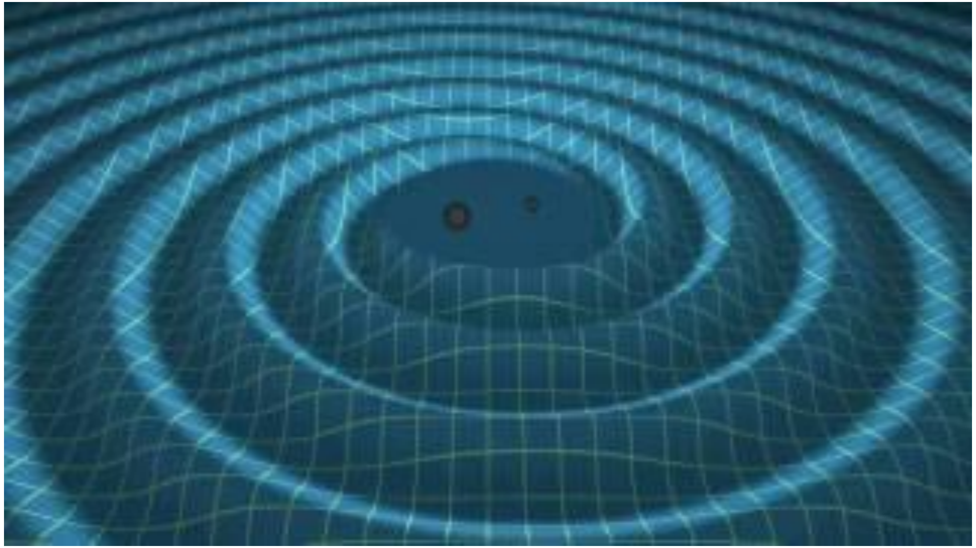
3rd Astro-COLIBRI multi-messenger astrophysics workshop
Sep 16 - 20, 2024

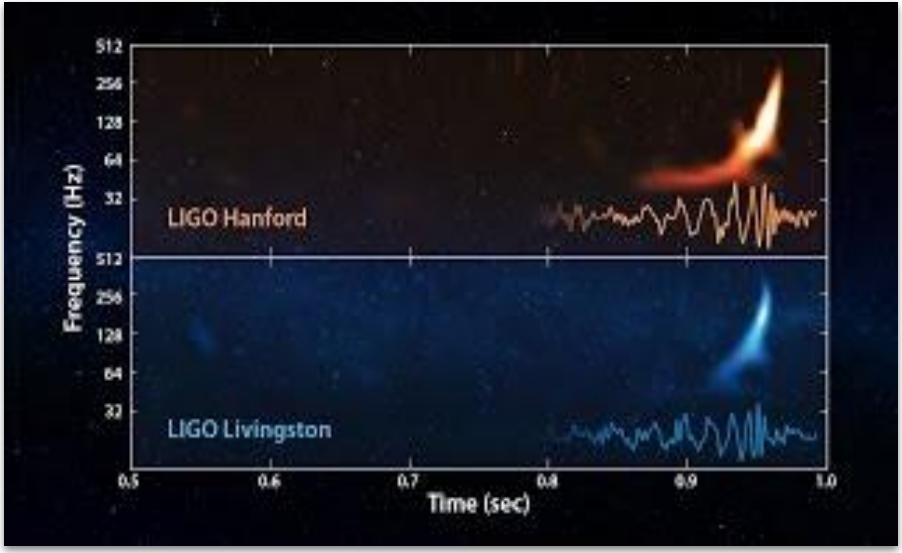
Constraining Astrophysical Observables using Gravitational Wave Background

Musfar Muhamed Kozhikkal

MMK, Siyuan Chen, Gilles Theureau, Melanie Habouzit and Alberto Sesana, ”Mass-redshift dependency of supermassive black hole binaries for the gravitational wave background,” MNRAS 531 (2024) 1 1931-1950, doi:10.1093/mnras/stae1219, [arXiv:2305.18293 [astro-ph.CO]].



