Theory of Relativity Seminar

(Wydział Fizyki UW and DBP NCBJ)

April 5 (Friday), 11:15; room 1.40, Pasteura 5
(Faculty of Physics, University of Warsaw)

Marek Abramowicz

Gothenburg University, Sweden
Copernicus Astronomical Centre, Warsaw
Silesian University, Czechia

Primordial black holes in the dark matter halo of our Galaxy

M. Abramowicz, M. Bejger,
A. Udalski. M. Wielgus,

Ap. J. Lett 2022, 935, L28

A Robust Test of the Existence of Primordial Black Holes in Galactic Dark Matter Halos

Do the primordial black holes exist in the dark matter halo of our Galaxy?

INTRODUCTION: MY ANSWER

No!

INTRODUCTION: MY OPINION

In a few years microlensing, LIGO-Virgo-Kagra, LMXRB and pulsars' count will definitely prove the PBHs non-existence.

The hypothetical primordial black holes **must** collide with the galactic neutron stars.

These collisions **must** form light black holes (LBH) with mases about $1 - 2\,M_\odot$

Hypothetical LBH events are detectable by microlensing and LIGO-Virgo-Kagra.

Statistics of the LBH events will soon definitely tell whether the PBH exist.

Zeldovich, Novikov (1966)
Hawking (1971)
Hawking, Carr (1974)
Hawking (1974)

I will **NOT** discuss today ideas and numerous details concerning the PBHs formation. There are more than 120,000 papers listed by ADS on the subject, including a recent review: *Observational evidence for primordial black holes: A positivist perspective,* Carr B.J., Clesse S., García-Bellido J., Hawkins M.R.S., Kühnel F., 2024, Physics Reports, 1054, 1-68. Here I describe **ONLY** a few consequences of the hypothetical collisions of the hypothetical PBHs with the Galactic neutron stars.

HAWKING'S EVAPORATION

QUANTUM GRAVITY HAWKING RADIATION

[1] Strong gravity's frequency: $\omega_{\rm H} = c/R_{\rm G}$

[2] $E_{\rm H} = \omega_{\rm H}\hbar = kT_{\rm H} \Rightarrow T_{\rm H} \sim \hbar\omega_{\rm H}/k$

[3] $T_{\rm H} = (\hbar c^3)/(8\pi k G M_\odot)(M/M_\odot)^{-1}$

[4] $T_{\rm H} = 6 \times 10^{-8}(M/M_\odot)^{-1}$ [^{o}K]

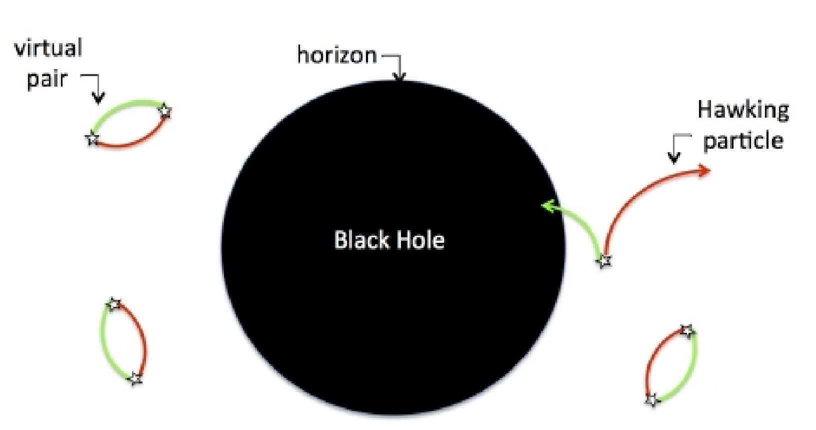
[5] Radiation flux: $F_{\rm H} \sim T_{\rm H}^4 \sim M^{-4}$

[6] Radiation power: $L_{\rm H} \sim F_{\rm H}\mathcal{A} \sim F_{\rm H}M^2 \sim M^{-2}$

[7] Radiation losses: $\partial_t(Mc^2) \sim L_{\rm H} \sim M^{-2}$

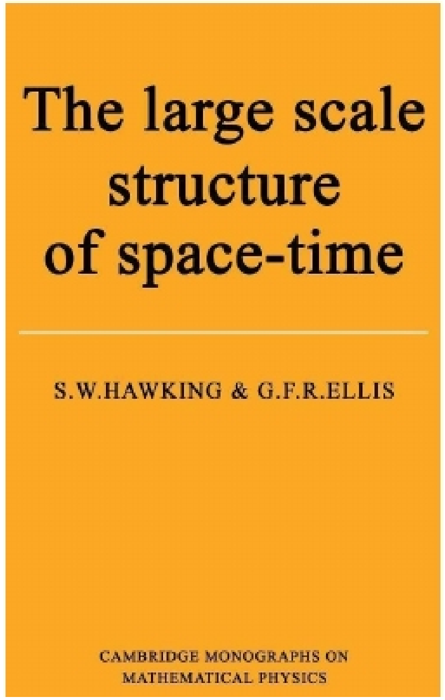
[8] Evaporation time: $M/t_{\rm H} \sim M^{-2} \rightarrow t_{\rm H} \sim M^3$

[9] For $t_{\rm H}$ = Hubble time: $M = 10^{15}$ [g]



Sciama's Cambridge team

D.W. Sciama, R. Penrose, S.W. Hawking, B. Carter, G.F.R. Ellis

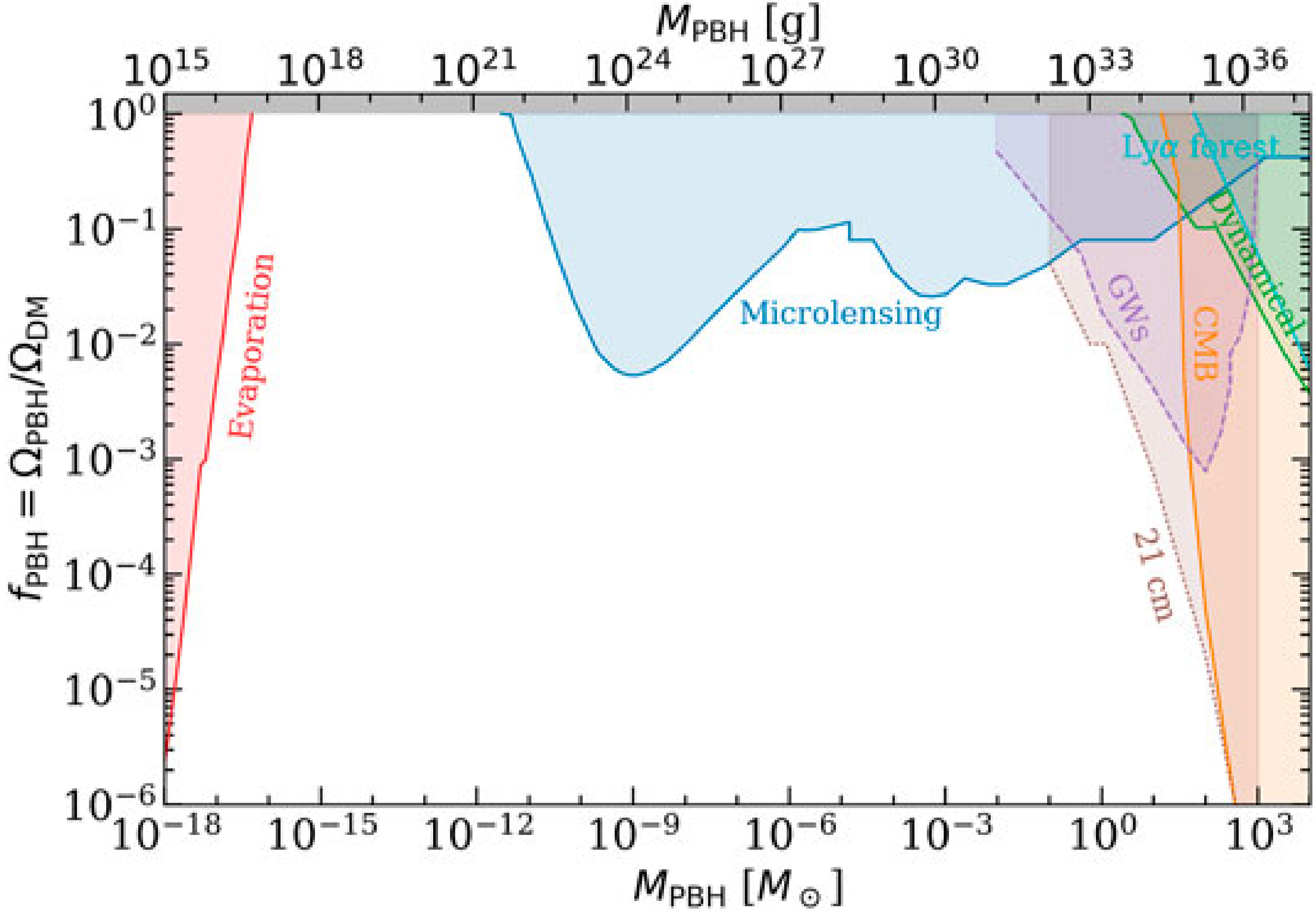


* Hawking radiation is negligible for astrophysical black holes

---

* It was never detected.

PBH MASS CONSTRAINTS: the asteroid-mass window



THE FIRST PAPER (NO CONSTRAINTS ON PBHs)

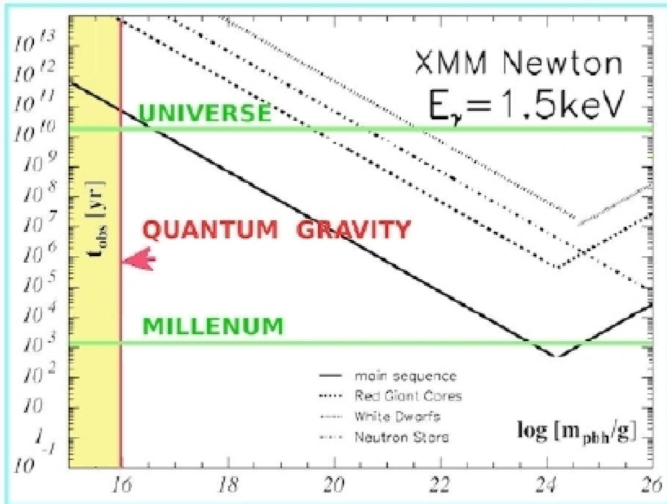
M.A. Abramowicz, **J.K. Becker**, P.L. Biermann, A. Garzilli, F. Johansson, L. Qian:
No Observational Constraints from Hypothetical Collisions of Hypothetical Dark Halo Primordial Black Holes with Galactic Objects,
Ap.J. 705, 659-669 (2009)

Was the Tunguska Event due to a Black Hole?

