The gravitational wave signals of Galactic neutron star neutron star (NS-NS) and neutron star white dwarf (NS-WD) binaries

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2017.07.04

In the conference of APRIM
Taibei • Taiwan

Outline

- Why Gravitational Wave (GW) radiation from NS-NS and NS-WD compact binaries ?

- Population of the two types of compact binaries
  - Current observations and theory

- GW radiation of NS-NS and NS-WD binaries
  - Foreground signal
  - Merging signal

- Summary

Why GW radiation from NS-NS and NS-WD binaries

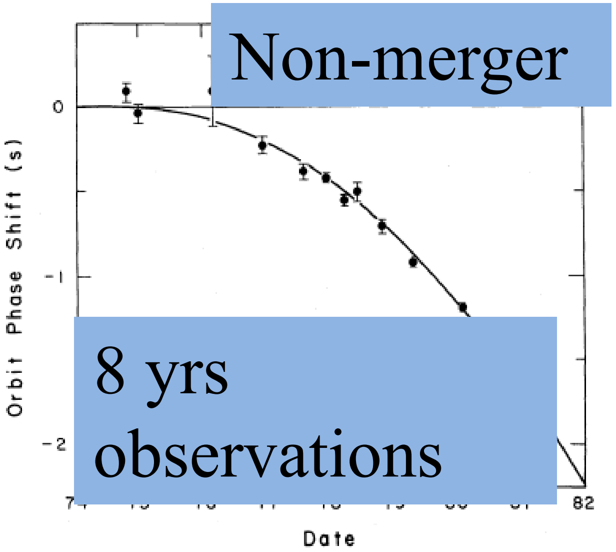
- Gravitational Waves : Oscillation of space-time,
  generated by motion of matter

- General Relativity: (Einstein1918, Landau+1975)
  - Change of geometry of space-time = change of energy-momentum
  - GW strain (h) = C * second-order differential of mass quadrupole

Understanding of GW can help us understand the relation between space-time and matter

Why GW radiation from NS-NS and NS-WD binaries

Observations of GW :



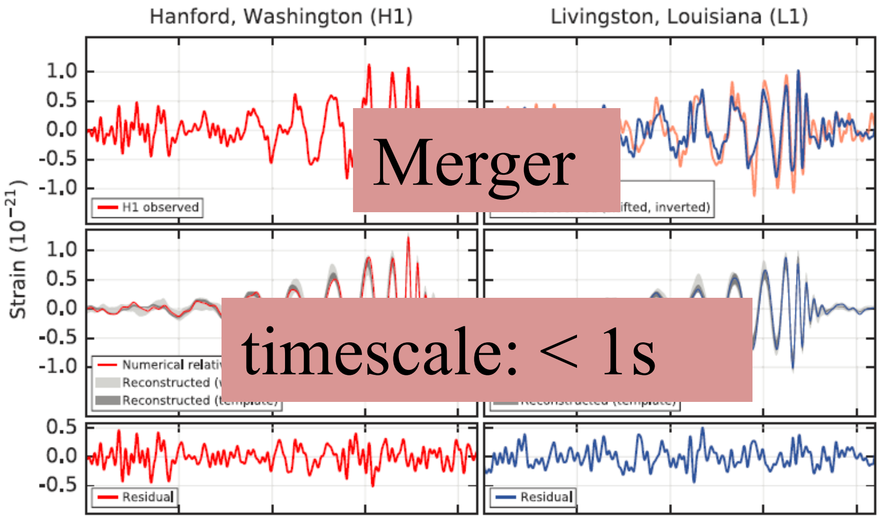
Pulsar binary:
PSR 1913-16
Taylor+1982, ApJ

– For a binary in weak field

– strain: $h \propto \frac{GM\mu}{a(1-e^2)}$ freq

– Orbital decay $\dot{a} = -\frac{64}{5} G^3 c^{\cdot}$

aLIGO bianry black holes: GW150914, GW151226, GW170104



Abbott+2016, PRL,
116, 241103
116, 061102
118, 221101

Why GW radiation from NS-NS and NS-WD binaries

W Uma type binaries
contact Main sequence binaries

Paczynski 1967, ACTA, Astro.

Binary	Period	$\mathfrak{M}_1/\mathfrak{M}_\odot$	$\mathfrak{M}_2/\mathfrak{M}_\odot$	$T_{collapse}$ (10^9 years)	$T_{nuclear}$ (10^9 years)
AB And	$0^{d}332$	[illegible]	[illegible]	2·0	1·7
i Boo	·268	[illegible]	0·68	1·9	3·4
TX Cnc	·383	2·5	1·3	1·7	0·4
VW Cep	·278	1·44	0·47	2·8	2·7
TW Cet	[illegible]	[illegible]	[illegible]	[illegible]	3·8
RZ Com	[illegible]	[illegible]	[illegible]	[illegible]	1·6
YY Eri	·321	0·76	0·50	6·4	20:
SW Lac	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ER Ori	·423	0·46	0·28	33	100:
U Peg	·375	1·35	1·1	3·1	3·4
RZ Tau	·416	1·8	0·97	3·6	1·3
W UMa	·334	1·30	0·65	3·7	3·8
AH Vir	·408	2·0	0·84	3·7	0·9

f : 0.01 mHz

Many such long-lived binaries

Superposition of GW signal if they radiate at same frequencies

Why GW radiation from NS-NS and NS-WD binaries

What are NS-NS and NS-WD binaries:

- End stage of star evolution
- Orbital separation can be ve… fore mass transfer
- Merging timesc…

f : 10~100 mHz

- Orbital separation at mass transfer :

Many binaries 10,000km, 10 ~ 100s)

- allow us to study the mass transfer phase of compact binary
- Track the origin of binaries and evolutionary history
- Test theory of star structure and evolution

