Gravitational waves from binary systems of compact objects

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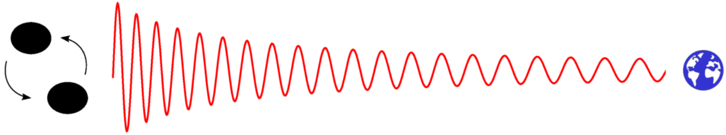


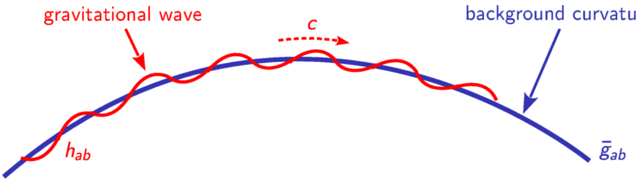
Outline

Outline

1. Gravitational waves
2. Gravitational-wave science
3. Intermediate mass-ratio inspirals

What is a gravitational wave ?

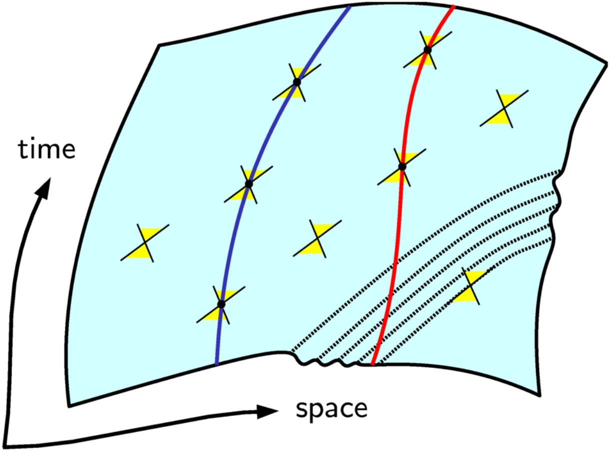
A gravitational wave is a tiny ripple in the curvature of spacetime that propagates at the vacuum speed of light



$$\Box h_{ab} + 2\bar{R}_{acbd}h^{cd} = -16\pi T_{ab}$$

Key prediction of Einstein's general theory of relativity

What is a gravitational wave ?



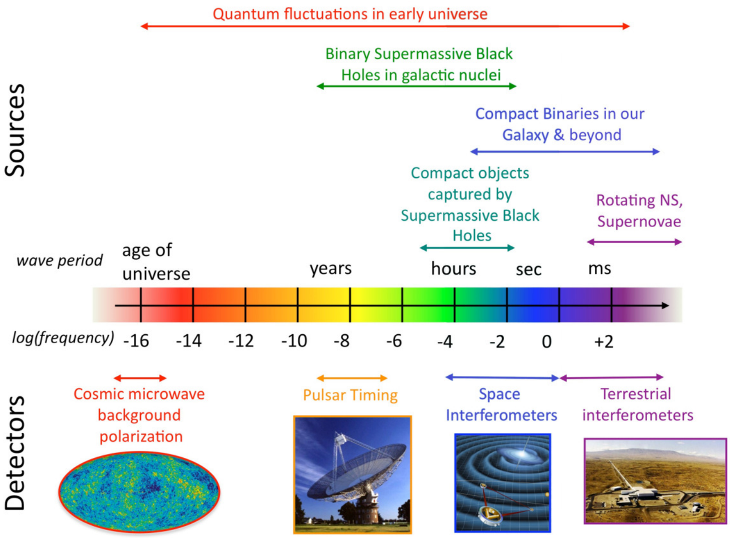
(Credit: E. Gourgoulhon)

Electromagnetic *vs* gravitational waves

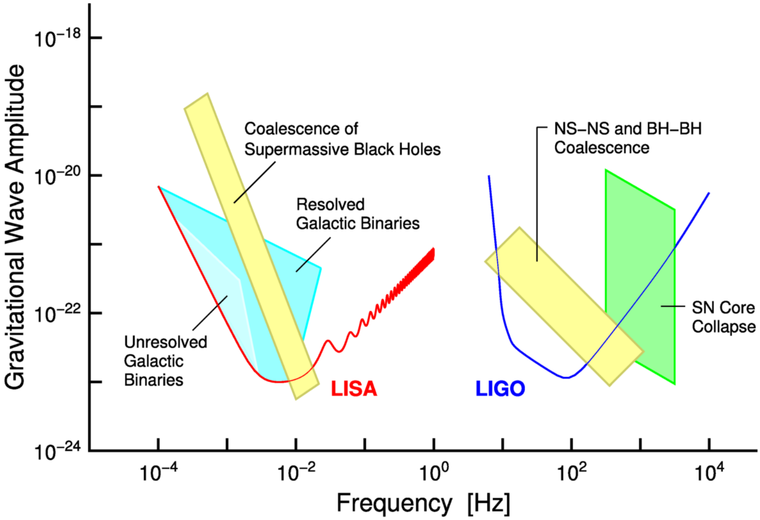
	Electromagnetic waves	Gravitational waves
Origin	electromagnetic field	spacetime curvature
Nature	waves in spacetime	waves of spacetime
Sources	accelerated charges	accelerated masses
Wavelength	$\ll$ size of source	$\gtrsim$ size of source
Structure	dipolar	quadrupolar
Coherence	low	high
Interaction	strong	weak
Detection	power	amplitude
Analogy	vision	audition

Complementary sources of information about the Universe

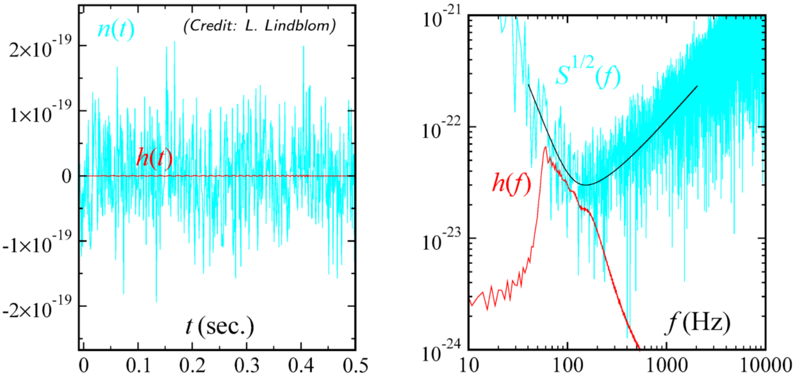
The gravitational-wave spectrum



Promising sources of gravitational waves

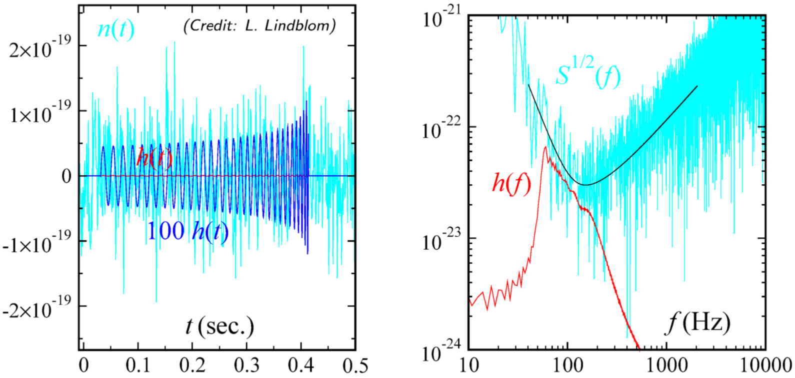


Need for accurate template waveforms



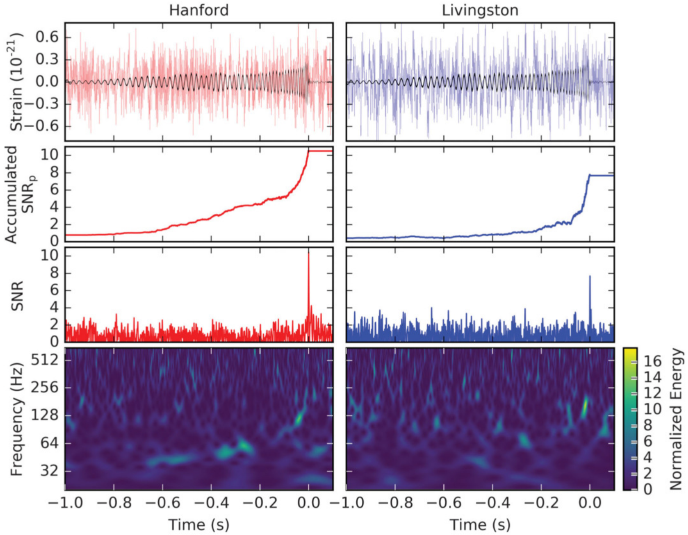
If the expected signal is *known in advance* then $n(t)$ can be filtered and $h(t)$ recovered by matched filtering $\longrightarrow$ **template waveforms**

