Dynamics of self-sustained vacuum

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* quantum vacuum as Lorentz invariant medium

* dynamics of quantum vacuum and decay of cosmological constant

* problem of remnant cosmological constant

* remnant cosmological constant from quantum chromodynamics

* response of vacuum energy to matter

$$\Lambda_{exp} \sim 2\text{-}3\ \varepsilon_{\text{Dark Matter}} \sim 10^{-123}\Lambda_{bare}$$

$$\Lambda_{bare} \sim \varepsilon_{\text{zero point}}$$

*it is easier to accept that $\Lambda = 0$ than 123 orders smaller

*magic word: *regularization*

wisdom of particle physicist:

$$\frac{1}{0} = 0$$

*Polyakov conjecture: dynamical screeneng of Λ by infrared fluctuations of metric

A.M. Polyakov

Phase transitions and the Universe, UFN **136,** 538 (1982)

De Sitter space and eternity, Nucl. Phys. **B 797**, 199 (2008)

*Dynamical evolution of Λ similar to that of gap Δ in superconductors after kick

V. Gurarie, Nonequilibrium dynamics of weakly and strongly paired superconductors: 0905.4498

A.F. Volkov & S.M. Kogan, JETP **38**, 1018 (1974)

Barankov & Levitov, ...

dynamic relaxation of vacuum to its equilibrium state

dynamics of Λ in cosmology

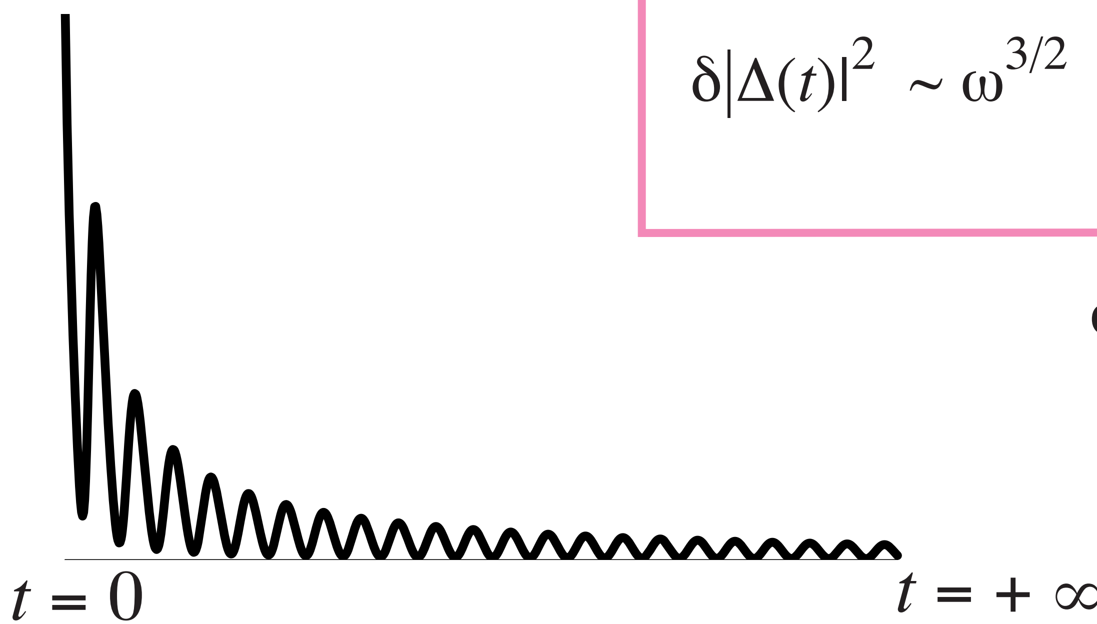
$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$\omega \sim E_{\rm Planck}$

dynamics of Δ in superconductor

$$\delta|\Delta(t)|^2 \sim \omega^{3/2} \frac{\sin \omega t}{t^{1/2}}$$

$\omega = 2\Delta$



intial states:

nonequilibrium vacuum with $\Lambda \sim E_{\rm Planck}^4$

superconductor with nonequilibrium gap Δ

final states:

equilibrium vacuum with $\Lambda = 0$

ground state of superconductor

$$\varepsilon(t) - \varepsilon_{\rm vac} \sim \omega \frac{\sin^2 \omega t}{t}$$

reversibility of the process

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$$\delta|\Delta(t)|^2 \sim \omega^{3/2} \frac{\sin \omega t}{t^{1/2}}$$