Why GW radiation from NS-NS and NS-WD binaries

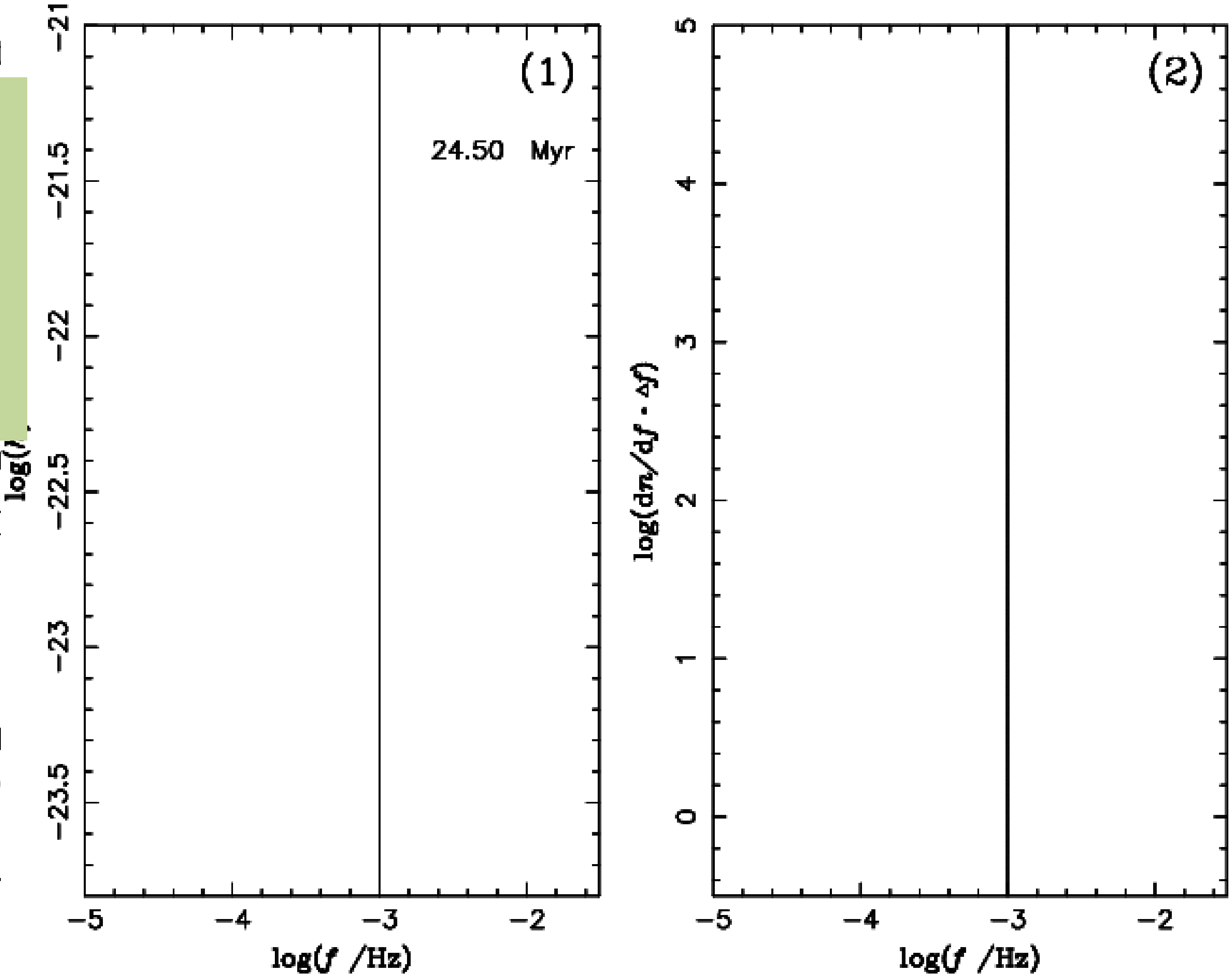
A stationar

GW from double white dwarfs

Yu & Jeffery, 2010, A&A

- This bac evolutic
- Aim to

e.g. Evans+ Hiscock200 Yu&Jeffery Belczynski+ Zhu+2013;



Population of the two types of compact binaries
Current observations and theory

DNS PSR	P_{orb} (d)	e	M	$\log_{10} \tau_{GW}$ (yr^{-1})	f_{orb} (Hz)
J0737−3039	0.102	0.09	Yes	7.9	1.1×10^{-4}
J1906+0746	0.17	0.09	Yes	8.5	6.8×10^{-5}
B1913+16	0.3	0.62	Yes	8.5	3.9×10^{-5}
B2127+11C	0.3	0.68	Yes	8.3	3.9×10^{-5}
J1756−2251	0.32	0.18	Yes	10.2	3.6×10^{-5}
B1534+12	0.4	0.27	Yes	9.4	2.9×10^{-5}
J1829+2456	1.18	0.14	No	10.8	9.8×10^{-6}
J1518+4904	8.6	0.25	No	12.4	1.3×10^{-6}
J1811−1736	18.8	0.83	Yes	13.0	6.2×10^{-7}
B1820−11	357.8	0.79	No	15.8	3.2×10^{-8}

~10 double neutron star (DNS, i.e. NS-NS) binaries

Population of the two types of compact binaries
Current observations and theory

- Numbers of observed pulsar-WD binaries in our Galaxy
  - 161 (Galactic disk: 131; Globular cluster: 30)
- Pulsars are observed by radio telescopes
- WD companion identified by optical telescopes

Where are the binaries with orbital periods < 0.1 days

- Orbital periods: 0.1~1230 days
- WD Mass: 0.1~1.5 solar mass
- Eccentricity: 0.0~0.7

selection effect

i) Doppler effects due to pulsar orbital motion drastically reduce the sensitivities of pulsar searches;

ii) Doppler beaming reduces the effective angle over which such pulsars are visible.

