



**LUND**  
UNIVERSITY

# The Physical Vacuum: Where Particle Physics Meets Cosmology

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*“We must be able to understand even those things  
which are impossible to imagine of..”*

*Lev Landau*

# The greatest challenge of Physics

## Nobel Prize 2011

“...for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”

Energy density of the Universe is dominated by Vacuum component!

What is the Vacuum? Where does its energy come from?  
And why is it “the greatest challenge”?

Vacuum energy from **Quantum Field Theory**

$$\langle \epsilon \rangle_{\text{QFT}} \sim - \int_0^{M_{Pl}} \frac{4\pi k^2 dk}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \sim -1.4 \cdot 10^{128} \frac{\text{GeV}}{\text{m}^3}$$

Total sum of *zero-point energy* fluctuations of known fields!

Vacuum energy from **Cosmology**

$$\langle \epsilon \rangle_{\text{Cosm}} \sim (4.1 \pm 0.5) \frac{\text{GeV}}{\text{m}^3}$$

*Observational data!*

**Oops!**

$$\langle \epsilon \rangle_{\text{QFT}} \sim 10^{128} \times \langle \epsilon \rangle_{\text{Cosm}}$$

**No single established framework** (including realistic GUT theories) cancels near to *130 orders of magnitude!*

# Outline

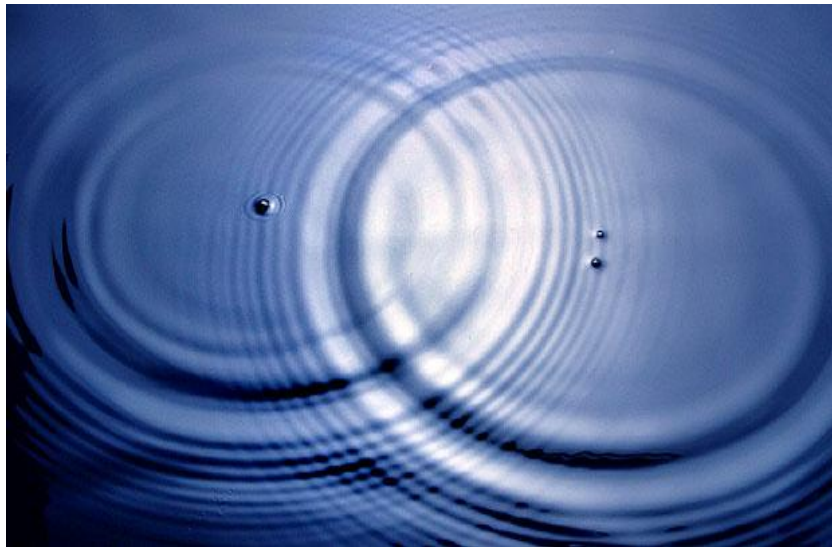
- Historical development of Vacuum ideas:  
**from Aether hypothesis to “geometrization” concept**
- The Physical Vacuum in Quantum Field theory  
and **Role of the Symmetries**
- The Role of Vacuum in **the Standard Model of Particle Physics**  
An idea of **SO(2) symmetry**: equivalence of quark-lepton generations,  
quark mixing, light neutrinos, new Dark Matter particles  
and “invisible” Higgs boson
- **Cosmological evolution of Vacuum** and Dark Energy problem  
Instability of QCD Vacuum and **Cosmological Yang-Mills fields**
- Summary and Outlook

# Prehistory: Aether

*Between XIX-XX centuries*

*Two major questions:*

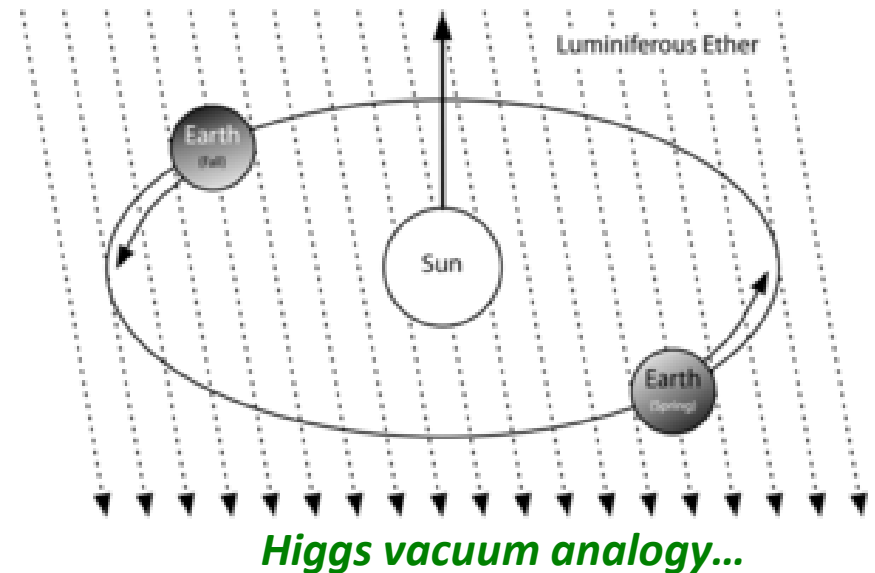
1. Aether (medium) properties?
2. Atom (matter/radiation) structure?



EM waves discovery

**Aether hypothesis**

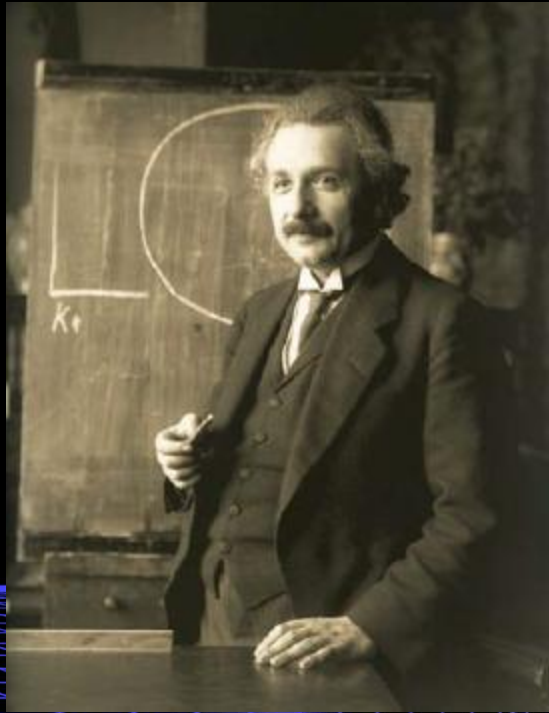
- **mechanistic ideology**
- **intuitive resistance of void**



**Existence of preferred frame of reference is proven to be wrong!**

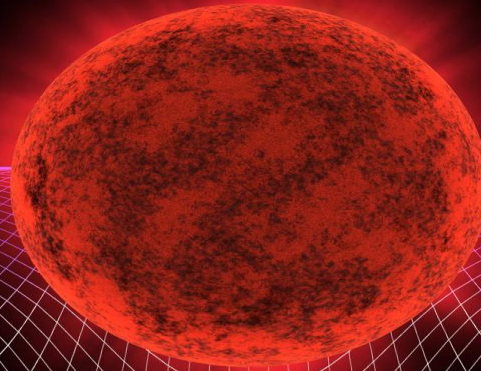


# Relativity: “geometrization” paradigm



“ According to the general theory relativity space without eather is unthinkable; in such space there would be no propagation of light, but also no possibility of existence for standards of space and time, nor therefore any space-time intervals in the physical sense..”