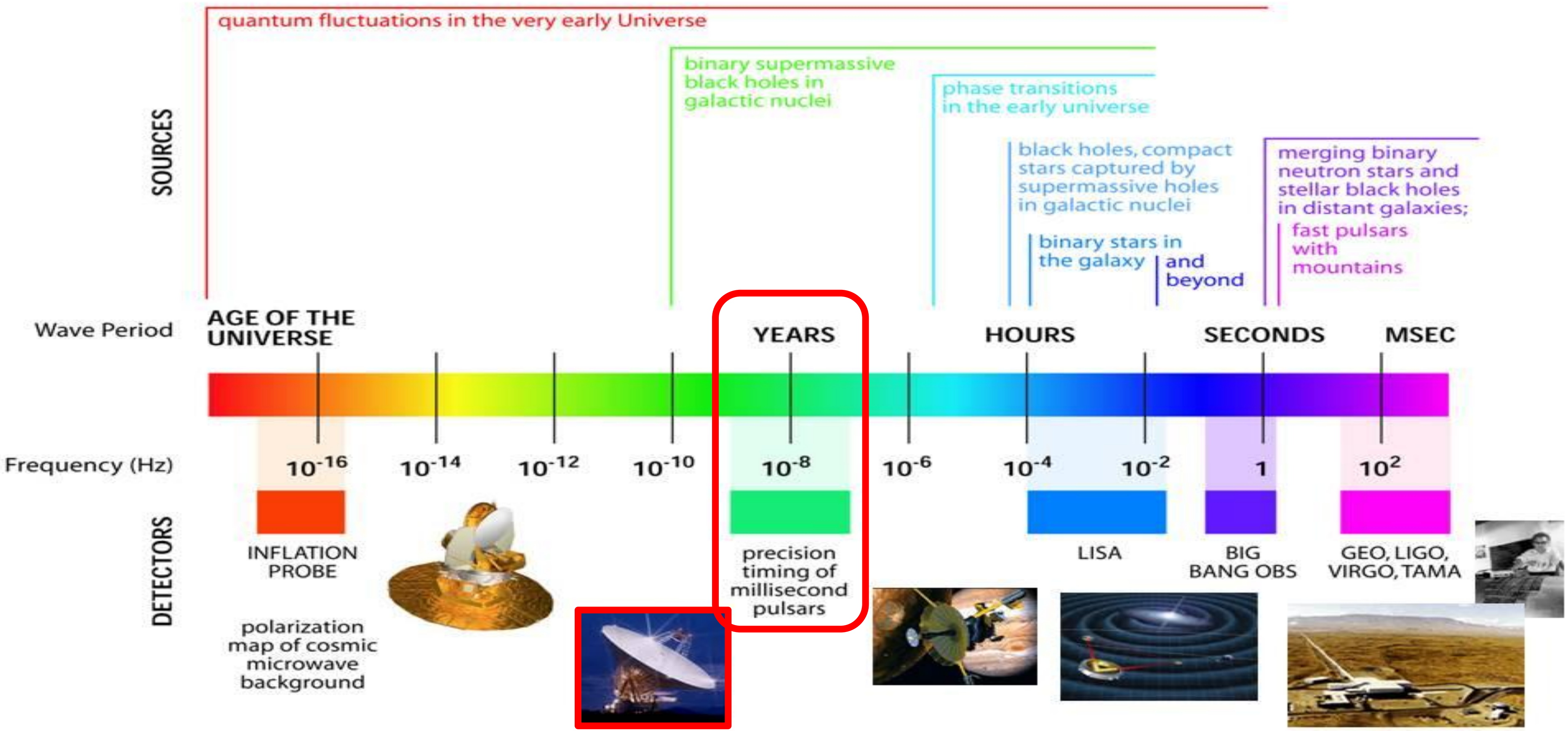
Credits: LIGO



Credits: LIGO

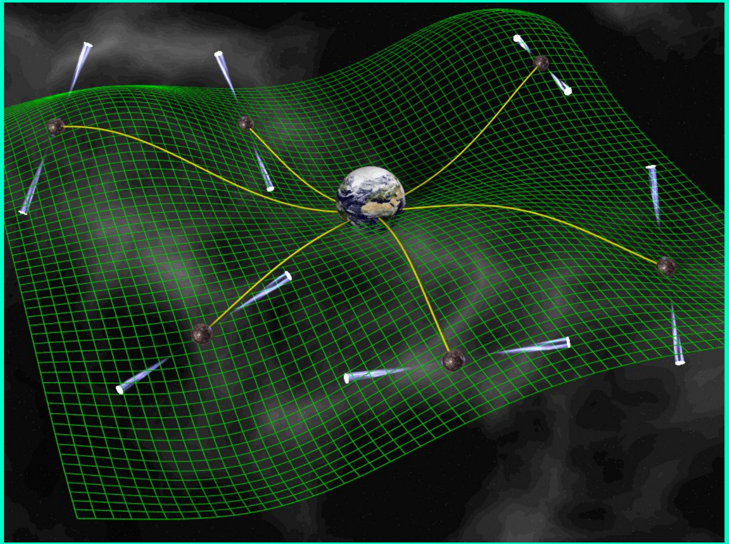
Gravitational waves are ripples in the curvature of spacetime caused by certain gravitational interactions, predicted by Einstein's theory of general relativity.

THE GRAVITATIONAL WAVE SPECTRUM

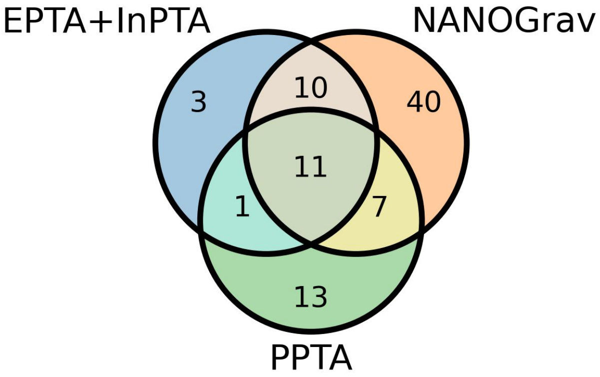


Credits: Chris Henze

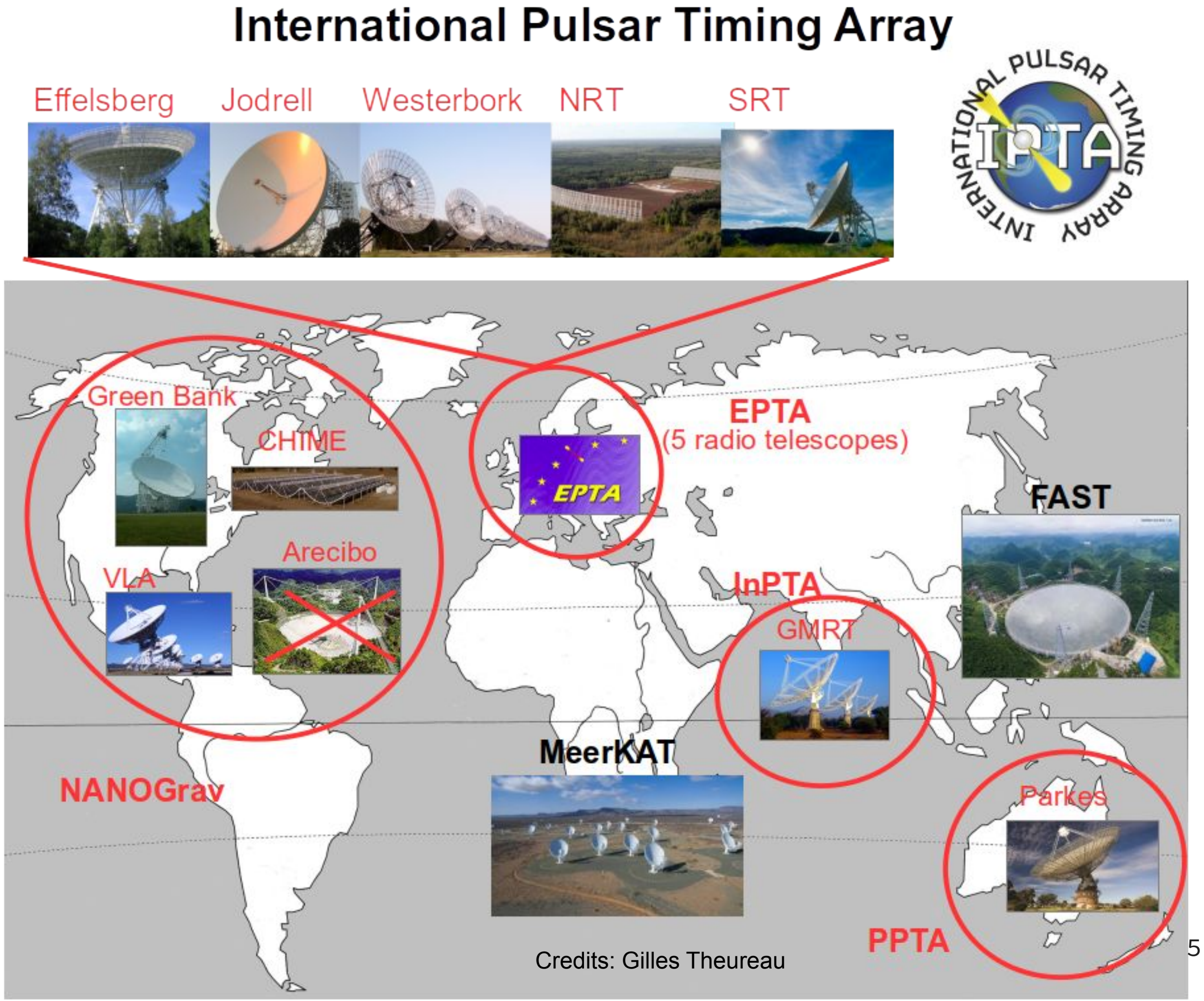
- Pulsars are rapidly spinning, high magnetized, dense neutron stars which emits coherent radio wave pulses along the its magnetic axes.
- The millisecond pulsars (MSPs), have very stable rotation periods in the order of milliseconds (1-10ms) observed with high timing precision (order of 100 ns).
- The gravitational wave cause distortion in spacetime and these signature of distortion will be seen in the time of arrival pulse of MSPs.
- GW effects are correlated for all pulsars, we need multiple pulsar observation for few years to get the GWB.