(Johnston & Kulkarni 1991; Ransom et al. 2003)

Population of the two types of compact binaries
Current observations and theory

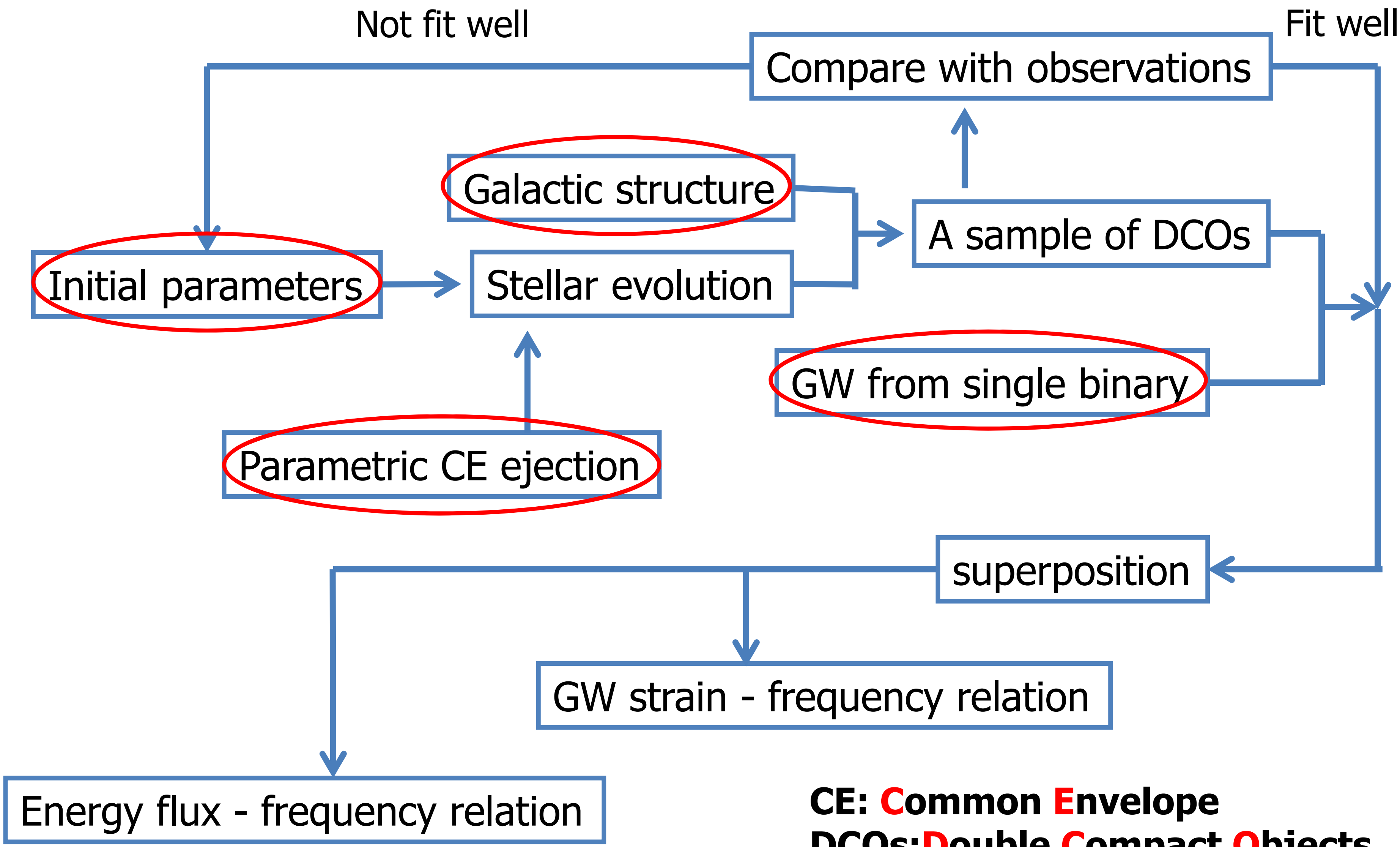
- The observation sample is not complete.

- Questions
  - How many ? Birth rates ? Merger rates ?
  - Distribution of orbital parameters ?
  - Spatial distribution ? … …
  - How the signal radiated ?

Population of the two types of compact binaries

Current observations and **theory**

Binary Population Synthesis



CE: Common Envelope
DCOs: Double Compact Objects

Population of the two types of compact binaries
Current observations and **theory**

Initial Parameters and stellar evolution

- Initial conditions
  - 1. Star formation history (constant, exponential, instantaneous)
  - 2. metallicity Z=0.001, 0.02 for the halo, disc & bulge
  - 3. Initial mass function $\xi(m) \propto \begin{cases} m^{-1.3}, & 0.1 \leqslant m/M_\odot < 0.5, \\ m^{-2.7}, & 0.5 \leqslant m/M_\odot \leqslant 100.0. \end{cases}$
  - 4. Mass ratio $n(1/q) = 1, 0.001 < 1/q < 1.$
  - 5. orbital period $\frac{da}{dn} = \begin{cases} \alpha_{sep}(\frac{a}{a_0})^k, a \leqslant a_0, \\ \alpha_{sep}, a_0 < a < a_1. \end{cases}$
  - 6. eccentricity $P_e = 2e$

- Stellar evolution model (e.g. Han1998; Hurley+2002,2003)

Population of the two types of compact binaries
Current observations and **theory**

Mass transfer phase (initial-final orbit separation)

When one star in a binary fills its Roche lobe Roche lobe overflow (RLOF) occurs.

