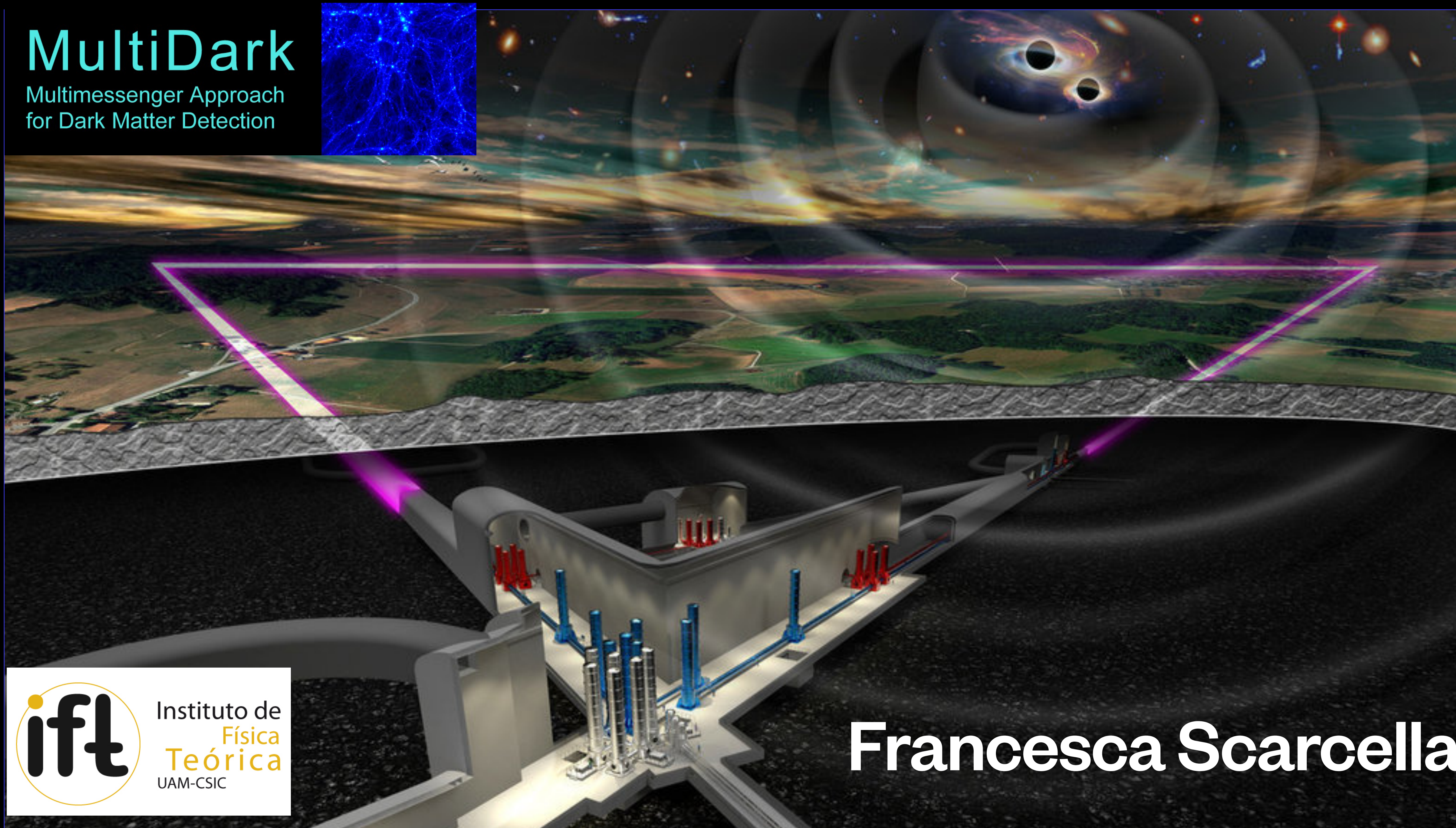
MultiDark
Multimessenger Approach
for Dark Matter Detection



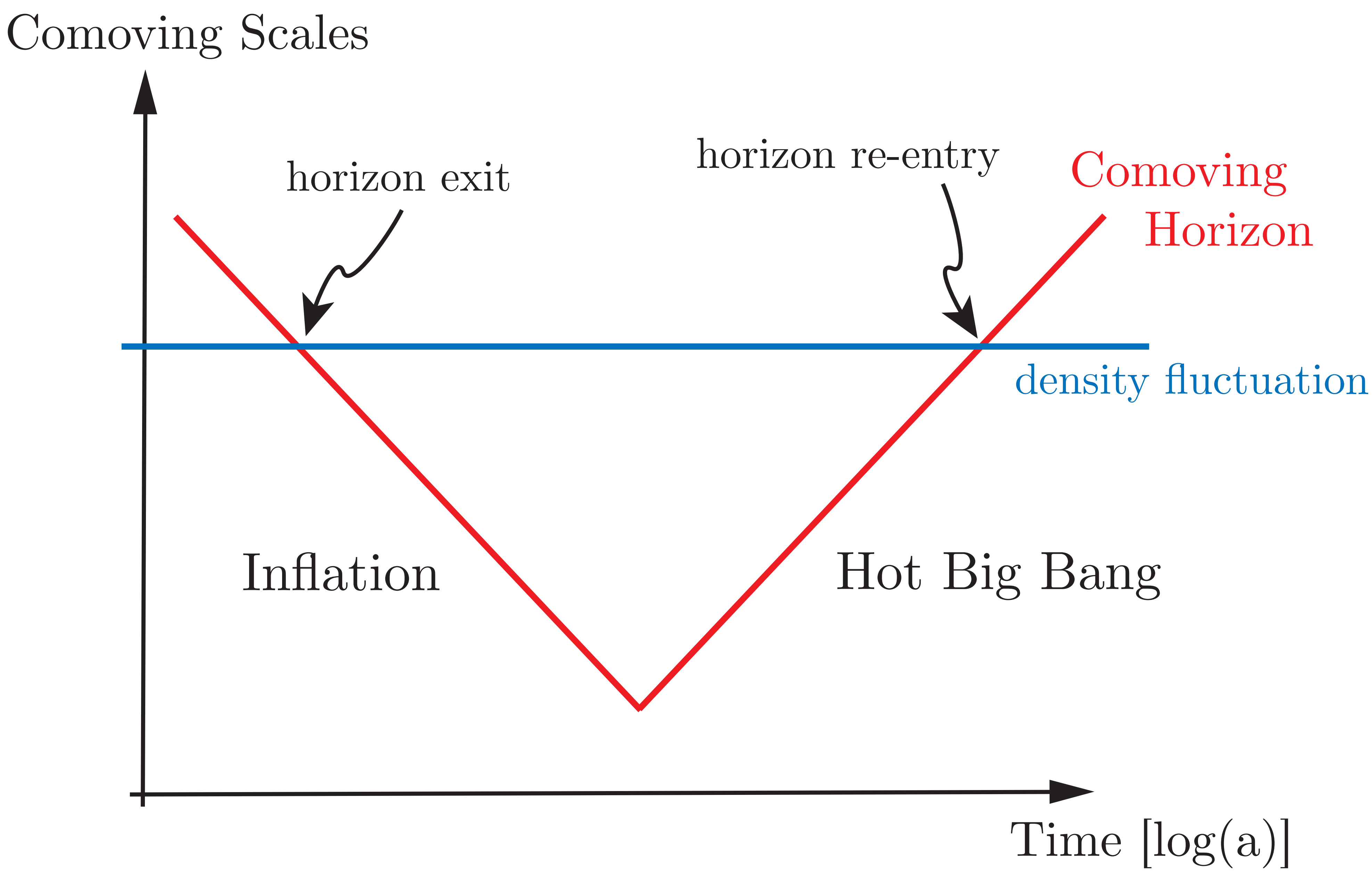
Instituto de Física Teórica
UAM-CSIC

Francesca Scarcella

Prospects for primordial black hole detection with high redshift gravitational wave observations

Primordial black holes (PBHs)

S. Hawking, MNRAS 152 (1971); Carr and Hawking, MNRAS 168 (1974)



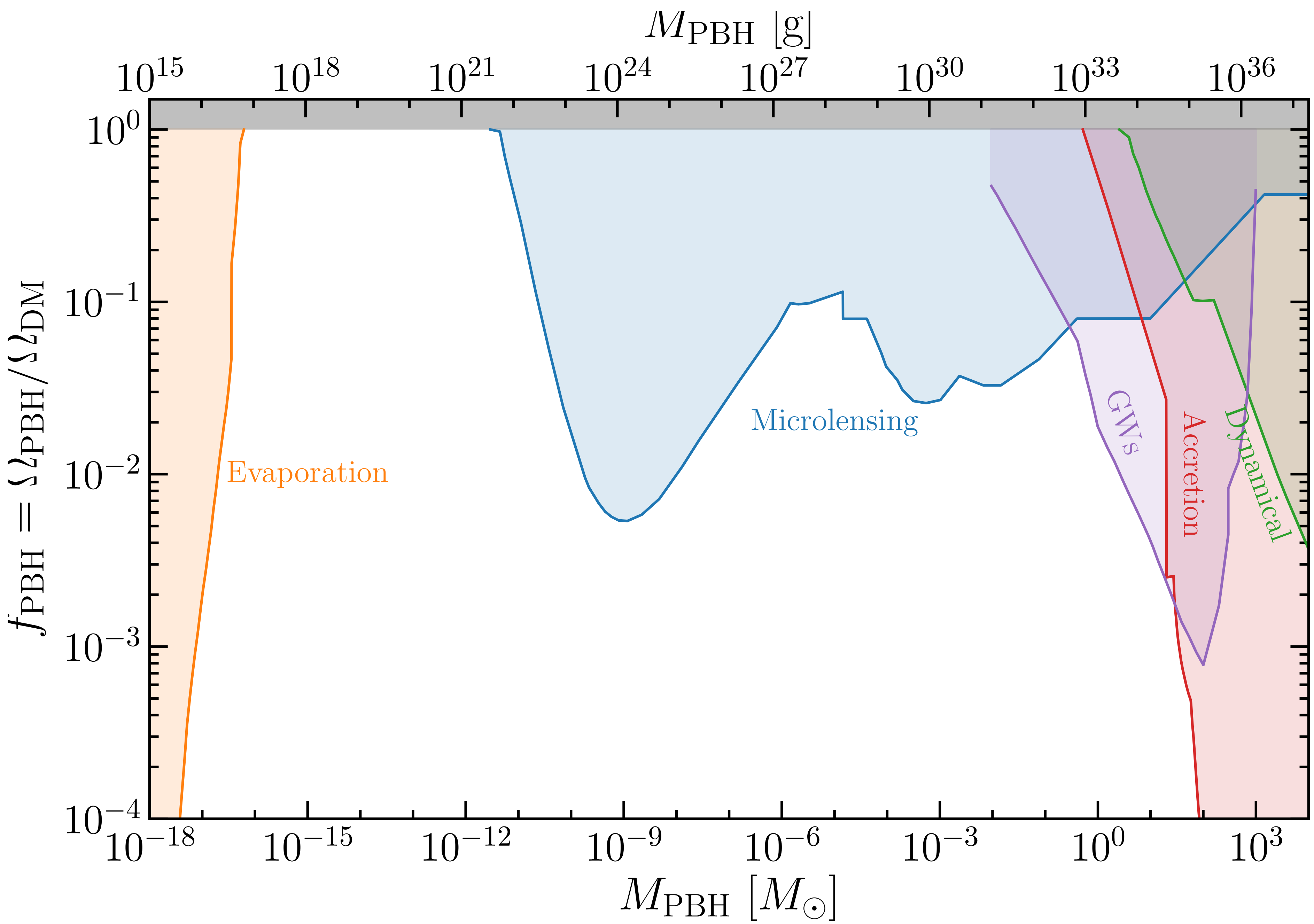
$$\frac{\delta\rho}{\rho} \gtrsim \frac{1}{3}$$

Primordial black holes as dark matter

- Cold
- Collisionless
- Neutral
- Stable
- Non-baryonic

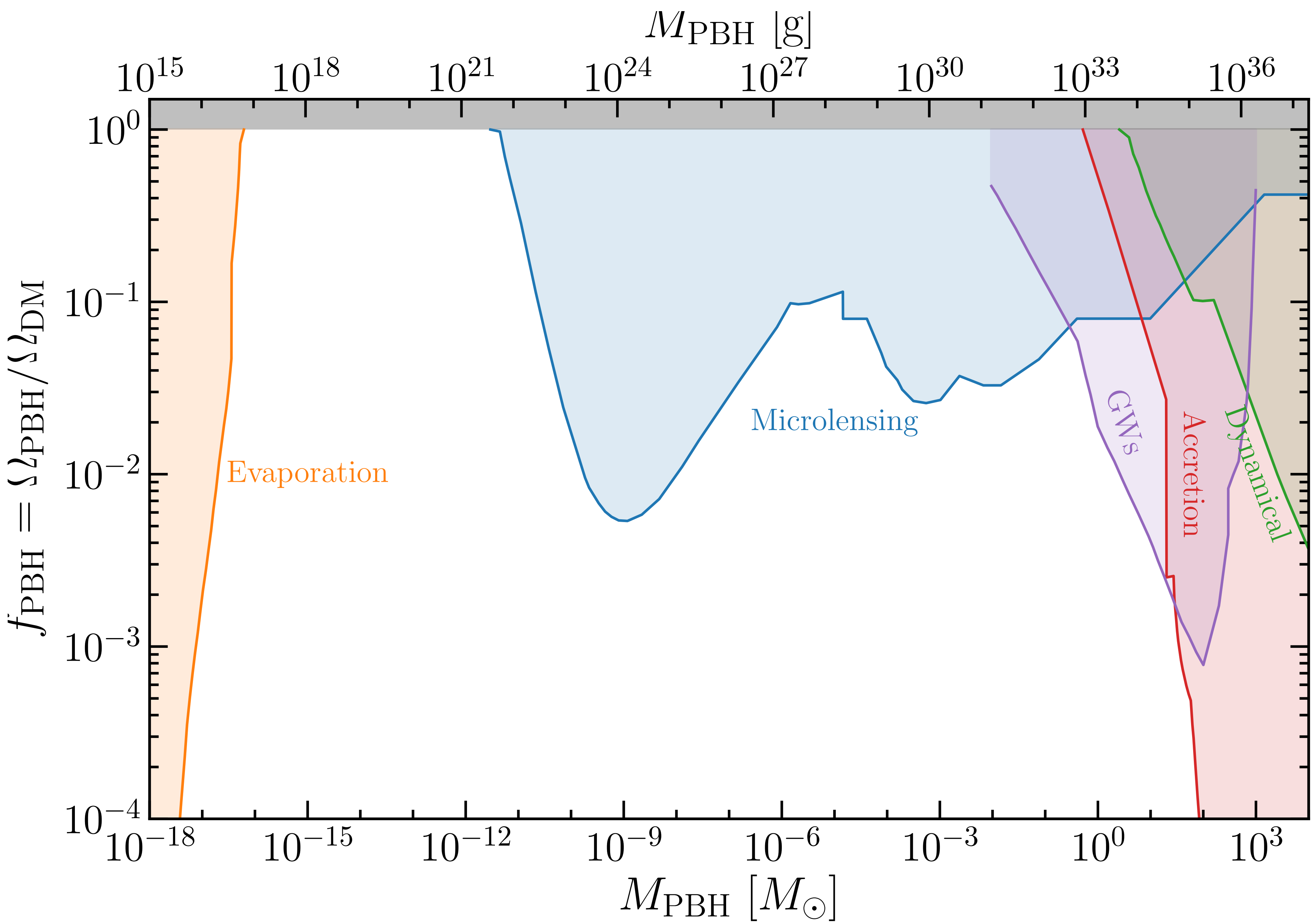
Small scale distribution of DM: not known!

Constraints



https://github.com/bradkav/PBHbounds

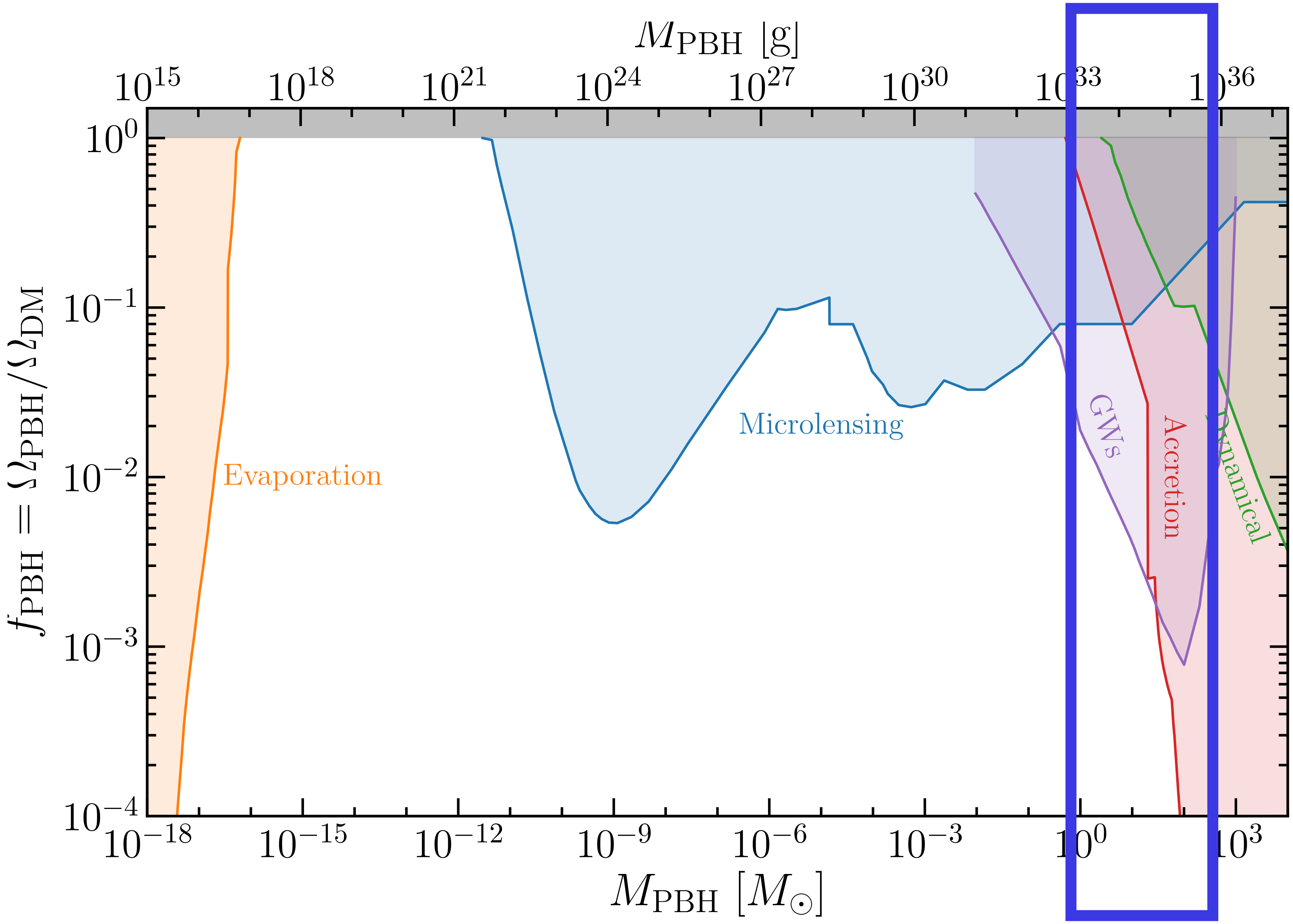
Constraints



https://github.com/bradkav/PBHbounds

Can primordial black holes be (a part of) ***the dark matter***?

Constraints



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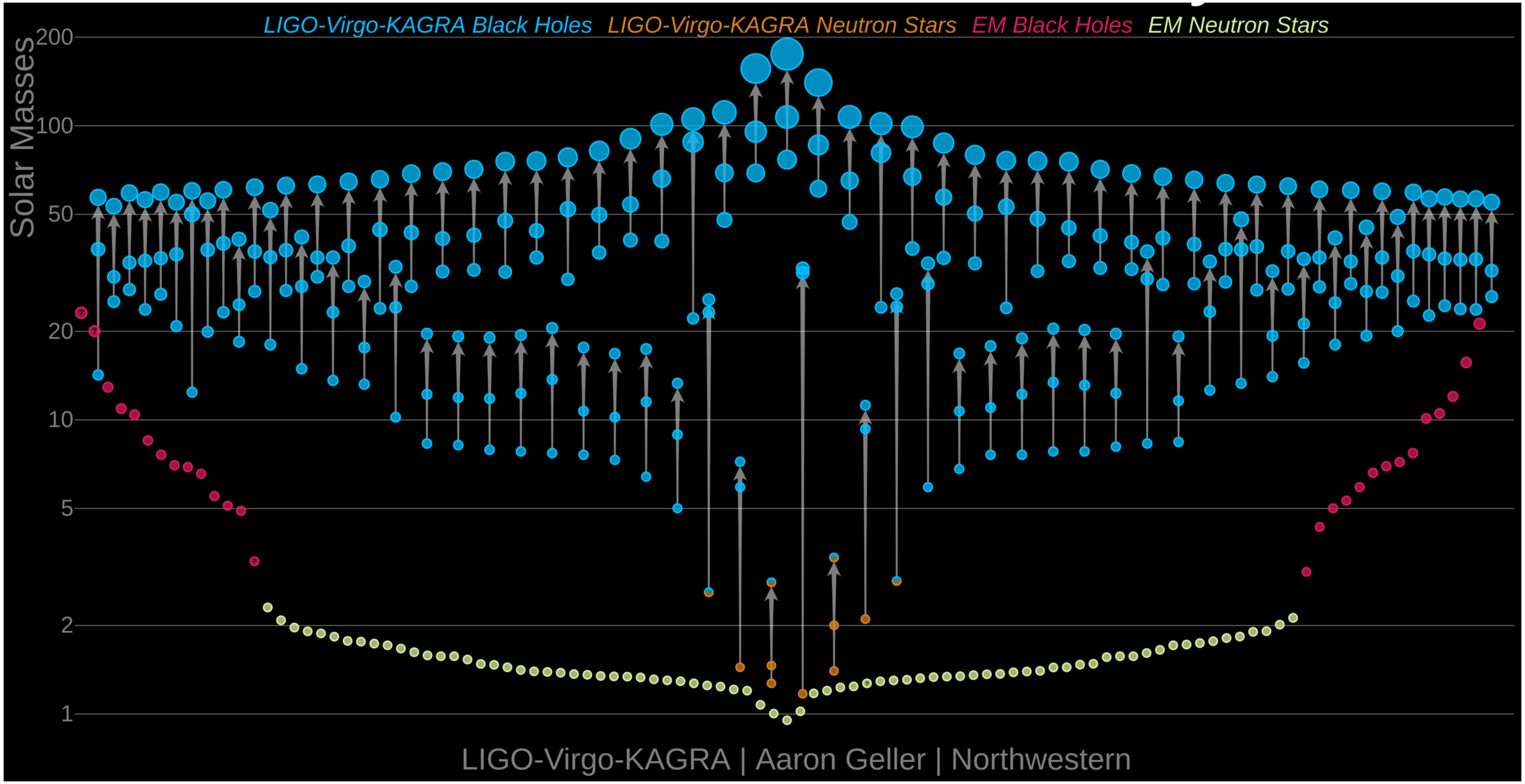
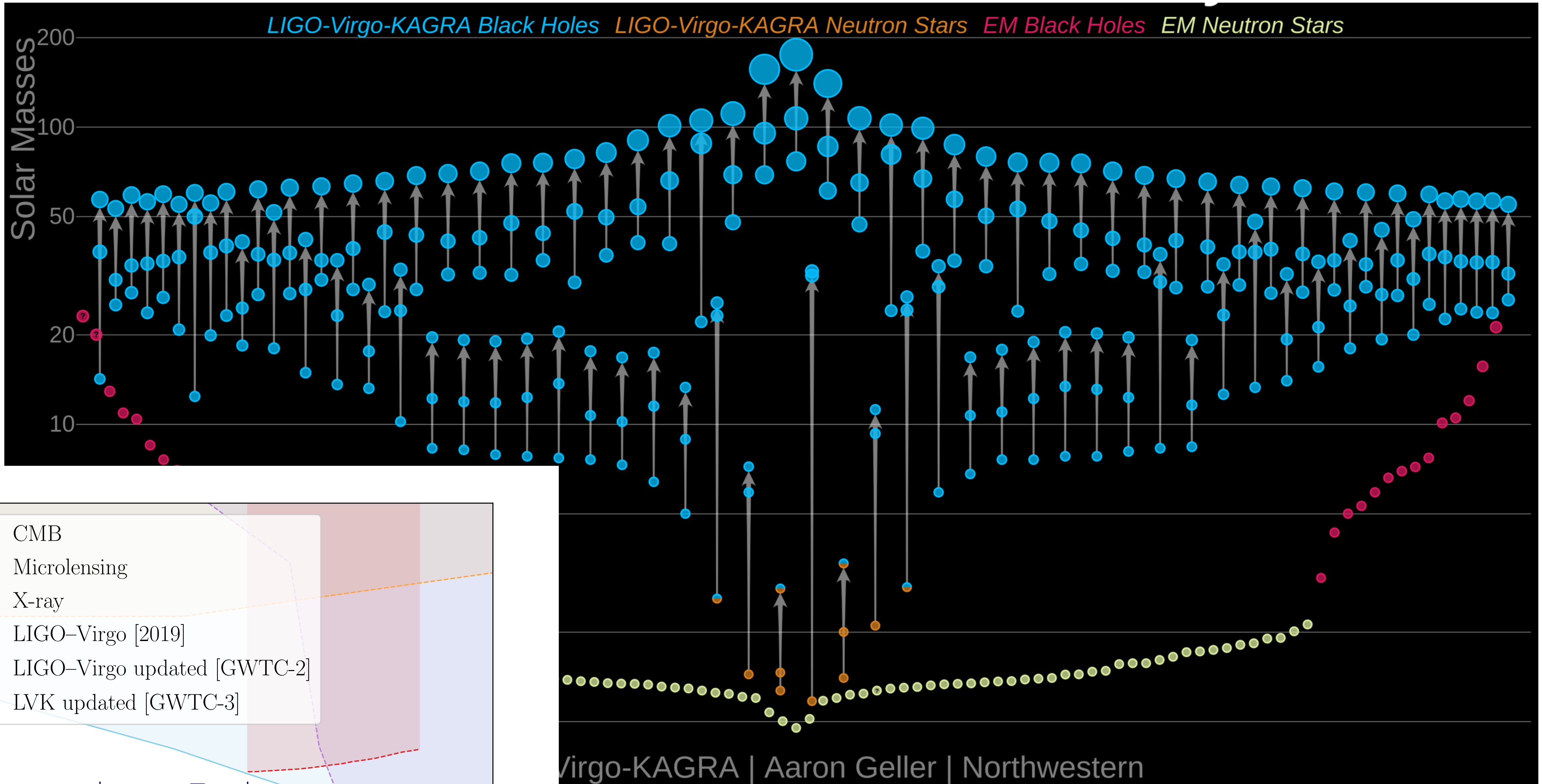
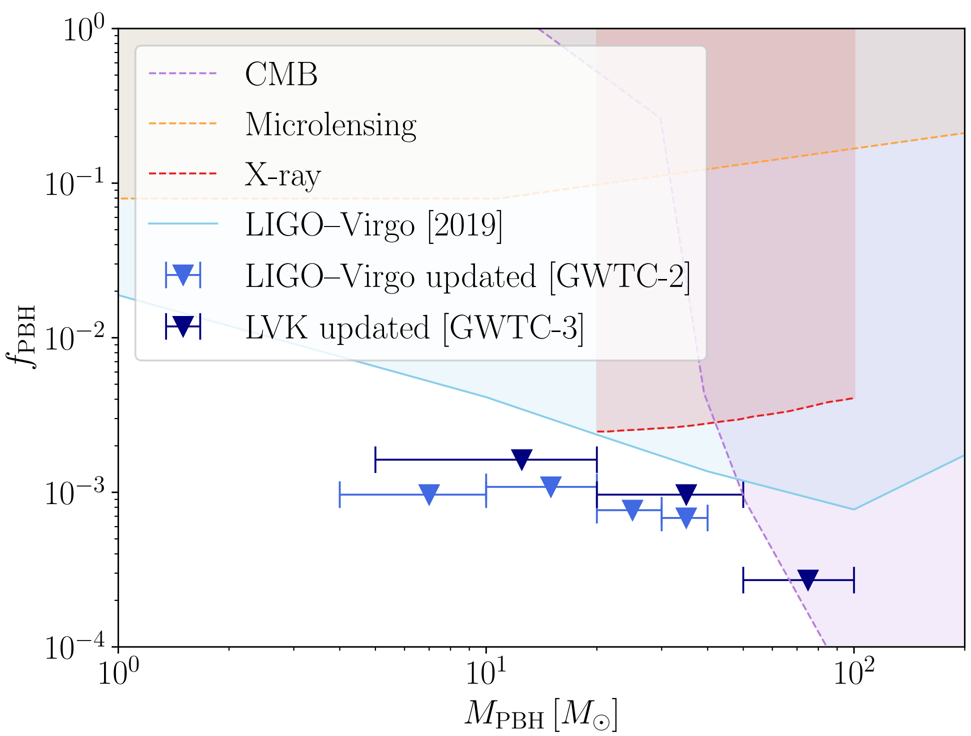


