History and puzzles of NS-NS binaries as gravitational wave sources

E. Sterl Phinney

Caltech

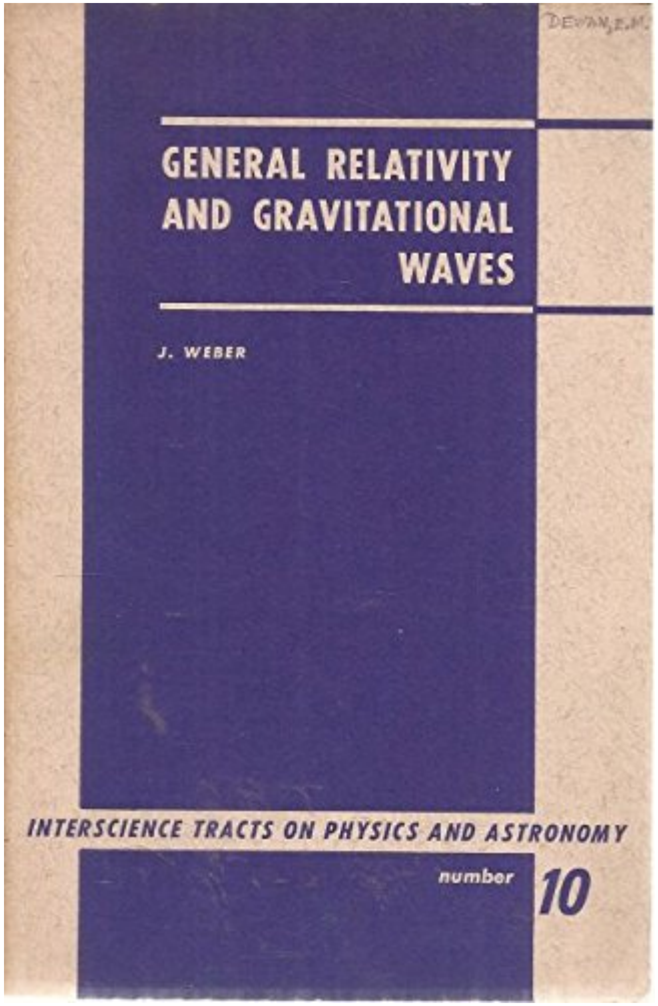
1961 textbook by Joseph Weber: outlines production and detection methods for gravitational waves.

1968: Weber claims detections of coincident bursts from two bar detectors separated by 1000km.

1970: Weber claims sidereal periodicity of the bursts from GC.

Theorists stymied: 10^4 bursts/y with 10^{53}erg/burst at 10kpc.

1972-1978: Braginsky, Drever, Garwin, Tyson, Amaldi…
fail to reproduce Weber detections.



Partridge & Wrixon 1972, Slusher & Tyson 1973, Dube 1973: first EM-GW searches (radio).

1962: Compact binaries as GW sources: it all began at lunch at the Caltech Athenaeum:

repeating nova (1913, 1946), P_b=81min

BINARY STARS AMONG CATACLYSMIC VARIABLES. II. NOVA WZ SAGITTAE: A POSSIBLE RADIATOR OF GRAVITATIONAL WAVES

The figures presented in this letter are uncertain because we have no satisfactory model for WZ Sge, and, in any case, they appear to place the direct detection of gravitational radiation at, or beyond, the extreme limits of possible measurement. Effects on the period produced by tidal forces and mass-loss or exchange may also complicate the picture. However, it is of interest that close double stars may radiate enough gravitational power to be astrophysically significant and even detectable.

ROBERT P. KRAFT
JON MATHEWS
JESSE L. GREENSTEIN

May 8, 1962
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY
AND
PHYSICS DEPARTMENT
CALIFORNIA INSTITUTE OF TECHNOLOGY

Kraft, Mathews & Greenstein 1962

Binary stars radiate energy in the form of gravitational waves (Landau and Lifshitz 1951). The radiated power for a circular orbit is

$$\frac{dE}{dt} = \frac{32}{5} \frac{G^4}{c^5} \frac{(\mathfrak{M}_1 + \mathfrak{M}_2)\, \mathfrak{M}_1^2 \mathfrak{M}_2^2}{a^5} . \qquad (1)$$

The loss of energy causes the stars to spiral in toward each other; if the stars were mass points, they would fall together in the finite time

$$T = \frac{5}{256} \frac{c^5 a^4}{G^3 \mathfrak{M}_1 \mathfrak{M}_2 (\mathfrak{M}_1 + \mathfrak{M}_2)} . \qquad (2)$$

the power radiated gravitationally is probably considerably larger than the stellar luminosity. For example, with $\mu = 0.2$, the gravitational loss is 1.3×10^{33} ergs $\sec^{-1}$; the stellar luminosity is 4×10^{31} ergs $\sec^{-1}$ for a bright white dwarf.

At the probable distance of WZ Sge (50–100 pc), the gravitational flux reaching the earth is quite small ($\sim 10^{-9}$ erg cm^{-2} sec^{-1} for $\mu = 0.2$). Detection of such a small flux appears to be very difficult. If two masses connected by a spring of length x are placed

Kraft, Mathews & Greenstein 1962

Alternatively, we might consider detecting the change in period of the binary. The rate of change of period is

$$\frac{dP}{dt} = -\frac{192\pi}{5}\frac{G^{5/2}}{c^5}\frac{\mathfrak{M}_1\mathfrak{M}_2(\mathfrak{M}_1+\mathfrak{M}_2)^{1/2}}{a^{5/2}}$$
$$= -\frac{12\pi^2 a^4}{P}\frac{dE/dt}{G^2(\mathfrak{M}_1+\mathfrak{M}_2)\mathfrak{M}_1\mathfrak{M}_2}. \quad (4)$$

In the present case, equation (4) becomes

$$\frac{dP}{dt} = -5.8\times10^{-12}\frac{\mu}{(1-\mu)^4}. \quad (4')$$

If, for example, $\mu = 0.2$, $dP/dt \sim -3\times10^{-12}$. In 15 years, the period will change by 0.001 sec. The total gain in phase over the 15 years due to the systematic shortening of the period would amount to about 60 sec, a small but probably detectable quantity.

