The Formation of Massive Black-Hole and Neutron-Star Binaries:

Understanding the Advanced LIGO detections

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- **the direct discovery of gravitational waves has started the era of gravitational-wave astronomy**

Nobel Prize in Physics 2017 to Thorne, Weiss and Barish

- **major surprise:** the merger of two massive stellar black holes (BHs)

I. Gravitational Waves and the aLIGO Discoveries

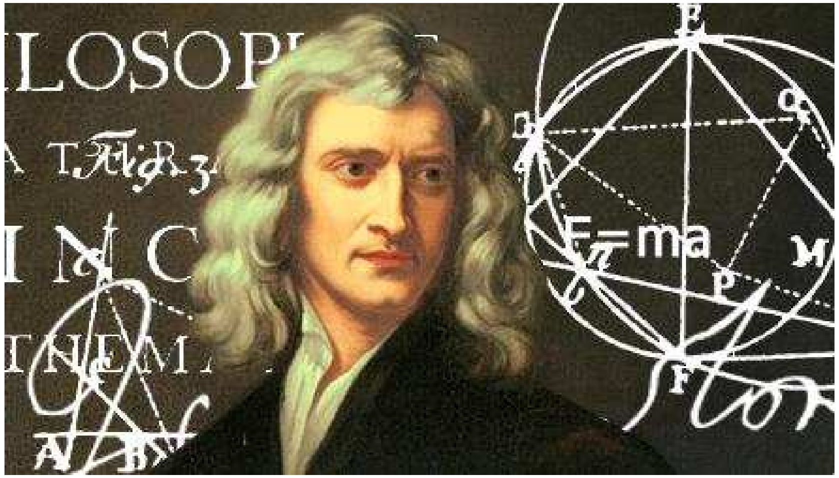
II. Channels for Forming BH+BH Binaries

III. Cosmological Simulations in the MOB Scenario

IV. GW170817: The Detection of a Neutron-Star Merger

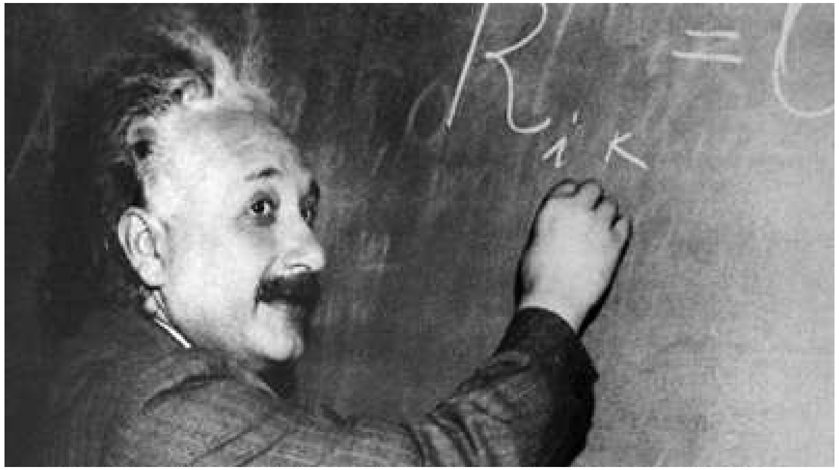
General Relativity and Gravitational Waves

Newton's Gravity



Time is absolute: space and time are given apriori

Einstein's General Relativity



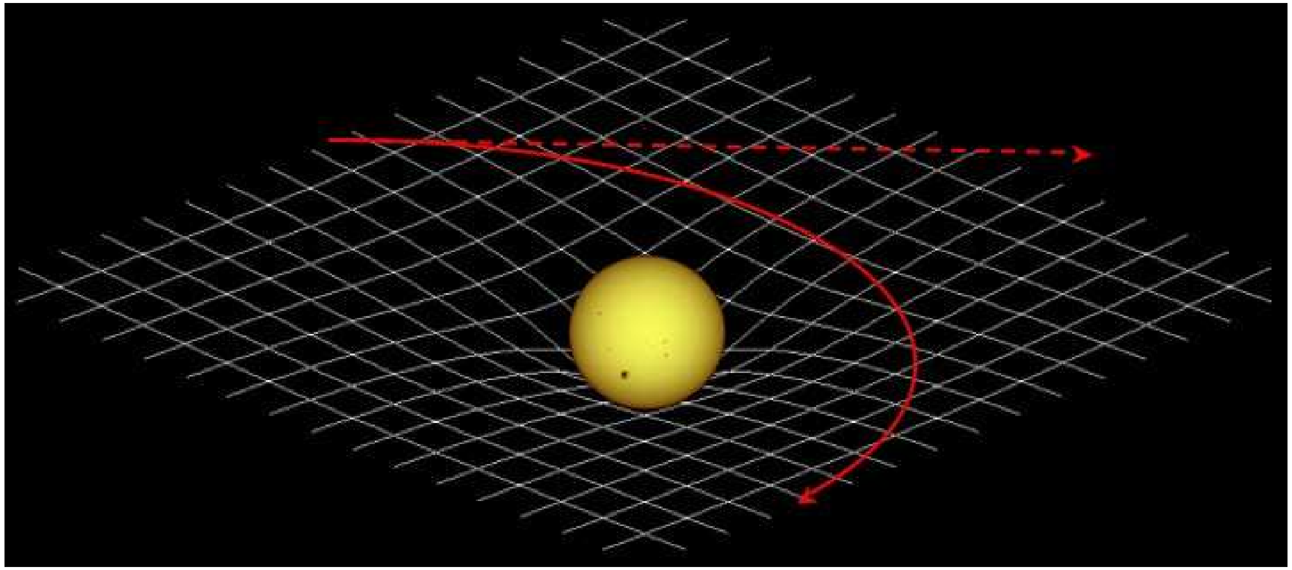
Spacetime is a **dynamic and elastic entity**, influencing and influenced by mass-energy

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

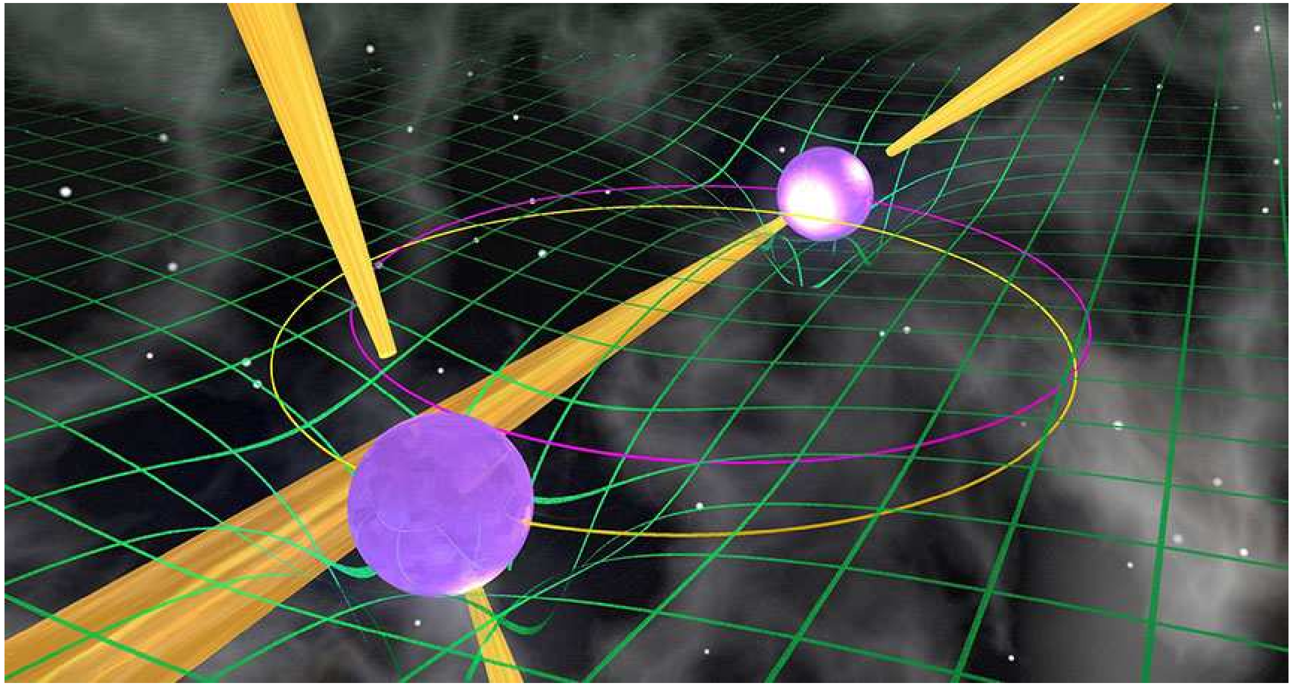
$$\mathbf{g}_{\mu\nu} = \eta_{\mu\nu} + \mathbf{h}_{\mu\nu}, \quad \rightarrow \Box \mathbf{h}_{\mu\nu} = -\frac{16\pi \mathbf{G}}{\mathbf{c}^4}\,\mathbf{T}_{\mu\nu}.$$

- masses **deform spacetime** geometry → generate **gravitational waves**, propagating with the **speed of light** (Einstein 1916)
- GWs are very **weak** and need massive, compact bodies

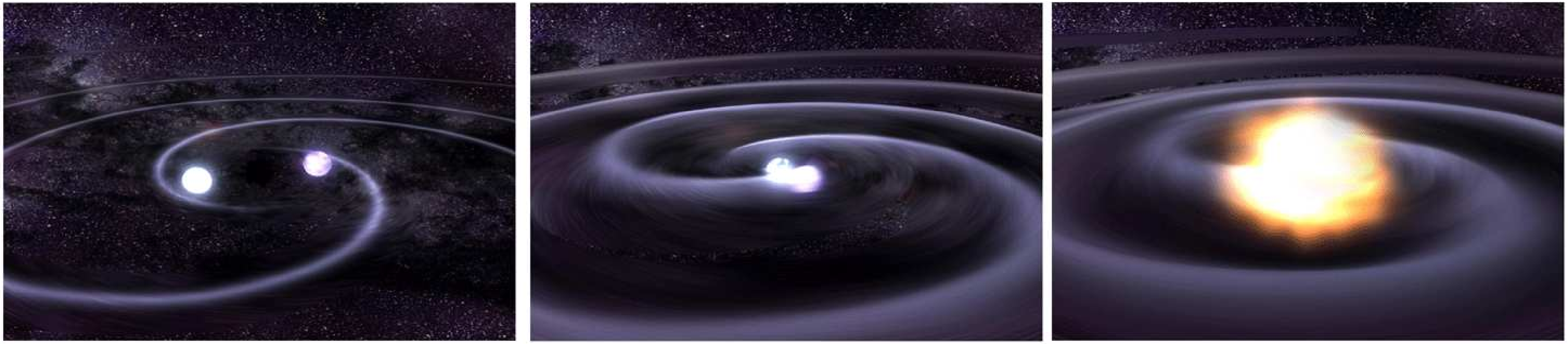
Space Curvature



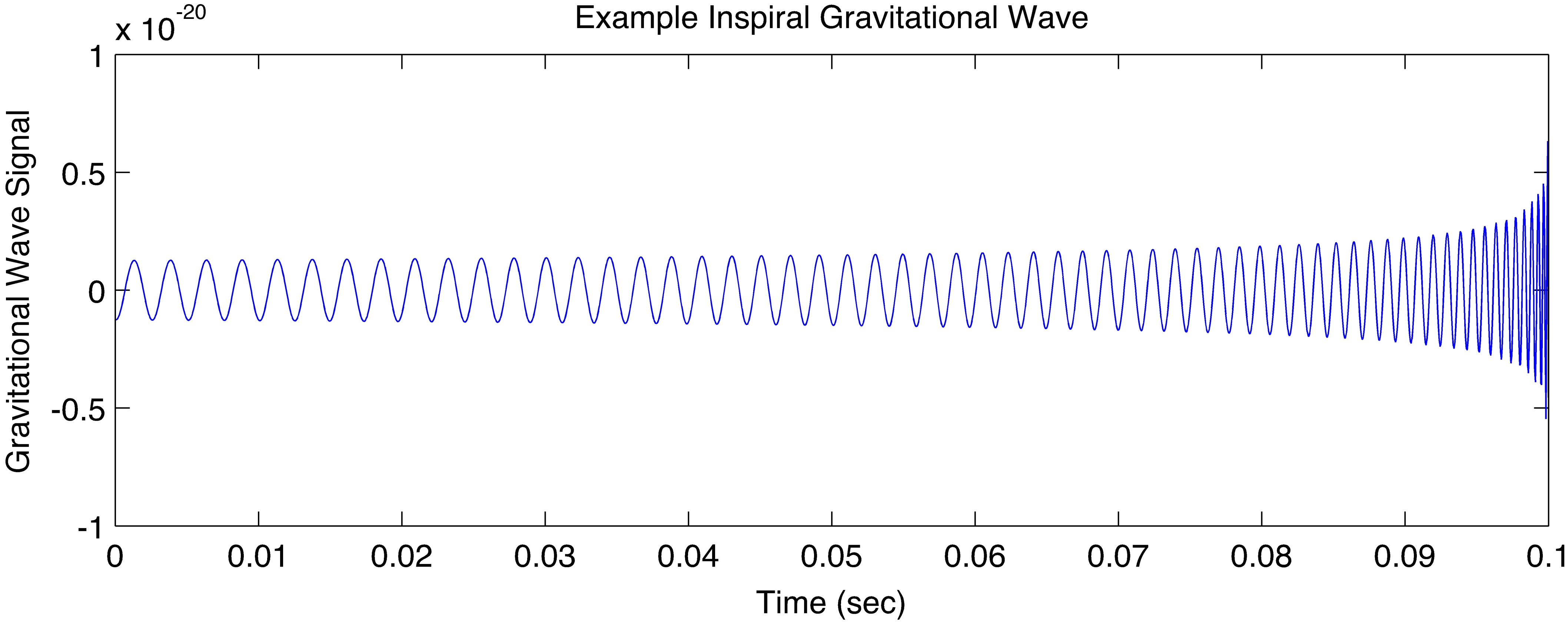
Double Neutron-Star Binaries as Gravitational-Wave Sources



Compact Binary Inspiral and Final Merger



(Strohmayer)

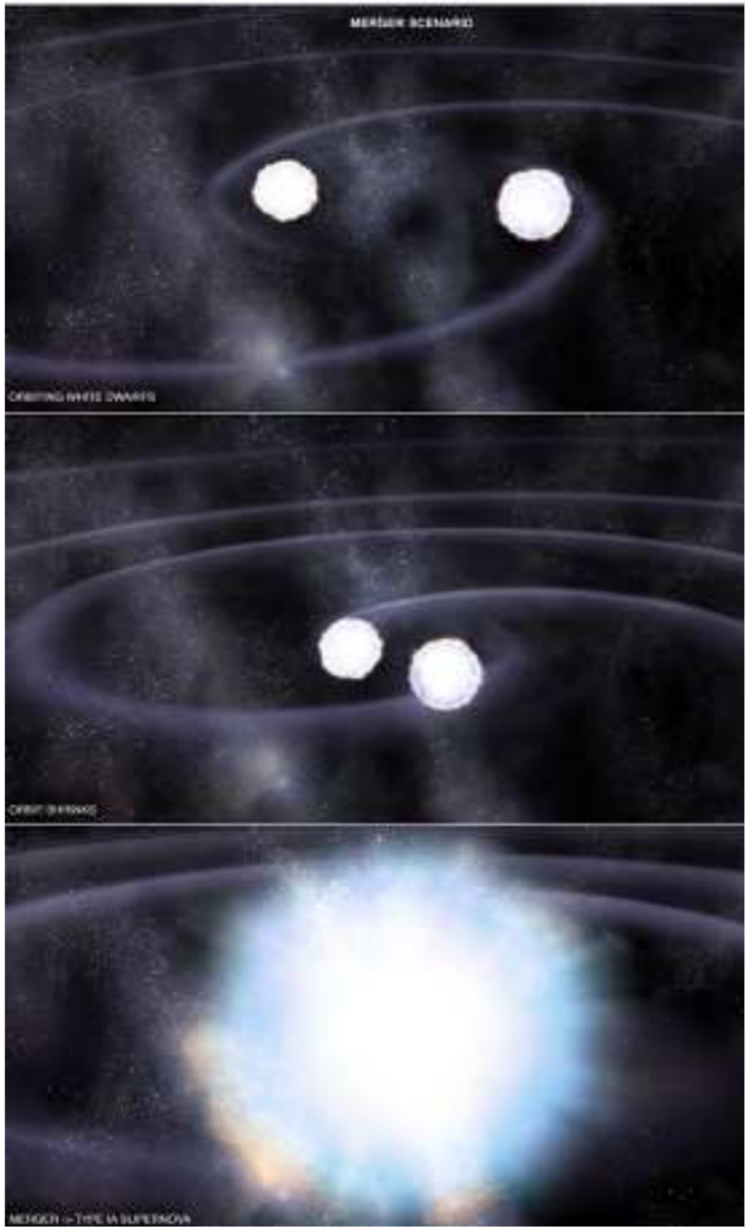


Compact Binary Mergers (NS/BH+NS/BH)

- 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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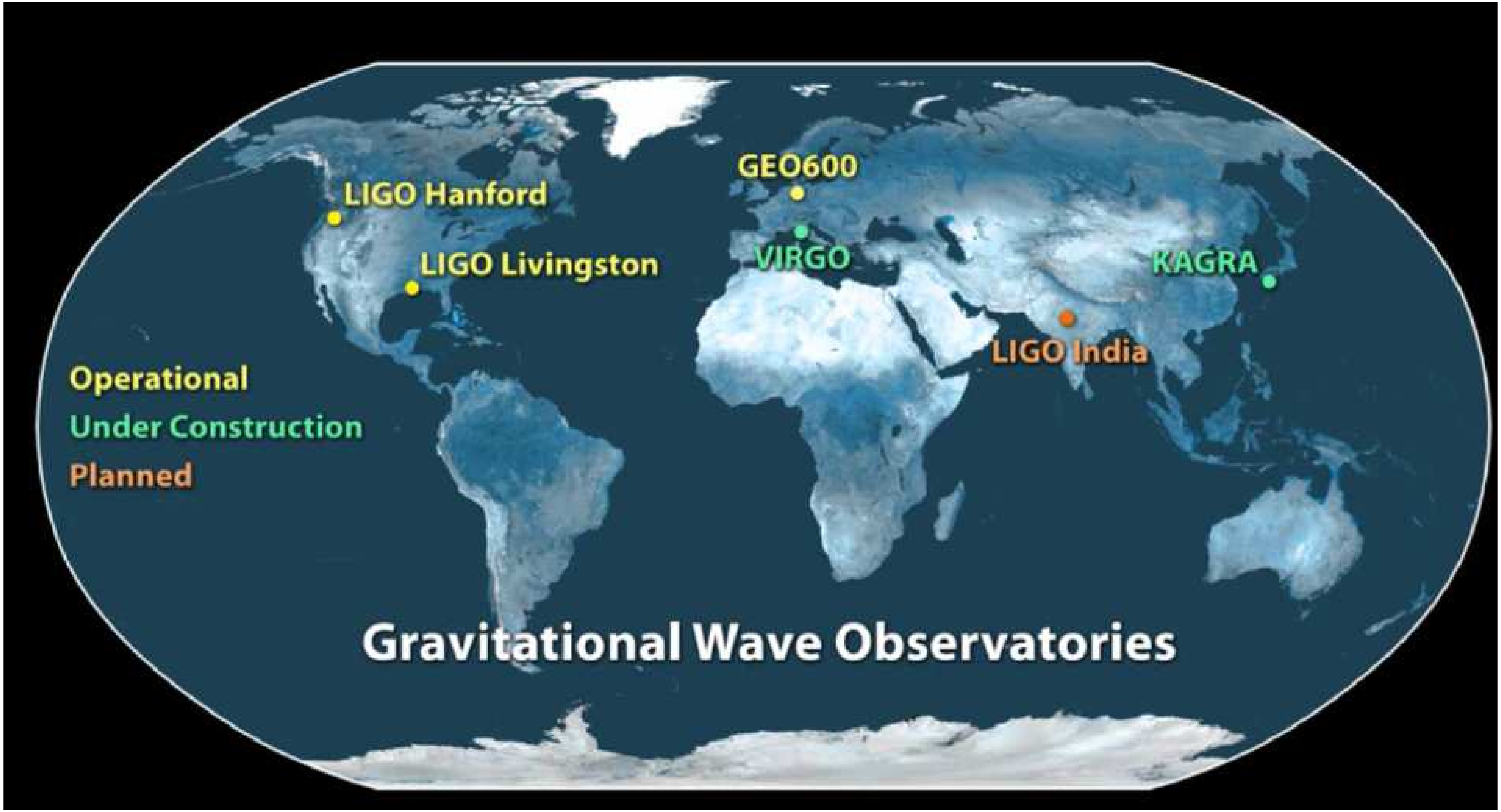
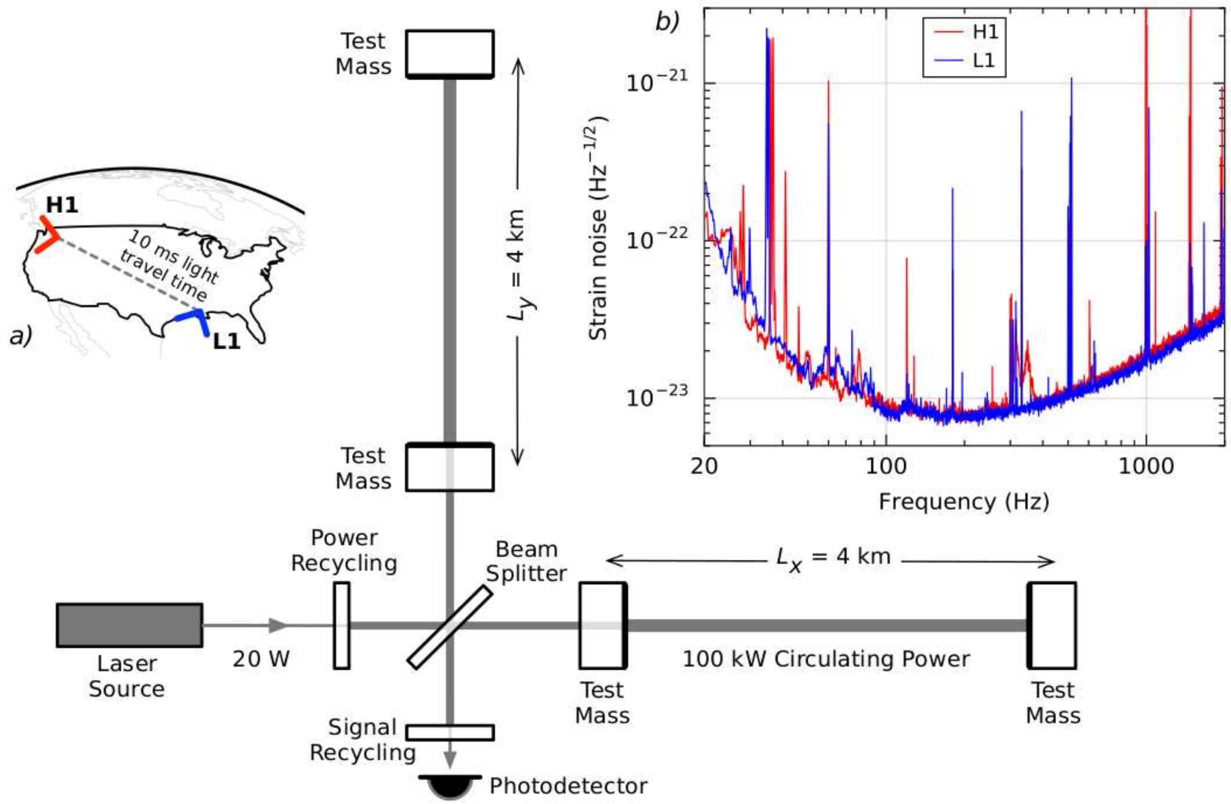


LIGO-India approved

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**!