GWTC-3 Catalog





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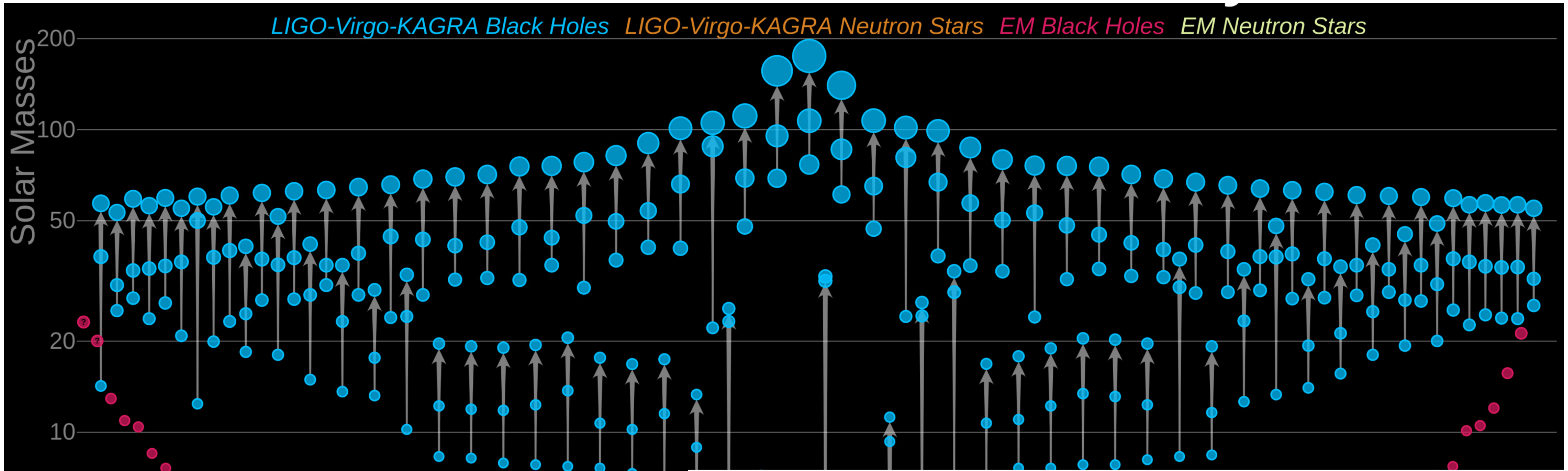
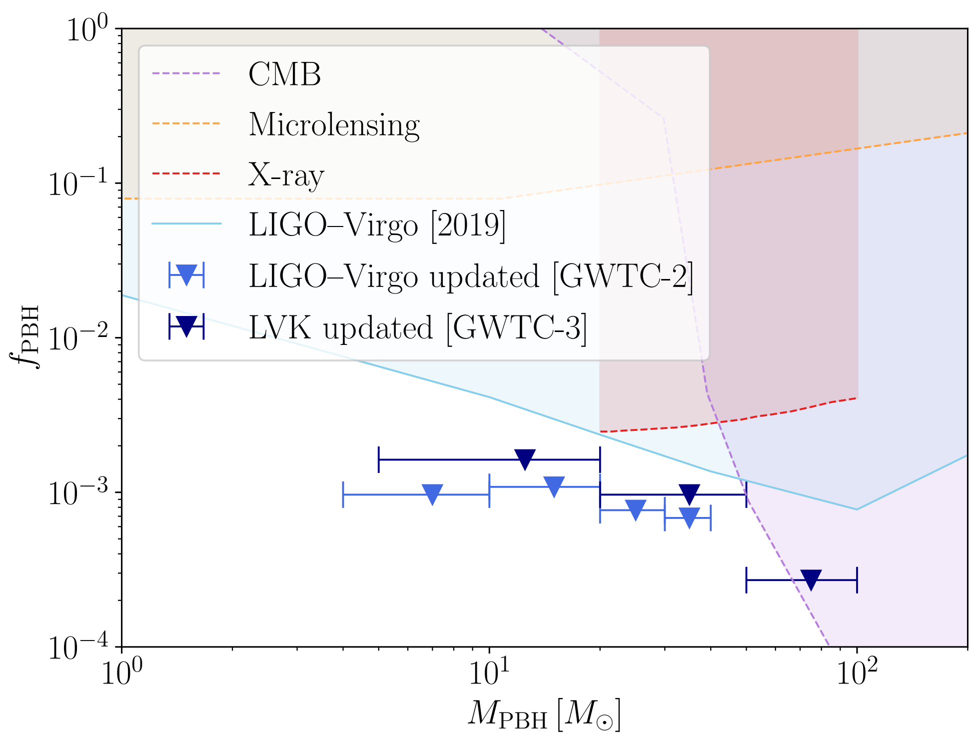
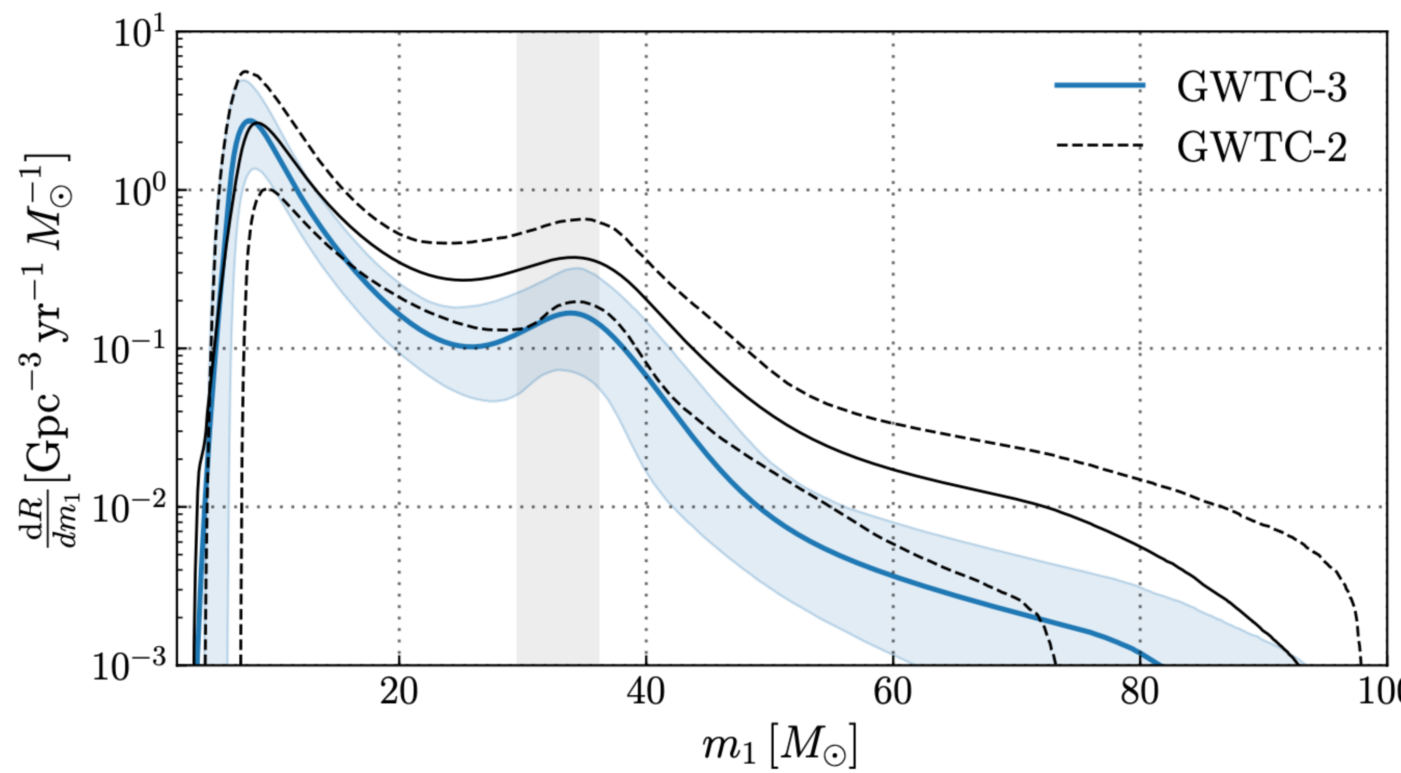
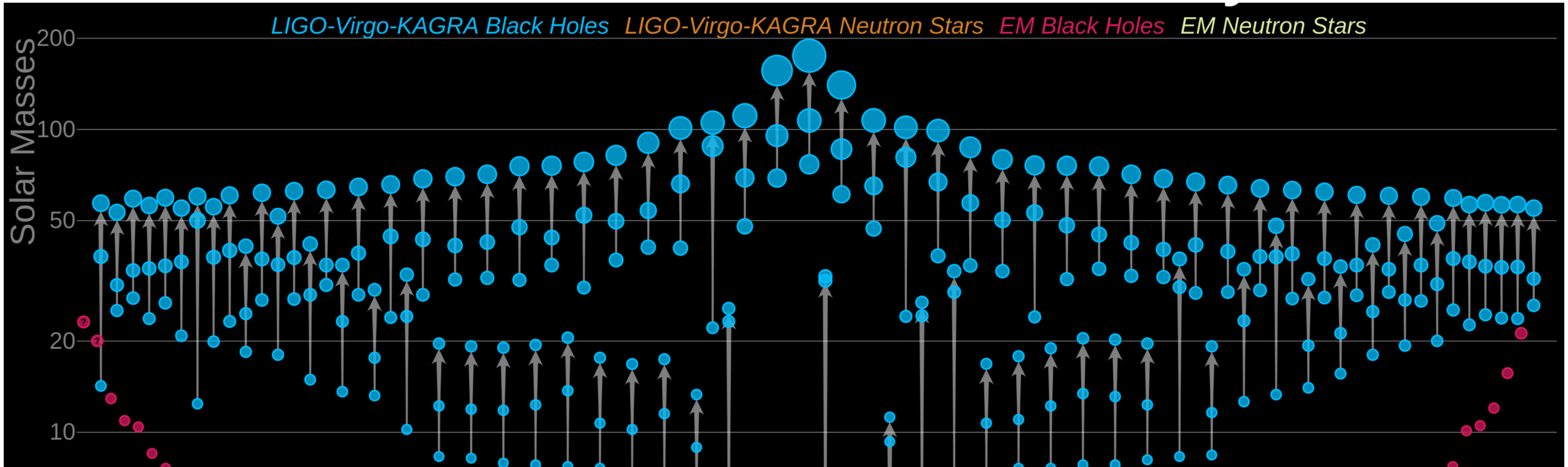
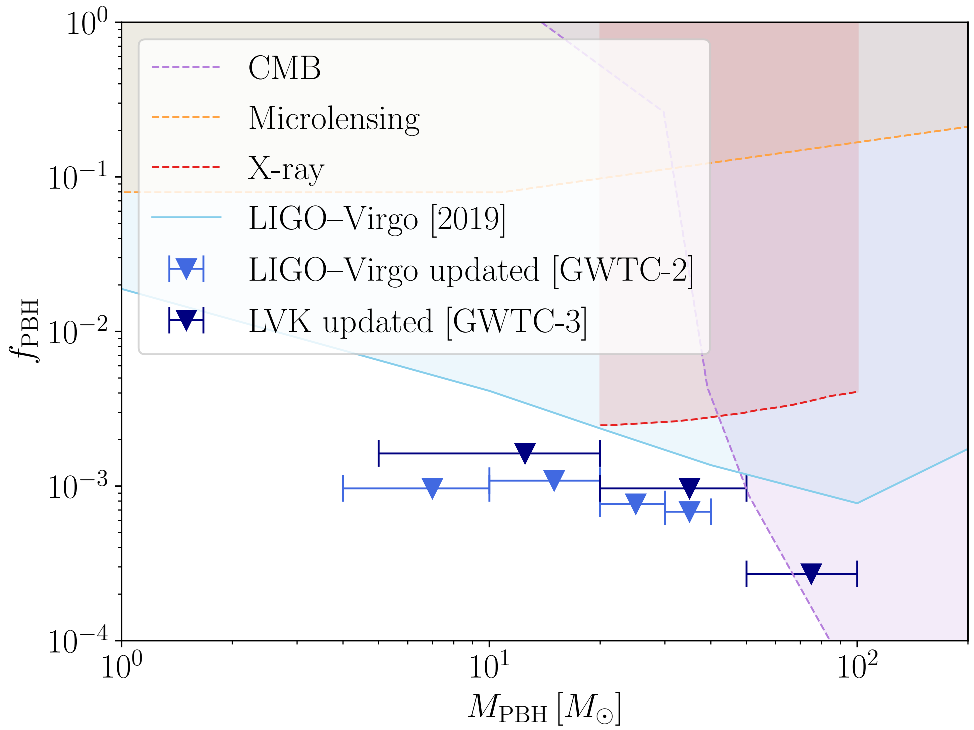
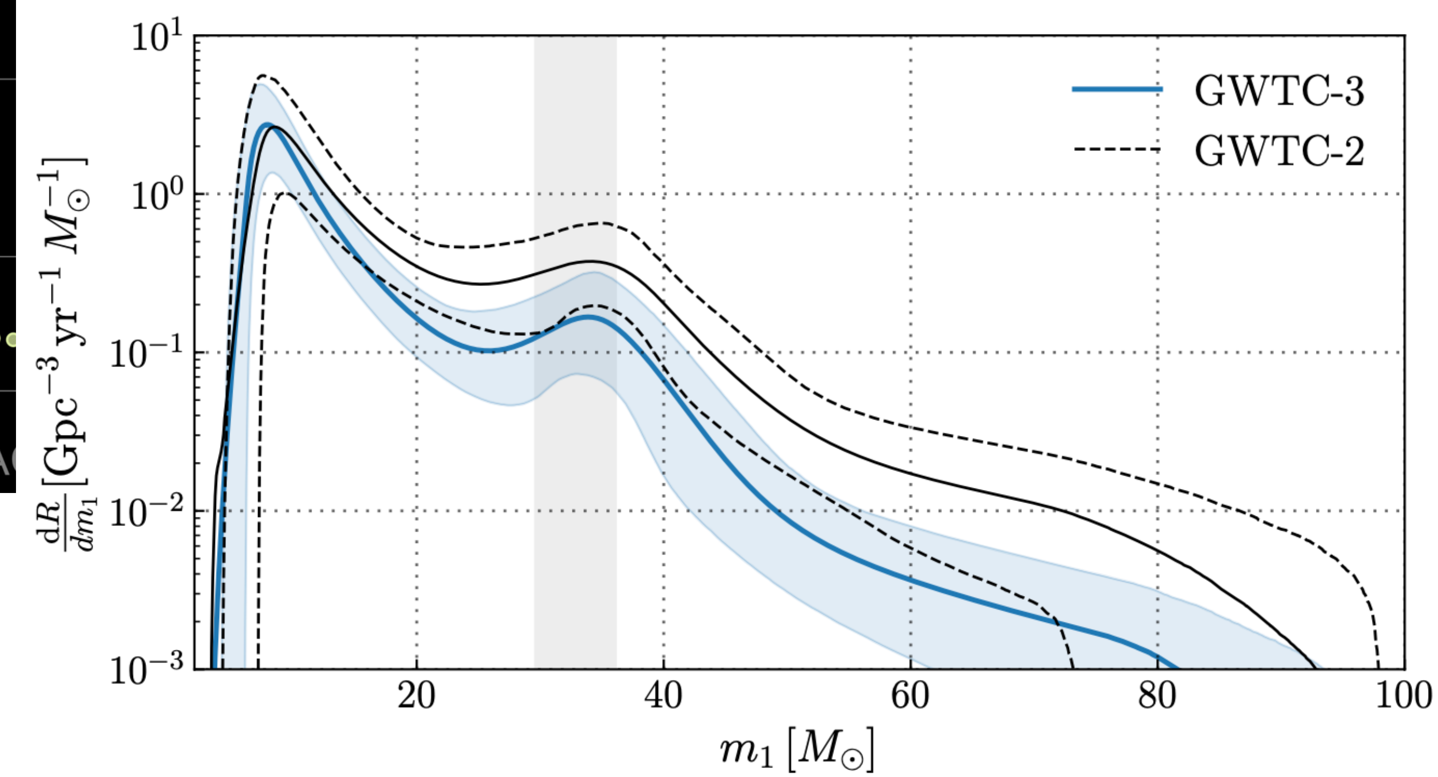

LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10


CMB
Microlensing
X-ray
LIGO–Virgo [2019]
LIGO–Virgo updated [GWTC-2]
LVK updated [GWTC-3]
f_{PBH}
$M_{\mathrm{PBH}}\,[M_\odot]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2


GWTC-3
GWTC-2
$\frac{dR}{dm_1}\,[\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}\,M_\odot^{-1}]$
$m_1\,[M_\odot]$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
40
60
80
100



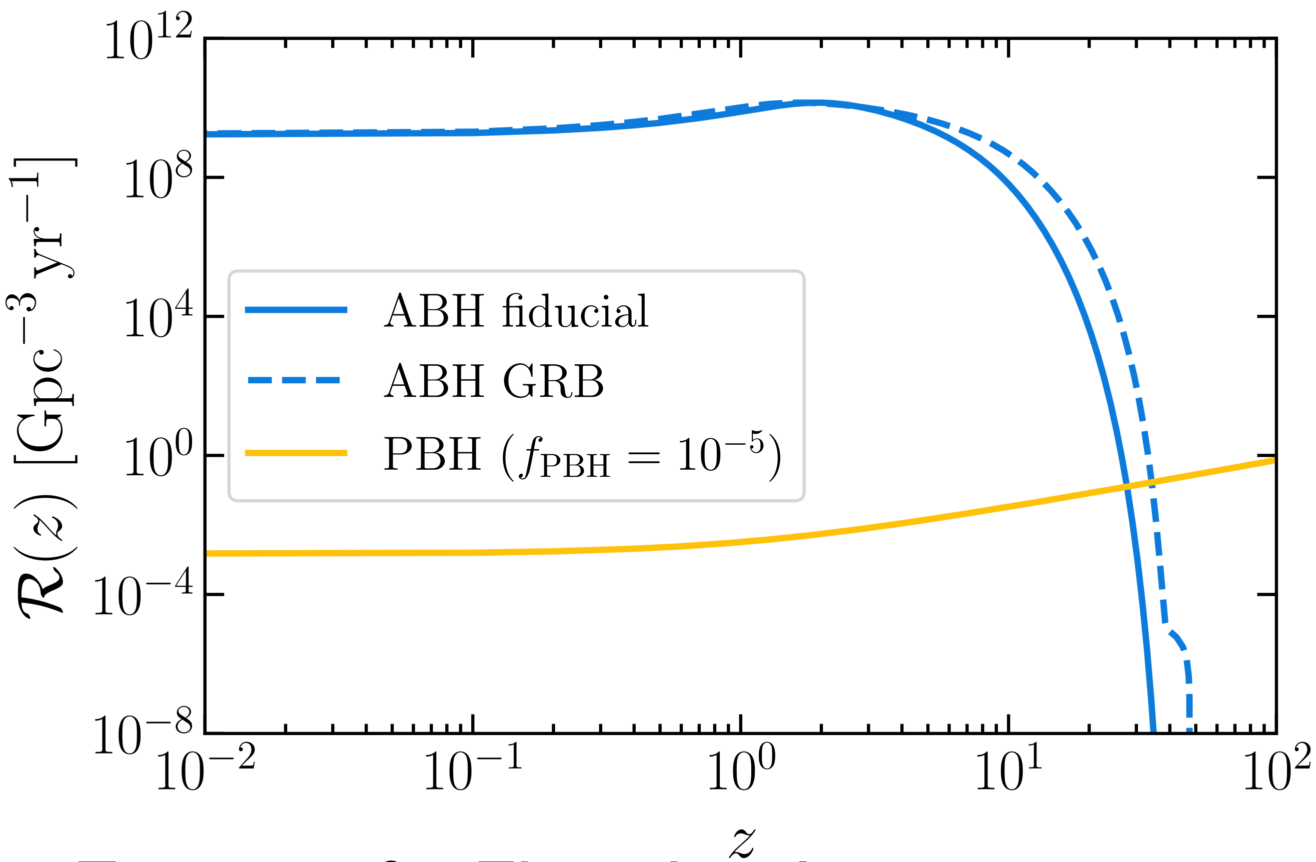


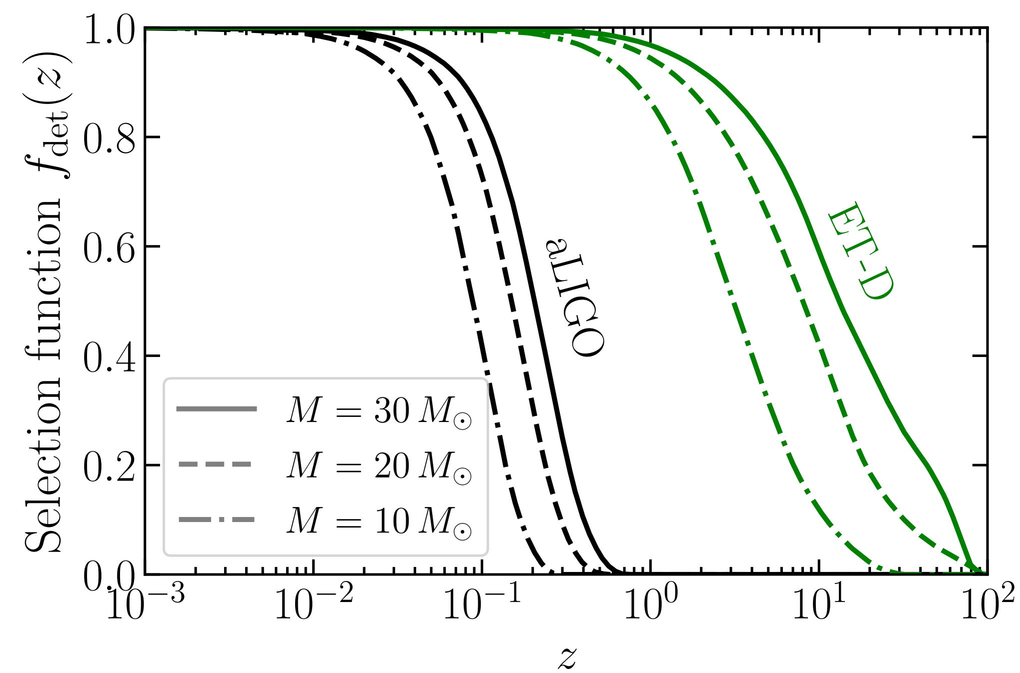


High redshift: ***no astrophysical*** background

Prospects for the Einstein Telescope

Can we identify primordial black holes with ***future gravitational wave observatories***?





