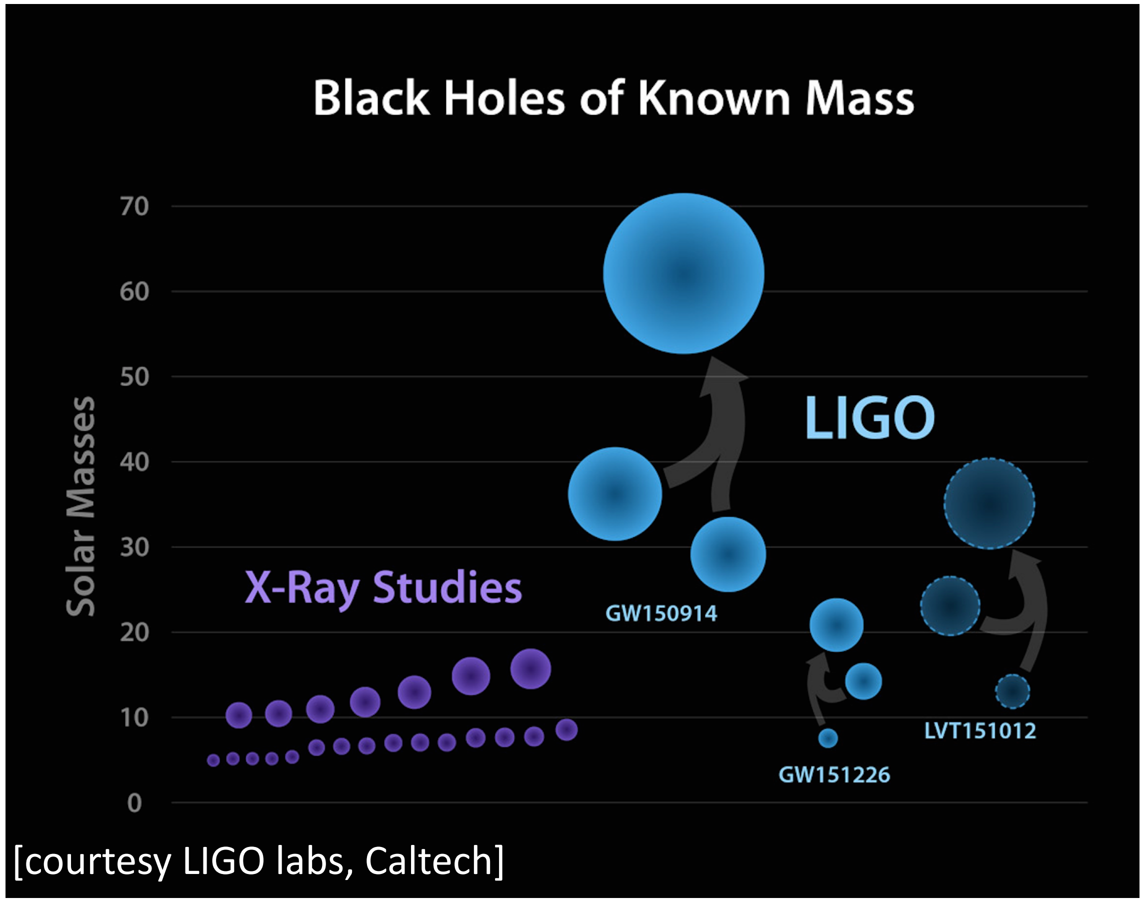
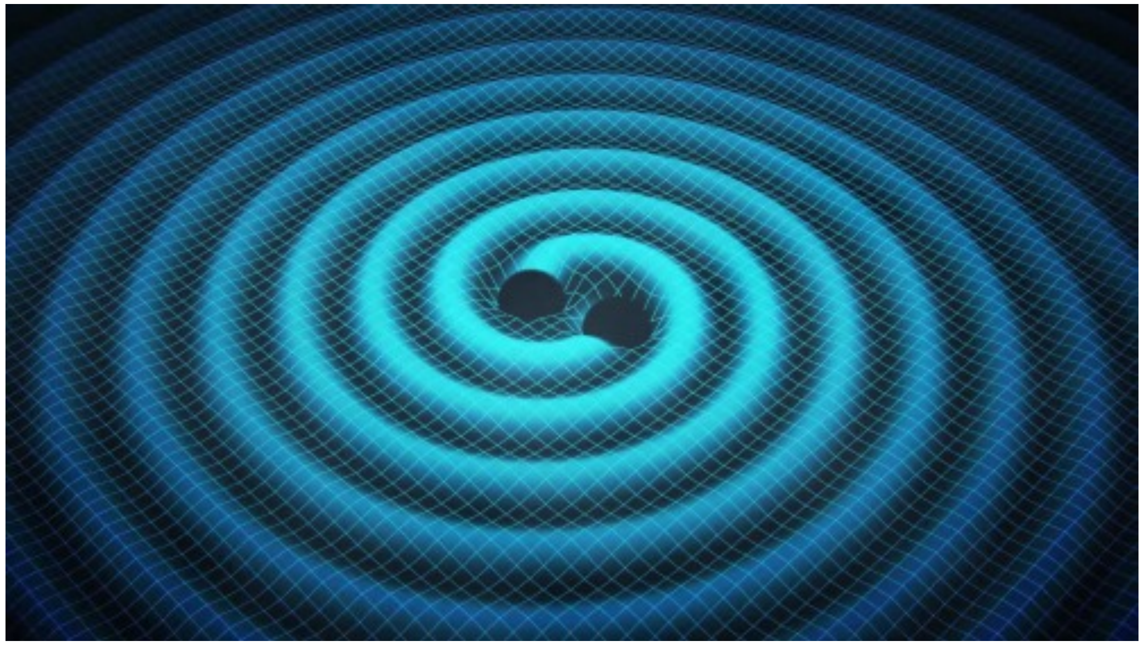
Clash of the Titans: new astrophysics of binary black holes from LIGO's observations





Samaya Nissanke
Radboud University, Nijmegen, the Netherlands
for the LIGO Scientific Collaboration & Virgo Collaboration

Radboud University

GR21, NYC, 12th July 2016

Main papers referenced in this talk

Discovery Paper: "Observation of Gravitational Waves from a Binary Black Hole Merger," arXiv:1602.03837, Physics Review Letters 116, 061102 (2016).

Astrophysical paper: "Astrophysical Implications of the Binary Black-Hole Merger GW150914," Astrophys. J. Lett. 818, L22 (2016).

Testing General Relativity: "Tests of general relativity with GW150914," arXiv: 1602.03841, Physics Review Letters 116, 221101 (2016).

Parameter Estimation: "Properties of the binary black hole merger GW150914," arXiv: 1602.03840, Physics Review Letters 116, 241102 (2016).

Stochastic Paper: "GW150914: Implications for the stochastic gravitational wave background from binary black holes", arXiv: 1602.03847, Physics Review Letters 116, 131102 (2016).

GW151226 discovery: "GW151226: Observation of Gravitational Waves from a 22 Solar-mass Binary Black Hole Coalescence," arXiv:1606.04755, Physics Review Letters 116, 241103 (2016)

O1 BBH paper: "Binary Black Hole Mergers in the first Advanced LIGO Observing Run," arXiv:1606.09619

Relevant Sessions at GR21

Special Sessions: Gravitational Wave Highlights, Tues 2-4; 4:30-6:30pm

Session C2: Gravitational Waves — searches and data analysis, Mon 2-4pm, Wed 2-3:30pm, Thurs 2-4pm

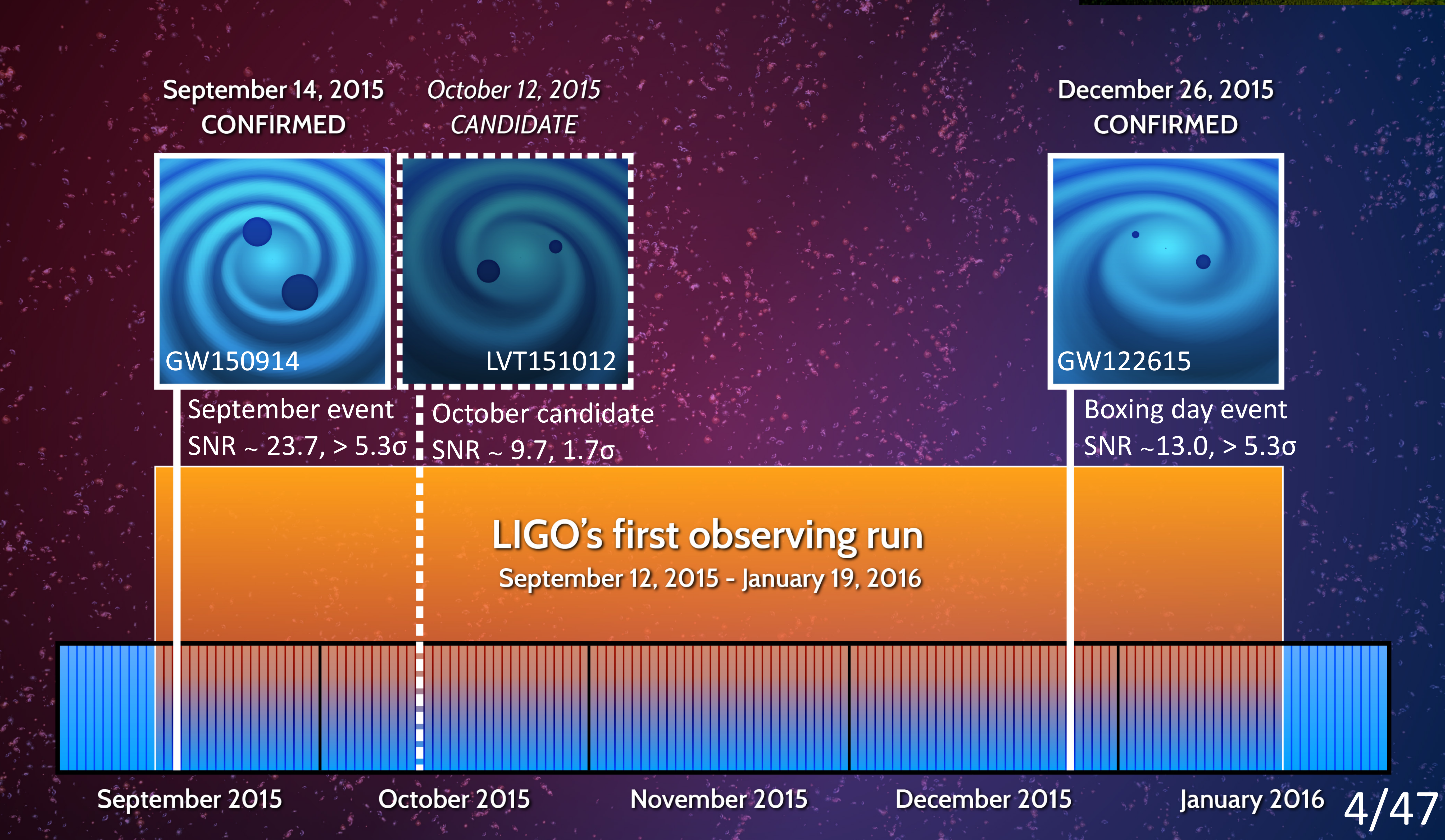
Session B2: Numerical Relativity, Mon, 2-6:30pm, Wed 5:30-6:30pm, Thurs 4:30-6:30pm

Session B3: Approximations, perturbation theory, and their applications, Mon 4:30-6pm, Wed 3:30-6:30, Thurs 4:30-6:30pm

Session B1: Relativistic Astrophysics, Mon, 2-6:30pm, Wed 2-5:30pm, Thurs 2-4pm

Session C3: Gravitational waves: Present and future of ground-based and space-based detectors, Wed 2-4pm; Thurs 2-3pm; Thurs 4:30-5:30pm

Main characters



Plan of Talk

Part 1: Retrieving Black Hole (BH) parameters

Part 2: Tests of General Relativity

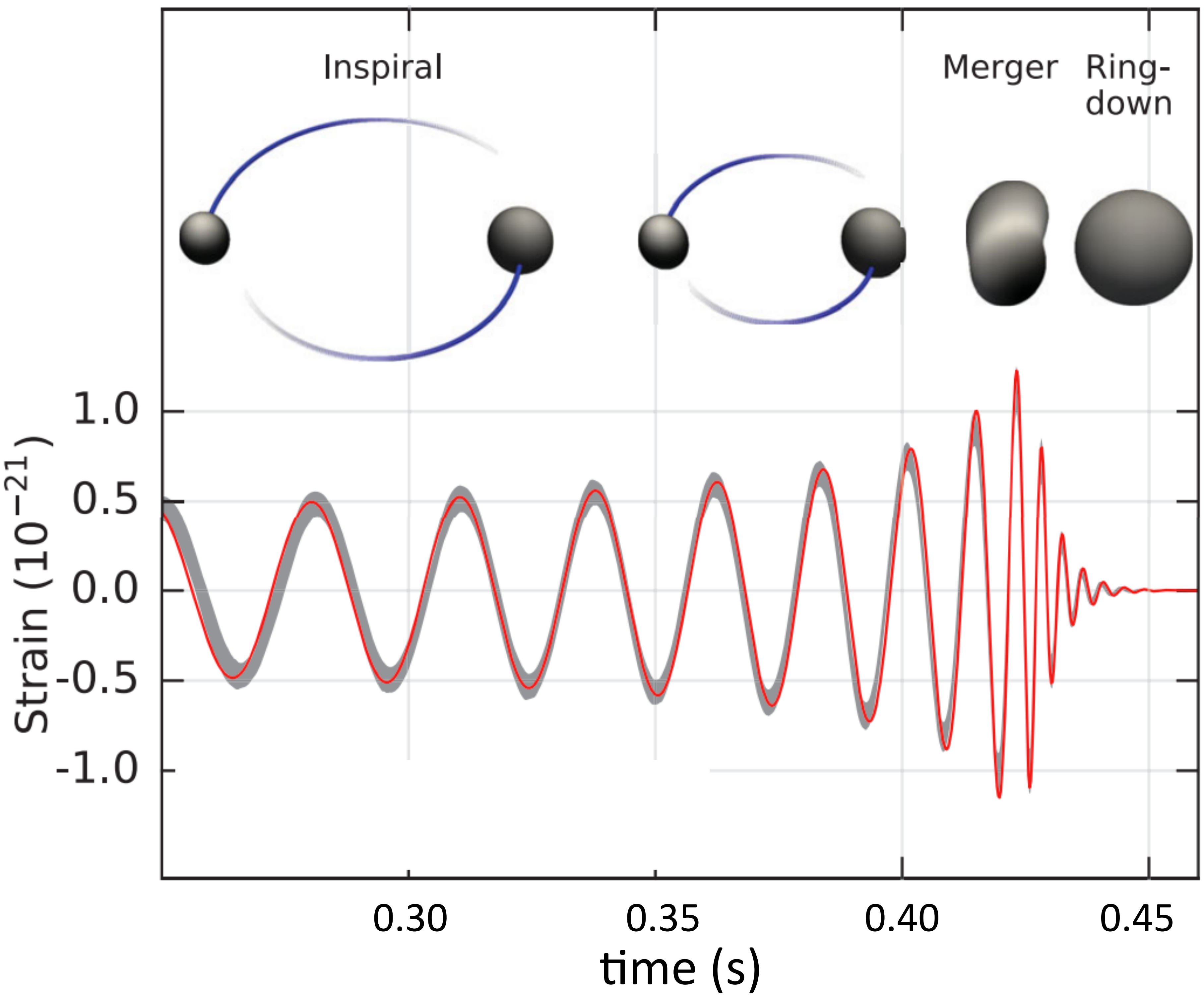
Part 3: Astrophysical Implications

Part 4: Perspective & what's next? [my views]

Part I:
Retrieving BH parameters
[if General Relativity is correct]

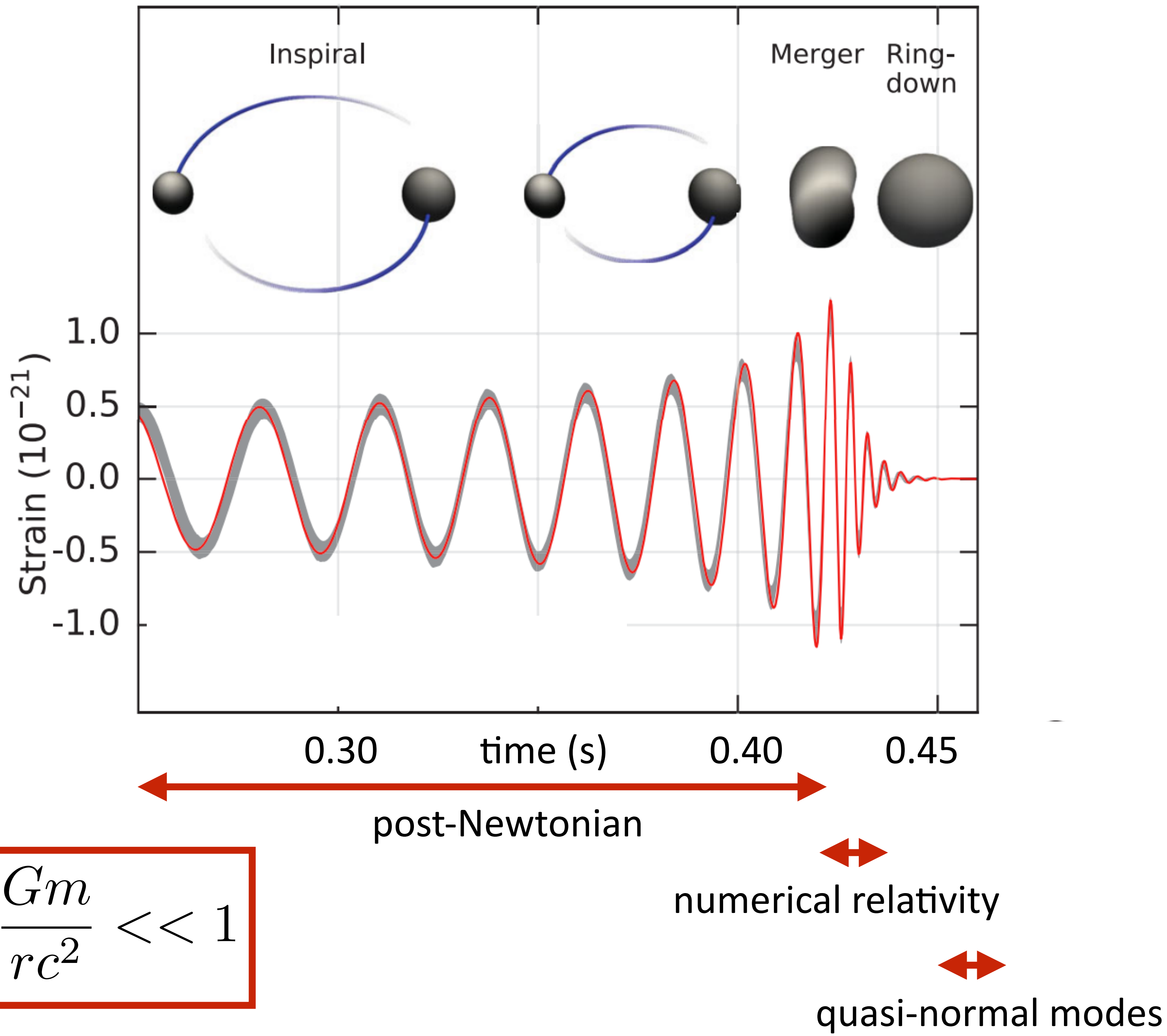
The GW waveform encapsulates Binary Black Hole Evolution

[see Gonzalez talk]



[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Decades of theoretical effort in source modelling

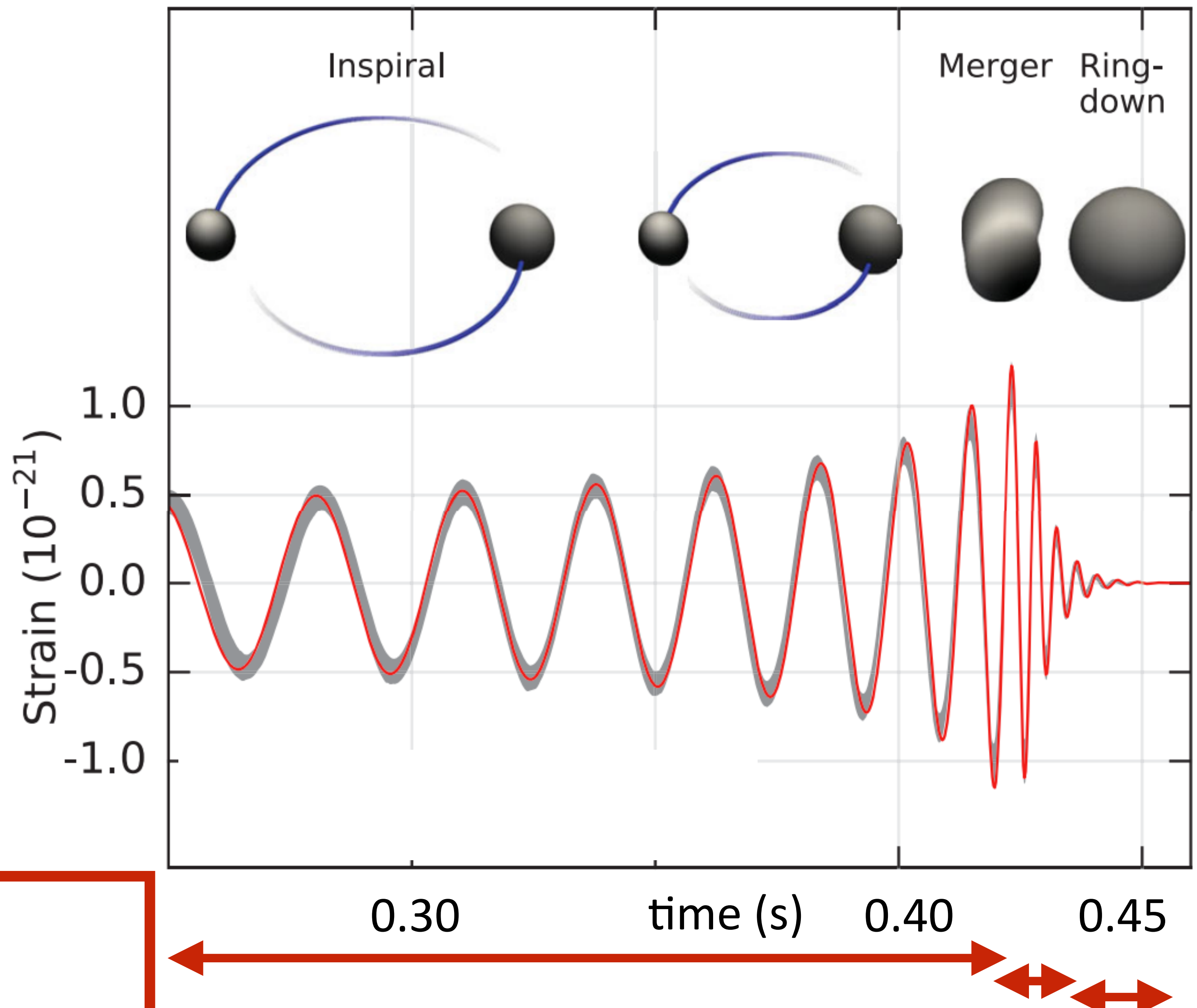


$$1\mathrm{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1$$

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Chirp mass drives inspiral waveform

