Title: The problem of vacuum energy from a particle physics perspective

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Abstract: The problem of vacuum energy is reviewed. The observational evidence in favor of a non-zero cosmological constant is described. I then discuss several possible explanations for how a theoretically natural huge value of vacuum energy could be adjusted down to the unnaturally tiny but observed value.

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THE PROBLEM OF VACUUM ENERGY FROM A PARTICLE PHYSICS PERSPECTIVE

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Perimeter Institute, October, 5, 2005

alias:

Lambda-term, Cosmological constant

Traditional GR point of view:

Lambda term (or cosmological constant) is GEOMETRICAL, while vacuum energy is PHYSICAL quantity.

They do not have anything in common

However, there is no way to

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Lambda term (or cosmological constant) is GEOMETRICAL, while vacuum energy is PHYSICAL quantity. They do not have anything in common

However, there is no way to distinguish between them.

PROBLEMS:

1. Theoretically: $\Lambda \approx \infty$.

Mismatch between theory and data:

50-100 ORDERS OF MAGNITUDE.

2. Majority point of view during long time and maybe even now:

$$\infty = 0$$

"Corrections are infinite but small"

(R. Feynman)

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2. Majority point of view during long time and maybe even now:

$$\infty = 0$$

“Corrections are infinite but small” (R. Feynman).

3. New independent pieces of data:
EMPTY SPACE (ANTI)GRAVITATES

4. Close proximity of $\rho_{vac} = const$ to $\rho_c \sim 1/t^2$ exactly today.

5. If antigravitating substance is not vacuum energy then WHAT?

CONTENT

1. Definition and history.

2. Data in favor of $\rho_{\rm vac} \neq 0$ (or $\rho_{\rm DE} \neq 0$).

3. Cosmology with $\Lambda \neq 0$.

4. Almost infinite contributions into ρ_{vac}.

5. Possible ways out.

Biographical notes

Name(s):

Cosmological constant, Λ-term, vacuum energy

or, maybe, dark energy.

Date of birth: 1918

Father A. Einstein: "The biggest blunder of my life" (after Hubble's discovery of cosmological expansion).

Many times assumed dead, probably erroneously.

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Date of birth: 1918

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Many times assumed dead, probably erroneously.

Well alive today.

Still not safe - many want to kill it.

SOME MORE QUOTATIONS:

LeMaittre: "greatest discovery, worth to make Eisntein's name famous".

Gamow: "λ raises its nasty head again" (after indications that quasars are accumulated near $z = 2$ in the 60s)

One parameter freedom in GR equations satisfying general covariance:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - g_{\mu\nu} \Lambda = 8\pi G_N T_{\mu\nu}^{(m)}$$

Introduced to make the universe stationary, Λ counterweights gravitational attraction. However, the solution is unstable.

Covariant conservation:

$$\mathbf{D}_\mu \left(\mathbf{R}^\mu_\nu - \frac{1}{2} \mathbf{g}^\mu_\nu \mathbf{R} \right) \equiv 0$$

automatic in metric theories.

Analogy to electrodynamics:

$$\partial_\mu \mathbf{F}^{\mu\nu} = 4\pi \mathbf{J}^\nu$$

Owing to anti-symmetry of $\mathbf{F}^{\mu\nu}$,

$$\partial_\mu \partial_\nu \mathbf{F}^{\mu\nu} \equiv 0$$

and the current MUST be conserved,

$$\partial_\mu \mathbf{J}^\mu = 0$$

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Due to covariant conservation law:

$$D_\mu \left(R^\mu_\nu - \frac{1}{2} g^\mu_\nu R \right) = 0$$

the energy-momentum tensor is also conserved:

$$D_\mu T^{\mu\,(m)}_\nu = 0,$$

and the condition (in metric theory):

$$D_\mu g^\mu_\nu \equiv 0,$$

the cosmological constant must be CONSTANT:

conserved:

$$\mathrm{D}_\mu \mathrm{T}_\nu^{\mu\,(\mathrm{m})} = 0,$$

and the condition (in metric theory):

$$\mathrm{D}_\mu \mathrm{g}_\nu^\mu \equiv 0,$$

the cosmological constant must be CONSTANT:

$$\Lambda = \mathrm{const}$$

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Models with $\Lambda = \Lambda(t)$ are not innocent, new fields to respect energy conservation condition are necessary or serious modifications of the theory, e.g. non-metric theories.

