frac{1}{3}$	80430 W^+/W^-
	LEPTONS	0.511 ELECTRON	105.7 MUON	1777 TAU	$\leftarrow -1$	$< 10^{-23}$ PHOTON
		$< 3 \cdot 10^{-6}$ NEUTRINO e	< 0.19 NEUTRINO μ	< 18.2 NEUTRINO τ	$\leftarrow 0$	theory: 0 GLUON
					$\rightarrow 0$	
						FORCE CARRIERS: BOSONS

They have all been produced in the laboratory

They have very different masses

What causes fundamental particles to have mass?

Theory of relativity:

Space and time are relative and entangled: spacetime (1905)

Space and time are dynamical: mass and energy curve the spacetime (1916)

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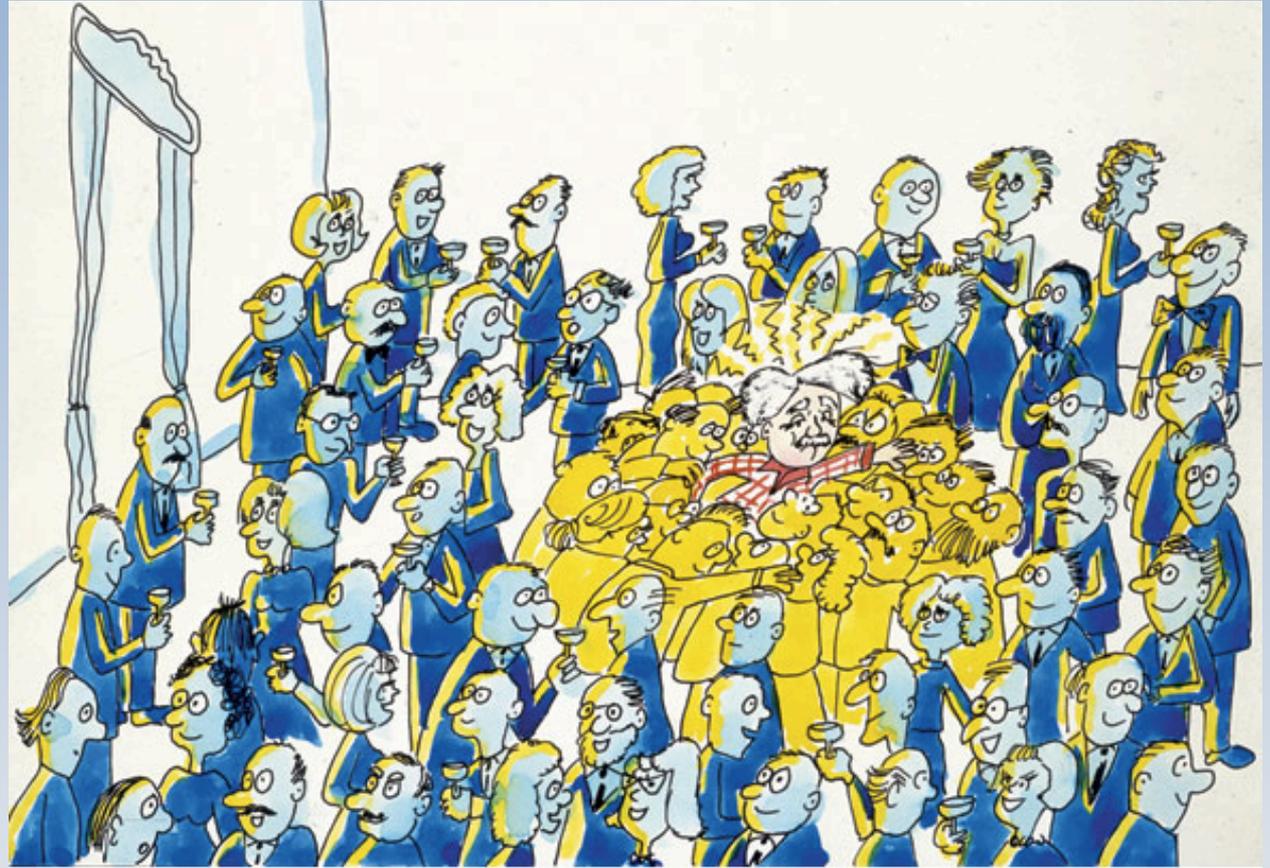
Space and time are dynamical: mass and energy curve the spacetime (1916)

$$E=mc^2$$



A field of Energy that permeates all of the space
- the essence of mass -

The Higgs Field



The Higgs field energy clusters into **the Higgs Particle**

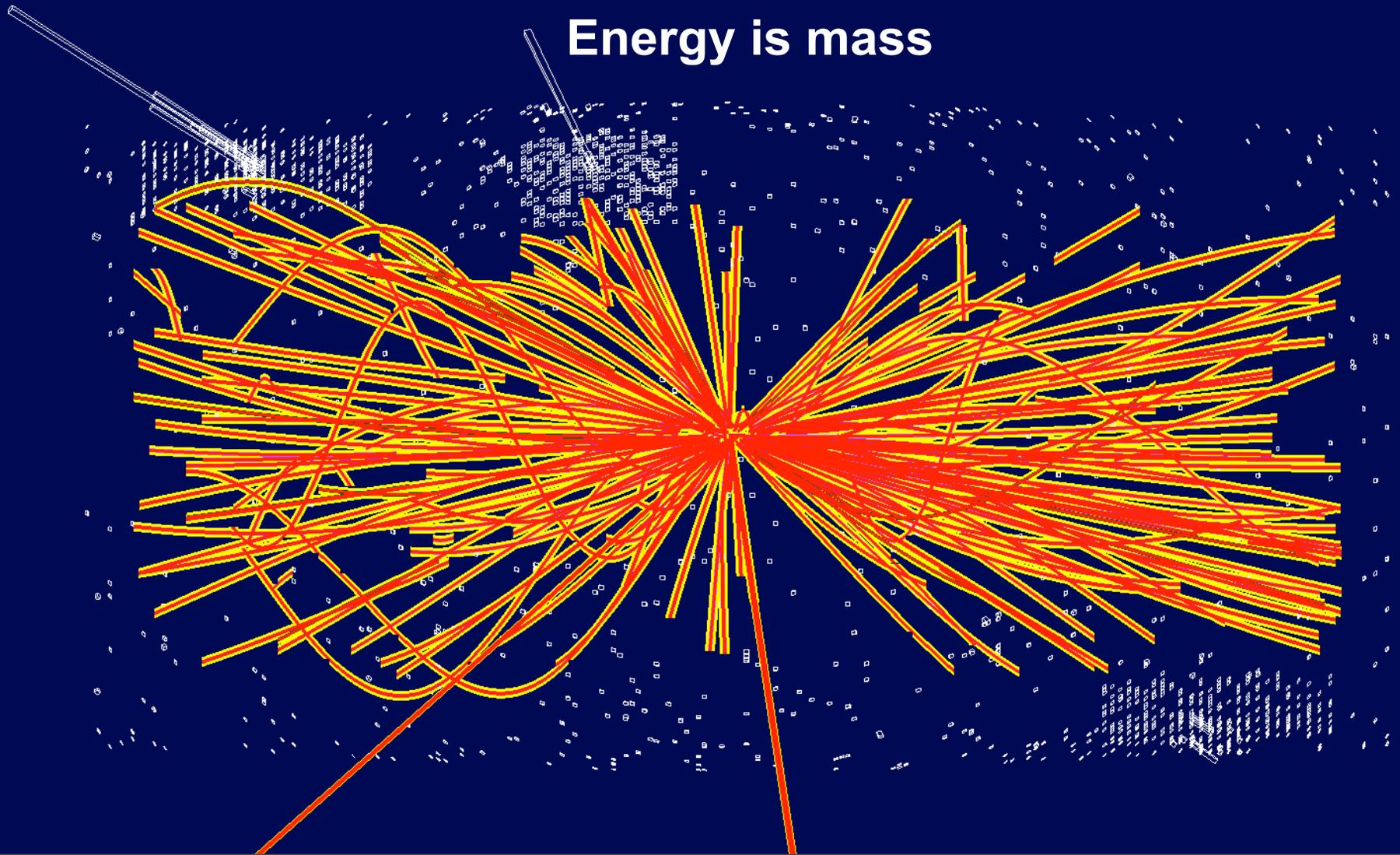
How do we search for the Higgs?

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Smashing Particles at High Energy Accelerators

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Smashing Particles at High Energy Accelerators



The TEVATRON @ Fermilab



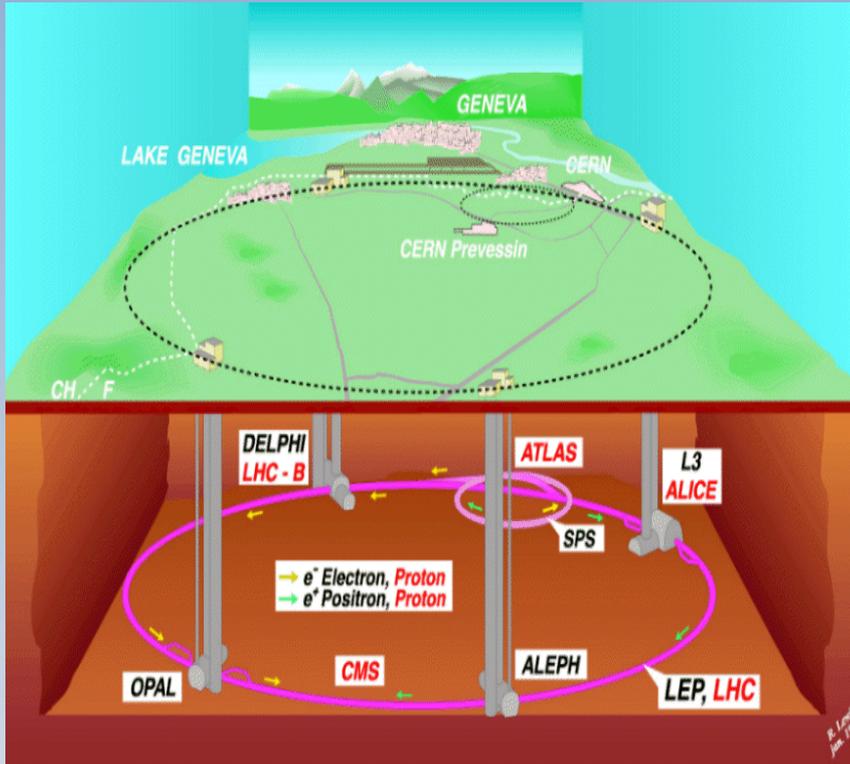
~ 4 miles circumference

Protons- anti-protons
of equal mass and energy ~ 1 TeV
collide against each other

Electric voltage accelerates particles
Magnetic fields bend the particles
path and focus the particle beams

