



UNIVERSITÀ
DEGLI STUDI
DI TRIESTE



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Towards a Multimessenger View of Tidal Disruption Events

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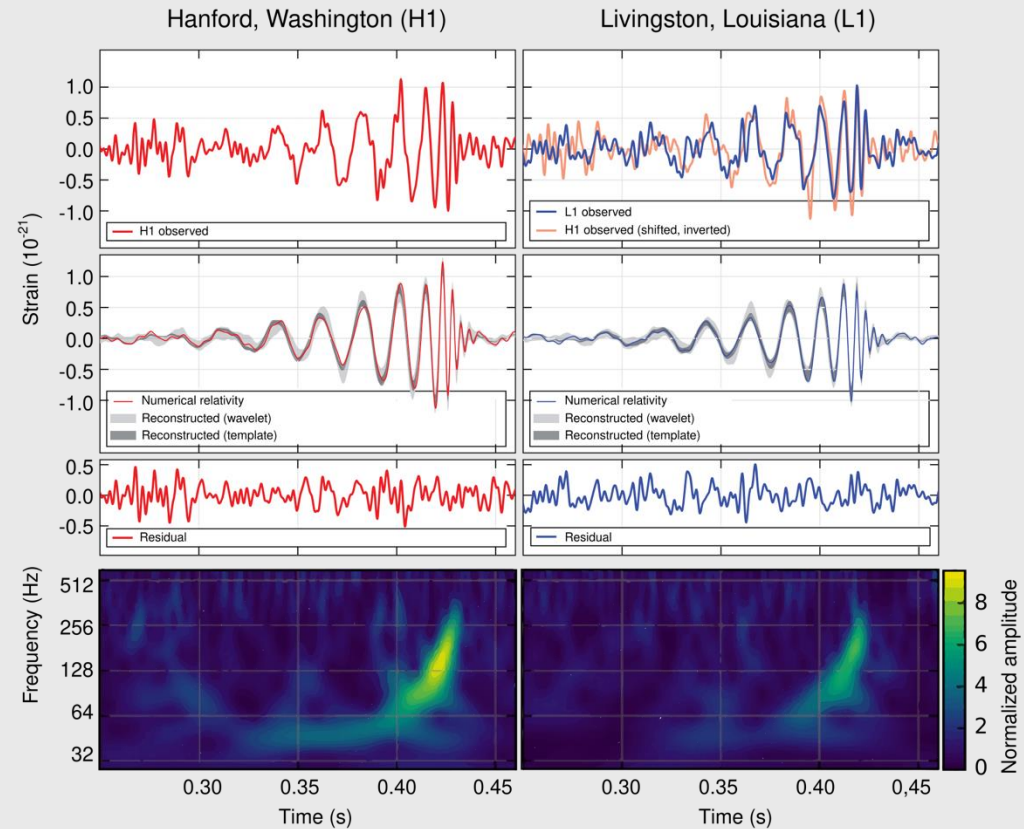
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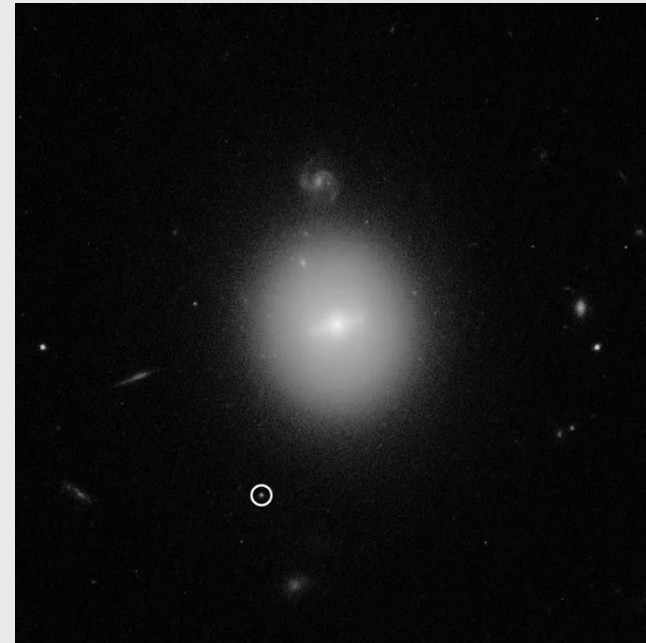
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BH classification

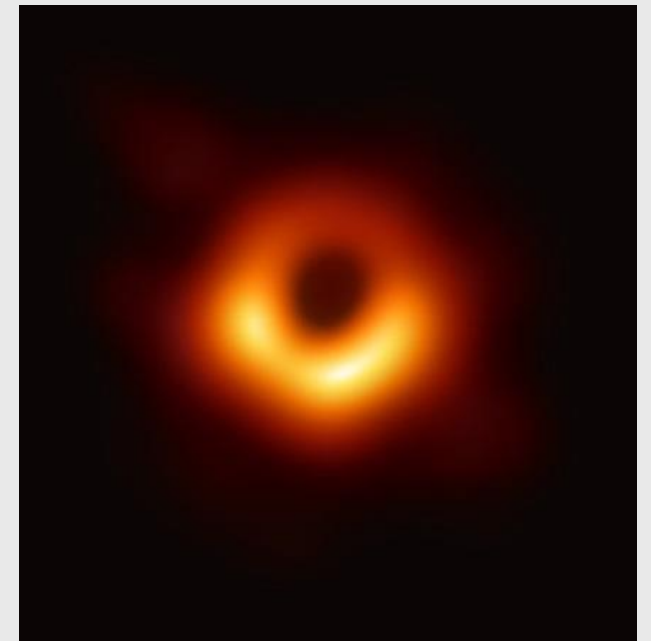


Stellar-mass black holes: $4 - 10^2 M_{\odot}$



NASA, ESA and D. Lin (Univ. of New Hampshire)

Intermediate-mass
black holes: $10^2 - 10^6 M_{\odot}$



EHT Collaboration

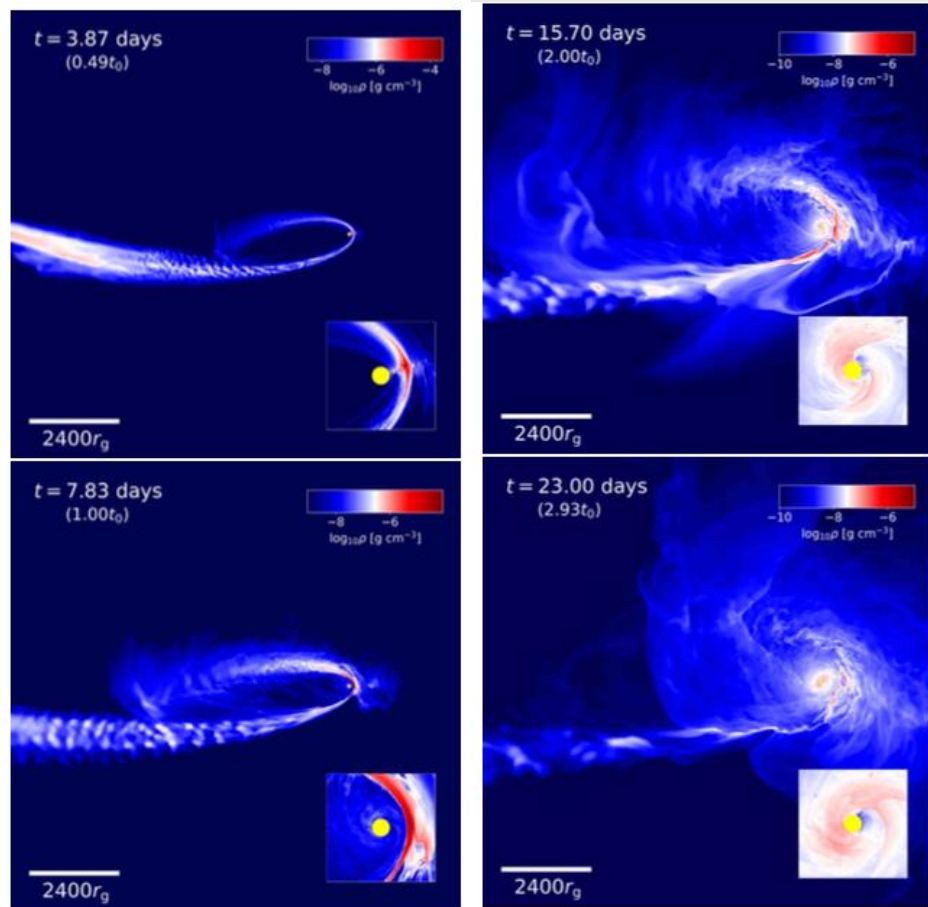
Supermassive black holes:
 $10^6 - 10^8 M_{\odot}$

What are TDEs?



