

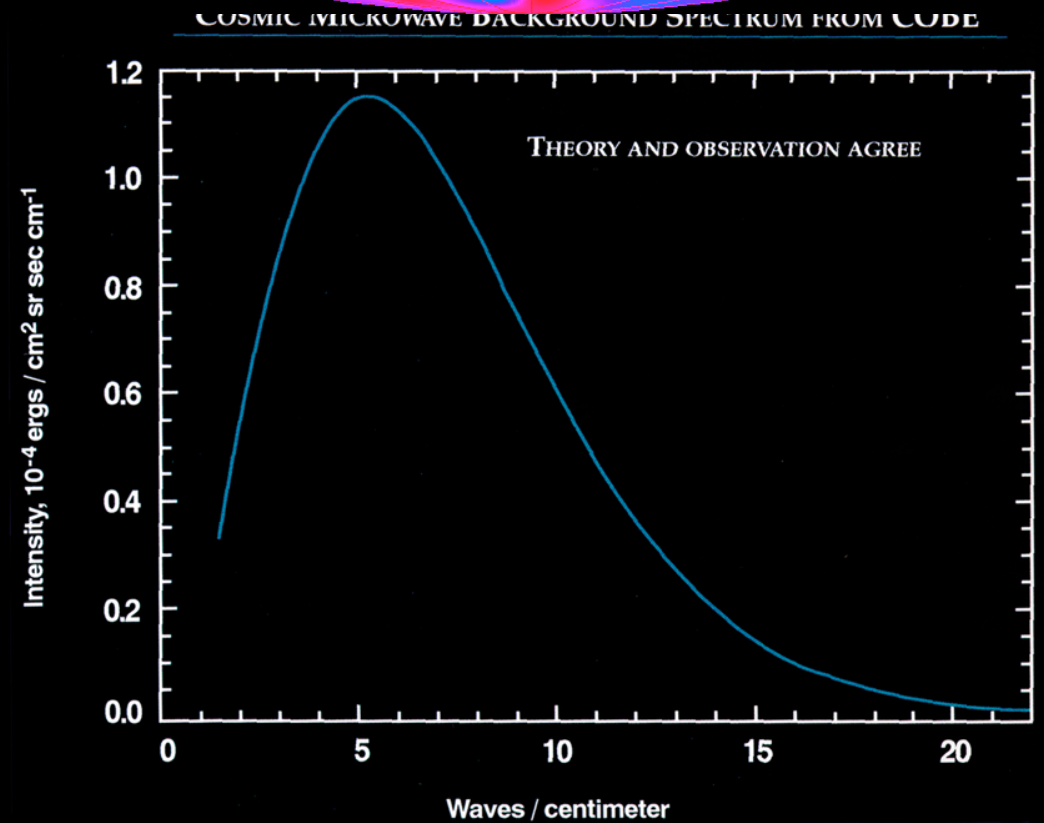
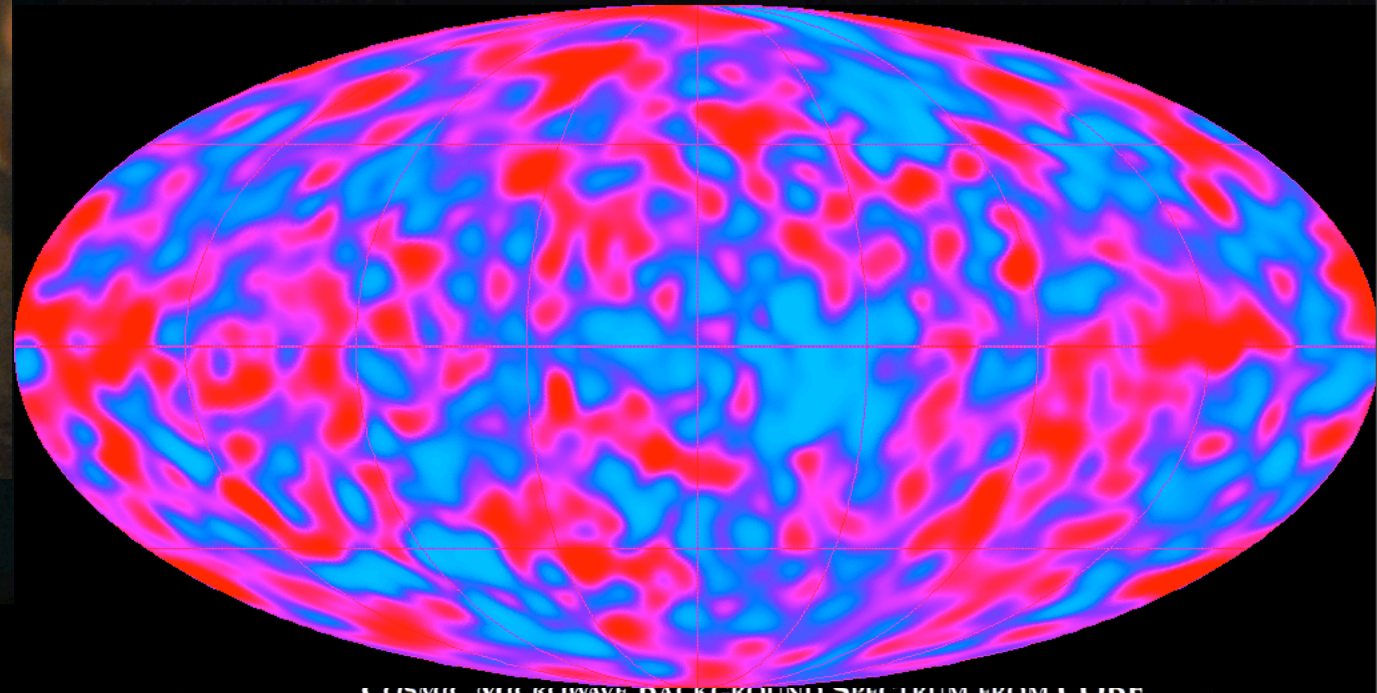
# Quantum Universe

Hitoshi Murayama (Berkeley)  
University of Tennessee, Jan 22, 2007



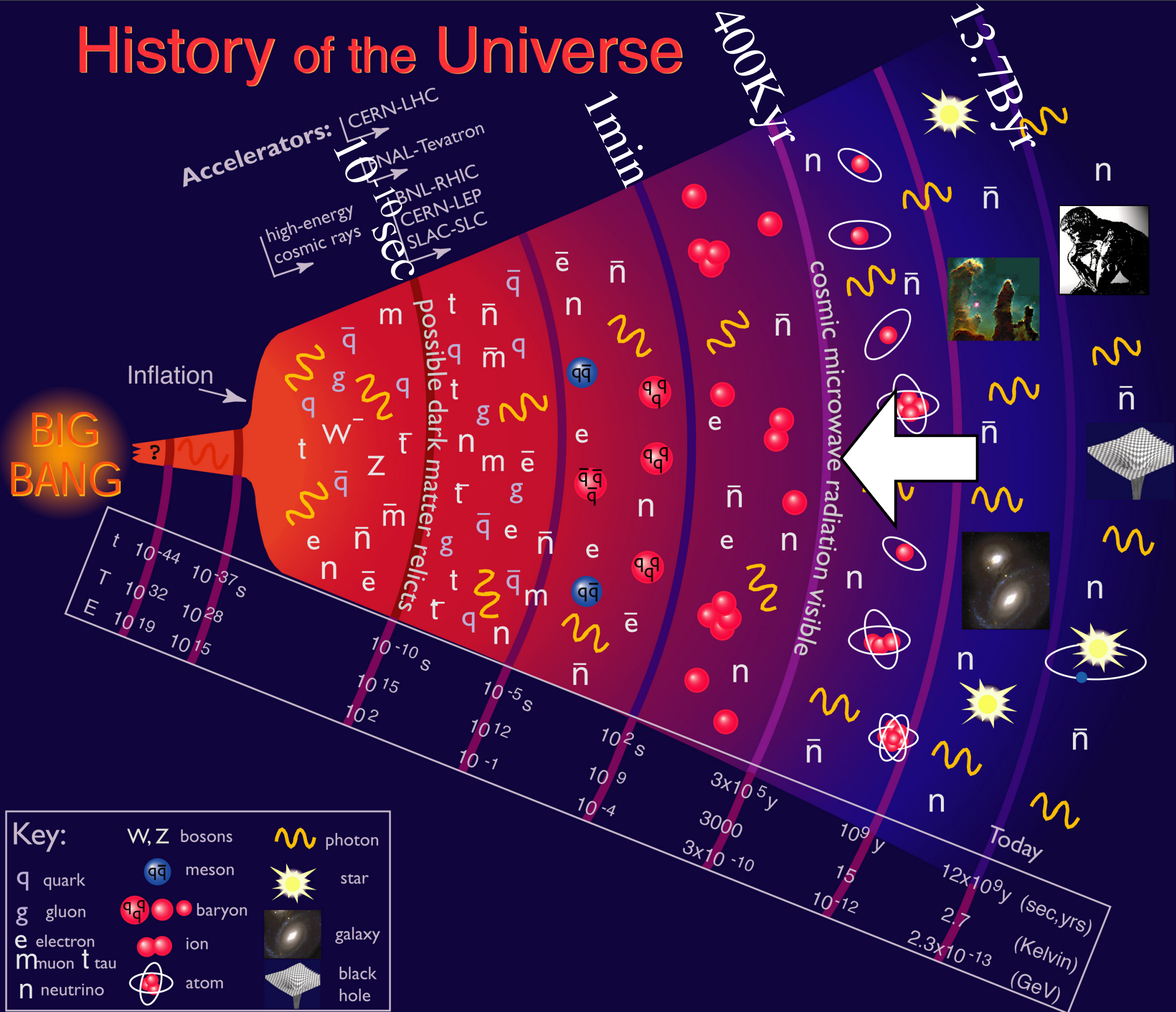


COBE showed  
quantum origin  
of the universe





# History of the Universe





# Quantum Universe

To understand physics at the largest scale:  
Universe

we need to understand the smallest scale:  
elementary particles

- What is the Universe made of?
- How did it come to be?
- Why do we exist?

*Moving from philosophy to physics*





*There are many  
things we don't see*



# Energy Budget of the Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Dark Field  $\sim 10^{62}\%$ ??

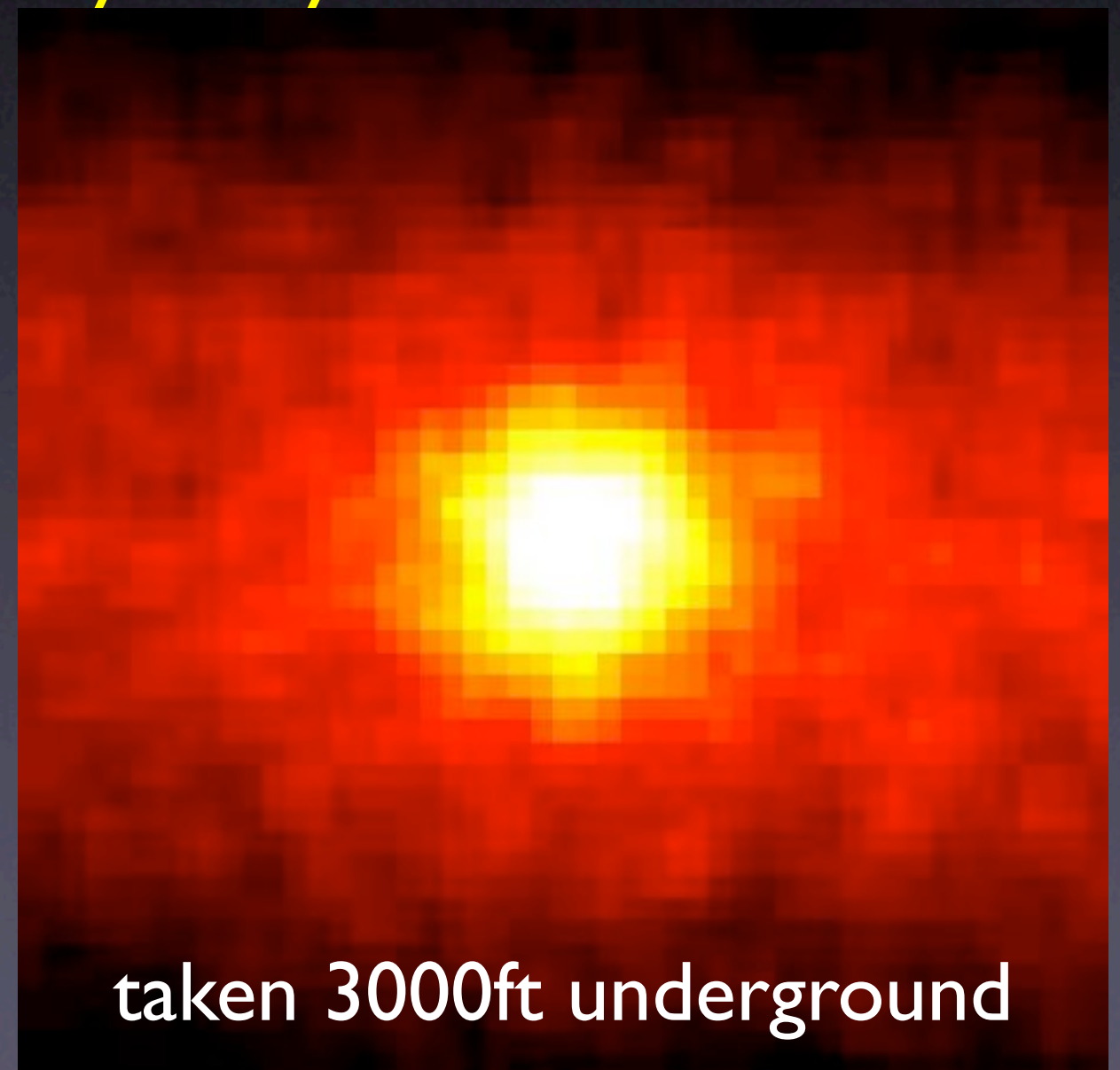
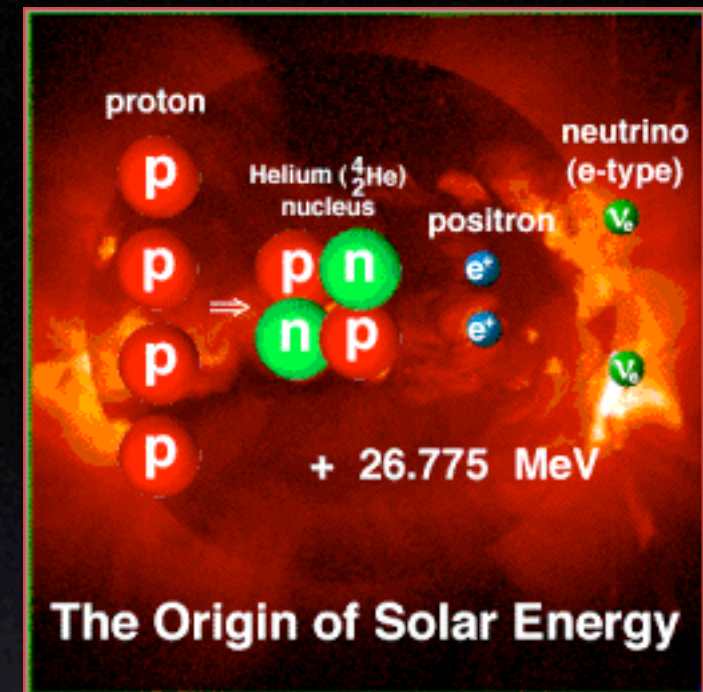




# Don't be afraid of invisibles

Pauli regretted to have predicted neutrinos  
nobody can detect

Trillions of them go through our body every  
second









Disney PRESENTS A PIXAR FILM



# THE INCREDIBLES

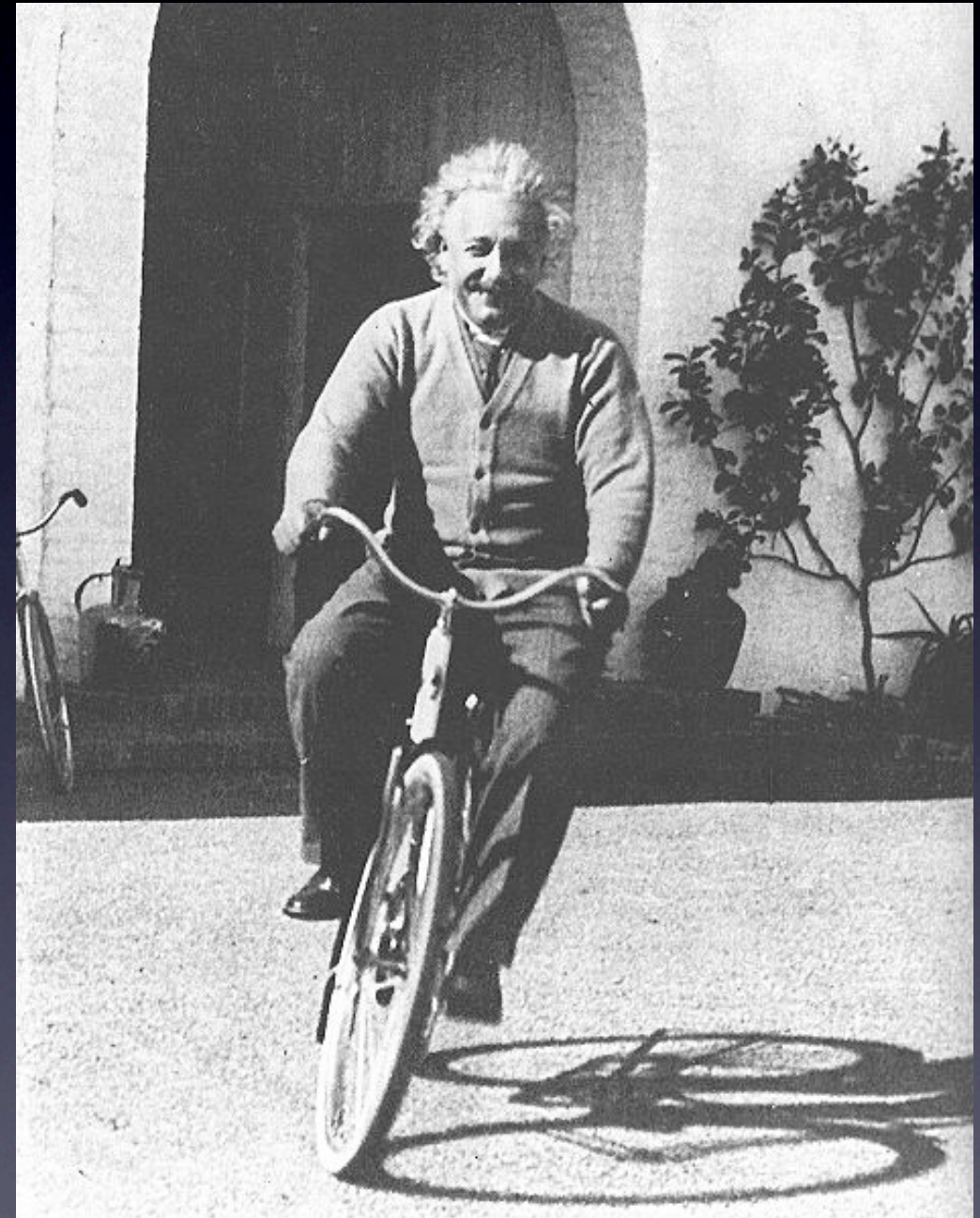
NOW PLAYING





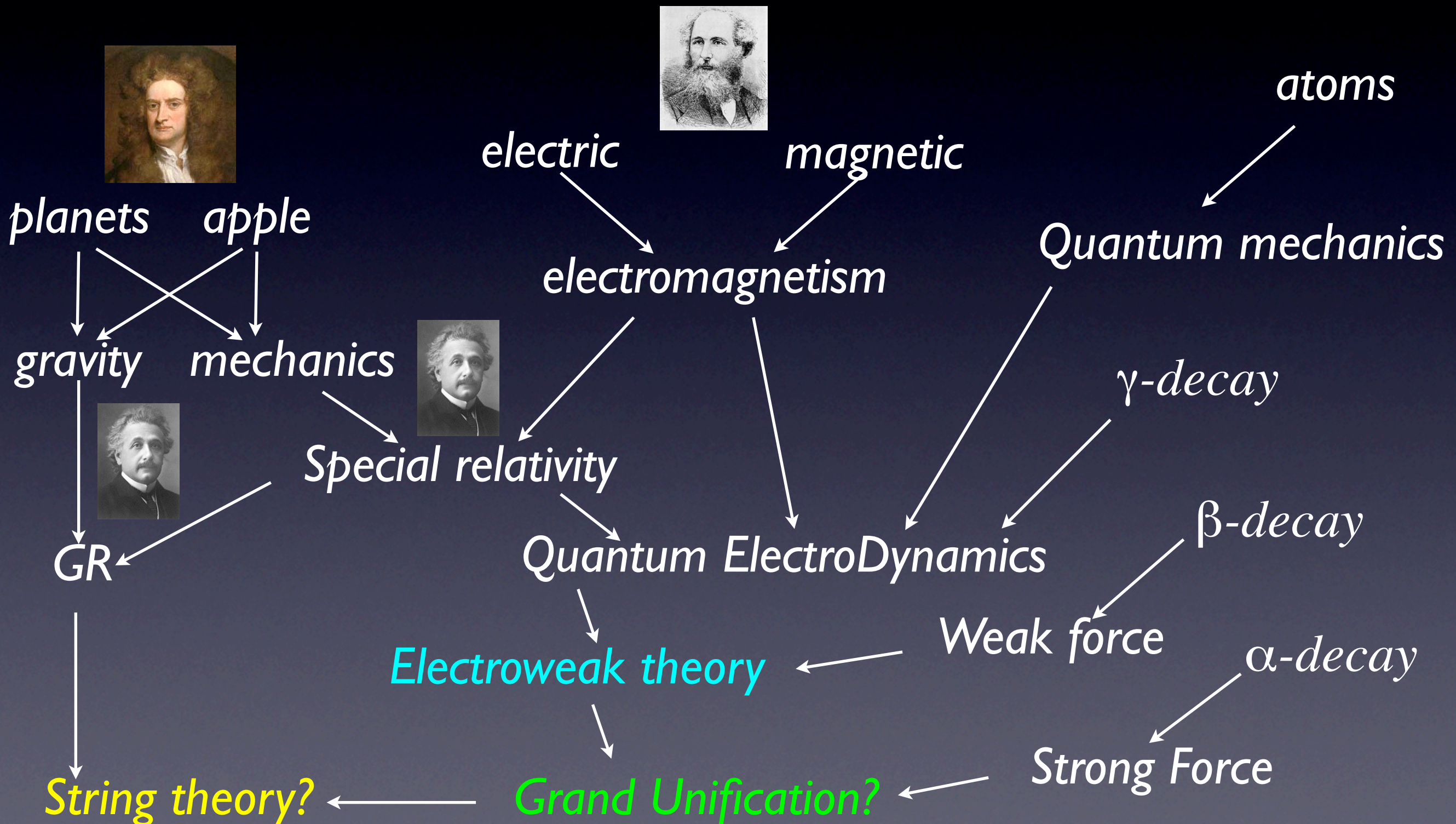
# Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)





