Probing the host environments of compact binaries

Aditya Vijaykumar

NBI Seminar

16th April 2024

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Research Interests

My past/current research in GWs falls into three categories.

- **Astrophysical environments of binaries [This Talk]**
- Physics of gravity: fundamental constants, exotic ultradense stars, lensing
- Analysis techniques: fast parameter estimation, eccentricity detection and interpretation

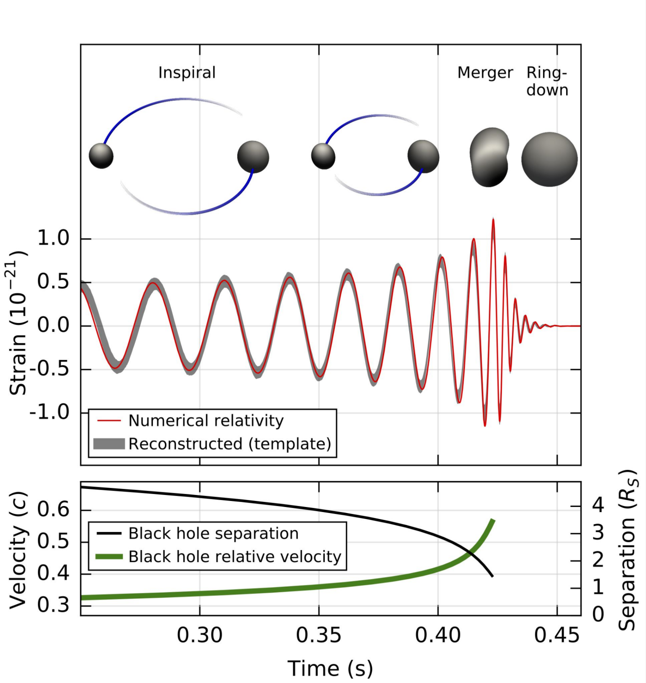
I would love to talk about these! Please reach out: aditya@utoronto.ca

Gravitational Waves

- So far, we have detected gravitational waves (GWs) from compact binary coalescences (CBCs) containing black holes and neutron stars.

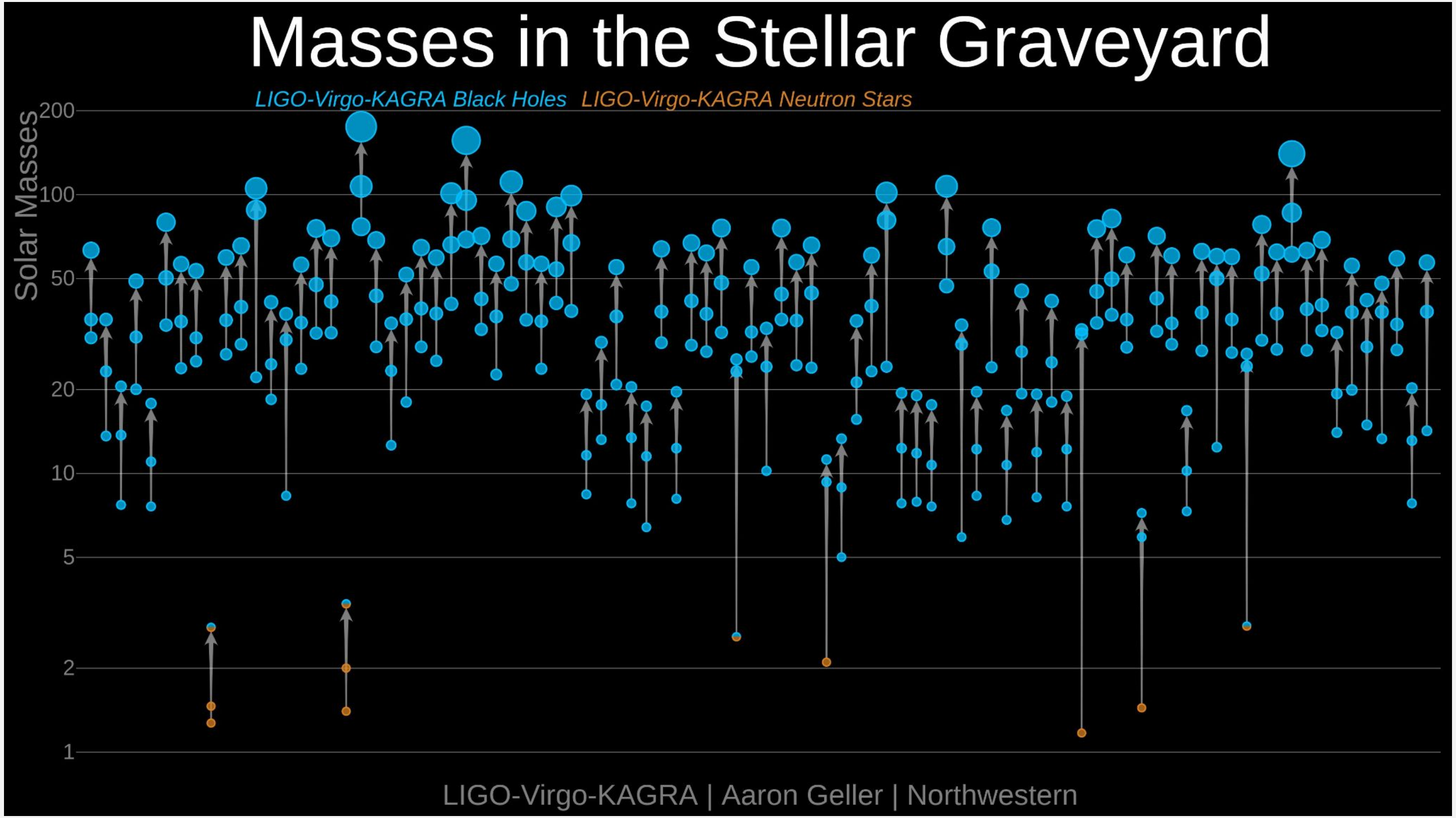
- GW signals from these have a very characteristic “chirping” feature: their frequency and amplitude increases with time.

- Typical detection range:
  - binary black holes (BBH) → z=0.5 (~3000 Mpc)
  - binary neutron stars (BNS) → z=0.05 (~200 Mpc).



Abbott+2016, arXiv:1602.03837

Gravitational Waves: The Present



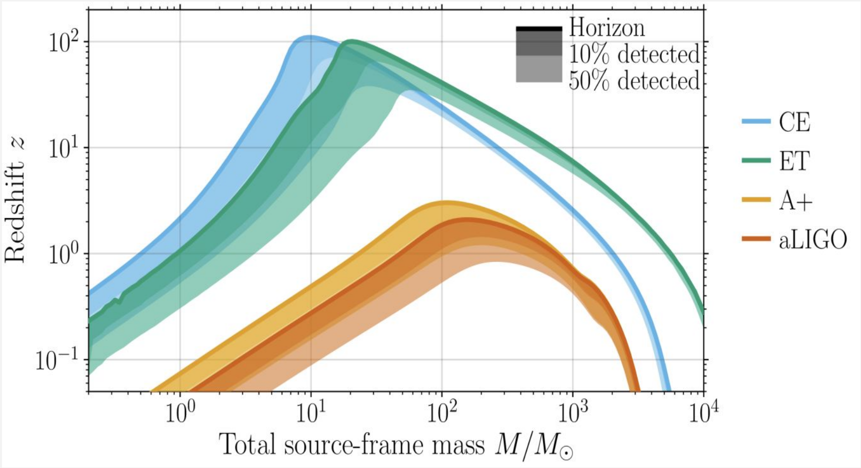
The LIGO-Virgo-KAGRA Collaboration (LVK) has reported a total of 90 detections of compact binary coalescences.

Gravitational Waves: The Future

- In the future, more sensitive detectors (Cosmic Explorer, Einstein Telescope) hence more distance reach and hence more events.

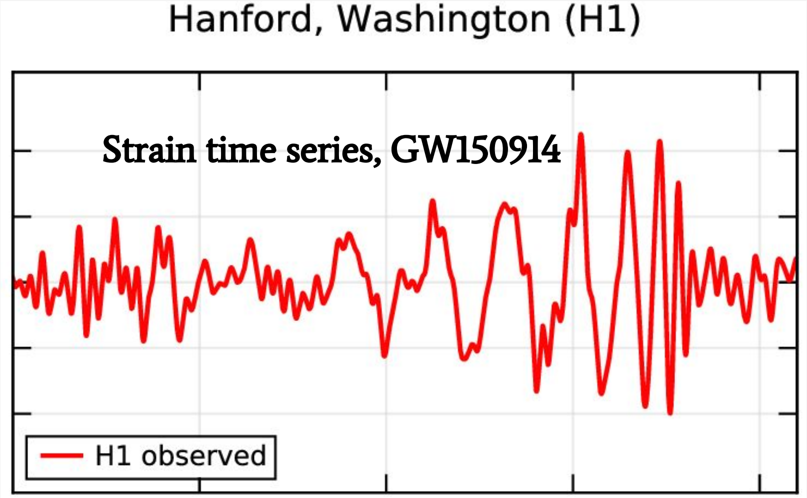
- ~ 0.5 million BBH events per year.

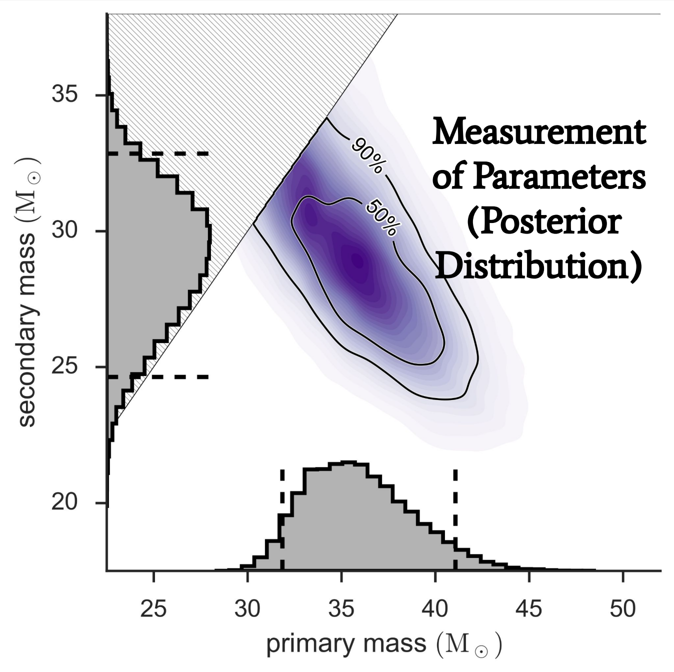
- Plus also detectors in the:
  - Millihertz regime (LISA)
  - Decihertz regime (DECIGO, LGWA, LILA)
  - Kilohertz regime (NEMO)



Hall & Evans (2019)

