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Stellar evolution constrains primordial black holes as dark matter candidates

M.S. Pshirkov[1,2], F. Capela[3], P.G. Tinyakov[4]

[1]Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky prospekt 13, 119992, Moscow, Russia
[2] Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia
[3]DAMTP,Centre for Mathematical Sciences,Wilberforce Road,Cambridge,CB30WA,United Kingdom
[4] Université Libre de Bruxelles, Service de Physique Théorique, CP225, 1050, Brussels, Belgium

PBHs as Dark Matter candidate

- Could be a viable alternative to particle dark matter

PROS

- Don't need to alter extremely well-tested SM
- Very cold and collisionless* (*advantage at the moment)
- Dark
- Extremely small cross-section: $\sigma \sim 10^{-56} (m/1\text{g})^2 \text{ cm}^2$

CONS

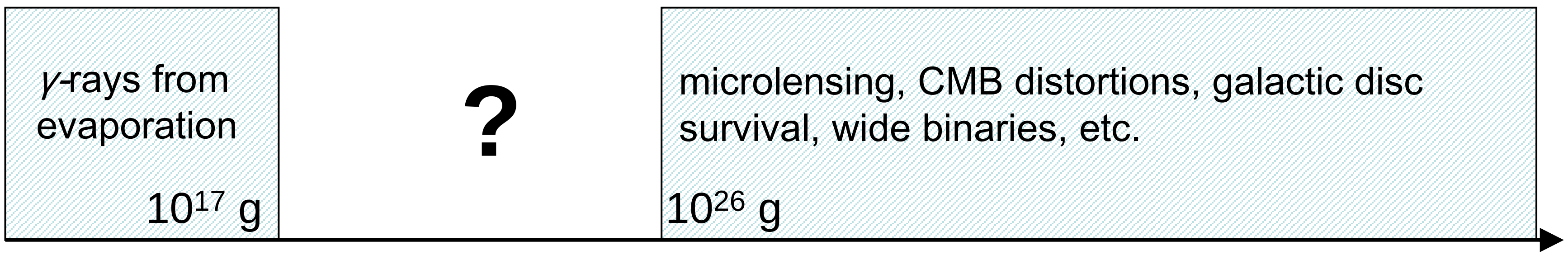
- Very difficult to form → very special density perturbation spectrum in the very Early Universe
- Extremely small cross-section: $\sigma \sim 10^{-56} (m/1\text{g})^2 \text{ cm}^2$

PBHs: their mass spectrum

- No specific mass scale (except, maybe, $M_{Pl}=10^{-5}$ g)
- Due to the Hawking evaporation we could get rid of all PBH with $m<10^{15}$ g

$$t_H = \frac{5120\pi G^2 M_{BH}^3}{\hbar c^4} = 10^{64}\left(\frac{M}{M_{\rm Sun}}\right)^3 \quad \text{years}$$

- At higher masses PBH could contribute to DM considerably



- 10^{17}-10^{26} g window remains mostly unconstrained

Closing the gap

- As stated above, PBHs are exceedingly small:

$$r_{BH}=10^{-8}\ (M_{BH}/10^{20}\ \mathrm{g})\ \mathrm{cm}$$

- Could considerably interact only with extremely dense matter

- The best candidate – neutron stars (NSs) with $\rho \sim 10^{15}$ g/cm^3.

- If a PBH *somehow* get captured by a NS, the latter one would be destroyed in a very short time, less than 10^6 years – thus simple observations of NS could be constraining.

How to get PBH inside NS?

- There are two similar ways:

  A. Simple capture by NS itself

  <u>B. multi-staged</u>

    I. Formation of DM mini-halo during the star-formation process

    II. Capture of DM from that mini-halo

    III. Sinking of DM closer to the central regions of the star

    IV. Supernova explosion/NS formation. The NS would inherit some fraction of DM. That would result in constraints on fraction of PBH in DM.

- We will mostly discuss the second option.

