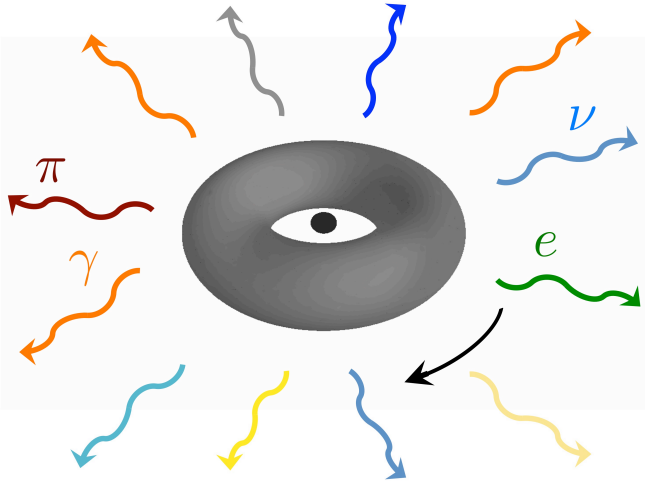
Dark micro-boson stars from PBH superradiance



João G. Rosa
University of Coimbra, Portugal

arXiv:2205.15277 (w/ John March-Russell) + work in progress (w/ Daniel Neves)

New Horizons in Primordial Black Holes – NEHOP 2025
Brussels, Belgium 21 May 2025

Main idea

Light PBHs as (feebly interacting) dark matter progenitors:

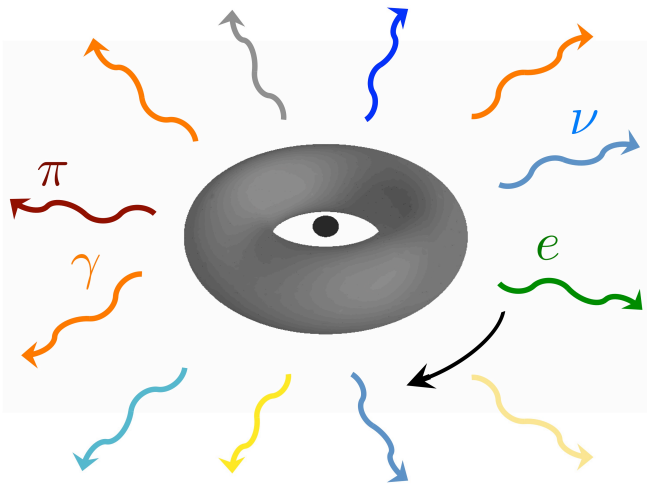
1. Hawking emission

[Khlopov, Barrau & Grain (2006); Fujita et al (2014); Allahverdi, Dent & Osinski (2018); Lennon, March-Russell, Petrossian-Byrne & Tillim (2018); Hooper, Krnjaic & McDermott (2019); Hooper et al (2020); …]

2. Superradiance (bosonic DM, spinning PBHs)

[see also Bernal, Perez-Gonzalez & Xu (2022)]

Possible end state with self-gravitating microscopic dark matter "stars"



Black Hole Superradiance

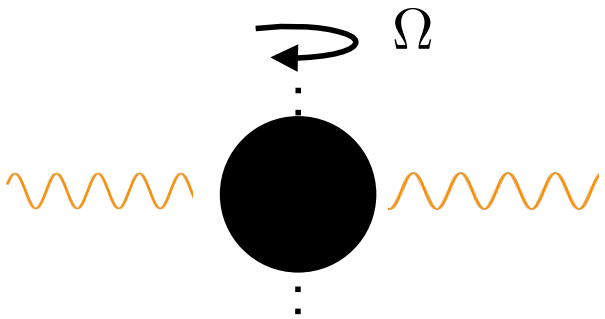
[see review by Brito, Cardoso & Pani (2015)]

Rotating absorber amplifies low frequency waves:

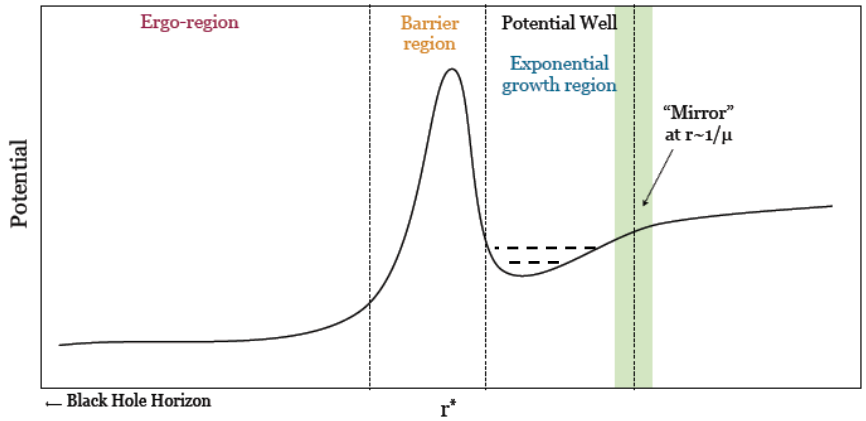
$$\ddot{\Phi} - \nabla^2\Phi + \gamma\dot{\Phi} = 0 \qquad\qquad \Phi \sim e^{-i\omega t + im\phi}$$

Rotating frame: $\phi' = \phi + \Omega t$ ➡ $\gamma\dot{\Phi} \sim -i\gamma(\omega - m\Omega)\Phi$

BH's gravitational potential confines massive bosonic fields ➡ Superradiant Instability!



$\omega < m\Omega$



[Arvanitaki *et al.* (2009)]

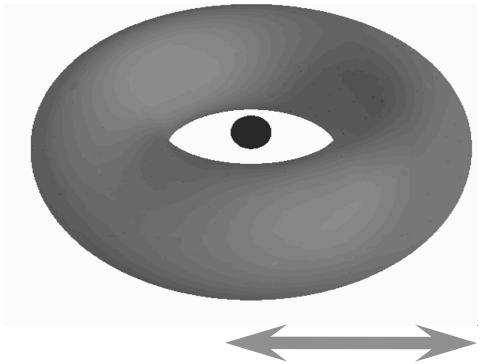
Black Hole Superradiance

[see review by Brito, Cardoso & Pani (2015)]

Hydrogen-like superradiant clouds: $\Phi \sim e^{-i\omega_R t + \omega_I t}$

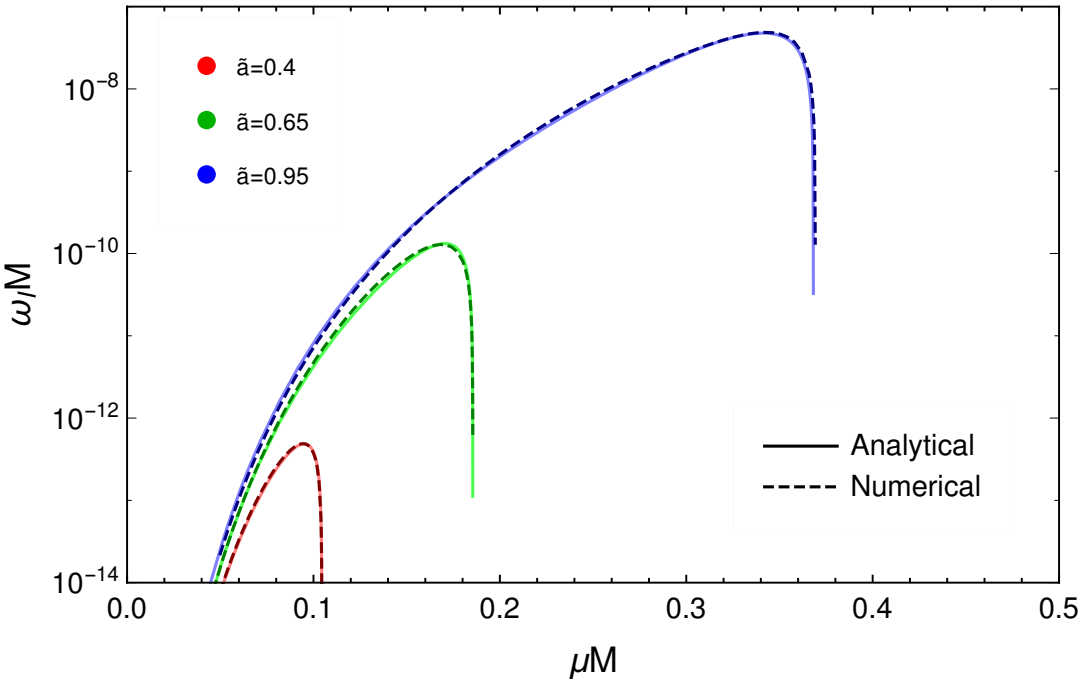
$$\omega_R \simeq \mu - \frac{\alpha^2}{2n^2}\mu \qquad \omega_I \simeq -C_{nl}(\omega_R - m\Omega)(1-\tilde{a}^2)^{l+\frac{1}{2}}\alpha^{4l+5}$$

where $\alpha = \dfrac{\mu M}{M_P^2} \ll 1.$



$$5r_B = \frac{5}{\alpha\mu}$$

$$n = 2, l = m = 1$$



[Ferraz, Kephart & JGR (2022)]

Black Hole Superradiance

[see review by Brito, Cardoso & Pani (2015)]

Superradiant instabilities occur for any low-mass bosonic field, including massive scalars and massive vectors:

[JGR & Dolan (2011); Pani *et al.* (2012); East & Pretorius (2017); Cardoso *et al.* (2018); Frolov *et al.* (2018); Dolan (2018)]

$$\Gamma_s = 2\omega_I \simeq \begin{cases} \frac{1}{24}(\tilde{a} - 4\alpha)\alpha^8\mu \ , & s = 0 \\ 4(\tilde{a} - 4\alpha)\alpha^6\mu \ , & s = 1 \end{cases}$$

Note: spherical topological for spin-1 superradiant clouds

Light slowly-rotating PBHs can produce heavy bosonic dark matter (at the expense of the PBH mass and spin)

$$\alpha = \frac{\mu M}{M_P^2} \simeq 0.004 \left(\frac{\mu}{1 \ \text{TeV}}\right) \left(\frac{M}{10^6 \ \text{kg}}\right)$$

Hawking emission

Hawking effect [Hawking (1974-75)]:

Black holes emit a nearly-thermal spectrum of particles for $T_H \gtrsim \mu$

$$T_H \simeq \frac{M_P^2}{8\pi M} \simeq 10 \left(\frac{10^6 \text{ kg}}{M}\right) \text{ TeV}$$

Black hole loses both mass and angular momentum:

$$\frac{dM}{dt} = -e_T \frac{M_P^4}{M^2}, \qquad \frac{dJ}{dt} = -e_J J \frac{M_P^4}{M^3}$$

$$\begin{pmatrix} e_T \\ e_J \end{pmatrix} = \sum_{i,l,m} \frac{1}{2\pi} \int_0^\infty dx \frac{\Gamma_{i,l,m}}{e^{2\pi(\omega - m\Omega)/\kappa} \pm 1} \begin{pmatrix} x \\ m\tilde{a}^{-1} \end{pmatrix} \qquad x = \frac{\omega M}{M_P^2}$$

Evaporation time: $$t_{ev} = \frac{M^3}{3 e_T M_P^4} \simeq 0.7 \left(\frac{M}{10^6 \text{ kg}}\right)^3 \text{ s}$$

Dark matter production by PBHs

Both PBH superradiance and Hawking emission can produce a large number of DM particles:

$$N_{SR} \simeq 2.1 \times 10^{27} \tilde{a}_0 \left(\frac{\Delta J}{J_0} \right) \left(\frac{M_0}{10^6 \mathrm{kg}} \right)^2 .$$

$$N_{HE} \simeq \begin{cases} 3.2 \times 10^{26} \left(\frac{M_0}{10^6 \mathrm{kg}} \right)^2 , & s = 0 \\ 5.3 \times 10^{25} \left(\frac{M_0}{10^6 \mathrm{kg}} \right)^2 , & s = 1 \end{cases}$$

Tune PBH abundance to match present DM yield
(PBH never dominate before evaporating away)