TDEs (Tidal Disruption Events) are astrophysical transients that occur when a star orbits sufficiently close to a Black Hole (BH), resulting in the star being torn apart by the tidal forces of the BH.

How do we characterize a TDE?



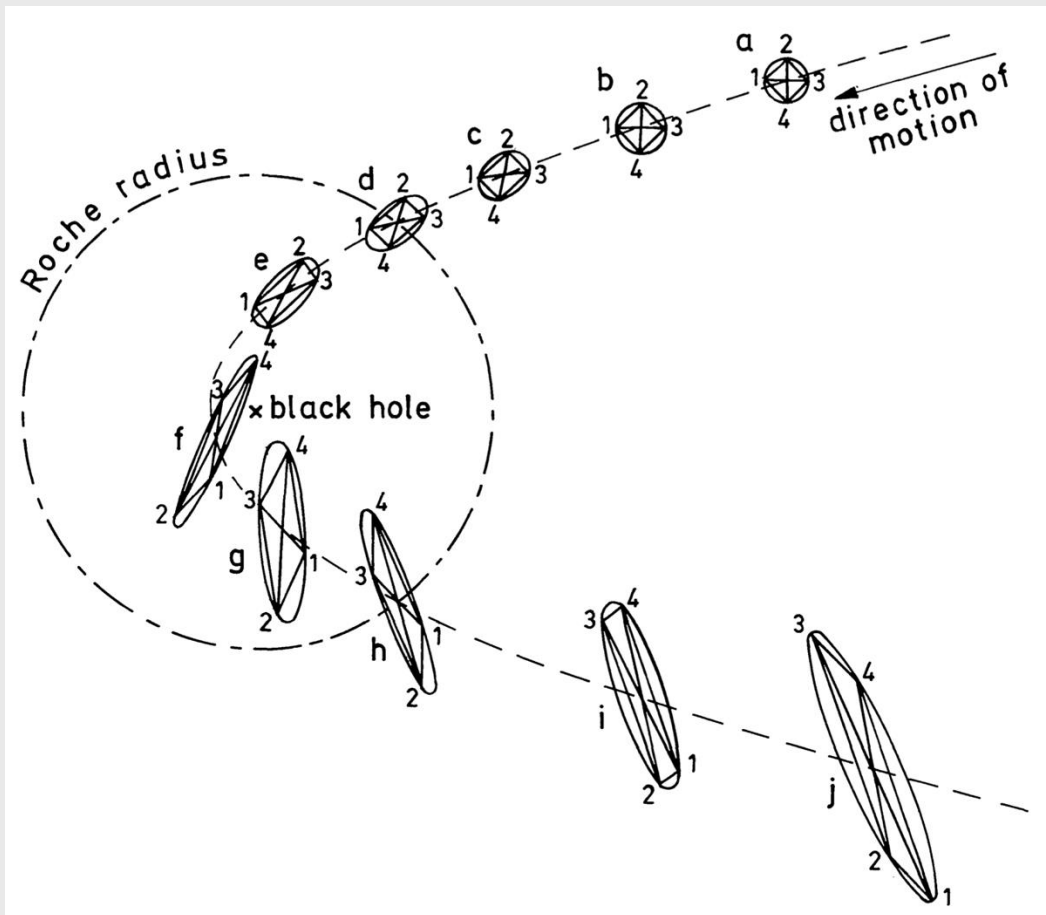
Ryu+23

Many are the parameters involved in the characterization of tidal disruption events:

- The mass M_{BH} of the black hole, together with its spin a
- The type of orbit and impact type: the ellipticity e of the orbit, the impact parameter which is defined as the ratio between the tidal radius of the BH and the distance at the pericenter of the stellar orbit $\beta = \frac{R_t}{R_p}$
- The orbital angle and the viewing angle of the event
- The main properties of the disrupted star: the mass m_* , the radius r_* , its stellar structure and composition

In principle, these parameters could be extracted by fitting theoretical models to observations, however, by degeneracies between stellar and BH properties.

Semi-analytical models

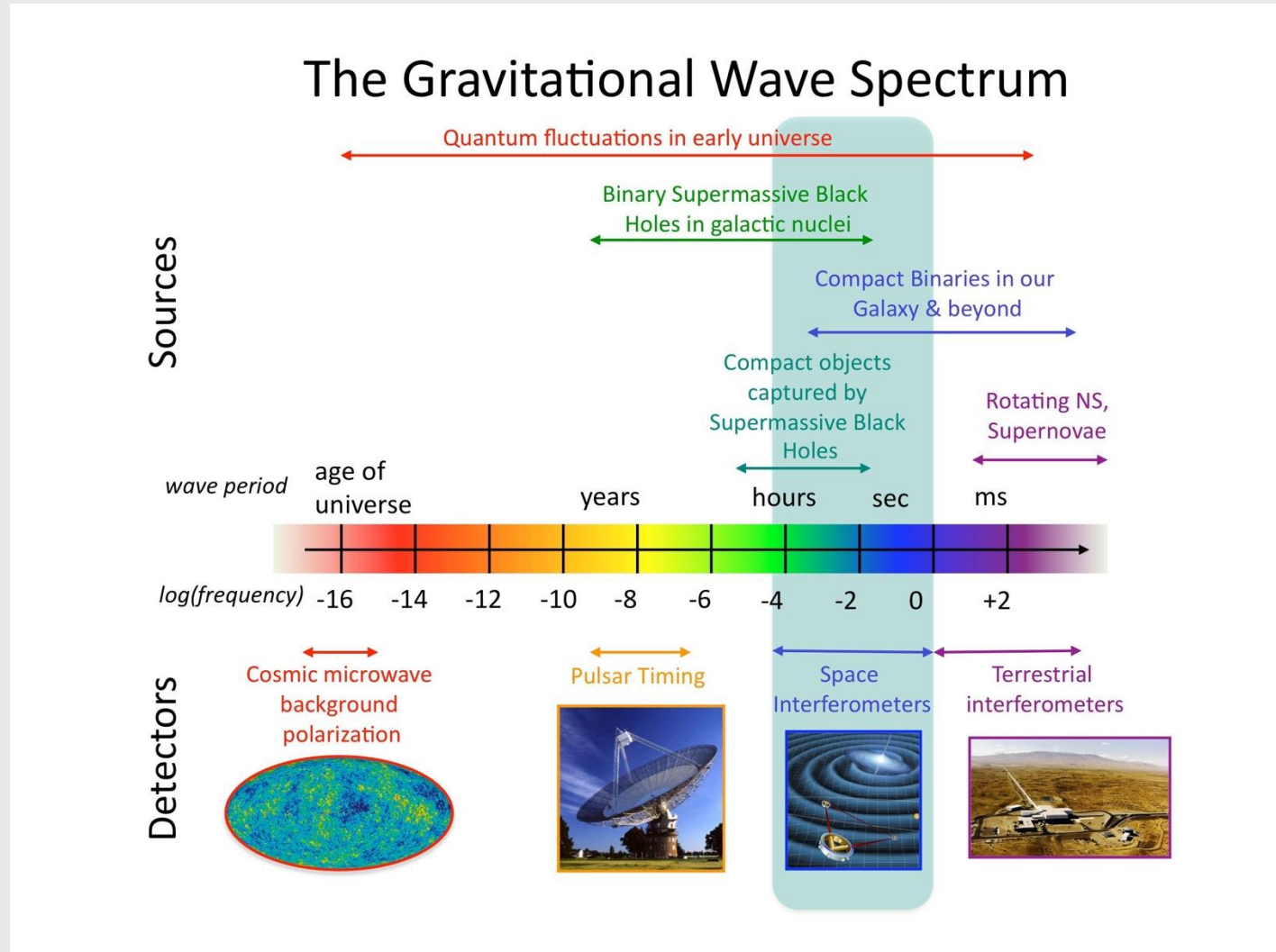
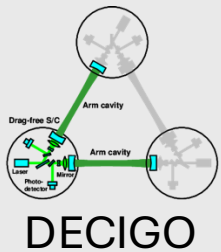


Carter&Luminet, 1986

One of the first analytical models of TDEs is the affine star model, first presented by Carter-Luminet in 1983. In a parabolic approximation of the stellar orbit, the following phases are identified:

1. Approximate equilibrium
2. The free-fall regime
3. The bounce
4. The free rebound and ejection

The GW spectrum

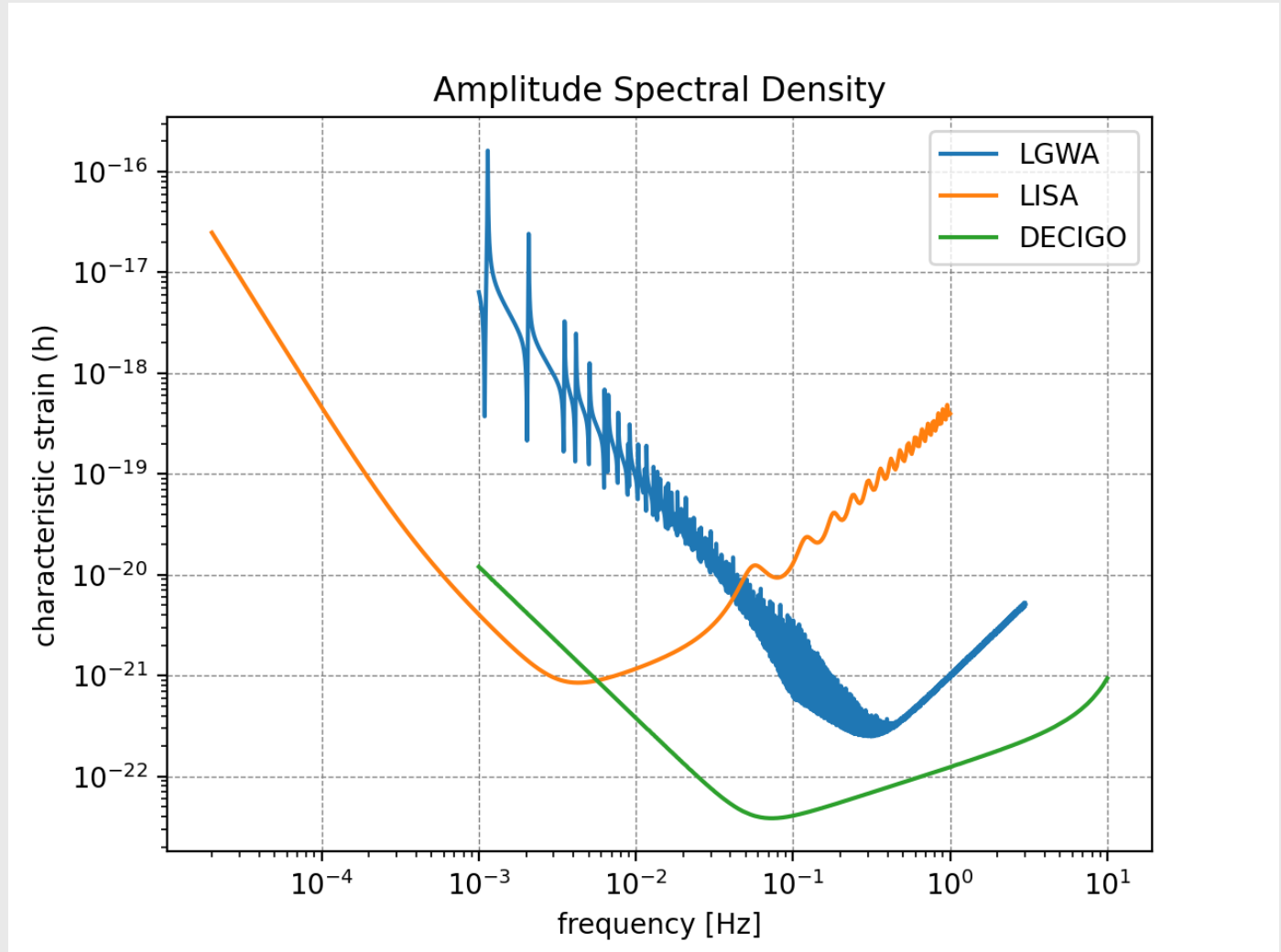


Different sources are responsible for emissions in different frequencies in the gravitational wave spectrum

From NASA

Space-based GW detectors: sensitivity

Future space-based detectors are notably most sensitive in the below-Hz region, with LISA probing the lowest frequency range below 1 *mHz*.



Analytical approach of GW counterparts of TDEs

Given the large amount of disrupted matter, we conclude that GW emission is expected during tidal disruption. Three are the phases during which GWs can be emitted:

1. GWs generated during the approach of the star to the BH:

$$h \sim 10^{-27}, f \sim 10^{-4} \text{Hz}$$

2. GW burst emitted when the star is disrupted at the pericenter
3. Final GW emission during circularization of the stellar debris, which is not compact enough to generate a significant perturbation.

For the disruption burst, assuming a supermassive BH (as for traditional TDE models), Kobayashi+14 obtain

$$h_{GW} \sim 10^{-22} \beta M_*^{4/3} R_*^{-1} M_{BH}^{2/3} d^{-1}$$

$$f_{GW} \sim 10^{-4} \text{Hz} \beta^{3/2} M_*^{1/2} R_*^{-3/2}$$

As we approximate the TDE GW signal to a monochromatic burst, the SNR can be calculated as the ratio between the strain h_{GW} and the characteristic noise ASD of the detector at the observed frequency $h_{det}(f_{obs})$:

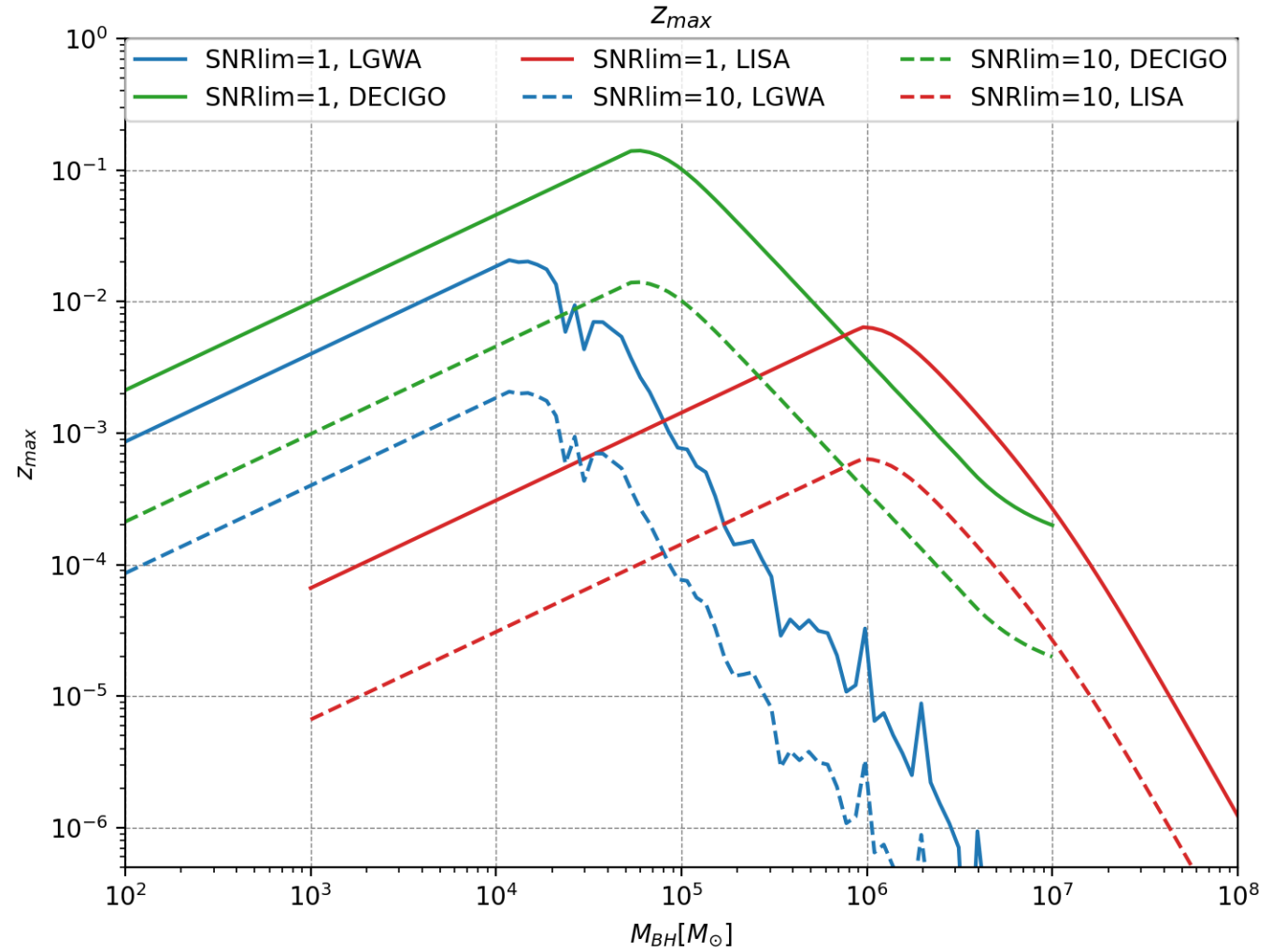
$$SNR = \frac{h_{GW}}{h_{det}(f_{obs})} = \frac{h_{GW}(m_{BH}, m_*, \beta, z)}{h_{det}(f_{obs}(\beta, m_*, z))}$$