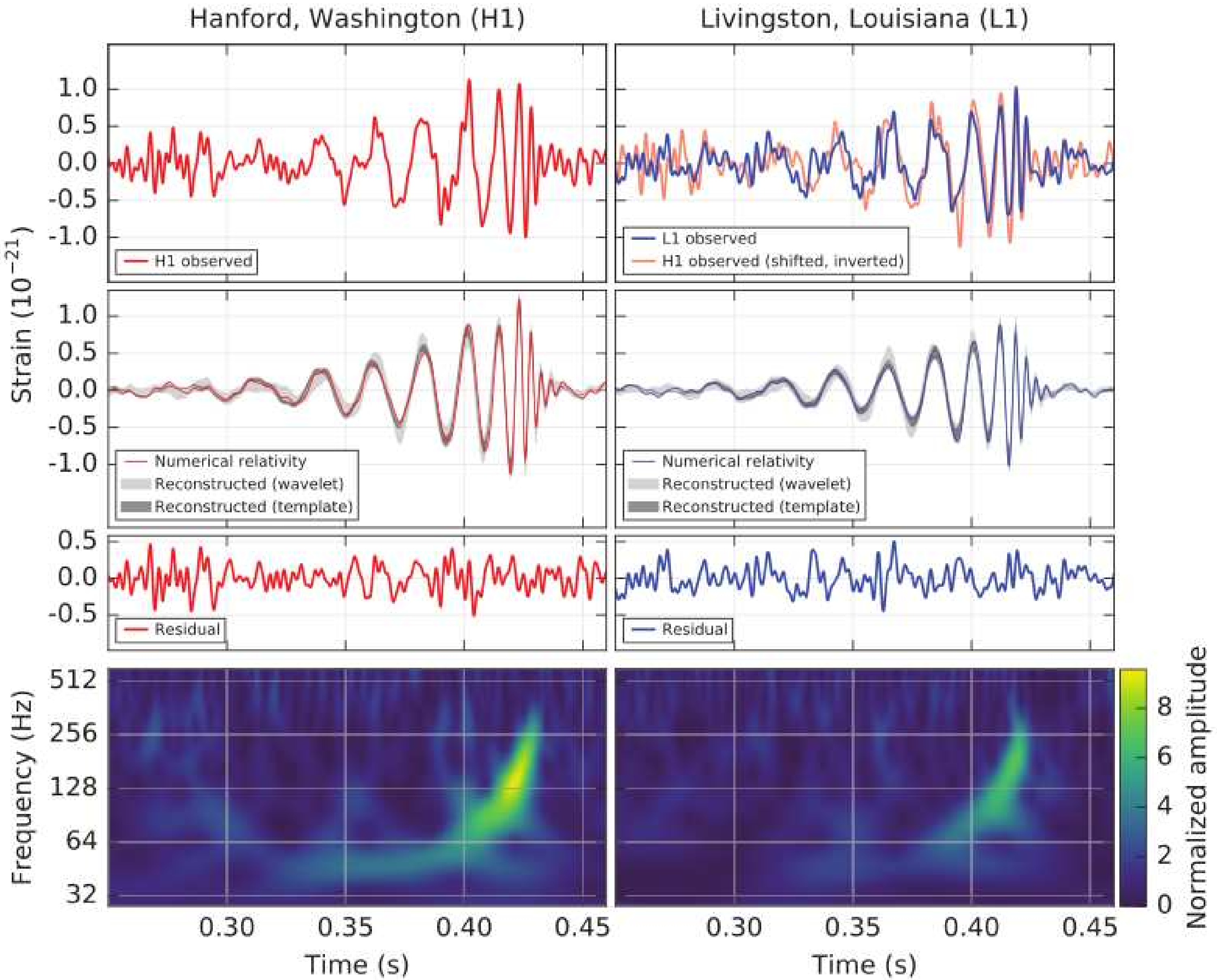
$$\Delta L = L\, h \sim 10^{-16}\,\mathrm{cm}$$

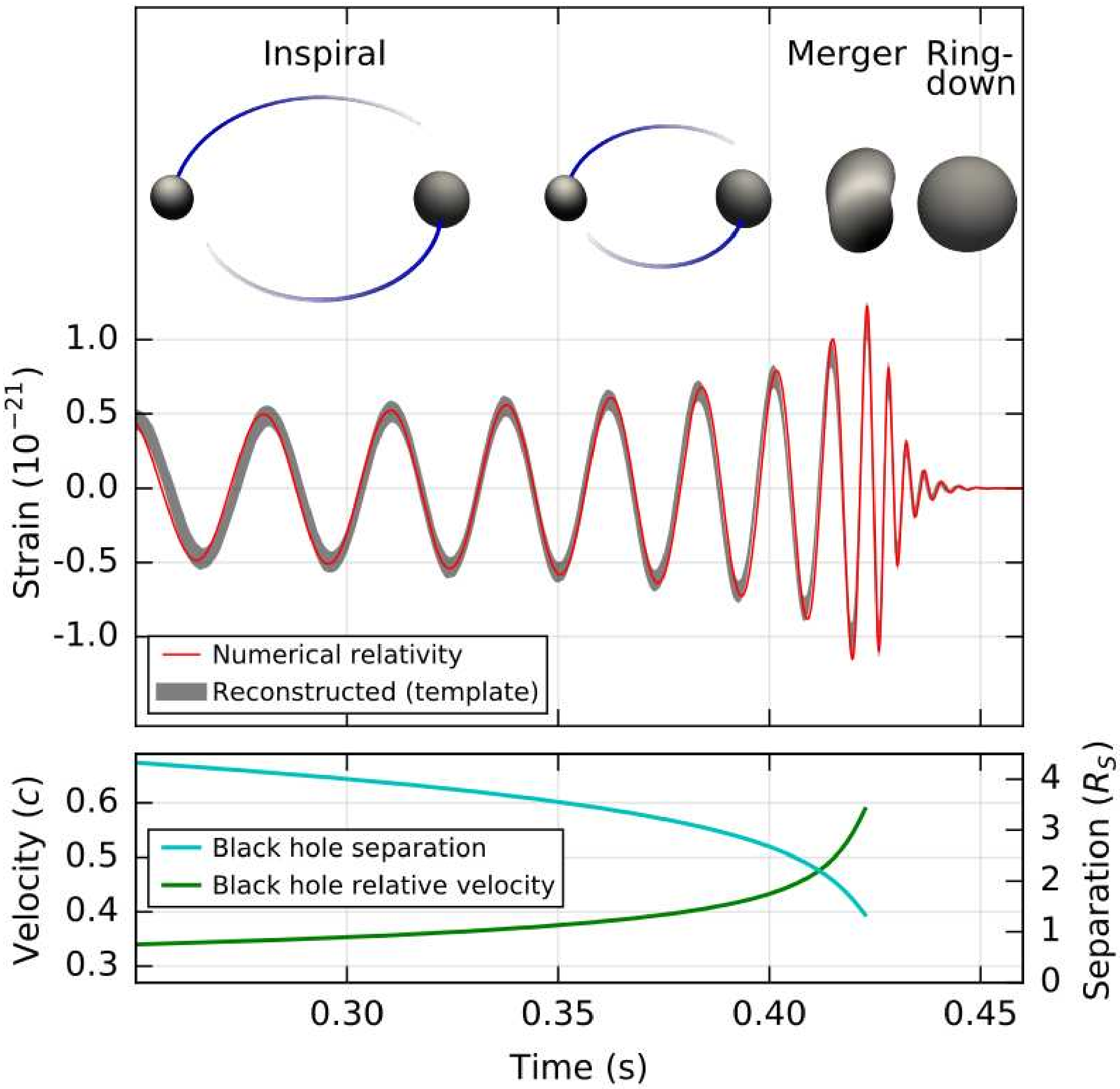
$$L = 4\,\mathrm{km} \Rightarrow h \sim 10^{-21}$$

(Credit: A. Buonanno 2016)

aLIGO Detection of Gravitational Waves

- surprise: merger of two massive ($\sim 30\,M_\odot$) black holes (chirp-mass: $28\,M_\odot$)
- [$M_1/M_2 \simeq 0.8 \pm 0.2$, $D \sim 400\,\mathrm{Mpc}$, $\mathrm{SNR} \gtrsim 20$, $\sim$ 5-sigma detection]





(Abbott et al. (LVC) 16)

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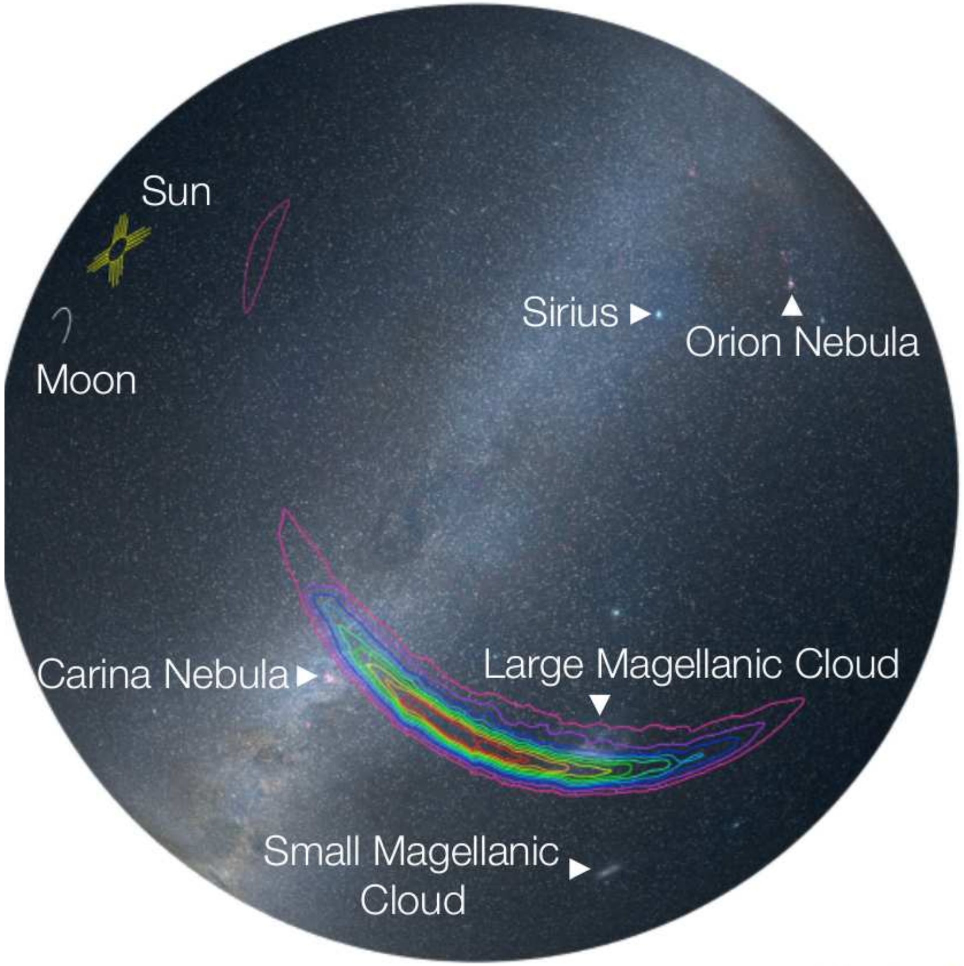
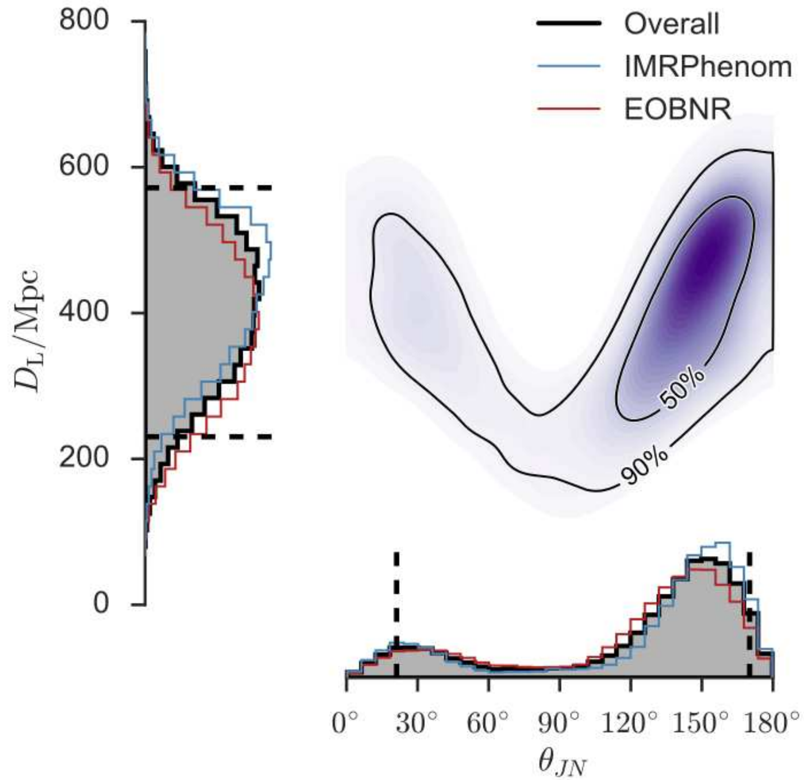
Unveiling GW150914's properties: sky location & distance



(Abbott et al. (LVC) 16)

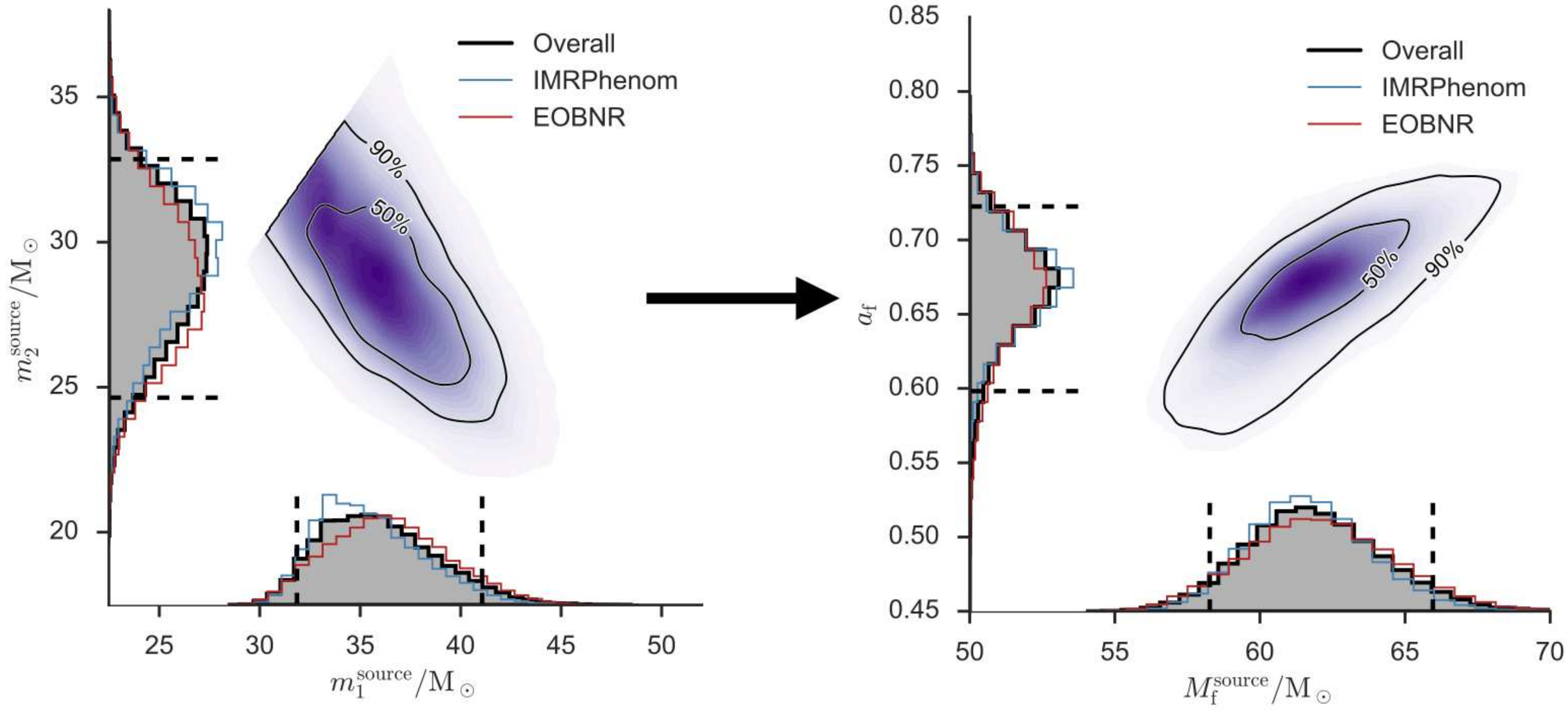


- **Face-off slightly favored** with respect to face-on.