Dark matter production by PBHs

Superradiance vs Hawking emission:

$$\frac{Y_{SR}}{Y_{HE}} = \epsilon_{SR}\frac{N_{SR}}{N_{HE}} \simeq \epsilon_{SR}\frac{\Delta J}{J_0} \times \begin{cases} \frac{\tilde{a}_0}{0.15}\ , & s=0 \\ \frac{\tilde{a}_0}{0.025}\ , & s=1 \end{cases}$$

superradiance efficiency

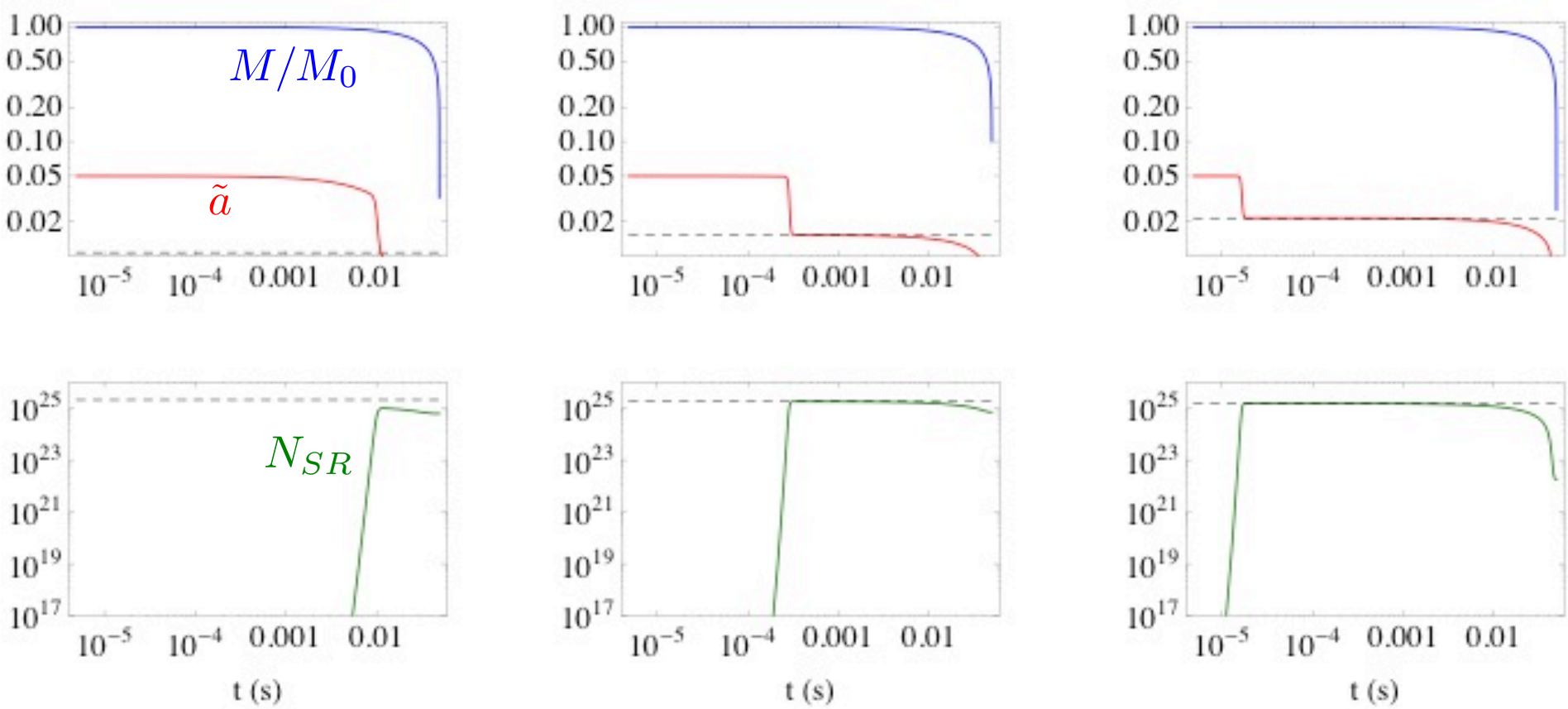
Hawking emission spins down a PBH, making superradiance less efficient:

$$\frac{dM}{dt} = -e_T\frac{M_P^4}{M^2} - \mu\Gamma_s N, \qquad \frac{dJ}{dt} = -e_J\frac{JM_P^4}{M^3} - \Gamma_s N\ , \qquad \frac{dN}{dt} = \Gamma_s N$$

$$e_T(\tilde{a}) \simeq \frac{0.0044}{1-\tilde{a}^2}(1+0.5\tilde{a}) \qquad e_J(\tilde{a}) \simeq 7.7 \times \frac{0.0044}{\sqrt{1-\tilde{a}^2}}$$

Dark matter production by PBHs

$$M_0 = 5 \times 10^5 \text{ kg} , \qquad \tilde{a}_0 = 0.05$$



$\mu = 1.4$ TeV $\qquad$ $\mu = 2.0$ TeV $\qquad$ $\mu = 2.8$ TeV

Efficiency of PBH superradiance

Full growth of superradiant cloud:

$$\Gamma_s t_{ev} \gtrsim (e_J/e_T - 2) \ln N_{SR} \sim \text{few} \times 100$$

Superradiant cloud reabsorption in quasi-stationary regime:

$$\frac{d\tilde{a}}{dt} = \tilde{a}(2e_T - e_J)\frac{M_P^4}{M^3} - \Gamma_s N(1 - 2\alpha\tilde{a})\frac{M_P^2}{M^2} \simeq 0$$

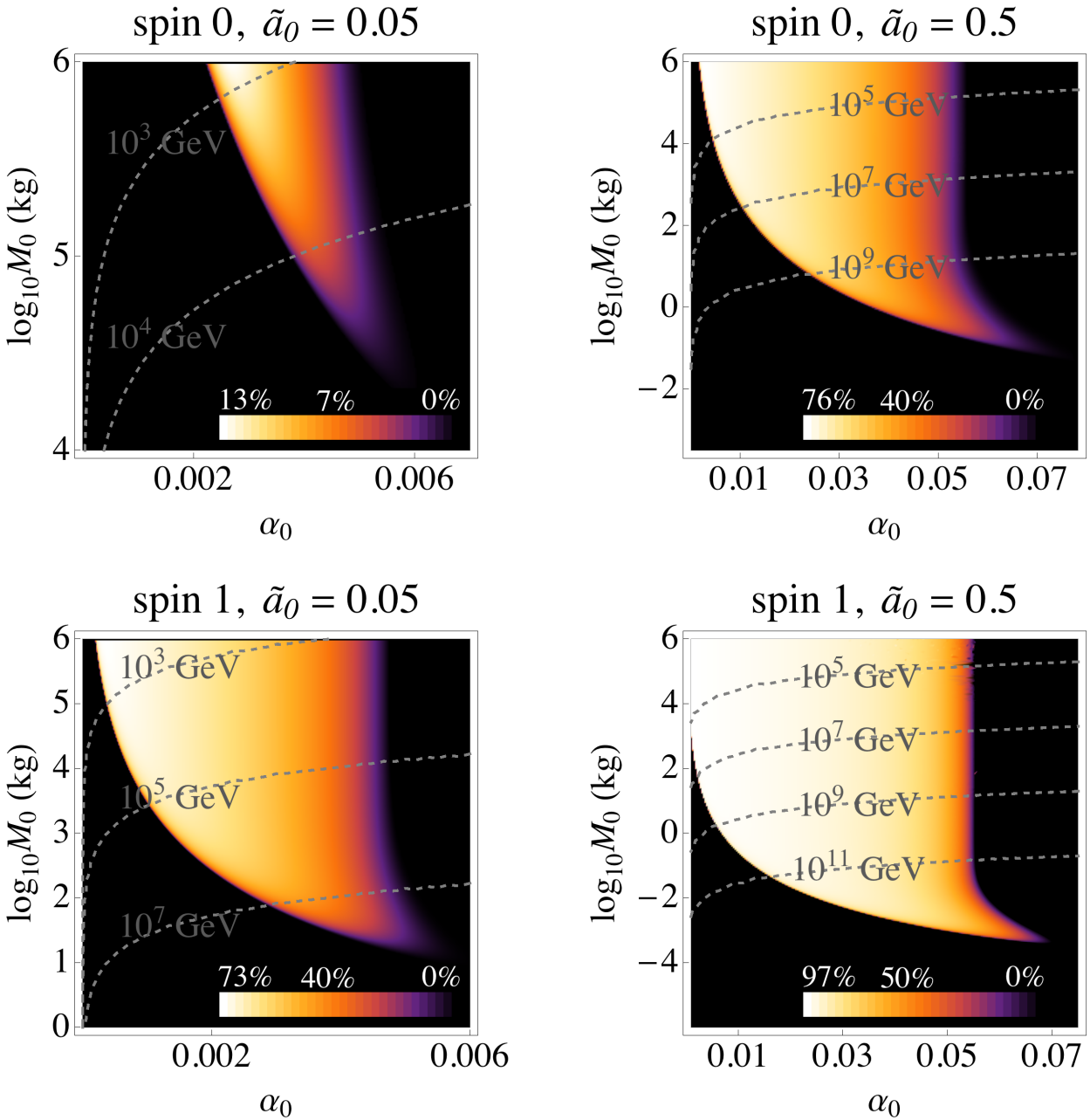
<0 (non-superradiant)

Negligible reabsorption:

$$|\Gamma_s| t_{ev} \simeq \frac{4(e_J/e_T - 2)\alpha}{3(\tilde{a} - 4\alpha)} \lesssim 1$$

Note: reabsorption effectively stops since $\Gamma_{s=0} \propto \alpha^9$, $\Gamma_{s=1} \propto \alpha^7$

Efficiency of PBH superradiance



What happens to the superradiant DM clouds?

PBHs evaporate adiabatically in an initial stage and SR clouds simply expand:

$$R_c \simeq \frac{5}{\alpha\mu}\ , \qquad \omega_B \simeq \frac{\alpha^2\mu}{4}$$

$$\xi = \frac{\dot{\omega}_B}{\omega_B^2} = \frac{16 e_T}{\alpha^3}\frac{M_P^2}{M^2} \lesssim 1$$

Evaporation becomes non-adiabatic when ξ~1 ("quantum quench"):

$$\frac{M_*}{M_c} \simeq \frac{0.44}{\epsilon_{SR}}\left(\frac{\Delta J}{J_0}\right)^{-1}\left(\frac{0.05}{\tilde{a}_0}\right)\left(\frac{0.003}{\alpha}\right)^{8/5}\left(\frac{10^6\ \mathrm{kg}}{M_0}\right)^{2/5}$$

Can DM clouds survive as self-gravitating boson stars?

From BH clouds to boson stars

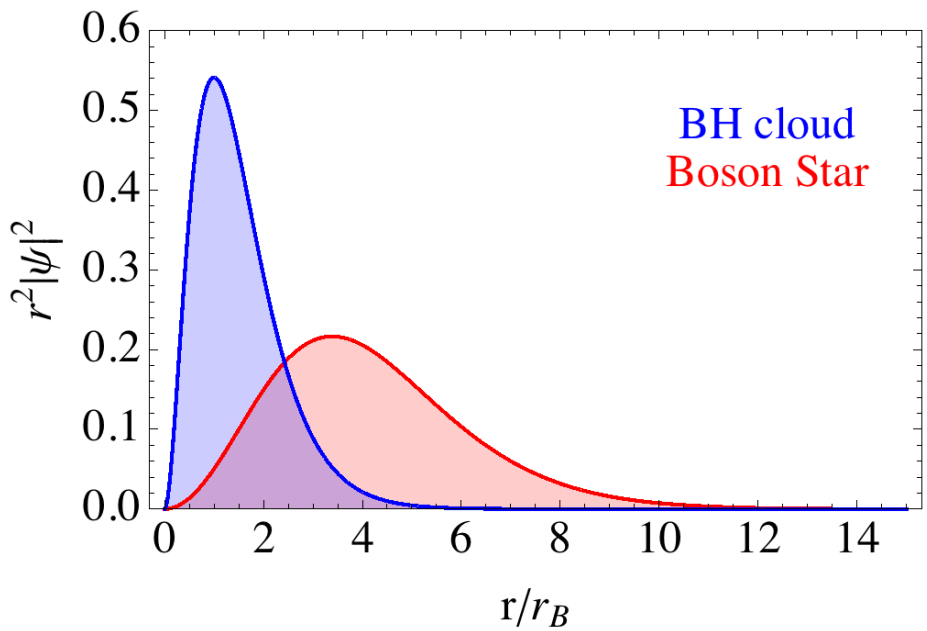
For $\alpha \ll 1$ we have a non-relativistic Schrodinger-Poisson problem:

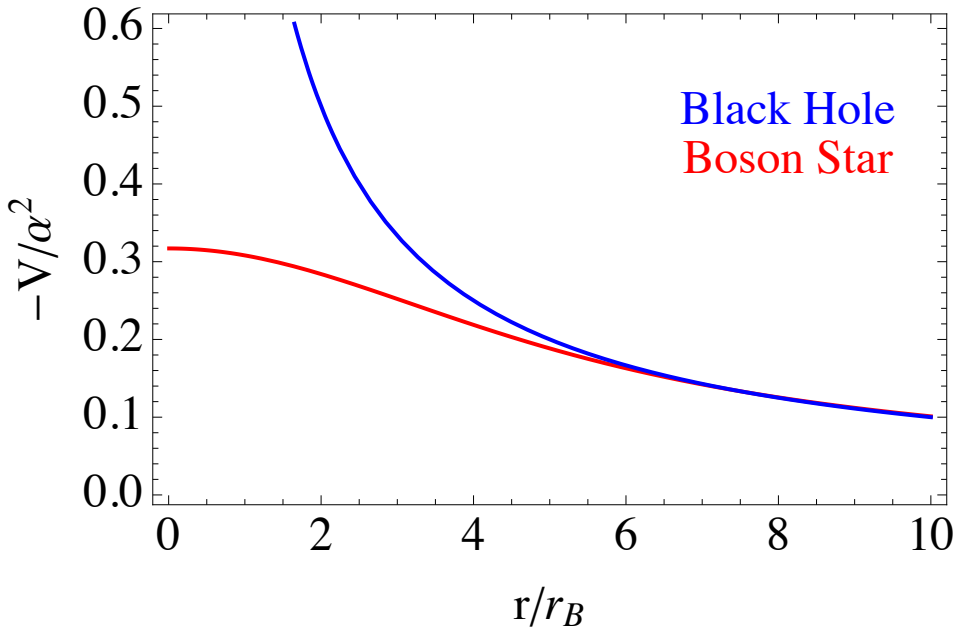
$$i\partial_t \psi = -\frac{1}{2\mu}\nabla^2\psi + \left(-\frac{\alpha(t)}{r} + \mu V\right)\psi \,,$$

$$\alpha(t) = \alpha_0 \left(1 - \frac{t}{t_{ev}}\right)^{1/3}$$

$$\nabla^2 V = 4\pi G\mu|\psi|^2$$

$$M_c = \mu \int d^3x |\psi|^2$$





[Ruffini & Bonazzola (1969)]

