Filling the gap: gravitational waveforms for intermediate mass ratio inspirals

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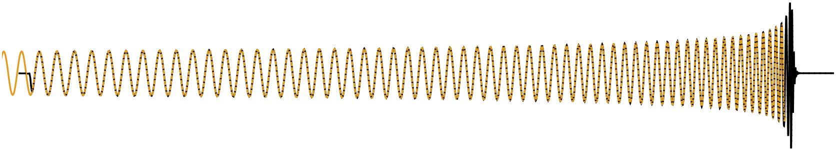
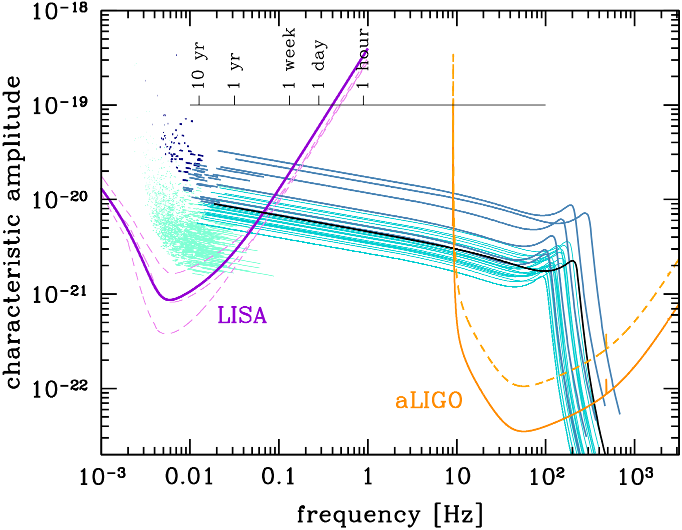


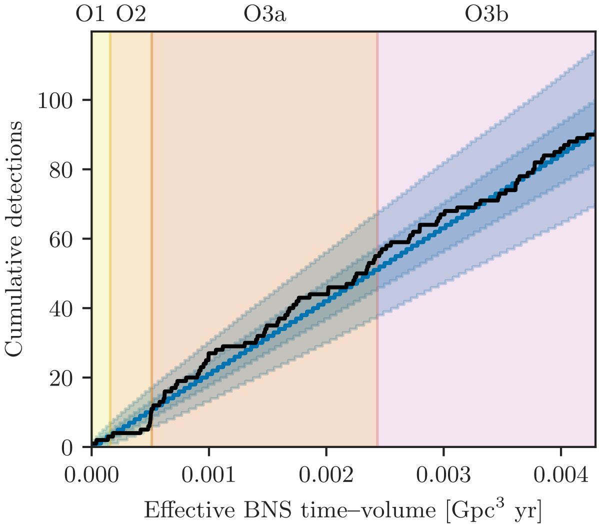
Multi-band gravitational-wave astronomy

[Sesana PRL 2016]



Current gravitational-wave detections

[LIGO-Virgo-KAGRA 2021]



OBSERVING RUN

01 — 2015 - 2016

Event	Primary mass	Secondary mass	Final mass
GW150914	36	31	63
GW151012	23	14	36
GW151226	14	7.7	21

02 — 2016 - 2017

Event	Primary mass	Secondary mass	Final mass
GW170104	31	20	49
GW170608	11	7.6	18
GW170729	50	34	80
GW170809	35	24	56
GW170814	31	25	53
GW170817	1.5	1.3	≤2.8
GW170818	35	27	60
GW170823	40	29	65