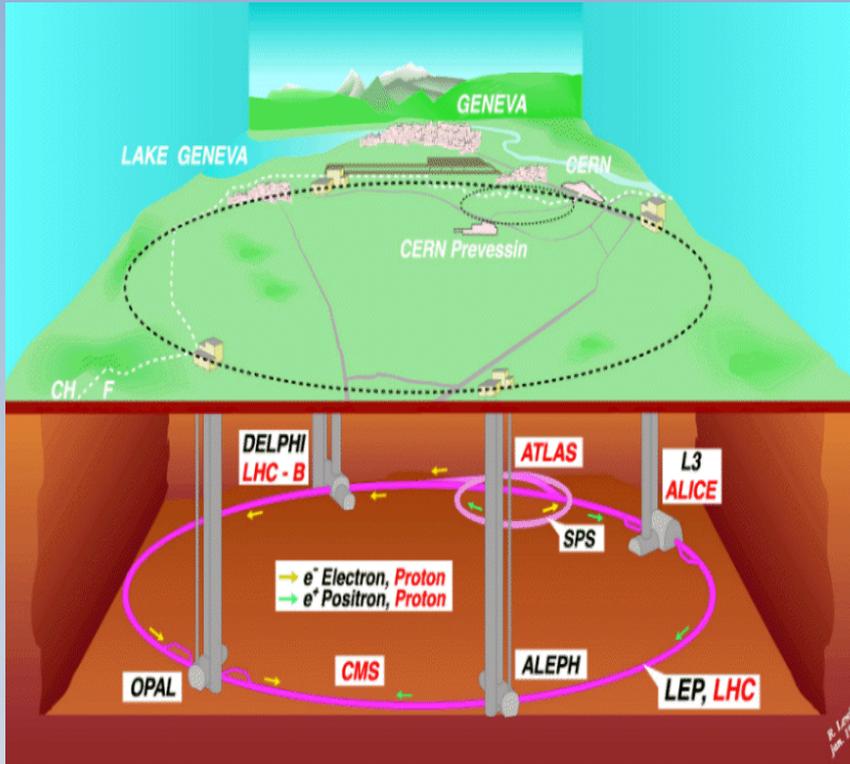


The Large Hadron Collider (LHC) @ CERN



- 17 miles circumference
- a billion proton-proton collisions per second!
- ~ 100 particles per collision

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So much energy... that it is like we transport ourselves to instants after the BIG BANG

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Shouldn't we expect to find particles consisting of
the initial particle constituents?**

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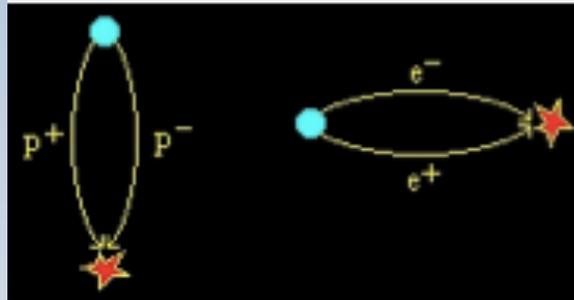
An element of chance in the microscopic world

Quantum fluctuations create and annihilate “virtual particles” in the vacuum

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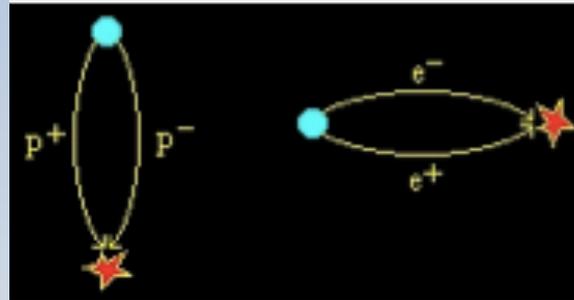
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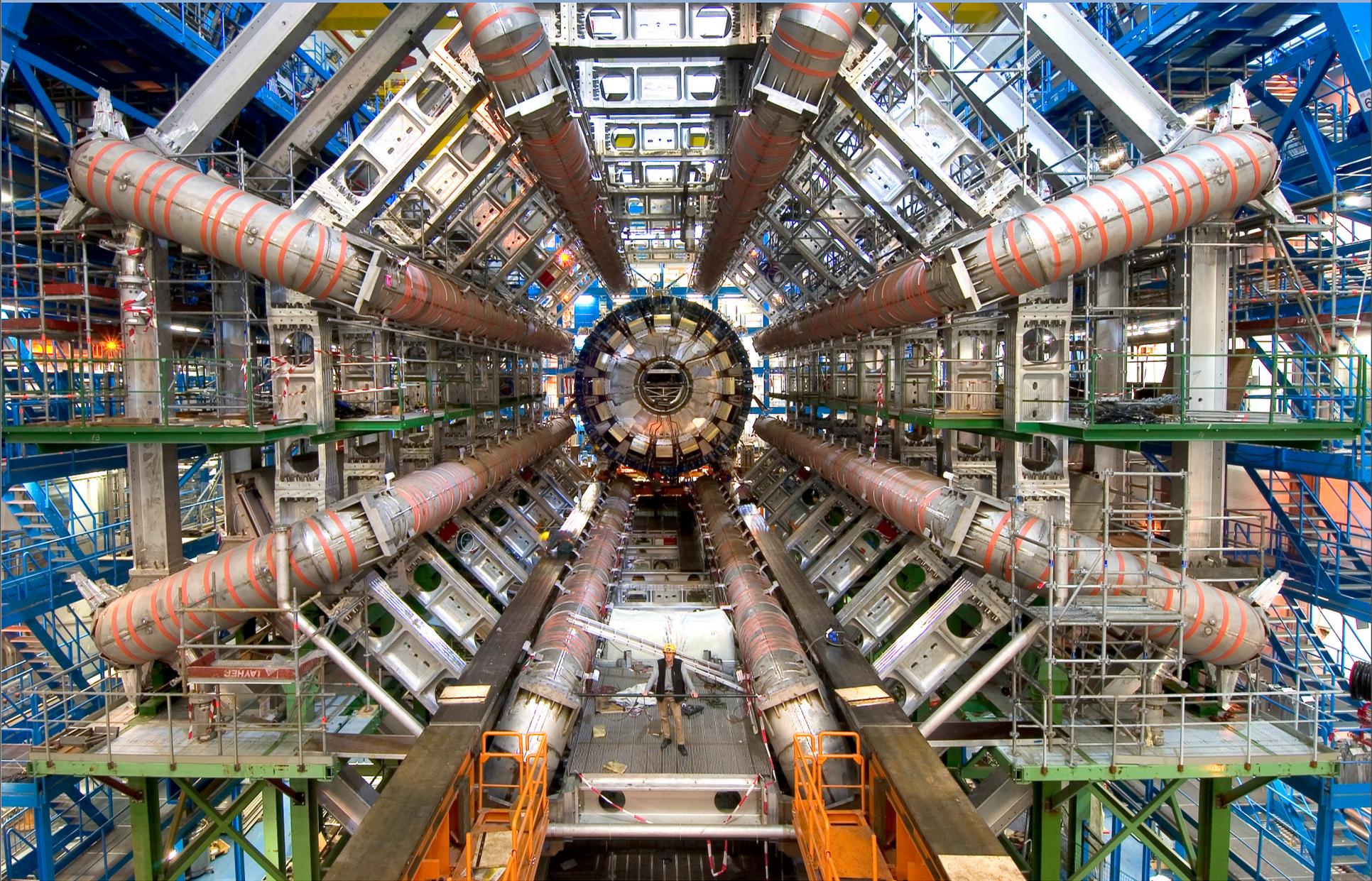
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Virtual particles + energy → real new particles

**Higgs particle: mass about 100 to 200 times the proton mass
is expected to be produced at the Tevatron or the LHC**

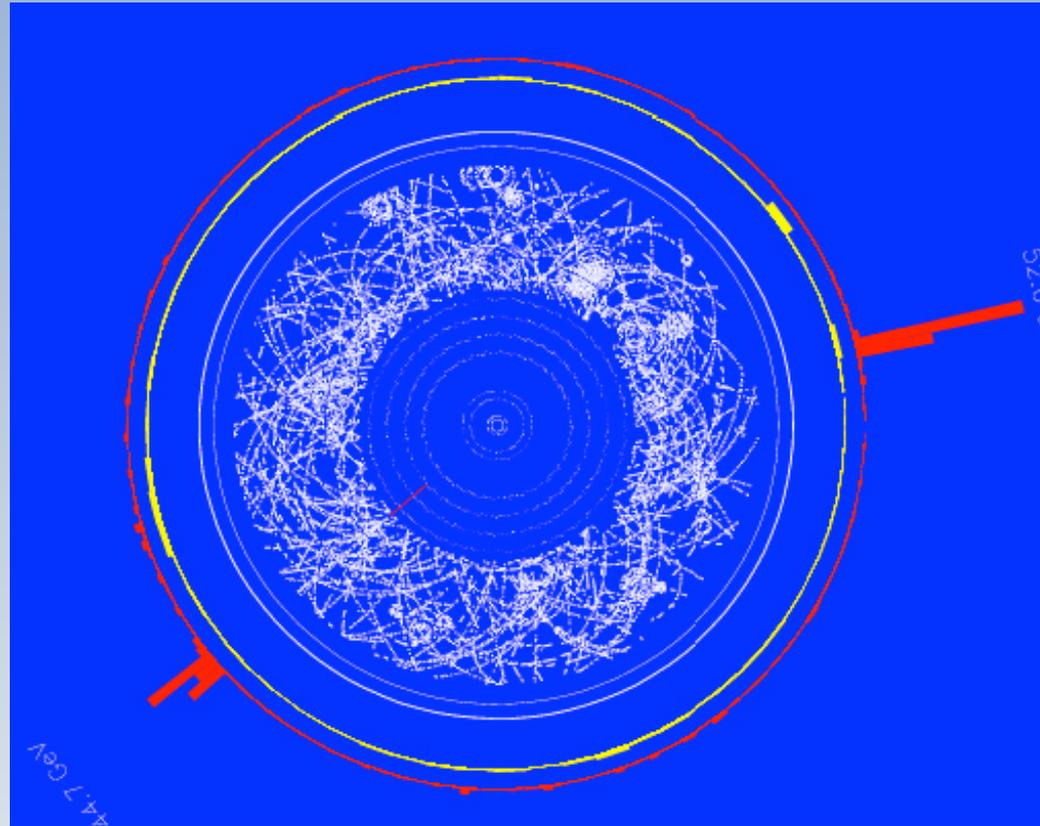
To look at the new particles we have powerful detectors



A new particle decays into the Standard Model Particle Zoo

We look for the tracks that a particle leaves behind

Higgs decaying to
2 energetic photons



We see signals when the layers of the detector
stop the particles as they fly out

Matter has Mass... Anti-matter too !

What is anti-matter ?

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What is anti-matter ?

$$\left(i\gamma^\mu \partial_\mu - m \right) \psi = 0$$

Matter has Mass... Anti-matter too !

What is anti-matter ?

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

The Power of Math:

The Dirac code

In 1928 Paul Dirac married

Einstein's Theory of Relativity

with Quantum Mechanics

and

predicted the existence of Antimatter



The Mystery of our Existence

We are made of Matter but there is also Anti-Matter

**Each matter particle has an anti-particle: an exact copy but...
with opposite electric charge**

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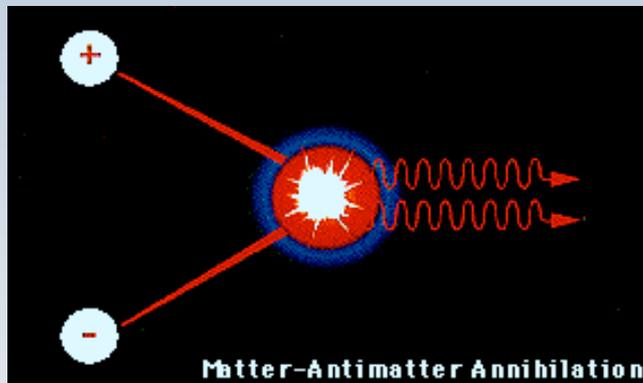
When matter meets anti-matter...

