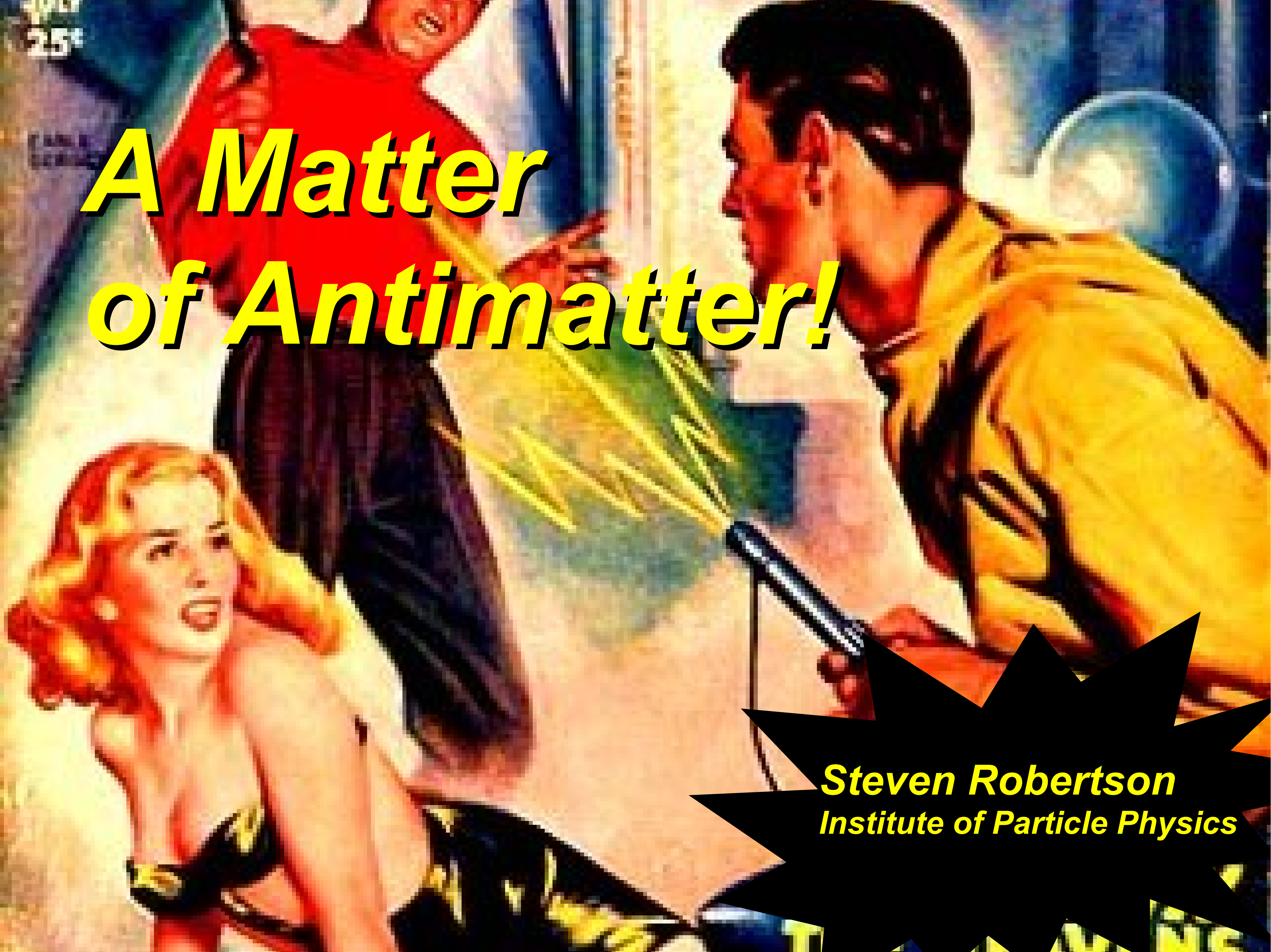
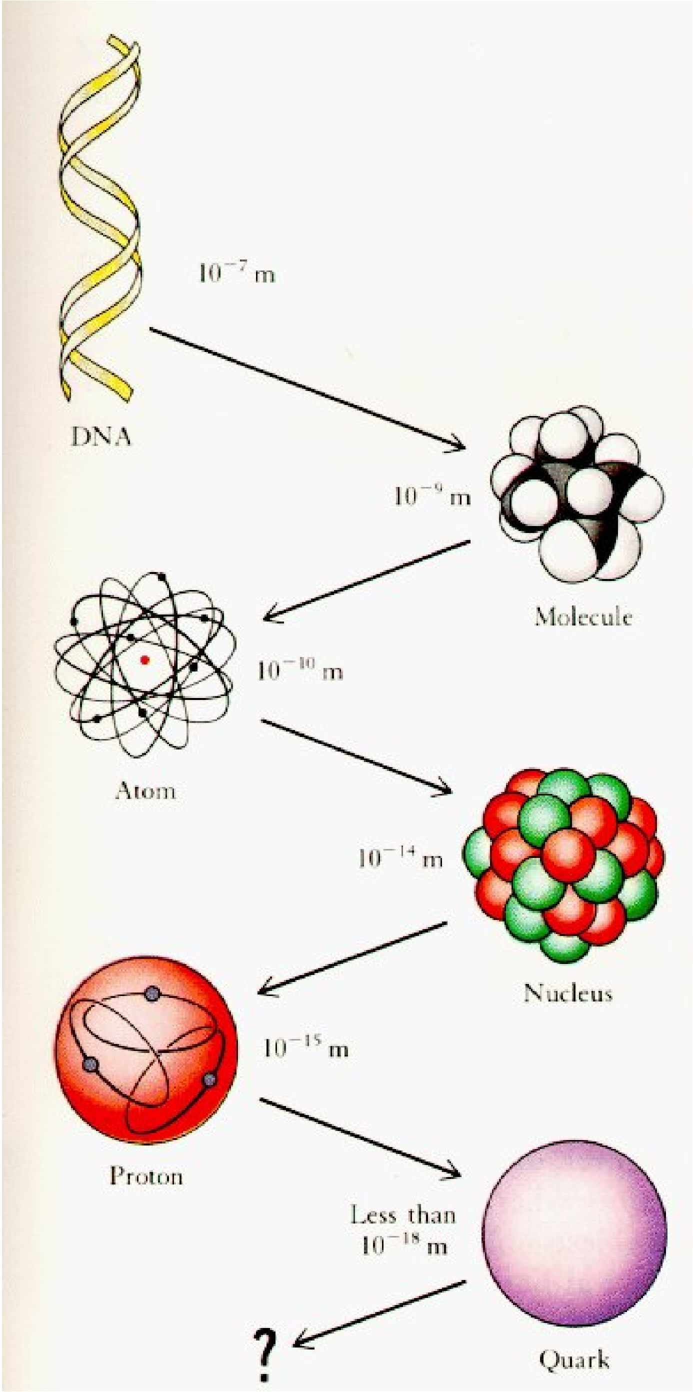


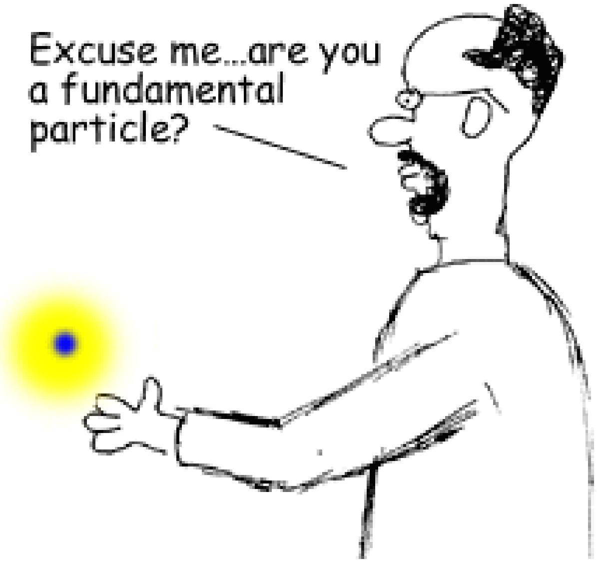
A Matter of Antimatter!

