**A HISTORY OF LIGO**

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**Appendix B. Sources of Gravitational Waves** **in the LIGO Frequency Band**

**Appendix B. Sources of Gravitational Waves** **in the LIGO Frequency Band** [draft [Version 2.3C, August 1, 2024, same as v2.2 with all changes accepted]

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| **Box B1. Readers’ Guide to Appendix** **B**  This appendix, except for Box B2, is intended to be accessible to scientifically literate general readers who do not have advanced undergraduate physics or engineering training. However, it will be helpful to have some understanding of the various kinds of objects that are known or speculated to exist in the distant universe. |

**B.1 Introduction**

**B.1.1 Characteristics of the Strongest GW Sources in our Contemporary Universe**

By the early 1970s it was confidently predicted that *the strongest sources of gravitational waves in the contemporary universe*[[1]](#footnote-1) *would be objects, or collections of objects, that are extremely compact (sizes not far larger than a black hole with the same mass) and highly dynamical (shapes that change rapidly, with speeds approaching the speed of light).* See Box B2 for a technical explanation.

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| **Box B2. Strongest Sources of Gravitational Waves: A Technical Explanation**  In section 0.1 of the Prolog, we described in words Einstein’s (1918) formula for the gravitational-wave strain produced by nonspherical accelerations of a source’s mass. The explicit form of that formula is  (1)  where is the wave’s strain, and are Newton’s gravitational constant and the speed of light,  is the distance from the source’s center of mass to the gravitational wave detector and is the double time derivative of the source’s quadrupole moment at retarded time . [Actually, and are tensors and there are tensorial subtleties in this equation, see, e.g., Sec. 36.7 of Misner et. al. (1973); but that is irrelevant for our purposes.] The magnitude of the quadrupole moment is , where and are the mass and size of that portion of the source which is varying in a nonspherical manner. Since the time derivative of is the speed , and is approximately their internal kinetic energy we can rewrite Equation (1) as  . (2)  The first expression says that the magnitude of the strain is approximately the mass-equivalent of the nonspherical internal kinetic energy, divided by to make it dimensionless. [the equivalence to the gravitational potential energy in the second term is discussed in the next paragraph – this one deals with the first approximation…]  For any realistic astrophysical system with huge, time varying internal kinetic energy, the source of its internal motions will be its self gravity. Energy conservation or the virial theorem dictates that the magnitude of the kinetic energy associated with nonspherical motions will be approximately the same as the magnitude of their gravitational potential energy, whence the second expression in Equation (2). [A quibble might be that the relevant “bulk” kinetic energy that can source gravitational waves is \*at most\* the gravitational potential energy; i.e., the kinetic energy that can source GWs cannot be larger, but can be smaller – e.g., because the motion is random (say, the thermal or quantum-mechanical pressure keeping a compact star from collapsing) or because it has too much symmetry (say, an axisymmetric accretion disk).]  Equation (2) tells us that the strongest sources will be those with the largest gravitational and kinetic energies associated with nonspherical motions. To have a huge gravitational energy, the source must be highly compact – almost as small as the black hole it would form if it were to collapse. To have a huge kinetic energy, the source’s internal motions must be nearly as fast as possible – as fast as the speed of light. |

**B.1.2 Four Classes of Gravitational Wave Sources**

In the early 1970s, Joseph Weber’s gravitational-wave experiments (Sec. 0.3 of the Prolog) and Weiss’s vision for GW interferometers (Secs. 1.1 and 1.2 of Chapter 1) triggered astrophysicists to try to predict what astrophysical systems would emit strong enough gravitational waves for detection. By 1978 (Smarr 1979)

Astrophysicists had divided these predicted sources into three classes: Burst Waves, Continuous Waves, and Stochastic Waves. Then in 1983, when Peter Saulson (in Section 2 of Linsay et al. 1983) pointed out that the waves from the *inspiral* of a compact binary (one made of black holes and/or neutron stars) will typically be more easily detected, by GW interferometers, than the burst waves from the *final collision and merger*, astrophysicists began to pull Compact Binaries out of the Burst class and into a class of their own. In the 2000s those four classes were adopted as a foundation for LIGO data analysis efforts (Sections 14n.2 and 14n.6). They are, specifically:

* The inspiral, collision and merger of compact binaries, i.e., binaries made from black holes and/or neutron stars – abbreviated ***CBC*** for compact binary coalescence.
* Sources of short gravitational wave bursts – abbreviated ***Burst*** sources.
* Sources whose waves continue, in a coherent, strong-wave fashion for as long as an observer cares to measure – abbreviated ***CW*** sources, for continuous waves.
* Sources that vary randomly and also last far longer than any observers’ measurements – abbreviated ***Stochastic*** sources.

To illustrate these four classes, here we list some of the most promising or plausible sources in each class, at the time of Advanced LIGO’s first observations (2015):

* ***CBC:*** 
  + **Binary black holes, BBH** – a pair of black holes that orbit each other, spiral inward due to loss of energy to gravitational waves, collide, and merge.
  + **Binary neutron stars, BNS**– a pair of neutron stars that orbit, inspiral, collide, and merge.
  + **Neutron star / black hole binaries, NSBH** – a black hole orbited by a neutron star that spirals inward and then is either swallowed whole by the BH, or is torn apart by the BH’s tidal gravity (tidal disruption) and then partially swallowed.
* **Burst*:***
  + **The final collision and ringdown** of a **BBH, BNS, or NSBH** – particularly when one object is a black hole so massive (intermediate mass black hole, **IMBH**) that the inspiral waves are at too low a frequency for LIGO to detect, so only the final burst of gravitational waves is seen.
  + **Core collapse supernovae, CCSNe –** the implosion of the core of a heavy star to produce a neutron star and release energy that ejects the heavy star’s outer layers. Various processes in CCSNe are expected to produce bursts of gravitational waves, neutrinos and gamma rays, as well as an electromagnetic supernova display.
  + **Collapsars**– the implosion of the cores of very massive stars to produce black holes with an accompanying burst of gravitational waves, a long gamma ray burst (longer than 2 seconds), and other emissions. [Should CCSNe and collapsars really be distinguished into two separate classes here? The type of electromagnetic signature, if any, accompanying core collapse presumably has a relatively small bearing on GWs, and may not have a unique association with the event – e.g., SNe may accompany some BH formation, not just NS formation; long GRBs probably do not accompany all collapsars, but do accompany some mergers (e.g., GRB 211211A, GRB 230307A).]
  + **Energetic excitations of isolated neutron stars**. For example, when the star is very strongly magnetized – a **magnetar** – and the magnetic field explosively rearranges itself.
* ***CW:*** 
  + **­Spinning NSs that are not symmetric around their spin axes.** The asymmetry can be due to, e.g., a deformed solid crust or core, a strong internal magnetic field (magnetars), or asymmetric accretion. These asymmetric NSs can occur in a variety of venues, for example:
  + **Isolated pulsars** – spinning NS’s that emit a rotating beam of electromagnetic waves.
  + **Binary pulsars** – where the pulsar is orbiting a companion, typically another neutron star. [with very few exceptions, the pulsars observed with NS companions are recycled pulsars, with very small spin period time derivatives – i.e., very weak spindowns, which therefore strongly limit any possible GW emission, so these seem like the least likely CW sources, right?]
  + **Low-mass X-ray binaries** – spinning NSs accreting gas from low-mass stellar companions.
  + **Spinning NSs with no observable electromagnetic emission.**
* **Stochastic:**
  + **Superposition of GWs from many discrete gravitational wave sources,** such as distant CBCs or extragalactic spinning NSs.
  + **Violent processes in the very early universe.** GWs that today are in the LIGO frequency band, ~ 100 Hz, have wavelength ~ 3000 km. The earliest and most optimal time to produce these waves, in the very early universe, was when the production region, with size of order one wavelength, extended all the way across the then observable universe, i.e. across the entire region where the source was in causal contact with itself. This turns out to have been when the universe was roughly seconds old, and the mean thermal energy of its particles was ~ GeV; see, e.g., Sec. 22.1 of Maggiore (2000). [[2]](#footnote-2) Among the violent processes that seem plausible at this optimal time and later are:
  + Any **first order phase transition** that might have occurred in the properties of the primordial matter at that epoch – though none is predicted at the relevant ~ GeV energy.
  + The evolution and decay of a **network of cosmic strings** formed before that epoch.

