Dynamics of self-sustained vacuum & cosmological "constant"

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Euler Institute, July 3, 2009

* 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

* remnant cosmological constant from electroweak physics

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

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

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

*magic word: *regularization*

wisdom of particle physicist: $\boxed{\frac{1}{0} = 0}$

*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

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

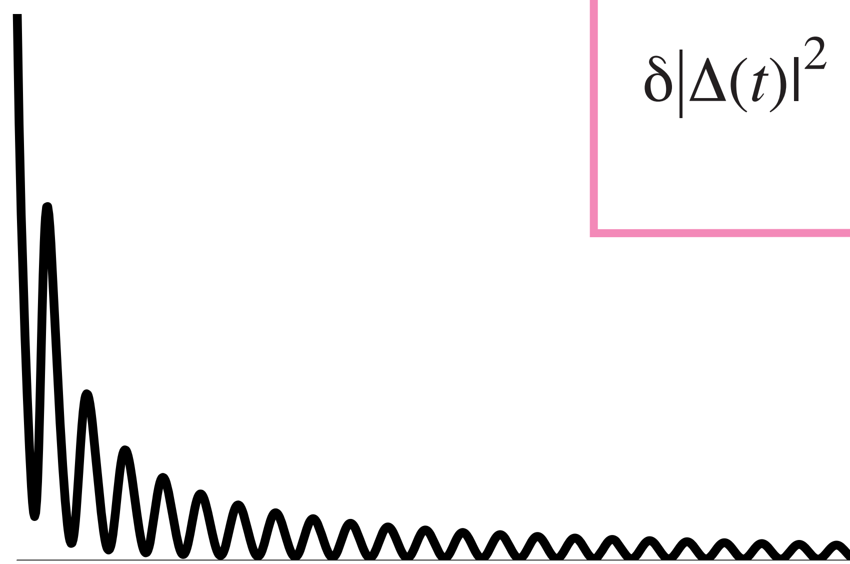
$\omega \sim E_{\rm Planck}$

F.R. Klinkhamer & G.E. Volovik
Dynamic vacuum variable & equilibrium approach in cosmology
PRD **78**, 063528 (2008)
Self-tuning vacuum variable & cosmological constant,
PRD **77**, 085015 (2008)

dynamics of Δ in superconductor

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

$\omega = 2\Delta$



$t = 0$ $t = +\infty$

intial states:

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

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

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

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

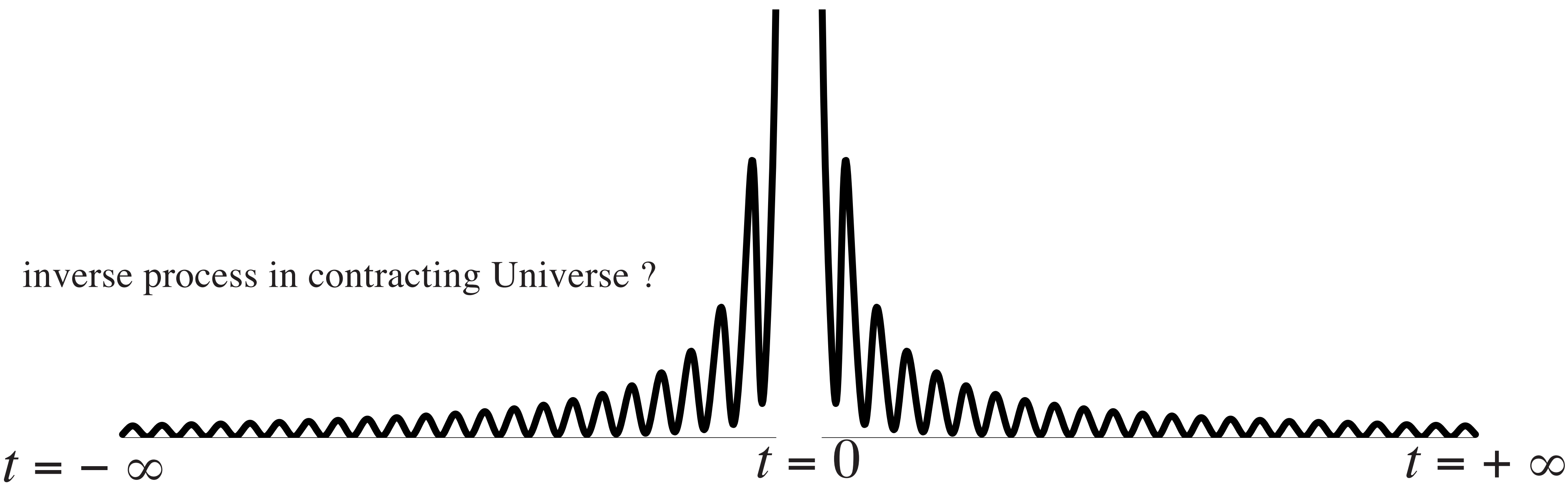
reversible energy transfer
from vacuum to gravity