Steven Robertson
Institute of Particle Physics



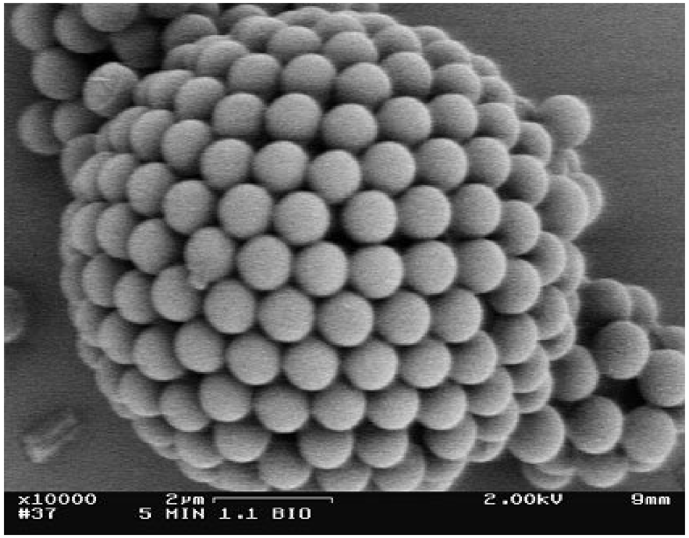
Particle physics experiments can be thought of as microscopes which resolve size scales a billion times smaller than atoms and molecules

"Fundamental" particles:
electrons, neutrinos, quarks, ???



How small is small?

If this thing was the size of the earth...

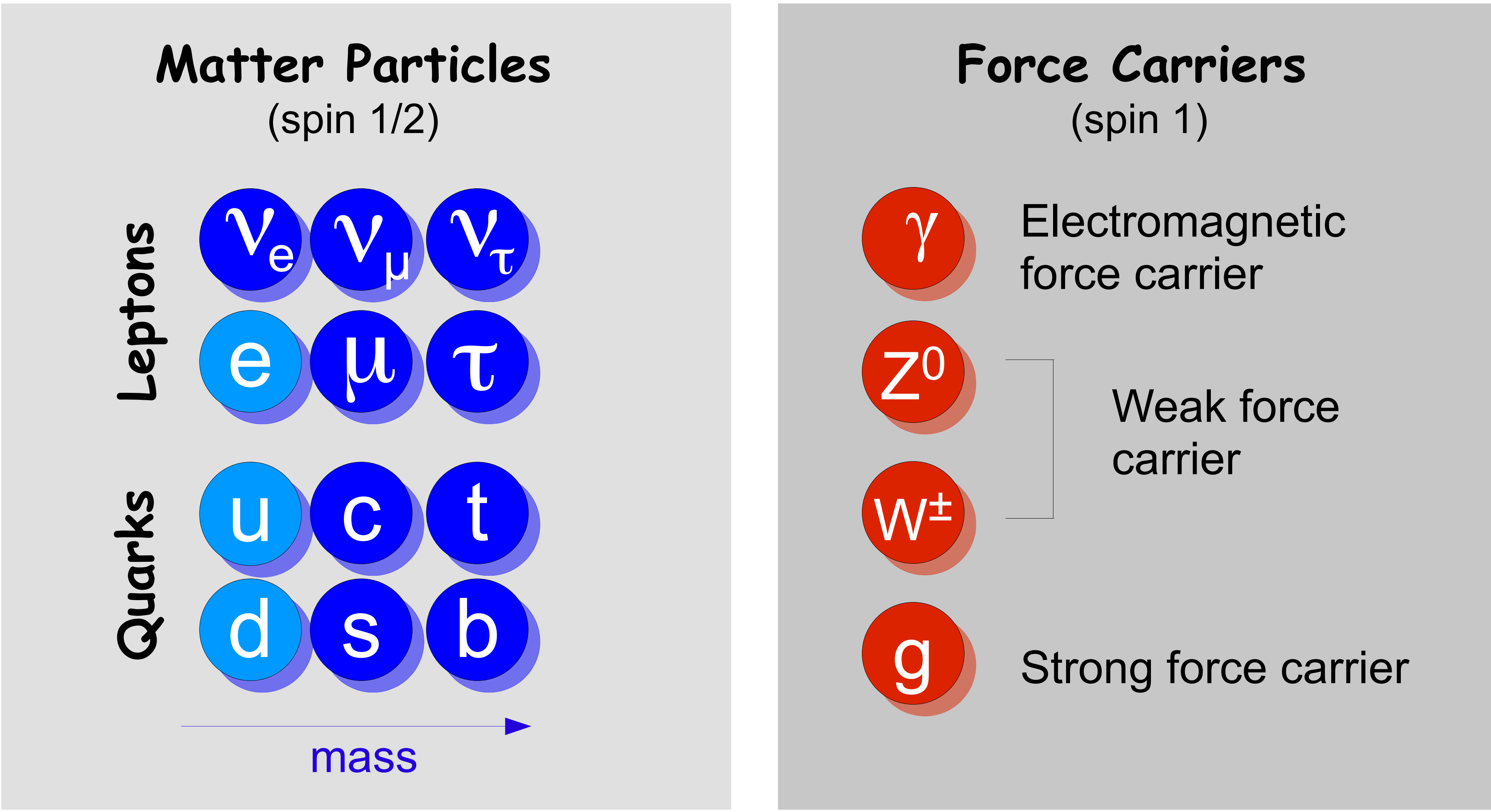


...then a proton would be this big .

Particle physicists would still need high power microscopes to make measurements at the level that we do now

An electron microscope image of a "colloidosome," a water droplet coated in colloid (polystyrene) beads.
Image Credit: David Weitz research laboratory at Harvard University. http://www.deas.harvard.edu/projects/weitzlab/

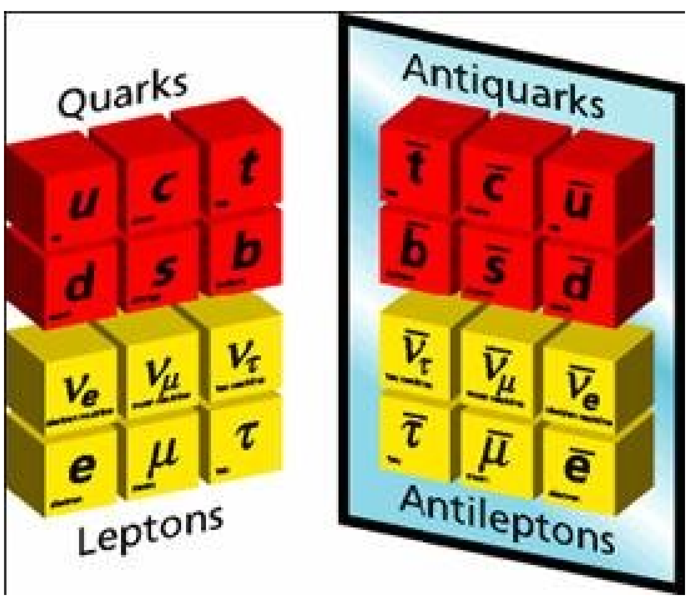
“Periodic table” of particles

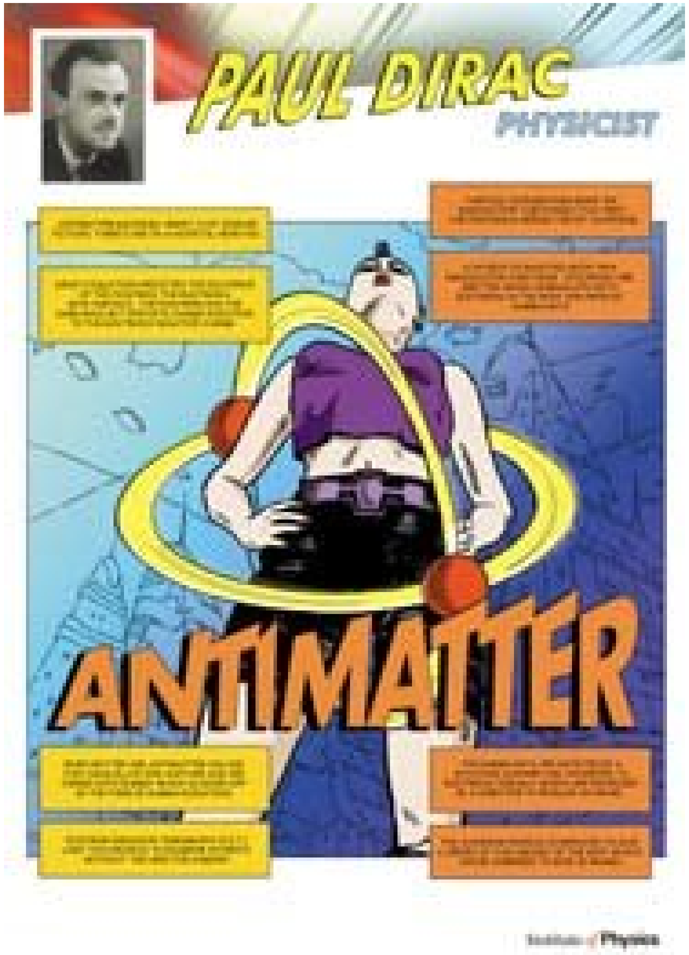


Antimatter

In 1928 physicist Paul Dirac predicted the existence of antimatter in order to interpret negative energy solutions to his equation

