

# Breaking degeneracies in BBH formation mechanisms

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Marie  
Sklodowska-Curie  
Actions

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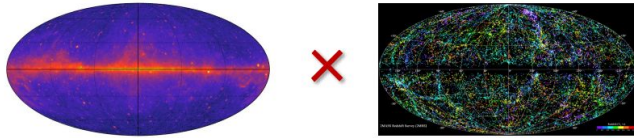


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# The idea behind this work

From N. Fornengo's talk: DMxLSS

## Cross correlations



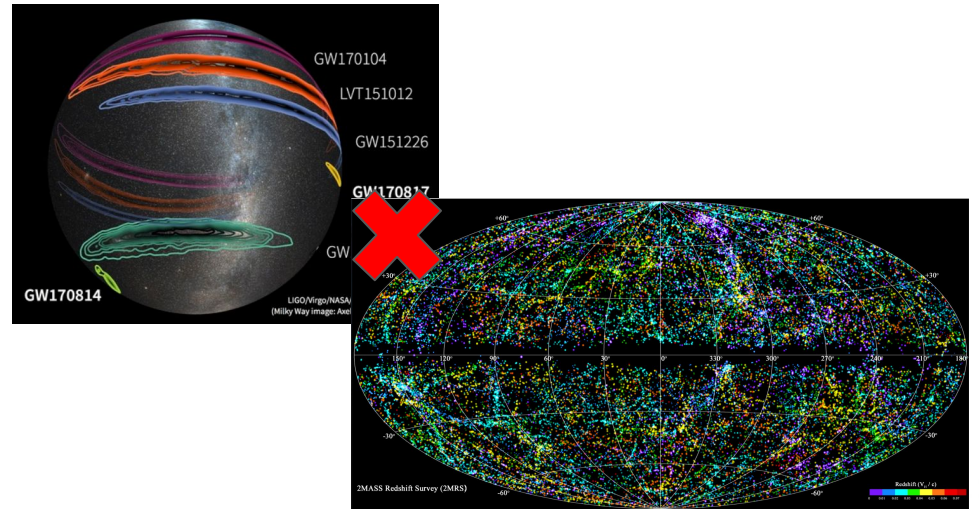
The fluctuations in the cosmic radiation fields need to be **statistically correlated** to the DM distribution in the universe

This **cross-correlation** is a statistical observable (it allows to infer **global information**, not identify individual sources) and exploits in a unified way two distinctive features of particle DM:

- An electromagnetic signal, manifestation of the particle nature of DM
- A gravitational probe of the existence of DM

It allows to 'add' distance (redshift) information to a probe (like gamma-rays) that does not have it

This talk: GWxLSS (Galaxies/DM "emits" GWs)



# A new challenge ahead in GW science

Precision is needed, accuracy is desired, but what about interpretability?

Bayesian statistics naturally highlights the limitations of our knowledge:

$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)} \implies p(\theta|d, M) = \frac{p(d|\theta, M)p(\theta|M)}{p(d|M)}$$

The situation is even worse in terms of Bayesian model selection:

$$\frac{p(M_1|d)}{p(M_2|d)} = \underbrace{\frac{p(d|M_1)}{p(d|M_2)}}_{B_{12}} \times \frac{p(M_1)}{p(M_2)}$$

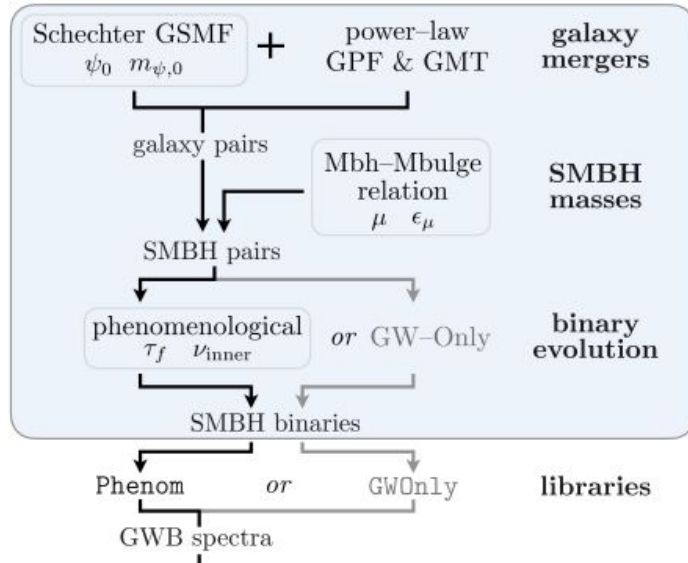
Q1. *What can we learn if the dimensionality of the theory is larger than that of the data?*

Q2. *How do we know whether we are even considering the correct theory (parameter) space?*