Need for accurate template waveforms



If the expected signal is *known in advance* then $n(t)$ can be filtered and $h(t)$ recovered by matched filtering $\longrightarrow$ **template waveforms**

An example: the event GW151226

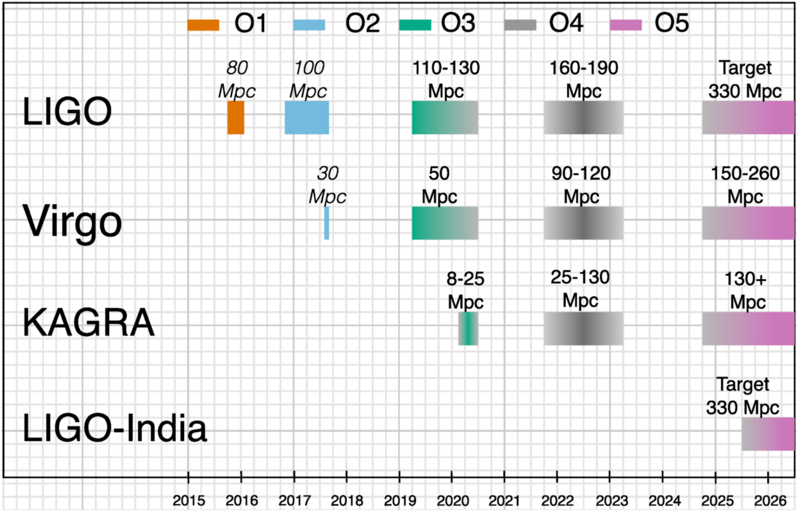


[PRL **116** (2016) 241103]

Outline

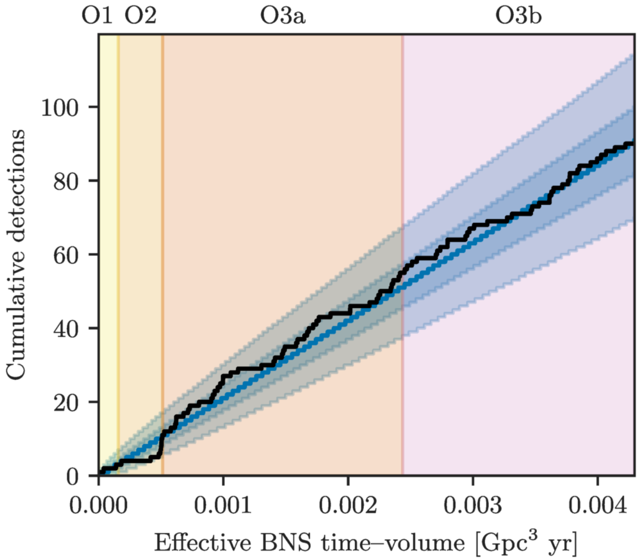
Ground-based interferometric detectors

Roadmap for ground-based detectors

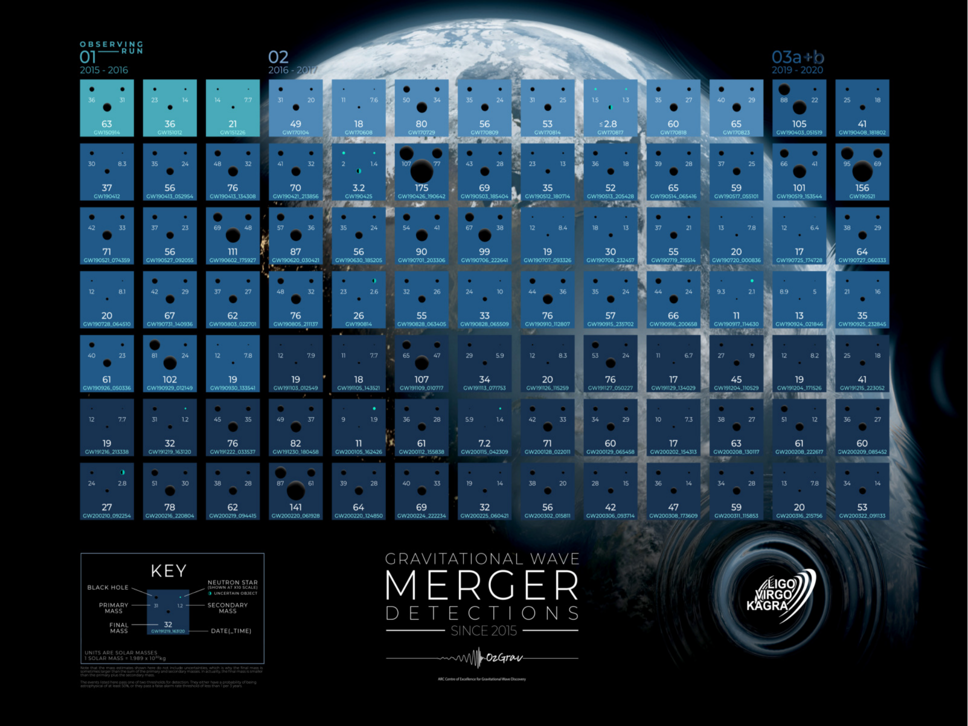


[LRR **23** (2020) 3]

Current gravitational-wave detections



[LIGO-P2000318 (2021)]


OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
03a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^30 kg
Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
LIGO
VIRGO
KAGRA

Gravitational-wave science

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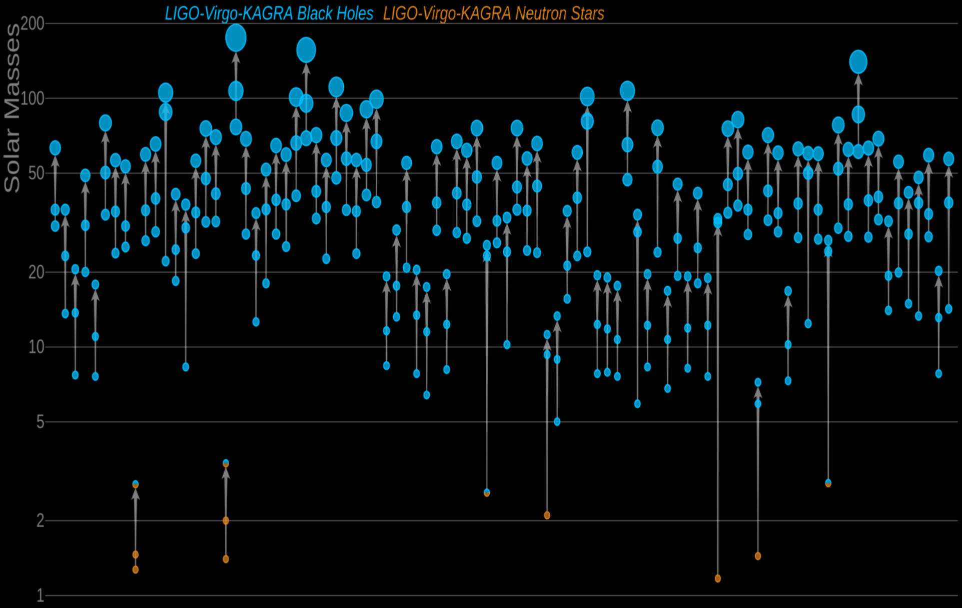
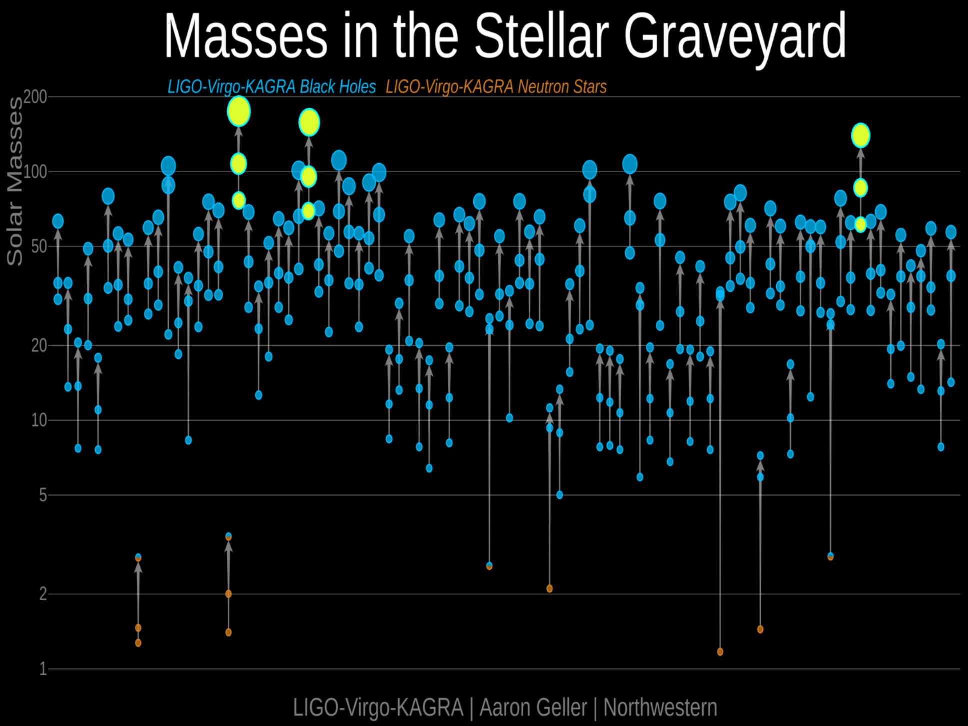
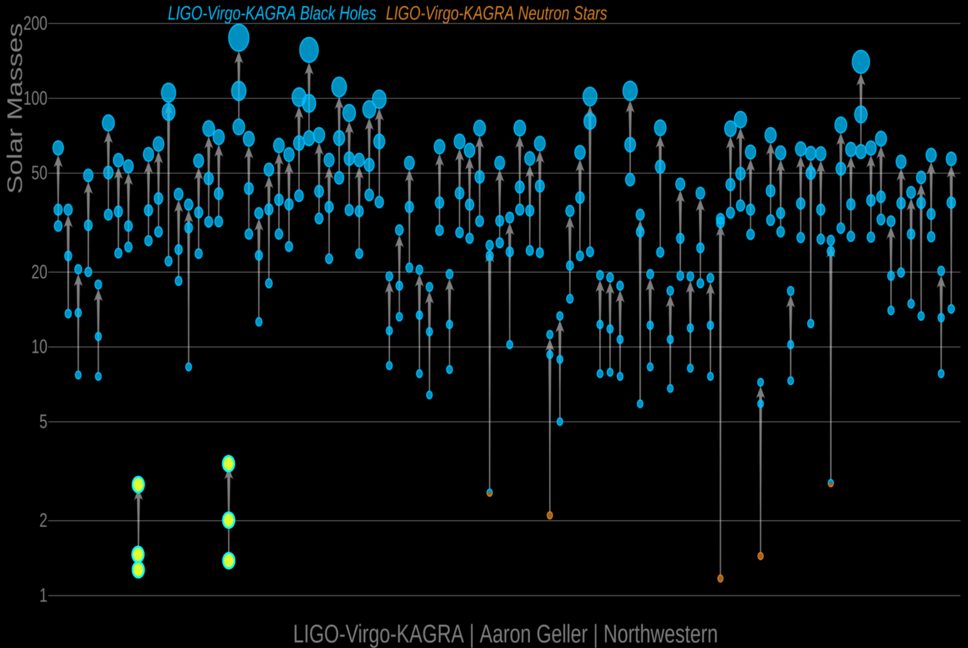
Masses in the Stellar Graveyard