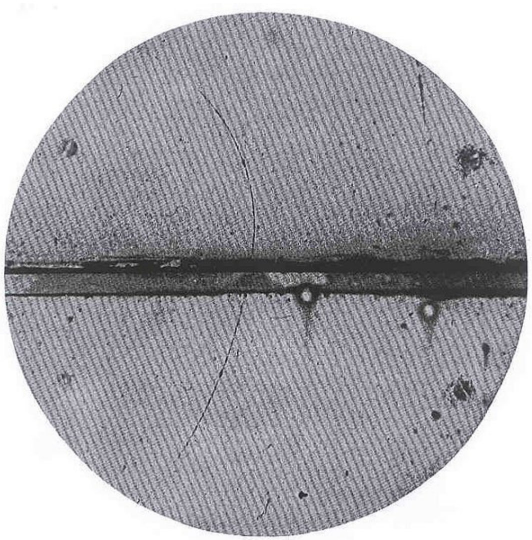
Quantum mechanical description of particles consistent with special relativity

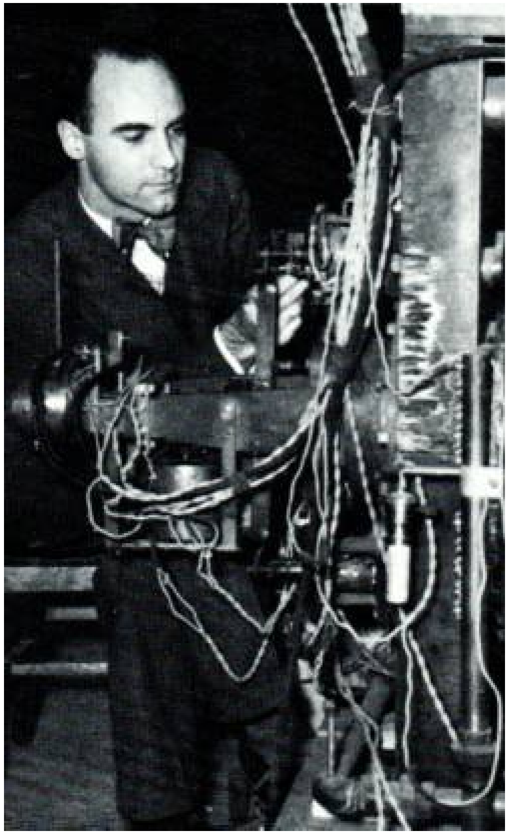




Existence of antimatter

Positron (anti-electron) was first observed by Carl Anderson in 1932 using cloud chamber photos of cosmic rays





* annihilation of positrons was likely observed by a Caltech grad student in 1930, but he didn't correctly interpret his result at such. Anderson later also observed the muon, but incorrectly identified it as a pion, but is still credited with the discovery.

So what good is it?

Only 5 Trillion Calories per drink!

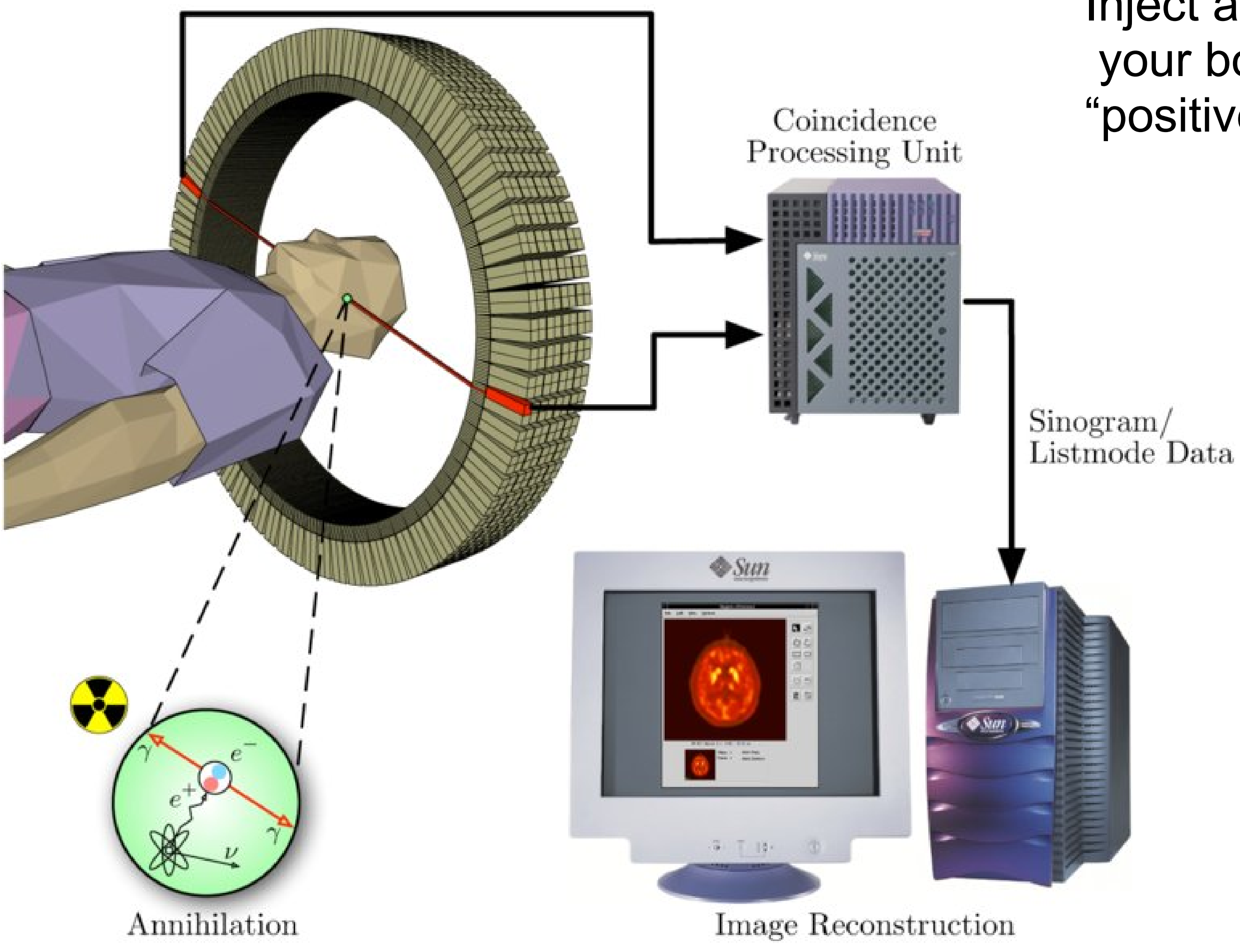
Antimatter is NOT an energy *source*

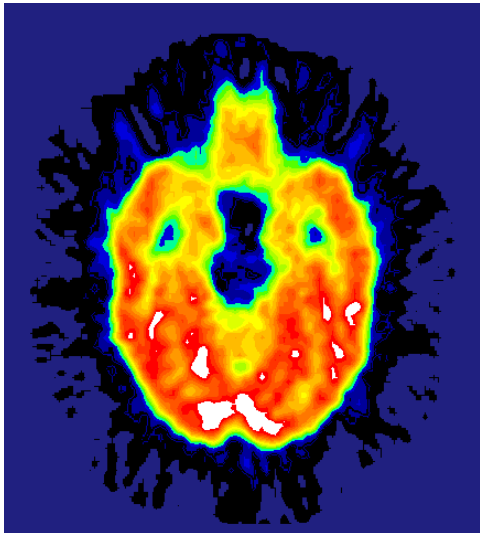
Since there is none around, we would have to create it first and it is a very inefficient process...

If all the antimatter ever made at CERN was annihilated with matter, it would produce enough energy to light a single electric light bulb for a **few minutes.** (electricity used to create it would have powered about 20000 lightbulbs for an entire year)

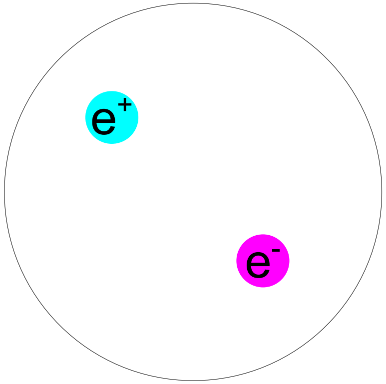
Positron Emission Tomography (PET)

Inject a radioactive "tracer" into your body which decays by "positive beta decay"



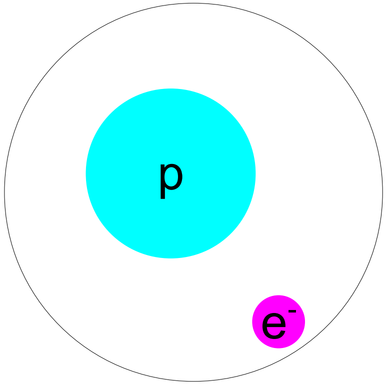


PET scan of the brain of BABAR physicist Adrian McKemey



Positronium

Can we get some fricken' sharks with fricken' positronium lasers on their fricken' heads?