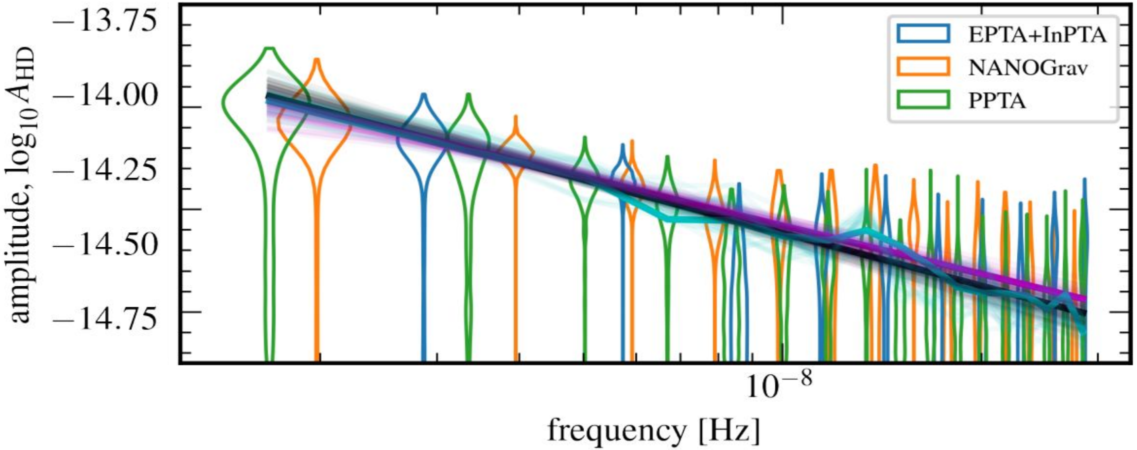
Credits: David Champion



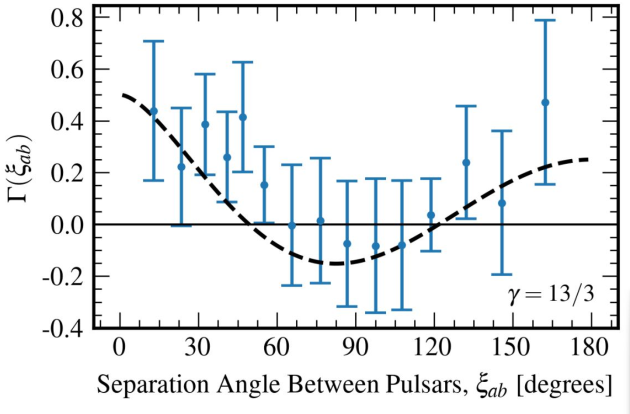
Credits: IPTA 2024



Credits: Gilles Theureau

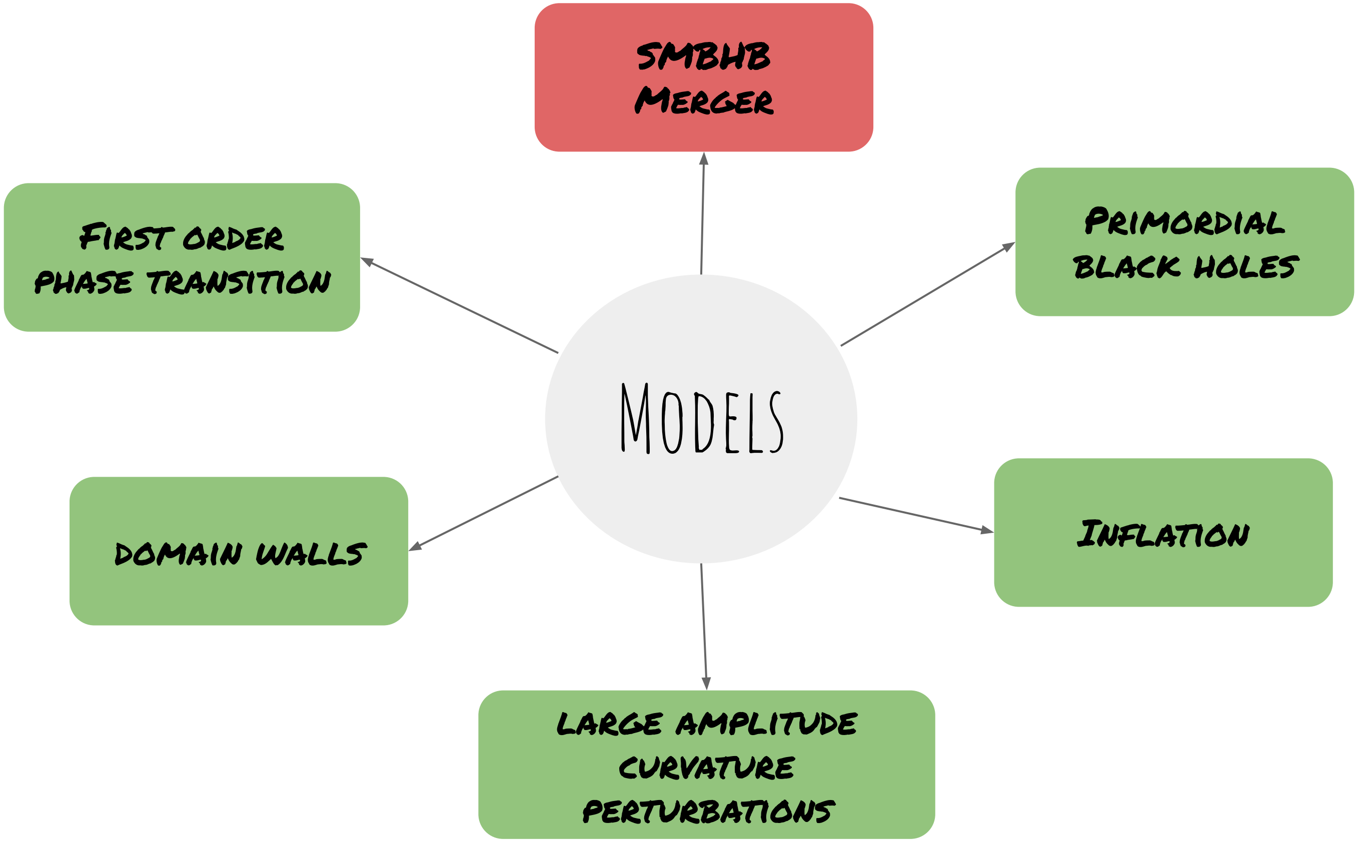


Credits: IPTA 2024

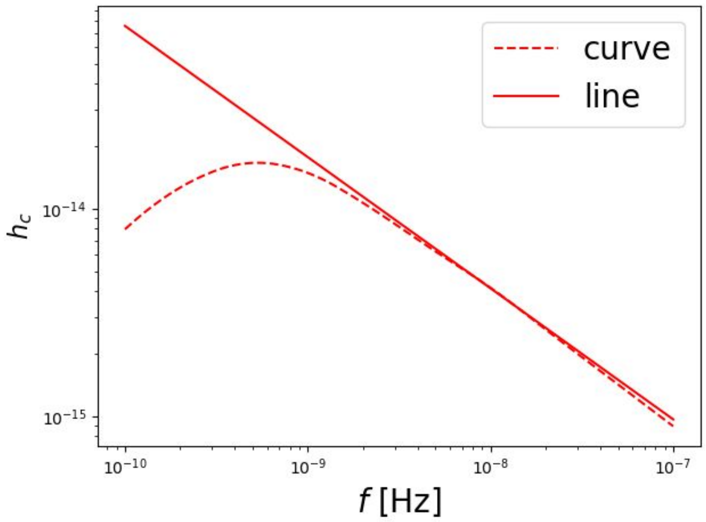


Credits: NANOGrav 2023

Gravitational wave background refers to the collection of gravitational waves that are continuously present in the universe, resulting from various astrophysical processes. Unlike transient events that produce detectable signals, the background consists of a superposition of many weak signals that cannot be individually resolved.


SMBHB
Merger
First order
phase transition
Primordial
black holes
Models
domain walls
Inflation
large amplitude
curvature
perturbations

- The GWB characteristic spectrum h_c we get from coalescence Super Massive Black Hole Binaries (SMBHBs) describes the GWs relative strength.
- A meter of space-time squashes and stretches by 10^{-15} m will produce a characteristic spectrum amplitude of 10^{-15}.



$$h_c^2(f) = \frac{4G}{\pi c^2 f} \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}M_{BH} \frac{\mathrm{d}E}{\mathrm{d}f_r} \int_0^1 \frac{\mathrm{d}^3 n}{\mathrm{d}z\, \mathrm{d}M_{BH}\, \mathrm{d}q_{BH}} \mathrm{d}q_{BH}$$

