Some Theoretical Questions

Alessandro Tronconi

INFN Sezione di Bologna

- Theory Group -

www-th.bo.infn.it

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20th Century Revolution

- The fundamental ideas of modern theoretical physics have been introduced early in the 20th century
- The description of **elementary particles and their interaction** based on **Special Relativity** (1905) and **Quantum Mechanics** is extremely accurate (**Quantum Field Theory**).
- Building blocks of QFT: the **Symmetries** of electromagnetism
  - Lorentz invariance
  - Gauge invariance

$$\vec{\nabla} \cdot \vec{E} = \rho/\epsilon_0$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

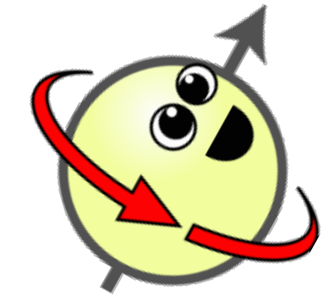
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Maxwell field equations (1862)

Fields and Particles

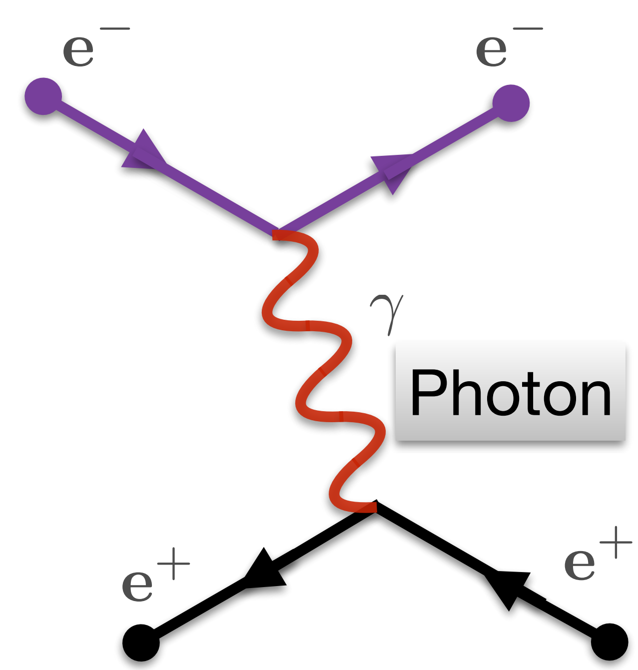
Fermion



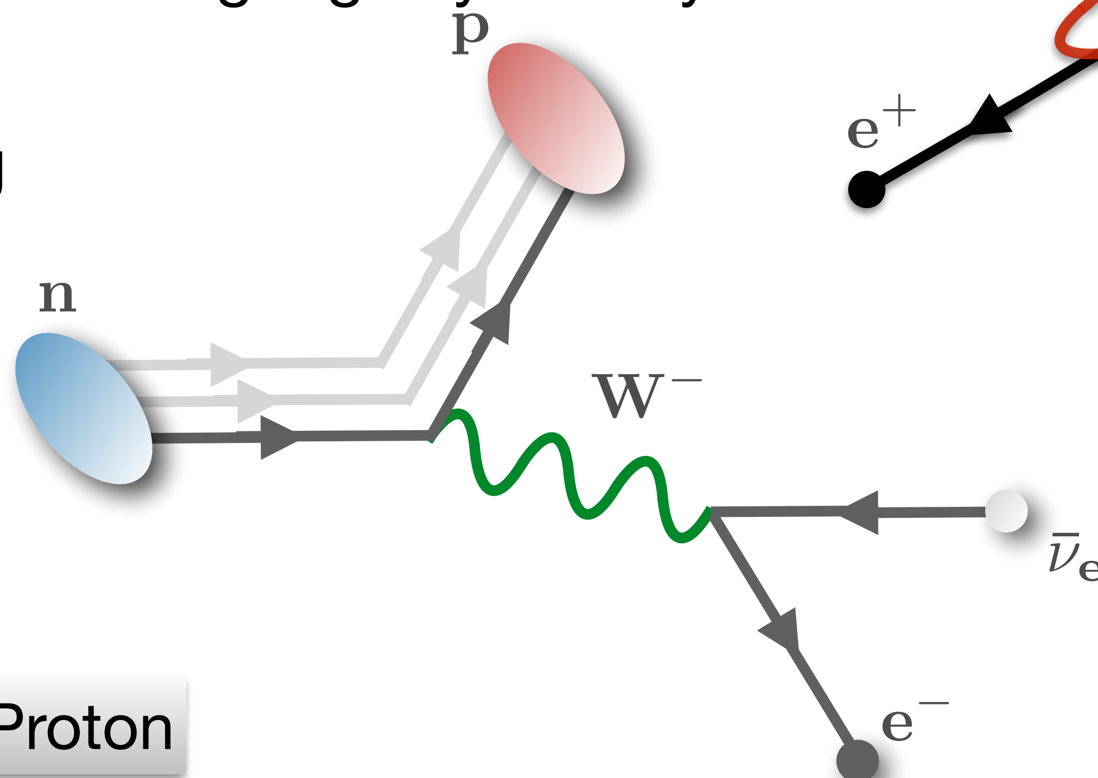
- Particles are similarly described by fields

Dirac Equation $$\left(i\hbar\partial\!\!\!/ - mc\right)\psi(x) = 0$$

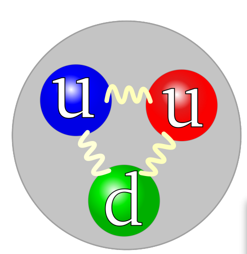
  - Relativistic quantum equation for the electron (Dirac - 1928) written on assuming the existence of **anti-matter** (positron - 1932)



- Wave-Particle dual description of Quantum Mechanics
  - virtual **photons** are exchanged in electromagnetic interactions
  - photons are massless as a consequence of gauge symmetry



