BINARY NEUTRON STARS
AND GRAVITATIONAL WAVES
AT LOW AND HIGH FREQUENCIES

AEI IMPRS GW LECTURES 7+8

Thomas Tauris – IFA, Aarhus University

Note: These lectures will be <u>recorded</u> and posted onto the IMPRS website

Dear participants,

We will record all lectures on "The Astrophysics of Compact Objects", including possible Q&A after the presentation, and we will make the recordings publicly available on the IMPRS lecture website at:

https://imprs-gw-lectures.aei.mpg.de

By participating in this Zoom meeting, you are giving your explicit consent to the recording of the lecture and the publication of the recording on the course website.

Albert-Einstein Institute Lectures 2021
Thomas Tauris @ Aarhus University

Lectures 1+2:   Wednesday May 12, 10:00 – 12:00

X-ray Binaries and Recycling Millisecond Pulsars

Lectures 3+4:   Friday May 14, 10:00 – 12:00

Spin and B-field Evolution of Neutron Stars (+ Black Hole Spins)

Lectures 5+6:   Wednesday May 19, 10:00 – 12:00

Formation of Binary Neutron Stars/Black Holes

Lectures 7+8:   Friday May 21, 10:00 – 12:00

Binary Neutron Stars and Gravitational Waves at Low and High Frequencies

You are most welcome to ask questions any time ☺

A brief chirp from a galaxy 1.4 billion light years away... Detection of gravitational waves!

GW150914, GW151012, GW151226, GW170104, GW170608, GW170729, GW170809, GW170814, GW170817, GW170818, GW170823, (O3.......)

Gravity regimes

(1) Quasi-stationary weak-field regime

(2) Quasi-stationary strong-field regime

(3) Radiative regime

(4) Highly relativistic regime

Solar system experiments

Binary pulsar experiments

GW astronomy

The Gravitational Wave Spectrum © NASA

Follow-up:
EM transient counterparts
….. and neutrinos

high freq. GWs **LIGO: 10 Hz − 1 kHz**

low freq. GWs **LISA: 0.1 mHz − 10 mHz**

$$* \quad \Delta E_{GW} < 10^{-8} \, M_\odot \, c^2$$

I. Transient (one-time) burst events: extragalactic

LIGO ❖ Colliding neutron star + black hole binaries

(**LISA** may detect these mergers too)

LIGO ❖ Supernova core collapse (Galactic!) *

LISA ❖ Supermassive black hole mergers

Alessandra Buonanno (AEI)
Masaru Shibata (AEI)

Maria Alessandra Papa (AEI)
Bruce Allen (AEI)

II. Persistent sources (continuous emission): Galactic

LIGO ❖ Pulsars or accreting NS

LISA ❖ Galactic resolved compact binaries (WD, NS, BH)

+ <u>many</u> other brilliant
AEI group leaders and staff members

Karsten Danzmann (AEI)

Central questions:

How do these BH/NS binaries form?

And how can we understand their properties (i.e. *masses* and *spins*)?

What are the GW spectra for LISA?

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Tauris & van den Heuvel (2006)

Fig. 16.16. Isochrones for the merging time of double neutron star binaries, as calculated by the authors. The curves correspond to values of (from left to right): 3×10^5 yr, 3 Myr, 30 Myr, 300 Myr and 3 Gyr, respectively. The five detected Galactic double neutron star systems are indicated with ★.

Tauris & van den Heuvel (2022)

Note:
ecc $\cong 0.7$
$\Rightarrow \tau_{GW} \downarrow$ x 10

Double neutron star mergers: **GW170817**

→ gravitational wave burst

→ short γ-ray burst

→ ejection of a few 0.01 $M_\odot$
  heavy r-process elements

→ macro/kilonovae (EM follow-up)

Abbott et al. (2017), Coulter et al. (2017),
Soares-Santos et al. (2017),
Smartt et al. (2017), Drout et al. (2017)

Review: Giacomazzo et al. (2019)
Shibata & Hotokezaka (2019)

NS+BH

Just et al. (2015)

New era of **multi-messenger** astrophysics

Detection of a **kilonova** (radioactive decay of heavy r-process elements)

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GW	**EM**	**NEUTRINOS**
• mass	• sky location	• neutrino physics
• spin	• host galaxy	• central engine
• eccentricity	• redshift	• SN explosions
• luminosity distance	• local environment	
• system orientation	• heavy r-process nucleosynthesis	
• BH/NS merger-rate density	• emission processes (kilonova)	
• evolution over cosmic time (primordial BHs, SMBH seeds)	• sGRB (central engine, beaming, jets, afterglow)	

- **Testing theories of gravity**
- **NS equation-of-state**
- **Cosmology**

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80 MoUs involving 170 instruments!!