First attempts to make time-dependent Lambda, 1935 by Bronshtein (Leningrad); strongly criticized by Landau.

Modern point of view - instead of l.h.s. put Λ into r.h.s. and call it the vacuum energy:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N \left(T^{(m)}_{\mu\nu} + \rho_{vac} g_{\mu\nu} \right)$$

Normalized to the critical energy density $\rho_c = 3H^2 m^2_{Pl}/8\pi$:

$$\Omega_V = \frac{\rho_{vac}}{\rho_c},$$

$$\rho_c \approx 10^{-29}\, g/cm^3 \approx 10^{-47}\, GeV^4.$$

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RISE AND FALL OF LAMBDA-TERM

1. Birth: $\Omega_V \approx 1$.

2. Hubble discovery of expansion, earlier Friedman solution: $\Omega_V \equiv 0$.

3. LeMaitre, De Sitter, later Eddington: one of the most important discoveries in GR.

4. Still non-zero Lambda is not accepted by majority.

5. QSO accumulation near z=2 explained by $\Omega_V \approx 1$. Later rejected

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6. From 60s to the end of the Millennium Lambda was identically zero.

Only a few treated it seriously, starting from Zeldovich.

7. End of 90s:

a) Universe age crisis.

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.

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b) $\Omega_{\rm m} = 0.3$, 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 $\Omega_{\rm tot} = 1$.

Spectrum of angular fluctuations of CMBR (position of the first peak) "measures" $\Omega_{\rm tot} = 1 \pm 0.05$.

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c) Dimming of high redshift 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,

$\rho_{\rm m} \sim 1/a^3$,

while $\rho_{\rm vac} = \rm const.$

Equilibration at $z \approx 0.7$.

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d) LSS and CMBR well fit theory if $\Omega_{\rm v} \approx 0.7$.

Theory: gravitational instability, flat spectrum of primordial fluctuations, cold dark matter (non-interactive?).

CONCLUSION:

$$\Omega_{\rm v} = 0.7$$

$$\rho_{\rm vac} \approx 10^{-47}\,\mathrm{GeV}$$

$$\Omega_{\rm m} = 0.3$$

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EVOLUTION OF VACUUM(-LIKE) ENERGY DURING COSMIC HISTORY

1. At inflation $\rho_{\mathbf{vac}} \sim 10^{100} \rho_{\mathbf{V}}^{\mathbf{now}}$ and was DOMINANT. But it was not real vacuum energy but vacuum-like energy of almost constant scalar field inflaton.

2. At GUT p.t. (if such era existed)

$$\delta\rho_{\mathbf{vac}} \approx 10^{60}\,\mathrm{GeV}^4$$

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$$\delta\rho_{\mathbf{vac}} \approx \mathbf{10^{60}}\,\mathrm{GeV}^{\mathbf{4}}$$

3. At electro-weak p.t.

$$\delta\rho_{vac} \approx 10^{8}\,\mathrm{GeV}^{4}$$

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4. At QCD p.t.

$$\delta\rho_{vac} \approx 10^{-2}\,\mathrm{GeV}^4$$

The magnitude of vacuum energies of gluon and chiral condensates are known from experiment!

After inflation till almost the present epoch ρ_{vac} was always sub-dominant

ρ_{vac} started to dominate energy density only recently at $z \approx 0.3$.