From BH clouds to boson stars

Approximating the self-gravitating potential as *1/r:*

- adiabatic evaporation: $\langle K \rangle = -\langle V_c + V_{BH} \rangle / 2$

- at non-adiabatic point (ξ=*1*):

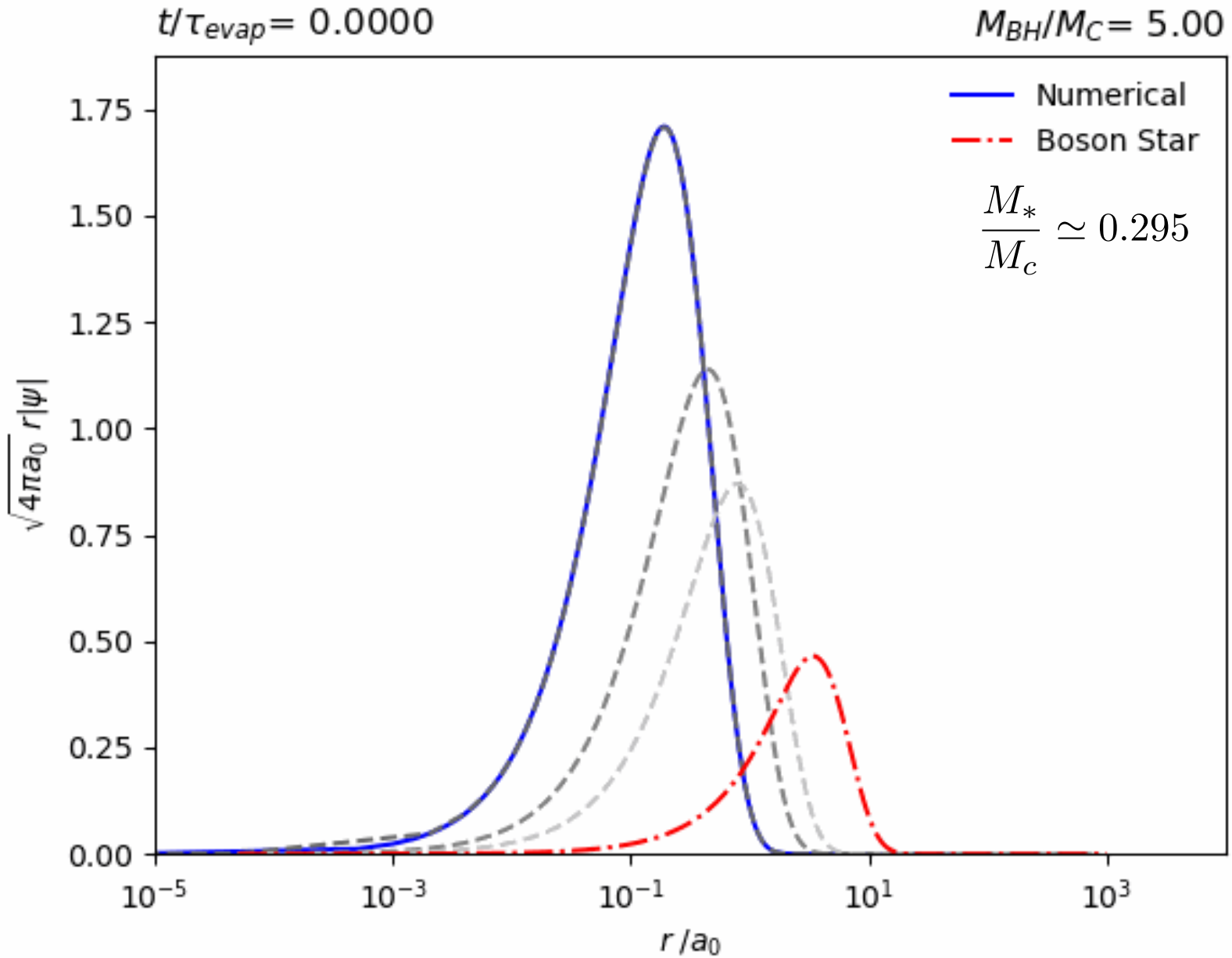
$$\langle E \rangle = \langle K \rangle + \langle V_c \rangle = (\langle V_c \rangle - \langle V_{BH} \rangle)/2 \quad \Rightarrow \quad M_* \lesssim M_c$$

Numerical simulations of Schrodinger-Poisson system (w/ evaporating BH) :

- spherical symmetry
- initial conditions:
  - stationary bound state (including self-gravity)
  - adiabatic regime
- modified Crank-Nicolson scheme
  (conserves norm & energy)

Daniel Neves

Numerical example



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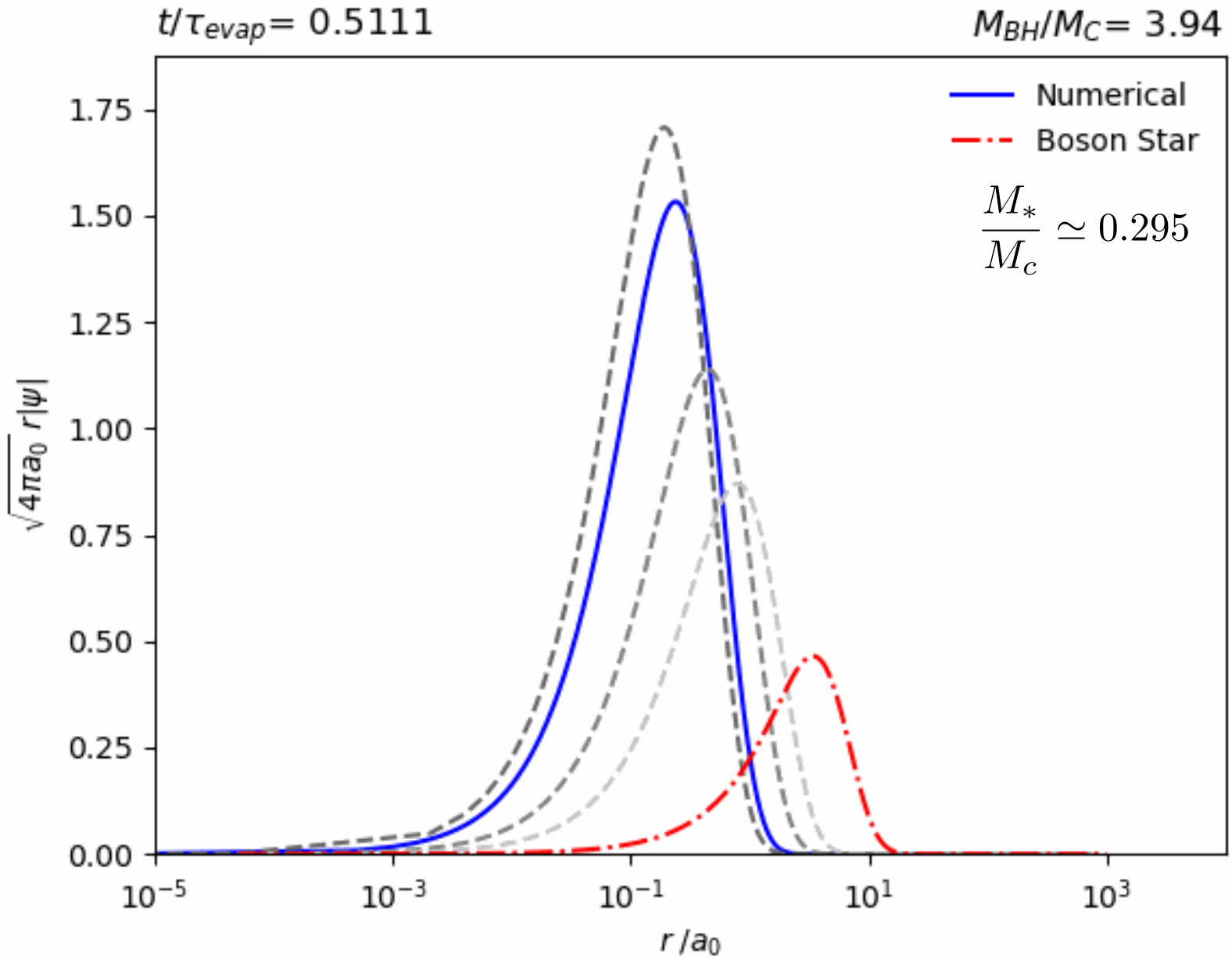

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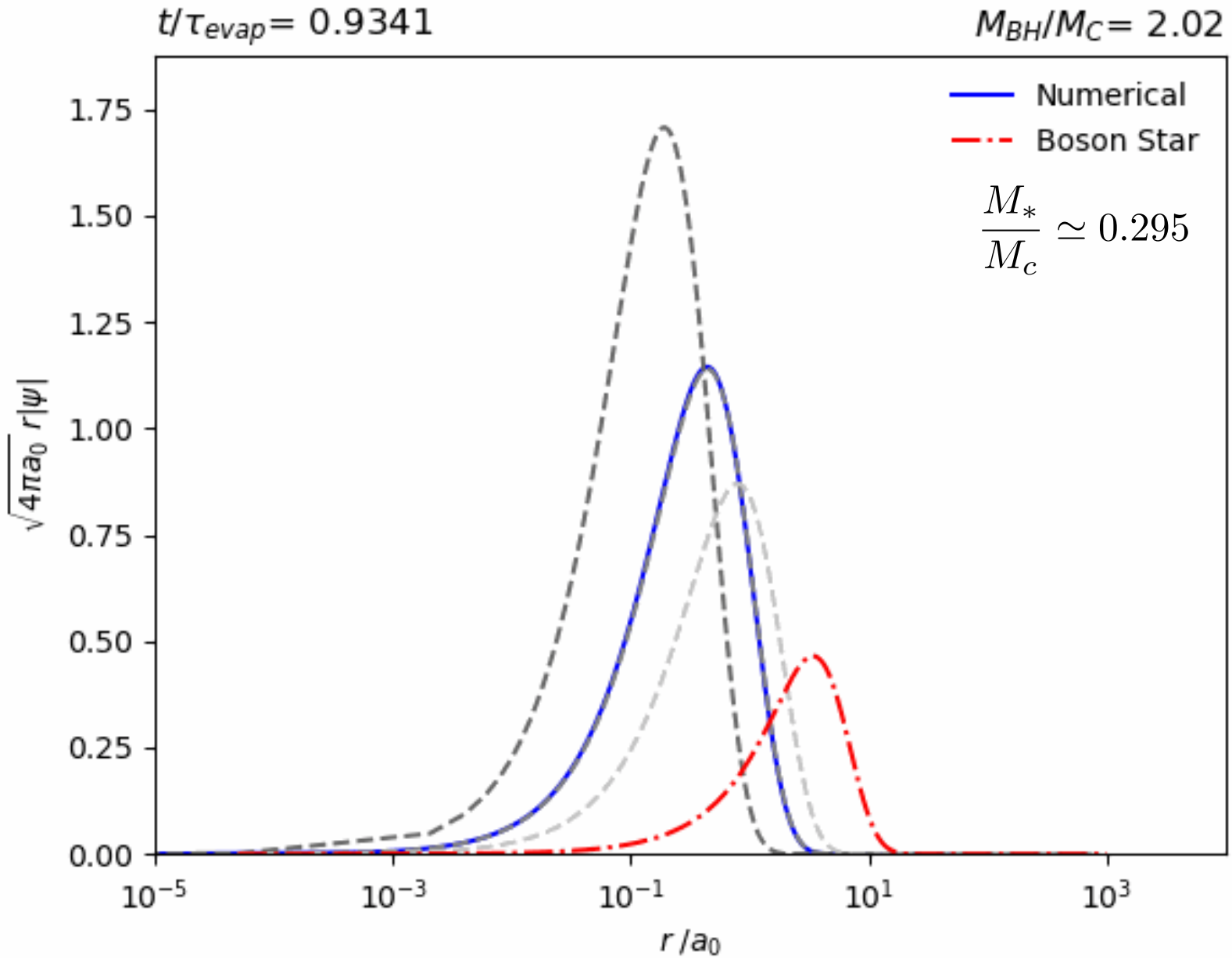