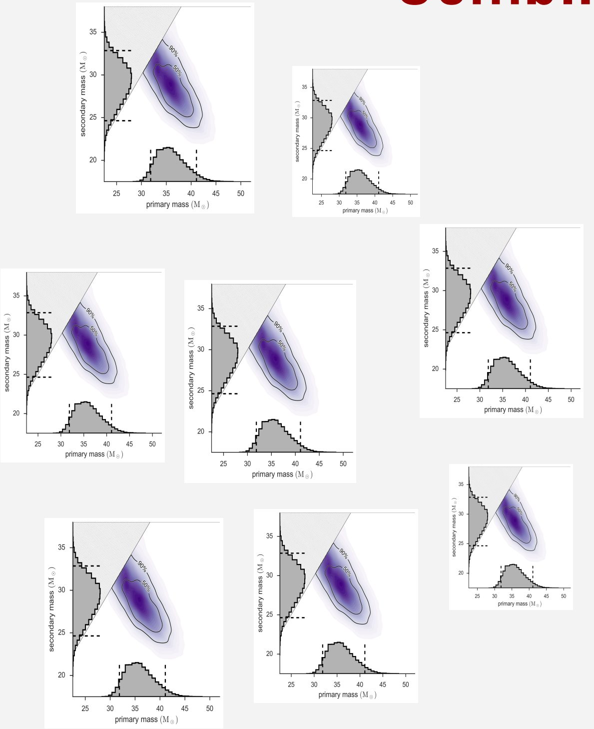
Uncertain Measuements





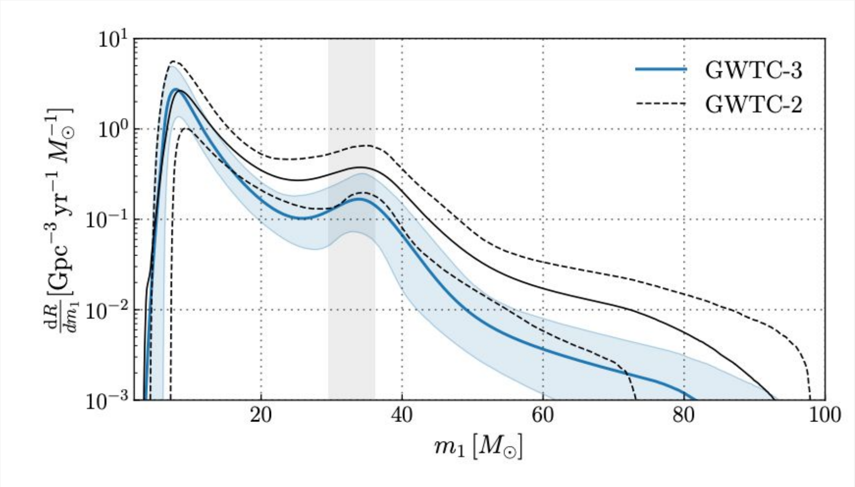
Abbott+ 2016, arXiv:1602.03837, arXiv:1602.03840

Combining Uncertain Measurements



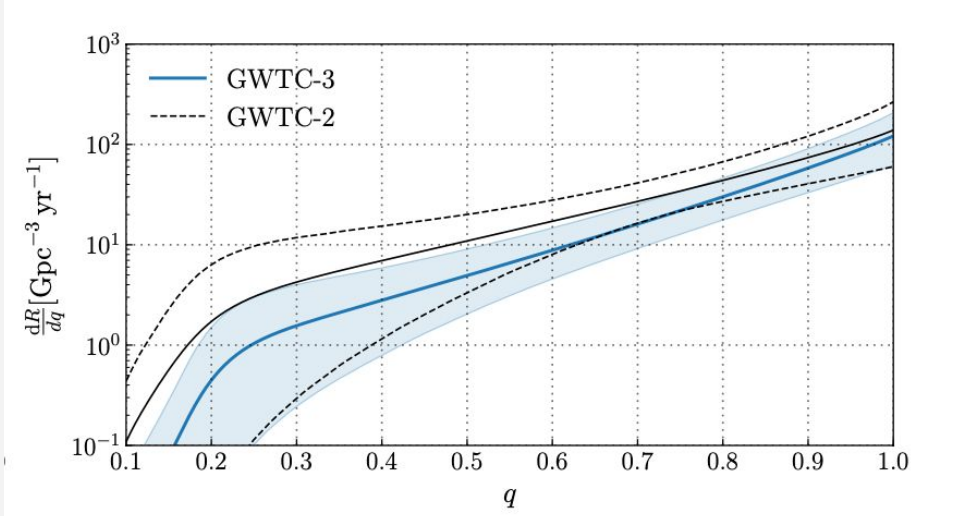
Many uncertain measurements from different sources

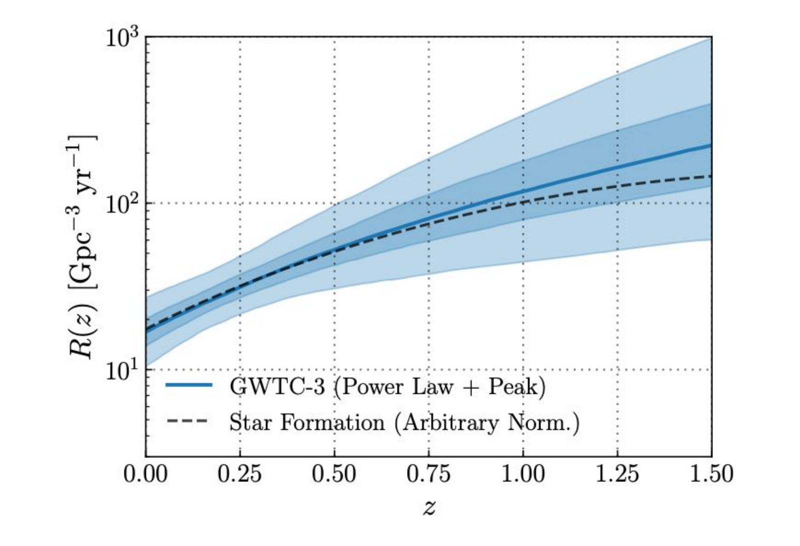
Correct for selection effects



Measurements of ensemble properties [LVK+, arXiv:2111.0363]

Combining Uncertain Measurements





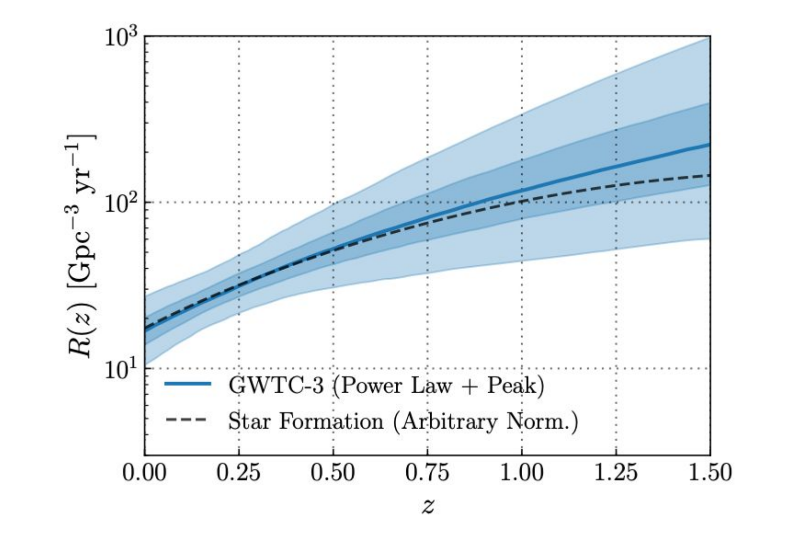
Measurements of ensemble properties [LVK+, arXiv:2111.0363]

Combining Uncertain Measurements

Compare these ensemble properties to astrophysical expectations and answer questions like:

- Where do binaries form and grow?
  - Galactic field?
  - Globular clusters?
  - AGN?
  - Something else???
- What can these binaries tell us about
  - Stellar collapse details?
  - Equation of state of neutron stars?

and many more!



Measurements of ensemble properties
[LVK+, arXiv:2111.0363]

Inferring host galaxy properties of LIGO-Virgo-KAGRA's black holes

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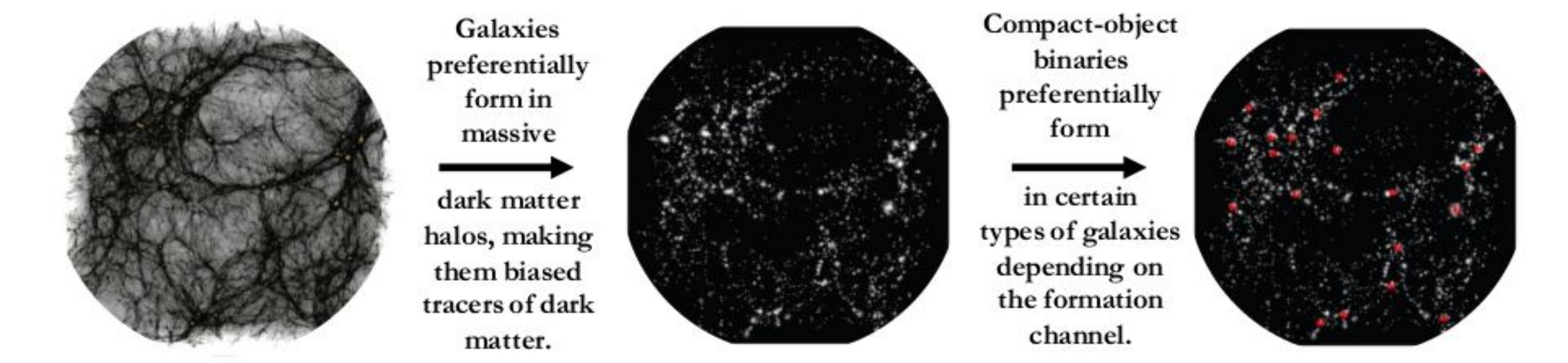
ABSTRACT

Observations of gravitational waves from binary black hole (BBH) mergers have measured the redshift evolution of the BBH merger rate. The number density of galaxies in the Universe evolves differently with redshift based on their physical properties, such as their stellar masses and star formation rates. In this work we show that the measured population-level redshift distribution of BBHs sheds light on the properties of their probable host galaxies. We first assume that the hosts of BBHs can be described by a mixture model of galaxies weighted by stellar mass or star formation rate, and find that we can place upper limits on the fraction of mergers coming from a stellar mass weighted sample of galaxies. We then constrain parameters of a physically motivated power-law delay-time distribution using GWTC-3 data, and self-consistently track galaxies in the UniverseMachine simulations with this delay time model to infer the probable host galaxies of BBHs over a range of redshifts. We find that the inferred host galaxy distribution at redshift $z = 0.21$ has a median star formation rate $\sim 0.9\, M_\odot \mathrm{yr}^{-1}$ and a median stellar mass of $\sim 1.9 \times 10^{10}\, M_\odot$. We also provide distributions for the mean stellar age, halo mass, halo radius, peculiar velocity, and large scale bias associated with the host galaxies, as well as their absolute magnitudes in the B- and $\mathrm{K_s}$-bands. Our results can be used to design optimal electromagnetic follow-up strategies for BBHs, and also to aid the measurement of cosmological parameters using the statistical dark siren method.

Connection between GWs and their hosts



Adapted from Wechsler and Tinker (2018)

Inferring Host Galaxies: Basic Idea

- Binary black holes form and evolve in galaxies.
  - Star forming galaxies? Massive galaxies? Something else?
  - Poor localization → No association of host galaxies on a per-event level

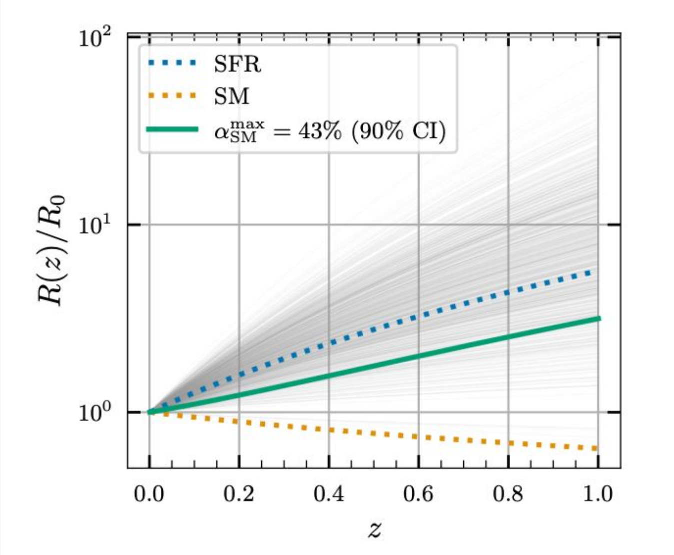
- The ensemble number density of binary black holes should track the number density of galaxies, as a function of redshift.

- So, the redshift evolution of BBHs measured from GWTC-3 data should already shed light on BBH host galaxies.

Galaxies evolve differently based on their properties

- A set of star forming galaxies will evolve consistently with cosmic star formation rate density: $(1 + z)^{2.7}$.
    - Will also refer to such galaxies as SFR-weighted galaxies.

- On the other hand, galaxies weighted by their stellar mass decrease with increasing redshift:
    - Lesser stars per unit volume at higher redshift.

