The Formation of Massive Black-Hole Binaries:
Understanding the Advanced LIGO detections

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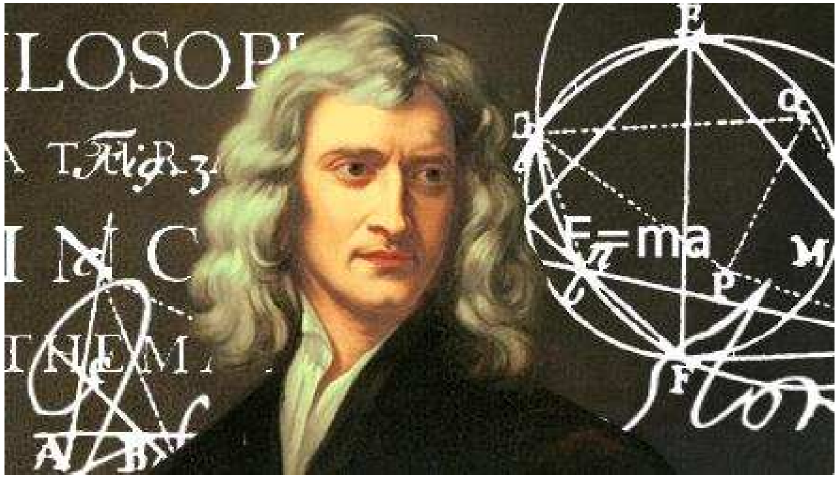
- **the direct discovery of gravitational waves has started the era of gravitational-wave astronomy**
- **major surprise:** the merger of **two massive stellar black holes (BHs)**

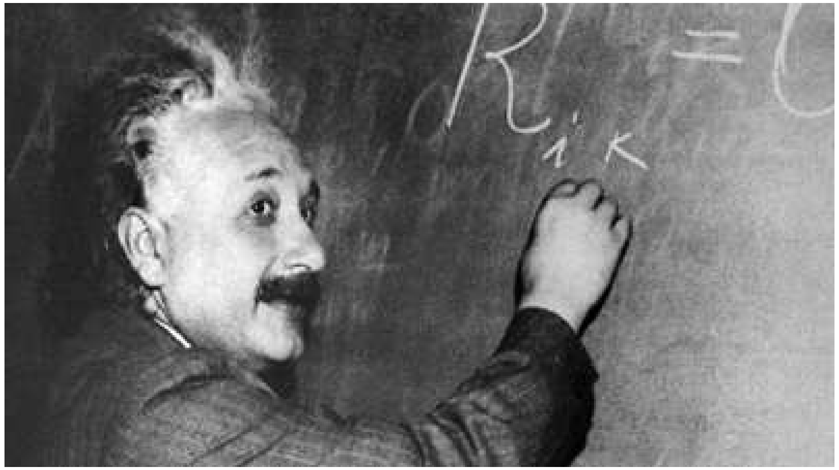
General Relativity and Gravitational Waves

Newton's Gravity



Time is absolute: space and time are given apriori

Einstein's General Relativity



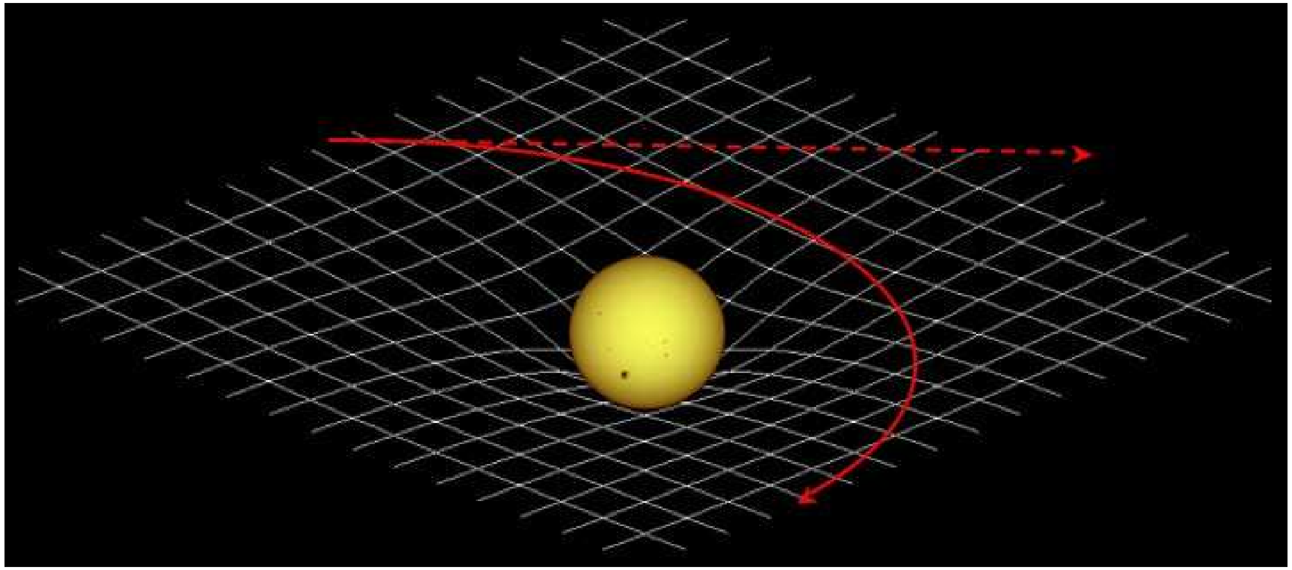
Spacetime is a **dynamic and elastic entity**, influencing and influenced by mass-energy

$$\mathbf{R}_{\mu\nu} - \frac{1}{2}\,\mathbf{g}_{\mu\nu}\mathbf{R} = \frac{8\pi \mathbf{G}}{\mathbf{c}^4}\,\mathbf{T}_{\mu\nu},$$

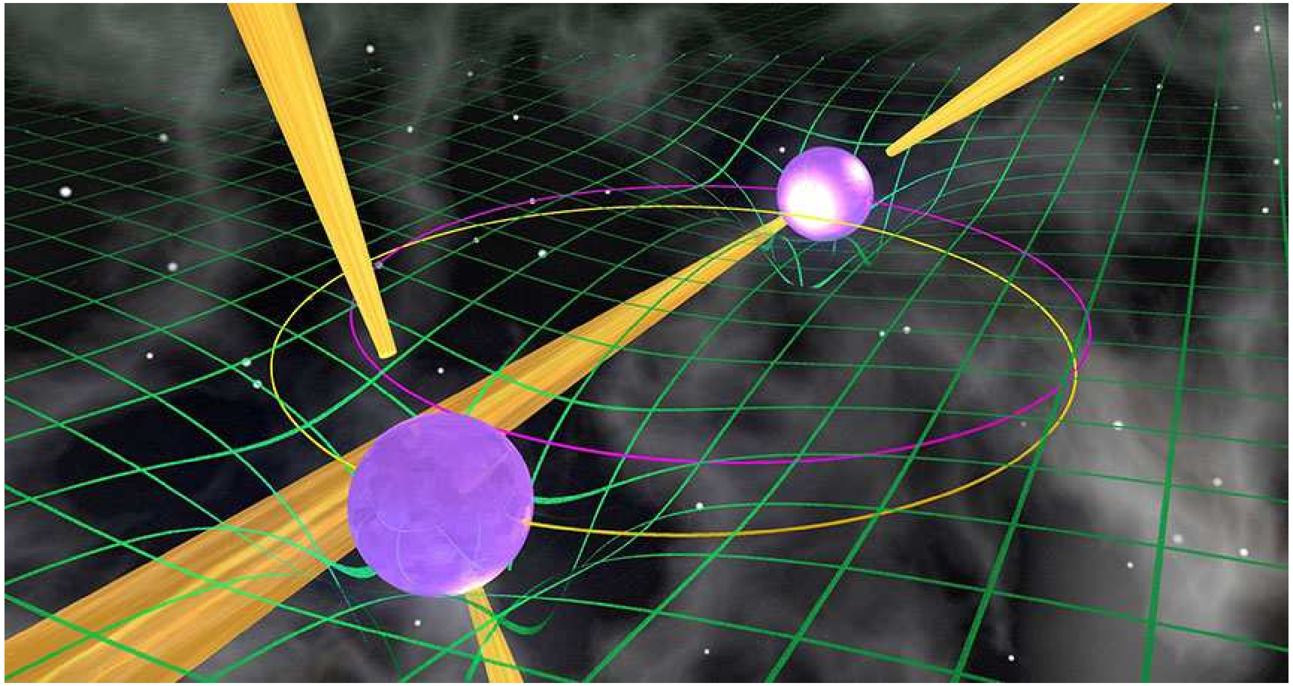
$$\mathbf{g}_{\mu\nu} = \eta_{\mu\nu} + \mathbf{h}_{\mu\nu}, \quad \rightarrow \; \Box \mathbf{h}_{\mu\nu} = -\frac{16\pi \mathbf{G}}{\mathbf{c}^4}\,\mathbf{T}_{\mu\nu}.$$

- masses deform spacetime geometry → generate gravitational waves, propagating with the speed of light (Einstein 2016)
- GWs are very weak and need massive, compact bodies

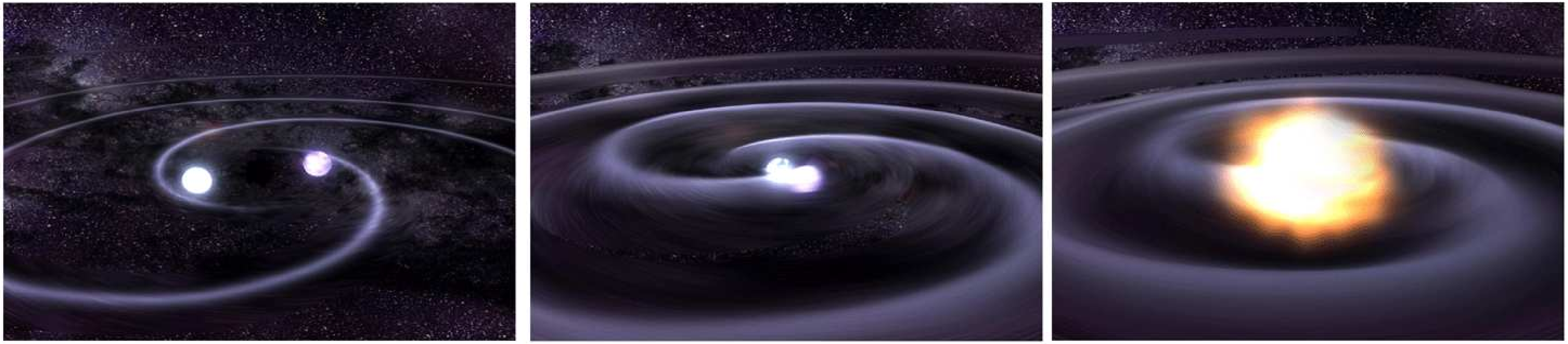
Space Curvature



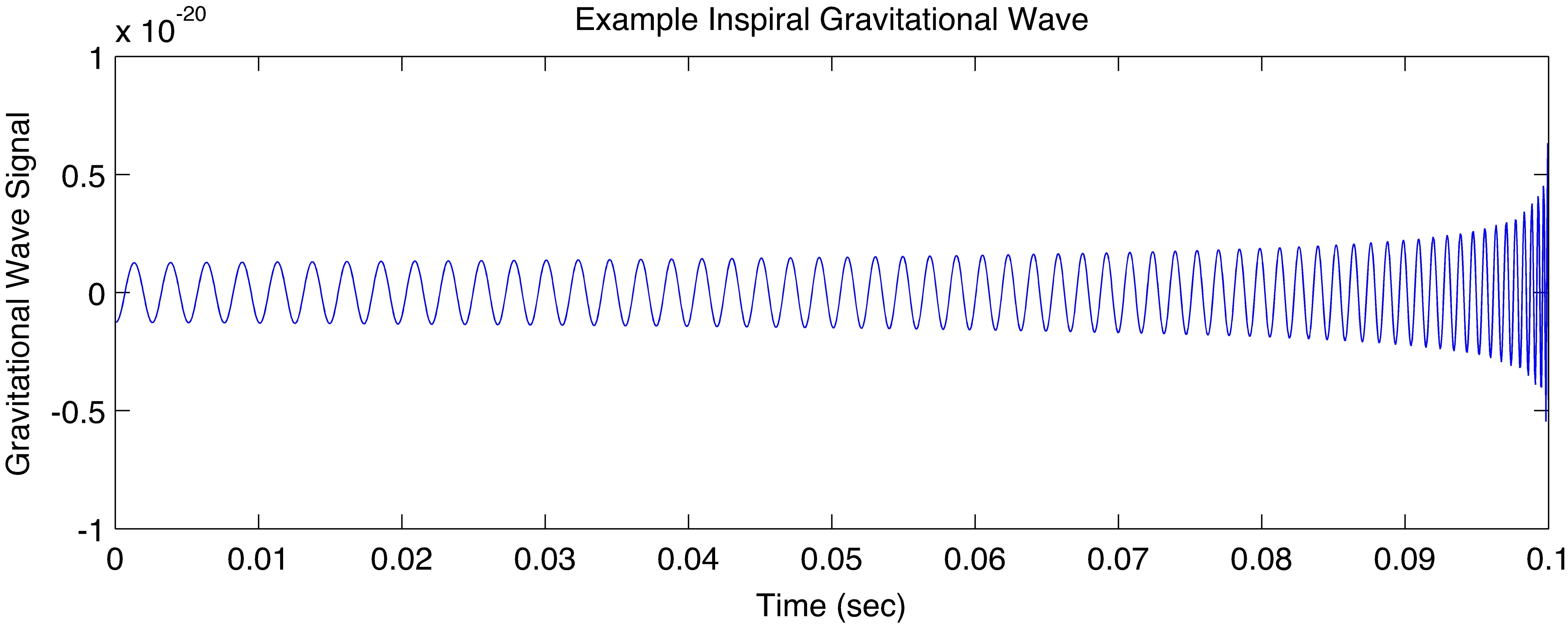
Double Neutron-Star Binaries as Gravitational-Wave Sources



Compact Binary Inspiral and Final Merger



(Strohmayer)

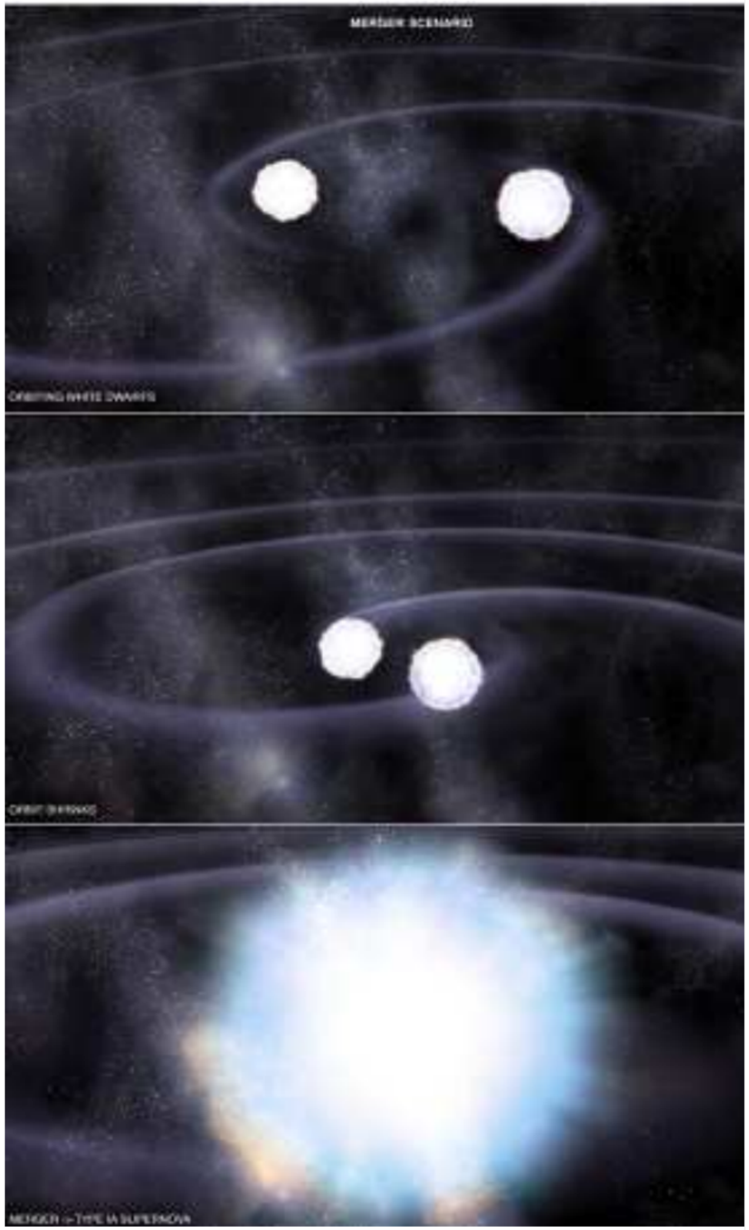


Compact Binary Mergers (NS/BH+NS/BH)

