LISA observations of GW190521-like binaries in an AGN environment

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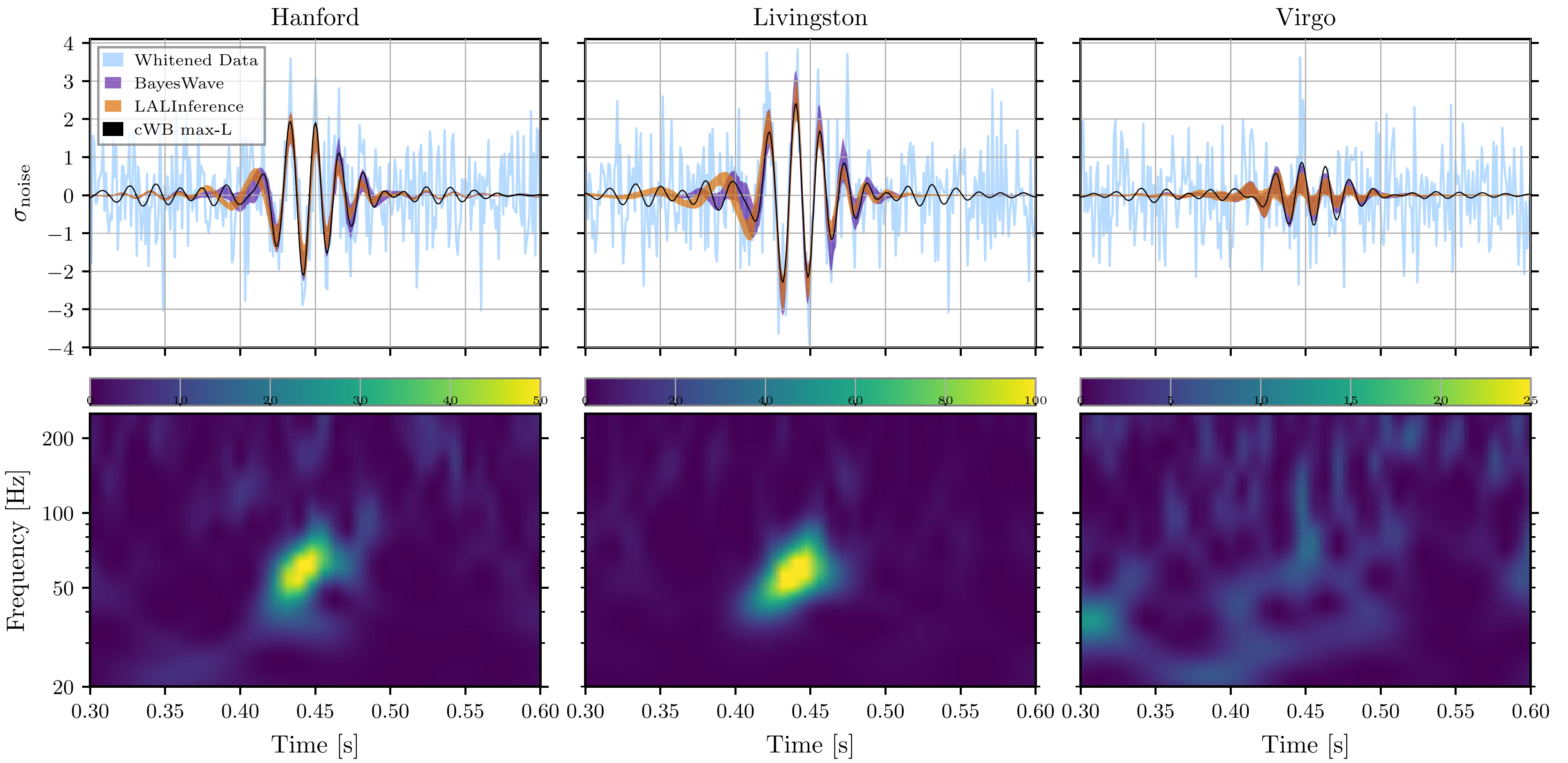
[arXiv:2205.08550]
[arXiv:2010.06056]
[arXiv:2007.08544]
[arXiv:2001.03620]

AG GdR OG

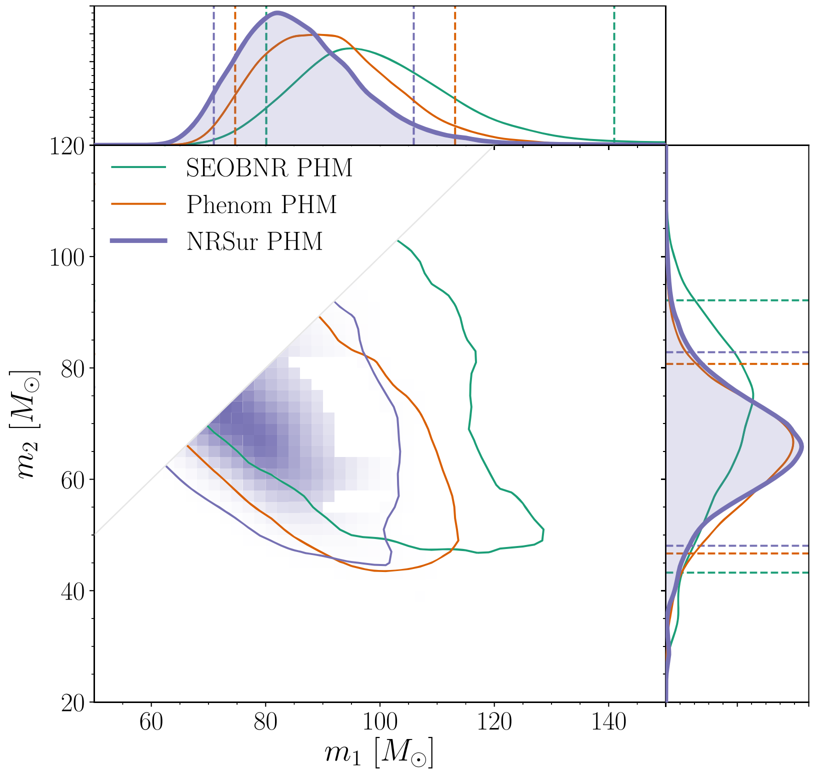
Toulouse - 2022-10-10

LVK GW190521: a massive BBH merger

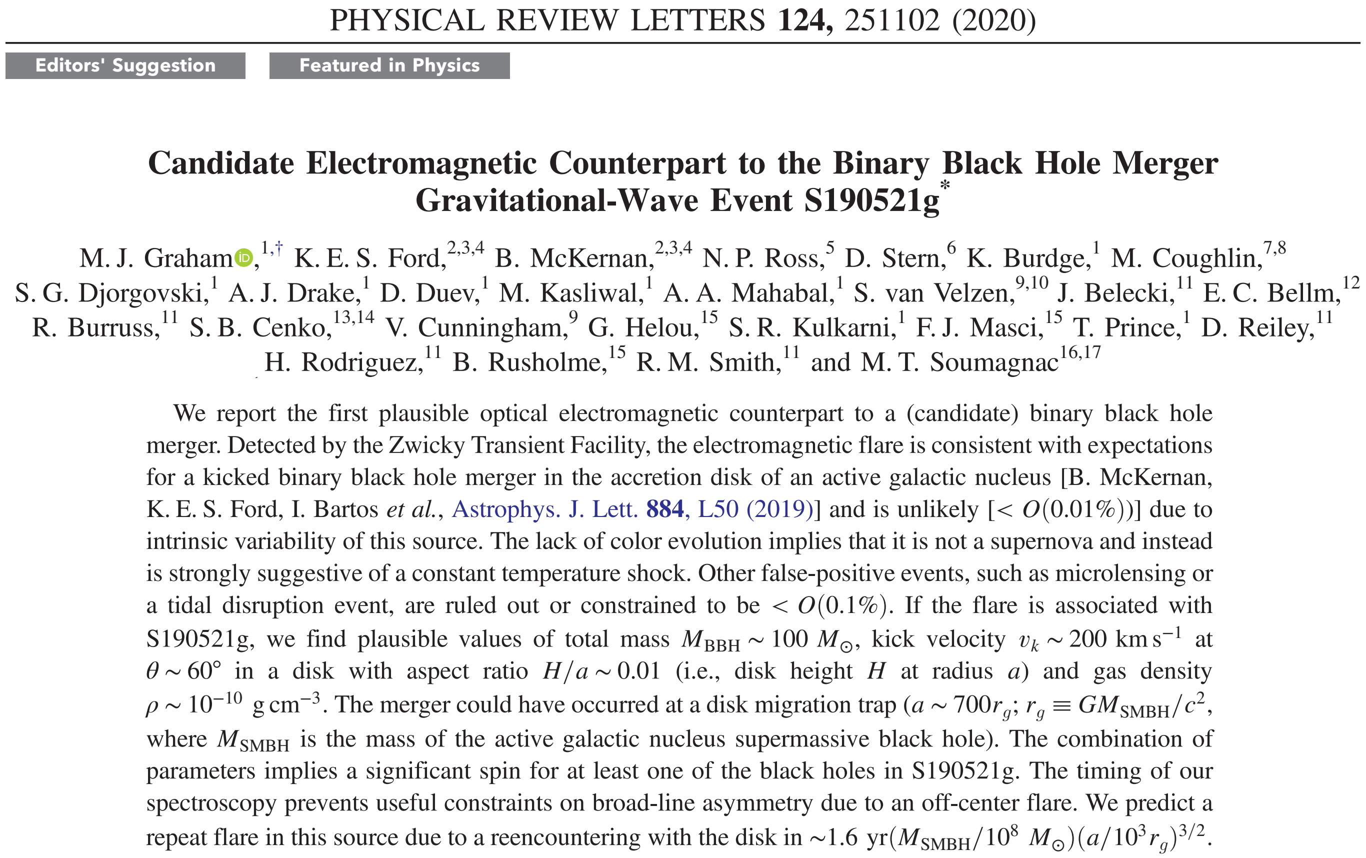


[arXiv:2009.01075]
[arXiv:2009.01190]

- An exceptionally massive (and distant) BBH merger detected by LIGO and Virgo
- Masses in the mass gap: origin of this system ? Hierarchical merger, accretion ?
- Discrepancies between waveform models for this merger-dominated signal: hints of precession, eccentricity ?



A ZTF counterpart to GW190521 ?



PHYSICAL REVIEW LETTERS **124,** 251102 (2020)

Editors' Suggestion **Featured in Physics**

Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*

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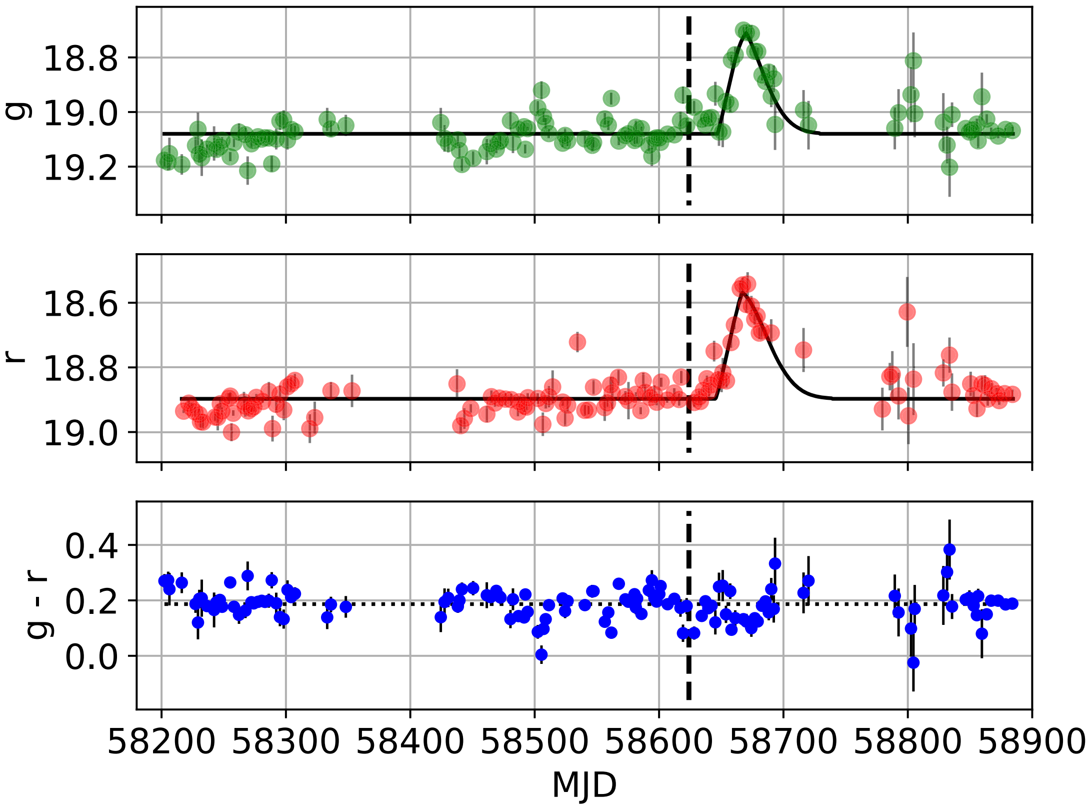
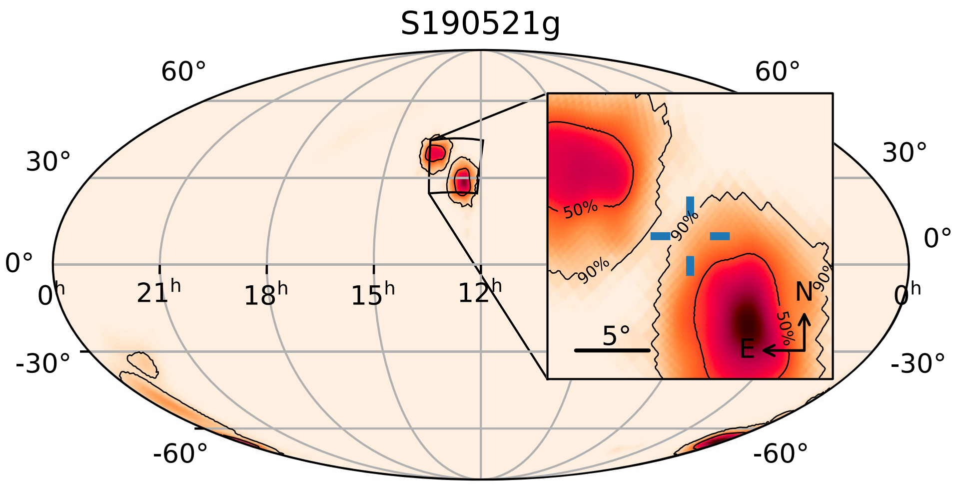
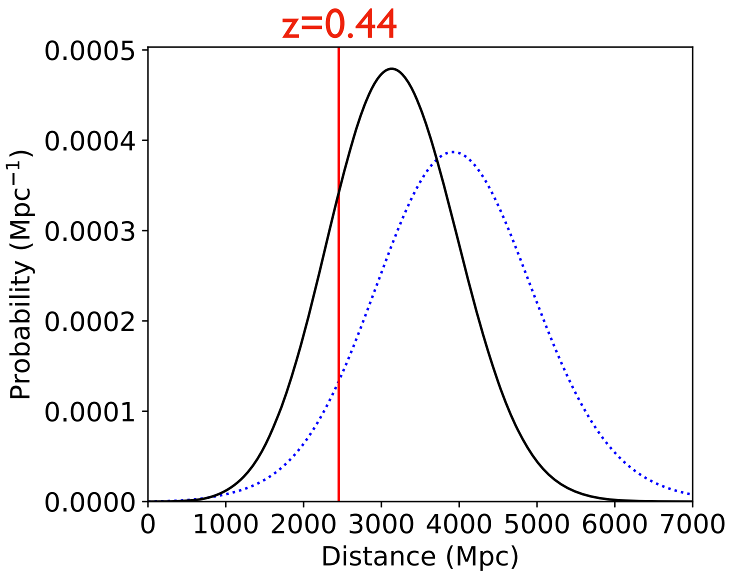
We report the first plausible optical electromagnetic counterpart to a (candidate) binary black hole merger. Detected by the Zwicky Transient Facility, the electromagnetic flare is consistent with expectations for a kicked binary black hole merger in the accretion disk of an active galactic nucleus [B. McKernan, K. E. S. Ford, I. Bartos *et al.*, Astrophys. J. Lett. **884**, L50 (2019)] and is unlikely [$< O(0.01\%)$] due to intrinsic variability of this source. The lack of color evolution implies that it is not a supernova and instead is strongly suggestive of a constant temperature shock. Other false-positive events, such as microlensing or a tidal disruption event, are ruled out or constrained to be $< O(0.1\%)$. If the flare is associated with S190521g, we find plausible values of total mass $M_{\rm BBH} \sim 100\ M_\odot$, kick velocity $v_k \sim 200\ {\rm km\,s^{-1}}$ at $\theta \sim 60°$ in a disk with aspect ratio $H/a \sim 0.01$ (i.e., disk height H at radius a) and gas density $\rho \sim 10^{-10}\ {\rm g\,cm^{-3}}$. The merger could have occurred at a disk migration trap ($a \sim 700 r_g$; $r_g \equiv GM_{\rm SMBH}/c^2$, where $M_{\rm SMBH}$ is the mass of the active galactic nucleus supermassive black hole). The combination of parameters implies a significant spin for at least one of the black holes in S190521g. The timing of our spectroscopy prevents useful constraints on broad-line asymmetry due to an off-center flare. We predict a repeat flare in this source due to a reencountering with the disk in $\sim 1.6\ {\rm yr}(M_{\rm SMBH}/10^8\ M_\odot)(a/10^3 r_g)^{3/2}$.

