"Dirty" gravitational-wave physics

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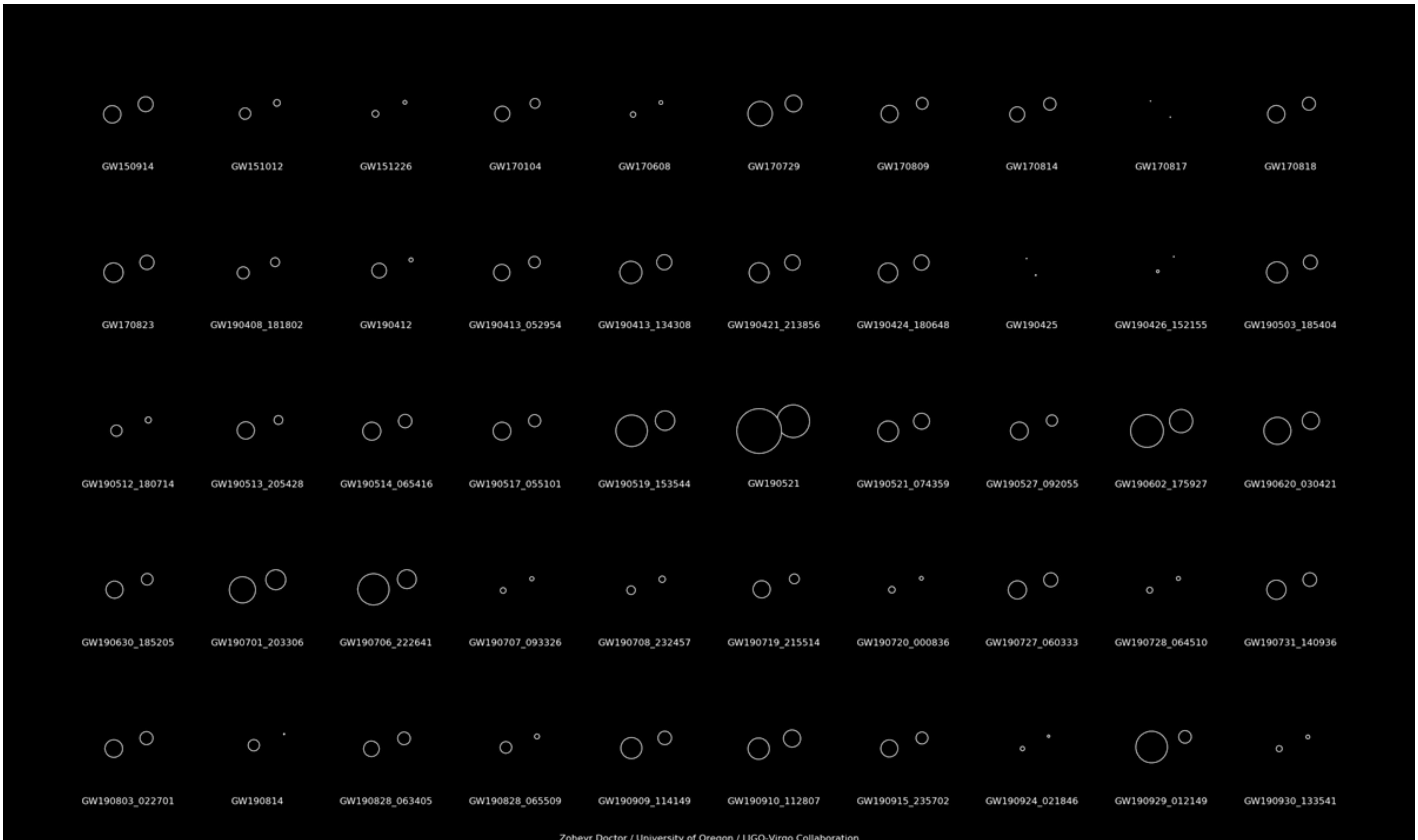
PERIMETER INSTITUTE

Paris Observatory, December 2020

with A. Toubiana, C. Miller arXiv:2010.05974
and with A. Toubiana, A. Caputo, et al. arXiv:2010.06056, arXiv:2001.03620

"DIRTY" VS "CLEAN"

Today's gravitational wave events

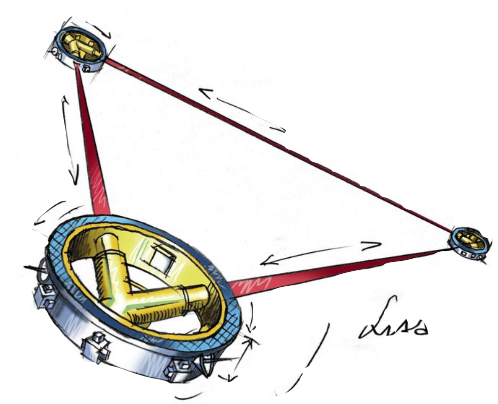


"DIRTY" VS "CLEAN"

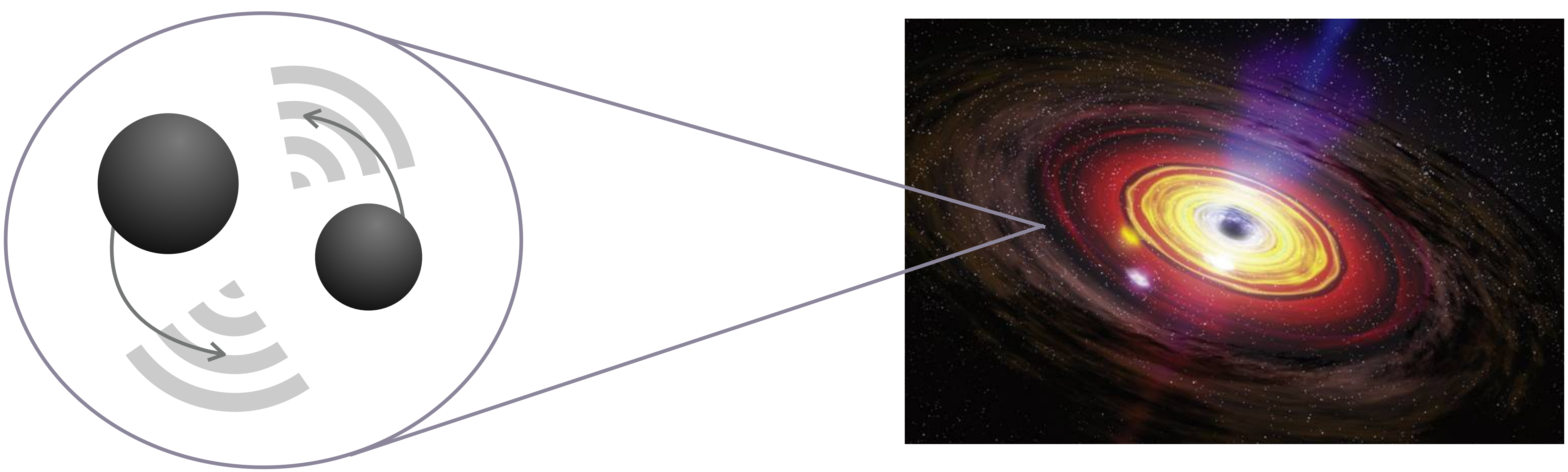
Today's gravitational wave events

Binaries detected by **LIGO/Virgo** are close to **merger**: dynamics are dominated by gravitational wave emission

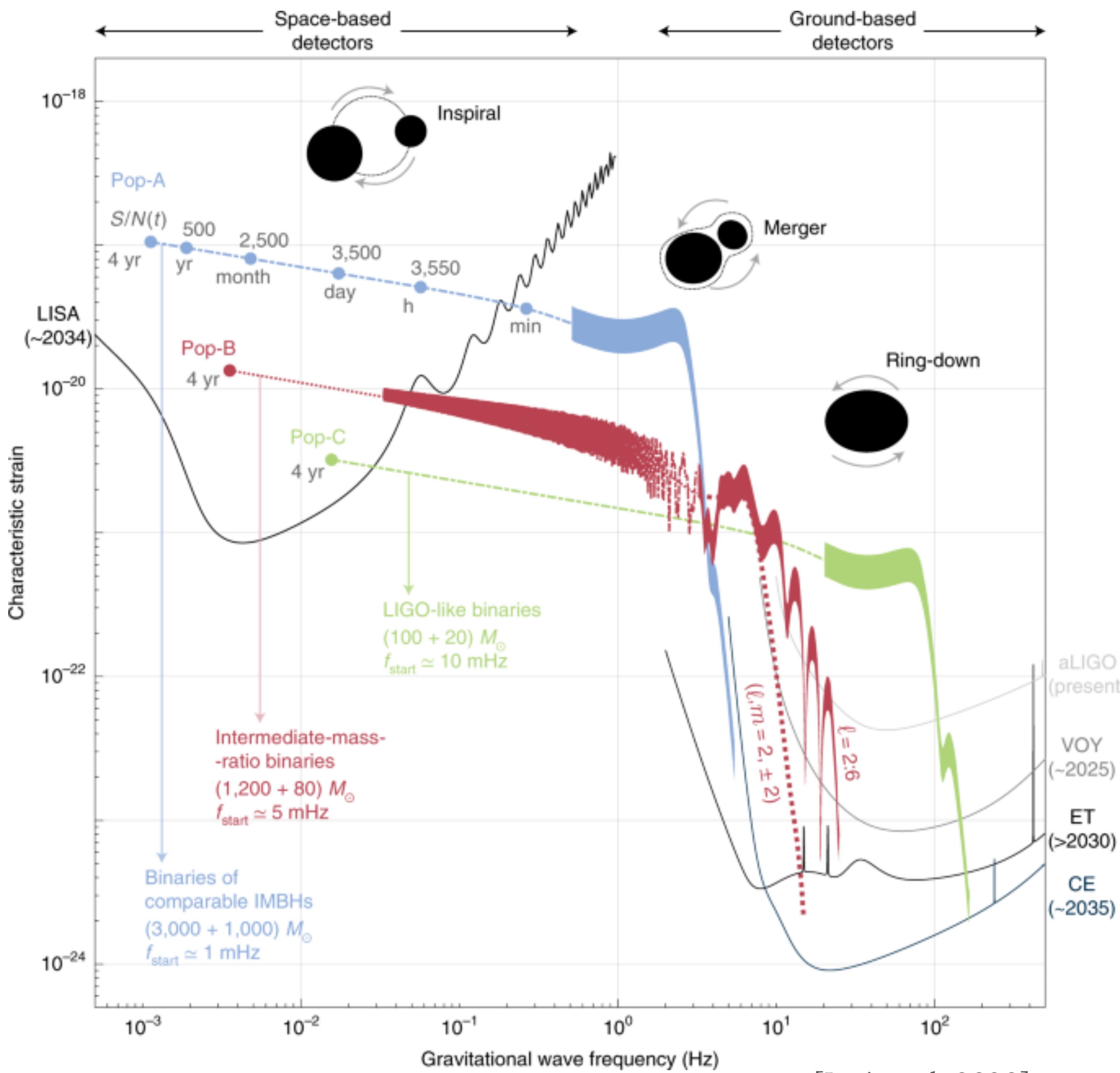
Tomorrow's



LISA will be sensitive to **lower frequencies**, other effects could be significant/dominant



LISA AND MULTIBAND

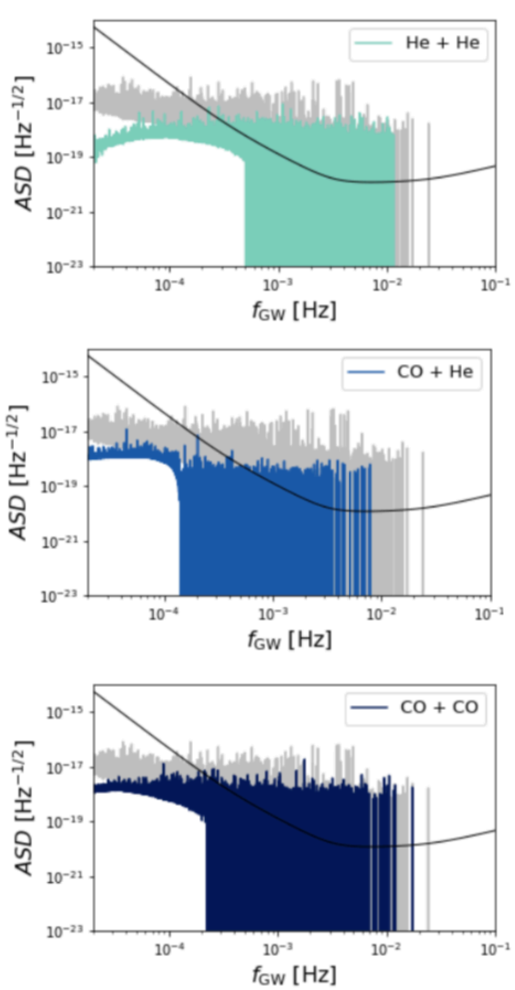


[Jani et al. 2020]

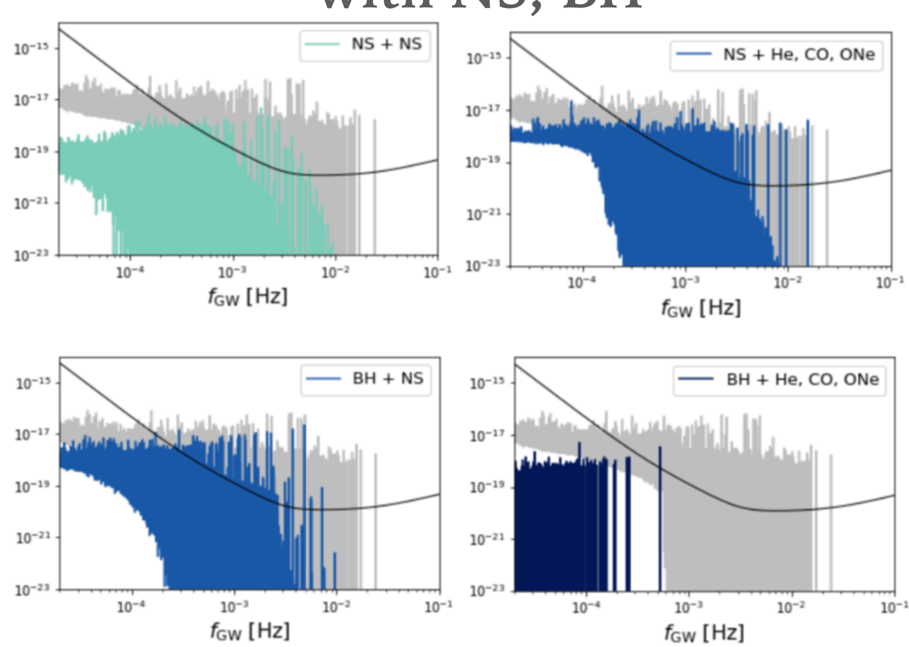
THE BINARIES

Black hole/star + star binaries:

