The mass-distribution of LIGO's events as a probe for primordial black holes

Ongoing works with:
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Ilias Cholis

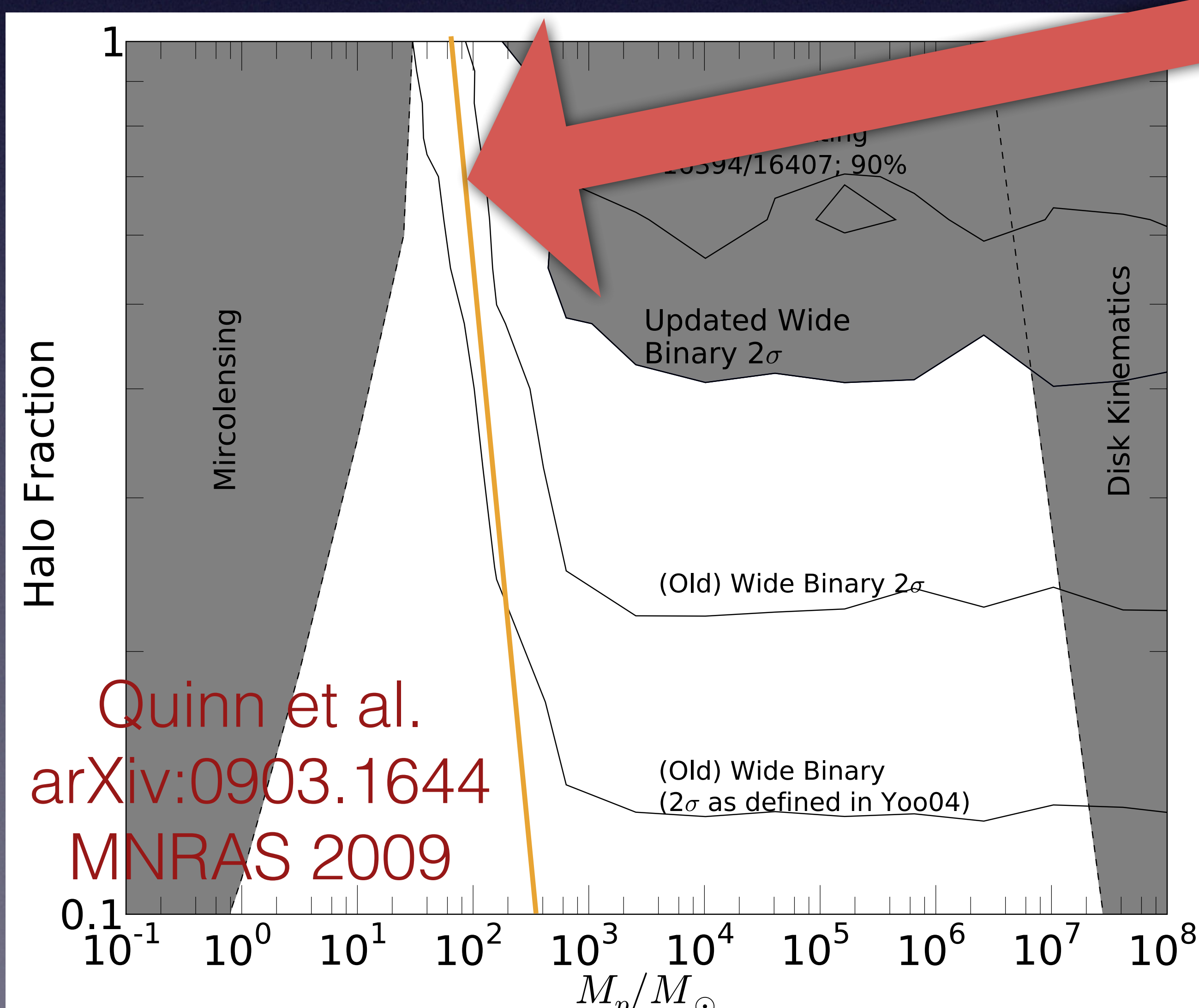
6/18/2024

Making a connection between BHs in the LIGO range and DM

Bird, **IC**, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess PRL 2016

Assuming Dark Matter is composed by Primordial BHs.

There was some allowed parameter space around ~20-70$M_\odot$



Quinn et al.
arXiv:0903.1644
MNRAS 2009

Back in 2016 when LIGO first results came around

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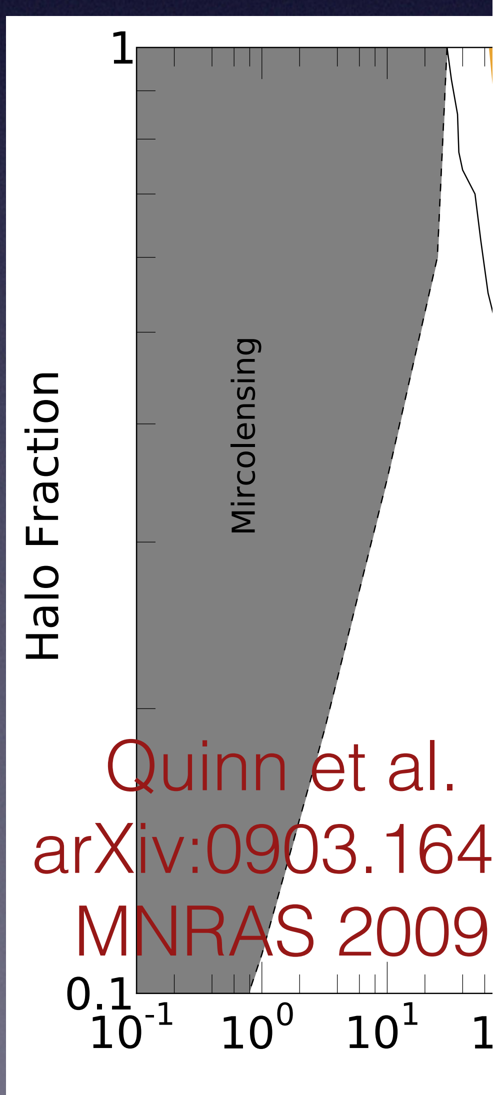
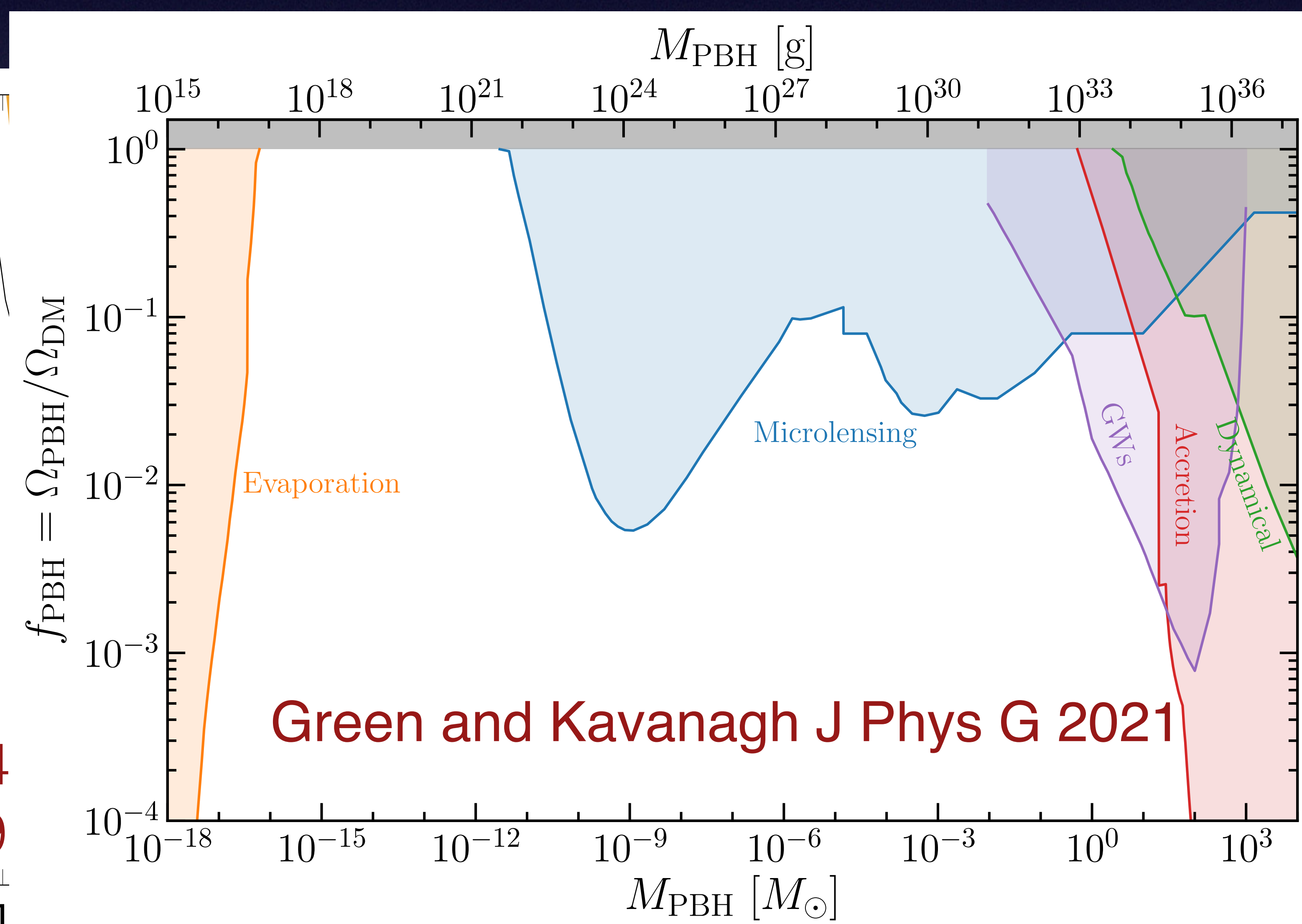


