Lecture 20, neutron star mergers, a quick summary

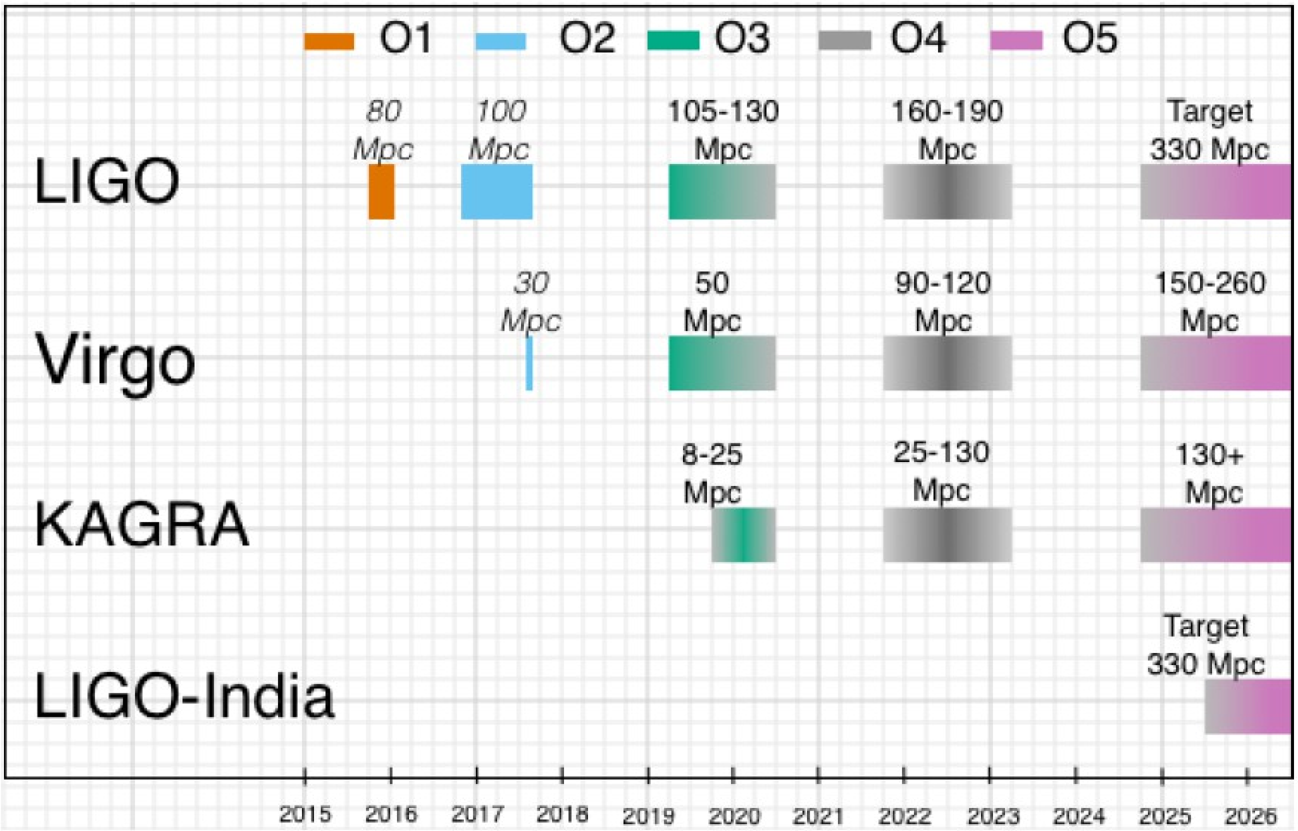
from Baiotti and Rezzolla,
Rept.Prog.Phys. 80 (2017) 9, 096901

The merger of binary neutron-stars systems combines in a single process: extreme gravity, copious emission of gravitational waves, complex microphysics, and electromagnetic processes that can lead to astrophysical signatures observable at the largest redshifts. We review here the recent progress in understanding what could be considered Einstein's richest laboratory, highlighting in particular the numerous significant advances of the last decade. Although special attention is paid to the status of models, techniques, and results for fully general-relativistic dynamical simulations, a review is also offered on initial data and advanced simulations with approximate treatments of gravity. Finally, we review the considerable amount of work carried out on the post-merger phase, including: black-hole formation, torus accretion onto the merged compact object, connection with gamma-ray burst engines, ejected material, and its nucleosynthesis.

from Eric Burns, Living Rev.Rel. 23 (2020) 1, 4

Abstract Neutron star mergers are the canonical multimessenger events: they have been observed through photons for half a century, gravitational waves since 2017, and are likely to be sources of neutrinos and cosmic rays. Studies of these events enable unique insights into astrophysics, particles in the ultrarelativistic regime, the heavy element enrichment history through cosmic time, cosmology, dense matter, and fundamental physics. Uncovering this science requires vast observational resources, unparalleled coordination, and advancements in theory and simulation, which are constrained by our current understanding of nuclear, atomic, and astroparticle physics. This review begins with a summary of our current knowledge of these events, the expected observational signatures, and estimated detection rates for the next decade. I then present the key observations necessary to advance our understanding of these sources, followed by the broad science this enables. I close with a discussion on the necessary future capabilities to fully utilize these enigmatic sources to understand our universe.

