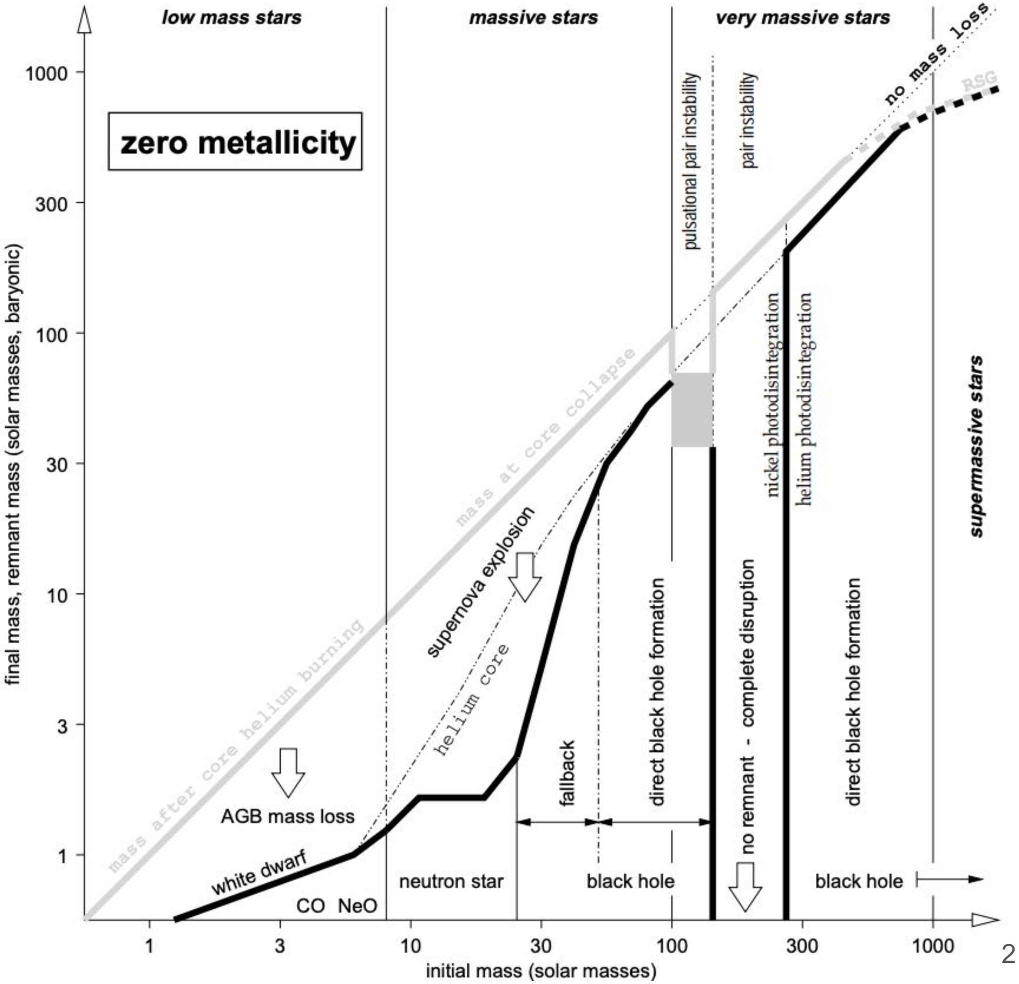
Properties and Astrophysical Implications of the 150Me Binary Black Hole Merger GW190521

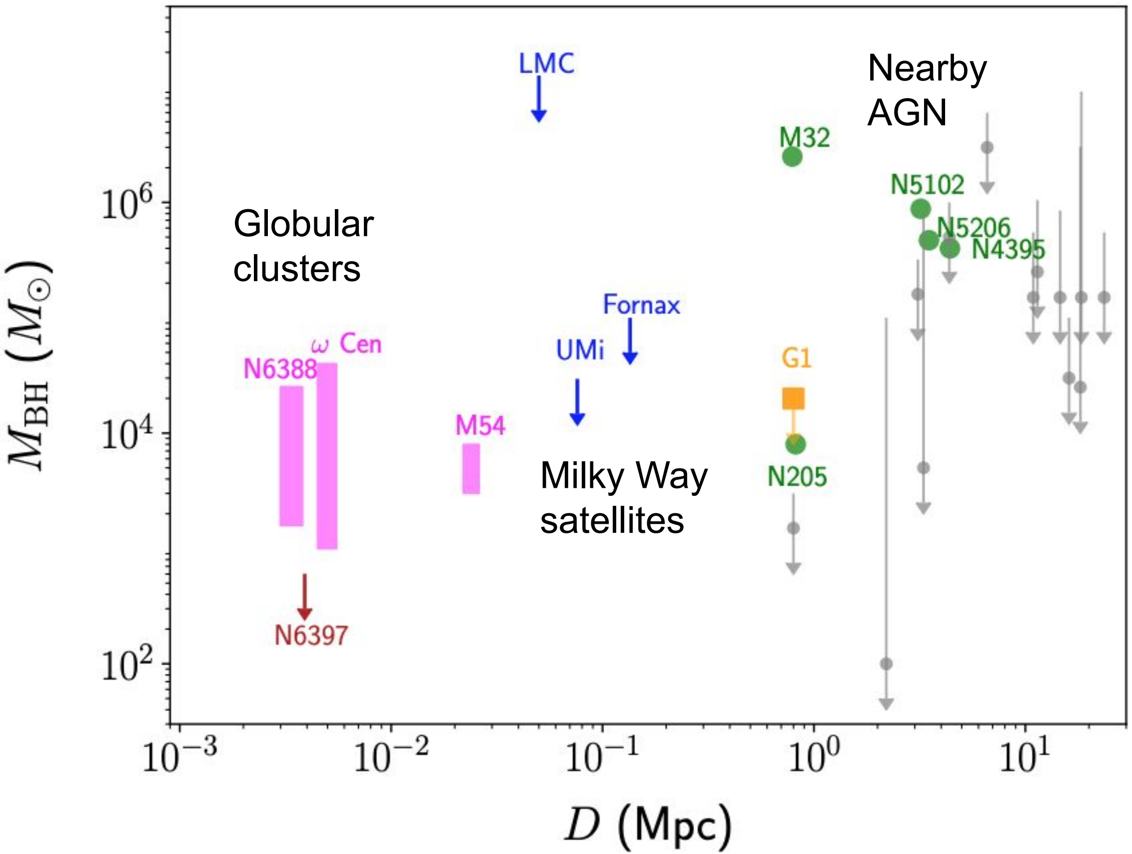
Abbott et al. 2020, ApJL, 900, 13, 27 pp.

