Quantum particle creation in gravastar formation

arXiv: 2203.14519

- Radiative gravastar with Gibbons-Hawking temperature -

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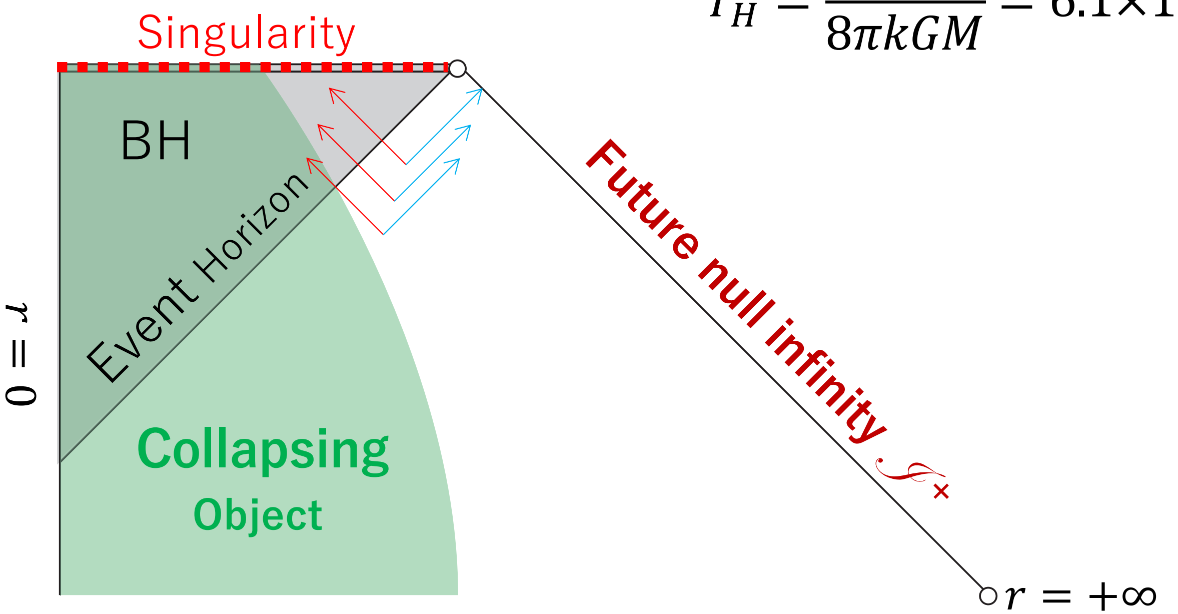
D4 Session, 7 July, 2022

Quantum radiation in black hole formation process

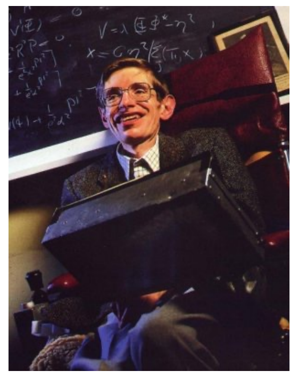
Free quantum field in the spacetime with gravitational collapse

Initial state : vacuum → final state : thermal radiation

$$T_H = \frac{\hbar c^3}{8\pi k G M} = 6.1\times 10^{-8}\left(\frac{M_\odot}{M}\right) K$$



