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Rencontre du groupe analyse de données

Observations of stellar-mass black holes with LISA

Stellar-mass black hole binaries (SBHBs)

- Individual masses up to $\mathcal{O}(10^2)M_\odot$
- Seen by LIGO/VIRGO
- Could be seen by LISA during their early inspiral
- Different types of behaviour while in LISA band:
  - Some will be slowly evolving in frequency (but not monochromatic)
  - Some will start chirping at the higher end of LISA band

Scientific interest

- Probe low frequency modifications to GW:
  - Deviations from GR (time varying G, dipolar radiation...)
  - Environmental effects (peculiar acceleration, accretion into BHs...)

- Electromagnetic follow-up

- Discriminate between astrophysical formation models:
  - Eccentricity

Plan

I) Characterisation of parameter estimation for SBHBs with LISA

II) Constraints on modified gravity

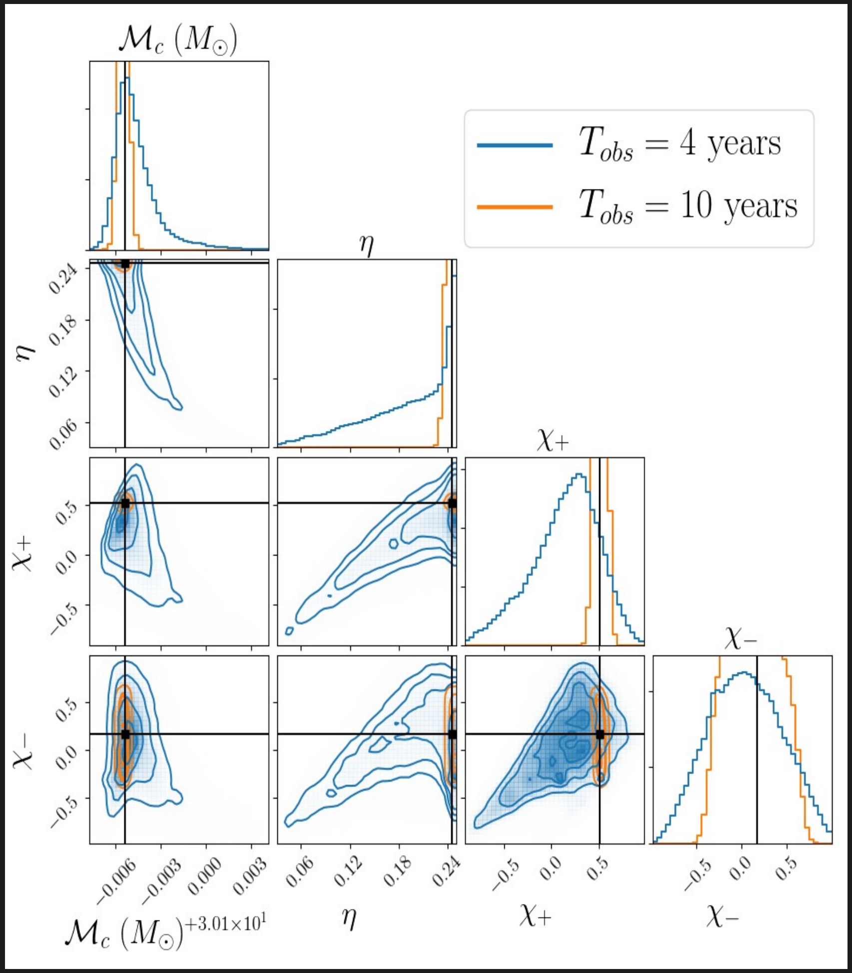
III) Probes of the astrophysical environment

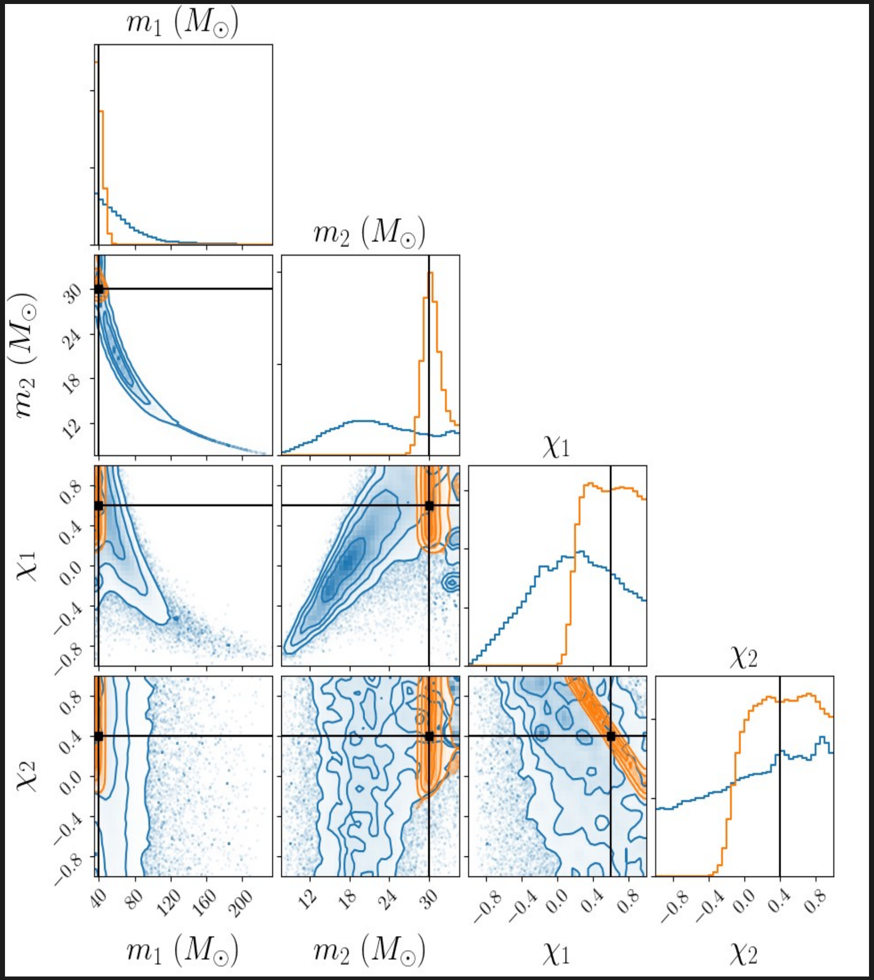
Exploration of parameter space

- Quasi-circular binaries, spinning but not precessing
- Start from fiducial system similar to GW150914
- Change few parameters at a time and assess the impact on PE
- Use PhenomD for the waveform, generate mock LISA data and perform full Bayesian analysis

m_1 ($M_\odot$)	40	
m_2 ($M_\odot$)	30	
$m_{1,s}$ ($M_\odot$)	36.2	
$m_{2,s}$ ($M_\odot$)	27.2	
t_c (yrs)	8	
f_0 (mHz)	12.7215835397	
χ_1	0.6	
χ_2	0.4	
λ (rad)	1.9	
β (rad)	$\pi/3$	
ψ (rad)	1.2	
φ (rad)	0.7	
ι (rad)	$\pi/6$	
D_L (Mpc)	250	
z	0.054	
T_{obs} (yrs)	4	10
SNR	13.5	21.5