If the adiabatic response of the radius of the mass donor is less than the change of its Roche lobe radius with respect to a change of mass, mass transfer will be unstable and a common envelope (CE) will form.

$$\left(\frac{\partial \ln R_{\rm donor}}{\partial \ln M_{\rm donor}}\right)_{\rm ad} < \left(\frac{\partial \ln R_{\rm RLOF}}{\partial \ln M_{\rm donor}}\right)_{\rm RLOF},$$

- Energy model
  - Binding energy of CE = change of orbital energy

$$\frac{G(m_1 - m_{1c})m_1}{\lambda r_{\rm L}} = \alpha_{\rm CE}\left(\frac{G m_{1c} m_2}{2a_{\rm f}} - \frac{G m_1 m_2}{2a_{\rm i}}\right)$$

- Angular moment model
  - Change of orbital angular momentum proportional to change of mass of donor star $\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma \frac{m_1 - m_{1c}}{m_1 + m_2}$

Population of the two types of compact binaries
Current observations and theory

- Numbers of NS-NS binaries in simulations

Star Formation	CE Ejection	Present Birth Rate $\times 10^{-5}\mathrm{yr}^{-1}$	Present Merger Rate $\times 10^{-5}\mathrm{yr}^{-1}$	Total Number
Continuous	α	$0.49 - 5.8$ (C8 - C15)	$0.49 - 5.7$ (C8 - C15)	$61 - 5.5 \times 10^4$ (C20 - C13)
Continuous	γ	$0.31 - 27$ (C32 - C37)	$0.27 - 11$ (C32 - C37)	$7.1 \times 10^3 - 1.9 \times 10^6$ (C32 - C37)
Instantaneous	α	0	0	$0 - 5.2 \times 10^4$ (C10,12,24 - C21)
Instantaneous	γ	0	$0 - 2.8$ (C34,36,48 - C45)	$6.4 \times 10^3 - 1.6 \times 10^6$ (C36 - C45)

Population of the two types of compact binaries
Current observations and **theory**

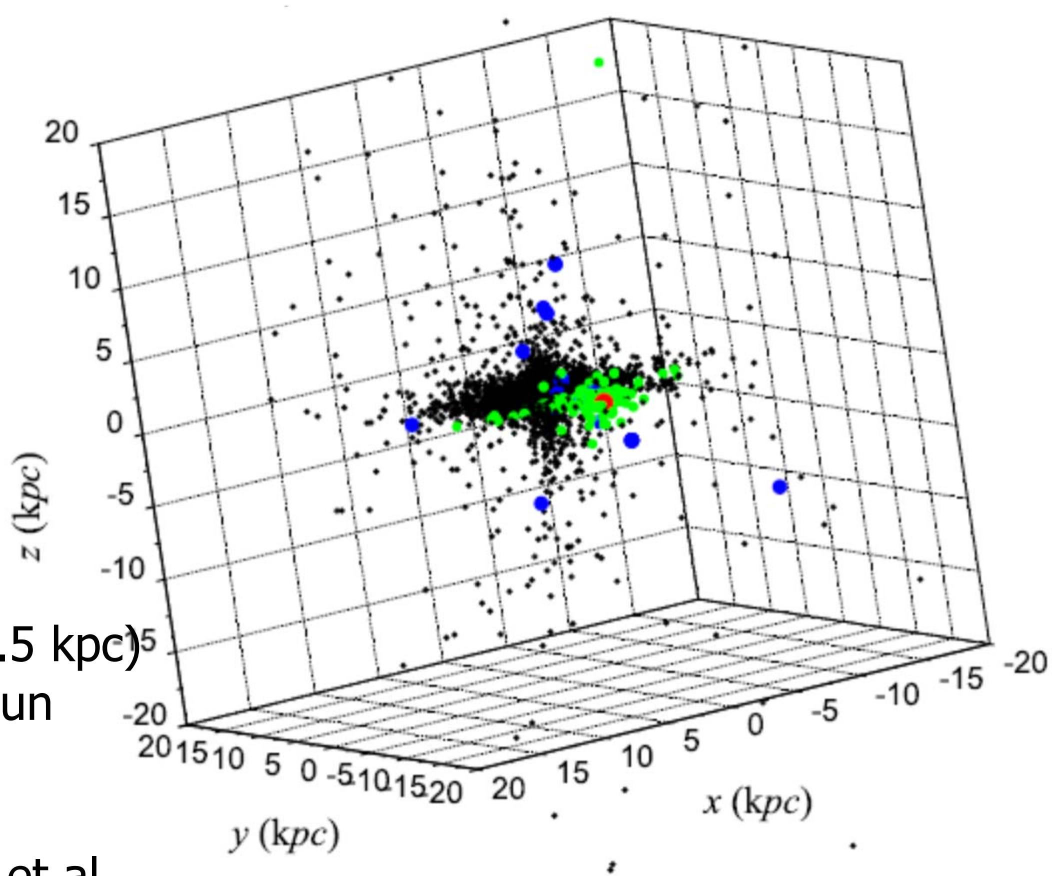
- Numbers of simulated NS-WD in our Galaxy