SOME SIMPLE FEATURES OF LAMBDA DOMINANT COSMOLOGY

In homogeneous and isotropic case the energy-momentum tensor has the diagonal form:

$$\mathbf{T}_\mu^\nu = \mathrm{diag}\,(\rho, -\mathbf{p}, -\mathbf{p}, -\mathbf{p})\,,$$

For vacuum (because of Lorentz invariance of vacuum) $T_\mu^\nu \sim g_\mu^\nu = \delta_\mu^\nu$ **and**

$$\mathbf{T}_\mu^{\nu\,(\mathrm{vac})} = \mathrm{diag}\,(\rho, \rho, \rho, \rho) \qquad (1)$$

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$$\mathbf{T}_\mu^{\nu\,(\mathbf{vac})} = \mathrm{diag}\,(\rho, \rho, \rho, \rho) \,, \qquad (1)$$

i.e. $\mathrm{p}_{\mathrm{vac}} = -\rho_{\mathrm{vac}}$.

(Maybe breaking of Lorentz can solve the problem?)

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Covariant energy conservation:

$$\dot{\rho} = -3\mathrm{H}\,(\rho + \mathrm{p})$$

Hence $\rho_{\mathrm{vac}} = \mathbf{const}$ and $H = const$, i.e.

$$\mathrm{a(t)} \sim \exp(\mathrm{Ht})$$

Expansion is ACCELERATED:

$$\frac{\ddot{\mathrm{a}}}{\mathrm{a}} = -\frac{4\pi \mathrm{G_N}}{3}\,(\rho + 3\mathrm{p}) > 0$$

For normal vacuum: $\rho_v = const$. However, there can be states with
$p \approx -\rho$ and $\rho \approx const$.

Slowly varying scalar field ϕ. Its energy-momentum tensor is

$$\mathbf{T}_{\mu\nu} = \mathbf{2}\phi_\mu\phi_\nu - \mathbf{g}_{\mu\nu}\left[\phi_\alpha\phi^\alpha - \mathbf{U}(\phi)\right]$$

For negligible ϕ_μ:

$$\mathbf{T}_{\mu\nu} \approx \mathbf{g}_{\mu\nu}\mathbf{U}(\phi)$$

If $U'(\phi) \neq 0$ the field slowly evolves down to equilibrium point.

$$T_{\mu\nu} = 2\phi_\mu\phi_\nu - g_{\mu\nu}\left[\phi_\alpha\phi^\alpha - U(\phi)\right]$$

For negligible ϕ_μ:

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If $U'(\phi) \neq 0$ the field slowly evolves down to equilibrium point.
If $U'(\phi) = 0$ but this is not the lowest minimum (or even maximum) the field can make quantum jump to the equilibrium.

New phenomenological parameter:

$$\mathbf{w} = \frac{\mathbf{p}}{\rho}$$

For homogeneous scalar field:

$$\mathbf{w} = -\frac{2\mathbf{U}(\phi) - \dot{\phi}^2}{2\mathbf{U}(\phi) + \dot{\phi}^2}$$

Hence for normal fields

$$-1 < \mathbf{w} < +1.$$

"Phantom": $\mathbf{w} < -1$ is possible only in pathological theory, e.g. higher spin

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"Phantom": $\mathbf{w} < -1$ is possible only in pathological theory, e.g. higher spin tensor fields with tt physical component (AD) or scalars with wrong sign of kinetic term (Caldwell).
Ultimately will turn apart everything.

CONTRIBUTIONS TO VACUUM ENERGY

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:**

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

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Bosonic/fermionic cancellation - Zeldovich prior to SUSY.

Supersymmetry:

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

$$\rho_{\rm vac} = 0$$

if the symmetry is UNBROKEN.

Soft SUSY breaking necessarily leads to

$$\rho_{\rm vac} \sim 10^8 \ \mathrm{GeV}^4 \neq 0$$

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

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

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Phase transitions in the course of cosmological cooling

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

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QCD is well established and experimentally verified science leads to conclusion that vacuum is not empty but filled with quark and gluon condensates:

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

both having NEGATIVE vacuum energy

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

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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?