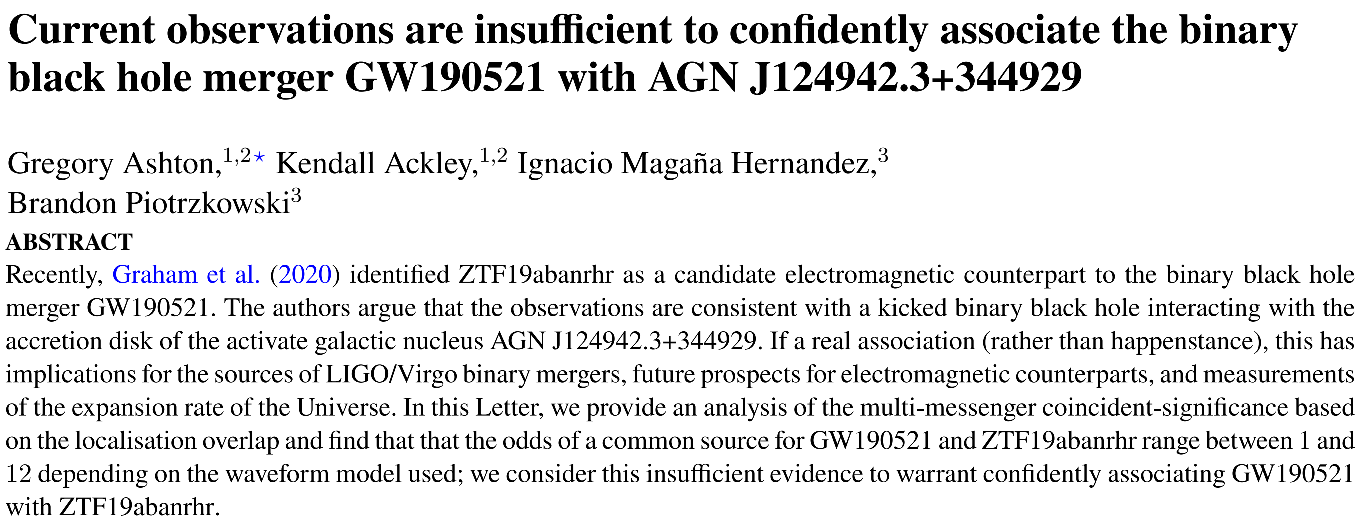






[arXiv:2006.14122]

Statistical evidence is debated…



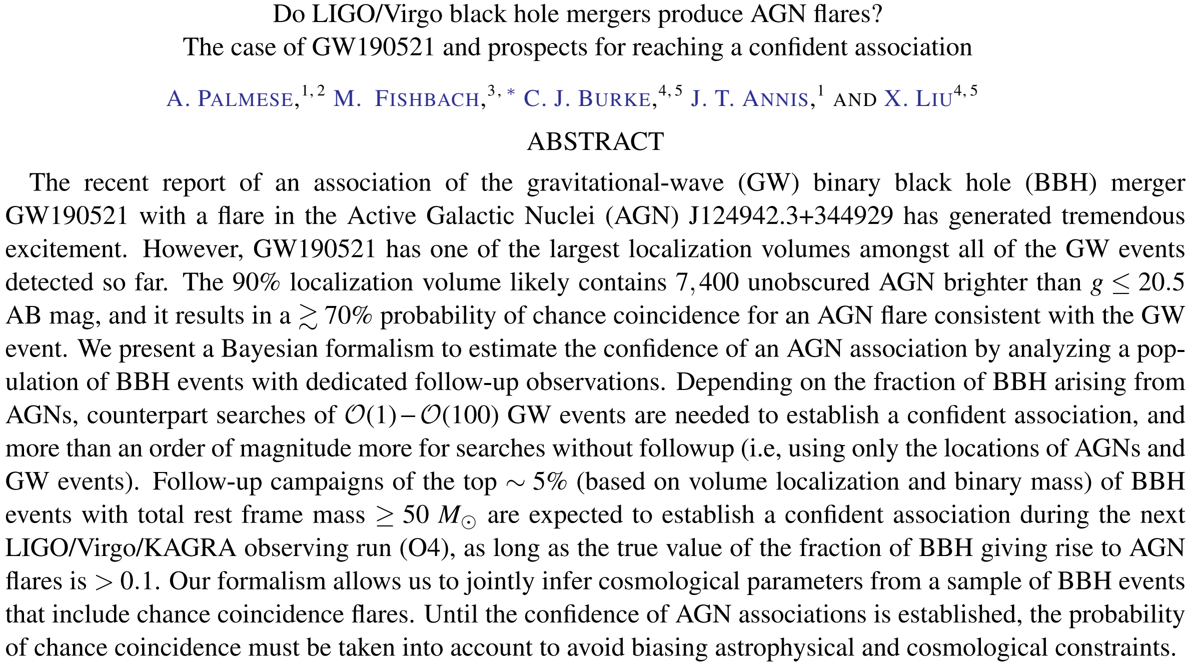
Current observations are insufficient to confidently associate the binary black hole merger GW190521 with AGN J124942.3+344929

Gregory Ashton,[1,2⋆] Kendall Ackley,[1,2] Ignacio Magaña Hernandez,[3]
Brandon Piotrzkowski[3]

ABSTRACT

Recently, Graham et al. (2020) identified ZTF19abanrhr as a candidate electromagnetic counterpart to the binary black hole merger GW190521. The authors argue that the observations are consistent with a kicked binary black hole interacting with the accretion disk of the activate galactic nucleus AGN J124942.3+344929. If a real association (rather than happenstance), this has implications for the sources of LIGO/Virgo binary mergers, future prospects for electromagnetic counterparts, and measurements of the expansion rate of the Universe. In this Letter, we provide an analysis of the multi-messenger coincident-significance based on the localisation overlap and find that that the odds of a common source for GW190521 and ZTF19abanrhr range between 1 and 12 depending on the waveform model used; we consider this insufficient evidence to warrant confidently associating GW190521 with ZTF19abanrhr.

[arXiv:2009.12346]



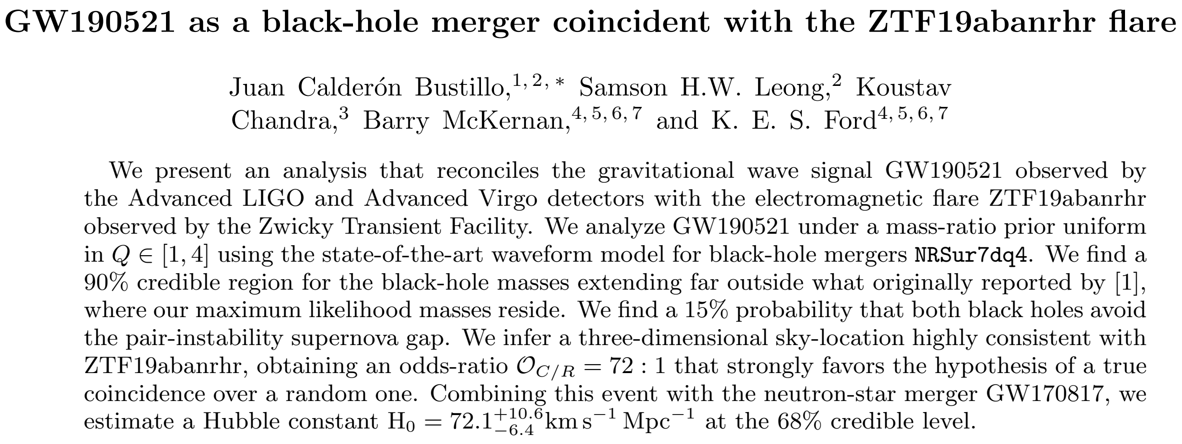
Do LIGO/Virgo black hole mergers produce AGN flares?
The case of GW190521 and prospects for reaching a confident association

A. PALMESE,[1,2] M. FISHBACH,[3,*] C. J. BURKE,[4,5] J. T. ANNIS,[1] AND X. LIU[4,5]

ABSTRACT

The recent report of an association of the gravitational-wave (GW) binary black hole (BBH) merger GW190521 with a flare in the Active Galactic Nuclei (AGN) J124942.3+344929 has generated tremendous excitement. However, GW190521 has one of the largest localization volumes amongst all of the GW events detected so far. The 90% localization volume likely contains 7,400 unobscured AGN brighter than $g \leq 20.5$ AB mag, and it results in a $\gtrsim 70\%$ probability of chance coincidence for an AGN flare consistent with the GW event. We present a Bayesian formalism to estimate the confidence of an AGN association by analyzing a population of BBH events with dedicated follow-up observations. Depending on the fraction of BBH arising from AGNs, counterpart searches of $\mathcal{O}(1)-\mathcal{O}(100)$ GW events are needed to establish a confident association, and more than an order of magnitude more for searches without followup (i.e, using only the locations of AGNs and GW events). Follow-up campaigns of the top $\sim 5\%$ (based on volume localization and binary mass) of BBH events with total rest frame mass $\geq 50\ M_\odot$ are expected to establish a confident association during the next LIGO/Virgo/KAGRA observing run (O4), as long as the true value of the fraction of BBH giving rise to AGN flares is > 0.1. Our formalism allows us to jointly infer cosmological parameters from a sample of BBH events that include chance coincidence flares. Until the confidence of AGN associations is established, the probability of chance coincidence must be taken into account to avoid biasing astrophysical and cosmological constraints.

[arXiv:2103.16069]



GW190521 as a black-hole merger coincident with the ZTF19abanrhr flare

Juan Calderón Bustillo,[1,2,*] Samson H.W. Leong,[2] Koustav Chandra,[3] Barry McKernan,[4,5,6,7] and K. E. S. Ford[4,5,6,7]

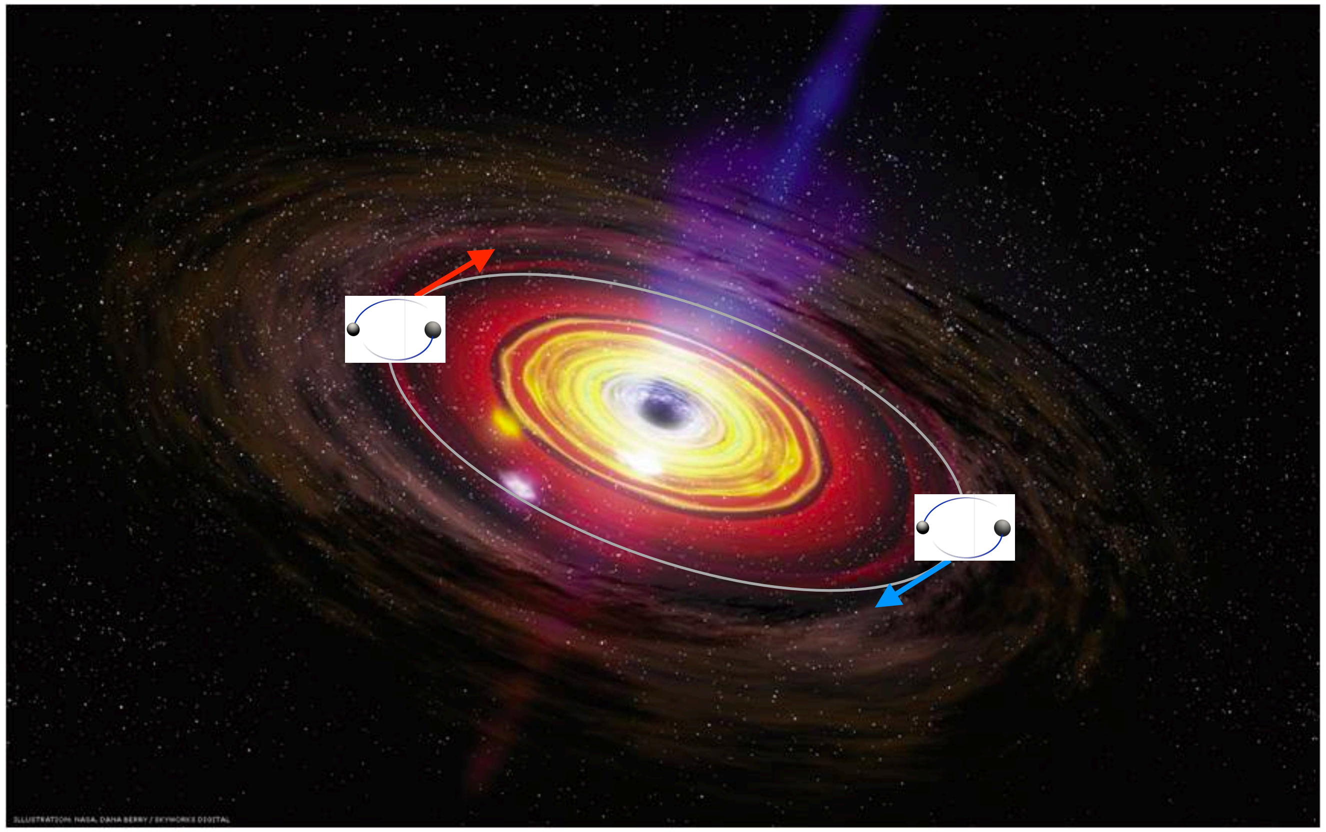
We present an analysis that reconciles the gravitational wave signal GW190521 observed by the Advanced LIGO and Advanced Virgo detectors with the electromagnetic flare ZTF19abanrhr observed by the Zwicky Transient Facility. We analyze GW190521 under a mass-ratio prior uniform in $Q \in [1,4]$ using the state-of-the-art waveform model for black-hole mergers `NRSur7dq4`. We find a 90% credible region for the black-hole masses extending far outside what originally reported by [1], where our maximum likelihood masses reside. We find a 15% probability that both black holes avoid the pair-instability supernova gap. We infer a three-dimensional sky-location highly consistent with ZTF19abanrhr, obtaining an odds-ratio $\mathcal{O}_{C/R} = 72:1$ that strongly favors the hypothesis of a true coincidence over a random one. Combining this event with the neutron-star merger GW170817, we estimate a Hubble constant $H_0 = 72.1^{+10.6}_{-6.4}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ at the 68% credible level.

[arXiv:2112.12481]

Scenario: LISA observations of an SBHB in an AGN disk

SBHB systems emitting from an orbit inside an AGN disk:

- BHs could be preferentially found in migration traps
- Potential formation channel ? Hierarchical mergers ?
- Matter environment: accretion, dynamical friction
- Potential standard sirens !



[Credit: S. Babak]

Effects on the GW signal ?

