VACUUM DARK ENERGY AND SPACETIME SYMMETRY

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Content:

1. **Vacuum Dark Energy presented by variable cosmological term**
2. **Regular cosmologies with Vacuum Dark Energy**
3. **Regular compact objects with de Sitter vacuum interiors**

Dark Energy:

$$p = w\rho; \quad w < -1/3; \qquad [\ddot{a} \sim -a(\rho + 3p)]$$

The best fit $w_{obs} = -1$ **(**$p = -\rho$**) cosmological constant**

In the Einstein equations with the cosmological constant

$$G^{\mu}_{\nu} + \lambda\delta^{\mu}_{\nu} = 0; \quad G^{\mu}_{\nu} = -\lambda\delta^{\mu}_{\nu} = -8\pi G T^{\mu}_{\nu}$$

cosmological term corresponds to de Sitter vacuum

$$T^{\mu}_{\nu} = (8\pi G)^{-1}\lambda\delta^{\mu}_{\nu}; \quad p = -\rho; \quad \rho = (8\pi G)^{-1}\lambda = const$$

Problem of the cosmological constant:

QFT: $\rho_{vac} = \rho_{Pl} = 5 \times 10^{93} g\ cm^{-3}$
Observations: $\rho_{vac} \simeq 3.6 \times 10^{-30} g\ cm^{-3}$
First Inflation: $\rho_{vac} \simeq \rho_{GUT} \simeq 5 \times 10^{77} g\ cm^{-3}$
Einstein equations: $\rho_{vac} = const$

Alternative: $\rho_{vac} = 0$ **for some reason (still unknown). Dark Energy of a non-vacuum origin which mimics** λ **when necessary.**

1. Vacuum as a medium

QFT does not contain an appropriate symmetry to zero out ρ_{vac}, or to reduce it to a certain non-zero value.

A relevant symmetry exists in General Relativity.

It follows from the Petrov classification for T_μ^ν

$$T_\mu^\nu = diag[\rho, -p_1, -p_2, -p_3]$$

Eigenvectors of $T_{\mu\nu}$ form a comoving reference frame with a time-like eigenvector representing a velocity.

The Einstein cosmological term corresponds to
the maximally symmetric de Sitter vacuum

$$T_\mu^\nu = (8\pi G)^{-1}\lambda\delta_\mu^\nu = \rho\delta_\mu^\nu; \quad p = -\rho \Leftrightarrow [(IIII)] \quad all\ eigenvalues\ equal$$

It has an infinite set of comoving reference frames which makes impossible to fix a velocity with respect to it *which is the most general intrinsic property of a vacuum [L.D. Landau, E.M. Lifshitz, Classical theory of fields]*. **T_μ^ν with [(IIII)] generates the maximally symmetric de Sitter spacetime for any underlying source model for T_μ^ν.**

A maximal symmetry [(IIII)] can be reduced to

$$p_k = -\rho \qquad (*)$$

invariant under the Lorentz boosts in the k-direction(s), *[I. Dymnikova, Gen. Rel. Grav. 24 (1992) 235; I. Dymnikova, Phys. Lett. B 472 (2000) 33]* $\longrightarrow$ **still impossible to single out a preferred comoving reference frame and thus to fix the velocity with respect to a medium specified by $(*)$.**

Vacuum Dark Fluid - defined by symmetry of its T_μ^ν

[I. Dymnikova, E. Galaktionov, Phys. Lett. B 645 (2007)]

Types of vacuum dark fluid:

[(IIII)] - isotropic vacuum dark fluid (de Sitter vacuum $\Rightarrow$ maximally symmetric de Sitter spacetime)

[(II)II], [(III)I], [(II)(II)] - anisotropic vacuum dark fluids (spacetime can contain regions of de Sitter vacuum with the restored maximal symmetry) — Can be associated with dynamical variable cosmological term with changing spacetime symmetry

$$\Lambda_\nu^\mu = (8\pi G)^{-1} T_\nu^\mu; \quad \Lambda \Rightarrow \Lambda_t^t = (8\pi G)^{-1} T_t^t$$