by Stephen Hawking

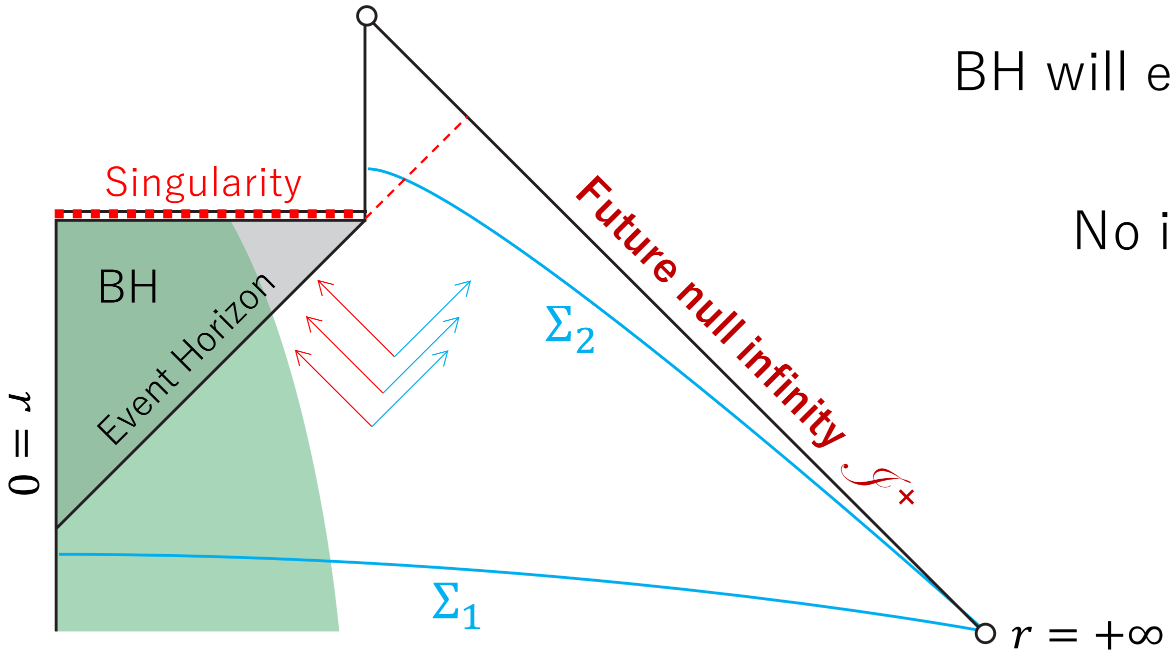


Information loss?!

$$T_H = \frac{\hbar c^3}{8\pi k G M} = 6.1\times 10^{-8}\left(\frac{M_\odot}{M}\right) K$$

Small M → High temperature T_H

BH will evaporate within finite time.



No information about BH on Σ_2

Information loss

Pure state → Mixed state

Not unitary evolution?

No such a problematic black hole should form.

Gravitational collapse may stop before horizon formation.

Horizonless ultra–compact objects (**black hole mimickers**) form.

Candidates

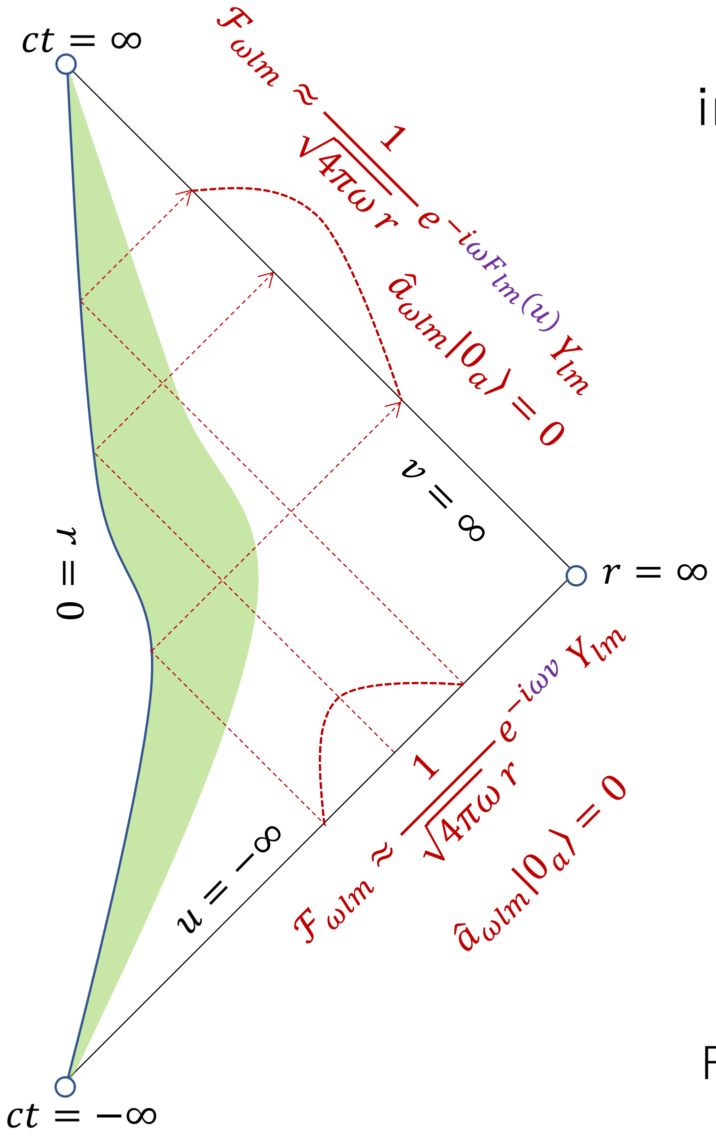
Fluid star, Boson star, Oscillaton, **Gravastar**, AdS bubble, Worm hole,
Fuzzvball, 2-2 hole, Collapsed polymer, Quantum bounce, black star,
Quantum star, Fire-wall, ⋯.