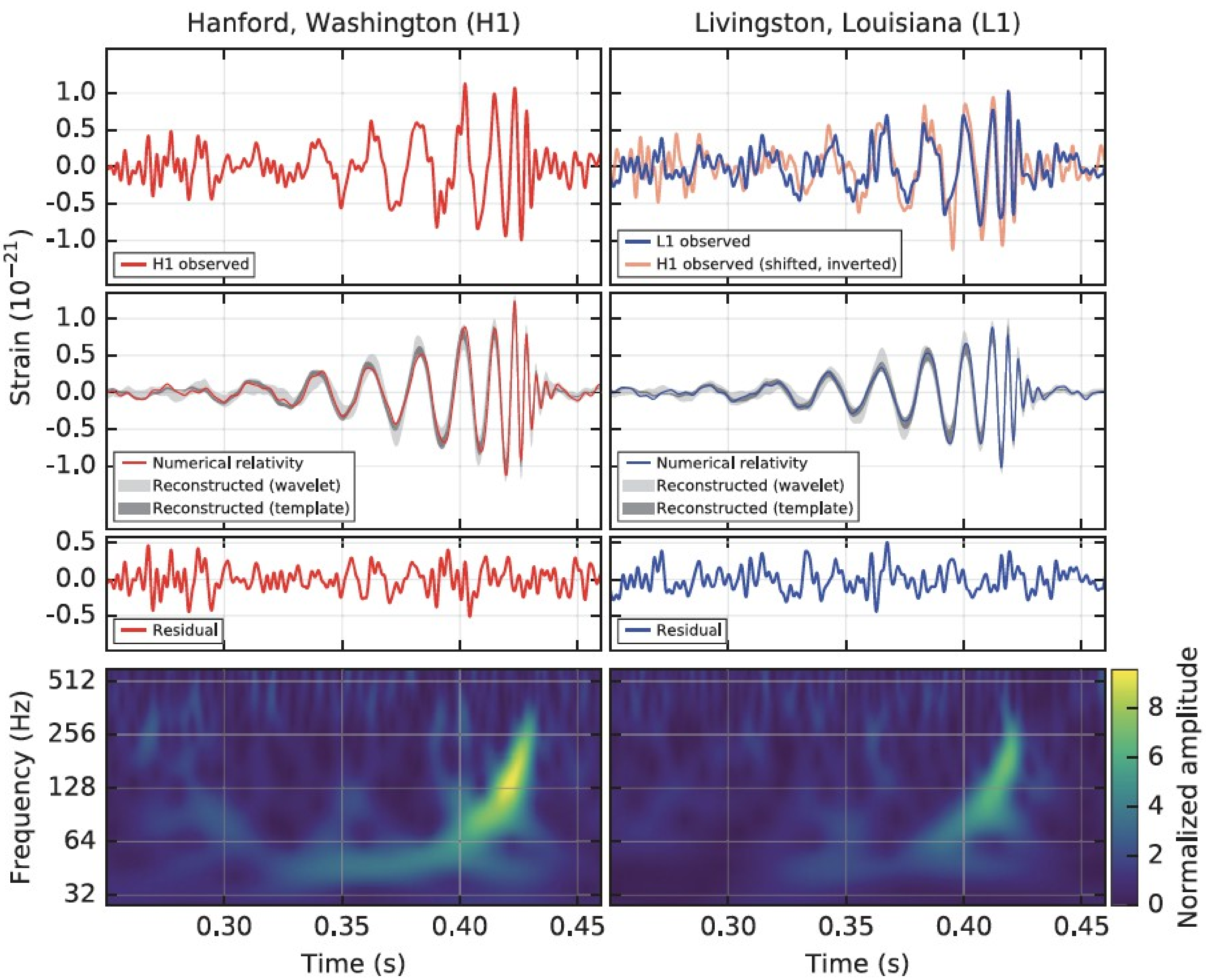
existing and planned gravitational wave facilities