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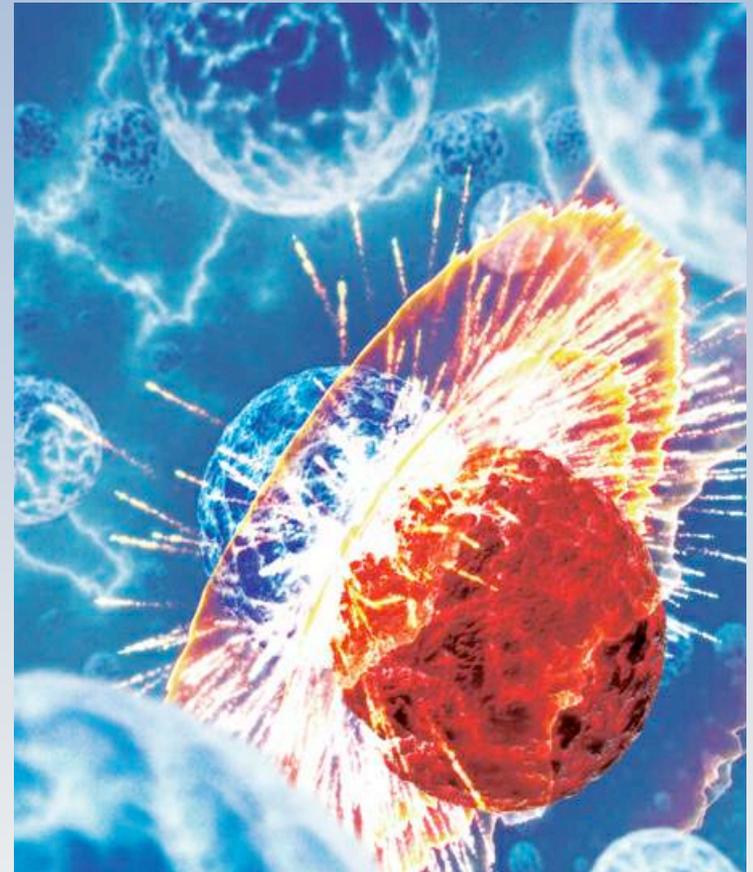
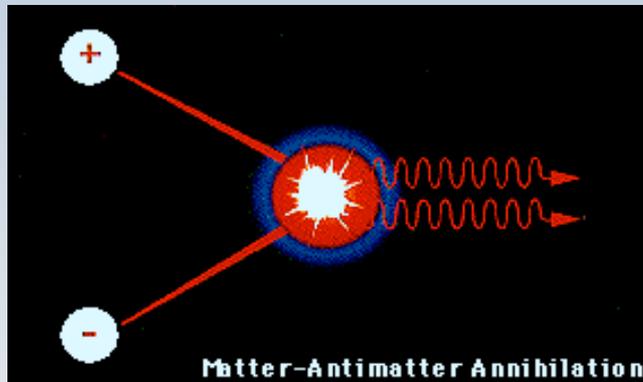


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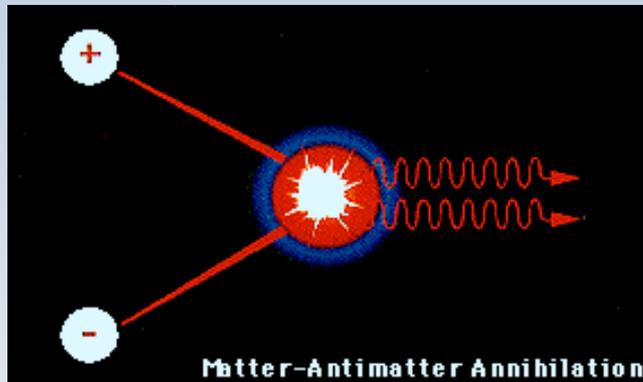


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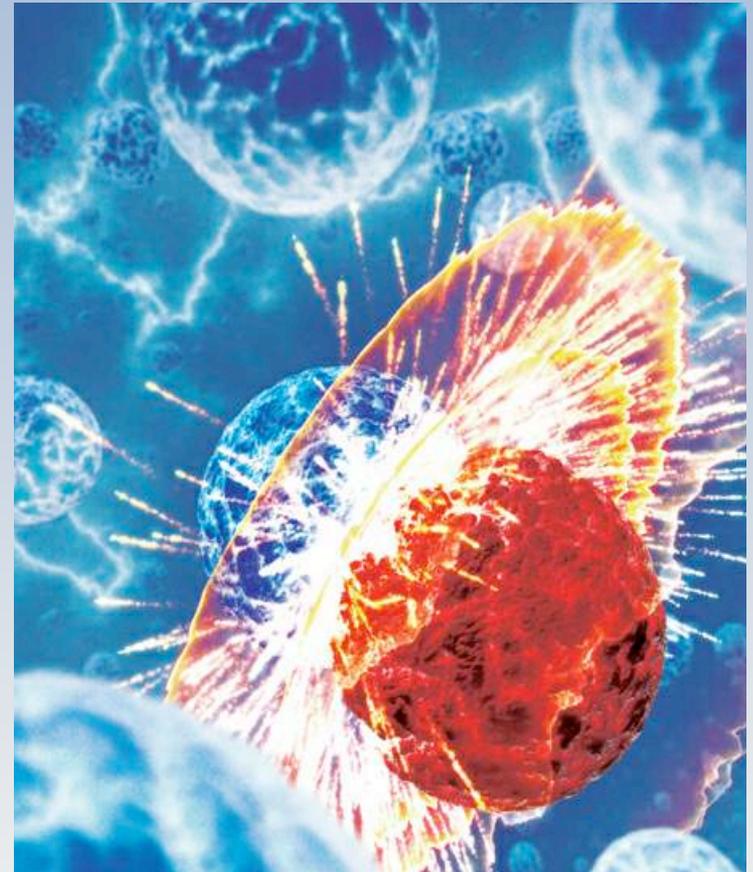
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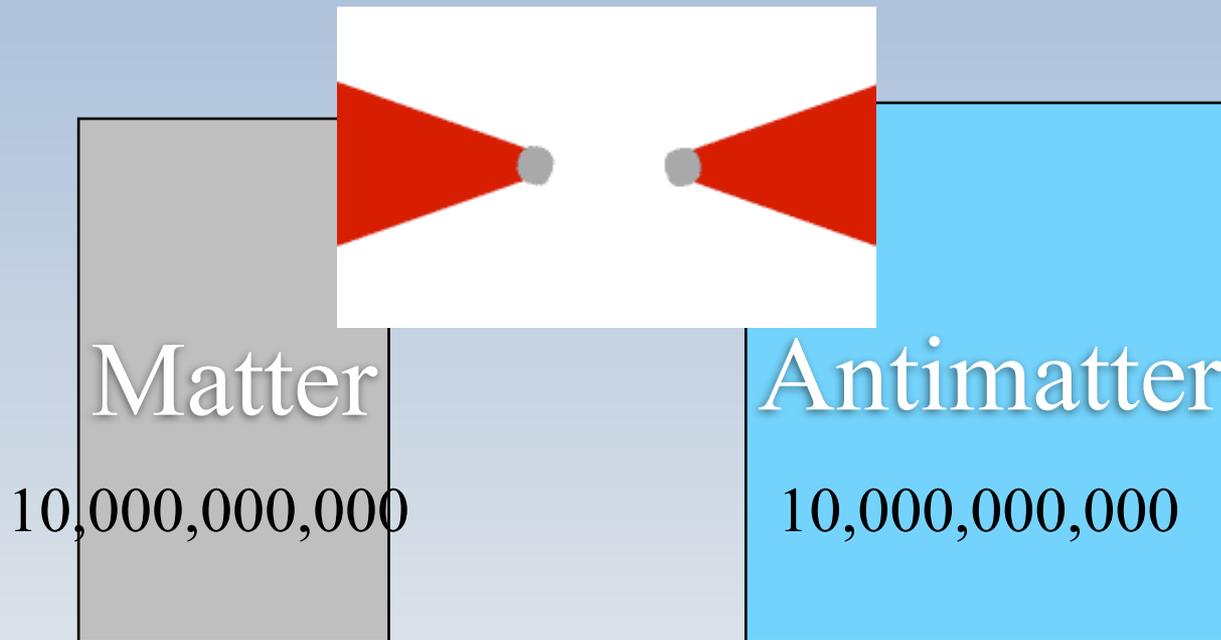
It annihilates into em radiation



At the BIG BANG :

