Alexandre Toubiana

LISA astrophysics WG meeting, 05/11/2024

Towards LISA population study

Based on

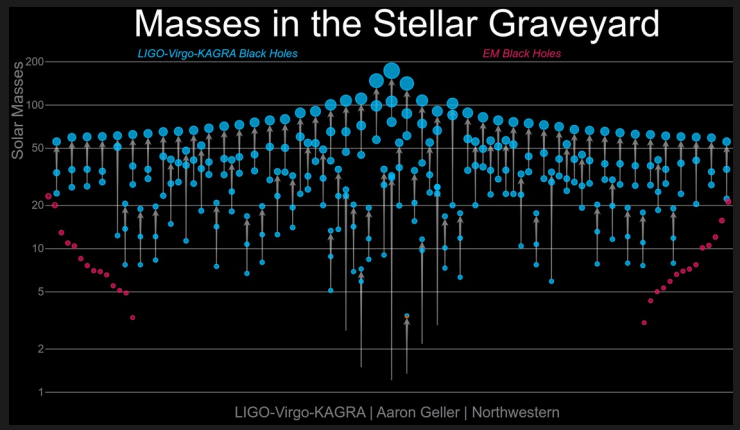
Toubiana, Karnesis, Lamberts, Miller A&A 2024

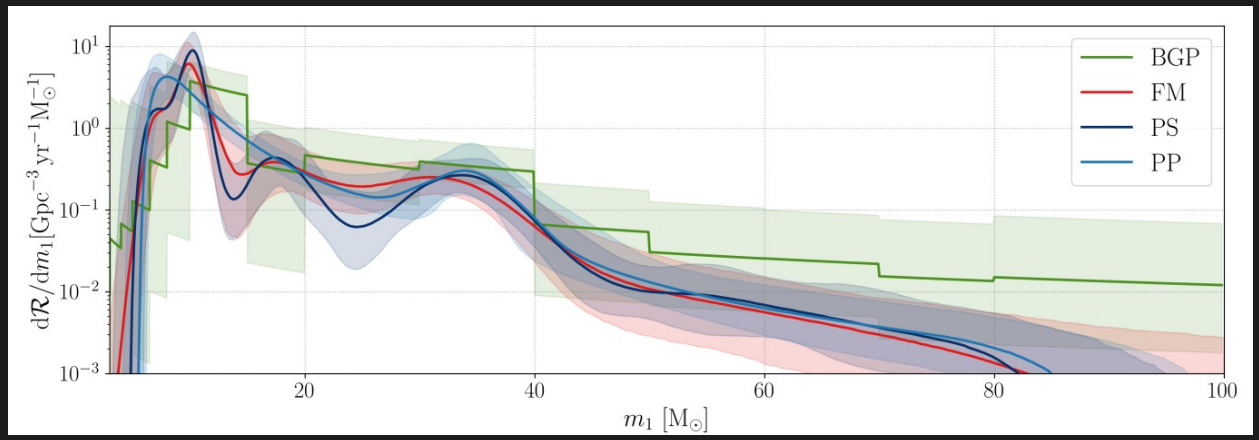
Toubiana, Sberna, Volonteri, Barausse, Babak, Enficiaud, Izquierdo-Villalba, Gair, Greene, Quelquejay Leclere astro-ph.GA:2410.17916

Toubiana, Gair, ongoing

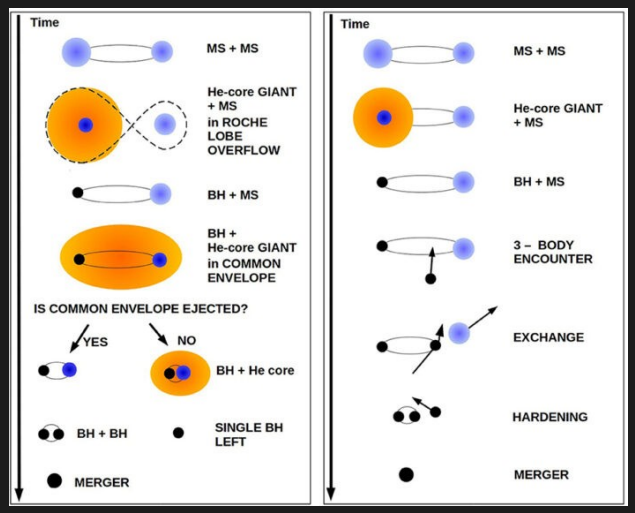
Santini, Karnesis, Toubiana, ongoing

Population studies





LVK, PRX 2023

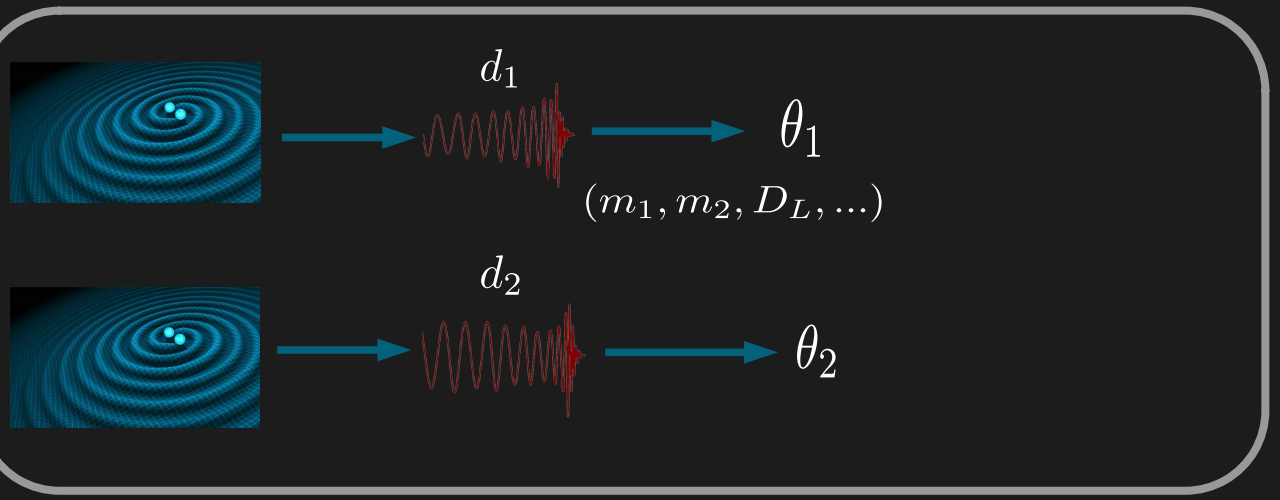


Mapelli, Front. Astron. Space Sci. 2020

Extract global properties of observations to allow the astrophysical interpretation

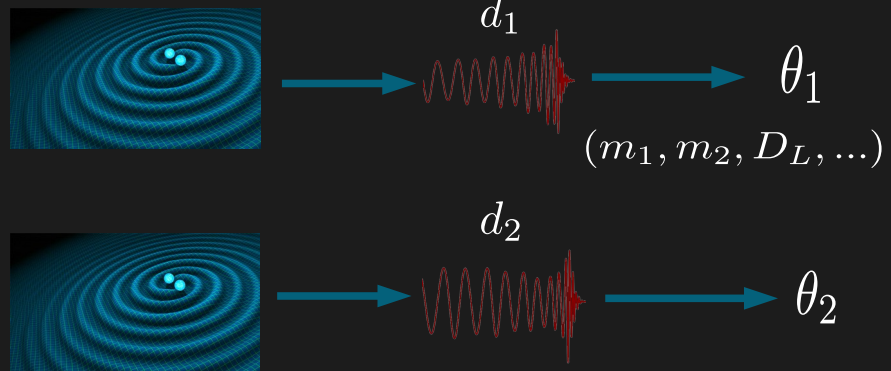
Steps for population studies

Parameter estimation

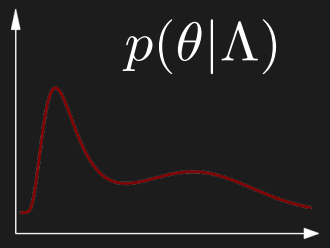


Steps for population studies

Parameter estimation



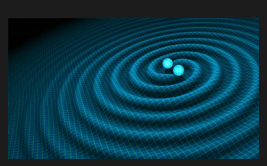
Population model



- astrophysical
- agnostic (parametric/non-parametric)

Steps for population studies

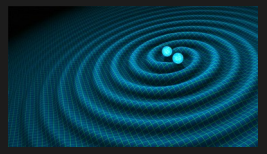
Parameter estimation



d_1

θ_1

$(m_1, m_2, D_L, ...)$



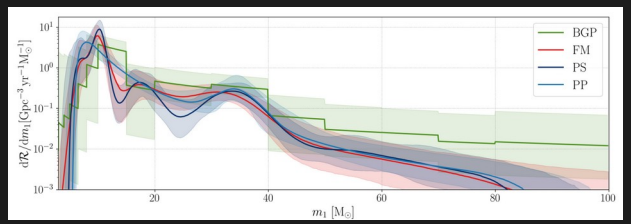
d_2

θ_2

$\{d_1, d_2, ...\}$

Hierachical Bayesian analysis

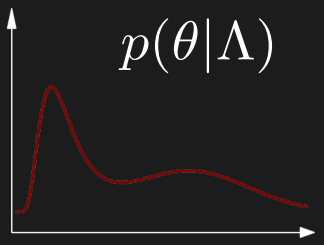
$p(\Lambda|\{d_1, d_2, ...\})$



LVK, PRX 2023

Population model

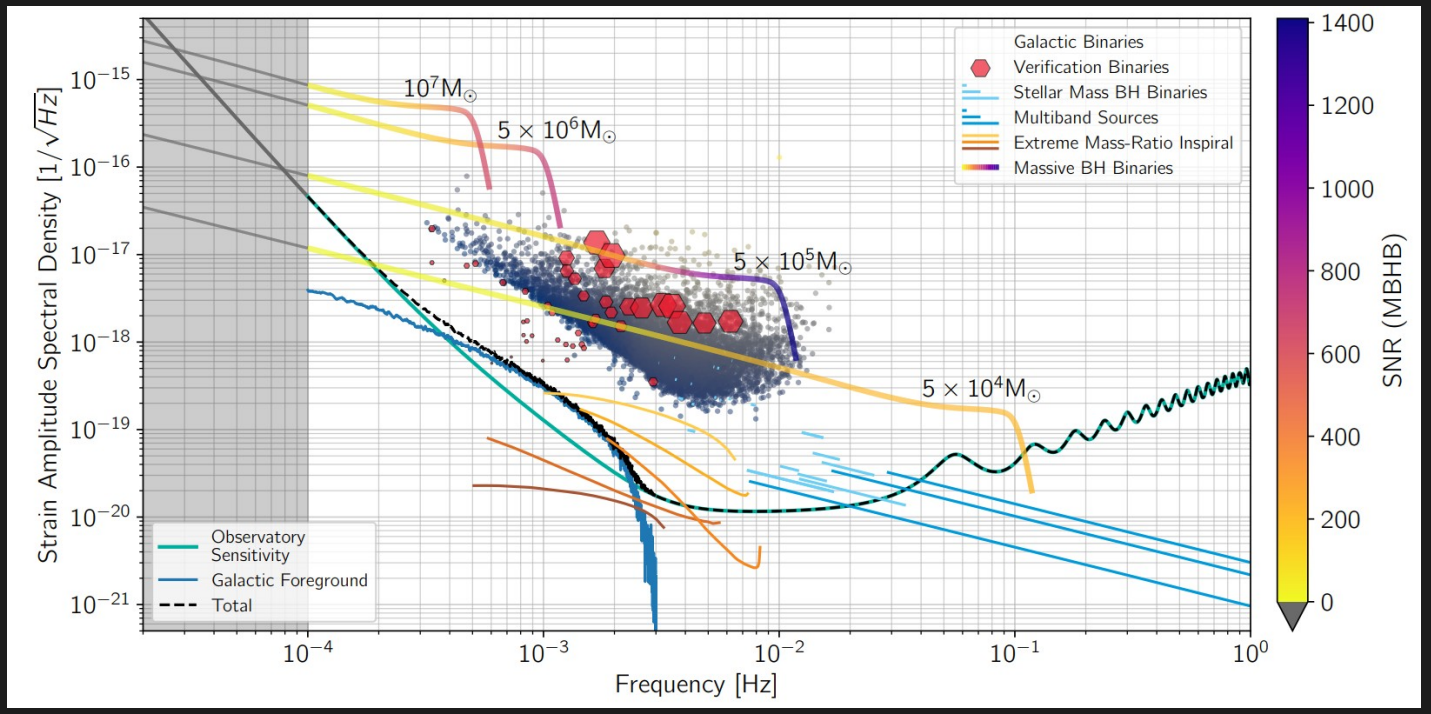
$p(\theta|\Lambda)$



- astrophysical
- agnostic (parametric/non-parametric)