Albert Einstein  
“Ather und die  
Relativitaetstheorie”  
(Berlin, 1920)

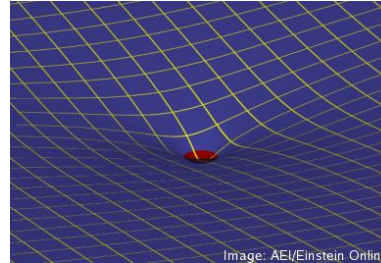


“Recapitulating, we may say that according to the general theory of Relativity space is endowed with physical qualities; in this sense there exists an aether...”

# “Geometrization” of interactions

Field – internal characteristics of the space-time itself – *defines its topology and geometry*

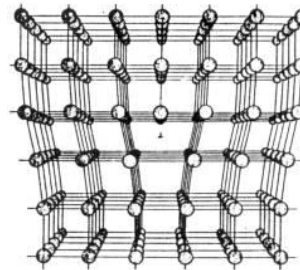
- “Curved” space-time



Gravitational interactions

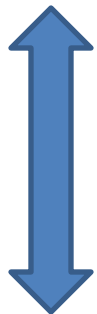
It is possible to think of more complicated topology:

- “Sliced” or “stratified” space-time

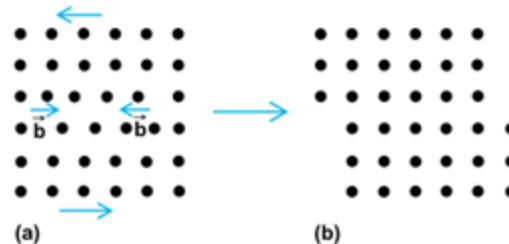


EM, weak and strong interactions & fermion fields

*Fields as different types of defects*

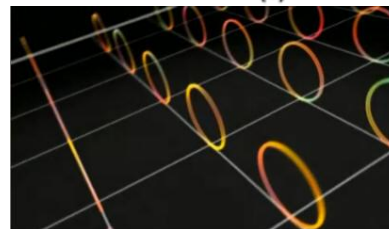


*Duality?*



- Extra dimensions

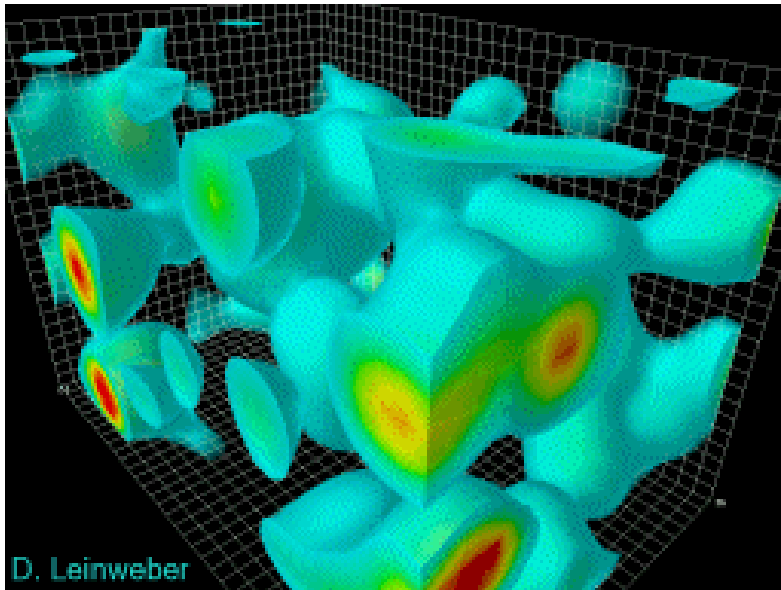
*KK compactification*



# Physical Vacuum: What is it?

## *Uncertainty principle*

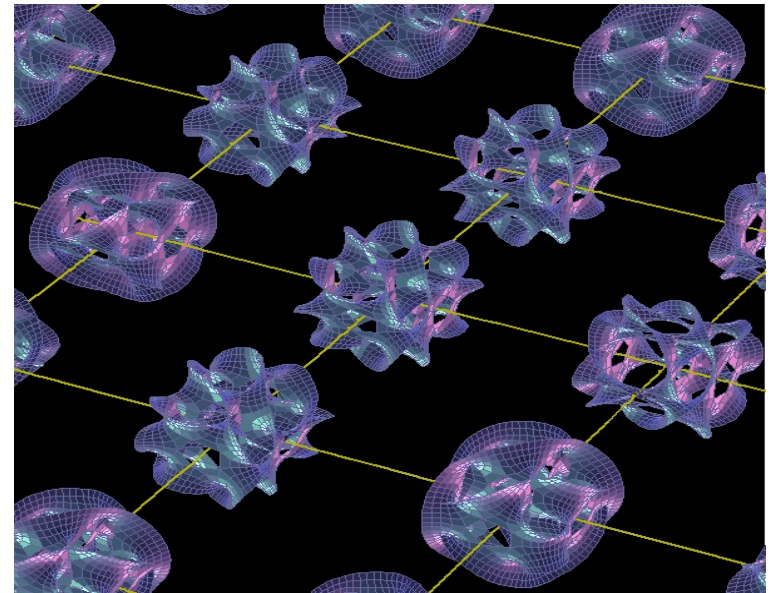
*It is impossible to have zeroth value and change rate of a quantum field in a fixed point of space*



*QCD Vacuum energy fluctuations (lattice)*

## *Geometry and topology of space time*

*Fields are internal characteristics of the space-time itself*



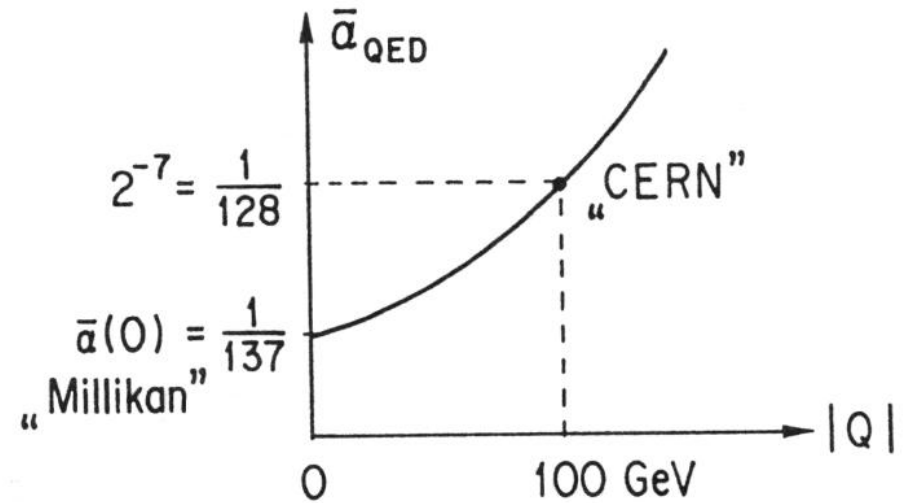
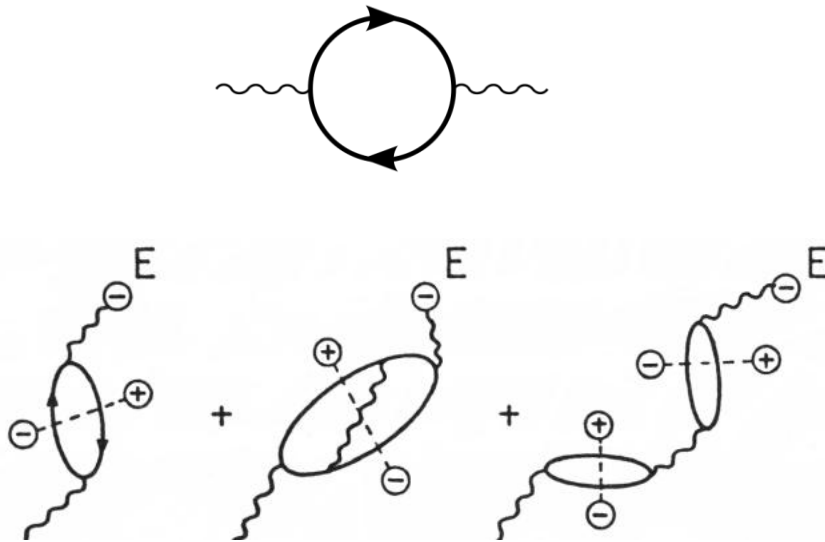
*Imagination of complicated space-time geometry*