in Pani & Cardoso(2017)

Quantum radiation due to the gravitational collapse to form a BH mimicker

Precedent studies for BH mimicker other that Gravastar：

A. Paranjape & T. Padmanabhan (2009)
Harada, Cardoso, Miyata (2019), Kokubu, Harada (2019),
Okabayashi, Harada, KN (2022), Okabayashi (2022)



Free scalar field in asymptotically flat spherically symmetric spacetime

$$\hat{\phi} = \sum_{l,m} \int_0^\infty d\omega \left[\hat{a}_{\omega lm}\mathcal{F}_{\omega lm} + \hat{a}^\dagger_{\omega lm}\mathcal{F}^*_{\omega lm}\right]$$

$$\mathcal{F}_{\omega lm}(t,r,\theta,\varphi) \approx \frac{\hbar^{\frac{1}{2}} c}{\sqrt{4\pi\omega}\, r}\left(e^{i\omega\times\infty} + e^{-i\omega v}\right) Y_{lm} \qquad \text{for } u \to -\infty$$

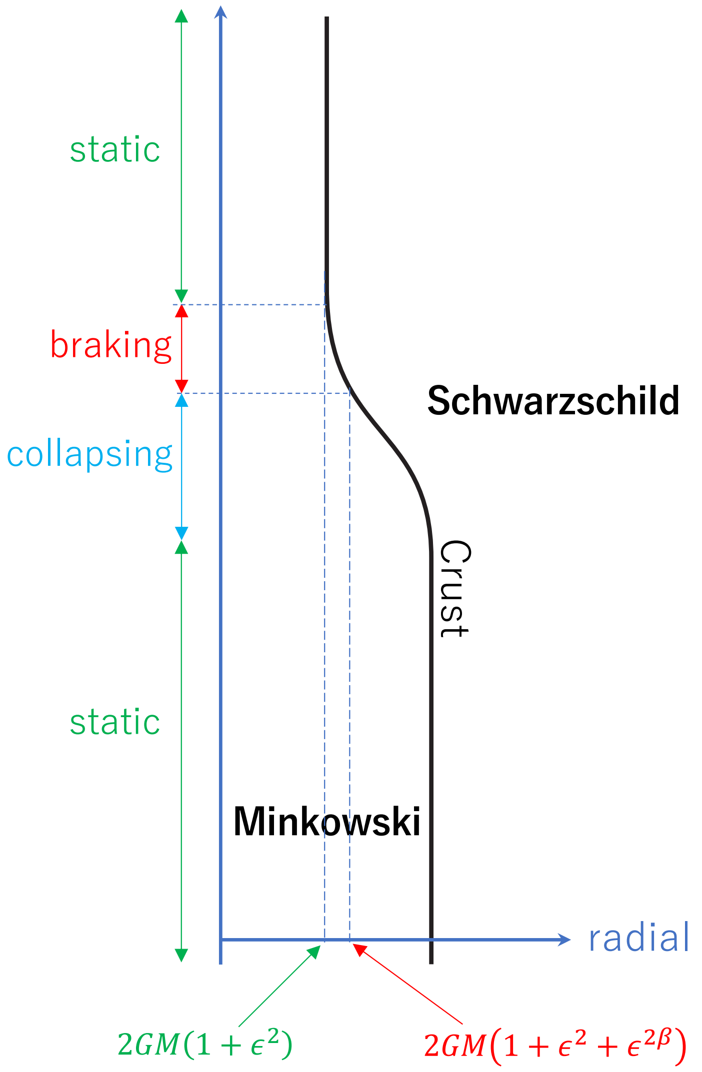
$$\approx \frac{\hbar^{\frac{1}{2}} c}{\sqrt{4\pi\omega}\, r}\left(e^{-i\omega F_{lm}(u)} + e^{-i\omega\times\infty}\right) Y_{lm} \qquad \text{for } v \to +\infty$$