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INTERMEDIATE SUMMARY

1. Known and huge contributions to ρ_{vac} but unknown mechanism of their compensation down to (almost) zero.

2. Observed today $\rho_{\mathrm{vac}} \sim \rho_{\mathrm{c}}$. WHY?

3. What is the nature of antigravitating matter? Consistent with $w = -1$, vacuum?

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Most probably all three problems are strongly coupled and can be solved only after adjustment of ρ_{vac} down to ρ_c is understood.

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POSSIBLE SOLUTIONS

1. Subtraction constant.
2. Anthropic principle.
3. Infrared instability of massless fields (gravitons) in DS space-time.
4. Dynamical adjustment.
5. Drastic modification of existing theory - breaking of general covariance, Lorentz invariance, rejection of the Lagrange/Hamiltonian principle, ... ???

Remember: we need to explain only

2. Anthropic principle.

3. Infrared instability of massless fields (gravitons) in DS space-time.

4. Dynamical adjustment.

5. Drastic modification of existing theory - breaking of general covariance, Lorentz invariance, rejection of the Lagrange/Hamiltonian principle, ... ???

Remember: we need to explain only one number or a function if $w \neq 1$.

Dynamical adjustment, as axionic solution of strong CP problem:

New field Φ (scalar of higher spin) coupled to gravity is necessary.

1) Vacuum energy $\rightarrow$ condensate of Φ

2) $\rho(\Phi)$ compensates original ρ_{vac}.

Byproducts of dynamical adjustment have many features of less ambitious models of modified gravity, e.g.

explicit breaking of Lorentz invariance, and

time dependent, unstable background

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Byproducts of dynamical adjustment have many features of less ambitious models of modified gravity, e.g. explicit breaking of Lorentz invariance, and time dependent unstable background and stable fluctuations over it.

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DYNAMICAL ADJUSTMENT

Generic predictions:

1. Change exponential expansion to power law one.

2. Compensation of vacuum energy is not complete but only down to terms of the order of $\rho_c(t)$.

3. Non-compensated energy may have an unusual equation of state.

Unfortunately, no realistic model found

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1. Change exponential expansion to power law one.

2. Compensation of vacuum energy is not complete but only down to terms of the order of $\rho_c(t)$.

3. Non-compensated energy may have an unusual equation of state.

Unfortunately, no realistic model found starting from 1982.

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EXAMPLES OF ADJUSTMENT

1. Non-minimally coupled scalar field (AD, 1982):

$$\ddot{\phi} + 3H\dot{\phi} + U'(\phi, R) = 0$$

with e.g. $U = \xi R\phi^2/2$.

Solutions are unstable if $\xi R < 0$.

Asymptotically:

$$\phi \sim t$$

and DS turns into Friedman, but

$$\mathbf{T}_{\mu\nu}(\phi) \neq \mathbf{F}\mathbf{g}_{\mu\nu}$$

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Solutions are unstable if $\xi R < 0$.

Asymptotically:

$$\phi \sim t$$

and DS turns into Friedman, but

$$\mathbf{T}_{\mu\nu}(\phi) \neq \mathbf{F}\mathbf{g}_{\mu\nu}$$

and the change of the regime is achieved due to weakening of gravitational coupling:

$$\mathrm{G_N} \sim 1/\mathrm{t}^2$$

3. Second rank tensor field $S_{\mu\nu}$ (AD, 1994):

$$\mathcal{L}_2 = \eta_1 \mathbf{S}_{\alpha\beta;\gamma}\mathbf{S}^{\alpha\gamma;\beta} + \eta_2 \mathbf{S}^{\alpha}_{\beta;\alpha}\mathbf{S}^{\gamma\beta}_{;\gamma} + \eta_3 \mathbf{S}^{\alpha}_{\alpha;\beta}\mathbf{S}^{\gamma;\beta}_{\gamma}$$