  (Yu, Han, Jeffery, 2017, submitted)

		bulge	disk	halo	Galaxy
$\alpha_{\rm CE}=0.5$	$\nu(\times10^{-4}\ {\rm yr}^{-1})$	0.7244	2.2815	0	3.0059
	$\nu_{\rm m}(\times10^{-4}\ {\rm yr}^{-1})$	0.7236	2.2789	0	3.0025
	$N_{\rm t}$	1680	5790	0	7470
$\alpha_{\rm CE}=1.0$	$\nu(\times10^{-4}\ {\rm yr}^{-1})$	1.3836	4.2427	0	5.6263
	$\nu_{\rm m}(\times10^{-4}\ {\rm yr}^{-1})$	1.3853	4.2406	0.0003	5.6262
	$N_{\rm t}$	7940	39920	680	48540
$\gamma=1.3^a$	$\nu(\times10^{-4}\ {\rm yr}^{-1})$	1.5622	4.7336	0.0008	6.2966
	$\nu_{\rm m}(\times10^{-4}\ {\rm yr}^{-1})$	0.8921	2.6519	0.0012	3.5452
	$N_{\rm t}$	1220020	3652260	3690	4875970
$\gamma=1.5$	$\nu(\times10^{-4}\ {\rm yr}^{-1})$	1.6573	5.2000	0.0056	6.8629
	$\nu_{\rm m}(\times10^{-4}\ {\rm yr}^{-1})$	1.4831	4.7225	0.0113	6.2169
	$N_{\rm t}$	533780	1581985	26130	2141900

Population of the two types of compact binaries
Current observations and theory

- Spatial distribution in our Galaxy
- Green : Observed disk pulsar-WD 131
- Blue : Observed pulsar-WD in
  globular clusters 30
- Black :
  simulated samples



Total mass of the Galaxy:
~6x10^11 Msun
Mass of stars: ~ 1.25x10^11 Msun

- Bulge: ~2x10^10 Msun (size: ~3.5 kpc)
- Disc, thin+thick : ~5.5x10^10 Msun
- Halo: 4x10^8 Msun +dark matter

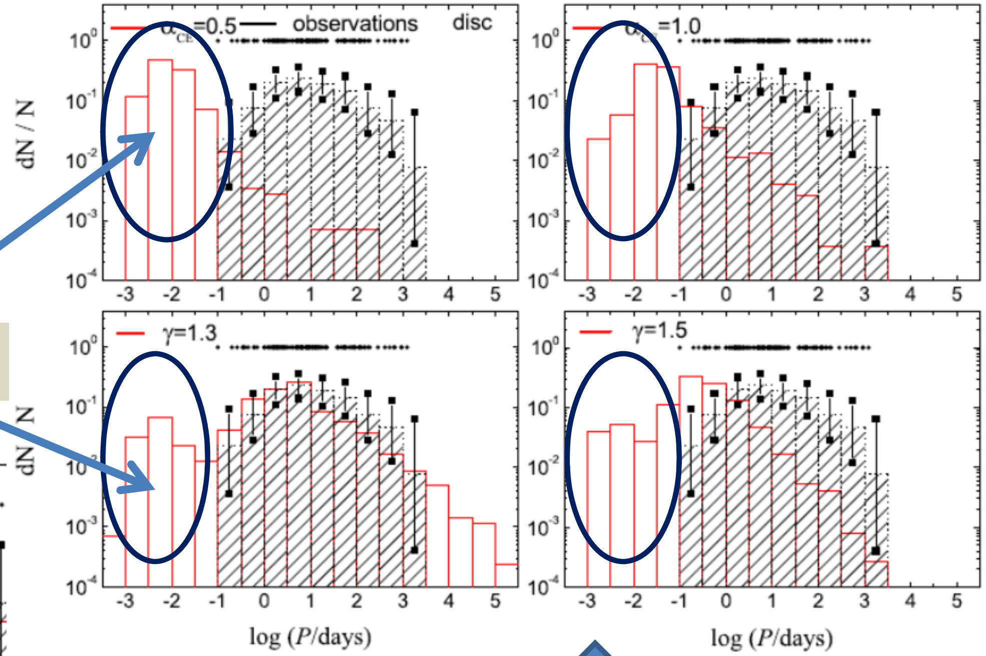
(e.g. Klypin+2002; Robin+2003; Bell et al. 2008)

