Multi-messenger avenues towards Primordial Black Hole detection

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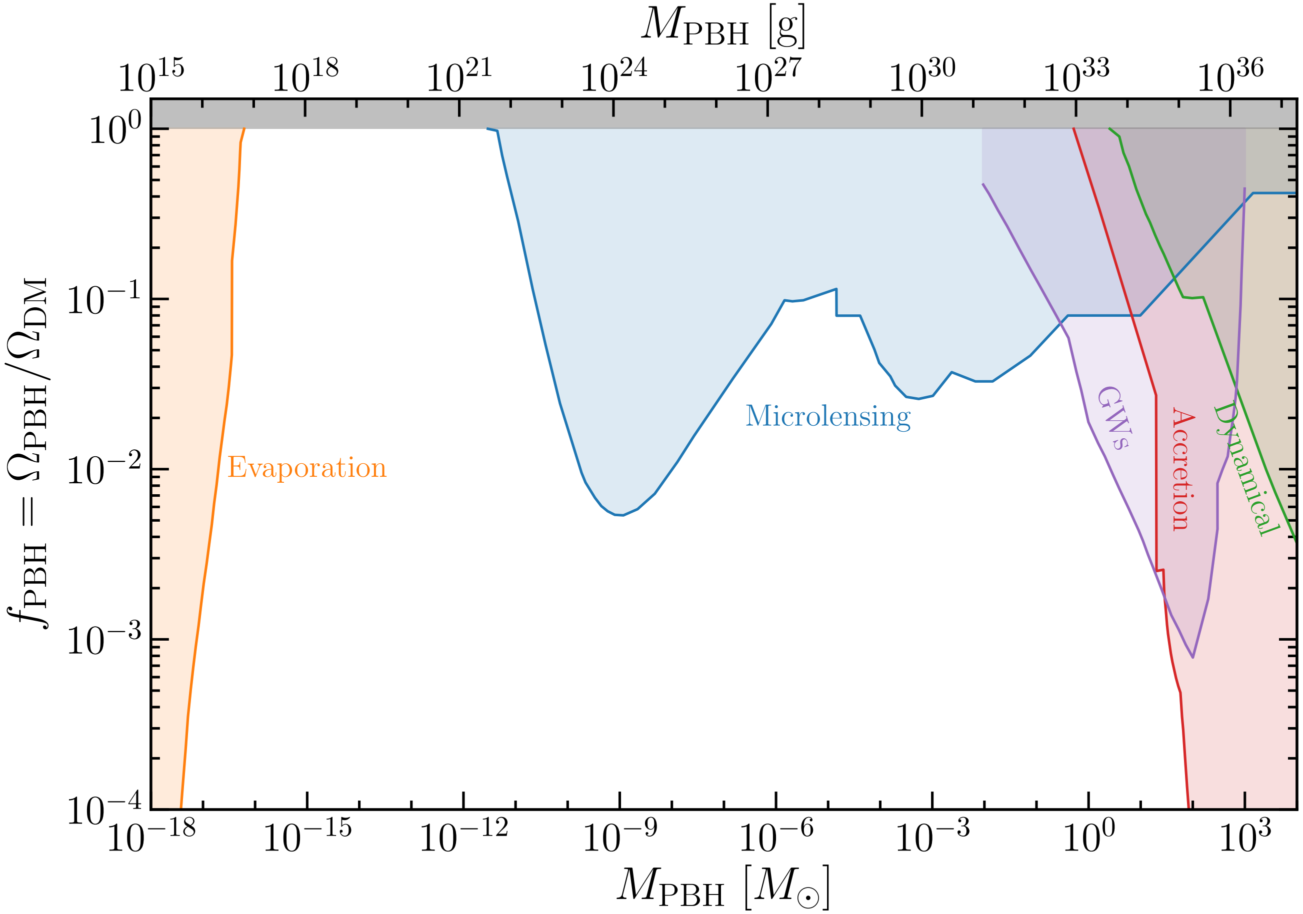
Primordial black holes (PBHs)

Zeldovich 67, Hawking MNRAS 152 (1971), Carr and Hawking MNRAS 168 (1974)

- BHs can form in early universe from ***collapse of overdense regions*** $\left(\frac{\delta\rho}{\rho} \gtrsim \frac{1}{3}\right)$
- Mass related to horizon size at time of formation



github.com/bradkav/PBHbounds

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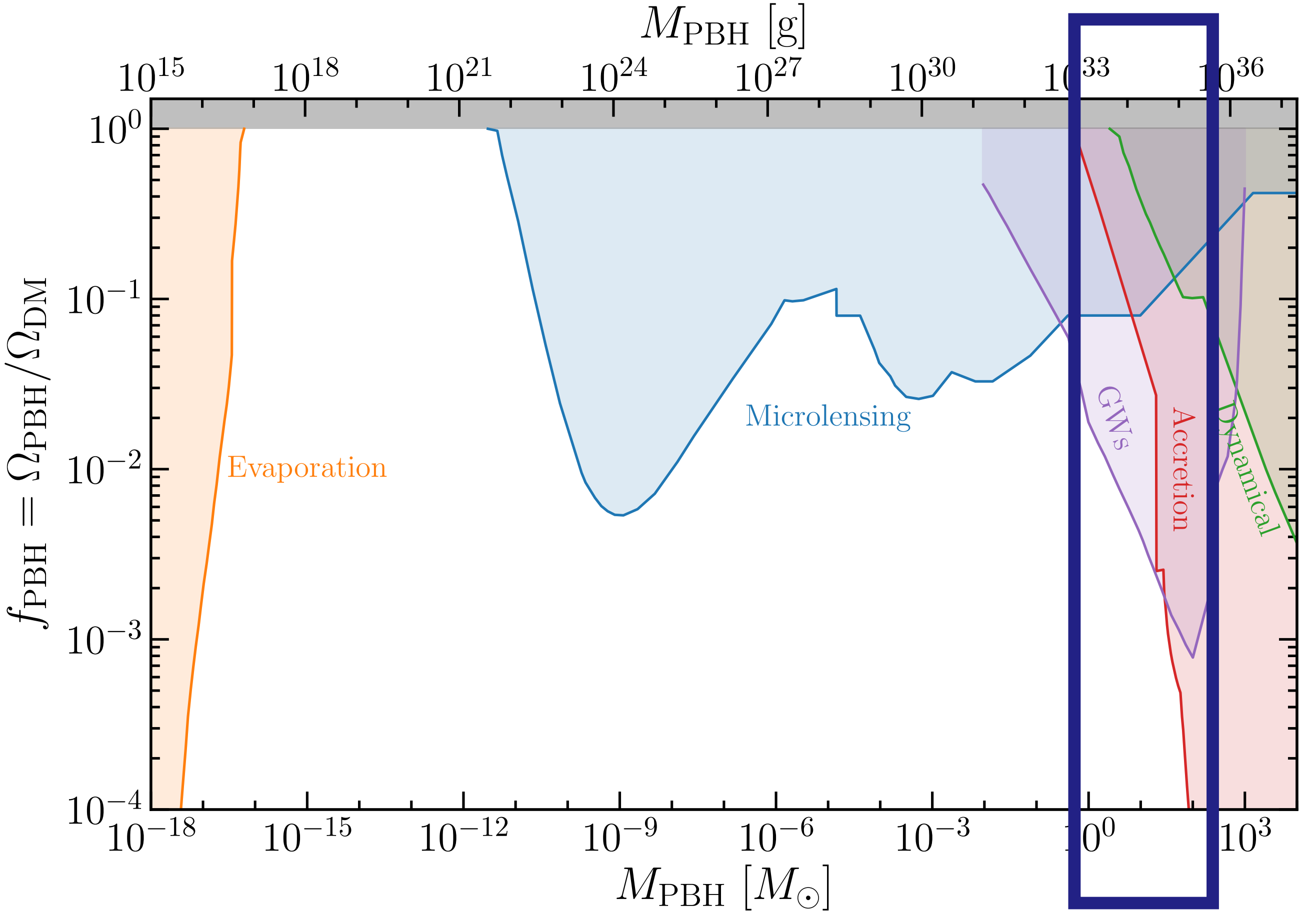

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Outline

(1) Detecting black holes in the Milky Way

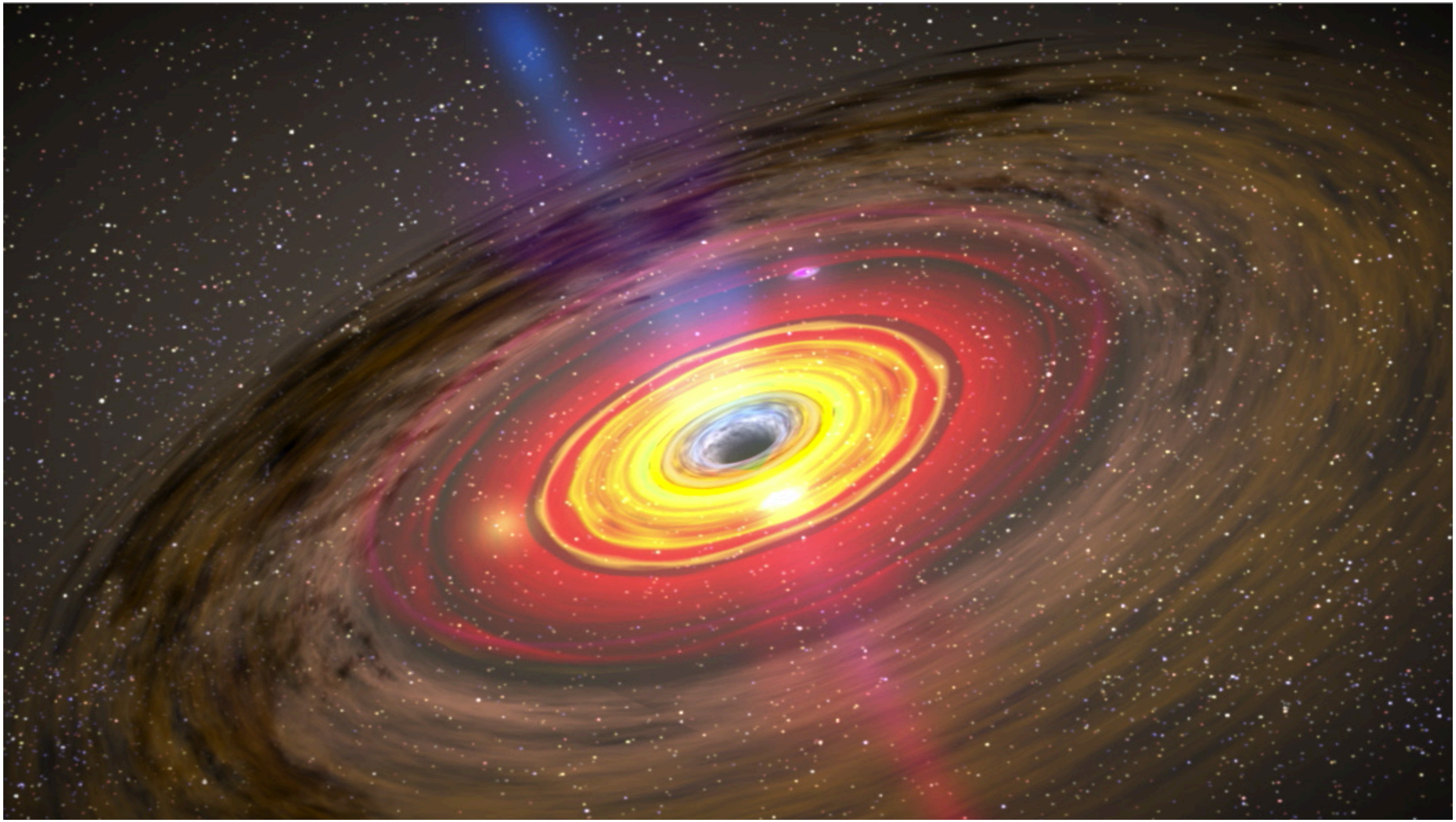
- ***Gas accretion***

Based on:
- F.Scarcella, D.Gaggero et al. 2012.10421 (MNRAS),
- F.Scarcella, D.Gaggero, J. Garcia-Bellido PoS ICRC2021 (2021) 565

