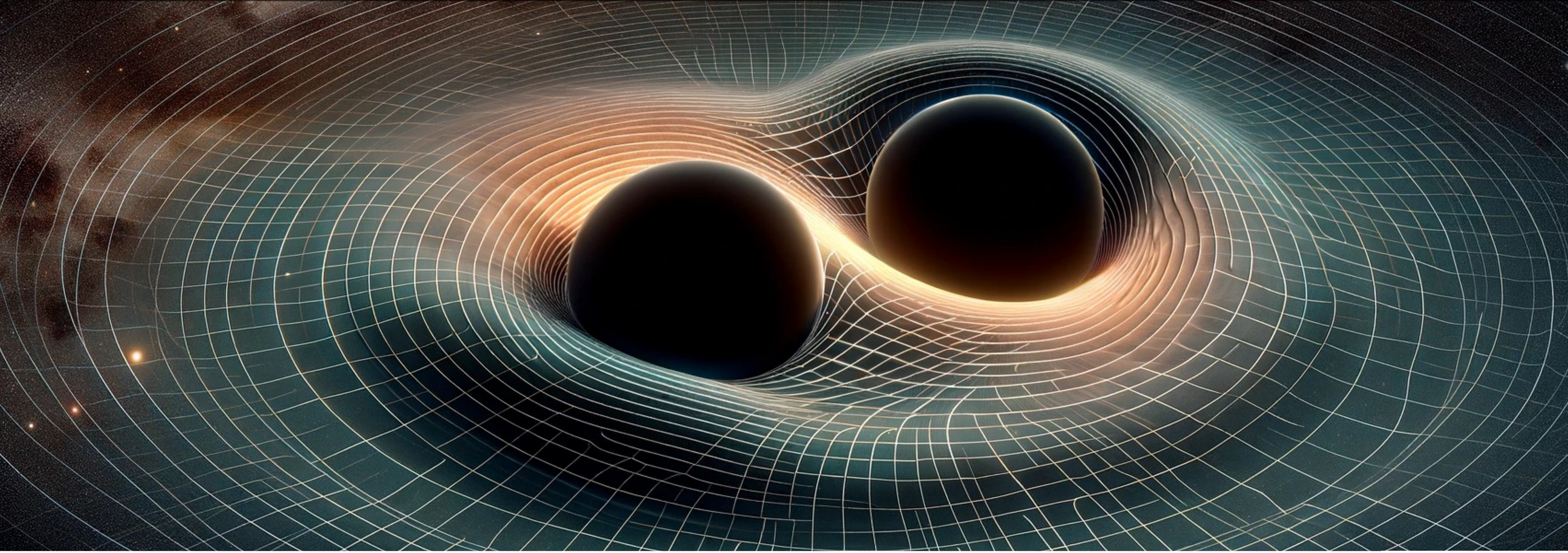
XIV Einstein Telescope Symposium | Maastricht | 06-10 May 2024

Gravitational wave signatures of intermediate-mass black holes

Gianluca Inguglia (*gianluca.inguglia@oeaw.ac.at*), Melvin Cap



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INSTITUT FÜR HOCHENERGIEPHYSIK

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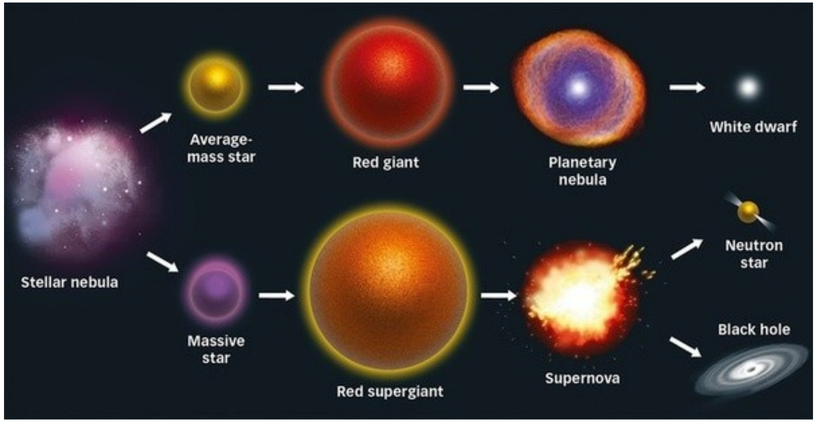
InterLeptons

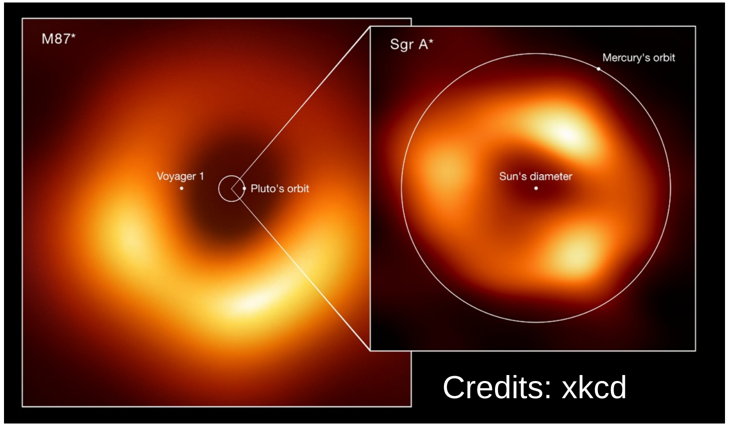
erc
European Research Council
Established by the European Commission

Stellar, supermassive and intermediate-mass black holes

Stellar black holes (SBHs)
- Masses ranging from 5* to few x10 $M_\odot$
- Forms in the final stage of evolution of stars from stellar collapse
- Can exist isolated or in binary systems



Supermassive black holes (SMBHs)
- Very large masses of $10^6 – 10^9$ $M_\odot$
- Typically located in the center of galaxies
- Grow through accretion disk of gas and dust around them
- Core of AGNs



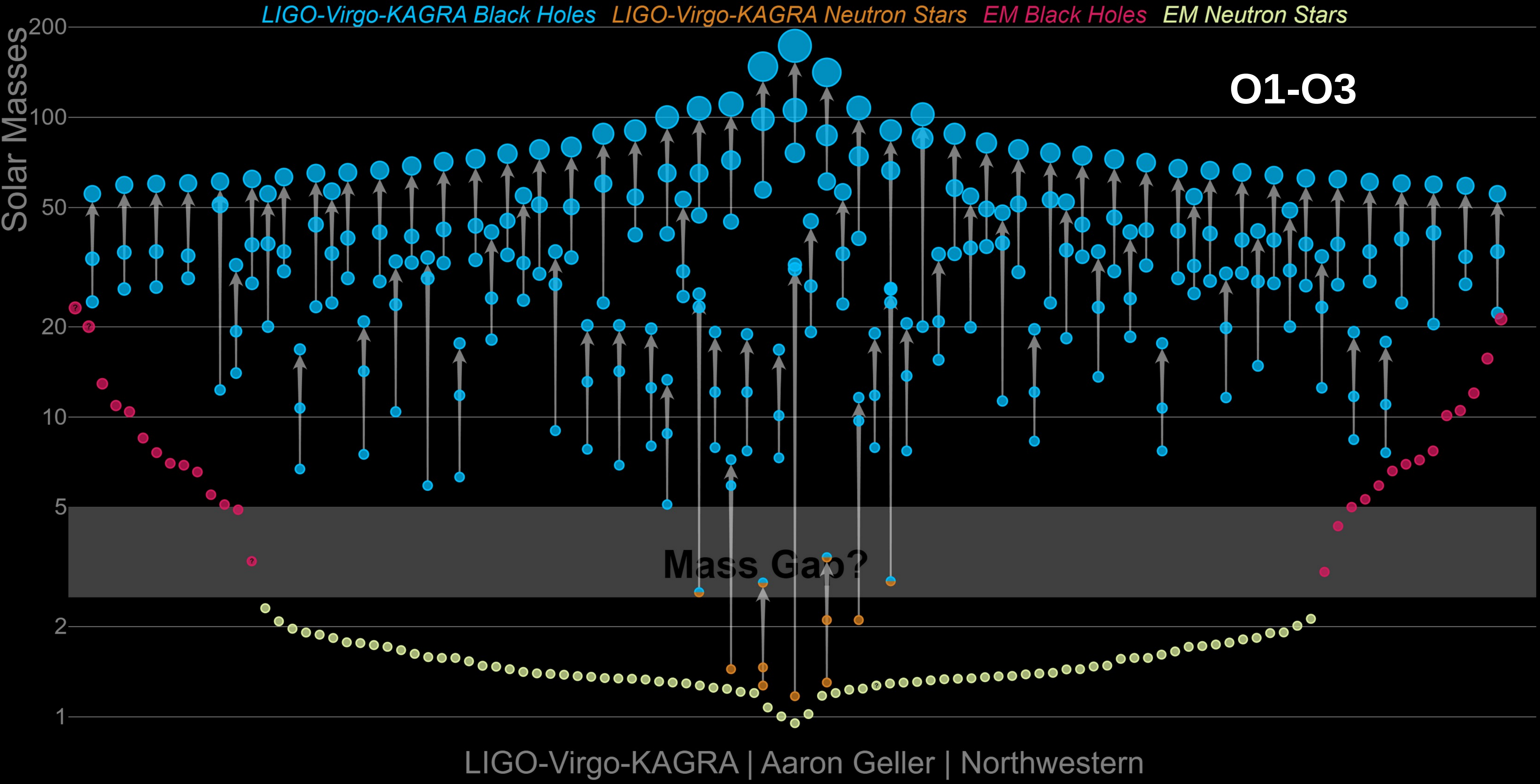
Credits: xkcd

Intermediate-mass black holes (IMBHs)
- Masses of the order of $10^2 – 10^5$ $M_\odot$
- Various models for their origin – no general consensus (ex. population III stars vs. hierarchical mergers)
- Difficult to detect. How do we even know they exists?

SBH — **IMBH** — **SMBH** → **$M_\odot$**

*Check the GWTC 3 population study and the recent GW230529_181500

Masses in the Stellar Graveyard



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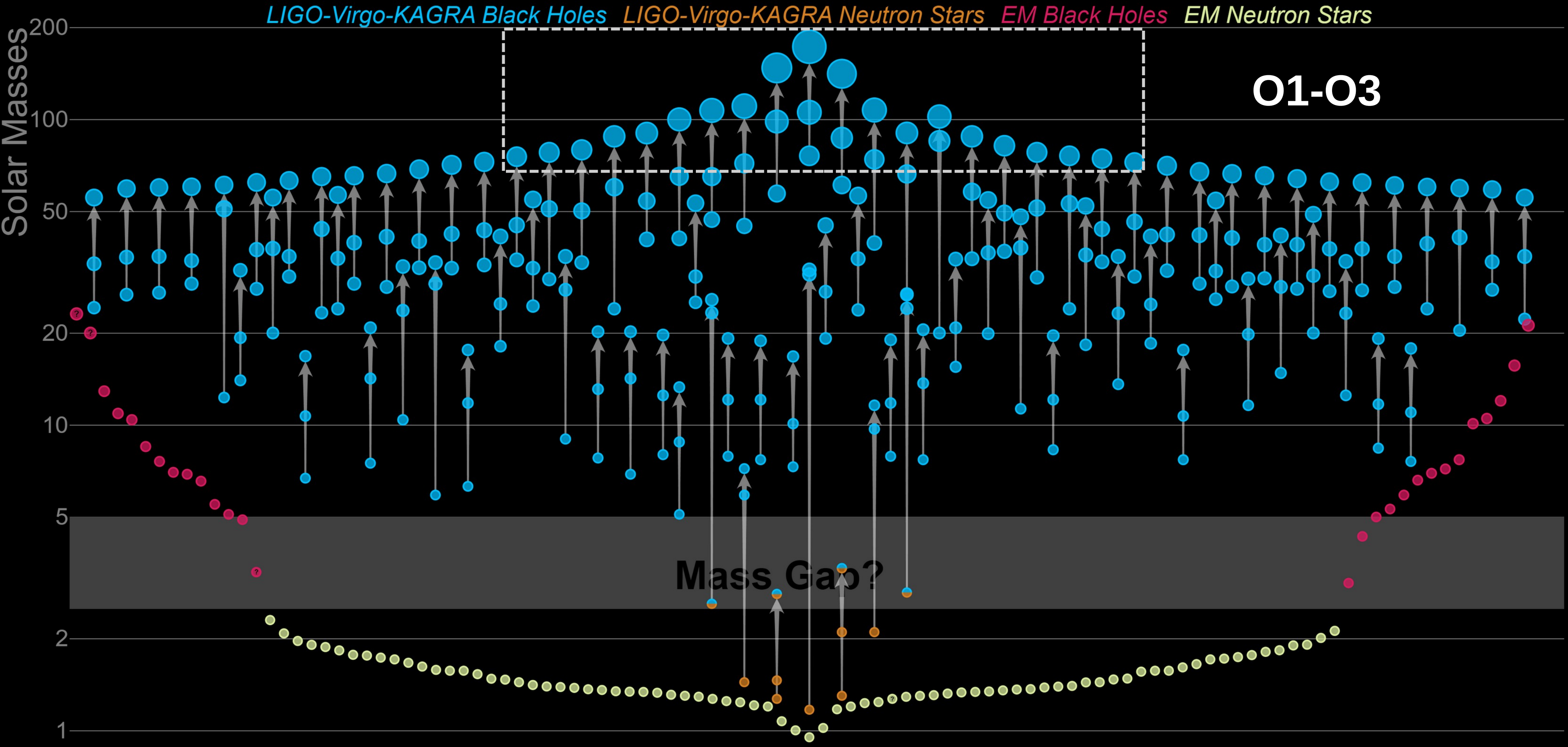
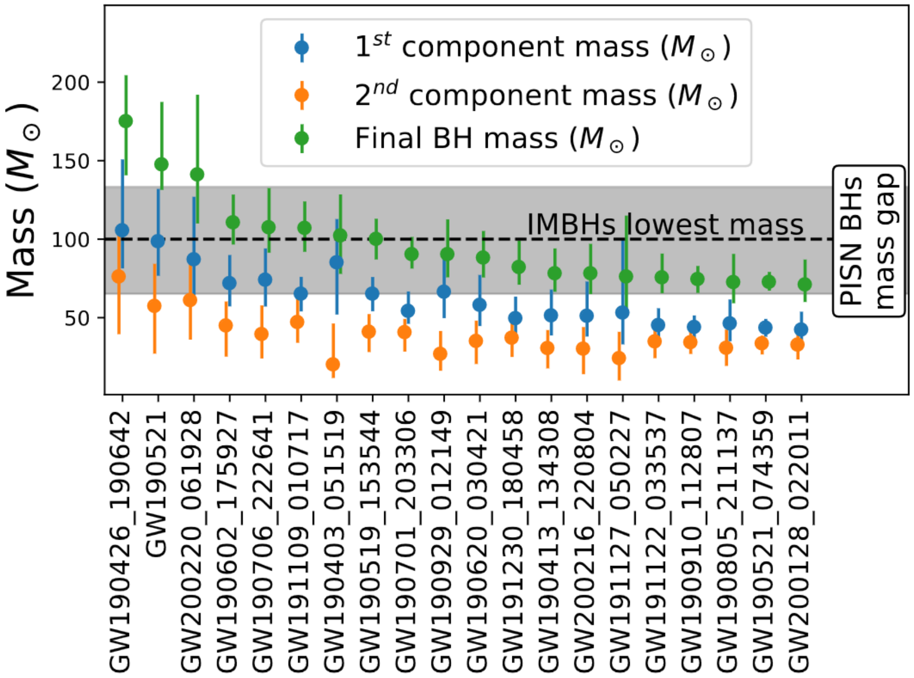


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

The 20 events detected in O1-O3 with the largest remnant masses



- Events are ordered as function of the final BH mass
- The dash line indicate the mass threshold for a BH to be called an IMBH
- The gray band is the pair-instability Supernova (PISN) BHs mass gap
  - Massive stars with cores in ~70-140 $M_\odot$
  - e^+e^- pair production in the core due to high p,T reduces the thermal pressure that balances gravity → partial collapse → PISN → complete star destruction, no remnant.