(Credit: A. Buonanno 2016)

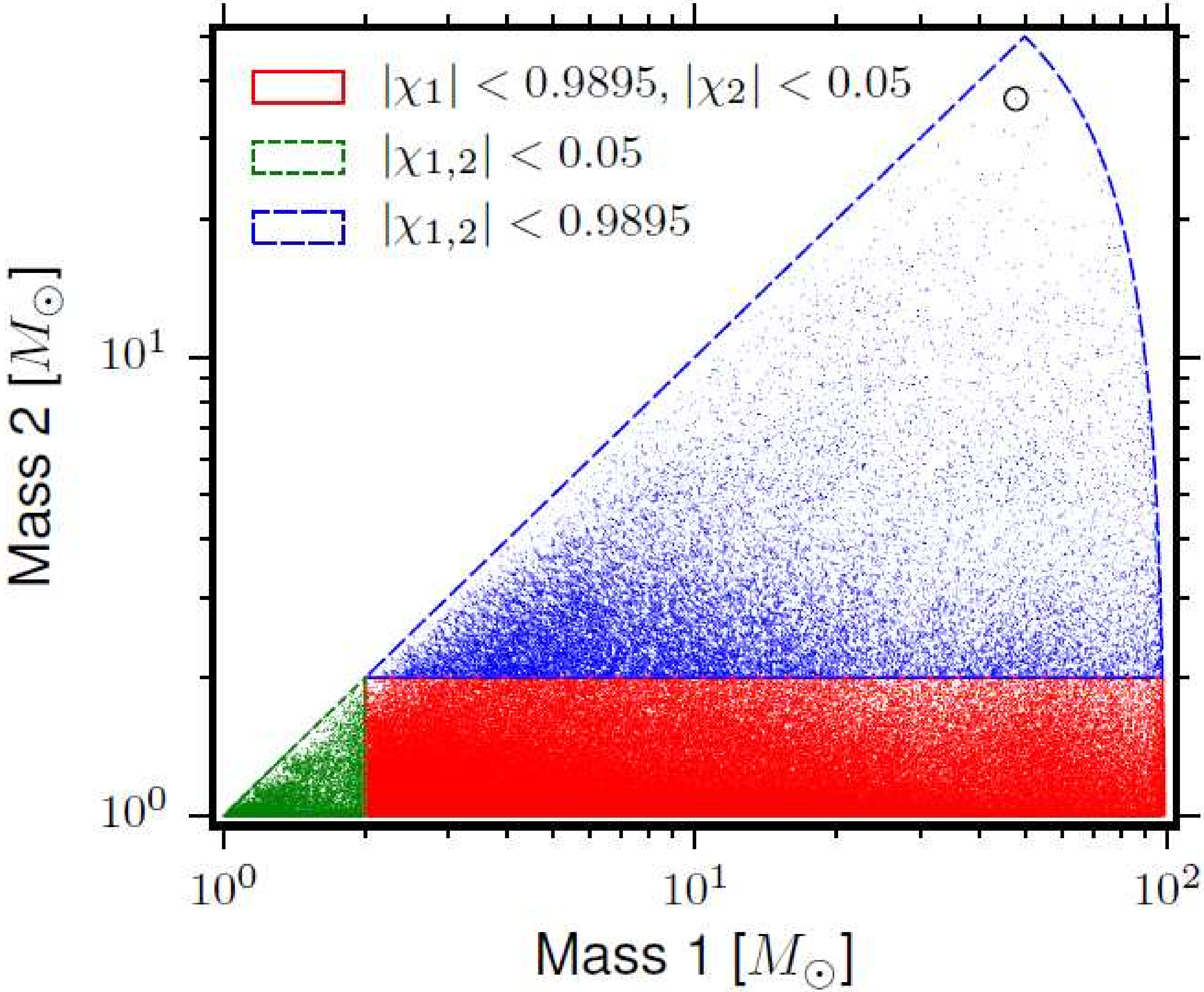
Unveiling GW150914's properties: masses & spins

(Abbott et al. (LVC) 16)



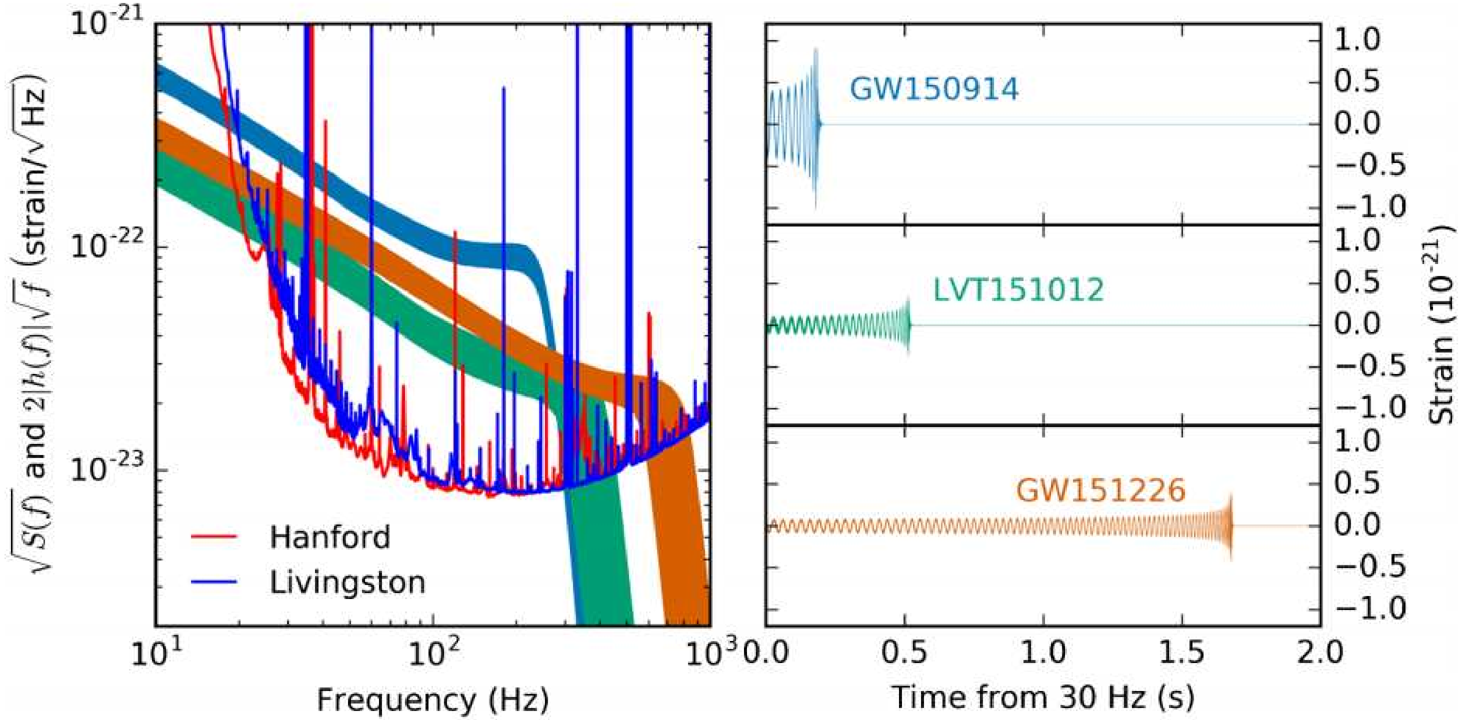
- **Final** black-hole **mass and spin** inferred from components posteriors and **NR formulae.**
- **3 solar masses** emitted **in GWs!**

(Credit: A. Buonanno 2016)



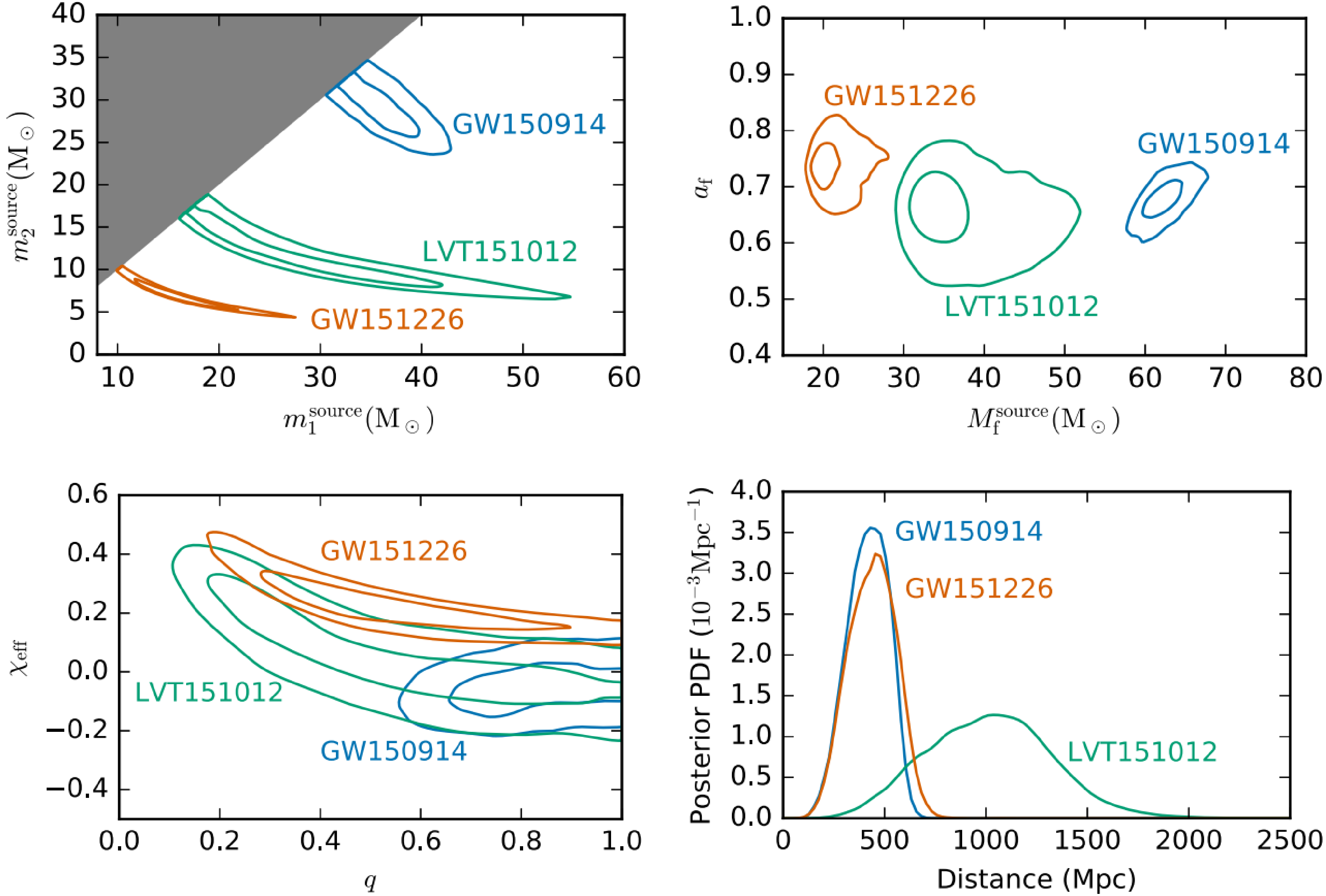
$|\chi_1| < 0.9895, |\chi_2| < 0.05$
$|\chi_{1,2}| < 0.05$
$|\chi_{1,2}| < 0.9895$
Mass 2 $[M_\odot]$
Mass 1 $[M_\odot]$
10^0
10^1
10^2

Results: First Science Run

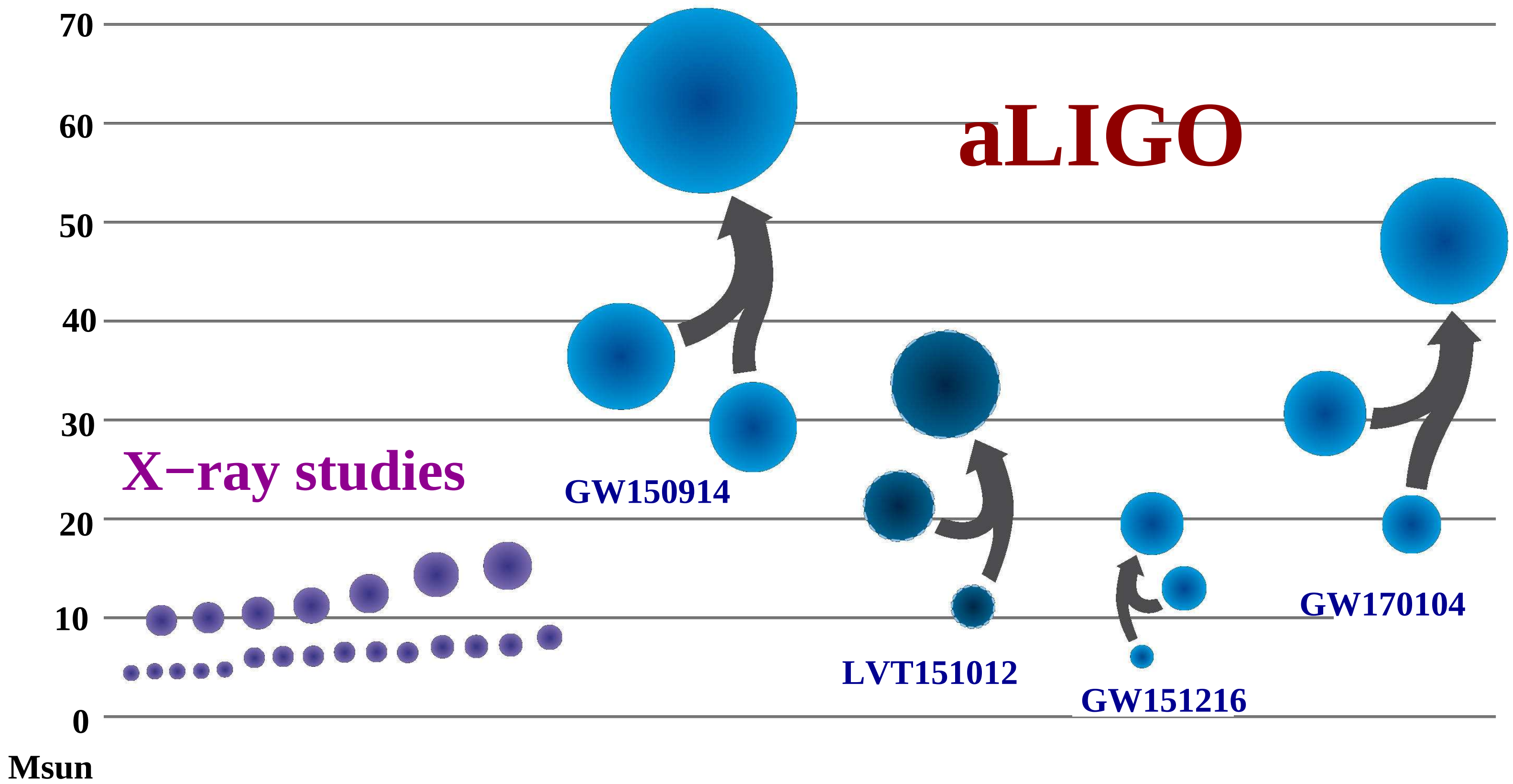


Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\text{source}}/\text{M}_\odot$	$36.2^{+5.2}_{-3.8}$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

BH+BH Parameters



Black-Hole Masses

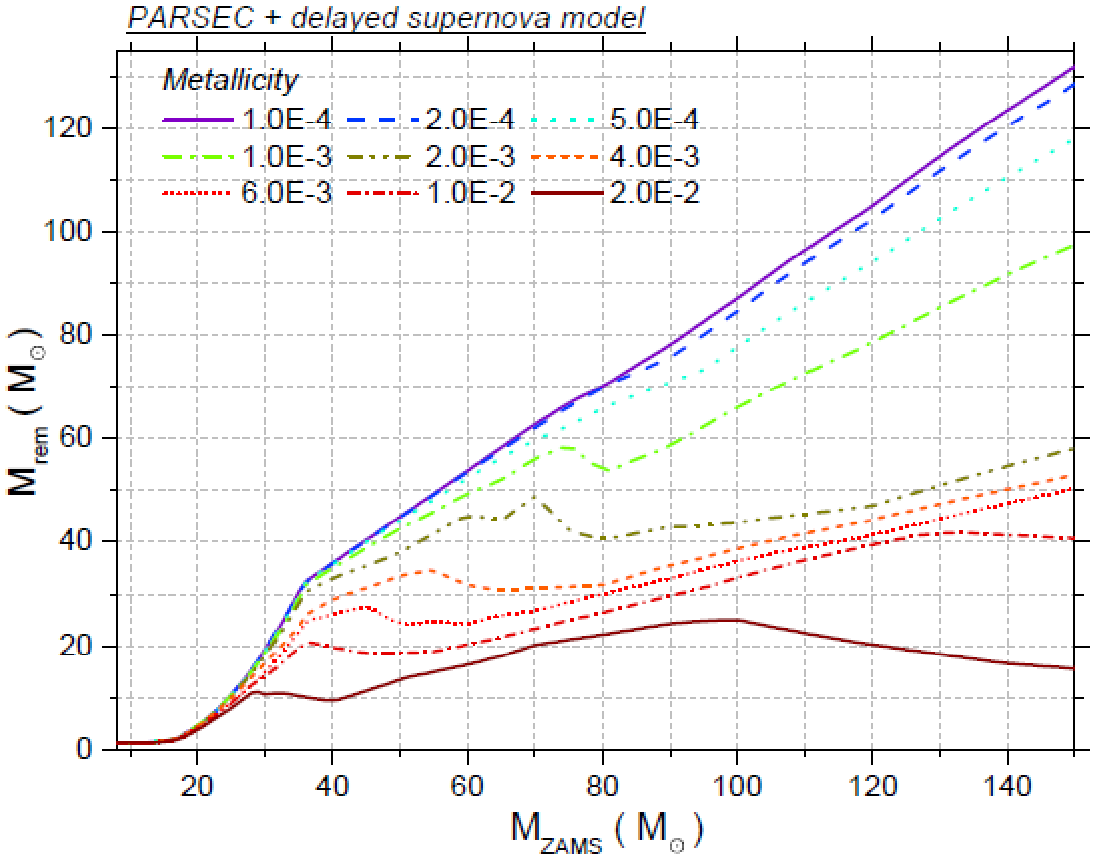


The BH Mass Spectrum as a Function of Mass

- BH masses depend on final stellar masses at core collapse (in particular for direct collapse)

→ depends on stellar-wind mass-loss history

→ lower metallicity → higher BH masses



Spera+ (2015)

The Formation of BH Binaries

- diversity of BH-BH properties

→ variety of formation channels

I. Dynamical formation in dense clusters

- in dense clusters: dynamical interactions → 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

Others: primordial BHs, population III stars, core fissioning, AGN disk models, gravastars, etc.

Primordial Black Holes

(e.g. Cholis, Kovetz, Raccanelli, . . . , 2016)

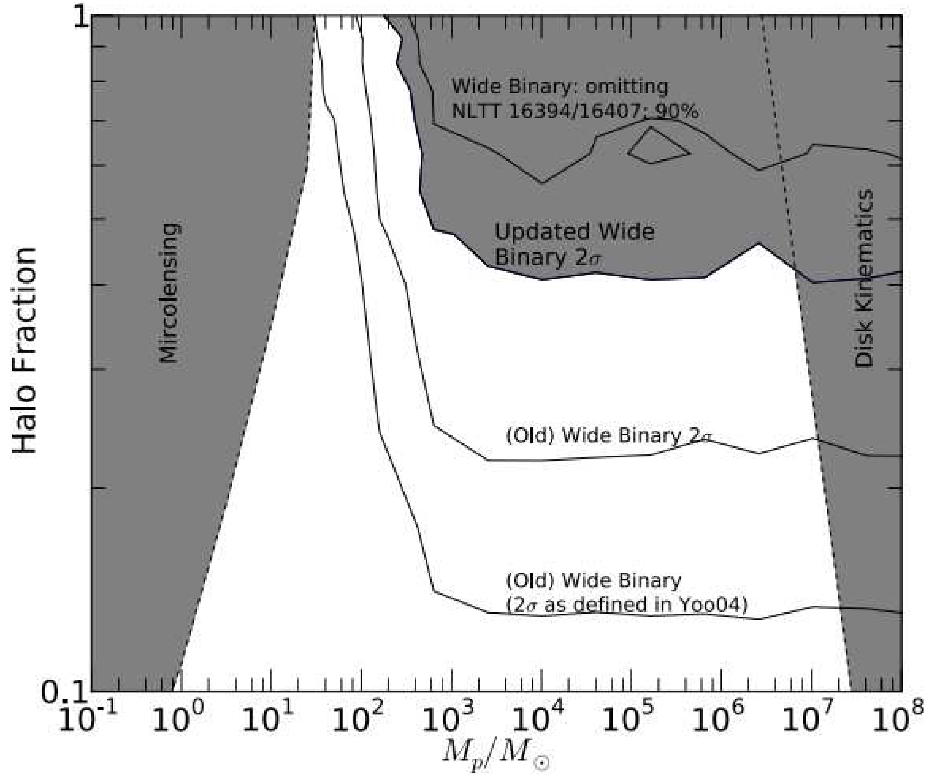
- primordial black holes can form from Big Bang density fluctations

→ captured into binaries → BH-BH mergers

key interest: Can they make up for the Dark Matter in Galactic halos?