03a+b — 2019 - 2020

Event	Primary mass	Secondary mass	Final mass
GW190403_051519	88	22	105
GW190408_181802	25	18	41
GW190412	30	8.3	37
GW190413_052954	35	24	56
GW190413_134308	48	32	76
GW190421_213856	41	32	70
GW190425	2	1.4	3.2
GW190426_190642	107	77	175
GW190503_185404	43	28	69
GW190512_180714	23	13	35
GW190513_205428	36	18	52
GW190514_065416	39	28	65
GW190517_055101	37	25	59
GW190519_153544	66	41	101
GW190521	95	69	156
GW190521_074359	42	33	71
GW190527_092055	37	23	56
GW190602_175927	69	48	111
GW190620_030421	57	36	87
GW190630_185205	35	24	56
GW190701_203306	54	41	90
GW190706_222641	67	38	99
GW190707_093326	12	8.4	19
GW190708_232457	18	13	30
GW190719_215514	37	21	55
GW190720_000836	13	7.8	20
GW190725_174728	12	6.4	17
GW190727_060333	38	29	64
GW190728_064510	12	8.1	20
GW190731_140936	42	29	67
GW190803_022701	37	27	62
GW190805_211137	48	32	76
GW190814	23	2.6	26
GW190828_063405	32	26	55
GW190828_065509	24	10	33
GW190910_112807	44	36	76
GW190915_235702	35	24	57
GW190916_200658	44	24	66
GW190917_114630	9.3	2.1	11
GW190924_021846	8.9	5	13
GW190925_232845	21	16	35
GW190926_050336	40	23	61
GW190929_012149	81	24	102
GW190930_133541	12	7.8	19
GW191103_012549	12	7.9	19
GW191105_143521	11	7.7	18
GW191109_010717	65	47	107
GW191113_071753	29	5.9	34
GW191126_115259	12	8.3	20
GW191127_050227	53	24	76
GW191129_134029	11	6.7	17
GW191204_110529	27	19	45
GW191204_171526	12	8.2	19
GW191215_223052	25	18	41
GW191216_213338	12	7.7	19
GW191219_163120	31	1.2	32
GW191222_033537	45	35	76
GW191230_180458	49	37	82
GW200105_162426	9	1.9	11
GW200112_155838	36	28	61
GW200115_042309	5.9	1.4	7.2
GW200128_022011	42	33	71
GW200129_065458	34	29	60
GW200202_154313	10	7.3	17
GW200208_130117	38	27	63
GW200208_222617	51	12	61
GW200209_085452	36	27	60
GW200210_092254	24	2.8	27
GW200216_220804	51	30	78
GW200219_094415	38	28	62
GW200220_061928	87	61	141
GW200220_124850	39	28	64
GW200224_222234	40	33	69
GW200225_060421	19	14	32
GW200302_015811	38	20	56
GW200306_093714	28	15	42
GW200308_173609	36	14	47
GW200311_115853	34	28	59
GW200316_215756	13	7.8	20
GW200322_091133	34	14	53

KEY

BLACK HOLE

NEUTRON STAR (SHOWN AT X10 SCALE)

UNCERTAIN OBJECT

PRIMARY MASS: 31 — SECONDARY MASS: 1.2

FINAL MASS: 32 — DATE(_TIME): GW191219_163120

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989×10^{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