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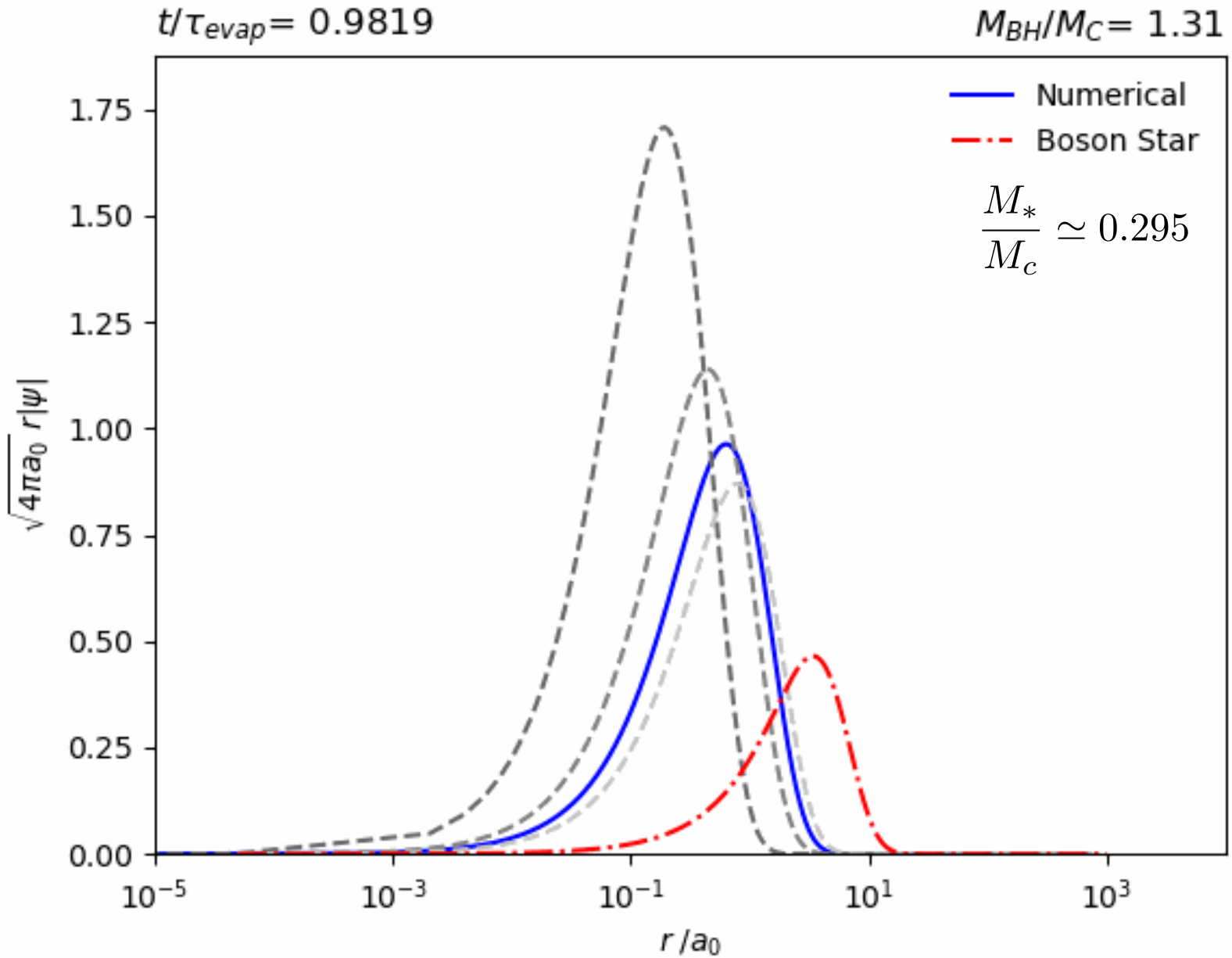

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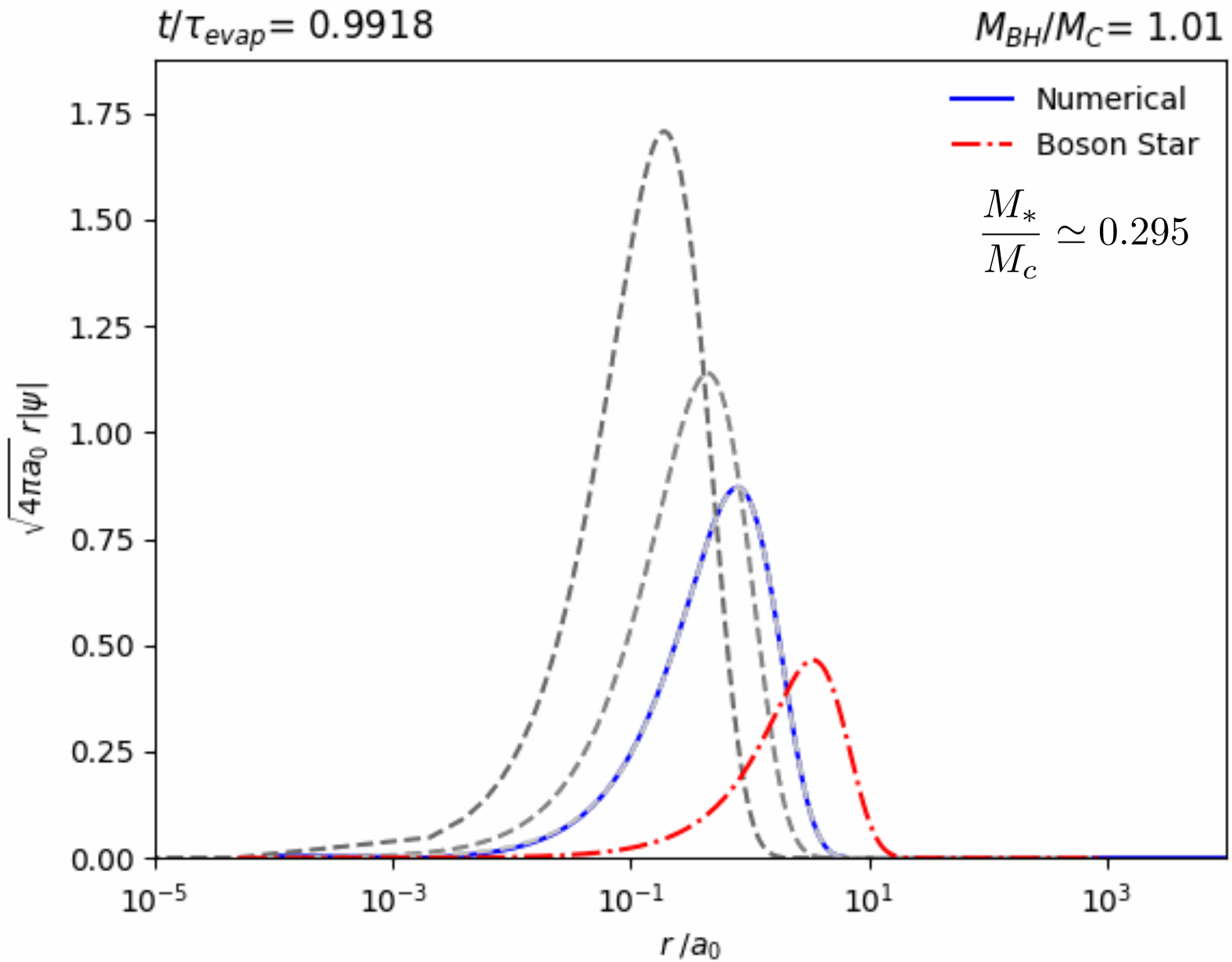

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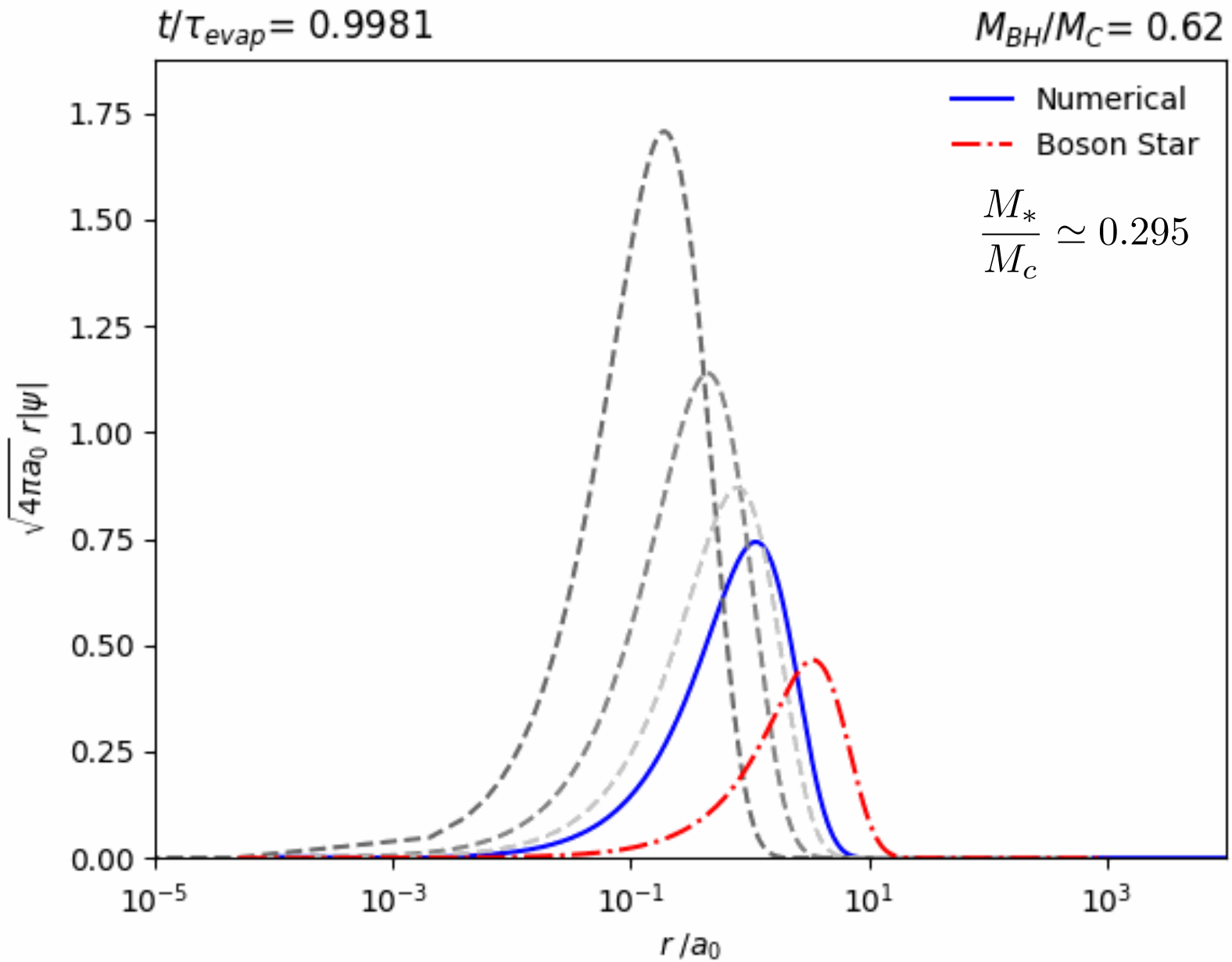

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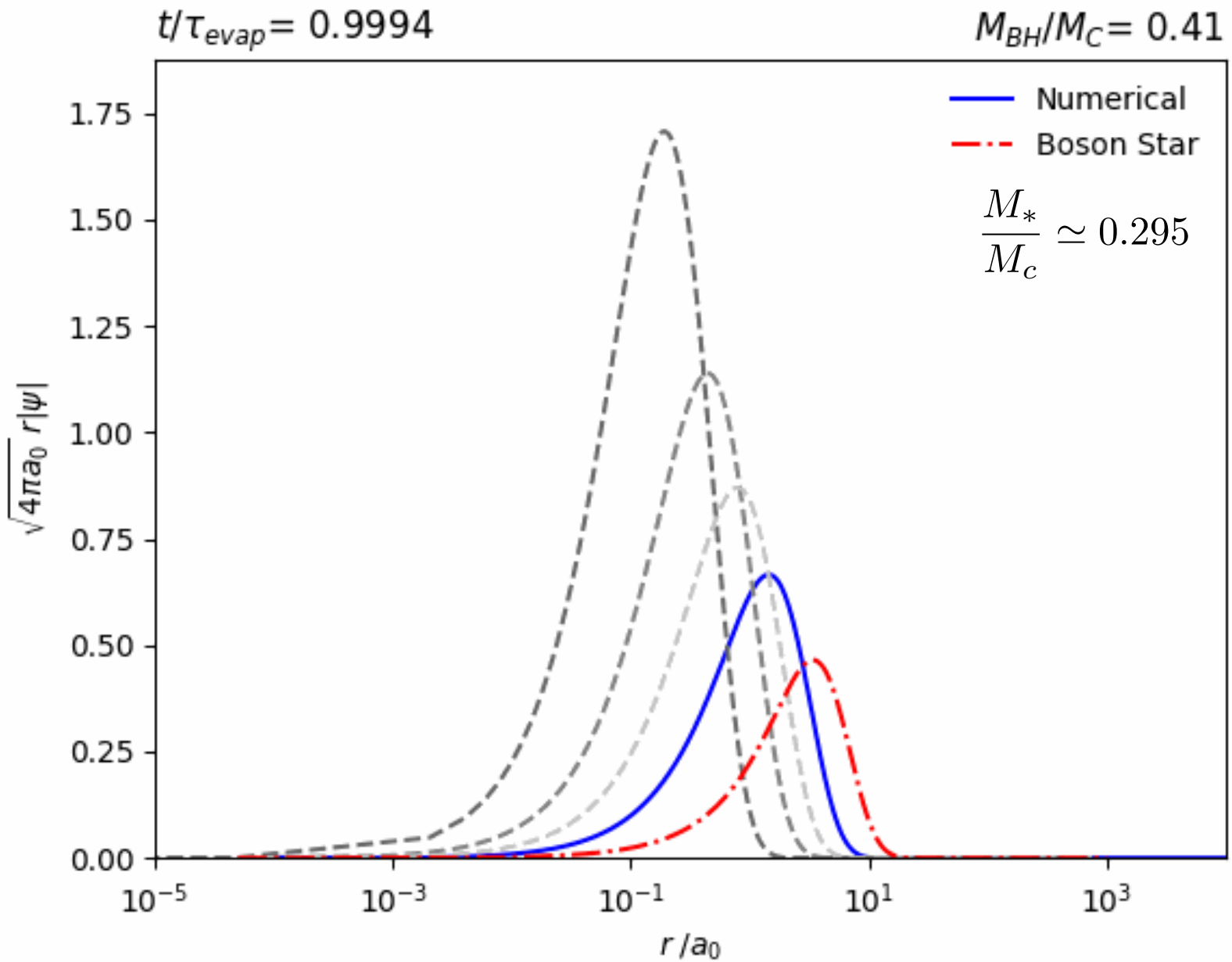