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

$$\omega = 2\Delta$$

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

inverse process in contracting Universe ?



Phenomenology of quantum vacuum

how to describe quantum vacuum & vacuum energy Λ ?

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

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

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

* **quantum vacuum is Lorentz-invariant**

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

Hawking suggested to introduce special field which describes the vacuum only
Hawking, Phys. Lett. B **134**, 403 (1984)

Vacuum variable

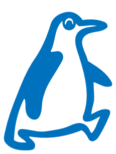
* quantum vacuum is a self-sustained medium,
  which may exist in the absence of environment

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

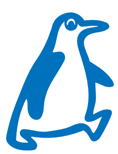
* q is analog of particle density n in liquids

q must be Lorentz invariant

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

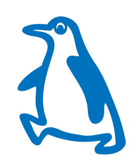


charge density n
is not Lorentz invariant



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

does such q exist ?



relativistic invariant conserved charges q

$$\boxed{\nabla_\alpha q^{\alpha\beta\gamma\ldots} = 0}$$

possible vacuum variables

$$\boxed{<q^{\alpha\beta}>_{vac} = q\, g^{\alpha\beta}}$$

$$\boxed{<q^{\alpha\beta\mu\nu}>_{vac} = q\, e^{\alpha\beta\mu\nu}}$$

$$\boxed{<q_{\alpha\beta\mu\nu}>_{vac} = q\,(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu})}$$

impossible

$$\boxed{<q^{\alpha}>_{vac} = 0}$$

Lorentz invariance of vacuum forbids vacuum vector fields:
only even rank tensors may describe the vacuum state

distinct from: D. Gal'tsov
Non-Abelian condensates as alternative for dark energy, arXiv:0901.0115

possible

$$\boxed{<\nabla_\alpha q_\beta>_{vac} = q\, g_{\alpha\beta}}$$

Polyakov deformation field,
modification of Jacobson Einstein-aether theory, ...

examples of vacuum variable q

4-form field

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

Duff & van Nieuwenhuizen
Phys. Lett. **B 94,** 179 (1980)
Hawking
Phys. Lett. **B 134**, 403 (1984)

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

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

gluon condensates in QCD

$$\boxed{\langle \mathbf{G}_{\alpha\beta}\mathbf{G}_{\mu\nu}\rangle = \frac{q}{12}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu})}$$

$$\boxed{q = \langle \mathbf{G}_{\alpha\beta}\mathbf{G}^{\alpha\beta}\rangle}$$

$$\langle \mathbf{G}_{\alpha\beta}\rangle = 0$$

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

$$\boxed{q = \langle \tilde{\mathbf{G}}_{\alpha\beta}\mathbf{G}^{\alpha\beta}\rangle}$$

topological
charge density

Einstein-aether theory (T. Jacobson)

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

dynamics of vacuum variable q and gravity $g_{\mu\nu}$ is universal
does not depend on particular realization of q

thermodynamics in flat space ***the same as in cond-mat***

conserved charge Q

$$\boxed{Q = \int dV\, q}$$

thermodynamic potential

$$\boxed{E - \mu Q = \int dV\, \Omega} \qquad \boxed{\Omega = \varepsilon(q) - \mu q}$$

Lagrange multiplier or chemical potential μ

equilibrium vacuum $d\Omega/dq = 0$ $\quad \boxed{d\varepsilon/dq = \mu}$

vacuum pressure

$$\boxed{\begin{gathered} P = -\, dE/dV = -\varepsilon + q\, d\varepsilon/dq = -\varepsilon + \mu q = -\,\Omega \\ E = V\, \varepsilon(Q/V) \end{gathered}}$$