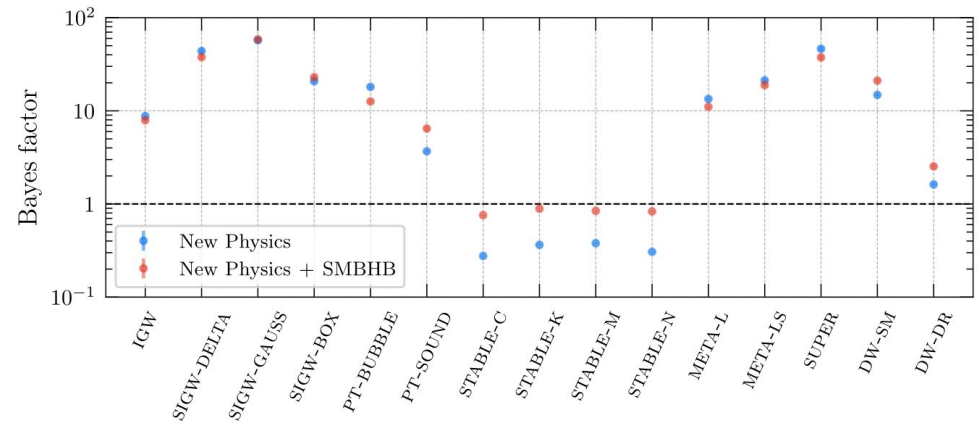
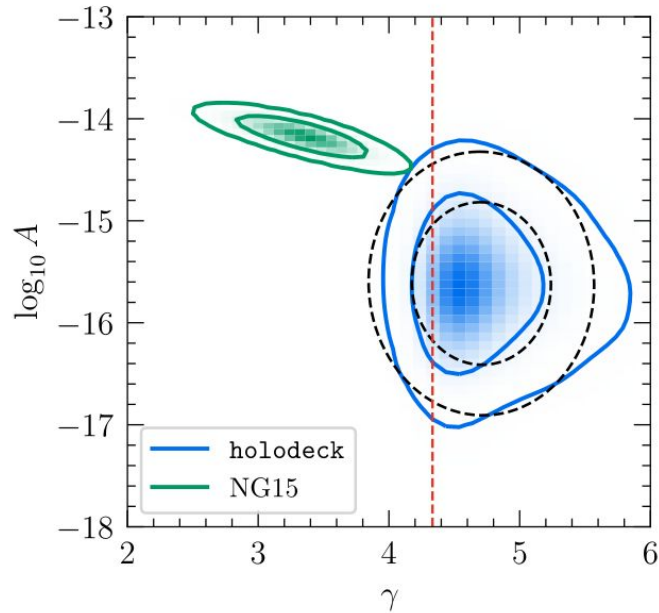
# Interpretation of PTA GW background

Are SMBHBs GW emission compatible with the observed signal?



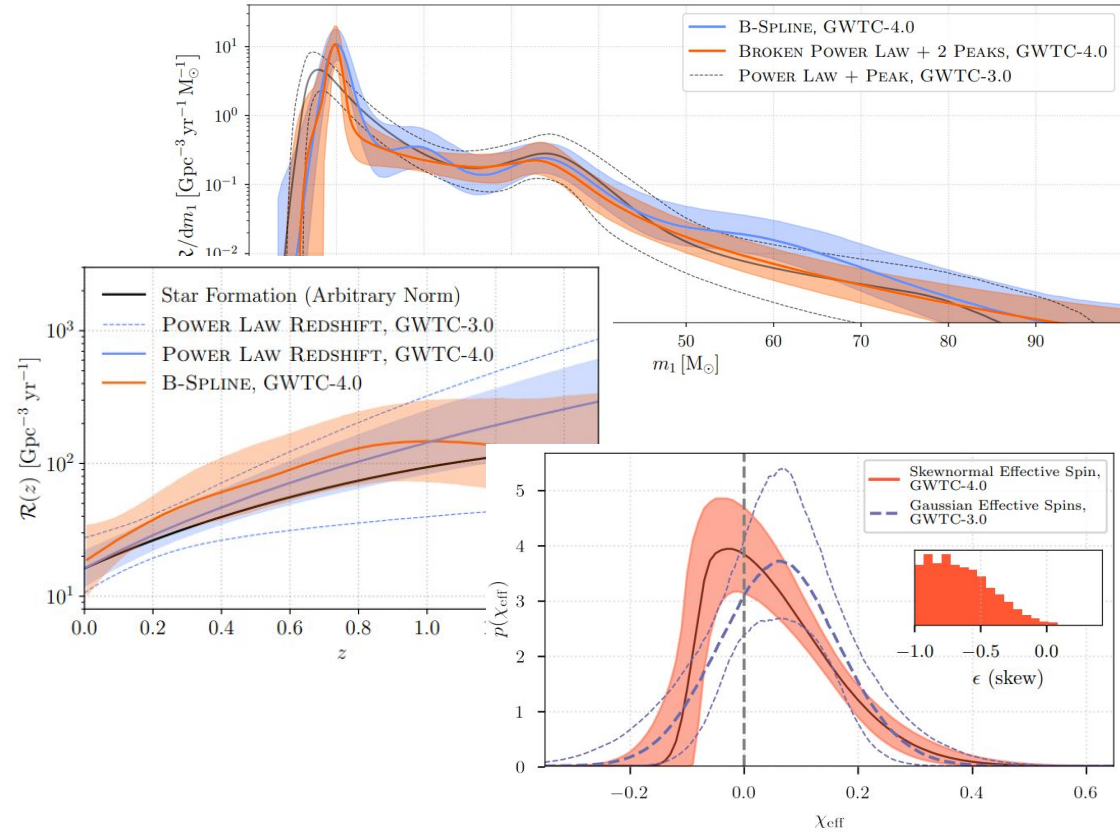
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# Interpretation of LVK GW events