Jackson, A. A. (CfR, University of Texas at Austin)
Ryan, Michael P. (Department of Astrophysics, Oxford)

Abstract: There have been many attempts to explain the Tunguska meteorite, ranging from the prosaic to the bizarre. We suggest that a black hole of substellar mass such as those that have been postulated by Hawking could explain many of the mysteries associated with the event.

Nature, Volume 245, pp. 88-89 (1973).



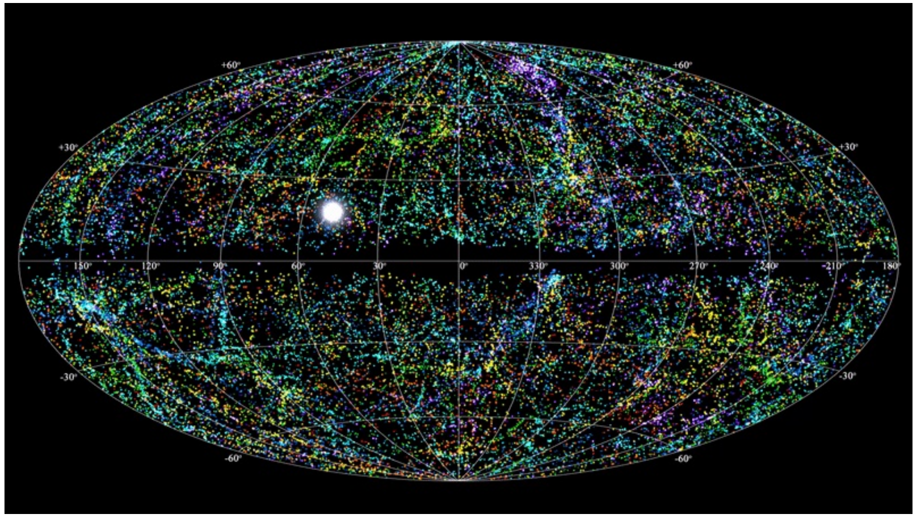
M.Abramowicz, J.K.Becker, P.L.Biermann, A.Garzilli, F.Johansson, L.Qian (2009) Ap.J. 705, 659; work done in Göteborg

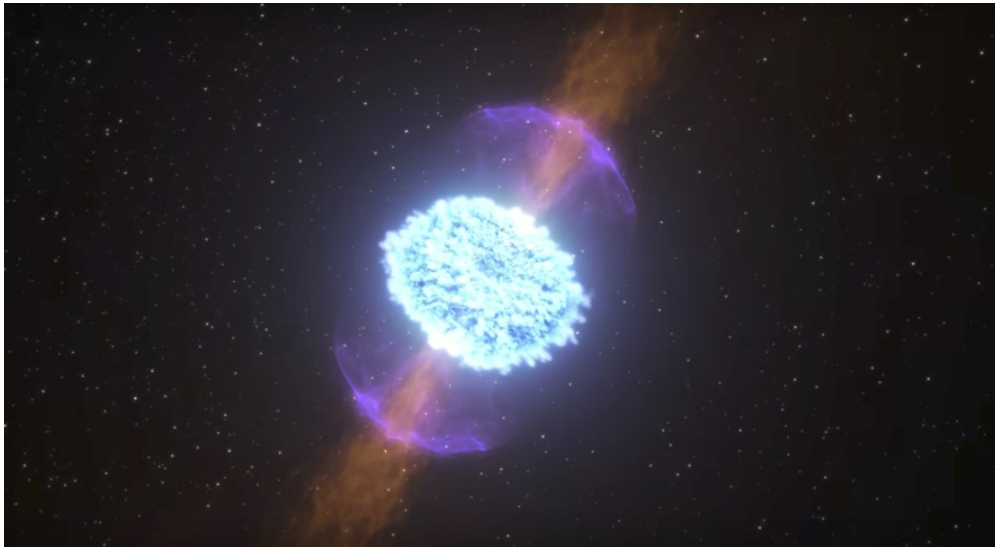
We examine the unexplored range, $10^{16} < m_{pbh} < 10^{26}$ g, investigating hypothetical collisions of PBHs with main-sequence stars, red giants, white dwarfs, and neutron stars in our Galaxy. Contrary to previous opinion and hopes, we found that such collisions are either too rare to be observed (if the PBH masses are typically larger than about 10^{20} g), or produce too little power to be detected (if the masses are smaller than about 10^{20} g).

M. Abramowicz, M. Bejger, M. Wielgus

Collisions of Neutron Stars with Primordial Black Holes as Fast Radio Bursts Engines

Ap. J. 2018, 868, 17, 7.





If primordial black holes constitute a non-negligible fraction of galactic dark-matter halos, they necessarily collide with galactic neutron stars, nest in their centers, and accrete the dense matter, eventually converting them to NS-mass black holes while releasing the NS magnetic field energy. Such processes may explain the fast radio bursts phenomenology.

SIX MAIN RESEARCH ISSUES

(M.Bejger, M.Wielgus and others)

First collision

Population synthesis

J.Becker

Capture

Flyby

Dynamical friction

A.Brandenburg, J.Horák

Bondi accretion

Oppenheimer-Snyder collapse

A.Brandenburg, T.Piran, J.Horák, Deepika Bollimpalli

Multiple collisions

A.Brandenburg, J.Horák

Observations' interpretation

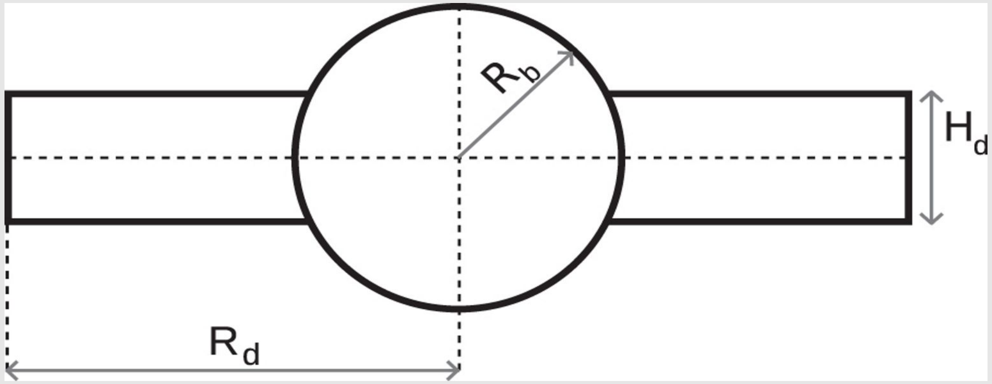
Data analysis

A.Udalski, P.Mróz, Ł.Stawarz, J.-P.Lasota,

In collisions of primordial black holes with neutron stars LOW MASS $\sim M_{\odot}$ BLACK HOLES are formed.

OUR POPULATION SYNTHESIS: METHOD

EQUATIONS



$i=1$ Neutron stars,
$i=2$ Stellar black holes,
$i=3$ Low mass black holes,
$i=4$ Primordial black holes.

$$\frac{\partial n_{(i)}}{\partial t} = \sum_{i=1}^{4} n_{(i)}\, n(k)\, C^{(i)(k)} + K_{(i)}$$

$$n_{(i)}\, n(k)\, C^{(i)(k)} = n_{(i)}\, n_{(k)} \frac{V^{(i)}}{V} R^2_{(i)}$$

EXPLANATION

$$H_d = 1.0\,\mathrm{kpc}$$
$$R_d = 30\,\mathrm{kpc}$$
$$R_b = 5.0\,\mathrm{kpc}$$

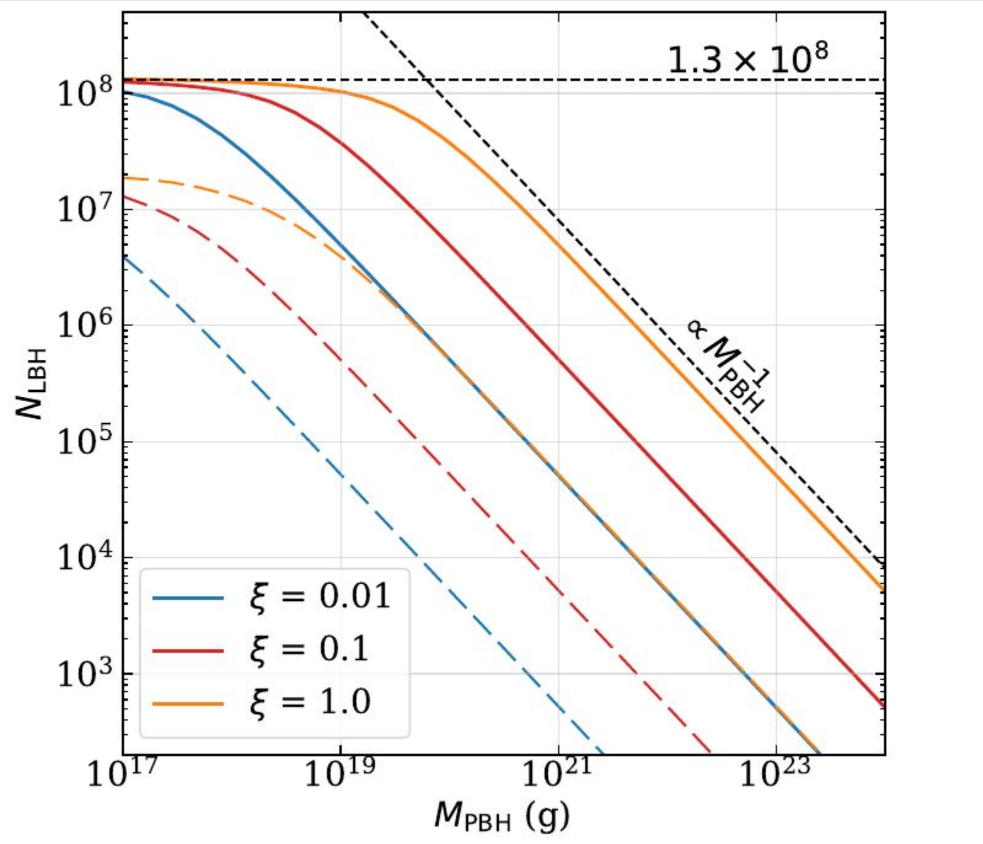
$$V(r) = \begin{cases} v_d = 220 \mathrm{km/s} & \text{if } r \geq R_b \\ \left(\frac{v_d\, r}{R_b}\right) & \text{otherwise} \end{cases}$$

$$\rho(r) = \begin{cases} \left(\frac{v_d^2}{4\pi\, G\, r^2}\right) & \text{if } r \geq R_b \\ \left(\frac{3v_d^2}{4\pi\, G R_b^2}\right) & \text{otherwise} \end{cases}$$

