Coalescences of IMBH binaries as sources for the future ET detector

Lucía Santamaría, Pau Amaro-Seoane

(Albert-Einstein-Institut Potsdam, Germany)

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IMBH binaries as seen by the GW detectors

The (disputed) existence of IMBHs

Modeling BBH coalescence

Event rates of IMBH binaries

Summary and Conclusions

Plan of the talk

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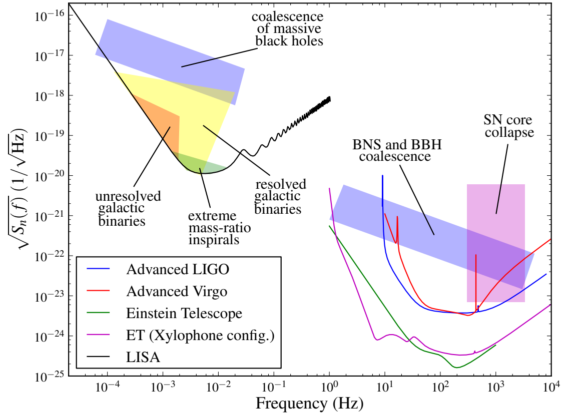
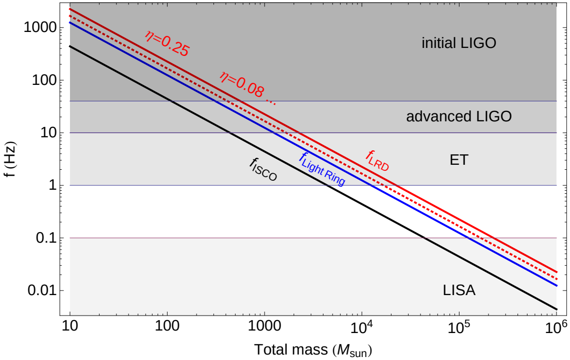
Different detectors for different sources



- Current ground-based GW astronomy: neutron-star binaries and solar-mass BBHs. Scarce sources (for now) - around-threshold events
- Space-based projects: SMBHs, EMRIs, galactic binaries. Abundance of sources - huge SNRs
- ET: IMBHs? Expected event rates? Foreground noise?

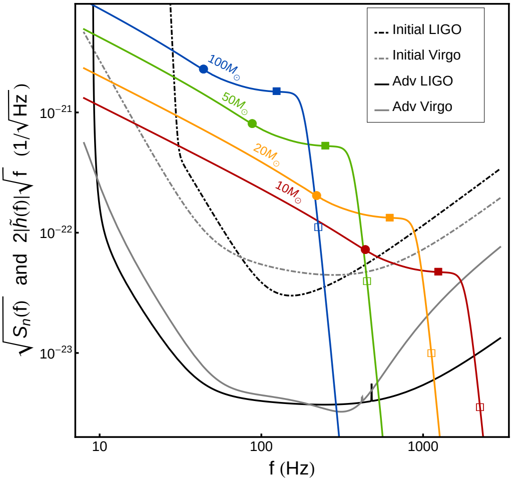
ET opens a window in the intermediate-mass region



- As total mass of the system increases, BBHs merge at lower frequencies
- Shown are the ISCO ($r = 6M$), Light ring ($r = 3M$) and Lorentzian ringdown (after merger) frequencies of equal-mass ($\eta = 0.25$) and 1:10 ($\eta = 0.08$) binary systems $\left[\eta \equiv \frac{m_1 m_2}{(m_1+m_2)^2}\right]$
- While LIGO's efforts are targeted towards stellar-mass binaries, LISA will see mergers of supermassive BBHs (and also IMBHs' *inspirals*)
- ET will open a window in the intermediate-mass region $10^2 - 10^4\, M_\odot$
- IMRIs and IMBH-IMBH binaries. In this talk: IMBHBs!

What advanced LIGO/Virgo will see vs what ET could see

At 100 Mpc – Sources for LIGO/Virgo



● : f_{ISCO}, ■ : $f_{\text{LightRing}}$, □ : f_{LRD},

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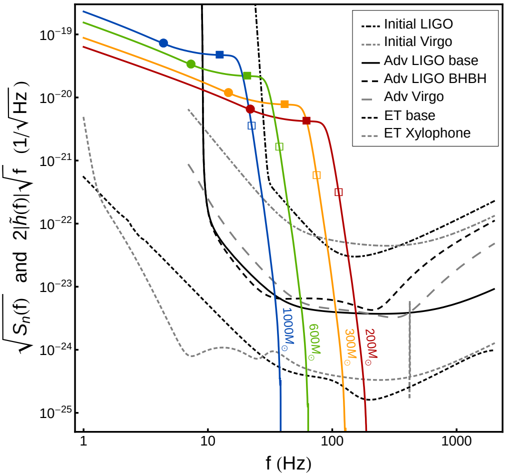