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]



chirp mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
$$= \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

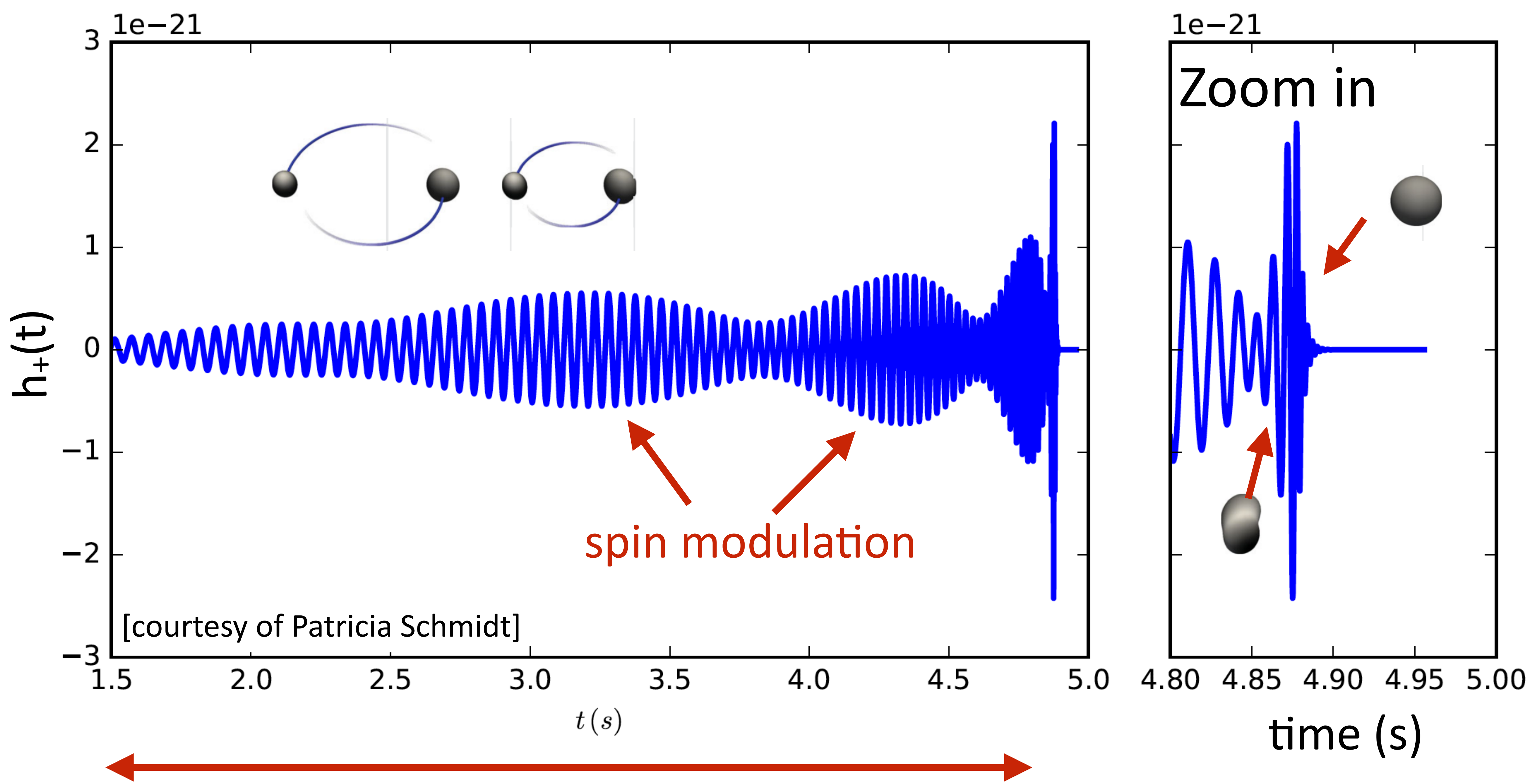
Inspiral ~ Chirp

driven by the chirp mass

Ringdown

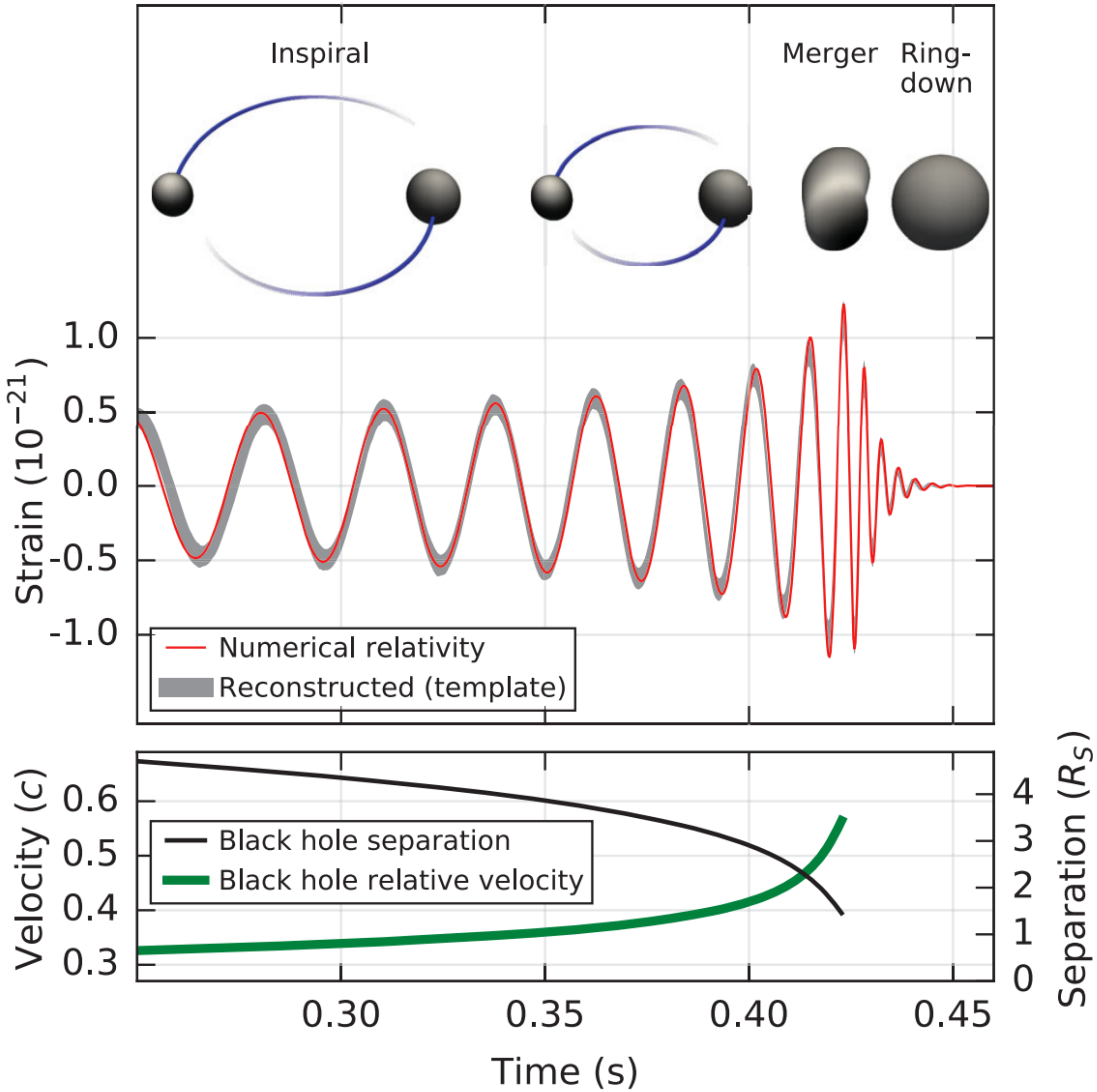
... remnant mass & spin

The GW waveform encodes source parameters



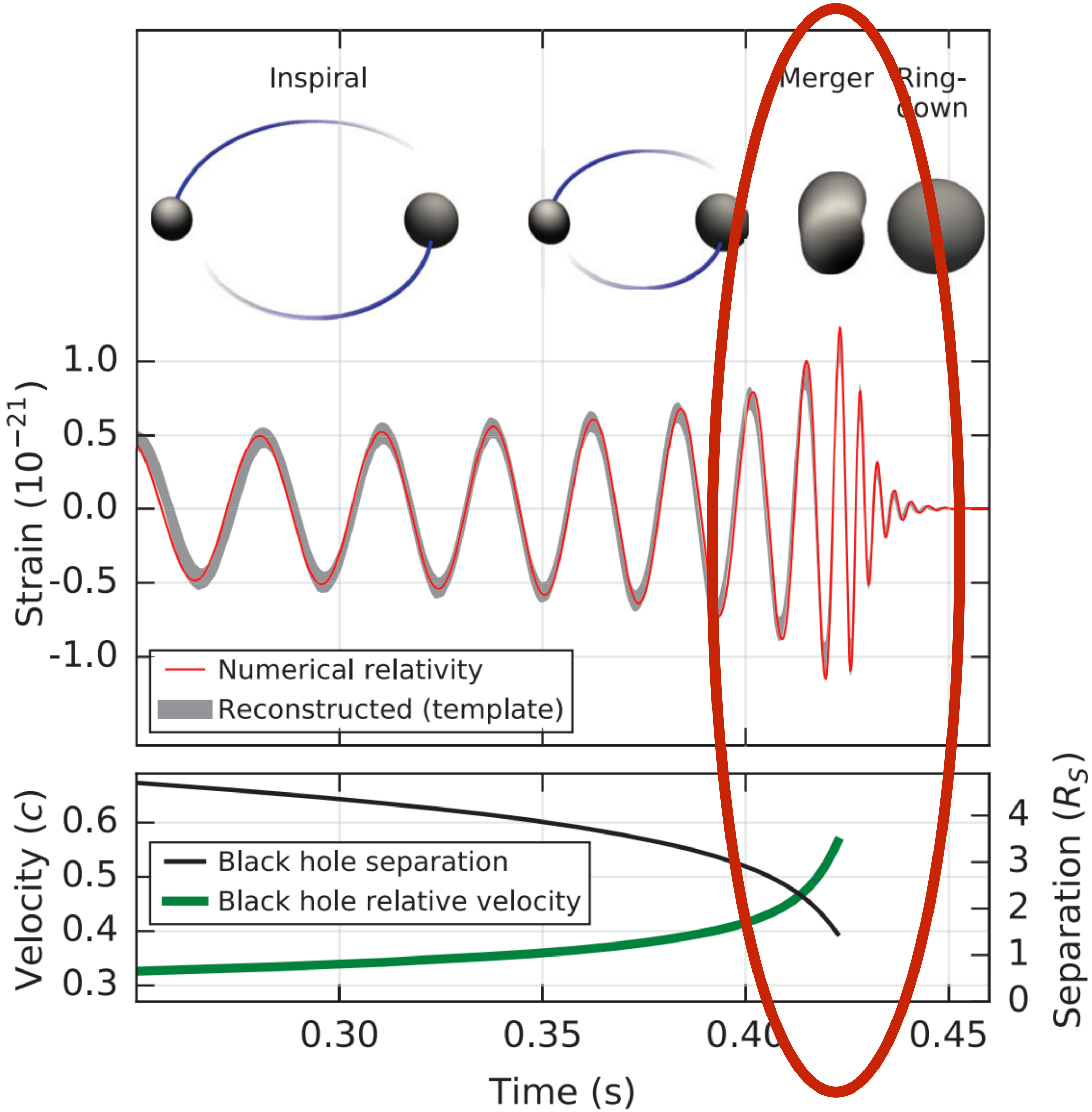
$\Phi_{\mathrm{GW}}(t)$ ⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), …

Necessity of Numerical Relativity



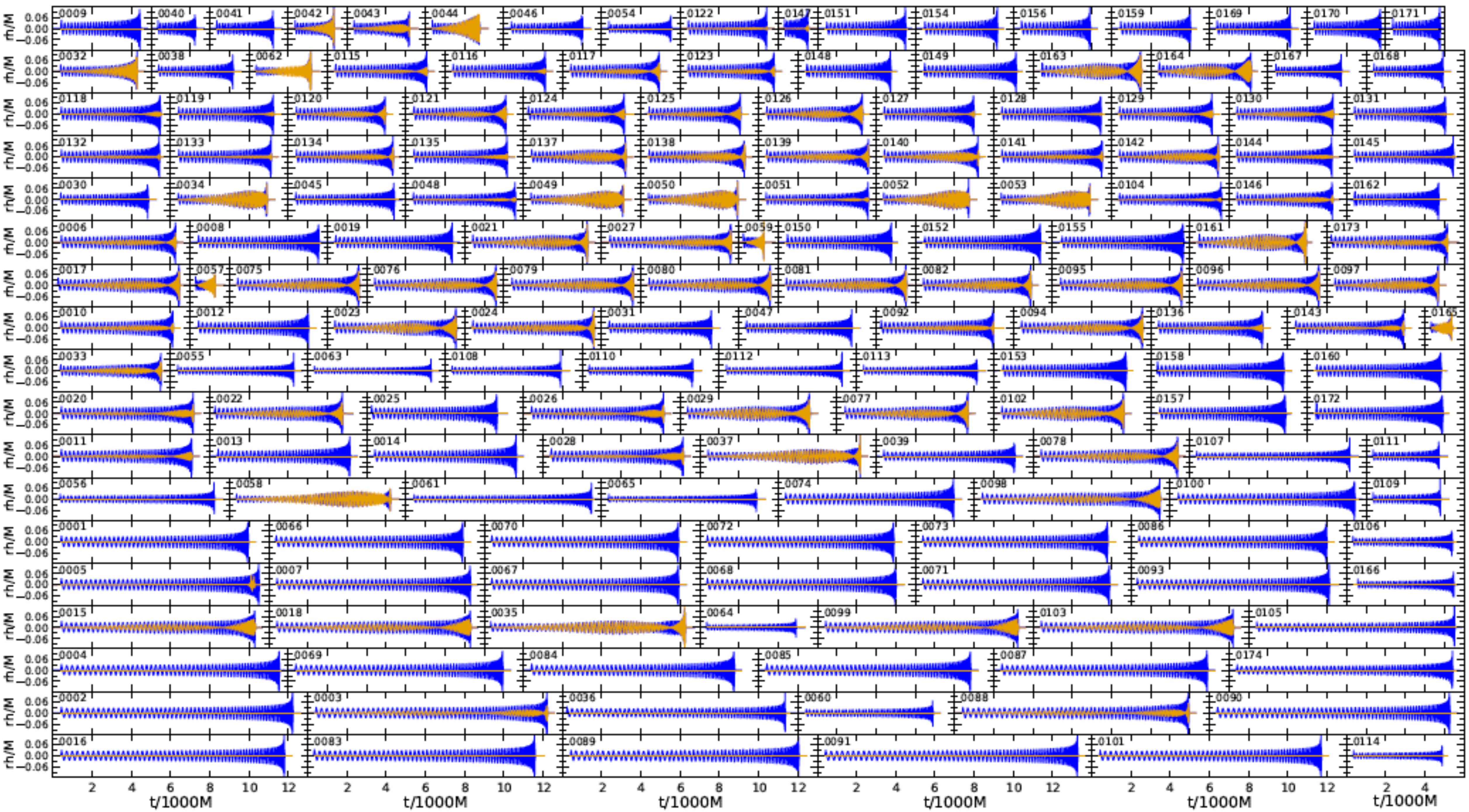
[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Unprecendented high velocity, dynamic regime of strong-field gravity



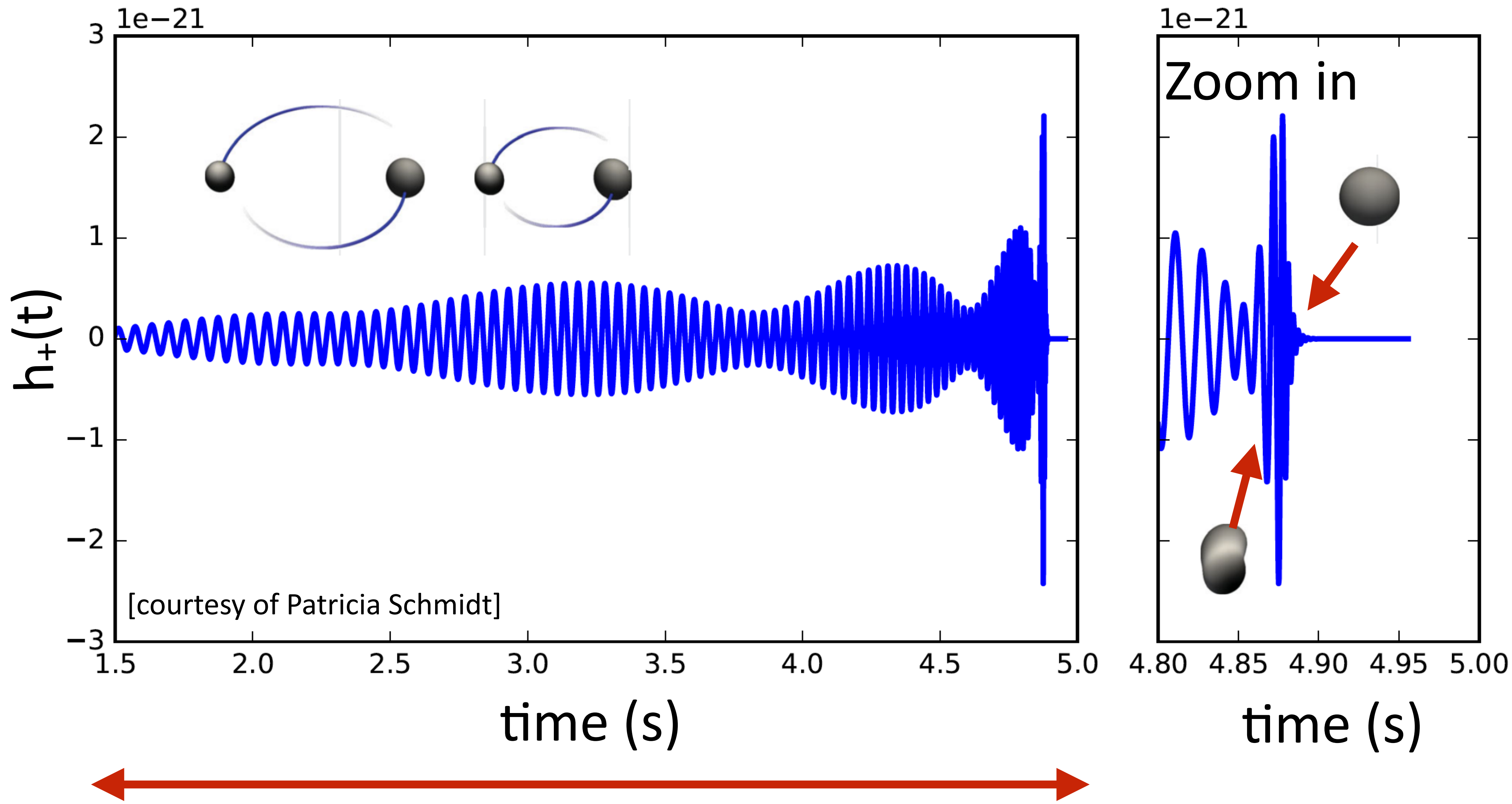
[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Different flavors of numerical relativity waveforms



[e.g., SXS Collaboration 2014; see also simulations by Cardiff, UIB, RIT and GATech;
combined analysis with several hundred simulations from all groups for GW150914 detailed in arXiv: 1606.01262]

Two classes of model waveforms used in O1



State-of-the-Art:

Inspiral-Merger-Ringdown Phenomenological Fit with Numerical Relativity

[Khan et al. 2016, Hannam et al. 2016]

&

Spinning Effective-One-Body Numerical Relativity [Taracchini et al., Purrer et al. 2016]

⇒ Allows for systematic error analysis and consistency check

Extract source information from GWs

h(t): 9-15 dimensions

+ Masses
+ Spins
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

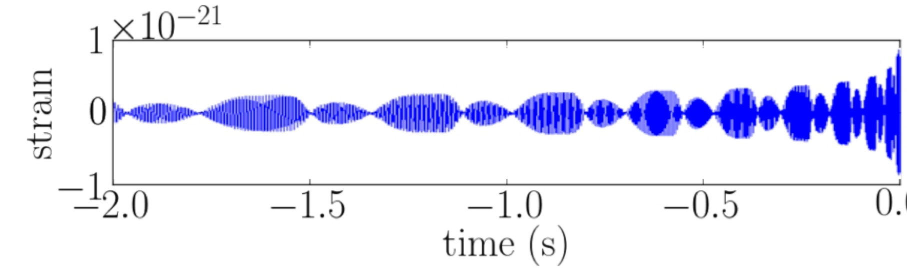
[see e.g. Cutler and Flanagan 1994, Poisson and Will 1996…]

Extract source information from GWs

h(t): 9-15 dimensions

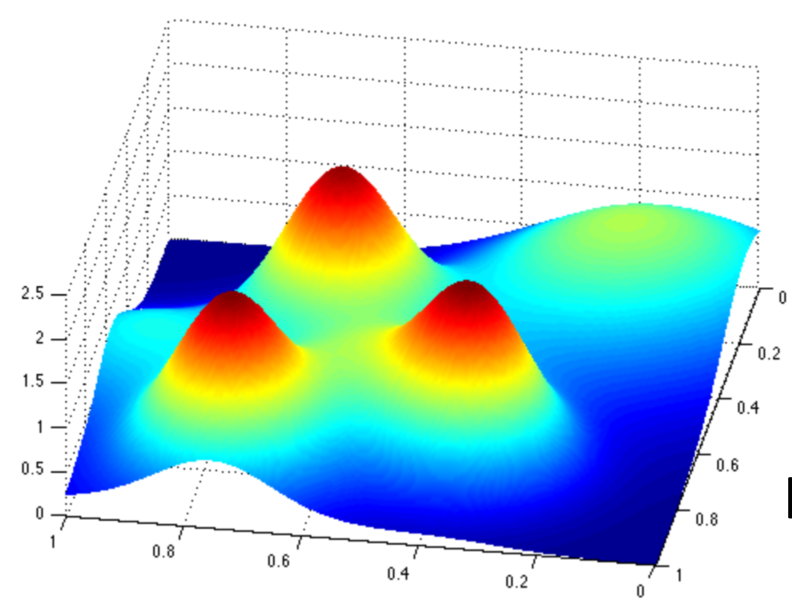
+ Masses
+ Spins
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