- compact binaries are brought together by gravitational radiation in a Hubble time if their orbital period is $\lesssim 10\,\mathrm{hr}$

Important as

- progenitors of short-duration gamma-ray bursts
  - ▷ different signatures for different mergers (NS+NS, NS+BH, BH+BH)
  - ▷ because of time delay can be far from star-forming regions (outside galaxy?)
- sources of r-process elements (rather than supernovae)
  - ▷ n-rich environment → can build up neutron-rich nuclei by successive n-rich captures onto iron-group seed elements (e.g. Au)
- candidates for the direction detection of gravitational waves with up-coming gravitational wave detectors (Advanced Ligo)



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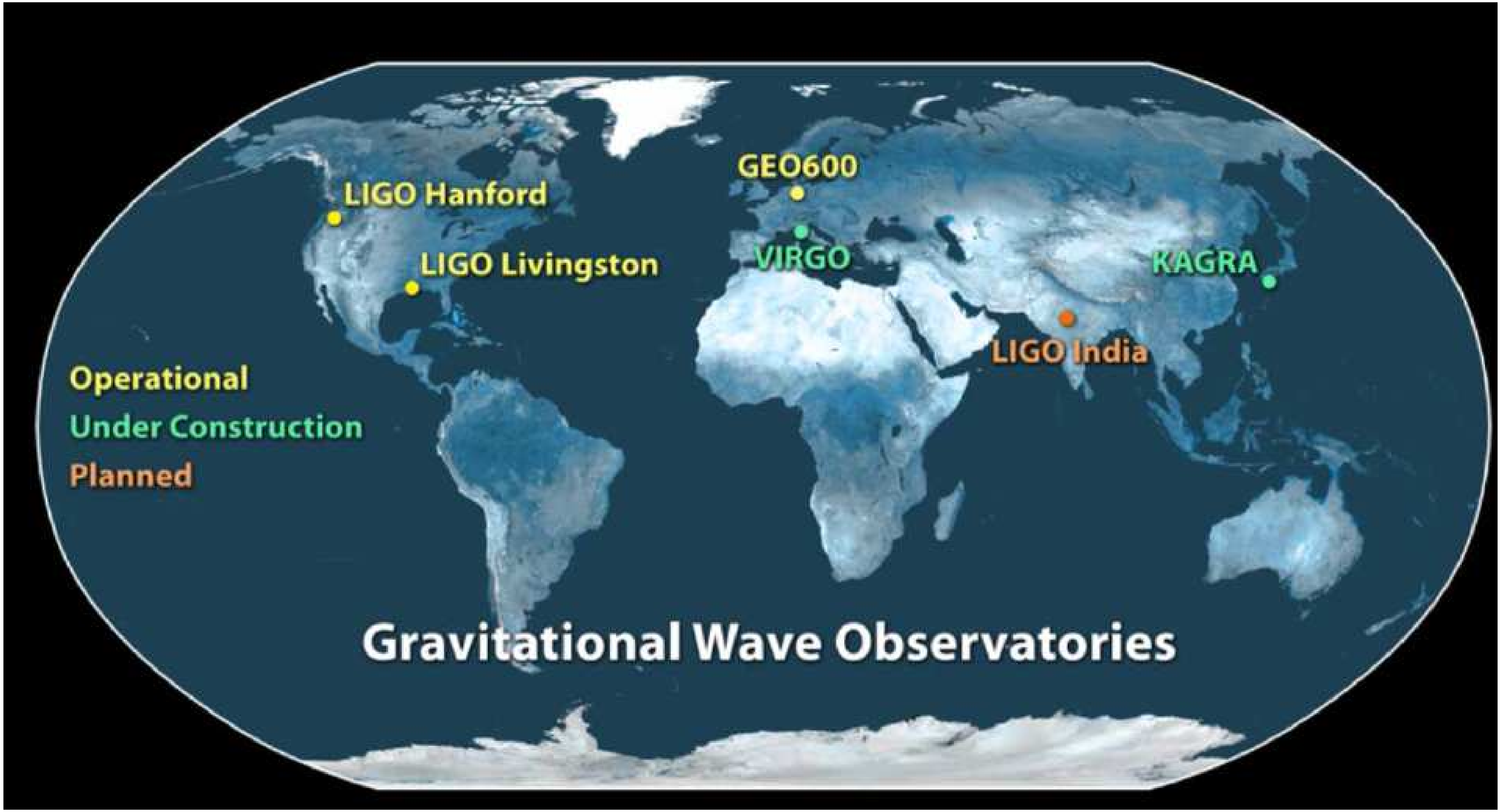
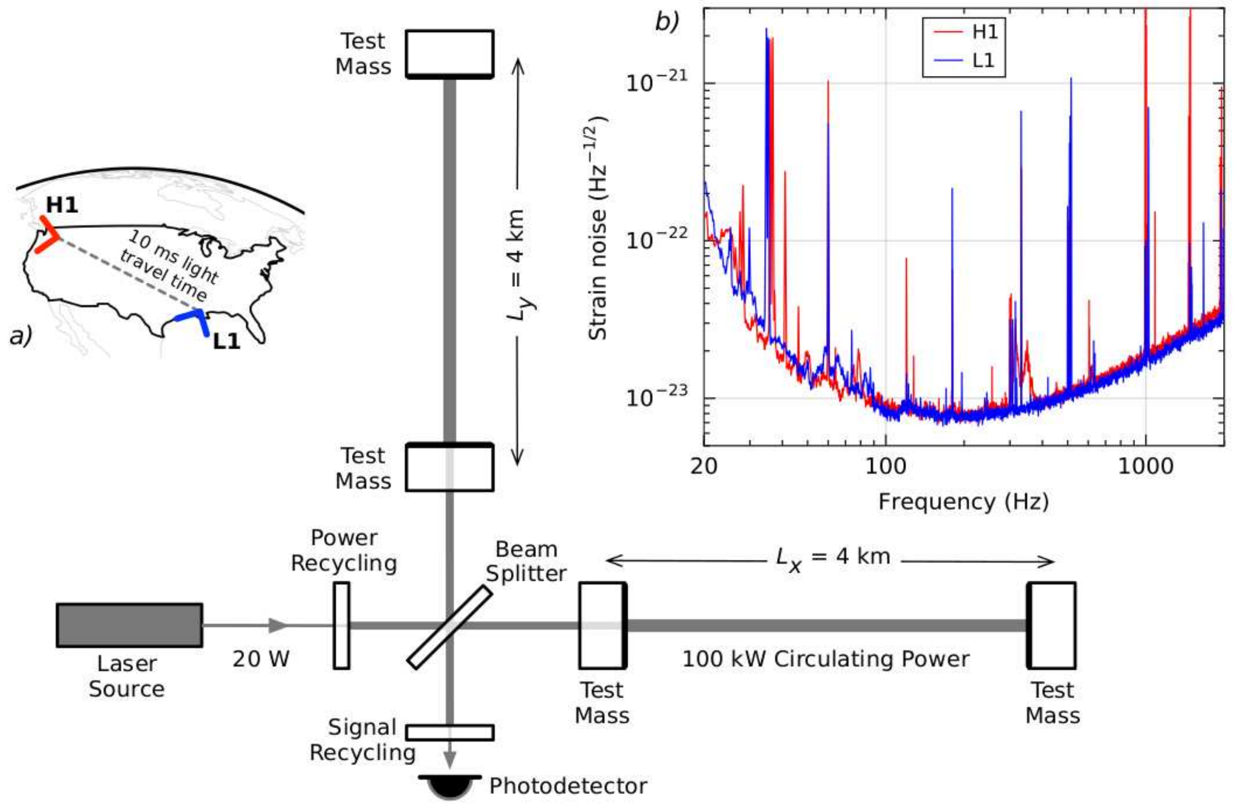


LIGO-India approved

Livingston/Hanford

First detection of gravitational waves passing through Earth

Abbott et al. (LIGO Scientific & Virgo Collaborations) 16



On **Sep 14, 2015**
at 09:50:45 UTC
GW was detected!

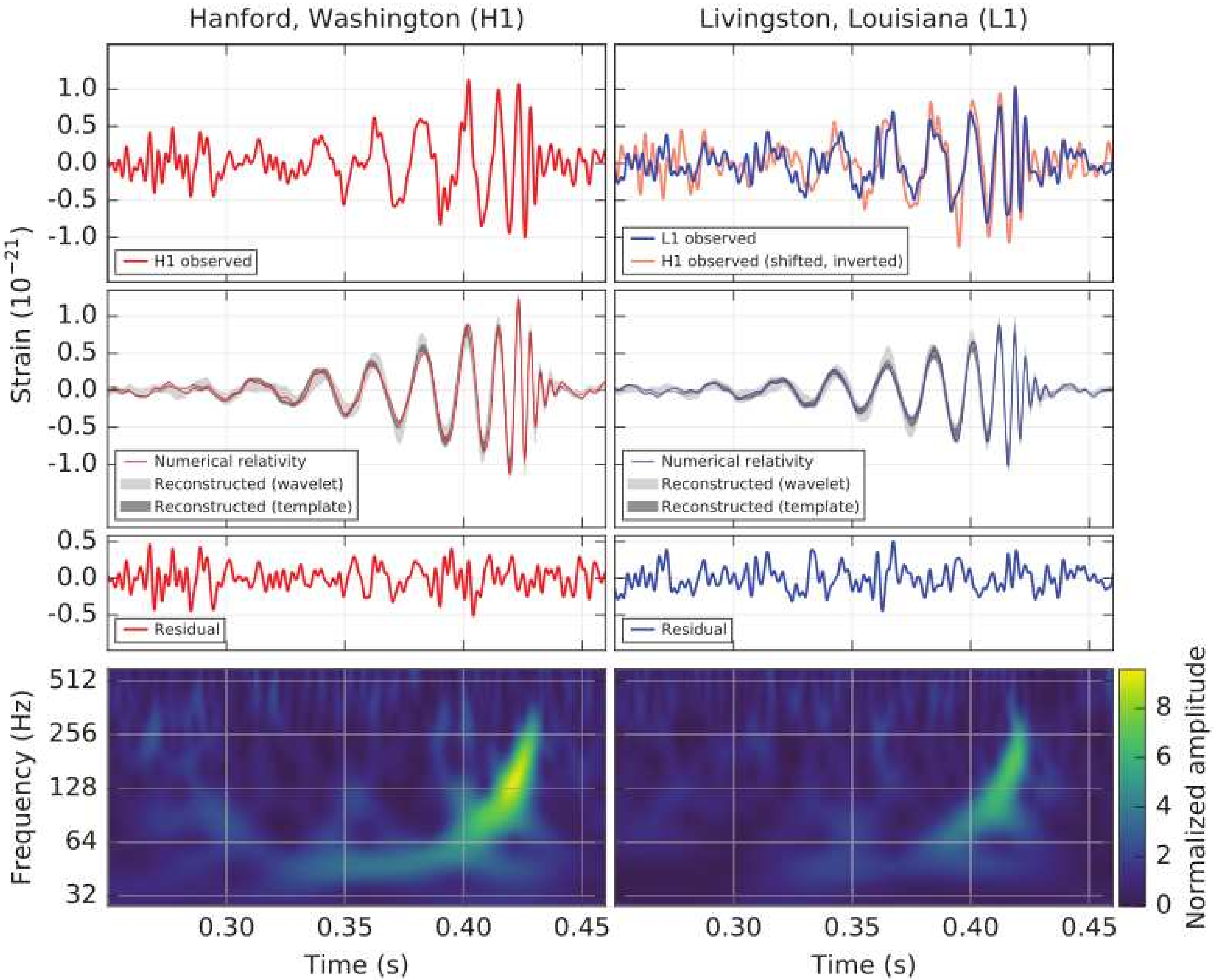
$$\Delta L = L\,h \sim 10^{-16}\,\mathrm{cm}$$

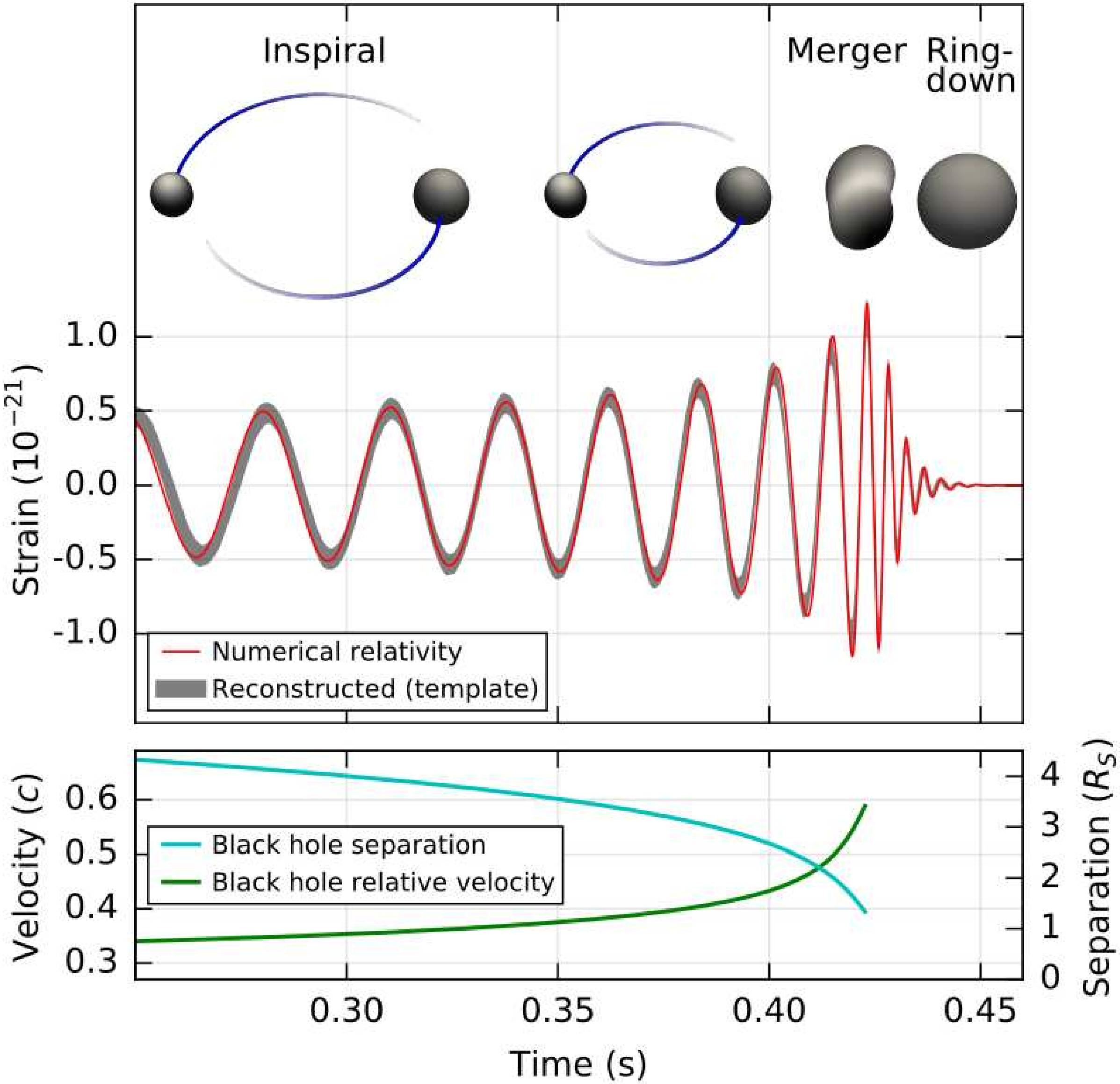
$$L = 4\,\mathrm{km} \Rightarrow h \sim 10^{-21}$$