Spherically symmetric vacuum

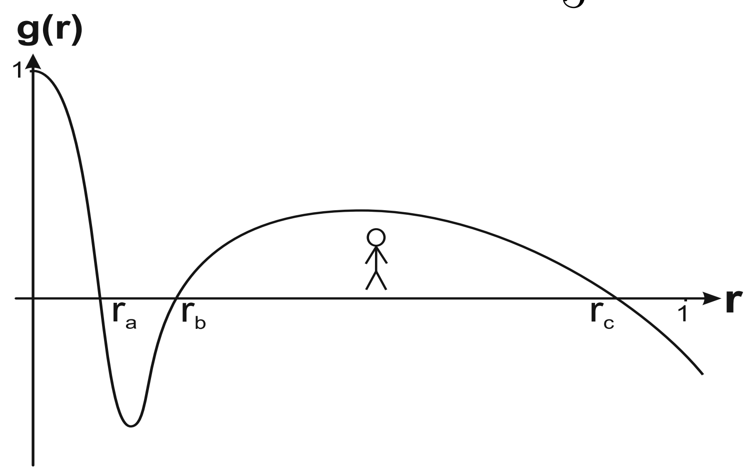
Regular spacetimes with de Sitter center: $T_t^t = T_r^r \quad (p_r = -\rho)$ *[I.Dymnikova, Phys. Lett. B472(2000)33; Class. Quant. Grav. 19(2002)725;]*

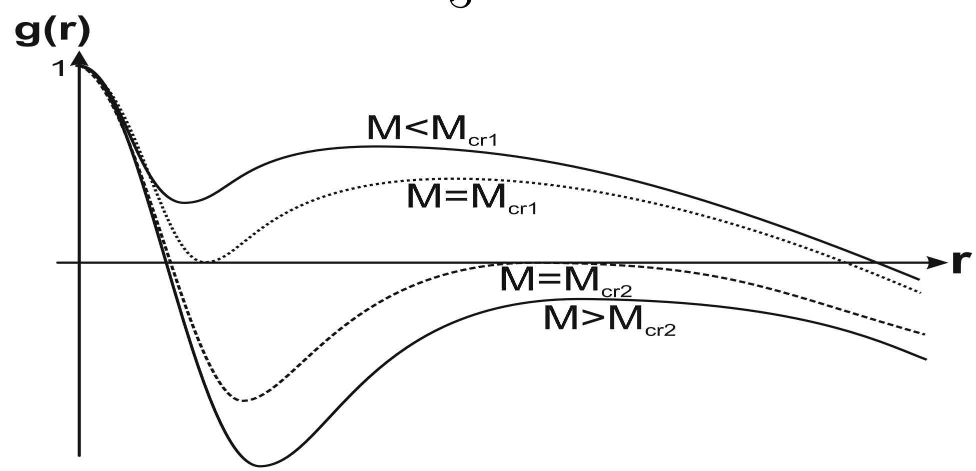
$$ds^2 = g(r)dt^2 - \frac{dr^2}{g(r)} - r^2 d\Omega^2; \quad g(r) = 1 - \frac{2G}{r}\mathcal{M}(r); \quad \mathcal{M}(r) = \int_0^r \rho(x)x^2 dx$$

Number of horizons $N_{horizons} \leq (2N_{vacuum\ scales} - 1)$ *[K.A. Bronnikov, I. Dymnikova, E. Galaktionov, Class. Quant. Grav. 29 (2012) 095025]*. **For 2 vacuum scales**