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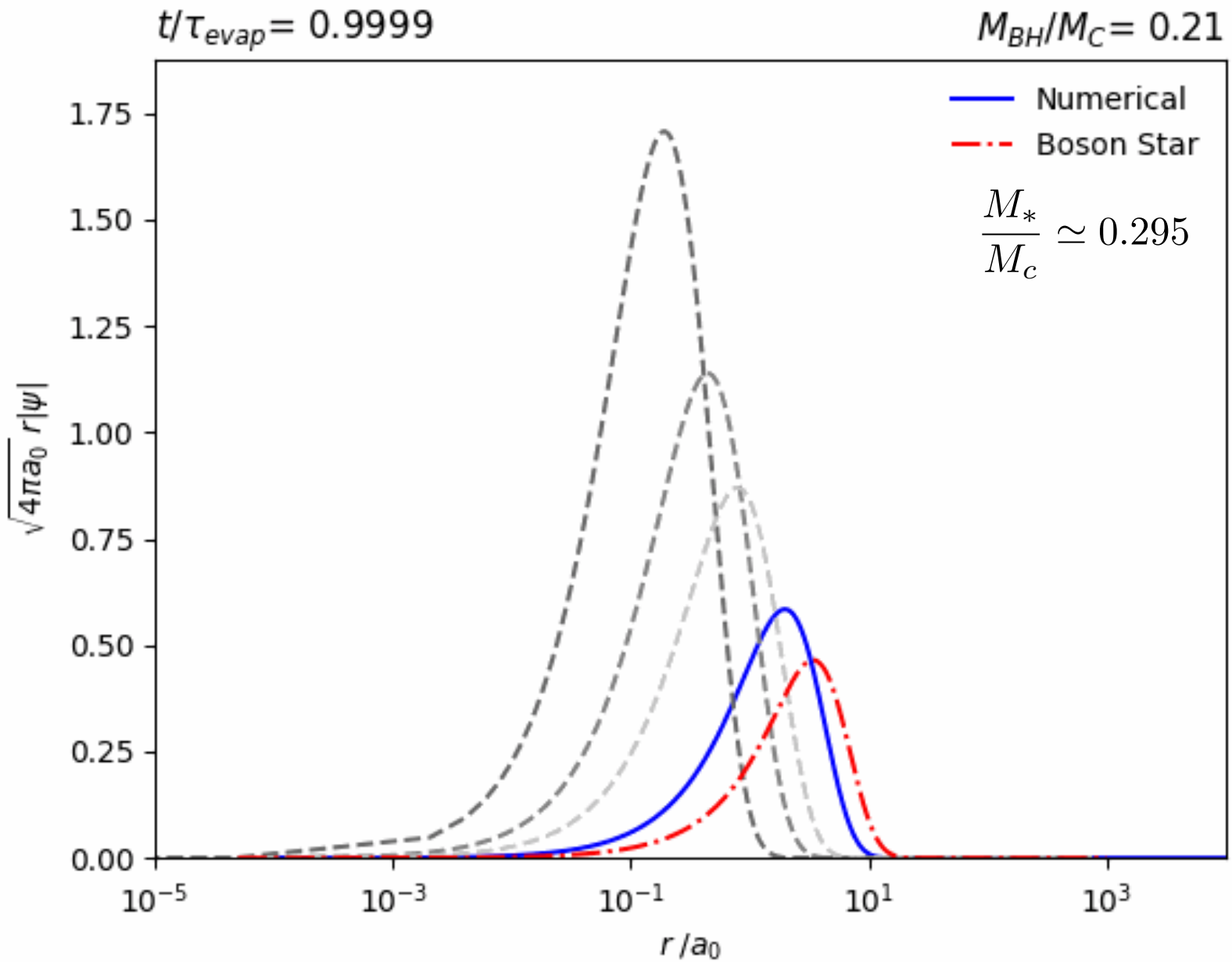

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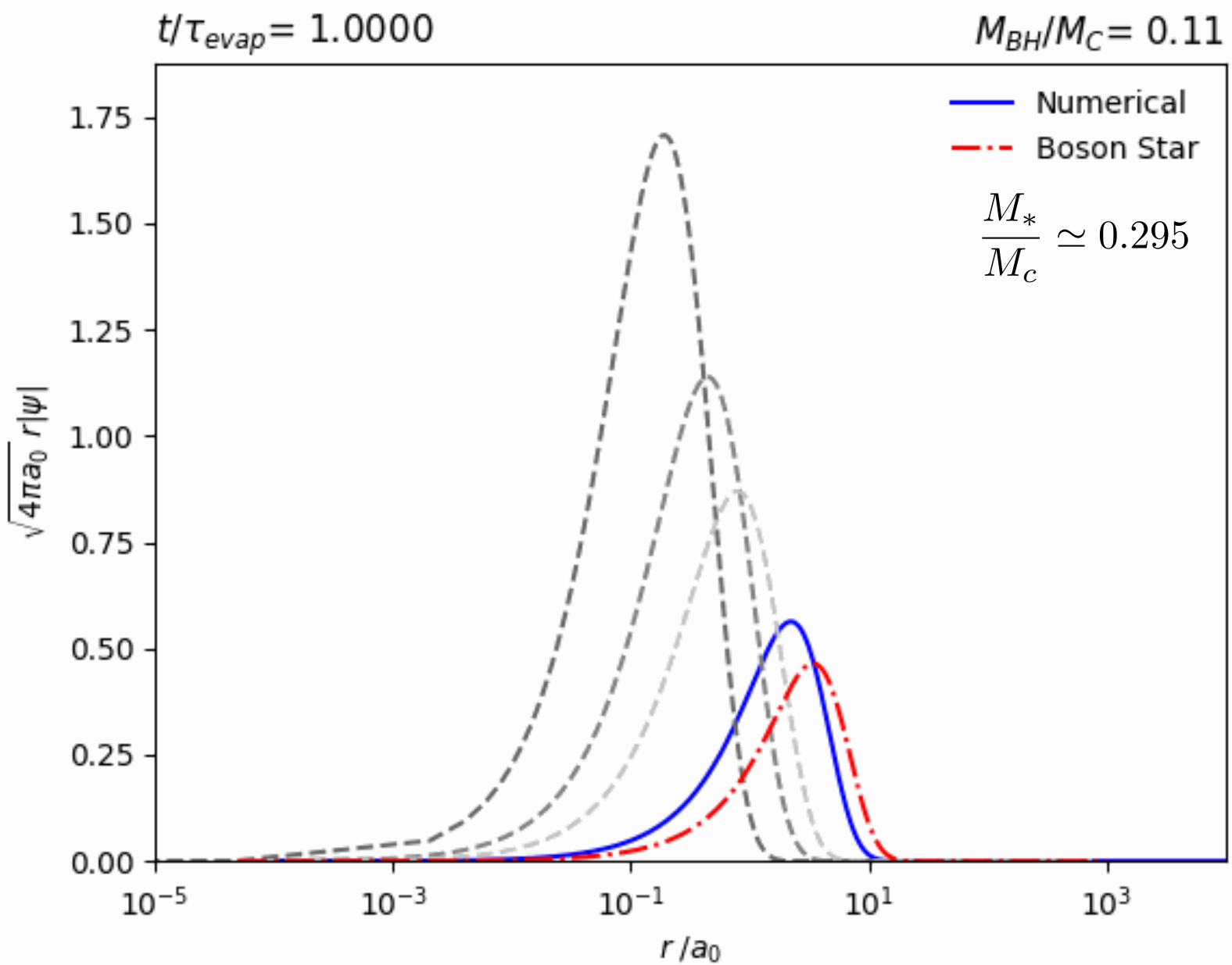

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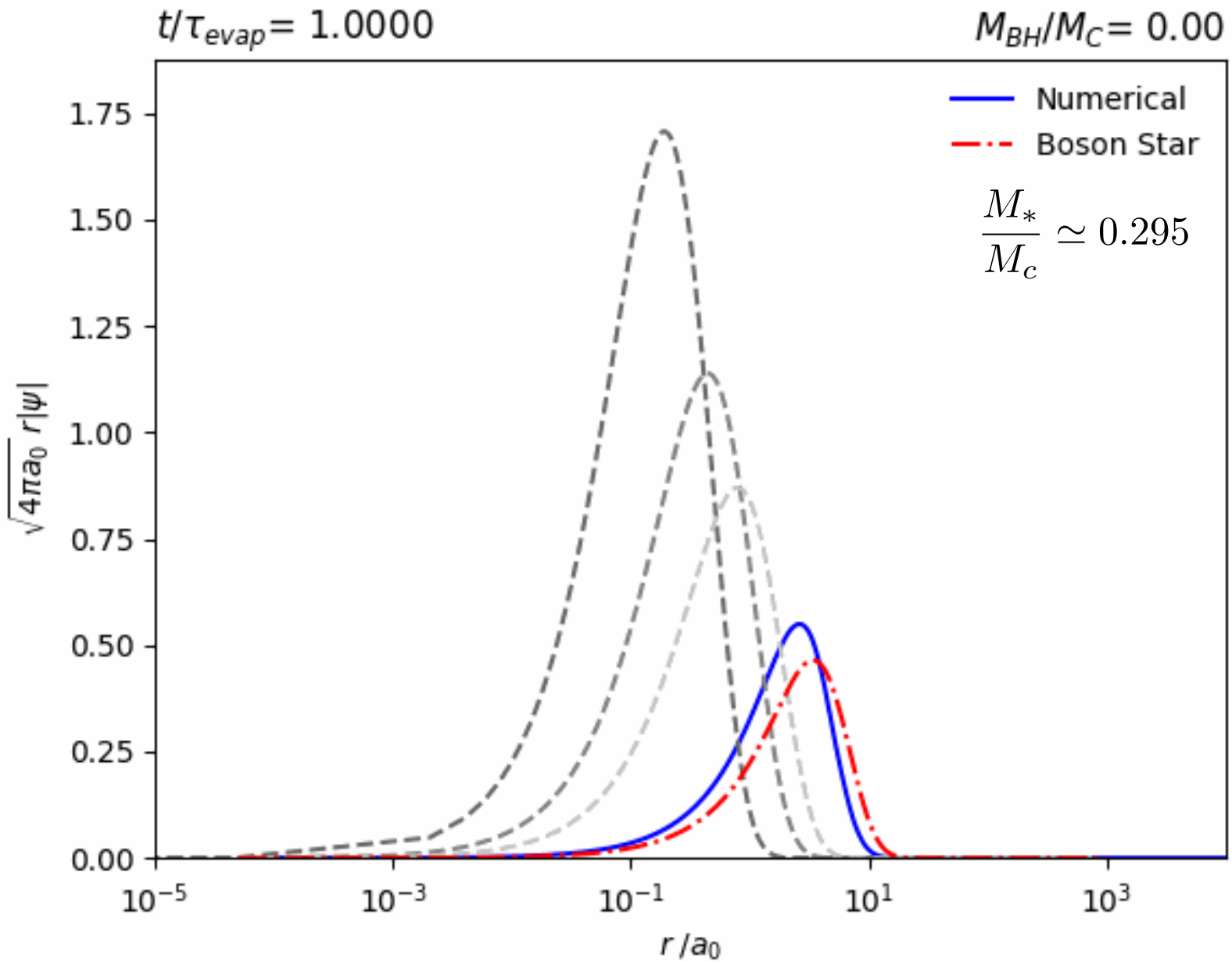

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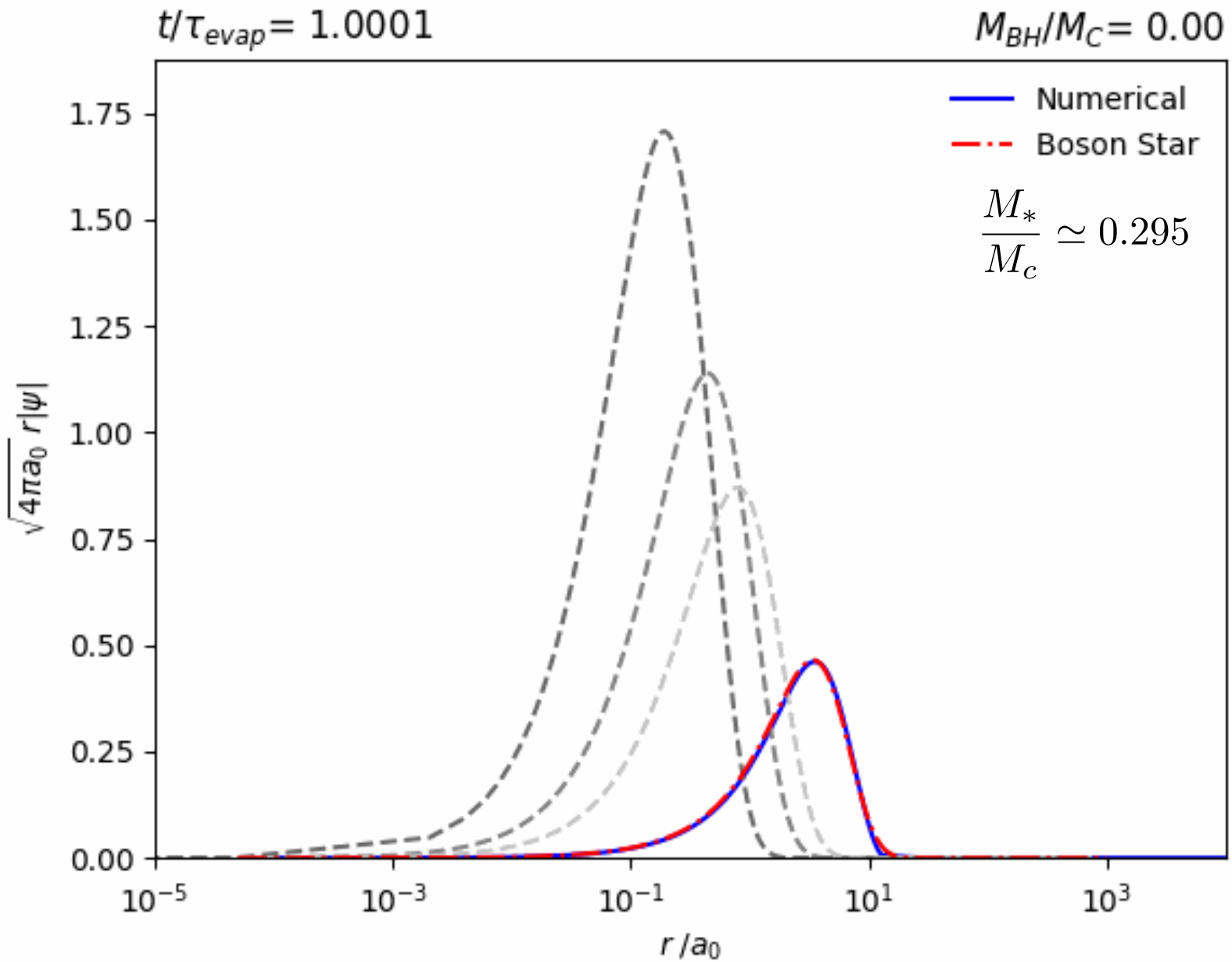