**B.1.3 Quick Overview of this Appendix**

In this appendix we sketch the history of astrophysicists’ ideas, estimates and knowledge about sources of gravitational waves in the LIGO frequency band, 10Hz – 10,000 Hz, from the 1960s when Weber was conceiving and building his bar detectors (Sec. 0.3 of the Prolog) to the 2010s when Advanced LIGO’s first searches were being planned (Chapter 20n). We confine ourselves to the few sources that, at any given time, were thought most promising. For a more thorough history see, e.g., this sequence of summaries of our knowledge at specific times: Press and Thorne (1972) [when Weiss conceived GW interferometers], Smarr (1979) [a two-week 1978 workshop on sources of gravitational waves], Appendix A of Vogt et. al. (1989) [the LIGO construction proposal], Thorne (2001) [in connection with the Advanced LIGO proposal], and LSC-Virgo (2014) [while advanced LIGO was being commissioned and its early searches planned].

**B.2 Sources before Weber’s 1969 announcement of gravitational waves**

In the 1960s, a vigorous effort was mounted by Stirling Colgate, Richard White, and Jim Wilson at Lawrence Livermore Laboratory to simulate on computers the collapse of a stellar core to form a neutron star—a process originally postulated by Fritz Zwicky in 1933 to explain supernovae, today called core-collapse supernovae, **CCSNe**. Impressed by progress, and seeing the very sharp bounce of the collapse when nuclear forces grabbed hold, astrophysicists began to think of such stellar core collapse—when nonspherical—as a promising source of gravitational waves. This view was reinforced in 1968 by the first observational evidence that neutron stars actually exist: the discovery of pulsars by Jocelyn Bell and Tony Hewish (Hewish et al. 1968). Although the supernova rate was known to be low—no more than once every 30-100 years in a galaxy like our own, some astrophysicists speculated there might be far more core collapses that produced no optical display (*silent supernovae*) than those which did, so the collapse rate might be as high as once per year in a galaxy like ours.

Little noticed at the time was a second promising source: binary neutron stars, **BNS**, pointed out and discussed by Freeman Dyson (1963) in a chapter titled “Gravitational Machines” within a book on *Interstellar Communication* that few astrophysicists read until many years later. [Lev Yungel’son sent me a scanned version of this visionary essay some years ago, though he told me it came from the book In the search for extraterrestial life, ed. Cameron, p.119. When I tried to track it down after Lev’s message, I found that it was submitted as an essay to the Gravity Research Foundation, where it won 4th prize in 1962, so this is presumably the original year: <https://www.gravityresearchfoundation.org/year#1962> (you can click on Dyson’s name to get the scanned essay)]

The 1965 discovery of the cosmic microwave background radiation, CMB, with its 3 K thermal (black body) spectrum triggered predictions that the universe’s big-bang birth should also have produced a **1 K thermal spectrum of stochastic, primordial gravitational waves** (Matzner 1968), but these waves were so weak[[3]](#footnote-3) (e.g., h ~ 10-36 at frequencies f ~ 100 Hz) that it seemed utterly hopeless to detect them.

**B.3. Source estimates in 1972, when Weiss proposed GW interferometers (Sec. 1.1.2)**

In June 1969, Joseph Weber’s announcement that his bar detectors were likely seeing gravitational waves (Sec. 0.3) triggered a large effort by astrophysicists to conceive of possible sources for his signals (Sec. 0.3) and to speculate about gravitational wave sources more generally. Weber’s announcement also triggered experimenters and theorists to brainstorm about possible types of gravitational wave detectors. Based on these speculations and brainstorming, Press and Thorne (1972) laid out a vision for Gravitational Wave Astronomy, including Table B1, in an article that went to press almost simultaneous with Rainer Weiss’s (1972) seminal paper (Sec. 1.2) on gravitational-wave interferometers.

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| Table B1. Gravitational-wave frequency bands, typical gravitational wave sources, and possible types of detectors, as envisioned by Press and Thorne (1972).  A picture containing receipt, text  Description automatically generated  Notes: By *Laboratory almost-free masses* was meant GW interferometers. By *Black holes* was meant black-hole collisions or holes that form by stellar collapse. |

In what has become the LIGO frequency band, 10 Hz to 10,000 Hz, core-collapse supernovae, **CCSNe**, were thought (wrongly, see below!) to be the most promising source. They had a respectable event rate of a few per year in the Virgo cluster of galaxies, and if collapses there were strongly nonspherical (as theorists in that early era thought some likely to be), their estimated wave amplitude at earth would be h ~ 10-20 to 2 x 10-22. **Colliding black holes** were recognized as strong emitters, but were extremely speculative with no basis for estimating event rates. One speculation was heavy black holes congregating in the centers of globular clusters and there colliding hierarchically – Wyller (1970), Peebles (1972). **Spinning, nonaxisymmetric neutron stars (pulsars)** were also thought promising, particularly the pulsar in the Crab Nebula. No attention was paid to binary neutron stars (BNS), nor to binary black holes (BBHs) formed by the evolution of massive binary stars.

But there were major new insights about **stochastic** **primordial gravitational waves**: Zel’dovich (XXXX1971) estimated that their interaction with high-energy particles was so weak that they likely would not have been thermalized even in the earliest moments after the big-bang singularity; they would travel to Earth unscathed by interactions with matter, bringing us direct information about the big-bang birth of our universe. And Misner (1969) and Rees (1971) speculated that the big bang might have been sufficiently chaotic to produce nonthermal primordial gravitational waves strong enough for detection—speculations that today are viewed with skepticism.

Finally, Shvartzman (1969) – a protégé of Zel’dovich – deduced an upper limit on any primordial gravitational waves that were produced before the era (universe age ~ one minute) when big-bang nucleosynthesis generated the universe’s helium and deuterium: If the waves’ energy density exceeded a certain value, the *nucleosynthesis limit*, it would speed up the expansion of the universe in the nucleosynthesis era, destroying the agreement between the predicted and observed abundances of primordial helium and deuterium. Schvartzman’s deduced value of this nucleosynthesis limit was ΩGW ≲ 4 ΩCMB ~ 4 x 10-4. Here Ω is the energy density in units of that required to close the universe. Over the ensuing years and decades, as the measurements of the primordial element abundances and the theory of big-bang nucleosynthesis have been improved, this nucleosynthesis limit has been tightened to ΩGW ≲ 10-5; see, e.g., Kolb and Turner (1990) and Maggiore (2000).

**B.4 Source estimates in 1976 when Thorne proposed GW experiment at Caltech (Sec. 1.3.4)**

By 1975-76, when Thorne was discussing with colleagues the advisability of creating at Caltech an experimental gravitational wave effort (Sec. 1.3.4), these speculations had not changed much, but there was beginning to be a better basis for estimating wave strengths. In a GW-astronomy vision paper following up on Press and Thorne (1972), which Thorne wrote in 1975-76 but which was delayed in publication (Thorne 1978), he displayed the source-strength diagram of Figure B1, which he called a “half-educated guess as to the strongest gravitational waves bathing the Earth”.

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| A close up of a map  Description automatically generated  Figure B1. Source-strength diagram for LIGO frequency band as of 1975-76 (Thorne 1978). |

In Figure B1, dots refer to dimensionless amplitude (left scale). Open circles refer to intensity (energy per unit area per unit frequency; right scale in units of 1 GPU = 100 J m-2 Hz-1). And circles with dots in the center refer to broad-band bursts (both scales). A dot standing alone refers to monochromatic, long-lasting waves (left scale). A dot connected by a straight line to an open circle refers to a damped ringing wave (gravitational wave *burst*) with maximum (initial) amplitude at the dot and total intensity at the circle. The distances to all shown burst waves are such that one “can reasonably expect several events per year”, except for those in the Milky Way whose rates were expected to be less (actually far less) than one per year—hence their dashed lines and dashed circles.

