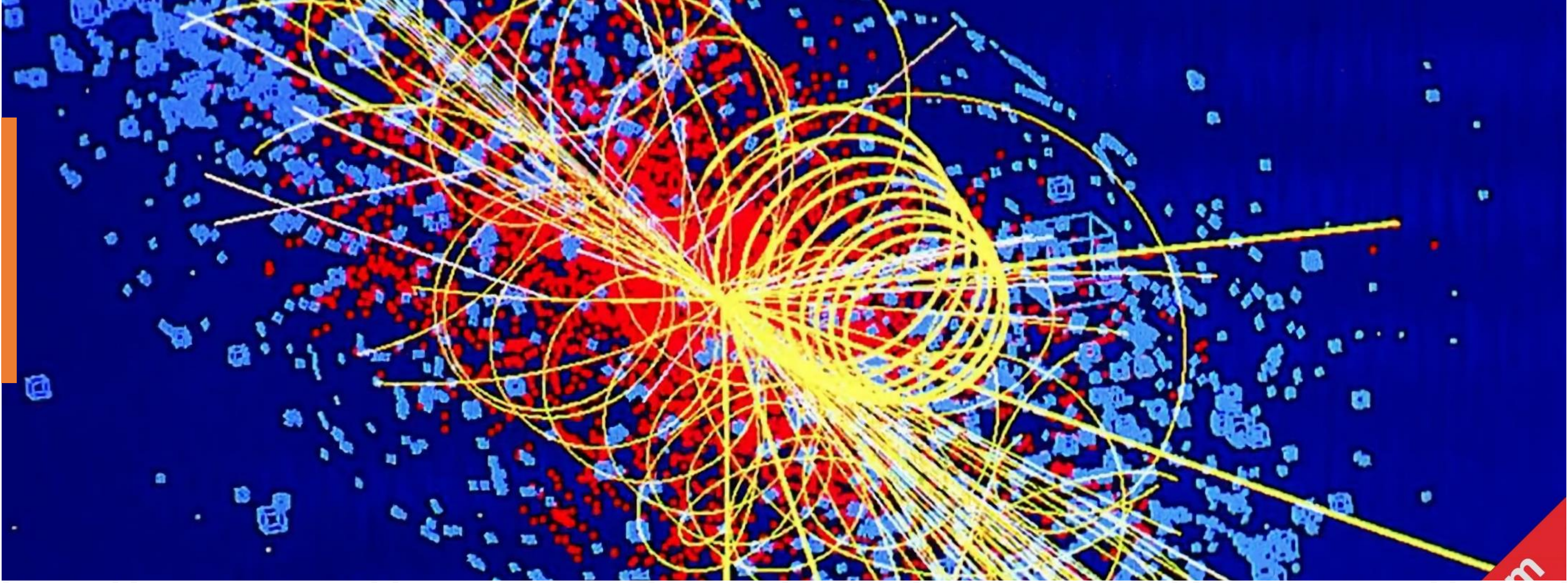

From Quarks to the Cosmos: The Interconnected Worlds of Particle Physics and Cosmology

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Outline

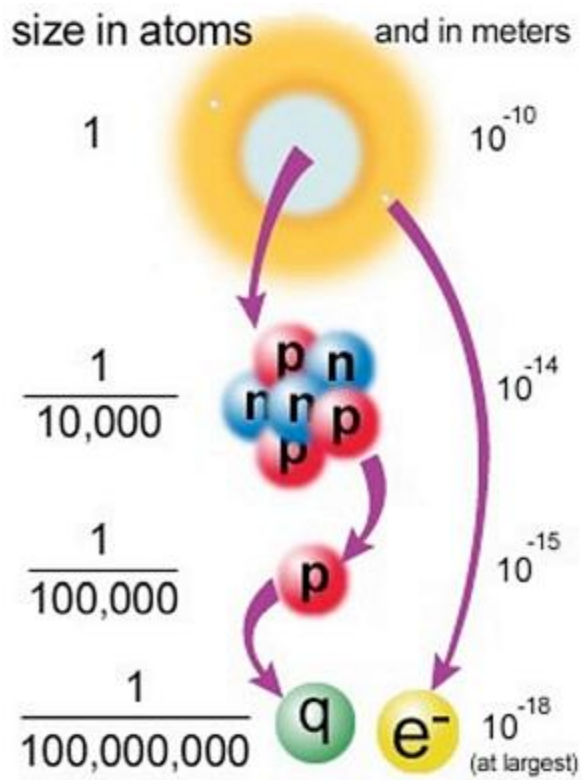
- **Introduction to Particle Physics**
- **Standard Model overview**
- **Beyond the Standard Model**
- **Standard Model of Cosmology**
- **Astro-particle Physics**
  - **Dark Matter**
  - **Dark Energy**
  - **Gravitational Waves**

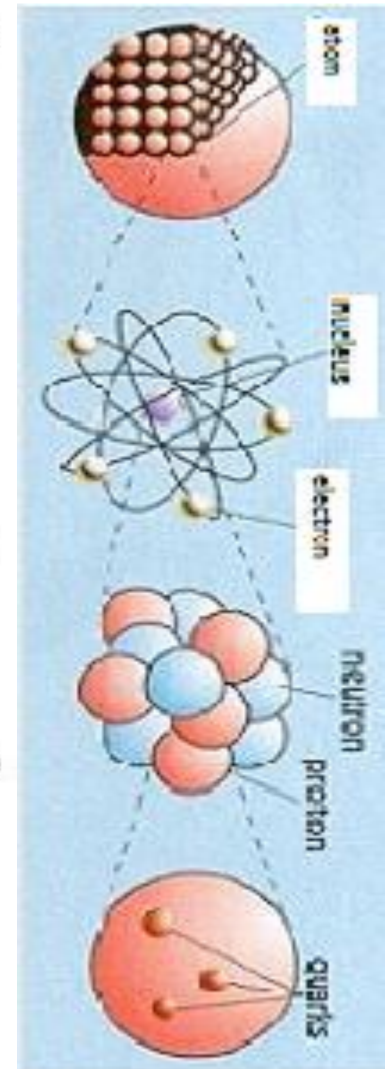
Aims of Particle Physics?

- To understand nature at it is most fundamental level.
- What are the smallest pieces of matter, and how do they make up the large-scale structures that we see today ?
- How and why do these 'fundamental particles' interact the way that they do?
- Understand the fundamental forces in nature.