Macho constraints: window
$M_{BH} = 30 - 500\,M_\odot$ (Quinn+ 2009)

- including other constraints: only 10 % (Carr+ 2017)

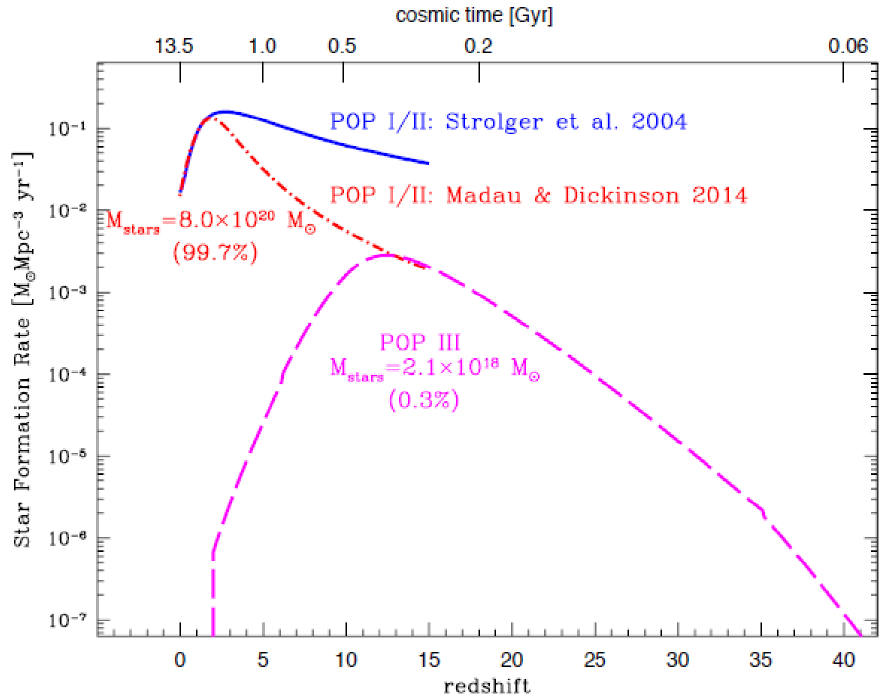


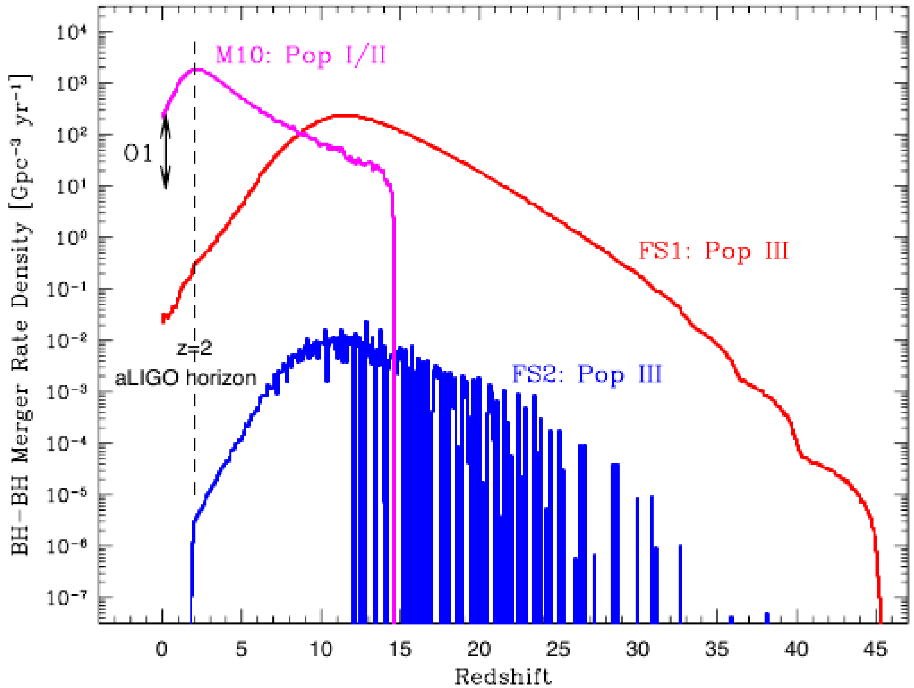
Quinn+ (2009)

BH-BH Mergers from Population III Stars

(e.g. Kinugawa+ 2016)

- Pop III stars naturally produce massive BHs
- top-heavy IMF (?)
- differences in stellar/binary evolution
- contribution probably less than 1 % at low z (Belczynski+ 2017)
  - ▷ low mass in Pop III population
  - ▷ mergers predicted to occur at high redshift





Belczynski+ (2017)

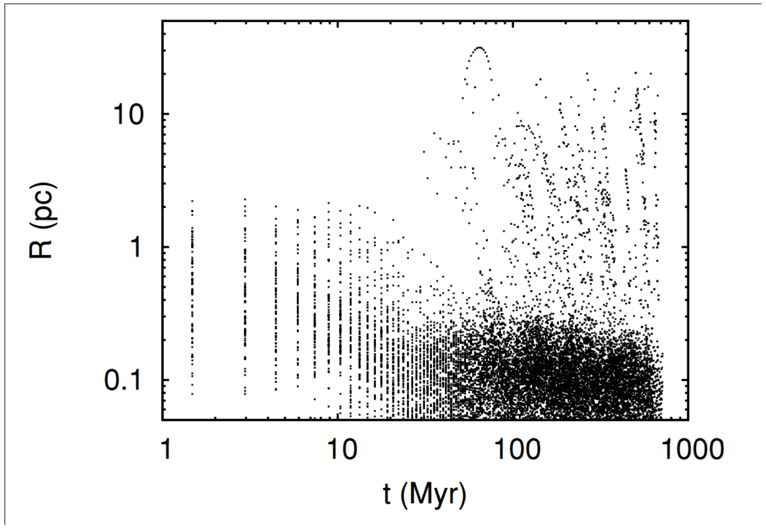
Dynamical Formation in Stellar Clusters

(e.g. Banerjee/Kroupa; Rasio/Rodriguez; Ziosi; Askar+)

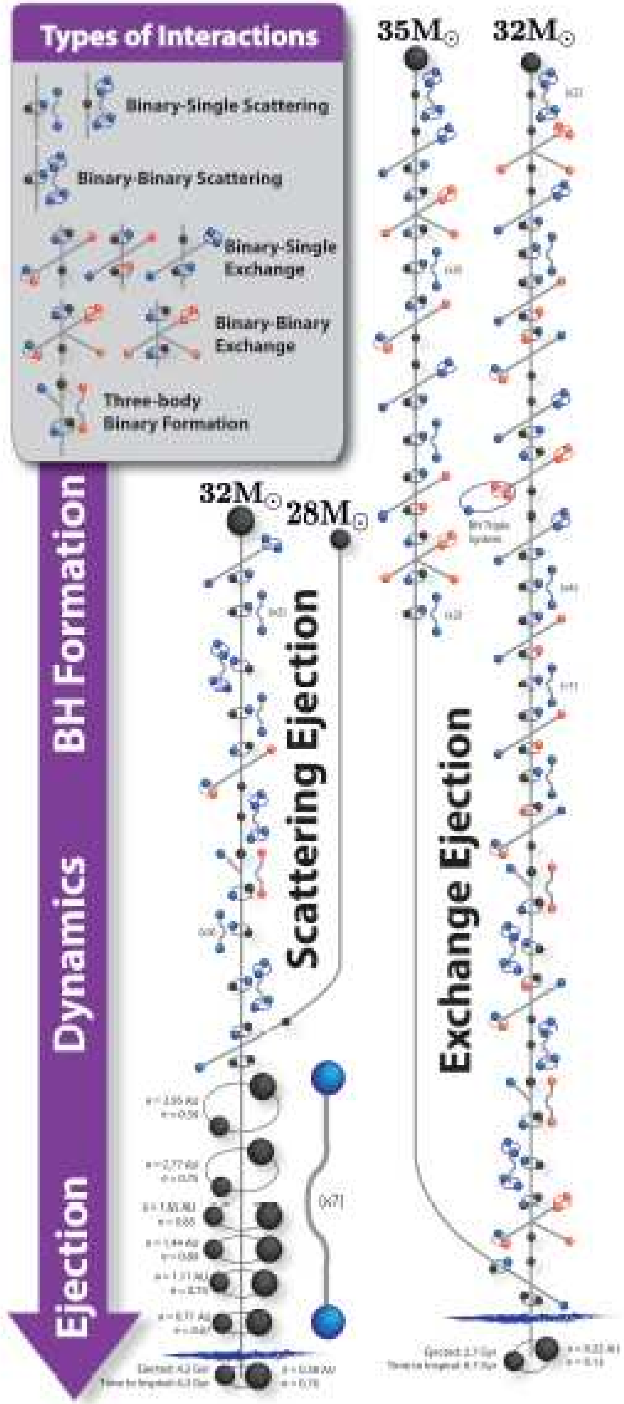
- BH-BH binaries form by dynamical interactions from isolated BHs

→ large formation efficiency (cf. ms pulsars, LMXBs in GCs: x 100; but 10 % total contribution)

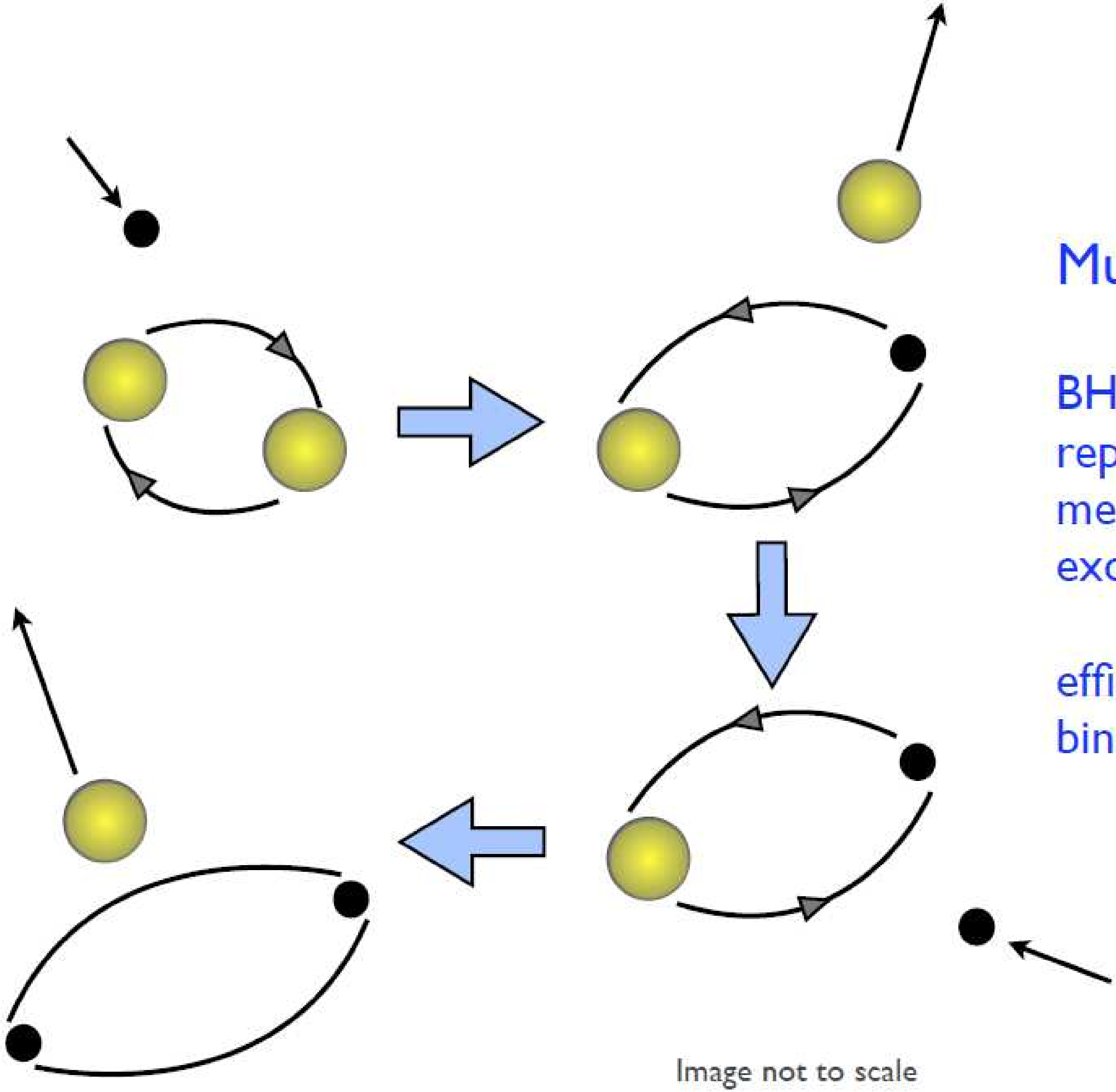
- three-body encounters → BH+BH binaries
- most BHs are ejected
- in dense clusters, possibility that BHs form sub-clusters of BHs (Spitzer instability)



Black-hole segregation (Banerjee et al. 2010)



Rodriguez+ (2016)



Multiple exchange:

BHs being more massive replace stellar binary members in successive exchange encounters;

efficient with primordial binaries

(Credit: Banerjee 2016)

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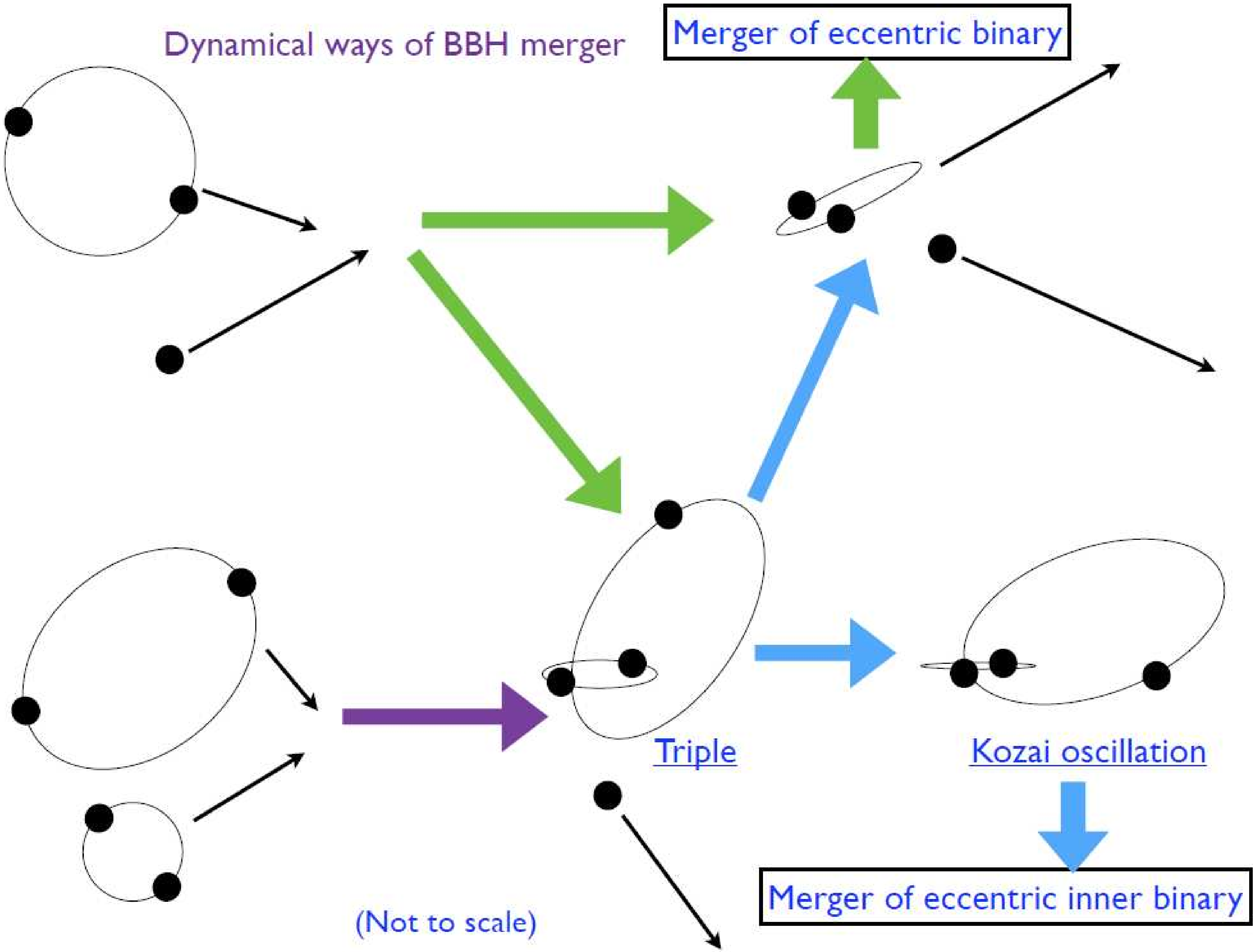
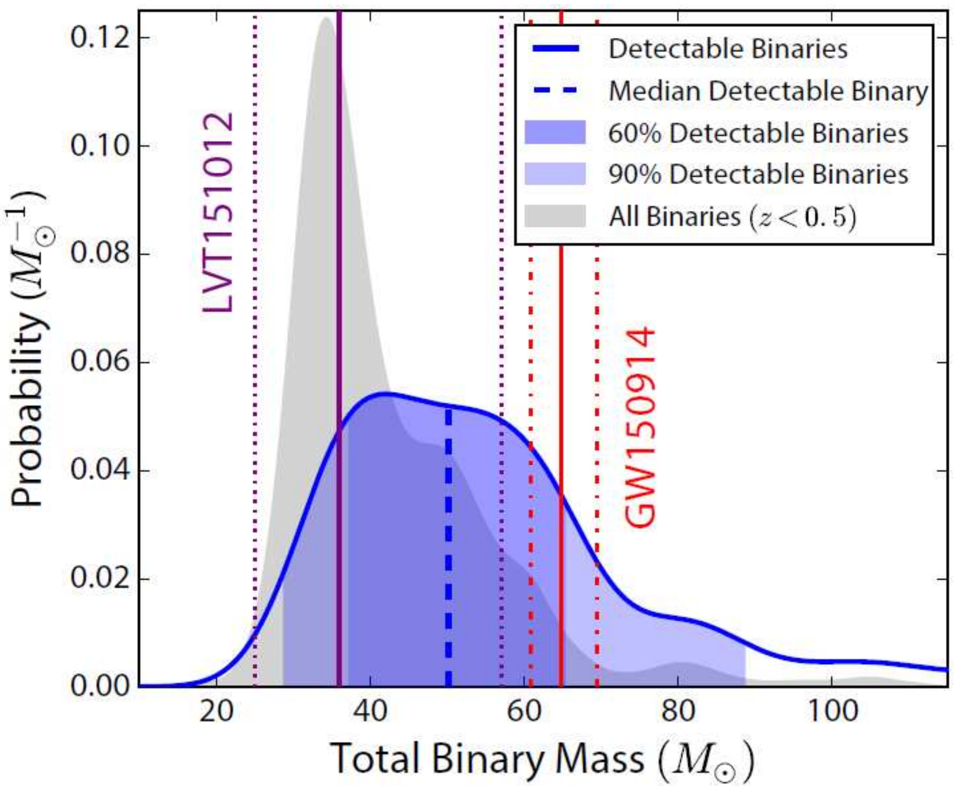
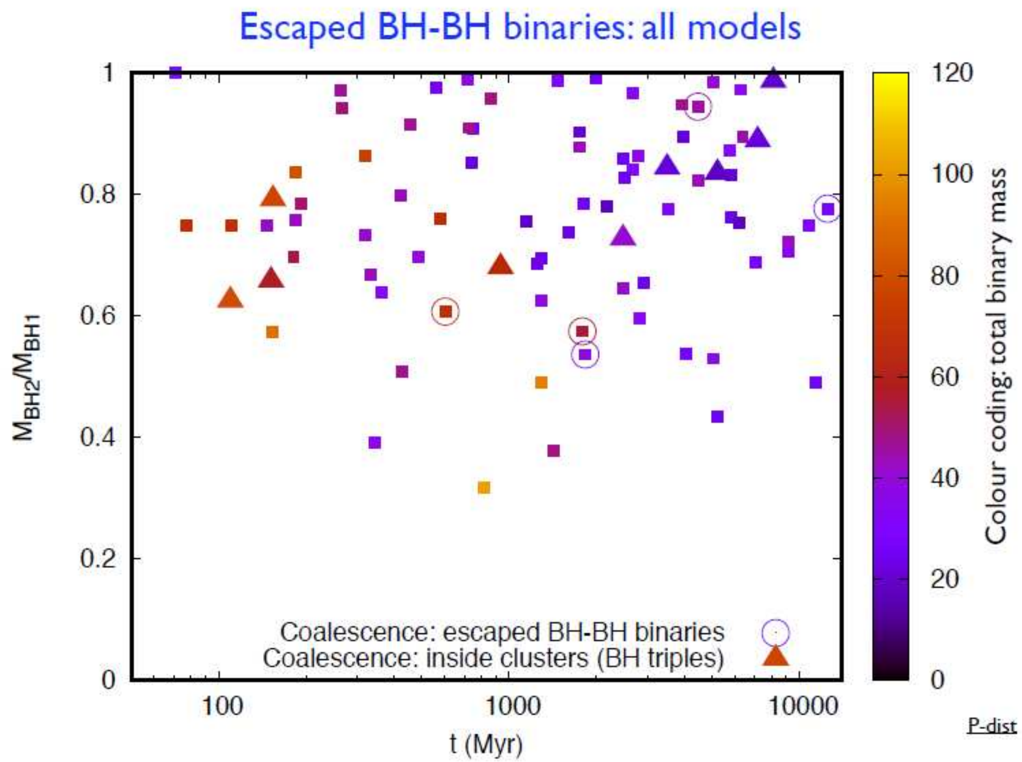


(Credit: Banerjee 2016)



Rodriguez+ (2016)

- tends to produce relatively massive BH binaries (GW150914?)
- lower-mass BH binaries in young, high-Z clusters (Chatterjee+ 2017)? Rate?