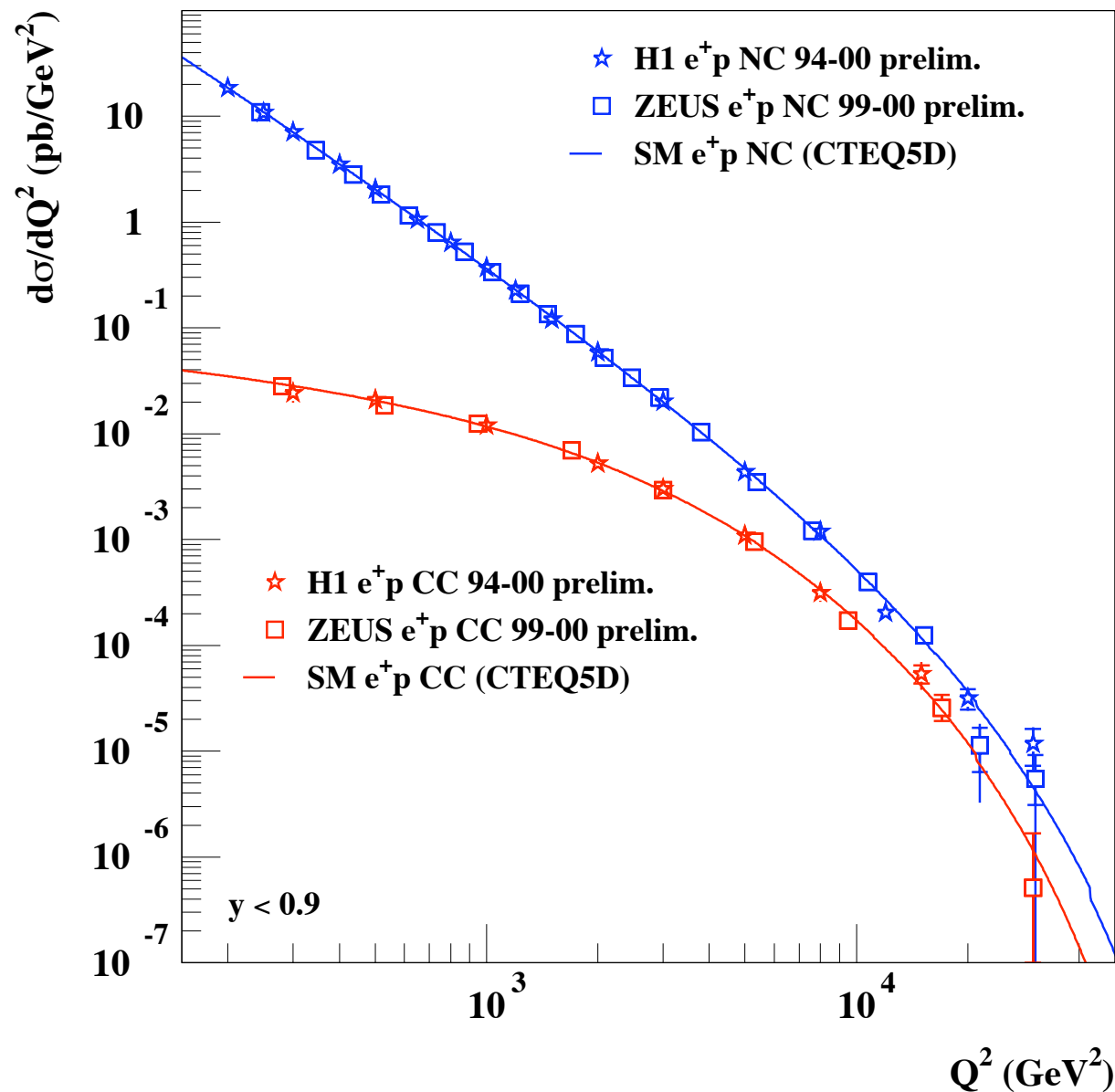
# History of Unification





# We are just about to achieve another layer of unification

*HERA ep collider*

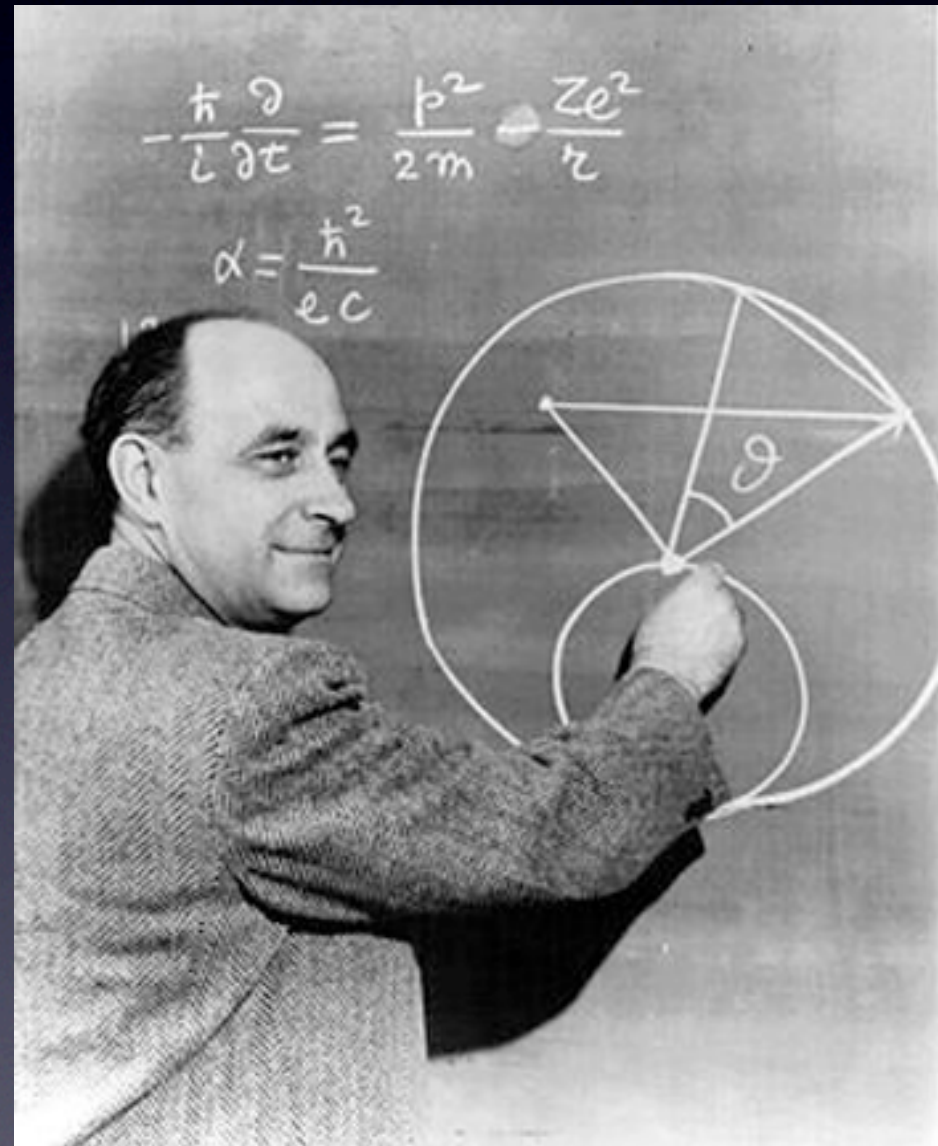


- Unification of electromagnetic and weak forces  
⇒ electroweak theory
- Long-term goal since '60s
- **We are getting there!**
- The main missing link:  
Dark Field



# Fermi's dream era

- Fermi formulated the first theory of the weak force (1933)
- *The required energy scale to study the problem known since then:  $\sim \text{TeV}$*
- We are finally getting there!





# Dark Matter





*Galaxies are held together by mass far bigger than all stars combined*



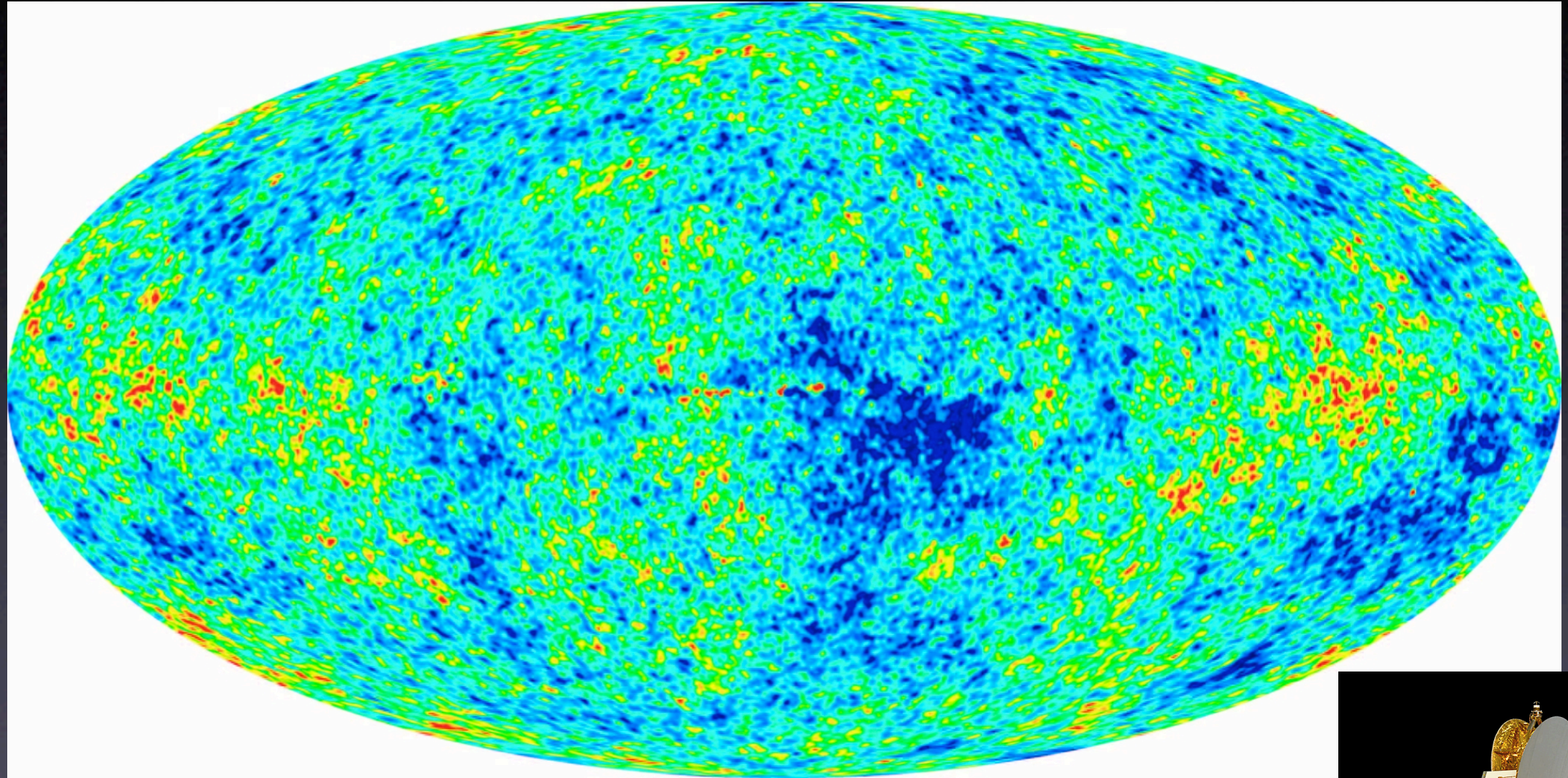
# You don't want to be there



collision at 3000 miles/sec



# Cosmological scales



- matter/all atoms= $6.03 \pm 0.03$

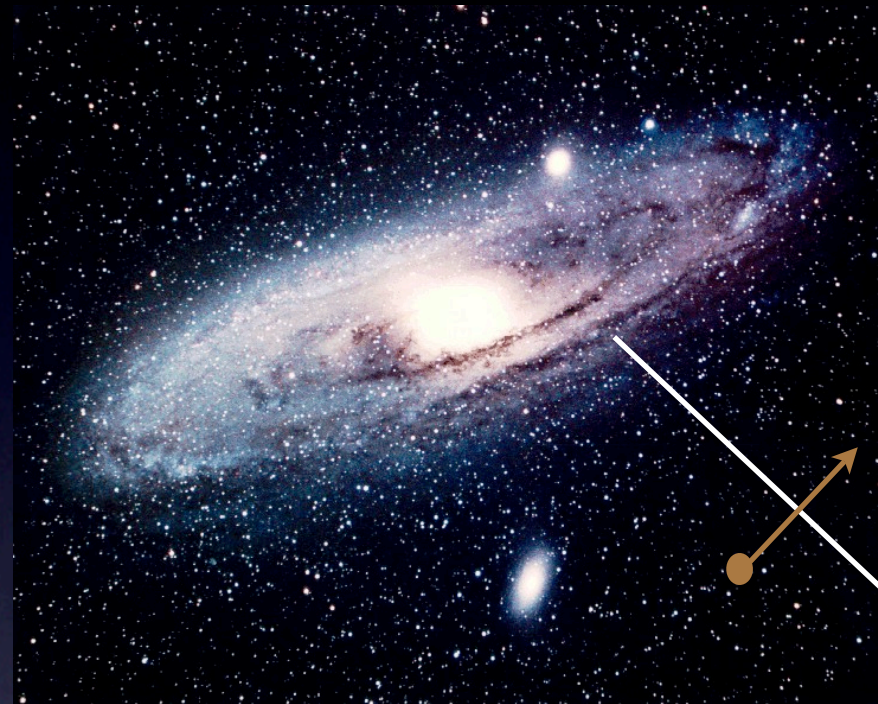




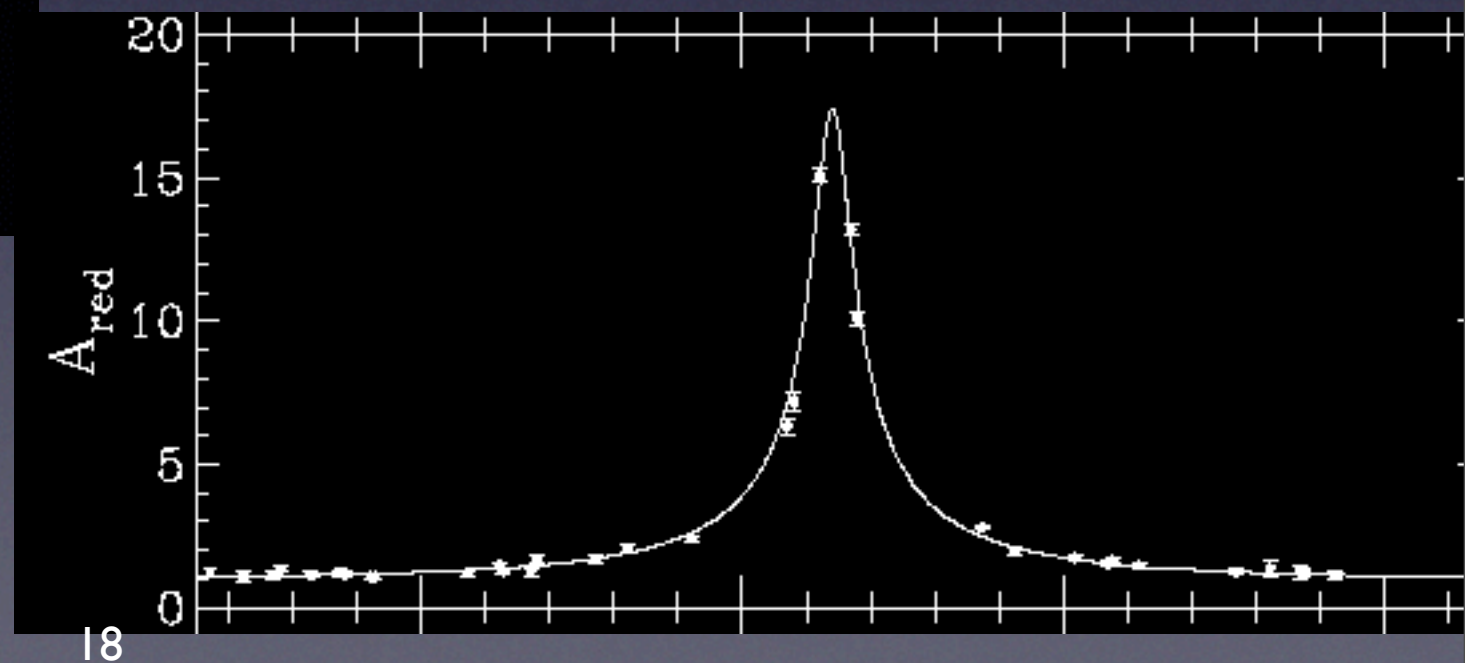
# Dim Stars?

Search for *MACHOs*  
(Massive Compact Halo Objects)