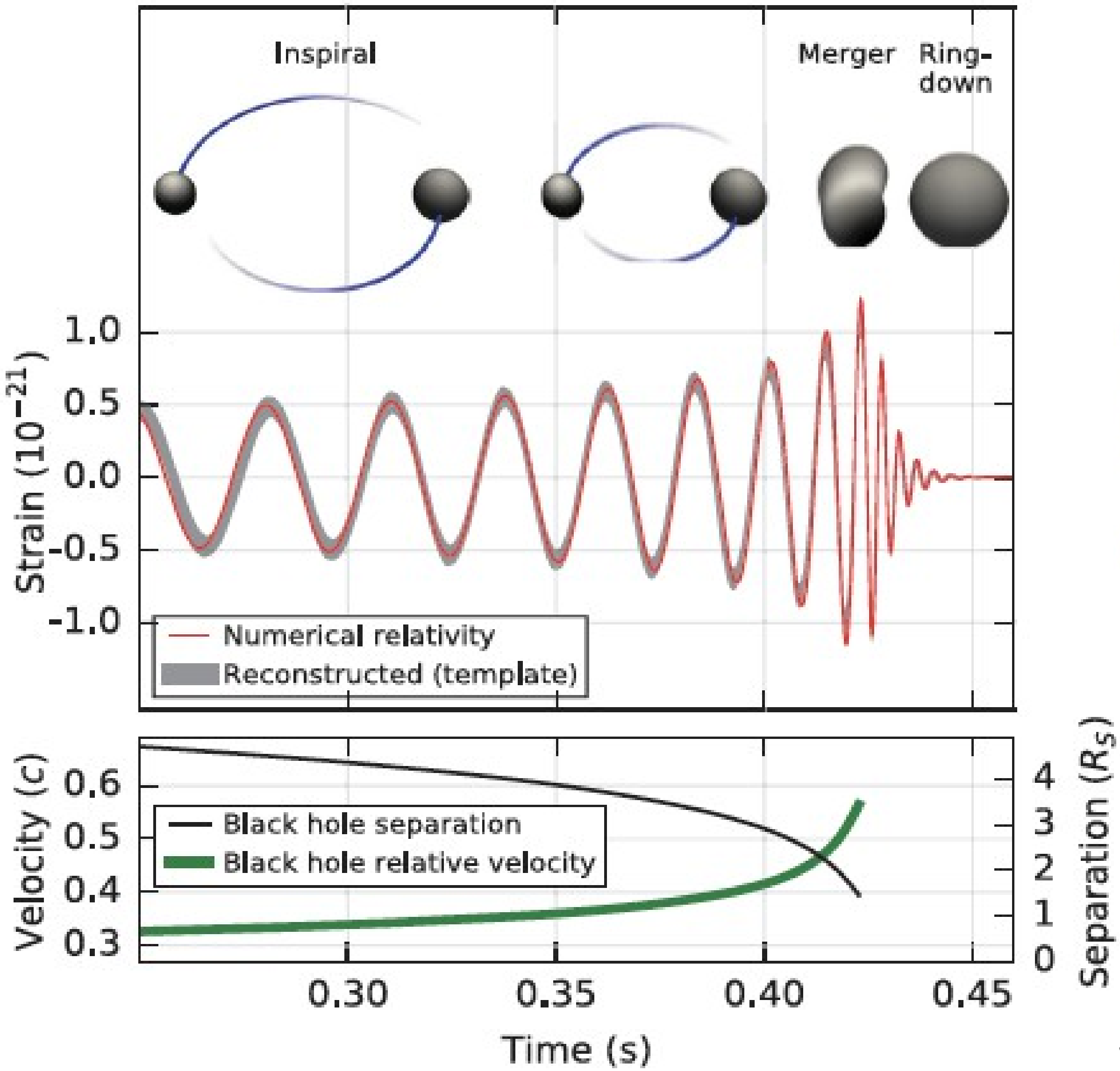
first observation of a binary black hole merger

Ligo collaboration,

PRL **116,** 061102 (2016)



