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Gravitational wave signatures of intermediate-mass black holes Gianluca Inguglia (gianluca.inguglia@oeaw.ac.at), Melvin Cap





ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN





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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



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?

Мo SBH **IMBH SMBH**

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



- 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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- Several events associated with the production of a BH in the PISN BHs mass gap
- Few events possibly associated with the production of an IMBH, GW100521 being the most significant



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





Very "short" signal \rightarrow a "**burst**"

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

-0.20

-0.15

-0.10

-0.05

Time (s)

0.00

0.05

0.10



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

9

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 few $10^3 M_{\odot}$ will be nicely visible with the final part of their inspiral detected
- GW transients due to systems with total mass of O(10⁴) 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)

0.6 Hrs

frequency (Hz)

10-



 10^{2}

 10^{3}

 10^{4}

Care needed when using approximants



Comparisons between NRSur7dq4 and Phenomenological Approximant

Care needed when using approximants



Comparisons between NRSur7dq4 and Phenomenological Approximant

We use NRSur7dq4 in the remaining part of this talk

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

Total mass, M

σ

Mass ratio,

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



Time (s)

Р

Mass ratio,

Higher order Modes a=1 M=100 a=1 M=200 a=1. M=300 g=1. M=400 1e-22 1e-22 1e-22 Total mass, M 5.0 5.0 -5.0 -5.0 0.0 --5.0 -5.0 -5.0 -7.5 -75--0.8 -0.4 -0.2 -0.8 -0.4 -0.2 -0.8 -0.2 -0.2 Time (s) Time (s) Time (s) Time (s) q=1.5, M=100 q=1.5, M=200 q=1.5, M=300 q=1.5, M=400 1e-22 1e-2 1e-2 1e-2 7.5 -7.5 5.0 -5.0 5.0 5.0 -2.5 25 - 1 0.0 -5.0 -5.0 -0.2 -0.8 -0.2 -0.2 -0.8 -0.6 -0.2 Time (s) Time (s) Time (s) Time (s) Waveforms generation based q=2, M=400 q=2, M=100 q=2, M=200 q=2, M=300 1e-22 1e-22 1e-2 on numerical relativity surrogate 7.5 5.0 5.0 model NRSur7dq4, V. Varma 2.5 2.5 2.5 et al. Phys. Rev. Research 1, 0.0 0.0 033015, ArXiv:1905:09300 -5.0 -0.8 -0.4 -0.2 -0.8 -0.4 -0.2 -0.8 -0.4 -0.2 -0.8 -0.6 -0.4 -0.2 Time (s) Time (s) Time (s) Time (s) System distance set arbitrarily a=2.5. M=100 q=2.5, M=200 a=2.5. M=300 a=2.5. M=400 1e-22 1e-22 1e-2 to 5 GPc for all waveforms. 7.5 -7.5 5.0 5.0 -5.0 -5.0 2.5 2.5 2.5 -Spin configuration 0.0 s₁=(0,0,1), s₂=(0,0,1) -5.0 -0.4 -0.2 -0.4 -0.2 -0.4 -0.2 Time (s) Time (s) Time (s) Time (s) q=3, M=100 q=3, M=200 q=3, M=300 q=3, M=400 1e-22 1e-22 1e-22 7.5 5.0 5.0 5.0 0.0 0.0 0.0 -2.5 -5.0 -5.0 -5.0 -5.0 -7.5 -0.6 -0.4 -0.2 0.0 -0.8 -0.4 -0.2 -0.8 -0.4 -0.2 0.0 -0.6 -0.4 -0.2

Time (s)

Time (s)

16

0.0

Time (s)