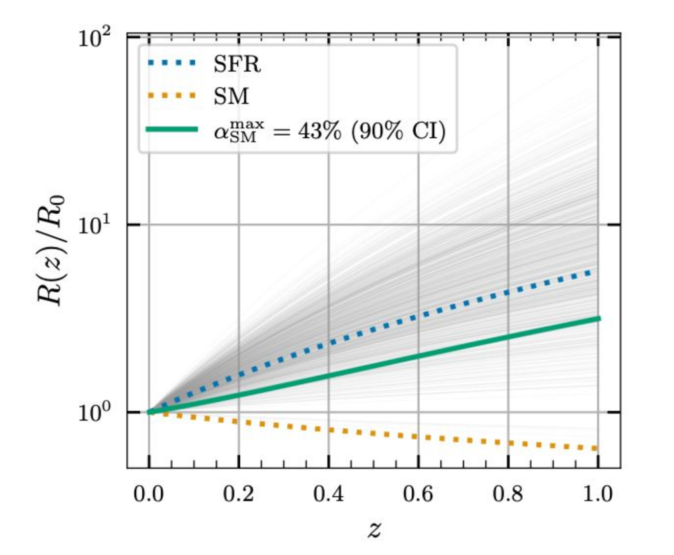


Simple Mixture model: stellar mass weighted galaxies + SFR weighted galaxies

Galaxies evolve differently based on their properties

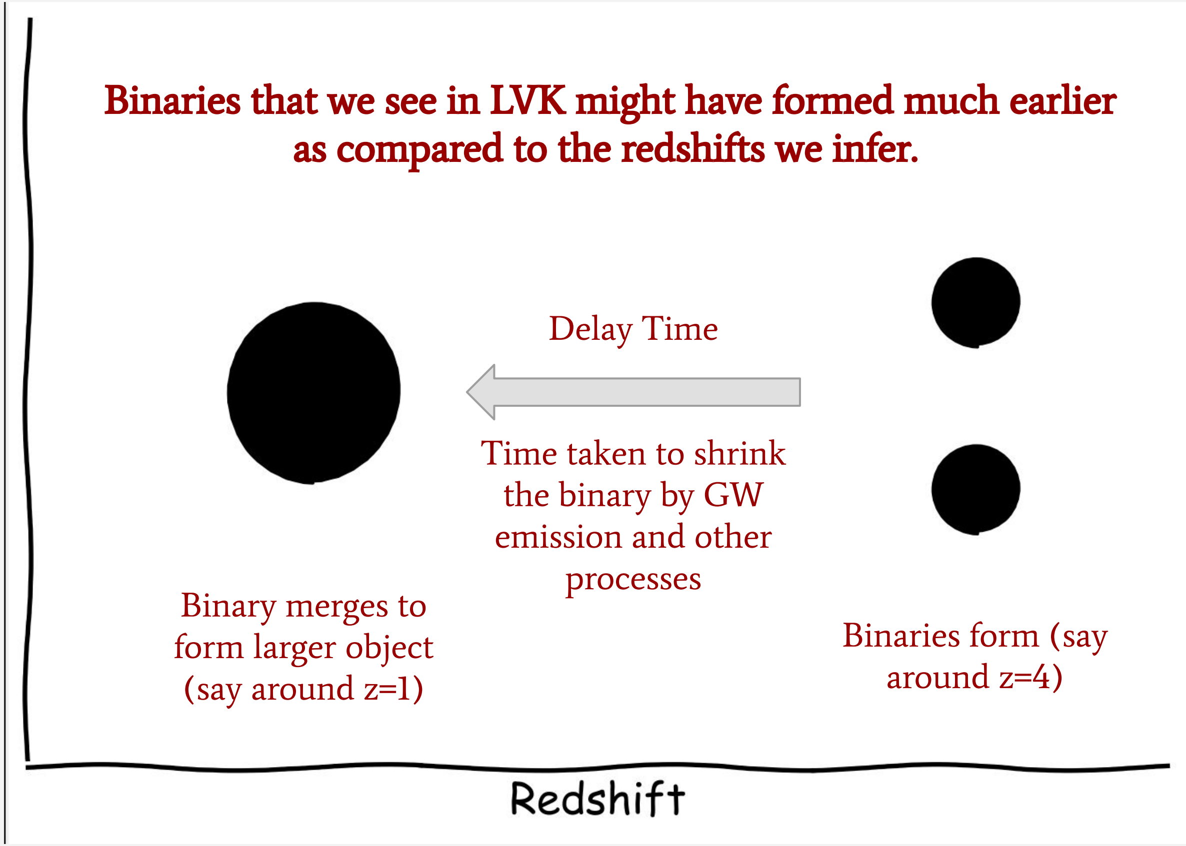
- Assume simple mixture model of SM-weighted and SFR weighted galaxies:
  - Typical assumption e.g. in short GRB/FRB literature and (also Adhikari+ 2020 in context of GWs)

- Compare with R(z) from GWTC-3
  - Purely stellar mass weighted host galaxies are ruled out.
  - Their maximum contribution to the total population is 43% [90% CL].



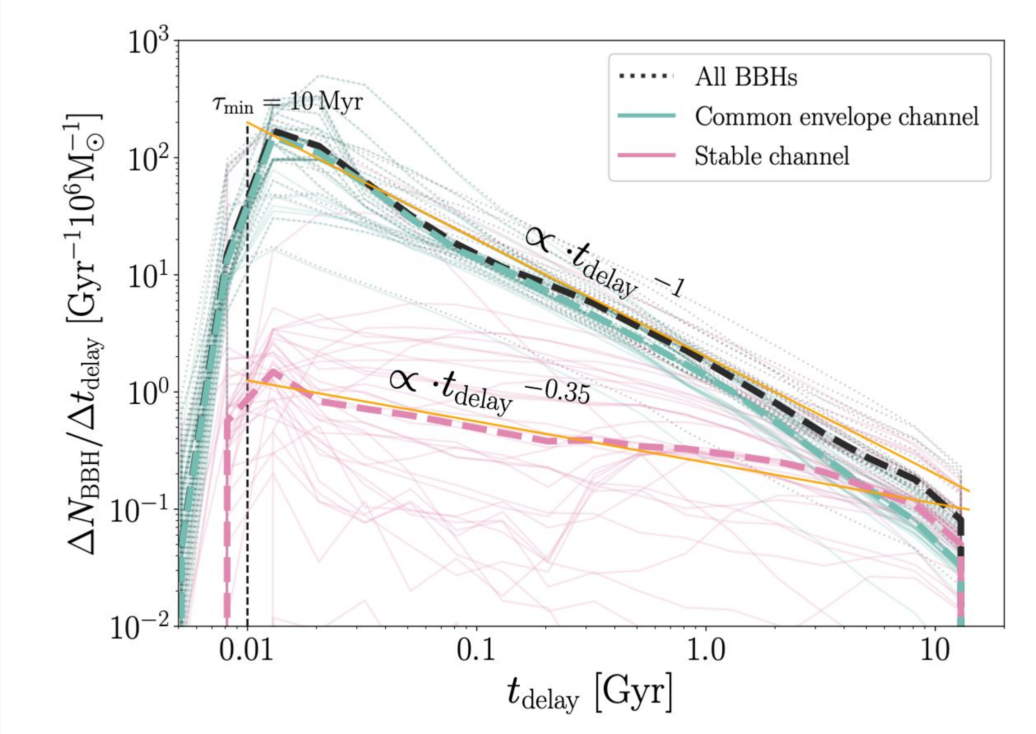
Simple Mixture model: stellar mass weighted galaxies + SFR weighted galaxies

Delay Time



Binaries that we see in LVK might have formed much earlier as compared to the redshifts we infer.
Delay Time
Time taken to shrink the binary by GW emission and other processes
Binary merges to form larger object (say around z=1)
Binaries form (say around z=4)
Redshift

Delay Time



Distribution of delay times from selected formation channels [Fishbach+Van Son, arXiv:2307.15284]

Physically-motivated prescription: galaxies+delay time

- Delay time distributions can be constrained from GWTC-3 data

$$R(t) = \int_0^\infty \mathrm{d}t_D \, R_f(t + t_D) \, p(t_D)$$

- Use power law delay time model parametrized by:
  - Minimum time delay tmin
  - Power law exponent alpha

- Constrain tmin < 2.23 Gyr, alpha < -1.55 [90% CL]. Consistent with other recent works [Fishbach and Van Son 2023, Turbang+ 2023]

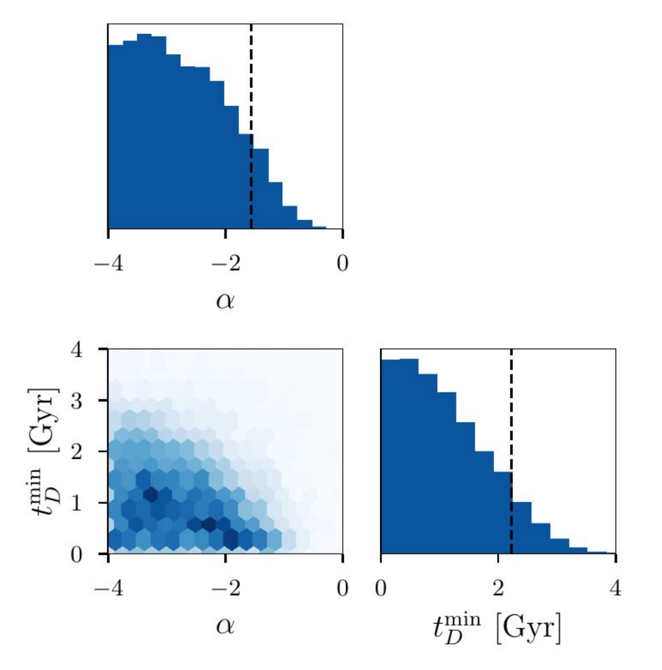


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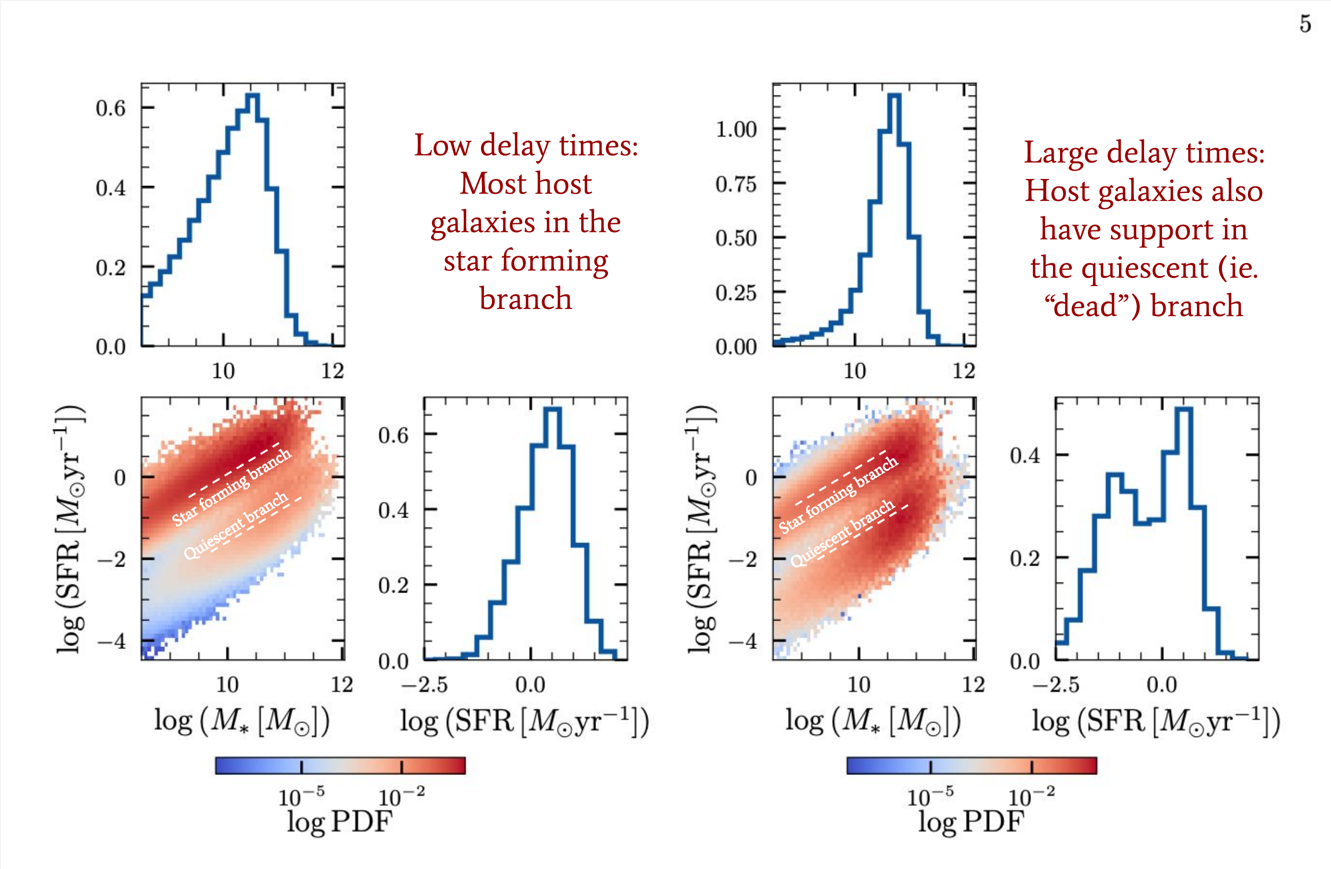
Illustration: Host galaxies at small and large delay times



Low delay times: Most host galaxies in the star forming branch

Large delay times: Host galaxies also have support in the quiescent (ie. "dead") branch

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Physically-motivated prescription: galaxies+delay time

- UniverseMachine simulations of galaxy evolution
  - Models the star formation and mass assembly history as a function of redshift
  - Instead of using first principles physics, populates galaxies into dark matter halos such that it is consistent with a large set of observations.