1963: Jon Mathews immediately gets a good grad student to work out the details for angular distribution and for eccentric case:

PHYSICAL REVIEW VOLUME 131, NUMBER 1 1 JULY 1963

Gravitational Radiation from Point Masses in a Keplerian Orbit

P. C. PETERS* AND J. MATHEWS
California Institute of Technology, Pasadena, California

(Received 18 January 1963)

The gravitational radiation from two point masses going around each other under their mutual gravitational influence is calculated. Two different methods are outlined; one involves a multipole expansion of the radiation field, while the other uses the inertia tensor of the source. The calculations apply for arbitrary eccentricity of the relative orbit, but assume orbital velocities are small. The total rate, angular distribution, and polarization of the radiated energy are discussed.

$$\frac{dP_1}{d\Omega}=\frac{1}{\pi}\frac{G^4}{c^5}\frac{m_1^2m_2^2(m_1+m_2)}{a^5}(1+\cos^2\theta)^2\sin^2 2(\phi-\psi),$$

angular distrib in 2 polariz

$$\frac{dP_2}{d\Omega}=\frac{4}{\pi}\frac{G^4}{c^5}\frac{m_1^2m_2^2(m_1+m_2)}{a^5}\cos^2\theta\cos^2 2(\phi-\psi),$$

$$\langle P\rangle=\frac{32}{5}\frac{G^4}{c^5}\frac{m_1^2m_2^2(m_1+m_2)}{a^5(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right). \quad (16)$$

Annual Reviews of Astronomy & Astrophysics, 1972

GRAVITATIONAL-WAVE ASTRONOMY[1,2]

WILLIAM H. PRESS[3] AND KIP S. THORNE

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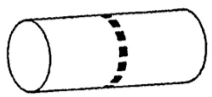
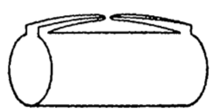
TABLE 1. Gravitational-wave frequency bands

Designation	Frequency (period)	Wave-length	Typical sources	Length of acoustically resonant antenna	Useful antennas
Extremely low frequency (ELF)	(10^7 sec) to (10^4 sec)	$\approx$.1 pc to $\approx$20 A.U.	Cosmological? Explosions in quasars and galactic nuclei Binaries		
Very low frequency (VLF)	(10^4 sec) to (10 sec)	$\approx$20 A.U. to 3×10^6 km	Short-period binaries Huge black holes ($\sim10^5$ to 10^8 $M_\odot$)	$\sim$25000 km to $\sim$25 km	Planetary resonances Free masses in deep space
Low frequency (LF)	1/10 Hz to 100 Hz	3×10^6 km to 3000 km	Pulsars	$\sim$25 km to $\sim$25 m	Lumped resonant antennas Heterodyne antennas Free masses in near space
Medium frequency (MF)	100 Hz to 100 kHz	3000 km to 3 km	Black holes (1–10^3 $M_\odot$) Collapse of stars Weber bursts Supernovae	$\sim$25 m to $\sim$2.5 cm	Resonant antennas (Weber) Laboratory almost-free masses

Binary NS do not appear: lumpy pulsars and supernovae were the `guaranteed sources'

TABLE 3. Three displacement sensors in operation in 1971

Type of sensor	Role in gravitational-wave receiver	Measured displacement and baseline	Frequency ν_{GW} of measured displacement	Bandwidth $\Delta\omega$ of measured displacement, $=1/$(resolution time)	References	Future improvements
Piezoelectric crystal (transducer)	Bonded to surface of Weber's vibrating cylinder 	$\sim 5\times10^{-15}$ cm in ~ 1 m (strains of $\sim 5\times10^{-17}$)	1660 Hz	~ 10 rad/sec	Weber (1969; 1970a, b, c; 1971a, b)	Lower temperature. Better piezoelectric materials.
Capacitor in resonant L-C circuit at ~ 10 MHz (modulator)	Placed between "horns" of Braginskii's vibrating cylinder 	$\sim 5\times10^{-15}$ cm in ~ 1 m (strains of $\sim 5\times10^{-17}$)	$\sim 10^{3}$ Hz	~ 10 rad/sec	Braginskii (1971)	Better oscillators. Lower EM detector noise. Superconducting resonant circuit. Change of resonator to superconducting microwave cavity. Measurable strains may well improve in next decade, to $h<10^{-20}$.
Laser interferometer (modulator)	Not yet used in gravitational-wave receiver	$\sim 8\times10^{-14}$ cm in ~ 12 cm (strains of $\sim 7\times10^{-15}$)	5×10^{3} Hz	~ 1 rad/sec	Moss et al (1971) and unpublished work	Higher laser power. Same or better displacement over much larger baseline. Measurable strains may well improve in next decade, to $h<10^{-20}$.

4. Proposed Antenna Design

The principal idea of the antenna is to place free masses at several locations and measure their separations interferometrically. The notion is not new; it has appeared as a gedanken experiment in F. A. E. Pirani's[9] studies of the measurable properties of the Riemann tensor. However, the realization that with the advent of lasers it is feasible to detect gravitational waves by using this technique grew out of an undergraduate seminar that I ran at M.I.T. several years ago, and has been independently discovered by Dr. Philip Chapman of the National Aeronautics and Space Administration, Houston.

Further improvements:

R.W.P. Drever 1977 *QJRAS* **18,** 9

R.L. Forward 1977 *Hughes Aircraft Co. Research Report* 511
[NB Forward is also author of 1980 *Dragon's Egg* "a textbook on neutron star physics disguised as a novel." and 10 other Sci Fi novels.]