(2) Detecting black holes at cosmological distances

- ***Gravitational waves***

Based on:
- Master thesis, Cristina Fernandez
- Master thesis, Tania Franco
- F.Scarcella, D.Gaggero et al. 2205.02639



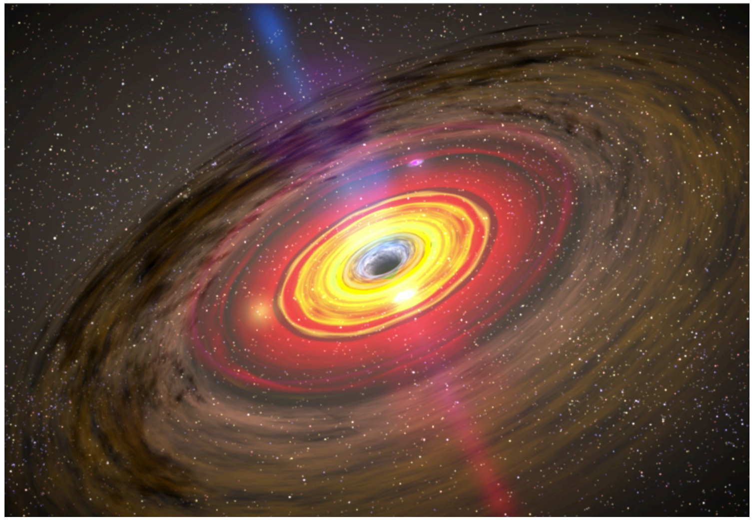
Gas accretion in the Milky Way

Based on:
- 2012.10421 (MNRAS) with D. Gaggero, M. Ricotti, G. Bertone et al.
- PoS ICRC2021 (2021) 565, 22xx.xxx with D. Gaggero, J. Garcia-Bellido

Detecting BHs in the Milky Way

BH expected to ***accrete gas*** from ***dense clouds***

- Non-thermal radiation (X-ray/radio)
- Large population of PBHs + clouds at GC
- Channel used to set bound on PBH abundance Manshanden et al. 1812.07967
- No accreting isolated BH identified so far



Goals

➡ Robustness of bound wrt ***astrophysical uncertainties***

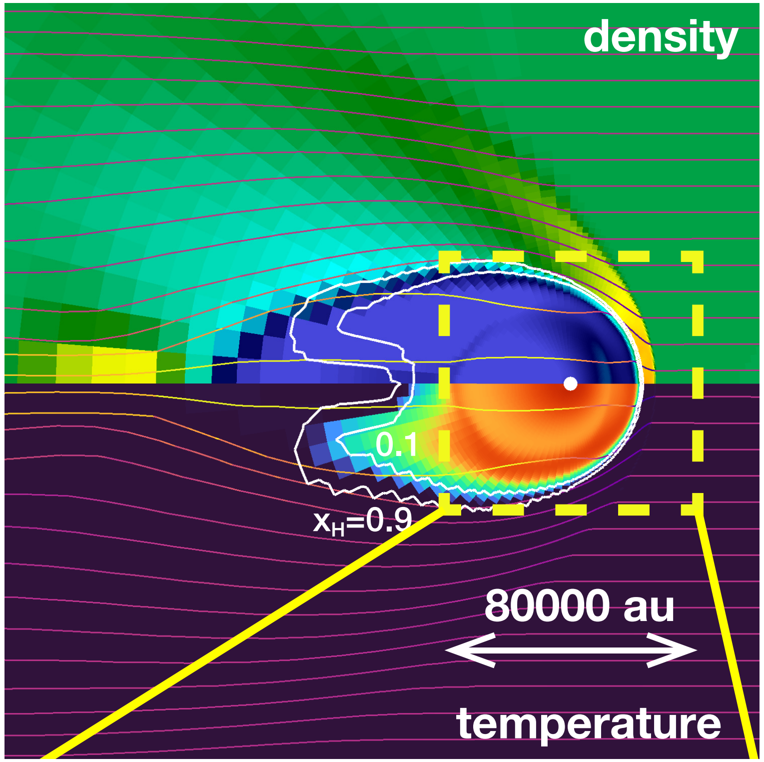
➡ Dependence bound on the ***PBH model (mass function)***

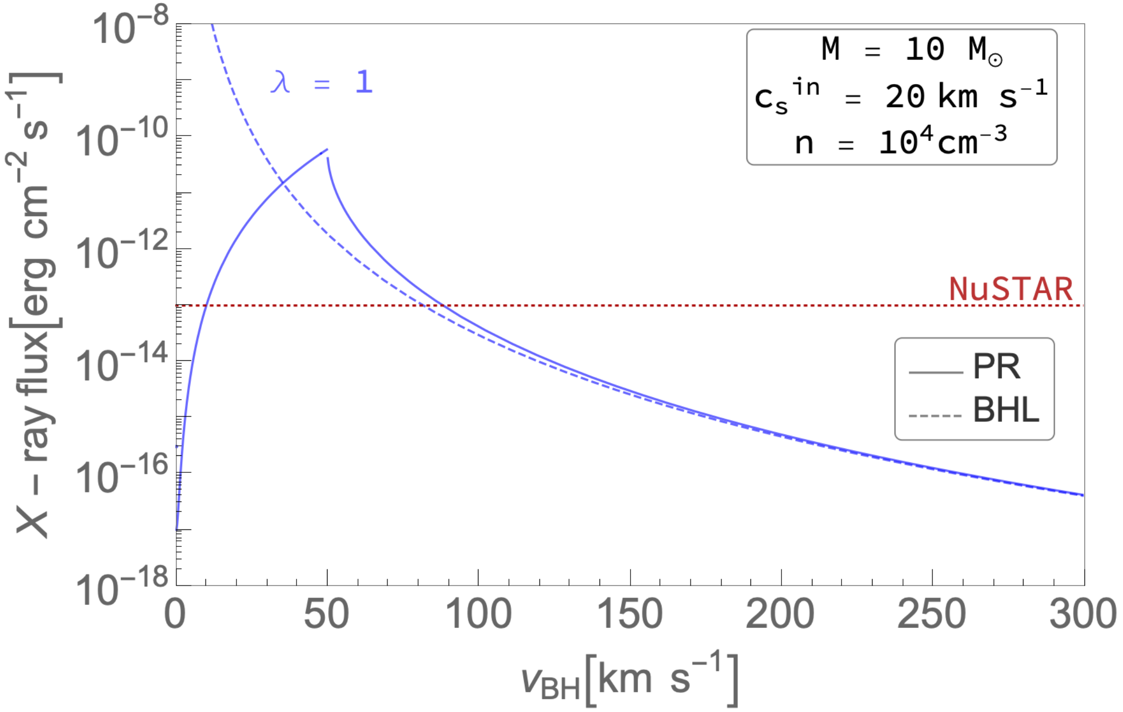
Modelling the accretion rate $L \propto \dot{M}^2$

Park-Ricotti model, ***radiative feedback***

211.0542, 2003.05625

$$\dot{M} = 4\pi \frac{(GM)^2 \rho_{\rm in}}{(v_{\rm in}^2 + c_{\rm s,in}^2)^{3/2}}$$





- ➡ Main variables M, $v_{\rm rel}$, n, $c_s^{\rm in}$
- ➡ Threshold effect

Modelling the accretion rate

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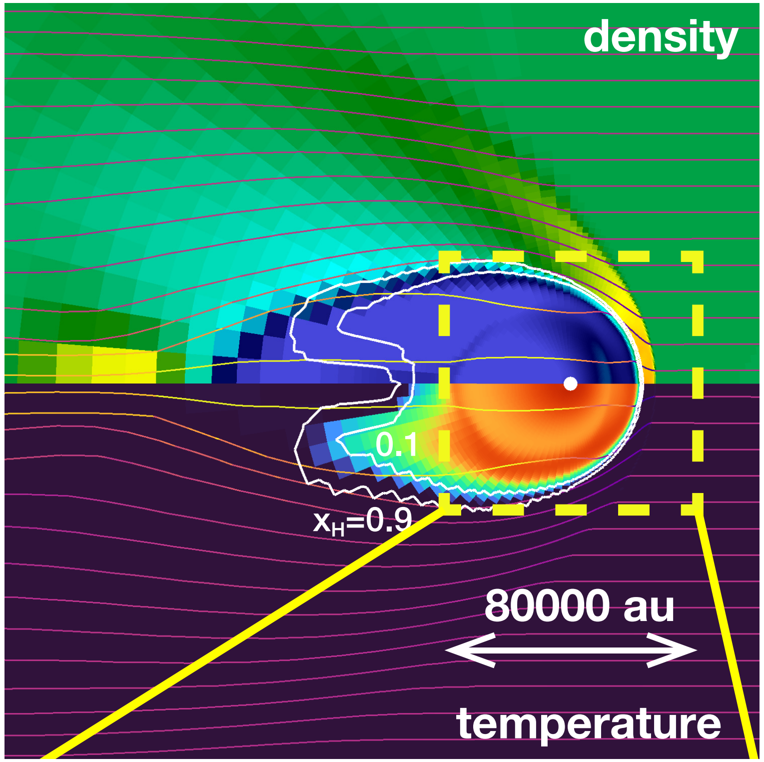
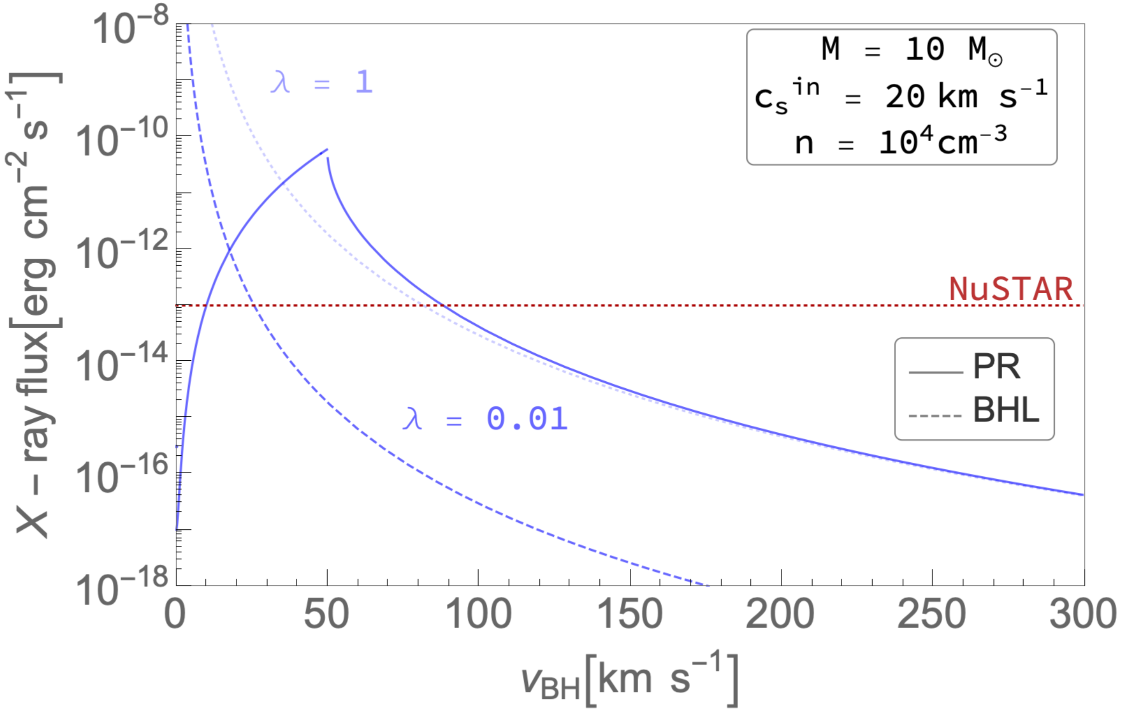