Ω is candidate for cosmological constant

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

equilibrium self-sustained vacuum

$$\boxed{\begin{gathered} d\Omega/dq = 0 \\ \Omega = -P = 0 \end{gathered}}$$

vacuum energies in equilibrium self-sustained vacuum

$$\boxed{\Omega = \varepsilon - \mu q = -P}$$

$$\boxed{q \sim \mu \sim E^2_{\rm Planck}}$$ **vacuum variable in equilibrium vacuum**

$$\boxed{\varepsilon\,(q) \sim E^4_{\rm Planck}}$$ **energy of equilibrium vacuum**

$$\boxed{\Omega = \underbrace{\varepsilon}_{E^4_{\rm Planck}} - \underbrace{\mu q}_{E^4_{\rm Planck}} = 0}$$

energy of equilibrium self-sustained vacuum

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

$$\boxed{\Lambda = \Omega = -P = 0}$$

nullification of cosmological constant 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 $\boxed{S = \int dV\, dt\, \varepsilon(q)}$

motion equation $\boxed{\nabla_\kappa (d\varepsilon/dq) = 0}$

solution $\boxed{d\varepsilon/dq = \mu}$

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

$$\boxed{\begin{gathered} q^2 = -\frac{1}{24} F_{\kappa\lambda\mu\nu} F^{\kappa\lambda\mu\nu} \\ F_{\kappa\lambda\mu\nu} = \nabla_{[\kappa} A_{\lambda\mu\nu]} \\ F^{\kappa\lambda\mu\nu} = q\, e^{\kappa\lambda\mu\nu} \end{gathered}}$$

Maxwell equation

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

general dynamics of q in curved space

action

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

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

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

Einstein tensor

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

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

matter

case of K=*const* restores original Einstein equations

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

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

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

Einstein tensor

cosmological term

matter

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

Minkowski vacuum solution

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

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

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

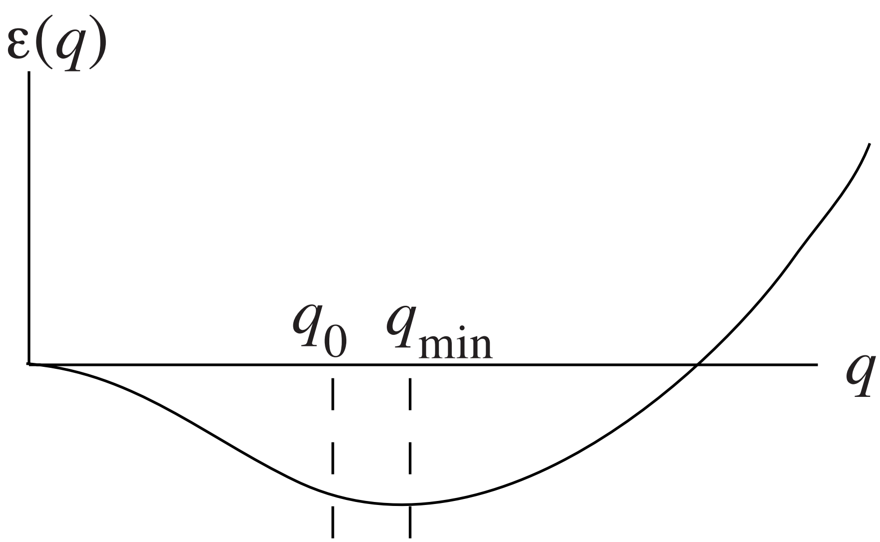
thermodynamic vacuum energy: $\varepsilon - \mu q = 0$