+ selection effects

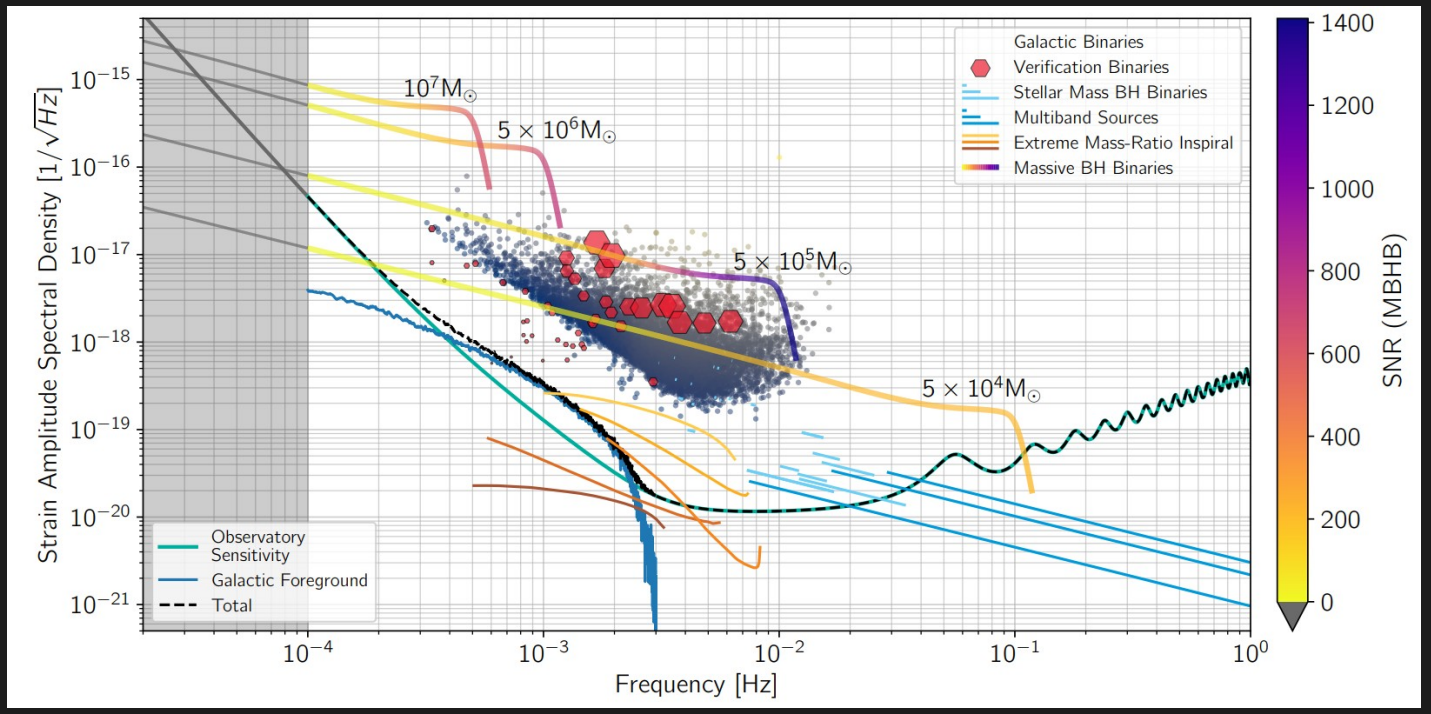
Challenges for LISA



LISA Redbook, 2024

- Lack of parametrised description of population of sources $p(\theta|\Lambda)$

Challenges for LISA



LISA Redbook, 2024

- Lack of parametrised description of population of sources $p(\theta|\Lambda)$
- Need to fit data all together (Global Fit), problem for hierarchical analysis:
  - signals are not independent
  - variable number of sources
  - selection function?

Massive black hole binaries

- Cosmological and semi-analytic models: explore impact of physical assumptions but high computational cost

- Toubiana+ PRD 2021: using a finite discrete set of model to describe the population can lead to biases

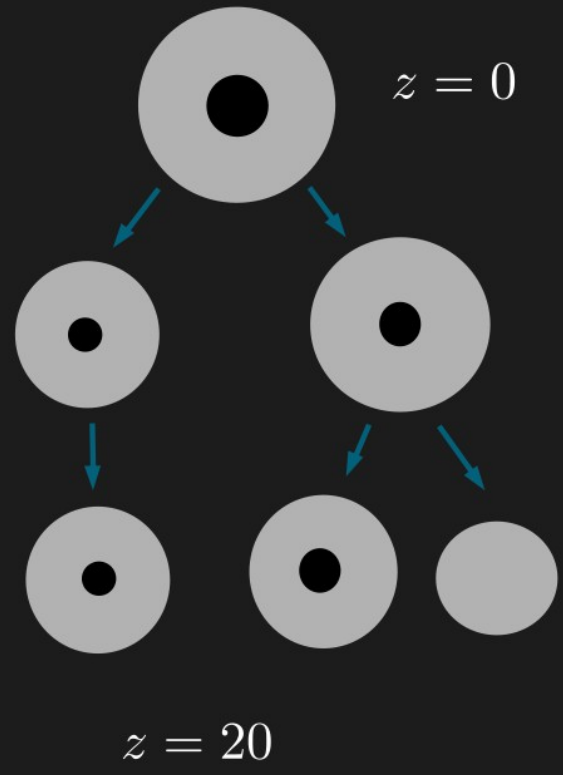
- Goal: develop a framework to describe the formation and evolution of massive black holes suited for analysing data (see also Langen, Tamanini, Marsat, Bortolas 2024)

Parametric model for massive black holes

POMPOCO: Parametrisation Of the Massive black hole POpulation for Comparison to Observations

(Toubiana, Sberna, Volonteri, Barausse, Babak, Enficiaud, Izquierdo-Villalba, Gair, Greene, Quelquejay Leclere astro-ph.GA:2410.17916)

- Press-Schechter for halo merger trees and parametric prescriptions for seeding, accretion and mergers



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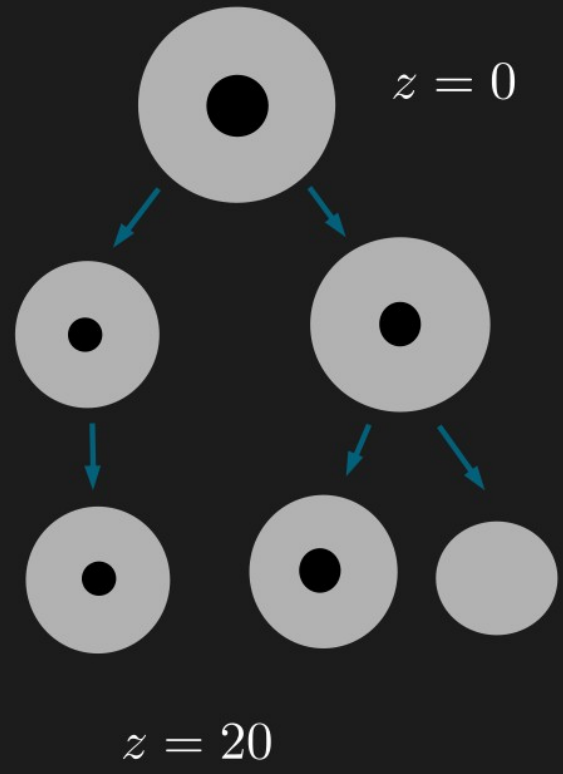
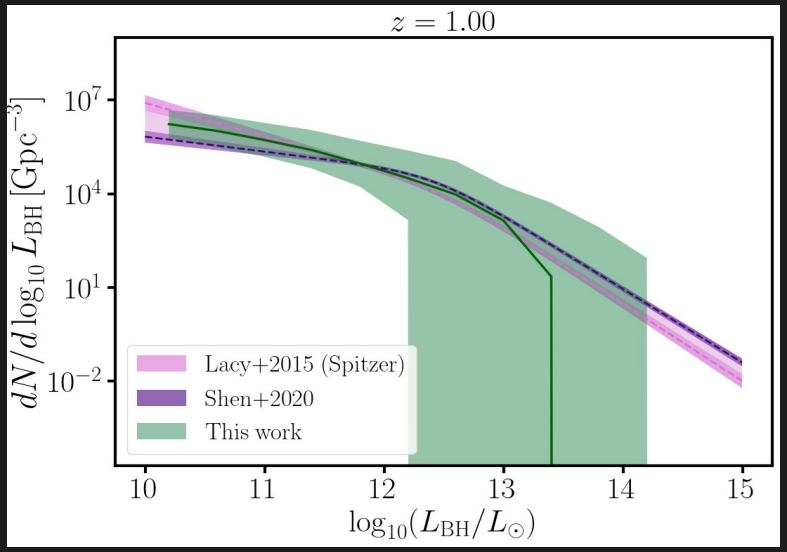
- Press-Schechter for halo merger trees and parametric prescriptions for seeding, accretion and mergers

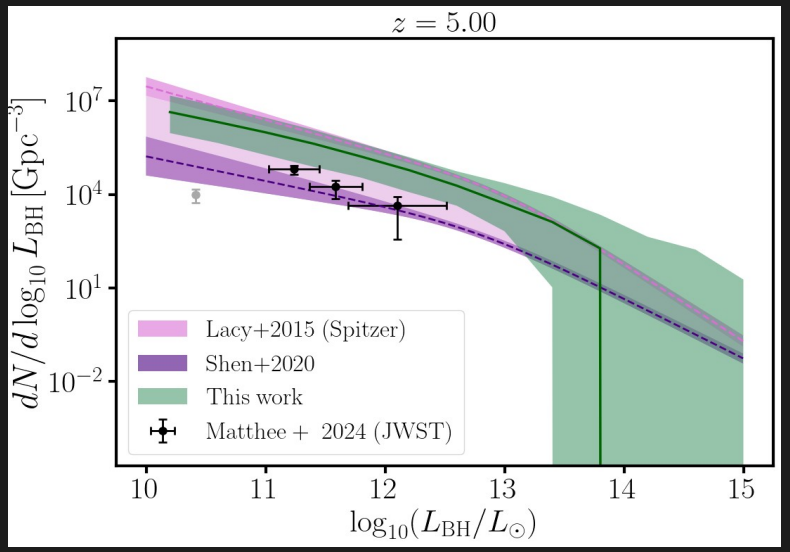
- Assess compatibility between electromagnetic observations and PTA GW spectrum, full Bayesian analysis gives posterior on the 12 parameters of POMPOCO



Results of POMPOCO



MBH luminosity distribution in the nearby Universe



MBH luminosity distribution in the distant Universe (JWST)

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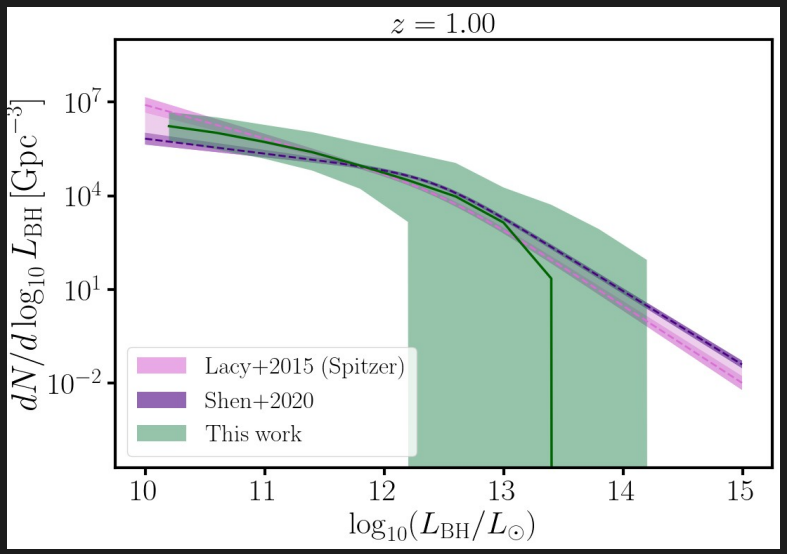

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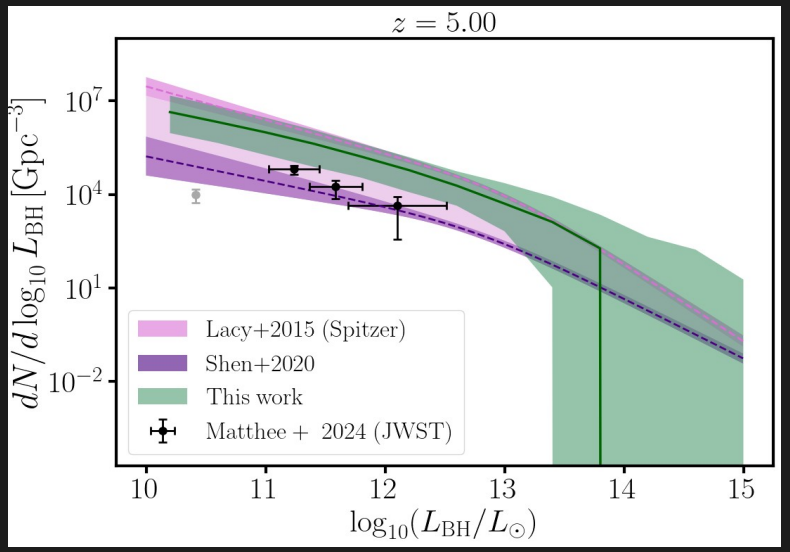