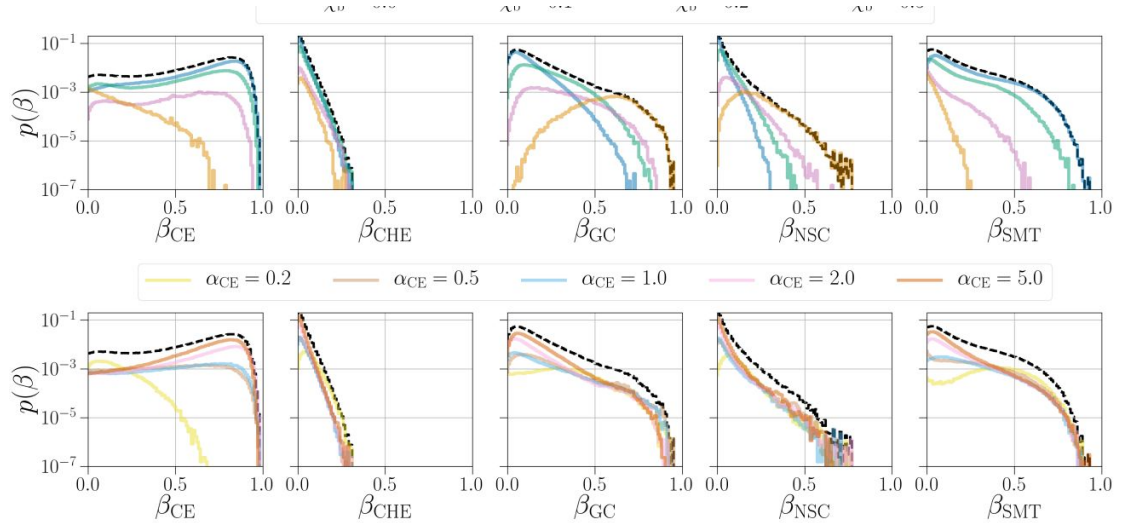
What can we learn from the measured properties of BH events? In other words, are we ready to perform model selection?



# Interpretation of LVK GW events

Zevin+, 2011.10057

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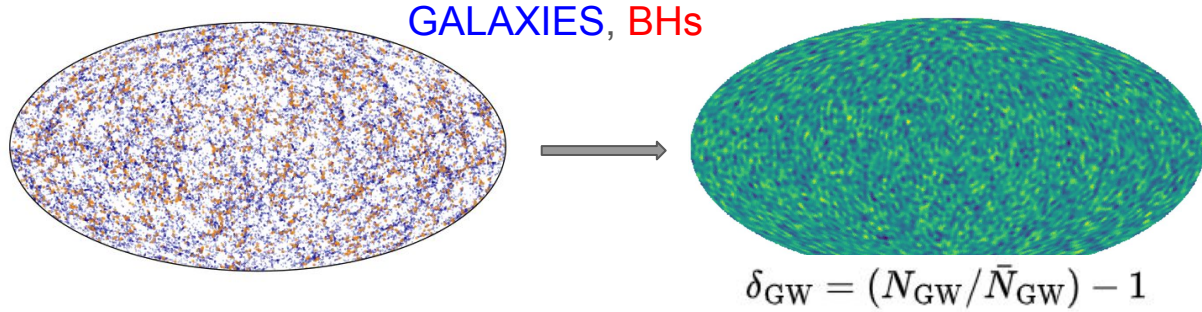
$\log_{10} \mathcal{B}_{\text{CE+GC}}^{\text{M}}$	CE+GC+PBH	CE+GC+NSC	CE+GC+SMT	CE+GC+NSC+PBH	CE+GC+SMT+PBH
w.o. GW190521	1.22	0.52	1.39	1.43	1.31
w. GW190521	2.38	-0.15	0.72	2.30	2.58