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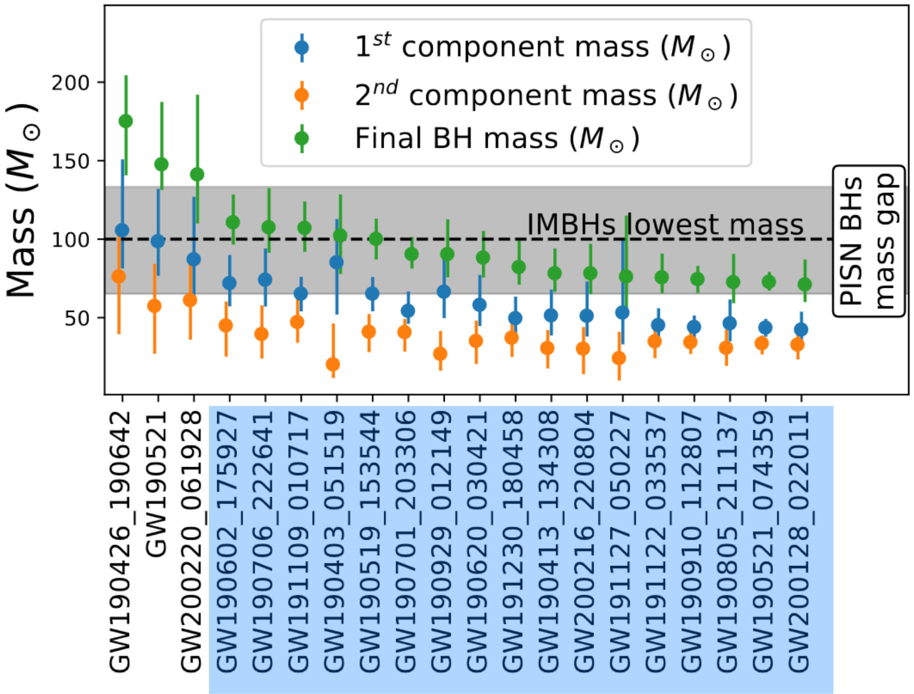

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- Several events associated with the production of a BH in the PISN BHs mass gap

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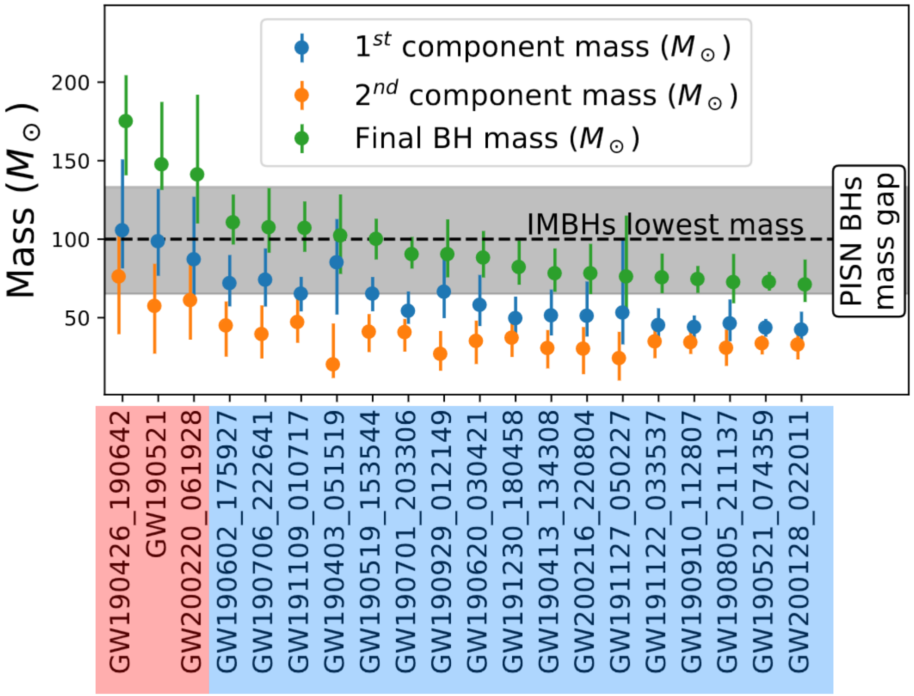

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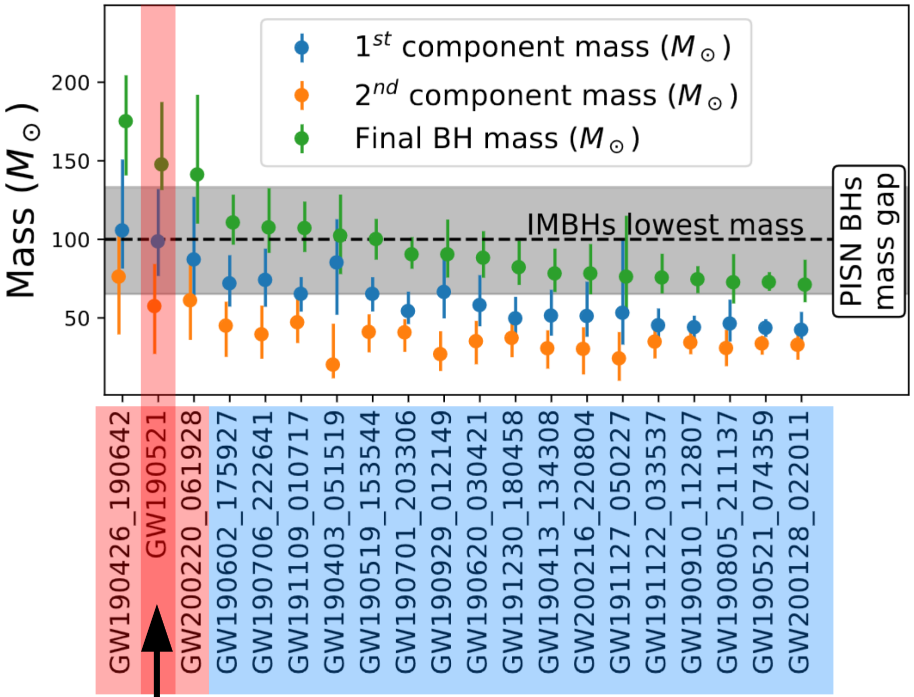
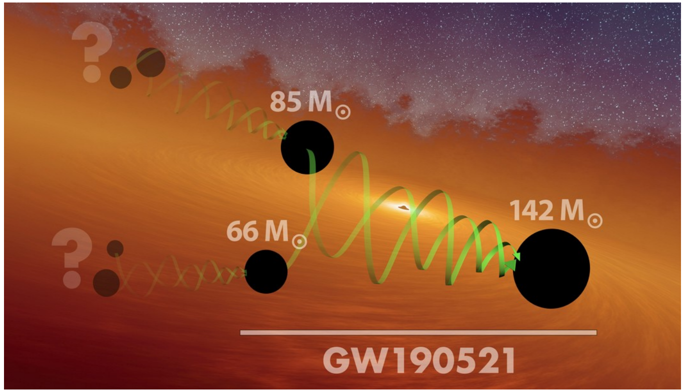
- Few events possibly associated with the production of an IMBH, GW100521 being the most significant

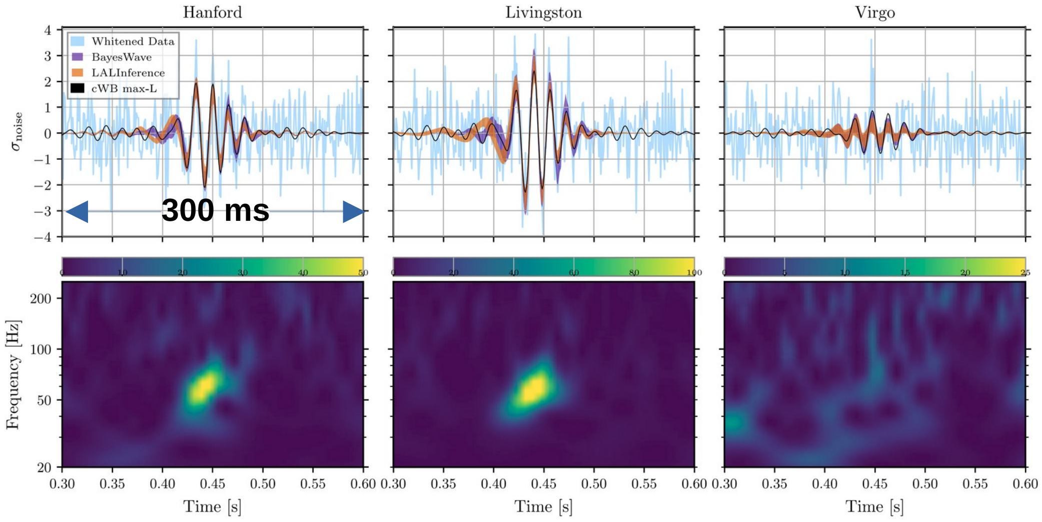
The 20 events detected in O1-O3 with the largest remnant masses



GW190521: First direct evidence of **IMBH**, but how did its 1st component form?

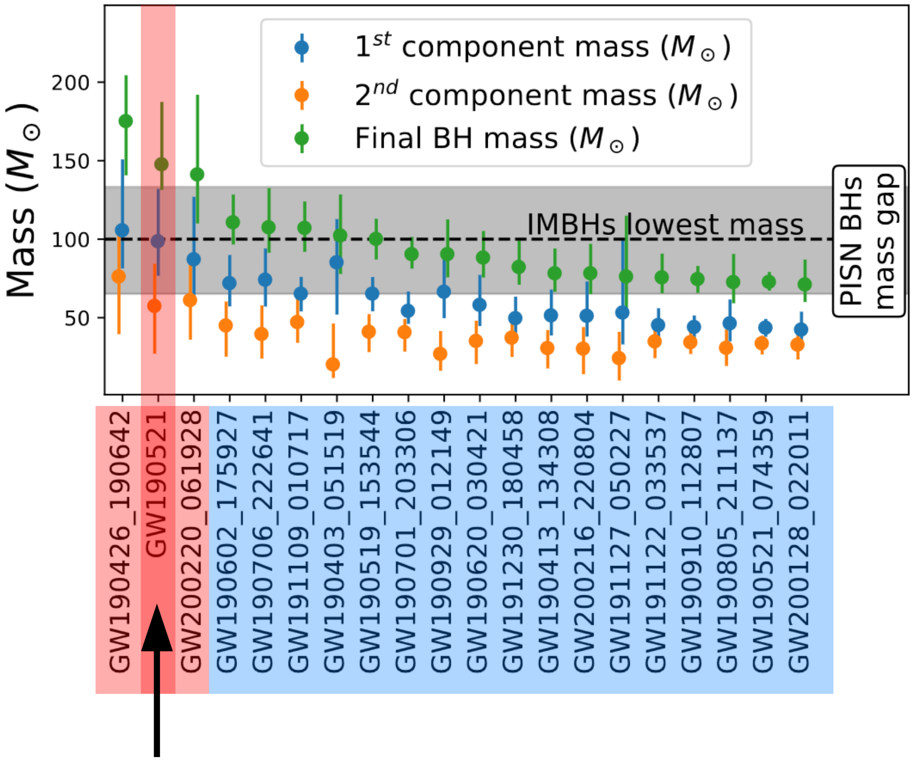


Phys. Rev. Lett. 125, 101102 (2020), arXiv:2009.01075



Very "short" signal → a "**burst**"