*Large Magellanic Cloud*

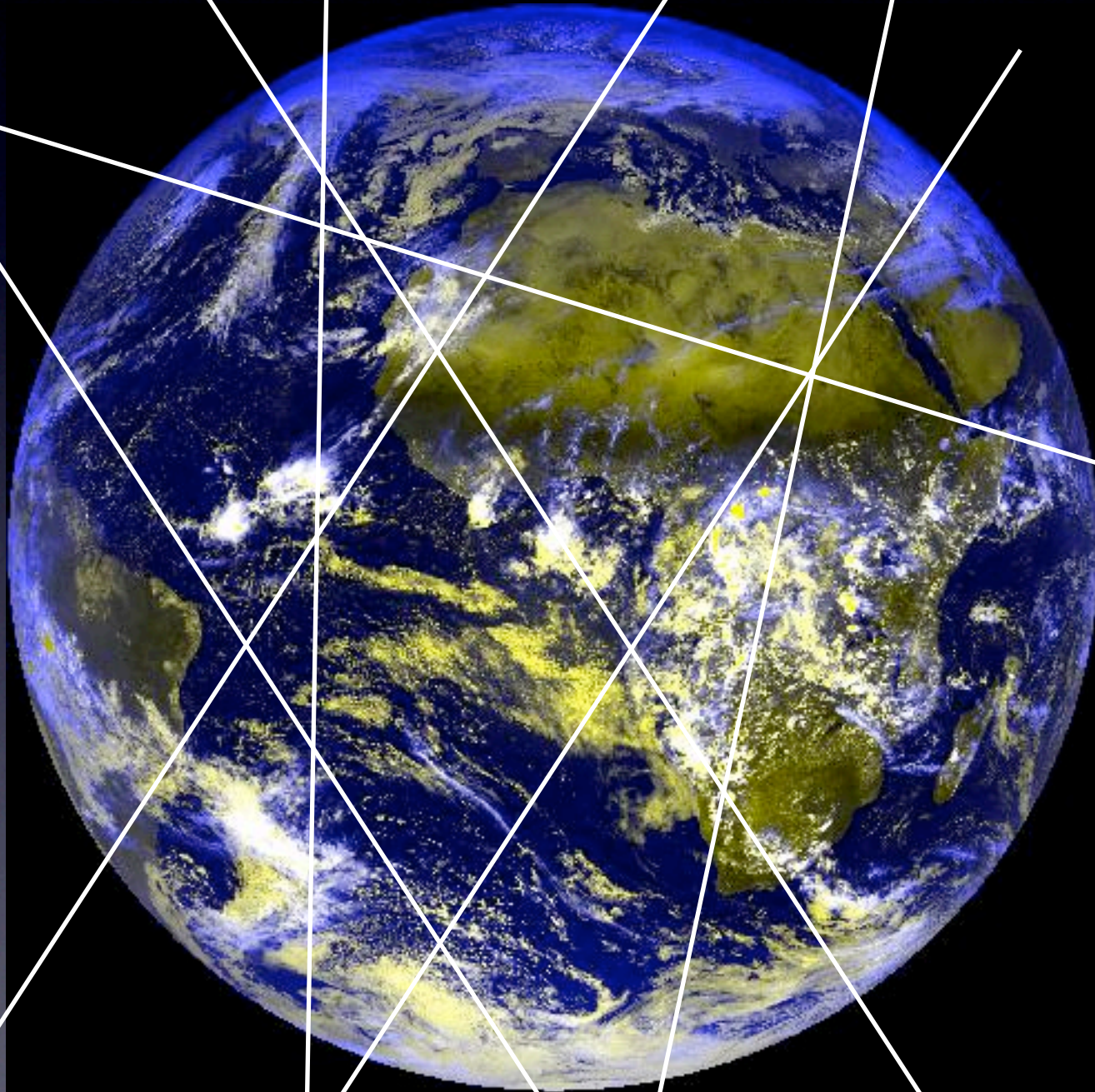


*Not enough of them!*





# MACHO $\Rightarrow$ WIMP



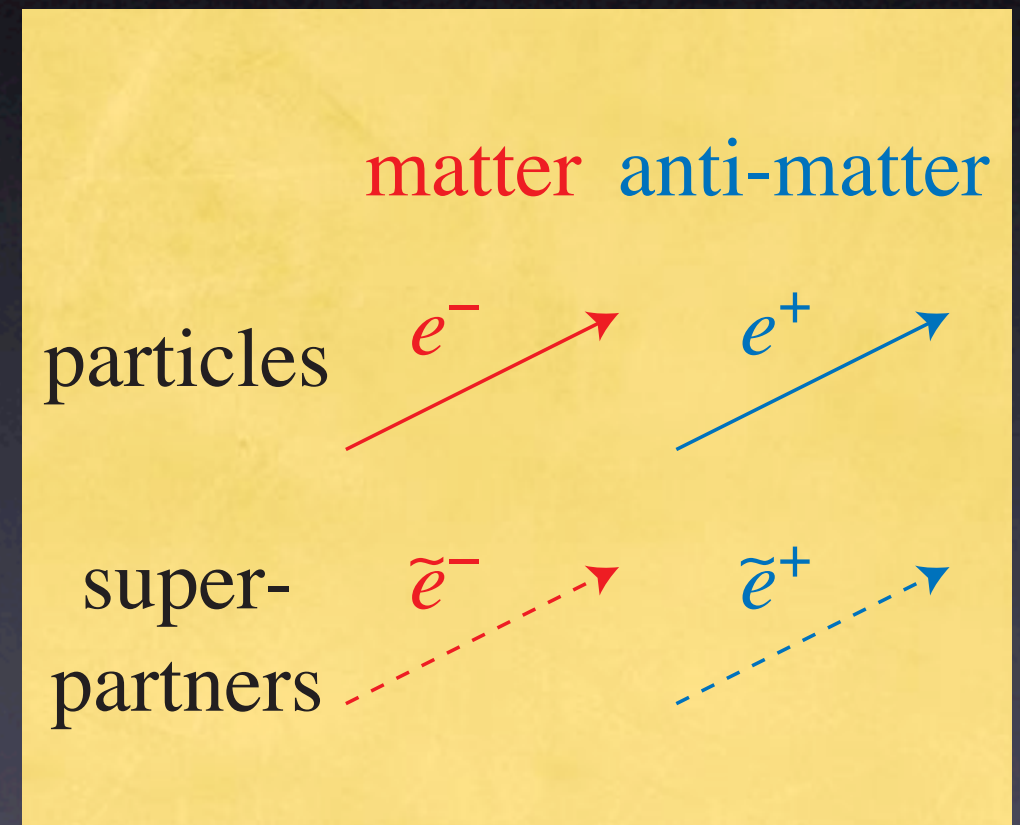
- It must be **WIMP** (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, *left-over from near-complete annihilation*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3} \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$



# Quantum Dimension

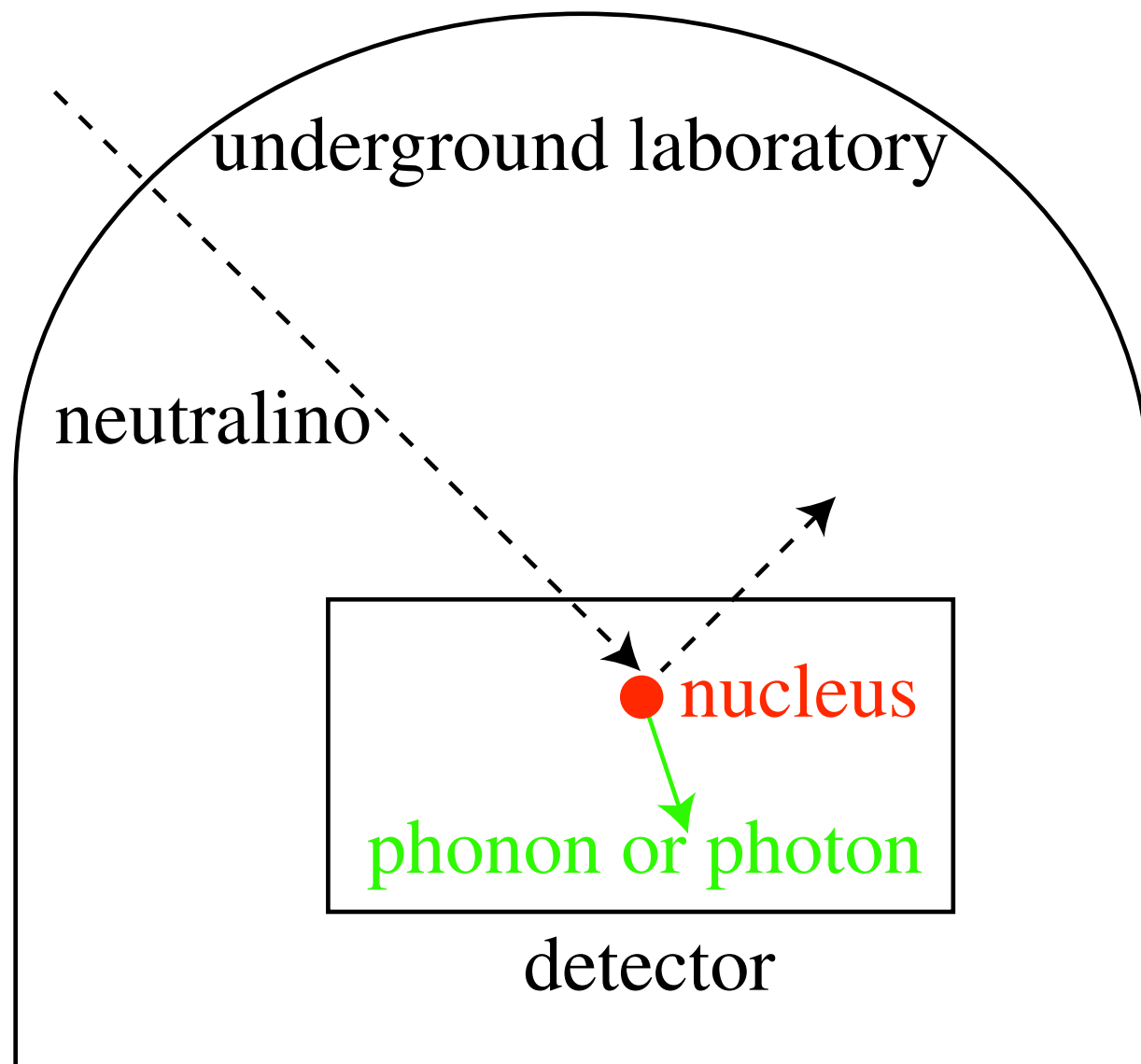
- every particle has anti-matter counterpart: doubled the number
- Nature may do it again
- suggested by string theory: supersymmetry
- The lightest superparticle is stable, neutral, weakly interacting  
⇒ Dark Matter candidate





# Finding Dark Matter

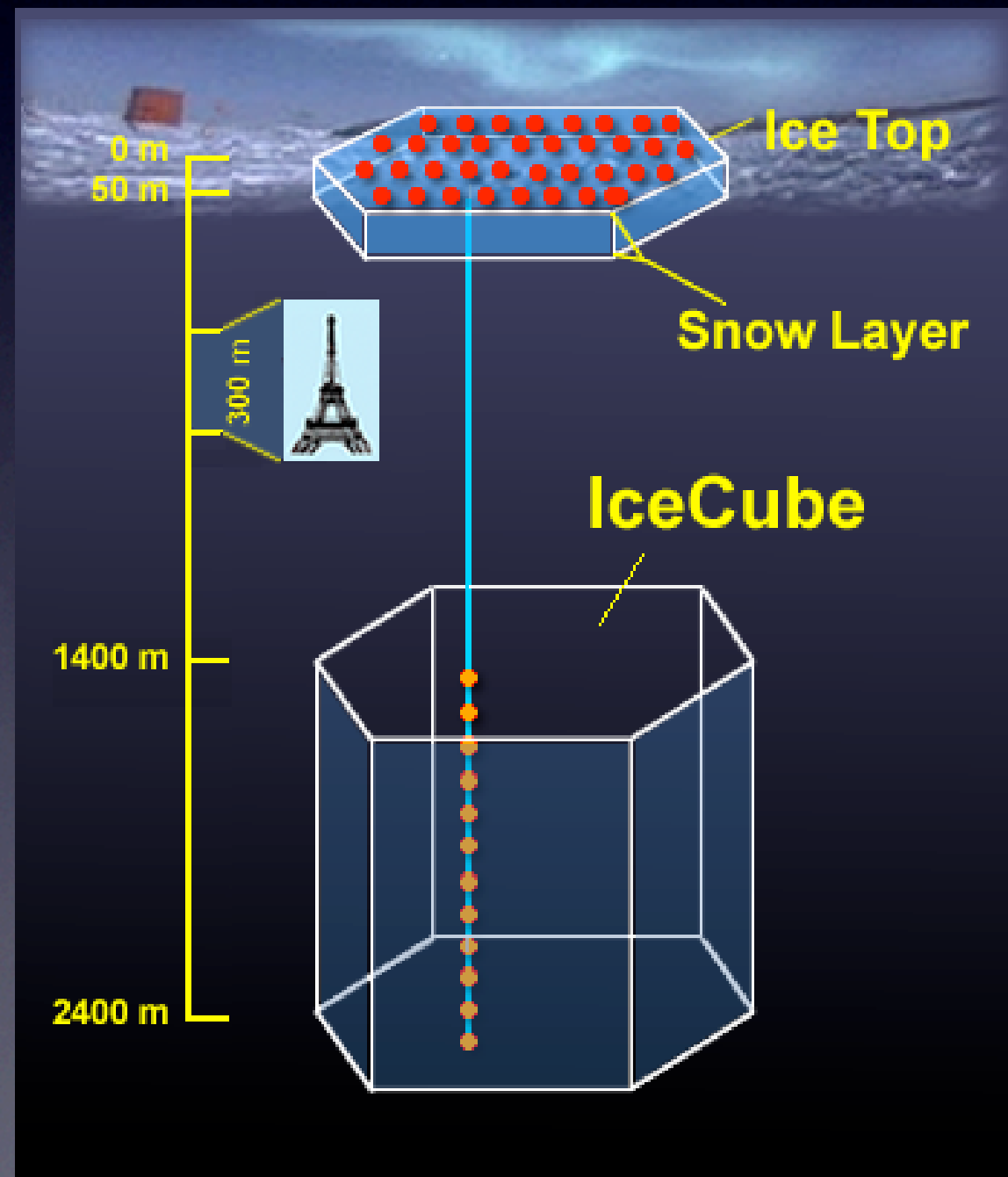
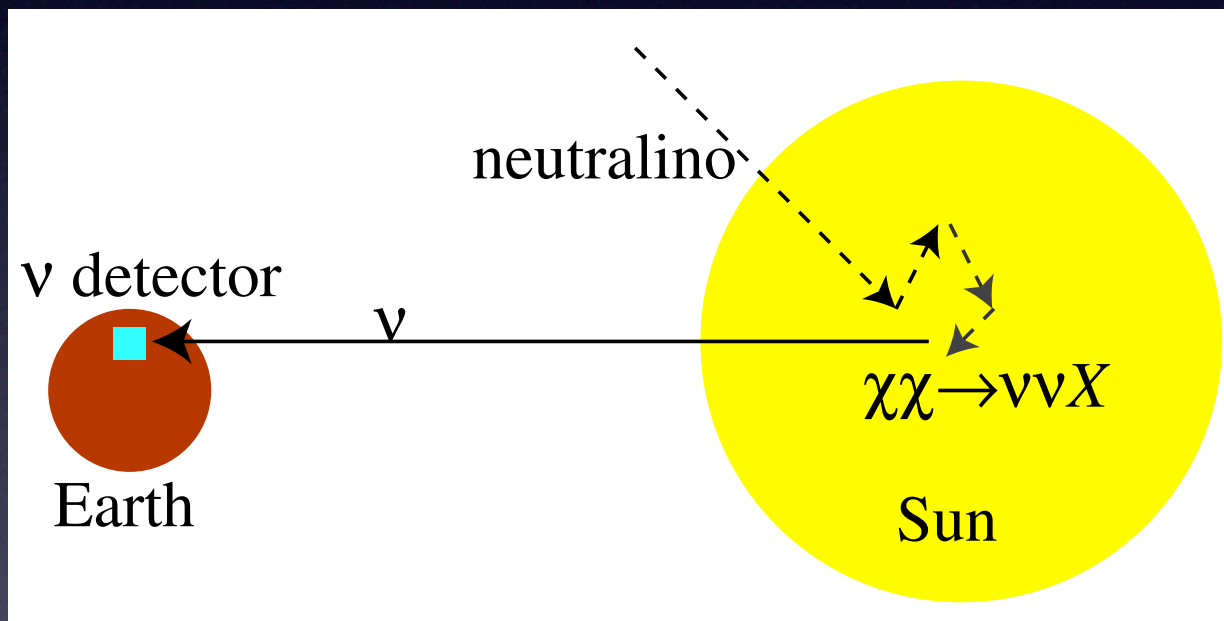
*Direct method*





# Finding Dark Matter

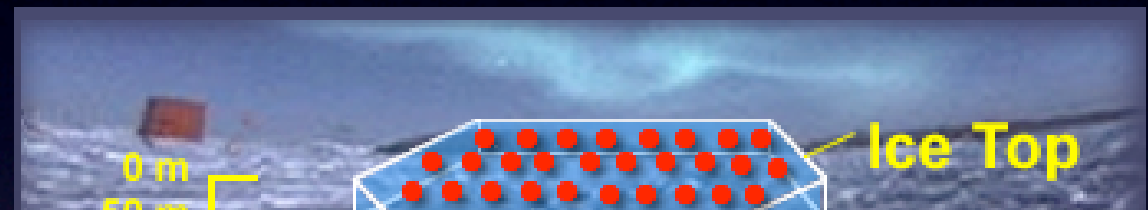
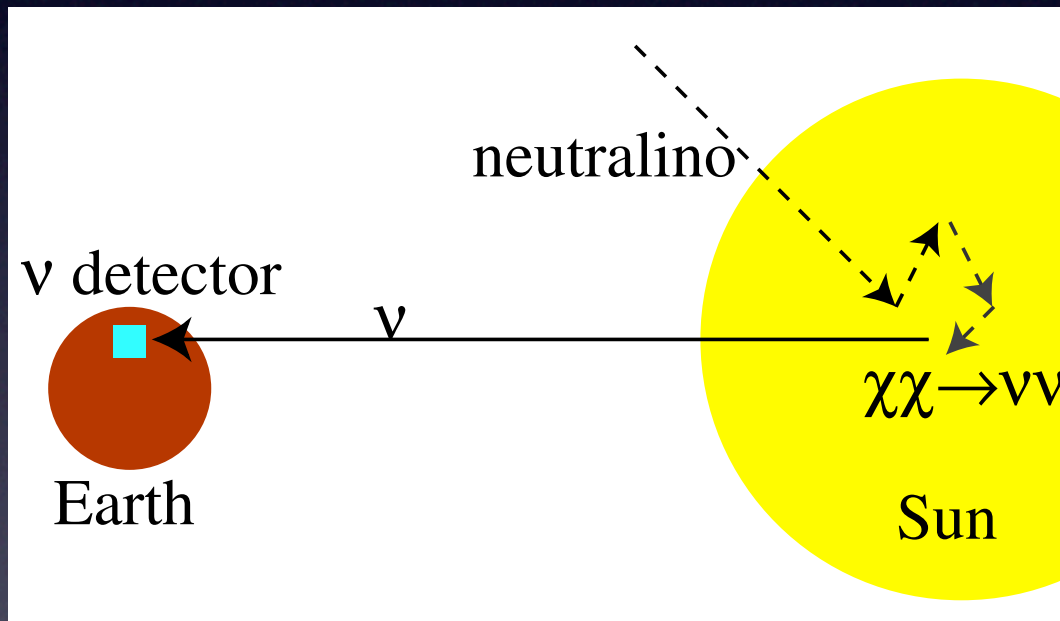
*Indirect method*





# Finding Dark Matter

*Indirect method*





# Large Hadron Collider (LHC)

*Recreating Big Bang*



*start in 2007*



# Large Hadron Collider (LHC)

*Recreating Big Bang*



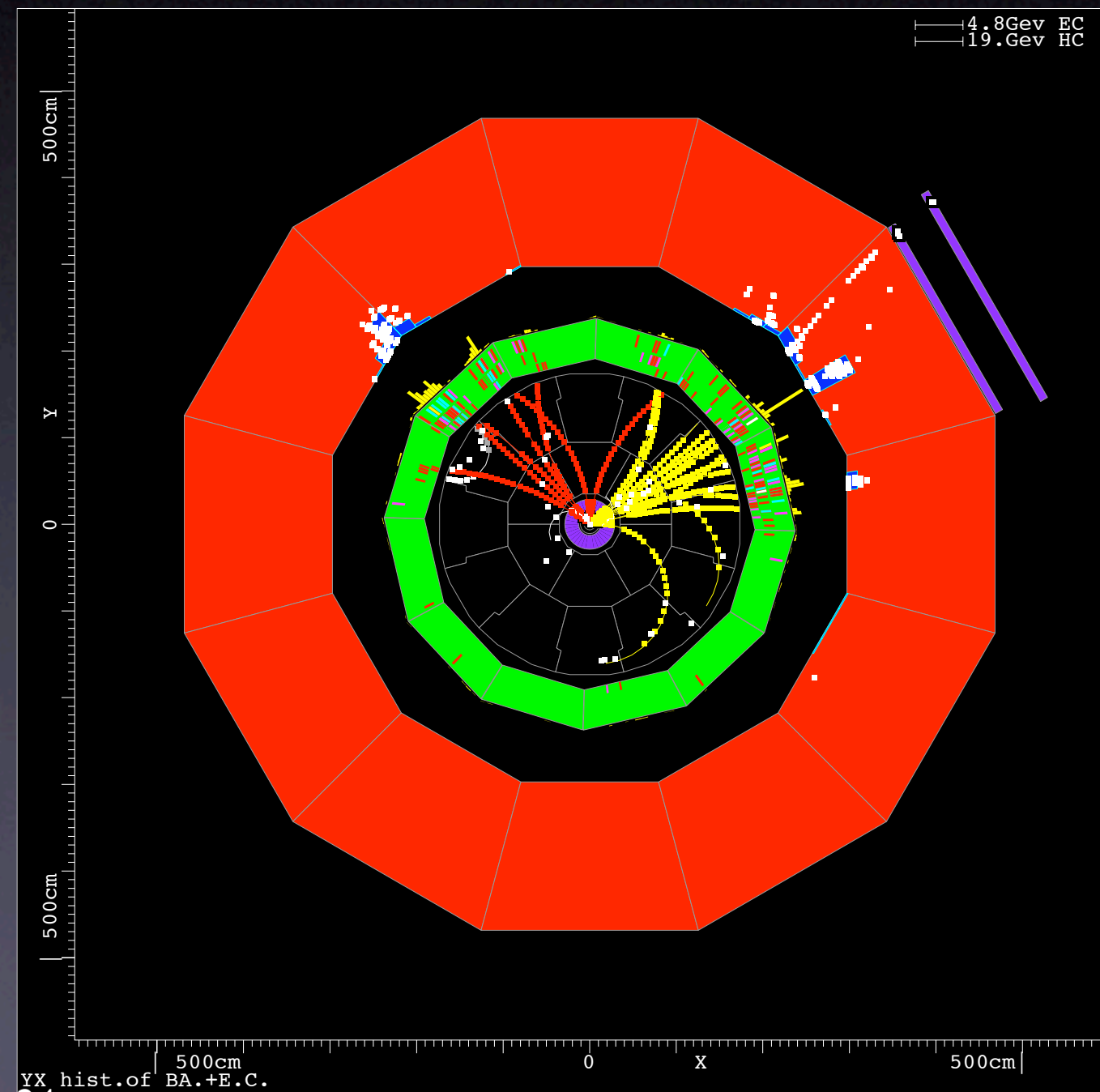


# Producing Dark Matter in the laboratory

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

“missing energy”  $E_{\text{miss}}$

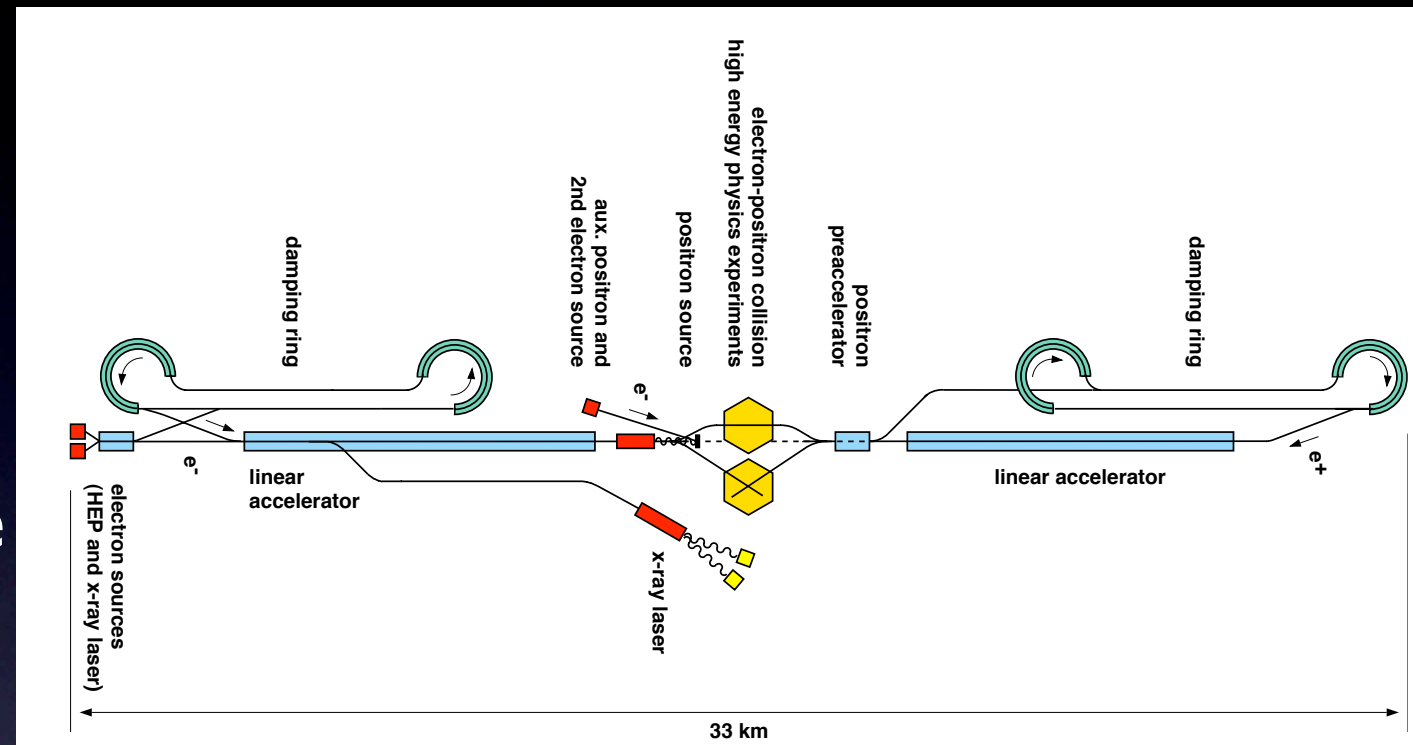
- **Something** is escaping the detector  
⇒ **Dark Matter!?**