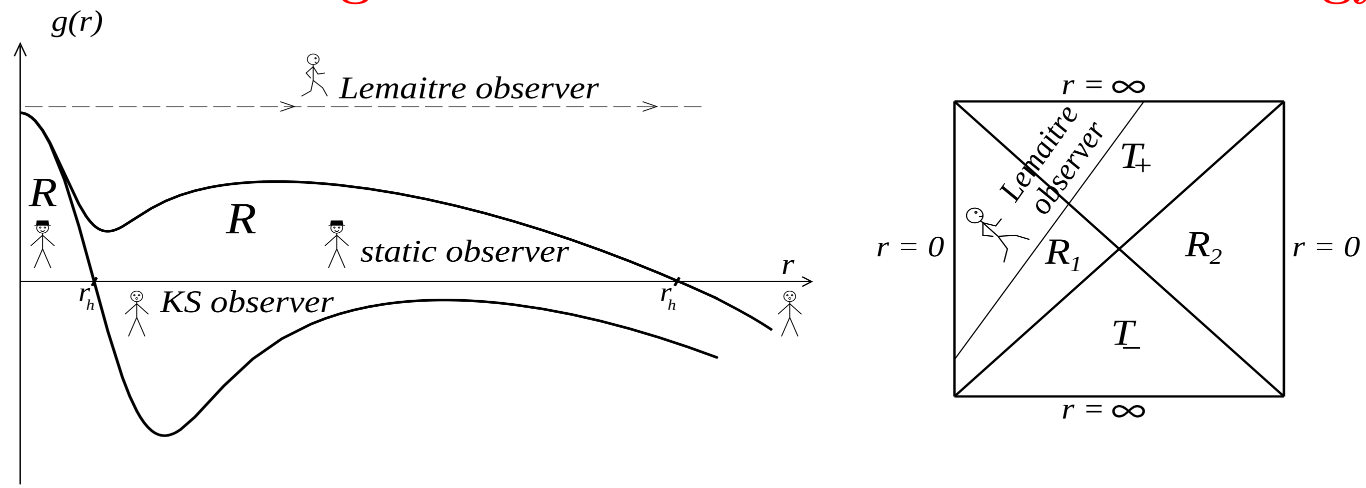
$$T^{\mu}_{\nu\,(deSitter)} = (8\pi G)^{-1}\Lambda\delta^{\mu}_{\nu} \longleftarrow \quad T^{\mu}_{\nu} \longrightarrow T^{\mu}_{\nu\,(deSitter)} = (8\pi G)^{-1}\lambda\delta^{\mu}_{\nu}$$

$$1 - \frac{\Lambda}{3}r^2 \quad \longleftarrow \quad g(r) \quad \longrightarrow \quad 1 - \frac{\lambda}{3}r^2$$





2. Regular cosmological models with vacuum dark energy



Lemaitre class models $ds^2 = d\tau^2 - b^2(R,\tau)dR^2 - r^2(R,\tau)d\Omega^2$, *review in [K.A. Bronnikov, I. Dymnikova, E. Galaktionov, Class. Quant. Grav. 29(2012)095025.]* **(i) Non-simultaneous de Sitter bang** $r(R,\tau) = 0$**;**
(ii) Anisotropic stage after inflation.

Kantowski type regular models $ds^2 = |g(t)|^{-1}dt^2 - |g(t)|dr^2 - t^2 d\Omega^2$
(i) Null bang from a horizon; (ii) Pre-bang information available

Regular T-models $ds^2 = e^{\alpha(t)}dt^2 - e^{\beta(t)}dx^2 - e^{\gamma(t)}d\Omega^2$ *[K.Bronnikov and I. Dymnikova, Class. Quant. Grav. 24 (2007) 5803]* **(i) existence of a Killing horizon; (ii) a null bang from horizon; (iii) pre-bang information available; (iv) creation of matter from anisotropic vacuum.**

Quantum thermodynamics of horizons

Horizon temperature *[G.W. Gibbons, S.W. Hawking, Phys. Rev. D15(1977)2738]*

$$kT_h = \frac{\hbar}{2\pi c}\kappa_h = \frac{\hbar c}{4\pi}|g'(r_h)|$$

The partition function calculated as the path integral for a canonical ensemble of metrics from the class $g_{tt}g_{rr} = -1$ **(**$T_t^t = T_r^r$**) at** $T_h = const$ *[T. Padmanabhan, Class. Quant. Grav. 19 (2002) 5387]*