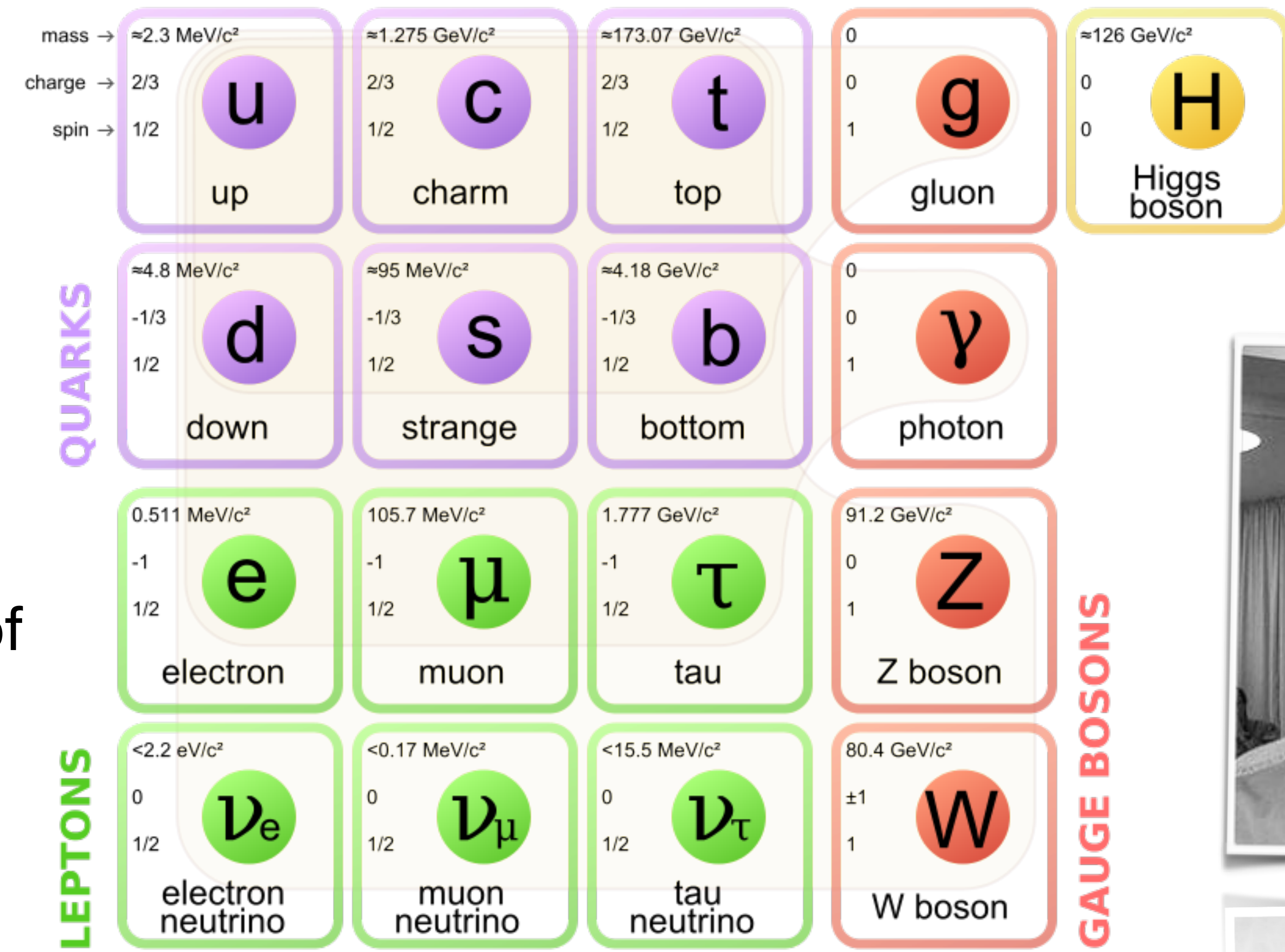
- **Weak force** (radiactive decays) and **strong force** (nuclei) are described by a **gauge symmetry**
- Gauge symmetry of weak force led to the prediction of the **Higgs particle**

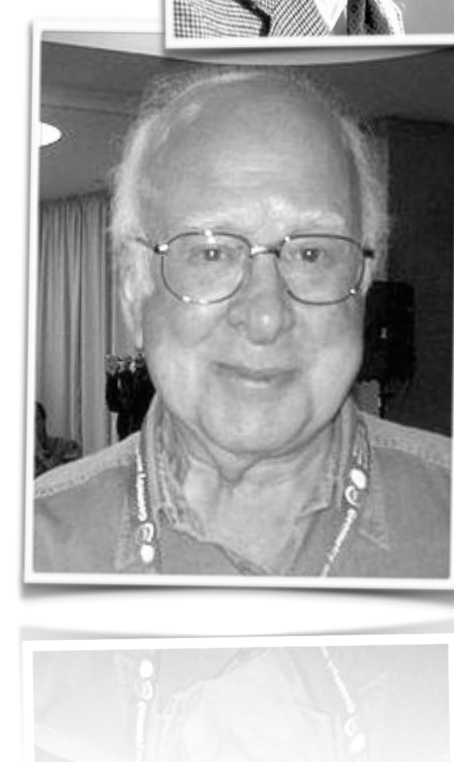


Proton

The Standard Model

- In 20th century theoretical physics was not only able to explain observations but to anticipate them!
  - The theoretical description finally emerged around 1970 is called **Standard Model (SM)**
- The original formulation predicted the existence of new particles discovered many years later!
- The last missing piece of the SM (Higgs Boson) was found in **2012**





The Plank Scale

- The evolution of the **large scales** structures, planets, stars, galaxies and that of the entire Universe is well explained by General Relativity (1916) and Particle Physics.

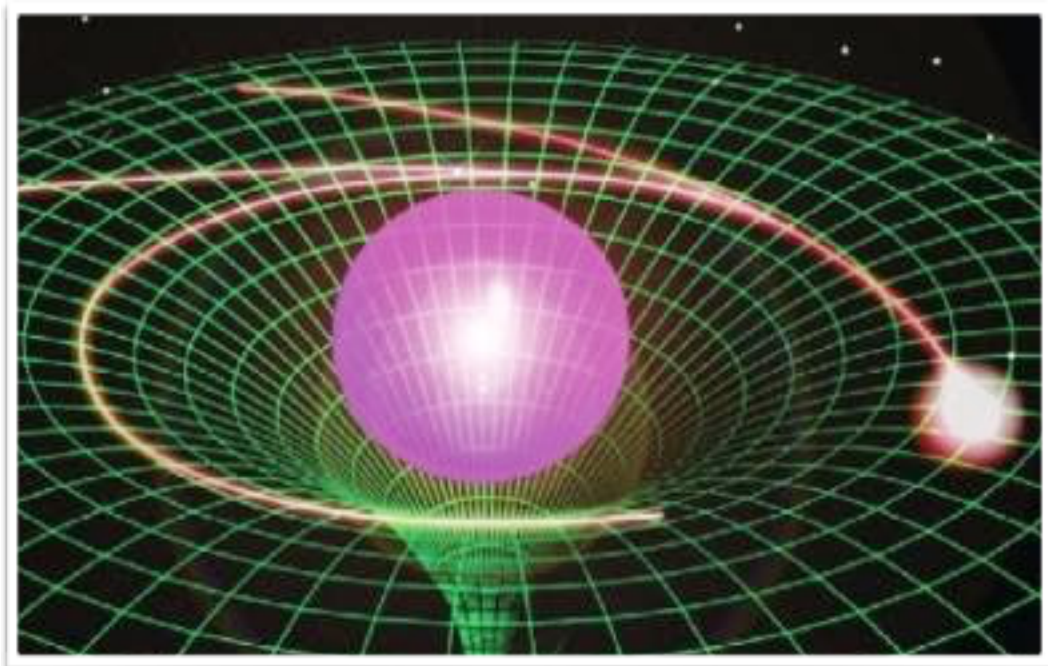
- General Relativity is a **classical** (field) theory and a **gauge theory**
- Gravitational interactions are a consequence of the curvature of space-time structure (**geometrodynamics**)

$$F_G = G_N \frac{m_1 m_2}{r^2} \quad \longrightarrow \quad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Newton's law — Einstein equations