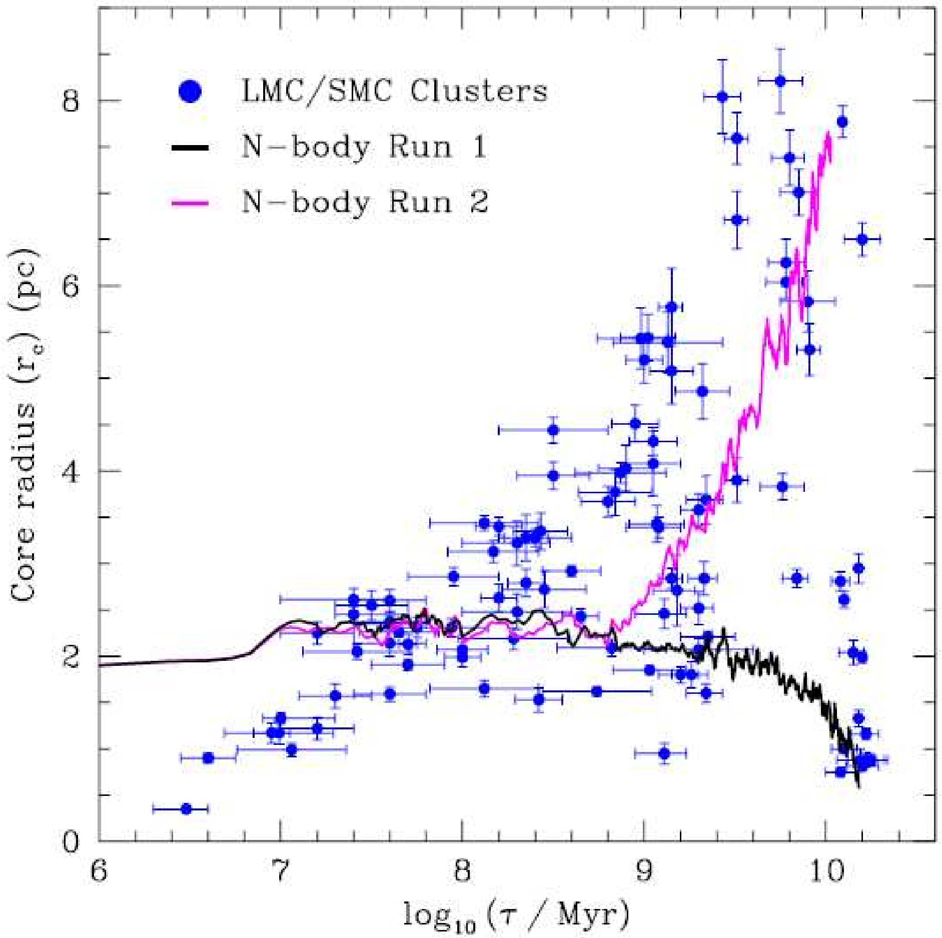


Banerjee+ (2016)

- masses correlated (but mass ratio not very close to 1)
- spins should be completely uncorrelated with the orbit
- aLIGO detection rates (e.g. Banerjee 2016): $10 - 300\,\mathrm{yr}^{-1}$

Principal Uncertainty: the first 3 Myr
(e.g. Davies+ 2017)

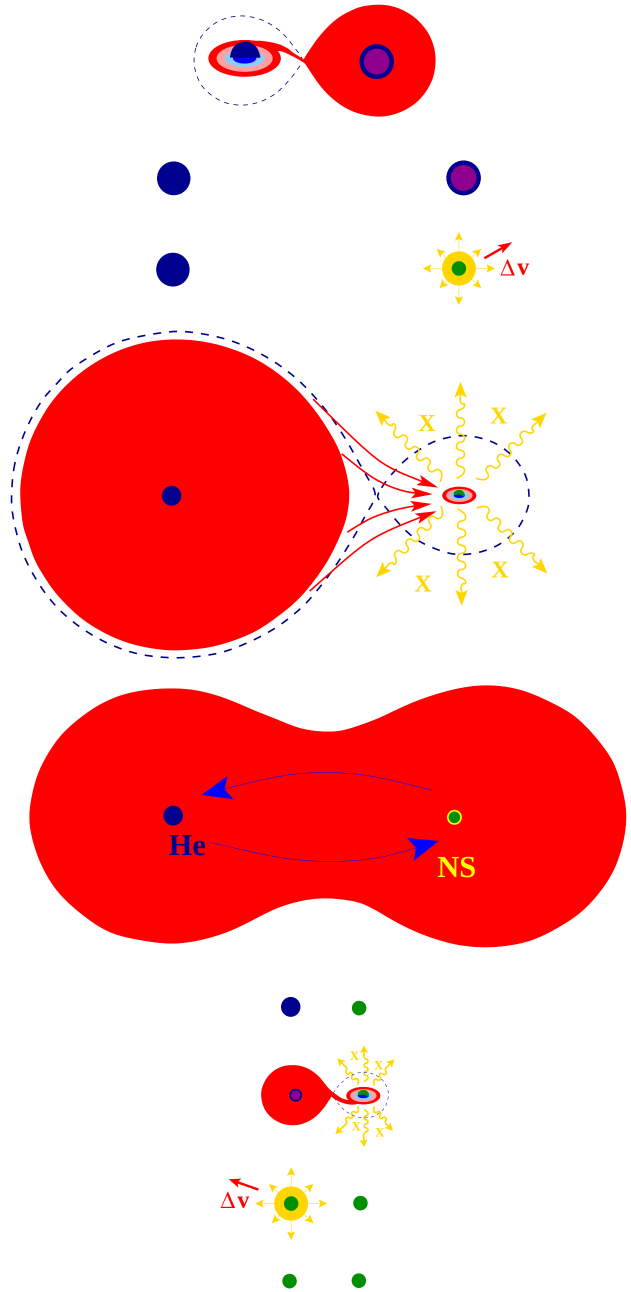
- initial condition for cluster simulations assume BH population
- strongly depends on the stellar evolution during BH formation phase
- supernova kicks? dynamical ejections?
- BH population affects cluster dynamics by dynamical heating
- clusters with large numbers of BHs are heated efficiently and have large core radii (Mackey+ 2007/2008)
- formation in nuclear clusters near galactic centres with higher densities?

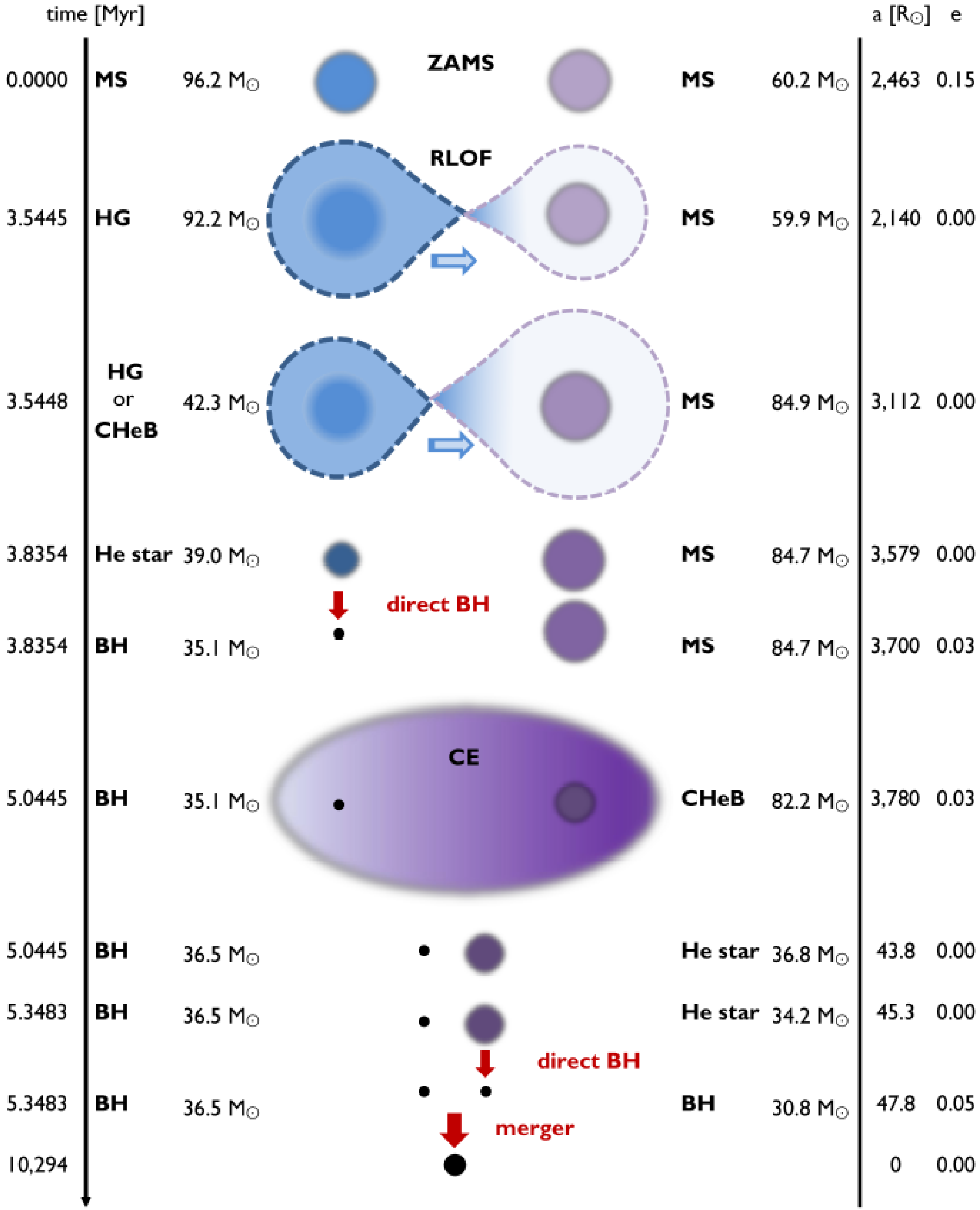


Mackey+ (2007/08)

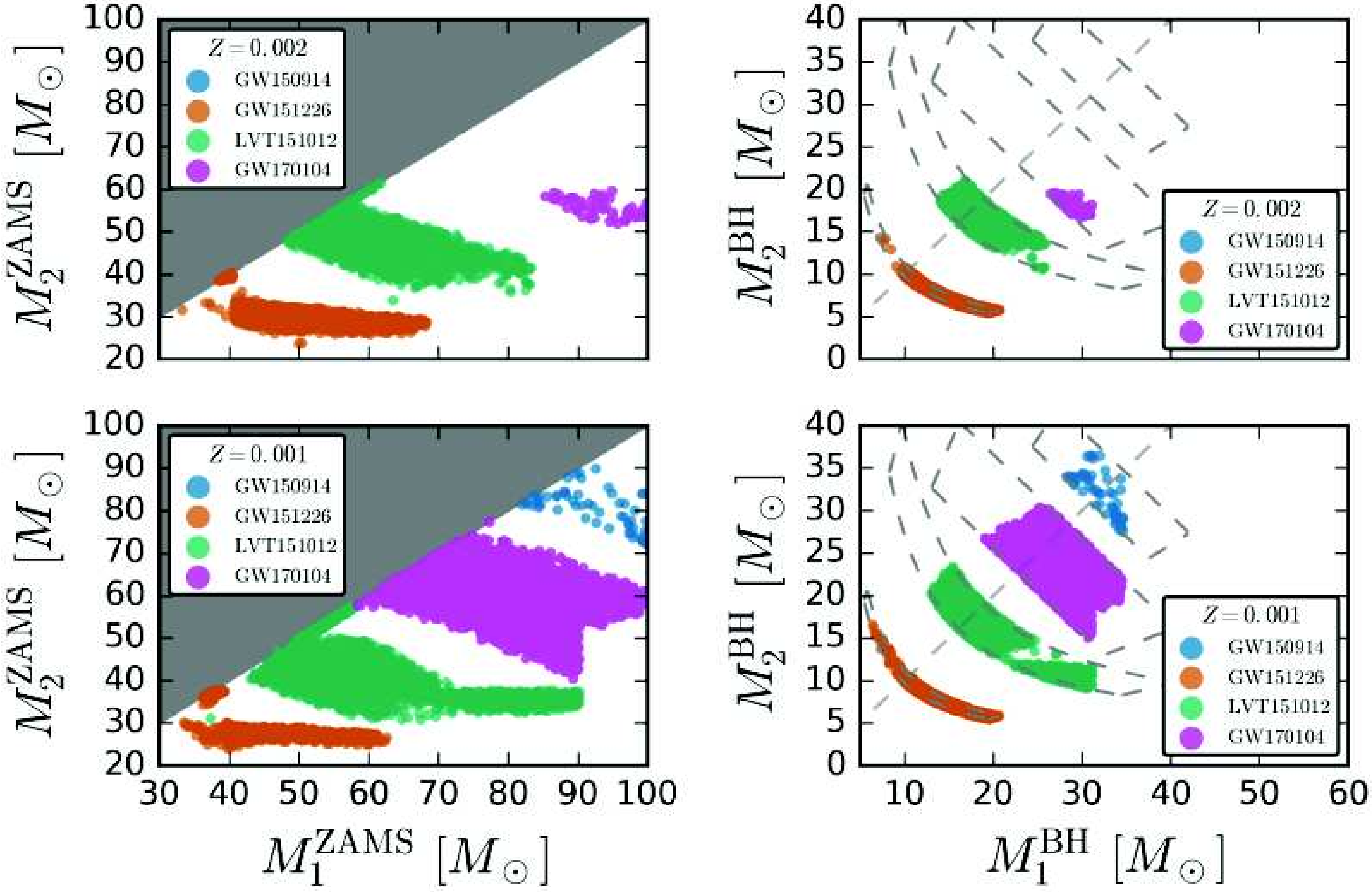
The Formation of BH+BH Binaries through Common-Envelope Evolution

- 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)



Stevenson+ (2017)

Principal Uncertainties

- treatment of CE phase
- it may be difficult to form the most massive BH binaries (very massive stars do not become red supergiants)

Predictions

- diversity of masses and mass ratios
- spins probably somewhat aligned with the orbit (uncertainties in understanding BH kicks!)

The Massive Overcontact Binary (MOB) Model

(Marchant, Langer, Podsiadlowski, Tauris, Moriya 2016;
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

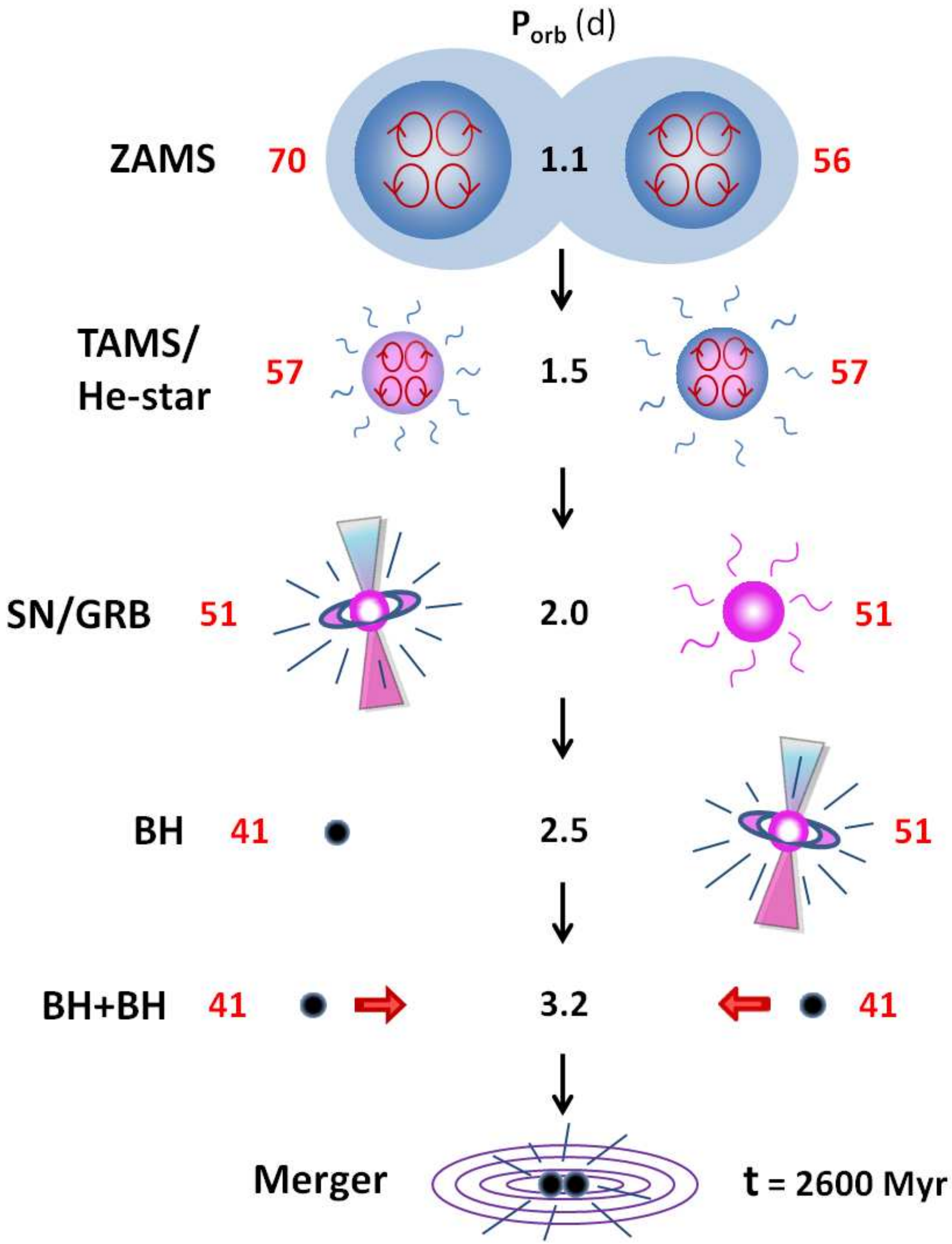
→ requires low metallicity

- most systems pass through contact phase on main sequence

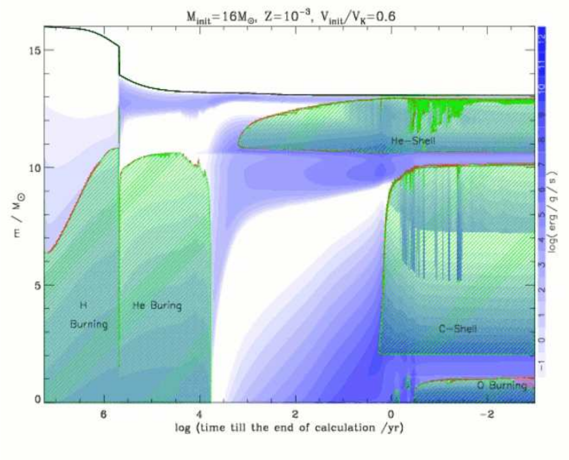
→ evolution drives systems towards mass ratio of 1

Model Description

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

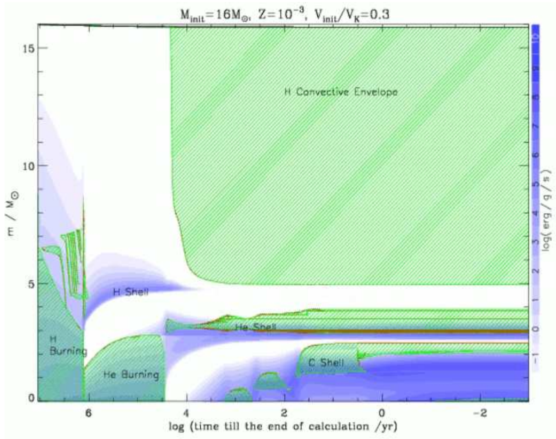


Marchant et al. (2016); after de Mink+ (2009); Mandel/de Mink (2016a,b)