Visibility horizons

If we fix a certain threshold on the SNR value SNR_{lim} , we can invert the previous equation for a redshift z ($z \ll 1$):

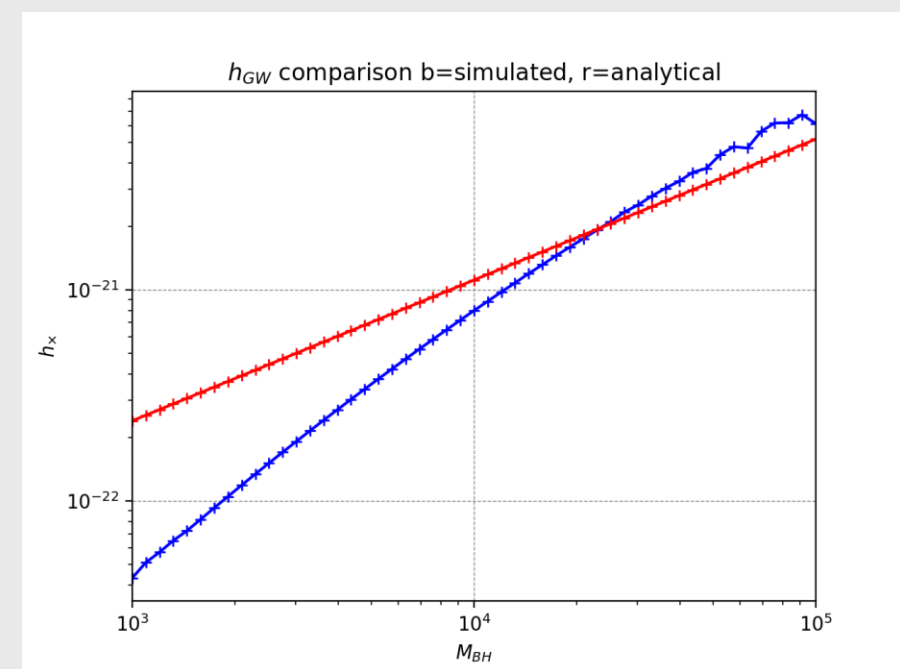
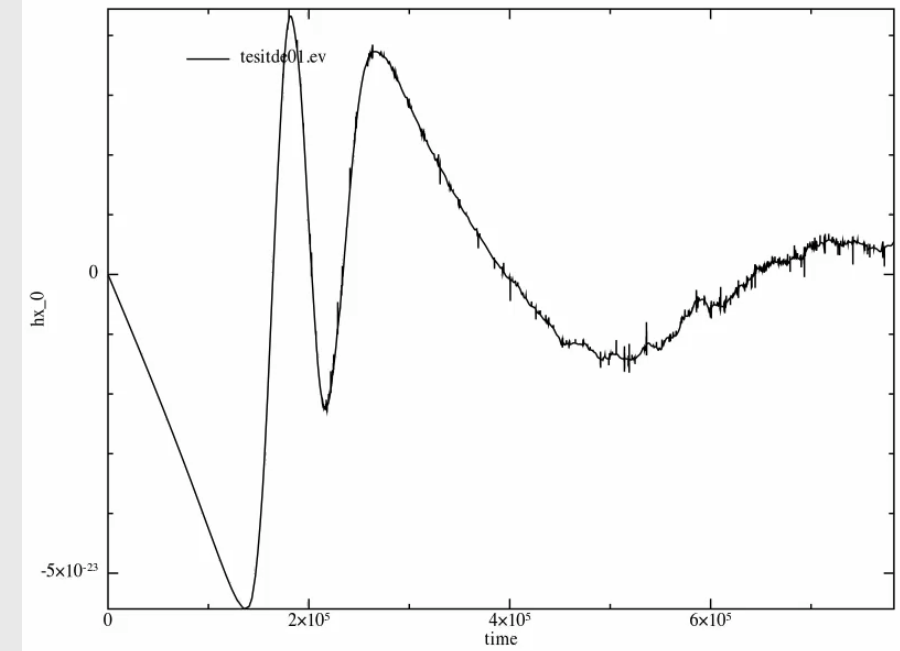
$$z \propto \frac{M_* M_{BH}^{2/3} f_{GW}^{2/3}}{SNR h_{det}(f_{GW})}$$

What we obtain are visibility horizons: depending on the parameters and given a threshold SNR, we obtain the maximum distance at which a TDE is detectable. Different colors represent different detectors, while different line styles represent $SNR_{lim} = 1$ or 10. The mass of the star is set at $m_* = 1 M_\odot$ (solar composition)



Analytical and numerical strain comparison

PHANTOM is the smoothed particle hydrodynamics code used for the simulation of gravitational waveforms of TDEs, which provides a number of pre-cooked configurations that are ready to be used (among them, grtde for TDE simulations in GR). Given the large dimensionality of the system, only some of the intrinsic parameters of a tidal disruption have been chosen: on the side, see the comparison between numerical h_{max} and analytical h_{GW} strains with respect to the parameters M_{BH} .

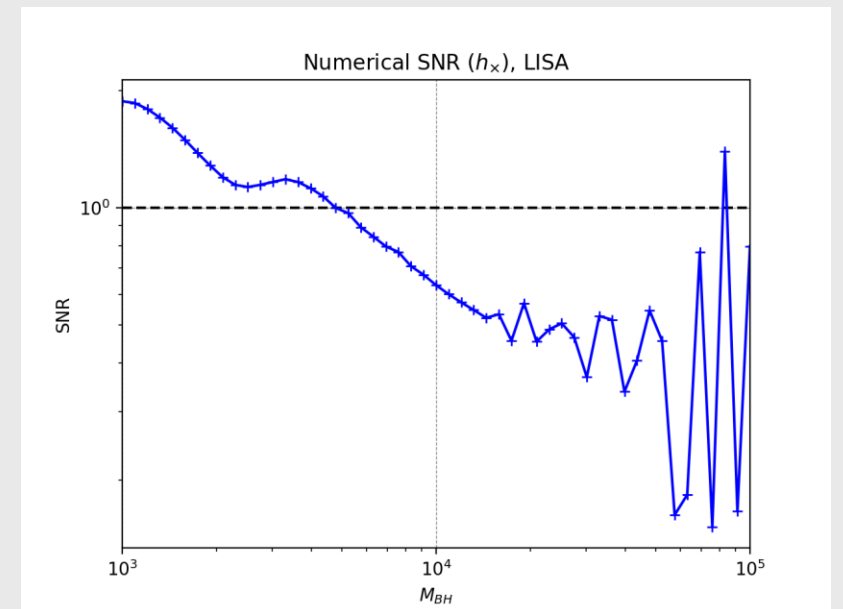
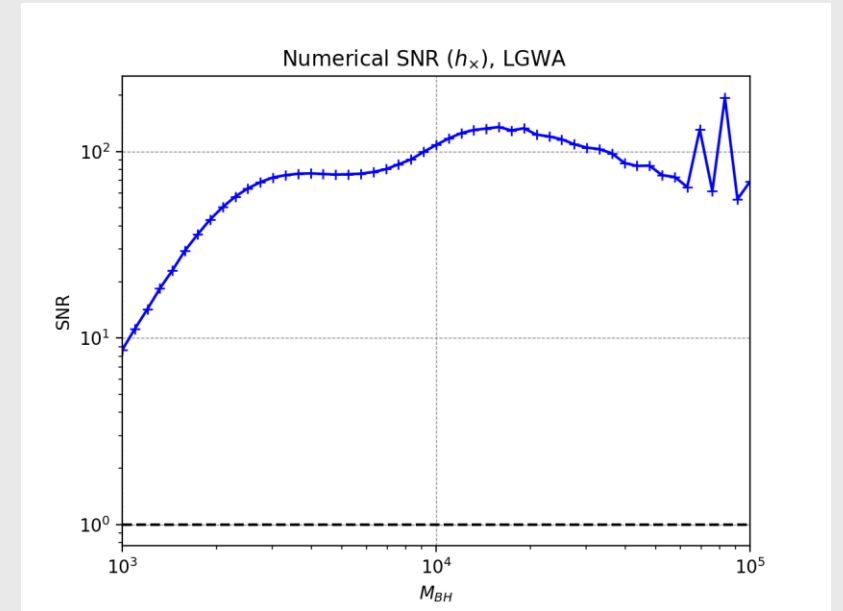