Forecast for Einstein telescope to assess:

- ability to ***detect*** PBH
- ability to ***measure*** PBH abundance

Prepared for submission to JCAP

arXiv: 2205.02639

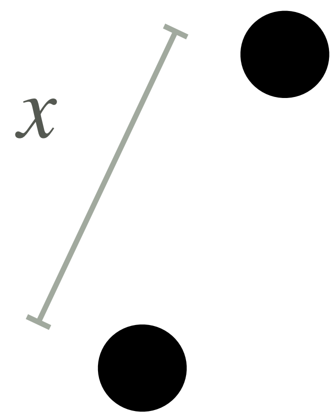
Dancing in the dark: detecting a population of distant primordial black holes

Matteo Martinelli,[a,b] Francesca Scarcella,[b] Natalie B. Hogg,[c,b] Bradley J. Kavanagh,[d] Daniele Gaggero,[e,f,b] and Pierre Fleury[c,b]

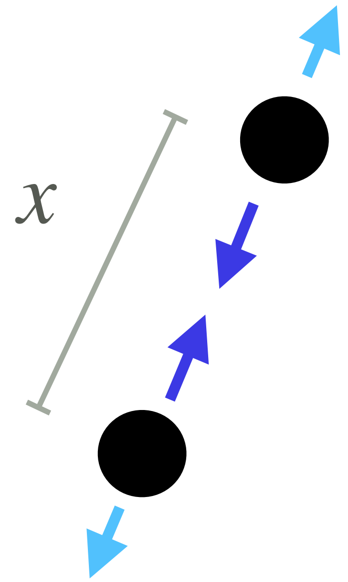
[a]INAF - Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio Catone (Roma), Italy
[b]Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid,

5 May 2022

Primordial BH binaries - early Universe



Primordial BH binaries - early Universe



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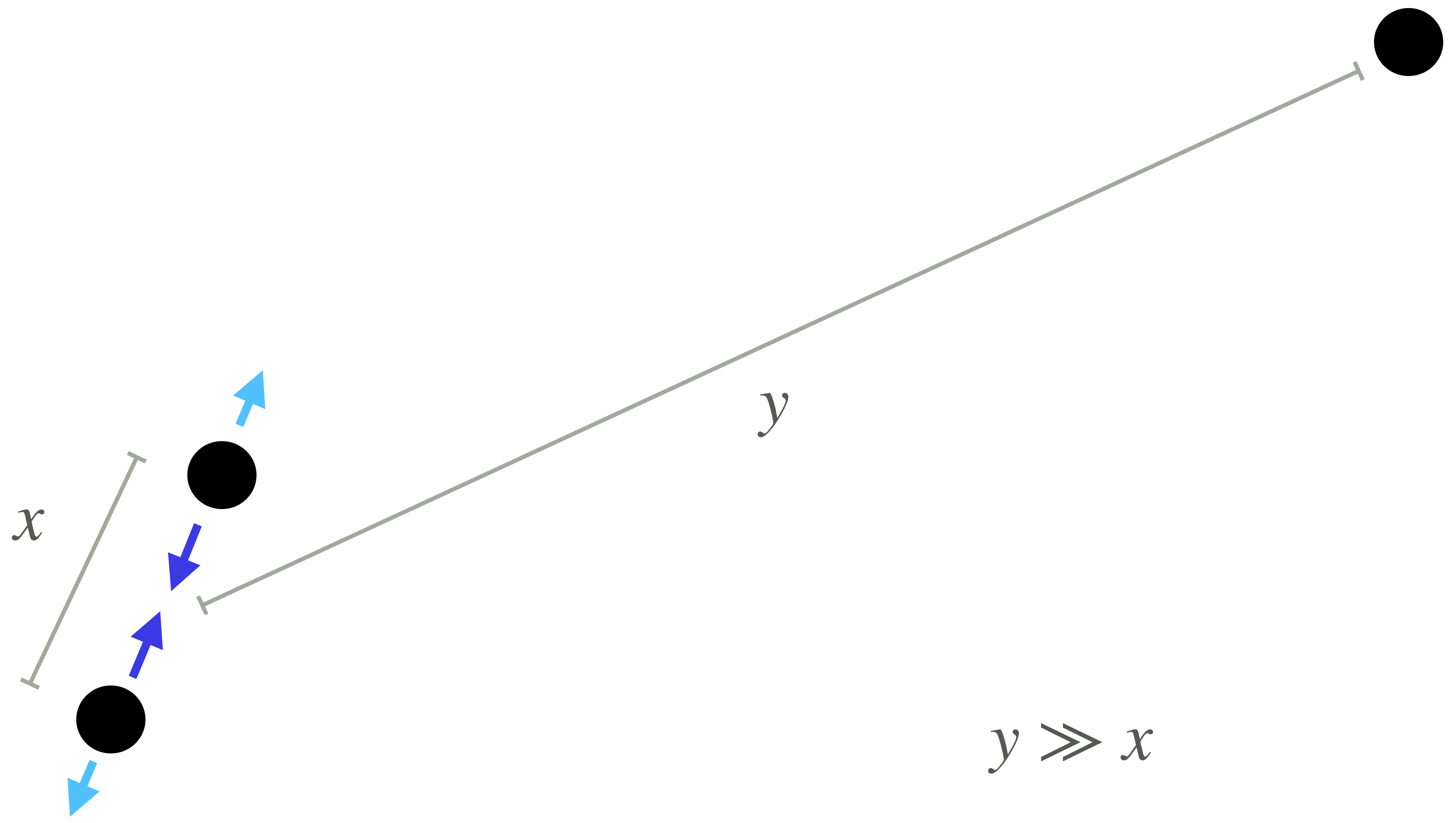
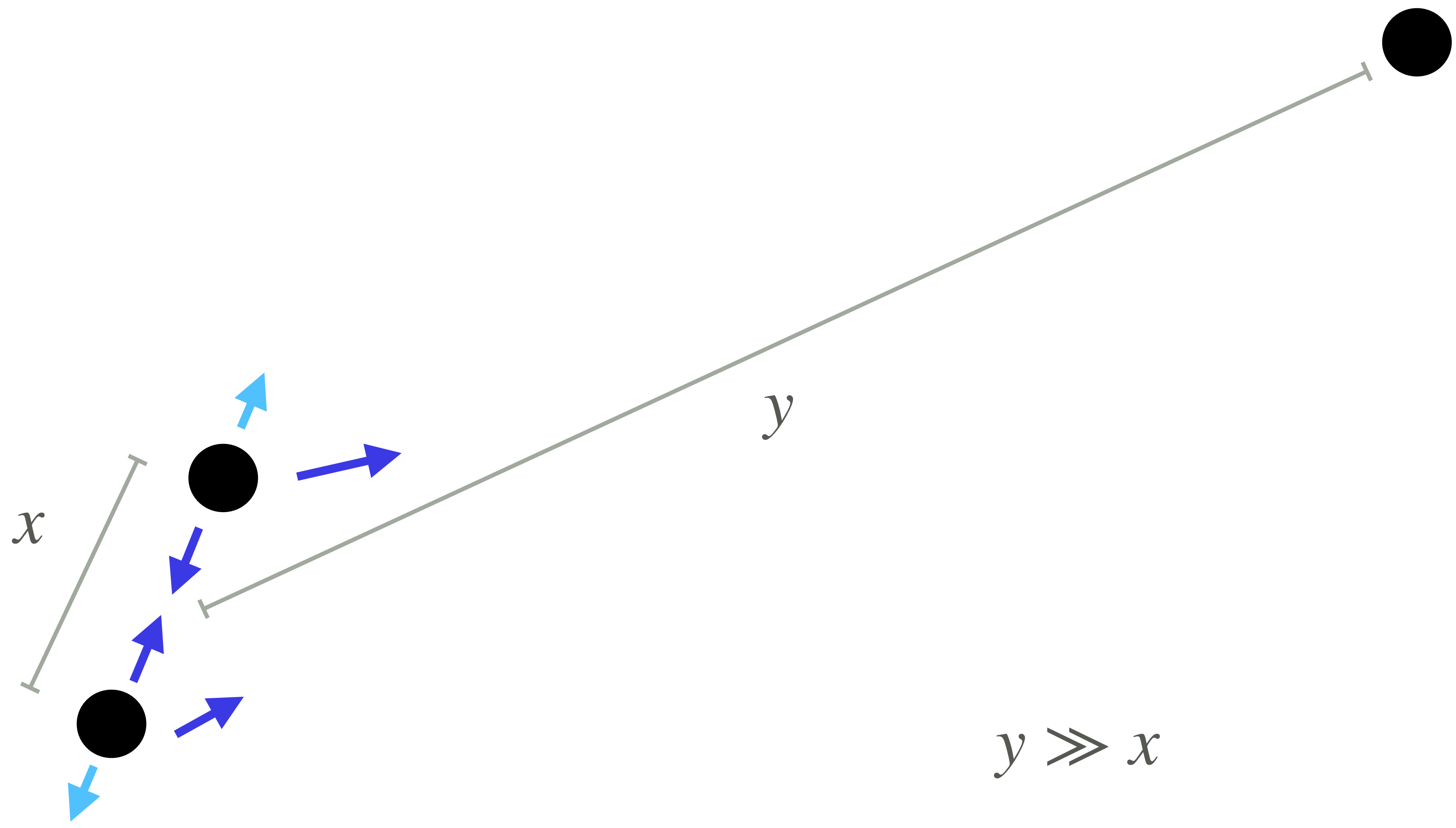
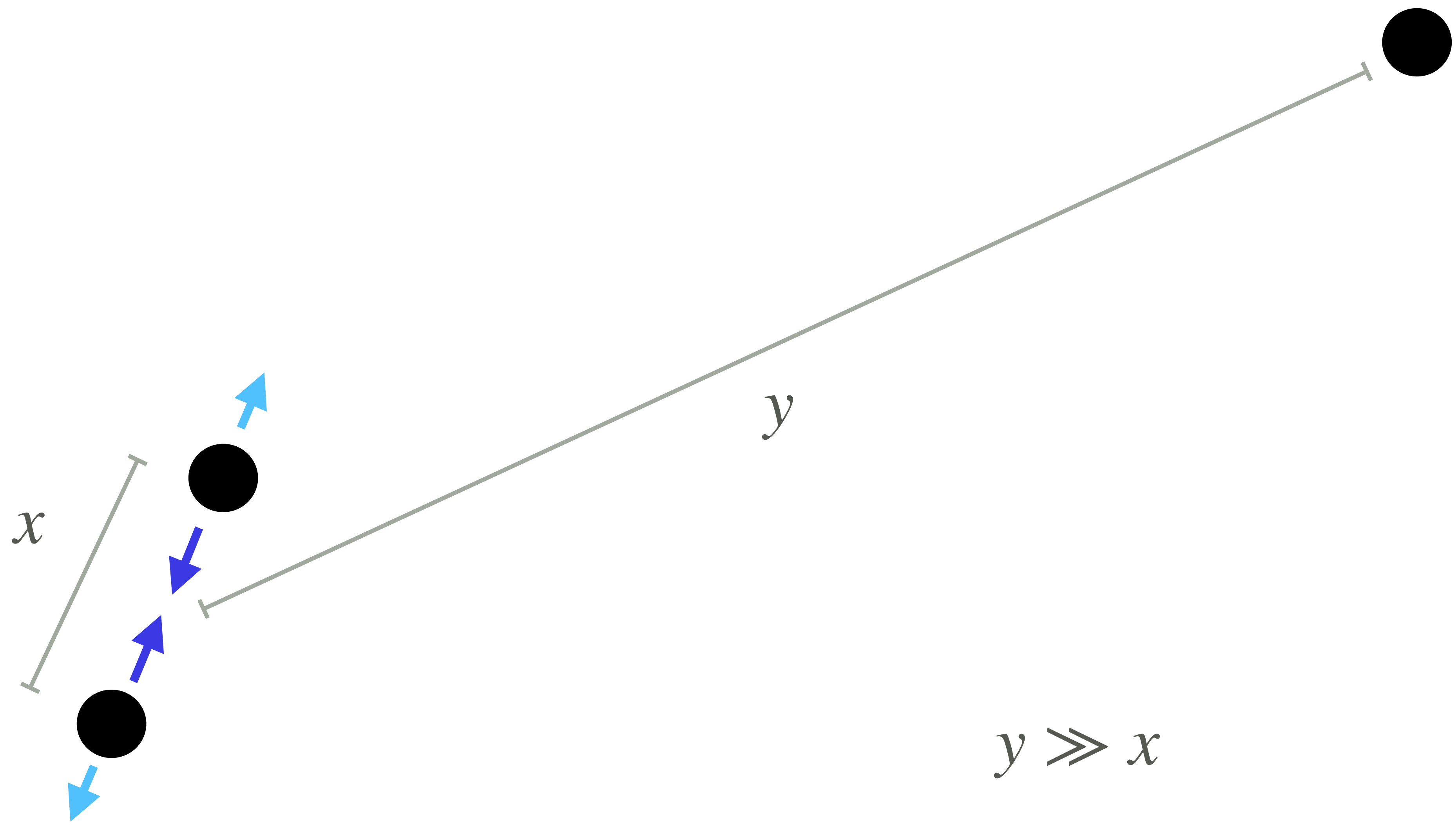


$y \gg x$

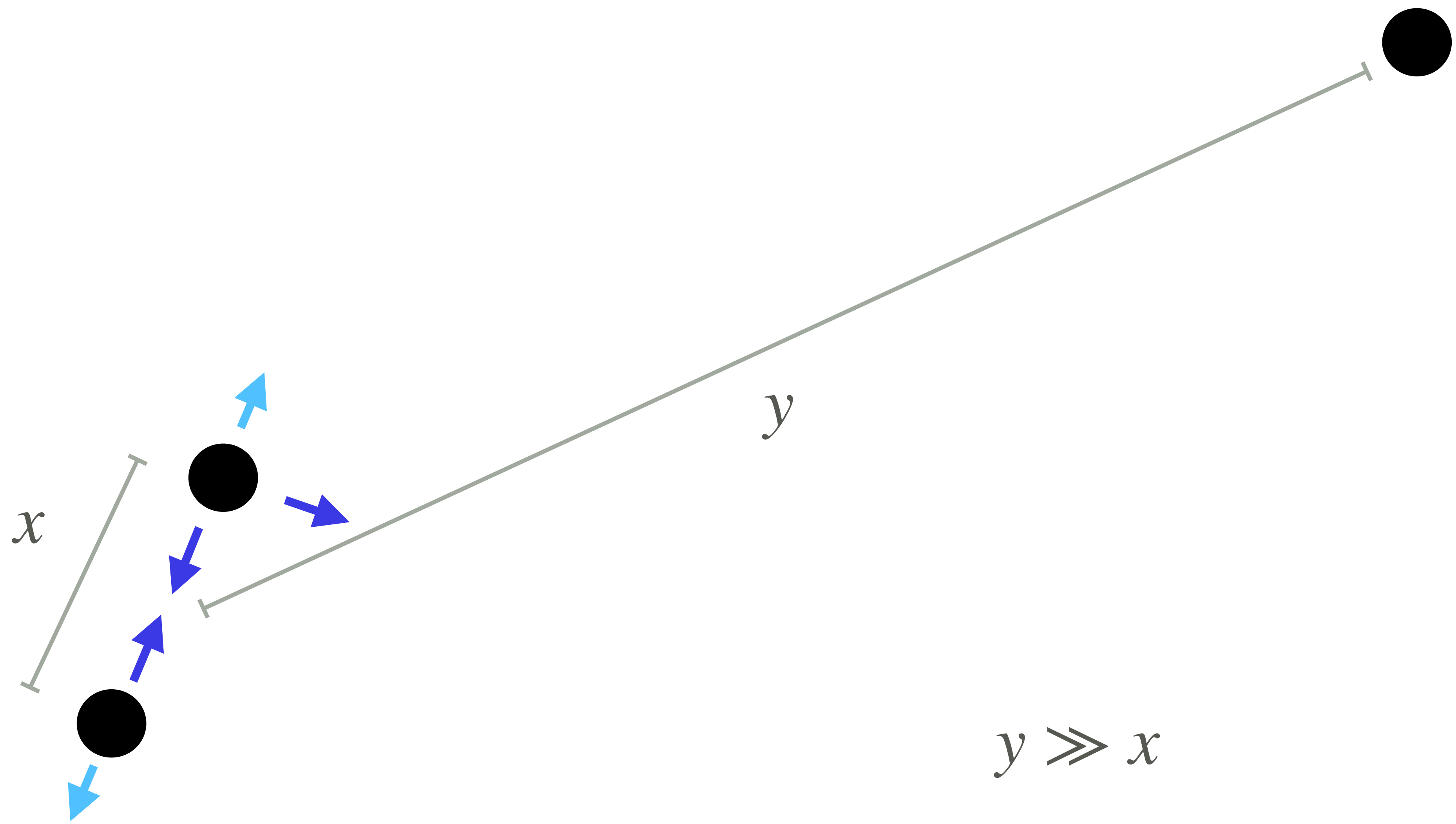
Primordial BH binaries - early Universe



Primordial BH binaries - early Universe



Primordial BH binaries - early Universe

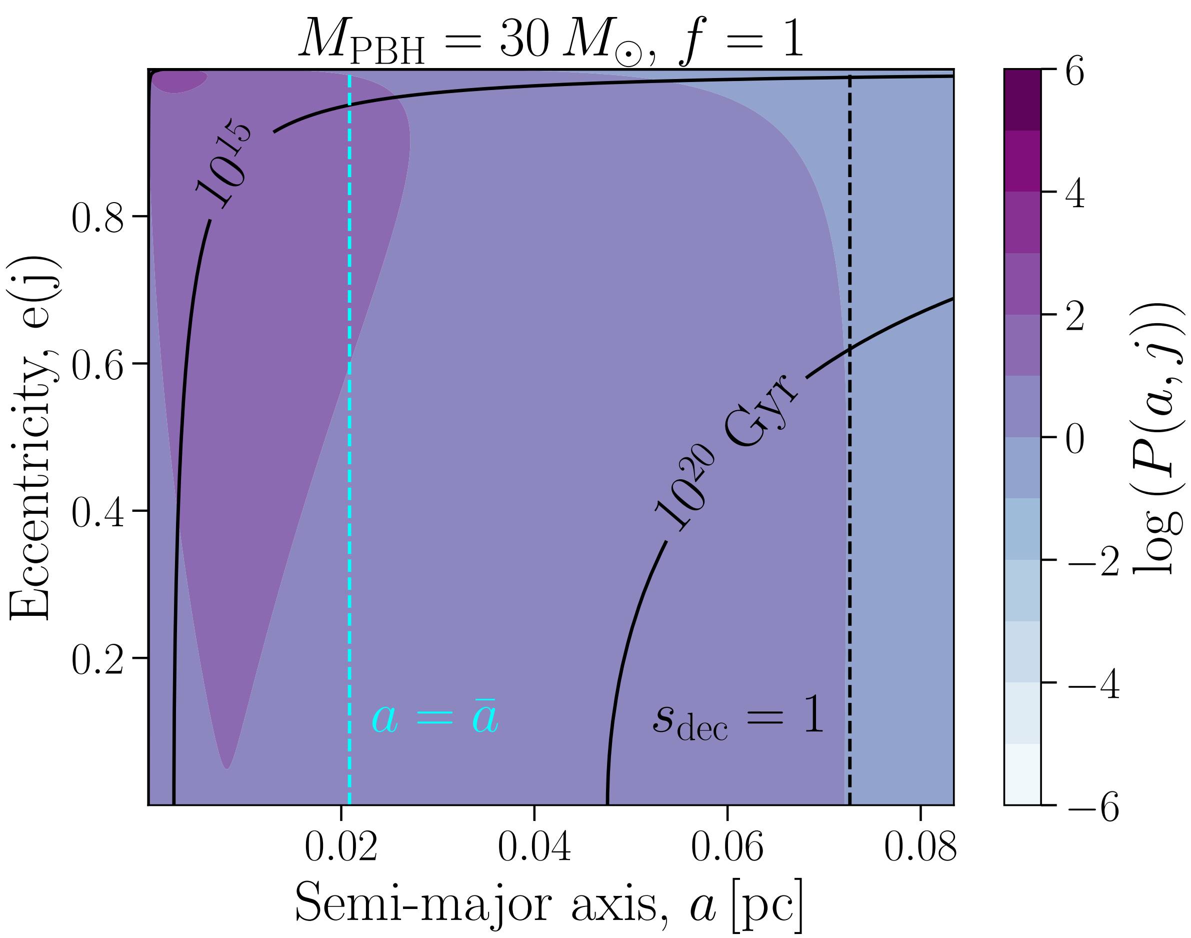


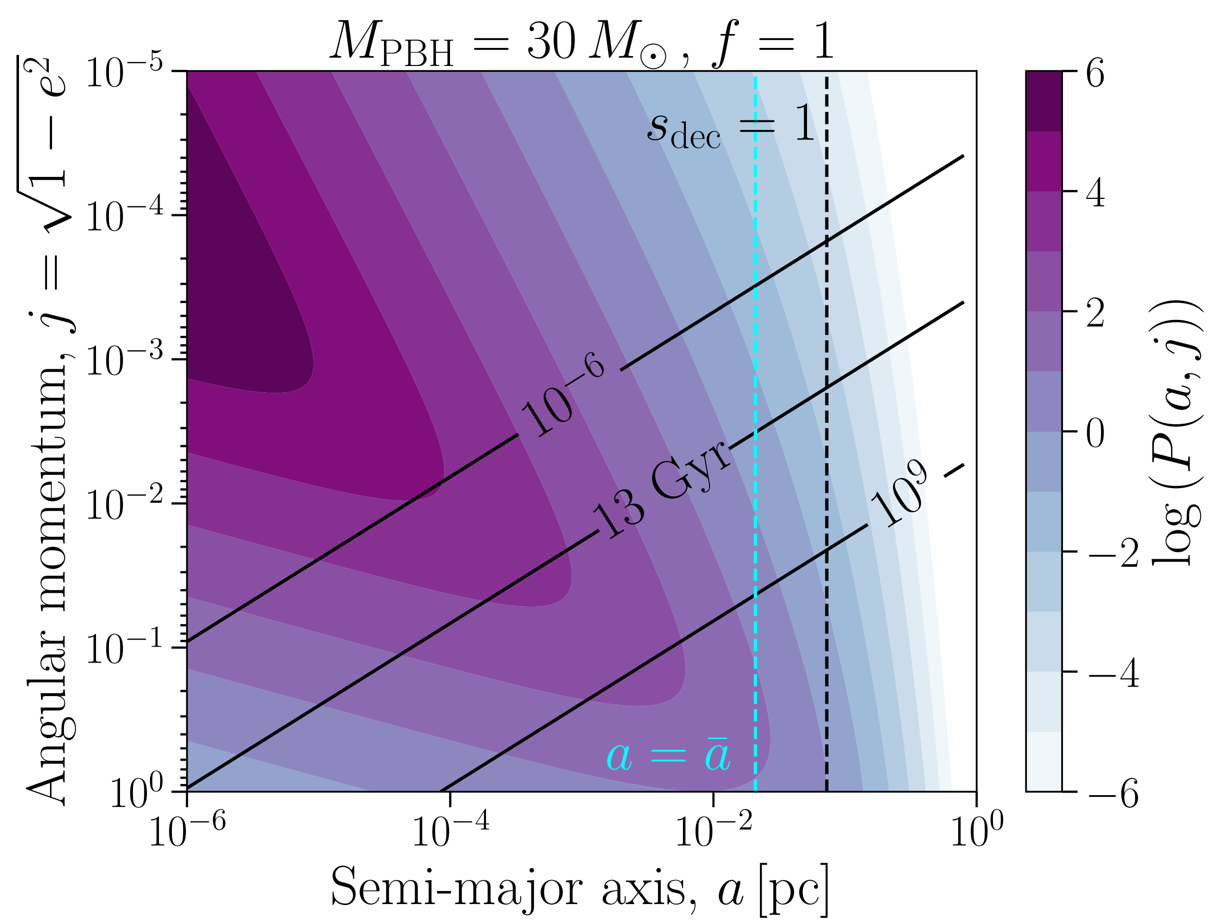
$y \gg x$

Merger rate of primordial binaries

Nakamura et al. 9708060, Ali-Haimoud et al. 1709.06576, Vaskonen et al. 1812.01930