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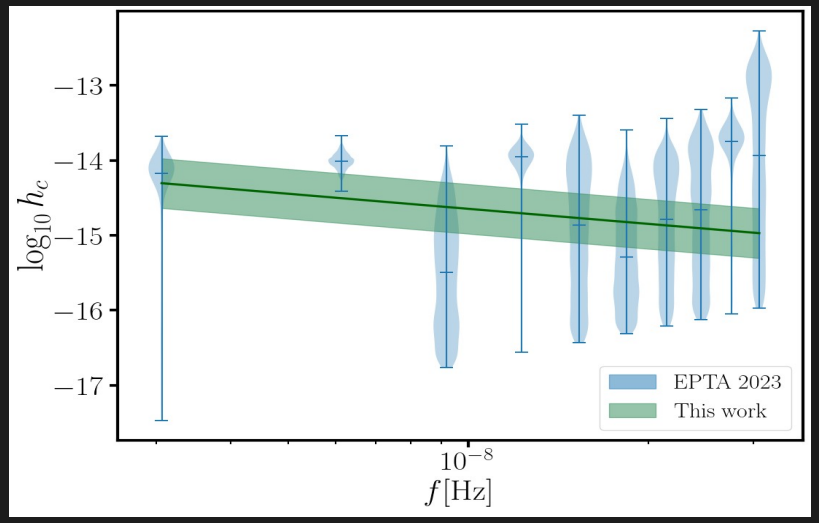

Pulsar Timing Array spectrum

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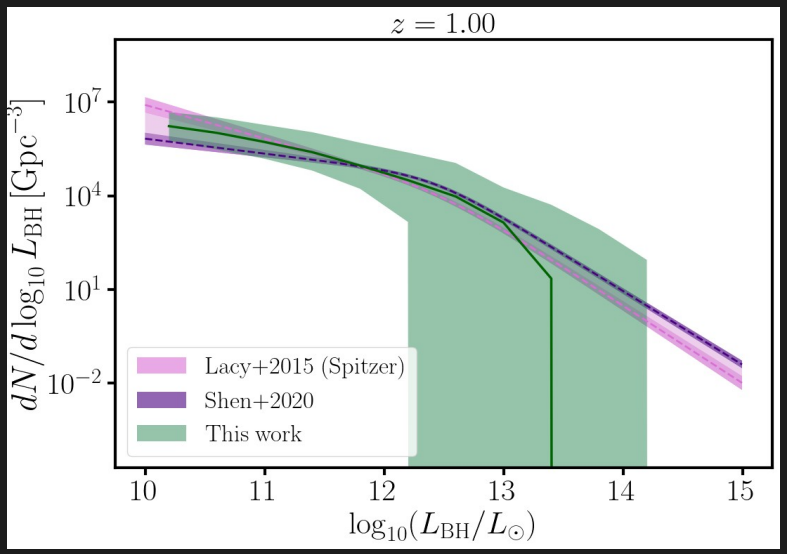

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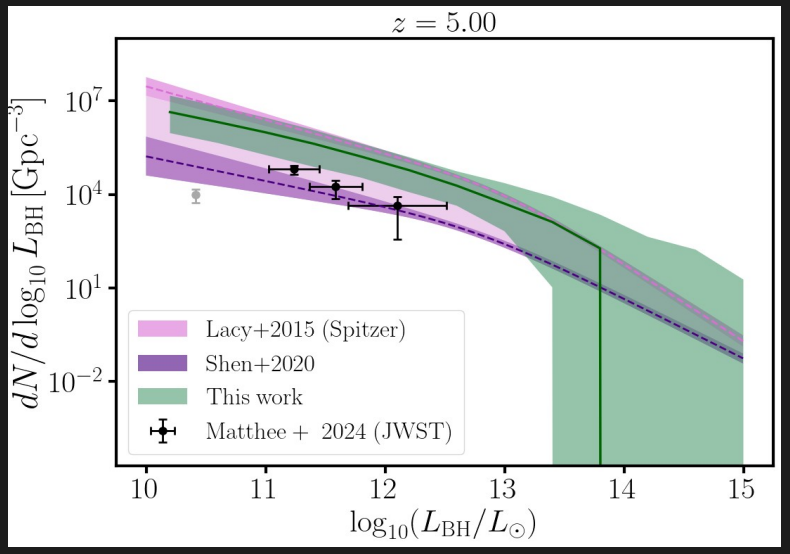

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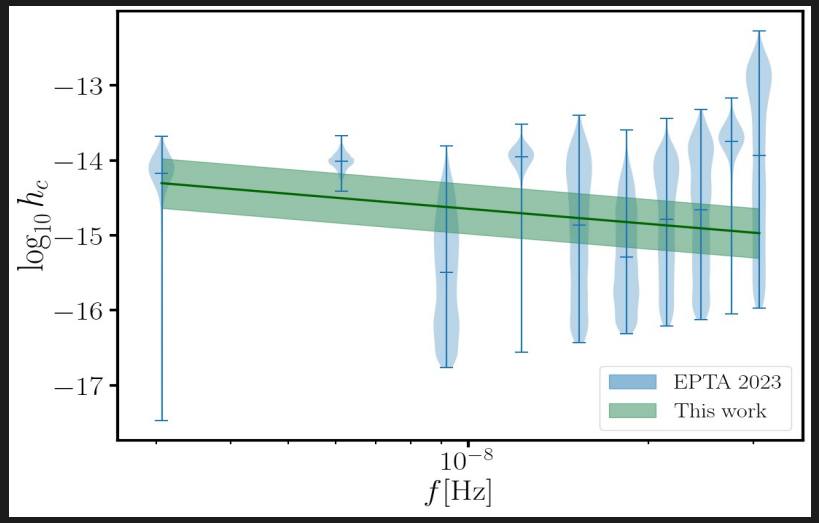

Pulsar Timing Array spectrum

LISA predictions very broad

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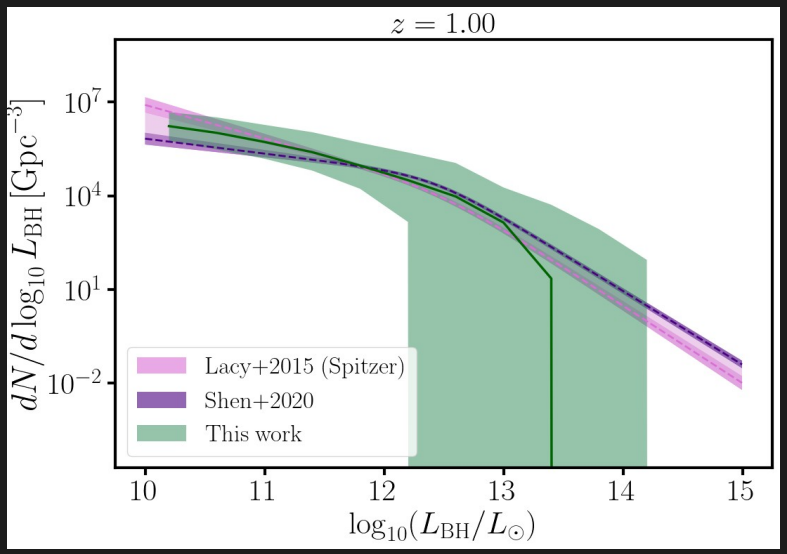

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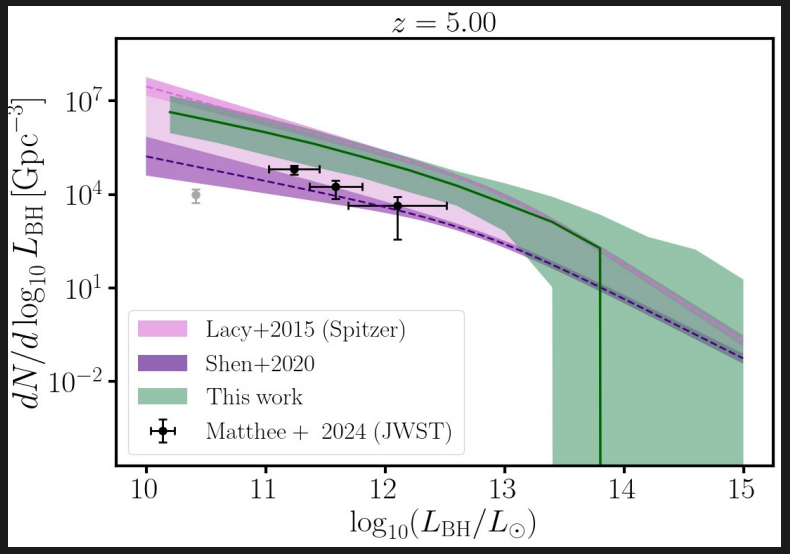

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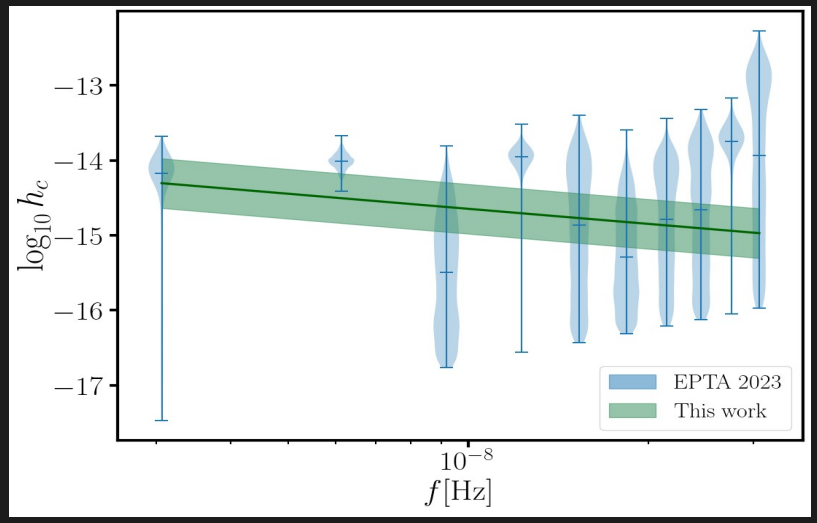


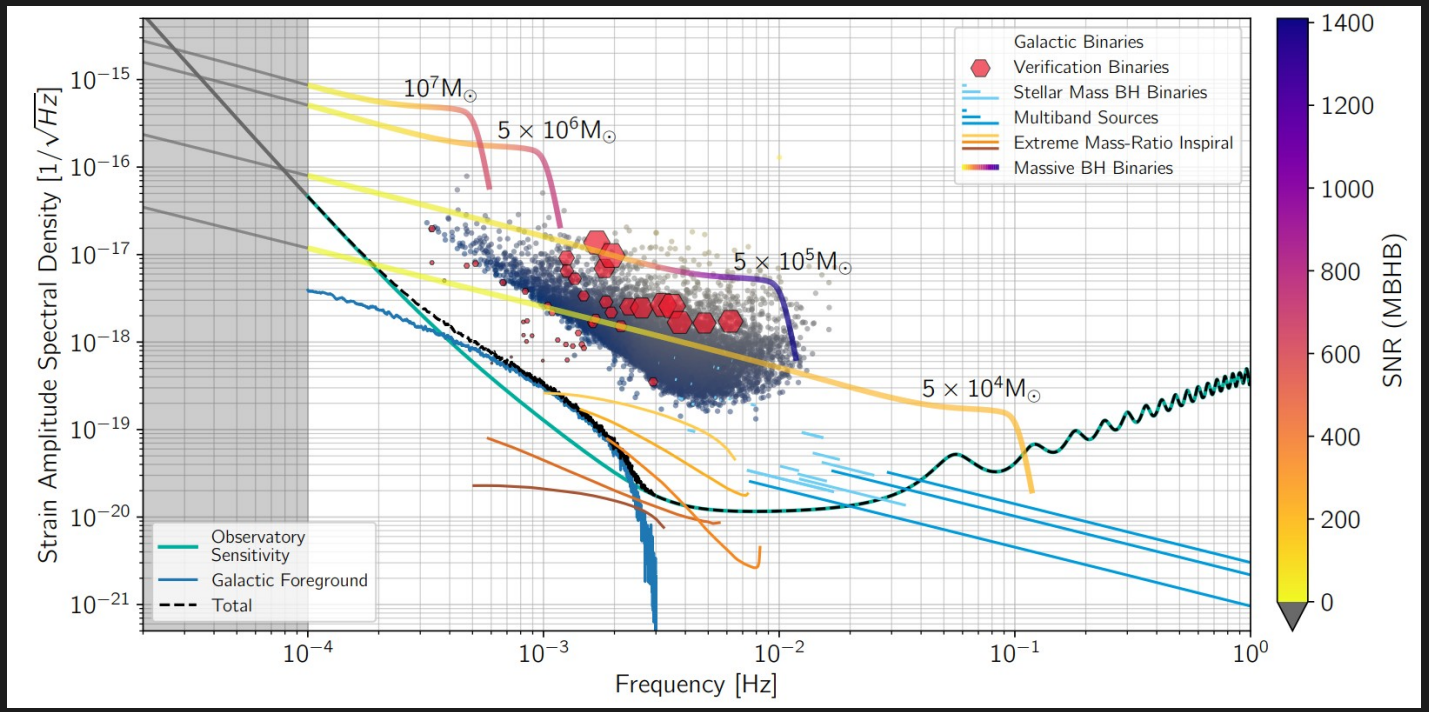
Pulsar Timing Array spectrum

LISA predictions very broad

Next:

- Refine model
- Include spins/eccentricity
- Mock LISA analysis

Double white dwarfs



LISA Redbook, 2024

- Stochastic foreground + resolvable population
- Impact of tidal effects and mass transfer?