Numerical SNR estimate

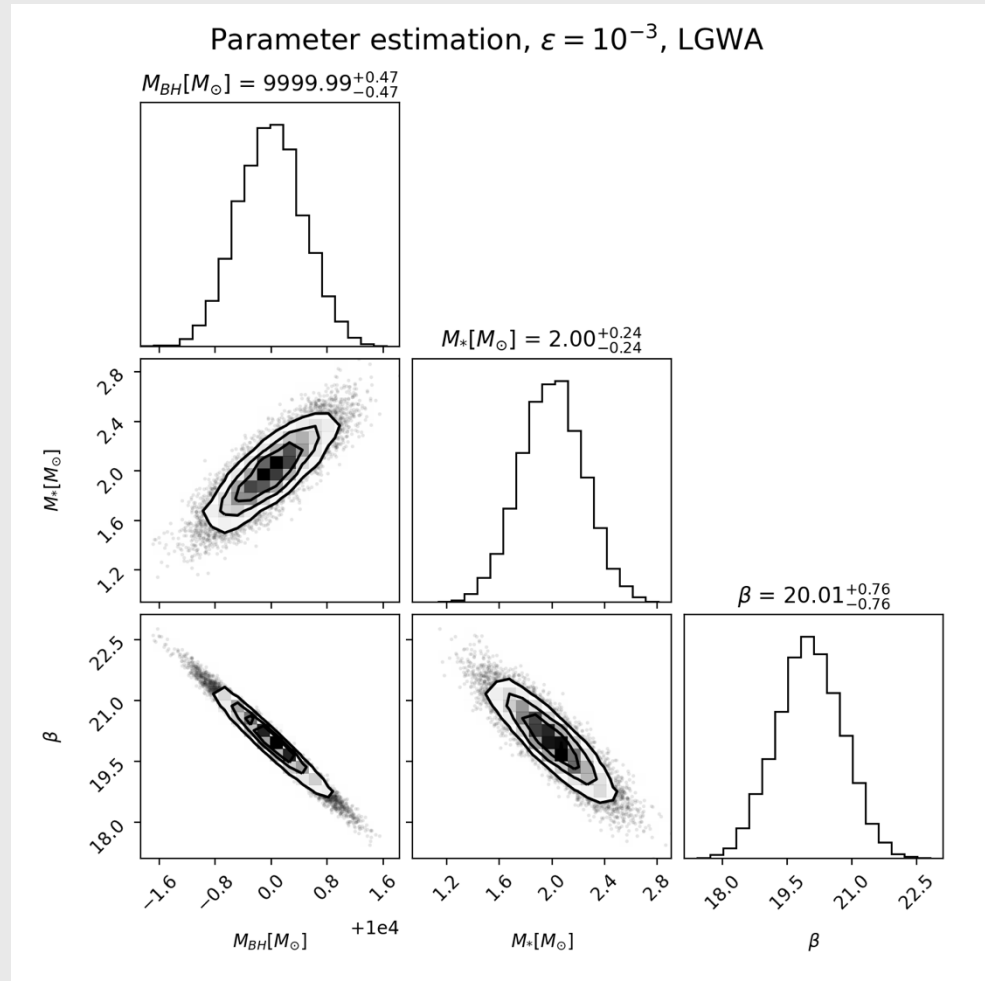
Given a detector output, the objective is to extract a signal: a well-known solution to this problem is *matched filtering*. By knowing *a priori* the form of the signal $\tilde{h}(f)$, the Signal-to-Noise Ratio is defined as

$$\rho^2 = \int_0^{+\infty} df \frac{4|\tilde{h}(f)|^2}{S_n(f)} = (\tilde{h}(f)|\tilde{h}(f))$$

To compare the response of the detectors LISA and LGWA, only M_{BH} is varied, while $m_* = 1 M_\odot$ (solar comp.) and $\beta = 15$ are fixed. The distance is fixed at $1 Mpc$.



Parameter estimation



Now that we have detected our signal $h(t)$, we can infer properties of the source through Bayesian analysis, and in particular the Fisher matrix formalism. We recall Bayes' theorem

$$p(\vec{\theta}|d) \propto \pi(\vec{\theta})L(d|\vec{\theta})$$

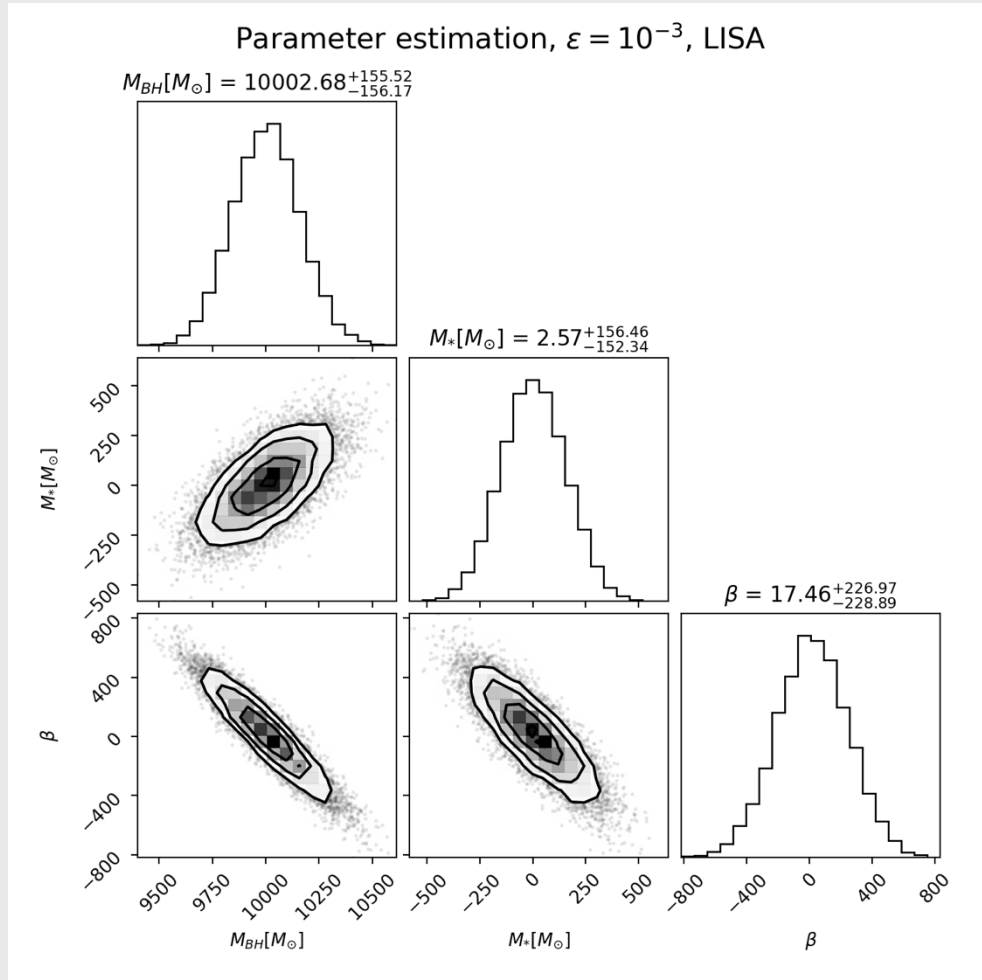
The likelihood $L(d|\vec{\theta})$ is defined as the probability of noise realization and is assumed to be well approximated by a multidimensional gaussian. This allows for quick estimates of the covariance matrix of the parameters through the Fisher matrix using the Cramer-Rao bound:

$$\Sigma_{ij} = [F_{ij}]^{-1} = \left[\left(\frac{\partial \tilde{h}}{\partial \theta_i} \middle| \frac{\partial \tilde{h}}{\partial \theta_j} \right) \bigg|_{\vec{\theta}_{inj}} \right]^{-1}$$