Energy emitted by the each individual binary as GWs per frequency. Function of e

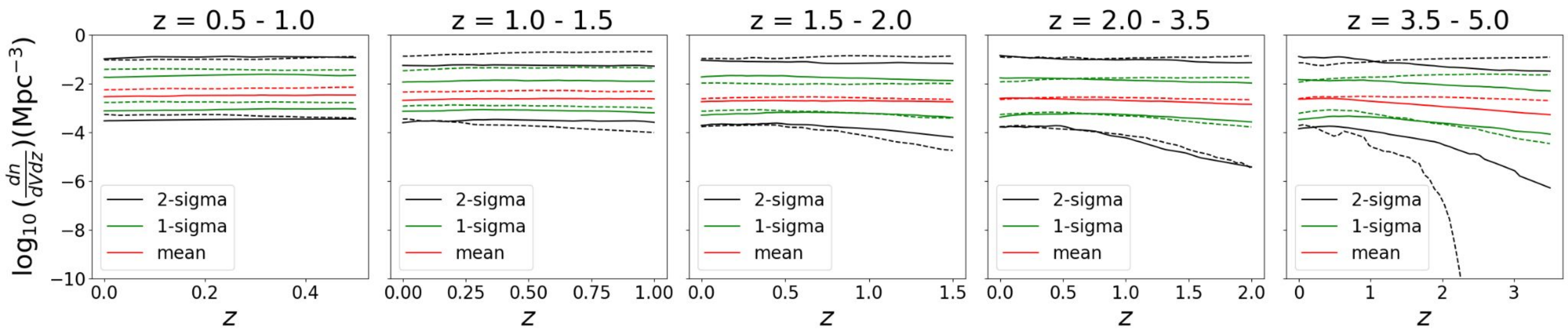
SMBHB merger rate

Merger Rate

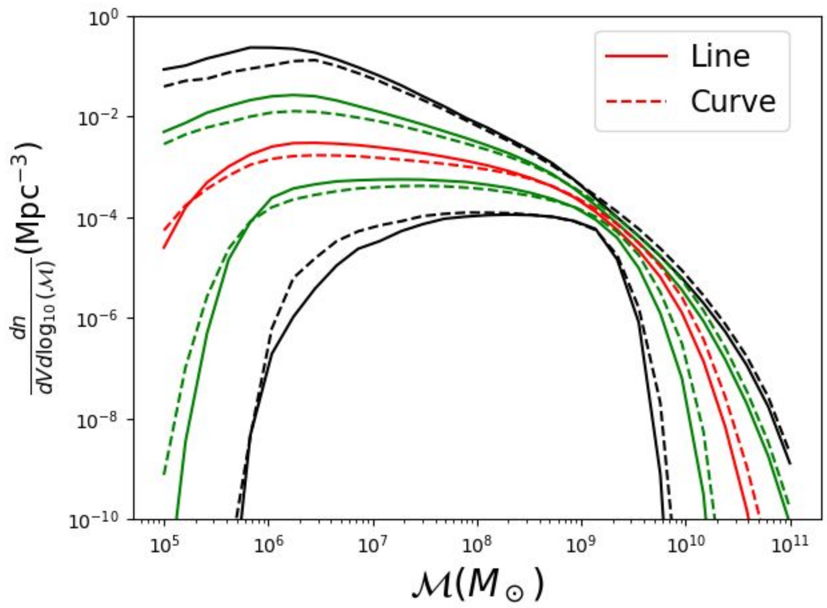
Comoving number density in Mpc^3 of SMBHB mergers

$$\frac{\mathrm{d}^3 n}{\mathrm{d}z\mathrm{d}M_{BH}\mathrm{d}q_{BH}} = \frac{10^{\Phi_0+z\Phi_I} f_0'}{M_0\tau_0}\left(\frac{0.4}{h_0}\right)^{\alpha_\tau}\left(\frac{M}{10^{11}}\right)^{\alpha_f-\alpha_\tau}\left(\frac{M}{M_0}\right)^{\alpha_0+z\alpha_I} e^{-M/M_0}(1+z)^{\beta_f-\beta_\tau} q^{\gamma_f-\gamma_\tau}\frac{\mathrm{d}t}{\mathrm{d}z}\frac{\mathrm{d}M}{\mathrm{d}M_{BH}}\frac{\mathrm{d}q}{\mathrm{d}q_{BH}}$$

Functions	Parameters
Galaxy Stellar Mass Function (GSMF)	$\Phi_0, \Phi_I, M_0, \alpha_0, \alpha_I$
Pair Fraction	$f_0, \alpha_f, \beta_f, \gamma_f$
Merger Timescale	$\tau_0, \alpha_\tau, \beta_\tau, \gamma_\tau$
BH-bulge mass parameters	$\alpha_*, \beta_*, \gamma_*, \epsilon$

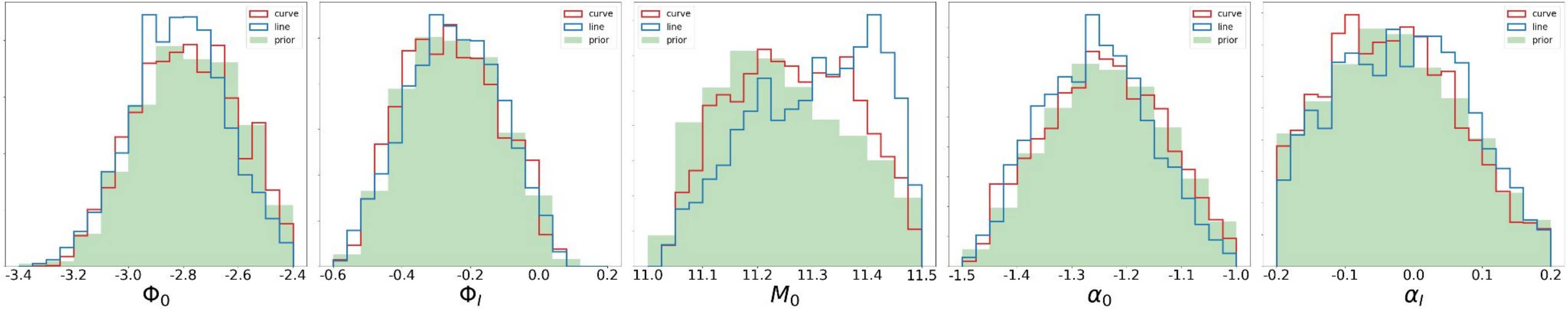

z = 0.5 - 1.0
z = 1.0 - 1.5
z = 1.5 - 2.0
z = 2.0 - 3.5
z = 3.5 - 5.0
$\log_{10}(\frac{dn}{dVdz})(\mathrm{Mpc}^{-3})$
0
−2
−4
−6
−8
−10
2-sigma
1-sigma
mean
z
0.0
0.2
0.4
0.00
0.25
0.50
0.75
1.00
0.5
1.0
1.5
2.0
0
1
2
3

Merger Rate

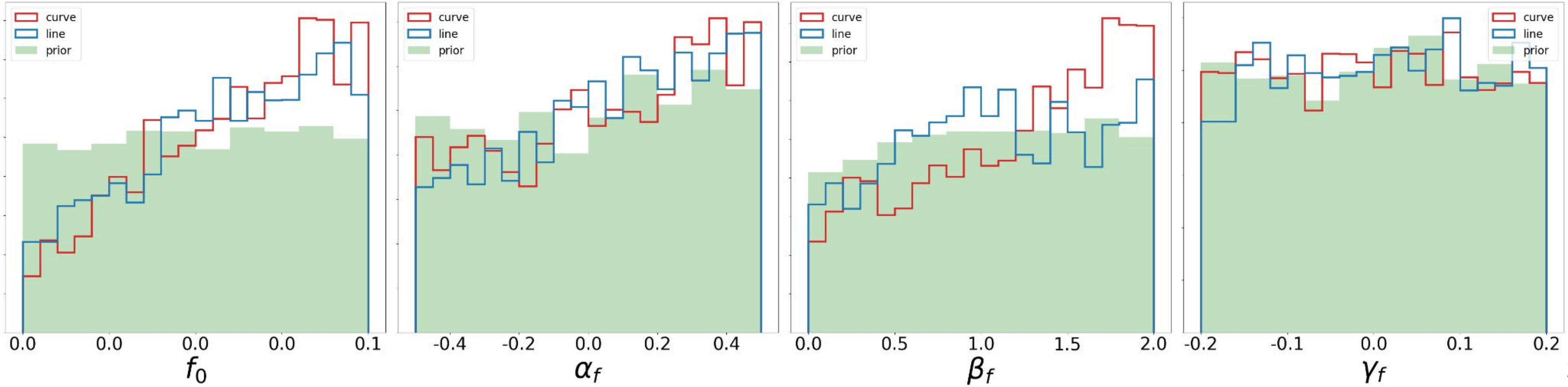

10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\frac{dn}{dV d\log_{10}(\mathcal{M})}(\mathrm{Mpc}^{-3})$
Line
Curve
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
$\mathcal{M}(M_\odot)$