# Linear Collider

- Electron-positron collider
- Super-high-tech machine
- Accelerate the beam over ten miles
- Focus beam down to a few nanometers and make them collide
- Precisely measure the dark matter properties



## International Linear Collider (ILC)





# How do we know what Dark Matter *is*?

- cosmological measurement of dark matter

- abundance  $\propto \sigma_{\text{ann}}^{-1}$

- detection experiments

- scattering cross section

- production at colliders

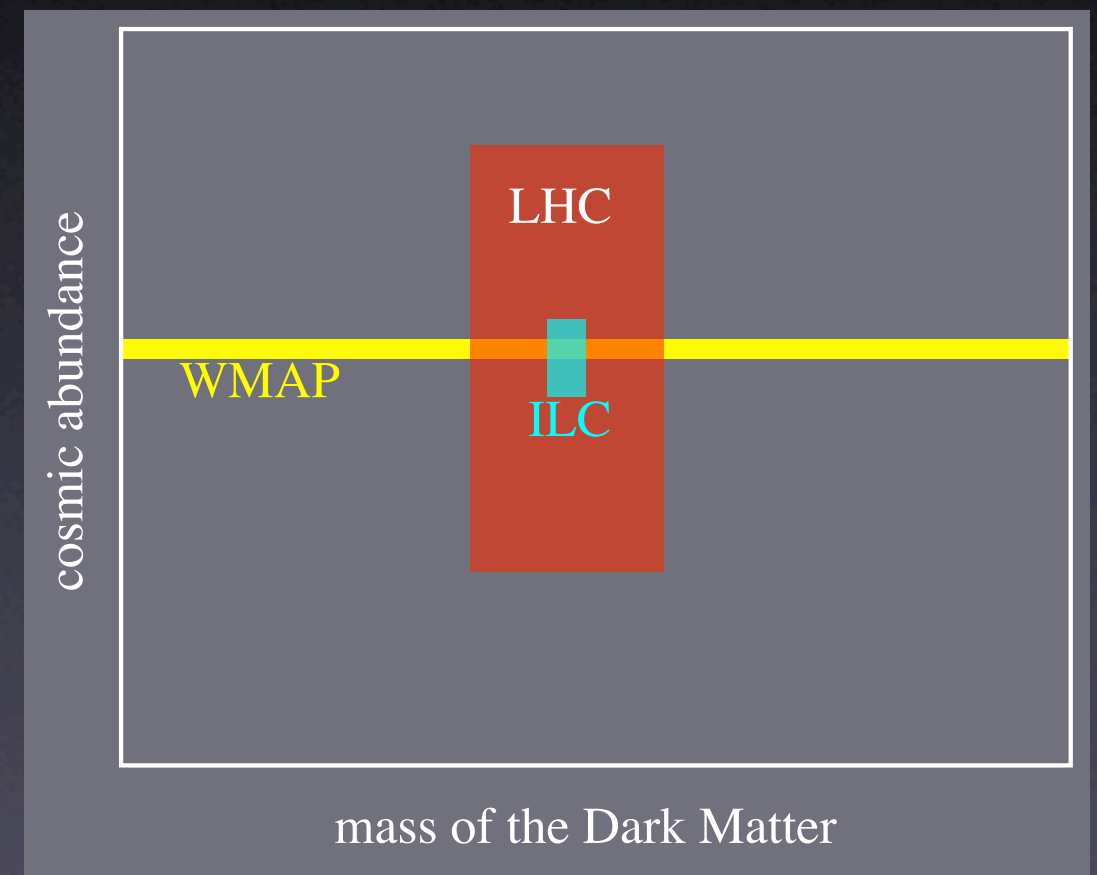
- mass, couplings

- can calculate cross sections

- If they agree with each other:

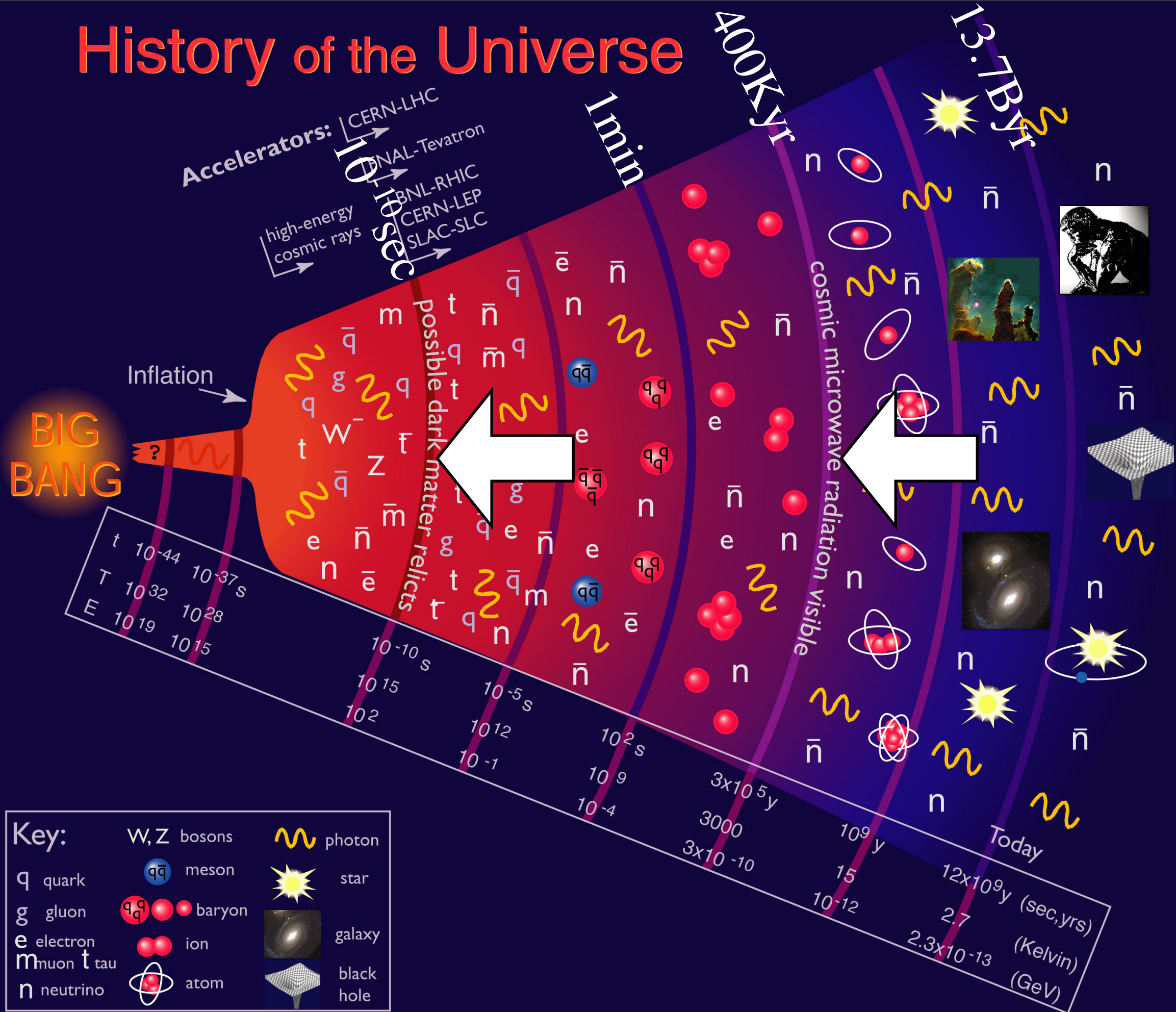
⇒ Will know *what Dark Matter is*

⇒ Will understand universe back to  $t \sim 10^{-10}$  sec





# History of the Universe



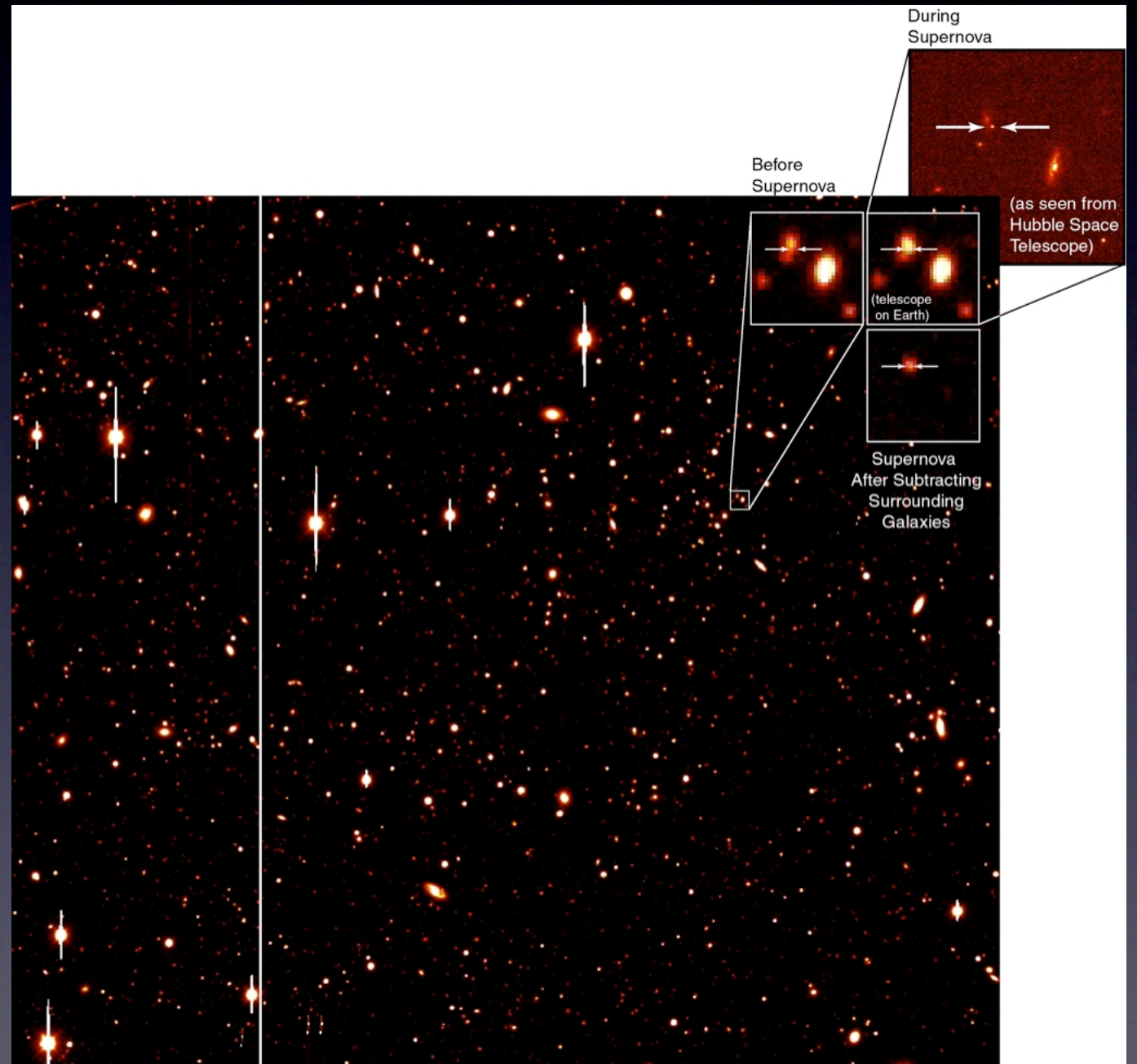


# Dark Energy



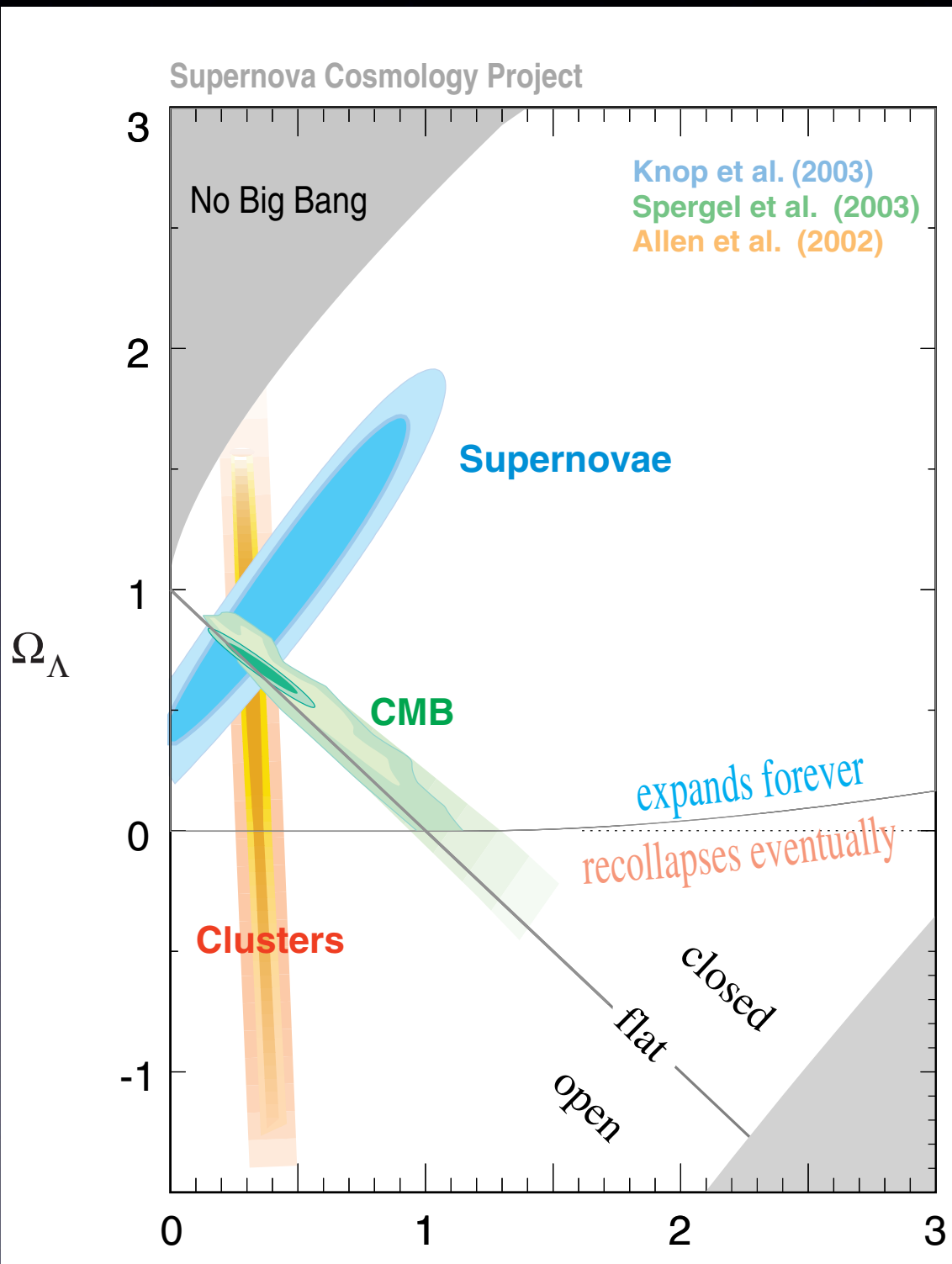
# Type-IA Supernovae

- Type-IA Supernovae “standard candles”
- *Apparent brightness*  
⇒ *how far (time)*
- *Know redshift*  
⇒ *expansion since then*
- Expansion of Universe is accelerating





# Accelerating Universe



- Einstein's equation

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3} \rho$$

- If the energy dilutes as Universe expands, it must slow down
- Need something that gains in energy as Universe stretches  
i.e, negative pressure
- The cosmological constant  $\Lambda$  has the equation of state  $w=p/\rho=-1$
- Generically called “Dark Energy”







# Embarrassment

- A naïve estimate of the cosmological constant in Quantum Field Theory:

$$\rho_{\Lambda} \sim M_{Pl}^4 = G_N^{-2} \sim 10^{120} \text{ times observation}$$

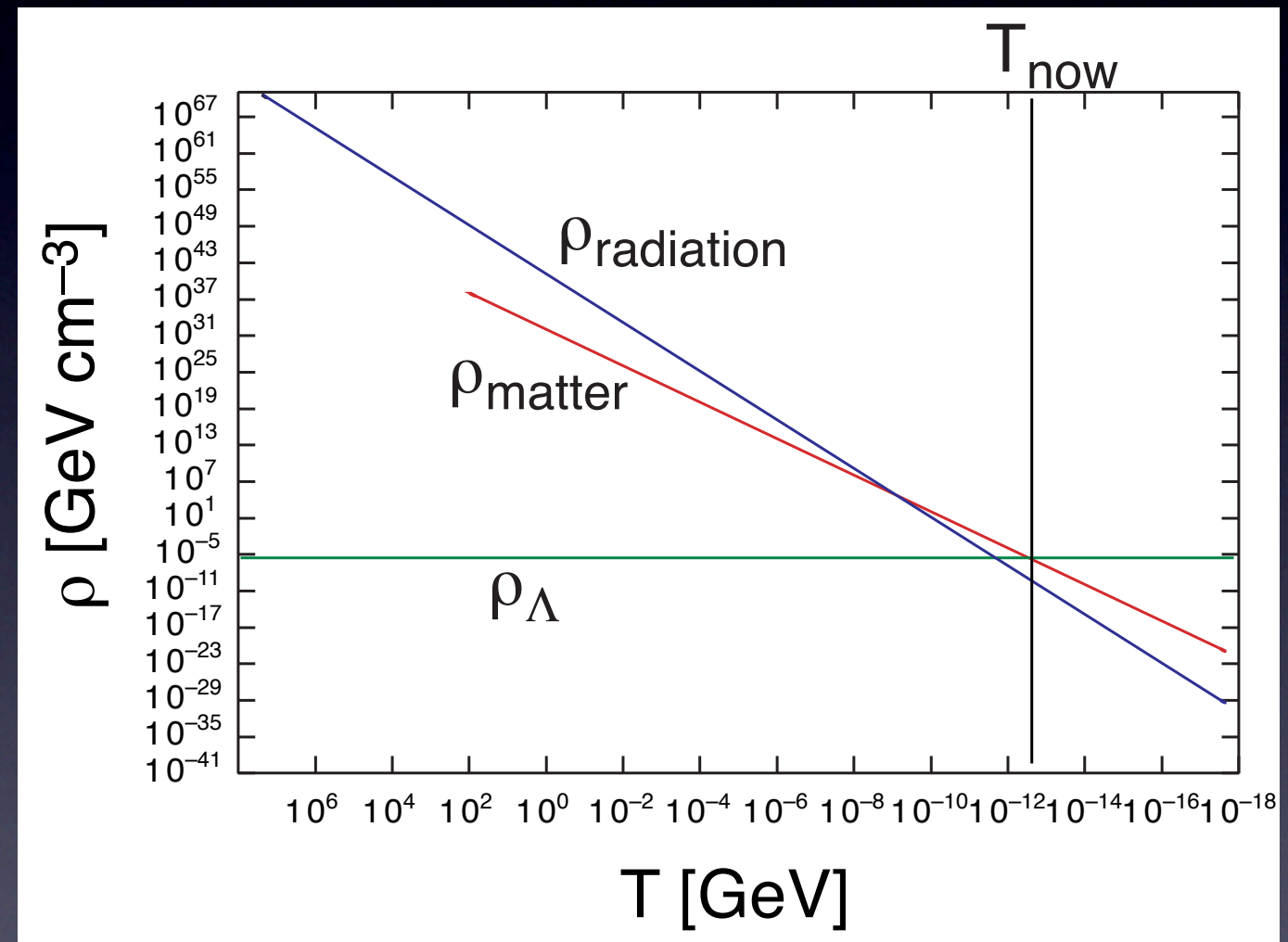
The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???



# Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- “Why Now” problem
- Actually a *triple coincidence problem* including the radiation
- If there is a deep reason for  $\rho_\Lambda \sim ((\text{TeV})^2/M_{Pl})^4$ , coincidence natural

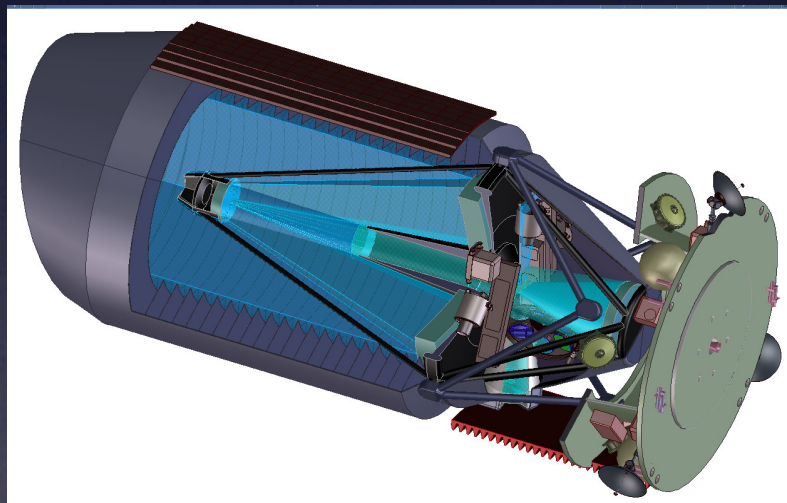


Arkani-Hamed, Hall, Kolda, HM



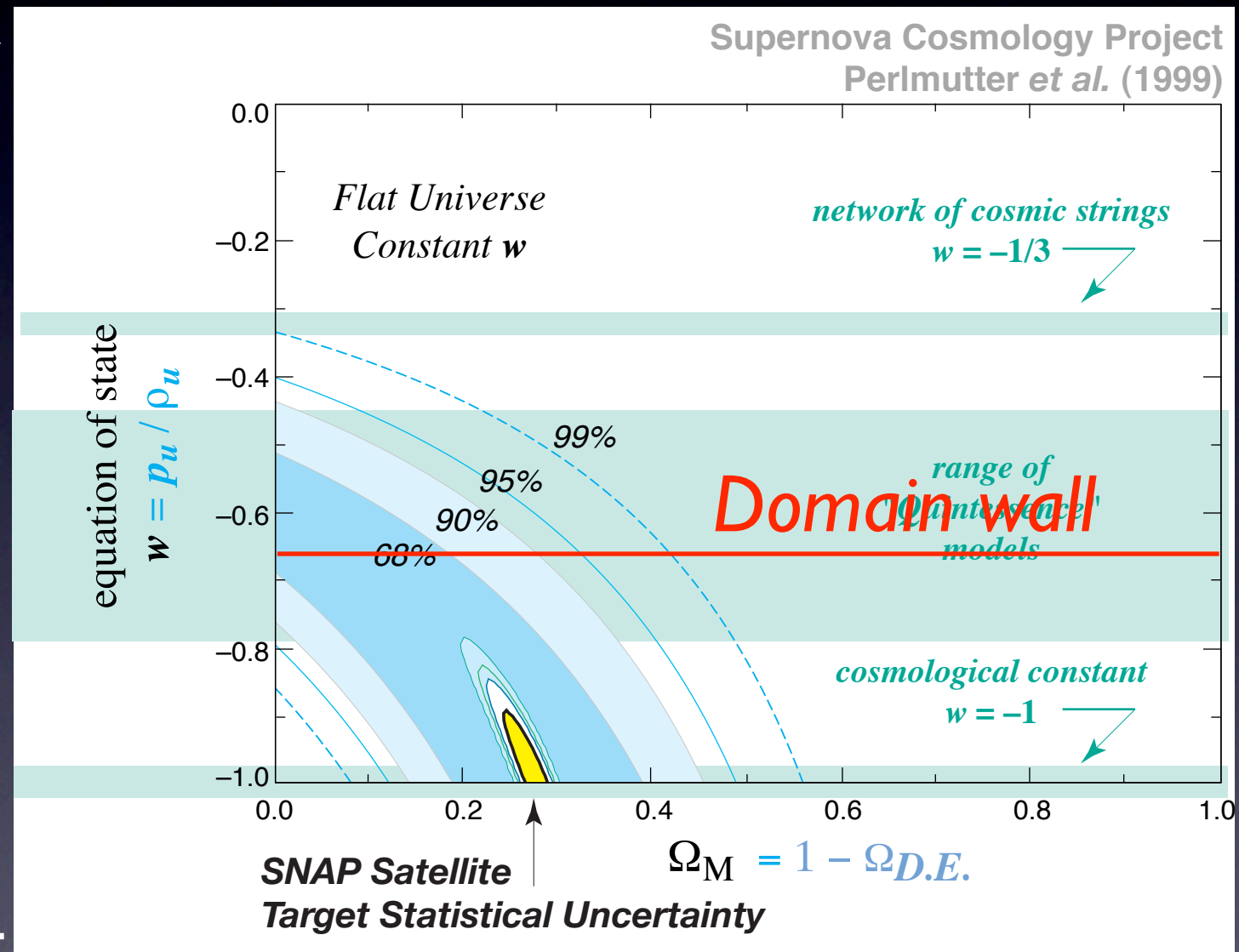
# What is Dark Energy?

- We have to measure  $w$
- For example with a dedicated satellite experiment



SNAP

- or on the ground: LSST



Friedland, HM, Perelstein

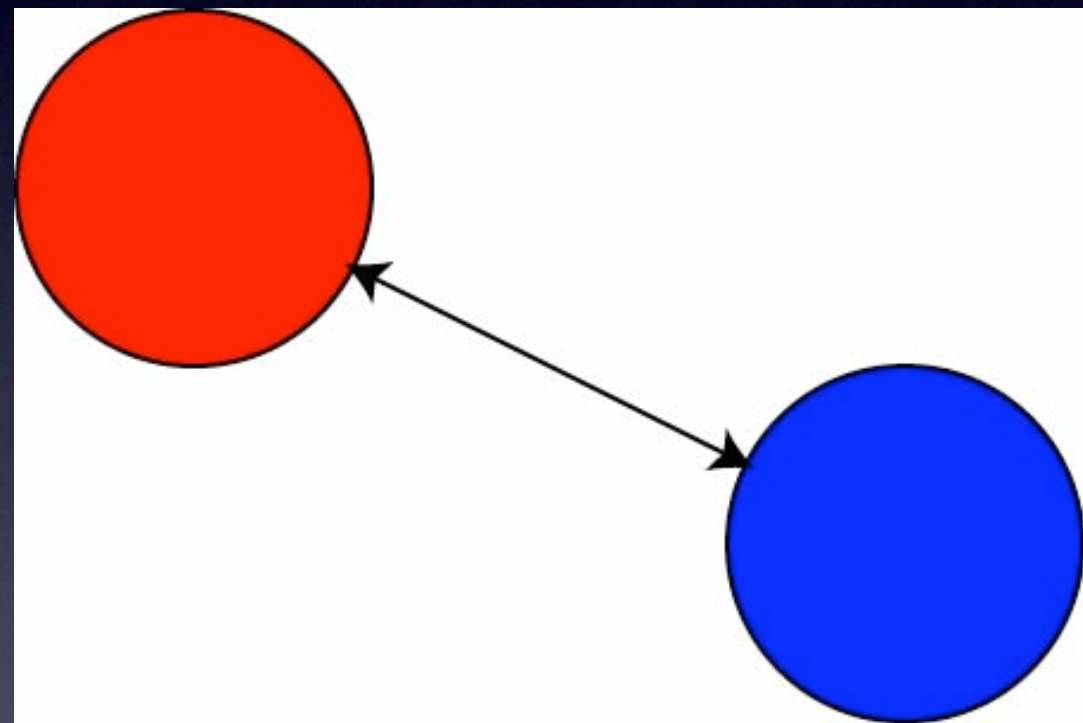


Dark Field  
=Cosmic Superconductor



# Mystery of the weak force

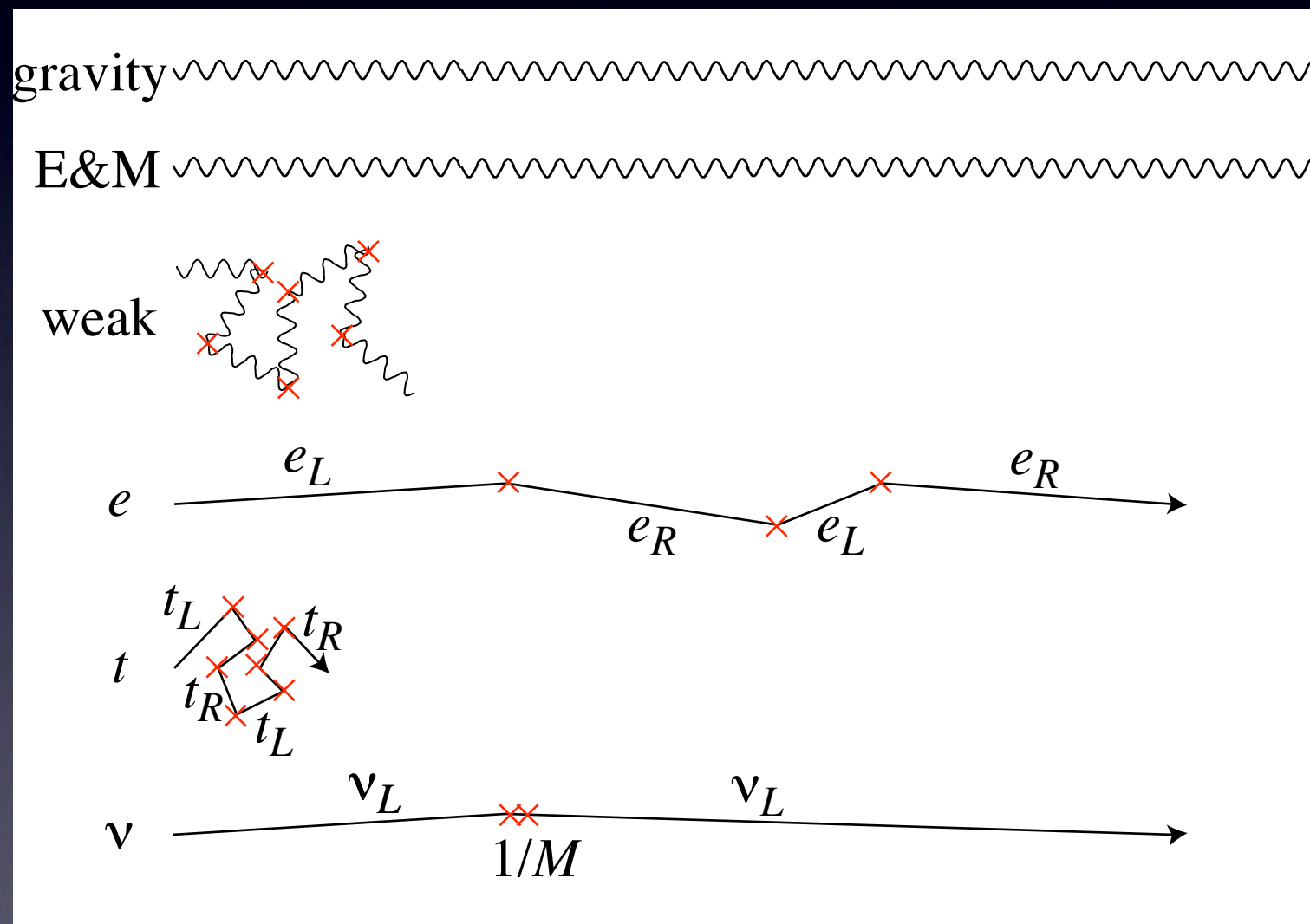
- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: ~0.3 TeV





# We are swimming in Dark Field

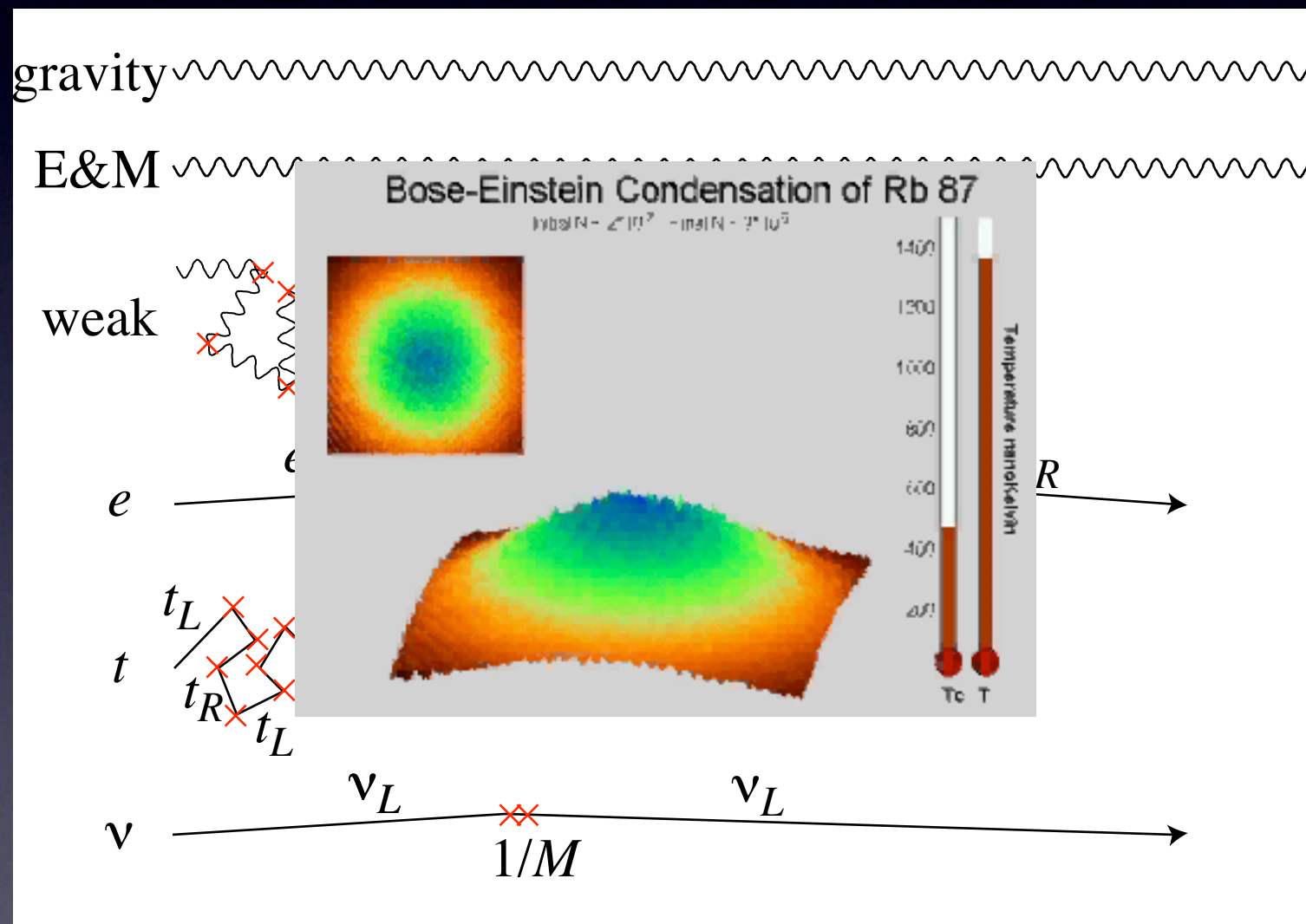
- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??





# We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
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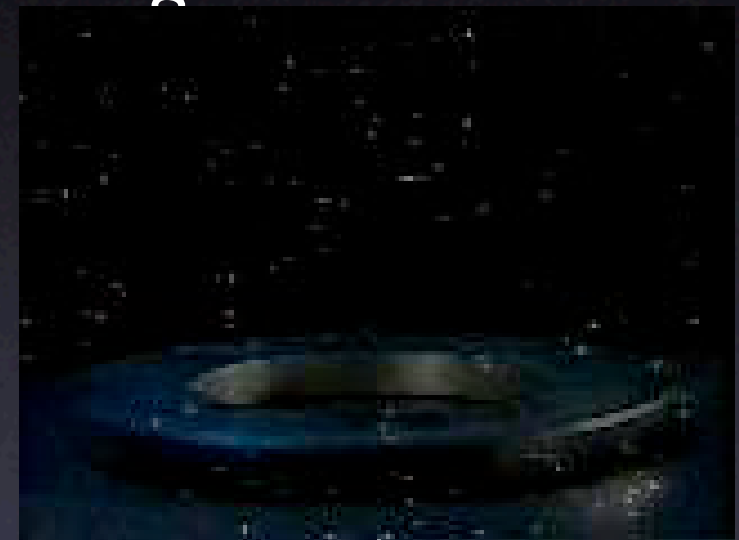




# Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the “penetration length”  
⇒ Magnetic field is short-ranged!
- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her “Universe”
  - But doesn’t know what the condensate is, nor why it condenses
  - Doesn’t have enough energy (gap) to break up Cooper pairs

That’s the stage where we are!





# Solving the Dark Field Problem

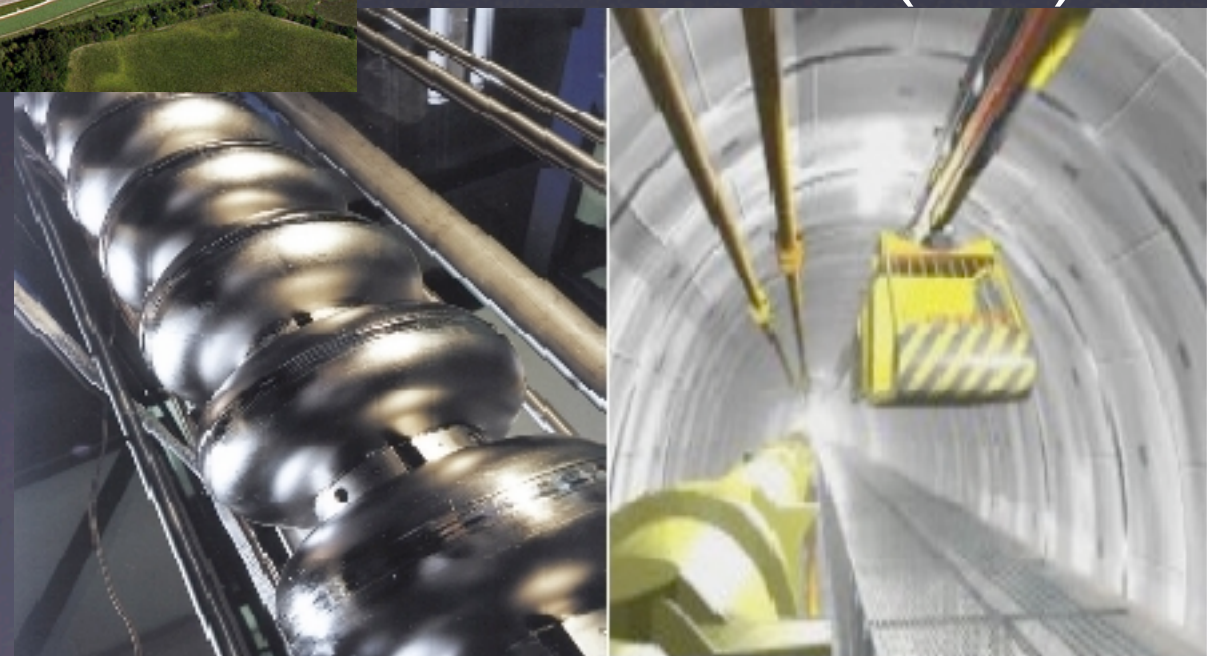


Tevatron

Large Hadron Collider (LHC)