WD-WD

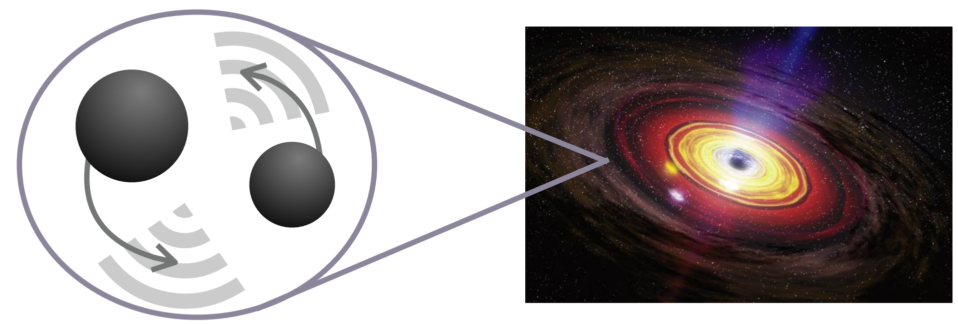


with NS, BH

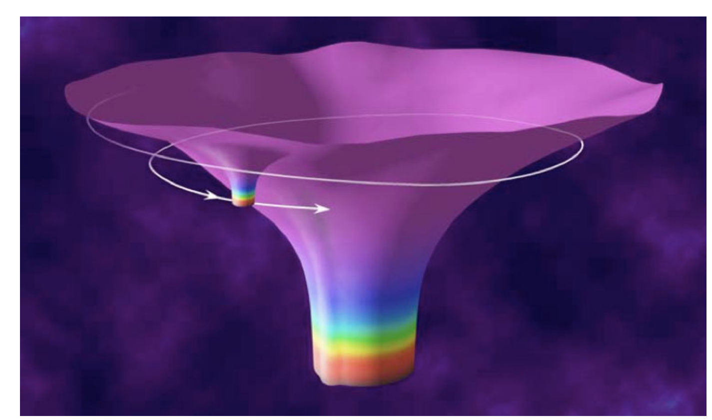


[COSMIC, Breivik et al. 2019]

Black hole binary in matter-rich environment:

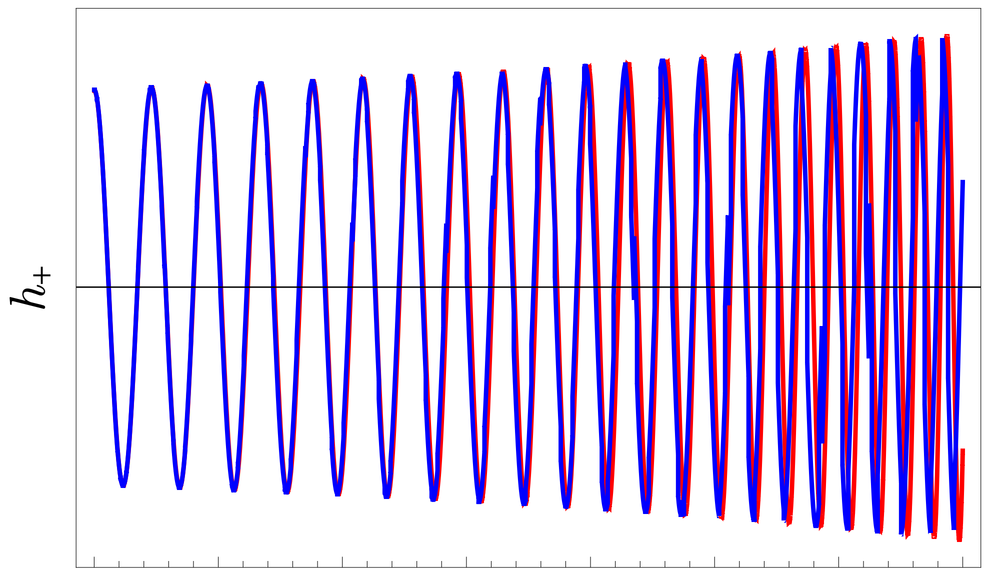


AGN binaries



Extreme-mass-ratio inspirals in thin accretion disks

MATTER EFFECTS IN GRAVITATIONAL WAVES



$$G_{\mu\nu}(g_{\mu\nu}) = 0$$

post-Newtonian template:

$$h \sim A f^{-7/6} e^{i\phi(f)}$$

$$\phi(f) = -\pi/4 + \phi_c + 2\pi f t_c + (\pi \mathcal{M} f)^{-5/3} \sum_{n=0} a_n (\pi \mathcal{M} f)^{n/3} + \dots$$

$$\sim v^n$$

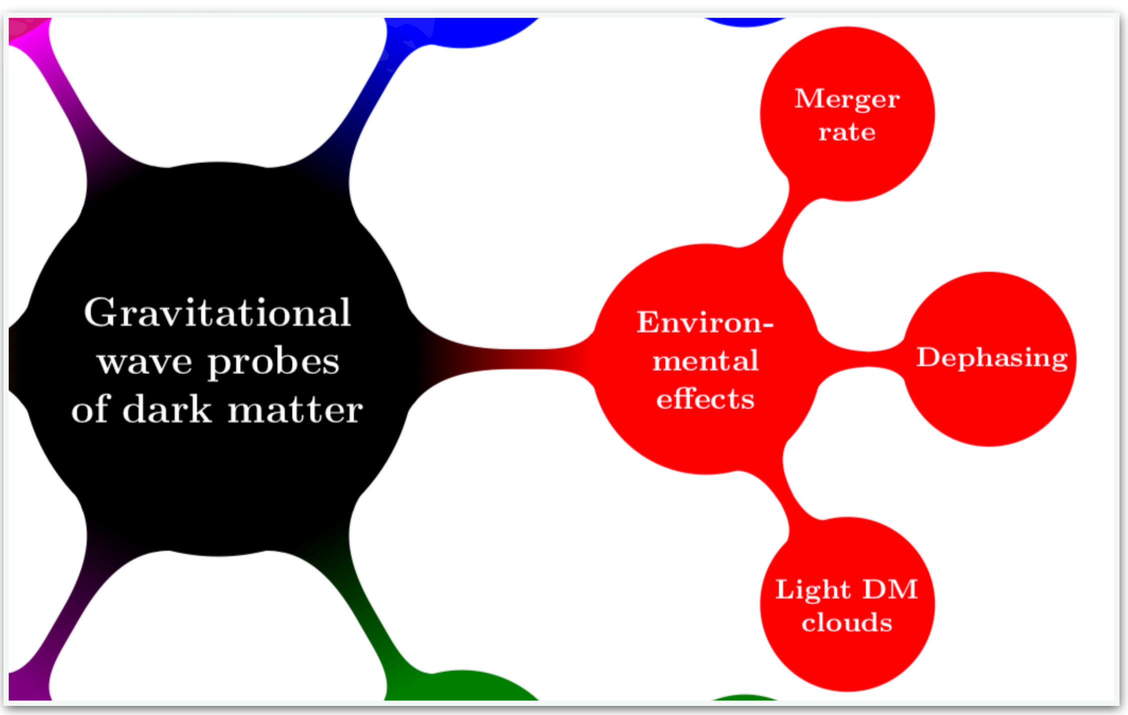
Matter effects cause a ***dephasing*** of the GW signal compared to the vacuum waveform.

MATTER EFFECTS: WHY CARE?

A **blessing** and a **curse**.

Test **population** models, *accretion* models, probe AGNs, ***multimessenger*** astronomy (**blessing**)

Dark matter effects. (**blessing**)



[Bertone et al. 2019]

MATTER EFFECTS: WHY CARE?

A **blessing** and a **curse**.

Matter effects vs **modified gravity**. (**curse**)

$$h \sim h_{\mathrm{GR}} e^{i\delta(f)}$$

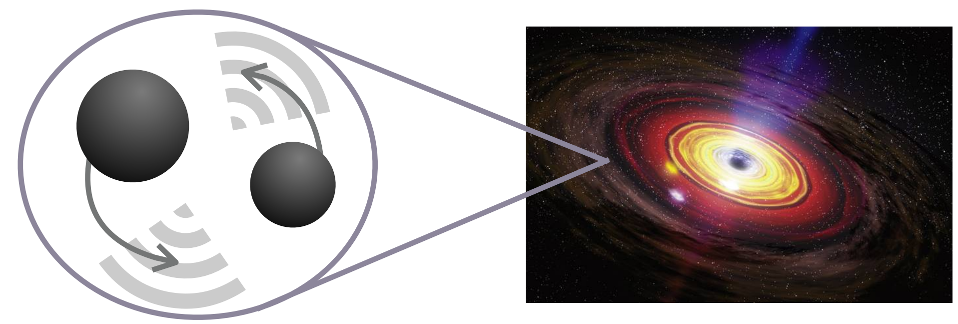
Dipole emission $\delta = b(\pi \mathcal{M} f)^{-7/3}$

Varying G $\delta = c(\pi \mathcal{M} f)^{-13/3}$

vs

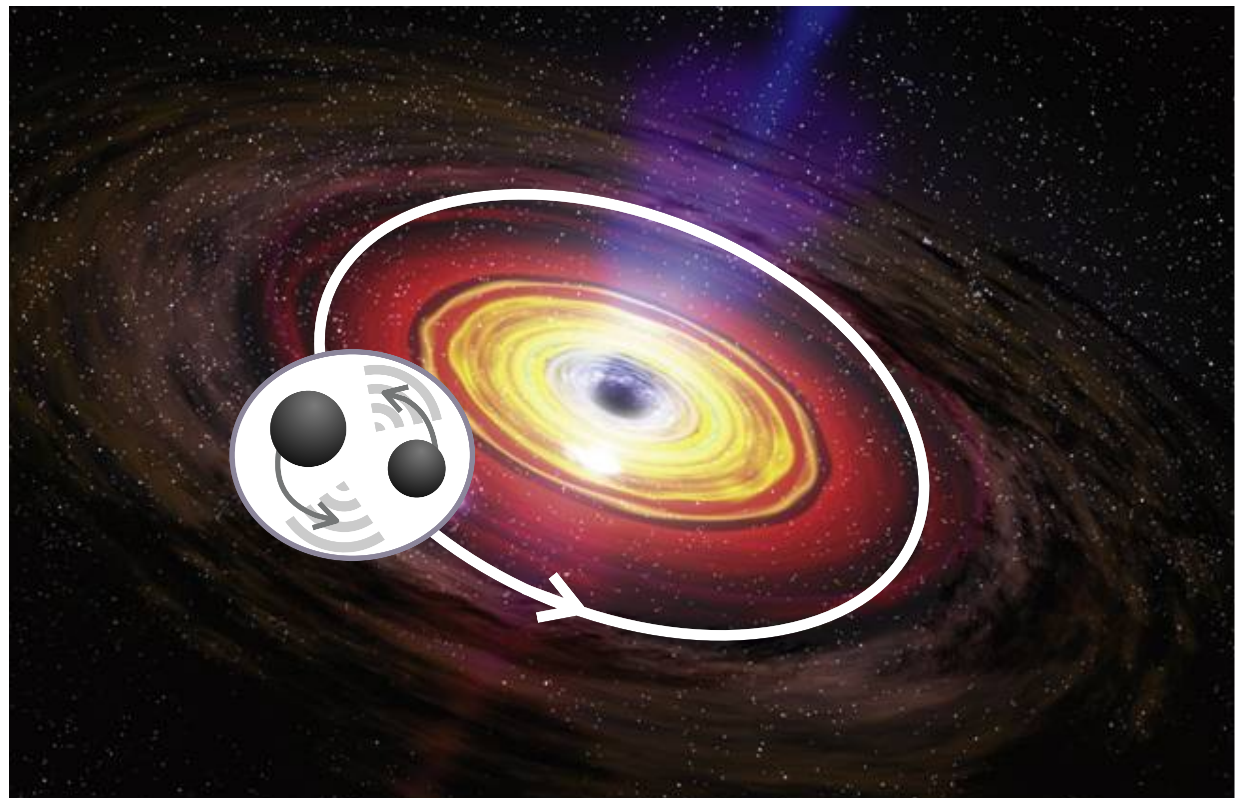
EXAMPLE 1: AGN BINARIES

Black hole binary in matter-rich environment:



AGN binaries

EXAMPLE 1: AGN BINARIES



Matter effects

Mass transfer/accretion

Dynamical friction

Natal kicks

...

[arXiv:2010.06056, arXiv:2001.03620]