Population of the two types of compact binaries
Current observations and theory

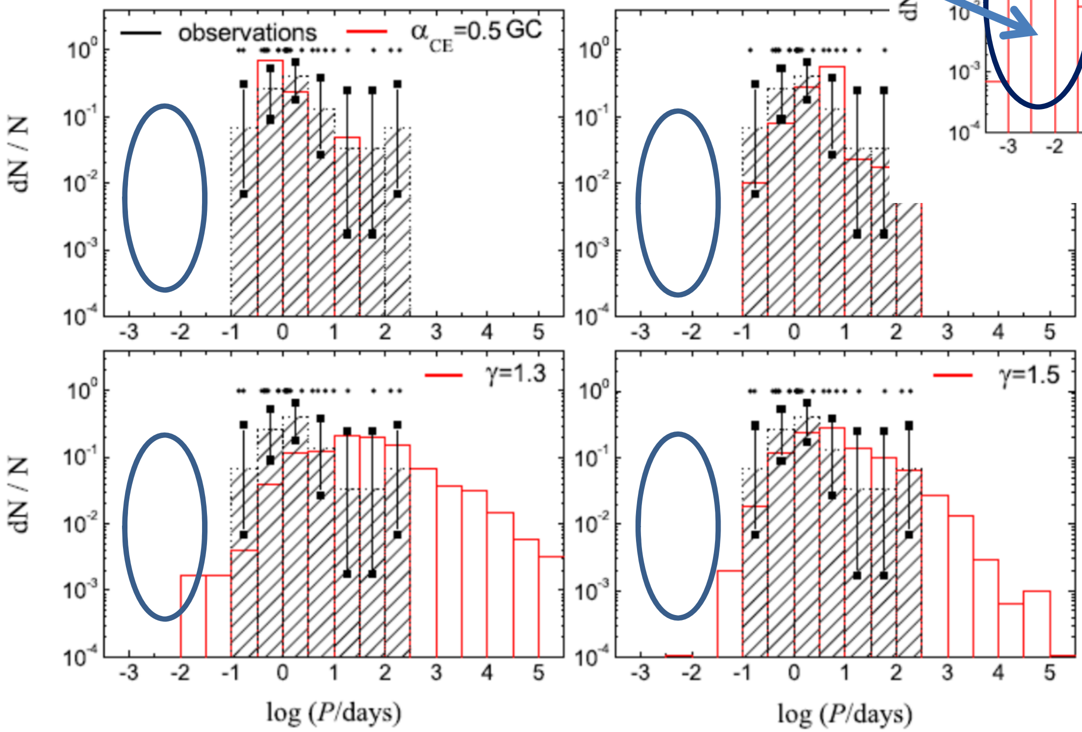
Distribution of orbital periods

1. Why there is difference between disk and globular cluster population?

2. Can we observe these binaries ?



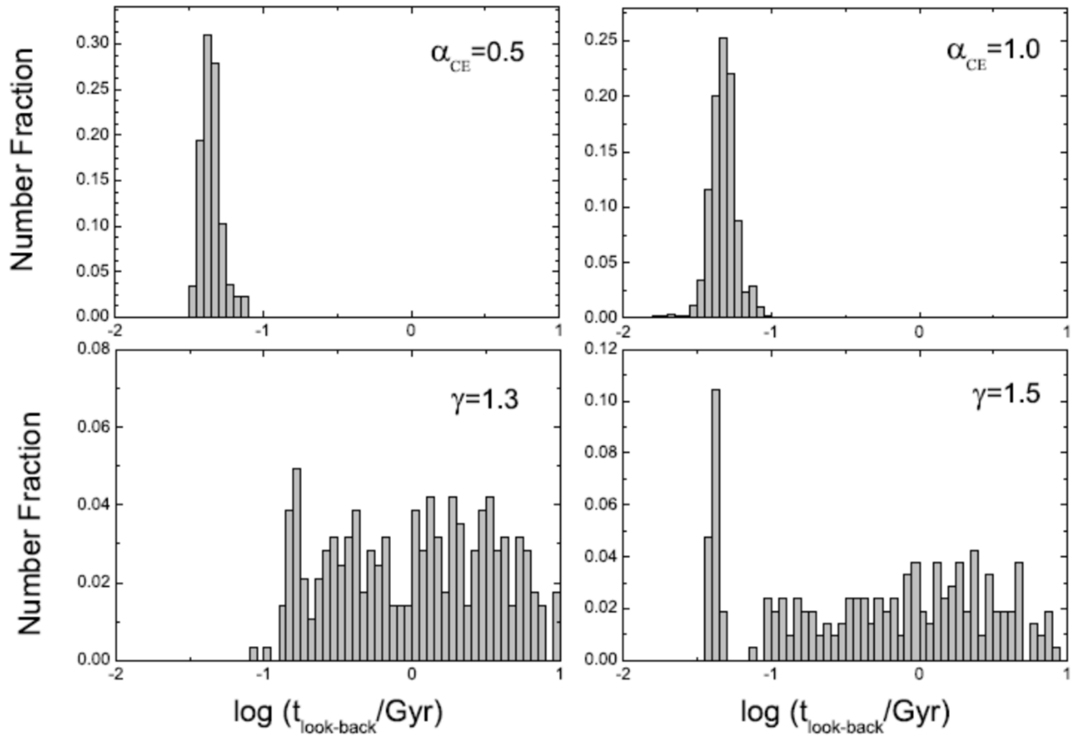
Disk population



Globular cluster population

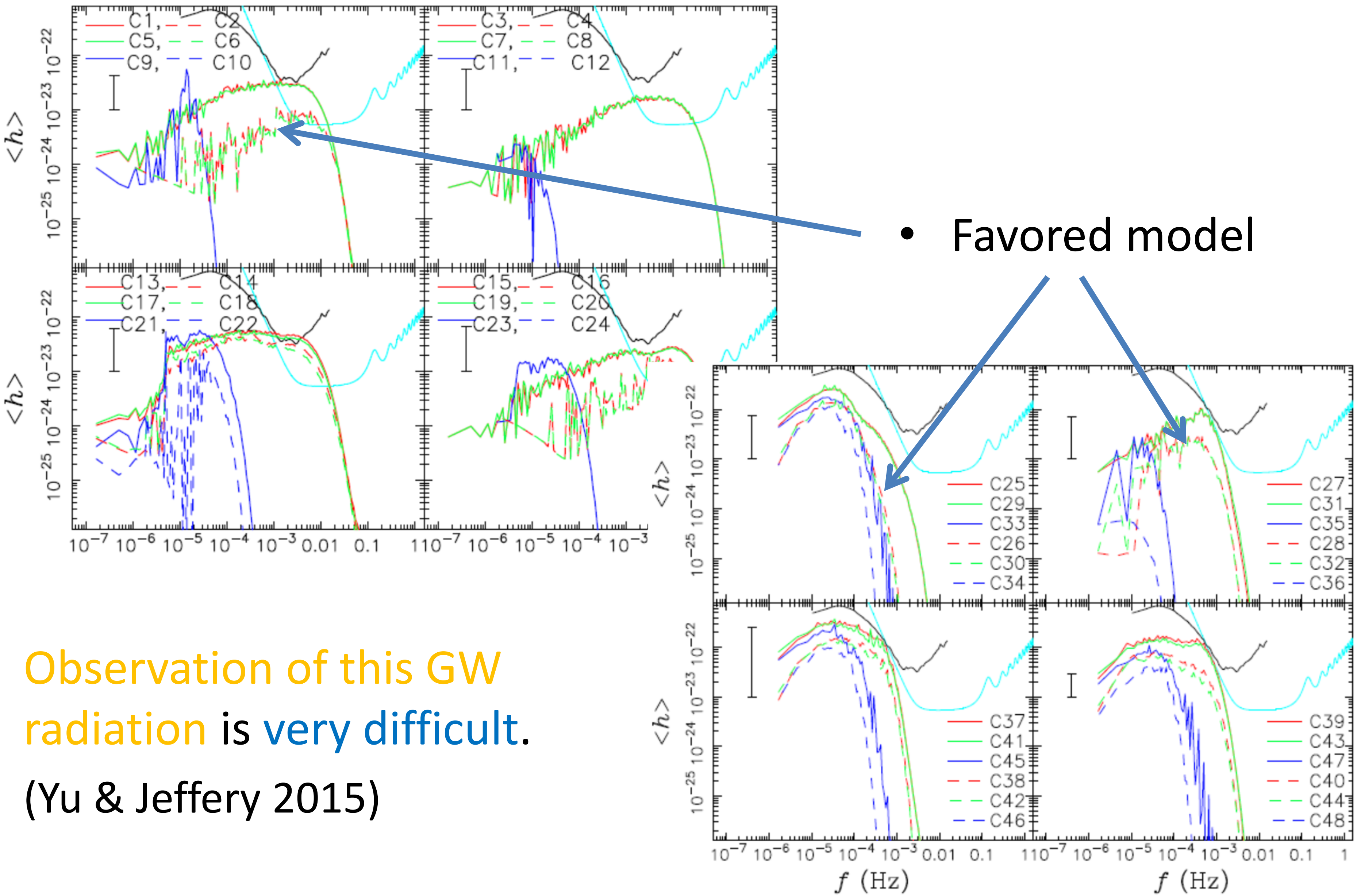
Population of the two types of compact binaries
Current observations and theory