Notice that the strongest waves had amplitudes *h*~10-20 and were from stellar core collapse (“**black hole births**” and “**neutron star births**”, i.e., **CCSNe**) whose gravitational-wave energy output was guessed (incorrectly) to be a few percent of a solar mass, and whose distances were chosen to be that to which one supernova occurs per year – about 10 Mpc, the distance of the M101 cluster of galaxies [M101 is the Pinwheel galaxy; people sometimes talk about the M101 group (Pinwheel + companions), but I don’t think I’ve heard of the M101 cluster…]. The second strongest LIGO-band waves had amplitudes h~10-21 and were from heavy **black hole collisions** in globular clusters – with *on average* one collision assumed to occur in each globular cluster over the cluster’s lifetime. These black-hole collisions were regarded as far more speculative than the supernova estimates, but have turned out to be far closer to the truth – though the line for these “globular-cluster holes” should have been continued on leftward in the figure to 10M⦿. Surprisingly, there is no mention of BBHs outside globular clusters, nor of BNSs. Thorne was a little dense:

The first BNS had been discovered observationally by Russell Hulse and Joseph Taylor (1975) about six months before Thorne began writing this vision paper: the **binary pulsar** PSR 1913+16 – a discovery that would result in the Nobel Prize to Hulse and Taylor. It took two years for theorists to catch on. But then, triggered by this discovery, Clark and Eardley (1977), followed up by Clark, van den Heuvel and Sutantyo (1979) and by Clark (1979), estimated the event rate for gravitational waves from **BNS mergers** based on statistics of observed massive X-ray binaries that may become BNSs when they die. Clark et al concluded that BNSs were rather promising with the strongest signal each year h ~ (a few) x 10-22. They also discussed the inspiral and merger of **BBHs** and **BHNS** binaries (formed from the deaths of ordinary binary star systems) but had no basis for estimating event rates.   
[Things get interesting here. One paper that’s probably worth mentioning is Tutukov & Yungelson, 1973 (http://adsabs.harvard.edu/abs/1973NInfo..27...70T ). They predicted that binary compact objects must naturally form as a result of massive binary evolution (albeit rarely, and at wide separations in their model). Here is my translation of the key paragraph of their text (the paper was published in Russian):  
“Let us consider the question of the break-up of the WR+R system at the moment of the explosion of the WR component. [R here refers to a compact remnant; WR is a Wolf-Rayet star, in this context a stripped naked He star. – I.M.] Of course, it is in principle possible that during the earlier evolutionary stages, both stars lose a significant fraction of their mass, and collapse will not be associated with significant mass loss.  The system will remain bound, and it will be possible to obtain systems of the type pulsar + pulsar or collapsar + collapsar.  However, a study of detected pulsars doesn’t give a single example of binarity, therefore such a possibility should be considered as having lowprobability, at least for most systems.”]  
[The other relevant theoretical paper preceding Hulse-Taylor observations was by van den Heuvel and De Loore, 1973 (<https://ui.adsabs.harvard.edu/abs/1973A&A....25..387V/abstract>). They analysed X-ray binaries like Cygnus X-3 and argued that ultra-compact binaries must also form; they even mention gravitational waves in the last paragraph of the paper, but only consider them during the X-ray binary phase (when they are negligible), not during the compact object binary phase that must follow.]

By 1976 there was also a major new insight about stochastic **primordial gravitational waves:** Leonid Grishchuk (1975) showed that, if there was an epoch In the very early universe in which the universe’s rate of expansion (the “Hubble rate”) exceeded the frequency of a primordial gravitational wave, then that expansion will have parametrically amplified the wave, and that amplification under appropriate conditions could have been enormous.[[4]](#footnote-4) This presaged and became the physical foundation for the amplification of primordial gravitational waves by our universe’s inflationary expansion, Sec. XXX below.

**B5. Source estimates in 1978 at Battelle Workshop on GW Sources**

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| Figure B2. Source-strength diagram for the strongest burst sources that arrive about once per year. From the 1978 Battelle conference (Smarr 1979). |

Most of the world’s leading GW researchers—astrophysicists, relativists and experimenters—gathered together in Seattle on July 24-August 4, 1978, for a highly productive and memorable workshop on sources of gravitational waves. On the last day, in a collective, long discussion, they summarized their best understanding of sources. Figure B2, from page 483 of the workshop proceedings (Smarr 1979) shows the estimated strengths of the strongest burst GW signals arriving about once per year in and near what would become LIGO’s frequency band. The red star is the first such signal observed by LIGO (37 years later), GW150914. The down pointing arrows indicate that the signal could be far smaller than the indicated strength. The strong sources are:

* SN – **supernovae** (CCSNe, stellar core collapse). At the time of the workshop, astrophysicists were struggling to estimate the strengths of the waves from these collapses. Sophisticated supercomputer models of supernovae were still all spherical (with modelers only beginning to contemplate nonsphericity), so – as throughout the past – the amount and details of the nonspherical motions that produce the gravitational waves had to be guessed. As a key to guessing, Saenz and Shapiro (1979) had recently developed vastly simplified “one-zone” ellipsoidal computer models of the rotating, collapsing and bouncing stellar core and had seen large asymmetries develop during the bounces, which produced GW energy outputs of ΔEGW ~0.01 M⦿ , in accord with earlier optimistic guesses. However, some sophisticated spherical supercomputer models, e.g., by Sato (1975), showed neutrinos trapped inside the stellar core and leaking out in such a way that that the core (roughly speaking) oozed inward instead of crashing down, rebounding sharply and bouncing. This suggested that in the real world, large asymmetries might not develop, and even if they did develop their dynamics might be so dissipative that their gravitational waves would be weak: orders of magnitude less than ΔEGW ~ 0.01 M⦿. Thus, the SN strength shown in Figure B2 was only an upper limit. [Side remark: The neutrino trapping in Sato’s models arose from weak neutral currents in the neutrino interactions, predicted by Glashow, Salaam and Weinberg, and discovered in 1974 by the Gargamelle collaboration at SLAC and by an experiment at SLAC led by Barry Barish, who 20 years later would become director of LIGO.]
* **SNN** – **supernova neutrinos** (the so-called gravitational memory of sudden neutrino emission). Their gravitational-wave strength in Figure B1, h ~ 10-21 at frequencies f<100Hz, was also a suspicious upper limit, for similar reasons.
* **CBD** – **compact binary destruction** (called CBC in Sec. B.1.2): **BNS, BBH, and BHNS mergers.** The range of wave strengths shown (minimum, probable and maximum; h ~ 10-21–10-22) are for BNS, from Clark, van den Heuvel and Sutantyo (1979), discussed above. Paul Clark’s lecture at this conference (Clark 1979) had a big impact on many conference participants; it triggered them to pay attention, for the first time, to BNSs as a promising gravitational wave source in the LIGO frequency band.
* **BHGC** **–Hierarchical BBH mergers in globular clusters**. See Figure B1 and associated discussion above.
* **NSCQ – Neutron-star core quakes**, i.e., damped neutron-star pulsations triggered by the analog of an earthquake in a hypothesized solid core of a neutron star.

Looking at the wave strengths in Figure B2, the workshop participants identified a gravitational wave strain h ~ 10-21 as an experimental target, at which waves might first be detected. Amazingly, that was the strength of the first signal seen by LIGO, 37 years later: the BBH GW150914, inserted into Figure B2 as a red star, which was a 60 M⦿ BBH in a galaxy 400Mpc from Earth, and may have been in a globular cluster (the BHGC of Fig. B1).

Shortly before the Workshop, Drever and Weiss asked Thorne what are the strongest gravitational waves that could possibly bathe the earth, given astrophysicists’ cherished beliefs about the structure of the universe and Einstein’s general relativistic laws of gravity. Thorne and his student Mark Zimmerman reported the answer at the Workshop and published the details in an obscure Festschrift volume (Zimmerman & Thorne 1980). The answer, for gravitational-wave bursts, is *h* = 10-14 fHz-1/2, where fHz is the GW frequency in Hz. Note that this is four orders of magnitude larger than any of the sources contemplated in Fig. B2. This “cherished-belief” estimate would come back to haunt LIGO in 1991, see Sec. B7 below.

At the Battelle Workshop, the participants also discussed and summarized source estimates for periodic (monochromatic) gravitational waves: Figure B3. Although the gravitational wave amplitudes shown are far below those estimated for burst sources (Fig. B2), these periodic waves can be detected at far lower strengths by integrating up the signal over time (Appendix C). The sources shown are:

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| Figure B3. Source-strength diagram for the strongest periodic sources. From the 1978 Battelle conference (Smarr 1979). |

* **Crab: the pulsar in the Crab nebula.** The maximum wave strength h ~ 2x10-25

Is an observational upper limit: Radiation reaction due to emitting waves stronger than this would spin the neutron star down more rapidly than the observed spin down. (This also explains the upper limit shown in Fig. B1.) The most probable (prob) amplitude and the minimum (min) amplitude estimates are based on the physics of the neutron-star crust, observations of starquakes (glitches in spin rate of the neutron star), and other neutron-star parameters (Zimmermann 1978).