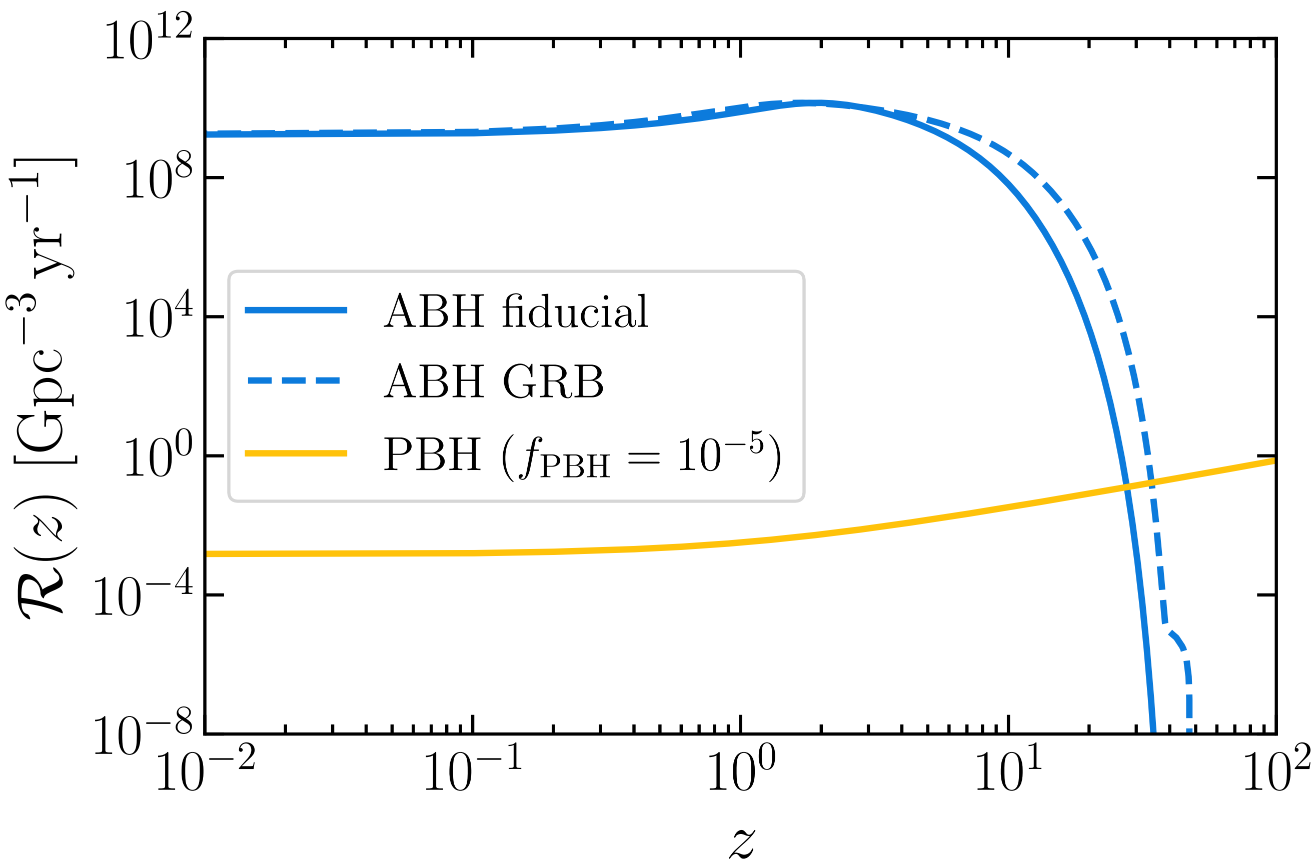
$$\tau(a,j) = \frac{3}{170}\frac{a^4}{M^3}j^7 \qquad j = \sqrt{1-e^2} \qquad j \sim \left(\frac{x}{\bar{x}}\right)^3$$

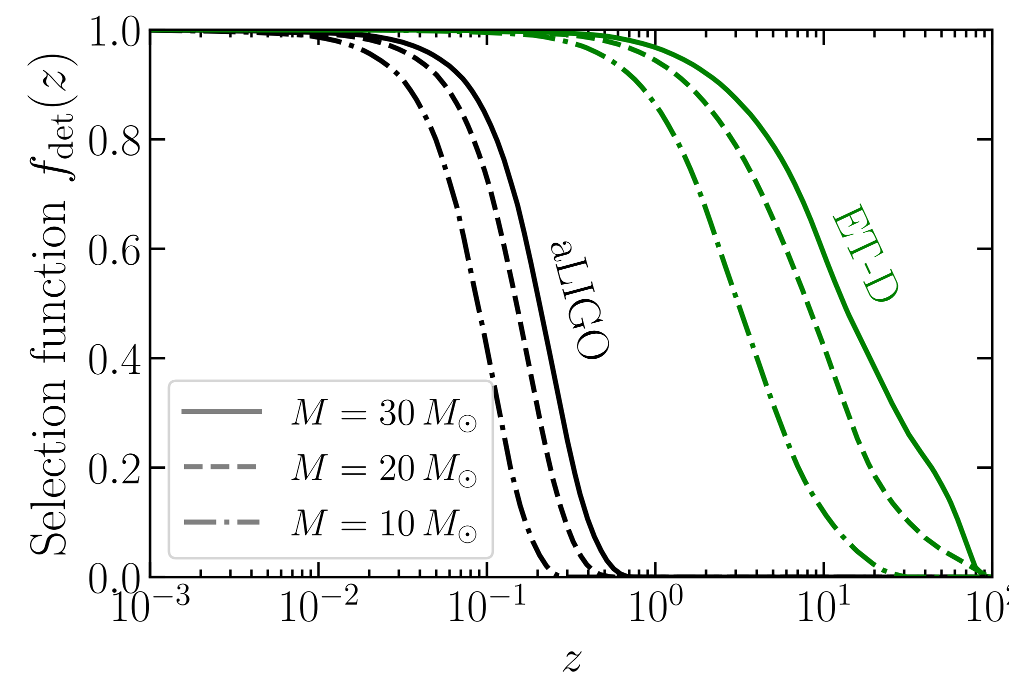




Small separations →very ***high eccentricity*** → ***short time to merger***

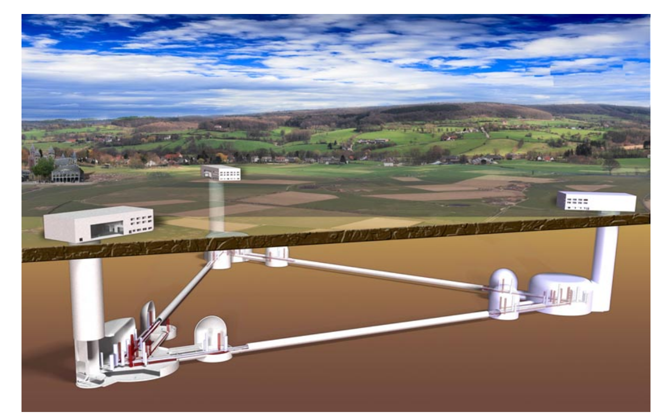
Prospects for the Einstein Telescope



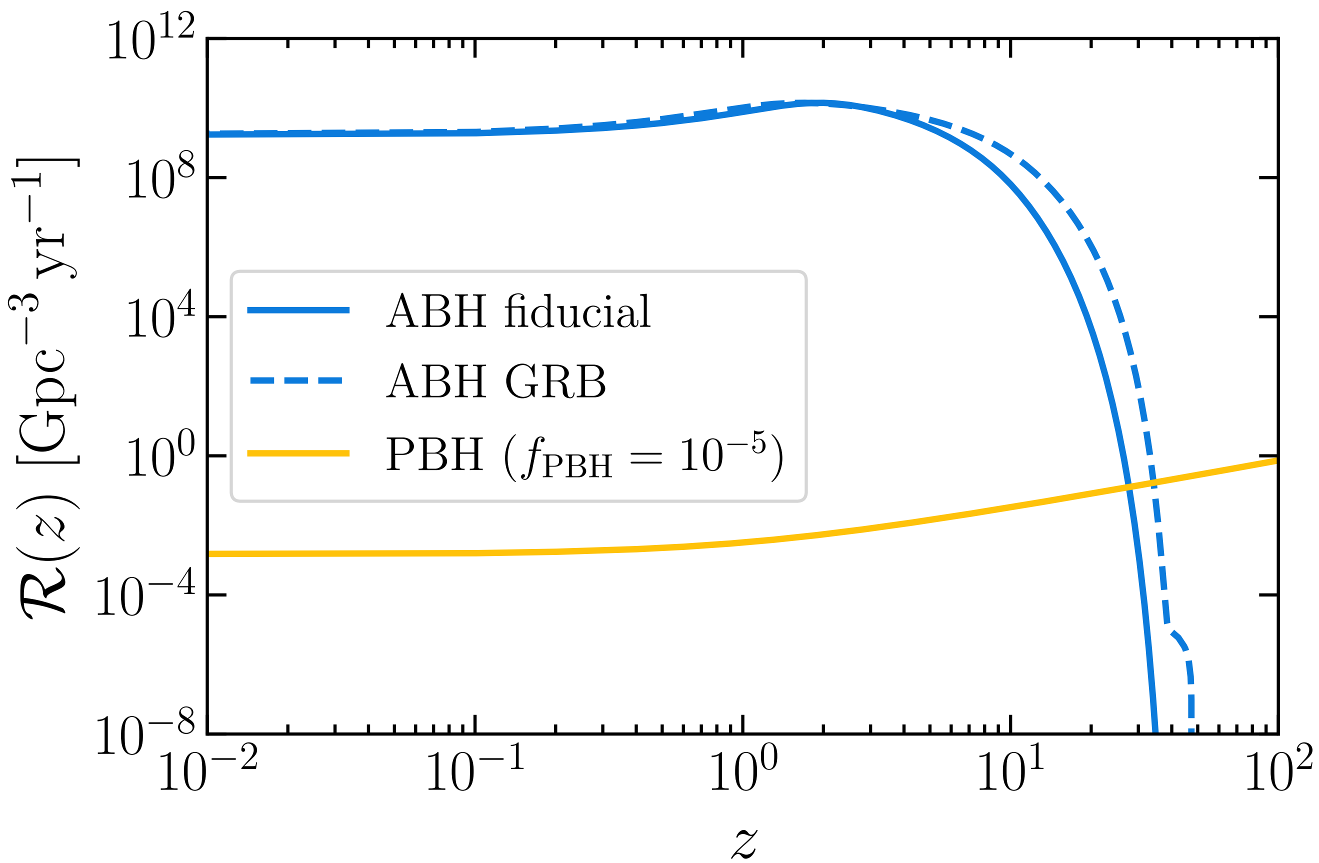


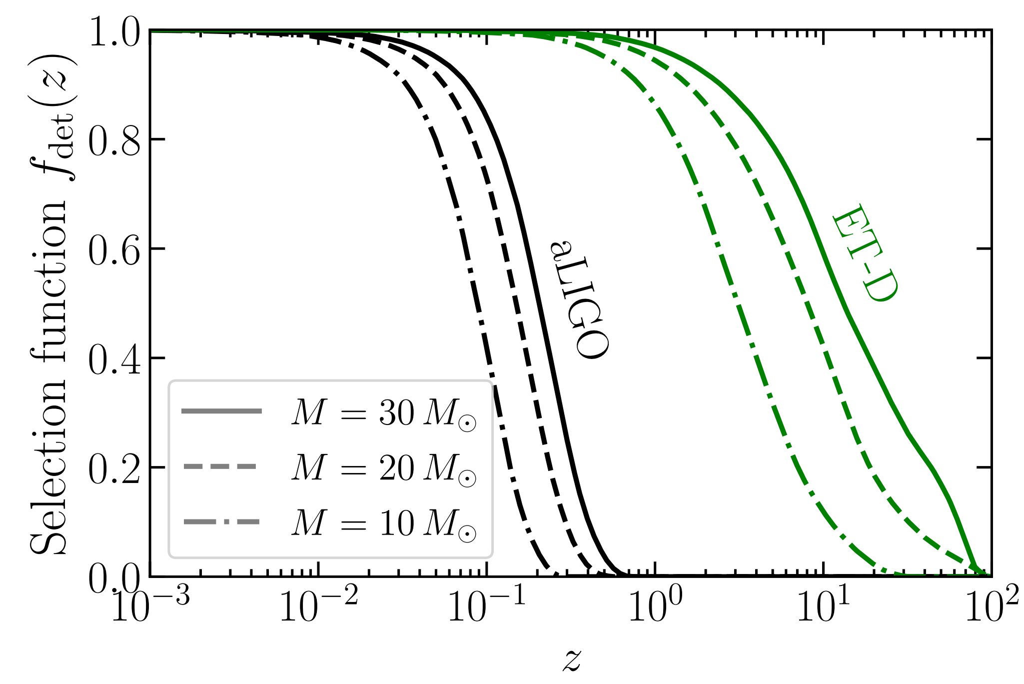
Forecast for Einstein telescope to asses:

- ability to ***detect*** PBH
- ability to ***measure*** PBH abundance



Prospects for the Einstein Telescope





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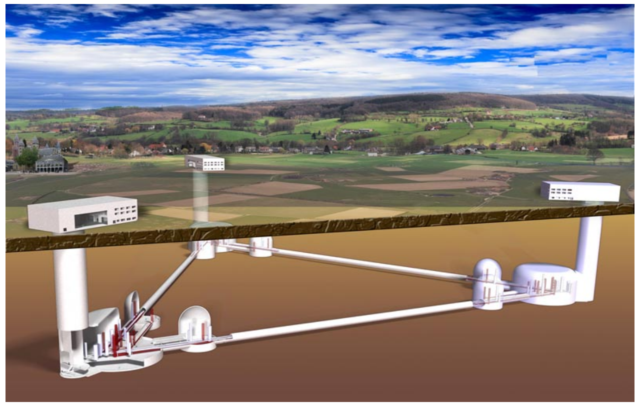
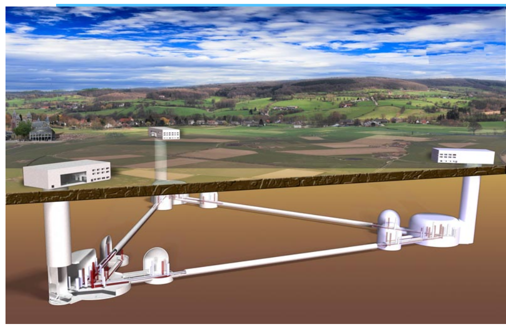


➡ Model the ***detector's response***



ET mock data generation

gitlab.com/matmartinelli/darksirens

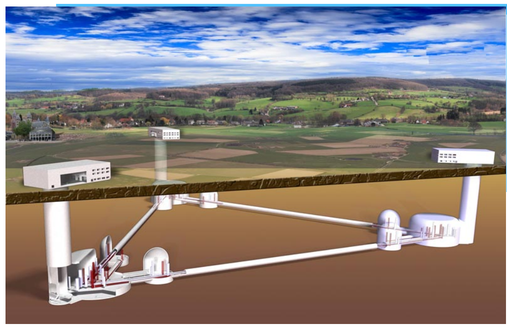
- Compute expected number of events ($T_{\rm obs}$)
- Each event (redshift, position, inclination) → ***waveform*** (PyCBC)
- ET antenna patterns → strain $h(f)$
- Compute ***signal-to-noise ratio*** ρ_i

$$\rho_i = \left[4 \int_{f_{\rm lower}}^{f_{\rm upper}} \mathrm{d}f \, \frac{h_i(f) h_i^*(f)}{S_n(f)} \right]^{\frac{1}{2}}$$

- Discard faint events ($\rho_i < 8$)
- Estimate ***<u>instrumental error on distance</u>*** $\sigma_i^{\rm inst}$

$$\sigma_i^{\rm inst} = 2\tilde{D}_i/\rho_i$$

- Extract observed value of D_L
- Obtain error on D_L including lensing effects



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Final result: ***mock catalog*** (D_i, σ_i)

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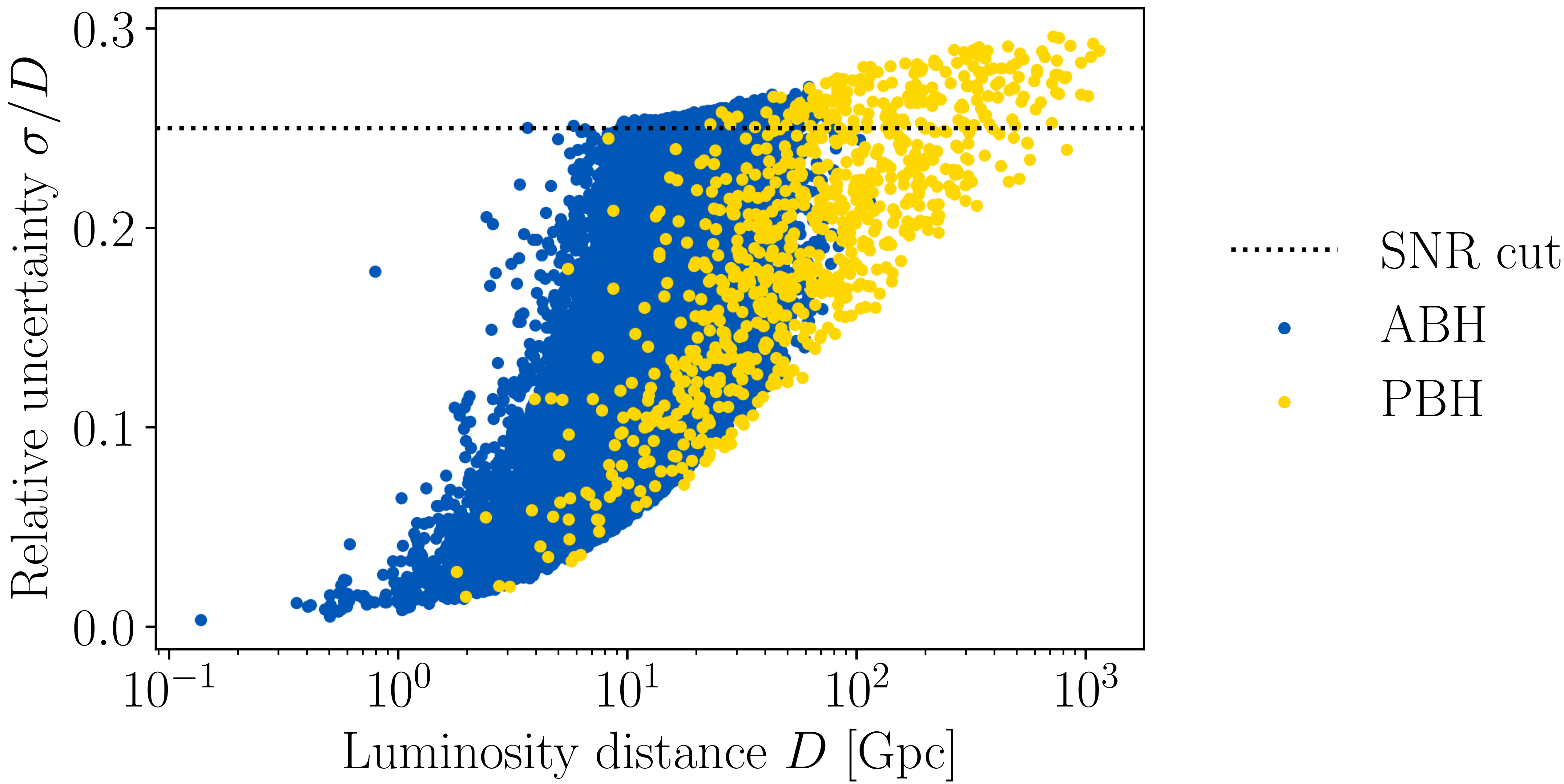