OUR POPULATION SYNTHESIS: RESULTS

PBHs NUMBER TODAY

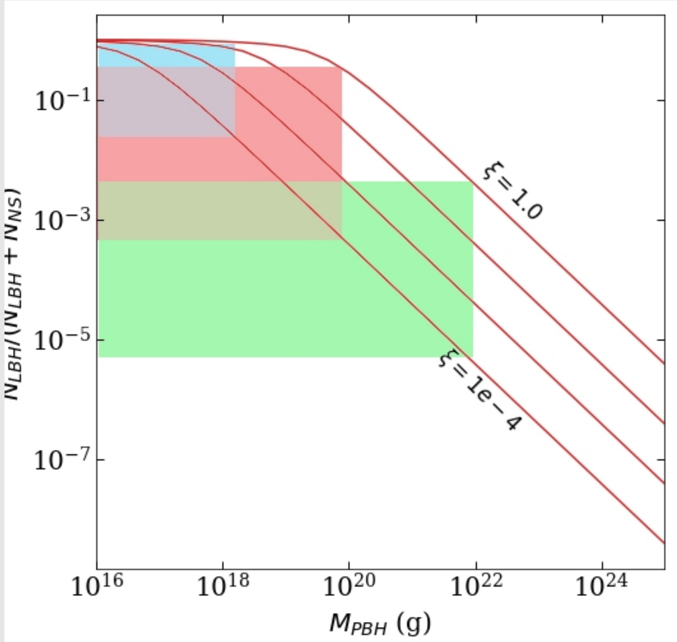
Number of LBHs after 13 Gyr



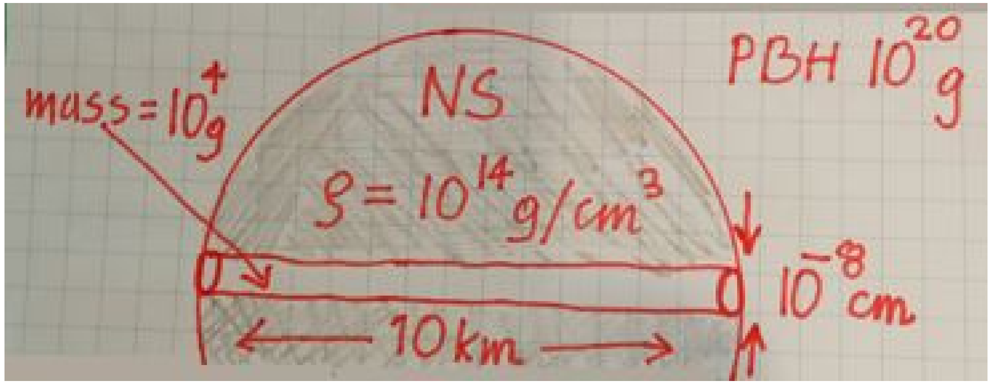
Note that even with a small fraction of PBHs in the DM halo,

$m < 10^{19}$ [g], $\xi = 0.01$

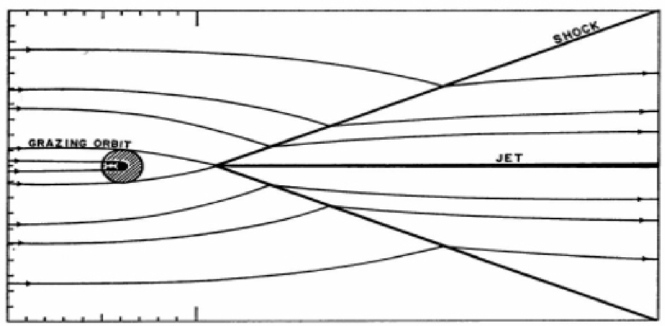
almost all Galactic NSs will be converted to LBHs.



DYNAMICAL FRICTION: Ruderman & Spiegel and E.Ostriker



A direct momentum exchange is negligible. Interaction between PBH and NS goes through dynamical friction



Ap.J., 1971

$$F_{DF} = -\frac{4\pi (Gm)^2}{v^2}\rho\, I$$

$$I_{sup} = \frac{1}{2}\ln\left(1 - \frac{1}{\mathcal{M}^2}\right) + \ln\left(\frac{vt}{r_0}\right)$$

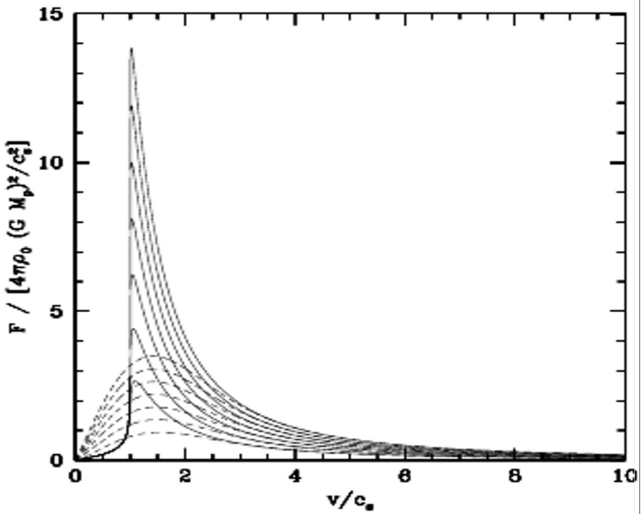
$$I_{sub} = \frac{1}{2}\ln\left(\frac{1+\mathcal{M}}{1-\mathcal{M}}\right)$$

Eve C. Ostriker

DYNAMICAL FRICTION IN A GASEOUS MEDIUM

1999

Ap.J. 513, 252



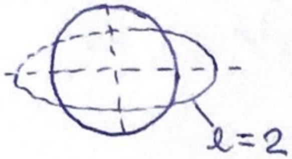
Dynamical friction (by J. Horák with A. Brandenburg and K. Bodnarenko)

(1) Stellar oscillations

→ there are many modes (p, g, f) [pressure → p, gravity → g], for us the most relevant are f (funamental) modes. In the case of a incompressible star: (Lord Kelving)

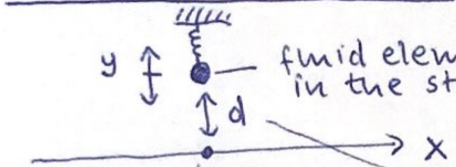
$$\omega^2 = \frac{2\ell(\ell+1)}{2\ell+1}\,\frac{GM}{R^3}$$

$\ell = 0$ .. no perturbation
$\ell = 1$ ... translation
$\ell = 2$ .. fundamental mode (node in center)
‖



... this mode maybe excited by the small black hole

(2) Mechanical analogy:



fluid element in the star (m) – we assume that it can move only in direction perpendicular to the BH trajectory ("VERTICAL" MODE)

distance of the element from BH trajectory

small BH (M_0)
motion: $x(t) = vt$

Dynamical friction

Gravitational force between the fluid element and BH:

$$F = \frac{G M_\bullet m}{R^2} \qquad \text{perpendicular component} \qquad F_\perp = \frac{G M m d}{R^3}$$

↑ distance of the fluid elm and BH : $R^2 = d^2 + (vt)^2$

$$F_\perp = \frac{G M_\bullet m\, d}{[d^2 + (vt)^2]^{3/2}}$$

This force excites oscillations of the fluid element:

$$\ddot{y} + \omega^2 y = \frac{F_\perp(t)}{m} \qquad (*)$$

Dynamical friction

We will calculate the energy the oscillator gets after passage. Intuitivelly, if passage is fast BH will pass almost without being noticed. If the passage is very slow the oscillator will adjust its phase so that it follows the BH and gain of energy will be also small, so there will be an optimal speed at which the transfer of energy to the oscillator is optimal (probably given by the period of the oscillator $\sim 1/\omega$)

Introducing complex variable $z \equiv \dot{y} + i\omega y$, (*) becomes:

$$\dot{z} - i\omega z = \frac{1}{m} F_{+}(t)$$

(note that energy of the oscillator is just $\frac{1}{2}|z|^2$ (per mass m))

Dynamical friction

General solution:

$$z(t) = A(t)\, e^{i\omega_0 t}$$

with

$$A(t) = \int_{-\infty}^{t} \frac{1}{m} F_\perp(t')\, e^{-i\omega t'}\, dt'$$

... assuming that at $t = -\infty$ there were no oscillations

we want to know amplitude after passage, at $t = \infty$:

$$A_f = \frac{1}{m} \int_{-\infty}^{\infty} F_\perp(t')\, e^{-i\omega t}\, dt =$$

↗ final

$$= GMd \int_{-\infty}^{\infty} \frac{e^{-i\omega t}}{[d^2 + (vt)^2]^{3/2}}\, dt \qquad (**)$$

although it looks simple, this integral resists even the residue theorem. But it can be expressed using second-order modified Bessel function:

Dynamical friction

Bessel function:

$$K_\nu(w) \equiv \frac{\Gamma(\nu+\frac{1}{2})(2w)^\nu}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{(\cos\xi)\,d\xi}{(w^2+\xi^2)^{\nu+\frac{1}{2}}}$$

in particular

$$K_1(w) = \frac{\frac{1}{2}\sqrt{\pi}\,(2w)}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{(\cos\xi)\,d\xi}{(w^2+\xi^2)^{3/2}}$$

Dynamical friction

Integral in (**):

$$\int_{-\infty}^{\infty} \frac{e^{-i\omega t}}{\left[d^2+(vt)^2\right]^{3/2}}\,dt = \int_{-\infty}^{\infty} \frac{\cos(\omega t)\,dt}{\left[d^2+(vt)^2\right]^{3/2}}$$

$e^{-i\omega t} = \cos(\omega t) - i\sin(\omega t)$ ← odd function: no contrib.