Franciolini+, 2105.03349



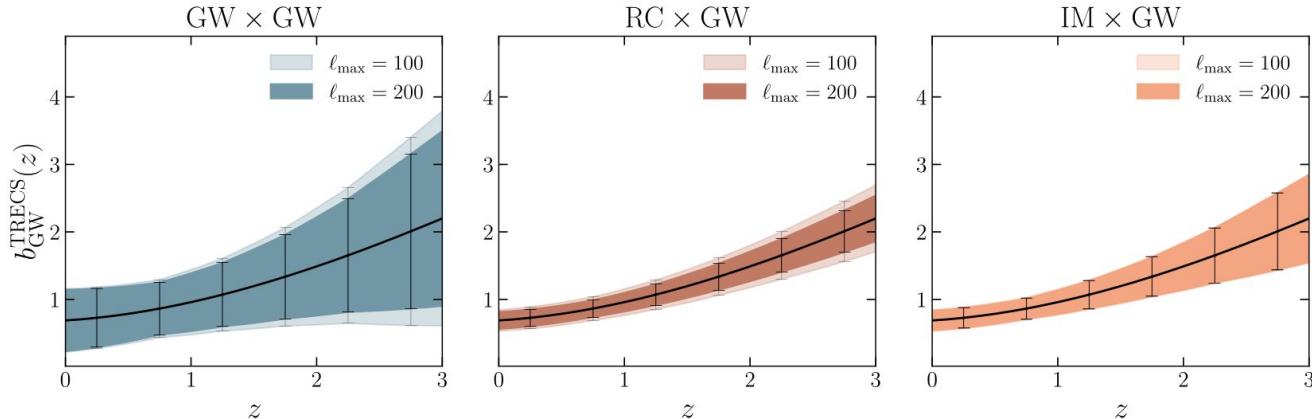
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# GW clustering as an additional handle



The name of the game is measuring the GW bias:

$$b_{\text{GW}}(z) \approx \sqrt{C_{\ell}^{\text{GW}}(z)/C_{\ell}^{\text{DM}}(z)}$$

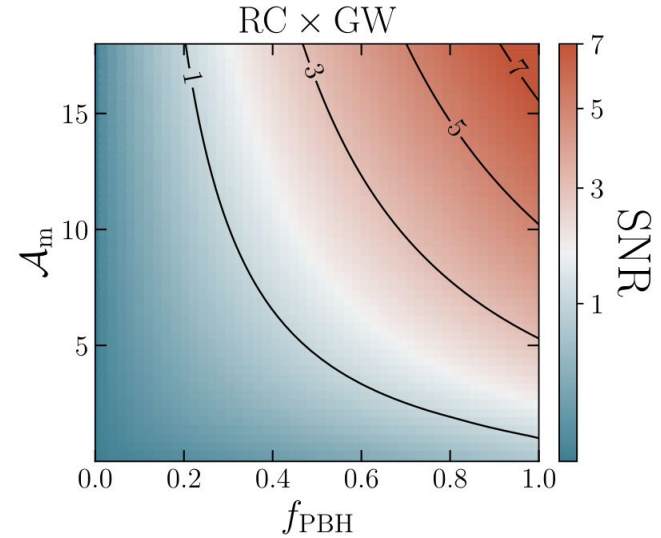
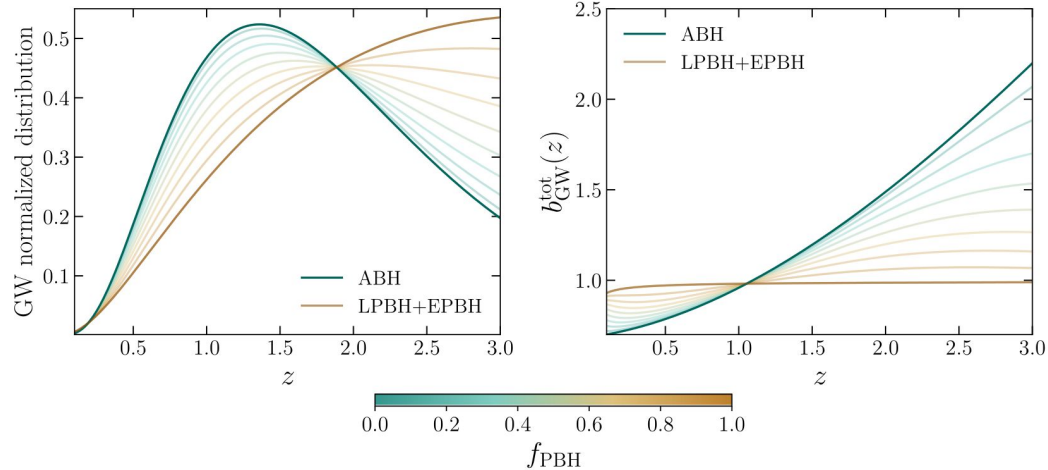


Example of performance with ETxSKAO

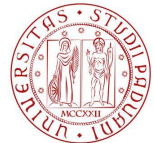
Bosi, Libanore, NB+, to appear in AASKAII

# Constraining the presence of “exotic” sources - PBH

General idea: any “exotic” GW source is very likely tied to a specific environment that is not that of stellar BHs.