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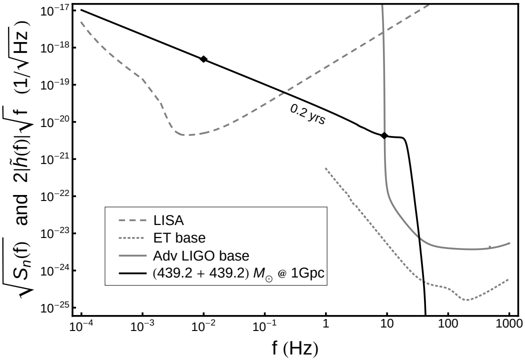
The ET and LISA



IMBHBs with masses of hundreds of $M_\odot$ could be seen by *both* LISA and the ET

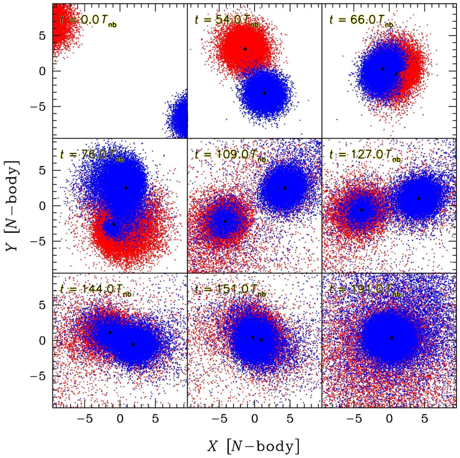
The long inspiral seen in the LISA band will allow for precise estimation of the parameters of the binary

The merger of the IMBHB within the ET band would produce high-SNR events

But do IMBHs exist?

There is indirect evidence but also uncertainties...

- If yes, formed after collapse of a Very Massive Star
- Double-cluster channel: in systems of two grav.-bound clusters, IMBHs sink down to the centers
- Single-cluster channel: in clusters with a fraction of primordial binaries $> 10\%$ *two* IMBH might form
- Observed ultraluminous X-ray sources could be explained by accretion onto IMBHs



BUT there are also works suggesting that VMSs will not form in this way
GW astronomy might as well beat traditional astronomy in this case!

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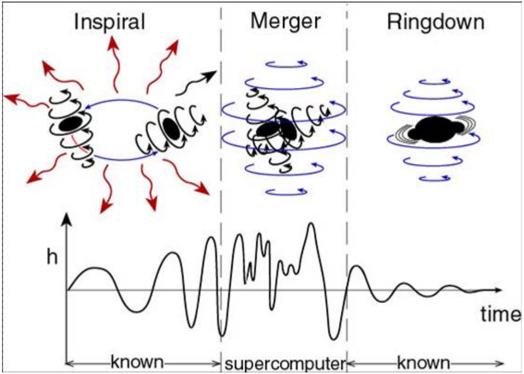
Theoretical models of BBHs coalescence

GW searches of known signals require templates
BBH coalescence: 2-body problem in GR in vacuum: $R_{\mu\nu} = 0$
Evolution of 2 distant BHs inspiralling around each other in a quasi-circular orbit
$\rightarrow$ for the moment we will ignore the role of eccentricity!



[Sketch credit: K. Thorne]

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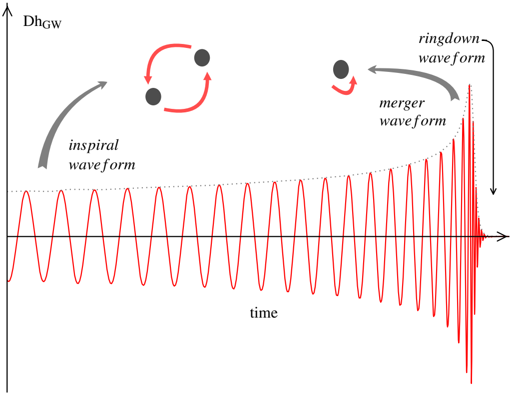

Given a model for the full BBH coalescence and a sensitivity curve we can compute expected SNR values, horizon distance, reach of the detector

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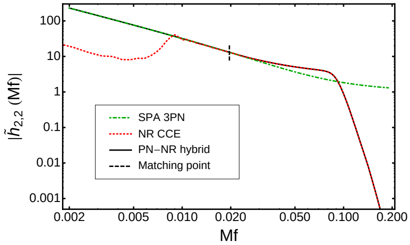
Phenomenological PN-NR model in the frequency domain



- $\tilde{h}(f) = A(f)e^{i\phi(f)}$
  For comparable-mass systems: radiation mainly in the $\ell = 2, m = 2$ mode
- Amplitude: PN with corrections up to 3PN + NR waveforms at null infinity new AEI Llama code + Cauchy characteristic extraction (Reisswig *et al.* 2009)
- Phase: PN up to 3.5PN + NR (but not needed for SNR calculations)
- Convenience of using a frequency domain model (SNR, horizon distance: integrals of FD quantities)
- Parametrized as function of (M, η, χ) for spin-aligned systems
  $\rightarrow$ Santamaria *et al.* to be submitted (2010)

Yes, but how many of those IMBHBs are out there?