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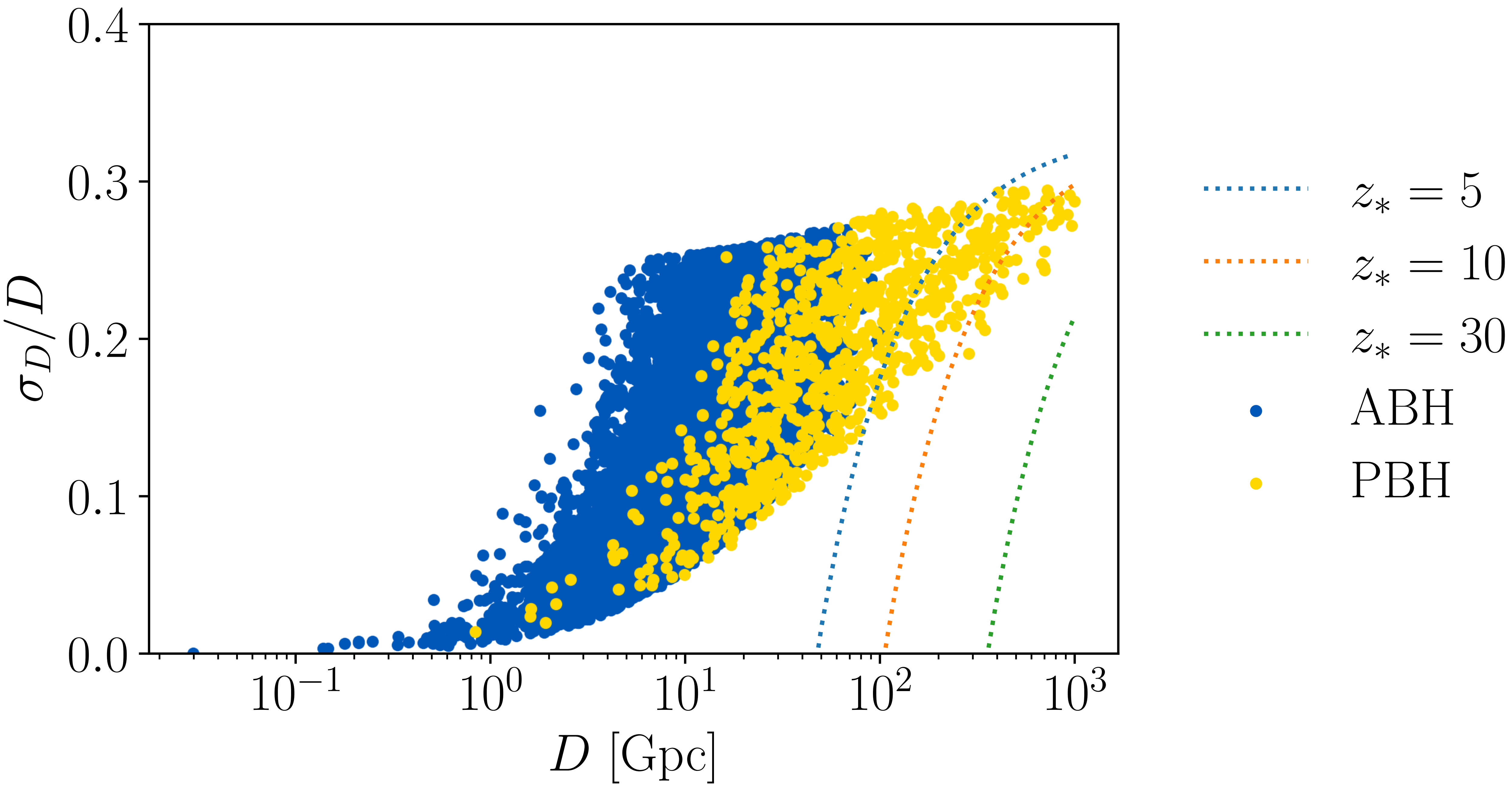
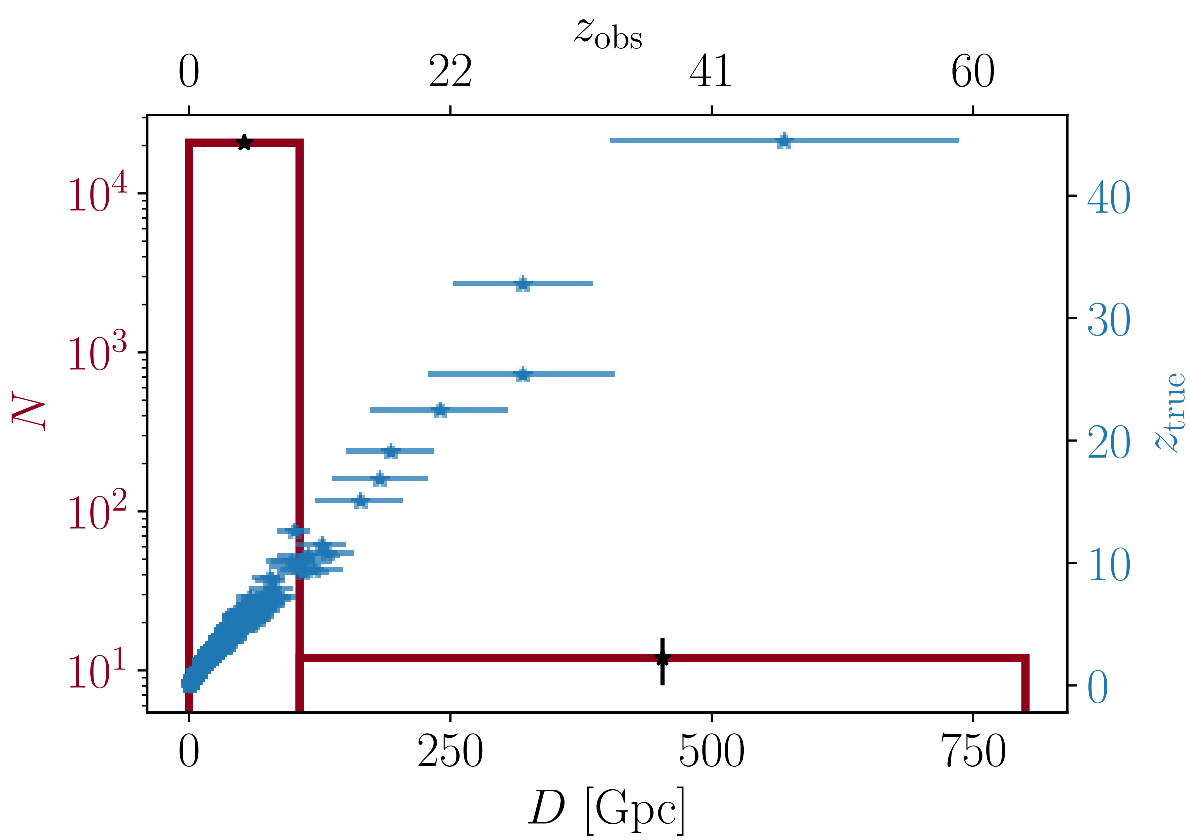
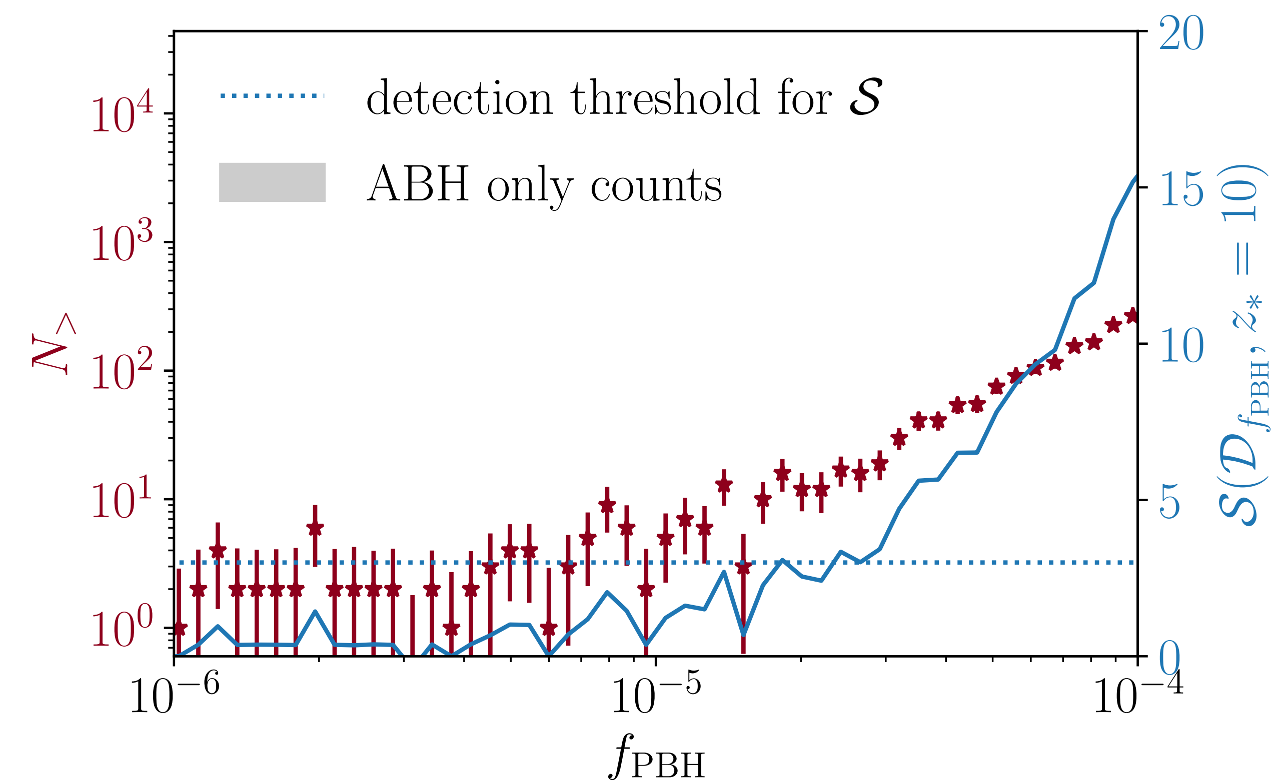


Data analysis - 1

Cut-and-count

- ***Divide data in two bins***, evaluate $N_>$: # events with $z > z^*$
- Generate catalogs for ***different values of*** $f_{\rm PBH}$, evaluate $N_>$
- Compare with null hypothesis: ***ABH only*** data set $\rightarrow N_> = 1 \pm 1.7$





- ***Smallest detectable fraction*** (3σ): $f_{\rm PBH} \approx 10^{-5} \rightarrow N_> = 16 \pm 5$

Likelihood analysis

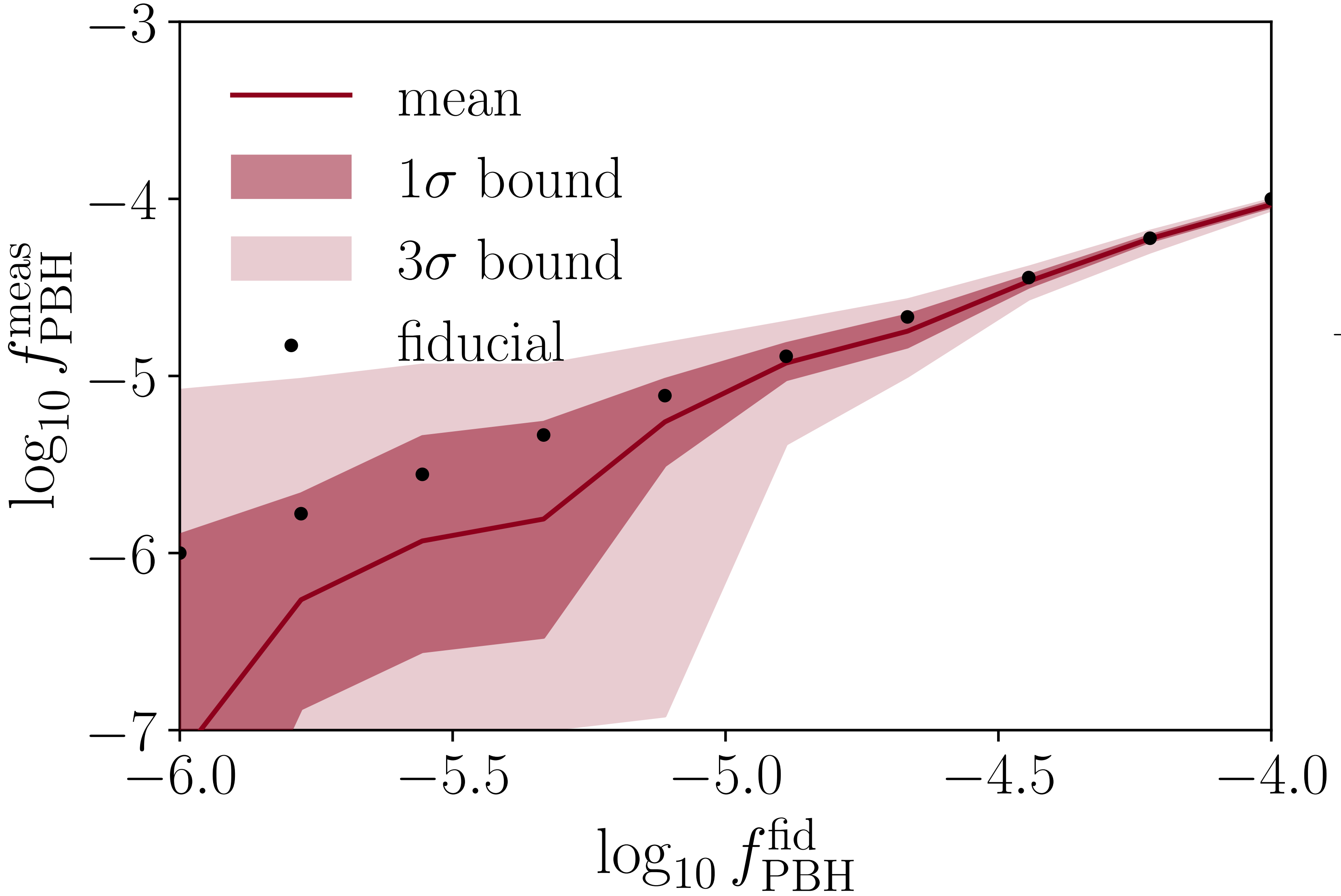
- ***Unbinned likelihood*** - probability of a set of observed events

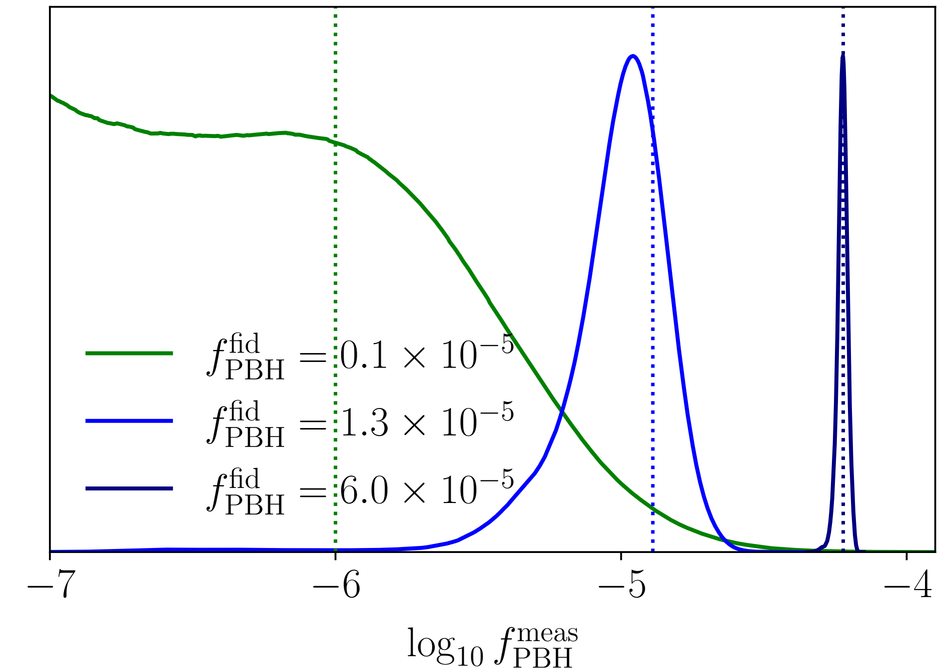
$$\mathscr{L}(f_{\rm PBH}\,|\,\mathscr{D}) = \frac{\bar{N}_{\rm obs}(f_{\rm PBH})^{N_{\rm obs}} e^{-\bar{N}_{\rm obs}(f_{\rm PBH})}}{N_{\rm obs}\,!} \times \prod_{i=1,N_{\rm obs}} p(D_i\,|\,f_{\rm PBH})$$

- ***Posterior distribution for*** $f_{\rm PBH}$

$$p(f_{\rm PBH}\,|\,\mathscr{D}) \propto \mathscr{L}(f_{\rm PBH}\,|\,\mathscr{D})\Pr(f_{\rm PBH})$$

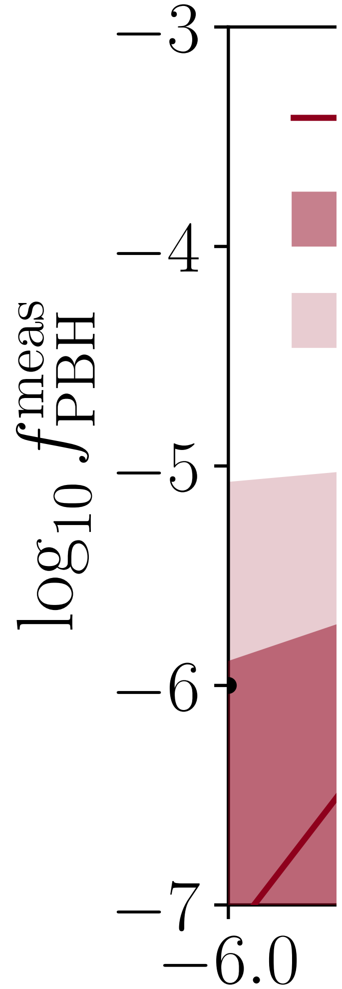
Posterior on $f_{\rm PBH}$

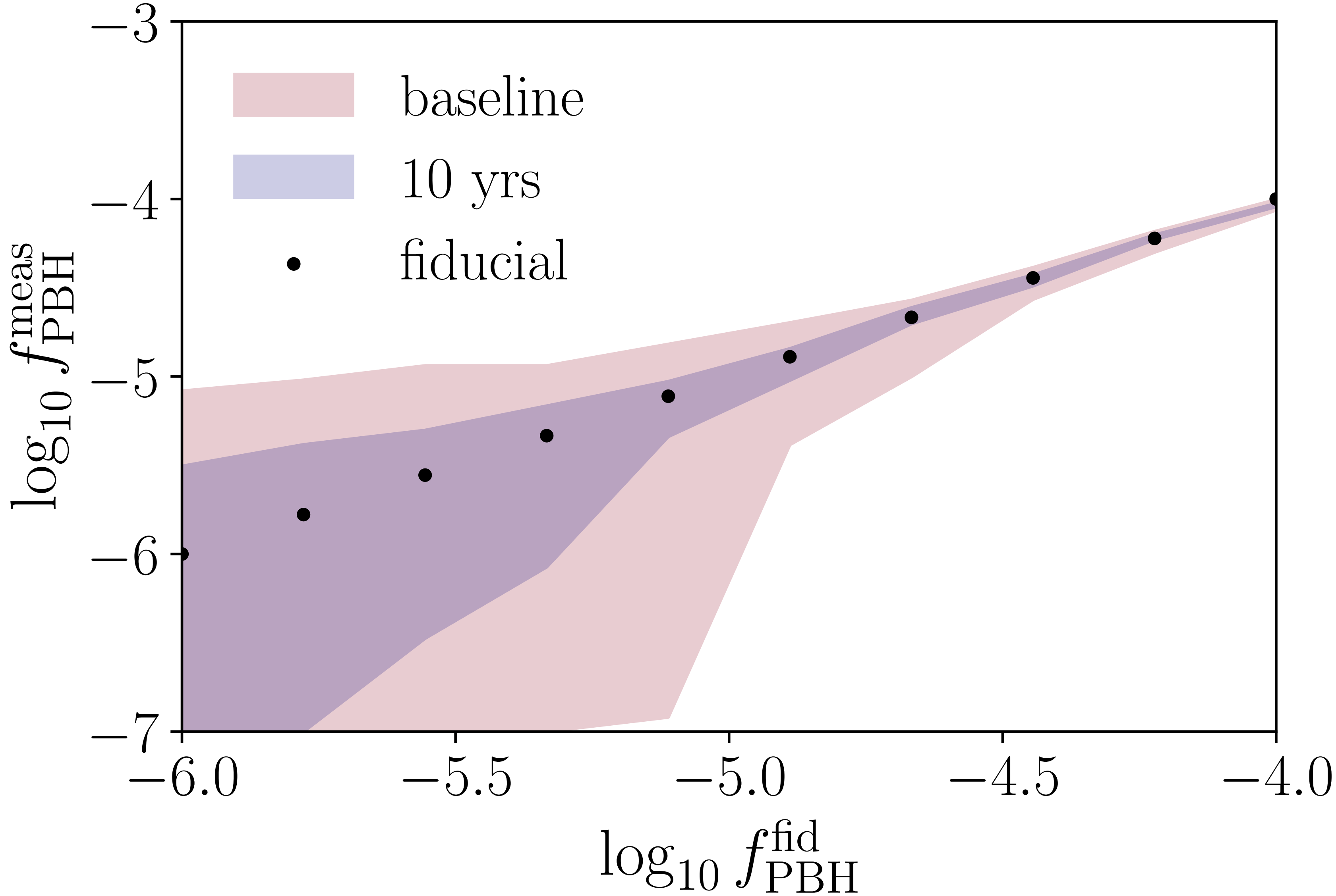


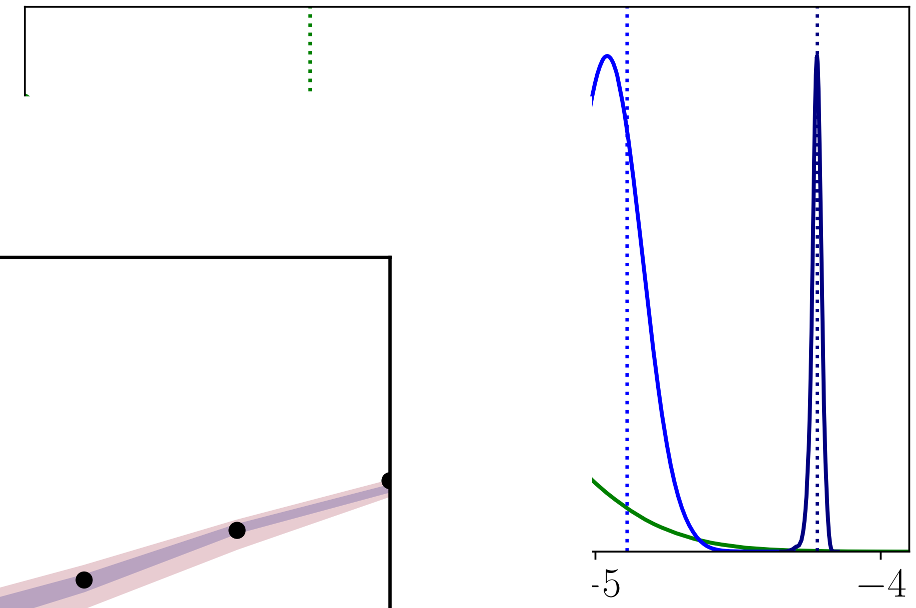


$f_{\rm PBH} \approx 10^{-5}$ measured with $\approx 30\,\%$ precision (3σ)

Posterior on $f_{\rm PBH}$







Conclusions

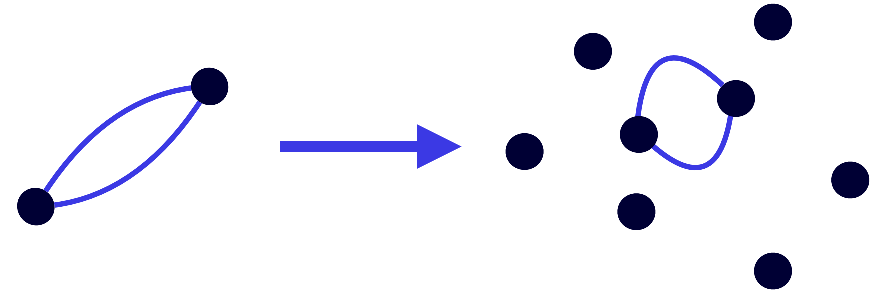
- ➡ ***Future observatories powerful tool to*** for identify PBH signal over astrophysical background
- ➡ Identify PBHs in ***abundance as small as*** $f_{\mathrm{PBH}} \approx 10^{-5}$

Caveats

- ➡ ***Signal*** modelling
  - Initial clustering
  - Broad / multi peaked mass function
- ➡ Astrophysical ***background***
  - Population III stars

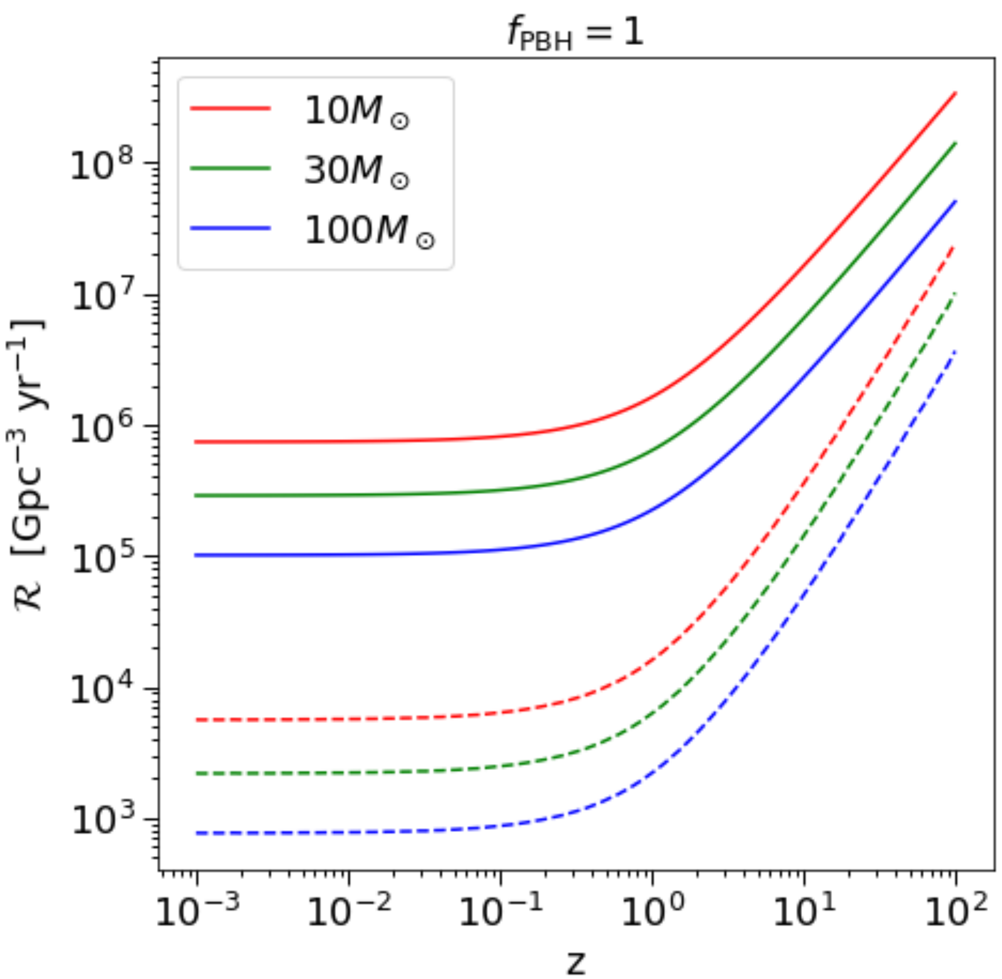

Thank you!