Parameter estimation (intrinsic parameters)





$$\mathcal{M}_c = \left(\frac{m_1^3 m_2^3}{m_1+m_2}\right)^{1/5} \qquad \eta = \frac{m_1 m_2}{(m_1+m_2)^2} \qquad \chi_{+,-} = \frac{m_1\chi_1 \pm m_2\chi_2}{m_1+m_2}$$

Discussion of the correlations

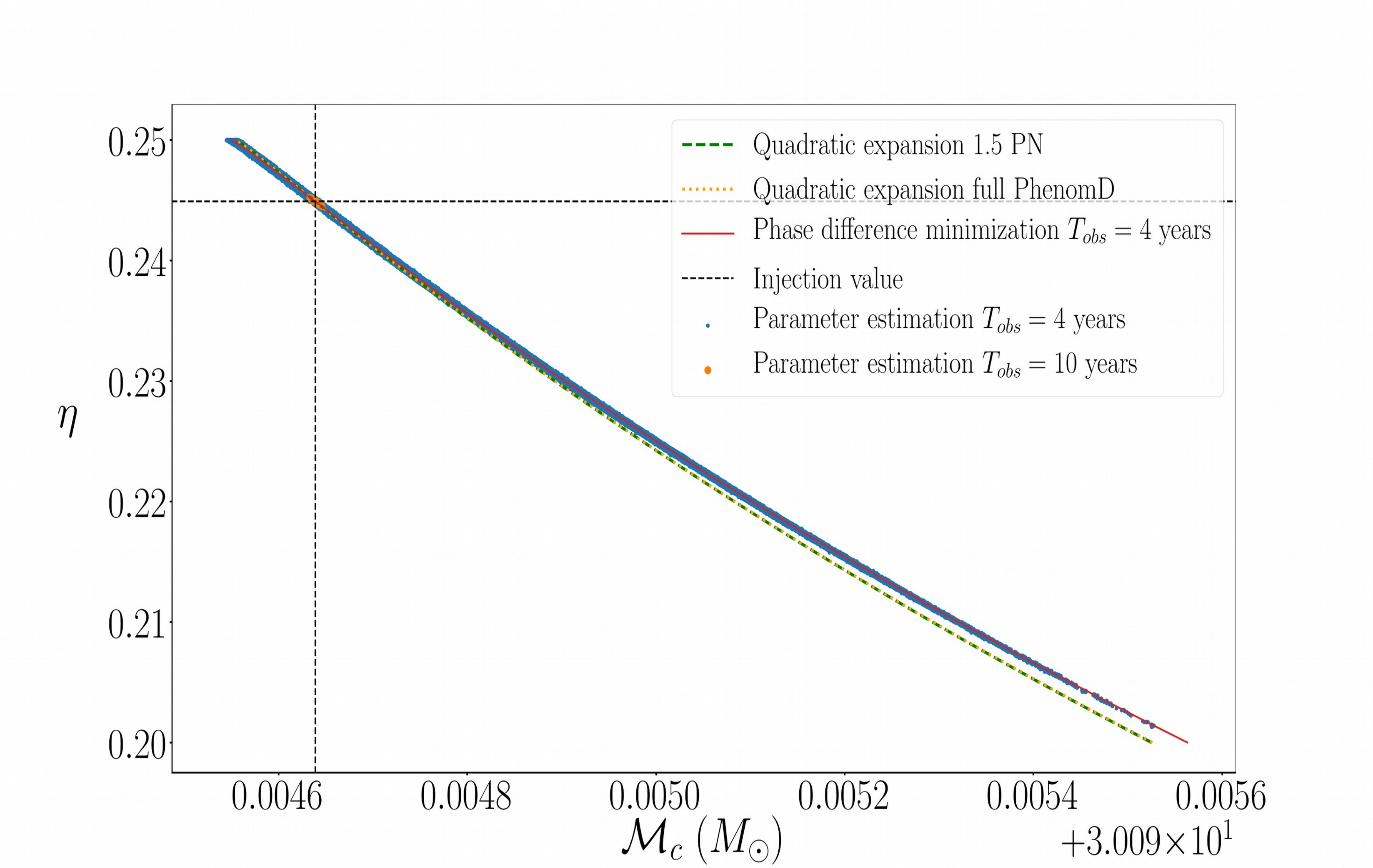
- $\mathrm{f}_0 = 12.7\ \mathrm{mHz} \quad \mathrm{f}_{4years} = 16.5\ \mathrm{mHz}$
- Toy model: fix all parameters but masses
- Taylor expand the phase:

$$\Psi(f) \simeq \Psi(f_0) + \underbrace{\frac{\mathrm{d}\Psi}{\mathrm{d}f}|_{f_0}}_{=0}(f - f_0) + \frac{1}{2}\frac{\mathrm{d}^2\Psi}{\mathrm{d}f^2}|_{f_0}(f - f_0)^2$$

- Set:

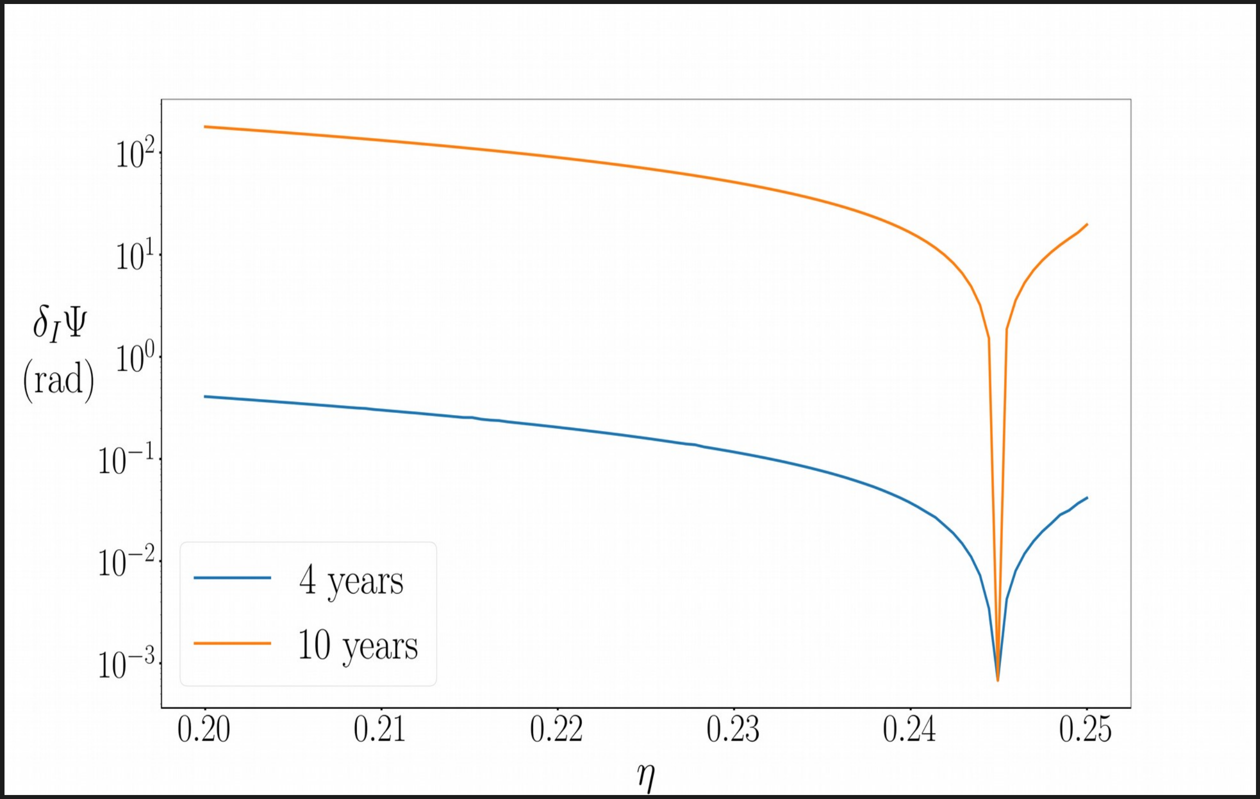
$$\frac{\mathrm{d}^2\Psi(\mathcal{M}_c, \eta)}{\mathrm{d}f^2}\ |_{f_0} = \frac{\mathrm{d}^2\Psi(\mathcal{M}_{c,inj}, \eta_{inj})}{\mathrm{d}f^2}\ |_{f_0}$$

