Truth and Beauty

and the Physics of the Dark

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QuarkNet Mtg.
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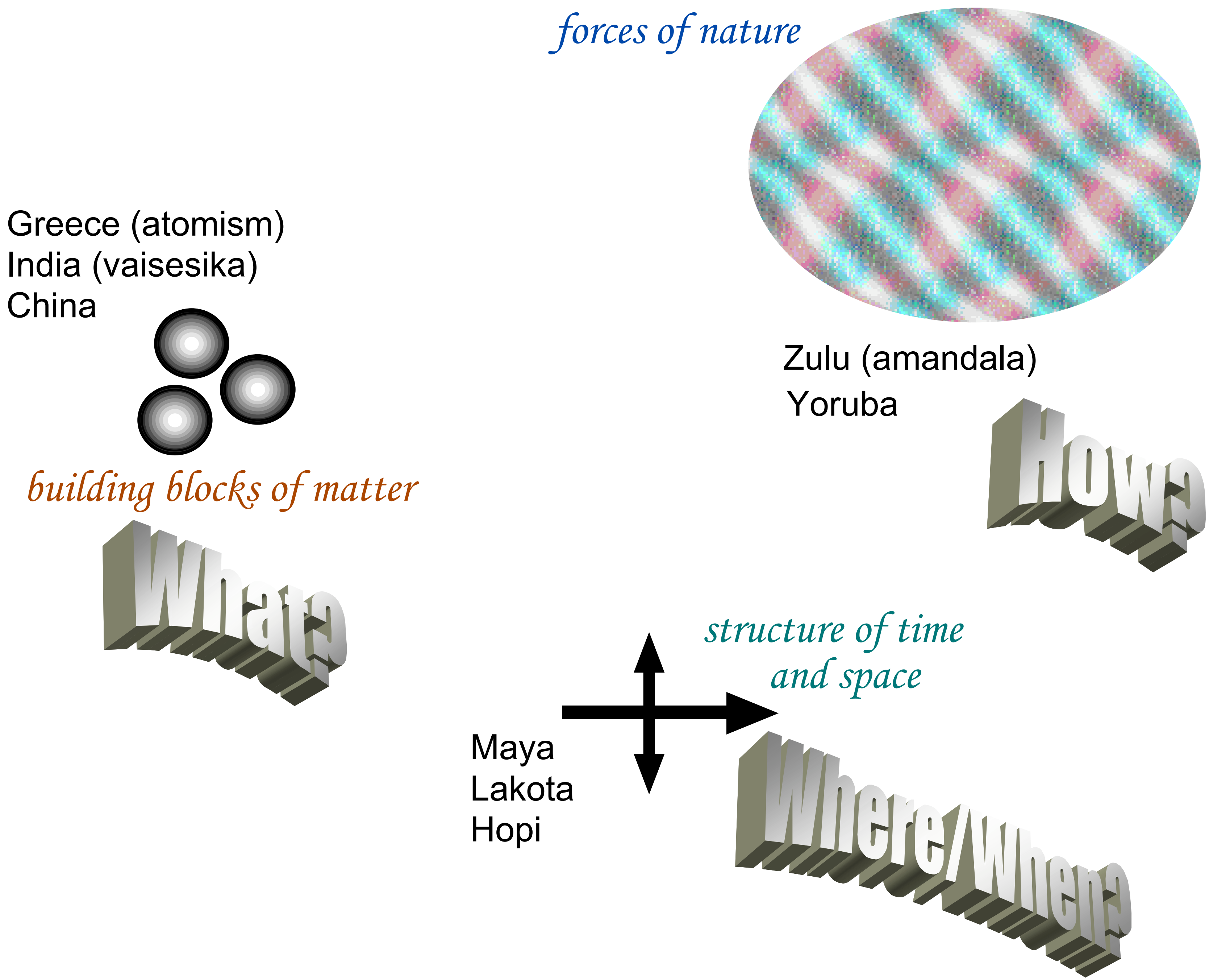
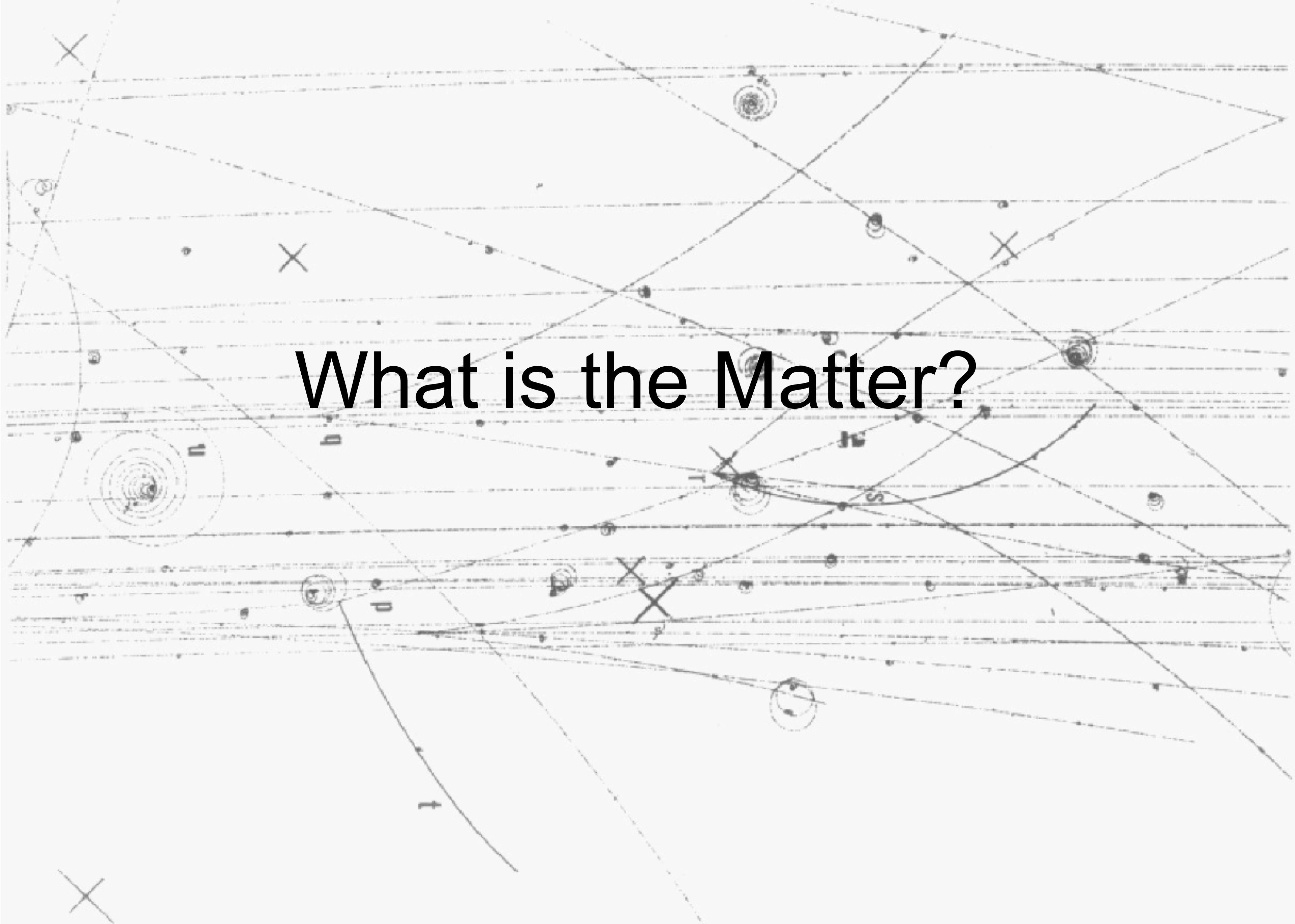

forces of nature
Zulu (amandala)
Yoruba
How?
Greece (atomism)
India (vaisesika)
China
building blocks of matter
What?
structure of time
and space
Maya
Lakota
Hopi
Where/When?

Foreshadowing…

- Let’s apply these questions to matter

- We’ll get three more specific questions
  - Why is most of universe ‘dark’?
  - Is our hunch on the origin of mass correct?
  - Why is there any matter in the universe, anyway!?

What is the Matter?