  Toubiana, Karnesis, Lamberts, Miller A&A 2024

Evolution of double white dwarfs

- Semi-analytic model for the evolution of DWDs after formation (provided by Astrid Lambert’s simulation)
- Includes the effect of GWs, tides, mass-transfer

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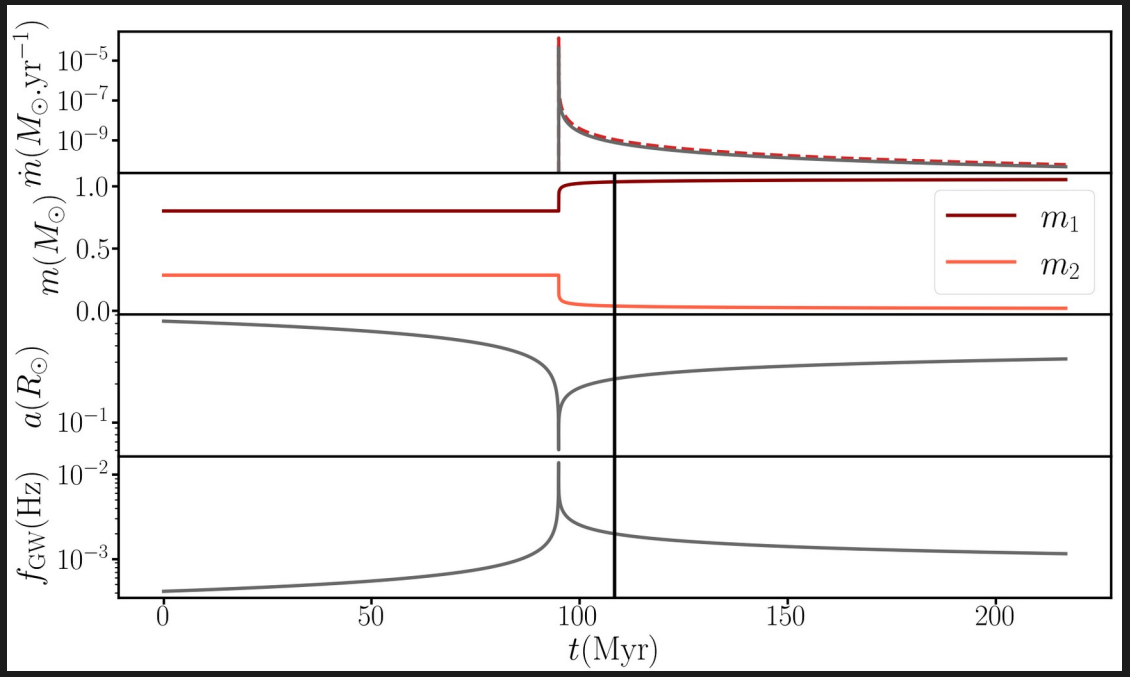

Separation evolution

Evolution of double white dwarfs

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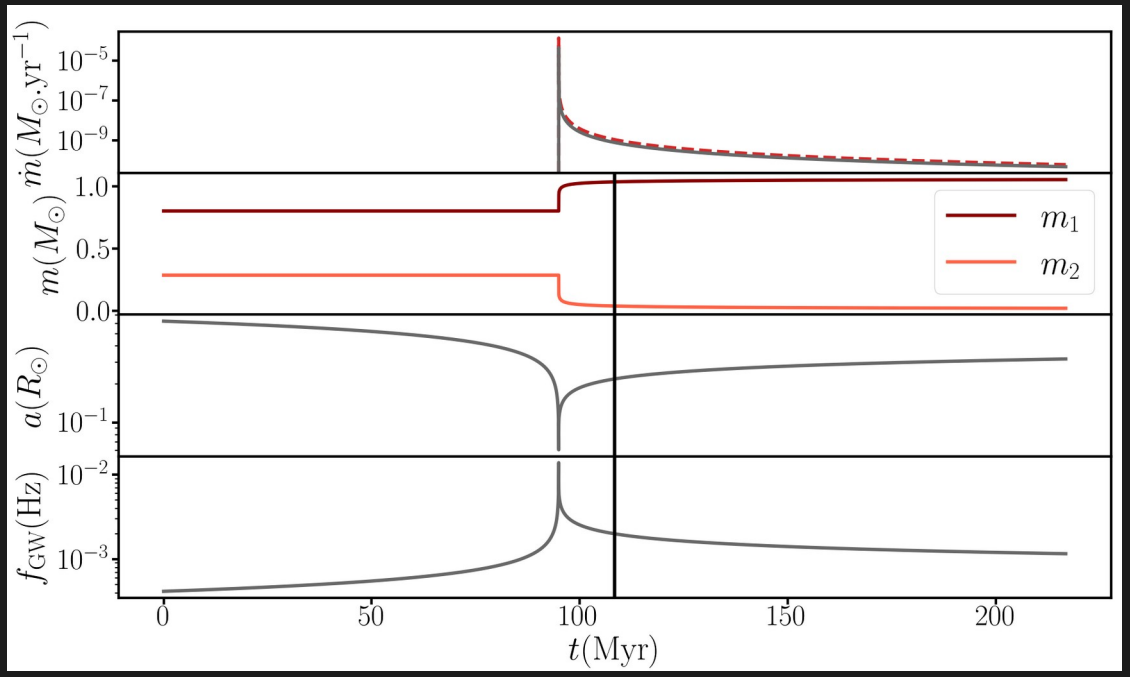
- Includes the effect of GWs, tides, mass-transfer



Mass-transfer rate

Masses evolution

Separation evolution

Evolution of double white dwarfs

- Semi-analytic model for the evolution of DWDs after formation (provided by Astrid Lambert's simulation)
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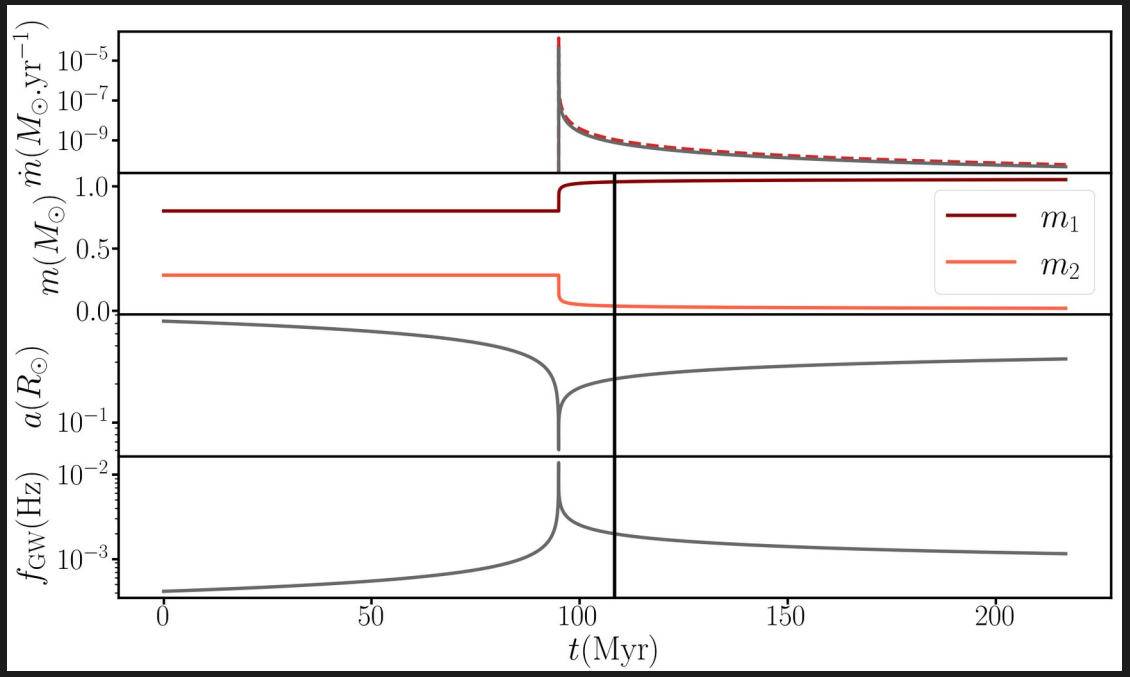

Mass-transfer rate

Masses evolution

Separation evolution

GW frequency evolution

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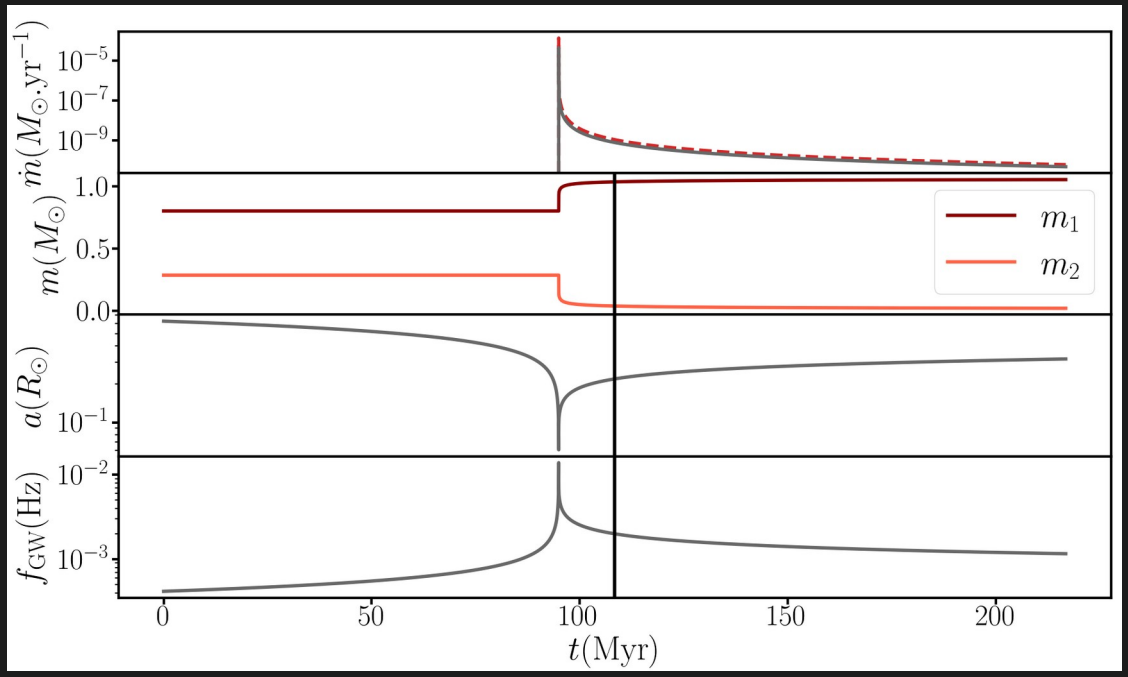