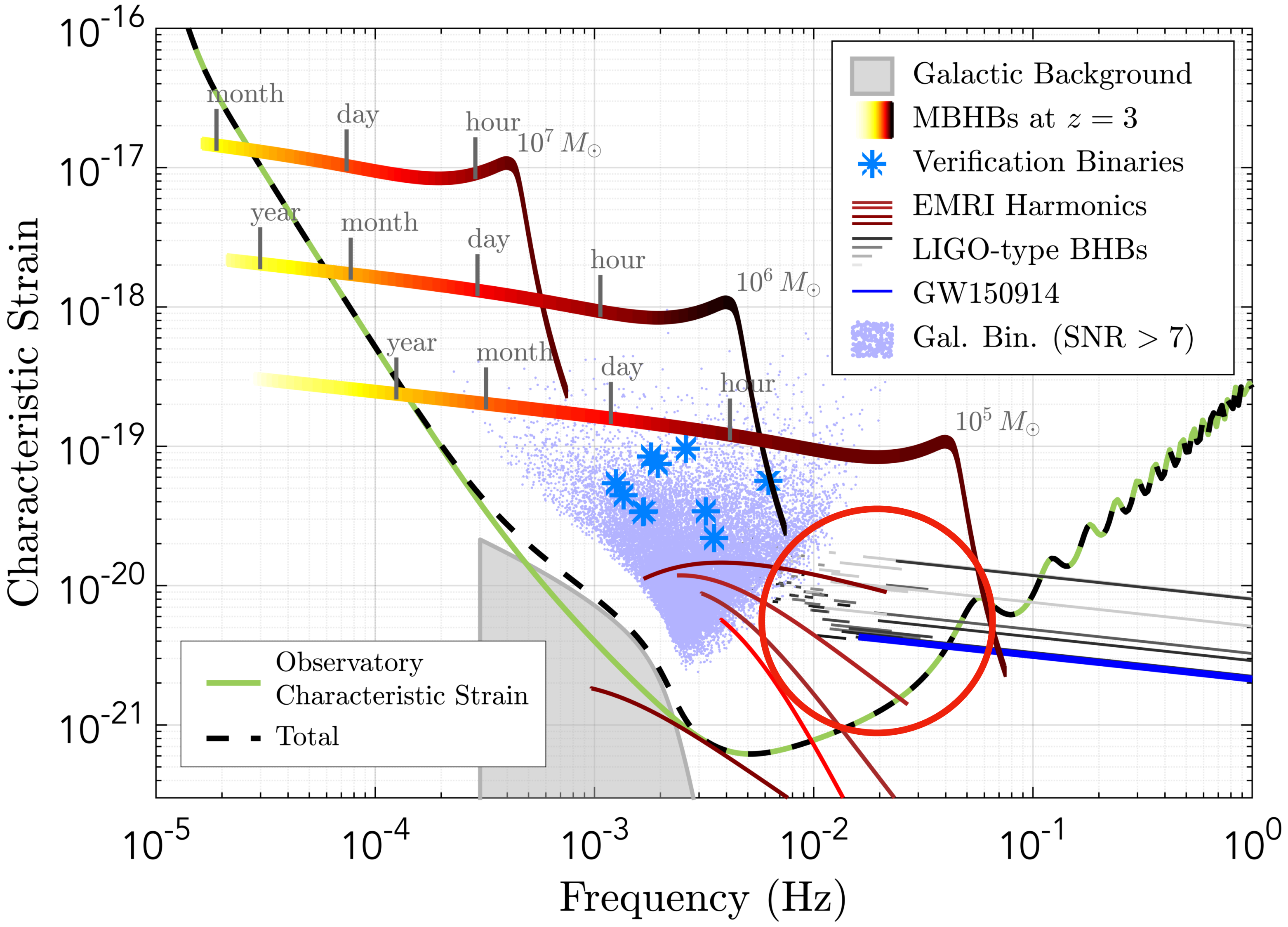
At low frequencies, in the LISA band:

- **Doppler modulation**
- **Shapiro time delay**
- **Gravitational lensing of GW**
- **Other relativistic effects** (de Sitter precession, Lense-Thirring precession, Kozai-Lidov) [Yu&Chen 2020]
- **Accretion** (-4PN) [Caputo&al 2020] [Toubiana&al 2020]
- **Dynamical friction** (-5.5PN) [Toubiana&al 2020]

This talk

A unique laboratory for astrophysics and fundamental physics

Stellar-mass black holes as LISA sources



LISA: different GW signals

- **MBHBs**: very loud, merger-dominated (mostly short)
- **SBHBs**: early inspiral, some chirping during LISA obs. (multiband ?)

- **GBs**: quasi-monochromatic, superposed
- **EMRIs**: long-lived, many harmonics
- **Stochastic backgrounds**
- **TDEs**

SBHB signal in LISA: Fourier-domain signal and response

Early inspiral signal

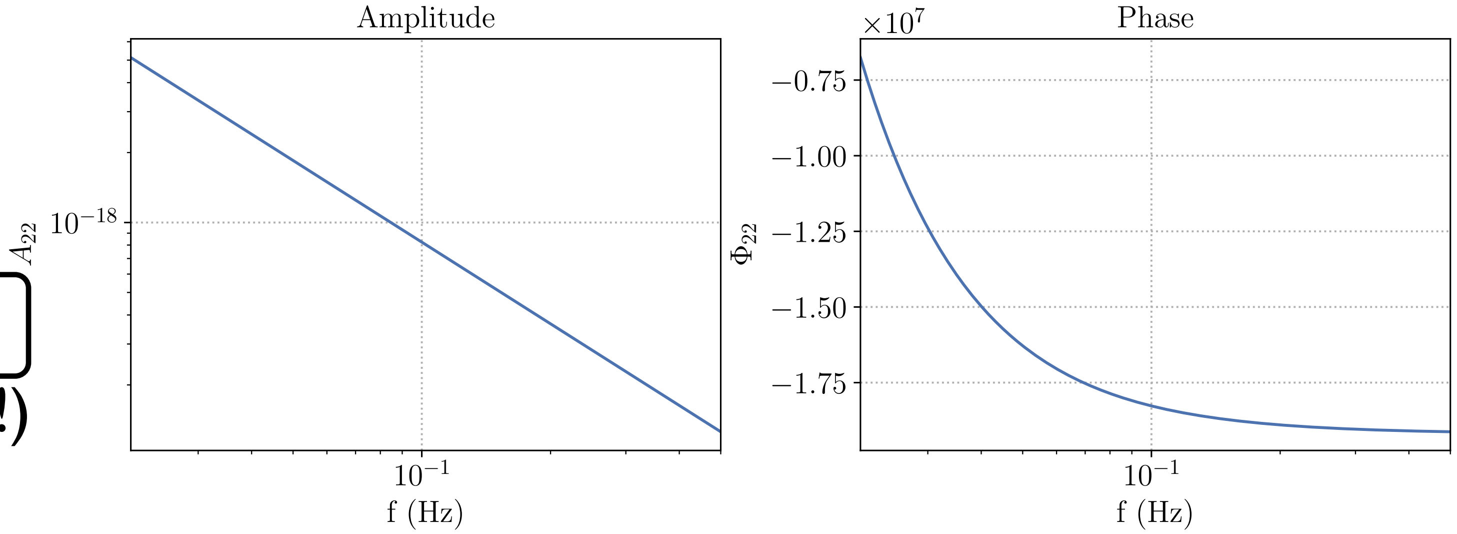
Here simple amplitude and phase

$$A(f) \sim f^{-7/6}$$

$$\Phi(f) \sim f^{-5/3}$$

Many phase cycles

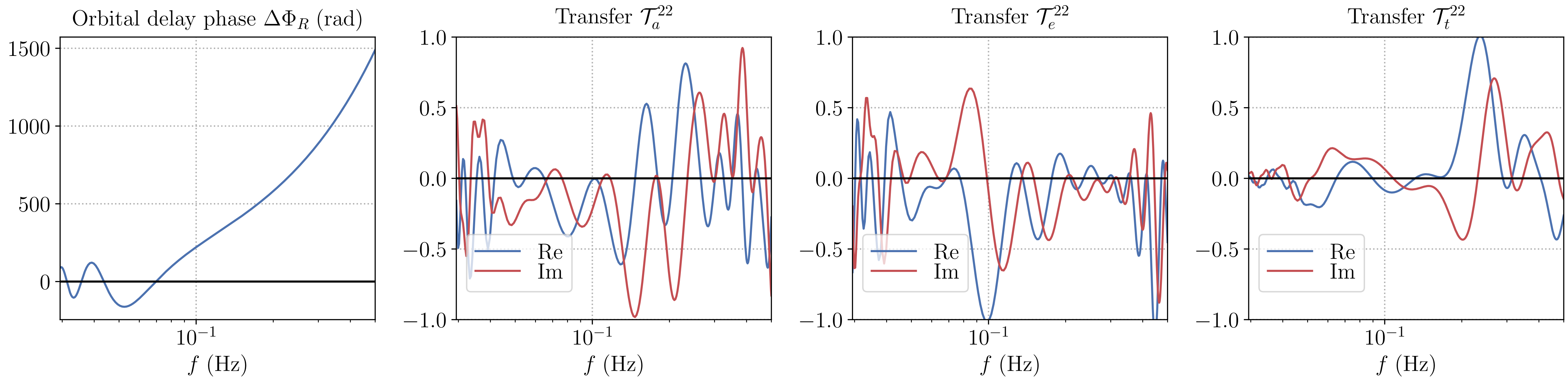
(but might have eccentricity+precession !)



Response decomposed

$$\mathcal{T}_{slr} = \frac{i\pi f L}{2}\,\mathrm{sinc}\left[\pi f L\left(1 - k\cdot n_l\right)\right]\exp\left[i\pi f\left(L + k\cdot(p_r + p_s)\right)\right] n_l\cdot P\cdot n_l(t_f)$$

+ Doppler phase (delay to the center of constellation): $\exp\left[2i\pi f k\cdot p_0(t_f)\right]$



Complicated modulations, long-lived signals
Departure from the low-frequency approx.
Large Doppler phase

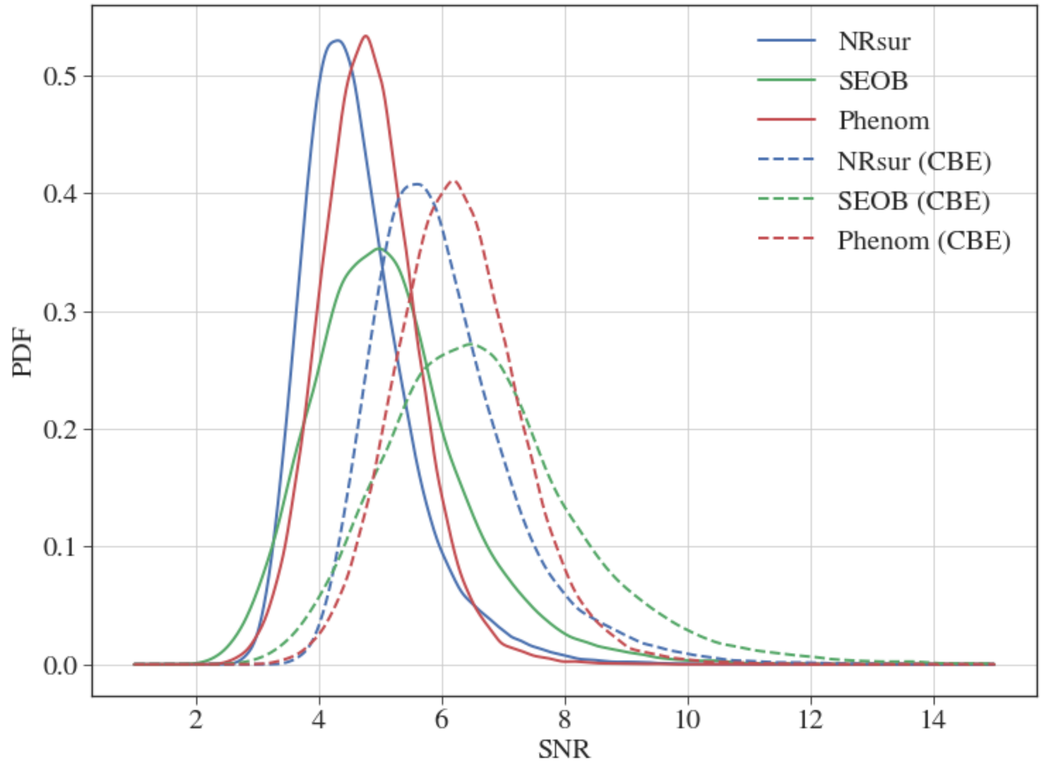
LISA rates for GW190521-like SBHBs

- Simulation from LVK population inference
- Analysis restricted to massive systems (>45Msol) or only for GW190521

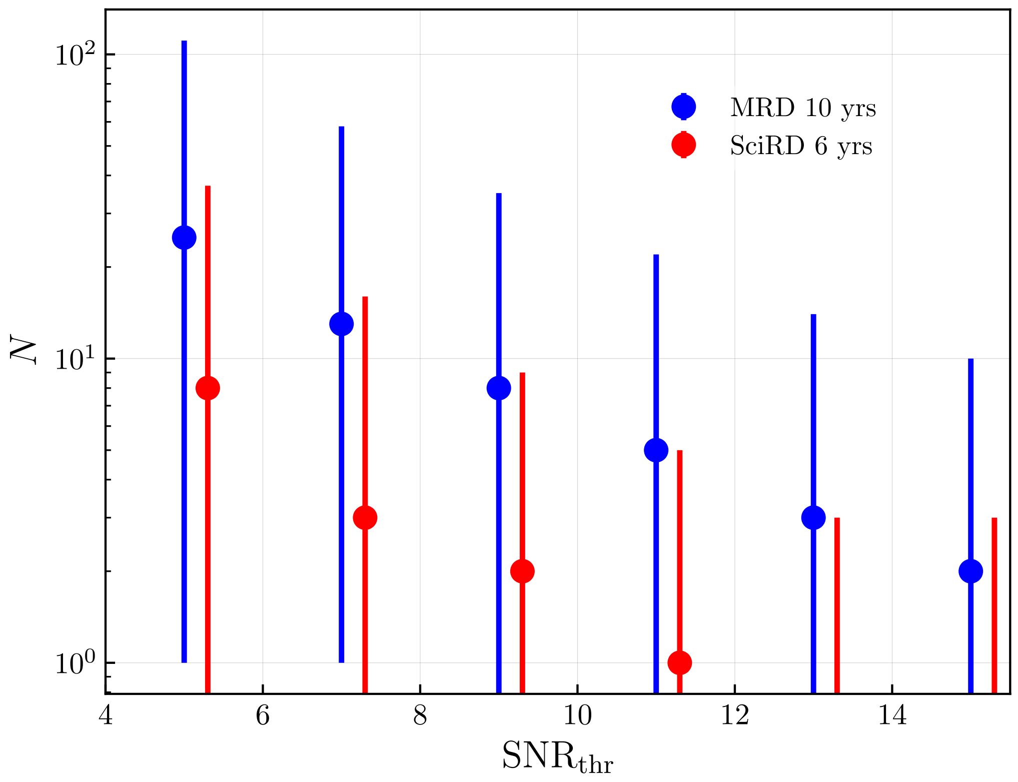
Signals detectable but challenging for LISA

noise, $T_{\rm obs}$, DC	GW190521-like	GWTC-3 massive	GWTC-3
SciRD, 10 yrs, 100%	7^{+24}_{-7}	5^{+45}_{-5}	22^{+44}_{-17}
SciRD, 6 yrs, 100%	4^{+14}_{-4}	2^{+25}_{-2}	10^{+28}_{-8}
SciRD, 6 yrs, 75%	2^{+10}_{-2}	1^{+16}_{-1}	6^{+22}_{-5}
MRD, 10 yrs, 100%	13^{+41}_{-13}	16^{+73}_{-16}	70^{+101}_{-47}
MRD, 10 yrs, 75%	11^{+38}_{-11}	10^{+66}_{-10}	43^{+74}_{-29}
MRD, 6 yrs, 75%	6^{+20}_{-6}	5^{+40}_{-5}	19^{+46}_{-15}