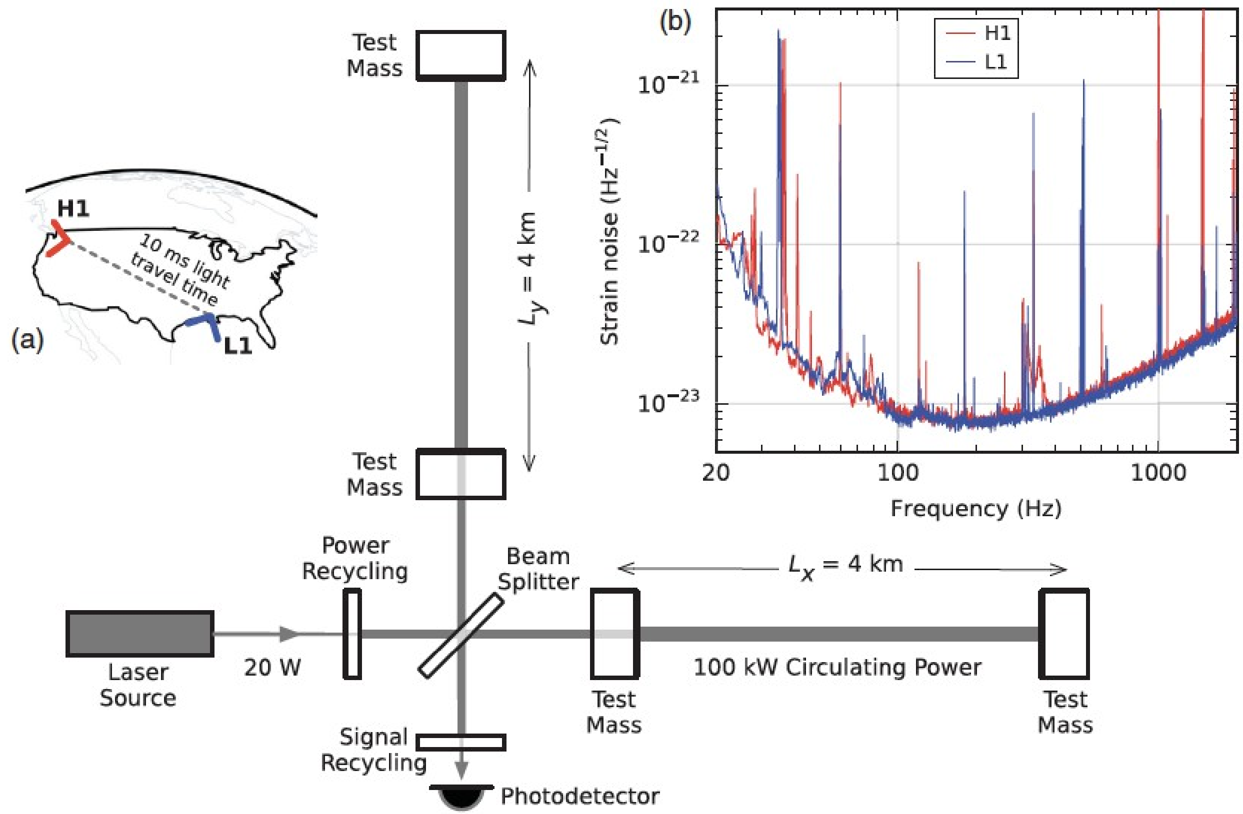
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Top: Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

