Dark Energy, large scale magnetic field and QCD.

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1.Vacuum Energy-definition.

- We treat gravity as an **effective low energy QFT**. Gravitons treated as quasiparticles which do not ``feel" all microscopical degrees of freedom, but only ``relevant excitations", similar to the excitations on a Fermi surface.

- This is a standard approach in all other fields of physics (condensed matter, with eV scale, not m_e, m_p)

- The basic problem on unnaturally small $10^{-120} M_{PL}^4$ cosmological constant is replaced by a different problem: what is the nature of a relevant scale?

- It has nothing to do with M_{PL}. Instead, it must be related to **IR** physics (not **UV** physics) through the boundary conditions, or point of normalization.

- We define the ``renormalized cosmological constant'' to be zero in Minkowski vacuum with metric $\eta_{\mu\nu} = \mathrm{diag}(1,-1,-1,-1)$ where the Einstein equations are consistently satisfied.

- It is a definition of our ``point of normalization''

- Effective QFT of gravity must predict the behaviour of the system in any other geometry of space-time after ``normalization procedure'' is performed.

- The ``renormalized energy density'' must be proportional to the deviation from the flat Minkowski vacuum. For example, it should be proportional to the Hubble constant H, or to the inverse size of manifold 1/L

2. Some remarks on θ dependent portion of the QCD vacuum energy

- The $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$ term is a key player in strongly interacting QCD
- $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} = \theta \partial_\mu K^\mu$ is total derivative, does not change the equation of motion. Still, it leads to the physically observable effects: dipole moment, $\eta' \to 2\pi$
- $\theta < 10^{-9}$ must be small (now) as it violates P, CP invariance in strong interactions.
- Still, θ parameter may play a crucial role during the QCD phase transition (source of CP violation) in early universe when it was order of one.

3. The θ- Dependence in Minkowski space

- The θ dependence in QCD determines the η' mass (Witten, Veneziano, 1979)

$$L = \frac{1}{2}\partial_\mu \eta' \partial^\mu \eta' - \frac{1}{\chi} Q^2 - \left(\theta - \frac{\eta'}{f_{\eta'}}\right) Q + N_f m_q | < \bar{q} q > | \cos\left[\frac{\eta'}{f_{\eta'}}\right]$$

$$Q \equiv \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}, \quad \chi = -\frac{\partial^2 \epsilon_{vac}(\theta)}{\partial \theta^2} = i \int d^4x < T\{Q(x), Q(0)\} >$$

- The topological susceptibility $\chi \neq 0$ does not vanish in spite of the fact that operator Q is total derivative

- Sign of $\chi < 0$ is negative (it is opposite to what one should expect from a physical degree of freedom)-- so the term "<u>the Veneziano Ghost</u>"

- Integrating out Q field produces η' mass with no any traces of massless (unphysical) ghosts.

- This is the old and well-known story when the theory is formulated in infinite Minkowski space.

- What would happen if the theory is defined on a finite manifold size L ~ 1/H ~ 10^{10} years, or/and if the universe is slowly expanding with rate H (FRLW universe)?

- We shall argue that there will be an extra amount of delocalized energy (eventually it will be identified with the **Dark Energy**).

- Important: this energy is originated from the (P-odd) Q-field sensitive to the boundaries L and expansion rate H

4. θ - related vacuum energy

- What would happen to the total (delocalized) energy if the system is defined on a finite manifold size L ~ 1/H ~ 10 G years, or/and if the universe is slowly expanding with rate H (FRLW universe)?

- ``Naive answer”: the corrections due to a finite size or expansion (~H) should be extremely small as all physical degrees of freedom are massive

$$\exp(-L\Lambda_{QCD}) \sim \exp(-\frac{\Lambda_{QCD}}{H}) \sim \exp(-10^{41})$$

- In reality, the physics could be much more interesting/complicated due to the topological nature of the θ vacua (sensitivity to boundaries)

5. Example: 2d Schwinger model

- The θ dependence, The U(1) anomaly, the anomalous Ward Identities, η' mass problem... are formulated/solved exactly in the same way as in 4d QCD.

- The Kogut-Susskind ghost (**KS**, 1975) has precisely correct properties (including $\chi < 0$) to solve all those problems.