1975: F. Estabrook & H. Wahlquist: Doppler Tracking of spacecraft

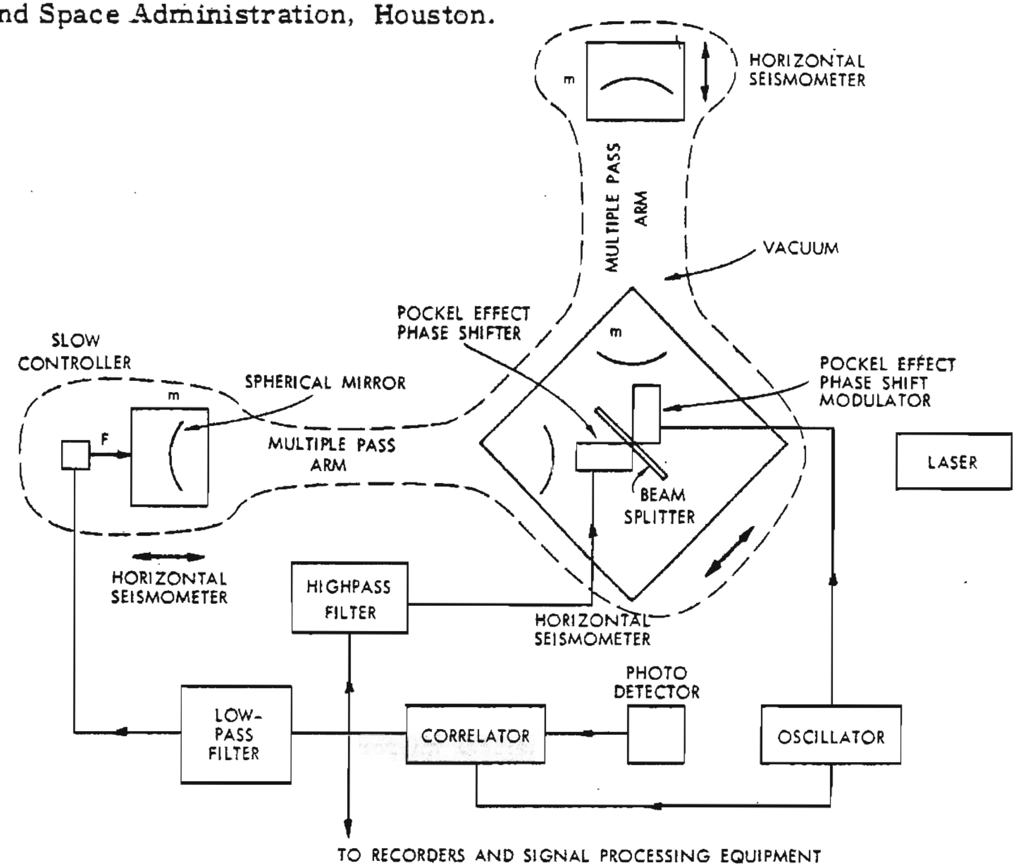


Fig. V-20. Proposed antenna.

THE ASTROPHYSICAL JOURNAL, 192:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

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Received 1974 March 13; revised 1974 July 12

ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

Subject headings: black holes — hydrodynamics — mass loss — neutron stars

1975

THE ASTROPHYSICAL JOURNAL, 195:L51–L53, 1975 January 15

DISCOVERY OF A PULSAR IN A BINARY SYSTEM

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Received 1974 October 18

ABSTRACT

We have detected a pulsar with a pulsation period that varies systematically between $0^{s}058967$ and $0^{s}059045$ over a cycle of $0^{d}3230$. Approximately 200 independent observations over 5-minute intervals have yielded a well-sampled velocity curve which implies a binary orbit with projected semimajor axis $a_1 \sin i = 1.0\ R_{\odot}$, eccentricity $e = 0.615$, and mass function $f(m) = 0.13\ M_{\odot}$. No eclipses are observed. We infer that the unseen companion is a compact object with mass comparable to that of the pulsar. In addition to the obvious potential for determining the masses of the pulsar and its companion, this discovery makes feasible a number of studies involving the physics of compact objects, the astrophysics of close binary systems, and special- and general-relativistic effects.

1977 post Hulse-Taylor discovery

THE ASTROPHYSICAL JOURNAL, **215**: 311–322, 1977 July 1

EVOLUTION OF CLOSE NEUTRON STAR BINARIES

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Received 1976 November 11; revised 1976 December 17

ABSTRACT

In binary systems consisting of two neutron stars, the orbit decays by gravitational radiation. A crude model shows that the less massive star may suffer either immediate tidal disruption or slow mass stripping when it reaches its Roche radius, depending on the initial masses and on the details of mass exchange or mass loss. Typical energy releases are 4×10^{52} ergs in gravitational waves before the onset of stripping, 2×10^{52} ergs in gravitational waves after the onset of stripping, 2×10^{53} ergs in neutrinos after the onset of stripping. The stripping process always ends in tidal disruption of the less massive star after a few seconds or a few hundred revolutions.

As the endpoint of binary stellar evolution, such events are estimated to occur only every ~ 100 yr out to a radius of 15 Mpc, and are thus less important than supernovae as sources of gravitational waves; the observed wave amplitude would be $h \sim 10^{-21}$. Such events may occur in Type II supernovae, if the collapsing stellar core rotates rapidly enough to fission into two neutron stars.

scaling as D^3 : 3/yr @ 100Mpc: but x10^2-10^3 overestimate since assumed 10^6y lifetime of young pulsars, not much longer life of old recycled pulsars.

a) *Density of Systems*

Lattimer and Schramm (1976) estimate that a lower limit on the birthrate of progenitors of double compact binaries in the galactic plane is approximately $2 \times 10^{-12}\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$. Since only a small fraction, denoted by β, may be expected to survive disruption by the second supernova, to become double neutron star binaries; and since the lifetime of the latter will probably be less than the age of the Galaxy, the rate of events in our Galaxy will be

$$\frac{dN}{dt} \sim 6 \times 10^{-6}\left(\frac{\beta}{10^{-2}}\right)\ \mathrm{yr}^{-1}\,. \tag{11}$$

Although no binary neutron star systems have yet been positively identified, PSR 1913+16 (Hulse and Taylor 1975) is a strong candidate, with a lifetime[2] of $\sim 10^8$ yr (Smarr and Blandford 1976).

