Gravitational waves from compact binaries

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Outline

Part 1

History of compact-binary research

Gravitational waves from binaries

Emission of gravitational waves

- Predicted by General Relativity (Einstein 1916, 1918)
- Problems with early attempts to compute energy loss (*e.g.*, Eddington 1922):
  - Only valid for gravitationally unbound systems
  - There always is a coordinate system in which the energy flux vanishes

Landau & Lifshitz, 1951:

For a circular binary:

$$\frac{dE}{dt} = -\frac{32}{5}\frac{G}{c^5}\left(\frac{M_1 M_2}{M_1 + M_2}\right)^2 a^4 \omega^6$$

Paczyński, 1967: GWs and the evolution of close binaries

Prove existence of GWs through binaries with MT:

"As soon as an adequate theory of evolution of those binaries will be available, an indirect observational check of the existence of gravitational radiation will be possible."

Period change:

From Landau & Lifshitz (1951), using $m_i \equiv M_i/M_\odot$:

$$\frac{dP}{dt} = -3.7 \times 10^{-6} \frac{m_1 m_2}{(m_1 + m_2)^{1/3}} P^{-5/3}$$

- This is measurable (over one year) only for $P < 10^3$ s
- Recent discovery: HZ 29 ($\equiv$ AM CVn):
  - $P \approx 18$ min
  - may be used to proof existence of GWs

Paczyński, 1967: GWs and the evolution of close binaries

Merger time:

$$T_0 = 3.2 \times 10^{-3}\,\mathrm{yr} \cdot \frac{(m_1 + m_2)^{1/3}}{m_1 m_2} P^{8/3}$$

$T_0 \approx$ Hubble time for $P \approx 14\,\mathrm{h}$:

- W UMa-type binaries:
  - $T_0 \sim T_{\mathrm{nuc}}$
  - AM loss due to gravitational waves may well affect evolution
- Novae
- U Gem-type binaries (dwarf novae), *e.g.* WZ Sge

WZ Saggitae:

- $M_1 \approx 0.59\,M_\odot$, $M_2 \approx 0.03\,M_\odot$, $P = 81.5\,\mathrm{min}$, $\dot{M} \approx 2 \times 10^{13}\,\mathrm{g/s}$
- Observed mass-transfer rate cannot be explained when constant mass and AM are assumed
- *“Suppose that the gravitational radiation is physically real [. . .] the agreement is reasonable.”*

Vila, 1971: Late evolution of close binaries

Grids of models:

- Evolution models for compact binaries under influence of AM loss due to GWs
- WD accretors with $M = 0.4, 0.7, 1.0\,M_\odot$
- Donor with $M < 0.1\,M_\odot$
- $X_{\rm donor} = 1.0, 0.75, 0.5, 0.0$
- $P_{\rm orb} \lesssim 1$ h

- Tabulates a, $\dot{M}$, t as a function of M, P
- Use models to identify observed systems

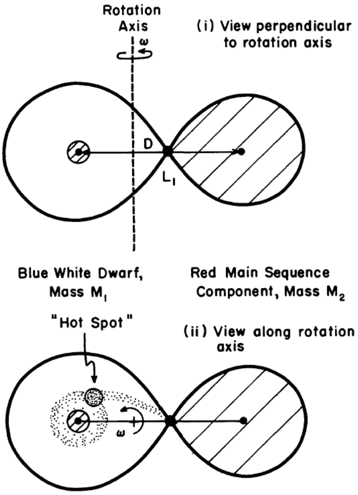
Application:

- Four $P \lesssim 1$ h systems known:
  - WZ Sge
  - EX Hya
  - VV Pup
  - HZ 29
- WZ Sge:
  - has most complete observational data
  - $\dot{M}$ matches models
- *"[. . .] in all cases considered, gravitational radiation was a* sina qua non *for mass transfer"*

AM CVn (HZ 29)

History of AM CVn:

- Peculiar spectrum: strong He I, no H (Malmquist, 1936; Humason & Zwicky, 1947; Greenstein & Matthews, 1957)
- QSO? (Burbidge, Burbidge & Hoyle, 1967); Hot star! (Wampler, 1967)
- Variability of 0.02 mag for 14 mag star, $P \approx 17.5$ min (Smak, 1967; Ostriker & Hesser, 1968)
- Photometry suggests (Warner & Robinson, 1972):
  - AM CVn is an eclipsing binary
  - the system has a disc with a hot spot due to mass transfer ("dwarf-nova model")
  - $P = 1051.0505 \pm 0.0005\,\mathrm{s} = P_{\mathrm{orb}}$



Faulkner, Flannery & Warner, 1972

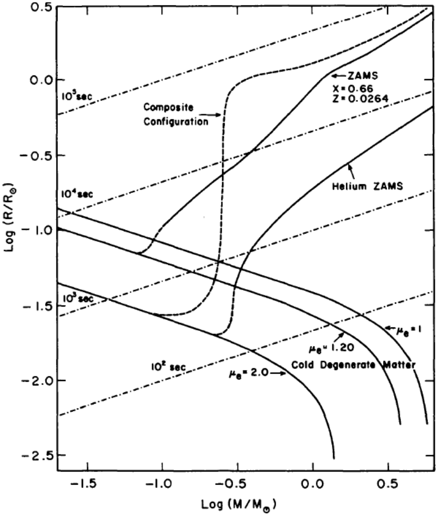
AM CVn (HZ 29)

Faulkner, Flannery & Warner, 1972:

- Kepler + Roche lobe:

$$P \approx 3.83 \times 10^4\ \mathrm{s} \left(\frac{\bar{\rho}_{\mathrm{donor}}}{\mathrm{g\,cm^{-3}}} \right)^{-1/2}$$

- AM CVn:
  - $\bar{\rho}_{\mathrm{donor}} \approx 1.3 \times 10^3\ \mathrm{g\,cm^{-3}}$
  - donor cannot contain hydrogen (see Fig.)
  - absence of H in spectrum confirms this
- Solutions (see Fig.):
  - He MS star — but this would dominate the spectrum and require larger v_{rad}
  - low-mass, degenerate He WD



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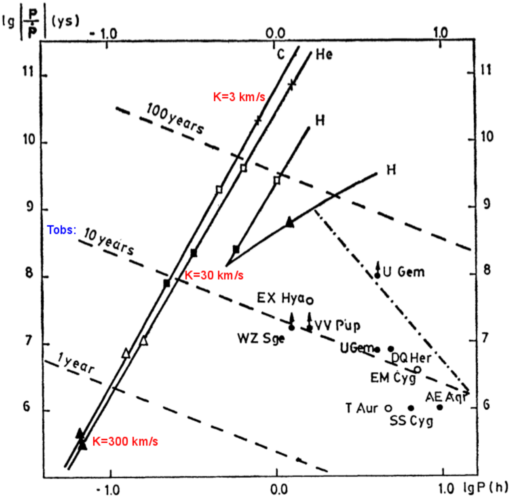
Conclusions:

- AM CVn is a “dwarf-nova” type binary, where the donor transfers mass to the accretor through a disc
- The donor of AM CVn is a degenerate He WD, with $M \sim 0.041\,M_\odot$
- The detached binary is brought into contact by angular-momentum losses due to GWs
- The donor survives the onset of mass transfer
- The evolution of the donor “freezes” when mass transfer starts
- This scenario can explain many observed properties, and GWs are the most prominent ingredient

Tutukov & Yungelson, 1979: analytic binary-evolution models



Tutukov & Yungelson, 1979

Conclusions:

- Some CVs may evolve under the influence of GWs, but more evidence needed
- The CVs with $P/\dot{P} \lesssim 10^8$ years need an additional AM-loss mechanism
- Mass transfer with $M_{\rm donor}/M_{\rm accretor} \gtrsim 0.83$ results in disruption of the donor
- If more than $\sim 10^{-5}$ of binaries with $P \lesssim 10\,$h contain two degenerates, DDs dominate the W UMas in detectable GWs

Ariel 1118–61

6.75 min period:

- X-ray source observed by Ariel 5 (Ives, Sanford & Bell-Burnell, 1975)
- Periodicity of 6.75 min assumed to be the orbital period by Pringle & Webbink (1975)
- Later, the periodicity was found to be the pulse period of the NS

Pringle & Webbink, 1975: NS-WD model:

- Assume that the 6.75 min period is orbital
- Donor must be WD with mass $\approx 0.12\,M_\odot$
- $\dot{M} \sim 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$
- This mass-transfer rate can be entirely explained by AM loss due to GW emission
- This model presents the canonical model for (low-mass) X-ray binaries
- (Alternative explanations for the periodicity are *rotation* and *pulsation*)

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Part 2

Gravitational-wave sources

Galactic double white dwarfs

Types and formation channels:

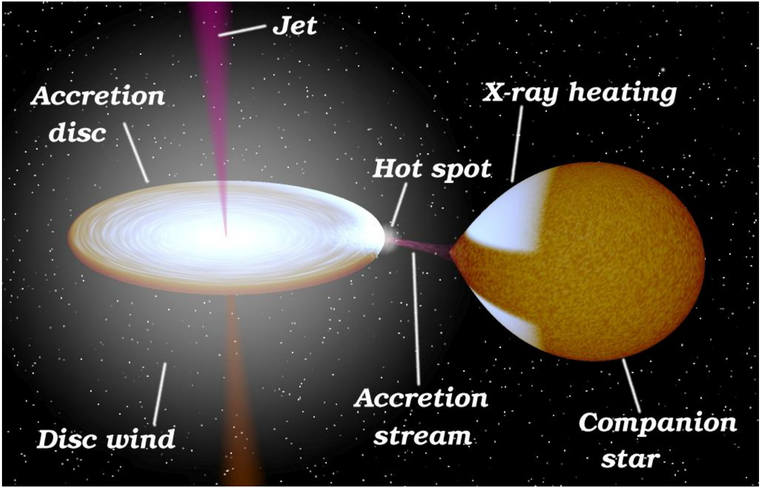
	ν	N	$N/N_{\rm gal}$	$N_{\rm Resolved}$	%
Types of WD binaries:					
He+He	1.34×10^{-2}	1.06×10^{8}	38.41%	19936	59.21%
CO+He	5.07×10^{-3}	4.11×10^{7}	14.89%	12852	38.17%
CO+CO	1.15×10^{-2}	1.08×10^{8}	39.13%	586	1.74%
ONeMg	2.13×10^{-3}	2.09×10^{7}	7.57%	296	0.88%
Formation channels:					
RLOF+CE	9.86×10^{-3}	8.27×10^{7}	29.96%	1061	3.15%
CE+CE	2.12×10^{-2}	1.84×10^{8}	66.67%	32609	96.85%
other channels	1.04×10^{-3}	9.3×10^{6}	3.37%	0	0
Total	3.21×10^{-2}	2.76×10^{8}		33670	

Yu & Jeffery (2010)

- Most Galactic DWDs form a noise *foreground*
- Resolved systems appear between $f \sim 1.4$ and $5.0\,$mHz ($P_{\rm orb} \sim 24 - 7\,$min)

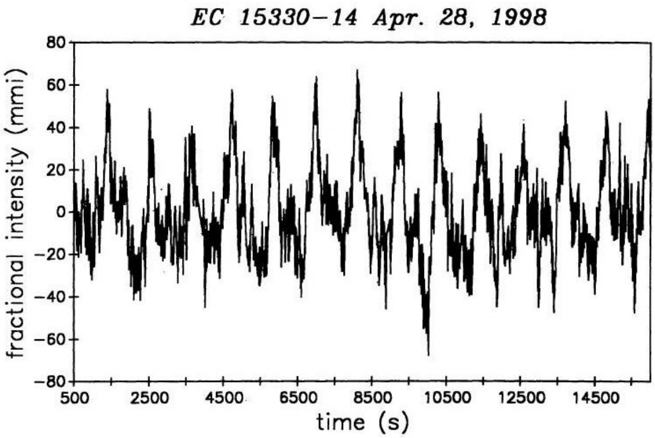
Cataclysmic variables

BinSim,
R. Hynes

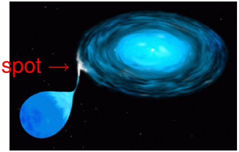


- WD accretor
- Optical emission comes from *hot spot*
- Accretion speed, hence luminosity, varies, sometimes dramatically

Photometric variability

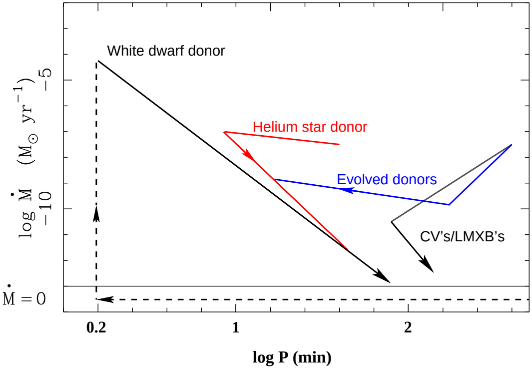


HP Lib (Seetha et al., 2000)



AM CVn systems

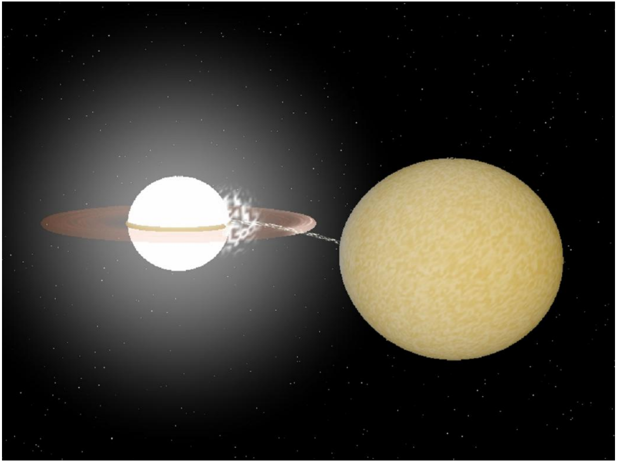
- $\sim$ 25 known
- He-dominated spectra:
  - CVs without H signature
  - H/He $\lesssim 10^{-5}$
  - H-poor donor fits in tighter orbit
- Short orbital periods: $\sim$ 5–65 min
- Main guaranteed LISA sources
- Possible donors:
  - He/hybrid He-CO white dwarf
  - helium star
  - evolved main-sequence star



