Compact objects
as the catalysts for vacuum decays

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02/11/2019@The 3rd IBS-KIAS Joint Workshop at High 1

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1808.01382

$$c = \hbar = M_G^2 = 1/(8\pi G) = 1$$

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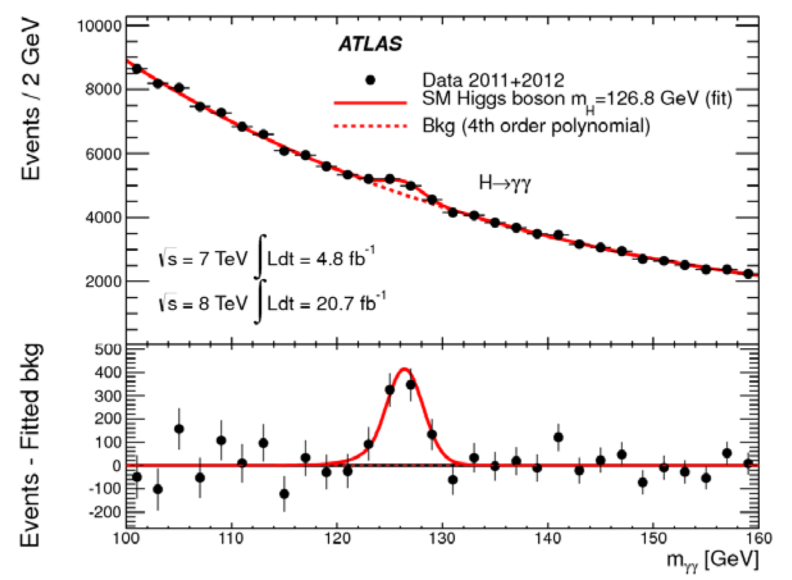
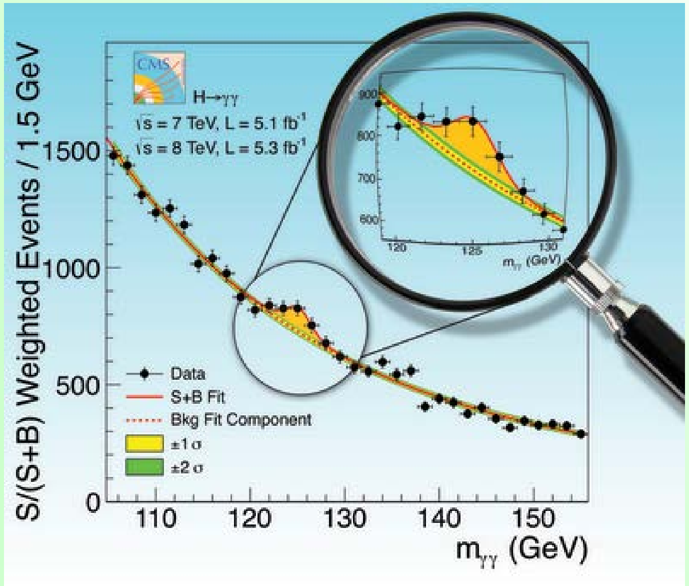
Introduction

A Higgs particle was found !!



http://www.atlas.ch/HiggsResources/



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

A Higgs particle with 125 GeV mass has been finally found.