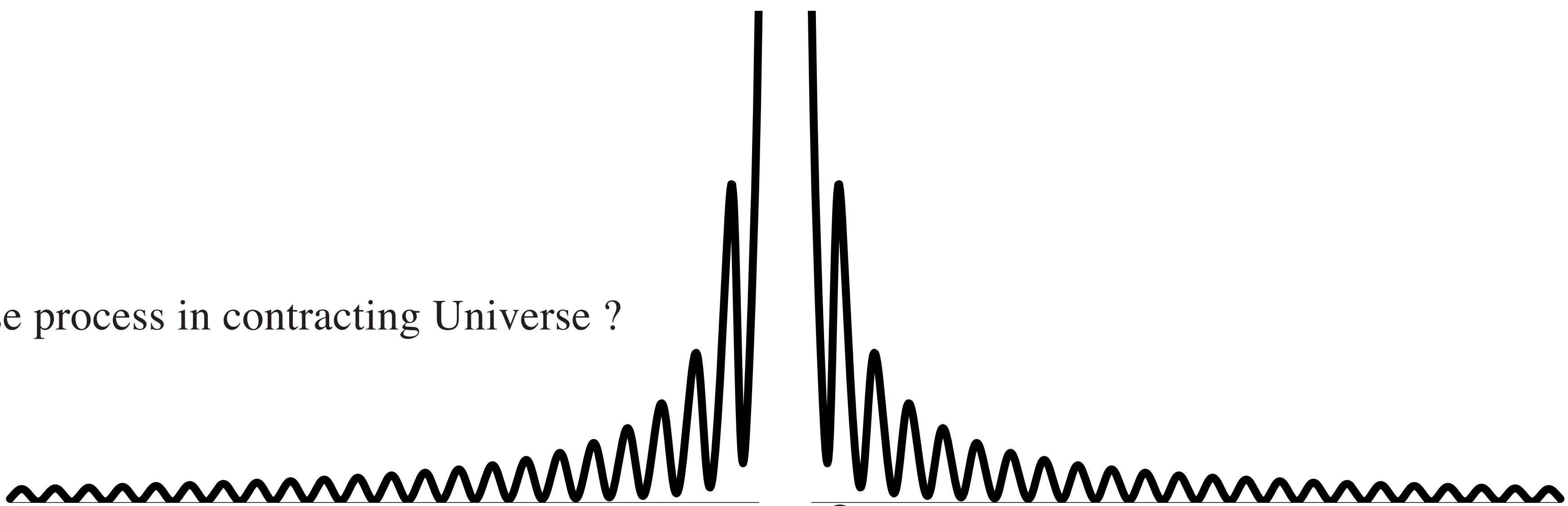
$$\omega \sim E_{\rm Planck}$$

$$\omega = 2\Delta$$

reversible energy transfer
from vacuum to gravity

reversible energy transfer
from coherent degree of freedom (vacuum)
to particles (Landau damping)

inverse process in contracting Universe ?



$t = -\infty$ $\quad$ $t = 0$ $\quad$ $t = +\infty$

how to describe quantum vacuum & vacuum energy Λ ?

$$\Lambda = \boxed{\varepsilon_{\rm vac} = w_{\rm vac} P_{\rm vac}}$$

* **quantum vacuum has equation of state w=−1**

* **quantum vacuum is Lorentz-invariant**

$$\boxed{w_{\rm vac} = -1}$$

* **quantum vacuum is a self-sustained medium, which may exist in the absence of environment**

* **for that, vacuum must be described by conserved charge q**

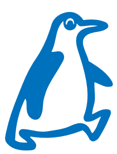
q **is analog of particle density n in liquids**

q must be Lorentz invariant

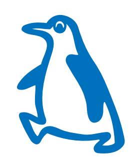
$$\boxed{L\, q = q}$$

charge density n is not Lorentz invariant

$$\boxed{L\, n = \gamma(n + \mathbf{v}\cdot\mathbf{j})}$$



does such q exist ?



relativistic invariant conserved charges q

possible

$$\nabla_\alpha q^{\alpha\beta} = 0$$

$$\nabla_\alpha q^{\alpha\beta\mu\nu} = 0$$

$$q^{\alpha\beta} = q\, g^{\alpha\beta}$$

$$q^{\alpha\beta\mu\nu} = q\, e^{\alpha\beta\mu\nu}$$

Duff & van Nieuwenhuizen
Phys. Lett. **B 94,** 179 (1980)

impossible

$$\nabla_\alpha q^{\alpha} = 0$$

$$q^{\alpha} = ?$$

examples of vacuum variable q

4-form field

$$F_{\kappa\lambda\mu\nu} = \nabla_{[\kappa} A_{\lambda\mu\nu]}$$

$$F_{\kappa\lambda\mu\nu} = q\,(-g)^{1/2}\, e_{\kappa\lambda\mu\nu}$$

$$q^2 = -\frac{1}{24} F_{\kappa\lambda\mu\nu} F^{\kappa\lambda\mu\nu}$$

gluon condensates in QCD

$$<\mathbf{G}_{\alpha\beta}\mathbf{G}_{\mu\nu}> = \frac{q}{12}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu})$$

$$q = <\mathbf{G}_{\alpha\beta}\mathbf{G}^{\alpha\beta}>$$

$$<\mathbf{G}_{\alpha\beta}> = 0$$

$$<\mathbf{G}_{\alpha\beta}\mathbf{G}_{\mu\nu}> = \frac{q}{24}(-g)^{1/2}\, e_{\alpha\beta\mu\nu}$$

$$q = <\tilde{\mathbf{G}}_{\alpha\beta}\mathbf{G}^{\alpha\beta}>$$

topological charge density

Einstein-aether theory (T. Jacobson)

$$\nabla_\mu u_\nu = q\, g_{\mu\nu}$$

dynamics of vacuum variable q and gravity do not depend on particular realization of q