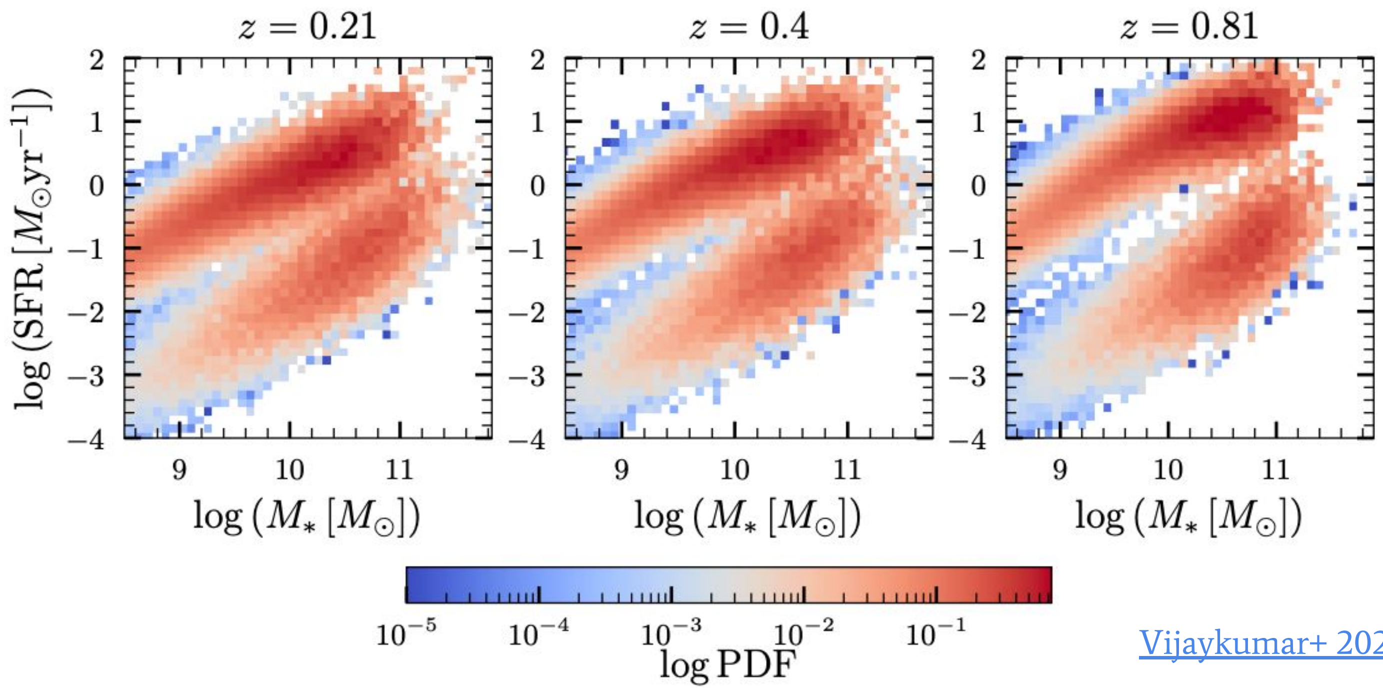
- Feed the delay time inference into UniverseMachine, and track every galaxy's star formation history with a delay time to calculate merger rate in each galaxy:

$$R_i^{\mathrm{merg}}(z_0) = \int \mathrm{d}t_D \, R_i^{\mathrm{SFH}}(t(z_0) + t_D) \times p(t_D)$$

  Same as the equation in the previous slide, written on a per galaxy level.

- Plot histograms of galaxies weighted by the merger rate.

Median inferred host galaxy distribution



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Host galaxy distribution at z=0.21

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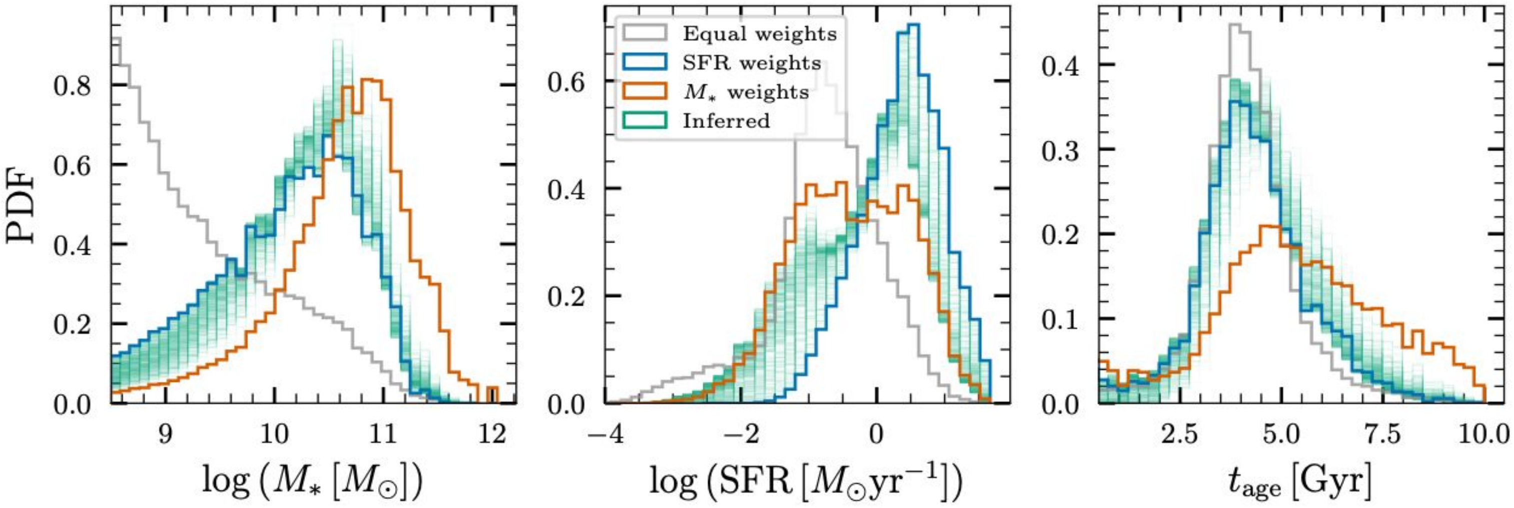
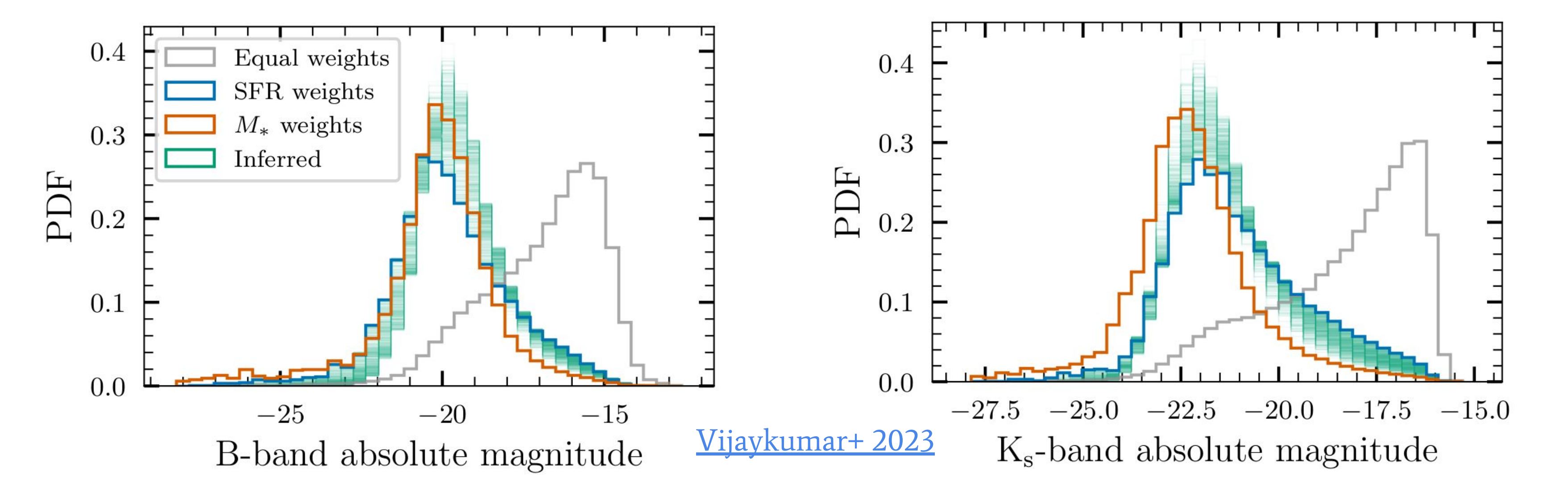


Properties are close to SFR-weighted galaxies, inconsistent with equally weighted galaxies
Story is similar at other redshifts.

B-band and Ks-band magnitudes at z=0.21

Calculate fluxes/magnitudes in the B-band and Ks-band.
These bands are used in dark siren analyses as proxies for SFR and stellar mass respectively.



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Summary

- Redshift evolution of the BBH merger rate inferred from GWTC-3 already sheds light on probable host galaxies of BBHs.
  - Purely stellar mass sample of galaxies is ruled out

- We develop a framework to combine delay time distribution constraints and galaxy star formation histories to constrain the set of host galaxies.

- Could be used to "weight" galaxies for measurement of Hubble constant using GW sources.

- Can be trivially extended to BNSs, NSBHs, astronomical transients/objects if they have a measured redshift evolution of rate/number density.