Taking β to be 10^{-2} for illustrative purposes (see Lattimer and Schramm 1976 for difficulty in estimating β), we expect approximately one event every 80 years out to the radius of the Virgo cluster ($\sim$15 Mpc).

where F is the energy flux at the Earth. Then, a binary neutron star system, with inclination θ, will produce a peak amplitude

$$h(t) \approx 6.6 \times 10^{-24}(1 + 6\cos^2\theta + \cos^4\theta)^{1/2} m_1^{3/4} m_2^{3/4}(m_1 + m_2)^{-1/4}(-\tau/1^{\mathrm{d}})^{-1/4}(d/15\ \mathrm{Mpc})^{-1}\,. \tag{13}$$

(Note that Press and Thorne 1972 give a value for h too large by a factor of 2.) The observed frequency ν is

$$\nu(t) \approx (2.1\ \mathrm{Hz}) m_1^{-3/8} m_2^{-3/8}(m_1 + m_2)^{1/8}(-\tau/1^{\mathrm{d}})^{-3/8}\,, \tag{14}$$

$$d\nu/dt \approx (9.2 \times 10^{-6}\ \mathrm{Hz\ s^{-1}}) m_1^{-3/8} m_2^{-3/8}(m_1 + m_2)^{1/8}(-\tau/1^{\mathrm{d}})^{-11/8}\,. \tag{15}$$

Representative values of h and ν at peak radiation are $\sim 10^{-21}$ and $\sim 10^3$, thus giving a flux comparable to the strongest known normal close binaries (cf. Braginsky 1965), for a distance of 15 Mpc.

Hence there is ample room for stripping. We have not calculated how much, if any, of the stripped neutron matter is ejected to infinity; we think it likely that some amount $\gtrsim 0.1\ M_\odot$ is ejected, with interesting implications for r-process and superheavy nucleosynthesis (cf. Lattimer and Schramm 1974, 1976; Pringle, Dearborn, and Fabian 1976).

1975: Rai Weiss & Kip Thorne share hotel in Washington DC room for NASA review, concoct plan for LIGO.

1977-1987: individual NSF grants to Weiss (MIT), Drever (Caltech), Thorne (Caltech).

1987: Robbie Vogt (Caltech) becomes combined Caltech/MIT LIGO director

1989: NSF proposal for 4km LIGO (Vogt, Raab, Drever, Thorne, Weiss)

1990: NSB and NSF approves funding for LIGO construction planning

1990-1994: astronomical community attacks LIGO, tries to defund.

1994: Barry Barish (Caltech) becomes LIGO director; NSF releases construction funding
LIGO construction starts

1997: Barish creates LSC (LIGO Scientific Collaboration for data analysis)

2002: LIGO starts scientific data taking. Advanced LIGO proposal submitted to NSF.

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

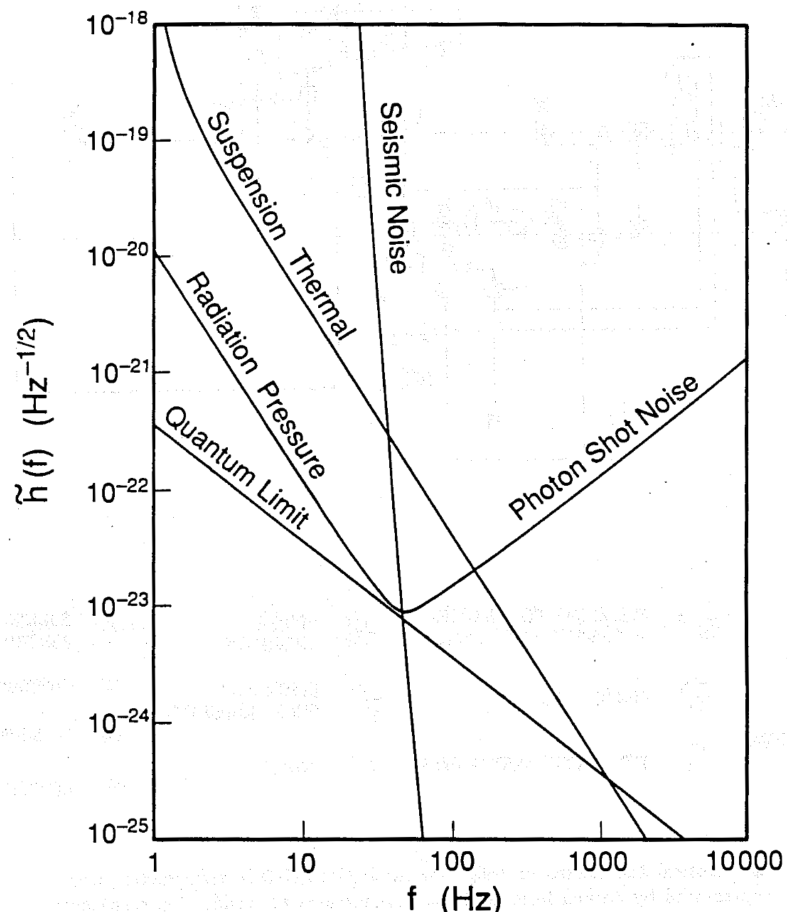


Figure V–3 Projected sensitivity of early LIGO interferometers in broad-band operation, in terms of strain amplitude spectral density, $\tilde{h}(f)$. The sensitivity at a given frequency is determined by the noise source that dominates at that frequency.