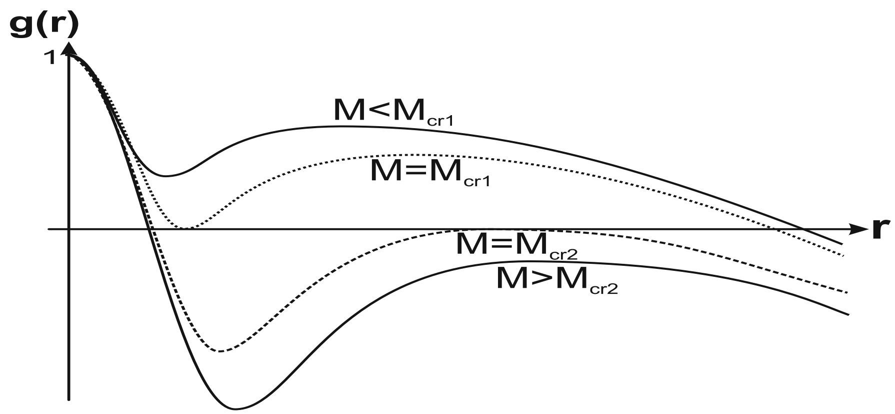
$$Z(kT_h) = Z_0 \exp\left[\frac{1}{4}\left(4\pi r_h^2\right) - \frac{1}{kT_h}\left(\frac{|g'|}{g'}\frac{r_h}{2}\right)\right] \propto \exp\left[S(r_h) - \frac{E(r_h)}{kT_h}\right] \quad \rightarrow$$

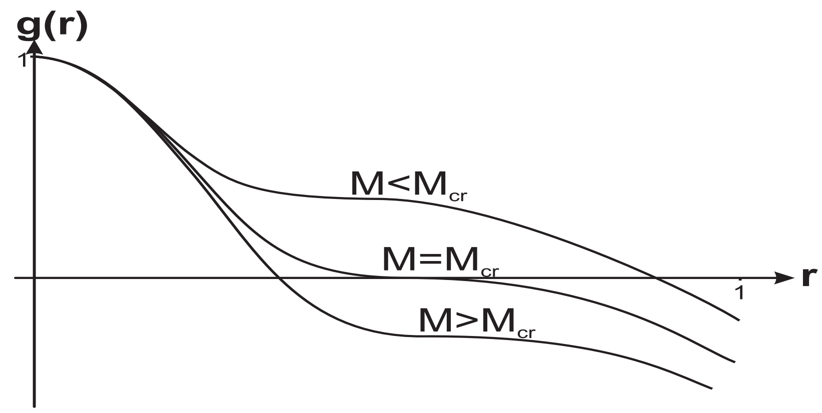
$$S_h = \pi r_h^2; \quad E_h = \frac{|g'|}{g}\frac{r_h}{2}; \quad C_h = dE_h/dT_h = \frac{2\pi r_h}{g'(r_h) + g''(r_h)r_h}$$

[I. Dymnikova and M. Korpusik, Phys. Lett. B 685 (2010) 12]

The Holographic Principle *[G. 't Hooft, gr-qc/9310026 (1993)]*: **The number of quantum degrees of freedom in a spatial volume is bounded from above by its surface area. Conjecture: a physical system can be completely specified by data stored on its boundary** *[L. Susskind, J. Math. Phys. 36 (1995) 6377; R. Bousso, Class. Quant. Grav. 17 (2000) 997]*.

Cosmological model singled out by the Holographic Principle:





$$kT_h = \frac{\hbar}{2\pi c}\kappa_h = \frac{\hbar c}{4\pi}|g'(r_h)|; \quad C_h = \frac{dE_h}{dT_h} = \frac{2\pi r_h}{g'(r_h) + g''(r_h) r_h}$$

