SCIENTIFIC AMERICAN Travel **BRIGHT HORIZONS 16**

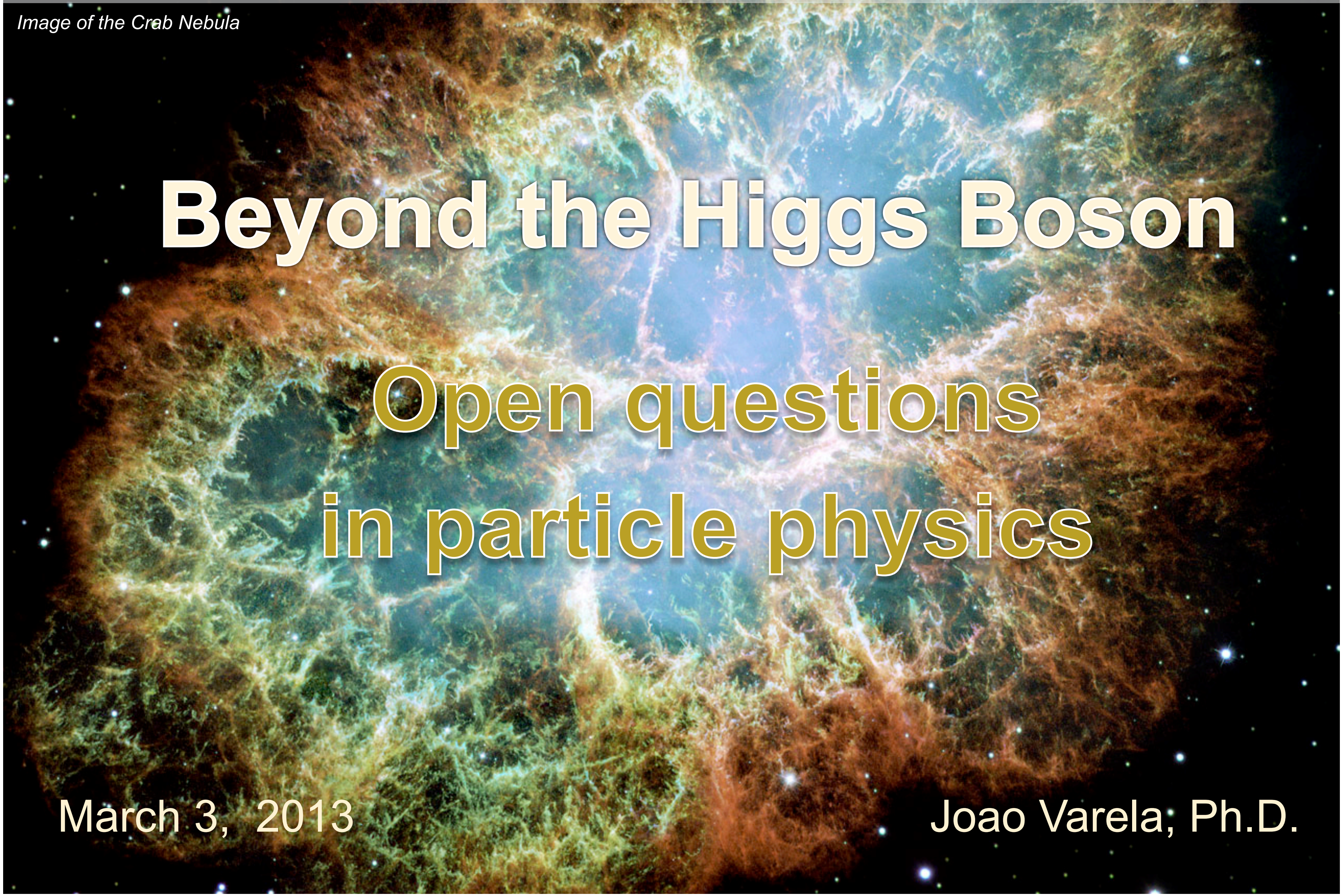


Image of the Crab Nebula

Beyond the Higgs Boson

Open questions in particle physics

March 3, 2013

Joao Varela, Ph.D.

Outline of the lecture

Unsolved mysteries

Theories beyond the Standard Model

The cosmological connection

Dark matter

Dark energy

What else could we find at LHC?

Unsolved mysteries

Beyond the standard model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

The standard model is incomplete

The Standard Model is still an incomplete theory.

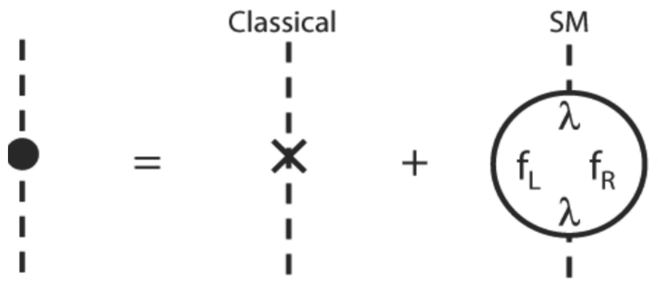
Does this mean that the Standard Model is wrong?

No. But we need to go beyond the Standard Model in the same way that Einstein's Theory of Relativity extended Newton's laws of mechanics.

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

This is known as the hierarchy problem

Three generations

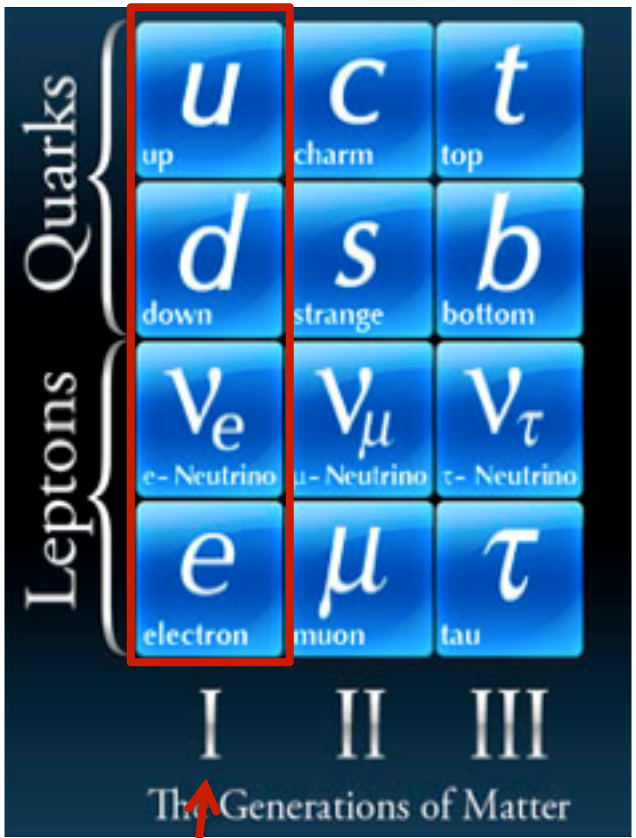
There are three "sets" of quark pairs and lepton pairs, called generations.

The generations increase in mass.

Higher generation particles decay into lower generation particles.

We do not know why there are three generations.

We do not have an explanation for the observed mass pattern



Every-day world

What are neutrinos telling us?

Neutrinos are the most mysterious of the known particles in the universe.

They interact so weakly that trillions of them pass through our bodies each second without leaving a trace.

Neutrinos of one generation mysteriously transform into neutrinos of the two other generations.

Neutrinos have mass, but the heaviest neutrino is at least a million times lighter than the lightest charged particle (electron).

Will neutrinos lead us toward the discovery of new physics?

What happened to the antimatter?

Experiments tell us that for every fundamental particle there exists an antiparticle.

The big bang almost certainly produced particles and antiparticles in equal numbers.

However our observations indicate that we live in a universe of matter, not antimatter.

What happened to the antimatter?

A tiny imbalance between particles and antiparticles must have developed early in the evolution of the universe.

Subtle asymmetries between matter and antimatter observed experimentally in the laboratory are insufficient to account for the observed matter domination.

Dark matter

The majority of the universe may not be made of the same type of matter as the Earth.

We infer from gravitational effects the presence of this dark matter, a type of matter that we cannot see.

There is strong evidence that it might not be made up of protons, neutrons, and electrons.

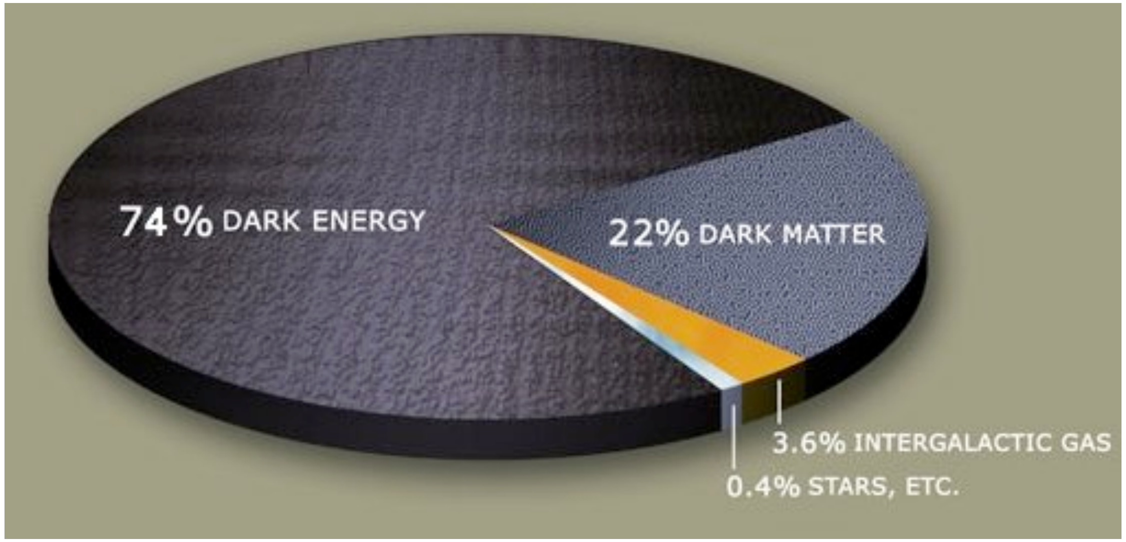
What is dark matter, then? We don't know.

Dark energy

What is the Universe made of? Stars and other visible matter account for 0.4%. Intergalactic gas is 3.6%.

What is the dark stuff which accounts for 96% of the Universe? Nobody knows.

It is one of the greatest mysteries of science



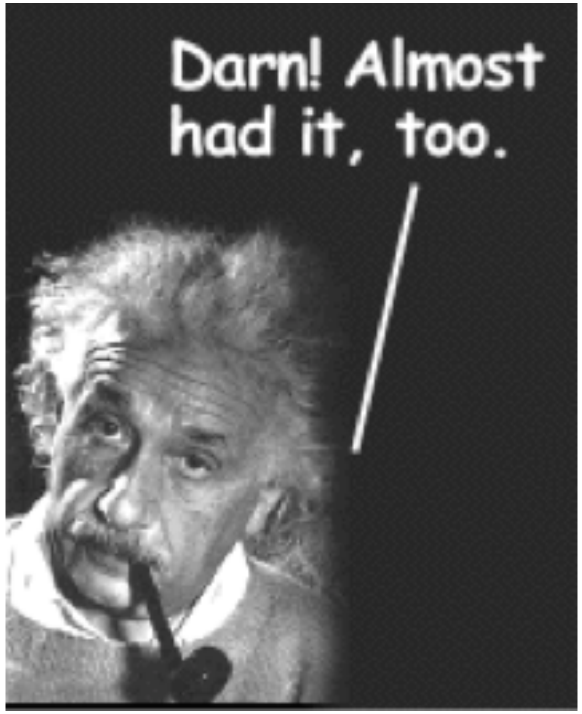
Theories beyond the Standard Model

Grand Unified Theory

Today, one of the goals of particle physics is to unify the various fundamental forces in a Grand Unified Theory which could offer a more elegant understanding of the organization of the universe.

James Maxwell took a big step toward this goal when he unified electricity and magnetism

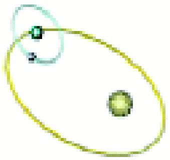
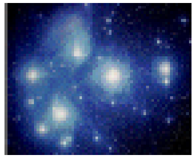
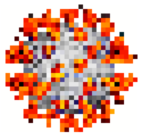
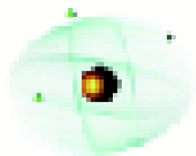
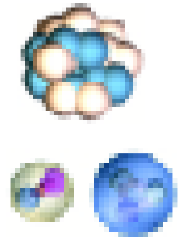
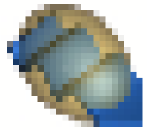
We now understand that at high energies the electromagnetic and weak forces are aspects of the same force.



In his later years Einstein attempted, but failed, to write a theory which united gravity and electricity.

Fundamental forces

	Gravity	Electromagnetic force	Strong force	Weak force
Strength:	10^{-40}	10^{-2}	1	10^{-6}
	Planets, stars, galaxies	Atoms, molecules, electromagnetic waves	Atomic nuclei	Radioactive decays
Distances	10^{6} - 10^{26}	10^{-6} - 10^{-10}	10^{-14} - 10^{-15}	$<10^{-18}$ m

Telescope

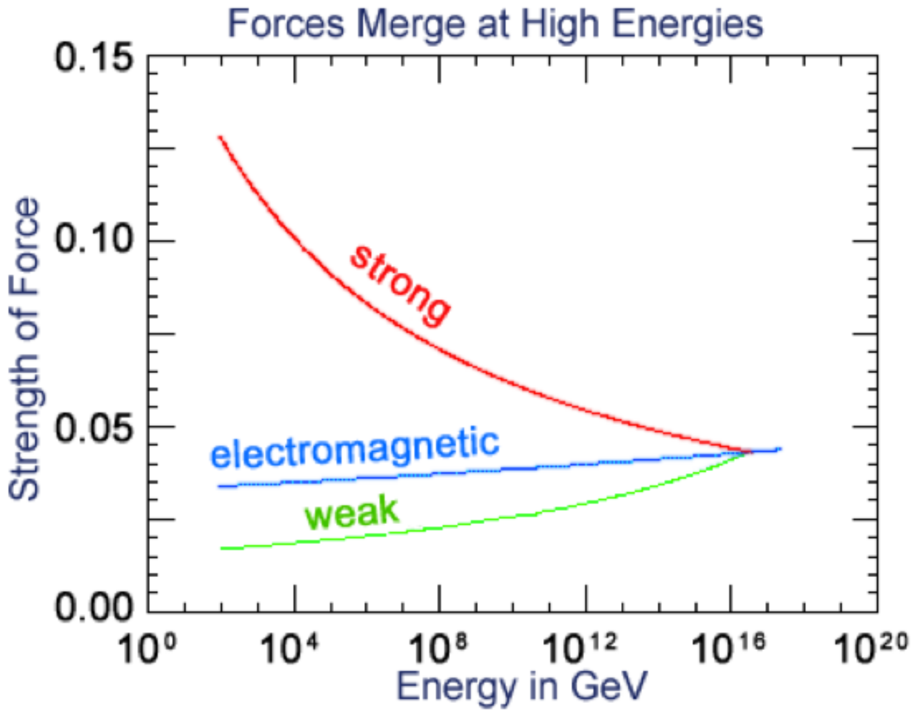
Microscope

Electron microscope

Accelerator

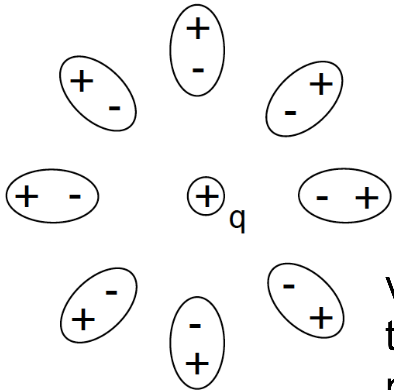
Forces and the Grand Unified Theory

Physicists hope that a Grand Unified Theory will unify the strong, weak, and electromagnetic interactions.



However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect?

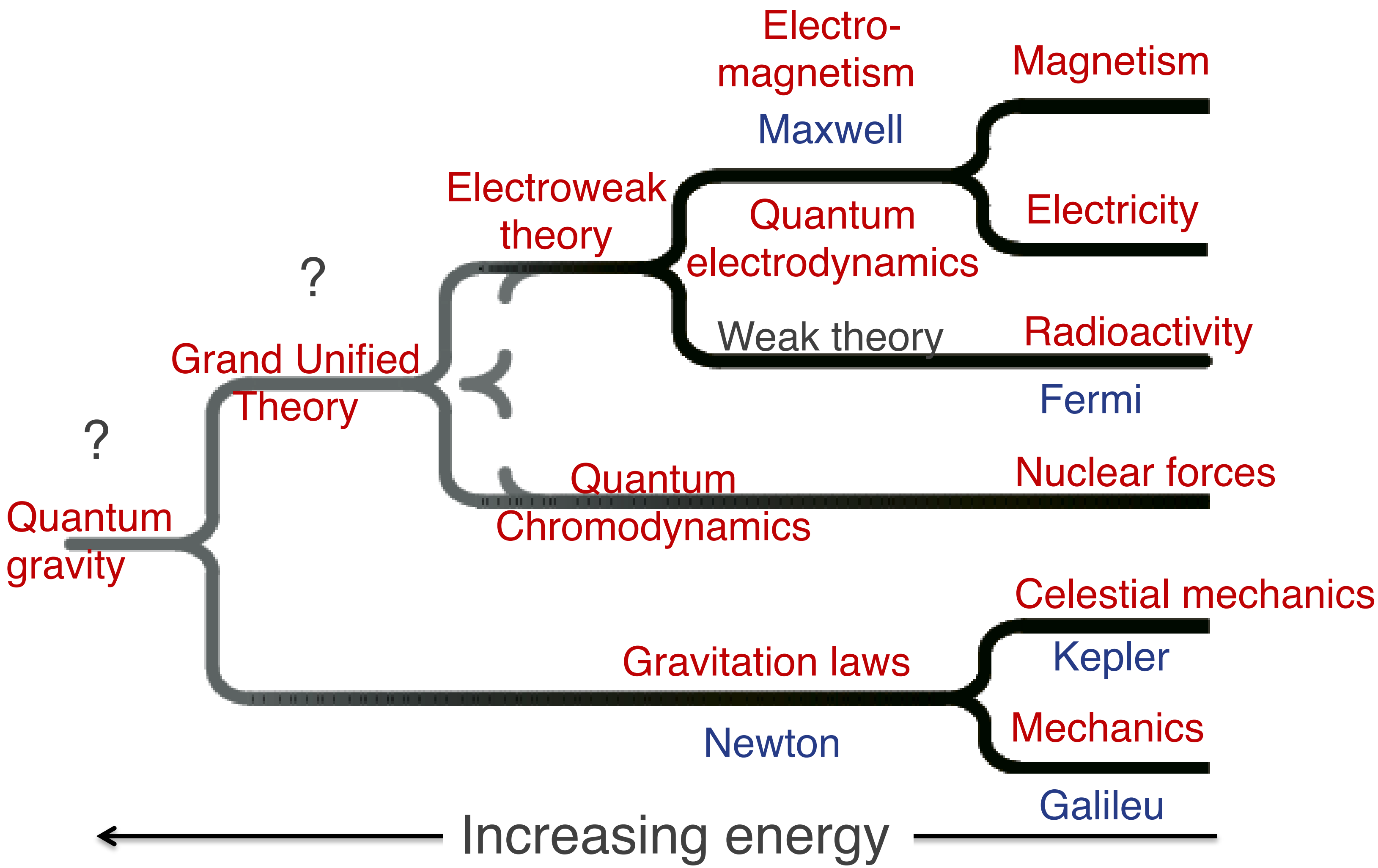
Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.



