# Particles and the Universe

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# Structure of matter and fundamental interactions

Macroscopic matter → Molecules → Atoms
→ Electrons + nucleons

e n,p

+ plethora of "*elementary*" particles

**However, there is a small number of "*really*" elementary particles which construct all other particles**

**The components of matter interact with four fundamental interactions**

# The fundamental interactions

(i) Strong nuclear 1

(ii) Electromagnetic $10^{-2}$

(iii) Weak nuclear $10^{-5}$

$n \rightarrow p\, e^- \,\bar{\nu}_e$

(iv) Gravitational $10^{-38}$

Microscopic range

Infinite range

Nuclear and subnuclear phenomena

Macrocosmos

# Classification of particles

**Particles are classified according to participation in strong interactions:**

**Particles** → Leptons: Q = 0, Q = -1 $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$ + anti-particles

**Particles** → Hadrons:
- Baryons: p, n, … (fermions)
- Mesons: $\pi^0$, $\pi^\pm$, … (bosons)

**Particle reactions**: a b → c d …

**Conservation laws**: Energy, momentum, angular momentum, electric charge → $e^-$ stability

**Non absolute**:
- Baryon number → p stability
- e- lepton number
- μ- lepton number
- τ- lepton number

# The constituents of hadrons

- Hadrons consist of "quarks"

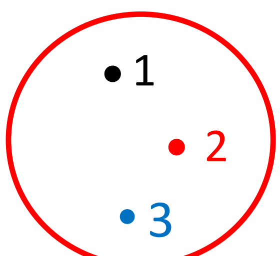
"flavors" Q = 2/3, Q = -1/3 $\binom{u}{d}$ $\binom{c}{s}$ $\binom{t}{b}$ + anti-particles

Each "quark" → three "colors": u → $u_1\ u_2\ u_3$

Color confinement:

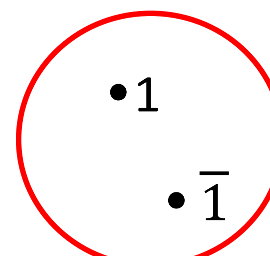
Baryons →

$p = u_1\ u_2\ d_3$




Mesons →

$\pi^0 = u_1\ \bar{u}_1 + \ldots$



# Conservation laws ↔ Symmetries

- Group of transformations leaving the dynamics "invariant": $g, g' \in G$ (Lie group) $\Rightarrow gg' \in G$ (manifold)

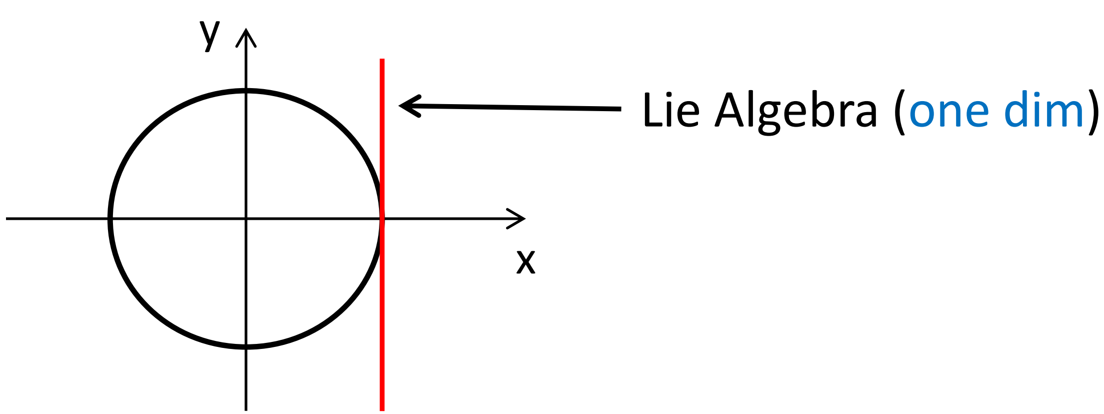
$$\forall \boldsymbol{g} \in \boldsymbol{G}: \boldsymbol{\mathcal{L}}(\boldsymbol{g}\boldsymbol{\psi}_1, \boldsymbol{g}\boldsymbol{\psi}_2, \dots) = \boldsymbol{\mathcal{L}}(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2, \dots)$$

The generators of such a group ⇔ Conserved quantities

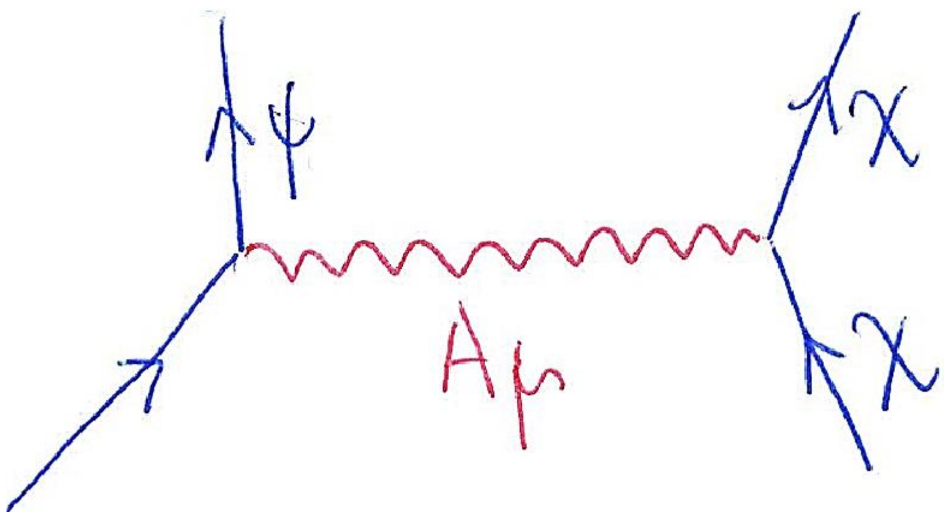
(The "generators" span the Lie Algebra, i.e. the tangent space at the identity element of $\boldsymbol{G}$)

Conservation of electric charge, baryon number, e- lepton number,… → $\boldsymbol{e}^{\boldsymbol{i\theta}} \in \mathbf{U}(\mathbf{1})$ symmetries

$\mathrm{U}(1) =$ circle (one dim manifold) → One generator



If we promote $U(1)_{EM}$ to local (gauge) ⇒ A gauge field $A_\mu$ (photon), carrier of electromagnetic interactions.




