Gravitational Echoes from the Early Universe: PBH Binaries in Clustered Environments

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04.07.2025
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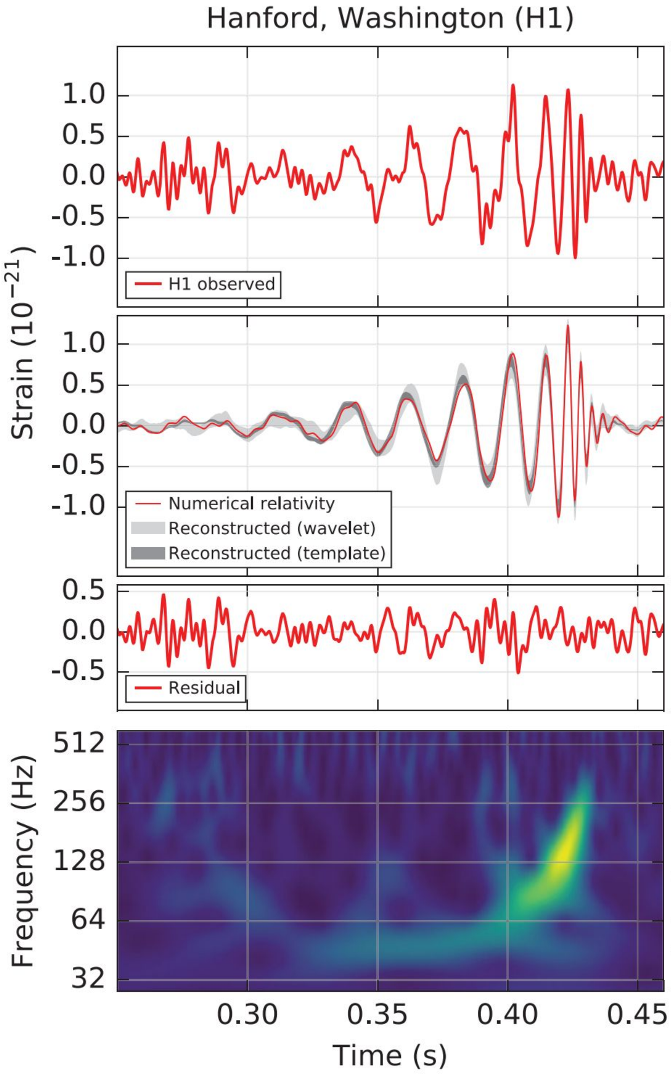
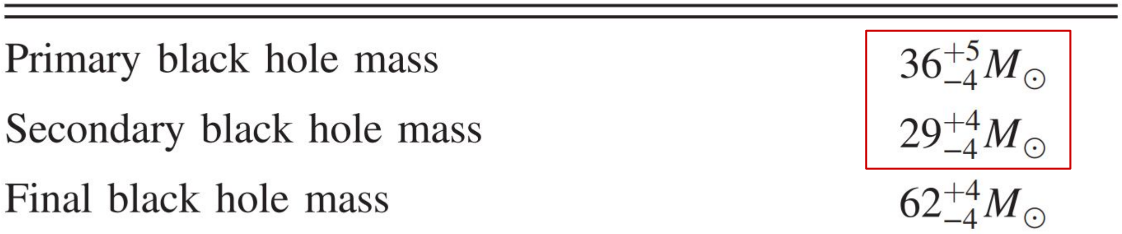


GW150914

[1] Observation of Gravitational Waves from a Binary Black Hole Merger LIGO arXiv:1602.03837

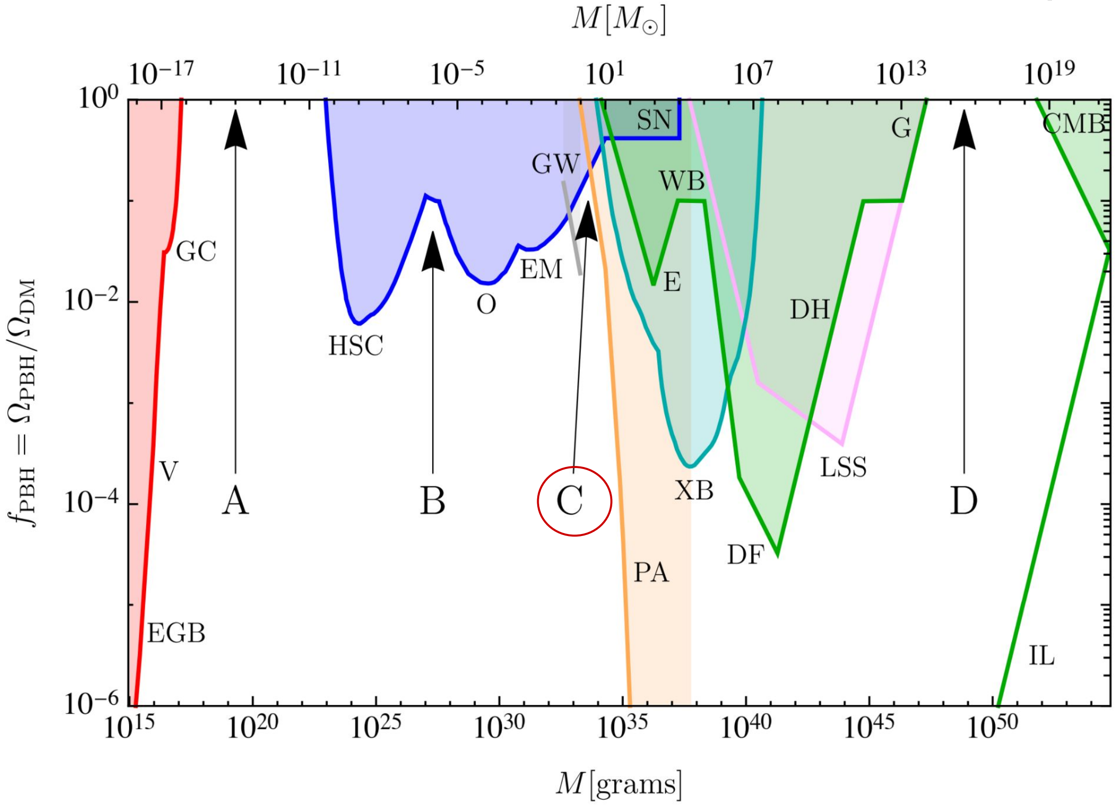
[2] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) “Properties of the Binary Black Hole Merger GW150914” 2016 arXiv:1602.03840