In dynamical spacetime, mode function is distorted without change of state $\hat{a}_{\omega lm}|0_a\rangle = 0$

⟶ Quantum Radiation

Radiation power : $P \approx \frac{\hbar c^2}{48\pi}\left(\frac{d \ln F'}{du}\right)^2 = \frac{\hbar c^2}{48\pi}\left(\frac{d \ln(1+z)}{du}\right)^2$

Precedent studies: a star composed of crust only with hollow inside



A. Paranjape & T. Padmanabhan (2009)
T. Harada, V. Cardoso, D. Miyata (2019), T. Kokubu & T. Harada (2019)

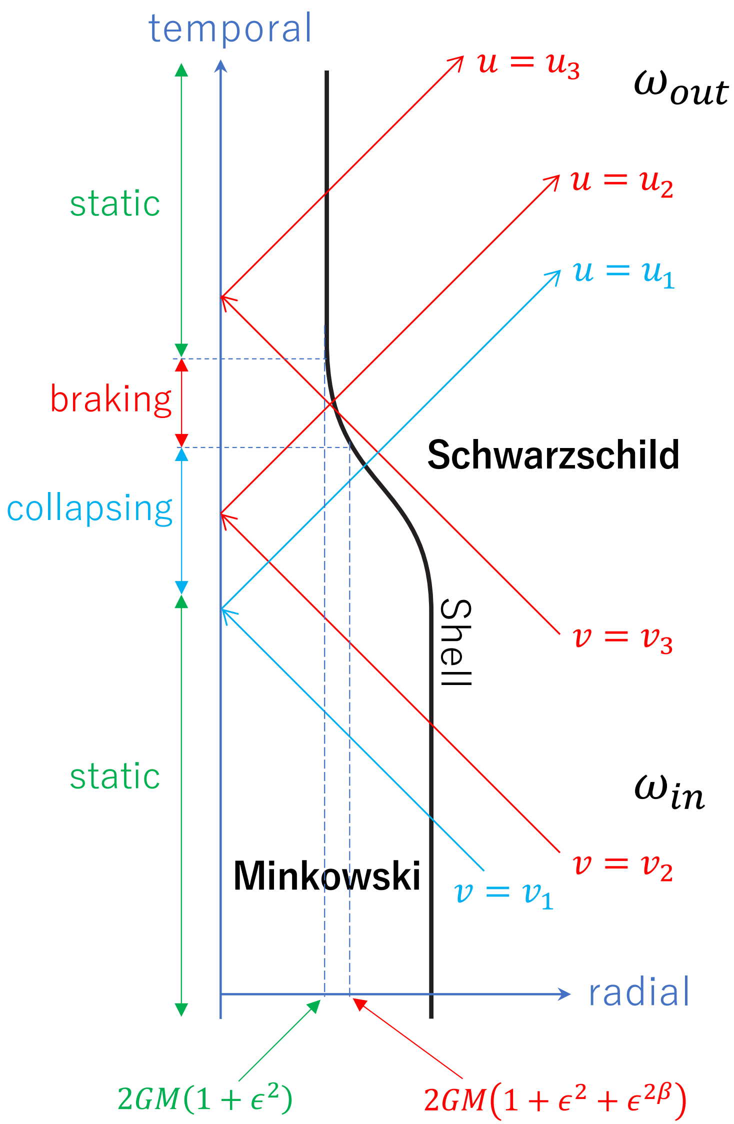
Inside= Minkowski geometry

$$ds^2 = -c^2dt^2 + dr^2 + r^2(d\theta^2 + sin^2\theta d\varphi^2)$$

Outside= Schwarzschild geometry

$$ds^2 = -c^2\left(1-\frac{2GM}{r}\right)dt^2 + \left(1-\frac{2GM}{r}\right)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\varphi^2)$$