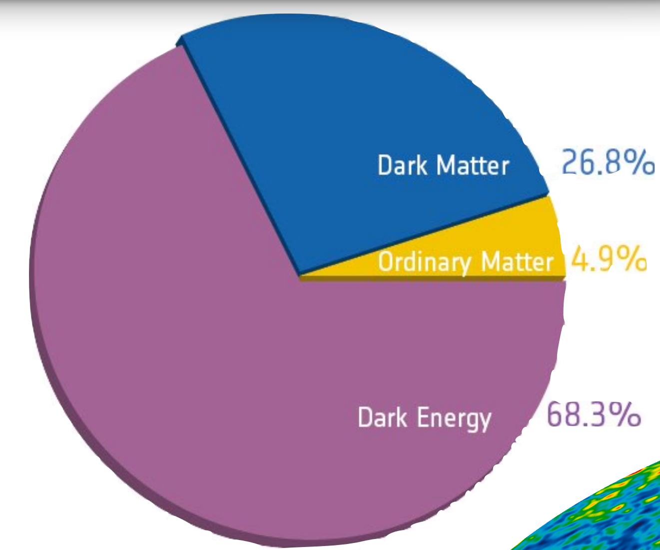
- Confirmed by experiments on different scales
- Predicts:
  - Gravitational waves
  - Black Holes (Wormholes)
  - **Planck scale**

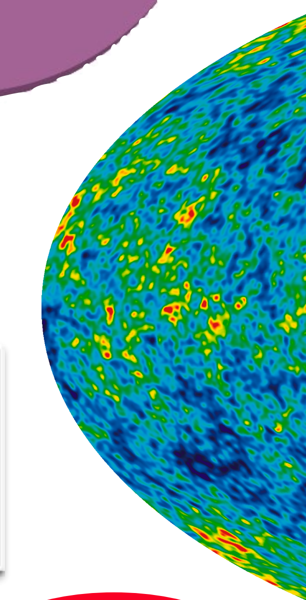
$$E_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}} c^2 \sim 10^{19}\ \text{GeV}$$

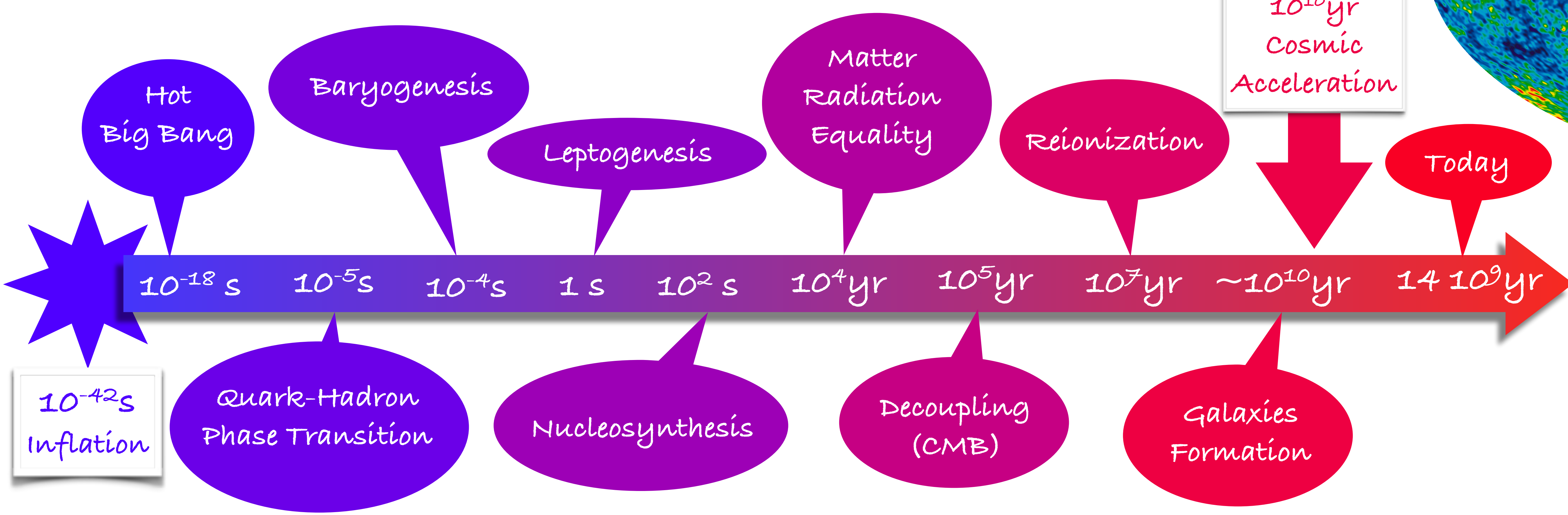


Standard Cosmological Model

- Astrophysical observations shed light on early phases of our Universe at energies close to the **Planck scale**
- Experimental data are becoming more and more accurate (10% precision)
- **Standard Cosmological Model (SCM)**: theoretical description of the cosmological evolution and universe constituents