Waltzing Binaries: Probing the Line-of-sight Acceleration of Merging Compact Objects with Gravitational Waves

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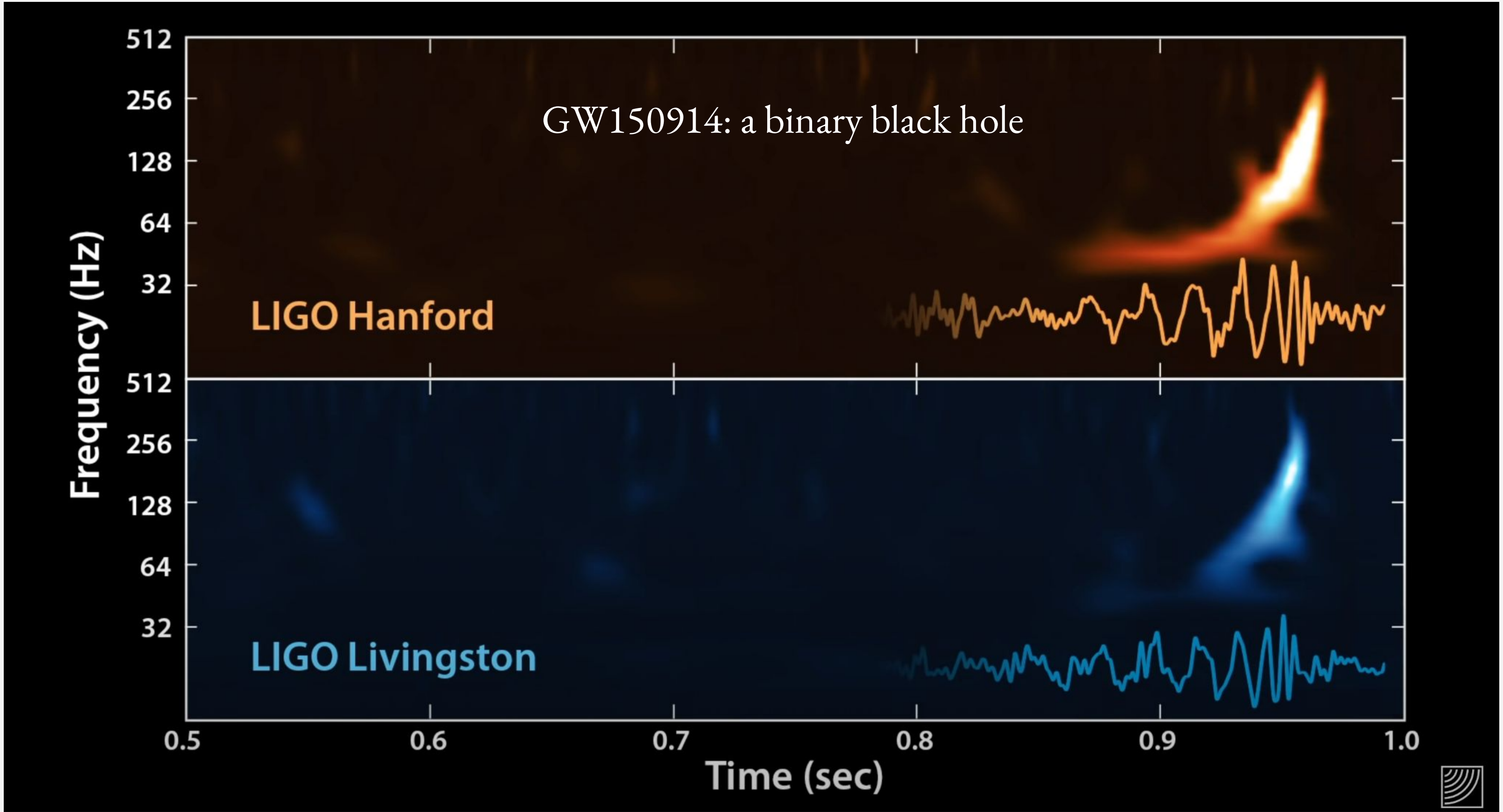
Abstract

The line-of-sight acceleration of a compact binary coalescence (CBC) event would modulate the shape of the gravitational waves (GWs) it produces with respect to the corresponding nonaccelerated CBC. Such modulations could be indicative of its astrophysical environment. We investigate the prospects of detecting this acceleration in future observing runs of the LIGO-Virgo-KAGRA network, as well as in next-generation (XG) detectors and the proposed DECIGO. We place the first observational constraints on this acceleration for putative binary neutron star mergers GW170817 and GW190425. We find no evidence of line-of-sight acceleration in these events at 90% confidence. Prospective constraints for the fifth observing run of the LIGO at A+ sensitivity suggest that accelerations for typical binary neutron stars (BNSs) could be constrained with a precision of $a/c \sim 10^{-7}\,[\mathrm{s}^{-1}]$, assuming a signal-to-noise ratio of 10. These improve to $a/c \sim 10^{-9}\,[\mathrm{s}^{-1}]$ in XG detectors, and $a/c \sim 10^{-16}\,[\mathrm{s}^{-1}]$ in DECIGO. We also interpret these constraints in the context of mergers around supermassive black holes.

What does a GW signal from a merging binary look like?



Credit: LIGO Scientific Collaboration

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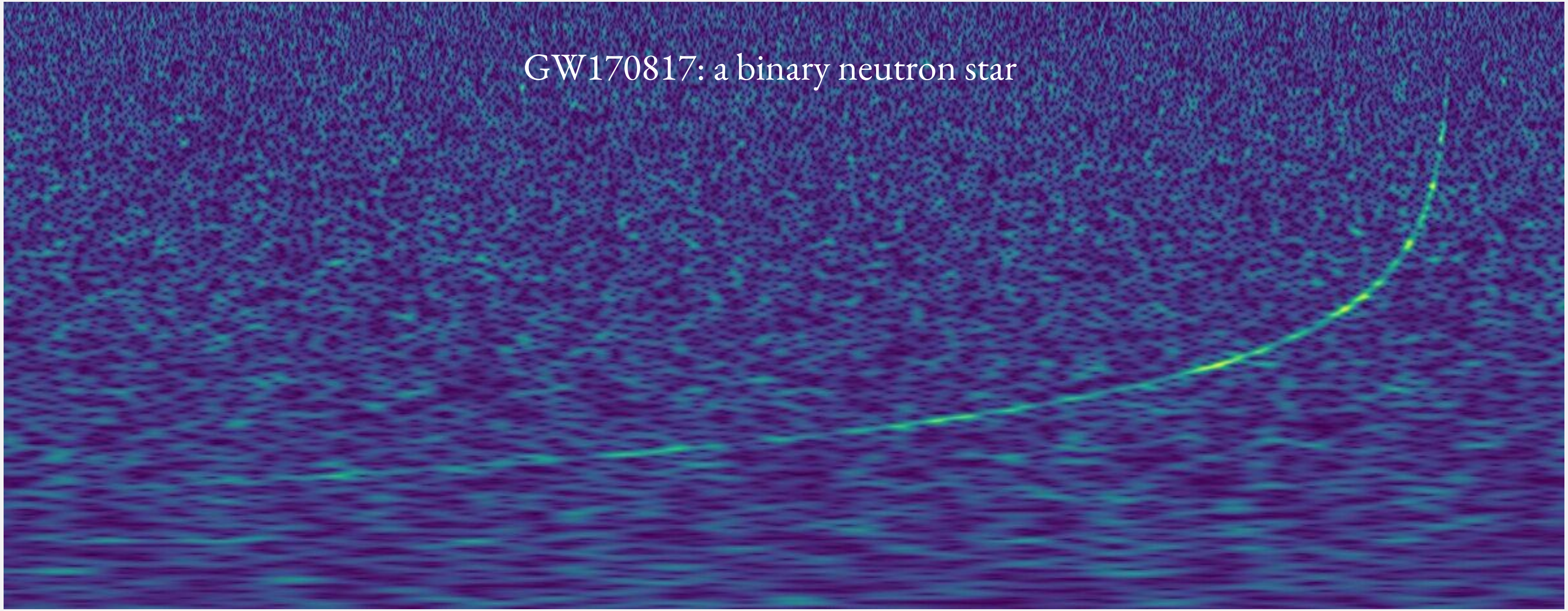
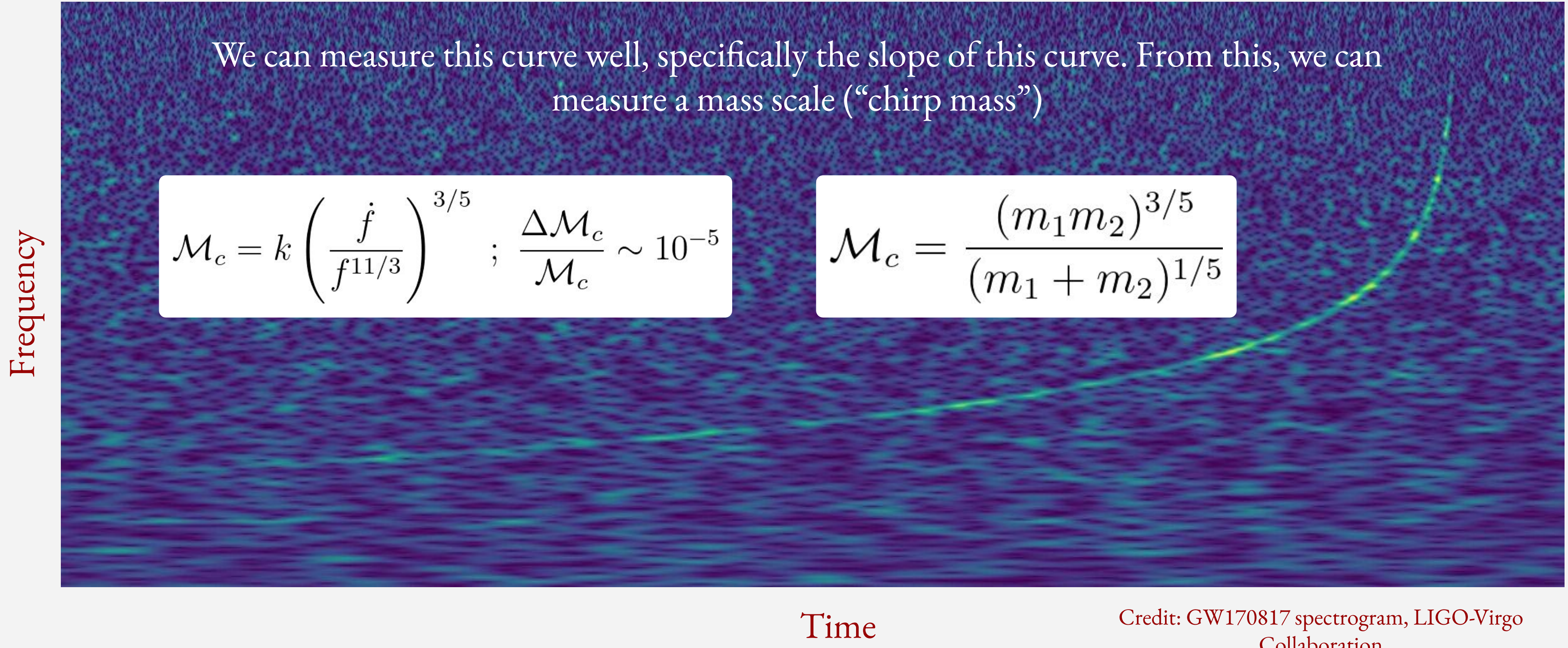


Frequency

Time

Credit: GW170817 spectrogram, LIGO-Virgo Collaboration

What does a GW signal from a merging binary look like?



We can measure this curve well, specifically the slope of this curve. From this, we can measure a mass scale ("chirp mass")

$$\mathcal{M}_c = k\left(\frac{\dot{f}}{f^{11/3}}\right)^{3/5} \; ; \; \frac{\Delta \mathcal{M}_c}{\mathcal{M}_c} \sim 10^{-5}$$

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Credit: GW170817 spectrogram, LIGO-Virgo Collaboration

What if the binary's centre-of-mass is moving?

If the binary has a velocity *v*, GWs will get redshifted (let's ignore cosmic expansion for now)

$$z_{\rm dop} = \frac{v}{c}$$

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$$\mathcal{M}_c \rightarrow \mathcal{M}_c(1 + z_{\rm dop})$$

What if the binary's centre-of-mass is accelerating?

$$\mathcal{M}_c \to \mathcal{M}_c(1 + z_{\rm dop})$$

- Constant velocity (i.e. constant redshift) → degenerate with the component masses, and hence cannot be measured.

What if the binary's centre-of-mass is accelerating?

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- Accelerating binary → Time-varying velocity → Time-varying chirpmass → Measurable!