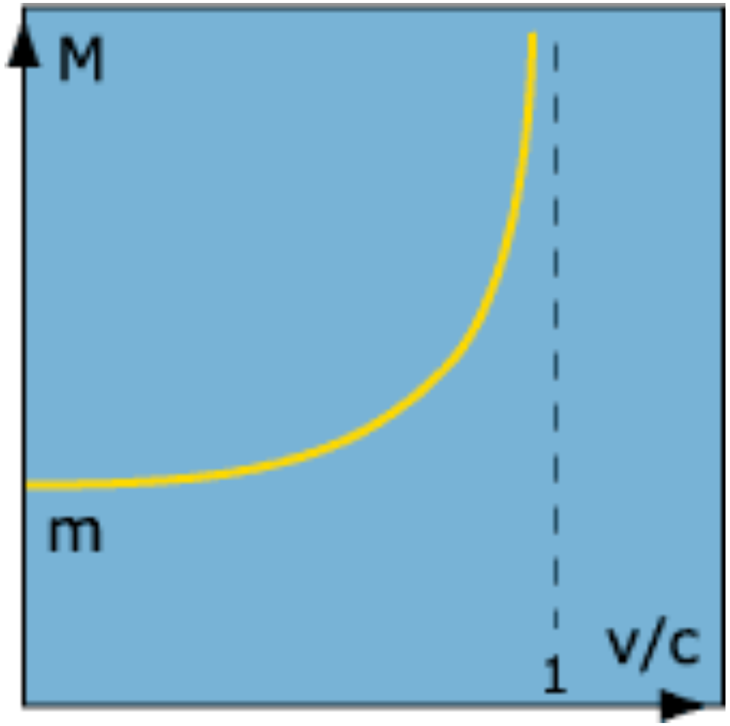
Mass

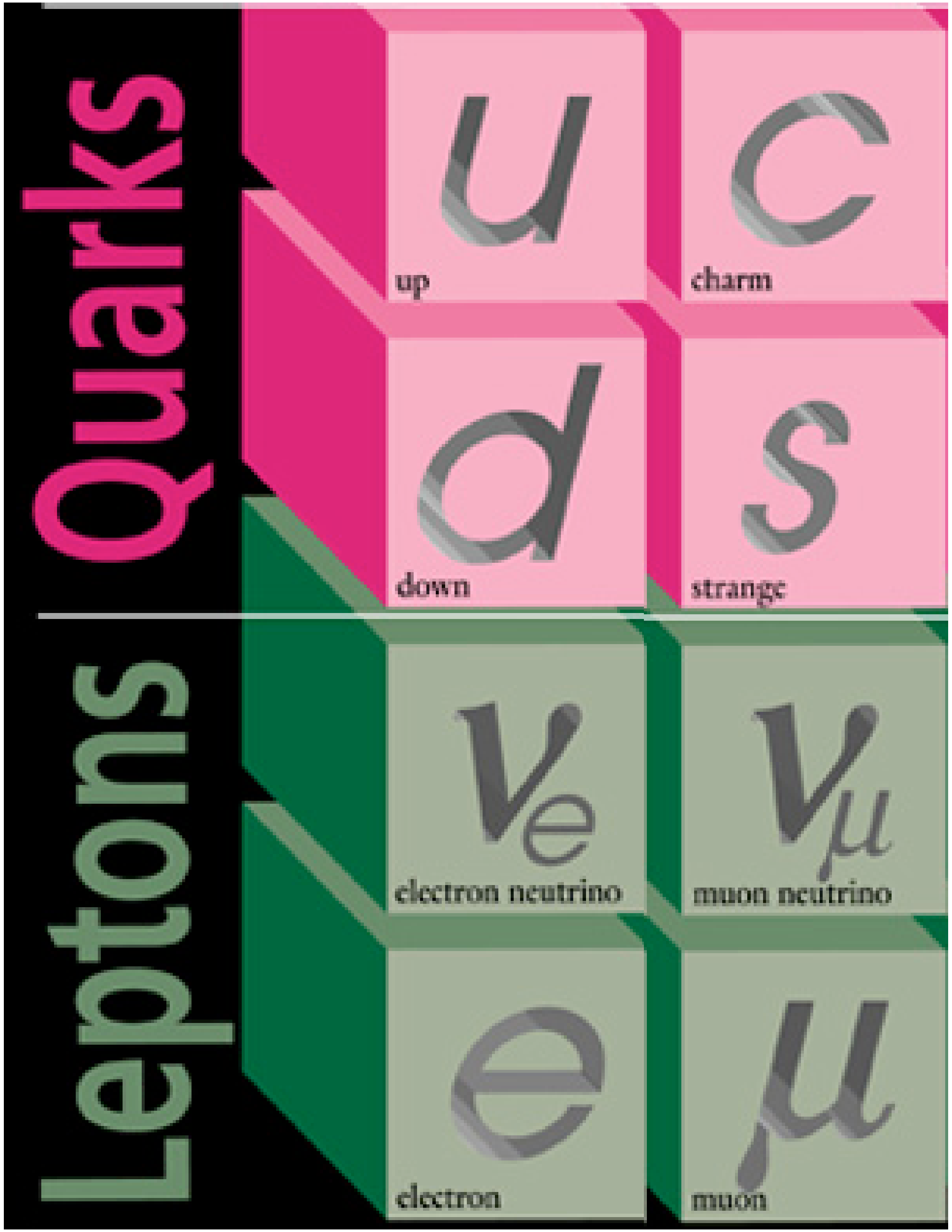
- **Inertial mass**
  - **A measure of how hard it is to move something, or change its motion**

F=ma

- **Relativity:**
  - **Mass as energy?**

$$E=mc^2$$



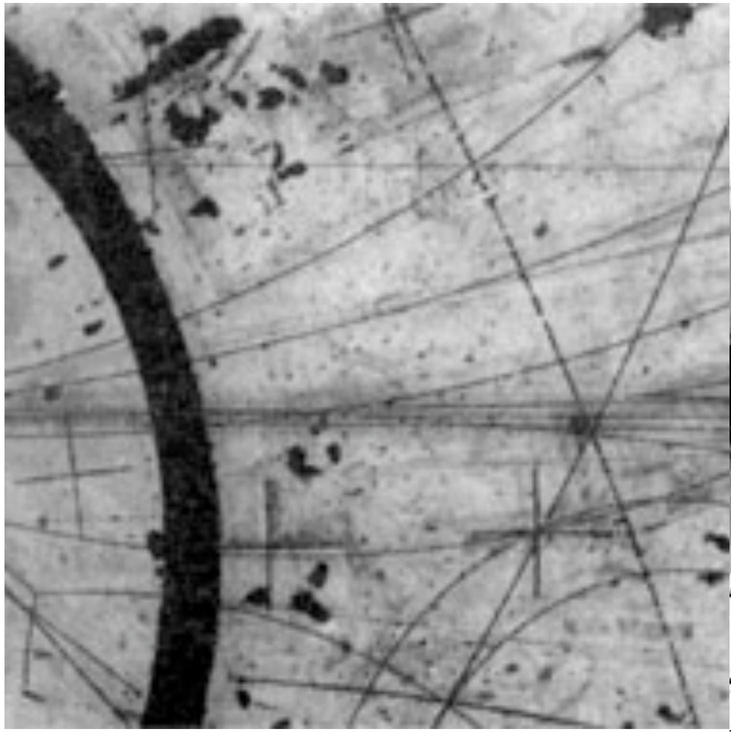


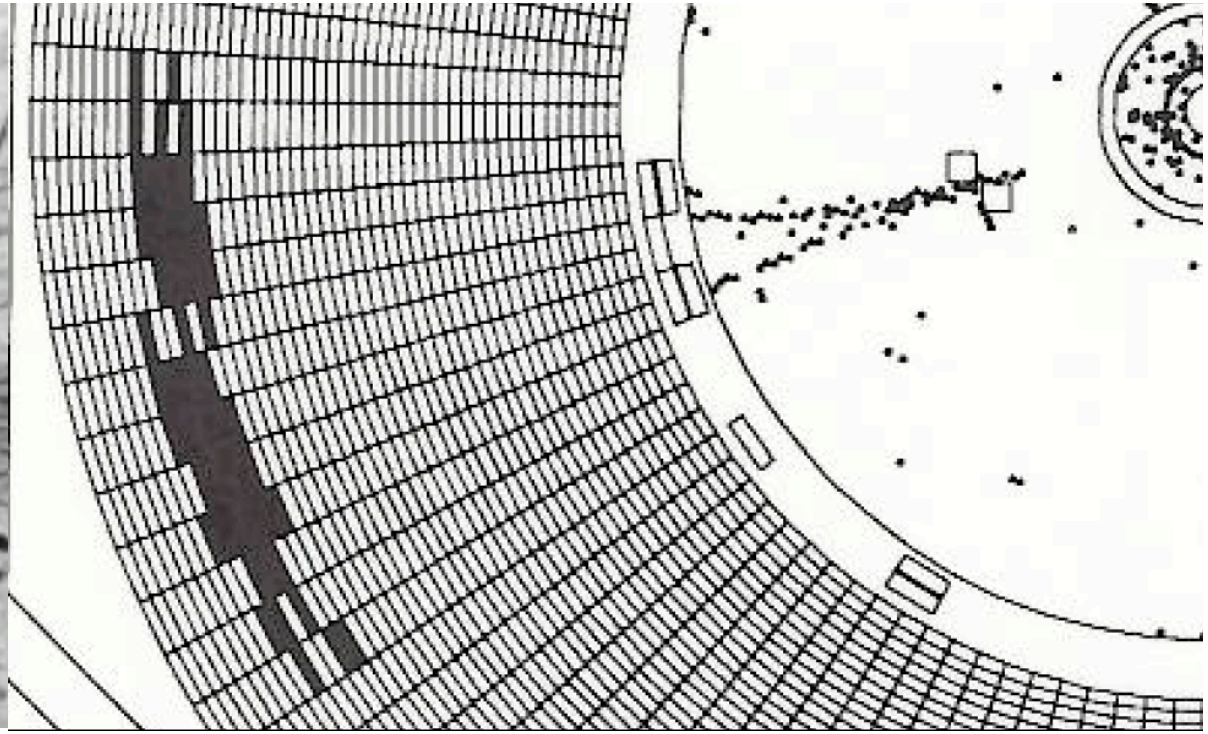
Comprise
heavy subatomic
particles

Why does
nature
need these?

In cosmic
rays

Antimatter



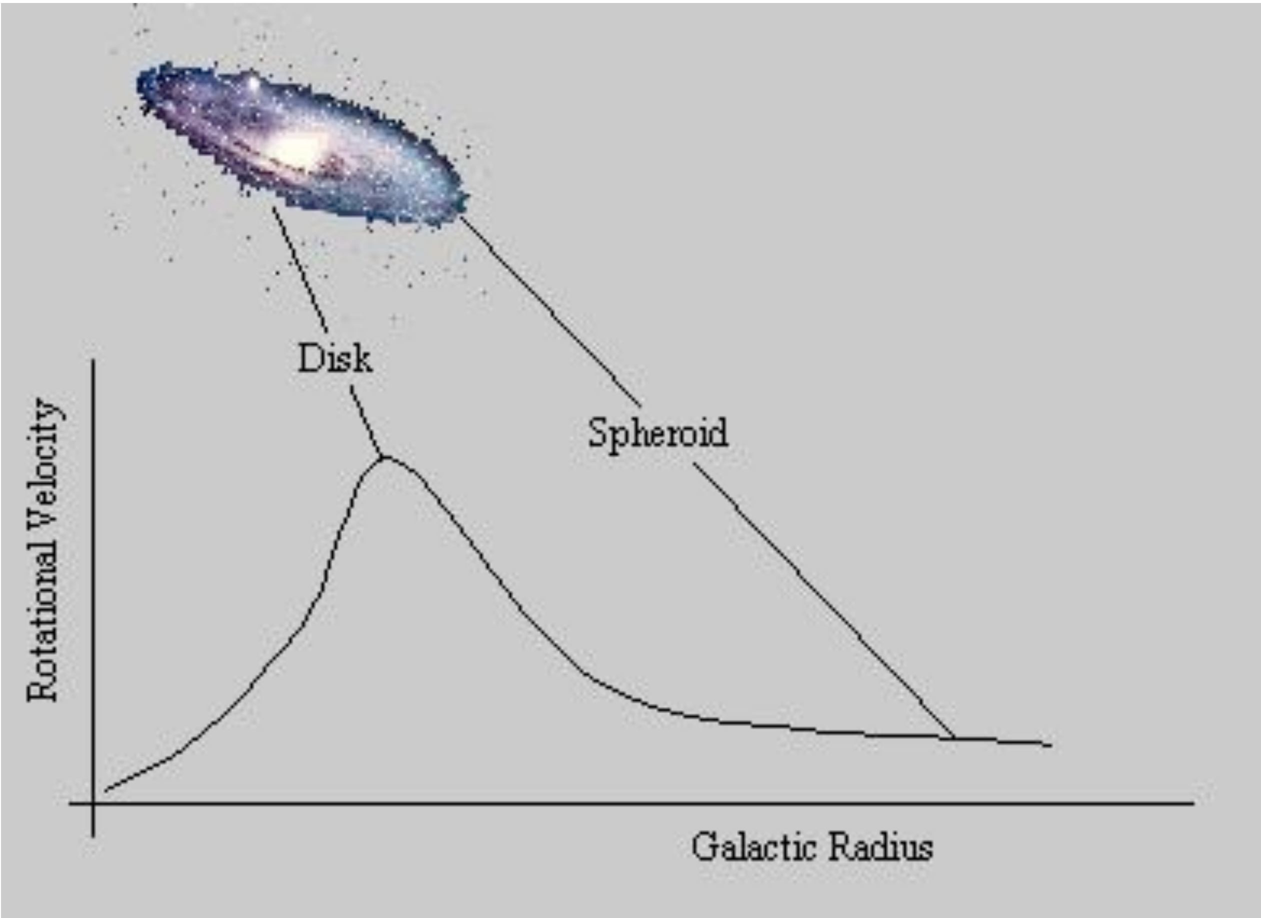


- Every particle has partner with opposite properties

Can you find the particle-antiparticle pair?