Components S_{tt} and isotropic part of $S_{ij} \sim \delta_{ij}$ are unstable:

$$(\partial_t^2 + 3H\partial_t - 6H^2)S_{tt} - 2H^2 s_{jj} = 0$$

$$(\partial_t^2 + 3H\partial_t - 6H^2)s_{tj} = 0$$

$$(\partial_t^2 + 3H\partial_t - 2H^2)s_{ij} - 2H^2\delta_{ij}S_{tt} = 0$$

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Ill-defined theory with "non-physical" components, T_{tt} and/or T_{ii} becoming physical?

Ogievetsky and Polubarinov:
"Photon and Notoph" - gauge theory of scalar field described by t-component of vector V_μ.

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In all the cases after some period of exponential expansion DS is changed into Friedman
and the dominant term in $T_{\mu\nu} \sim g_{\mu\nu}$ but G_N is time-dependent.

More important: in all the models above expansion rate is not related to the usual matter.

4. Scalar with "crazy" coupling to gravity (Mukohayama, Randall, 2003; AD, Kawasaki, 2003:)

$$A = \int d^4x\sqrt{g}\left[-\frac{1}{2}(R + 2\Lambda) + F_1(R) + \frac{D_\mu\phi D^\mu\phi}{2R^2} - U(\phi, R)\right]$$

Solution tends to

$$R \sim \rho_{vac} + U(\phi) = 0$$

It has some nice features ("almost realistic"), $H = 1/2t$, etc.

$$+\frac{D_\mu\phi D^\mu\phi}{2\,R^2} - U(\phi, R)\Bigg]$$

Solution tends to

$$R \sim \rho_{vac} + U(\phi) = 0$$

It has some nice features ("almost realistic"), $H = 1/2t$, *etc*

but unstable.

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Equation of motion for Φ:

$$\mathbf{D}_\mu \left[\mathbf{D}^\mu \phi \left(\frac{\mathbf{1}}{\mathbf{R}} \right)^{\mathbf{2}} \right] + \mathbf{U}'(\phi) = \mathbf{0}.$$

GR equations for the trace,
with $\mathbf{F_1 = C_1 R^2}$:

$$-\mathbf{R} + \mathbf{3} \left(\frac{\mathbf{1}}{\mathbf{R}} \right)^{\mathbf{2}} (\mathbf{D}_\alpha \phi)^{\mathbf{2}} - \mathbf{4} \left[\mathbf{U}(\phi) + \rho_{\mathbf{vac}} \right]$$

$$-\mathbf{6D^2} \left[\mathbf{2C_1R} - \left(\frac{\mathbf{1}}{\mathbf{R}} \right)^{\mathbf{2}} \frac{(\mathbf{D}_\alpha \phi)^{\mathbf{2}}}{\mathbf{R}} \right] = \mathbf{T}^\mu_\mu$$