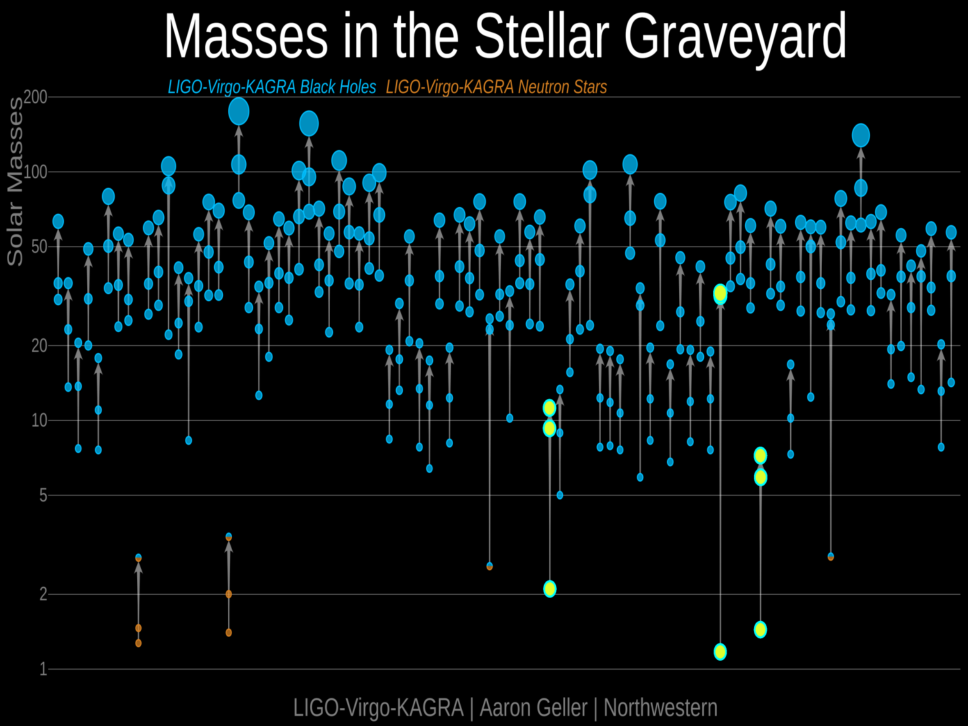


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

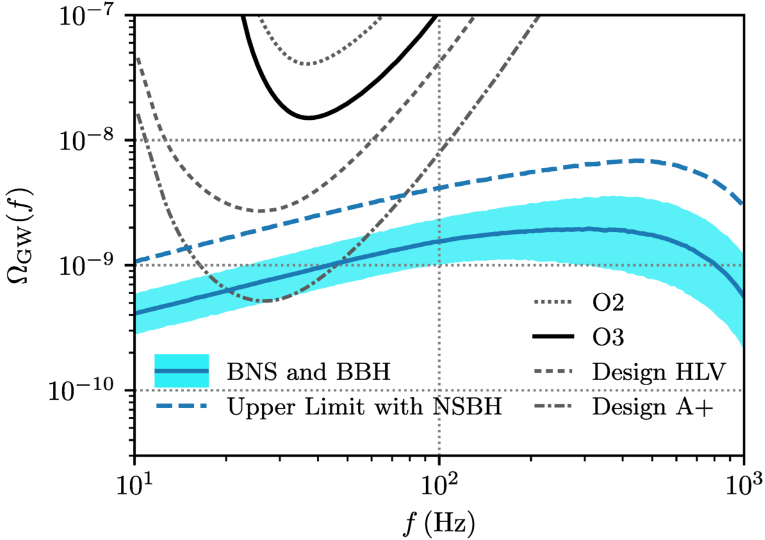

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard




Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Isotropic gravitational-wave background



[PRD **104** (2021) 022004]

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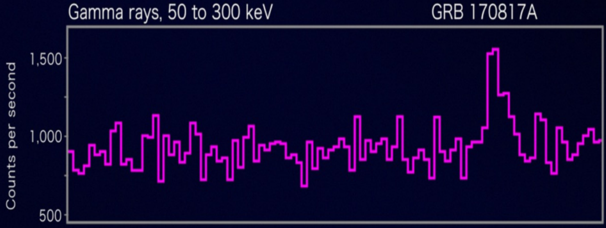
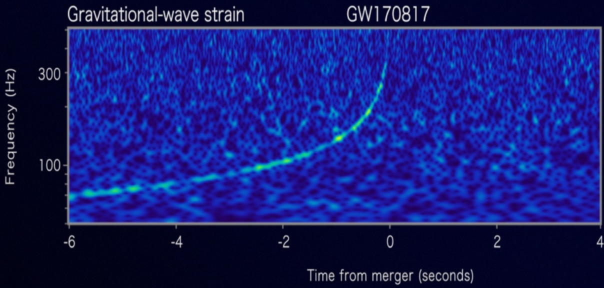
Fermi