The triple-horizon spacetime is distinguished by the quantum dynamics of the cosmological horizon as the only thermodynamically stable final product of its evaporation. *[I. Dymnikova, Int. J. Mod. Phys. D 21 (2012) 1242007]*. **Evaporation stops when** $T_h = 0$; $C_h \to \infty$, **at** $g(r_t) = g' = g'' = 0$, **which define uniquely** M_{cr}, r_t **and** q_{cr} $(q^2 = \rho_\Lambda/\rho_\lambda)$. **Estimate with the density profile** *[I. Dymnikova, Gen. Rel. Grav. 24 (1992) 235]* $\rho(r) = \rho_\Lambda e^{-r^3/r_\Lambda^2 r_g}$; $r_\Lambda^2 = \frac{3}{8\pi G\rho_\Lambda}$, **with** $\rho_\Lambda = \rho_{GUT}$ **and** $E_{GUT} \simeq 10^{15}$ **GeV, gives** $q_{cr}^2 \simeq 1.37\times 10^{107}$ $(q_{obs}^2 \simeq 1.39\times 10^{107})$, $r_t = 5.4 \times 10^{28} cm$, $M_{cr} = 2.33 \times 10^{56} g$, $\rho_\lambda \simeq 3.6 \times 10^{-30} g\ cm^{-3}$.

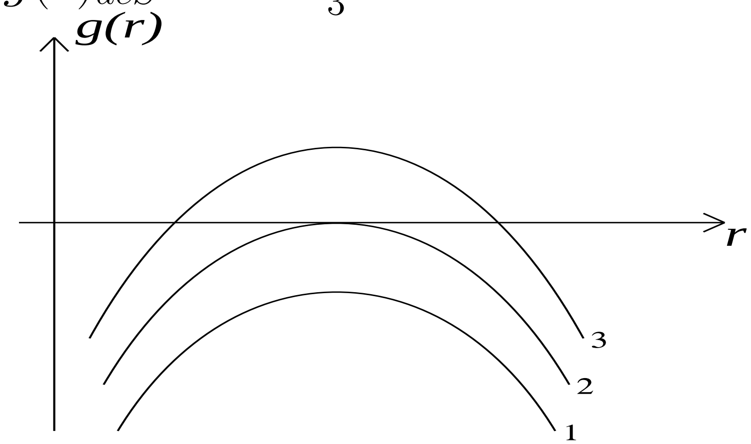
3. Regular compact objects with de Sitter interior

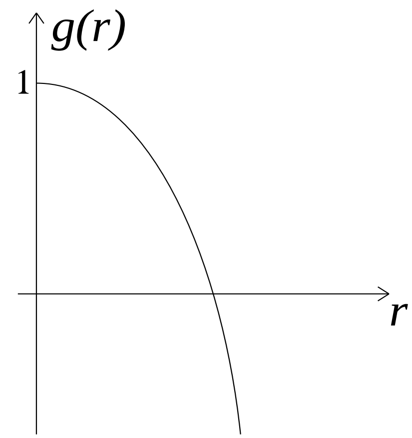
Black hole remnants

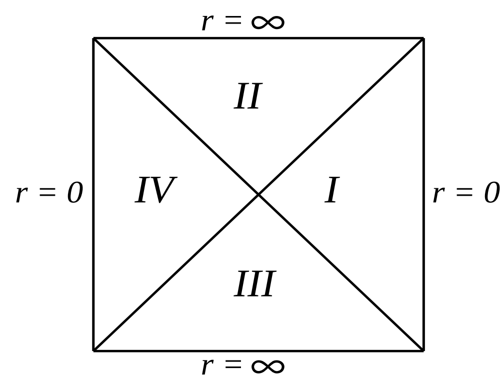
BH remnants are considered as a reliable source of dark matter for about three decades *[J.H. McGibbon, Nature 329 (1987) 308; E.J. Copeland et al, Phys.Rev. D 49 (1994) 6410; B.J. Carr et al, Phys. Rev. D 50 (1994) 4853]*.

Singular BH Remnant - Existential problem: **No evident symmetry or quantum number preventing complete evaporation** *[L. Susskind, J. Math. Phys. 36 (1995) 6377; G.F.R. Ellis, arXiv:1310.4771 (2013)]*.