The parameters of the detected black holes indicate their possible primary origin.



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$

Spectrum of PBH mass limitations (monochromatic)

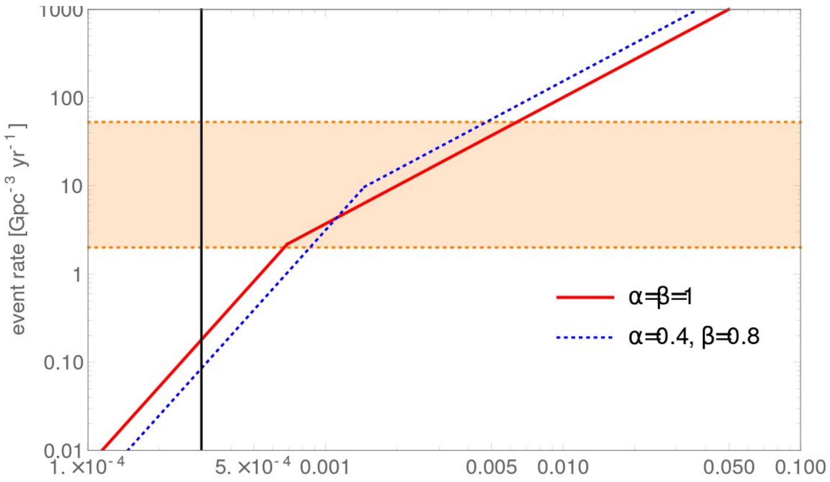


[3] Primordial Black Holes as Dark Matter Candidates

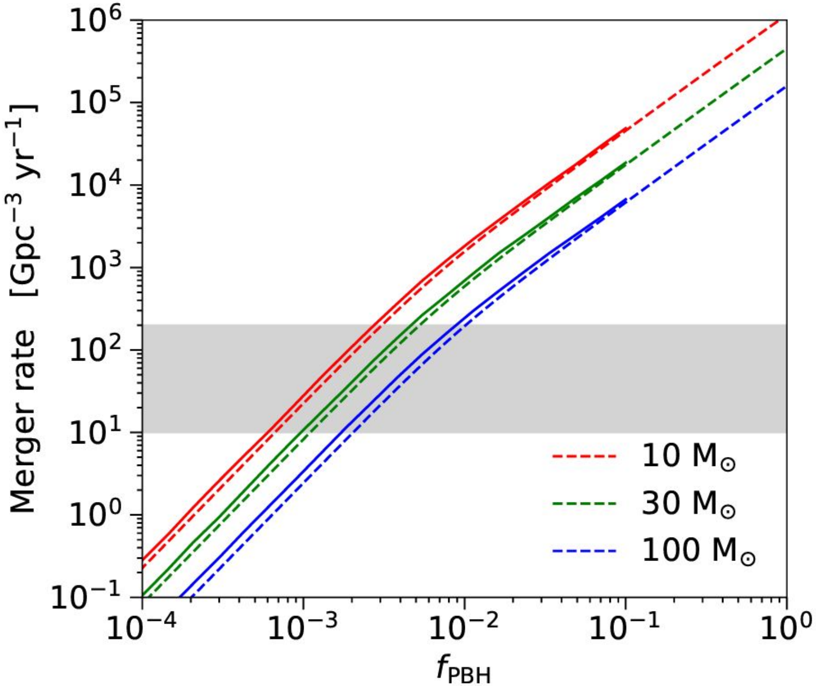
Bernard Carr, Florian Kuhnel

arXiv:2110.02821 [astro-ph.CO]

Merger rate



[4] Misao Sasaki "Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914" arXiv:1603.08338



[5] Bradley J. Kavanagh "Black Holes' Dark Dress: On the merger rate of a subdominant population of primordial black holes" arXiv:1805.09034

Number of GW signals per year and Gpc^3.