Quinn et al. arXiv:0903.164 MNRAS 2009



Green and Kavanagh J Phys G 2021

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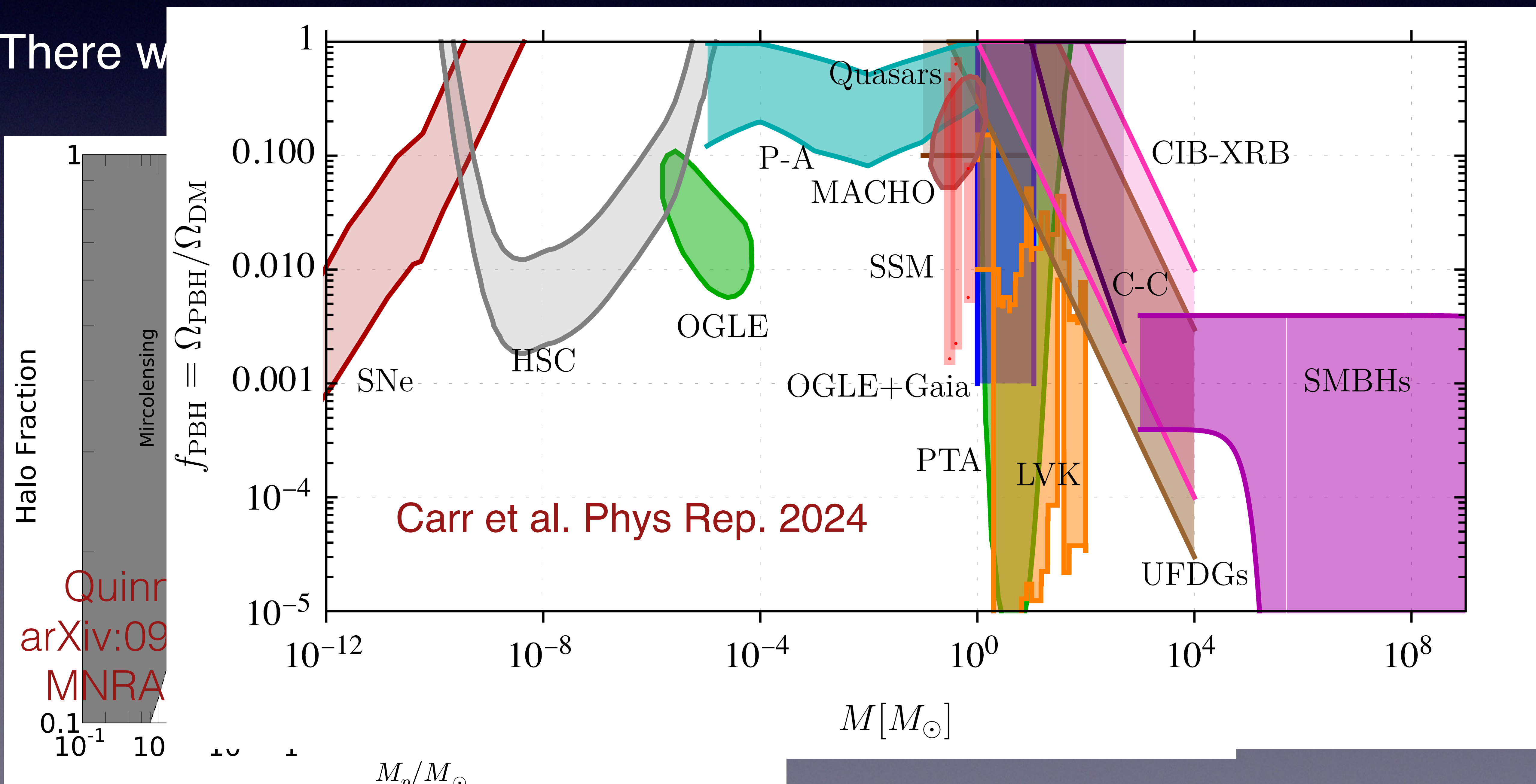
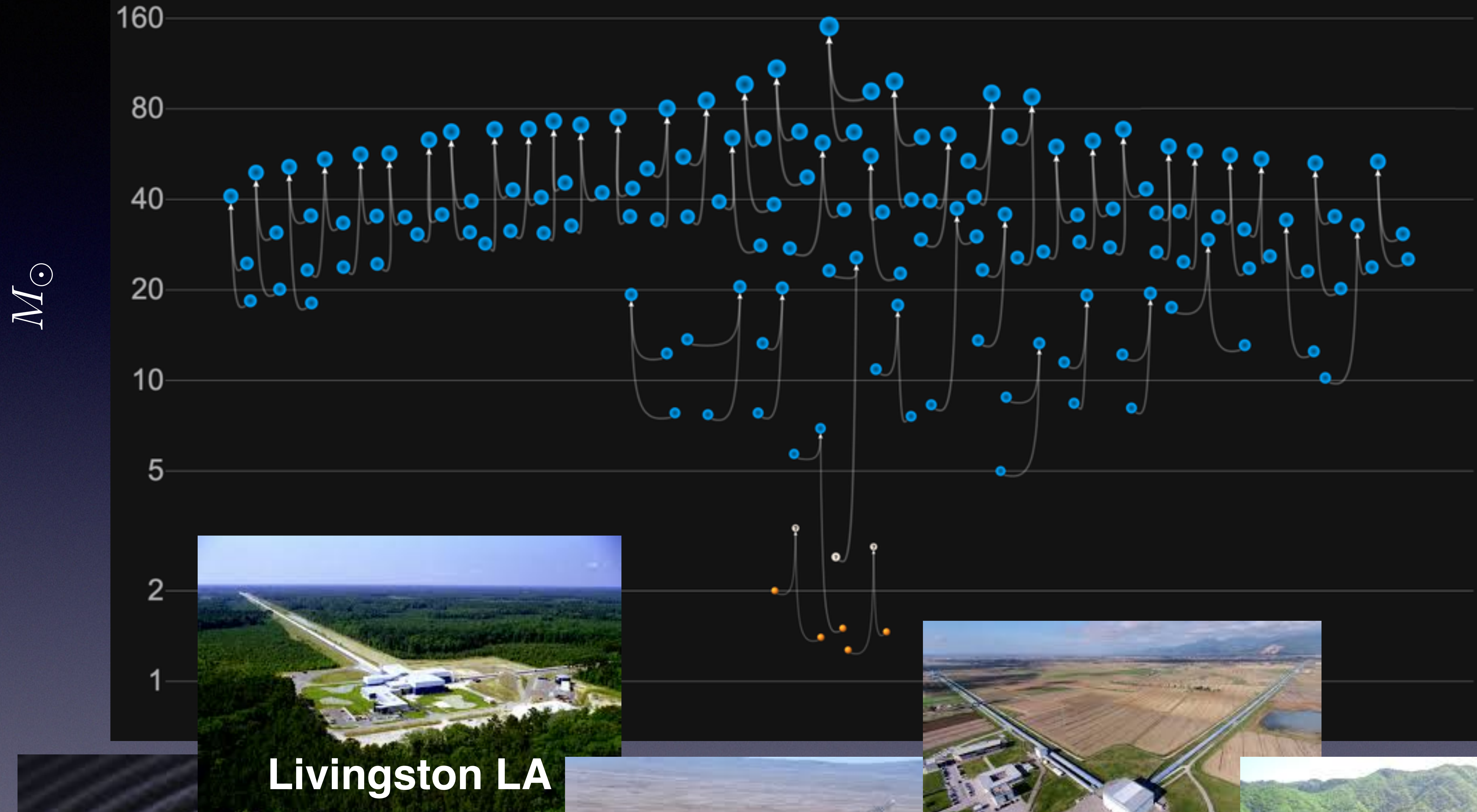
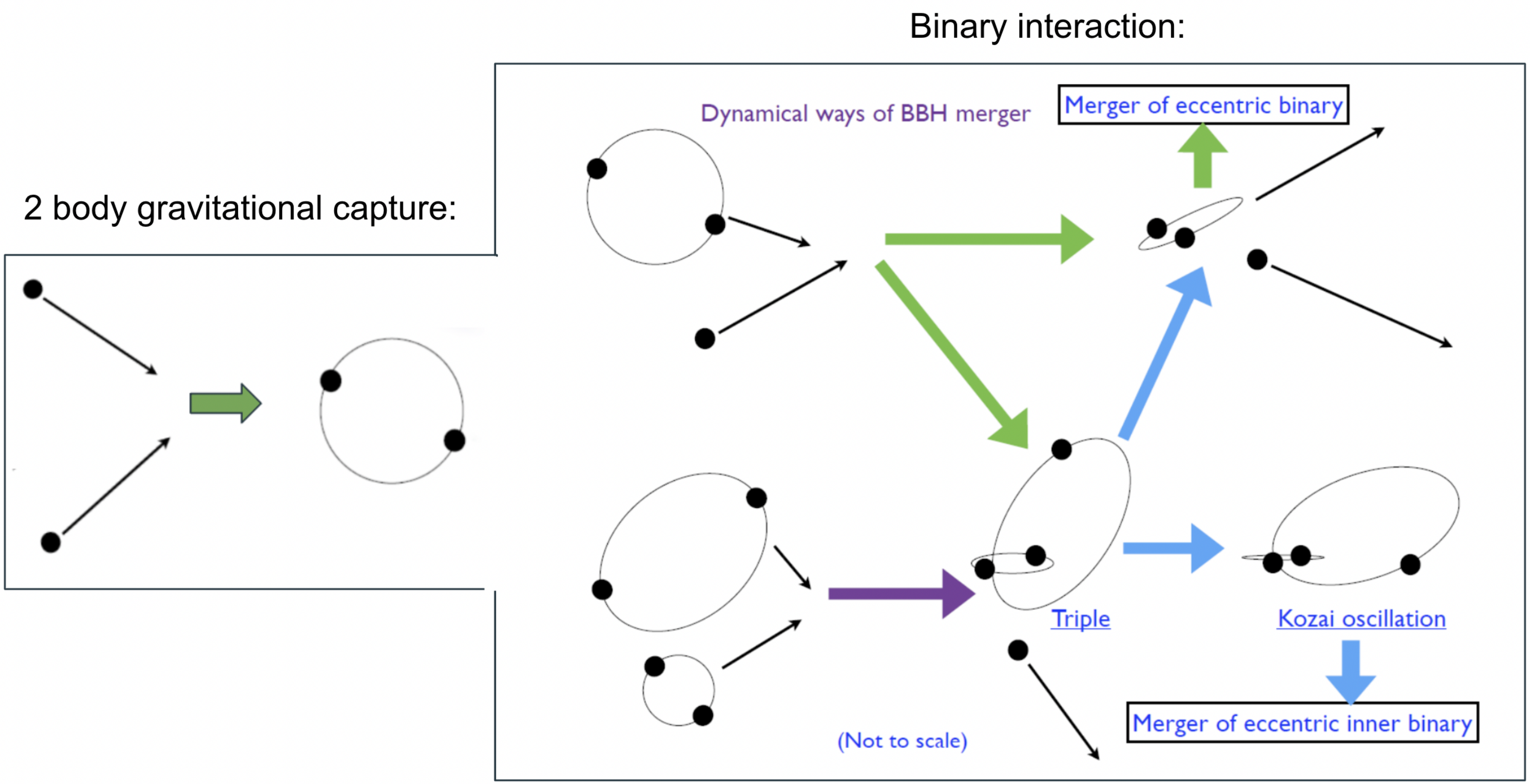