(Credit: A. Buonanno 2016)

aLIGO Detection of Gravitational Waves

- **surprise:** merger of two massive **($\sim 30\,\mathrm{M}_\odot$)** black holes **(chirp-mass: $28\,\mathrm{M}_\odot$)**
- **[$\mathrm{M}_1/\mathrm{M}_2 \simeq 0.8 \pm 0.2$, $\mathrm{D} \sim 400\,\mathrm{Mpc}$, $\mathrm{SNR} \gtrsim 20$, $\sim$ 5-sigma detection]**





(Abbott et al. (LVC) 16)

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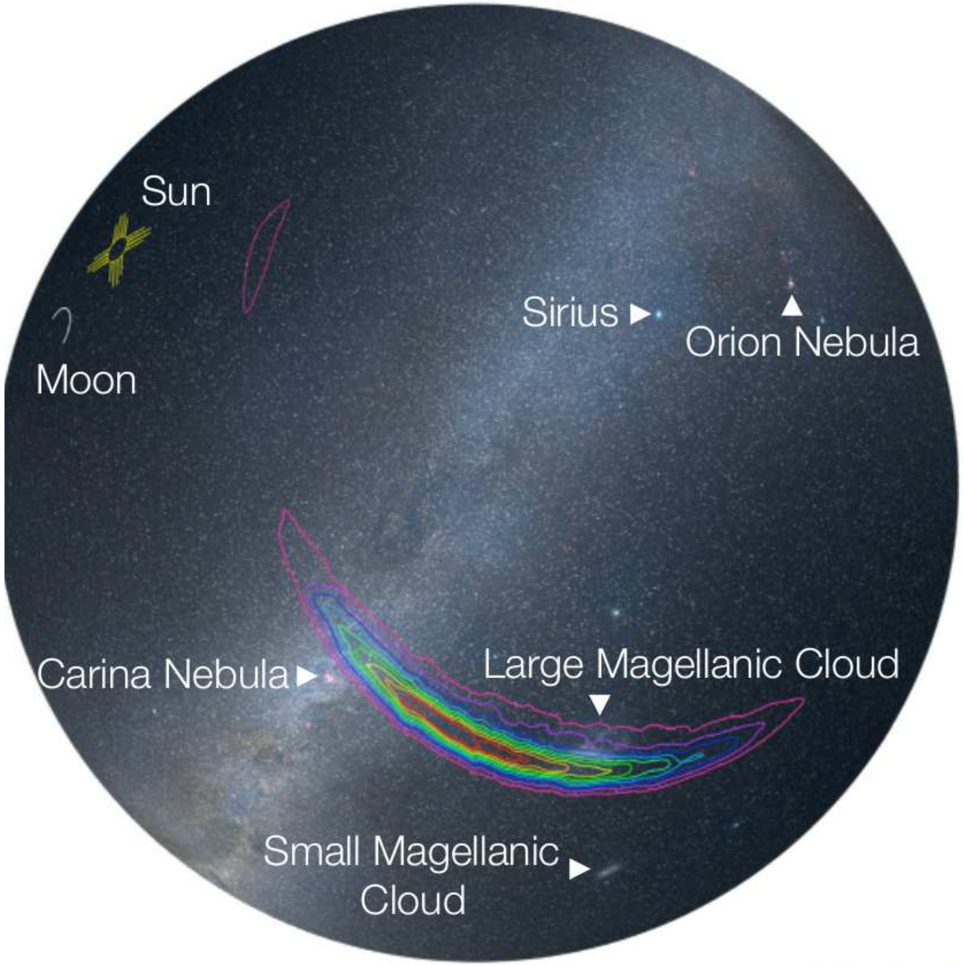
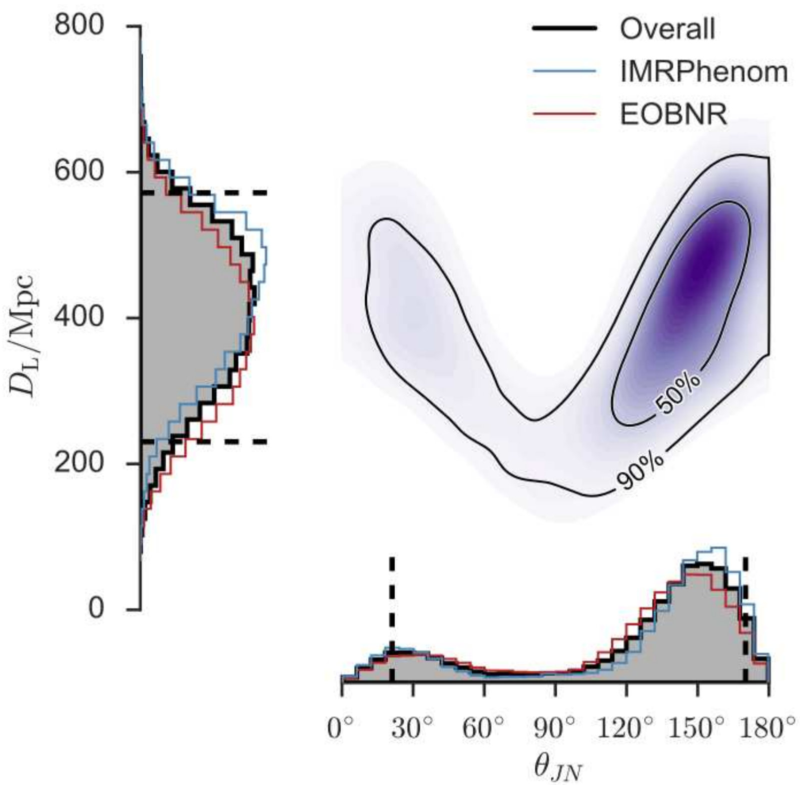
Unveiling GW150914's properties: sky location & distance



(Abbott et al. (LVC) 16)

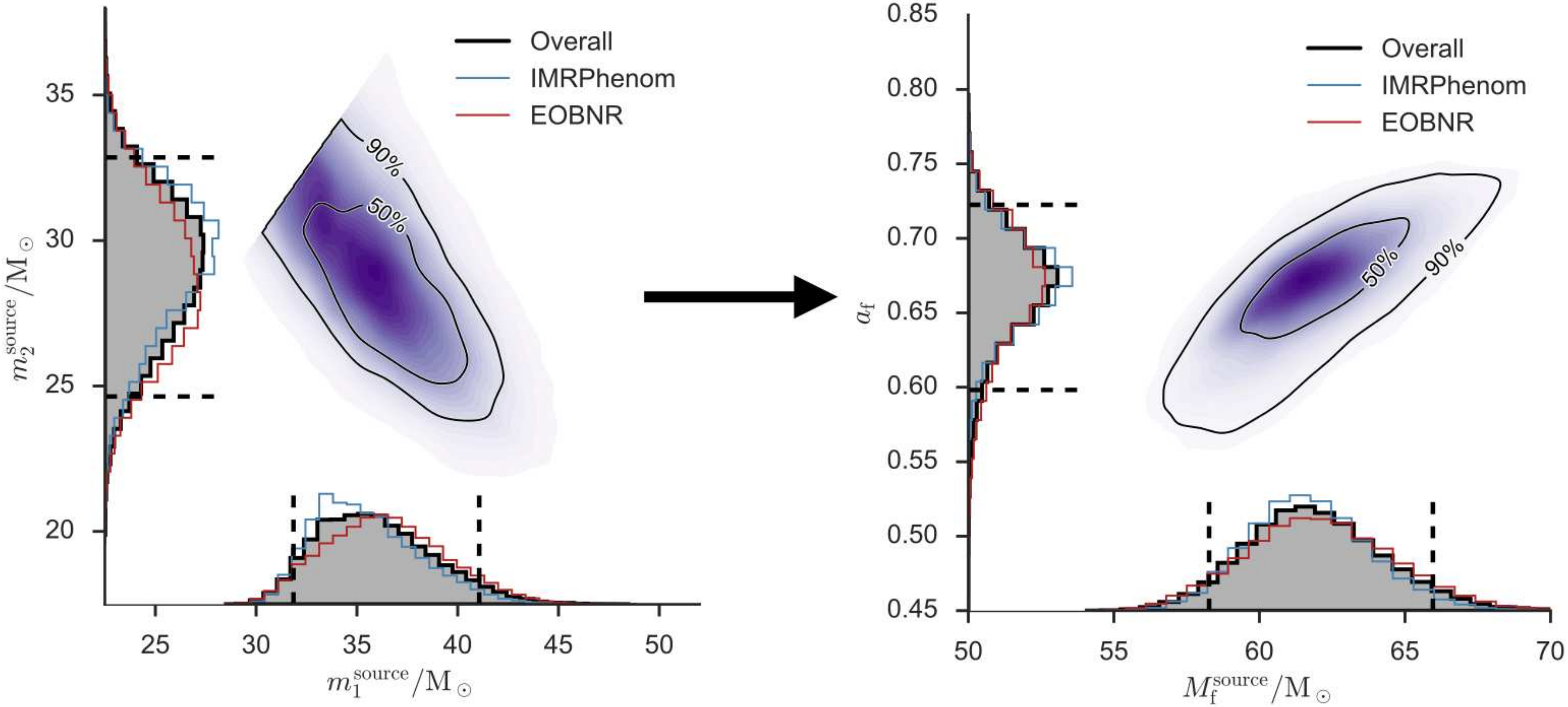


- **Face-off slightly favored** with respect to face-on.

(Credit: A. Buonanno 2016)

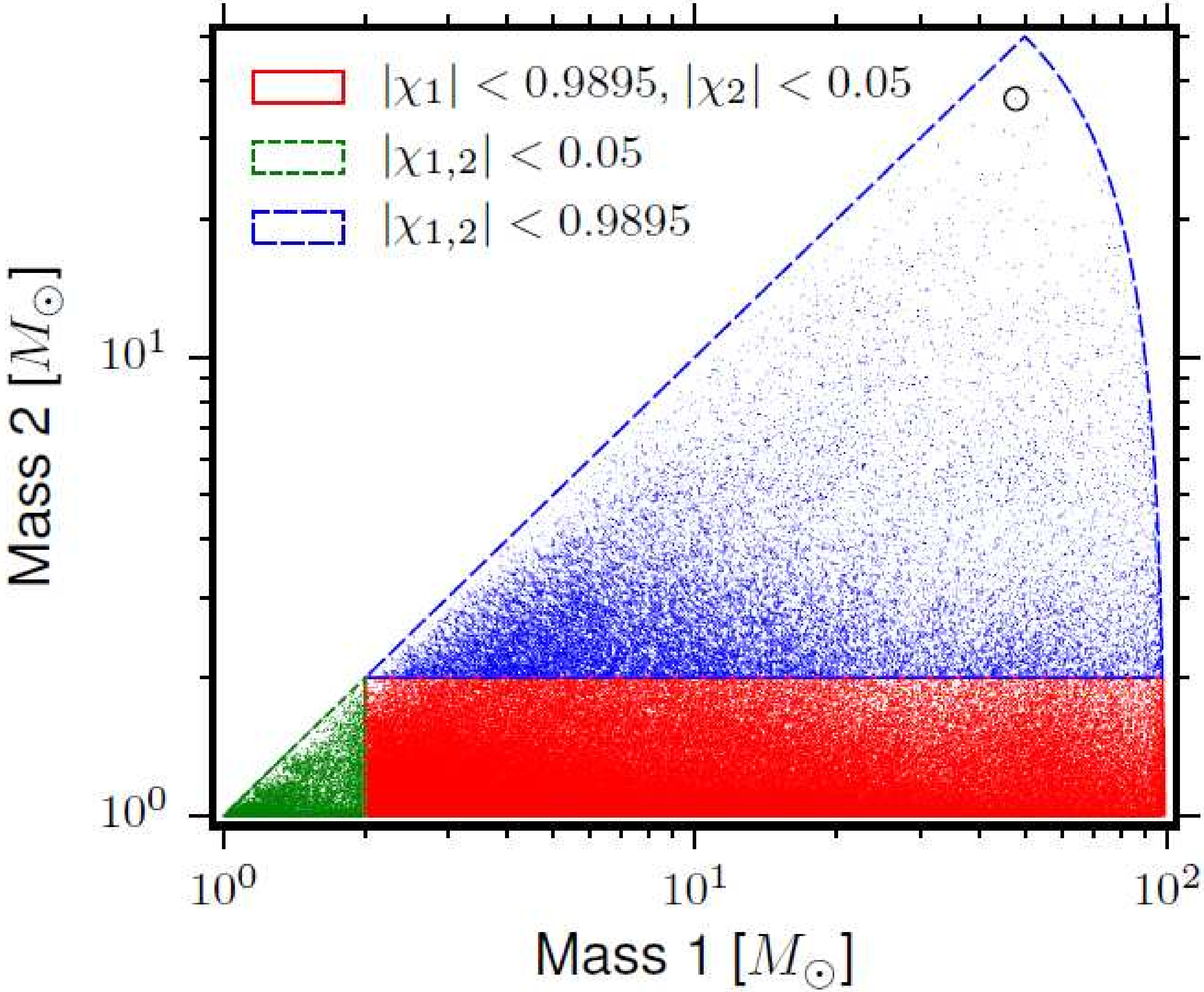
Unveiling GW150914's properties: masses & spins

(Abbott et al. (LVC) 16)



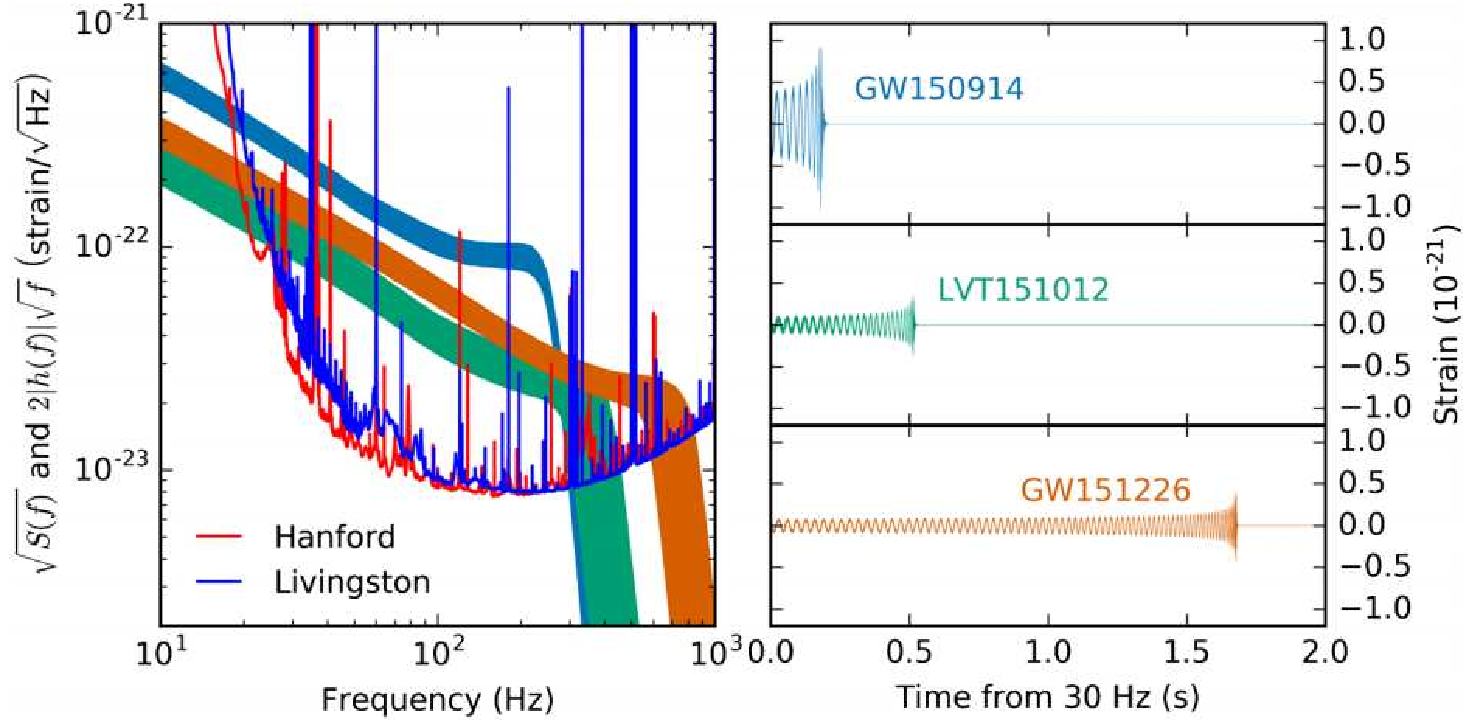
- **Final** black-hole **mass and spin** inferred from components posteriors and **NR formulae.**
- **3 solar masses** emitted **in GWs!**