DM mini-halo

- GMC (M=10^5 M$_\odot$, ρ~500 cm^{-3}) fragmenting into much smaller and denser prestellar cores (M~M$_\odot$, ρ~10^6 cm^{-3})
- Some tiny fraction of the DM is gravitationally bound to PC:

$$\rho_{DM,bound} = \overline{\rho}_{DM} \frac{4\pi}{3} \left(\frac{3|\phi_0|}{\pi \overline{v}^2} \right)^{3/2}$$

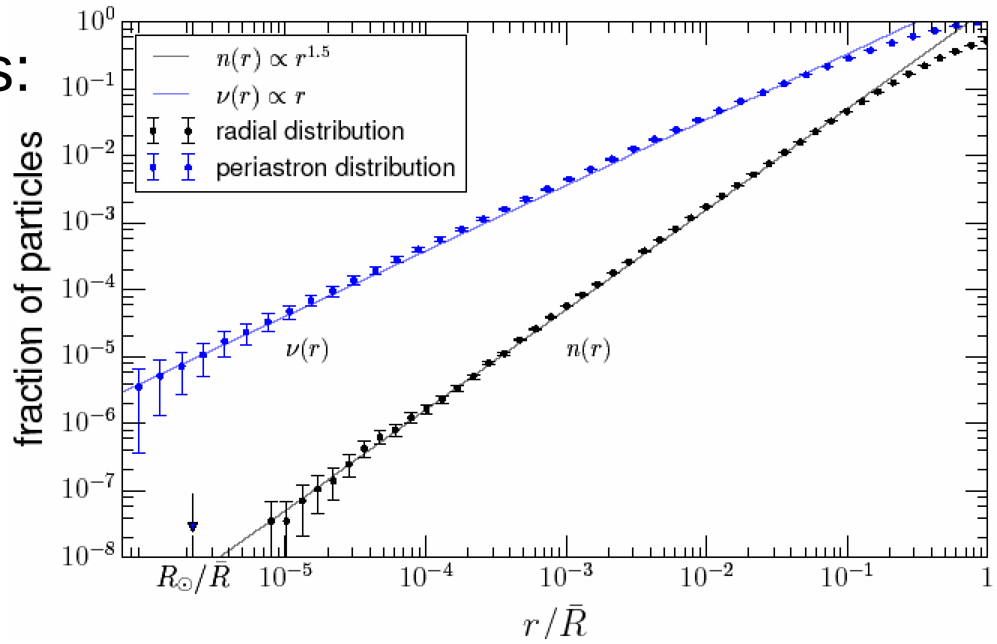
- Effect ~velocity dispersion$^{(-3)}$, ~DM concentration => interested in regions with high abundance of slow-moving DM
- The best candidate would be globular clusters of primordial origin – could form already at z=10-12
- The DM density could be as high as 10^4 GeV/cm^{-3} in the very beginning, v~7 km/s.
- The effect is easily rescalable.

DM mini-halo. Adiabatic contraction

- Prestellar core undergoes process of contraction
- DM follows the gravitational pull and concentrates in the deepening gravitational well
- The process takes much longer than the free-fall time $t_{ff} \sim (G\rho)^{-1/2}$, so certain adiabatic invariants are conserved:
  - Angular momentum (central field)
  - $\oint p\,dq = ET$
- That allows us to perform simulations: inject 30 millions test particles and evolve their orbits in the gravitational field of the gradually increasing central mass. Finally, we get some cuspy distribution $\rho(r) \sim r^{1.5}$

DM mini-halo. Adiabatic contraction

- Most of the particles reside on the very elongated orbits: there are much more particles that ever come within some *r*, than there within *r* at any given moment.
- Enhancement factor is around 2×10^3 for $r=R_\odot$



- This could be a very large reservoir for DM – if we could only capture it effectively. Now everything is defined by DM-nucleon interactions
- From now on we would stick to one particular candidate – PBHs.

Capture of PBHs from mini-halo

- The capture proceeds in two stages:
  1. PBH spends most of its time outside the star, losing small fraction of its energy at each subsequent passage via dynamical friction