FOCUSING on the Stellar mass range

The LIGO-VIRGO-KAGRA list of GW Events' masses



Possible paths for mergers of stellar-mass PBHs in dark matter halos

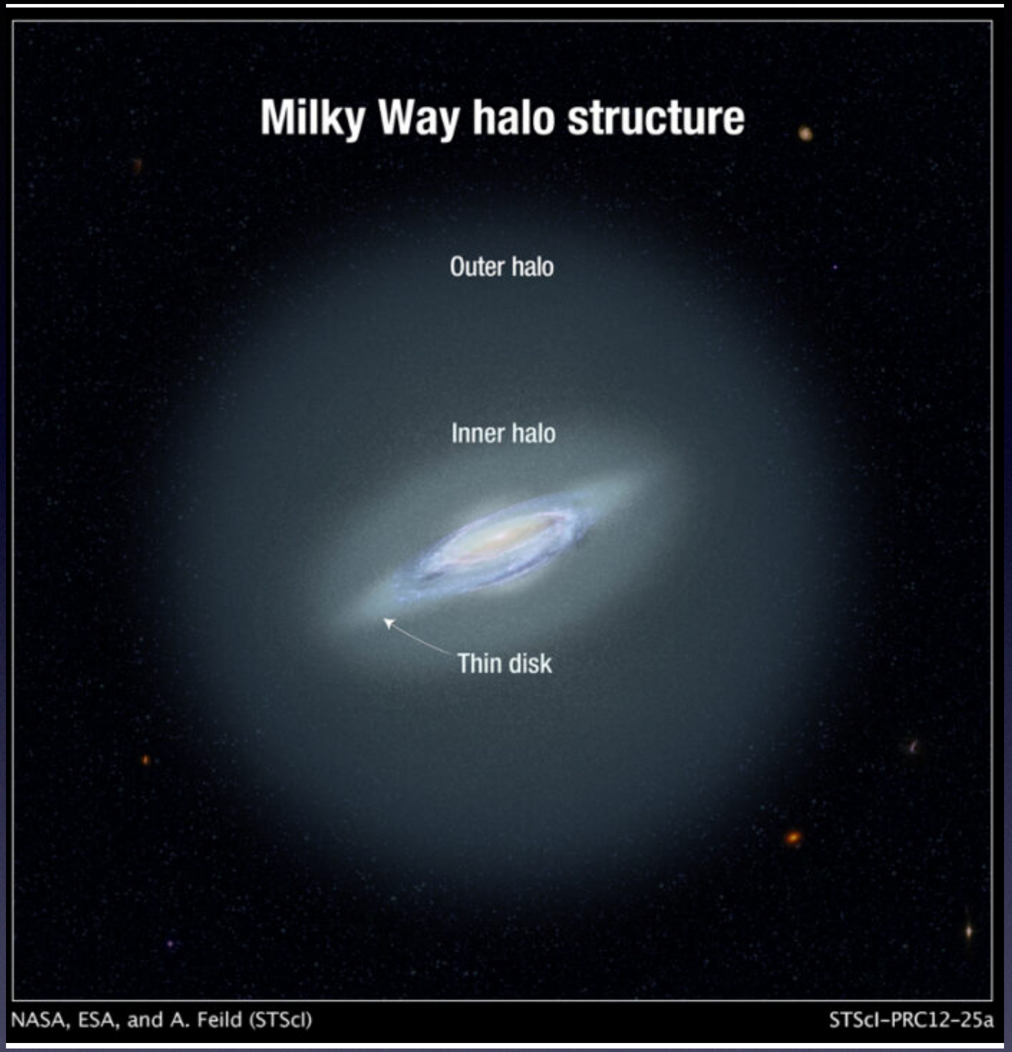


How fast do two BHs form a binary (from direct captures)?

$$\sigma = 2^{3/7}\,\pi \left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v}{c}\right)^{-18/7}$$

In easy units:

$$\sigma = 1.37 \times 10^{-14}\, M_{30}^2\, v_{199}^{-18/7}\, \mathrm{pc}^2$$



Assuming an NFW profile for the PBHs:

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/R_s)\cdot(1+r/R_s)^2}$$

One gets a Rate of PBHs mergers:

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2\, \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh} \rangle \; dr$$

Updates on PBH merger rates

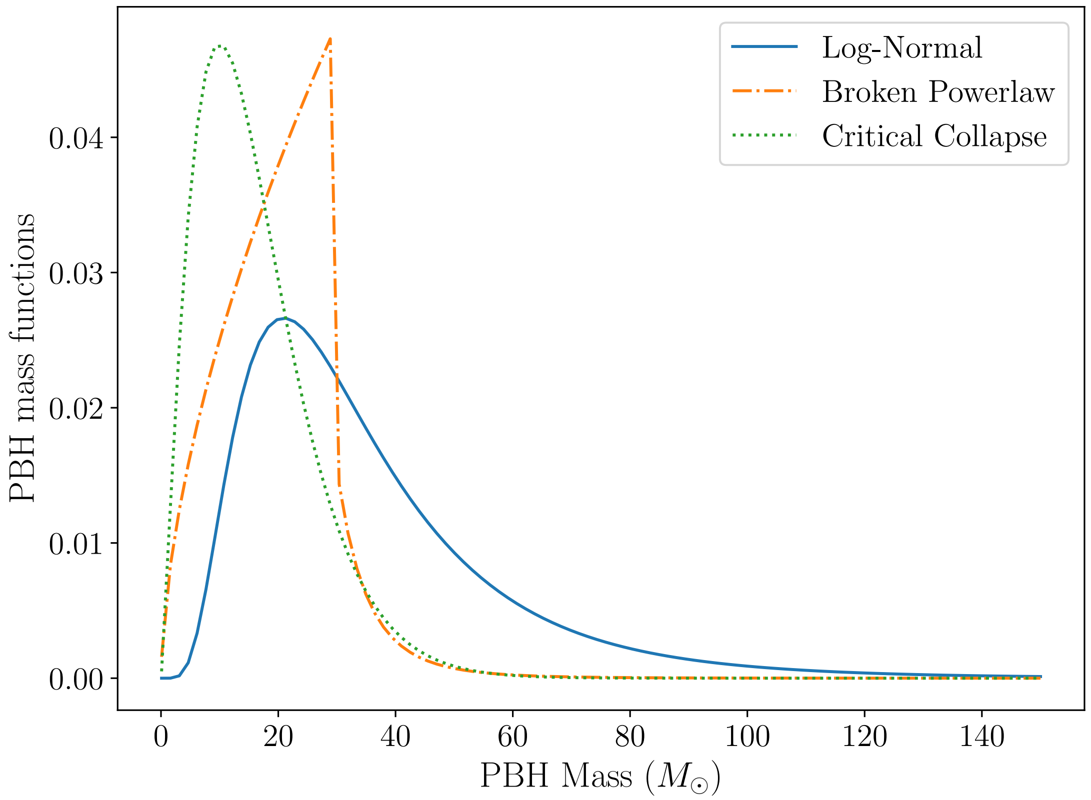
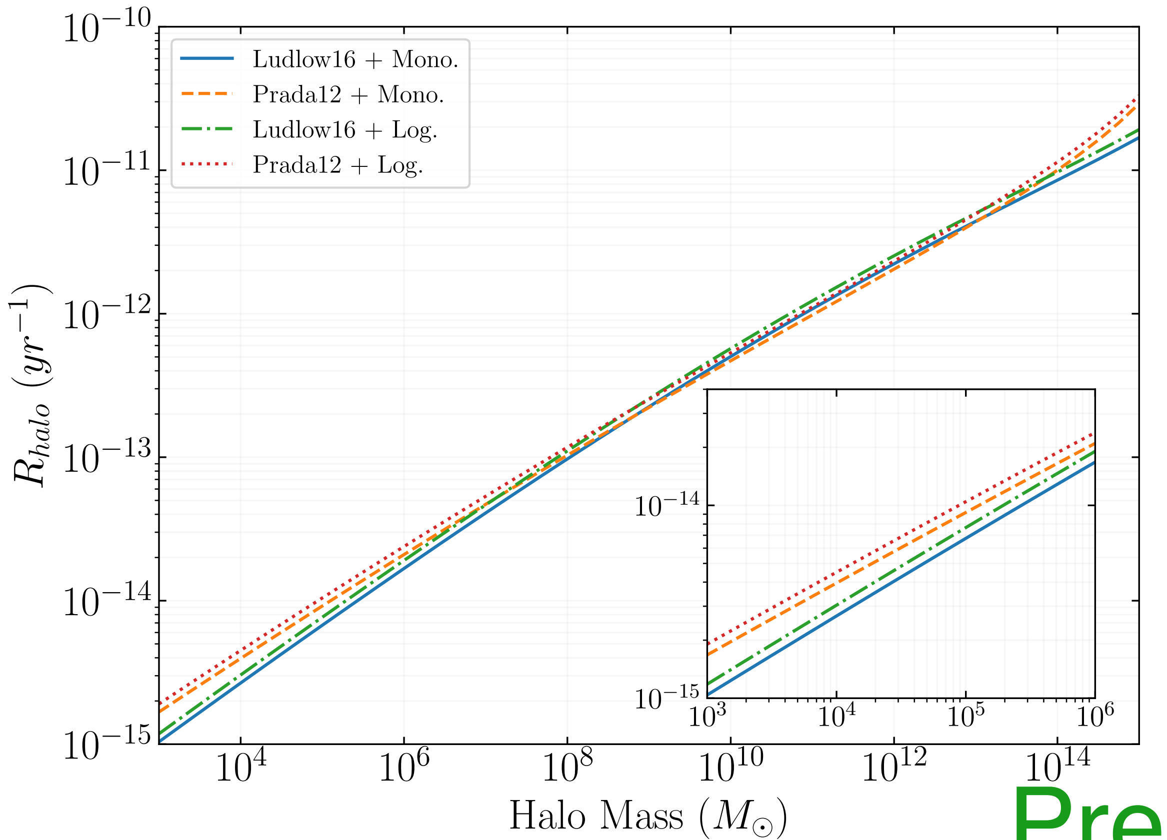
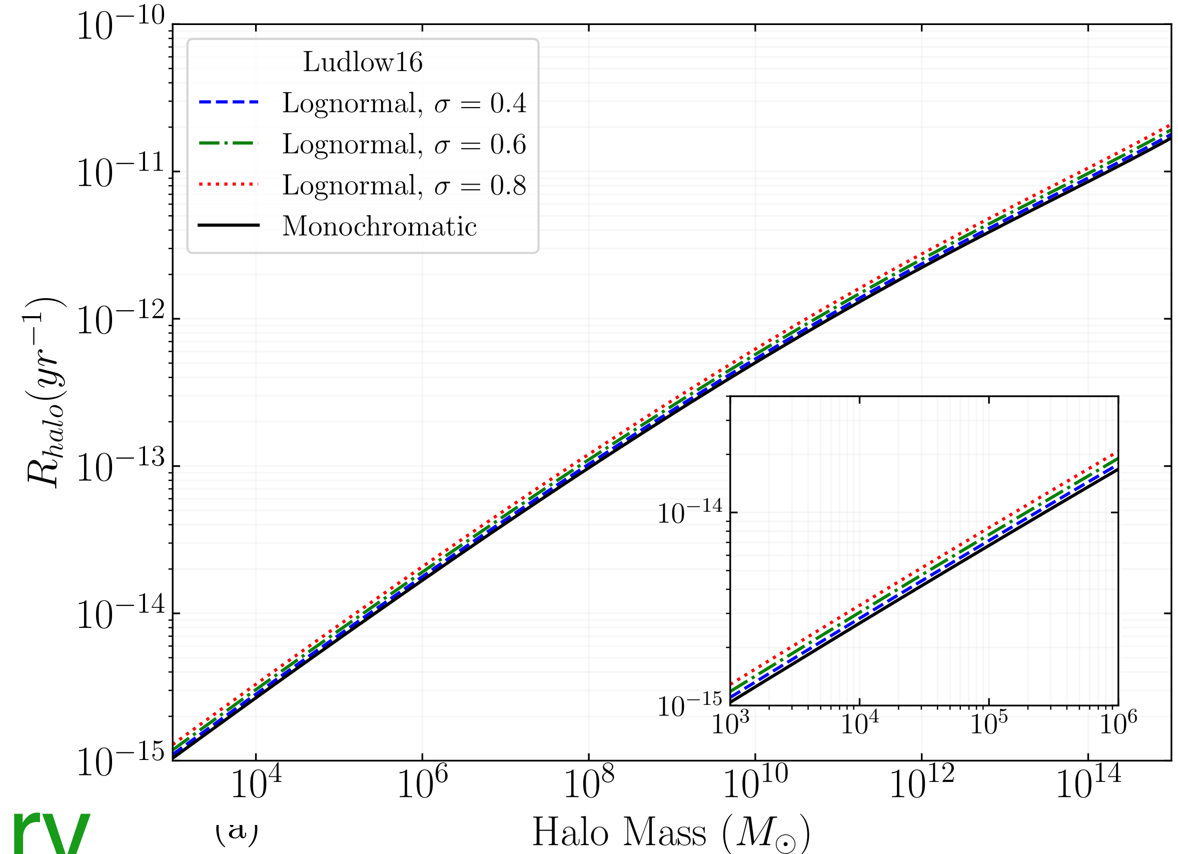