(Credit: A. Buonanno 2016)



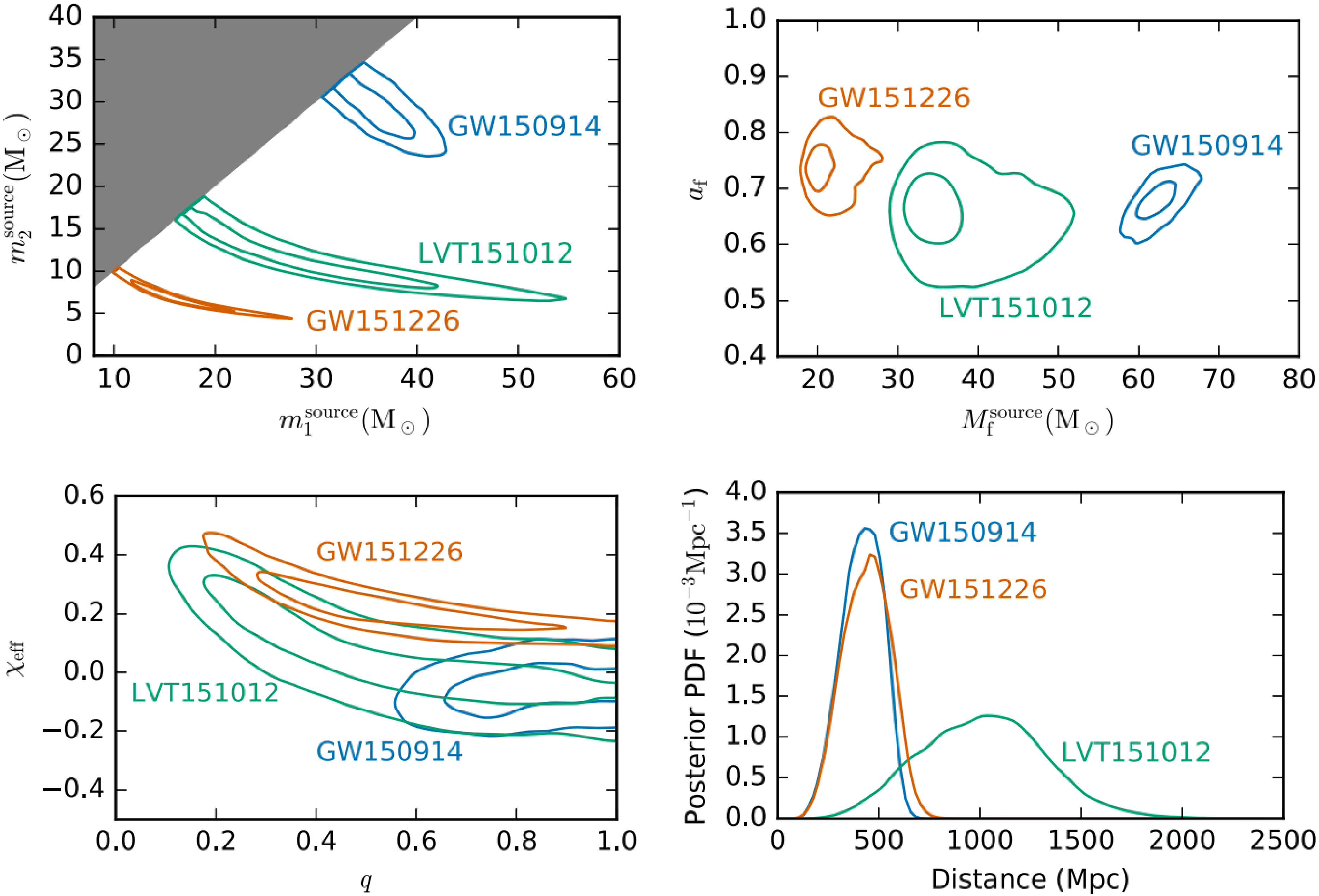
$|\chi_1| < 0.9895$, $|\chi_2| < 0.05$
$|\chi_{1,2}| < 0.05$
$|\chi_{1,2}| < 0.9895$
Mass 2 [$M_\odot$]
Mass 1 [$M_\odot$]
10^0
10^1
10^2

Results: First Science Run



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/{\rm deg}^2$	230	850	1600

BH+BH Parameters



The Formation of Merging BH+BH Binaries

Note: high black-hole mass expected for low metallicity (stellar winds depend on metallicity)

I. Dynamical formation in dense clusters

- in dense clusters: dynamical interactions $\rightarrow$ close BH+BH binaries

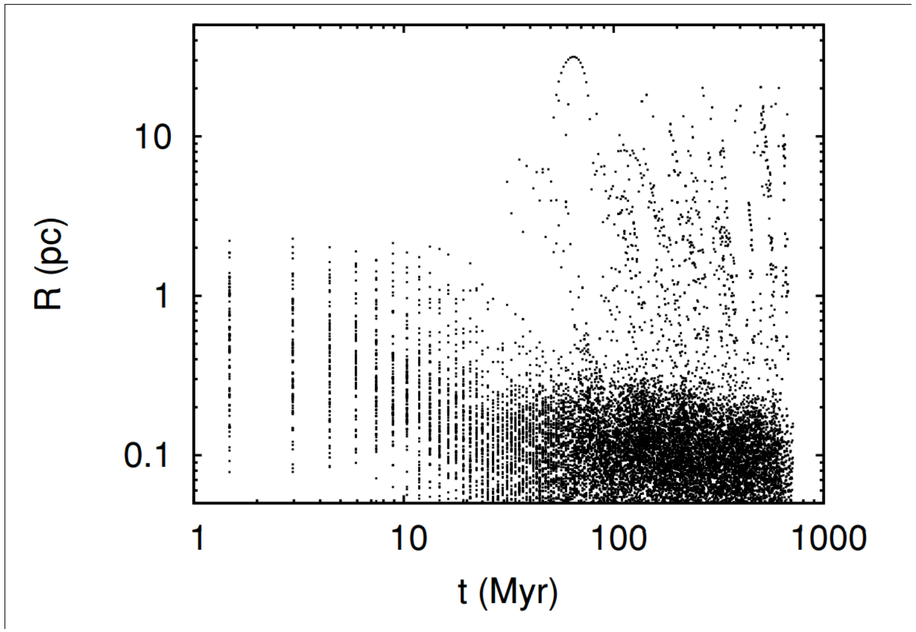
II. Non-dynamical formation

- common-envelope scenarios: conversion of wide binary to close binary
- homogeneous evolution scenarios: close binary from the beginning

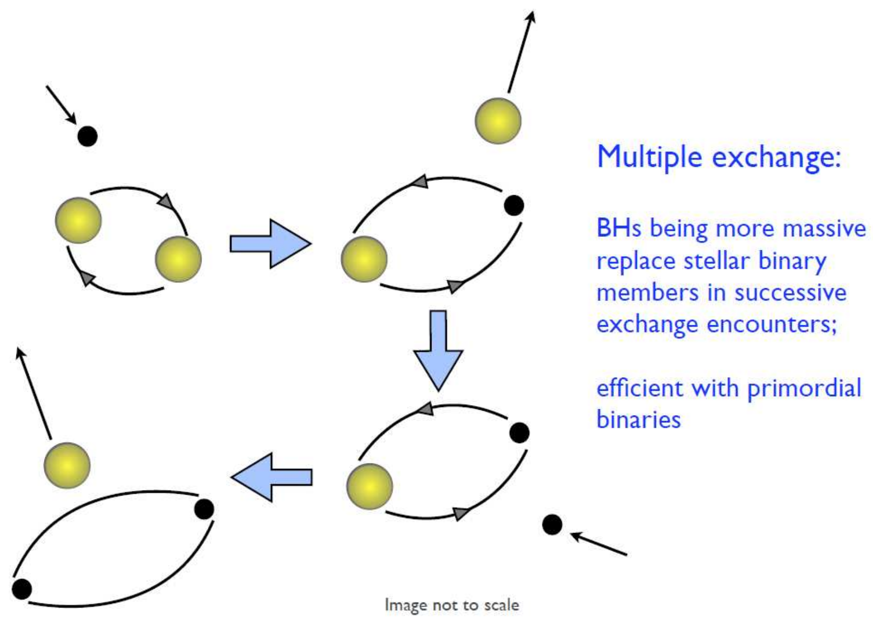
Dynamical Formation in Stellar Clusters

(e.g. Banerjee, Baumgardt, Kroupa (2010), Rasio, Rodriguez, etc.)

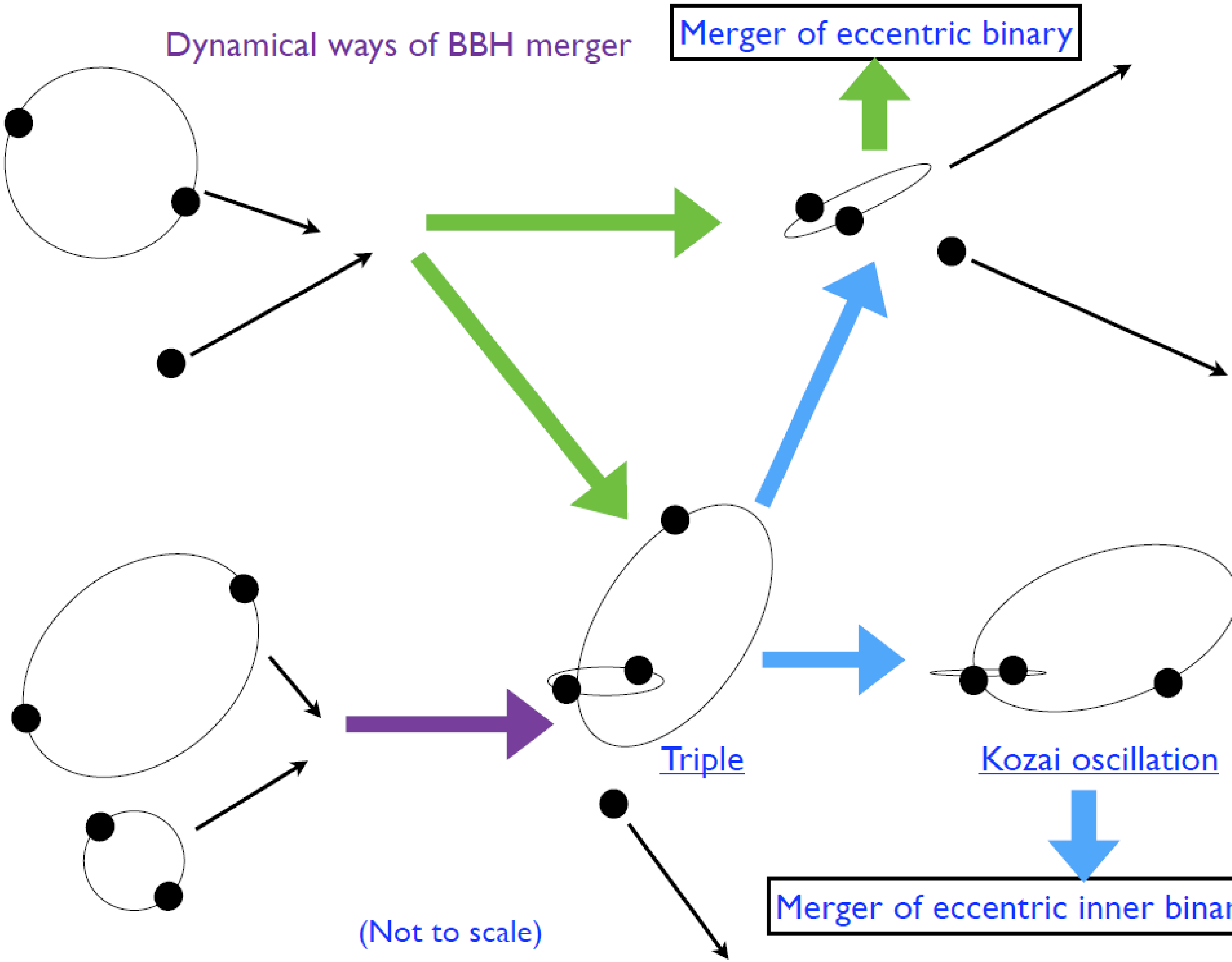
- in dense clusters, BHs segregate quickly and can form sub-clusters of BHs (Spitzer instability)
- three-body encounters $\rightarrow$ BH+BH binaries
- most are ejected, but some harden sufficiently to ultimately merge
- aLIGO detection rates (e.g. Banerjee 2016): $10 - 300\,\mathrm{yr}^{-1}$



Black-hole segregation (Banerjee et al. 2010)



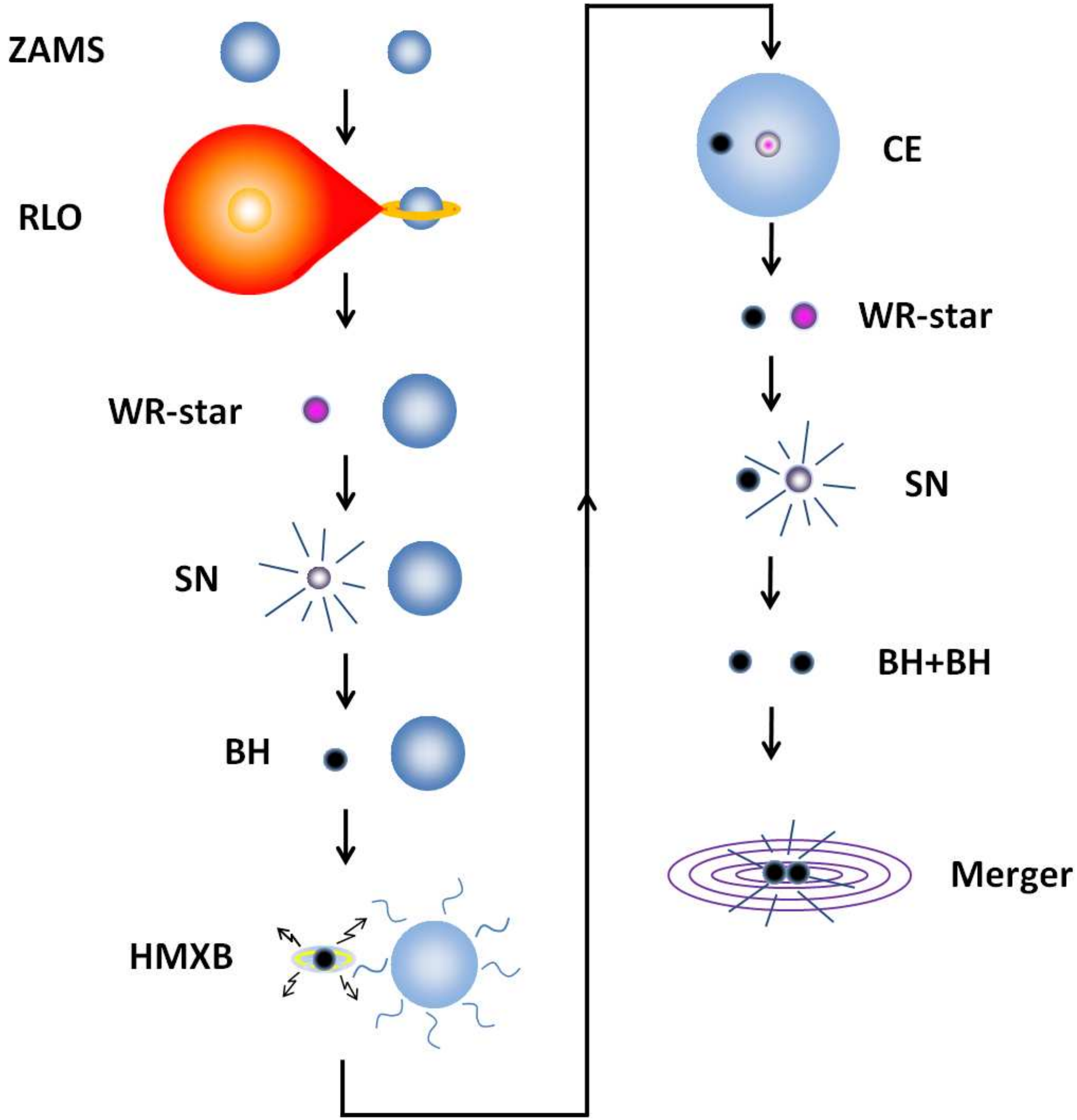
(Credit: Banerjee 2016)