$\left[d^2+(vt)^2\right]$: even func

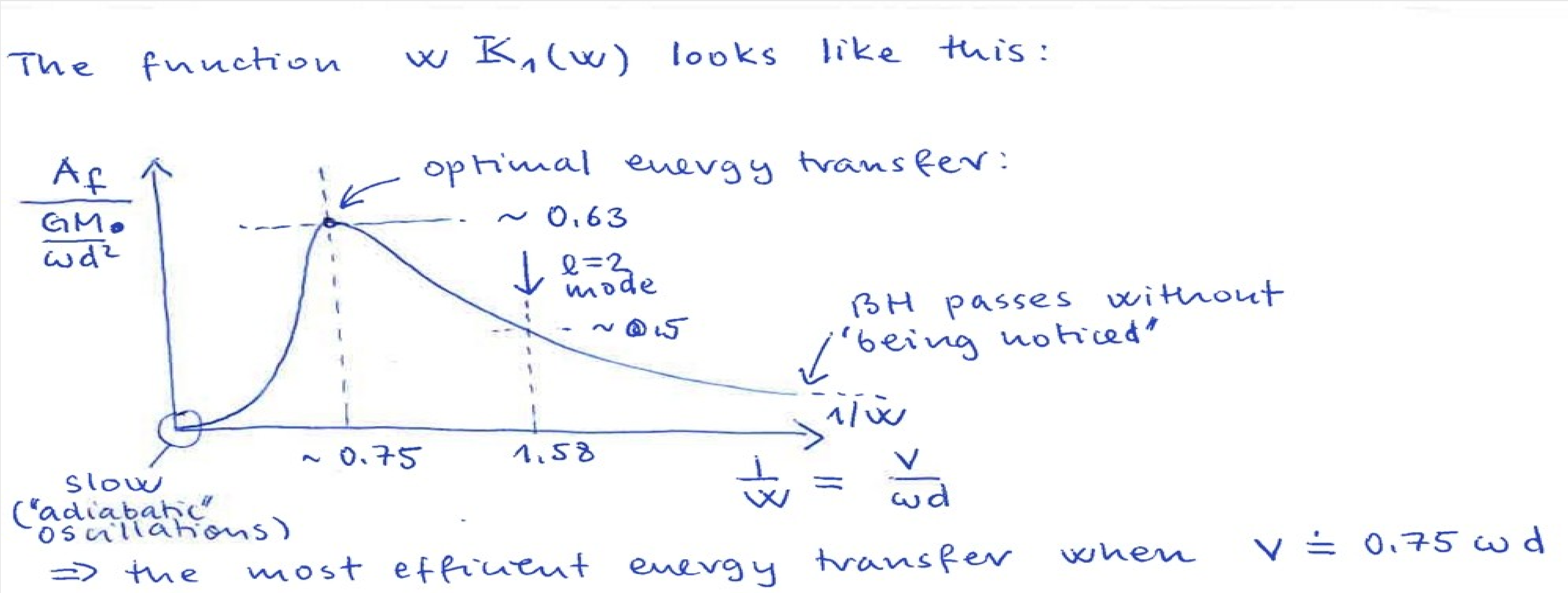
$$\omega t = \xi, \qquad \omega\,dt = d\xi$$

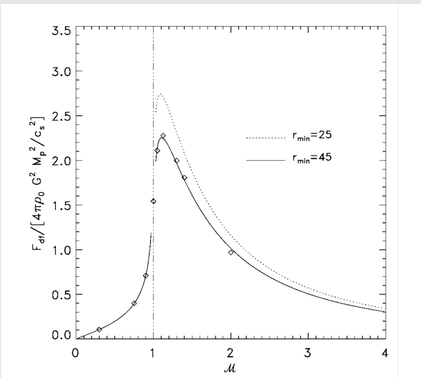
$$= \int_{-\infty}^{\infty} \frac{\cos(\xi)\,d\xi}{\omega\left[d^2+\frac{v^2}{\omega^2}\xi^2\right]^{3/2}} =$$

$$= \int_{-\infty}^{\infty} \left(\frac{\omega^2}{v^3}\right) \frac{(\cos\xi)\,d\xi}{\left[\frac{\omega^2 d^2}{v^2}+\xi^2\right]}, \qquad \frac{\omega^2 d^2}{v^2} \equiv W^{*2}$$

$$A_f = GMd\,\frac{\omega^2}{v^3}\,K_1(W^*) = \frac{GM}{vd}\,W^* K_1(W^*) = \frac{GM}{\omega d^2}\,W^{*2} K_1(W)$$

Dynamical friction

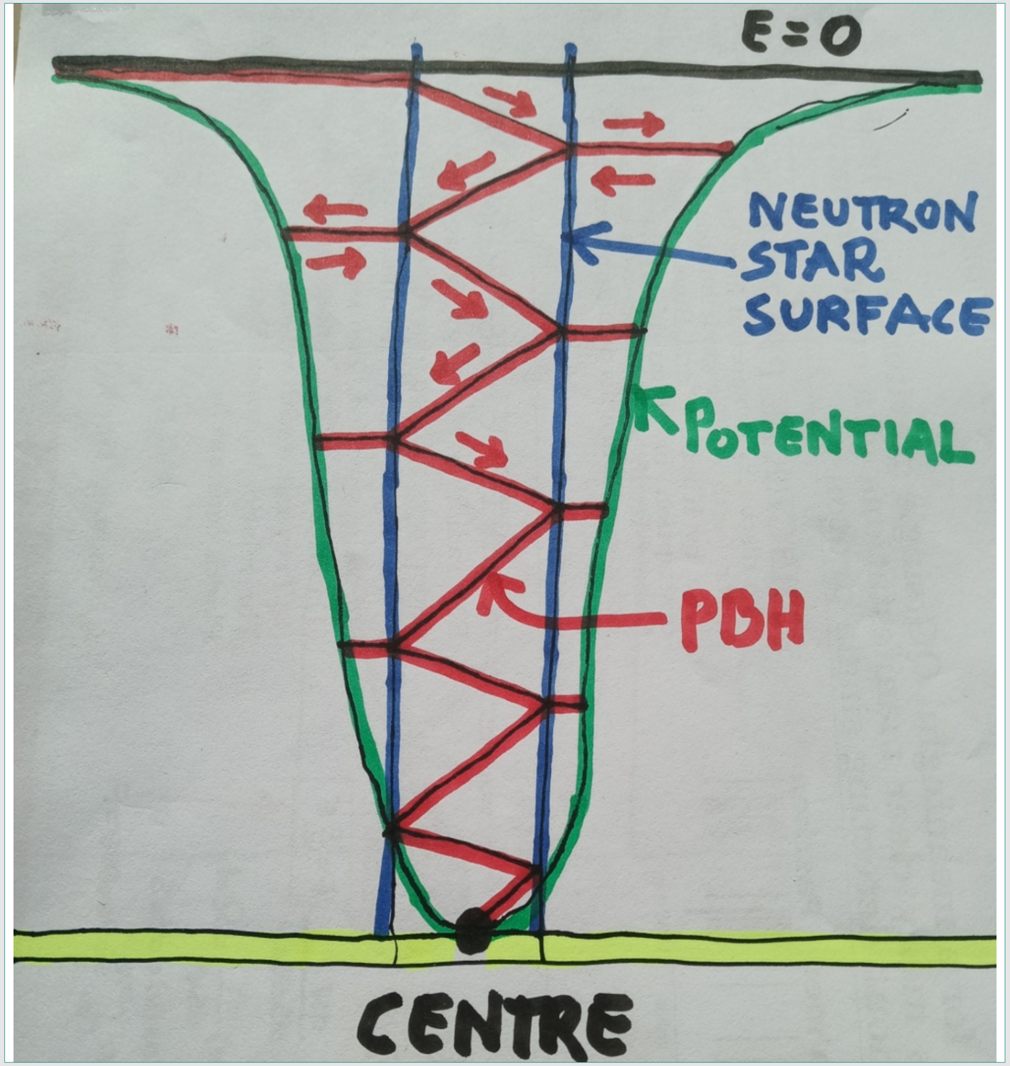


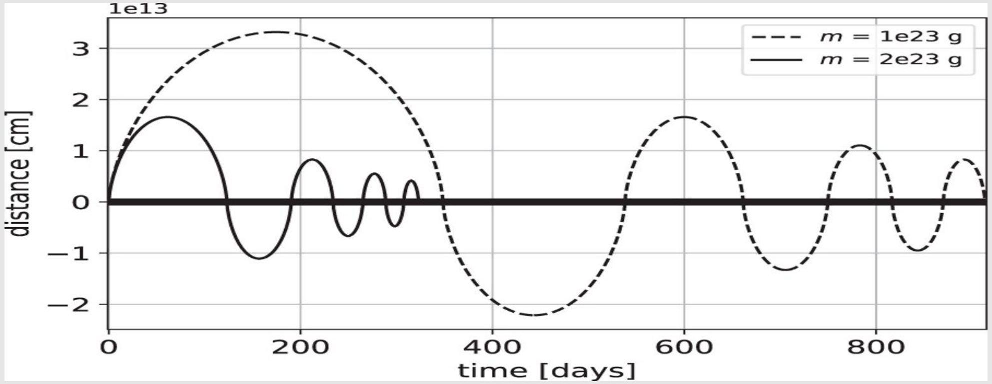


$$\ddot{r} = -\Omega_K^2 r - \left[\frac{G^2 M^3}{R} c_S^3\right] \dot{r}$$

$$t_{DF} = 2 t_G \left(\frac{c_S}{c}\right)^3 \left(\frac{R}{R_G}\right)^{3/2} \left(\frac{M}{m}\right) = 10^3 \text{ yrs for } m = 10^{20}\,\text{g}$$

DYNAMICAL FRICTION: EFFECTIVE POTENTIAL





This is a very **fast** process: $m \sim 10^{20}$ g PBH reaches the NS centre in $t \sim 10^{3}$ yr.

BONDI ACCRETION

Phys.Rev. D 103, id.L081303, 2021

The classic estimate of the Bondi accretion time t_B:

$$\dot{M}_B = \frac{\pi \rho G^2 m^2}{c_S^3} = \frac{m}{t_B}$$

$$t_B = \left(\frac{R}{R_G}\right)^2 \left(\frac{R}{c}\right) \left(\frac{M}{m}\right)$$

$$t_B = \left(10\right) \left(10^{-5}[\mathrm{s}]\right) \left(\frac{10^{33}\,[\mathrm{g}]}{m}\right)$$

It agrees with recent sophisticated derivations and numerical calculations.

Neutron Stars Harboring a Primordial Black Hole: Maximum Survival Time

Thomas W. Baumgarte[1] and Stuart L. Shapiro[2,3]

[1] *Department of Physics and Astronomy, Bowdoin College, Brunswick, Maine 04011*
[2] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
[3] *Department of Astronomy and NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*

We explore in general relativity the survival time of neutron stars that host an endoparasitic, possibly primordial, black hole at their center. Corresponding to the minimum steady-state Bondi accretion rate for adiabatic flow that we found earlier for stiff nuclear equations of state (EOSs), we derive analytically the maximum survival time after which the entire star will be consumed by the black hole. We also show that this maximum survival time depends only weakly on the stiffness for polytropic EOSs with $\Gamma \geq 5/3$, so that this survival time assumes a nearly universal value that depends on the initial black hole mass alone. Establishing such a value is important for constraining the contribution of primordial black holes in the mass range $10^{-16} M_\odot \lesssim M \lesssim 10^{-10} M_\odot$ to the dark-matter content of the Universe.

mass to date. We then may rewrite (16) as

$$t_{\max} \simeq 1 \times 10^6 \mathrm{s} \left(\frac{10^{-10} M_\odot}{M_0}\right) \simeq 2 \times 10^7 \mathrm{s} \left(\frac{10^{22}\mathrm{g}}{M_0}\right), \quad (17)$$

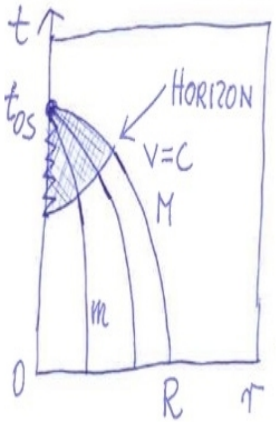
resulting in values that are remarkably close to those

This is a very fast process $t_B \sim 10\,\mathrm{yrs}$ for $m \sim 10^{20}\,\mathrm{g}$.