Explicitly map out: $p(\boldsymbol{\theta}|s) \propto p(\boldsymbol{\theta})\mathcal{L}_{\mathrm{total}}(s|\boldsymbol{\theta})$



Likelihood

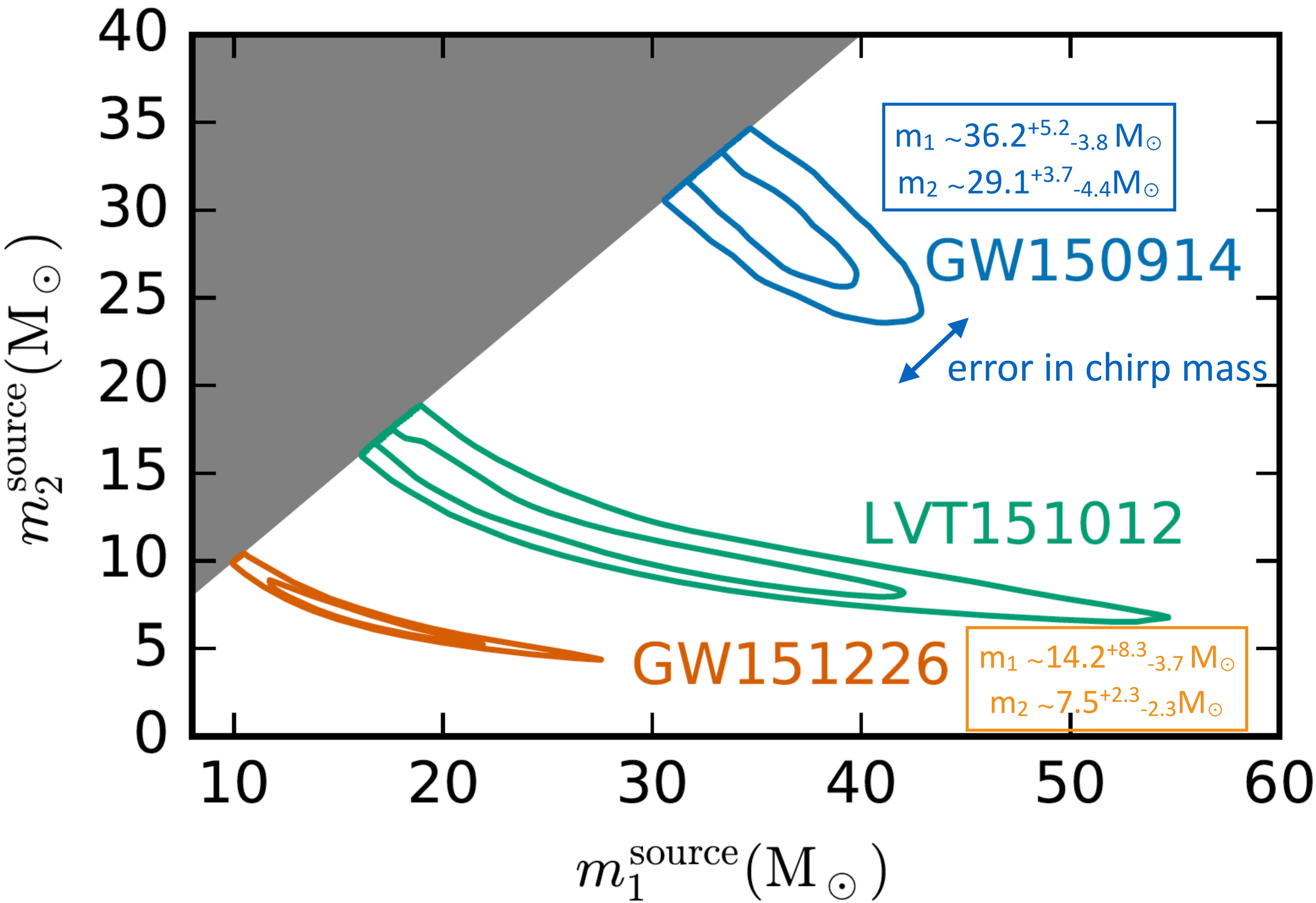
parameter 1

parameter 2

using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

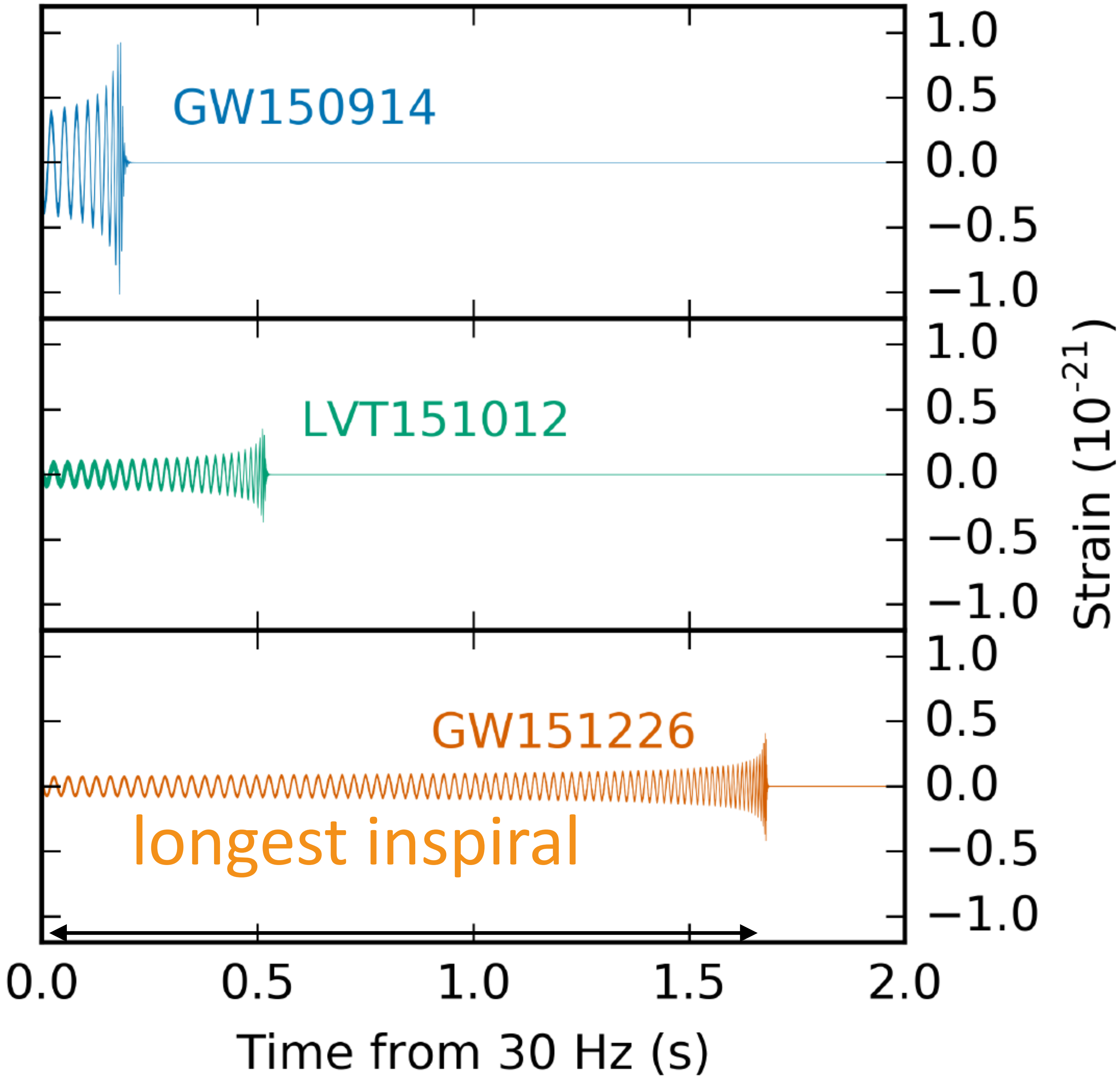
[see e.g. Veitch et al. 2015;
LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]

Diversity of BH masses and errors …



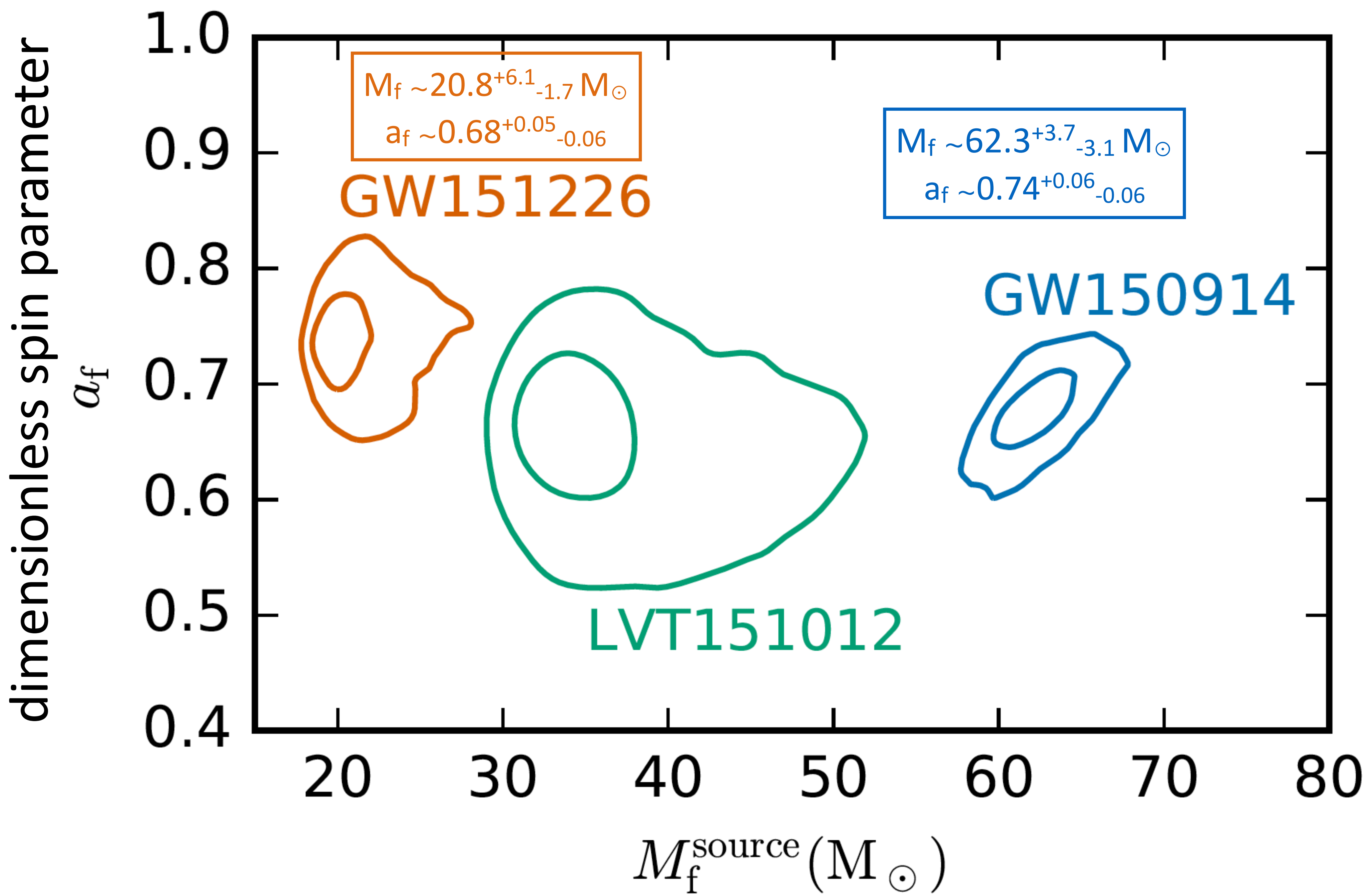
[LVC, arXiv:1606.09619, 2016]

… length of the chirp signal



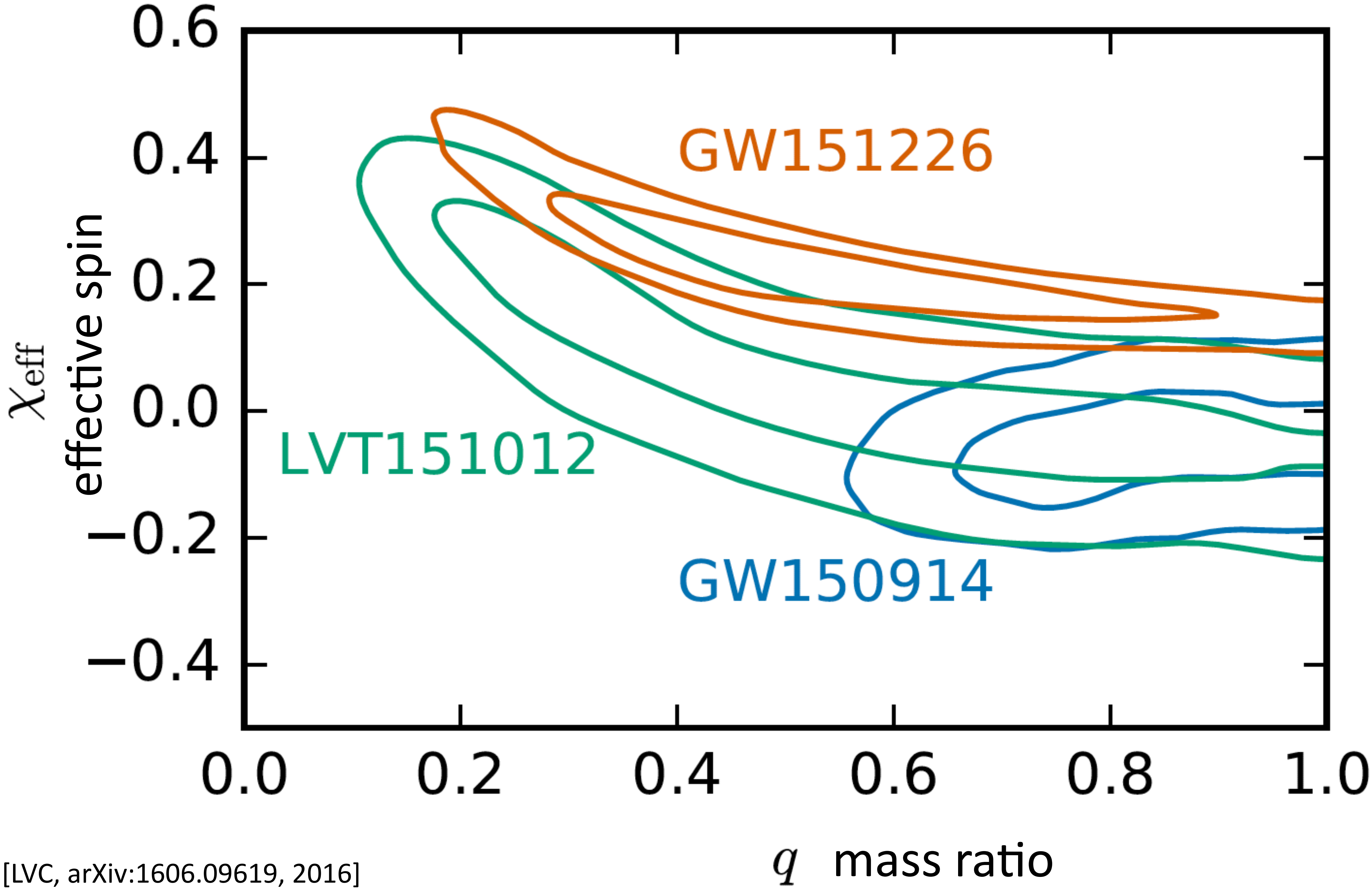
[LVC, arXiv:1606.09619, 2016; see also http://www.soundsofspacetime.org to listen to the chirps]

Remnant BH masses & spins



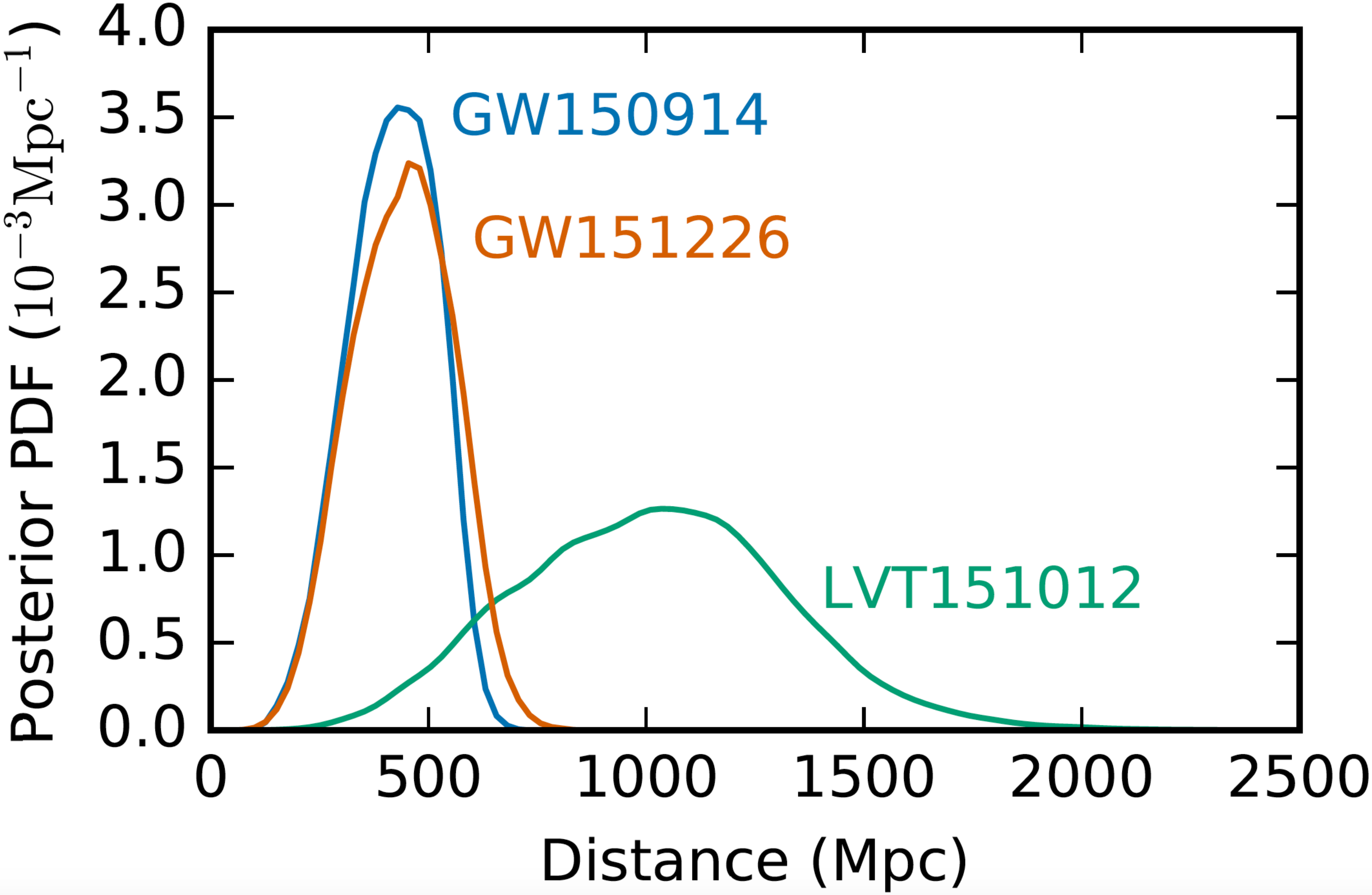
[LVC, arXiv:1606.09619, 2016]

Challenge: large degeneracies between mass ratio and effective spin



[LVC, arXiv:1606.09619, 2016]

Luminosity distance: beyond existing spectroscopic galaxy catalogs



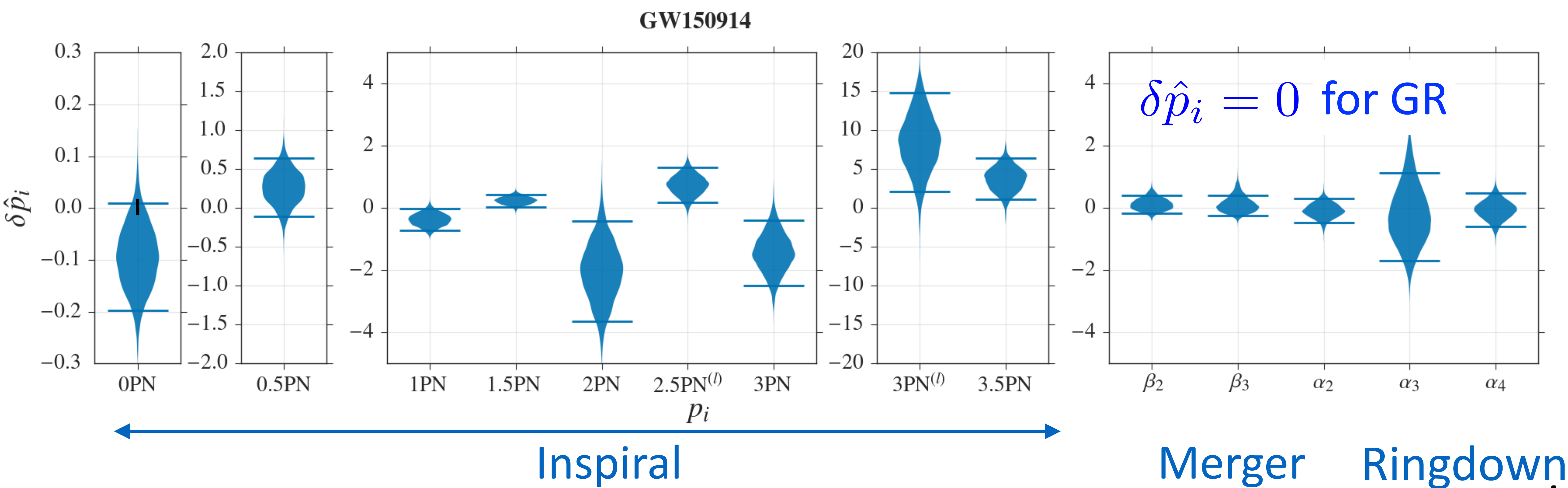
[LVC, arXiv:1606.09619, 2016]

