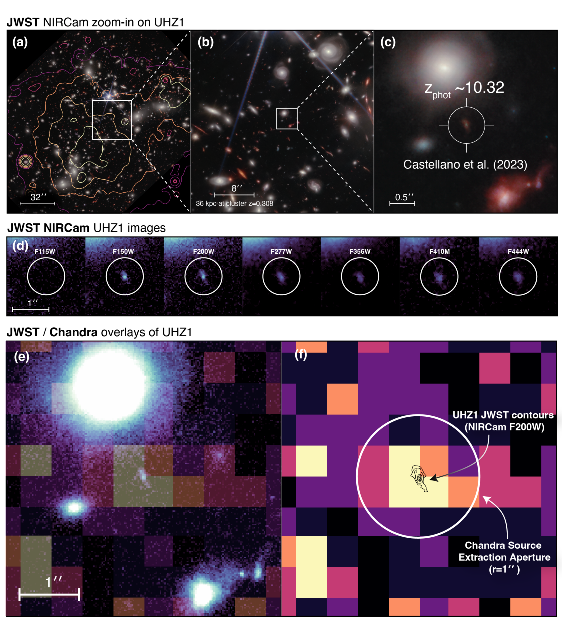
Dark and Shiny Dresses around Primordial Black Holes and interplay with other DM Candidates

Daniele Gaggero

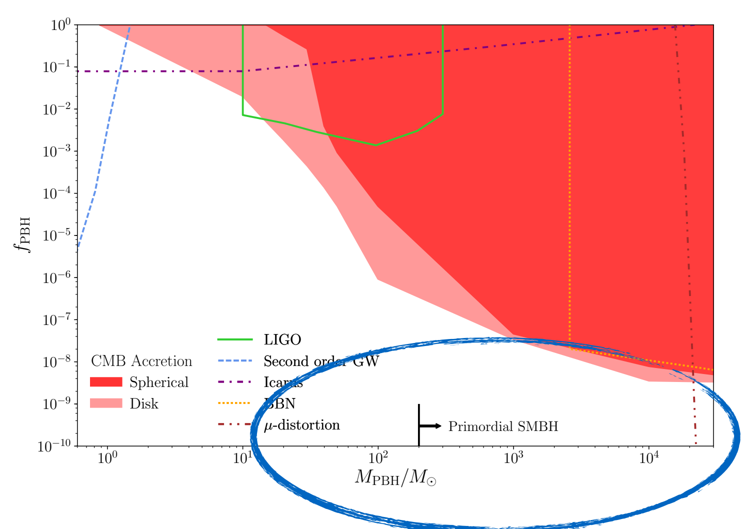
INFN
PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

A sub-dominant population of PBHs?

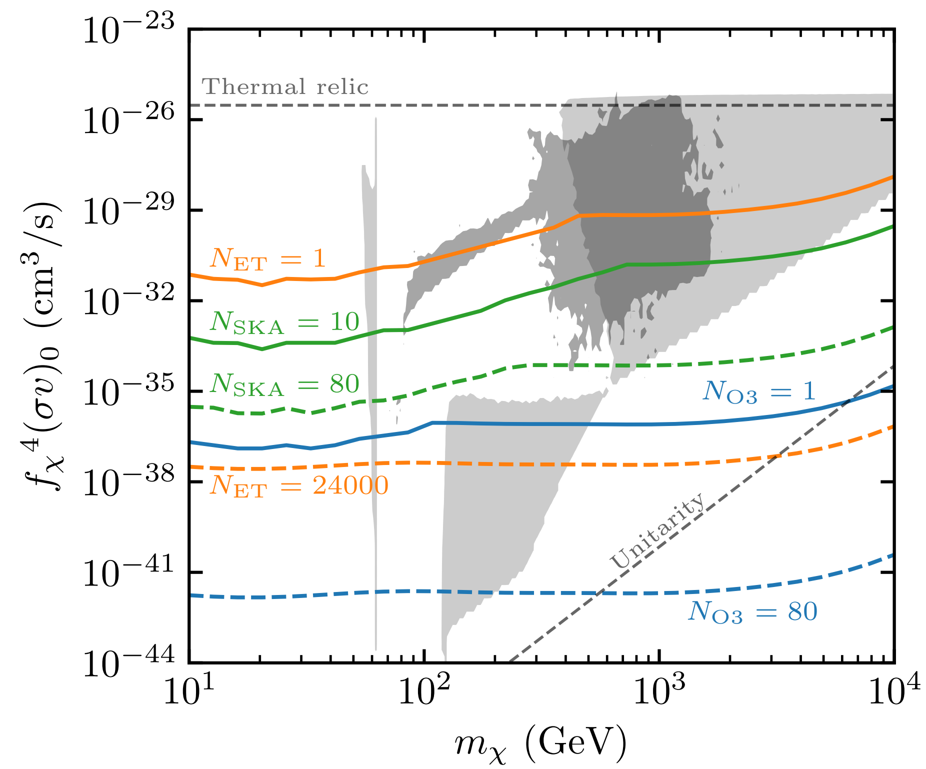
- A discovery of a sub-dominant population of DM in the form of (massive) PBHs could:
  - Reveal non-trivial **early-universe physics**
  - Solve the problem of the **SMBH seed**?
  - Help us set stringent **upper limits** on other DM candidates



Bogdan+ 2305.15458

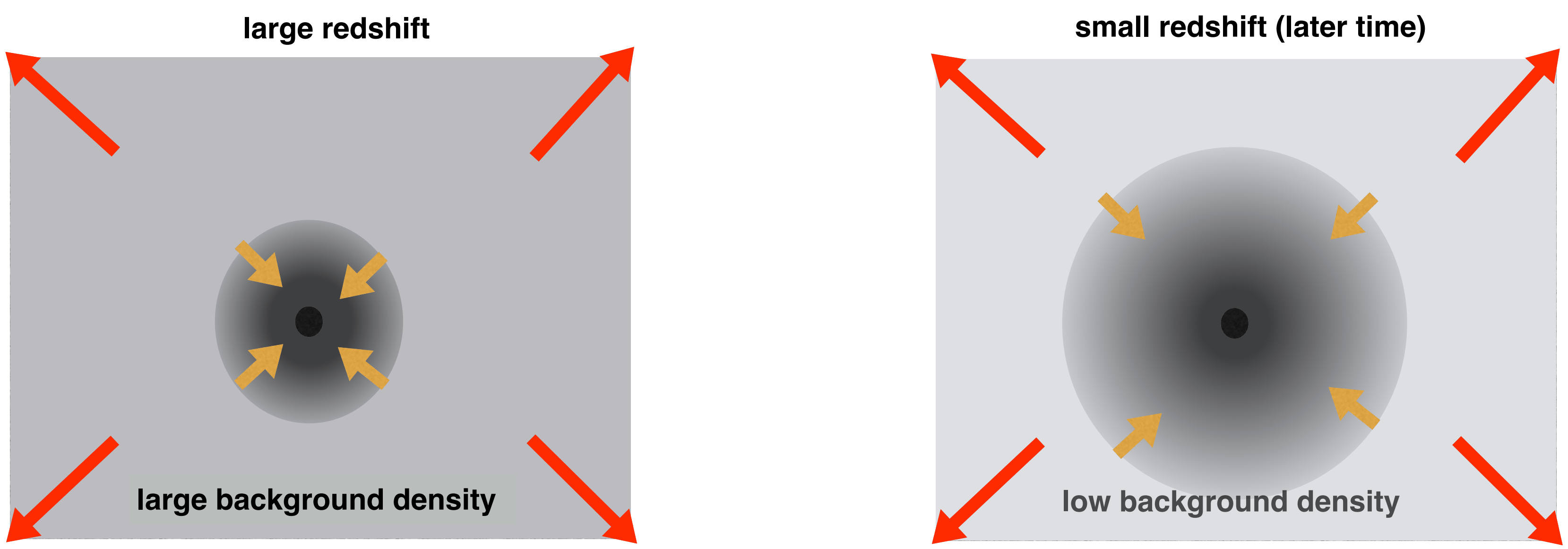


Serpico+ 2002.10771



The importance of the "Dark Dress"

- **Sub-dominant population of PBHs** immersed in another form of DM, expanding and diluting
- Accretion of **DM mini-halos**: Balance between **gravitational pull** and **expansion of the universe**



$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{G M_{\mathrm{PBH}}}{r^2} + (\dot{H} + H^2) r \,,$$

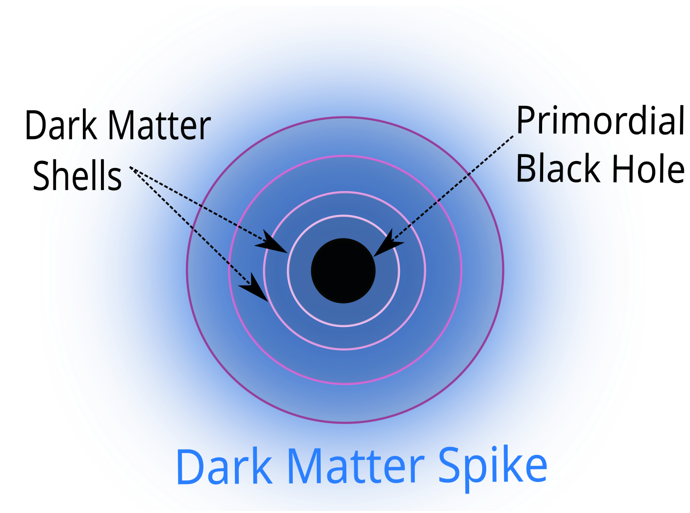
Turn-around radius for a generic DM shell

$$G M_{\mathrm{PBH}} = (1 + 3\omega) \frac{H^2}{2} r_{\mathrm{ta}}^3 .$$

- A PBH can accrete a DM halo with $M_{Halo} = M_{PBH}$ at the end of the radiation era ($z = z_{eq}$)

Sub-dominant population of PBHs: The "Dark Dress"

- Simple analytical computation (DM particles are frozen in at turn-around with their density matching the background density):

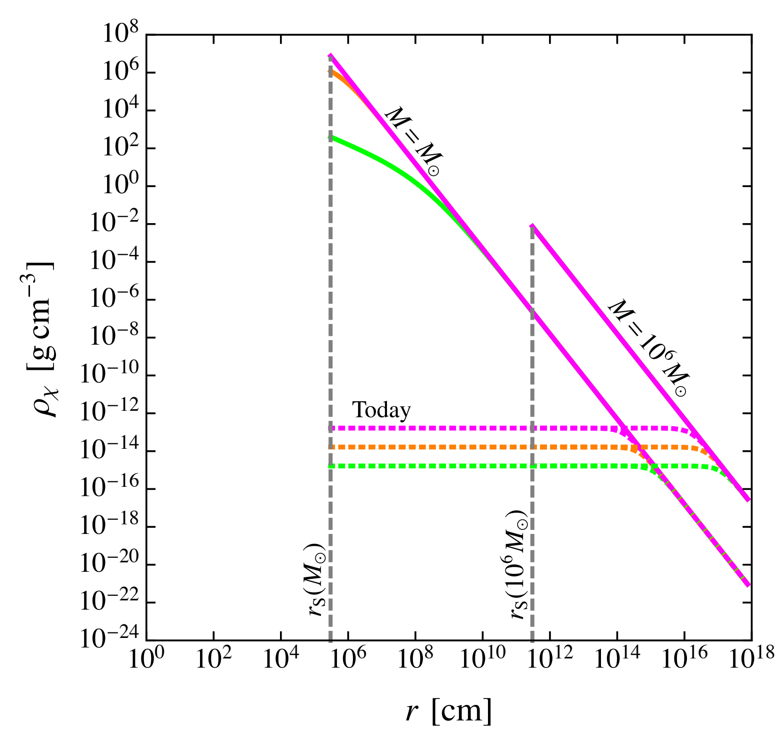


$$r_{\rm ta} \simeq \left(2\,G\,m_{\rm pbh}\,t_{\rm ta}^2\right)^{1/3}$$

$$\rho_{\rm sp}(r) \simeq \frac{\Omega_{\rm cdm}}{\Omega_{\rm m}}\frac{\rho_{\rm eq}}{2}\left(2\,G\,m_{\rm pbh}t_{\rm eq}^2\right)^{3/4} r^{-9/4}$$

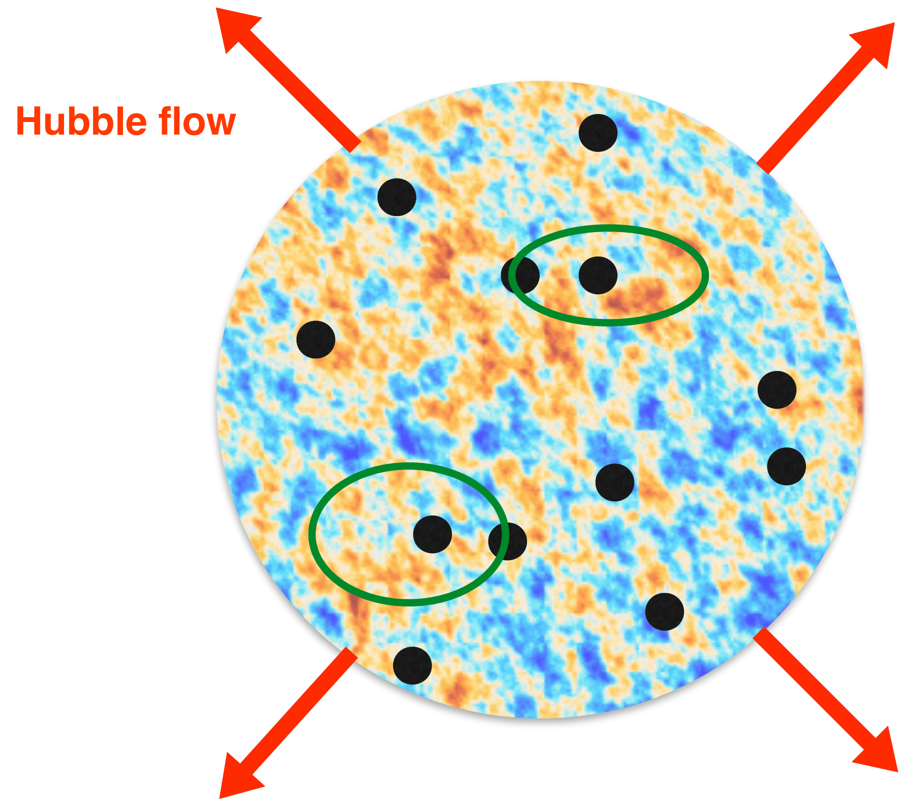
Analytical and numerical computations in [Bertschinger, ApJS 1985; Sten Delos *et al.* 1712.05421; Gosenca *et al.* 1710.02055; Adamek et al. 1901.08528]

- *Recent developments:* Computation of profile as function of:
  - BH mass and DM particle mass,
  - Temperature of kinetic decoupling [Boudaud+ 2106.07480, Carr+ 2011.01930]



Dark Dress in action: The merger rate story

A) Binaries formed in the early Universe



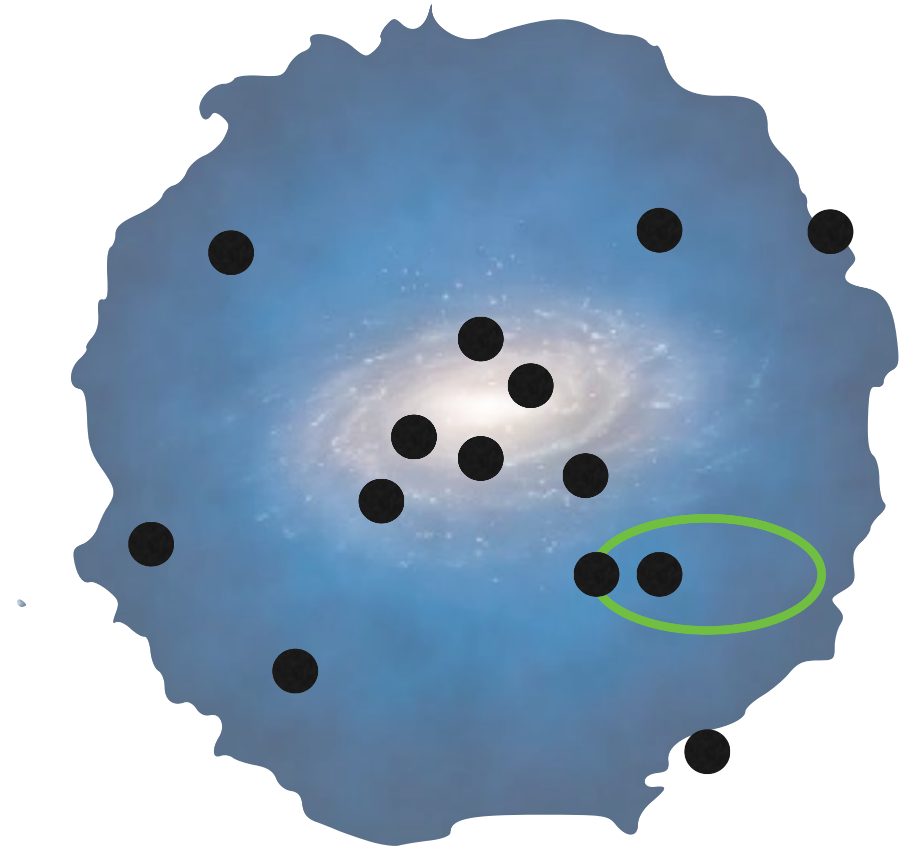
Require:

$$M_{\rm BH} R^{-3} > \rho(z) \text{ before } z_{\rm eq}$$

- If most of the DM is made of PBHs, most pairs form a binary deep in the radiation era.
- If $f_{PBH} < 0.01$, only rare pairs with small separation form binary systems.