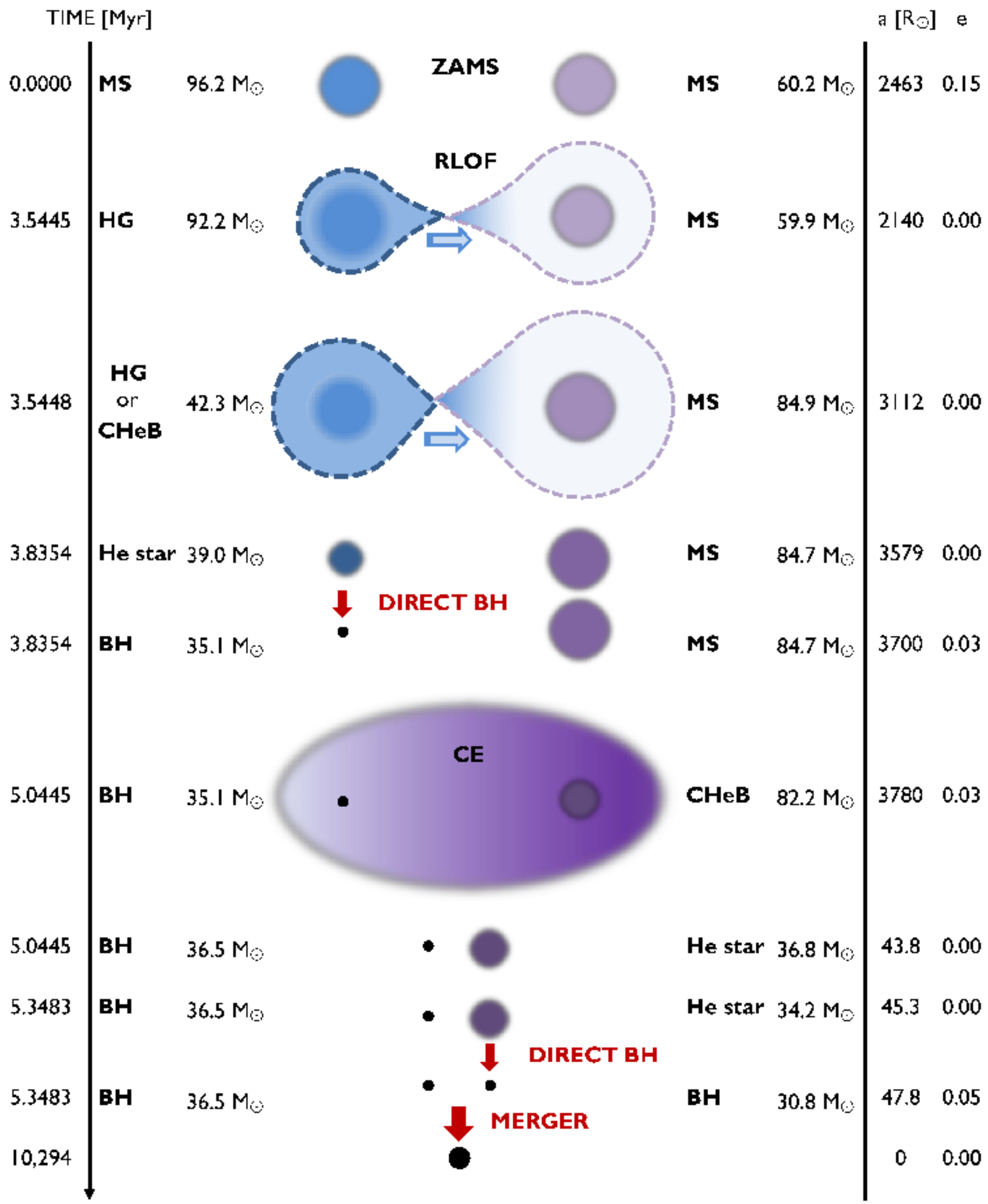


(Credit: Banerjee 2016)

The Formation of BH+BH Binaries through Common-Envelope Evolution

- the progenitors of black holes are big stars
- need to get them into a close orbit to merge
- possible solution: common-envelope evolution
- standard scenario to produce compact NS+NS binaries (Hulse-Taylor pulsar, PSR J0737-3039)
- problem with black holes:
  - ▷ difficult to form two black holes (requires late mass transfer)
  - ▷ but possible with some fine-tuning
  - ▷ rates highly uncertain (Belczynski et al. [2016] vs. Kruckow, et al. [2016])





Belczynski (2016)

The Massive Overcontact Binary (MOB) Model

(Marchant et al. 2016; also de Mink & Mandel 2016a,b)

- initial homogeneous evolution is enforced by tidal locking in a very close massive binary (de Mink et al. 2009)
- needs to avoid binary widening by stellar wind mass loss

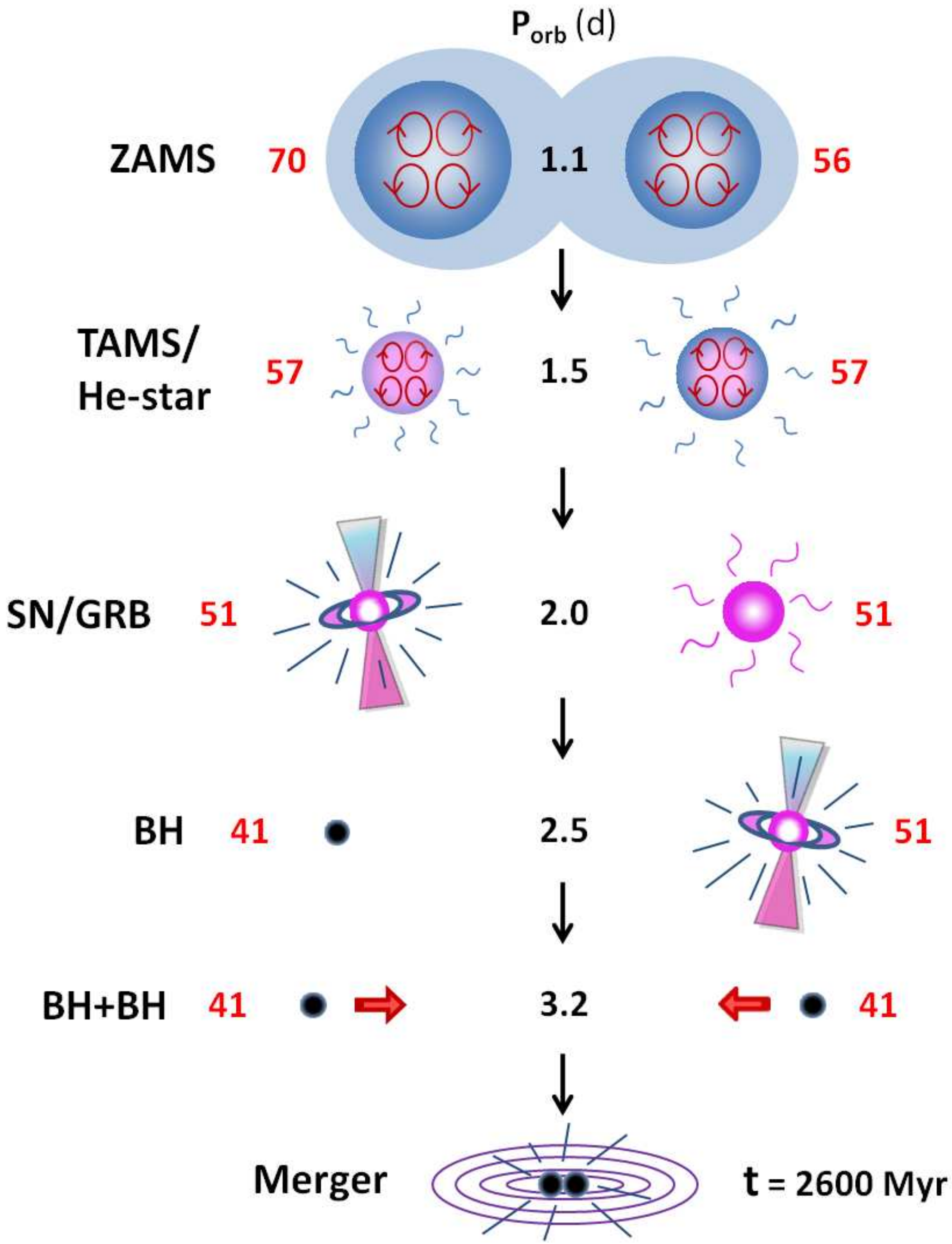
$\rightarrow$ requires low metallicity

- most systems pass through contact phase on main sequence

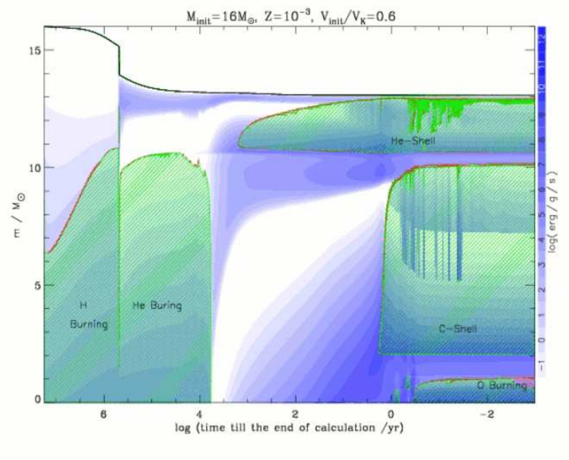
$\rightarrow$ evolution drives systems towards mass ratio of 1

Model Description

- uses latest MESA code (Paxton et al. 2015)
- with binary evolution fully implemented (Marchant)
- mass loss:
  - ▷ Vink (2001) $\times 1/3$ (H-rich), Hamann (1995) (no H)
  - ▷ $\dot{M} \propto Z^{0.85}$

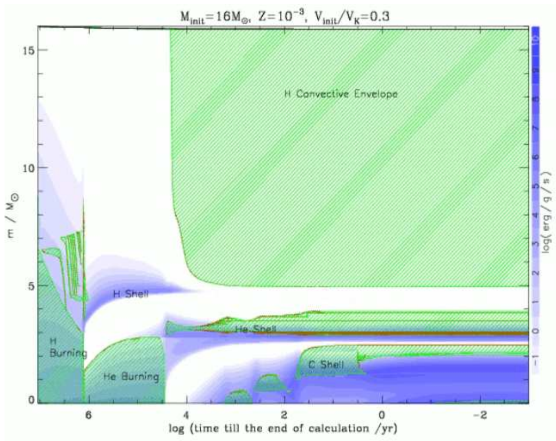


Marchant et al. (2016)

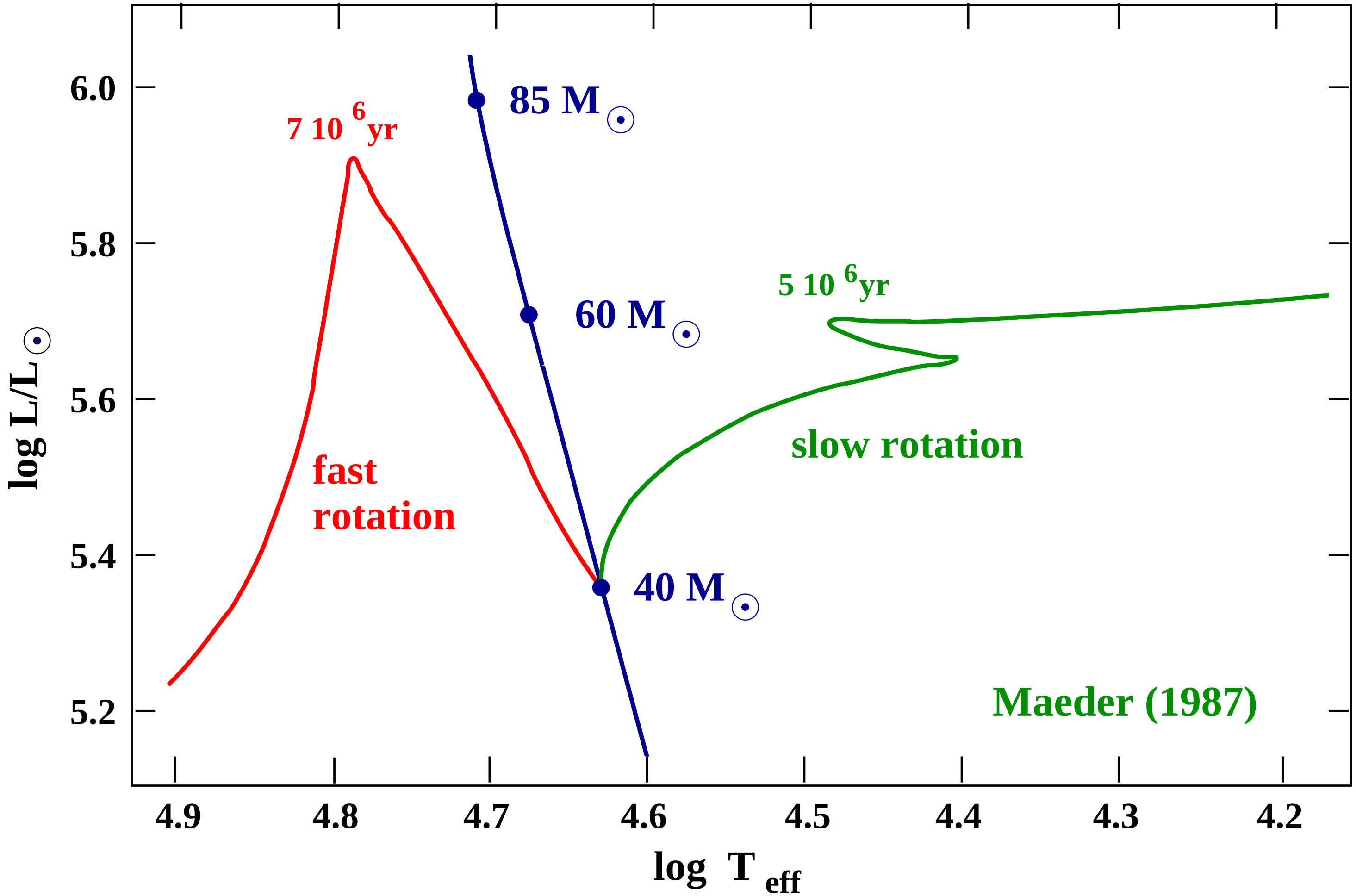


M_init=16M⊙, Z=10^-3, V_init/V_K=0.6
m / M⊙
H Burning
He Buring
He-Shell
C-Shell
O Burning
log (time till the end of calculation /yr)
log(erg / g / s)