GW transients associated with the production of an IMBH are difficult to detect



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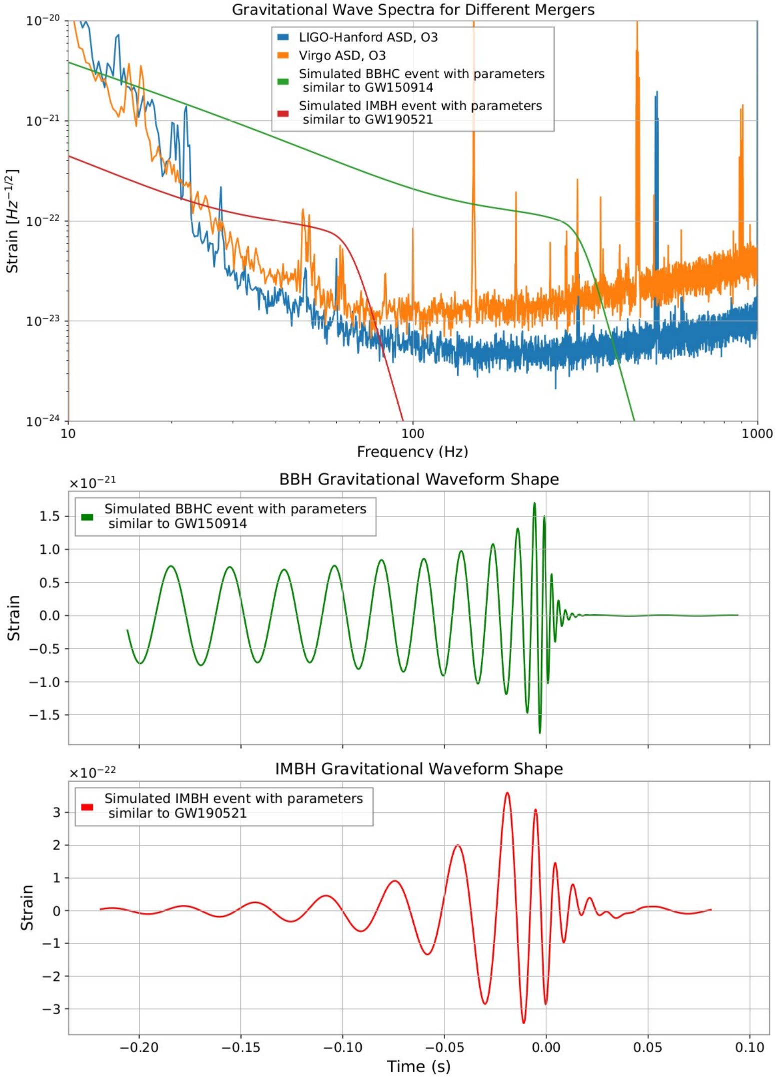
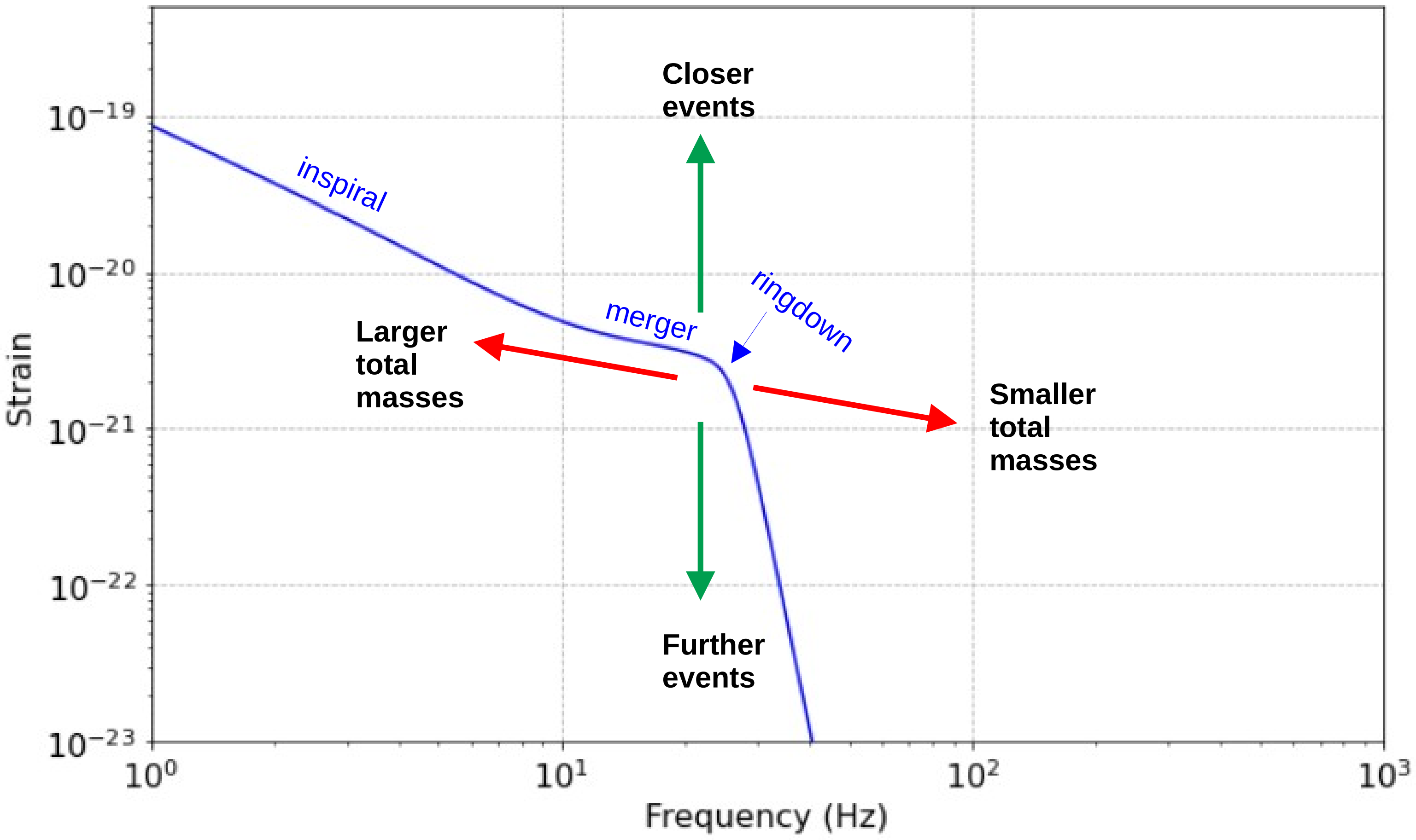


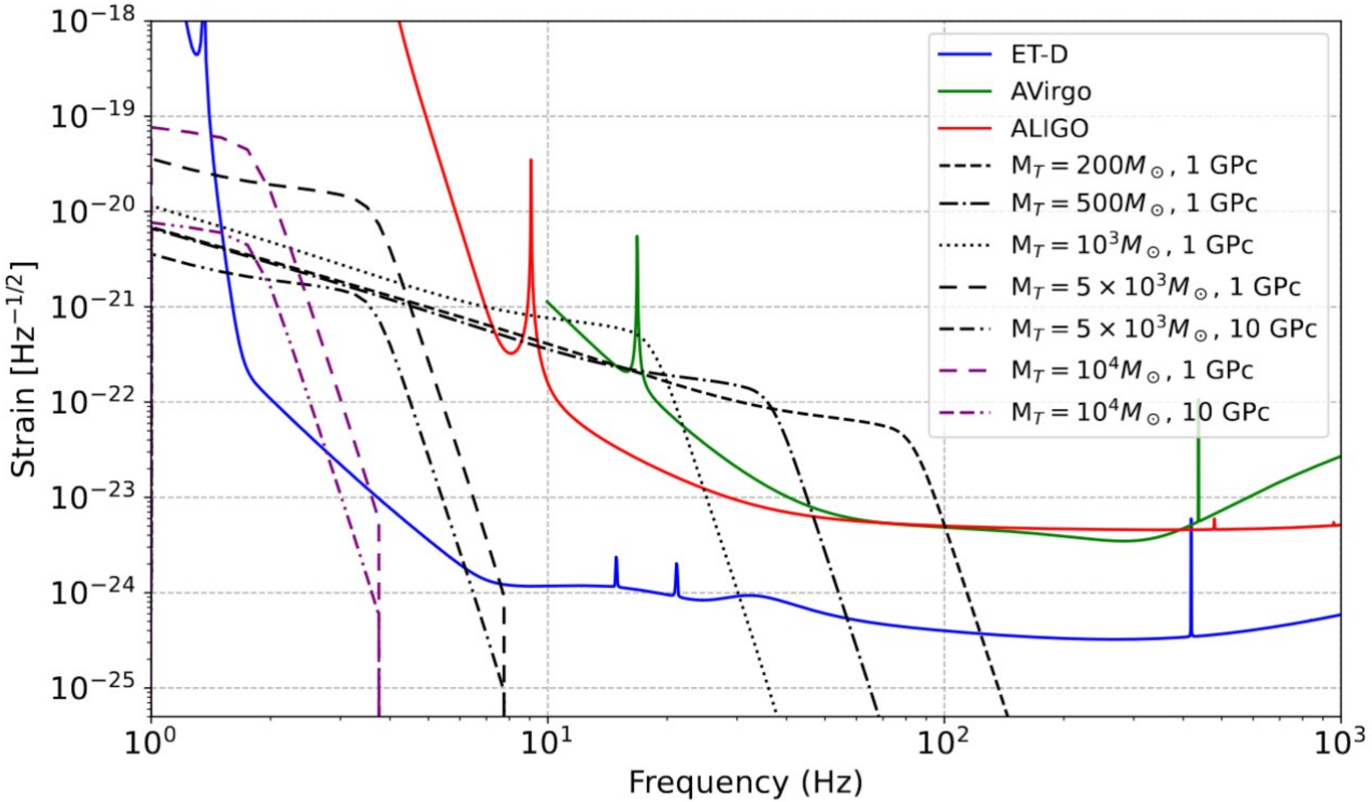
DATA (ASD, in blue and yellow) and simulations (GW spectra and waveforms) using PyCBC pipeline with phenomenological models

Effects of mass and distance on GW strain signals



IMBH GW signals and detector sensitivities: mass and distance insight

Preliminary study, uses **IMRPhenomD** as waveform approximant.
Unofficial sensitivity curves obtained from https://dcc.ligo.org/LIGO-T1500293/public



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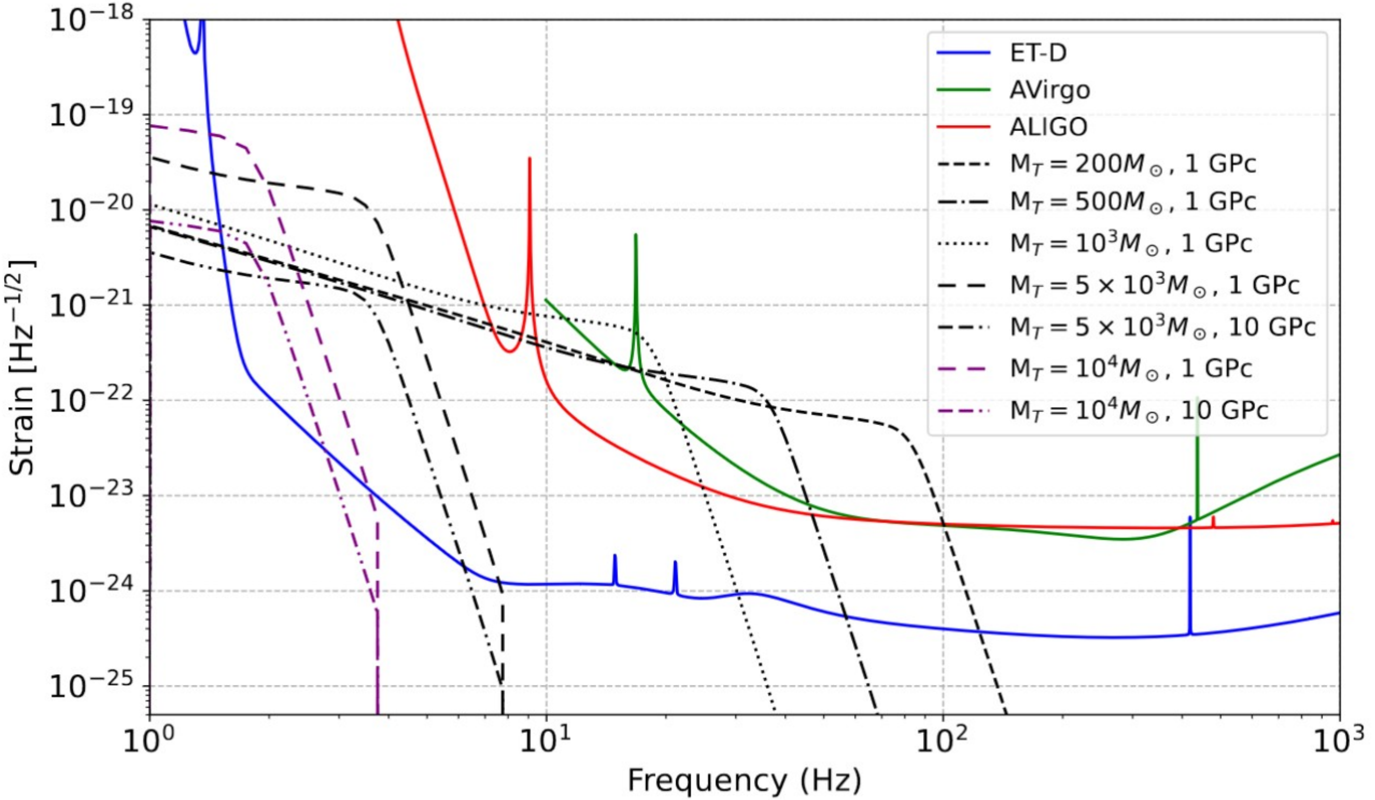
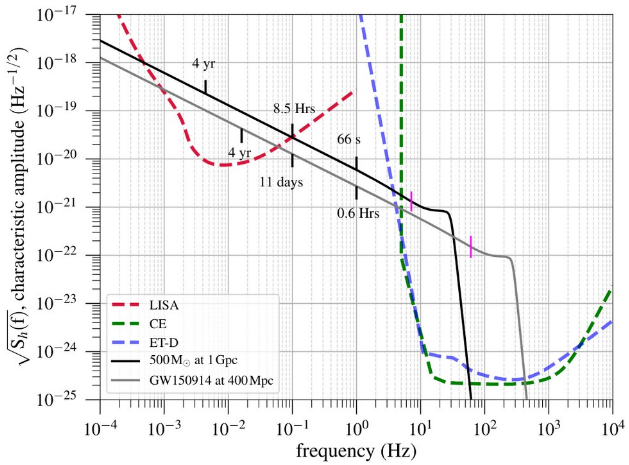


- GW transients due to systems with total mass up to fewx 10^3 $M_\odot$ will be nicely visible with the final part of their inspiral detected
- GW transients due to systems with total mass of O(10^4) $M_\odot$ will appear as burts, but will be announced well in advance by LISA (see also Datta et al., Phys. Rev. D 103, 024036 (2021), 2006.12137)