- ➡ Main variables M, $\mathrm{v}_{\rm rel}$, n, $\mathrm{c}_{\rm s}^{\rm in}$
- ➡ Threshold effect

Expected number of visible sources

Semi-analytic study of impact of uncertainties on the predictions

$$N^{\mathrm{sources}}(\phi^*) = N^{\mathrm{tot}} \int_{\phi(\mathrm{v}_{\mathrm{BH}}, M, d, \{p_i\}) > \phi^*} P(\mathrm{v}_{\mathrm{BH}}) P(M) P(r) P(n)\, \mathrm{d}\mathrm{v}_{\mathrm{BH}}\, \mathrm{d}M\, \mathrm{d}r\, \mathrm{d}n$$

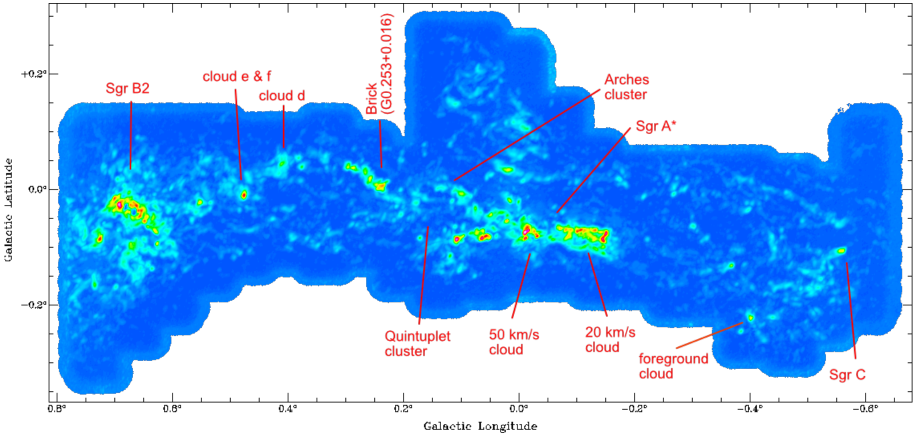
Modelling the ***BH population***:

- Spatial distribution (NFW)
- Velocity distribution (MB)
- Mass distribution

Modelling the ***molecular clouds***:

- Density distribution $P(n) \propto n^{-\beta}$

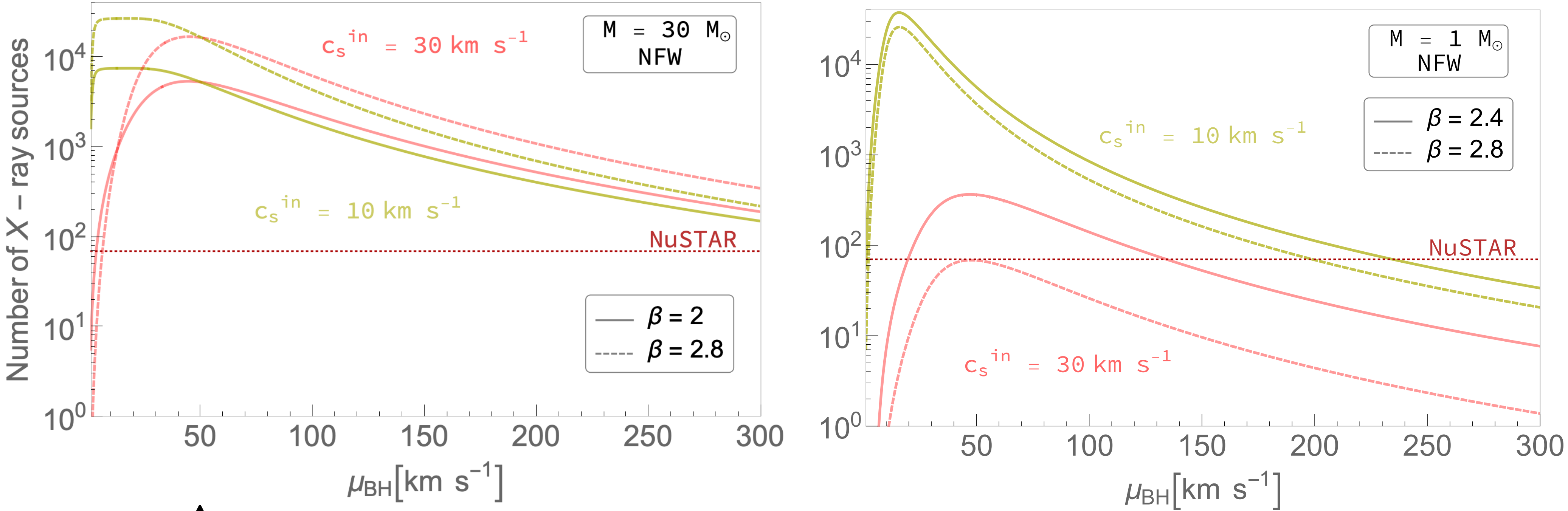
Ferrière et al: 0702532



- Temperature ***of ionised 'bubble'*** (c_s^{in})

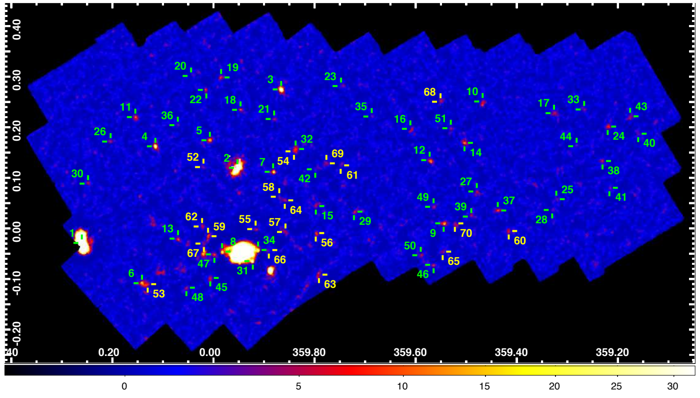
Results: number of X-ray sources (monochromatic)

$f_{\rm PBH} = 1$



Eddington
inversion
formula

NuSTAR survey: 3-40 keV, ~70 sources GC, 1605.03882



Results: abundance constraints

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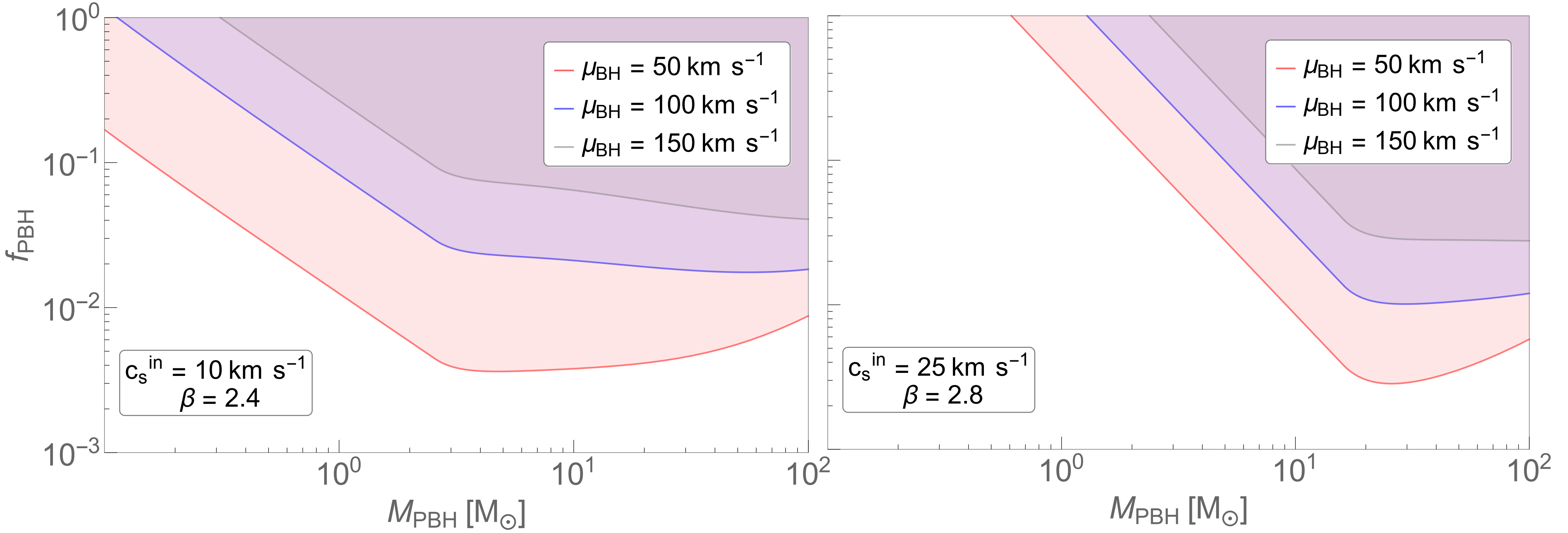

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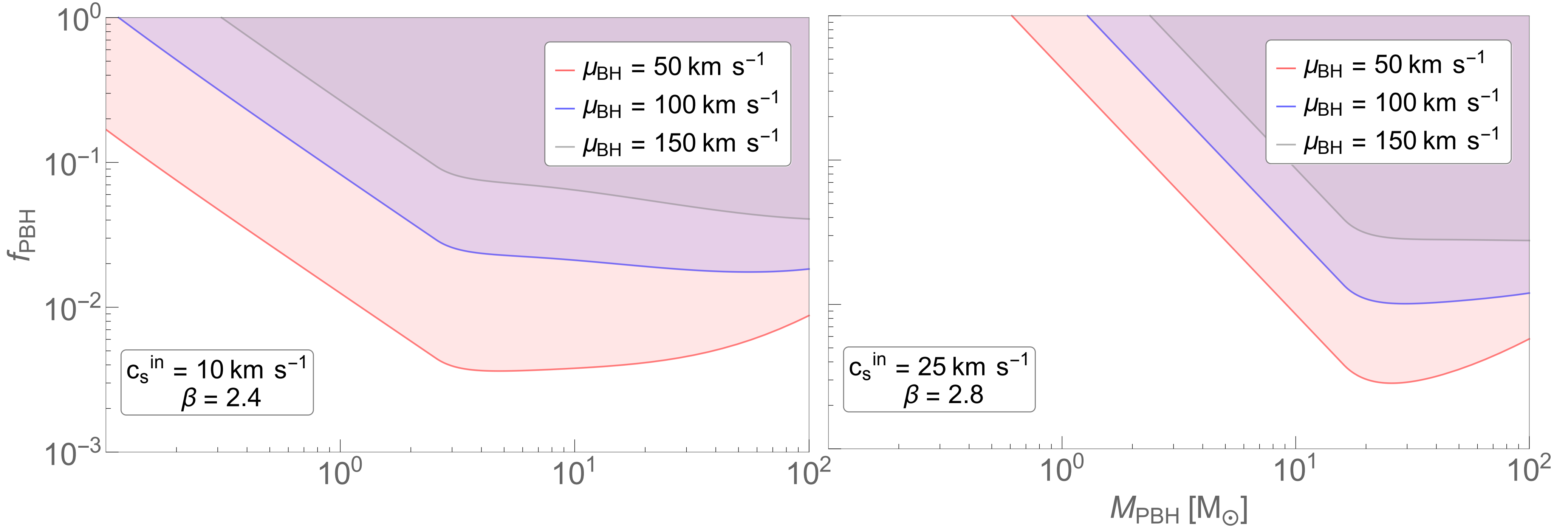