Vacuum polarization

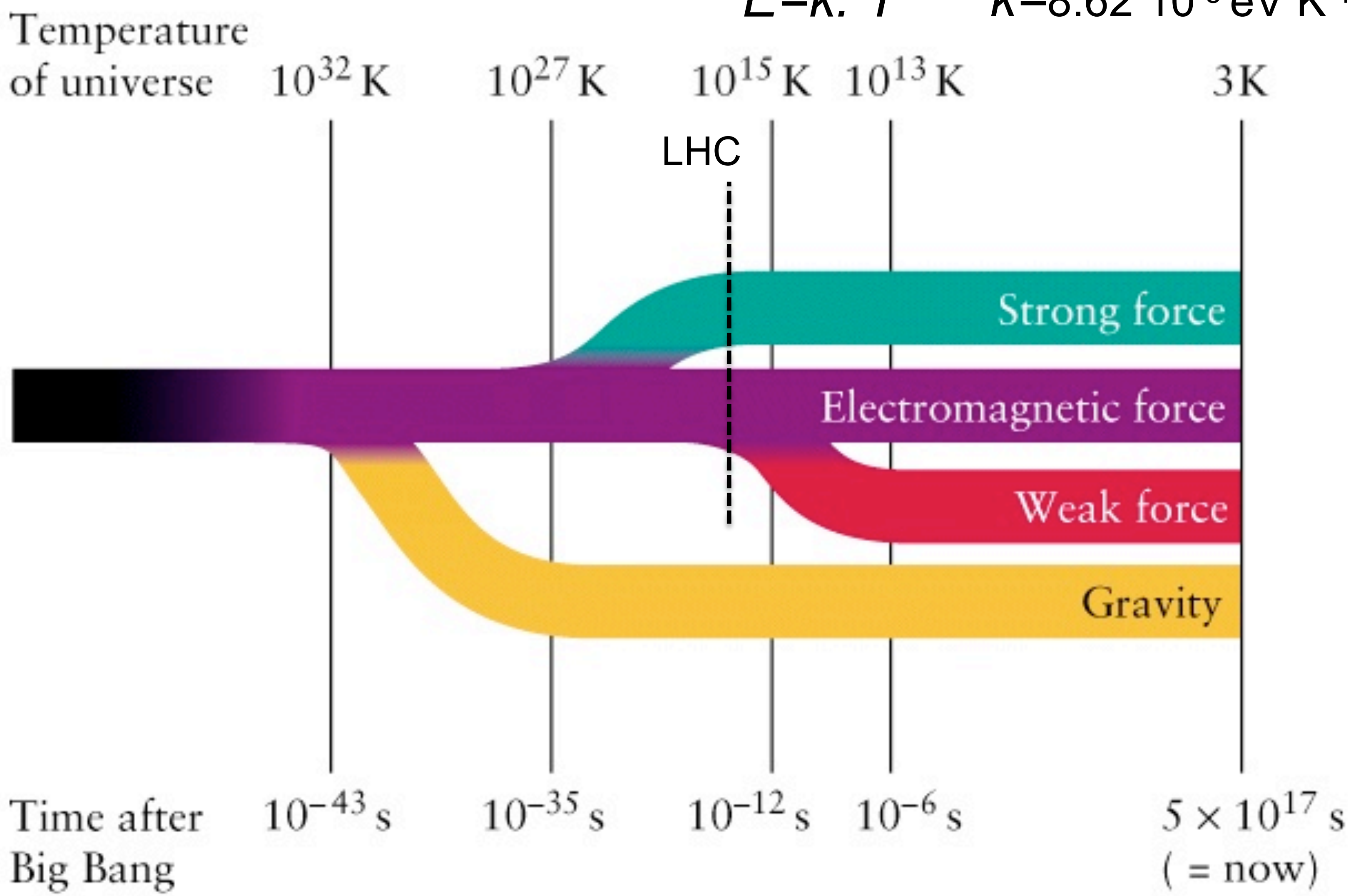
virtual pairs around the charge q are polarized

Unification of the Forces



Forces and expansion of the Universe

$E = k.\ T$ $\quad k = 8.62\ 10^{-5}$ eV K^{-1}



Unification energy

At the GUT unification energy everything would be highly symmetric.
This symmetry is broken at lower energies to give the different masses and force strengths we see.

Example: A liquid (high energy) is symmetric and looks the same from all directions – as it freezes (low energy) it loses that symmetry and crystals form with preferred directions.

Current theories are associated with certain ’symmetry groups' which obey the mathematics of group theory.

The simplest GUT is labeled SU(5) and has 24 gauge bosons.

Proton decay

In GUTs there are new vector bosons mediating a new interaction.

These bosons are called **leptoquarks** and can change quarks into leptons.

Leptoquarks would lead to proton decay to mesons and leptons.

One can calculate the proton lifetime in the GUT Model

- The mass of the X and Y particles is assumed to be around the GUT unification energy → $M_{X,Y} \sim 10^{15}$ GeV/c^2

This gives a proton lifetime between 2 x 10^{28} and 6 x 10^{30} years

Current measurements give > 10^{31} to 10^{32} years depending on the decay mode

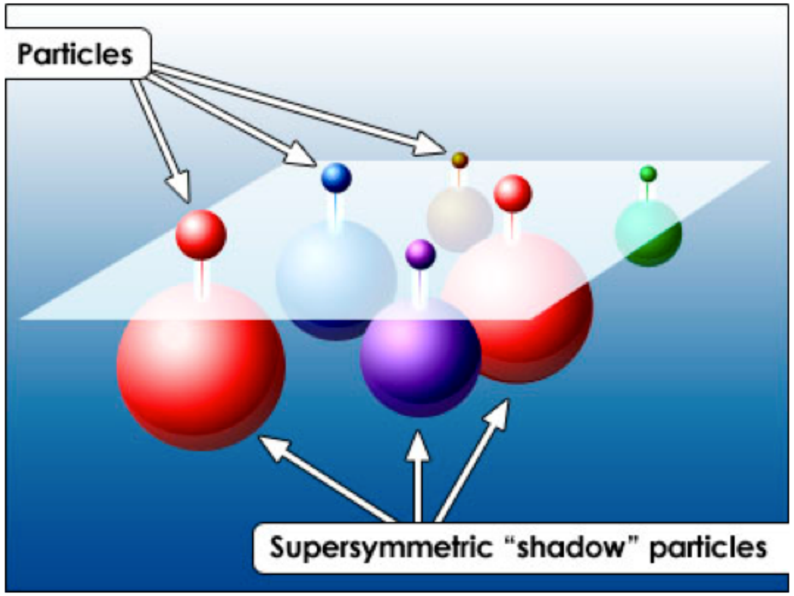
Supersymmetry

Some physicists attempting to unify gravity with the other fundamental forces have proposed a new fundamental symmetry:

- Every fundamental matter particle should have a massive "shadow" force carrier particle,
- and every force carrier should have a massive "shadow" matter particle.

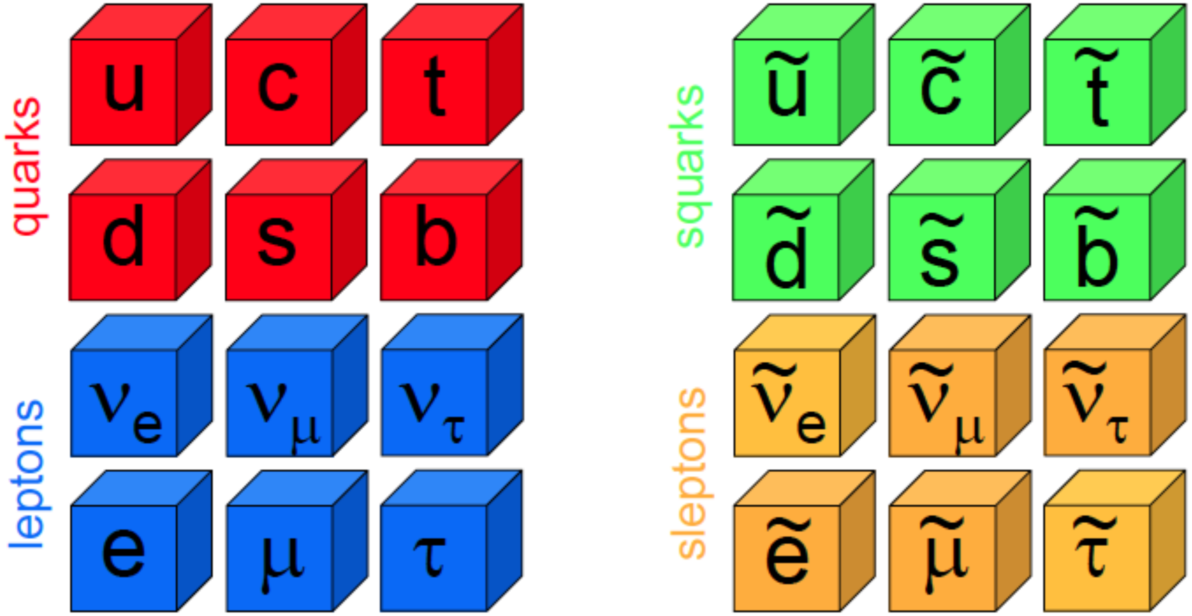
This relationship between matter particles and force carriers is called supersymmetry (SUSY)

No supersymmetric particle has yet been found, but experiments are underway at CERN to detect supersymmetric partner particles.



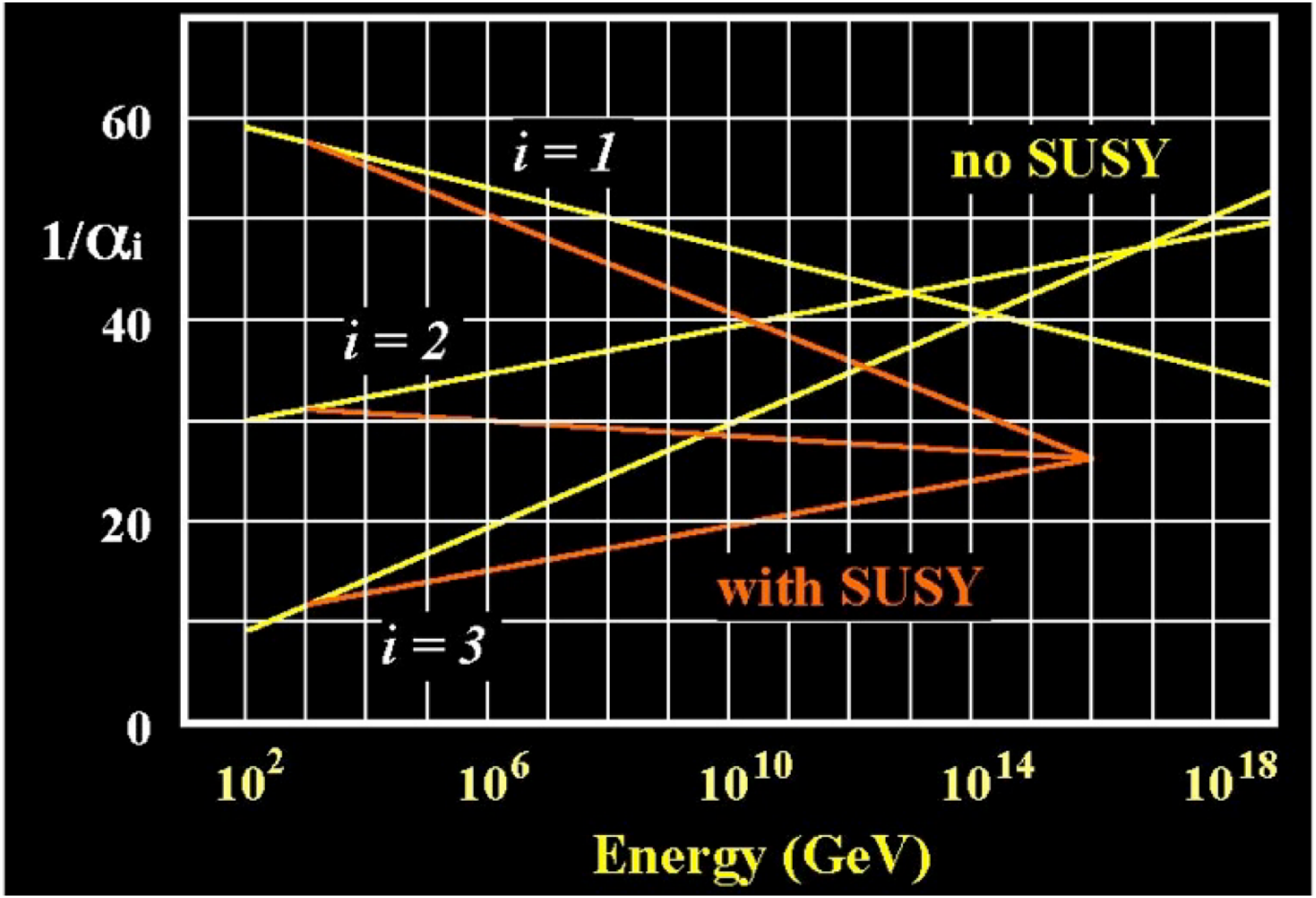
Supersymmetry

Double the whole table with a new type of matter?

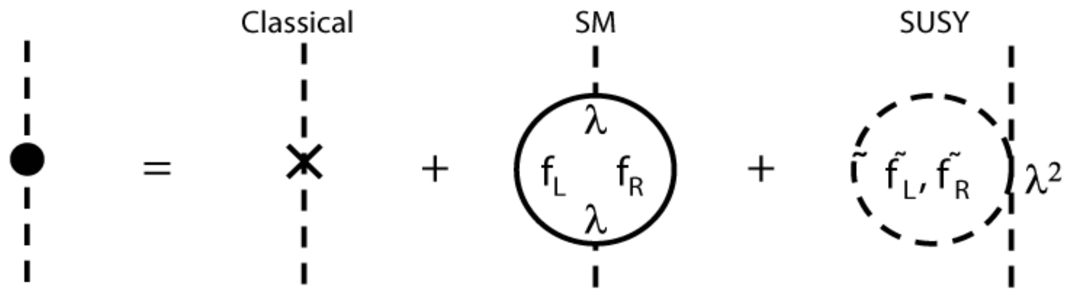


Heavy versions of every quark and lepton
Supersymmetry is broken

The temptation unification



SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

Cancellation

$$m_h^2 = (m_h^2)_0 \boxed{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \dots$$

$$\approx (m_h^2)_0 + \boxed{\frac{1}{16\pi^2}(m_{\tilde f}^2 - m_f^2)\ln(\Lambda/m_{\tilde f})} ,$$

Superpartners fix this:

- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

Extra dimensions

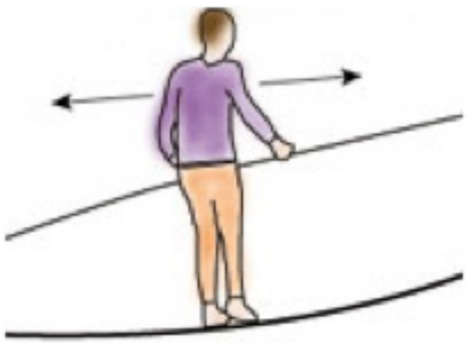
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

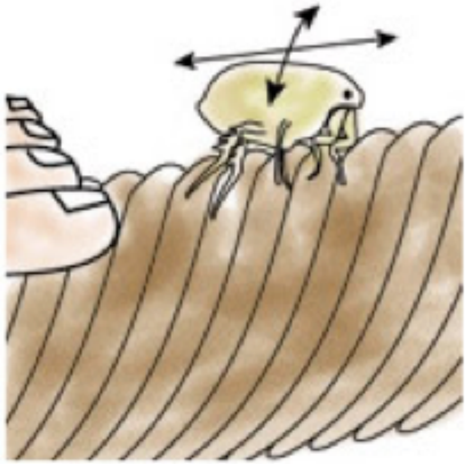
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

The flea can move forward and backward as well as side to side: **two dimensions**

But one of these dimensions is a small closed loop.





Motivations for extra dimensions

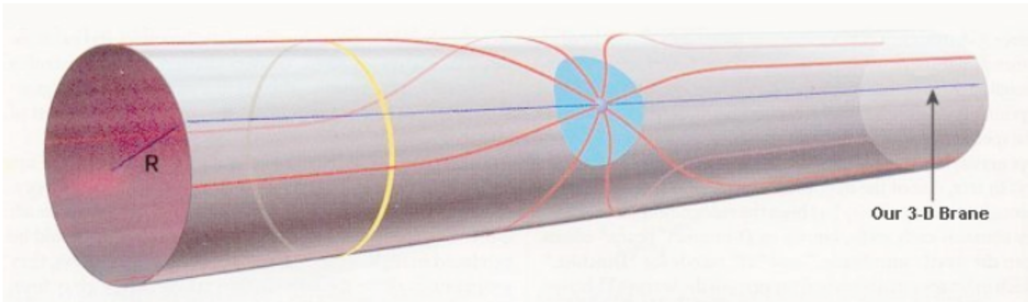
Original motivation: explain why the gravity is so much weaker than all other interactions.