- **Tidal deformation and NS EoS**

S. Roswogg

GW phase depends on tidal deformability parameter:

$$\Lambda \propto k\,(R\,/\,M)^5$$

$$\lambda \equiv -\frac{Q_{ij}}{\mathcal{E}_{ij}} \qquad \Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3}k_2\left(\frac{Gm}{Rc^2}\right)^{-5}$$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

$$q = m_2/m_1 \leq 1$$

Flanagan & Hinderer (2008)

+ NICER
ask Tim Dietrich!
arXiv: 2105.08688

NGC 4993
d = 40 Mpc (z=0.009, 130 mill. ly)

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$v_{red} \sim 0.1\ c$

$v_{blue} \sim 0.25\ c$

Kilonova light curves suggest the existence of a hyper massive neutron star prior to collapse to a black hole

EM suggests neutron star merger

Blue KN Ejecta
internal shocks
gamma-rays?
open field lines (outflow)
Ω
v_e $\bar{v}_e$
$Y_e > 0.25, v \sim 0.2\text{-}0.3\ c$
neutrino-heated layer
$R_{sh} \sim v\ t_{rem}$
HMNS

Metzger, Thompson, Quataert ApJL **856** 101 (2018)

Slide provided by Duncan Brown

Ben Margalit

Slide provided by Duncan Brown

The merger remnant also places a constraint on the maximum neutron star mass

The remnant NS cannot be long lived, or there would be too much energy in the EM observantion

$$M_{\max} \leq 2.17 M_\odot \ (90\%)$$

Margalit and Metzger ApJL 850 19 (2018)

Coughlin, Dietrich, Margalit, Metzger arXiv:1812:04803

Slide provided by Duncan Brown

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Heavy r-process
elements synthesis

Fig. 11.2 Top panel: Solar r-process abundances as a function of nuclear mass number A. The values are taken from Sneden et al. (2008). Bottom panel: Typical r-process path in the nuclear chart and the corresponding β-decay half-lives according to Möller et al. (2003). Stable isotopes are marked in black and the magic neutron numbers are indicated by vertical dotted lines. The overlay of the two panels demonstrates how regions of large $T_{1/2}$ at the magic neutron numbers are responsible for the r-process abundance peaks after decay to stability

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Mass ejecta and electron fraction

1) Dynamical ejecta (tidal disruption)

2) Disk ejecta (viscous heating and MHD)

Total amount of ejecta (few 0.001 M_{sun} to 0.1 M_{sun}) depends on:

- NS+NS $\rightarrow$ prompt BH formation or MNS (meta stable, Δt = 10 ms – 10 s)
- Mass ratio (q < 0.8 leads to larger yield)
- NS radius and BH spin

Important output parameters are: mass, velocity and electron fraction (Y_e).

Y_e is of key importance for determing the abundance of r-process elements, which again determine the opacity of the EM emission.

- **Masses**

- **Spins**

- **B-fields**

- **Orbital period**

- **Eccentricity**

- **Age at merger time**

- **Kicks**

- **Location relative to host galaxy**

- **Merger rates**

Thomas Tauris

RECIPE

- Binary stellar evolution

- Population synthesis
  (input distributions and stellar grids)

- Galactic star formation rate
  (formation history of massive binaries)

- Galactic potentials
  (to probe location of mergers in host galaxies)

- Extrapolation to local Universe
  (scaling-law of galactic number density)

1 billion

Notes on

POP. SYNTHESIS

1. Reproduction of LIGO rates is *no* success criterion on its own
2. Can Galactic sources be reproduced? (properties of HMXBs, DNSs, etc.)
3. Is the input physics reasonable? Is the evolution self consistent? *
4. Watch out for papers that claim they can explain everything!

* E.g. Stellar evolution (Z)
Klencki et al. (2020)

Progenitors of gravitational wave mergers:
Binary evolution with the stellar grid based code COMBINE

Matthias U. Kruckow,[1][*] Thomas M. Tauris,[2,1] Norbert Langer,[1,2] Michael Kramer,[2] Robert G. Izzard[3]

Population synthesis using Monte Carlo techniques:
Typically one billion binaries are evolved

Dense stellar grid* calculated with BEC
- age
- mass
- core mass
- radius
- luminosity
- effective temperature
- envelope structure parameter

- semi-major axis (orbital period)
- eccentricity
- galactic position
- velocity

Initial distribution functions
(M_1, M_2, a, e, Z*, v_{rot}*)

He-star (WR-star) tracks

Merger rate of double neutron star binaries in a Milky Way-like galaxy: 3–14 Myr $^{-1}$

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advanced LIGO

Capricornus Supercluster

Ophiuchus Supercluster

Corona-Borealis Supercluster

Capricornus Void

Hercules Superclusters

Corona Borealis Void

Boötes Superclusters

Pavo-Indus Supercluster

Microscopium Void

Centaurus Supercluster

Shapley Supercluster

Boötes Void

Hydra-Centaurus Supercluster

Sculptor Void

Sculptor Superclusters

Virgo Supercluster

Hydra

Pisces-Cetus Superclusters

Coma Supercluster

Perseus-Pisces Supercluster

Ursa Major Supercluster

Fornax Void

Phoenix Supercluster

Canes-Major Void

Leo Superclusters

Columbia Void

Sextans Superclusters

Horologium Supercluster

Columba Supercluster

Range:
 NSNS merger 200 Mpc
 NSBH merger 600 Mpc
 BHBH merger   3 Gpc
                (Z=0.5)

DNS detection rate:
 1-5 per year
 (Milky Way: 3-14 Myr $^{-1}$)

Highly uncertain

Main uncertainties:
CE evolution, kicks

You are here!