$m_\gamma = 0$ ⇒ infinite range of EM interactions

The other U(1)'s (baryon, lepton numbers) remain "global" → they do not imply any "interaction", only conservation laws (may not be absolute).

# Electroweak theory

# (Weinberg, Salam, Glashow 1967)

A gauge theory with Group **$SU(2)_L \times U(1)_Y \supseteq U(1)_{EM}$ ($SU(2)_L \ni U$** (2x2 matrices) with **$U^\dagger U = 1$, $\det U = 1$** and act on the (L-handed) quark/lepton doublets. As a manifold is a 3 dim sphere in 4 dims.**)**

$\Rightarrow$ Four generators $\rightarrow$ Four gauge fields

82GeV 92GeV

$\gamma$ $W^+$ $W^-$ $Z^0$ (CERN, Rubbia 1984)

photons Carriers of weak interactions

$W^\pm$, $Z^0$ acquire masses from the spontaneous breaking

**$SU(2)_L \times U(1)_Y \xrightarrow[\langle\varphi\rangle\neq 0]{} U(1)_{EM}$** ($\varphi =$ Higgs field) $\rightarrow$ microscopic range of Weak interactions .

The associated Higgs Boson $\rightarrow$ discovered in 2012 at CERN with $m_H \approx 125$ GeV

# Strong Interactions

Gauge theory with Group **$SU(3)_c$** $\ni$ **U** (3x3 matrices) with **$U^\dagger U = 1$, $\det U = 1$** acting on the three 'colors' $\Rightarrow$

**Quantum Chromodynamics (QCD)**

$SU(3)_C$ is 8 dim → Eight Gauge bosons (Gluons), the carriers of Strong Interactions.

$SU(3)_C$ is unbroken → Gluons are of zero mass, but "Strong Interactions" are of microscopic range because of "Confinement" of color:

The asymptotic states are "colorless"

**QCD** → Asymptotic freedom (force gets weaker at smaller distances )
Gross/Politzer/Wilczek (Nobel Prize 2004)

# Supersymmetric Standard Model

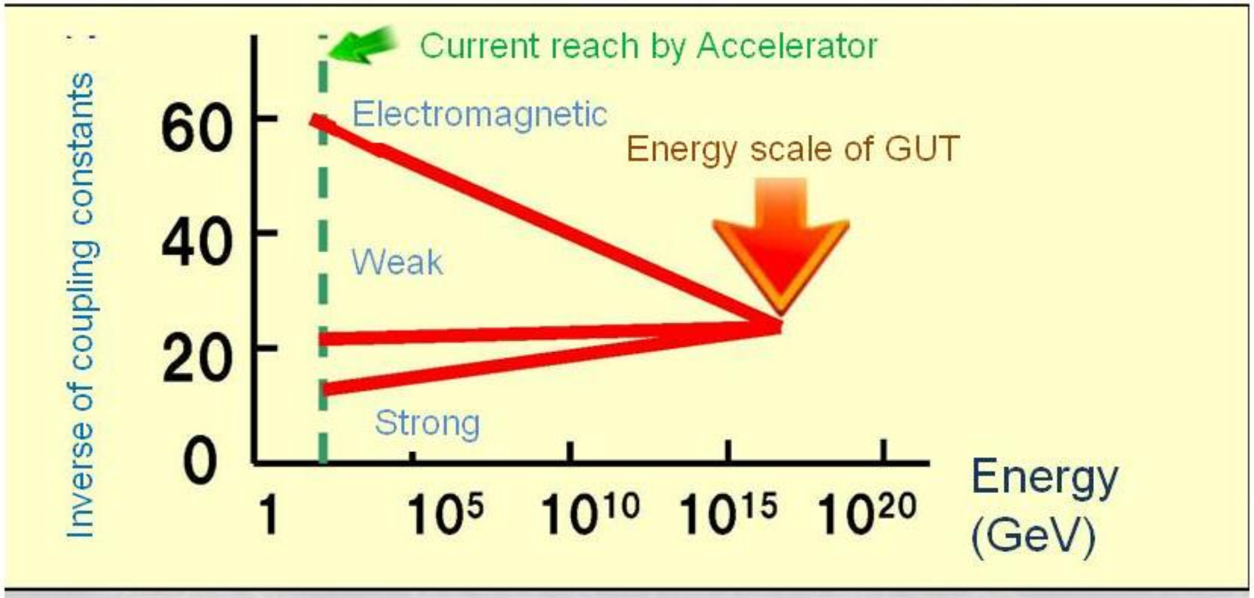
Putting everything together

→ "Standard Model" with **$G = SU(3)_C \times SU(2)_L \times U(1)_Y$**

Imposing "Supersymmetry" which doubles the particles (a boson for each fermion and a fermion for each boson)

⇒ "Supersymmetric Standard Model"

# Unification of the 3 interactions

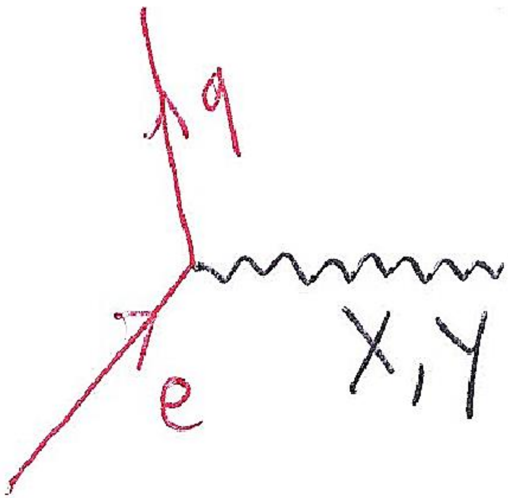



The Unification requires "Supersymmetry" if we assume " A great desert".