Discussion of the correlations



Discussion of the correlations

- Define $\delta\Psi = \max_I |\Psi_d(f) - \Psi_h(f)|$
- I is the frequency range within LISA band spanned over $T_{\rm obs}$
- For each value of η find $\mathcal{M}_c$ that minimises $\delta\Psi$

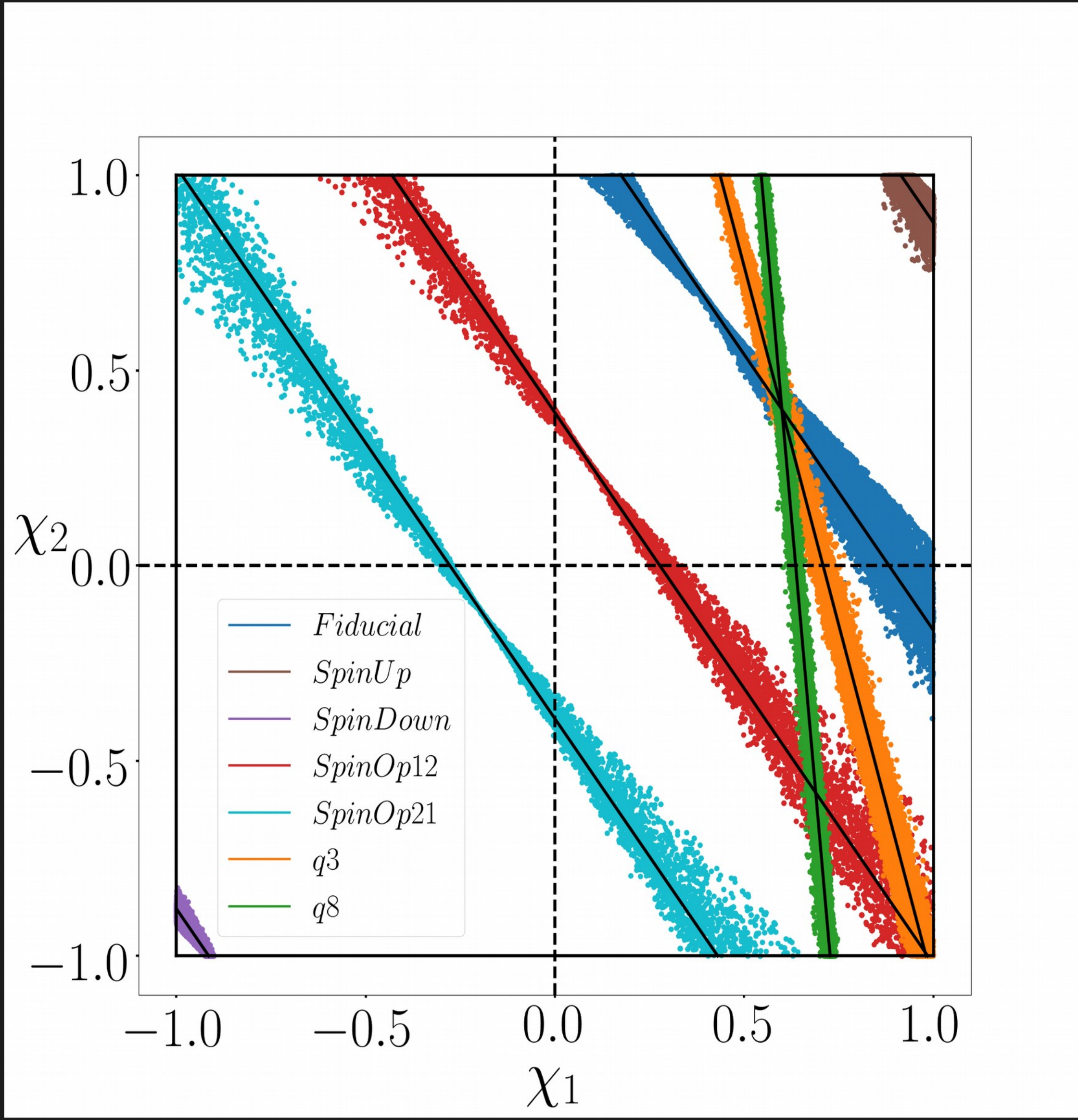


Extent of the correlations

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

- Define $\chi_{PN} = \frac{1}{113}(94\chi_s + 19\frac{q-1}{q+1}\chi_a)$
- The 1.5PN coefficient reads $(-16\pi + \dfrac{113}{3}\chi_{PN})\eta^{-3/5}$
- Best measured spin combination

Extent of the correlations



$T_{\mathrm{obs}} = 10$ years

Extent of the correlations

- When observing at low frequencies, terms above 1.5PN are note relevant

- Shifts in χ_{PN} can be compensated by changes in η

  such that $(-16\pi + \frac{113}{3}\chi_{PN})\eta^{-3/5}$ is kept constant

- **Parameter estimation depends crucially on the chirp of the system!**

Measurement of parameters

- $\mathcal{M}_c$ measured within $10^{-2}\%$
- For chirping systems:
  - individual masses measured within 20%
  - χ_{PN} measured within 0.01, χ_+ within 0.1
- Error on t_c improves from 1 day to 30 s for chirping systems

- Sky location typically measured within $0.4\ \mathrm{deg}^2$
- Distance within $40 - 60\%$ $\longrightarrow$ $\mathcal{M}_{c,s}$ within 1%

Toubiana, Marsat, Babak, Baker and Dal Canton
arXiv:2007.08544

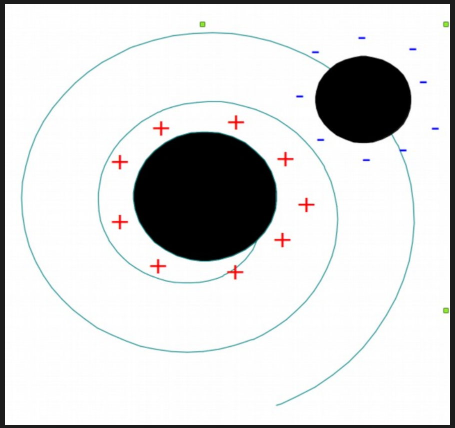
Modifications to GR

- GW computations are lengthy and difficult
- Few full computations and simulations in modified gravity theories
- Phenomenological approach (parameterised post Einsteinian framework):