Sasaki+ PRL 2017
Ali-Haimoud+ 2017
Raidal+ 2018

B) Binaries formed after close encounters within a DM halo

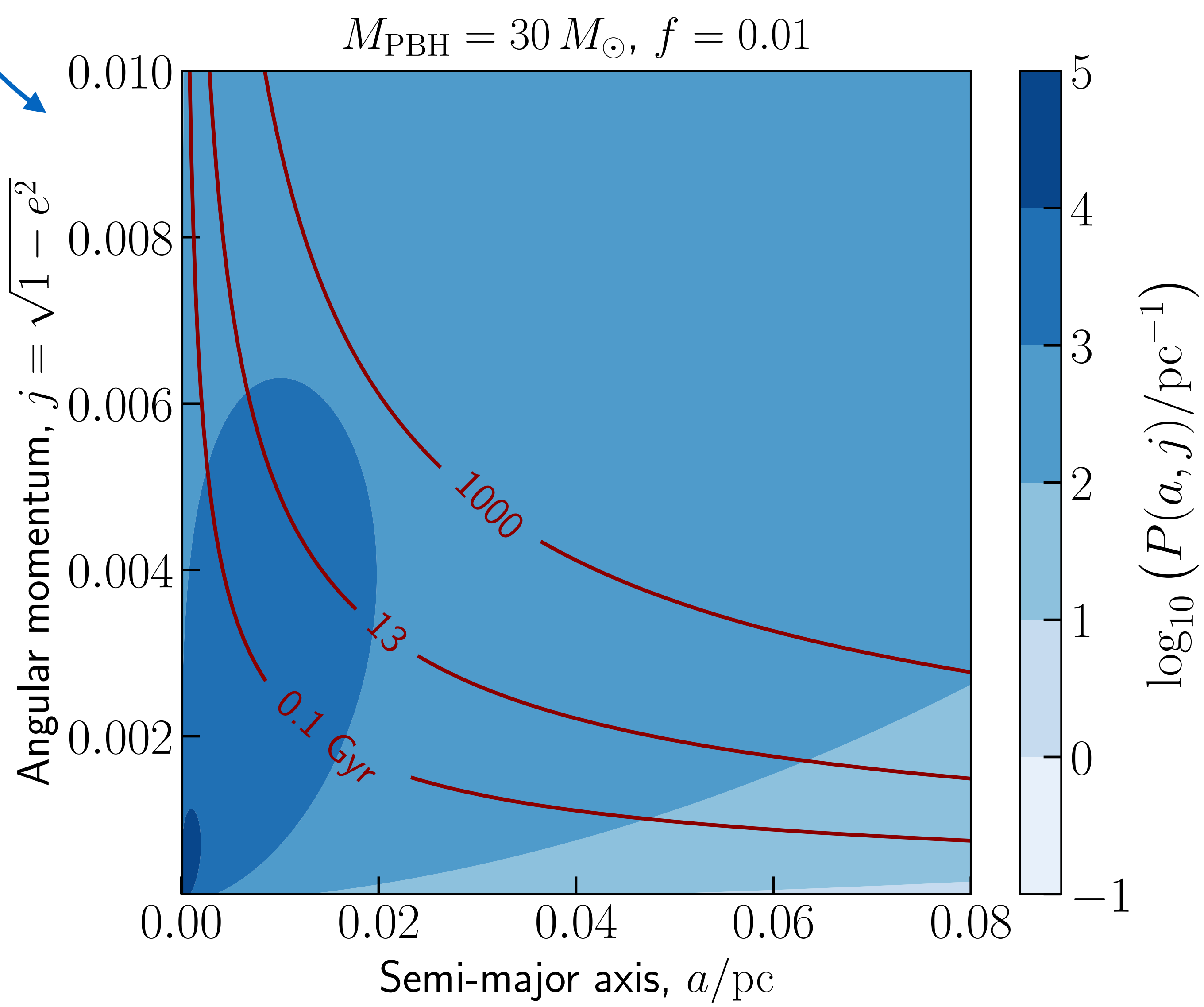


$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2$$

Bird+ PRL 2017
Clesse, García-Bellido, PDU 2016

- Probability distribution of PBH binaries that form deep in the radiation era
- The angular momentum stems from the torque exerted by all the other PBHs

$e > 0.9999$



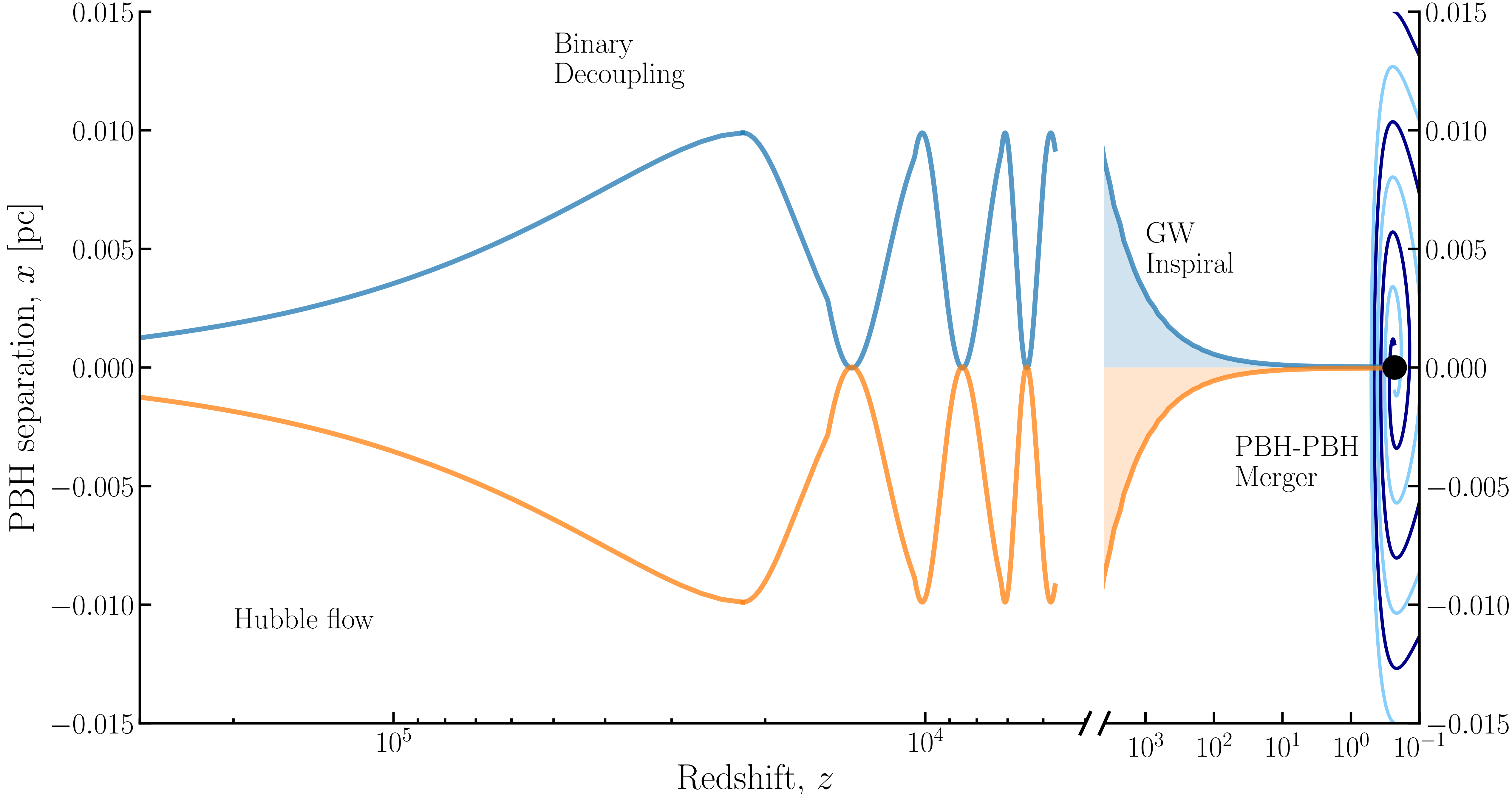
$$t = \frac{3}{170}\frac{a^4}{M^3}j^7 .$$

$$P(t) = \int_{a_{\min}}^{a_{\max}} P(a, j(a,t)) \left(\frac{\mathrm{d}j}{\mathrm{d}t}\right) \mathrm{d}a$$

$$\langle \mathcal{R} \rangle = n_{\rm PBH} \int_0^1 P(t[z])\, \mathrm{d}z \, .$$

Sasaki+ PRL 2017
Ali-Haimoud+ 2017

Dark Dress in action: The merger rate story

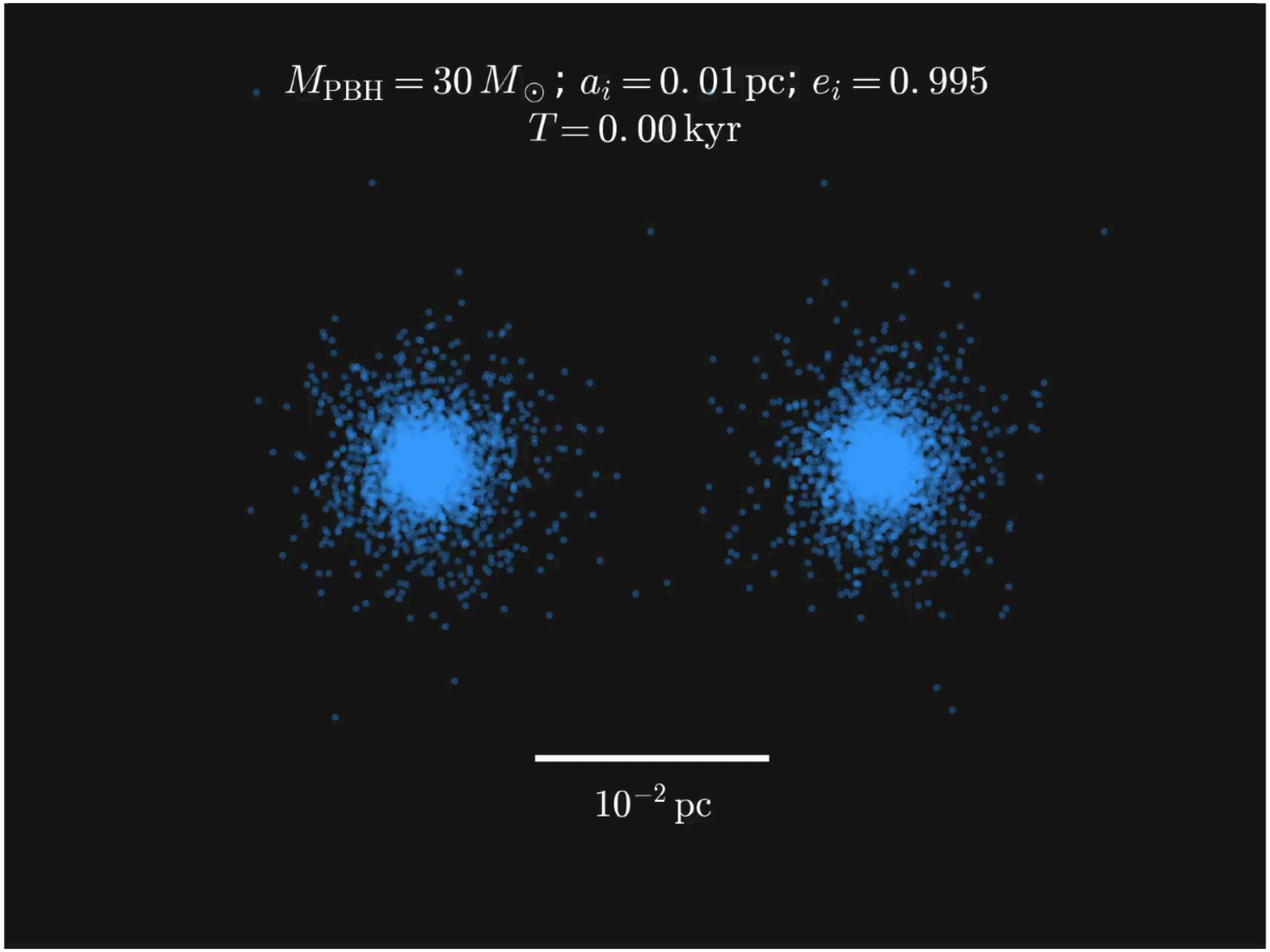


$a = 0.01\,\mathrm{pc}$

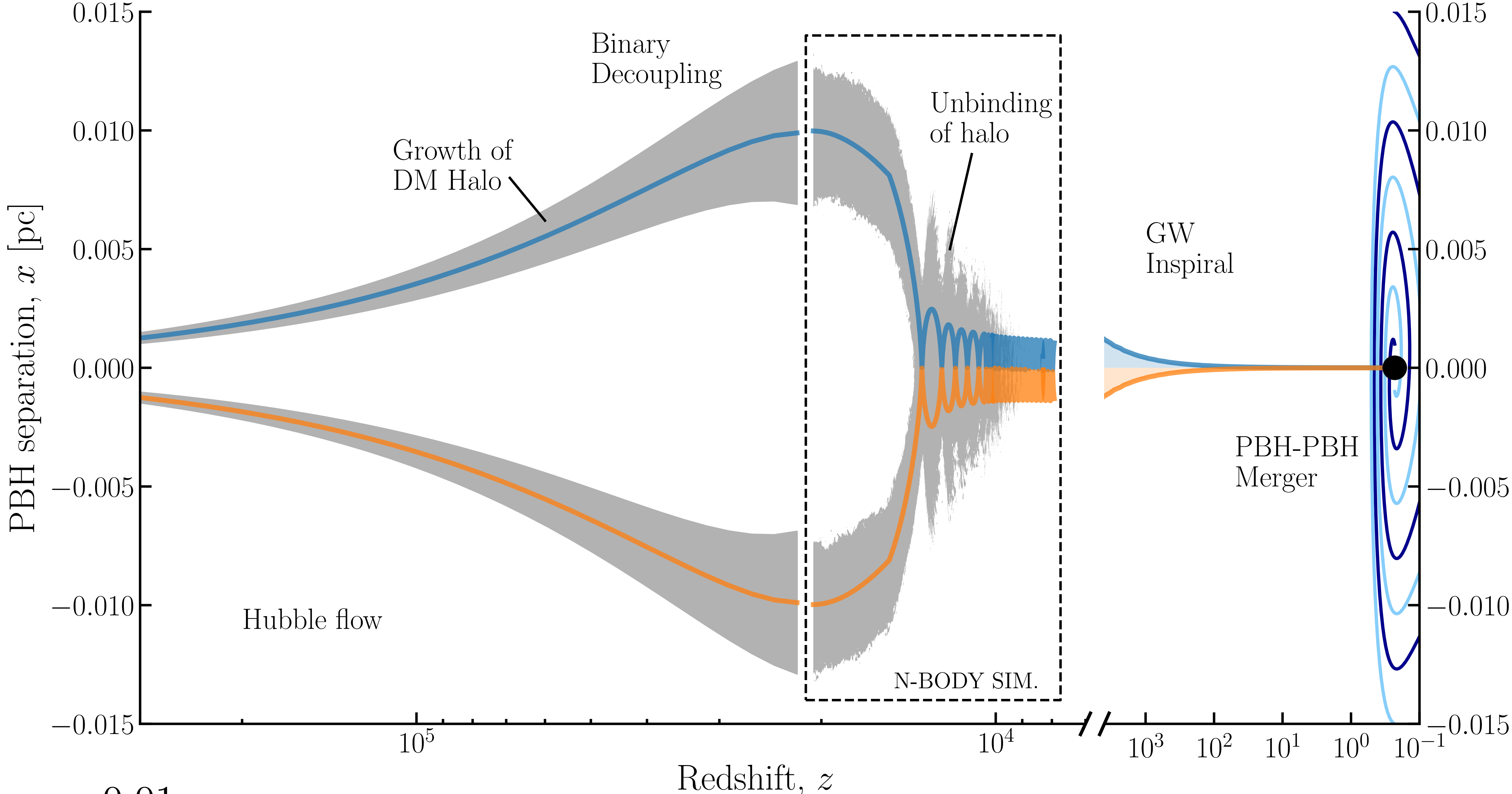
$e = 0.995$

Courtesy of B. Kavanagh

What is the impact of the Dark Dress?



$$\frac{\mathrm{d}E_{\rm DF}}{\mathrm{d}t} = 4\pi (G m_2)^2 \rho_{\rm DM}(r_2)\, \xi(v)\, v^{-1} \log\Lambda$$



$a_i = 0.01\,\mathrm{pc}$

$e_i = 0.995$

$$\frac{\mathrm{d}E_{\mathrm{DF}}}{\mathrm{d}t} = 4\pi(Gm_2)^2\rho_{\mathrm{DM}}(r_2)\,\xi(v)\,v^{-1}\log\Lambda$$

A model for the Dark Dress impact

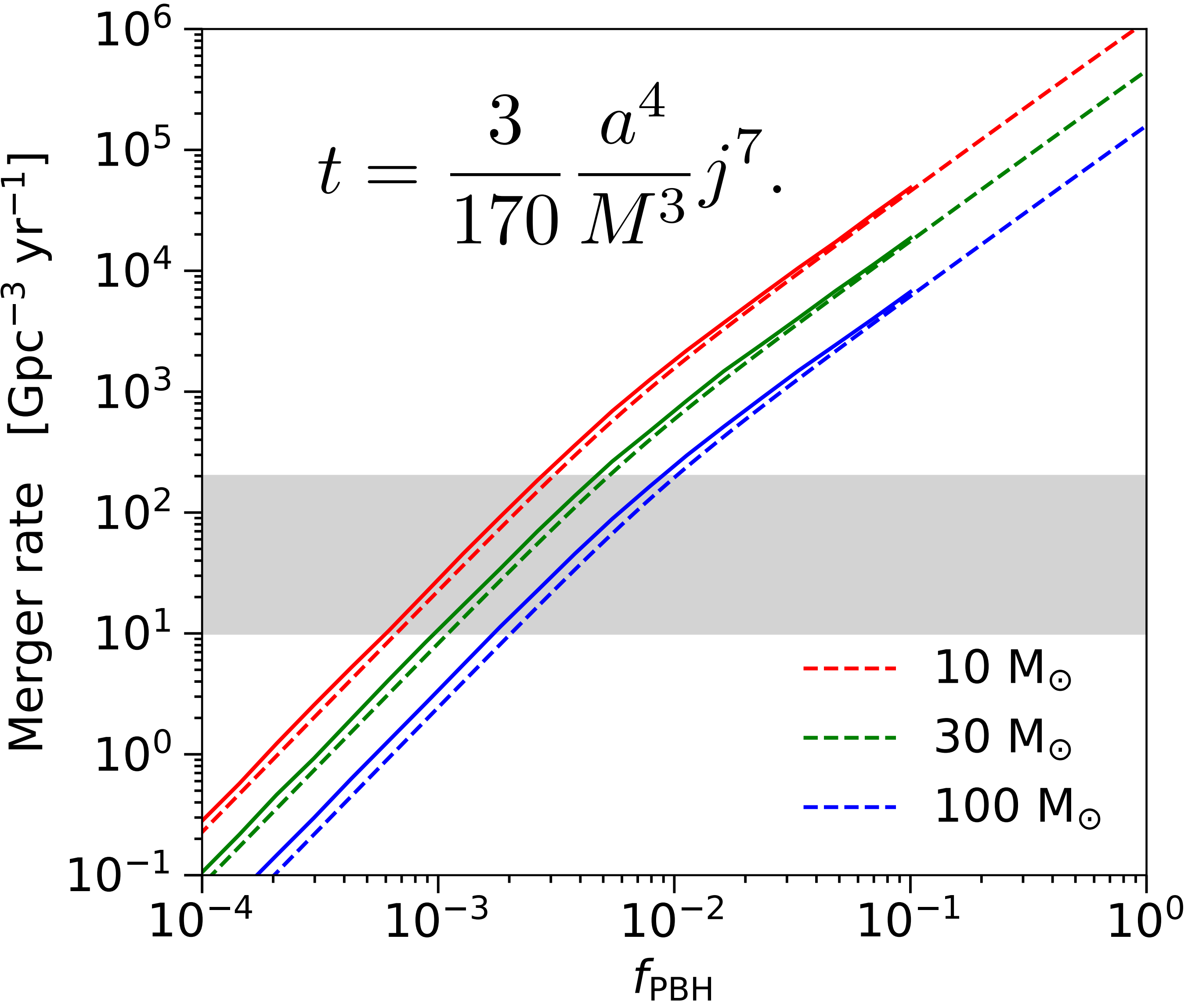
- The binary **shrinks** and **hardens**
- The work done by dynamical friction **heats and unbinds** the DM halo
- For very eccentric orbits there is very **little exchange of angular momentum** between the PBHs and the DM particles: For large eccentricity the orbits are almost radial
- Shrinking and hardening are not independent. **Merger rate roughly conserved**

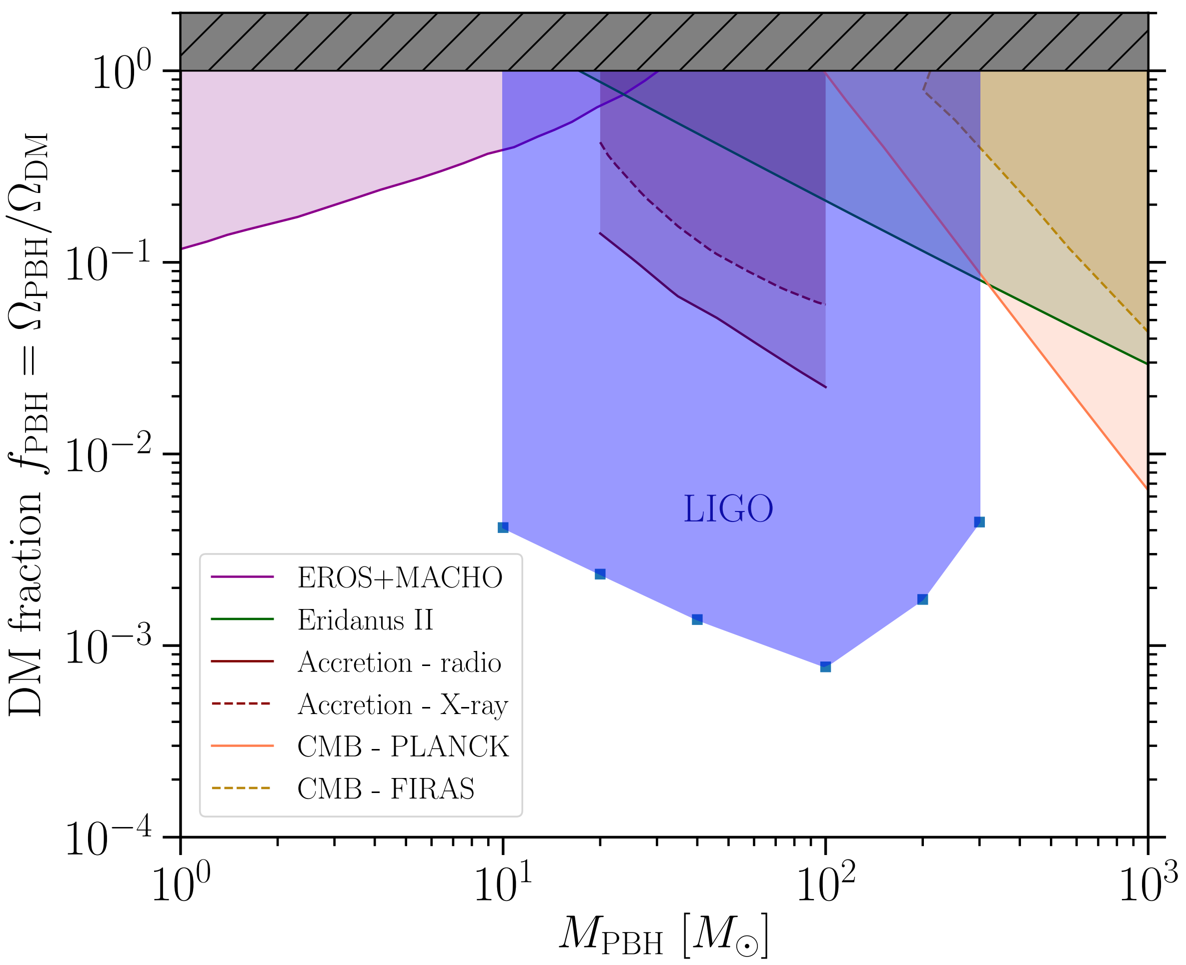
$$E^{\rm bind}(r_{\rm in}) = -4\pi G_N \int_{r_{\rm in}}^{\infty} \frac{M_{\rm enc}(r)}{r}\, r^2 \rho_{\rm DM}(r)\, {\rm d}r\,. \qquad E_i^{\rm orb} + 2\, E^{\rm bind}(r_{\rm min}/2) = E_f^{\rm orb}\,.$$

$$a_f(a_i) = \frac{G_N M_f^2 a_i}{G_N M_{tot}^2 + 4 a_i E^{\rm bind}(r_{\rm in})}\,. \qquad j_f = \sqrt{\frac{a_i}{a_f}} j_i \qquad t_f = \sqrt{\frac{a_i}{a_f}}\, t_i\,,$$