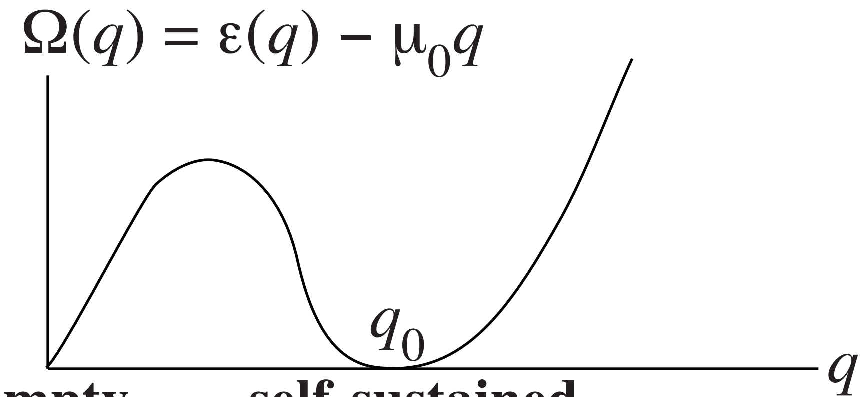
Model vacuum energy

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

Minkowski vacuum solution

$$\boxed{d\varepsilon/dq = \mu \qquad \varepsilon - \mu q = 0} \longrightarrow \boxed{q = q_0 \qquad \mu = \mu_0 = -\frac{1}{3\chi q_0}}$$





empty space $q = 0$

self-sustained vacuum $q = q_0$

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

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

Minkowski vacuum (q-independent properties)

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

energy density of vacuum **pressure of vacuum**

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

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

compressibility of vacuum

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

$$\langle(\Delta\Lambda)^2\rangle = \langle(\Delta P)^2\rangle$$

pressure fluctuations

natural value of Λ determined by macroscopic physics

$$\boxed{\Lambda = 0}$$

natural value of χ_{vac} determined by microscopic physics

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

volume of Universe is large:

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

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

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"

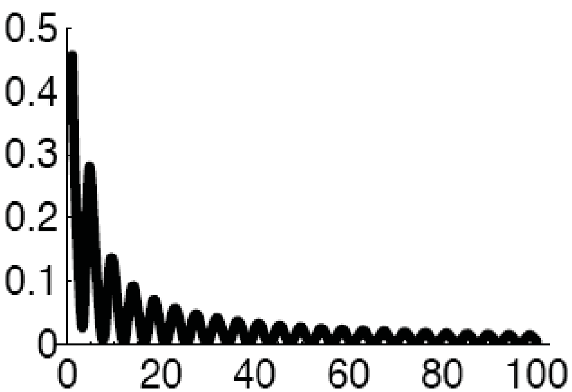
$$H(t) = \frac{\dot{a}(t)}{a(t)} = \frac{2}{3t}\left(1 - \cos \omega t\right)$$

Hubble parameter

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

Newton "constant"

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



$$<\Lambda(t_{\mathrm{Planck}})> \sim E^4_{\mathrm{Planck}}$$

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

natural solution of the main cosmological problem ?

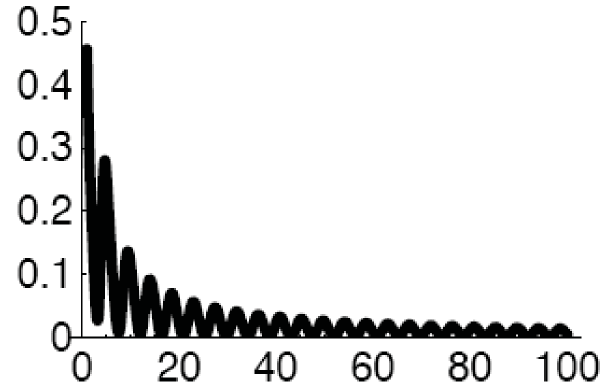
Λ relaxes from natural Planck scale value to natural zero value