On the side, we see an example: as $\vec{\theta}_{inj}$, the following parameters have been chosen:

$$M_{BH} = 10^4 M_\odot, \quad m_* = 2 M_\odot, \quad \beta = 20$$

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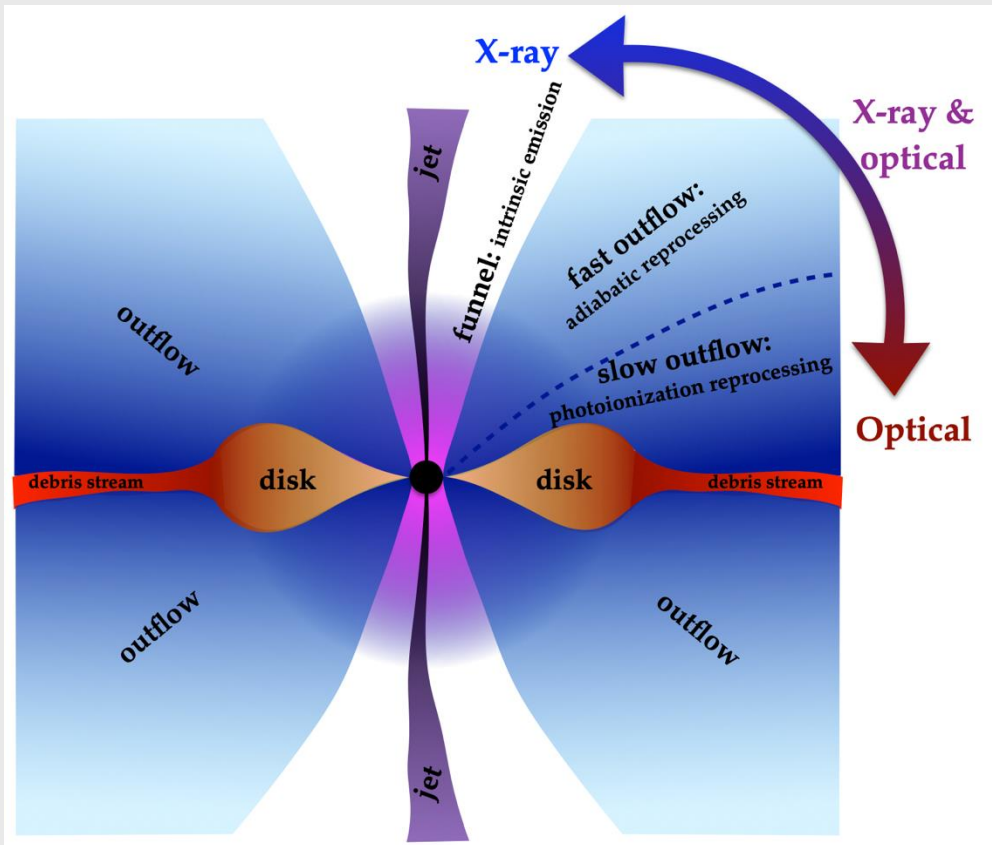
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Conclusions

- TDE gravitational counterparts will give us a completely new insights into this type of event, especially focusing on TDEs by IMBHs:
 - Through both analytical and numerical methods, we have obtained SNR, visibility horizons, and parameter estimation of the initial system
 - As of now, extraction of parameters is very difficult from EM observations, as well as information on the time elapsing between disruption and start of the emission
 - Existence of higher-mass IMBHs is still debated and no direct observation of them has been made*: parameter estimation of a GW detection of a TDE by a IMBH would be conclusive
- TDEs as Multimessenger sources (EM, GW, neutrinos)

What's next in my PhD – EM emission models of TDEs



Dai+18

3D GRMHD codes can describe the different emission types that have been observed in TDEs:

- Montecarlo simulations return the spectrum type with respect to the angle of emission, which track the propagation of photons in 3D
- Depending on the angular position of the debris, we find different reprocessing mechanisms of the radiation (high ionization / electron recombination)
- Shift in the spectrum towards the X-ray bands at increasing angle (with respect to the mid-plane)

→ what happens with WD – IMBH TDEs? What emission do we expect?

Backup slides

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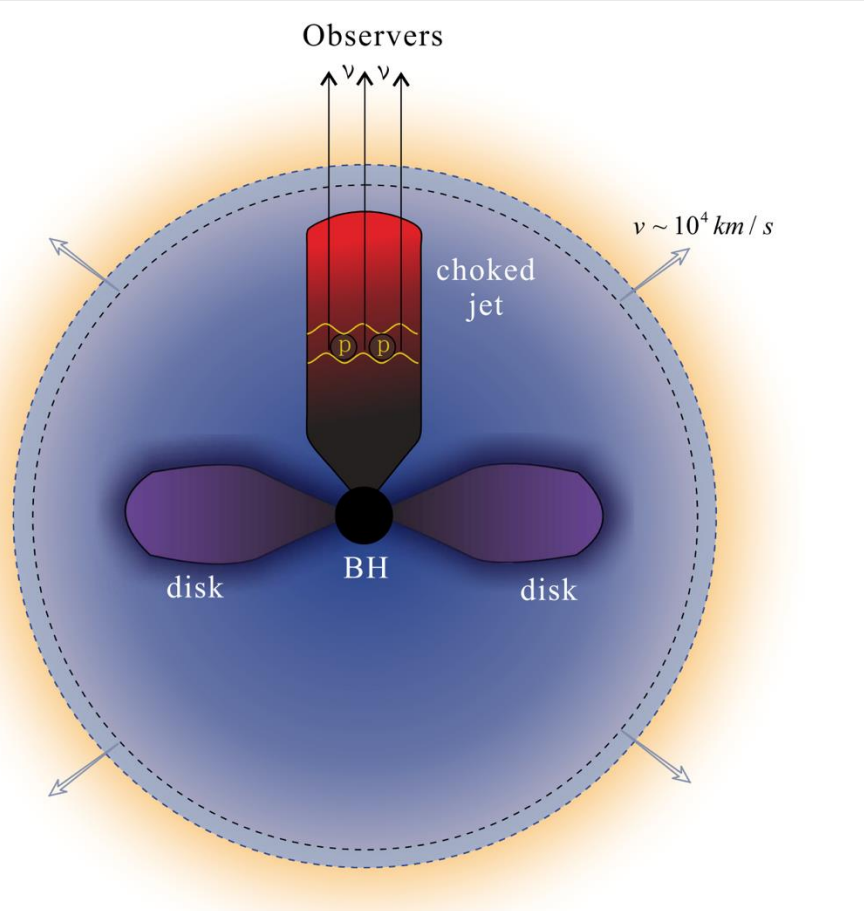
LGWA



LGWA white paper



Neutrino counterparts of TDEs



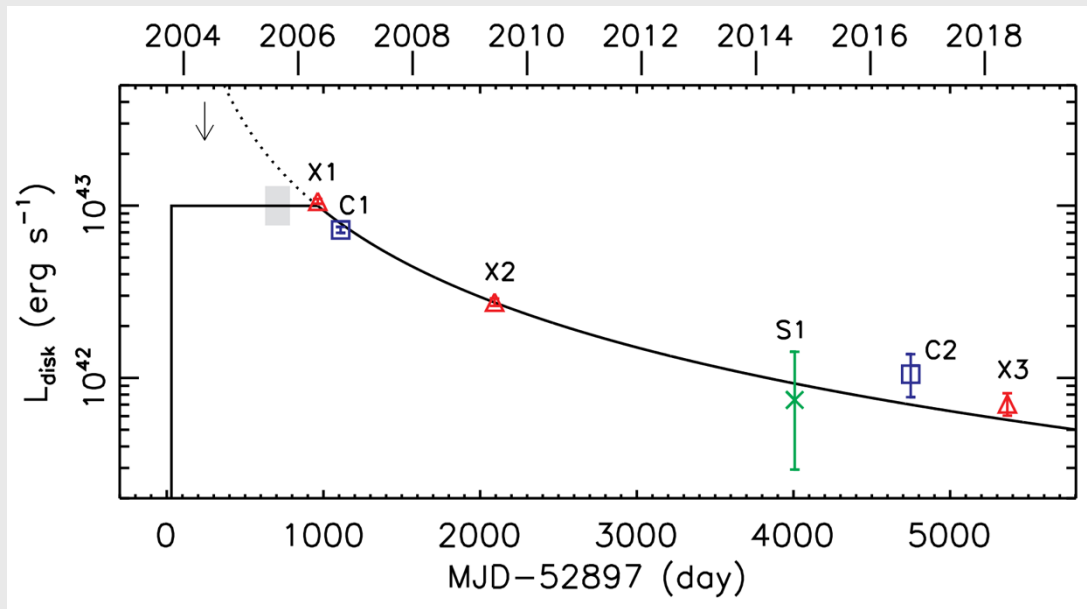
Zheng+23

Neutrino counterparts have also been detected in the events AT2019dsg, AT2019fdr and AT2019aalc. These events are not jetted, and models associate this feature to the production of neutrinos. Neutrino production can occur (Zheng+23) when the relativistic jet is choked by an outer envelope, which is expanding with a velocity $v \sim 10^4 \text{ km/s}$. The jet is collimated by the cocoon pressure to a cylinder shape and is choked inside the envelope. Internal shocks occurred within the jet accelerate cosmic-ray protons, which produce neutrinos observed by us.