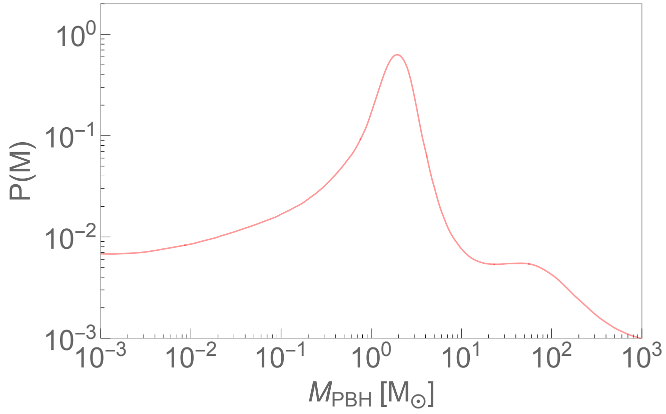

Jedamzik 1996, Byrnes et al. 2018, Carr et al. 2019

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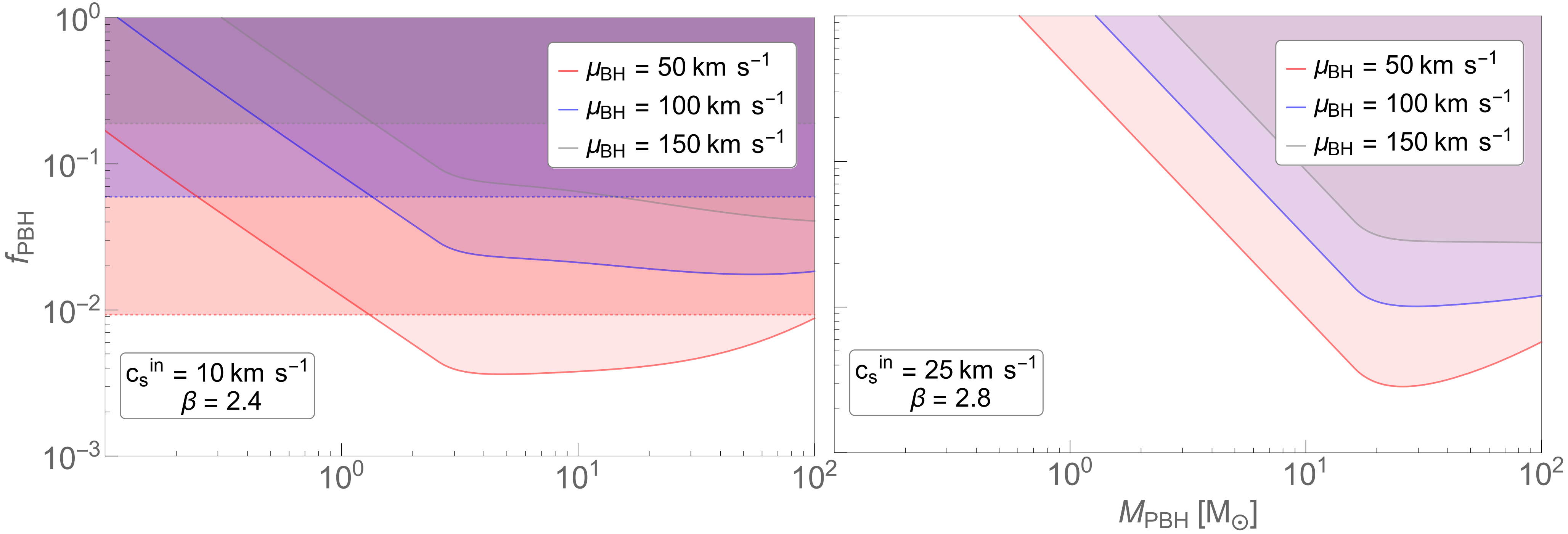

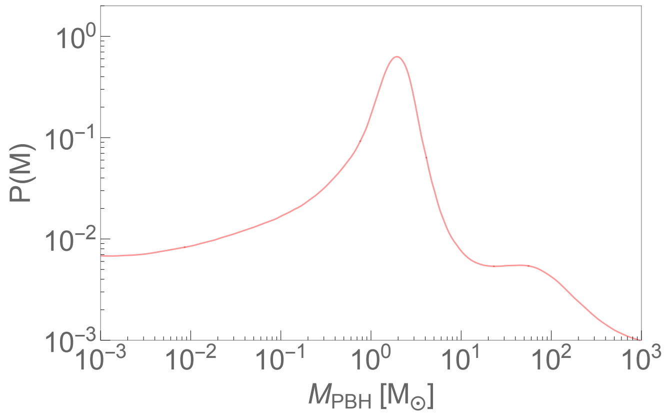

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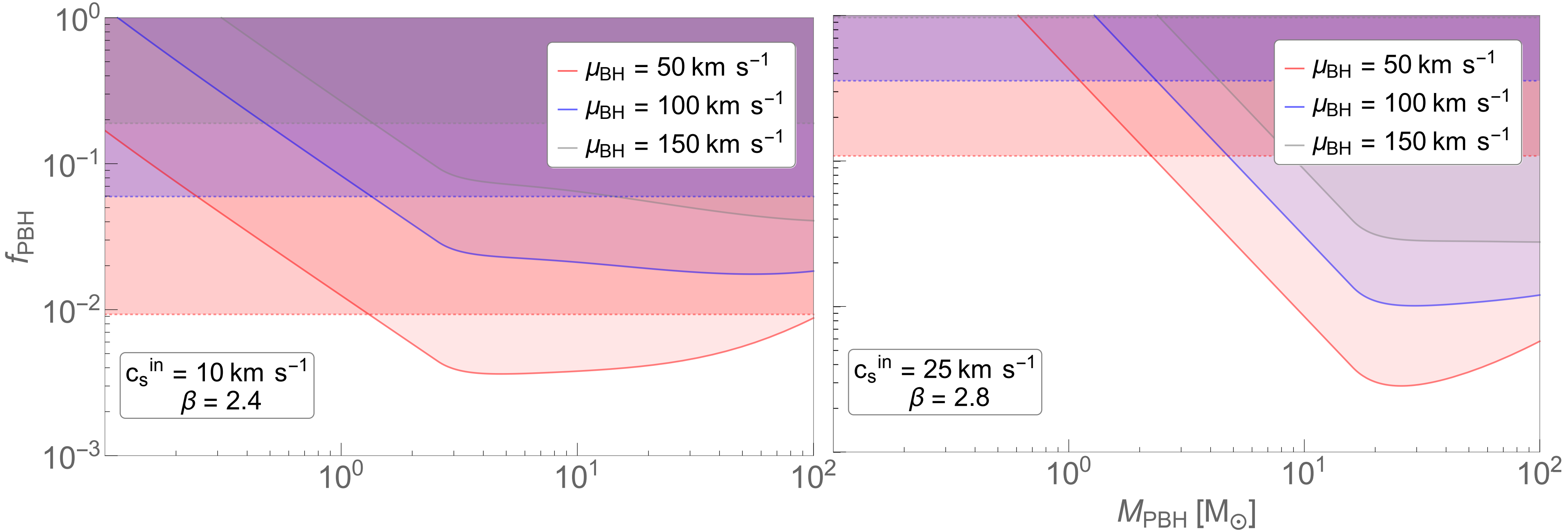

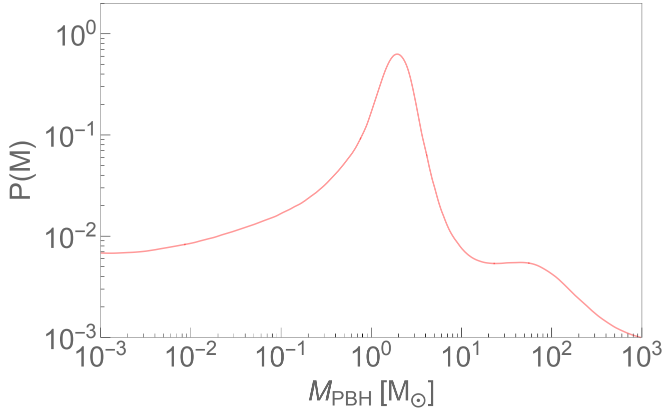

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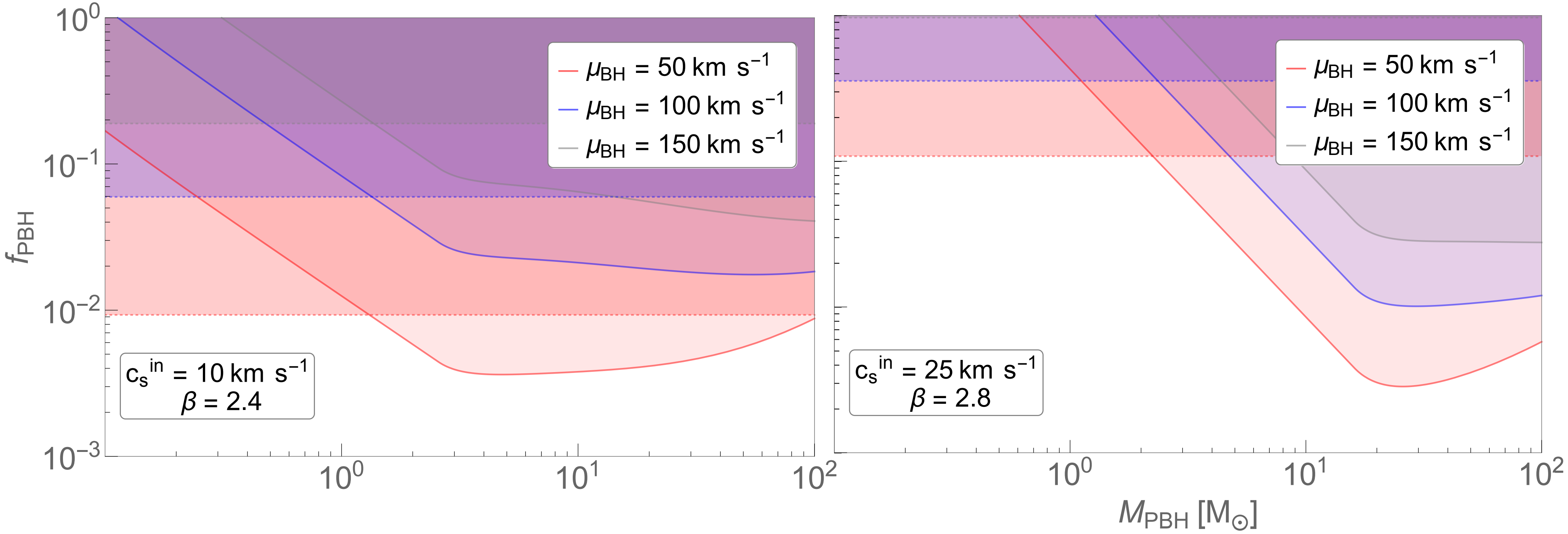