Line
Curve

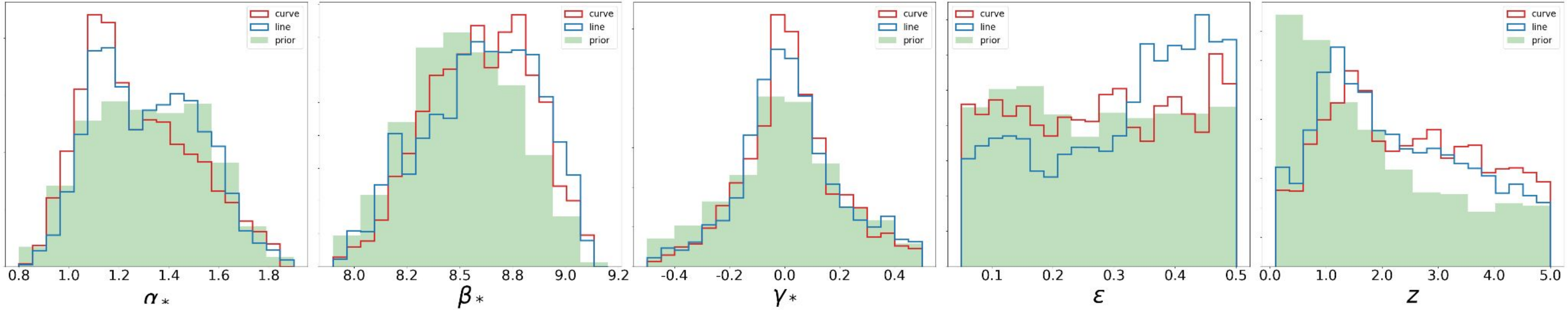
Galaxy Stellar Mass Function



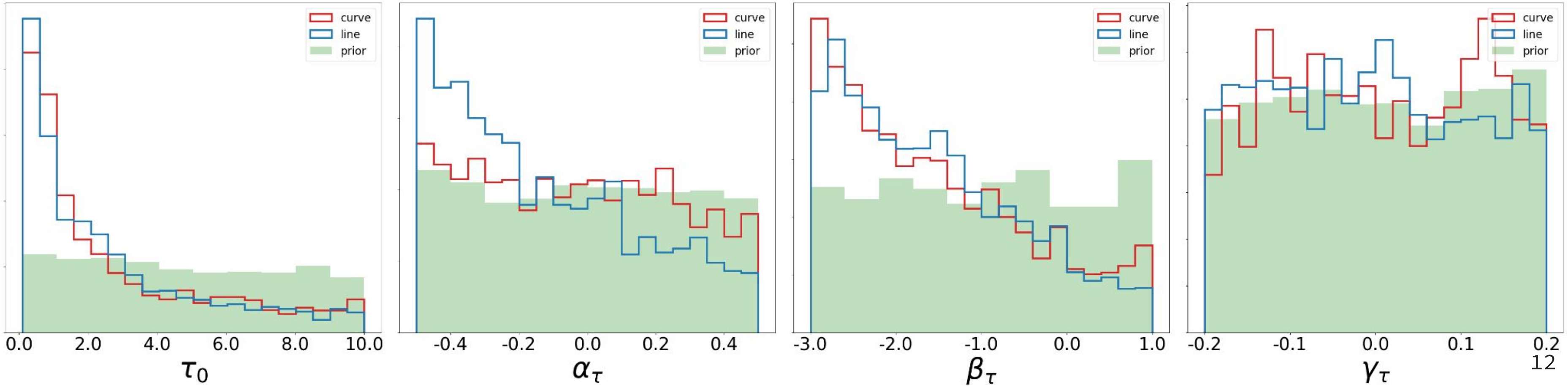
Pair fraction



BH-bulge mass relation

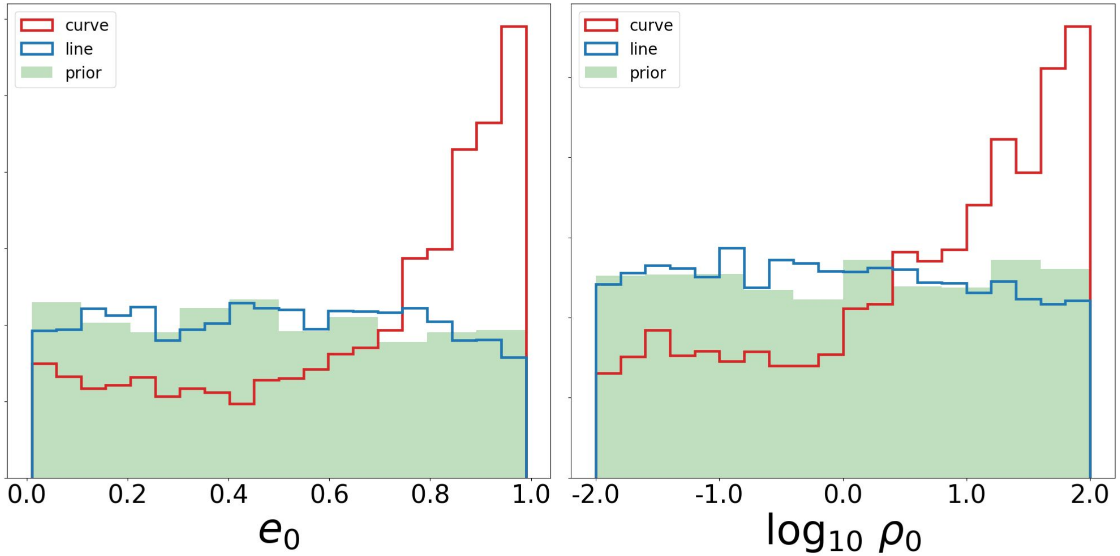


Merger timescale

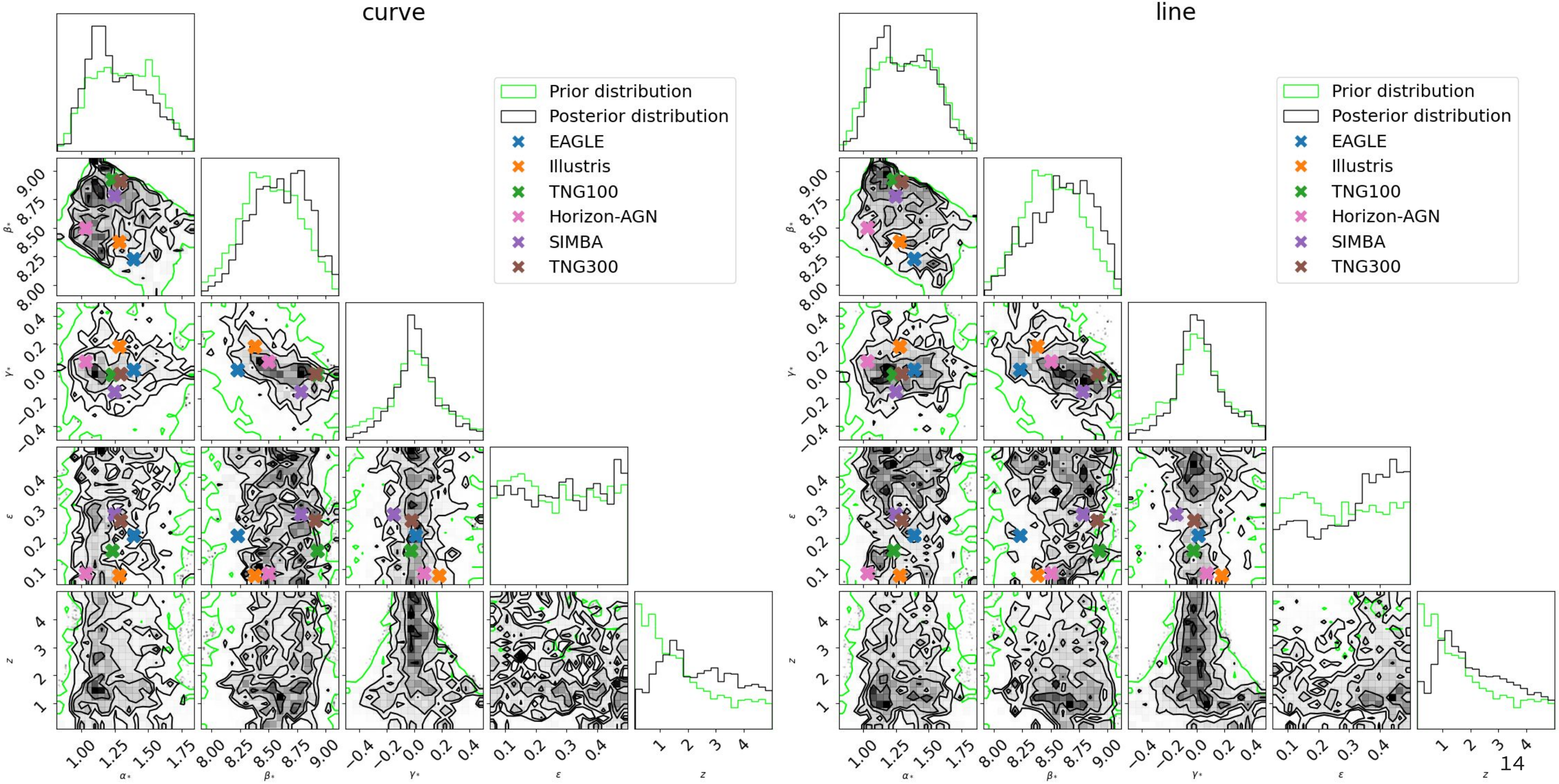


Binary eccentricity

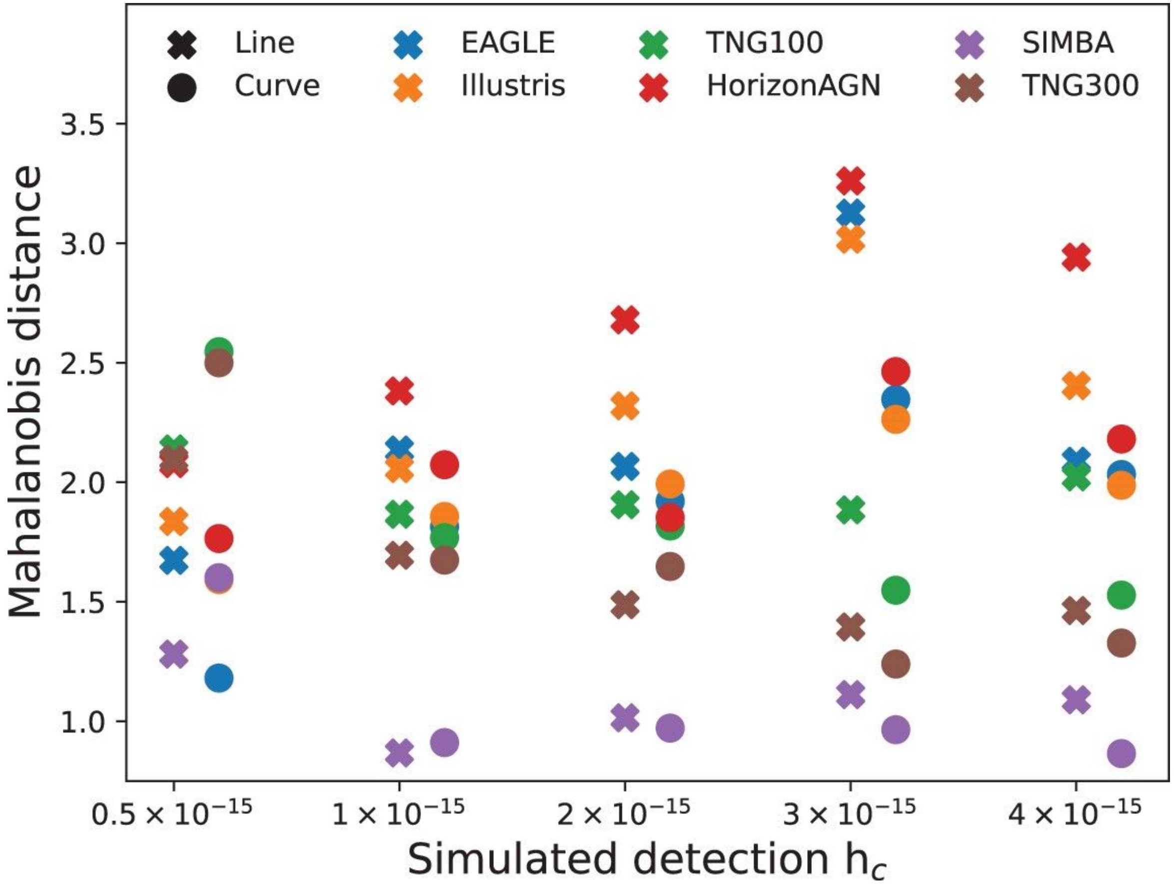
Stellar density factor

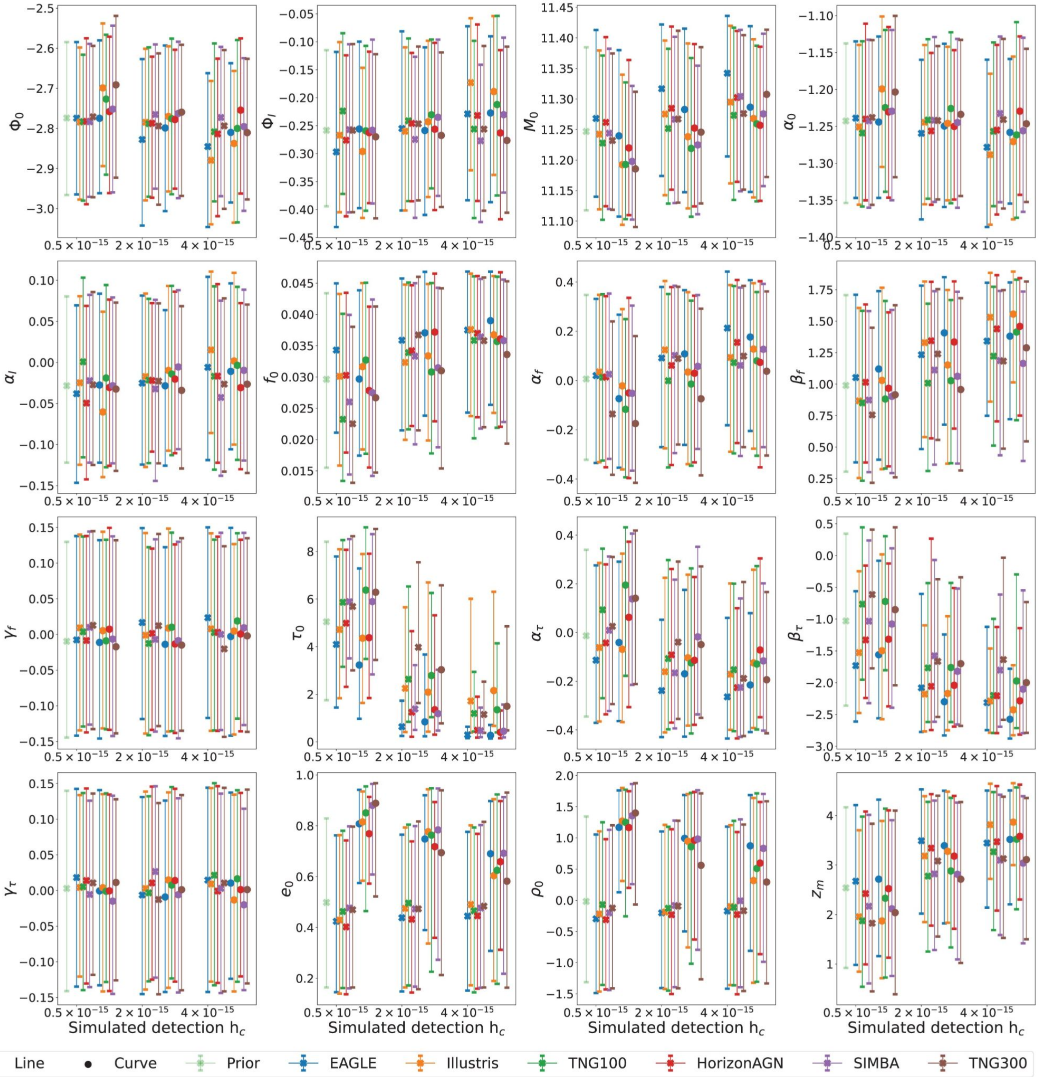


BH-BULGE MASS RELATION



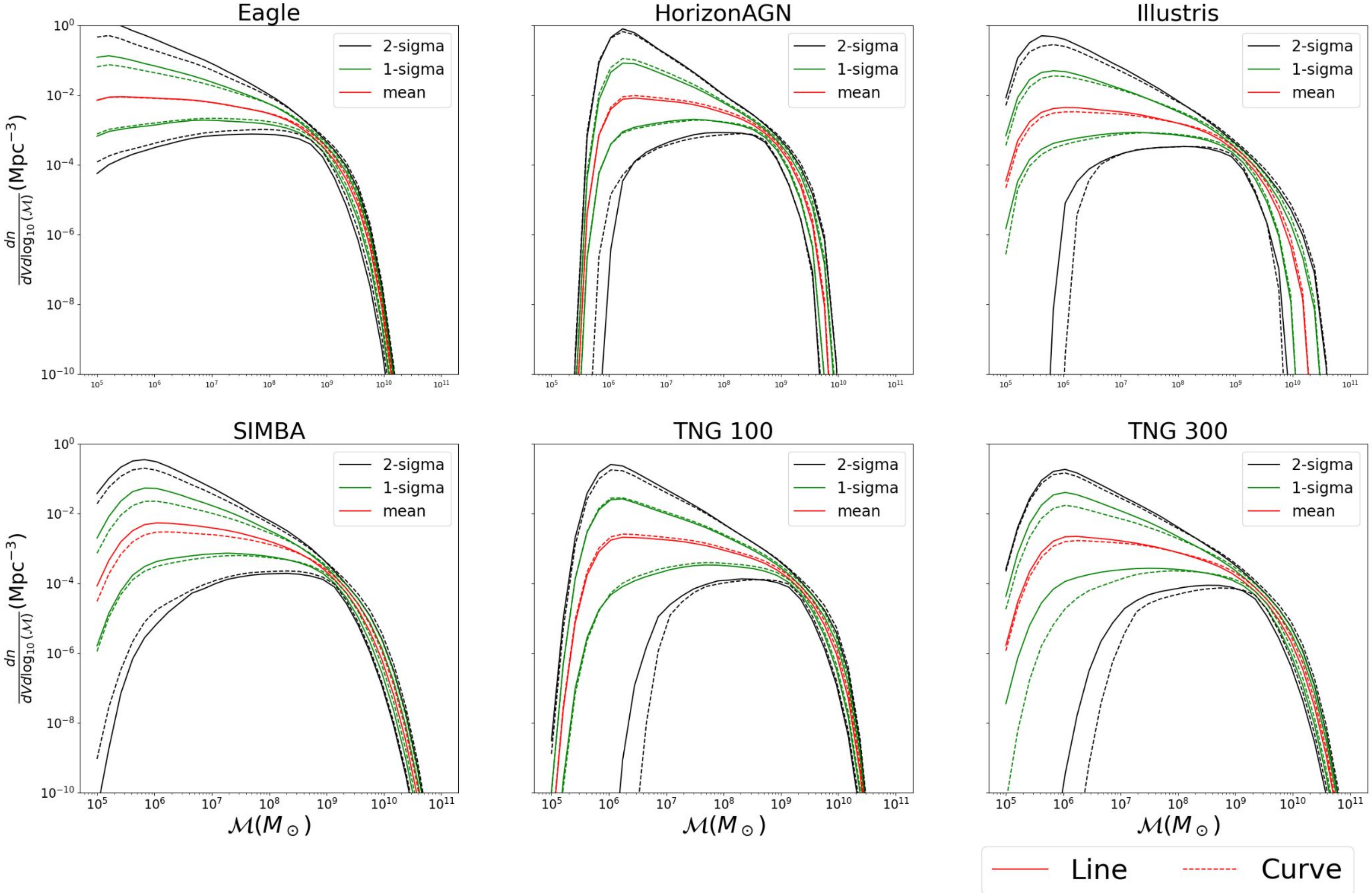
Large scale cosmological simulations