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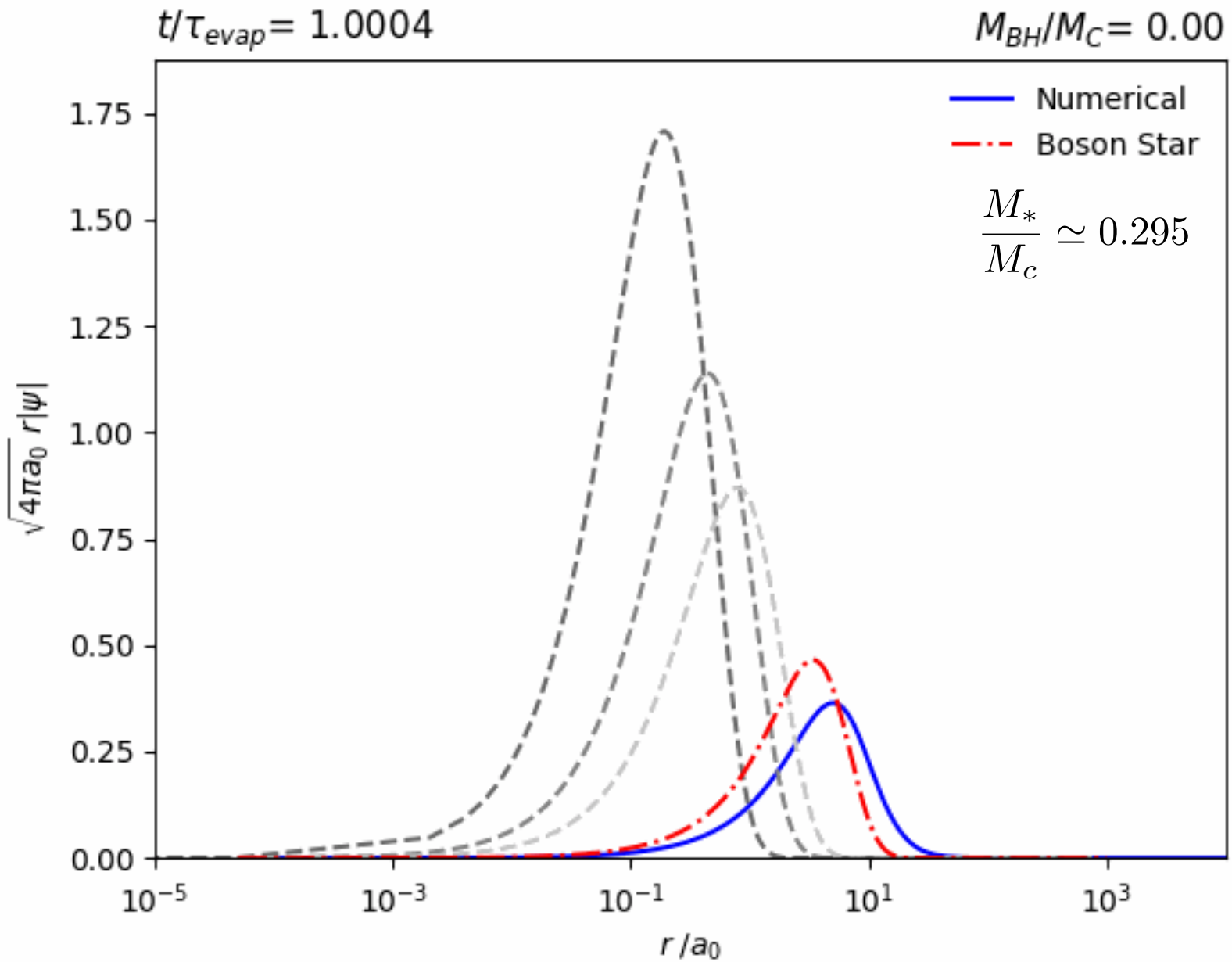

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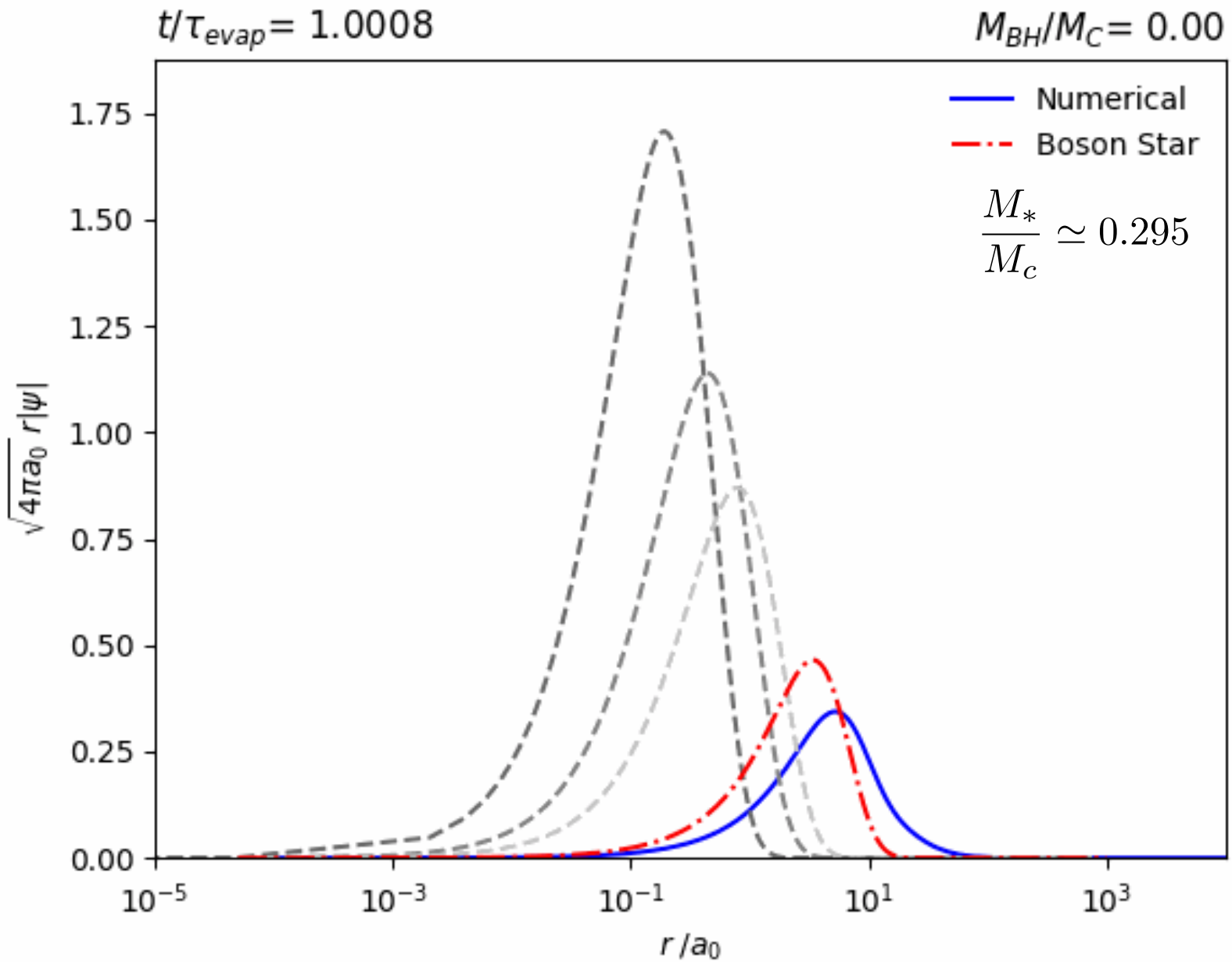

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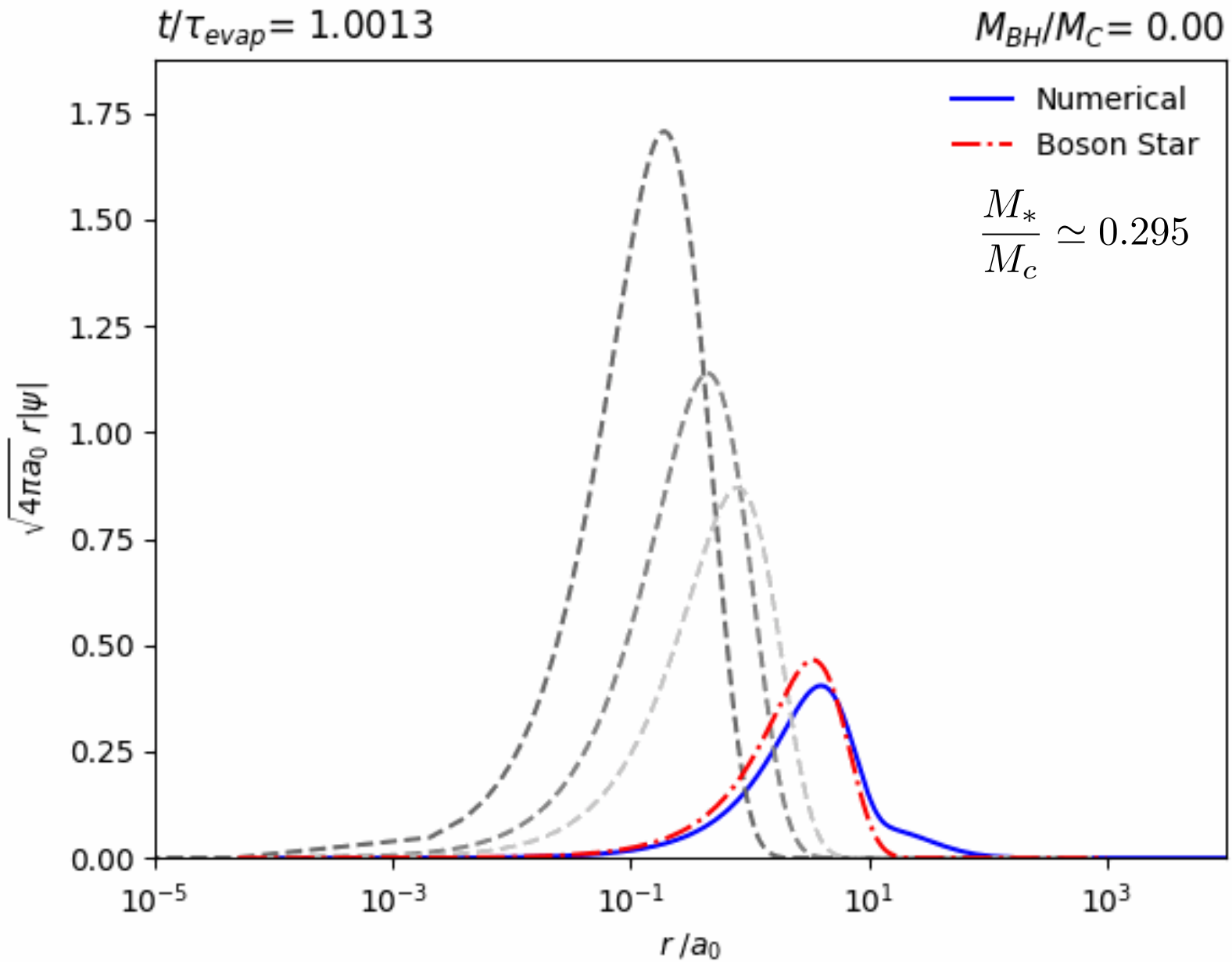