- KS-ghost ϕ_1 , its partner ϕ_2, the massive physical η' the θ dependence... are described by KS Lagrangian:

$$\begin{aligned}\mathcal{L}_{\mathcal{KS}} &= \frac{1}{2}\partial^\mu\eta'\partial_\mu\eta' + \frac{1}{2}\partial^\mu\phi_2\partial_\mu\phi_2 - \frac{1}{2}\partial^\mu\phi_1\partial_\mu\phi_1 - \frac{m_{\eta'}^2}{2}\eta'^2 \\ &- m_q < \bar{q}q > \cos\left(\theta + 2\sqrt{\pi}(\eta' + \phi_2 - \phi_1)\right)\end{aligned}$$

- The χ would get a wrong sign without KS ghost.

- KS ghost is unphysical (ϕ_1 is cancelled by ϕ_2). Still, KS ghost contributes to the vacuum energy and the topological susceptibility, saturates WI, solves $U(1)_A$

- One can exactly compute the θ dependent portion of the energy with exact result

$$\Delta E \equiv E(L) - E_{Minkowski} = E\left(1 + O(\frac{1}{m_{\eta'}L})\right)$$

- The model has a single physical massive η'. Still, energy correction is linear in L^{-1}, not $\exp(-L)$.

- The **Casimir-like effect** occurs in the model with a single massive physical degree of freedom! It can be interpreted in terms of contact term/boundary conditions. Topological zero modes become <u>percolating cluster</u> sensitive to the boundaries.

6. Casimir like effect in 4d QCD

- One can keep explicitly the Veneziano ghost in the system (it is a longitudinal component of K_μ).

- One can derive the low energy effective Lagrangian which describes massive η',the θ axion, the Veneziano ghost ϕ_1 and its partner ϕ_2. It has precisely the KS form.

- If the Casimir like effect takes place in 4d QCD similar to 2d QED, the extra θ -dependent portion of the vacuum energy will be

$$\Delta E \sim \frac{2N_f|m_q < \bar{q}q > |}{m_{\eta'}L} \sim \frac{2N_f|m_q < \bar{q}q > |H}{m_{\eta'}} \sim (4.3 \cdot 10^{-3}\mathrm{eV})^4$$

$$\rho_\Lambda \simeq (2.3 \cdot 10^{-3}\mathrm{eV})^4, \; where \; \frac{1}{L} \sim H \simeq 1.5 \cdot 10^{-33} eV, \; \text{observations}$$

- No any other fields from the Standard Model may contribute to ΔE (e.g. $\Delta E(\text{Higgs}) \sim \exp(-m_H L) \sim \exp(-10^{43})$).

7. The Veneziano Ghost in 4d. details. (conventional picture in Minkowski space)

- One can explicitly demonstrate that the low energy lagrangian for U(1)_A degrees of freedom in 4d QCD is <u>identical</u> to the 2d Kogut- Susskind lagrangian (including θ term and KS ghost).

Veneziano ghost' s partner

Veneziano ghost

$$\mathcal{L} = \frac{1}{2}\partial_\mu\eta'\partial^\mu\eta' + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1$$
$$- \frac{1}{2}m_{\eta'}^2\eta'^2 + m_q|<\bar{q}q>|\cos\left[\theta + \frac{\eta' + \phi_2 - \phi_1}{f_{\eta'}}\right]$$

- The Veneziano ghost is introduced to account for the "wrong" sign in χ. It gives the same physics as the Witten's contact term and provides the η' mass.

- The negative sign in the Lagrangian does not lead to any problems (unitarity, causality...) when auxiliary (similar to Gupta-Bleuler in QED) conditions on the physical Hilbert space are imposed:

$$(\phi_2 - \phi_1)^{(+)} \, |\mathcal{H}_{\rm phys}\rangle = 0 \, .$$

positive frequency part enters this condition!

- the hamiltonian has sign minus for the ghost. However, the expectation value for any physical state vanishes as a result of GB condition,

$$\mathrm{H} = \sum_k \omega_k \left(b_k^\dagger b_k - a_k^\dagger a_k \right) \, . \qquad < \mathcal{H}_{\rm phys} | \mathrm{H} | \mathcal{H}_{\rm phys} >= 0 \, .$$

- It is similar to what happens in QED when two unphysical photon's polarizations cancel each other as a result of Gupta-Bleuler conditions.