$$h = h_{GR} e^{i\beta u^b} \qquad u = \pi \mathcal{M}_c f$$

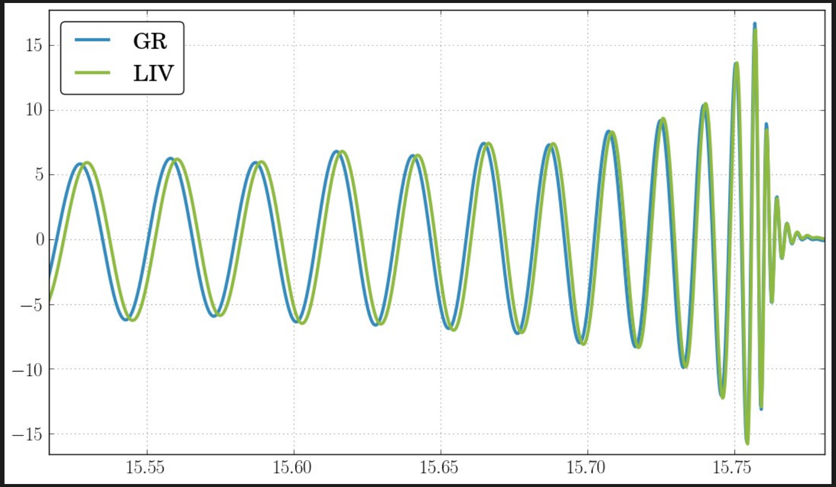
Modifications to GR

- Dipolar radiation: $\dot{E} = \dot{E}_{GR}(1 + B_{\rm BH} v^{-2})$



$\beta \propto B_{\rm BH}$
$b = -7/3$

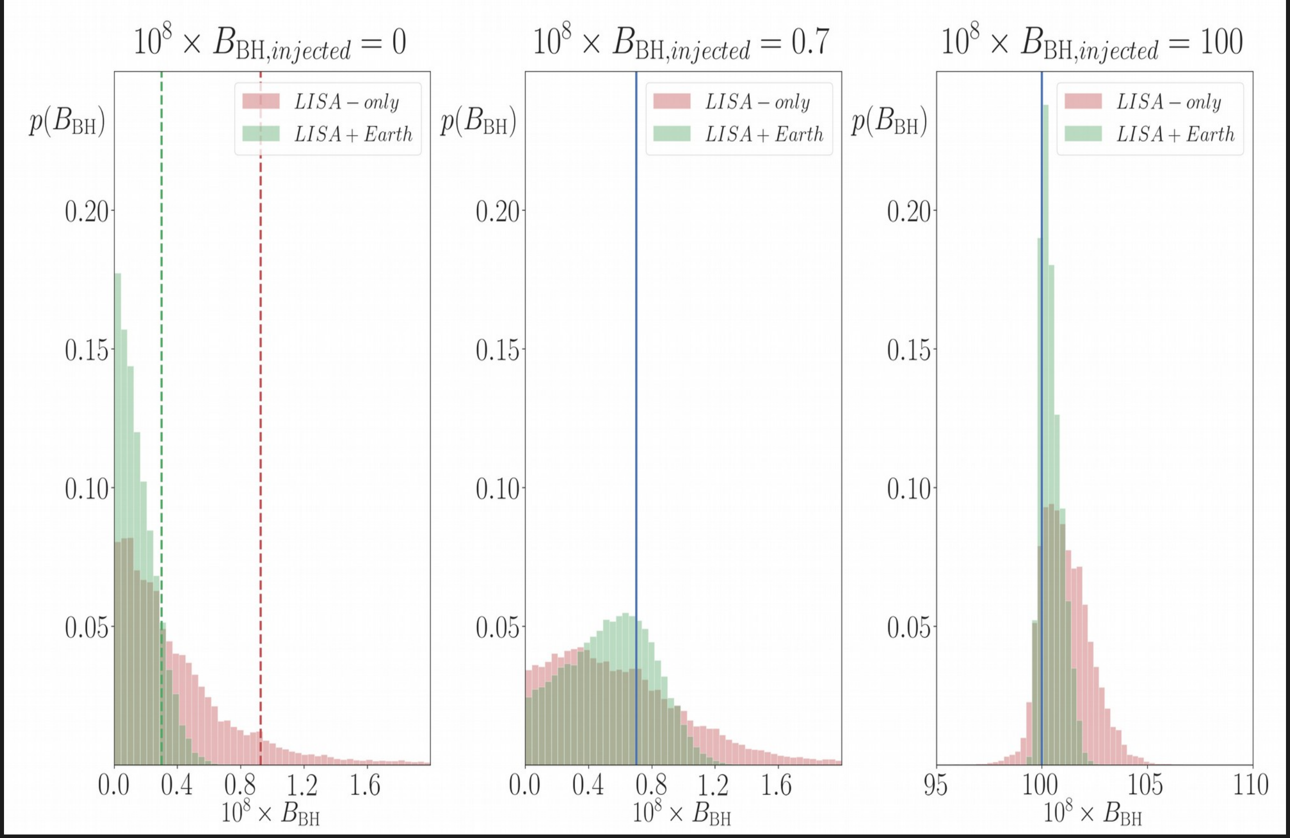
- Modified dispersion relation: $E_g^2 = p^2c^2 + m_g^2 c^4$



$\beta \propto \mathcal{M}_c D_L m_g^2$
$b = -1$

Constraints on modifications

	B_{BH}	
	LISA-only	*LISA+Earth*
System 1(t_c = 8.3 years)	$< 1.1\ 10^{-7}$	$< 1.1\ 10^{-7}$
System 1(t_c = 4.0 years)	$< 9.2\ 10^{-9}$	$< 3.2\ 10^{-9}$
System 1(t_c = 2.5 years)	$< 6.8\ 10^{-8}$	$< 7.2\ 10^{-9}$
System 2	$< 1.5\ 10^{-8}$	$< 4.6\ 10^{-9}$
System 3	$< 1.9\ 10^{-7}$	$< 2.5\ 10^{-8}$
Current constraints	$< 4 \times 10^{-2}$	



	m_g (eV)	
	LISA-only	*LISA+Earth*
System 1(t_c = 8.3 years)	$< 9.3\ 10^{-23}$	$< 2.5\ 10^{-23}$
System 1(t_c = 4.0 years)	$< 2.0\ 10^{-23}$	$< 1.5\ 10^{-23}$
System 1(t_c = 2.5 years)	$< 3.1\ 10^{-23}$	$< 2.5\ 10^{-23}$
System 2	$< 1.2\ 10^{-23}$	$< 1.2\ 10^{-23}$
System 3	$< 3.5\ 10^{-23}$	$< 2.0\ 10^{-23}$
Current constraints	$< 1.8 \times 10^{-24}$	

$LISA+Earth$ restrict t_c, "fake multiband"