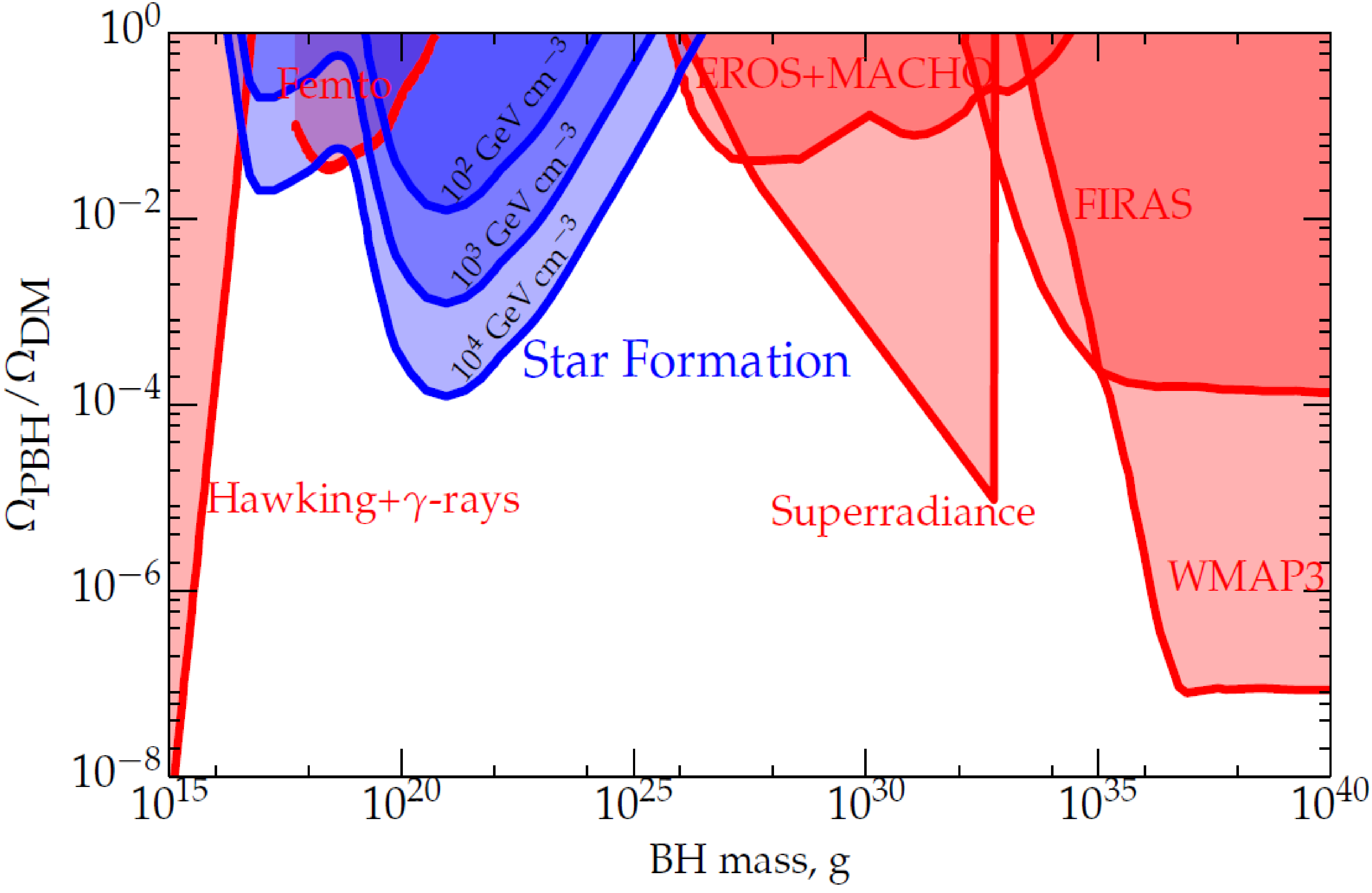
$$t \sim 4\times 10^2 \tau \sim \frac{100\pi R_*^{5/2} v_{esc}^2}{G m_{BH} \sqrt{G M_*} \ln\Lambda} \sim 2\times 10^8 \,\mathrm{yrs}\left(\frac{10^{22}\,\mathrm{g}}{m_{BH}}\right)$$

  2. when the PBH is fully inside the star it starts to gradually lose energy and sink to the centre. The duration of this stage is considerably shorter

- If in the lifetime of the star $N_{BH} \geq 1$ PBHs of mass m_{BH} would sink to the centre, we would have some constraints:

$$\frac{\Omega_{PBH}}{\Omega_{DM}} \leq \frac{1}{N_{BH}}$$

Constraints



Conclusions

- Mere observations of compact objects in regions with high DM density could considerably constrain PBH as the main DM constituent

- Observations of NSs in dwarf spheroidals would constrain PBHs in a broad 10^{20}-10^{24} g range