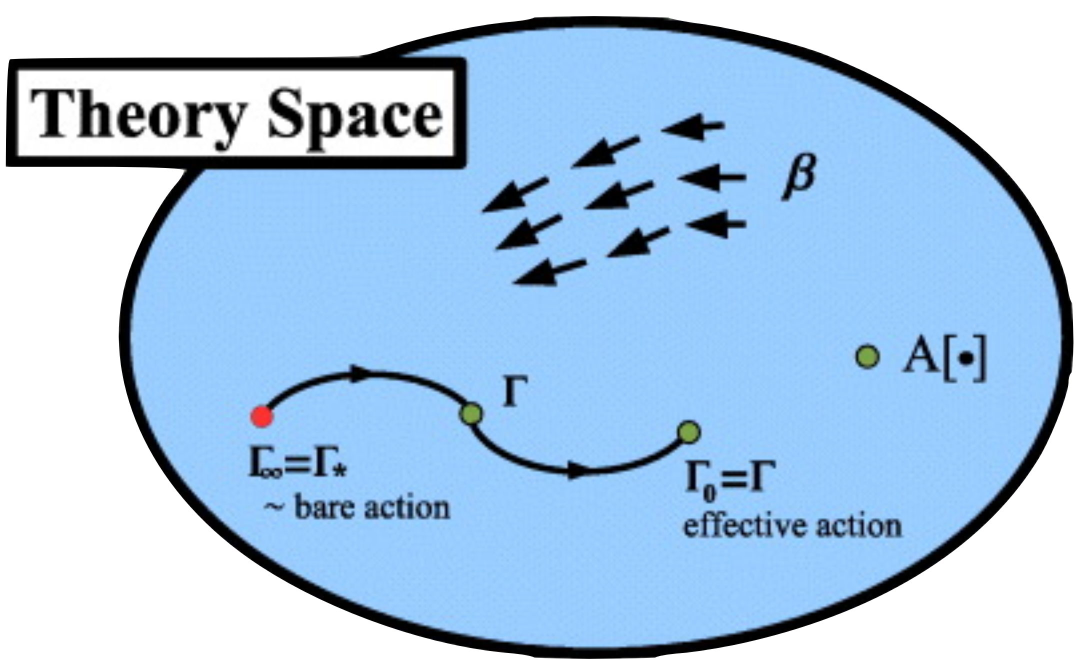


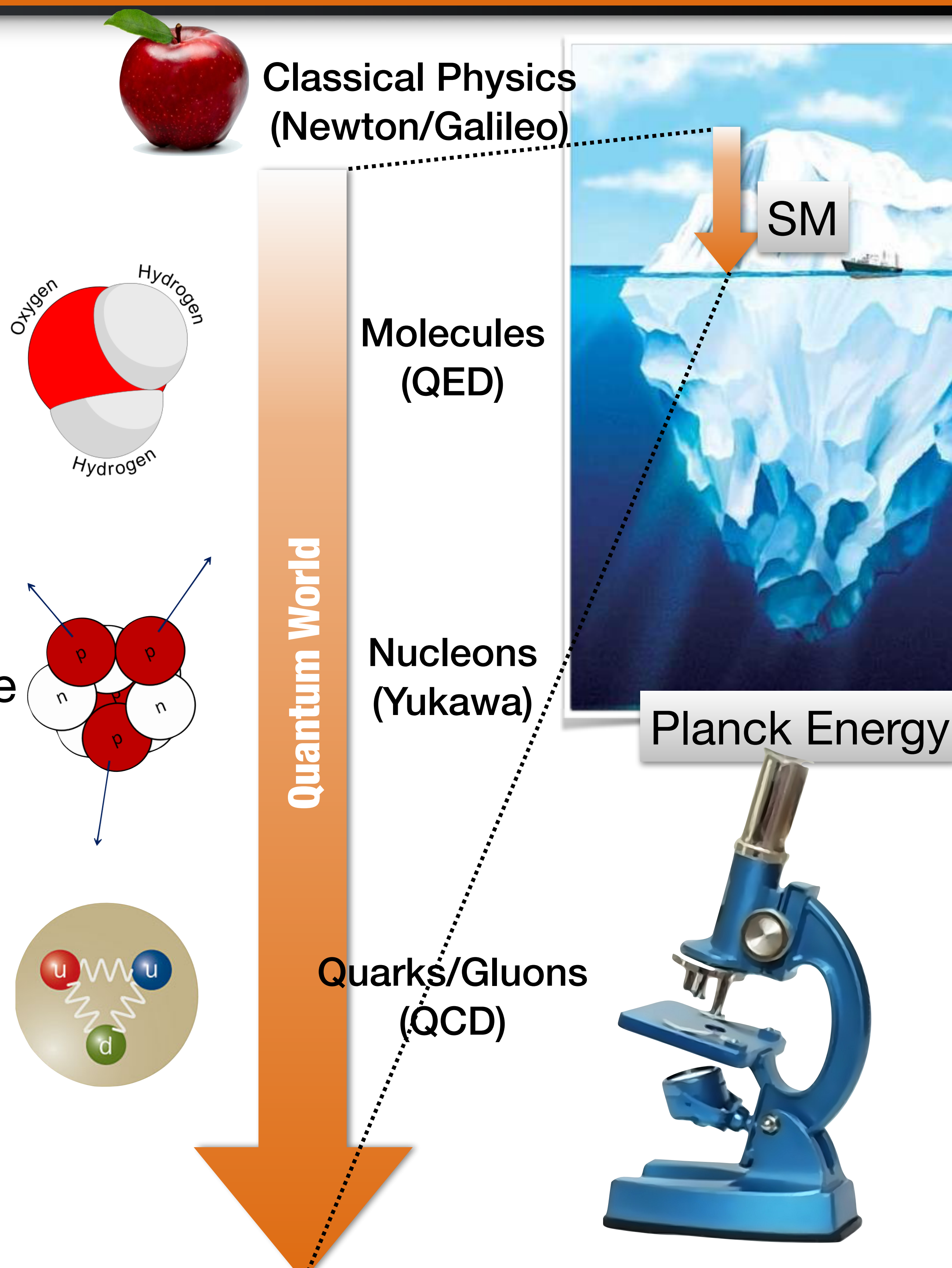




The Ultimate Goal

- Description of physical phenomena depends on **scales**
- Increasing energy is like using a more and more powerful **microscope** and details emerge
- Any physical theory can be thought as a “low energy” **effective description** of a more general theory
- Theorists’ ultimate goal is the quest for the **theory of everything**

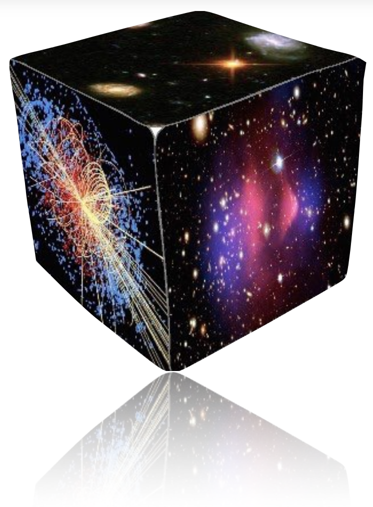




The New Challenges

- Despite their success theorists believe these SMs are not complete theories
  - **Experimental problems:**
    - evidence of Dark Matter
    - neutrino masses
    - large matter-antimatter asymmetry
    - origin of the substance which drives cosmic acceleration (Inflaton & Dark Energy)
  - **Conceptual problems:**
    - many free parameters (masses, couplings,…)
    - large difference between SM scale and the fundamental scale of gravity (Planck scale) - hierarchy problem
    - unification of the fundamental forces
    - comprehension of quantum gravity