The impact on the bound

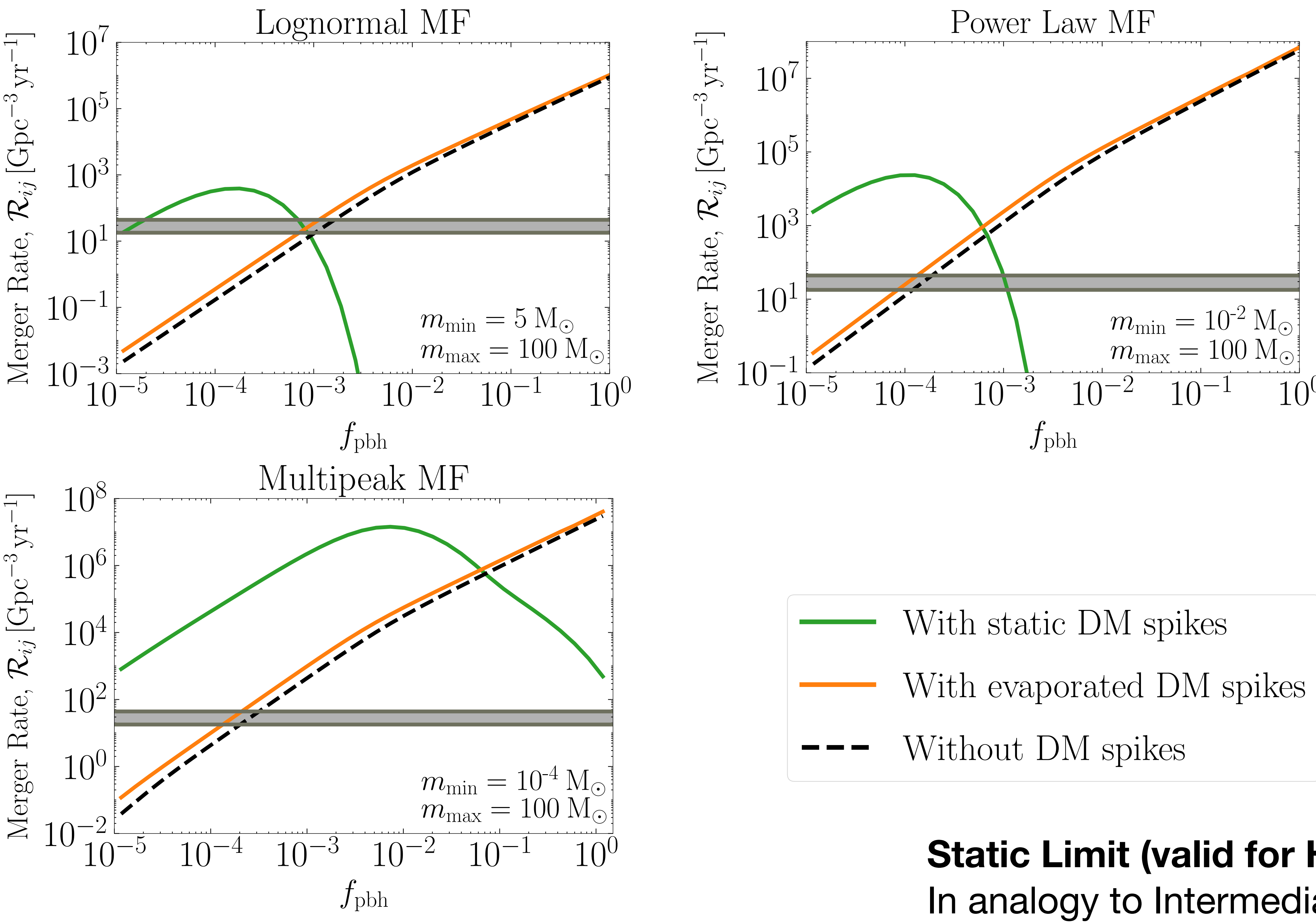
$$\rho(r) \propto r^{-3/2}.$$





- B.J. Kavanagh, D. Gaggero, G. Bertone, 1805.09034
- Pilipenko, Tkacev, Ivanov, 2205.10792

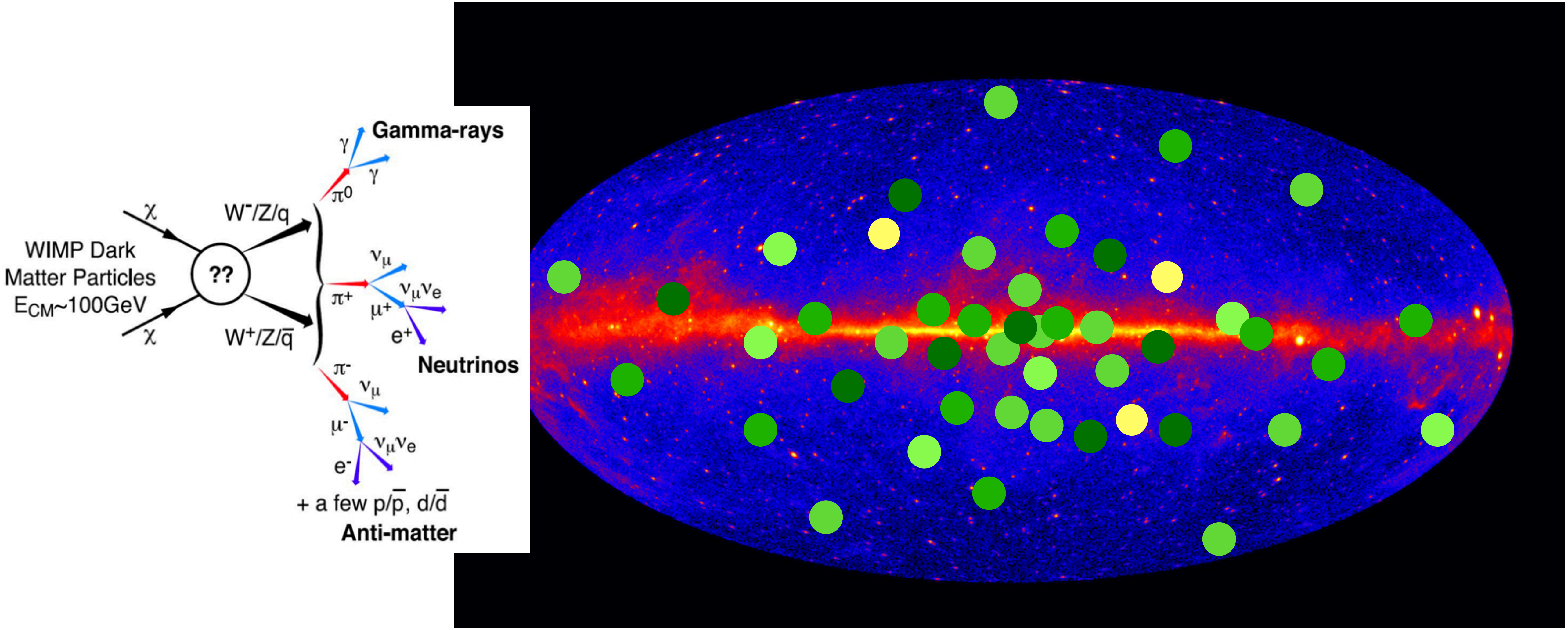
Developments: High mass ratio binaries. Phenomenology is more complex.



Static Limit (valid for High mass ratio).
In analogy to Intermediate Mass Ratio Inspiral (IMRI) systems in which a lighter object inspirals into another object of intermediate mass. The spike stays!

Jangra, Kavanagh, Diego 2304.05892

Dark Dresses become shiny.



Fermi/NASA

“Almost all or almost nothing” argument

- If the bulk of the **DM is made of WIMPs**, and PBH exists as a subdominant component, the dark dresses would emit **gamma rays and neutrinos**

PRIMORDIAL BLACK HOLES AS DARK MATTER: ALMOST ALL OR ALMOST NOTHING

BRIAN C. LACKI[1,2] & JOHN F. BEACOM[1,2,3]

Draft version October 23, 2018

ABSTRACT

Primordial black holes (PBHs) are expected to accrete particle dark matter around them to form ultracompact minihalos (UCMHs), if the PBHs themselves are not most of the dark matter. We show that if most dark matter is a thermal relic, then the inner regions of UCMHs around PBHs are highly luminous sources of annihilation products. Flux constraints on gamma rays and neutrinos set strong abundance limits, improving previous limits by orders of magnitude. Assuming enough particle dark matter exists to form UCMHs, we find that $\Omega_{\rm PBH} \lesssim 10^{-4}$ (for $m_{\rm DM}c^2 \approx 100$ GeV) for a vast range in PBH mass. We briefly discuss the uncertainties on our limits, including those due to the evolution of the UCMH luminosity as it annihilates.

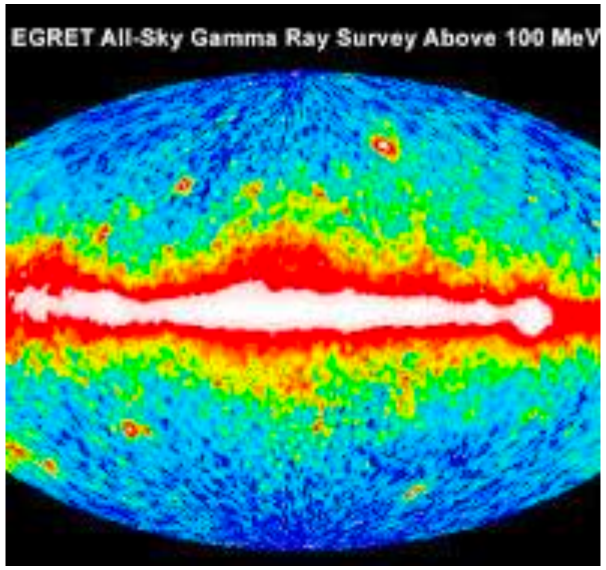
Subject headings: dark matter — early universe — diffuse radiation — gamma rays: diffuse background

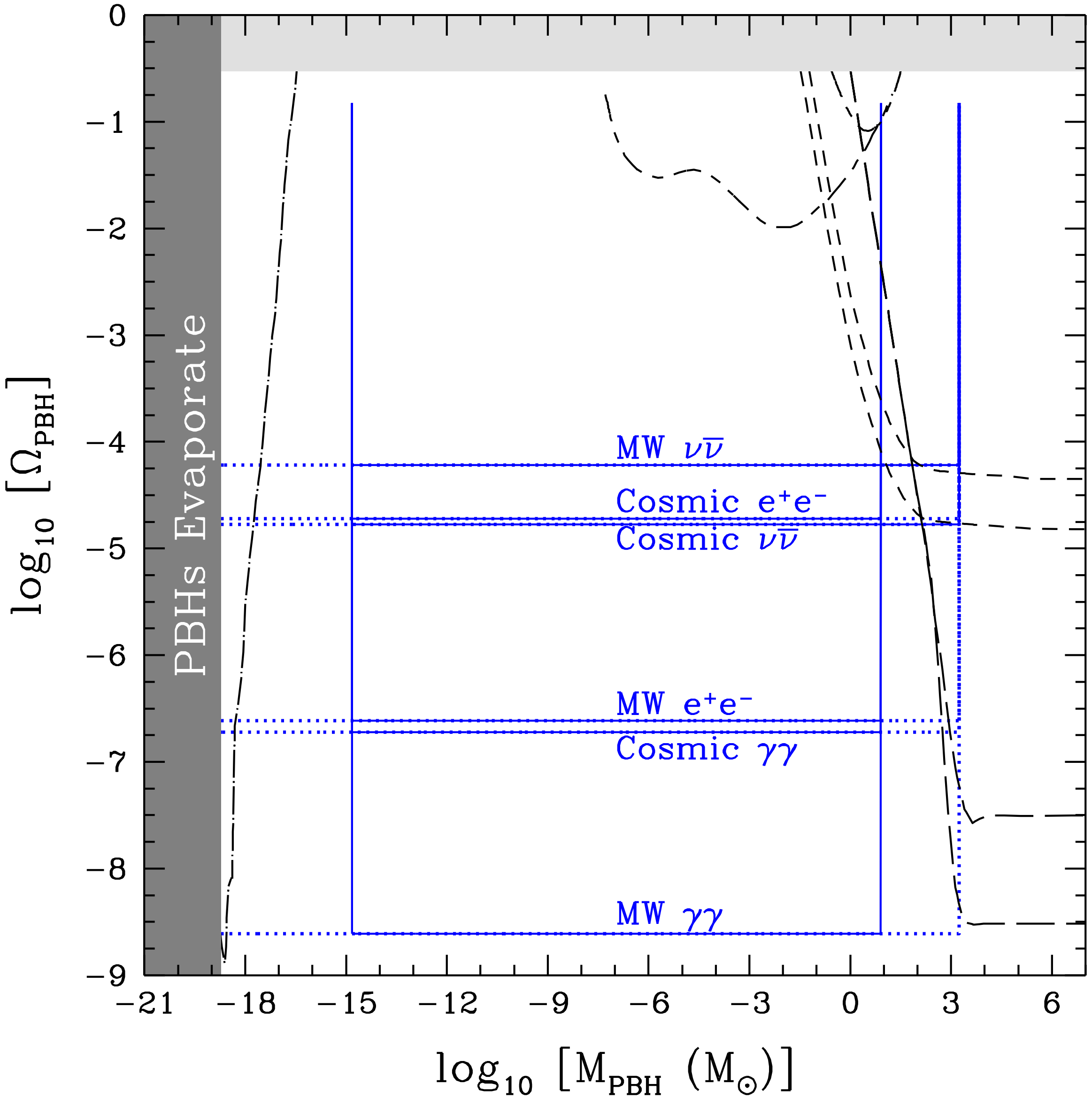
"Almost all or almost nothing" argument

- The dark dresses would show up as a contribution to:
  - Galactic *gamma-ray (unidentified sources)* in the GeV - TeV domain
  - *Isotropic extra-Galactic gamma-ray background*
  - *Neutrino flux*

- **Strong upper limits** on PBH abundance, if DM made of WIMPs

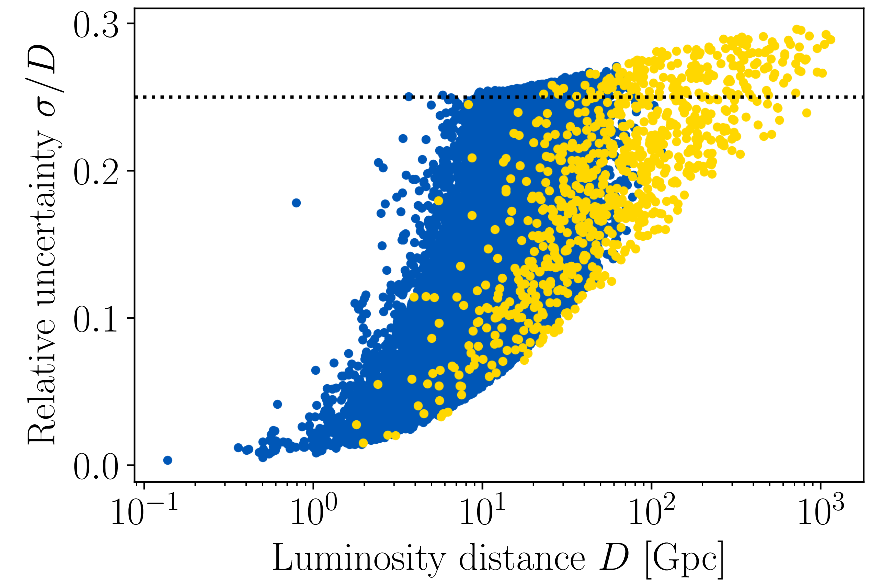
- Data used:
  - **EGRET** gamma-ray data
  - AMANDA/IceCube upper limits

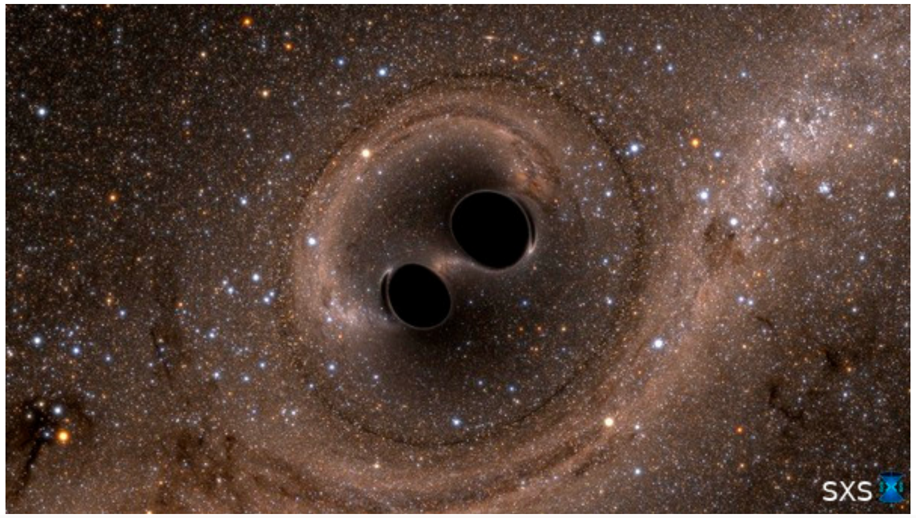


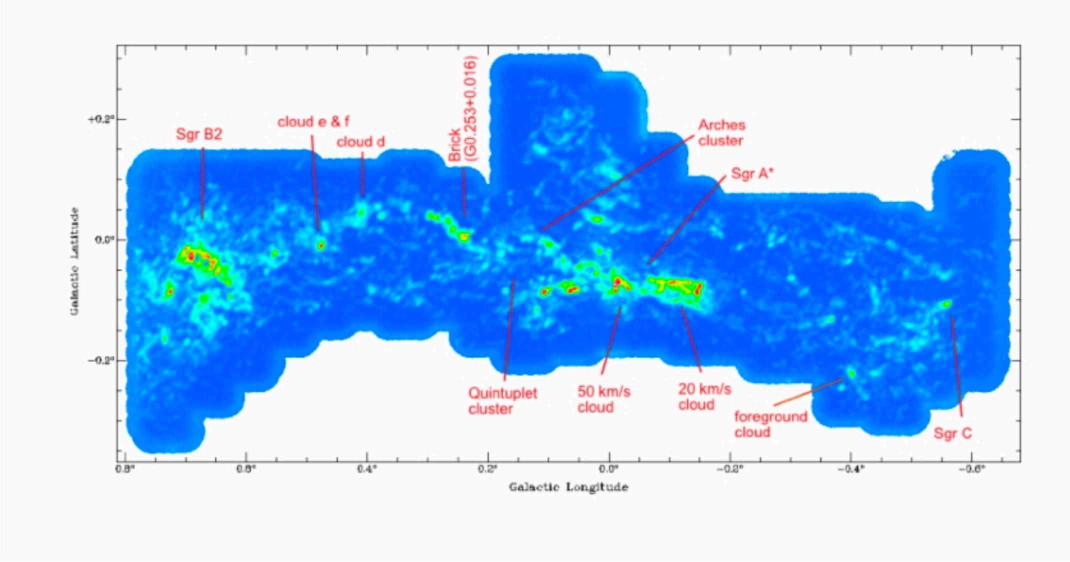


See also:
Boucenna+, 1712.06383
Carr+, 2011.01930

- Let us **assume that PBHs will be discovered** following one of the following avenues:
    - Detection of **high-redshift** events
    - Detection of a **sub-solar** BH in the GW signal
    - Detection of **radio emission** associated to a PBH population in the GC region