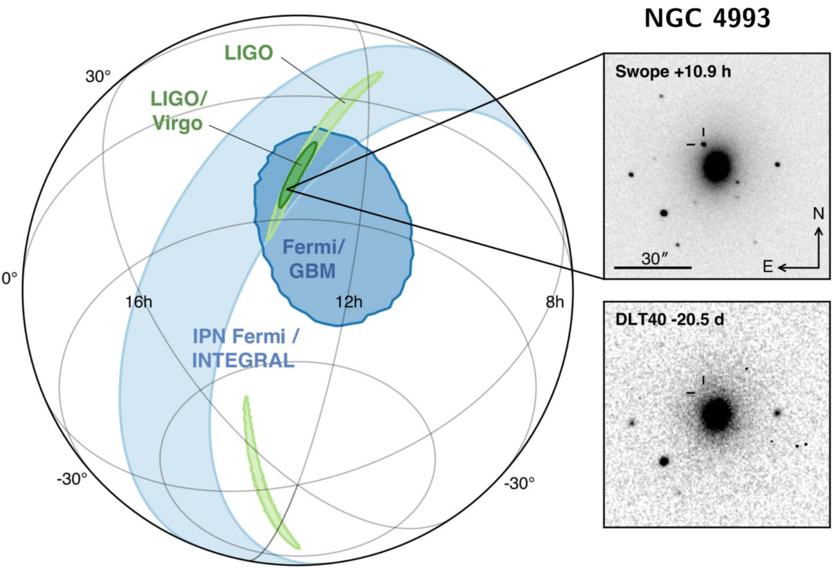

Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500

LIGO


Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

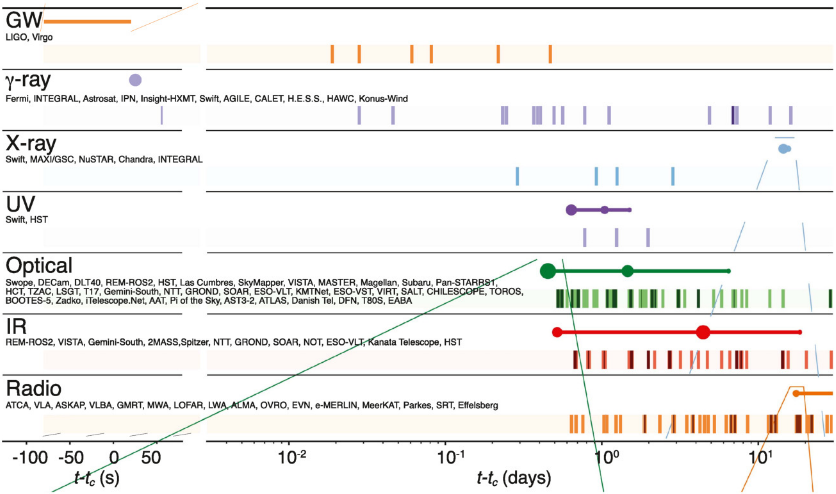
[ApJ **848** (2017) L12]

A binary neutron star merger



[ApJ **848** (2017) L12]

Multi-messenger astronomy



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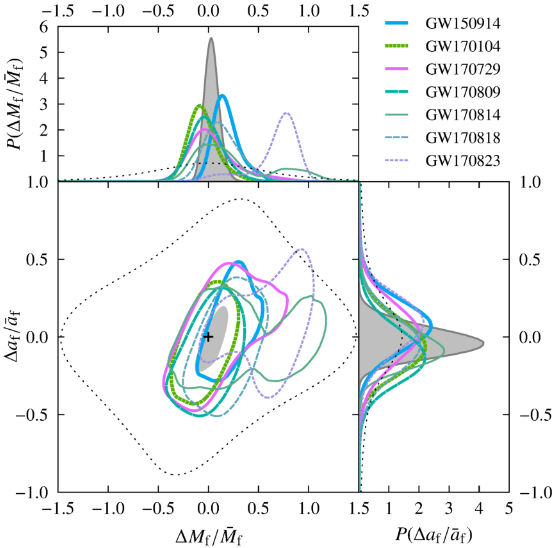
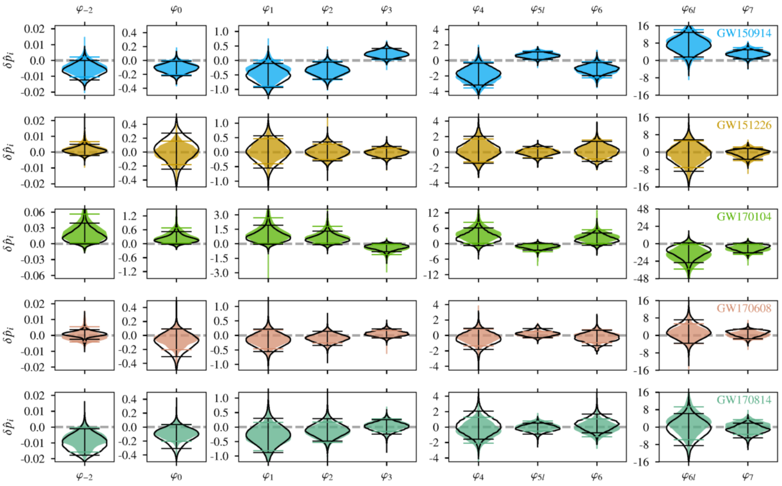
Consistency test for final mass and spin



[PRD **100** (2019) 104036]

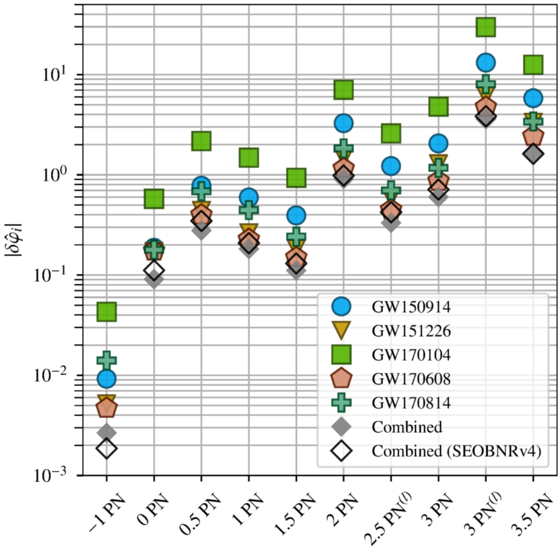
Constraining post-Newtonian parameters



$$\Phi(f) \propto \sum_{i=-2}^{7} \varphi_i \, f^{(i-5)/3}$$

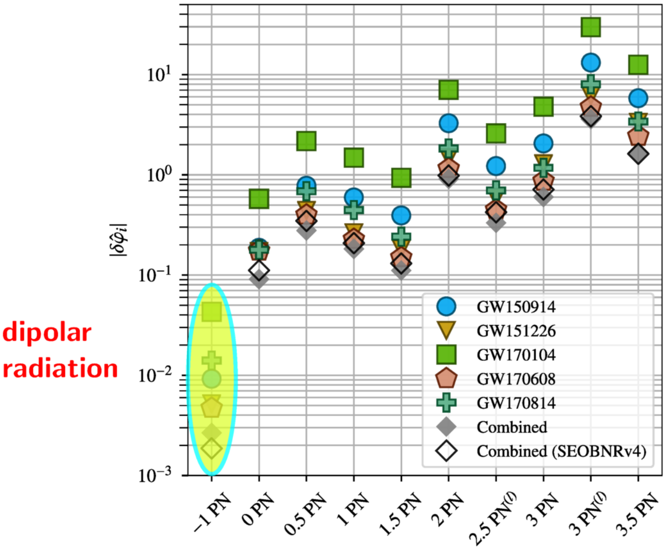
[PRD **100** (2019) 104036]

Constraining post-Newtonian parameters



[PRD **100** (2019) 104036]

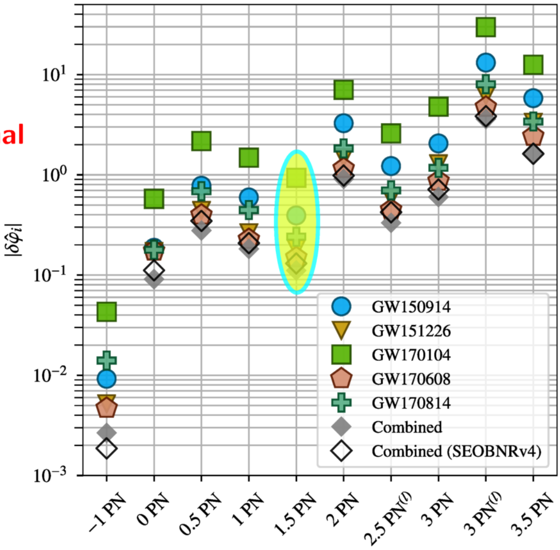
Constraining post-Newtonian parameters



[PRD **100** (2019) 104036]

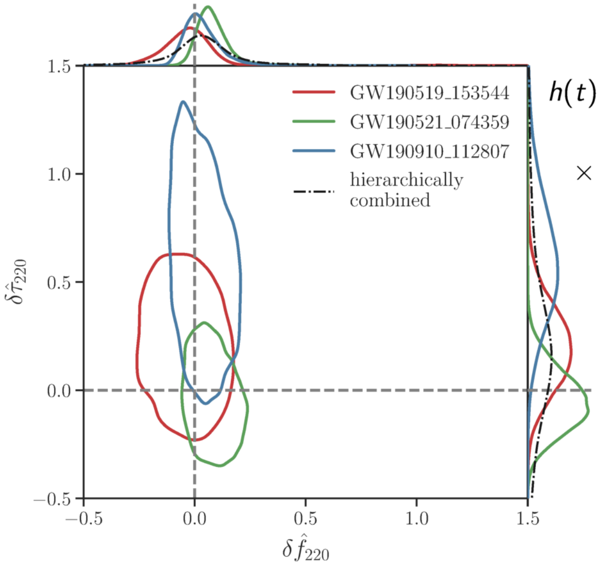
Constraining post-Newtonian parameters

gravitational wave tail



[PRD **100** (2019) 104036]

Null test for Kerr black hole ringdown



$$h(t) \propto \sum_{lmn} A_{lmn}\, e^{-t/\tau_{lmn}}$$

$$\times \cos\left(2\pi f_{lmn} t + \phi_{lmn}\right)$$

[PRD **103** (2021) 122002]