- I use the Veneziano (rather than the Witten's) approach as it can be easily generalized for a time dependent, accelerating background when $T \neq 0$.

8. Accelerating system/curved space.

- The Minkowski separation (of positive frequency modes from negative ones) is maintained throughout the whole space as a consequence of Poincare invariance.

- A transition from a complete orthonormal set of modes to different one (the so-called Bogolubov's transformations) in **accelerating system** will always mix positive frequency modes with negative frequency ones.

- As a result of this mixture, the vacuum state defined by a particular choice of the annihilation operators will be filled with particles in a different system.

9. Toy model. Veneziano Ghost in the Rindler space. Unruh effect.

- The Rindler metric describes a constantly accelerating system when L(R)-observers do not ever have access to the entire space-time

$$ds^2 = e^{2a\xi}(d\eta^2 - d\xi^2), \quad t = \frac{e^{a\xi^R}}{a}\sinh a\eta^R, \quad x = \frac{e^{a\xi^R}}{a}\cosh a\eta^R$$

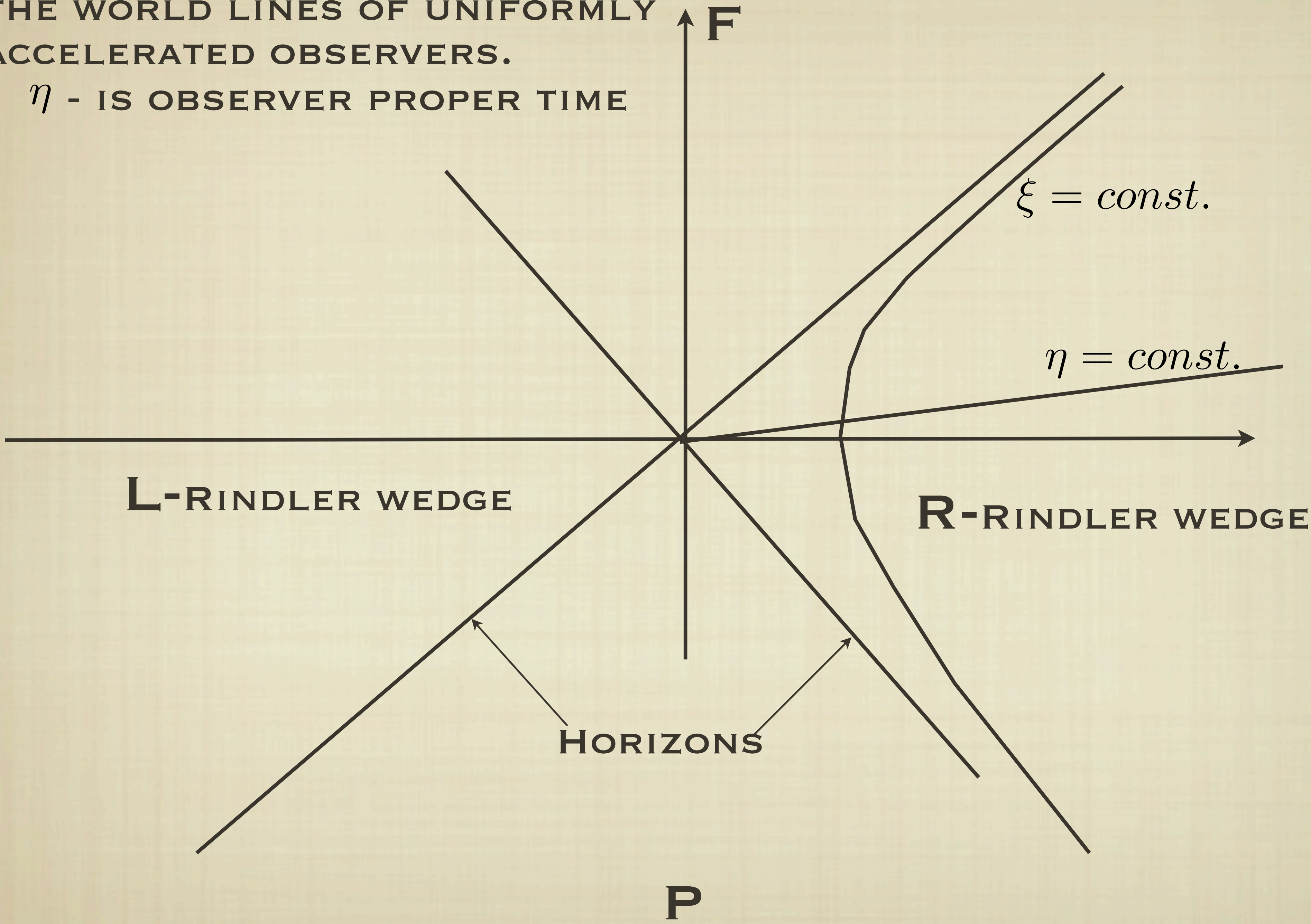
- Bogolubov's coefficients are known exactly for this case (mixing the positive and negative modes).