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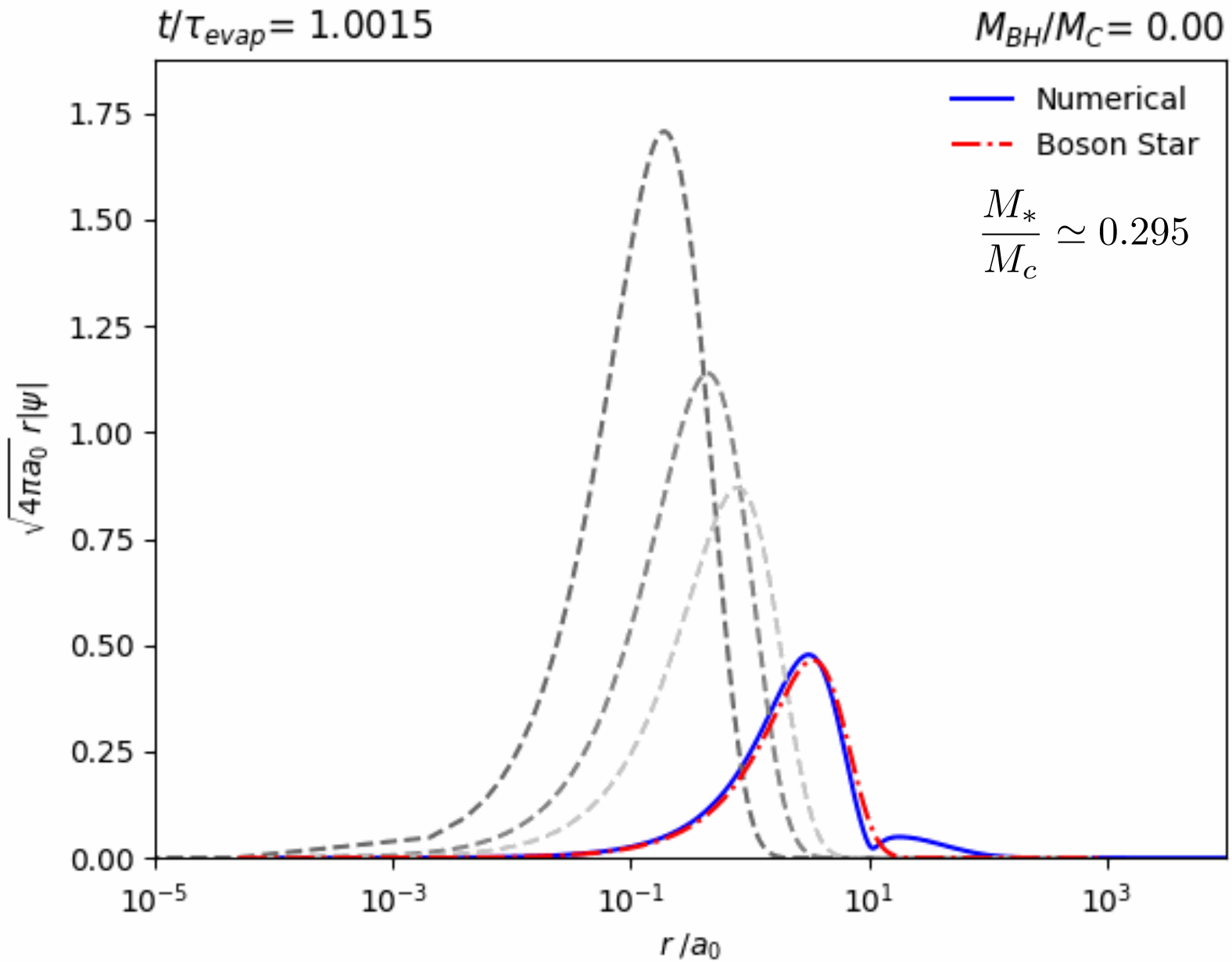

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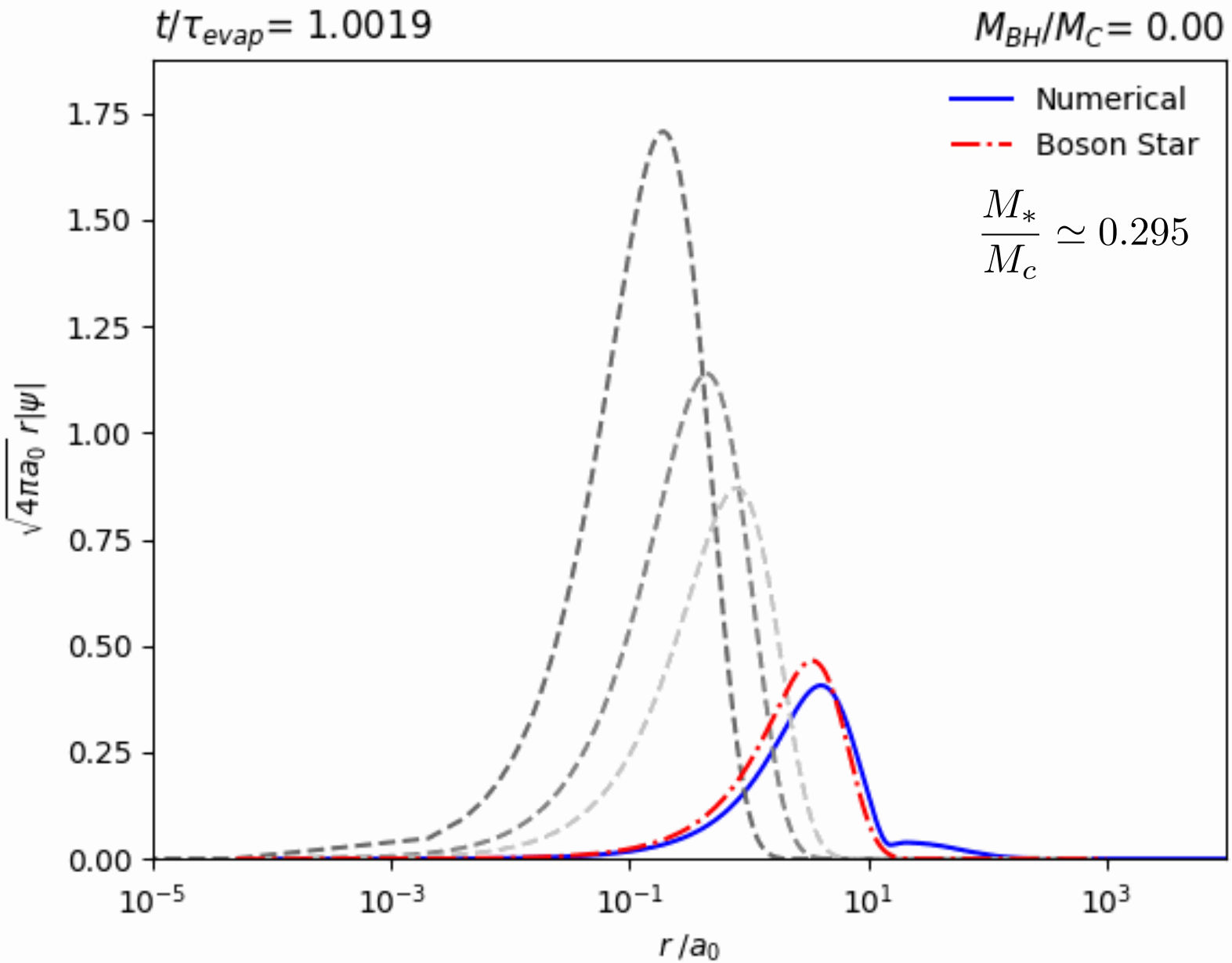

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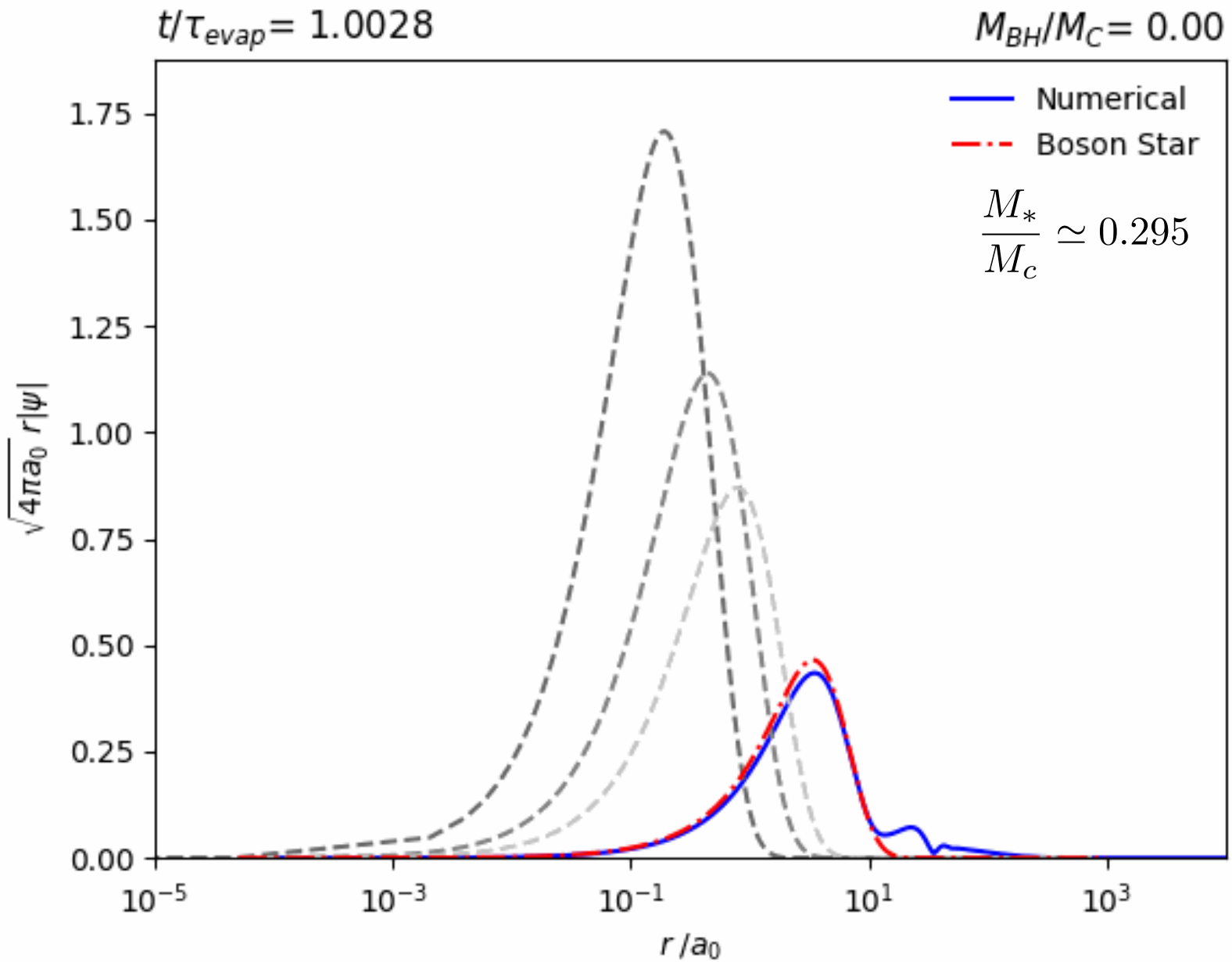

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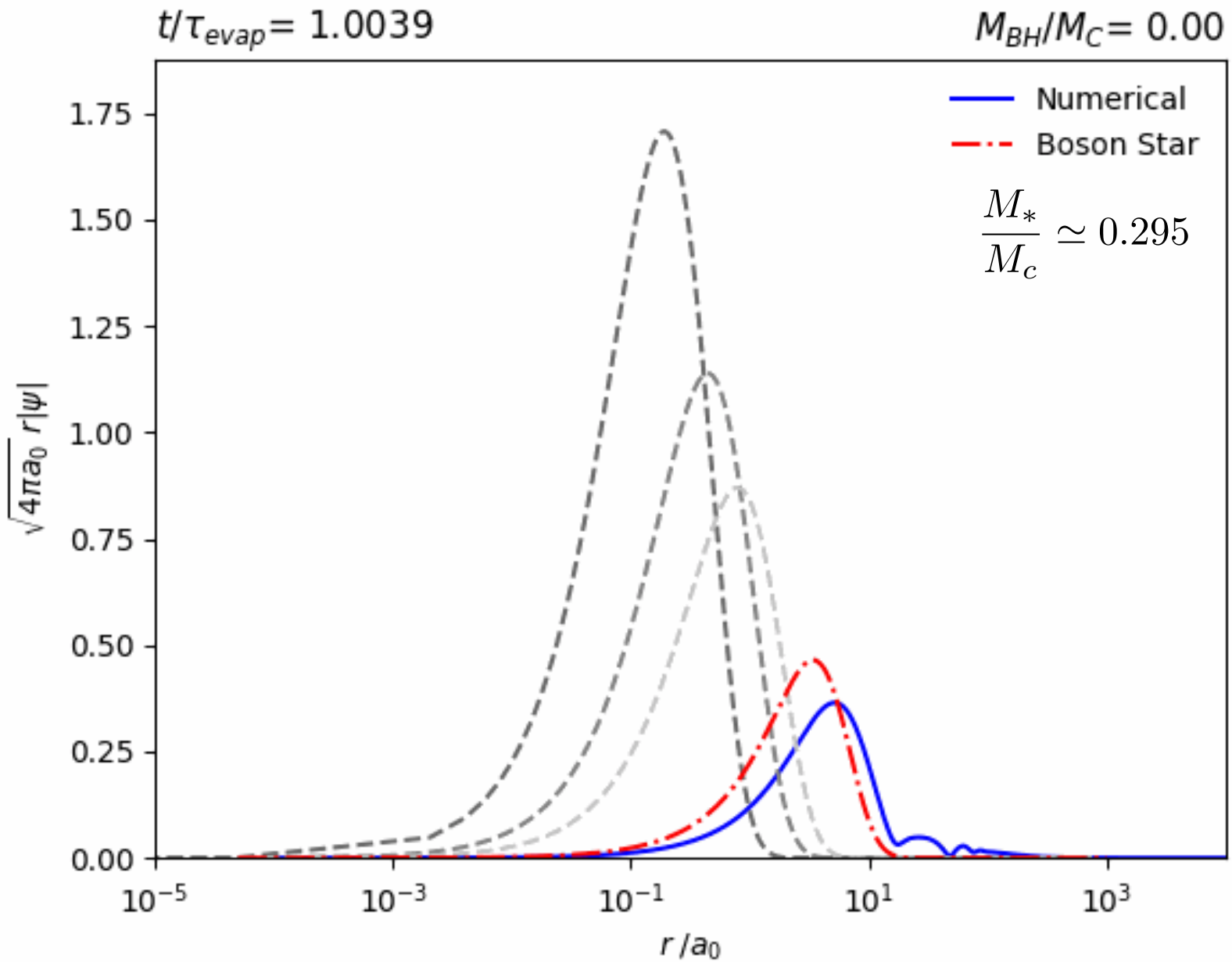