Running of the couplings

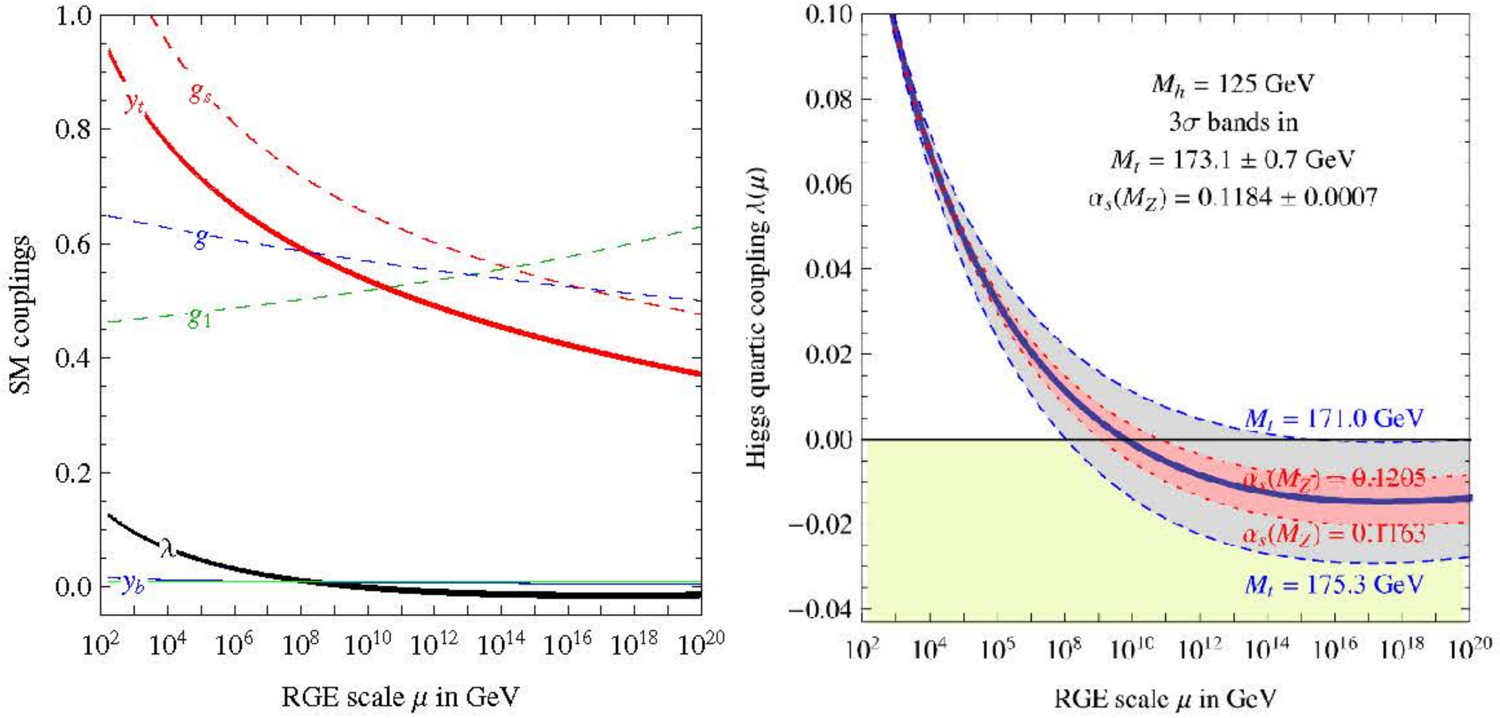


Figure 1. *Left*: SM RG evolution of the gauge couplings $g_1 = \sqrt{5/3}g'$, $g_2 = g$, $g_3 = g_s$, of the top and bottom Yukawa couplings (y_t, y_b), and of the Higgs quartic coupling λ. All couplings are defined in the $\overline{\text{MS}}$ scheme. The thickness indicates the $\pm 1\sigma$ uncertainty. *Right*: RG evolution of λ varying M_t and α_s by $\pm 3\sigma$.

(Degrassi et al. 2013)

The Higgs self-coupling can be negative at high energies.

Unstable vacuum ???