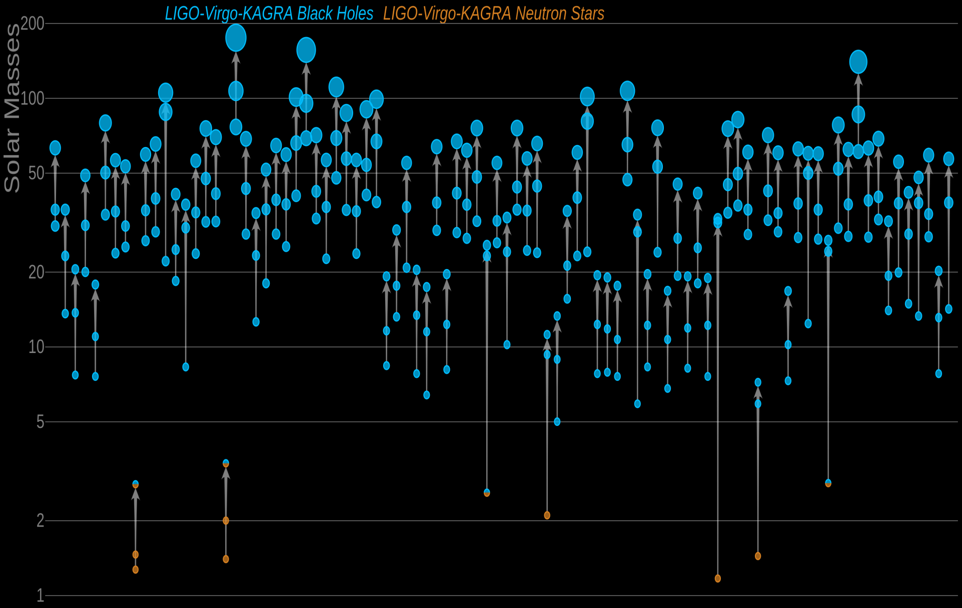
SINCE 2015

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

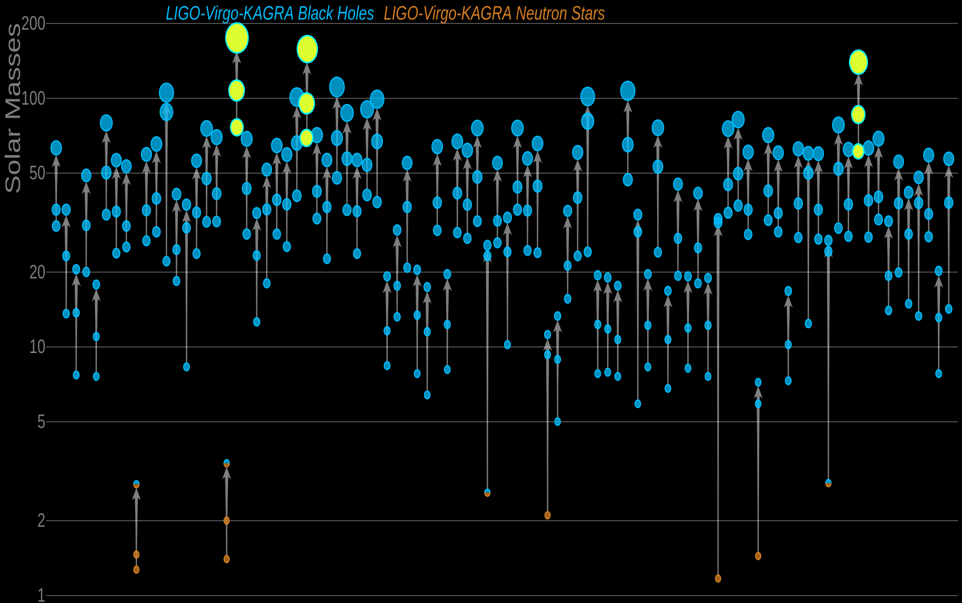
LIGO VIRGO KAGRA

Masses in the Stellar Graveyard



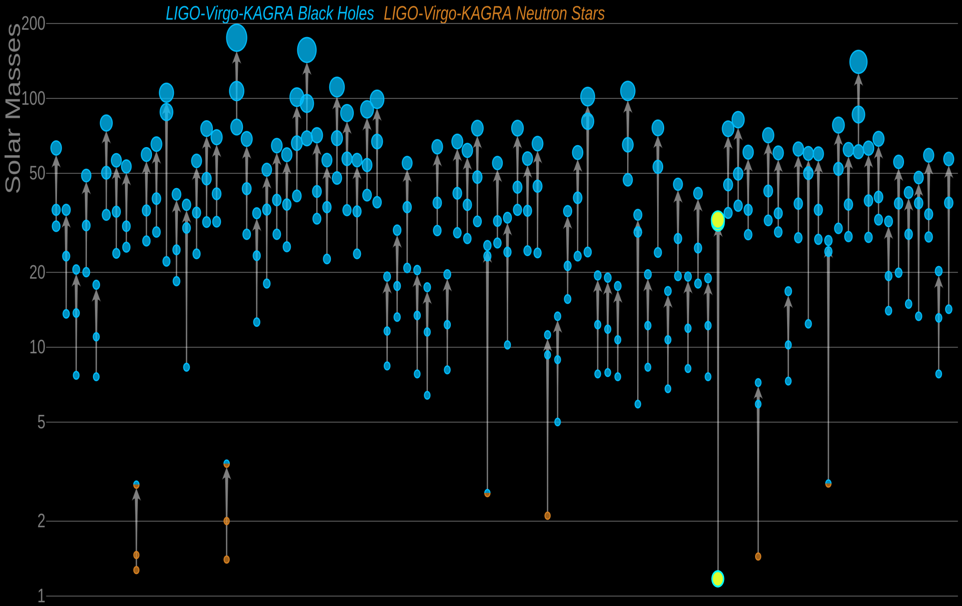
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