(Nelemans et al. 2010)

Direct impact

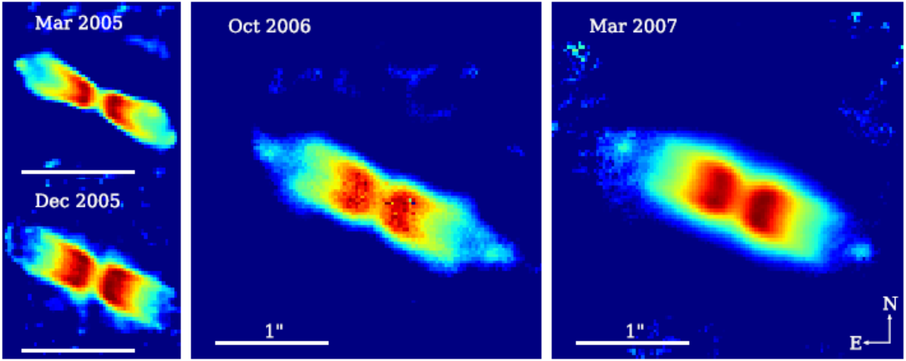
- At very short orbital period ($P \lesssim 10$ min!): no room for accretion disc
- Mass-transfer stream impacts WD surface directly $\rightarrow$ X-rays
- Prediction: if $\dot{M}$ remains high: He novae, or SNe .Ia



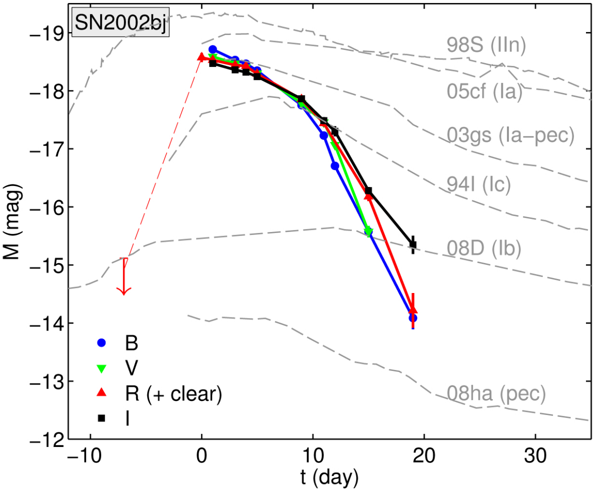
BinSim, R. Hynes: `http://www.phys.lsu.edu/~rih/binsim/`

First He nova: V445 Puppis

- Found in 2000 (Kato et al. 2001)
- Expansion of the shell mapped using adaptive optics on the VLT, in Chile (Woudt et al. 2009)

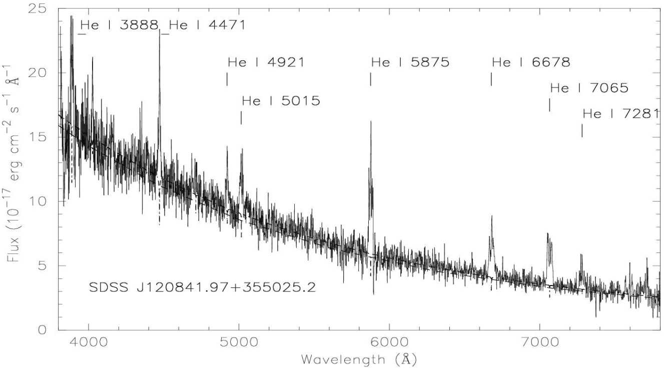


First .Ia supernova?



(Poznanski et al. 2010, Science)

Systematic search for new ultracompacts: SDSS

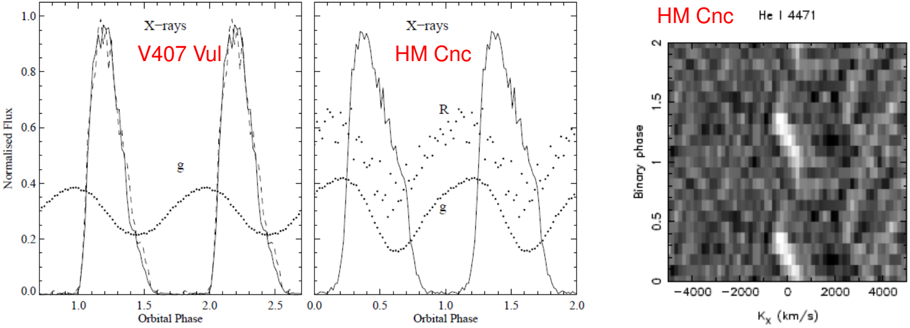


- H poor → strong He lines in spectrum
- SDSS spectroscopy and follow-up yielded 13 new systems

(Roelofs et al. 2005, 2009, Anderson et al. 2005, 2008, Rau et al. 2009)

- Newly discovered systems help determine space density
- Problem: there are $\sim 10\times$ fewer AM CVn systems than theory predicts

First ultracompact systems



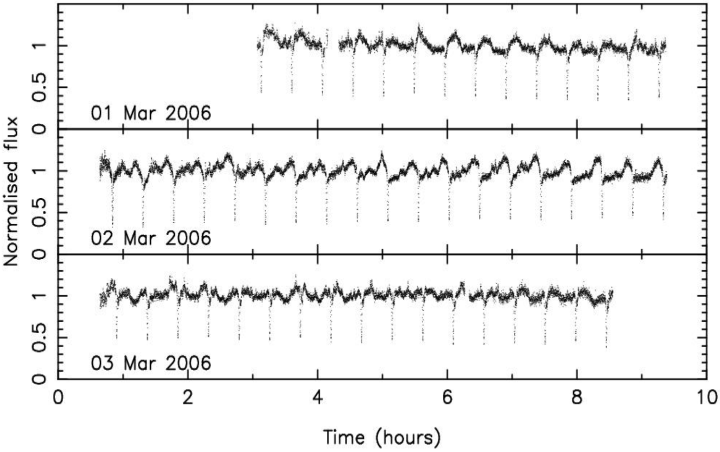
(Motch et al. 1996; Israel et al., 1999; Burwitz & Reinsch 2001)

(Roelofs et al. 2010)

- Two systems previously known from X-ray emission
- Ultrashort periods now confirmed using 10 m Keck-telescope:
  - HM Cnc: shortest known period: 5.4 min

First eclipsing system

- Eclipsing systems help in mass determination
- SDSS J0926+3624:



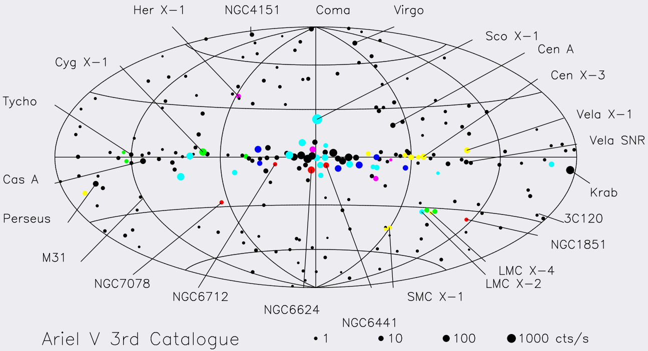
(Marsh et al., 2006; 2010)

Ultracompact X-ray binaries

X-ray binaries:

- Bright X-ray sources: in galactic plane, concentrated towards galactic centre
- 14 bright X-ray sources in globular clusters
- Binaries with $P_{\rm orb} \lesssim 60$ min are called *ultra-compact*

Ariel V X-ray map of the sky:

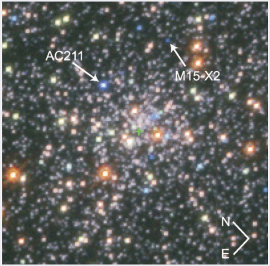


XRBs are overabundant in GCs:

- 1 in 10^9 stars in galaxy is XRB
- 1 in 10^6 stars in globular clusters is XRB

Direct period measurement

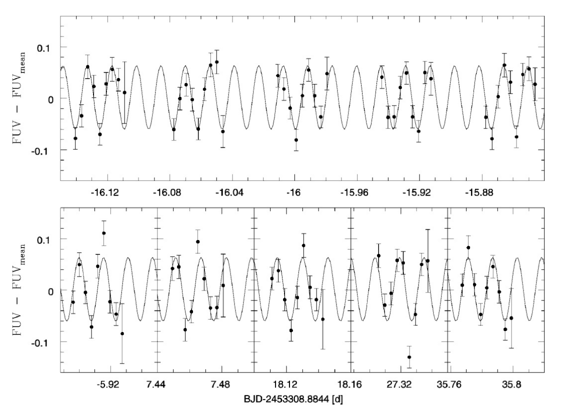
M 15-X2



White & Angelini, 2001; Guhathakurta, 1996

- FUV study (less crowding)
- Magnitude modulation: 0.06m
- $>$ 3000 cycles
- Period: 22.6 min.

Magnitude modulation



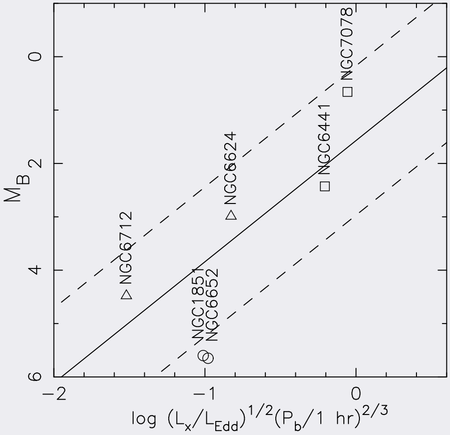
Dieball et al., 2005

Indirect period indication

Optical vs. X-ray flux

- Optical flux from reprocessed X-rays in disc
- Scales with X-ray flux and size of disc
- Hence, $f_{\mathrm{opt}}/f_{\mathrm{X}} \propto R_{\mathrm{disc}} \propto a_{\mathrm{orb}}$

Van Paradijs & McClintock, 1994



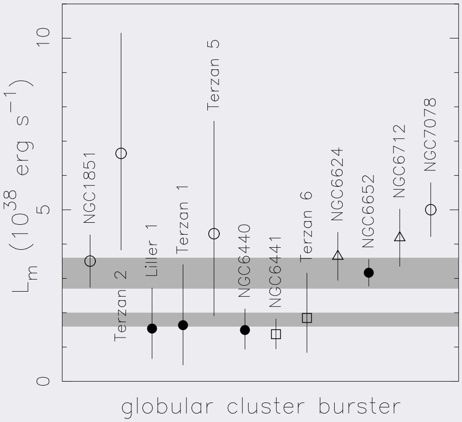
□ normal P   △ ultra-short P   O unknown P

Verbunt & Lewin (2006)

Indirect period indication

Burst maximum

- Maximum luminosity during burst is Eddington luminosity: $L_{\text{Edd}} = \frac{4\pi cGM}{\sigma_{\text{T}}}$
- Electron scattering cross section depends on hydrogen content: $\sigma_{\text{T}} = 0.2\ (1 + X)\ \frac{\text{cm}^2}{\text{g}}$



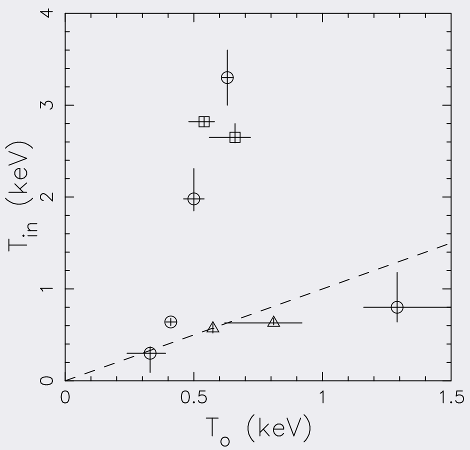
□ normal P △ ultra-short P O unknown P

Kuulkers et al. (2003)

Indirect period indication

X-ray spectrum

- Temperature T_0 of the seed photons comes from a Compton model
- Temperature T_{in} is observed from the inner disk
- Ultracompacts show $T_0 \sim T_{\text{in}}$



□ normal P △ ultra-short P O unknown P

Adapted from Sidoli et al. (2001)

X-ray sources in globular clusters

Known period information

Cluster	Position	P_{orb}	Indirect indication		
			low f_{opt}/f_x	burst max.	spectrum
NGC 1851	0512–40	?	U	U	U
NGC 6440	1745–20	8.7 hr	—	—	N
NGC 6440	1748–20	57.3 min	—	—	—
NGC 6441	1746–37	5.7 hr	—	N	N
NGC 6624	1820–30	11.4 min	U	U	U
NGC 6652	1836–33	?	U	U	U
NGC 6712	1850–09	21/13 min	U	U	U
NGC 7078	2127+12b	17.1 hr	—	—	—
NGC 7078	2127+12a	22.6 min	—	U	—
Terzan 1	1732–30	?	—	—	—
Terzan 2	1724–31	?	—	U	N
Terzan 5	1745–25	?	—	—	U
Terzan 6	1751–31	12.4 hr	—	—	N
Liller 1	1730–33	?	—	—	—