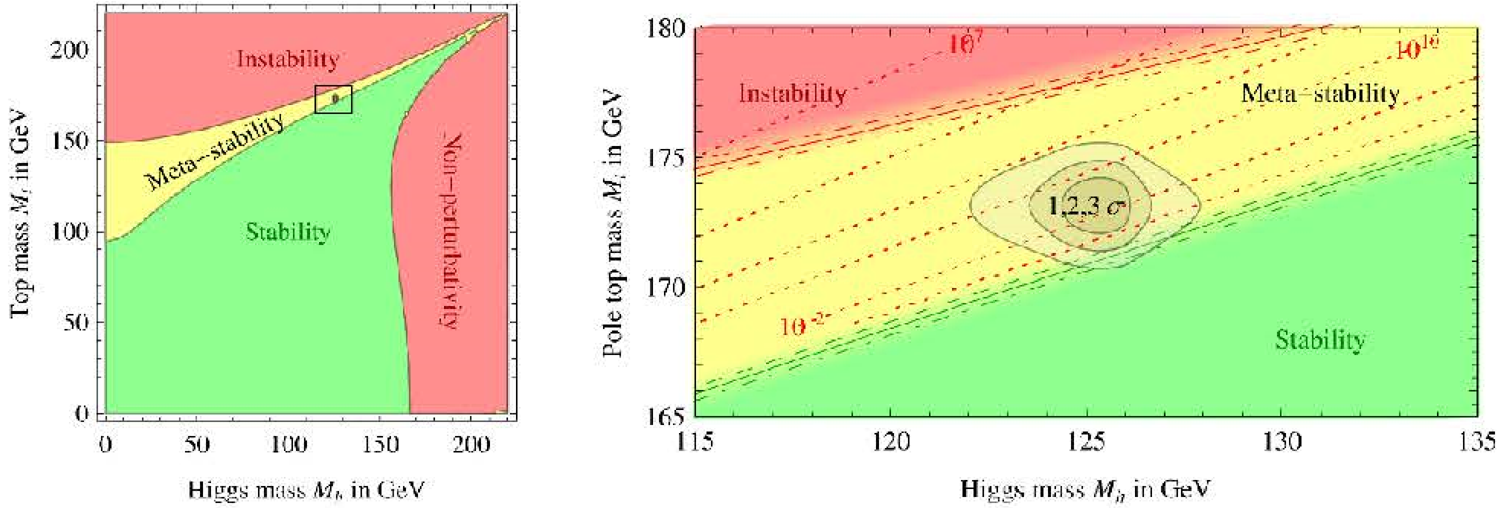


Figure 5. Regions of absolute stability, meta-stability and instability of the SM vacuum in the M_t–M_h plane. *Right*: zoom in the region of the preferred experimental range of M_h and M_t (the gray areas denote the allowed region at 1, 2, and 3σ). The three boundaries lines correspond to $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale Λ in GeV assuming $\alpha_s(M_Z) = 0.1184$.

(Degrassi et al. 2013)

Our vacuum might be in a meta-stable state, in which the time scale of the tunneling is longer than cosmic age,

Chigusa et al. shows that, with the best-fit values of the SM parameters, the decay rate of the EW vacuum per unit volume is about 10^{-554}/Gyr/Gpc^3.

These calculations are based on the homogeneity and isotropy of the Universe. (More precisely, O(4) bounce)

What happens if there is an impurity, which can break homogeneity ?

Black holes as bubble nucleation sites

Hiscock and, later, many people pointed out that
(primordial) black holes can catalyze vacuum decays around them
and significantly enhance the nucleation rate !!

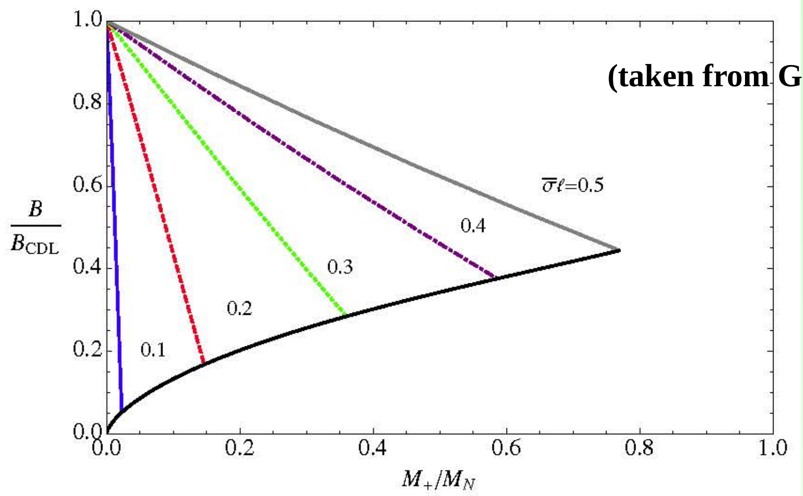
$$\Gamma \propto e^{-B} = e^{-B_0 + \Delta S}$$

decay rate (arrow to Γ)

on-shell Euclidean action (arrow to B_0)

change of Bekenstein entropy < 0 (arrow to ΔS)

(e.g. Gregory et al. 2014)



(taken from Gregory et al. 2014)

B < $B_{\rm CDL}$ indicates enhancement of the decay rate.