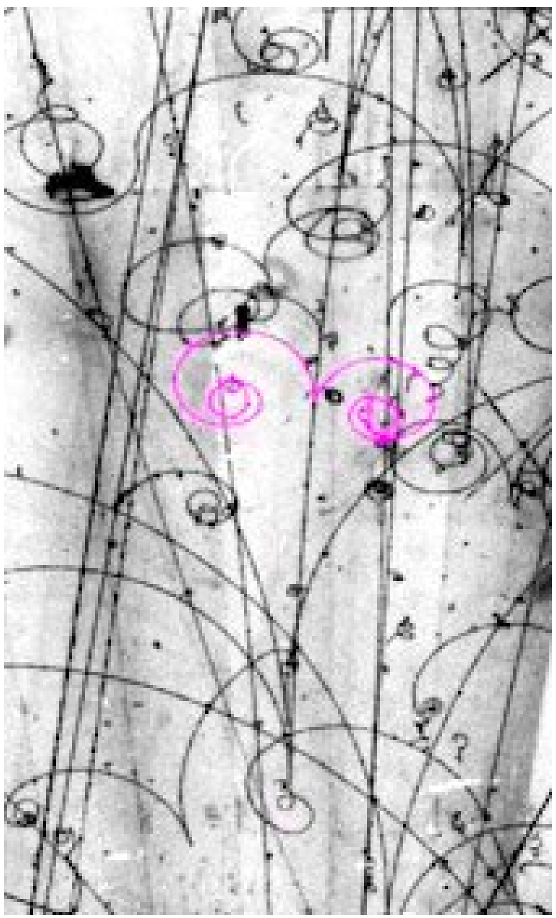
Hydrogen atom

Maybe

http://physics.ucr.edu/People/Home/Mills/html/ps_laser.htm

Matter and antimatter are produced as pairs of particles with opposite characteristics

- “**Evil twin**” model...

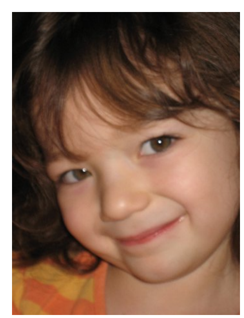


Physics Phun Phact: Electrons were named from the Greek word “elektron” meaning “amber” (i.e. fossilized tree sap)

Electron (e-)

Same mass, opposite charge

Positron (e+)



Same mass, opposite personality

“Good Amber”

“Evil Amber”

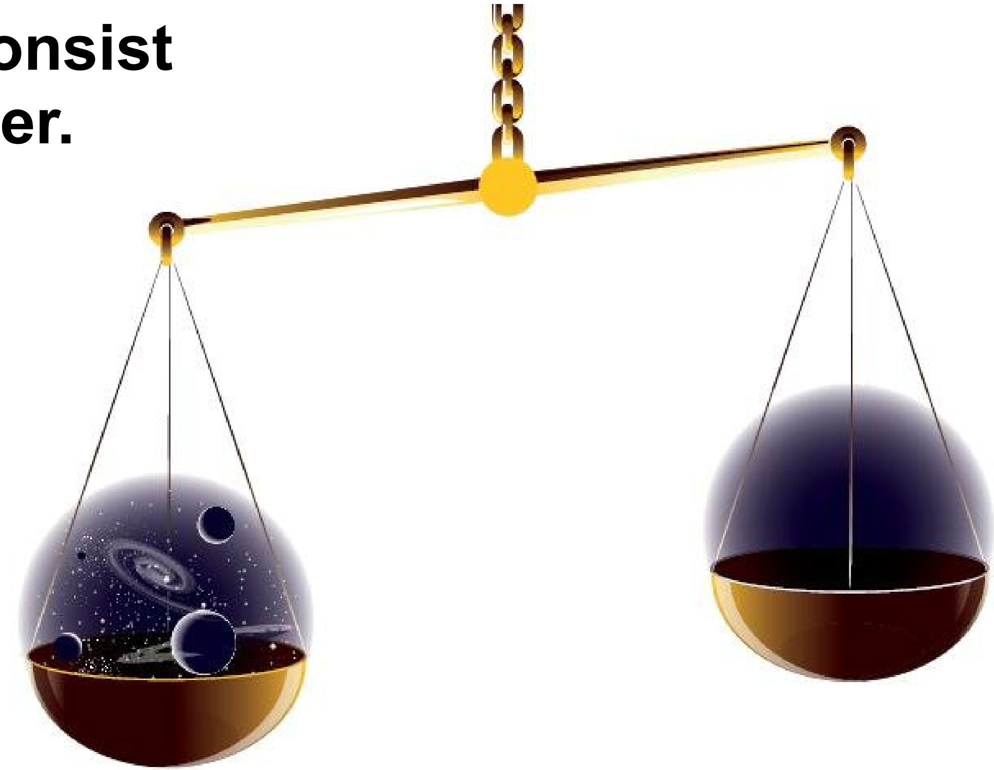
p

$\bar{\mathbf{p}}$

Big Problem

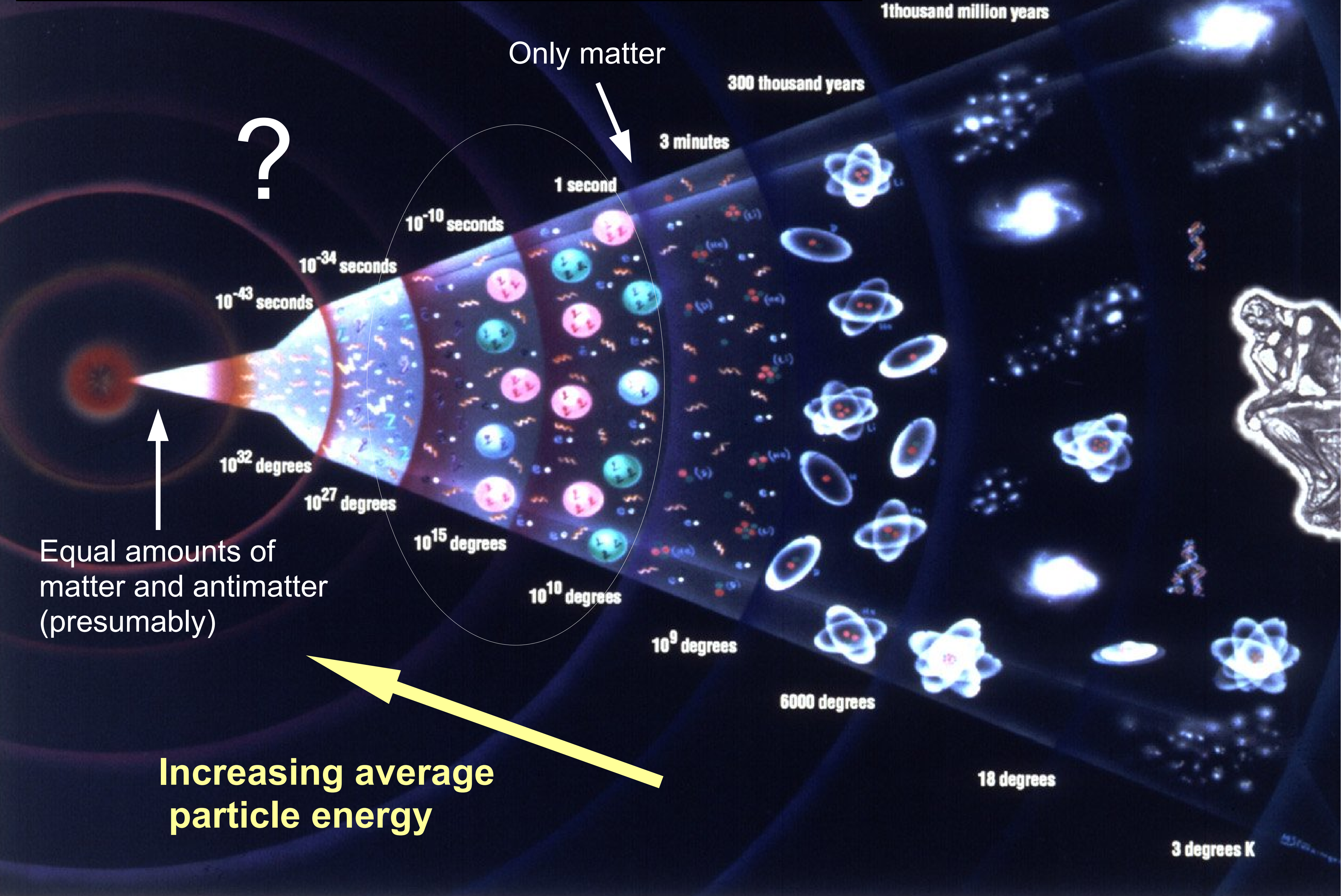
The universe appears to consist essentially entirely of matter.