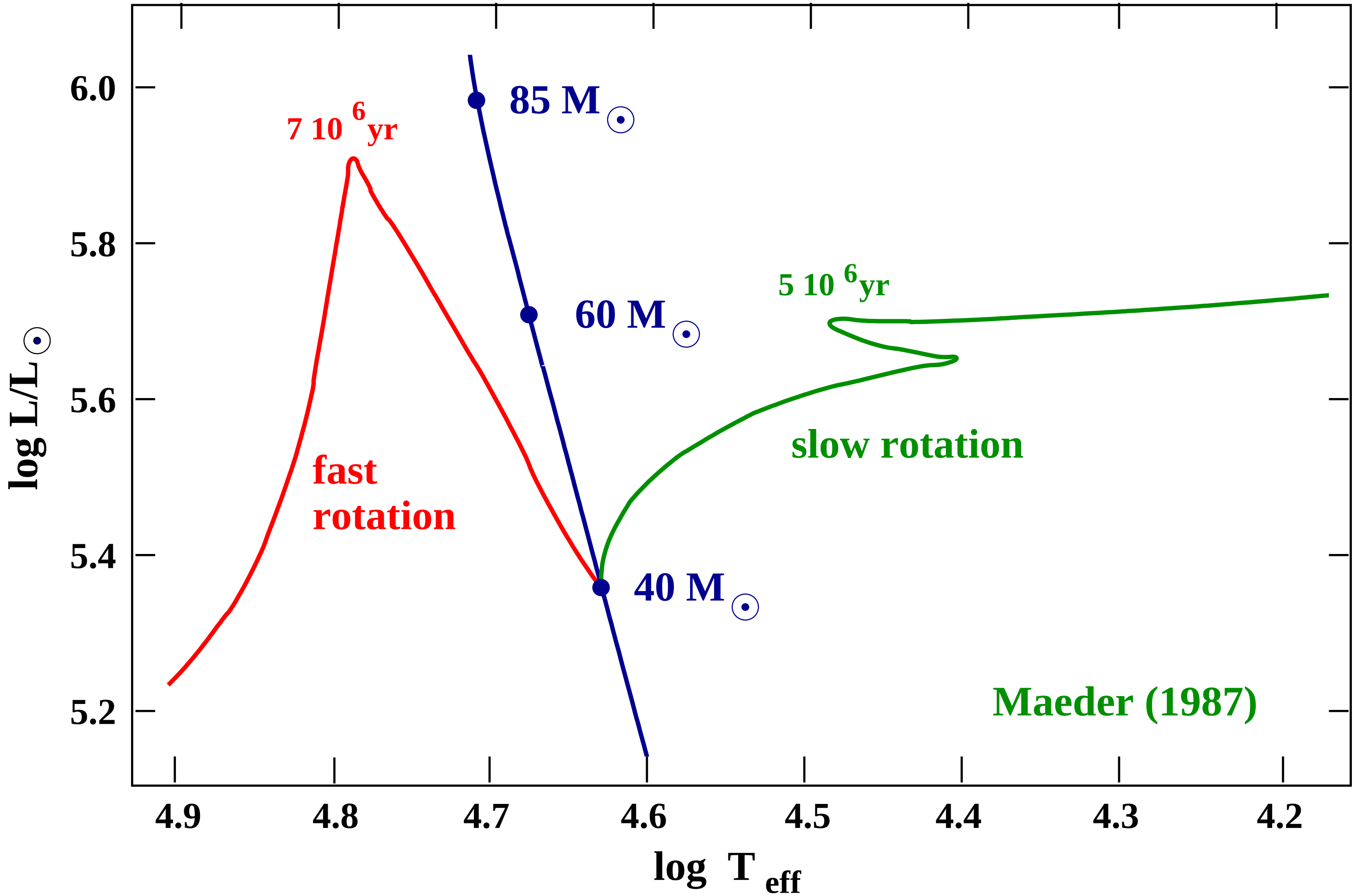


M_init=16M_⊙, Z=10^-3, V_init/V_K=0.6
H Burning
He Buring
He-Shell
C-Shell
O Burning
m / M_⊙
log (time till the end of calculation /yr)
log(erg / g / s)

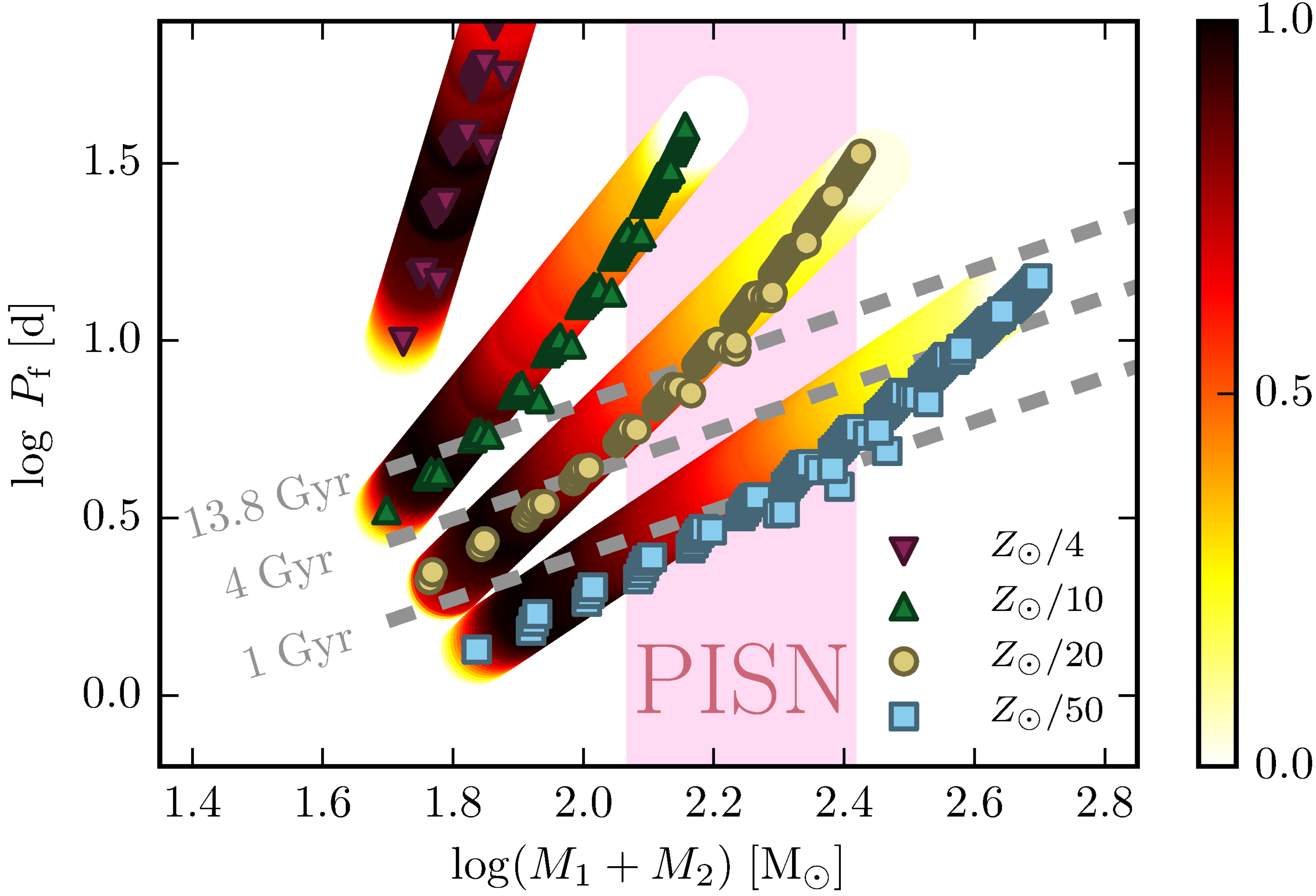
Yoon (2005/6)



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



85 M⊙
60 M⊙
40 M⊙
7 10^6 yr
5 10^6 yr
fast rotation
slow rotation
Maeder (1987)
log L/L⊙
log T_eff



Marchant et al. (2016)

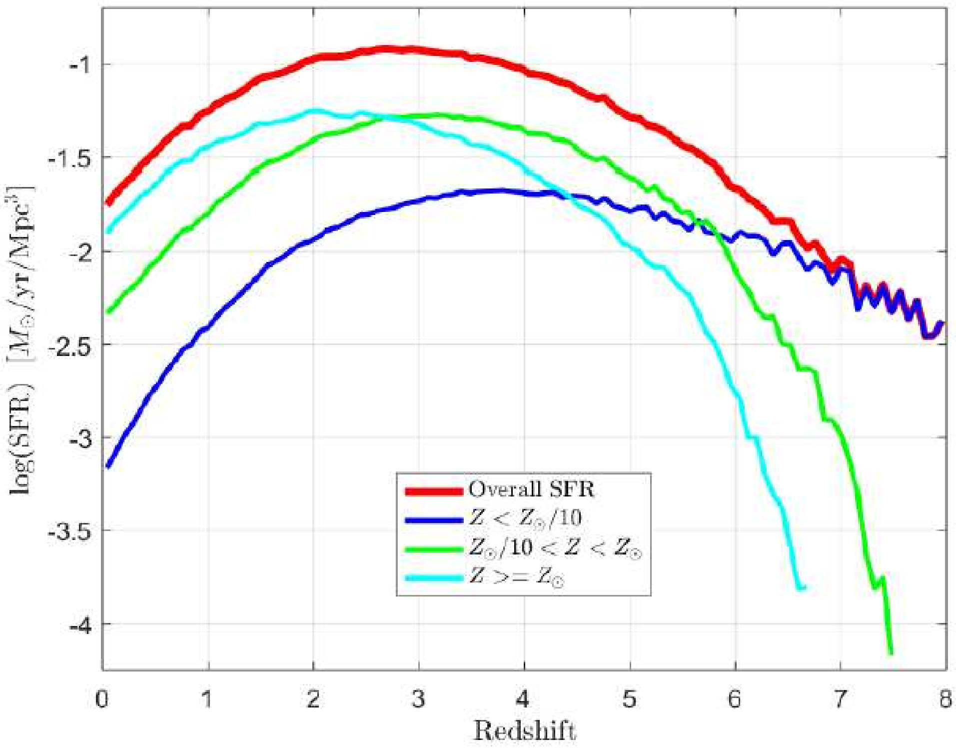
depends on metallicity-dependent stellar winds

Cosmological Simulations of BH+BH Mergers in the MOB Scenario

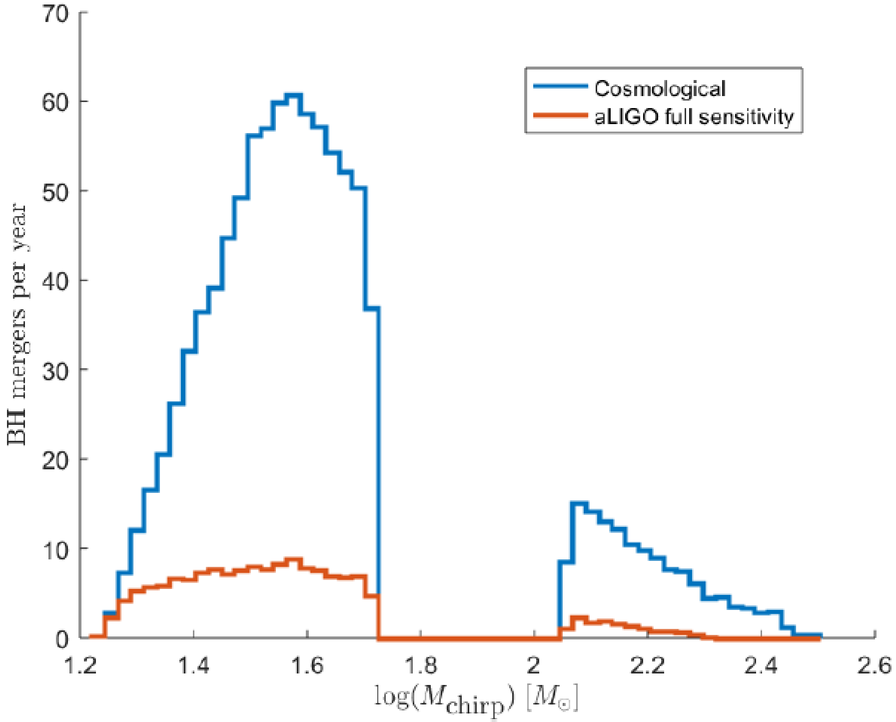
Lise du Buisson, Podsiadlowski[1]

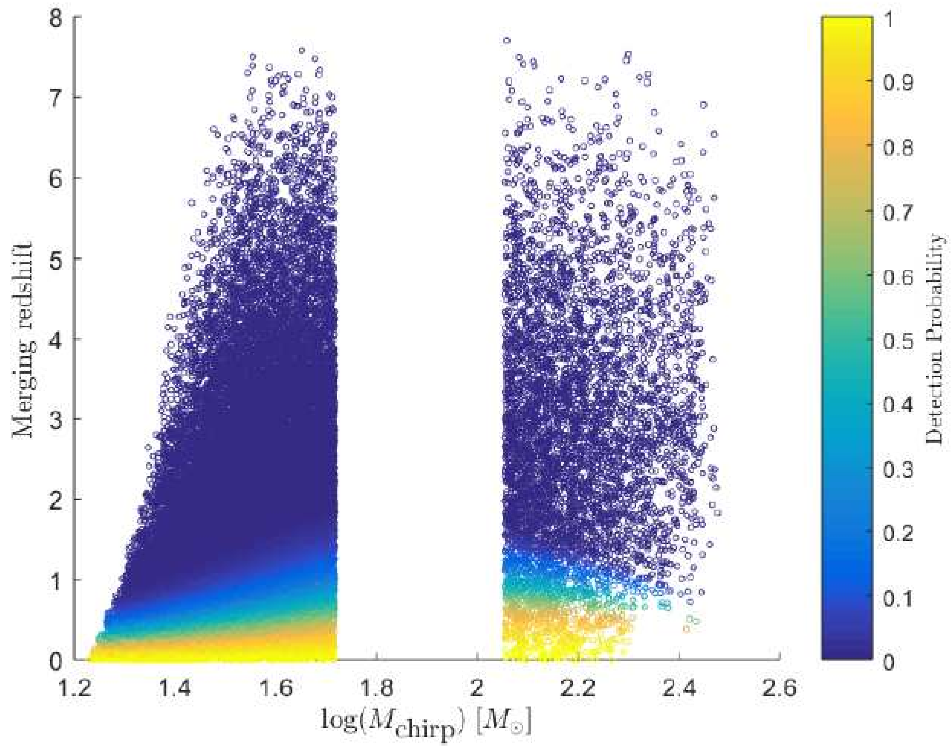
- use full cosmological simulations to simulate rates of GW sources as a function of z and Z (plus LGRBs, PISNe)
- simulations by Taylor & Kobayashi (2014)
  - ▷ self-consistent hydrodynamical simulations with star formation, SN and AGN feedback, and chemical enrichment
  - ▷ fit key observables, such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

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



Based on Taylor & Kobayashi (2014)





du Buisson et al. (2017)

- form **massive BH+BH systems** ($\gtrsim 25\,M_\odot$)
- at very low metallicity ($Z_\odot/50$): **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: $70\,yr^{-1}$ below and $7\,yr^{-1}$ above PISN gap)

→ probe **massive stellar evolution** throughout the Universe

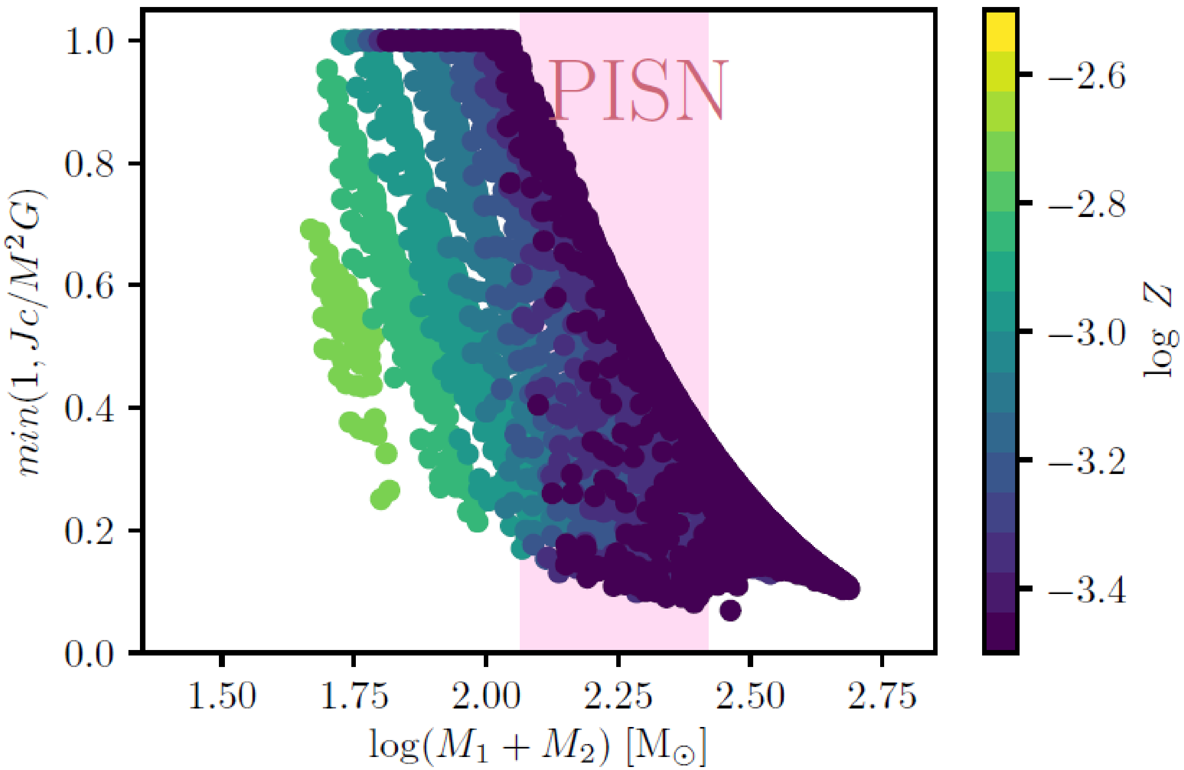
- known observational counterparts (e.g. double He-star binary (SMC) with $M_1 = 66\,M_1$, $M_2 = 61\,M_2$, $P_{orb} = 19.3\,d$)

Basic Predictions

- easier to form massive BH binaries
- 10 % above PISN gap
- mass ratio close to 1 (≥ 0.9?)
- spins vary depending on metallicity, probably correlated with orbit (but depends on BH formation process)

Main Issues

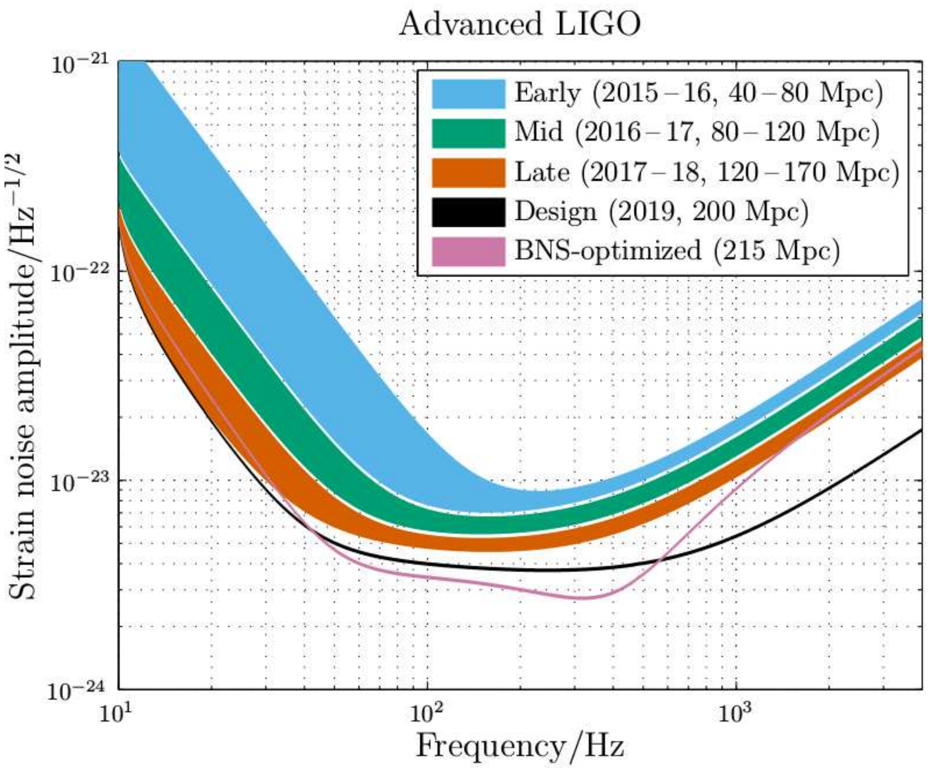
- treatment of rotational mixing untested
- wind mass loss prescription essential (also associated angular momentum loss)



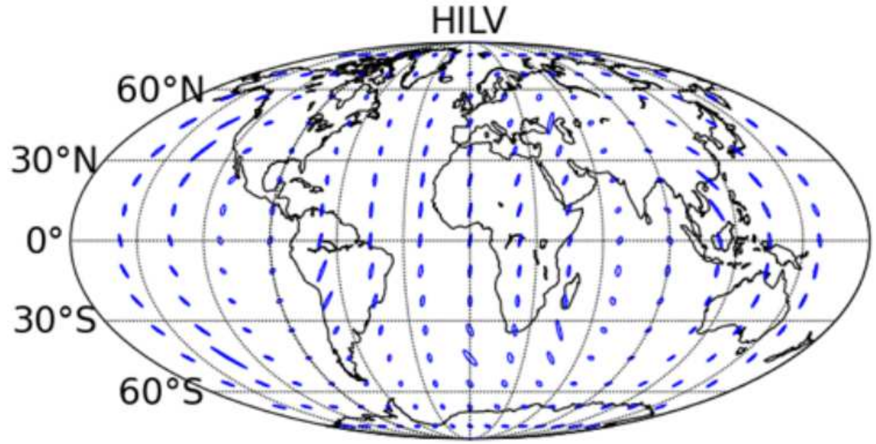
Marchant+ (2017)

Advanced LIGO roadmap until 2019

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



LIGO-India just approved!