- The cancellation between the Veneziano ghost and its partner does not hold for the accelerating Rindler observer.

$$< 0|\omega_k \left(b_k^{(R,L)\dagger} b_k^{(R,L)} - a_k^{(R,L)\dagger} a_k^{(R,L)} \right) |0 >= \frac{2\omega}{(e^{2\pi\omega/a} - 1)}.$$

$\xi = const.$ CORRESPONDS TO THE WORLD LINES OF UNIFORMLY ACCELERATED OBSERVERS.

η - IS OBSERVER PROPER TIME



Technical reason for non-cancellation:

- The ground state for Minkowski observer is defined as usual

$$a_k|0>=0\,,\quad b_k|0>=0\,,\quad \forall k\,.$$

- The vacuum for R-Rindler observer is defined as

$$a_k^L|0_R>=0\,,\quad a_k^R|0_R>=0\,,\quad b_k^L|0_R>=0\,,\quad b_k^R|0_R>=0\,,\quad \forall k\,.$$

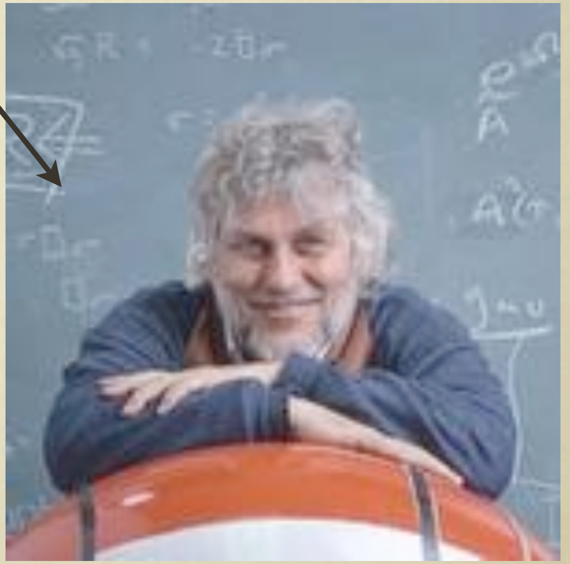
- The Bogolubov's coefficients are known to mix positive and negative frequency modes:

$$a_k^L=\frac{e^{-\pi\omega/2a}a^{1\dagger}_{-k}+e^{\pi\omega/2a}a_k^2}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}\qquad a_k^R=\frac{e^{-\pi\omega/2a}a^{2\dagger}_{-k}+e^{\pi\omega/2a}a_k^1}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}$$

$$b_k^L=\frac{e^{-\pi\omega/2a}b^{1\dagger}_{-k}+e^{\pi\omega/2a}b_k^2}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}\qquad b_k^R=\frac{e^{-\pi\omega/2a}b^{2\dagger}_{-k}+e^{\pi\omega/2a}b_k^1}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}.$$

- No cancellation between the Veneziano ghost and its partner could occur as a result of opposite sign (-) in commutation relations and negative sign (-) in Hamiltonian.

