Detection of Gravitational Waves and Neutrinos from Astronomical Events

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Outline

- Sources of both GW and neutrinos.
- Detection of GW and neutrino signals.
- Summary and physics potential.

Sources of both GW and neutrinos

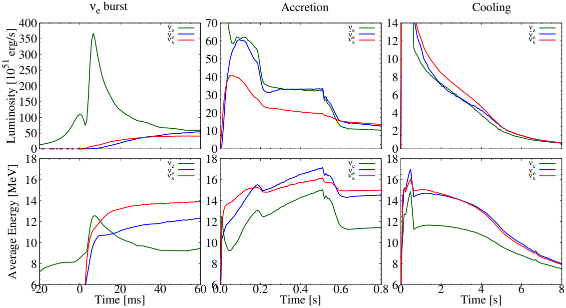
- Core-collapse supernovae.
- Merging binary stars.
    - Binary neutron stars.
    - Black hole-neutron star system.

Core-collapse supernovae

- Total energy released: $\sim 10^{53}$ erg.
- Neutrino takes away $\sim$99% of total energy. Neutrinos from SN1987A have been observed.
- GW is believed to be emitted during SN explosion. Many mechanisms are related with GW emission.

Neutrino emission of SNe

- Three phases of SN explosion have characteristic neutrino emission.
  - ν_e burst: neutronization releases large amount of ν_e in $\sim$10 ms.
  - Accretion phase: capture of $e^{\pm}$ on the PNS gives rise to the emission of $\bar{\nu}_e$ and ν_e
  - Cooling phase: PNS cools down by emitting all flavors of neutrino.



GW emission of SNe

- As optical observations have found anisotropies in SN explosion, it is believed that there will be GW emission during SN explosion.
- There are many different mechanisms that can lead to GW emission in SN explosion.
  - Rotating core collapse and bounce. This is the most extensively modeled mechanism.
  - Nonaxisymmetric rotational instabilities.
  - Postbounce convective and SASI.
  - PNS core pulsation.
  - Anisotropic neutrino radiation.

Rotating core collapse and bounce

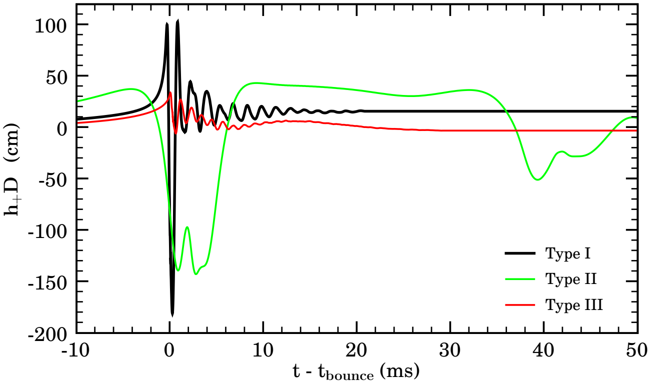


Figure: GW from rotating core collapse and bounce (Ott, Class.Quant.Grav. 26 (2009) 063001). D is distance. 10 kpc $\approx 3 \times 10^{22}$ cm