Shaded bar - observed merger rate measured by LIGO

Black line - the upper limit on rate from the nondetection of the CMB spectral distortion

The *solid lines* on the right graph are the merger rate of PBHs in the *halo of dark* matter particles, the *dotted lines* are without a halo.

See also: [6] Yury Eroshenko "Gravitational waves from the merger of two primordial black hole clusters" arXiv:2302.05167

Merger rate[4] (uniform distribution)

$$dP = \frac{9}{\bar{x}^6} x^2 y^2 dx dy.$$

a - semi-major axis,
e - eccentricity,
j - dimensionless angular momentum

$$j = \sqrt{1 - e^2}$$

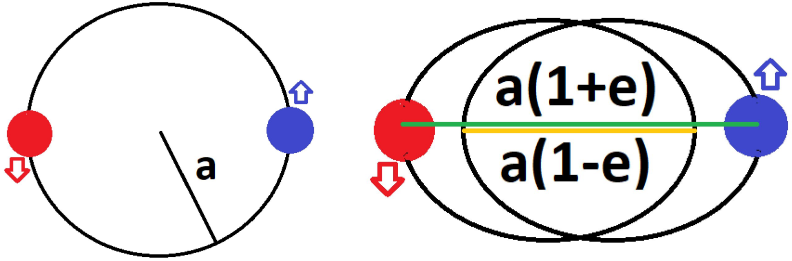
$$\bar{x} = \left(\frac{M_{\mathrm{BH}}}{\rho_{\mathrm{BH}}(z_{\mathrm{eq}})} \right)^{1/3}$$

$$\boxed{dP = \frac{3}{4} f^{3/2} \bar{x}^{-3/2} a^{1/2} j^{-2} \, da dj}$$

$$\boxed{t = Q a^4 j^7,} \quad Q = \frac{3}{170} (G M_{\mathrm{BH}})^{-3}$$

c - coalescence

Merger rate = $n_{\mathrm{BH}} \lim\limits_{\Delta t \to 0} \dfrac{P_c(t_0) - P_c(t_0 - \Delta t)}{\Delta t}$

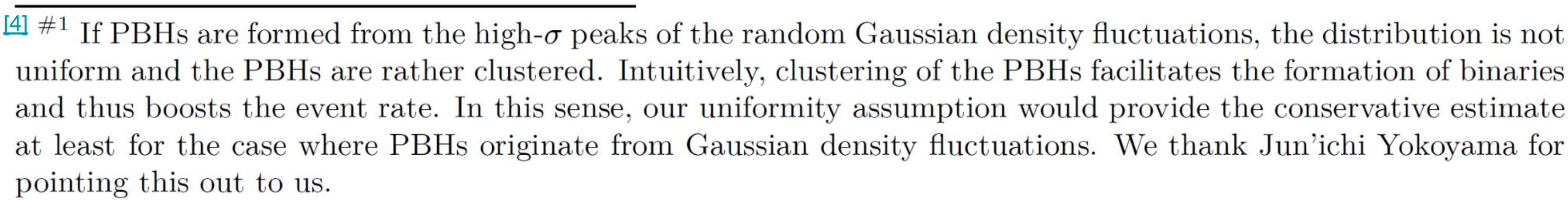


e = 0
(j = 1)

e, j ∈ (0,1)

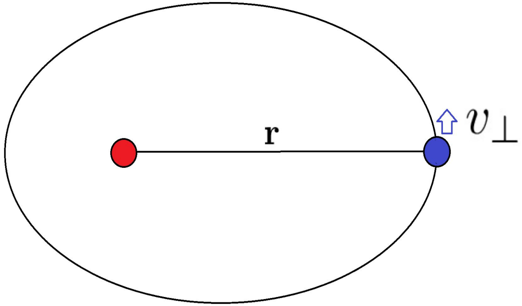
1. We select the share of primary black holes in the hidden mass.
2. We calculate the average initial distance, angular momentum j and semimajor axis a.
3. We calculate the probability of forming a PBH binary.
4. Move on to the time dependence (the probability of a pair with (a, j) merging at some point in time) and integrate.
5. We get the rate of mergers.