Areal radius of crust : $r = R_s(\tau)$ ← given

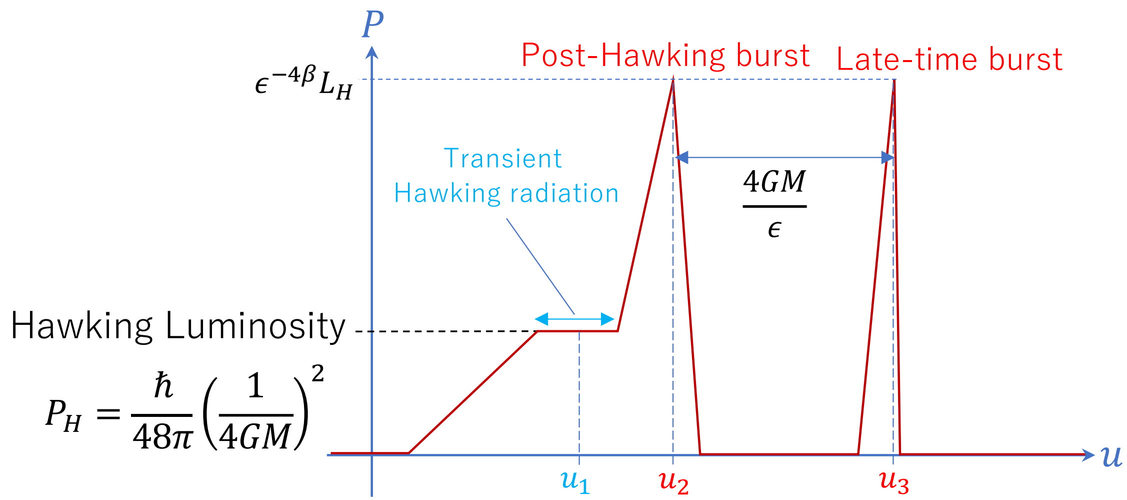


Radiation power $P = \frac{\hbar c^2}{48\pi}\left(\frac{d\ln(1+z)}{du}\right)^2$

$$1 + z = \frac{\omega_{in}}{\omega_{out}}$$

$P \approx constant$ ➡ Thermal Spectrum $\quad k_B T = \sqrt{\frac{12\hbar P}{\pi}}$

C. Barcelo, S. Liberati, S. Sonego, M. Visser (2011)



Schematic diagram of temporal variation of the radiation power

Just before the formation of a BH, vacuum phase transition occurs,
forming a GRAvitational VAcuum condensate STAR
(**GRAVASTAR**)

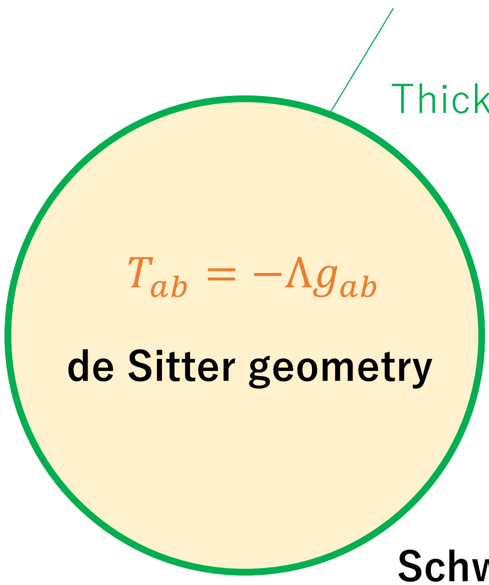
P.O. Mazur and E. Mottola (2004)