What if the binary's centre-of-mass is accelerating?

$$\mathcal{M}_c \to \mathcal{M}_c(1 + z_{\rm dop})$$

- Constant velocity (i.e. constant redshift) → degenerate with the component masses, and hence cannot be measured.
- Accelerating binary → Time-varying velocity → Time-varying chirpmass → Measurable!
- Specifically, for a GW170817-like signal, if

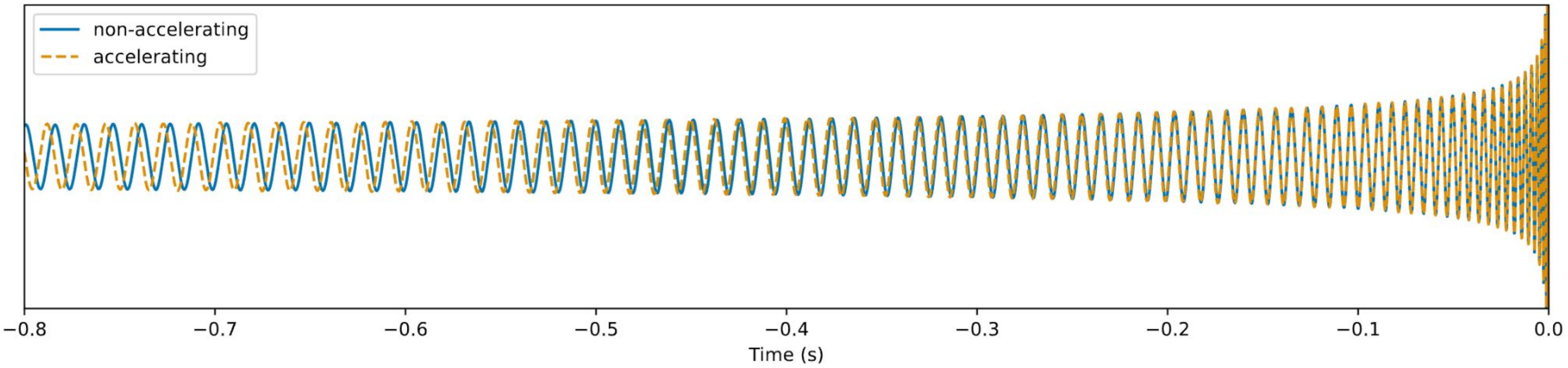
$$\frac{aT}{c} > 10^{-5} \implies \frac{a}{g} > 3$$

We can measure the acceleration.

What if the binary's centre-of-mass is accelerating?

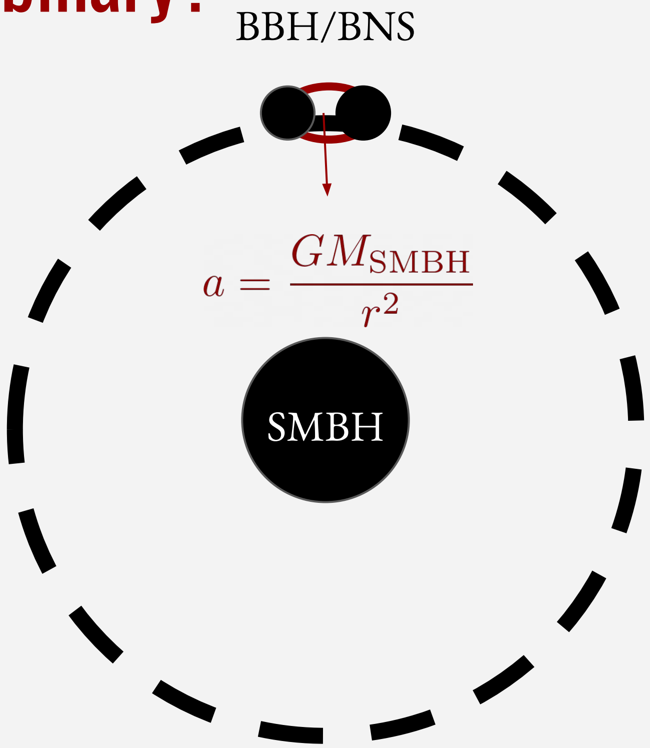
$$\Delta\Psi(f) = \frac{25\Gamma M}{65536\eta^2}v^{-13}\left[1 + \left(\frac{743}{126} + \frac{22}{3}\eta\right)v^2 - \frac{64\pi}{5}v^3 + \left(\frac{1755623}{84672} + \frac{32633}{756}\eta + \frac{367}{12}\eta^2\right)v^4 - \left(\frac{20807}{210} + \frac{574}{15}\eta\right)\pi v^5 + \left\{-\frac{28907482848623}{35206617600} + \frac{9472}{75}\pi^2 + \frac{13696}{105}\gamma + \frac{13696}{105}\ln(4v) + \left(\frac{3311653861}{1524096} - \frac{451}{6}\pi^2\right)\eta + \frac{2030687}{18144}\eta^2 + \frac{66287}{648}\eta^3\right\}v^6 - \left(\frac{158992529}{317520} + \frac{1015907}{1890}\eta - \frac{419}{945}\eta^2\right)\pi v^7\right].$$

What if the binary's centre-of-mass is accelerating?



How to accelerate a binary?

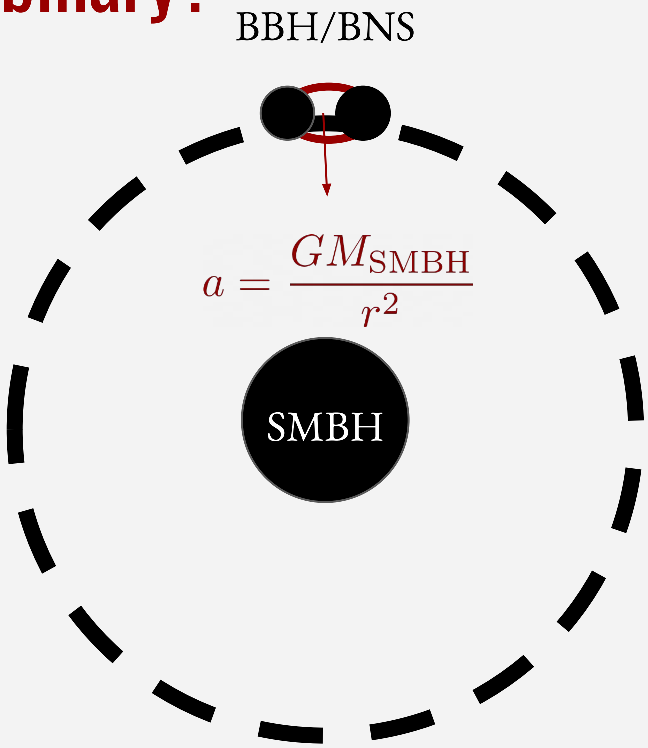
- Accelerated motion (eg. circular motion) is common in astrophysics.
- Binaries near SMBHs, in globular clusters, or even in the galactic field have some acceleration.
    - Where binaries form and grow is an open question. Measurements of acceleration can help with this!



How to accelerate a binary?

Typical values of acceleration

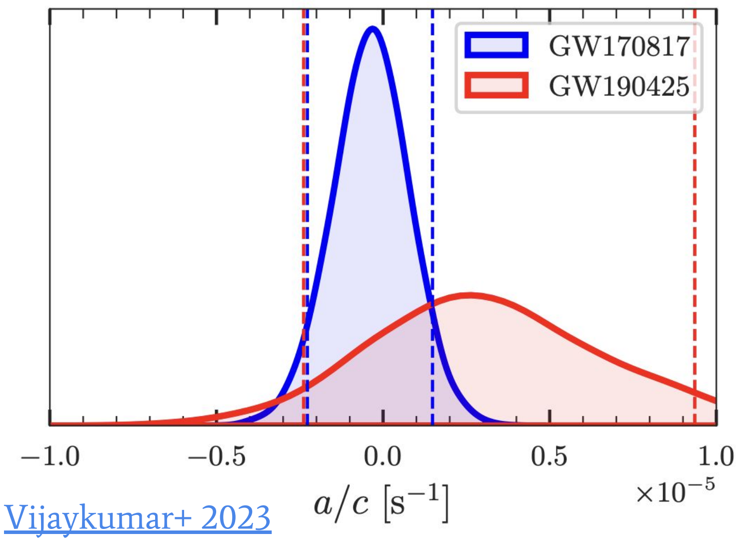
- Galactic Field: $a/c \sim 10^{-17}$ -- 10^{-15} s^{-1}
- Globular Clusters: $a/c \sim 10^{-16}$ --10^{-12} s^{-1}
- Near SMBHs: $a/c \sim 10^{-10}$ -- 10^{-6} s^{-1}



Measurement from GW170817 and GW190425

- We first estimate the acceleration from the BNS events GW170817 and GW190425, ideal for this measurement since they are low mass events.

- Both measurements are consistent with zero acceleration.



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Measurement from GW170817 and GW190425

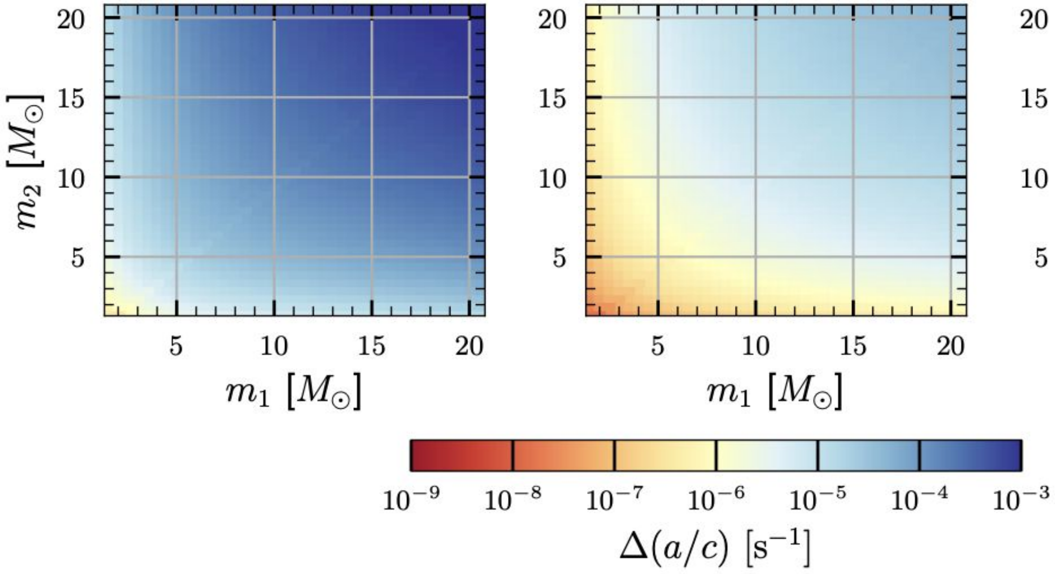
$$a/c = 4.65 \times 10^{-12} \left(\frac{M_{\rm BH}}{10^{10} M_\odot}\right) \left(\frac{r}{1{\rm pc}}\right)^{-2} \cos\theta \ {\rm s}^{-1}$$

- Using this measurement, we constrain the distance of GW170817 from the centre of its galaxy to: $r > 12.1\ {\rm AU}$
  - This uses the fact that we *know* the mass of the SMBH nearest to GW170817.
  - However, this constraint is rather weak, since we also know the actual distance of GW170817 wrt the SMBH (~2 kpc).

- On the other hand, since we do not know the mass of GW190425's host galaxy, we place a SMBH-mass dependent constraint on its distance from the galactic centre

$$r > 7.2 \times (M_{\rm BH}/10^8 M_\odot)^{1/2}\ {\rm AU}$$

Measurability of acceleration



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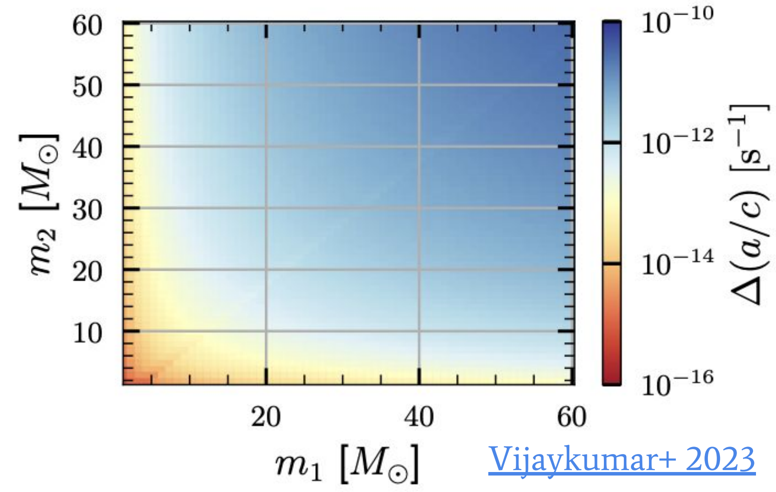
At SNR=10 using O5, Cosmic Explorer and Einstein Telescope from left to right.

Measurability of acceleration in decihertz detectors

- DECIGO, which is a proposed space-based deci-hertz detector (as opposed to ~10 Hz for LIGO-like detectors) promises spectacular constraints on the acceleration.