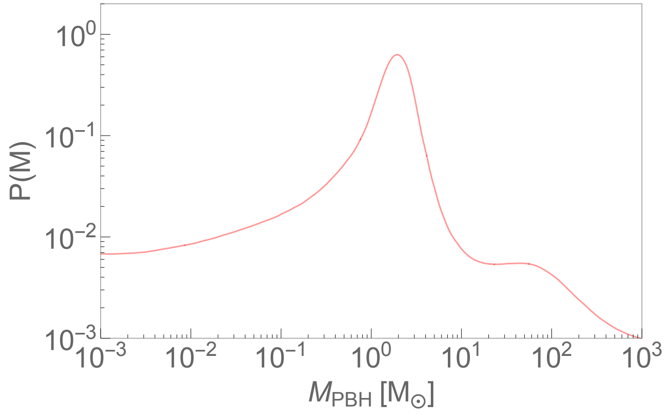

➡ Dominated by 1 $M_\odot$ peak: large uncertainties

➡ In progress: Bayesian posterior on $f_{\rm PBH}$

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Jedamzik 1996, Byrnes et al. 2018, Carr et al. 2019

(1) Summary

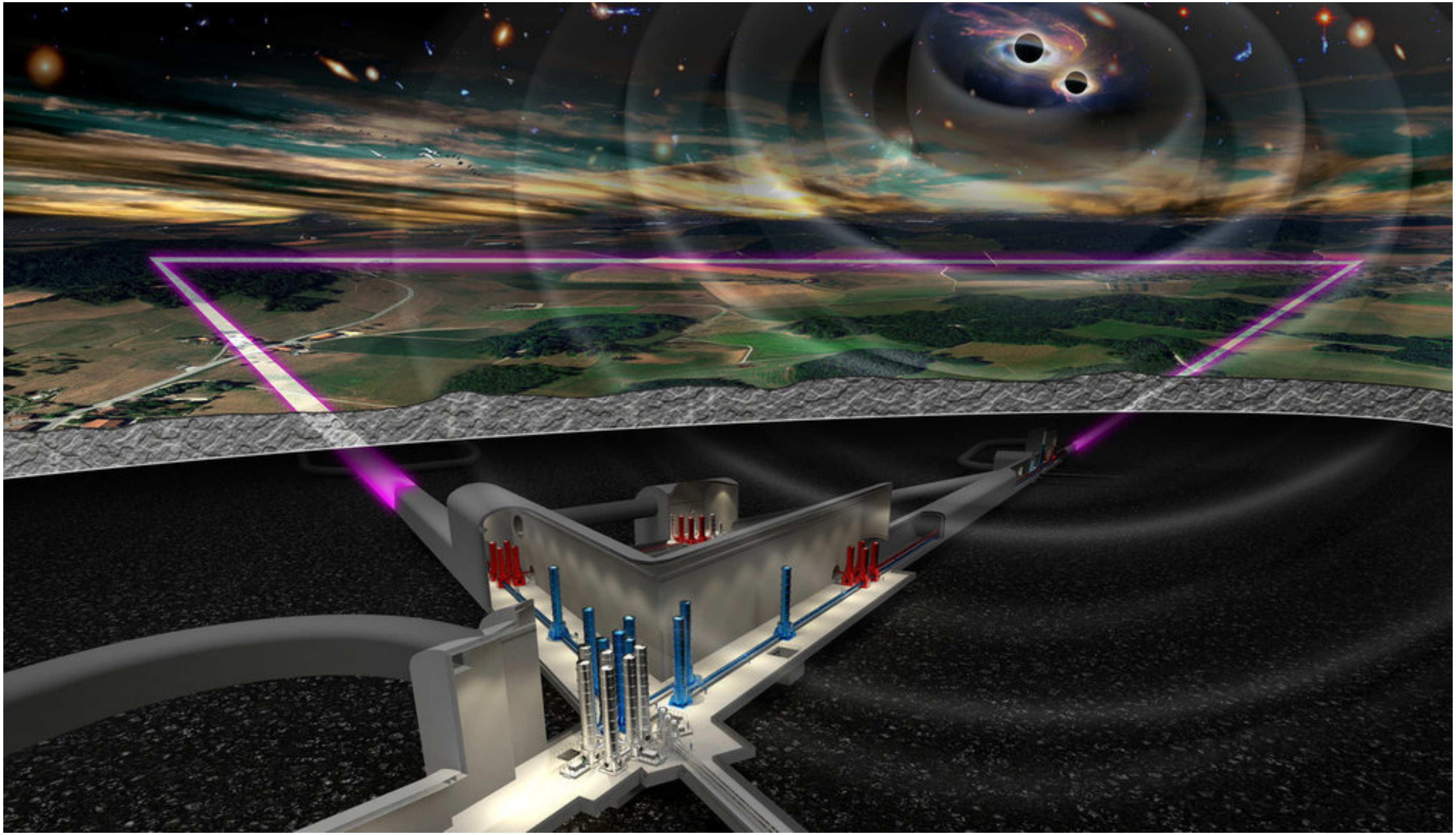
- ➡ Useful channel to ***constrain PBH abundance*** *above* $\sim 10\,M_\odot$
- ➡ ***Large uncertainties*** for PBH mass $\sim 1\,M_\odot$
- ➡ Uncertainties ***reflected on multimodal mass function***

Caveats

- ➡ PBH ***spatial distribution*** (correlation with cloud positions, ***clusters***)
- ➡ PBH velocity dispersion

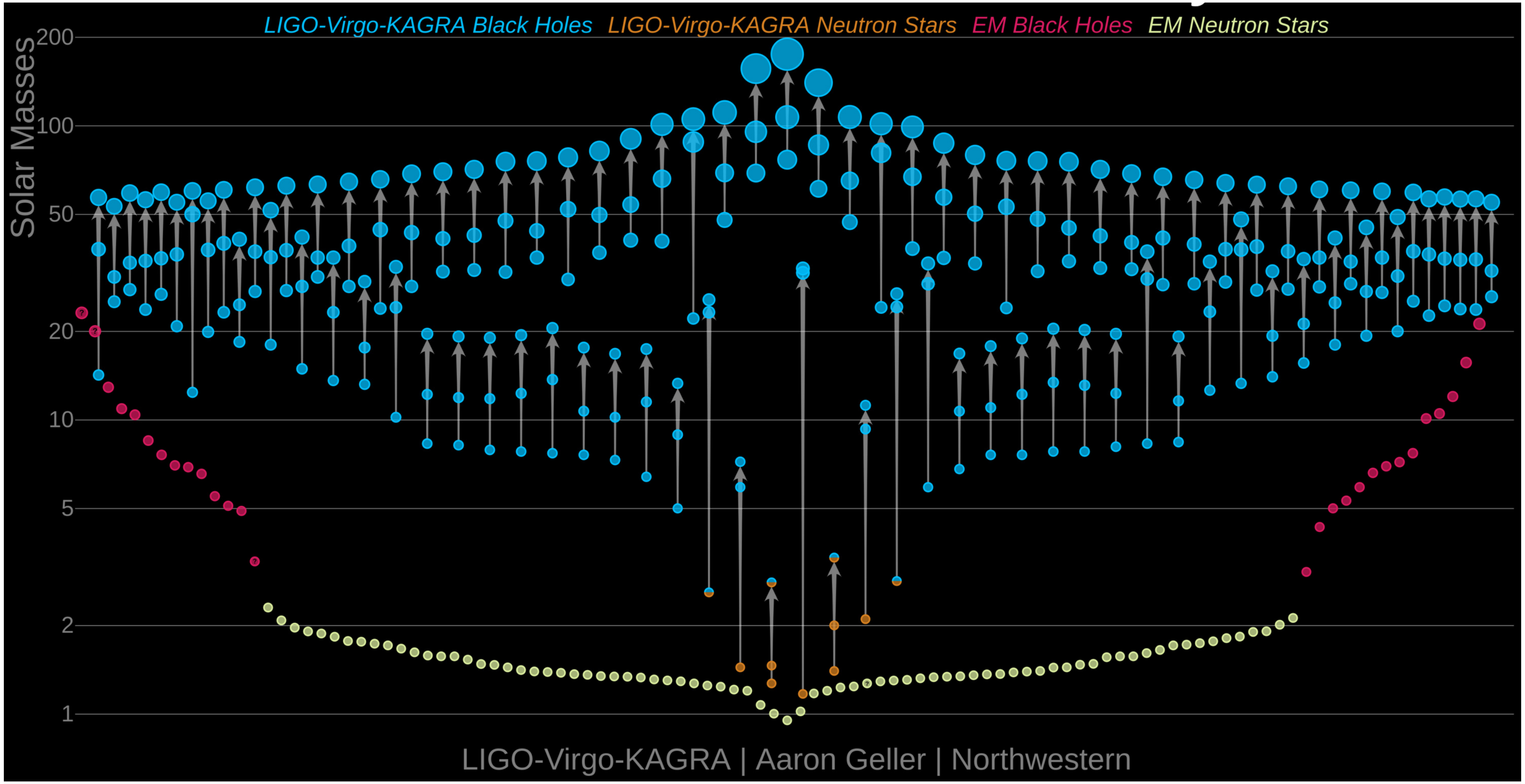
Prospects

- ➡ Identification of sources as BH - ***dedicated multi-wavelength analysis***
- ➡ Identification of sources as ***PBH or ABH - challenging***