FIG. 6: Distributions of PBH mass: a) lognormal, broken power-law (BPL), and critical collapse (CC) mass function. b) log-normal distributions across various σ values

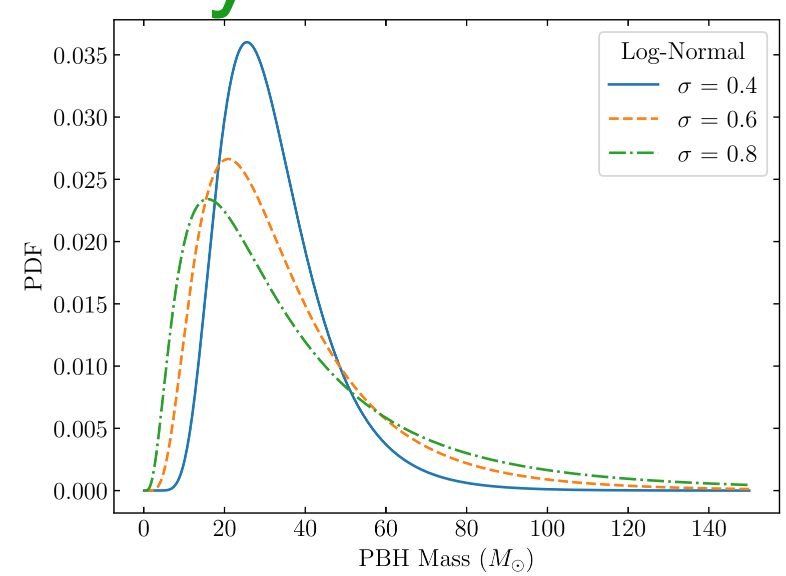
Aljaf and IC (in progress)

Updates on PBH merger rates





Preliminary

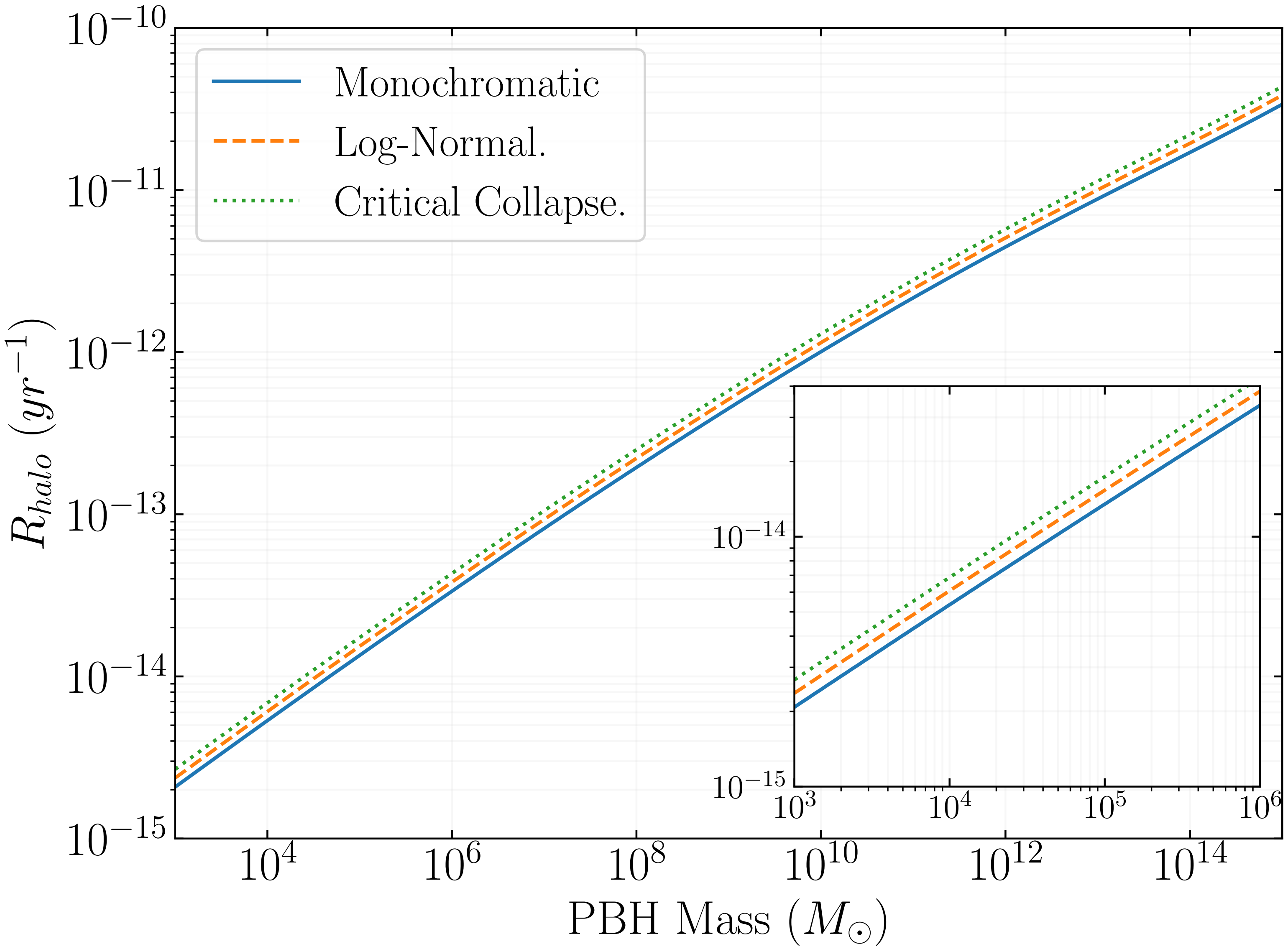


Taking a distribution of PBH-mass to peak around 30 $M_\odot$

Rates evaluated a redshift z=0

Aljaf and IC (in progress)

Updates on PBH merger rates

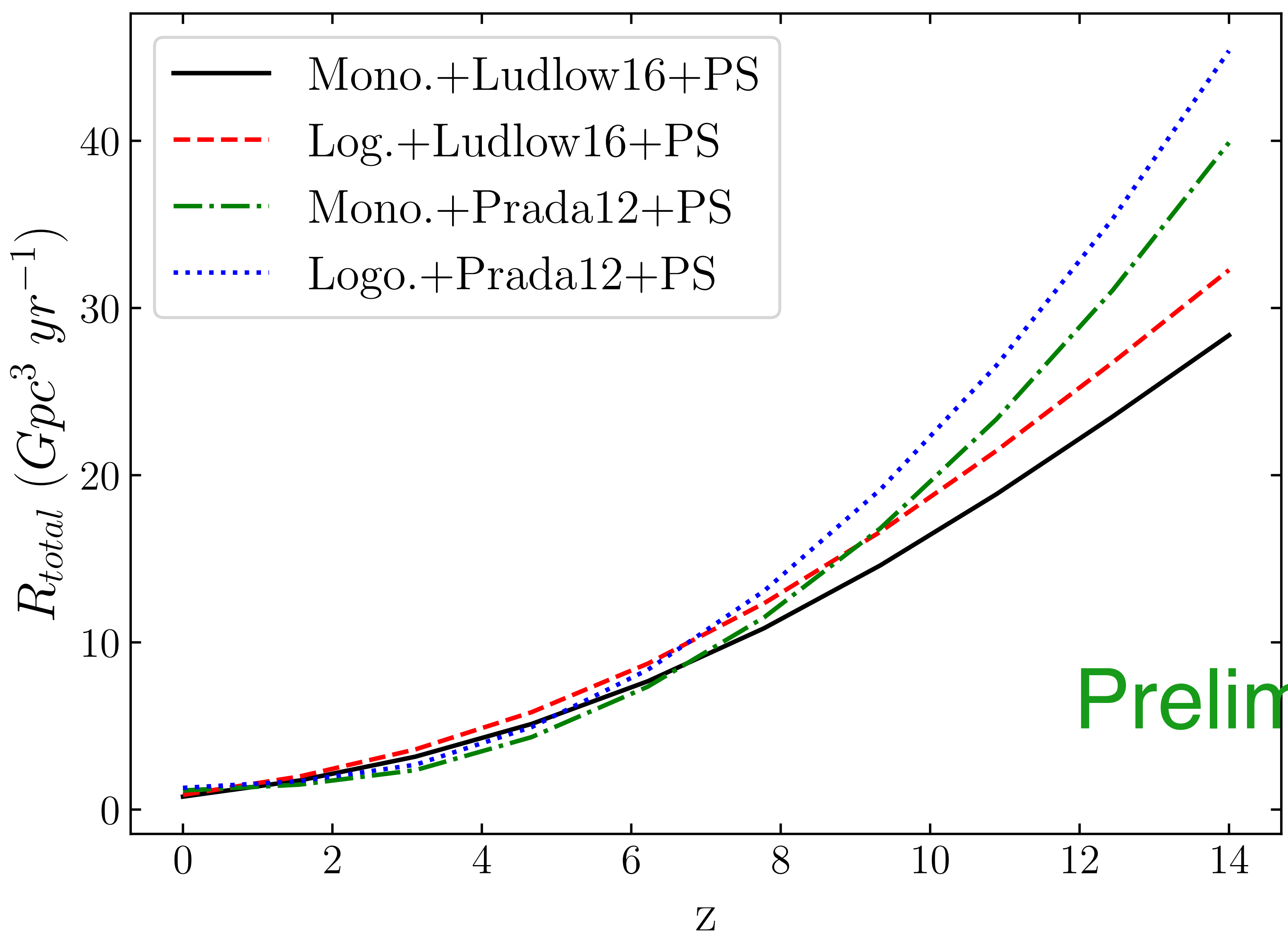


Taking a distribution of PBH-mass to peak around 30 $M_{\odot}$

Rates evaluated a redshift z=0

Aljaf and IC (in progress)

Direct capture PBH merger rates vs redshift
Assuming all DM is in PBHs



Preliminary

Aljaf and IC (in progress)

FIG. 7: The total merger rate for Press-Shecter mass function

PBH merger rates from three-body interactions

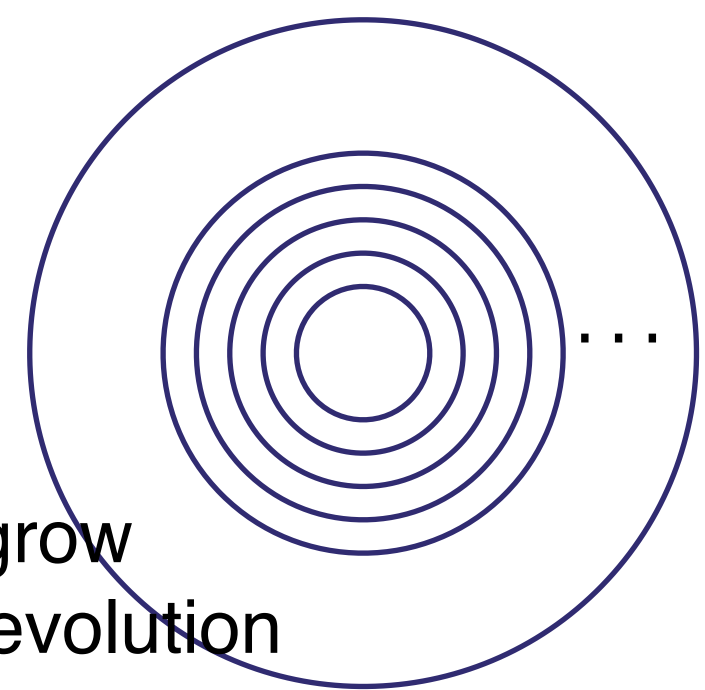
Within a DM halo some PBHs will be as single objects and others will be in binaries. We take a certain fraction of them in binaries. Of those binaries only those satisfying,

$$a_h = \frac{G m_1}{4 v_{dis}^2} \quad \text{with} \quad v_{dis.}(r) = \sqrt{\frac{2GM(r)}{r}}$$

will be hard binaries (surviving interactions with other PBHs)