The black hole mass function and the pair instability gap



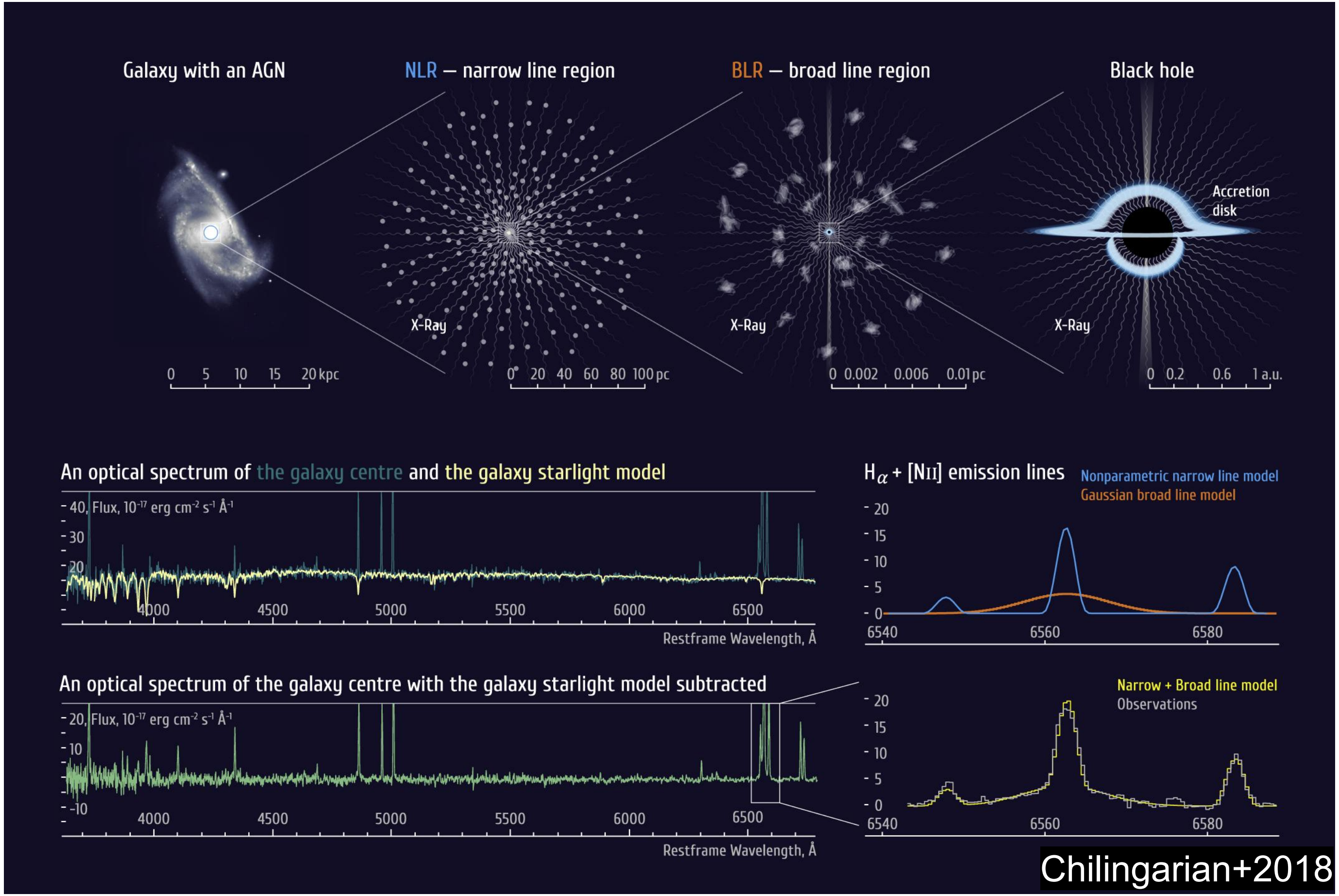
Heger & Woosley 2002

Demographics of Intermediate mass black holes



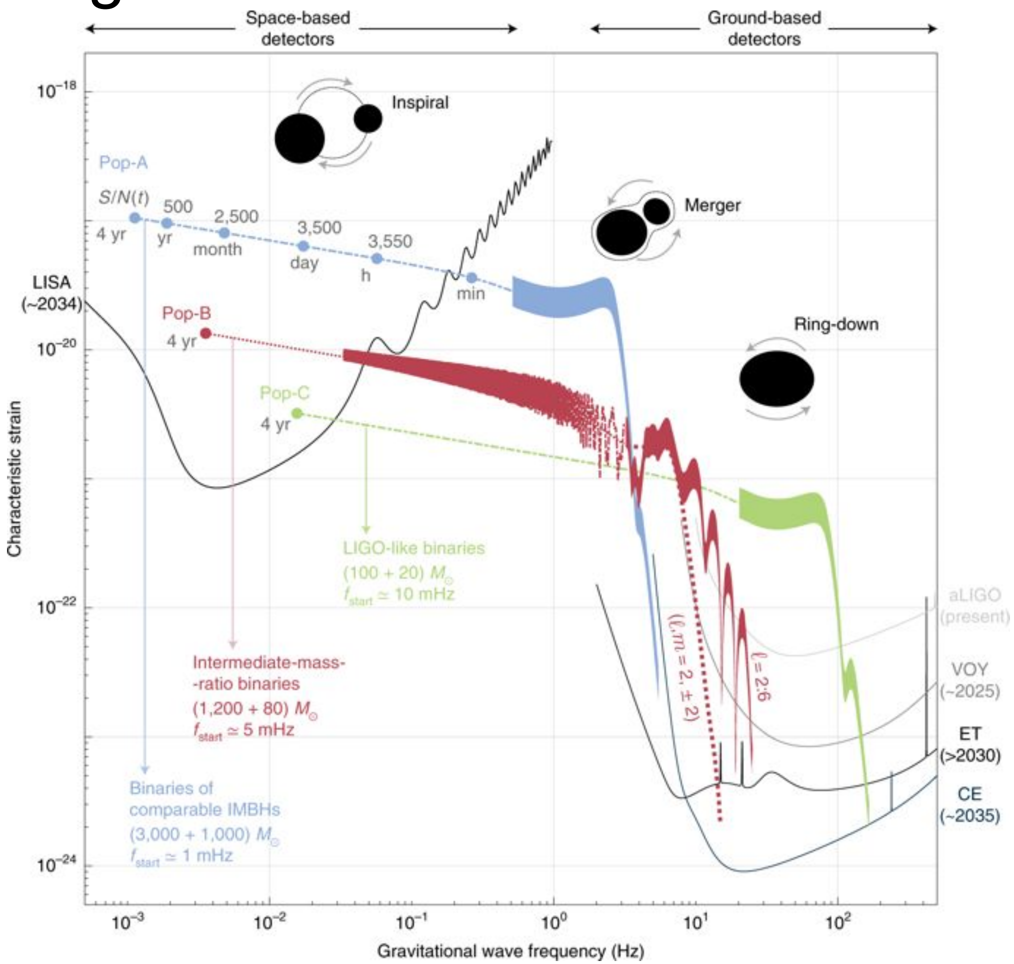
Greene+ 2019