Gravity and Mass

- **Mass seems to be the 'charge' of gravity**

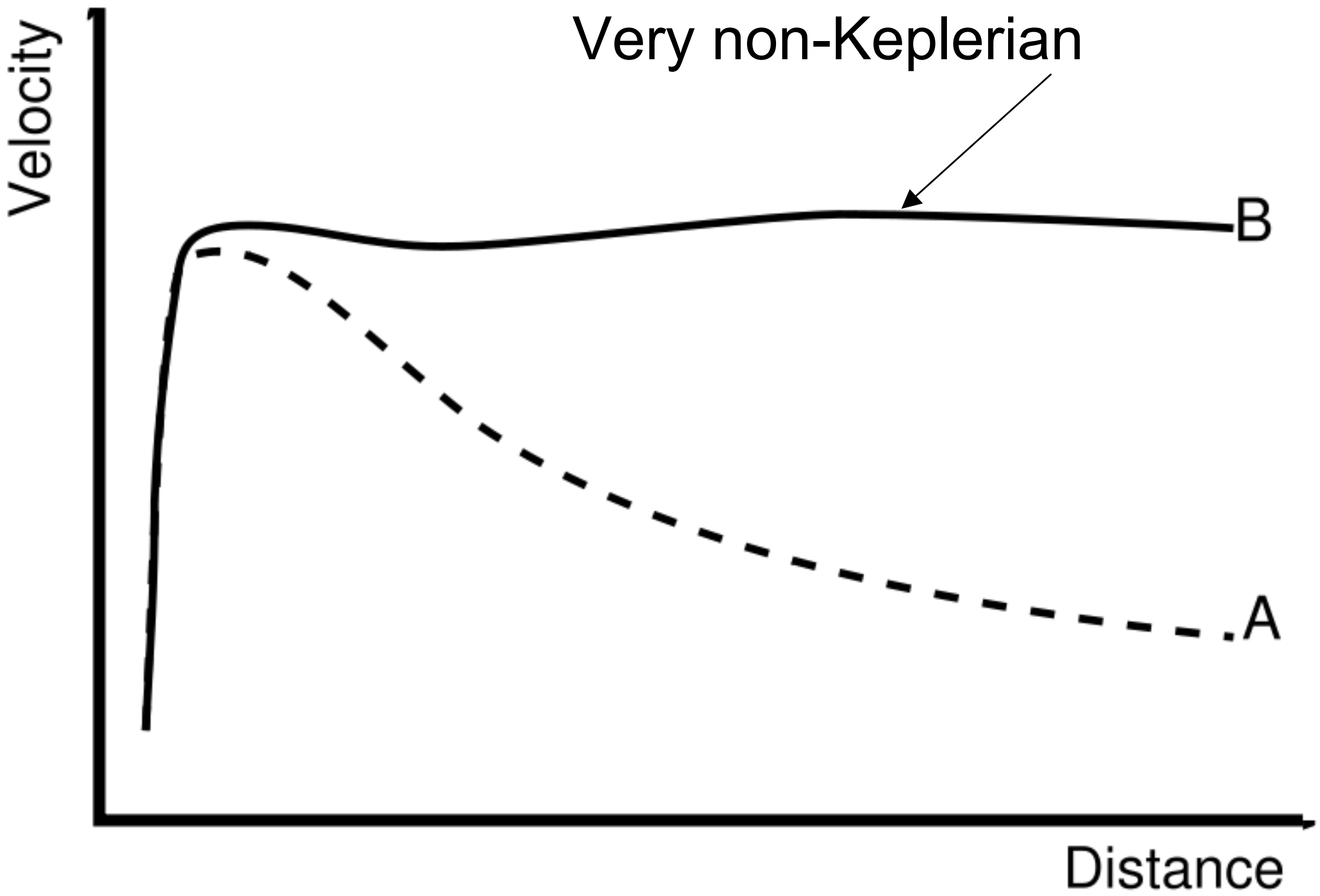


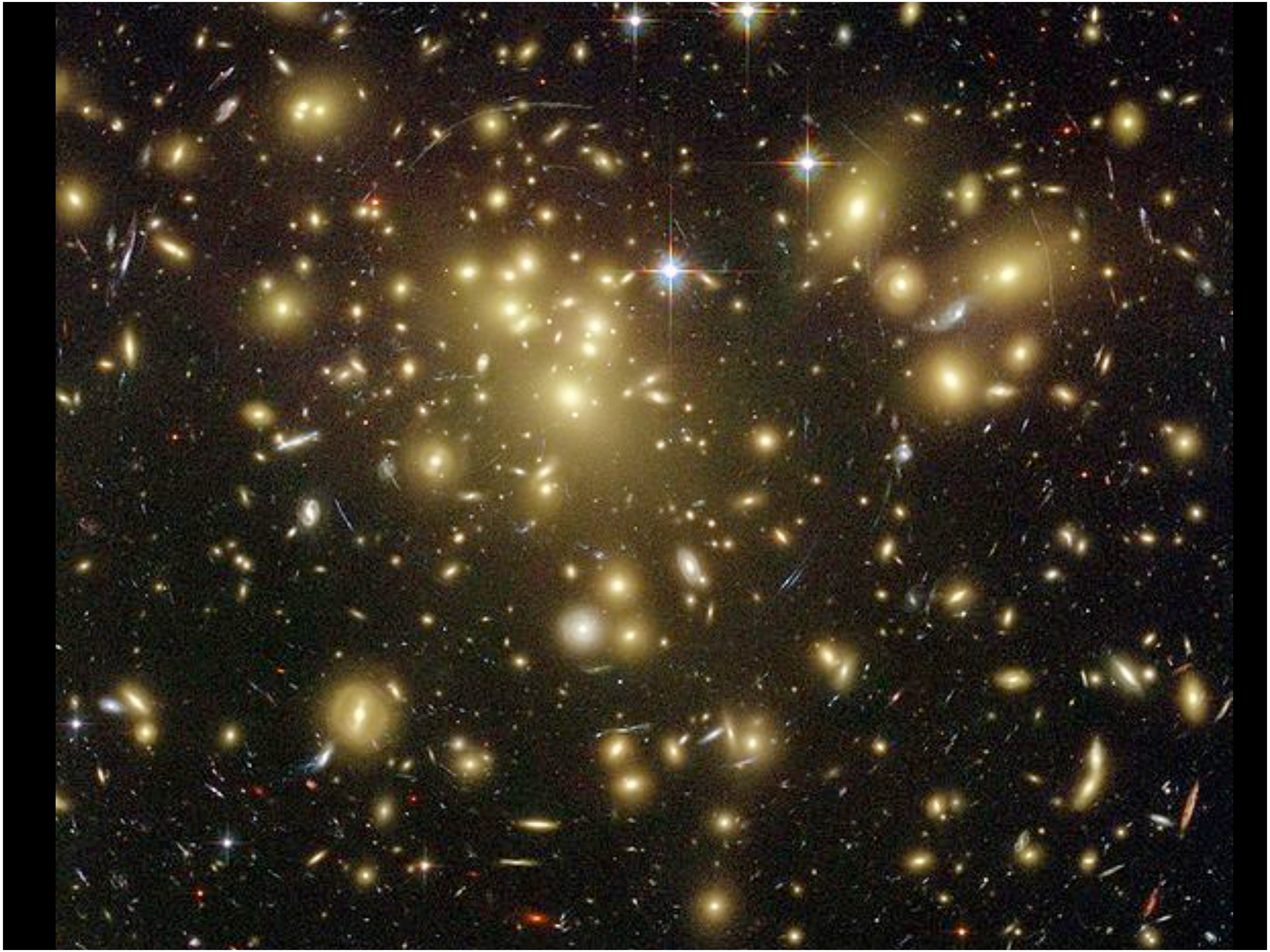
Gravity weaker with increasing distance

Keplerian motion:

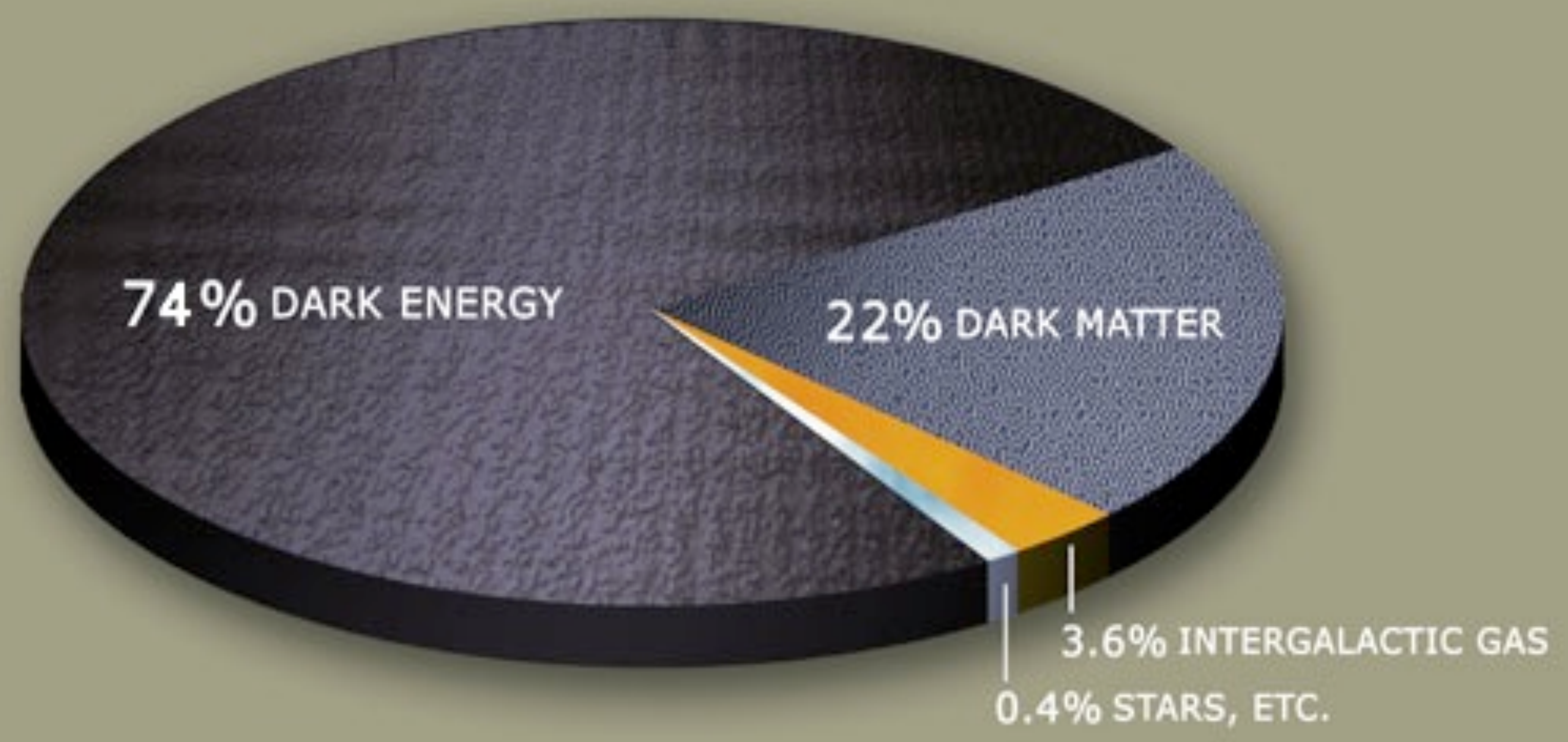
Once outside of mass distribution, velocity decrease