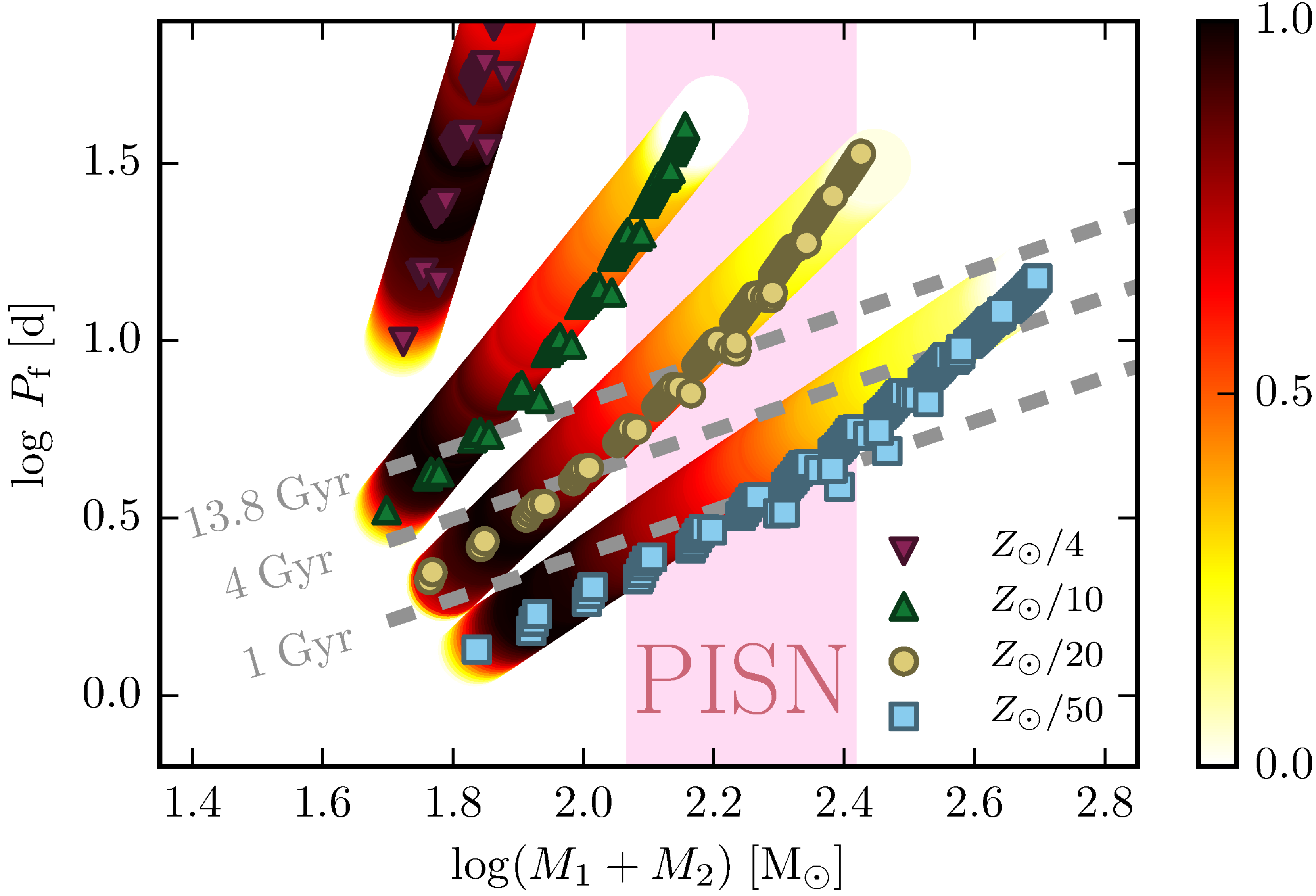
Yoon (2005/6)



M_init=16M⊙, Z=10^-3, V_init/V_K=0.3
m / M⊙
H Convective Envelope
H Shell
He Shell
C Shell
H Burning
He Burning
log (time till the end of calculation /yr)
log(erg / g / s)



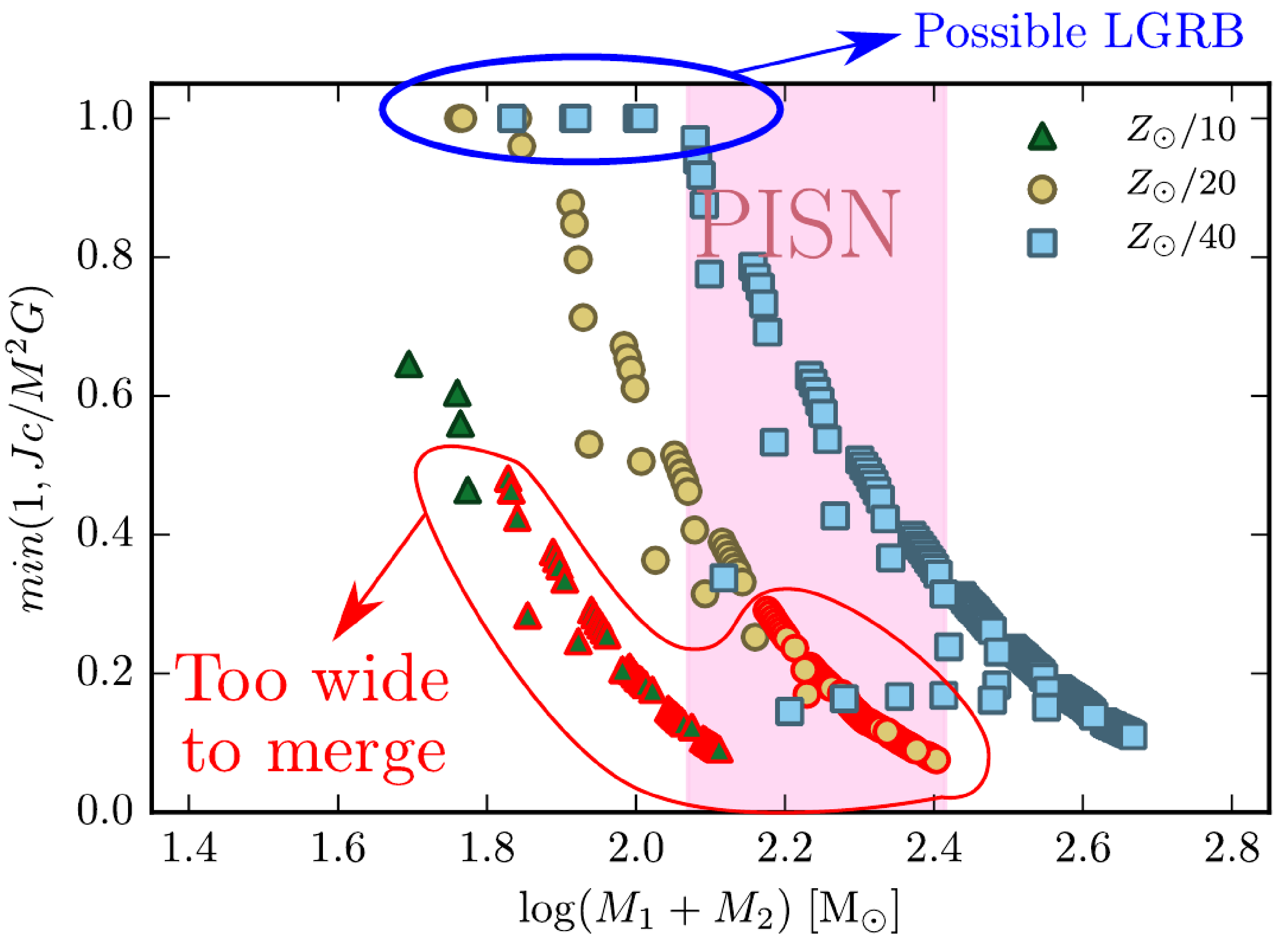
7 10 6 yr
85 M⊙
60 M⊙
40 M⊙
5 10 6 yr
fast rotation
slow rotation
Maeder (1987)
log L/L⊙
log T eff
6.0
5.8
5.6
5.4
5.2
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2



Marchant et al. (2016)

depends on metallicity-dependent stellar winds

Final BH spins and LGRBs

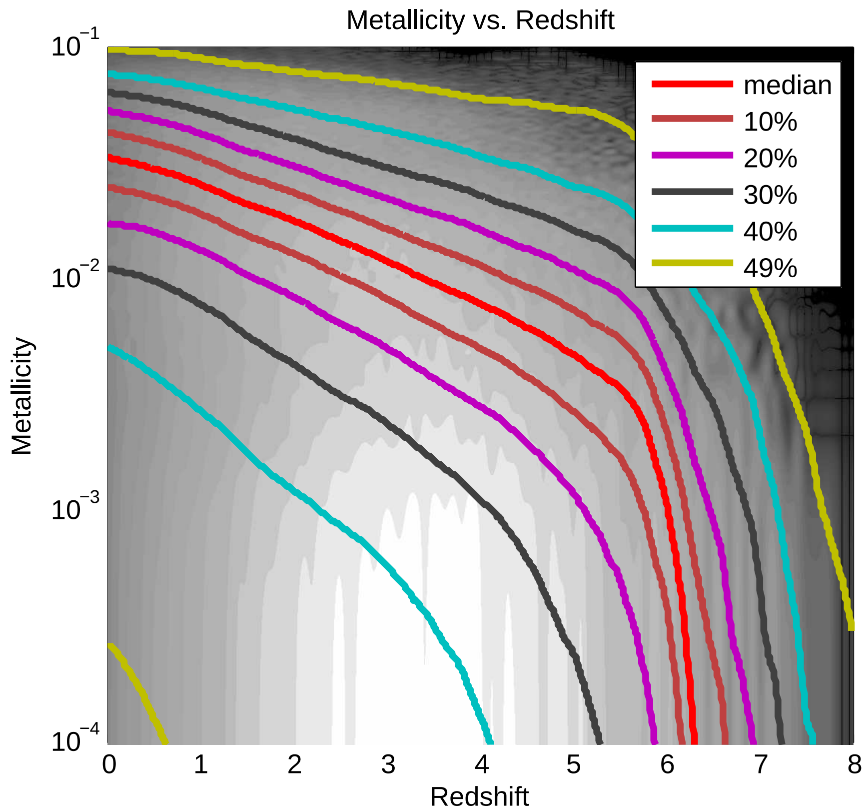


Marchant et al. (2016)

Cosmological Simulations of BH+BH Mergers in the MOB Scenario

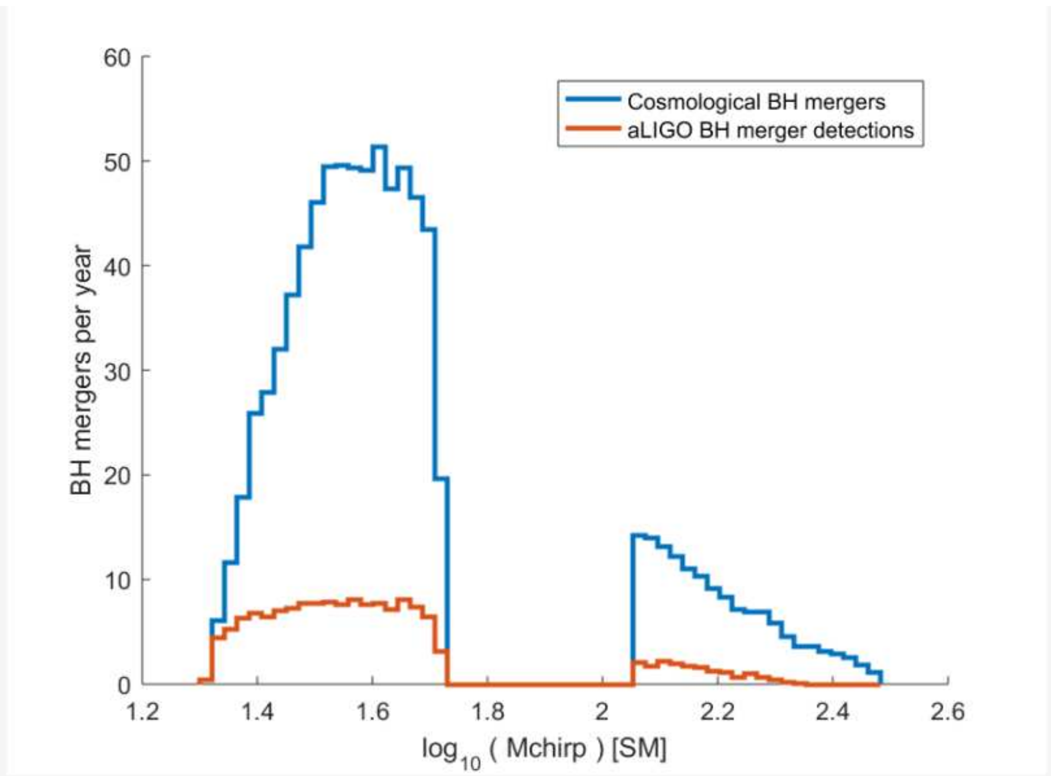
Lise du Boisson, Podsiadlowski[1]

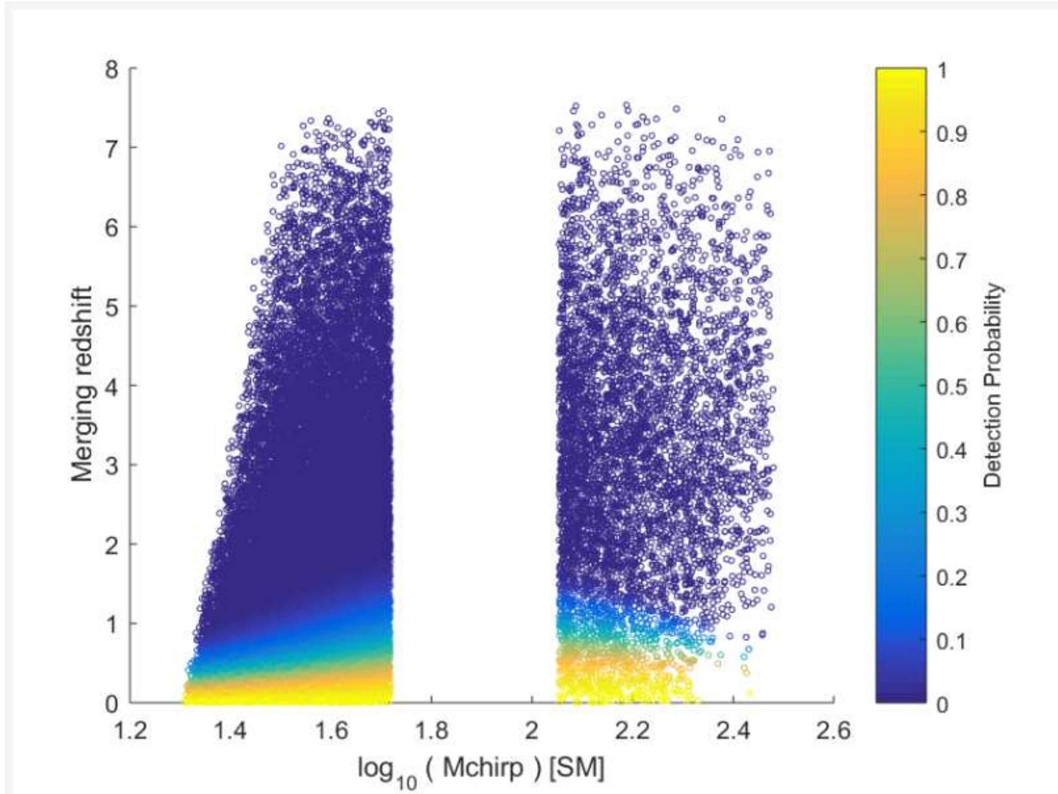
- use full cosmological simulations to simulate rates of GW sources as a function of z and Z (plus LGRBs, PISNe)
- simulations by Taylor & Kobayashi (2014)
  - ▷ self-consistent hydrodynamical simulations with star formation, SN and AGN feedback, and chemical enrichment
  - ▷ fit key observables, such as the galaxy mass-metallicity relations, metallicity gradients, etc.