Third body effects

Doppler modulation

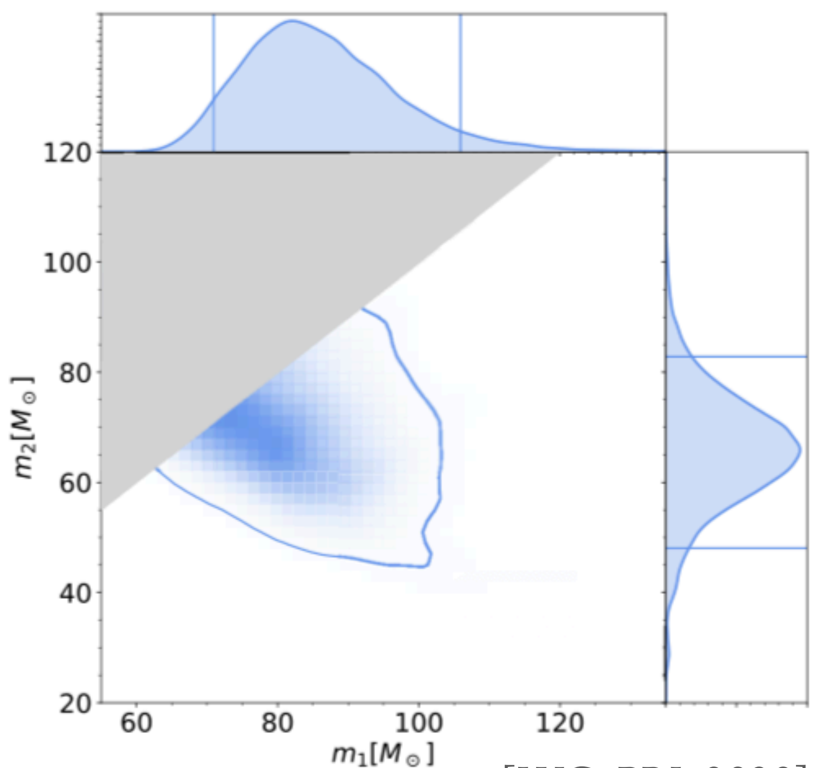
Gravitational lensing

Shapiro time-delay

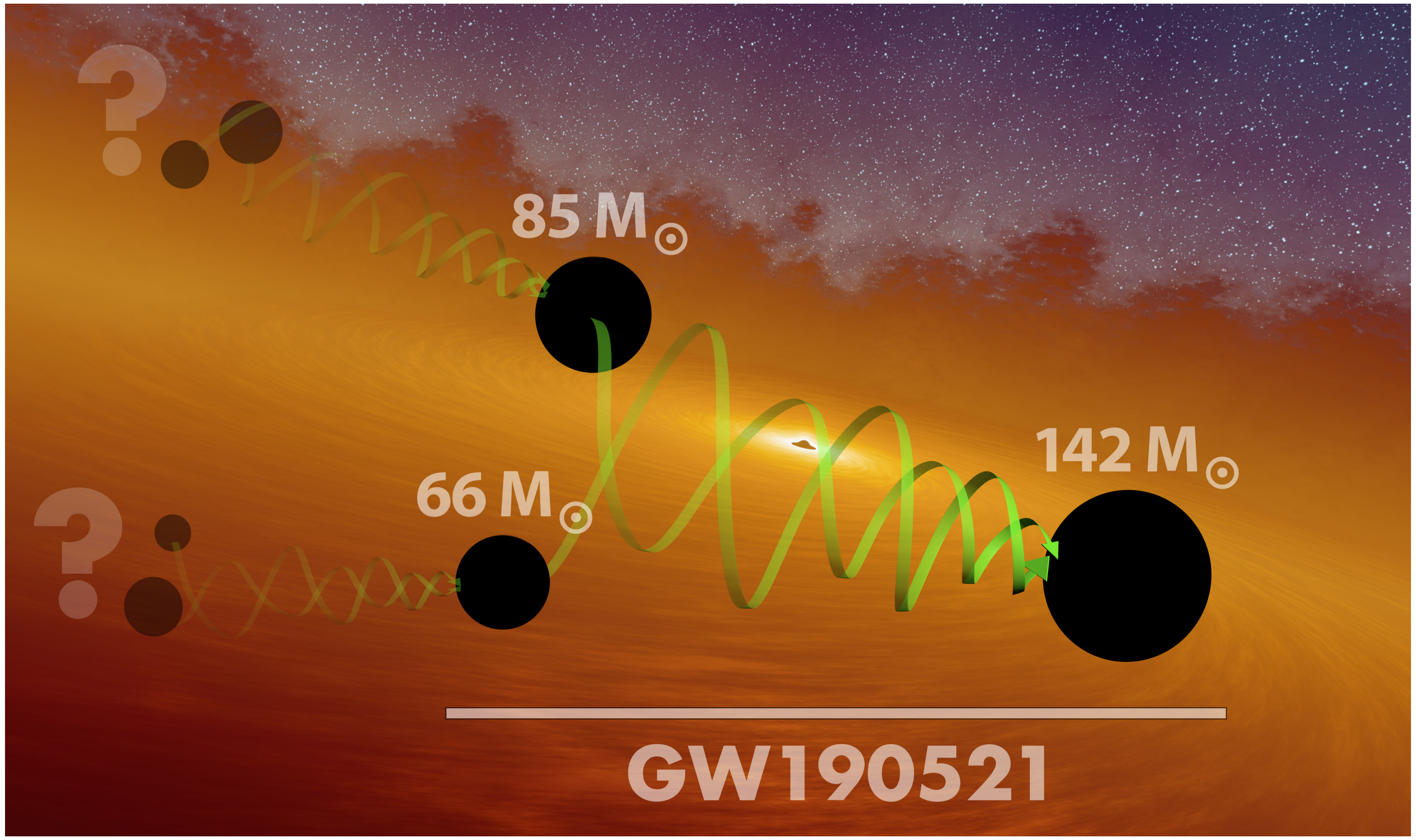
...

[arXiv:2001.03620]

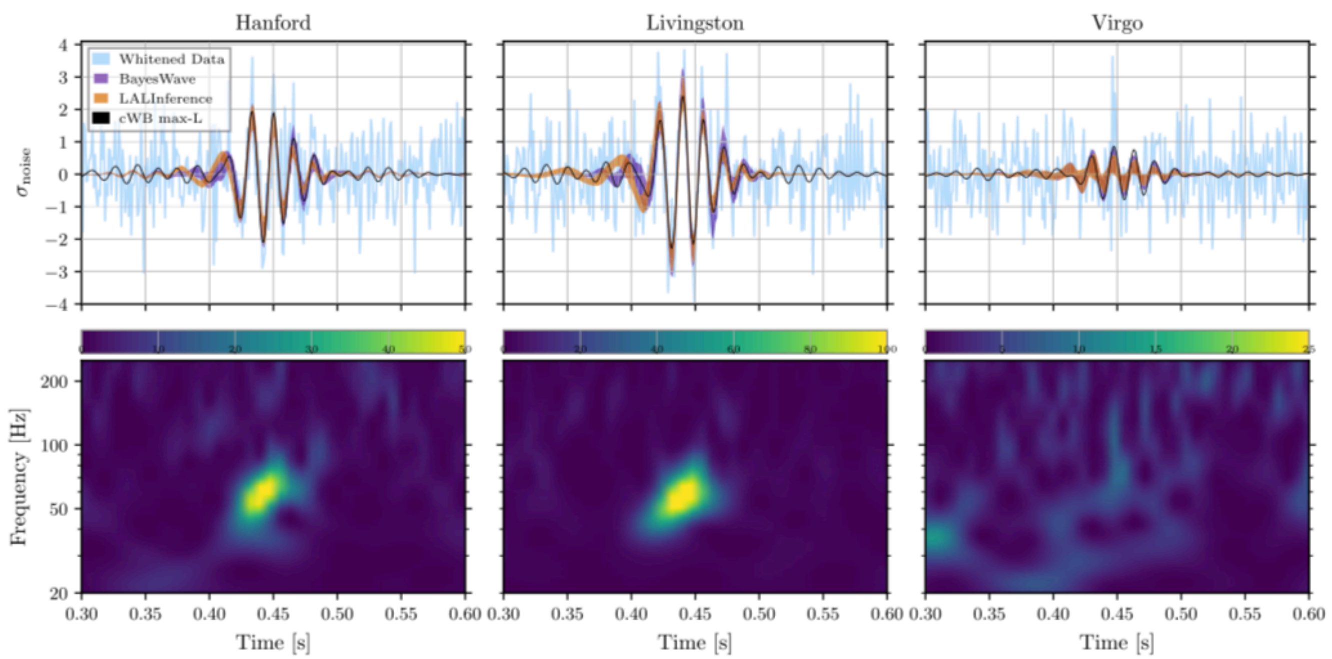
GW190521



[LVC, PRL 2020]

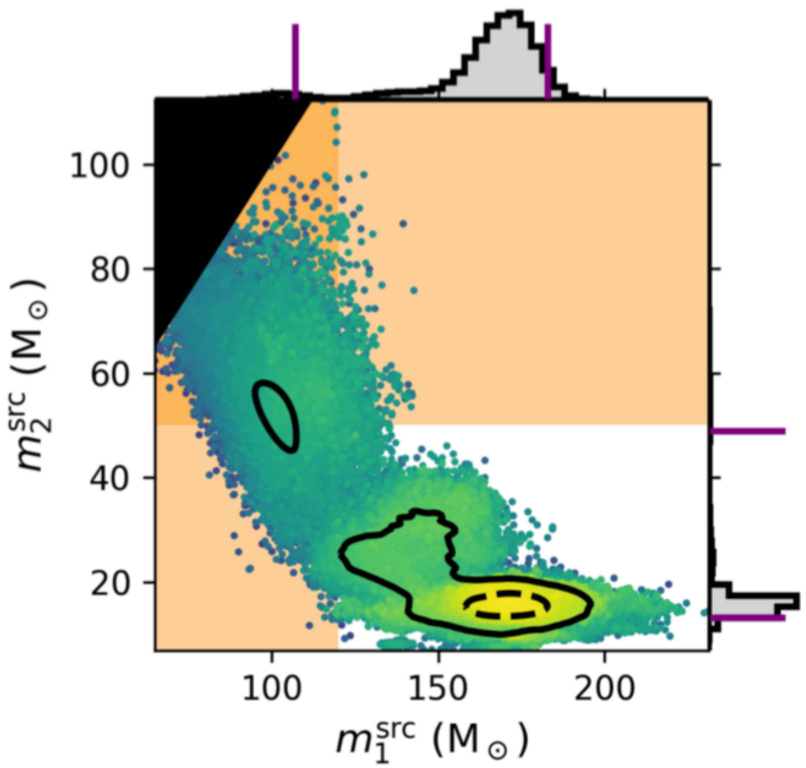


LIGO/Caltech/MIT/R. Hurt (IPAC).

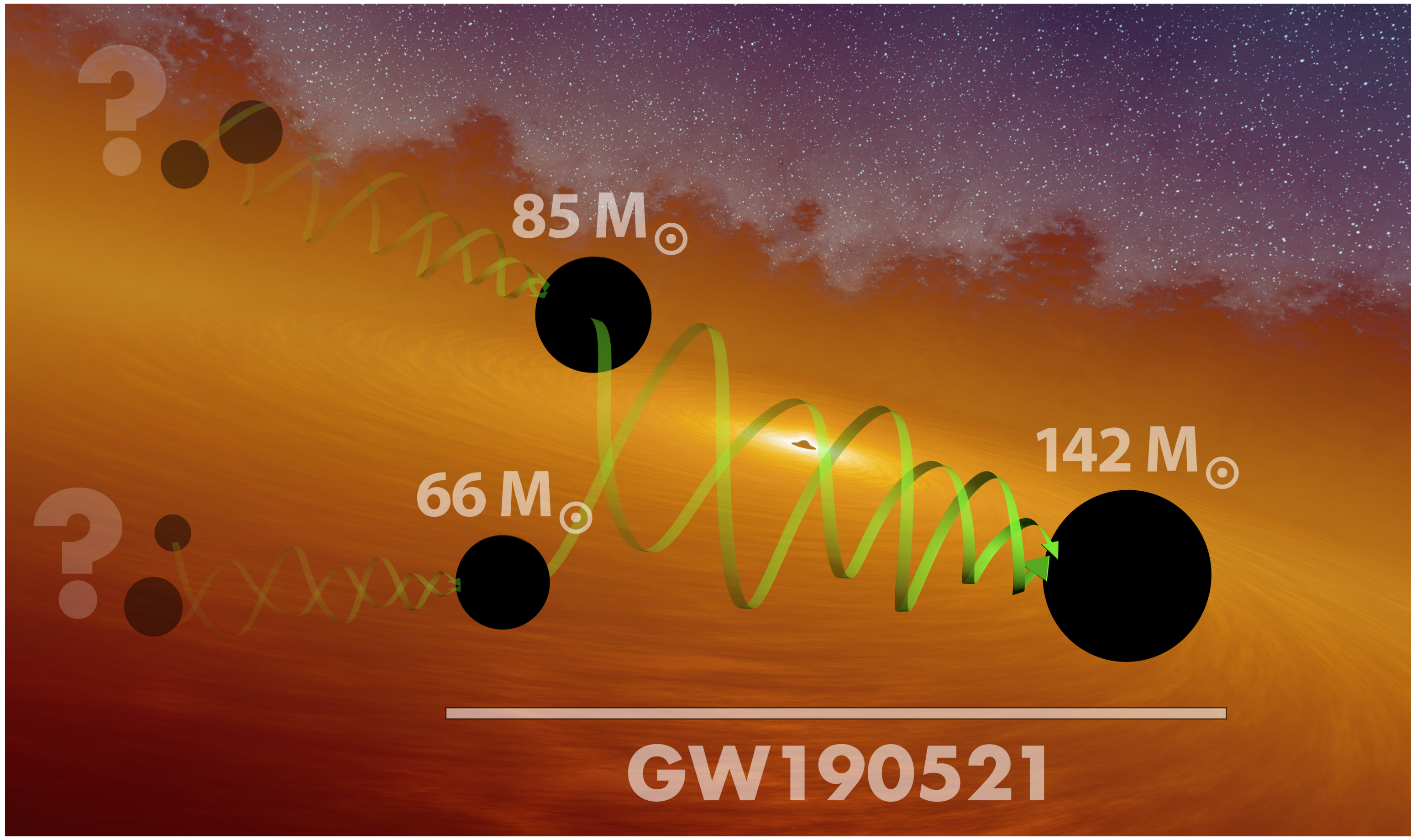


[LVC, PRL 2020]

GW190521



[Nitz, Capano 2020]



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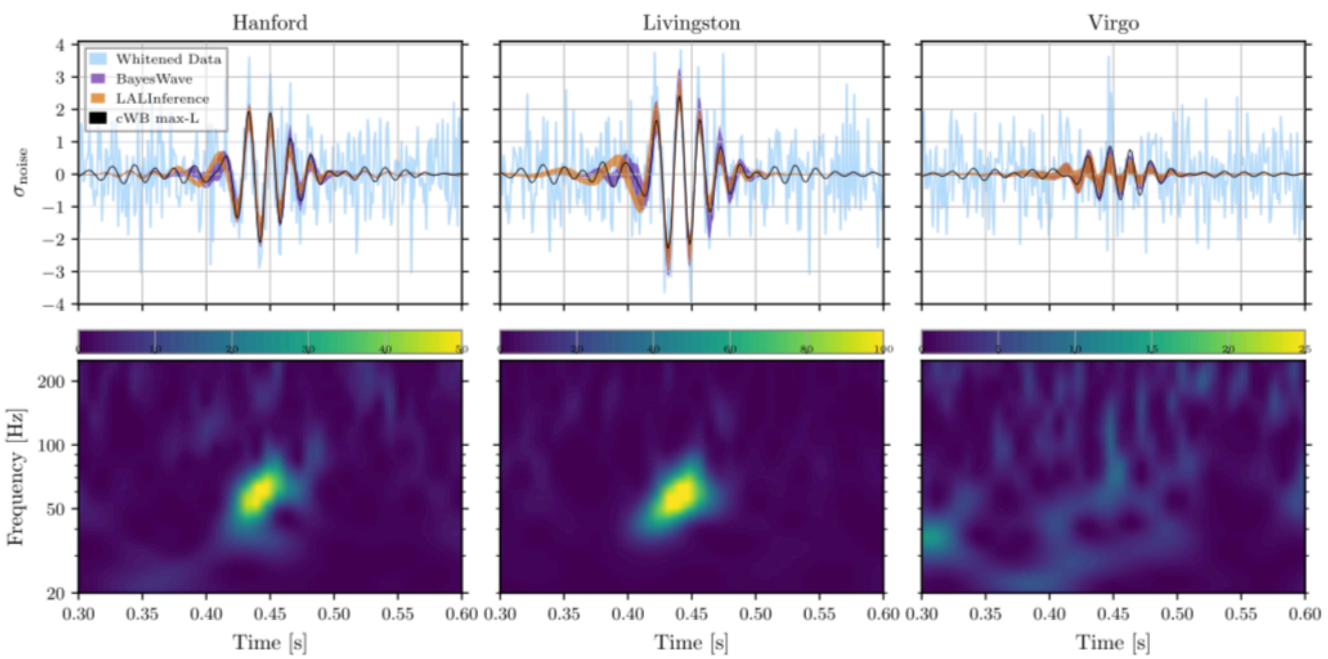
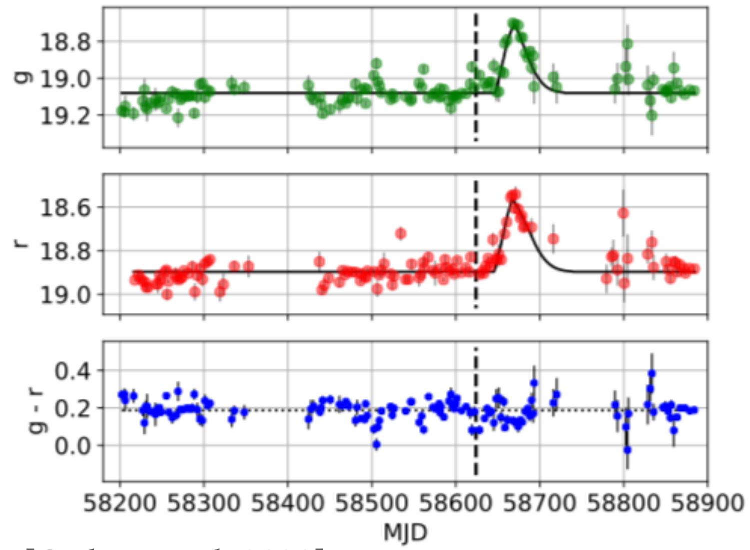