***Zeroth fluctuations of non-deformed geometrical structures!***



# Vacuum in Perturbation Theory: Abelian case

## Screening of electric charge in QED

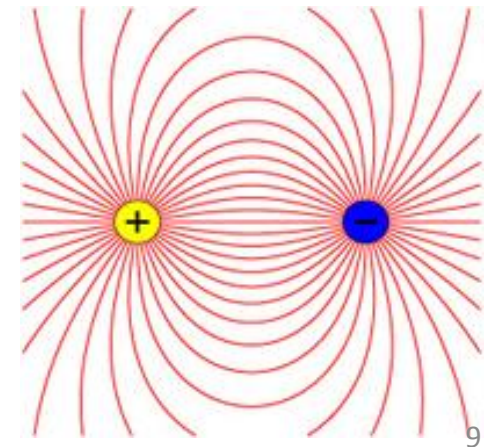


Long range EM interactions

"Running" electric charge

$$e \rightarrow e(r) = e \left\{ 1 - \frac{\alpha}{3\pi} \ln \frac{r}{r_e} + O(\alpha^2) \right\}$$

At larger distances EM interaction becomes weaker!





# Vacuum in Perturbation Theory: Non-Abelian case

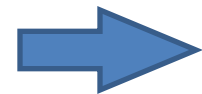
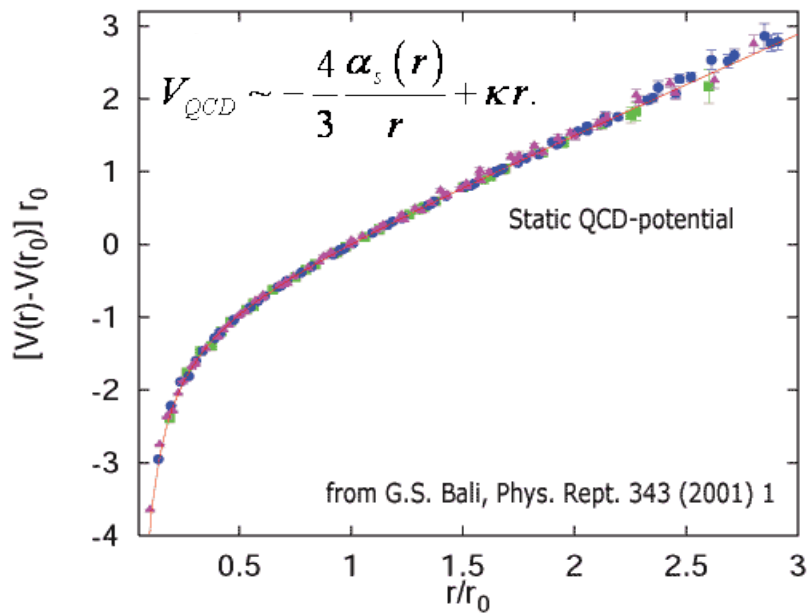
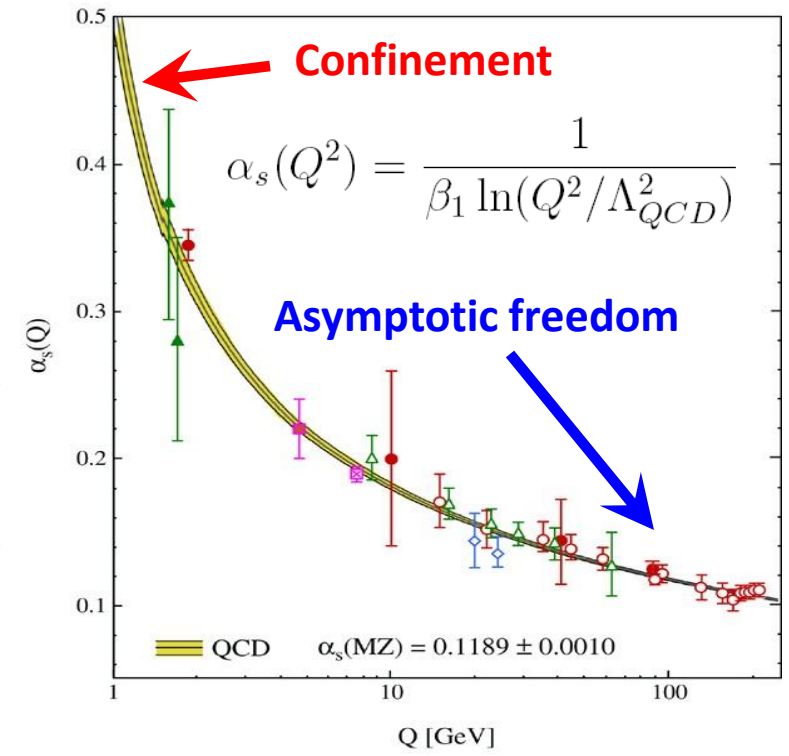
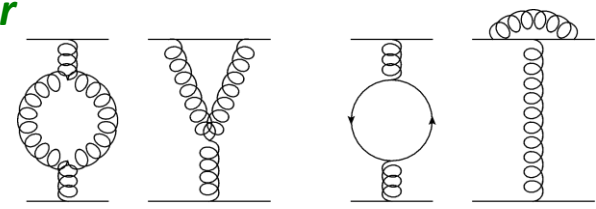
**Running QCD coupling**  $\alpha_s = \frac{g^2}{4\pi}$

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s). \quad \beta(\alpha_s) = - \left( 11 - \frac{2n_f}{3} \right) \frac{\alpha_s^2}{2\pi}$$