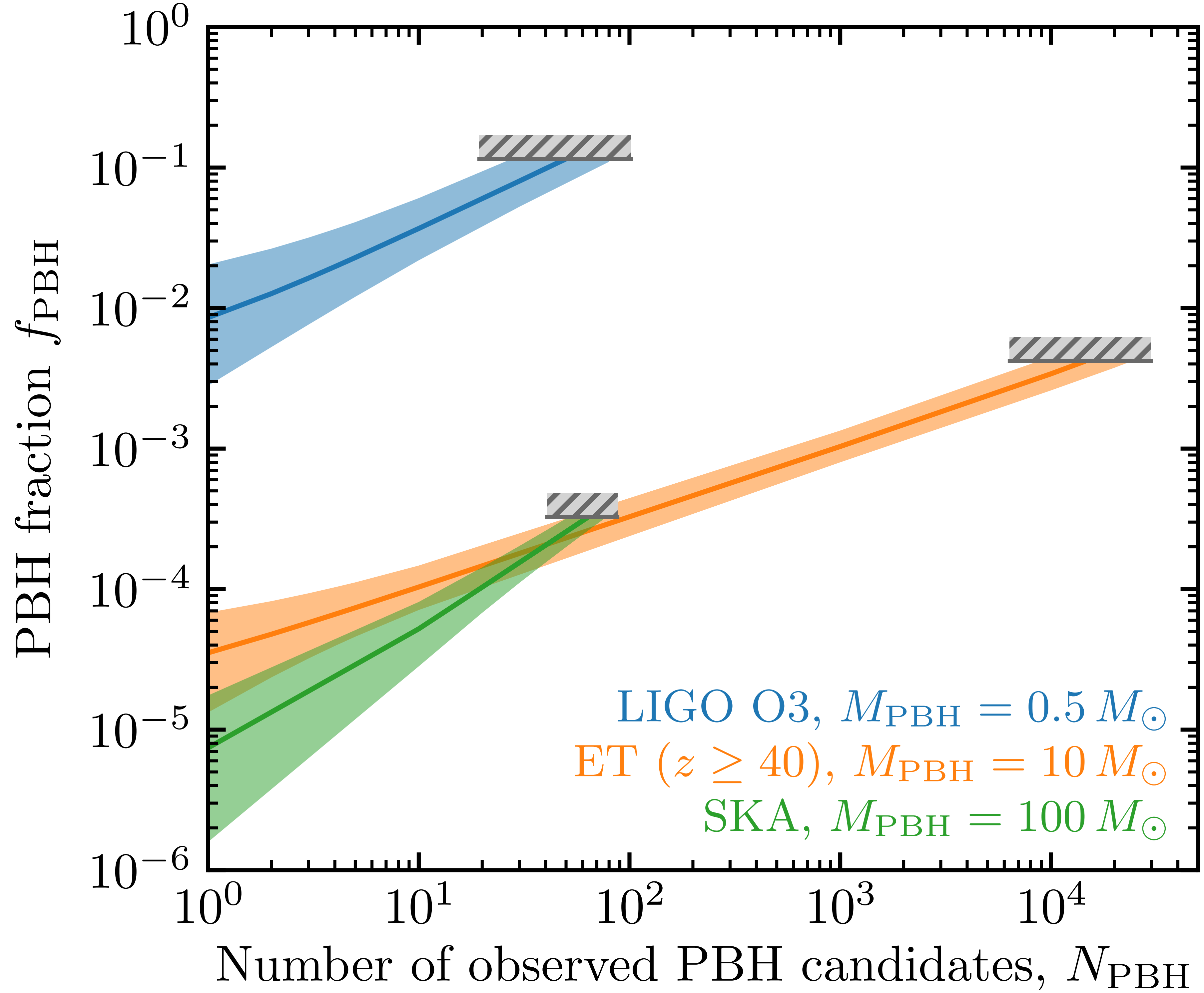






Let us turn the argument around…

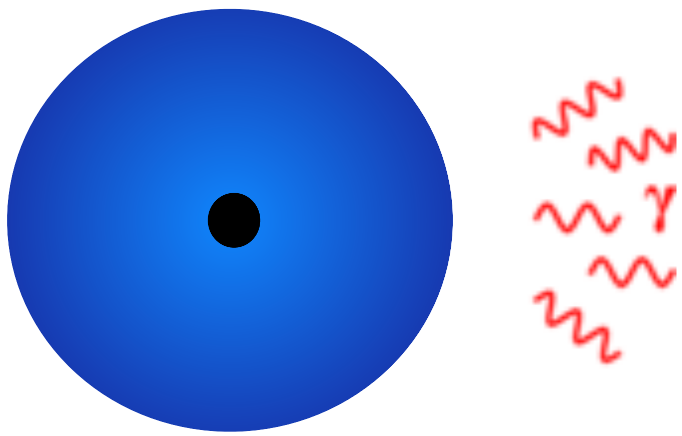
Bertone, Coogan, **DG**, Kavanagh, Weniger, 1905.01238

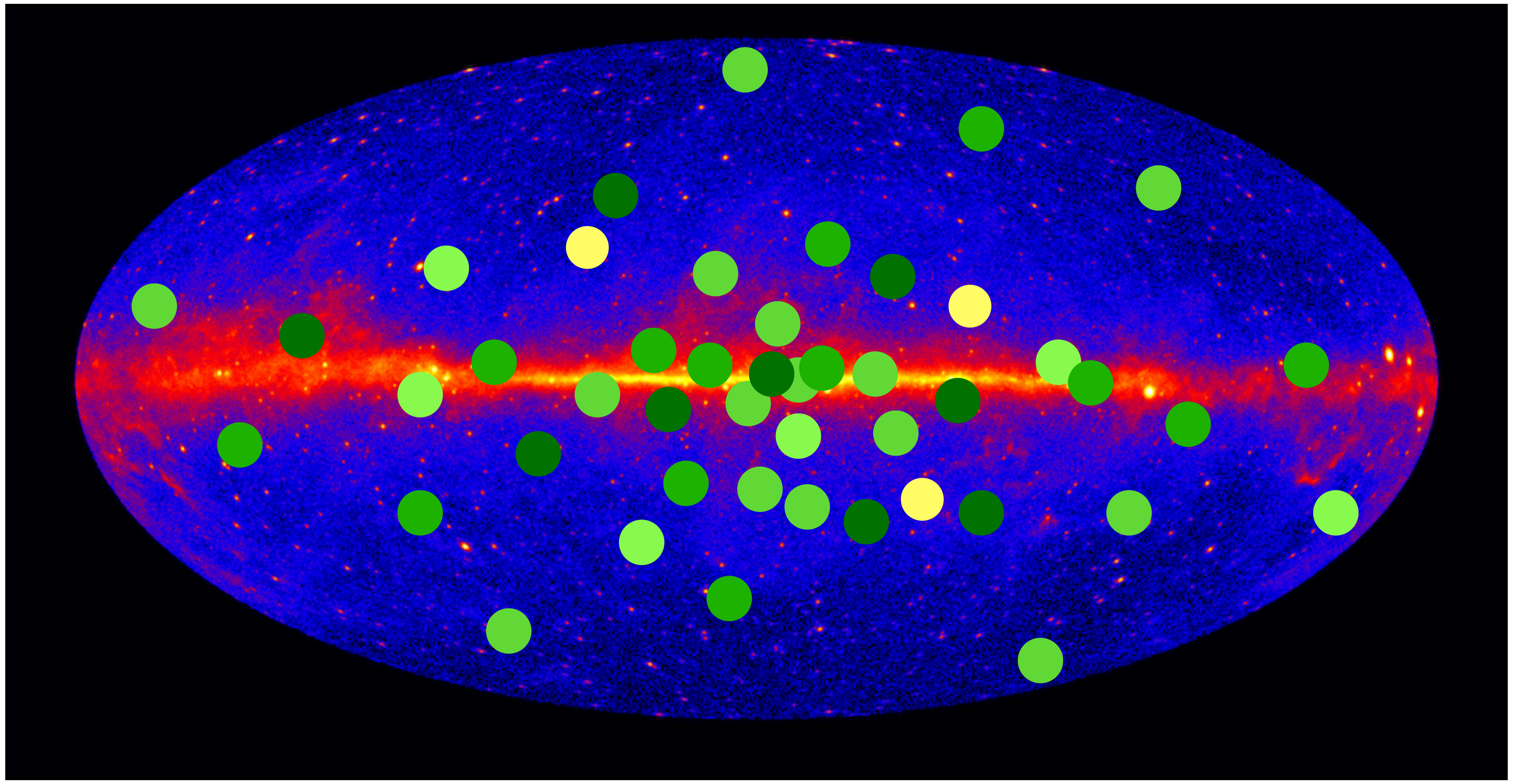


Monte Carlo analysis: Point Source Limit

- PBH mini-spikes as Galactic Gamma-ray point sources
- Fermi-LAT data

- **Step 1**: We place PBHs in the Milky Way halo





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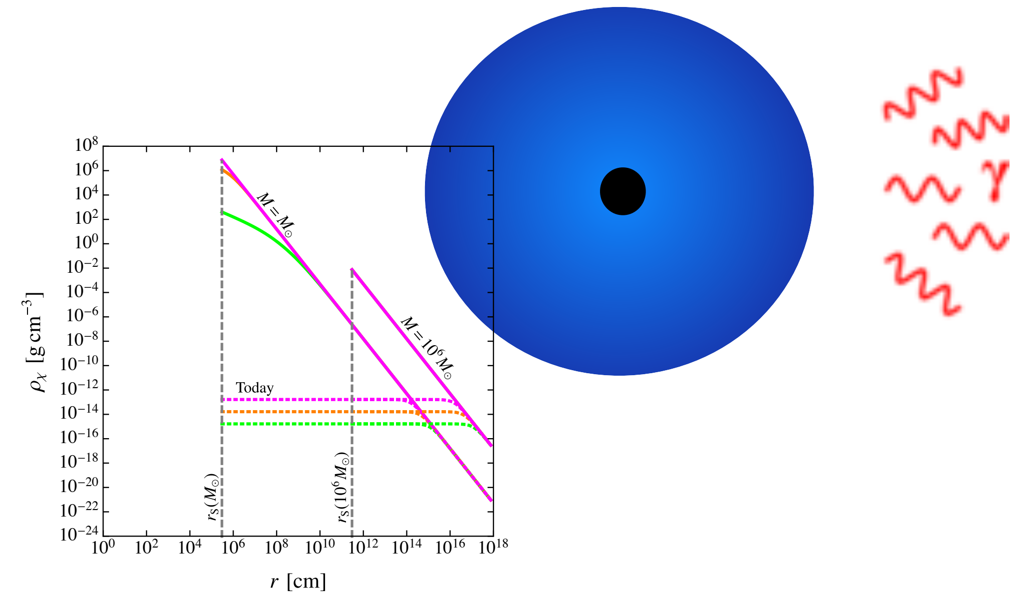
Monte Carlo analysis: Point Source Limit

- PBH mini-spikes as Galactic Gamma-ray point sources
- Fermi-LAT data

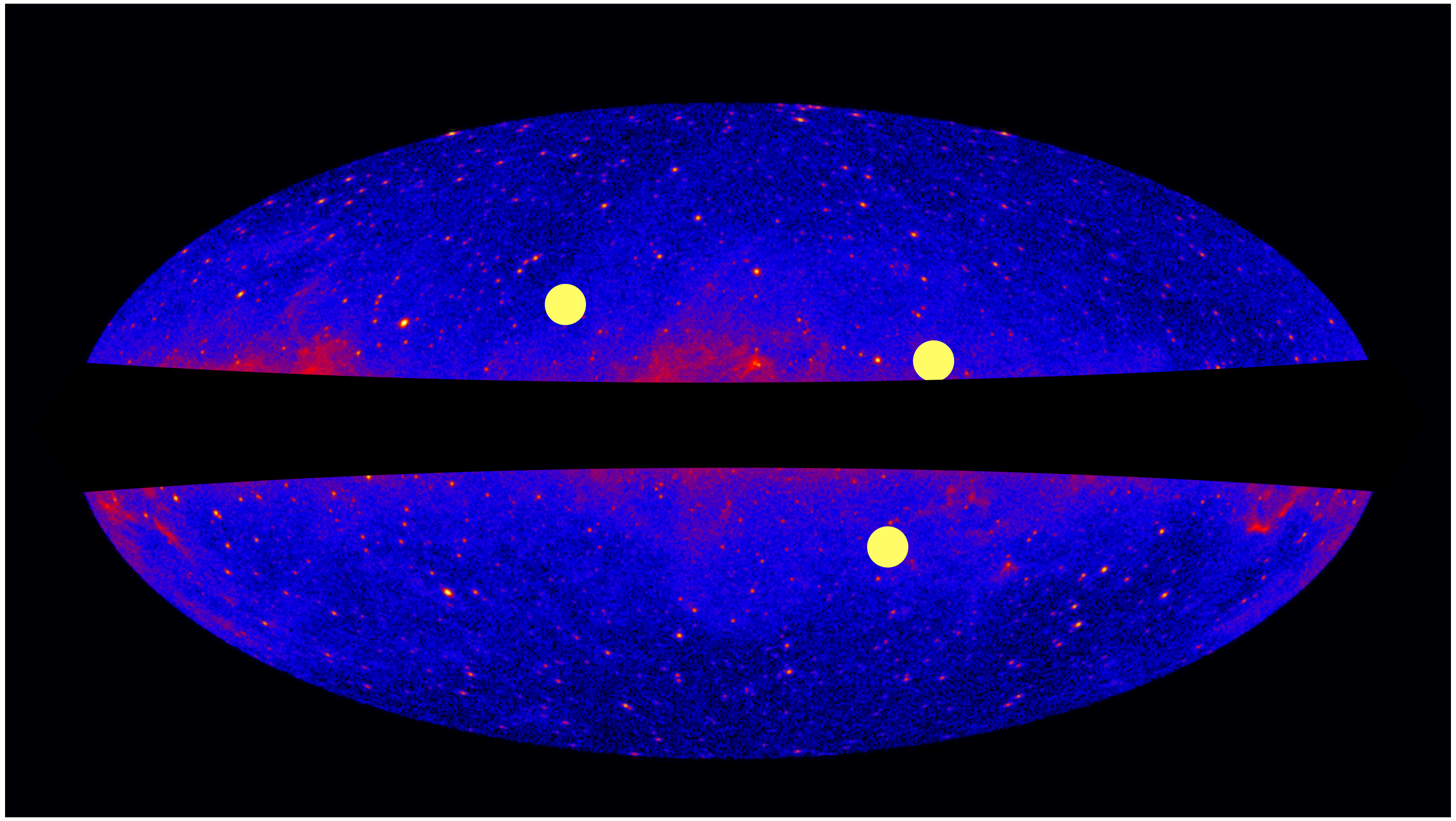
- **Step 1**: We place PBHs in the Milky Way halo
- **Step 2**: Assess detectability



$$\Gamma_{\rm PBH} = \frac{\langle \sigma v \rangle}{m_\chi^2} 4\pi \int_0^\infty \rho(r)^2 r^2 dr$$

$$\Gamma_{\rm PBH} = \frac{4\pi \langle \sigma v \rangle \rho_{\rm max}^2 r_{\rm cut}^3}{m_\chi^2}$$

$$\phi_{\rm PBH}^{\rm point}(E) = \frac{\Gamma}{4\pi d^2} \frac{{\rm d}N_\gamma}{{\rm d}E}(E)$$



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Monte Carlo analysis: Point Source Limit

- PBH mini-spikes as Galactic Gamma-ray point sources
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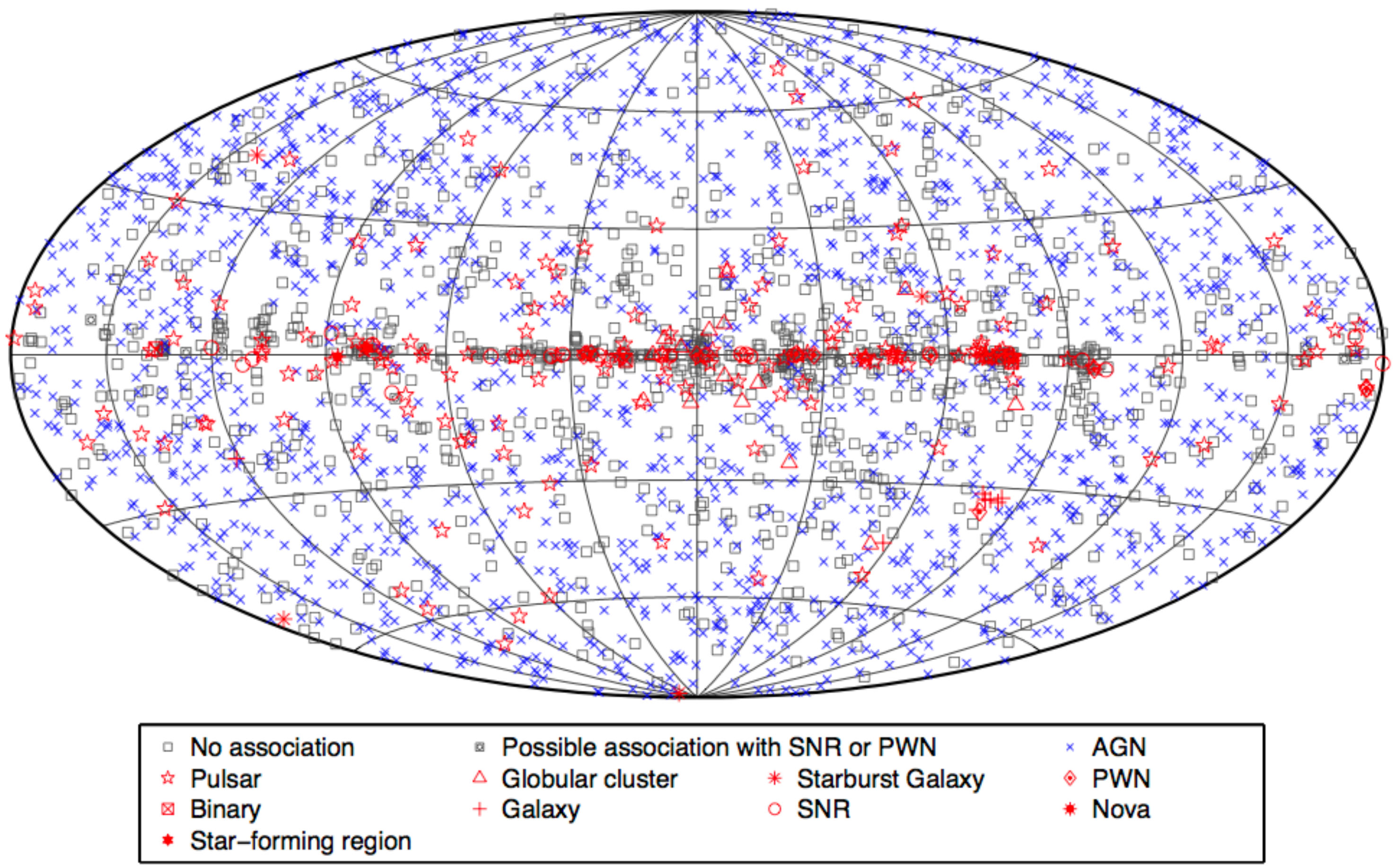
- **Step 1**: We place PBHs in the Milky Way halo
- **Step 2**: Assess detectability
- **Step 3: Require N < 19 (3FGL unassociated sources compatible with DM annihilation)**