Example: Low mass active galactic nuclei

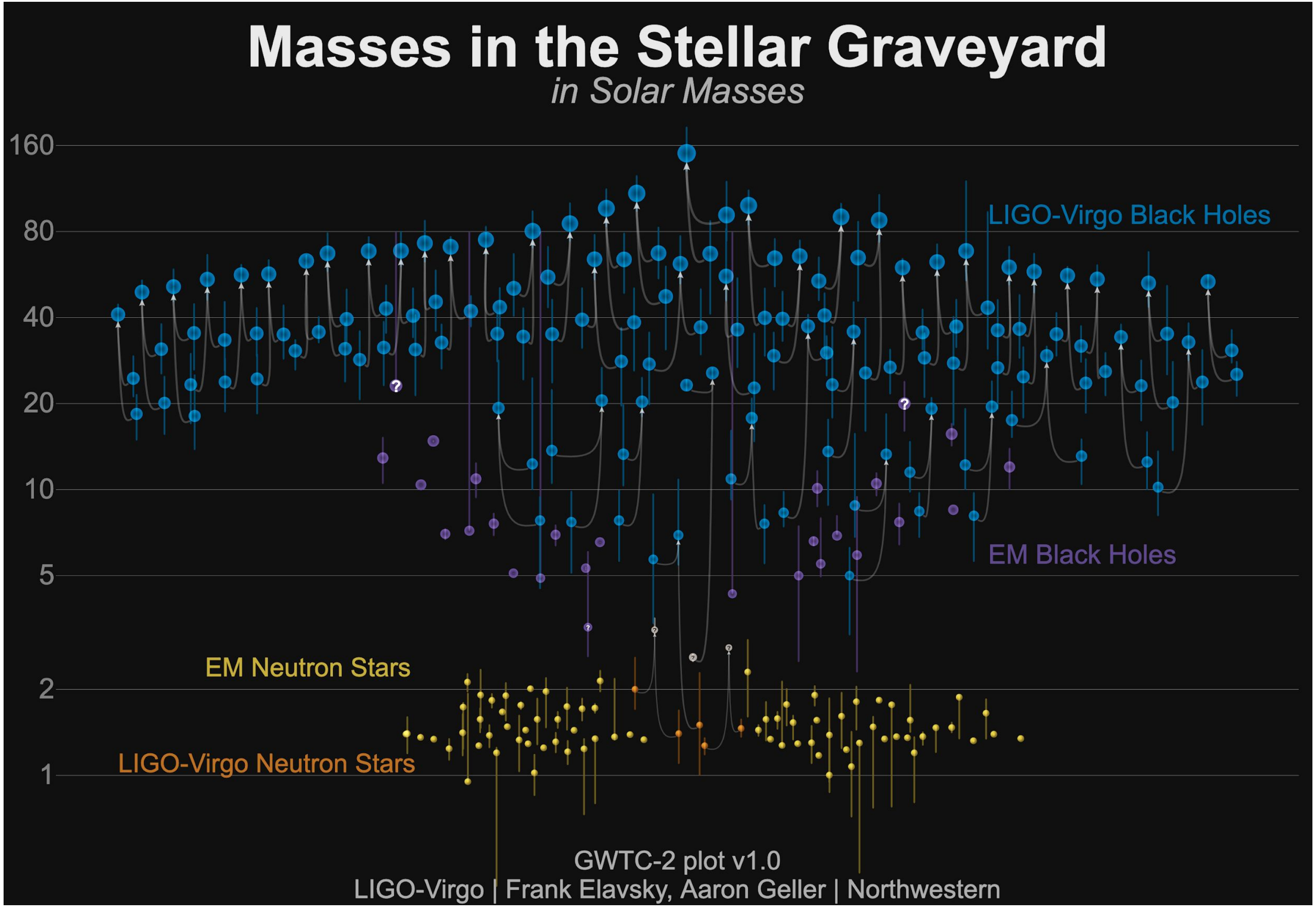


Chilingarian+2018

Detectability in gravitational waves

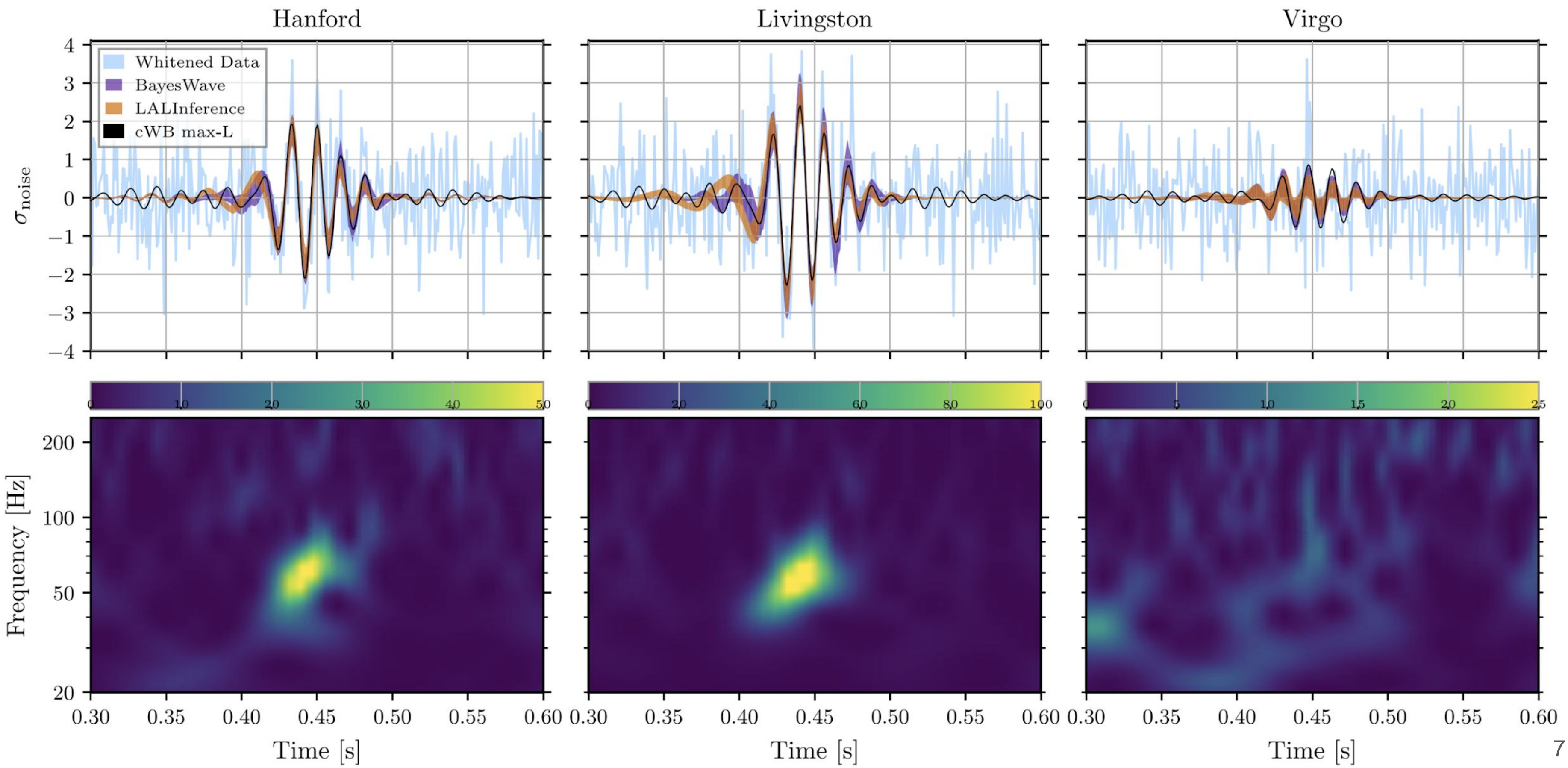


Jani+ 2019

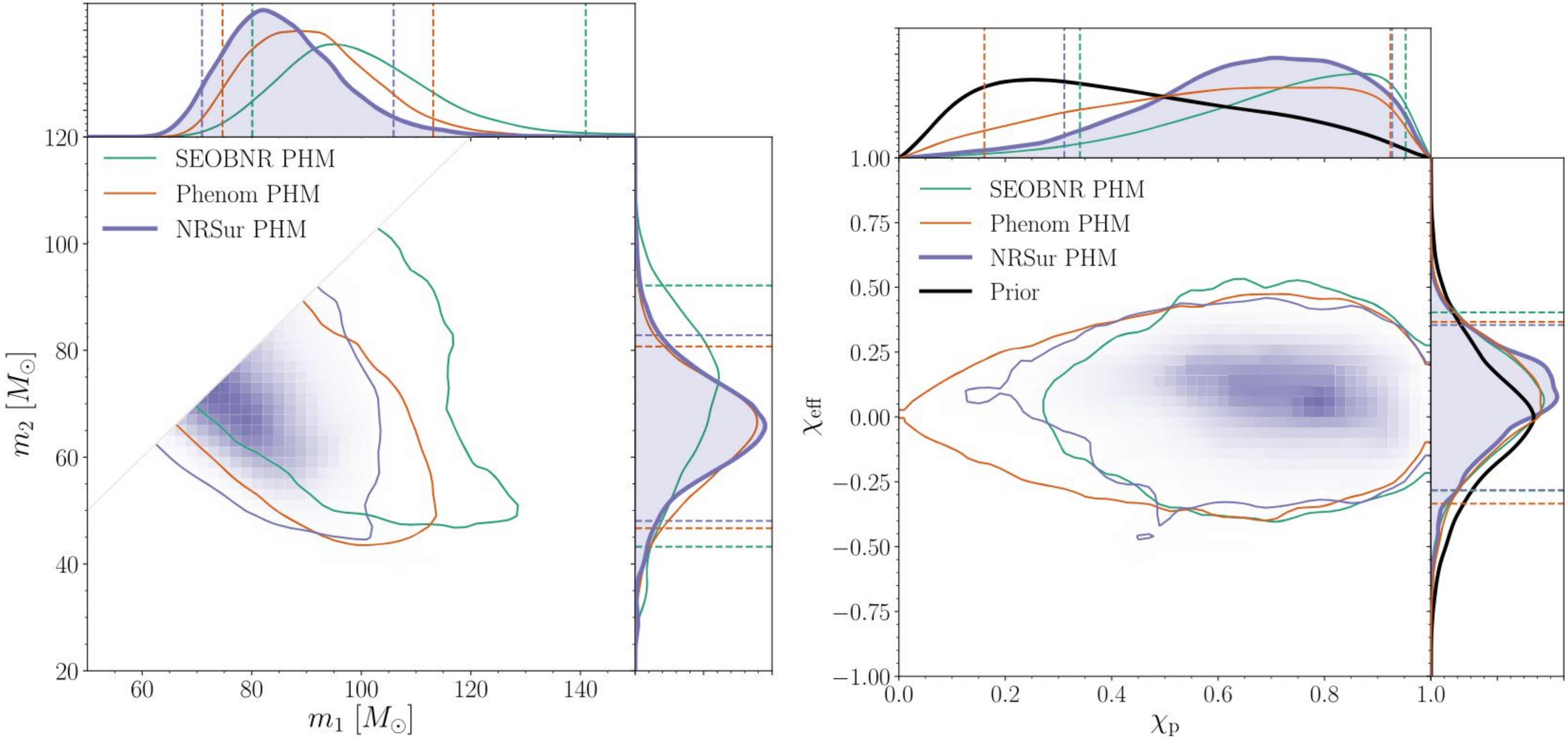