So we can assume that at Unification a larger gauge group emerges (the smallest possible is **SU(5)**)

$$SU(5) \xrightarrow[M_X \sim 10^{16}GeV]{<\phi_{24}>} SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow[M_W \sim 100GeV]{<\phi_5>} SU(3)_C \times U(1)_{EM}$$

⇒ Existence of 12 more gauge fields (X, Y) with $m_{X,Y} \sim 10^{16}$ GeV → violate "Baryon number"




⇒ "Proton decay" $\mathbf{p \to e^+ + \pi^0}$, for example "Super-Kamiokande" ⇒ Lower bound on proton lifetime $\sim 10^{34}$ years

GUT is consistent with

$\alpha_s \equiv \frac{g_3^2}{4\pi} \approx 0.1184$ and $\sin^2\theta_W \equiv \frac{e^2}{g_2^2} \approx 0.23116$

It explains the quantization of "electric charge" and predicts the existence of "Magnetic monopoles".

It can provide small masses to neutrinos and thus explain "*v* oscillations".
In some cases, it predicts Cosmic Strings, domain walls, …

# Microcosmology

**Is the study of the initial stages of universe evolution in accordance with particle physics**

**SBB cosmology** → The universe began "$13.8 \times 10^9$ years" ago with a "BIG BANG". It was concentrated within an "infinitesimal" volume with "infinite" T and space-time emerged together with matter.

After "Big Bang" and for $t \geq t_{Pl} = 10^{-43}$ sec, quantum fluctuations of "gravity" ceased →

"Classical Gravity" (The general relativity theory) + GUTs for the other 3 interactions (quantum + relativistic)

# Phase transitions of the universe

As the universe expanded and cooled after the BIG BANG, it underwent a series of "**phase transitions**"

**SU(5)**

**initial "light"**

≡ soup of massless quarks, leptons, X, Y, …

$T \sim 10^{16}$ GeV

$t \sim 10^{-37}$ s

**X,Y become massive**

**$SU(3)_C \times SU(2)_L \times U(1)_Y$**

(i) creation of **Baryon Asymmetry** (violation of Baryon number C, CP, lack of thermal equilibrium)

(ii) creation of **Magnetic Monopoles**

$T \sim 100$ GeV

$t \sim 10^{-10}$ s

**$SU(3)_c \times U(1)_{EM}$**

$T \sim 1$ GeV

$t \sim 10^{-4}$ s

**Confinement**

(quarks → hadrons)

$T \sim 1$ MeV

$t \sim 180$ s

**nucleosynthesis**

(successful prediction of abundances of H, D, $^3He$, $^4He$, $^7Li$)

$t\sim$ 3000 yr

$t\sim$ 300 000 yr

$t\sim$ 200 000 000 yr

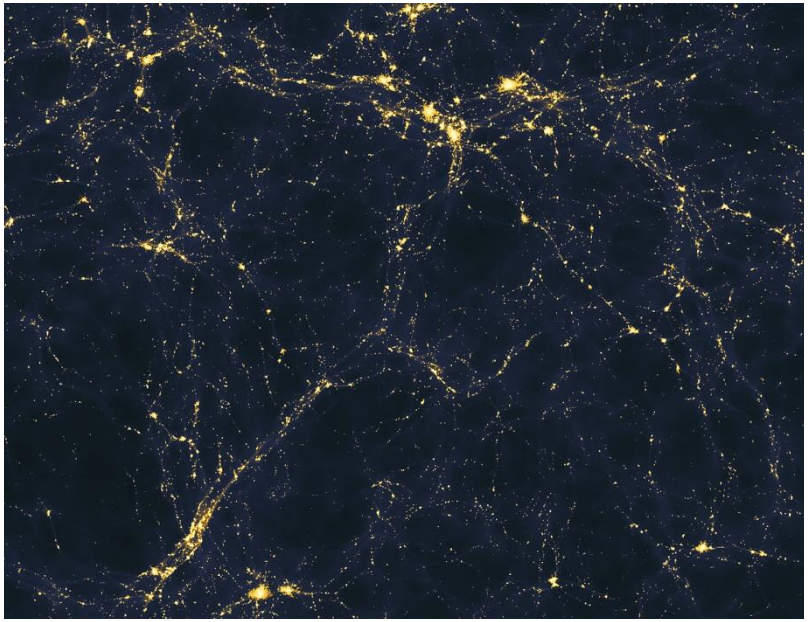
**Matter domination**

**Decoupling of matter and radiation**

**structure formation** (galaxies, filaments, great voids, …)

(i) **Creation of atoms**

(ii) **Creation of Cosmic Microwave Background Radiation (CMBR)** of **2.7 K,** "echo" of initial light (1964)



50 Million light yrs

# Successes of
# BIG BANG cosmology + GUTs

(i) Expansion of the Universe (Hubble's law)

(ii) Generation of BAU (excess of baryons over antibaryons) by the X,Y decay at GUT transition

(iii) Successful "Nucleosynthesis"