Mass-transfer rate

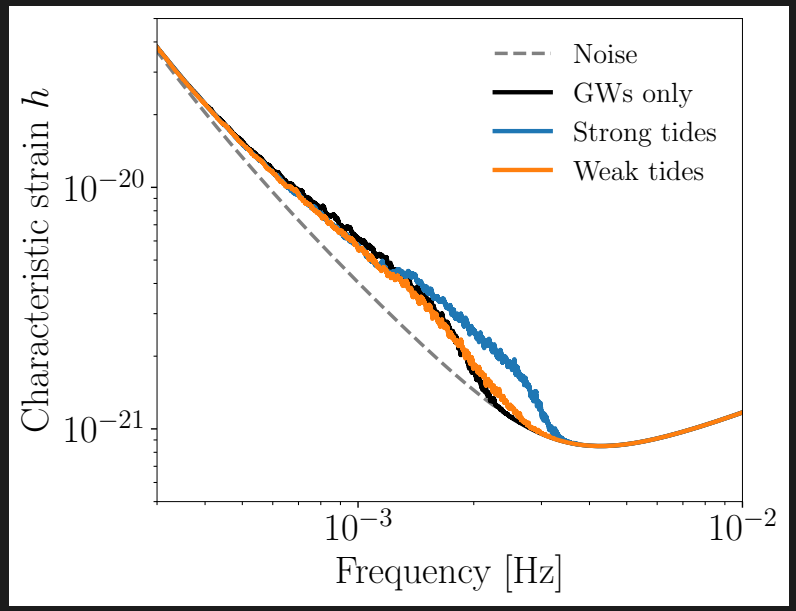
Masses evolution

Separation evolution

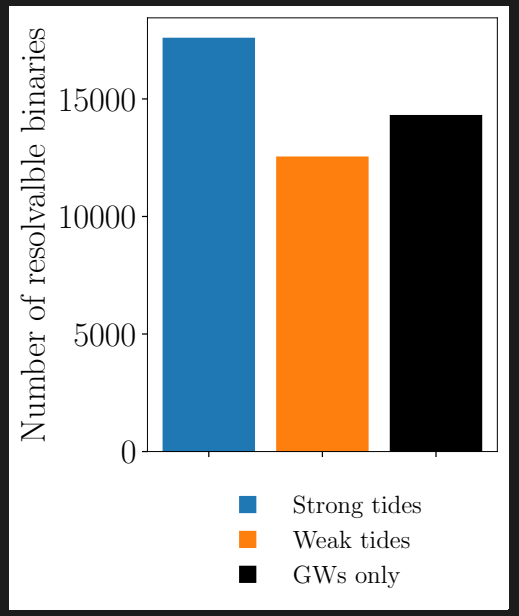
GW frequency evolution

- Tides help the binaries "survive" mass transfer

Impact on LISA observations



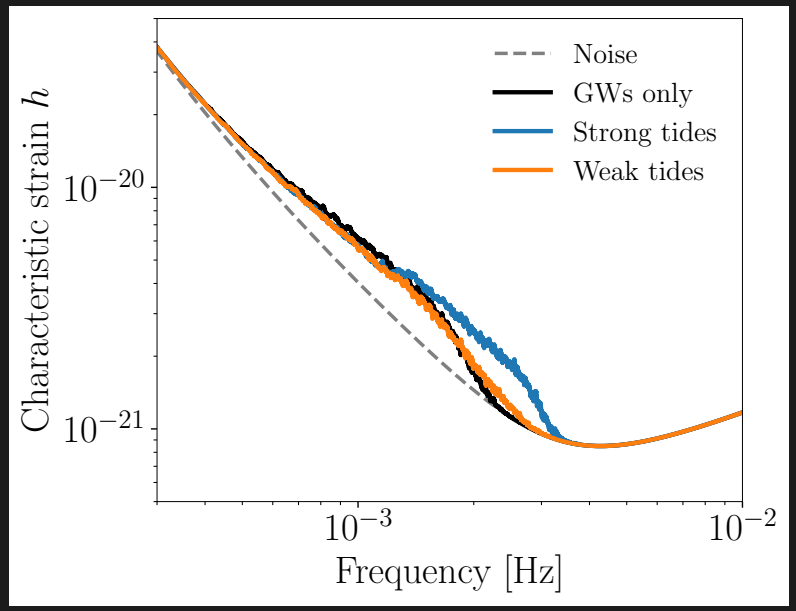
Total noise



Number of resolvable sources

- Foreground can be used to measure intensity of tidal effects (Santini, Toubiana, Karnesis, on going). Other astrophsysical features?

Impact on LISA observations



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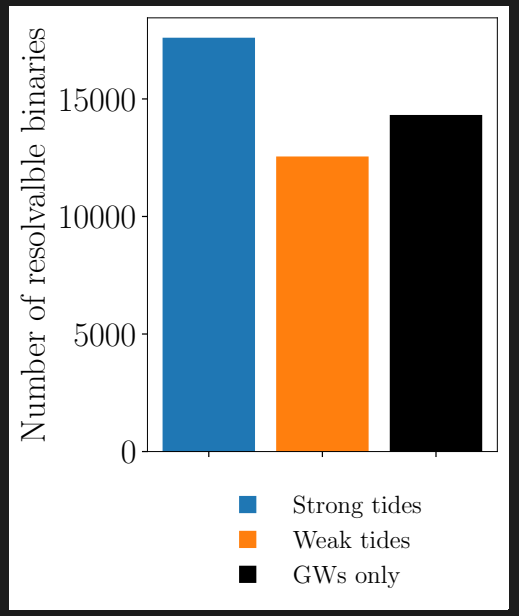


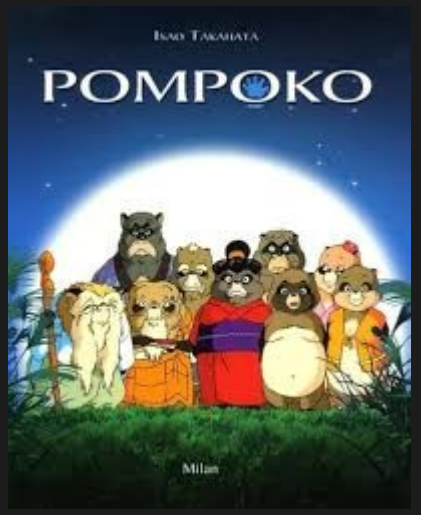
Number of resolvable sources

- Foreground can be used to measure intensity of tidal effects (Santini, Toubiana, Karnesis, on going). Other astrophsysical features?
- Combine foreground and resolvable sources for population study (Toubiana, Gair, on going):
  - inverse-mapping from foreground to underlying population?
  - “Selection function”?
  - confusion between populations?

Conclusions

“New” and numerous sources in LISA require new modelling and analysis techniques. Many challenges to be tackled!

POMPOCO, credits: L. Sberna

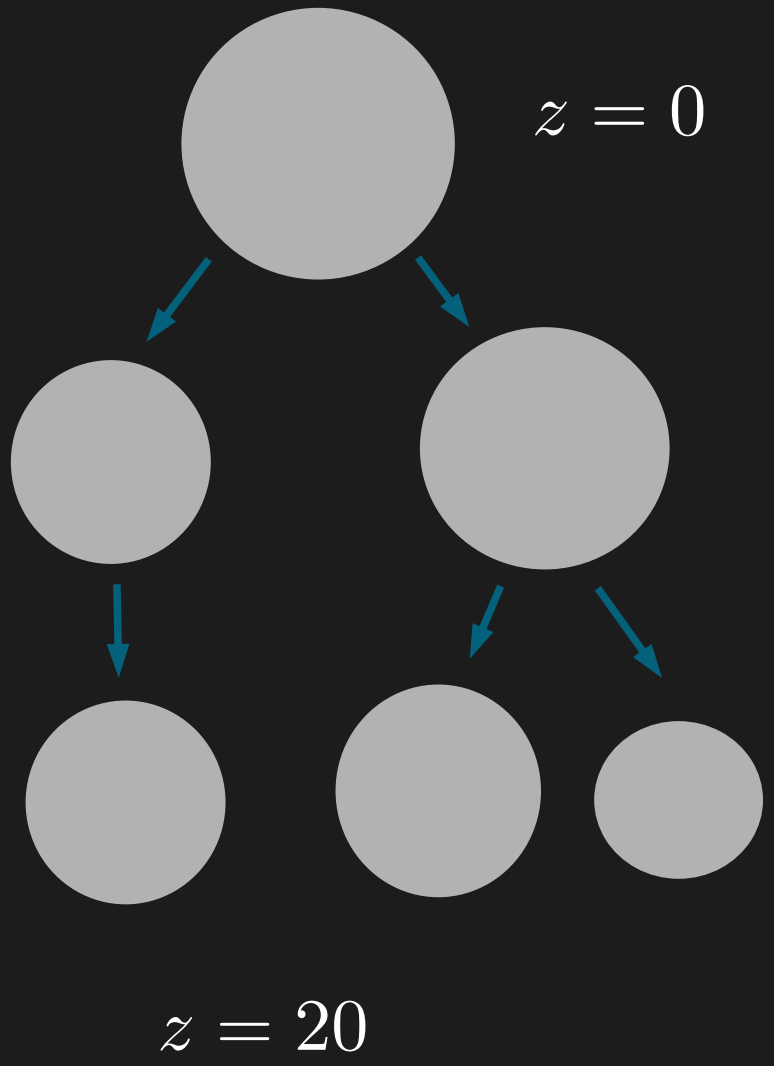


POMPOKO, credits: Studio Ghibli

Thank you for your attention!

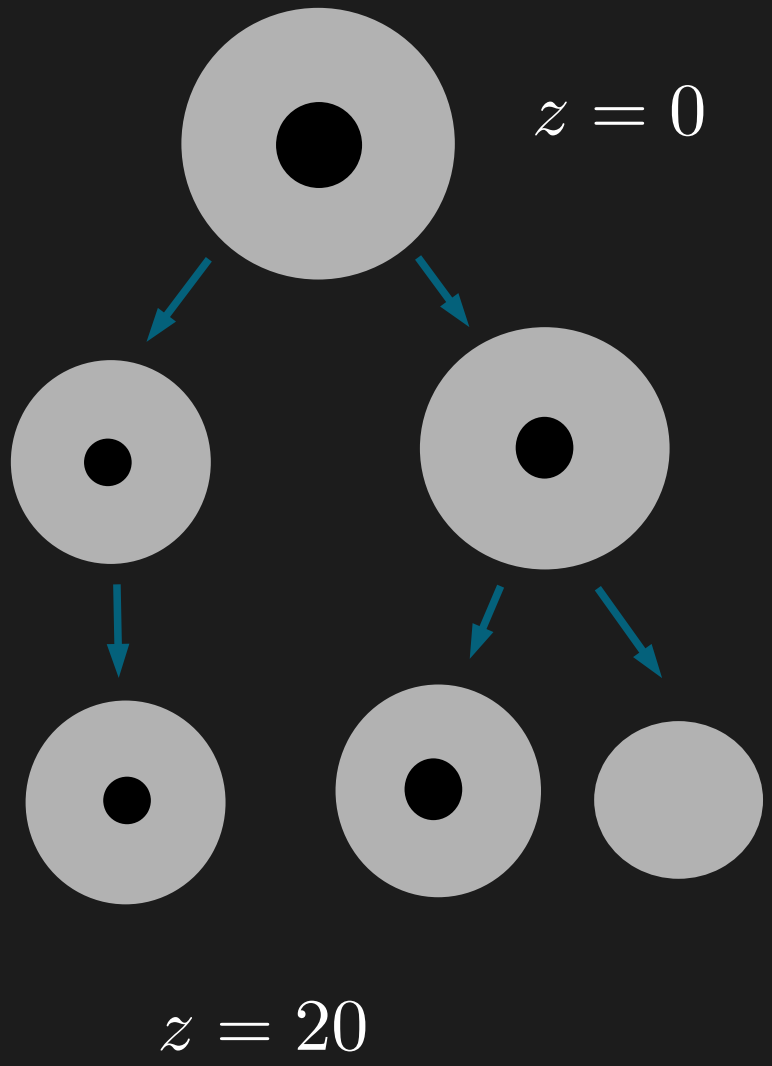
Merger tree

- Extended Press-Schechter (Parkison+2007)



Merger tree

- Extended Press-Schechter (Parkison+2007)
- Evolve MBHs using parametric prescriptions instead of semi-analytic ones
- Gain in computational power



Seeding

- Seed leaf halos at $z \geq 10$ with $M_{\mathrm{halo}} > M_{\mathrm{cut}}$ with probability f_{BH}

- Draw mass from log-normal distribution

$$\mathcal{N}(\log(\mu_0), \sigma_m)$$

- Limit to 10% of baryonic mass of halo

Accretion

$$\dot{m} = f_{\rm Edd}(1-\epsilon)\dot{m}_{\rm Edd},\ \epsilon = 0.1$$

- Two accretion modes:
  - steady mode: draw $f_{\rm Edd}$ every $T_{\rm steady}$

$$p(\log_{10} T_{\rm steady}) = \mathcal{U}[10^{-3}, 0.5]{\rm Gyr}$$

$$p(f_{\rm Edd}) \propto f_{\rm Edd}^{\gamma_{\rm steady}-1}, f_{\rm Edd} \in [10^{-4}, 1]$$

  - burst mode: draw $f_{\rm Edd}$ after major halo merger ($q_h > 0.13$), valid for time $t_{\rm burst}$

$$p(f_{\rm Edd}) \propto f_{\rm Edd}^{\gamma_{\rm burst}-1}, f_{\rm Edd} \in [10^{-2}, 10]$$

- Stop accretion for $z < z_{\rm cut}$, and

$$\log_{10} m_{\rm MBH} > \log_{10} m_{\rm MBH,0}(1+z)^{\alpha}$$

BH mergers

Following halo mergers:

- If major halo merger, ($q_h > 0.13$) black holes form a binary that merges after $t_{\mathrm{dyn.\ fric.}} + t_{\mathrm{delay}}$
- If minor halo merger, BHs in secondary halo sink for $t_{\mathrm{dyn.\ fric.}}$ before forming a binary that merges within t_{delay}