Some remarks



[4] $^{\#1}$ If PBHs are formed from the high-σ peaks of the random Gaussian density fluctuations, the distribution is not uniform and the PBHs are rather clustered. Intuitively, clustering of the PBHs facilitates the formation of binaries and thus boosts the event rate. In this sense, our uniformity assumption would provide the conservative estimate at least for the case where PBHs originate from Gaussian density fluctuations. We thank Jun'ichi Yokoyama for pointing this out to us.

$$\begin{cases} p = \dfrac{L^2}{m_2^2\alpha}, \qquad \alpha = G(m_1+m_2), \\ |L| = r m_2 v_\perp, \\ a = \dfrac{p}{j^2}, \end{cases} \qquad \Rightarrow j^2 = \frac{r^2 v_\perp^2}{a\alpha},$$



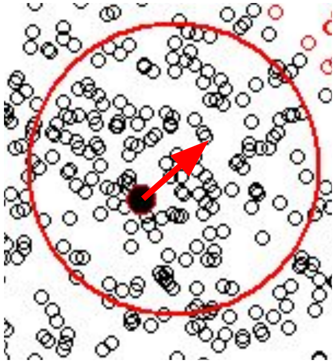
A small increase in the perpendicular velocity, and hence **in angular momentum,** causes **a sharp increase in the fusion time.**

$$\boxed{t = Qa^4 j^7,}$$

Clustering of primary black holes (non-uniform distribution)

Velocity dispersion

1.

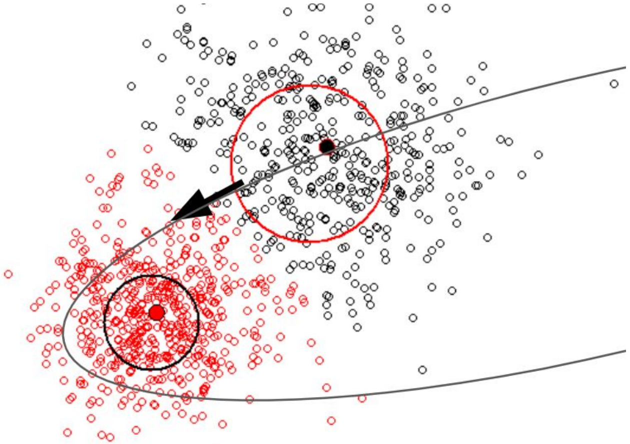


$$\sigma = \eta\sqrt{\frac{GM_{\text{cl}}}{R_{\text{cl}}}}$$

$$\sigma_{\text{PBH}} = \sigma\sqrt{\frac{m_i}{m_{\text{PBH}}}}$$

Cluster intersection

2.



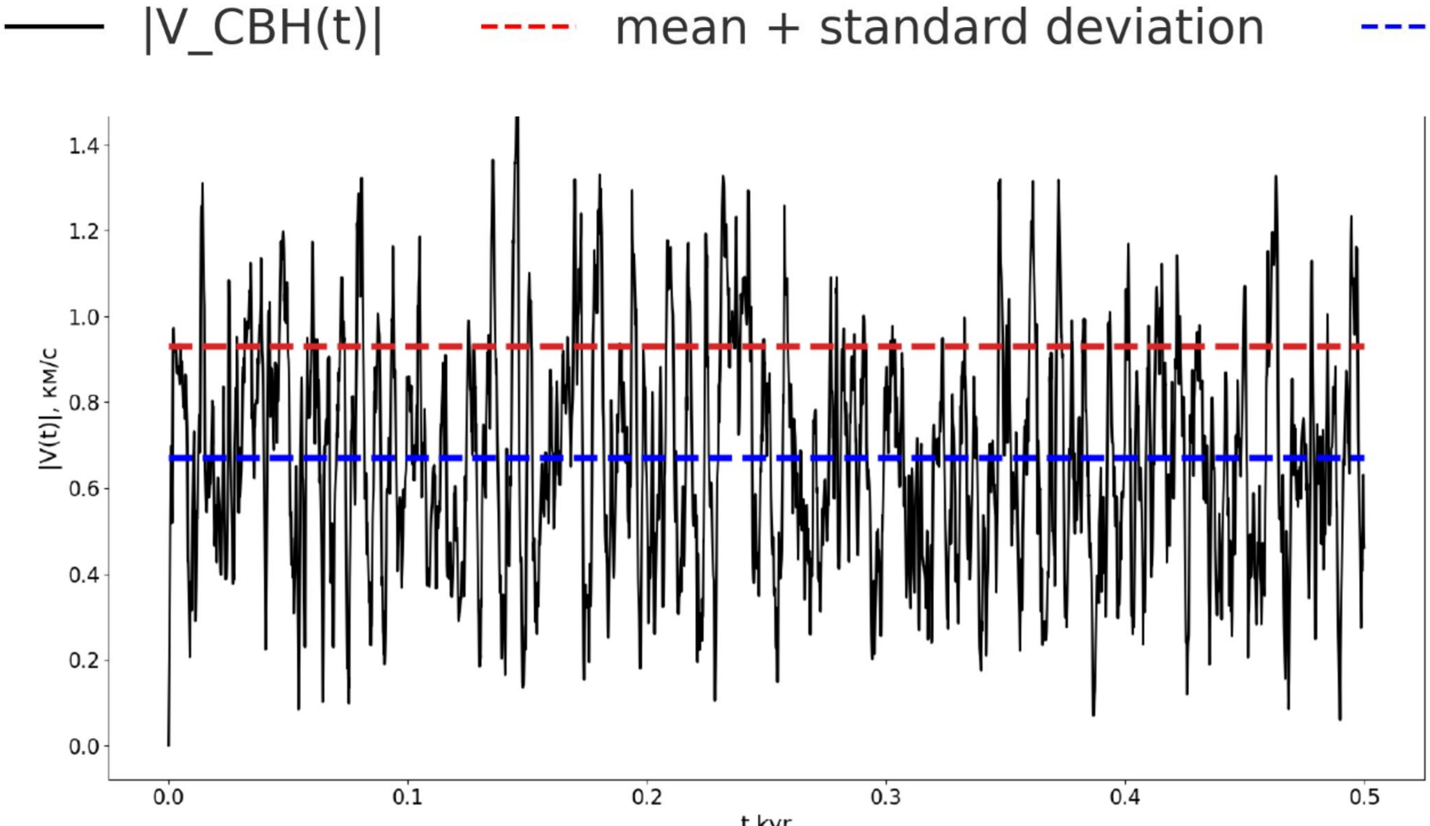
Goals:

- Development of an environment for modeling (N-body) cluster dynamics.
- Simulation of double primordial black holes surrounded by clusters of smaller primordial black holes.
- Study of the evolution of such a system (**how orbital parameters change)**
- Explore how **lifespan changes.**

[7] Clusters of Primordial Black Holes / K. M. Belotsky [et al.] // The European Physical Journal C. — 2019. — Vol. 79, no. 3. arXiv: 1807.06590

[8] G.Vorobyev gitlab.com/MirumeYato/pygra

Magnitude of Central Black Hole Velocity

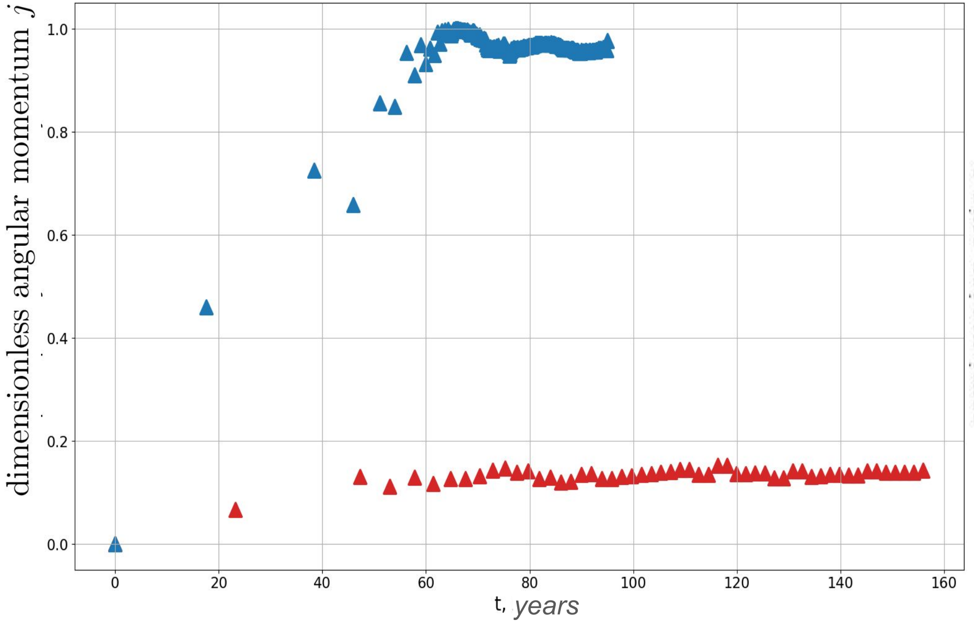


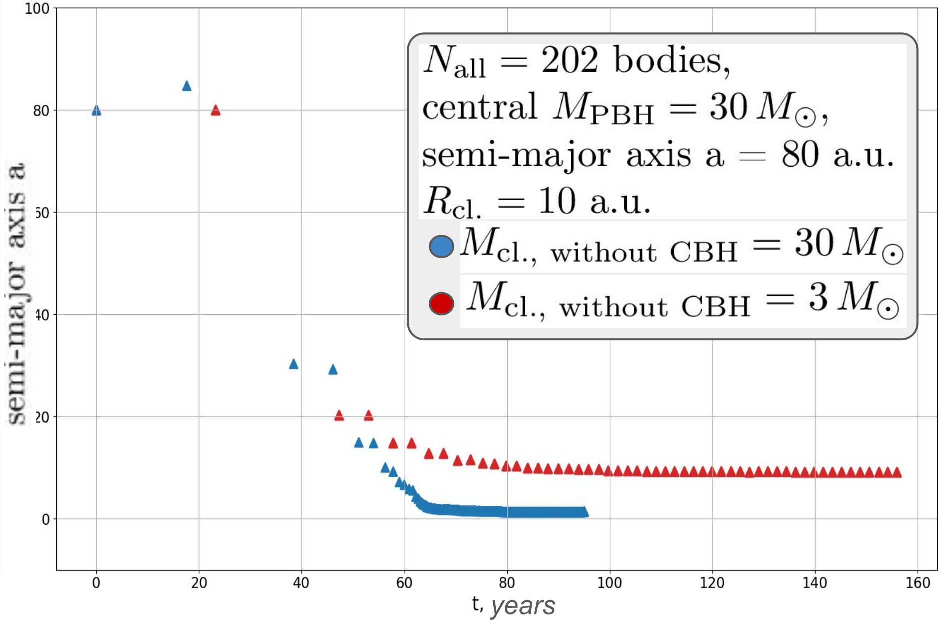
$$\sigma = \eta\sqrt{\frac{GM_{\text{кл}}}{R_{\text{кл}}}}$$

$$\sigma_{\text{ЦЧД}} = \sigma\sqrt{\frac{m_i}{m_{\text{ЦЧД}}}}$$

Binary system of central black holes surrounded by less massive black holes (j = 0)