(iv) CMBR

# Shortcomings

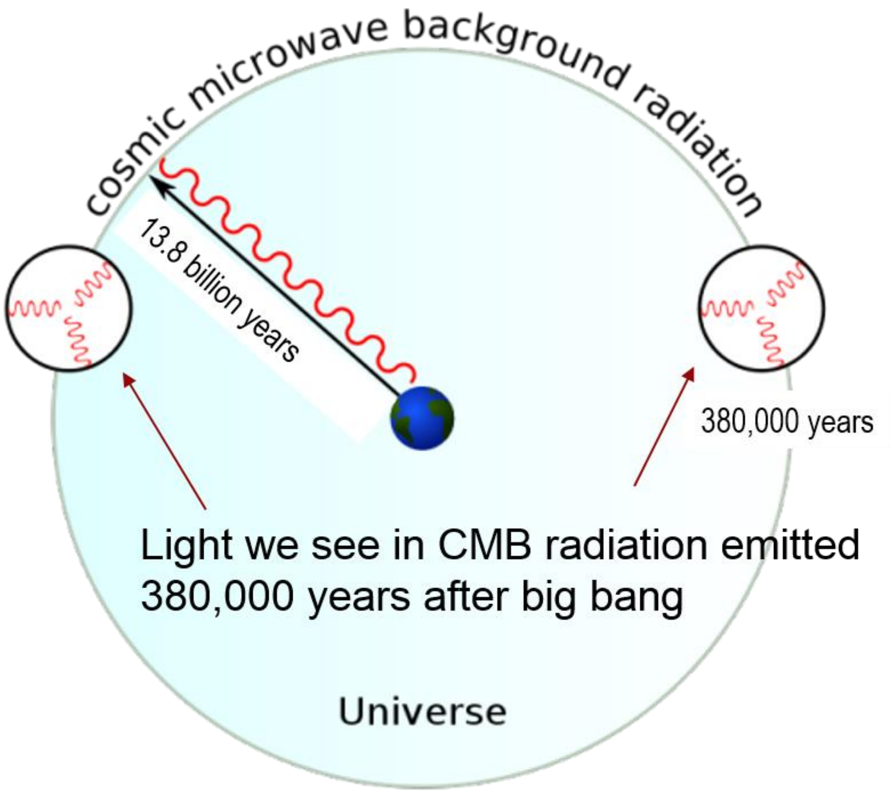
i. “**Magnetic Monopole Problem**”: During GUT transition → Magnetic Monopoles = topologically stable localized deviations from vacuum with radius **~ $M_X^{-1}$, energy $M_X/\alpha_G$** and net magnetic charge. Their density is too large at Nucleosynthesis destroying its successful predictions.

ii. Planck measurements on CMBR + other observations → **Present universe is flat** (of zero 3-dim curvature) within 1% (**$\Omega = \rho/\rho_C = 1 \pm 0.01$**). So following the evolution backwards in time → It must have started being flat to a “great accuracy”.

**Question**: How come the universe started flat to many many decimals, although it could have any curvature positive or negative? (**Flatness problem**)

# Shortcomings

iii. "**Horizon Problem**": CMBR emitted at $t \approx 300\,000$ yr from the "last scattering surface" at a distance $\approx 13.8 \times 10^9$ light yr.
**COBE/WMAP/Planck** → The T of CMBR is the same from all directions with accuracy $\delta T / T = 6 \times 10^{-6}$



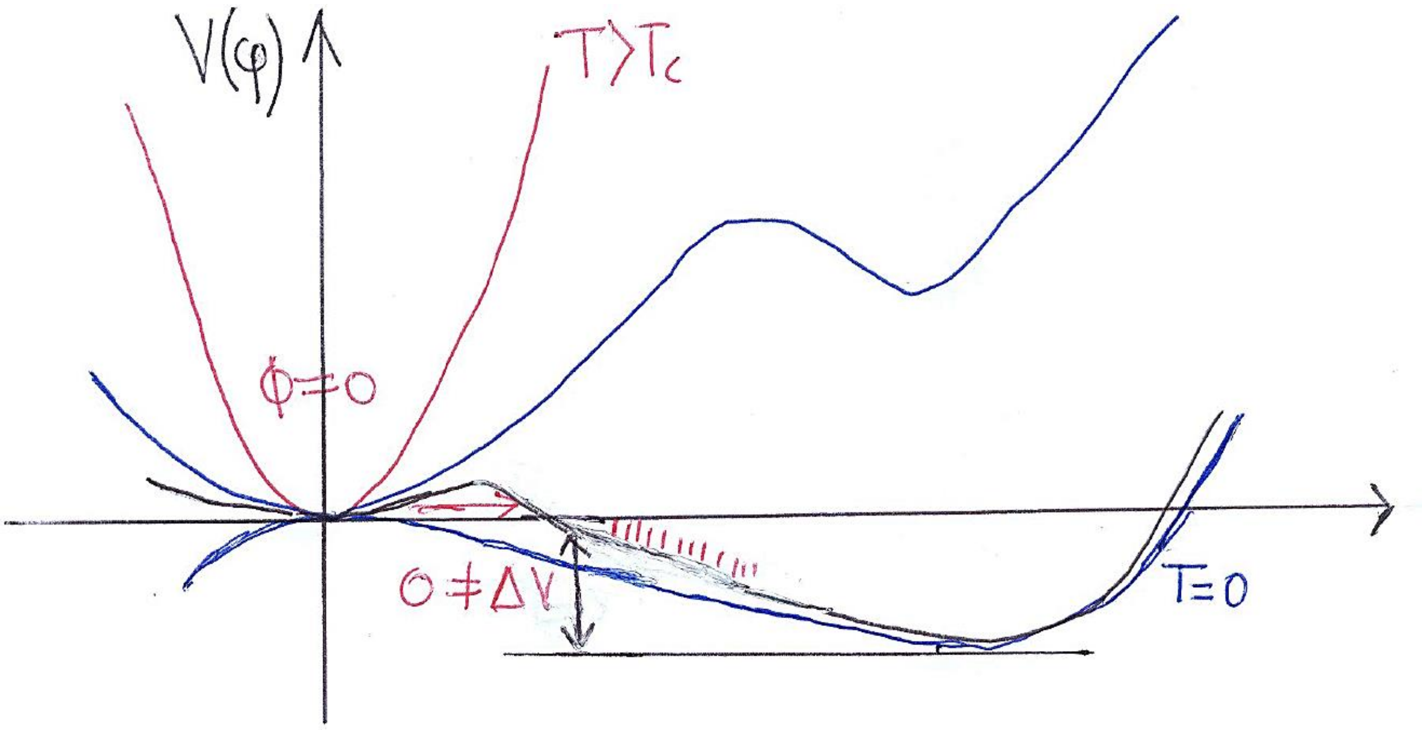

**"last scattering surface"**

Regions that emitted CMBR had no time to communicate causally after the BIG BANG ($t = 0$) before emitting radiation.