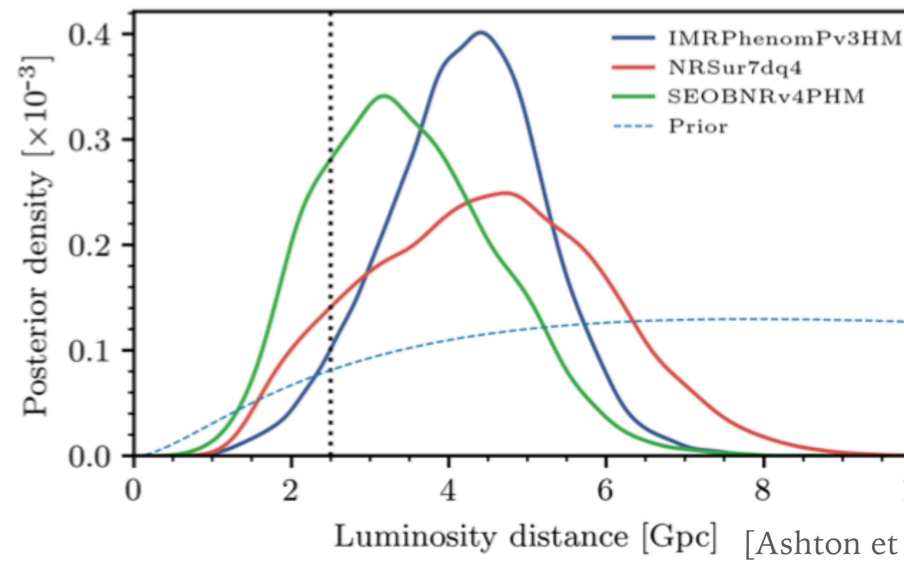
[LVC, PRL 2020]

GW190521: ELECTROMAGNETIC COUNTERPART?

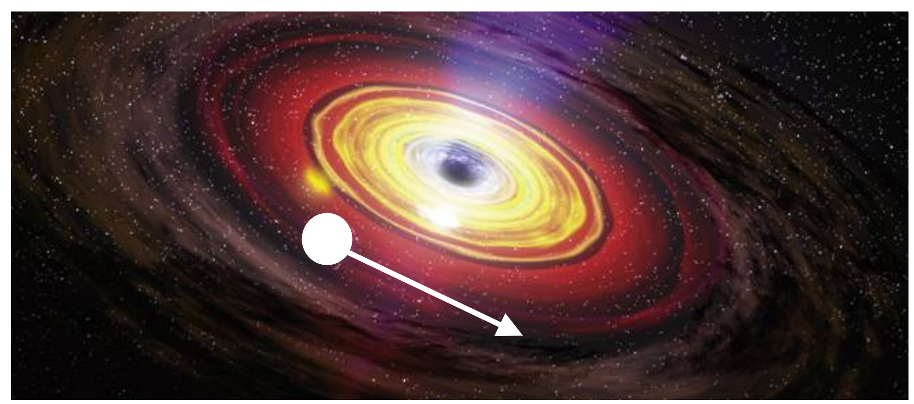
Optical flare detected by the Zwicky Transient Facility



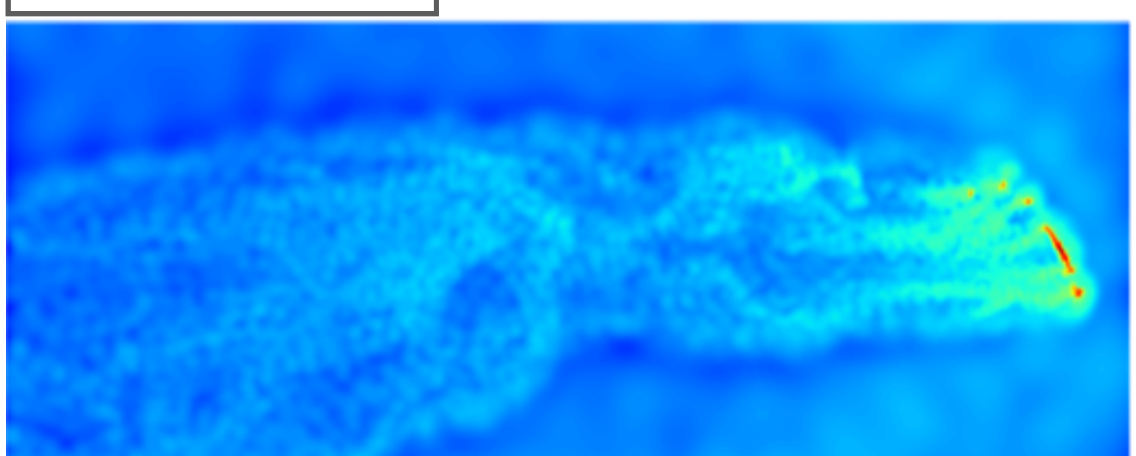
[Graham et al. 2020]



[Ashton et al. 2020]

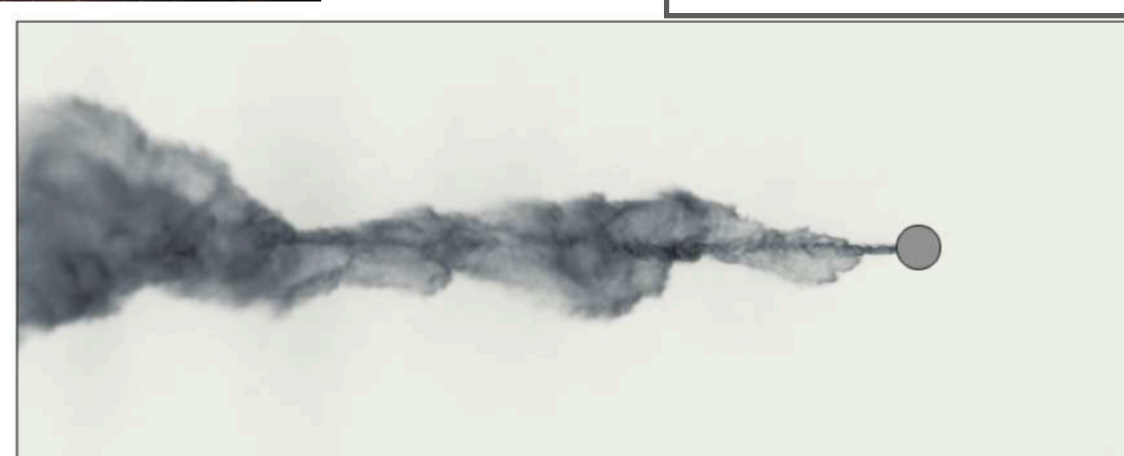


Ram pressure



[Steinhauser et al. 2016]

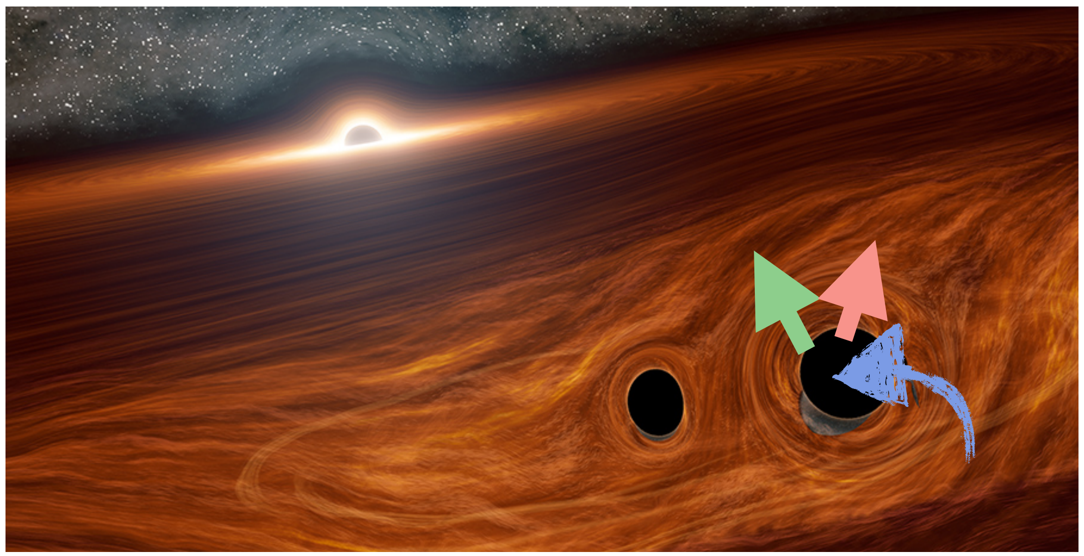
Boyle accretion



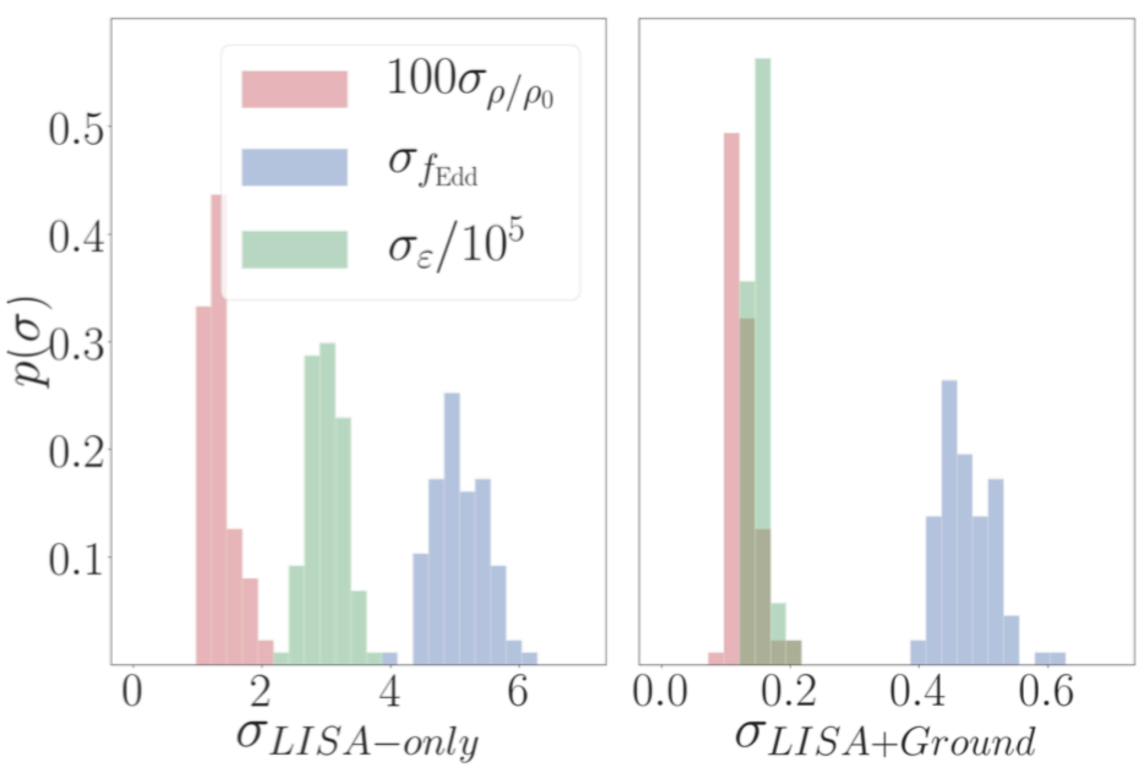
[Moeckel Throop 2009]

GW190521-LIKE BINARIES SEEN BY LISA

Detectability of accretion, friction, constant peculiar acceleration



Effect of multiband



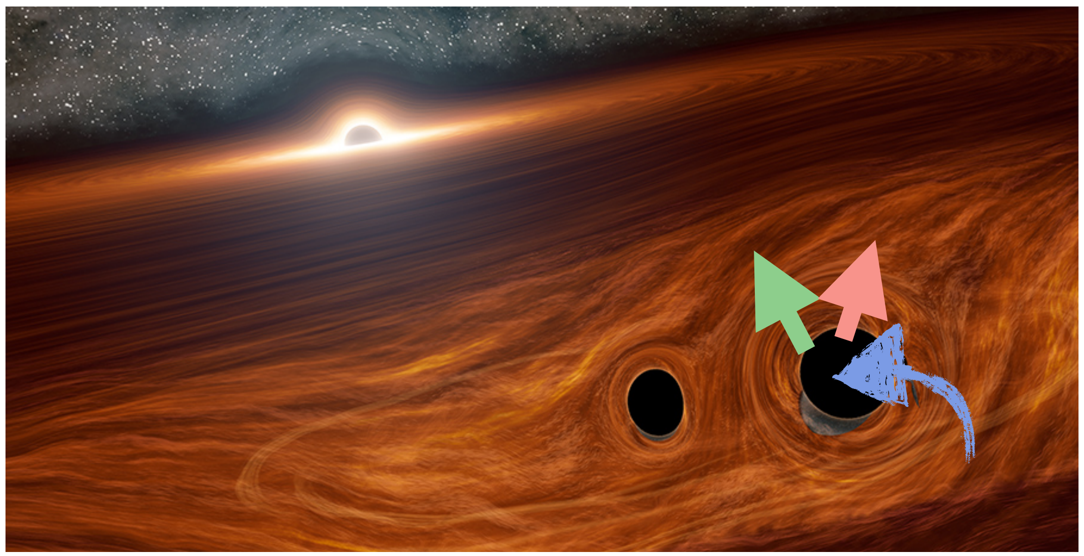
$$\tilde{\phi}_{\rm accretion} \sim -f_{\rm Edd}\left[\pi f \mathcal{M}(1+z)\right]^{-13/3}$$