The Elementary Blocks of Matter

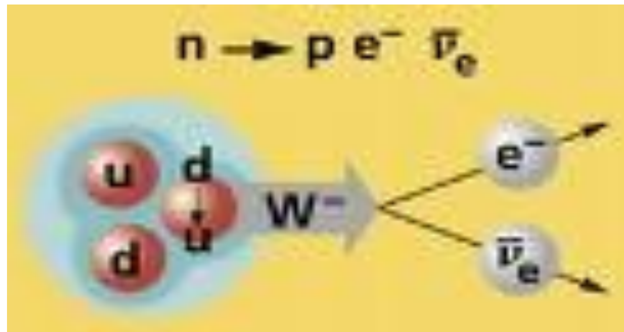
- Matter is made of molecules
- Molecules are built out of atoms
- Atoms are made of nuclei and electrons
- Nuclei are assemblies of protons and neutrons
- Protons and neutrons are quarks bound together





➢ The volume of an atom corresponds to 10^24 times the volume of an electron.
➢ Classically, matter contains a lot of void
➢ Quantum mechanically, this void is populated by pairs of virtual pairs Of particles

Neutrinos



- In 1930s beta decay was not understood – there was *missing energy*
- *Pauli* grudgingly introduced a new particle to account for this – the *neutrino*
- The electron and neutrino are collectively called *leptons*

The Fundamental Particles

- **There are only 12 fundamental particles of matter (also the *antiparticles*)**

Family	Quarks		Antiquarks	
	Q = +2/3	Q = -1/3	Q = -2/3	Q = +1/3
1	u	d	$\bar{u}$	$\bar{d}$
2	c	s	$\bar{c}$	$\bar{s}$
3	t	b	$\bar{t}$	$\bar{b}$

Family	Leptons		Antileptons	
	Q = -1	Q = 0	Q = +1	Q = 0
1	e^-	n_e	e^+	n_e
2	m^-	n_m	m^+	n_m
3	t^-	n_t	t^+	n_t

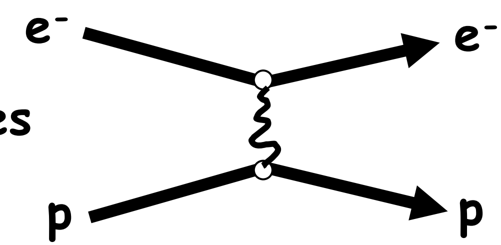
What About Forces?

- **Particles interact with each other via forces**
- **There are four types – *gravity*, *electromagnetism* and the *strong* and *weak* nuclear forces**
- **Each is described by the *exchange of a force-carrying particle* between the matter particles**

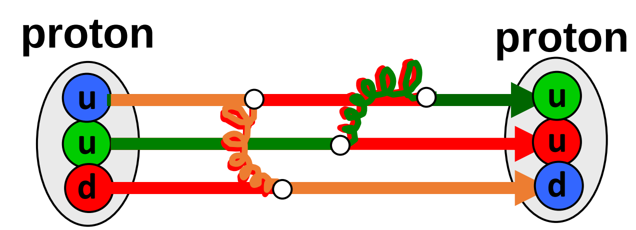
Interaction	Exchanged quantum *(source ch)*	Range (m)	Relative Strength	Examples in nature
Strong	gluon *colour*	10^{-15}	1	proton (quarks)
Electromagnetic	photon *electric*		$<10^{-2}$	atoms
Weak	W, Z *hypercharge*	$<10^{-17}$	10^{-5}	radioactivity
Gravity	graviton ? *mass*		10^{-38}	solar system

Three Fundamental Forces

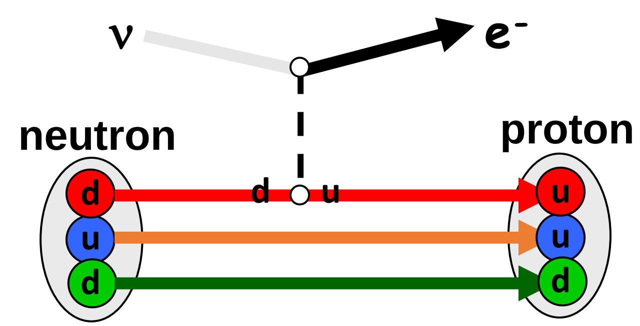
- **ELECTROMAGNETIC**: photon (γ)
  - couples to electrically charged particles
  - no self-interaction, massless



- **STRONG**: 8 gluons (g)
  - couple to color-charged quarks
  - change color charge of quarks
  - self-interacting, massless

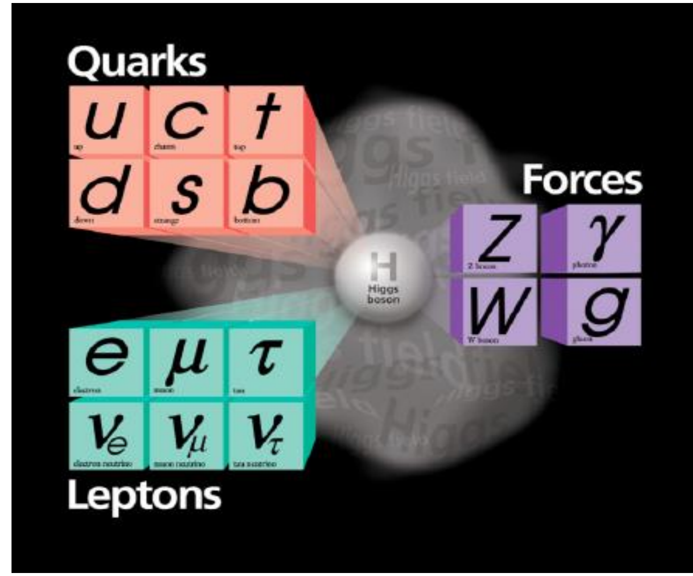


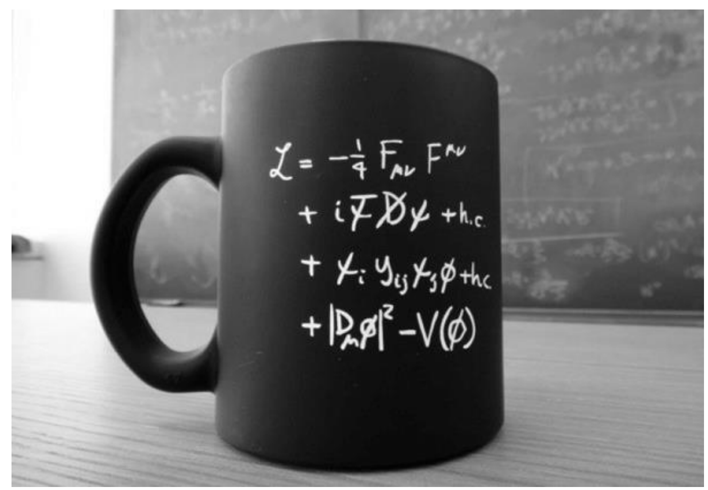
- **WEAK**: $W^{\pm}$ and Z^0 bosons
  - couple to all fermions
  - $W^{\pm}$ transforms particles
  - self-interacting, **MASSIVE**



Standard Model (SM)

- A theoretical model of interactions of elementary particles
  - Symmetry:
    - ❖ SU(3) x SU(2) x U(1)
  - "Matter particles"
    - ❖ quarks: up, down, charm, strange, top bottom
    - ❖ leptons: electron, muon, tau, neutrinos
  - "Force particles"
    - ❖ Gauge Bosons: γ (electromagnetic force)
      $W^{\pm}$, Z (weak force)
      g gluons (strong force)
  - Higgs boson
    - ❖ Spontaneous symmetry breaking of SU(2)
    - ❖ mass





SM Masses

- Gauge bosons W & Z have masses
  - This is why the weak force is weak.
  - Putting them in by hand breaks the gauge invariance.