Mazur-Mottola model

Crust is composed of stiff matter

$P = \sigma$

Thickness $\approx \ell_{pl} \equiv G^{-\frac{1}{2}}$



Radius

$R \approx 2GM \approx \sqrt{\frac{3}{\Lambda}}$

Schwarzschild

A candidate of a black hole mimicker

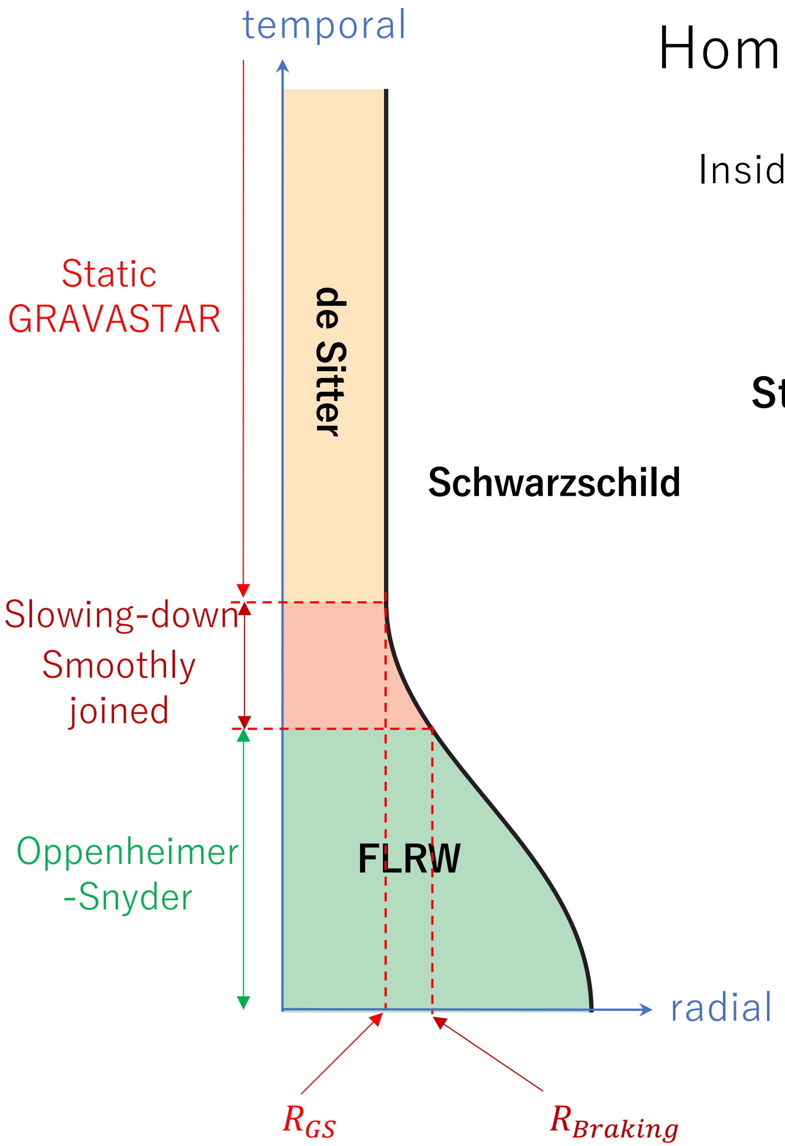
Just before the BH formation, a gravastar may form by the gravitational vacuum condensate.

Input parameters in the present model

- Vacuum energy Λ
- Radius of gravastar

Artificial motion of crust is assumed.

Homogeneous dust sphere → GRAVASTAR



Inside = Friedmann-Lemaitre-Robertson-Walker (FLRW) geometry

$$ds^2 = a^2(\eta)[-d\eta^2 + d\chi^2 + sin^2\chi(d\theta^2 + sin^2\theta d\varphi^2)]$$

Static GRAVASTAR Phase

Areal radius : $R_{GS} \approx 2GM\left[1 + \left(\epsilon^2 + \alpha\epsilon^{2\beta}\right)cot\chi_i\right]$ ← constant

$$0 < \alpha < 1, \quad 0 < \beta < 1$$

Comoving radius : $\chi_s = sin^{-1}\frac{R_{GS}}{a(\eta)}$ $(\leftrightarrow\ a(\eta)sin\chi_s = R_{GS})$ ← dynamical