thermodynamics in flat space

the same as in cond-mat

conserved charge Q

$$Q = \int dV\, q$$

thermodynamic potential

$$\Omega = E - \mu Q = \int dV\, (\varepsilon\, (q) - \mu q)$$

Lagrange multiplier or chemical potential μ

pressure

$$P = -\, dE/dV = -\varepsilon + q\, d\varepsilon/dq$$

$$E = V\, \varepsilon(Q/V)$$

$$d\Omega/dq = 0$$

equilibrium vacuum

$$d\varepsilon/dq = \mu$$

equilibrium self-sustained vacuum

$$d\varepsilon/dq = \mu$$

$$\varepsilon - q\, d\varepsilon/dq = -P = 0$$

vacuum energy & cosmological constant

equilibrium self-sustained vacuum

$$d\varepsilon/dq = \mu$$

$$\varepsilon - q\, d\varepsilon/dq = -P = 0$$

$$q \sim \mu \sim E^{2}_{Planck}$$

vacuum variable in equilibrium self-sustained vacuum

$$\varepsilon\,(q) \sim E^{4}_{Planck}$$

energy of equilibrium self-sustained vacuum

pressure

$$P = -\varepsilon + q\, d\varepsilon/dq = -\Omega$$

$$\Lambda = \Omega = \varepsilon - \mu\, q$$

cosmological constant

$$P = -\Omega$$

equation of state

$$\Lambda = \varepsilon - \mu q = 0$$

cosmological constant in equilibrium self-sustained vacuum

$$E^{4}_{Planck} \qquad E^{4}_{Planck}$$

***self-tuning*: two Planck-scale quantities cancel each other in equilibrium self-sustained vacuum**

dynamics of q in flat space

whatever is the origin of q the motion equation for q is the same

action

$$S = \int dV\, dt\, \varepsilon(q)$$

motion equation

$$\nabla_\kappa (d\varepsilon/dq) = 0$$

solution

$$d\varepsilon/dq = \mu$$

integration constant μ in dynamics
becomes chemical potential in thermodynamics

4-form field $F_{\kappa\lambda\mu\nu}$ as an example of conserved charge q in relativistic vacuum

$$q^2 = -\frac{1}{24} F_{\kappa\lambda\mu\nu} F^{\kappa\lambda\mu\nu}$$

$$F_{\kappa\lambda\mu\nu} = \nabla_{[\kappa} A_{\lambda\mu\nu]}$$

$$F^{\kappa\lambda\mu\nu} = q\, e^{\kappa\lambda\mu\nu}$$

Maxwell equation

$$\nabla_\kappa \left(F^{\kappa\lambda\mu\nu}\, q^{-1} d\varepsilon/dq\right) = 0 \quad \rightarrow \quad \nabla_\kappa (d\varepsilon/dq) = 0$$

general dynamics of q in curved space

action

$$S = \int d^4x\, (-g)^{1/2} \left[\, \varepsilon(q) + K(q)R \,\right] + S_{matter}$$

gravitational coupling $K(q)$ is determined by vacuum and thus depends on vacuum variable q

motion equation

$$d\varepsilon/dq + R\, dK/dq = \mu$$

integration constant

Einstein equations

$$K\left(Rg_{\mu\nu} - 2R_{\mu\nu}\right) + \left(\varepsilon - \mu q\right)g_{\mu\nu} - 2\left(\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda\right)K = T_{\mu\nu}$$

Einstein tensor

cosmological term $\neq \varepsilon\, g_{\mu\nu}$

$$\nabla_\mu T^{\mu\nu} = 0$$

matter

case of *K=const* restores original Einstein equations

$$K = \frac{1}{16\pi G}$$

G - Newton constant

motion equation

$d\varepsilon/dq = \mu \qquad q = \text{const}$

original Einstein equations

$$\frac{1}{16\pi G}\left(R g_{\mu\nu} - 2R_{\mu\nu}\right) + \Lambda g_{\mu\nu} = T_{\mu\nu} \qquad \Lambda = \varepsilon - \mu q$$

Λ - cosmological constant

Minkowski solution

Maxwell equations

$$d\varepsilon/dq + R\, dK/dq = \mu$$

Einstein equations

$$K\left(Rg_{\mu\nu} - 2R_{\mu\nu}\right) + \left(\varepsilon - \mu q\right)g_{\mu\nu} - 2\left(\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda\right)K = T_{\mu\nu}$$