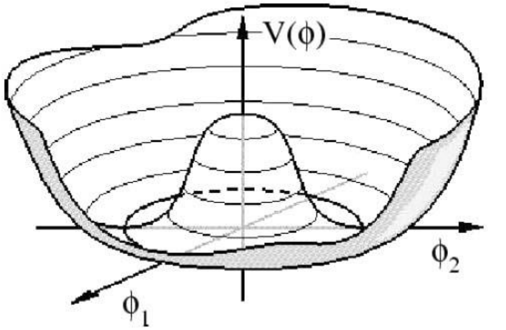
- Fermions have masses
  - Parity violation in weak interactions can be accommodated without breaking the gauge invariance only if fermion masses are zeros
  - Theory is not renormalizable, needs new physics at some scale L; this new physics must take care of the divergences somehow...

Higgs Boson field

- 1964: Peter Higgs – one can give mass to vector field without breaking gauge invariance

- potential of conventional complex scalar field ($s = 0$)

$$V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$



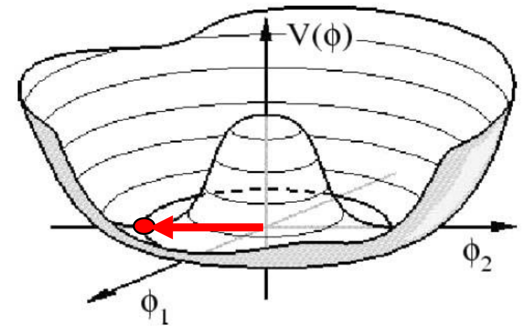
- The lowest energy state for ϕ is not ϕ=0
  - field has non-zero vacuum expectation value
  - vacuum is going to be filled with non-zero field— New Age Ether!
- Require local gauge invariance for ϕ

$$L = \left(\partial^\mu \phi^* \partial_\mu \phi + \mu^2 |\phi|^2 - \frac{\lambda}{2} |\phi|^4 \right) + \left(-J^\mu A_\mu + g^2 \phi^* \phi A_\mu A^\mu \right) + \left(-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right)$$

Higgs Mechanism

- Expand ϕ around local minimum:

$$\phi(x) = e^{i\alpha(x)}\left(v_0 + h(x)\right)$$



- Re-write *L* in terms real *h(x)* and α*(x)*...
- Gauge field appears to have mass:

$$g^2\phi^*\phi A_\mu A^\mu \quad \rightarrow \quad g^2 v_0^2 A_\mu A^\mu + \ldots h A_\mu A^\mu + \ldots h^2 A_\mu A^\mu$$

- Mass is proportional to vacuum expectation value v_0 and coupling *g*

$$W_\mu^\pm = \frac{W_\mu^1 \pm W_\mu^2}{\sqrt{2}}, \quad Z_\mu^0 = \frac{gW_\mu^3 - g' B_\mu}{\sqrt{g+g\prime}} \Longrightarrow M_W = \frac{gv}{2}, \quad M_Z = \sqrt{g^2 + g'^2} v/\sqrt{2}$$

- Orthogonal combination to Z is massless photon

$$A_\mu^0 = \frac{gW_\mu^3 + g' B_\mu}{\sqrt{g+g\prime}}$$

Remarks on SM Higgs Mechanism

- Generate mass for W,Z using Higgs mechanism
  - Higgs VEV breaks SU(2) x U(1)$\rightarrow$U(1)em
  - Single Higgs doublet is minimal case
- Before spontaneous symmetry breaking:
  - Massless W_i, B, Complex Φ
- After spontaneous symmetry breaking:
  - Massive $W^{\pm}$,Z; massless γ; physical Higgs boson H

Count degrees of freedom

Fermion Masses in the SM

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right)$$

Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Scalar couplings to fermions:

$$L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

- Effective Higgs-fermion coupling

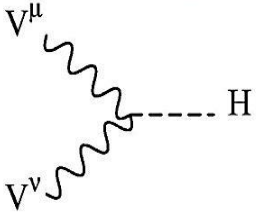
$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v + H \end{pmatrix} d_R + h.c.$$

- Mass term for down quark

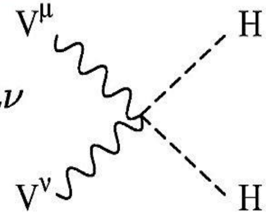
$$\boxed{\lambda_d = -\frac{m_d\sqrt{2}}{v}}$$

Higgs Boson Feynman Rules

- Couplings to EW gauge bosons $(V=W,Z)$:

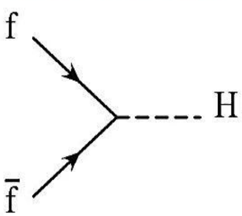


$= 2i\frac{M_V^2}{v}g^{\mu\nu}$



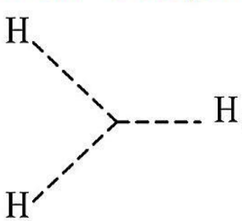
$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$

- Couplings to fermions $(f = l, q)$:

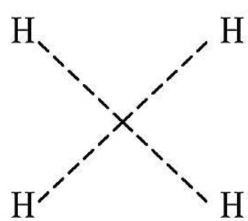


$= -i\frac{m_f}{v}$

- Self-couplings:



$= -3i\frac{M_H^2}{v}$



$= -3i\frac{M_H^2}{v^2}$

- **Higgs couples to heavy particles**
- **No tree level coupling to photons (γ) or gluons (g)**
- **$M_H^2=2v^2\lambda \Rightarrow$ large M_H is strong coupling regime**

SM Overview

- Standard Model is defined by
  - 4-dimension QFT (Invariant under Poincare group)
  - Symmetry: Local SU(3)C x SU(2)L x U(1)Y
  - Particle content (Point particles):
    - 3 fermion (quark & Lepton) Generations
    - No Right-handed neutrinos → Massless Neutrinos
  - Symmetry breaking: one Higgs doublet

- No candidate for Dark Matter
- SM does not include gravity.

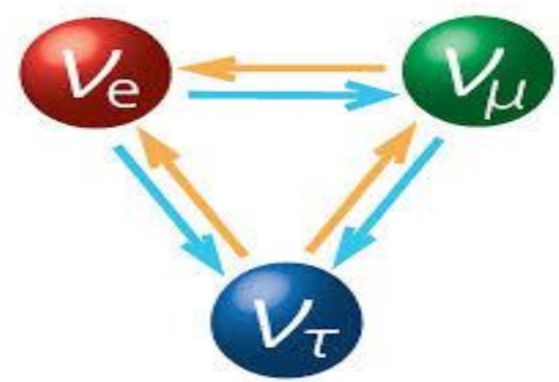
Evidence for Physics beyond SM

Three firm observational evidences of new physics BSM:

1. <u>Neutrino Masses</u>

   The discovery of the neutrino oscillations in the nineties of the last century in Super-Kamiokande experiment implies that neutrinos are massive.