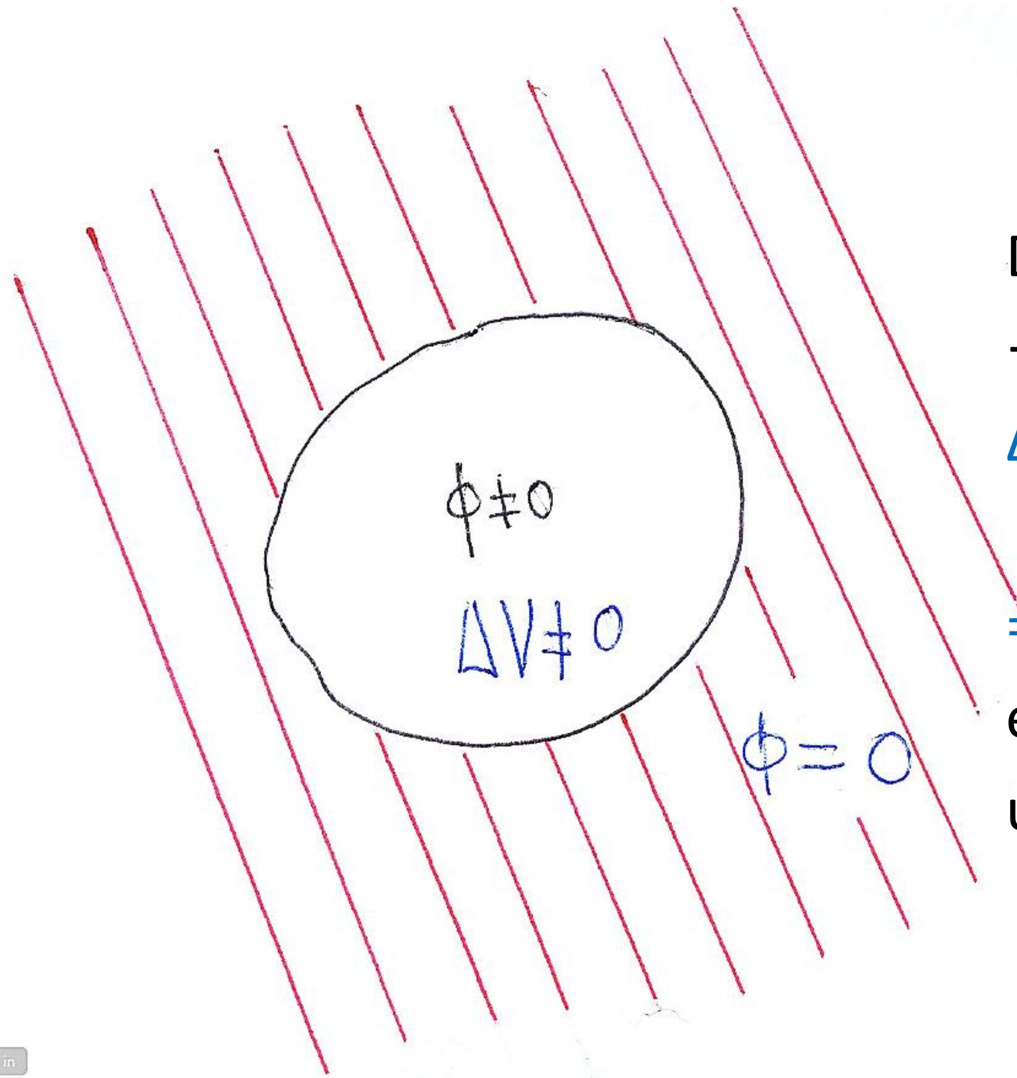
**How come thermodynamic equilibrium was established?**

# Cosmological Inflation
## a period of exponential expansion

- Solves all three puzzles in one go




ϕ = Inflaton (a Higgs field connected with GUT breaking)




Due to "quantum tunneling"

→ A bubble is created with $\phi \neq 0$, $\Delta V \neq 0$, almost constant.

⇒ The bubble expands exponentially fast and covers our universe several times.

# Inflation automatically solves all puzzles

i. "Magnetic Monopoles" are diluted so that they do not cause any problem.

ii. Exponential expansion can bring to zero any preexisting "curvature"

iii. It can also establish "causal communication" between regions of the "last scattering surface"

On the top of these, it transforms the quantum fluctuations of the "inflaton" into classical metric perturbations

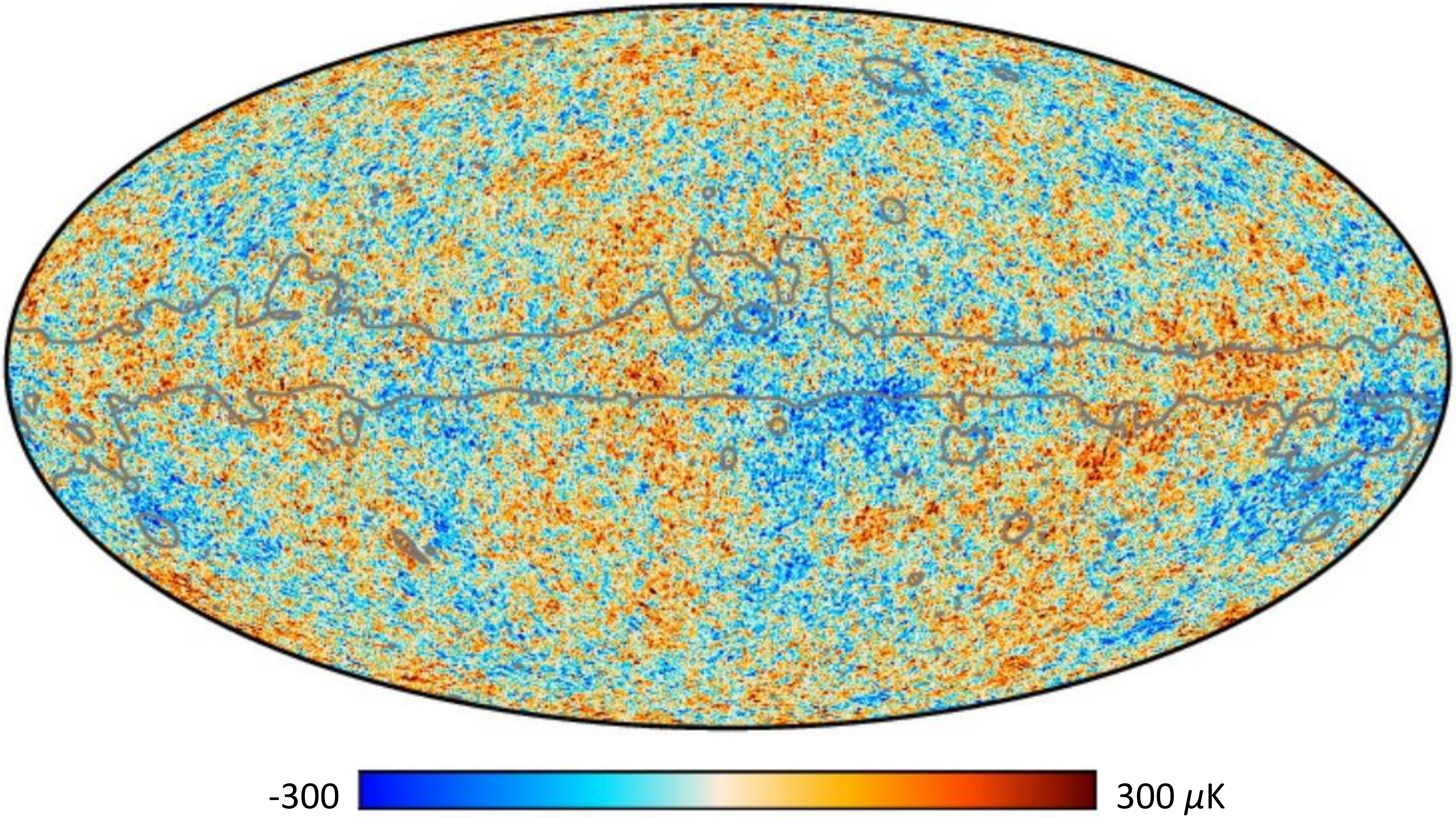
$\Rightarrow$ Density perturbations $\delta\rho/\rho \approx 5.6 \times 10^{-5}$ (primordial)