@design sensitivity: 1–5 detections per yr

Kruckow, Tauris, et al. (2018), MNRAS

GW170817

$Z = 0.0088 \approx Z_{NGC4993}$

We find age solutions from
< 100 Myr to > 10 Gyr

Our NS mass solutions for GW170817
are typical for Galactic DNS systems

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NGC 4993

Kruckow et al. (2018), MNRAS

For NGC 4993, the escape velocity at the location of GW170817 is about 350 km s^{-1} (Pan et al. 2017), much larger than the typical systemic velocities we obtain in our simulations.

Kruckow et al. (2018), MNRAS

GW190425
$M_{chirp} = 1.44\ M_{sun}$

$M_{total} = 3.3\ M_{sun}$

$(\chi < 0.05)$

GW170817:
$R = 1540\ +/-\ ^{3200}_{1220}\ Gpc^{-3}\ yr^{-1}$

GW190425:
$R = 1090\ +/-\ ^{1720}_{800}\ Gpc^{-3}\ yr^{-1}$

New combined rate (GWTC-2):
$R = 320\ +/-\ ^{490}_{240}\ Gpc^{-3}\ yr^{-1}$

Kruckow (2020), A&A

Fig. 3. Progenitor masses of GW190425 at Milky Way like metallicity in the default simulation. The color indicates the time until the GW merger. The Models are selected according to the reported binary mass of $3.4^{+0.3}_{-0.1}$ $M_\odot$ and chirp mass of $1.44^{+0.02}_{-0.02}$ $M_\odot$, where errors mark the 90 per cent confidence interval (The LIGO Scientific Collaboration et al. 2020). The solid black line marks the binaries with equal primary and secondary mass. On the top are the primary masses collapsed to a probability distribution.

Kruckow et al. (2018), MNRAS

Kruckow et al. (2018), MNRAS

$Z_{MW} = 0.0088$

NS-NS, $100 \times$NS-BH, BH-NS, BH-BH

$Z_{IZw18} = 0.0002$

Detection rates

local Universe

@design sensitivity: 1–5 detections per yr

GW170817

Z_{MW}	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.36 M$_\odot^{2.5}$	9.85×10^0 yr^{-1} Gpc^{-3}	0.28 yr^{-1}	3.47×10^1 yr^{-1} Gpc^{-3}	0.98 yr^{-1}
NS-BH	20.0 M$_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	15.7 M$_\odot^{2.5}$	1.80×10^1 yr^{-1} Gpc^{-3}	5.88 yr^{-1}	4.72×10^1 yr^{-1} Gpc^{-3}	15.43 yr^{-1}
BH-BH	233 M$_\odot^{2.5}$	6.01×10^{-1} yr^{-1} Gpc^{-3}	2.92 yr^{-1}	3.08×10^0 yr^{-1} Gpc^{-3}	14.95 yr^{-1}
Z_{IZw18}	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.27 M$_\odot^{2.5}$	1.00×10^1 yr^{-1} Gpc^{-3}	0.27 yr^{-1}	3.28×10^1 yr^{-1} Gpc^{-3}	0.87 yr^{-1}
NS-BH	32.3 M$_\odot^{2.5}$	6.61×10^{-3} yr^{-1} Gpc^{-3}	0.00 yr^{-1}	1.55×10^{-2} yr^{-1} Gpc^{-3}	0.01 yr^{-1}
BH-NS	35.5 M$_\odot^{2.5}$	1.54×10^1 yr^{-1} Gpc^{-3}	11.40 yr^{-1}	5.32×10^1 yr^{-1} Gpc^{-3}	39.34 yr^{-1}
BH-BH	1720 M$_\odot^{2.5}$	1.68×10^1 yr^{-1} Gpc^{-3}	603.02 yr^{-1}	3.45×10^1 yr^{-1} Gpc^{-3}	1235.27 yr^{-1}
optimistic	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.31 M$_\odot^{2.5}$	7.09×10^1 yr^{-1} Gpc^{-3}	1.94 yr^{-1}	1.59×10^2 yr^{-1} Gpc^{-3}	4.37 yr^{-1}
NS-BH	19.4 M$_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	21.9 M$_\odot^{2.5}$	1.34×10^1 yr^{-1} Gpc^{-3}	6.11 yr^{-1}	2.44×10^1 yr^{-1} Gpc^{-3}	11.17 yr^{-1}
BH-BH	275 M$_\odot^{2.5}$	4.34×10^1 yr^{-1} Gpc^{-3}	248.34 yr^{-1}	1.09×10^2 yr^{-1} Gpc^{-3}	623.03 yr^{-1}

$Z = 0.0088 \approx Z_{NGC4993}$

Kruckow et al. (2018), MNRAS

GW merger rates	$Z_{MW} = 0.0088$	$Z_{IZw18} = 0.0002$
NS-NS	$2.98^{+0.15}_{-0.24} \times 10^{-6}$ yr^{-1}	$2.82^{+0.16}_{-0.27} \times 10^{-6}$ yr^{-1}
NS-BH	$0.00^{+0.00}_{-0.00} \times 10^{0}$ yr^{-1}	$1.33^{+0.13}_{-0.22} \times 10^{-9}$ yr^{-1}
BH-NS	$4.05^{+0.35}_{-0.59} \times 10^{-6}$ yr^{-1}	$4.57^{+0.26}_{-0.37} \times 10^{-6}$ yr^{-1}
BH-BH	$2.64^{+0.05}_{-0.07} \times 10^{-7}$ yr^{-1}	$2.96^{+0.50}_{-0.55} \times 10^{-6}$ yr^{-1}

~ 3 DNS mergers Myr^{-1} MWEG^{-1}

Other investigations are much more (too?) optimistic
(i.e. predicting much higher rates ☺). We will see…..