Problem with the complete evaporation: $g(r)_{Schw-deS} = 1 - \frac{2GM}{r} - \frac{\lambda}{3}r^2 \longrightarrow g(r)_{deS} = 1 - \frac{\lambda}{3}r^2$



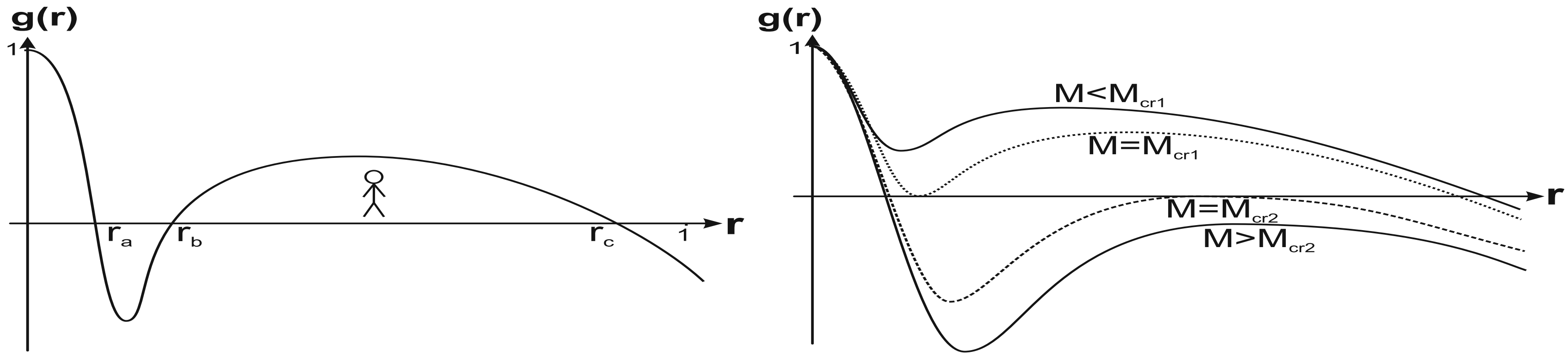




Actually - how to evaporate a singularity?

A loop quantum gravity provides arguments in favor of a regular black hole with de Sitter interior *[A. Perez, Class. Quant. Grav. 20 (2003) R43; C. Rovelli, Quantum Gravity, Cambridge Univ. Press (2004); L. Modesto, hep-th/0701239; A. Bonanno, M. Reuter, Phys. Rev. D 73 (2006) 083005; P. Nicolini, Int. J. Mod. Phys. A 24 (2009) 1229; R. Banerjee et al, Phys. Lett. B 686 (2010) 181]*.

Regular black hole remnants with de Sitter interior

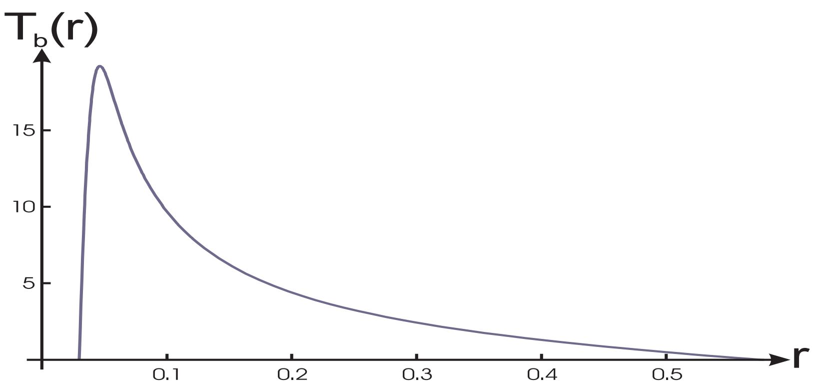


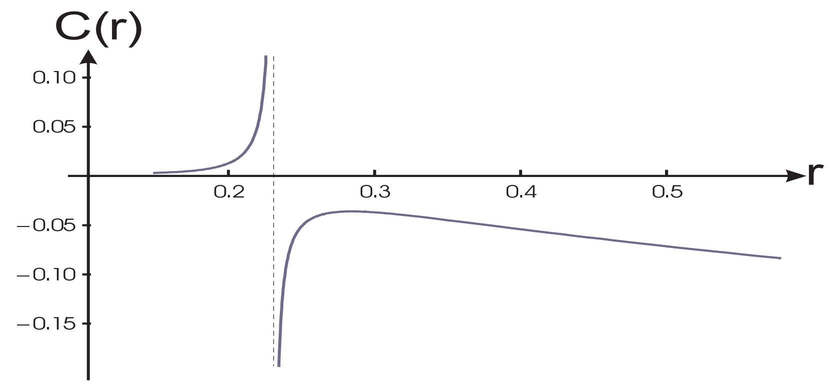
Evolution during evaporation: $r_a \rightleftharpoons r_b$