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

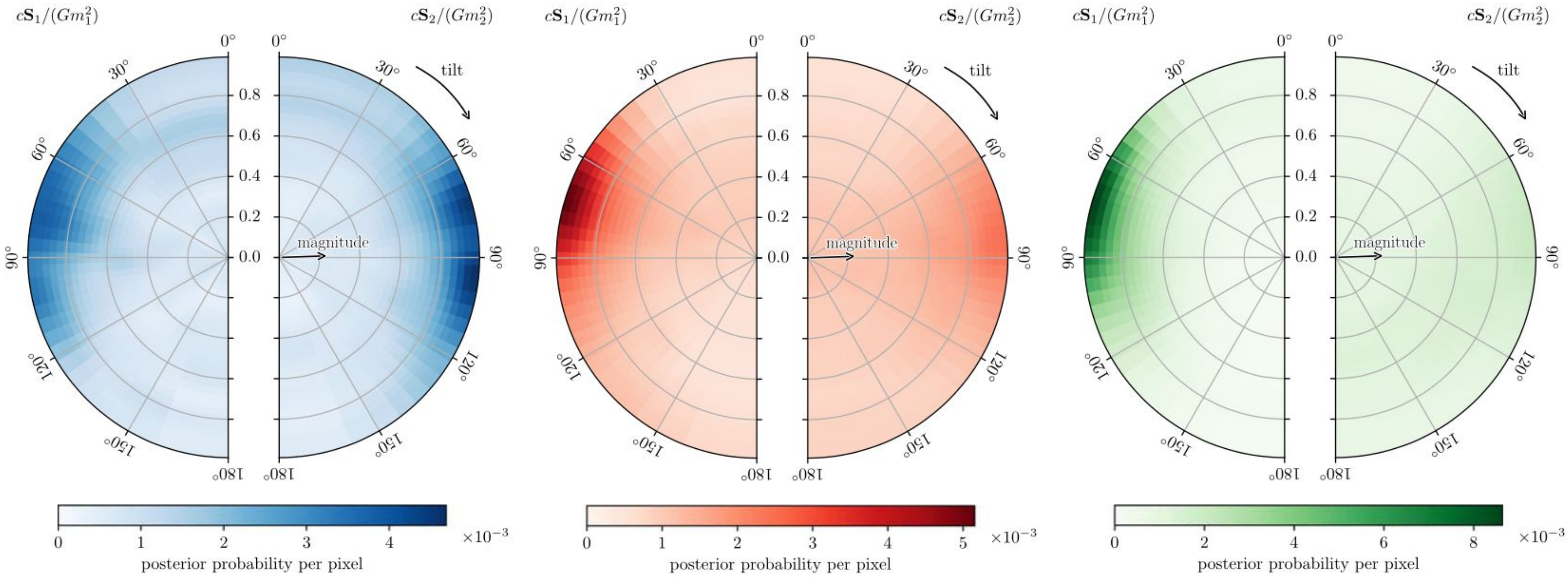
GW190521



Hanford
Livingston
Virgo
Whitened Data
BayesWave
LALInference
cWB max-L
$\sigma_{\rm noise}$
Frequency [Hz]
Time [s]
Time [s]
Time [s]