- if we had started with a conventional scalar field we would derive a well-known formula for Plank spectrum for radiation at $T = a/(2\pi)$ observed by a Rindler observer in Minkowski vacuum which is conventional Unruh effect



The cancellation fail to hold for the accelerating Rindler observer because the properties of the operator which selects the positive frequency modes with respect to Minkowski time t and observer's proper time η are not equivalent.

10. Veneziano ghost in accelerating system. Interpretation.

- One can study the same system using BRST quantization for selection of the physical Hilbert space (instead of Gubta- Bleuler formulation). The result is the same: the BRST operator as constructed by the Rindler observer does not annihilate the Minkowksi vacuum state.

- the nature of the effect (extra amount of the vacuum energy observed by the accelerating observer in comparison with the Minkowski observer) is the same as the conventional Unruh effect when the Minkowski vacuum $|0>$ is restricted to the Rindler wedge with no access to the entire space time.

- We interpret the extra contribution to the energy observed by an accelerating observer as a result of formation of the squeezed state which can be coined as the "ghost condensate" rather than a presence of "free particles" at $T = a/2\pi$ prepared in a specific mixed state.

$$|0> = \prod_k \frac{1}{\sqrt{(1-e^{-2\pi\omega/a})}} \exp\left[e^{-\pi\omega/a}\left(b_k^{R\dagger} b_{-k}^{L\dagger} - a_{-k}^{R\dagger} a_k^{L\dagger}\right)\right] |0^R> \otimes |0^L>$$

- We interpret the ghost contribution to the energy as a convenient way to account for a nontrivial infrared physics at the horizon and/or the boundary (there are no asymptotic ghost states).

- It is possible that the same physics, in principle, can be described without the ghosts (such a description however would be much more technically complicated).

11. Fine tuning without ``fine tuning''.

- A number of fine tuning issues such as coincidence problem, drastic separation of scales, etc may find a simple and universal explanation within this framework, without new fields, new interactions, new symmetries...

- For example, vacuum energy is determined by the deviation from Minkowski flat space-time,

$$\Delta E = [E(L,H) - E(L=\infty, H=0)] \sim H\Lambda_{QCD}^3 \sim (10^{-3}\mathrm{e}V)^4$$

- Why does it happen now?

$$3H^2M_{PL}^2 \sim \Delta E \quad \Longrightarrow \quad \tau \sim H^{-1} \sim \frac{M_{PL}^2}{\Lambda_{QCD}^3} \sim 10 \text{ Gyr}$$

- Typical wavelengths contributing to the "ghost condensate" is $k \sim H^{-1} \sim 10^{10} yr$, which is a property of the Bogolubov's coefficients. This type of matter (large wavelengths) is drastically different from anything else in the Universe as it does not clump.

- The nature of this ``fine tuning without fine tuning'', is not a result of supersymmetry or any other extra symmetries imposed on the system (there are in fact, none), but it comes about from the auxiliary conditions on the physical Hilbert space which accommodate the gigantic span of scales $H/\Lambda_{QCD} \sim 10^{-41}$

- No any other fields from the SM contribute to the dark energy ~ H (they are massive and their contribution is suppressed $\sim \exp(-\frac{m}{H})$).

12. Possible Tests.

- 1/L corrections in topological susceptibility can be measured in the lattice QCD simulations

- CMB (through integrated Suchs-Wolfe effect) is sensitive to the size of the universe.
  Our prediction: $L \simeq 17 H^{-1}$ (to match observational DE)
  Present constraint: $L > 6.8 H^{-1}$

- P-odd correlations in CMB are predicted as a consequence of P-odd nature of the dark energy field.

- The large scale magnetic field may be induced as a result of interaction with dark energy fields through a known conventional triangle anomaly