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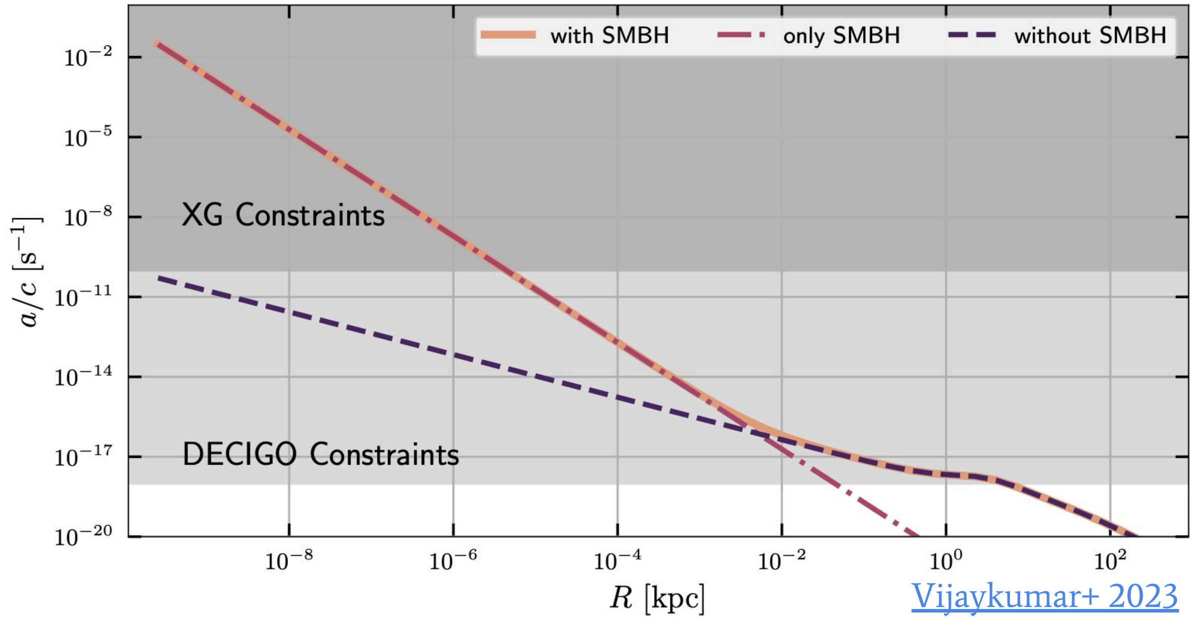
Prospects

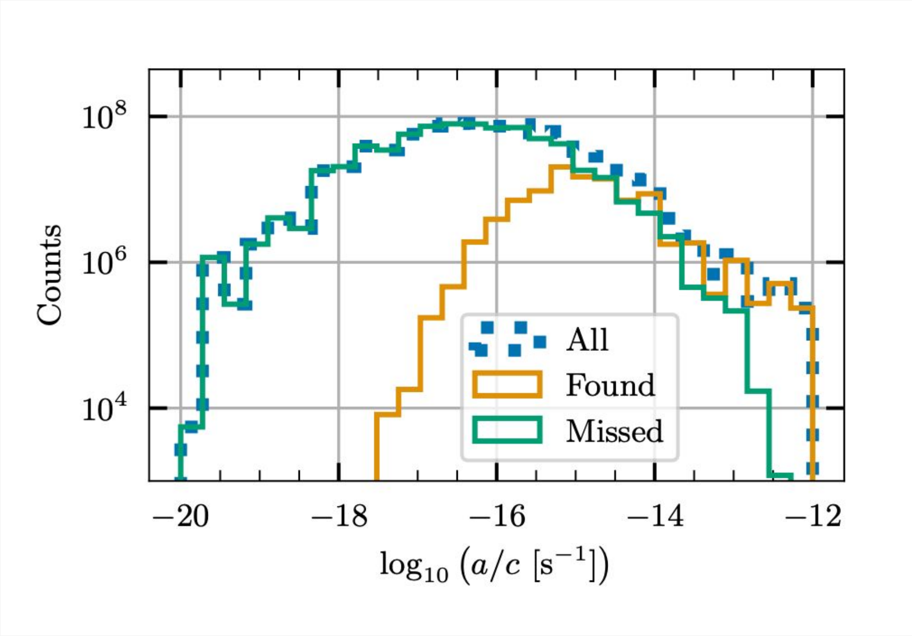


[Vijaykumar+ 2023]

Accelerations in a Milky Way like galaxy. While Einstein Telescope can probe distances ~1000 Schwarzschild radii, DECIGO can probe distance right out to ~5 kpc from the centre.

Prospects

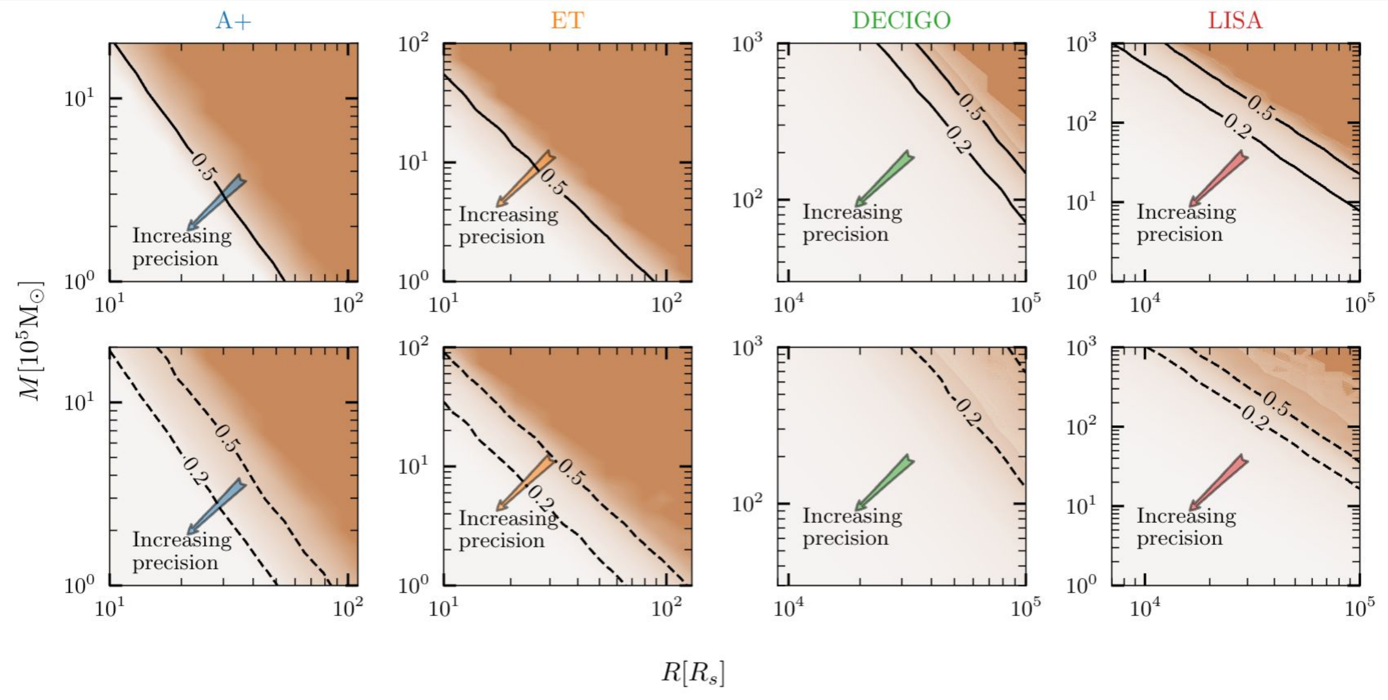
Accelerations in globular clusters, derived from the Cluster Monte Carlo simulations [Kremer+ 2020]



About 12% of all events coming from globular clusters will have detectable accelerations in DECIGO.
[Tiwari, Vijaykumar+ 2023, arXiv:2307.00930]

Prospects (Extremely Preliminary)

Measuring higher time-derivatives of the acceleration (jerk, snap,…) can inform the mass of the environment as well as the distance from the centre of the environment (and maybe also mass profiles!).



Summary

- Acceleration can be measured with GW events. Best constraints come from low-mass events.
- Acceleration measured with GW170817 and GW190425 are consistent with zero.
- Future detectors will measure acceleration with very high precision, thus probing formation environments of binaries.
- Future Work: can we measure jerk, snap, crackle, pop etc.? :)

Thanks for Listening!

Get in Touch!

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Backup Slides

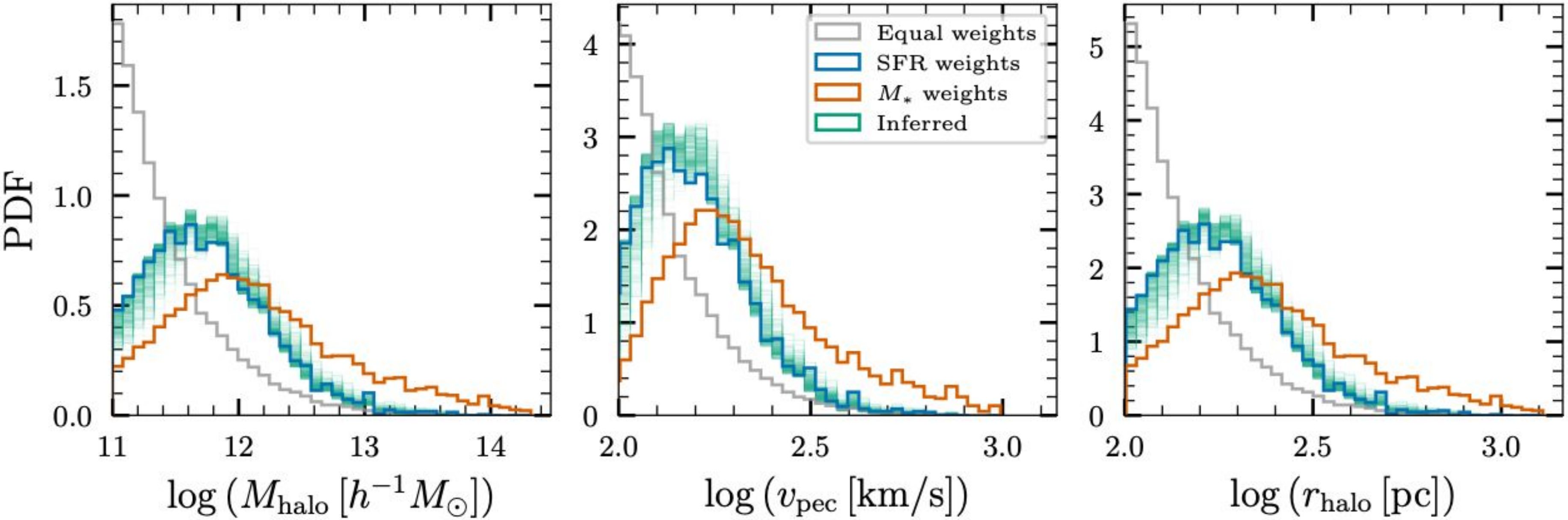
Effect on GW signal

- Formally, acceleration affects the waveform at -4 Post Newtonian (PN) order (leading contribution).
    - The coefficient only depends on *(mass)* * *(acceleration / speed of light)*.