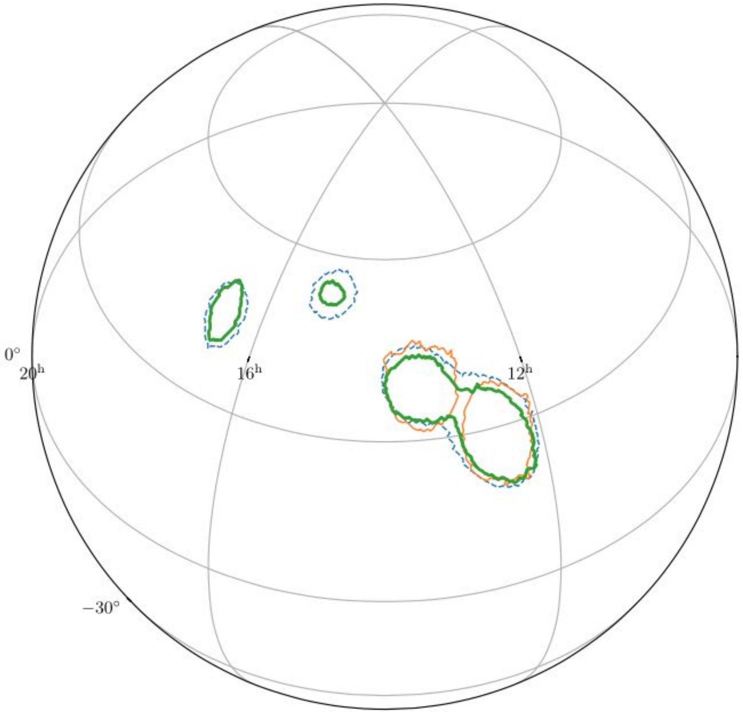


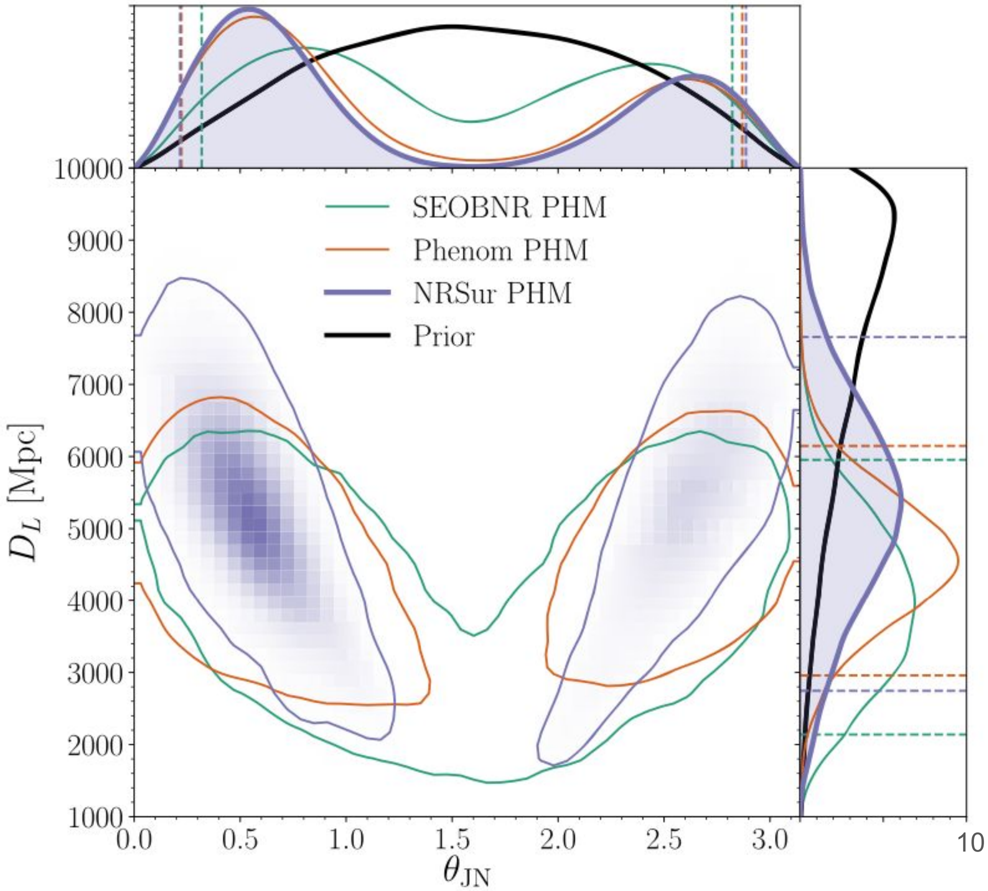
SEOBNR PHM
Phenom PHM
NRSur PHM
120
100
80
60
40
20
60
80
100
120
140
$m_2\ [M_\odot]$
$m_1\ [M_\odot]$
SEOBNR PHM
Phenom PHM
NRSur PHM
Prior
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0.0
0.2
0.4
0.6
0.8
1.0
$\chi_{\rm eff}$
$\chi_{\rm p}$


$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
tilt
magnitude
0°
30°
60°
90°
120°
150°
180°
0.0
0.2
0.4
0.6
0.8
posterior probability per pixel
×10⁻³

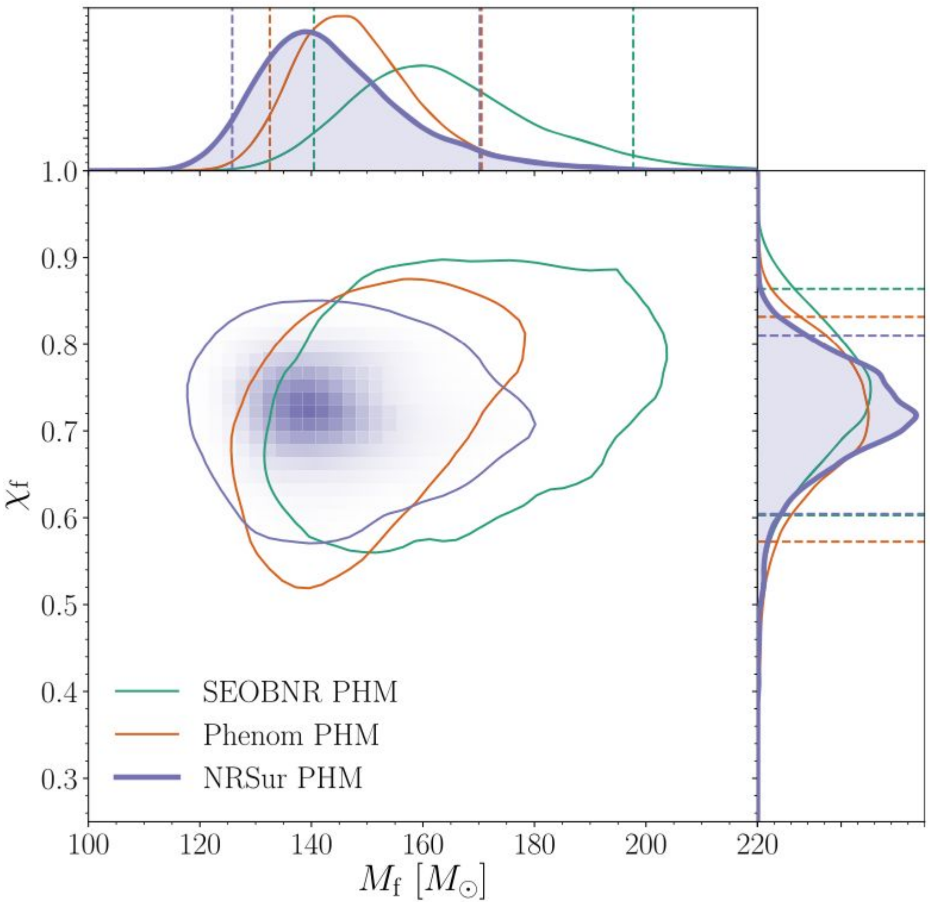
Where?

At z ~ 0.8, mass measurements are affected by inferred source distance!





The fate of the remnant



~ 7.5 solar masses radiated in GWs!

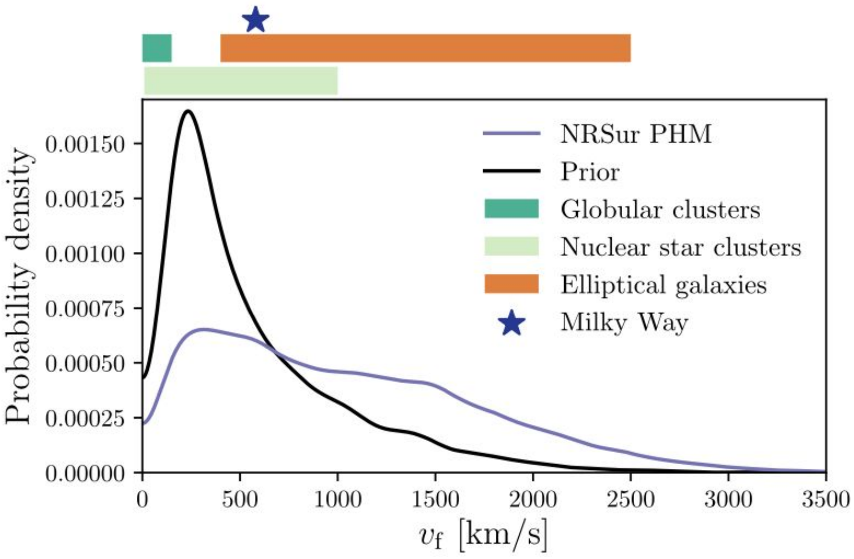


Table 1
Source Properties for GW190521: Median Values with 90% Credible Intervals That Include Statistical Errors