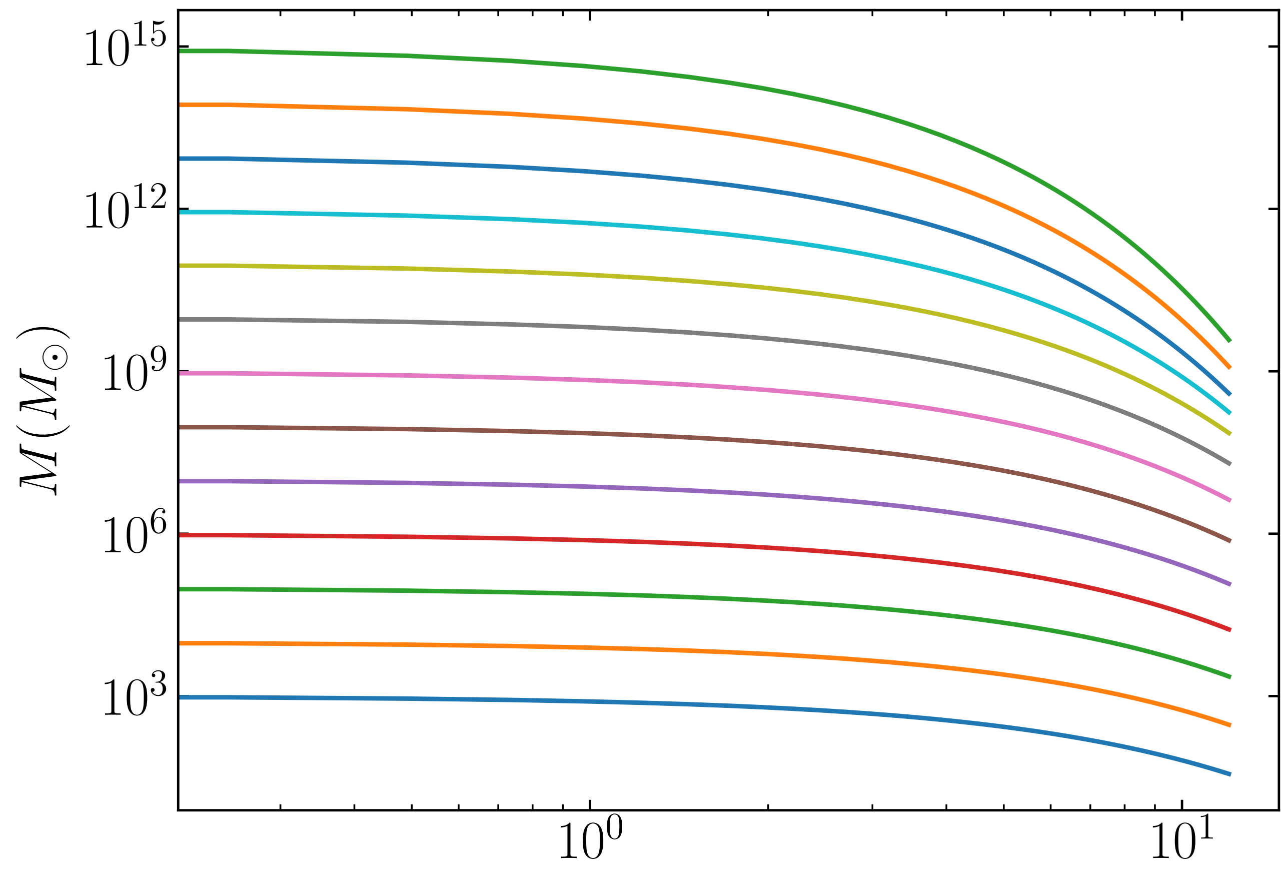
This depends on the of the PBH-binaries location within the DM halo and the properties (mass and concentration) of the DM halo at a given redshift

We subdivide the DM halos in 10 rings and evolve them since redshift of 12



The rings grow with the halo's evolution

Evolution of the total halo mass (we evolve each sub-shell)



We evolve the properties of the PBH hard-binaries:

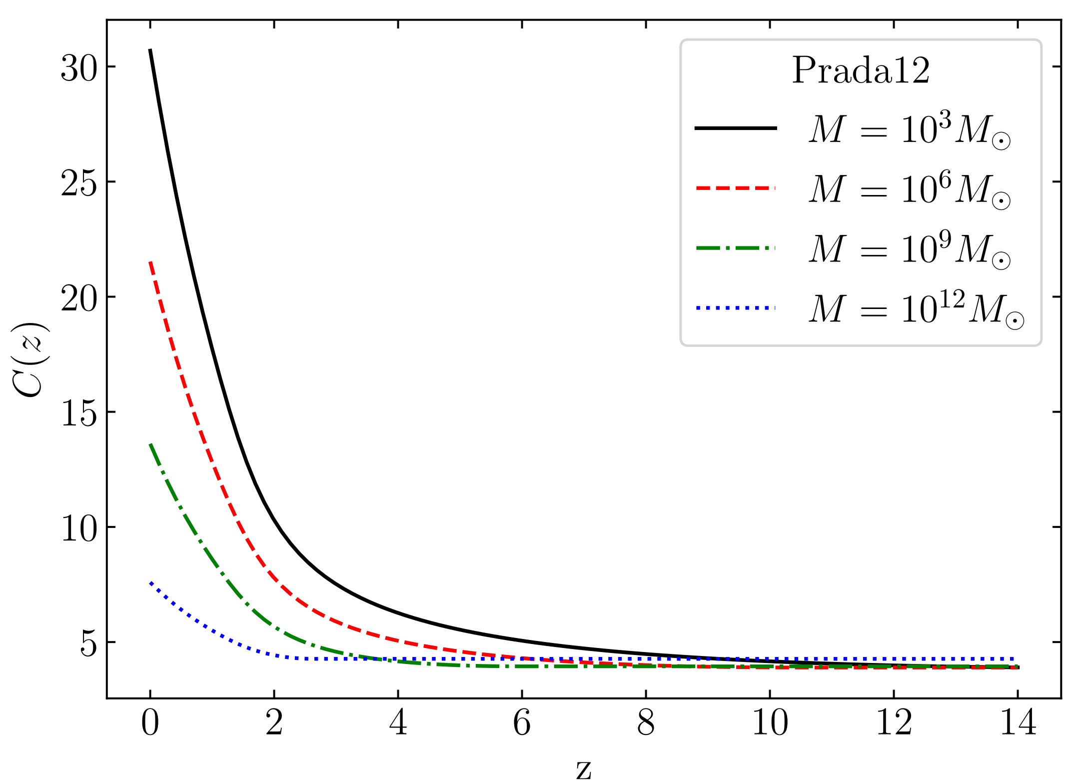
$$\frac{da}{dt} = -\frac{G H \rho_{\text{environment}}}{\sigma_{\text{environment}}} a^2 - \frac{64}{5}\frac{G^3}{c^5 a^3} \times (m_1 + m_2) \cdot (m_1 \cdot m_2)\, F(e)$$

Peters GW emission terms

$$\frac{de}{dt} = \frac{G H K \rho_{environment}}{v_{dis.}} a - \frac{304}{15}\frac{G^3}{c^5 a^4} \times (m_1 + m_2)\,(m_1 \cdot m_2)\, D(e)$$

Aljaf and IC (in progress)