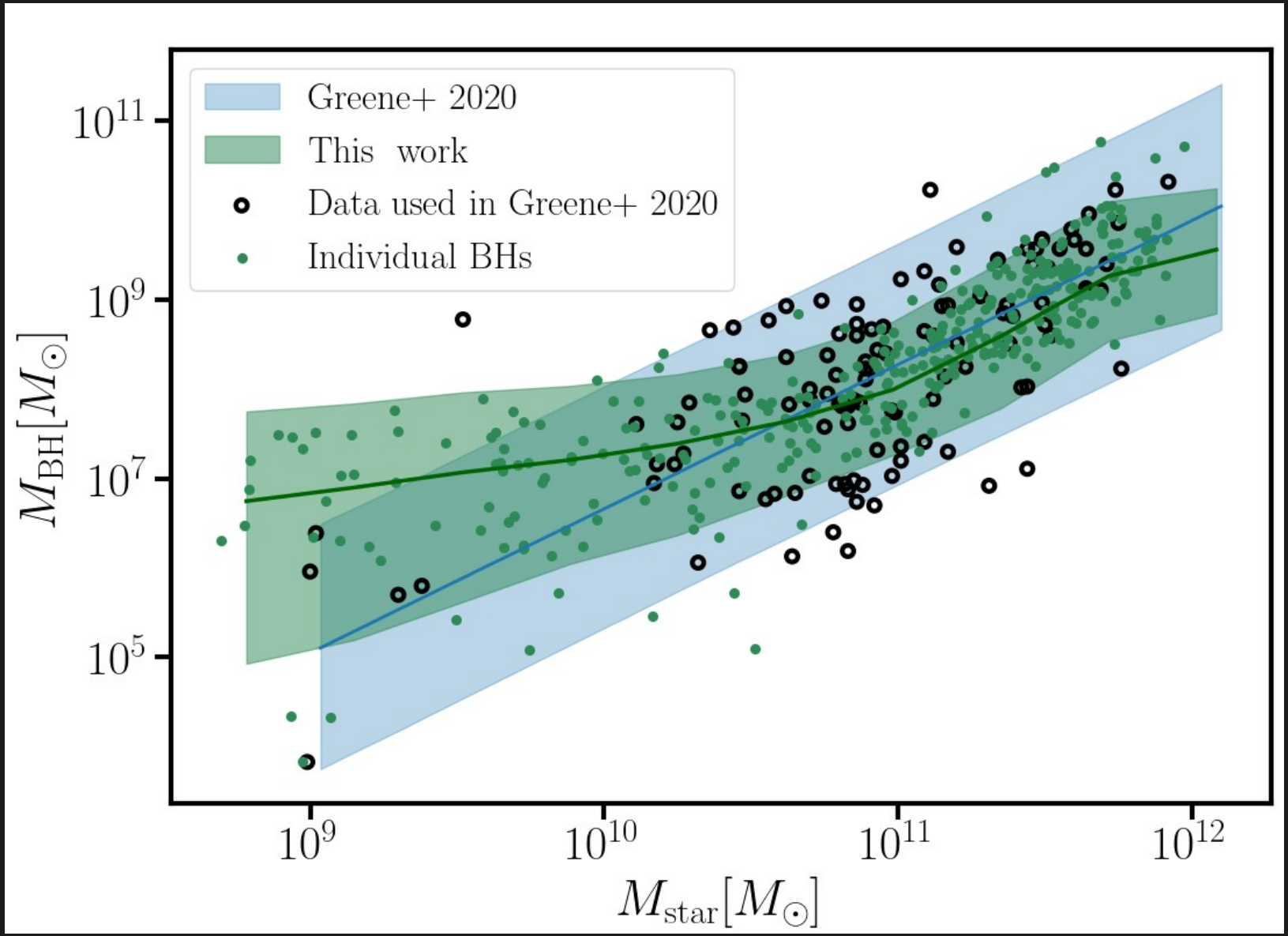
- $t_{\mathrm{dyn.\ fric.}}$ computed from Volonteri et al. 2003
- For triple/quadruple systems use results of Bonetti et al. 2018

Summary of the model

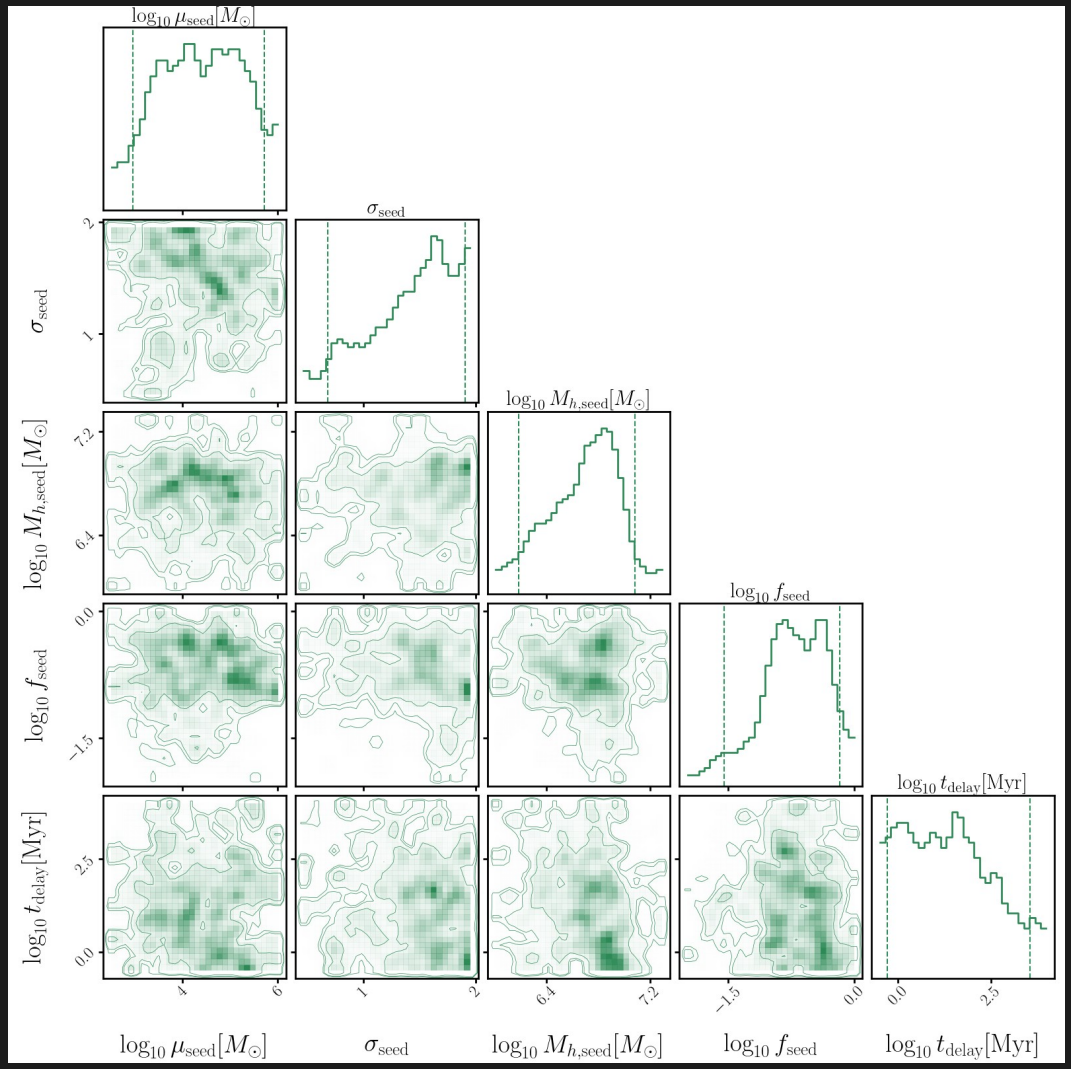
- 12 free parameters:
  - seeding:
    $$\mu_{\rm seed},\ \sigma_{\rm seed},\ M_{h,{\rm seed}},\ f_{\rm seed}$$
  - accretion:
    $$\gamma_{\rm burst},\ t_{\rm burst},\ \mu_{\rm steady},\ \sigma_{\rm steady},\ z_{\rm cut}, m_{\rm cut,0},\ \alpha_{\rm cut}$$
  - Merger: $t_{\rm delay}$

- ~1h to run 500 parameters
- Run MCMC to fit observations

Mstar-Mbh


Greene+ 2020
This work
Data used in Greene+ 2020
Individual BHs
10^{11}
10^{9}
10^{7}
10^{5}
$M_{\rm BH}[M_\odot]$
10^{9}
10^{10}
10^{11}
10^{12}
$M_{\rm star}[M_\odot]$

Posterior on hyperparameters



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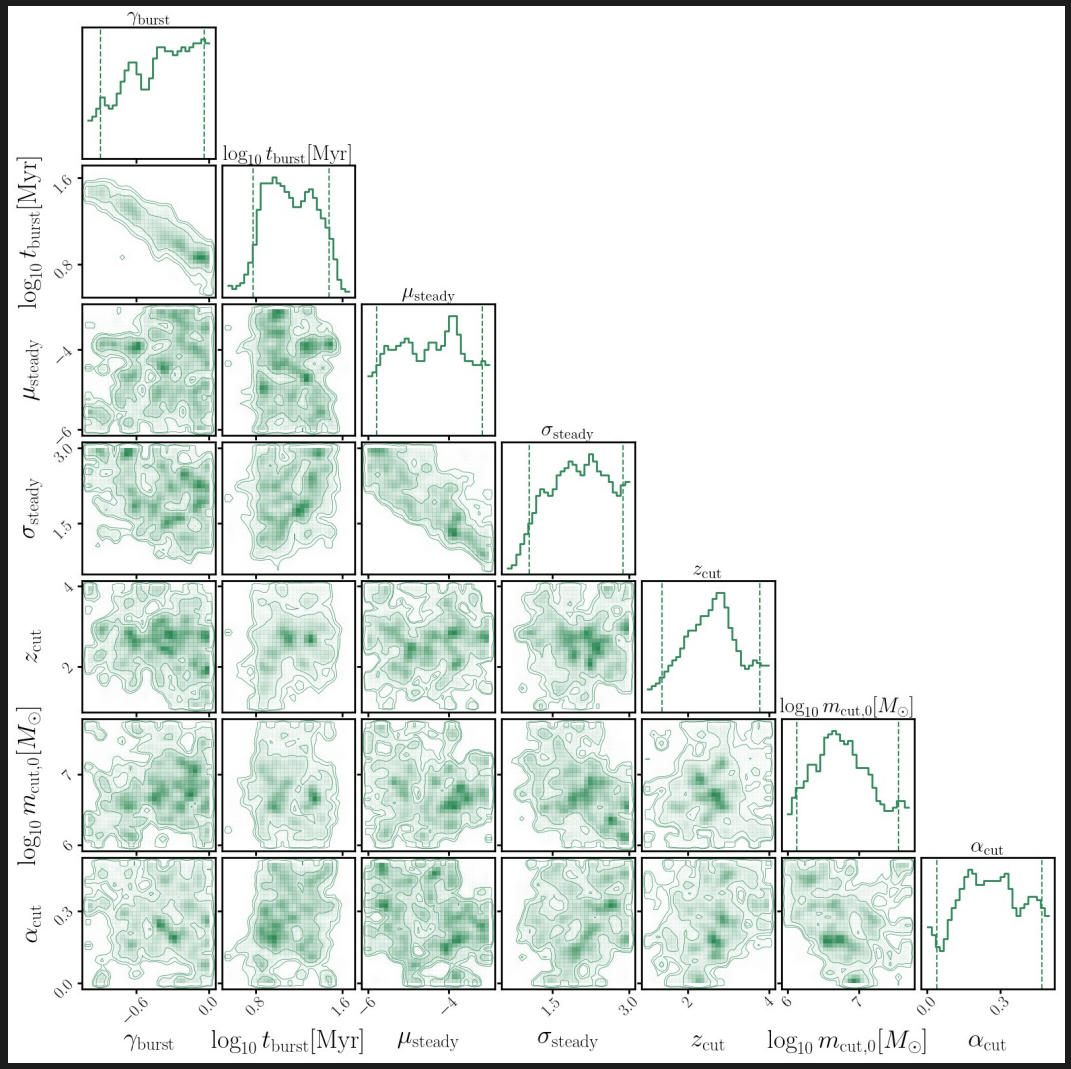
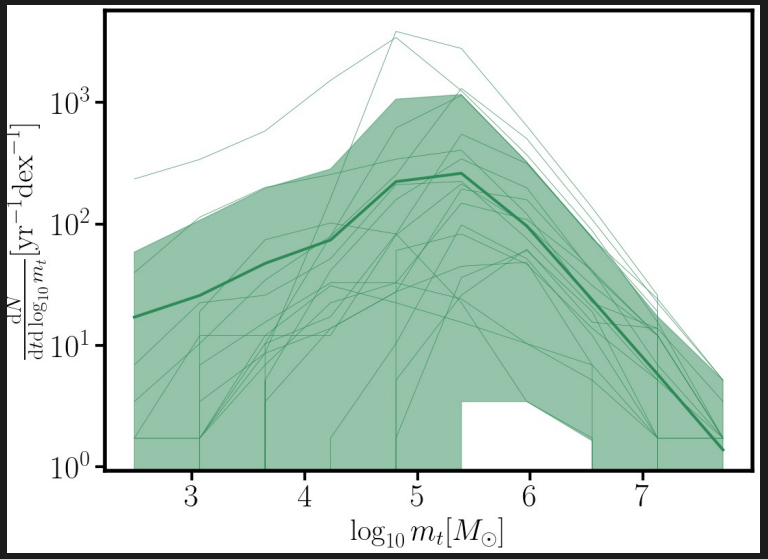
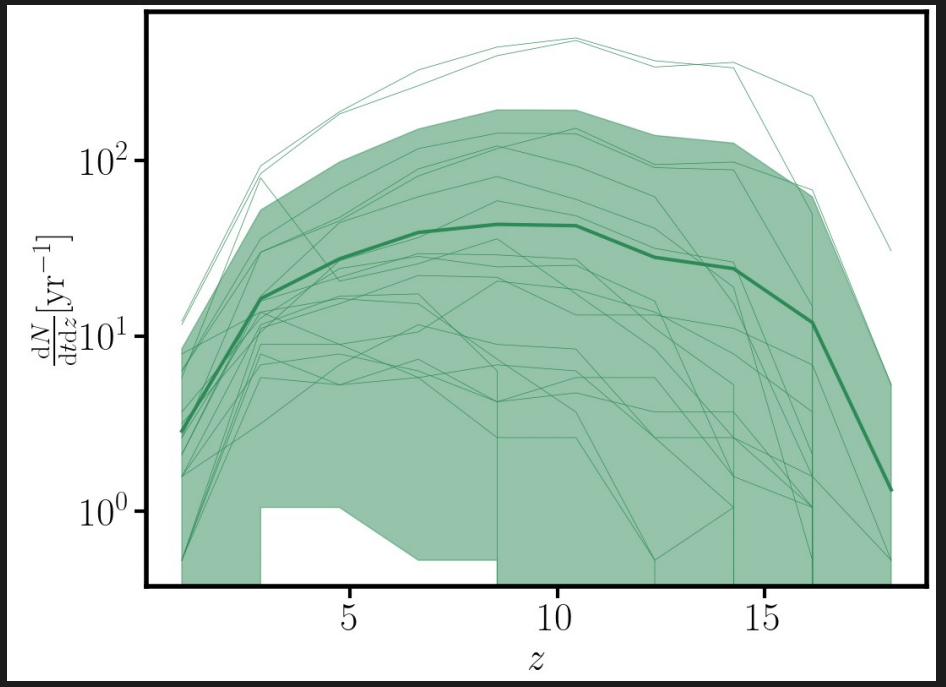
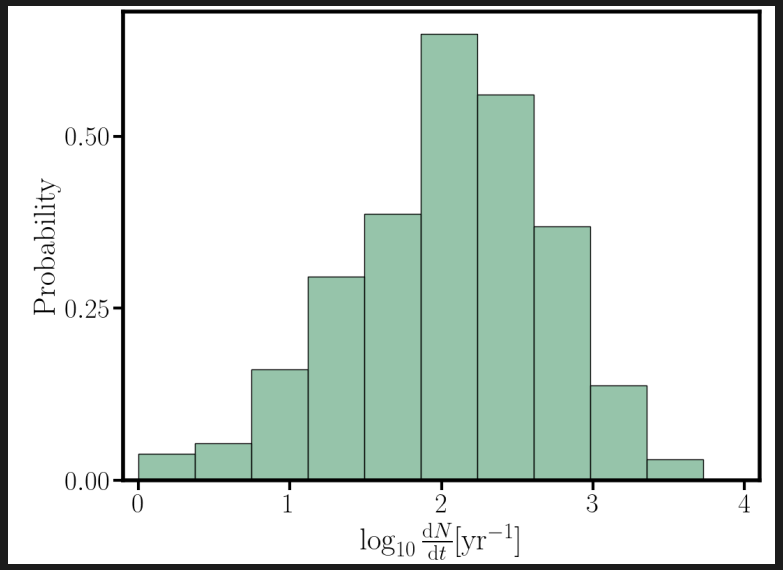