THE FINAL COLLAPSE

Pressure-less collapse, the famous analytic solution

Oppenheimer & Snyder, PRL, 1 September 1939

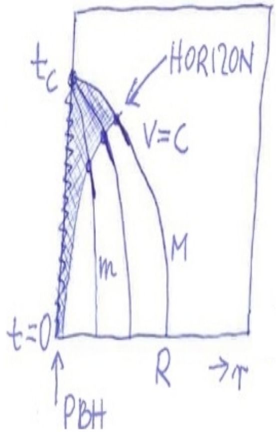


$$t_{OS} = \frac{1}{2}\left(\frac{R_G}{c}\right)\left(\frac{R}{R_G}\right)^{3/2}$$

$$t_{OS} \approx 10^{-5}\,[\mathrm{s}]$$

Realistic NS matter collapse, numerical simulations

With A. Brandenburg (et al.) at NORDITA



?? $t_C \approx t_{Bondi}$

?? Final mass

?? Shocks, bouncing solutions

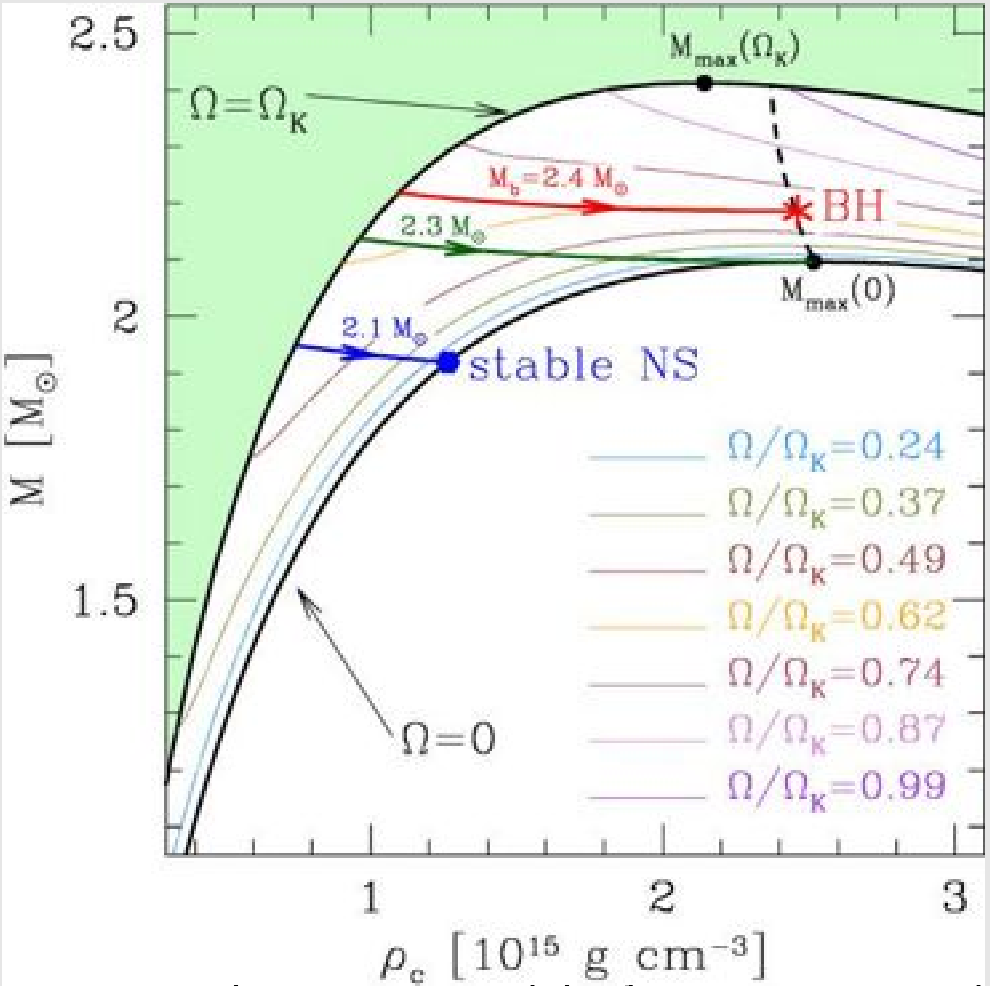
?? Rotation

?? Magnetosphere decay (no hair)

?? FRB repeaters

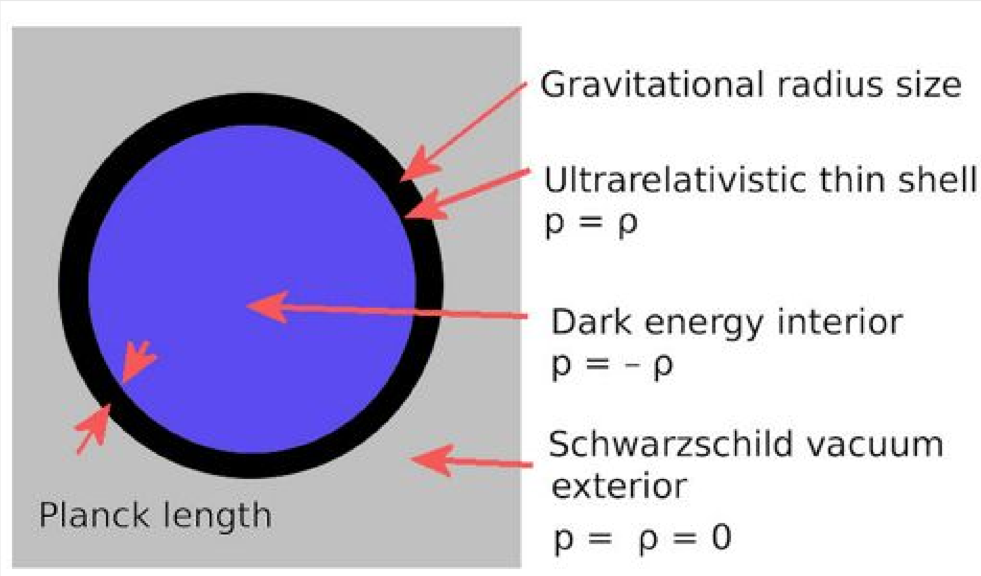
OTHER POSSIBILITIES. NEW PHYSICS?

SUPRAMASSIVE NEUTRON STARS
Falcke H. & Rezzolla L. 2014 A&A, 562



Fast rotation, super critical mass, magnetic braking, instability, collapse to LBH

GRAVASTARS
Mazur P.O. & Mottola E. 2001, ArXiv



BOSON STARS
Bustillo J.C. et al. 2021, Phys. Rev. Lett.

GW190521, the most energetic LIGO-Virgo merger, may be the head-on collision of two boson stars.

MORE ON EXOTIC OBJECTS
Cardoso, V. & Pani, P. 2019
Living Reviews in Relativity, 22, 4

POINT TO STRESS

If PBH exists, they set a lower limit for the LBHs number in the Galaxy, obviously independent of any other possible sources of LBHs.

MICROLENSING SEARCH

NO STRONG CONSTRAINTS

⋆ **Only 13 LBH/NS candidates** ⋆

A reachable range of limit for the very low PBH masses is far from the asteroidal PBHs window. Microlensing cannot directly rule out today such objects. In addition, if the number of hypothetical LBHs with $m \sim 1 M_\odot$, formed by collisions of asteroidal-mass PBHs with NS, is below a percentage of DM, present results cannot rule it out either.

NOTE: OGLE-2011-BLG-0462, once a controversial *Isolated Mass-gap Black Hole or Neutron Star*, is now proven by observations with the Hubble Telescope to certainly be a $\sim 8 M_\odot$ black hole.