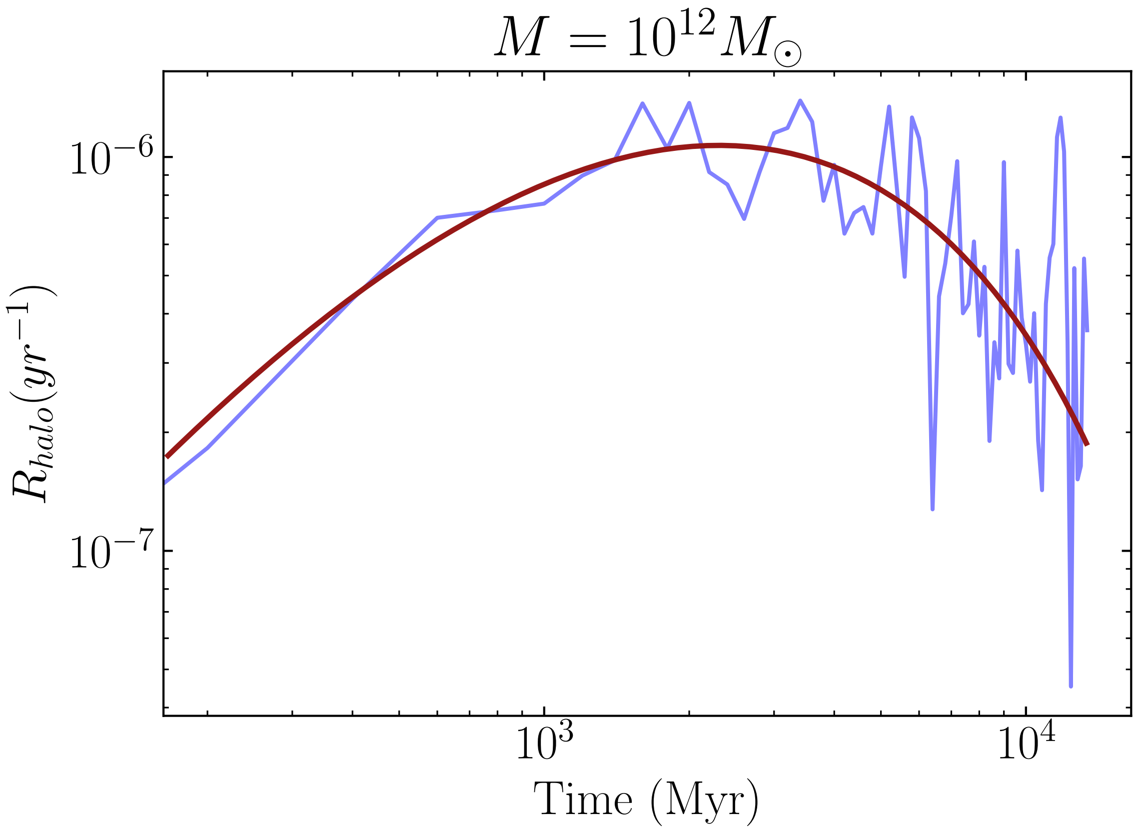
Interaction with PBH-binary environment

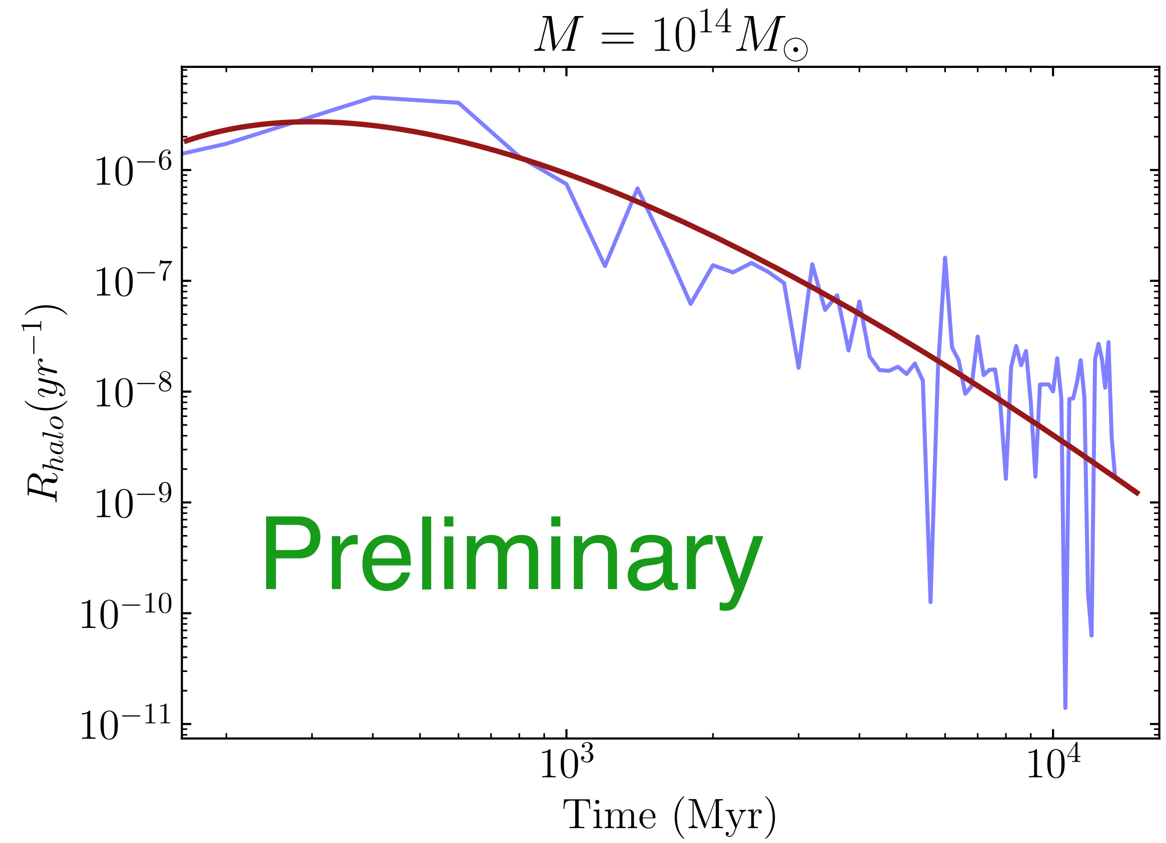


Environment (mass, concentration, density, velocity dispersion) evolve with time

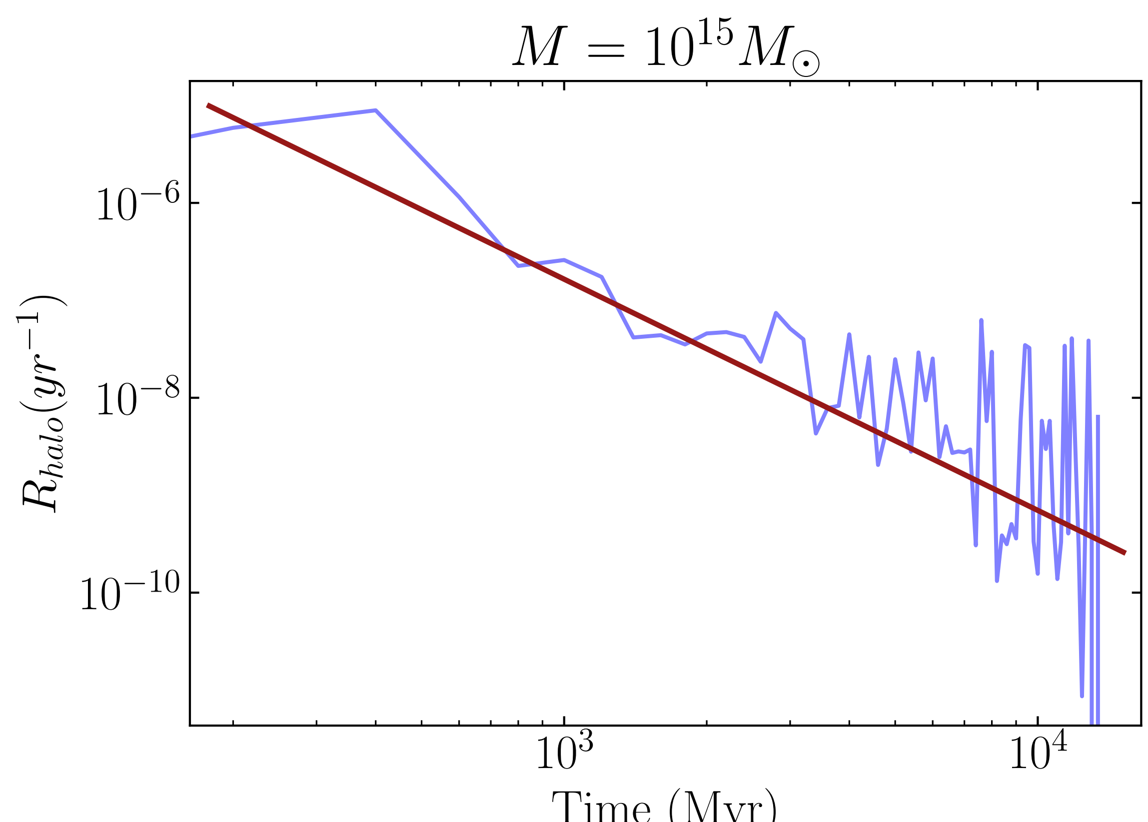
PBH merger rates from three-body interactions vs time

Mass is halo mass at z=0





Smaller PBH halos have a peak merger rate at later times…



Aljaf and IC (in progress)

We are in the process of including an updated three-body contribution

Connecting to the LIGO-VIRGO-KAGRA list of Binary Merger Events

The O1, O2, O3 (GWTC-3) list of LVK events

Name	**FAR**$_{\rm min}$ (yr^{-1})	$p_{\rm astro}$	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	**First appears in**
GW150914	$< 1 \times 10^{-5}$	> 0.99	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	[13]
GW151012	7.92×10^{-3}	> 0.99	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	[14]
GW151226	$< 1 \times 10^{-5}$	> 0.99	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	[15]
GW170104	$< 1 \times 10^{-5}$	> 0.99	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	[16]
GW170608	$< 1 \times 10^{-5}$	> 0.99	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	[17]
GW170729	1.80×10^{-1}	0.98	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	[2]
GW170809	$< 1 \times 10^{-5}$	> 0.99	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	[2]
GW170814	$< 1 \times 10^{-5}$	> 0.99	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	[18]
GW170817	$< 1 \times 10^{-5}$	> 0.99	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	[19]
GW170818	$< 1 \times 10^{-5}$	> 0.99	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	[2]
GW170823	$< 1 \times 10^{-5}$	> 0.99	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	[2]
GW190408_181802	$< 1 \times 10^{-5}$	> 0.99	$24.6^{+5.1}_{-3.4}$	$18.4^{+3.3}_{-3.6}$	$18.3^{+1.9}_{-1.2}$	$-0.03^{+0.14}_{-0.19}$	[4]
GW190412_053044	$< 1 \times 10^{-5}$	> 0.99	$30.1^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$13.3^{+0.4}_{-0.3}$	$0.25^{+0.08}_{-0.11}$	[20]

Abbott et al. PRX 2023

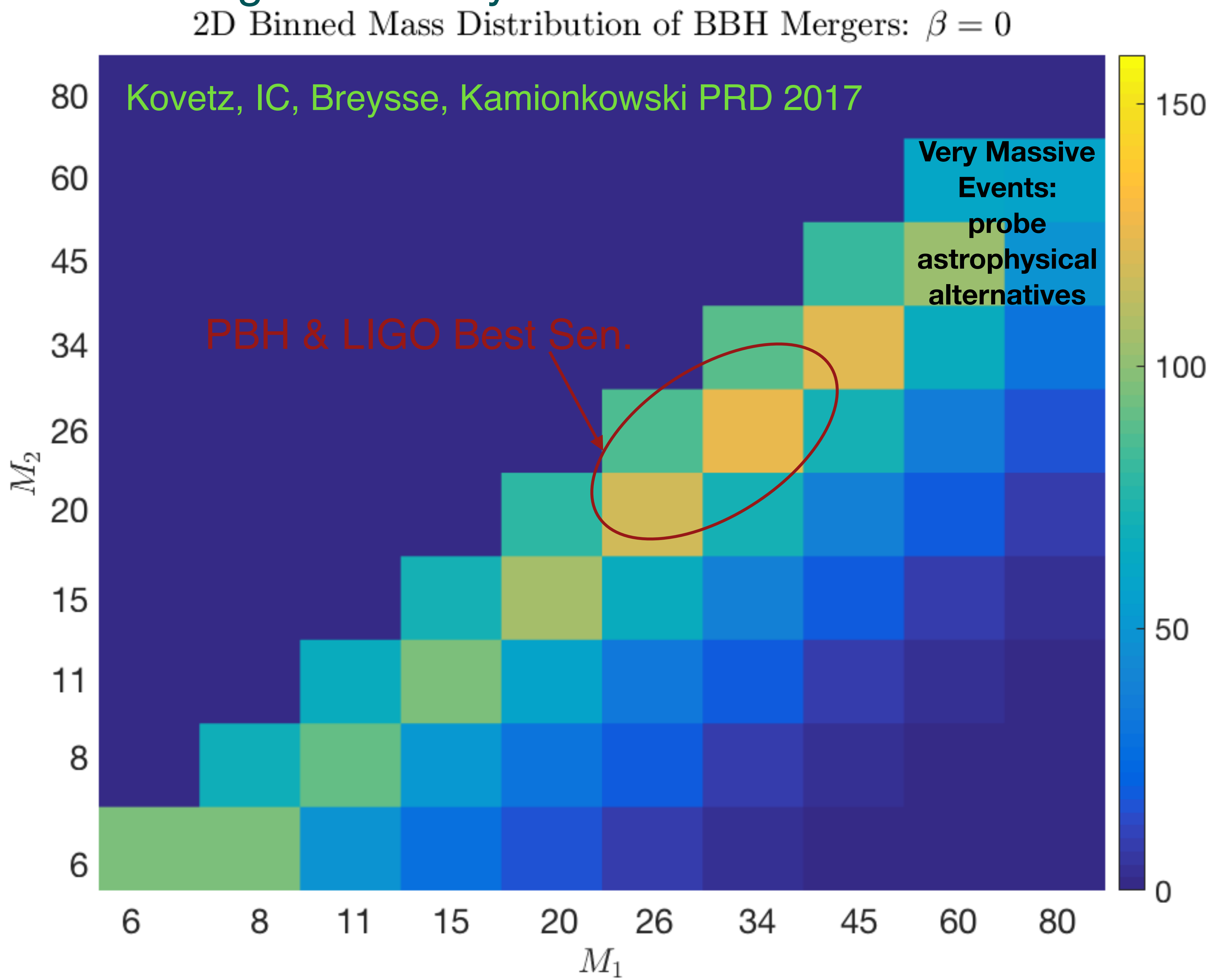
...