(a) Grow in the late universe to become non-linear → Formation of structure (galaxies, …) via gravitational collapse of matter.

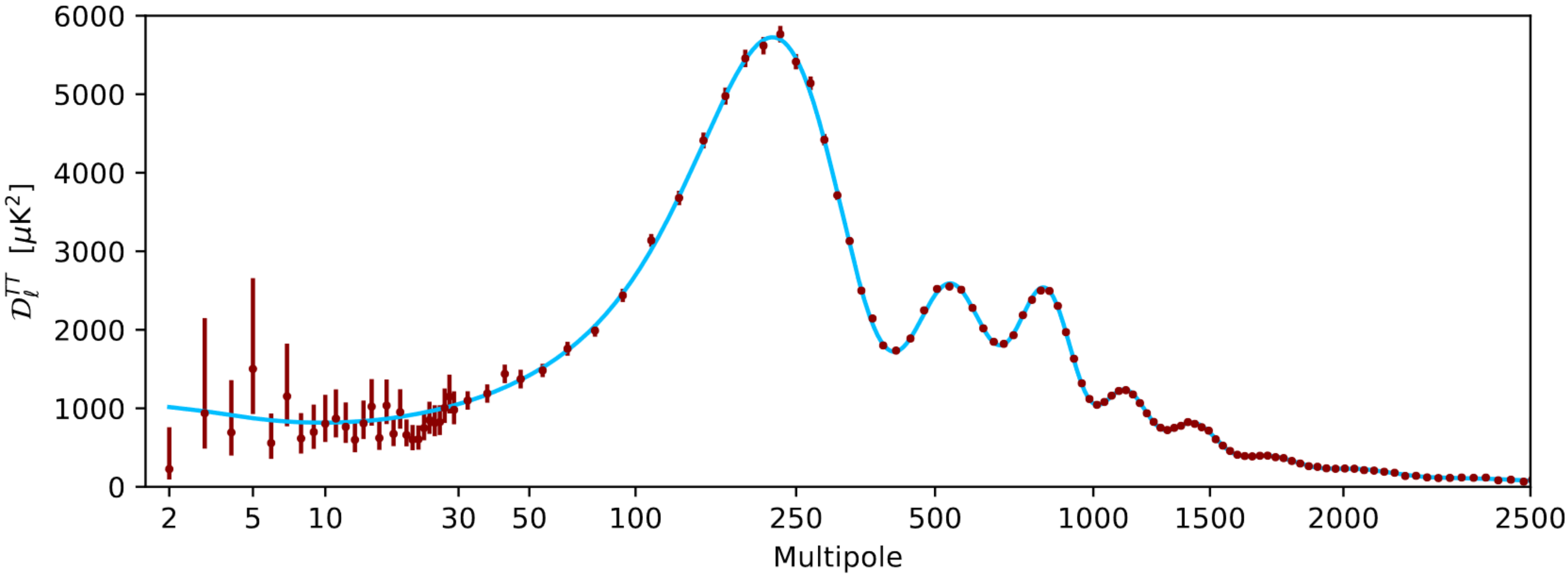
(b) Generate the "temperature fluctuation" $\delta T/T \approx 6 \times 10^{-6}$ in the "CMBR" measured by COBE/WMAP/Planck.

The predictions of "inflation" can fully agree with all experiments!

# Planck 2018 results



# Planck 2018 results



# Dark Energy

Inflation:

(i) present universe is exactly flat ($\Omega=\rho/\rho_C = 1$) and thus will keep expanding for ever.

(ii) 'Matter" is only 27% of the universe

Question: What is the rest 73% made of?

In 1997-8, observations on "Supernovae Ia" (which we see now as they were in previous time) → The expansion then was slower than it is today → The expansion of the universe is "accelerating"!

This can be explained if more than 2/3 of the energy in the universe is in the form of "Cosmological Constant", i.e. it is not diluted by the expansion (negative pressure) exactly as in "inflation".

Question: Are we about to enter a "new" Inflationary phase?

WMAP/Planck confirm that 73% of the energy density in the universe in the form of "Dark Energy", i.e. something close to a Cosmological Constant.

# Dark Matter

Study of Nucleosynthesis + Planck result → Baryonic (visible) Matter is only 4.84%. So, about 27% - 5% ≈ 22% of the universe is “DARK MATTER”.

Question: What is the nature of Dark Matter?
It was shown that “Dark Matter” should be mainly “cold”, i.e. consisting of particles with $m \neq 0$ which have small velocities and interact with the other particles only “gravitationally”.