Value	Initially	Finally
j_{blue}		0.977
$a_{\text{blue.}}$	80 a.u.	1.5 a.u.
j_{red}		0.14
a_{red}	80 a.u..	9.2 a.u.
coalescence time (blue)		1687 t_{uni}
coalescence time (red)		3 t_{uni}





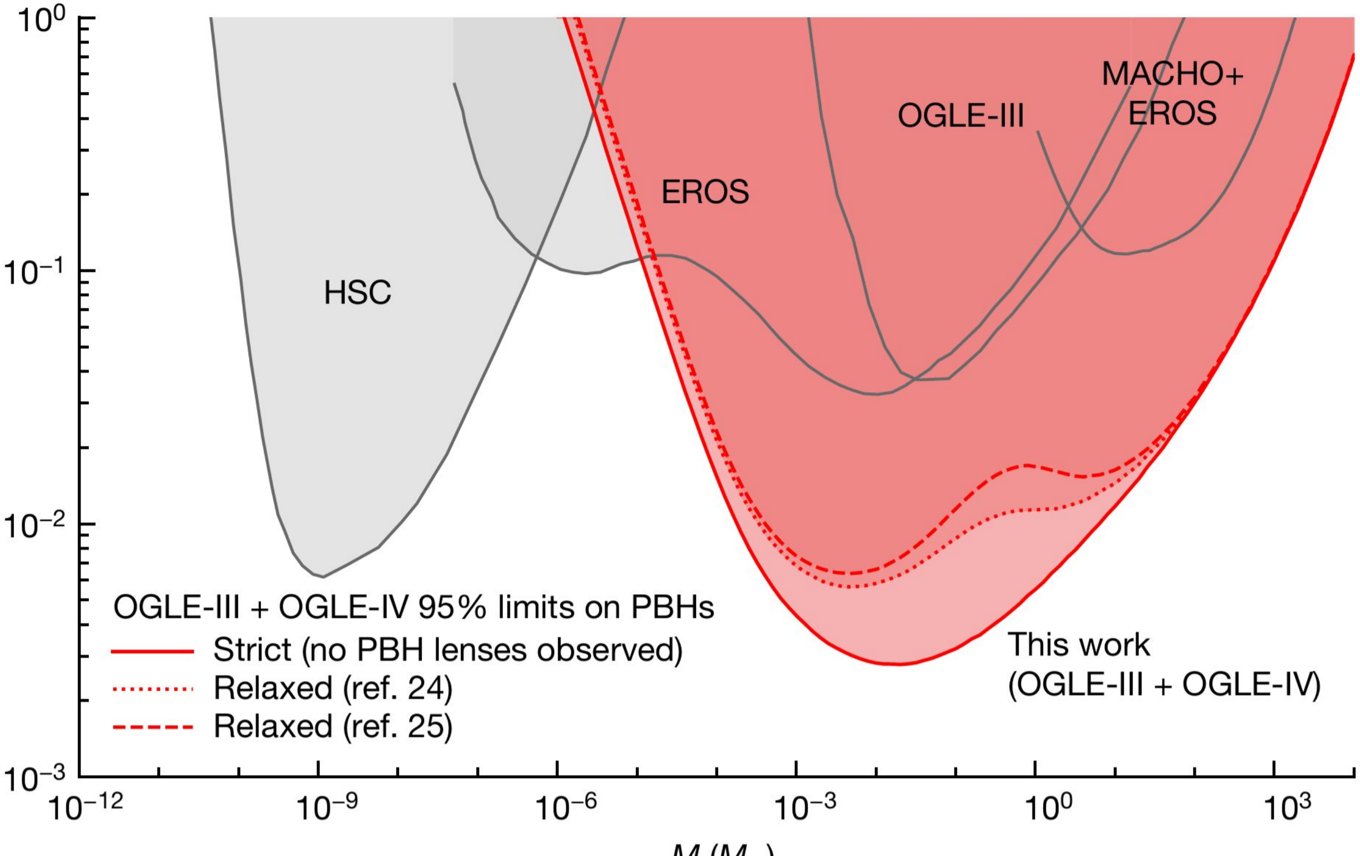
*t_uni = 13 * 10e9 years*

Summary

In this work, we have conducted a concise review of key challenges in modern cosmology, celebrated achievements in gravitational-wave astronomy, and the intriguing concept of primordial black holes (PBHs). Our study has encompassed the following key accomplishments:

- **Development of a PyGra** shell designed for generating initial conditions and conducting N-body simulations to model the phenomena under consideration.
- Critical analysis of the **calculation accuracy of the** employed **methods** through various illustrative examples.
- Execution of a comprehensive simulation involving a system consisting of two homogeneous **BH clusters**, each featuring massive central black holes. Examination and analysis of the **evolution of orbital parameters** within the binary system composed of central black holes, drawing insights from the acquired data.
- Estimation of the **'lifetime' of these binary systems** and the subsequent confirmation of **an increase in their lifespans** within the observed evolutionary context. This extended 'lifetime' serves to relax **constraints on the contribution of primordial black holes to the hidden mass in the universe.**

No massive black holes in the Milky Way halo
arXiv:2403.02386



Thank you for your attention

Величина	Было	Стало
j_1	0.069	0.883
a_1	50 а.е.	3.6 а.е.
j_2	0.227	0.536
a_2	5.1 а.е.	1.71 а.е.
Время жизни 1	t_{uni}	1485 t_{uni}
Время жизни 2	0.4 t_{uni}	2.3 t_{uni}

выбирается j > 0

Пример 1: Nобщ. = 22 тела, 20 из них с суммарной массой m(Σi) = 20M⊙ и два центральных по M(ЦЧД) = 100M⊙, a = 5.1 а.е., j = 0.2265;

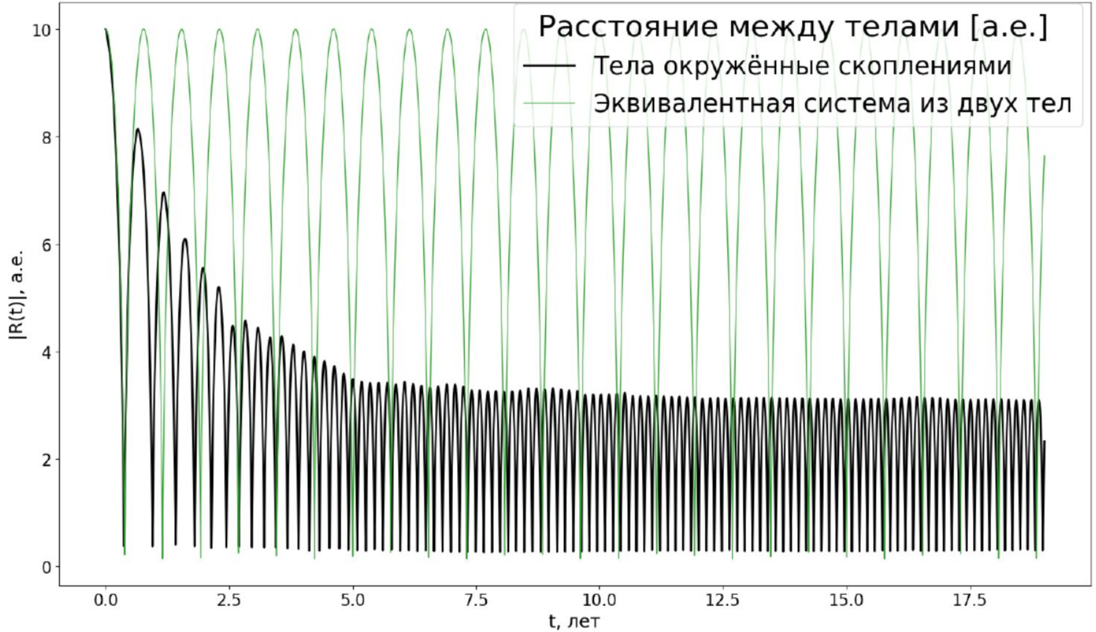


Рисунок 4.4 — Эволюция параметров орбиты двойной системы тел окружённых скоплениями для примера 1

Величина	Было	Стало
j_1	0.069	0.883
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Время жизни 1	t_{uni}	1485 t_{uni}
Время жизни 2	0.4 t_{uni}	2.3 t_{uni}

Пример 2: Nобщ. = 22 тела, 20 из них с суммарной массой m(Σi) = 20M☉ и два центральных по M(ЦЧД) = 100M☉, a = 50 а.е., j = 0.07).