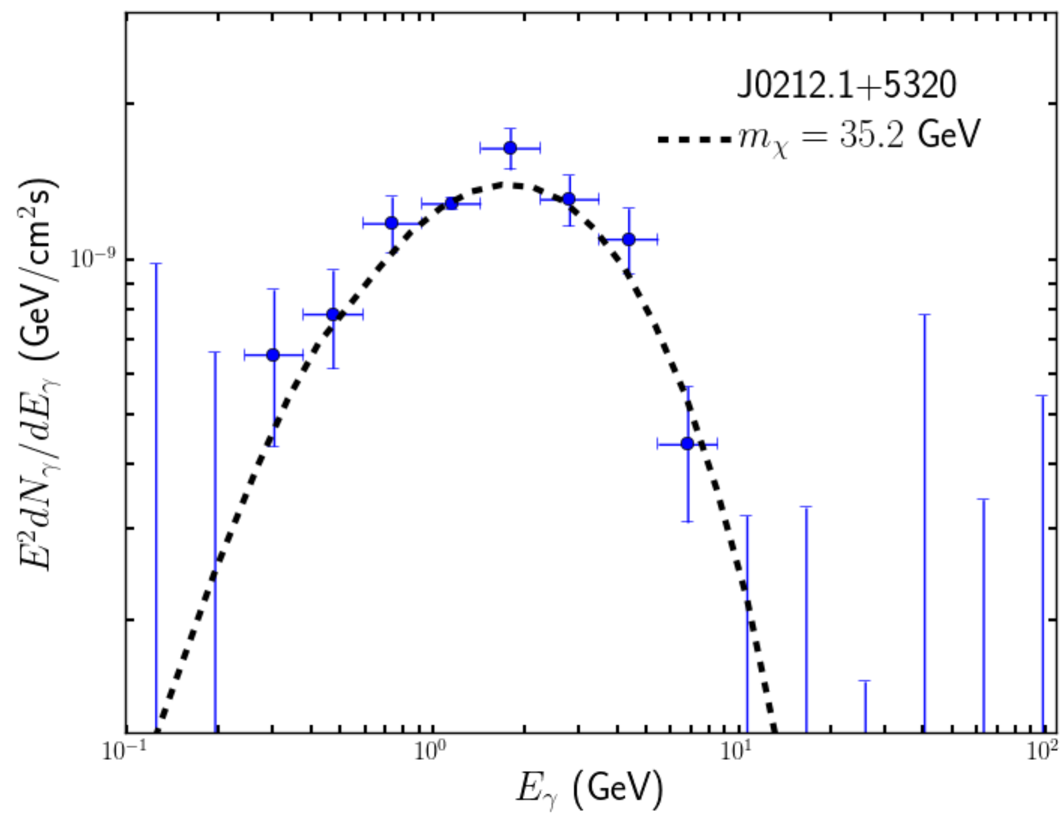


Monte Carlo analysis: Point Source Limit

- PBH mini-spikes as Galactic Gamma-ray point sources
- Fermi-LAT data

- **Step 1**: We place PBHs in the Milky Way halo
- **Step 2**: Assess detectability
- **Step 3: Require N < 19 (3FGL unassociated sources compatible with DM annihilation)**

- Bright (*$F > 7 \times 10^{-10}$ cm^{-2} s^{-1}*),
- Located far away from the Galactic Plane (|b| > 20 deg),
- No signs of variability
- Spectral shape is compatible with that predicted from annihilating DM particles

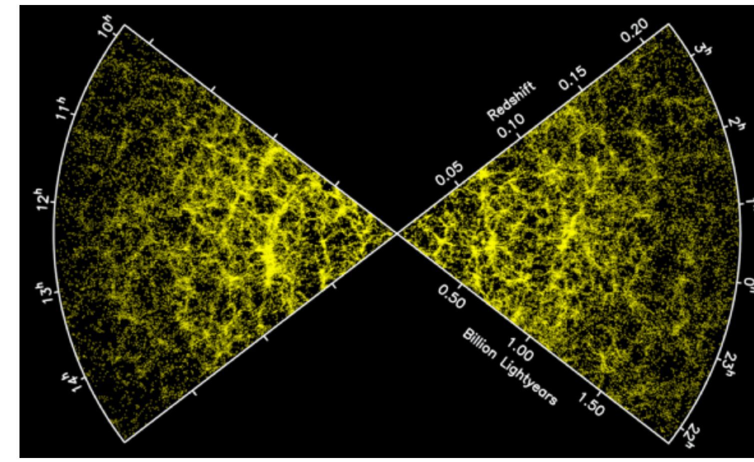


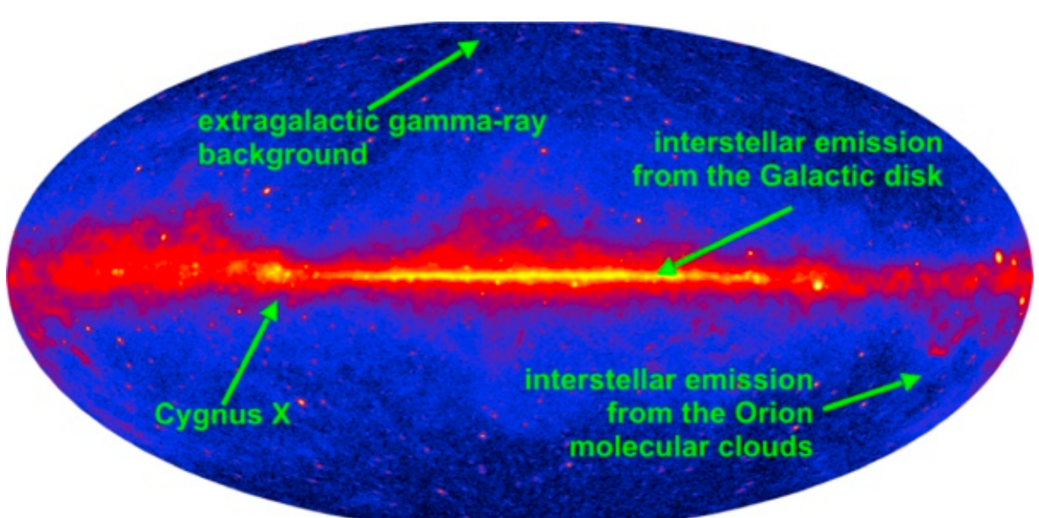
Bertoni+ 1504.02087
Coronado-Blázquez 1910.14429

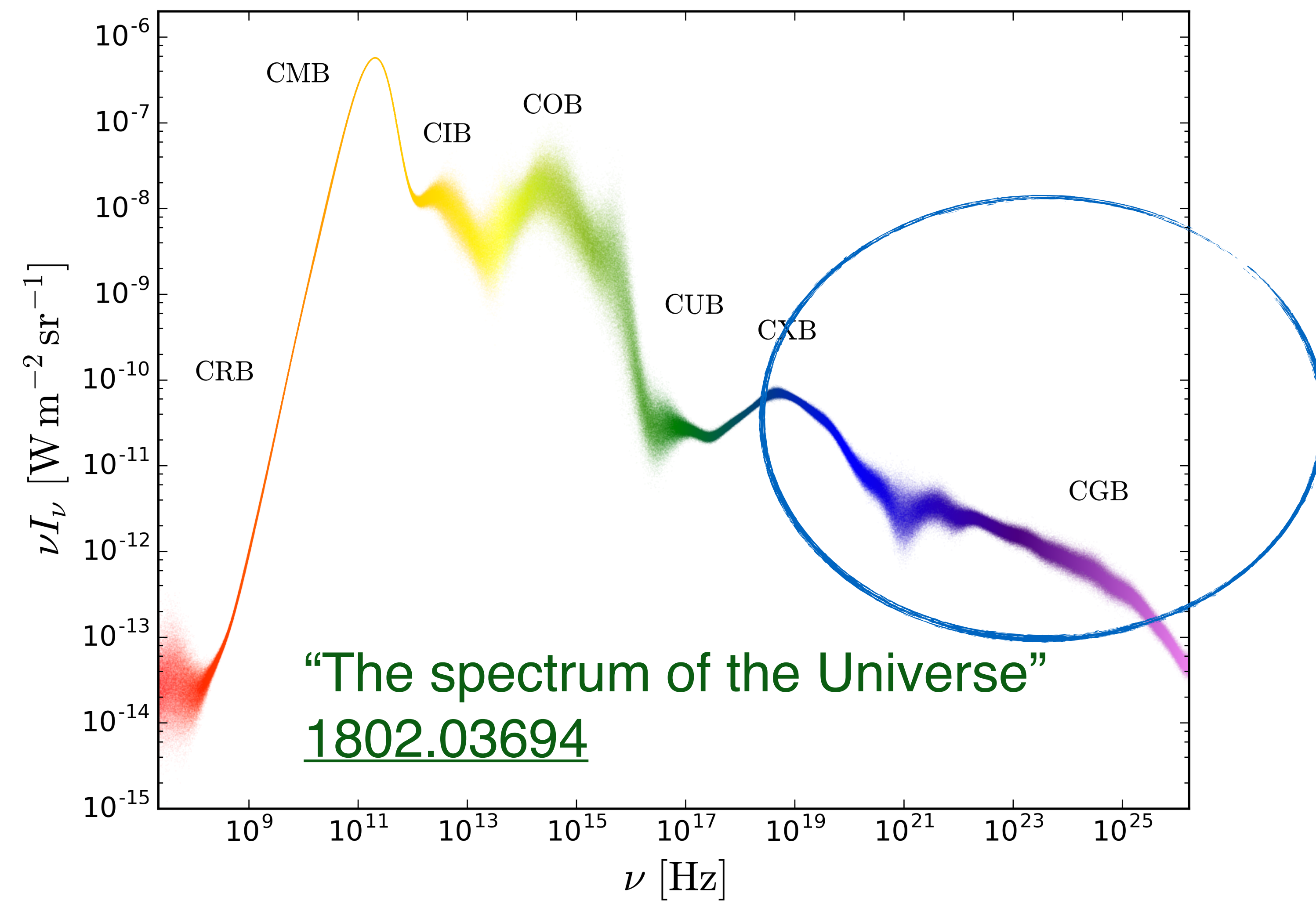
Monte Carlo analysis: Diffuse gamma-ray limit

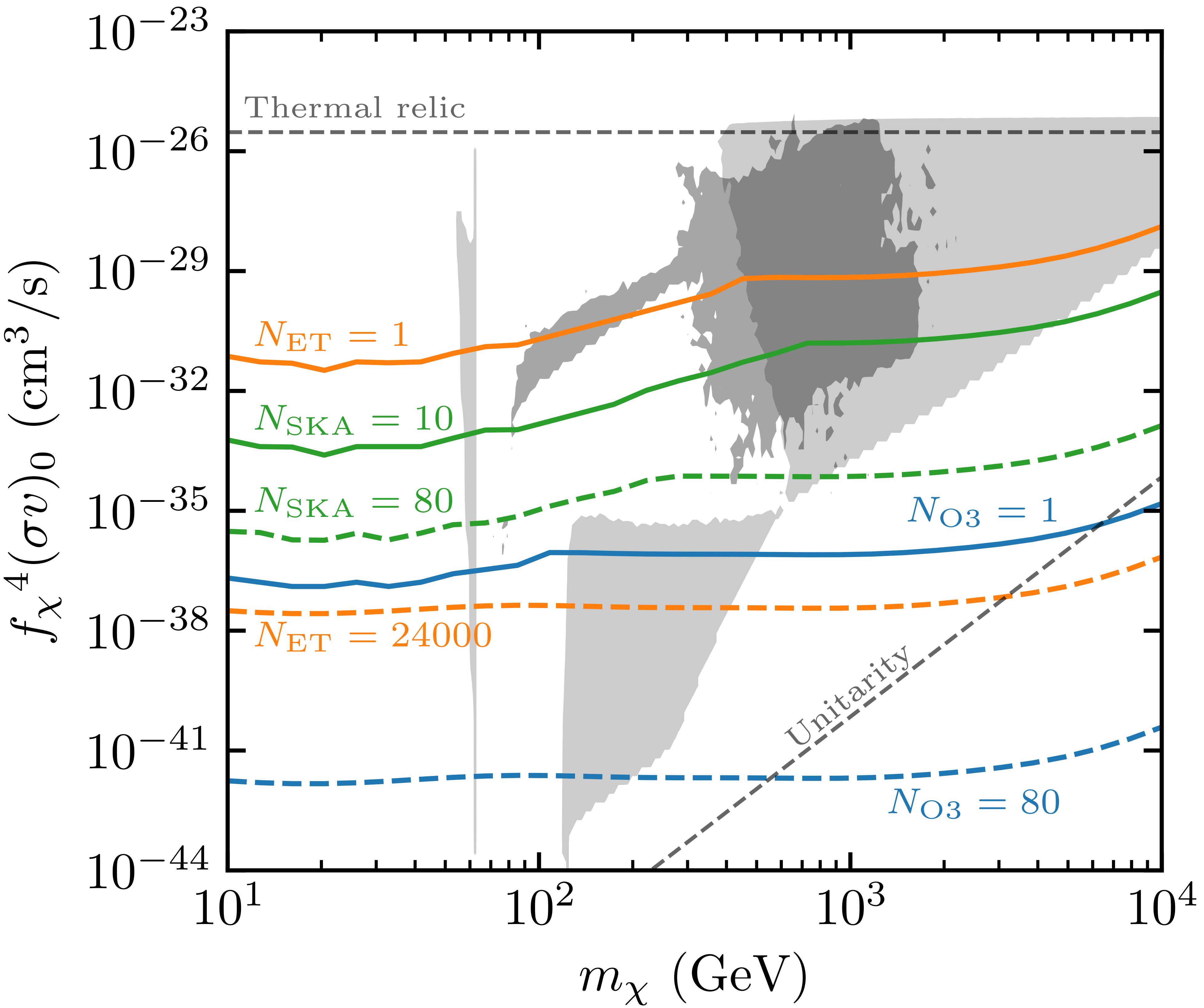
- **PBH mini-spikes required not to overshoot the "Spectrum of the Universe"**
- Fermi-LAT energy band under consideration

$$\phi^{\rm ex}_{\rm PBH}(E) = \frac{\Gamma}{4\pi}\,\frac{\hat{f}_{\rm PBH}\,\rho_{\rm DM}}{M_{\rm PBH}}\int_0^z {\rm d}z\,\frac{e^{-\tau(E,z)}}{H(z)}\,\frac{dN_\gamma}{dE}\,((1+z)E)\,.$$



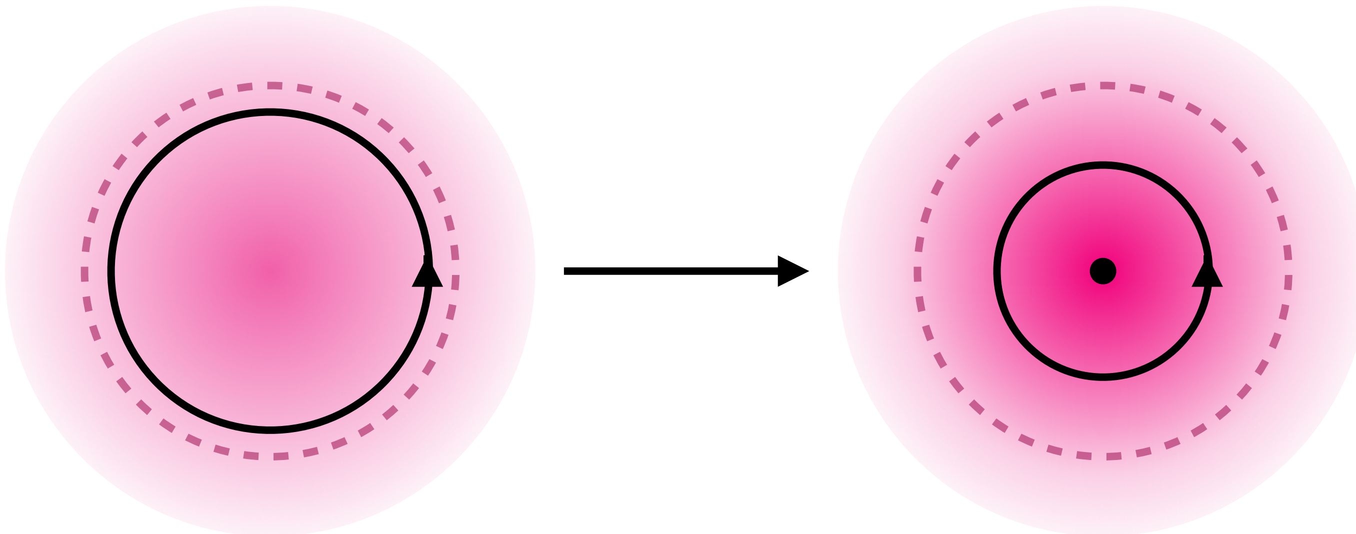


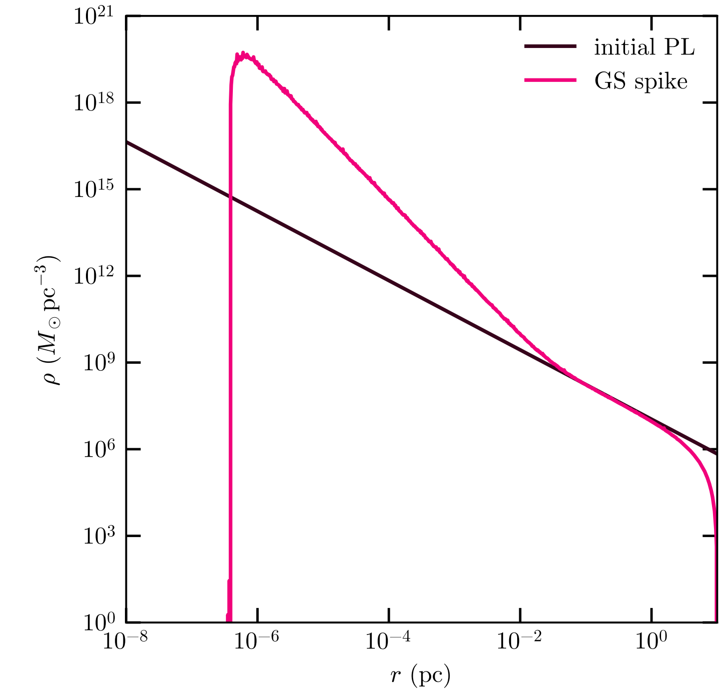




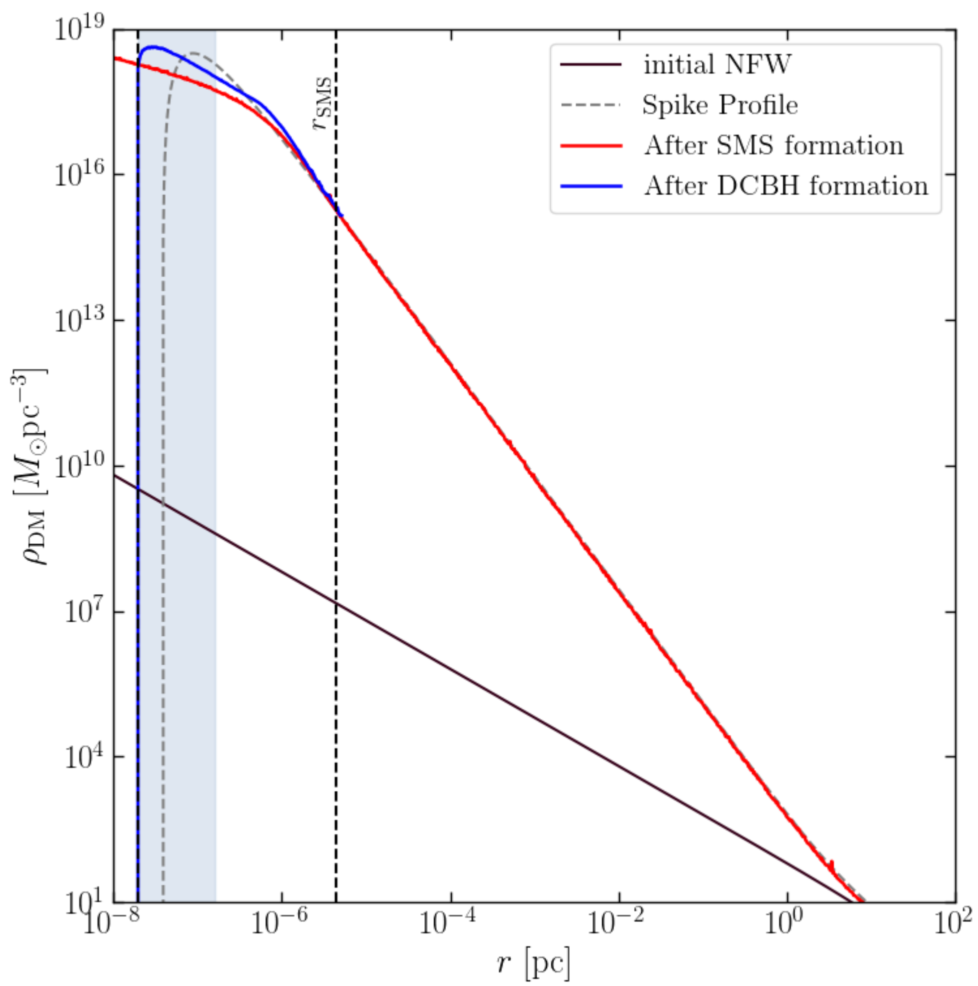
G. Bertone, A. Coogan, **DG**, B.J. Kavanagh, C. Weniger, 1905.01238