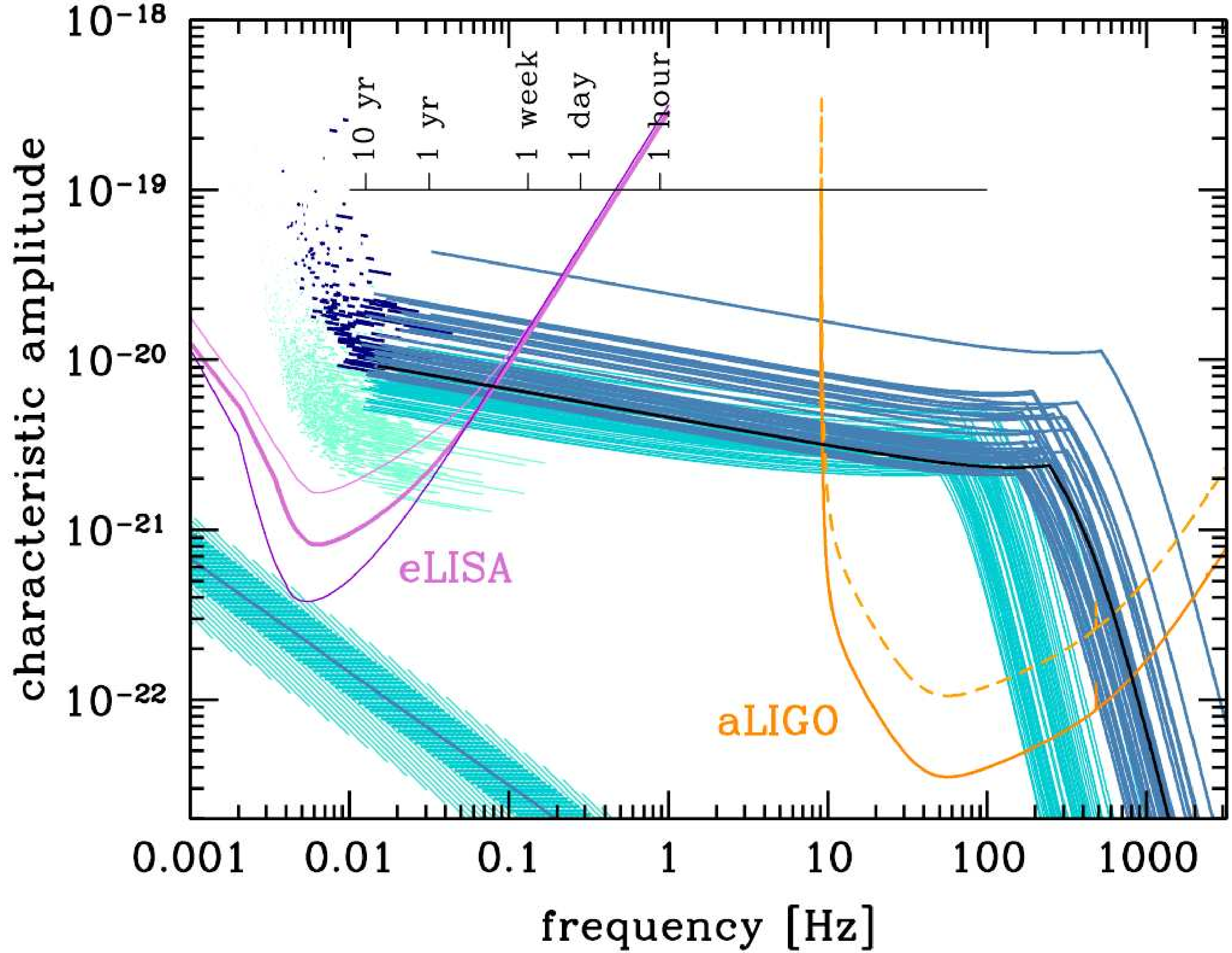
- **Few** square degrees!

Detection rates @ design sensitivity:

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

(Credit: A. Buonanno 2016)

Sesana 2016



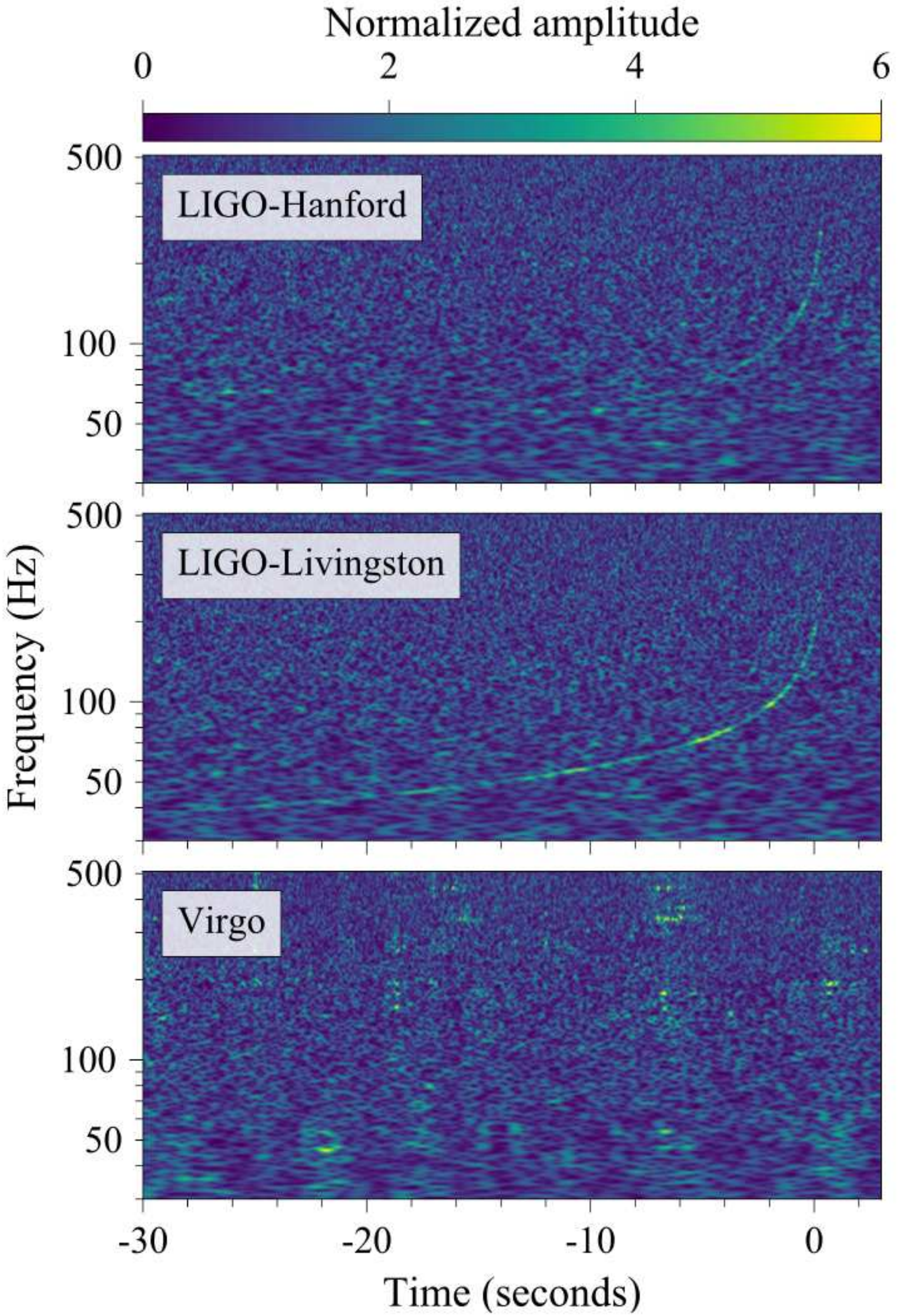
(Sesana)

Future Outlook

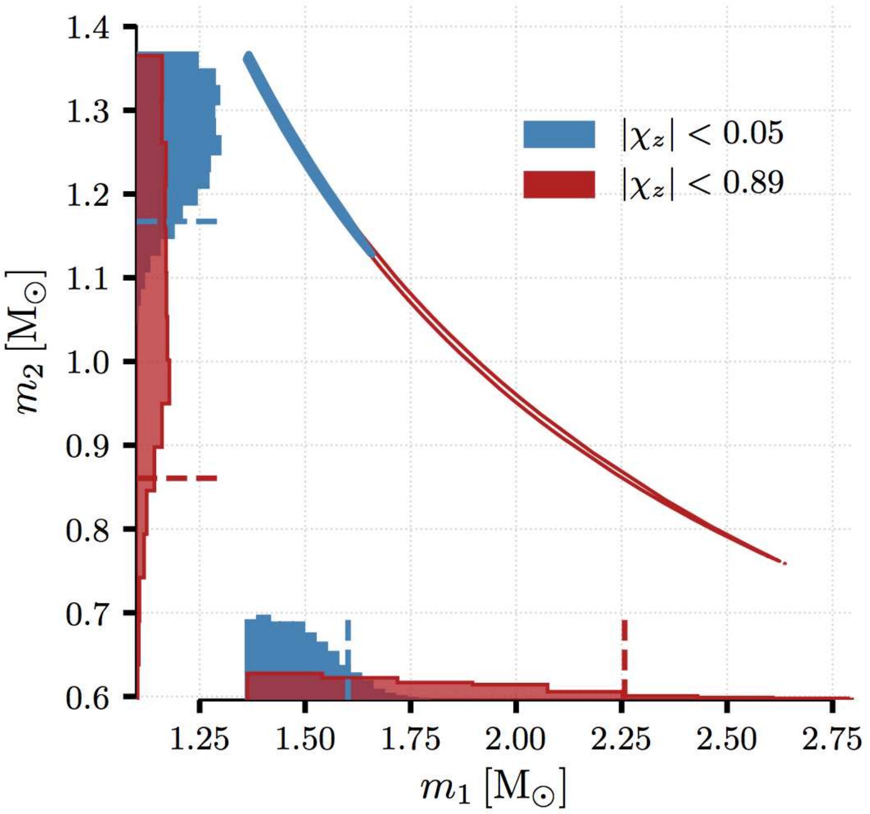
- **present aLIGO rate: 1 every 2 weeks (?); future rate: 1 every day or 2 (?)**
- **all three channels may be at work (interesting rates)**
- **distinguish between different models based on**
  - ▷ **BH+BH chirp mass distribution**
  - ▷ **mass ratios**
  - ▷ **spins and their alignments**
  - ▷ **ratio 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**

GW170817: The detection of the first neutron-star merger

- discovered on August 17
- announced on October 16
- principal science objective of aLIGO
- only expected to be seen in O3
- also independently detected as short-duration gamma-ray burst and basically in all electromagnetic wavebands: X-rays, optical, infrared, radio in the follow-up
- not seen in neutrinos
- flood of 40+ papers made public on October 16
  - ▷ 1 PRL
  - ▷ 8 Science papers
  - ▷ 7 Nature papers
  - ▷ 24 ApJL papers



Abbott+ (2017a)



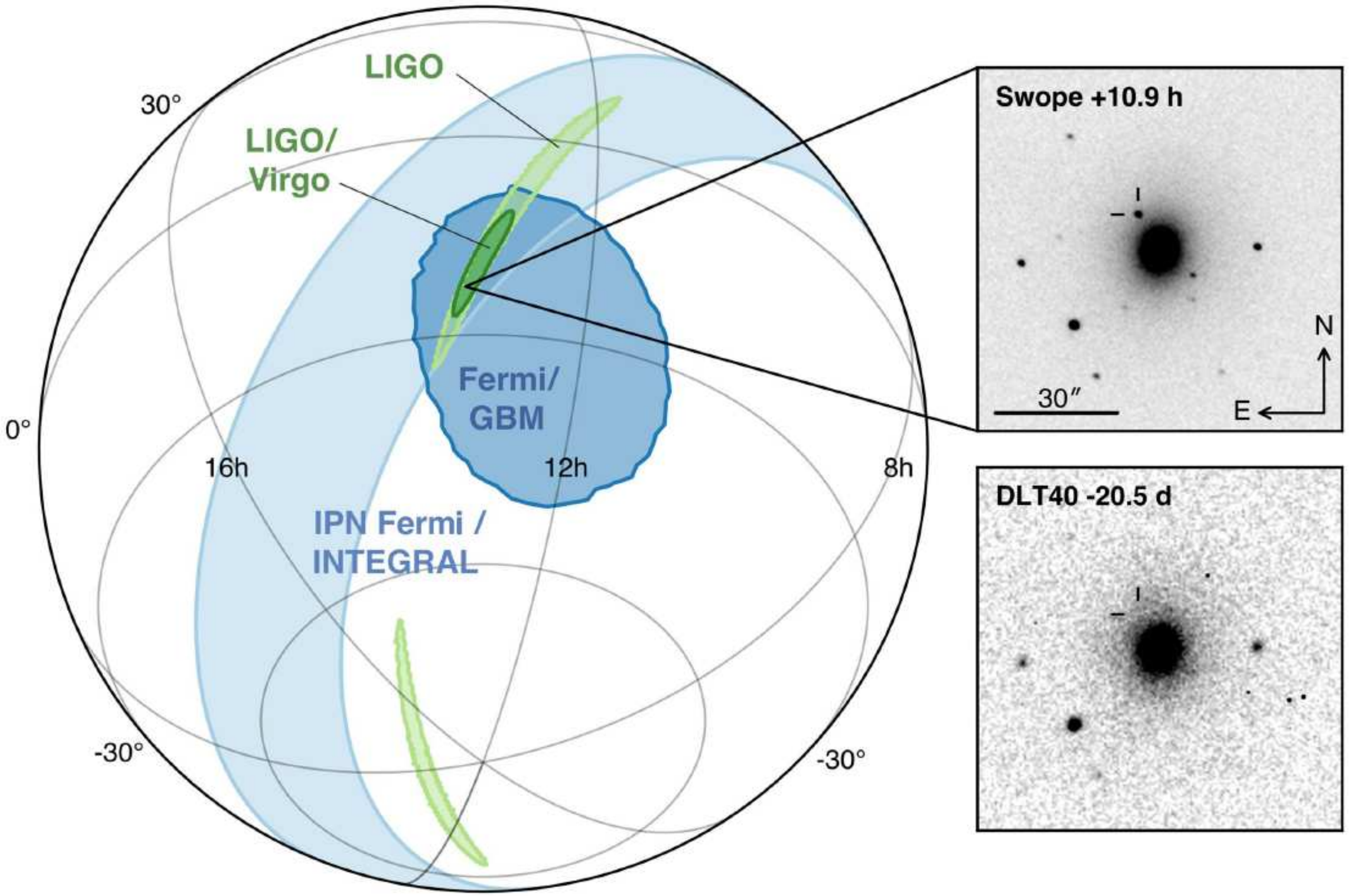
Gravitational-wave signal

- observed for 100 s (S/N=32)
- inferred masses
  - ▷ individual masses: $1.17 - 1.60\,\mathrm{M}_\odot$
  - ▷ combined mass: $2.74^{+0.04}_{-0.01}\,\mathrm{M}_\odot$
- high inferred rate: $3 \times 10^{-5} - 5 \times 10^{-4}\,\mathrm{MWEG}^{-1}\,\mathrm{yr}^{-1}$
- Fermi detection of short GRB: 1.7 s later:

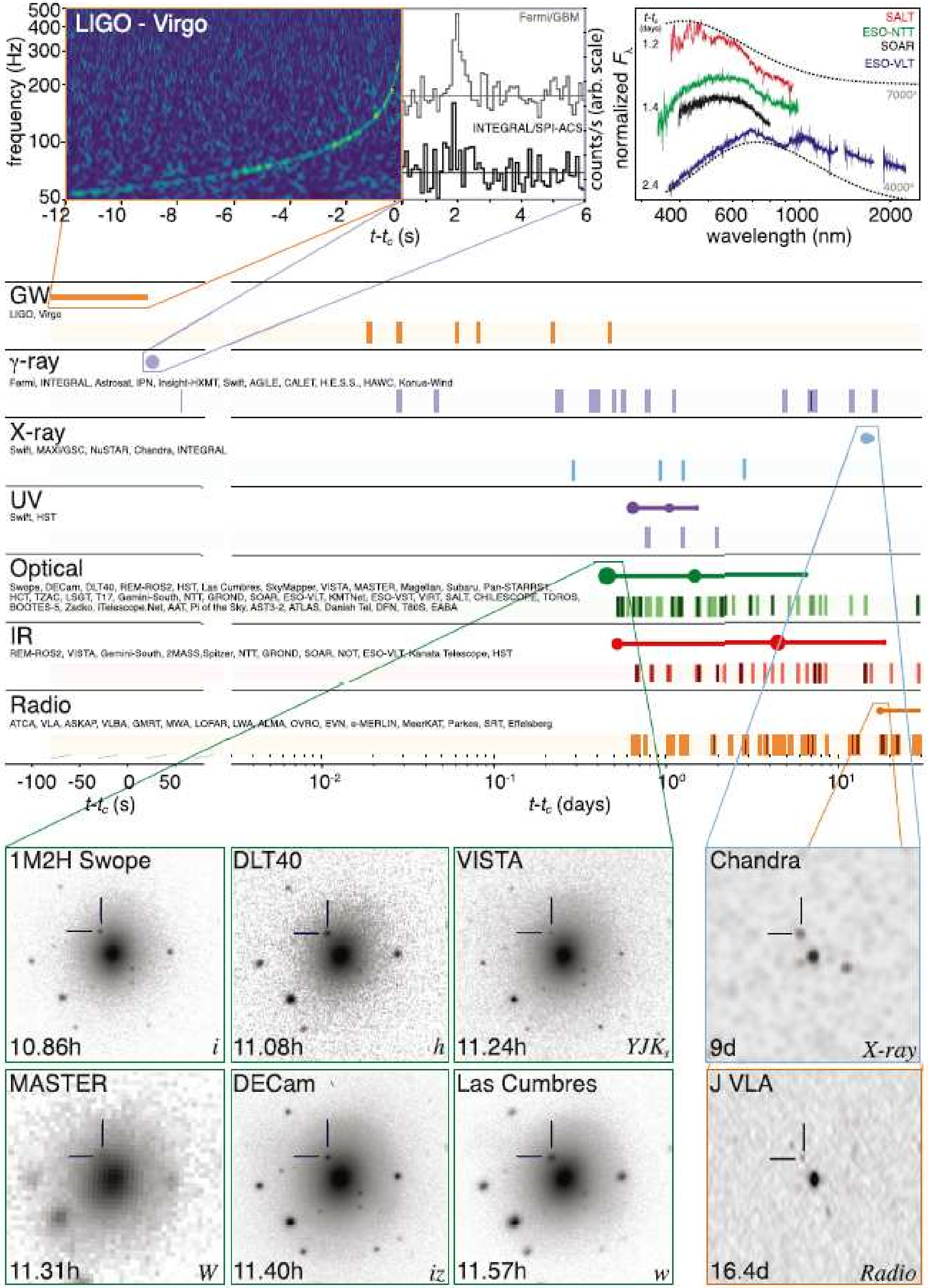
  speed of GW $\sim$ speed of light
- with Virgo detection: excellent localization: $28\,\mathrm{deg}^2$

→ galaxy NGC 4993 at 41 Mpc

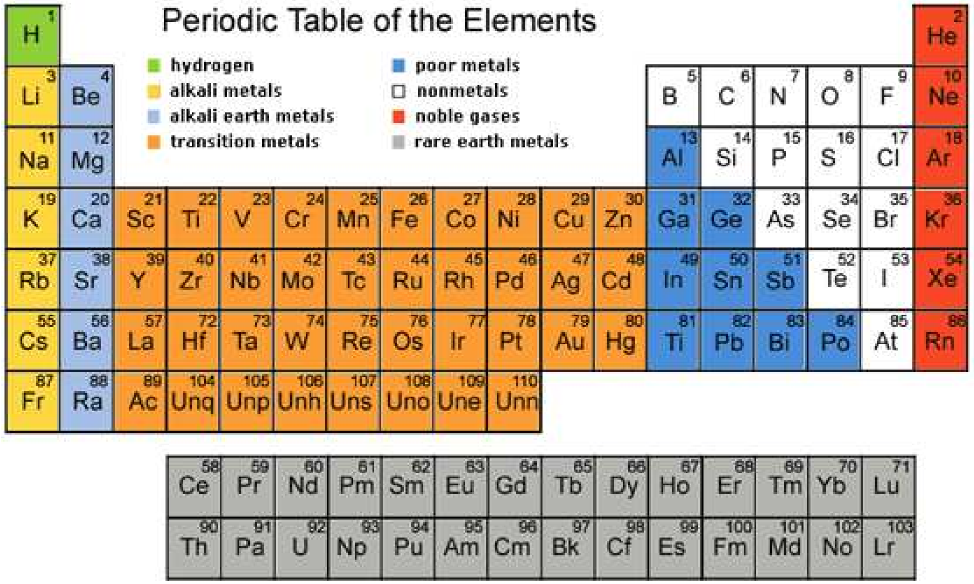
→ Hubble constant: $70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