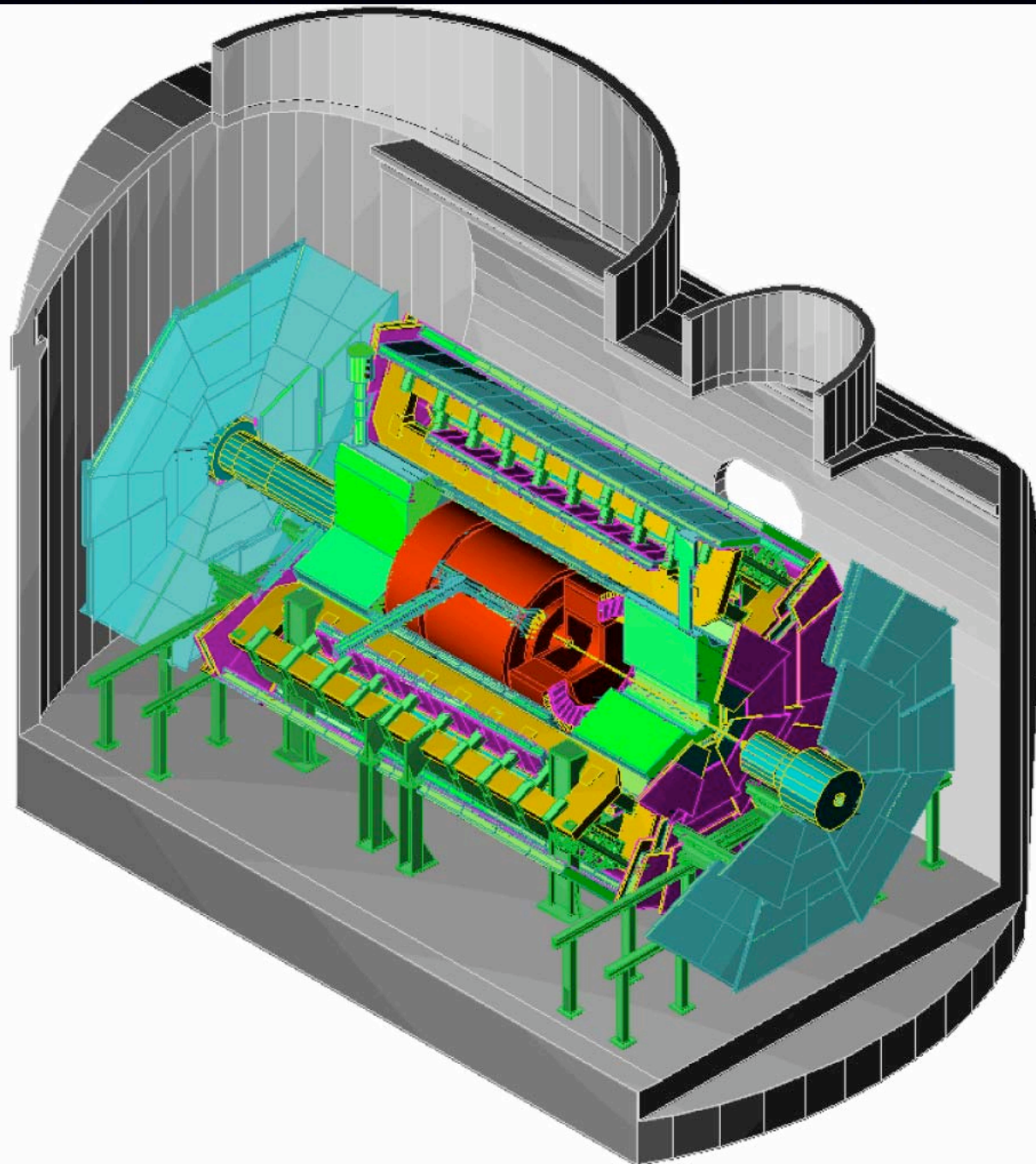


International Linear Collider (ILC)

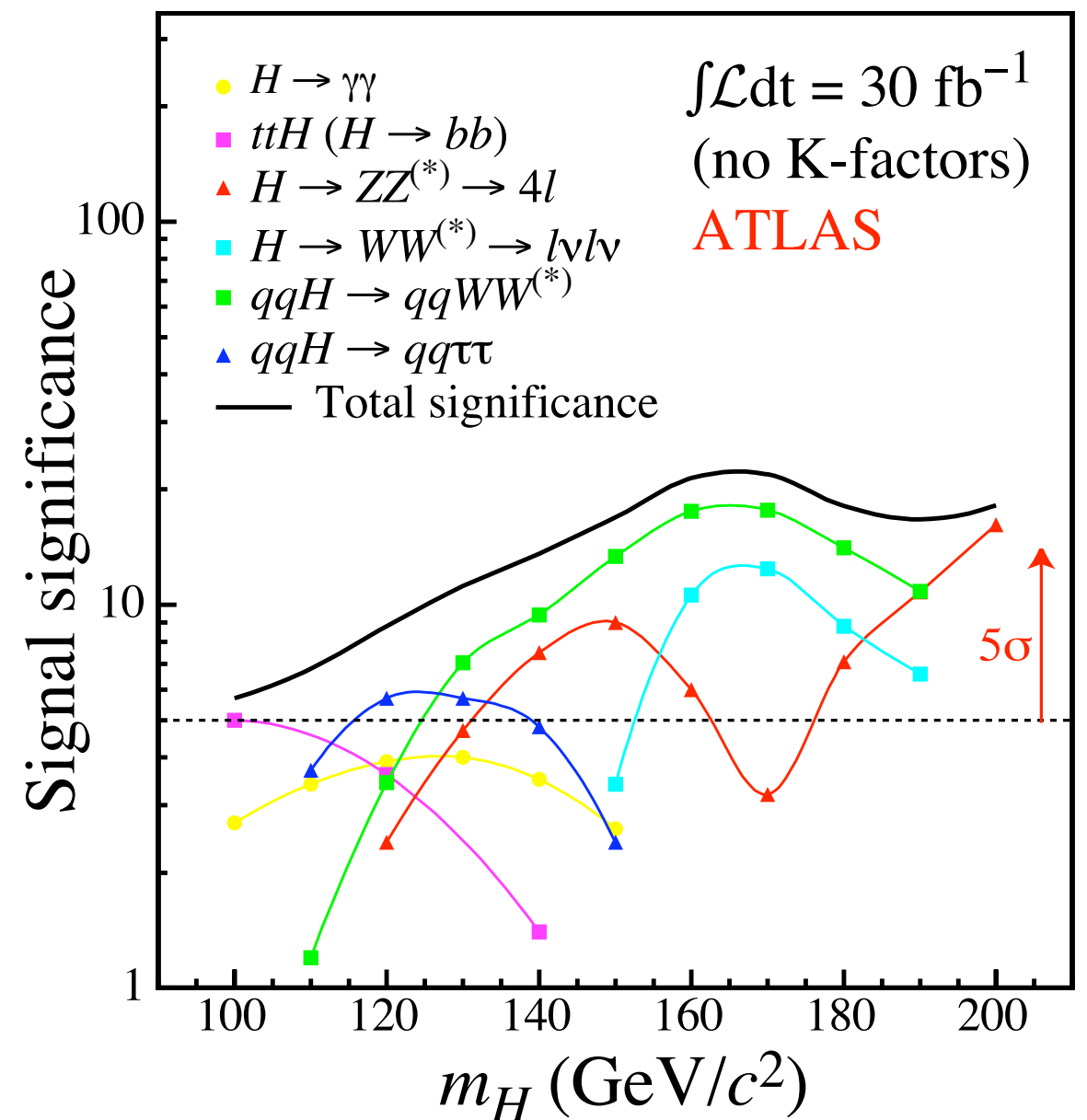




# Higgs at ATLAS



## Robust discovery





# Post-Higgs Problem

- We see “what” is condensed
- But we still don’t know “why”
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation  
 $\sim \text{TeV} \ll M_{\text{Pl}} = 10^{15} \text{TeV}$
- Explanation most likely to be at  $\sim \text{TeV}$  scale because this is the relevant energy scale



# Three Directions

## History repeats itself

- Crisis with electron solved by anti-matter
- Double #particles again  $\Rightarrow$  supersymmetry

## Learn from Cooper pairs

- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite  
 $\Rightarrow$  technicolor

## Physics as we know it ends at TeV

- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV  
 $\Rightarrow$  hidden dimensions (0.1 mm to  $10^{-17}$  cm)



# More Directions

- Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)
- Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)
- Fat Higgs (Composite)
- Higgsless and  $W^\pm$  as Kaluza-Klein boson
- technicolorful supersymmetry



SUSY

EXTRA DIMENSION

Randall  
Sundrum II

techni-  
color  
topcolor

Scherk  
- schwarz

Randall-  
Sundrum I

large extra

$\delta=2$

$\delta=3$

$\delta=4$

$\delta=5$

$\delta=6$

$\delta=7$   
M theory

mSUGRA

composite

anomaly  
med

+ SUGRA + non-  
decoupling

gauge  
med

gaugino  
med

G

$Z'_{LR}$

$Z'_{\psi}$

$Z'_{SM}$

$Z'_{\chi}$

$Z'_{\eta}$

$4\kappa$

dim



THOUGHT OF

NOT YET

NOT YET  
THOUGHT  
OF

NOT YET  
THOUGHT OF

TC-TC  
bosonic TC  
composite Higgs  
hypercolor  
supercolor  
techni-GIM  
extended TC

effective susy  
N=1  
N=2  
N=4  
N=8  
MSSM  
NMSSM  
unified SM  
axigluon

6th gen  
5th gen  
4th gen

lepto quark

fractionally charged

vector-like family

shadow matter

milli-charged

mono-pole

5th gen  
4th gen

triplet Higgs

general 2HDSM

Type 2

Type II

spontaneous CP

superweak

Weinberg's 3HD

milli-weak

Majoron

axion

familon

NGB

axion  
axino

quintessence

k-essence

composite w, z

contact

string

IB

IA

heterotic

matrix M

F

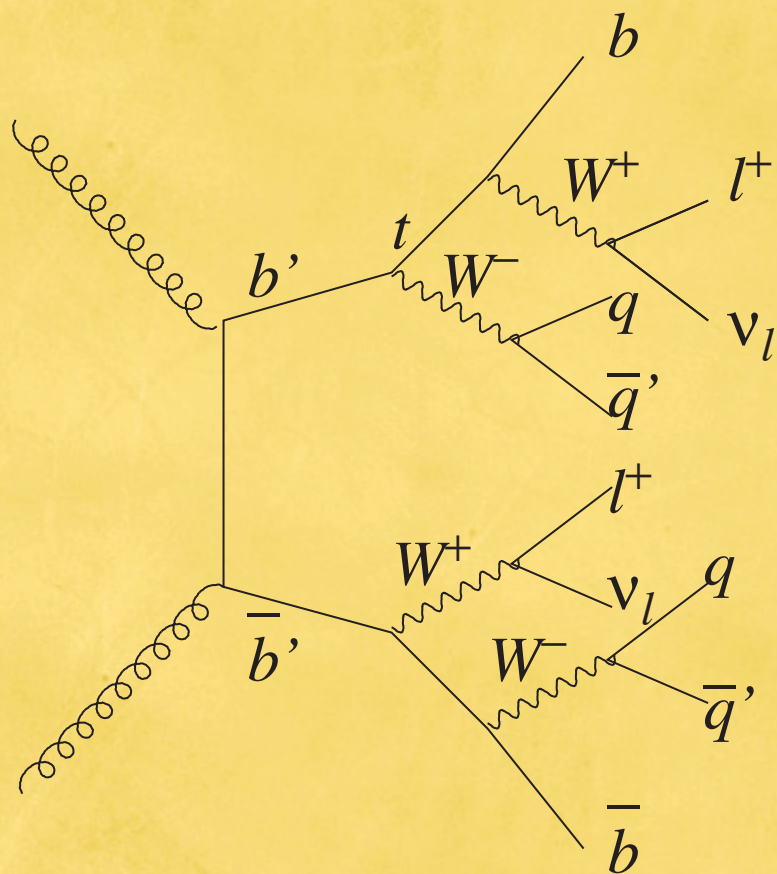
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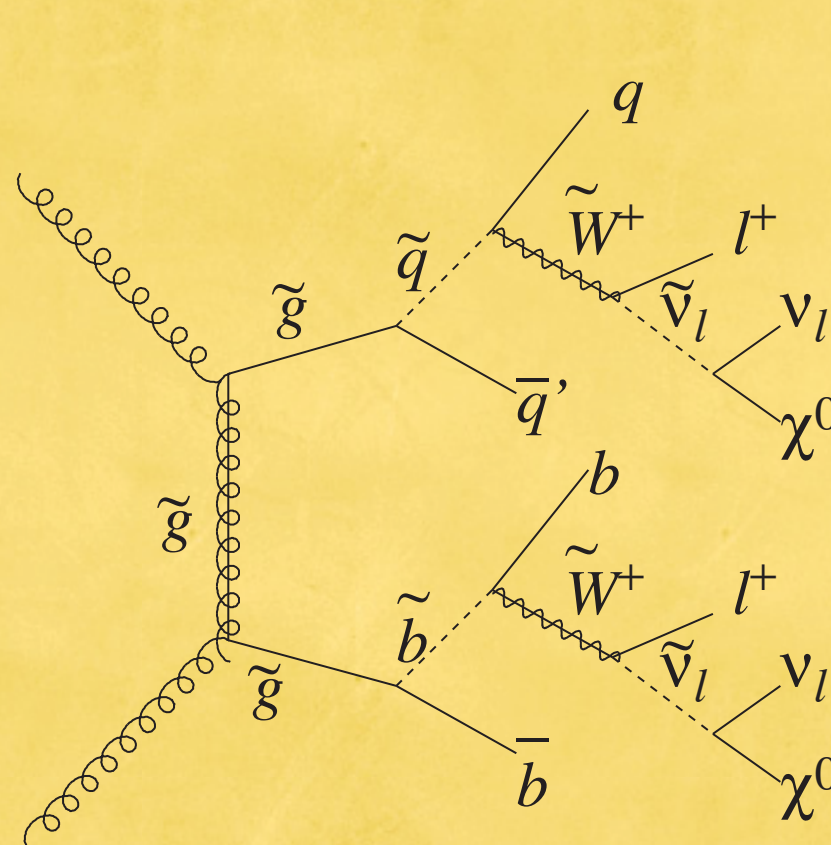


# New physics looks alike

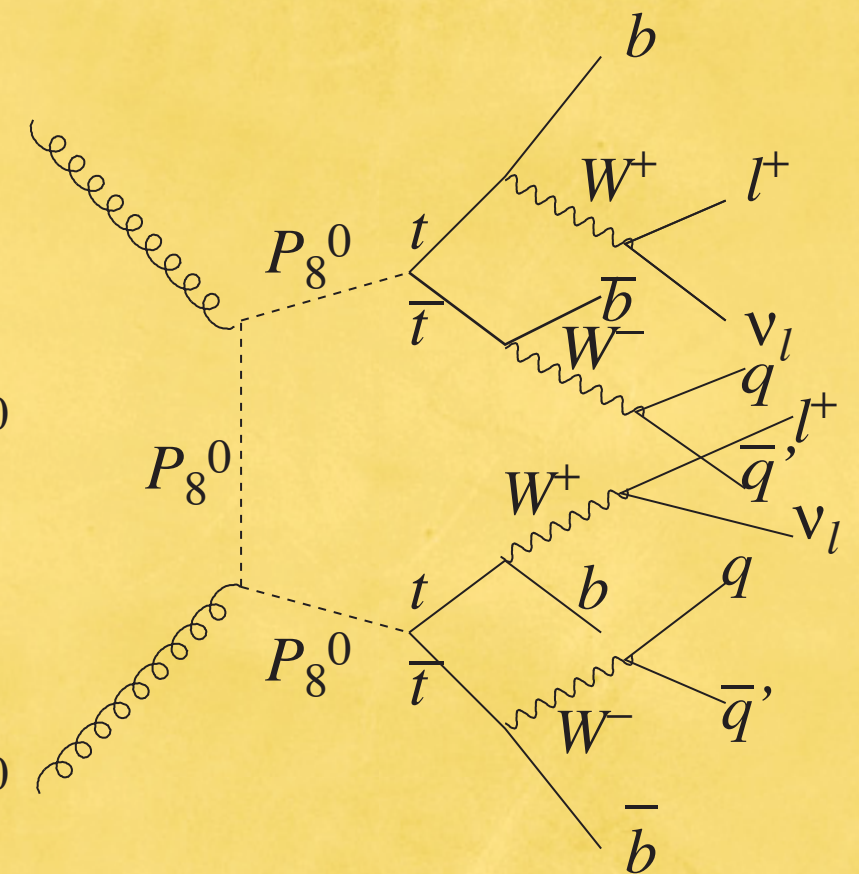
missing  $E_T$ , multiple jets,  $b$ -jets, (like-sign) di-leptons



4th generation



SUSY



technicolor

+Universal extra dimension, little Higgs with T-parity



# Need absolute confidence

As an example, supersymmetry  
“New-York Times level” confidence



# The New York Times

July 23, 2008

## The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

“New-York Times level” confidence  
still a long way to

“Halliday-Resnick” level confidence

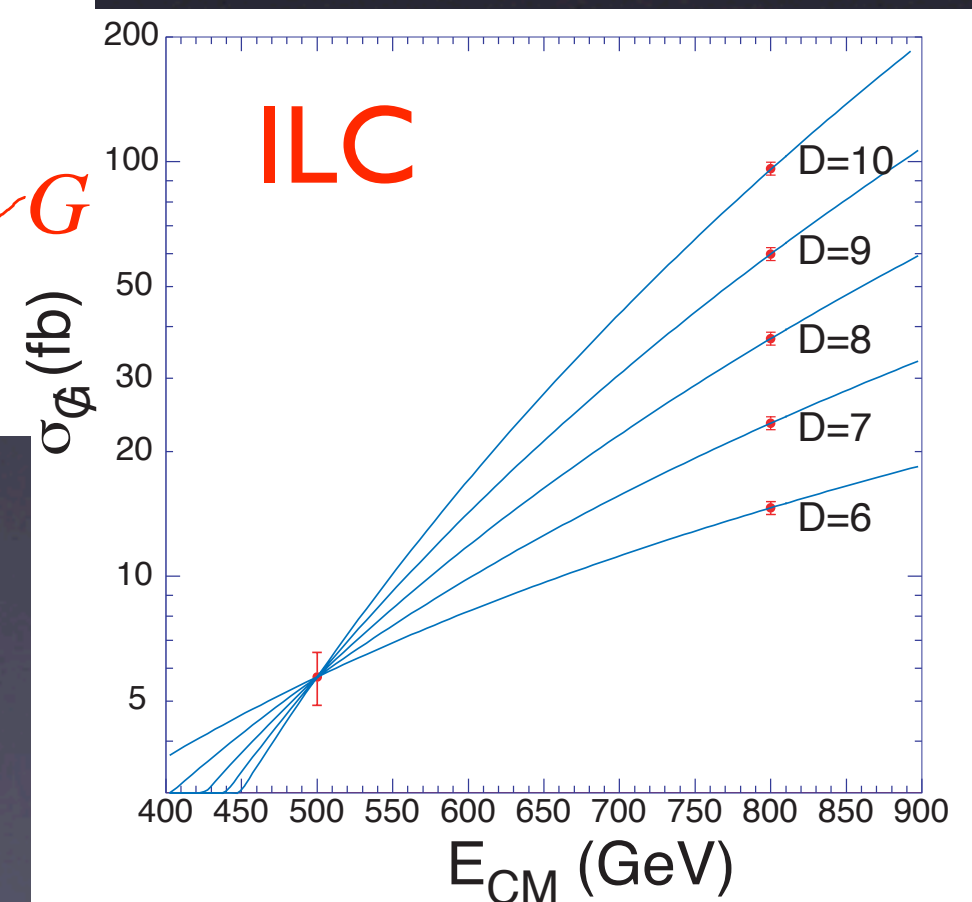
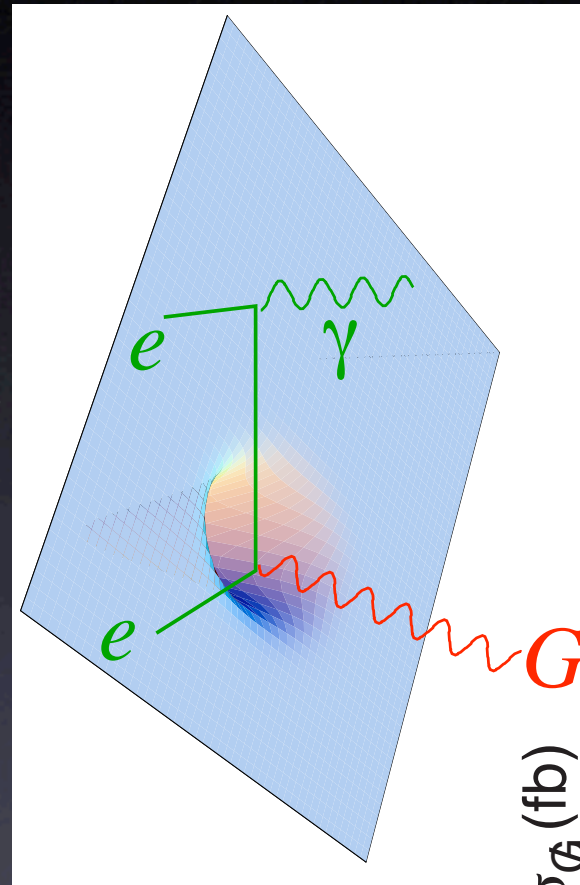
“We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances.”



# Hidden Dimensions

- Hidden dimensions
- Can emit graviton into the bulk
- Events with apparent energy imbalance

⇒ How many extra dimensions are there?