Based on Taylor & Kobayashi (2014)

[1] : plus Kobayashi, Taylor, Marchant, Langer, Tauris, Mandel, de Mink





du Buisson et al. (2017)

- form massive BH+BH systems ($\gtrsim 25\,\mathrm{M}_\odot$)
- at very low metallicity ($\mathrm{Z}_\odot/50$): bimodal mass distribution with systems below and above pair-instability supernova (PISN) gap (no BH formation)
- very massive BH+BH mergers can be detected with aLIGO throughout the Universe (prediction: $140\,\mathrm{yr}^{-1}$ below and $14\,\mathrm{yr}^{-1}$ above PISN gap)

$\rightarrow$ probe massive stellar evolution throughout the Universe

- known observational counterparts (e.g. double He-star binary (SMC) with $\mathrm{M}_1 = 66\,\mathrm{M}_1$, $\mathrm{M}_2 = 61\,\mathrm{M}_2$, $\mathrm{P}_{\mathrm{orb}} = 19.3\,\mathrm{d}$)

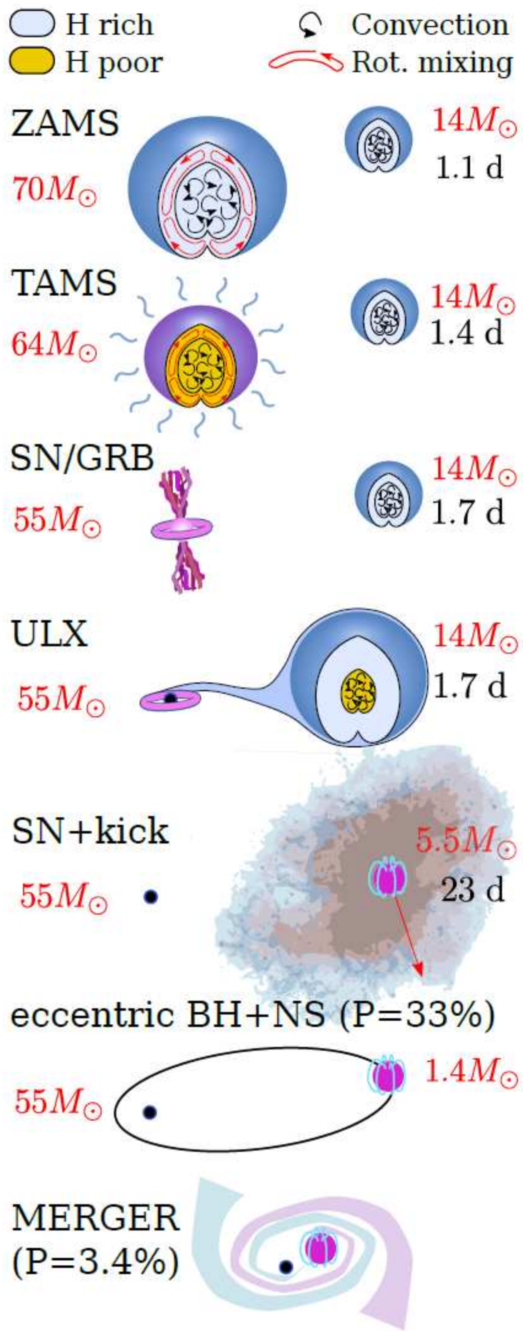
Ultraluminous X-ray sources (ULXs) from chemically homogeneous evolution

(Marchant+ 2017)

- ULXs have luminosities $> 10^{39}\,\mathrm{erg/s}$
- probably stellar BH binaries (not intermediate-mass BHs) with super-Eddington radiation (plus beaming?)
- optical counterpart problem: massive optical counterparts require more massive black holes ($\sim 50\,\mathrm{M_\odot}$) (Madhusudhan et al. 2008)
- for mass ratios $\mathbf{q} \simeq 0.1 - 0.4$
  - ▷ massive black holes with massive companion

rate: up to ~ 2 (per SFR $[\mathrm{M_\odot/yr}]$)

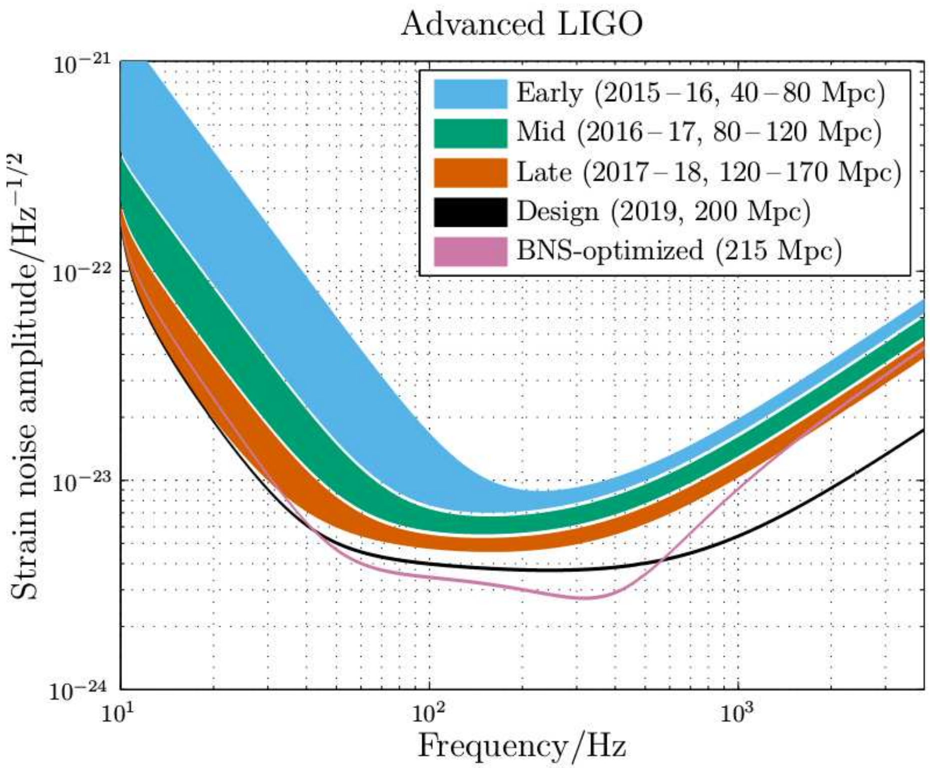
- ▷ metallicity dependent
- ▷ lead to the formation of NS+BH binaries



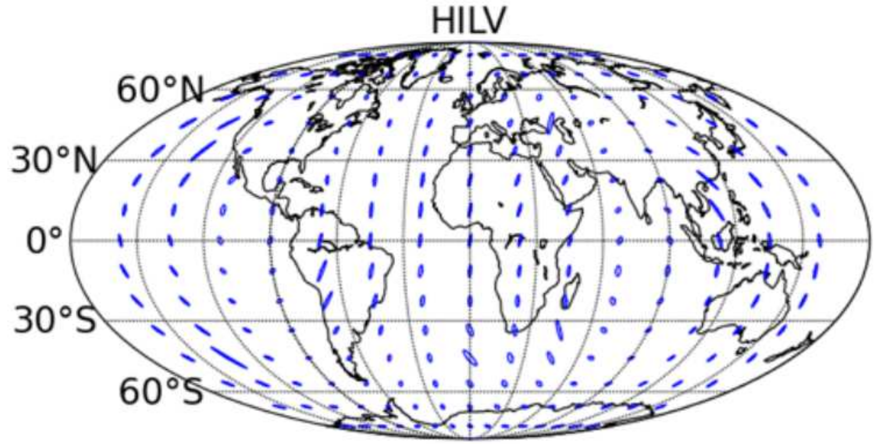
Marchant, Langer, Podsiadlowski+ (2017)

Advanced LIGO roadmap until 2019

Aasi et al. (The LIGO Scientific & Virgo Collaborations) 13



LIGO-India just approved!



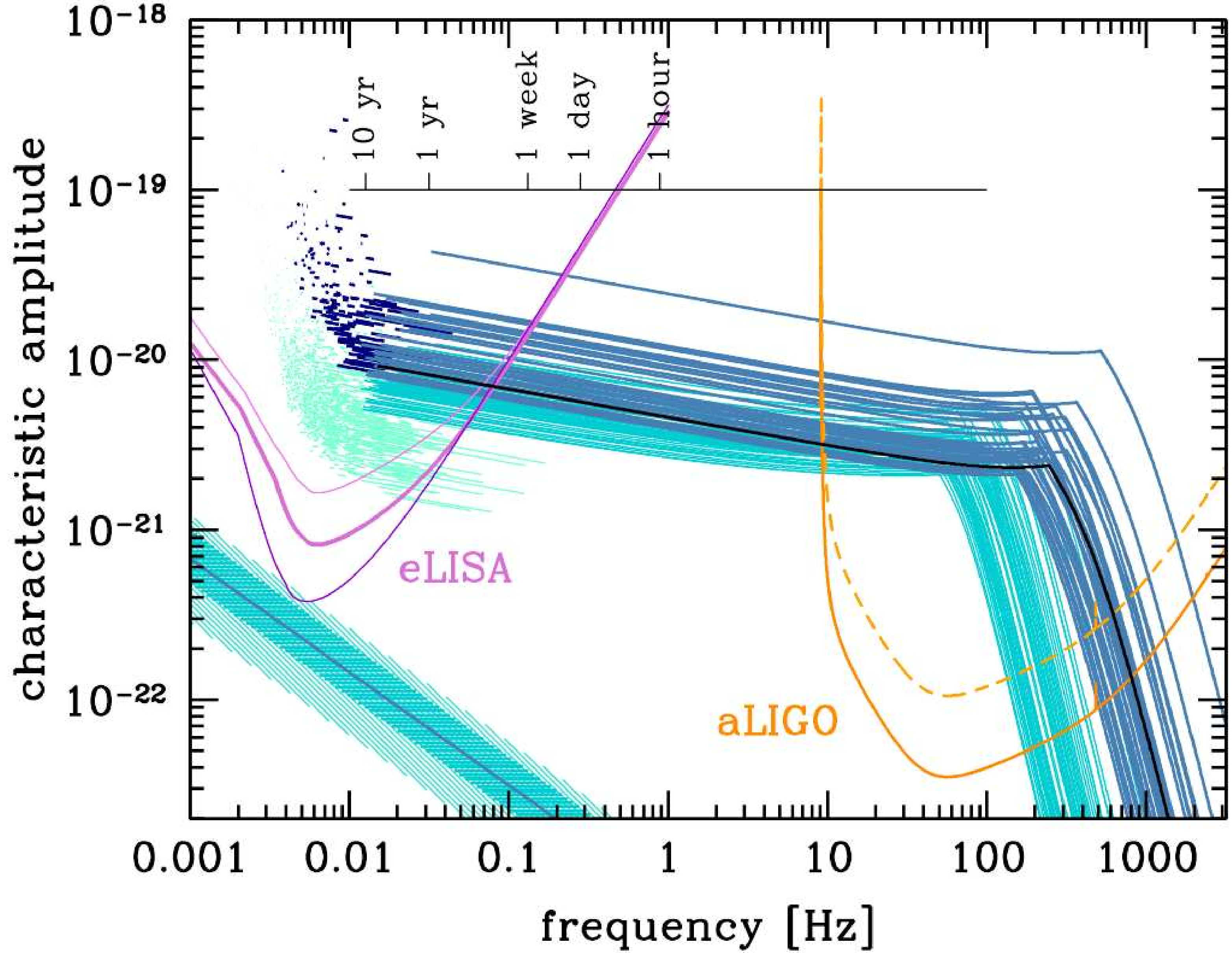
- **Few** square degrees!

Detection rates @ design sensitivity:

- **NS-NS: 0.2 - 200 per year**
- **BH-BHs: tens to hundreds per year!**

(Credit: A. Buonanno 2016)

Sesana 2016

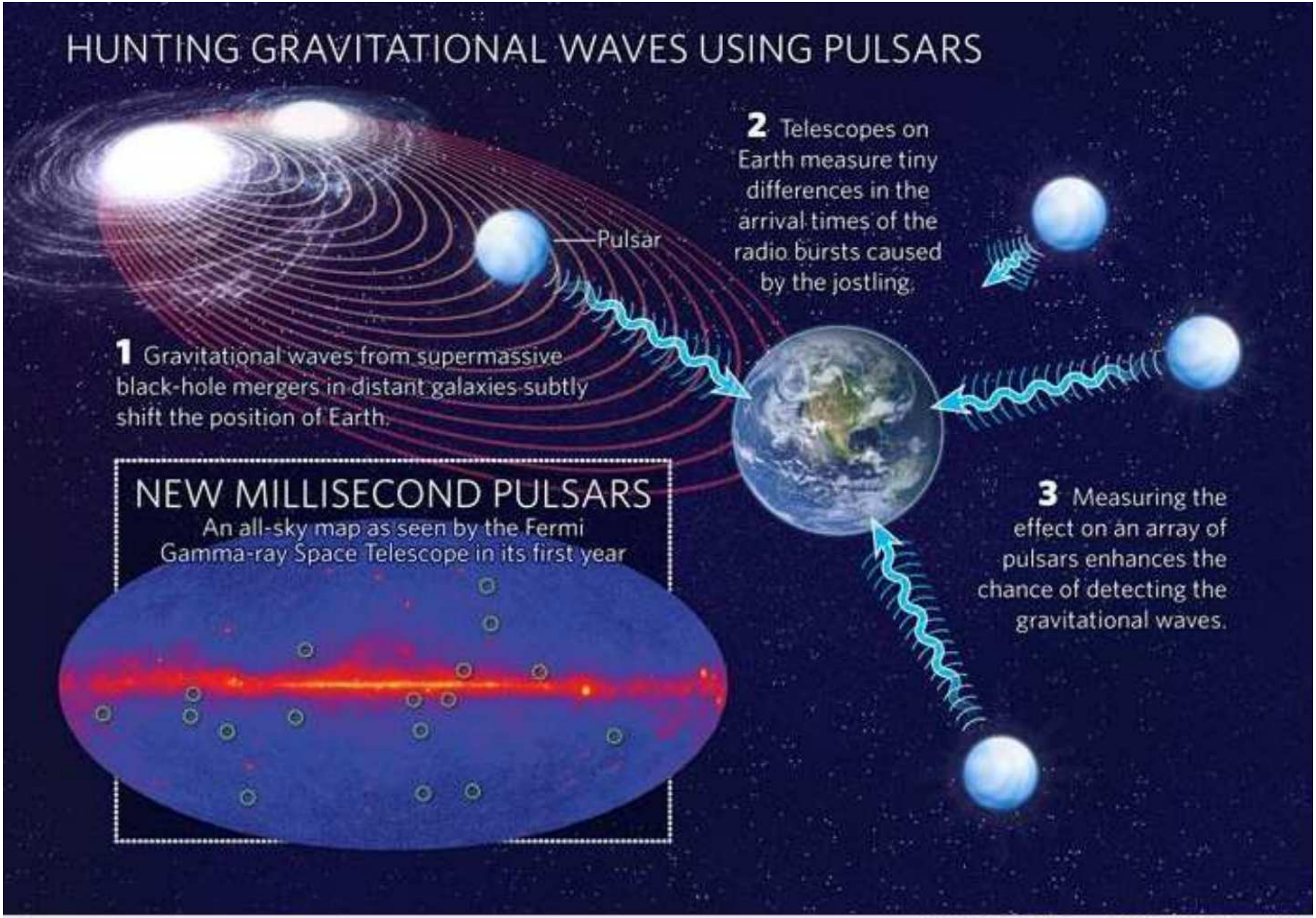


(Sesana)

Conclusions and Future Outlook

- present aLIGO rate: 1 every 2 weeks (?); future rate: 1 every day or 2 (?)
- all three channels may be at work (interesting rates)
- distinguish between different models based on
  - ▷ BH+BH chirp mass distribution
  - ▷ mass ratios
  - ▷ spins and their alignments
  - ▷ ratio of NS+NS to BH+BH mergers
  - ▷ host galaxies
- MOB Prediction: aLIGO should discover mergers of intermediate-mass black holes ($M_{tot} \sim 200 - 300\,M_\odot$)
  - ▷ already detectable in the ring-down phase