Toubiana, Marsat, Babak, Baker and Barausse
arXiv:2004.03626

Probing the astrophysical environment

Perturbative effects

$$h = h_{\text{vacuum}} e^{i\beta u^b}$$

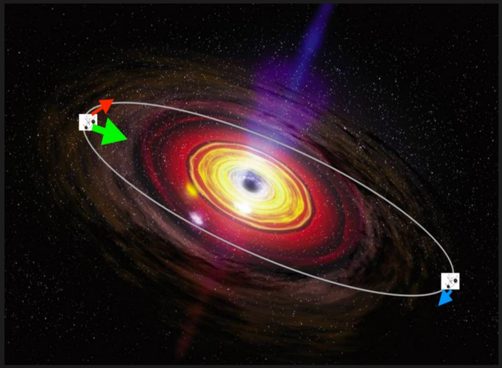
$$u = \pi \mathcal{M}_c f$$

Constant acceleration

$$\epsilon = 4.3 \times 10^5 \frac{M_{\text{MBH}}}{10^8 M_\odot} \left(\frac{1\ \text{pc}}{a}\right)^2$$

$$\beta \propto \epsilon$$

$$b = -13/3$$



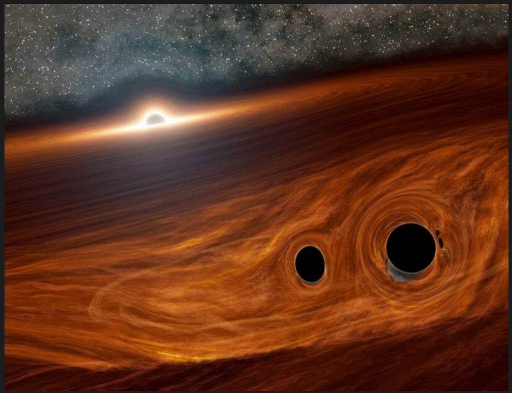
Credits: Stanislav Babak

Accretion onto the binary components

$$\dot{m}_i = f_{\text{Edd}} \dot{m}_{\text{Edd}}$$

$$\beta \propto f_{\text{Edd}}$$

$$b = -13/3$$



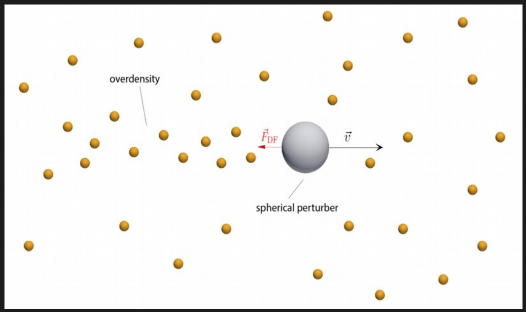
Credits: Franziska Schmidt

Dynamical friction

$$\rho_0 = 10^{-10} \text{g.cm}^{-3}$$

$$\beta \propto \rho$$

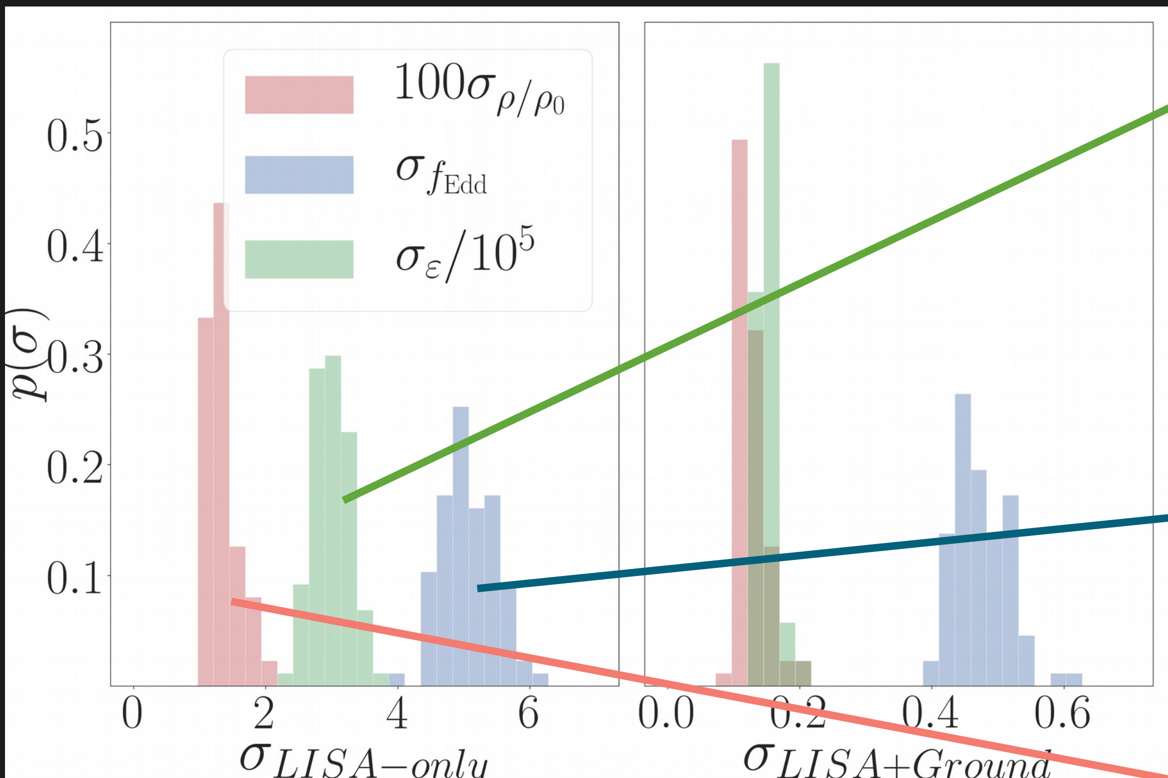
$$b = -16/3$$

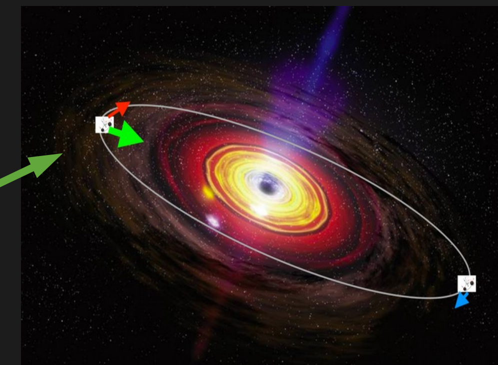


Credits: Caltech/R. Hurt (IPAC)

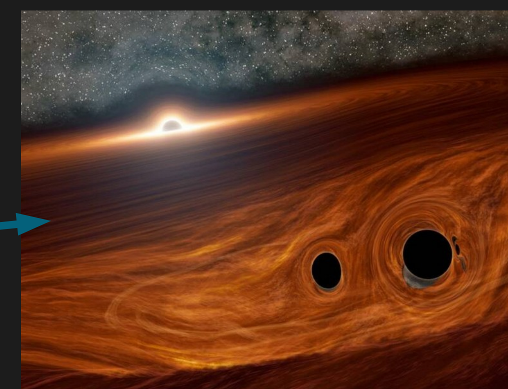
Probing the astrophysical environment of GW190521