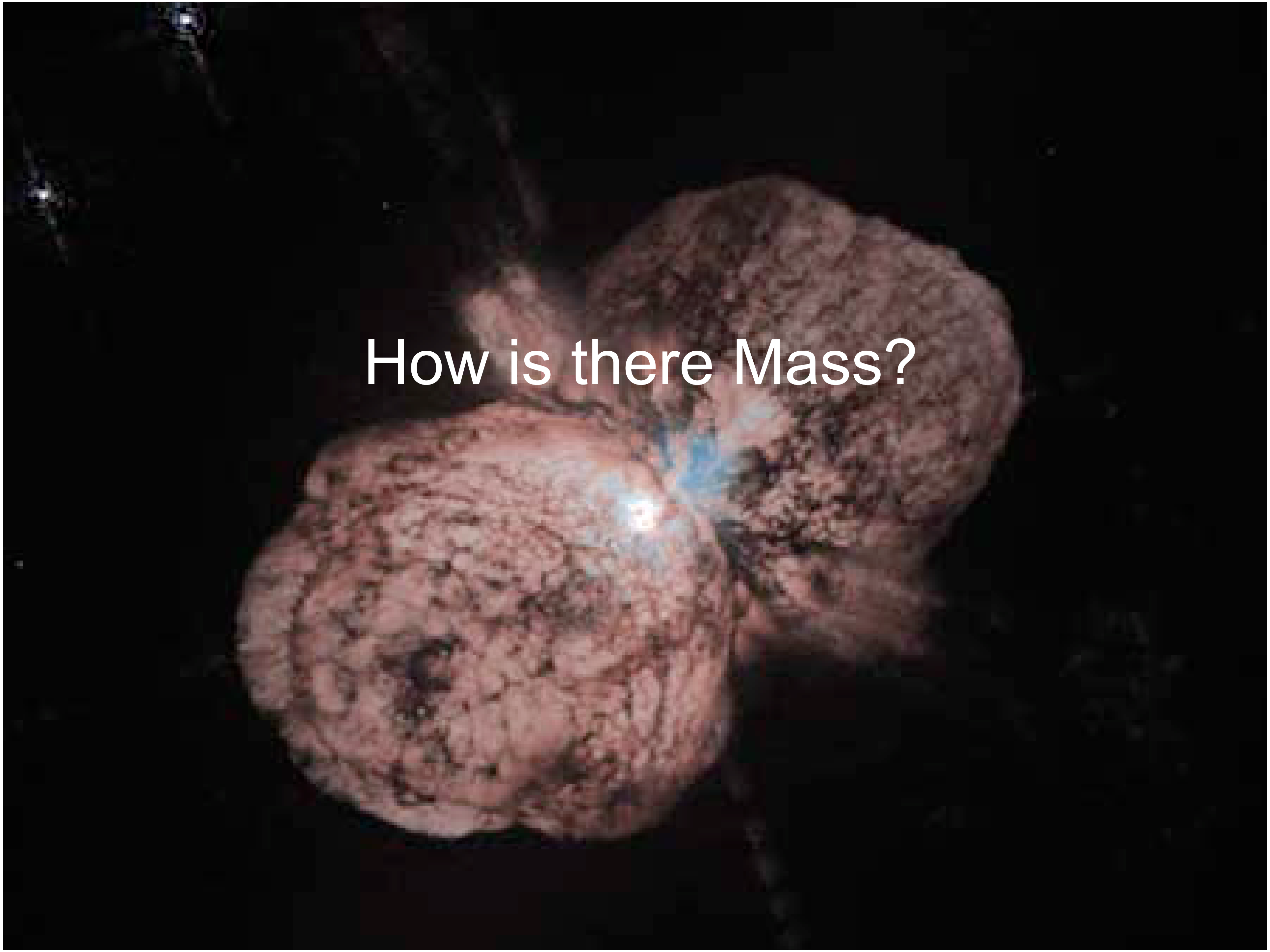
Galactic Rotation





Most matter unidentified!

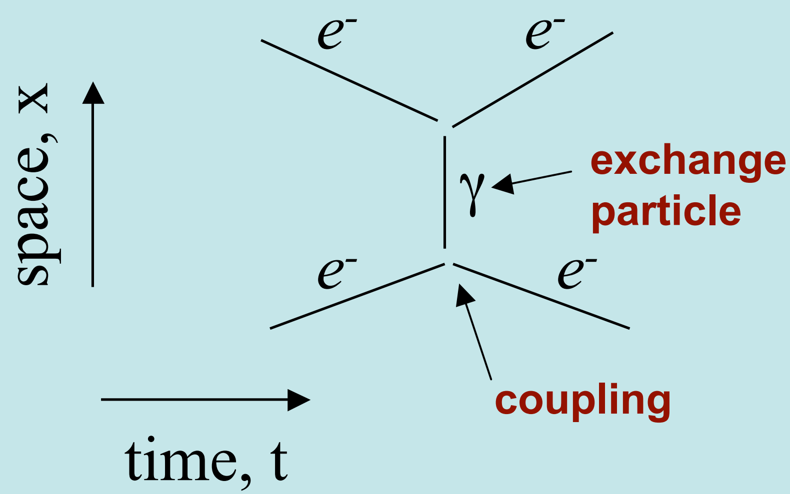



How is there Mass?

Fundamental Interactions

- **Four 'forces' of nature** — **strength**
  - Strong — 1
  - Weak — 1/100,000
  - Electromagnetic — 1/100
  - Gravity — $1/10^{38}$

(Strong and Weak: **nuclear forces**)



Think of two skaters
- one throws heavy ball to another
- thrower looses momentum
- receiver gains momentum

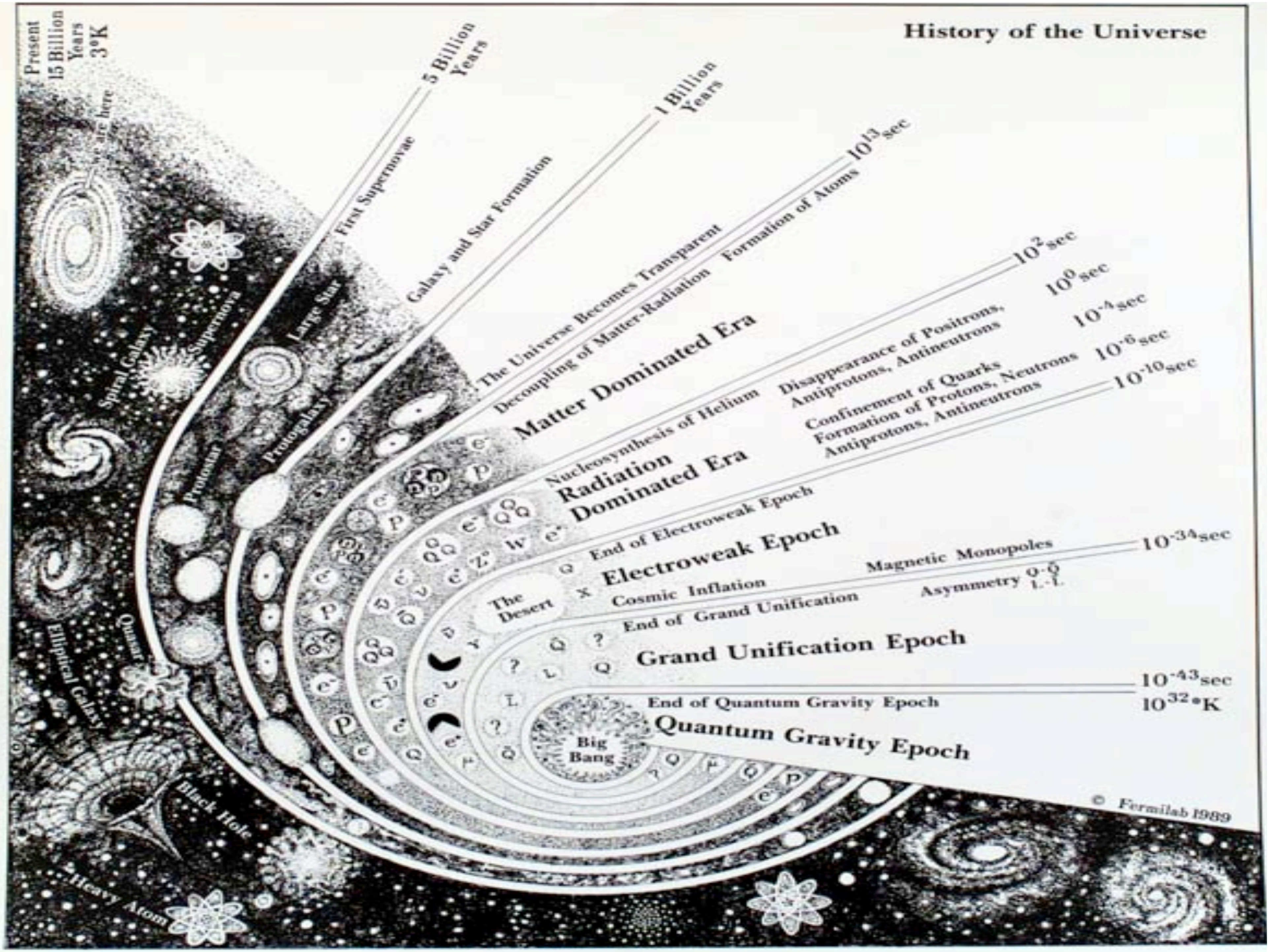
- **Strong interaction → gives masses of protons, neutrons**
- **'Higgs particle' → gives masses of exchange particles for weak interaction**

Higgs is ‘sticky’

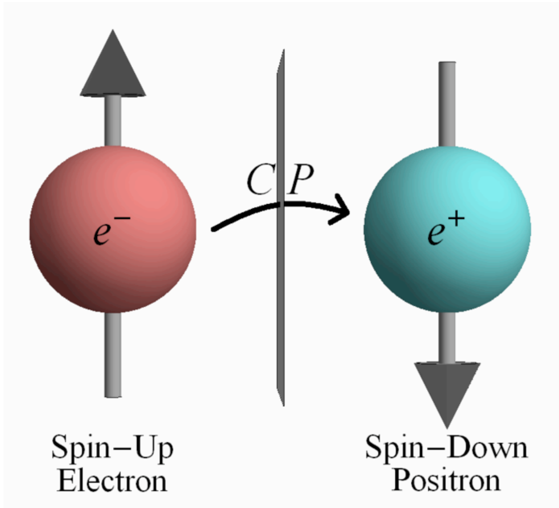
Impedes **change in motion** of quarks and leptons
(i.e. ‘gives’ mass)

- **Stickiness termed ‘coupling’**
  - **Coupling is proportional to particle mass**
  - **Value for each particle not predicted: it’s just a number**

When and Where is there Mass?