If matter and antimatter are produced equally (and disappear by annihilating with each other) how can an imbalance arise?



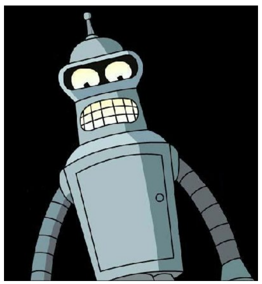
"Baryon Asymmetry of the Universe"

History of the Universe



Evil Twins

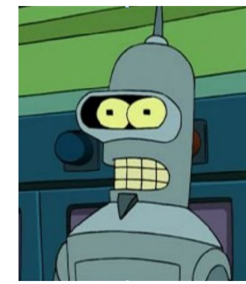
Matter | **Antimatter**



d

If evil twins are exact copies of the original, then neither side can win

$\bar{d}$



s

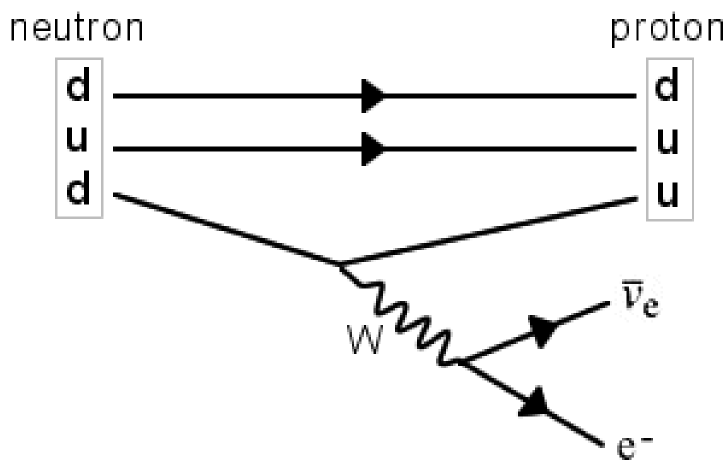
Fortunately, nature has introduced a subtle flaw, permitting good to triumph over evil...
(at least sometimes)

$\bar{s}$

b

$\bar{b}$

The Weak Interaction



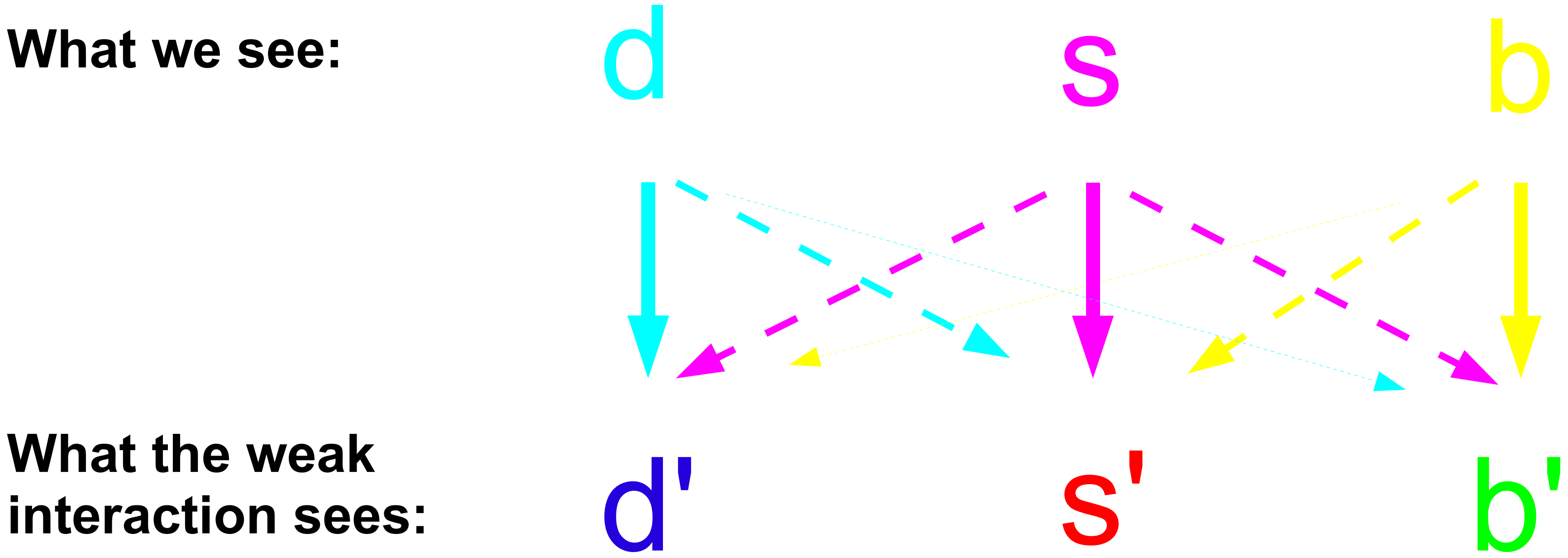
Beta radioactive decay via the weak interaction

The weak interaction
- is a fundamental force
(like gravity, electromagnetism and the strong nuclear force)

- has this strange ability to change one type of quarks into a different type of quarks

...but it gets worse

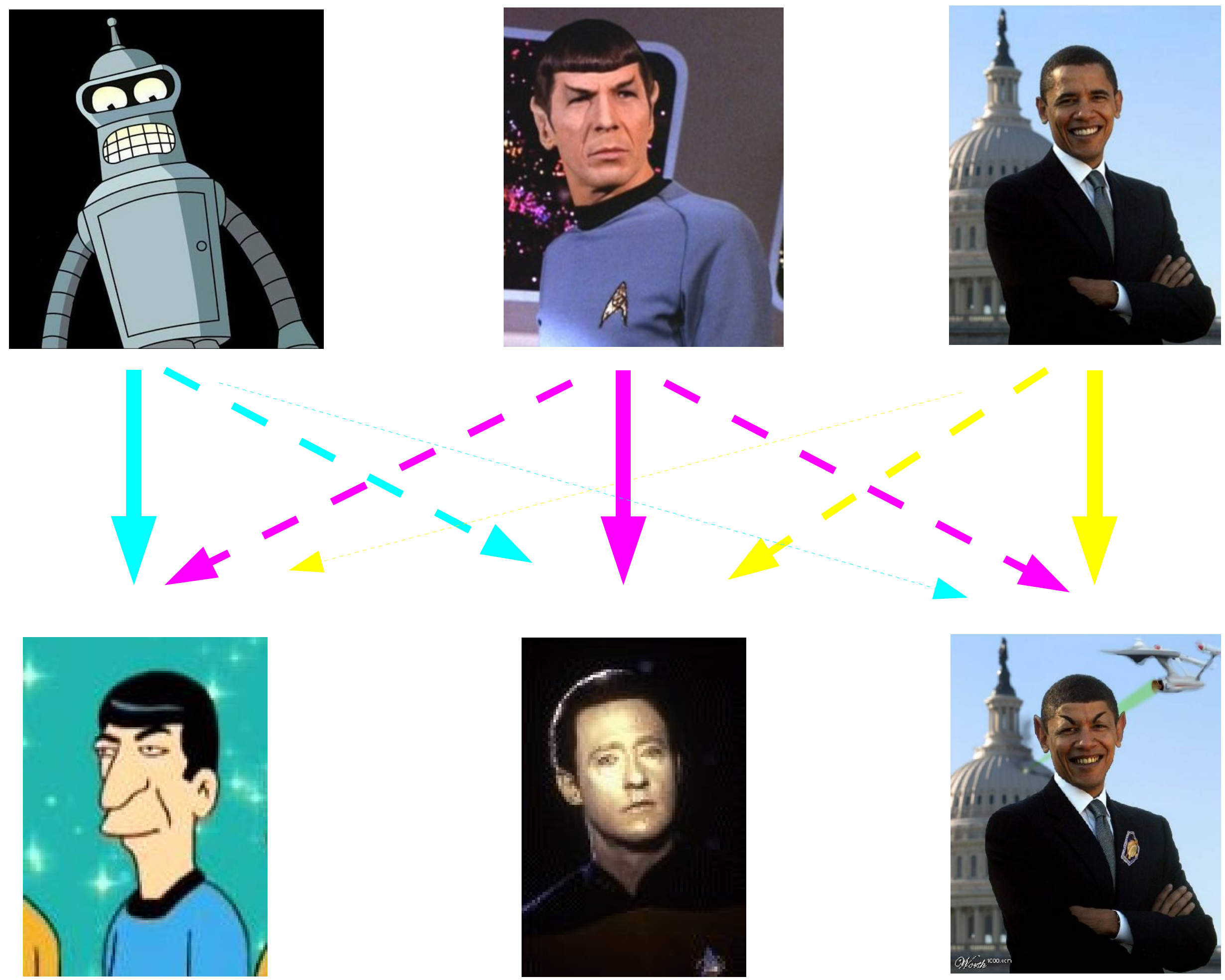
Quarks interact as though they are actually a mixture of the three different “generations”