Gravitation constant in Newton's Law relates to Planck mass scale.

$$|F| = G_N \frac{m_1 m_2}{R^2} \qquad M_{planck} = 1/\sqrt{G_N} = 1.2x10^{19}\,GeV$$

In comparison the Electroweak scale is ~ 100 GeV

If there were more than 3 spatial dimension (and only gravity operated in the extra rolled up ones), the Plank scale could be of the order of Electroweak scale.



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

TeV sized extra dimensions

Some models consider TeV^{-1} size Extra Dimensions (1 TeV^{-1}=2x10^{-19}m)

If particles propagate in these (small) extra dimensions, we get Kaluza-Klein tower of states of increasing masses:

Particle excitations in the extra dimensions

Signature: high mass copies of SM gauge bosons, like an heavy Z boson

String theory

Modern physics has good theories for quantum mechanics, relativity, and gravity.

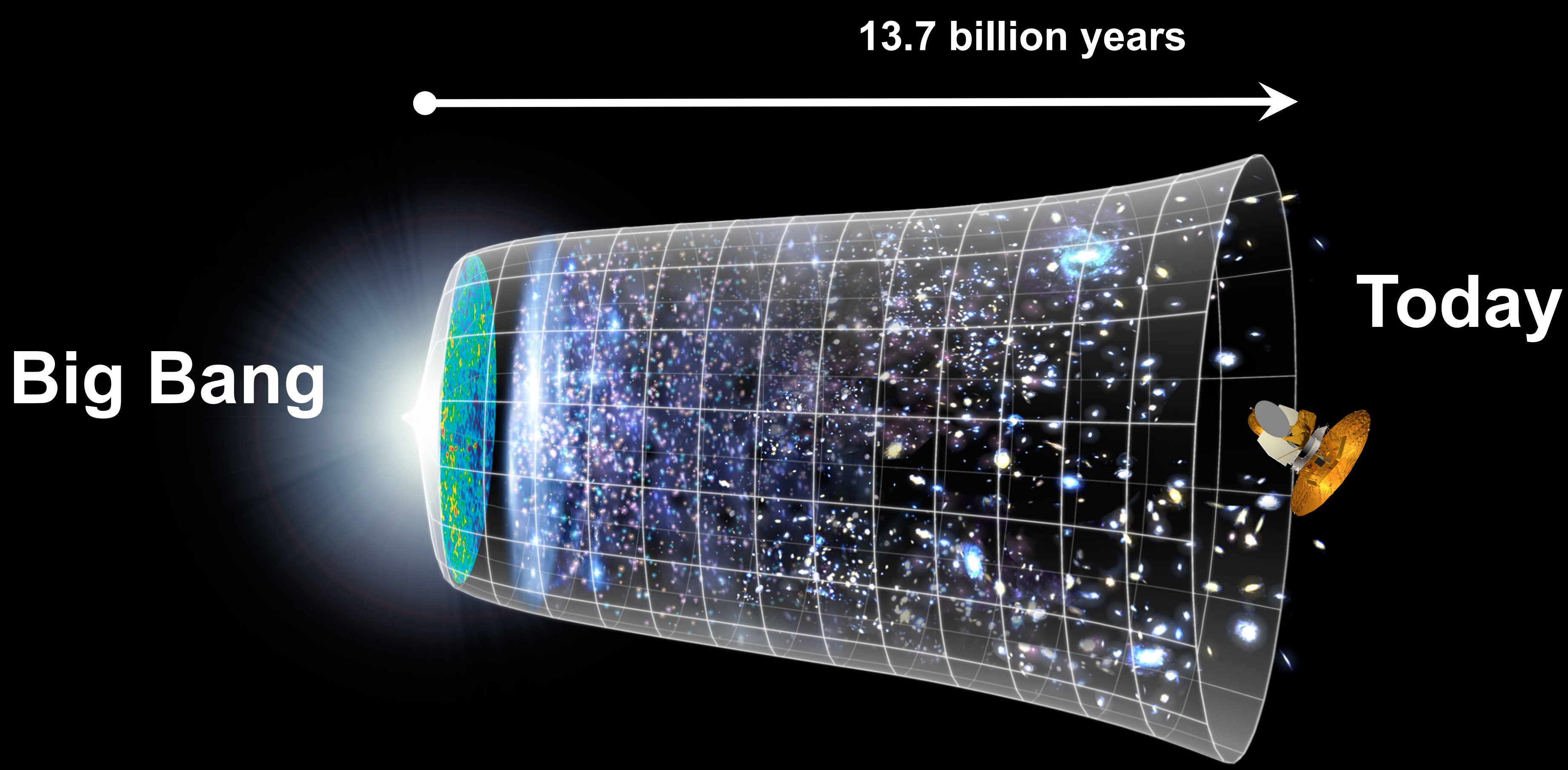
But these theories do not quite work with each other.

String Theory, one of the recent proposals of modern physics, suggests that in a world with three ordinary dimensions and some additional very "small" dimensions, particles are strings and membranes.

There are not precise predictions from String Theories yet.

The cosmological connection

Timeline of the Universe

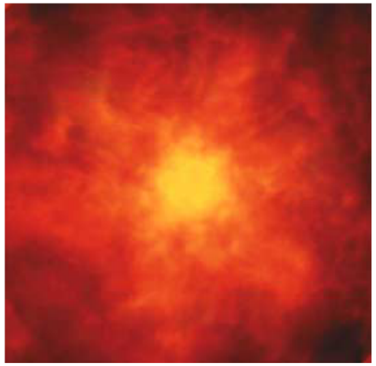


LHC recreates the conditions one billionth of a second after Big Bang

NASA/WMAP Science Team

The Big Bang theory

10^{-43} s



Big-Bang

The Universe goes through a superfast inflation

Gravity decouples from other forces.

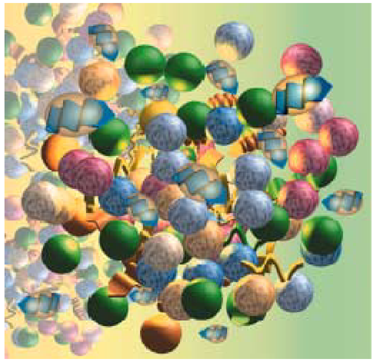
10^{-32} s

End of inflation

Quarks and leptons
Matter-antimatter symmetry

Decoupling of strong and electroweak forces

10^{-10} s

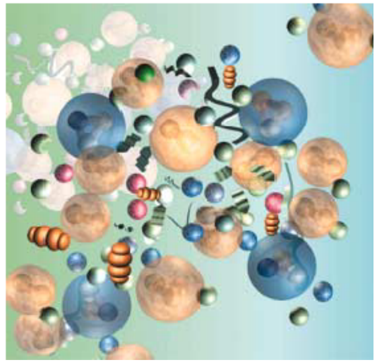


Electroweak era

Excess of matter over antimatter

Decoupling of electromagnetic and weak forces

10^{-4} s

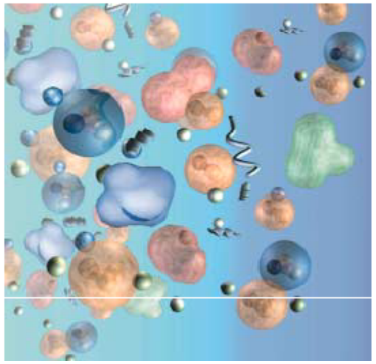


Protons & neutrons

Quarks combine to make protons and neutrons

The Big Bang theory

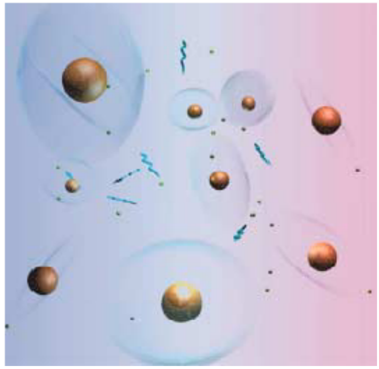
100 s



Nuclei

Protons and neutrons combine to make Helium nuclei

380'000 years



Atoms

Electrons and nuclei form atoms

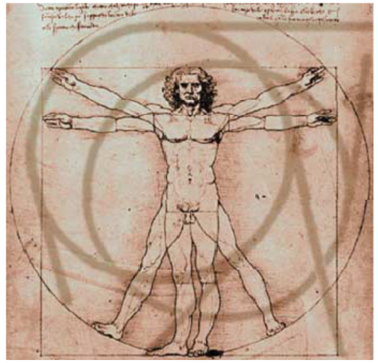
The Universe become transparent to light

1000 million years

Galaxies

Hydrogen and helium gas form galaxies

13700 million years



Humanos

Molecules, DNA, Life, Humans

Measuring the cosmos

We can measure cosmic distances using **Standard Candles**:

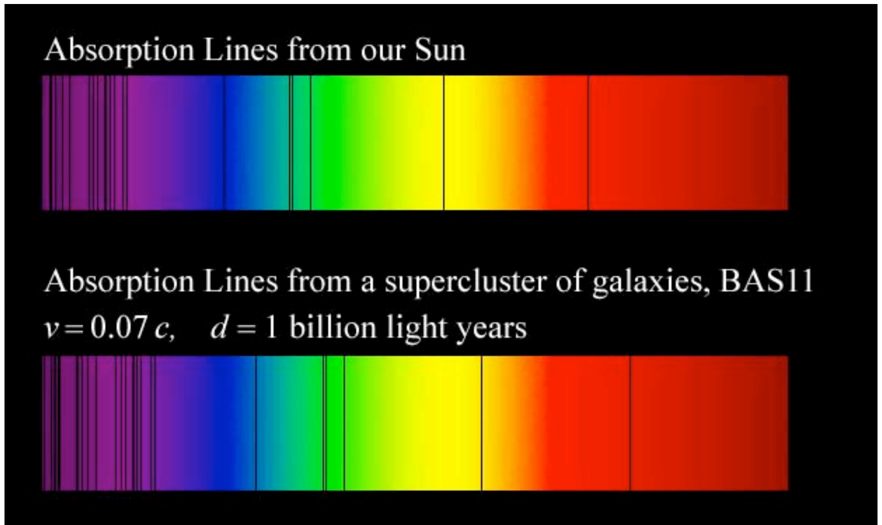
- More distant sources are dimmer.
- We need "standard" sources bright enough to be seen far away.

We can measure velocity using the **redshift** of emitted light:

- wavelength of light emitted by a moving object is changed by the Doppler effect
- the larger the shift, the larger the velocity

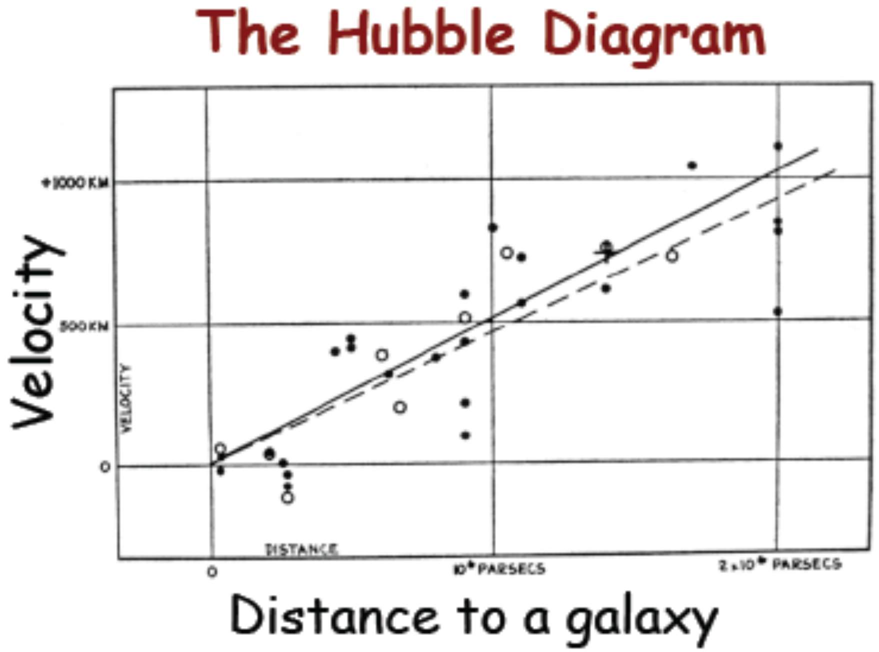
Standard Candles

More distant sources are dimmer

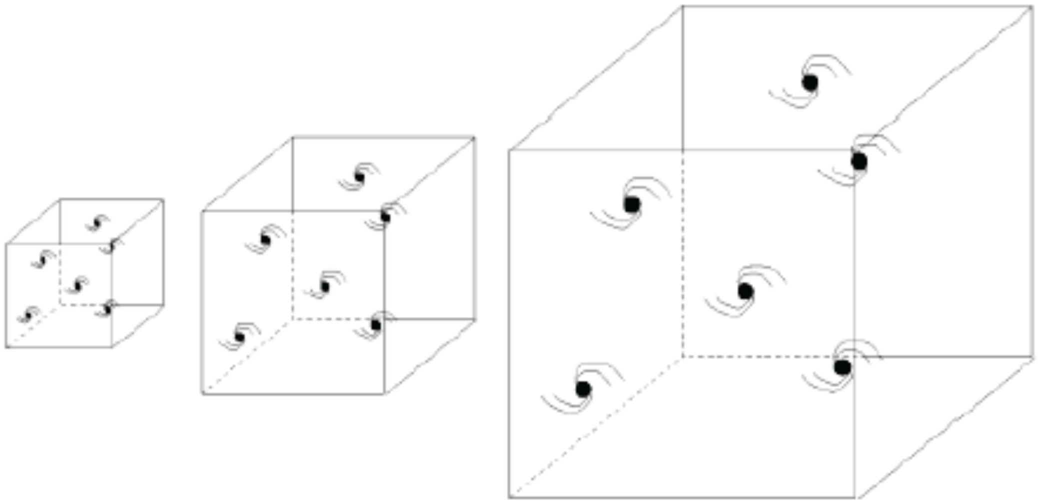


Discovery of the Expanding Universe

Vesto Melvin Slipher (1917)
Edwin Hubble (1929)



The space itself expands,
and carries galaxies with it
The further apart they are,
the faster they move apart



Discovery of Cosmic Microwave Background

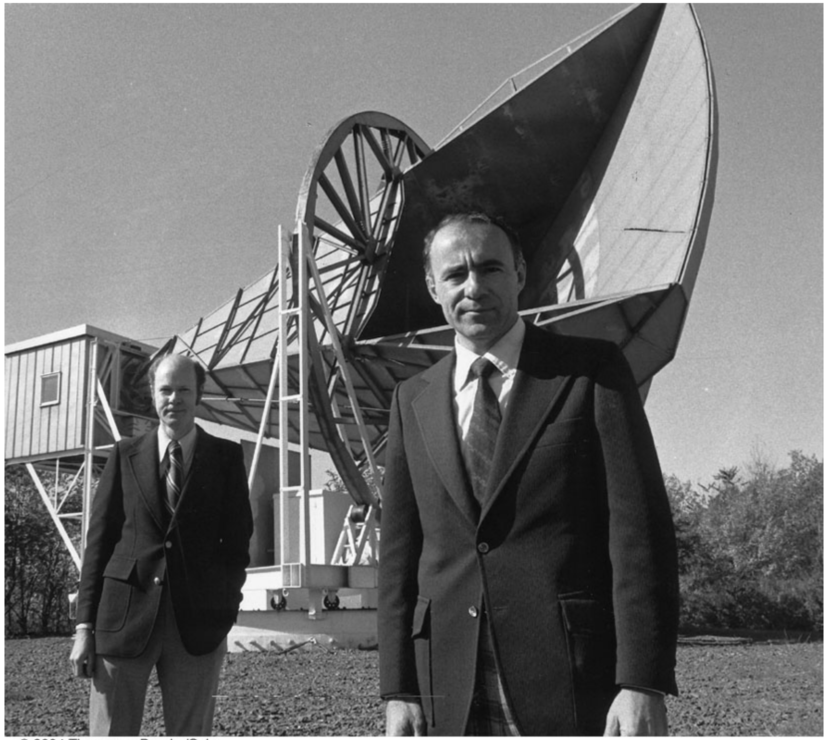
Cosmic Microwave Background (CMB) radiation was discovered by American radio astronomers Arno Penzias and Robert Wilson in 1964

Cosmic background radiation was left over from an early stage in the development of the universe (380’000 years after Big Bang).

The photons that existed at the time of atom formation have been propagating ever since.