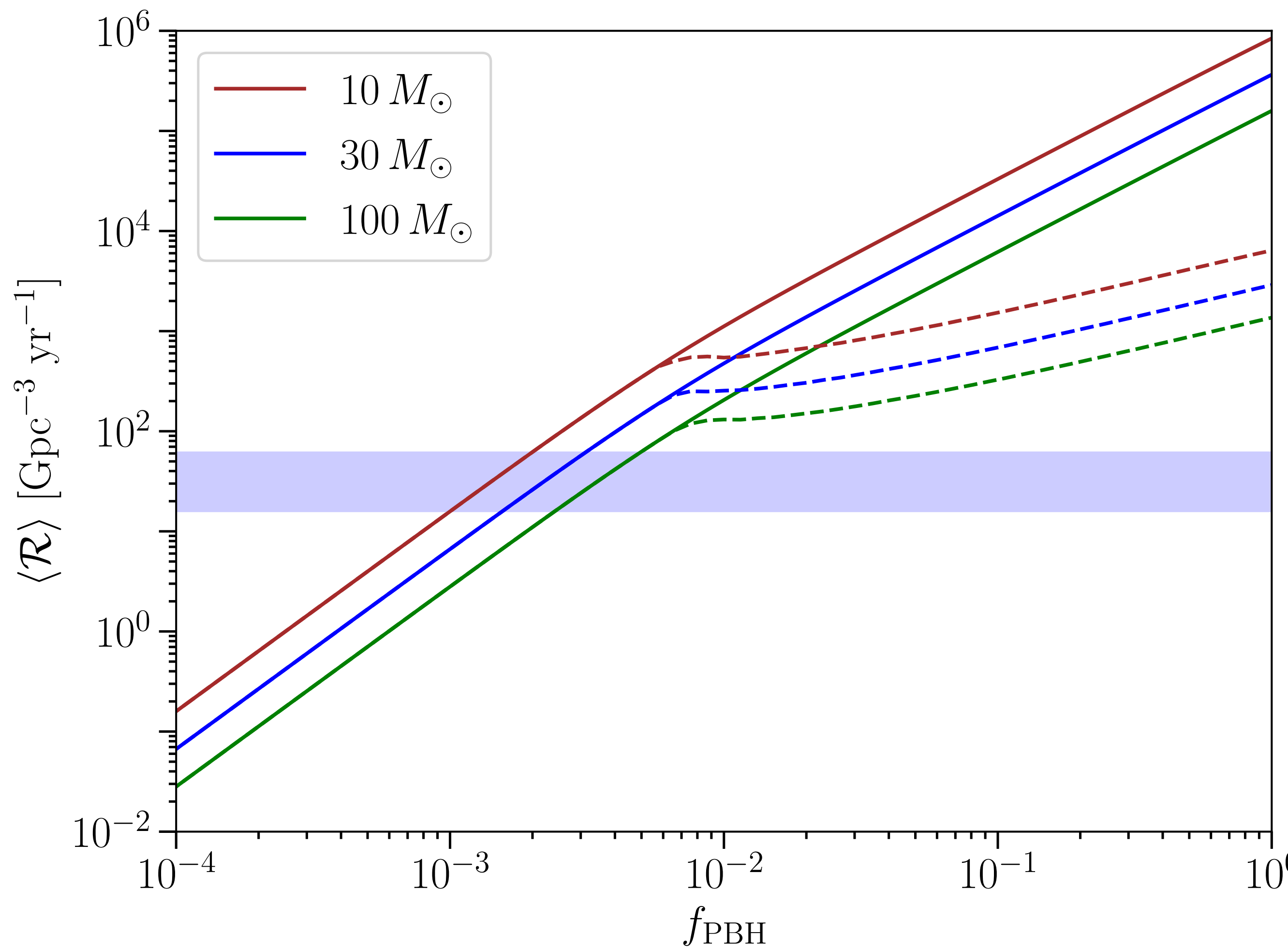
Impact of late-time ***clustering*** on merger rate :



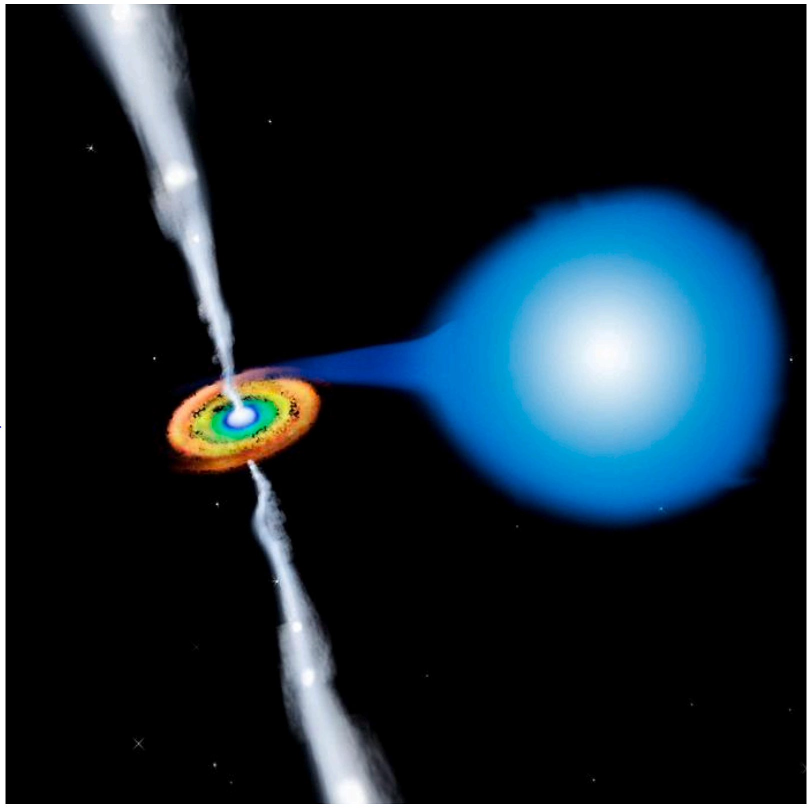
Jedamzik 2006.11172

- early formation of structures
  Inman et al. 1907.08129
- ***gravo-thermal instability*** Vaskonen et al. 1908.09752
  De Luca et al. 2009.04731
- ***negligible*** for $f_{\rm PBH} \lesssim 10^{-3}$



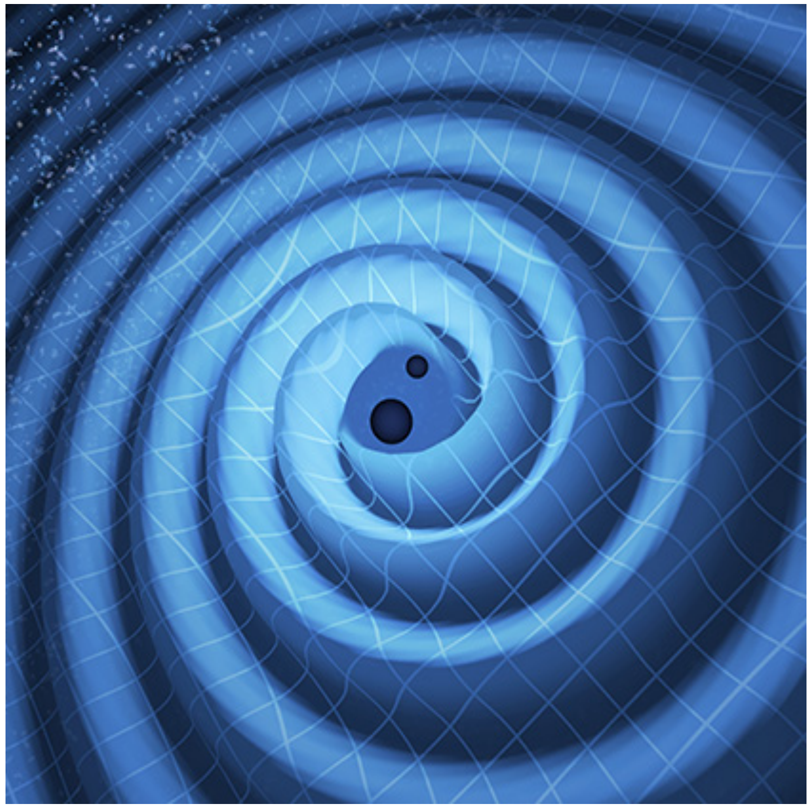


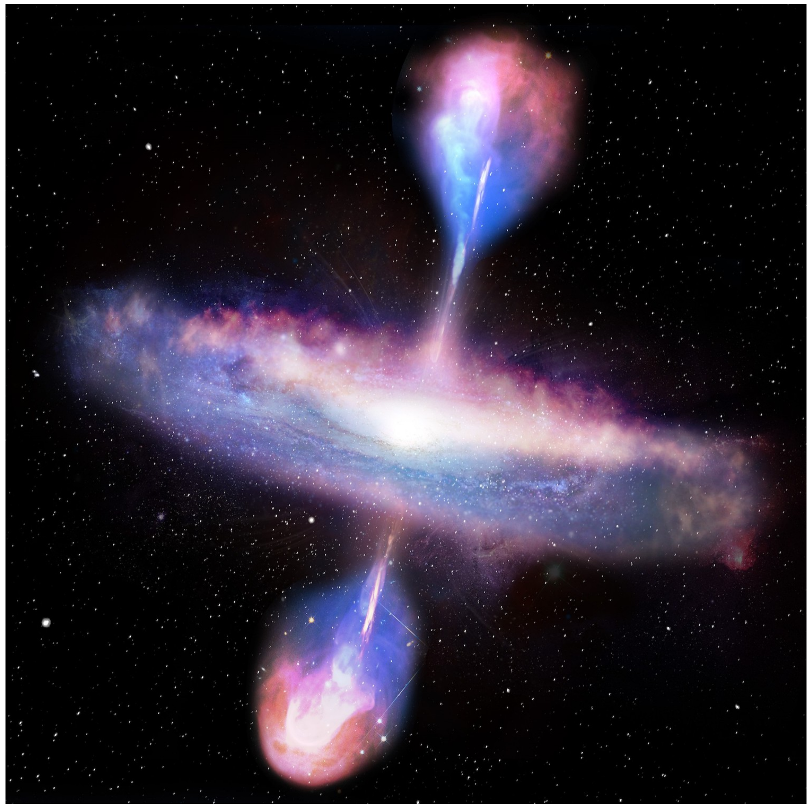
Black hole observations



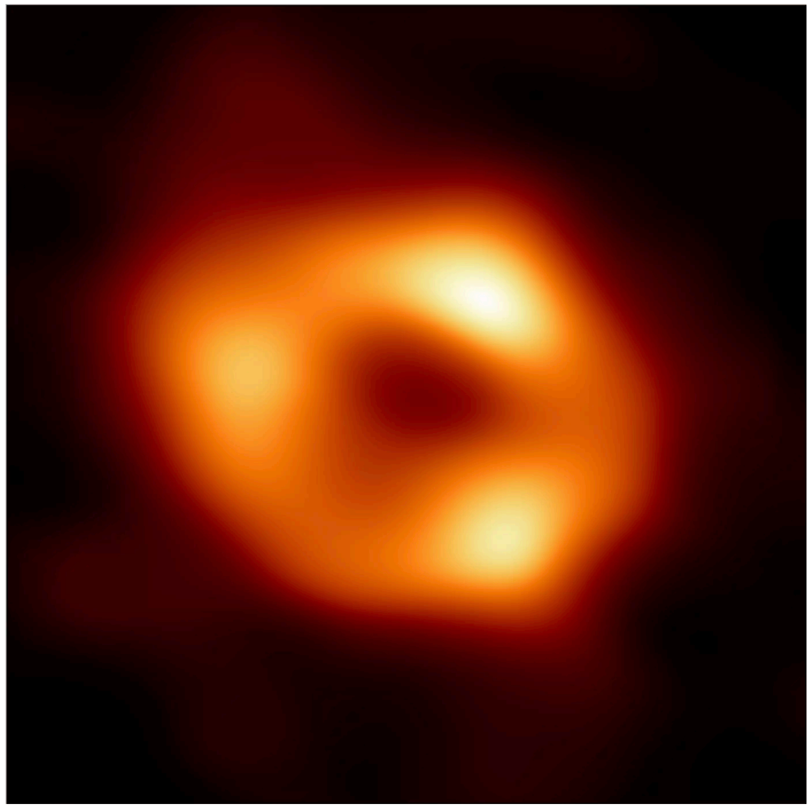
X-ray binaries

Gravitational waves



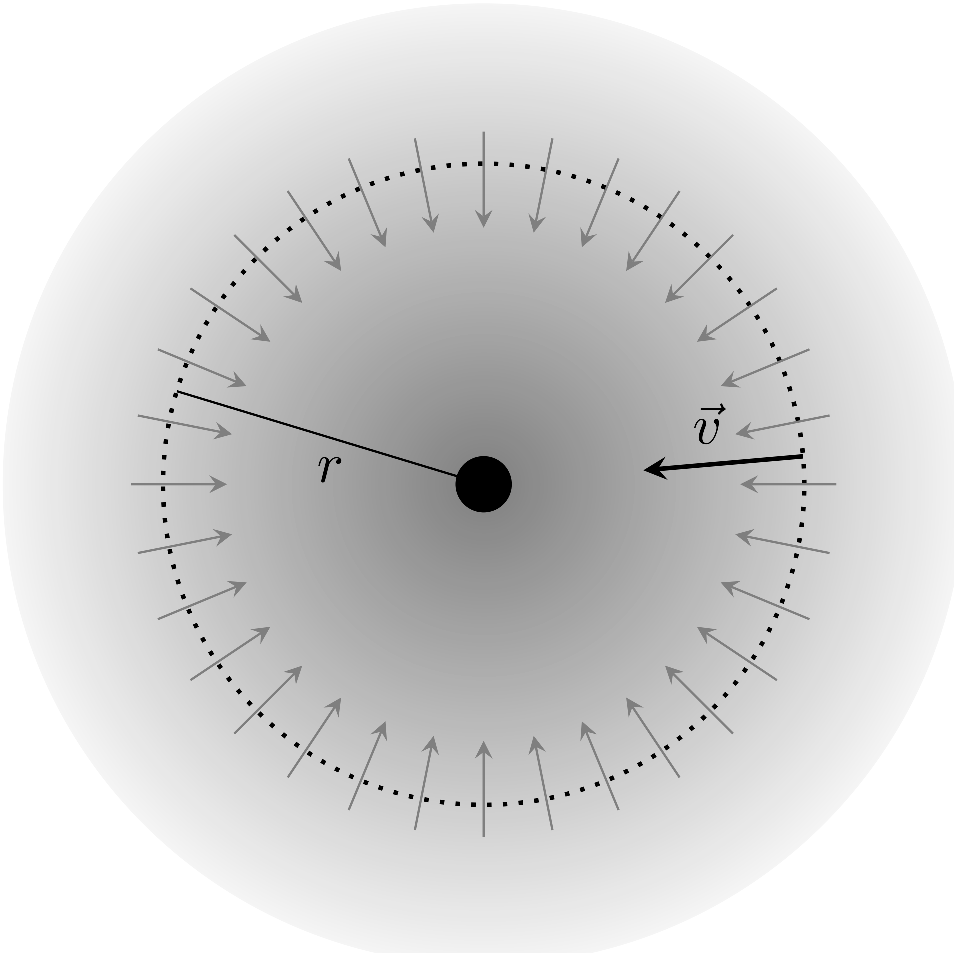


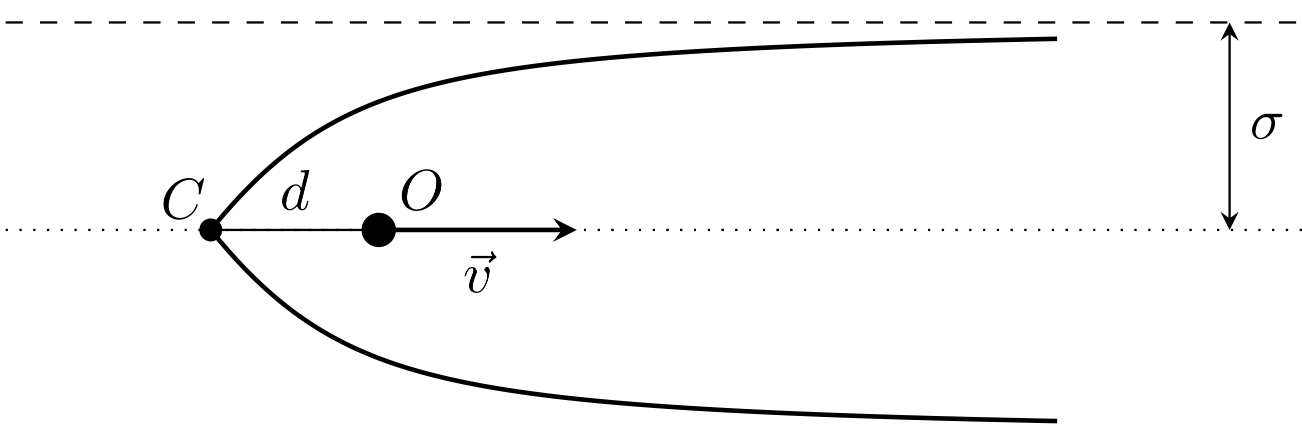
Quasars



Event Horizon Telescope

Accretion: textbook approach





- Simple textbook model for accretion onto a moving compact object
- Ruled out by observations
- suppression factor $\lambda \sim 10^{-2} - 10^{-3}$
- Does not take into account radiative feedback

Accretion: analytical model - I

- BHL accretion within the ionized region

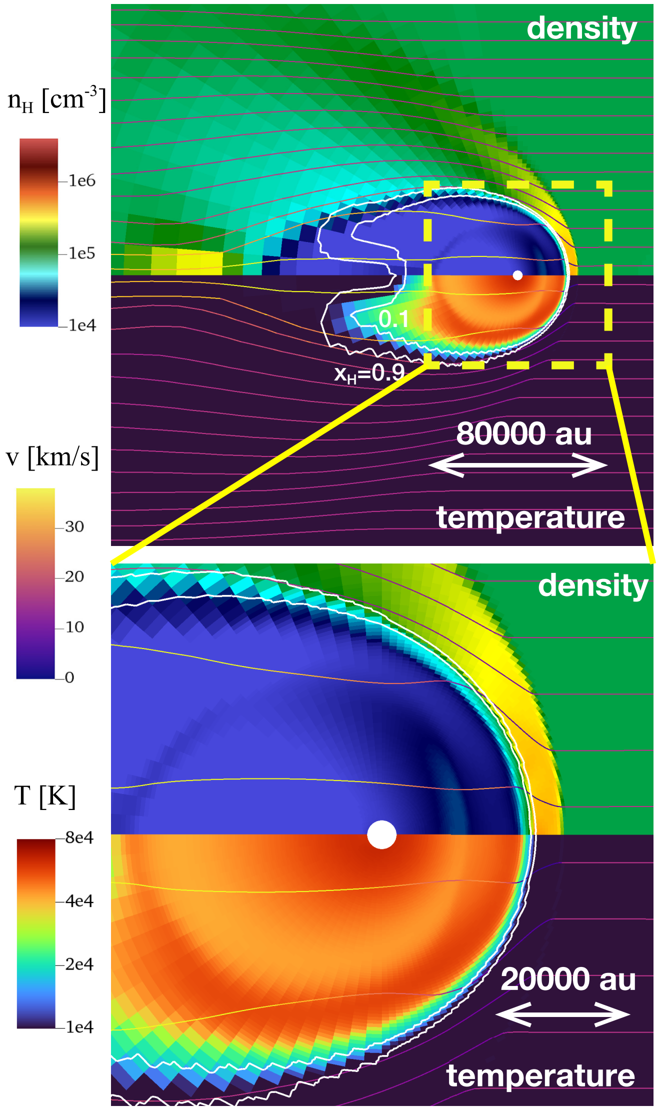
$$\dot{M}_{\rm BHL} = 4\pi \frac{(GM)^2 \rho}{(\mathrm{v}_{\rm BH}^2 + c_s^2)^{3/2}} \,,$$

- Euler's equations at ionization front:

$$\boxed{\begin{aligned} \rho_{\rm in}\, \mathrm{V}_{\rm in} &= \rho \mathrm{V}_{\rm BH} \\ \rho_{\rm in}\left(\mathrm{v}_{\rm in}^2 + c_{\rm s,\,in}^2\right) &= \rho\left(\mathrm{v}_{\rm BH}^2 + c_{\rm s}^2\right) \end{aligned}}$$

At low velocities, a bow shock is formed in front of the ionization front

Flux is deflected and accretion rate lowers



Accretion: analytical model -II

Solving Euler's equations at the ionization front:

$$\rho_{\rm in}\,\mathrm{V}_{\rm in} = \rho \mathrm{V}_{\rm BH}$$
$$\rho_{\rm in}\left(\mathrm{v}_{\rm in}^2 + c_{\rm s,\,in}^2\right) = \rho\left(\mathrm{v}_{\rm BH}^2 + c_{\rm s}^2\right)$$

$$\rho_{\rm in} = \rho_{\rm in}^{\pm} \equiv \rho \frac{\mathrm{v}_{\rm BH}^2 + c_{\rm s}^2 \pm \sqrt{\Delta}}{2\,c_{\rm s,in}^2}\,, \qquad \Delta \equiv (\mathrm{v}_{\rm BH}^2 + c_{\rm s}^2)^2 - 4\,\mathrm{v}_{\rm BH}^2\,c_{\rm s,in}^2$$

$$\mathrm{v}_{\rm in} = \frac{\rho}{\rho_{\rm in}}\mathrm{v}_{\rm BH}$$

Valid for $\mathrm{v}_{\rm BH} \leq \mathrm{v}_{\rm D}$ or $\mathrm{v}_{\rm BH} \geq \mathrm{v}_{\rm R}$, where:

$$\mathrm{v}_{\rm R} = c_{\rm s,in} + \sqrt{c_{\rm s,in}^2 - c_{\rm s}^2} \approx 2c_{\rm s,in}\,,$$

$$\mathrm{v}_{\rm D} = c_{\rm s,in} - \sqrt{c_{\rm s,in}^2 - c_{\rm s}^2} \approx \frac{c_{\rm s}^2}{2c_{\rm s,in}} \ll 1\mathrm{km/s}\,.$$

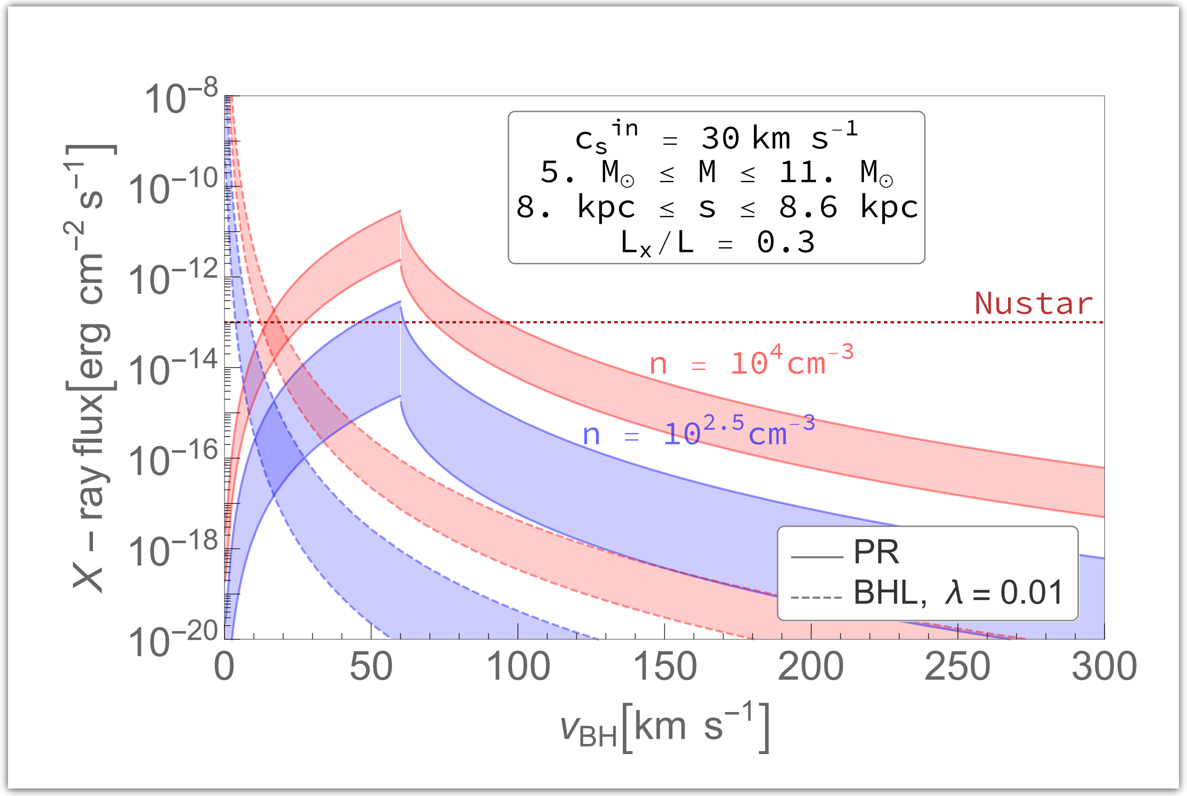
In the intermediate velocity regime eq. A not valid (shock). We have instead:

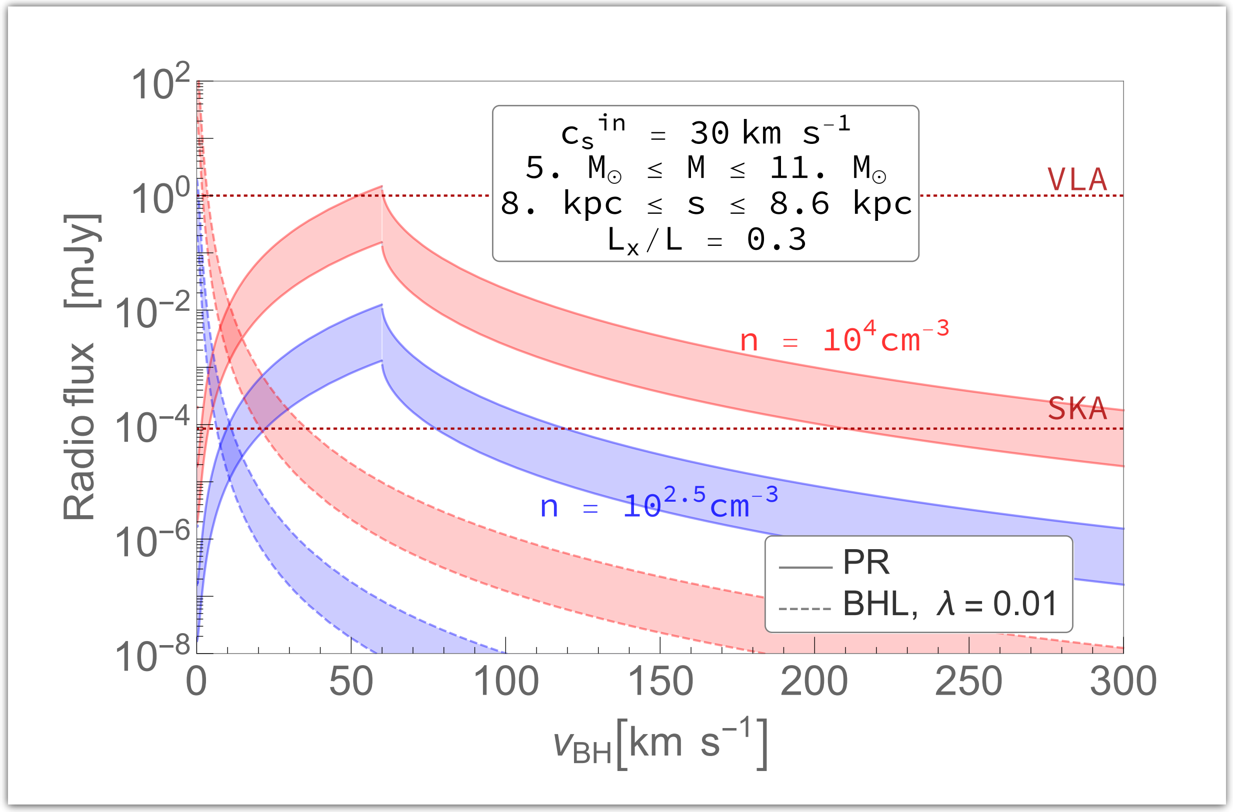
$\mathrm{v}_{\rm in} \approx c_{\rm s,in}$ (observed from simulations) →

$$\rho_{\rm in} = \rho_{\rm in}^0 \equiv \rho \frac{\mathrm{v}_{\rm BH}^2 + c_{\rm s}^2}{2\,c_{\rm s,in}^2}$$

From eq. B

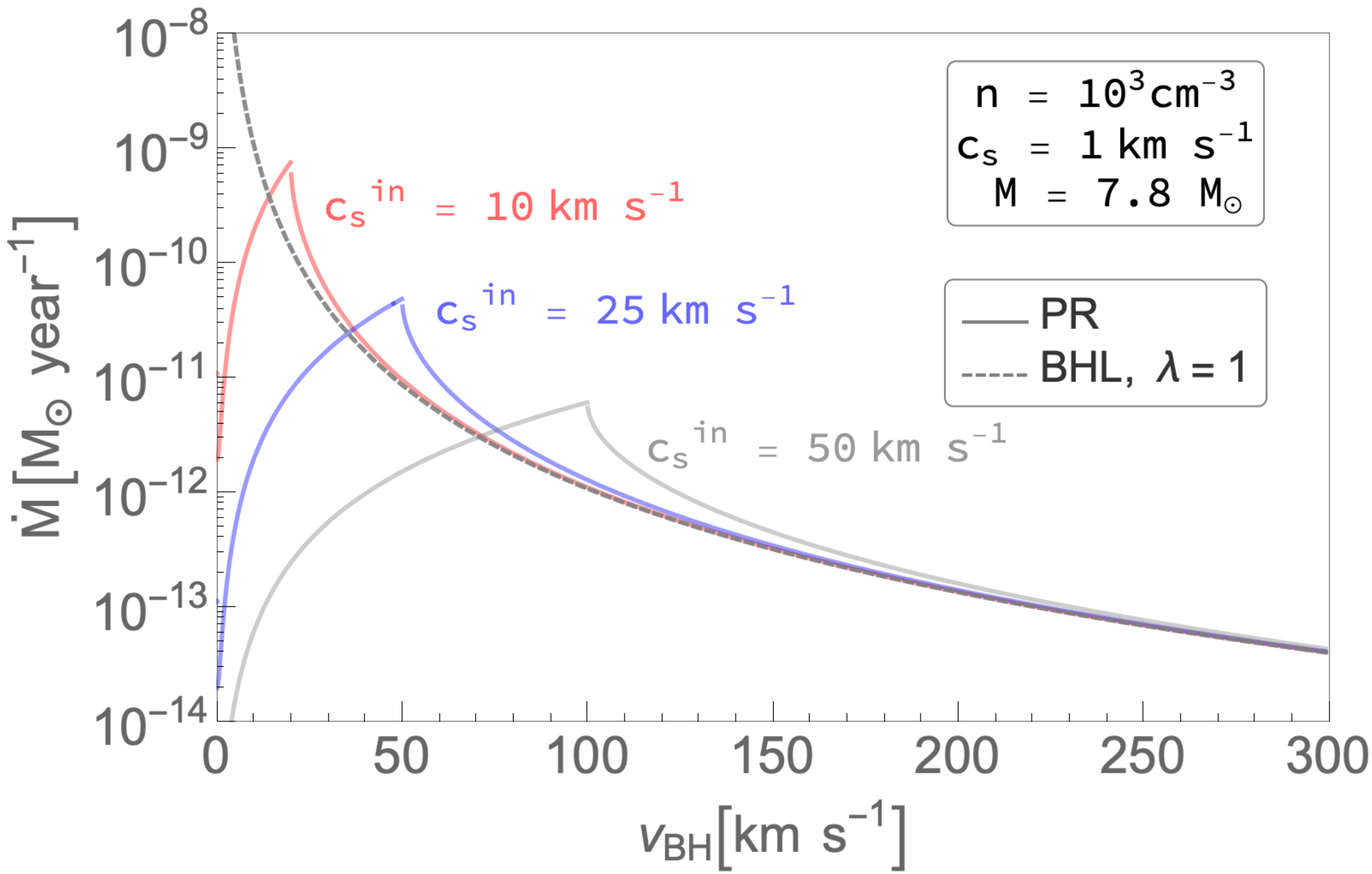
X-ray and radio fluxes: CMZ



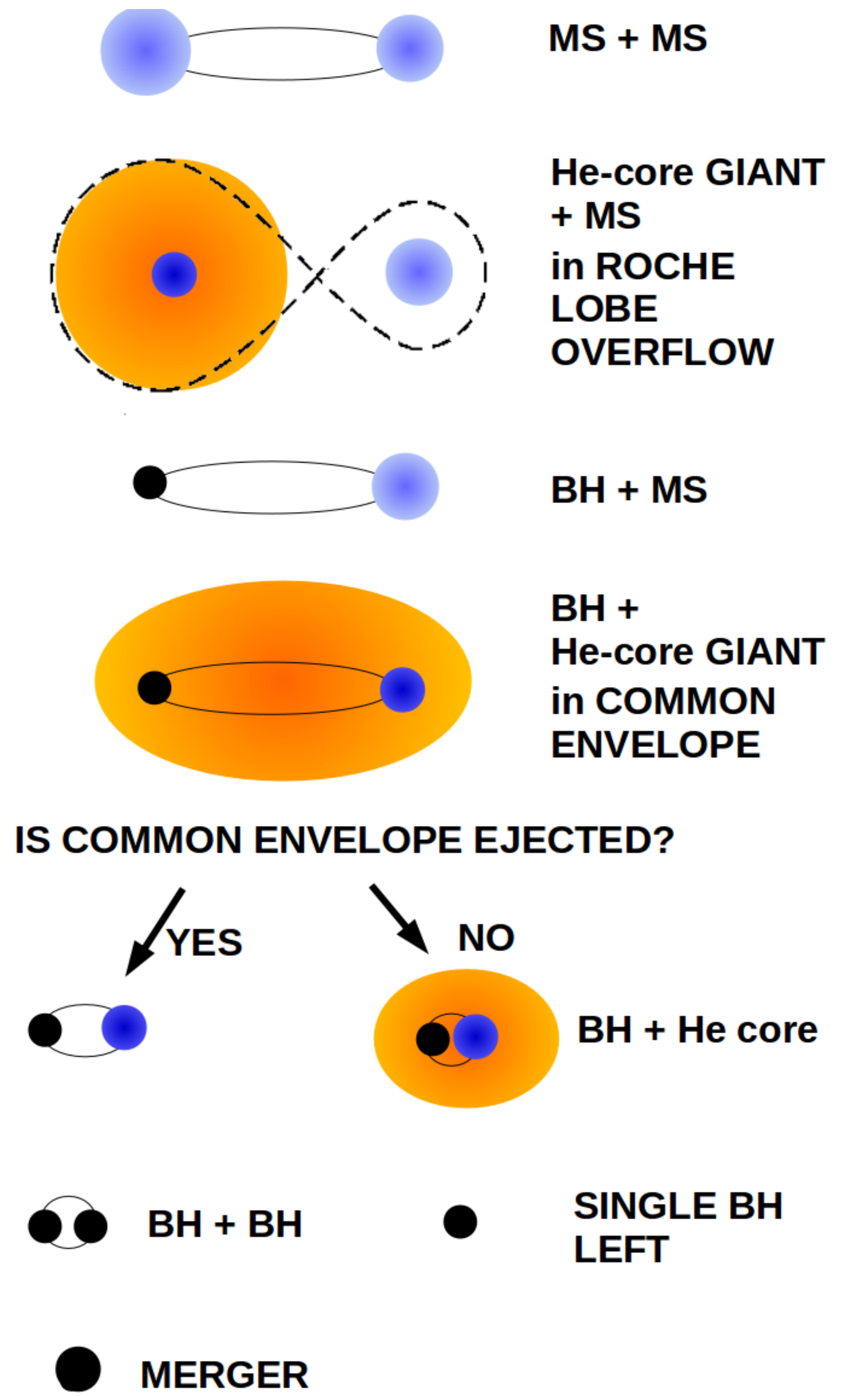


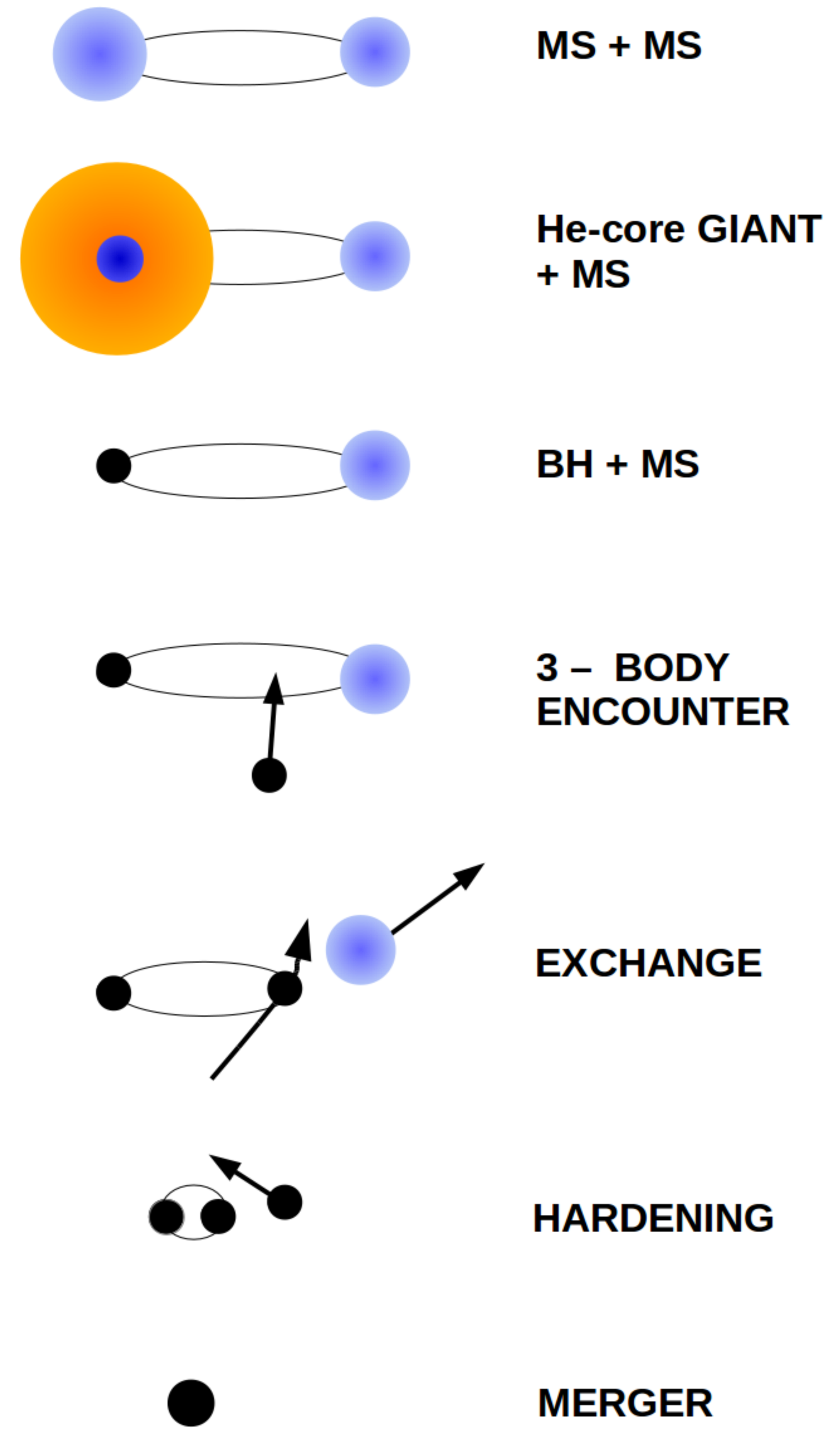
Detectable sources -> different in the two scenarios

Large population could be unveiled by SKA

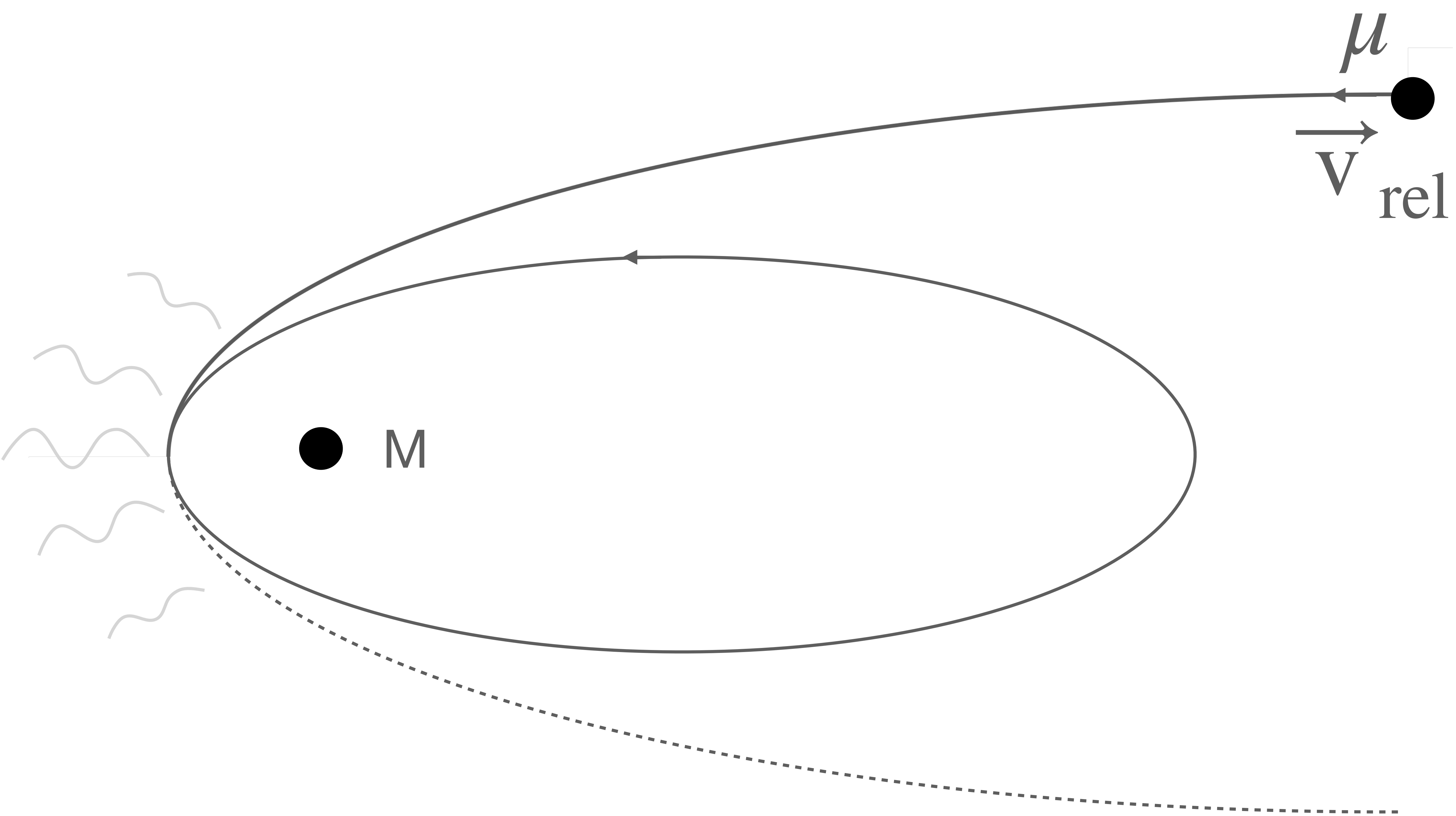


$\dot{M}\,[M_\odot\ \mathrm{year}^{-1}]$
$v_{BH}[\mathrm{km\ s}^{-1}]$
$n = 10^3 \mathrm{cm}^{-3}$
$c_s = 1\ \mathrm{km\ s}^{-1}$
$M = 7.8\ M_\odot$
PR
BHL, $\lambda = 1$
$c_s^{in} = 10\ \mathrm{km\ s}^{-1}$
$c_s^{in} = 25\ \mathrm{km\ s}^{-1}$
$c_s^{in} = 50\ \mathrm{km\ s}^{-1}$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0
50
100
150
200
250
300



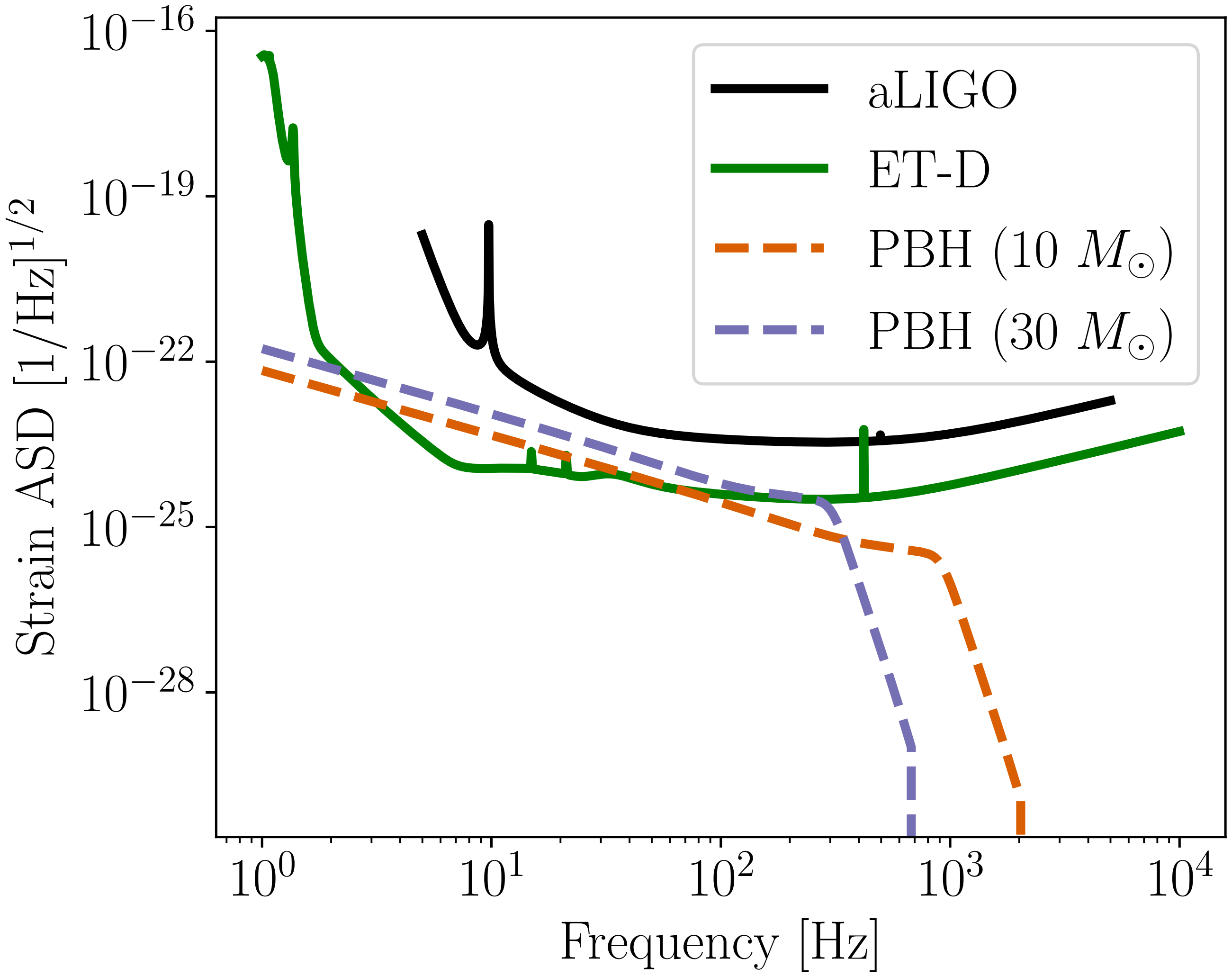


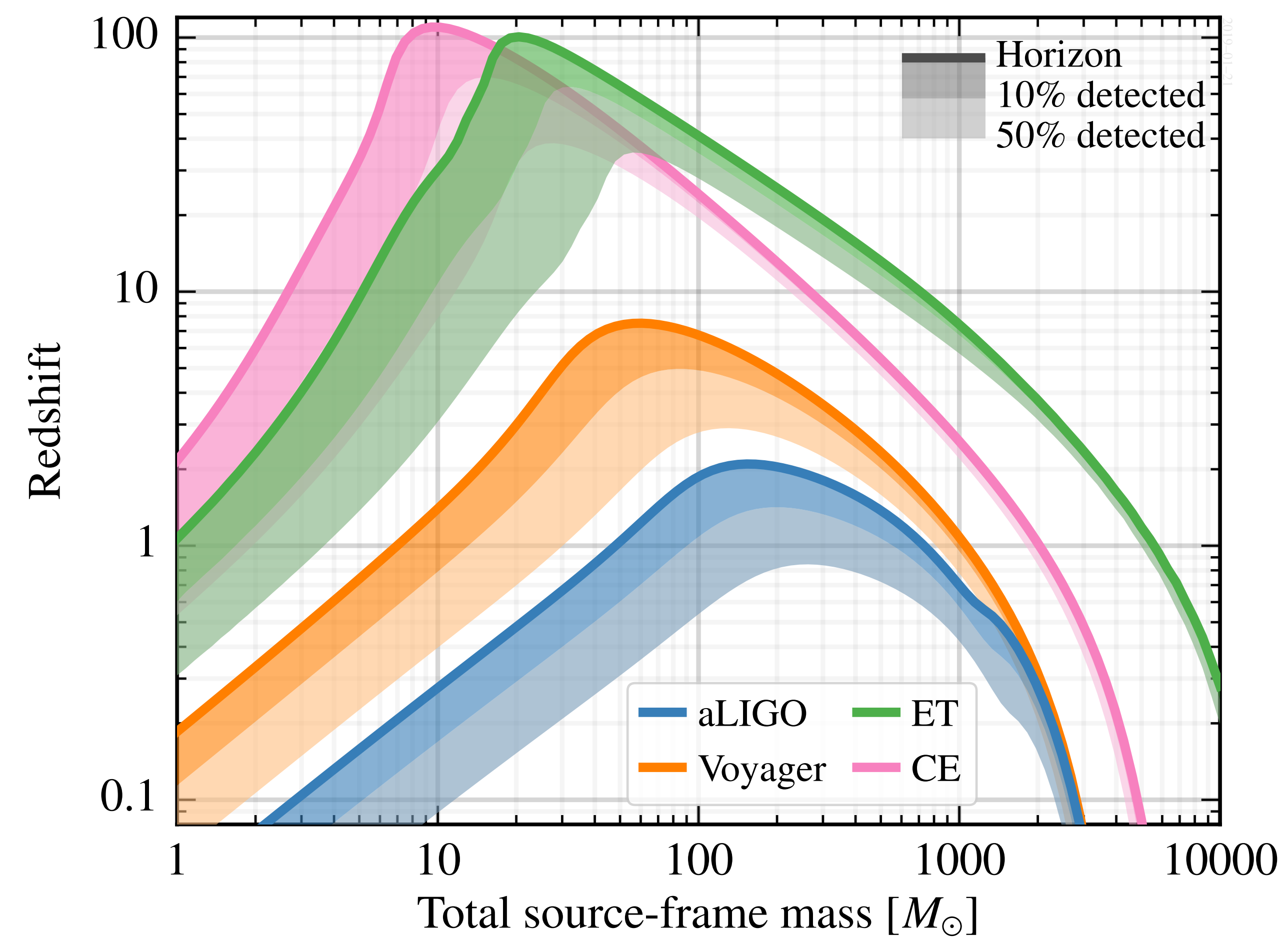
$$\mathscr{R}_{\mathrm{ABH}}(z[t], M) = \mathscr{N} \int_{t-\Delta t_{\min}}^{t-\Delta t_{\max}} \mathrm{d}t_{\mathrm{f}}\ P(t - t_{\mathrm{f}})\, \mathscr{R}_{\mathrm{SF}}(t_{\mathrm{f}})$$