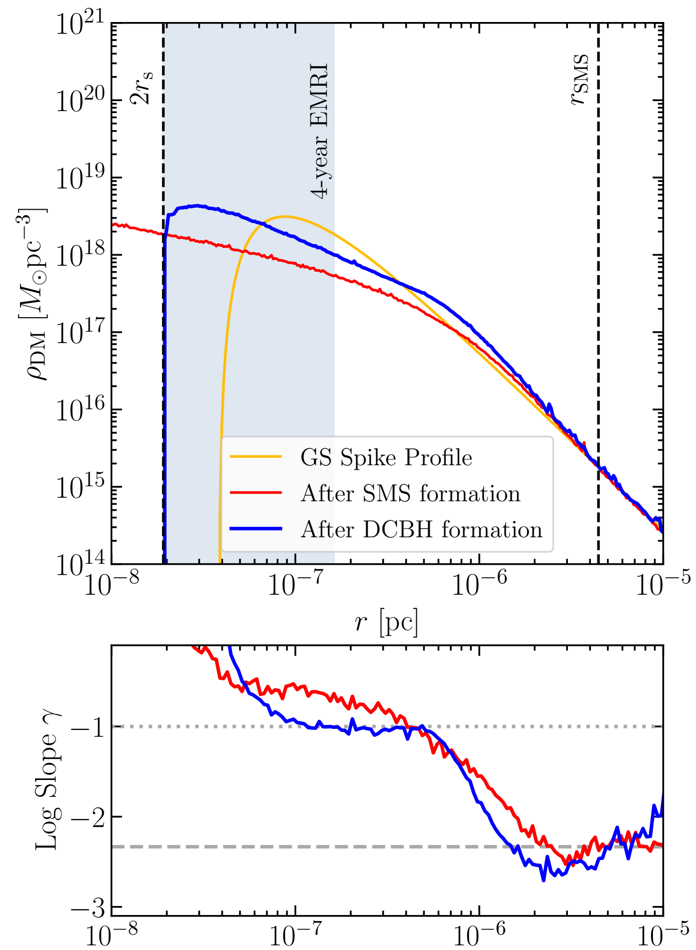
Dark Dresses around IMBH as well





Quinlan et al., 9407005
Gondolo and Silk, 9906391

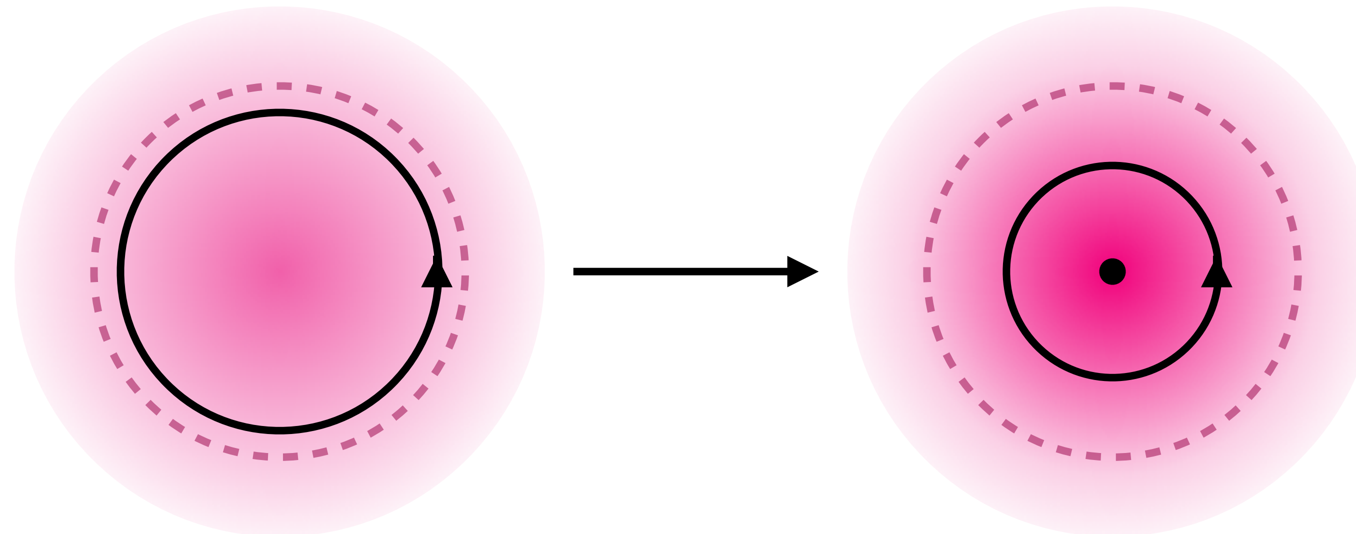




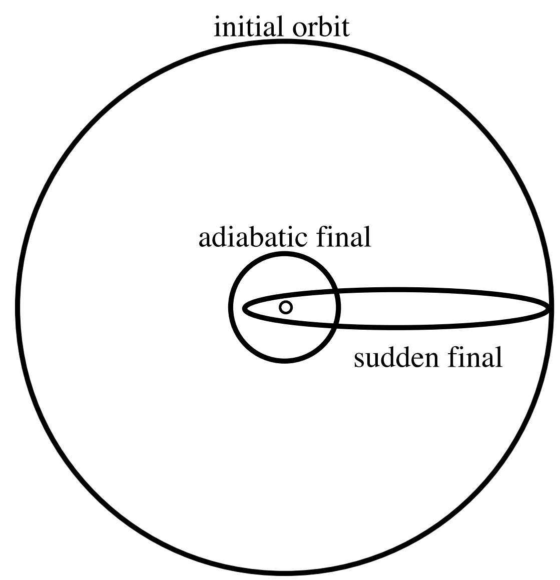
Gianfranco Bertone, Renske Wierda, DG, Bradley Kavanagh, Marta Volonteri, Naoki Yoshida, *2404.08731*

Dark Dresses around IMBH as well

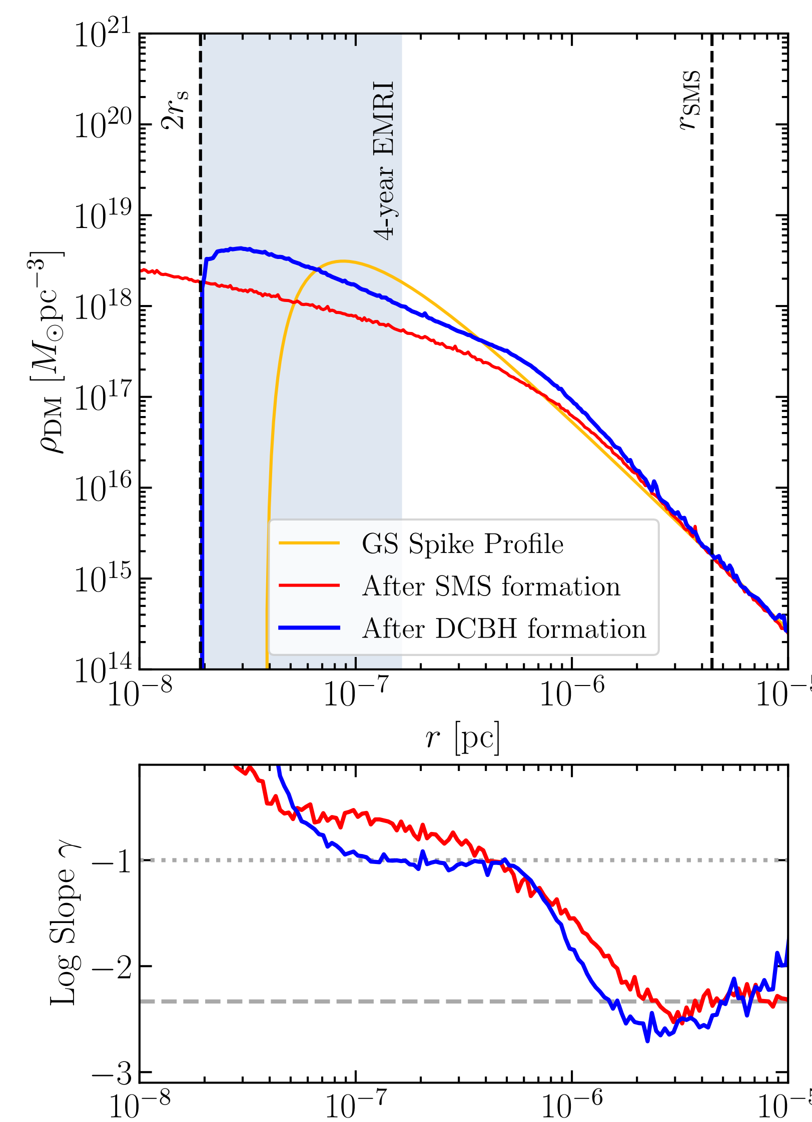
- **First step:** formation of a super massive star (SMS) at the center of a small DM halo (*M_{SMS} ~ 10^5 M_{Sun}*; *M_{DM} ~ 10^7 M_{Sun}*; *z ~ 15*)



- **Second step:** Direct collapse of the SMS to a Direct-Collapse Black Hole (DCBH)



- **Third step:** Final (adiabatic) growth by accretion of the remaining baryonic matter.



Detectable and measurables in GWs!

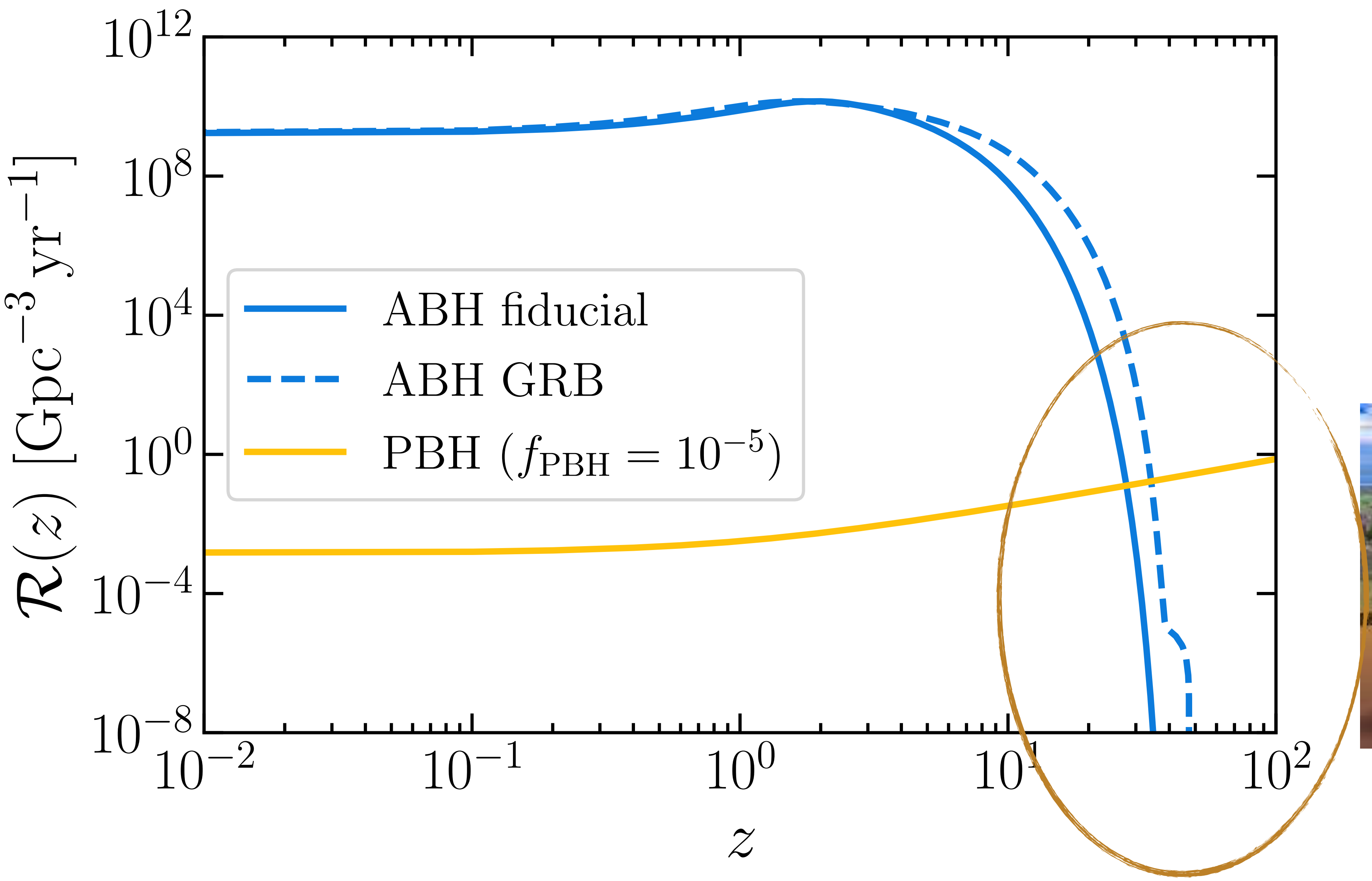
- Kavanagh+ 2002.12811 (PRD)
- Coogan+ 2108.04154 (PRD)
- Cole+ 2211.01362 (Nature Astronomy)

Conclusions

- PBHs — if present as a sub-dominant population — can grow a **DM "dress"** around them
  - The impact of the Dark Dress on the **PBH merger rate** is (unexpectedly) small for equal-mass-ratio events. **It can be relevant in general.**
  - The **Dark Dress can shine in gamma rays** if DM is mostly made of WIMPs.
  - A detection of PBHs would allow to set the most **stringent limits** ever on the **WIMP** annihilation cross section
  - Dark Dresses could help to understand DM properties!

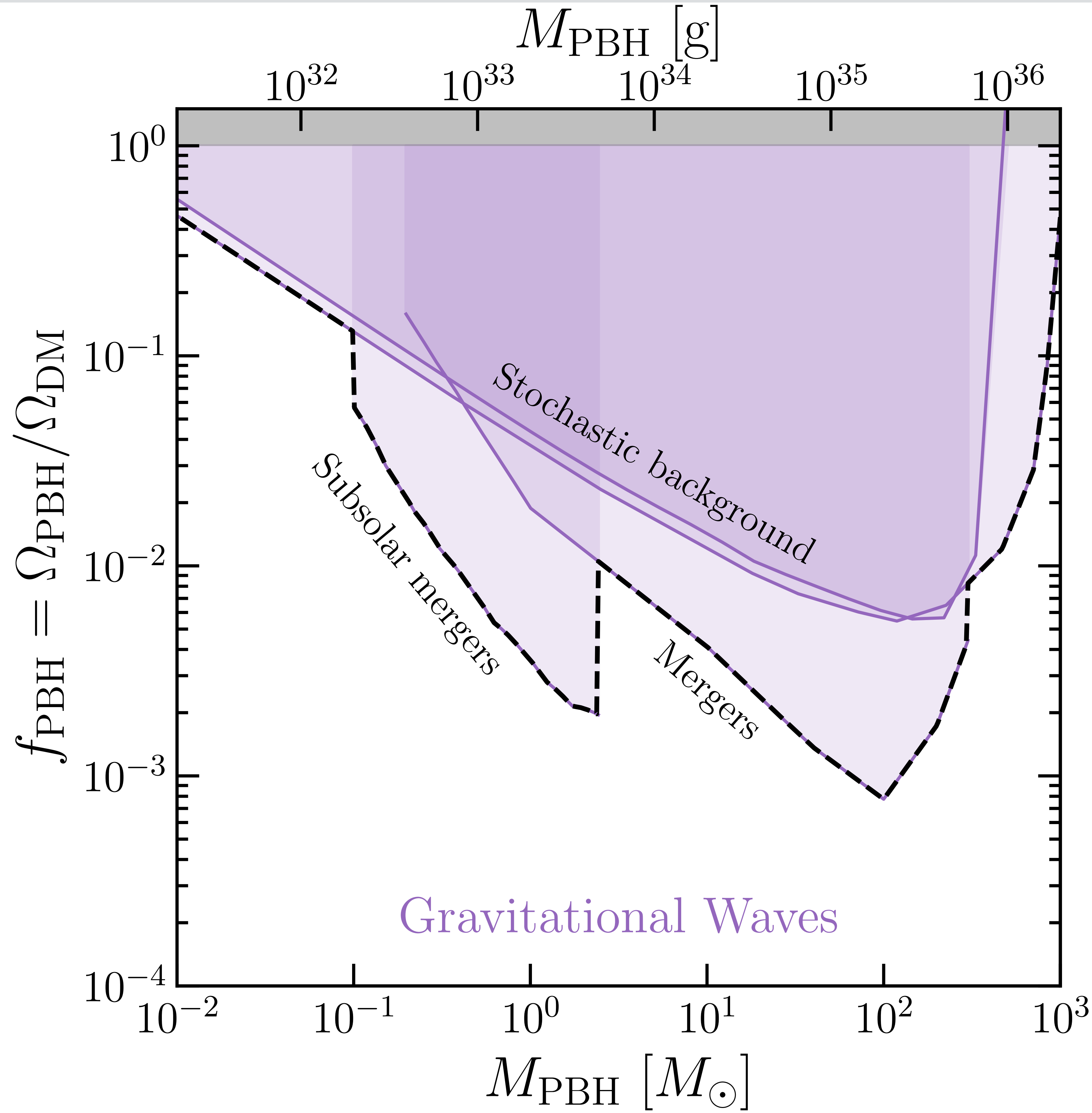
Backup

The PBH merger rate **increases** at increasing redshift. Dominant contribution in the Dark Ages. **Science Case for ET and CE**