* **Vela: the pulsar in the Vela nebula.** Same as Crab (Zimmermann 1978).
* **YP: Youngest Pulsar** - A hypothetical neutron star 10 kpc from Earth in our Milky Way galaxy that was born spinning rapidly 10 years ago in a supernova hidden from view by obscuration, and has been spinning down due to gravitational wave emission ever since.
* **SIRR: Spinup Instability in Rapidly Rotating neutron star** – A neutron star that is being spun up by accretion from a companion to the point where the Chandrasekhar (1970) – Friedman & Schutz (1978), **CFS**, radiation-reaction instability creates and maintains a non-axisymmetric shape that generates gravitational waves. The star is assumed to be in our galaxy at a typical distance 10 kpc from Earth.
* **SIEQ**: **Spinup instability of Equilibrated neutron star:** A similar hypothetical star that is being spun up by accretion, but in this case has a non-axisymmetric ellipticity ε ~10-4 near its crystal breaking strain (or what was thought to be the breaking strain in 1978). The spinup torque is counterbalanced by the gravitational-radiation-reaction spindown torque.

The last three sources give some sense of the kinds of discrete sources astrophysicists were thinking about in 1978.

**Stochastic** sources of GWs were also discussed at the Workshop. No plausible sources strong enough to give any hope of detection were identified in the LIGO frequency band.

**B6. Source estimates in mid 1980s when the LIGO Project was founded and under Troika leadership (Sec. 3.5)**

In the next few years after the Battelle Workshop, the astrophysics community became more and more convinced that the gravitational-wave energies emitted by supernovae are orders of magnitude less than ΔEGW ~ 0.01 M⦿. With this sinking of supernovae, and with Saulson’s 1983 realization that the waves from the *inspiral* of a compact binary will typically be more easily detected, by GW interferometers, than the burst waves from the *final collision and merger* (Sec. B.1.2 above), ***compact binary mergers (BBH, BNS and BHNS) became the most favored sources in the LIGO frequency band, with spinning, nonaxisymmetric neutron stars (pulsars) also promising. This assessment did not change much in the 30 years between then and LIGO’s first GW discovery.*** The main things that did change, though not by a lot, were estimates of the event rates and wave strengths from these sources.

In 1984 and 1985, NSF encouraged the LIGO team to submit proposals for an Engineering design of LIGO. Two successive proposals were submitted but failed to garner sufficient enthusiasm from referees to move forward (Sec. 3.5.4). Both proposals included discussions of sources based largely on the 1978 Battelle Workshop but with some updating. The strengths of the waves from hypothetical burst sources (supernovae and compact binary inspiral/merger) were compared with the noise in two strawman LIGO detectors in a figure reproduced here as Fig. B4. The source strengths, plotted as a function of frequency, were characterized by the gravitational-wave amplitude *h* times the square root of the number of cycles of waves *n* in a bandwidth equal to frequency; the upward-plotted interferometer noise was the rms fluctuations of strain h in a bandwidth equal to frequency. The height of a source above the noise at any chosen frequency is the amplitude signal to noise ratio SNR in a bandwidth equal to frequency fo, i.e., the band from f=0.62fo to f=1.62fo (a unit logarithmic frequency centered on fo). To be detectable with confidence, that SNR needed to be about 8 or more.

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| Figure B6. Burst and CBC source strengths, and interferometer rms noise, from the 1984 and 1985 LIGO Engineering design proposals XXXXX. See text for explanation of the various curves. |

Two interferometers were shown: the first one that was tentatively planned to operate in the proposed LIGO facilities (with noise about 20 times worse than the ultimately constructed Initial LIGO interferometers) and a very advanced interferometer, with noise roughly three times lower than advanced LIGO.

The supernovae (SN) were characterized by their distance from Earth and their GW energy output in M⦿, ranging from 10-3 to 10-9 M⦿ (reflecting the range of estimates in the mid 1980s). The compact binaries shown were BNSs with identical 1.4 M⦿ neutron stars at various distances; and BBHs with identical 10 M⦿ black holes at various distances. During the binary’s inspiral the waves swept rightward with increasing frequency, along the arrowed lines. The strengths of the inspiral waves were known fairly well from post-Newtonian calculations (Appendix C). Those from the final collision and merger were not very well known; to learn them would require numerical relativity simulations (Appendix C). With this way of plotting the wave strengths and detector noises, astrophysicists could pick their own estimates of event rates as a function of distance from earth and see the implications for detectability.

Thorne, for his own planning purposes (June 1986, unpublished) made estimates of the probability of LIGO’s seeing its first gravitational waves as a function of the wave strength. He plotted those probabilities on this figure by hand in red ink. His probabilities were based on his reading of the Clark, van den Heuvel, Sutantyo (1979) estimates for BNSs (see above), and also based on some gut feelings that BBHs, with masses ~7 times larger than BNSs and so volumes searchable ~ 7x7x7 ~ 350 times larger [technically, 7^{2.5} rather than 7^3 for an inspiral spanning the detector bandwidth, since \tilde{h}(f) \propto M\_c^{5/6} , right? ], might be seen somewhat sooner than BNSs. Notice that his estimated probability was about 50 per cent for wave strengths hrms ~ 10-21, which was his and his colleagues’ targeted wave strength at the 1978 Battelle Workshop and would be the actual strength of the first signal (from a BBH) that LIGO would ultimately see – an agreement that was primarily luck, not wisdom!

In 1986, Bernard Schutz in Cardiff identified the observables that can be extracted from an observed gravitational waveform produced by an inspiraling BBH or BNS (Schutz 1986): the direction to the binary, its orbital inclination to our line of sight, the direction the two objects move around their orbit, the chirp mass, *Mc* = (*M*1 *M*2)3/5 /(*M*1*+M*2)1/5 where *M*1 and *M*2 are the object’s masses, and the binary’s luminosity distance. Schutz immediately recognized the implications for cosmology: with gravitational astronomy providing luminosity distances and electromagnetic astronomy providing redshifts, the combination, ***multimessenger astronomy***, might have a significant impact on our cosmological understanding of the universe. This gave significant added impetus for pushing forward.

During 1978 into the mid 1980s, there were no major new insights about **periodic sources.** However, there was major progress on **stochastic sources:**

An early epoch of **Inflationary expansion of the universe** was conceived in 1979-82 by Starobinsky (1979) , Guth (1981), Linde (1982) and Albrecht and Steinhardt (1982), and then further revised and developed by others, as a plausible (and indeed, to many theorists compelling) means for solving some observational mysteries: the origin of the fluctuations that grew into galaxies and clusters of galaxies, the near homogeneity and isotropy of the universe aside from those fluctuations, the near spatial flatness of the universe, and the absence of magnetic monopoles. This epoch of inflation, from age ~10-36 sec to ~10-32 sec, if it truly did occur, must have parametrically amplified by Grishchuk’s mechanism (Sec. B.4 above) whatever gravitational waves came out of the the big-bang singularity (the “Planck era”). It quickly became fashionable to assume, following Starobinsky, that those initial, Planck-era waves were the minimum allowed by the laws of quantum physics: *vacuum fluctuations*; and the resulting **primordial gravitational waves** today were then deduced, in the simplest and most compelling version of inflation (now called **standard inflation**) to have energy densities ΩGW ~ 10-15 spread roughly uniformly (d Energy / d ln f ~ constant) over all frequencies from 1/(age of universe) to ~ XX. In the LIGO frequency band, this is far too weak to be detectable by even Cosmic Explorer, the envisioned 2030s successor to LIGO (Sec. 23n.3.3 ~~20.2~~). But is likely to be detectable in other frequency bands in coming decades: GW periods of hundreds of millions to billions of years via the primordial GWs’ imprint on the polarization of the cosmic microwave background, CMB (Kamionkowski et al. 1997), and GW periods of seconds by a mid 21st century space-based GW detector called the Big Bang Observer (Phinney 2006).