BH-BH:

LIGO/Virgo: 23.9 +/- $^{14.9}_{8.6}$ Gpc^{-3} yr^{-1} (Abbott et al. 2021)

We find: 0.6–35 Gpc^{-3} yr^{-1} (Kruckow et al. 2018)

(depending on metallicity and galaxy-density scaling)

Our rate is sensitive to CE physics (factor 10↑ if using α_{CE}=0.8 vs α_{CE}=0.5).

NS-NS:

LIGO/Virgo: 320 (+490 -240) Gpc^{-3} yr^{-1} (Abbott et al. 2021)

We find: 10–35 (10–400)* Gpc^{-3} yr^{-1} (optimizing all input physics incl.*smaller kicks)

BH-NS: should be detected more often than NS-NS by a factor 10!
We expect detections in O3 or O4.

local Universe

Z_{MW}	$\langle M^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.36 $M_\odot^{2.5}$	9.85×10^0 yr^{-1} Gpc^{-3}	0.28 yr^{-1}	3.47×10^1 yr^{-1} Gpc^{-3}	0.98 yr^{-1}
NS-BH	20.0 $M_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	15.7 $M_\odot^{2.5}$	1.80×10^1 yr^{-1} Gpc^{-3}	5.88 yr^{-1}	4.72×10^1 yr^{-1} Gpc^{-3}	15.43 yr^{-1}
BH-BH	233 $M_\odot^{2.5}$	6.01×10^{-1} yr^{-1} Gpc^{-3}	2.92 yr^{-1}	3.08×10^0 yr^{-1} Gpc^{-3}	14.95 yr^{-1}
Z_{IZw18}	$\langle M^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.27 $M_\odot^{2.5}$	1.00×10^1 yr^{-1} Gpc^{-3}	0.27 yr^{-1}	3.28×10^1 yr^{-1} Gpc^{-3}	0.87 yr^{-1}
NS-BH	32.3 $M_\odot^{2.5}$	6.61×10^{-3} yr^{-1} Gpc^{-3}	0.00 yr^{-1}	1.55×10^{-2} yr^{-1} Gpc^{-3}	0.01 yr^{-1}
BH-NS	35.5 $M_\odot^{2.5}$	1.54×10^1 yr^{-1} Gpc^{-3}	11.40 yr^{-1}	5.32×10^1 yr^{-1} Gpc^{-3}	39.34 yr^{-1}
BH-BH	1720 $M_\odot^{2.5}$	1.68×10^1 yr^{-1} Gpc^{-3}	603.02 yr^{-1}	3.45×10^1 yr^{-1} Gpc^{-3}	1235.27 yr^{-1}
optimistic	$\langle M^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.31 $M_\odot^{2.5}$	7.09×10^1 yr^{-1} Gpc^{-3}	1.94 yr^{-1}	1.59×10^2 yr^{-1} Gpc^{-3}	4.37 yr^{-1}
NS-BH	19.4 $M_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	21.9 $M_\odot^{2.5}$	1.34×10^1 yr^{-1} Gpc^{-3}	6.11 yr^{-1}	2.44×10^1 yr^{-1} Gpc^{-3}	11.17 yr^{-1}
BH-BH	275 $M_\odot^{2.5}$	4.34×10^1 yr^{-1} Gpc^{-3}	248.34 yr^{-1}	1.09×10^2 yr^{-1} Gpc^{-3}	623.03 yr^{-1}

+ additional candidates from Princeton group

11* events in O1 and O2

10 BH+BH mergers
1 NS+NS merger

When?

~ 50 events in O3a + 03b   03a

x BH+BH mergers 23
? **y** NS+NS mergers 1(3)
z BH+NS mergers 2(4)
mass gap 2(3)

- We predict ~10 times more detections of mixed BH/NS mergers compared to double NS mergers

Observational selection bias against?

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Heavy r-process elements: Beniamini et al. (2016): $5.0–20.0×10^{-4}$ per CC SN.

Our default and "optimistic" estimates of a DNS merger rate = $3.0–14.0$ Myr^{-1} MWEG.
Combined with a Galactic CC SN rate of about 0.01 yr^{-1}
$\rightarrow$ translates into a relative merger rate of about $3.0–14.0×10^{-4}$ per CC SN.

sGRBs: Wanderman & Piran (2015): $2.2–6.4$ **f^{-1}** yr^{-1} Gpc^{-3}
where f^{-1} is a beaming factor in the range $1 < f^{-1} < 100$.

sGRB are expected from both DNS and mixed NS/BH mergers,
adding our simulated merger-rate densities we get $25–86$ yr^{-1} Gpc^{-3}.
These numbers agree for $f^{-1} = 4–40$ (Metzger & Berger 2012; Fong et al. 2015).