Part II:
Tests of General Relativity in dynamical strong-field gravity

Deviations from GR Waveform Coefficients

Introduce parameterized violations of GR: $p_i \rightarrow p_i(1 + \delta\hat{p}_i)$

$$\Psi_{\mathrm{GW}}(f) = \sum_i [\psi_i + \psi_{il} \log f] f^{(i-5)/3} + \Phi^{\mathrm{MR}}[\beta_i, \alpha_i]$$



[LVC, arXiv:1606.09619, 2016; arXiv: 1602.03841, PRL 116, 221101, 2016]

Deviations from GR Waveform Coefficients

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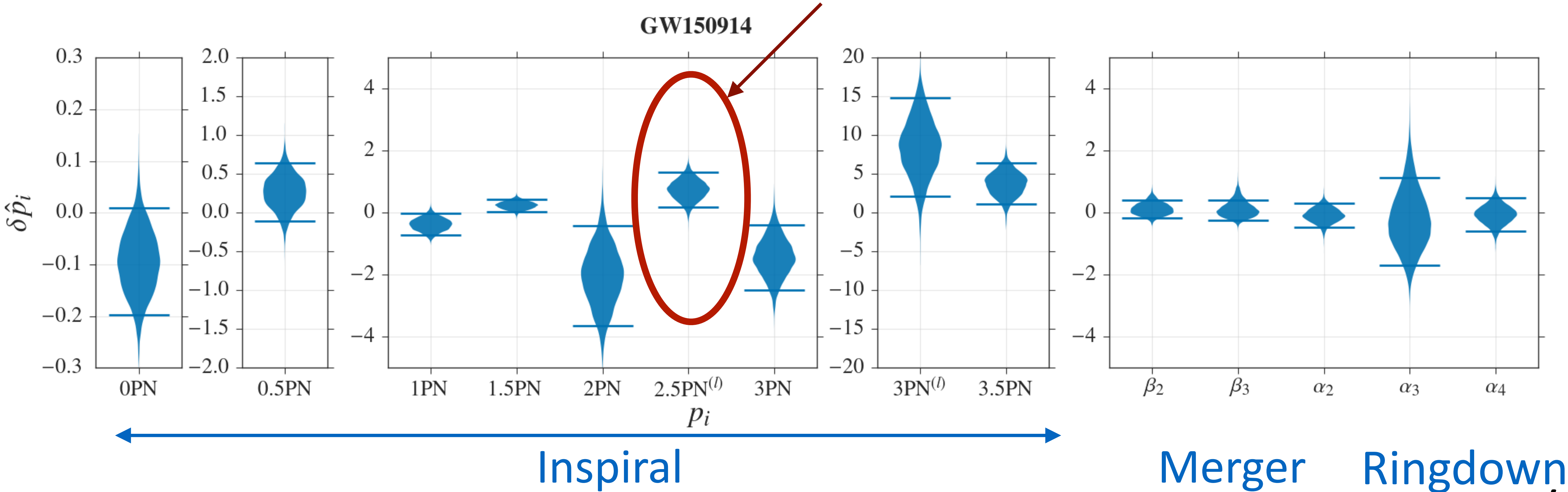
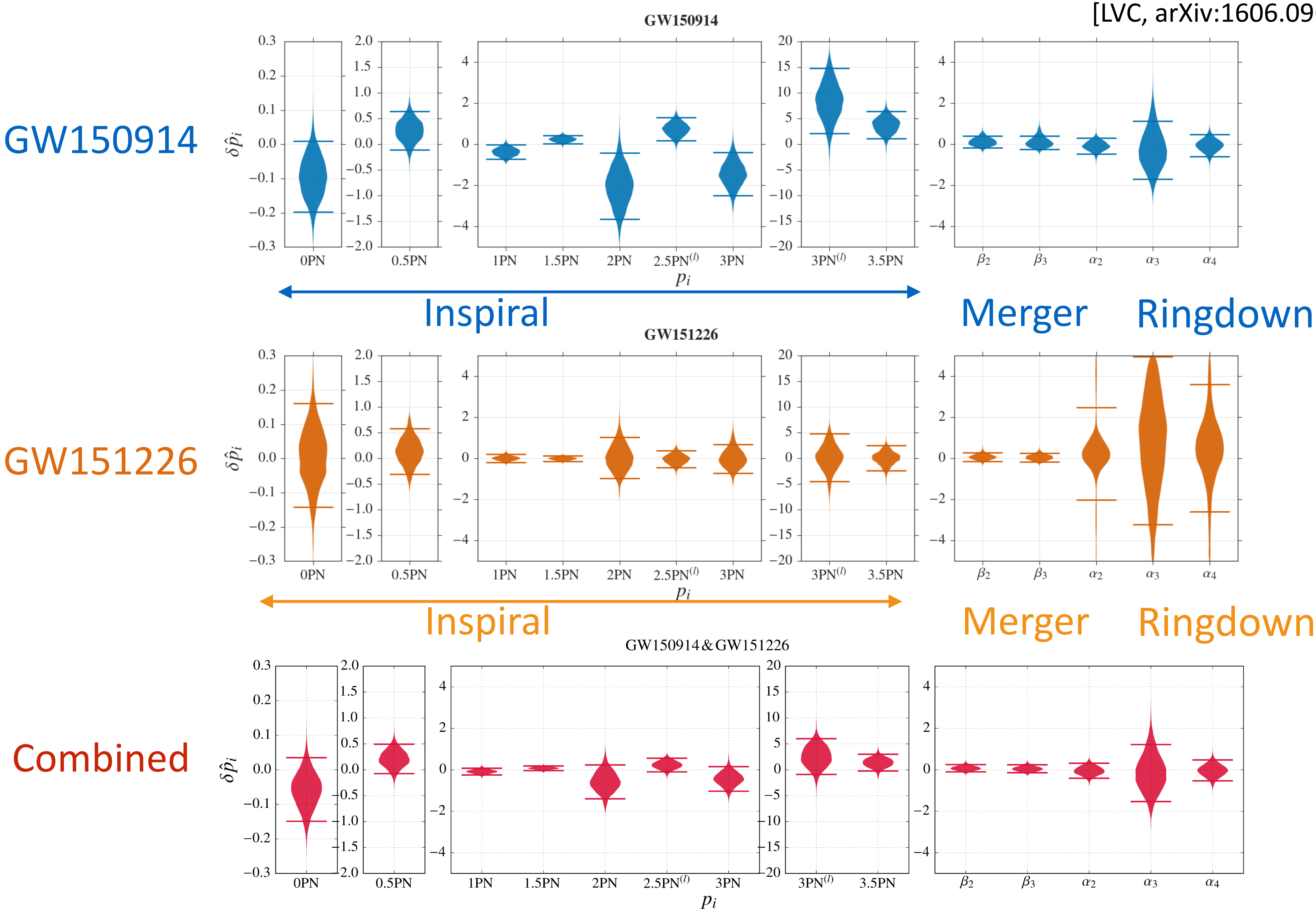
tail - backscattering of GWs by curved spacetime



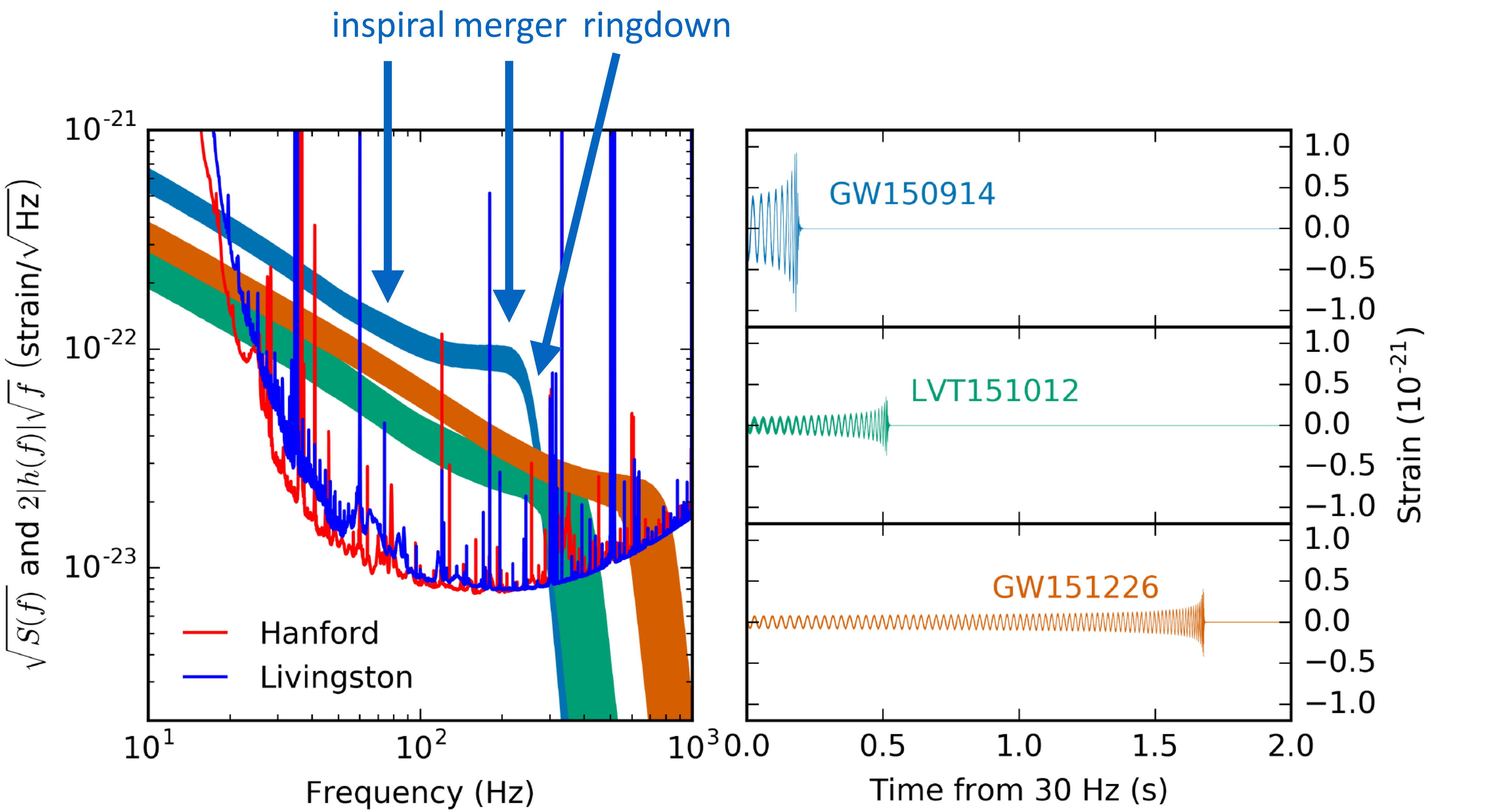
[LVC, arXiv:1606.09619, 2016; arXiv: 1602.03841, PRL 116, 221101, 2016]

… two events constrain different parts of waveform

[LVC, arXiv:1606.09619, 2016]



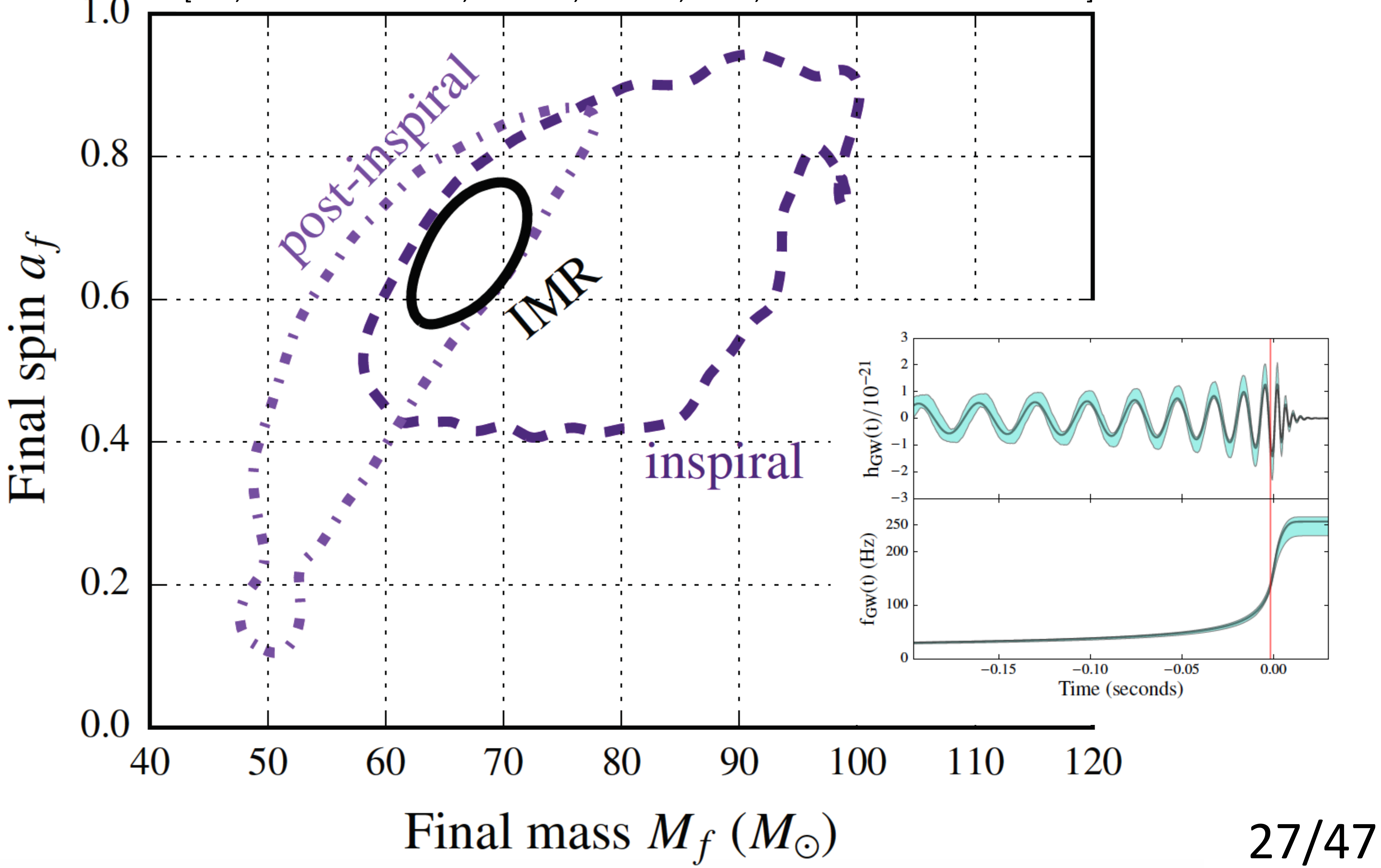
… GW150914 merger + ringdown in the detector noise bucket!



[LVC, arXiv:1606.09619, 2016]

GW150914: Inspiral vs. merger-ringdown consistency

[LVC, arXiv:1606.09619, PRL 116, 221101, 2016; see also Ghosh et al. 2016]



GW150914: Massive Graviton Bounds

- massive graviton dispersion relation:

$$E^2 = p^2c^2 + m_g^2c^4$$

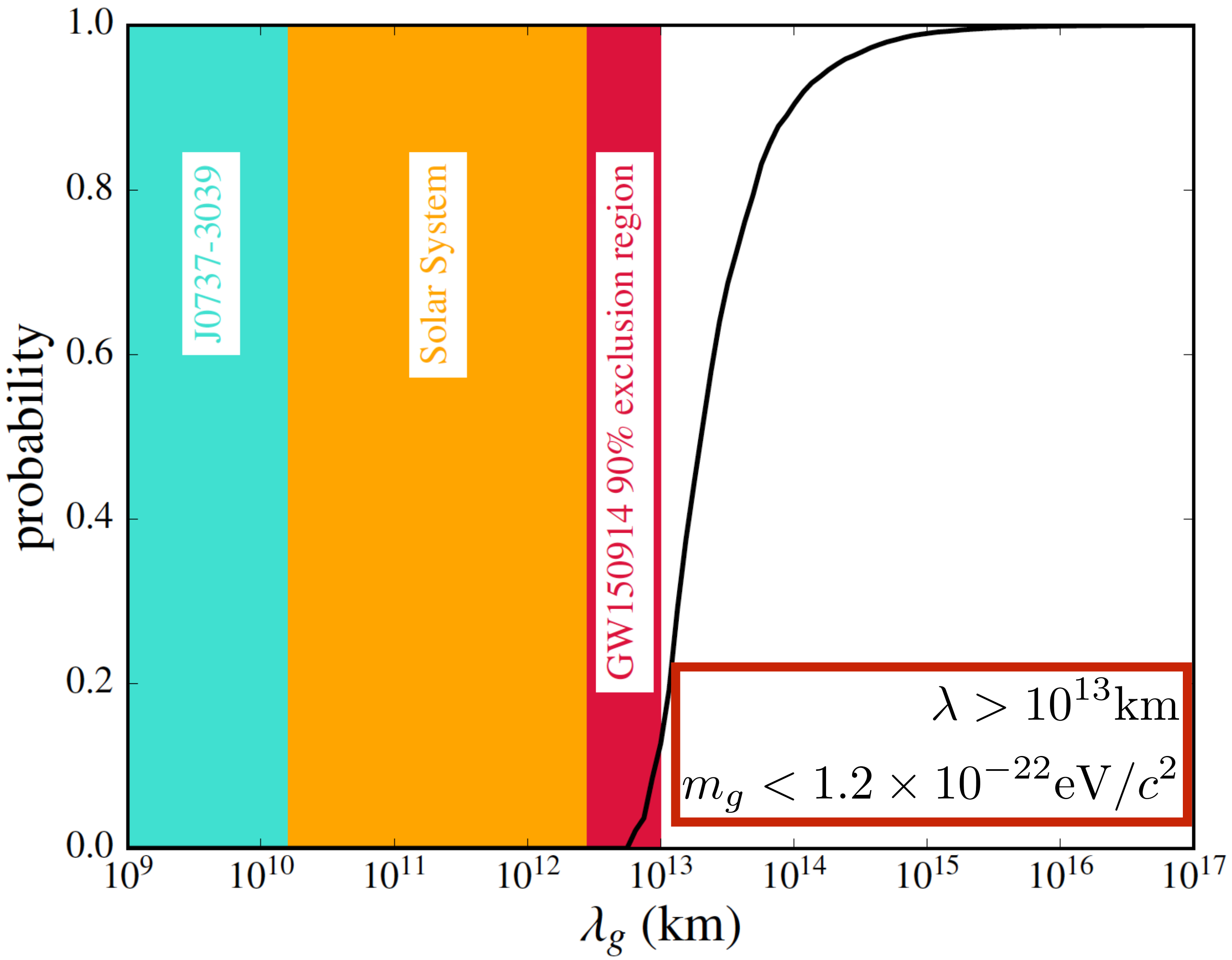
where $\lambda_g = \dfrac{h}{m_g c}$

- higher frequencies arrive earlier:

$$\left(\frac{v_g}{c}\right)^2 = 1 - \frac{h^2c^2}{\lambda_g^2 E^2}$$

- waveform distortion:

$$\delta\Phi(f) = \frac{\pi D c}{\lambda_g^2(1+z)f}$$



[LVC, PRL 116, 221101, 2016]

Part III: Implications for Astrophysics

i) how to form heavy BHs?

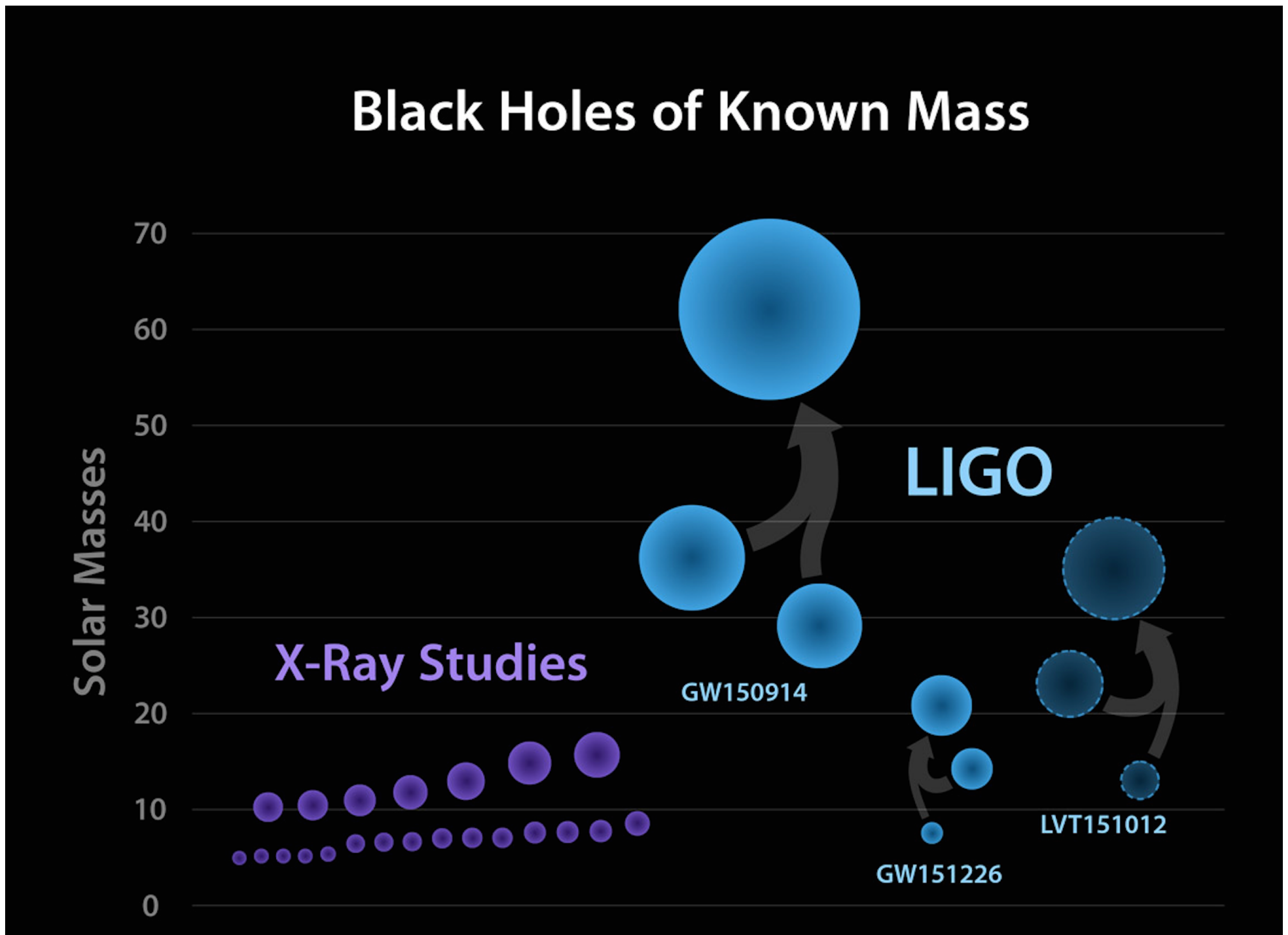
ii) how & where do binary black holes (BBH) form?

iii) astrophysical rates ?

iv) absence of an EM counterpart

[see Branchesi's talk] ?