**Phase transitions in the early universe** (Sec. B.1.2 above) were also identified, in the early 1980s, as plausible sources of both stochastic gravitational waves and the fluctuations that grew into galaxies and galaxy clusters (Witten (1984), Hogan (1986)). Witten and Hogan focused on QCD and Electroweak phase transitions, whose gravitational waves today would be at f ~ 10-7 and ~ 10-5 Hz, far below LIGO’s frequency band. As noted in Sec. B.1.2, there are no known phase transitions that would have produced gravitational waves in the LIGO band; but that has not prevented LIGO physicists from hoping.

**Networks of** **cosmic strings** (Sec. B.1.2 above) were also identified, in the early 1980s, as plausible sources of the fluctuations that grew into galaxies (Vilenkin 1981a; Zeldovich 1980) and as sources of stochastic gravitational waves (Vilenkin 1981b). These cosmic strings have nucleon-scale diameters and mass per unit length that could be as large as μ ~ 1021 kg/m (so G μ /c2 ~ 10-6), and they have tensions τ equal to their rest-mass energy per unit length, τ = μc2, so when they are plucked, bending waves travel down them at the speed of light c= , generating gravitational waves. Each string gravitationally deforms space around itself so the circumference of any circle C around the string is related to its radius R by C/R=2π(1-4Gμ/c2). When a string crosses through itself, it is predicted to reconnect with high probability forming a closed loop, and vibrations of these loops produce gravitational waves. A network of these cosmic-length strings might have been formed in a GUT (Grand unified theory) phase transition in the very early universe, and models of the network formation and evolution by Vilenkin (1981b) and others predict a gravitational wave spectrum [energy density rather than spectrum?] ΩGW ~ 10-4 (G μ /c2)1/2 in LIGO’s frequency band that could be strong enough for detection by LIGO, if the string network does form and μ is large enough; see Fig. B8 below.

**Black Holes from massive pre-galactic, population III stars:** In the early to mid 1980s, Carr (1980), Carr, Bond and Arnett (1984) and others speculated that there may have been a population of massive pre-galactic, “population III” stars that collapsed to form black holes and black-hole binaries that might inhabit the halos of galaxies like our own; and they speculated that the gravitational waves from the collapses and from the BBH mergers might superpose to produce a stochastic gravitational-wave background strong enough for LIGO to detect; Fig. B8 below. [Maybe mention that people are still thinking about mergers of Pop III stars as possible individually observable GW sources? Unrelated, but are primordial black hole mergers worth a mention?]

**B7. Source estimates in the 1989 LIGO Construction Proposal and the following few years**

Appendix A of volume 1 of the 1989 LIGO Construction Proposal (Vogt et al. 1989) contains a summary of what was known by then about sources of GWs that LIGO might detect.[[5]](#footnote-5) The estimates were not significantly changed from the mid 1980s (Fig. B6 and last section). Box 4.4n and Fig. 4.2 in Sec. 4, extracted from the construction proposal (Vogt et al. 1989), describe the scientific payoff that LIGO could bring and show a diagram similar to the earlier Fig. B6 above, which compares projected noise curves for the initial LIGO interferometer and an advanced LIGO interferometer, with source strengths from various hypothetical burst and CBC sources. The similar diagrams for periodic and stochastic sources, extracted from the proposal, are shown in Figs. B7 and B8.

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| Fig.B7. Hypothetical periodic sources of gravitational waves compared to projected noises of LIGO detectors, from 1989 LIGO construction proposal. |

In the **periodic figure B7** the Possible Advanced Detector noise curve is the envelope of minima of noise curves for detectors that are narrow-banded via signal recycling to search for periodic waves. The sources shown are: 1. Best estimate (labeled ***guess***) and upper ***limit*** based on observed spindown rates for several known pulsars (Vela, Crab, and PSR1937+214). 2. A neutron star that is emitting GWs due to the ***CFS instability,*** with the resulting spindown counterbalanced by spinup due to accretion from a companion star, and the accretion producing an X-ray flux Fx .The X-ray source Sco X-1 was speculated to be an example, so the GW strain h (proportional to Fx1/2 ) is plotted for values of Fx from Sco X-1 to Sco X-1/1000. 3. GWs from a hypothetical population of very young pulsars in our galaxy, being spun down by gravitational wave emission; Blandford had shown that the GW amplitude h of the strongest such waves depends only on the mean time τB between births of such pulsars – plotted for τB = 100, 104, and 106 years. 4. GWs from spinning neutron stars with specified distances r and ellipticities ε.

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| Fig.B8. Hypothetical stochastic sources of gravitational waves compared to projected noises of LIGO detectors, from 1989 LIGO construction proposal. Here ΩGW= (1/ρclose) dρGW/d ln f, where ρGW is the energy density in GWs, and ρclose is the energy density that would close the universe. |

In the **stochastic Figure B8** the Possible Advanced Detector noise curve the same as in Figure B7. The source curves shown are: 1. **Solid lines**: hypothetical GW background radiation with frequency-independent energy densities ΩGW, per unit logarithmic frequency interval (in units of the energy density to close the universe). 2. **Cosmic Strings dashed line:** stochastic GWs from a network of cosmic strings with mass per unit length Gμ/c2 = 10-6 (the canonical upper end of plausible values) formed in the GUT phase transition; see end of Sec. B6 above. 3. **Population III Black Hole dashed line**: Estimated upper limit (Carr 1980) on the superposition of GWs from BH births and BBH mergers for hypothetical Population III stars as described at end of Sec. B6 above.

**B8. History of estimates of compact-binary merger rates**

In 1991, with strong backing from review committees and the National Science Board in hand, NSF included funding for LIGO construction in the FY 1992 budget that President Bush submitted to Congress (Sec. 4.4.1). Several influential astronomers strongly opposed the LIGO funding (Sec. 4.4.3). Among their arguments was a claim that the LIGO team was greatly overestimating the source strengths. See Sec. 4.4.3 for details. These claims seem to have been based on the community’s overestimates of supernova GW strengths in the 1970s (Secs. B.2-B.5 above) and perhaps on the Zimmerman-Thorne (1980) cherished-belief exercise (Sec. B.4 above), neither of which were part of the scientific case for LIGO funding.

Spurred by this controversy, Sterl Phinney (1991) and independently Ramesh Narayan, Tsvi Piran and Amotz Shemi (1991) reexamined the best understood source: binary neutron stars. By then astronomers had discovered in our galaxy three binary pulsar systems (BNSs that contain a pulsar from which the gradual orbital decay due to GW emission could be measured), whose neutron stars would spiral together and merge in less than the age of the universe. These three gave a far better basis for estimating BNS merger rates in the universe than had previously been available. Phinney, and Narayan et. al. arrived at the same estimate: the distance to which there would be one BNS merger per year is about 300Mpc. Phinney gave a semi-firm lower limit of 50 Mpc and an “ultraconservative” upper limit of 1500 Mpc. Narayan et. al. estimated a one-per-year distance for BHNS mergers about the same as for BNS, 300 Mpc.

Soon thereafter, Steinn Sigurdsson and Lars Hernquist (1993) [published the same month?: Kulkarni et al., 1993, http://adsabs.harvard.edu/abs/1993Natur.364..421K] revisited the source that Wyller (1970) and Peebles (1972) had identified (Secs. B.2-B.4): heavy black holes sinking to the centers of globular clusters and there colliding. They argued that at least one BBH merger was likely to occur in each core-collapse globular cluster, which means at least one BBH signal per year out to 1000 Mpc.

This was the beginning of an epoch in which – driven by (at least seeming) astrophysical understanding and by the construction of LIGO – astrophysicists worked hard to improve their estimates of compact-binary merger rates. Table B2 shows the development of these estimates over time, from the earliest estimates in the 1970s to the rates that LIGO and Virgo have actually measured as of 2020.