- Assuming that formation of IMBHs in stellar cluster is possible
- Following Fregeau *et al.* (2006) and Miller (2002)
- The integral to compute is

$$R = \frac{dN_{\mathrm{event}}}{dt_0} = \int_0^{z_{max}} \frac{d^2 M_{\mathrm{SF}}}{dV_c dt_e} g_{\mathrm{cl}} g \frac{dt_e}{dt_0} \frac{dV_c}{dz} \int_{M_{cl,min}}^{M_{cl,max}} \frac{d^2 N_{cl}}{dM_{SF,cl} dM_{cl}} dM_{cl} dz$$

  - R is the event rate observed at $z = 0$
  - $dt_e/dt_0 = (1+z)^{-1}$ and dV_c/dz rate of change of comoving volume (depends on cosmological model)
  - $d^2 M_{\mathrm{SF}}/dV_c dt_e$ star formation rate in mass per unit of comoving volume per unit of local time (peaks at $1 < z < 2$ then decreases and stays $\sim$ constant)
  - $d^2 N_{cl}/dM_{SF,cl} dM_{cl}$ distribution function of clusters over individual cluster mass M_{cl} and total star-forming mass in clusters $M_{\mathrm{SF,cl}}$ ($\propto 1/M_{cl}^2$)
  - g fraction of clusters where IMBH are formed (??? $g \sim 0.1$)
  - g_{cl} fraction of star-forming mass that goes into star clusters more massive than $10^{3.5} M_\odot$ (??? $g_{cl} \sim 0.1$)
  - z_{max} Maximum redshift to which ET is capable of seeing an IMBHB coalescence (can be calculated given expected GW signal and PSD)

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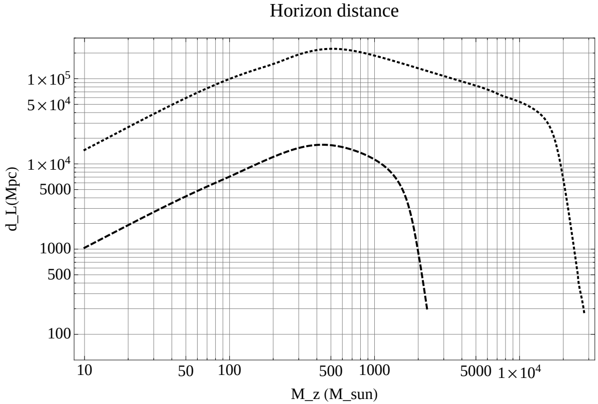
How far is ET capable of seeing?

Horizon distance: distance at which a detector can detect a waveform from an optimally oriented, overhead source at an SNR threshold of 8.



[......... ET - - - adv LIGO]

$\boxed{z_{max}(ET) \sim 20}$ $\Rightarrow$ could even probe seed BHs

* for the $\eta = 0.25$ non-spinning waveform shown before. Orbital hang-up configurations with large spins might yield horizon distances $\sim 50\%$ larger!

And what are the final numbers?

We follow Fregeau *et al* (2006) but consider the *two* possible channels for IMBH formation [Amaro-Seoane & Freitag (2006)]

$$\Gamma^{\rm doub} = P_{\rm merg}\, P_{\rm ra}\, \Gamma^{\rm sing}$$

($P_{\rm ra}$ probability that a cluster gets into the runaway phase)
($P_{\rm merg}$ probability for two clusters to collide)

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Fregeau *et al* (2006) estimate $d_L = 2Gpc(z \approx 0.4)$ for advanced LIGO, which yields (pessimistic and optimistic values depending on the estimations for g and g_{cl})

For Advanced LIGO:

$$\Gamma^{\rm total}_{\rm Adv.\,LIGO} \in [(0)\, 11,\, 300]\ {\rm yr}^{-1}.$$

For the ET:

$$\Gamma^{\rm total}_{\rm ET} \in [(0)\, 4000,\, 6 \cdot 10^4]\ {\rm yr}^{-1}$$

These numbers are obviously encouraging enough to expect that IMBHBs will be potentially important sources for advanced LIGO/Virgo and the ET

But NOTE that the rates are greatly underestimated for ET, which will see up to $z \sim 20$. Work is in progress to recalculate the expected event rates for the ET [Amaro-Seoane & Santamaria (2010)]

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Conclusions

- IMBH detection would be of extreme importance for theoretical astrophysics. This rather speculative scenario could be solved within the next decade (with advLIGO) and/or later with the ET
- Single- and double-cluster channel: possible formation channels for IMBH binaries in stellar clusters
- LISA will only see the inspiral stage, for IMBH binaries merge outside its band
- Detection and characterization of compact binary coalescence rely on theoretical source models. For IMBHBs, comparable-mass scenarios expected (PN+NR appropriate)
- Large SNR events will be associated to the merger and ringdown of IMBH systems within the sensitivity band of the ET. Computation of z_{max} indicates that the ET will see to very high distances - this translates into large expected event rates!
- Prospects for detection and characterization of IMBH binaries with the ET look very encouraging

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