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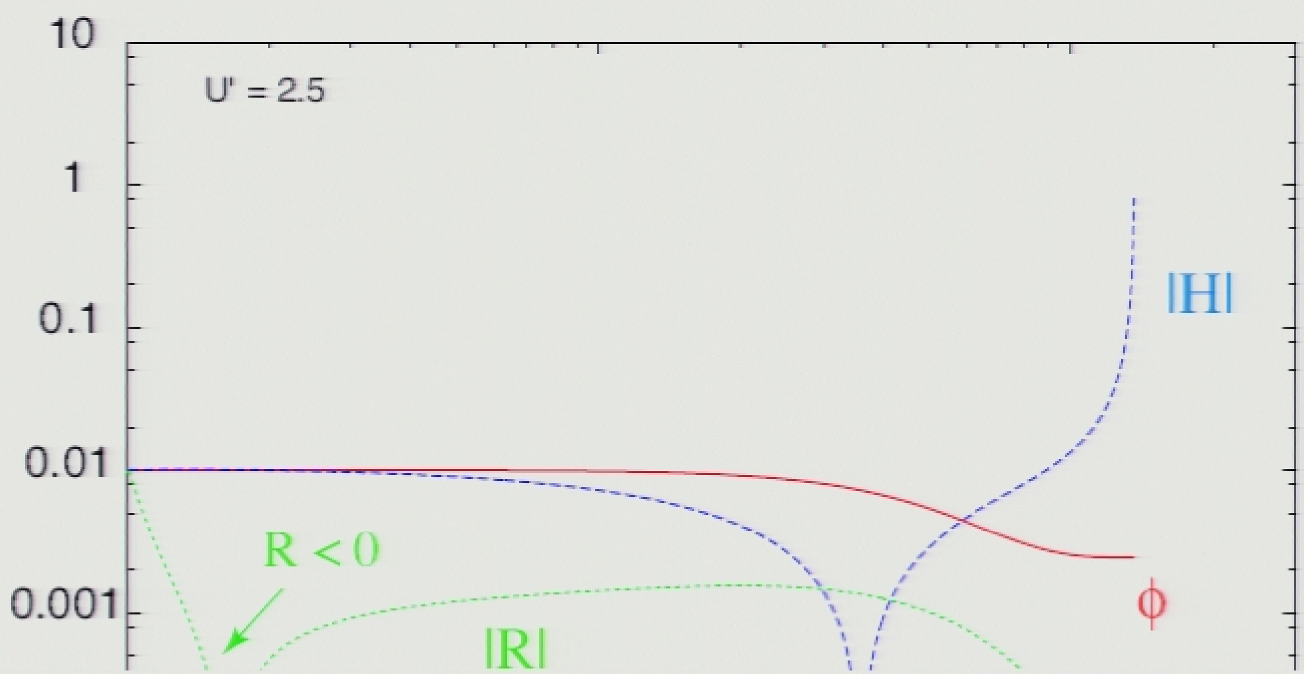