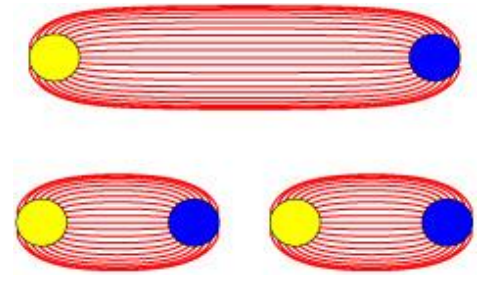


**Nobel Prize 2004:**  
*Gross, Wilczek; Politzer*

**Color charge anti-screening**



**Short range strong interactions**



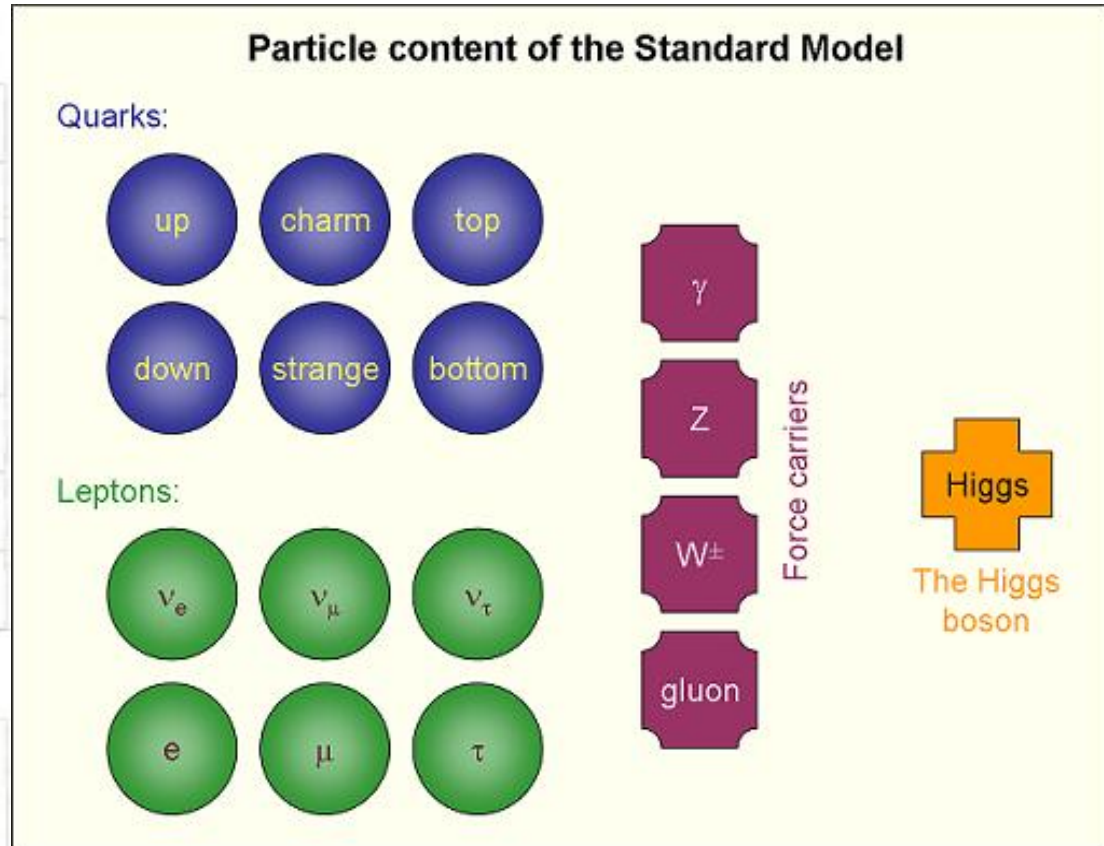
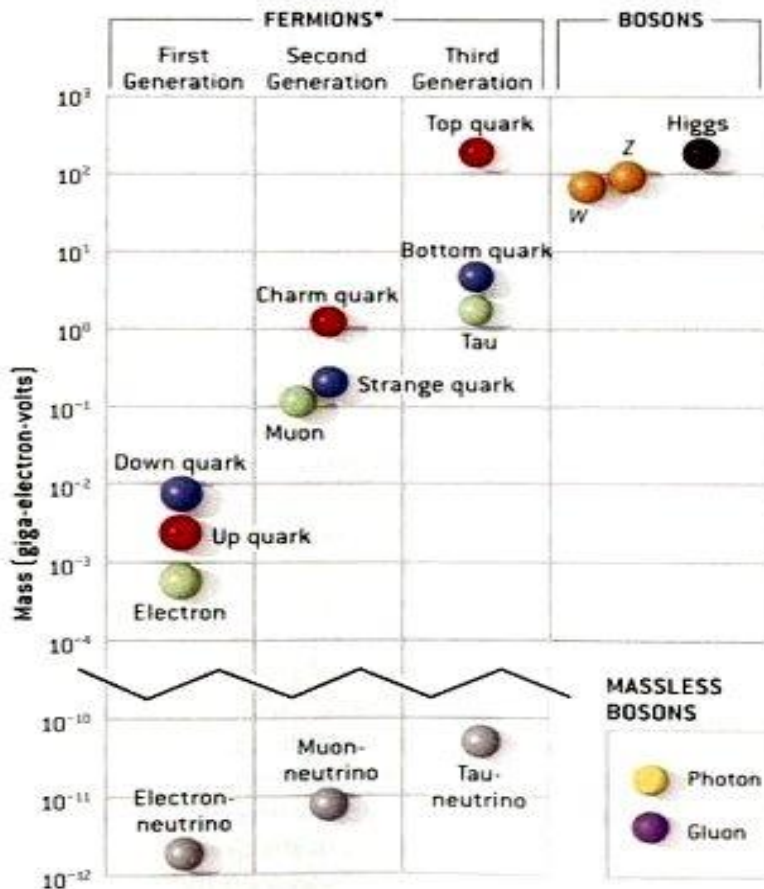
**Color confinement!**

# Geometry of non-perturbative vacuum

- **Electromagnetic vacuum**
  - ✓ space-time “stratified” structure is charge-neutral;
  - ✓ can be in a *non-deformed state*;
  - ✓ delocalized zero-point fluctuations fill up the whole space-time
- **“Weak” vacuum (Higgs condensate)**
  - ✓ space-time “stratified” structure is *spontaneously deformed*;
  - ✓ layers are “weakly” charged;
  - ✓ deformations (shifts) are regular and *continuous*;
  - ✓ is *classically determined* and zero-point fluctuations only slightly disturb it
- **“Strong” or QCD vacuum (Quark-Gluon condensate)**
  - ✓ space-time “stratified” structure is *spontaneously deformed*;
  - ✓ layers carry different “color” charges;
  - ✓ deformations are *localized* and determined totally by quantum effects;
  - ✓ such a structure is *not classically determined*

**Physical Vacuum is the quantum superposition of substructures (vacuum condensates) constantly transforming one into another**

# Standard Model of Particle Physics: open issues



*Phenomenologically very successful!*

**BUT!** *There are open issues:*

- **Color confinement**, hadronisation and hadron structure (QGC substructure)
- **EW symmetry breaking** and mass splitting problem (Higgs condensate substructure)
- **Origin of quark mixing parameters**, e.g. no hypernuclei (unknown vacuum?)
- **Quark-lepton symmetry** and generations problem (unknown vacuum?)

# Origin of mass: QCD Vacuum and hadron structure

Perturbative picture of Vacuum breaks down at hadronic scales!

Static quark-gluon condensate properties:

- vacuum is degenerated:

- ✓  $E = 0 \rightarrow$  infinite number of potentials;
- ✓ the same energy, but different topological number;
- ✓ infinitely degenerated system of **topologically different vacuum structures** separated by infinitely high potential walls

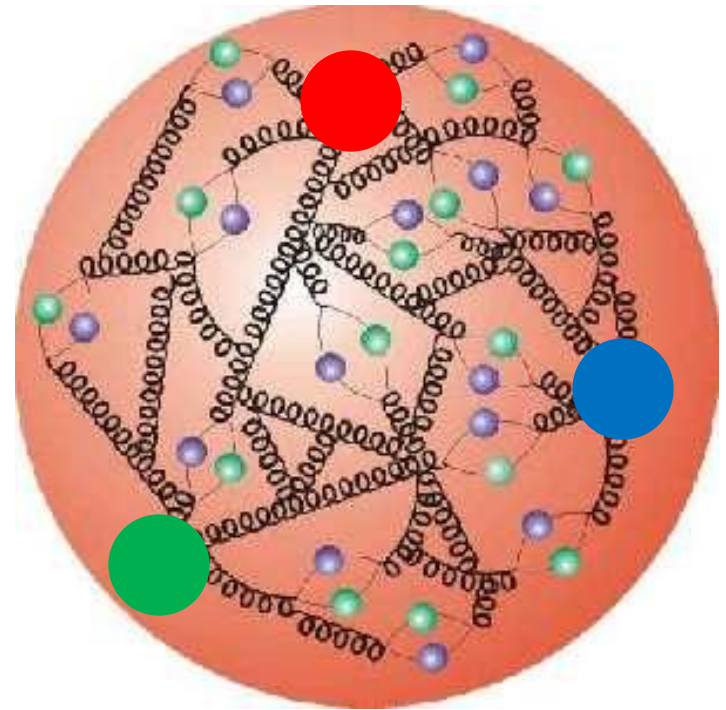
- quantum vacuum is a **united set of classical vacua**:

- ✓ appears as a result of **tunnelling between different topological states** of “stratified” space-time

- gluon fluctuations due to **tunneling**:

- ✓ quasilocal pseudoparticles carrying chromomagnetic and chromoelectric charges (instantons/dyons);
- ✓ dyons get clusterized into structures with **zeroth chromoelectric charge**;
- ✓ **stabilized by valence quarks**  $\rightarrow$  **hadrons!**

**½ of nucleon mass – from QCD vacuum**

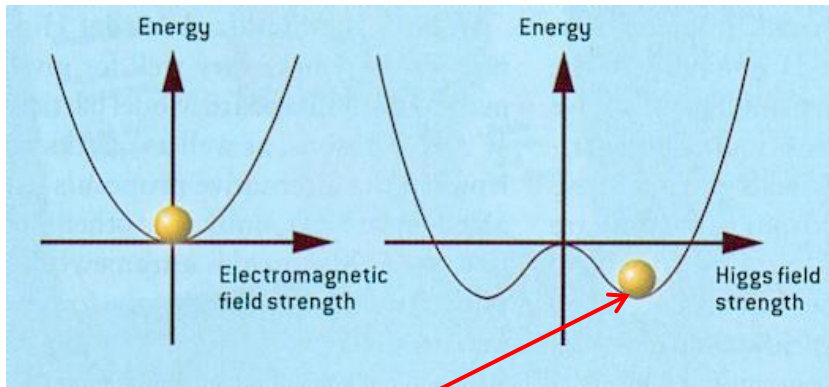


**No dynamics yet!**

**Small  $u, d$ -quark masses (i.e. Higgs condensate) are crucial for formation of QG condensate!**



# Origin of mass: “Weak” Vacuum and SSB



Higgs condensate

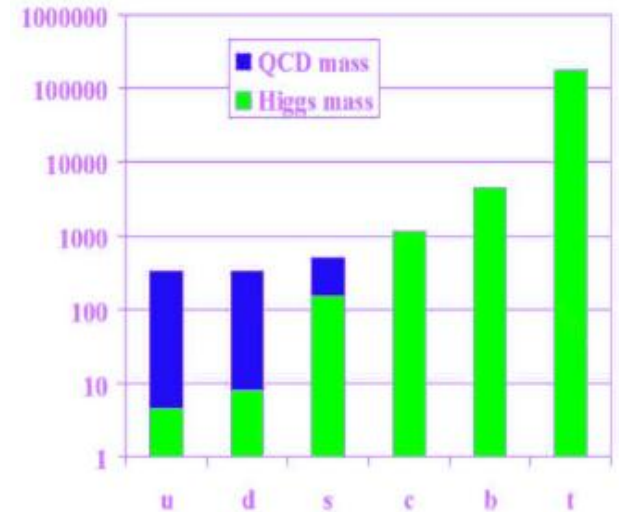
- due to *spontaneous deformations of the space-time “layers”, “weak” vacuum gain non-zeroth energy*

$$\langle v_{vac} \rangle \sim 245 \text{ GeV}$$

- *by interacting with Higgs condensate collective fluctuations gain frequencies (or field quanta gain masses)*

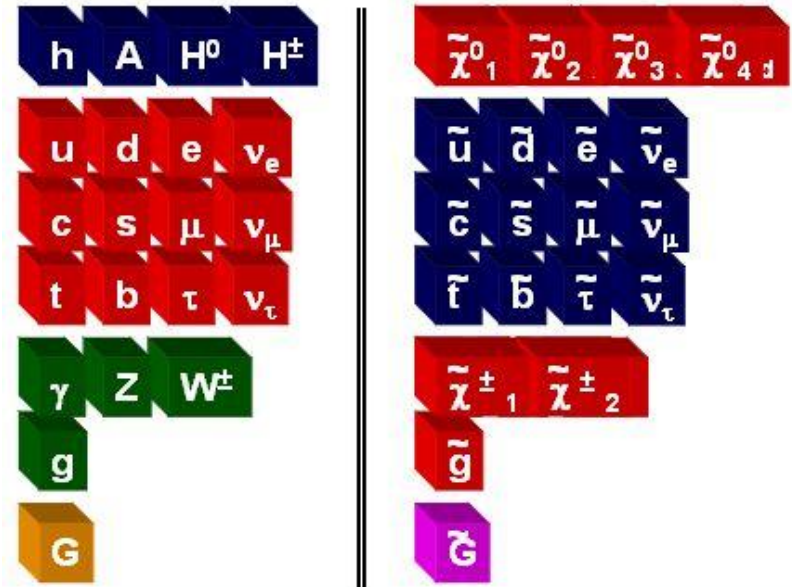
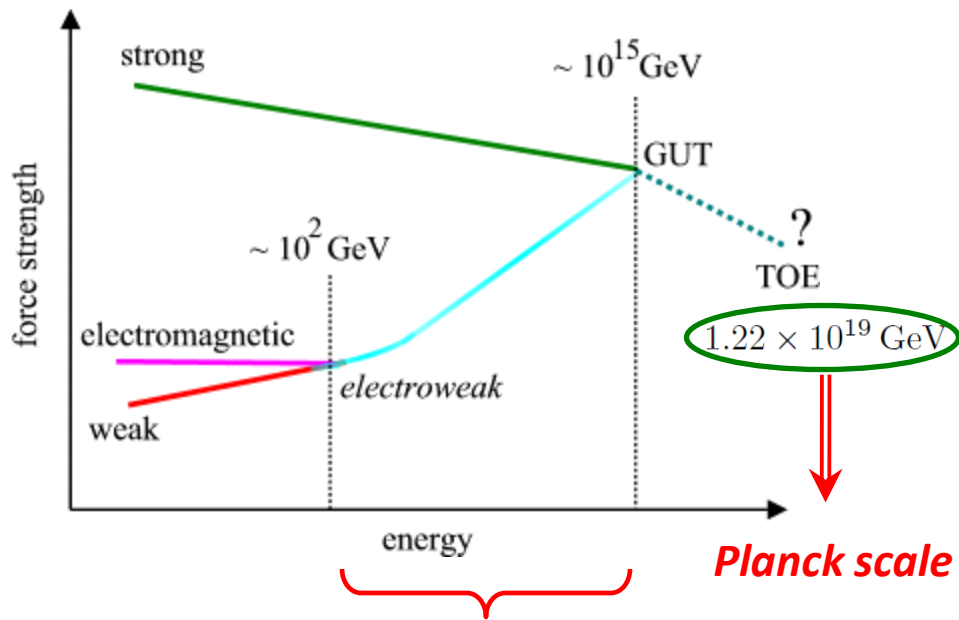
At the moment we do not understand:

- *why small mass (e.g. u,d,e...) is formed at a huge scale!*
- *why neutrino is >10000 times lighter than electron, and 10 billion times lighter than t-quark!*
- *why SIMILAR particles (within the same families) interact with Higgs condensate VERY DIFFERENTLY!*