present value of Λ

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

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

dynamics of Λ:
from Planck to present value

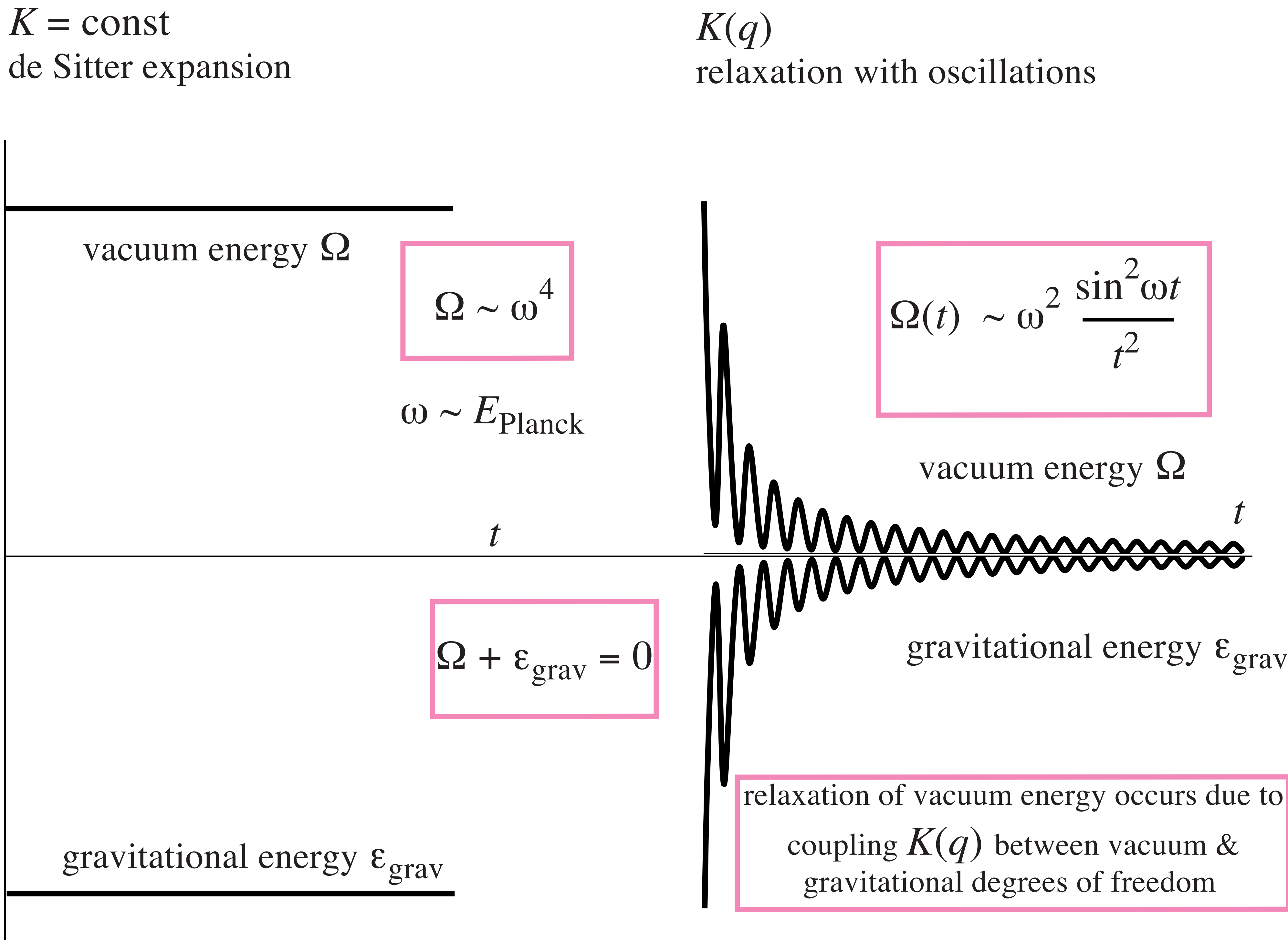


$$<\Lambda(t_{\mathrm{Planck}})> \sim E^4_{\mathrm{Planck}}$$

$$<\Lambda(t_{\mathrm{present}})> \sim E^2_{\mathrm{Planck}} \,/\, t^2_{\mathrm{present}} \sim 10^{-120}\, E^4_{\mathrm{Planck}}$$