History of the Universe
Present
15 Billion Years
3°K
We are here
5 Billion Years
1 Billion Years
10^{13} sec
10^{2} sec
10^{0} sec
10^{-4} sec
10^{-6} sec
10^{-10} sec
10^{-34} sec
10^{-43} sec
10^{32} °K
First Supernovae
Galaxy and Star Formation
The Universe Becomes Transparent
Decoupling of Matter-Radiation
Formation of Atoms
Matter Dominated Era
Nucleosynthesis of Helium
Disappearance of Positrons, Antiprotons, Antineutrons
Confinement of Quarks
Formation of Protons, Neutrons
Antiprotons, Antineutrons
Radiation Dominated Era
End of Electroweak Epoch
Electroweak Epoch
Magnetic Monopoles
Cosmic Inflation
Asymmetry Q-Q̄ L-L̄
End of Grand Unification
Grand Unification Epoch
End of Quantum Gravity Epoch
Quantum Gravity Epoch
The Desert
Big Bang
Spiral Galaxy
Supernova
Large Star
Protogalaxy
Protostar
Quasar
Elliptical Galaxy
Black Hole
Heavy Atom
© Fermilab 1989

Symmetry



- Charge
- Parity
- physics ‘invariant’ when change these properties
  - CP product a stronger symmetry than C or P alone

… but CP Violation in weak interactions discovered!

K^0 ($s\bar{d}$) —time→ $\overline{K^0}$ ($\bar{s}d$)

This process allows to determine: can start with one CP value, and end up with another one!

Third Generation

- In 1973
  - If there exists a 3rd generation of quarks and leptons…

…this can accommodate CP violation

In 1976:

"We have discovered 64 events of the form

$e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + at least 2 undetected particles

for which we have no conventional explanation."

Problem is, observed level of CP violation can't explain matter over antimatter .

To summarize…

What is the nature or origin of dark matter?

Does the Higgs particle exist?

Why is there only matter, and no antimatter, in the universe?

Beauty

“The scientist … studies [nature] because he takes pleasure in it; and he takes pleasure in it because it is beautiful.”

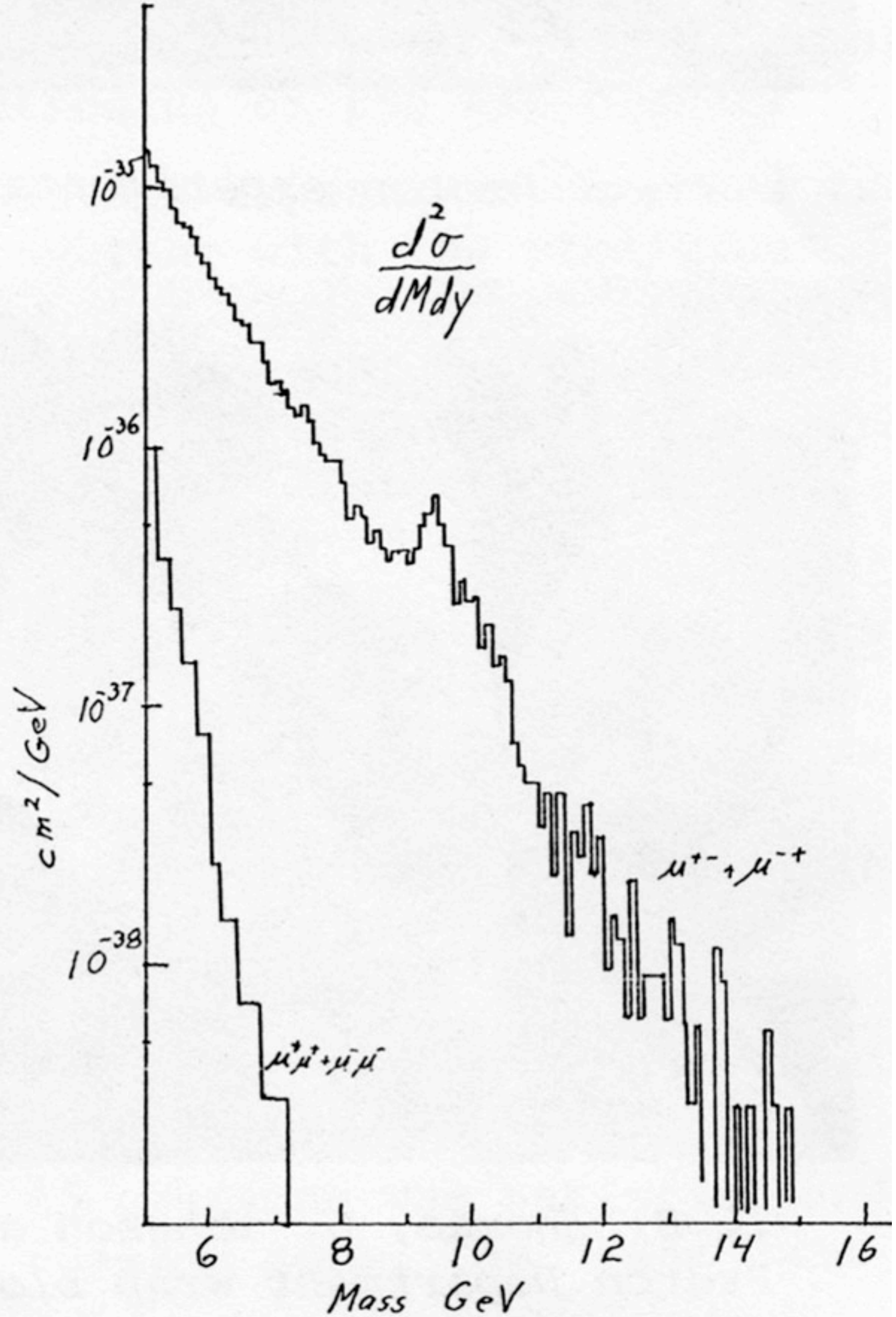
H. Poincare

“The measure in which science falls short of art is the measure in which it is incomplete as science.”

J. Sullivan, in *Athenaeum* (1919)

Discovery of

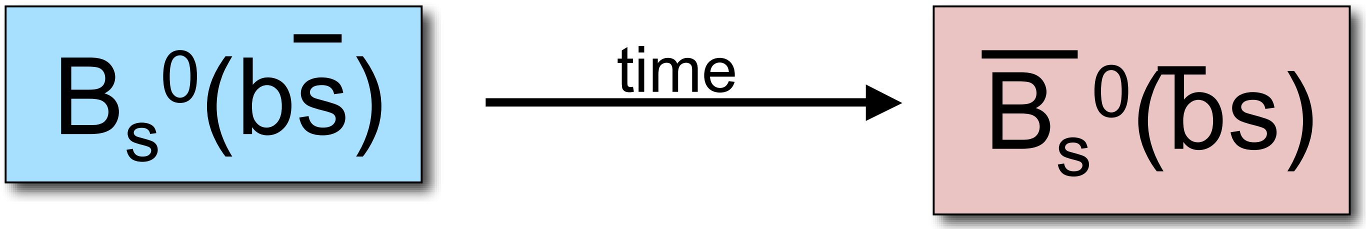
- 1977
- A heavier version of the down and strange quarks




EMC-260-147

A new testing ground

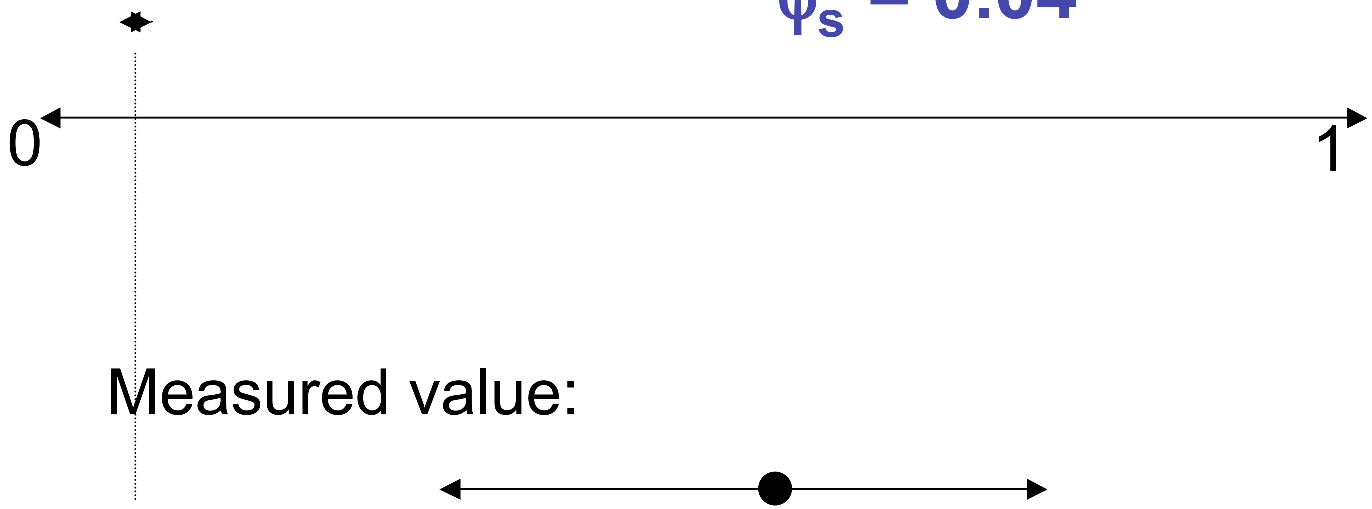
- Particles comprised of *b*-quarks
  - Very analogous to K^0