Einstein tensor — **cosmological term** — **matter**

$$\nabla_\mu T^{\mu\nu} = 0$$

Minkowski vacuum solution

$$R = 0 \qquad d\varepsilon/dq = \mu$$

$$\Lambda = \varepsilon(q) - \mu q = 0$$

vacuum energy in action: $\varepsilon\,(q) \sim E^4_{\mathrm{Planck}}$

thermodynamic vacuum energy: $\varepsilon - \mu q = 0$

Model vacuum energy

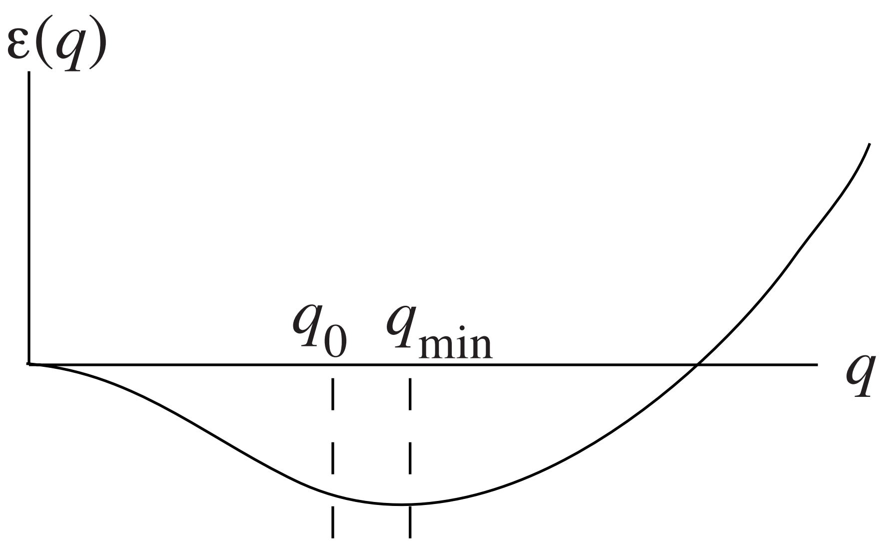
$$\varepsilon(q) = \frac{1}{2\chi}\left(-\frac{q^2}{q_0^2} + \frac{q^4}{3q_0^4}\right)$$

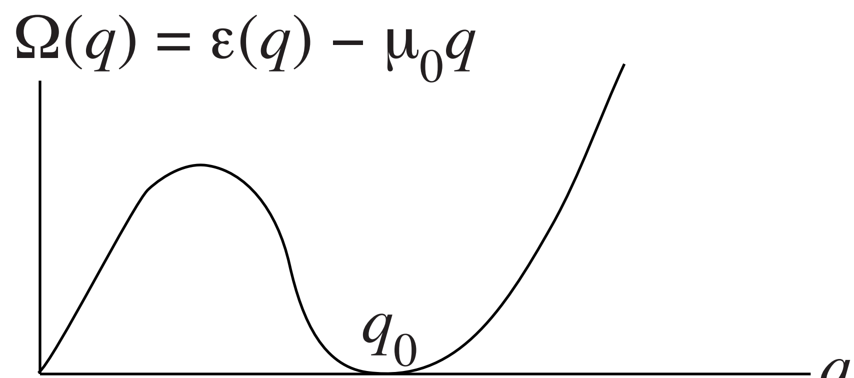
Minkowski vacuum solution

$$d\varepsilon/dq = \mu$$
$$\varepsilon - \mu q = 0$$

→

$$q = q_0$$
$$\mu = \mu_0 = -\frac{1}{3\chi q_0}$$





empty space $q = 0$

self-sustained vacuum $q = q_0$

vacuum compressibility

$$\chi = -\frac{1}{V}\frac{dV}{dP}$$

$$\frac{1}{\chi} = \left(q^2\, d^2\varepsilon/dq^2\right)_{q=q_0} > 0$$

vacuum stability

Minkowski vacuum (q-independent properties)

$$\Lambda = \Omega_{vac} = -P_{vac}$$

energy density of vacuum (↑ Ω_{vac}) — **pressure of vacuum** (↑ P_{vac})

$$P_{vac} = -\, dE/dV = -\, \Omega_{vac}$$

$$\chi_{vac} = -(1/V)\, dV/dP$$

compressibility of vacuum

$$<(\Delta P_{vac})^2> = T/(V\chi_{vac})$$

$$<(\Delta\Lambda)^2> = <(\Delta P)^2>$$

pressure fluctuations

natural value of Λ determined by macroscopic physics

$$\Lambda = 0$$

natural value of χ_{vac} determined by microscopic physics

$$\chi_{vac} \sim E^{-4}_{\mathbf{Planck}}$$

volume of Universe is large:

$$V > T_{CMB}/(\Lambda^2\chi_{vac})$$

$$V > 10^{28}\, V_{hor}$$

dynamics of q in curved space: relaxation of Λ

motion equation

$$d\varepsilon/dq + R\, dK/dq = \mu$$

Einstein equations

$$K\left(Rg_{\mu\nu} - 2R_{\mu\nu}\right) + g_{\mu\nu}\Lambda(q) - 2\left(\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda\right)K = T_{\mu\nu}^{\text{matter}}$$

$$\Lambda(q) = \varepsilon(q) - \mu_0 q$$

dynamic solution: approach to equilibrium vacuum

$$q(t) - q_0 \sim q_0 \frac{\sin \omega t}{t}$$

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$$H(t) = \frac{\dot{a}(t)}{a(t)} = \frac{2}{3t}\left(1 - \cos \omega t\right)$$

$$\omega \sim E_{\text{Planck}}$$

similar to scalar field with mass $M \sim E_{\text{Planck}}$

A.A. Starobinsky, Phys. Lett. **B 91**, 99 (1980)

Relaxation of Λ (generic q-independent properties)

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

cosmological "constant"

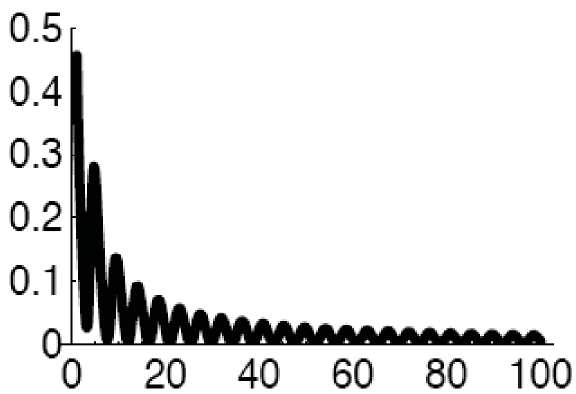
$$H(t) = \frac{\dot{a}(t)}{a(t)} = \frac{2}{3t}\left(1 - \cos \omega t\right)$$

Hubble parameter

$$G(t) = G_N \left(1 + \frac{\sin \omega t}{\omega t}\right)$$

Newton "constant"

$\omega \sim E_{Planck}$



$$<\Lambda(t_{Planck})> \sim E_{Planck}^4$$

$$\Lambda(t = \infty) = 0$$

natural solution of the main cosmological problem ?