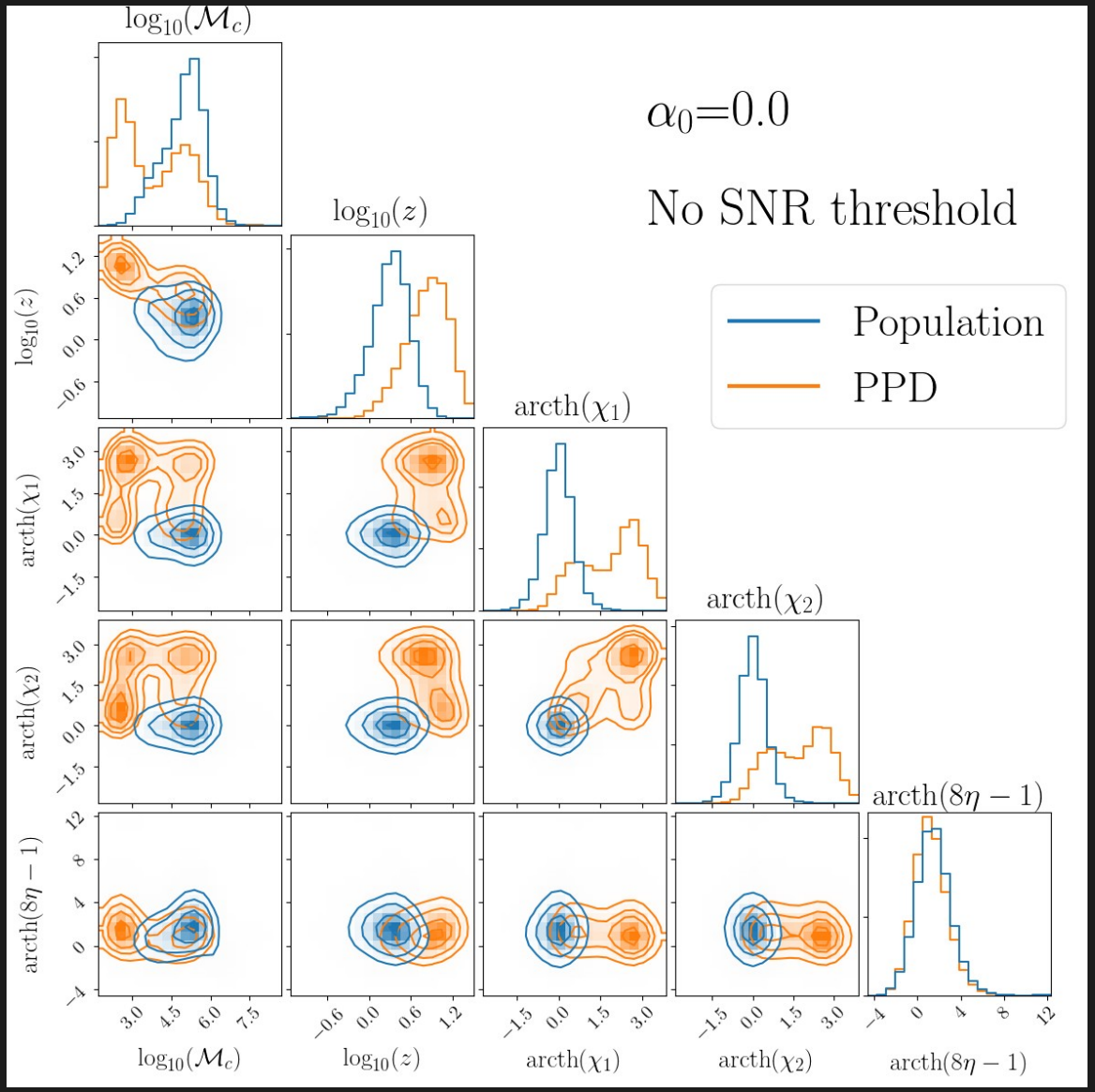
LISA prediction





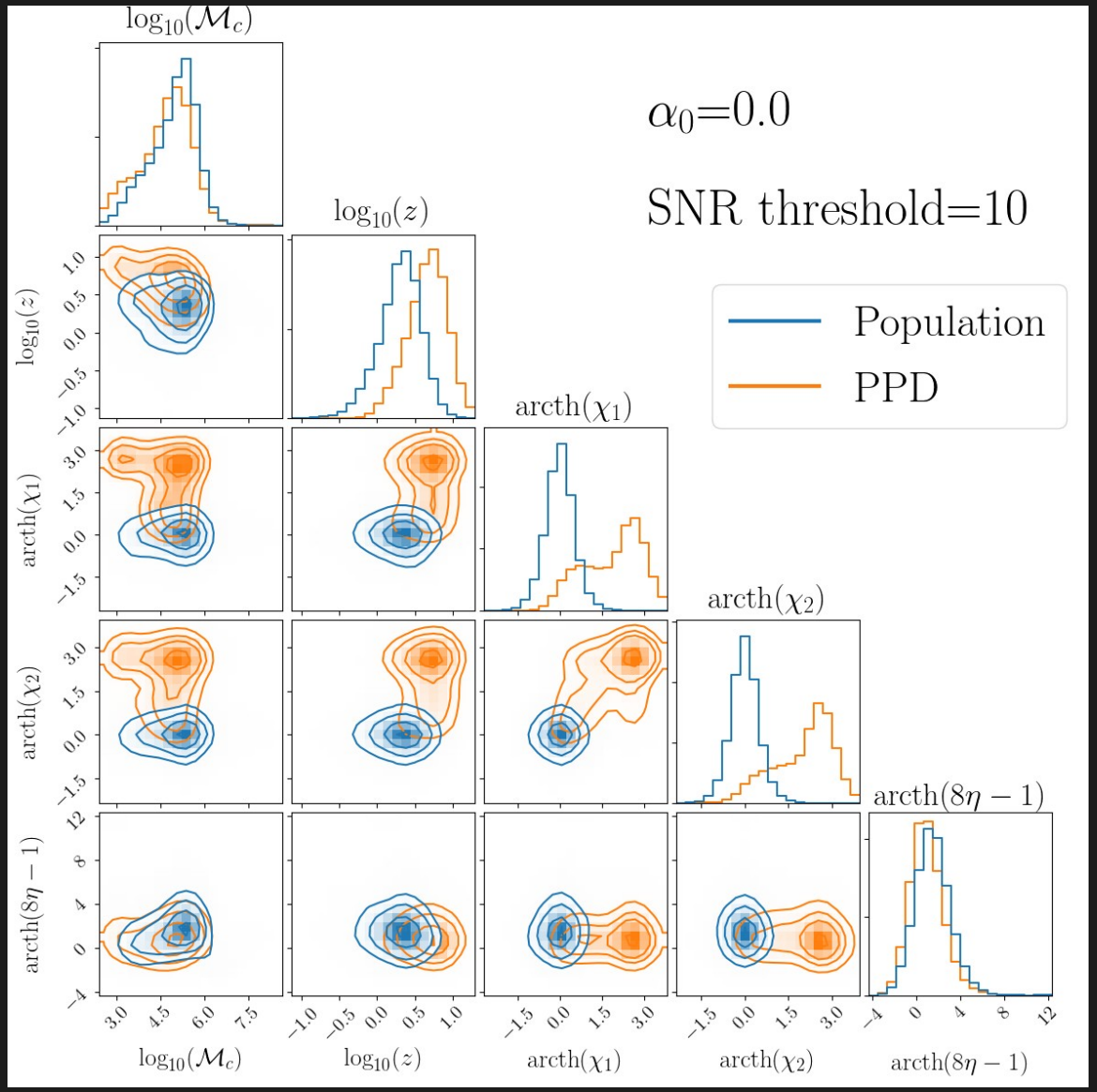


“Systemtatics” in population



Toubiana +, PRD 2021

“Systemtatics” in population



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POMPOKO

- Pompoco: Parametrisation Of the Massive black hole POpulation for Comparison to Observations ?