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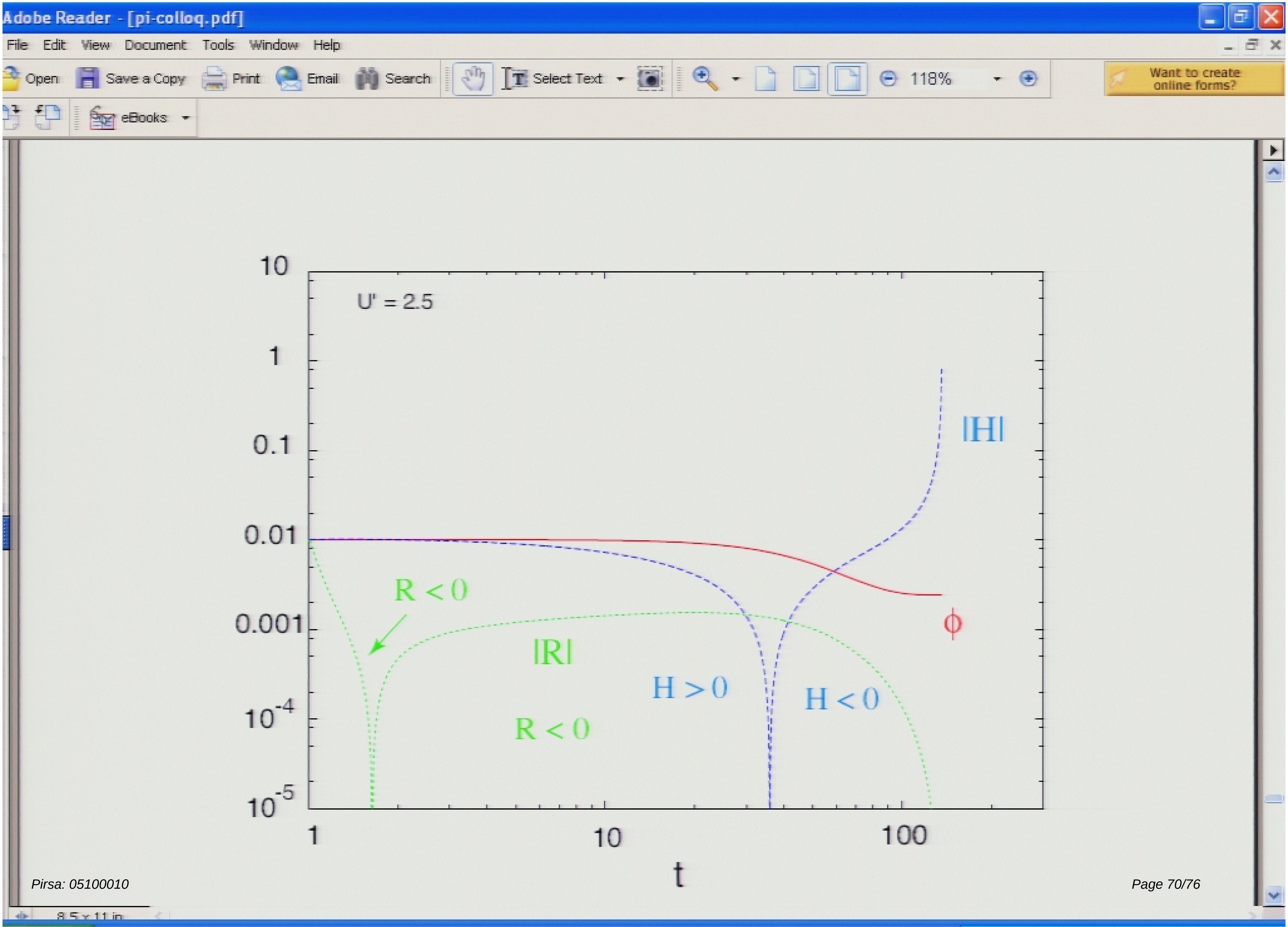
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U' = 2.5
|H|
R < 0
|R|
H > 0
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ϕ
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1
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t