$$kT_h = \frac{\hbar c}{4\pi}|g'(r_h)|; \;\; r_h = r_a, r_b, r_c; \quad C_h = \frac{2\pi r_h}{g'(r_h) + g''(r_h) r_h}$$

[I. Dymnikova, M. Korpusik, Phys.Lett.B 685(2010)12; Entropy 13 (2011)1967].

A regular black hole leaves behind a thermodynamically stable double-horizon remnant generically related to vacuum dark energy.





In a maximum $C_h = dE_h/dT_h$ **is broken:** $\rightarrow$ **2-nd order phase transition** *[I.Dymnikova, M.Korpusik, Phys. Lett. B685(2010)12]* **- quantum cooling.**

Maximal temperature and mass of the remnant

$$T_{tr} \simeq \alpha T_{Pl}\sqrt{\rho_{int}/\rho_{Pl}}; \quad M_{remnant} \simeq \beta M_{Pl}\sqrt{\rho_{Pl}/\rho_{int}}$$

For the case of the density profile $\rho \propto \exp\left(-F_{cr}/F\right)$, $F \propto r_g/r^3$, $F_{cr} \propto 1/r_\Lambda^2$ **(regularization by vacuum polarization effects)**

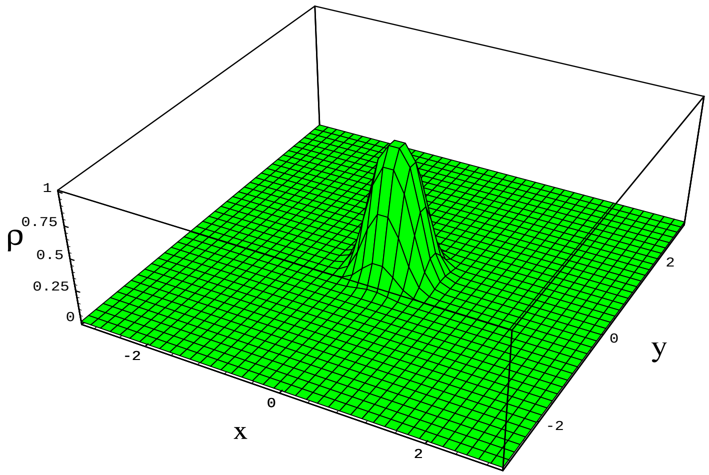
$$\rho(r) = \rho_\Lambda e^{-r^3/r_\Lambda^2 r_g}; \quad r_\Lambda^2 = \frac{3}{8\pi G\rho_\Lambda}; \quad \rho_\Lambda = \rho(r \rightarrow 0); \quad r_g = 2GM,$$

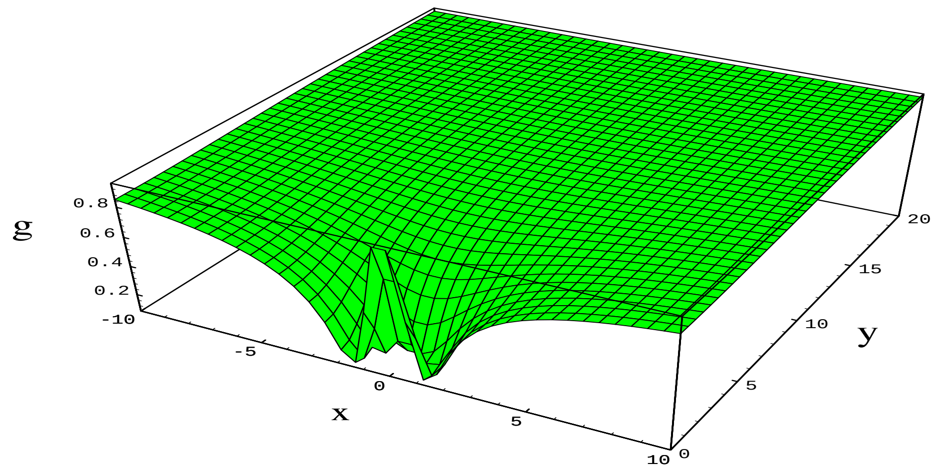
for $\rho_\Lambda = \rho_{GUT}$ **and** $M_{GUT} \simeq 10^{15}$ **GeV, temperature at the phase transition and mass of the remnant**