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

balance between vacuum and gravitational energies



cold matter simulation

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

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

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

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

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

relaxation of vacuum energy mimics expansion of cold dark matter

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

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

equilibrium vacuum is obtained from equation

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

microscopic vacuum energy

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

equilibrium solution**:**

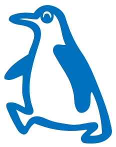
$$\boxed{u_{\mu\nu} = q g_{\mu\nu}}$$

$q = const$

vacuum variable

cosmological constant

$$\boxed{\Lambda = \Omega(q_0) = 0}$$



macroscopic thermodynamic vacuum energy:
from energy momentum tensor

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

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

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

relativistic quantum vacuum vs cond-mat

microscopic energy

natural Planck scale

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

natural atomic scale

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

macroscopic energy

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

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

in the absence of environment

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

$$\Omega = -P = 0$$

two microscopic quantities cancel each other without fine tuning

self tuning due to $\boxed{\textbf{thermodynamics}}$

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

$$\boxed{\Lambda \sim G^2 \lambda^6_{QCD}}$$

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

close to present cosmological constant

supports suggestion by Zeldovich

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

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

Lifshitz point

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

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

Lifshitz point in QCD

effective gluon mass diverges in k -> 0 limit

$z = -1$

$$\boxed{m(\mathrm{k}) \sim \frac{\lambda^2_{\mathrm{QCD}}}{\mathrm{k}}}$$

Gribov picture of confinement

$z = -2$

$$\boxed{m(\mathrm{k}) \sim \frac{\lambda^3_{\mathrm{QCD}}}{\mathrm{k}^2}}$$

alternative picture of confinement
Cabo et al. arXiv:0906.0494

remnant cosmological constant from QCD

estimation of vacuum energy in expanding Universe

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

$z = -1$

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

Gribov scenario

$z = -2$

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

Cabo et al. arXiv:0906.0494

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

$$\boxed{\Omega \sim \lambda_{QCD}^2 H^2}$$

negligible correction to Einstein action

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

$$\boxed{\Omega \sim \lambda_{QCD}^3 |H|}$$

dominates at small Hubble parameter H

asymptotic de Sitter state due to infrared QCD

$$\boxed{\Omega \sim \lambda_{QCD}^3 |H|}$$

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

de Sitter

$$\boxed{H \sim G\, \lambda_{QCD}^3}$$

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

close to present cosmological constant

supports suggestion by Zeldovich

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

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

J. Bjorken, The classification of universes, astro-ph/0404233

R. Schutzhold, Small cosmological constant from the QCD trace anomaly? *PRL* **89**, 081302 (2002)

Klinkhamer & Volovik, Gluonic vacuum, q-theory & the cosmological constant, *PRD* **79**, 063527 (2009)

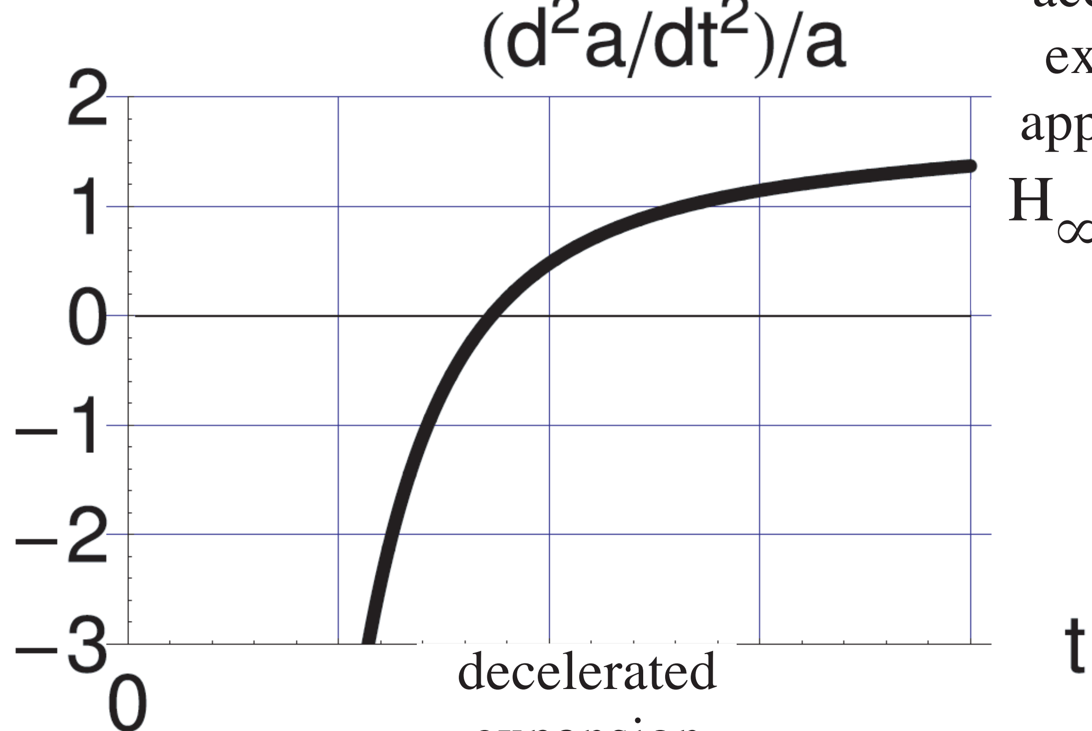
Urban & Zhitnitsky,

The cosmological constant from the Veneziano ghost which solves the U(1) problem in QCD, 0906.2162