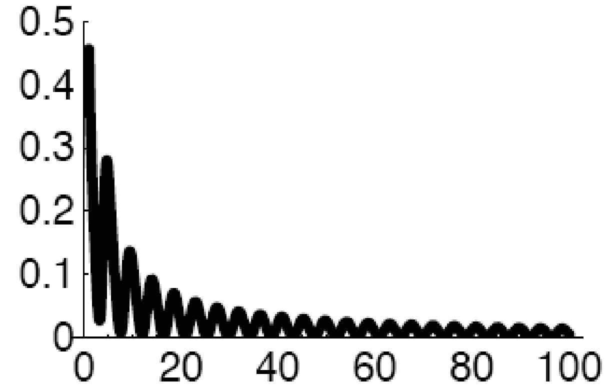
Λ relaxes from natural Planck scale value to natural zero value

present value of Λ

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$$\omega \sim E_{\text{Planck}}$$

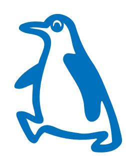
dynamics of Λ:
from Planck to present value



$$<\Lambda(t_{\text{Planck}})> \sim E_{\text{Planck}}^4$$

$$<\Lambda(t_{\text{present}})> \sim E_{\text{Planck}}^2 \,/\, t_{\text{present}}^2 \sim 10^{-120}\, E_{\text{Planck}}^4$$

coincides with present value of dark energy
something to do with coincidence problem ?



cold matter simulation

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$$H(t) = \frac{\dot{a}(t)}{a(t)} = \frac{2}{3t}\left(1 - \cos \omega t\right)$$

$$<H(t)> = \frac{2}{3t}$$

$$<a(t)> \sim t^{2/3}$$

$$<\Lambda(t)> \sim \frac{E^2_{\rm Planck}}{t^2} \sim E^4_{\rm Planck} \frac{a^3(t_{\rm Planck})}{a^3(t)}$$

relaxation of vacuum energy mimics expansion of cold dark matter

$$\rho(t)\, a^3(t) = {\rm const}$$

though equation of state corresponds to Λ

$$\Lambda = \Omega = -P$$

$$\Omega = \varepsilon(q) - \mu\, q$$

another example of vacuum variable: from 4-vector

version of Ted Jacobson's Einstein-Aether theory

energy density $\varepsilon_{vac}(u^{\mu}{}_{\nu})$ **of vacuum is function of** $u^{\mu}{}_{\nu} = \nabla_{\nu} u^{\mu}$

equilibrium vacuum is obtained from equation

$$\delta\varepsilon_{vac}/\delta u^{\mu} = \nabla_{\nu}(\delta\varepsilon_{vac}/\delta u^{\mu}{}_{\nu}) = 0$$

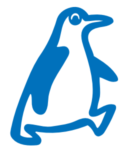
equilibrium solution**:**

$$u_{\mu\nu} = q g_{\mu\nu}$$

$q = const$

vacuum variable

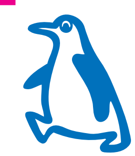
microscopic vacuum energy



$$\varepsilon_{vac}(q) \sim E^{4}_{\mathbf{Planck}}$$

cosmological constant

$$\Lambda = \Omega(q_0) = 0$$



macroscopic thermodynamic vacuum energy:
from energy momentum tensor

$$T_{\mu\nu} = \delta S/\delta g^{\mu\nu} = (\varepsilon_{vac}(q) - q\, d\varepsilon_{vac}/dq)\, g_{\mu\nu}$$

It is $T_{\mu\nu}$ **which is gravitating, thus cosmological constant is**

$$\Lambda = \Omega(q) = \varepsilon_{vac}(q) - q\, d\varepsilon_{vac}/dq$$

relativistic quantum vacuum vs cond-mat

microscopic energy

natural Planck scale

$$\varepsilon_{\mathrm{vac}}(q) \sim E^4_{\mathbf{Planck}}$$

natural atomic scale

$$\varepsilon(n) \textit{ is atomic}$$

macroscopic energy

$$\Omega = \varepsilon(q) - q\, d\varepsilon/dq = -P_{\mathrm{vac}}$$

$$\Omega = \varepsilon(n) - n\, d\varepsilon/dn = -P$$

in the absence of environment

$$\Lambda = \Omega = -P_{\mathrm{vac}} = 0$$

$$\Omega = -P = 0$$

two microscopic quantities cancel each other without fine tuning

self tuning due to **thermodynamics**

Why is the present Λ nonzero ?

remnant cosmological constant from infrared QCD (*highly speculative*)

Klinkhamer -Volovik
Gluonic vacuum, *q*-theory, and the cosmological constant
Phys. Rev. **D 79**, 063527 (2009)