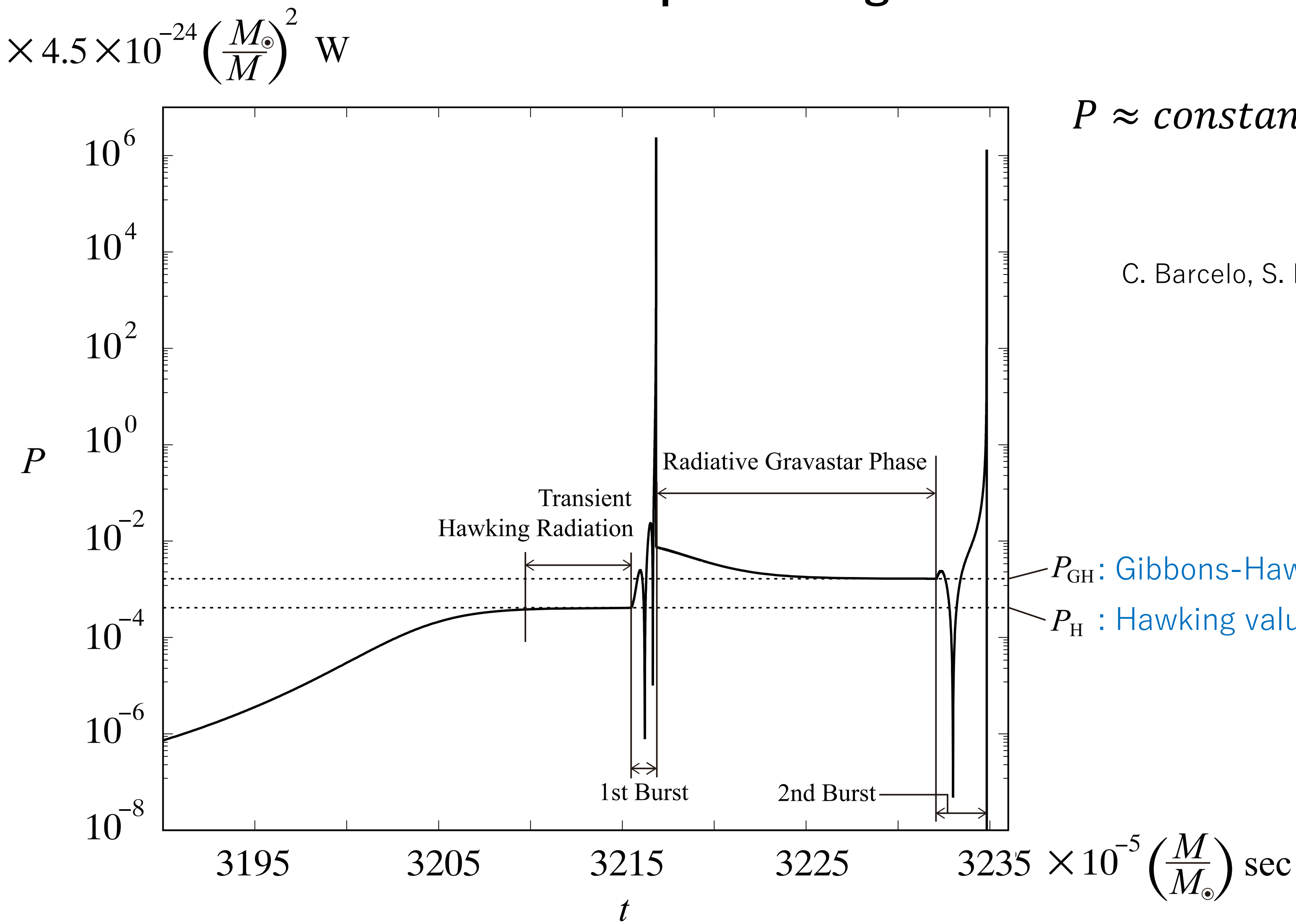
Scale factor : $a(\eta) = \frac{1}{Hsin(\eta - \eta_c)}$ ← de Sitter geometry

$$(0 < \eta - \eta_c < \pi)$$

How to determine $H \equiv \sqrt{\frac{\Lambda}{3}}$

$$1 - H^2 R_{GS}^2 = 1 - \frac{2GM}{R_{GS}}$$

Radiation power in gravastar formation



P_{GH} : Gibbons-Hawking value

P_H : Hawking value

$P \approx constant$ → Thermal Spectrum

C. Barcelo, S. Liberati, S. Sonego, M. Visser (2011)

$$T_H = \frac{1}{8\pi GM}$$

$$T_{GH} = \frac{H}{2\pi}$$

KN, Okabayashi, Harada
arXiv:2203.14519

Summary and Discussion

Constant radiation power $\left|(\sqrt{P})'\right| \ll P$ → Thermal spectrum

C. Barcelo, S. Liberati, S. Sonego, M. Visser (2011)

Even without the formation of event horizon, thermal radiation is produced.

Transient Hawking radiation in collapsing phase $k_B T = k_B T_H := \dfrac{\hbar c^3}{8\pi G M}$

Paranjape & Padmanabhan (2009)

Radiative GRAVASTAR in early phase KN, Okabayashi, Harada (arXiv: 2203.14519)

Gibbons-Hawking temperature of the de Sitter core $k_B T = k_B T_{GW} := \dfrac{\hbar H}{2\pi} \approx \dfrac{\hbar c^3}{4\pi G M} = 2 k_B T_H$

Duration: $\Delta t \approx \dfrac{GM}{2c^3} ln \left| \dfrac{2GM}{R_{GS} - 2GM} \right|$

The physical reason is still unclear….