- Measure the CP violating parameter after 5 years of data-taking

- Prediction of CP violating phase

$\phi_s = 0.04$



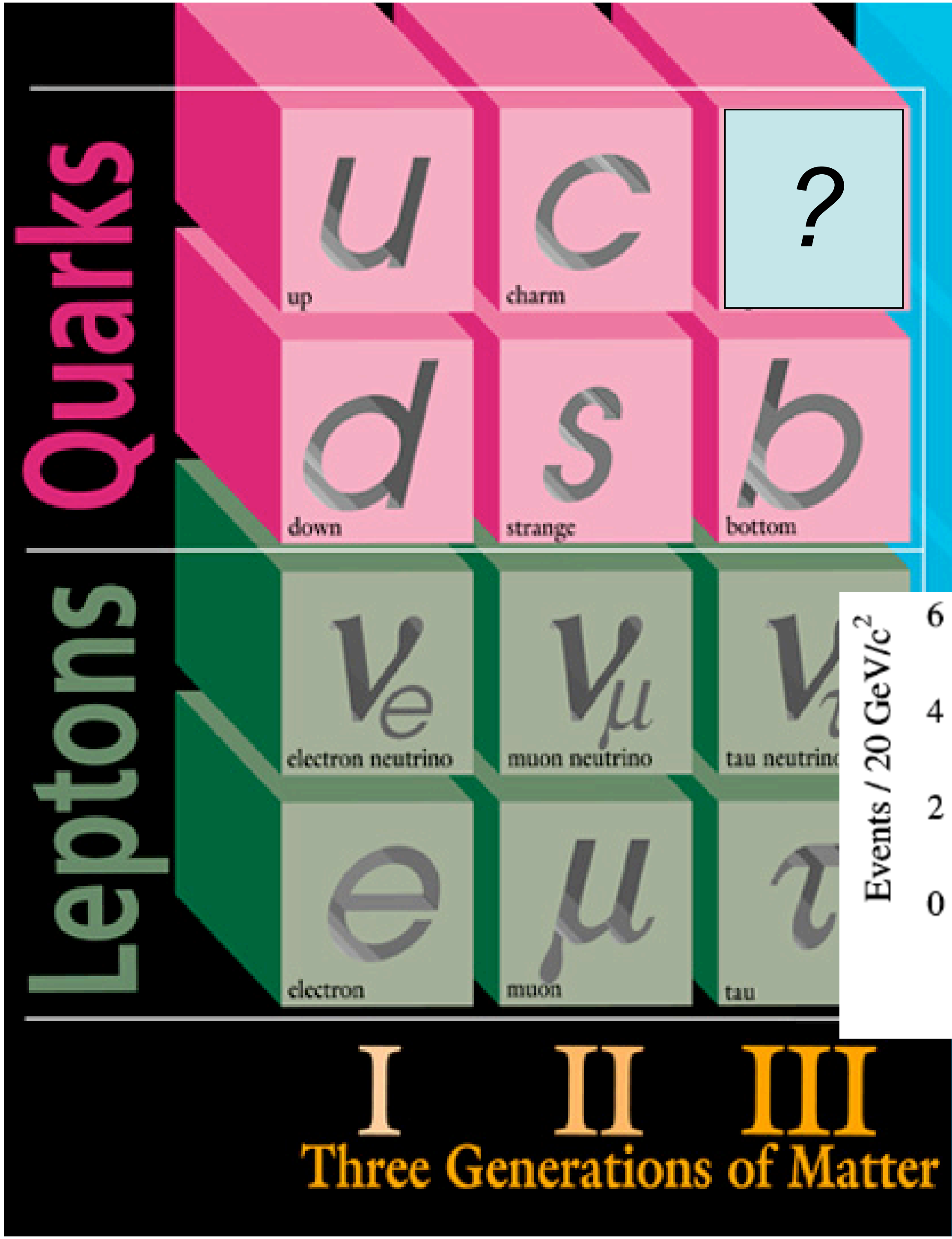
$\phi_s = 0.57 + 0.25 - 0.30$

5% chance of agreement

What might this mean?

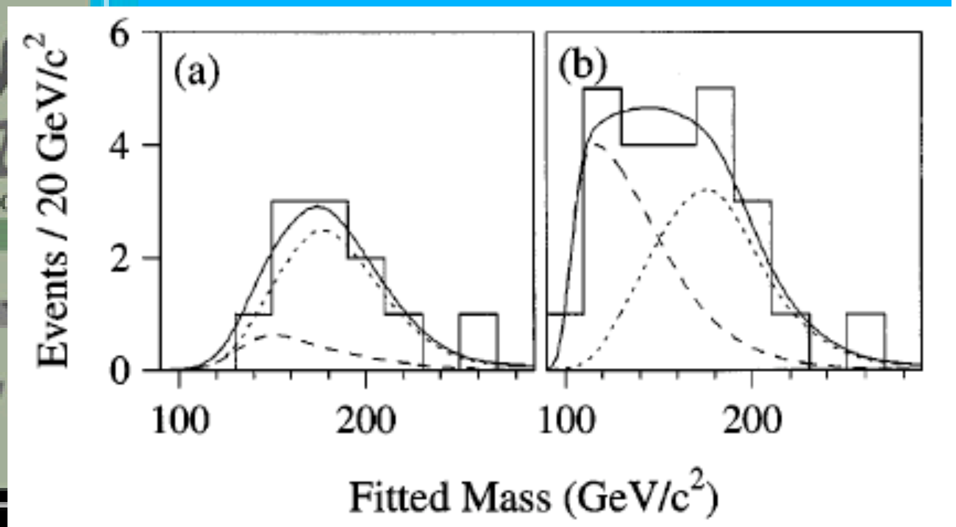
- There are extra particles we have not already identified
  - our calculations are incomplete
  - should include effects from, say, a 4th generation of fermions
- There may be a new symmetry (and interaction)
  - One candidate (called 'supersymmetry') also gives us **dark matter**!

Truth

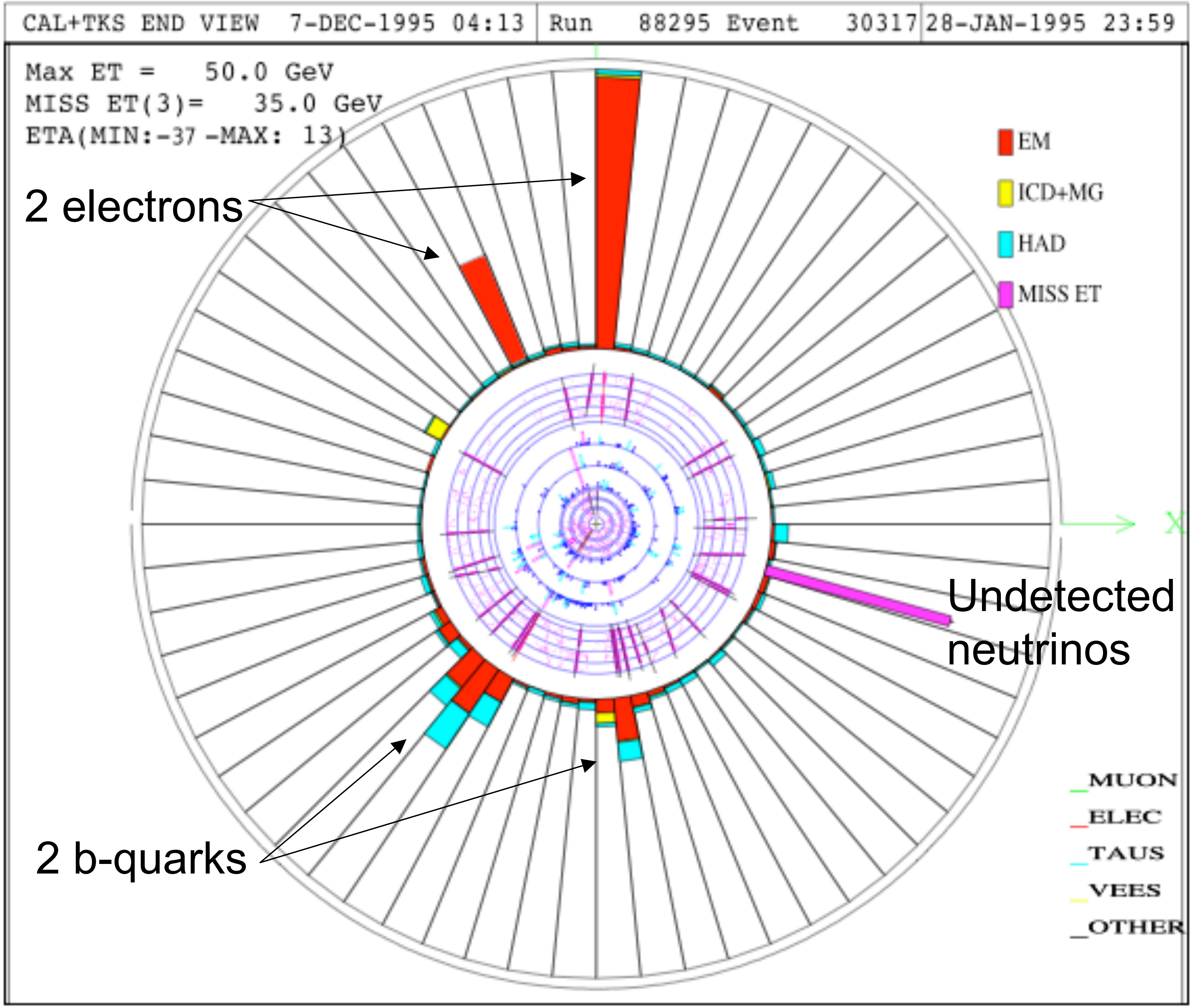


‘Last’ fermion?

- Alias: ‘top quark’
- Firmly predicted



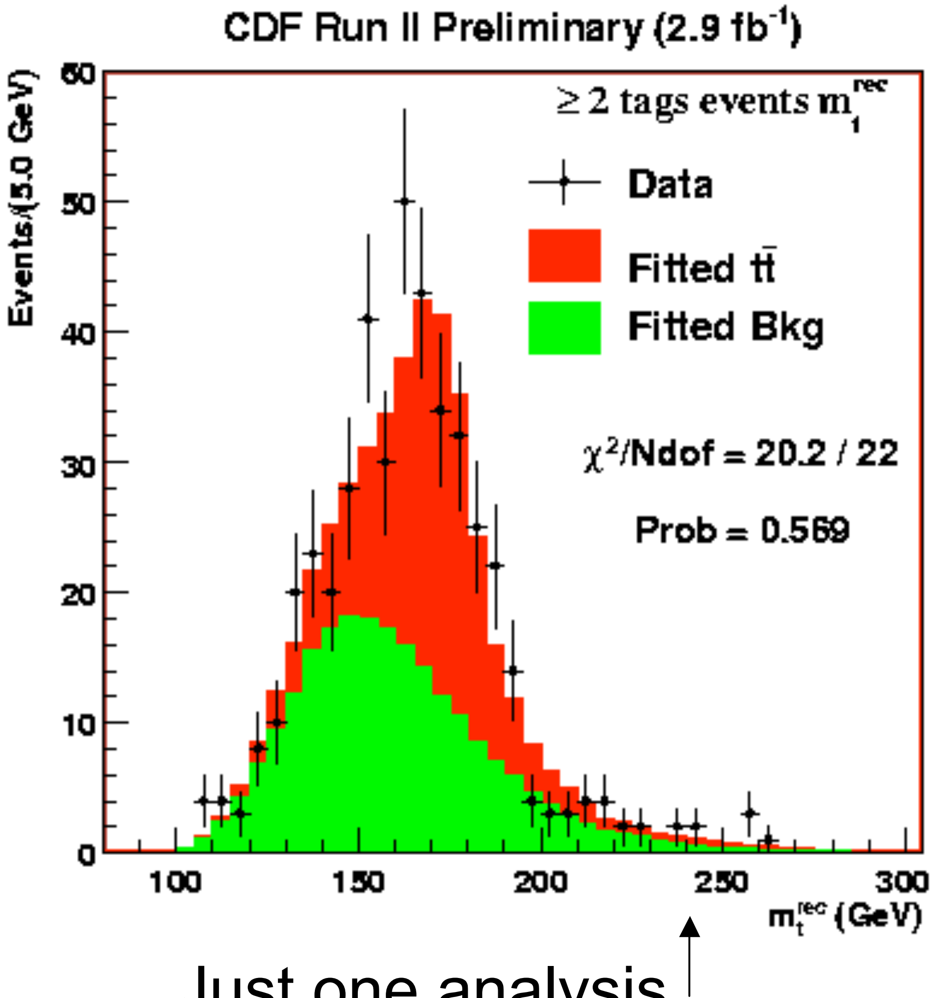
Discovery 1995 .