Quarks interact as though they are actually a mixture of the three different "generations"

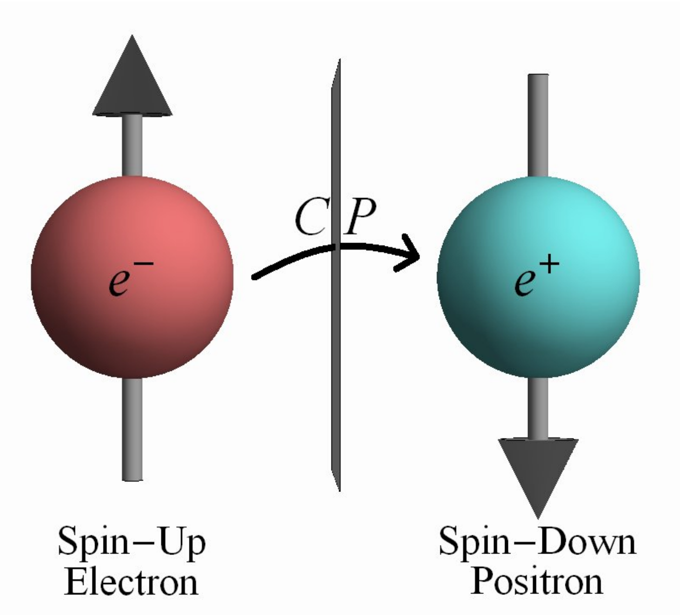
What we see:

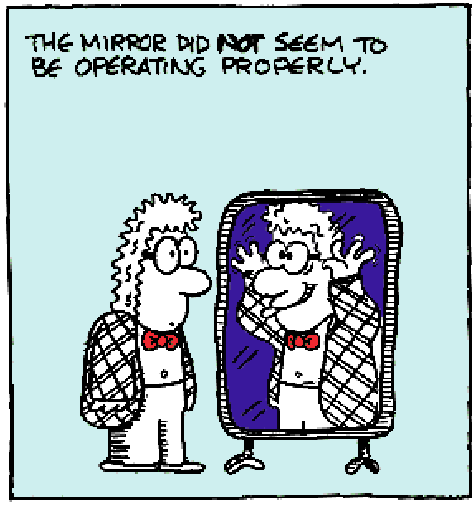
What the weak interaction sees:



Mixing of the quark generations by the weak interaction introduces enough confusion ("degrees of freedom") that the weak force does not treat antiquarks in exactly the same way as the quarks...

...or at least that is how we've been assuming it works, for the past 30 years or so





Violation of **CP** symmetry is necessary, but not sufficient to create an imbalance between matter and antimatter in the universe

1964 - Cronin & Fitch observed CP violation in K^0 decays:

$K_L \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow \pi^0 \pi^0$ (0.2%)

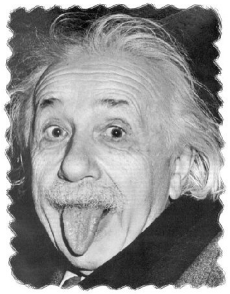
1973 - Kobayashi & Maskawa devised 3-generation scheme for quarks, with mixing from the weak interaction

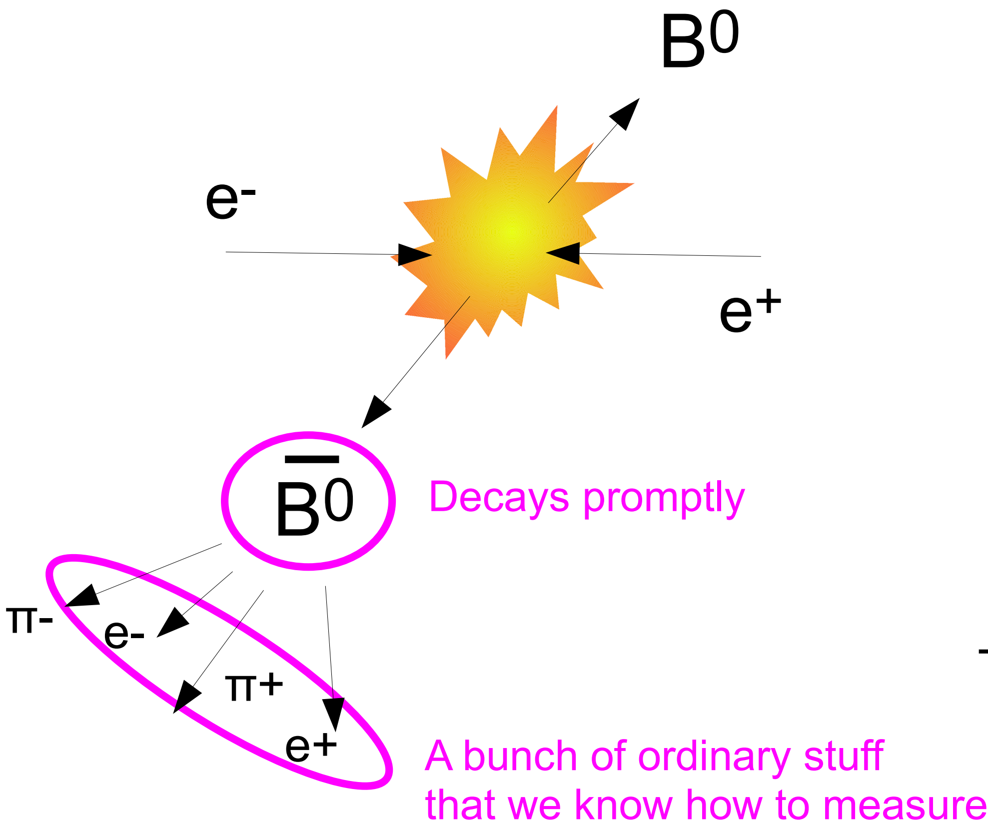
Makoto Kobayashi,
KEK, Tsukuba, Japan

Toshihide Maskawa,
YITP, Kyoto University, and
Kyoto Sangyo University, Japan

It was later realized that all this implied that there could be very large CP asymmetries in decays of “B meson” particles...