Is there any candidate for such an impurity other than BHs ?

Yes, there are many others !!!

Compacts objects such as monopoles, neutron stars, axion stars, oscillons, Q-balls, black hole remnants, gravastars, and so on…

Is there any crucial difference between BHs and the other compact objects ?

Yes !!!

While BHs have horizons,
the others not

~~Black holes~~ as bubble nucleation sites

Compact objects

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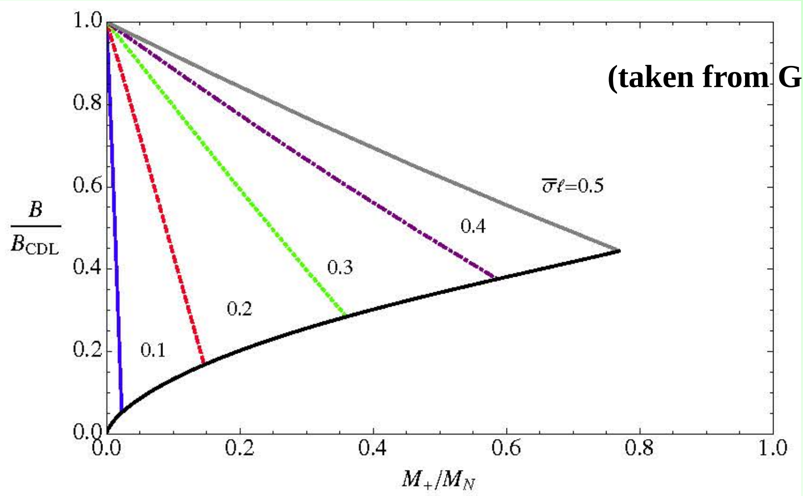
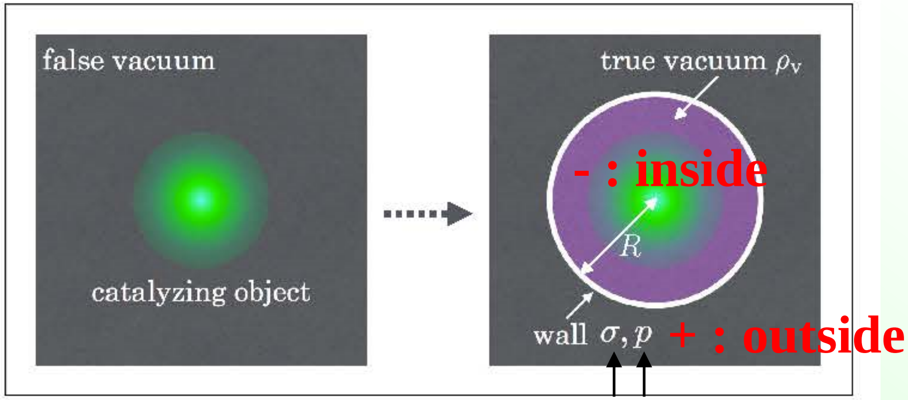


(taken from Gregory et al. 2014)

B < B_{CDL} indicates enhancement of the decay rate.

Formulation

Let us consider the nucleation of a thin wall vacuum bubble around a spherical object.



energy density, pressure of the bubble

FIG. 1. A schematic picture showing a vacuum decay catalyzed by a static and spherical object.

The metric inside and outside of the bubble :

$$ds^2 = -C_\pm(r_\pm)dt_\pm^2 + D_\pm(r_\pm)dr_\pm^2 + r_\pm^2 d\Omega_2^2$$

Specified by Einstein Eqs.