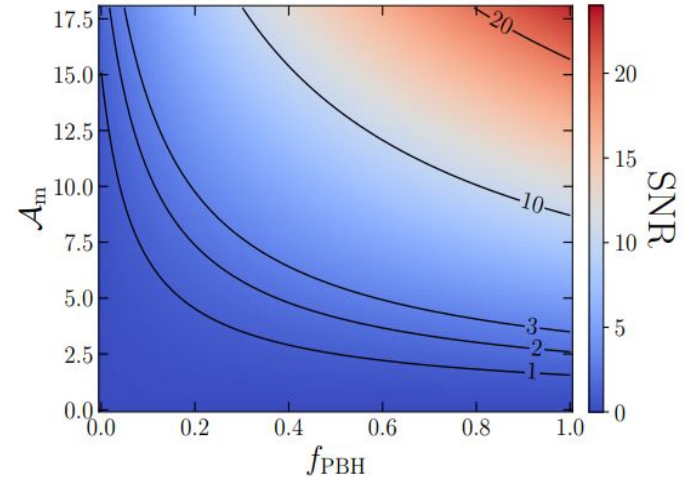
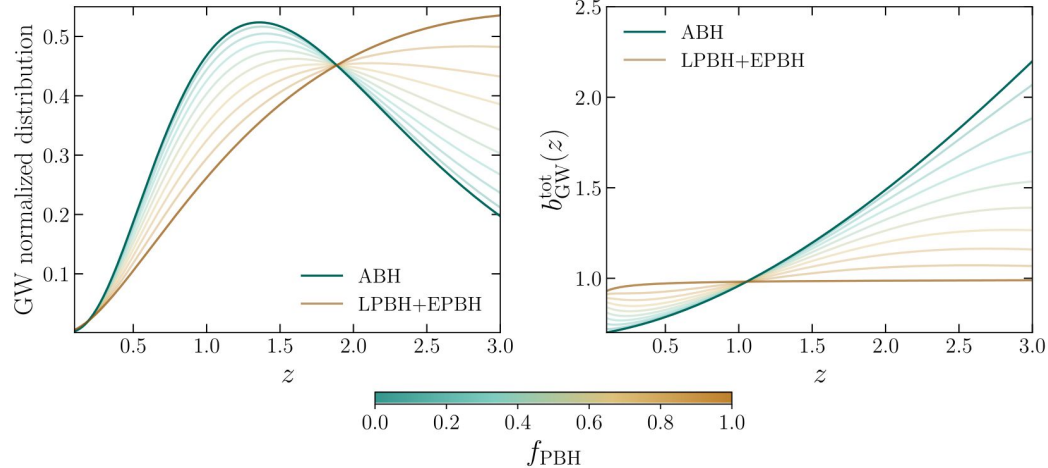
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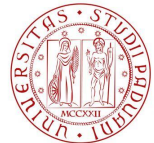
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Bosi, NB+, 2306.03031

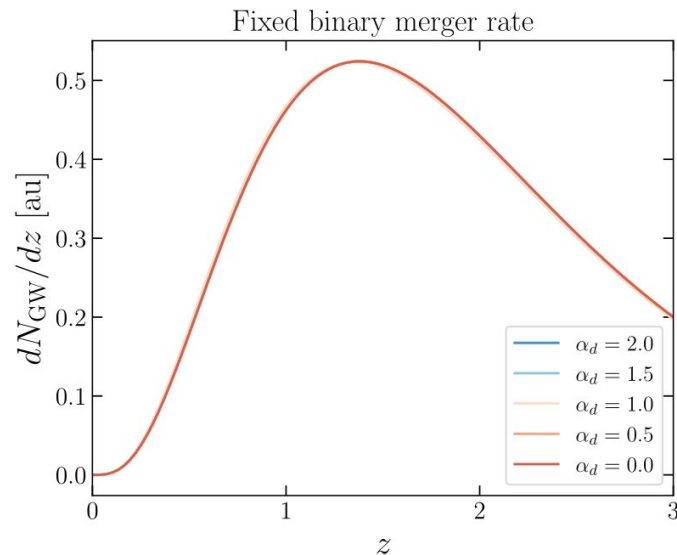
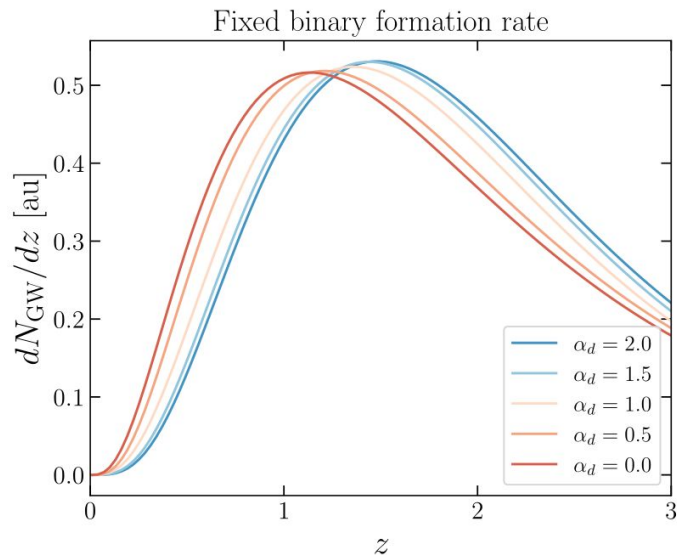