Diversity of BH masses



[courtesy LIGO labs, Caltech]

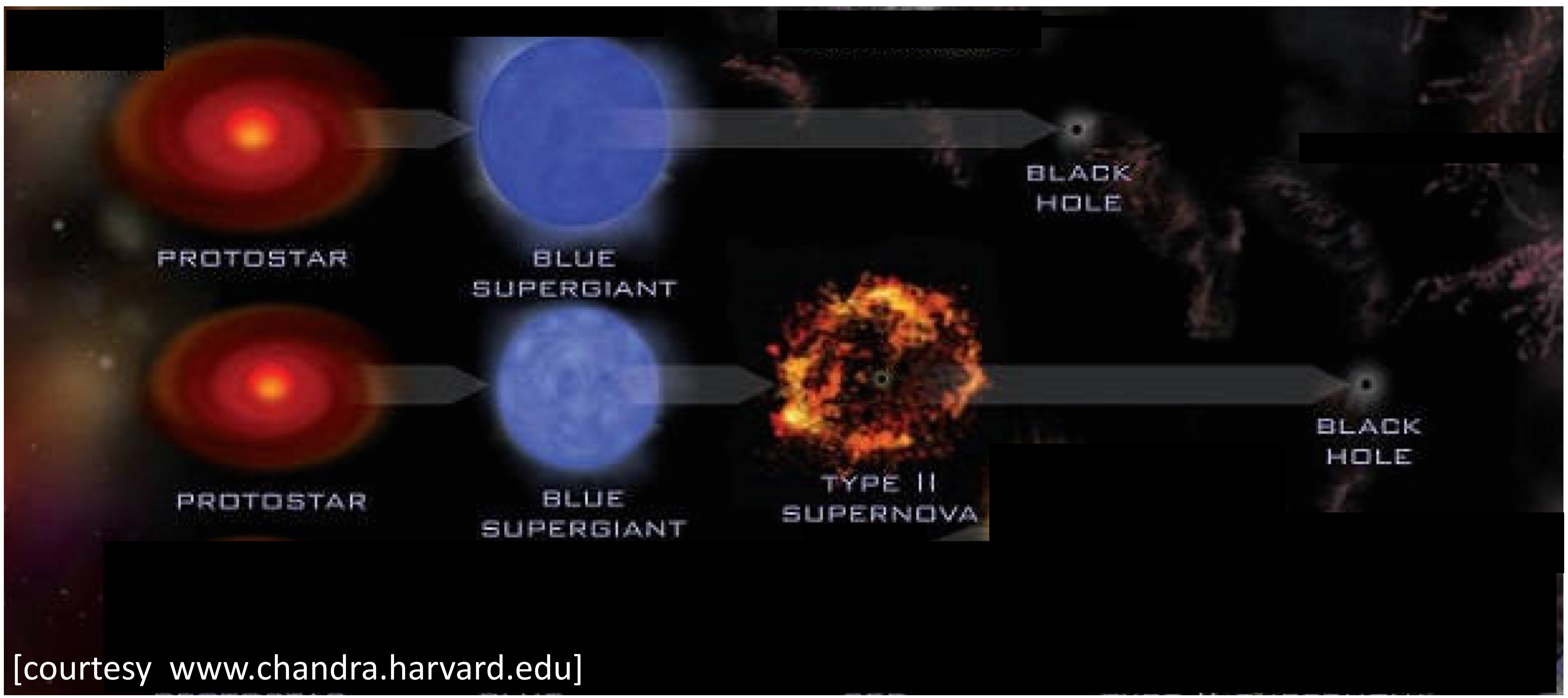
22 (19 Galactic) X-ray binaries with dynamical mass measurements $< 20\, M_\odot$

[see review Cesares & Jonker 2014 & references therein]

GW150914:
Heavy ($> 25\, M_\odot$) BHs

How to make a stellar-mass BH?

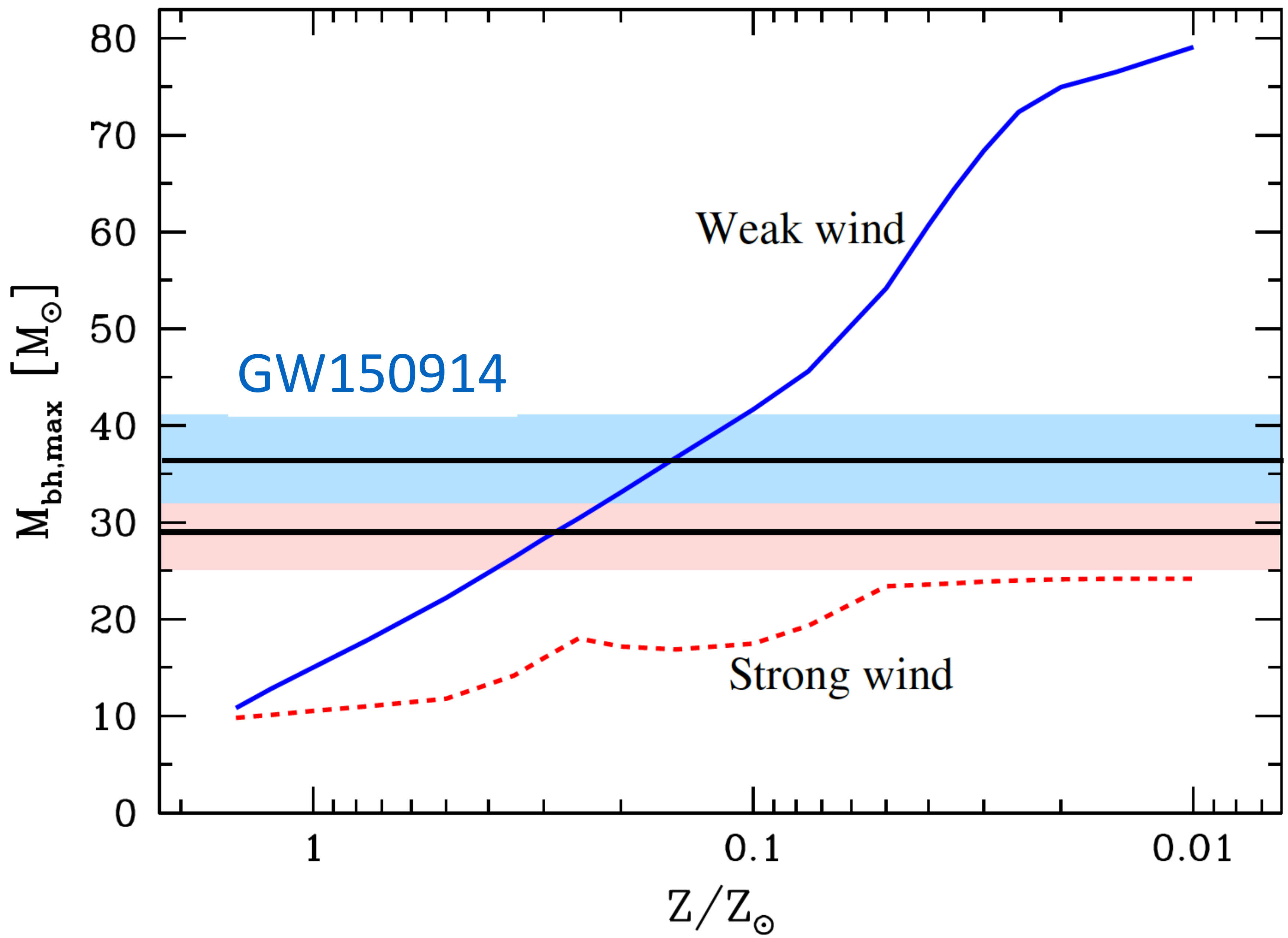
Stellar core collapse at end of lives of massive stars:
direct formation or fallback? first stars?



[courtesy www.chandra.harvard.edu]

Recipe for making heavy BHs

[LVC, ApJL 818, L22, 2016; adapted from Belczynski et al. 2010]



Low metallicity with $Z < 0.5\ Z_\odot$ (solar) and weak massive stellar winds

Tale of two binaries

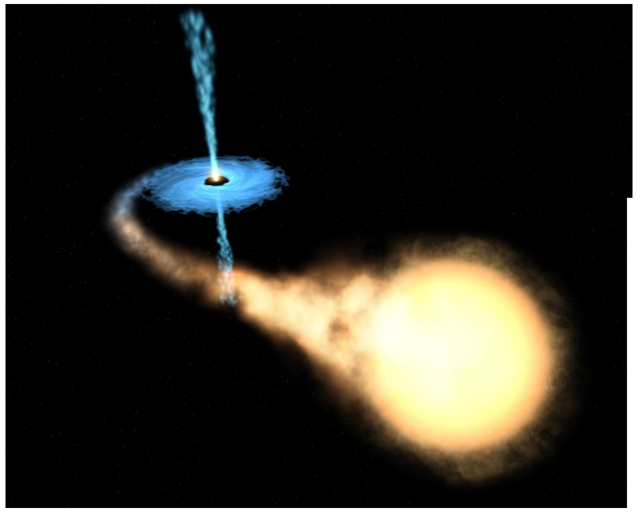
[see review by Miller 2016;
LVC, ApJL 818, L22, 2016]

Isolated Binary in Field

range of binary interactions

low redshift to Pop III

rapidly rotating massive stars



[e.g., Tutukov & Yungelson 1993, Lipunov+97, … Belczynski+10, Mandel +deMink 16, Marchant+16, Belczynski+04, Kinugawa+14]

Dense Environments (e.g., Clusters)

BHs sink towards cluster core

Dynamical interaction -> pairs

Binaries ejected with inspiral < Hubble time

[e.g., Portegies Zwart+00, O'Leary +06, Downing+10, Morscher+13, Ziosi+14.; NB Galactic Center: Miller+Lauburg+09, O'Leary+09, Koscis+12, Bartos+16, Stone+16]

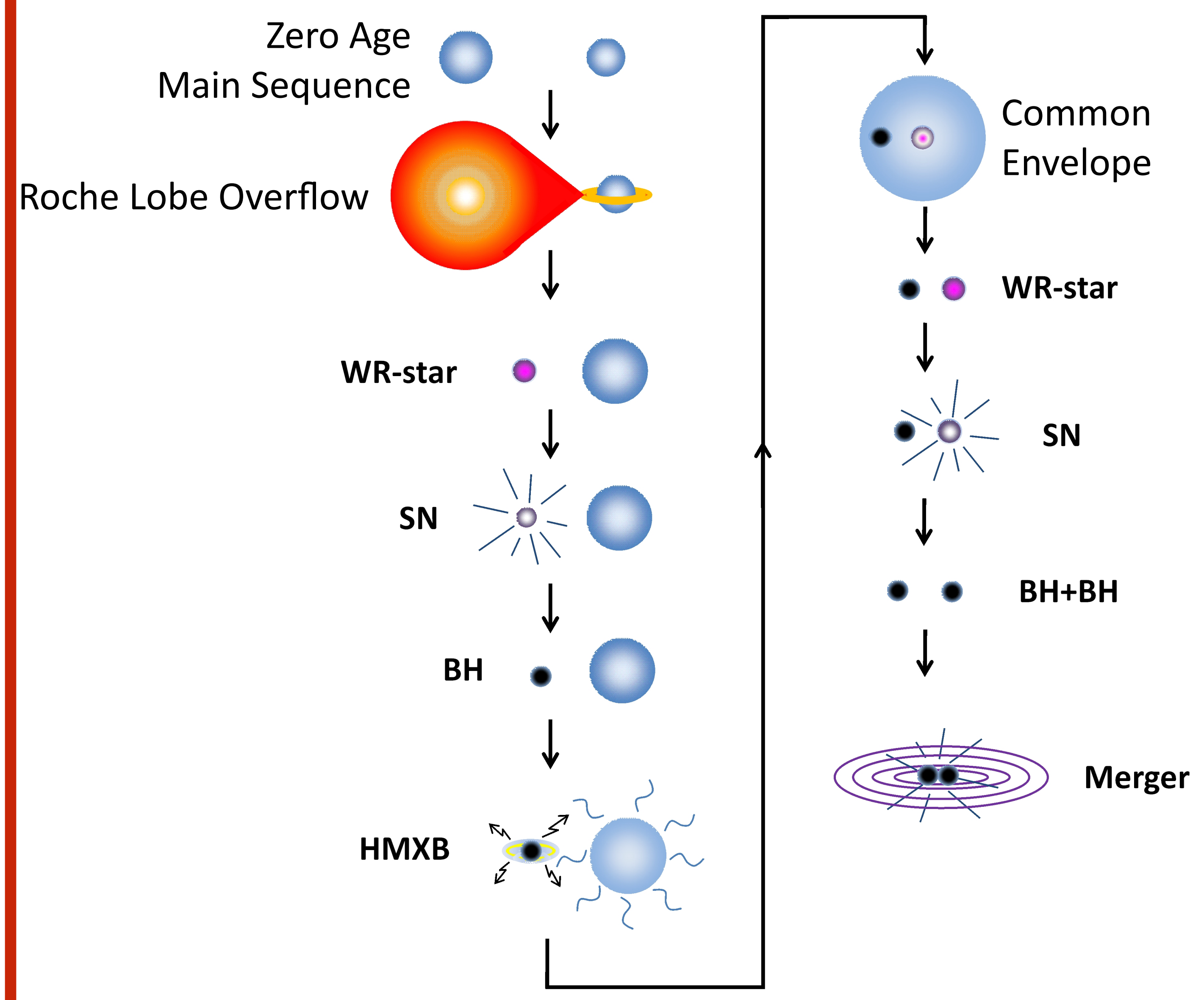
Lifecycle of Isolated Binary Massive Stars

Rare but important (feedback, chemical enrichment)

Complex physics in multi-staged evolutionary process

Supernova, Common Envelope, Mass Transfer, BH natal kicks

~ 6 to 9 steps: survival is 0.01-10%



[figure from Marchant et al. 2016]

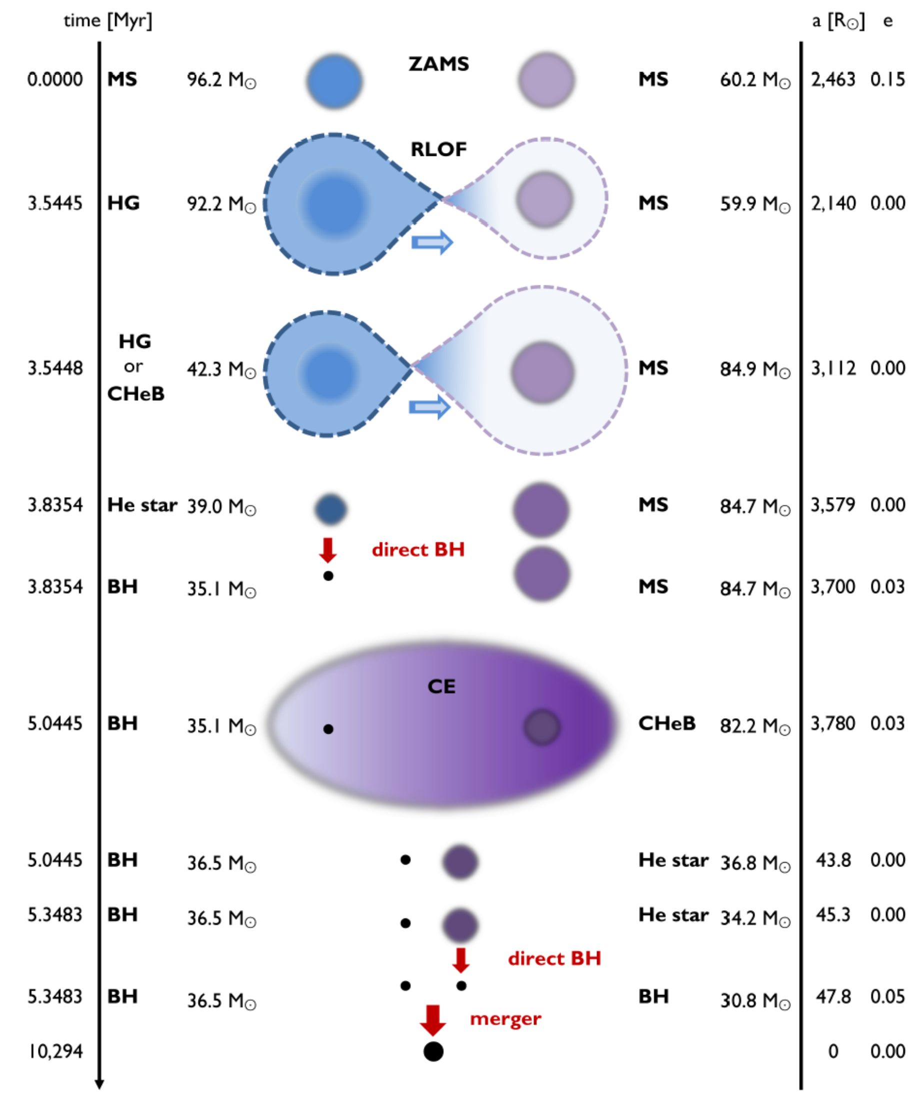
GW150915 & GW151226:
both field and cluster formation are possible

Isolated Binaries:

GW150914; weaker winds & weak metallicity.
GW151226; tension with the chemically homogenous model & dark matter models.

[e.g., Bird et al. 2016]

local Universe; recent formation, short merger delay time -or- early Universe formation with a long merger delay time



[Belczynski et al. 2016;
see also Kinagawa et al. 2016,
Eldridge et al. 2016, ...]

Cluster:

metallicity lower than solar

~1 Gyr to form binaries, wide range of delay times

How to discriminate between formation channels

Isolated Binaries:

Spins - preferentially aligned

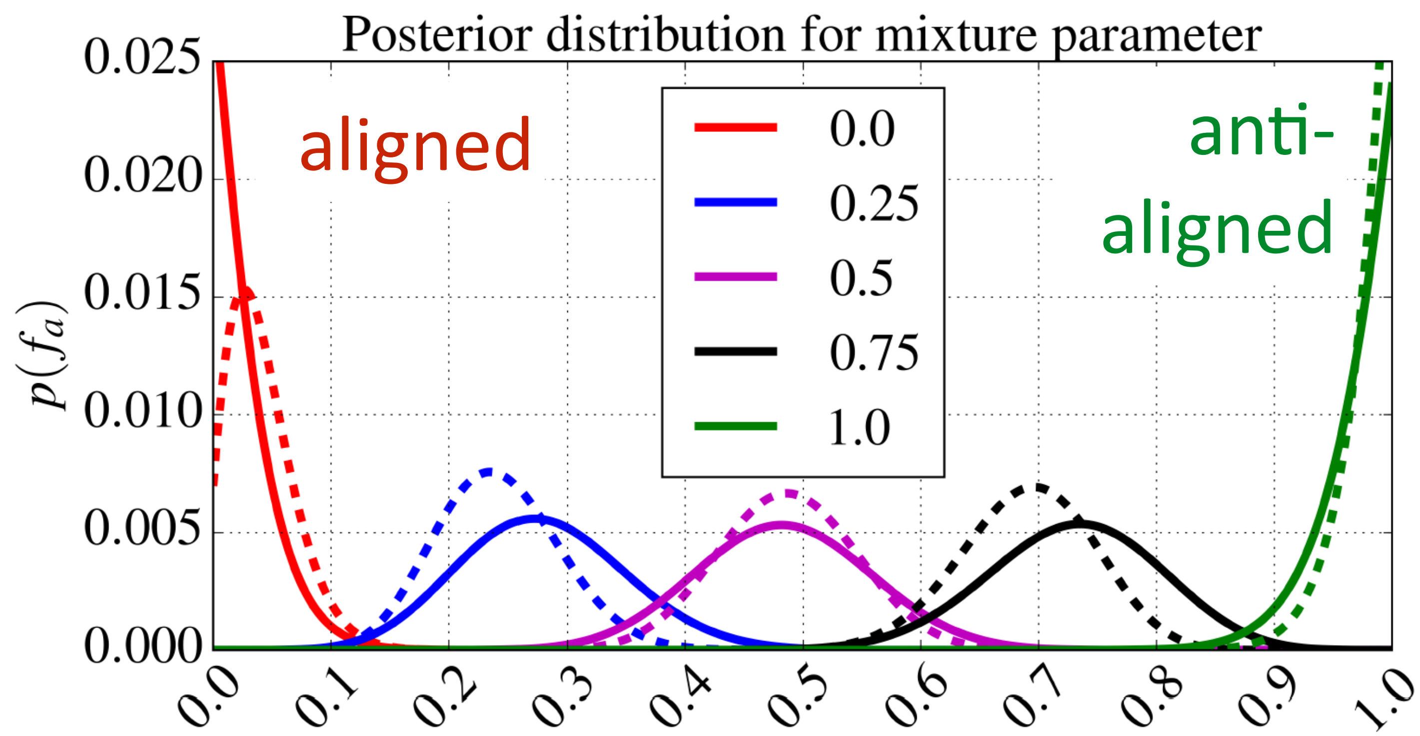
mass ratios < 0.5 are difficult to form

Dense Environment:

Spins - all configurations

mass ratios - all allowed

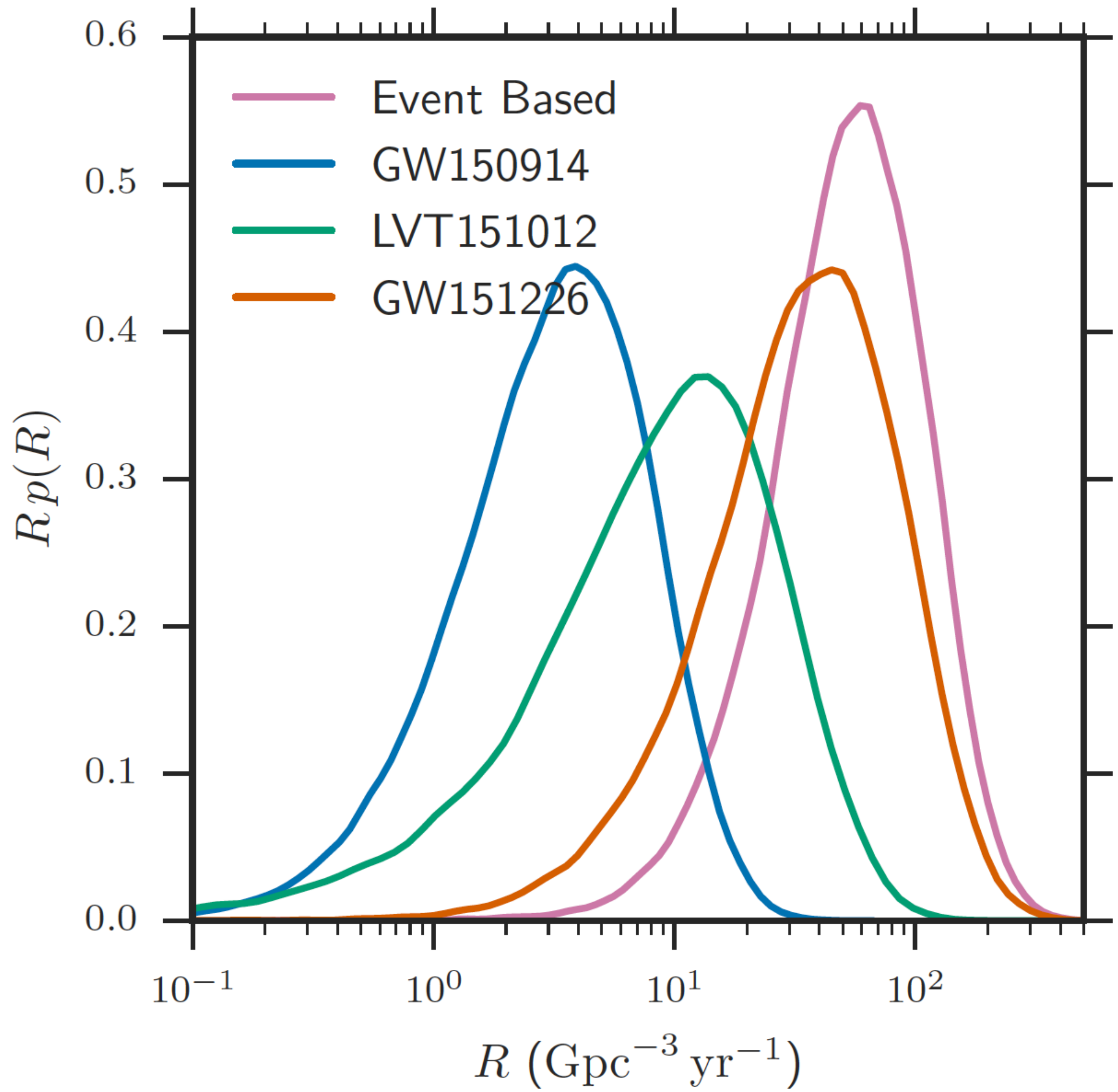
[Vitale et al. 2015]



f_a: mixing parameter between formation channels

⇒ 10% for 200 events

Astrophysical rates could soon probe formation scenarios



9 - 240 Gpc^{-3} yr^{-1}

Excludes < 10 Gpc^{-3} yr^{-1} ⇒

Isolated

Disfavours a v. low common envelope binding energy or v. high BH natal kicks (> several hundred km s^{-1})

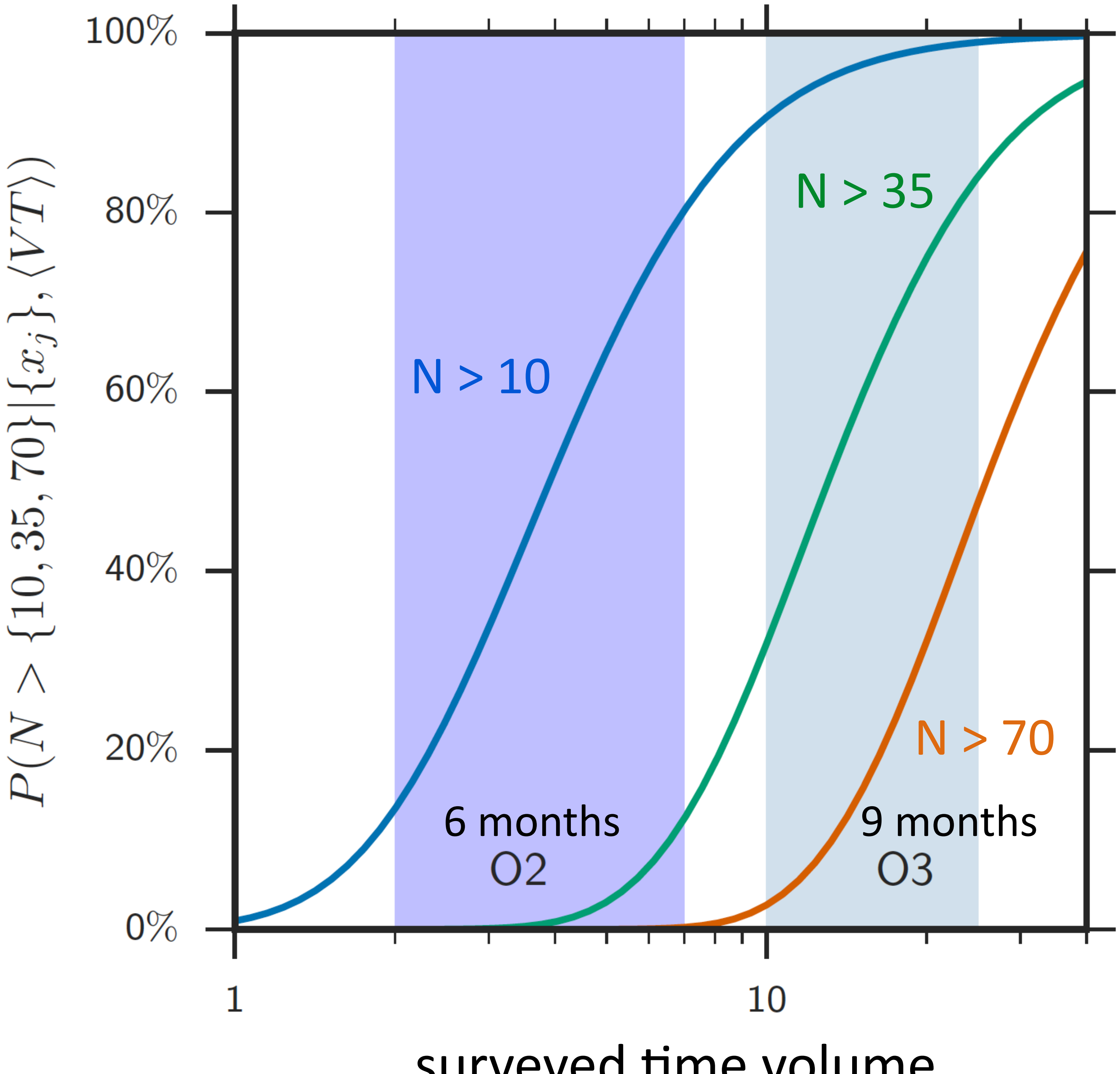
Dynamical

Disfavours low-mass clusters

[LVC, arXiv:1606.09619, 2016; see Tom Dent's talk this afternoon]

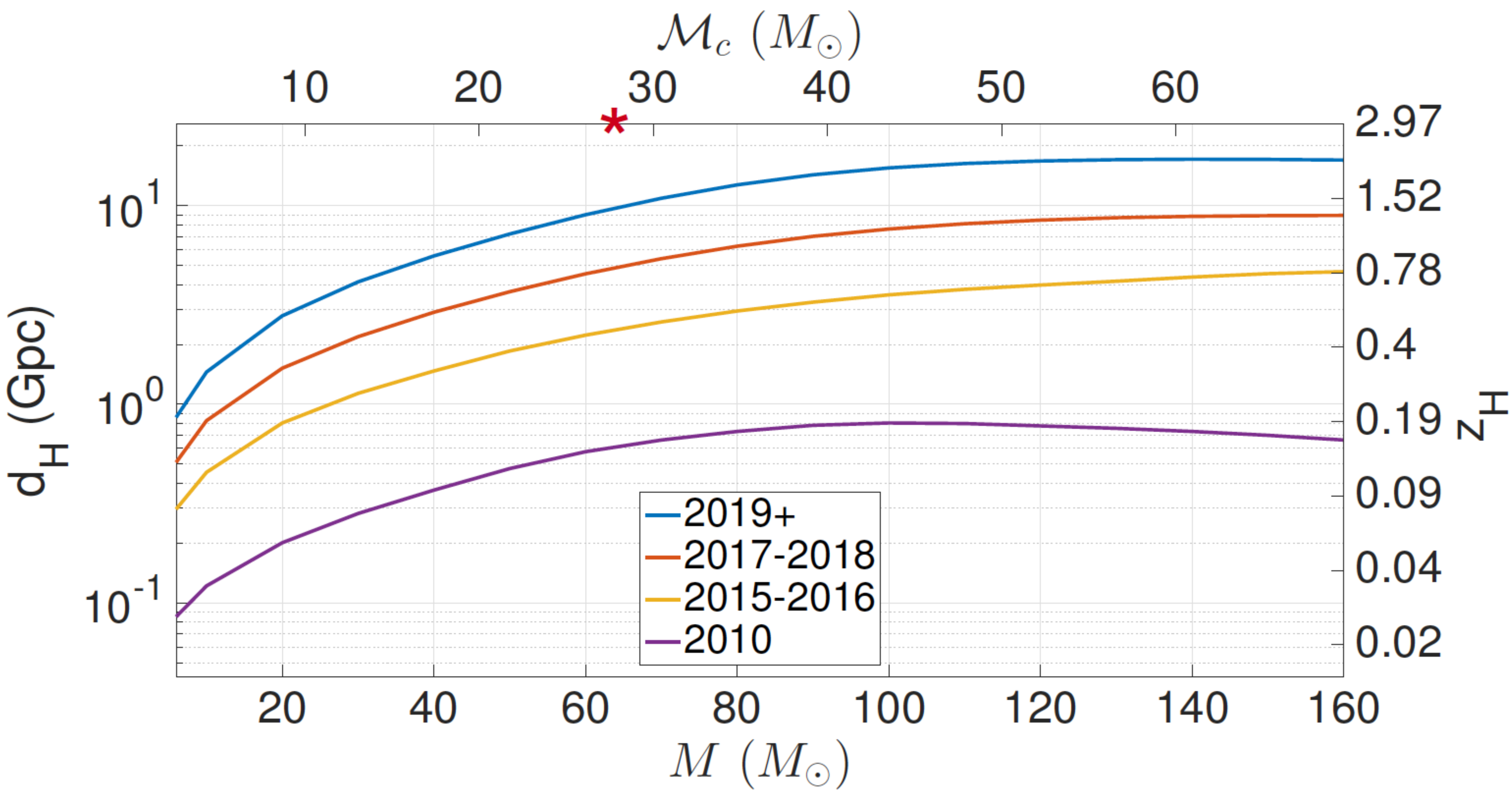
Future perspectives

Tens of BH detections in the next few years



[LVC, arXiv:1606.09619, 2016]

BBH detections out to redshifts of a couple

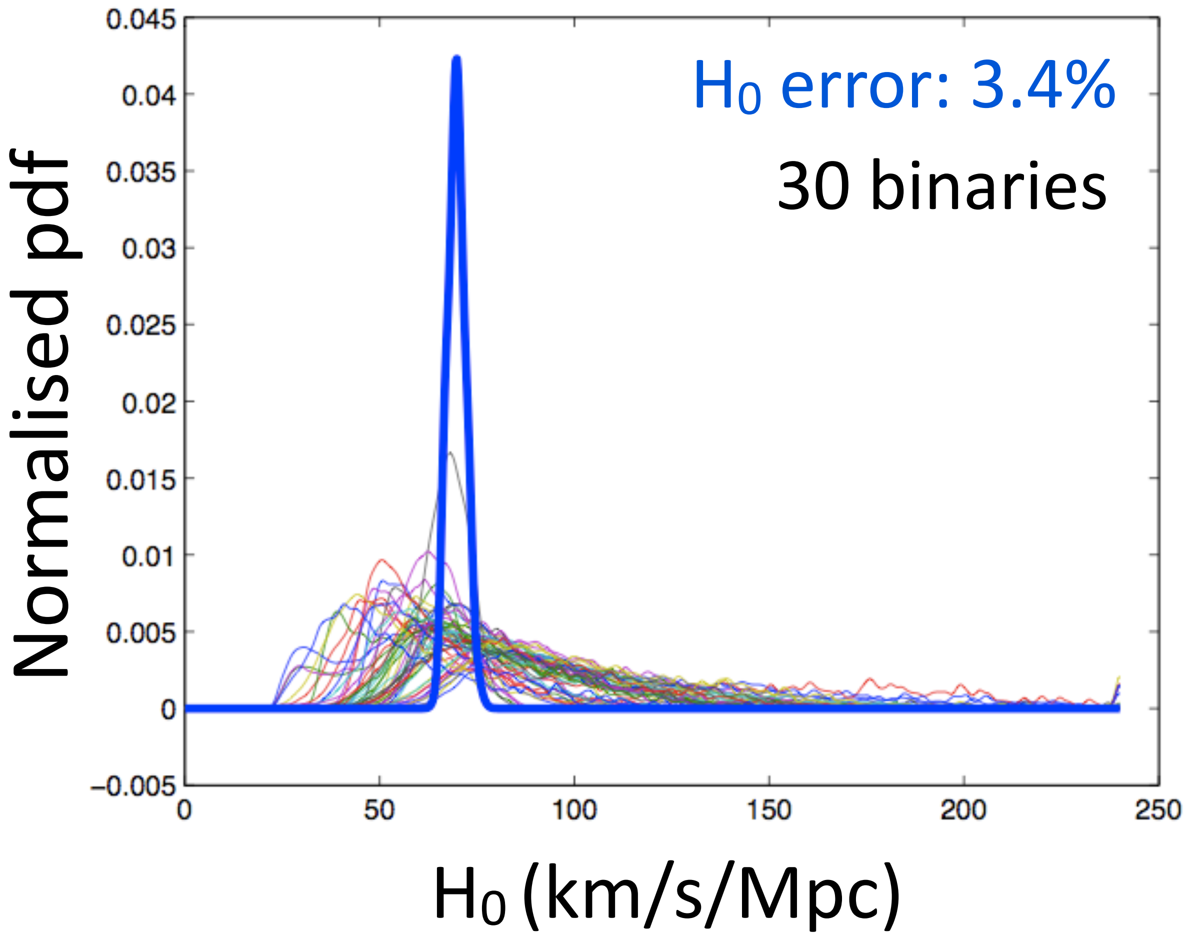


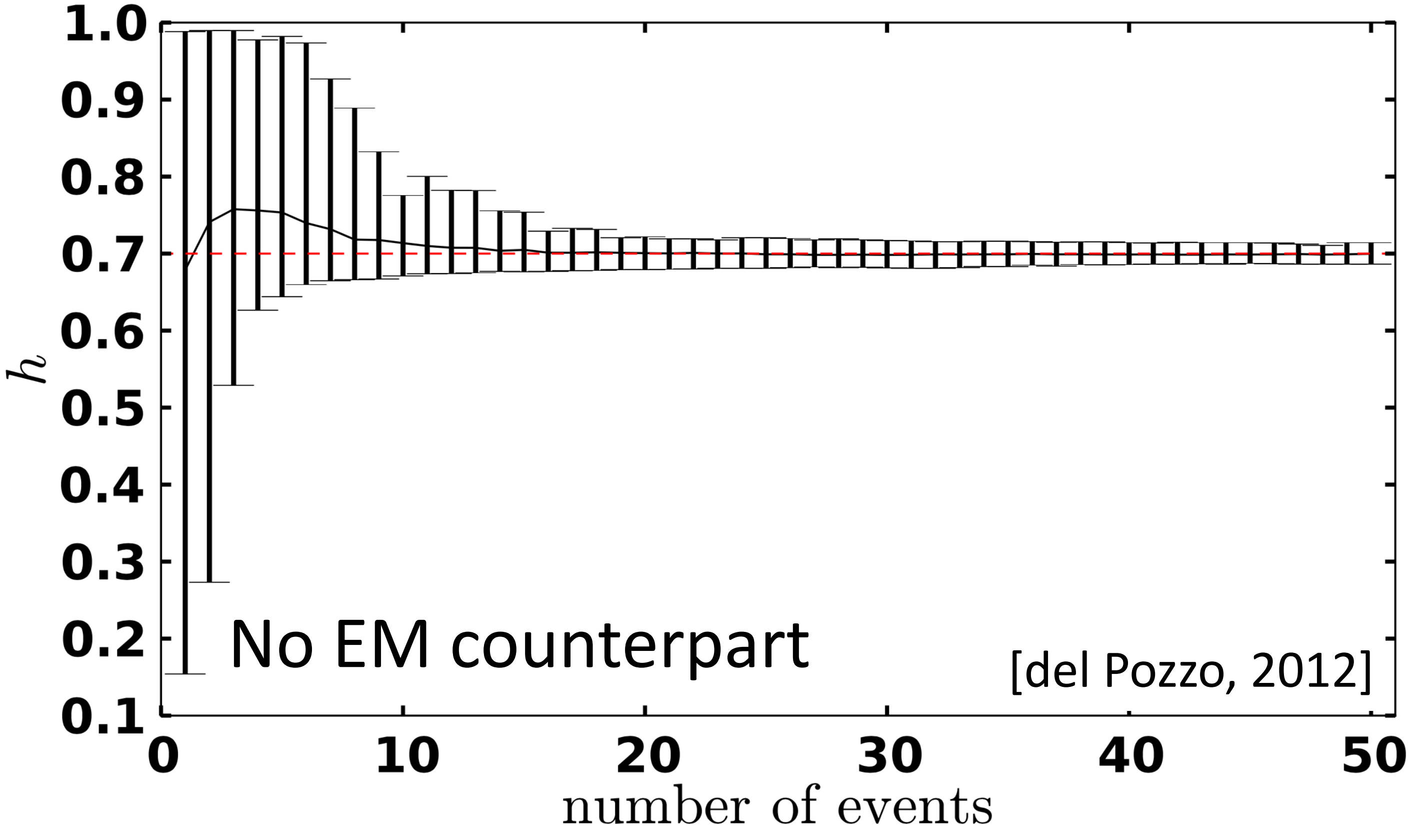
[LVC, ApJL 818, L22, 2016]

GW enable a few % error in Hubble constant … importance of populations !!!

[see also Schutz 1986, Dalal et al. 2006,
Sathyaprakash et al. 2010,
Messenger et al. 2012, Taylor et al. 2012, …]

[Nissanke et al., 2010,13]



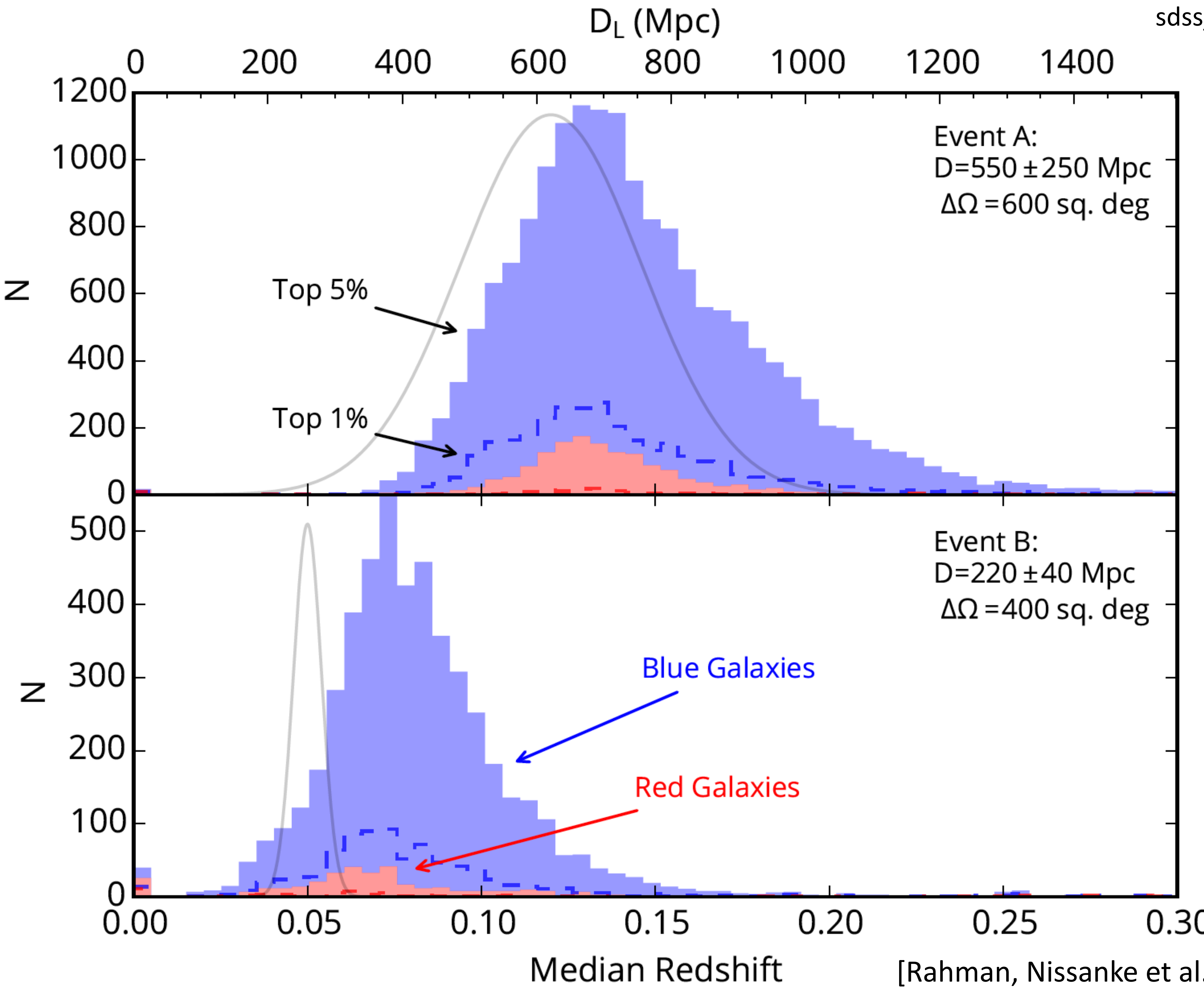


Similar reasoning applies detecting BH kicks, testing GR and neutron star equation of states …

[e.g., Lasky et al. 2016, Yunes et al. 2013, Meidam et al. 2014, Lackay & Wade 2014, Agathos et al. 2014,15]