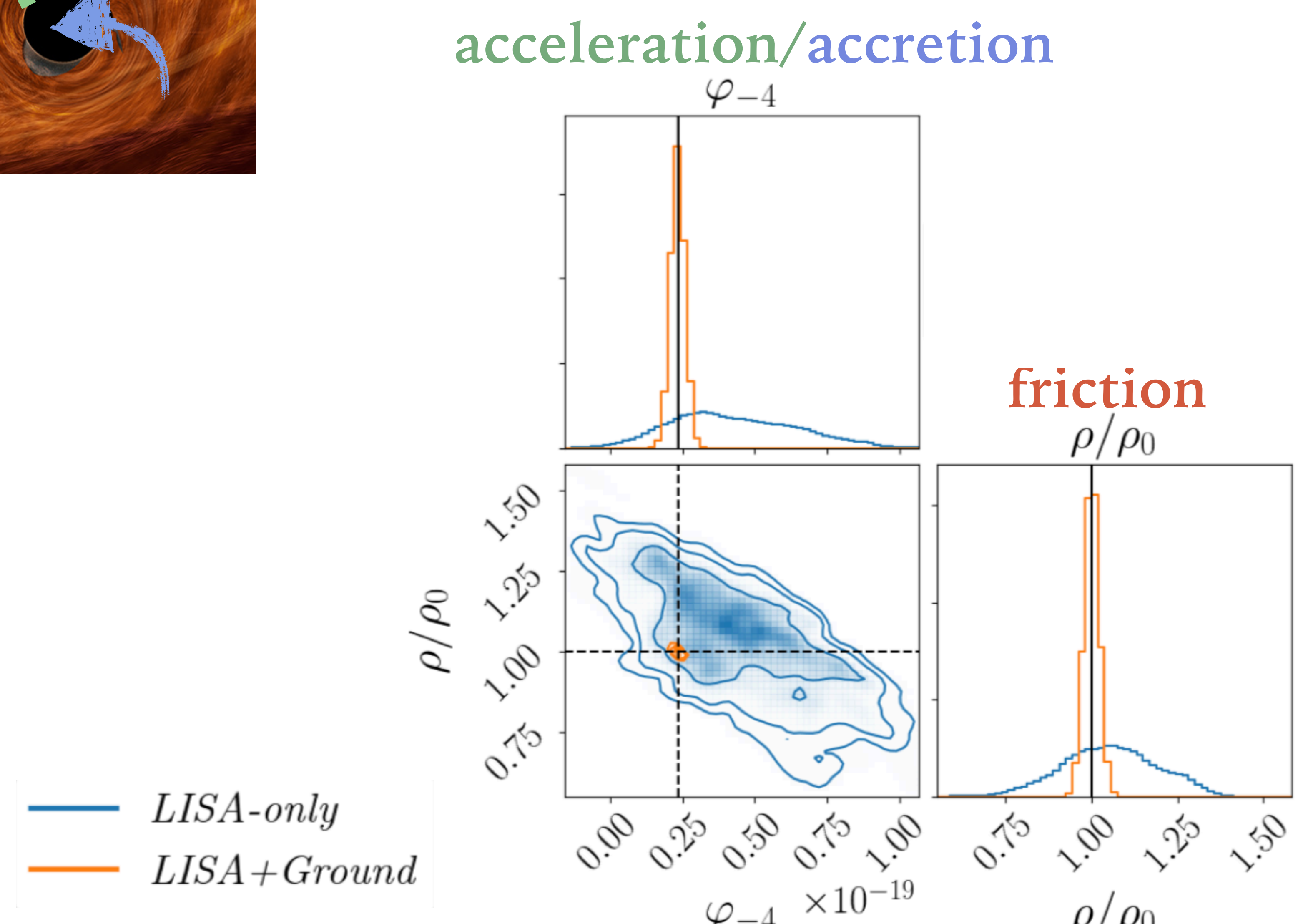
$$\tilde{\phi}_{\rm acceleration} \sim \epsilon\left[\pi f \mathcal{M}(1+z)\right]^{-13/3}$$

$$\tilde{\phi}_{\rm dyn\,fr} \sim \rho\left[\pi f \mathcal{M}(1+z)\right]^{-16/3}$$

GW190521-LIKE BINARIES SEEN BY LISA

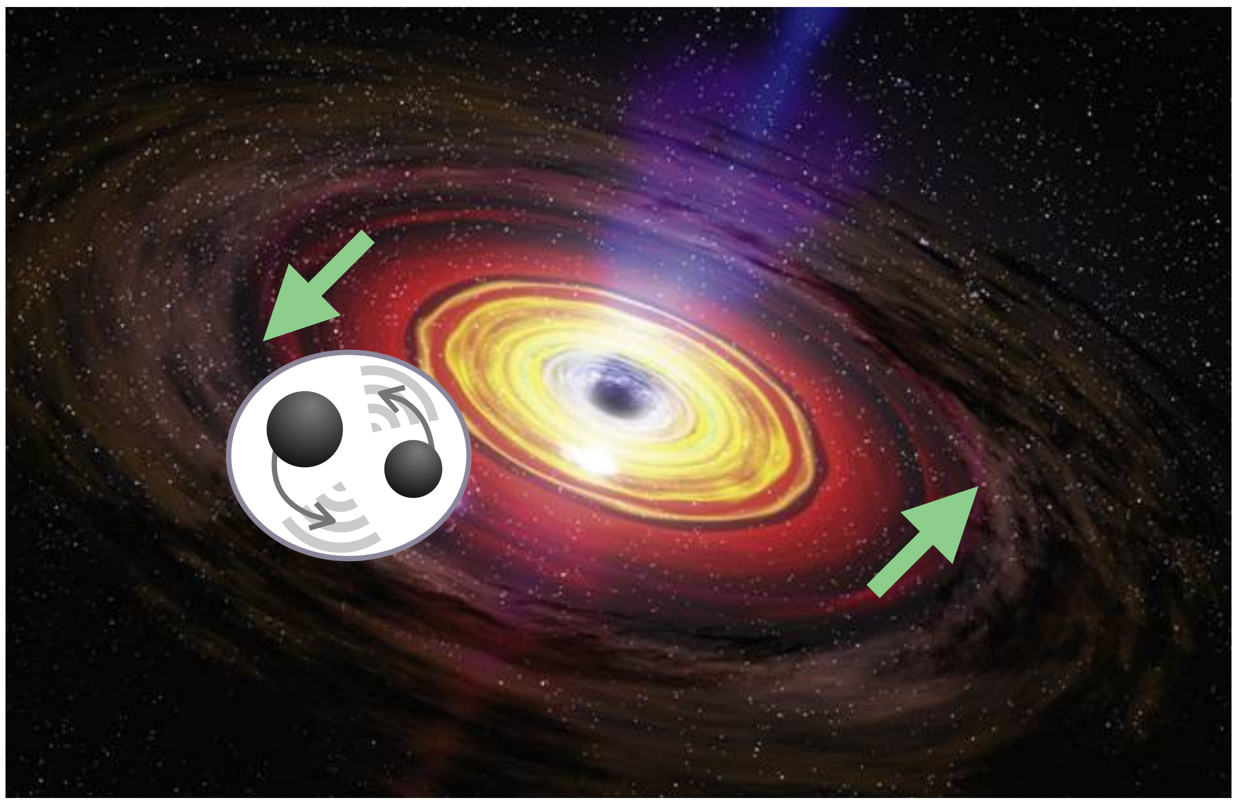
Detectability of accretion, friction, constant peculiar acceleration <u>together</u>

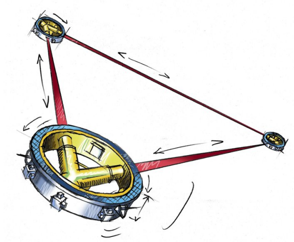




GW190521-LIKE BINARIES SEEN BY LISA

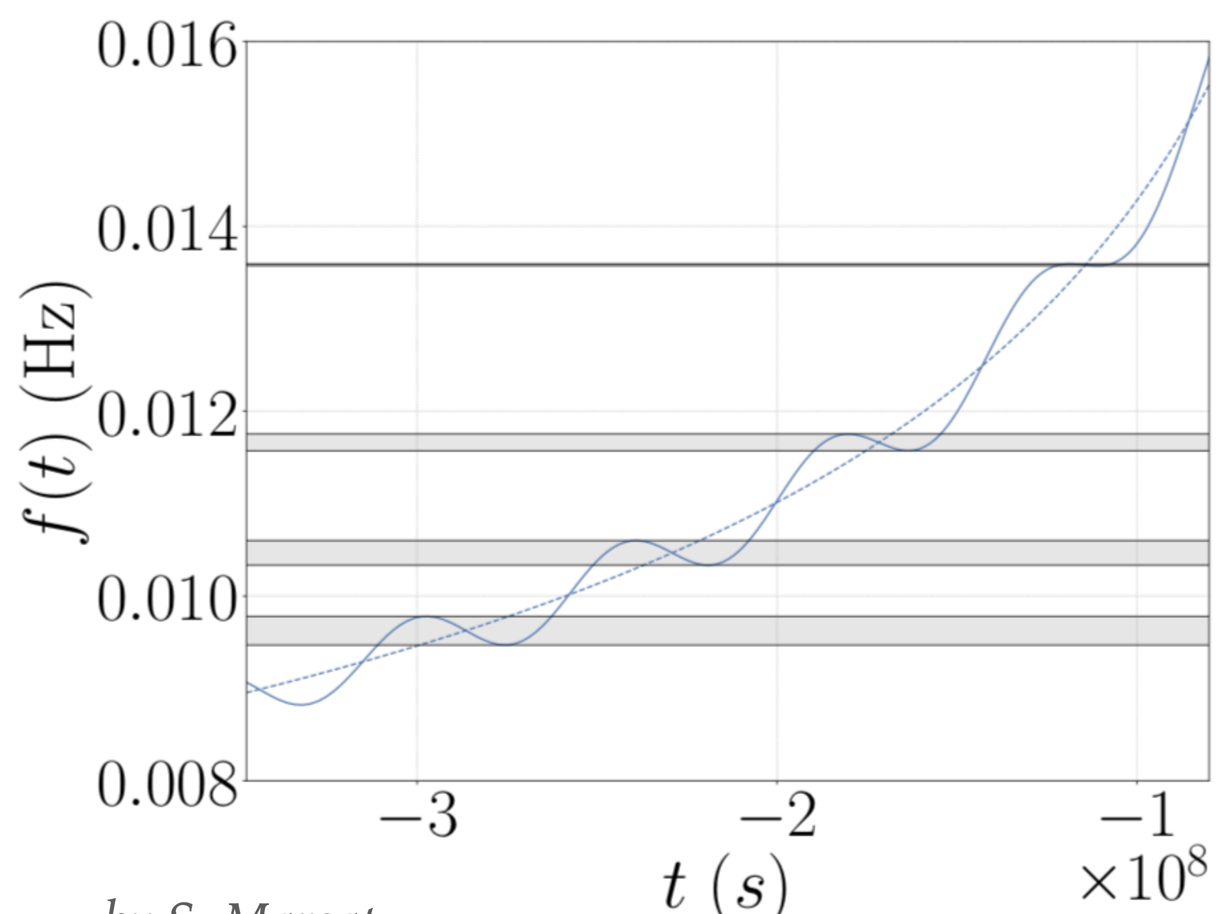
Doppler effect





$$s(t) = h(t + d^{\parallel}(t))$$

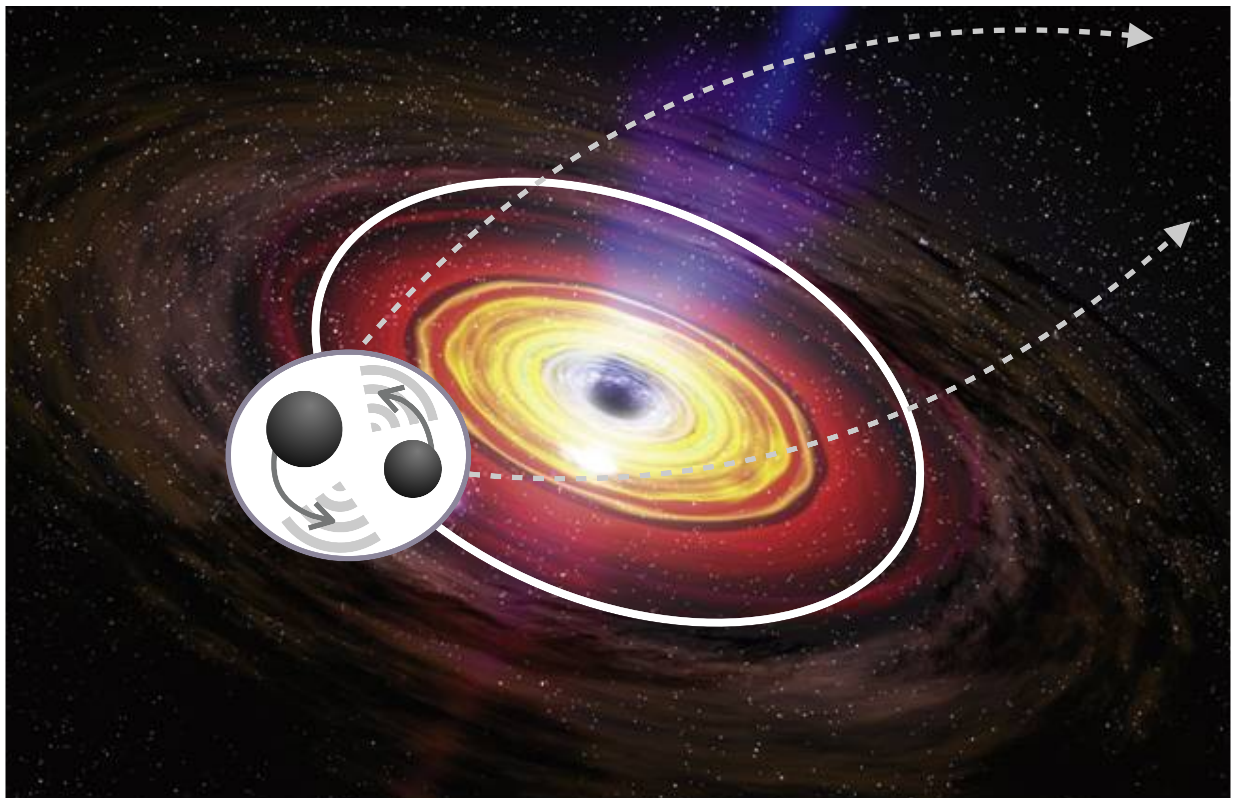
$$d^{\parallel}(t) = a \cos \iota \sin(\Omega t + \phi_0)$$