Toubiana et al.
arXiv:2010.06056

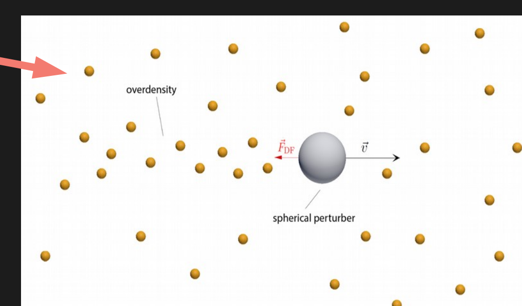




Credits: Stanislav Babak



Credits: Franziska Schmidt

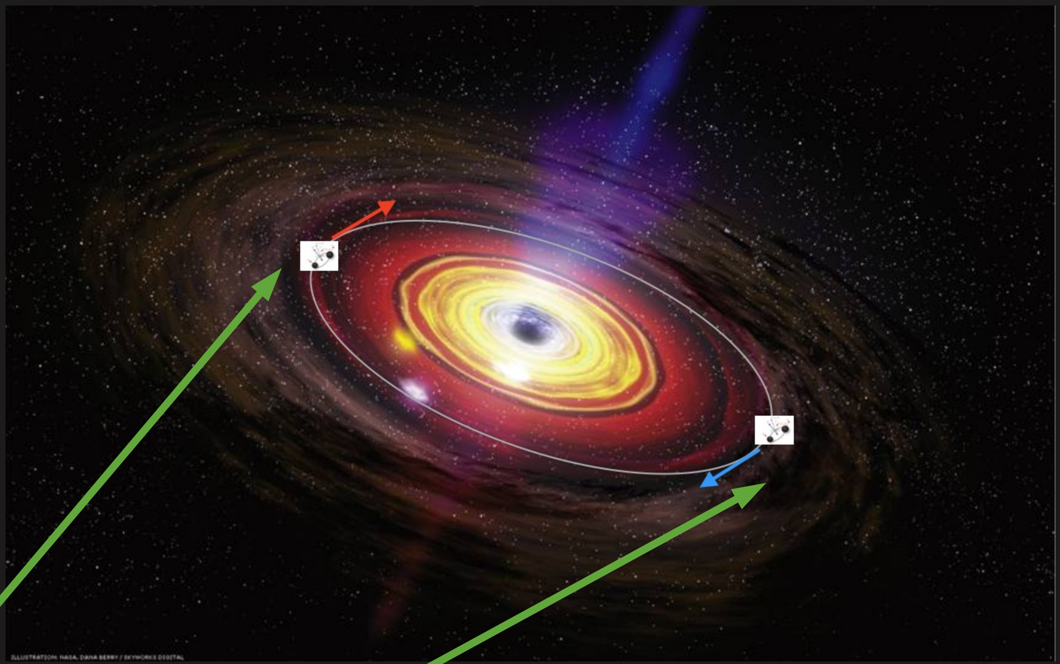


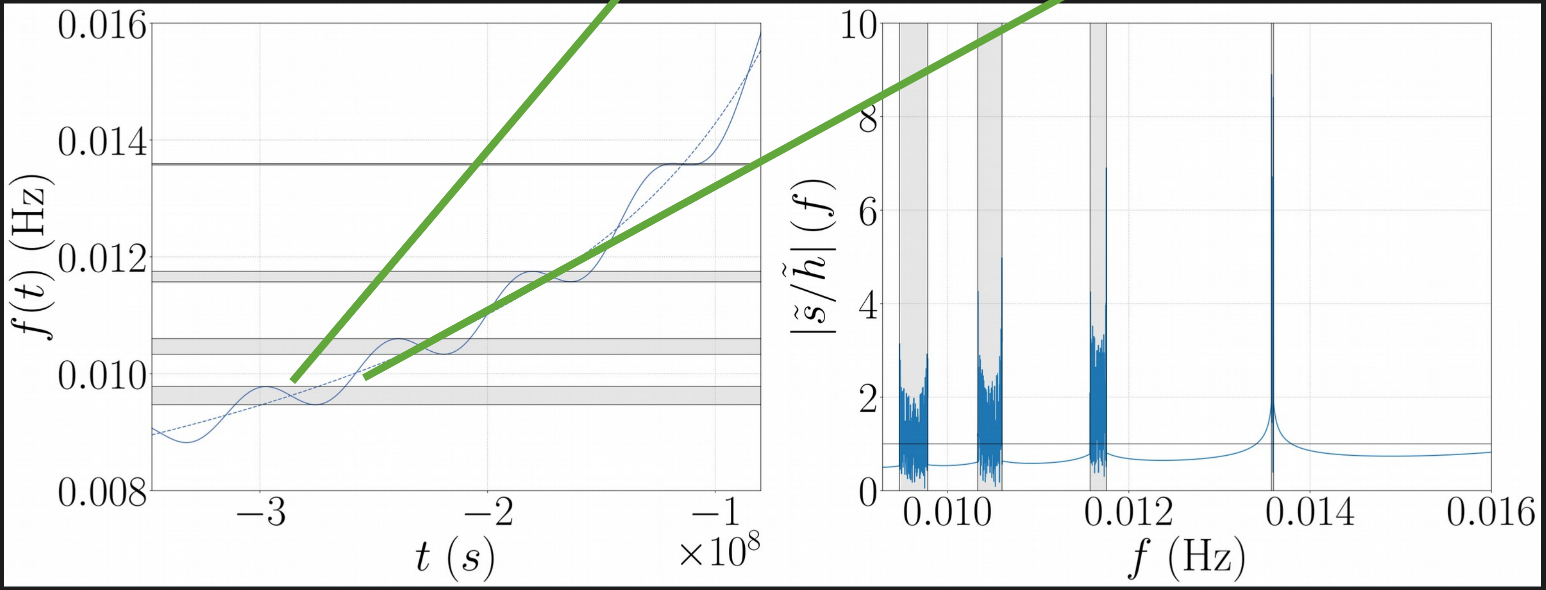
Credits: Caltech/R. Hurt (IPAC)

- Accretion for $f_{\rm Edd} \gtrsim 5$
- Gas density for $\rho \gtrsim 10^{-12}\mathrm{g.cm}^{-3}$
- Acceleration for $a \lesssim 0.4$ pc $M_{\rm MBH} = 10^8\ M_\odot$

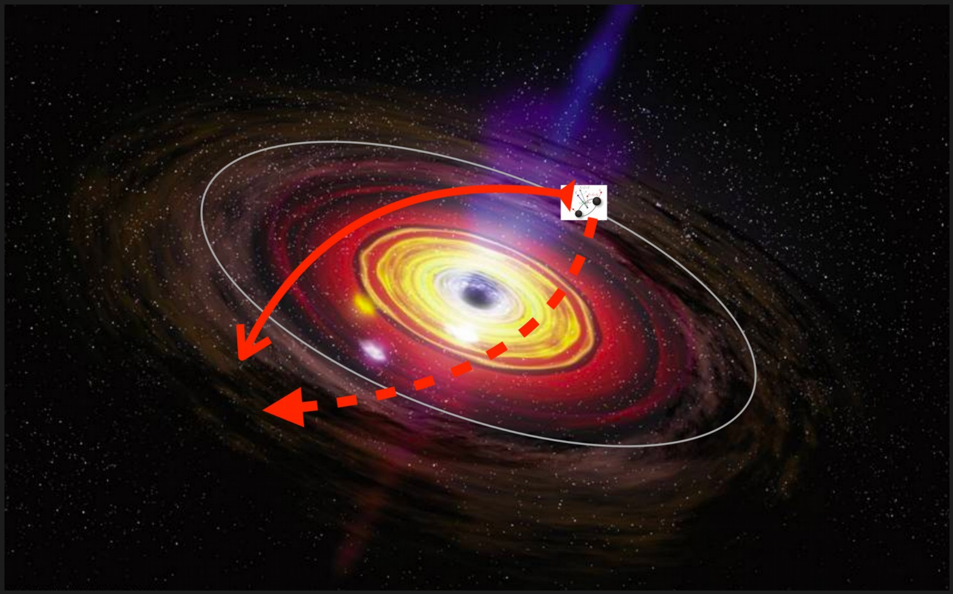
Non perturbative effects for GW190521

- Doppler shift in frequency due to orbital motion $a \lesssim 0.2\ \mathrm{pc}$
- Strong modulation: chirping/anti-chirping
- Non-trivial modification of GW signal