Cosmological constant, violation of cosmological isotropy & CMB, 0906.3541

asymptotic de Sitter state from q-theory with QCD

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



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

decelerated expansion

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 $f(R) = R + |R|^{1/2}$

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

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

action

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

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

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

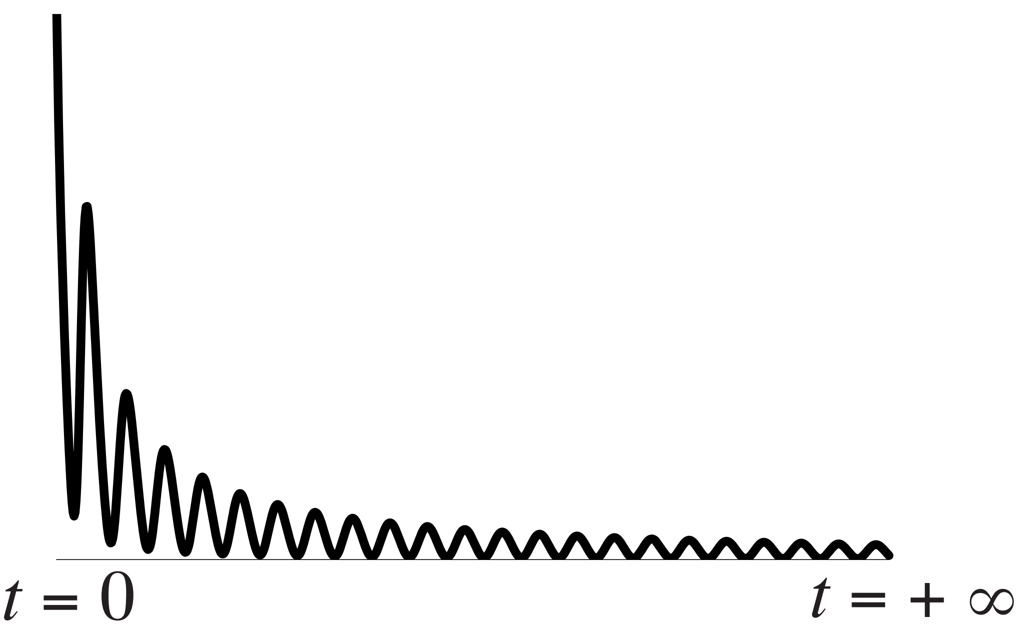
$$\boxed{H \sim G\, q_0^{3/4}} \qquad\qquad \boxed{\Lambda \sim G^2 q_0^{3/2}}$$