Klinkhamer
Gluon condensate, modified gravity, and the accelerating Universe
arXiv:0904.3276

de Sitter expansion and nonzero Λ are induced by QCD anomaly

$$\Lambda \sim G^2 \lambda_{QCD}^6$$

$\lambda_{QCD} \sim 100$ MeV is QCD energy scale

close to present cosmological constant

supports suggestion by Zeldovich

$$\Lambda \sim G^2 m_{proton}^6$$

JETP Lett. **6**, 316 (1967)

Lifshitz point

$$\omega^2 = k^2 + m^2(\mathrm{k})$$

$$m(\mathrm{k}) = \frac{k^{z}}{\lambda^{z-1}}$$

Lifshitz point in QCD

effective gluon mass diverges in k -> 0 limit

$z = -1$

$$m(\mathrm{k}) \sim \frac{\lambda_{QCD}^2}{\mathrm{k}}$$

Gribov picture of confinement

$z = -2$

$$m(\mathrm{k}) \sim \frac{\lambda_{QCD}^3}{\mathrm{k}^2}$$

alternative picture of confinement
Cabo et al. arXiv:0906.0494

remnant cosmological constant from QCD

estimation of vacuum energy in expanding Universe

$$E = \frac{1}{2} \sum_k [\omega(k, H) - \omega(k, 0)] \sim \frac{1}{2} \sum_k [m(k, H) - m(k, 0)]$$

$z = -1$

$$m(k) \sim \frac{\lambda_{QCD}^2}{k}$$

Gribov scenario

$z = -2$

$$m(k) \sim \frac{\lambda_{QCD}^3}{k^2}$$

Cabo et al. arXiv:0906.0494

$$m(k, H) \sim \frac{\lambda_{QCD}^2}{(k^2 + H^2)^{1/2}}$$

$$E \sim \lambda_{QCD}^2 H^2$$

negligible correction to Einstein action

$$m(k, H) \sim \frac{\lambda_{QCD}^3}{k^2 + H^2}$$

$$E \sim \lambda_{QCD}^3 |H|$$

dominates at small Hubble parameter H

asymptotic de Sitter state due to infrared QCD

$$E_{vac} \sim \lambda^3_{QCD} |H|$$

$$H^2 = (8\pi/3)\, G E_{vac}$$

de Sitter

$$H \sim G \lambda^3_{QCD}$$

$$\Lambda = E_{vac} \sim G^2 \lambda^6_{QCD}$$

close to present cosmological constant

supports suggestion by Zeldovich

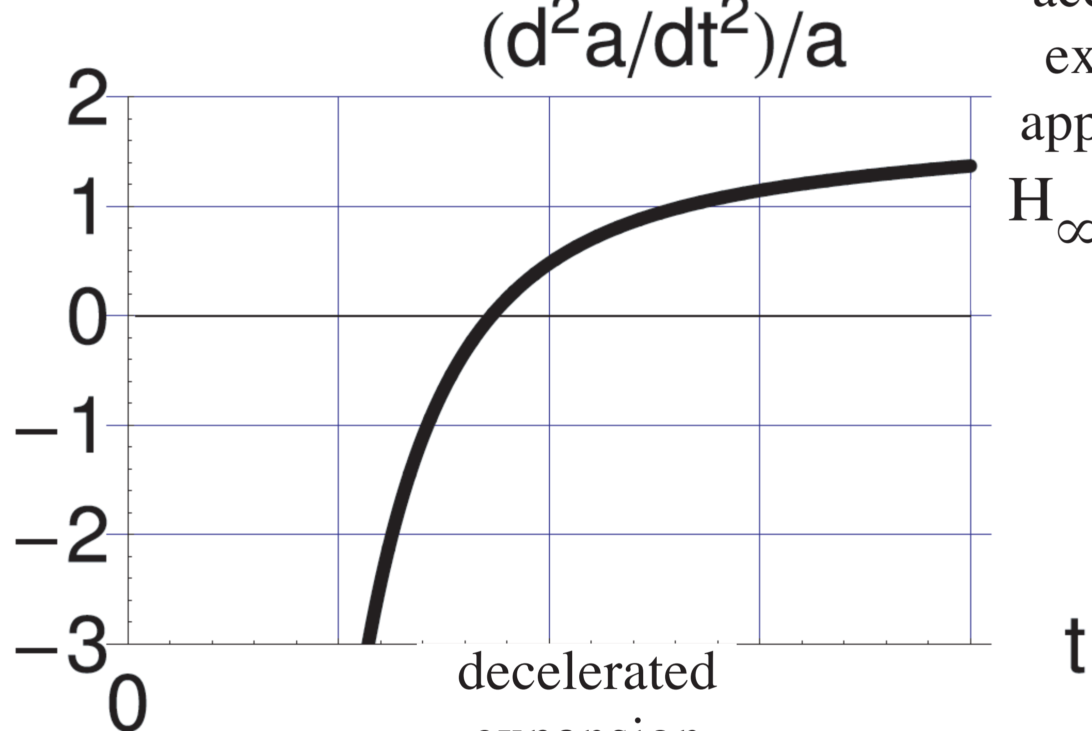
$$\Lambda \sim G^2 m^6_{proton}$$

JETP Lett. **6**, 316 (1967)