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# What about purely astrophysical sources?

The merger rate is not a primary properties of any physically motivated scenario.

$$R(z) = \int_{t_{d,\min}}^{t(z)} dt_d p(t_d) R_{\text{BFR}}(z_f(z, t_d)), \quad p(t_d) \propto t_d^{-\alpha_d}$$



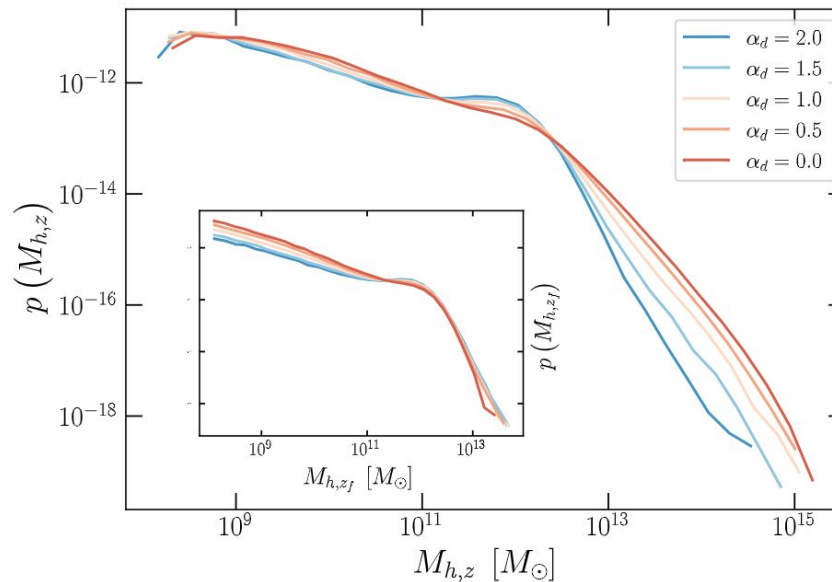
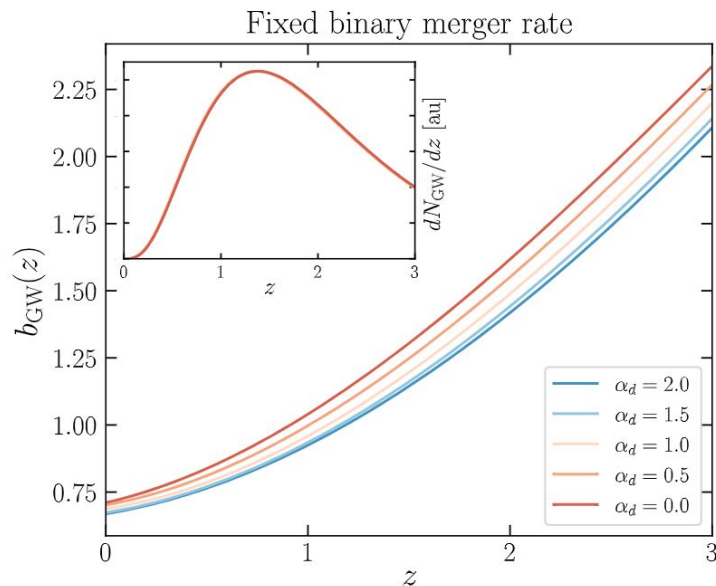
The world we would like to live in