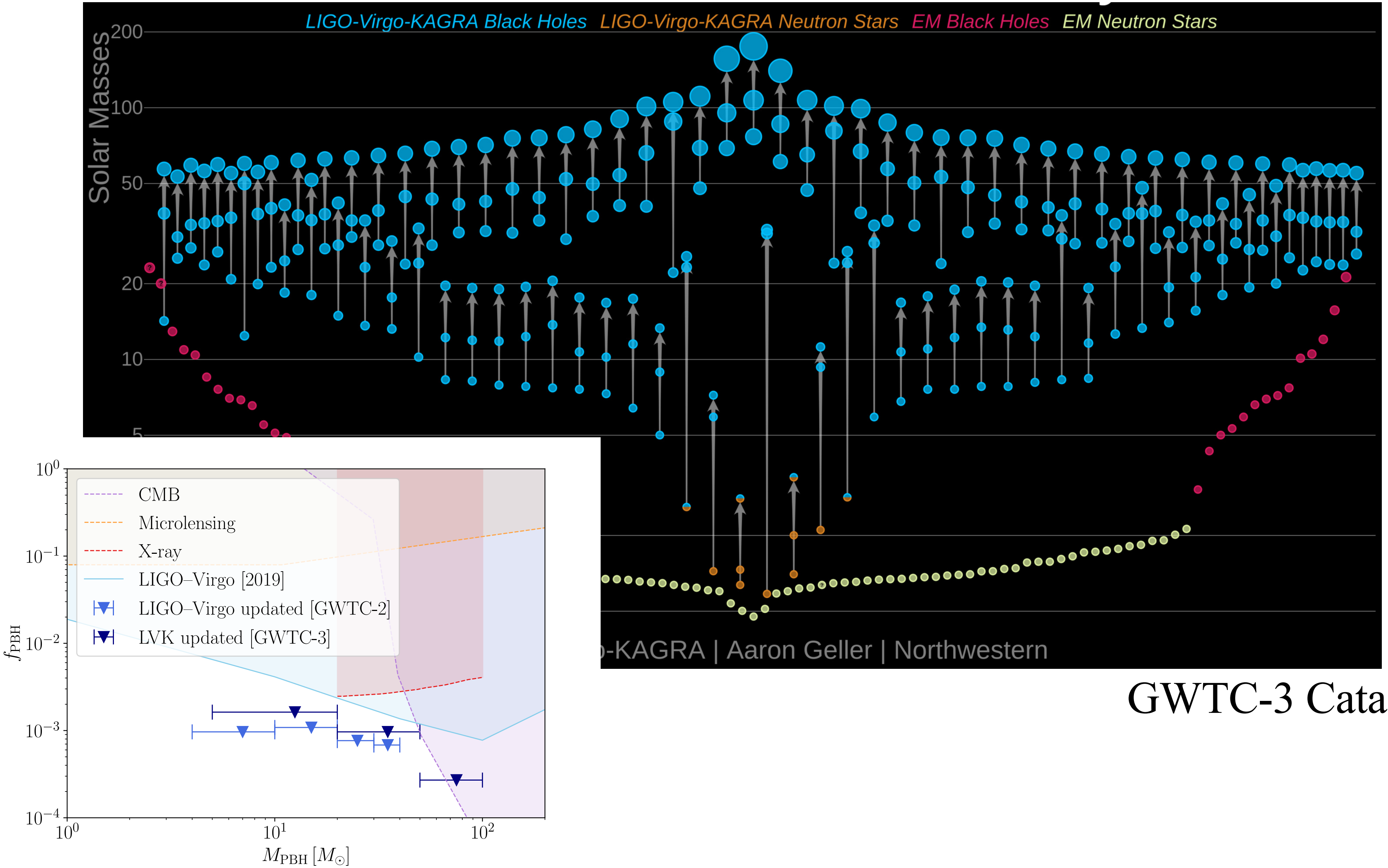


Black hole mergers at high redshift

Based on 2205.02639 with M. Martinelli, N. Hogg, P. Fleury, D. Gaggero, B. Kavanagh



GWTC-3 Catalog



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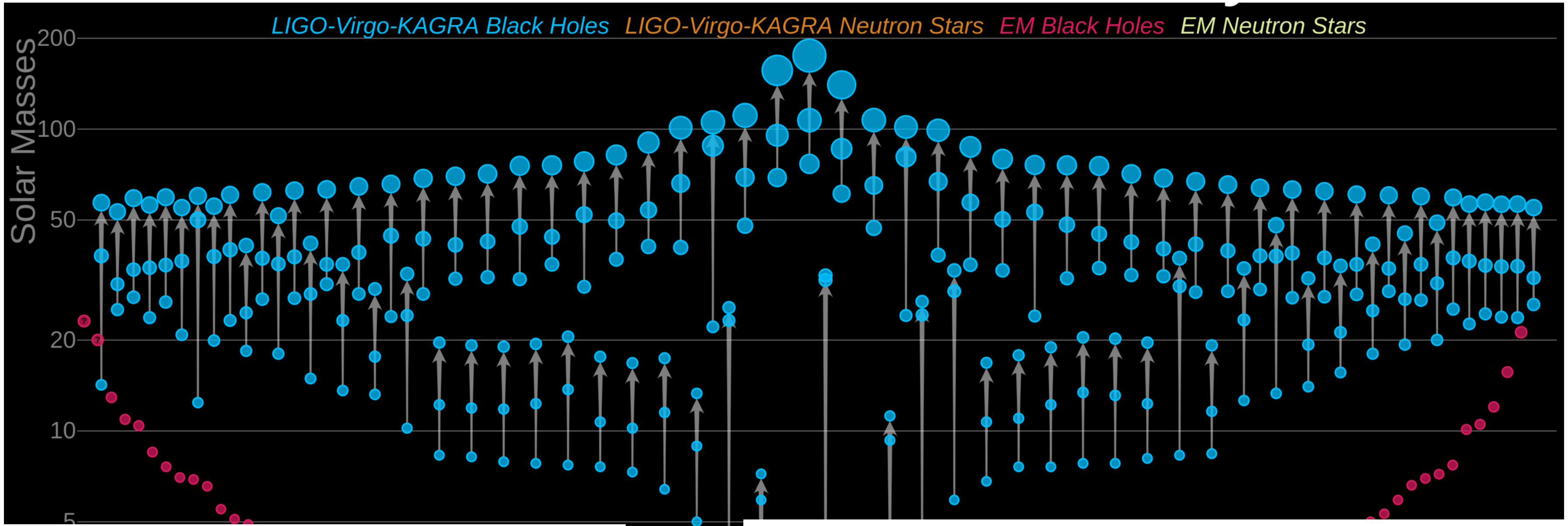
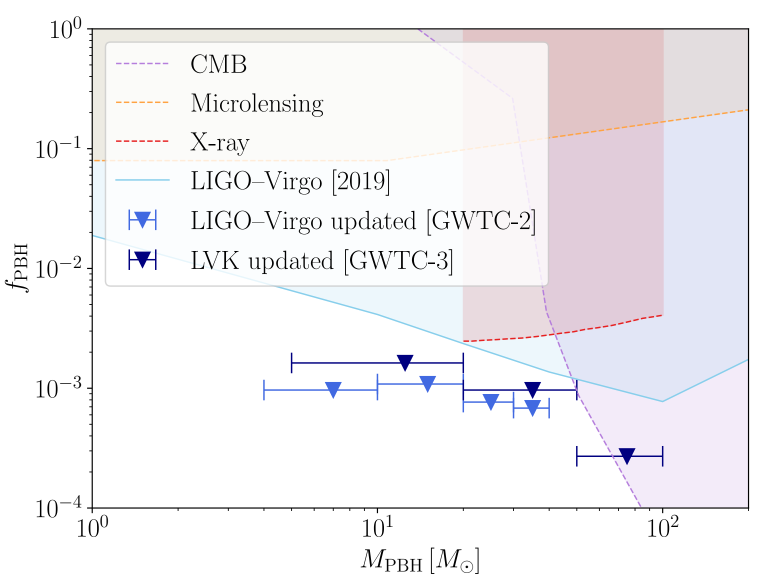
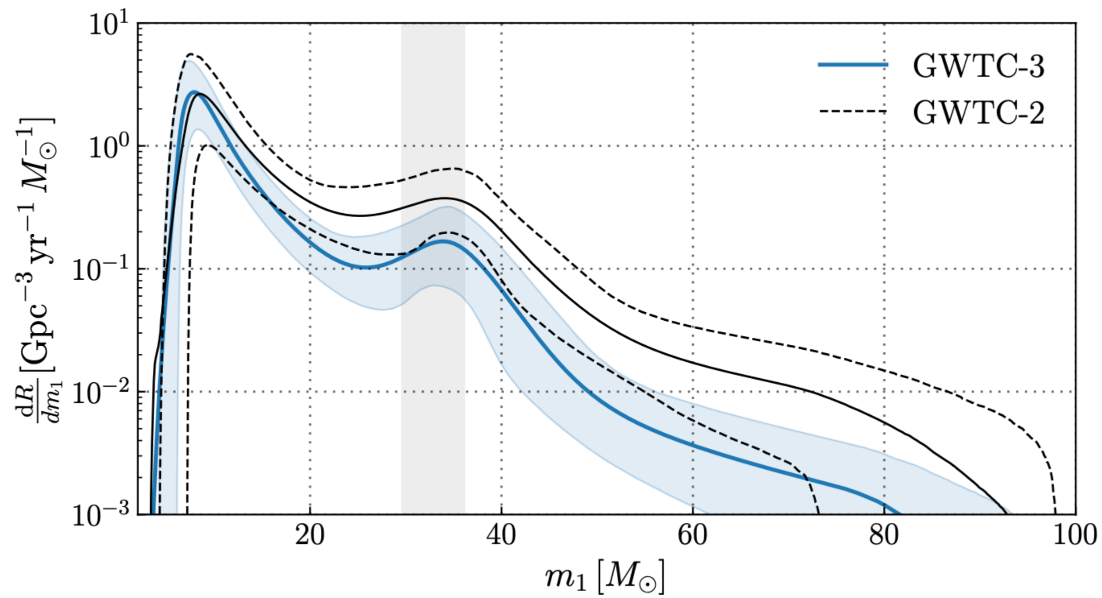
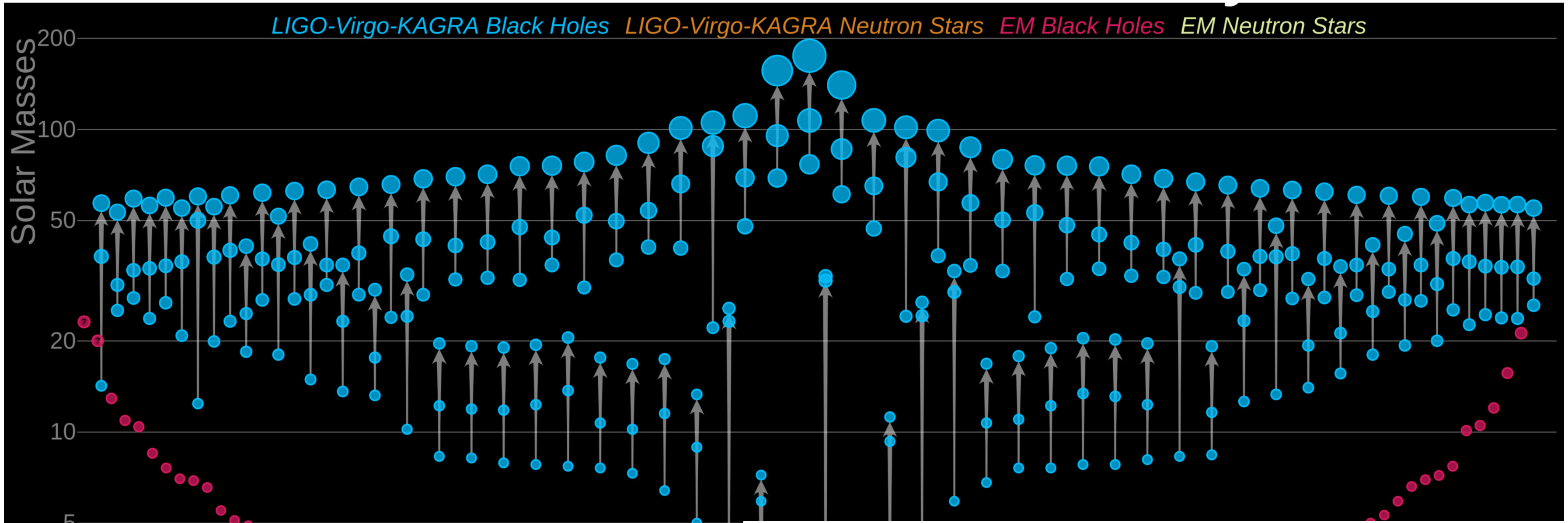
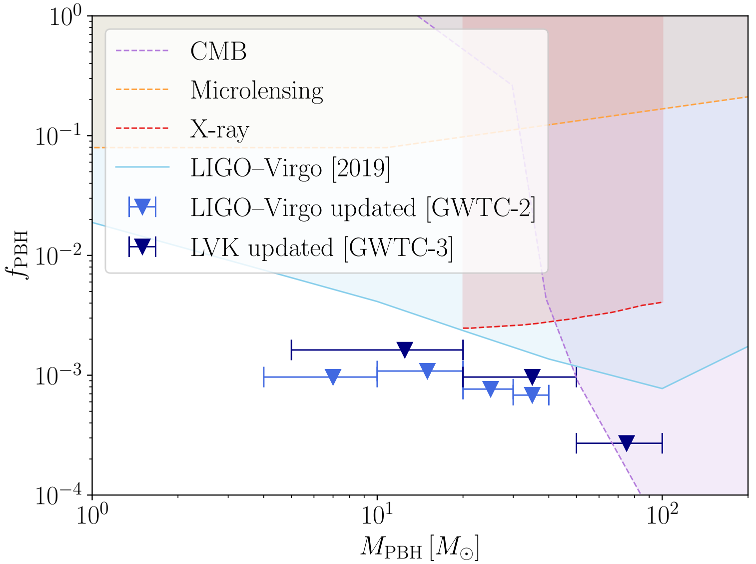
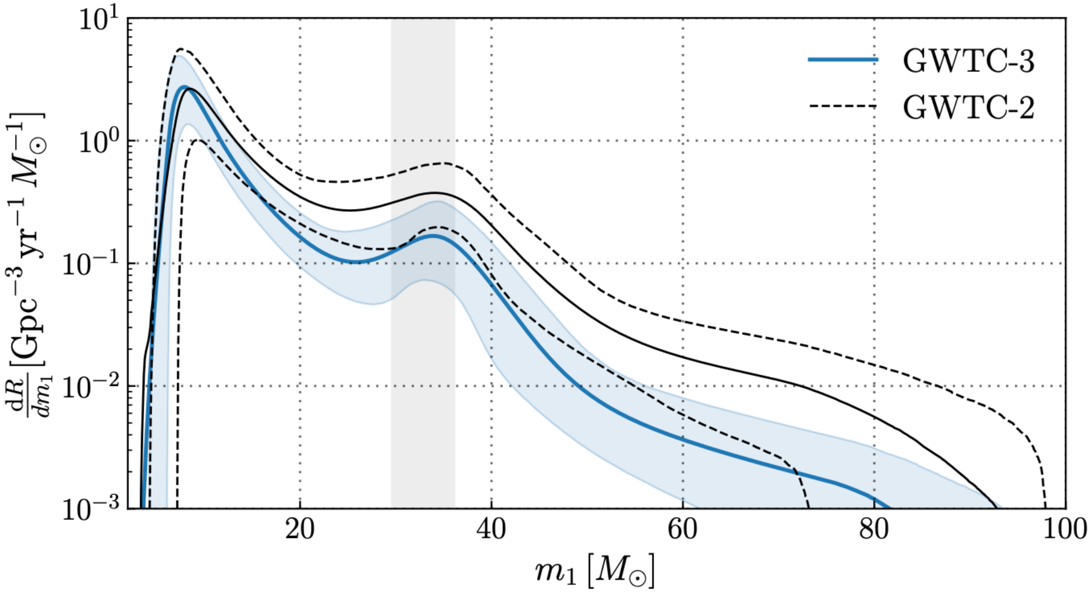

LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
-KAGRA


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


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



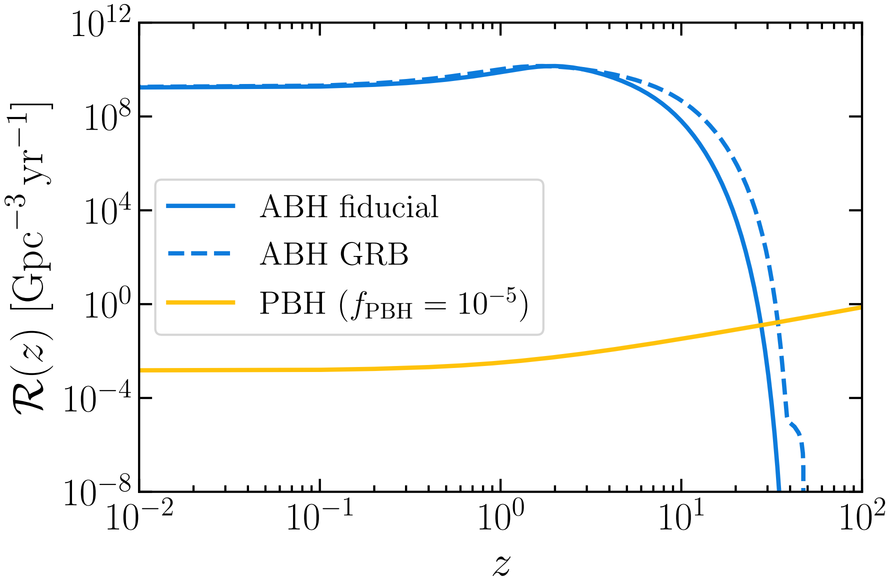


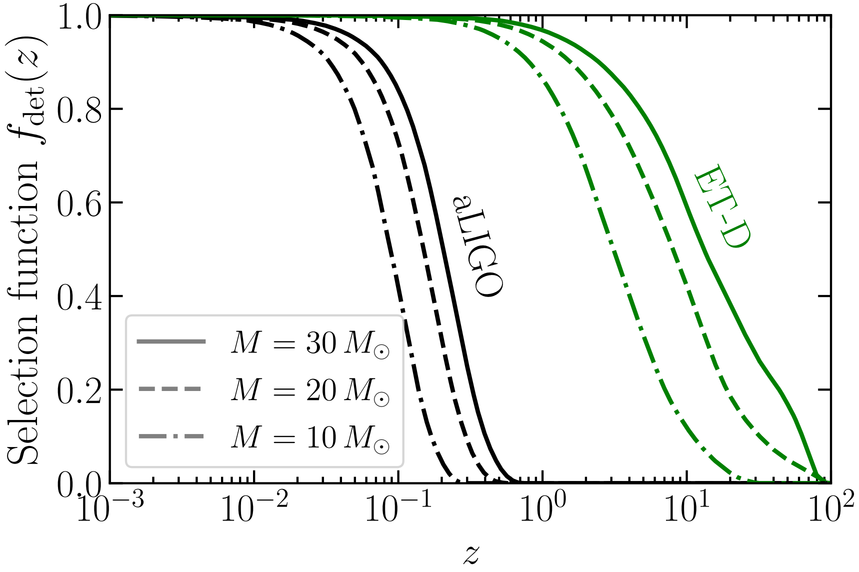


Clean channel: high redshift (***no astrophysical*** background)

Prospects for the Einstein Telescope

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



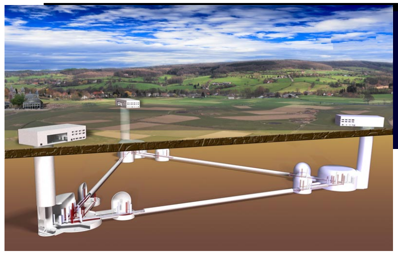


Forecast for Einstein telescope to asses:

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

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

➡ ***Simulate*** PBH merger events and ***detector's response***



ET mock data generation

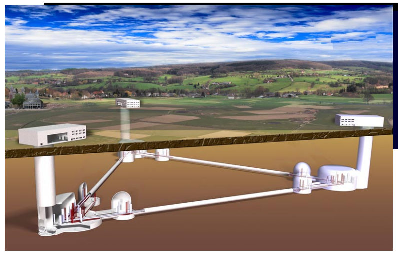
gitlab.com/matmartinelli/darksirens

Sketch of the ***mock data generation*** algorithm:

- 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
- Discard faint events ($\rho_i < 8$)
- Draw ΔD_i ***instrumental error on distance*** from Gaussian
- Extract observed value of D_L
- Obtain error on D_L including lensing effects

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

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



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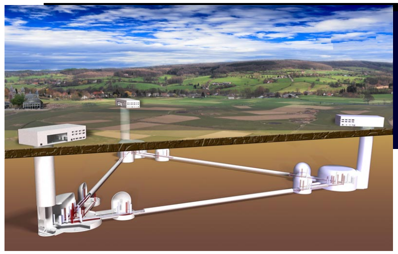
Final result: ***mock catalog*** (D_i, σ_i)



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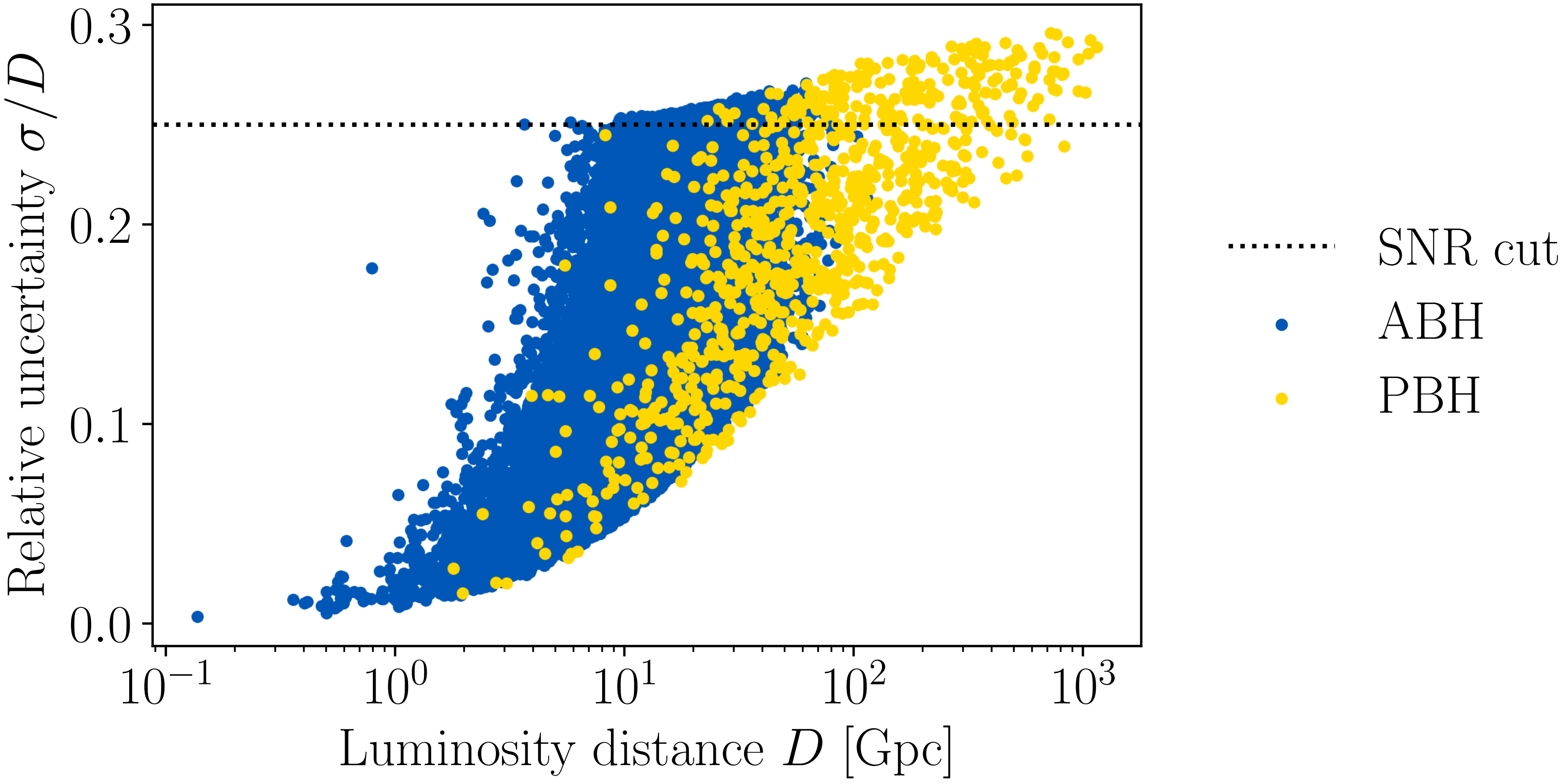
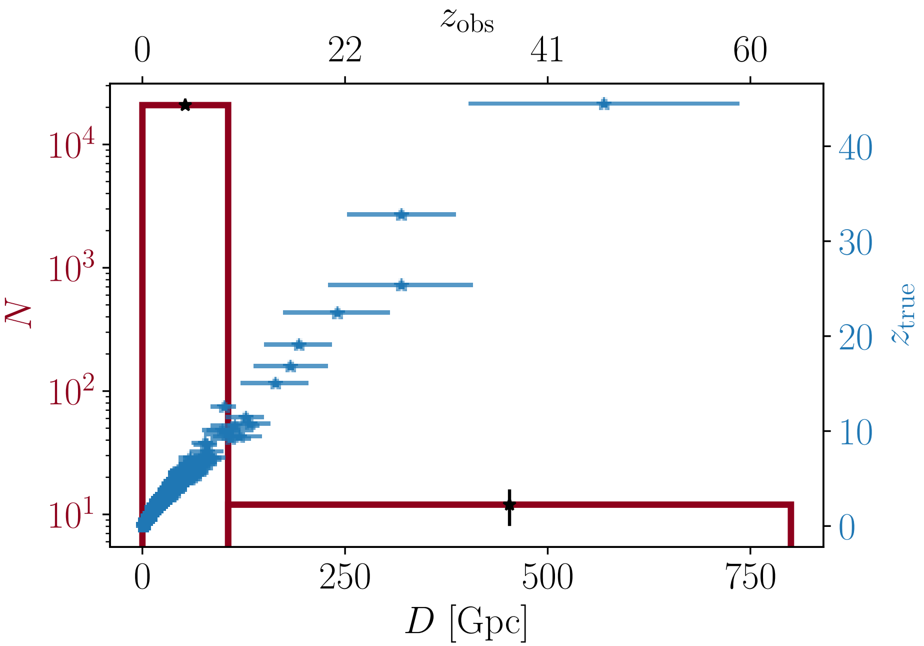