Equal amounts of Matter and Anti-matter

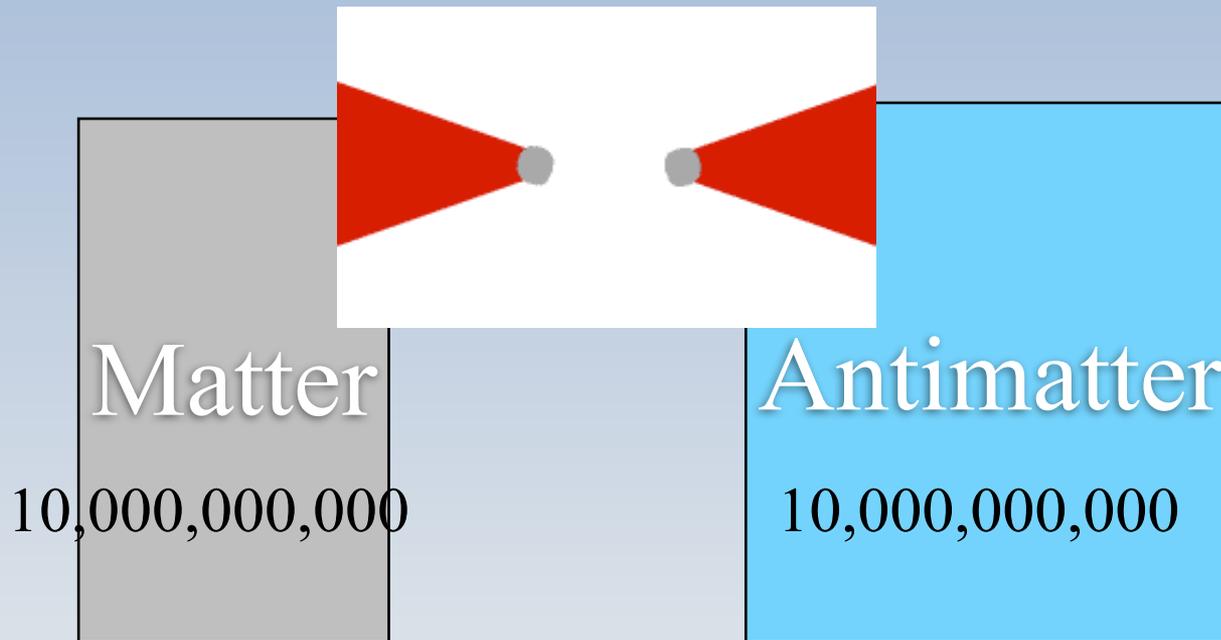
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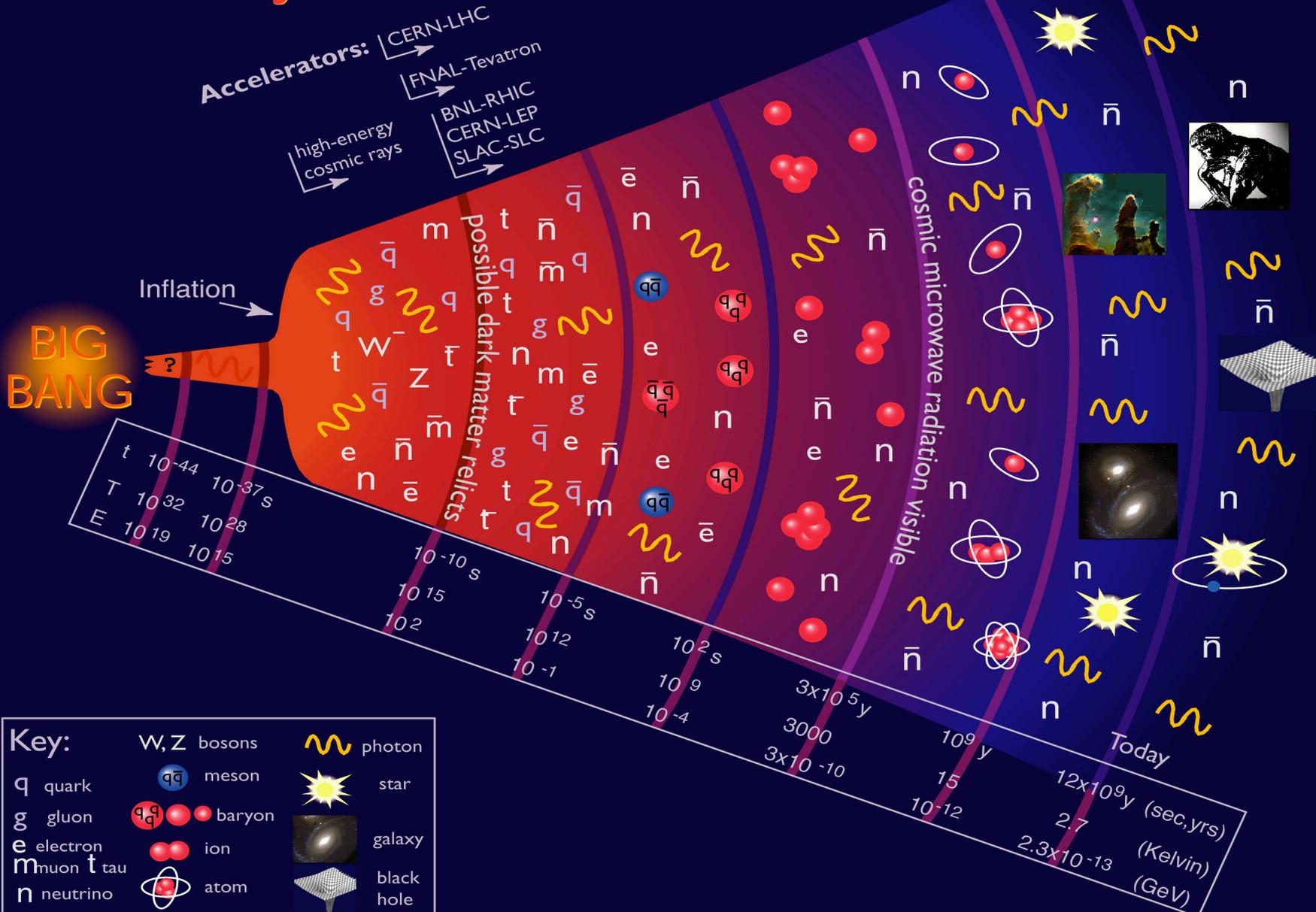
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A tiny amount of matter survived ...

History of the Universe



Today: Matter-Antimatter Asymmetry

Matter	Antimatter
1(us)	0

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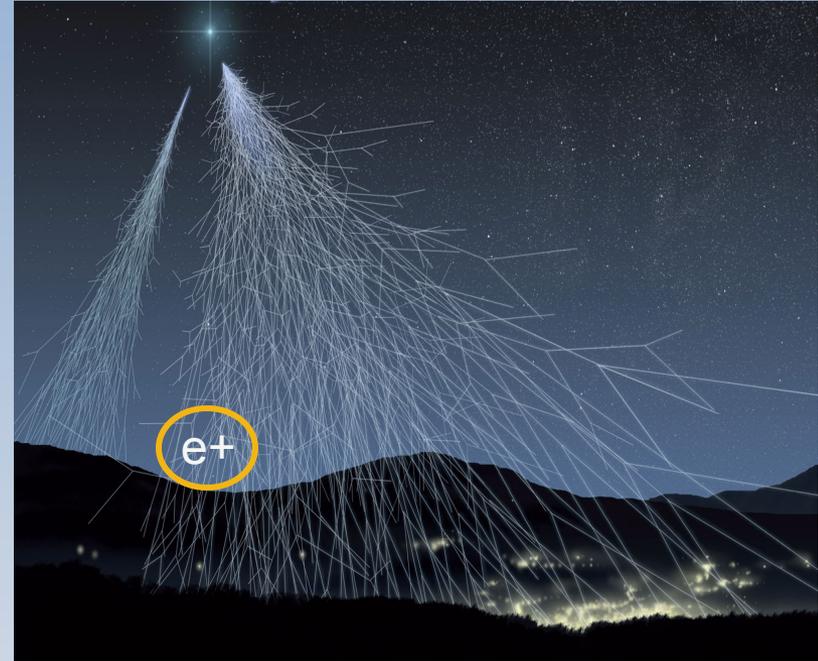
Matter	Antimatter
1(us)	0



New York Times (May 2010): D0 experiment at Fermilab finds new evidence of symmetry breaking that could explain our existence