CAL+TKS END VIEW 7-DEC-1995 04:13
Run 88295 Event 30317
28-JAN-1995 23:59
Max ET = 50.0 GeV
MISS ET(3)= 35.0 GeV
ETA(MIN:-37 -MAX: 13)
EM
ICD+MG
HAD
MISS ET
2 electrons
Undetected neutrinos
2 b-quarks
X
MUON
ELEC
TAUS
VEES
OTHER

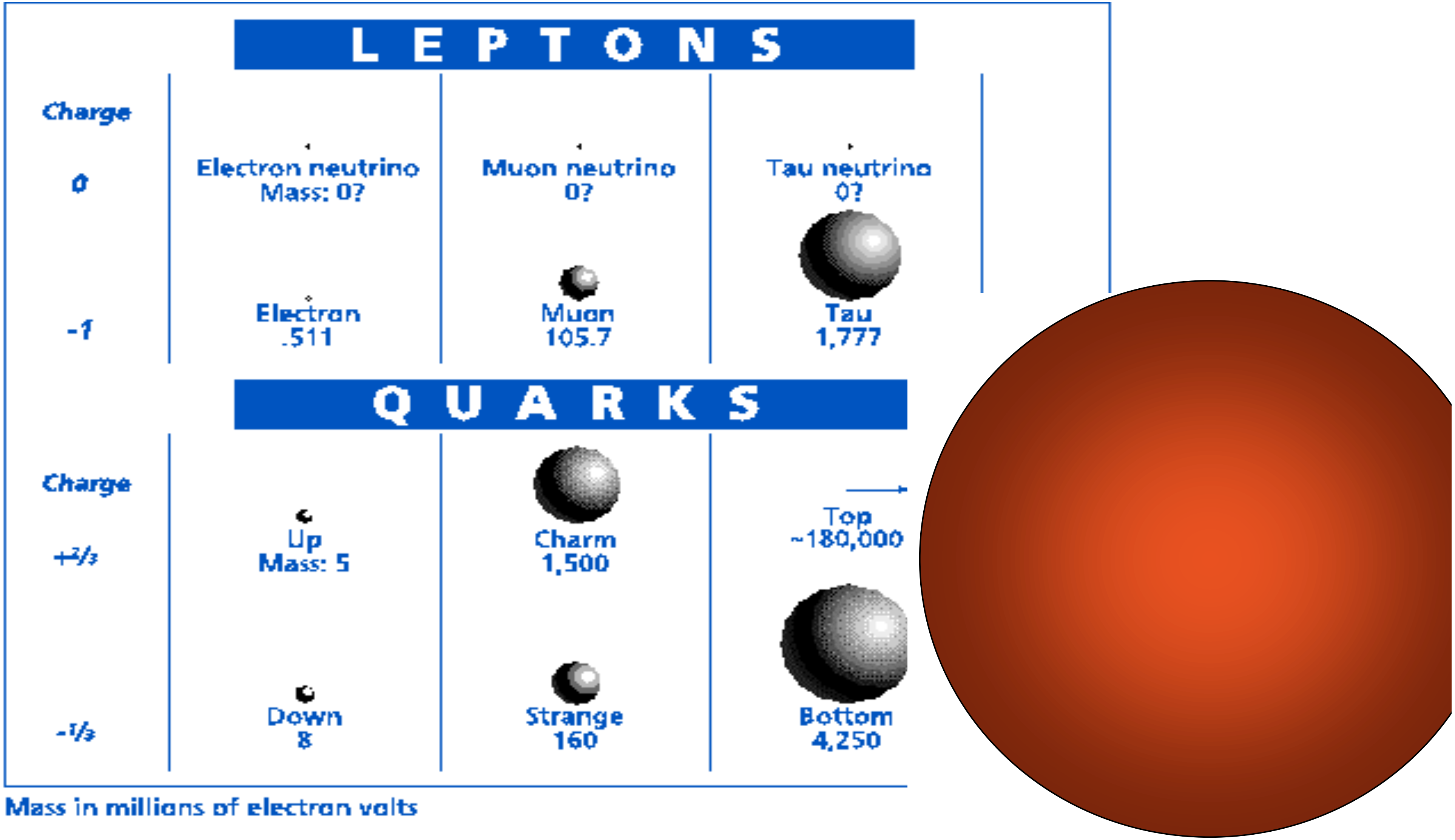
Top mass measurement

- Very heavy: tells us about Higgs

- Two experiments
- Dozens of people
- Several different analyses
- 8 years of data-taking



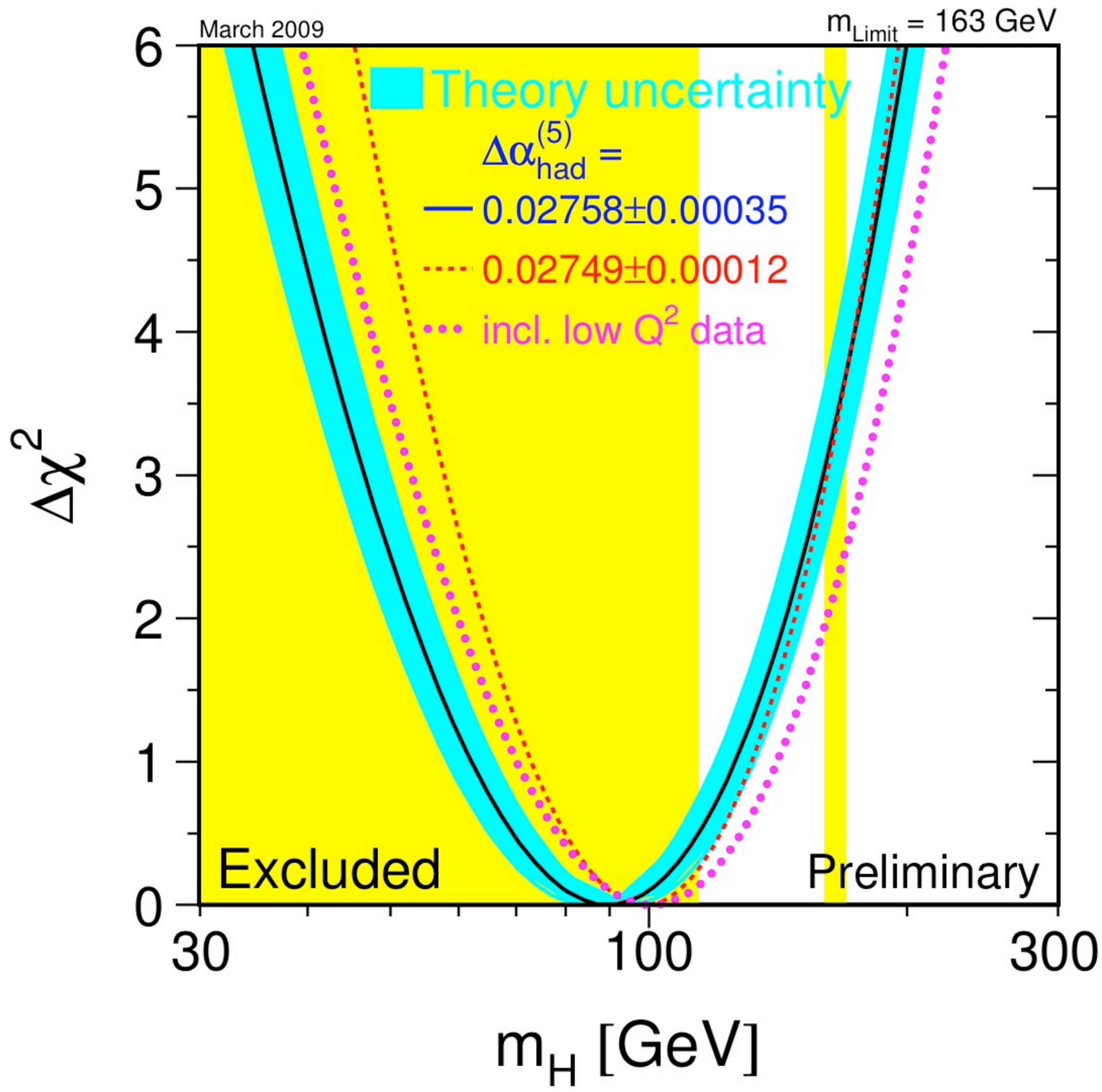
Just one analysis



Heavier than an entire Gold atom!

- **Most massive particle known**

- **Can constrain or 'predict' the Higgs mass**



Wait, something's odd…

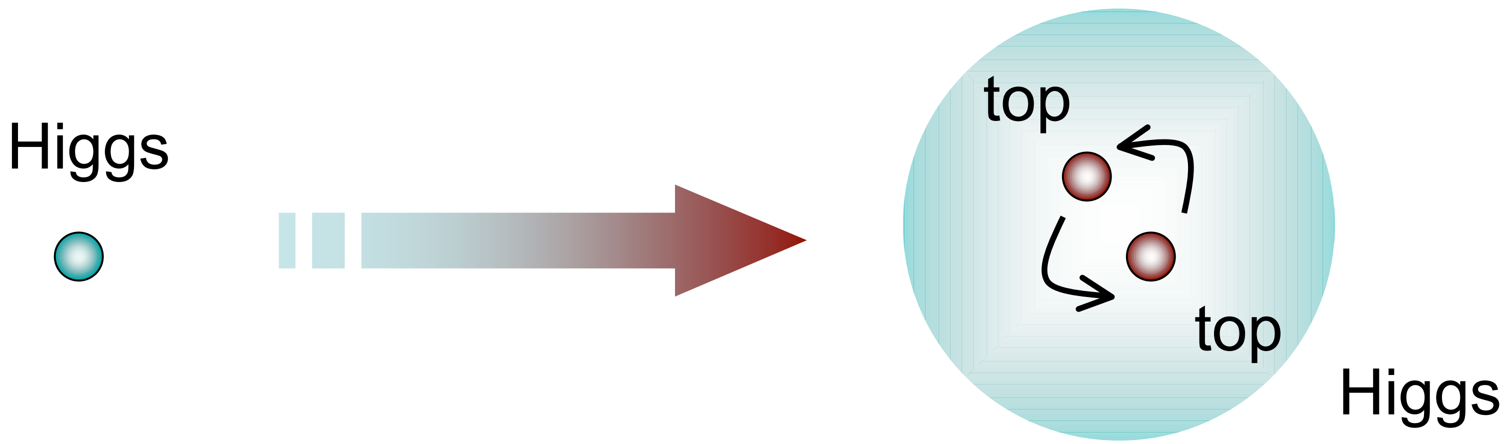
- Mass proportional to 'coupling' to Higgs
  - For electron: $= 2.9\times10^{-6}$
  - For top: **= 0.995±0.007**

≈ 1.0 to within 0.7%!