Nonaxisymmetric rotational instabilities

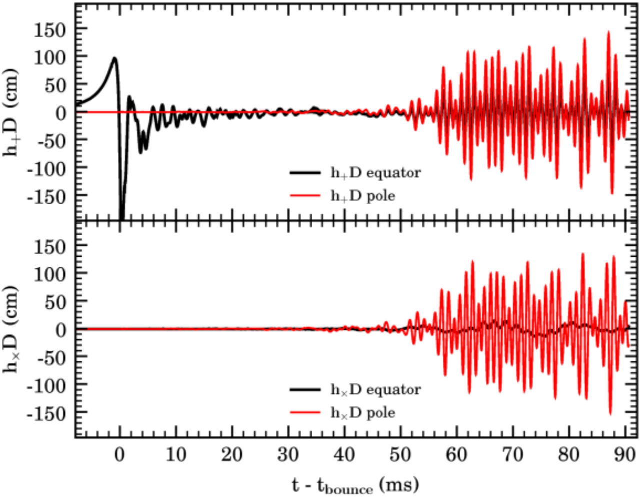
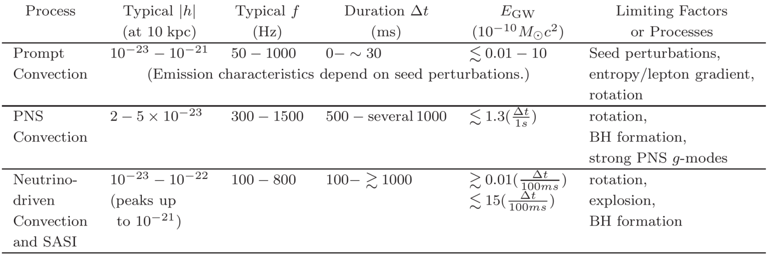


Figure: GW from nonaxisymmetric rotational instabilities (Ott, Class.Quant.Grav. 26 (2009) 063001).

Postbounce convection and SASI



Process	Typical $\lvert h \rvert$ (at 10 kpc)	Typical f (Hz)	Duration Δt (ms)	E_{GW} ($10^{-10} M_{\odot} c^2$)	Limiting Factors or Processes
Prompt Convection	$10^{-23} - 10^{-21}$	$50 - 1000$	$0- \sim 30$	$\lesssim 0.01 - 10$	Seed perturbations, entropy/lepton gradient, rotation
	(Emission characteristics depend on seed perturbations.)				
PNS Convection	$2 - 5 \times 10^{-23}$	$300 - 1500$	$500 -$ several 1000	$\lesssim 1.3(\frac{\Delta t}{1s})$	rotation, BH formation, strong PNS g-modes
Neutrino-driven Convection and SASI	$10^{-23} - 10^{-22}$ (peaks up to 10^{-21})	$100 - 800$	$100- \gtrsim 1000$	$\gtrsim 0.01(\frac{\Delta t}{100ms})$ $\lesssim 15(\frac{\Delta t}{100ms})$	rotation, explosion, BH formation

Figure: GW from postbounce convective and SASI (Ott, Class.Quant.Grav. 26 (2009) 063001).

Non-radial PNS pulsation

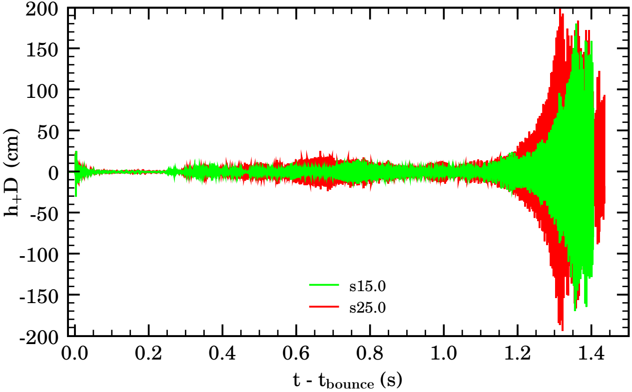


Figure: GW from PNS pulsation (Ott, Class.Quant.Grav. 26 (2009) 063001).

Anisotropic neutrinos

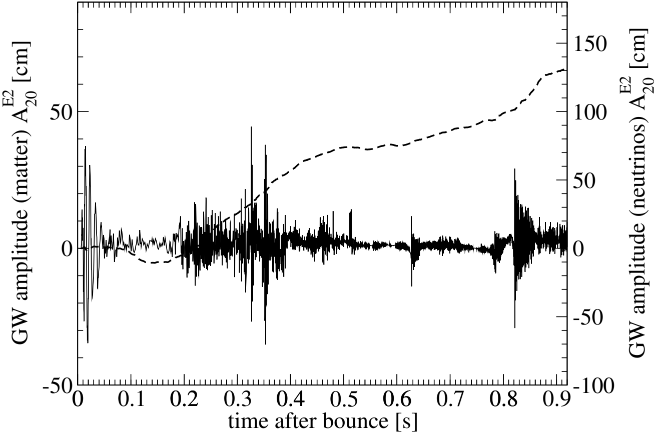


Figure: Matter (solid) and neutrino (dashed) contribution to GW from Mueller,Janka,Marek, ApJ 766 (2013) 43.