The CMB radiation has a thermal black body spectrum at a temperature of 2.7 Kelvin

Peak spectral density occurs at a frequency of 160 GHz, corresponding to a 1.87 mm wavelength

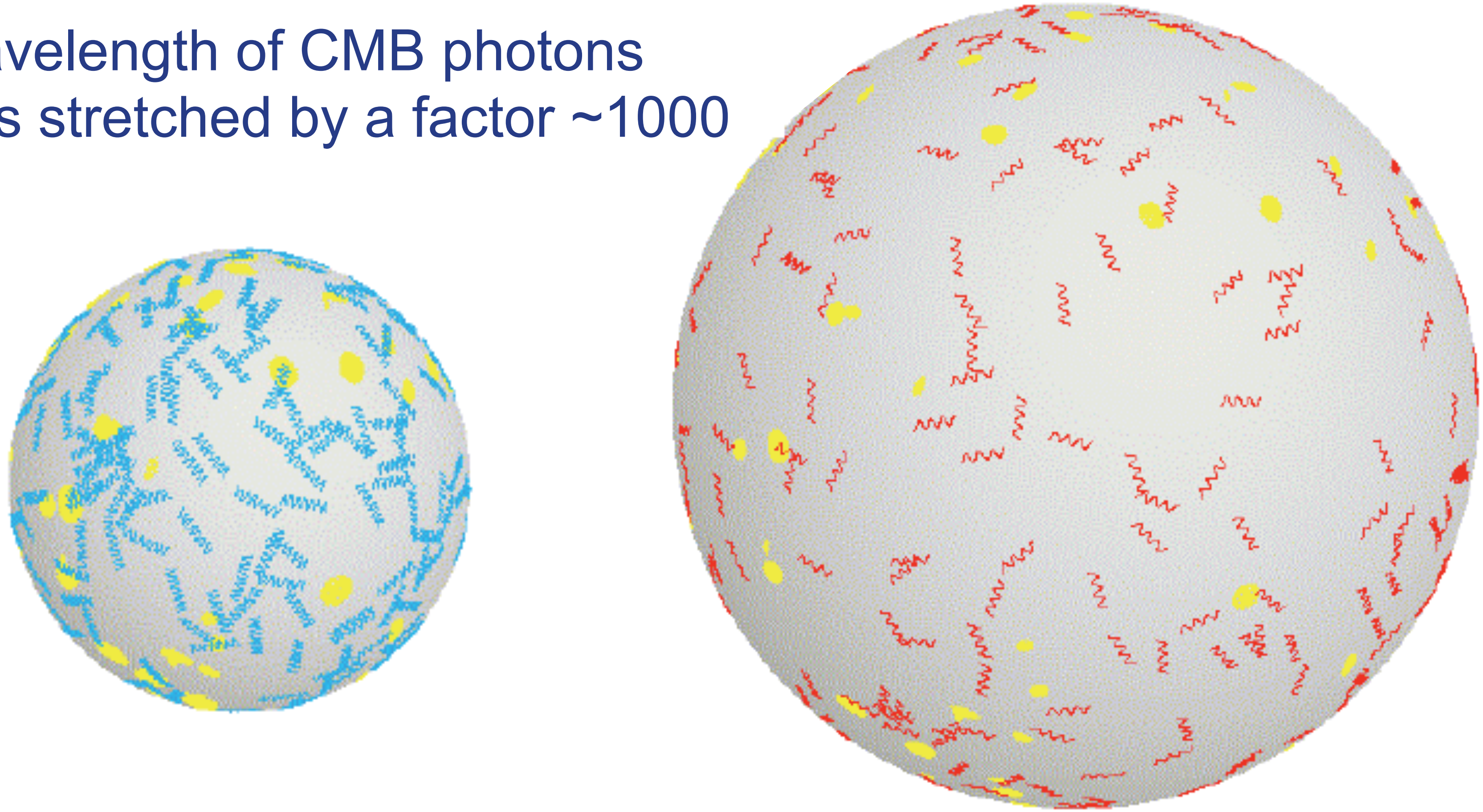


Arno Penzias and Robert Wilson
1978 Nobel Prize

Redshift in expanding space

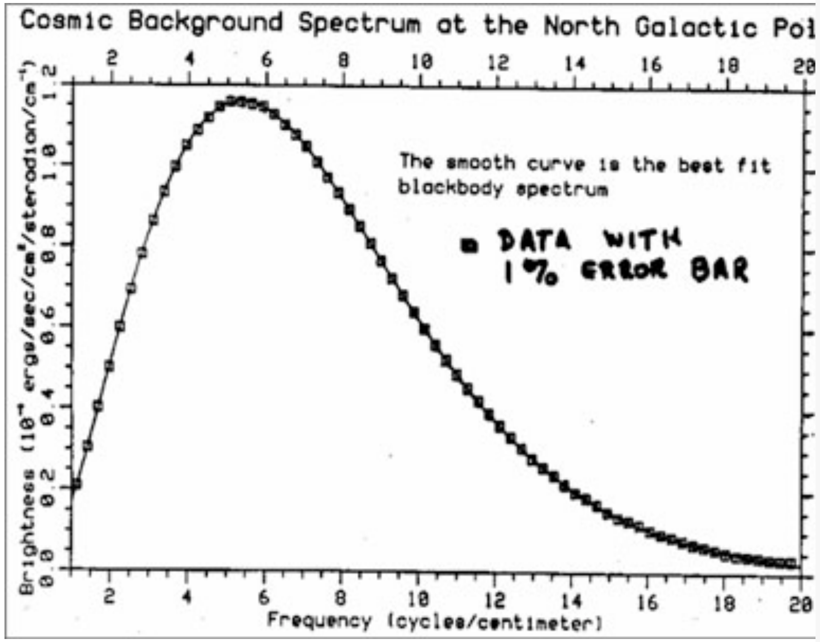
The space expansion stretches the photons, so they become redder: this is what we call **cosmological redshift**

Wavelength of CMB photons was stretched by a factor ~1000



1992: COBE

Blackbody spectrum of cosmic microwave radiation

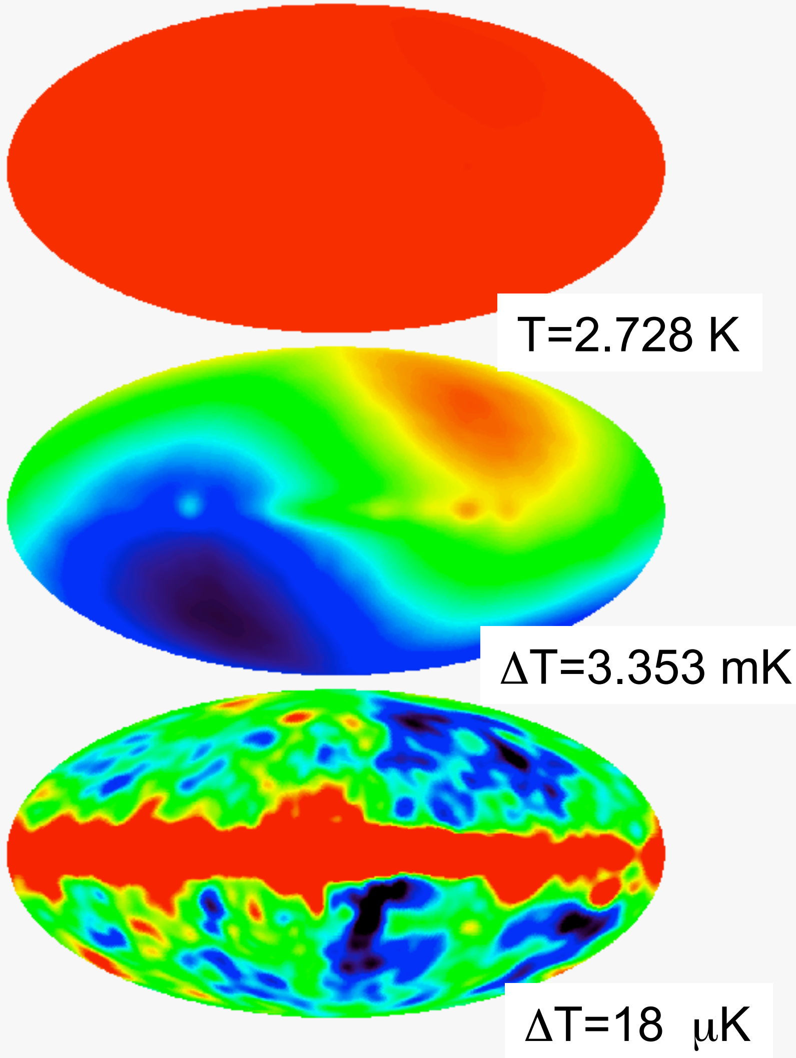


M. Plank (1900)

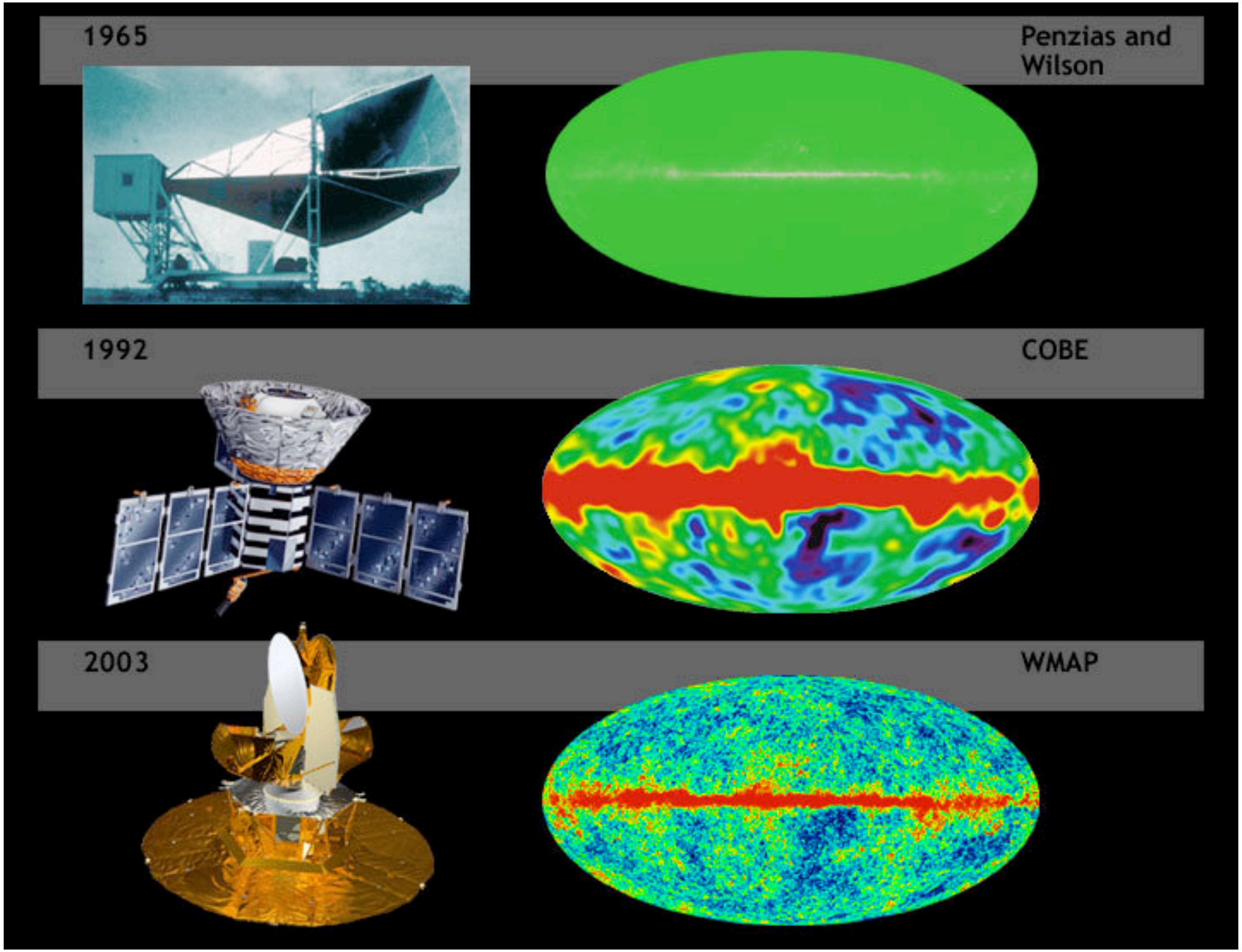
Electromagnetic radiation from a body in thermal equilibrium

$u(\nu) = 8\pi h\nu^3/c^3.(\exp(h\nu/kT)-1)^{-1}$

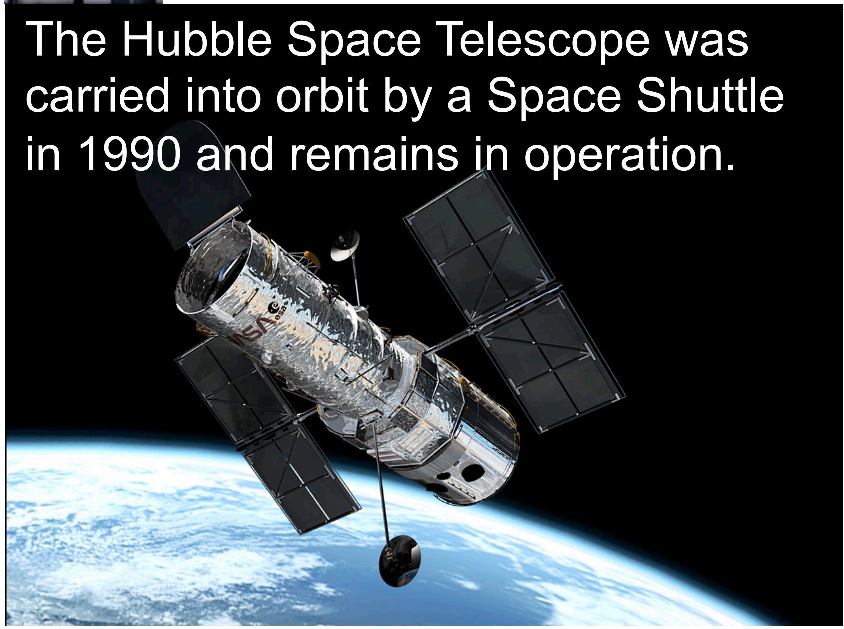
Sky maps of CMB radiation



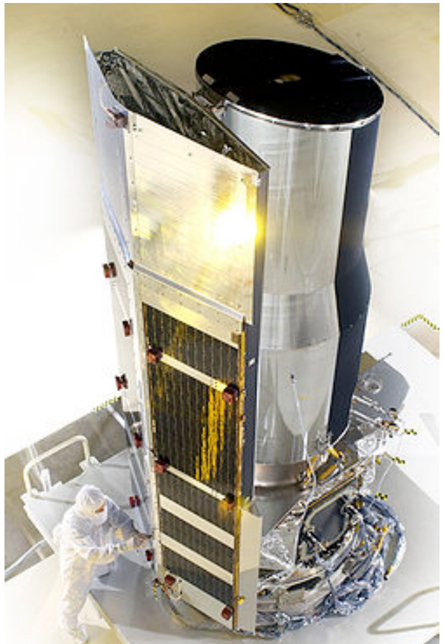
Measurements of CMB radiation



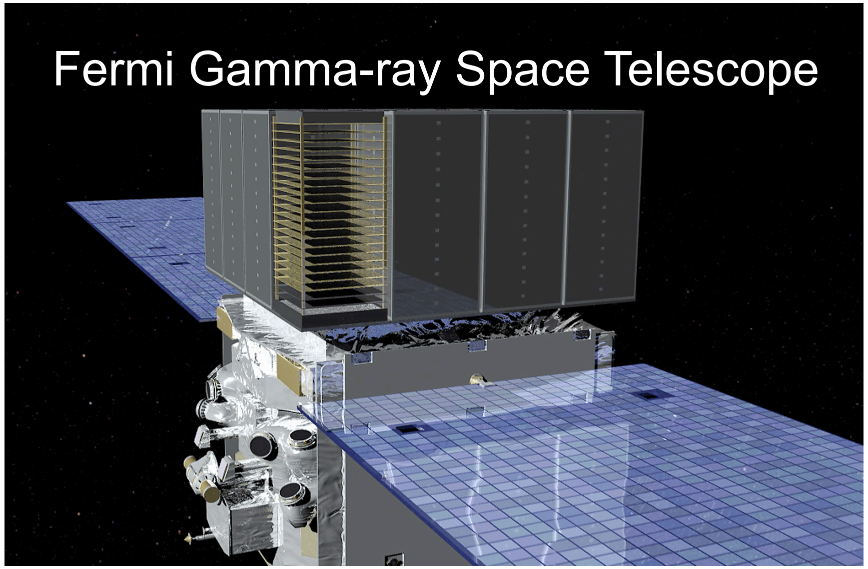
Great observatories in Space



The Hubble Space Telescope was carried into orbit by a Space Shuttle in 1990 and remains in operation.



The Spitzer Space Telescope (SST) is an infrared space observatory launched in 2003.

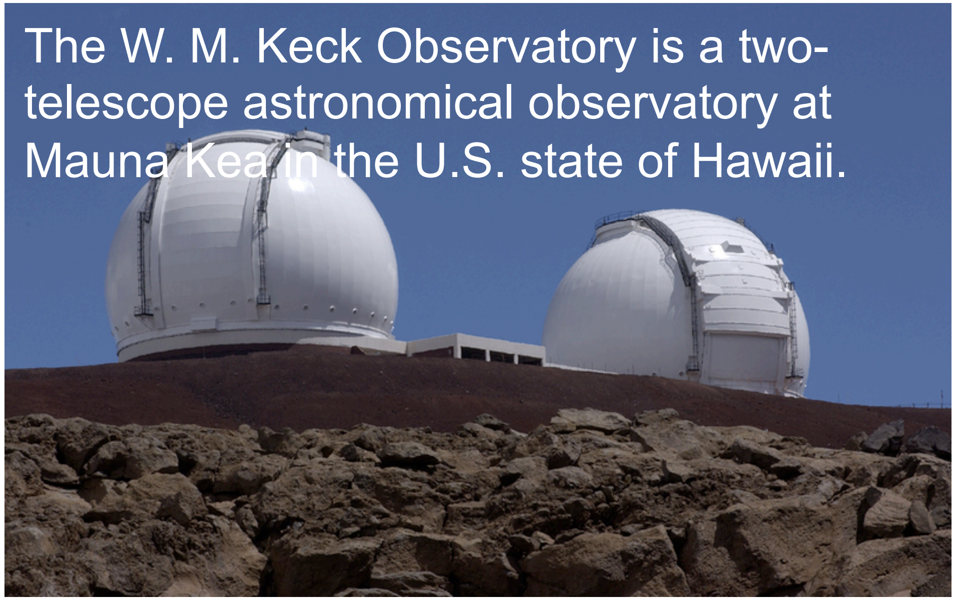


Fermi Gamma-ray Space Telescope

The Chandra X-ray Observatory is a space telescope launched by NASA on July 23, 1999.