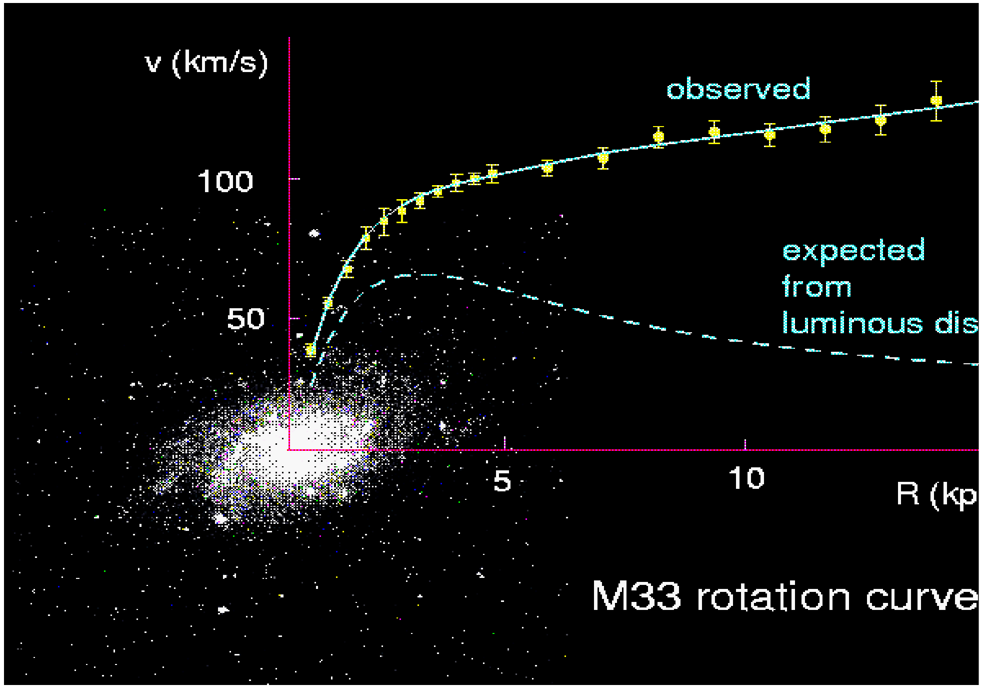
$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= \delta_{\alpha\beta} \\
&-4\sum_{i<j} \mathrm{Re}[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}]\sin^2\left[\frac{\Delta m^2_{ij}}{4E}L\right] \\
&+2\sum_{i<j} \mathrm{Im}[U_{\alpha i}U^*_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin\left[\frac{\Delta m^2_{ij}}{2E}L\right]. \quad (8)
\end{aligned}
$$



- n_e , n_μ , n_τ are not mass eigenstates
- Mass states are n_1 , n_2 , and n_3
- Lepton number not conserved

2. Dark Matter

- Most astronomers, cosmologists and particle physicists are convinced that 90% of the mass of the Universe is due to some non-luminous matter, called `Dark Matter/Energy'.



- The explanation for these flat rotation curves is to assume that disk galaxies are immersed in extended dark matter halos

Standard Model of Cosmology

- In 1915 Einstein realized that GR:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

predicted an expanding universe which was in conflict with his philosophical belief.

- He introduced the cosmological constant (Λ) to force the universe to be static:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- In 1929 Hubble showed that the universe is expanding. Einstein immediately dropped the cosmological constant, calling it *"the biggest mistake of my life"*.

- In 1920's Friedman used the GR to create a theory of homogeneous and isotropic universe with the metric

$$ds^2 = dt^2 - a(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin\theta^2 d\phi^2) \right]$$

with $k = 1, -1, 0$ for closed, open and flat Friedman universe.

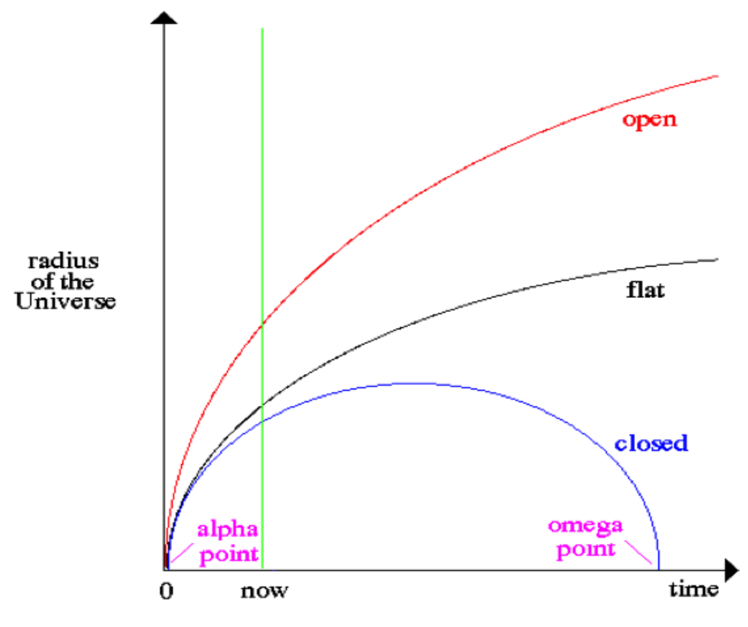
- The evolution of the scale factor $a(t)$ is given by Einstein equations:

$$\begin{aligned} \ddot{a} &= -\frac{4\pi}{3} G(\rho + 3p) a, \\ \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} &= \frac{8\pi}{3} G\rho. \end{aligned}$$

where ρ is the energy density of mater in the universe and p is its pressure.

Cosmological Critical Density

- Cosmologists express the mass density averaged over the Universe, ρ, in units of the critical density, $\rho_c \sim 10^{-29}\ g\ cm^{-3}$
- $\rho_c = 3\ H^2/M_P^2$ (M_P is reduced Planck mass, H is Hubble parameter)
- The ratio $\Omega = \rho/\rho_c$ is defined
- If $\rho > \rho_c$ ($\Omega > 1$) the Universe expands to a maximum, then contracts leading to an inverse Big Bang (closed Universe).
- If $\rho < \rho_c$ ($\Omega < 1$)) the Universe expands forever (open Universe).
- $\Omega = 1$: the geometry of the Universe is flat.



Beyond General Relativity

- General Relativity is a beautiful scheme for describing the gravitational field.

- Despite the important experimental success of General Relativity, there are several theoretical reasons indicating that gravitational phenomena may change radically from the predictions of Einstein's theory at very short distances.

- A main motivation comes from studies of unifying all fundamental forces in the framework of a consistent quantum theory, that leads to a full description of the early universe.