$$h_+ D = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\theta A_{20}^{E2}$$

Merging binary stars

- GW emission is undetstood well. GW strength is much larger than that of SNe.
- Neutrino emission can be comparable to SNe.
- Two situations:
    - Binary neutron stars.
    - Black hole-neutron star system.

GW emission of merging BNS

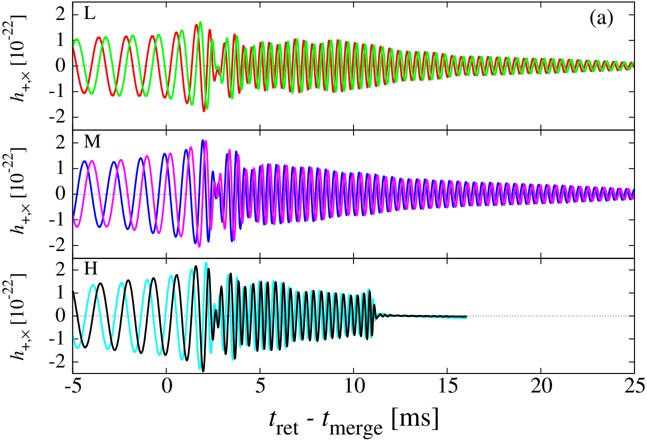


Figure: GWs of merging BNS 100 Mpc away. (Sekiguchi et. al., Phys.Rev.Lett. 107 (2011) 051102)

Neutrino emission of merging BNS

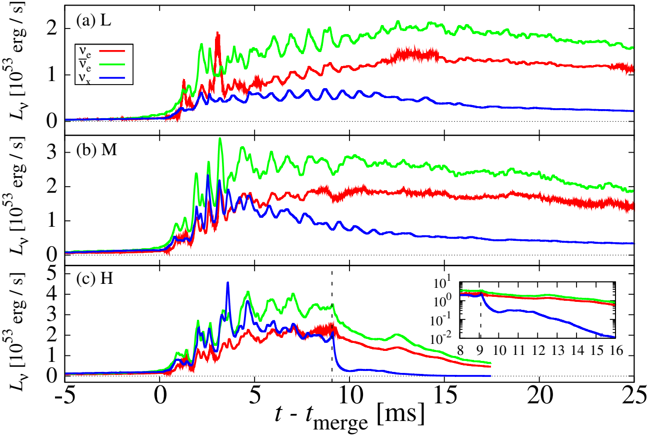


Figure: Neutrino luminosities of merging BNS. (Sekiguchi et. al., Phys.Rev.Lett. 107 (2011) 051102)

Neutrino emission of merging BH-NS

Table: Observed $E^*(L^*)$ and emitted $E(L)$ averaged neutrino energies (luminosities) for an AD-BH and for a PNS. (Caballero et. al., Phys.Rev. D80 (2009) 123004)

	E(MeV) Disk	E^*(MeV) Disk	E(MeV) PNS	L(ergs/s) Disk($\times 10^{53}$)	L^* (ergs/s) Disk($\times 10^{53}$)
$\bar{\nu}_e$	29.6	23.4	15	3.7	2.4
ν_e	21.1	17.3	12	2.3	1.6
$\bar{\nu}_x$	33	26	25	4.6	3.0
ν_x	33	26	25	4.6	3.0

Detection of GW and neutrino signals

- If we only consider the astronomical events in the Galaxy and nearby SMC/LMC, both the neutrino and GW events can be observed (by JUNO and aLIGO, e.g.).
- If the astronomical event happens 1 Mpc away, then JUNO will observe no neutrino signal, while GW signal may still be detected by aLIGO.
- Core-collapse SN rate in the Galaxy and SMC/LMC is estimated to be about one per 30-50 years, while merging binary stars have much smaller rate.