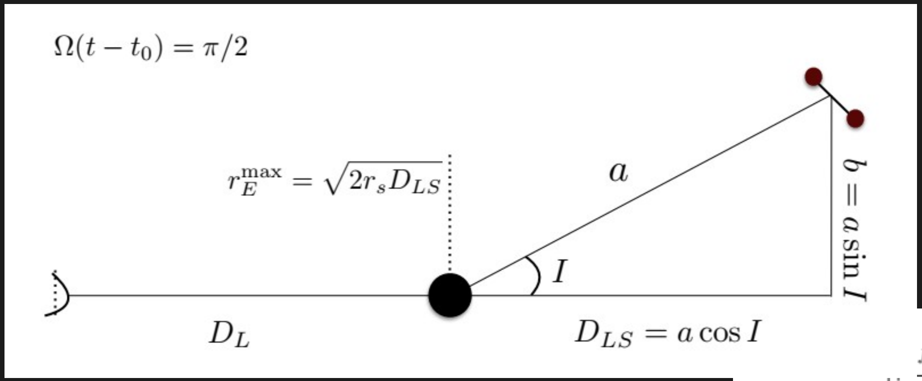


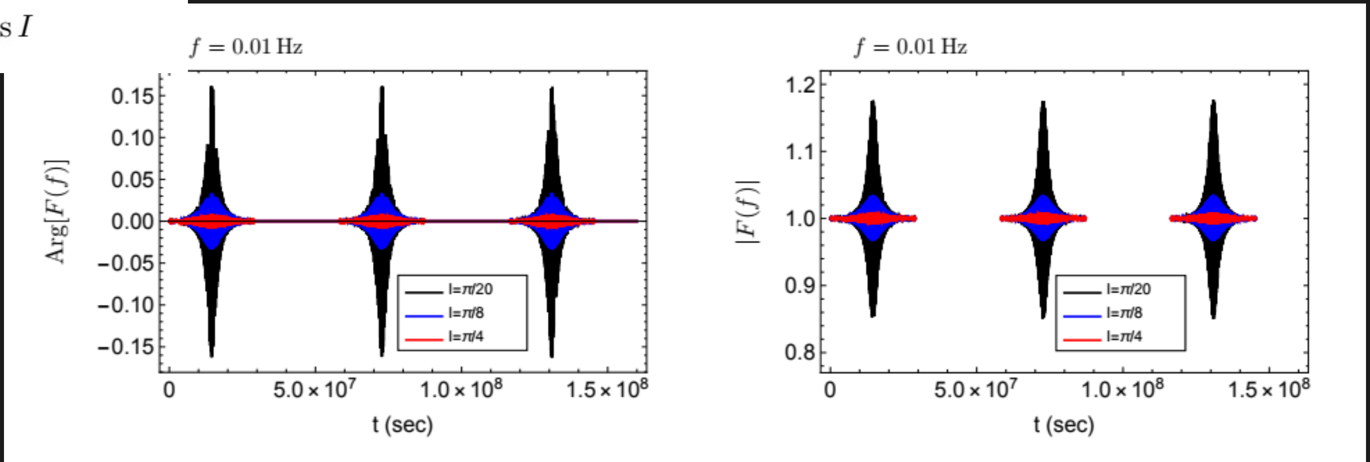


Non perturbative effects for GW190521



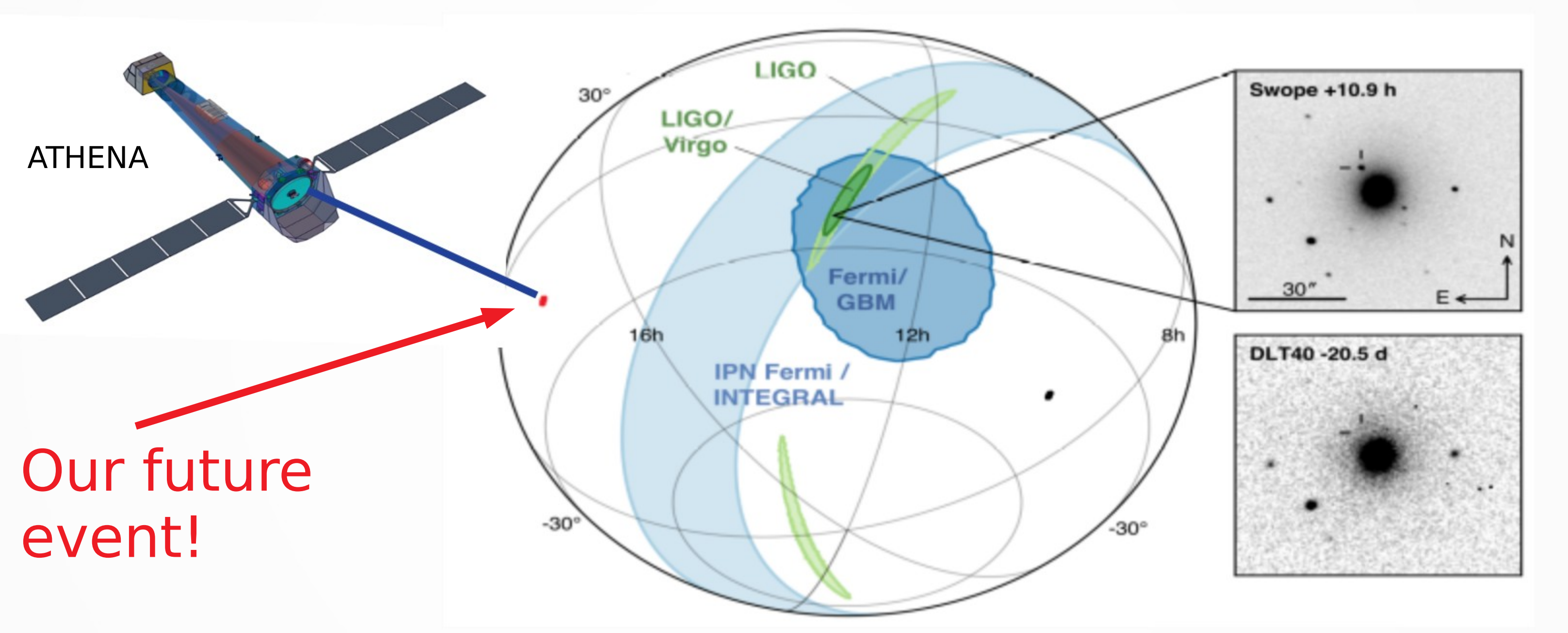
- Lense for SMBH:
  - Periodic
  - two images, time shifted, different magnification
  - strongly depends on the geometry