two regimes of vacuum dynamics

decay with oscillations

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

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

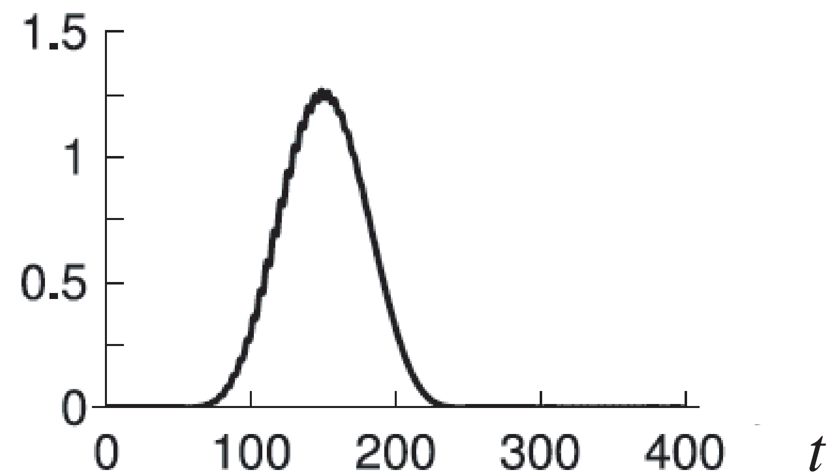


response to perturbation of matter

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

$w(t)$ matter equation of state

$\Lambda(t) \,/\, H^4(t)$



Klinkhamer & Volovik, arXiv:0905.1919

remnant cosmological constant from electroweak crossover

response to perturbation of matter without dissipation

$$\boxed{\Lambda_0(t) \sim \left(w(t) - 1/3\right)^2 H^4(t)}$$

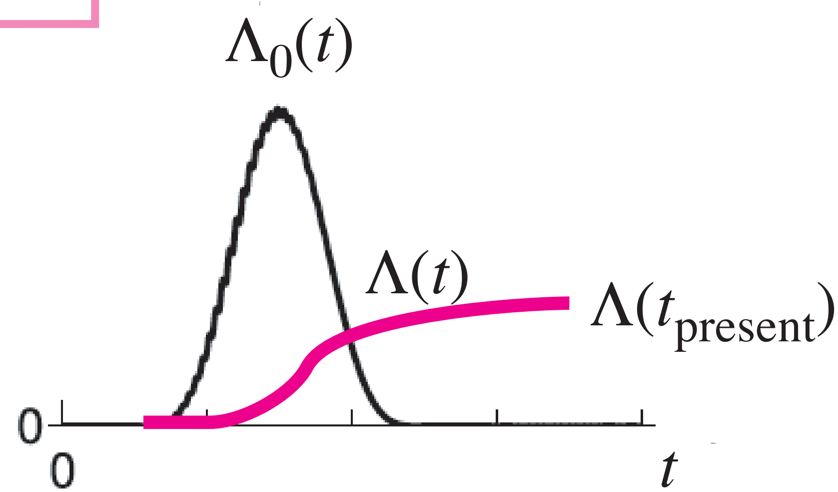
$w(t) - 1/3 \neq 0$ during electroweak crossover, when $H(t_{ew}) \sim E^2{}_{ew} / E_{Planck}$

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

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

this may explain present value of Λ

$$\dot{\Lambda} = -\Gamma(t)\left(\Lambda(t) - \Lambda_0(t)\right)$$



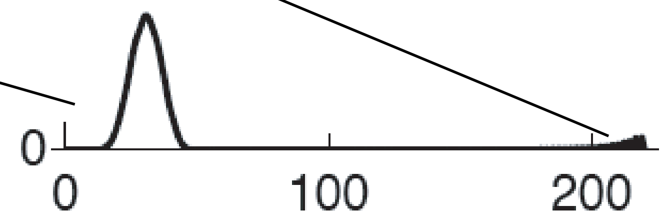
Klinkhamer & Volovik, arXiv:0905.1919

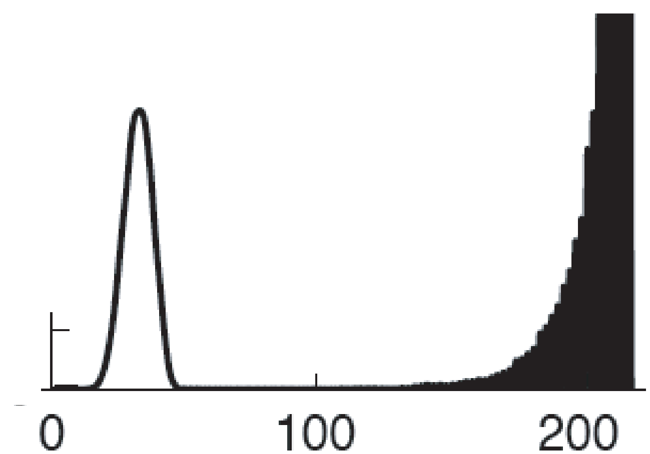
vacuum instability in contracting universe

response to perturbation of matter

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

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

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

* vacuum energy has Planck scale value in equilibrium

  but this energy is not gravitating

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

* gravitating energy which enters Einstein equations

  is thermodynamic vacuum energy

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

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

* thermodynamic energy

  of equilibrium

  self-sustained vacuum

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

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

* small remnant cosmological constant may come from :

  QCD, electroweak crossover, radiation/dissipation

  or other minor effects at late stage of expansion,

  which destroy perfect balance between vacuum and gravity

* this is open question