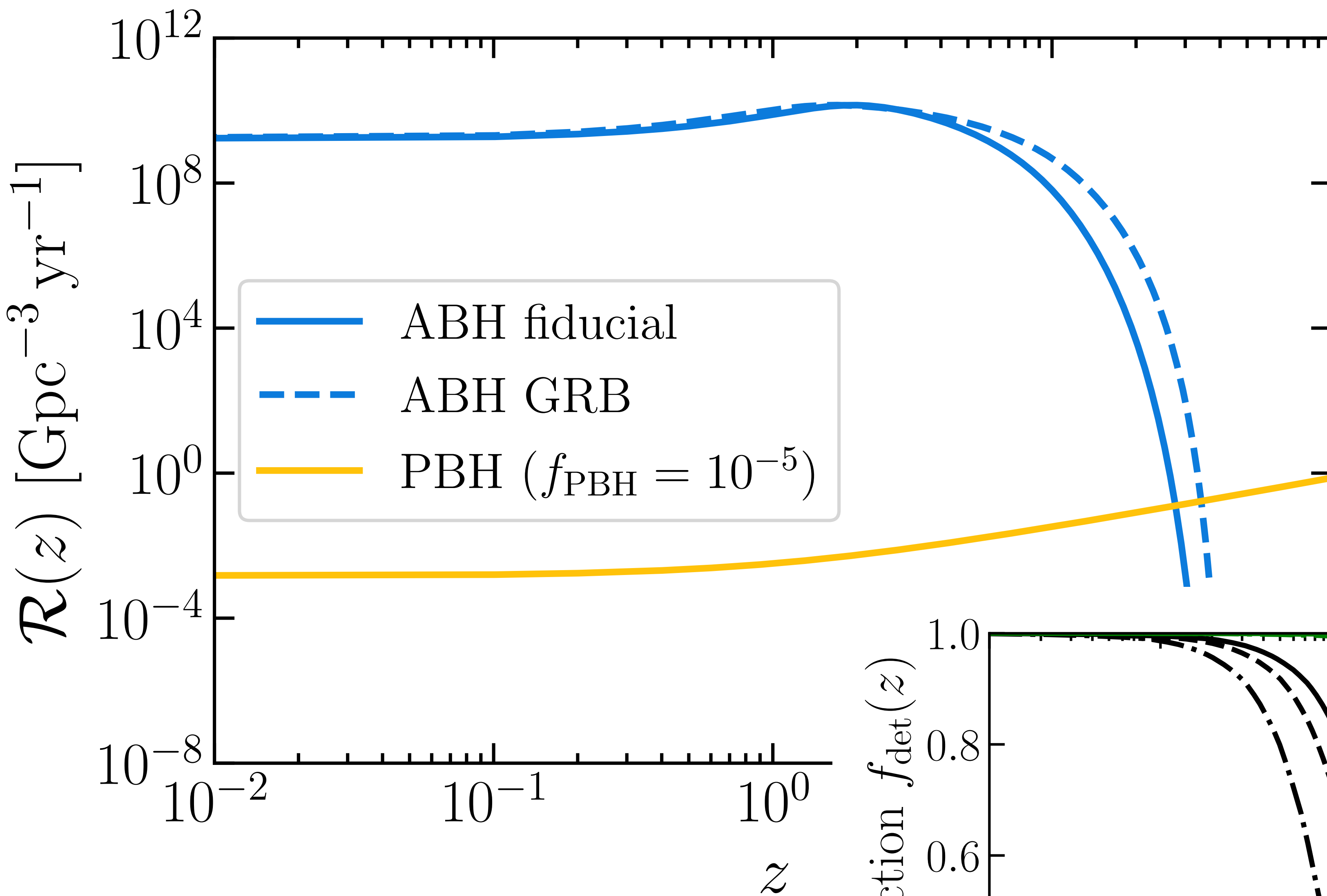
μ
$\vec{v}_{rel}$
M

Einstein telescope

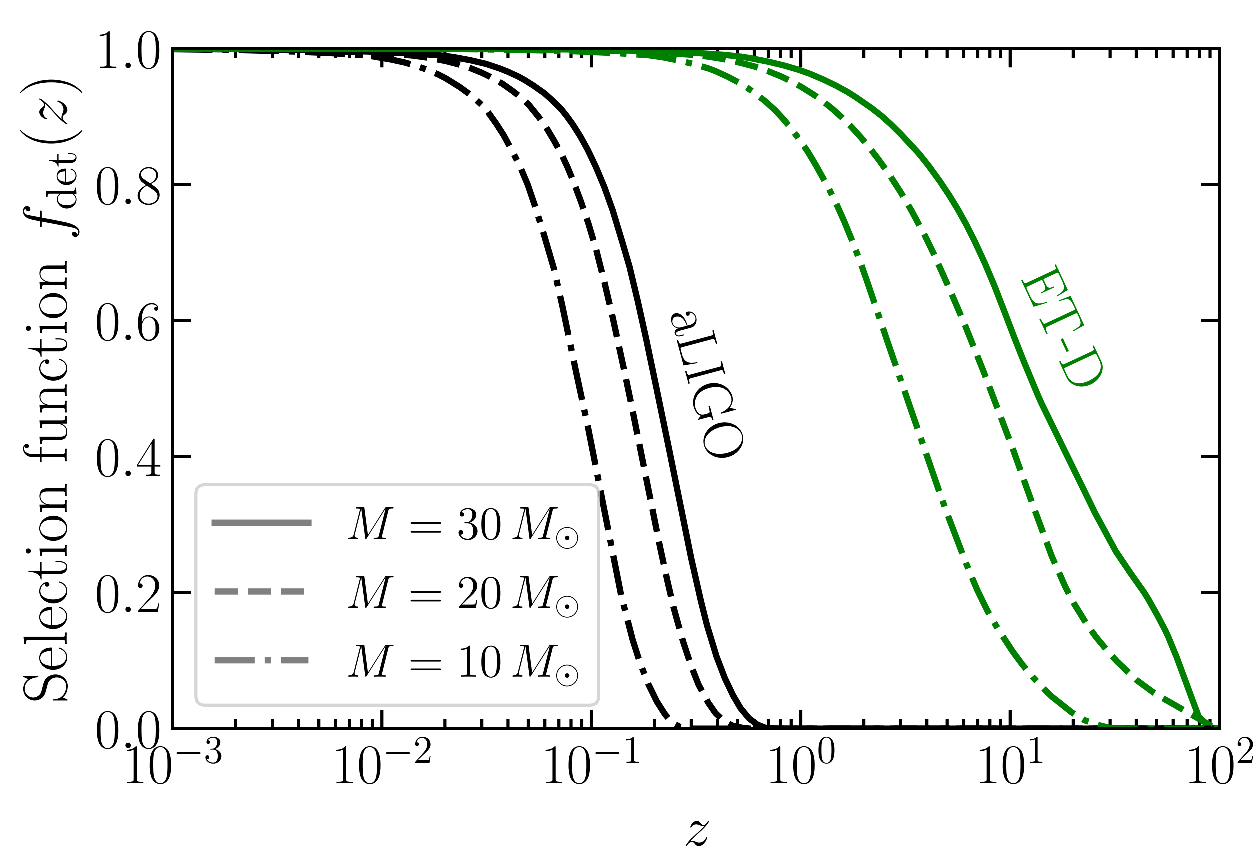




Observed merger rate



$$R_{\rm det}(z) = f_{\rm det}(z)\,\frac{\mathscr{R}(z)}{1+z}\,\frac{\mathrm{d}V_{\rm c}}{\mathrm{d}z}$$



Mock data generation

$$F_+ = \frac{\sqrt{3}}{2}\left[\frac{1}{2}(1+\cos^2\theta)\cos(2\phi)\cos(2\psi) - \cos\theta\sin(2\phi)\sin(2\psi)\right],$$

$$F_\times = \frac{\sqrt{3}}{2}\left[\frac{1}{2}(1+\cos^2\theta)\cos(2\phi)\sin(2\psi) + \cos\theta\sin(2\phi)\cos(2\psi)\right].$$

$$h(t) = F_+(\theta,\phi)\, h_+(t) + F_\times(\theta,\phi)\, h_\times(t)$$

$$\rho_i = \left[4\int_{f_{\mathrm{lower}}}^{f_{\mathrm{upper}}} \mathrm{d}f\, \frac{h_i(f)h_i^*(f)}{S_n(f)}\right]^{\frac{1}{2}}$$

$$\sigma_i^{\mathrm{inst}} = 2\tilde{D}_i/\rho_i$$

$$p(\bar{D}\,|\,D_i) = \frac{1}{\sqrt{2\pi\sigma_i}}\exp\left[-\frac{(\bar{D}-D_i)^2}{2\sigma_i^2}\right]$$

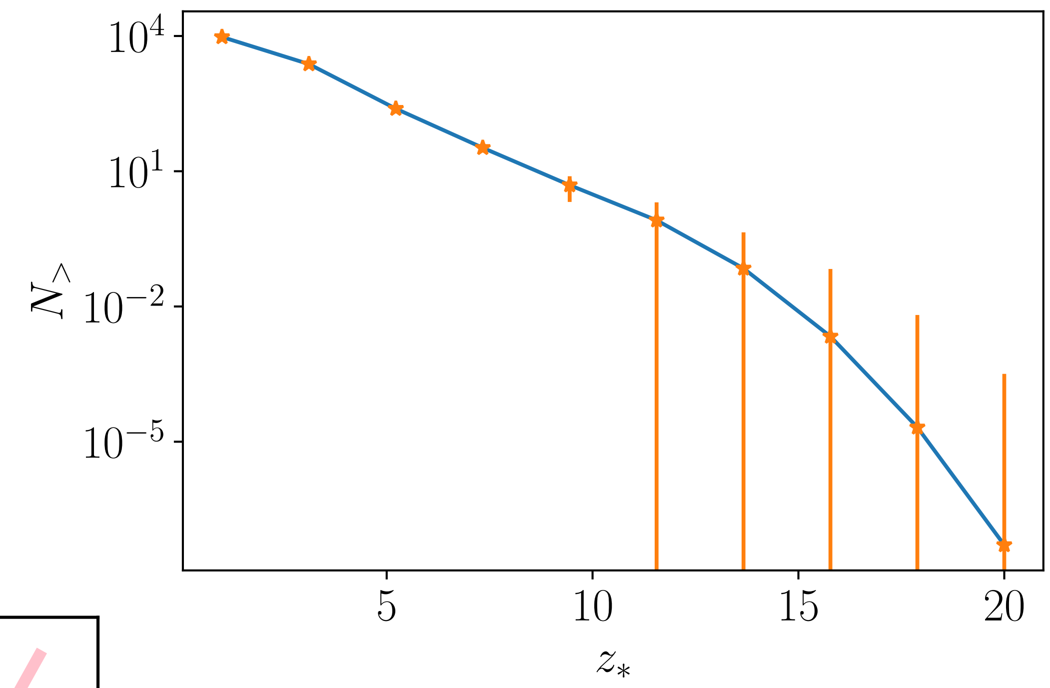
$$\sigma_i^2 = \left(\sigma_i^{\mathrm{inst}}\right)^2 + \left(\sigma_i^{\mathrm{lens}}\right)^2$$

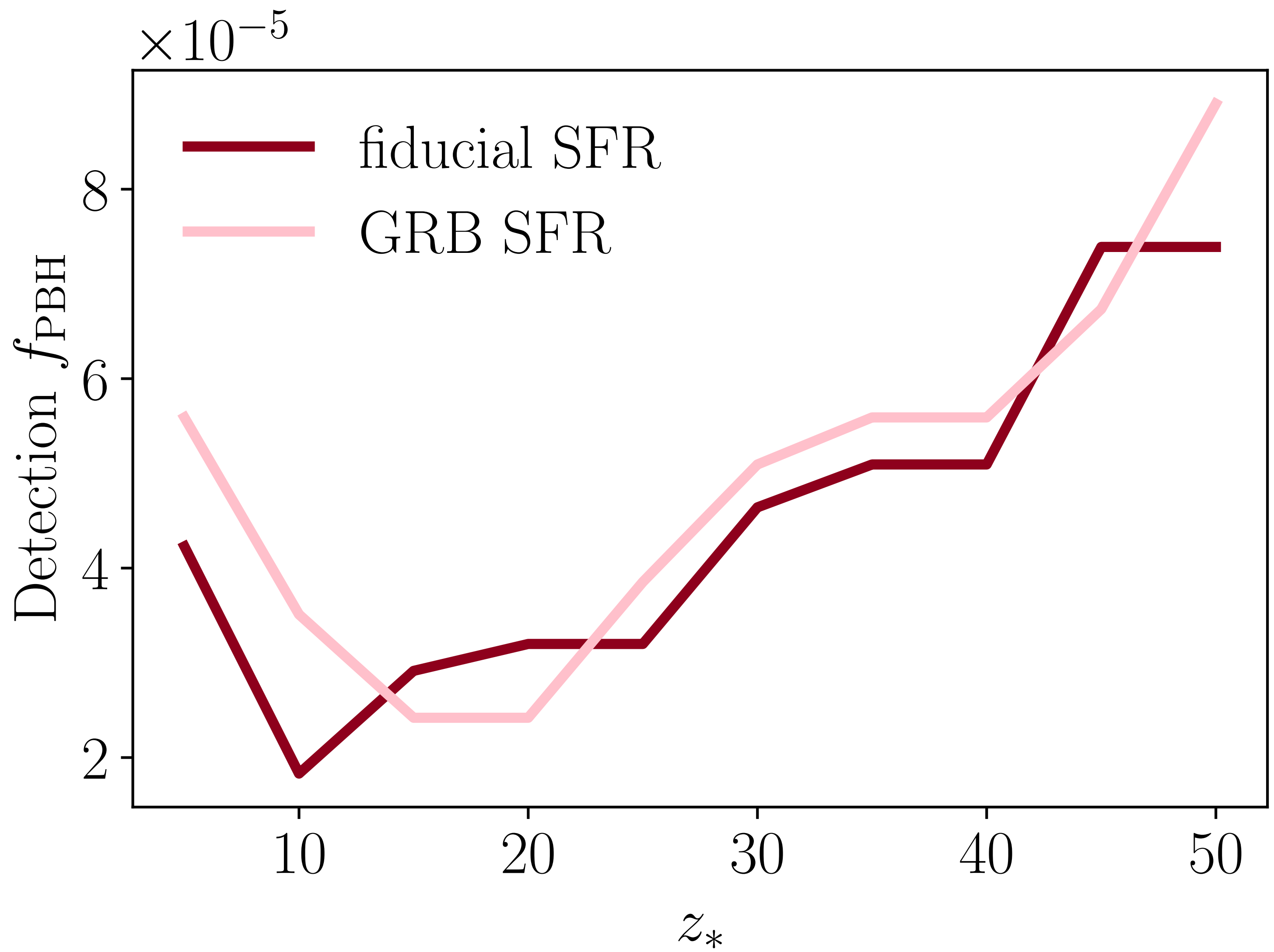
Cut and count

$$\mathcal{S}(\mathcal{D}_{f_{\rm PBH}}, z_*) \equiv \frac{\left| N_>(\mathcal{D}_{f_{\rm PBH}}, z_*) - N_>(\mathcal{D}_0, z_*) \right|}{\sqrt{\sigma^2_>(\mathcal{D}_{f_{\rm PBH}}, z_*) + \sigma^2_>(\mathcal{D}_0, z_*)}}$$

Cut and count

Threshold dependance





Likelihood analysis

$$p(f_{\rm PBH}\,|\,\mathscr{D}) \propto \mathscr{L}(f_{\rm PBH}\,|\,\mathscr{D})\Pr(f_{\rm PBH})$$

Probability of a set of observed events

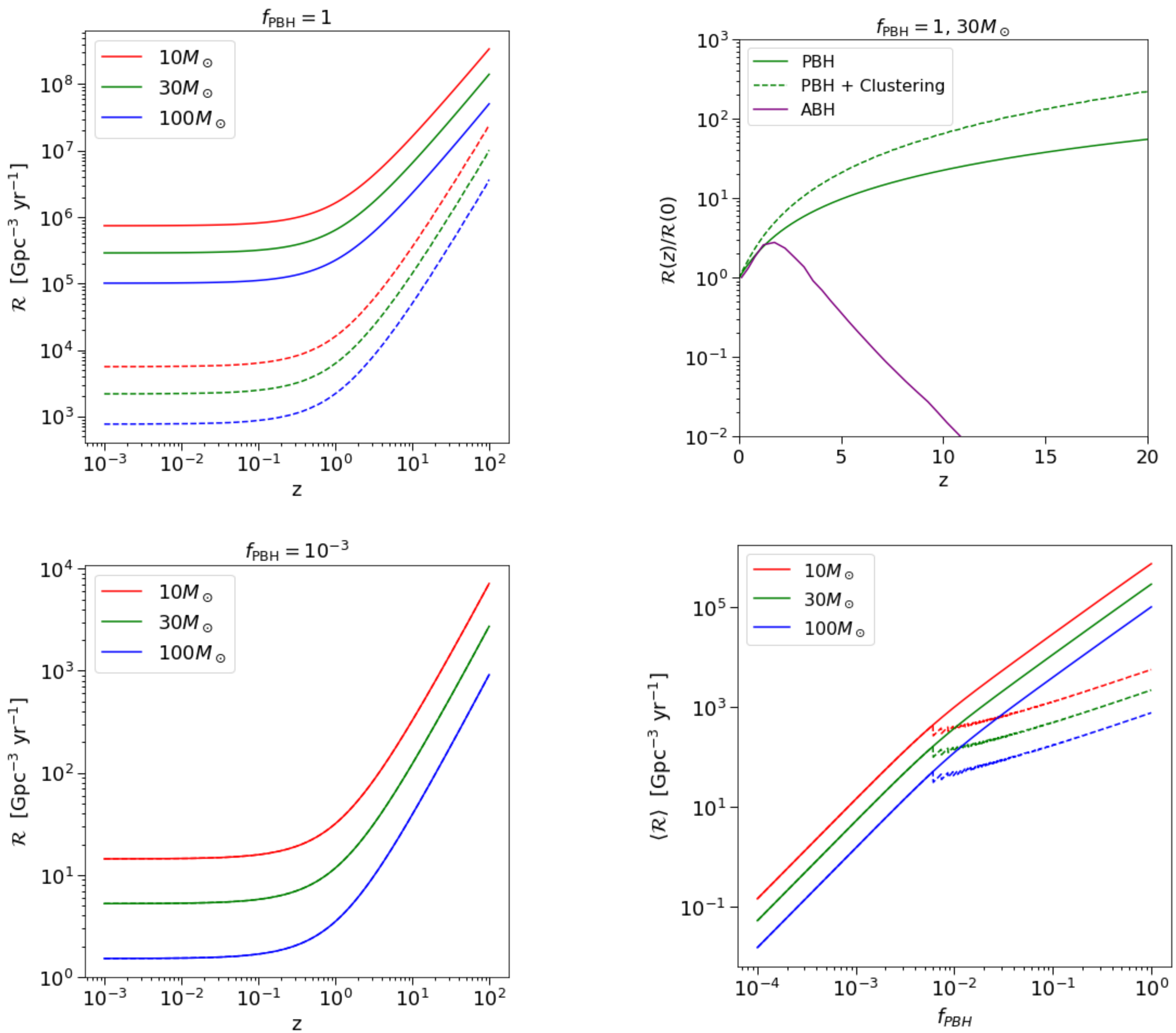
$$\mathscr{L}(f_{\rm PBH}\,|\,\mathscr{D}) = \frac{\bar{N}_{\rm obs}(f_{\rm PBH})^{N_{\rm obs}} e^{-\bar{N}_{\rm obs}(f_{\rm PBH})}}{N_{\rm obs}\,!} \times \prod_{i=1,N_{\rm obs}} p(D_i\,|\,f_{\rm PBH})$$

$$p(D_i\,|\,f_{\rm PBH}) \propto \int \frac{p(\bar{D}_i\,|\,D_i)}{\tilde{p}(\bar{D}_i)}\, p(\bar{D}_i\,|\,f_{\rm PBH})\, {\rm d}\bar{D}_i$$

$$p(\bar{D}\,|\,f_{\rm PBH})\,{\rm d}\bar{D} = \frac{N_{\rm ABH}}{\bar{N}_{\rm obs}}\, p_{\rm ABH}(\bar{D})\,{\rm d}\bar{D} + \frac{N_{\rm PBH}}{\bar{N}_{\rm obs}}\, p_{\rm PBH}(\bar{D}\,|\,f_{\rm PBH})\,{\rm d}\bar{D}$$

$$p(D\,|\,\bar{D}) = \frac{p(\bar{D}\,|\,D)}{\tilde{p}(\bar{D})}\,\tilde{p}(D)$$

Merger rate


$f_{\rm PBH} = 1$
$10M_\odot$
$30M_\odot$
$100M_\odot$
$\mathcal{R}$ [Gpc^{-3} yr^{-1}]
z
$f_{\rm PBH} = 1, 30M_\odot$
PBH
PBH + Clustering
ABH
$\mathcal{R}(z)/\mathcal{R}(0)$
z
$f_{\rm PBH} = 10^{-3}$
$10M_\odot$
$30M_\odot$
$100M_\odot$
$\mathcal{R}$ [Gpc^{-3} yr^{-1}]
z
$10M_\odot$
$30M_\odot$
$100M_\odot$
$\langle\mathcal{R}\rangle$ [Gpc^{-3} yr^{-1}]
f_{PBH}