Electromagnetic counterparts

Caputo et al. arXiv:2001.03620



Sky localisation of GW171917 by the LIGO/VIRGO collaboration

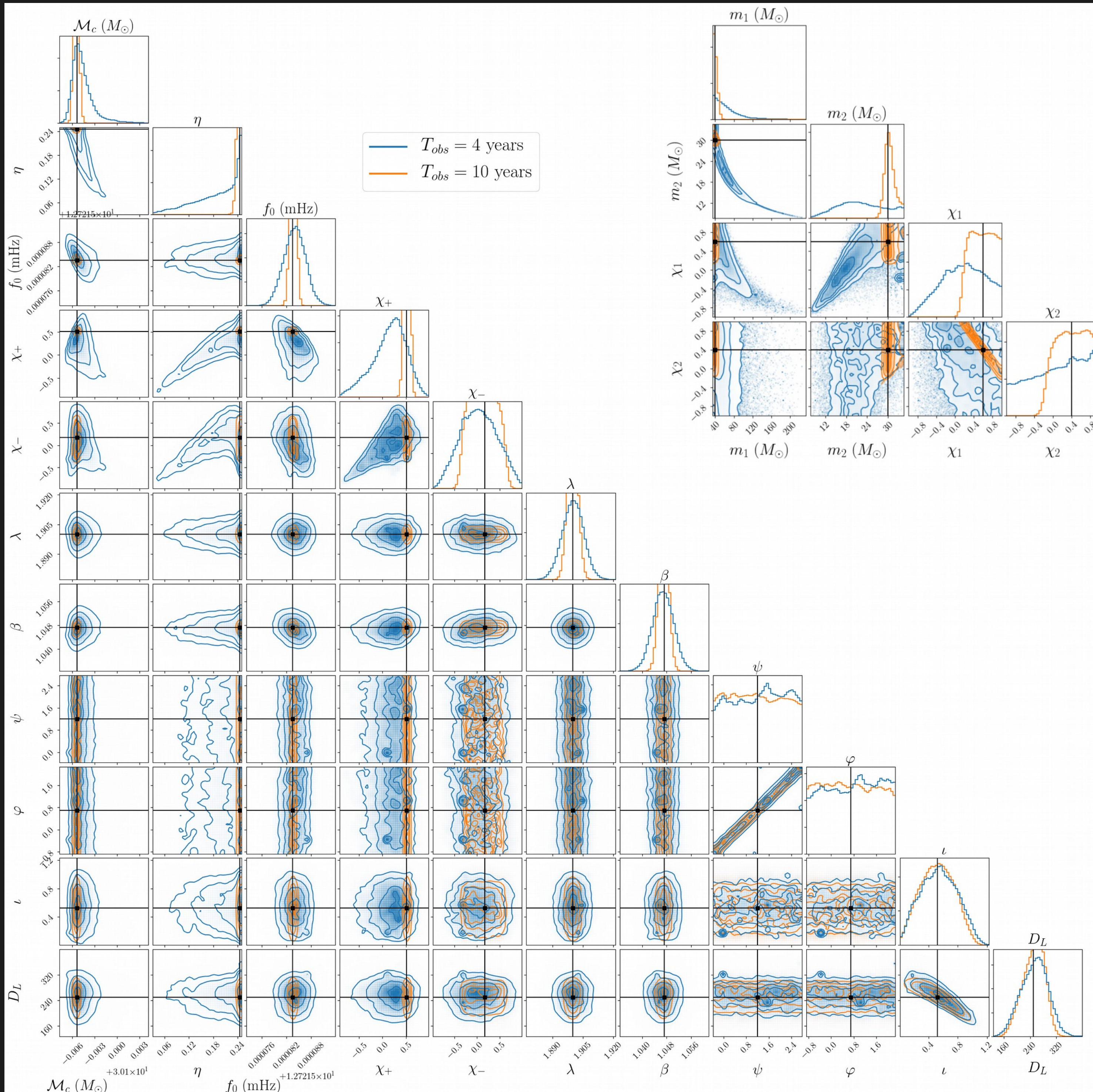
$$T_{\rm obs} \simeq 8 \times 10^{-2} \left(\frac{1}{f_{\rm Edd}}\right)^2 \left(\frac{M_\odot}{M_{\rm tot}}\right)^2 \left(\frac{D_L}{Mpc}\right)^4 \text{hours}$$

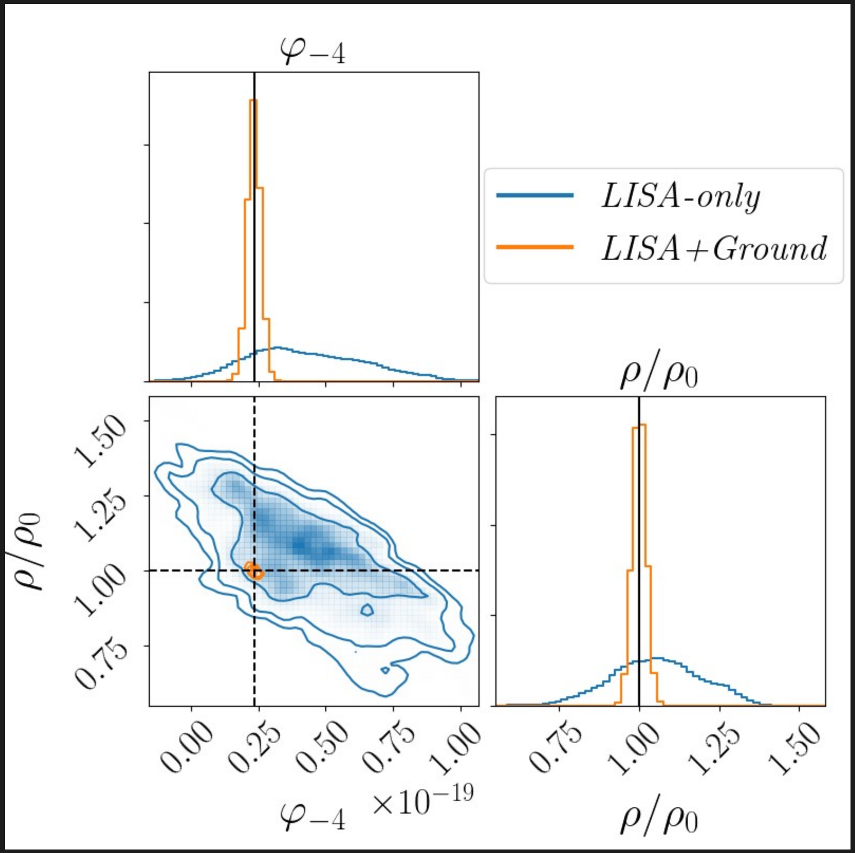
$\mathcal{O}(1\text{h} - 1 \text{ day})$ for $M_{\rm tot} = \mathcal{O}(10^2 - 10^3) M_\odot$ $f_{\rm Edd} = 1$

Conclusions

- Observation of SBHBs with LISA would allow for a lot of interesting science (population study, tests of GR, probe astrophysical environment, early warnings for EM telescope and ground based detectors…)
- PE for SBHBs depends crucially on the chirp, but always very precise measurement of chirp mass and sky location
- Crucial to disentangle between modifications to GR and environmental effects
- First step towards multiband study
- Need to figure out the detectability

Thank you for your attention!


$T_{obs} = 4$ years
$T_{obs} = 10$ years
$\mathcal{M}_c\ (M_\odot)$
η
f_0 (mHz)
χ_+
χ_-
λ
β
ψ
φ
ι
D_L
$m_1\ (M_\odot)$
$m_2\ (M_\odot)$
χ_1
χ_2
$+3.01\times10^1$
$+1.27215\times10^1$



$$f_{\rm Edd} = 5$$

$$\rho = \rho_0$$

$$a = 0.4 \text{ pc}$$

$$M_{\rm MBH} = 10^8 \ M_\odot$$

$$\varphi_{-4} = \varphi_{\rm accretion} + \varphi_{\rm acceleration}$$