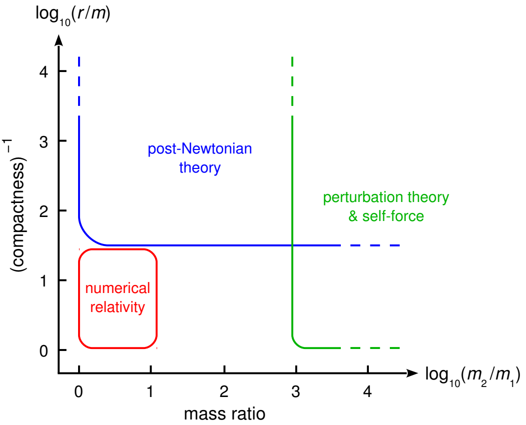
Systematic uncertainties in modeling IMRIs

[LIGO-Virgo-KAGRA 2021]

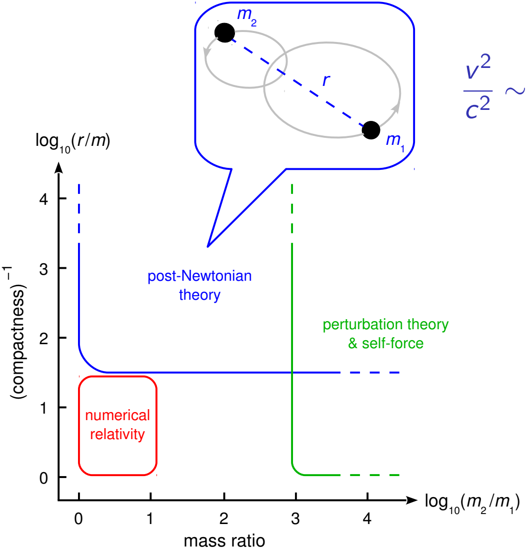
The mass ratio of GW191219_163120's source is inferred to be $q = 0.038 \pm 0.005$*, which is extremely challenging for waveform modeling, and thus there may be systematic uncertainties in results for this candidate.*

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.

Modeling coalescing compact binaries



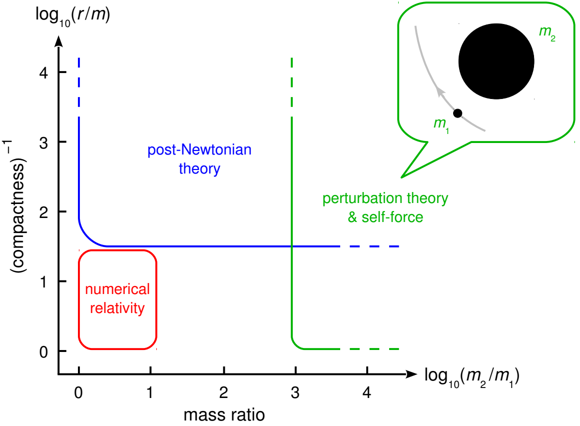
Modeling coalescing compact binaries



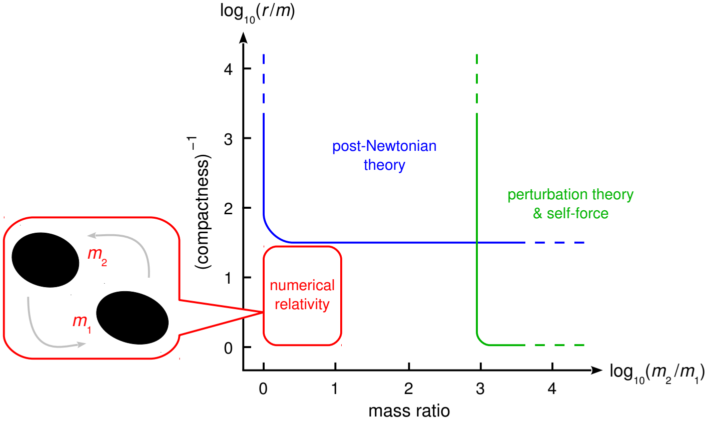
$$\frac{v^2}{c^2} \sim \frac{Gm}{c^2 r} \ll 1$$