GW190521 LISA SNR

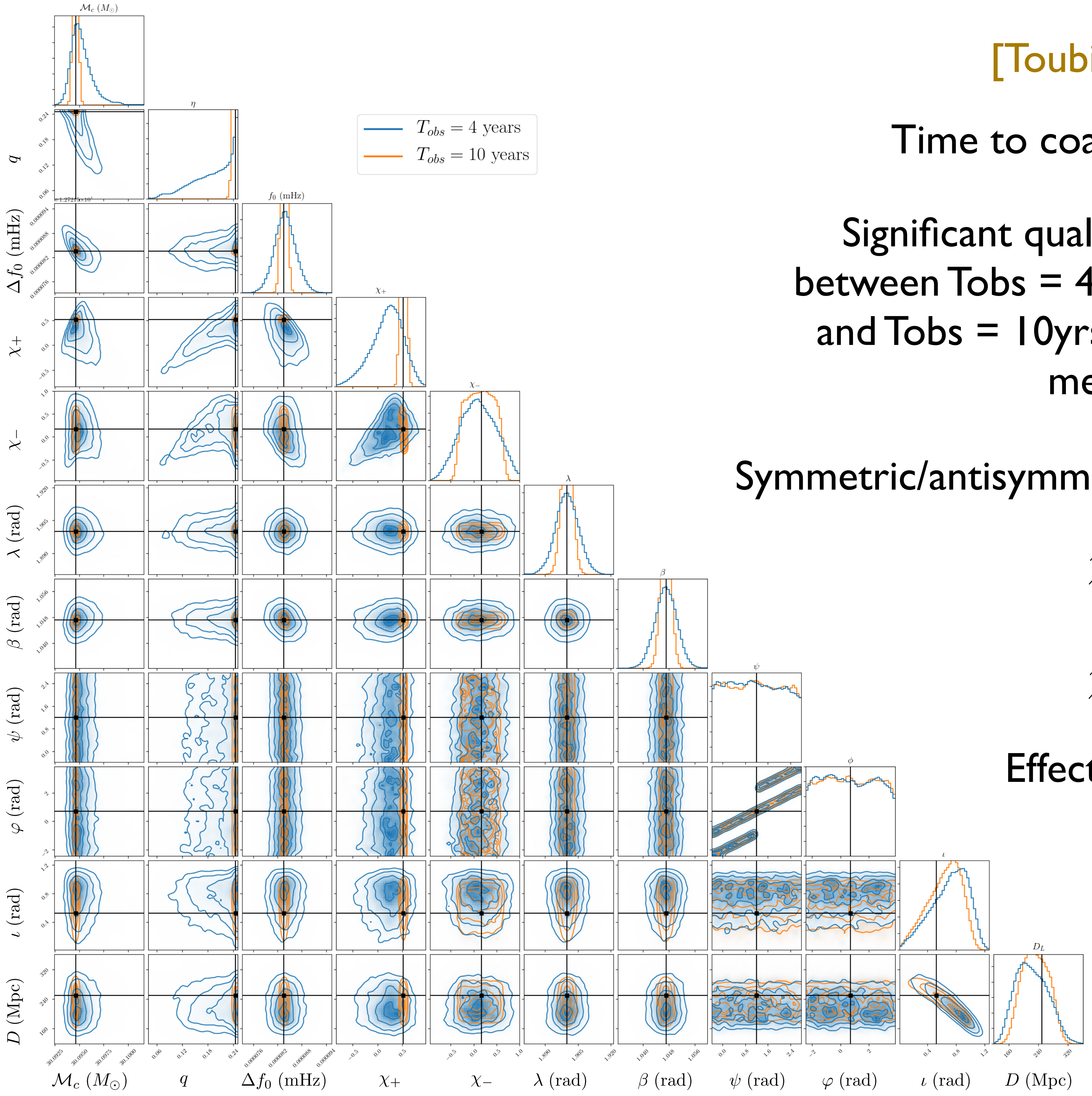


GW190521 LISA rate



Detection might require a high SNR [Moore&al 2019]
however archival searches are possible

Parameter Estimation result for SBHB example



[Toubiana&al 2020]

Time to coalescence: Tc = 8yrs

Significant qualitative differences between Tobs = 4yrs (slowly chirping) and Tobs = 10yrs (chirping towards merger)

Symmetric/antisymmetric spin combinations:

$$\chi_+ = \frac{m_1 \chi_1 + m_2 \chi_2}{m_1 + m_2}$$

$$\chi_- = \frac{m_1 \chi_1 - m_2 \chi_2}{m_1 + m_2}$$

Effective spin measured best

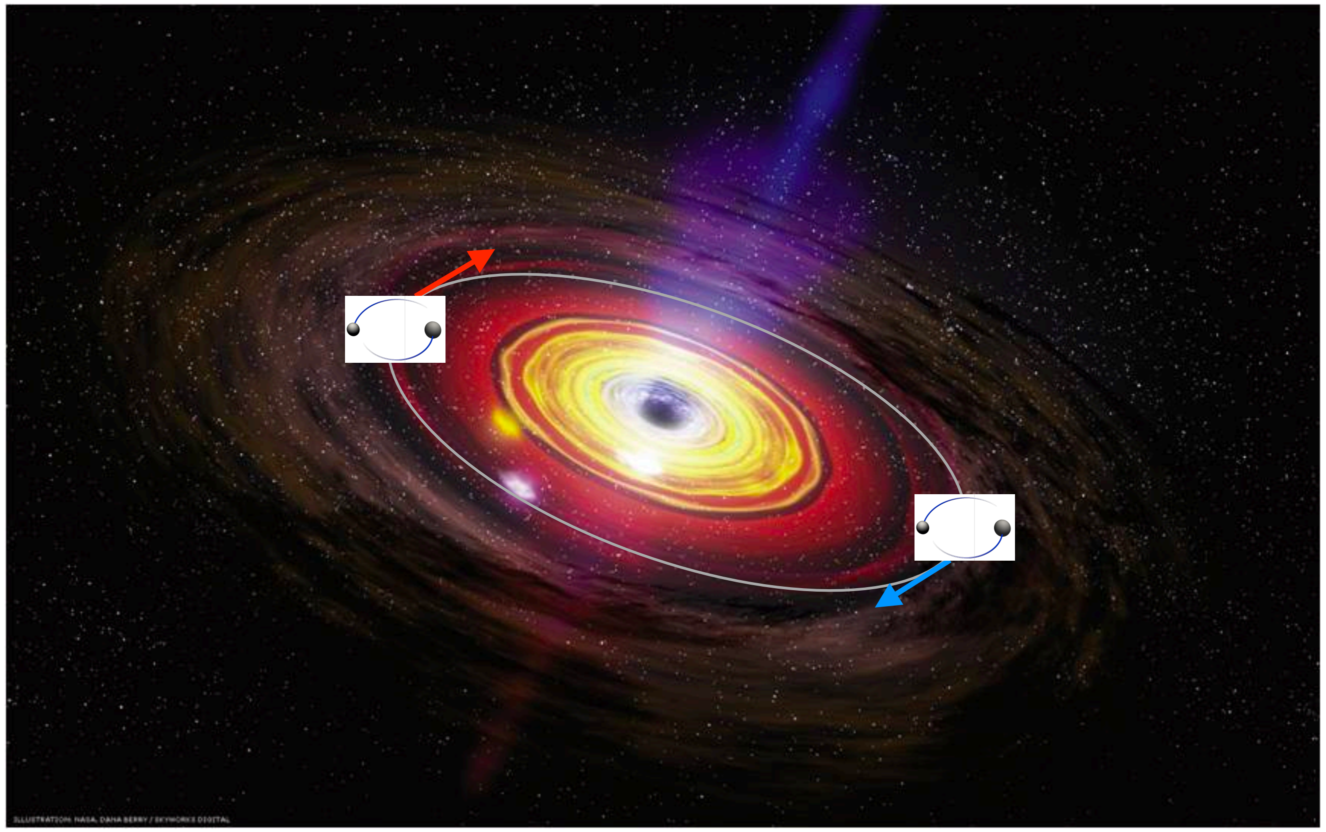
See also:

[Buscicchio&al 2021]
[Klein&al 2022]

SBHB emitting GW from an AGN disk

Effects on the waveforms

- **Doppler modulation**
- **Shapiro time delay**
- **Gravitational lensing of GW**
- **Other relativistic effects** (de Sitter precession, …)
- **Accretion**
- **Dynamical friction**



[Credit: S. Babak]

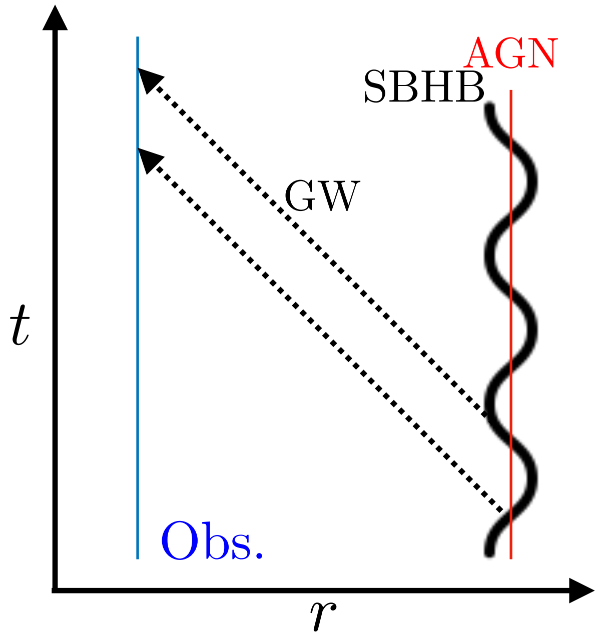
Doppler modulation

Time-varying propagation delay:

$$s(t + r(t)) = h(t)$$

(analogous to LISA Doppler delay, but on emission side)

- Constant speed: absorbed in redshift
- Acceleration: formally -4PN term, like accretion [Bonvin&al 2016] [Inayoshi&al 2017] [Tamanini&al 2019]
- Beyond: effect of observing a full orbit ?



Doppler delay

$$s(t) \simeq h(t + d(t))$$

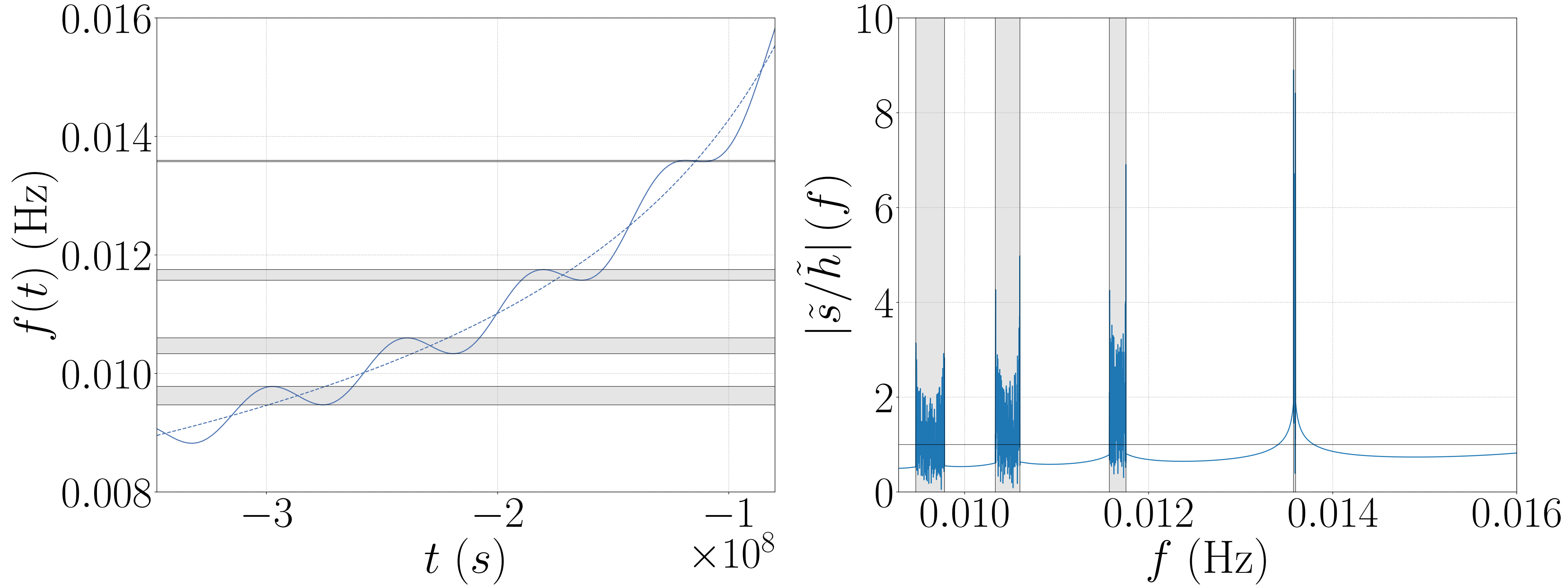
$$d(t) = -\frac{R_{\mathrm{AGN}}}{c} \sin\theta_{\mathrm{AGN}} \cos\left(\Omega_{\mathrm{AGN}} t - \phi_{\mathrm{AGN}}\right)$$

Example AGN orbit (inspired from Graham&al):

$$M_{\mathrm{AGN}} = 10^8 M_\odot$$
$$R_{\mathrm{AGN}} = 700 M_{\mathrm{AGN}}$$
$$\theta_{\mathrm{AGN}} = \pi/3$$
$$v/c \sim 0.04$$

Large contribution to the phasing !

$$2\pi f a \sim 2 \times 10^4\,\mathrm{rad} \left(\frac{M}{10^8 M_\odot}\right)\left(\frac{f}{10\,\mathrm{mHz}}\right)\left(\frac{a}{700M}\right)$$

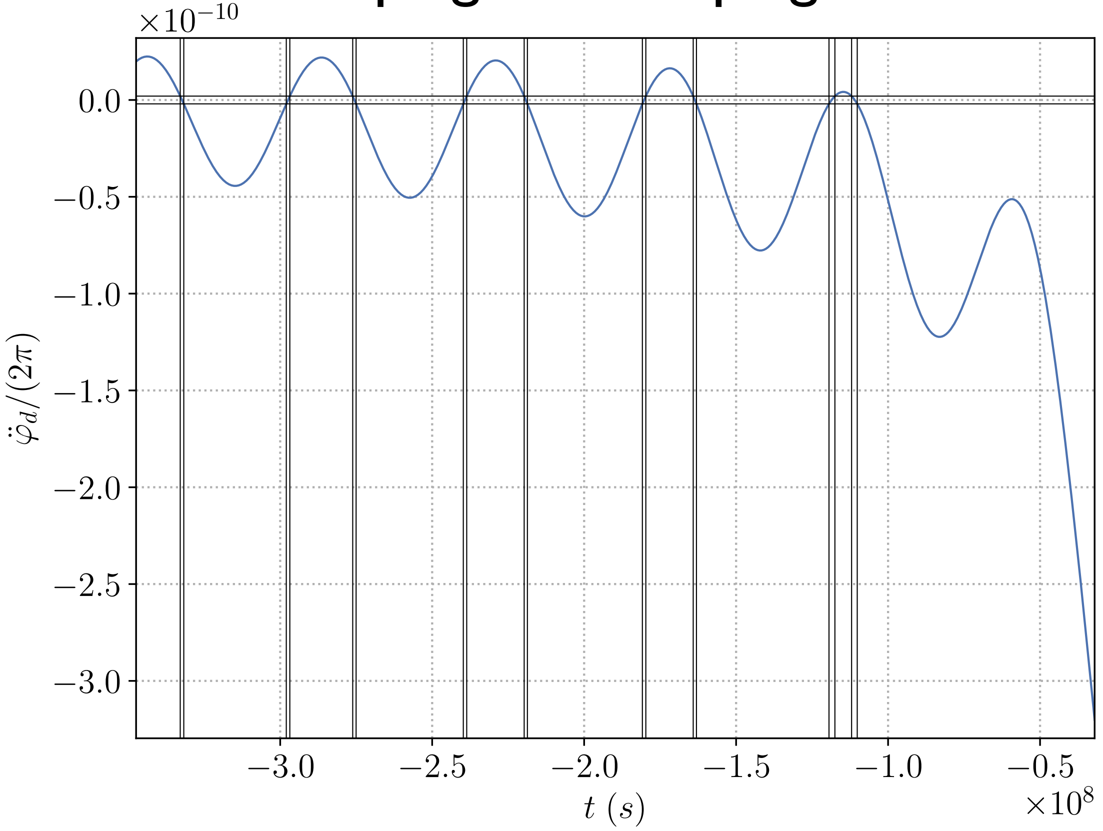


[Toubiana&al 2020]