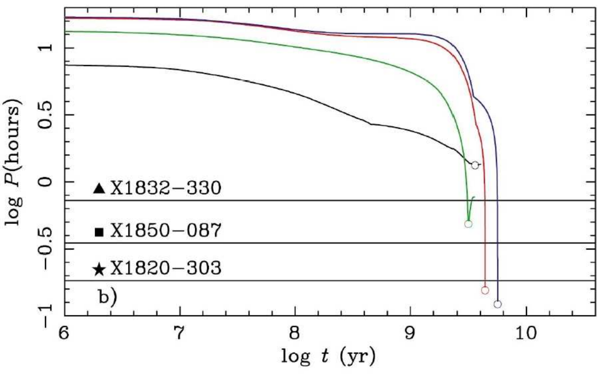
- Up to 7 of the 14 X-ray binaries in globular clusters are ultra-compact!
- 11-min system has negative $\dot{P}$ (see talk by S. Prodan on Thursday)

Magnetic capture

Scenario:

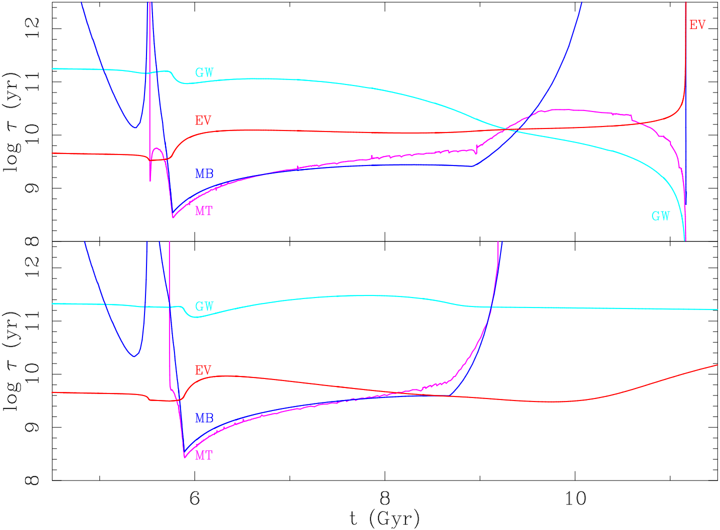
- Low-mass donor, NS accretor
- Mass transfer starts around TAMS
- Lose angular momentum through magnetic braking
- Minimum period can be as low as 5 min.
- Period derivative can be negative during mass transfer

Example:



Podsiadlowski et al., 2002

Magnetic capture: timescales



van der Sluys et al., 2005

Magnetic capture: statistics

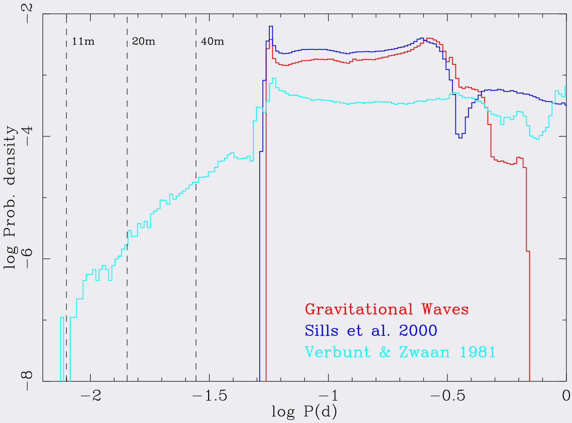
Population synthesis:

- Compute large numbers of binaries
- Use different, more realistic(?) MB prescriptions

Conclusions:

- Very finely tuned input parameters required to produce UCXBs
- Too many longer-period systems produced per 11-minute system
- Lower limit for saturated MB similar to that for no MB
- No systems below $\sim 70\,\mathrm{min}$

$Z = 0.01$, 10^7 binaries

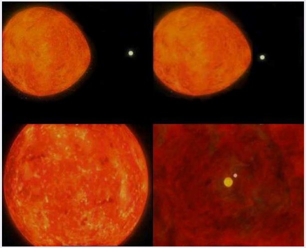


Van der Sluys, Verbunt & Pols, 2005

Direct collisions

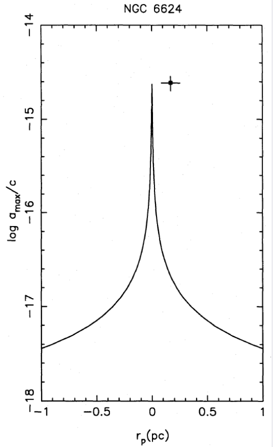
Star collisions occur in GCs:

- Star density up to 10^6 times higher than in solar neighbourhood
- Probability of collisions 10^{12} times higher
- Direct collisions most likely for subgiants
- Binary with NS and core of subgiant is formed



After the collision:

- A NS-WD binary is formed
- Gravitational radiation shrinks the orbit
- Orbital period increases as soon as mass transfer starts
- Observed X-ray binaries should always have positive $\dot{P}$
- The 11-min system has a measured $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15} \mathrm{s}^{-1}$ (see talk by S. Prodan on Thursday)

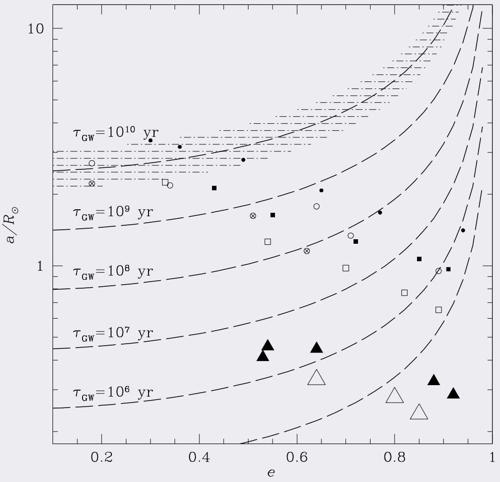


Van der Klis et al., 1993

Direct collisions

NS-subgiant collisions:

- Open/closed symbols: $0.8, 0.9\, M_\odot$ star
- Triangles, squares and circles show how far star was evolved
- Symbol size scales with collision probability
- Dashed lines for $1.4 + 0.25\, M_\odot$
- Hashed area for $M_{\rm tot} \pm 0.2\, M_\odot$