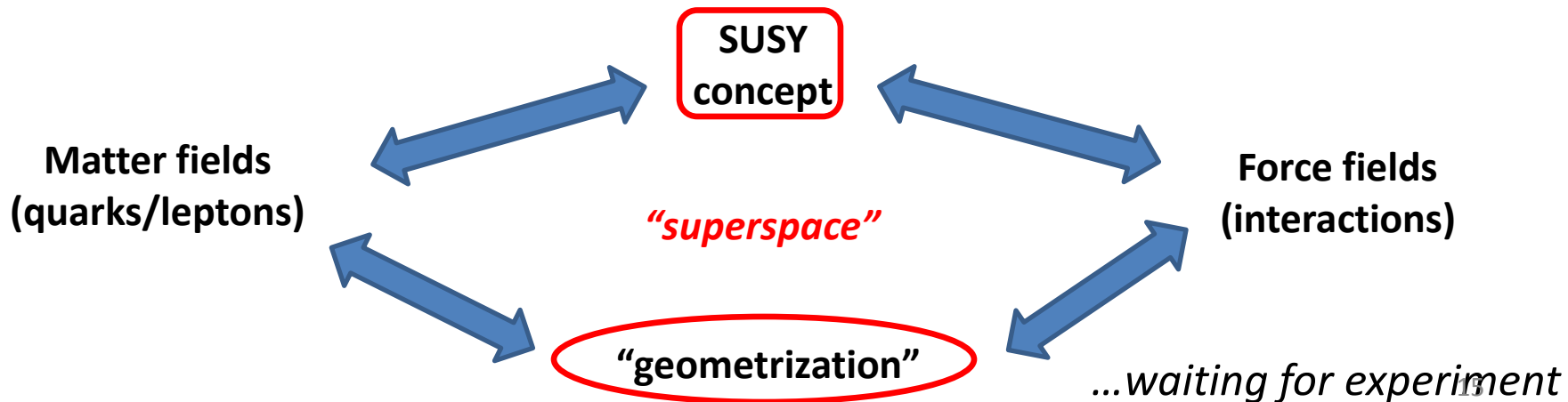


New vacuum structures or peculiar quantum features of non-Abelian vacuum???

# Unification: new vacuum substructures?



*“super-gauge desert” or something very interesting???*



# New ideas: “familon” symmetry SO(2)

...one of the possibilities to address on the same footing

- the **Higgs sector problem** (invisible Higgs boson)
- the **quark-lepton generations problem** (new symmetry)
- the **quark mixing problem**
- small neutrino masses

*Extension of SM by flavor  
SO<sub>f</sub>(2) symmetry*

*See e.g.: Kim’86, Fukugita’89, Danko’01, Chang’02  
Burduzha’08, Volchansky’11*

**“familon” symmetry is spontaneously broken! (NN GM)**

$$q = \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix} \approx \begin{pmatrix} 0 & 1,2 & 174 \\ 0 & 0,118 & 4,3 \end{pmatrix} \text{ GeV}$$

$$\ell = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0,106 & 1,78 \end{pmatrix} \text{ GeV}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**Quark/lepton representations:**

**Vector:**  $q_{L_A}, u_{R_A}, d_{R_A}, \ell_{L_A}, e_{R_A}, \nu_{R_A},$

**Scalar:**  $q_{L_3}, u_{R_3}, d_{R_3}, \ell_{L_3}, e_{R_3}, \nu_{R_3},$

$A = 1, 2$

**Two-doublet Higgs sector:**

$$H'_1 = e^{\frac{i}{2}g_1\theta + \frac{i}{2}g_2\theta_a\tau_a} (H_1 \cos \omega + H_2 \sin \omega),$$

$$H'_2 = e^{\frac{i}{2}g_1\theta + \frac{i}{2}g_2\theta_a\tau_a} (-H_1 \sin \omega + H_2 \cos \omega),$$

$$\text{CP } H_A = H_A^+.$$

**New real scalar field  
(EW singlet, SO(2) vector):**

$$\Phi'_1 = \Phi_1 \cos \omega + \Phi_2 \sin \omega,$$

$$\Phi'_2 = -\Phi_1 \sin \omega + \Phi_2 \cos \omega,$$

$$\text{CP } \Phi_A = \Phi_A.$$

**Fundamental (EW):  
vector SO(2):**

# Spontaneous “familon” symmetry breaking

*usual EW scale:*

$$\langle v_{vac} \rangle \sim 245 \text{ GeV}$$

**single light scalar  
Higgs boson**

$$h^0 \quad m_h \sim 100 \text{ GeV}$$

**massless Goldstone  
weakly interacting familon**

$$f$$

*new “familon” scale:*

$$u \gg v$$

$$H^\pm, H, A, \Phi_{1,2}$$

**..are far away from experimentally  
accessible energy scales!**

**Experimental constraints on familon decays of fermions:**

$$\Gamma(\tau^- \rightarrow e^- f) / \Gamma(\tau^- \rightarrow e^- \nu \bar{\nu}) < 1,5 \times 10^{-2}$$

$$\Gamma(\mu \rightarrow e f) / \Gamma(\mu \rightarrow e \nu \bar{\nu}) < 3 \times 10^{-4}$$



$$u \gtrsim 10^8 - 10^9 \text{ GeV}$$

**Non-perturbative interactions of  
the Higgs and Quark-Gluon condensates:**

$$m_f^2 = \frac{\langle 0 | \frac{\alpha_s}{\pi} G_{\mu\nu}^a G_a^{\mu\nu} | 0 \rangle m_\Phi^2}{3u^4}$$

**“familon mode”  
is dominant  
in Higgs decay:**

$$\frac{\Gamma(h^0 \rightarrow \bar{b}b)}{\Gamma(h^0 \rightarrow ff)} = \frac{1}{2} \left( \frac{m_b m_{h^0}}{2\xi v^2} \right)^2 \approx 10^{-2} \quad \text{Higgs boson is invisible!}$$