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Falsifying scalar-tensor theories

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

$$\left|c_g/c - 1\right| < 10^{-15}$$

[PRL **119** (2017) 251304]

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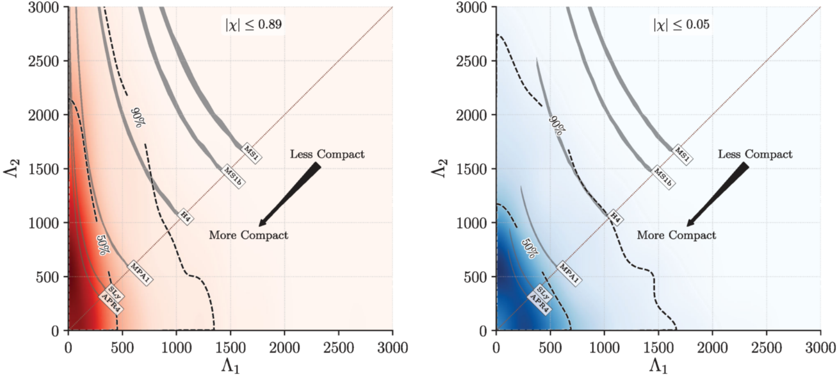
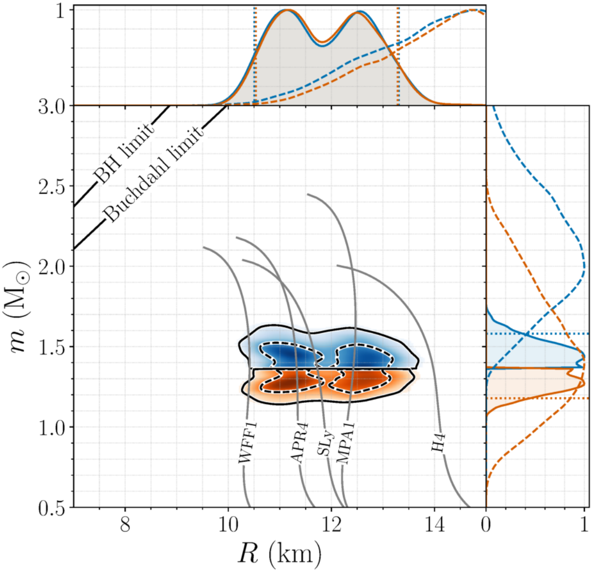
Tidal deformability of neutron stars



$$\Lambda \propto \left(\frac{c^2 R}{Gm}\right)^5$$

[PRL **119** (2017) 161101]

Mass, radius and equation of state



[LIGO-P1800115 (2018)]

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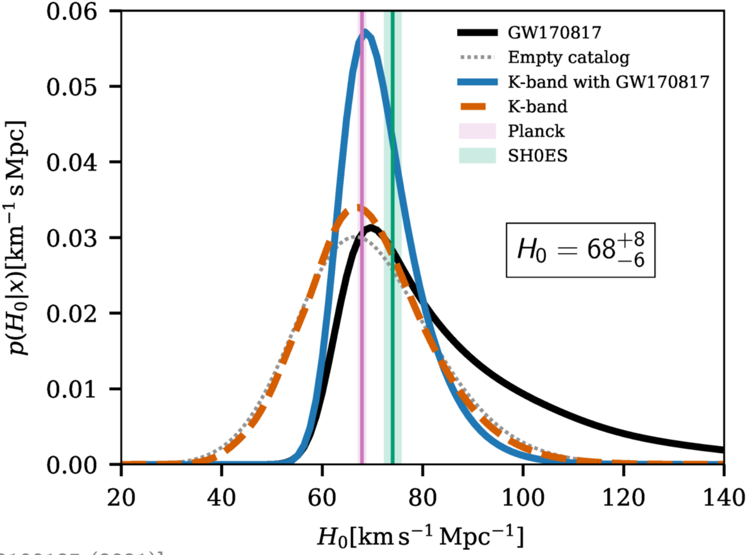
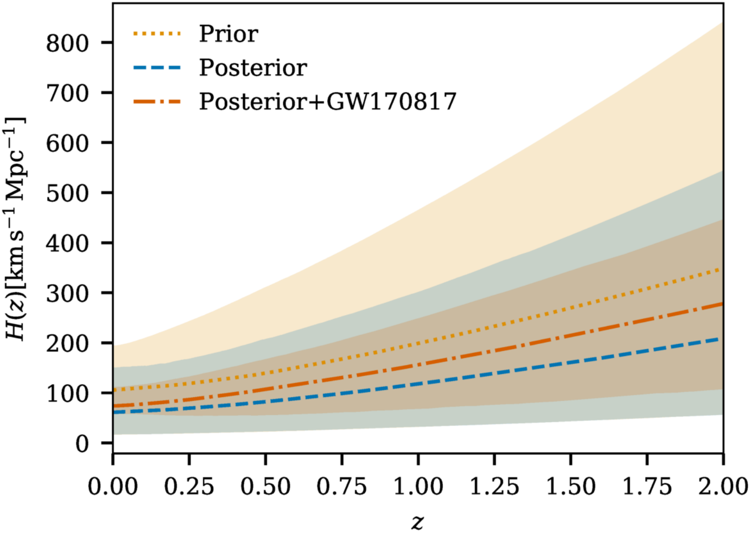
Independent measure of Hubble's constant



[LIGO-P2100185 (2021)]

Evolution of the Hubble parameter



[LIGO-P2100185 (2021)]

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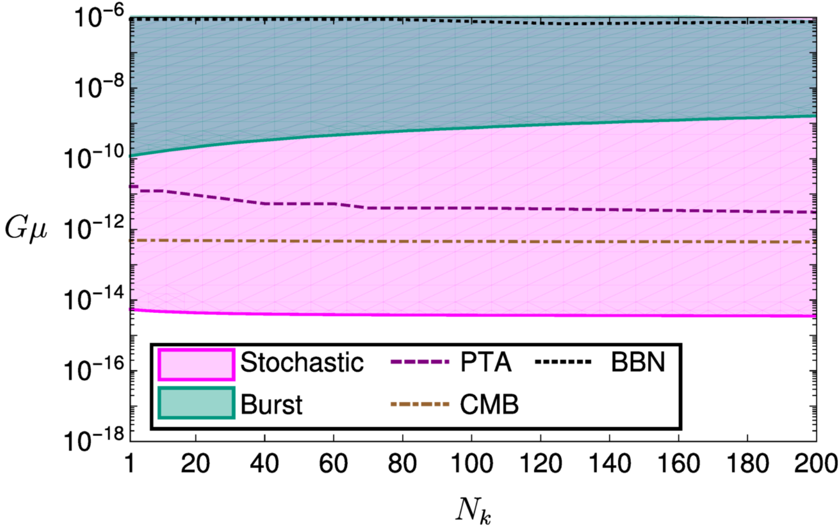
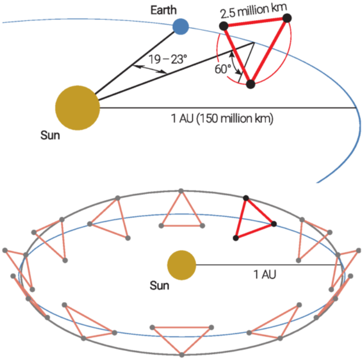
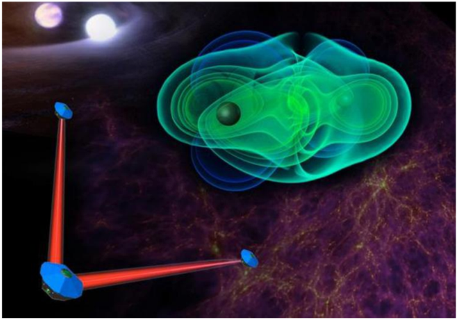
Constraints on cosmic strings



[PRL **126** (2021) 241102]