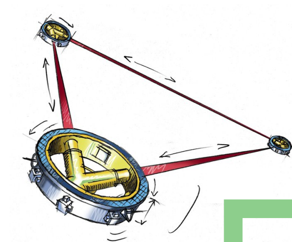


by S. Marsat

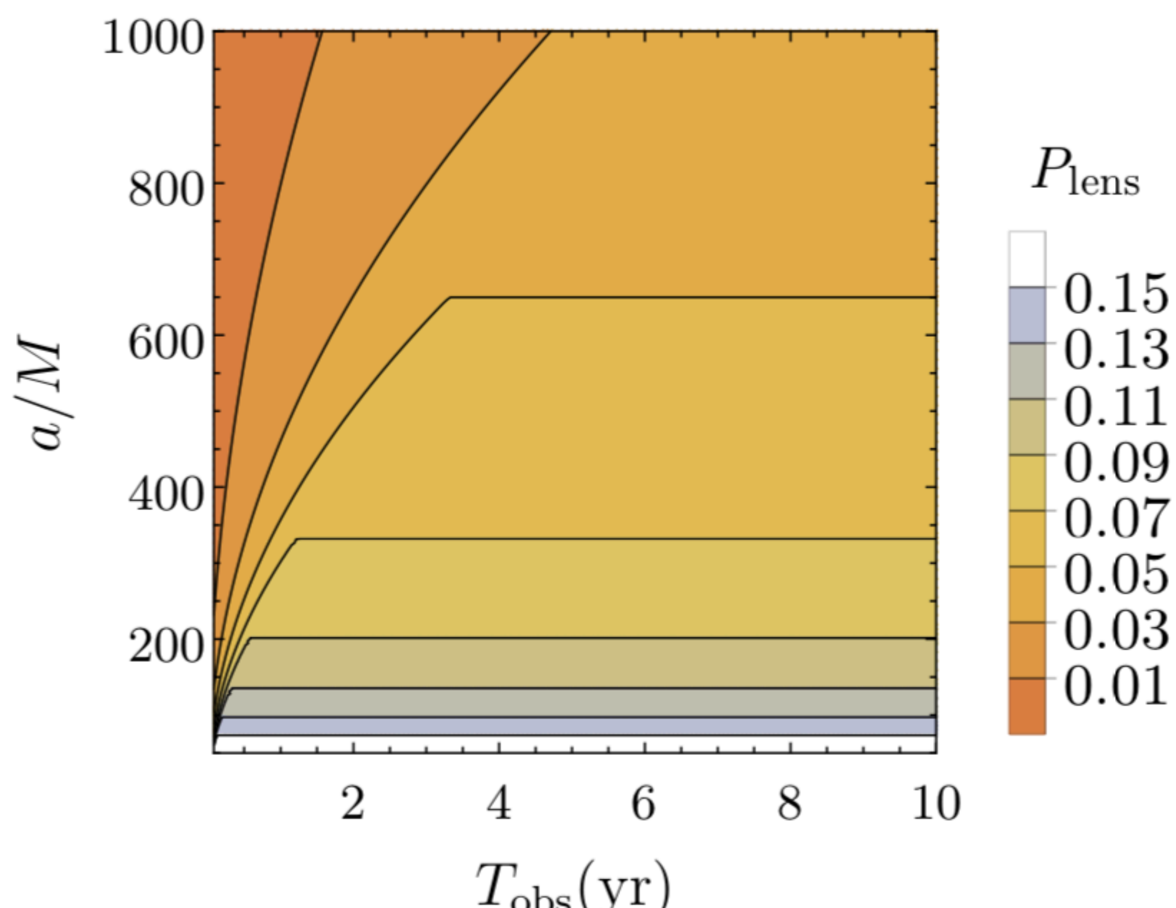
GW190521-LIKE BINARIES SEEN BY LISA

Strong **gravitational lensing**





$$h^L(t) = \left[|\mu_+|^{1/2} - i\,|\mu_-|^{1/2} e^{2\pi i f \Delta t} \right] h(t)$$



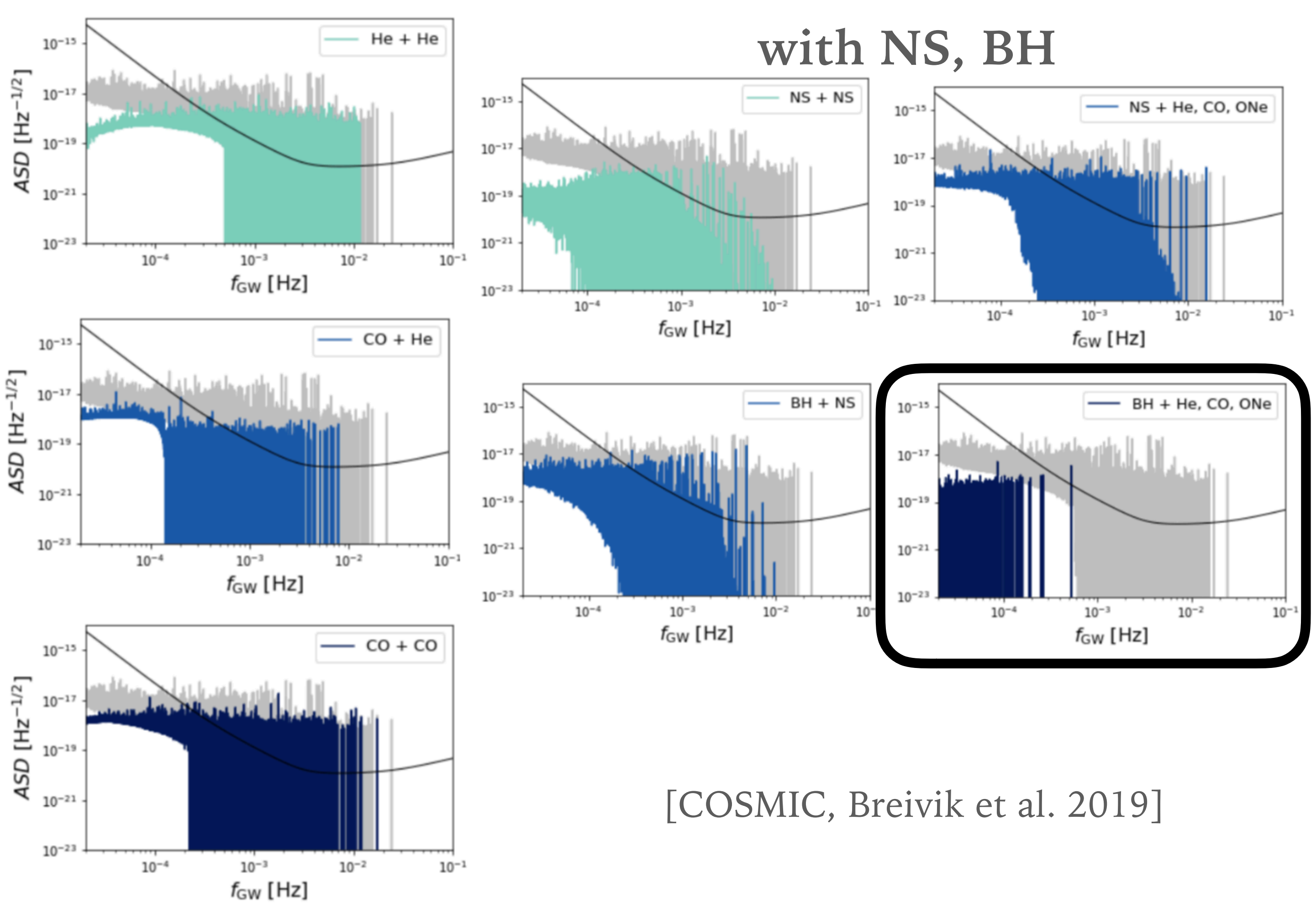
by G. Cusin

EXAMPLE 2: GALACTIC BINARIES

Black hole/star + star binaries:

WD-WD

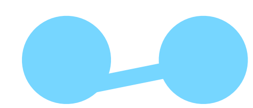
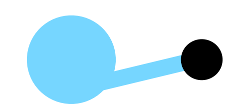
with NS, BH



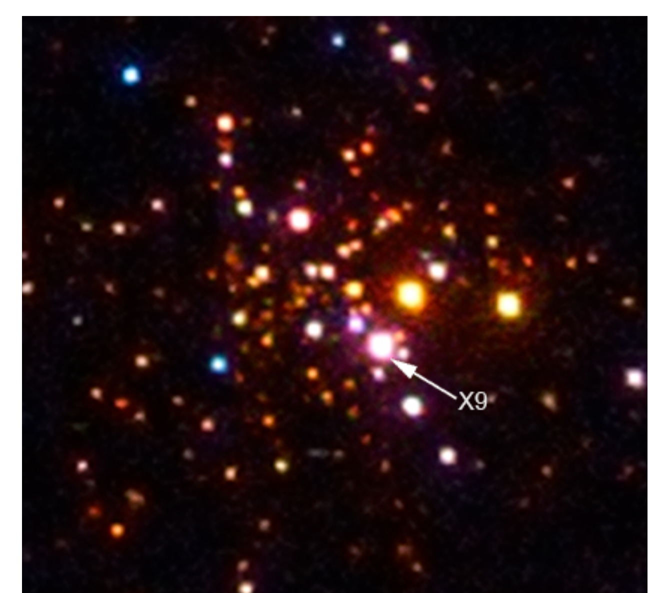
[COSMIC, Breivik et al. 2019]

WHITE DWARF–BLACK HOLE BINARIES

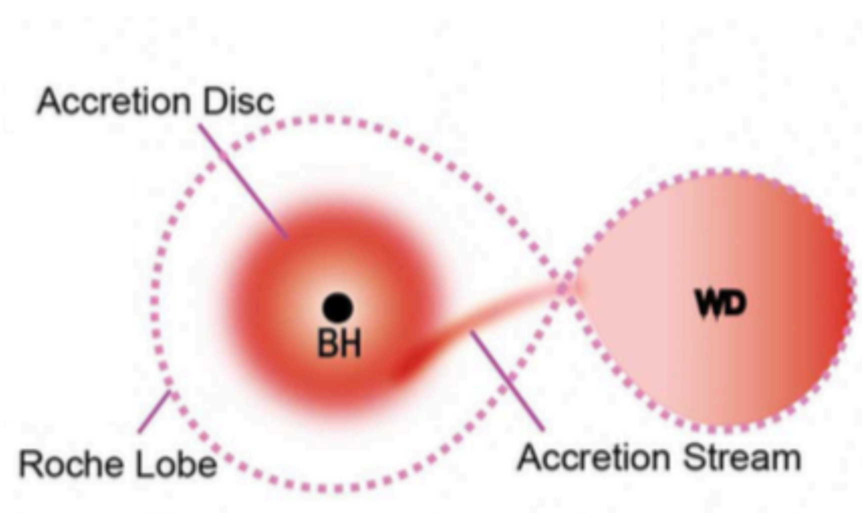
Black hole/star + star binaries:

WD WD	WD BH
	
$10^6 - 10^8$	$10^2 - 10^4$

- **Less numerous** in the Galaxy than white dwarf binaries [Hurley et al. 02]
- …but higher **SNR** in LISA! (SNR $\sim \mathcal{M}^{2/3}$)
- Limited observational evidence: **X9 in globular cluster 47 Tuc**



WD–BH: MASS TRANSFER EVOLUTION

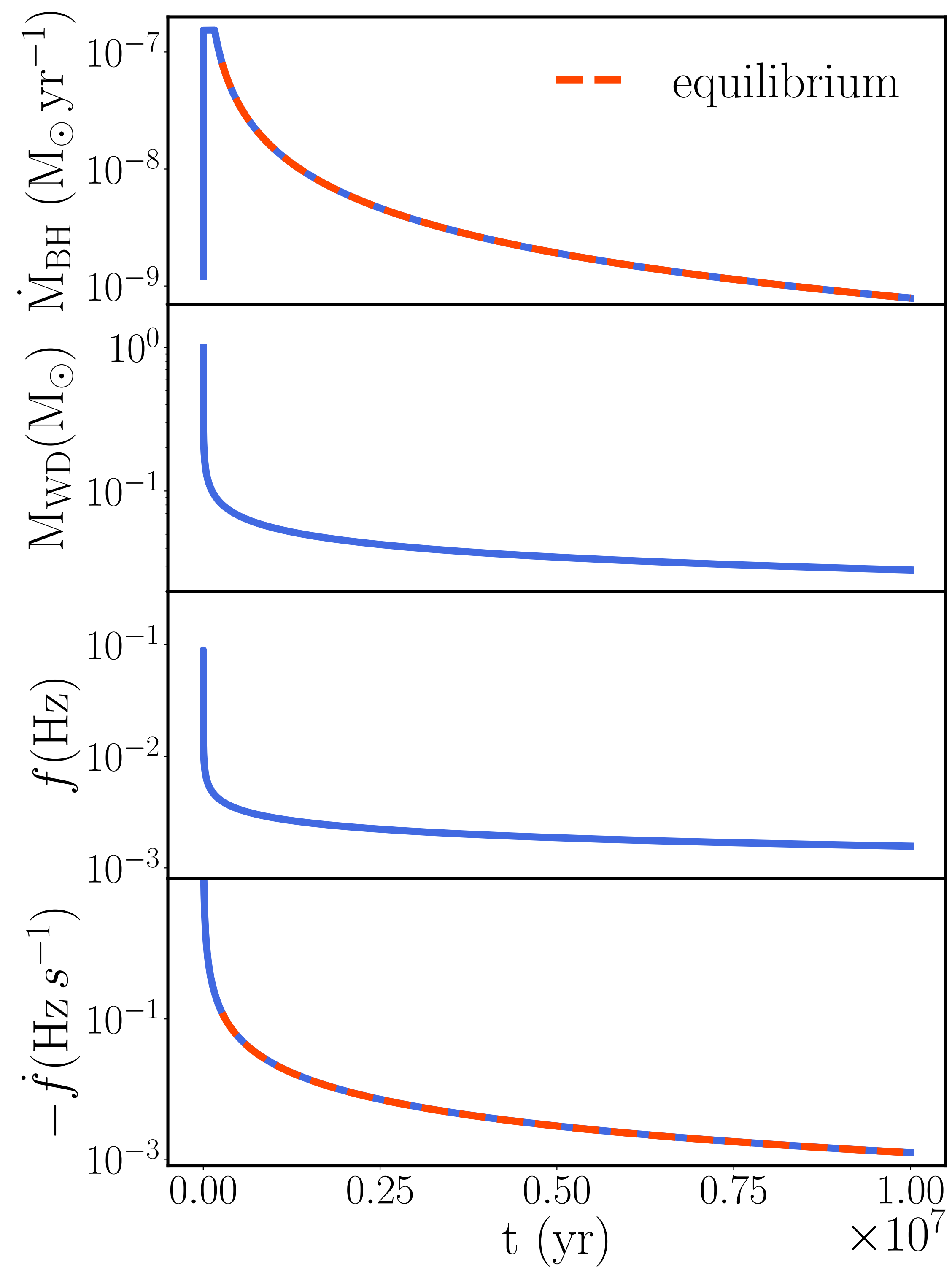


[adapted from Marsh et al. 03]