We use binary black hole mergers with a false alarm rate (FAR) $< 1\ {\rm yr}^{-1}$

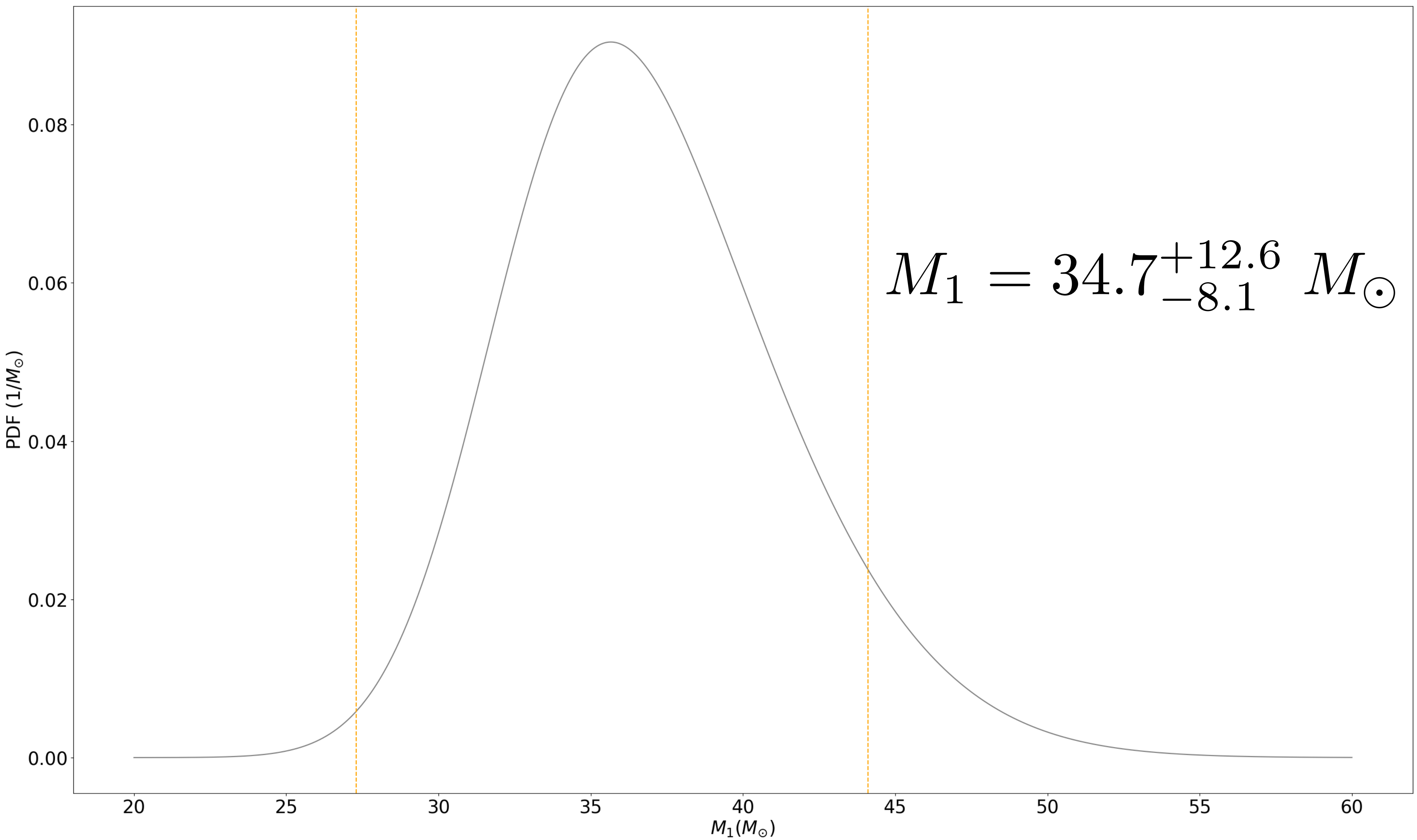
Take M_1 and M_2 values

El Bouhaddouti and IC (in progress)

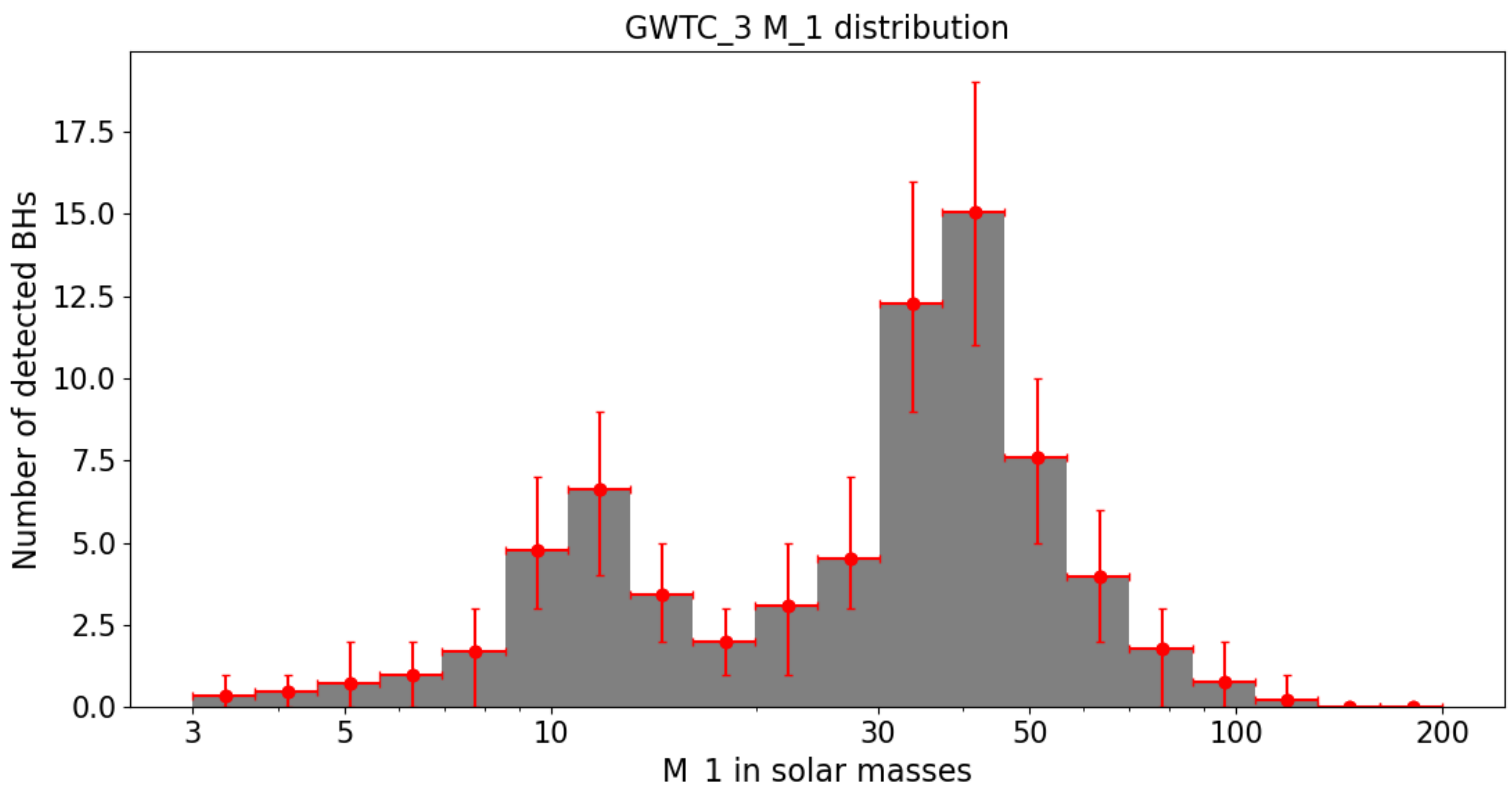
With aLIGO design sensitivity



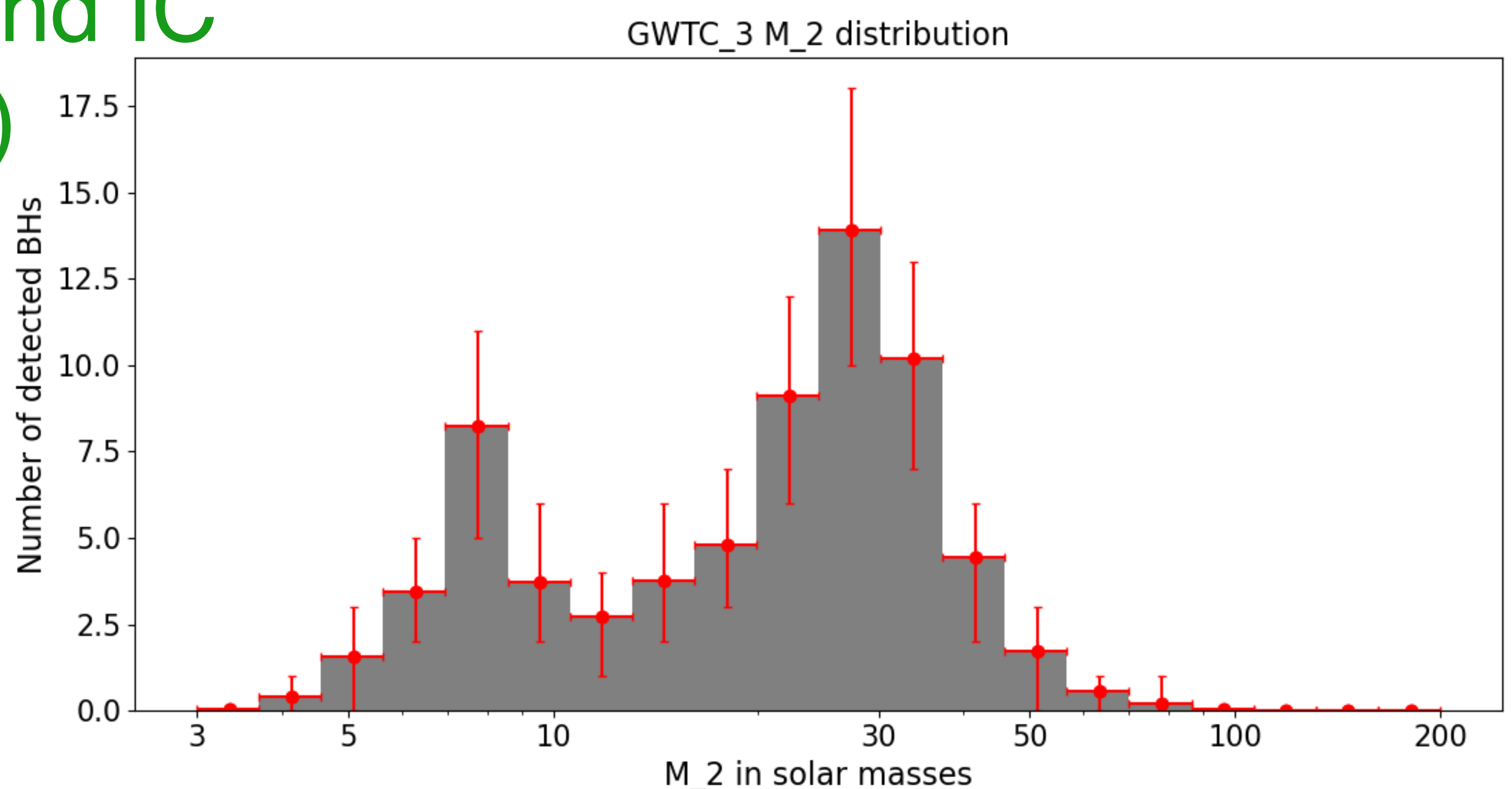
Using a skew-normal distribution for each BBH merger event,



And then summing up the M_1 and M_2 distributions



El Bouhaddouti and IC
(in progress)