Waveform Model	NRSur PHM	Phenom PHM	SEOBNR PHM
Primary BH mass m_1 ($M_\odot$)	85^{+21}_{-14}	90^{+23}_{-16}	99^{+42}_{-19}
Secondary BH mass m_2 ($M_\odot$)	66^{+17}_{-18}	65^{+16}_{-18}	71^{+21}_{-28}
Total BBH mass M ($M_\odot$)	150^{+29}_{-17}	154^{+25}_{-16}	170^{+36}_{-23}
Binary chirp mass $\mathcal{M}$ ($M_\odot$)	64^{+13}_{-8}	65^{+11}_{-7}	71^{+15}_{-10}
Mass ratio $q = m_2/m_1$	$0.79^{+0.19}_{-0.29}$	$0.73^{+0.24}_{-0.29}$	$0.74^{+0.23}_{-0.42}$
Primary BH spin χ_1	$0.69^{+0.27}_{-0.62}$	$0.65^{+0.32}_{-0.57}$	$0.80^{+0.18}_{-0.58}$
Secondary BH spin χ_2	$0.73^{+0.24}_{-0.64}$	$0.53^{+0.42}_{-0.48}$	$0.54^{+0.41}_{-0.48}$
Primary BH spin tilt angle θ_{LS_1} (deg)	81^{+64}_{-53}	80^{+64}_{-49}	81^{+49}_{-45}
Secondary BH spin tilt angle θ_{LS_2} (deg)	85^{+57}_{-55}	88^{+63}_{-58}	93^{+61}_{-60}
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.08^{+0.27}_{-0.36}$	$0.06^{+0.31}_{-0.39}$	$0.06^{+0.34}_{-0.35}$
Effective precession spin parameter $\chi_{\rm p}$	$0.68^{+0.25}_{-0.37}$	$0.60^{+0.33}_{-0.44}$	$0.74^{+0.21}_{-0.40}$
Remnant BH mass $M_{\rm f}$ ($M_\odot$)	142^{+28}_{-16}	147^{+23}_{-15}	162^{+35}_{-22}
Remnant BH spin $\chi_{\rm f}$	$0.72^{+0.09}_{-0.12}$	$0.72^{+0.11}_{-0.15}$	$0.74^{+0.12}_{-0.14}$
Radiated energy $E_{\rm rad}$ ($M_\odot c^2$)	$7.6^{+2.2}_{-1.9}$	$7.2^{+2.7}_{-2.2}$	$7.8^{+2.8}_{-2.3}$
Peak Luminosity $\ell_{\rm peak}$ (erg s^{-1})	$3.7^{+0.7}_{-0.9} \times 10^{56}$	$3.5^{+0.7}_{-1.1} \times 10^{56}$	$3.5^{+0.8}_{-1.4} \times 10^{56}$
Luminosity distance $D_{\rm L}$ (Gpc)	$5.3^{+2.4}_{-2.6}$	$4.6^{+1.6}_{-1.6}$	$4.0^{+2.0}_{-1.8}$
Source redshift z	$0.82^{+0.28}_{-0.34}$	$0.73^{+0.20}_{-0.22}$	$0.64^{+0.25}_{-0.26}$
Sky localization $\Delta\Omega$ (deg^2)	774	862	1069

Consistency of GW190521 signal with a merger event

S/N_{90} metric of data 4096 s surrounding detection event is = 6.34, $p = 0.26$, consistent with detector noise

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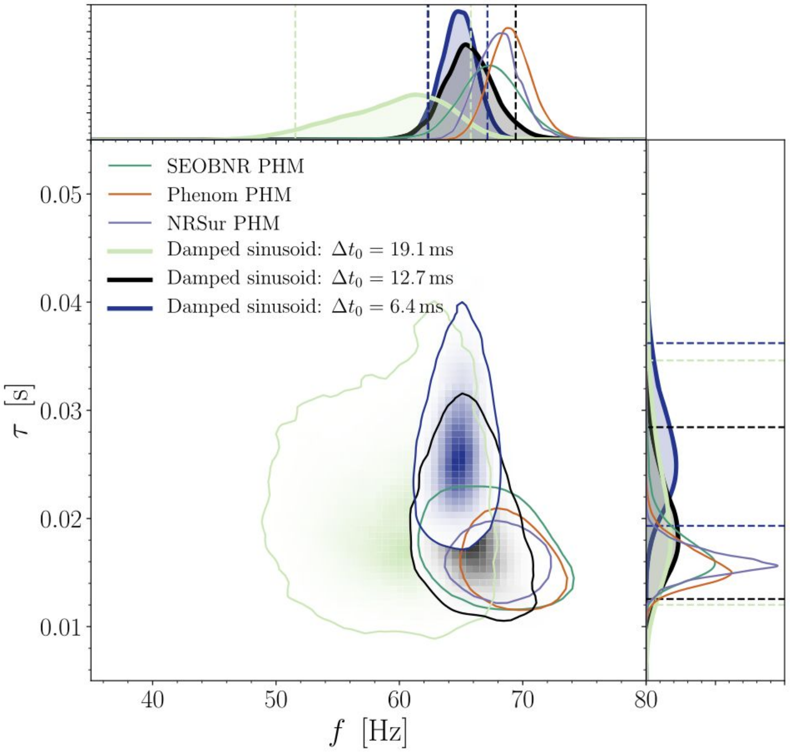
Ringdown frequency *f* ~66 Hz, dampening timescale τ = 12-28 ms



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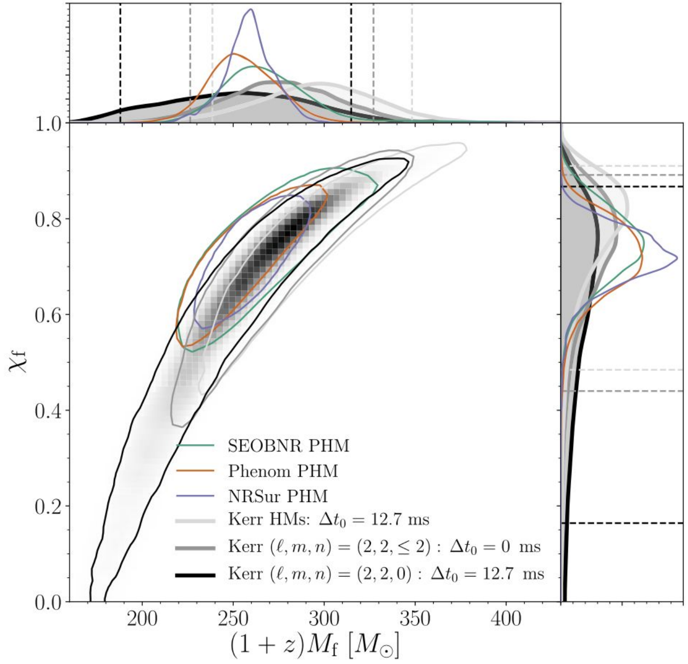
Ringdown frequency *f* ~66 Hz, dampening timescale τ = 12-28 ms

M_f^{det} = 220 to 350 M$_\odot$, χ_f ~0.66



Volumetric rates for GW190521-similar events

Merger rate searched over O1, O2, O3a is 0.13 +/- 0.3, 0.1 $\mathrm{Gpc^{-3}\ yr^{-1}}$