- Look-back time distribution in the disk



- If we cut off the recent star formation, as in the case of globular cluster, we will NOT see those short orbital period binaries.

GW radiation of NS-NS binaries



- Favored model

Observation of this GW radiation is very difficult.

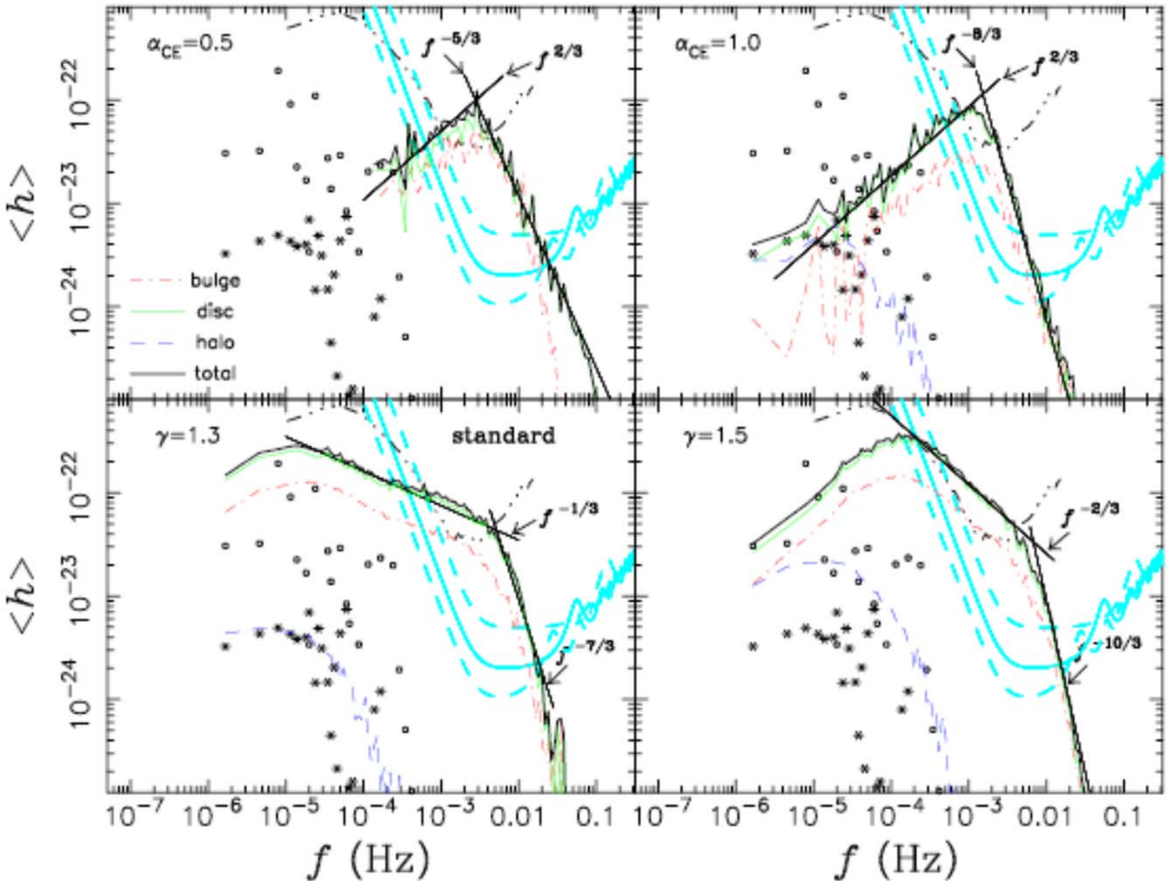
(Yu & Jeffery 2015)

GW radiation of short orbital period NS-WD binaries

We may see the GW radiation of those short orbital period NS-WD binaries by space-based detector, like eLISA