(r₊ = r₋ = R on the wall)

$$\left(C_\pm = D_\pm^{-1} = f_\pm(r_\pm) \equiv 1 - 2GM(r_\pm)/r_\pm + H_\pm^2 r_\pm^2, \quad H_+ = 0, \; H_-^2 \equiv -\frac{8\pi G}{3}\rho_V, \quad M(r_\pm) \equiv \int_0^{r_\pm} d\bar{r}_\pm 4\pi\bar{r}_\pm^2 \rho_C(\bar{r}_\pm)\right)$$

Israel's junction condition:

$$\begin{cases} K_{AB}^{(+)} - K_{AB}^{(-)} = -8\pi G\left(S_{AB} - \frac{1}{2}h_{AB}S\right), \\ K_{AB}^{(\pm)} = \mathrm{diag}\left(-\frac{d\beta_\pm}{dR}, \beta_\pm R, \beta_\pm R\sin^2\theta\right), \\ S^A{}_B \equiv \mathrm{diag}\left(-\sigma, p, p\right), h_{AB} \equiv \mathrm{diag}\left(-1, R^2, R^2\sin^2\theta\right), \end{cases}$$

Energy momentum tensor on the wall

induced metric on the wall

coordinate on the wall, $\xi^A = (\tau, \theta, \phi)$

$$\beta_\pm \equiv \epsilon_\pm\sqrt{f_\pm + (dR/d\tau)^2}$$

Formulation II

Israel's junction condition:

$$K_{AB}^{(+)} - K_{AB}^{(-)} = -8\pi G\left(S_{AB} - \frac{1}{2}h_{AB}S\right)$$

(A= B =τ)

$$\frac{d}{dR}\left(\beta_- - \beta_+\right) = -8\pi G\left(\sigma/2 + p\right),$$

(A= B =θ, φ)

$$\left(\beta_- - \beta_+\right) = 4\pi G\sigma(R)R$$

$$\left(\beta_\pm \equiv \epsilon_\pm\sqrt{f_\pm + (dR/d\tau)^2}\right)$$

$$\sigma = m^{1-2w}R^{-2(1+w)},$$

(m :typical mass scale of wall, w = σ/ p)

$$\left(\frac{dz}{d\tau'}\right)^2 + V(z) = -1,$$

$$V(z) \equiv -\frac{a}{z} - \frac{z^2}{4}\left[\frac{z^{2(1+w)}\bar{m}^{2w-1}}{4\pi\bar{H}^{2w+1}} - \frac{4\pi\bar{H}^{2w+1}}{z^{2(1+w)}\bar{m}^{2w-1}}\right]^2 \leq 0.$$

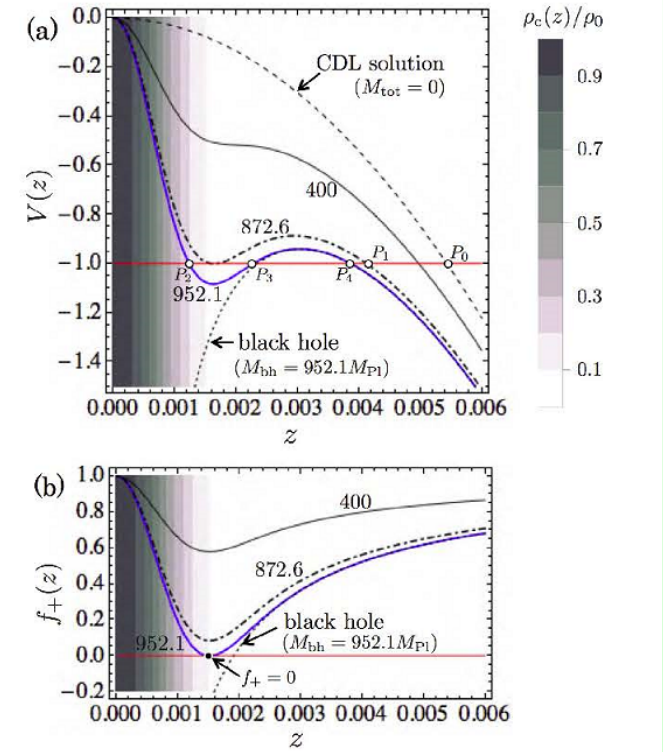
$$z \equiv H_-R,\ \ \tau' \equiv H_-\tau,\ \ a \equiv 2GMH_-,$$

$$\bar{m} \equiv m/M_{\rm Pl},\ \ \bar{H} \equiv H_-/M_{\rm Pl}.$$

For the nucleation (instanton), we need to take the Euclidean time.