What could the “Dark Matter” particles be?
(i) LSP = the lightest supersymmetric particle
This is protected by “R-parity” symmetry from decaying ⟹remains in the universe for ever (many calculations of its relic density have been performed)
(ii) **Axions** (connected with the problem of CP violation in Strong Interactions
(iii) …
Can we detect Dark Matter?
The “LSPs” can be detected by their scattering by “protons“
Many experiments in progress → No positive results so far
Detection of Axions is even harder.

# Quantum Gravity

So far, we considered "Gravity" at the "classical" (non-quantum) level and separately from the other 3 interactions which are described by "relativistic Quantum Field Theory" and possibly unified in a GUT.

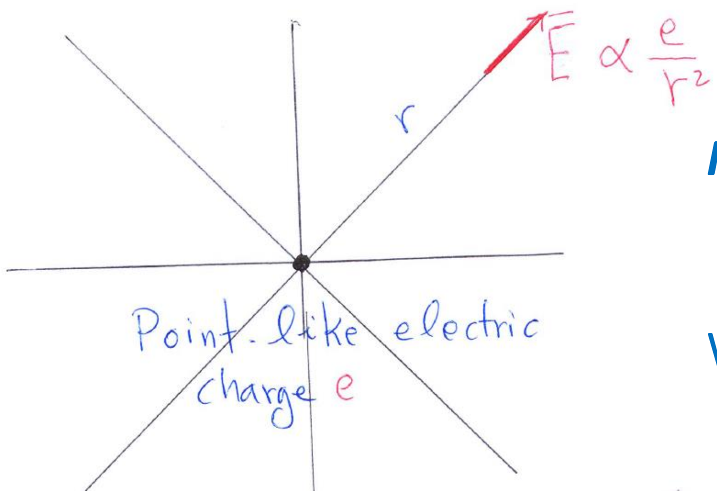
Questions: (a) Can gravity be quantized as the other interactions?
(b) Can be unified with the other 3 interactions → "a Theory of everything"?

'Quantum Gravity" phenomena are expected to appear at very high energies $\sim m_{Pl} = 2.44 \times 10^{18}$ GeV or small distances $\sim l_{Pl} \sim 10^{-33}$ cm or small times $\sim t_{Pl} \sim 10^{-43}$ s ($m_{Pl} = G^{-1/2}/\sqrt{8\pi}$ , $G$: Newton's constant)
(i) So, quantum fluctuations of "Gravity" play a role very near the "BIG BANG" for $t \leq t_{Pl} \equiv m_{Pl}^{-1}$
(ii) Also, possible "primordial Gravity waves" could originate from the quantum fluctuations of Gravity during "Cosmological Inflation"
(May be detected in the future)

# Renormalizability

In trying to construct a '*Quantum Field Theory*' for '*Gravity*' we encounter problems with "*Renormalizability*".

To understand the meaning of '*Renormalizability*', let us take as example '*Classical Electrodynamics*' :




Energy of the **E** – field $\propto$

$$\int_0^\infty E^2 4\pi r\, dr = 4\pi e^2 \int_0^\infty \frac{dr}{r^2} \equiv \infty$$

***Relativity*** → Every elementary particle is point – like

→ Energy of its **E** – field is "*infinite*"

We must then assume that its 'bare' mass is **-** ∞

→ the final mass = ∞ - ∞ is *finite.*

The situation appears also in '*Quantum Electrodynamics*' where we encounter several '*meaningless*' infinities in calculating various processes.

However, all these *‘infinities’* can be systematically gathered and put inside two parameters (*the mass and charge of electron*).

We then take the *‘bare’* parameters *‘infinite’*, so that their final *‘Renormalized’* values are finite = their experimental values.

This complicated mathematical procedure is called *‘Renormalization’* and the theories where it applies are called *‘Renormalizable’*.

The 3 interactions (except Gravity) are *‘Renormalizable’* (’T Hooft/Veltman)

→ With a *‘finite’* number of experiments we determine the values of a *‘finite ’* number of parameters.

→ Everything else can be predicted → *“Predictability”*

The problem with *‘Quantum Gravity’* is that it is not *‘Renormalizable’* .

# String Theory

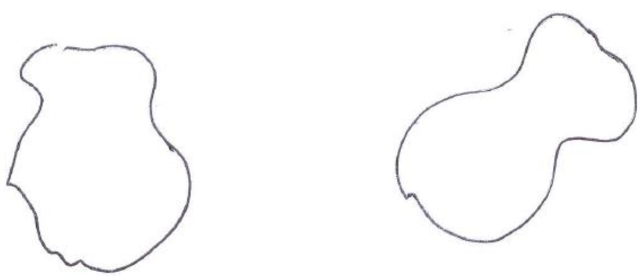
The theory of "(*super*) *strings* " was proposed to cure this difficulty and also unify '*Gravity* ' with the other interactions

→ **" Theory of Everything ".**

The idea is that the '*fundamental objects* ' are not point – like particles but ' one dimensional ' 'strings'.

Adding *"Supersymmetry "* → *"Superstrings "* .

So, we have strings of size $\sim l_{Pl} \sim 10^{-33}$ cm which vibrate, but for the present energies look like " *point particles* ".



The various *'vibrational '* modes of strings appear as particles with different *"charges ".*

So, there is a *"unified "* description of all particles and their *"interactions ".*

The abandonment of point particles → removes *'infinities'*.

It is believed that *"String Theory"* → *'finite'* results.

One of the vibrational modes is the *"graviton"* (carrier of gravitational interactions).

So, we can in principle describe *'Quantum Gravity '* and the other 3 interactions in a *"unified way"* → *"The theory of everything".*

However, there are some important *' shortcomings '* of *" String theory".*

**(i)** Initially, we thought → A *"unique "* solution of ' String theory '

→ Very high *"predictability".*

However, we now know → *"A huge number"* of solutions ($\sim 10^{500}$) ↔ *"Landscape "* with a huge number of hills, valleys → A huge number of *"minima"* .

*"Anthropic principle"* : The minimum (solution) corresponding to our Universe had the right conditions so as to produce Us eventually.