Before discussing this table, a digression: Thorne recalls thinking it likely in the 1990s, and perhaps even in the mid 1980s, that LIGO would see GWs from BBHs before BNSs. His reason was that, for the relevant mass ranges, the distance to which LIGO can see roughly equal mass binaries is proportional to the binaries’ component masses, which in that era seemed likely to be ~15 M⦿ for BHs vs ~1.5 M⦿ for NSs, so BBHs could likely be seen ~10 times farther than BNSs. Correspondingly, the volume of universe searched for BBHs would likely be ~103 = 1000 times greater than for BNSs [see earlier comment – should probably be 102.5 for a bandwidth-spanning source]. And it seemed to Thorne that this factor ~1000 would likely outweigh the presumed larger BNS merger rate per unit volume. Indeed, as astrophysicists’ estimates of the distances for one event per year progressed in the 1990s (Note 3 to Table B2), they corroborated this. However, Thorne – badly burned by astrophysicists’ attacks on his public pronouncements about event rates (Sec. 4.4.3) -- was reticent to make any such prediction in public. So instead he simply encouraged students and colleagues privately to focus on binary black holes as a likely strongest LIGO source.[[6]](#footnote-6)

Table B2. For compact binaries: estimated distance, in Mpc, to which there is one merger per year

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Reference and year | BNS  min | BNS  **best** | BNS  max | BHNS  min | BHNS  **best** | BHNS  max | BBH  field  min | BBH  field  **best** | BBH  Field  max | BBH  GC  min | BBH  GC  **best** | BBH  GC  max |
| Thorne (1978) |  |  |  |  |  |  |  |  |  |  | **400** |  |
| Clark and Eardley (1977) |  | **70** |  |  |  |  |  |  |  |  |  |  |
| Clark et. al. (1979) | 60 |  | 200 |  |  |  |  |  |  |  |  |  |
| Phinney (1991) | 50 | **300** | 1500 |  |  |  |  |  |  |  |  |  |
| Narayan et al (1991) |  | **300** |  |  | **300** |  |  |  |  |  |  |  |
| Sigurdsson & Hernquist (1993) |  |  |  |  |  |  |  |  |  |  | **1000** |  |
| Kalogera (2001) | 30 |  | 300 | 50 |  | 700 | 100 |  | 600 | 100 |  | 300 |
| Kalogera et al (2004) | 30 | **60** | 200 |  |  |  |  |  |  |  |  |  |
| Kalogera et al (2007) |  |  |  |  |  |  | 100 | **360** | 1300 |  |  |  |
| O’Shaughnessy  et al (2008) |  |  |  | 60 | **200** | 700 |  |  |  |  |  |  |
| Abadie et al (2010) | 30 | **60** | 300 | 60 | **200** | 740 | 90 | **360** | 1300 |  |  |  |
| LIGO observed  LIGO-Virgo (2020) | 55 | **75** | 120 |  |  |  | 180  Field +GC | **220**  Field +GC | 270  Field +GC | 180  Field +GC | **220**  Field +GC | 270  Field +GC |

Notation: best – best estimate. GC – merger of BBHs near centers of globular clusters. field – BBH mergers in the “field”, i.e., not in globular or other dense star clusters, where black holes sink to the center and meet. [There are NSBH merger rate estimates as well from slightly later LIGO-Virgo papers, after these were detected in early 2020, that could be included.]

Brief description of the references:

* Thorne (1978) – first very rough estimate of distance for one detectable BBH merger per year of black holes that have sunk to the centers of globular clusters and found each other and collided (Peebles 1972; Wyller 1970). Estimate based on an average of one merger per globular cluster; Sec. B.3.
* Clark and Eardley (1977) – first estimate of BNS merger rate after the discovery of the first binary pulsar; Sec. B.3.
* Clark et. al. (1979) – improved estimate of BNS merger rate; Sec. B.3 and Fig. B.2.
* Phinney (1991) and Narayan et al (1991) – estimates of BNS merger rate during political battle over LIGO construction; based on three observed binary pulsars that will merge in less than the age of the universe; Sec. B6.
* Sigurdsson & Hernquist (1993) – estimate of BBH merger in globular clusters based on one such merger in each core-collapse cluster; Sec. B6.
* Kalogera (2001) – In 2000 the astrophysicist Vicky Kalogera joined the LIGO Scientific Collaboration, bringing many years of knowledge and experience on the evolution of binary systems. She quickly became the leader of efforts to estimate merger rates of compact binaries. For this reference, which documented the scientific case for designing and building the Advanced LIGO interferometers, she assembled the best recent estimates for the merger rates of all three types of compact binaries: BNS, NSBH, and BBH; estimates based both on observational data and on population synthesis models (statistical evolution, often by her own research group, of observed binary systems that can become BNS, NSBH, or BBH at later stages, but not yet observed).
* Kalogera et al (2004) – the last major revision of the estimated BNS merger rate before LIGO’s discovery of gravitational waves. This revision was occasioned by the discovery of a highly relativistic binary pulsar J0737-3039, whose properties drove the estimated rate upward.
* Kalogera et al (2007) – the last major revision of the estimated BBH merger rate before LIGO’s discovery of gravitational waves.
* O’Shaughnessy et al (2008) – the last major revision of the estimated BHNS merger rate before LIGO’s discovery of gravitational waves. [The papers listed above are all very important, but perhaps the wording “the last major revision”, here and in the bullet points above, may surprise some of the people from outside Vicky’s group (and even some within it), since there was a lot of continuing work on rates predictions up to 2015. The Living Review in Relativity by Mandel & Broekgaarden attempts to uncritically list the key contributions \*after\* 2010 in tables / figures (see <https://arxiv.org/abs/2107.14239> for the latest public version, superceeding the LRR one). These include not just similar-in-spirit population synthesis models with different assumptions, but also some other ways of getting observationally motivated estimates – e.g., from observed short GRB rates under the (now known to be incorrect) assumption that these have a 1-to-1 relationship to BNS mergers. Obviously, listing any more models here is impractical, but perhaps some alternative choice of wording could avoid unintentionally slighting other authors.]
* Abadie et al (2010) – The “official” predictions of the LIGO/Virgo collaboration, discussed in Sec. 20n.1; based on Table 4 of this paper.
* LIGO-Virgo (2020) – LIGO’s measurements of the BNS and BBH merger rates as of the 2020 release of the second LIGO-Virgo GW Transient Catalog. [use GWTC3 rates, to also include NSBH?]

Notice that:

1. The measured BNS distance for one event per year, 75 Mpc, is in remarkably good agreement with the most recent of the estimates (Kalogera et al. 2004) and also – fortuitously – with the first estimate ever made (Clark & Eardley 1977). However, the true merger rate turned out to be (300/75)3 = 64 times higher than the very careful estimates made during the controversy over LIGO construction (Narayan et al. 1991; Phinney 1991). The three observed binary pulsars used to underpin those careful estimates were not representative of the universe’s binary neutron star population. Given the statistics of small numbers of observations (just three), this is not very surprising. [The GWTC-2 BNS rate estimate is based on even smaller statistics – only two events, not even three. ☺ And the rate is probably over-estimated there, judging by the paucity of subsequent detections: we got very lucky very early with GW170817 in particular.]
2. LIGO’s observational data (LIGO-Virgo 2020) show evidence of BBH mergers both in the field and in globular clusters, though the evidence as of 2020 is far from definitive. The observed total rate of mergers, one per year out to 220 Mpc, is (360/220)3 = 4 times higher than the most recent of the estimates for BBH mergers in the field (Kalogera et al. 2007), and larger than either of the estimates for BBHs in globular clusters (Sigurdsson & Hernquist 1993; Thorne 1978). [Again, I can imagine a few readers who might object to the wording. E.g., the observed BBH merger rates are consistent with the ranges predicted by both globular cluster models from Bae et al. 2014 and field models from Dominik et al. 2015, just to pick two papers that were published before aLIGO turned on from figure 3 of the Mandel & Broekgaarden LRR.]
3. During the 1990s the “best estimate” distance to which LIGO could see one BNS each year became about 60 Mpc, compared to about 300 Mpc for BBHs, corresponding to a rate per unit volume ~63 = 216 times higher for BNS than BBH – which indeed was turning out to be substantially outweighed by the estimated 1000 times larger volume searched for BBHs.
4. LIGO has seen GWs from compact binary mergers that may be NSBH, but the measured mass of the lighter body is such that it might be a BH rather than NS, so as of 2020 there is not yet an observed rate for NSBH mergers. [Aside: I am \*personally\* quite confident that GW200115 was an NSBH with a canonical NS mass – see <https://ui.adsabs.harvard.edu/abs/2021ApJ...922L..14M> -- and the over-stated uncertainty in the LVK estimates is a consequence of the analysis choices… ☺ ]

**B9. Estimates for GW sources in 2001 when the final design and construction of advanced LIGO was proposed**

In 1990, when the National Science Board approved the LIGO construction proposal (Sec. 4.4), astrophysicists significantly intensified their efforts to conceive and understand sources that LIGO might detect. The fruits of this were rich by eleven years later, when planning for initial-LIGO data analysis was getting underway (Sec. 14n.2.1) and when the LIGO team was putting together the proposal for final design and implementation of the advanced LIGO interferometers (Sec. 4.3.3). Figure B9 and Box B3, from the Science Case for that proposal (Thorne et al. 2001),[[7]](#footnote-7) gives some sense of that richness. The box explains a number of sources plotted in the figure, plus other sources not plotted there.