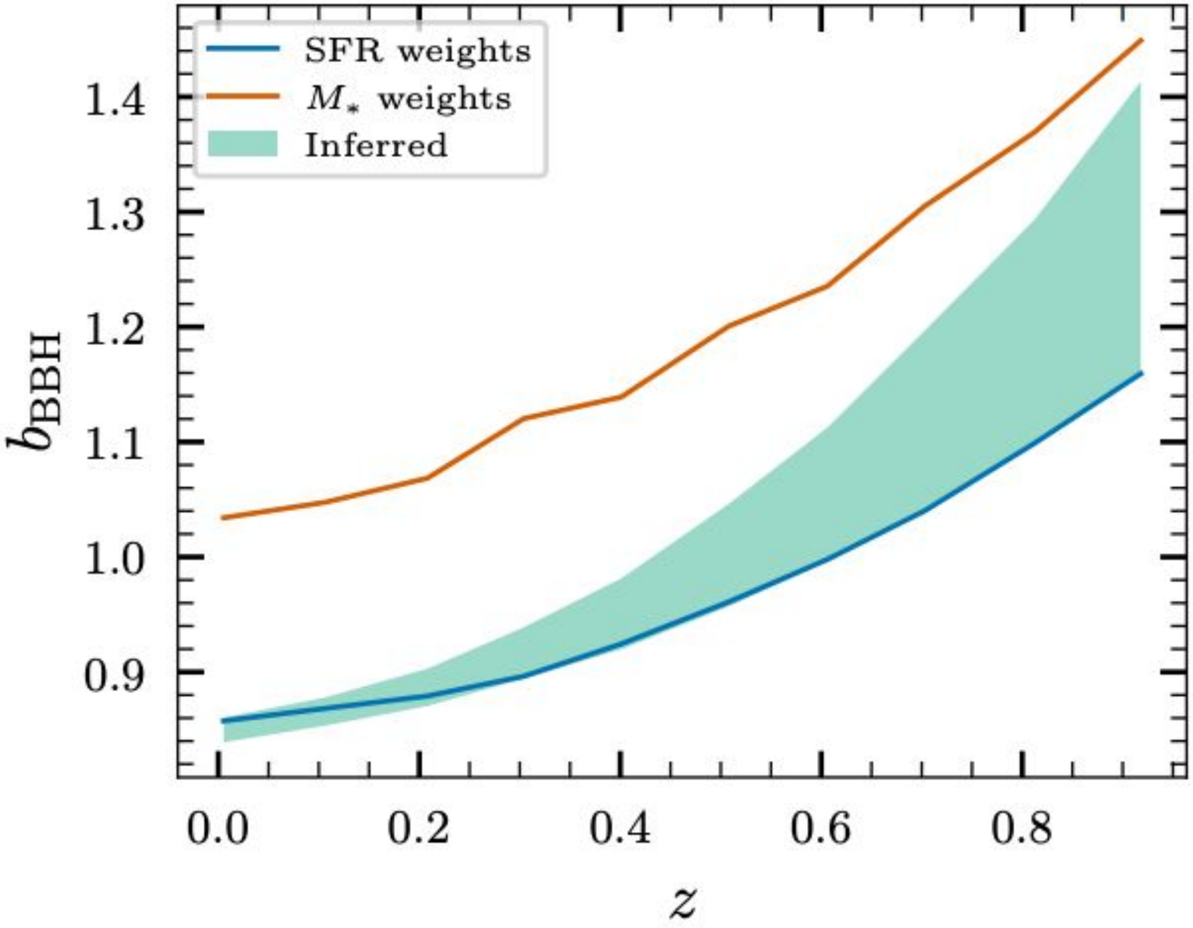
$$\Delta\Psi(f) = \frac{25}{65536\,\eta^2}\left(\frac{GM}{c^3}\right)\left(\frac{a}{c}\right) v_f^{\;-13}\left[1+\sum_{k=0}^{7}\alpha_k v_f^k\right]$$

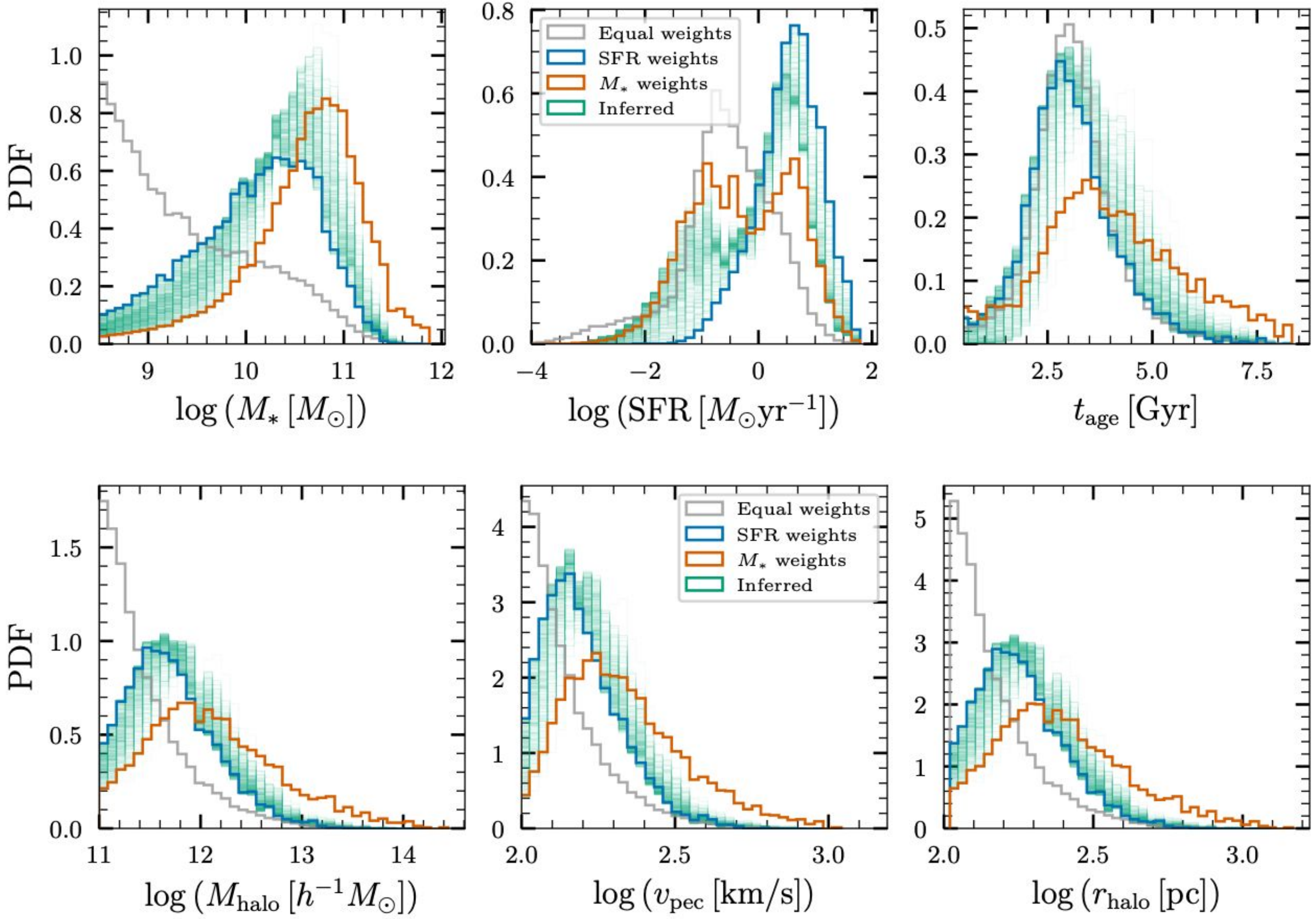
    - Since $v \sim f^{1/3}$, the effect is prominent at lower frequencies, and binaries with more low-frequency content (ie. low mass) would give best measurements of acceleration.

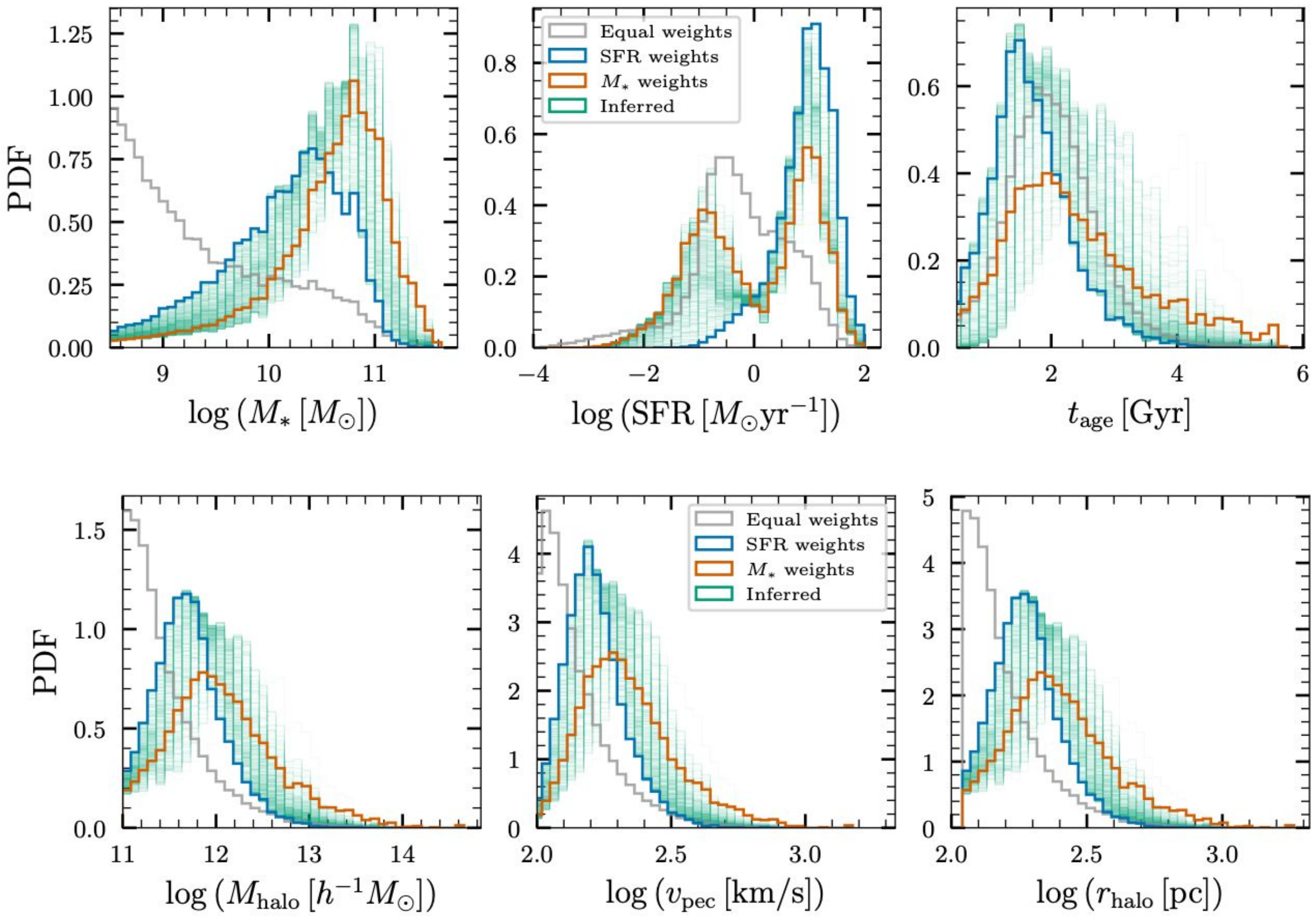
Question: How measurable is this acceleration, and what can we say about the environments of these mergers with the measurement?



PDF
0.0
0.5
1.0
1.5
11
12
13
14
log (M_halo [h^-1 M_⊙])
0
1
2
3
4
2.0
2.5
3.0
log (v_pec [km/s])
Equal weights
SFR weights
M_* weights
Inferred
0
1
2
3
4
5
2.0
2.5
3.0
log (r_halo [pc])


SFR weights
M_* weights
Inferred
b_{BBH}
1.4
1.3
1.2
1.1
1.0
0.9
0.0
0.2
0.4
0.6
0.8
z


Equal weights
SFR weights
M_* weights
Inferred
PDF
$\log(M_* [M_\odot])$
$\log(\mathrm{SFR} [M_\odot \mathrm{yr}^{-1}])$
t_{age} [Gyr]
$\log(M_{\mathrm{halo}} [h^{-1} M_\odot])$
$\log(v_{\mathrm{pec}} [\mathrm{km/s}])$
$\log(r_{\mathrm{halo}} [\mathrm{pc}])$



PDF
log $(M_* [M_\odot])$
Equal weights
SFR weights
M_* weights
Inferred
log (SFR $[M_\odot \mathrm{yr}^{-1}]$)
t_{age} [Gyr]
PDF
log $(M_{\mathrm{halo}} [h^{-1} M_\odot])$
Equal weights
SFR weights
M_* weights
Inferred
log $(v_{\mathrm{pec}}$ [km/s])
log $(r_{\mathrm{halo}}$ [pc])