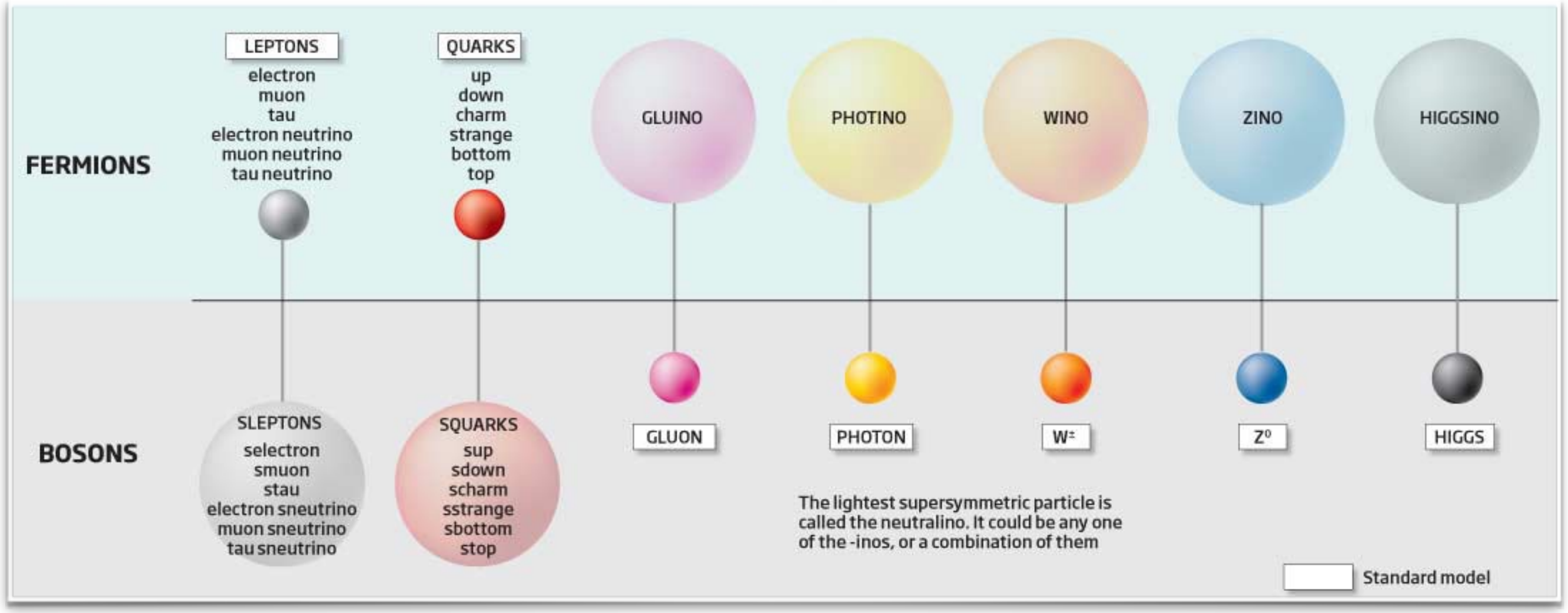
Hot Topics in Theoretical Physics



- Theorists usually tackle these problem either from the particle physics side or from the gravity side…
  - **Particles Physics**
    - Beyond the SM model building: SUSY, GUT, …
    - analytical/numerical description of particle phenomenology at colliders
    - study of more advanced/theoretical questions
  - **Gravity side**
    - model building: inflation, dark matter/energy
      - evolution and observations of the cosmological perturbations
      - modified gravity theories
    - different approaches to quantum gravity/cosmology
    - black holes dynamics and thermodynamics

Supersymmetry

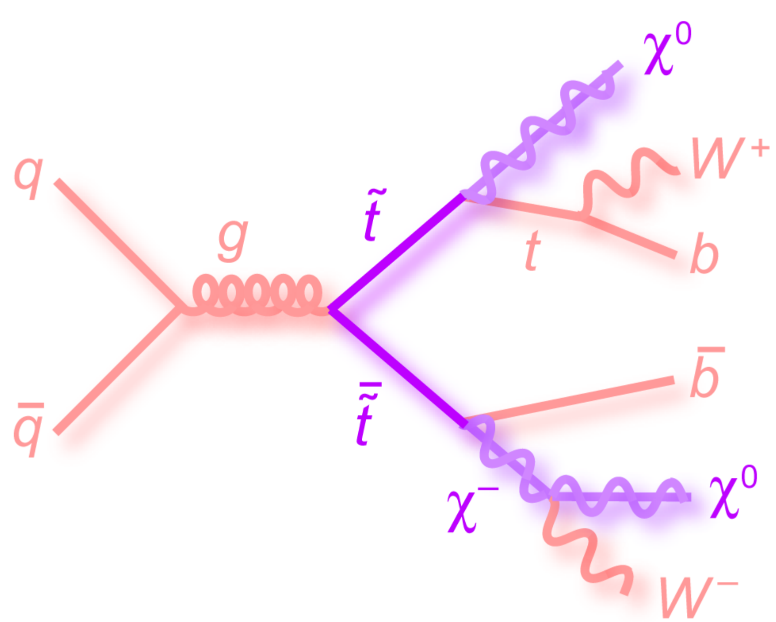
- **Supersymmetry** (SUSY) is a symmetry between fermions and bosons
- It has not been observed in nature yet

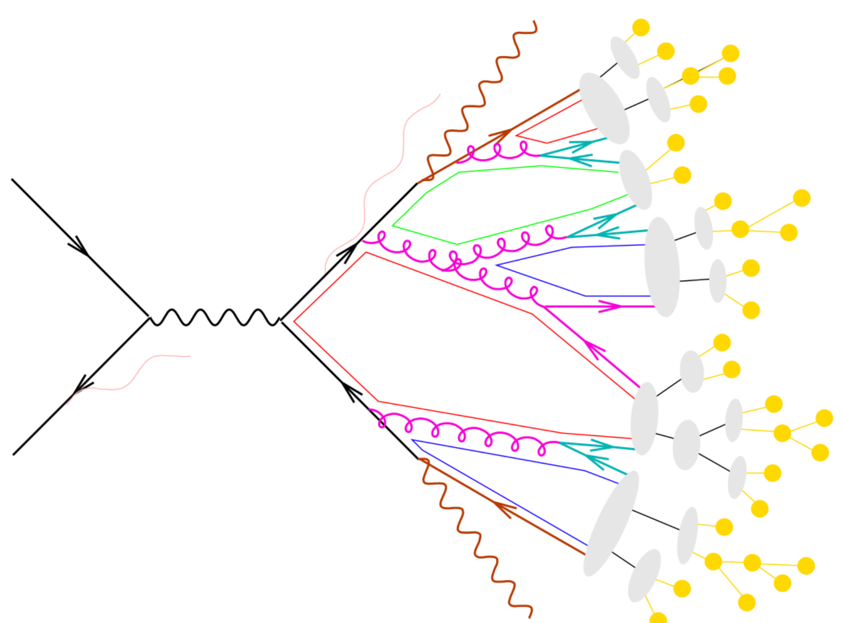


- SUSY is the leading candidate for physics beyond the SM
  - it can explain the hierarchy problem
  - it yields gauge couplings unification
  - it provides dark matter candidate
- SUSY plays a crucial role in constructing well-behaved string theory
- It is a powerful tools for obtaining exact results in strongly coupled quantum field theories

Colliders Phenomenology

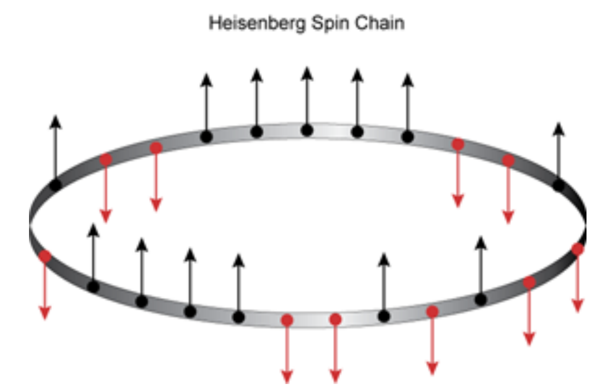
- A typical scattering event at a modern colliders is very complicated
- Still an accurate theoretical description of what happens is needed
  - Higher order calculations
  - **non perturbative** aspects of QCD (hadronization)
  - increasing precision **Monte Carlo** simulations
  - Renormalization group and effective theories