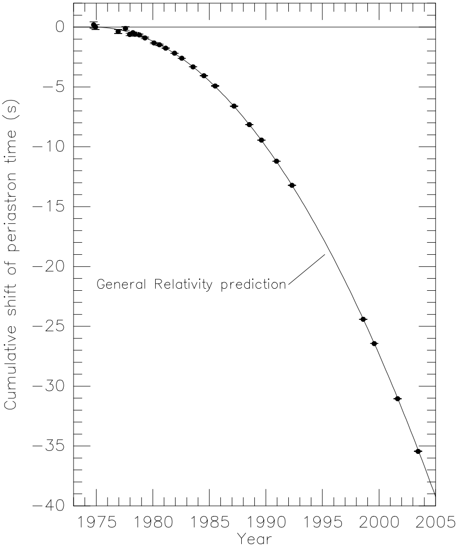


Lombardi et al., 2006

The Hulse-Taylor pulsar

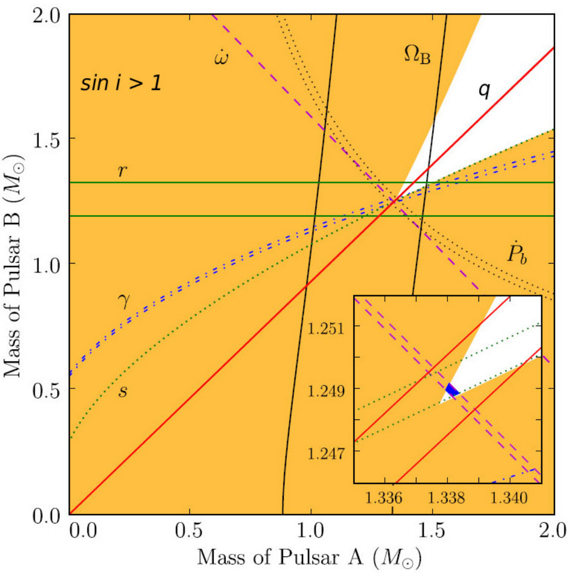
PSR B1913+16:

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)	-2.4184 (9)
$M_{\rm PSR}(M_\odot)$	1.4414 (2)
$M_{\rm cmp}(M_\odot)$	1.3867 (2)



(Weisberg & Taylor, 2004)

The binary pulsar



(Kramer et al., 2006; Breton et al., 2008)

PSR J0737-3039:

- orange region: sin $i > 1$
- q: mass ratio
- s, r: Shapiro delay shape and range
- $\dot{\omega}$: periastron advance
- P_b: orbital-period decay
- γ: gravitational redshift and time dilation
- Ω_B spin precession rate of pulsar B

Part 3

Direct detection of gravitational waves

Electromagnetic vs. gravitational waves

Electromagnetic waves:

- are waves that propagate through spacetime
- are produced incoherently by many (small) atoms
- have a short wavelength compared to their source size
- are caused by the relatively strong electromagnetic force
- have frequencies $\gtrsim 10^6$ Hz
- are measured by energy $\rightarrow \quad L(r) \sim 1/r^2$

Gravitational waves:

- are waves in the metric of spacetime
- are produced coherently by a few large masses
- have a long wavelength compared to their source size
- are caused by the weak gravitational force
- have frequencies $\lesssim 10^3$ Hz
- are measured by amplitude $\rightarrow \quad h(r) \sim 1/r$

Why detect them?

Physics:

- direct measurement of GWs and verification of GR
- direct observation of black holes
- verify that GWs travel at the speed of light, *i.e.* that the graviton rest mass = 0
- verify that GWs act transversely, *i.e.* that the graviton spin = 2

Astrophysics: LIGO/Virgo

- the ripping apart of neutron stars, their implosion to a black hole
- black holes eating neutron stars, BH-BH collisions
- core-collapse supernovae
- hills on pulsars

Astrophysics: LISA

- galactic compact binaries
- extragalactic supermassive black holes
- extreme mass-ratio inspirals
- IMBH inspirals?

Why detect them?

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- direct measurement of GWs and verification of GR
- direct observation of black holes
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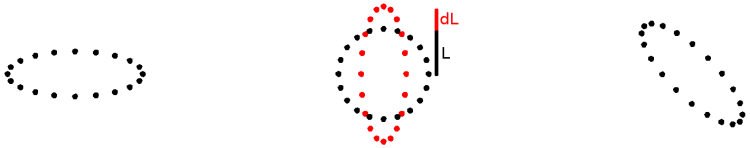
Gravitational waves

Gravitational waves. . .

- propagate transversely at the speed of light
- are quadrupole radiation at the lowest order
- stretch and squeeze spacetime in two polarisations
- allow us to measure their amplitude



- Strain: $h(t) = h_+(t)F_+(t) + h_\times(t)F_\times(t) = \frac{\delta L(t)}{L} \sim 10^{-22}$

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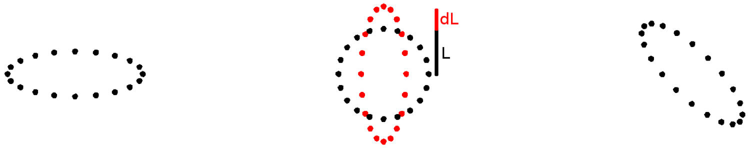

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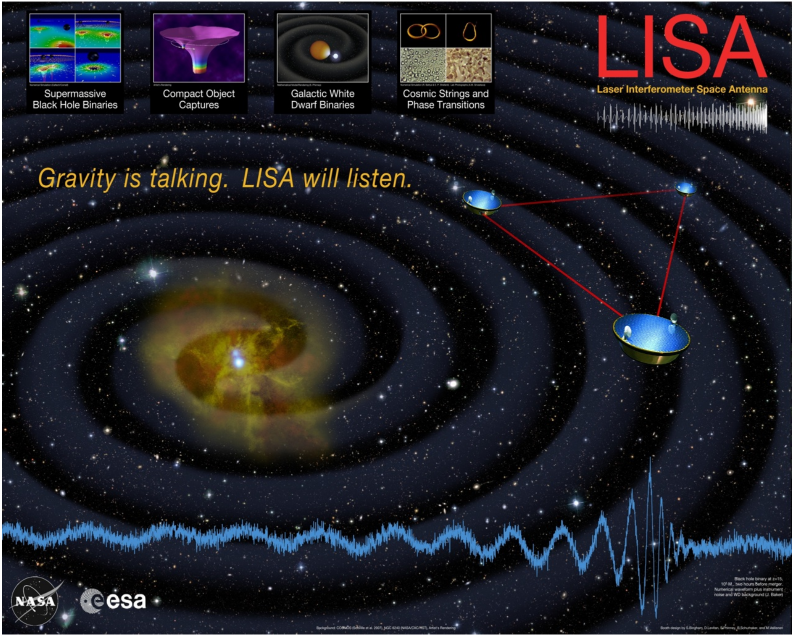
Laser Interferometer Space Antenna (LISA)

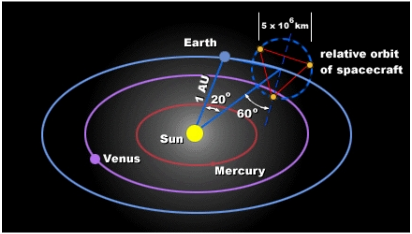


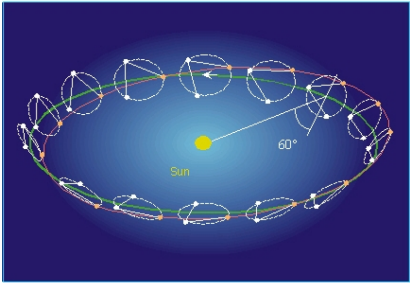
Laser Interferometer Space Antenna (LISA)

Mission:

- 3 spacecraft, 6 test masses
- Triangular configuration, arm length $\sim 5 \times 10^6$ km
- Detector is in solar orbit, trailing the Earth by 20°, in a plane inclined by 60°
- 1 Watt laser beams between spacecraft
- Low-frequency sensitivity: 0.1 mHz – 0.1 Hz ($P_{\rm orb} \sim 20$ s – 5 h)

- Mission length ≥ 5 yr
- LISA Pathfinder must test technology ($\sim$ 2012?)
- Launch $\gtrsim$ 2020 – 2025?