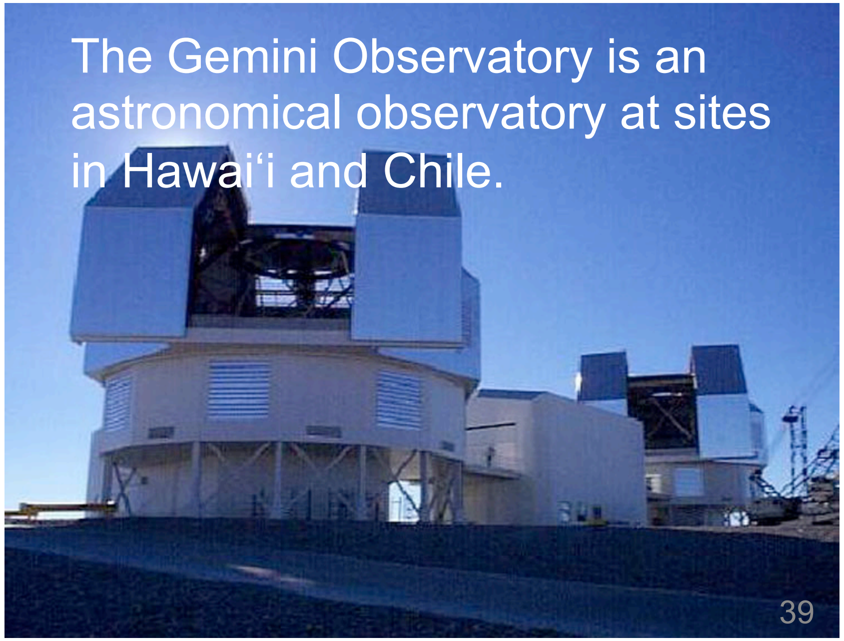
Large telescopes on Earth

The Very Large Telescope (VLT) is a telescope operated by the European Southern Observatory on Cerro Paranal in the Atacama Desert of northern Chile.



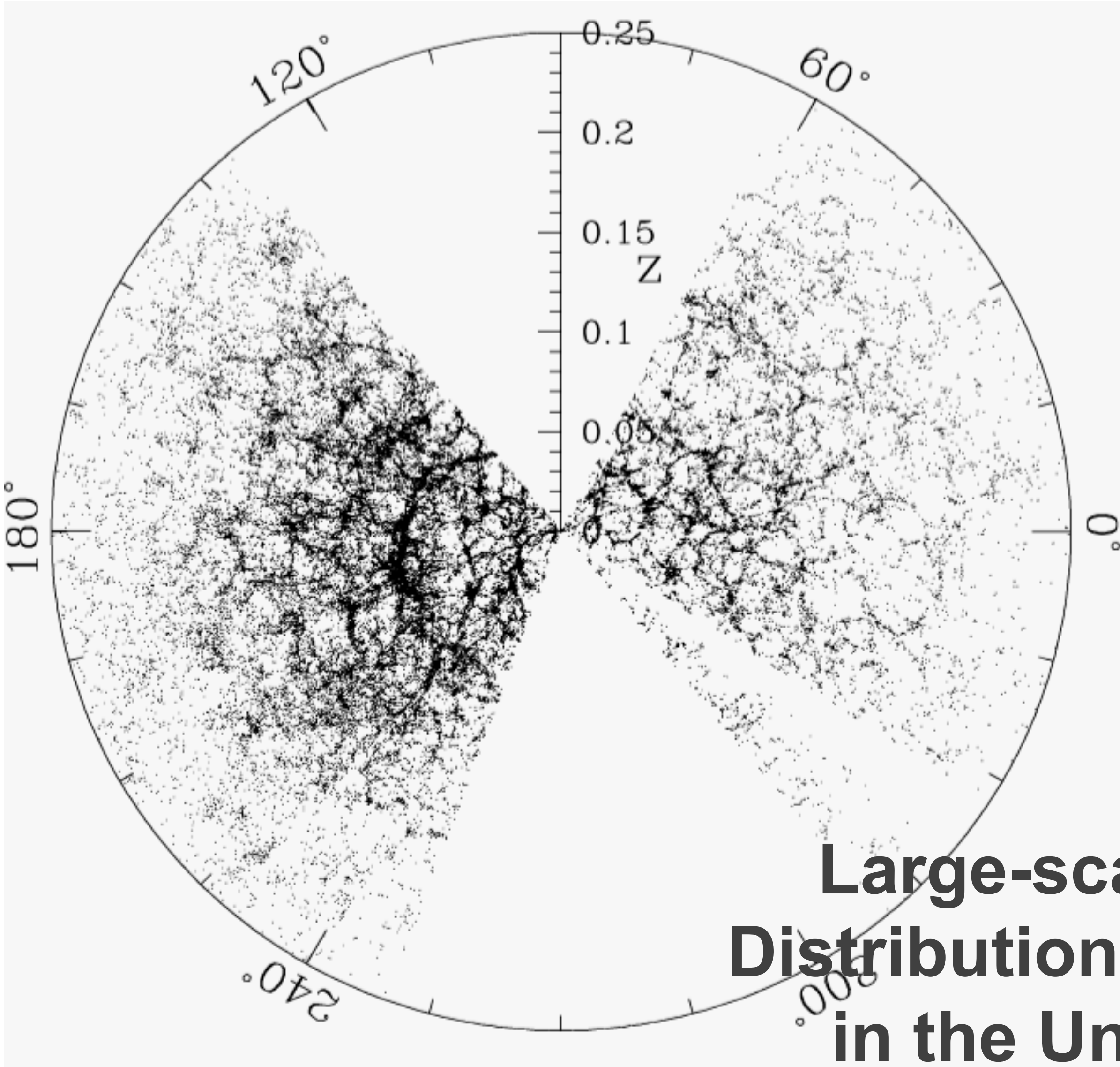
The W. M. Keck Observatory is a two-telescope astronomical observatory at Mauna Kea in the U.S. state of Hawaii.

The Magellan Telescopes are a pair of optical telescopes located at Las Campanas Observatory in Chile.



The Gemini Observatory is an astronomical observatory at sites in Hawaiʻi and Chile.

Sloan Digital Sky Survey



Large-scale structure: Distribution of 10^6 galaxies in the Universe today

Dark matter

Looking back in time

Constellation Andromeda:
starlight left stars 50-500 years ago!

With binoculars:

How far back in time are you looking now?

M31 Andromeda Galaxy

***Over two million years* back in time!**

© Robert Gendler http://www.robgendlerastropics.com

The blurry "nebula" is another galaxy, similar to our Milky Way: **Andromeda Galaxy or M31.**

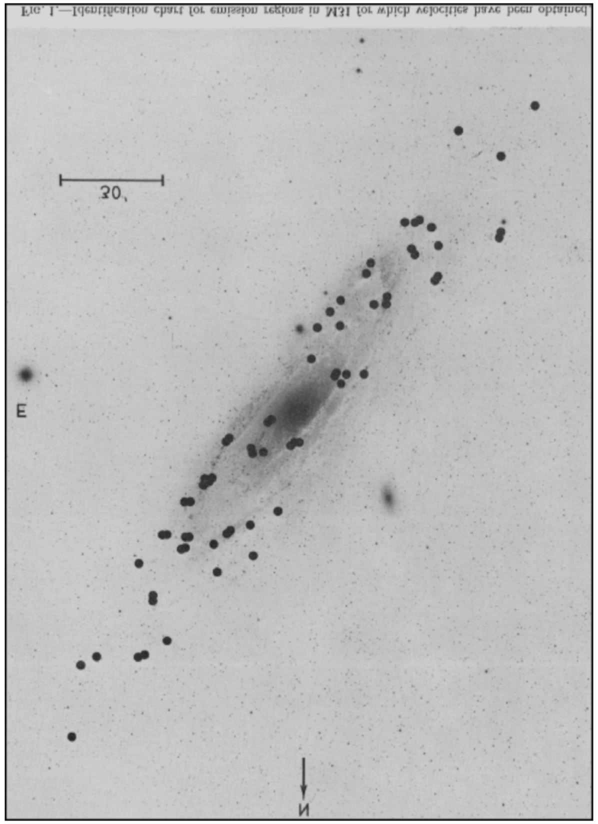
Orbiting speed of Andromeda stars

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

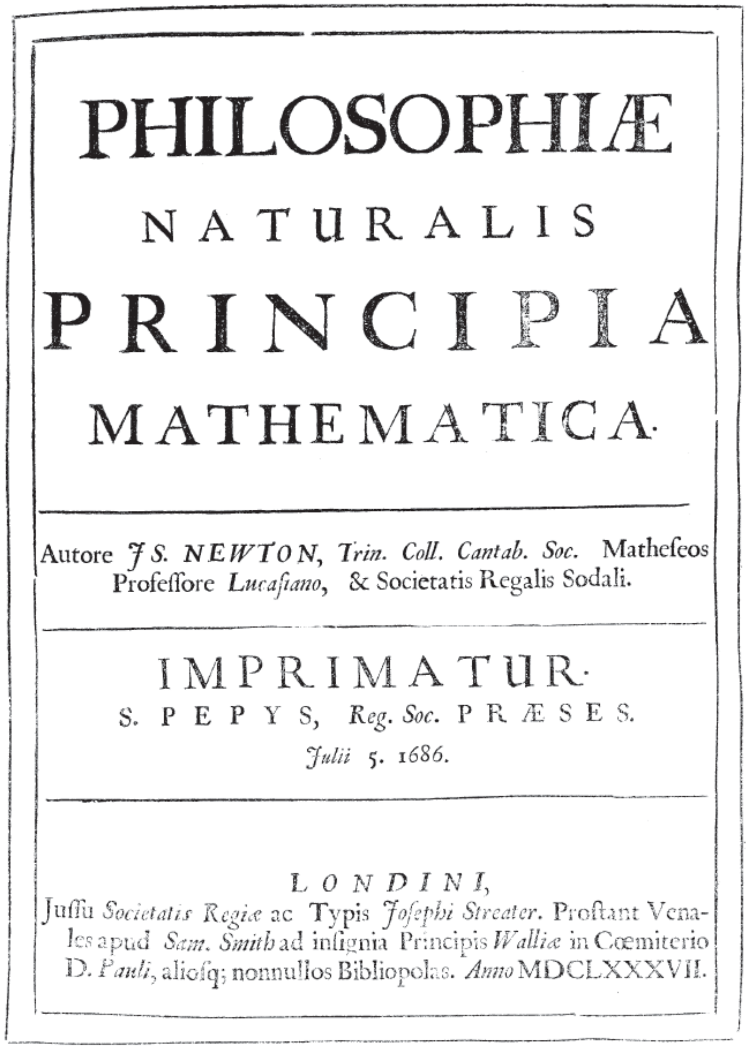
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

AIP Emilio Segre Visual Archives, Rubin Collection



The speed of an orbiting star measures the total mass of everything inside the orbit.

Newton’s Universal Law of Gravity



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater.* Proſtant Venales apud *Sam. Smith* ad inſignia Principis *Walliæ* in Cœmiterio D. *Pauli*, alioſq; nonnullos Bibliopolas. *Anno* MDCLXXXVII.

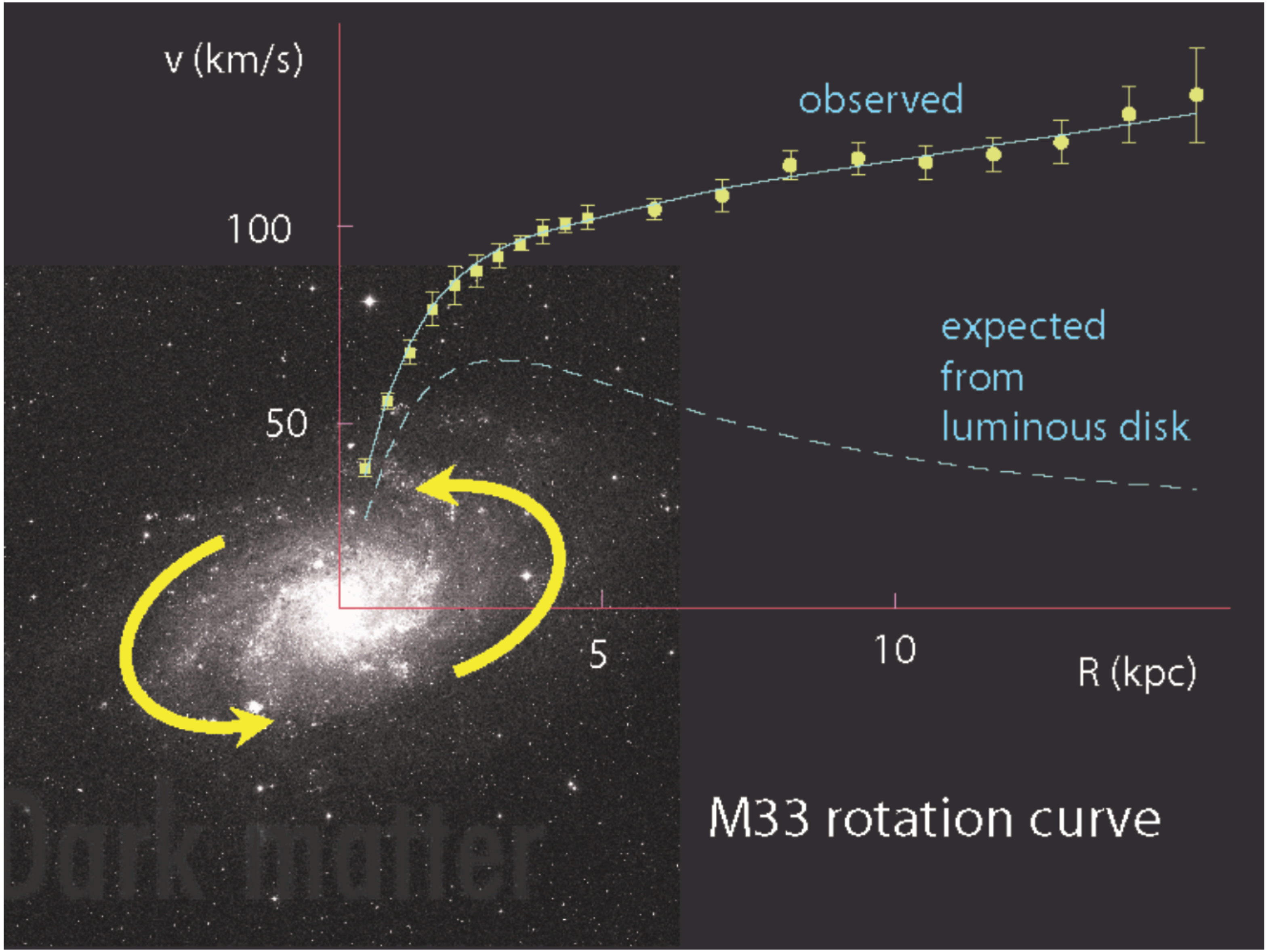
Same force is responsible for:

- Apples falling to earth
- Moon orbiting earth
- Jupiter’s moons orbiting Jupiter
- Earth orbiting the sun

Further away from orbit center, orbital speed is slower.

Orbit speed measures mass inside orbit.

The dark matter problem



What is the dark matter?

Must be invisible matter (“dark matter”) to account for these observations.

What in the world (out of this world?) is that?

After 40 years, answer still unknown.

“Ordinary matter” makes up only about 1/6 of the matter in the universe.

The rest is something else!

Could it be SUSY particles?

For every "normal" force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

These "…inos" are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

Dark energy

A Theory of the Universe

A theory of the Universe must rely on the theory of gravity.

In 1911-1917, Albert Einstein developed a revolutionary new theory of gravity, the General Relativity.

Presence of mass/energy determines the geometry of space.

Geometry of space determines the motion of mass/energy.

Thus, the matter and energy content of the Universe determines its evolution.

The Cosmological Constant

Einstein modified the original equations of General Relativity, introducing a **Cosmological Constant** to achieve a stationary Universe.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Geometry of space

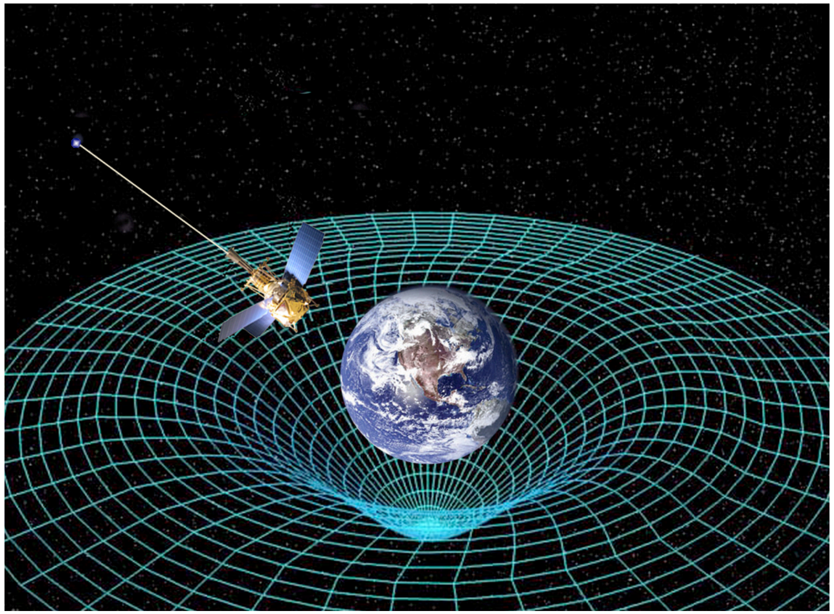
Matter and energy

Cosmological constant

The cosmological constant has the same effect as an intrinsic energy density of the vacuum.

A positive vacuum energy density implies a negative pressure, and accelerated expansion.

Quoting physicist John Archibald Wheeler:
"Matter tells space how to curve and space tells matter how to move."



Cosmological models

Describe the expansion history of the universe.
First developed by Alexander Friedmann in 1922 and Georges Lemaitre in 1927.