Modeling coalescing compact binaries

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



Modeling coalescing compact binaries



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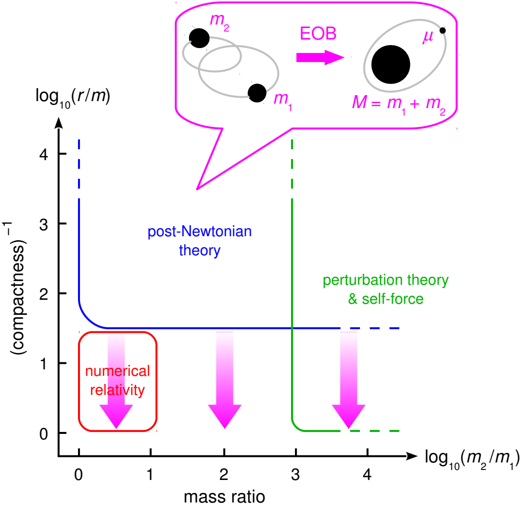
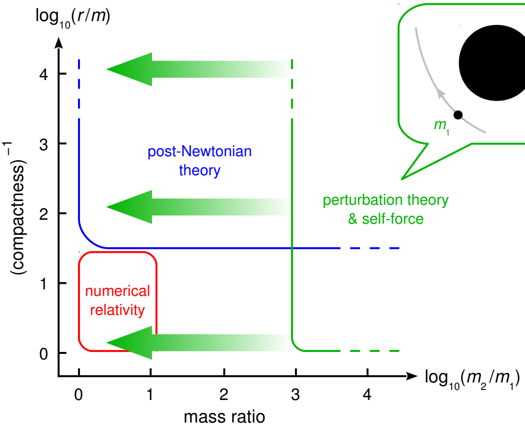


Modeling coalescing compact binaries

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



Perturbation theory for comparable masses

Relativistic orbital dynamics

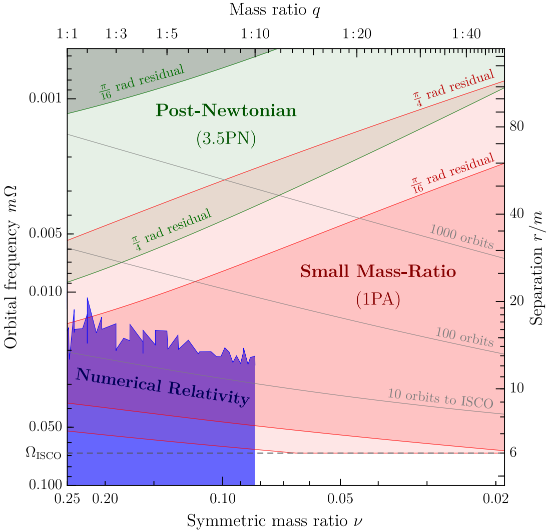
- Periastron advance [Le Tiec *et al.* PRL 2011; PRD 2013]
- Binding energy [Le Tiec, Buonanno & Barausse PRL 2012]
- Surface gravity [Le Tiec & Grandclément CQG 2018]

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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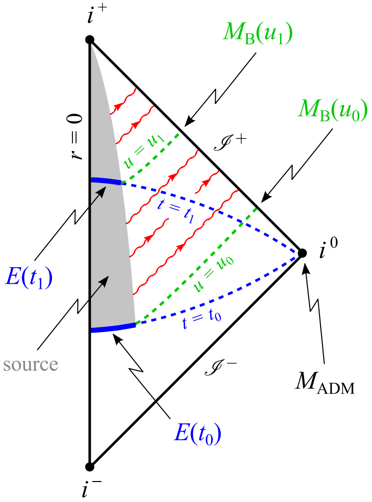
Orbital evolution *via* energy balance