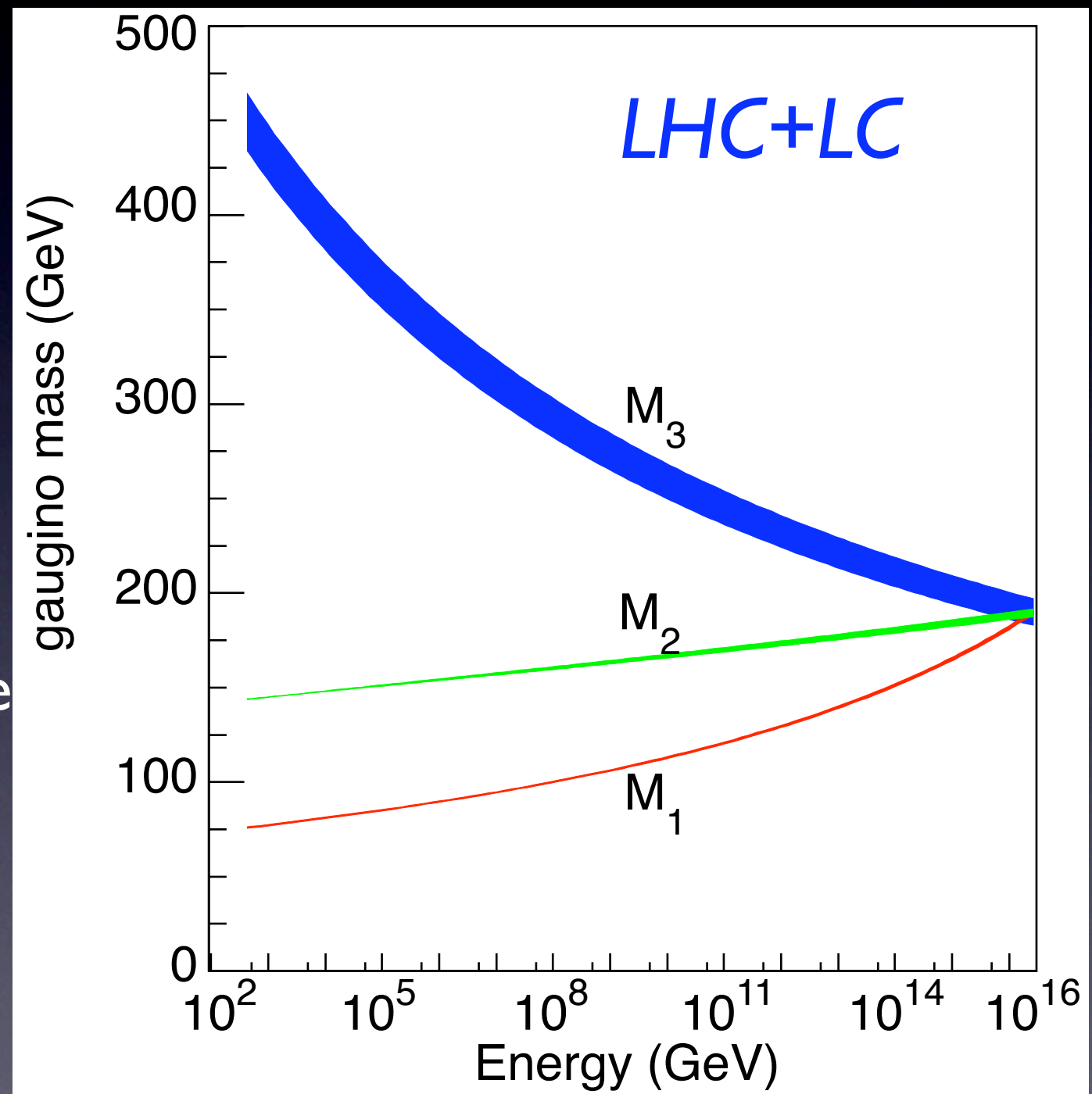


# Superpartners as probe

- Most exciting thing about superpartners beyond existence:

They carry information of small-distance physics to something we can measure

“Are forces unified?”





# Anti-Matter





1955  
anti-proton  
in Berkeley



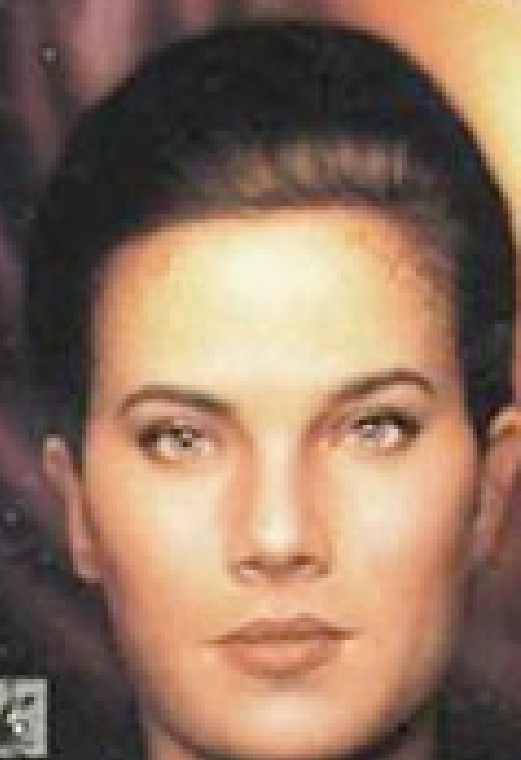


#8

# STAR TREK

## DEEP SPACE NINE

### ANTIMATTER



With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!

John Vornholt



BESTSELLING AUTHOR OF *DIGITAL FORTRESS*

# DAN BROWN



A NOVEL

# ANGELS & DEMONS

"A breathless, real-time adventure...Exciting, fast-paced, with an unusually high IQ." —*San Francisco Chronicle*



# Matter and Anti-Matter

## Early Universe

1,000,000,001

1,000,000,000

*matter*

*anti-matter*



# Matter and Anti-Matter Current Universe

|  
•  
us

*matter*

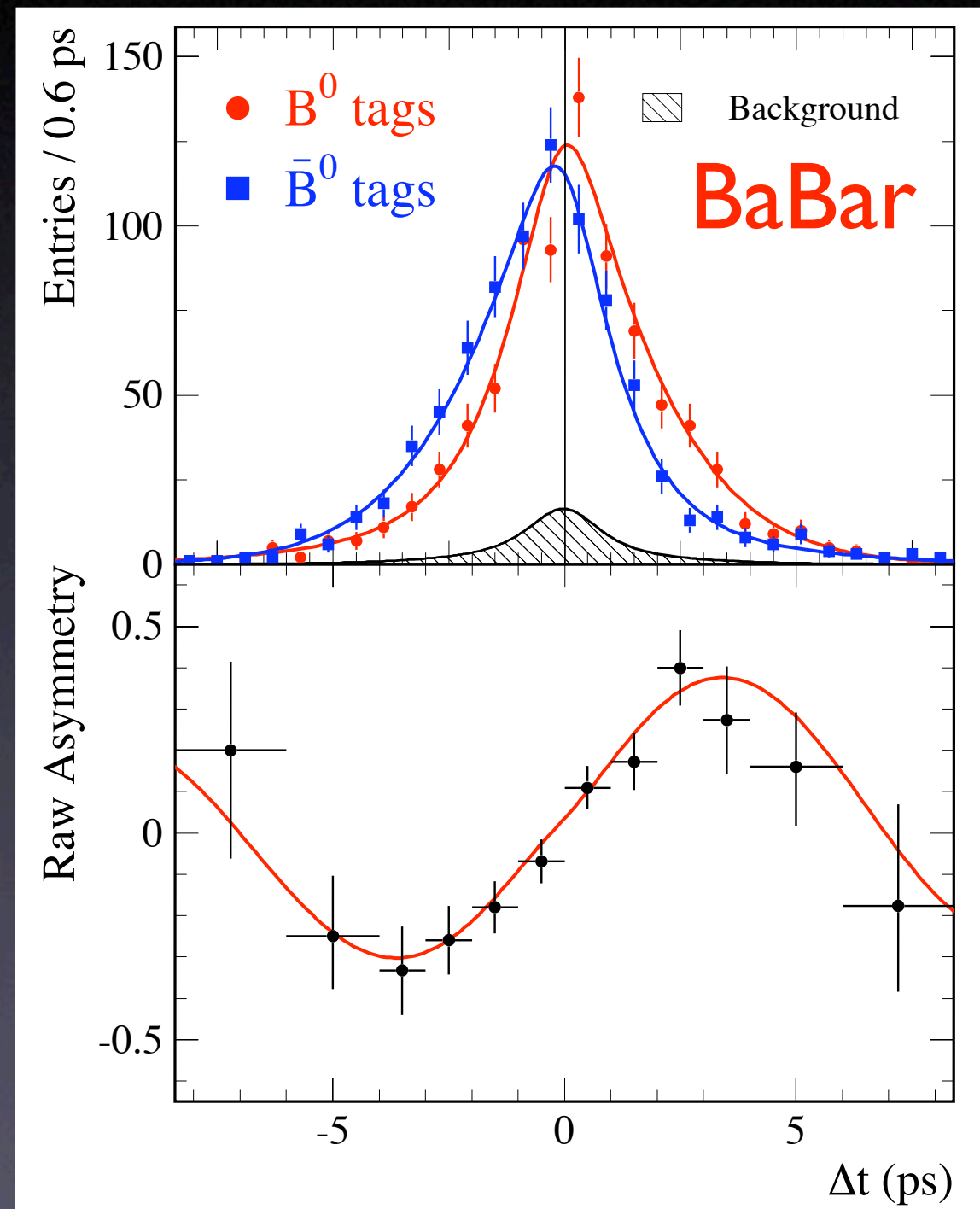
*anti-matter*

The Great Annihilation



# CP Violation

- Is anti-matter the exact mirror of matter?
- 1964 discovery of CP violation
- But only one system, hard to tell what is going on.
- 2001, 2002 Two new CP-violating phenomena
- But no CP violation observed so far is not large enough to explain the absence of anti-matter

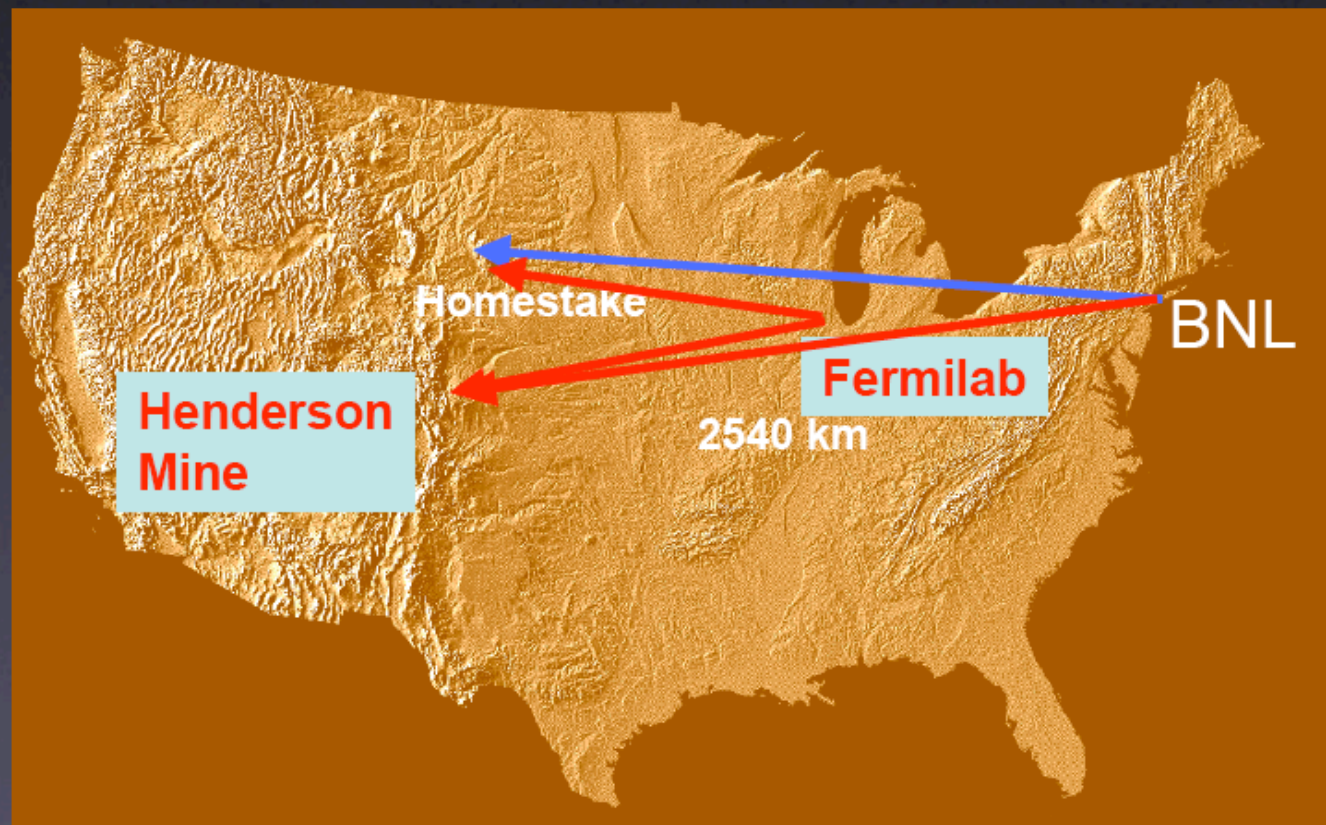




# Leptogenesis

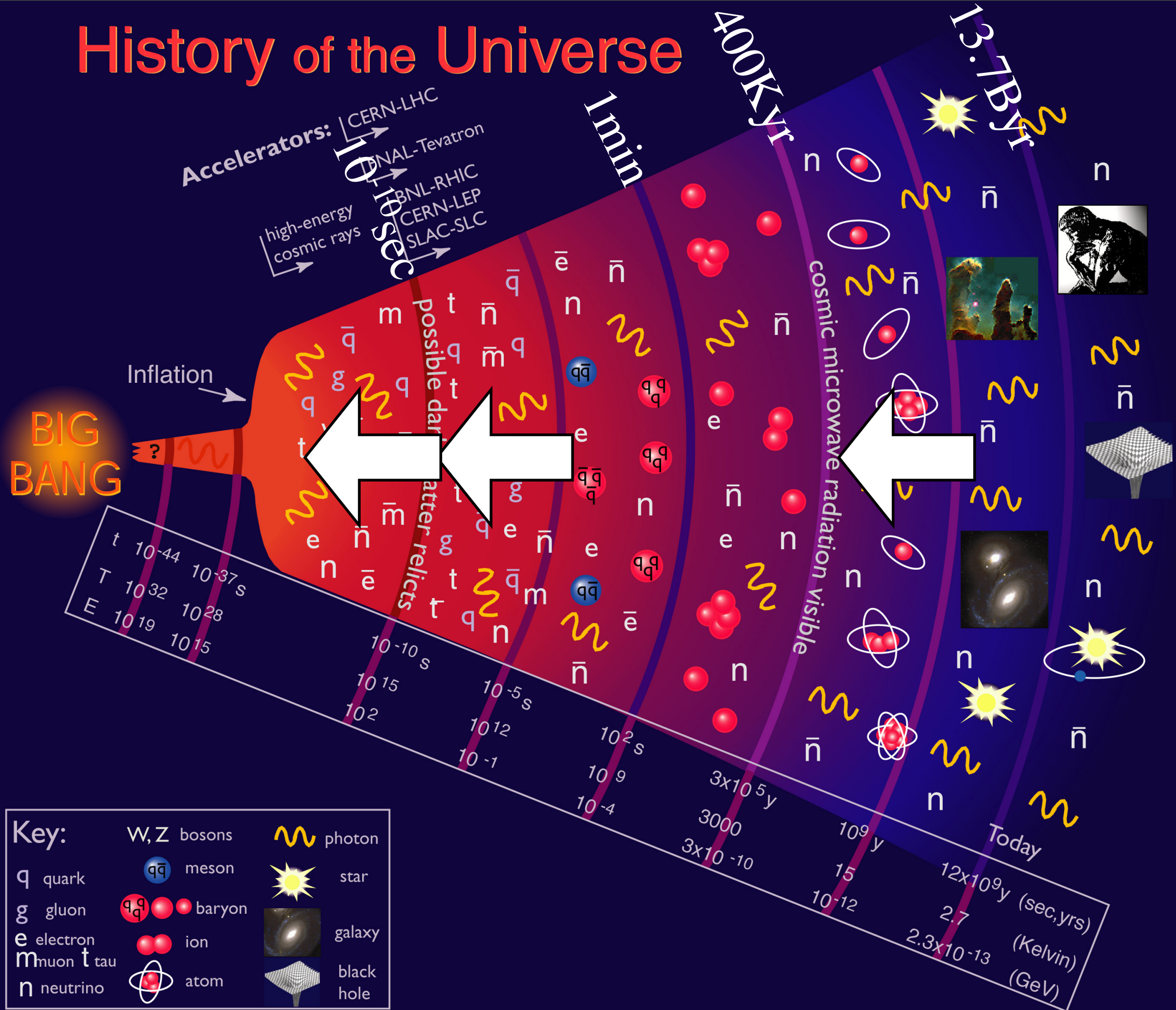
- Neutrinos have mass (1998-2002)
- Neutrinos may be **their own anti-particles**
- They can **transform matter to anti-matter** and vice versa
- Maybe they are responsible for our existence!

Shoot the beams over thousands of kilometers to see CP violation in neutrinos





# History of the Universe

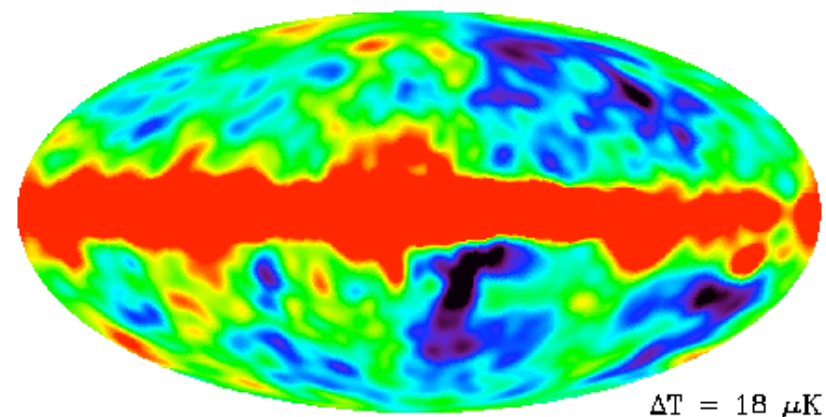
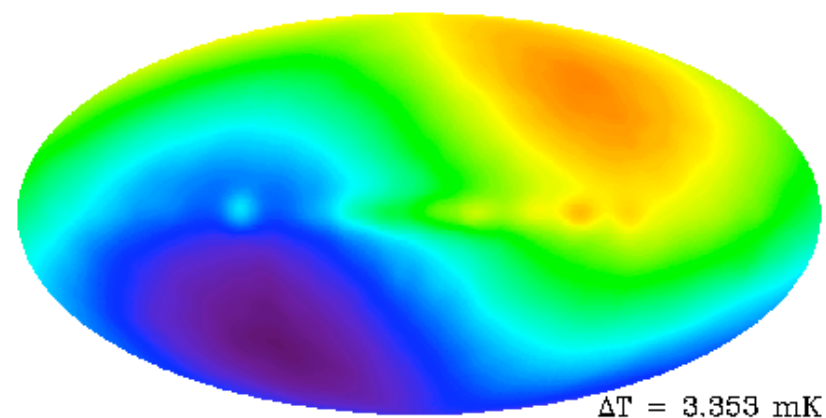
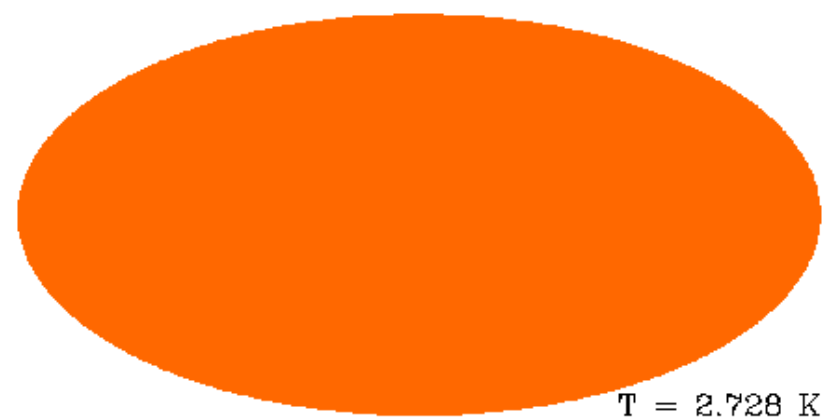




# Inflation



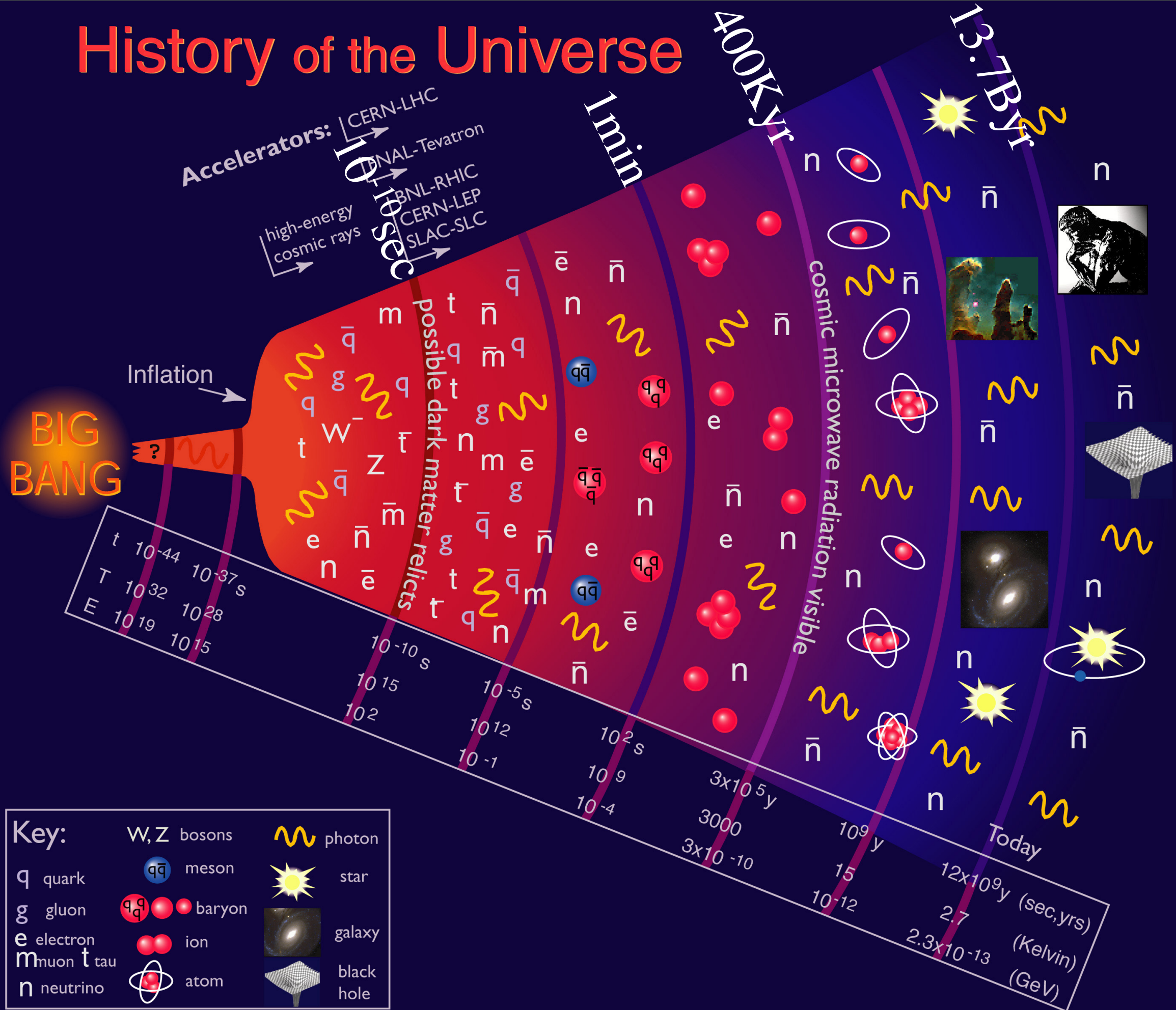
# Why do they all look the same?



- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication



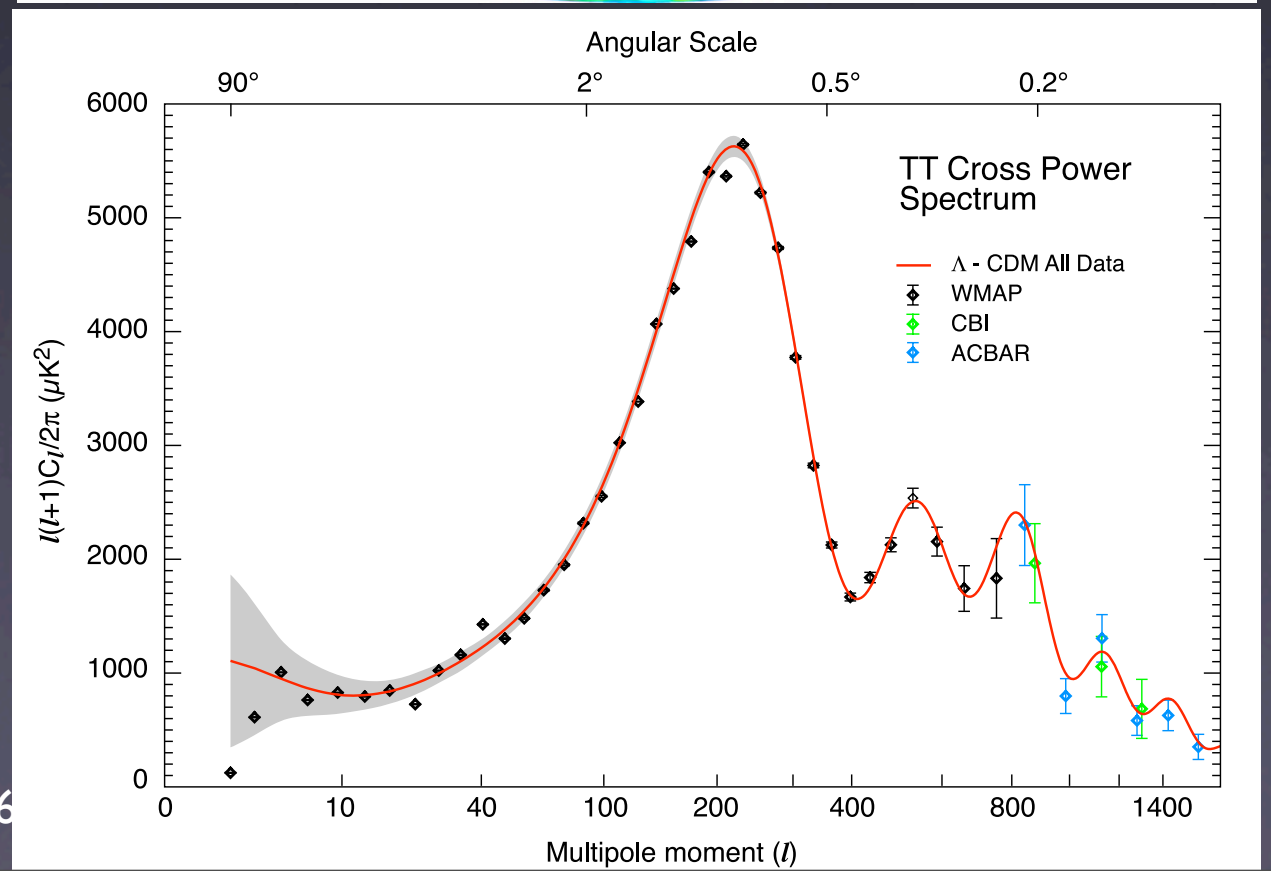
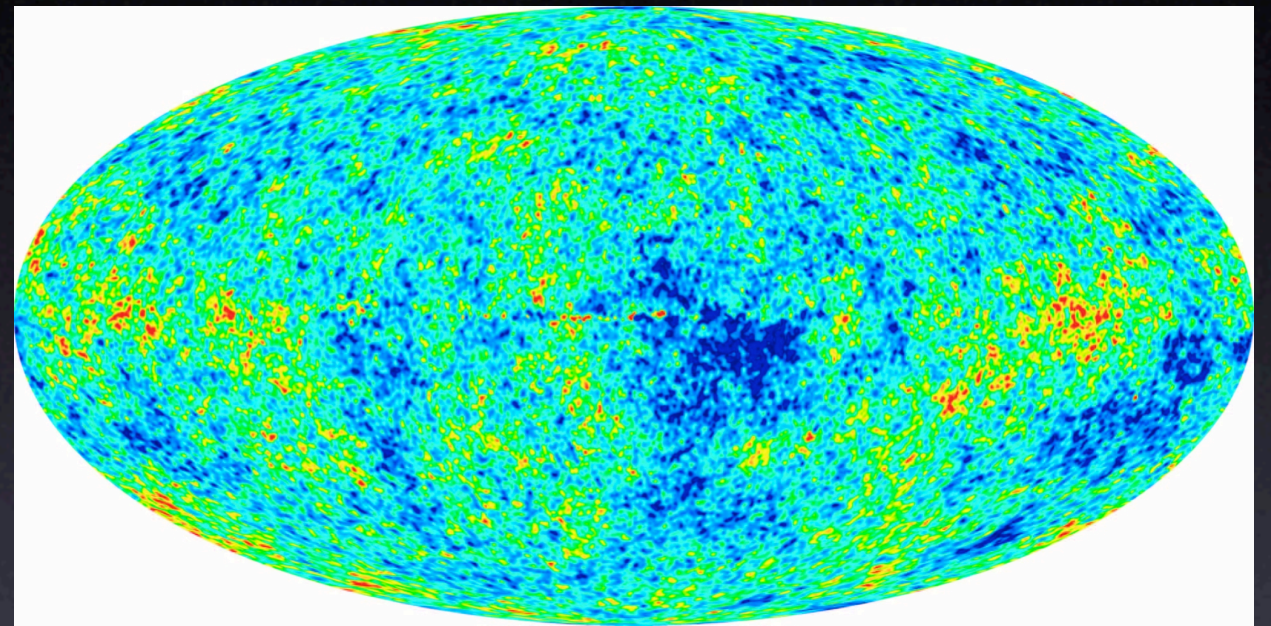
# History of the Universe





# Seeds for structure

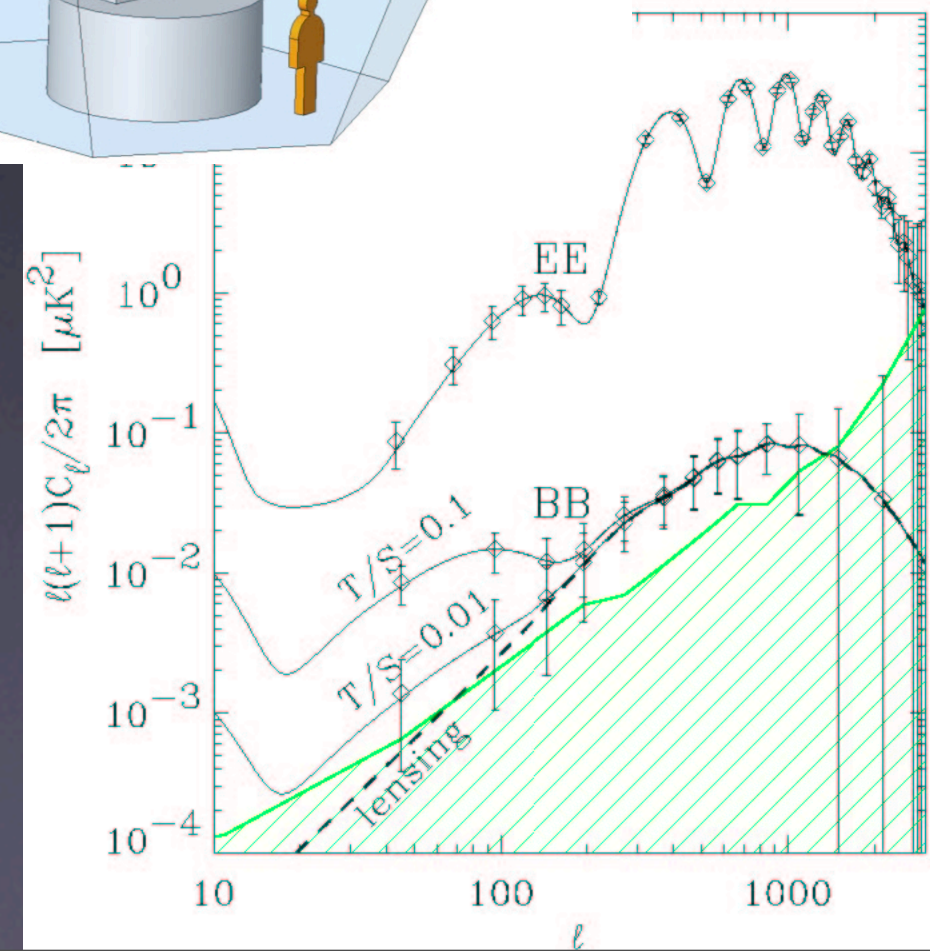
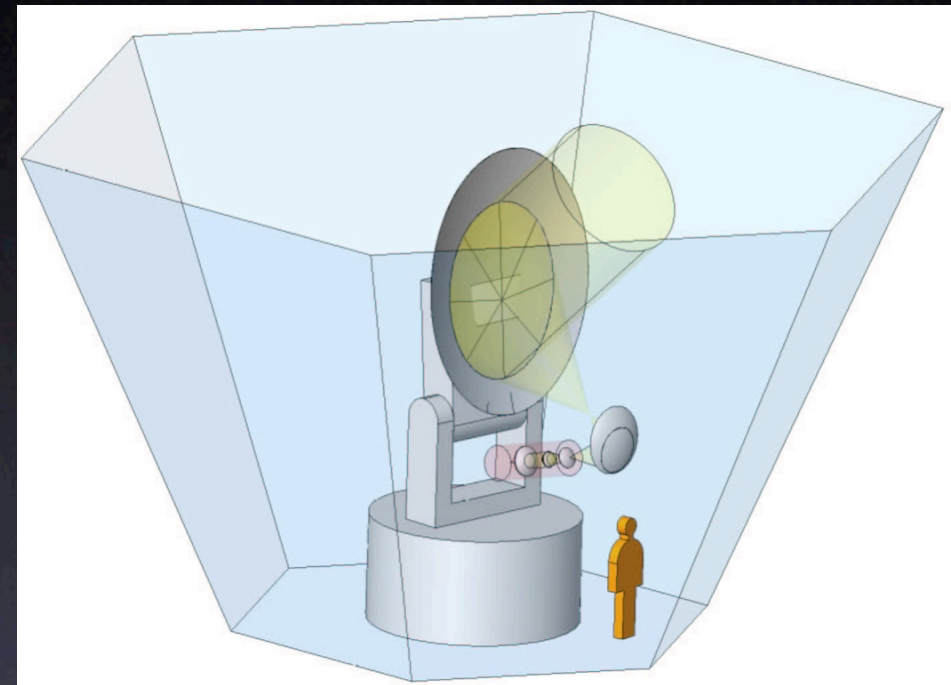
- **Cosmic Inflation** stretched the new-born microscopic space to our entire visible universe
- Observed density fluctuation is due to quantum fluctuation of inflaton
- **E-mode polarization** consistent with this picture





# How do we know it really happened?

- **everything** gets quantum fluctuation, including **gravitons**
- Gravitons from quantum fluctuation gives **B-mode polarization in CMB**
- The size is directly proportional to the **inflationary energy scale**  
⇒ e.g., **POLARBEAR**





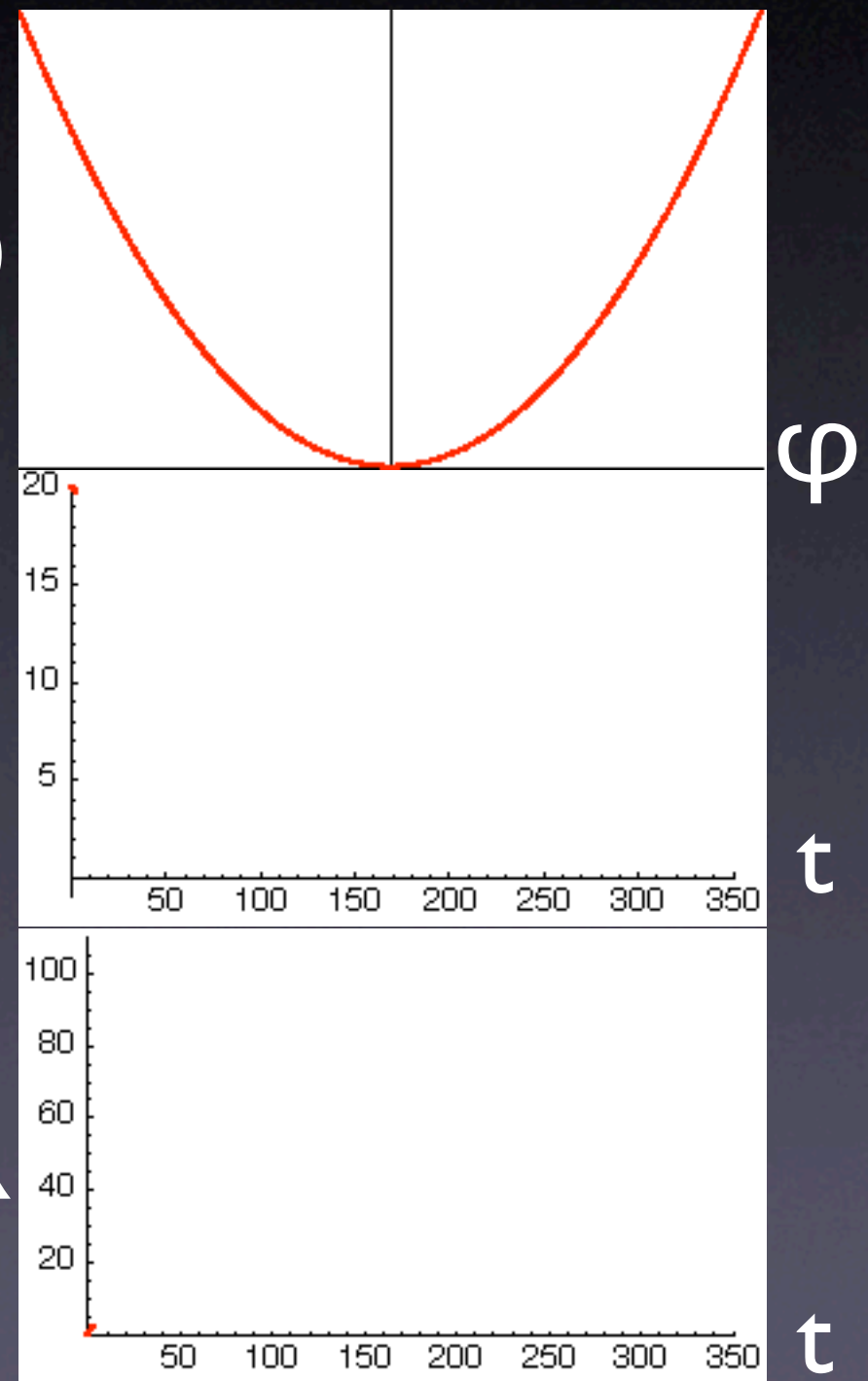
# Putting them together

- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

$V(\varphi)$

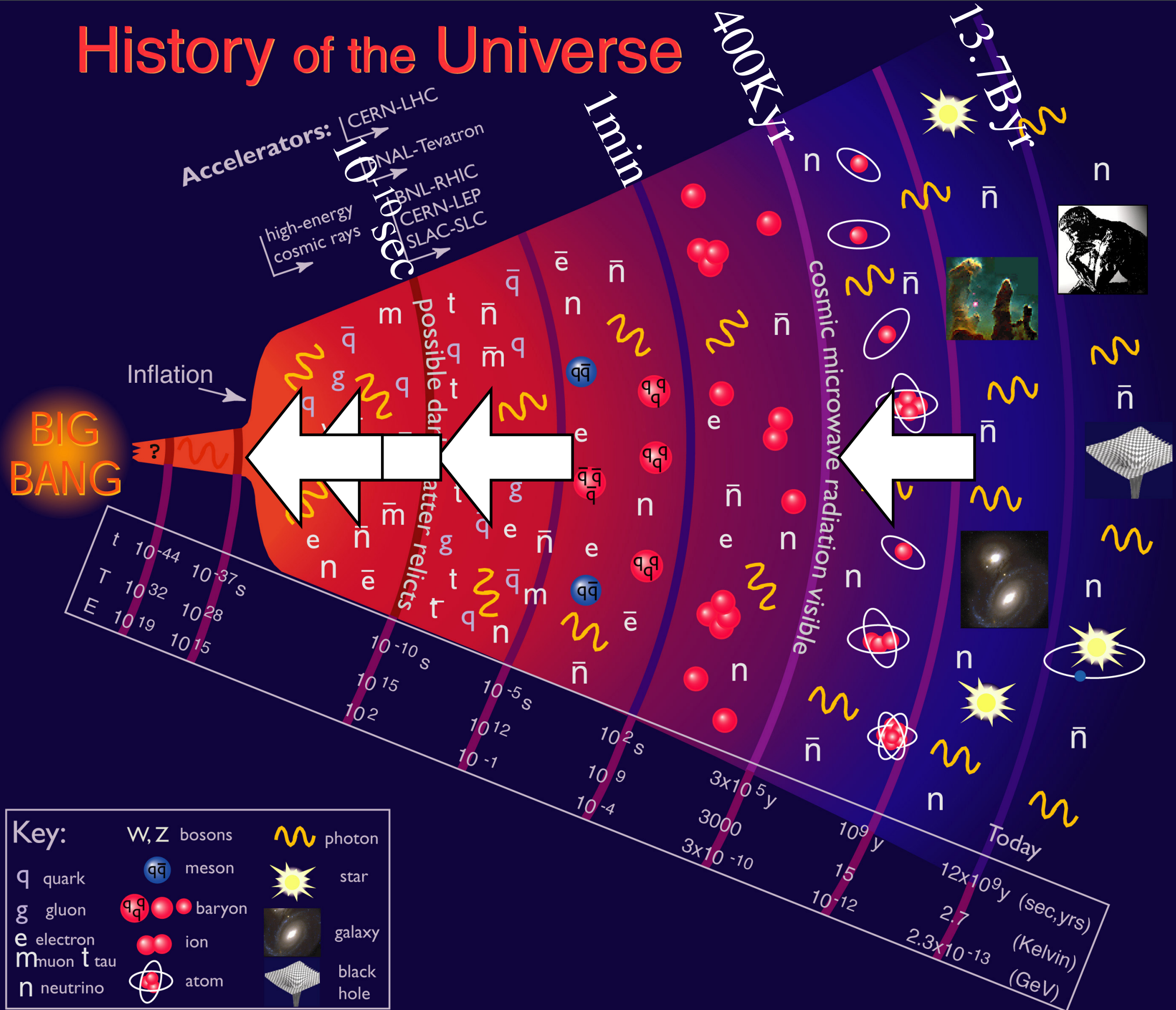
$\varphi$

$\log R$





# History of the Universe





# Conclusions

- Consistent picture of the universe emerged
- Yet, unknown components: **Dark matter**, **Dark Energy**
- where did the **anti-matter** go?
- What is **Dark Field**? Why is it there?
- Universe emerged from quantum physics
- New experiments gearing up to solve these puzzles



As we know,  
There are **known knowns**.  
There are things we know we know.  
We also know  
There are **known unknowns**.  
That is to say  
We know there are some things  
We do not know.  
But there are also **unknown unknowns**,  
The ones we don't know  
We don't know.

—Feb. 12, 2002, Department of Defense  
news briefing