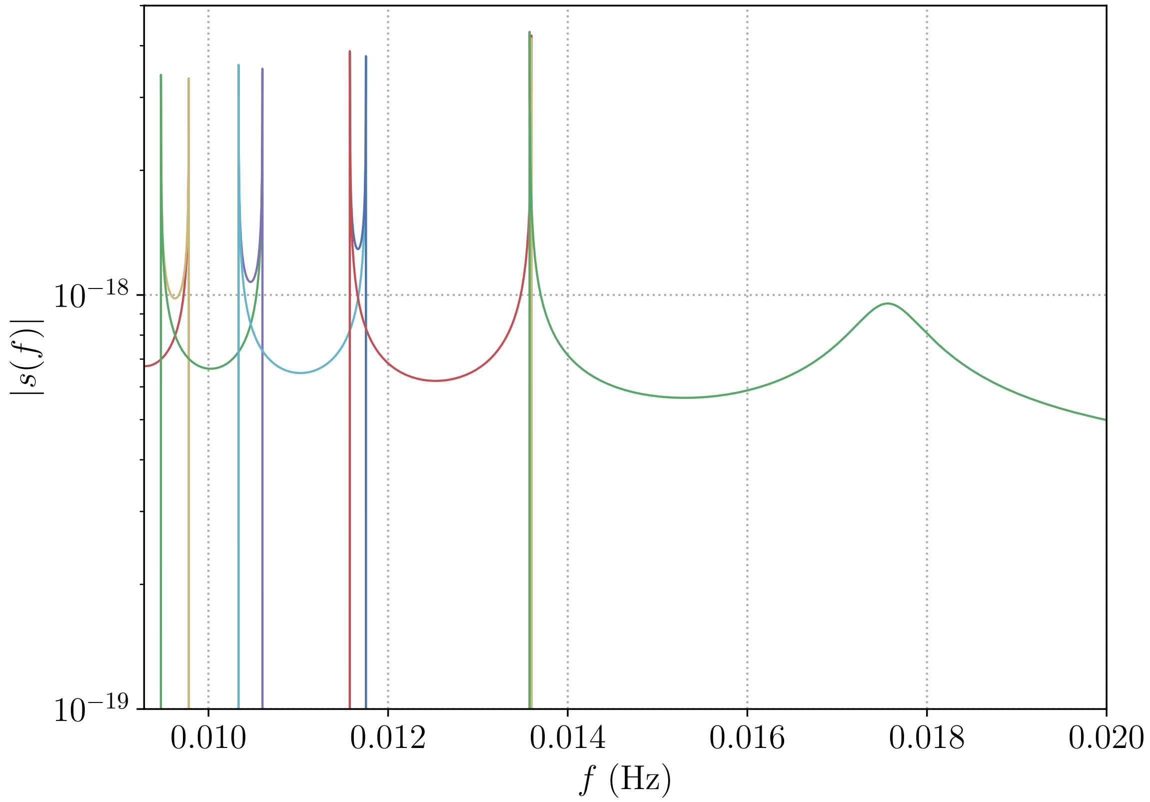
Effect of the Doppler delay large enough to dominate the GW chirping rate
Creates anti-chirping bands

Implementation: signal decomposition

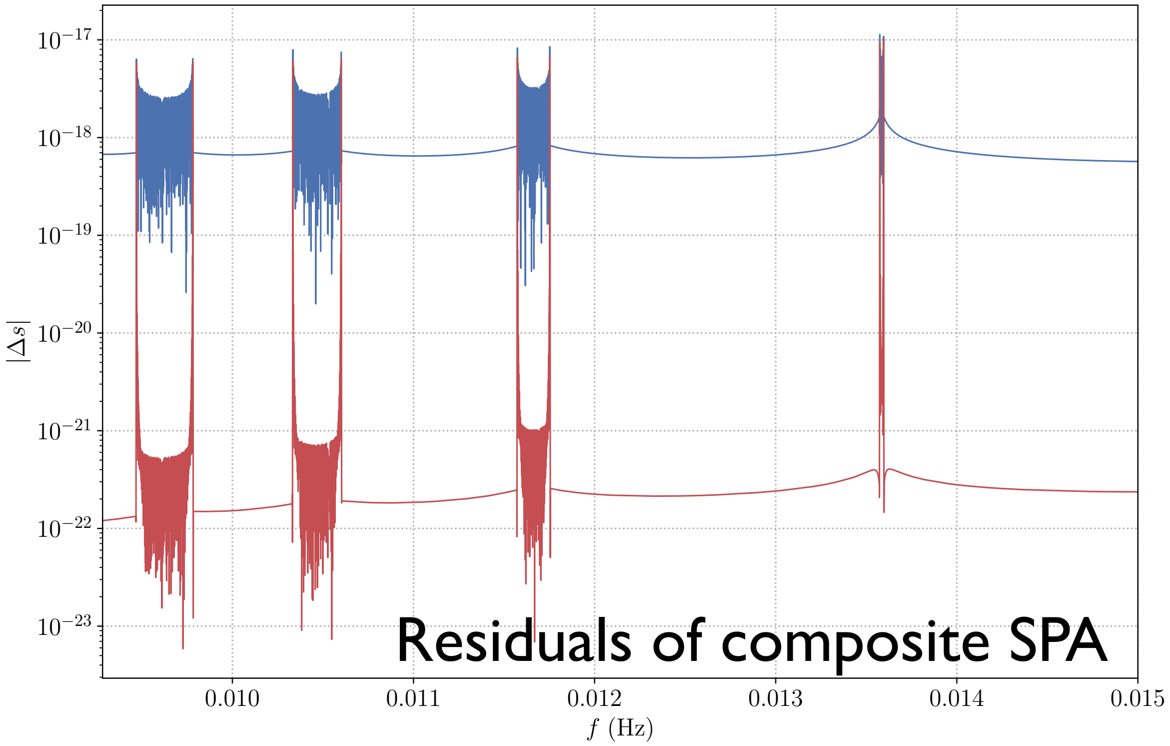
Chirping/anti-chirping bands



Spectra of individual signal pieces



- Decompose signal in chirping/anti-chirping bands
- Ignore quasi-monochromatic turnarounds
- Apply Stationary Phase Approximation (SPA) to individual bands
- Apply standard FD LISA response on each



Residuals of composite SPA

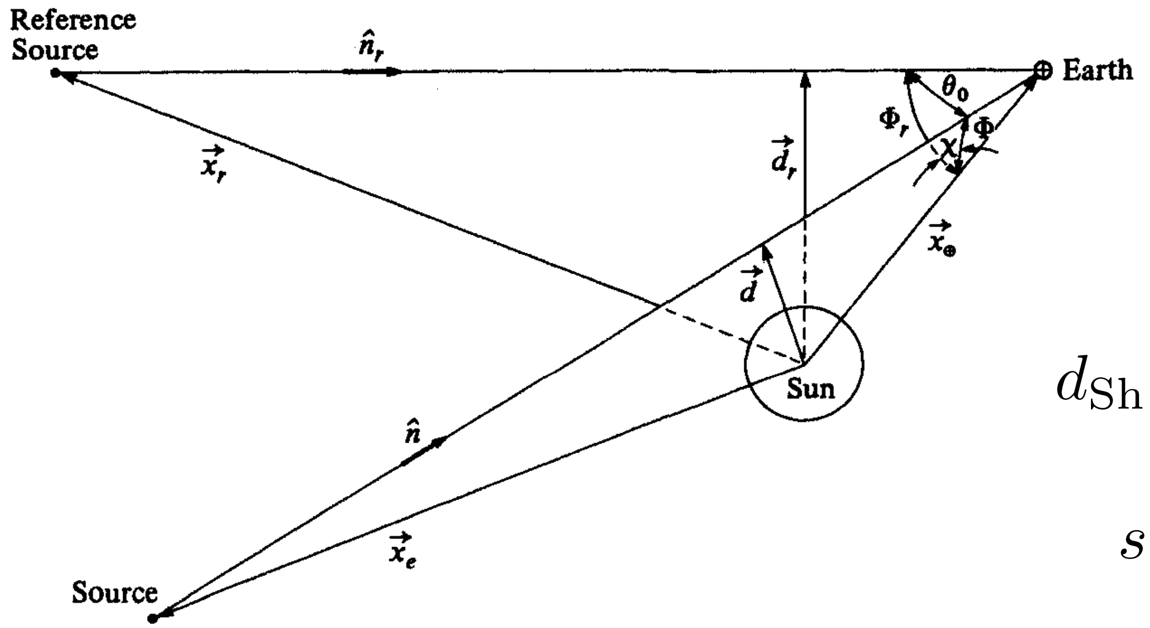
Keep sparse representation for FD amplitude/phase for each band
Signal: superposition of bands

likelihood: ~10-20ms

Shapiro time delay

[C. M. Will, Theory and Experiment in Gravitational Physics]

Figure 7.1. Geometry of light-deflection measurements.



$$t - t_e = |\mathbf{x} - \mathbf{x}_e| + (1+\gamma) m \ln\left[\frac{r(t) + \mathbf{x}(t)\cdot\hat{\mathbf{n}}}{r_e + \mathbf{x}_e\cdot\hat{\mathbf{n}}}\right]$$

At reception $t = t_r \, , x = x_r$

Ignore $\ln[r_r/r_e] = \mathrm{const} \qquad (r_r \gg r_e)$

$$d_{\mathrm{Sh}}(t) = \frac{2GM_{\mathrm{AGN}}}{c^3} \ln\left[1 + \sin\theta_{\mathrm{AGN}} \cos\left(\Omega_{\mathrm{AGN}} t - \phi\right)\right]$$

$$s(t) = h(t + d_{\mathrm{Doppler}}(t) + d_{\mathrm{Shapiro}}(t))$$

Main Doppler: $\propto R_{\mathrm{AGN}} \sin\theta_{\mathrm{AGN}}$

Large effect but can only measure this combination
(radius projected along the line of sight)

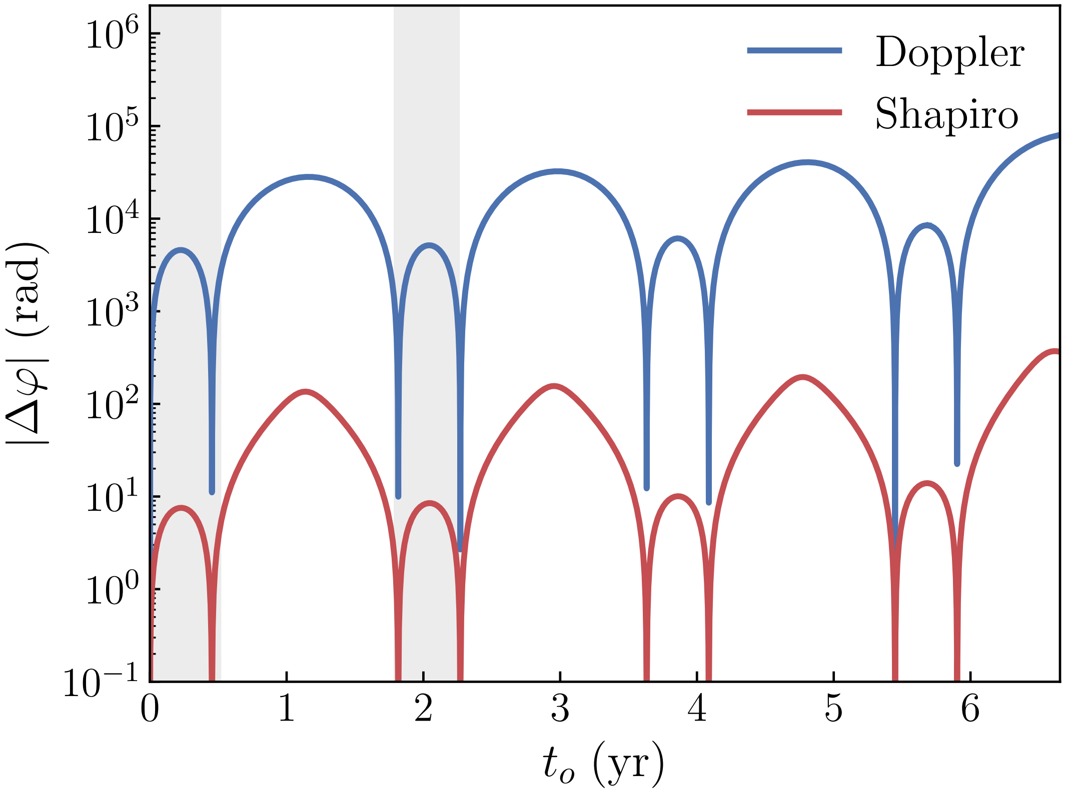
Including the Shapiro time delay will break degeneracies
between the AGN parameters

Doppler and Shapiro time delays in our signal

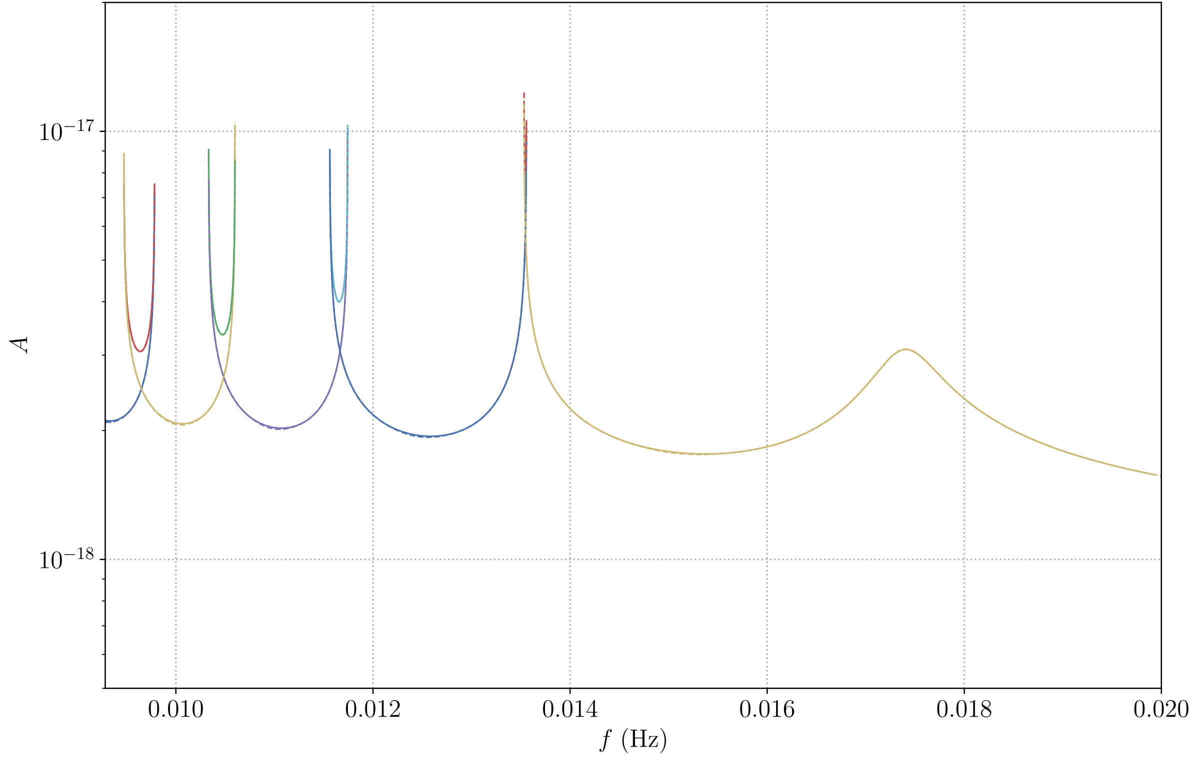
Main Doppler and Shapiro delays:

$$d(t) = -\frac{R_{\mathrm{AGN}}}{c} \sin\theta_{\mathrm{AGN}} \cos\left(\Omega_{\mathrm{AGN}} t - \phi_{\mathrm{AGN}}\right)$$