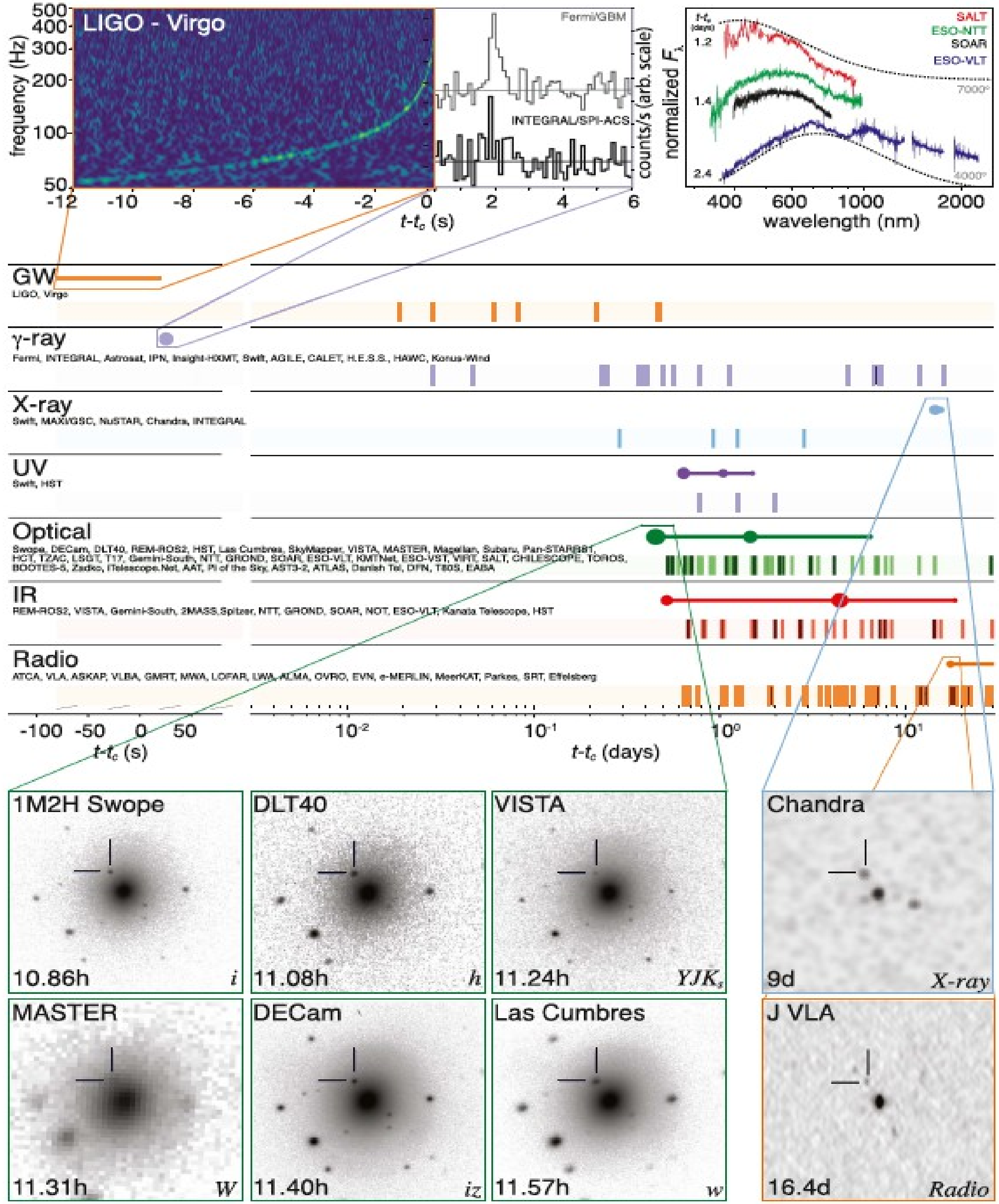
Schwarzschild radius R_S = 210 km



Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

multi-messenger detection of the first binary neutron star merger GW170817

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20



The merger of two neutron stars is predicted to give rise to three major detectable phenomena: a short burst of γ-rays, a gravitational wave signal, and a transient optical/near-infrared source powered by the synthesis of large amounts of very heavy elements via rapid neutron capture (the r-process)[1–3]. Such transients, named "macronovae" or "kilonovae" (refs 4-7), are believed to be centres of production of rare elements such as gold and platinum[8]. The most compelling evidence so far for a kilonova was a very faint near-infrared rebrightening in the afterglow of a short γ-ray burst[9,10] at $z = 0.356$, although findings indicating bluer events have been reported[11]. Here we report the spectral identification and describe the physical properties of a bright kilonova associated with the gravitational wave source GW 170817[12] and γ-ray burst GRB 170817A[13,14] associated with a galaxy at a distance of 40 Mpc from Earth. Using a series of spectra from ground-based observatories covering the wavelength range from the ultraviolet to the near-infrared, we find that the kilonova is characterized by rapidly expanding ejecta with spectral features similar to those predicted by current models[15,16]. The ejecta is optically thick early on, with a velocity of about 0.2 times light speed, and reaches a radius of ~ 50 astronomical units in only 1.5 days. As the ejecta expands, broad absorption-like lines appear on the spectral continuum indicating atomic species produced by nucleosynthesis that occurs in the post-merger fast-moving dynamical ejecta and in two slower (0.05 times light speed) wind regions. Comparison with spectral models suggests that the merger ejected 0.03–0.05 solar masses of material, including high-opacity lanthanides.

a historical note:

expanding neutron star matter as site for the r-process was first proposed by

Lattimer and Schramm, Astrophys. J. Lett. 192 (1974) L145

and

Lattimer, Mackie, Ravenhall, and Schramm, Astrophys. J. 213 (1977) 225

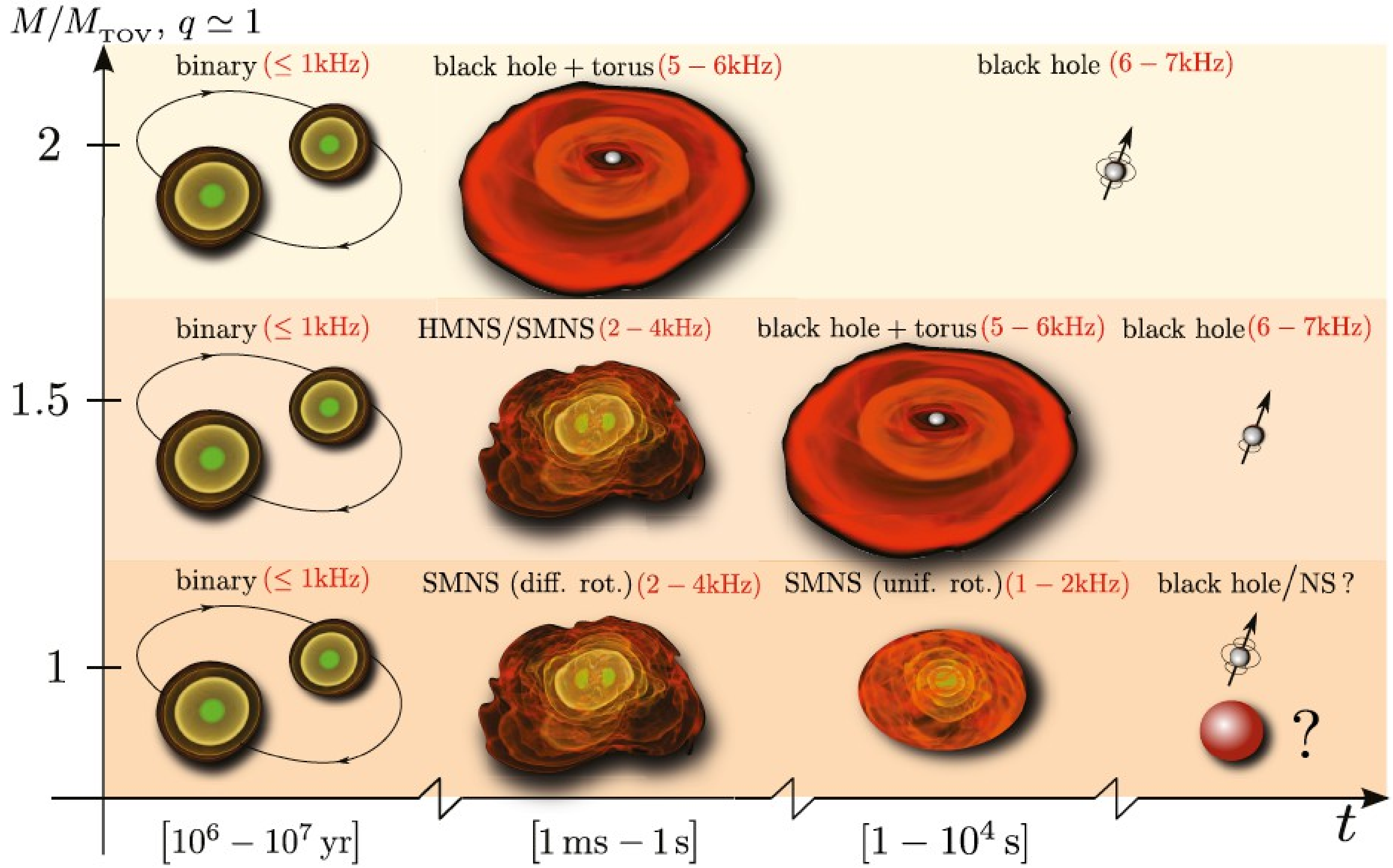
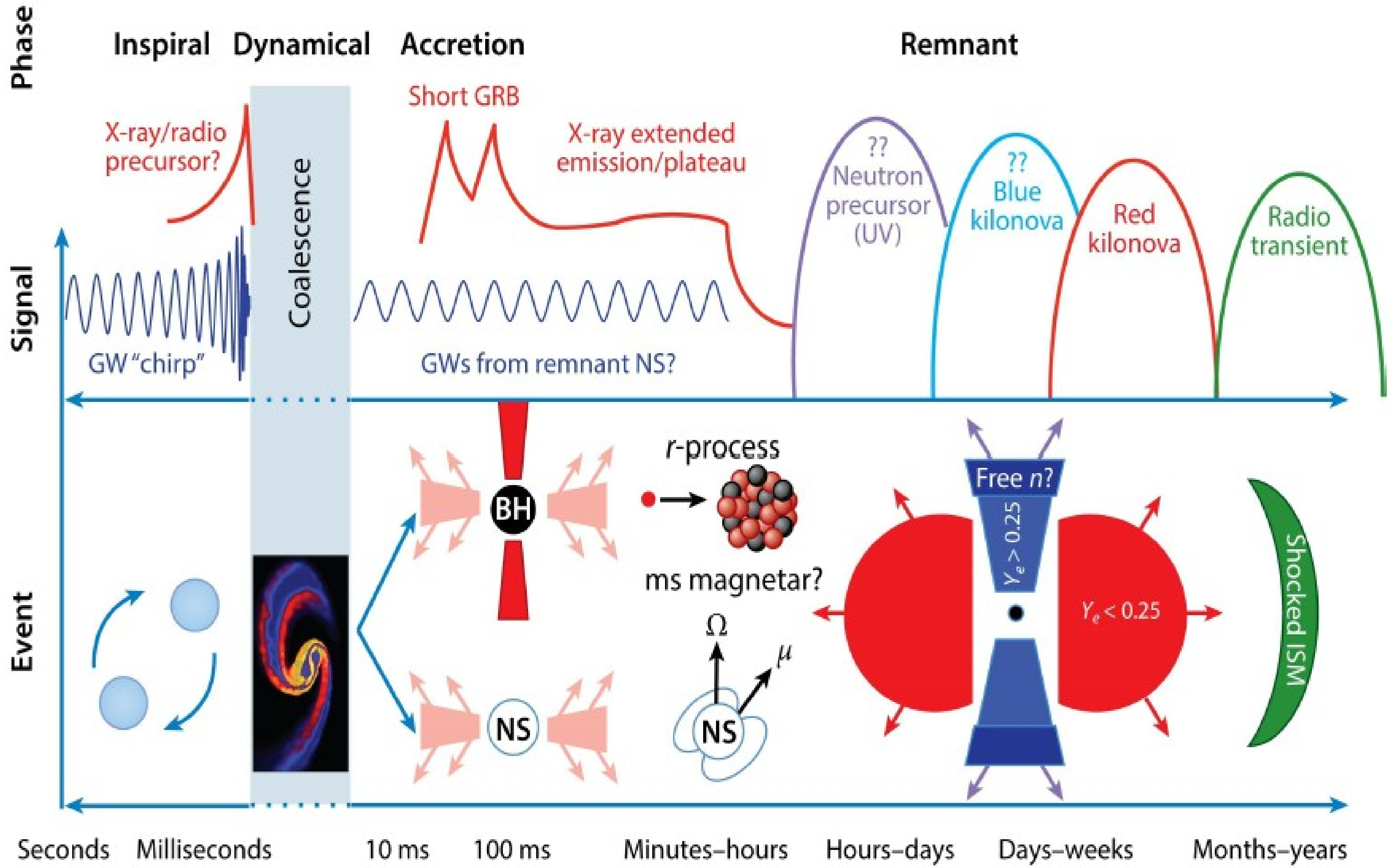