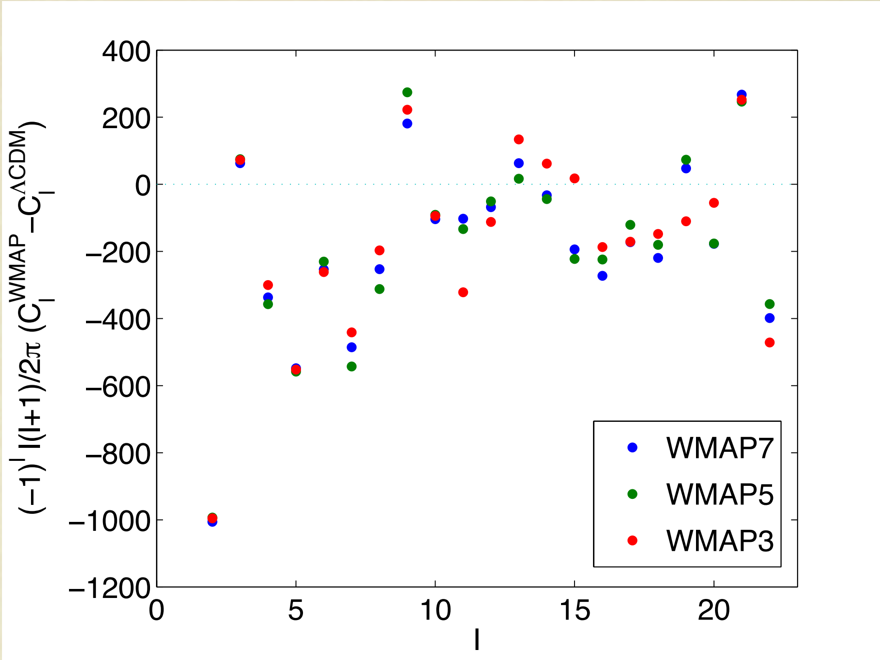
13. Observations: P- violation on very large scales in the Universe. CMB

- P parity asymmetry of WMAP

$$\vec{x'} = -\vec{x},$$
$$\vec{x'} = \vec{x} - 2\vec{n}(\vec{x}\cdot\vec{n})$$

- Reflection symmetry

- Mirror symmetry



- Fig. indicates: there exists power deficit (excess) at most even (odd) multipoles as it is weighted with $(-1)^l l(l+1)$.

- 100+ papers on asymmetry with typical titles: " Is the Universe odd?", " anomalous parity asymmetry..." etc
(the plot is from paper by Naselsky et al, 2010)

14. Large scale magnetization of the Universe.

- Ever increasing correlation lengths:

- 1. Galaxies- $B \sim \mu\mathrm{G}$ on (1-30) kpc scale
  2. Cluster of galaxies- similar strengths have been observed over distances reaching Mpc scale.
  3. Fields are not associated with individual galaxies.
  4. Recent hints on magnetization (with similar intensity) of gigantic superclusters (~100 Mpc)
  5. Alignment of quasar's polarizations (~ 1.5Gpc).

- High redshifts: $B \sim \mu\mathrm{G}$ field were present at much earlier epoch, z~5 when dynamo mechanism did not have enough time to operate

- Conventional theoretical models (including inverse cascade) fail to explain such correlation lengths with similar strengths at all scales.

15. Large scale magnetization from interaction with (P-odd) DE- field.

- Standard triangle anomaly unambiguously fixes the interaction between DE fields and Electromagnetic field,

$$\mathcal{L}_{(\phi_2-\phi_1)\gamma\gamma} = \frac{\alpha}{4\pi} N_c \sum Q_i^2 \left(\frac{\eta' + \phi_2 - \phi_1}{f_{\eta'}} \right) F_{\mu\nu}\tilde{F}^{\mu\nu} \, .$$

- One can estimate the EM energy and magnetic field B induced by this interaction:

$$\rho_{EM} \simeq < \vec{B}^2 > \simeq \frac{\alpha}{2\pi} H\Lambda^3_{QCD}, \quad \text{where} \;\; \rho_{DE} \simeq H\Lambda^3_{QCD}$$

$$< B > \sim \sqrt{\frac{\alpha}{2\pi} H\Lambda^3_{QCD}} \sim \mu\text{G}$$

- Our picture suggests that $B \sim \mu\text{G}$ indeed will be correlated on very large scales(consistent with observations). No any fitting parameters are involved in our estimate of $B \sim \mu\text{G}$.