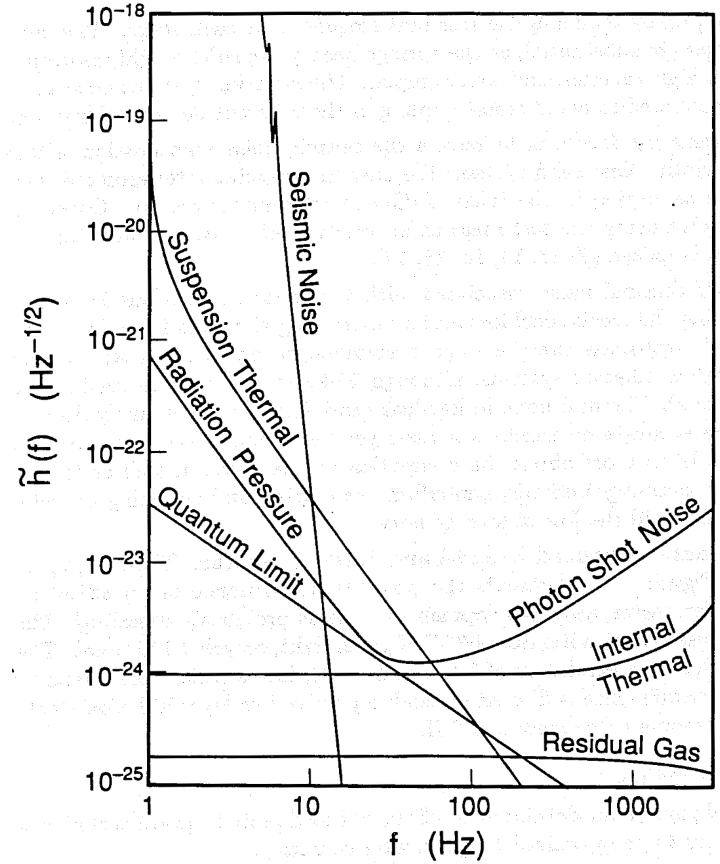


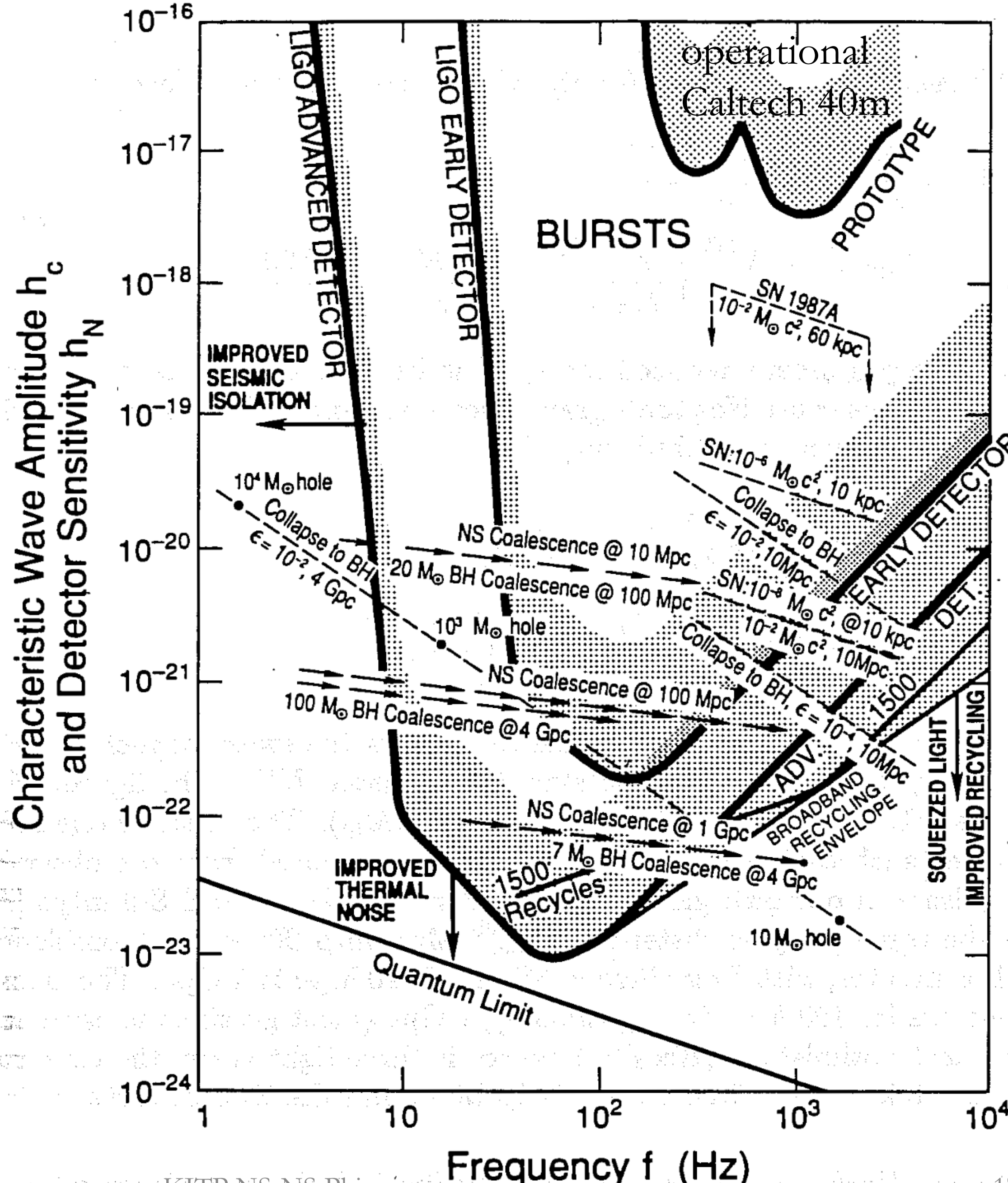
Figure V–4 Projected sensitivity of a possible advanced LIGO interferometer, in terms of strain amplitude spectral density, $\tilde{h}(f)$. The parameters that set the level of the various sources of noise are as follows: 4-km arms, 1-ton test masses of fused silica with mechanical Q = 10^6, 60 W of bright–fringe power, broad-band recycling with 100 recycles, suspension Q = 10^9, residual gas = 10^{-9} torr hydrogen or 10^{-10} torr water.

1989 Proposal: initial LIGO design

Advanced LIGO possibilities (1 ton mirrors!)