FIG. 1. Schematic diagram illustrating the various stages in the evolution of an equal-mass binary system of neutron stars as a function of the initial mass of the binary. Depending on the initial total mass of the binary M, and on how it relates to the maximum mass of a nonrotating neutron star $M_{\rm TOV}$, the binary can either collapse promptly to a black hole surrounded by a torus (top row), or give rise to an HMNS (or an SMNS) that ultimately collapses to a black hole and torus (middle row), or even lead to a SMNS (first differentially and subsequently uniformly rotating) neutron star that eventually yields a black hole or a nonrotating neutron star (bottom row). Also indicated in red are the typical frequencies at which gravitational waves are expected to be emitted [Adapted from Ref. [59] by permission of Oxford University Press www.oup.com].

fig. taken from Baiotti-Rezzolla review

HMNS: Hyper Massive Neutron Star
SMNS: Supra Massive Neutron Star

expected electromagnetic and gravitational wave signals from neutron star mergers



Fernández, R., & Metzger, B. D. 2016, Annu. Rev. Nucl. Part. Sci., 66, 23

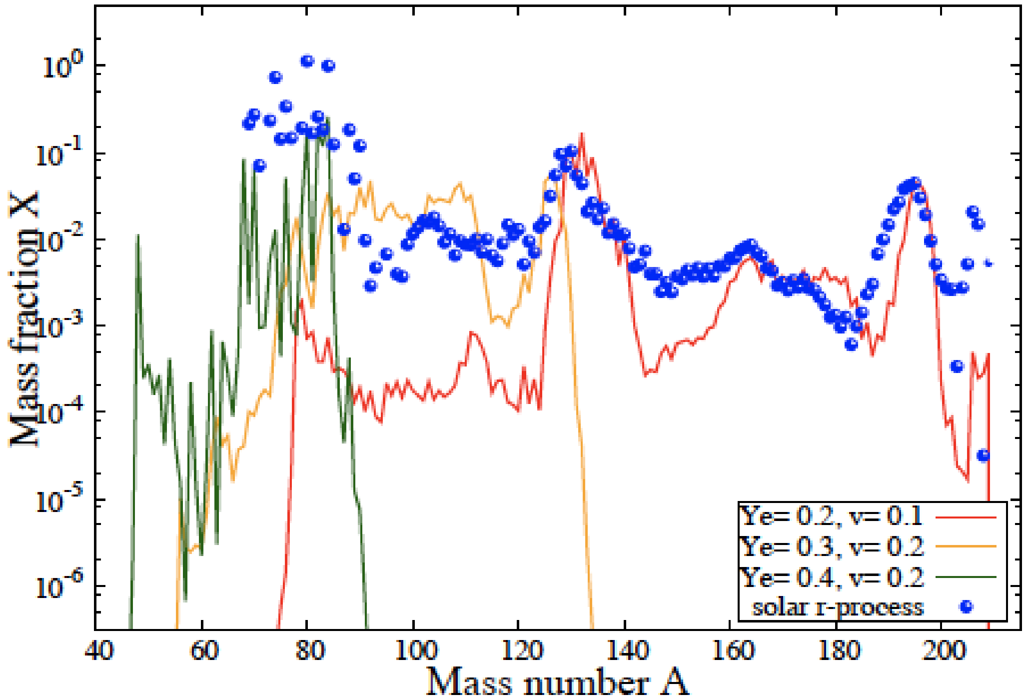
kilo-nova prediction in 2010

Metzger, B. D.; Martínez-Pinedo, G.; Darbha, S.; Quataert, E.; Arcones, A.; Kasen, D.; Thomas, R.; Nugent, P.; Panov, I. V.; Zinner, N. T. (August 2010). "Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei".

Monthly Notices of the Royal Astronomical Society. 406 (4): 2650. arXiv:1001.5029

The most promising astrophysical sources of kHz gravitational waves (GWs) are the inspiral and merger of binary neutron star(NS)/black hole systems. Maximizing the scientific return of a GW detection will require identifying a coincident electromagnetic (EM) counterpart. One of the most likely sources of *isotropic* EM emission from compact object mergers is a supernova-like transient powered by the radioactive decay of heavy elements synthesized in ejecta from the merger. We present the first calculations of the optical transients from compact object mergers that self-consistently determine the radioactive heating by means of a nuclear reaction network; using this heating rate, we model the light curve with a one dimensional Monte Carlo radiation transfer calculation. For an ejecta mass $\sim 10^{-2} M_{\odot} [10^{-3} M_{\odot}]$ the resulting light curve peaks on a timescale ~ 1 day at a V-band luminosity $\nu L_{\nu} \sim 3 \times 10^{41} [10^{41}]$ ergs s^{-1} ($M_{V} = -15[-14]$); this corresponds to an effective "f" parameter $\sim 3 \times 10^{-6}$ in the Li-Paczynski toy model. We argue that these results are relatively insensitive to uncertainties in the relevant nuclear physics and to the precise early-time dynamics and ejecta composition. Since NS merger transients peak at a luminosity that is a factor $\sim 10^{3}$ higher than a typical nova, we propose naming these events "kilo-novae." Due to the rapid evolution and low luminosity of NS merger transients, EM counterpart searches triggered by GW detections will require close collaboration between the GW and astronomical communities. NS merger transients may also be detectable following a short-duration Gamma-Ray Burst or "blindly" with present or upcoming optical transient surveys. Because the emission produced by NS merger ejecta is powered by the formation of rare r-process elements, current optical transient surveys can directly constrain the unknown origin of the heaviest elements in the Universe.

data for solar r-process are qualitatively well described for reasonable kilonova configurations, see: Daniel Siegel, Eur. Phys. J. A 55 (2019) 11, 203



Abundances for two cases (red and orange lines) that can both reproduce the bolometric luminosity evolution. While both produce r-process material, one case produces the third r-process peak ($Y_e = 0.2$ and $v = 0.1$c), but the other ($Y_e = 0.3$ and $v = 0.2$c) does not. Thus, from the bolometric lightcurve alone the absence/presence of lanthanides cannot be inferred. For comparison, we also show a case (green line) with large $Y_e = 0.4$ ($v = 0.2$c) that only produces elements with $A < 90$. That case does not fit the bolometric luminosity.

summary:

many facts point to an appreciable contribution from neutron star mergers to heavy element production. neutron densities of order $10^{24}/cm^3$ are required (about $1 g/cm^3$ of neutrons !!!) It was argued that, in a single neutron star merger, between 3 and 13 earth masses of Au can be produced, see
Sid Perkins, Science AAA 20 March 2018

however, with only 2 neutron star mergers detected as of today, there is still much room for debate

see, e.g. Anna Frebel and Timothy Beers
Physics Today 71 (2018) 30