- There are some urgent issues in cosmology which require a knowledge of the fundamental theory, beyond the GR:

    - Dark Energy (late expansion of universe)
    - Dark matter
    - Inflation
    - Creation of particles after inflation,

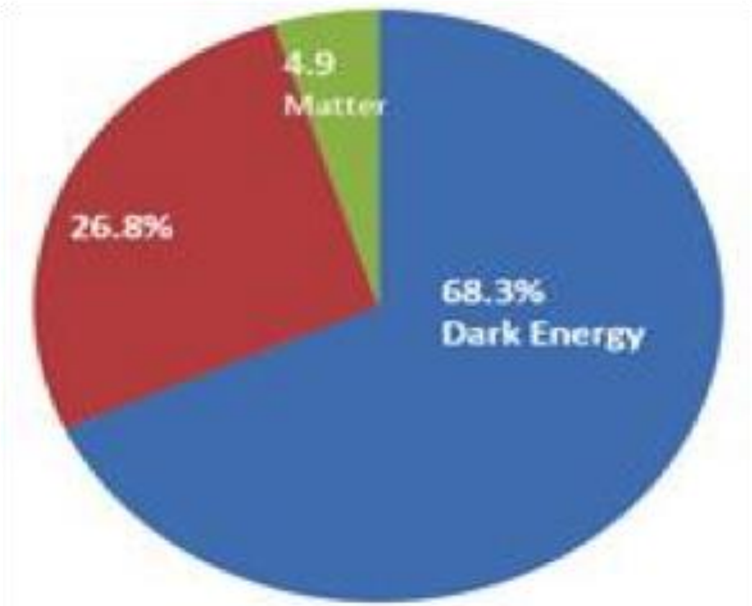
Particle Physics - Cosmology Interface

- Dark Matter and Dark Energy have established a profound connection between Particle Physics and Cosmology.
- Particle Physics explores the fundamental building blocks of the universe, seeking to identify dark matter particles.
- Cosmology investigates the large-scale structure and evolution of the universe, with dark energy influencing its fate.
- The interplay between these fields enhances our understanding of both the smallest and largest scales in the cosmos.
- The early Universe is an ideal testing ground for new fundamental theories.
- Challenging problems of cosmology: baryon asymmetry of the Universe, dark matter and dark energy, etc., needs theoretical concepts from particle physics

Universe as we know it today

- Most astronomers, cosmologists and particle physicists are convinced that 90% of the mass of the Universe is due to some non-luminous matter, called `Dark Matter/Energy‘

- Ordinary matter is characterized by its tendency to clump together and often emits light.
- Dark matter is an elusive form of mass that remains undetected as it does not emit light. Its existence is inferred from the gravitational influences it exerts.
- Dark energy is a hypothetical form of energy that appears to be the source of a repulsive force, causing the acceleration of the universe's expansion.

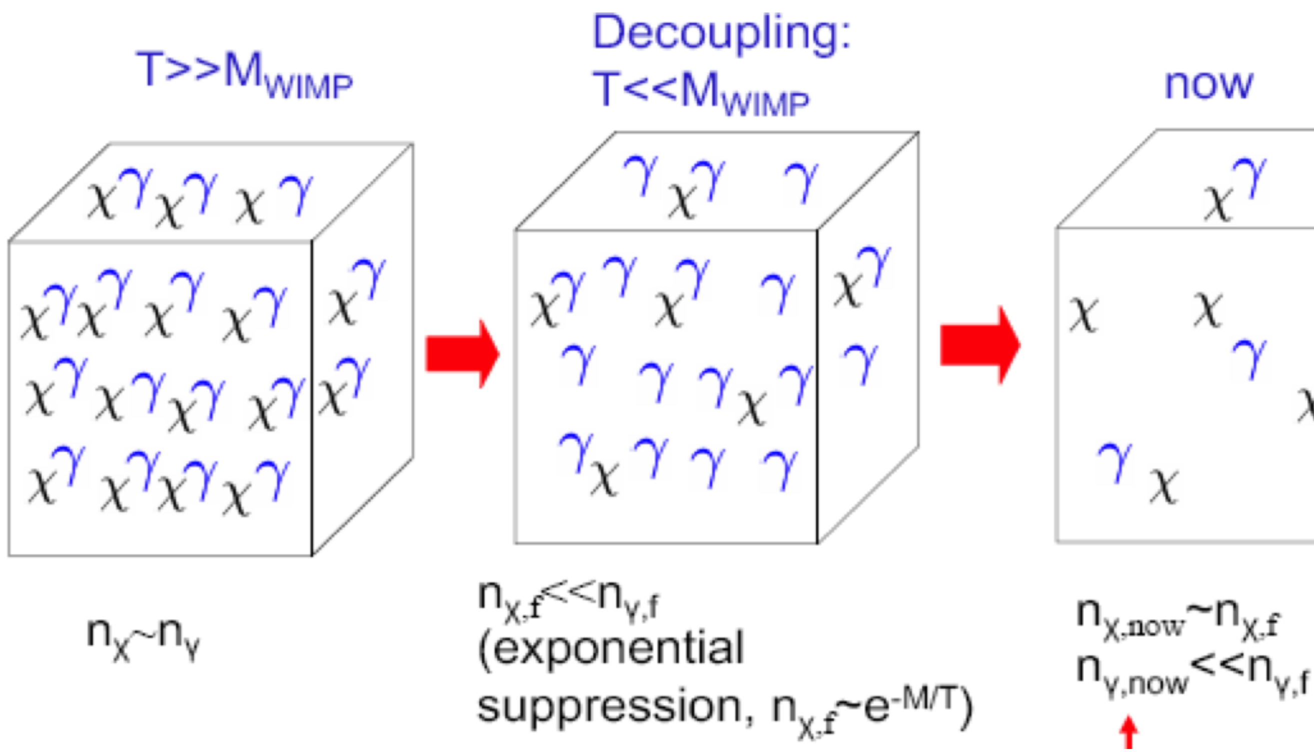


What is DM made of ?

- The Big-Bang nucleosynthesis, which explains the origin of the elements, sets a limit to the number of baryons that exists in the Universe: $\Omega b < 0.04$.
- Dark Matter must be non-baryonic.
- The properties of a good Dark Matter candidate:
  - stable (protected by a conserved quantum number),
  - relic abundance compatible to observation,
  - electrically neutral, no color,
  - weakly interacting (i.e., WIMP).
- No such candidate in the Standard Model.
- SM describes the interactions between quarks, leptons & the force carriers very successfully.
- NP beyond SM (SUSY) provides this type of candidate for dark matter

Dark Matter Candidates

- WIMPs are very interesting candidates for dark matter in the Universe.
- They were in thermal equilibrium with the SM particles in the early Universe, and decoupled when they were non-relativistic.