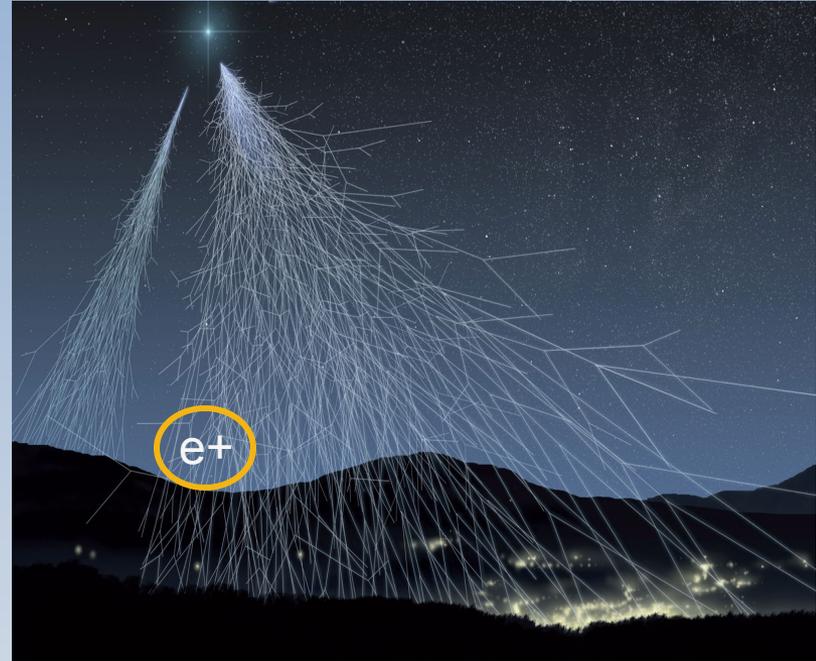
Nature creates anti-matter

- *The First Observation of Antimatter: A Cosmic Discovery*



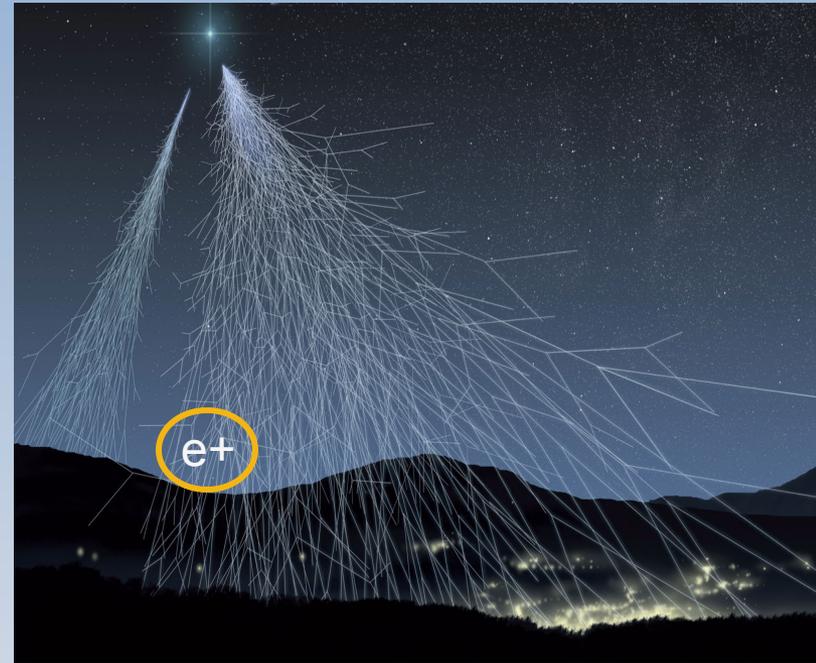
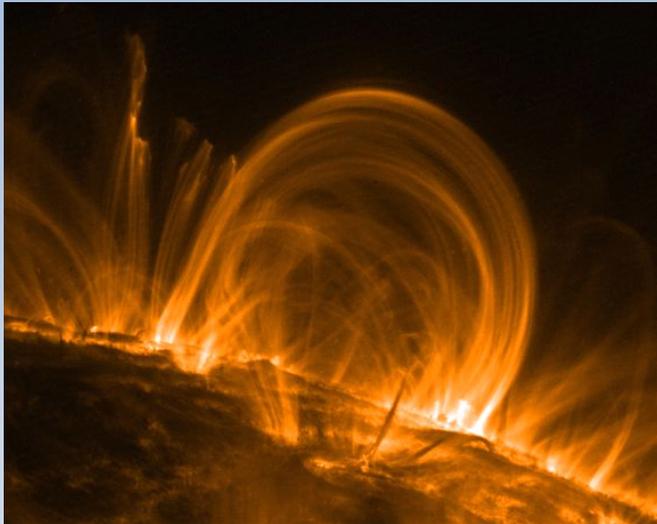
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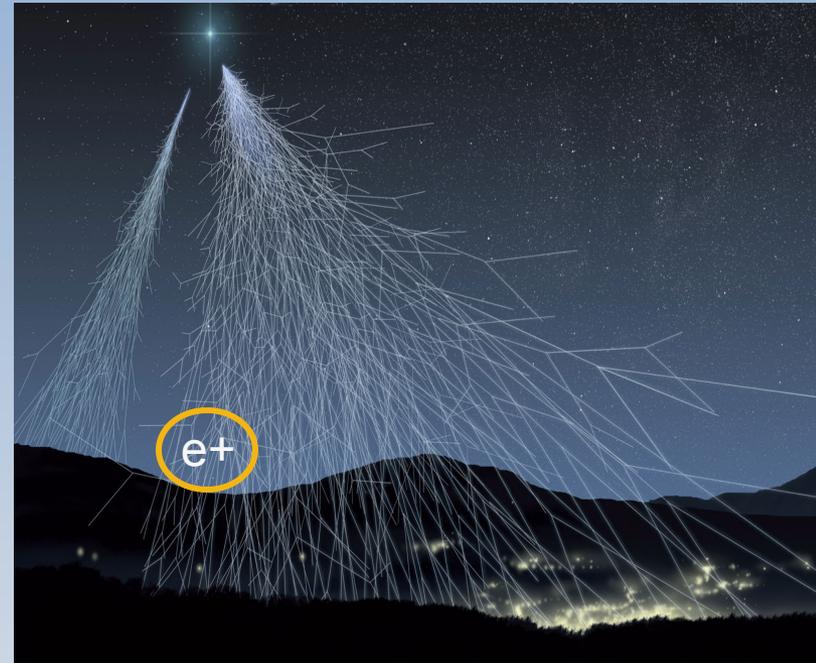
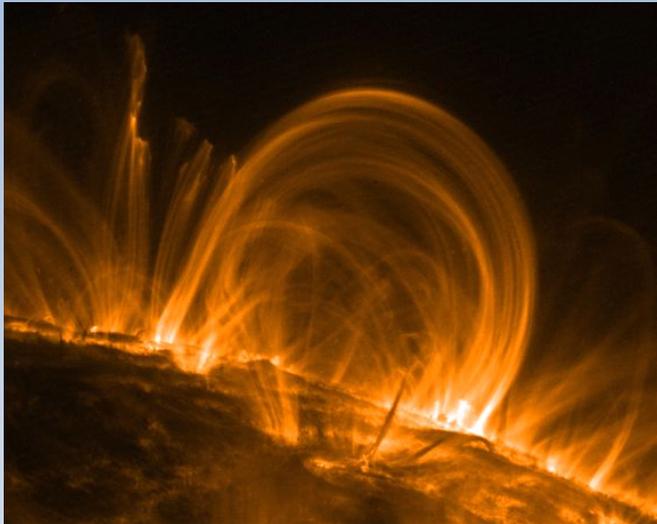
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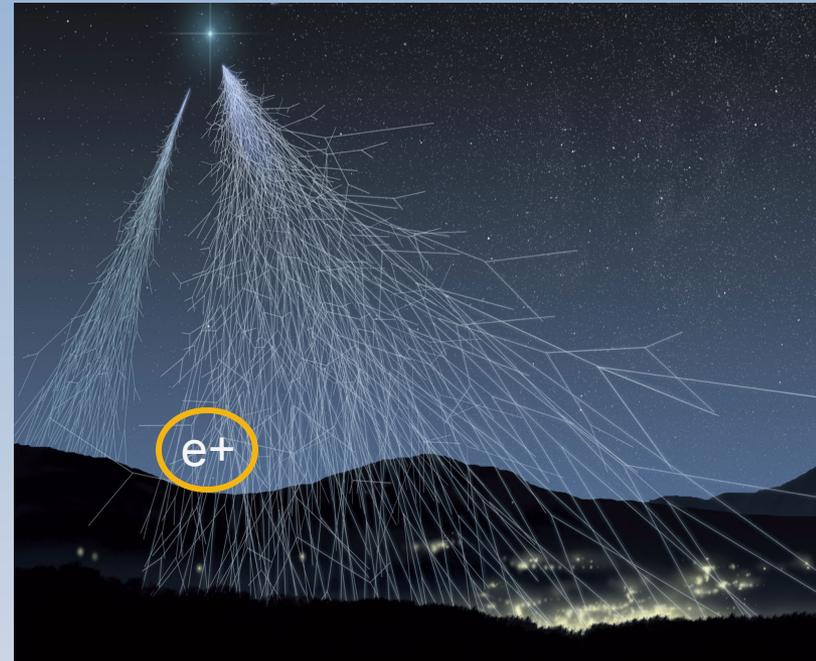
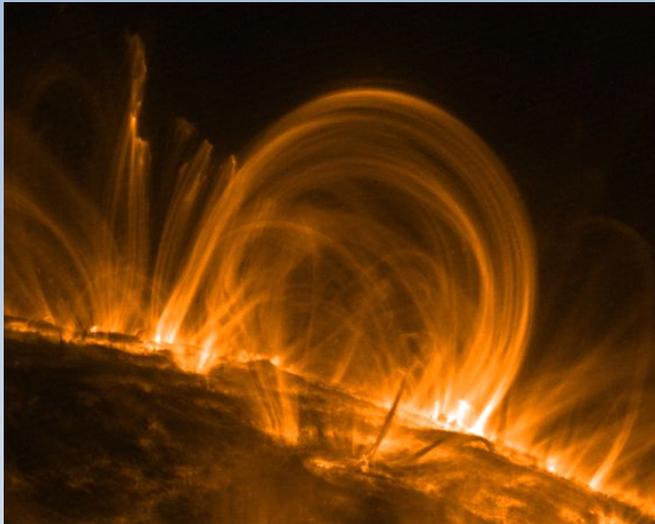
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- *Earthly Antimatter from Radiation*

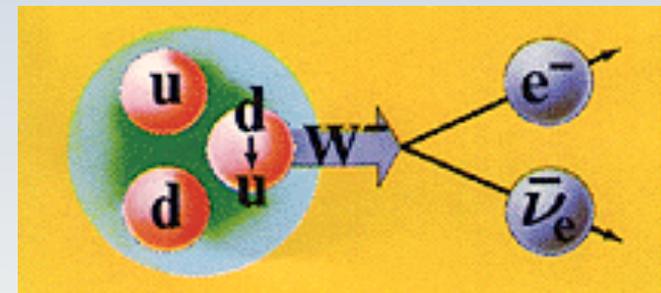
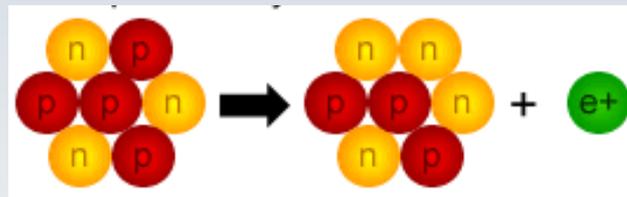
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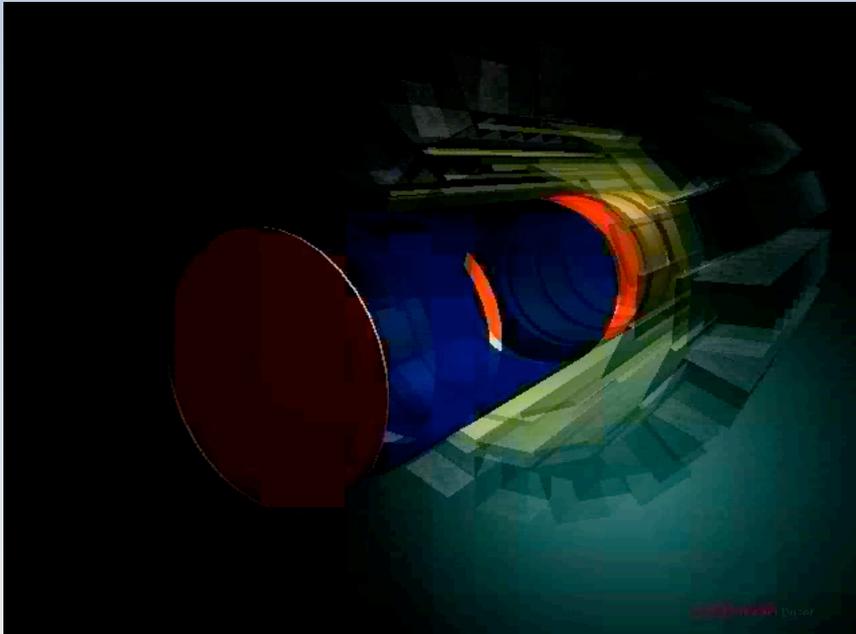
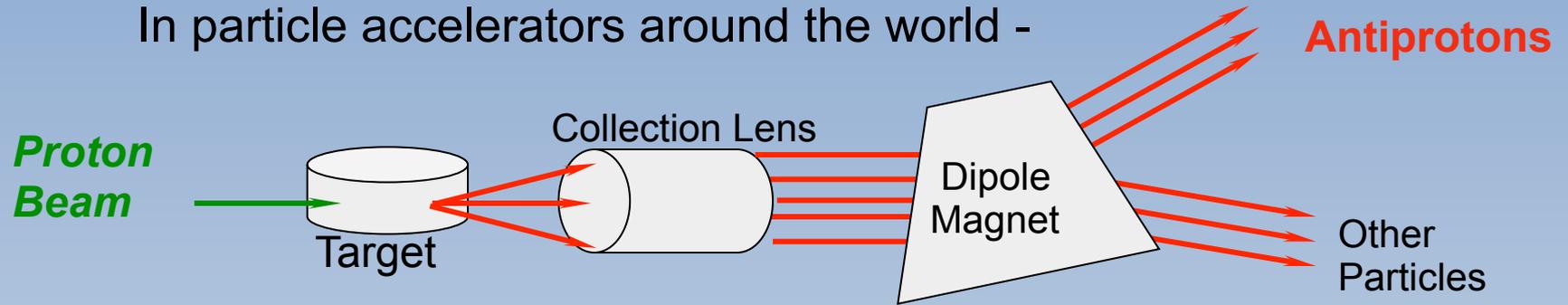
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unstable atom with
too few neutrons