How to look for CP violation





Very big number

$$E = m\,c^2$$

Total available energy

Amount of stuff
you can create

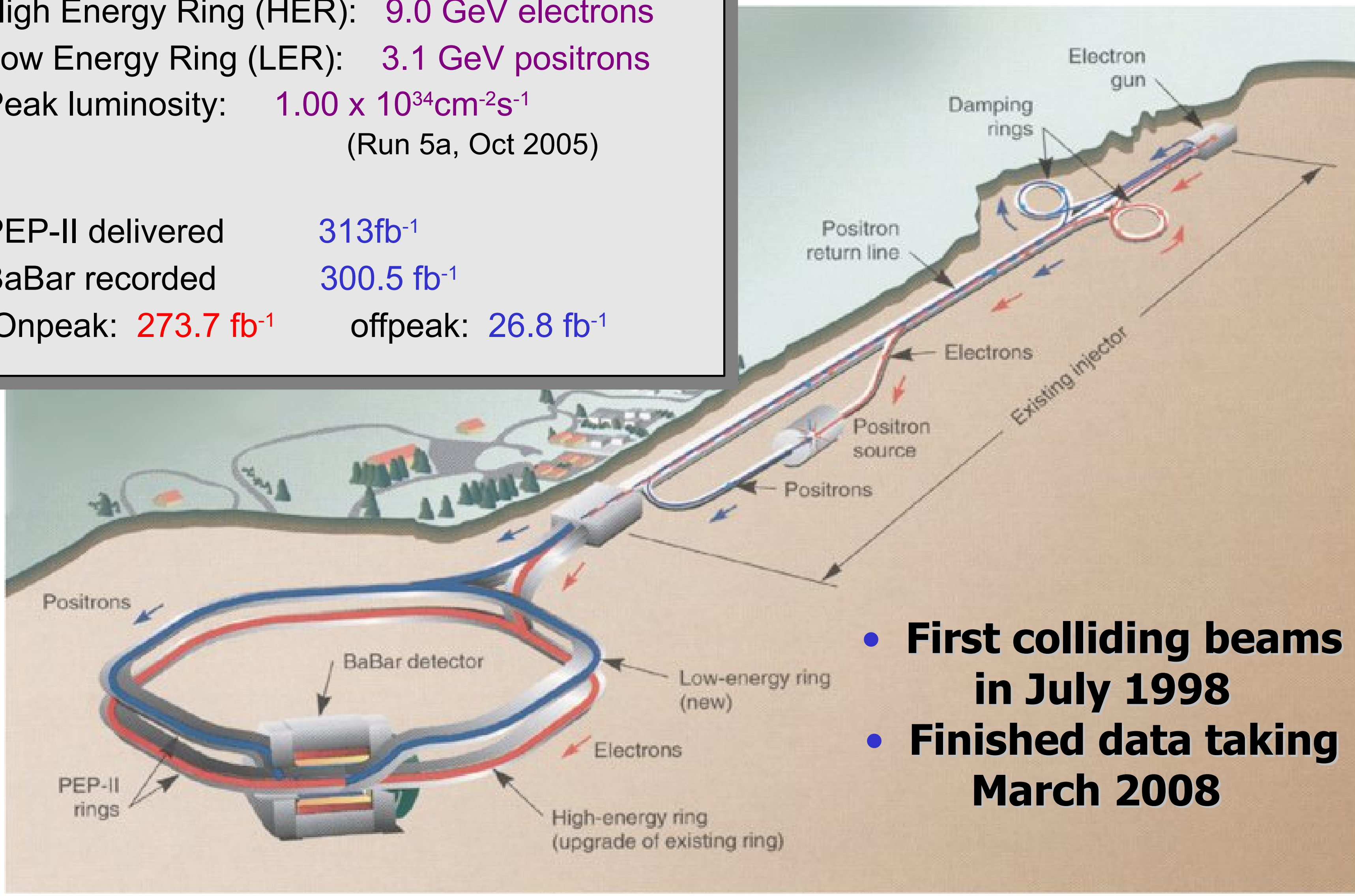
Compare the decays of the B^0 and anti-B^0

Then do this again, about a billion times....

PEP-II Asymmetric B Factory

High Energy Ring (HER): 9.0 GeV electrons
Low Energy Ring (LER): 3.1 GeV positrons
Peak luminosity: 1.00 x $10^{34} cm^{-2} s^{-1}$
(Run 5a, Oct 2005)

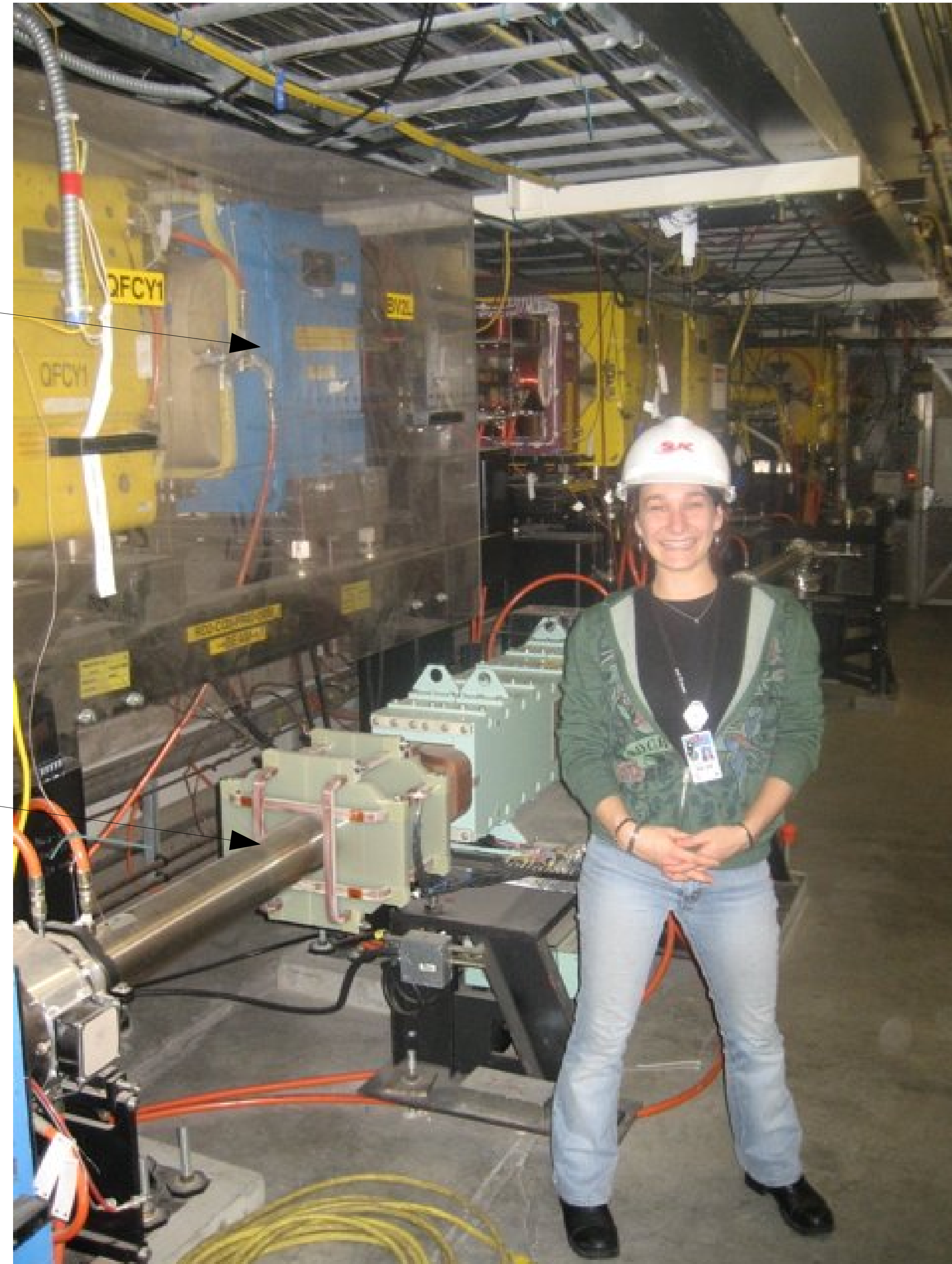
PEP-II delivered $313 fb^{-1}$
BaBar recorded $300.5 fb^{-1}$
Onpeak: $273.7 fb^{-1}$ offpeak: $26.8 fb^{-1}$



- **First colliding beams in July 1998**
- **Finished data taking March 2008**

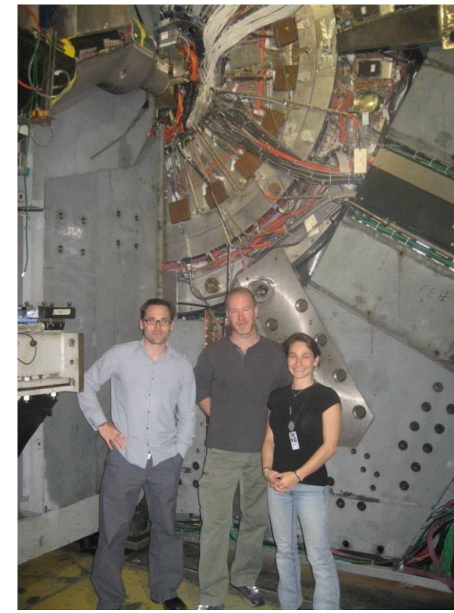
“antimatter beam”

“matter beam”