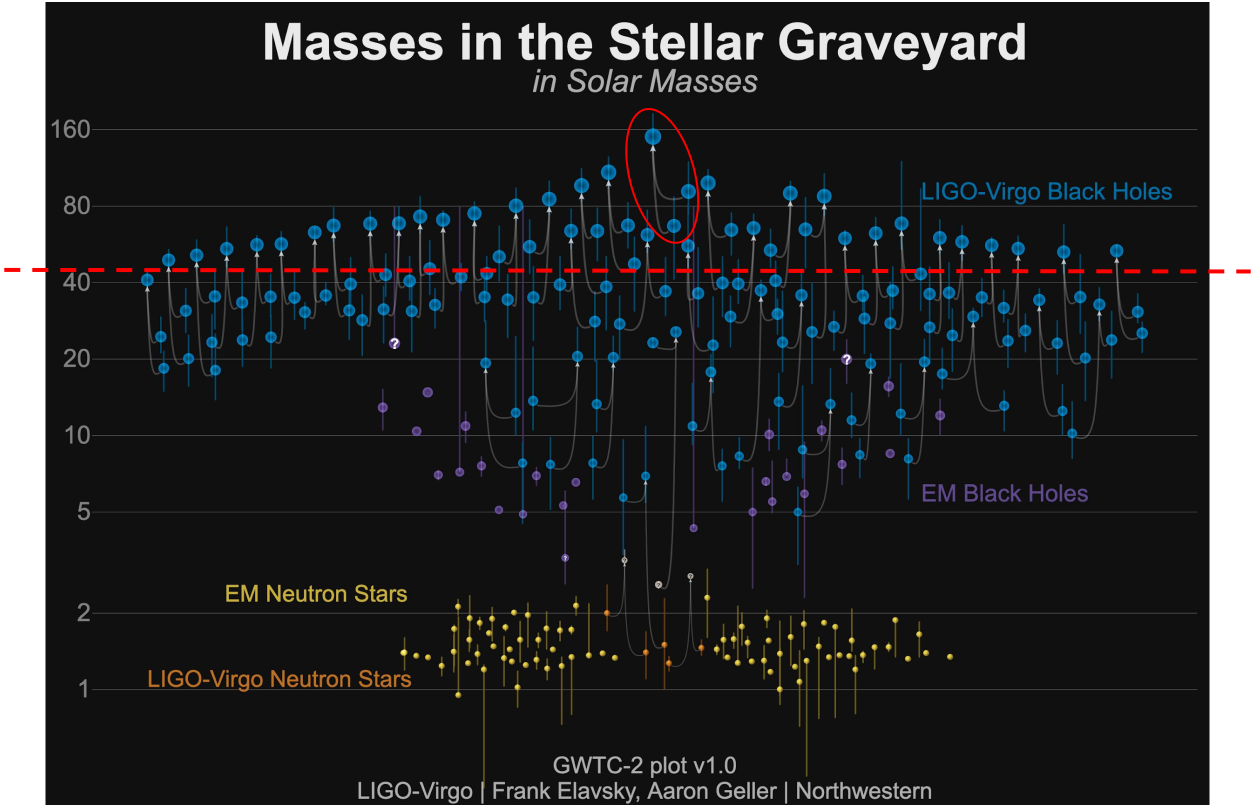
Compare to 1-23 $\mathrm{Gpc^{-3}\ yr^{-1}}$ for GW190814-like events

Compare to ~200-3000 $\mathrm{Gpc^{-3}\ yr^{-1}}$ BNS events (Abbott et al. 2020)

~2-30 $\mathrm{Gpc^{-3}\ yr^{-1}}$ for BBH events (~1-4 $\mathrm{Gpc^{-3}\ yr^{-1}}$ in globular clusters, Antonini & Gieles 2020)

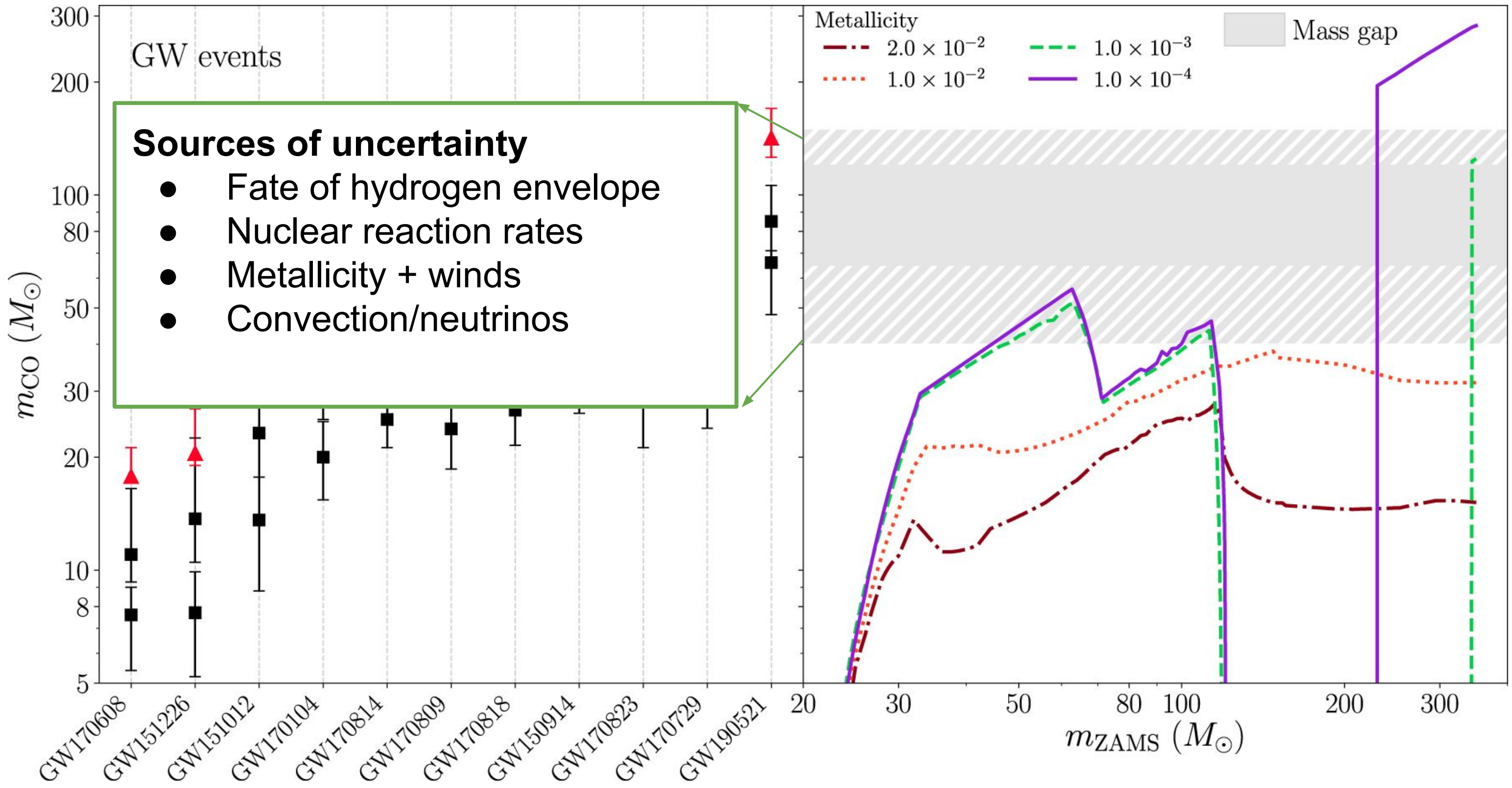
0.01 to 0.06 $\mathrm{Gpc^{-3}\ yr^{-1}}$ for NS-BH events in globular clusters (Ye et al. 2020)