Martinelli, Scarcella, Hogg, Kavanagh, **DG**, Fleury, 2205.02639

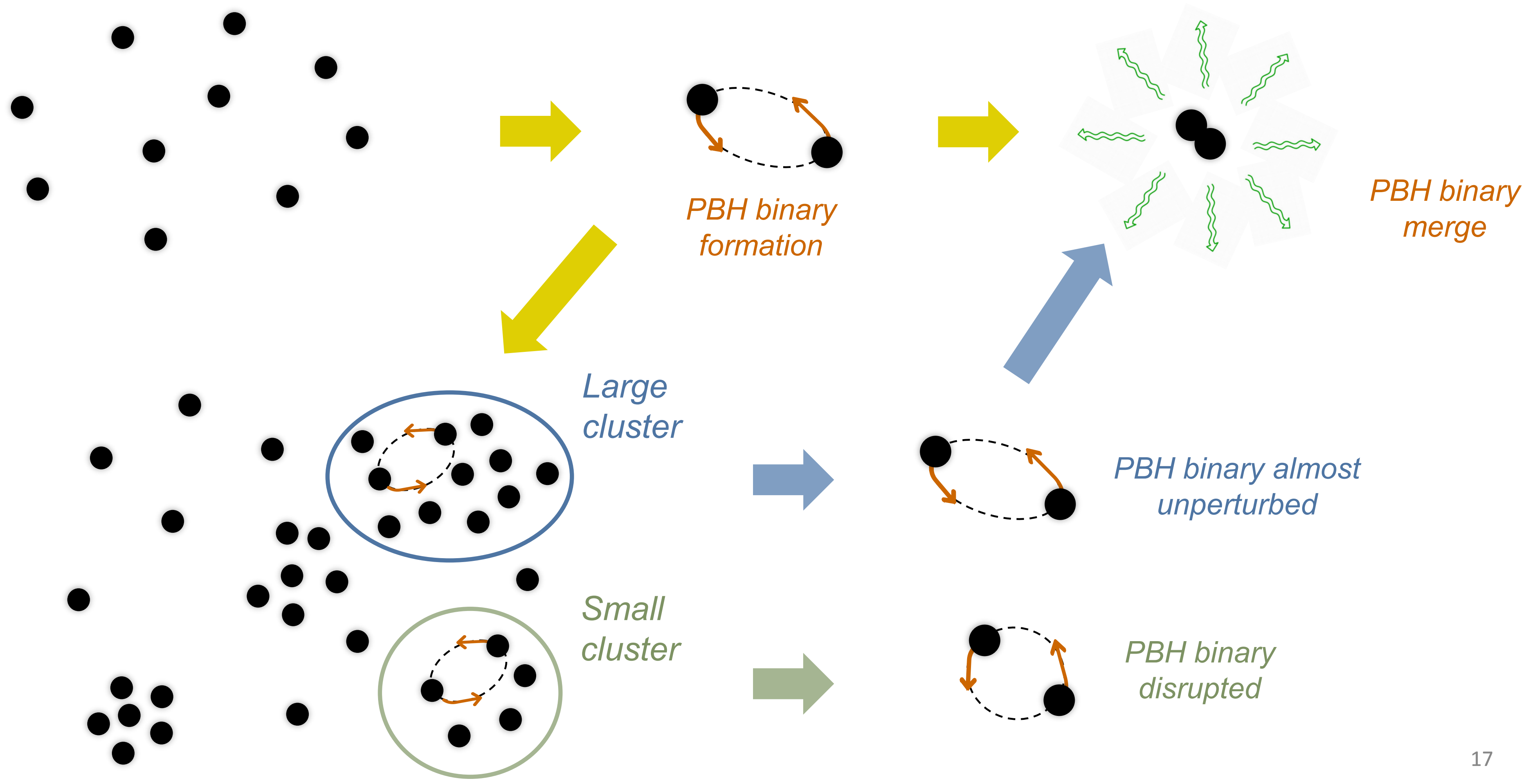
GW bounds



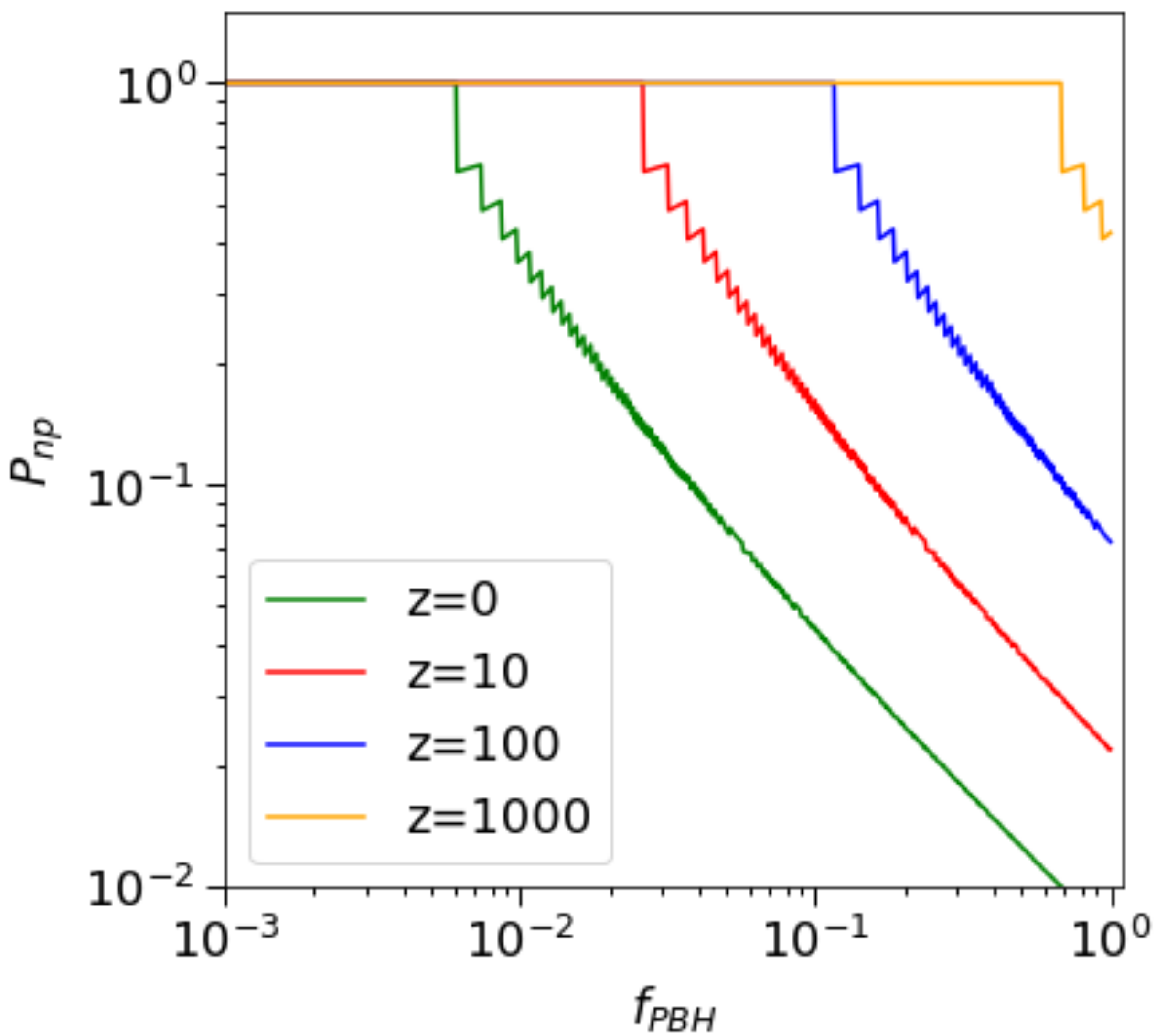
$M_{\rm PBH}$ [g]
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$
Stochastic background
Subsolar mergers
Mergers
Gravitational Waves
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$M_{\rm PBH}$ $[M_\odot]$

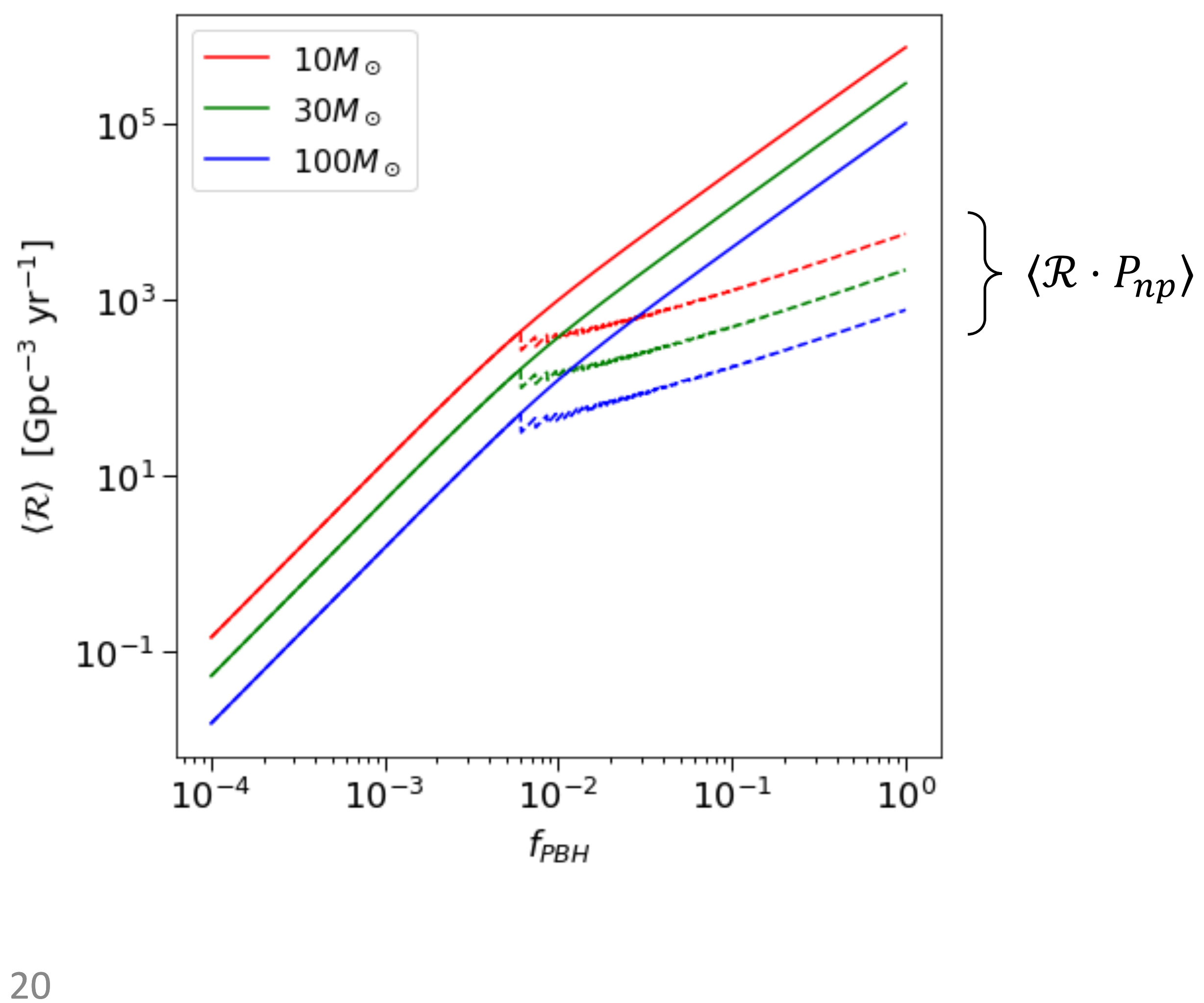
Caveats: Clustering

- PBH density fluctuations grow and eventually form **clusters** and non-linear structures.
- If the cluster halo core undergoes **gravothermal instability** —> more frequent binary encounters.
- Perturbed binaries typically harden and do not contribute to the merger rate anymore -> **suppression** of the merger rate



Caveats: Clustering



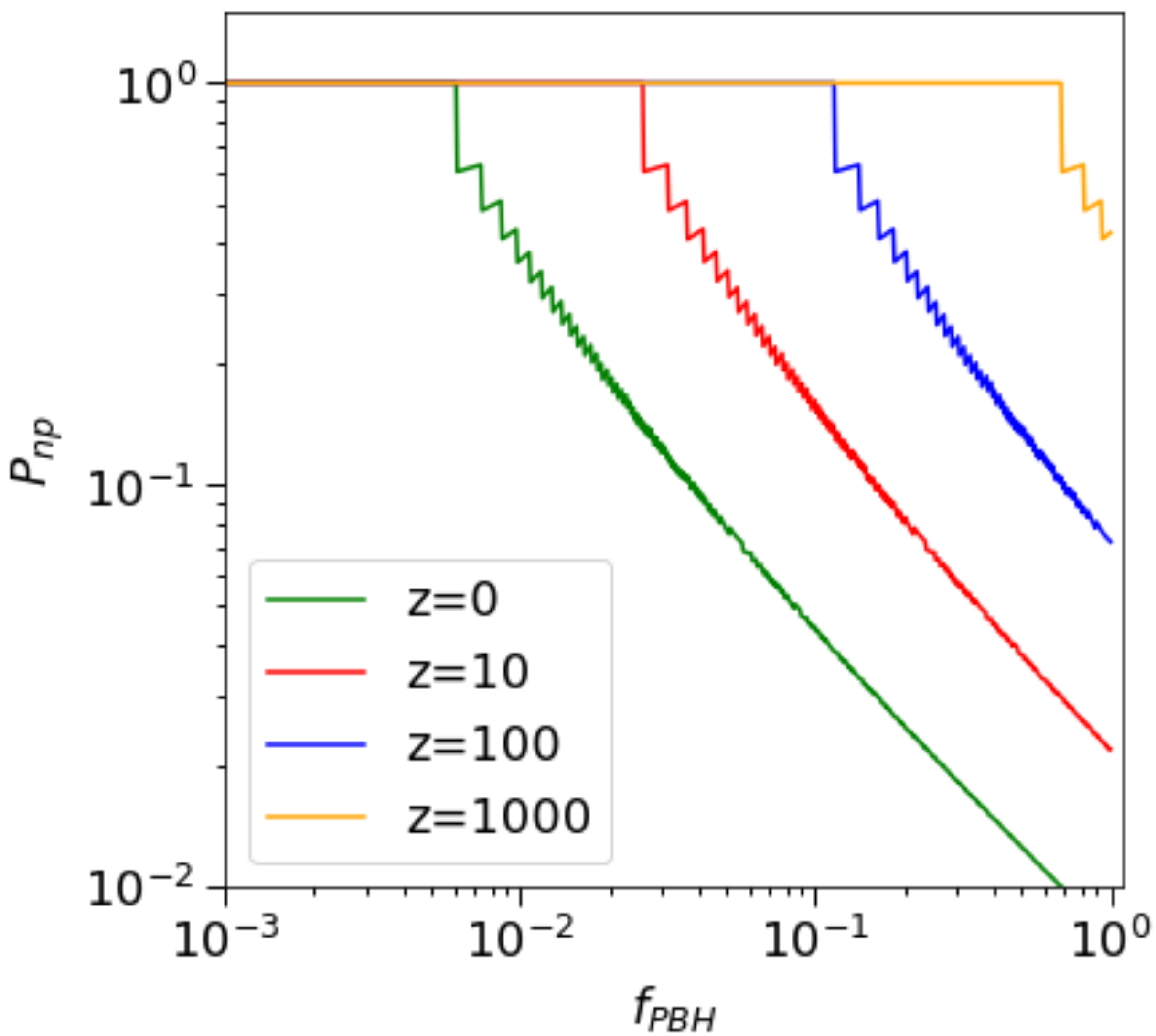


Raidal et al. *"Formation and Evolution of Primordial Black Hole Binaries in the Early Universe"* 1812.01930

Figure from C. Fernández Suárez, *M.Sc.Thesis* (IFT Madrid)

Scarcella et al. 2205.02639

Stasenko&Belotski 2307.12924



Raidal et al. *"Formation and Evolution of Primordial Black Hole Binaries in the Early Universe"* 1812.01930

Figure from C. Fernández Suárez, *M.Sc.Thesis* (IFT Madrid)

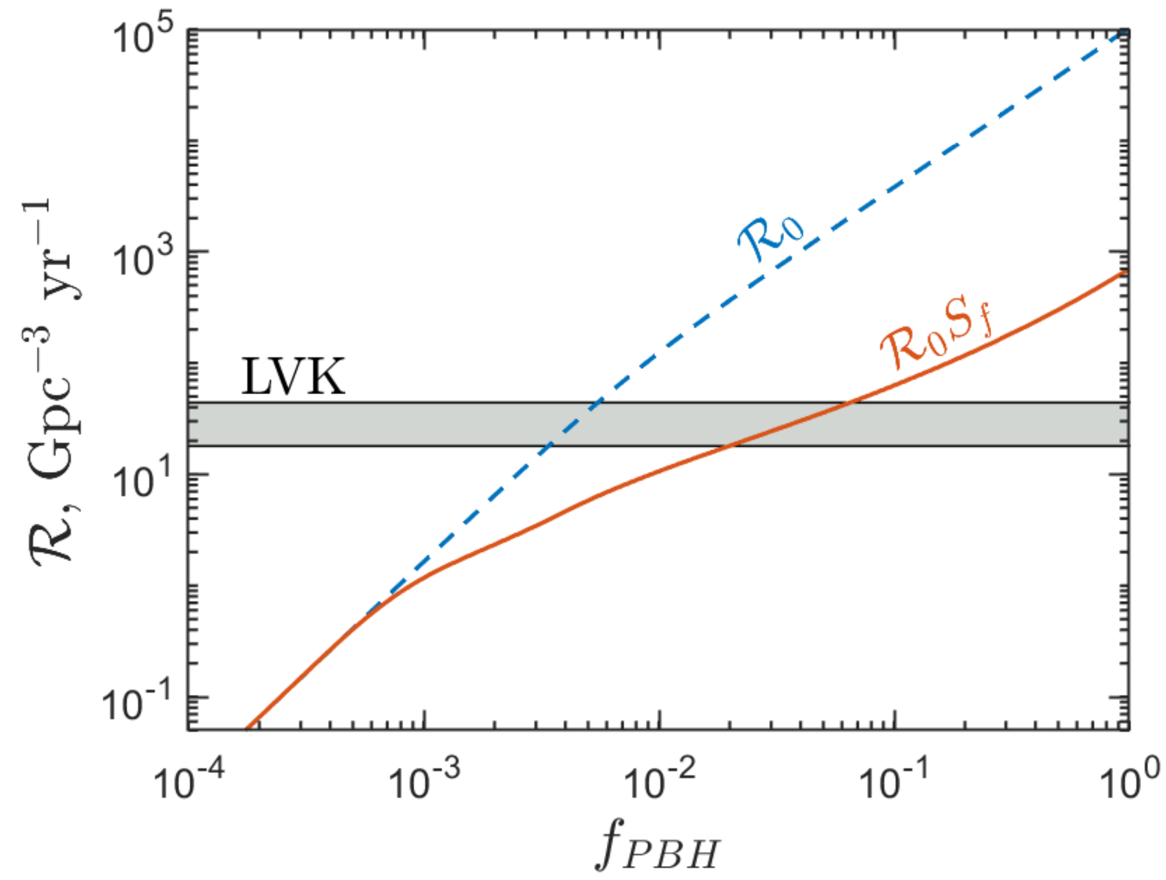
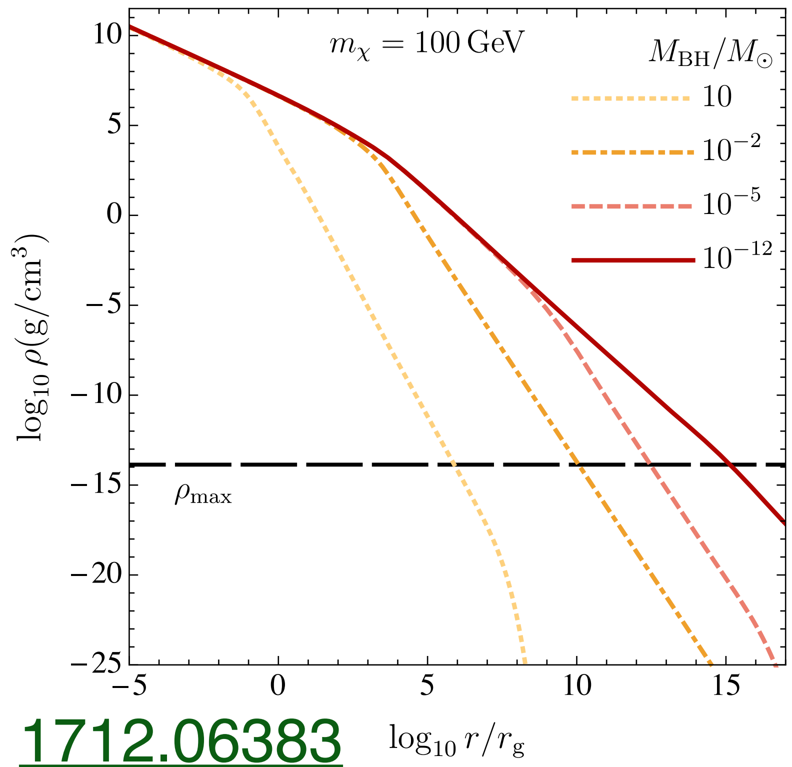


Figure 5. The PBH merger rate with the suppression factor (solid line) and without it (dashed line). The shaded area is the PBH merger rate inferred by the LIGO-Virgo-KAGRA collaboration $\mathcal{R} = 17.9 \div 44\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Abbott et al. 2023)