LISA: Galactic binaries

Detached binaries:

- Double white dwarfs:
  - abundant; most common endpoint of evolution: $\sim 3 \times 10^8$, $\sim 3 \times 10^4$ resolved (Yu & Jeffery, 2010)
  - several tens discovered (*e.g.* Saffer 1988, Marsh 1995)
  - so far, only few in the LISA band
- White-dwarf–neutron-star binaries:
  - typically WD + pulsar
  - long periods
  - no systems in LISA band found, several expected
- Double neutron stars:
  - earliest discovered (Hulse & Taylor 1975)
  - 8 known
  - PSR J0737–3039 has $P = 2.4\,\mathrm{h}$ ($f = 2.3 \times 10^{-4}$ Hz)

Interacting binaries:

- AM CVn stars:
  - white dwarf accretes He-rich material from a compact donor (*e.g.* Warner 1995)
  - periods 5.4 – 65 min
- Ultracompact X-ray binaries:
  - $\sim$ 27 known, 8 with known periods 11–50 min
  - donor typically He rich, sometimes CO rich
  - up to half of the 14 observed LMXBs in GCs is ultracompact

(Nelemans, 2009)

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LISA: verification binaries

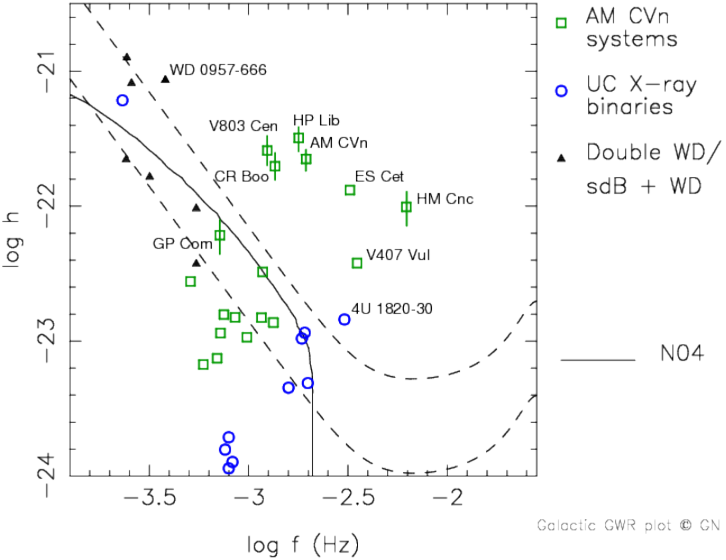
Properties of known binaries:

Type	Number	P (min)	$M_1\,(M_\odot)$	$M_2\,(M_\odot)$	d (pc)
AM CVn	25	5.4 – 65.1	0.55 – 1.2	0.006 – 0.27	100 – 3000
CVs	6	59 – 85	$\gtrsim 0.7$	0.10 – 0.15	43 – 200
DWDs	5	60 – 200	0.2 – 0.6		100 – 1100
UCXBs	5	11 – 20	$\sim 1.4?$	0.03 – 0.06	5k – 12k

http://www.astro.ru.nl/∼nelemans/dokuwiki/doku.php?id=lisa_wiki

- $\dot{P}$ measured for:
  - AM CVns RX J0806.3+1527 and V407 Vul
  - LMXB 4U 1820–30
- 3 out of 5 UCXBs are in globular clusters

LISA: verification binaries



Nelemans, 2009; Roelofs et al., 2007, 2010

Mock LISA data challenges (MLDCs)

Round 1 (2006):

1. Single galactic binaries / verification binaries / resolvable binaries
2. Massive black-hole binaries
3. EMRIs

Round 2 (2007):

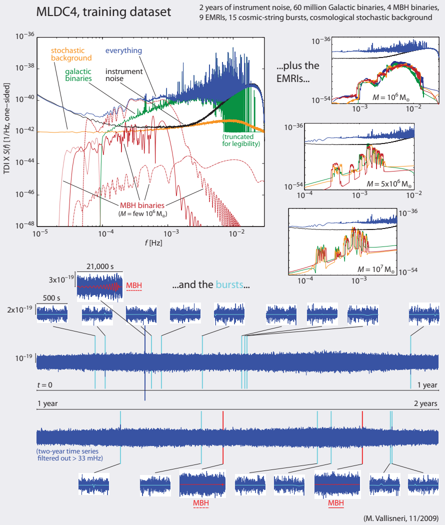
1. Galactic foreground: 30M monochromatic galactic binaries + 25 verification binaries
2. The Whole Enchilada: (1) + 4–6 BH binaries + 5 EMRIs

Round 3 (2008):

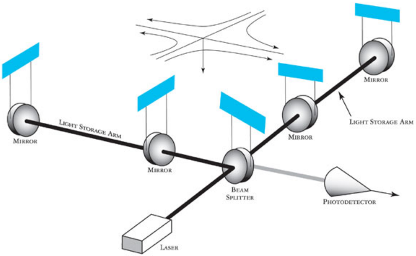
1. Galaxy with chirping binaries
2. MBH binary over galactic confusion
3. EMRIs
4. Cosmic string bursts
5. Stochastic backgrounds

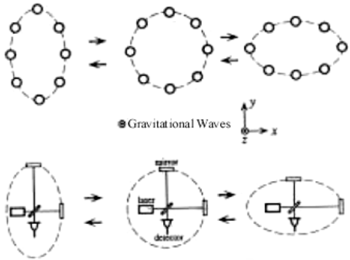
Round 4 (2011):

- Round 3, all in one data set:



Laser Interferometer GW Observatory (LIGO)





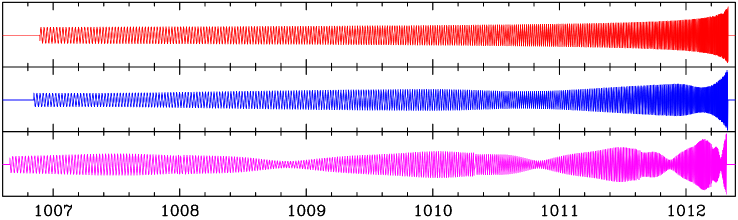
Laser Interferometer GW Observatory (LIGO)

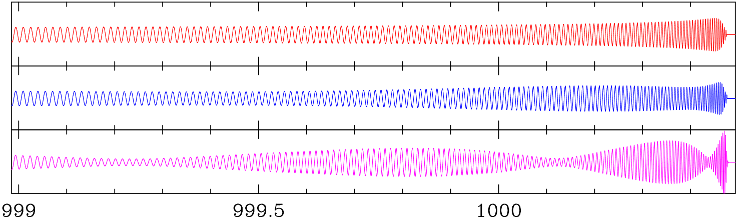
- LLO: Livingston, Louisiana (L1: 4 km)
- LHO: Hanford, Washington (H1: 4 km, H2: 2 km)
- Virgo: Pisa, Italy (V: 3 km)
- LIGO South: western Australia (20??, 5 km)
- Large Scale Cryogenic GW Telescope (LCGT), Japan ($\sim$ 2016?)