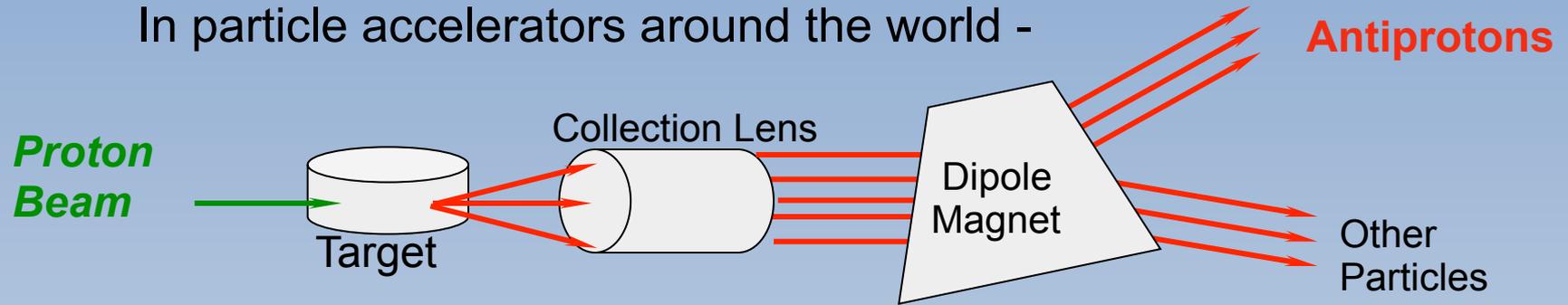
We create anti-matter

In particle accelerators around the world -

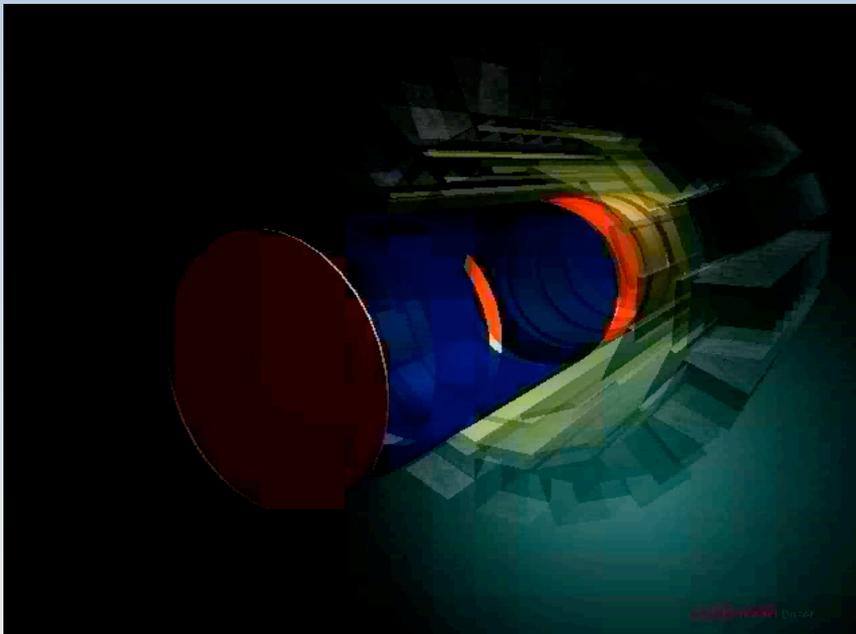


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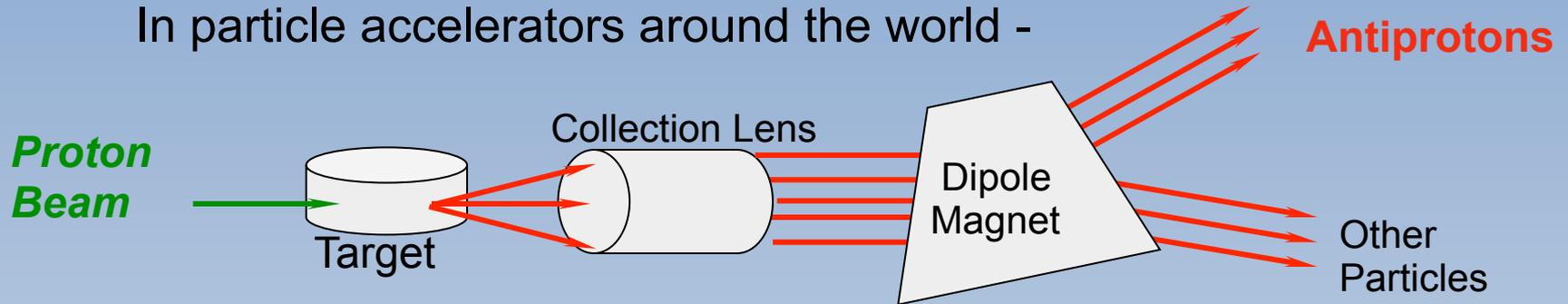


We can store it → Vacuum + Magnetic and Electric fields to confine it

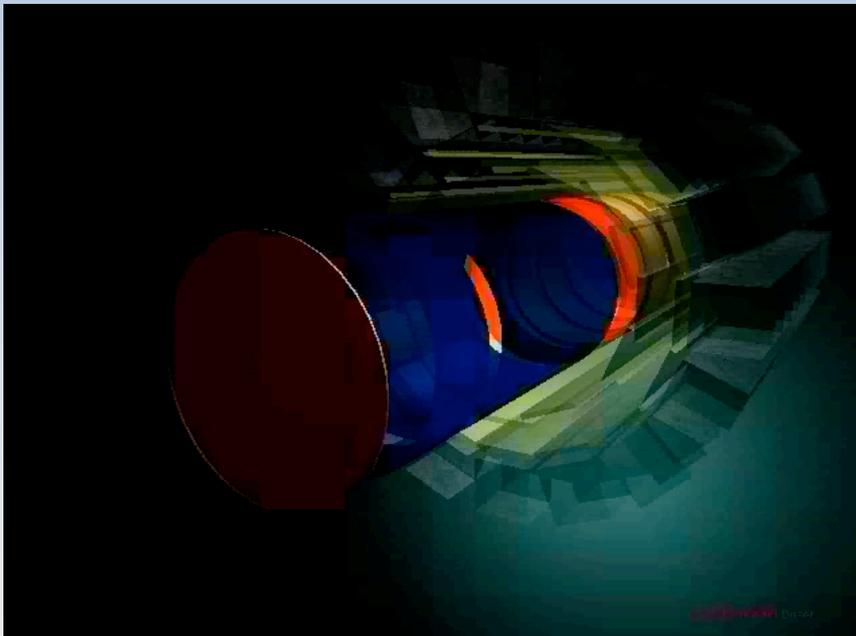


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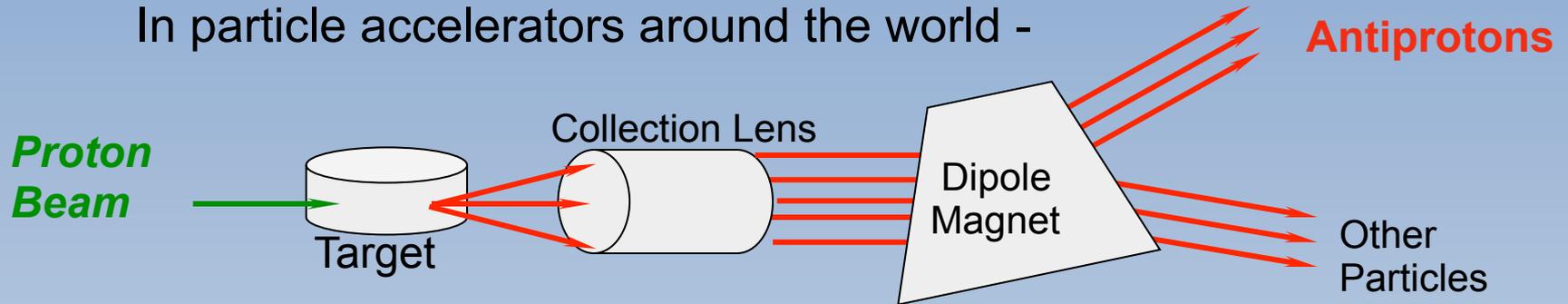


At Fermilab

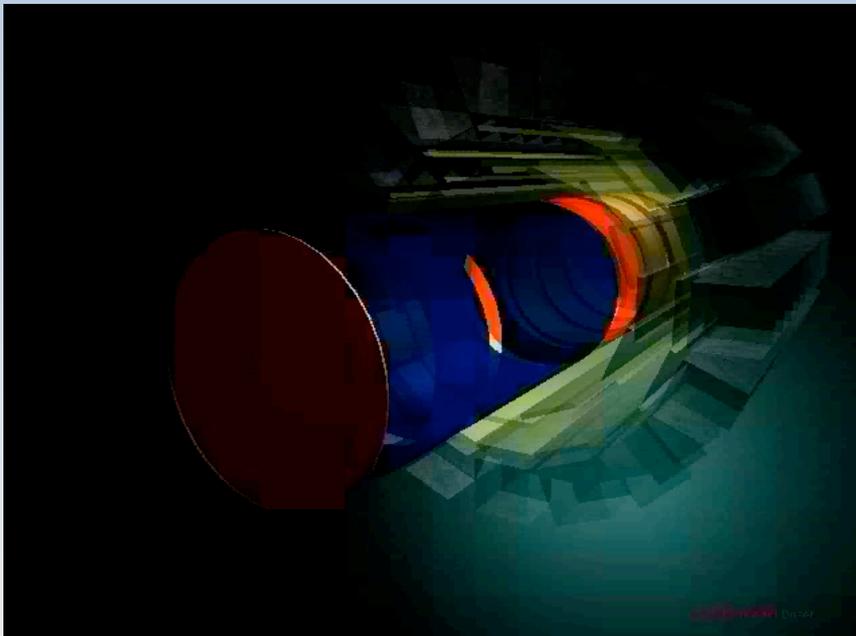
We store antiprotons at high energies in beams inside mile long rings

We create anti-matter

In particle accelerators around the world -



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At Fermilab

We store antiprotons at high energies in beams inside mile long rings

At CERN

Proof of Anti-atom Creation

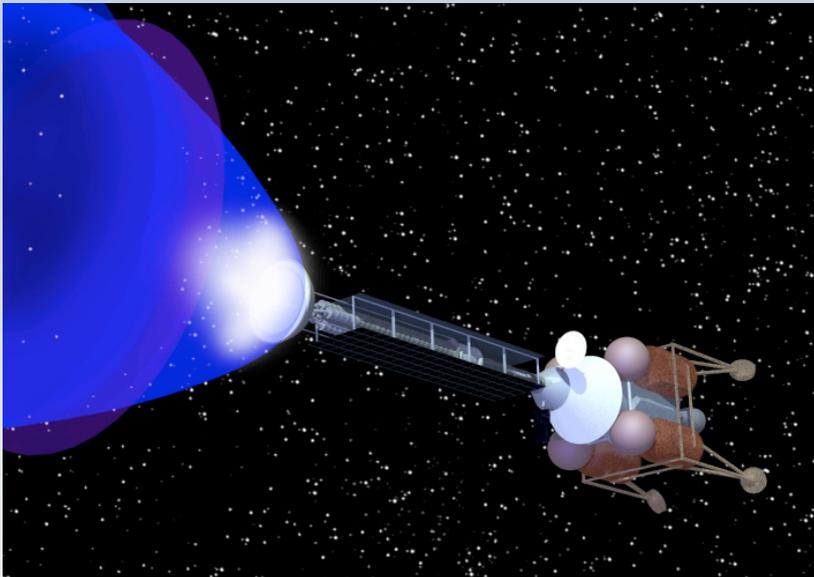
simultaneous annihilations of antiproton and positron with matter

Anti-matter could be used in many different ways:

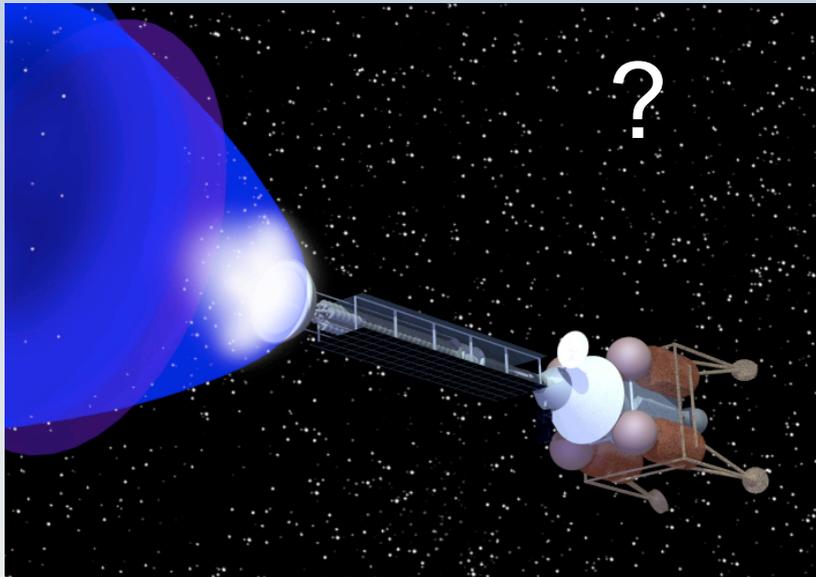
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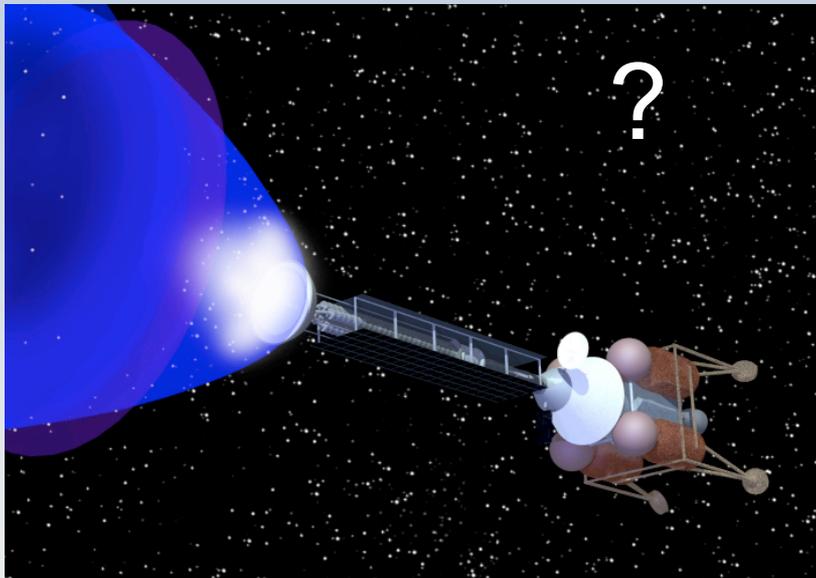
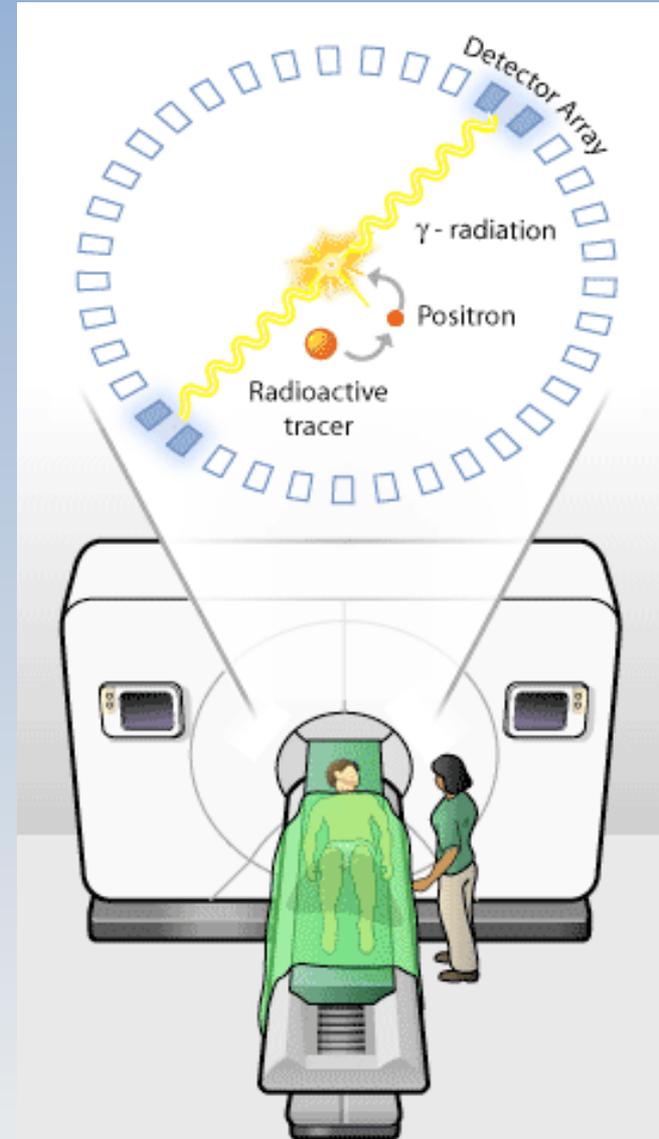
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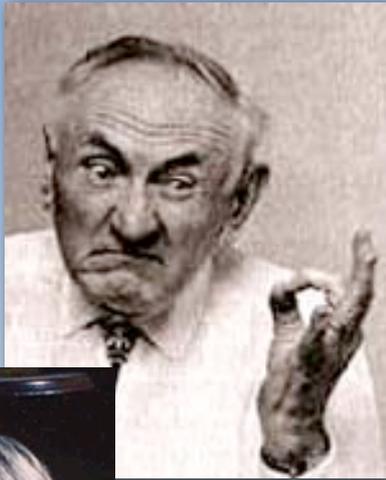


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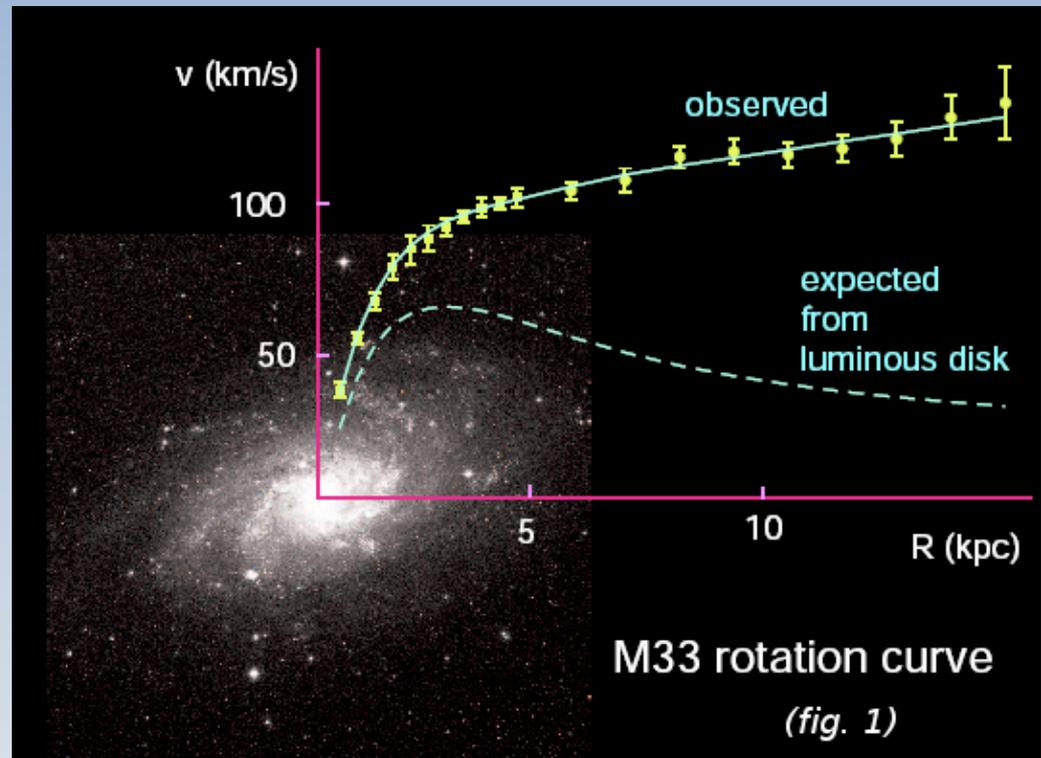
The Mysteries of the Dark Universe

Also R. Kolb's talk



*Fritz Zwicky / Vera Rubin
...discover Dark Matter*

The rotational velocity of galaxies



Shows that there must be a lot of matter that we cannot see

Dark Matter makes ~ 85 % of all the matter in the universe!

The power of the dark side

Holds the Universe together



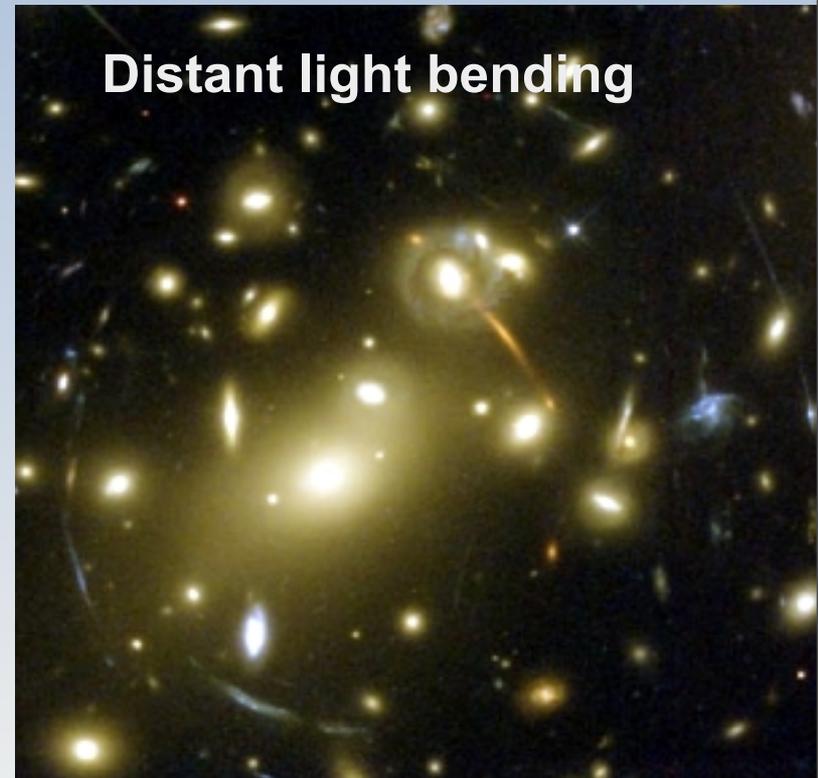
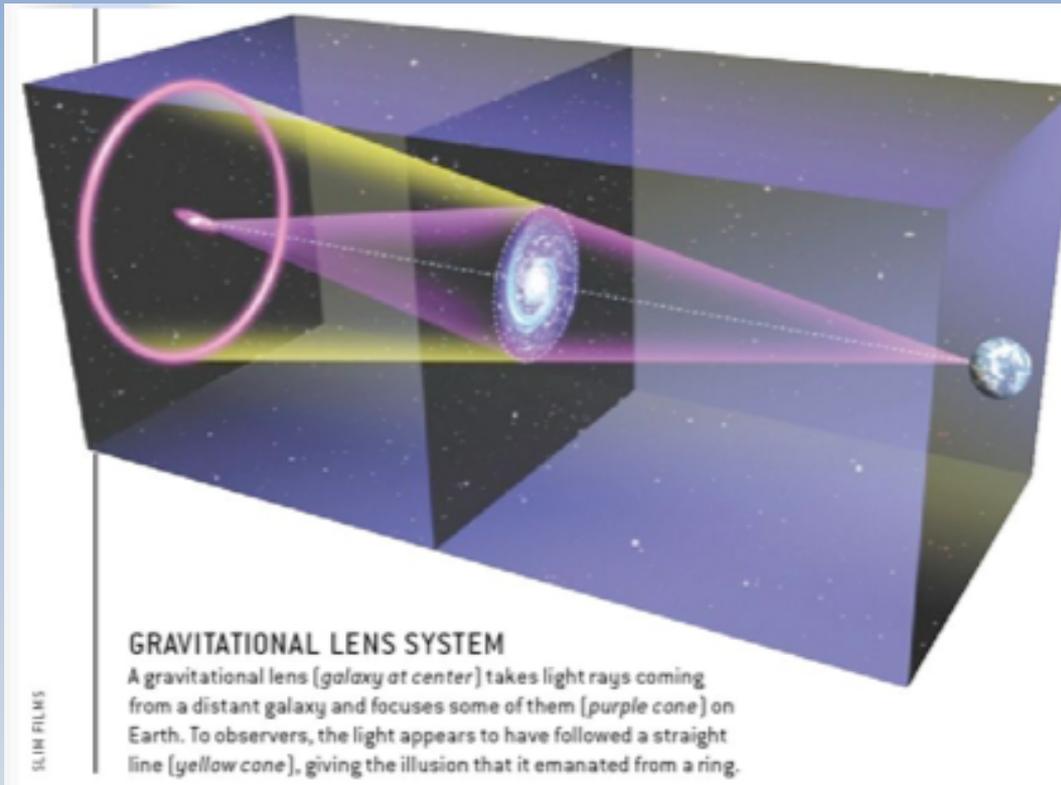
What is dark matter?