- Frequency : (1 ~ 30) mHz
- Peak Amplitude : 10^-22
- Independent of models

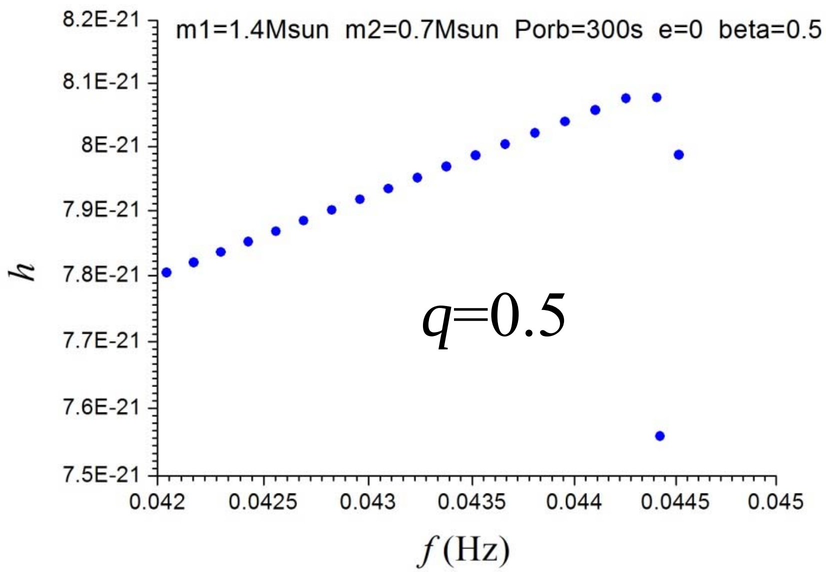
(Yu, Han, Jeffery, 2017, submitted)

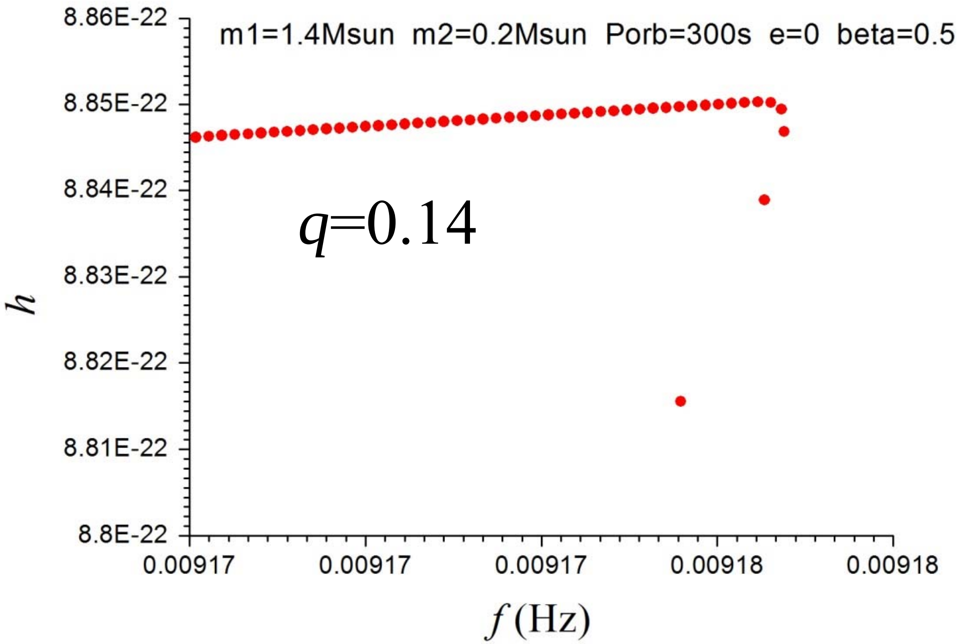


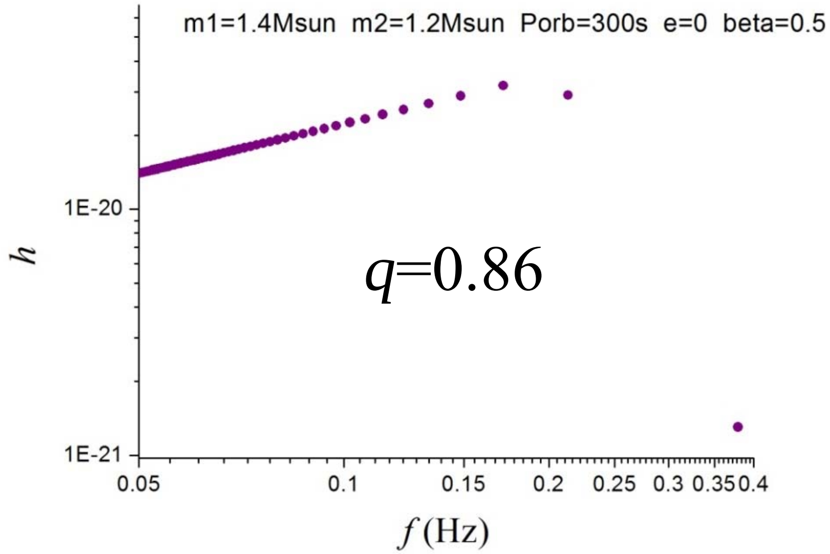
- Lines:
  - Predicted GW signal
- Points:
  - Calculated GW signal from observed NS-WD

GW radiation of merging NS-WD binaries

- Can we see mass transfer from merging NS-WD using space based GW detector ?







q=Mwd/Mns

Summary

- The GW foreground of NS-NS binaries is negligible, though their merging signal need to be considered.

- There are many NS-WD binaries observed by radio and optical telescopes, but lack of short orbital period binaries.

- Theory indicate that the short orbital period binaries may exist, and significantly contribute to the GW foreground which is detectable by space-based GW detector.

- Mass transfer phase of merging NS-WDs may be also seen by space-based GW detector.

- Thank you!