Gaussian ansatz: $\rho_{\rm C}(r) = \rho_0 e^{-r^2/\xi^2}$

(e.g. ξ= 10^3 $M_{\rm Pl}^{-1}$)



$$\left(\bar{H} = 10^{-6}, \bar{m} = 6\times10^{-4}, w = -1\right)$$

FIG. 2. The effective potential (a) and f_+ (b) for the horizonless object with $M_{\rm tot}/M_{\rm Pl} = 0$ (CDL solution), 400 (a black solid line), 872.6 (a black dashed-dotted line), and 952.1 (a blue solid line) and for a BH with $M_{\rm tot}/M_{\rm Pl} = 952.1$ (a black dotted line) are shown.

$$M_{\rm tot} \equiv \int_0^\infty dr' 4\pi r'^2 \rho_{\rm C}(r')$$

: total mass of compact objects

Decay rate

The Euclidean action Bco can be calculated from the bounce solution:

$$B_{\rm CO} = \frac{1}{4G}\oint d\tau_{\rm E}(2R - 6GM + 2GM'R)\left(\frac{\beta_+}{f_+} - \frac{\beta_-}{f_-}\right).$$

Euclidean proper time of the wall

The decay rate :

$$\Gamma_{\rm D} \sim R_{\rm CDL}^{-1}\sqrt{\frac{B_{\rm CO}}{2\pi}}\exp(-B_{\rm CO}).$$

compare

$$\Gamma_{\rm C} \equiv H_{\rm C} \simeq 10^{-61} M_{\rm Pl}$$

(the inverse of cosmological time)

Compactness parameter :

$$c \equiv \frac{\xi}{2GM_{\rm tot}}. \qquad \left(\rho_{\rm C}(r) = \rho_0 e^{-r^2/\xi^2}\right)$$

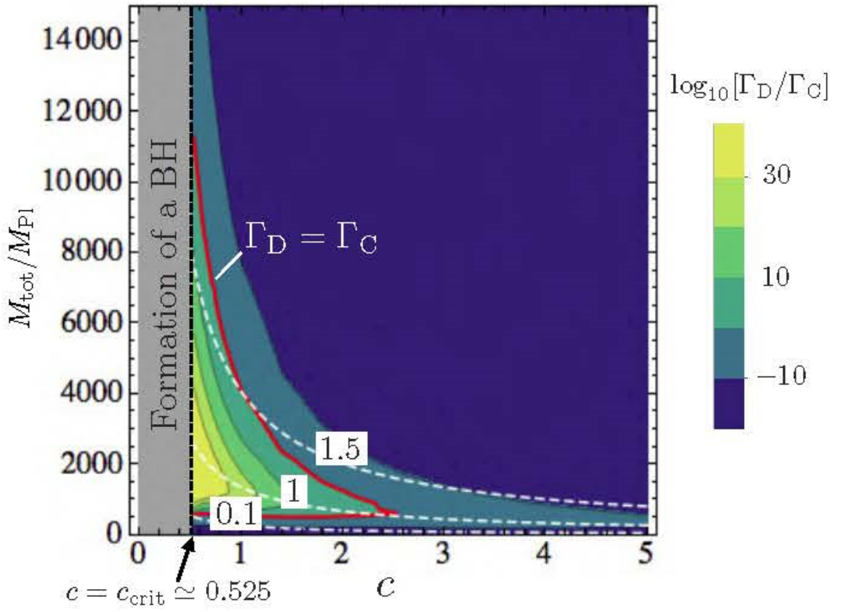


FIG. 3. A plot of the ratio of the decay rate, $\Gamma_{\rm D}$, to the inverse of the cosmological time, $\Gamma_{\rm C}$, as a function of the mass and compactness of the horizonless object. The contour of $\Gamma_{\rm D} = \Gamma_{\rm C}$ (red solid line) and contours of $\xi/R_{\rm CDL}$ (white dashed lines) are marked for reference. In the case of $c \leq c_{\rm crit} \simeq 0.525$ (gray shaded region), the object inevitably collapses to a BH since a function $f_+(r)$ has zero points there.