**Can Dark Matter be made of familons? Why not!**



# ...Towards cosmological scales

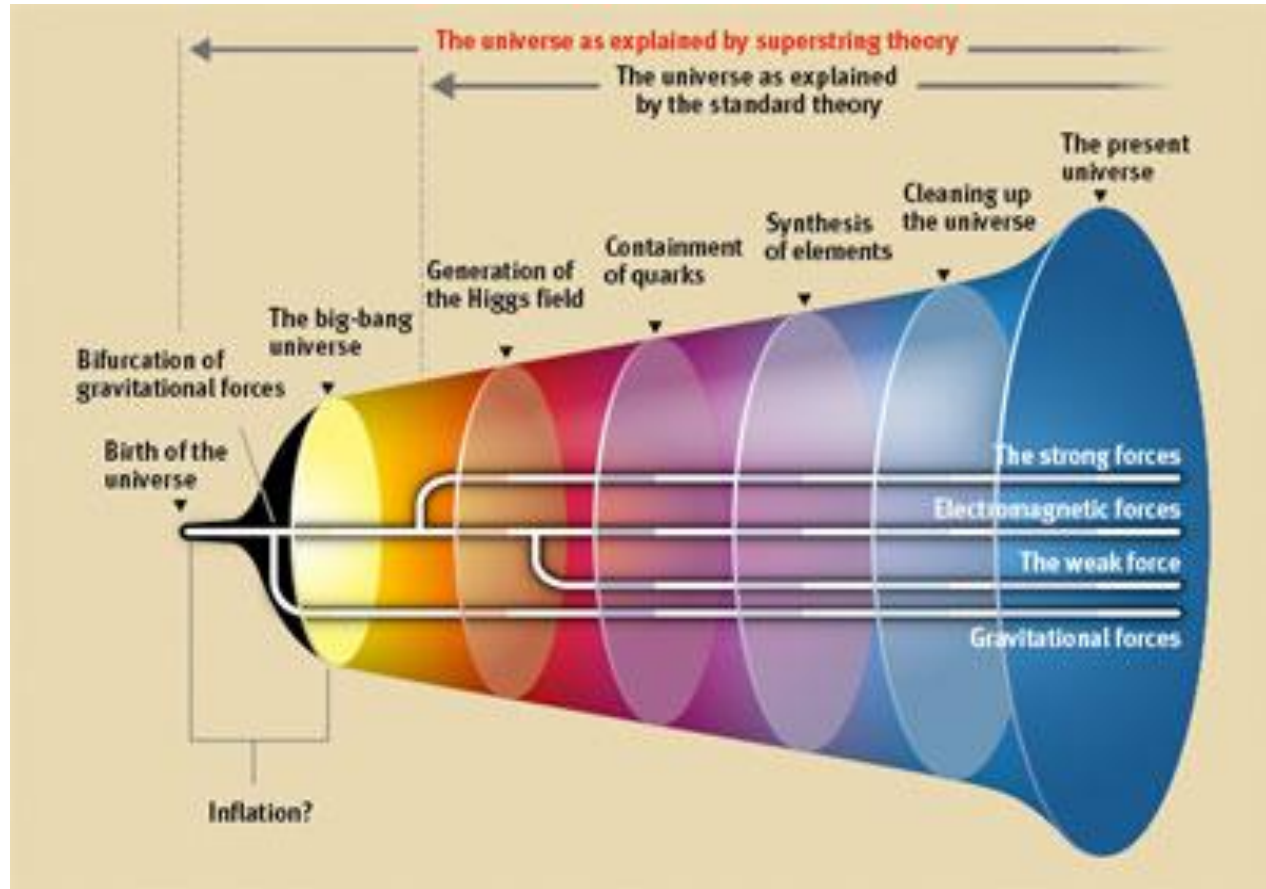
125 Mpc/h



Observable Universe as a footprint of microscopic quantum fluctuations and vacuum topology in the Past...



# Cosmological evolution of Vacuum



**Inflation due to enormous vacuum energy!**

Highly Non-equilibrium vacuum

Relativistic phase transitions

Decelerating Universe  $Z > 0.5$

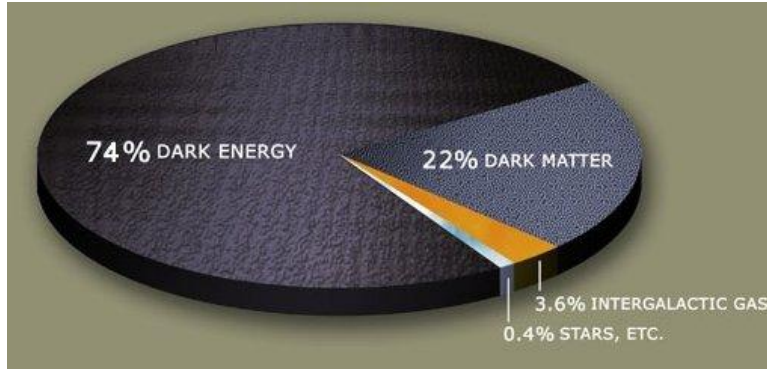
**Accelerating Universe**

**Vacuum has transformed many times during Universe expansion!**

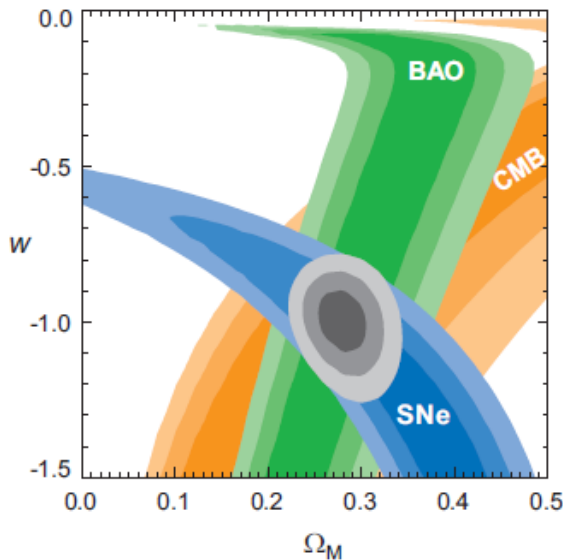
# “False” Vacuum and Dark Energy

$$\Omega_0 = \Omega_\Lambda + \Omega_{DM} + \Omega_b + \Omega_\gamma + \Omega_\nu$$

*Do we live in the “false” vacuum?*

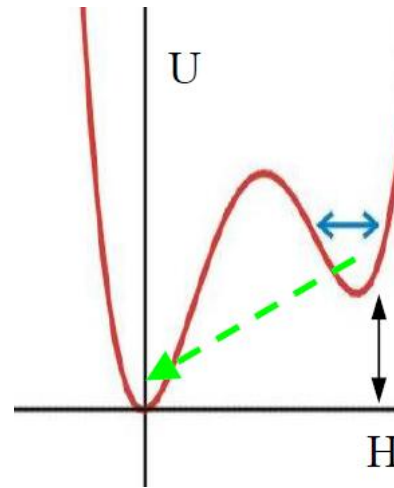


## DE equation of state



$$w \equiv P/\rho = -0.94 \pm 0.1$$

( $w=-1$  for pure  $\Lambda$ -term)



$$\lambda = 0.73 \pm 0.03 \rho_c$$

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 10.54 h^2 \text{ GeV}/\text{m}^3$$

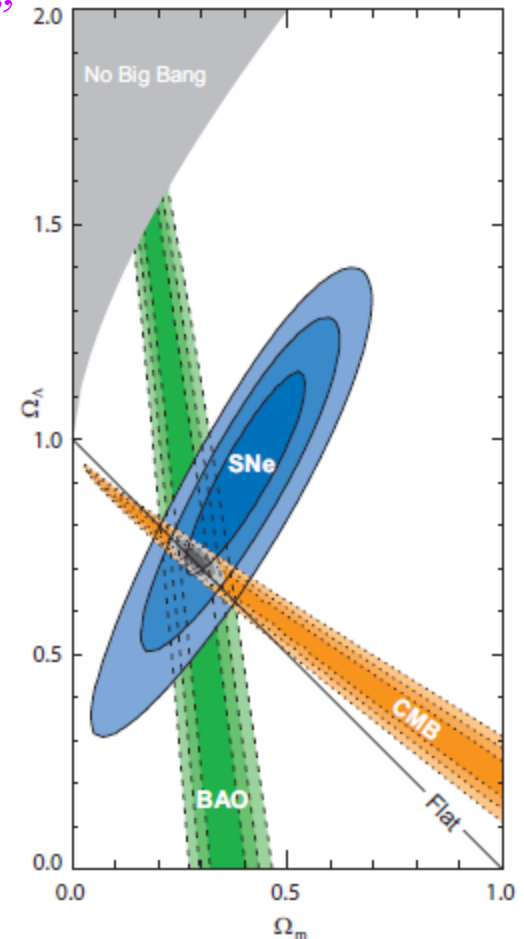
$$h = 0.73 \pm 0.03$$



$$\lambda \simeq 4.1 \pm 0.5 \text{ GeV}/\text{m}^3$$

$$\simeq (3.1 \pm 0.8 \text{ meV})^4$$

$$\simeq 6.6 \pm 0.8 \cdot 10^{-10} \text{ J}/\text{m}^3$$



Frieman et al, Annu.Rev. Astron. Astrophys. 46 (2008) 385

# Vacuum is “self-tuning”?

“False” vacuum has incredibly wrong energy scale!