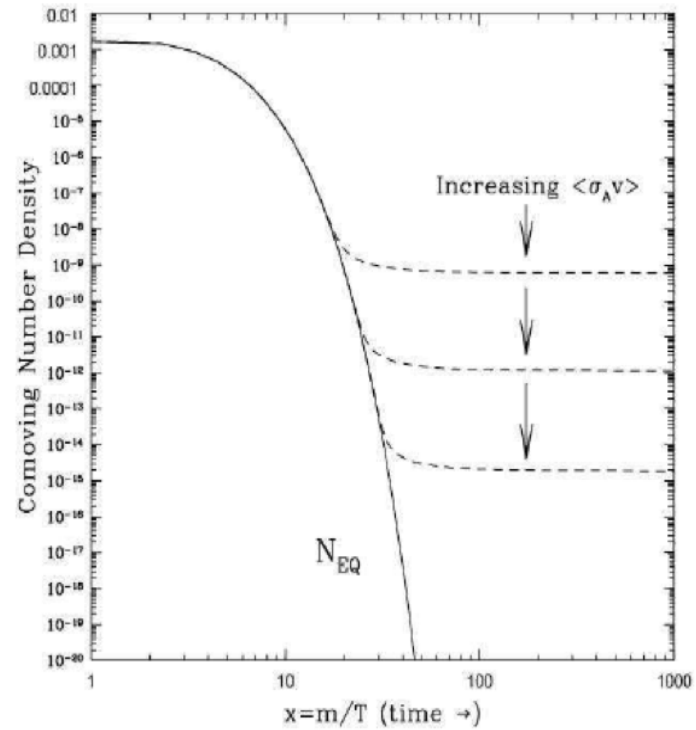


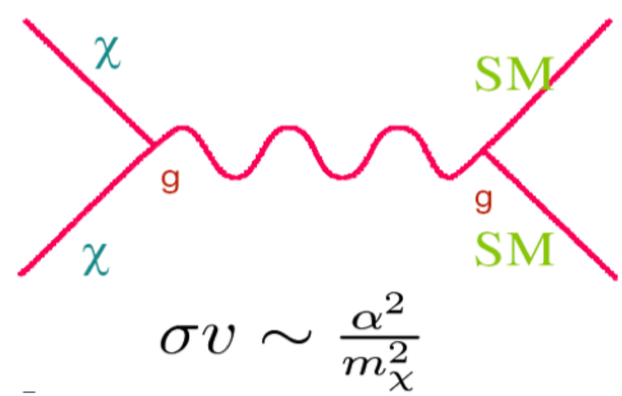
Dark Matter Relic Abundance

- WIMP starts out in thermal equilibrium. It freezes out due to the expansion of universe.
- With standard history, we can compute the relic density today.

$$\Omega_{DM} \sim \frac{7 \times 10^{-27} cm^3 s^{-1}}{<\sigma_{ann} v>}$$

- For WIMP with $\sigma \sim \alpha^2/m_{weak}^2 \Rightarrow \sigma \sim 10^{-9}\ GeV^{-2} \Rightarrow <\sigma_{ann} v> \sim 10^{-26}\ cm^3 s^{-1}$.
- This number is close to the value we need to obtain the observed density of the Universe.
- This is a possible hint that new physics at the weak scale provides us with a reliable solution to the dark matter problem





Dark Energy

- Dark Energy, an unexplained force, is causing galaxies to move away from each other at an accelerated rate, counteracting the gravitational pull.
- It acts like anti-gravity.
- Space between clumps is not empty : Dark Energy !
- Dark Energy density is the same at every point of space : ”homogeneous”.

Ω_b = 0.05	visible clumping
Ω_{DM} = 0.27	invisible clumping
Ω_{DE} = 0.68	invisible homogenous

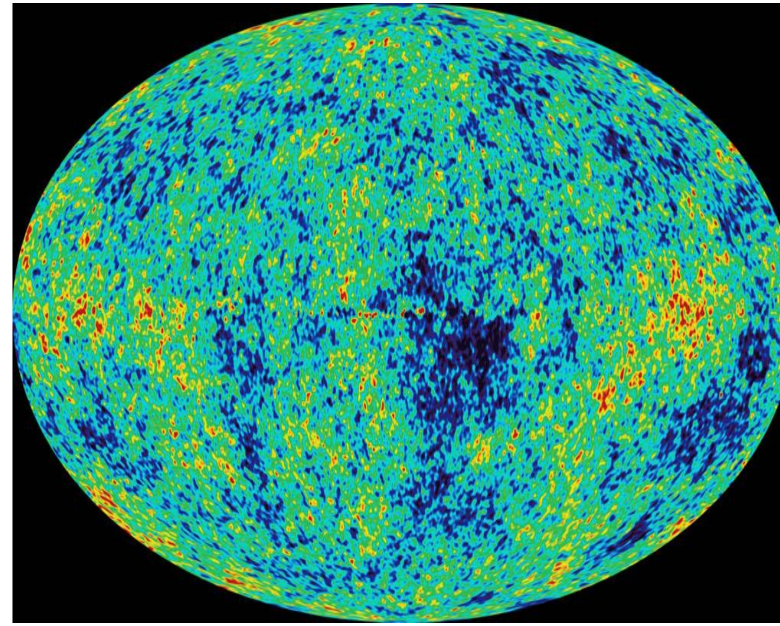
- Predictions for dark energy cosmologies – The expansion of the Universe accelerates today !
- Increase of Ω_{DE} causes accelerated expansion of the Universe.
- Change from deceleration to acceleration a few billion years ago

Evidence for Dark Energy

- A supernova is a huge explosion in space when a star becomes extremely bright for a short time. It happens when a star reaches the end of its life and releases a lot of energy.
- Type Ia supernovae are standard candles, allowing precise distance measurements.
- Distant Type Ia supernovae appear fainter than expected, indicates the universe is expanding at an accelerating rate.
- Supernovae have played a crucial role in providing evidence for the accelerated expansion of the universe.
- Nobel Prize in Physics 2011 awarded for the discovery of accelerating cosmic expansion.

Evidence for Dark Energy

- The CMB provides indirect evidence for the existence of dark energy through its influence on the large-scale structure and expansion of the universe.
- The CMB is a faint glow of radiation left over from the early universe, originating about 380,000 years after the Big Bang when the universe became transparent to photons.



- CMB indicate that the universe is close to flat: $\Omega_{total} = 1$
- Total amount of matter in universe as measured from the CMS accounts for only about 30%.
- This implies existence of an additional for of energy to account for the remaining 70%

What is Dark Energy ?

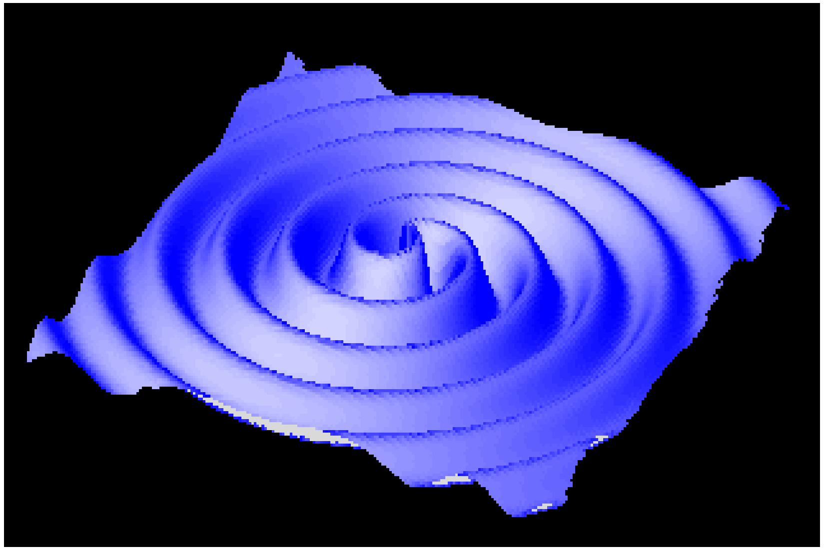
- Dark energy is an unknown form of energy which permeates all of space and tends to accelerate the expansion of the universe.