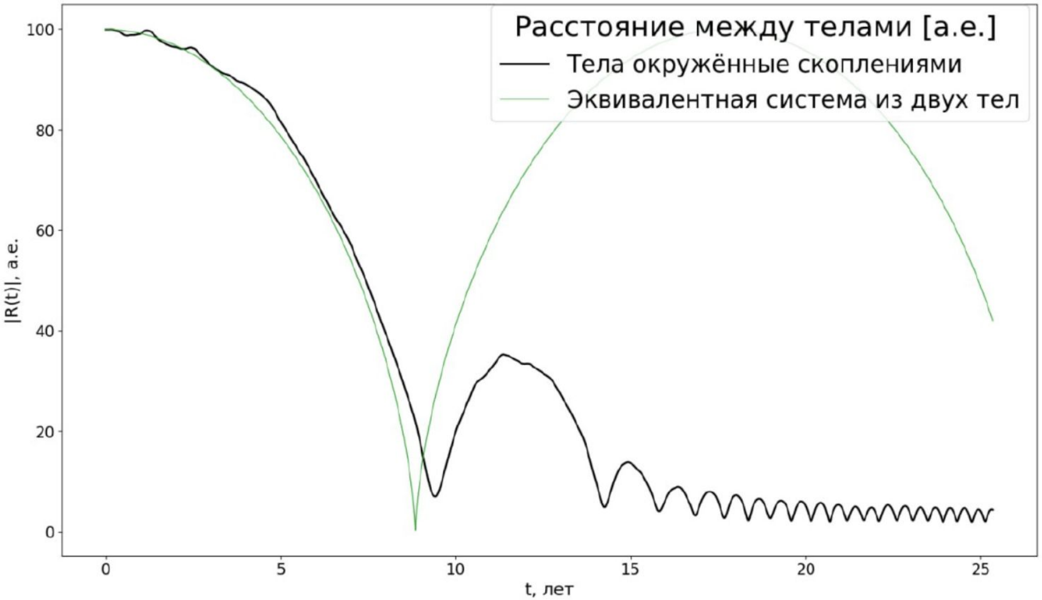

Рисунок 4.5 — Эволюция параметров орбиты двойной системы тел окружённых скоплениями для примера 2

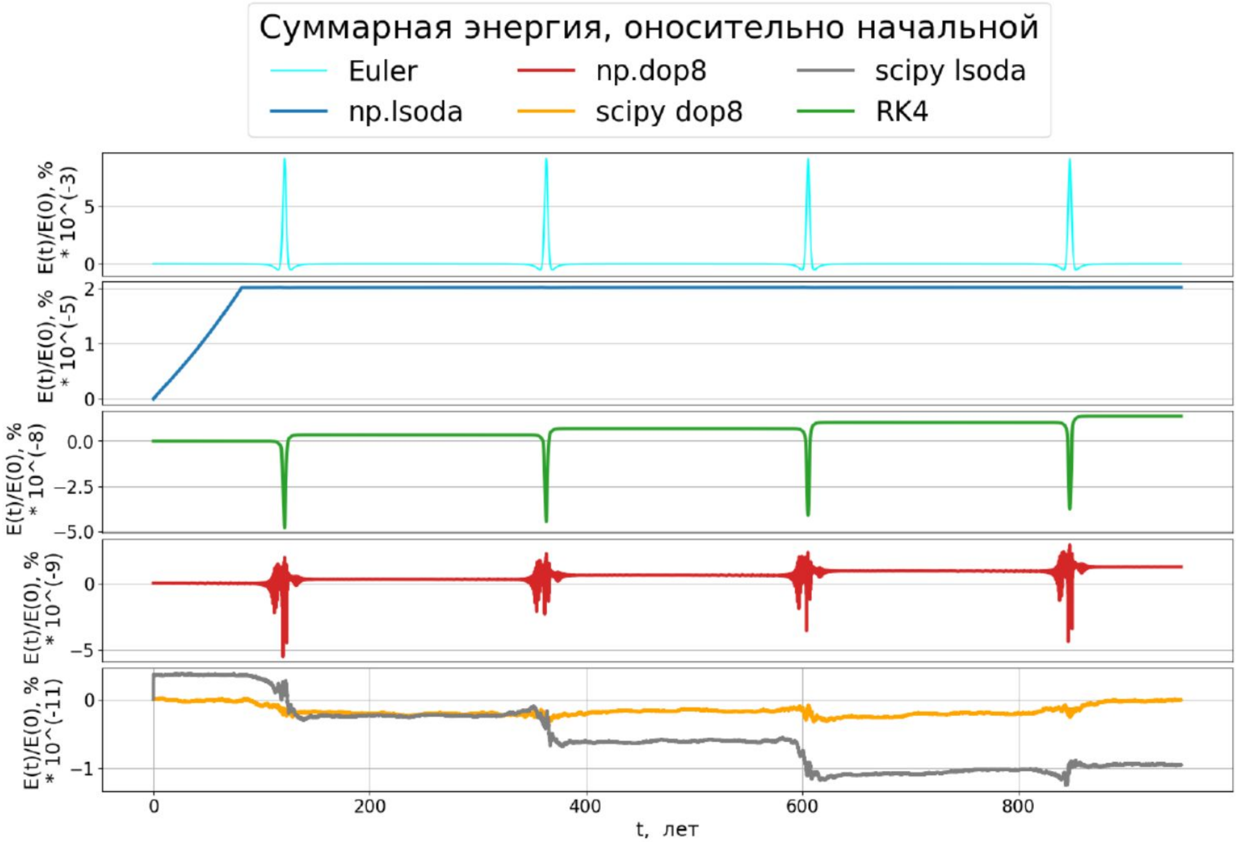

Рисунок В.2 — Графики зависимости нормированной суммарной энергии системы от времени для разных методов. Нормировка происходит на значение суммарной энергии в начальный момент времени, значение указано в процентах