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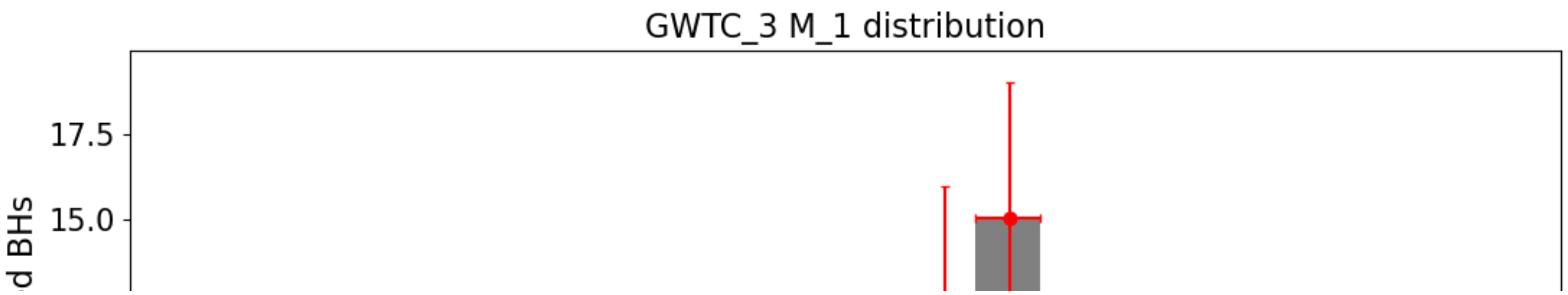
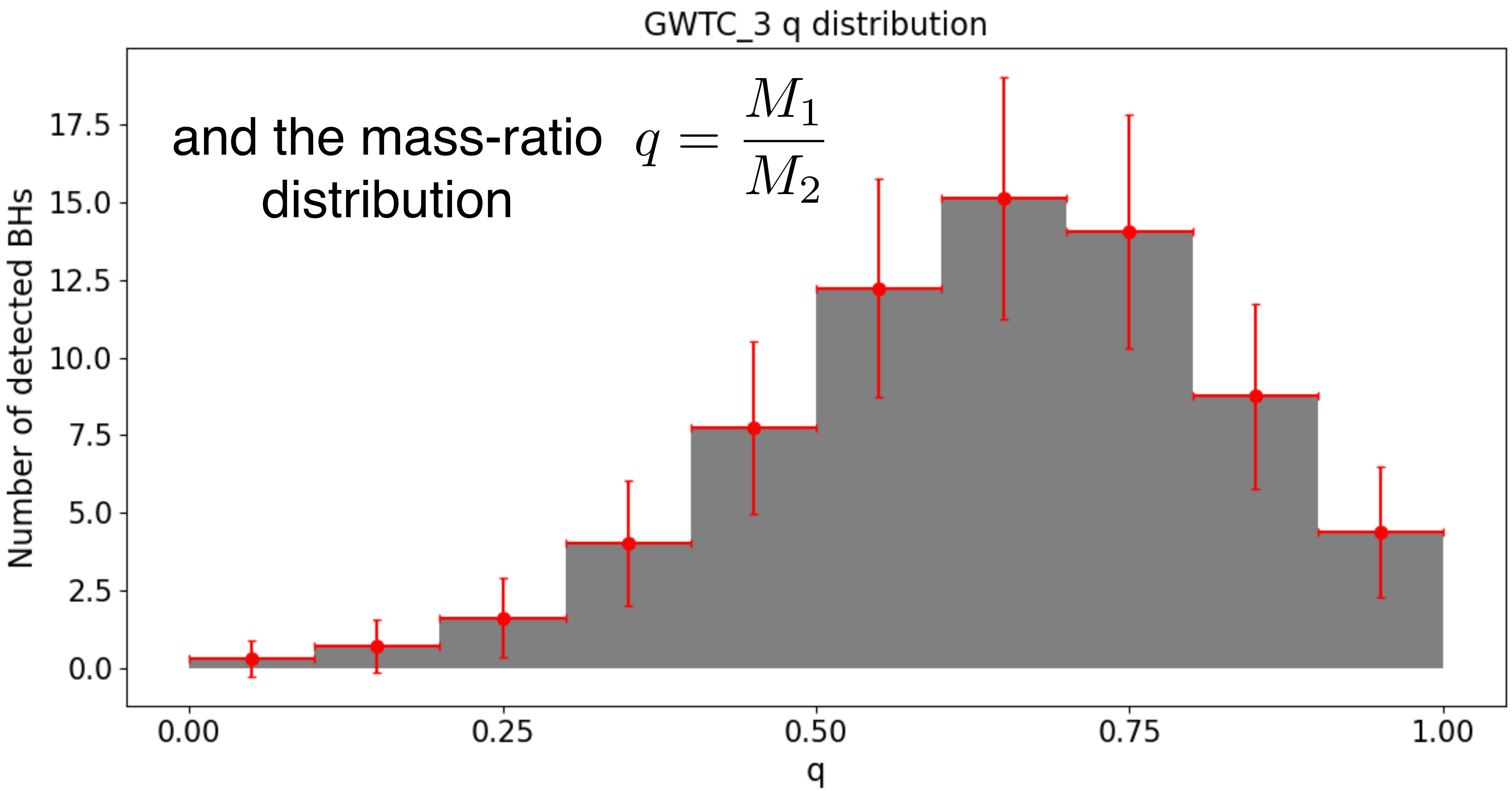
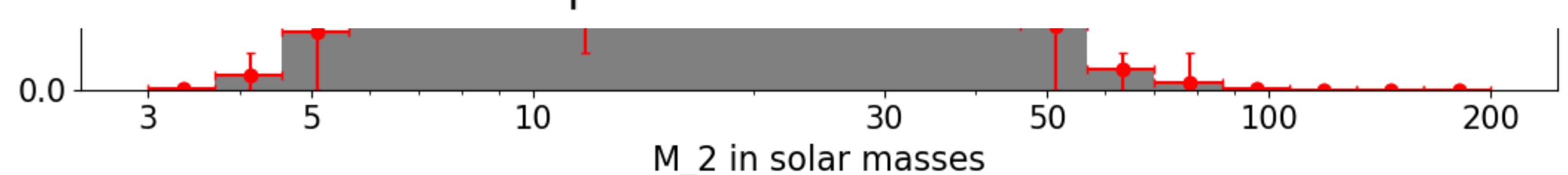


and the mass-ratio $q = \frac{M_1}{M_2}$ distribution





We then simulate BBH populations.

I) A regular population of stellar-origin BBHs with:

$$\frac{dN}{dM_1} \propto H[M_1 - M_{min}]\, M_1^{-\alpha}$$

or

$$\frac{dN}{dM_1} \propto H[M_1 - M_{min}]\, M_1^{-\alpha}\, exp\{-\frac{M_1}{M_{cut}}\}$$

with

$$\frac{dN}{dq} \propto q^{\beta}$$ and $$\frac{dN}{d(z+1)} \propto (1+z)^{\kappa}$$

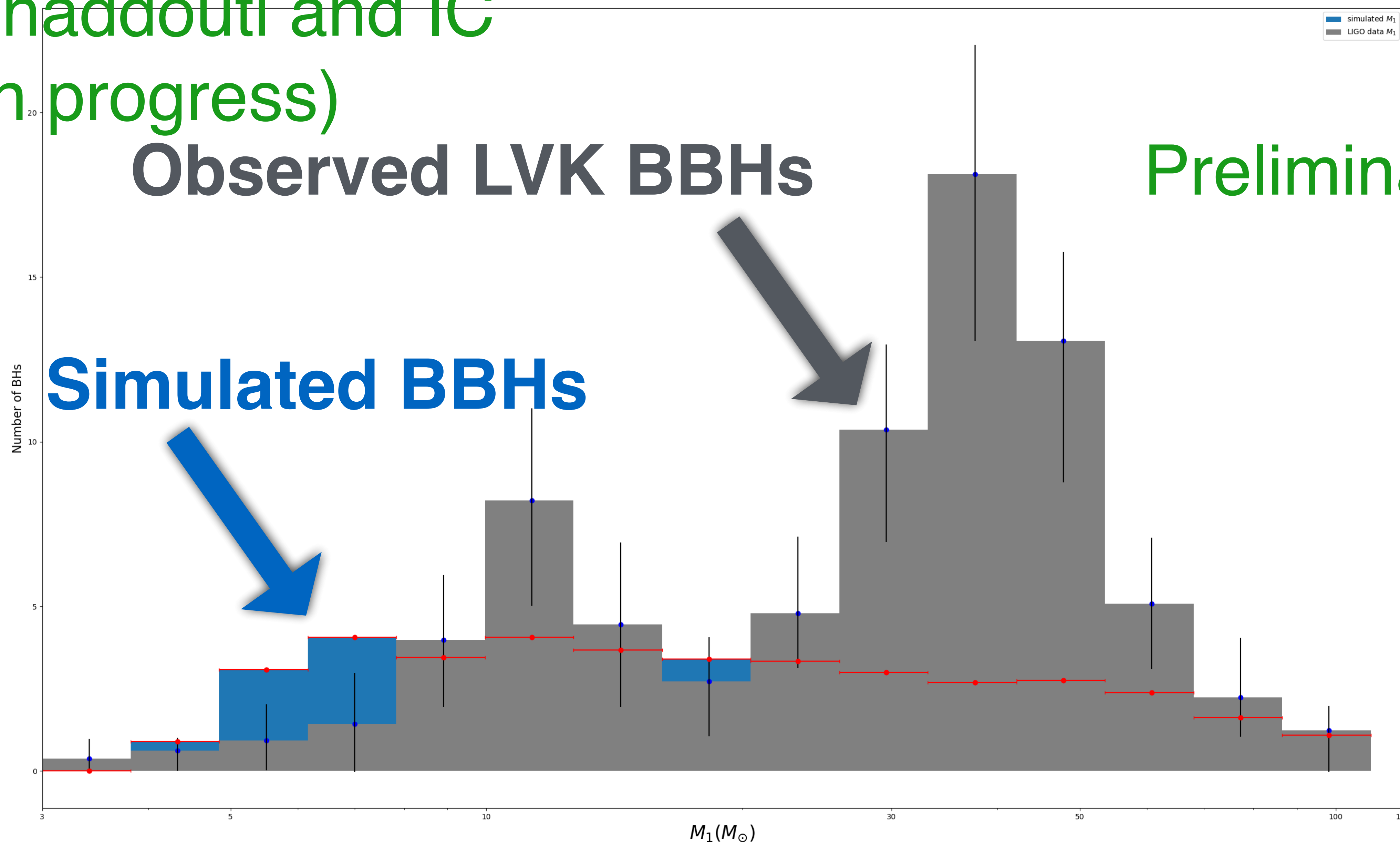
II) A Binary PBH population

And calculate the Signal to Noise ratio for the LVK sensitivities

And then fit to the LVK data

An example of $\alpha = 2.52, \beta = 0.2, \kappa = 2.9$

El Bouhaddouti and IC (in progress)



We find that the second peak at ~40 solar masses forces us to assume somewhat strange assumptions on the stellar-origin BBH population. However, LVK O4 runs will truly determine if indeed this is significant enough. In the process of deriving PBH limits.

Conclusions

- The rate of stellar-mass PBHs mergers from direct captures depends only within a factor of 3 on the exact mass-distribution (for the LIGO-Virgo-KAGRA range)
- We have included three-body PBH-binary to PBH interactions by evolving the DM halos properties. Most of the three-body interactions happen early on in the history of the DM halos.
- At early times the three-body interactions are important to include
- We are in the process of updating PBH limits form the LIGO-Virgo-KAGRA observations

Acknowledgements

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Thank you!