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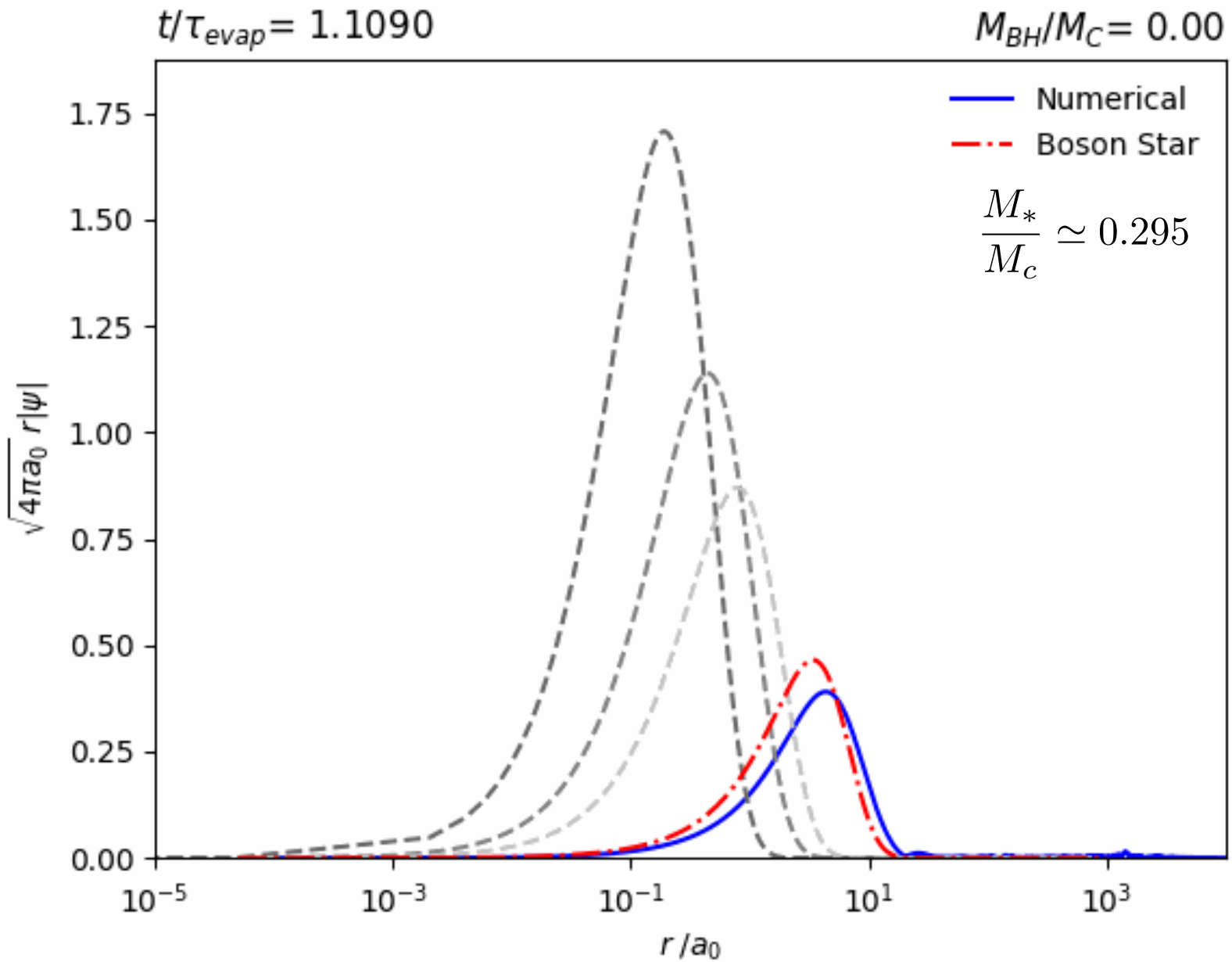

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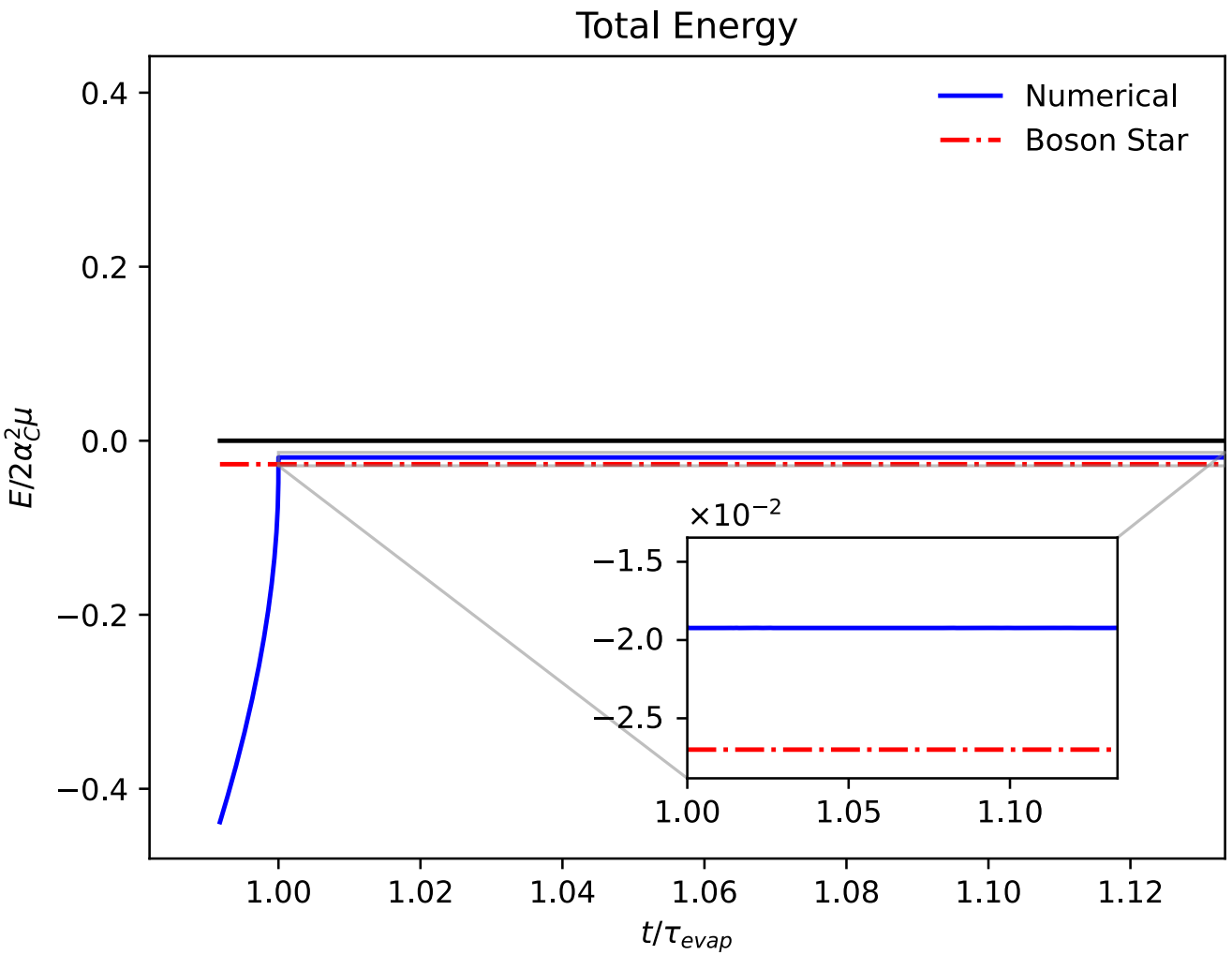
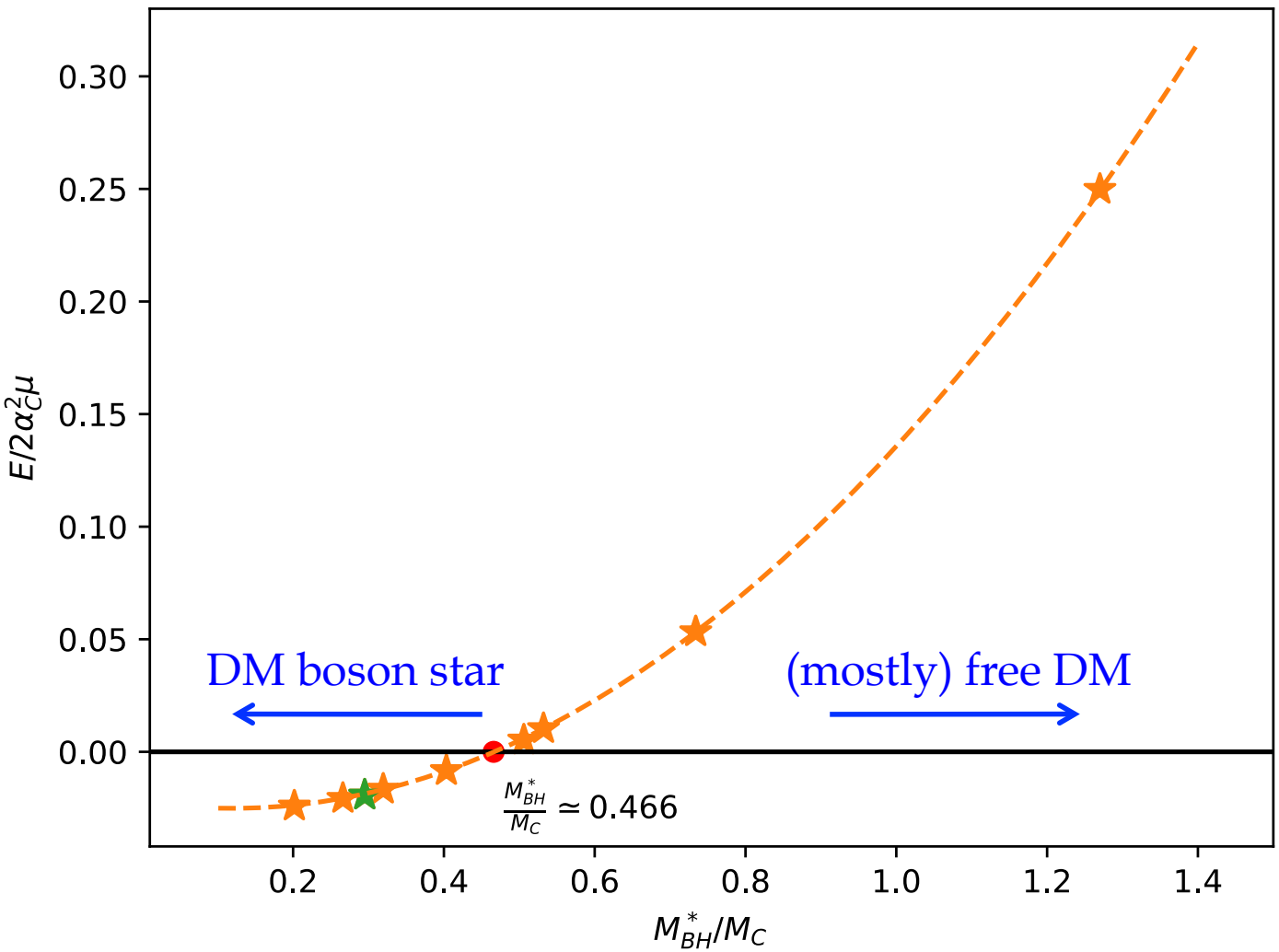


Numerical results



Properties of DM "boson stars"

$$R_{BS} \simeq \frac{5.5}{\epsilon_{SR} f_{BS}} \left(\frac{0.003}{\alpha_0}\right)^3 \left(\frac{0.05}{\tilde{a}_0}\right) \left(\frac{M_0}{10^6 \text{ kg}}\right) \left(\frac{\Delta J}{J_0}\right)^{-1} \text{ pm}$$

$$M_{BS} \simeq 150 \epsilon_{SR} f_{BS} \left(\frac{\alpha_0}{0.003}\right)^3 \left(\frac{\tilde{a}_0}{0.05}\right) \left(\frac{M_0}{10^6 \text{ kg}}\right) \left(\frac{\Delta J}{J_0}\right) \text{ kg}$$

↓

Mass loss in transition + rotating BS instability
[Sanchis-Gual *et al.* (2019/20); Dmitriev *et al.* (2021)]

We expect them to be rare in solar neighbourhood:

$$\Phi \simeq 5 \times 10^{-4} f_{SR} f_{BS} \left(10 \text{ kg}/M_{BS}\right) \text{ km}^{-2}\text{yr}^{-1}$$

but with large enhancement of non-gravitational cross-sections
(e.g. coherent scattering off nuclei [Hardy *et al.* (2015)])

Summary

- Gravitational DM production: PBH evaporation + superradiance
- Superradiant DM clouds may survive after PBH evaporation
- DM "boson stars": microscopic size but huge number of particles

Future work:

- Numerical simulations beyond spherical symmetry
- Phenomenology/detection of DM micro-boson stars

Thank you!