High Energy Messengers from the non-thermal Universe: from Gravitational Waves to the electromagnetic spectrum

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1. GW theory introduction

2. LIGO and Virgo Observatories: working principles

3. GW sources and observations

4. Multi-messenger Astronomy

5. Cosmology with GWs
Gravity is responsible for attraction (Newtonian force) and waves (radiation) much like as electromagnetism

- **Electromagnetism** $A_\mu$, $\mu \in (0..3)$
  1. 1 Coulomb degree of freedom, constrained by sources
  2. 2 radiative d.o.f.
  3. 1 gauge d.o.f.

- **Gravity** $g_{\mu\nu}$, symmetric 2-tensor, 10 components
  1. 4 constrained degrees of freedom
     (Newtonian potential + General Relativistic generalisations)
  2. 2 radiative d.o.f.
  3. 4 gauge d.o.f.

1&3 propagate with “the speed of thought” (Eddington ’22)
GW polarisations

Gauged fixed metric after discarding $h_{0\mu}$ components, which are not radiative: transverse waves

$$h_{ij} = \begin{pmatrix}
  h_+ & h_\times & 0 \\
  h_\times & -h_+ & 0 \\
  0 & 0 & 0
\end{pmatrix}$$
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The LIGO and Virgo observatories

Observation run **O1** Sept 12th ’15 - Jan 19th ’16

**O1** data, \( \sim 130 \) days, with 49.6 days of actual data, PRX (2016) 4, 041014, 2 detectors

**O2** is currently on-going, Dec. ’16 \( \sim \) Sept ’17
data analysis will be published soon after

**O3**, 3 detectors, foreseen to start in Aug 2018, last \( \sim 1 \)yr

In 2020+ Japanese KAGRA and Indian INDIGO will join the collaboration
Light intensity $\propto$ light travel difference in perpendicular arms

Effective optical path increased by factor $N \sim 500$ thanks to Fabry-Perot cavities

Phase shift $\Delta \phi \sim 10^{-8}$ can be measured $\sim 2\pi N\Delta L/\lambda \rightarrow \Delta L \sim 10^{-15}/N$ m
Almost omnidirectional detectors

\[ h_{det} = h_+ F_+ \]

\[ F_{+, \times} L \]

\[ F_{+, \times} H \]

\( h_{+, \times} \) depend on source, \( F_{+, \times} \) on relative orientation source/detector
GW across the spectrum

The Gravitational Wave Spectrum

Sources
- Quantum fluctuations in the very early Universe
- Binary supermassive black holes in galactic nuclei
- Phase transitions in the early universe
- Black holes, compact stars captured by supermassive holes in galactic nuclei
- Binary stars in the galaxy and beyond
- Merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains

Wave Period
- Age of the Universe
- Years
- Hours
- Seconds
- Msec

Frequency (Hz)
- $10^{-16}$
- $10^{-14}$
- $10^{-12}$
- $10^{-10}$
- $10^{-8}$
- $10^{-6}$
- $10^{-4}$
- $10^{-2}$
- 1
- $10^{2}$

Detectors
- Inflation Probe
- Polarization map of cosmic microwave background
- Precision timing of millisecond pulsars
- LISA
- Big Bang OBS
- GEO, LIGO, VIRGO, TAMA

A xylophone of GW detectors

http://www.astro.gla.ac.uk/users/martin/powersof60/future.html
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Astro sources emitting transient GWs/EM radiation

- Coalescing binary systems of compact objects $M_c \equiv (m_1 m_2)^{3/5} M^{-1/5} \equiv \eta^{3/5} M$

$$\Delta E_{GW} \sim 4 \times 10^{-2} M_{\odot} \left( \frac{M_c}{1.2 M_{\odot}} \right)^{5/3} \left( \frac{f_{max}}{1 \text{ kHz}} \right)^{2/3}$$

A good proxy of the $f_{max}$ is the Innermost Stable Circular Orbit frequency

$$f_{ISCO} = \frac{1}{6 \sqrt{6}} \frac{1}{M} \approx 2 \text{ kHz} \left( \frac{M}{M_{\odot}} \right)^{-1}$$

For NS-BH ejected material supposed to produce short ($< 2 \text{ sec}$) GRBs $E_{\gamma} \sim \text{keV-MeV}$, ejected sub-relativistic material may produce radio signals

$\nu$: baryon loaded jets may emit $\nu$: TeV-PeV $\nu$s @ $\gamma$ emission

$\nu$: low energy $\nu$s (10 MeV) emitted, e.g. by SN1987A

- Core-collapse of massive stars, $10^{-8} \lesssim E_{GW}/M_{\odot} \lesssim 10^{-5} \rightarrow$ long GRBs $\nu$: sudden magnetic re-configuration can produce high-energy $\nu$s