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



- Bondi mass-loss formula

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

- Gravitational binding energy

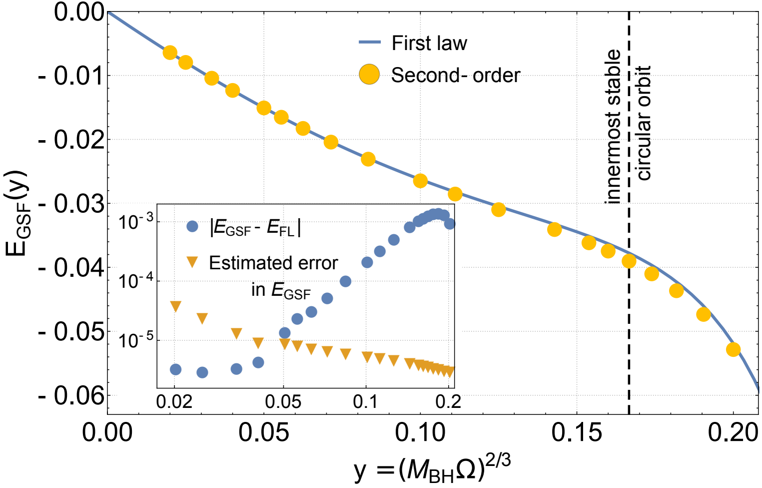
$$E \equiv M_B - M_{BH} - \mu$$

- Orbital frequency evolution

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

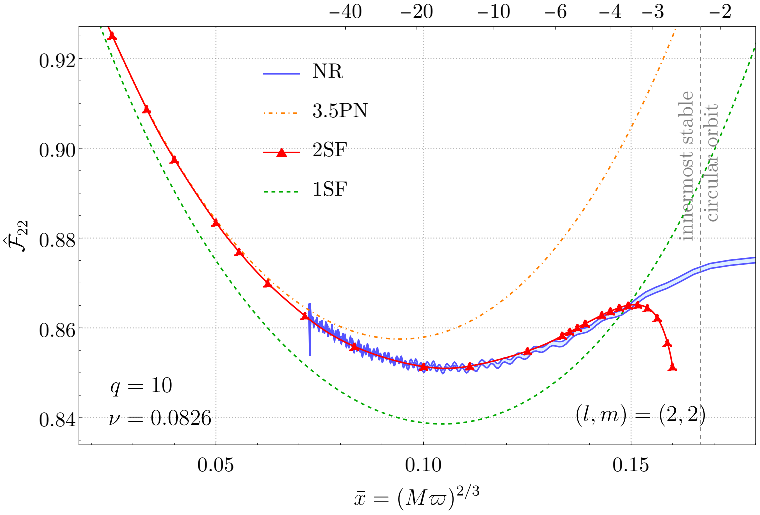
Second-order binding energy

[Pound *et al.* PRL 2020]



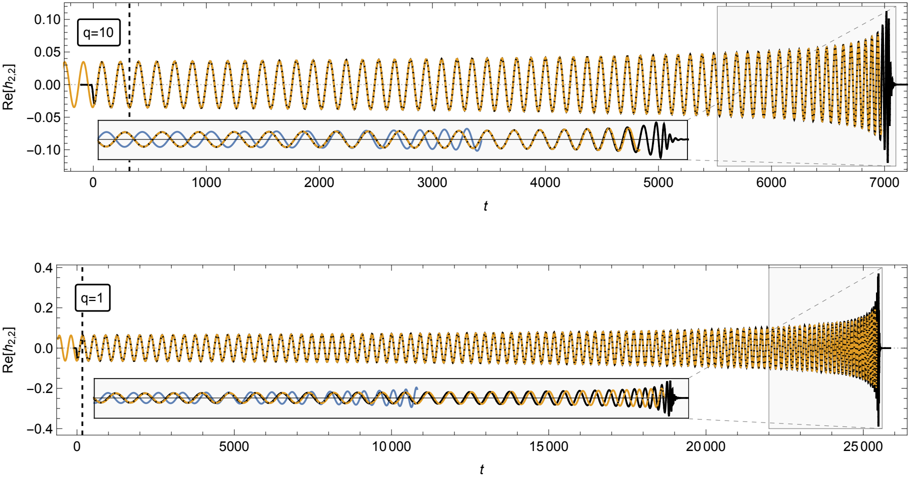
Second-order energy flux

[Warburton *et al.* PRL 2021]