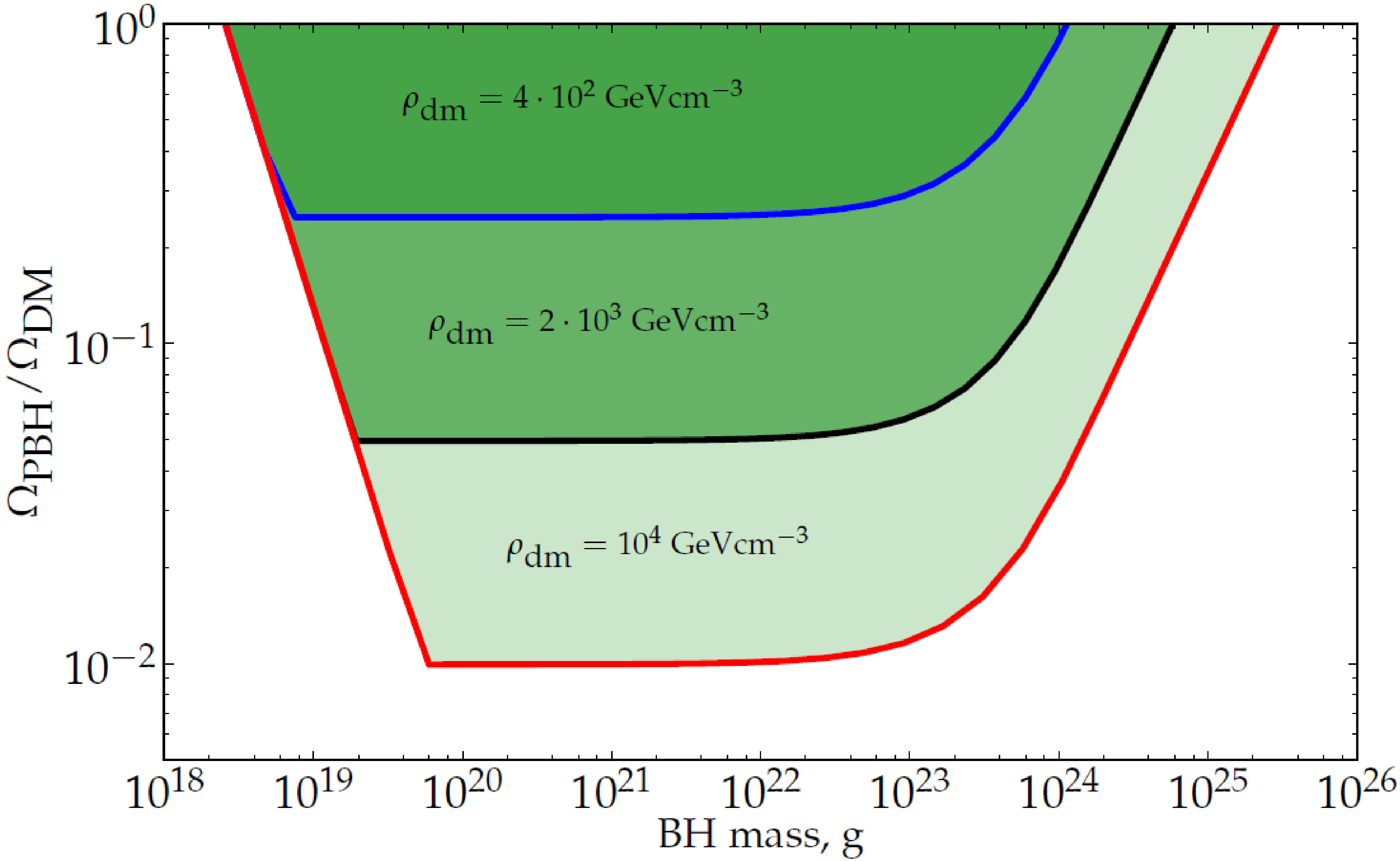
- If some old GCs are of primordial origin that would effectively rule out PBHs in 10^{16}-10^{25} g range (Ω_{PBH}~1), thus completely closing the last remaining possible window.

THANK YOU!