- isolated neutron star with sudden energy release

E.g. star-quakes exciting non-radial modes $10^{-16} \lesssim E_{GW}/M_{\odot} \lesssim 10^{-6}$ possibly $\rightarrow$ soft $\gamma$ repeaters emitting repetitive flares (0.1 sec, $10^{42}-10^{47}$ erg/sec) $\nu$: sudden magnetic re-configuration can produce high-energy $\nu$s

M. Branchesi JoP Conf. Ser. (2016)
Wave generation: localised sources

Einstein formula relates $h_{ij}$ to the source quadrupole moment $Q_{ij}$

$$Q_{ij} = \int d^3x \rho \left( x_i x_j - \frac{1}{3} \delta_{ij} x^2 \right) \quad \nu^2 \approx G_N M / r$$

$$h_{ij} = \frac{2 G_N}{D} \frac{d^2 Q_{ij}}{dt^2} \approx \frac{2 G_N \mu \nu^2}{D} \cos(2\phi(t))$$

$$f = 2\text{kHz} \left( \frac{r}{30\text{Km}} \right)^{-3/2} \left( \frac{M}{3M_\odot} \right)^{1/2} < f_{\text{Max}} \approx 12\text{kHz} \left( \frac{M}{3M_\odot} \right)^{-1}$$

$$\nu = 0.3 \left( \frac{f}{1\text{kHz}} \right)^{1/3} \left( \frac{M}{M_\odot} \right)^{1/3} < \frac{1}{\sqrt{6}}$$

Geometric factor to keep account of transversality projection (angular momentum $L$ of the binary, observation direction $N$)

$$h_+ \propto \frac{1 + \cos^2(\theta_{LN})}{2}$$

$$h_\times \propto -\cos(\theta_{LN})$$

No direction for which emission vanishes: quadrupolar motion is bi-dimensional → not all motion components can be collinear ($\theta_{LN} \sim \pi/2$) with $N$ (unlike dipolar motion for the electromagnetic case)
The 2 confirmed GW events + 1 candidate trigger

LIGO/Virgo PRX (2016) 4, 041014

LIGO/Virgo PRX (2016) 4, 041014
Bank with over 200k templates is prepared, matched-filtering computed against all wfs. Spin somehow neglected for low masses (anyway non-precessing) because

- astrophysically spin of neutron stars $\chi \equiv |\text{Spin}|/m^2 < 0.1$
- impractical as number of templates would explode!

LIGO/Virgo PRX (2016) 4, 041014
The signal

LIGO/Virgo PRL 116, 061102 (2016)
Could have it happened by chance?

Given the high number of trials (∼ 250k templates) in correlating with data, check needed for random coincidences

False alarm rate estimated by counting coincidences between the two detectors with time-shifted data coincidences at delay ≥ 10msec are not GWs

# coincidences at amplitude ρc > 12 / # shifts ∼ 10⁻⁸

LIGO/Virgo PRX (2016) 4, 041014

False alarm rate for GW events: < 1/200,000 yrs!
What constraints on masses/spin/distances magnitudes?

Mass uncertainties $\gtrsim 10\%$ @ 90% C.L.

$$h_+ \propto \frac{1 + \cos^2(\theta_{LN})}{2}$$

$$h_\times \propto -\cos(\theta_{LN})$$

Spin magnitude $\chi_{\text{eff}} \parallel L$

$$\chi_{\text{eff}} \equiv \left(\frac{S_1}{m_1} + \frac{S_2}{m_2}\right) \cdot \frac{L}{M}$$

LIGO/Virgo PRX (2016) 4, 041014
Horizon distances vs. rate estimation

\[ 9 < \text{Rate}_{BH-BH} / (Gpc^3 \, yr) < 240 \]

Galaxy density \( \sim 2 \times 10^7 / Gpc^3 \)

LIGO/Virgo PRL 116 (2016)

Electromagnetically (galactic) NS-NS system observed (10^8 years from coalescence, few hours period), no NS-BH

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From X and gamma rays to GWs

SPSAS-HighAstro - May 31st
Astro predictions, upper bounds from science run5/6/O1 and measure from O1.