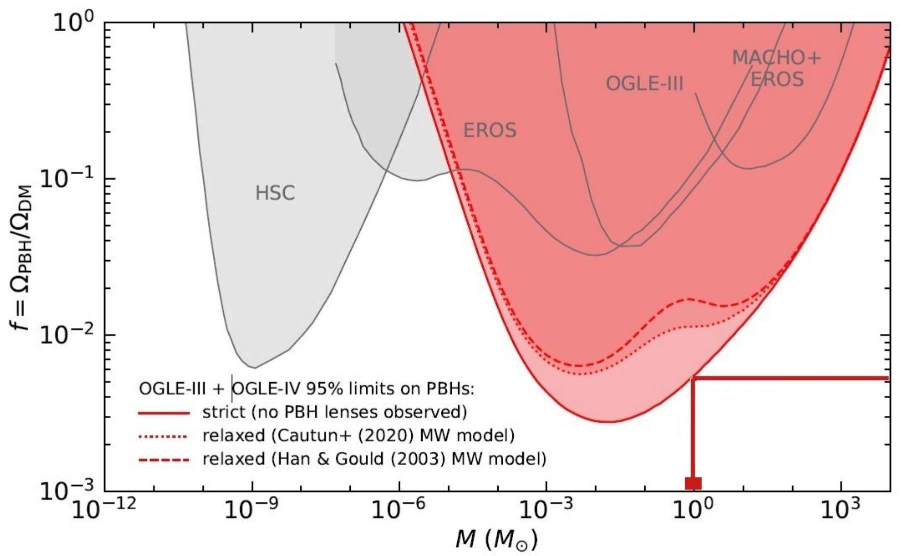
THE RECENT OGLE RESULTS

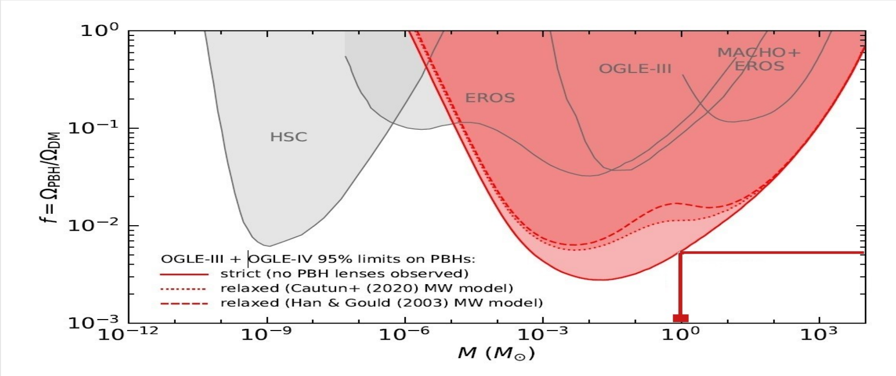
⋆ **arXiv:2403.02386v1** ⋆

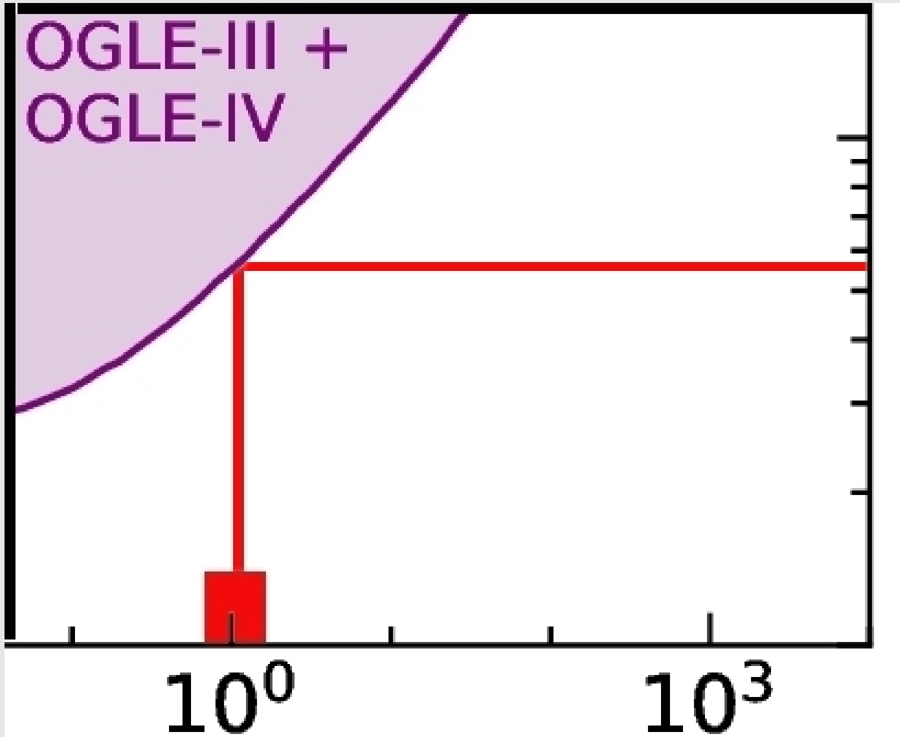
No massive black holes in the Milky Way halo

Przemek Mróz[1*], Andrzej Udalski[1], Michał K. Szymański[1], Igor Soszyński[1], Łukasz Wyrzykowski[1], Paweł Pietrukowicz[1], Szymon Kozłowski[1], Radosław Poleski[1], Jan Skowron[1], Dorota Skowron[1], Krzysztof Ulaczyk[1,2], Mariusz Gromadzki[1], Krzysztof Rybicki[1,3], Patryk Iwanek[1], Marcin Wrona[1], Milena Ratajczak[1]

[1*]Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, Warszawa, 00-478, Poland.







The total mass of DM in the Galaxy is around $\mathcal{M}_{DM} \approx 10^{12}\, M_\odot$ and the total mass of all NSs in the Galaxy is $\mathcal{M}_{NS} \approx 10^9\, M_\odot$. Therefore, if most of the NSs would be transformed into the LBHs, the fraction $f = (\mathcal{M}_{BH})/(\mathcal{M}_{DM})$ in the mass range $\sim 10^0\, M_\odot$ would be $f = 10^{-3}$, i.e. only about $4 - 5$ times smaller than the sensitivity of the present OGLE search.

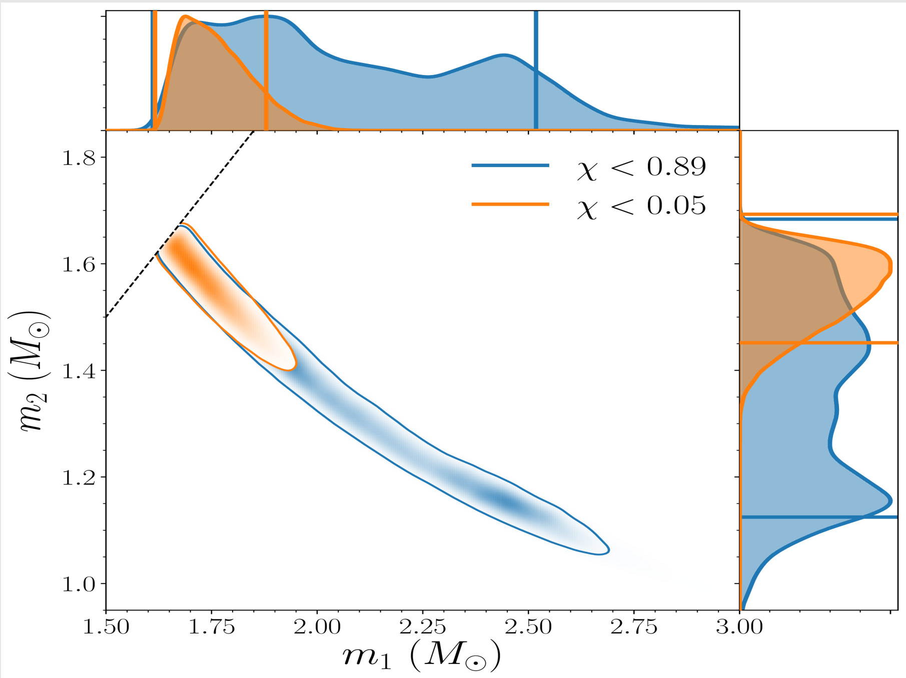
LIGO-VIRGO-KARGA SEARCH

PARTICULAR EXAMPLES

GW190425

(also GW170817, GW191219-163120)

The chirp mass for is $1.44^{+0.02}_{-0.02} M_\odot$ (90% confidence). Spin versus mass ratio degeneracy: the heavier component mass is $1.62M_\odot - 1.88M_\odot$ (low-spin) and $1.61M_\odot$ – $\mathbf{2.52M_\odot}$ (high-spin); for the lighter component $1.45M_\odot - 1.69M_\odot$ (low-spin) and $\mathbf{1.12M_\odot}$ – $1.68M_\odot$ (high-spin).



FUTURE PERSPECTIVES

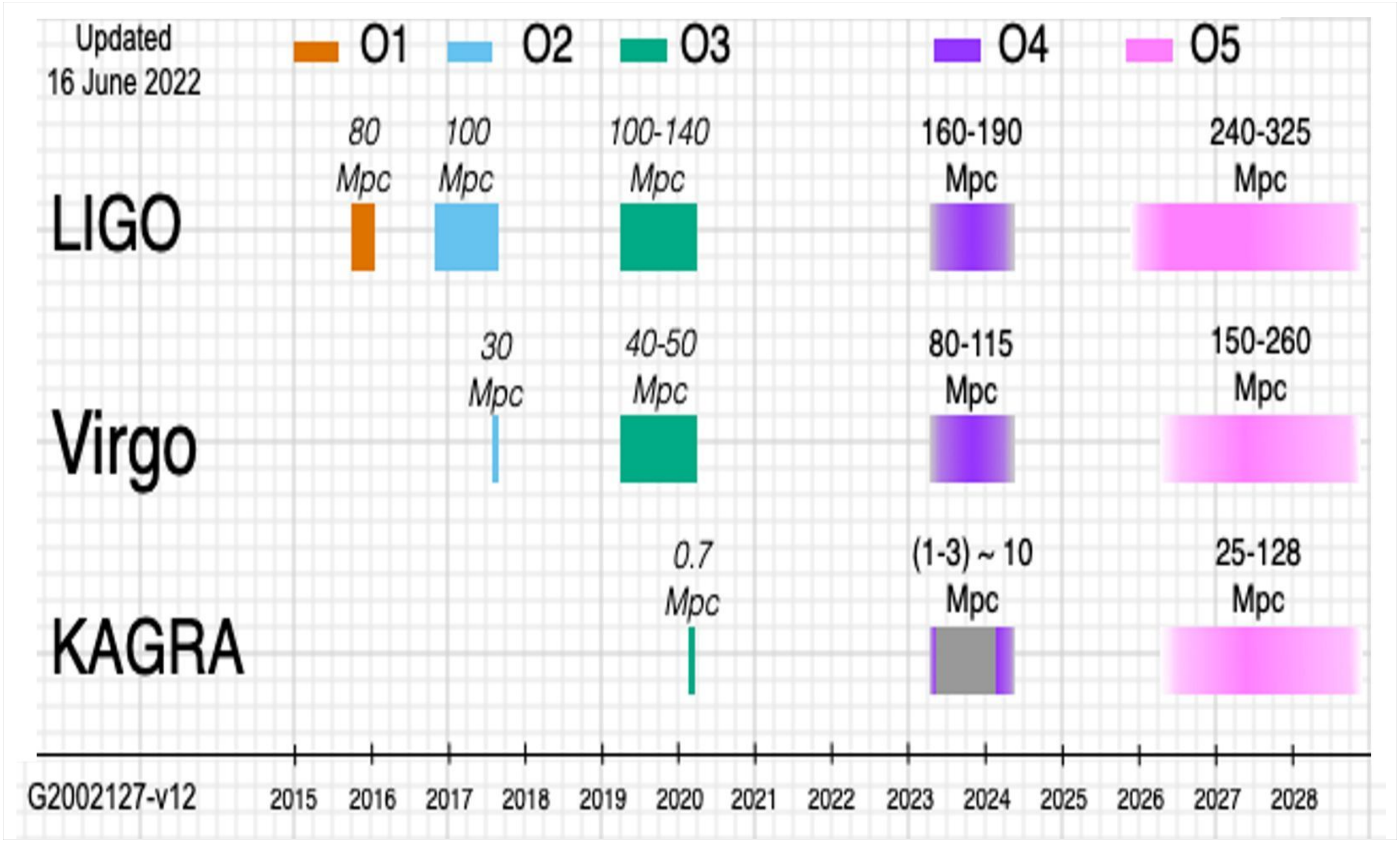
(M. Bejger, private communication)

No conclusive results yet. Only about dozen candidates for LBH/NS in the O3 catalogue.