A TDE by an Intermediate-mass BH

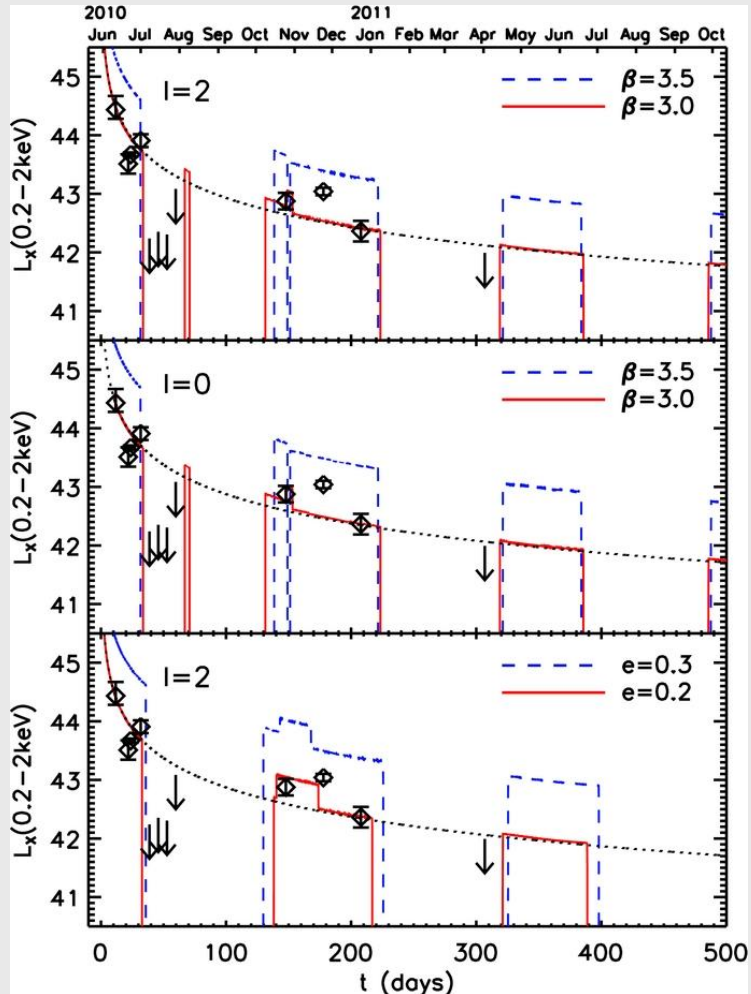
The X-ray source **3XMM J215022.4-55108** was detected during 2006 and 2009 in two XMM-Newton observations and one Chandra observation (Lin+18, Lin+20):

- Very high emission temperature of around $3 \times 10^6 K$
- Unlike AGNs, where the spectrum is dominated by a power-law with a slope independent by the BH mass, in TDEs emission temperatures and BH masses are related, resulting in an estimate of $M_{BH} = 10^4 M_{\odot}$
- Subsequent multi-wavelength follow-ups have corroborated the interpretation of this event as a TDE by an IMBH, with a $t^{-5/3}$ power law decay



Lin+20

A TDE by a Supermassive BH binary

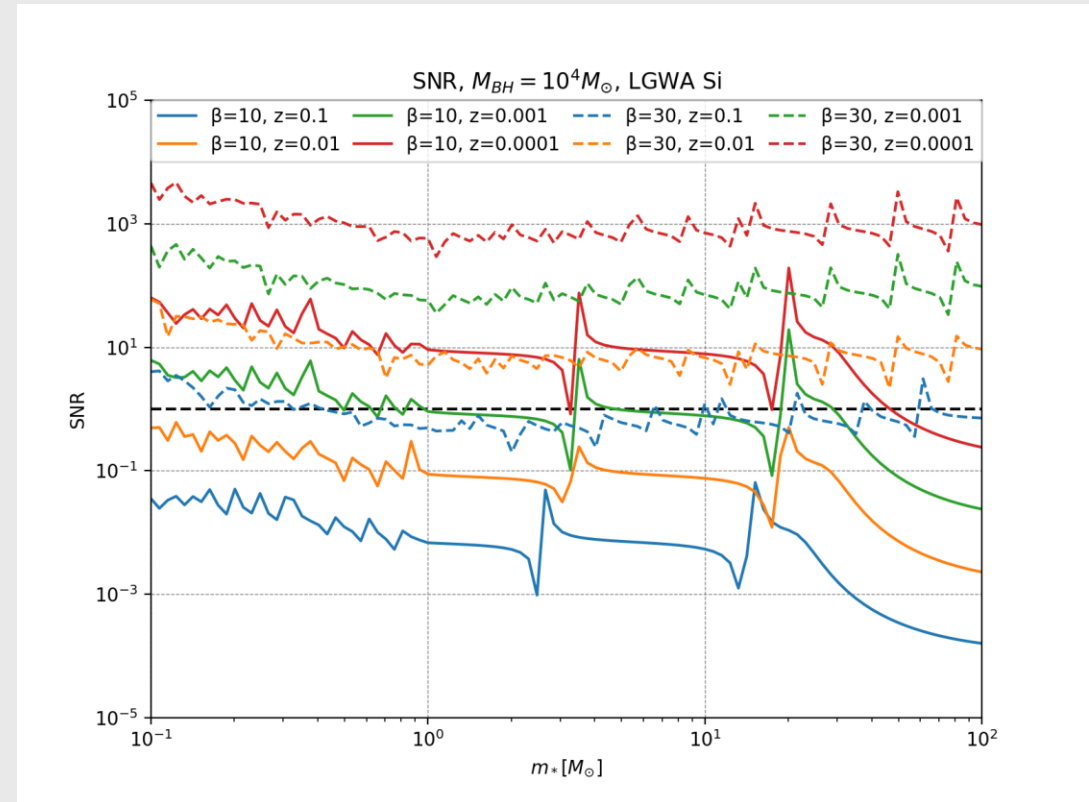
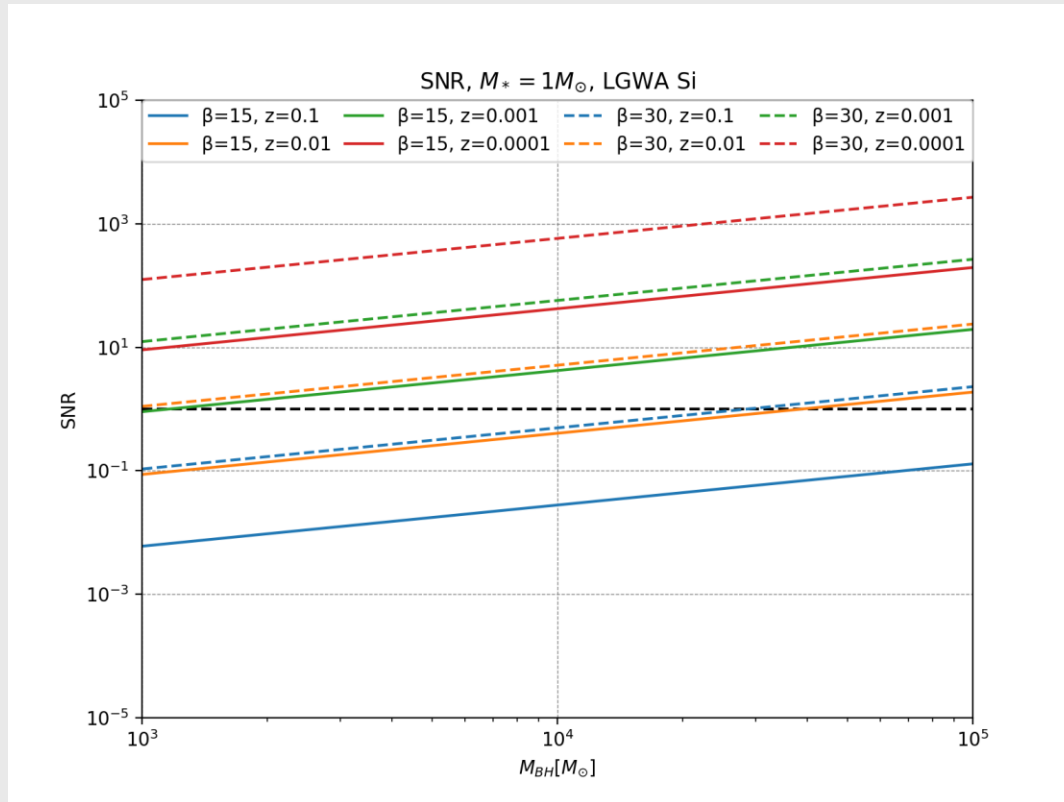