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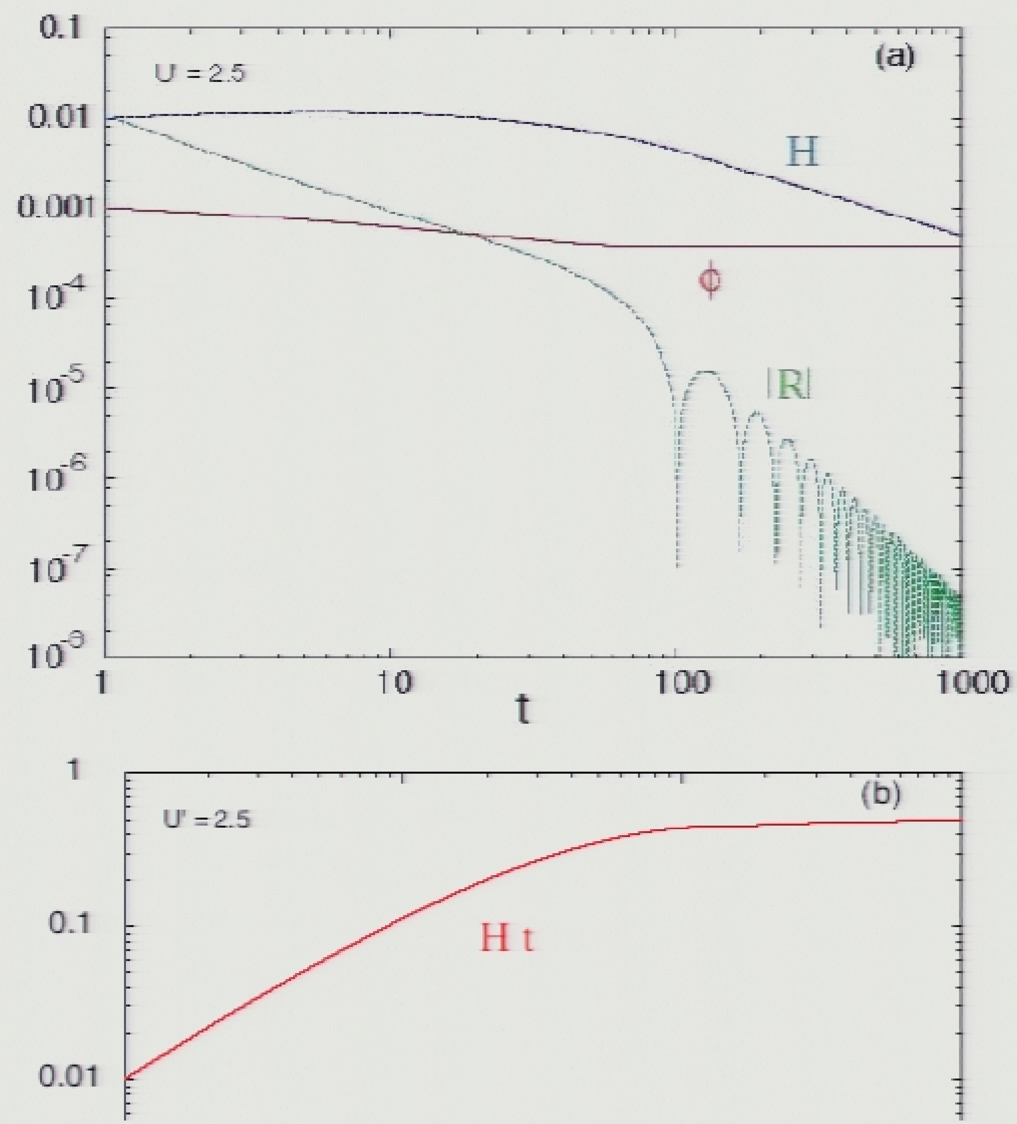
A desperate attempt to improve the model:

$$\frac{(\mathbf{D}\phi)^2}{\mathbf{R}^2} \to -\frac{(\mathbf{D}\phi)^2}{\mathbf{R}\,|\mathbf{R}|}.$$



0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
10
100
1000
t
U = 2.5
(a)
H
φ
|R|
1
0.1
0.01
U' = 2.5
(b)
H t

More general action with scalar field (AD, Kawasaki, 2003) not yet explored:

$$
\mathbf{A} = \int \mathbf{d}^4\mathbf{x}\sqrt{-\mathbf{g}}\Big[-\mathbf{m}_{\mathbf{Pl}}^2(\mathbf{R} + 2\boldsymbol{\Lambda})/16\pi
+\mathbf{F}_1(\mathbf{R}) + \mathbf{F}_2(\phi, \mathbf{R})\mathbf{D}_\mu\phi\mathbf{D}^\mu\phi
+\mathbf{F}_3(\phi, \mathbf{R})\mathbf{D}_\mu\phi\mathbf{D}^\mu\mathbf{R} - \mathbf{U}(\phi, \mathbf{R})\Big]
$$

Moreover $R_{\mu\nu}$ and $R_{\mu\nu\alpha\beta}$ can be also included.

CONCLUSION

1. Some compensating agent must exist!
QCD demands that.

2. Quite natural to expect that ρ_{vac} is not completely compensated and

$$\Delta\rho \sim \rho_{\mathbf{c}}$$

3. Realistic model is needed, it can indicate what is w: is it (-1) or different.

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4. Theoretical prior:
A STRANGE FORM OF ENERGY LIVES IN THE UNIVERSE it must be included into data analysis.