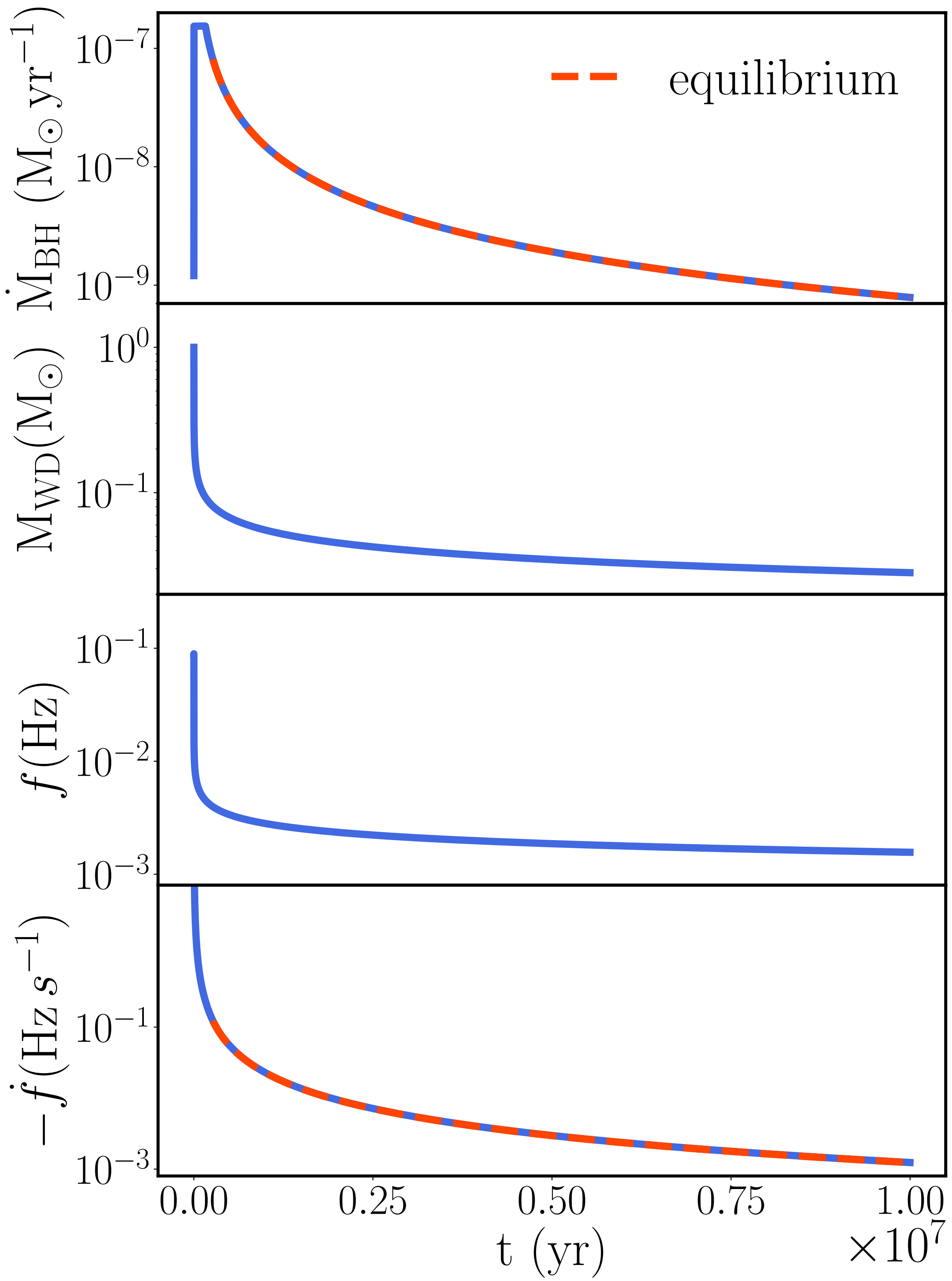
$$\dot{J}_{\rm orbit} + \dot{J}_{\rm BH} + \dot{J}_{\rm WD} = -\dot{J}_{\rm GW} - \dot{J}_{\rm wind}$$

T=0 K

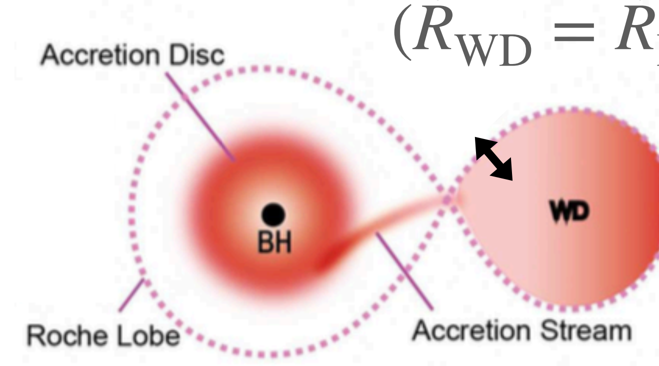
tidally locked ($\tau_{\rm sync} \sim q^2$)



WD-BH: MASS TRANSFER EVOLUTION



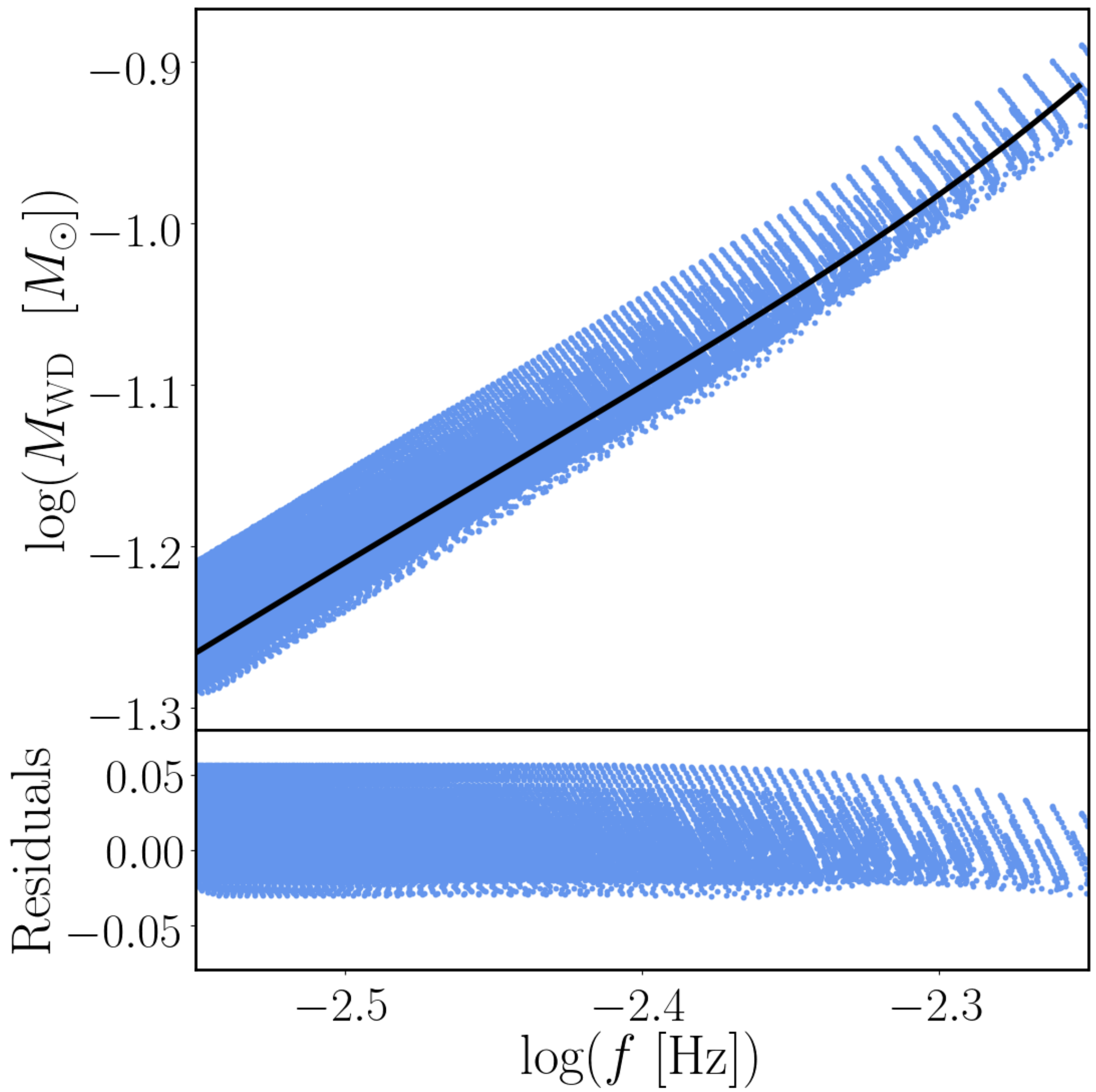
$(\dot{R}_{WD} = \dot{R}_{RL})$

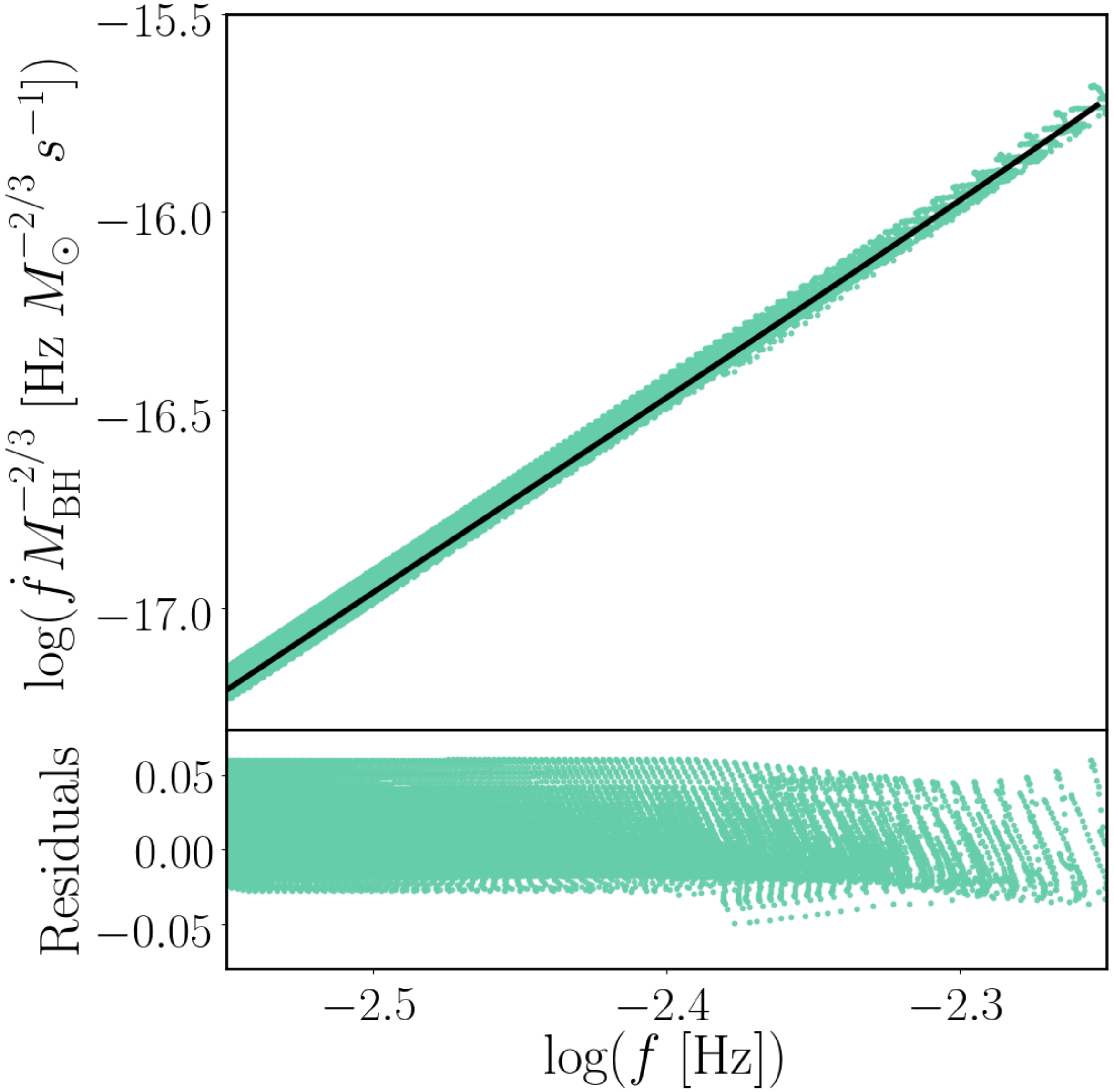


the increase in the Roche lobe compensates the one in the WD's radius

$$\dot{\Delta} = R_2 \left[\left(\zeta_{WD} - \zeta_{r_L} \right) \frac{\dot{M}_{WD}}{M_{WD}} - \frac{\dot{a}}{a} \right] = 0$$

WD–BH: EVOLUTIONARY TRACKS (1)





Also *WD-WD binaries*
From GW frequency to **WD mass** ✔

New relation!
From frequency derivative to **BH mass** ✔

WD–BH: GW (LISA) OBSERVATIONS

Breivik et al. 2018, accreting WD binaries, LISA+GAIA

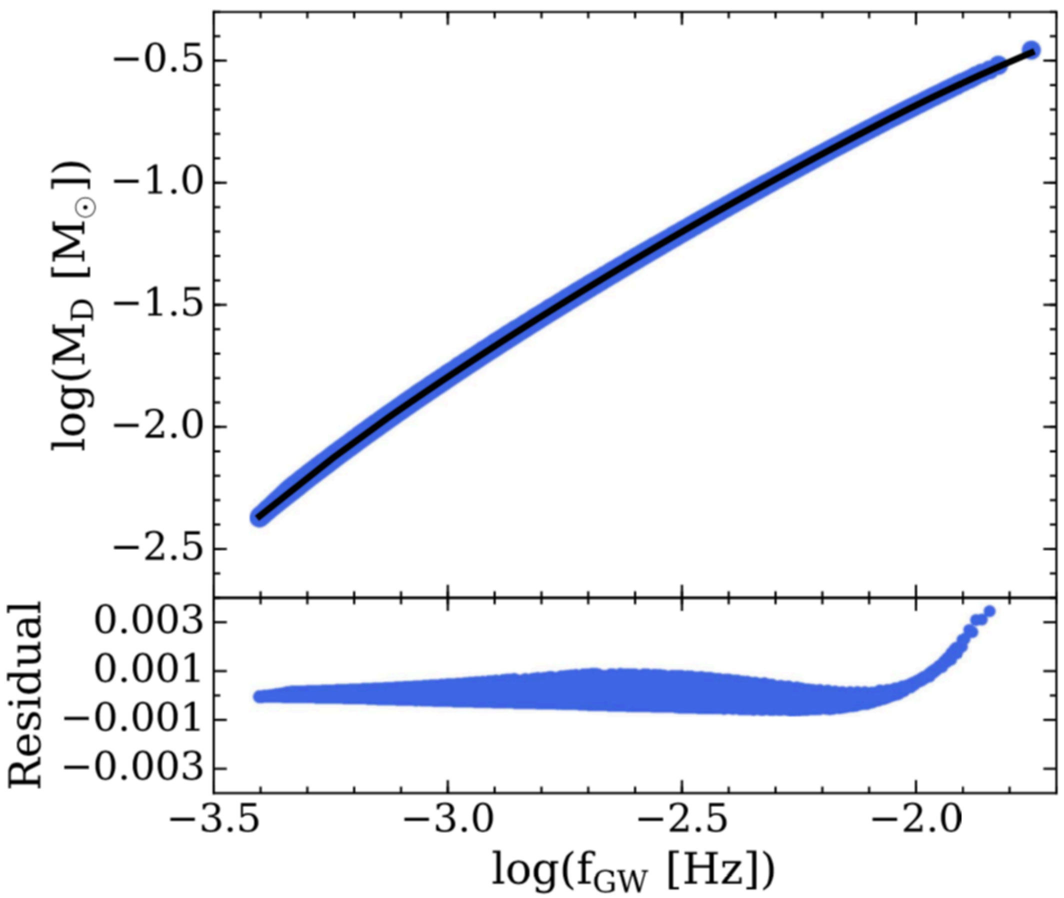


Figure 1. Donor mass vs. GW frequency tracks for all modeled DWD systems and the residuals (M_D–$M_{D,fit}$) of the fit evaluated for each point on the tracks.