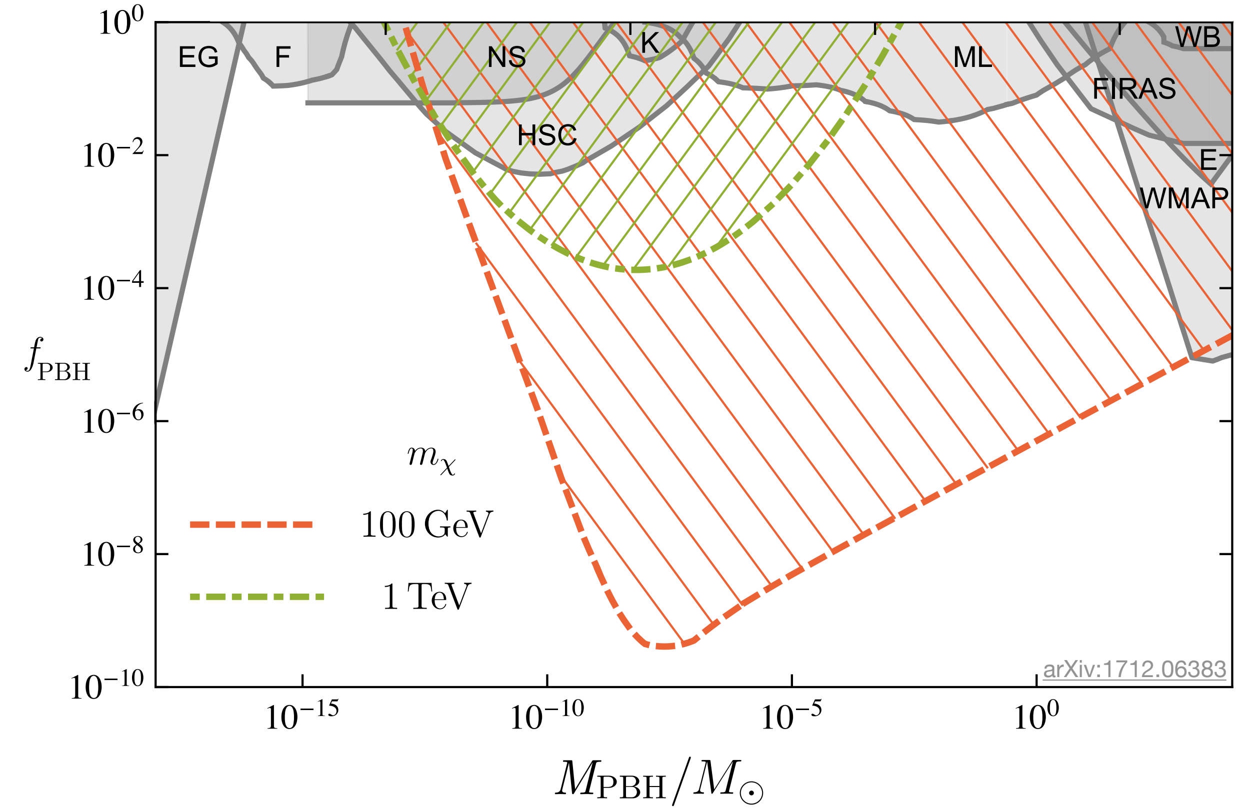
Scarcella et al. 2205.02639

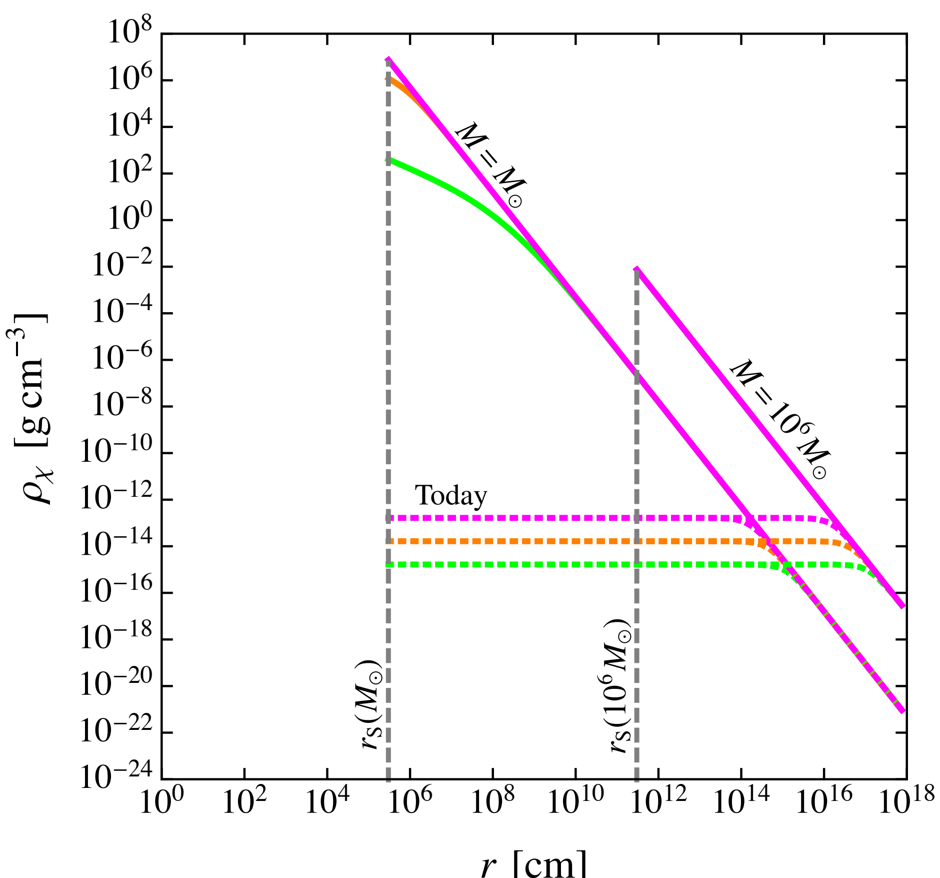
Stasenko&Belotski 2307.12924

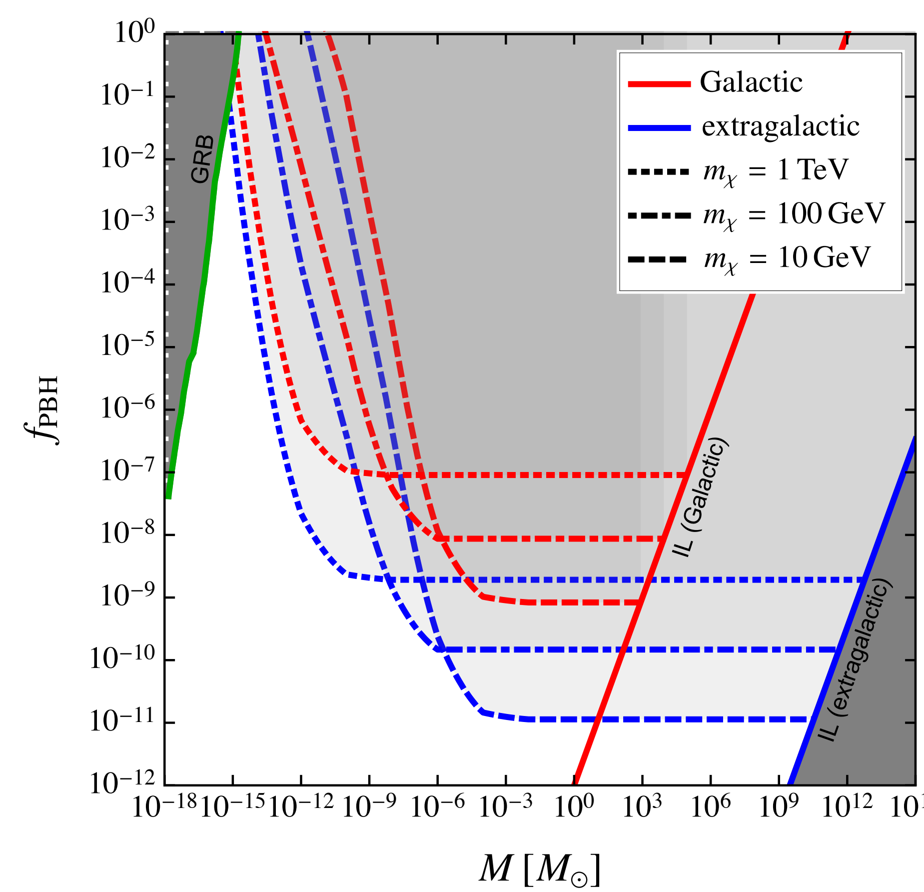
“Almost all or almost nothing”: Fermi-LAT-based



Boucenna+, [1712.06383]

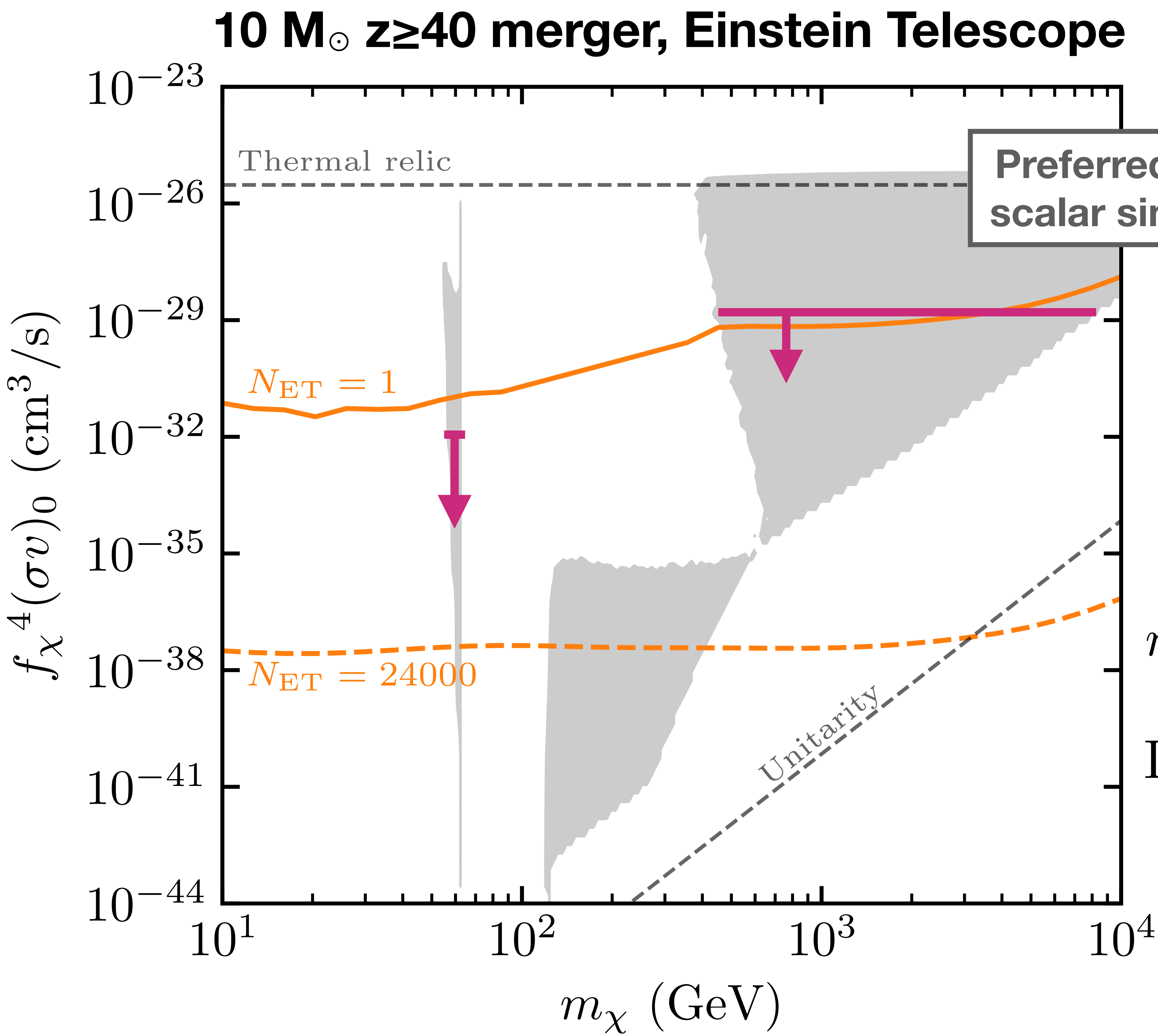






Carr+, [2011.01930]

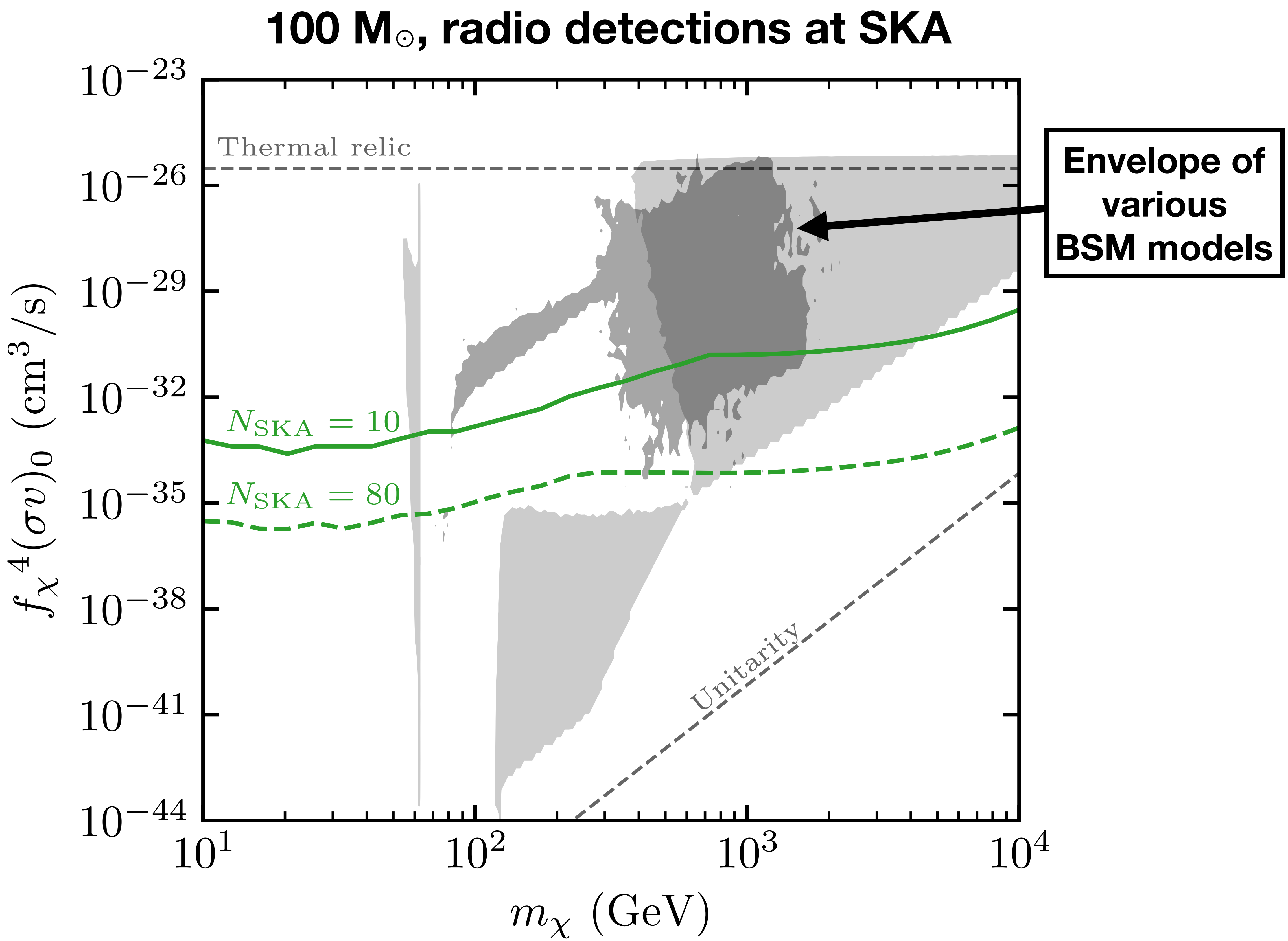
The results



$f_\chi < 0.1$

$$r_{\rm cut} \propto f_\chi^{4/9}$$

$$\Gamma \propto \left[f_\chi^4(\sigma v_{\rm rel})_0\right]^{1/3}.$$



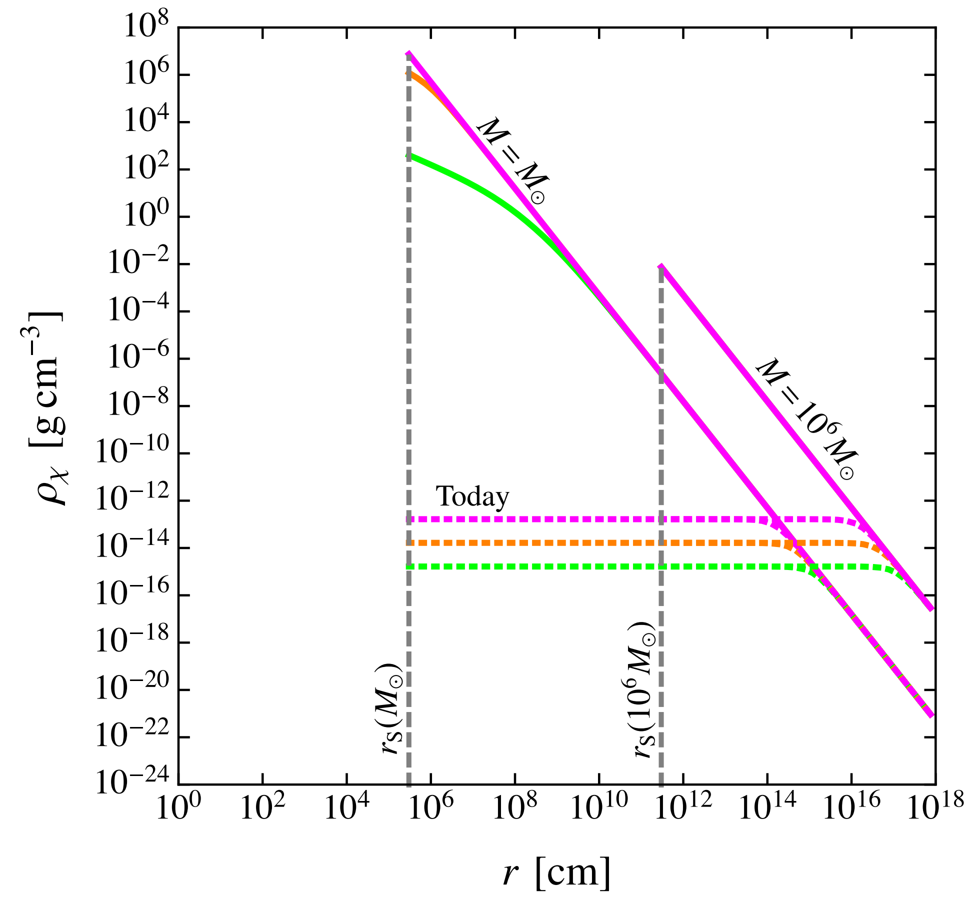
100 M☉, radio detections at SKA
Thermal relic
$N_{\rm SKA} = 10$
$N_{\rm SKA} = 80$
Unitarity
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^{-35}
10^{-38}
10^{-41}
10^{-44}
10^{1}
10^{2}
10^{3}
10^{4}
$f_\chi{}^4(\sigma v)_0$ (cm^3/s)
m_χ (GeV)
Envelope of various BSM models

IMBH Spike Formation Details

- **WIMP annihilation**: Constant density core [Adamek+ 1901.08528, Carr+ 2011.01930]

$$\rho_{\rm max} = \frac{m_\chi}{\langle\sigma v\rangle t_0} \simeq \left(\frac{m_\chi}{100{\rm GeV}}\right)\left(\frac{3\times10^{-26}{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle}\right)\left(\frac{4\times10^{17}{\rm s}}{t_0}\right) \times 1.5\times10^{-14}{\rm g/cm}^3, \quad (13)$$

$$r_{\rm cut} = \left(\frac{\rho_{\rm eq}}{2\rho_{\rm max}}\right)^{4/9}\left(2GM_{\rm PBH}\, t_{\rm eq}^2\right)^{1/3} \simeq \left(\frac{m_\chi}{100{\rm GeV}}\right)^{-4/9}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{1/3} 1.3\times10^{-7}{\rm kpc}\, h^{-1}. \quad (14)$$



- **WIMP Kinetic Decoupling**: Constant density core [Eroshenko 1607.00612, Carr+ 2011.01930]

$$\tilde{\rho}_i(r) = \frac{\rho_{\chi,\,{\rm spike}}(r)\,\rho_{\rm KD}}{\rho_{\chi,\,{\rm spike}}(r) + \rho_{\rm KD}}\,.$$

Spike profile can change if some DM candidates are considered [Hannuksela+ 1906.11845]

In several cases, a **core** can form
Positive detection -> Upper limits on DM properties