- Michelson interferometers
- Frequency sensitivity: $f \sim 40 - 1600\,\mathrm{Hz}$
- $\delta L = 10^{-22} \times L \approx 10^{-16}\,\mathrm{cm}$ (atomic nucleus $\sim 10^{-15}\,\mathrm{cm}$)

Inspiral waveforms with increasing spin

LIGO and Virgo detect the last $\sim$10 s of a binary inspiral:





$a_{\rm spin} \equiv S/M^2 = 0.0$, 0.1 and 0.5

LIGO/Virgo CBC results for S5/VSR1

- LIGO Science run 5 (S5)
- Virgo Science Run 1 (VSR1)
- May – September 2007
- $M_{\rm tot}$ = 2–35 $M_\odot$
- No detections
- Upper limits more than an order of magnitude larger than optimistic expectations

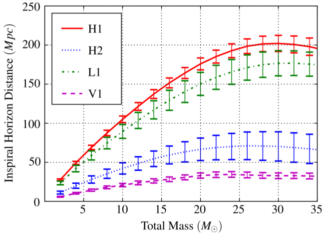
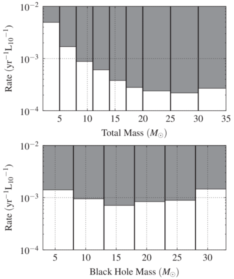


TABLE I. Summary of results. The horizon distance is averaged over the time of the search. The cumulative luminosity combines the detection efficiency with the galaxy catalog luminosity. Here, the value is the time-weighted average of the cumulative luminosity for each month. Many uncertainties are included in the calculation of the upper limit and they are summarized over all months. The effects of spin on BNS systems are negligible and not reported here.

	BNS	BHNS	BBH
Component Masses ($M_\odot$)	1.35/1.35	5.0/1.35	5.0/5.0
Horizon Distance (Mpc)	~30	~50	~90
Cumulative Luminosity (L_{10})	370	1600	8300
Calibration Error	13%	14%	14%
Monte Carlo Error	17%	17%	18%
Waveform Error	19%	18%	16%
Galaxy Distance Error	−16%	−13%	−13%
Galaxy Magnitude Error	29%	30%	31%
Nonspinning Upper Limit ($\mathrm{yr}^{-1} L_{10}^{-1}$)	8.7×10^{-3}	2.2×10^{-3}	4.4×10^{-4}
Spinning Upper Limit ($\mathrm{yr}^{-1} L_{10}^{-1}$)	...	2.7×10^{-3}	5.3×10^{-4}



(Abadie et al., PRD 82, 102001, 2010)

Predicted detection rates of binary inspirals

Horizon distances (Mpc):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	32	67	160
Advanced LIGO/Virgo	364	767	1850

Detection-rate estimates (yr^{-1}):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	$2 \times 10^{-4} - 0.2$	$7 \times 10^{-5} - 0.1$	$2 \times 10^{-4} - 0.5$
Advanced LIGO/Virgo	$0.4 - 400$	$0.2 - 300$	$0.4 - 1000$

Estimates assume $M_{\rm NS} = 1.4\, M_\odot$ and $M_{\rm BH} = 10\, M_\odot$

Abadie 2010; talk by Ilya Mandel

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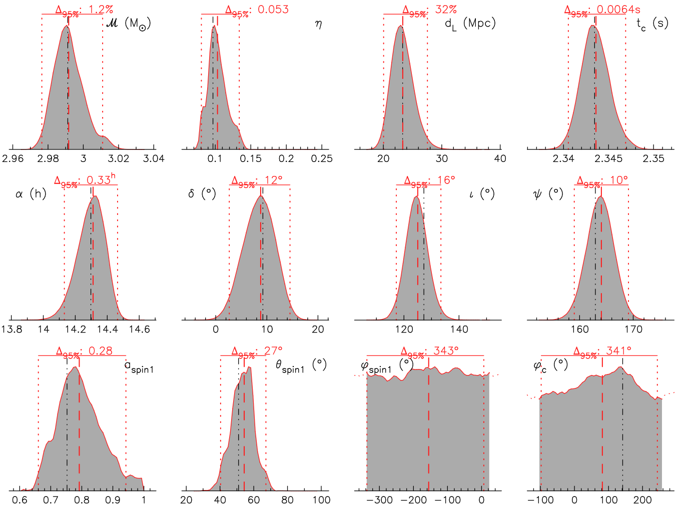
Parameter-estimation on a BH-NS signal



van der Sluys et al., 2008

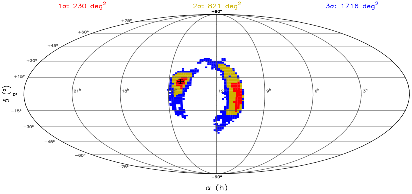
Parameters:

- H1, L1, V
- $M = 10, 1.4\, M_\odot$
- $d_L = 22.4\,\mathrm{Mpc}$
- $a_{\mathrm{spin}} = 0.8$, $\theta_{\mathrm{SL}} = 55^\circ$
- $\Sigma\,\mathrm{SNR} \approx 17.0$
- simulated noise

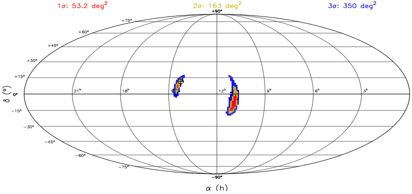
- Black dash-dotted line: injection
- Red dashed line: median
- Δ's: 95% probability

Sky position for signals with different spins

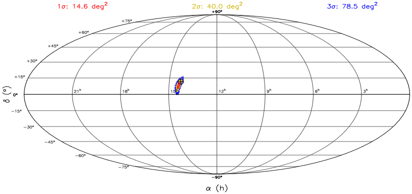
Spinning BH, non-spinning NS:
$10 + 1.4\, M_\odot$, 16–22 Mpc, Σ SNR=17



2 detectors, $a_{\rm spin} = 0.0$
2-σ accuracy: $821^{\circ 2}$



2 detectors, $a_{\rm spin} = 0.5$
2-σ accuracy: $163^{\circ 2}$



3 detectors, $a_{\rm spin} = 0.5$
2-σ accuracy: $40^{\circ 2}$

van der Sluys et al., 2008; Raymond et al., 2009

Conclusions

Gravitational waves . . .

- . . . are physical! (since the ’60s/’70s)
- . . . bring detached binaries to Roche-lobe overflow
- . . . influence or drive mass transfer in compact binaries

Ultracompact binaries . . .

- . . . have $P_{\rm orb} \lesssim 1$ h
- . . . are strongly influenced by GW angular-momentum loss
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- . . . have been up, running and observing for a few years
- . . . have a working data-analysis pipeline
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End...