1989 NSF proposal,
Fig A-4a
APPENDIX A (Thorne): THE PHYSICS OF GRAVITATIONAL WAVES, AND COMPARISON OF SOURCE STRENGTHS WITH DETECTOR SENSITIVITIES

(Fig A-4b gives "more reliable" continuous sources: mountains on pulsars and LMXBs. (esp Crab, Vela, Sco X-1).
Fig A-4c gives stochastic backgrounds: primordial BH, cosmic strings, …



THE ASTROPHYSICAL JOURNAL, 380: L17–L21, 1991 October 10

1991: discovery of PSR 1534+12 (Wolszczan+)
& PSR 2127+11C (Prince+)

THE RATE OF NEUTRON STAR BINARY MERGERS IN THE UNIVERSE: MINIMAL PREDICTIONS FOR GRAVITY WAVE DETECTORS

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Received 1991 July 3; accepted 1991 July 25

ABSTRACT

Of the many sources which gravitational wave observatories might see, merging neutron star binaries are the most predictable. Their waveforms at the observable frequencies are easy to calculate. And three systems which will merge in less than a Hubble time have already been observed as binary pulsars: two in the disk of our Galaxy, and one in a globular cluster. From the lifetimes and positions of these, we infer with confidence a lower limit to the merger rate in our Galaxy and globular cluster system. Taking the merger rate in other galaxies to scale with the star formation rate, we compute the merger rate expected in the local universe. An ultraconservative lower limit to the rate gives three per year within 1 Gpc. Our *best* estimate, still conservative in that it considers only systems like those already observed, gives three per year within 200 Mpc. An upper limit of three mergers per year within 23/*h* Mpc is set by the rate of Type Ib supernovae. The rates of black hole binary mergers and black hole–neutron star binary mergers are model-dependent, but could be comparable to the given rate of neutron-star binary mergers.

$$R = \sum_i^d \frac{1}{V_{\rm max}(i)\tau(i)} V_{\rm Gal} \qquad \tau = P/(2\dot{P}) + \tau_{\rm mrg}$$

$= 3\times10^9$y (PSR 1534+12)
$= 4\times10^8$y (PSR 1913+16)
$= 3\times10^8$y (PSR 2127+11C) -globular

- Currently 13 NS-NS pulsars known
  - (of which 2 might still be NS-WD).
  - 12 in disk, 1 in globular cluster M15
  - in 12 NS-NS systems (formerly double pulsar is double counted as both young & recycled):
    - 2 young, unrecyled pulsars, which will merge in $<10^{10}$y.
    - 6 recycled pulsars, which will merge in $<10^{10}$y.
    - 5 recycled pulsars in long orbit period systems with $t_{mrg}>10^{11}$y.

THE ASTROPHYSICAL JOURNAL, **308**:L43–L46, September 15

1986

GAMMA-RAY BURSTERS AT COSMOLOGICAL DISTANCES

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Received 1986 May 12; accepted 1986 June 23

ABSTRACT

We propose that some, perhaps most, gamma-ray bursters are at cosmological distances, like quasars, with a redshift $z \approx 1$ or $z \approx 2$. This proposition requires a release of supernova-like energy of about 10^{51} ergs within less than 1 s, making gamma-ray bursters the brightest objects known in the universe, many orders of magnitude brighter than any quasars. This power must drive a highly relativistic outflow of electron-positron plasma and radiation from the source. The emerging spectrum should be roughly a black body with no annihilation line, and a temperature $T \approx (E/4\pi r_0^2 \sigma)^{1/4}$. As an example the spectrum would peak at about 8 MeV for the energy injection rate of $\dot{E} = 10^{51}$ ergs s^{-1} and for the injection radius $r_0 = 10$ km.

We propose that three gamma-ray bursts, all with identical spectra, detected from B1900+14 by Mazets, Golenetskii, and Gur'yan and reported in 1979, were all due to a single event multiply imaged by a gravitational lens. The time intervals between the successive bursts, 10 hr to 3 days, were due to differences in the light travel time for different images. The required mass of the lens is 10^{10} $M_{\odot}$, just right for a galaxy.

½ ain't bad (B1900+14=SGR in LMC!).

1989

Combine NS-NS, GW, r-process and gamma-ray bursts.

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

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NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

The binary pulsar system will coalesce in roughly 10^8 yr. Using this fact together with the pulsar birth rate and the observed

THE ASTROPHYSICAL JOURNAL, 507:L59–L62, 1998 November 1

TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

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Received 1998 July 27; accepted 1998 August 26; published 1998 September 21

ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be used to estimate the parameters of a transient as a function of poorly known input parameters. The mergers may be detected with high-redshift supernova searches as rapid transients, many of them far away from the parent galaxies. It is possible that the mysterious op ... n star mergers, since they typically have no visible

$$t_m \approx 1.5\beta^{1/2} t_c = 0.98 \text{ days} \left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{-1/2} \left(\frac{\kappa}{\kappa_e}\right)^{1/2}. \quad (12)$$

The peak luminosity is

$$L_m \approx 0.88\beta^{1/2} L_0 = 2.1 \times 10^{44} \text{ ergs s}^{-1} \times \left(\frac{f}{0.001}\right) \left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{1/2} \left(\frac{\kappa}{\kappa_e}\right)^{-1/2}. \quad (13)$$

What will future NS-NS mergers look like?

- Diversity of total mass: final state = stable NS, short-lived NS, BH. Does this depend on Z/age (sGRB/GW ratio varies?).
- Diversity of inclination angles (30deg most probable near flux limit, but not for nearby!) –red vs blue.
- Diversity of jet powers –choked/break out or not? Misdirected sGRB or not?
- Other sources of gamma-ray or blue emission (just needs tiny fraction of mass, shocks)?
- Diversity of hosts (will be clue to progenitor).