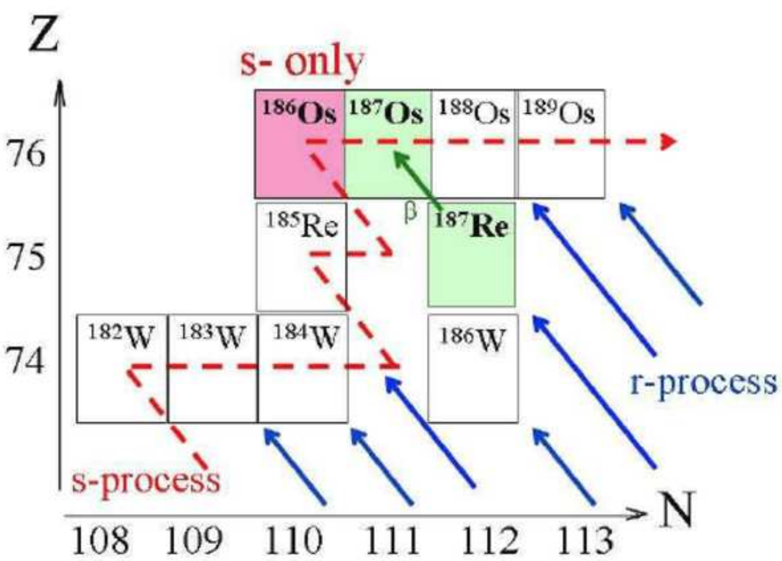


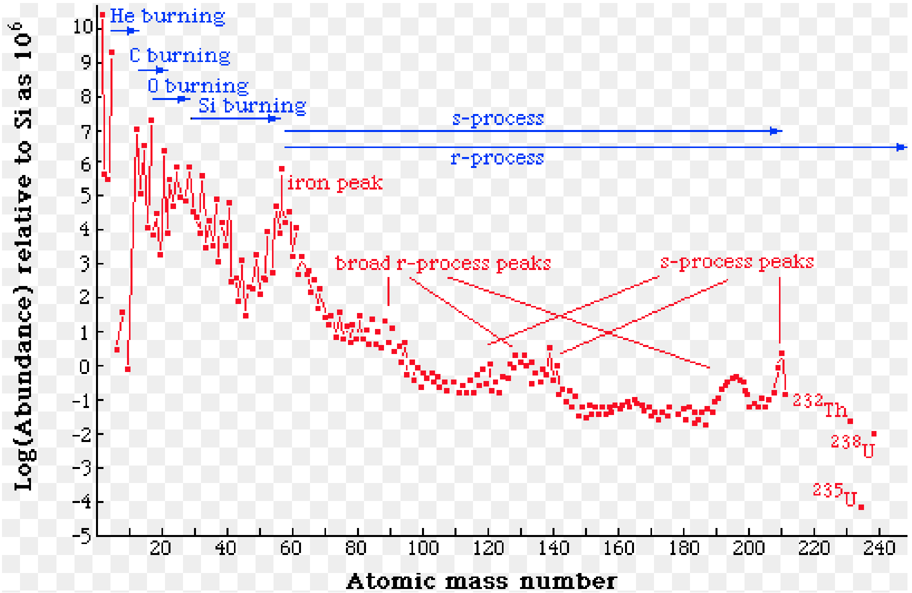
Abbott+ (2017b)

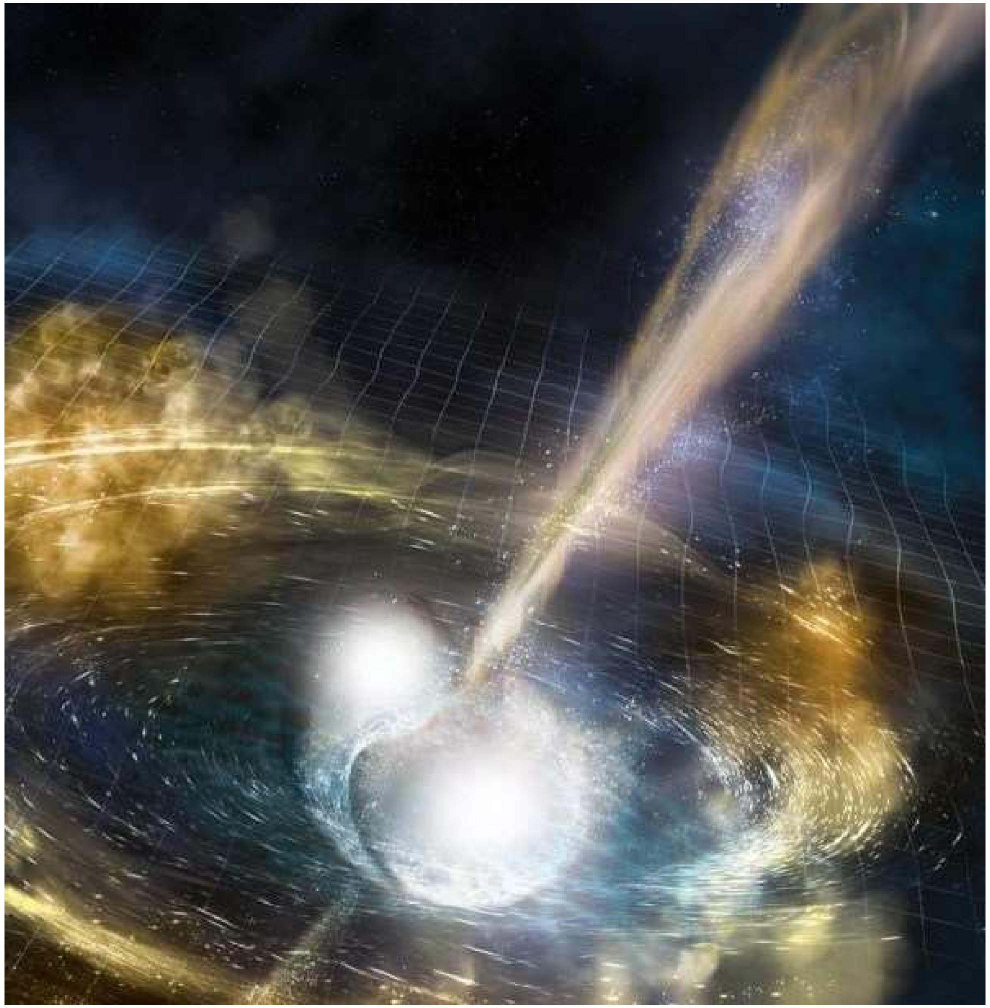


Multi-messenger astronomy (Abbott+ 2017b)

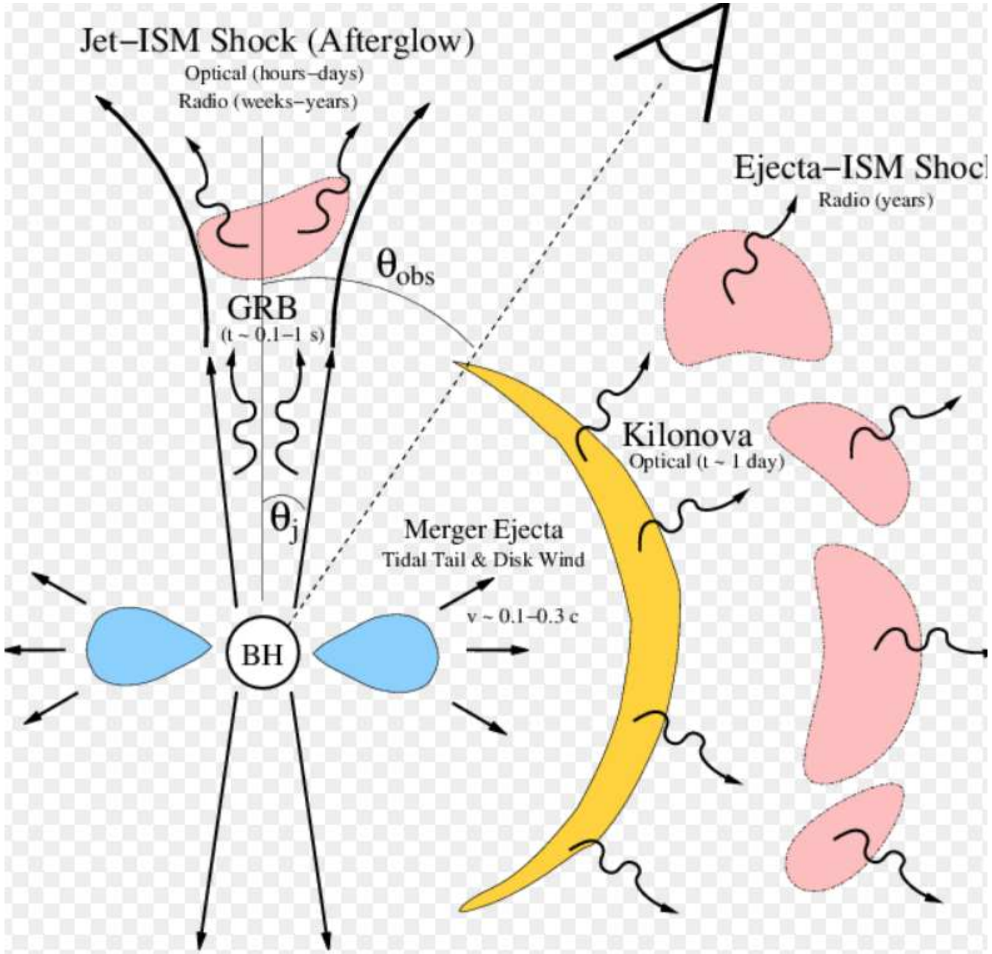

Periodic Table of the Elements
hydrogen
alkali metals
alkali earth metals
transition metals
poor metals
nonmetals
noble gases
rare earth metals
H 1 He 2
Li 3 Be 4 B 5 C 6 N 7 O 8 F 9 Ne 10
Na 11 Mg 12 Al 13 Si 14 P 15 S 16 Cl 17 Ar 18
K 19 Ca 20 Sc 21 Ti 22 V 23 Cr 24 Mn 25 Fe 26 Co 27 Ni 28 Cu 29 Zn 30 Ga 31 Ge 32 As 33 Se 34 Br 35 Kr 36
Rb 37 Sr 38 Y 39 Zr 40 Nb 41 Mo 42 Tc 43 Ru 44 Rh 45 Pd 46 Ag 47 Cd 48 In 49 Sn 50 Sb 51 Te 52 I 53 Xe 54
Cs 55 Ba 56 La 57 Hf 72 Ta 73 W 74 Re 75 Os 76 Ir 77 Pt 78 Au 79 Hg 80 Ti 81 Pb 82 Bi 83 Po 84 At 85 Rn 86
Fr 87 Ra 88 Ac 89 Unq 104 Unp 105 Unh 106 Uns 107 Uno 108 Une 109 Unn 110
Ce 58 Pr 59 Nd 60 Pm 61 Sm 62 Eu 63 Gd 64 Tb 65 Dy 66 Ho 67 Er 68 Tm 69 Yb 70 Lu 71
Th 90 Pa 91 U 92 Np 93 Pu 94 Am 95 Cm 96 Bk 97 Cf 98 Es 99 Fm 100 Md 101 No 102 Lr 103


Z
s- only
186Os
187Os
188Os
189Os
185Re
β
187Re
182W
183W
184W
186W
76
75
74
r-process
s-process
108 109 110 111 112 113
N

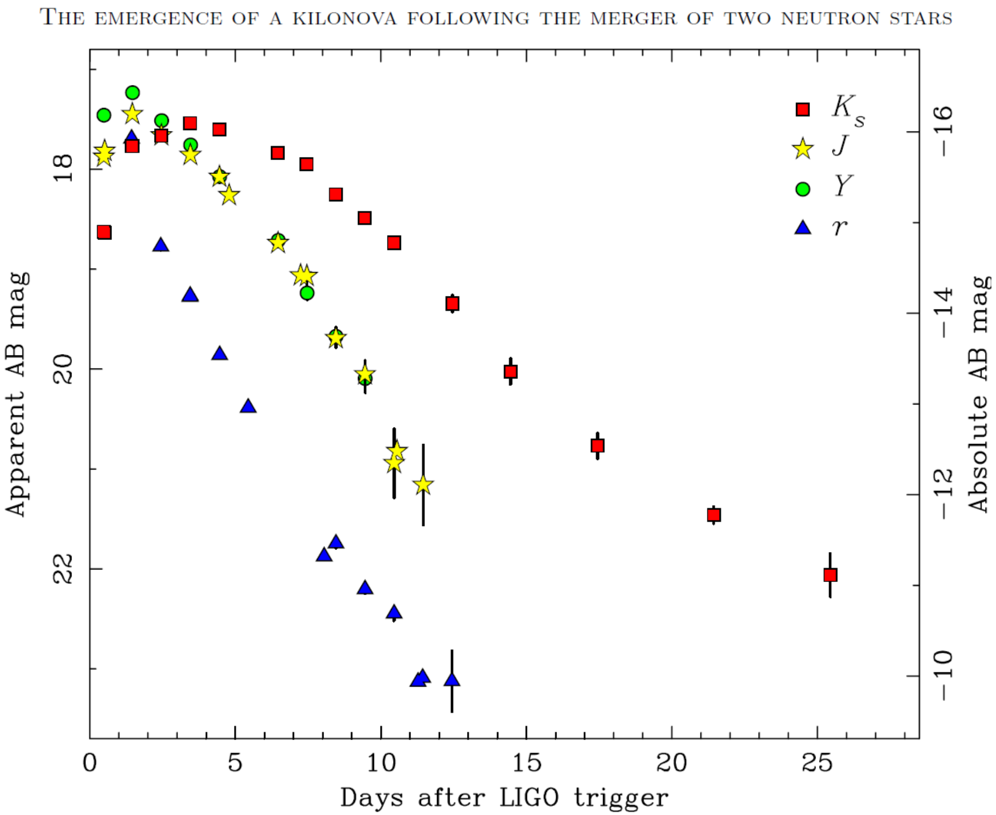

He burning
C burning
O burning
Si burning
s-process
r-process
iron peak
broad r-process peaks
s-process peaks
232Th
238U
235U
Log(Abundance) relative to Si as 10^6
Atomic mass number
10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5
20 40 60 80 100 120 140 160 180 200 220 240



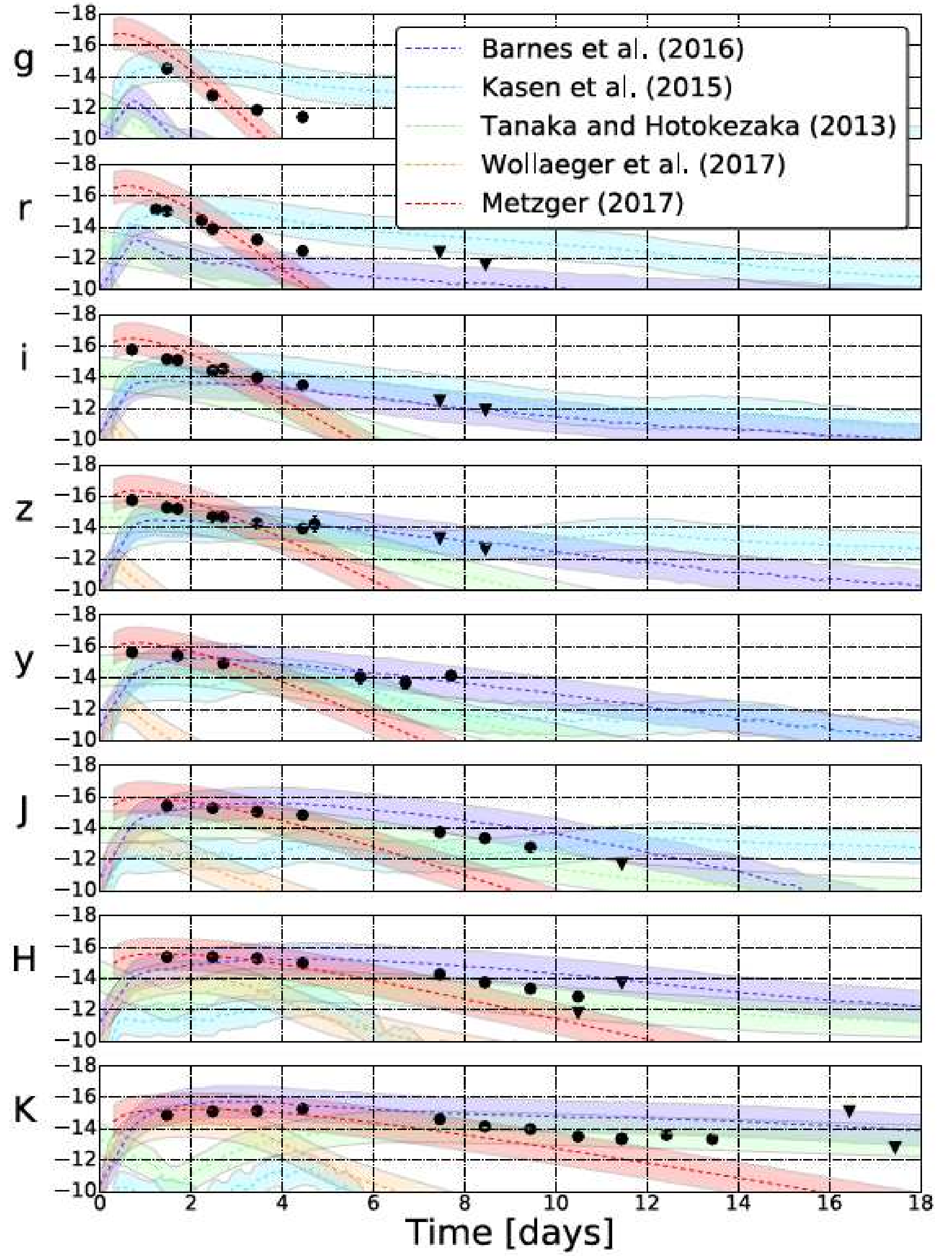
kilonova



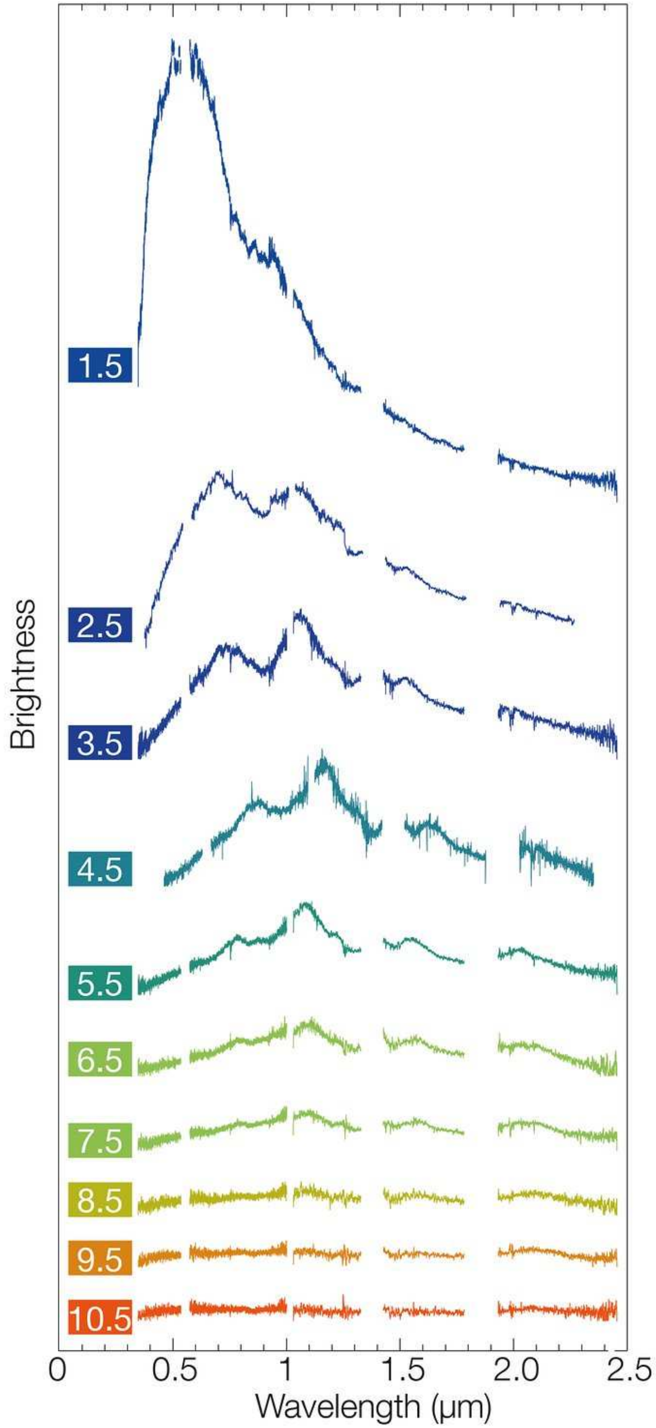
Brian Metzger



Tanvir+ (2017)



Smartt+ (2017)



ESO X-Shooter spectra

- two-component spectra (as predicted)
  - ▷ early spectrum blue → neutrino-driven wind ejecta with low neutron fraction ($0.05\,c$)
  - ▷ later spectra → IR → lanthanide-rich dynamical ejecta ($\sim 0.2\,c$)
  - ▷ dynamical ejecta mass: $0.03 - 0.05\,M_\odot$
- consistent with forming all r-process elements in the Universe (preliminary)

short-duration GRB

- $1.7\,$s after GW, duration: $2\,$s
- $E_{iso} \simeq 4 \times 10^{46}\,$erg

→ off-axis GRB ($> 26^\circ$)

The importance GW170817

- achieved principal science objective of aLIGO
- confirmed neutron-star mergers as important gravitational-wave sources
- confirmed the NS-NS merger – short GRB connection
- confirmed NS-NS mergers as prime source of heavy element nucleosynthesis (r-process) (instead of supernovae)

Some open questions

- apparent high NS-NS merger rate: real or luck?
- short GRB was unusually weak (orientation effect?)
- larger ejecta masses $\rightarrow$ need to refine kilonova models