- Coupling unpredicted and arbitrary value
  - very unlikely to just happen to be 1.00
    - An equation with a constant = 1 doesn't actually need the constant
  - So what's going on with the top quark?
    - Top appears to be special

Implications?

- Top may be more fundamental than we thought

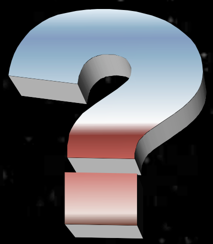


–May suggest extra dimensions,

•may accommodate dark matter

•May explain weakness of gravity

Final thoughts



- Higgs, if it exists, will be discovered soon
- CP violating phase to be measured well at LHC
- Is the top quark fundamental?

Hints of new physics?

Backup slides

Four Fundamental Forces

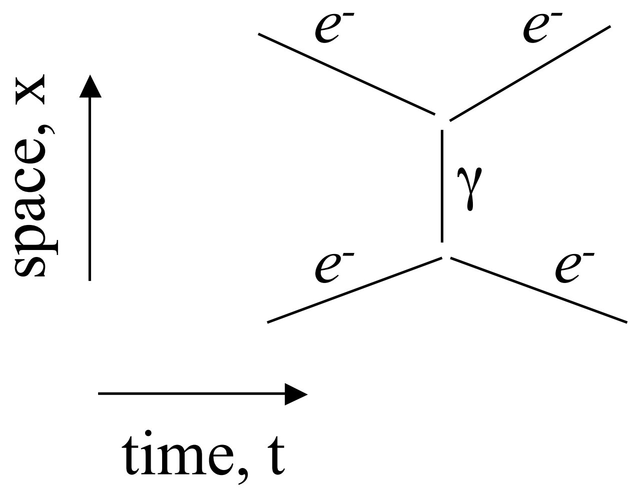
- Two nuclear forces
  - strong, responsible for holding atomic nucleus together
  - weak, responsible mainly for particle decay

force	coupling	range(cm)	strength
strong	color	10^{-18}	1
electromagnetic	charge	∞	0.01
weak	flavor	10^{-15}	10^{-5}
gravity	mass	∞	10^{-38}

- Only quarks interact via strong interaction
- Dark matter only interacts by gravity, and maybe the weak interaction

Interactions as Momentum Exchange

- **conservation of momentum**
- **think of forces as interactions**
  - two particles interact by exchanging a messenger particle
    - eg. electromagnetism uses the photon

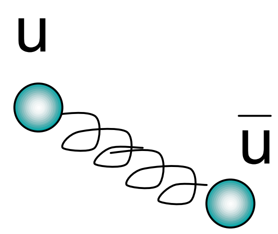


Think of two skaters
- one throws heavy ball to another
- thrower looses momentum
- receiver gains momentum

- exchanged particle
  - transfers momentum from one interacting particle to another

Baryonic Matter

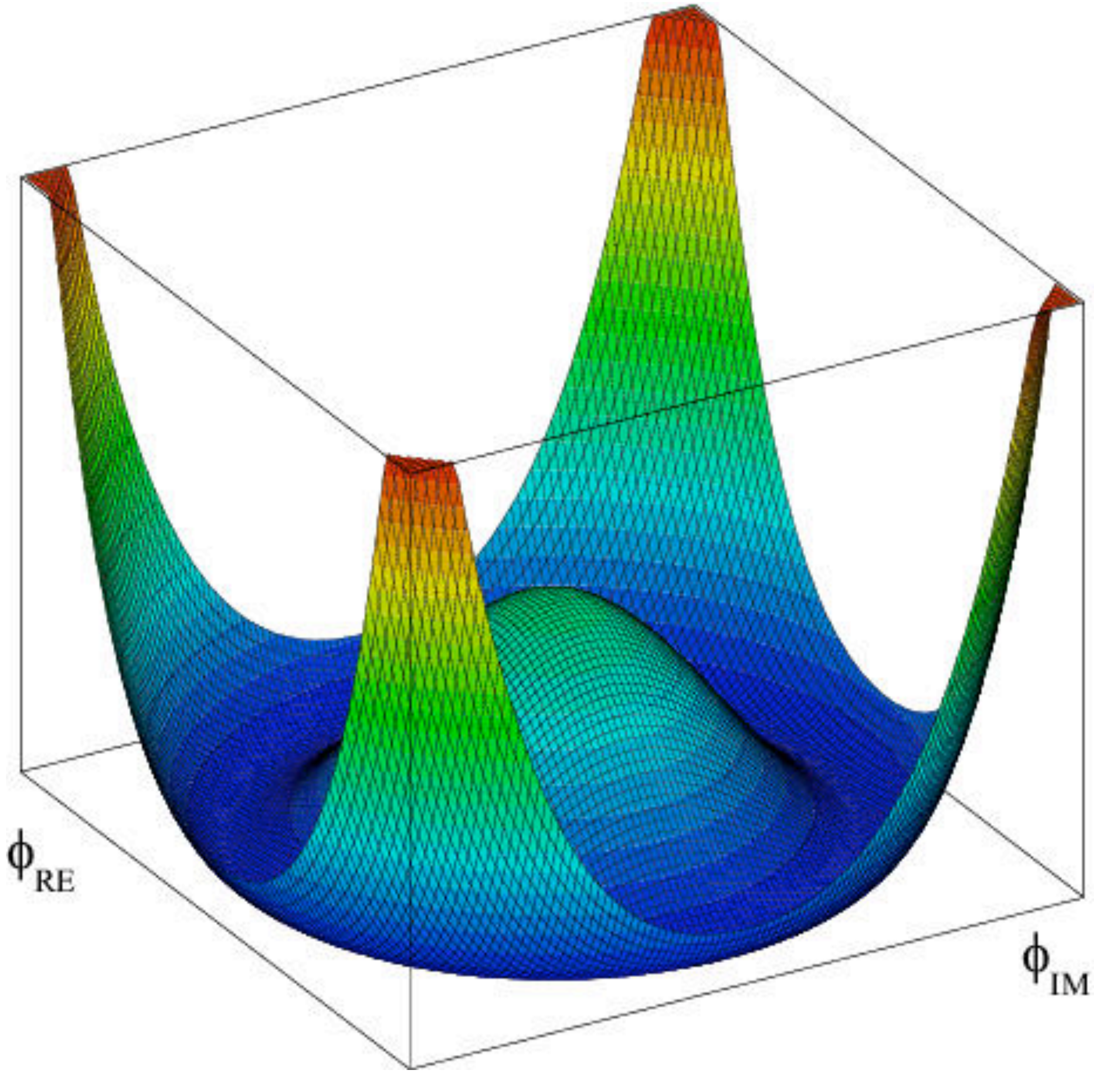
- **Strong interaction**
  - **tightly binds quarks and gluons into composite particles**
  - **Proton and neutron**
    - **'baryons'**
    - **stable in a nucleus**
- **Almost all mass we see is baryonic**



a pion (π)

$$M_{\pi} >> m_{u} + m_{\bar{u}}$$

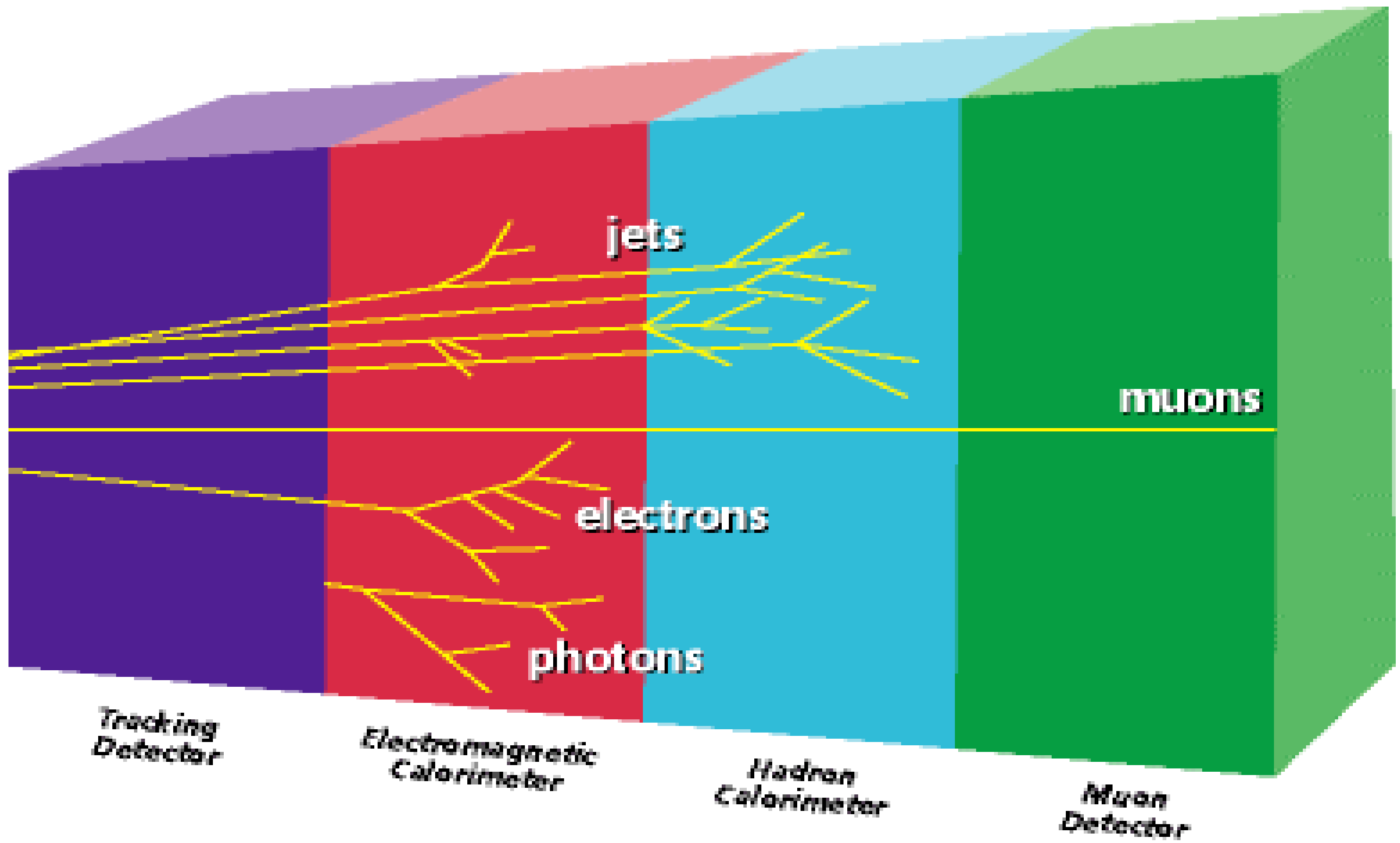
A more fundamental mechanism



- **Lowest energy state**
  - **Doesn’t correspond to zero mass**

- **So W/Z have mass!**

Higgs particle


jets
muons
electrons
photons
Tracking Detector
Electromagnetic Calorimeter
Hadron Calorimeter
Muon Detector

3 jet vs. 2 jet mass