**(ii)** Although there exist very many solutions → None of them reproduces *'exactly'* our Universe.

# Predictions of String Theory

- There exist *'10 dimensions'* (or 11 in the case of M theory).

'Six' of them are *'compactified',* i.e. they are strongly curved to form a *'6 dimensional'* compact manifold of size $\sim l_{Pl} \sim 10^{-33}$ cm.

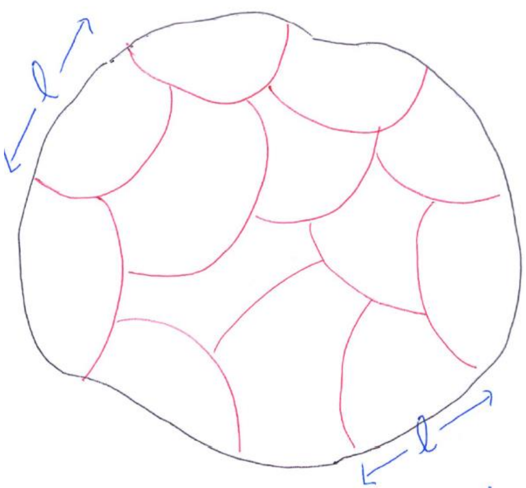
- The other 4 dimensions remain 'open' and correspond to the usual *"spacetime".*

- The geometric structure of the compactified dimensions determines many of the phenomena in *'spacetime '.*

Strings allow us to discuss *"Quantum Gravity"* → Gives us the possibility to approach *'BIG BANG'* ( initial singularity at $t = 0$)
for $t \leq t_{Pl} \sim 10^{-43}$ s or consider $t < 0$ too (before *BIG BANG*).

One problem we can now address is the *"problem"* of *"initial conditions "* for Inflation.

Inflation takes place at "$t \sim 10^{-37}$ s $\gg t_{Pl}$ " , where we need a *"large"* homogenized region as initial condition for Inflation to start.




However, this region consists of many regions of smaller size $\sim l$ , which had no time to communicate causally so as to become homogenized at the *'onset '* of Inflation.

→ This is again a problem of *'initial conditions'*.

So we need a *'first stage '* of Inflation near or before *BIG BANG* to provide the necessary *'homogenization'* required for *'conventional'* Inflation.

One possible solution → '*pre – BIG BANG*' scenario.

Imagine that we travel '*backwards*' in time and pass through the '*initial singularity*' at $t = 0$, which is though '*smoothed*' by strings and enter the realm of '*negative times*' ( before *BIG BANG*).

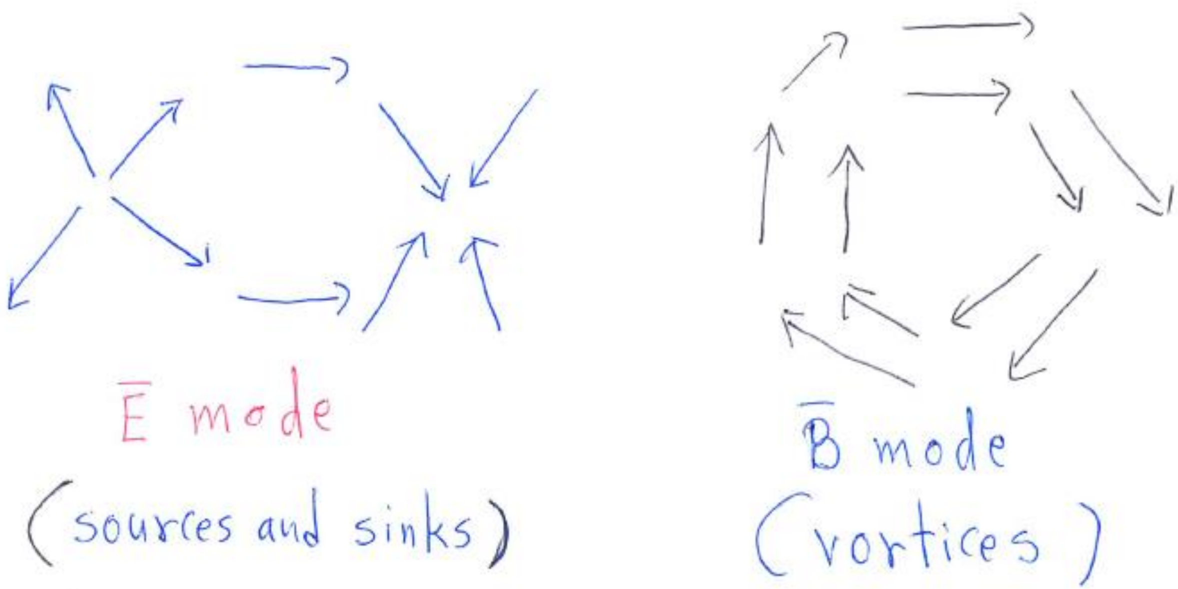
There, during the motion of the '*Universe*' towards the '*initial singularity*', we have conditions of very high curvature and the '*extra dimensions*' contract and "*compactify*" → *Inflation* (accelerated expansion) in the 4 open dimensions.

This can be the 1st stage of *Inflation* → Initial conditions for the '*conventional*' *Inflation* or can be the main Inflation → producing the density perturbations too.

We should be very careful with these considerations since the physics of strings is not fully understood or solved yet.

Another application of *"Quantum Gravity"* could be the explanation of the origin of *"primordial gravity waves"* if such waves are detected.

***BICEP2*** → Observed the *'polarization'* of *'CMBR'*




Subtracting the *'$\bar{B}$ mode'* from ***'polarized dust'*** → there is a remaining *'$\bar{B}$ mode'* which could be due to ***'primordial gravity waves'*** from Inflation.

'Planck' did not confirm this conclusion of *BICEP*, which underestimated the *'foreground'* from polarized dust.

However, possible existence of primordial gravity waves which may be measurable in the foreseeable future cannot be excluded.

These waves could originate from tensor (gravitational) quantum fluctuations during Inflation which become Classical fluctuation (i.e. gravity waves) as they exit the *"Inflationary horizon"*

→ So *'Quantum Gravity'* is required to understand these waves.