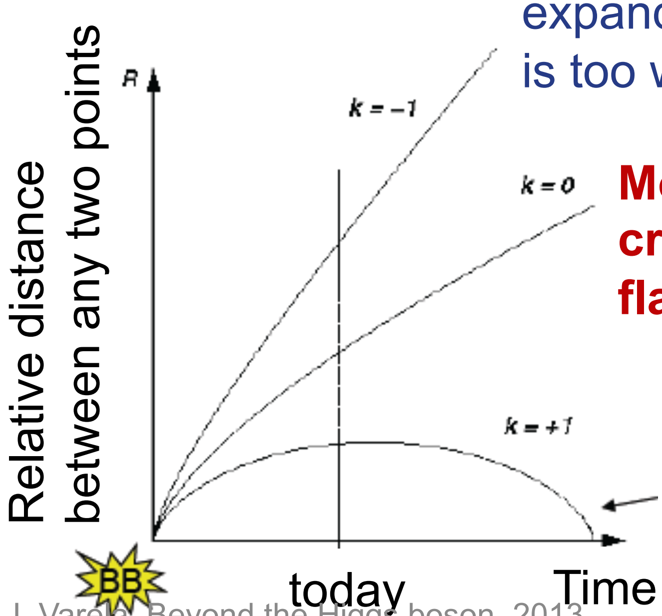
Critical energy density

$$\rho_{crit} \approx 6.5 \times 10^{-30} \text{ g cm}^{-3}$$
$$\Omega = \rho / \rho_{crit}$$

Models with a low density expand forever, as the gravity is too weak

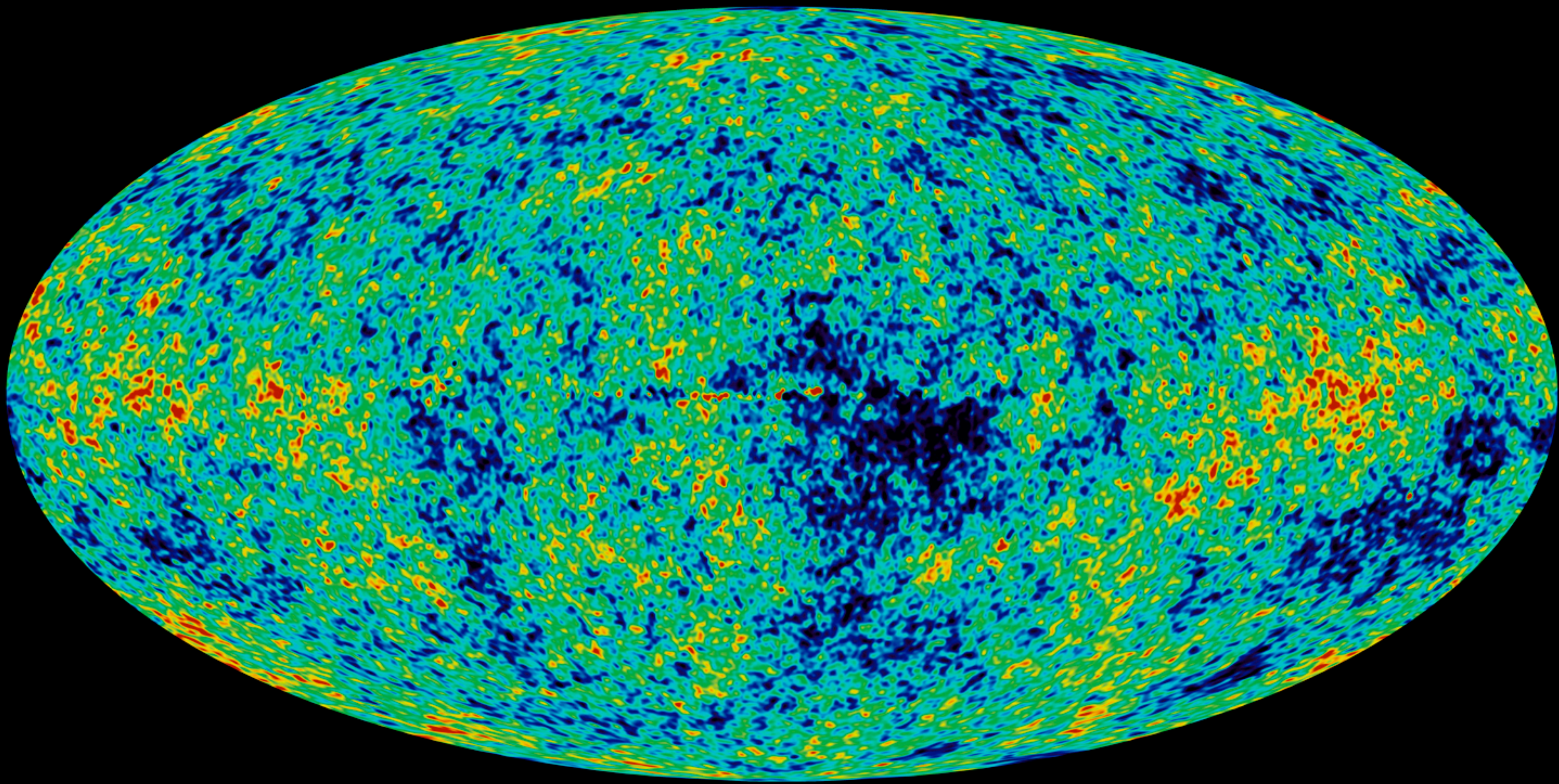
Models with an exact critical density are spatially flat and expand forever

Models with a high density recollapse in a “big crunch”



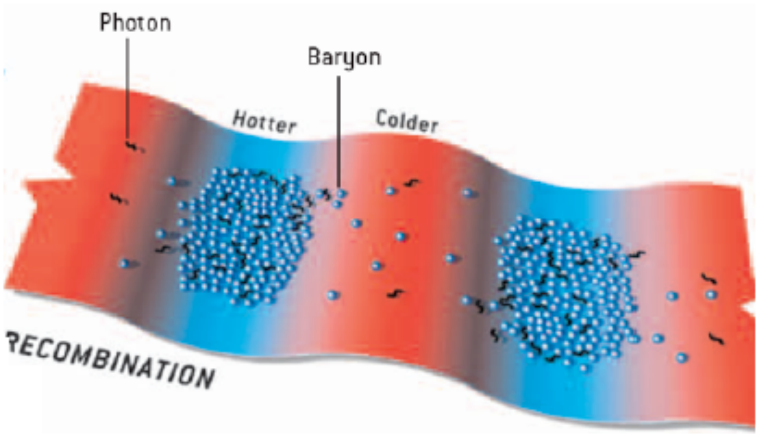
In our Universe Ω is close to 1. Why?

WMAP: The Universe circa 380,000 yrs



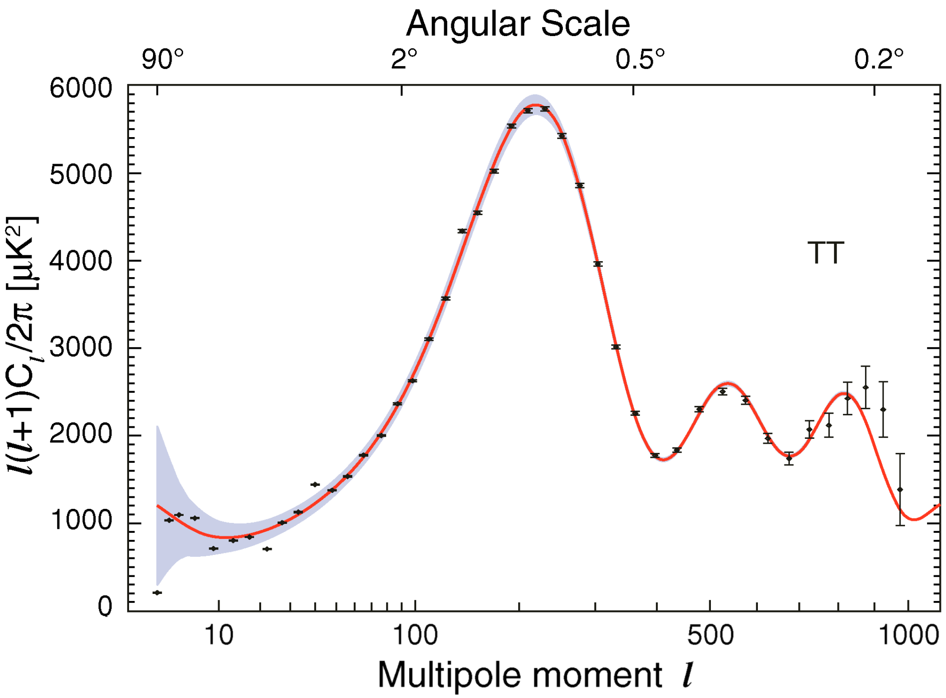
±0.001% Fluctuations

WMAP measurements



In the early universe, there are tiny density fluctuations, and the matter and radiation fall to the densest spots.

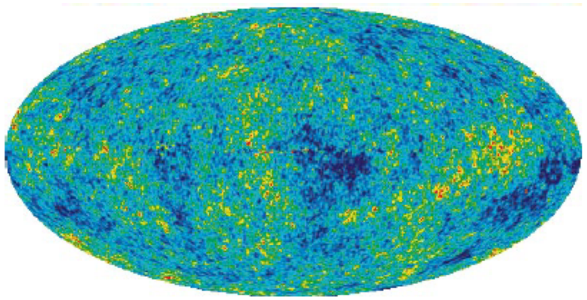
That generates giant sound waves, which can be seen as temperature fluctuations in the Cosmic Microwave Background



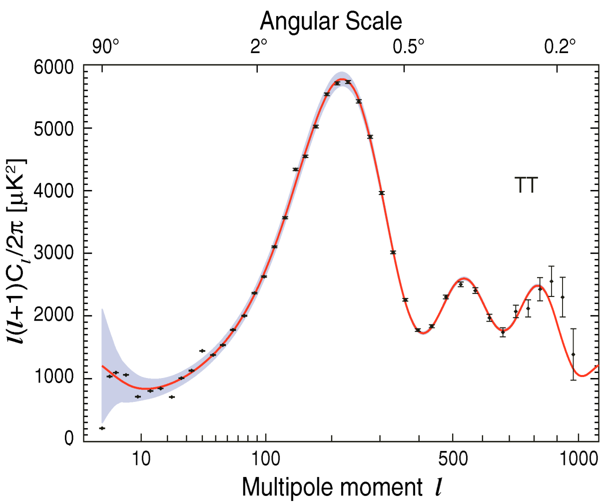
Parameter	Symbol	Best fit (WMAP only)
Age of the universe (Ga)	t_0	13.74 ±0.11
Hubble's constant (km/Mpc·s)	H_0	70.0 ±2.2
Baryon density	Ω_b	0.0463 ±0.0024
Physical baryon density	$\Omega_b h^2$	0.022 64 ±0.000 50
Cold Dark matter density	Ω_c	0.233 ±0.023
Physical cold dark matter density	$\Omega_c h^2$	0.1138 ±0.0045
Dark energy density	Ω_Λ	0.721 ±0.025

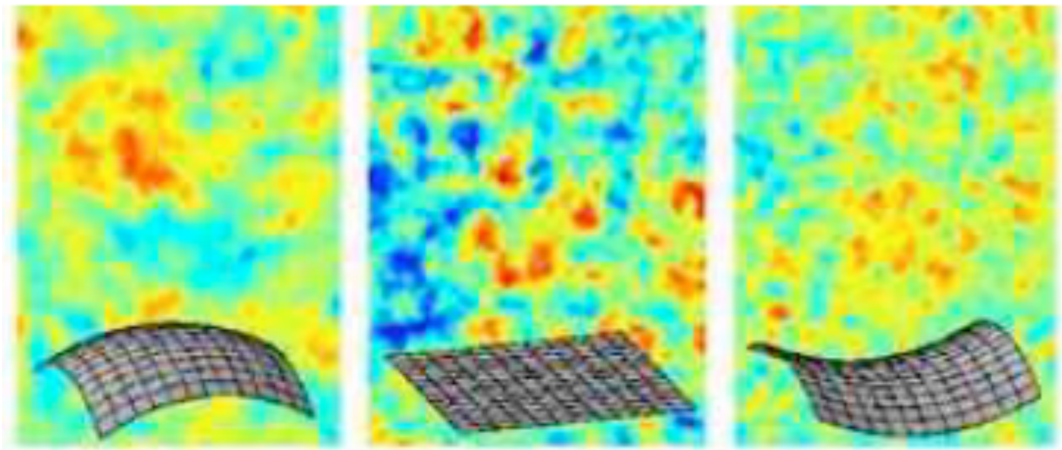
The Universe is flat

The physical size of the horizon at the time of cosmic microwave emission can be computed.



Comparing it to the observed angular size of CMB fluctuations we can determine the cosmic geometry - and it is flat, $\Omega = 1$

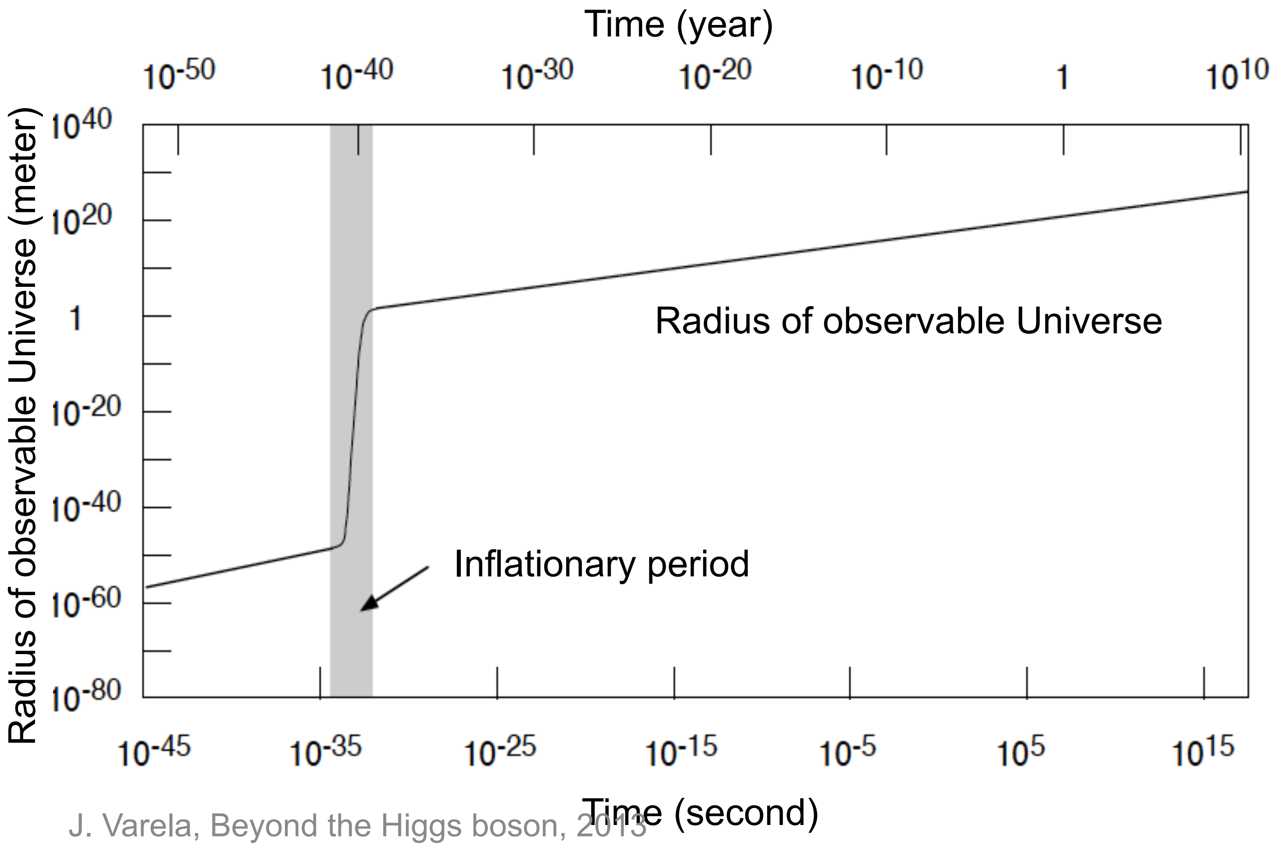




Cosmological inflation

In the very early universe, the physical vacuum undergoes a transition from a high energy state to a low energy state.

The resulting energy shift drives a dramatic exponential expansion.



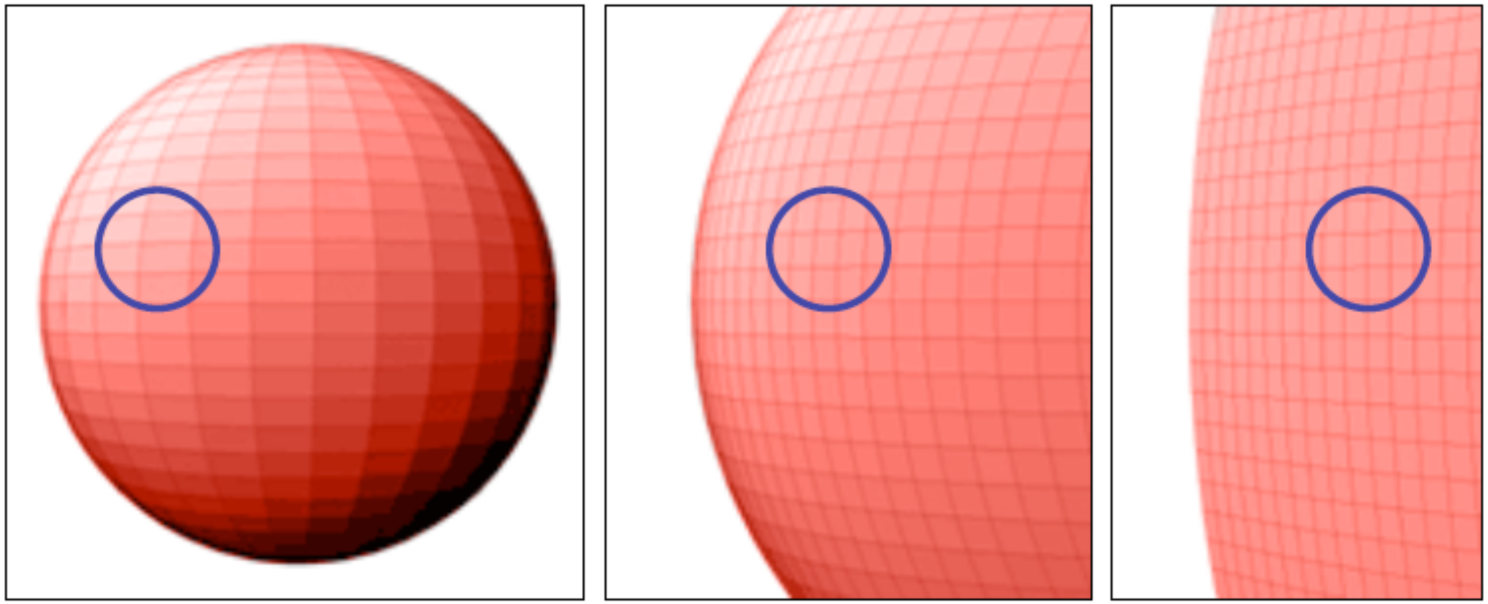
The inflation theory was developed independently in the late 1970’s by Alan Guth, Alexey Starobinsky, and others

Solving the flatness problem

As the universe inflates, the local curvature becomes negligible in comparison to the vastly increased “global” radius.