$$\begin{aligned} \rho_{vac} &\sim M^4 \sim 1 \text{ GeV}^4, && \text{strong interactions} \\ &\sim 10^8 \text{ GeV}^4, && \text{electroweak interactions} \\ &\sim 10^{76} \text{ GeV}^4, && \text{gravitational interactions} \end{aligned} \quad \longleftrightarrow \quad \rho_\Lambda \sim \rho_c \sim 10^{-46} \text{ GeV}^4$$

**This is due to the following:**

- **At the moment, we understand very little about dynamics of different known Vacuum substructures in real time and their interplay between each other**
- **New Vacuum substructures (new symmetries) at high energy scales are needed for correct description of Universe evolution!**

The general belief: a compensation of **the gravitational part** to the vacuum energy → when gravity and quantum physics are made consistent (e.g. “**graviton condensate**”)

In principle, a compensation of **EW contribution is possible in SUSY**

**What about compensation of the QCD vacuum energy? No obvious way!**



# Cosmological evolution of Yang-Mills fields

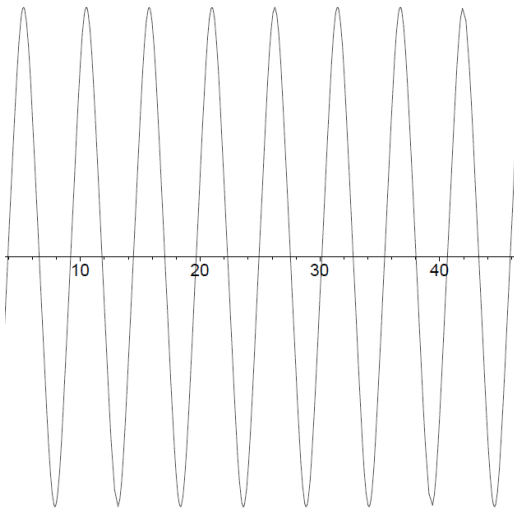
We assume: **the gluon field with unbroken non-Abelian symmetry fills up the whole Universe!**  
 (it could be produced at **the stage of Inflation**)

*Friedman flat Universe:*

$$g_{\mu\nu} = a^2(\eta)g_{\mu\nu(M)}$$

*Non-linear solution:*

$$A(\eta) \simeq A_0 \cos\left(\frac{6}{5} A_0 \eta\right)$$



*Classical YM fields equations:*

$$\frac{3}{\kappa} \frac{a'^2}{a^4} = \frac{3}{2g_{YM}^2 a^4} (A'^2 + A^4),$$

$$A'' + 2A^3 = 0.$$



**Equations are unstable w.r.t. radiation corrections!**



*Lagrangian of the gluonic field taking into account vacuum polarisation in one-loop approximation:*

$$L_{YM} = -\frac{1}{4g_{YM}^2} \frac{F_{\alpha\beta}^a F_a^{\alpha\beta}}{\sqrt{-g}} \left[ 1 + \frac{\beta}{2} \ln\left(\frac{J}{\Lambda_{QCD}^4}\right) \right] = -\frac{11}{128\pi^2} \frac{F_{\mu\nu}^a F_a^{\mu\nu}}{\sqrt{-g}} \ln\left(\frac{J}{\Lambda_{QCD}^4}\right),$$

$$J = \frac{1}{\xi^4} \frac{|F_{\alpha\beta}^a F_a^{\alpha\beta}|}{\sqrt{-g}}, \quad \sqrt{-g} = a^4(\eta),$$

*In Hamilton gauge and homogeneous/isotropic Universe:*

$$A_i^a = \begin{cases} \delta_i^a A(\eta), & i, a = 1, 2, 3 \\ 0, & i = 1, 2, 3; a > 3 \end{cases}$$

# QCD Vacuum and Dark Energy

Classical YM fields equations **with vacuum polarisation:**

$$\frac{6}{\kappa} \frac{a''}{a^3} = \varepsilon - 3p + 4\bar{\Lambda} + T_{\mu}^{\mu, YM}, \quad T_{\mu}^{\mu, YM} = \frac{33}{16\pi^2} \frac{1}{a^4} (A'^2 - A^4)$$

$$\frac{\partial}{\partial \eta} \left( A' \ln \frac{6e|A'^2 - A^4|}{a^4(\xi\Lambda_{QCD})^4} \right) + 2A^3 \ln \frac{6e|A'^2 - A^4|}{a^4(\xi\Lambda_{QCD})^4} = 0.$$

**Exact solution with constant energy exists!**

$$\frac{6e(A'^2 - A^4)}{a^4(\xi\Lambda_{QCD})^4} = 1$$

Constant contribution energy-momentum tensor of the Universe **with opposite sign to the instanton one!**



$$T_0^{0, tot} = T_0^{0, mat} + \bar{\Lambda} + \frac{33}{64\pi^2} \frac{(\xi\Lambda_{QCD})^4}{6e} \quad \Lambda_{QCD} \simeq 280 \text{ MeV}$$

$$\frac{33}{64\pi^2} \frac{(\xi\Lambda_{QCD})^4}{6e} + \Lambda_{inst} = 0, \quad \Lambda_{inst} \simeq -265^4 \text{ MeV}^4 \quad \xi \simeq 4$$

**Vacuum energy** (QCD part only):

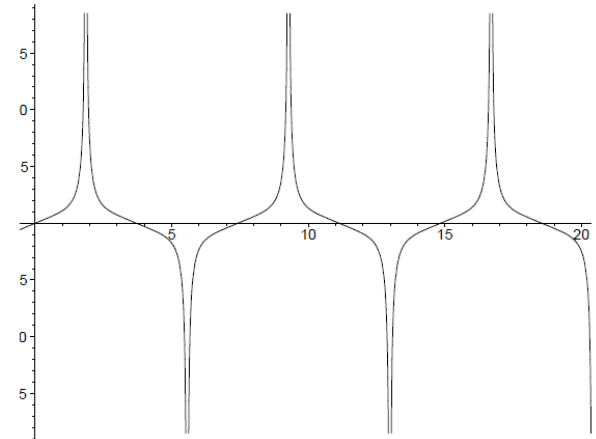
$$\bar{\Lambda} = \Lambda_{inst} + \Lambda_{cosm}$$



**instanton QCD vacuum contribution**

**observable cosmological constant**

**Classical solution is not stable w.r.t QCD vacuum fluctuations!**



**Dynamical cancellation of the quark-gluon condensate contribution!**

# Summary and outlook

## *In quantum physics:*

Vacuum is *the self-consistent system of vacuum condensates* – non-wave excitation modes of quantum fields (wave modes are particles!) – produced in the processes of relativistic phase transitions in Early Universe

## *From geometry point of view:*

The Physical Vacuum is formed *by zero-point fluctuations of non-deformed geometry* of space-time

The Physical Vacuum *affects all basic properties of particles* and their interactions

Extremely complicated structure of the Physical Vacuum exhibit intrinsic *“self-tuning” of its parameters with enormous precision* giving rise to the Structure Formation in our Universe, and ultimately to the appearance of biological and intelligent systems (Anthropic Principle)

Understanding of the *non-perturbative dynamics of the Physical Vacuum* is the biggest challenge of modern Theoretical Physics, and all major problems of the Standard Model of Particle Physics and Cosmological Evolution seem to be related to it

**NOW AN EXITING ERA IN UNDERSTANDING OF THE STRUCTURE AND THE FUNDAMENTAL ROLE OF THE PHYSICAL VACUUM COMES...!!!**