Statistical host galaxy demographics with no counterpart

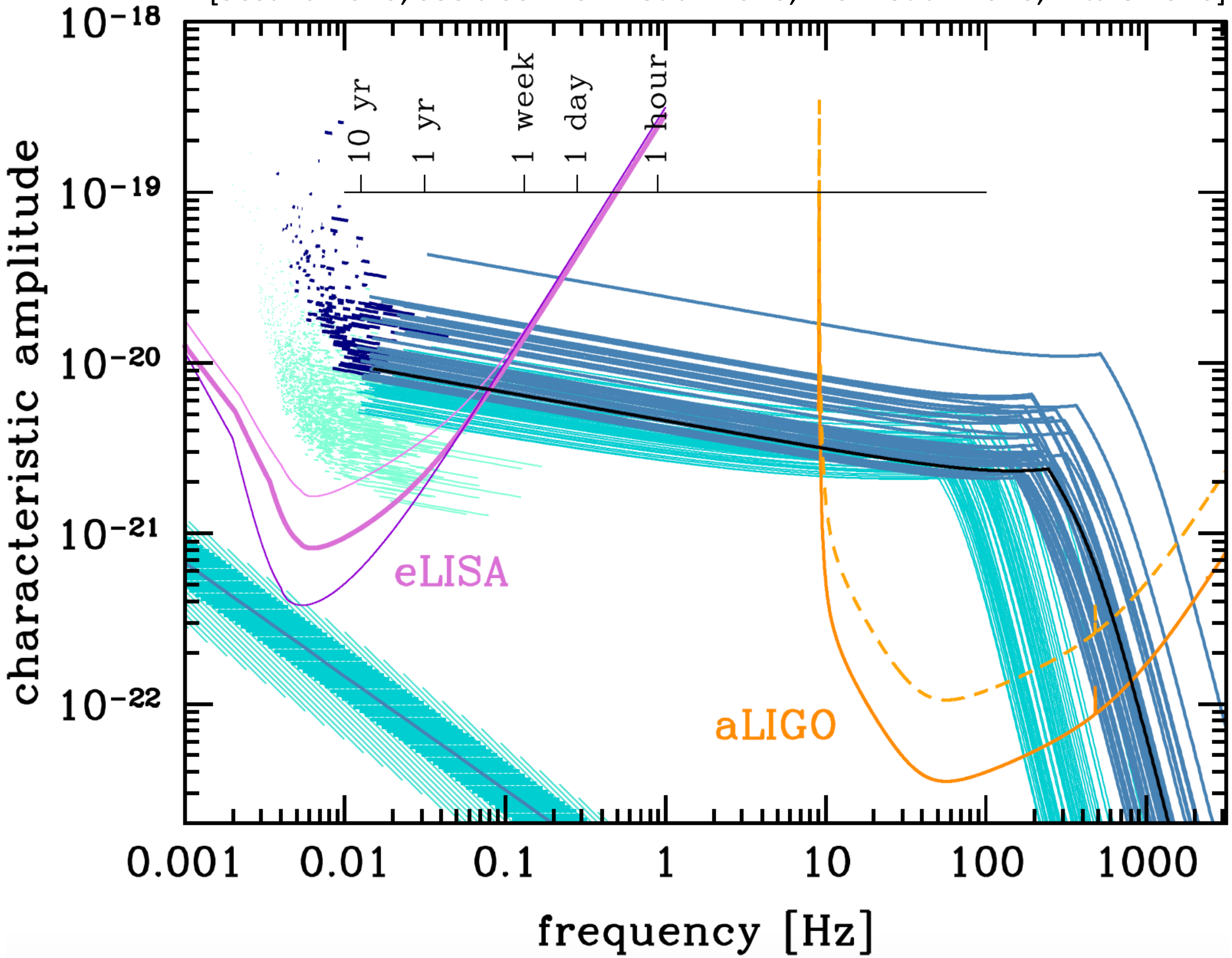
SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html



[Rahman, Nissanke et al., in prep]

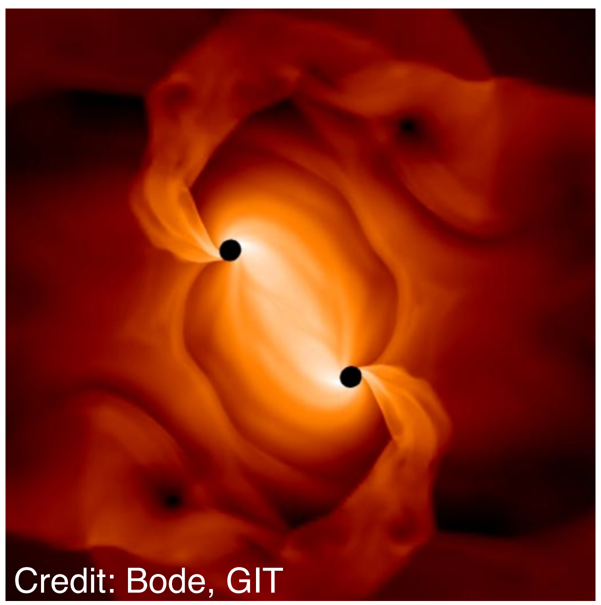
Hundreds of resolvable BHB by space-based GW detectors before they enter LIGO- Virgo band

[Sesana 2016; see also Brevik et al. 2016, Klein et al. 2016, Vitale 2016]



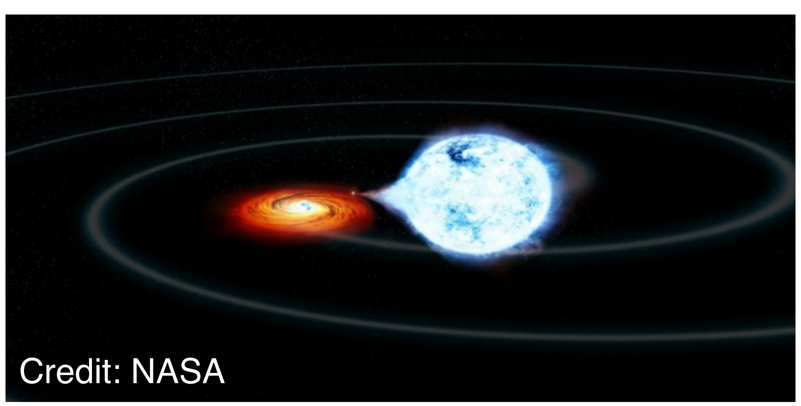
Plethora of other GW sources

Low Frequency GWs



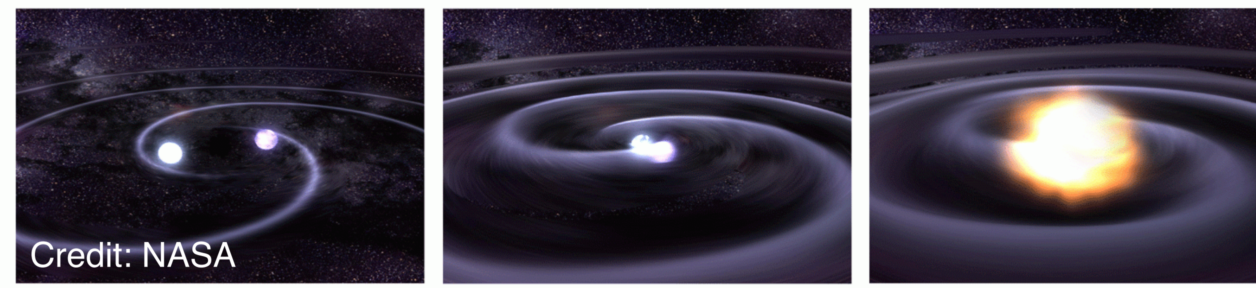
Supermassive Black Hole Binary Mergers with gas

AM CVn (mass-transferring White Dwarfs)

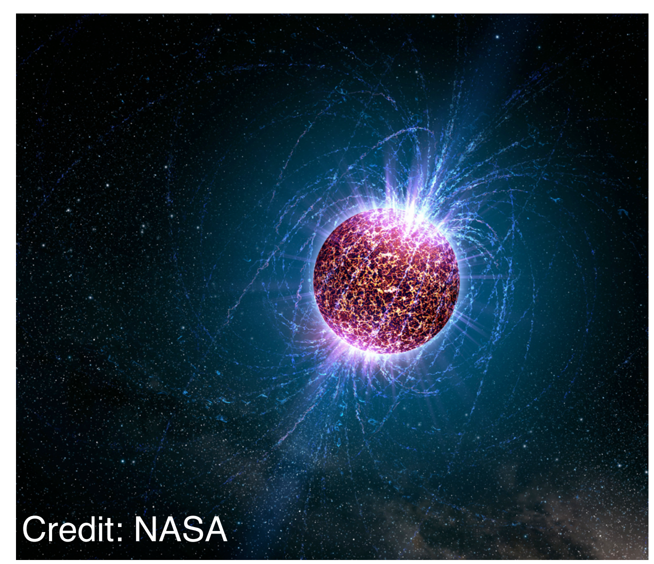


High Frequency GWs

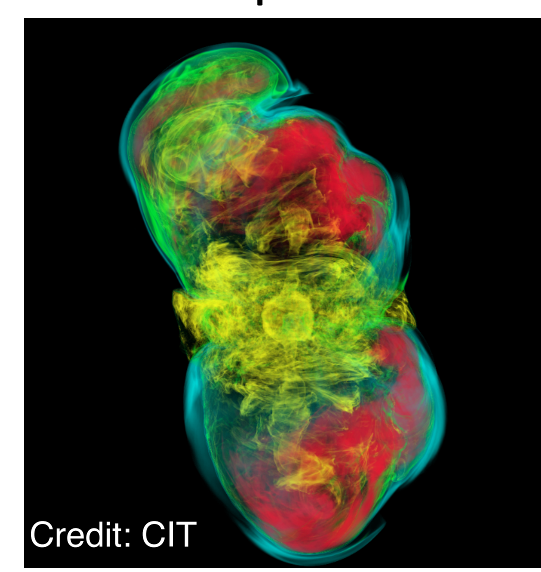
Neutron Star Binary Mergers



Pulsar



Supernova



First-order phase transitions, superstring kink and cusps, inflationary signature, new sources

Combine & interpret GW + Electromagnetic (EM)

from the GW chirp

- Masses
- Spins
- NS radii
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

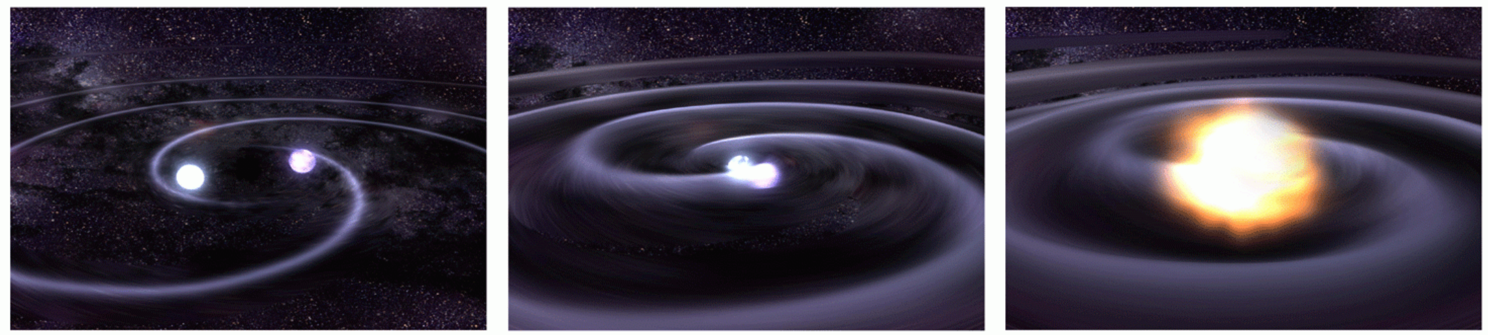
from EM signature

- Mass ejecta and velocity
- Magnetic field strength
- Energetics and Beaming
- Redshift, Accurate Position
- Nuclear Physics -> Opacities
- Stellar populations
- Previous binary evolution & mass loss

Strong signal binary: Characterization

Population: Demographics, ecology and census

Recent change: we now have the potential to detect GW and EM radiation



Gravitational radiation

EM radiation

Learn about sources' <u>dynamic</u> and <u>fundamental properties</u>

Learn about sources' <u>environment</u> and <u>energetics</u>

The immediate future is loud and bright!

Immediately: GW detector sensitivity & network increases => Tens of BBH mergers yr^{-1} and first EM-GW detections

Tests of GR: population constraints and single source studies; test of no-hair theorem.

Astrophysical implications:

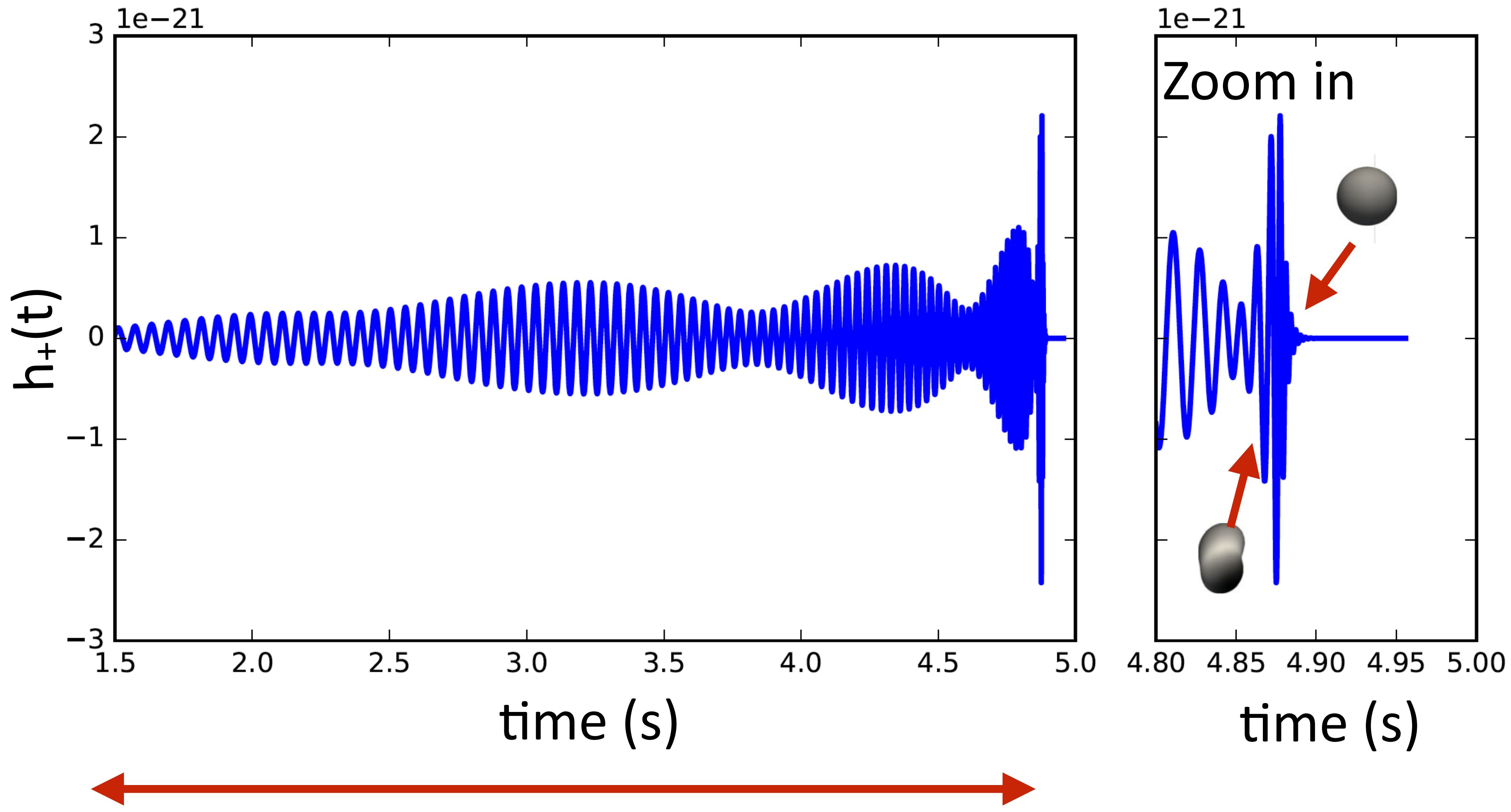
1) Constraints from rates and spin/mass ratios: binary stellar evolution & BHs through cosmic history;
2) EM-GW joint characterization: learn about the nature and environments(circumstellar, etc…), neutron star equation of state, internal structure;
3) Cosmological constraints $H_{0;}$ geometry and dynamics of large scale structure.

What needs to be done urgently:

1) GW waveform : spin and fast characterization for BBHs, alternative theories of gravity
2) EM-GW joint characterization & statistical tools required now (to make detection!)

Beyond LIGO, Virgo era: Witness the opening of the entire GW spectrum with CMB, PTAs, eLISA, new generation ground based detectors …

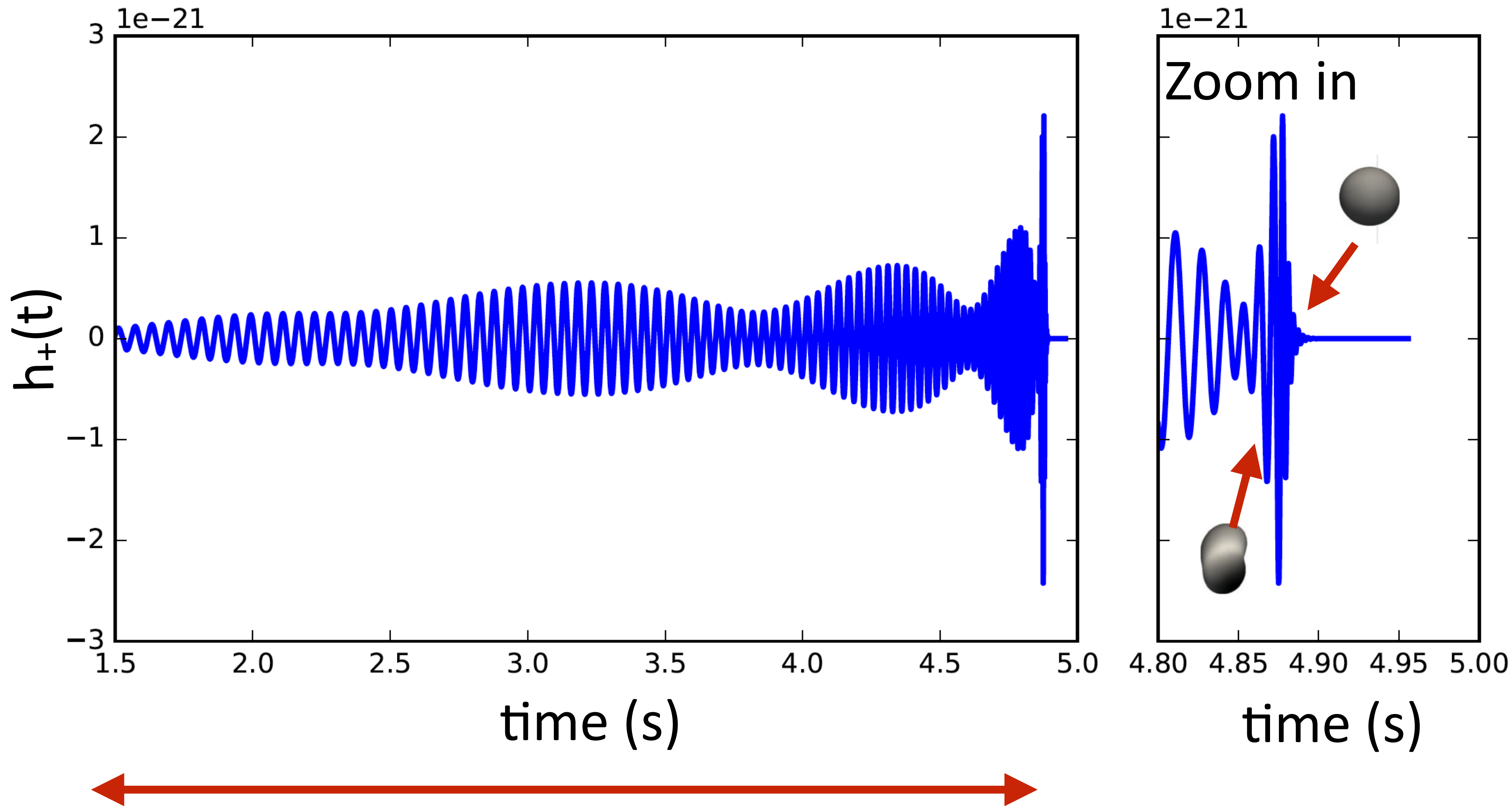
The GW waveform encodes source parameters



$$h_M(t) = F_+ h_+ + F_\times h_\times$$

Detector Antennae Functions (source position, polarization angle)