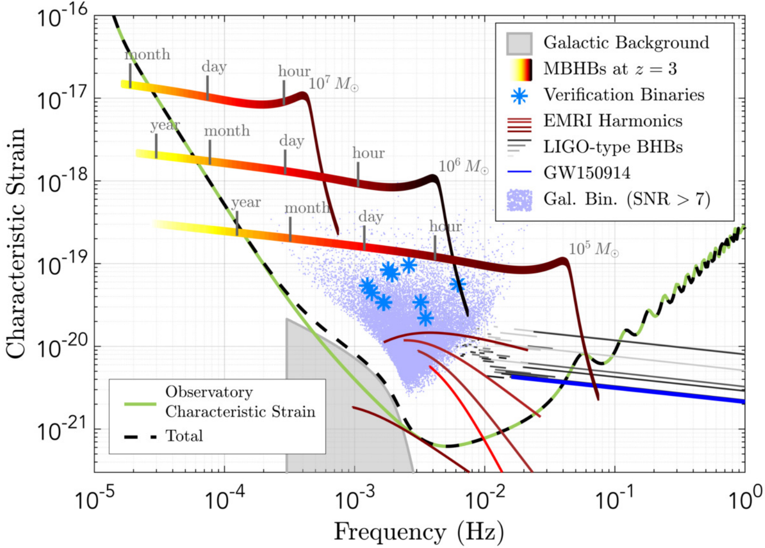
LISA: a gravitational antenna in space



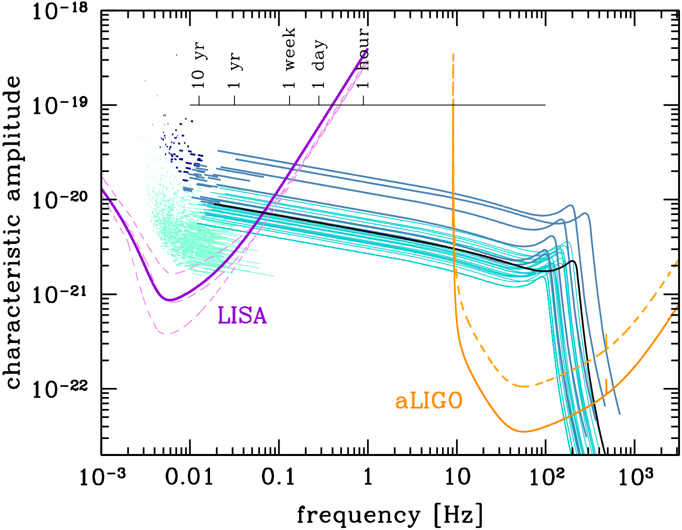


The *LISA mission* proposal was accepted by ESA in 2017 for L3 slot, with a launch planned for 2034 [http://www.lisamission.org]

LISA sources of gravitational waves



Multi-band gravitational-wave astronomy



[PRL **116** (2016) 231102]

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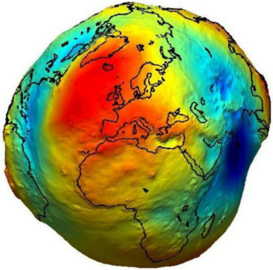
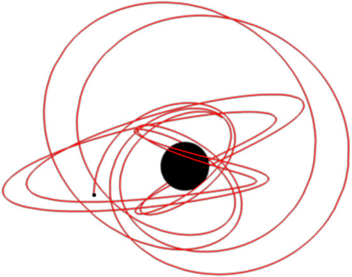
Do black holes have hair?

Geodesy



$M_{\ell m}$ arbitrary

Botromeladesy



$M_\ell + iS_\ell = M(ia)^\ell$

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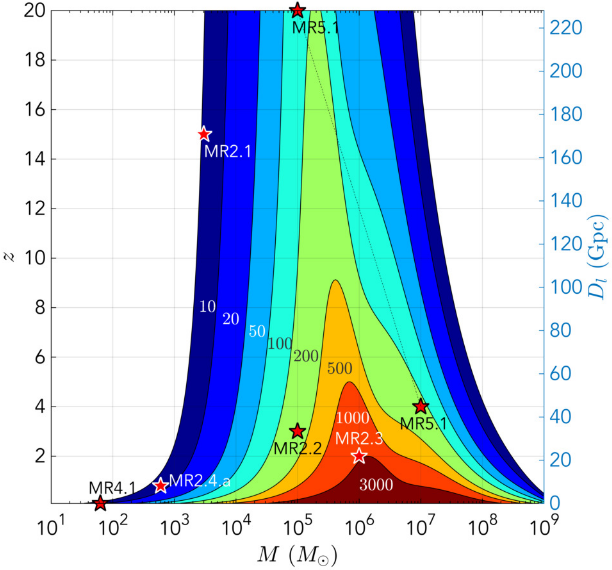
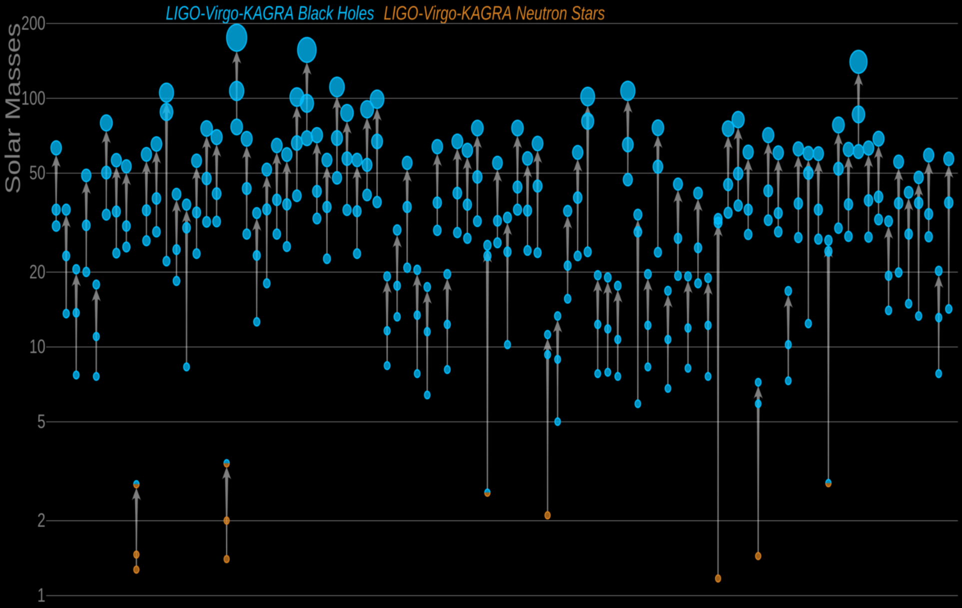
- Phase transitions during primordial Universe

How do massive black holes form?



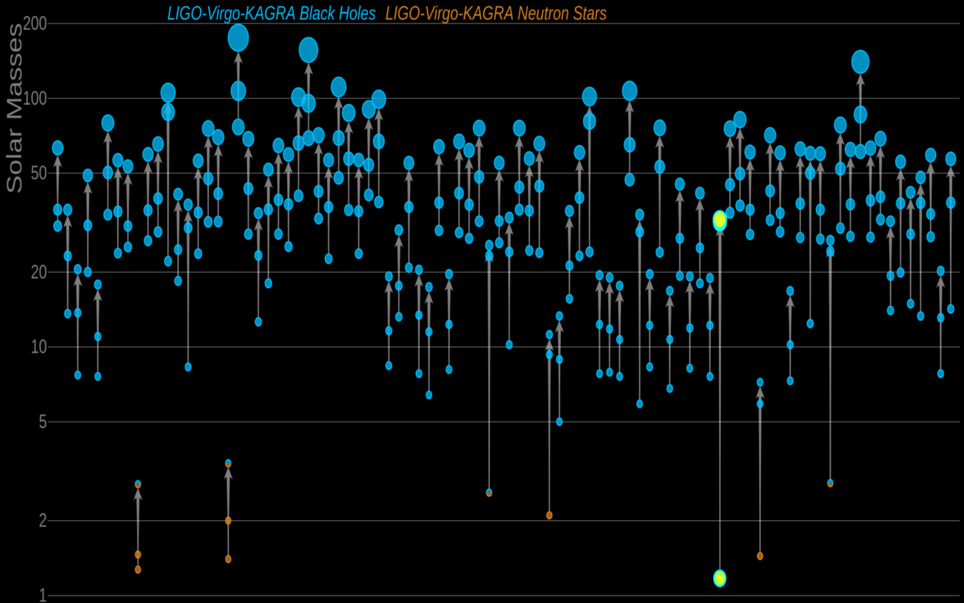
Outline

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard



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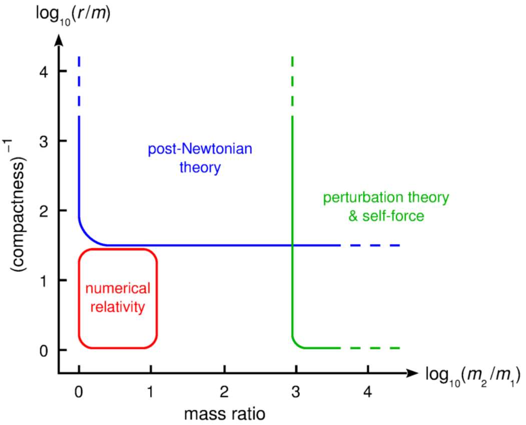
Systematic uncertainties in modeling IMRIs

The mass ratio of GW191219_163120's source is inferred to be $q = 0.038^{+0.005}_{-0.004}$, *which is extremely challenging for waveform modeling, and thus there may be systematic uncertainties in results for this candidate.*

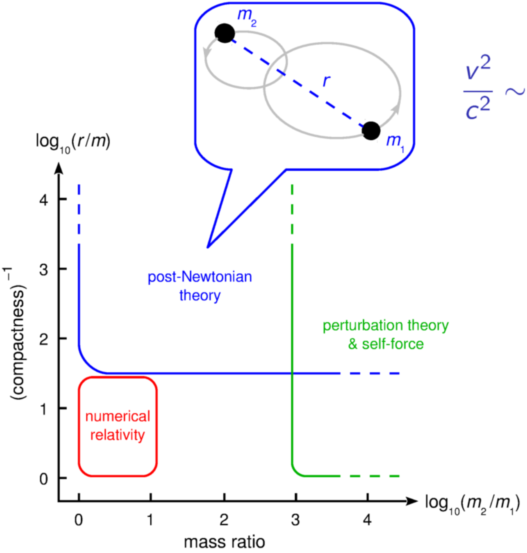
Modeling of higher-order multipole moments is particularly important for inferring the properties of systems with unequal masses, and may impact inference of parameters including the mass ratio, inclination and distance.