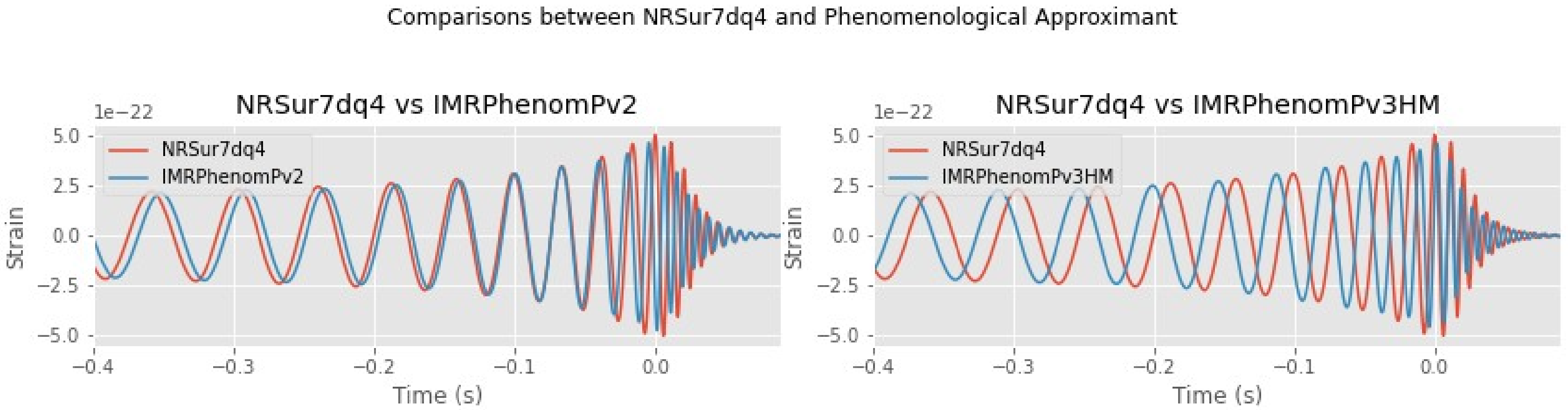


From Peters' formula (1964)

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad t = \frac{5}{256}\left(\frac{c^3}{GM_c}\right)^{5/3}\left(\frac{1}{\pi f}\right)^{8/3}$$

→ IMBHs' coalescence will be for years within the sensitive region of LISA who can in turn provide details to ET: multiband GW studies

Care needed when using approximants



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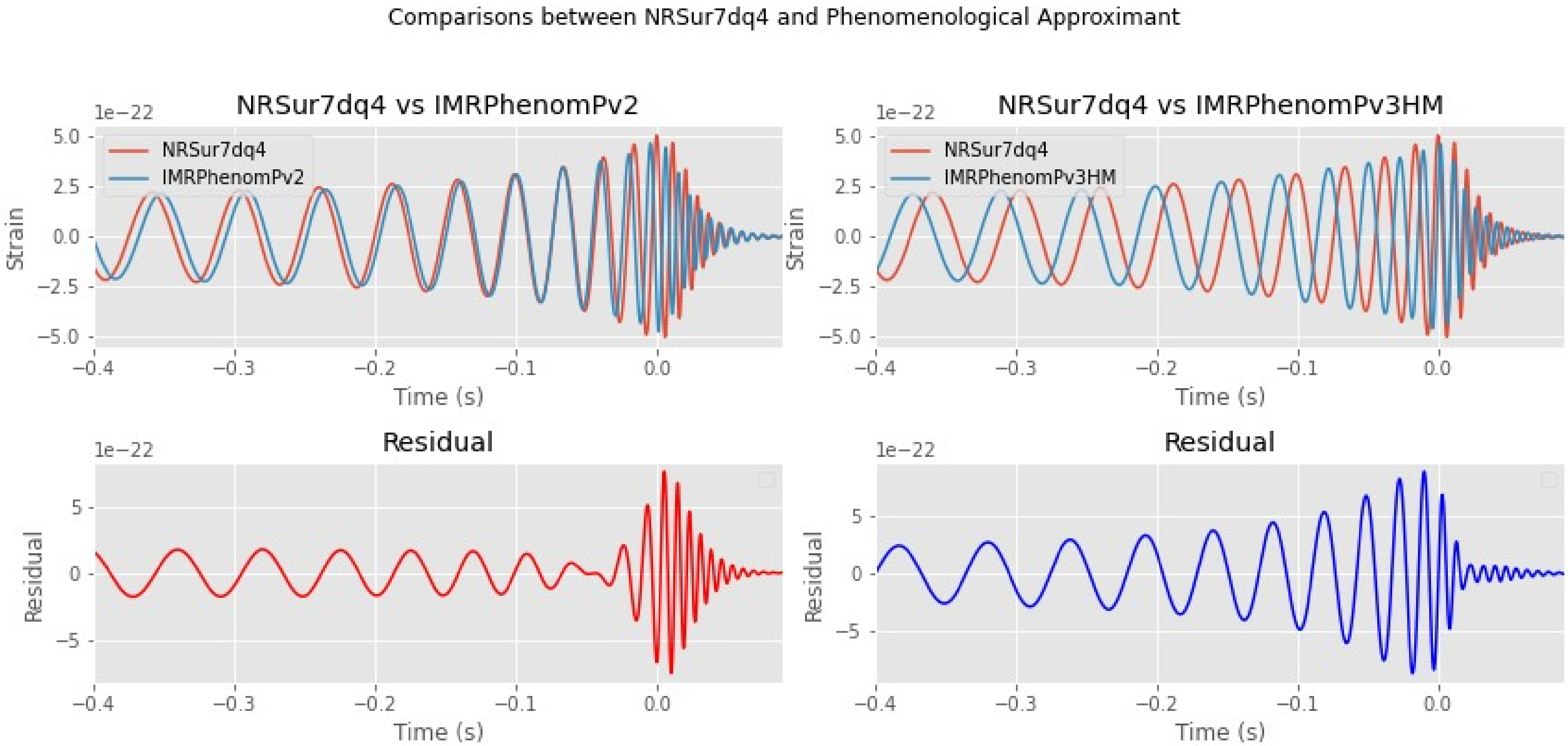
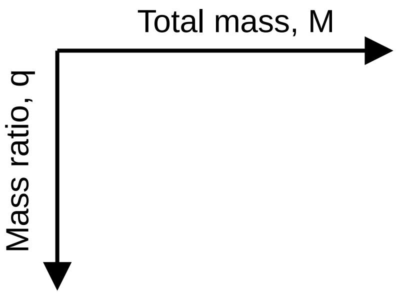
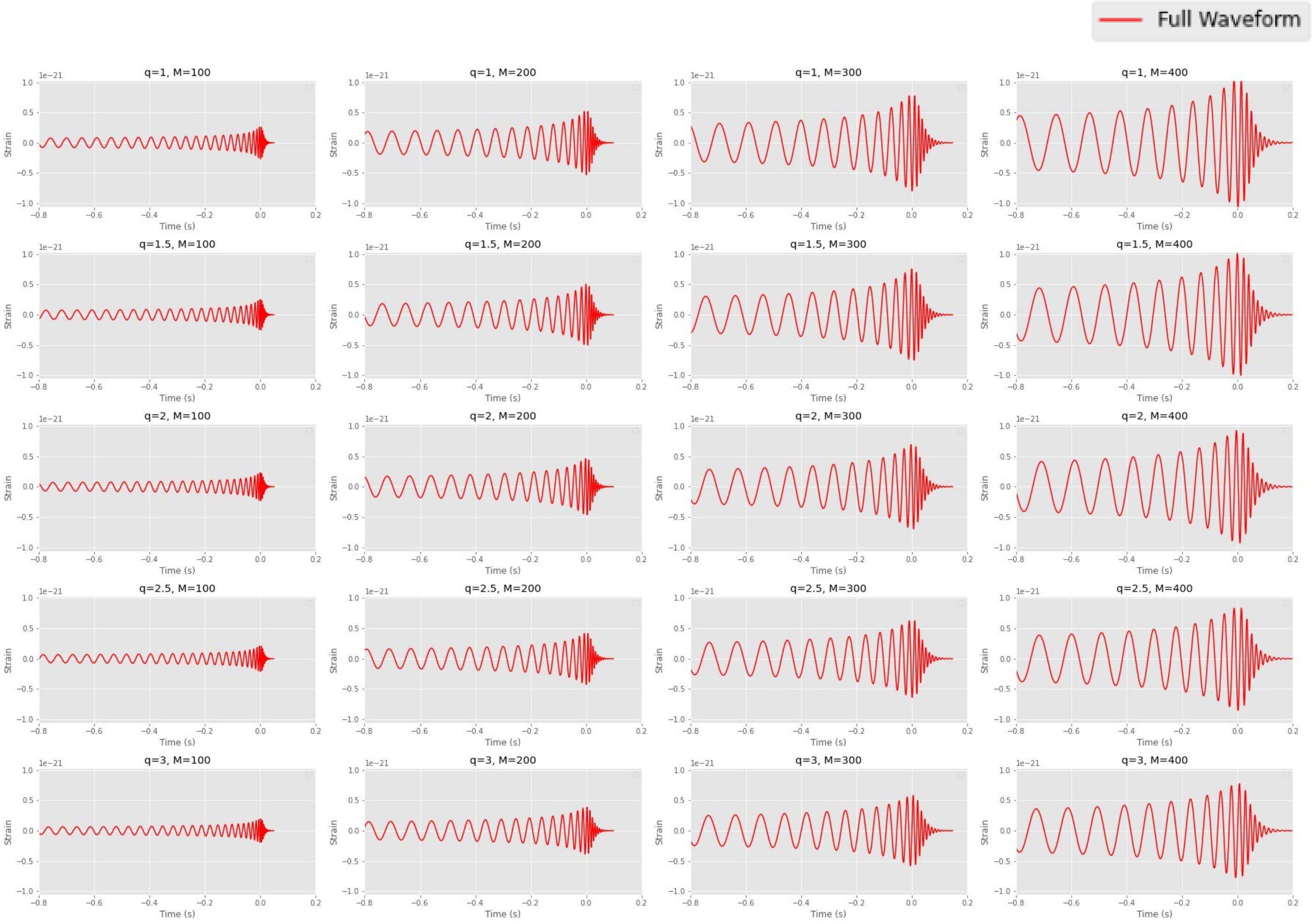


We use **NRSur7dq4** in the remaining part of this talk

GWs from BBHC resulting in the production of an IMBH





Waveforms generation based on numerical relativity surrogate model **NRSur7dq4**, V. Varma et al. Phys. Rev. Research 1, 033015, ArXiv:1905:09300

System distance set arbitrarily to **5 GPc** for all waveforms.

Spin configuration
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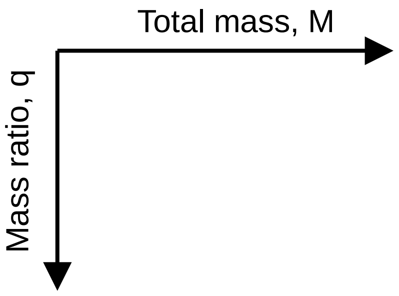

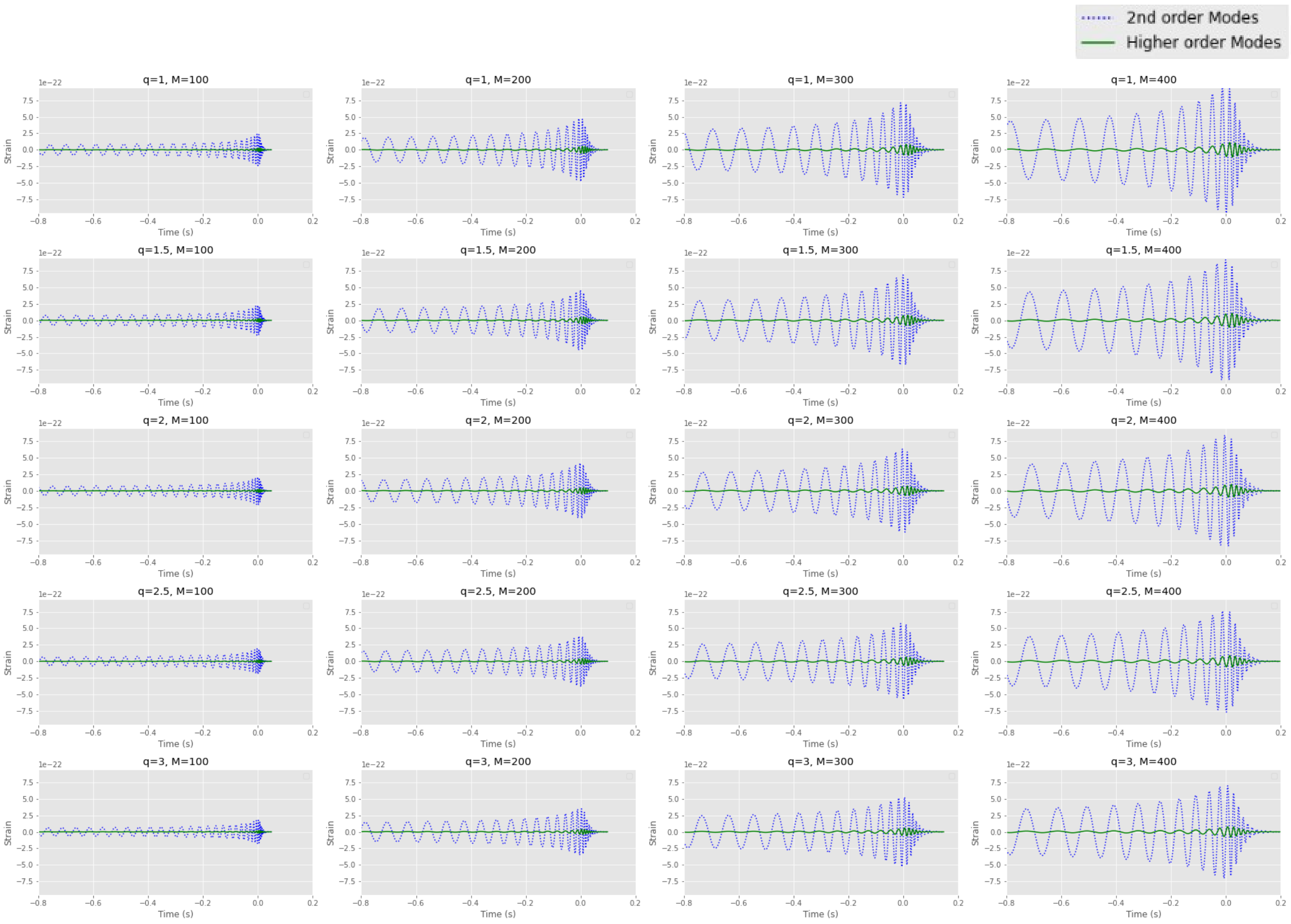

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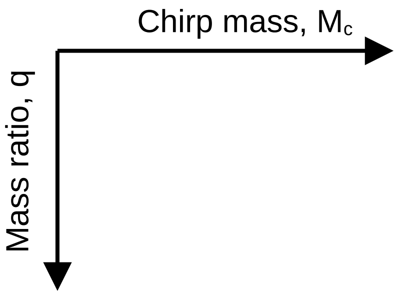