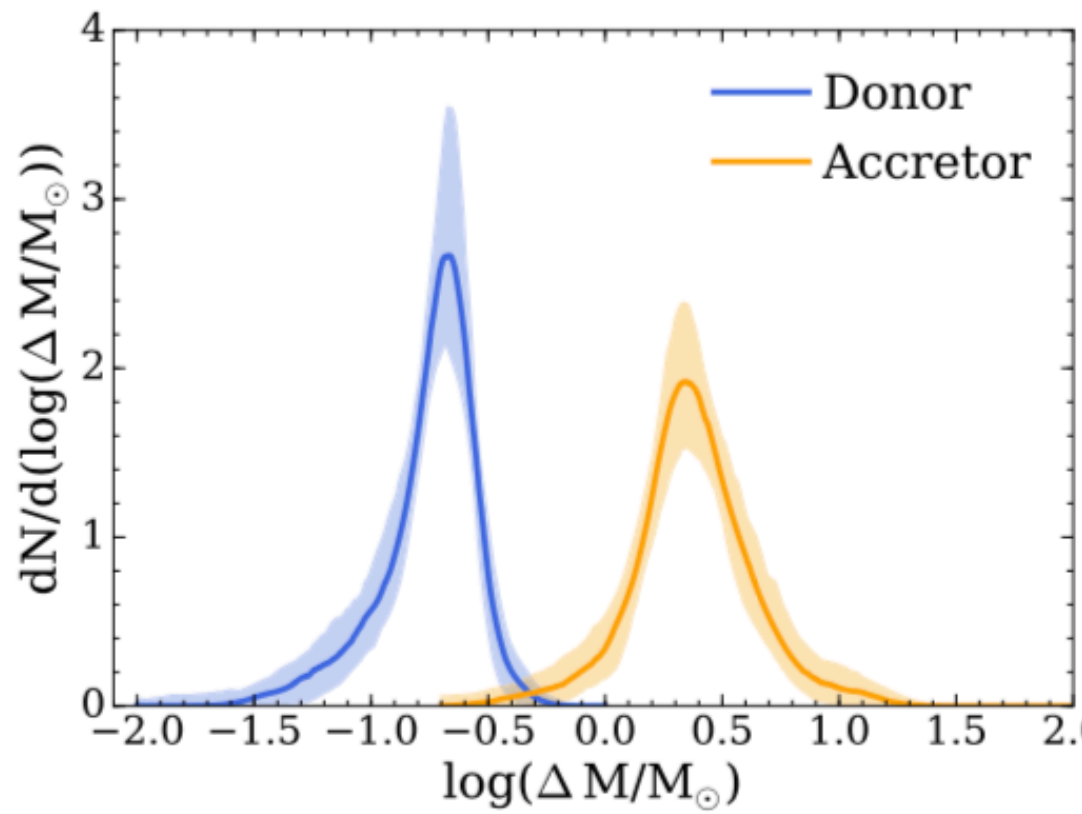
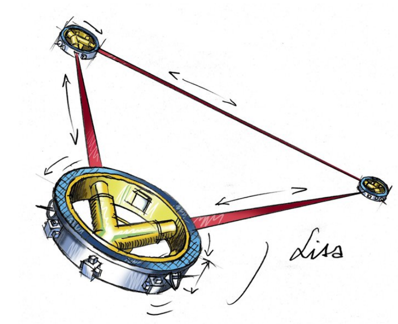


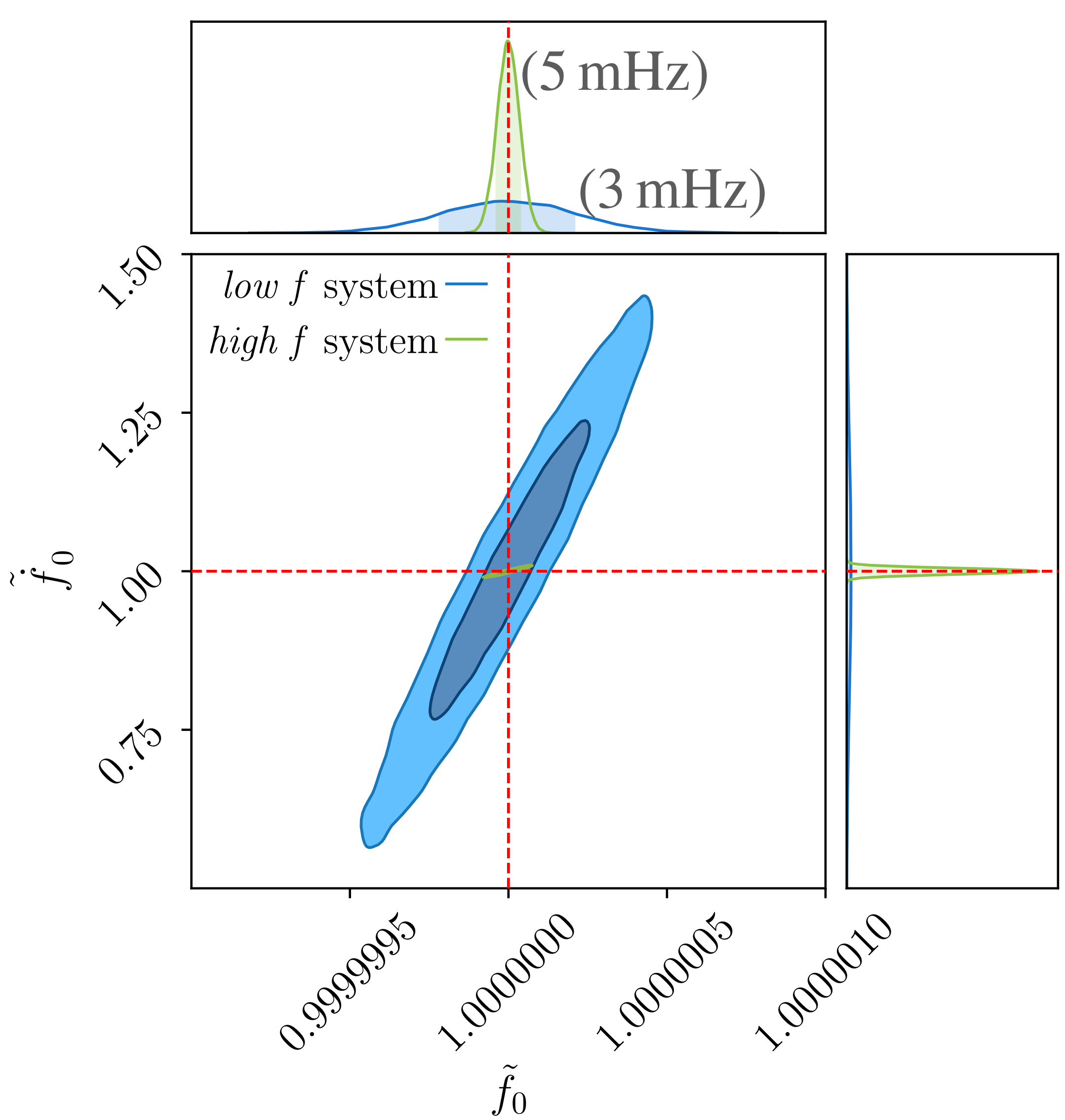
Figure 3. Measurement errors for donor masses (blue) and accretor masses (orange). The shaded regions show 5%–95% percentile spread for our 100 population realizations.

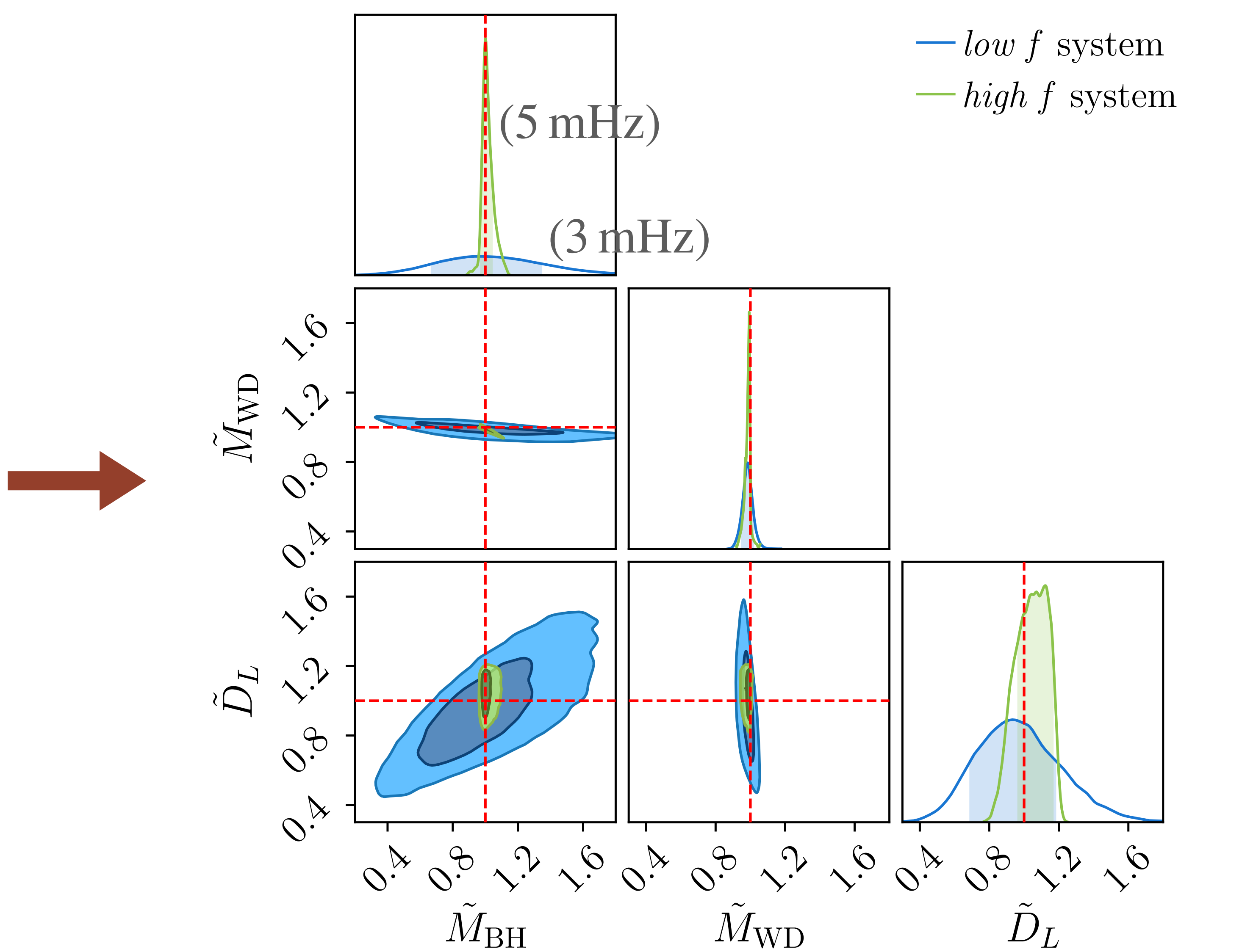
WD–BH: GW (LISA) OBSERVATIONS

With LISA observations alone we **can infer both masses**



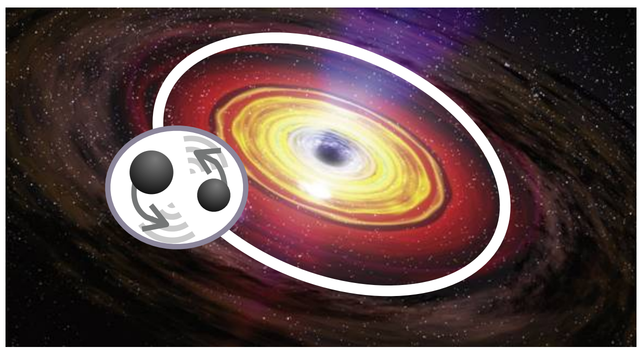
$$h \sim h_0 \cos(\phi_0 + 2\pi f_0 t + \pi \dot{f}_0 t^2)$$





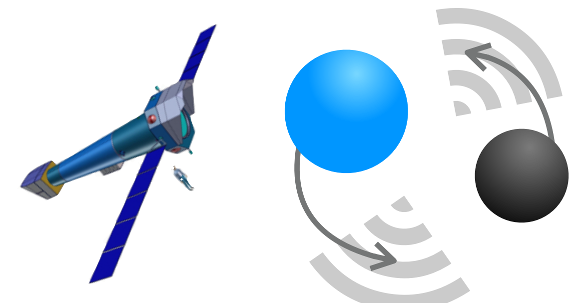
WHAT'S NEXT

Exciting targets for the LISA mission:



AGN binaries

- 1-100 events in LISA
- **EM** targets (< 1 deg^2)
- Need techniques to analyze Doppler shifted signals



WD-BHs

- Can infer **masses** with **GWs alone**
- **EM** targets (X-ray, e.g. Athena)
- Refine modelling and population expectations

Other "dirty" targets

Double WDs with low tidal couplings

Common envelope stage

Extreme-mass-ratio inspirals in thin accretion disks

Illustration ~ Private collection-Yachats, Oregon

Thank you!

Laura Sberna

Paris Observatory, December 2020

PERIMETER INSTITUTE

with A. Toubiana, C. Miller arXiv:2010.05974
and with A. Toubiana, A. Caputo, et al. arXiv:2010.06056, arXiv:2001.03620