[LIGO-P2000318 (2021)]

Modeling coalescing compact binaries



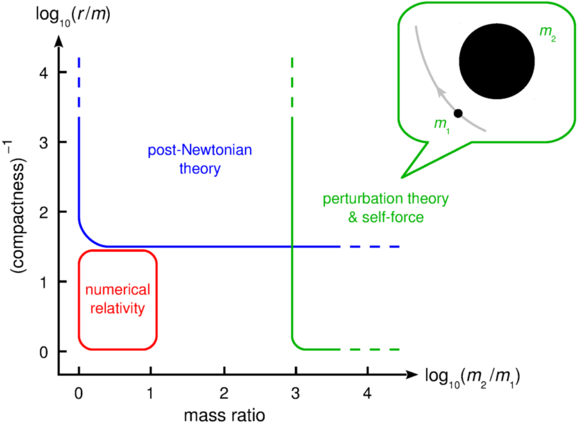
Modeling coalescing compact binaries



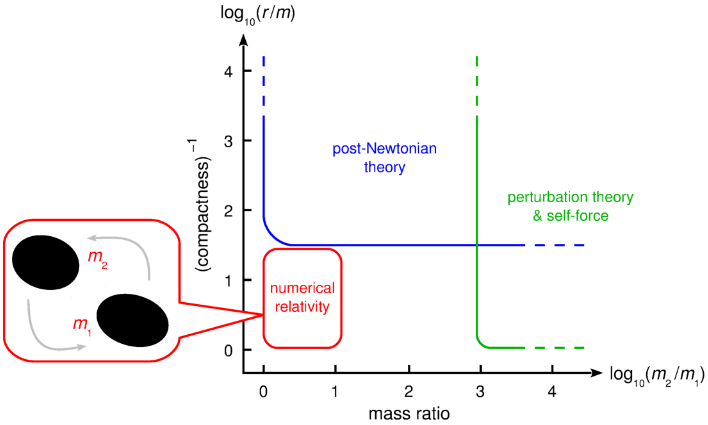
$$\frac{v^2}{c^2} \sim \frac{Gm}{c^2 r} \ll 1$$

Modeling coalescing compact binaries

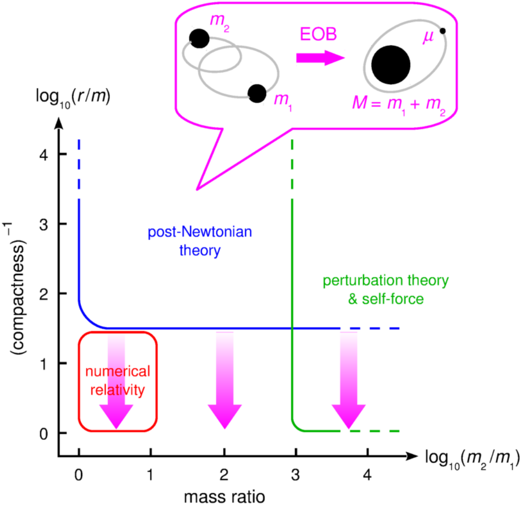
$$q \equiv \frac{m_1}{m_2} \ll 1$$



Modeling coalescing compact binaries

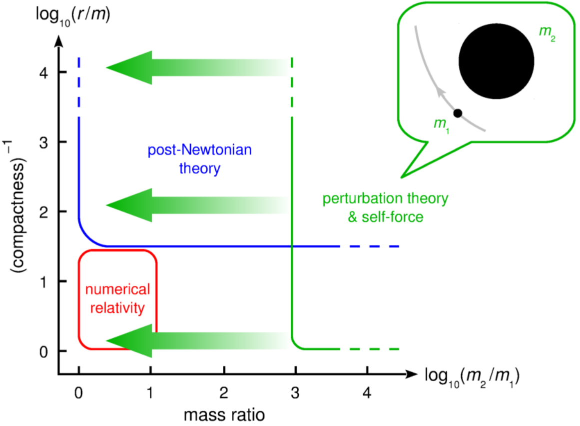


Modeling coalescing compact binaries



Modeling coalescing compact binaries

$$q \equiv \frac{m_1}{m_2} \quad \rightarrow \quad \nu \equiv \frac{m_1 m_2}{m^2}$$



Perturbation theory for comparable masses

Relativistic orbital dynamics

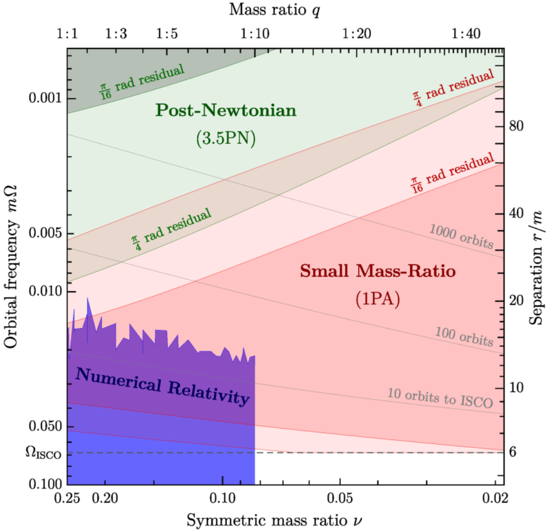
- Periastron advance [Le Tiec *et al.* PRL 2011; PRD 2013]
- Binding energy [Le Tiec, Buonanno & Barausse PRL 2012]
- Surface gravity [Le Tiec & Grandclément CQG 2018]

Gravitational-wave emission

- Recoil velocity [Fitchett & Detweiler ApJ 1984, Nagar PRD 2013]
- Head-on waveform [Anninos *et al.* PRD 1995, Sperhake *et al.* PRD 2011]
- Inspiral phasing [van de Meent & Pfeiffer PRL 2020]
- Inspiral energy flux [Warburton *et al.* PRL 2021]

Perturbation theory for comparable masses

[van de Meent & Pfeiffer PRL 2020]



Second order gravitational self-force program

- *Second-order gravitational self-force*
  A. Pound, PRL **109** (2012) 051101
- *Practical, covariant puncture for second-order self-force calculations*
  A. Pound & J. Miller, PRD **89** (2014) 104020
- *Second-order perturbation theory: Problems on large scales*
  A. Pound, PRD **92** (2015) 104047
- *Second-order perturbation theory: The problem of infinite mode coupling*
  J. Miller, B. Wardell & A. Pound, PRD **94** (2016) 104018
- *Nonlinear gravitational self-force: Second-order equation of motion*
  A. Pound, PRD **95** (2017) 104056
- *Second-order self-force calculation of gravitational binding energy in compact binaries*
  A. Pound, B. Wardell, N. Warburton & J. Miller, PRL **124** (2019) 021101
- *Two-timescale evolution of extreme-mass-ratio inspirals: Waveform generation scheme for quasicircular orbits in Schwarzschild spacetime*
  J. Miller & A. Pound, PRD **103** (2021) 064048
- *Gravitational-wave energy flux for compact binaries through second order in the mass ratio*
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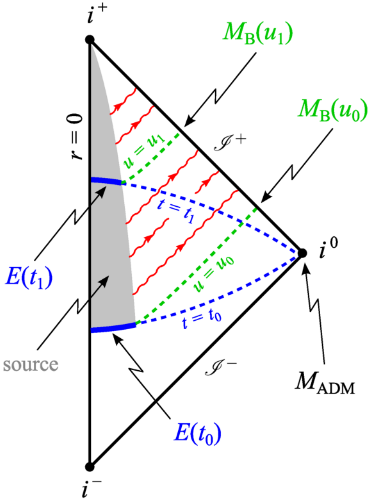
Orbital evolution *via* energy balance

[Bondi *et al.* 1962; Sachs 1962]