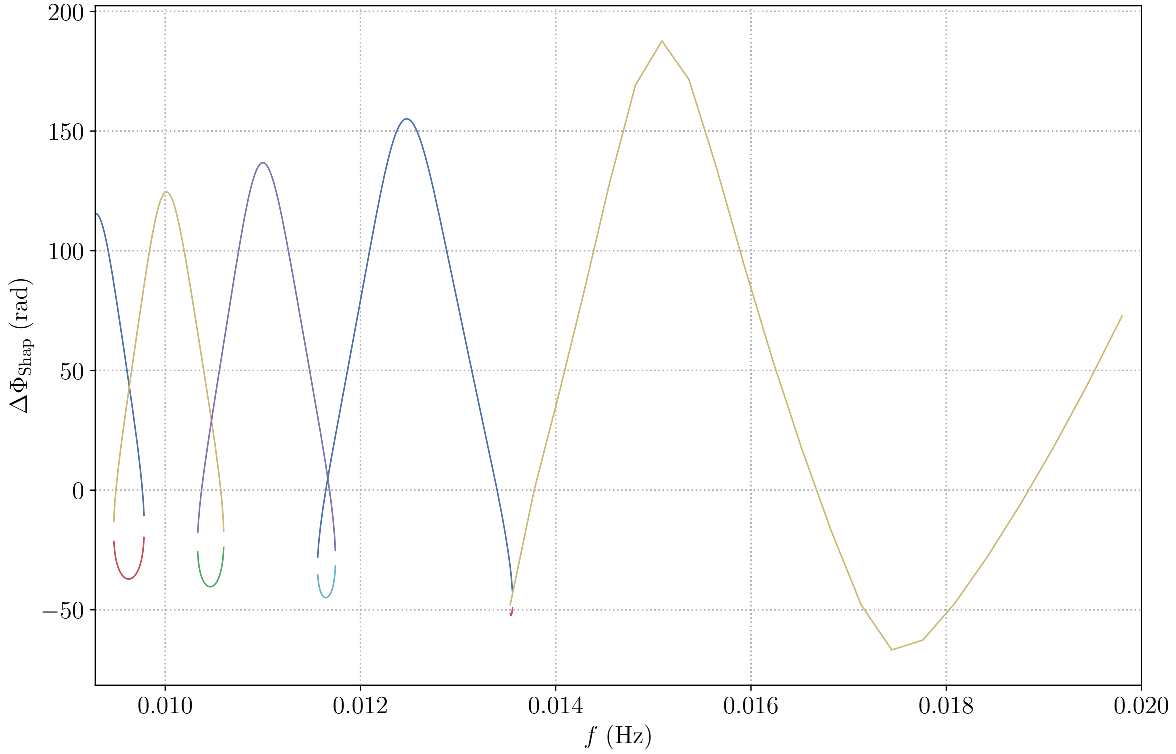
$$d_{\mathrm{Sh}}(t) = \frac{2GM_{\mathrm{AGN}}}{c^3} \ln\left[1 + \sin\theta_{\mathrm{AGN}} \cos\left(\Omega_{\mathrm{AGN}} t - \phi\right)\right]$$



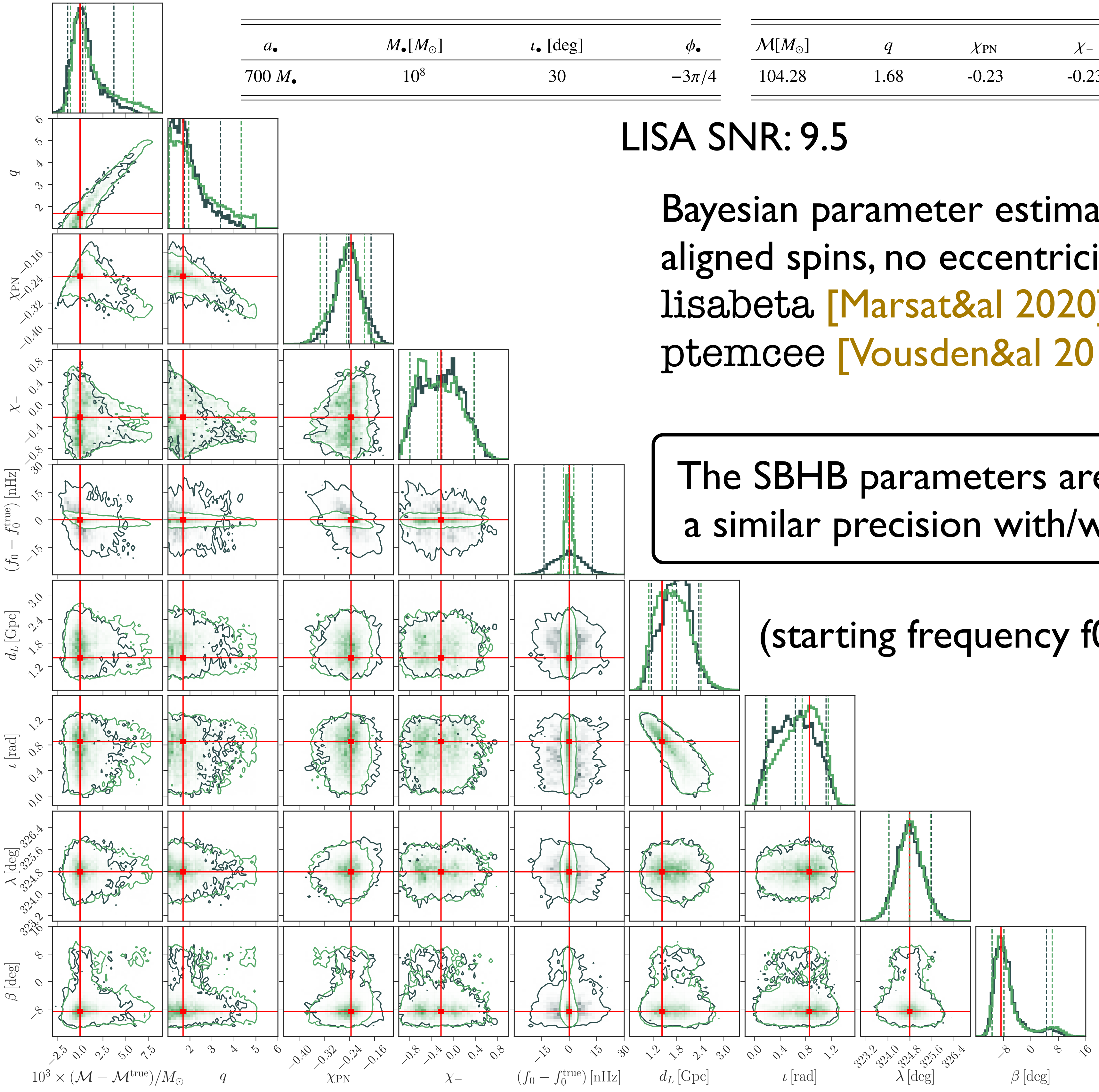
FD bands (almost unchanged)



Shapiro phase FD



Parameter estimation with and without the AGN



$a_\bullet$	$M_\bullet[M_\odot]$	$\iota_\bullet$ [deg]	$\phi_\bullet$
700 $M_\bullet$	10^8	30	$-3\pi/4$

$\mathcal{M}[M_\odot]$	q	$\chi_{\rm PN}$	χ_-	d_L [Gpc]
104.28	1.68	-0.23	-0.23	1.4

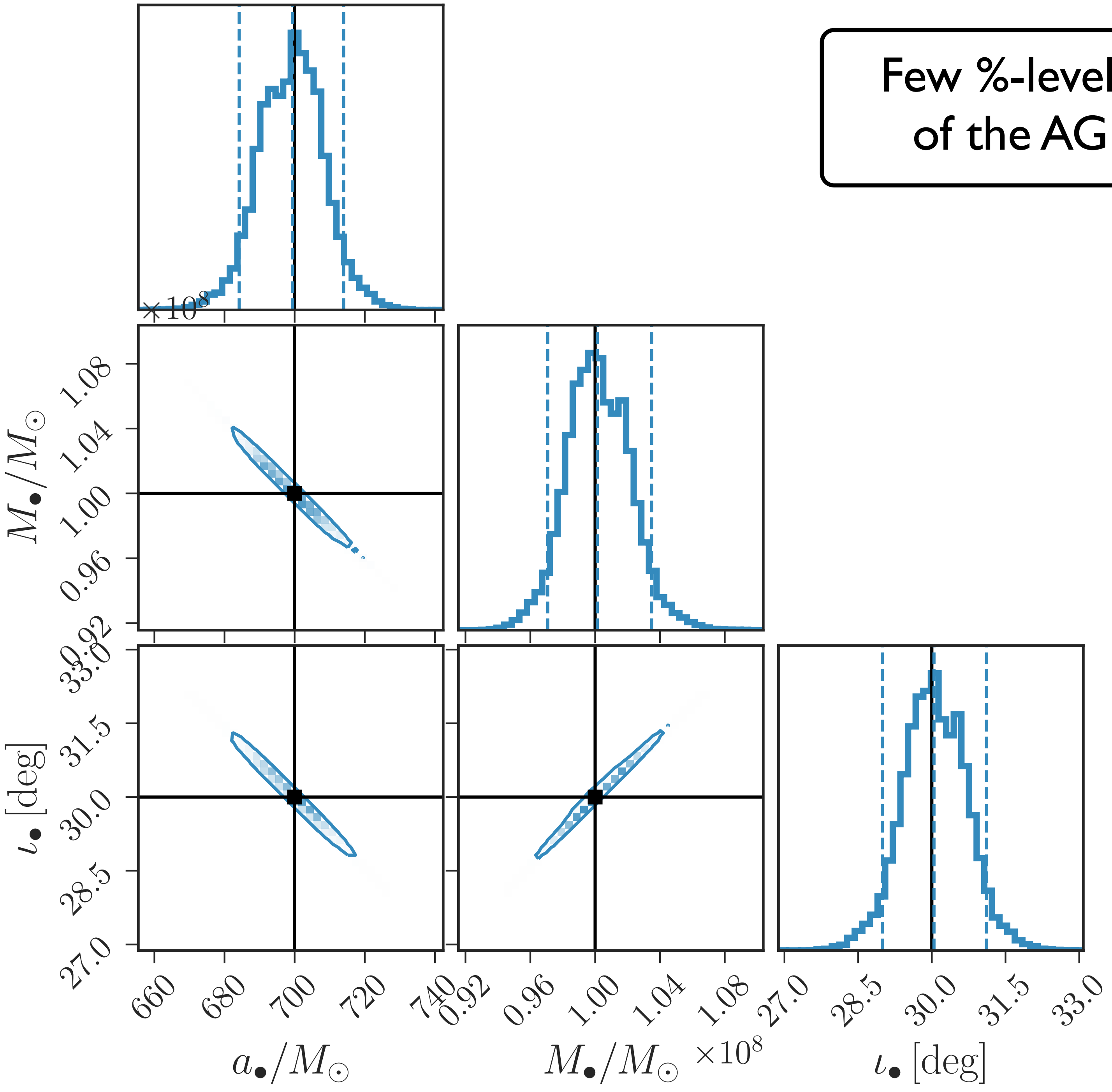
LISA SNR: 9.5

Bayesian parameter estimation (0-noise, aligned spins, no eccentricity)
`lisabeta` [Marsat&al 2020]
`ptemcee` [Vousden&al 2015]

The SBHB parameters are recovered with a similar precision with/without the AGN

(starting frequency f0 redefined)

Parameter estimation for the AGN params

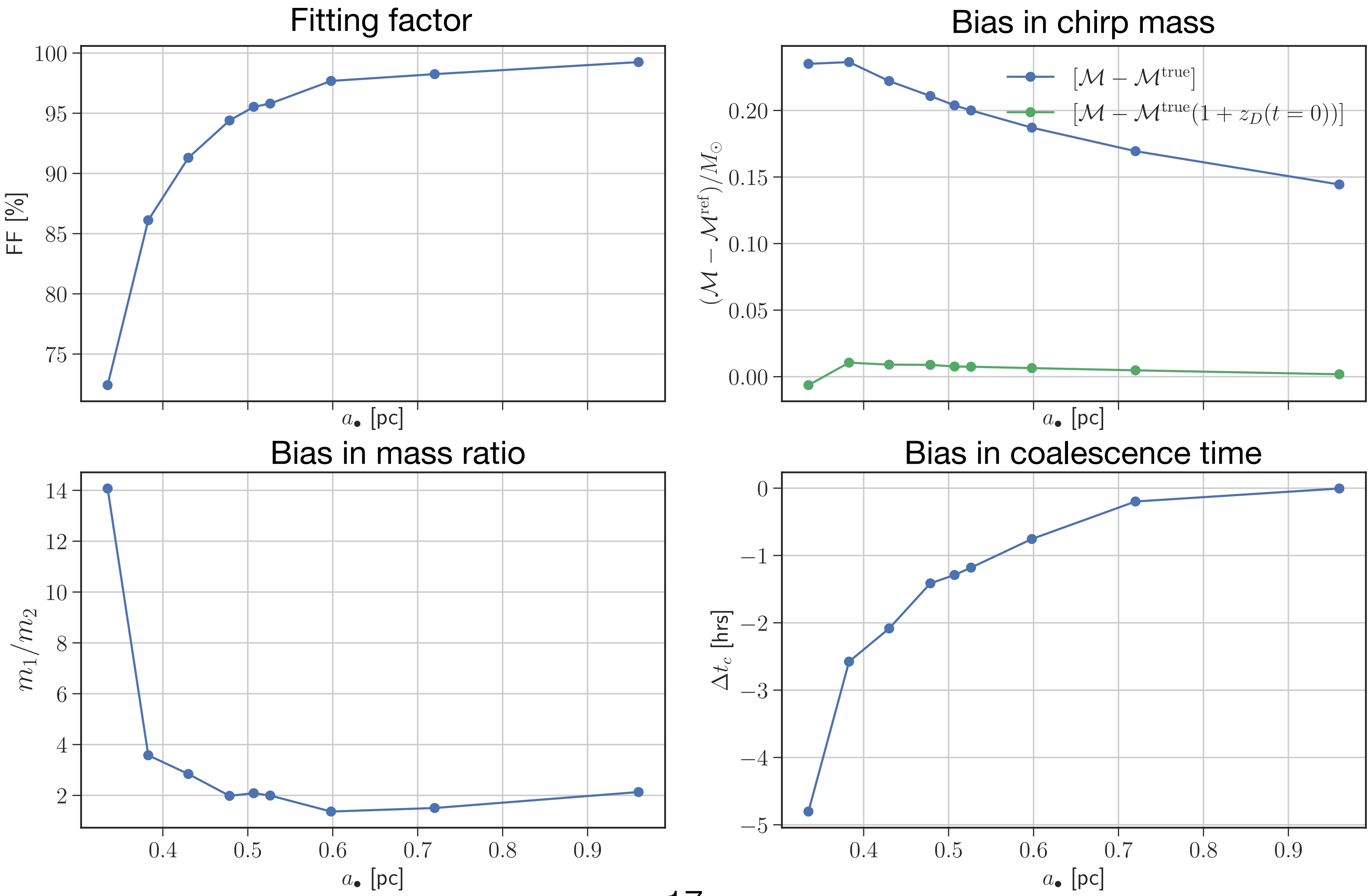


Few %-level determination of the parameters of the AGN orbit from GW phasing alone

- Shapiro delay present for generic inclinations, breaks degeneracies
- Recover the limit of an accelerating binary at large separations
- Difficulty of detection ? SBHBs are already hard to detect, the parameter space is larger here
- Remains to explore the parameter space

The large separation limit

- For larger separations, we recover a constant-acceleration regime, then a constant-speed regime (peculiar velocity)
- Fitting factors: indicating SNR loss
- Best fit parameters: would we get parameter biases with templates for ordinary binaries ?
- Computationally difficult (exploring the whole parameter space)