Table 5. Variations in DCO formation and merger rates for a MW-like galaxy caused by changing the values of selected key input parameters (columns 3 to 9). The default input parameters are listed in Table 2 and the resulting rates are shown in the second column. The binary types refer to the first and second compact objects formed. The pure uncertainties of Poissonian statistics are between 10^{-11} yr^{-1} and 10^{-8} yr^{-1}.

		α_{CE}	β_{min}	α_{RLO}	α_{th}	q_{limit}	α_{IMF}	$m^{p}_{max} = m^{s}_{max}$
	upper:	0.80	0.79	0.24	0.70	4.0	3	150 M$_\odot$
	lower:	0.20	0.50	0.15	0.30	1.5	2	80 M$_\odot$
Formation rates	default	α_{CE}	β_{min}	α_{RLO}	α_{th}	q_{limit}	α_{IMF}	$m^{p}_{max} = m^{s}_{max}$
NS-NS (yr^{-1})	6.81×10^{-6}	$^{+2.37}_{-1.72}\times10^{-6}$	$^{-0.63}_{+3.02}\times10^{-6}$	$^{-0.69}_{+1.06}\times10^{-6}$	$^{+0.35}_{-1.32}\times10^{-7}$	$^{+3.17}_{-1.01}\times10^{-6}$	$^{-0.33}_{+2.08}\times10^{-5}$	$^{-1.91}_{+1.05}\times10^{-8}$
NS-BH (yr^{-1})	5.49×10^{-9}	$^{+2.01}_{-0.04}\times10^{-8}$	$^{+1.20}_{-0.36}\times10^{-8}$	$^{+1.14}_{-0.50}\times10^{-8}$	$^{-0.77}_{-1.23}\times10^{-9}$	$^{+1.11}_{-0.05}\times10^{-7}$	$^{-0.35}_{+3.79}\times10^{-8}$	$^{-1.15}_{-1.69}\times10^{-9}$
BH-NS (yr^{-1})	1.49×10^{-5}	$^{+1.96}_{-3.26}\times10^{-6}$	$^{+0.17}_{-1.23}\times10^{-5}$	$^{+1.28}_{-2.73}\times10^{-6}$	$^{+1.05}_{-0.70}\times10^{-6}$	$^{+4.55}_{-1.28}\times10^{-5}$	$^{-0.10}_{+1.38}\times10^{-4}$	$^{+9.37}_{-9.15}\times10^{-7}$
BH-BH (yr^{-1})	2.27×10^{-6}	$^{+2.35}_{-0.30}\times10^{-6}$	$^{+1.06}_{-0.19}\times10^{-6}$	$^{+1.08}_{-0.28}\times10^{-6}$	$^{+2.88}_{-1.80}\times10^{-7}$	$^{+3.87}_{-0.02}\times10^{-5}$	$^{-0.16}_{+2.99}\times10^{-5}$	$^{+4.37}_{-1.11}\times10^{-6}$
GW merger rates	default	α_{CE}	β_{min}	α_{RLO}	α_{th}	q_{limit}	α_{IMF}	$m^{p}_{max} = m^{s}_{max}$
NS-NS (yr^{-1})	2.98×10^{-6}	$^{+7.75}_{-0.64}\times10^{-7}$	$^{-0.51}_{+2.71}\times10^{-6}$	$^{-5.67}_{+8.64}\times10^{-7}$	$^{-2.60}_{+1.47}\times10^{-7}$	$^{+0.85}_{-4.66}\times10^{-7}$	$^{-1.46}_{+9.68}\times10^{-6}$	$^{-3.11}_{-0.67}\times10^{-8}$
NS-BH (yr^{-1})	0.00×10^{0}	$^{+1.20}_{+0.01}\times10^{-8}$	$^{+2.58}_{+0.00}\times10^{-10}$	$^{+3.87}_{+0.00}\times10^{-10}$	$^{+1.94}_{+0.00}\times10^{-10}$	$^{+1.94}_{+0.00}\times10^{-9}$	$^{+0.00}_{+1.34}\times10^{-9}$	$^{+0.65}_{+1.93}\times10^{-10}$
BH-NS (yr^{-1})	4.05×10^{-6}	$^{+0.81}_{-2.09}\times10^{-6}$	$^{+0.25}_{-3.56}\times10^{-6}$	$^{+2.94}_{-7.65}\times10^{-7}$	$^{+4.25}_{-2.49}\times10^{-7}$	$^{+2.88}_{-2.73}\times10^{-6}$	$^{-0.26}_{+3.56}\times10^{-5}$	$^{+1.32}_{-1.61}\times10^{-7}$
BH-BH (yr^{-1})	2.64×10^{-7}	$^{+2.19}_{-0.25}\times10^{-6}$	$^{+0.01}_{+1.91}\times10^{-7}$	$^{+0.17}_{+4.45}\times10^{-8}$	$^{+3.11}_{-1.41}\times10^{-7}$	$^{+1.15}_{+0.10}\times10^{-6}$	$^{-0.19}_{+3.84}\times10^{-6}$	$^{+3.86}_{-1.96}\times10^{-7}$

GW merger rates of a MW-like galaxy and their dependence on applied kicks and assumptions on EC SNe. The binary types ... the first and second compact objects formed.