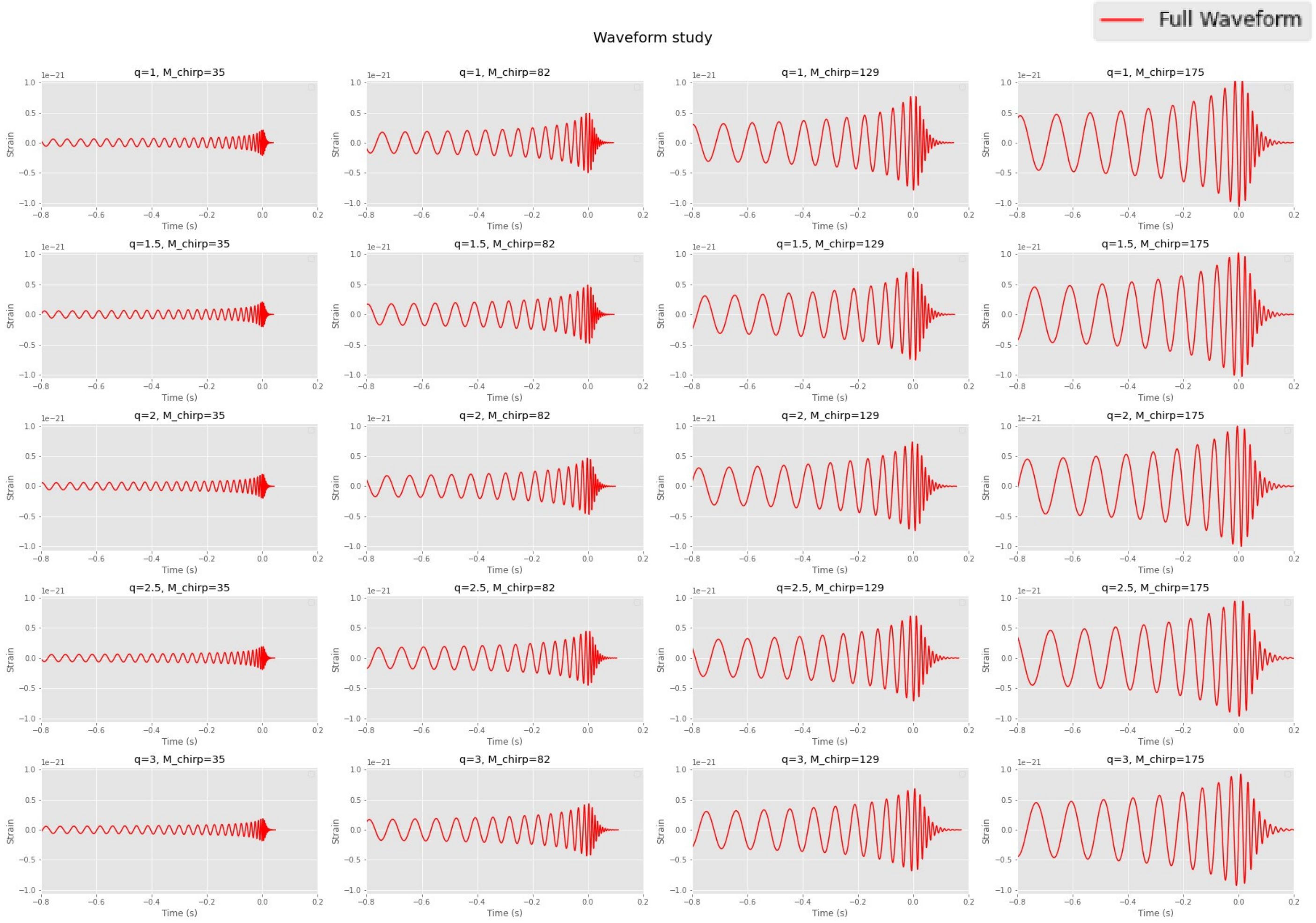

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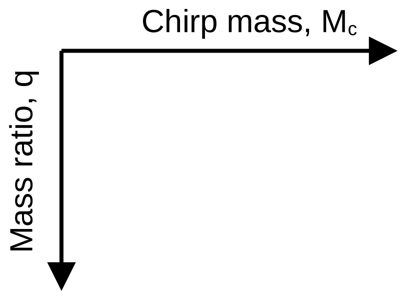

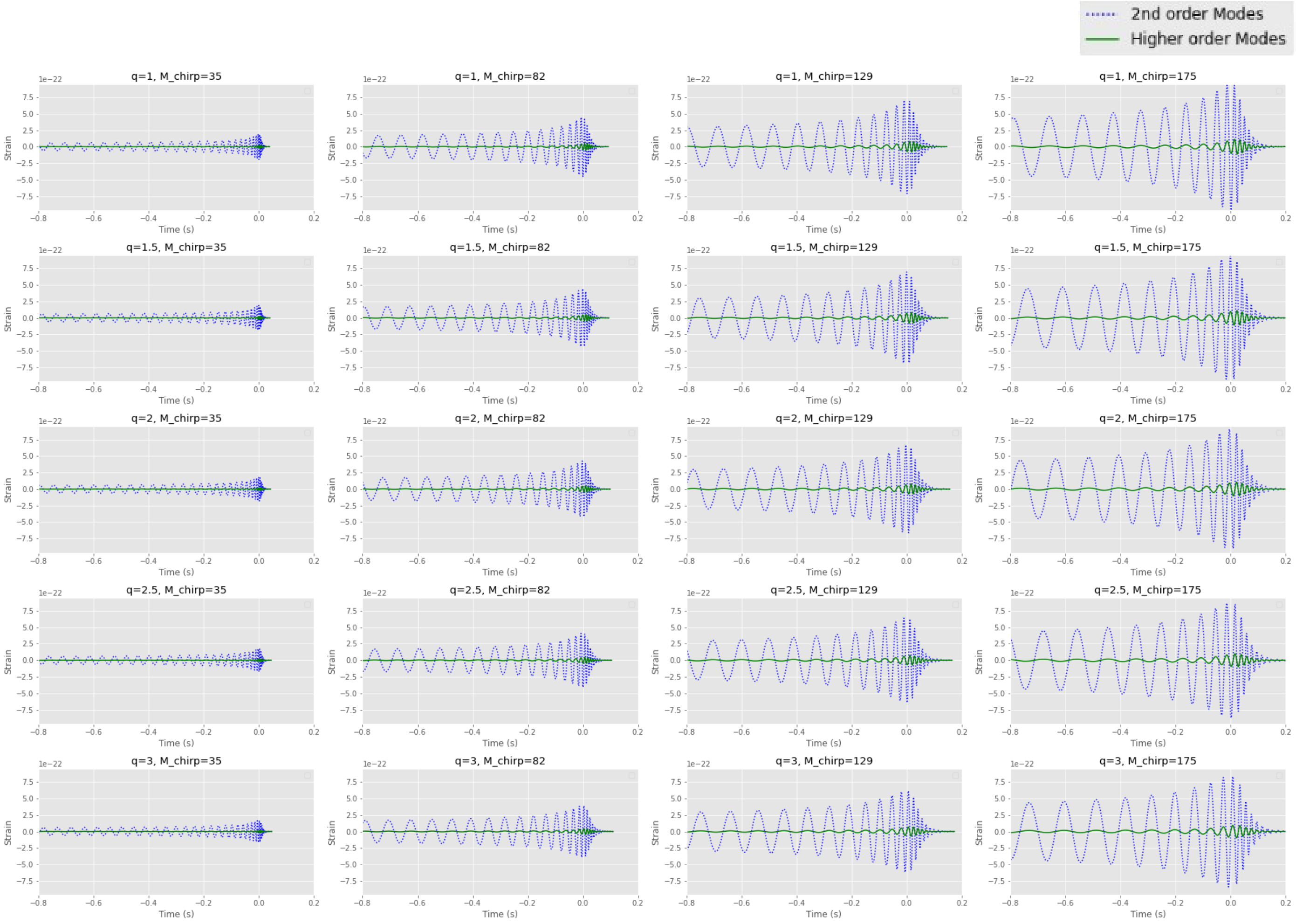

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Inclination

Mass ratio, q

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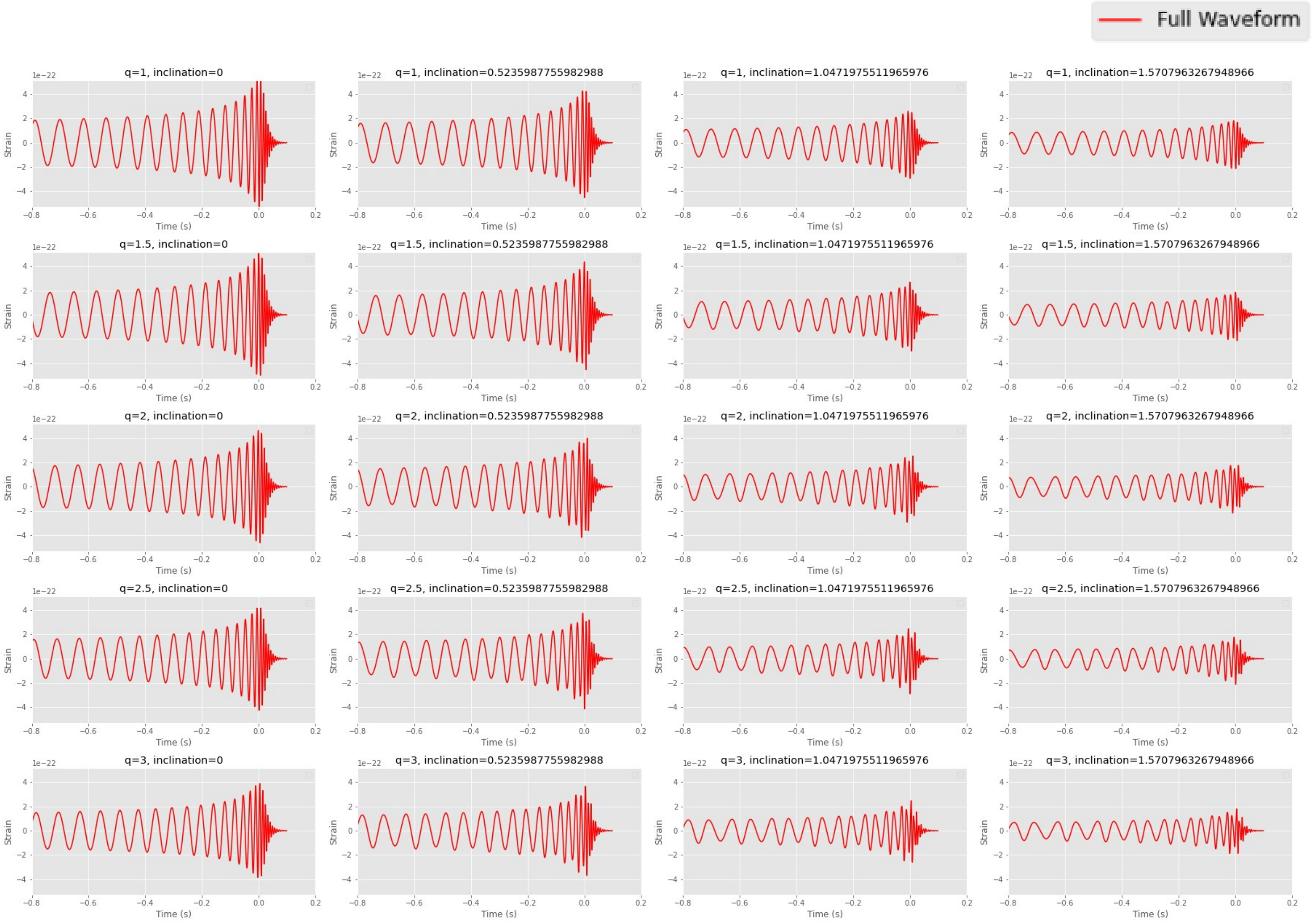

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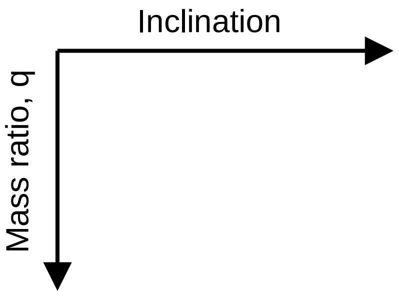