······ 2nd order Modes

Р

Mass ratio,

Full Waveform Waveform study 1.0 -1e-21 a=1 M chirp=35 q=1, M chirp=82 q=1, M chirp=129 q=1, M chirp=175 1e-21 le-21 le-21 1.0 10 Chirp mass, M_c 0.5 0.5 -0.5 -0.8 -0.4 -0.2 -0.8 -0.4 -0.8 -0.2 -0.2 -0.2 Time (s) Time (s) Time (s) Time (s) 1.0 -le-21 1.0 -1e-21 q=1.5, M_chirp=35 q=1.5, M_chirp=82 q=1.5, M_chirp=129 q=1.5, M_chirp=175 1e-2 1e-2 0.5 0.0 --0.2 -0.8 -0.2 -0.8 -0.8 -0.6 -0.2 Time (s) Time (s) Time (s) Time (s) Waveforms generation based 1.0 -21 1e-21 q=2, M_chirp=35 q=2, M_chirp=82 q=2, M_chirp=129 q=2, M_chirp=175 1e-2 1e-23 1.0 on numerical relativity surrogate model NRSur7dq4, V. Varma 0.5 et al. Phys. Rev. Research 1, 0.0 -033015, ArXiv:1905:09300 -0.5 -0.5 -0 5 -0 9 -1.0 -0.8 -0.4 -0.2 -0.8 -0.4 -0.2 0.0 -0.8 -0.4 -0.2 0.0 -0.8 -0.6 -0.4 -0.2 Time (s) Time (s) Time (s) Time (s) System distance set arbitrarily 1.0 -le-21 1.0 -1e-21 q=2.5, M_chirp=175 q=2.5, M_chirp=35 q=2.5, M_chirp=82 q=2.5, M_chirp=129 1e-2 1.0 to 5 GPc for all waveforms. 0.5 0.5 U 0.0 Spin configuration 0.0 s₁=(0,0,1), s₂=(0,0,1) -0.5 -04 -0.2 -0.6 -0.6 -0.4 -0.2 0.0 -0.4 -0.2 Time (s) Time (s) Time (s) Time (s) 1.0 -21 1.0 -1e-21 10 -21 q=3, M_chirp=175 q=3, M_chirp=35 q=3, M_chirp=82 q=3, M_chirp=129 10-2 1.0 0.5 0.5 0.0 --0.5 -0.5 -1.0 -0.6 -0.4 -0.2 0.0 -0.8 -0.4 -0.2 0.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 -0.8 -0.6 -0.4 -0.2 0.0 Time (s) Time (s) Time (s) Time (s)

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Chirp mass, M_c

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



р

Mass ratio,

Full Waveform g=1 inclination=0 g=1_inclination=1.0471975511965976 g=1 inclination=1.5707963267948966 g=1 inclination=0.5235987755982988 10-22 1e-22 Inclination Time (s) Time (s) Time (c) Time (c) q=1.5, inclination=0 q=1.5, inclination=0.5235987755982988 1e-22 q=1.5, inclination=1.0471975511965976 1e-22 q=1.5, inclination=1.5707963267948966 Time (s) Time (s) Time (s) Time (s) Waveforms generation based q=2, inclination=1.0471975511965976 q=2, inclination=0 1e-22 q=2, inclination=0.5235987755982988 q=2, inclination=1.5707963267948966 1e-22 10-77 on numerical relativity surrogate model NRSur7dq4, V. Varma et al. Phys. Rev. Research 1, 033015, ArXiv:1905:09300 Time (s) Time (s) Time (s) System distance set arbitrarily Time (s) g=2.5, inclination=0 1e-22 q=2.5, inclination=0.5235987755982988 1e-22 q=2.5, inclination=1.0471975511965976 g=2.5, inclination=1.5707963267948966 to 5 GPc for all waveforms. Spin configuration s₁=(0,0,1), s₂=(0,0,1) -0.4 Time (s) Time (s) Time (s) Time (s) q=3, inclination=0 1e-22 q=3, inclination=0.5235987755982988 q=3, inclination=1.0471975511965976 q=3, inclination=1.5707963267948966 10-77 10-77 -0.6 -0.4 -0.2 0.0 -0.6 -0.2 -0.6 -0.4 -0.2 0.0 Time (s) Time (s) Time (s) Time (s)

р

Mass ratio,



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

Relative Power vs Mass Ratio



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.

- 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

Frequency [Hz]







From(link) Data quality up to the third observing run² 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 $(M_{DM} \sim 0.1 - 10^3 \text{ KeV})$





Ex. Fermionic dark matter "spikes" imprinted in GW signals

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

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

Intermediate Mass Black Hole

Dark Matter 'spike'

 m_2

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

This translates to a lower bound on the fermionic DM mass, given an observation of density ρ_{obs} .



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σ

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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 $P_{tot} = \sum_{i=1}^{N} P_i$



2nd order, M=500 2nd order, M=1000 2nd order. M=100 2nd order, M=200 - 0.975 075 3 - 0.945 - 0.915 0.889 1.0 , 0.795 1.0 0.795 1 0.5 10 15 20 Inclination 10 15 Inclination 0.5 1.0 1.5 Inclination 0.0 0.5 2.0 00 05 2.0 00 Inclination higher order, M=100 higher order, M=200 higher order, M=500 higher order, M=1000 0.18 0.18 - 0.18 - 0.15 0.00 1 0.5 1.0 1.5 2.0 0.0 0.5 1.0 1.5 0.5 10 15 20 0.0 2.0 0.0 0.5 1.0 1.5

Inclination

Inclination

Inclination

Contour Plots of Relative Power

Inclination