GW190521 in context



99th percentile of primary masses: 45 Msun

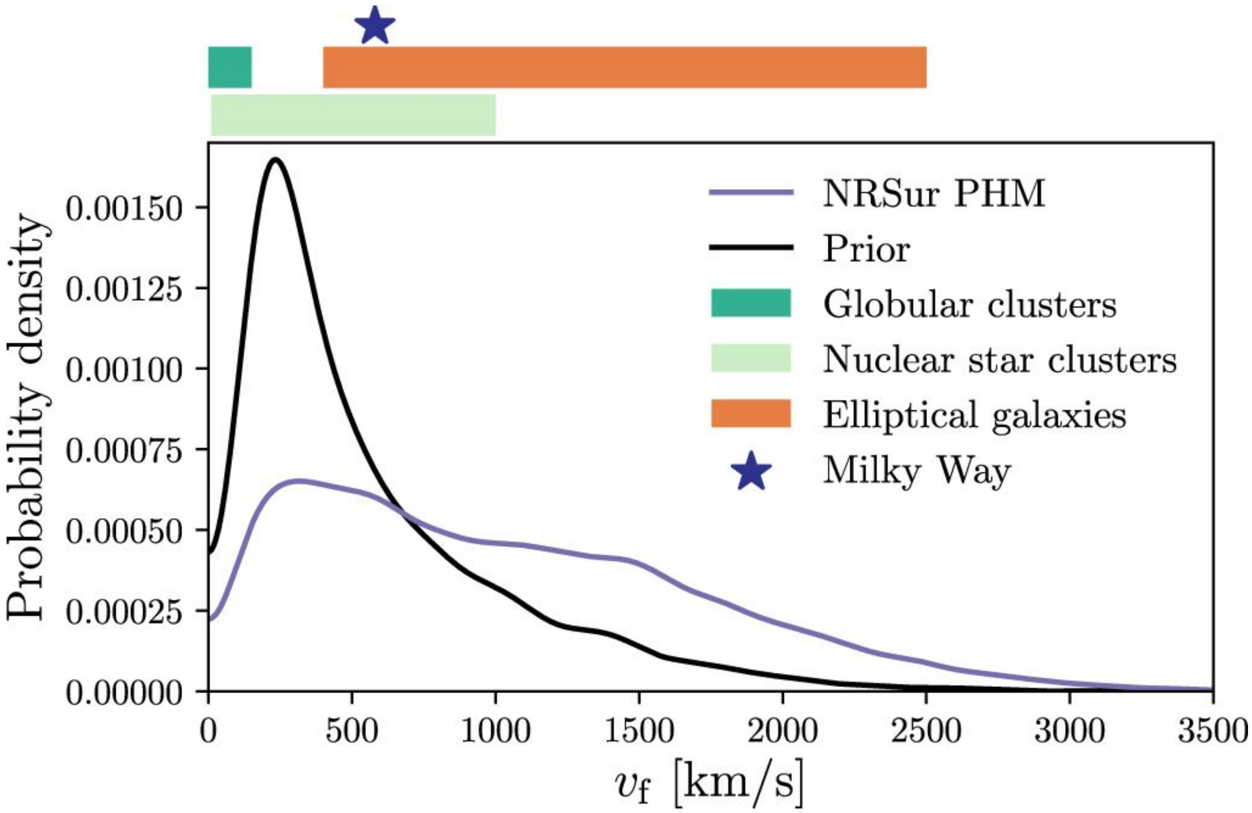
Uncertainties in the PI Mass Gap



Sources of uncertainty

- Fate of hydrogen envelope
- Nuclear reaction rates
- Metallicity + winds
- Convection/neutrinos

Hierarchical Merger Scenario



Forming a system with a 2g BH: Tradeoff between density of environment and escape velocity

Hierarchical Merger Scenario

Qualitatively, 2g + 2g scenario favored over 1g + 2g

q ~ 1

High component spins, ~0.7

Effective spin ~0

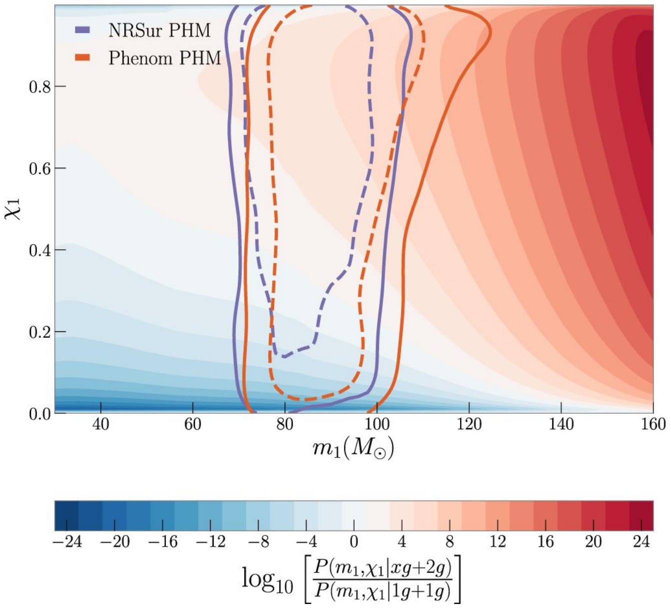
Hierarchical Merger Scenario

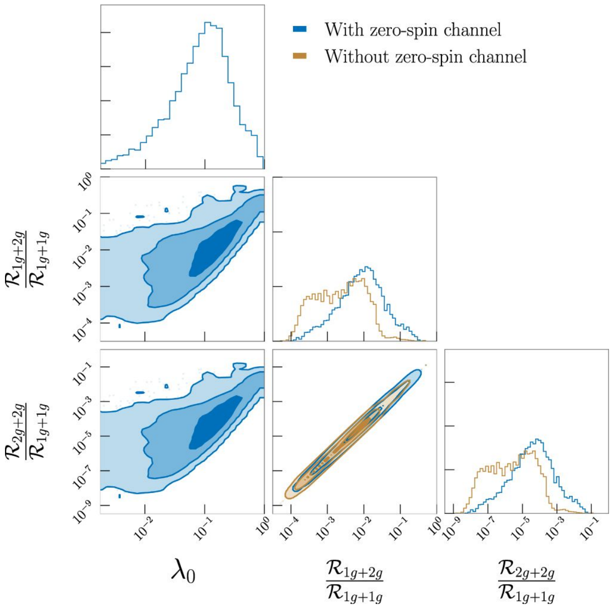
Modelling merger rates of a 1g+2g and 2g+2g systems

Lower limit of mass gap modelled as 50 +/- 10 Msun

5e5 Msun and 1e8 Msun cluster environments

Inclusion of zero-spin 1g BHs





Hierarchical Merger Scenario

Conclusion:

"...we find that GW190521 is most likely to be of 1g+1g origin, because the merger remnants of BBHs with large component spins are often subject to kicks that eject them from low-mass clusters"

Stellar Merger Scenario

Helium-core giant collides with main sequence companion → Star with oversized hydrogen envelope remains → Direct collapse to ~60-100 Msun BH w/o PI/PPI

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Dynamical interactions? Triple system?
Need better constraints

AGN Disk Scenario

BHs in AGN disks form 2g BHs easily due to gas torques and high v_esc means they won't be ejected

EM counterpart possible

Expected mass ratios and rates uncertain

Alternate Scenarios

Eccentric Mergers	~1% of merging binaries in dense environments ~5% of mergers in triple systems
Strong Lensing	-expected lensing rate too low -no counterpart to event detected
Primordial BH Mergers	Mass distribution and merger rates of PBHs too uncertain
Cosmic string GW burst	Observed waveform inconsistent with cosmic string template
CCSN	-waveform inconsistent with long duration/broadband signals -no EM counterpart detected

Conclusions

-Signal of GW190521 seems consistent with the merger of two high-mass black holes

-This event is thought to be a 1g+1g merger, inconsistent with the boundaries of the PI mass gap for the primary BH

-Short duration and low bandwidth of burst opens up possibility of other progenitor scenarios

-Future LVC observing runs could detect more BBHs at high redshifts

-LISA to detect more high mass BBHs