The world we actually live in



# What about purely astrophysical sources?

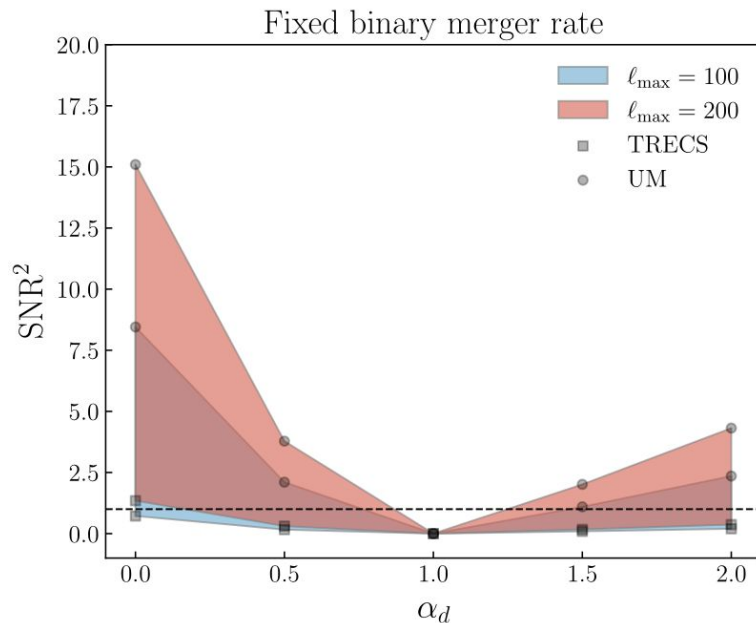
One possible way forward in breaking this degeneracy is to find a second “clock” that describes BBH formation. In this case, by measuring the GW bias!



# Distinguishability of different models

Even in this simple example, there is hope to distinguish models with different time-delay distributions.

This is not the end of the story, since different halo mass-SFR relations returns quite different predictions. Thus, the need of more accurate astrophysical observations!

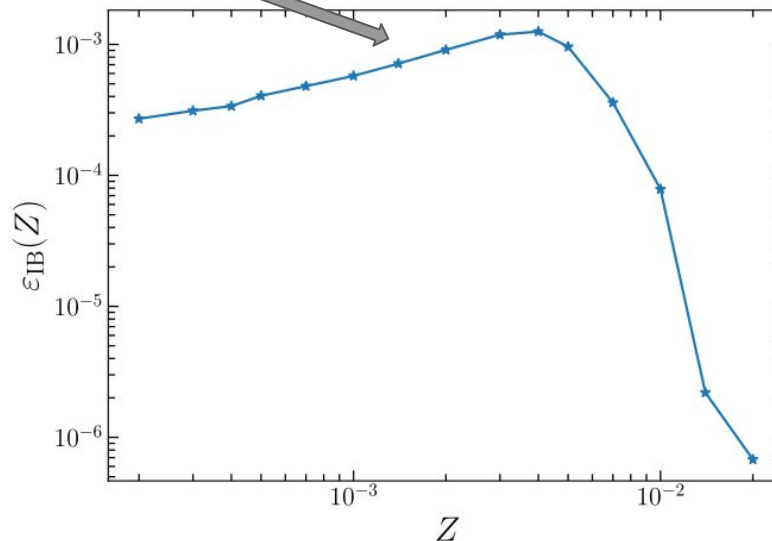
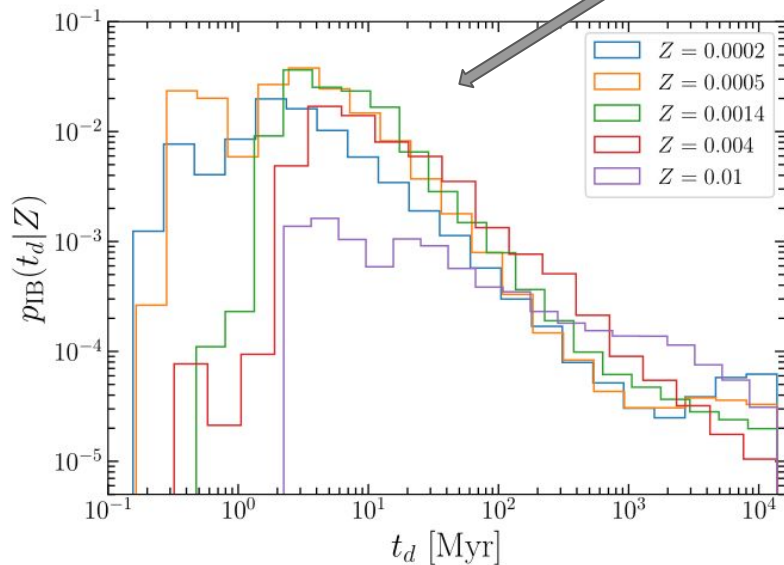


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# However, reality is not as simple...