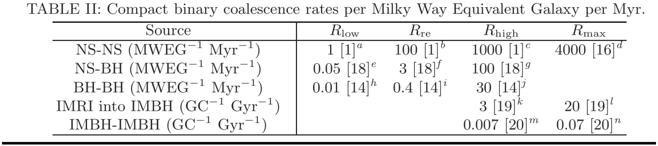
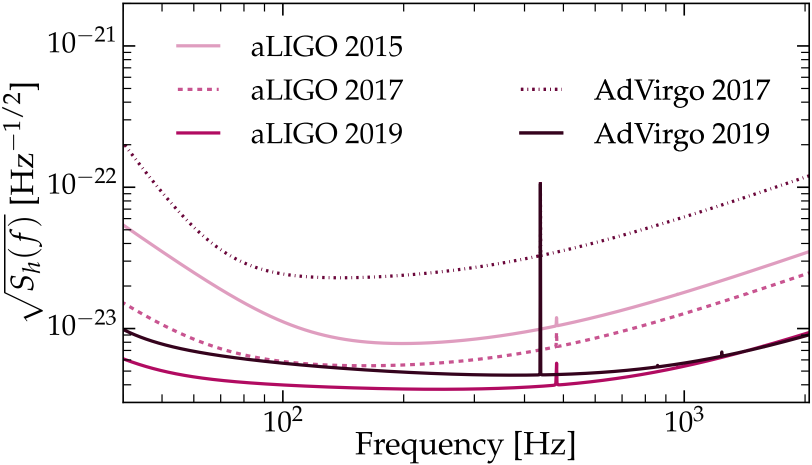


TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	R_{low}	R_{re}	R_{high}	$R_{\max}$
NS-NS (MWEG^{-1} Myr^{-1})	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH (MWEG^{-1} Myr^{-1})	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH (MWEG^{-1} Myr^{-1})	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19][k]	20 [19][l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20][m]	0.07 [20][n]

Figure: Merging binary stars rate in Galaxy. (LIGO, Class.Quant.Grav.27:173001,2010)

GW detection ability

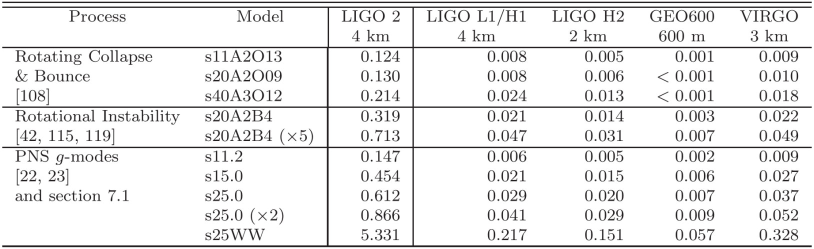


Detection of GW from SNe

- The GW signals from SNe have typical frequencies of several hundred Hz, which is suitable for aLIGO to detect them.
- The GW amplitude from a SN 10 kpc away can be as large as $\sim 10^{-21}$, which is large enough for aLIGO.
- The signal-to-noise ratio (SNR) can be used to describe the detectability of GW.

$$(\mathrm{SNR})^2_{\mathrm{optimal}} = 4 \int_0^\infty \frac{|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2}{S(f)} \, df \ ,$$