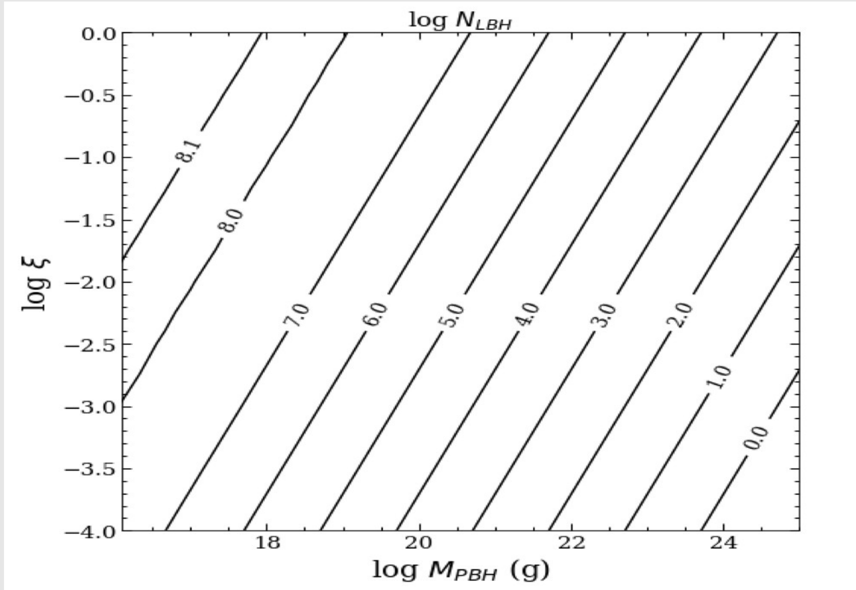
BUT

there are surprises in the unpublished O4 results.

PLANNED IMPROVEMENTS



SUGGESTIONS BY CAMBRIDGE COLLEAGUES (25)



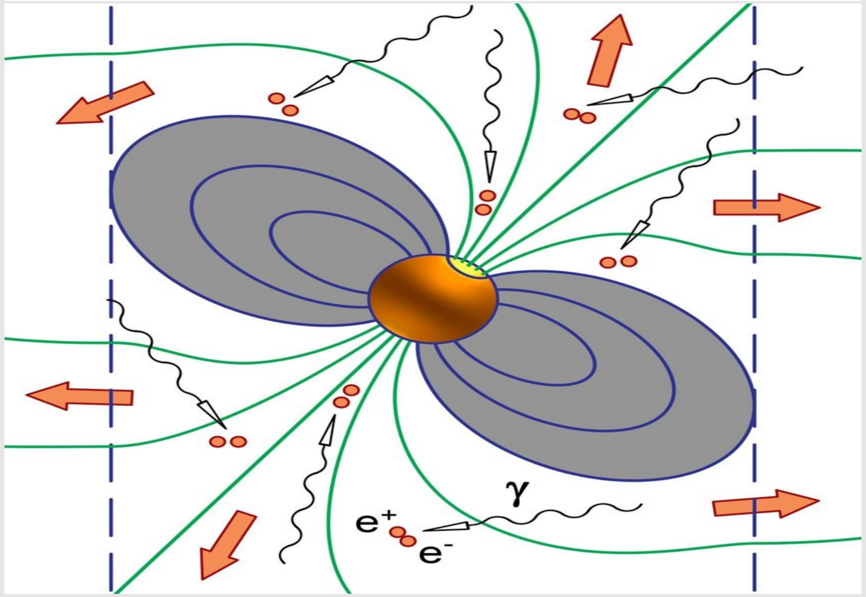
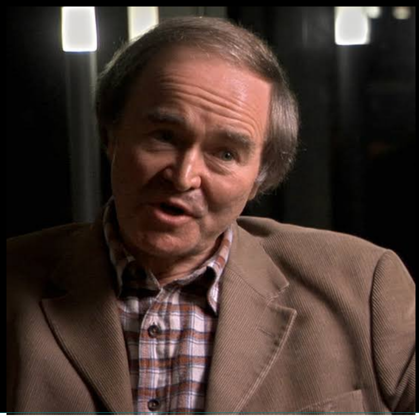
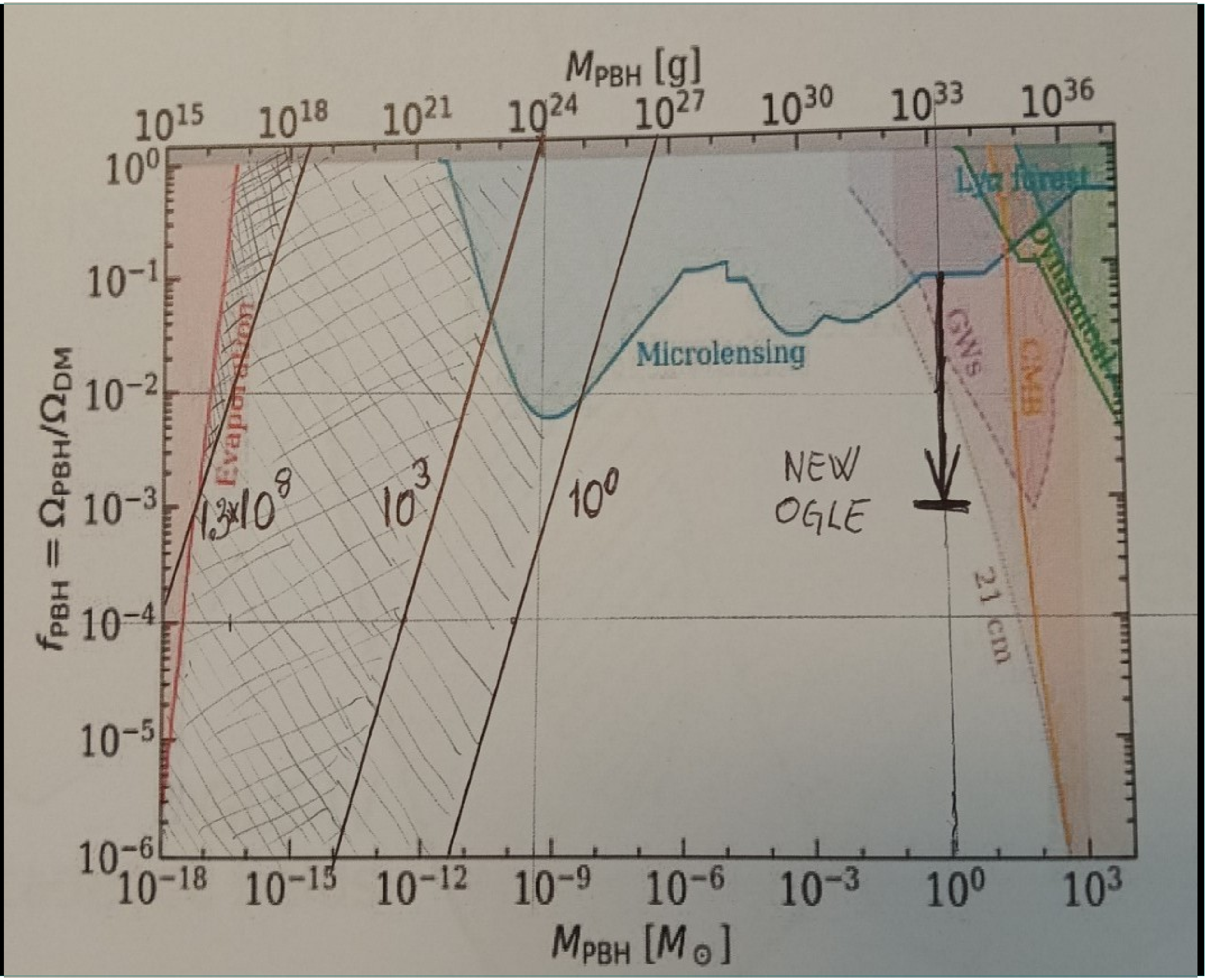


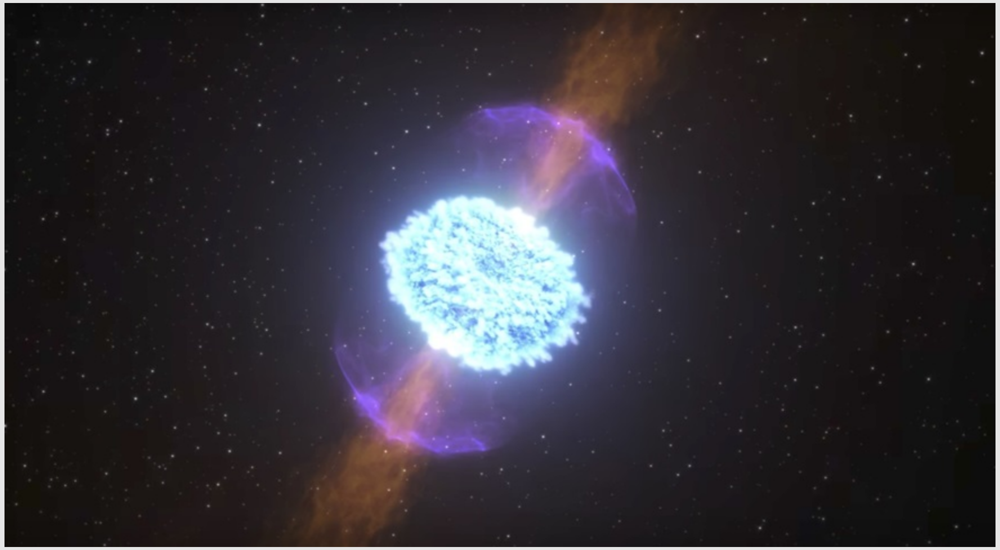
FIGURE SUGGESTED TO US BY B. CARR





CONCLUSIONS AND PROBLEMS

If the hypothetical primordial black holes exist, they must collide with Galactic neutron stars, and produce the low mass black holes.



1. The NS-BH mass gap ⋆

Collisions of PBH with NS not only produce LBH but also reduce the present day number of NS from the number anticipated from the supernova rate only. There are two astrophysical situations in which one may be sure that a compact object is the neutron star: pulsars are neutron stars, and in some LMXRB we may argue that one component of the LMXRB is a neutron star:

2. Number of pulsars ⋆

3. Number of NS in LMXRB ⋆

---

4. The final collapse ⋆

T H E E N D

For a clickable pdf copy of these slides write to

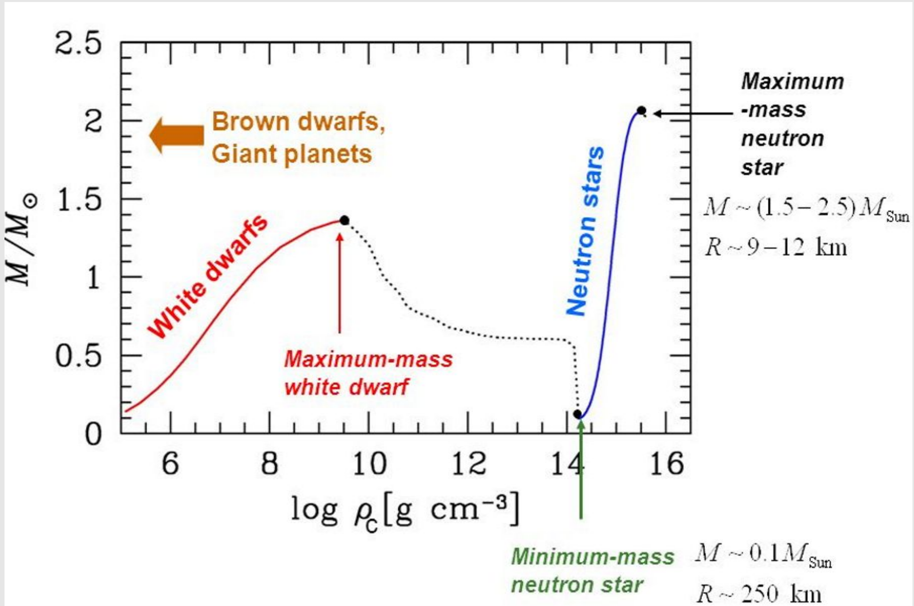
marek.abramowicz@physics.gu.se

★ ★ ★ ★ ★ ★

MINIMUM STELLAR ORIGIN BH MASS

THEORY

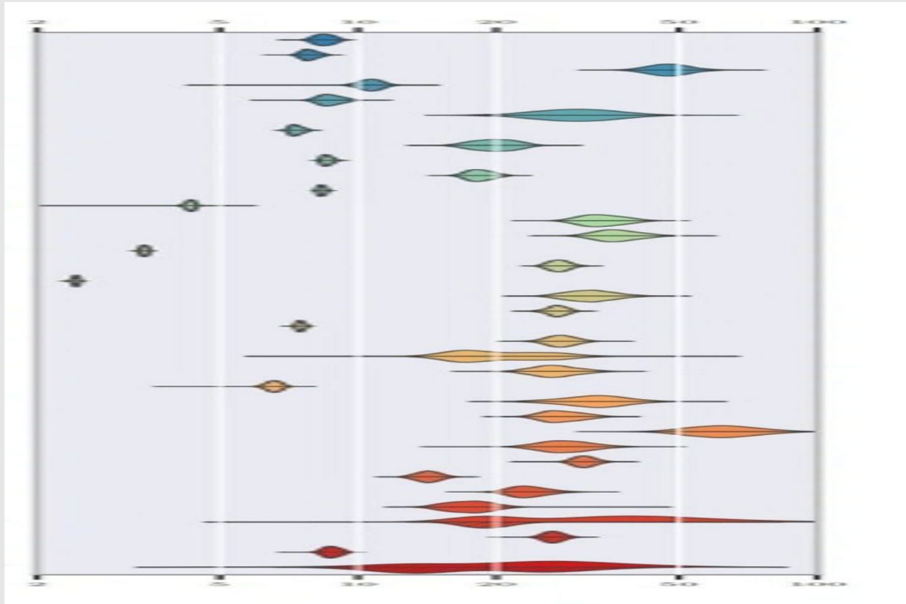
Numerical simulations (collapse)



OBSERVATIONS

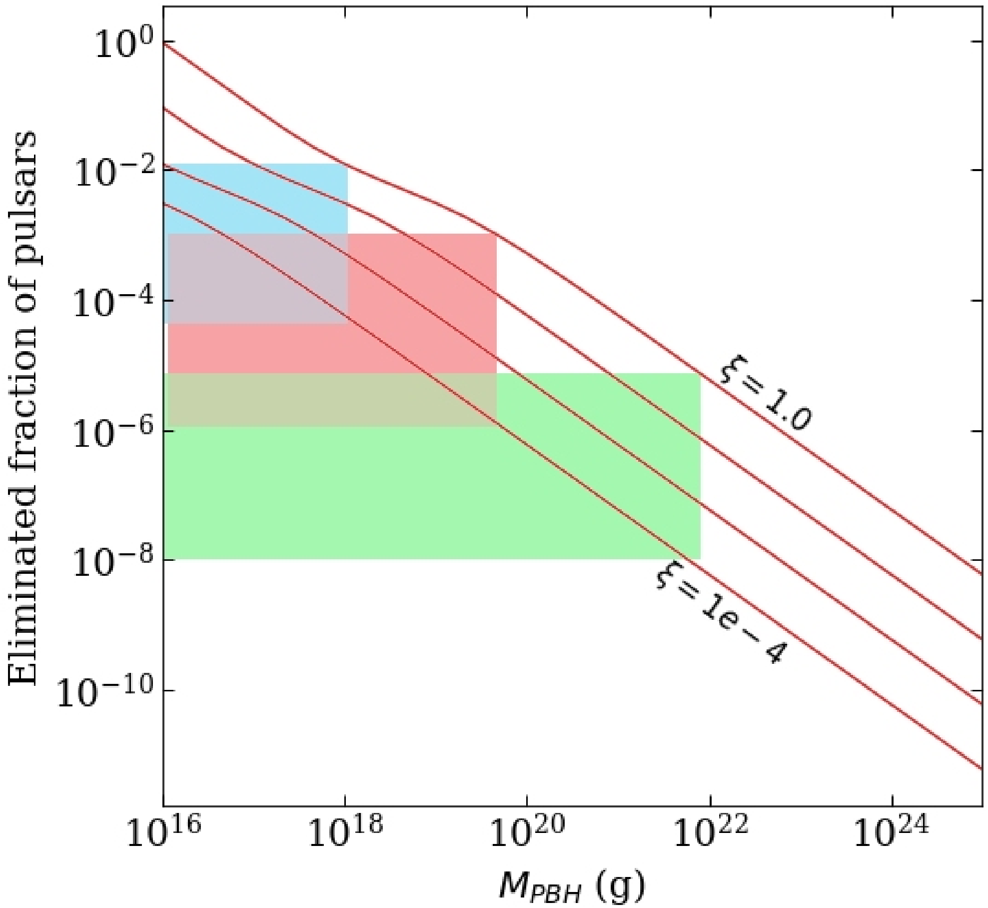
No NS-BH mass gap?

BH massses in LMXB show a NS–BH mass gap, but LXMBs occupy a small and specific part of the BH evolutionary parameter space: they do not faithfully represent the whole Galactic population.



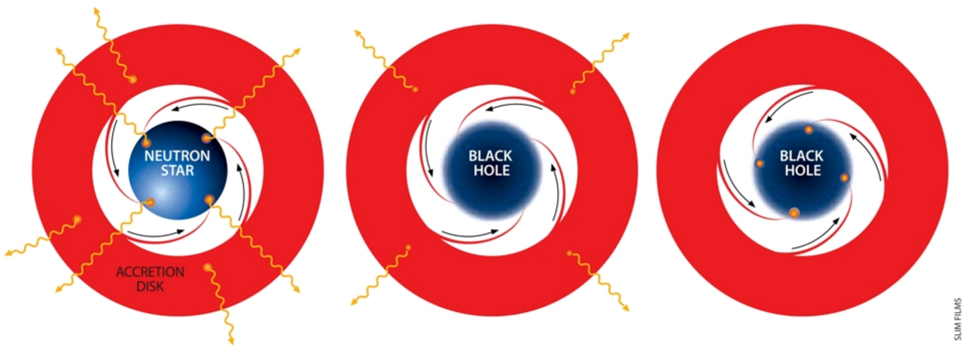
BH in non-LMXB do not show evidence of a sharp NS-BH mass gap. LIGO-Virgo have found mass-gap BH both as the merger remnant ($\sim 3\,M_\odot$ GW170917 and $3.4\,M_\odot$ GW190425) and merger components ($\sim 2.6 M_\odot$ GW190814). OB110462 is the first measured isolated Galactic NS or mass-gap BH

NUMBER OF PULSARS (by M. Wielgus)

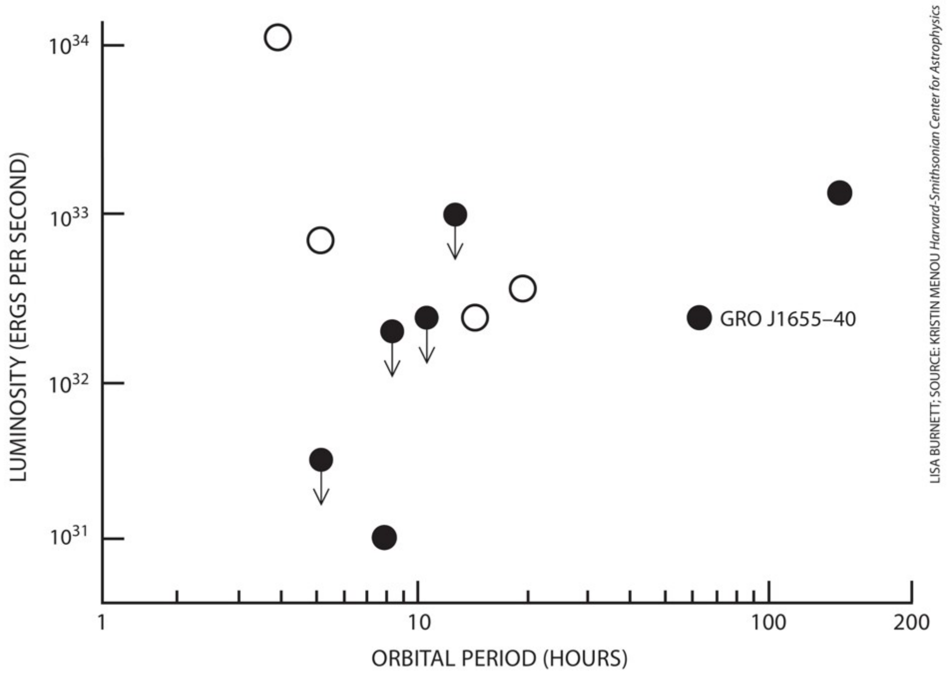


Pulsars live only about 10^7 years and during this short time only an insignificant fraction of them will be killed by PBHs.

NSs versus LBH in LMXRBs (from J.-P. Lasota Sci. Amer. article)



THREE STYLES OF ACCRETION give off radiation in different ways. As gas spirals onto a neutron star, it releases much of its energy on impact (*left*). But gas spiraling into a black hole does not have an impact; it simply vanishes through the horizon. Either the gas releases energy before it reaches the horizon (*center*)—as it will if its density is high, so that gas atoms collide—or it carries the energy with it to the grave (*right*). Astronomers can use the style of radiation to deduce which type of object is present.



PROOF OF BLACK HOLES has come from a comparison of the brightness (*vertical axis*) of objects heavier than 3 solar masses (*black circles*) and lighter than 3 solar masses (*white circles*). The heavier bodies are fainter than the lighter ones even if they have the same orbital period (*horizontal axis*). Yet two objects with the same orbital period accrete matter at the same rate and should therefore emit roughly the same amount of radiation. The discrepancy can be explained if matter and energy are disappearing from our universe—as only a hole could accomplish. (The arrows indicate upper limits on a measurement.)

Draft version November 16, 2023
Typeset using LaTeX twocolumn style in AASTeX631

X-ray Binaries Hosting Light Black Holes?

Lukasz Stawarz,[1] Marek Abramowicz,[2,3,4] Jean-Pierre Lasota,[5,3] and Maciek Wielgus[6]