The decay rate is drastically enhanced if the radius of the compact object ξ is comparable with the radius of CDL bubble and c is of the order of unity.

Comparison with the catalyzing effect of black holes

BH case:

$$\Gamma_{\mathrm{D}} \sim R_{\mathrm{CDL}}^{-1}\sqrt{\frac{I_{\mathrm{E}}}{2\pi}}\exp(-B_{\mathrm{bh}}+\Delta S).$$

$$(I_{\mathrm{E}} = B_{\mathrm{bh}} + |\Delta S|)$$

CO case:

$$\Gamma_{\mathrm{D}} \sim R_{\mathrm{CDL}}^{-1}\sqrt{\frac{B_{\mathrm{CO}}}{2\pi}}\exp(-B_{\mathrm{CO}}).$$

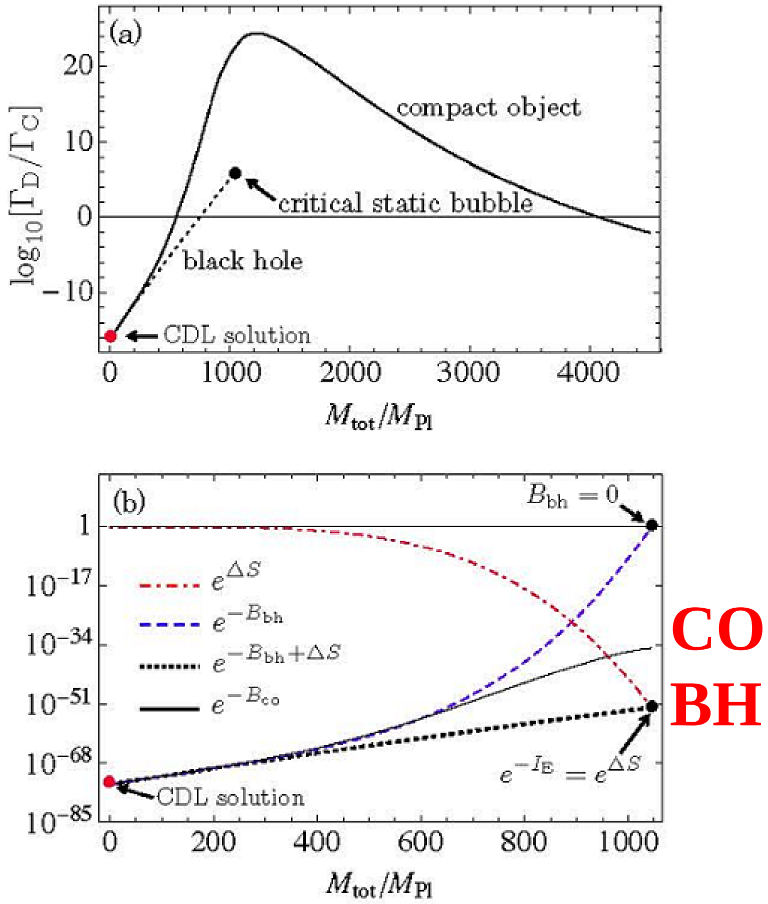


FIG. 4. The vacuum decay rates around a BH with mass $M_{\rm tot}$ (a dotted line) and that around a horizonless compact object, whose mass is $M_{\rm tot}$ and compactness is fixed with $\xi/2GM_{\rm tot}=1$, (a solid line) are shown. Red and black points show the decay rate of the CDL solution and a critical static solution, respectively.

The decay rate with the compact object is larger than that with the BH thanks to the absence of the decrement of Bekenstein entropy.

Summary

- We have proposed a new possibility that compact objects catalyze the vacuum decay efficiently, which can give yet another new constraint on the abundance of compact objects.
- The bubble nucleation rate is drastically enhanced around a compact object if the size of the horizonless object is comparable with the radius of CDL bubble and its compactness is of the order of unity.
- We have shown that the decay rate with the compact object is larger than that with the BH thanks to the absence of the decrement of Bekenstein entropy.
- We have more tasks to do…