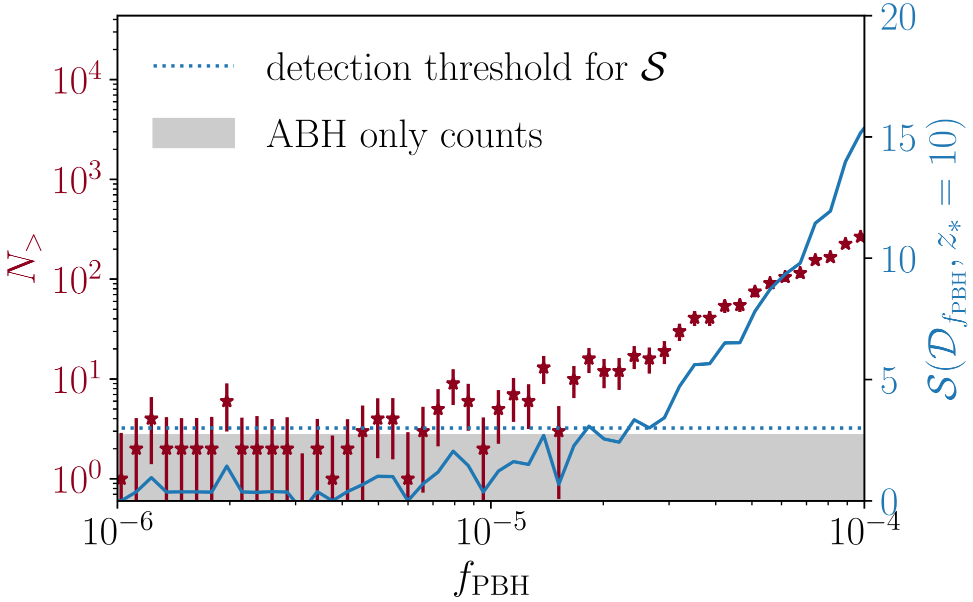
Final result: ***mock catalog*** (D_i, σ_i)

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 → $N_> = 1 \pm 1.7$





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

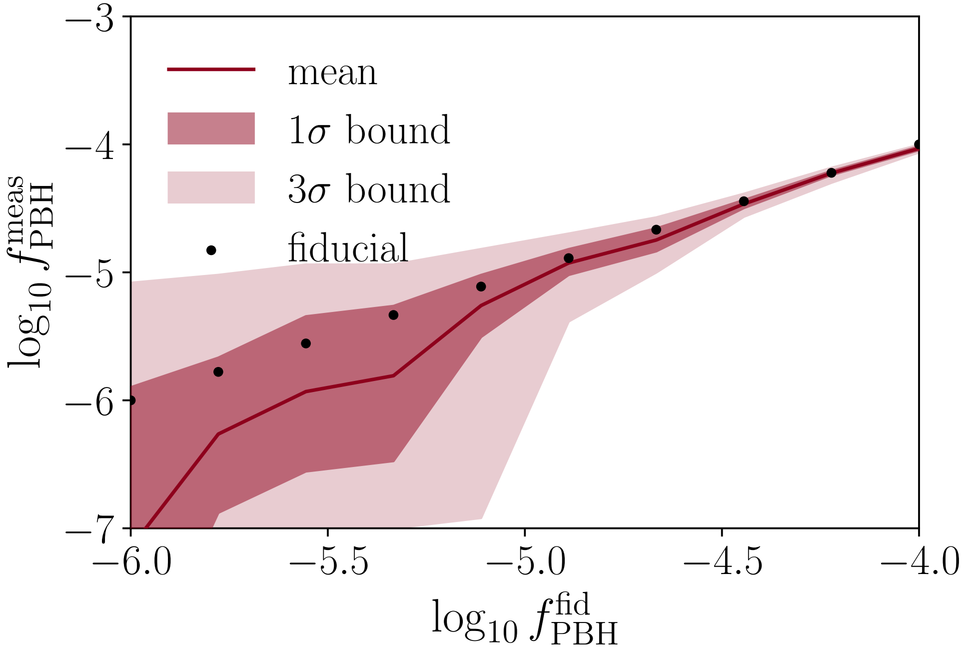
Data analysis - 2

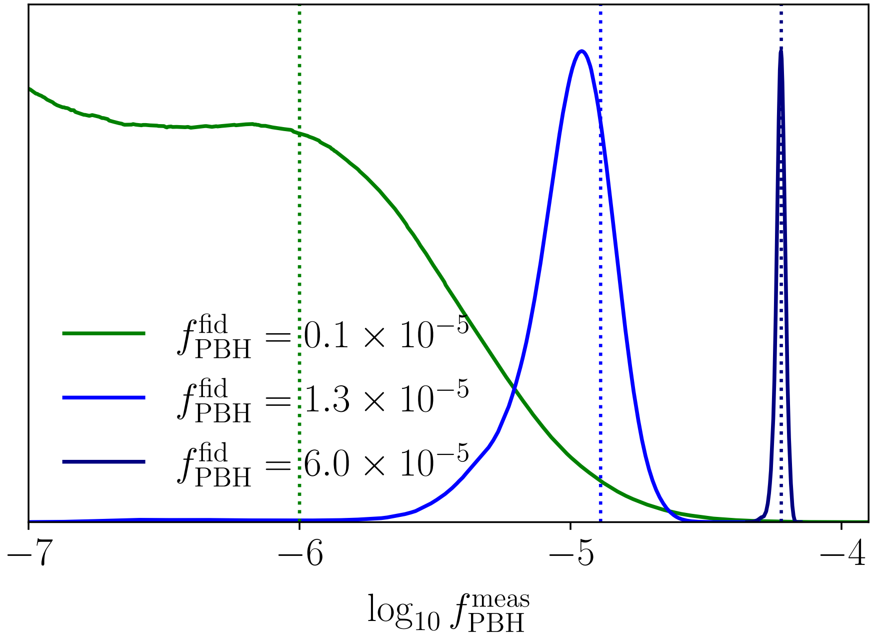
- ***Unbinned likelihood*** - probability of a set of observed events

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

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

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





Data analysis - 2

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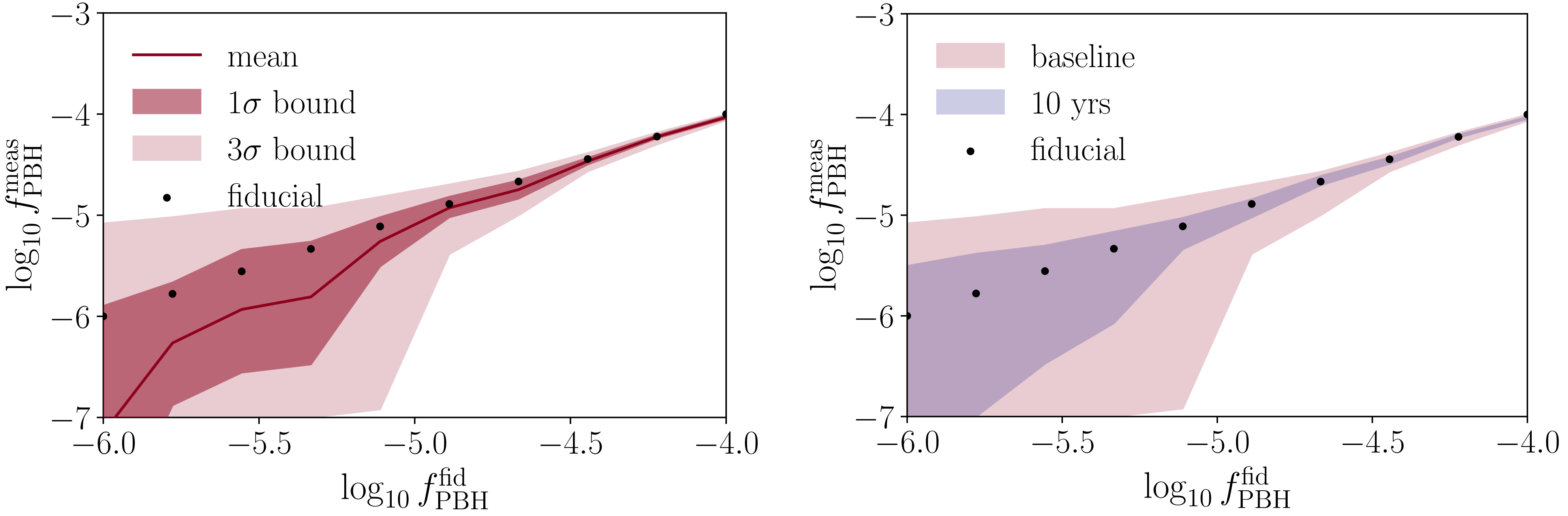
- ***Posterior distribution*** *for* f_{PBH}

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



(2) Summary

- ➡ ***Future GW observatories: powerful tool*** to identify PBH signal
- ➡ Measure PBHs in ***abundance as small as*** $f_{\mathrm{PBH}} \approx 10^{-5}$

Caveats

- ➡ ***Signal*** modelling (mass function, initial clustering, …)
- ➡ Astrophysical ***background*** (pop III stars)

- ➡ Provided a ***public tool*** for generation of GW mock data

gitlab.com/matmartinelli/darksirens

Thank you