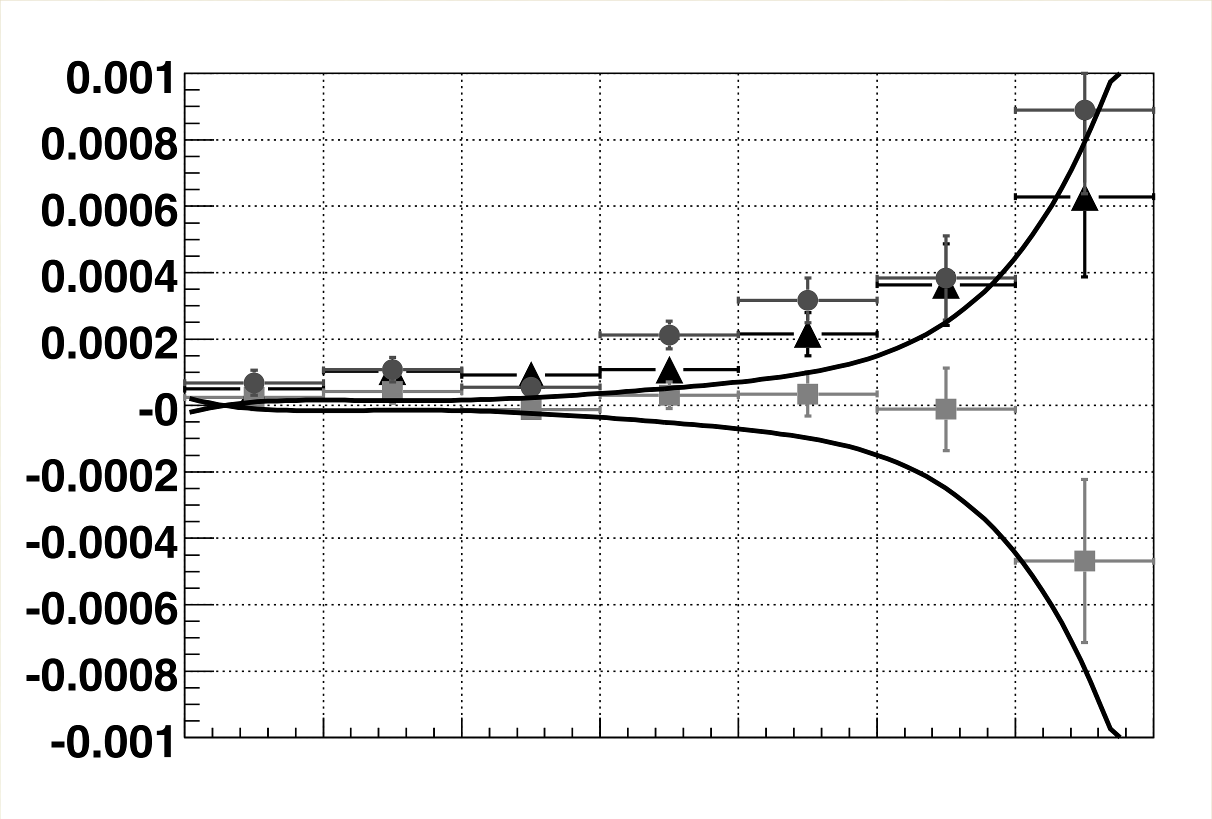
Instead of Conclusion

- the DE observed in our universe might be a result of mismatch between the vacuum energy computed in slowly expanding universe and in flat Minkowski space $\Delta E_{vac} \sim H\Lambda^3_{QCD} \sim (10^{-3}\mathrm{eV})^4$

- A number of fine tuning problems is automatically resolved as a result of auxiliary conditions on the physical Hilbert space which accommodate the gigantic span of scales without a new symmetry.

- Direct consequences of this framework:
  1. large correlation scales of the magnetic field in the universe $B_0 \sim \sqrt{\frac{\alpha}{\pi}} \cdot H\Lambda^3_{QCD} \sim \mu\mathrm{G}$
  2. P-odd correlations in CMB as consequence of P-odd nature of the DE field.

Another θ related effect: Parity violation at RHIC



STAR data.

Charged particle asymmetry parameters as a a function of centrality bins selected on the basis of charged particle multiplicity. Points are STAR data for Au+Au at 62 GeV: circles are $\pi^+\pi^+$, triangles are $\pi^-\pi^-$ and squares are $\pi^-\pi^+$