GW merger rates	default	small kicks*	large EC SN kicks**	small EC SN mass window***
			$w_{ECSN} = w_{FeCCSN}$	1.37 M$_\odot \leq m^{ECSN}_{CO-core} < 1.38$ M$_\odot$
NS-NS (yr^{-1})	2.98×10^{-6}	9.34×10^{-6}	1.54×10^{-6}	2.30×10^{-6}
NS-BH (yr^{-1})	0.00×10^{0}	1.94×10^{-10}	6.46×10^{-11}	1.29×10^{-10}
BH-NS (yr^{-1})	4.05×10^{-6}	7.59×10^{-6}	4.04×10^{-6}	4.04×10^{-6}
BH-BH (yr^{-1})	2.64×10^{-7}	3.05×10^{-7}	2.65×10^{-7}	2.66×10^{-7}

* half of all default kick magnitudes. ** similar to FeCC SNe, see Table 1. *** the default is 1.37 M$_\odot \leq m^{ECSN}_{CO-core} < 1.435$ M$_\odot$.

Galactic distribution of merging neutron stars and black holes – prospects for short gamma-ray burst progenitors and LIGO/VIRGO

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host galaxies. To help investigate the physical nature of short- and long-duration gamma-ray bursts, we compute the distances of merging neutron stars (NS) and/or black holes (BH) from the centres of their host galaxies, as predicted by their formation scenario combined with motion in galactic potentials. Furthermore, we estimate the formation rate and merging rate of these massive double degenerate binaries. The latter is very important for the prospects of detecting gravitational waves with LIGO/VIRGO. We find that the expected detection rate for LIGO II is $\sim$850 yr^{-1} for galactic field sources and that this rate is completely dominated by merging double black hole (BHBH) binaries. Even LIGO I may detect such an event ($\sim$0.25 yr^{-1}). Our preferred model estimates the Galactic field double neutron star (NSNS) merger rate to be $\sim$1.5 $\times$ 10^{-6} yr^{-1}. For BHBH systems this model predicts a merger rate of $\sim$9.7 $\times$ 10^{-6} yr^{-1}. Our studies also reveal an accumulating numerous population of very wide-orbit BHBH systems which never merge ($\tau \gg \tau_{\mathrm{Hubble}}$).

Key words: black hole physics – gravitational waves – methods: numerical – binaries: close – stars: neutron – gamma-rays: bursts.

For the historical record   Voss & Tauris (2003):

- Realistic CE binding energies
- Case BB RLO (evolved He-stars)
- Multi-component NS kick dist.

Table 6. The expected LIGO/VIRGO detection rates of compact mergers.

Systems	Galactic merger rate	LIGO I	LIGO II
NSNS	1.5×10^{-6} yr^{-1}	6.0×10^{-4} yr^{-1}	2.0 yr^{-1}
NSBH	8.4×10^{-8} yr^{-1}	1.7×10^{-4} yr^{-1}	0.6 yr^{-1}
BHNS	5.0×10^{-7} yr^{-1}	1.0×10^{-3} yr^{-1}	3.4 yr^{-1}
BHBH	9.7×10^{-6} yr^{-1}	2.5×10^{-1} yr^{-1}	840 yr^{-1}

300 Mpc (NSNS sensitivity)

LIGO O3a: ~ 1 BHBH per week
        (~ 52 per year)
        @ 120 Mpc

$52 \times (300/120)^3 = \underline{812 \text{ yr}^{-1}}$

Equal to prediction in 2003 within 3%

Tauris & van den Heuvel (2022)

$M_{NS} = 1.174(4) M_{sun}$ is the lowest NS mass determined accurately

AEI 2021

Kruckow et al. (2018)

Binary effects!
1st SN: wide binary
to survive later CE
(small kick is often
 from ECNSe)

2nd SN: tight binary
to produce merger
(larger kicks are ok)

Do ECSNe produce NSs which are more massive by ~ 0.06 M$_{sun}$?
(after correction for accretion)

Tauris & van den Heuvel (2022)

Table 1.4: Properties of 20 DNS systems with published data (including a few unconfirmed candidates).