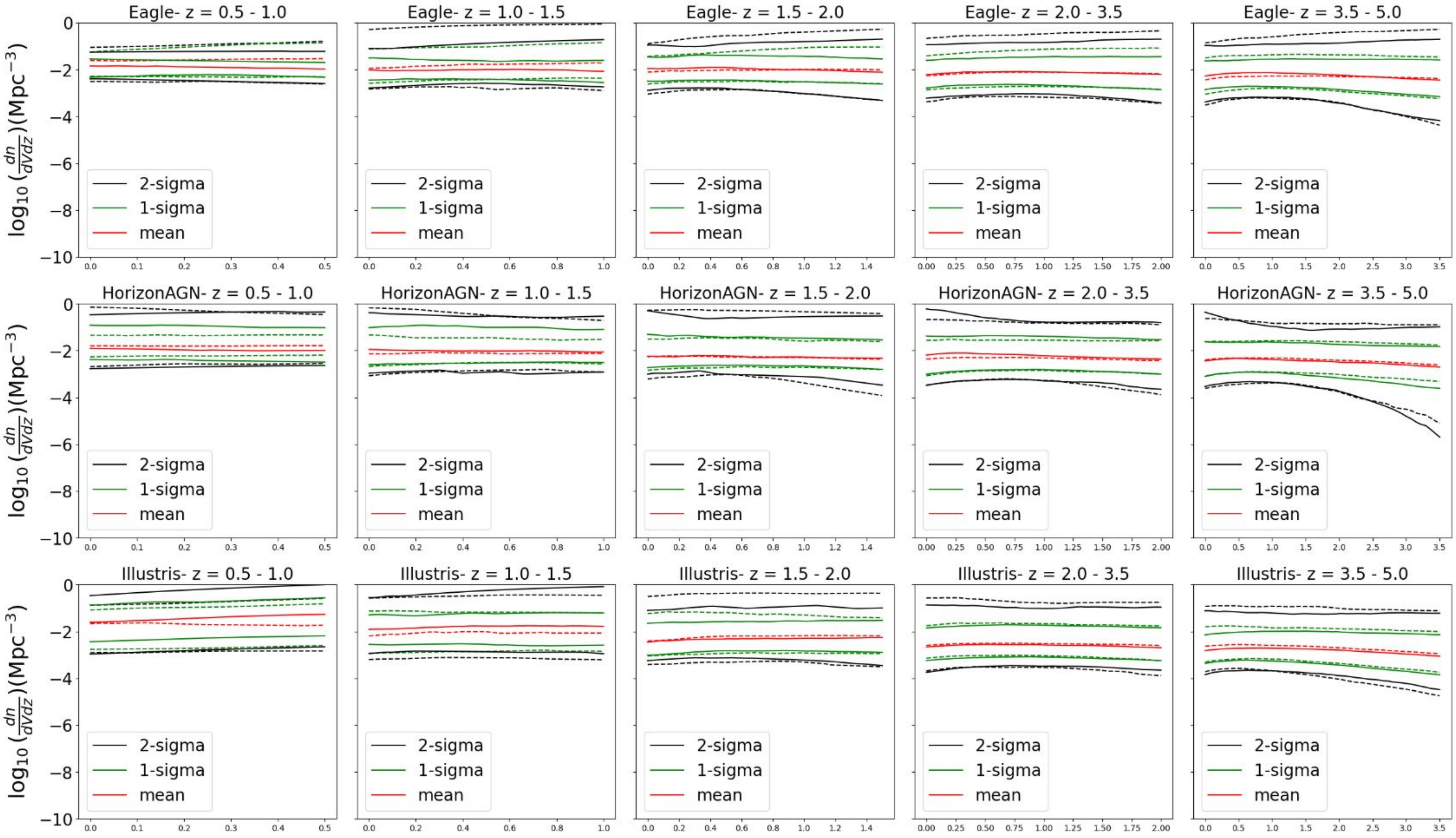


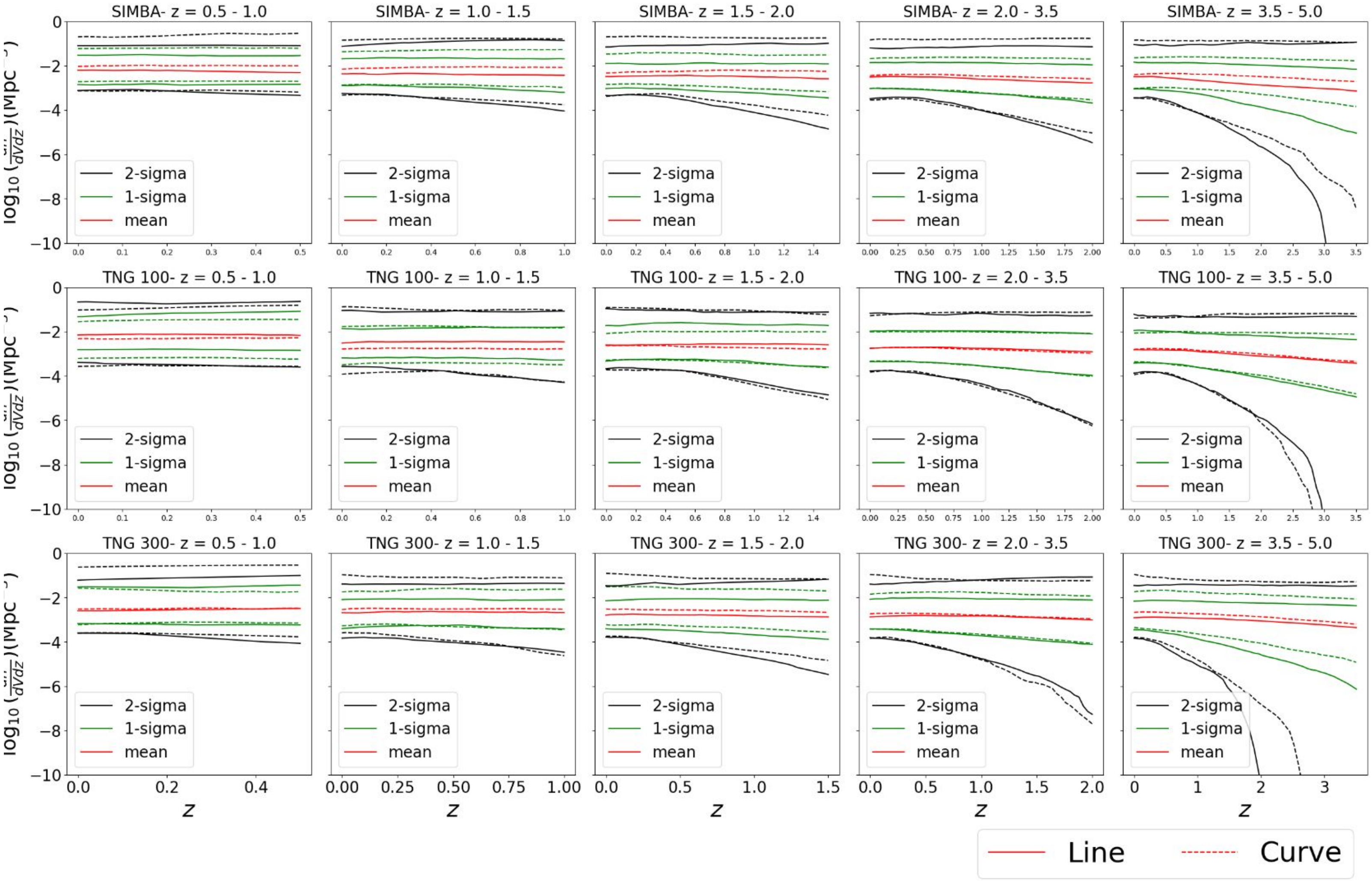


Φ_0
Φ_l
M_0
α_0
α_l
f_0
α_f
β_f
γ_f
τ_0
α_τ
β_τ
γ_τ
e_0
ρ_0
z_m
0.5×10^{-15} 2×10^{-15} 4×10^{-15}
Simulated detection h_c
Simulated detection h_c
Simulated detection h_c
Simulated detection h_c
Line
Curve
Prior
EAGLE
Illustris
TNG100
HorizonAGN
SIMBA
TNG300

Merger Rate


Eagle
HorizonAGN
Illustris
SIMBA
TNG 100
TNG 300
2-sigma
1-sigma
mean
$\frac{dn}{dV d\log_{10}(\mathcal{M})}(\mathrm{Mpc}^{-3})$