- Dark energy is the most accepted hypothesis to explain the observations since the 1990s indicating that the universe is expanding at an accelerating rate.

- Two important candidates:
    - Cosmological Constant
    - Quintessence

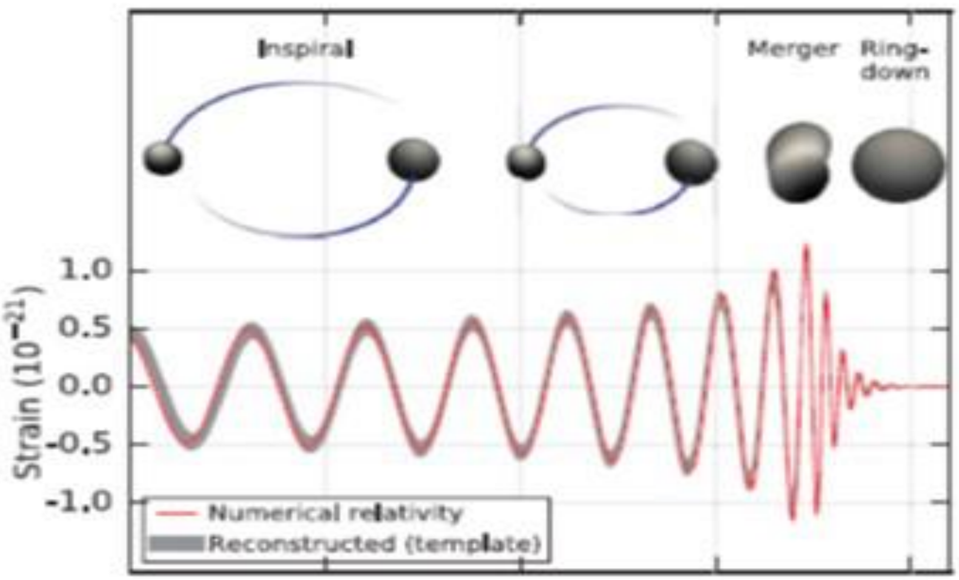
Gravitational Waves

- When a charge accelerates, the electric field surrounding the charge redistributes itself. This change in the electric field produces an electromagnetic wave, which is easily detected.
- When the curvature varies rapidly due to motion of the object(s), curvature ripples are produced. These ripples of the space-time are Gravitational-waves.
- Gravitational-waves propagate at the speed of light.
- The stretching and shrinking is on the order of 1 part in 10^{21}. Therefore, gravitational waves would be difficult to detect.
- Large astronomical events could create measurable spacetime waves such as the collapse of a neutron star, a black hole or the Big Bang.



Gravitational Wave Experiments

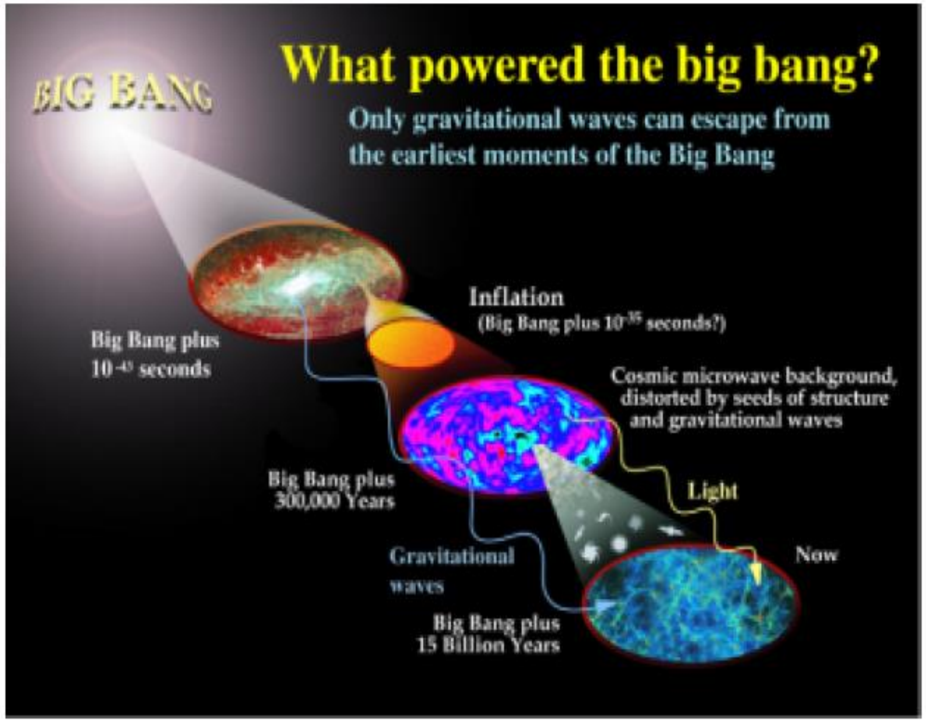
- **LIGO collaboration considered gravitational waves produced from two massive black holes of 36 and 29 solar masses, merged to form a spinning 62-solar mass black hole, about 1.3 billion light years away.**