Radio Pulsar	Type	P (ms)	$\dot{P}$ (10^{-18})	B $(10^9$ G)	P_{orb} (days)	e	M_{psr} $(M_\odot)$	M_{comp} $(M_\odot)$	M_{total} $(M_\odot)$	δ (deg)	Dist. (kpc)	v^{LSR**} (km s^{-1})	τ_{gwr} (Myr)
J0453+1559[a]	recycled	45.8	0.186	1.1	4.072	0.113	1.559	1.174	2.734	–	1.07	82	∞
J0509+3801[b]	recycled	76.5	7.93	7.2	0.380	0.586	~ 1.34	~ 1.46	2.805	–	1.56	–	579
J0737−3039A[c]	recycled	22.7	1.76	1.8	0.102	0.088	1.338	1.249	2.587	< 3.2	1.15	32	86
J0737−3039B[c]	young	2773.5	892	410	−||−	−||−	1.249	1.338	−||−	130 ± 1	−||−	−||−	−||−
J1411+2551[d]	recycled	62.5	0.0956	0.66	2.616	0.170	< 1.62	> 0.92	2.538	–	1.13	–	∞
J1518+4904[e]	recycled	40.9	0.0272	0.33	8.634	0.249	***	***	2.718	–	0.63	30	∞
B1534+12[f]	recycled	37.9	2.42	2.8	0.421	0.274	1.333	1.346	2.678	27 ± 3	1.05	143	2730
J1753−2240[g]	recycled	95.1	0.970	2.5	13.638	0.304	–	–	–	–	3.46	–	∞
J1755−2550[h]*	young	315.2	–	270	9.696	0.089	–	> 0.40	–	–	10.3	–	∞
J1756−2251[i]	recycled	28.5	1.02	1.6	0.320	0.181	1.341	1.230	2.570	< 34	0.73	39****	1660
J1757−1854[j]	recycled	21.5	2.63	2.2	0.184	0.606	1.338	1.395	2.733	–	19.6	–	76
J1811−1736[k]	recycled	104.2	0.901	2.7	18.779	0.828	< 1.64	> 0.93	2.57	–	5.93	–	∞
J1829+2456[l]	recycled	41.0	0.0525	0.42	1.176	0.139	< 1.38	> 1.22	2.59	–	0.74	–	∞
J1906+0746[m]*	young	144.1	20300	470	0.166	0.085	1.291	1.322	2.613	–	7.40	–	309
J1913+1102[n]	recycled	27.3	0.161	0.83	0.206	0.090	~ 1.65	~ 1.24	2.888	–	–	–	470
B1913+16[o]	recycled	59.0	8.63	7.3	0.323	0.617	1.440	1.389	2.828	18 ± 6	9.80	241	301
J1930−1852[p]	recycled	185.5	18.0	16	45.060	0.399	< 1.32	> 1.30	2.59	–	1.5	–	∞
J1946+2052[q]	recycled	17.0	0.92	1.0	0.078	0.064	< 1.31	> 1.18	2.50	–	1.5	–	46
J0514−4002A[r]*	GC	5.0	0.00070	0.016	18.79	0.888	~ 1.25	~ 1.22	2.473	–	12.1	–	∞
J1807−2459B[s]*	GC	4.2	0.0823	0.18	9.957	0.747	1.366	1.206	2.572	–	3.0	–	∞
B2127+11C[t]	GC	30.5	4.99	3.7	0.335	0.681	1.358	1.354	2.713	–	12.9	–	217

Globular cluster sources! These NSs were most likely recycled in LMXBs (WD progenitors as donor stars) which were afterwards disrupted and the recycled NSs were paired with other NSs.

9/10 Galactic DNS mergers are from isolated binaries
(1/10 are in globular clusters)

LIGO DNS merger rate density: 320 Gpc^{-3} yr^{-1} ⇒ ~30 Myr^{-1} MWEG^{-1} (GWTC-2)
i.e. at least ~1400 DNSs in the MW in the pipeline with $\tau_{GW} < 46$ Myr SCIENCE FICTION!!

Codes on the market:

binary_c

BPASS

Brussels

ComBinE

COMPAS

MOBSE

POSYDON

Scenario Machine

SeBa

SEVN

StarTrack

Sample papers:

Stevenson et al. (2017)

Giacobbo & Mapelli (2018)

Chruslinska et al. (2018)

Vigna-Gomez et al. (2018)

Kruckow et al. (2018)

Neijssel et al. (2019)

Belczynski et al. (2018, 2020)

Breivik et al. (2020)

Wu et al. (2020)

Tang et al. (2020)

Bavera et al. (2020, 2021)

Shao & Li (2021)

Santoliquido et al. (2021)

Eccentricity, e

Semi-major axis, a (R$_{sun}$)

Kruckow, Tauris, et al. (2018), MNRAS

Important calibration data!!!

Do not trust population synthesis if it cannot reproduce observed Galactic DNS systems

NS mass ratios

- **Spin distributions of BHs and NSs**

$| X_{\text{eff}} | < 0.35$ at the 90% credible level for all events!
(degeneracy between projected spins and
orbital inclination, masses)

$$\chi_{eff} \equiv \frac{1}{M}\left(m_1\chi_1 + m_2\chi_2\right)$$

3G ?

Provides a clue to their astrophysical origin
e.g. Baibhav et al. (2020)

- **Tests of GR and other gravity theories**

LIGO Hanford Data (shifted)

LIGO Livingston Data

- **Multi-messenger astrophysics**
- ✓ **GWs**
- ✓ **Optical**
- ✓ **X-rays**
- ✓ **Radio**
- ✓ **...more**

NS+WD LISA SOURCES

Thomas Tauris

LISA
~2034

Earth

2.5 million km

20°

60°

1 AU (150 million km)

Sun

3G
~ ?