Liu+14

Another very interesting observation has been the Binary Black Hole candidate from galaxy SDSS J120136.02+300305.5 (Liu+14):

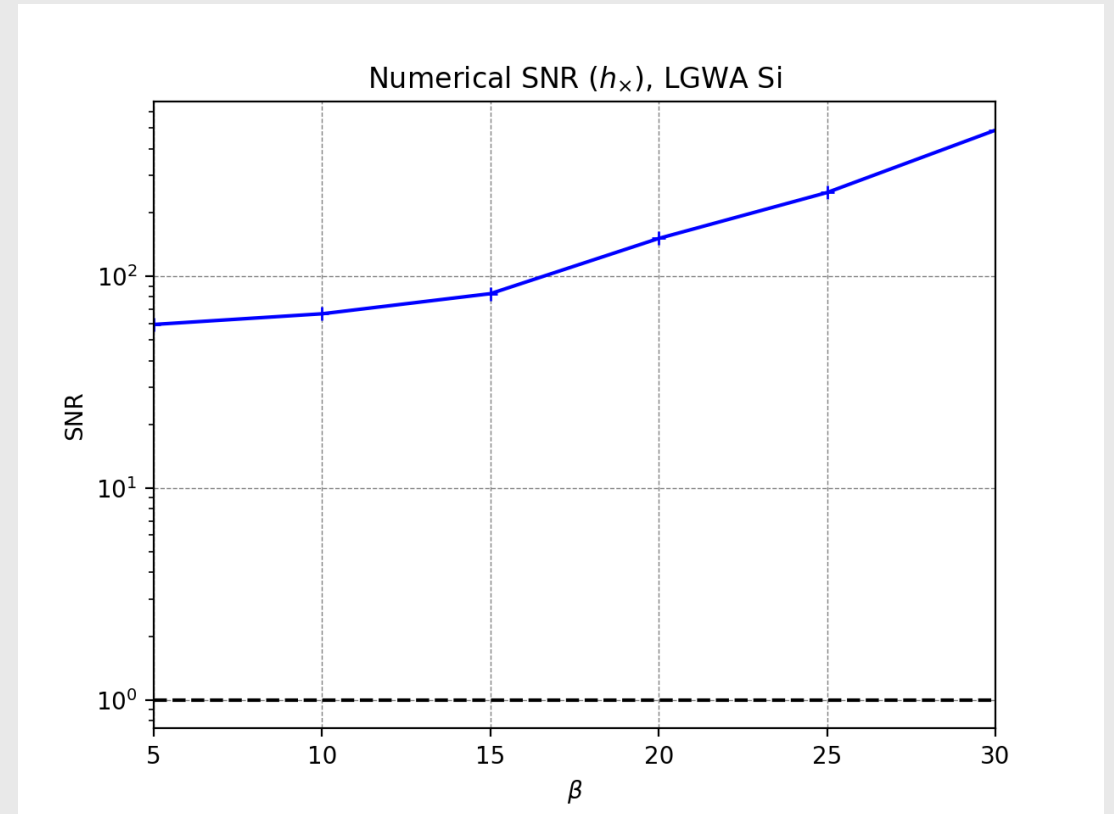
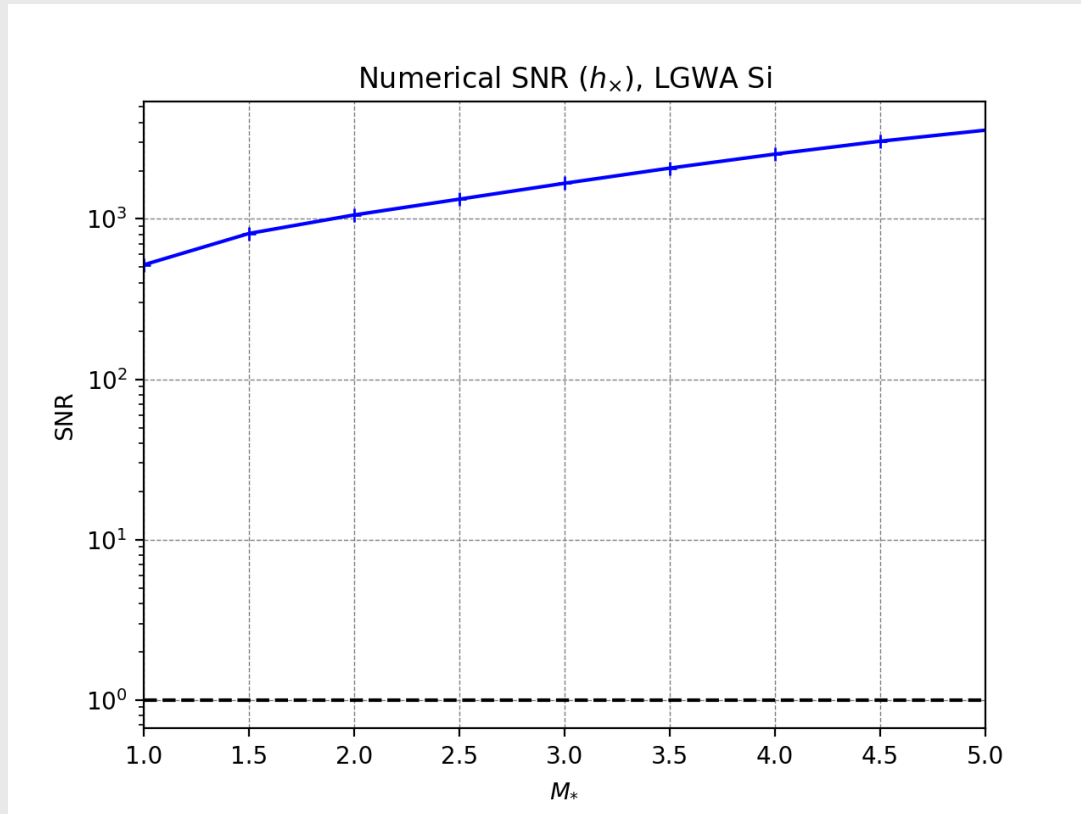
- After the initial flare, the typical $t^{-5/3}$ decay is observed, but after about a month there is a sudden drop of the luminosity by an order of 50 in a week
- After 115 days, X-ray signal reappears, which again follows the $t^{-5/3}$ decay
- Through the timing of the lightcurve interruptions, information regarding the black holes can be deduced, such as spin, q value, orbital period of the binary system

Analytical SNR estimate



Analytical estimate of the SNR of for LGWA. Left: $m_* = 1 M_\odot$ is fixed, while different values of β and z are represented in color and line style. On the x-axis we find M_{BH} . Right: $M_{BH} = 10^4 M_\odot$ is fixed, while different values of β and z are represented in color and line style. On the x-axis we find m_* .

Numerical SNR estimate – LGWA



Numerical estimate of the SNR for the detector LGWA Si and Nb. Only M_* or β is varied, while $M_{BH} = 10^4 M_\odot$ and $\beta = 15$ are fixed. The distance is fixed at 1 Mpc.