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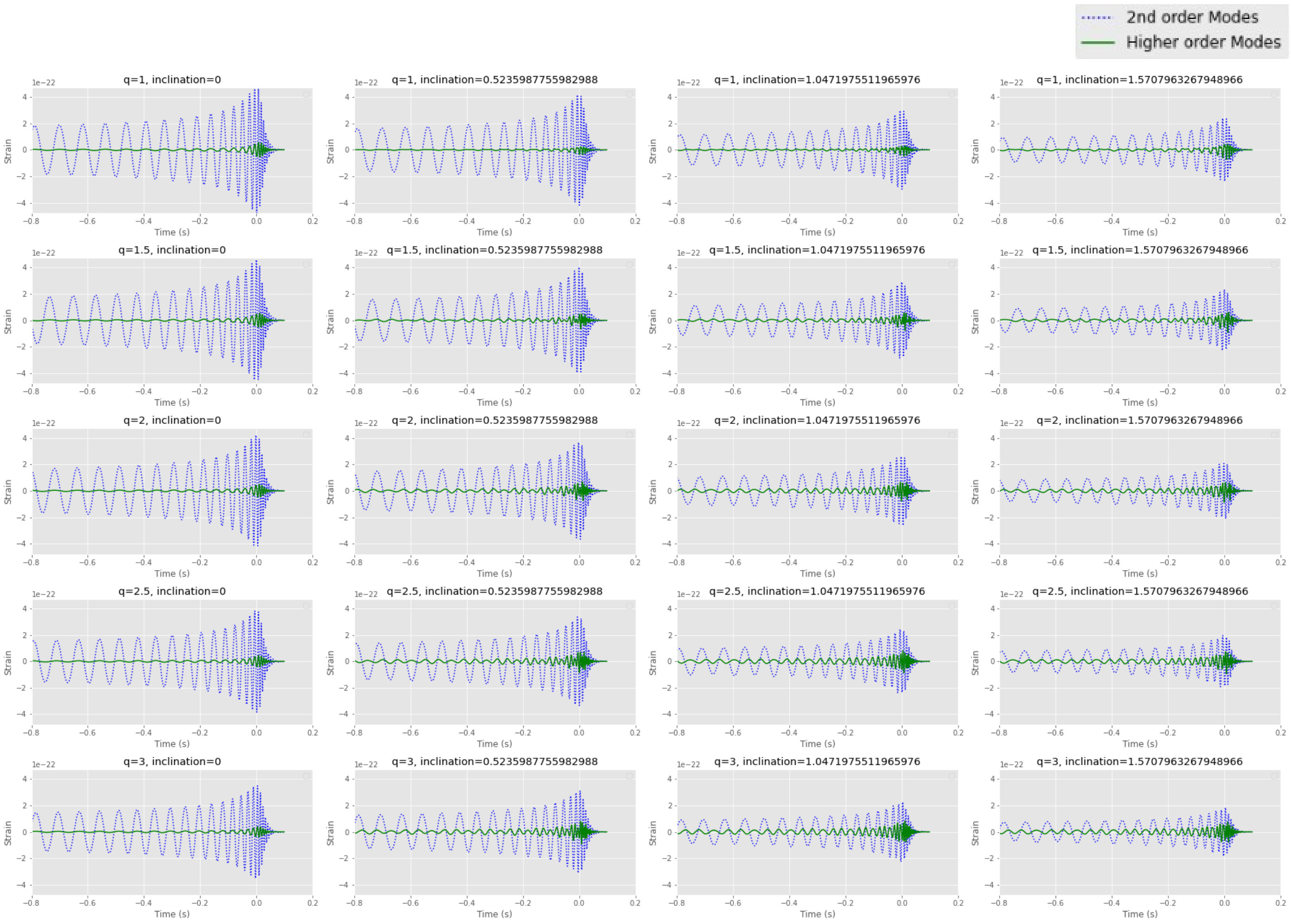
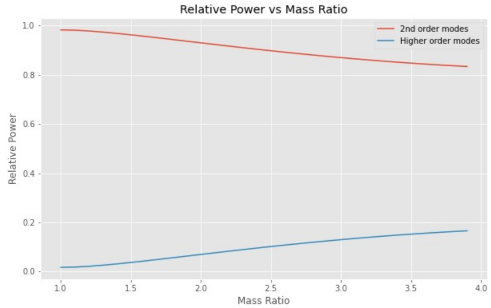


Use of relative power as a metric to assess the impact of higher-order modes

- $P^{rel}{}_i = P_i / P_{tot}$
- $where\ P_i = \frac{1}{N}\sum_{i=1}^{N} | \frac{\partial h_i(t)}{\partial t} |^2\ and\ P_{tot} = \sum_{i=1}^{N} P_i$



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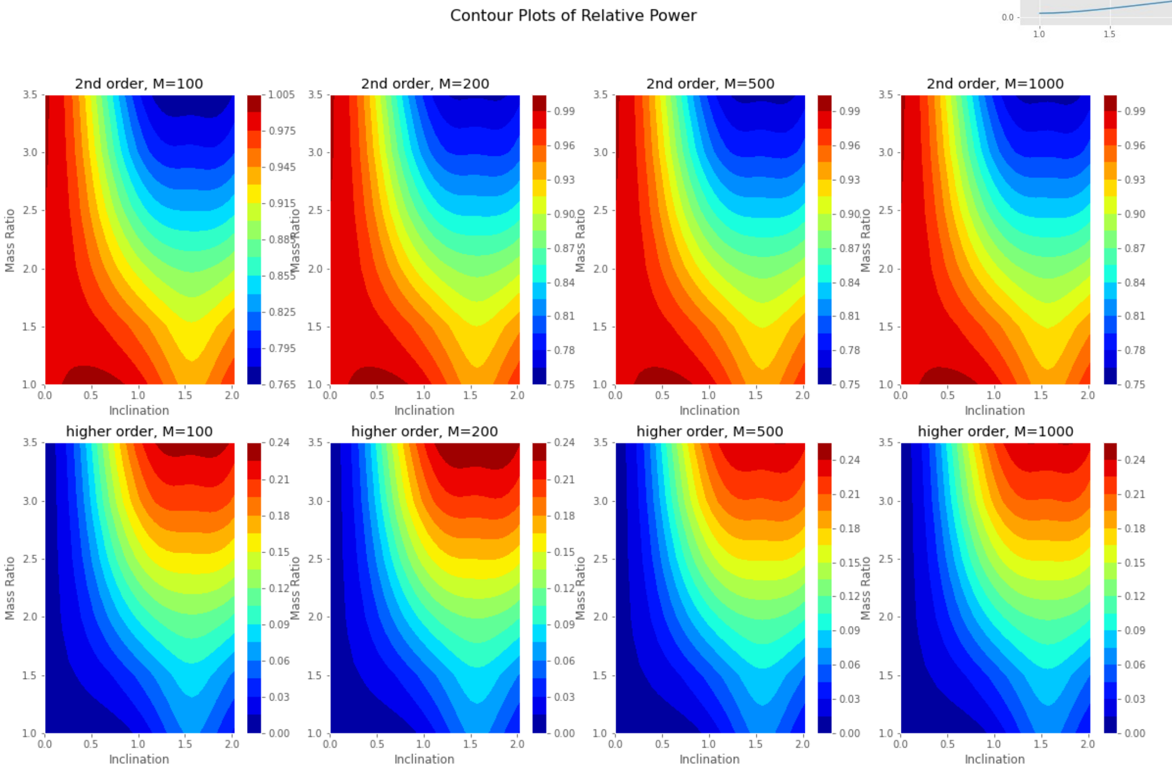

- Relative power show the relative contribution of various modes to the total waveform.
- It shows that higher-order modes can be as large as 20%
- On the left plot a 2D contour plot for different masses and total masses, different mass ratios and different inclinations.

Conclusions

- IMBHs are very interesting objects that can help our understanding of **fundamental physics** / **astrophysics** / **cosmology**

- Gravitational waves originating from the **production of an IMBH** are difficult to be detected and require detector sensitivity to **low frequency (<100 Hz)**

- LISA will detect the inspiral phase (years!) and warn ET of the future incoming GWs, dedicated analysis pipelines can be tuned: **Multiband GW astrophysics**

- **Higher-order modes** becomes more and more relevant for events with larger masses / mass ratios / orientations etc. and **can be as large as 20-30%**

- A template matching and consequent statistical analysis that doesn’t appropriately account for **higher-order** modes will/might **introduce a bias in the parameters estimation**

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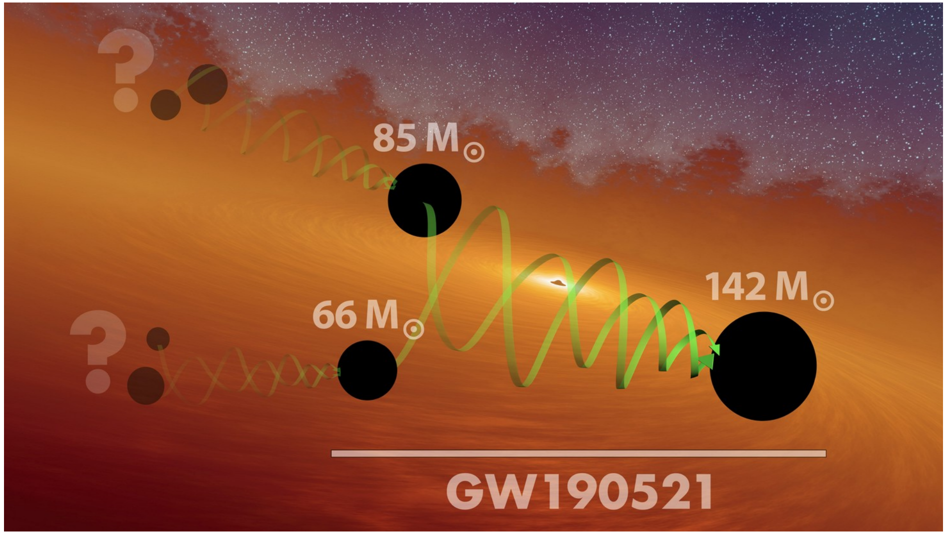
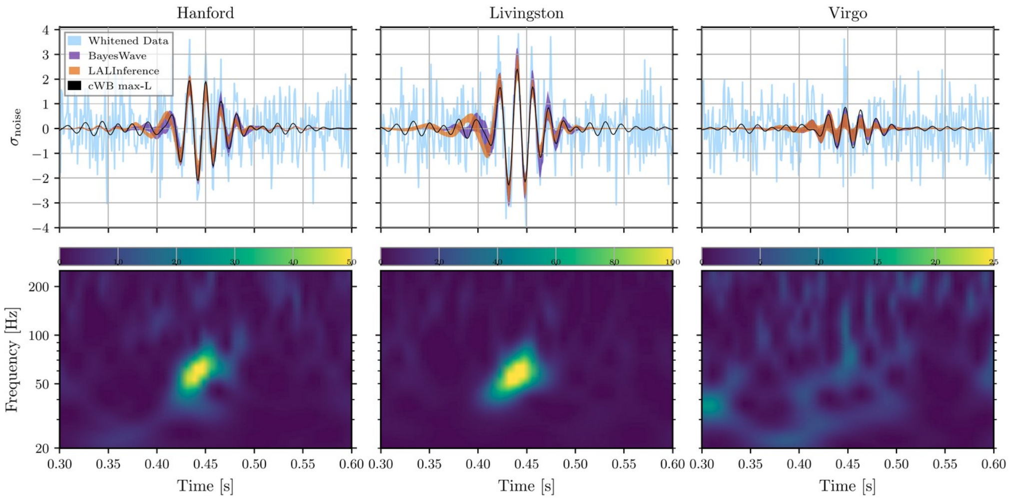
Positions in my group in Vienna at HEPHY – OEAW will become available soon.

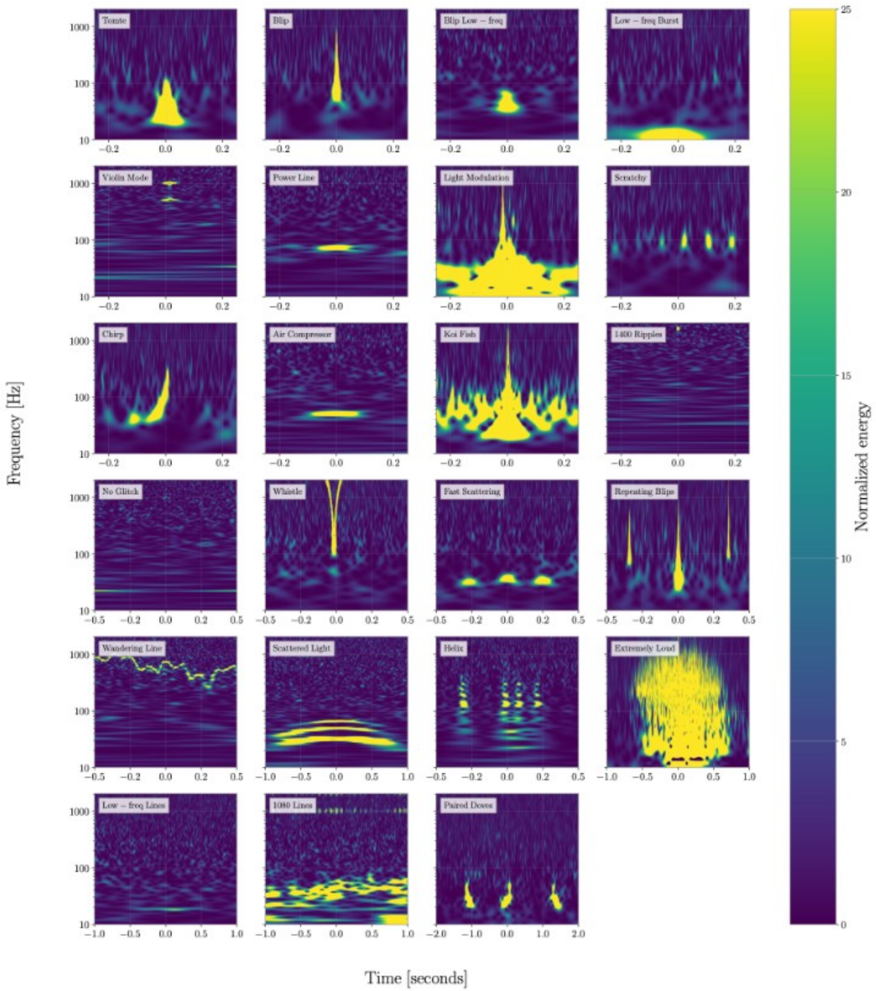
First call for a long-term postdoc to launch these days. Come and talk to me if interested!

Thank you for your attention!