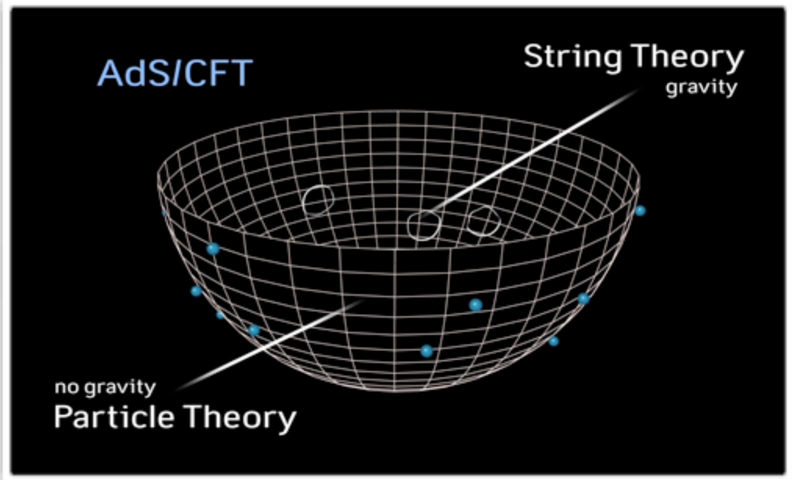


Integrable Systems

- Integrable systems possess many conserved quantities and are useful for studying non perturbative phenomena

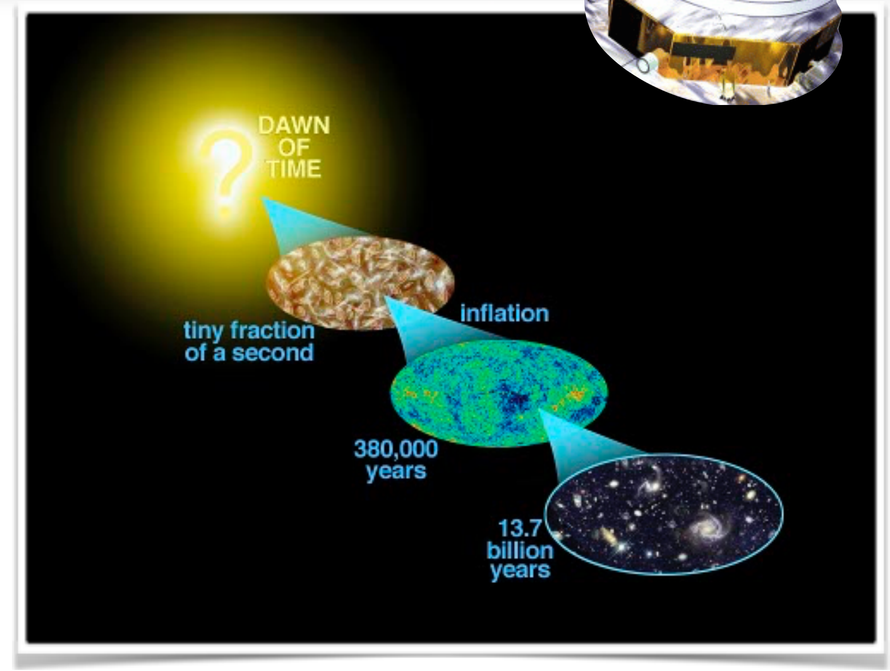


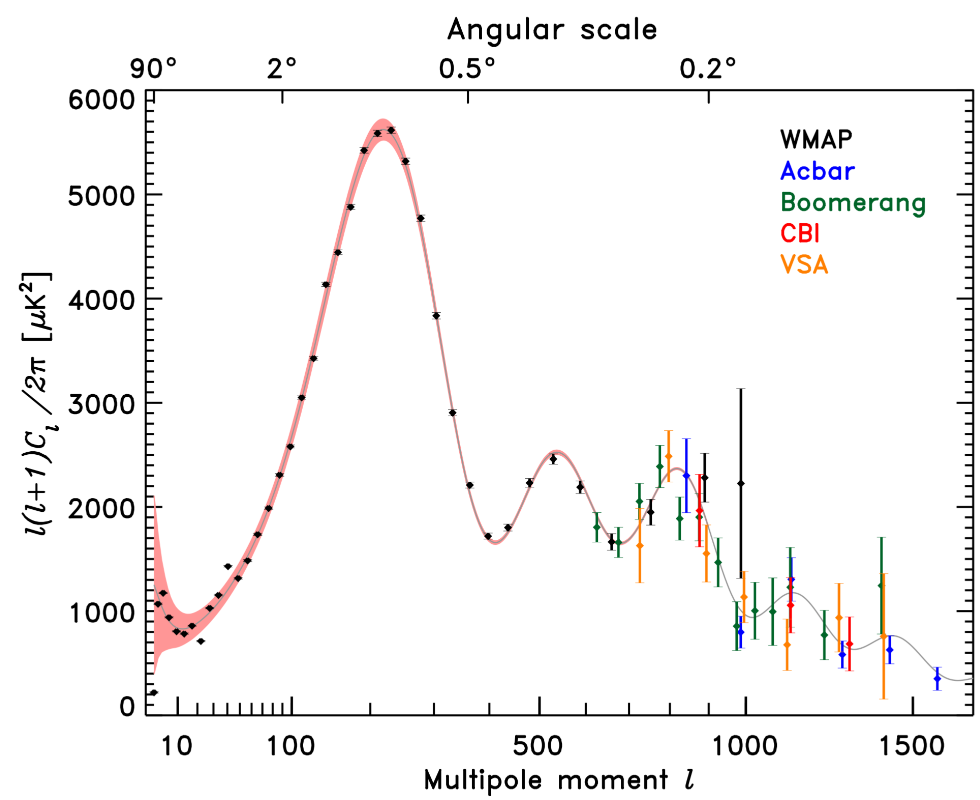
- Wide range of application from physics to pure mathematics:
  - Conformal (Field) Theories are integrable systems central
    - in the construction of String Theory
    - in the study of 2-D statistical systems and 1-D quantum systems
  - Supersymmetric Gauge Theories used to explore the strong coupling regime
    - Dual to String Theories on curved Space-Time