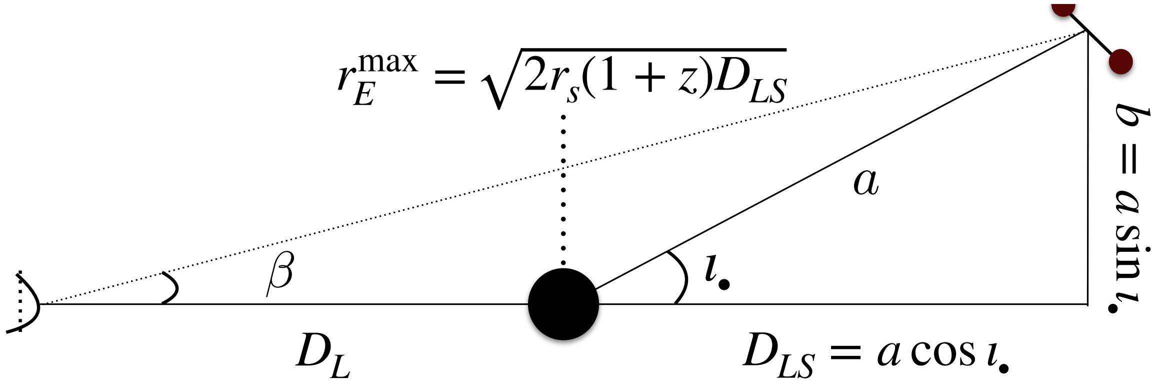


Lensing of GW by the central AGN [Preliminary]

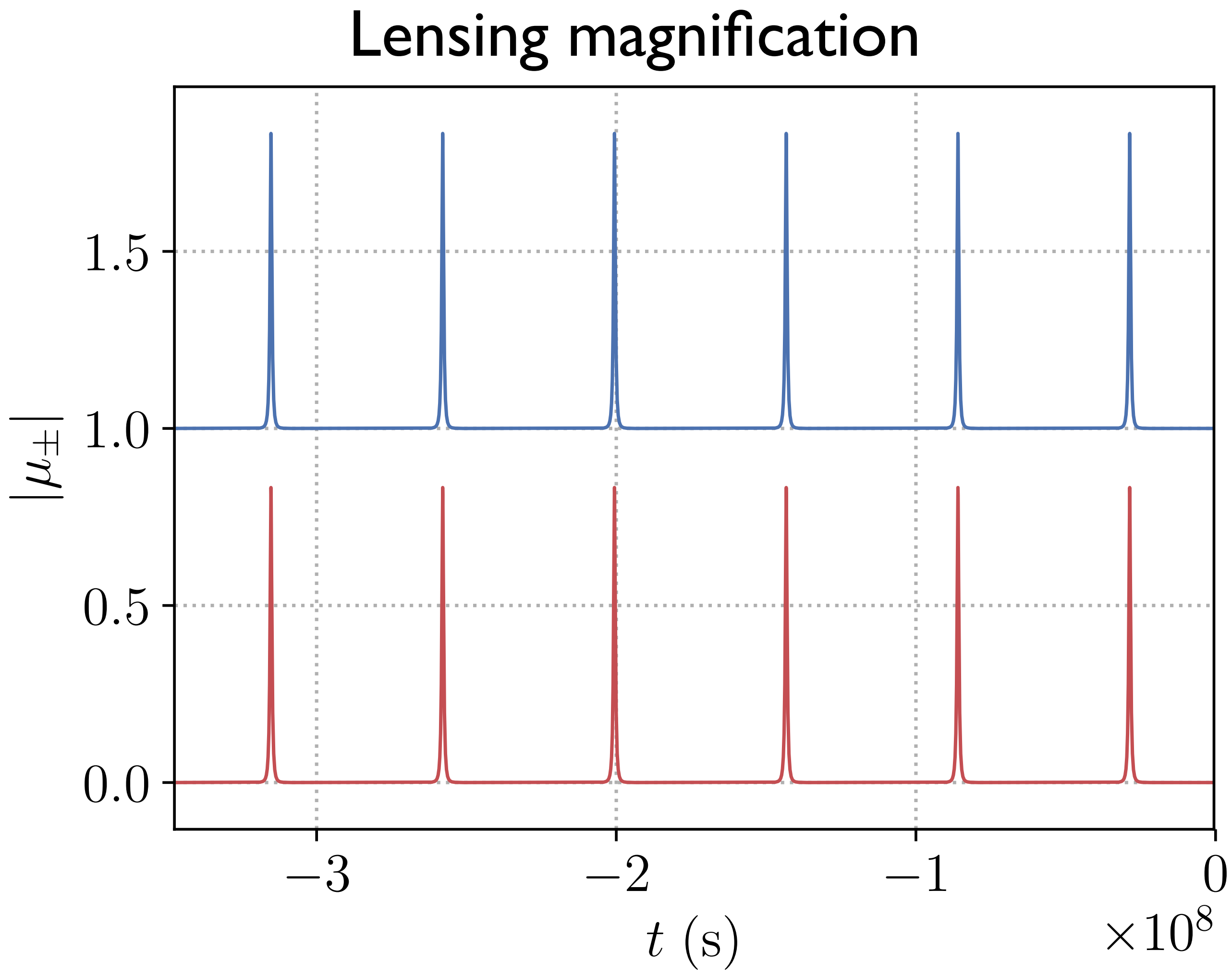
Lensing setting

$$y = \frac{b}{r_E}$$

$$\mu_\pm = \frac{1}{2} \pm \frac{(y^2+2)}{(2y\sqrt{y^2+4})}$$

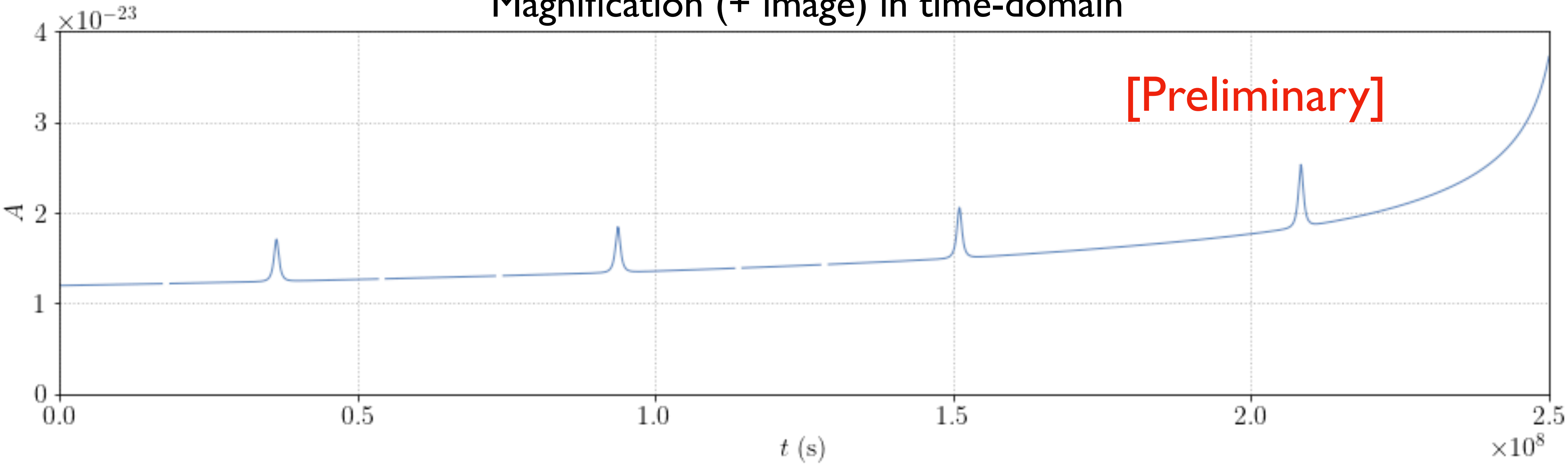


- Lensing limited to edge-on systems
- Two images: primary and secondary, delayed
- Magnification of both images when behind the lens
- **Contribution of lensing to the delay** (geometrical delay), not captured by Shapiro delay
- Here geometric optics; wave optic effects relevant



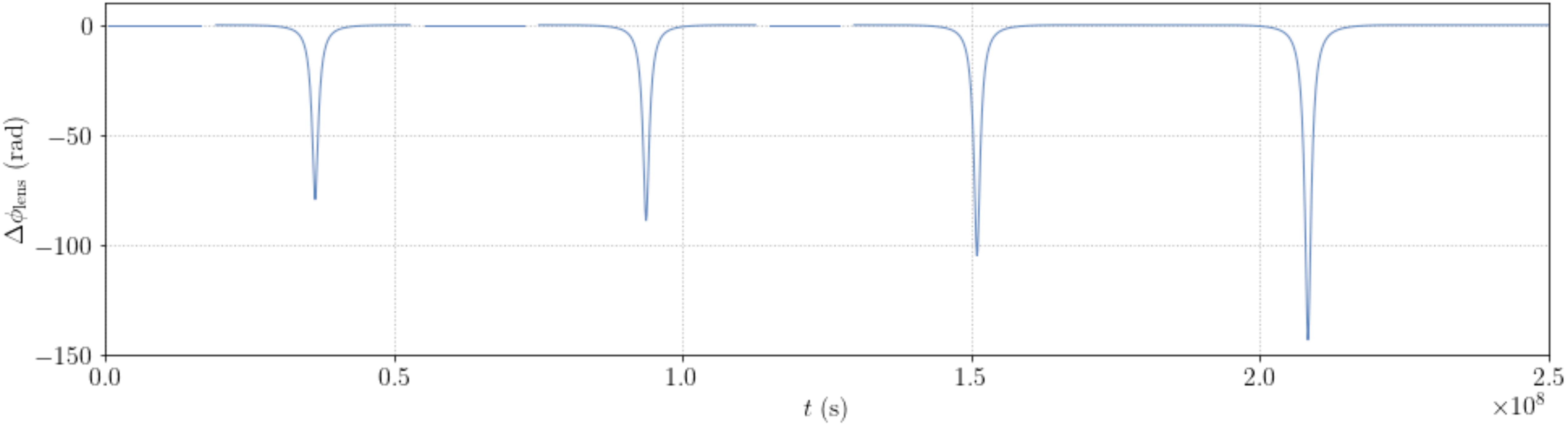
Lensing effects for the primary image

Magnification (+ image) in time-domain

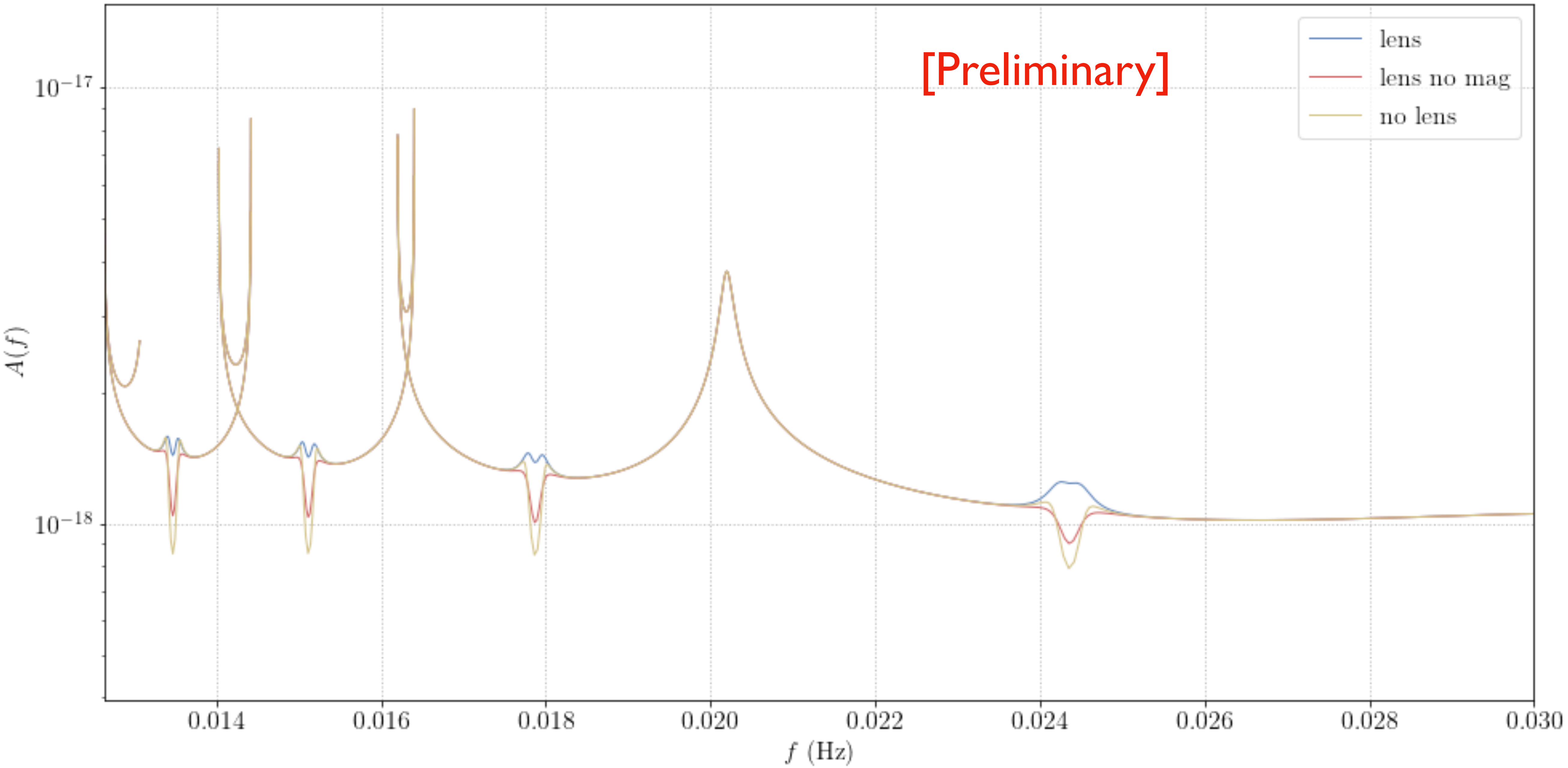


[Preliminary]