SNR of GW signal

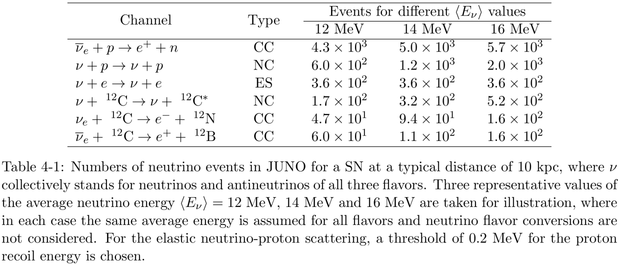


Process	Model	LIGO 2 4 km	LIGO L1/H1 4 km	LIGO H2 2 km	GEO600 600 m	VIRGO 3 km
Rotating Collapse	s11A2O13	0.124	0.008	0.005	0.001	0.009
& Bounce	s20A2O09	0.130	0.008	0.006	< 0.001	0.010
[108]	s40A3O12	0.214	0.024	0.013	< 0.001	0.018
Rotational Instability	s20A2B4	0.319	0.021	0.014	0.003	0.022
[42, 115, 119]	s20A2B4 (×5)	0.713	0.047	0.031	0.007	0.049
PNS g-modes	s11.2	0.147	0.006	0.005	0.002	0.009
[22, 23]	s15.0	0.454	0.021	0.015	0.006	0.027
and section 7.1	s25.0	0.612	0.029	0.020	0.007	0.037
	s25.0 (×2)	0.866	0.041	0.029	0.009	0.052
	s25WW	5.331	0.217	0.151	0.057	0.328

Figure: GW SNR of a SN 3.9 Mpc away (Ott, Class.Quant.Grav. 26 (2009) 063001).

Detection of neutrinos from SNe

- There will be about 10^4 neutrino events in JUNO for a SN 10 kpc away.
- 6 channels can be used to detect SN neutrinos.



Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Table 4-1: Numbers of neutrino events in JUNO for a SN at a typical distance of 10 kpc, where ν collectively stands for neutrinos and antineutrinos of all three flavors. Three representative values of the average neutrino energy $\langle E_\nu \rangle = 12$ MeV, 14 MeV and 16 MeV are taken for illustration, where in each case the same average energy is assumed for all flavors and neutrino flavor conversions are not considered. For the elastic neutrino-proton scattering, a threshold of 0.2 MeV for the proton recoil energy is chosen.

Figure: Result from JUNO yellowbook.

Detection of neutrinos from merging stars

- The luminosity and average energy of neutrinos are similar with that of SNe, so the events detected in JUNO are also similar.

	$\bar{\nu}_e + p \to n + e^+$	$\nu + e \to \nu + e$
SK(32 kton)	9100	390
UNO(580 kton)	165000	7100
Hyper-K(1Mton)	284000	12280
Amanda(680 OM)	74000	2800
IceCube(4800 OM)	522500	20200
PNS(SK)	8300	320

Table: Neutrino events from a merging BH-NS system 10 kpc away (Caballero et. al., Phys.Rev. D80 (2009) 123004).

Detection of GW from merging stars

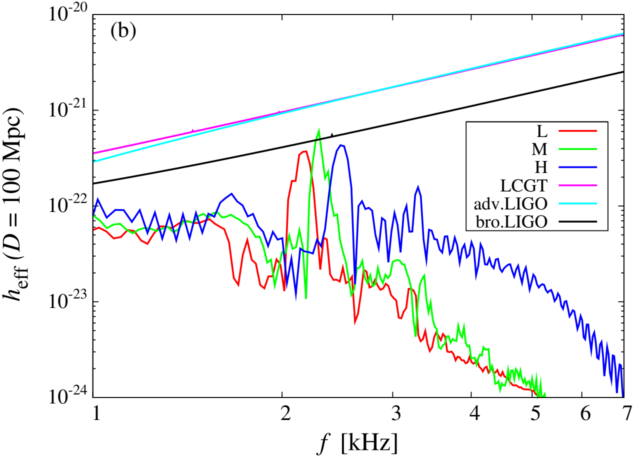


Figure: Effective amplitude of GW for merging BNS 100 Mpc away. (Sekiguchi et. al., Phys.Rev.Lett. 107 (2011) 051102)

Summary and physics potential

- SNe in the Galaxy are good sources of both neutrino and GW signals.
- Merging binary stars are as good as SNe. However they are very rare in the Galaxy.
- GW and neutrino signals together can give constrains on SN explosion mechanism.
- GW has no dispersion, so the GW signals can provide accurate time information of SN explosion or star merging, which can be combined with neutrino signals to test something like absolute neutrino mass and Lorentz invariance.

Thanks!