Cosmic Inflation

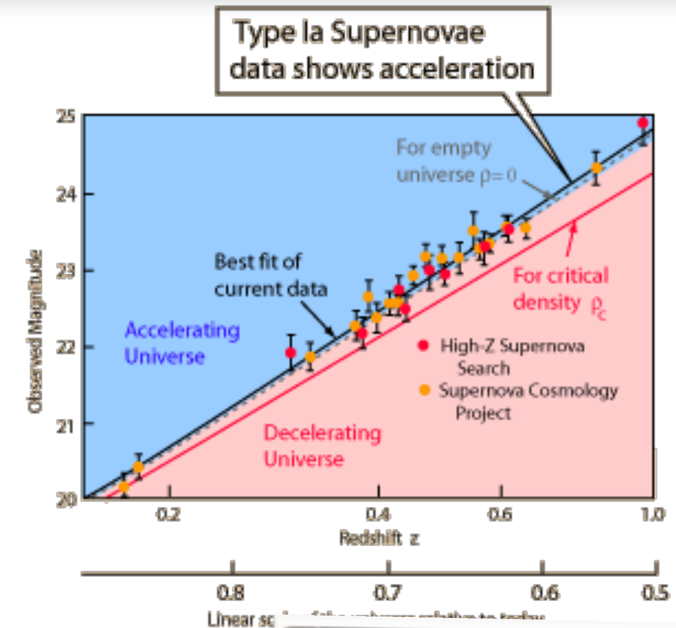
- Primordial mechanism generating the seeds of cosmological perturbations
- Is driven by some sort of exotic matter (**inflaton**)
- Amplifies quantum phenomena occurring near the Planck scale
  - CMBR inhomogeneities are the relics of inflation (**Planck experiment**)
  - Inflation may encode signals originated by quantum gravitational effects
  - Different theoretical models, with diverse inspiration, are currently studied and compared with observations (**Higgs inflation**?)
  - Indirect evidence for existence of **gravitational waves** (BICEP2?)

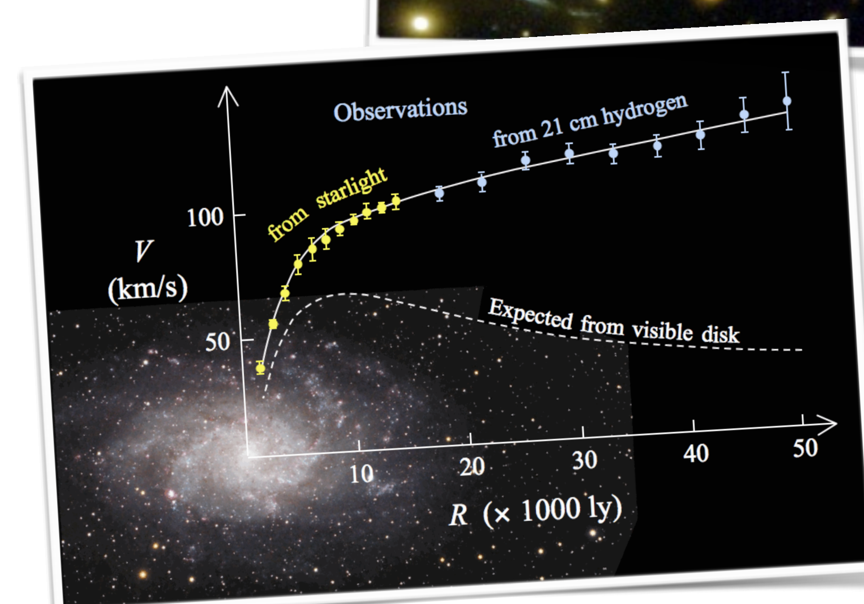




Dark Substances

- Universe evolution seems mainly determined by invisible fluids (**95%**): **Dark Matter** and **Dark Energy**
- Experimental evidence confirmed by independent observations
- Model building:
  - Search for exotic matter
  - Modification of laws of gravity at large distances
  - **Dark Matter is a bridge between cosmology and particle physics beyond the SM**
  - Dark Energy origin seems more profound
    - vacuum energy (quantum effect)
    - geometric effect (cosmological constant)
    - Similar to the inflaton



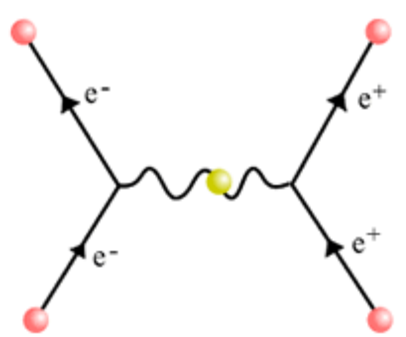


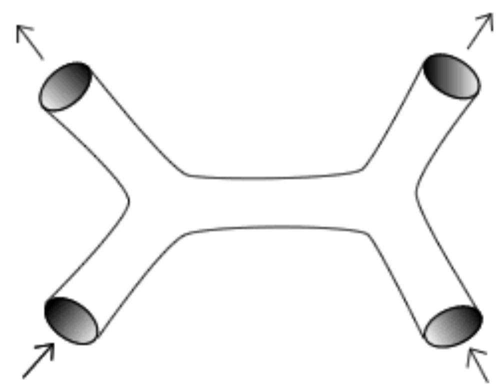
Black Holes

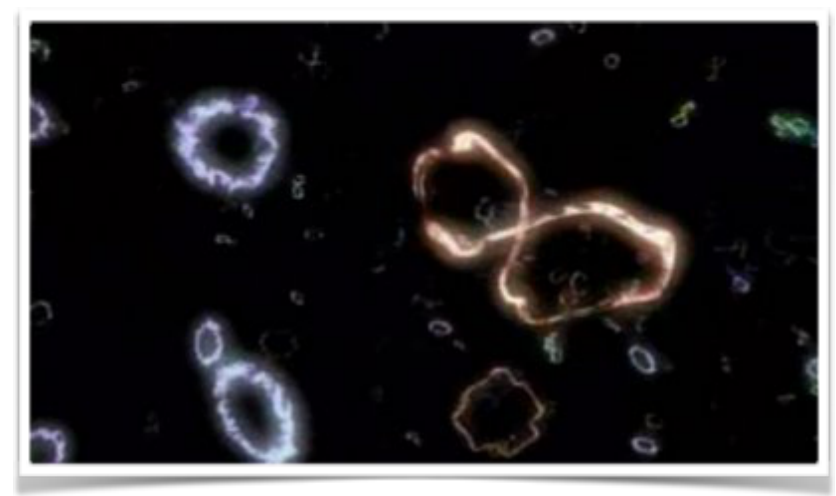
- Astrophysical objects predicted by General Relativity
- Event Horizon: unidirectional membrane
- Indirect evidence of their existence on astrophysical scales (they are black…)
- May be created in accelerators (?)
- Theory predicts they **evaporate** slowly (Hawking radiation - 1974)
- Evaporation can be described by thermodynamical quantity such as temperature, **entropy**
  - the profound meaning of such a description is unclear
  - hidden quantum nature of Black Holes
- Analog counterpart: **acoustic black holes** may form in fluids and Hawking radiation measured in laboratory

String Theory

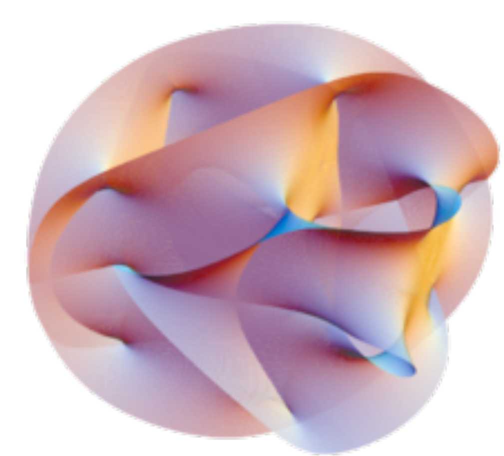
- String Theory is one of the major candidates to consistently describe gravity at the Planck scale
- Elementary particles are described by a single extended object: a **vibrating string**
- Very elegant theory with **one** parameter: string tension
- Divergence free