Glitches can mimic a real signal, plan to use Autoencoder and/or CNN



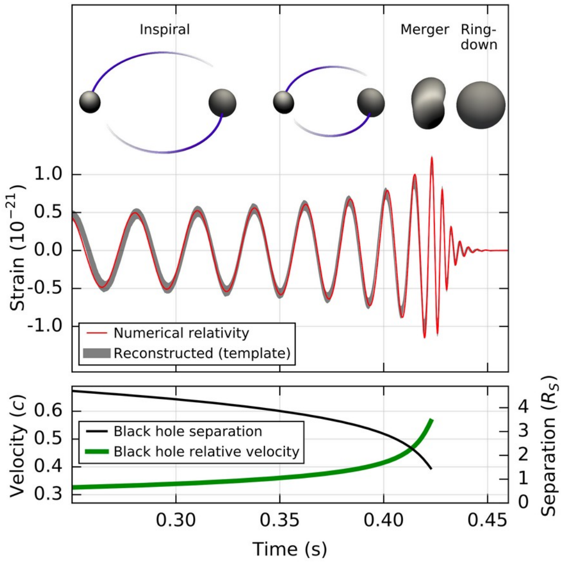




From(link) Data quality up to the third observing run of Advanced LIGO: Gravity Spy glitch classifications

Example of fundamental physics research opportunities with the Einstein Telescope (personal choice)

- **Dark matter**
  - exotic compact objects (boson stars, fermionic DM stars, etc. M_{DM}~MeV–GeV)
  - axion clouds (M_{DM}~10^{-19} 10^{-10} eV), dark matter accreting on compact objects (M_{DM}~0.1 – 10^3 KeV)



Ex. Fermionic dark matter “spikes” imprinted in GW signals

Consider a system of a degenerate fermionic DM, the Fermi velocity is

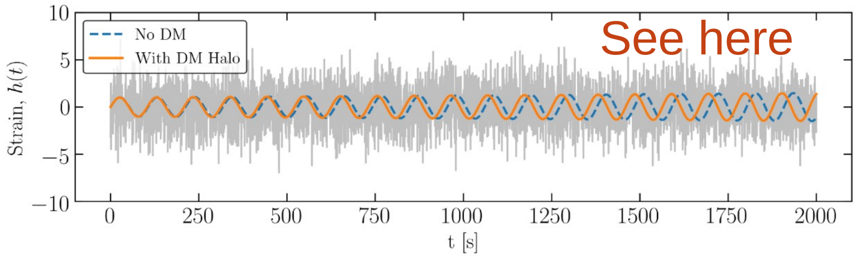
$$v_F = \left(\frac{6\pi^2\hbar^3\rho}{m_{\rm DM}^4 g}\right)^{1/3}. \quad (5)$$

For the density spike to be stable, the Fermi velocity must be less than the escape velocity of the BH plus DM spike system

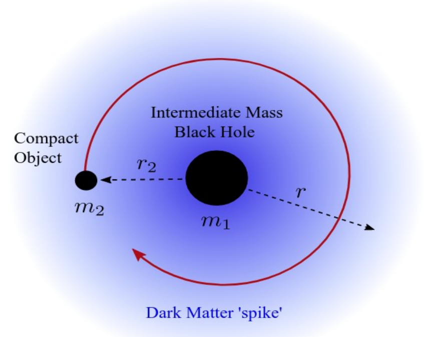
$$v_F \leq v_{esc} \equiv \sqrt{\frac{2G\,(M_{\rm BH}+M_\chi)}{R}} \simeq \sqrt{\frac{2GM_{\rm BH}}{R}}. \quad (6)$$

This translates to a lower bound on the fermionic DM mass, given an observation of density $\rho_{\rm obs}$,

$$m_{\rm DM} \gtrsim 30\,{\rm keV}\left(\frac{\rho_{\rm obs}}{10^{20}\,{\rm GeV/cm^3}}\frac{2}{g}\right)^{1/4}\left(\frac{R}{20M_{\rm BH}}\right)^{3/8}.$$



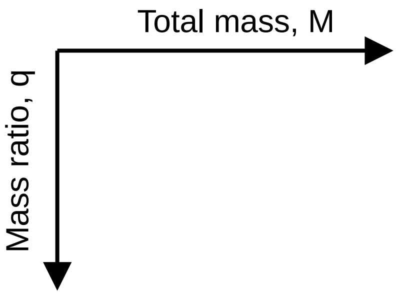
See here

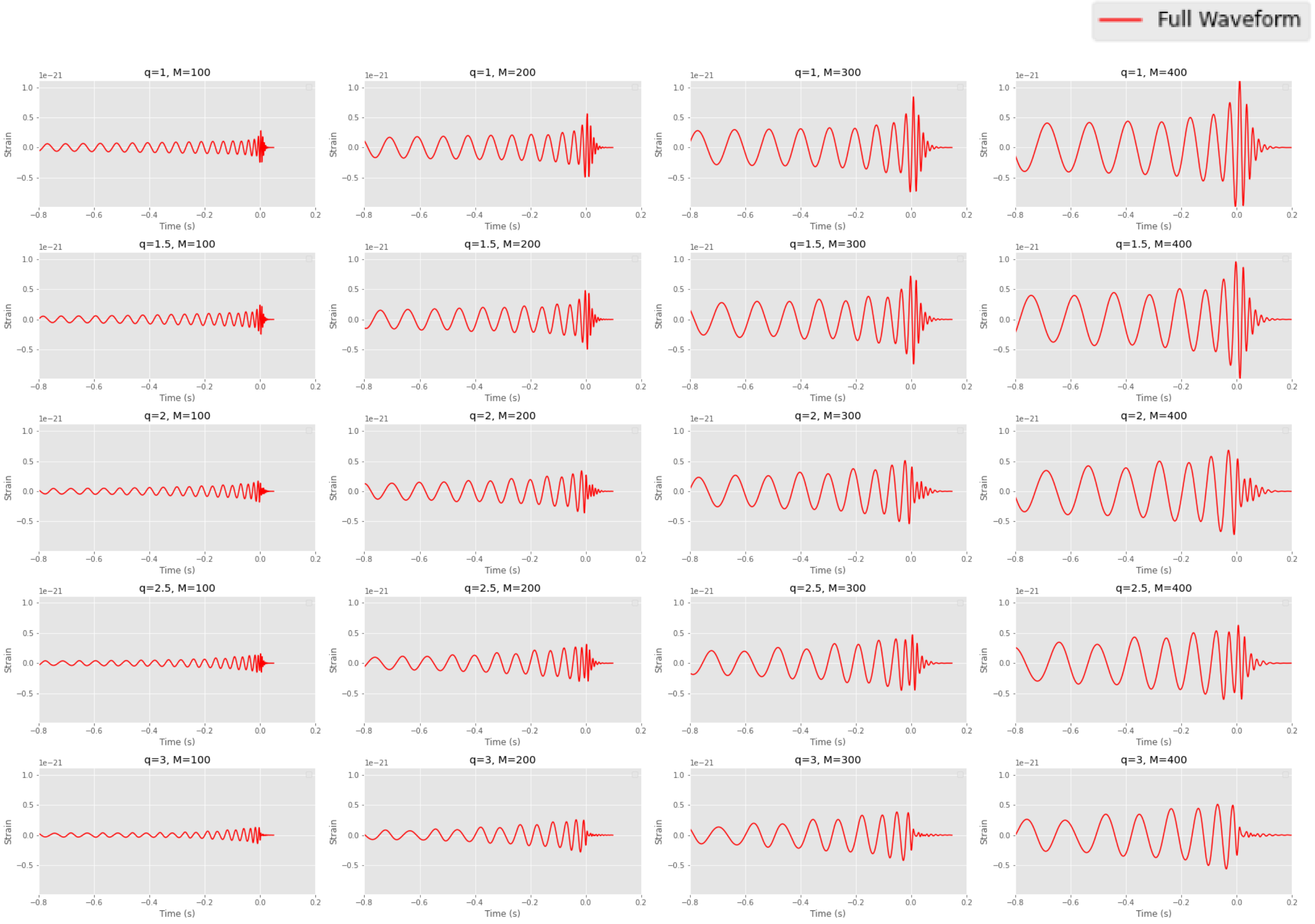


ArXiv: 210804154

ArXiv: 1906.11845

GWs from BBHC resulting in the production of an IMBH





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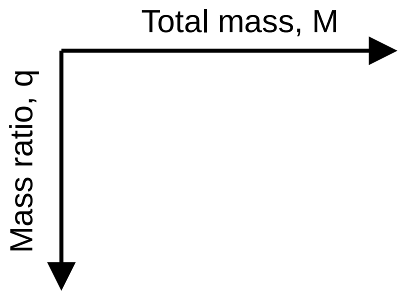

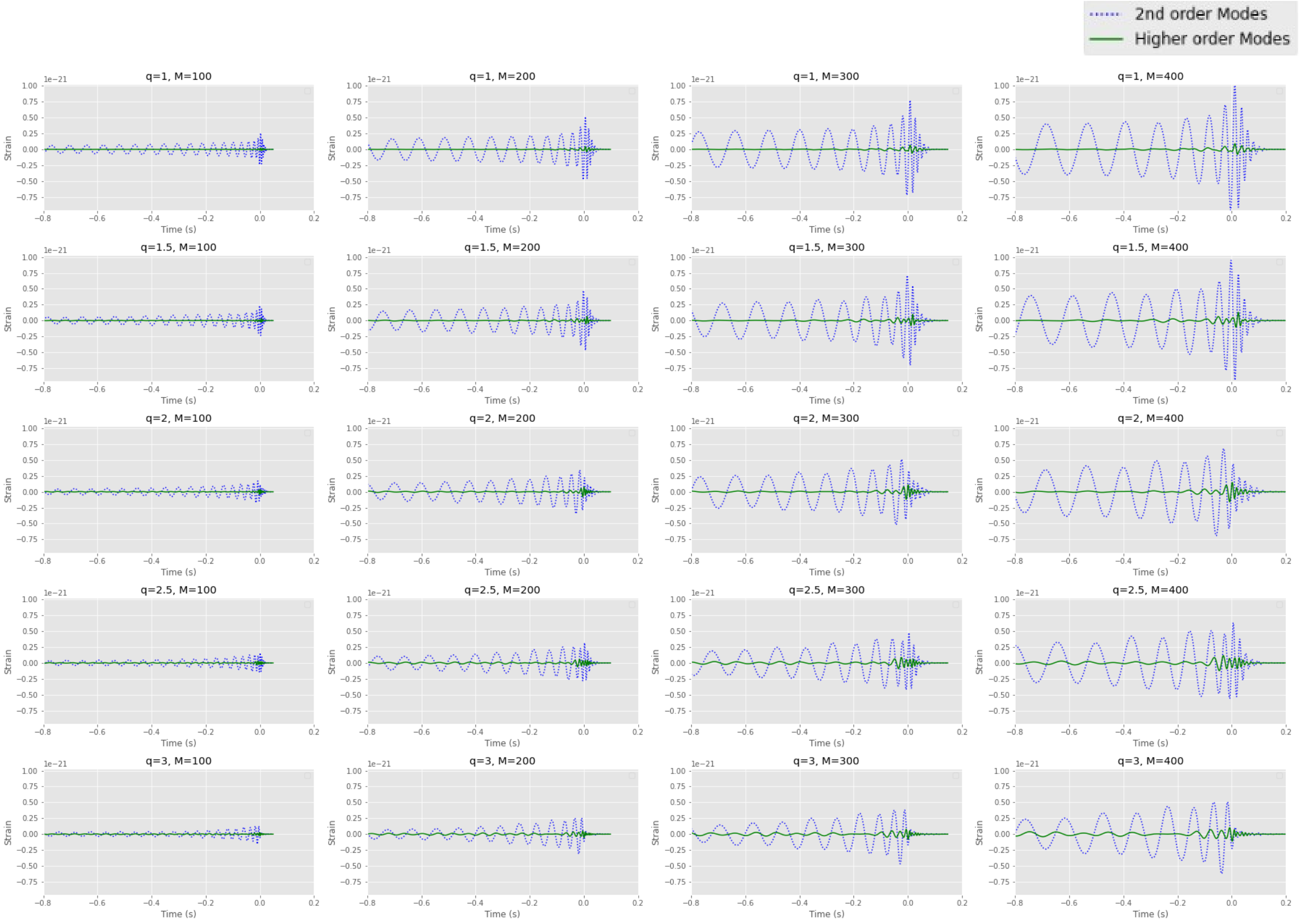

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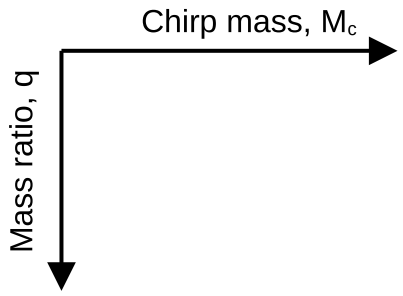