Evolution of double white dwarfs

- Angular momentum balance equation:

$$\dot{J_{\rm orb}} + \dot{J}_1 + \dot{J}_2 = \dot{J_{\rm GW}} + \dot{J_{\rm loss}}$$

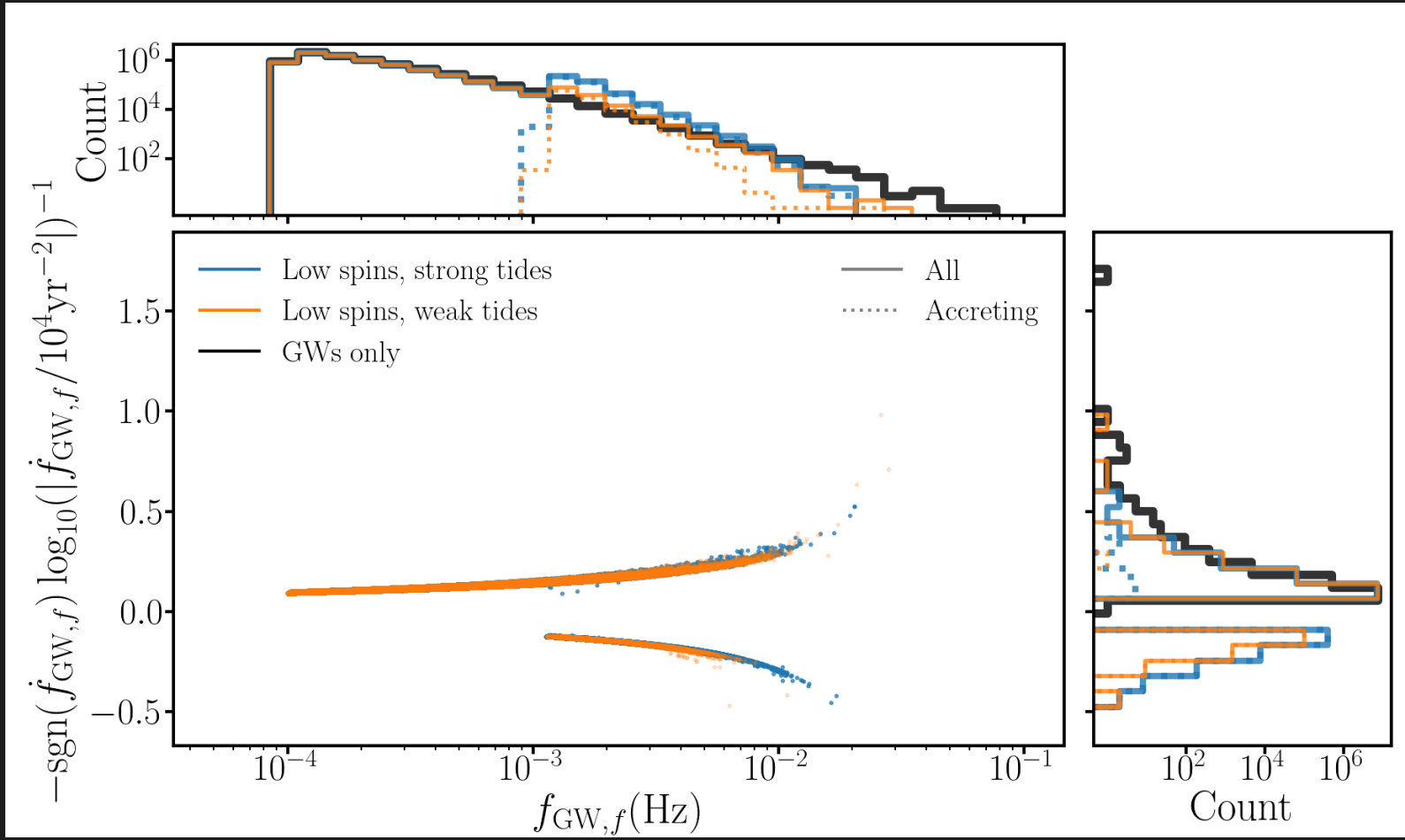
- Evolution of WD's angular momentum:

$$\dot{J}_i = j_i \dot{m}_i - \frac{I_i}{\tau_{s,i}} (\omega_i - \omega_{\rm orb})$$

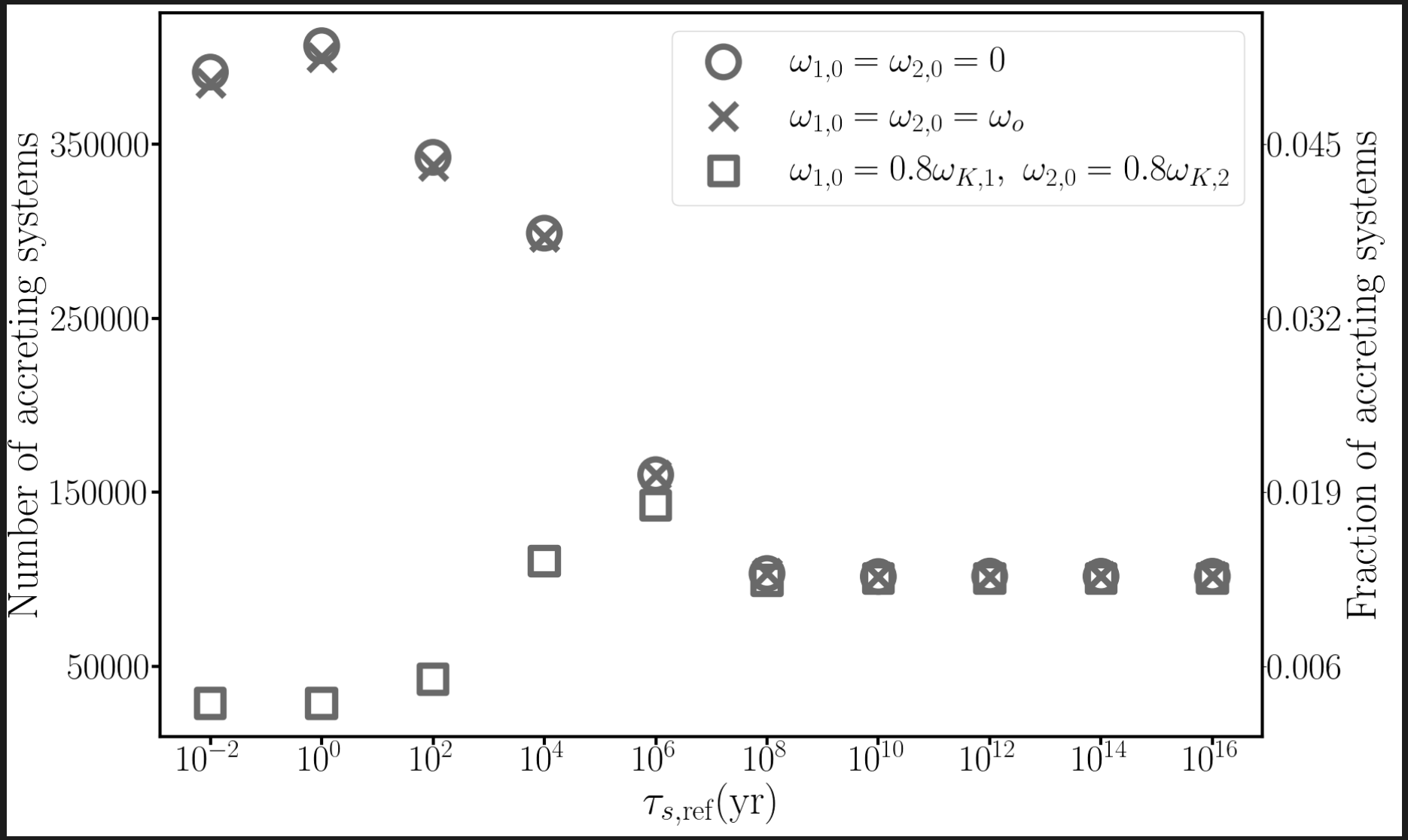
- Scaling of synchronisation timescale:

$$\tau_{s,i} \propto \left(\frac{m_i}{m_{-i}} \right)^2 \left(\frac{a}{R_i} \right)^6$$

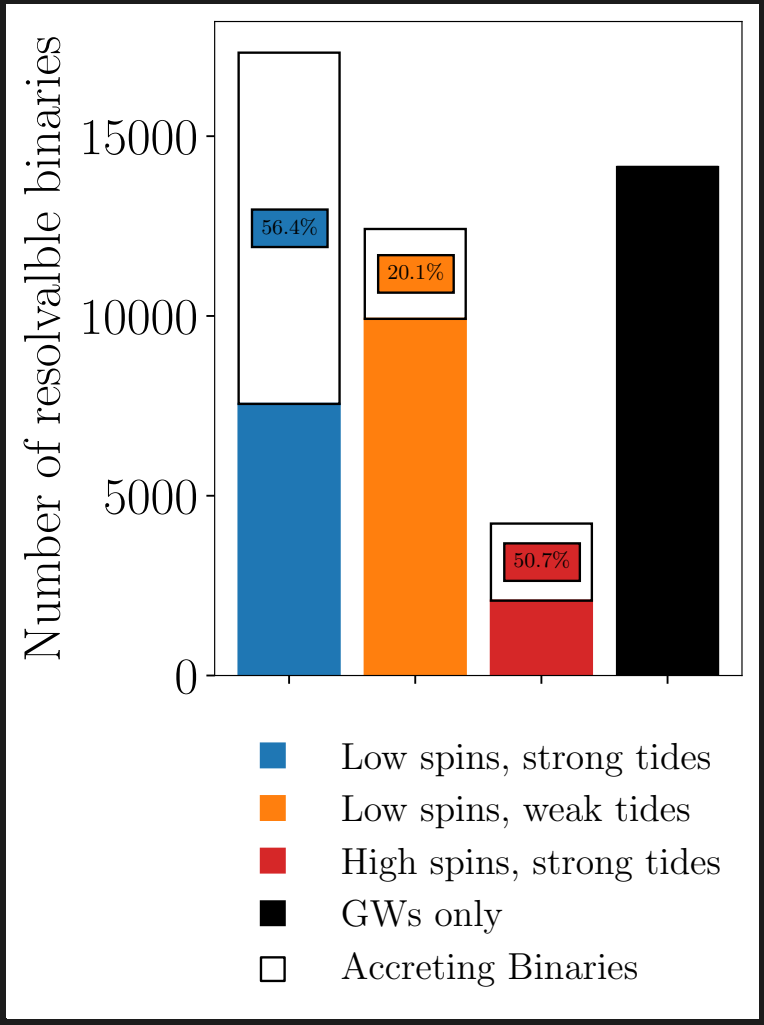
Double white dwarf population



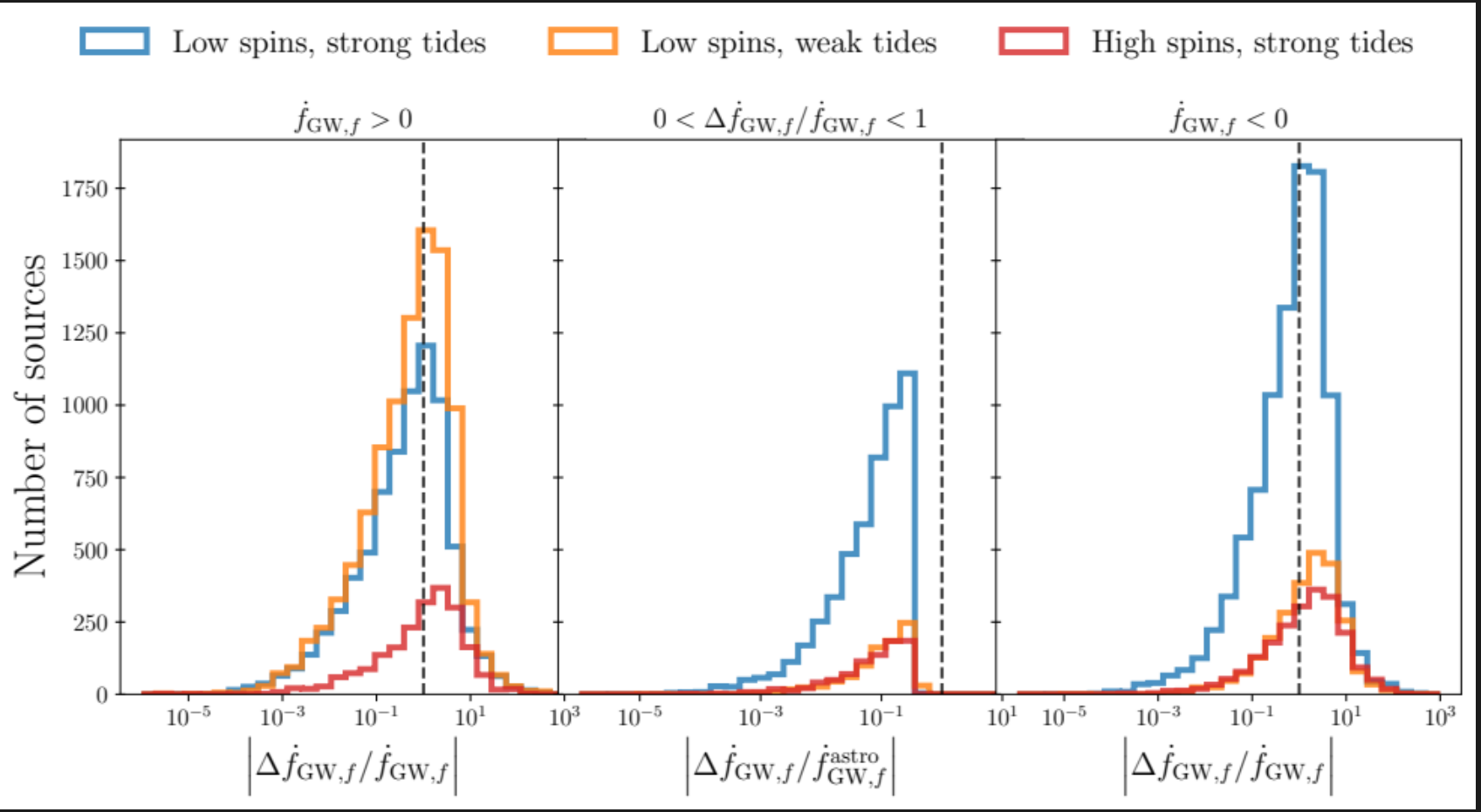
Double white dwarf population



Double white dwarf population



Double white dwarf population



$$\dot{f}^{\mathrm{astro}}_{\mathrm{GW}} = \dot{f}_{\mathrm{GW}} - \dot{f}^{\mathrm{GR}}_{\mathrm{GW}}$$