- Bondi mass-loss formula

$$\frac{\mathrm{d}M_B}{\mathrm{d}u} = -\mathcal{F}(u)$$

- Gravitational binding energy

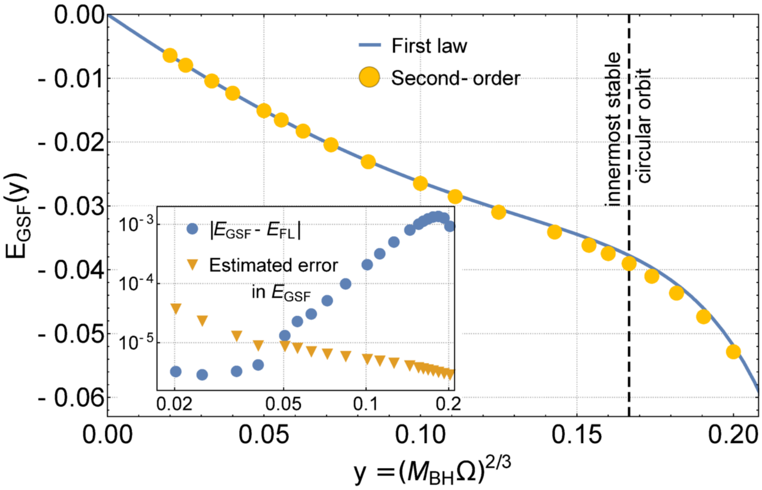
$$E \equiv M_B - M_{BH} - \mu$$

- Orbital frequency evolution

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = -\frac{\mathcal{F}(\omega)}{E'(\omega)}$$

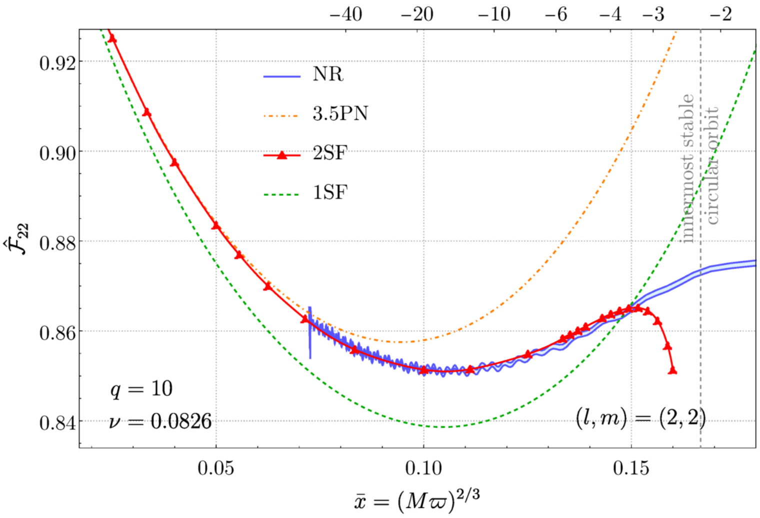
Second-order binding energy

[Pound *et al.* PRL 2020]



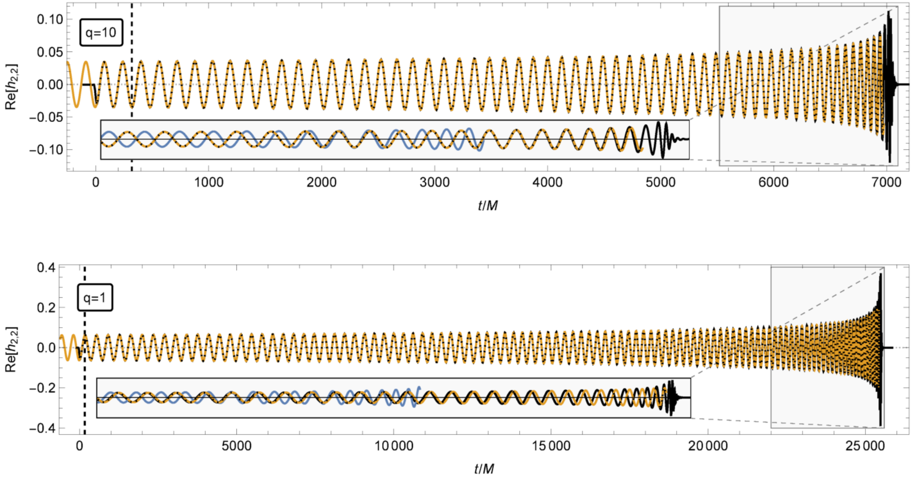
Second-order energy flux

[Warburton *et al.* PRL 2021]



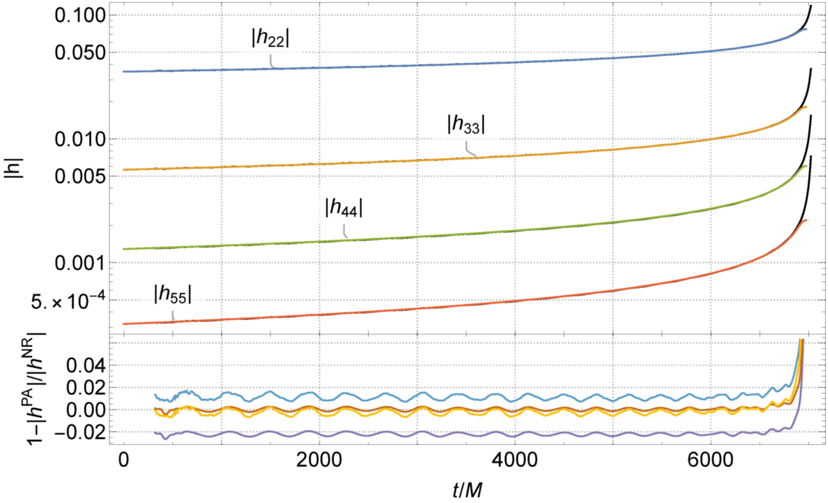
Gravitational waveforms

[Wardell *et al.*, submitted 2022]



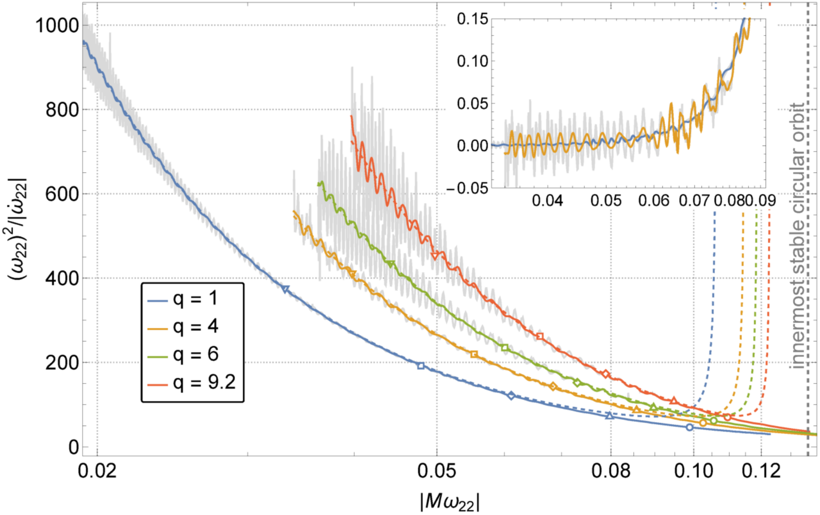
Mode waveform amplitudes

[Wardell *et al.*, submitted 2022]



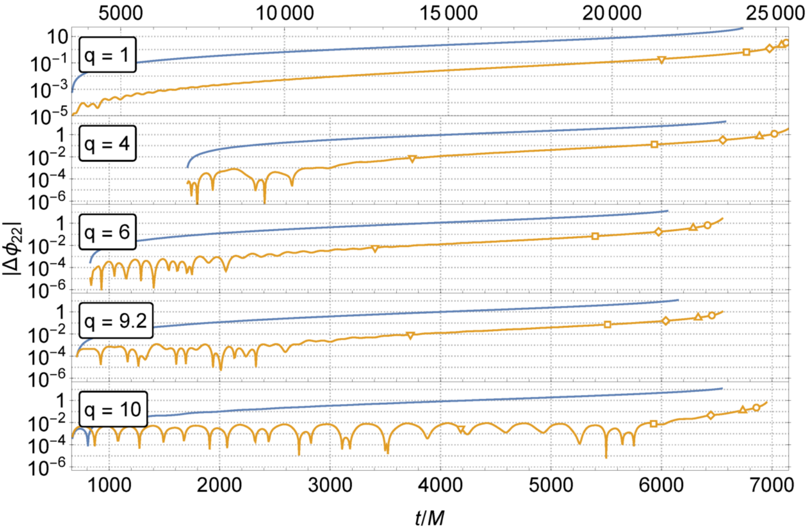
Waveforms frequency evolution

[Wardell *et al.*, submitted 2022]



Accumulated dephasing

[Wardell *et al.*, submitted 2022]



Summary and prospects

- Intermediate mass ratio inspirals (IMRIs) are promising gravitational-wave sources for LIGO-Virgo and LISA
- IMRIs are chalenging for existing modeling techniques and current templates are not reliable for $q \gtrsim 30$
- Post-adiabatic waveforms agree remarkably well with the results from full numerical relativity with $1 \leqslant q \leqslant 10$
- Second-order gravitational self-force theory will be used to model EMRIs, IMRIs and possibly comparable-mass systems
- In the near future: transition to plunge / add black hole spin