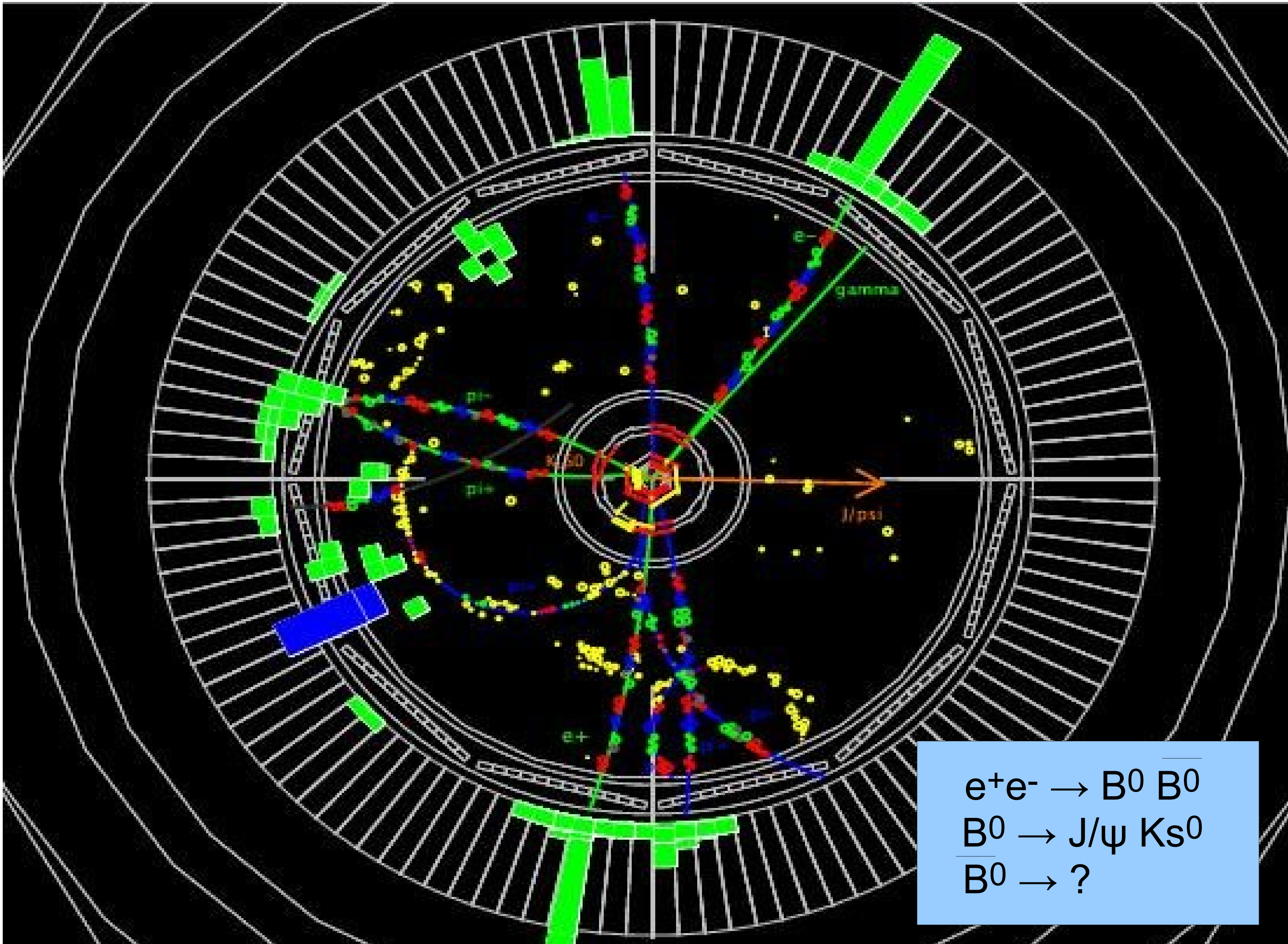


Tetatron collider at Fermilab colliders protons (p) with anti-protons ($\bar{p}$)

BABAR experiment



SLAC NATIONAL ACCELERATOR LABORATORY



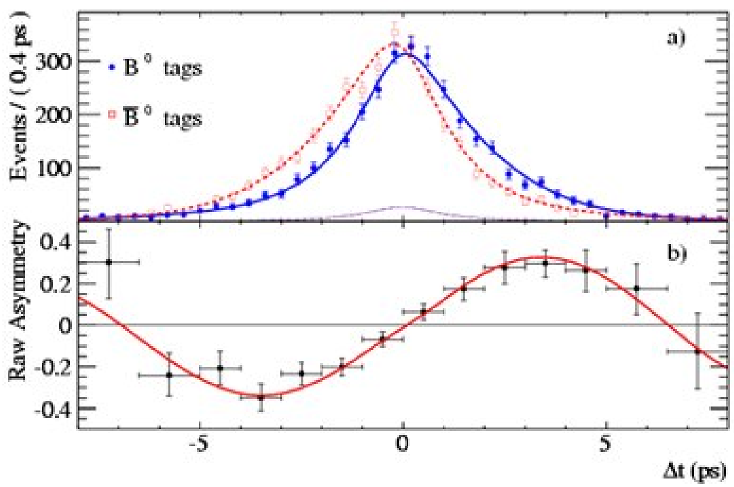
$e^+e^- \to B^0 \, \overline{B^0}$

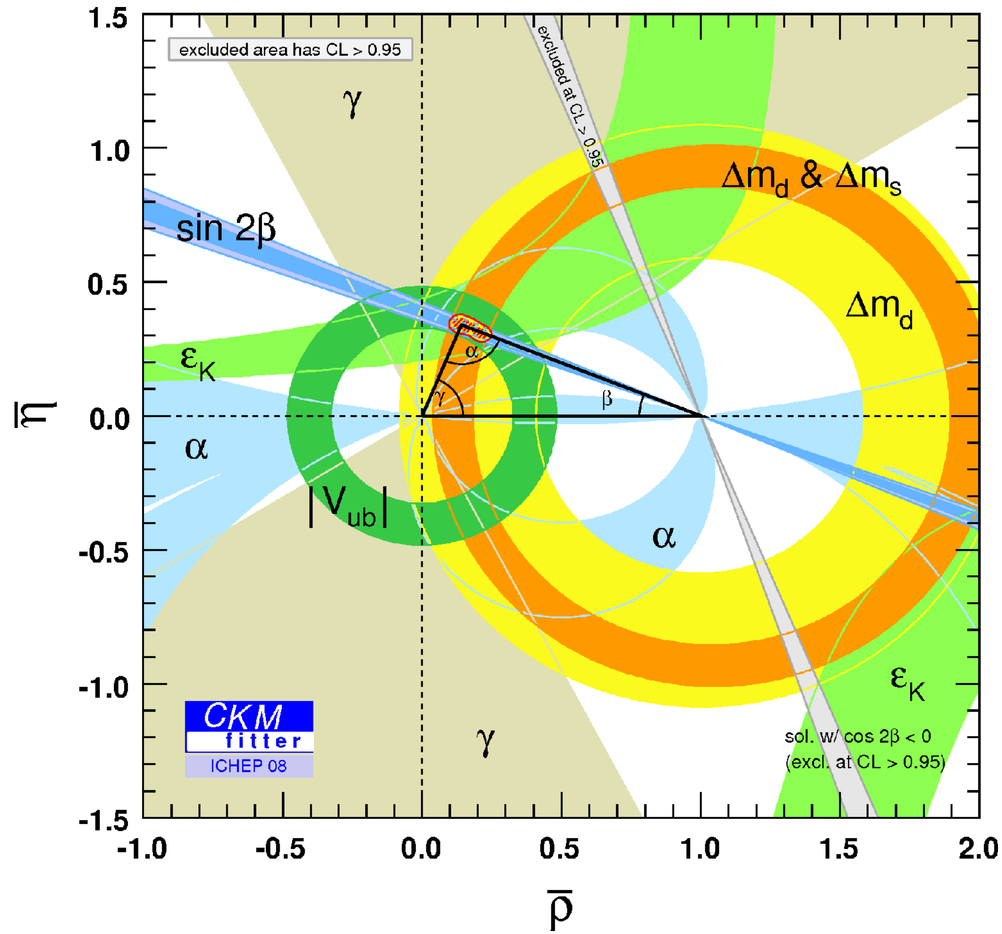
$B^0 \to J/\psi \; Ks^0$

$\overline{B^0} \to ?$

And the results are in...

b quarks behave slightly differently than their antimatter counterparts!





Behaviour is exactly as was predicted back in 1972...

2008 Nobel Prize

"for the discovery of the origin of the **broken symmetry** which predicts the existence of at least three families of quarks in nature"

CP

Makoto Kobayashi,
KEK, Tsukuba, Japan

Toshihide Maskawa,
YITP, Kyoto University, and
Kyoto Sangyo University, Japan

"It is only in recent years that scientists have come to fully confirm the explanations that Kobayashi and Maskawa made in 1972. It is for this work that they are now awarded the Nobel Prize in Physics. They explained broken symmetry within the framework of the Standard Model, but required that the Model be extended to three families of quarks... As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier."

Great!   Problem solved....

...except that the Kobayashi – Maskawa mechanism turns out to give too little matter-antimatter asymmetry by a factor of a trillion or so

- Antimatter exists...but there is none of it around
- Quarks are “fundamental” particles...but we can change them into other quarks
- Antimatter is the “mirror image” of matter...except that the mirror is flawed
- “Weak” CP violation is the only known way that nature can favour matter over antimatter...but we still get it wrong by a factor of a trillion or so