Lensing-specific (+ image) dephasing in time-domain



Lensing effects in the Fourier domain

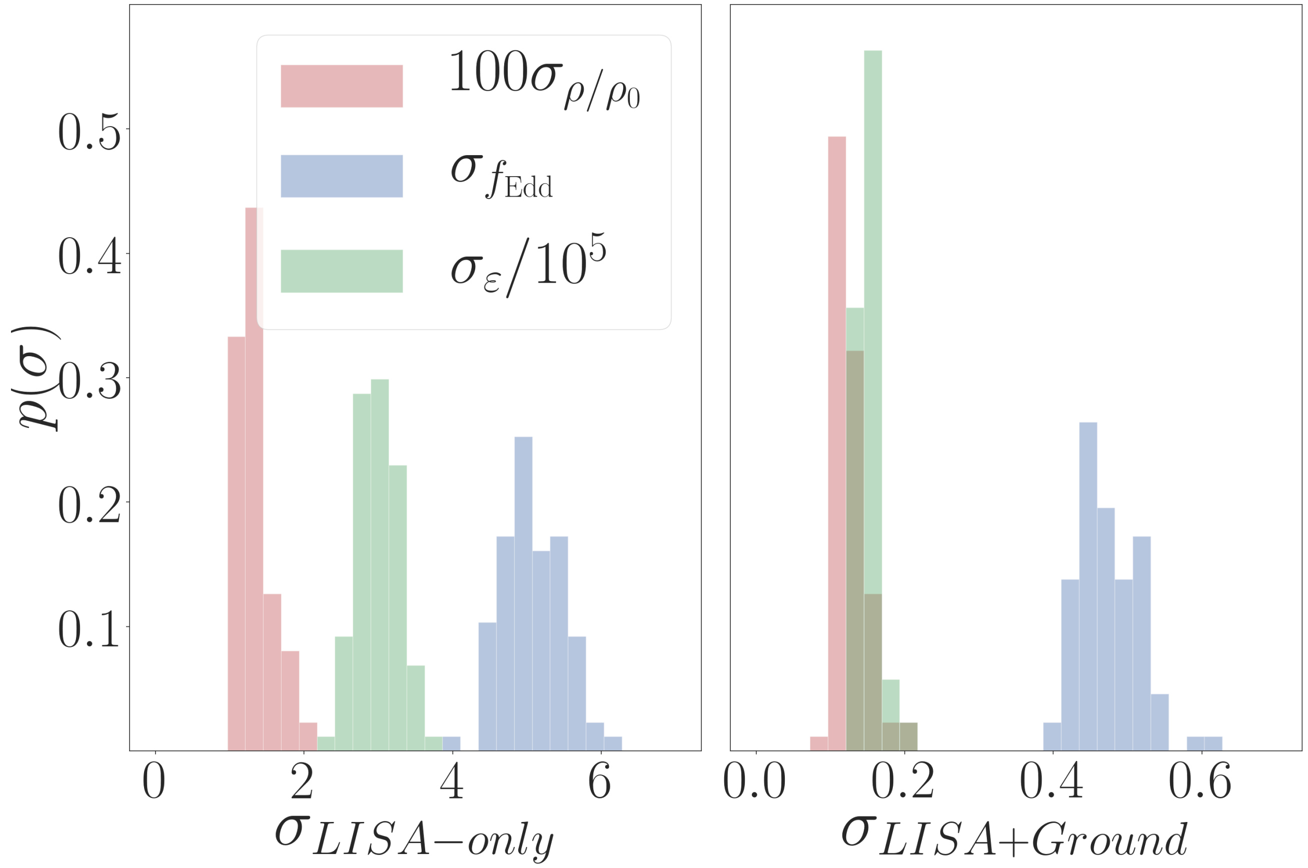


Overlap lens/no lens 30%
Lensing delay a priori detectable

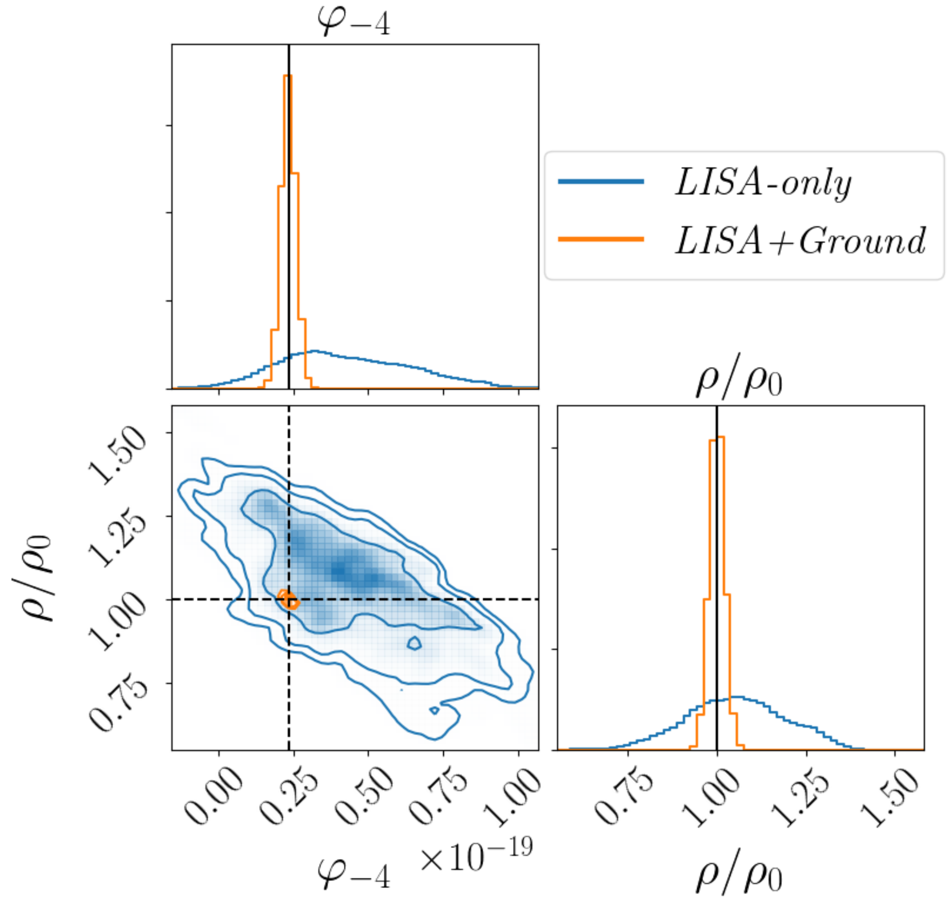
Summary & outlook

- Investigated proposed SBHB systems in orbit in an AGN disks
- LISA rates for GW190521-like systems: observable but challenging
- Observations at low frequencies with LISA crucial to see the imprint of the environment
- Strong modulations of the GW signal due to the orbit: Doppler delay, Shapiro delay
- Built a compact and efficient waveform model with these effects
- The Shapiro delay breaks degeneracies and allows to determine all AGN parameters to few-percent precision
- Recovered the isolated system limit and investigated parameter biases
- (Exploratory) lensing contributions to the delays
- Much more to explore ! Parameter space, archival analysis SNR<8, other relativistic effects…

Matter effects



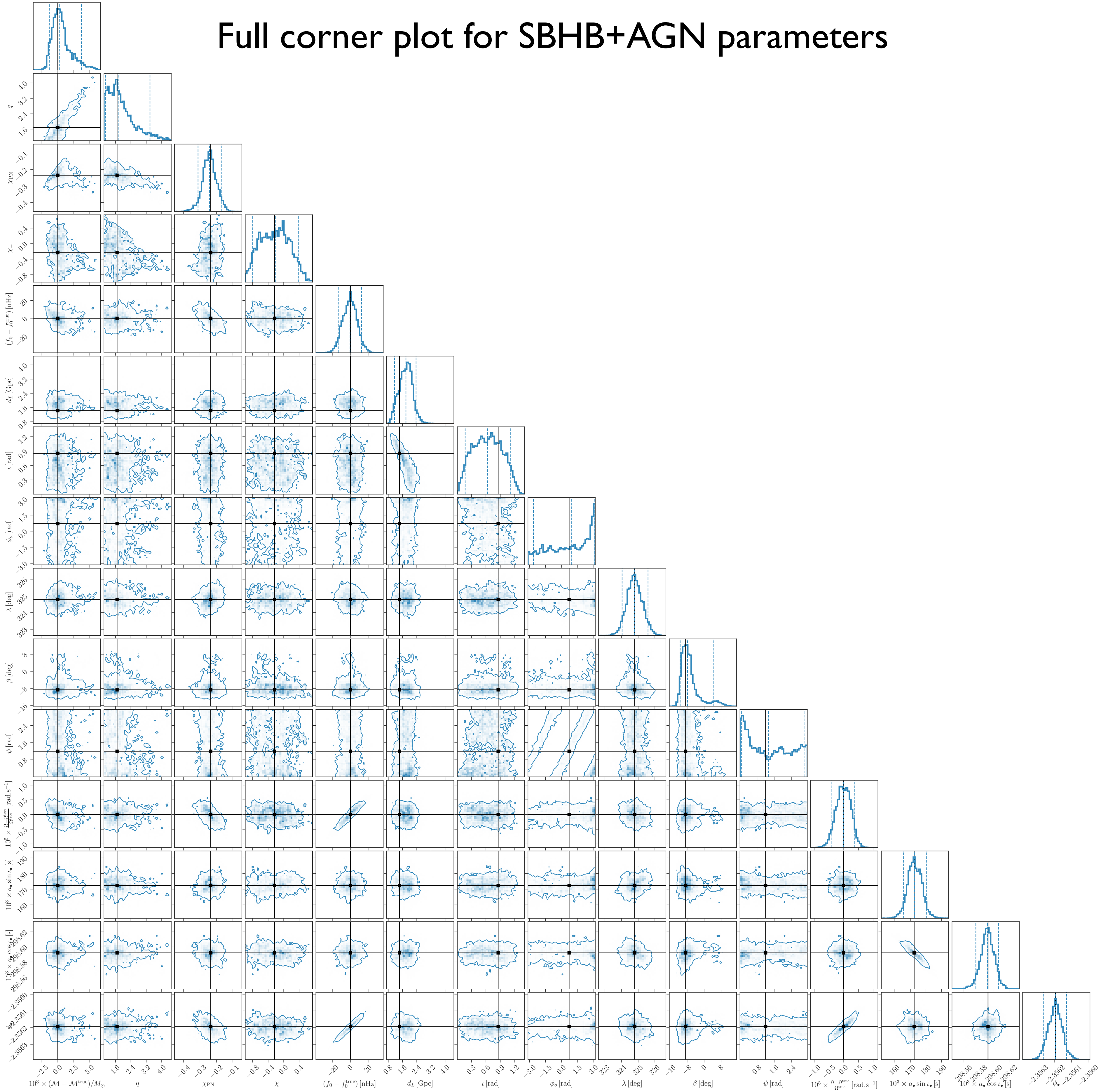
- Constrains with 0 injection
- Gas density, Eddington fraction, acceleration parameter



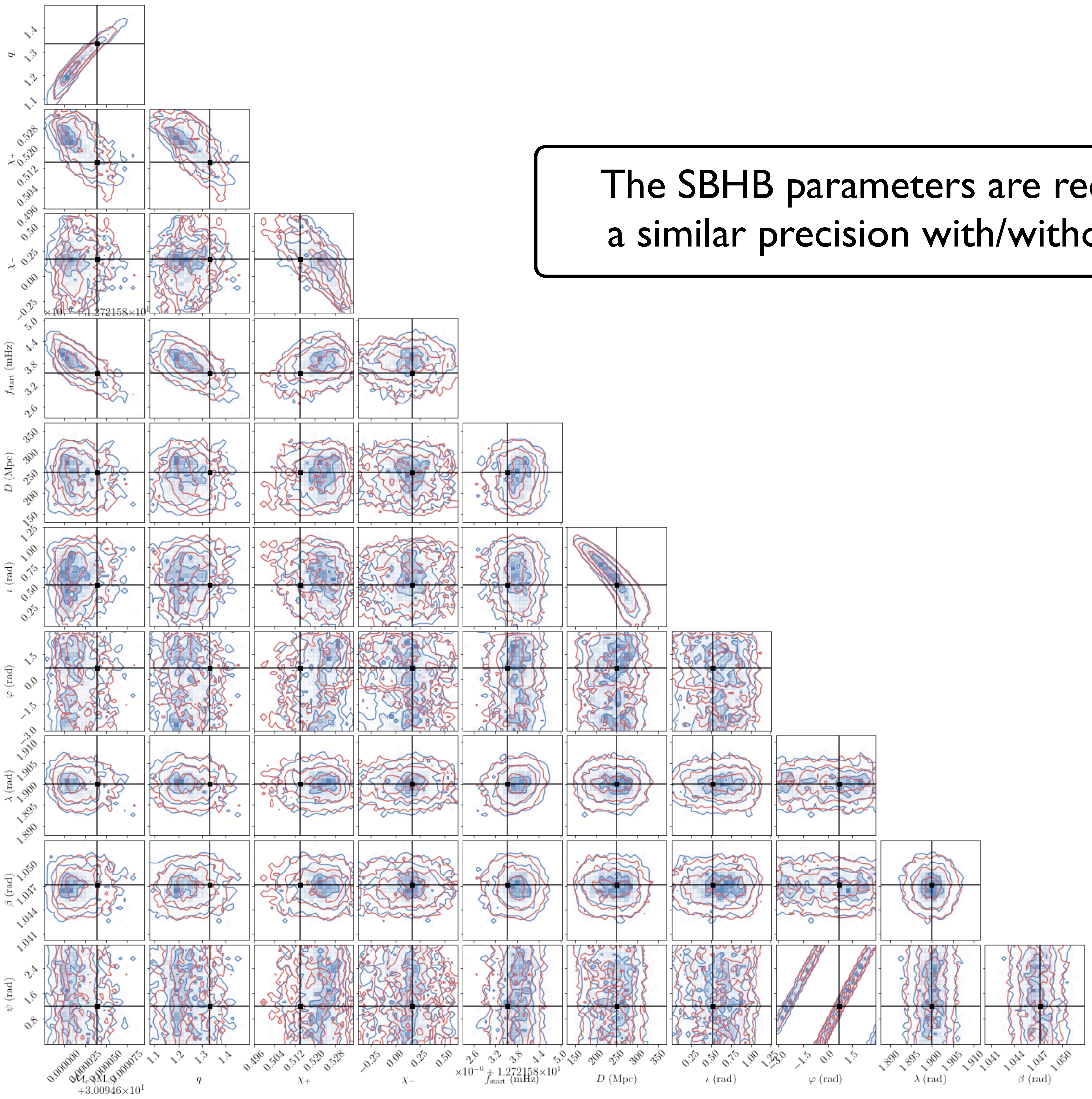
- Injection with all effects and non-0 value
- Acceleration/accretion -4PN, dynamical friction -5.5PN
- Recovery of -4PN phase parameter and gas density

[Toubiana&al 2020]

Full corner plot for SBHB+AGN parameters

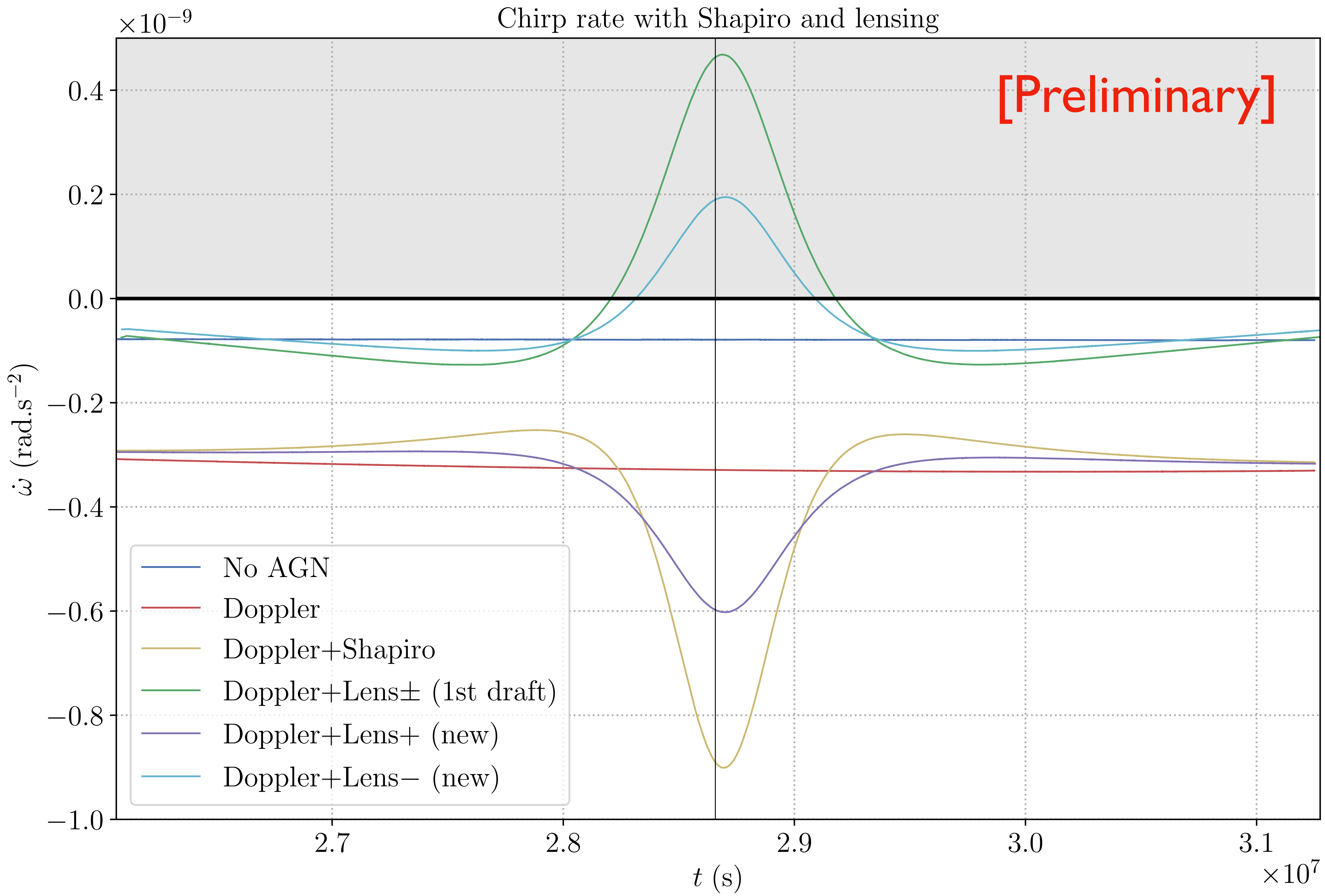


Parameter estimation with and without the AGN



The SBHB parameters are recovered with a similar precision with/without the AGN

Lensing passage and chirp rate



Secondary image signal breaks the SPA…