In the figure and box, *WB IFO* means the standard, wide-band advanced-LIGO interferometers that were actually built, and *NB IFO* means an advanced-LIGO interferometer whose noise spectrum is narrow-banded by giving the signal recycling mirror a very high reflectivity, with its frequency minimum adjusted to some target frequency by adjusting the precise location of the mirror (Sec. 2.6.3); this NB IFO has never yet been implemented and as of 2021 there are no plans to do so[[8]](#footnote-8). *Silica* (fused silica, i.e., quartz) and *Sapphire* refer to the substrates of the interferometers’ mirrors.

This figure, by contrast with previous ones in this appendix, shows in a single diagram CBC, periodic, and stochastic sources; it does so by introducing a new convention for plotting source strengths that is described in the figure caption, and in greater detail in the advanced LIGO proposal.

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| Fig. B9, The noise h ̃(f) in several LIGO interferometers plotted as a function of gravity-wave frequency f, and compared with the estimated signal strengths h ̃s(f) from various sources. The interferometers are Initial LIGO, and Wide Band (WB) and Narrow Band (NB) Advanced LIGO .The signal strength h ̃s(f) is defined in such a way that, *wherever a signal point or curve lies above the interferometer’s noise curve, the signal, coming from a random direction on the sky and with a random orientation, is detectable with a false alarm probability of less than one per cent*. From the Science Case for Advance LIGO (Thorne et al. 2001). |

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Among the major new insights about sources, in 1989-91, were these:

***Compact Binary Coalescence, CBC:***

**Event rate estimates:** In the late 1990s Vicky Kalogera and other astrophysicists joined the newly formed LIGO Scientific Collaboration (LSC; Chapter 13n). Kalogera led a project to estimate CBC event rates through *population syntheses*– models of the evolution of the universe’s population of compact binaries and their stellar progenitors, informed by a wide range of astronomical observations. The LSC fostered interactions between the astrophysicists, instrumentation scientists, and LIGO data analysts, which informed the effort to improve the reliability of CBC event rates. The rates shown in Box B3 and in Box B2 from 2001 onward were much influenced by this. [This somewhat repeats text around line 784]

**Gamma ray bursts:** The sources of these bursts, which were first discovered in the 1960s by the U.S. Vela satellites, remained a mystery for decades, until 1997, when fading x-ray and optical afterglows were discovered in distant galaxies and were compellingly interpreted as from fireballs created by supernovae and/or BHNS binary mergers and/or BNS mergers; see the gamma-ray-burst entry in Box B3.

***Burst Sources of GWs***

**Cusps and Kinks on Cosmic Strings:** Recall (Sec. XXX) that, if cosmic strings form in the very early universe, their self intersections reconnect with high probability, producing loops whose vibrations generate gravitational waves that might be strong enough for LIGO to detect. The point of reconnection is a kink on the loop – a location where the tangent vector is discontinuous, i.e., an ultrasharp bend; and further self-intersections and reconnections produce more kinks. Each kink persists and travels along the string at the speed of light, generating a sharp GW burst.

Vibrations of the string loops can also produce momentary cusps at which the tangent vector reverses direction and which momentarily move at light speed.

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| Fig. B10, Example of a gravitational waveform from a cusp and from a kink on a cosmic string. The waveforms always have these shapes. |

Damour and Vilenkin (2001) computed the *gravitational waveforms of these cusps and kinks* (Fig. B10) and their strengths, and deduced that (i) they make the string network’s stochastic background highly non-Gaussian, (ii) they will occasionally stick up above the stochastic background and (iii) they may be detectable by LIGO.

***Periodic Sources [CW]:***

**R-modes in neutron stars:**In 1998 Nils Andersson (1998) discovered that r-modes of moderately rapidly rotating neutron stars are driven unstable by gravitational radiation reaction, i.e., are a specific case of the CFS instability; and it quickly became likely that among all CFS-unstable modes, these are likely to be the ones of greatest importance for gravitational-wave emission. (These modes consist of quadrupolar circulation patterns for which the restoring force is Coriolis.) As of 2001, careful studies of the relative strength of viscous damping and radiation-reaction driving suggested that, if a protoneutron star created in a stellar core collapse is born spinning faster than about 100 revolutions per second, the r-mode instability will dominate and the r-modes may radiate gravitational waves strong enough for advanced LIGO to see out to the distance of the Virgo cluster of galaxies.

***Low-mass X-ray binaries, LMXBs****:* These are a family of X-ray sources, identified observationally in 1995, that appear to be neutron stars (or, sometimes, black holes) accreting gas from a low-mass, normal-star companion. The stars’ spin periods cluster in the range ~300 to 600 revolutions per second. Bildsten XXXX proposed a highly plausible explanation: that the accretion is producing an asymmetry in the neutron star that radiates gravitational waves whose spin-down torque balances the action’s spinup torque – in which case the strength of the emitted gravitational waves can be inferred directly from the observed X-ray flux. Figure B9 shows as large black dots the inferred gravitational wave amplitude and frequency for seven LMXBs, and shows a large black star for the X-ray source Sco X-1 assuming it is also an LMXB.

***Stochastic Sources***

**Pre-Big-Bang Cosmology**: Brustein, Gasperini, Giovannini and Veneziano (1995), in a first, tentative effort to combine superstring theory with cosmological inflation, produced a new description of the early universe, radically different from previous ones, called the pre-big-bang model. In this model fundamental string effects cause the gravitational-wave spectrum to rise steeply at high frequencies – most likely at frequencies above LIGO’s band, but possibly in or below it. The result could be a stochastic background of gravitational waves strong enough for LIGO to detect. This model is a cautionary warning that standard inflation, with its very weak LIGO-band waves, might turn out to be wrong.

**Superposition of Emission from Supernovae in Distant Galaxies:** Blair and Ju (1996) pointed out that, if the efficiency with which supernovae convert their mass into gravitational waves exceeds 10-5, then the superposition of their waves could be a stochastic background detectable by advanced LIGO.

**B.10. Estimates of GW Sources in 2014, The Year Before Advanced LIGO’s First Gravitational Wave Search**

In 2014 the LIGO Scientific Collaboration and Virgo Collaboration together produced a White Paper (LSC-Virgo 2014) on planned advanced-LIGO / advanced-Virgo gravitational wave searches and associated astrophysics. This white paper included an overview of gravitational wave sources that would be searched for and plans for the searches. From the source overview one can identify major new insights about sources that were developed in 2001 – 2014; among them are these:

***Stochastic Sources***

**Superposition of waves from BNSs and other present-era sources:** Planning for advanced LIGO observations triggered a large number of astrophysicists to carry out detailed estimates of the stochastic background in the LIGO band produced by superposition of all the universe’s sources of various sorts. Regimbau (2011) collated and reviewed these estimates and also what is known about how the statistical properties of these superposed backgrounds might differ from those of gravitational waves from the early universe. Not surprisingly, the background from binary neutron star (BNS) inspirals was deemed likely to dominate in the LIGO frequency band (Regimbau 2011; Wu et al. 2012). Other sources, whose superposed background might be detectable by LIGO include CCSNe, colapsars, r-modes in newborn neutron stars, and magnetars.

**Inflationary Cosmology:** There are an enormous number of different models for inflation. The simplest and most compelling model is called *standard inflation* and predicts a stochastic background with energy density ΩGW ~ 10-15 much too small for even future incarnations of LIGO to detect (Sec. B6). During this 2001-2014 period, several plausible variants of inflation were developed that predict, beginning with vacuum fluctuations, substantially higher ΩGW, high enough for advanced LIGO to detect (Barnaby et al. 2012; Cook & Sorbo 2012).