$\mathcal{M}(M_\odot)$
Line
Curve


Eagle- z = 0.5 - 1.0
Eagle- z = 1.0 - 1.5
Eagle- z = 1.5 - 2.0
Eagle- z = 2.0 - 3.5
Eagle- z = 3.5 - 5.0
HorizonAGN- z = 0.5 - 1.0
HorizonAGN- z = 1.0 - 1.5
HorizonAGN- z = 1.5 - 2.0
HorizonAGN- z = 2.0 - 3.5
HorizonAGN- z = 3.5 - 5.0
Illustris- z = 0.5 - 1.0
Illustris- z = 1.0 - 1.5
Illustris- z = 1.5 - 2.0
Illustris- z = 2.0 - 3.5
Illustris- z = 3.5 - 5.0
$\log_{10}(\frac{dn}{dVdz})(\mathrm{Mpc}^{-3})$
2-sigma
1-sigma
mean


SIMBA- z = 0.5 - 1.0
SIMBA- z = 1.0 - 1.5
SIMBA- z = 1.5 - 2.0
SIMBA- z = 2.0 - 3.5
SIMBA- z = 3.5 - 5.0
TNG 100- z = 0.5 - 1.0
TNG 100- z = 1.0 - 1.5
TNG 100- z = 1.5 - 2.0
TNG 100- z = 2.0 - 3.5
TNG 100- z = 3.5 - 5.0
TNG 300- z = 0.5 - 1.0
TNG 300- z = 1.0 - 1.5
TNG 300- z = 1.5 - 2.0
TNG 300- z = 2.0 - 3.5
TNG 300- z = 3.5 - 5.0
2-sigma
1-sigma
mean
z
Line
Curve

Gravitational Wave Background is a persistent feature of the universe.

Expand multi-messenger astrophysics with gravitational wave detections.

Thank You!