Merged masses of NS+NS systems

System	M_T ($M_\odot$)	M_{PSR} ($M_\odot$)	M_c ($M_\odot$)	Merged mass (solar masses) (adopting R=12km)
	Systems with well-measured component masses			
J0453+1559	2.734(4)	1.559(5)	1.174(4)	2.29
J0737−3039	2.58708(16)	1.3381(7)	1.2489(7) y	2.12
B1534+12	2.678463(8)	1.3330(4)	1.3455(4)	2.19
J1756−2251	2.56999(6)	1.341(7)	1.230(7)	2.11
J1906+0746	2.6134(3)	1.291(11) y	1.322(11) ?	2.14
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)	2.29
B2127+11C g	2.71279(13)	1.358(10)	1.354(10)	2.21

Ozel+Freire 2016

If 2.1<M_{max}<2.3 Msun, some NS+NS will end as massive NS, some as BH.

If M_{max} >2.3 Msun, ALL known NS+NS will end as very massive NS, not BH.

Importance of Max NS mass

NS-NS mergers

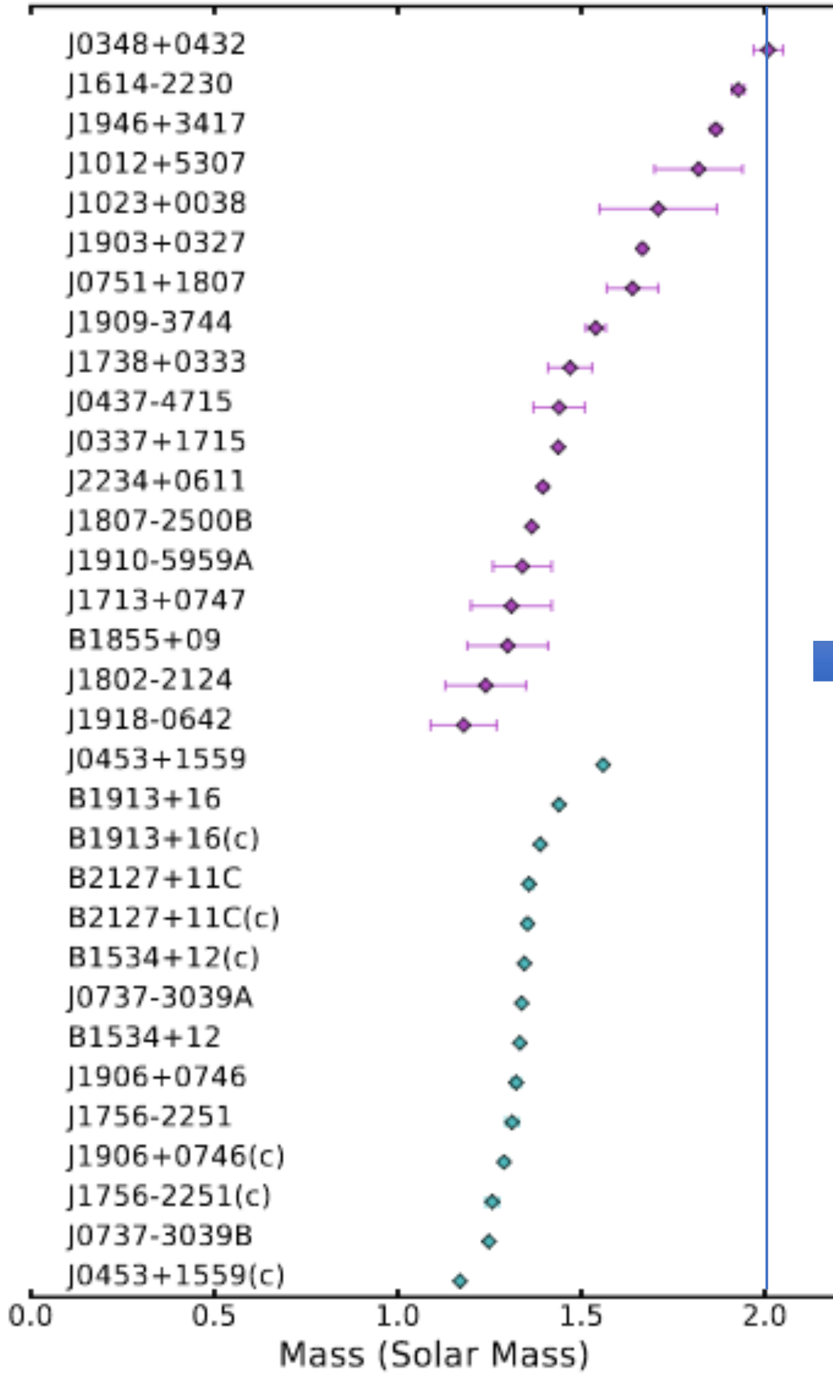
- If Max NS mass >2.1-2.3 Msun, some known NS-NS mergers will form *stable* very massive (2.1-2.2$M_\odot$) NS.
- If Max NS mass <2.1Msun, all known NS-NS mergers will collapse to ~2.4Msun BH within a few seconds –accretion disk powered GRB possible.

Massive star core collapse

- If Max NS mass<2.2 Msun, collapse of massive cores to BH releases so little binding energy that no stellar envelope is ejected ("stars just disappear": Kochanek 2008).
- If >2.2 Msun, loss of binding mass causes outer envelope to expand and escape: low speed luminous red nova (Nadezhin 1980, Lovegrove & Woosley 2013; as possibly observed by Adams+ arXiv:1609.01283).

M(PSR B1957+20)=2.4(2)$M_\odot$; improvements coming soon. Severe EOS constraint

Accurately measured neutron star masses from pulsar timing (red: PSR+WD, blue: PSR+NS (?)



?

Antoniadis+ 2016

Rate Problem

- GW 170817 host NGC 4993 is old stellar population
  - Pulsar derived NS-NS merger dominated by short delay-time systems.
  - Proposed ways to enhance rate are via even shorter delay-time systems (e.g. 2^{nd} spiral-in in He red-giant phase) of such short life none would be seen in MW.
  - Neither of these can give a high rate in old pop like NGC 4993: they strongly weight current (age $<10^{7.5}$y) star-forming regions.
- Long delay-time systems have low birthrate in pulsar-derived models, and population synthesis.
  - So very surprising that first, nearby system would be old, long-delay.
- *Unless* old systems have low or zero pulsar radio luminosity. In which case MW should be full of old, radio-quiet NS-NS binaries (100s for each 1913+16 or 1534+12 -like system).
  - Alternatively, Belczynski+ arXiv:1712.00632 propose homogeneous evolution (rotationally mixed in close tidally locked binaries): might work with *extremely* optimistic parameters. Would occur only for low Z: no young ones visible in MW if radio fades, so allows high merger rate in old systems w/o violating MW pulsar constraints. Could explain drop in Eu/Fe with Fe/H (cf Hotosezaka talk).