Supplementary

$M_\bullet/M_\odot$	ρ_{PSC}, GeV cm^{-3}	M_{bound}, g
1	2×10^1	4.4×10^{19}
2	5.2×10^1	2.5×10^{20}
3	9.2×10^1	7.2×10^{20}
4	1.4×10^2	1.5×10^{21}
5	1.9×10^2	2.6×10^{21}
6	2.4×10^2	4.2×10^{21}
7	3×10^2	6.2×10^{21}
8	3.6×10^2	8.7×10^{21}
10	5×10^2	1.6×10^{22}
12	6.4×10^2	2.4×10^{22}
15	8.7×10^2	4.3×10^{22}

Supplementary



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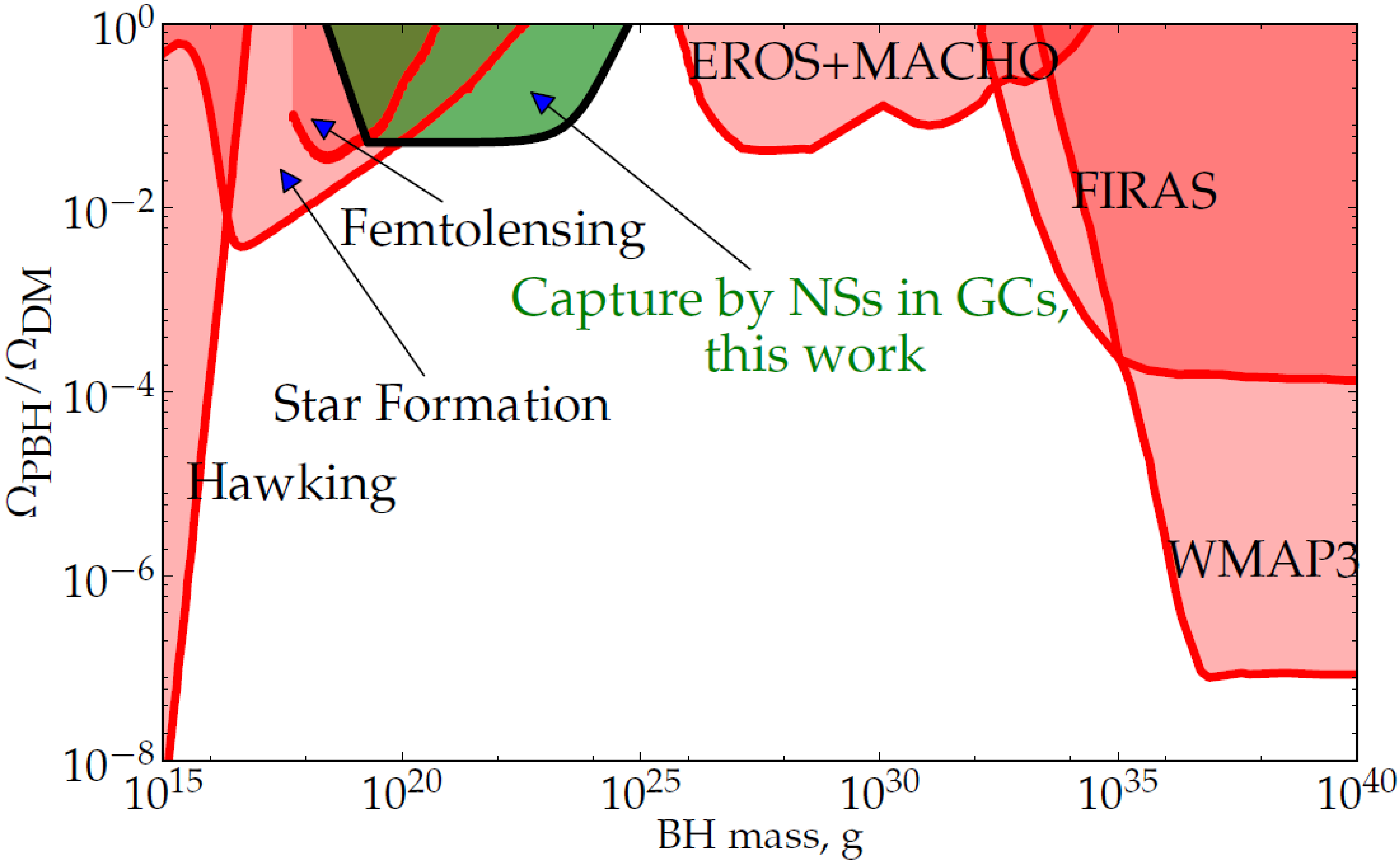

Supplementary

arXiv:1209.6021

arXiv:1301.4984

arXiv:1402.4671

arXiv:1403.7098