Locally the universe becomes extremely close to flat (in the region that is observable now).

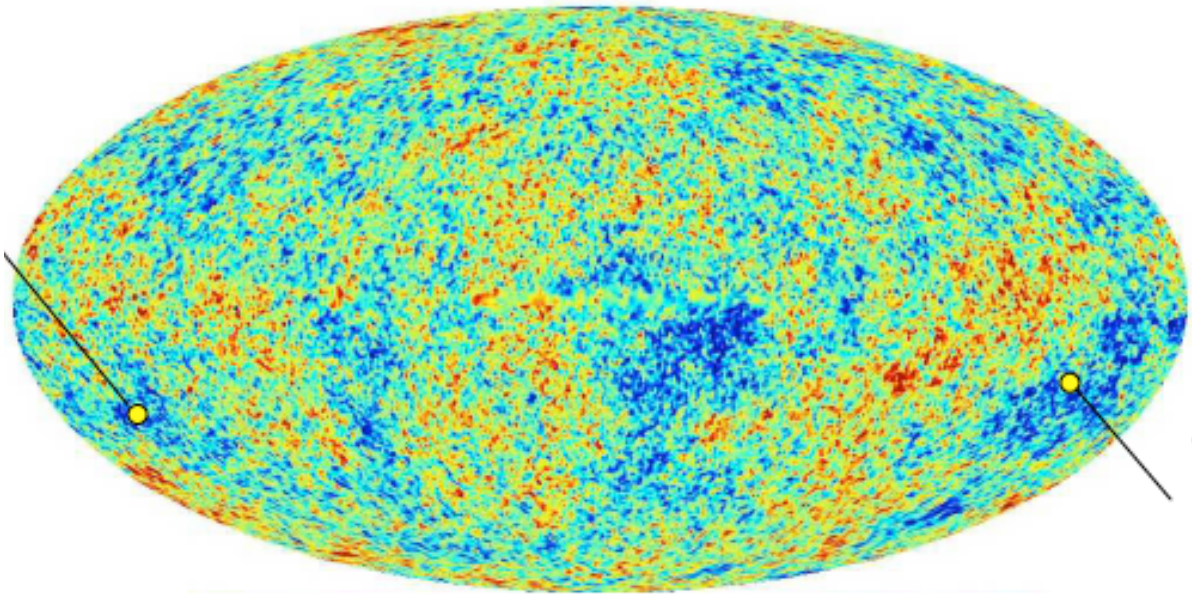
Thus, at the end of the inflation, $\Omega \simeq 1$



Solving the horizon problem

Cosmic Microwave Background, released when the universe was 380,000 years old, is uniform to a few parts in a million.
Yet the projected size of the causal horizon at the time is only ~ 1°

How did this spot…



…know to have the exact same temperature as this spot?

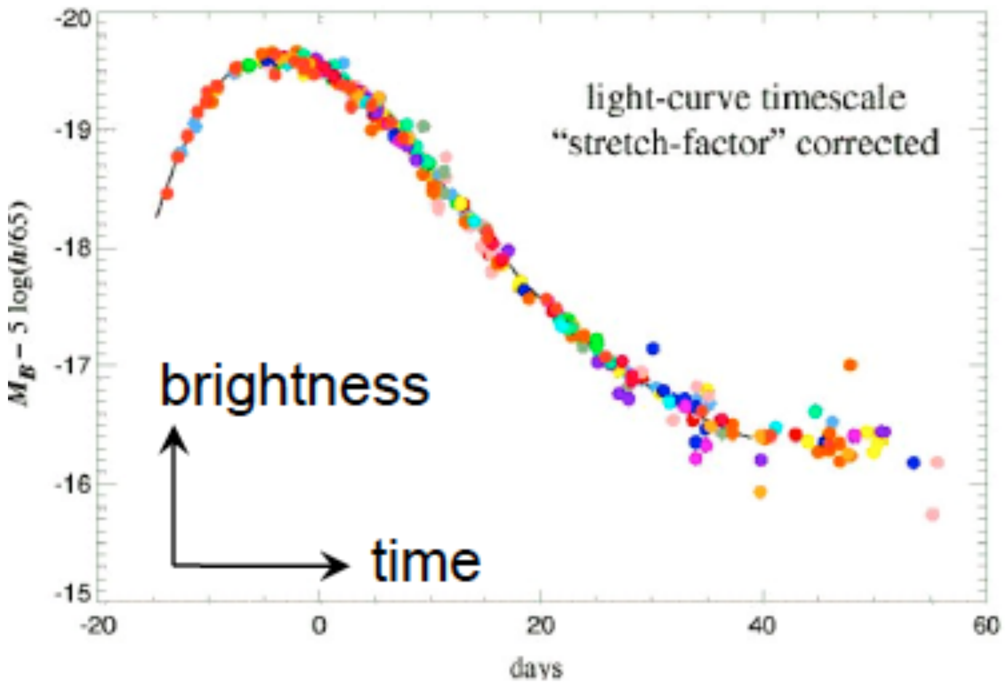
The answer:
They used to be much closer together before the inflation, and in thermal equilibrium.
The inflation carried them apart.

Supernovae: a new Standard Candle

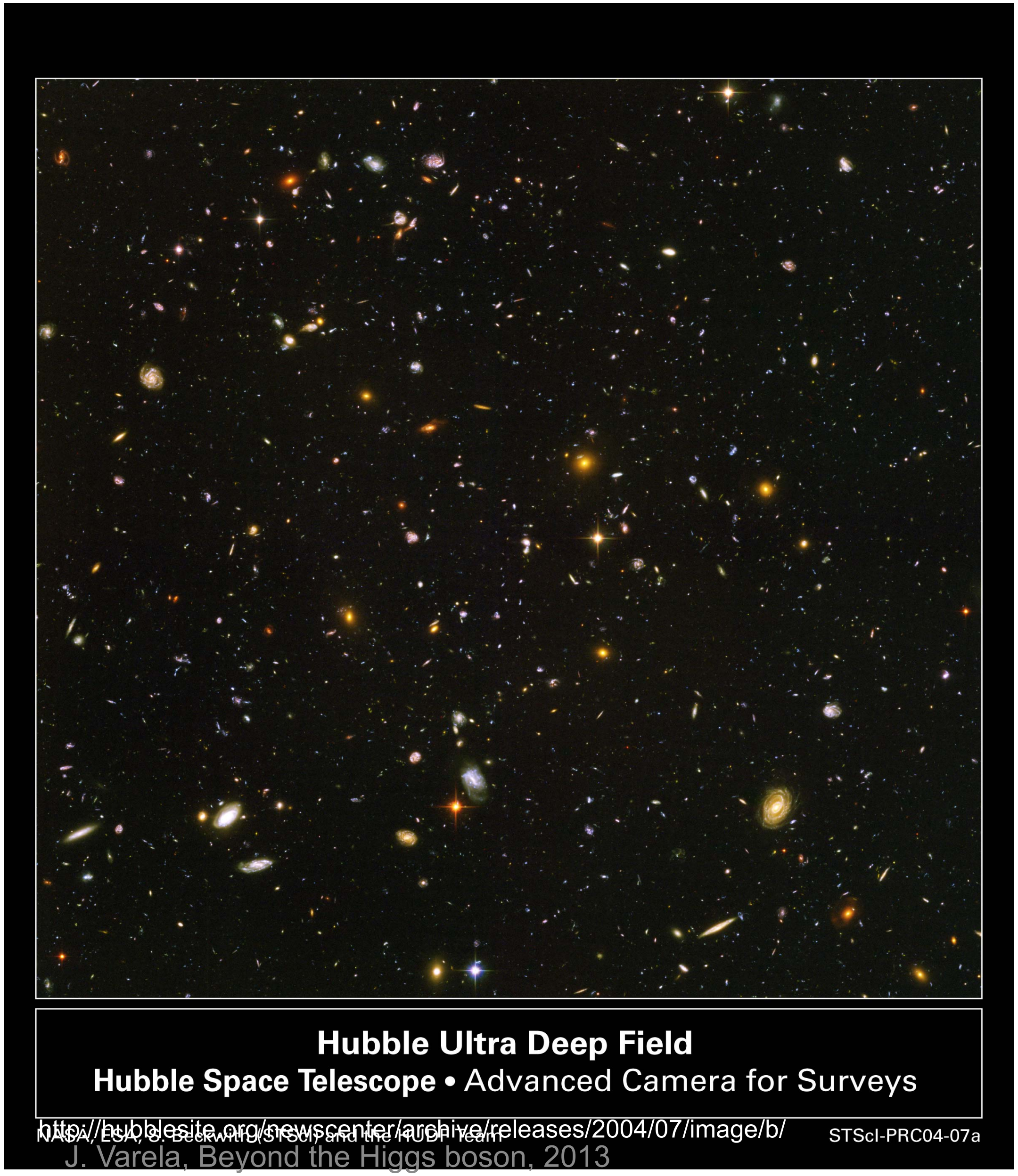
- Massive stars become unstable at the end of their lives, and explode (SN of type II).
- Alternatively, a white dwarf star accretes gas from a companion star, gets too massive, and explodes (SN of type Ia).

Their peak brightness can be standardized to ~ 10% accuracy.
They are as bright as an entire galaxy.

Multiwavelength X-ray, infrared, and optical compilation image of Kepler's supernova remnant, SN 1604.



Powerful telescopes



http://hubblesite.org/newscenter/archive/releases/2004/07/image/b/

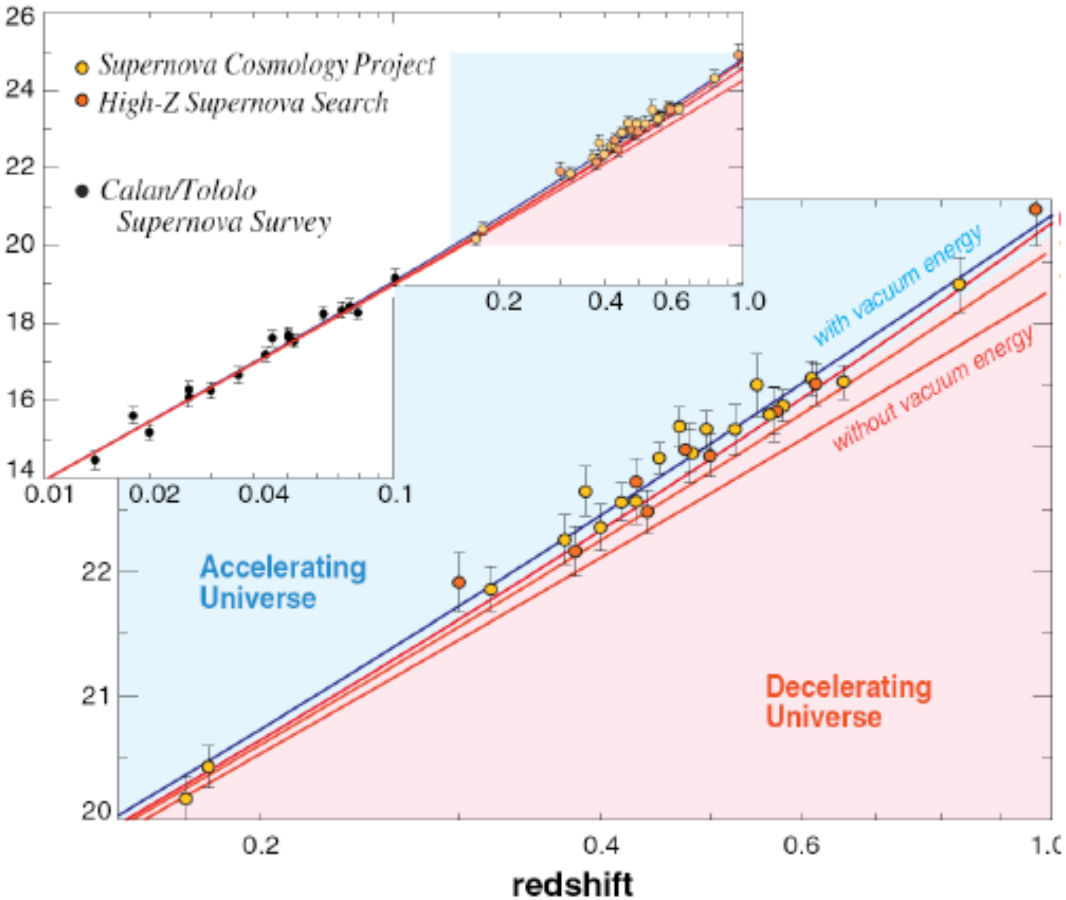
About 10,000 galaxies in this picture, 1/10 size of the moon as we look at it from earth.

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

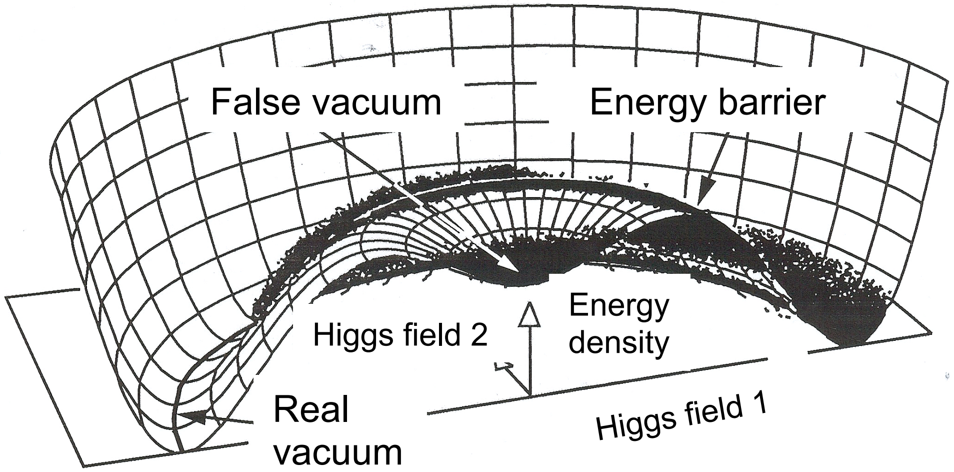
They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space



Higgs like field and inflation

Before the inflation (10^{-34} s), the Higgs-like field is trapped is a state of false vacuum.



The Universe undergoes a super-cooling transition: the temperature decreases below the phase transition point but the Higgs field stays in the false vacuum state.

While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation) and the energy stored in the Higgs field increases.

Inflation stops when the Higgs field decays to the real vacuum.

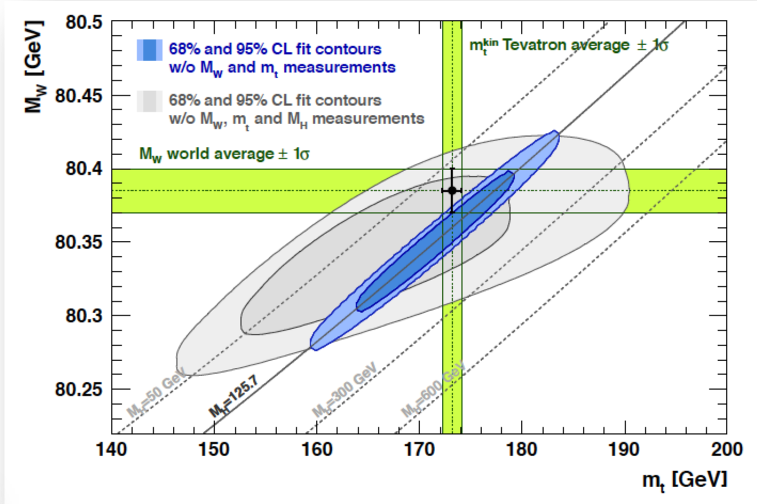
The energy released by the Higgs field is converted into matter particles.

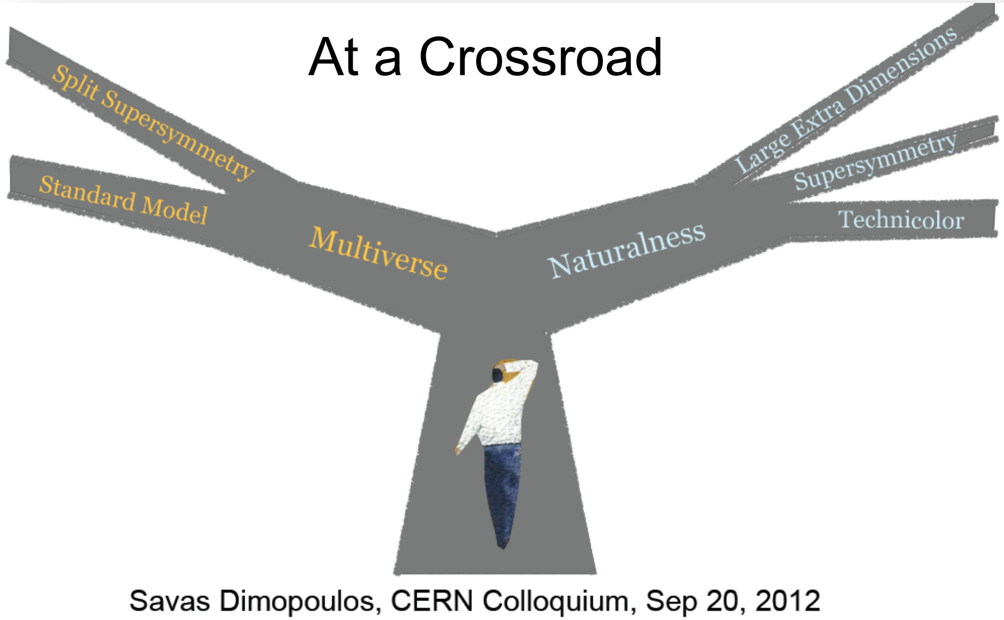
What else could we find at LHC?