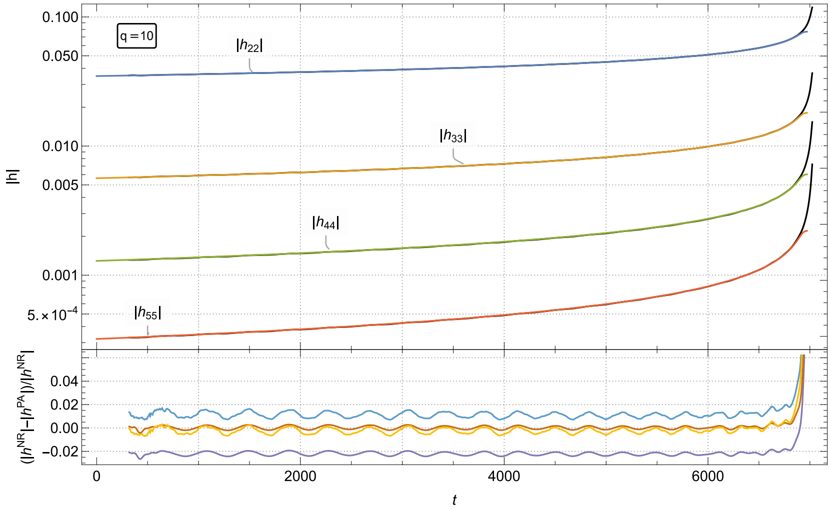
Gravitational waveforms

[Wardell *et al.* 2021]



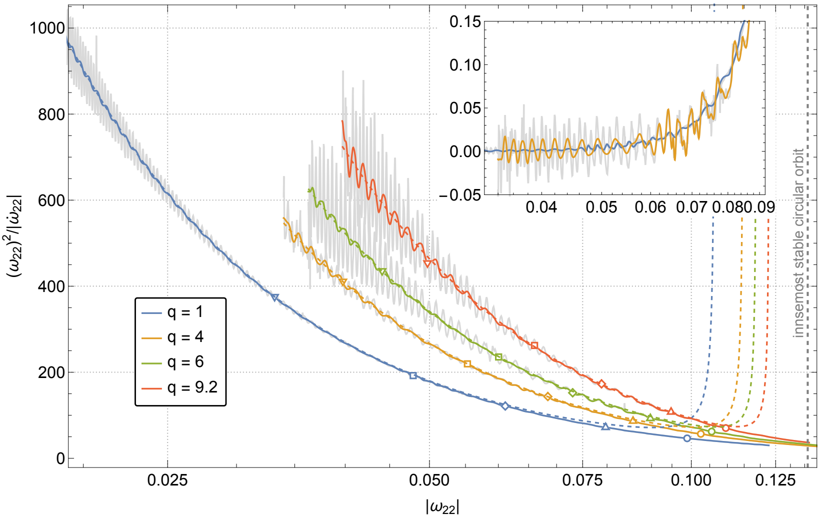
Mode waveform amplitudes

[Wardell *et al.* 2021]



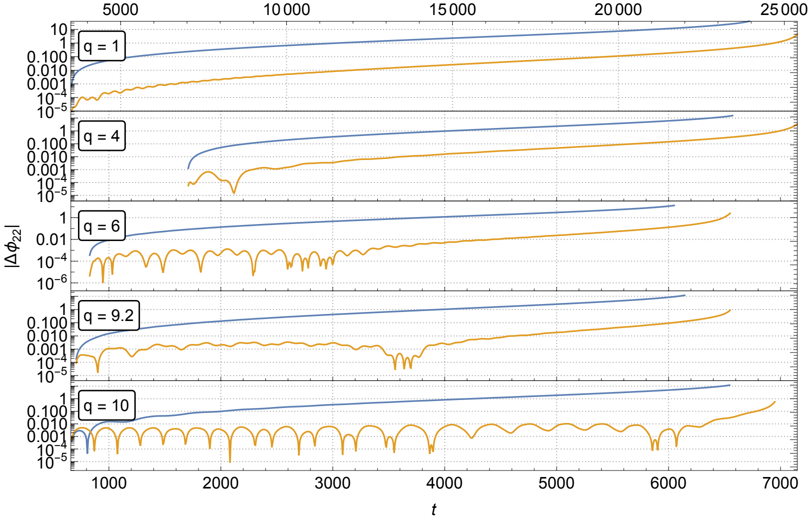
Waveforms frequency evolution

[Wardell *et al.* 2021]



Accumulated dephasing

[Wardell *et al.* 2021]



Summary

- 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 future: transition to plunge / add black hole spin