Phinney 1991 w/ new systems in red

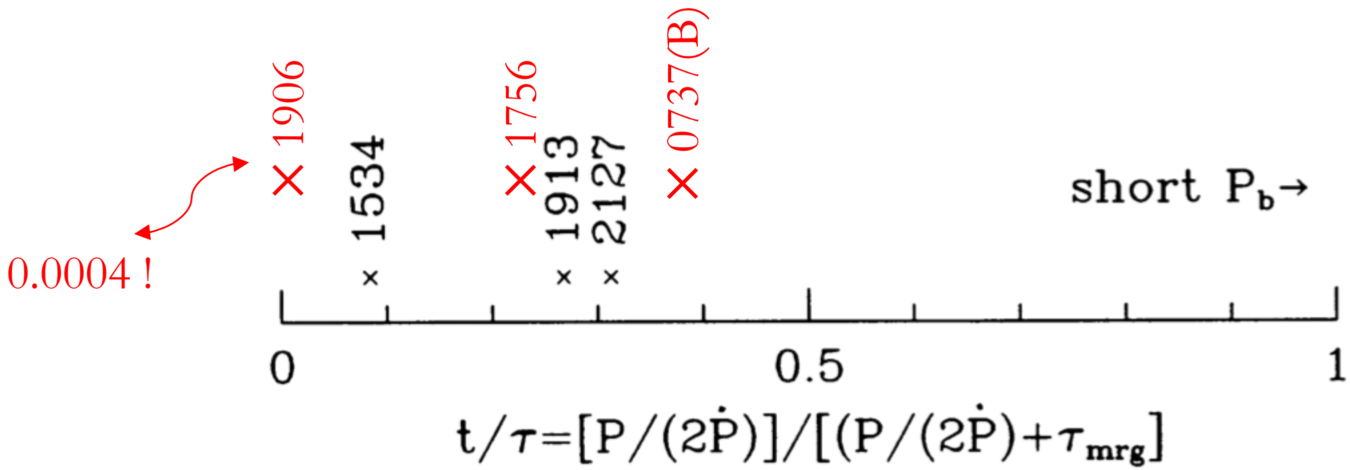


FIG. 1.—Where in their total lifetimes τ are each of the three neutron star binary pulsars. In the absence of luminosity or torque decay, old binaries should be uniformly distributed on the line. Binaries close to the right-hand edge would have short orbital periods and be hard to detect. Pulsars would be bunched at the right if there were torque decay, or if many still had periods close to their birth periods, so $P/(2\dot{P}) \gg t$. If the radio luminosity L decreases as the pulsar spins down [e.g., $L = L_0(1 + t/t_0)^{-1}$], a flux-limited sample would be bunched at the left [$\langle t \rangle \simeq \tau/\ln(\tau/t_0)$ for $t_0 \ll \tau$], as observed. As more binaries are discovered, these luminosity and period selection effects can be removed without modeling by giving each pulsar a weight $1/V_{max}$. A uniform distribution of weights would indicate that $P/(2\dot{P})$ was a good estimate of age.

Clearly pulsars fade before they merge, seemingly to invisibility since none yet with t/τ >0.4

Scaling Milky Way merger rates to the universe

- Milky Way:
  - SFR=1.6(2)$M_\odot$/y (Kroupa IMF)
  - M_{bulge}=0.9(1)×$10^{10}M_\odot$.
  - M_{disk}=5(1)×$10^{10}M_\odot$.

  Licquia+Newman 2015

- z=0 universe:
  - SFR density = 0.025(2) $M_\odot$/y/Mpc^3
  - of which 20% in starbursts

  Bothwell, Kenicutt+ 2011; use IR+UV
  - Stellar mass density =3.2×$10^8 M_\odot Mpc^{-3}$
  - Cole+ 2001 (based on J,K IR LF)

→Scaled by current star formation (<10^7y):
Rate=MW rate*0.016/Mpc^3

vs Scaled by blue light (10^{8-9}y):
Rate=MW rate*0.01/Mpc^3
[Phinney 1991 → "LIGO standard"]

vs Scaled by stellar mass (<10^{10}y):
Rate=MW rate*0.005/Mpc^3

More fun for predictions: WD+NS mergers. Higher rate than NS-NS.

Pulsar	**Period (ms)**	P_b **(days)**	**Eccentricity**	**Pulsar Mass ($M_\odot$)**	**Companion Mass ($M_\odot$)**	**Companion Type**
			Young Pulsars in Relativistic Binaries			
J1906+0746[2]	144.1	0.166	0.085	$1.291^{+0.011}_{-0.011}$	$1.322^{+0.011}_{-0.011}$	WD or NS
J1141−6545[3]	393.9	0.198	0.17	$1.27^{+0.01}_{-0.01}$	$1.02^{+0.01}_{0.01}$	WD
B2303+46[4]	1066.4	12.3	0.66	$1.34^{+0.10}_{-0.10}$	$1.3^{+0.10}_{-0.10}$	WD

SDSS 1257+5429 P_b=0.19d, M_{WD}=0.9$M_\odot$, M_X =1.6/sin i $M_\odot$, D=50pc!

cf Thompson+ 2009, Paschalidis+ 2011 (TZO+disk -> BH), Metzger 2012 (sublum Ia), Margalit & Metzger 2016 (but consider CO WD) -> planets (cf Phinney & Hansen 1993); Low mass He WD versions proposed for Ca rich transients (Perets+ 2010, Lyman+ 2014)