  - It predicts:
    - existence of (compactified) **extra dimensions**
    - huge variety of particles besides graviton and SM particles
    - supersymmetry
    - **axions** as candidates for Dark Matter

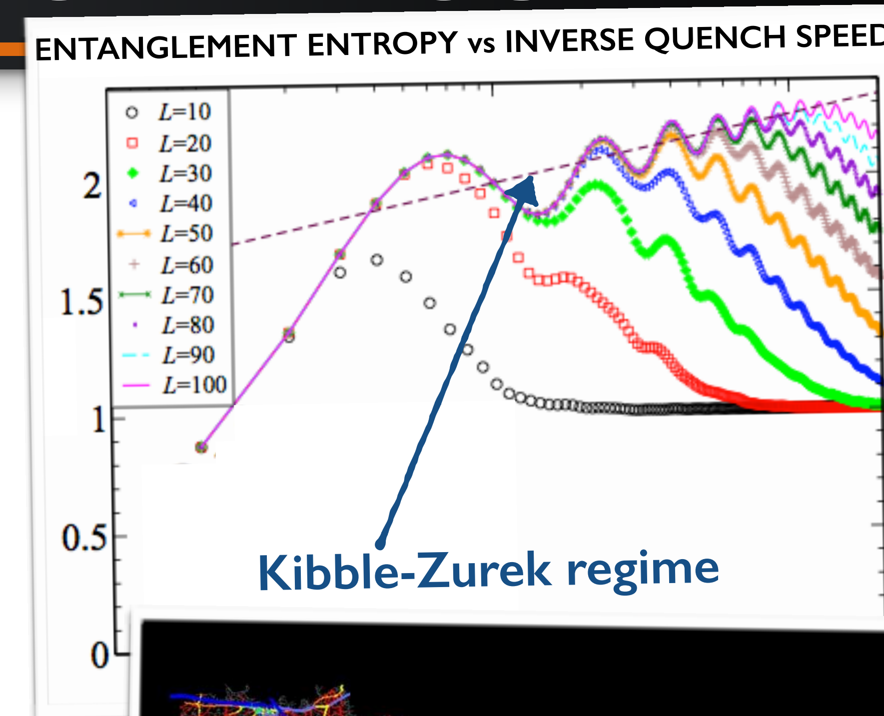


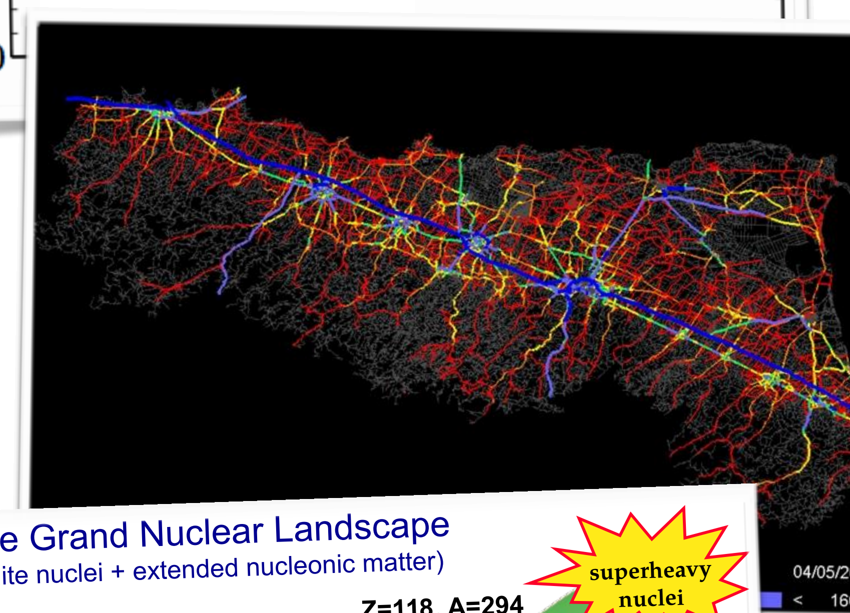
Other Theoretical Activities

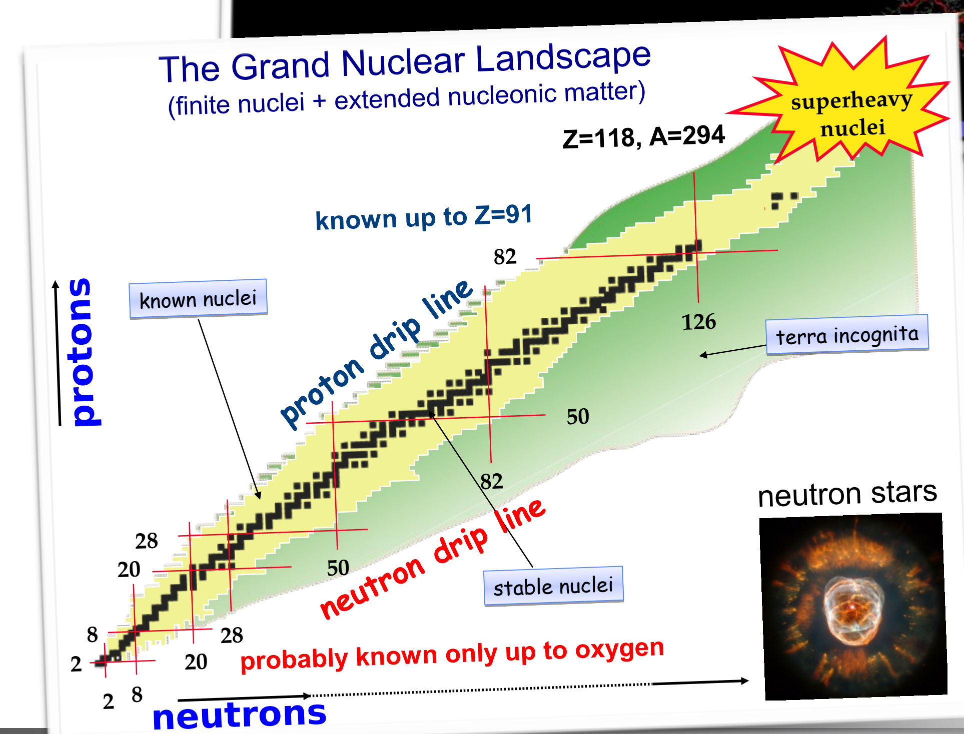
- **QUANTUM**: Entanglement and dynamics of extended closed systems crossing a Quantum Phase Transition; Geometry of quantum space of states

- **PIECES**: Statistical Physics for stochastic dynamical networks with applications to transport systems and biochemical networks

- **MANYBODY**: Theoretical Methods in physics of strong interaction, low energy QCD, nuclear structure and collective excitations, hyper nuclear physics







Thank You!

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