BH - BH merger,

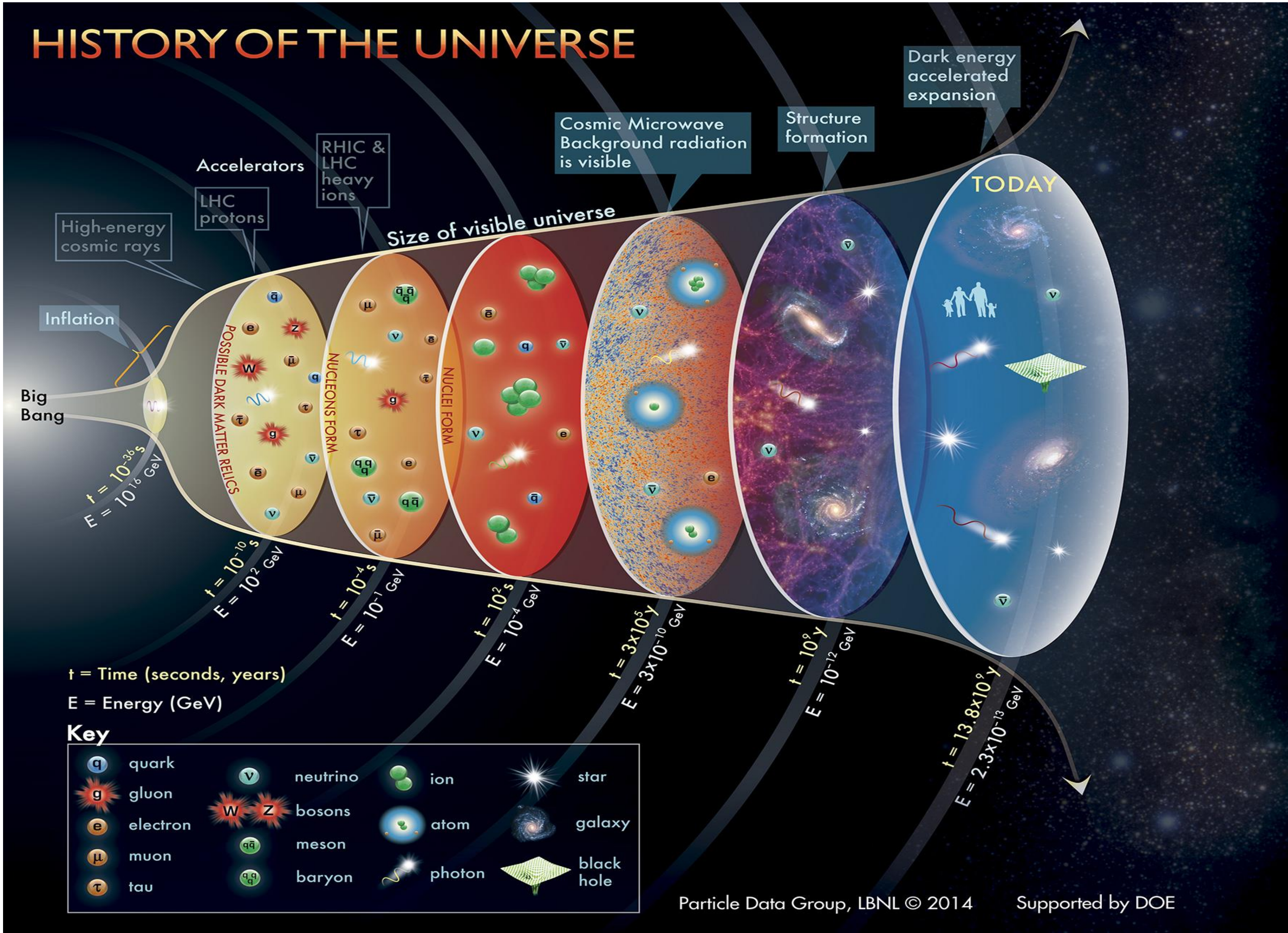
GW150914

- **Since then, countless GW events have been detected by observatories across the globe.**

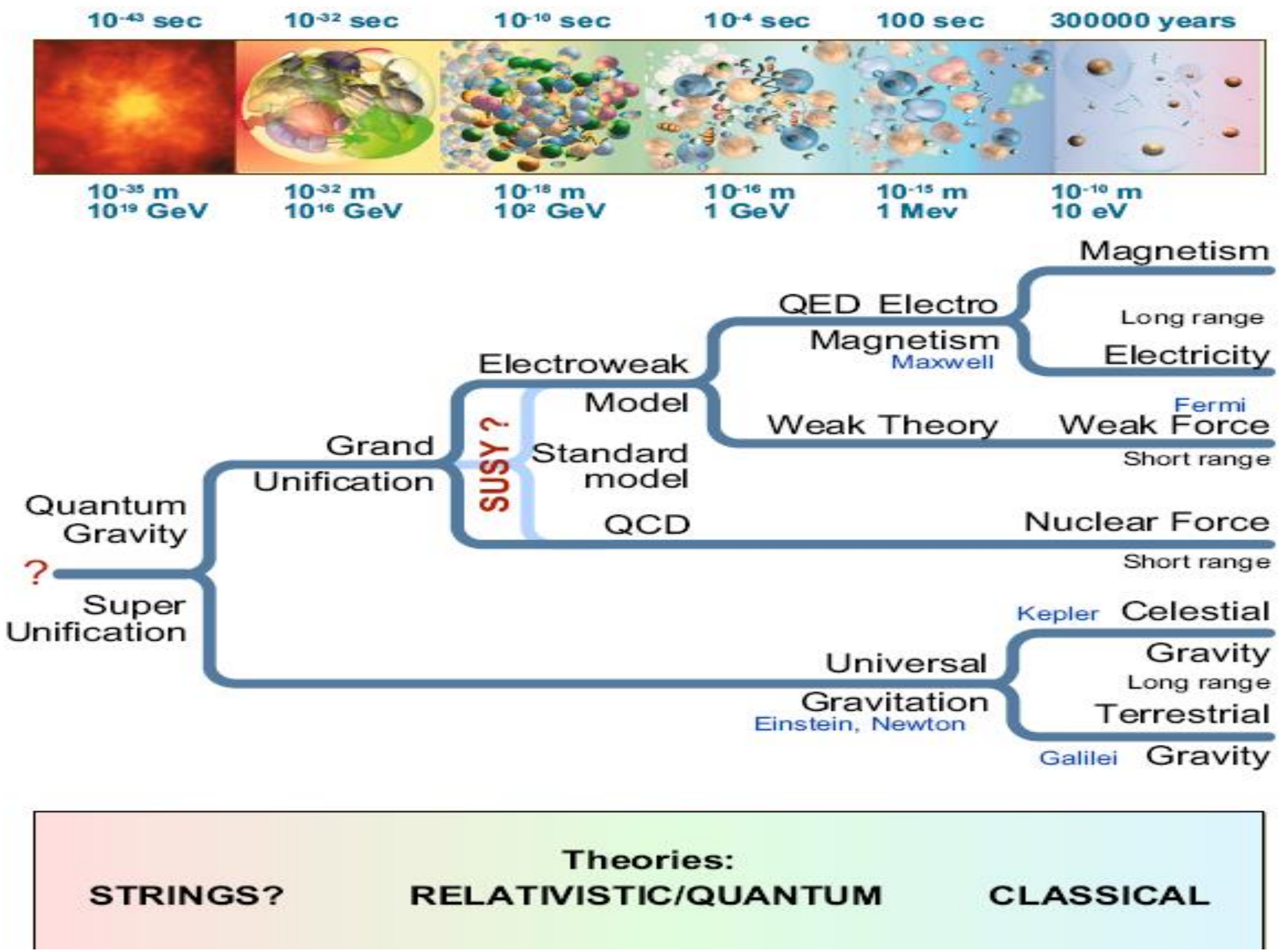


- Stochastic GWs arise from a large number of random, independent events combining to create a cosmic GW background.
- The Big Bang and Cosmic Inflations are expected to be prime candidates for the production of the many random processes needed to generate stochastic GWs, which may carry information about the origin and history of the universe.
- Similar backgrounds could be produced by a combination of many simultaneous inspirals, bursts, or continuous signals from throughout the Universe.

Unveiling the Universe



High Energy Physis



Conclusions

- Discovery of any New Physics beyond the SM of particle physics and the SM of cosmology would be a revolution of physics in 21st century.
- The importance of the LHC for the future of high energy physics cannot be overemphasized.
- The detection of GWs has initiated the era of GW cosmology and opened a new window to investigate the very early stages of the evolution of the Universe.
- Underground physics is crucial to detect Dark Matter. Even if it is discovered LHC, only their direct detection due to their presence in our galactic halo will confirm that they are the sought-after DM of the Universe.

Thank you