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EM counterparts of binary coalescences

Binary coalescences involving a neutron star can give rise to energetic outflows at different timescale/wavelength

- Relativistic jet → prompt short $\gamma$-ray burst (GRB) duration $\lesssim 1$ sec followed by X, optical, radio afterglows (hrs – days)
- Rapid neutron capture in the sub-relativistic ejecta can produce a kilonova or macronova, with optical and near-infrared signal (hours – weeks)
- Eventually radio blast from sub-relativistic outflow (months to years)

Several seconds prior to or tens of minutes after merger, coherent radio burst lasting milliseconds may be emitted

Arrival direction estimated from time delays (and amplitude modulation)

Triangulation will allow a better sky localisation
(down to $\sim$ few$^{\circ2}$ with $> 3$ detectors)

GW vs. EM $\leftrightarrow$ time vs. space localisation

74 groups with space/ground facilities for a joint EM-LIGO/Virgo program: 63 in O1
Detailed GW sky map (masses) not promptly available: accurate analysis requires time!
Mass range $\rightarrow$ distance $\rightarrow$ galaxy localisation

Accurate mass (sky reconstruction) sent out 20 (120) days after event:
No candidate found: stellar BBH $\rightarrow$ EM/$\nu$
(density and magnetic fields typical of interstellar medium)
25 teams spanning 19 order of magnitude in wave-length with a variety of coverage of the 600 deg$^2$ of the sky map:

- $\gamma$, $X$ observatories: complete coverage down to $10^{-9}$erg/(cm$^2$s)
  minimal flux $10^{-13} - 10^{-11}$ by SWIFT XRT ($\sim$keV, 5 deg$^2$)

- **optical** tiled jointly 900 deg$^2$.
  GW Range for a NS-BH $\sim 70$ Mpc: GRB would have been detectable at that distance and similar depths in optical and IR bands (app. magnitude 17-24)

- **near infrared, radio**: wide fields down to mJy flux densities, narrow-field VLA could identify localised radio transient down to $\mu$Jy ($f \gtrsim$ GHz)

Verify association with 20 short GRB during O1

GW searched in a [-5,+1) sec window with GRB
GW constraints far from EM exclusion distance, but extrapolation to design Advanced LIGO sensitivity (2 years of data) will lead to detection/non-trivial constraints

LIGO/Virgo arXiv:1611.07947, APJ in press
Isolated binary in galactic field
A binary system of massive stars ($M_{binary} \sim 100M_{\odot}$) can go through a common envelope phase that shrinks considerably the orbit and align the spins $\rightarrow$ collapse to black holes
Lower metallicity $\rightarrow$ lower star mass loss


Izzard et al. Proc. IAU 2012
Globular Cluster: medium with high density of black holes/stars, when 3 black holes meet one is ejected and the binary shrinks

T. Hartwig et al. arXiv:1603.05655

Remnants of the first stars, produced at $z \sim 6$ can give only a small contribution to the total rate

Primordial black-holes? viable if $10^{-2} \lesssim \frac{M_{BH}}{M_\odot} \lesssim 1$ (constraints from evaporation, microlensing and CMB) but could grow later to 20-100 $M_\odot$ by merger

If present in globular cluster may also explain their cosmological abundance as dark matter

Black holes of known mass

New astronomical era ahead of us!
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Coalescing binary systems are standard sirens:

\[
h(t) = \frac{G_N \eta M^{5/3} f_s^{2/3}}{D} \cos \left[ \phi \left( t_s \right) \right]
\]

In cosmological settings source and observer clocks tick differently:

\[
dt_o = (1 + z) dt_s \quad f_o(1 + z) = f_s
\]

\[
h(t_o) = \frac{G_N \eta f_o^{2/3} M^{5/3}(1 + z)^{2/3}}{a(t_o)D} \cos \left[ \phi \left( t_s(t_o) \right) \right]
\]
Measuring $H_0$

Coalescing binary systems are standard sirens:

$$h(t) = \frac{G_N \eta M^{5/3} f_s^{2/3}}{D} \cos [\phi(t_s)]$$

In cosmological settings source and observer clocks tick differently:

$$dt_o = (1 + z)dt_s \quad f_o(1 + z) = f_s$$

$$h(t_o) = \frac{G_N \eta f_o^{2/3} M^{5/3} (1 + z)^{2/3}}{(1 + z)a(t_o)D} (1 + z) \cos [\phi(t_s(t_o)))]$$

$$\phi(t_s/M) = \phi(t_o/M(1 + z)) \implies$$

$$\phi(t_o/M) = \phi(t_s/M) \quad \mathcal{M} \equiv M(1 + z)$$
Standard sirens cosmology: Determining $H_0$

Hubble law: $z = H_0 d_L$

$D_L$ can be measured, $z$ degenerate with $M$, however if

- the source in the sky has been localised $(\alpha, \delta)$
- GW sources are in the galaxy catalogue with known red-shift

$$P(z, D_L|c_i) = \int dM d\theta d\alpha d\delta P(D_L M, \theta, \alpha, \delta|c_i) \pi(z, |\alpha, \delta)$$

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From X and gamma rays to GWs
SPSAS-HighAstro - May 31st
31 / 33
GW150914
Observation of Gravitational Waves when Black Holes Collide