COSMOLOGICAL PROBLEMS GRAN SASSO, 2015

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Problems and questions.

1. What are DM objects? About 100 candidates. In 1990 there was 10. Expected next century one!

2. What is the mechanism of cosmological acceleration: DE or modified gravity, or what else?

Equation of state of DE: $P = w\rho$, $w = -1$ or $w > -1$, or $w < -1$?

3. Cosmic conspiracy. Seemingly unrelated densities of different forms of matter have comparable magnitudes:

$$\Omega_b \sim \Omega_{DM} \sim \Omega_{DE} \, .$$

4. The mechanism of baryogenesis?
5. Is there abundant cosmic antimatter of primordial origin? Search for antinuclei: PAMELA, BESS, AMS.
6. 0.511 - line from Galactic center?
7. Excess of high energy positrons. PAMELA, AMS.
8. Origin of UHECR.

9. Mechanism of creation of super-heavy BH. Early quasar creation with eveloved chemistry?

10. Gamma-bursters, seen at high z.

11. Origin of large scale galactic and intergalactic magnetic fields.

12. Low multipole anomalies in CMB.

13. BBN and ^7Li.

14. Dark radiation; sterile neutrinos.

15. The mechanism of inflation? Is it the only optoin?

Beyond SCM.

Multi-dimensional cosmologies, small extra dimensions or large extra dimensions. Do we live in domain wall? (Rubakov, Shaposhnikov, Phys. Lett. B125 (1983) 136.

Prior inflation (pre-big-bang?) Quantum gravity? Quantum space-time. Terra incognita.

HUGE PROBLEM: who killed vacuum energy almost to nothing?

Problem of vacuum energy. Maybe the observed DE is simply vacuum energy, however the estimated value of ρ_{vac} is by 50-100 orders of magnitude larger than the observed one.

Contributions to vacuum energy.

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1. Bosonic vacuum fluctuations:

$$\langle \mathcal{H}_b \rangle_{vac} = \int \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2} \langle a_k^\dagger a_k + b_k b_k^\dagger \rangle_{vac}$$
$$= \int \frac{d^3k}{(2\pi)^3} \omega_k = \infty^4 .$$

2. Fermionic vacuum fluctuations:

$$\langle \mathcal{H}_f \rangle_{vac} = \int \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2} \langle a_k^\dagger a_k - b_k b_k^\dagger \rangle_{vac}$$
$$= \int \frac{d^3k}{(2\pi)^3} \omega_k = -\infty^4 .$$

Bosonic/fermionic cancellation - Zeldovich prior to SUSY.

Supersymmetry:

$N_b = N_f$ and $m_b = m_f$, then

$$\rho_{vac} = 0 \, .$$

if the symmetry is UNBROKEN.

Soft SUSY breaking necessarily creates:

$$\rho_{vac} \sim m^4_{SUSY} \geq 10^8 \text{ GeV}^4 \neq 0 \, .$$

Broken SUGRA allows for $\rho_{vac} = 0$ but the natural value is

$$\rho_{vac} \sim m_{Pl}^4 \sim 10^{76}\ \mathrm{GeV}^4.$$

Plenty of phase transitions in the course of cosmological cooling

$$\delta\rho_{vac} \gg 10^{-47}\ \mathrm{GeV}^4.$$

Troubling mystery:
proton is a bound state of three quarks with masses about 5 MeV each. So its mass should be 15 MeV minus binding energy, instead of 938 MeV.

QCD is well established and experimentally verified science leads to conclusion that vacuum is not empty but filled with quark (Gell-Mann, Oakes, Renner) and gluon (SVZ) condensates:

$$\langle \bar{q}q \rangle \neq 0, \quad \langle G_{\mu\nu} G^{\mu\nu} \rangle \neq 0\,,$$

both having NEGATIVE vacuum energy

$$\rho_{vac}^{QCD} \approx -10^{45} \rho_c.$$

Vacuum condensate is destroyed by quarks and the proton mass is:

$$m_p = 2m_u + m_d - \rho_{vac} l_p^3$$

$m_u \sim m_d \sim 5$ **eV.**

Who adds the necessary "donation" to make the OBSERVED $\rho_{vac} > 0$ and what kind of matter is it?

Something must "live" in vacuum who donates positive contribution to ρ_{vac} compensating ρ_{QCD} with fantastic precision, 10^{-45}.

Resolution is unknown. It could be dynamical adjustment, modification of gravity in such a way that ρ_{vac} does not gravitate, infrared screening, anthropic principle with almost infinite set of subtraction constants, ... ???

Solution of the DE problem is most probably impossible without understanding of the mechanism of compensation of vacuum energy.
However, phenomenological description of DE may be instructive. The problem is aggravated by the cosmic coincidence: $\Omega_{DE} \sim \Omega_{DM} \sim 1$, while $\rho_{DM} \sim 1/a^3$ and $\rho_{DE} \sim const$.

Data in favor of DE:

a) Universe age crisis, last century. **With $H \geq 70$ km/sec/Mpc the universe would be too young, $t_U < 10$ Gyr, while stellar evolution and nuclear chronology demand $t_U \geq 13$ Gyr.**

b) $\Omega_m = 0.3$, measured by several independent ways: mass-to-light ratio, gravitational lensing, galactic clusters evolution (number of clusters for different red-shifts z).
On the other hand:
inflation predicts $\Omega_{tot} = 1$ and it is indeed observed: spectrum of angular fluctuations of CMBR (position of the first peak) "measures" $\Omega_{tot} = 1 \pm 0.03$.

c) Dimming of high z supernovae.
Cannot be explained by dust absorption because it was found that the effect is non-monotonic in z. At larger z dimming decreases. Indeed,
$\boldsymbol{\rho_m \sim 1/a^3}$**, while** $\boldsymbol{\rho_{vac} = const.}$
Equilibration at z $\approx$ **0.7.**
d) LSS and CMBR well fit theory if $\boldsymbol{\Omega_{\mathrm{v}} \approx 0.7}$. **Suppression of fluctuations at large scales due to DE.**

Direct measurement of acceleration. **Dimming of high redshift supernova, if they are standard candles means that they are at a larger distance. i.e. the universe expands faster than expected. Nonmonotonic dependence on z excludes light absorption on the way. Nobel Prize of 2011: S. Perlmutter, B.P. Schmidt, and A.G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".**

Two main possibilities, but none solves the vacuum energy problem:

1. Slowly varying massless or very light scalar field.

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} g_{\mu\nu} \left[(\partial\phi)^2 - U(\phi) \right].$$

2. Gravity modification at large scales:

$$S = \frac{m_{Pl}^2}{16\pi} \int d^4x \sqrt{-g} [R + F(R)] + S_m .$$

Nonlinear function of R leads to higher order equations of motion. Care should be taken of instability, gravitational singularities, ghosts(?), tachyons(?).

THE END