The standard model and beyond

Standard Model

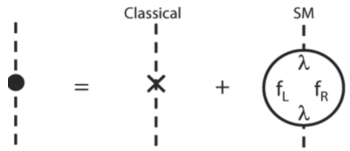
The astonishing brain power of a certain ape species





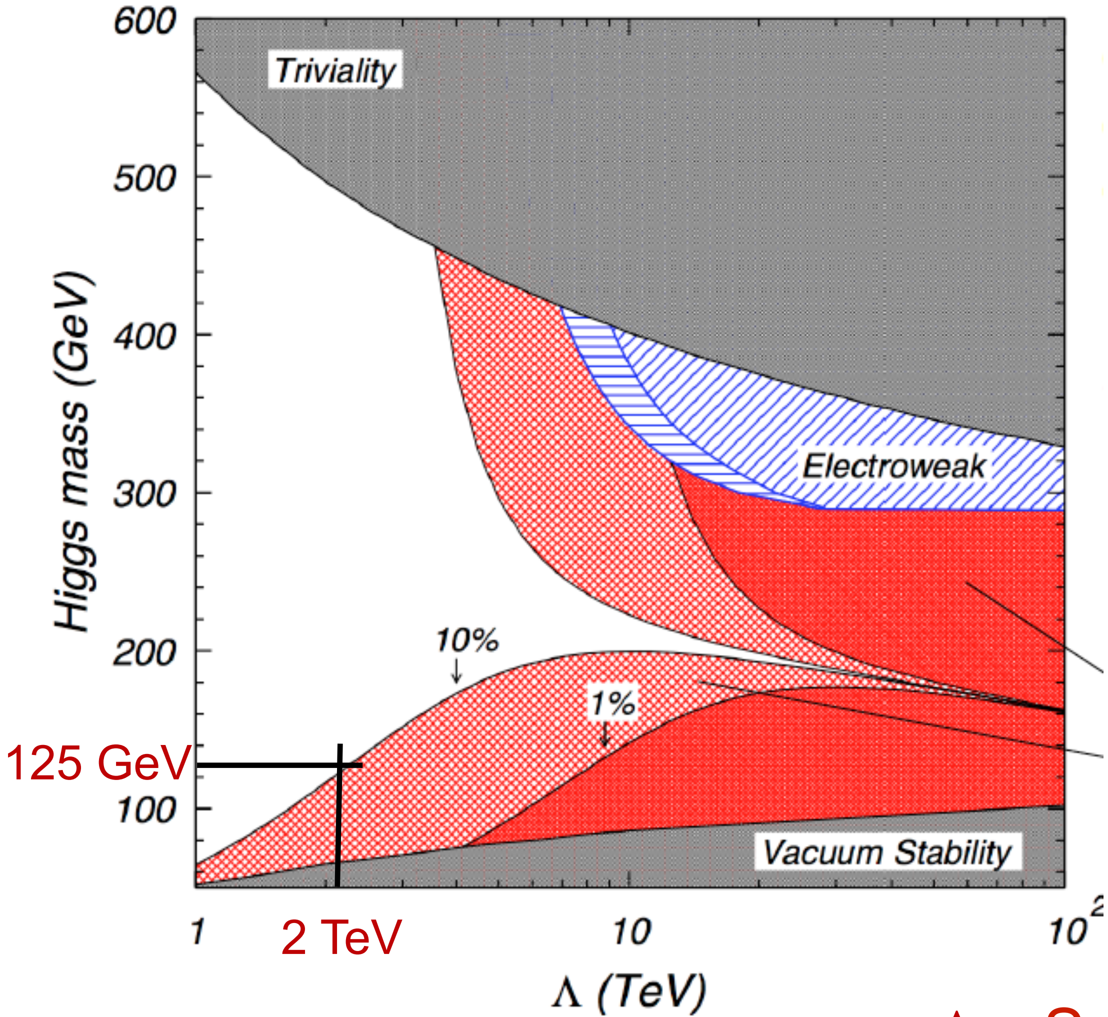
Higgs mass is a huge problem:

Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

New physics at a few TeV?



Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

Excluded to avoid fine-tuning

Λ – Scale of New Physics

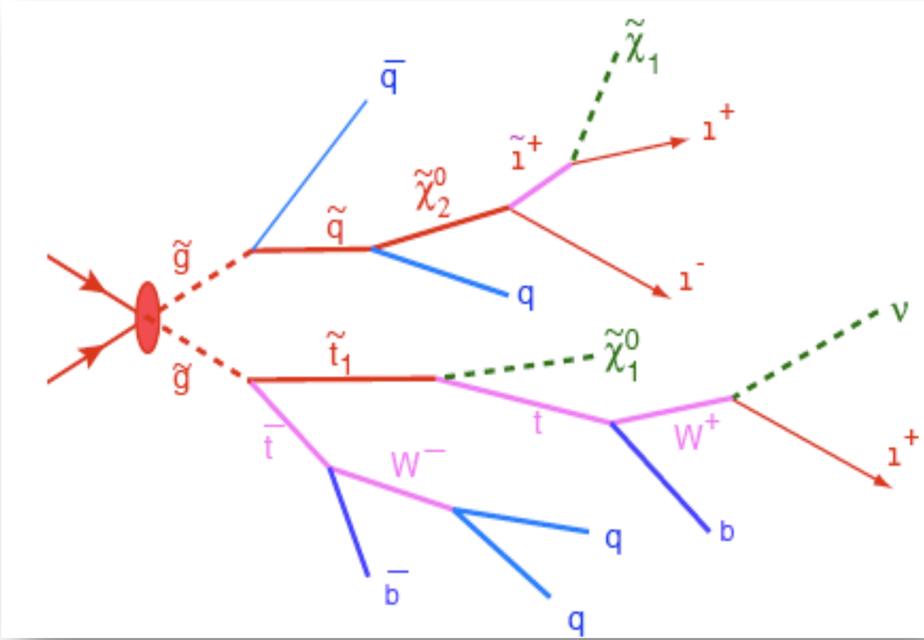
Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

Search for Supersymmetry



Missing Energy:
- from LSP

Multi-Jets:
- from cascade decay

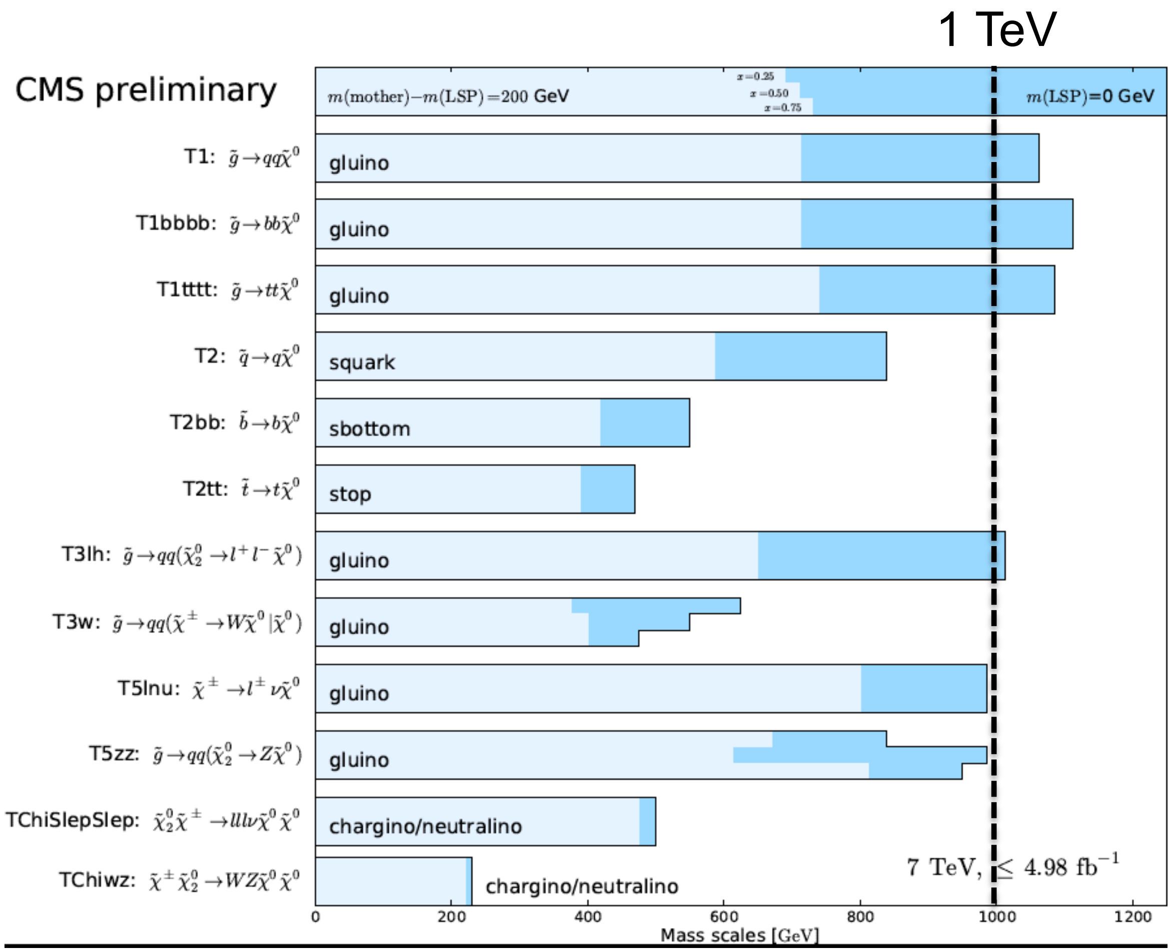
Multi-Leptons:
- from cascade decay particles

R-Parity Conserving SUSY:

- Supersymmetric particles are produced in pairs
- LSP – Lightest Supersymmetric Particle

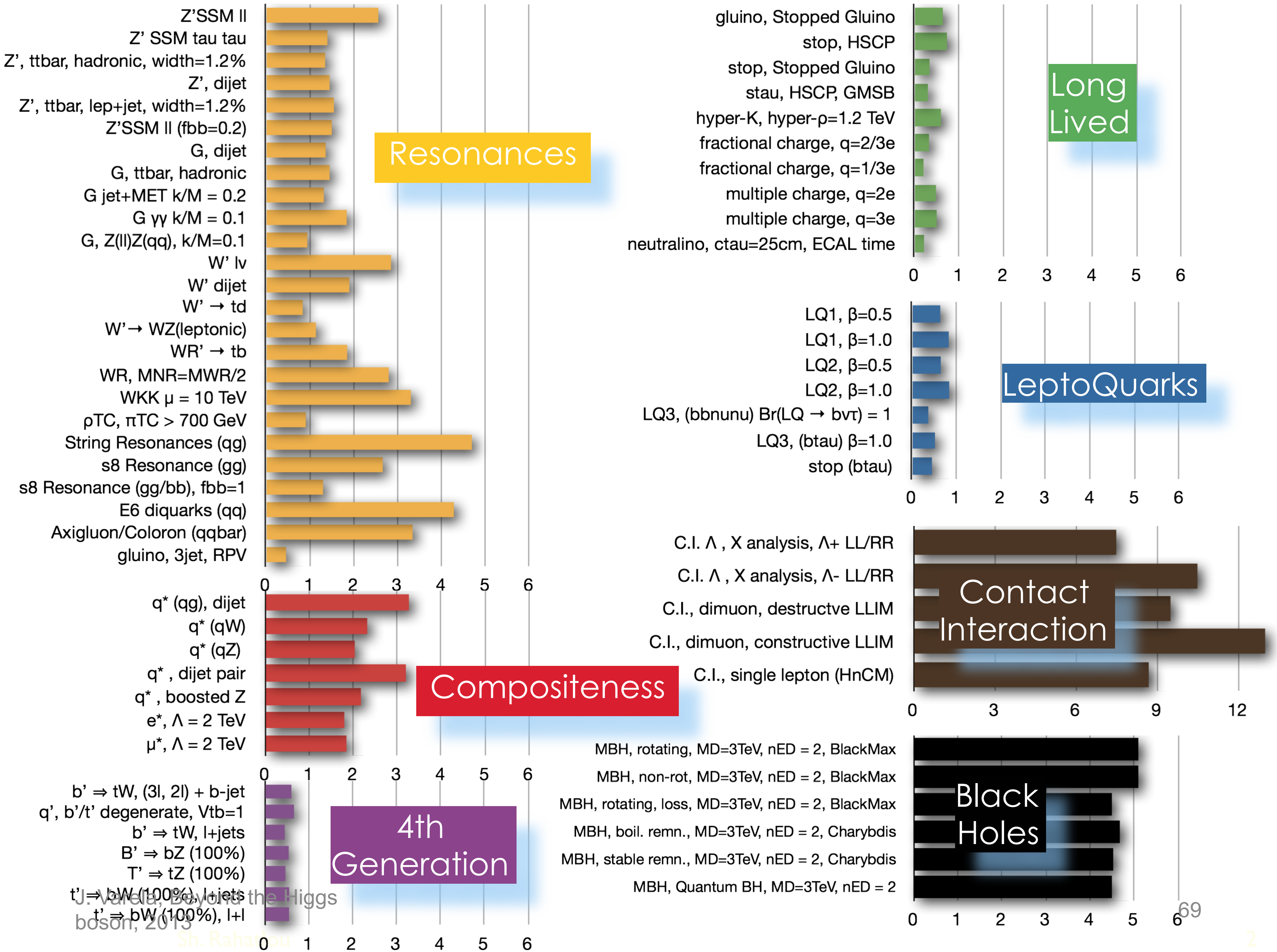
Results of SUSY searches

CMS searches have excluded SUSY particles up to 0.5-1 TeV

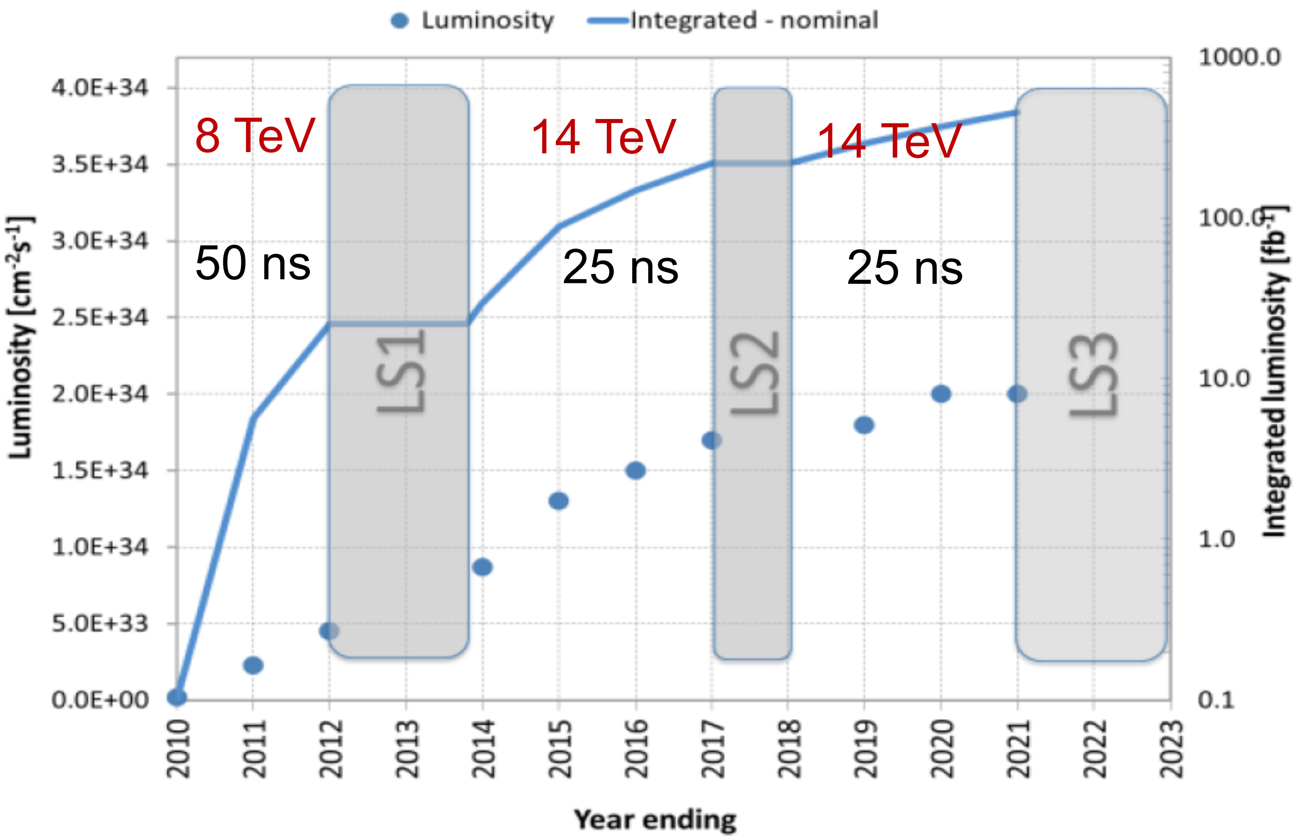


Exclusion regions

Mass of SUSY particle


Resonances
Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lv
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5 6
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5 6
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t'⇒bW (100%), l+jets
t' ⇒ bW (100%), l+l
0 1 2 3 4 5 6
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 5 6
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
0 1 2 3 4 5 6
Contact Interaction
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., dimuon, destructve LLIM
C.I., dimuon, constructive LLIM
C.I., single lepton (HnCM)
0 3 6 9 12
Black Holes
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5 6

LHC projections



14 TeV

HL-LHC

Luminosity-leveled at 5×10^{34} Hz/cm^2

7×10^{33} Hz/cm^2
30 fb^{-1}

LS1

2×10^{34} Hz/cm^2
300 fb^{-1}

LS3

10^{35} Hz/cm^2
3000 fb^{-1}

CMS Upgrades: Phase 1 Upgrade

Phase 2 Upgrade

Major outstanding problems in Quantum Physics

Mass hierarchy problem

Explain dark matter and dark energy

Grand Unification of particles and forces

Combine General Relativity and Quantum Theory in a single theory.

Solve the fundamental problems of Quantum Mechanics

Explain the values of constants in nature

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