J. Bjorken, The classification of universes, astro-ph/0404233
R. Schutzhold, *PRL* **89**, 081302 (2002)
Klinkhamer & Volovik, *Phys*. *Rev*. **D 79**, 063527 (2009)
Urban & Zhitnitsky,
The cosmological constant from the Veneziano ghost which solves the U(1) problem in QCD, 0906.2162

asymptotic de Sitter state from q-theory with QCD

Klinkhamer
Gluon condensate, modified gravity, and the accelerating Universe
arXiv:0904.3276



accelerated expansion approaching $H_\infty \sim G\,\lambda_{QCD}^3$

Carneiro & Tavakol
On vacuum density, the initial singularity and dark energy
arXiv:0905.3131

$$H(t) = H_\infty \frac{\exp(3H_\infty t)}{\exp(3H_\infty t) - 1}$$

q-theory with QCD and f(R) theory

at small curvature R approaches particular f(R) theory with $f(R) = R + |R|^{1/2}$

$$\lambda^3_{QCD}\,|H| \;\to\; \lambda^3_{QCD}\,|R|^{1/2}$$

$$q = \langle \mathbf{G}_{\alpha\beta}\mathbf{G}^{\alpha\beta}\rangle \sim \lambda^4_{QCD}$$

action

$$S = \int d^4x\,(-g)^{1/2}\left[\,\epsilon(q) - \mu q + KR + q^{3/4}|R|^{1/2}\,\right] + S_{matter}$$

$$\epsilon(q) - \mu q = q \ln \frac{q}{q_0} \qquad q_0 = \lambda^4_{QCD}$$

here q_0 is equilbrium value of gluon condensate in equilibrium vacuum with $\Omega = \Lambda = 0$

however instead of equilibrium vacuum the Universe approaches de Sitter state with

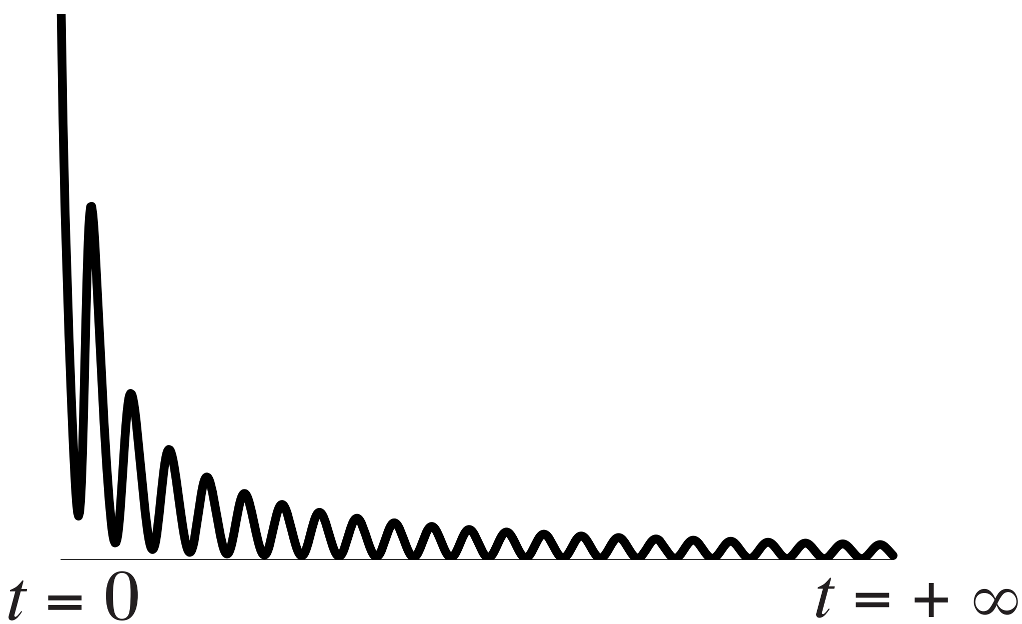
$$H \sim G\, q_0^{3/4} \qquad \Lambda \sim G^2 q_0^{3/2}$$