***CBC and Burst Sources***

**Sources of Gamma Ray Bursts:** Already in the 1990s it became clear from observations that there are two classes of gamma ray bursts: *short bursts* (durations less than about 2s) with hard spectra (preponderance of higher energy gamma rays), and *long bursts* (durations longer than about 2s) with soft spectra.

In the early 2000s observations revealed that *many long bursts are associated with supernovae* (Woosley & Bloom 2006), and may be energized by collapse of a massive stellar core to form a black hole—by a *collapsar*, though there may be more than one type of source for these long bursts.

And in the 2000s, a combination of observations and modeling suggested that the *short bursts may be produced by the final mergers of BNSs and/or* BHNSs (Nakar 2007).

**Kilonovae:** In 2010, Metzger et. al. (2010)published the results of a pioneering theoretical model of the optical/infrared (IR) transient (afterglow) of the mergers of neutron star binaries (BNS) and neutron star / black hole binaries (NSBH). Their model focused on the nuclear reactions in the merger, the radioactive decay of the reaction products in the merger remnant, the heating of the remnant by that decay, and the resulting evolution of the remnant’s light curve. They gave the name *kilonova* to this optical/IR display. [There was quite a bit of work on kilonovae (without that name) between Li & Paczynski (1998, https://arxiv.org/abs/astro-ph/9807272) and Metzger’s paper, most notably by Rosswog and collaborators (e.g., <https://ui.adsabs.harvard.edu/abs/2005ApJ...634.1202R>). ] Three years later, Berger, Fong and Chernock (2013) discovered [Might be better to at least share the discovery credit with Tanvir et al., <http://adsabs.harvard.edu/abs/2013Natur.500..547T> -- there is some unpleasant history that’s probably best avoided for the purposes of this story] a kilonova (i.e., an optical transient matching the Metzger et al predictions) associated with a short hard gamma-ray burst, thereby verifying, at least in this case, the association of short hard gamma bursts with a BNS or NSBH merger and kilonova.[[9]](#footnote-9)

**Eccentric BBHs in Galactic Nuclei:**Ever since the 1980s [KIP CHECK] astrophysicists have speculated that stellar-mass black holes in the central regions of galaxies will congregate near the supermassive black hole that typically lives there, and finding each other, may capture each other, forming a binary system – a capture BBH. Motivated by anticipated advanced LIGO observations, O’Leary, Kocsis and Loeb (2009) carried out a detailed Fokker-Planck analysis of the likely formation and evolution of a population of such BBHs. They deduced that LIGO would might see between one and 100 mergers of such BBHs per year, and that most of these coalescing BBHs would be highly eccentric (e > 0.9) when they entered the LIGO frequency band. [I recall that much of the community considered these estimates to be implausible from the time they appeared. A more realistic channel for forming eccentric BH binaries that preceded the first LIGO detection was developed by Samsing and collaborators (e.g., <http://adsabs.harvard.edu/abs/2014ApJ...784...71S>) – GW bremsstrahlung captures during chaotic 3-body interactions in the midst of binary + single scattering events.] This triggered Kocsis and Levin (2012) to compute gravitational waveforms for the inspiral and merger of highly eccentric BBHs. Their waveforms consisted of many repeated short GW bursts for minutes or even days (depending on the orbital eccentricity), followed by a powerful GW chirp and then a merger burst.

**Intermediate Mass Ratio Inspirals, IMRIs:** Also since the 1980s [KIP CHECK] astrophysicists have speculated that intermediate-mass black holes (IMBHs, masses ~ 100 to 1000 Msun) might form in the centers of some globular star clusters, and might capture an occasional neutron star or far smaller black hole into orbit around itself. Motivated by LIGO and these speculations. Mandel et. al. (2008) carried out numerical simulations of these captures and the subsequent evolution of the small object’s orbit. They concluded that 1. the orbit shrinks due to three-body interactions with other stars in the cluster, becoming small enough that gravitational radiation reaction takes over. The small object then spirals inward, emitting gravitational waves, and gets swallowed by the IMBH. 2. The rate of such events could be high enough for advanced LIGO to see a few. Brown et. al. (2007) have shown that the observed gravitational waveforms from such an intermediate mass ratio inspiral (IMRI) carry information about physical nature of the body into which the small object spirals: if that body is not a black hole, then the waveforms may reveal that, or at least place limits on deviations from a black hole.

**Intermediate Mass Black Hole (IMBH) Mergers in Globular Clusters:** We conclude this history of human speculations and results about GW sources by returning to one of the very earliest speculations – that heavy black holes might congregate in the cores of globular clusters and there collide and merge hierarchically (Peebles 1972; Wyller 1970). In preparation for advanced LIGO’s GW searches, the LSC/Virgo scientists revisited this (LSC-Virgo 2014), and reached a cautiously hopeful conclusion about prospects to see the GWs from these mergers.

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1. The meaning of and reason for this “contemporary universe” caveat will be explained in the *Stochastic* portion of this section, below, particularly footnote 2. [↑](#footnote-ref-1)
2. This illustrates the meaning and reason for the “contemporary universe” caveat in footnote 1 above: The contemporary universe is the current era in which strong sources of gravitational waves are isolated from each other and cover regions tiny compared to the observable universe. The early universe processes that produce the strongest GWs today are expected to have extended across the entire observable universe at the time of their violence. [↑](#footnote-ref-2)
3. For the predicted temperature of 1K, the peak of the Planck spectrum of the waves is at frequency f ~ 1011 Hz. At frequencies much below that peak (the Rayleigh-Jeans regime), the waves’ characteristic amplitude [Eq. (65) of Thorne (1987)] is = 1.1 x 10-36 (T/1 K)1/2 (f/100 Hz)1/2 . [↑](#footnote-ref-3)
4. The historical context of this discovery is described in Grishchuk’s obituary (Braginsky et al. 2012), from which the following is adapted: In the early 1970s, it was almost universally believed that the equations governing all fundamental physical fields are conformally invariant. This implied that the isotropic expansion of the Universe, no matter how rapid, could never create particles of any kind, including no gravitons (gravitational waves). Grishchuk was skeptical of this claim. From Einstein's field equations, he deduced the equation that governed gravitational waves in the early, isotropically expanding Universe, he showed that this equation is *not* conformally invariant, and using it he predicted the parametric amplification described in the text. On this basis, he deduced that a rich spectrum of primordial gravitational waves *could* have emerged from the Big Bang. This broke the mistaken “conformally invariant” mindset of cosmologists of the early 1970s, forcing them to accept that other particles could have been created, along with gravitons, by rapid expansion early expansion. But no mechanism for such rapid expansion was then (1975) known; it came a few years later, in the form of *inflation.* [↑](#footnote-ref-4)
5. This was largely based on the discussion of gravitational-wave sources in a very long vision for gravitational-wave astronomy that Thorne had published two years earlier (Thorne 1987) [↑](#footnote-ref-5)
6. Two examples: 1. At Thorne’s urging, Flanagan and Hughes (1998) inserted into their abstract “BBHs might well be the first sources detected by LIGO-VIRGO…” followed by a variant of Thorne’s mass ratio argument. 2. In a very long memo to colleagues at other institutions, commenting about a manuscript on which the colleagues were seeking advice, Hughes and Thorne (1996) wrote: “Our own best guess is that black hole binaries will be significantly more numerous in LIGO data than neutron star binaries, but that is only a guess, so we don’t advertise it.” [↑](#footnote-ref-6)
7. Soon after writing that proposal, Thorne and Cutler (2002) expanded it into a review of sources of gravitational waves in all frequency bands, not just LIGO’s band. [↑](#footnote-ref-7)
8. There are a couple of reasons for this. As the NB curve shows, the sensitivity improvement over a narrow bandwidth comes at the expense of poorer sensitivity at other frequencies. In addition, the high reflectivity of the signal recycling mirror means that the interferometer becomes very sensitive to optical loss in the signal recycling cavity, so achieving even the narrow-band benefit is challenging. The preferred approach to improving high-frequency sensitivity in 2021 is a combination of high laser power and squeezing, and also widening the bandwidth with the signal recycling mirror. [↑](#footnote-ref-8)
9. As is now well known, Advanced LIGO would go on to confirm this association with its discovery of the BNS gravitational wave signal GW170817 with a short hard gamma ray burst and an optical/IR kilonova; Chapter 22n. [↑](#footnote-ref-9)