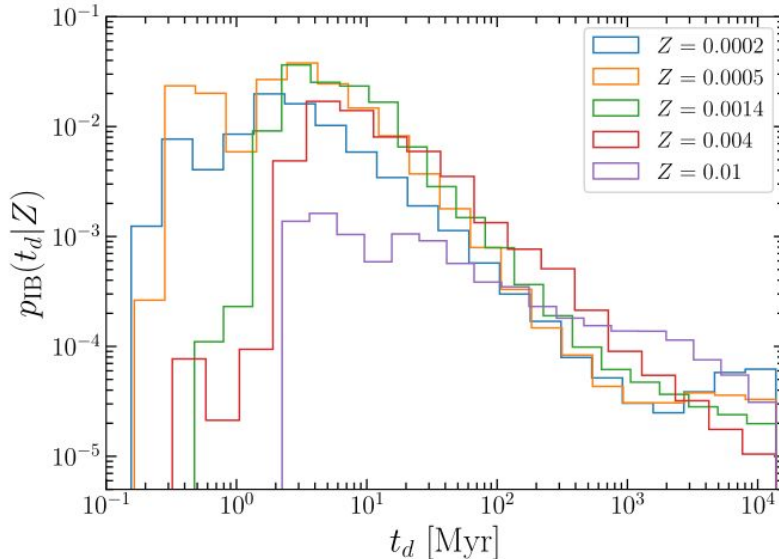
Taking one step further towards a realistic model of isolated binaries

$$R(z) = \int_{t_{d,\min}}^{t(z)} dt_d dZ p(t_d|Z) \frac{\varepsilon(Z)}{\langle M_{\star}^{\text{tot}} \rangle} \dot{\rho}_{\text{CSFR}}(z_f)$$

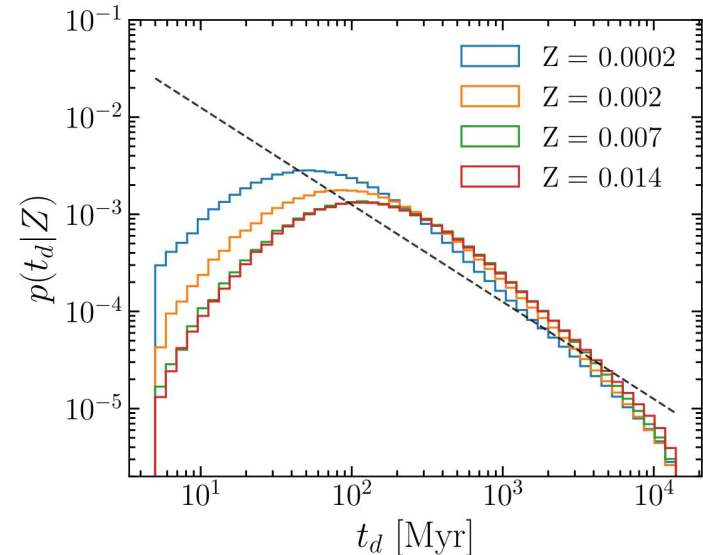


# ... But it opens the door to study different BBH populations!

BBH populations that formed via different channels have different time delay distributions and trace LSS in different fashions.



Isolated binary channel



Dynamical formations in GC

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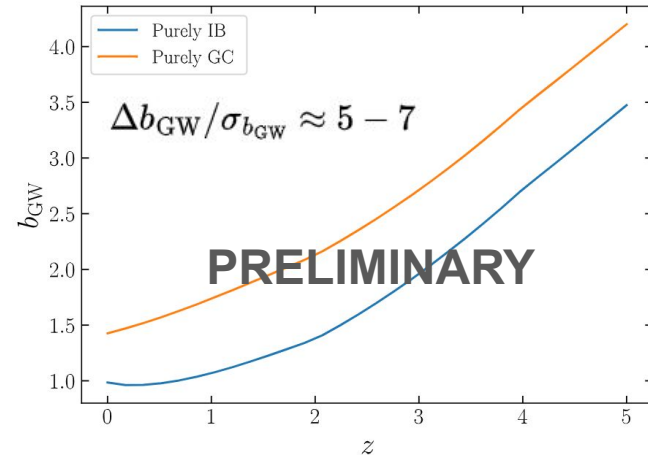
BBH populations that formed via different channels have different time delay distributions and trace LSS in different fashions.

In terms of clustering, galaxies and GC trace differently DM halos.

$$\{M_h\} \sim \text{pdf} \left( \varepsilon_{\text{GC}}(M_{\text{GC}}, Z) \frac{d^4 n_{\text{GC}}}{dM_h dM_* dZ dM_{\text{GC}}} \right)$$

$$\{M_h\} \sim \text{pdf} \left( \varepsilon_{\text{IB}}(Z) \frac{d^4 n_{\text{gal}}}{dM_h dM_* dZ d\text{SFR}} \right)$$

$$\longrightarrow b_{\text{GW}}^{\text{GC/IB}} = n_{\text{GW}}^{-1} \int dM_h \frac{dn_h}{dM_h} \langle N_{\text{GW}}^{\text{GC/IB}} | M_h \rangle b_h$$



# Conclusions

Moving forward, our primary goal should be looking for additional observables to carve through the astonishing large parameter space of stellar evolution into compact objects.

GWxLSS cross-correlations provide a motivated handle in breaking such degeneracies, especially in cases where the analysis benefits from extra “clocks”.

Complementary information coming from halo/galaxy evolution will certainly help in better characterize the environment where GW events live!