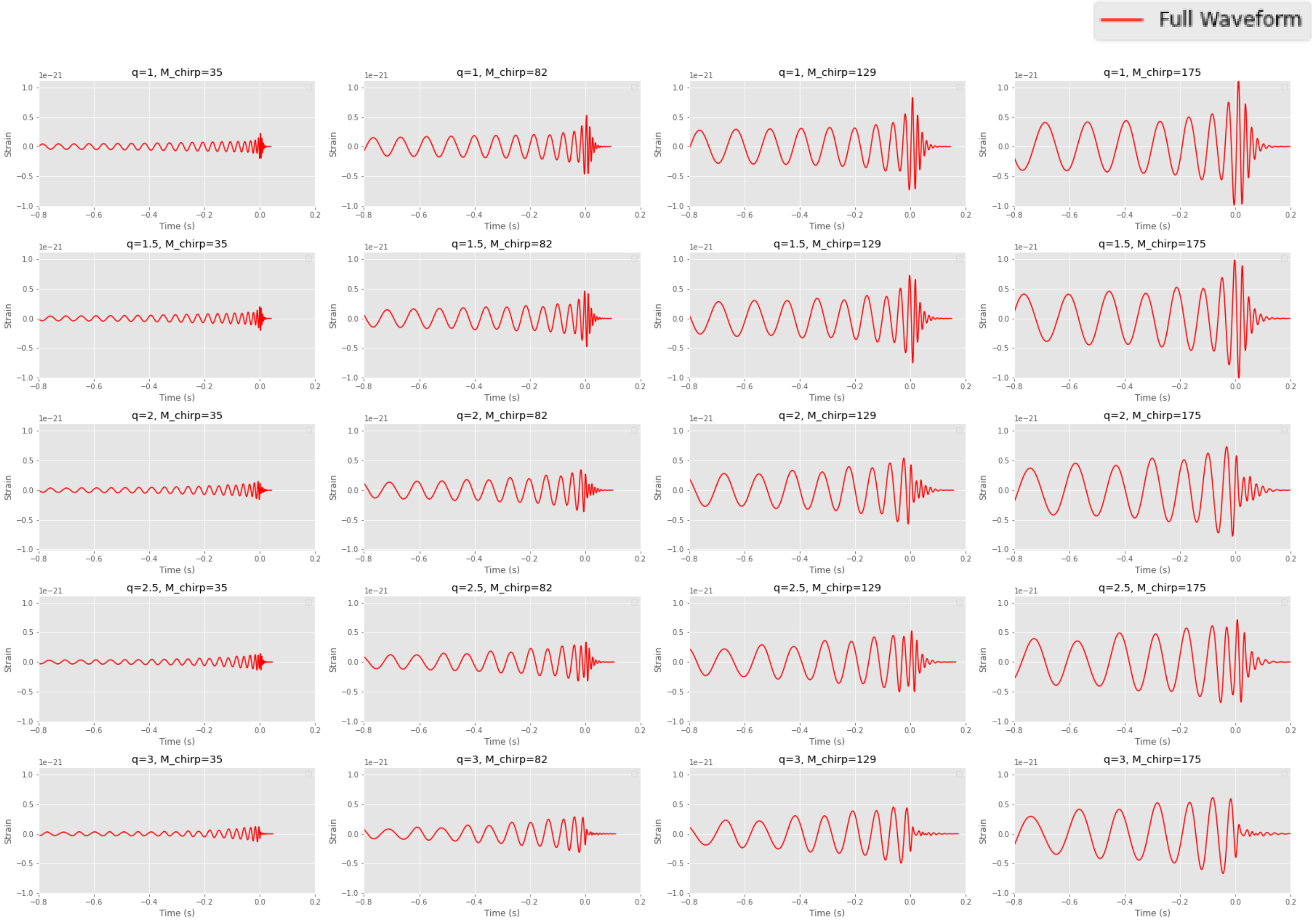

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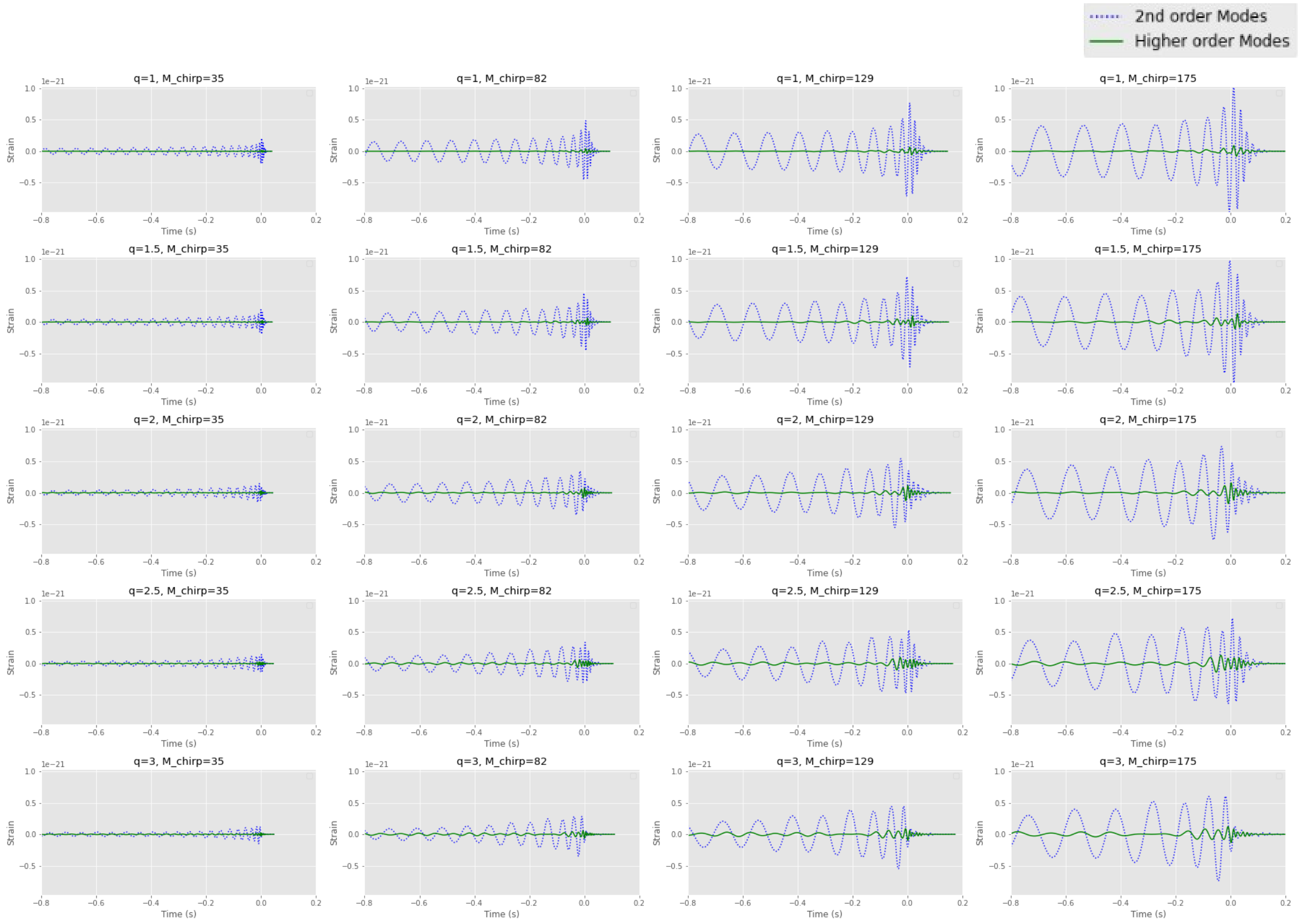
Chirp mass, M_c

Mass ratio, q

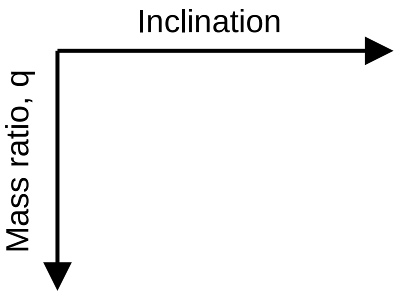


Waveforms generation based on numerical relativity surrogate model **NRSur7dq4**, V. Varma et al. Phys. Rev. Research 1, 033015, ArXiv:1905:09300

System distance set arbitrarily to **5 GPc** for all waveforms.

Spin configuration
s_1=(1,0,0), s_2=(0,-1,0)

GWs from BBHC resulting in the production of an IMBH



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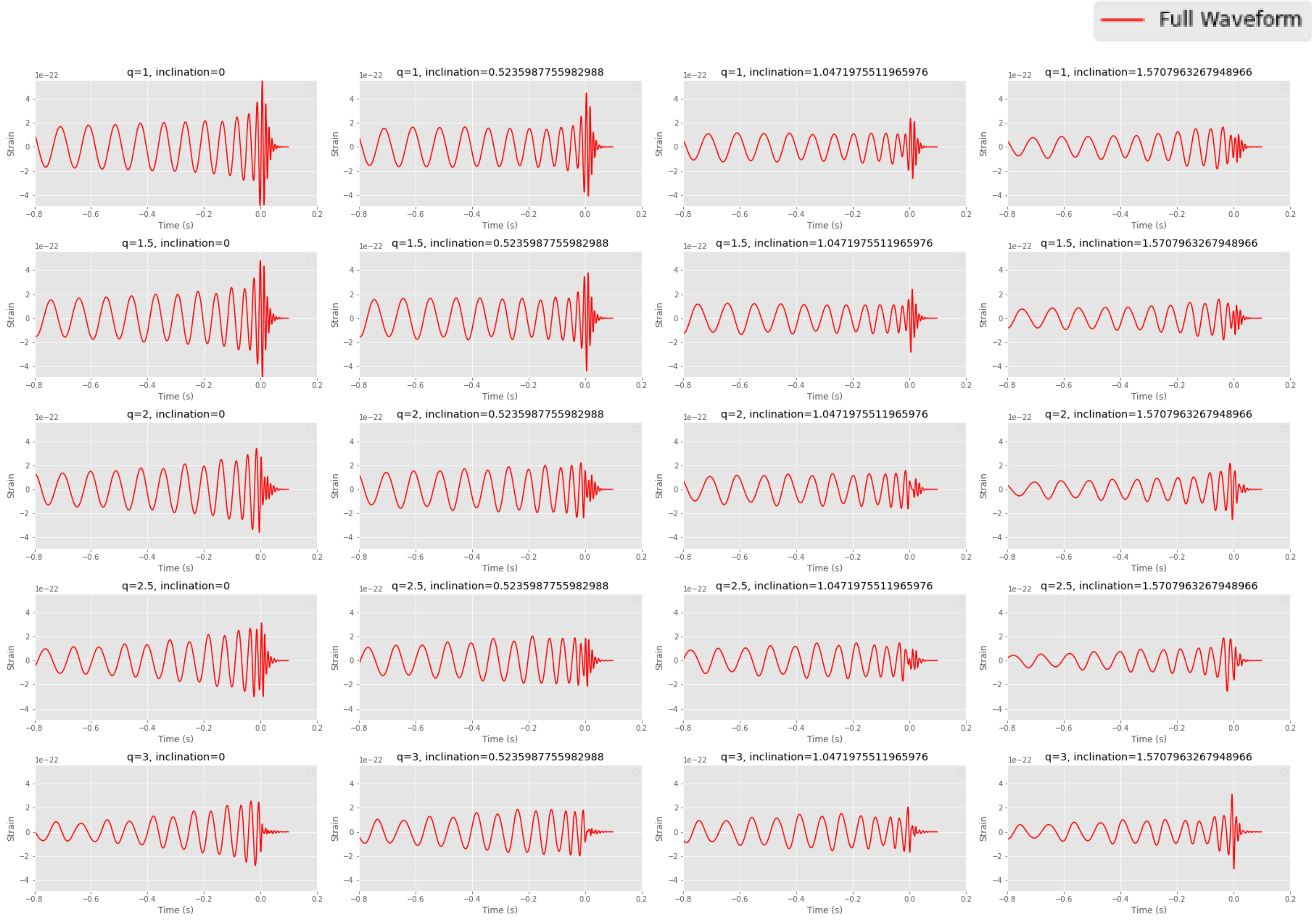

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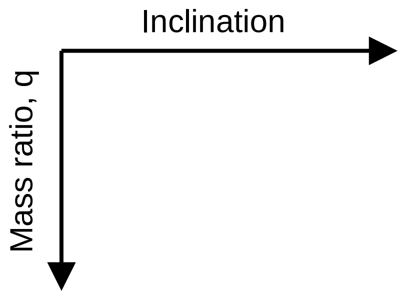

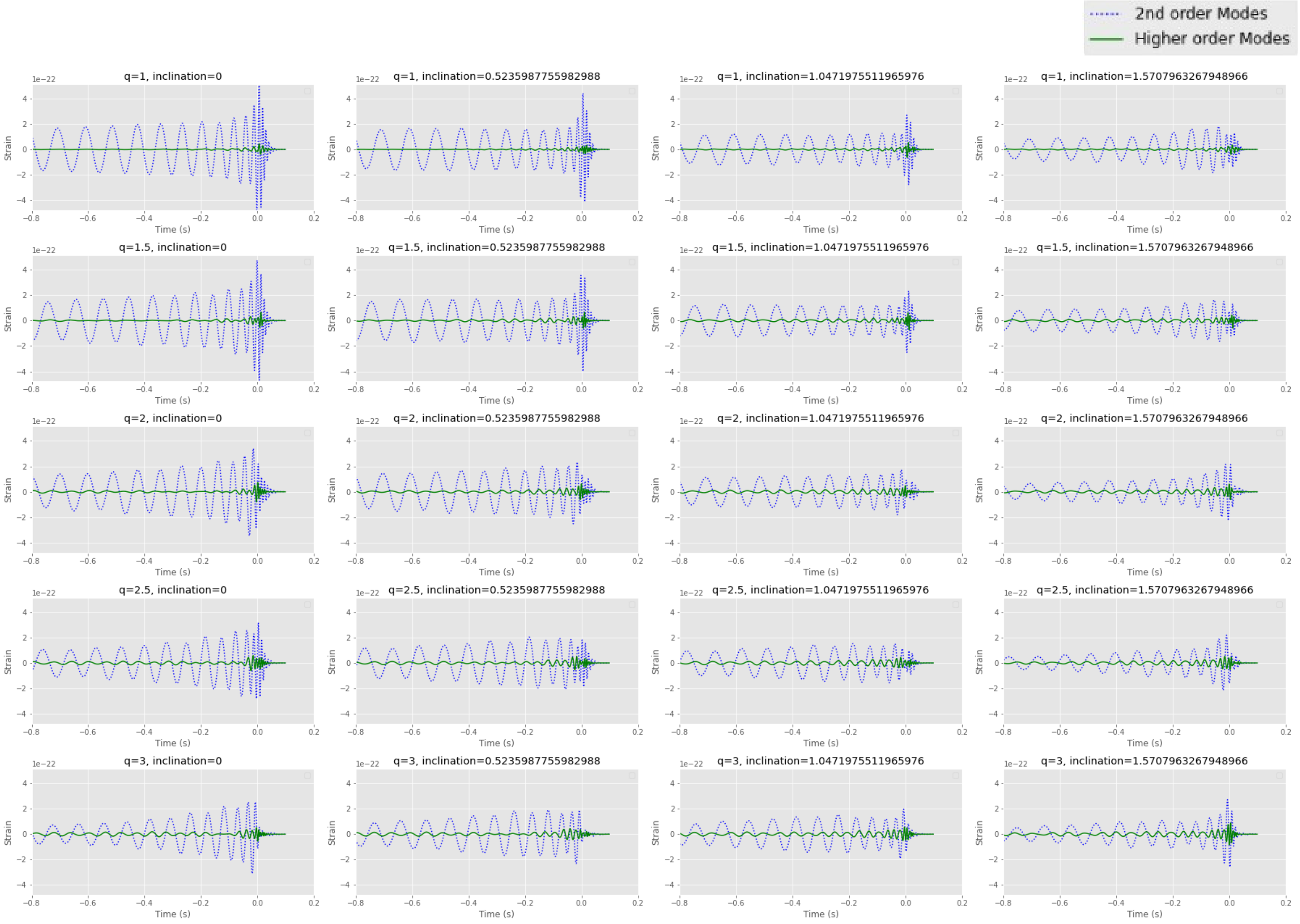

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Use of relative power as a metric to assess the impact of higher-order modes

Work in progress that needs to be understood in detail

- $P^{rel}{}_i = P_i / P_{tot}$
- $where\ P_i = \frac{1}{N} \sum_{i=1}^{N} |\frac{\partial h_i(t)}{\partial t}|^2\ and\ P_{tot} = \sum_{i=1}^{N} P_i$