EINSTEIN TELESCOPE

COSMIC EXPLORER

Ask for 3 detectors
(~ 1 billion € each)

3G Science Book

THE SCIENCE CASE FOR THE NEXT GENERATION OF GROUND-BASED GRAVITATIONAL-WAVE DETECTORS

- Detect all BH-BH mergers out to $z \sim 20$
- Detect the BH seeds evolving into SMBHs
- Possibly detect primordial BHs
- Determine the NS EoS to extreme precision
- etc.

AEI 2021

The space-born observatory **LISA** (2034)
will detect thousands of resolvable **Galactic GW sources**
(besides millions of signals below the confusion limit)

WD, NS, BH

Sesana (2016)

First calculations of stable mass transfer from a WD to a NS
(Sengar, Tauris, Langer & Istrate 2017), MNRAS Letters

Tauris (2018), PRL

Strong synergies between GWs and EM observations

$$\dot{J}_{ORB} = \dot{J}_{GW} + \dot{J}_{MB} + \dot{J}_{LS} + \dot{J}_{ML}$$

Sengar et al. (2017)

AEI 2021

Tauris (2018), Phys.Rev.Lett.

Determine NS mass to a high accuracy (4%) via new method (He WD mass is known!)

Tauris (2018), Phys.Rev.Lett.

$$h_c \approx \sqrt{N_{cycles}} \; \sqrt{2} \, h_0 = \sqrt{2 f_{gw} T_{obs}} \; h_0 \qquad h_0 = \sqrt{\frac{32}{80}} \; \frac{\pi^{2/3} G^{5/3} f_{gw}^{2/3} M_{chirp}^{5/3}}{c^4 \, d_L}$$

Tauris (2018), Phys.Rev.Lett.

There should be ~150 NSWD binaries detectable in GWs in the Milky Way
(Based on known millisecond pulsars with low-mass He WDs in our Galaxy)

Tauris (2018), Phys.Rev.Lett.

Competition between GW radiation and orbital widening from mass transfer

RLO

- The **chirp mass** ($\dot{f}_{gw}$) can only be **measured** for LISA binaries with large SNR and which are close to their minimum orbital period where $\dot{f}_{gw}$ is largest.

$$\dot{f}_{gw,min} \sim \frac{4}{T^2} \frac{1}{SNR}$$

$$\simeq 2.5 \times 10^{-18} \left(\frac{100}{SNR}\right) \left(\frac{4\,yr}{T}\right)^2 \,Hz\,s^{-1}$$

$$\frac{\Delta\mathcal{M}}{\mathcal{M}} \simeq 3.8 \times 10^{-7} \left(\frac{100}{SNR}\right) \left(\frac{4\,yr}{T}\right) \left(\frac{1\,mHz}{f_{gw}}\right)$$

$$+ 1.6 \times 10^{-2} \left(\frac{100}{SNR}\right) \left(\frac{4\,yr}{T}\right)^2 \left(\frac{10^{-16}\,Hz\,s^{-1}}{\dot{f}_{gw}}\right)$$

$\gtrsim 0.005$

- However, **combining GWs and EM observations** can also be used to get $\dot{f}_{gw}$ e.g. optical observations of WDs or radio pulses from NSs/Fermi sources. (Breivik et al. 2018, Hermes et al. 2012, Abdo et al. 2009).

- It is anitipated that measuring $\dot{f}_{gw}$ is possible for 25% of the resolved LISA sources (Amaro-Seoane et al. 2012).

- **Tidal and mass-transfer interactions, and donor-disk torques**, will most likely not prevent detection of $\dot{f}_{gw}$, but could make it more **challenging** (Kremer et al. 2017, Stroeer & Nelemans 2009, van Haaften et al. 2012, Marsh et al. 2004).

Discovery of a ***dual-line*** GW binary   Tauris (2018), Phys.Rev.Lett.

NS moment of inertia

$$I_{zz}\varepsilon = \left(\frac{2}{5}\right)^{1/2} (2\pi)^{-4/3} G^{2/3} \left(\frac{f_{\rm orb}^{1/3}}{f_{\rm spin}}\right)^2 \mathcal{M}^{5/3} \left(\frac{h_{\rm spin}}{h_{\rm orb}}\right)$$

LIGO

ellipticity

LISA

Independent on the distance to the binary

Chen, Tauris, Han & Chen (2021), MNRAS

Linking LMXBs, MSPs, UCXBs and GW sources

- We have a fairly good understanding of DNS formation in general.
  - ❖ Success: spins, amount of mass accreted, orbital parameters
  - ❖ Mediocre: masses, kicks
  - ❖ Failure: common envelope, B-fields, lowest mass NSs

- Strong **synergies** between
  - o stellar evolution
  - o X-ray binaries
  - o SNe
  - o GWs

- Future work
  - ➤ Formation and evolution of compact binary stars **self-consistently** …. until grav. collapse and apply these models as **realistic** SN input

  - ➤ Numerical modelling of **Galactic LISA sources** containing NSs

Stars

SNe

Compact Objects

Gravitational Waves

Binary Interactions

Thanks
Jonathan Gair
Andre Schirotzek

Advert

Physics of Binary Star Evolution
Princeton University Press, spring 2022

Thomas Tauris & Ed van den Heuvel

Thank you students

I hope you enjoyed my lectures.
Looking forward to visit AEI another time.

Stay safe and take care everyone!