$$T_{tr} \simeq 0.2 \times 10^{11}\mathrm{GeV}; \quad M_{remnant} \simeq 0.3 \times 10^{11}\mathrm{GeV}$$

Gravitational vacuum soliton, G-lump, with de Sitter interior (non-singular non-dissipative particle-like structure taking itself together by its own self-interaction).

[I. Dymnikova, Int.J.Mod.Phys. D5 (1996) 529; Class.Quant.Grav. 19 (2002) 725].





Energy of G-lump in the minisuperspace model

$E_n = \hbar\omega(n + \frac{1}{2}) - \frac{G\mathcal{M}(r_m)}{r_m} E_{Pl}; \quad \omega = \sqrt{\tilde{p}_\perp(r_m)\Lambda} c$

****

Mass of objects with de Sitter interior $M = (2G)^{-1} \int_0^\infty \Lambda_t^t r^2 dr$ **is generically related to de Sitter vacuum and to breaking of space-time symmetry from the de Sitter group in the origin.**

Regular primordial black holes, their remnants and G-lumps can arise during first and second (100-200 MeV *[D. Boyanovsky et al, Annual Review of Nuclear and Particle Science 56 (2006) 441]*) **inflationary stages in a quantum collapse of primordial fluctuations . They can capture available particles and form graviatoms - gravitationally bound** ($\alpha_G = GMm/\hbar c$) **quantum systems with charged particles** *[I. Dymnikova, M. Fil'chenkov, AHEP ID 746894 (2013)]*.

OBSERVATIONAL SIGNATURES

I. Graviatom radiation *[I. Dymnikova,M.Fil'chenkov, AHEP ID 74689(2013)]*

For a non-relativistic captured particle, graviatom is described by

$$-\frac{\hbar^2}{2m}\Delta\psi + U(r)\psi = E\psi; \quad U(r) = \frac{mc^2}{2}\left(-\frac{2G\mathcal{M}(r)}{r} + \frac{r_g r_q}{2r^2}\right).$$

The potential includes the DeWitt conservative self-force for a charged particle of mass m **and charge** q.

For the case of the density profile $\rho(r) = \rho_\Lambda e^{-r^3/r_\Lambda^2 r_g}; \quad r_\Lambda^2 = \frac{3}{8\pi G\rho_{Lambda}}$

$$\hbar\omega = 0.678\hbar c/r_{deS} = 0.678 \times 10^{11} GeV (E_\Lambda/E_{GUT})^2$$

Observational possibilities - detection of photons up to $10^{11.5}$ **GeV** *[O.E. Kalashev, G.I. Rubtsov, S.V. Troitsky, Phys. Rev. D 80 (2009) 103006]*.

CONCLUSIONS

(i) Classification of stress-energy tensors presents possibility to introduce in general setting dynamical variable cosmological term with changing spacetime symmetry.

(ii) Holographic principle singles out the Lemaitre class cosmological dark energy model with relaxing vacuum density and tightly fixed non-zero final value of vacuum density dictated by quantum dynamics of cosmological horizon (*Detailed description in the next talk*).

(iii) Applying the density profile related to vacuum polarization effects and choice of the GUT scale for inflation gives the present value of vacuum density in remarkable agreement with observations.

(iv) Dynamically variable cosmological term describes also (in the proper mapping) regular compact objects with the de Sitter vacuum interiors: regular black holes, their remnants and G-lumps.

(v) Mass of objects is generically related to interior de Sitter vacuum and to breaking of spacetime symmetry from the de Sitter group in the origin.