→ **The Era of GW Astronomy has Really Arrived**



NASA/DOE/Fermi LAT Collaboration

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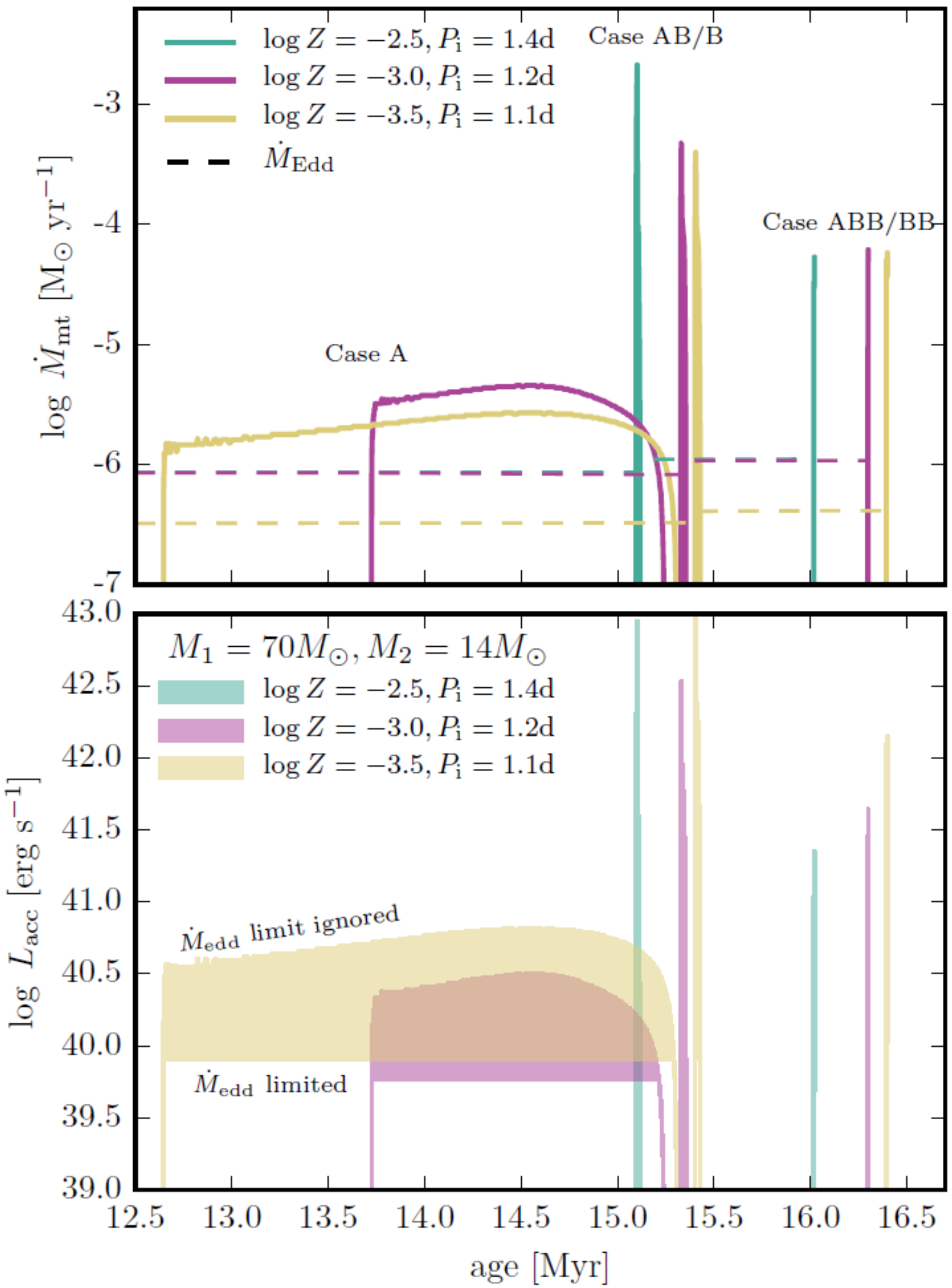
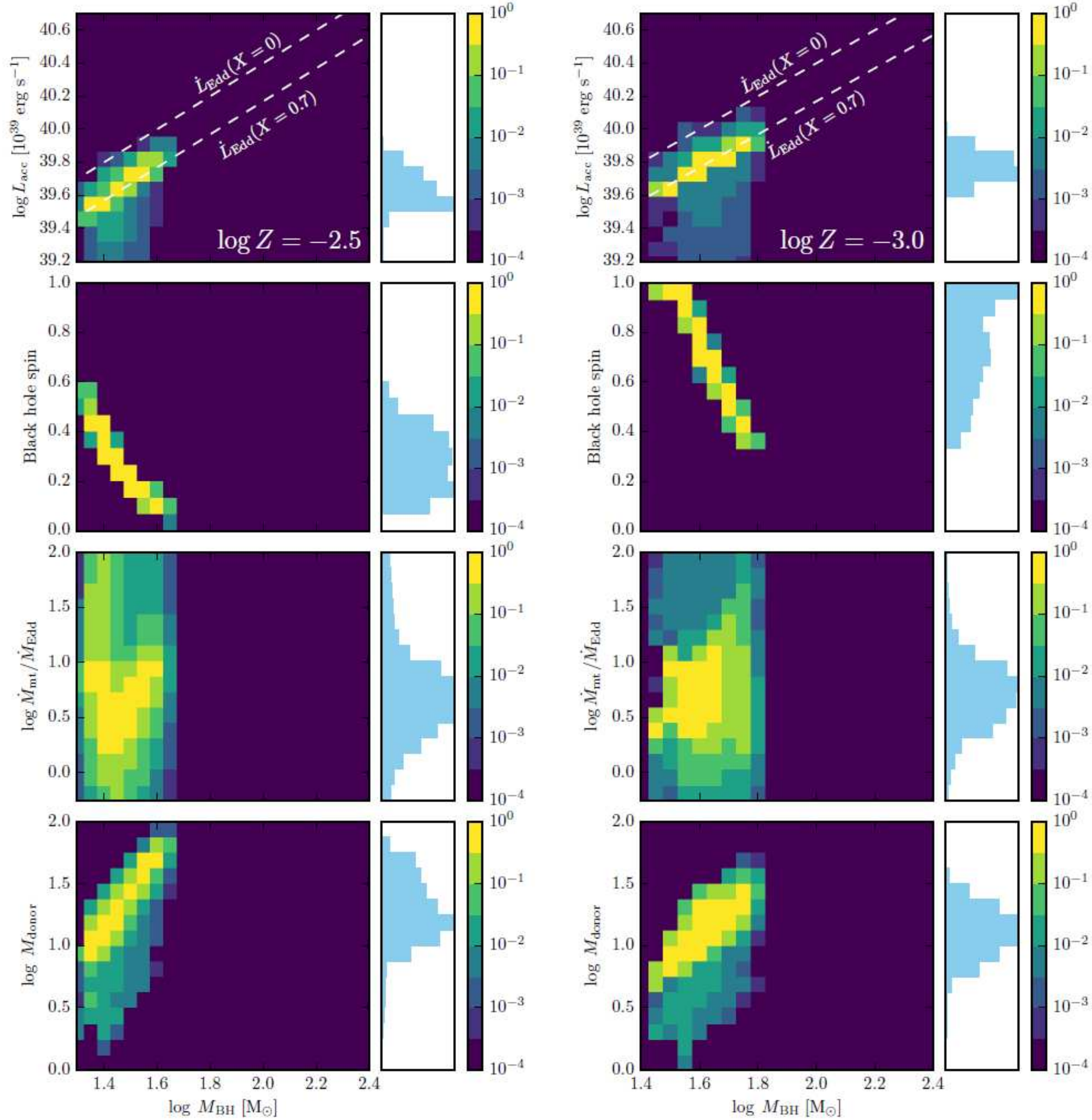
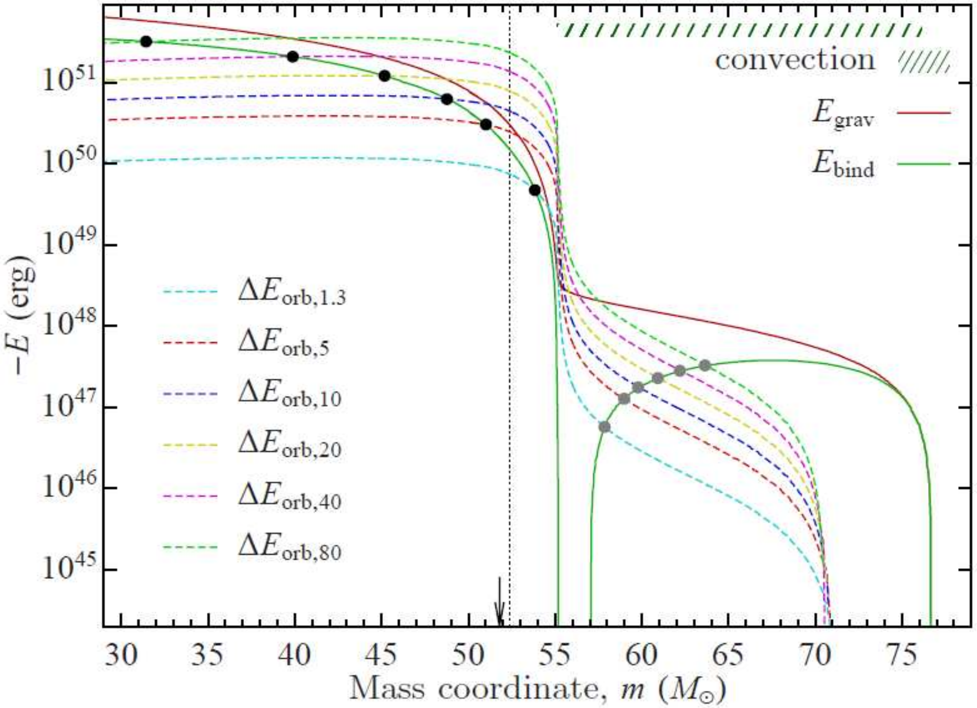
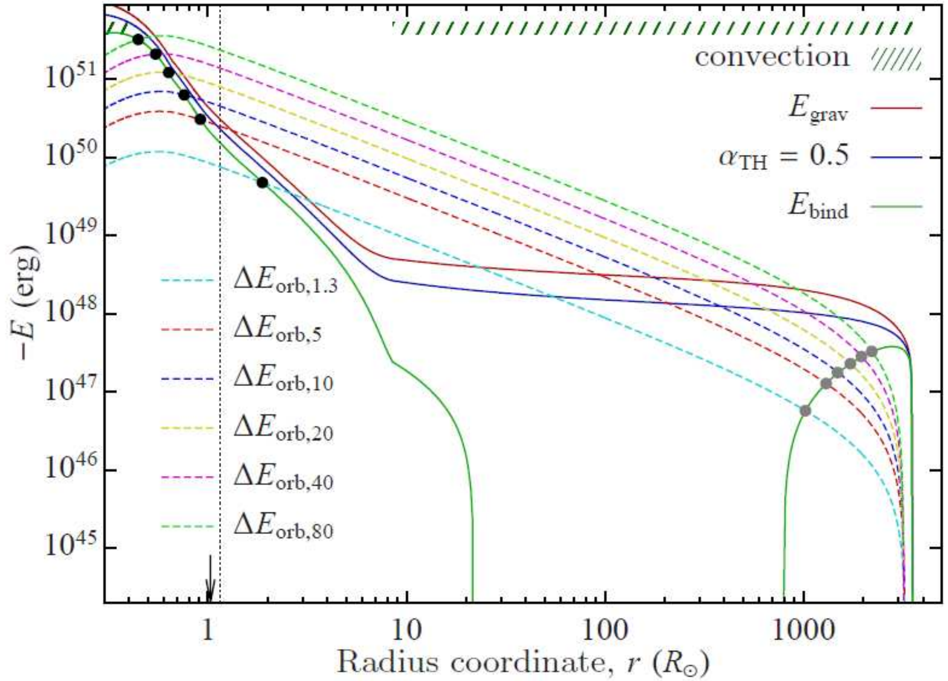


log $Z = -2.5, P_i = 1.4$d
log $Z = -3.0, P_i = 1.2$d
log $Z = -3.5, P_i = 1.1$d
$\dot{M}_{\rm Edd}$
Case AB/B
Case ABB/BB
Case A
log $\dot{M}_{\rm mt}$ [M$_\odot$ yr^{-1}]
-3
-4
-5
-6
-7
$M_1 = 70 M_\odot, M_2 = 14 M_\odot$
log $Z = -2.5, P_i = 1.4$d
log $Z = -3.0, P_i = 1.2$d
log $Z = -3.5, P_i = 1.1$d
$\dot{M}_{\rm edd}$ limit ignored
$\dot{M}_{\rm edd}$ limited
log $L_{\rm acc}$ [erg s^{-1}]
43.0
42.5
42.0
41.5
41.0
40.5
40.0
39.5
39.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
age [Myr]



log Z = −2.5
log Z = −3.0
$\dot{L}_{\rm Edd}(X=0)$
$\dot{L}_{\rm Edd}(X=0.7)$
$\log L_{\rm acc}$ [10^{39} erg s^{-1}]
Black hole spin
$\log \dot{M}_{\rm mt}/\dot{M}_{\rm Edd}$
$\log M_{\rm donor}$
$\log M_{\rm BH}$ [M$_\odot$]



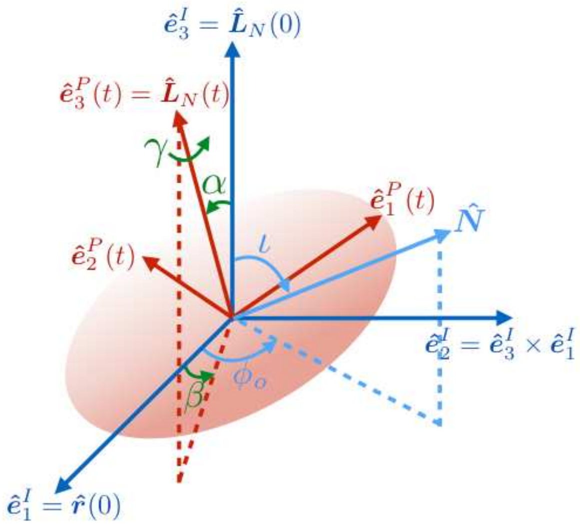


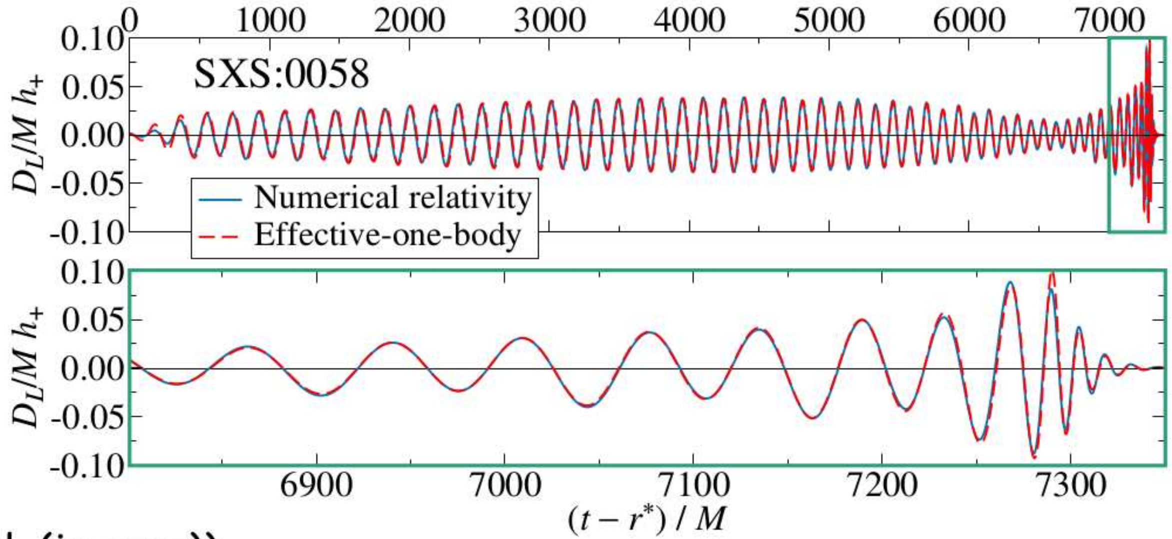
Kruckow et al. (2016)

- massive red-supergiant ($88\,\mathrm{M}_\odot$, $3530\,\mathrm{R}_\odot$)
- issue for BPS: location of core boundary $\rightarrow$ very different binding energy

- for massive companions form wide non-merging binaries ($> 50\,\mathrm{R}_\odot$)
- further spiral-in due to envelope expansion? (not modelled in α formalism)
- can form systems like GW150914 with fine-tuning, but rate estimates very uncertain

Spinning precessing waveform models





(Pan et al. 14, Babak et al. (in prep))

- **Single** effective-**spin precessing** waveform model in **frequency domain** (IMR phenomenological, 13-independent parameters) (Hannam et al. 14)

- **Double-spin precessing** waveform model in **time domain** (EOBNR, 15-independent parameters) (Pan et al. 14, Babak et al. (in prep)).
  [Analysis is ongoing.]

(Credit: A. Buonanno 2016)