The GW waveform encodes source parameters

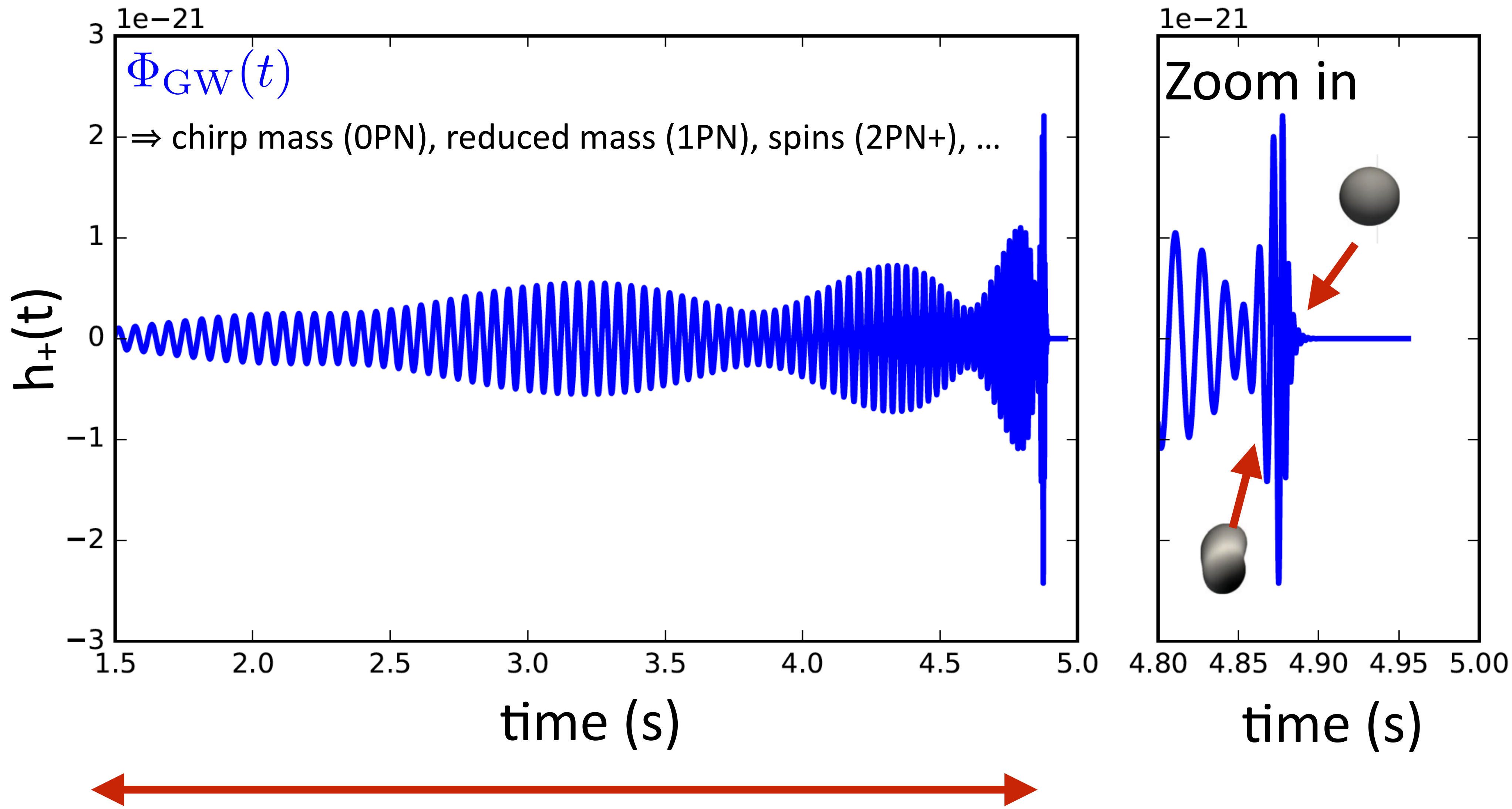


$$h_M(t) = F_+ h_+ + F_\times h_\times$$

$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

$$h_\times(t) = \frac{B[\mathcal{M}\, f(t)]}{D}(\cos\iota)\sin\Phi_{\rm GW}(t)$$

The GW waveform encodes source parameters



$$h_M(t) = F_+ h_+ + F_\times h_\times$$

$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

frequency; distance; inclination angle; GW Phase

$$h_\times(t) = \frac{B[\mathcal{M}\, f(t)]}{D}(\cos\iota)\sin\Phi_{\rm GW}(t)$$

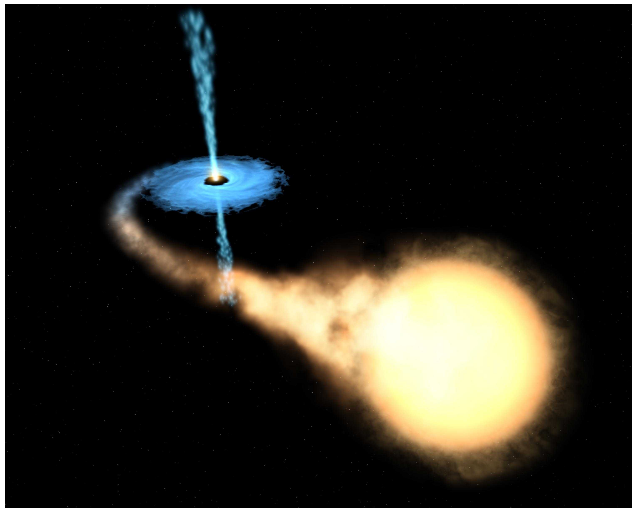
Lifecycle of Isolated Binary Massive Stars

Rare but important (feedback, chemical enrichment)

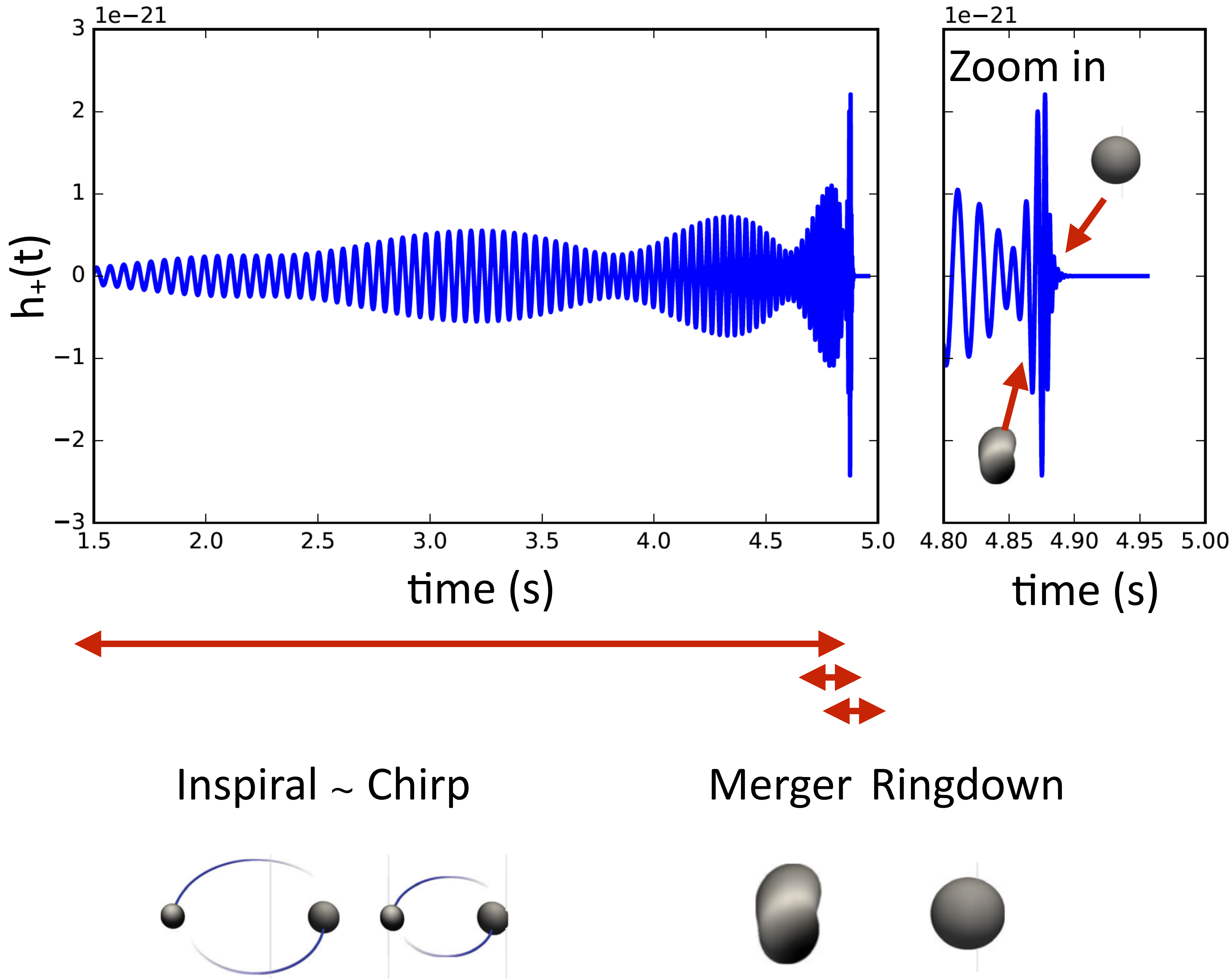
Complex physics in multi-staged evolutionary process

Chemically-homogenous model

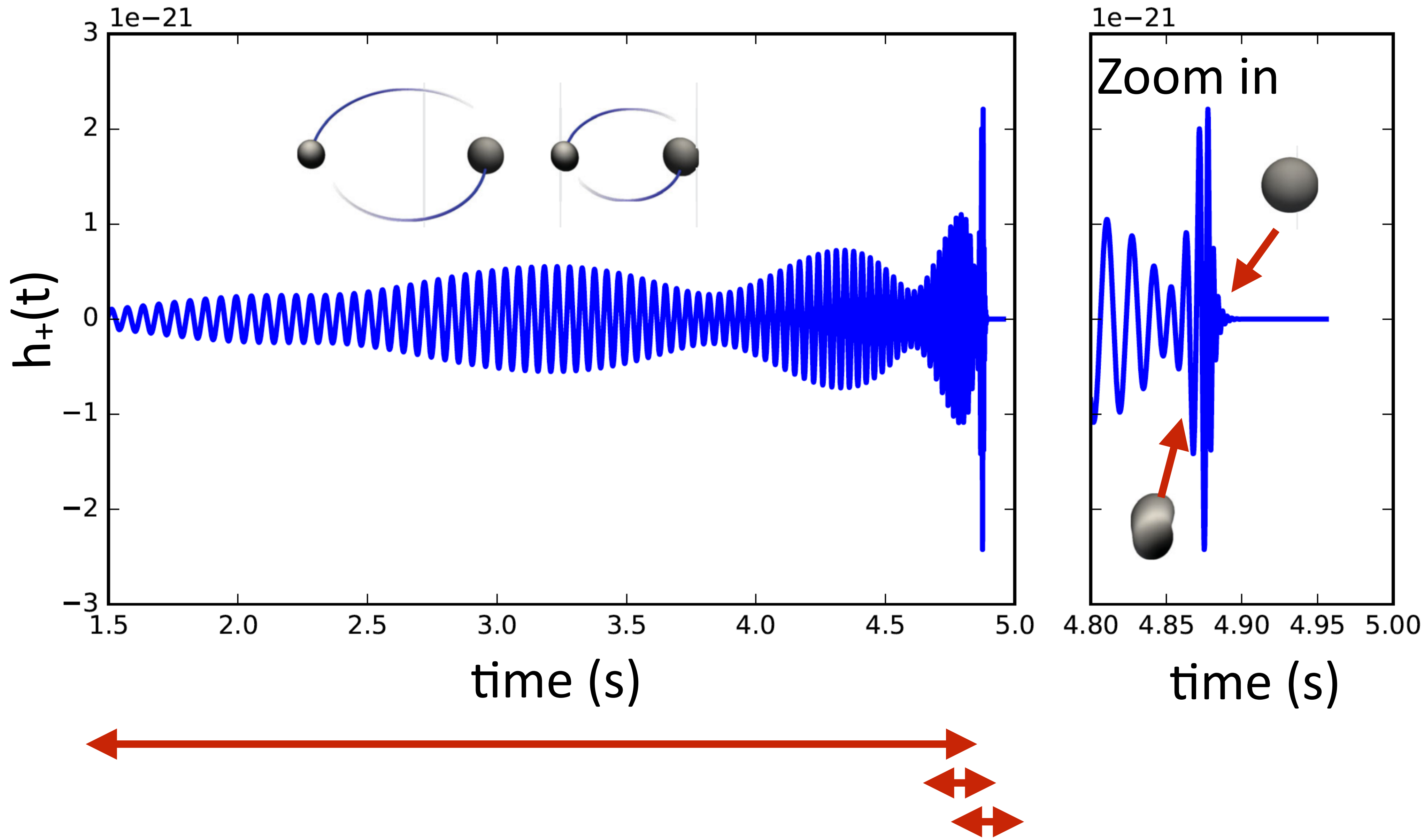
Tale of two binaries



GW waveform describes Binary Black Hole evolution



Decades of theoretical effort in source modelling



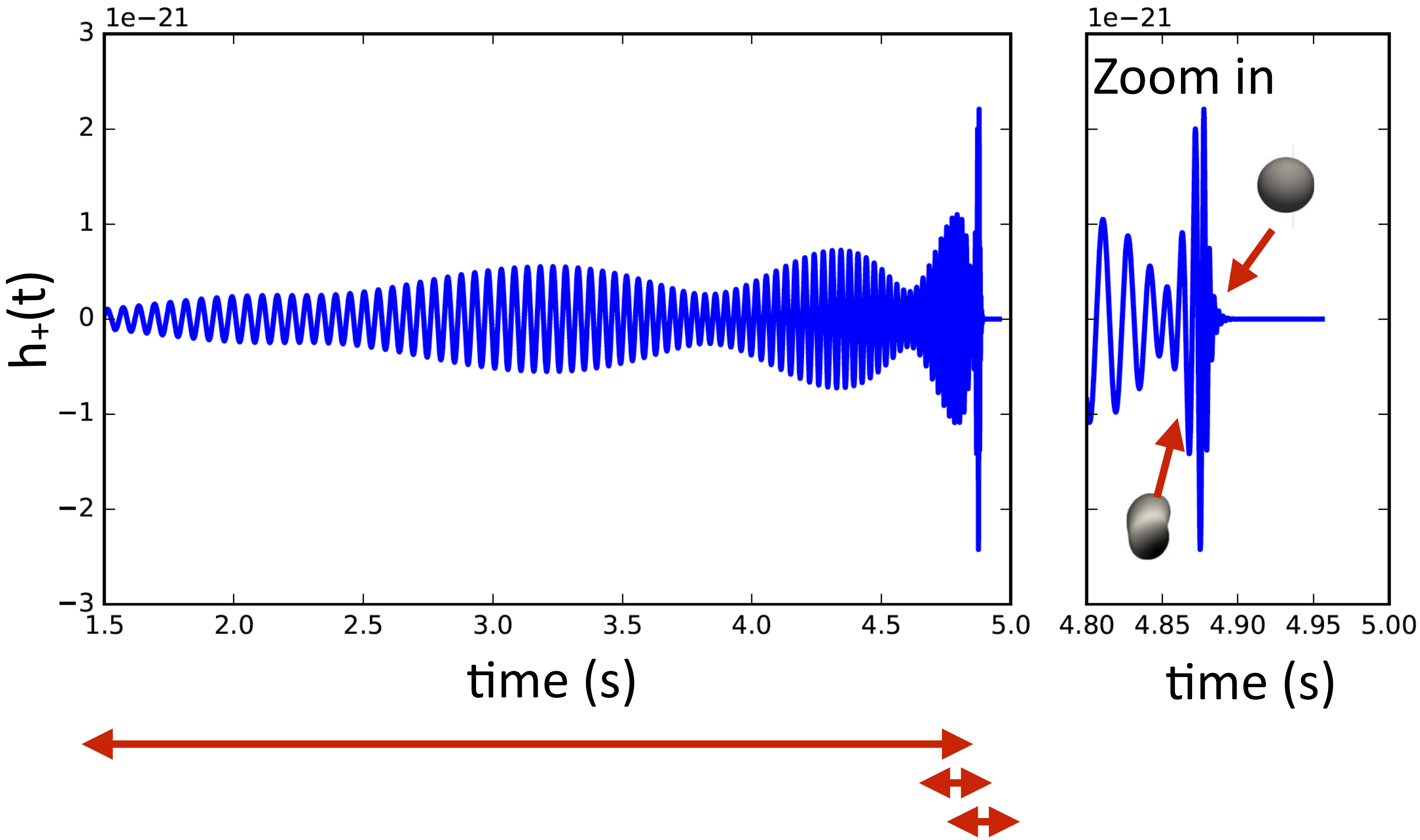
post-Newtonian

numerical relativity

quasi-normal modes

$$1\text{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1$$

Chirp mass drives inspiral waveform



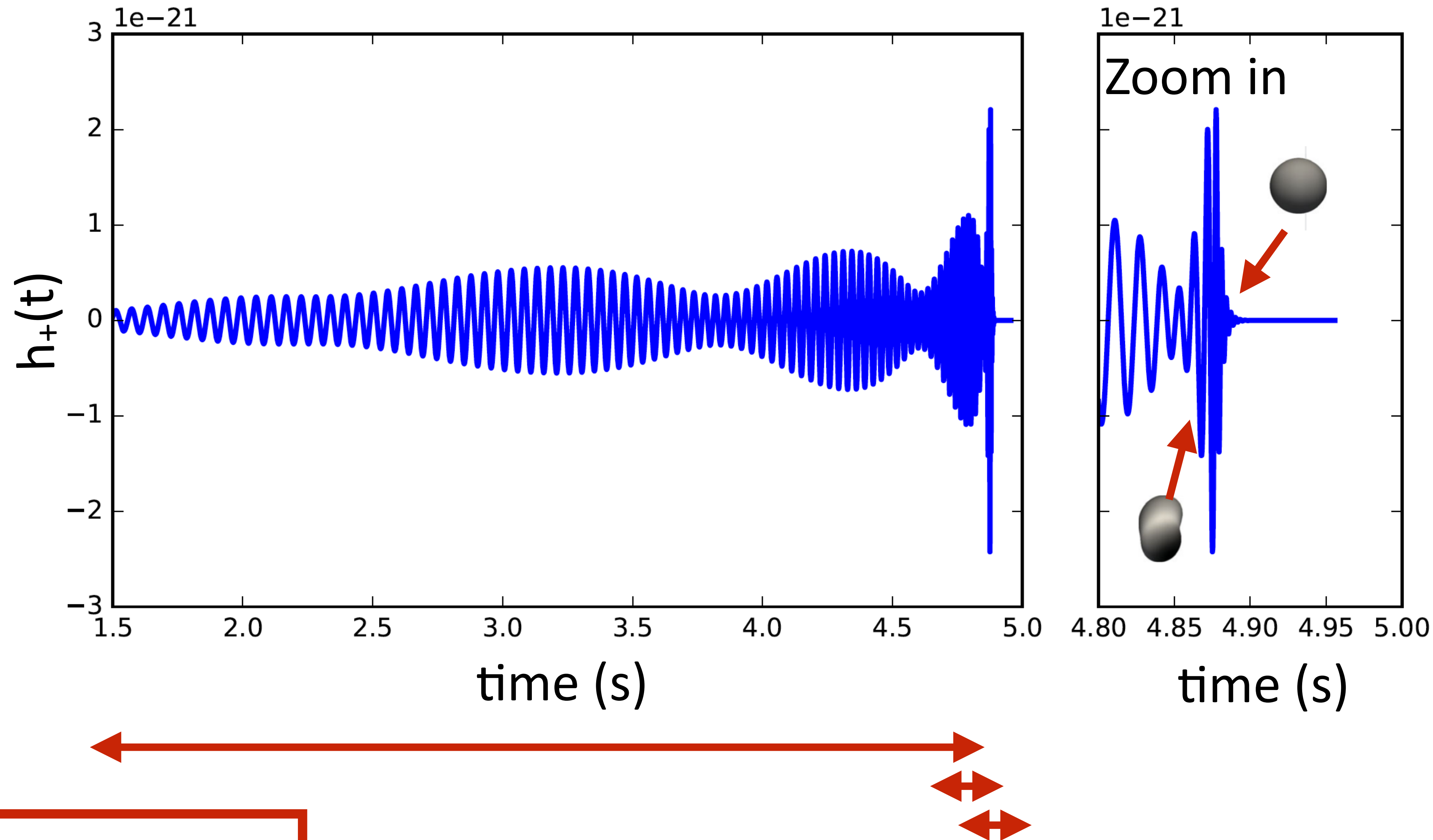
Inspiral ~ Chirp

Ringdown

<u>driven</u> by the chirp mass

... remnant mass & spin

Chirp mass drives inspiral waveform



chirp mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$= \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

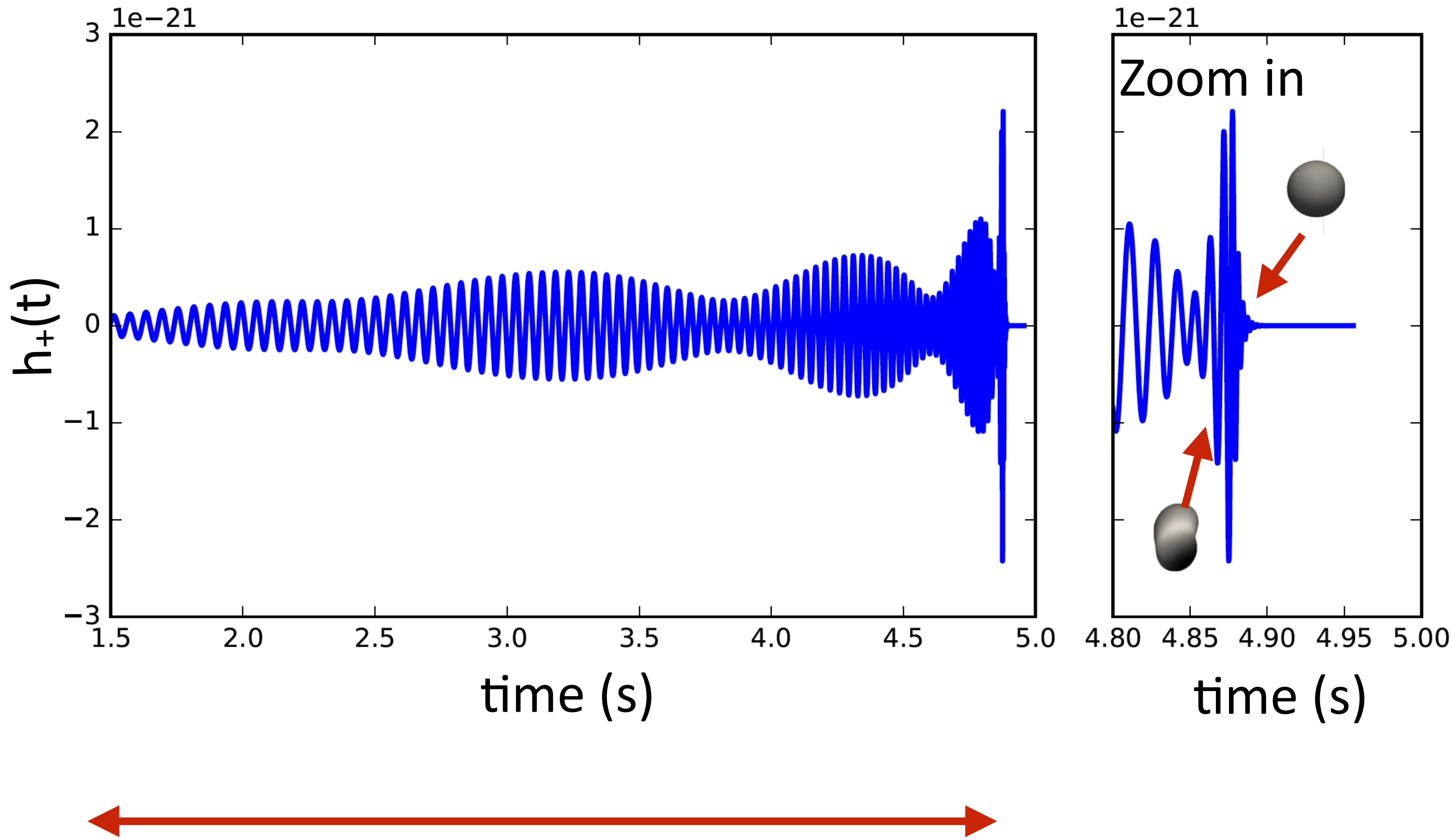
Inspiral ~ Chirp

driven by the chirp mass

Ringdown

... remnant mass & spin

Chirp mass drives inspiral waveform



$\Phi_{\mathrm{GW}}(t)$ ⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), ...