What are its properties?

Does it have substructure?

...

How to see Dark Matter?



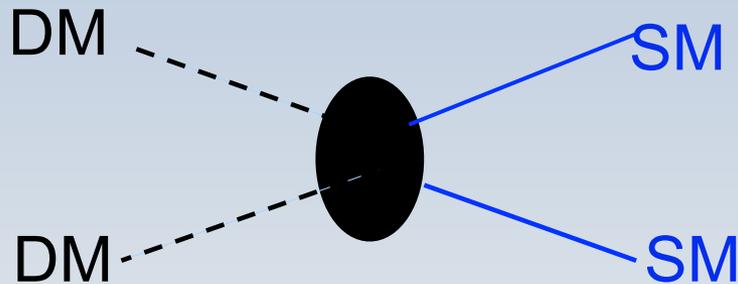
Light deflection due to warping of space near massive objects: [gravitational lensing](#)

The History of the Dark Matter Abundance

- Dark matter produced in the hot early Universe can pair-wise annihilate (therm. equilibrium)



- Dark Matter density decreases as the Universe expands



and finally DM annihilation stops

- The *smaller* the rate for pair annihilation, the *larger* is the Dark Matter abundance observed today

What is Dark Matter?

- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed dark matter abundance:

$$M_{\text{DM}} \sim 100 - 1000 \text{ proton masses}$$

and fits well with a weakly interacting particle = **WIMP**

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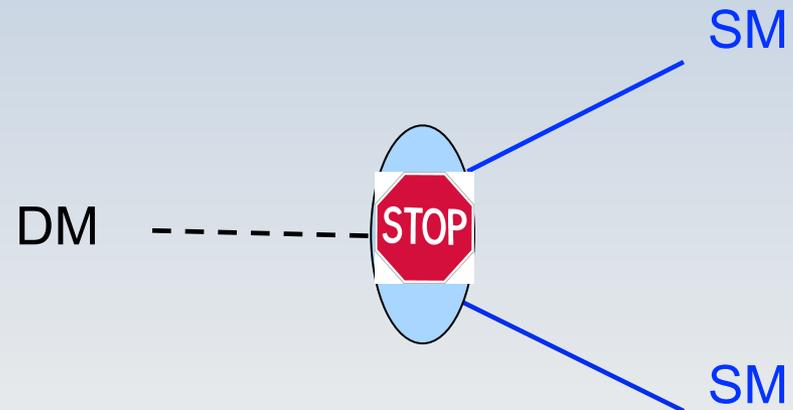
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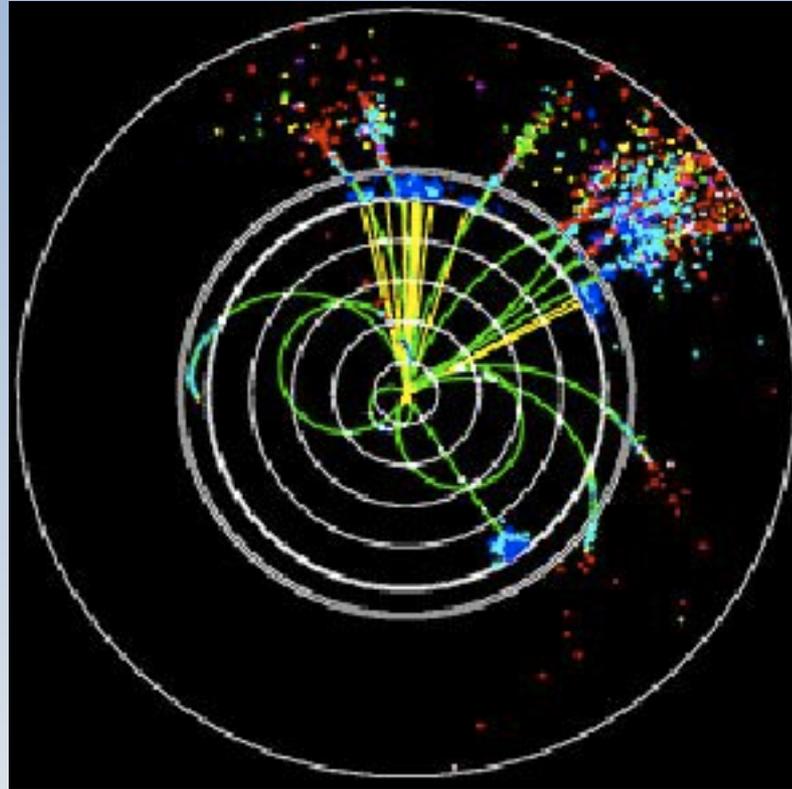
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Can we create Dark Matter smashing regular particles at very high speed?



We count the energy we put in and the energy that comes out
if a lot is missing we created Dark Matter

Missing Energy Signals at Tevatron or the LHC

Neutrinos → ok, but too light, too little

Missing Energy Signals at Tevatron or the LHC

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Game Changing Discoveries at the LHC

Missing Energy Signals at Tevatron or the LHC

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New Dimensions of Space

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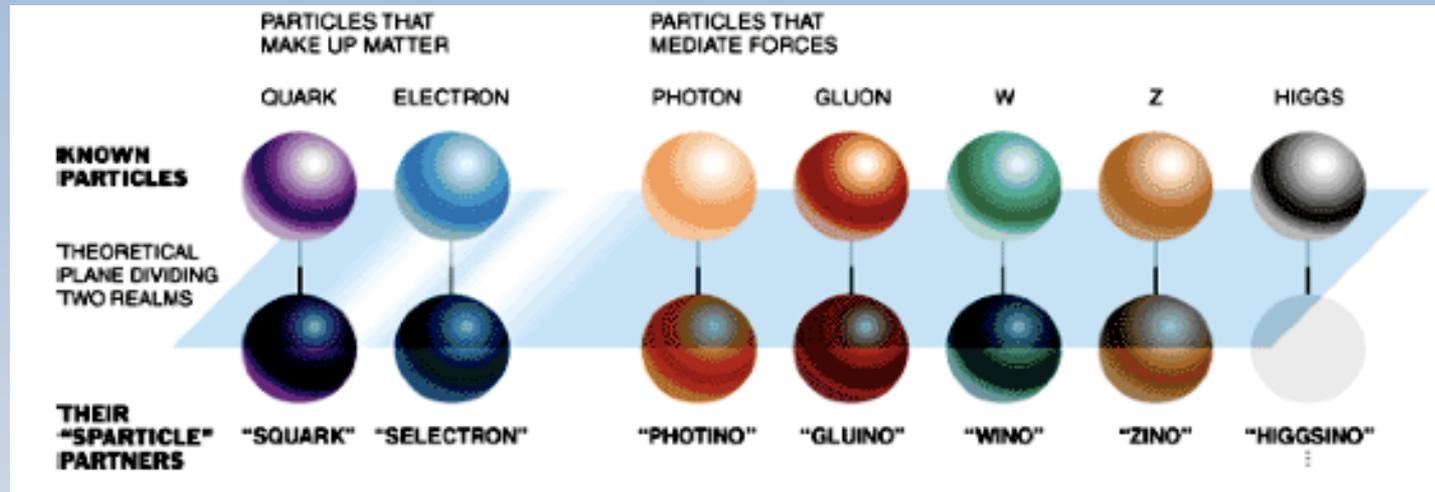
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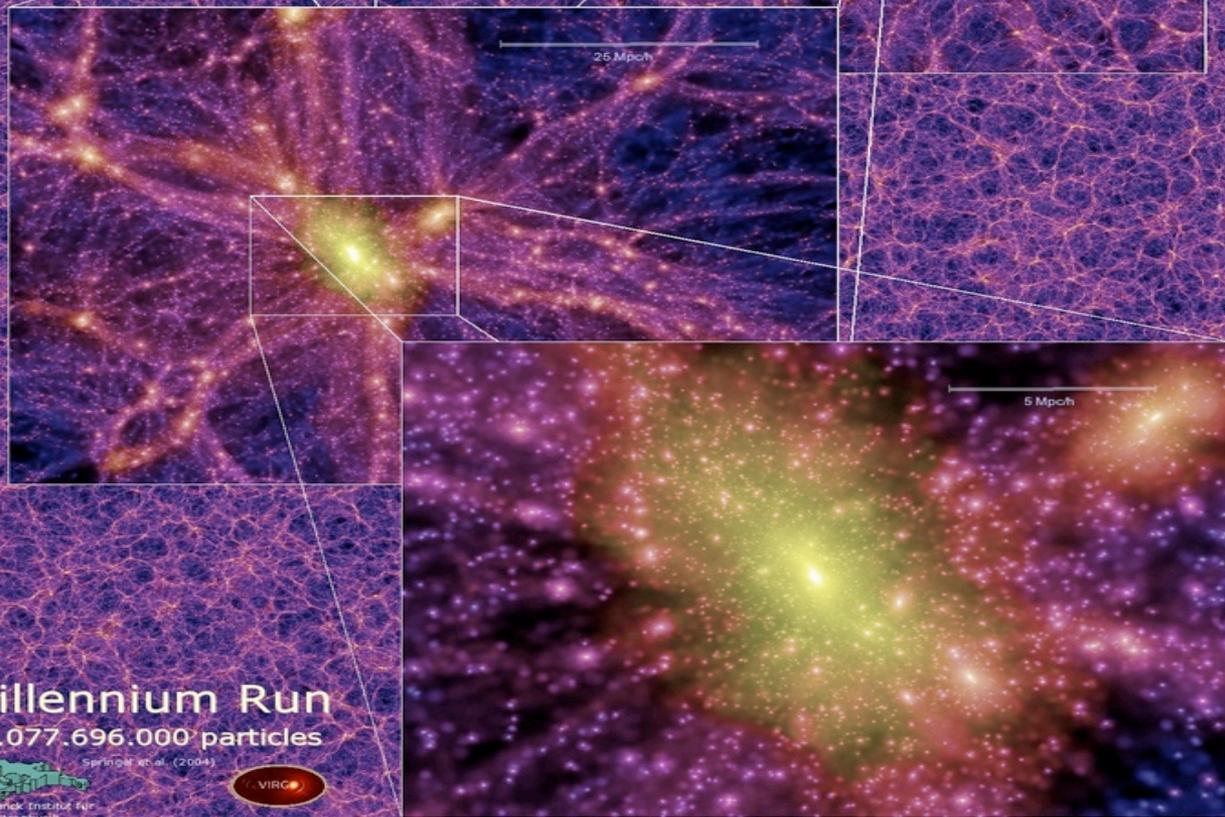
Supersymmetry : A New Symmetry of Nature

Every known particle has a partner particle we have not yet seen



- Has a Higgs particle as needed to solve the mystery of mass
- The lightest SUSY particle is a perfect Dark Matter candidate
- It can explain the origin of the Matter – Antimatter imbalance

*The mysteries of mass and matter
are yet to be revealed*



Millennium Run
10,077,696,000 particles

Springel et al. (2004)