two regimes of vacuum dynamics

decay with oscillations

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

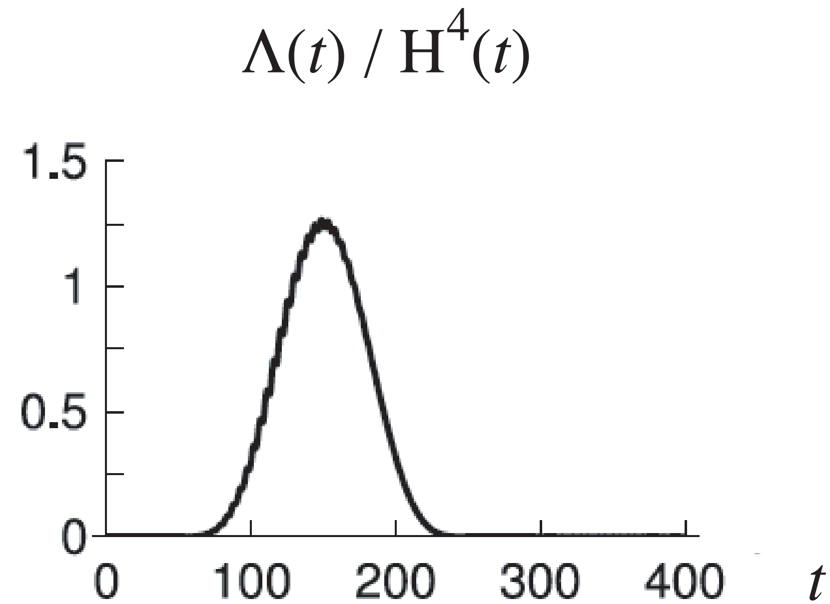
$\omega \sim E_{\mathrm{Planck}}$



response to perturbation of matter

$$\Lambda(t) \sim (w^2(t) - 1/3)^2 H^4(t)$$ + small oscillations

$w(t)$ matter equation of state



Klinkhamer & Volovik, arXiv:0905.1919

remnant cosmological constant from electroweak crossover

response to perturbation of matter without dissipation

$$\Lambda_0(t) \sim (w^2(t) - 1/3)^2 H^4(t)$$

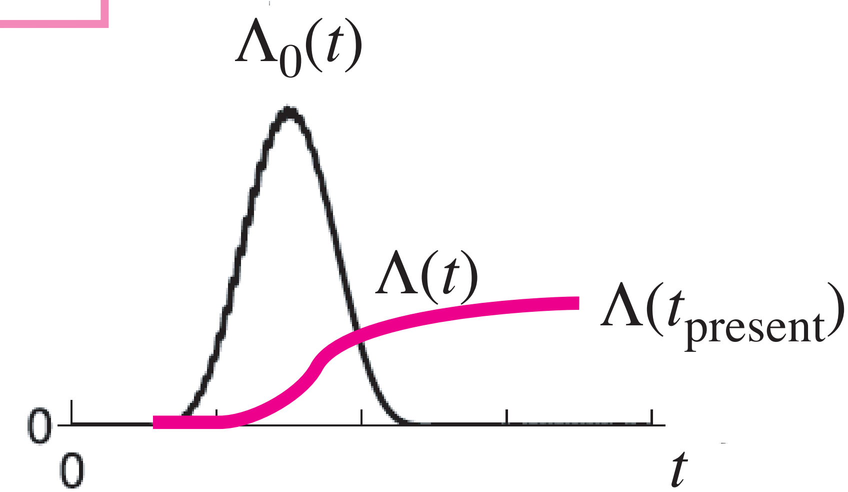
$w(t)-1/3 \neq 0$ during electroweak crossover, when $H(t_{ew}) \sim E^2_{ew} / E_{Planck}$

$$\Lambda_0(t_{ew}) \sim H^4(t_{ew}) \sim E^8_{ew} / E^4_{Planck} \sim \Lambda(t_{present})$$

if for some reason $\Lambda(t)$ become frozen after crossover

this may explain present value of Λ

$$\dot{\Lambda} = -\Gamma(t)\,\big(\,\Lambda(t)-\Lambda_0(t)\,\big)$$



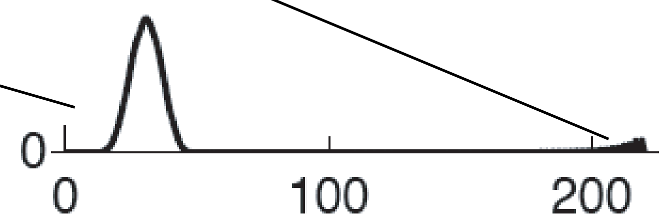
Klinkhamer & Volovik, arXiv:0905.1919

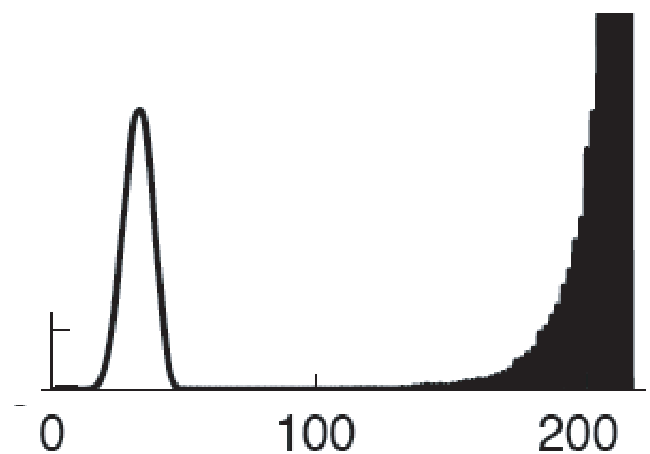
vacuum instability in contracting universe

response to perturbation of matter

$$\Lambda(t) \sim \left(w^2(t) - 1/3\right)^2 H^4(t) + \text{small oscillations}$$

Klinkhamer & Volovik, arXiv:0905.1919





catastrophic growth of oscillating vacuum energy & collapse

conclusion

properties of relativistic quantum vacuum as a self-sustained system

* quantum vacuum is characterized by conserved charge q

q has Planck scale value in equilibrium

$$\varepsilon(q) \sim E_{\mathrm{Planck}}^4$$

* vacuum energy has Planck scale value in equilibrium

but this energy is not gravitating

$$T_{\mu\nu} = \Lambda g_{\mu\nu} \neq \varepsilon(q) g_{\mu\nu}$$

* gravitating energy which enters Einstein equations is thermodynamic vacuum energy

$$T_{\mu\nu} = \Lambda g_{\mu\nu} = \Omega(q) g_{\mu\nu}$$

$$\Omega(q) = \varepsilon - q\, d\varepsilon/dq$$

* thermodynamic energy of equilibrium vacuum

$$\Omega(q_0) = \varepsilon(q_0) - q_0\, d\varepsilon/dq_0 = 0$$

* non-equilibrium vacuum with large initial Λ relaxes with fast oscillations

* small remnant cosmological constant may come from QCD