LIGO/Virgo/GEO/KAGRA science

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May 24th 2012
Outline

1. Observational results
   - Upper limits

2. Science with advanced detectors
   - Fundamental Physics
   - Astrophysics
   - Cosmology

3. Summary
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The 2 LIGO’s and Virgo ended their joint science runs on October 20th 2010.
Advanced detector sensitivities

Science run for LIGO/Virgo due to restart by the end of 2014
KAGRA due to join in 2017
Burst signals

- Supernovae and collapsing stars: typical amplitude

\[ h \sim 10^{-21} \left( \frac{E_{GW}}{10^{-7} m_\odot} \right) \left( \frac{1 \text{msec}}{T} \right)^{1/2} \left( \frac{1 \text{kHz}}{f} \right) \left( \frac{50 \text{kpc}}{D} \right) \]

Limits for signals centered at different freq's

1.7 yr of data, LIGO/Virgo arXiv:1202.2788
Burst signals

- Supernovae and collapsing stars, typical amplitude

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Typical \( E_{GW} \) for \( D=50\text{kpc} \)
signals centered at different freq’s

1.7 yr of data, LIGO/Virgo arXiv:1202.2788
Triggered searches: Gamma Ray Bursts

Long ($\sim 2$ secs) associated with core-collapse SuperNovae

Swift, Fermi, MAXI, SuperAGILE, INTEGRAL, IPN

Short ($\sim 1$ sec) $\sim$ binary inspiral

Both may produce GW & EM radiation
Coincidence with Gamma Ray Bursts

Search in a $-600 \div +60$ sec window around the GRB event

- 150 analyzed via an un-modeled burst search excluded within $D_{\text{burst}} \sim 17 \text{ Mpc} (E_{\text{GW}}/10^{-2} M_{\odot})^{1/2}$ for signals at 150 Hz
- 24 analyzed via matched filtering with coalescing binary signals $D_{\text{NS-NS}} \sim 17 \text{ Mpc}$\quad M_{\text{NS}} \sim 1.4 \pm 0.2$
  $D_{\text{BH-NS}} \sim 29 \text{ Mpc}$\quad M_{\text{NS}} \sim 1.4 \pm 0.4\quad M_{\text{BH}} \sim 10 \pm 6$

Distance cumulative distributions:

GRB & follow-up

GRB 05113 found in M31 @ \( D = 3.5 \) Mpc
dedicated analysis excluded binary coalescence origin

Rapid detection GW-triggers
follow-up image analysis

↓

joint GW-EM detection
GW-triggers will be followed-up
in the radio, optical and X bands
with \( O(30') \) latency

Triggered searches: neutrinos

GW search in coincidence with High Energy Neutrinos $\gtrsim 100\text{GeV}$
Possible sources: long GRB, supernovae, cosmic strings...
No significant trigger in $T_{\text{obs}} \simeq 100$ days

\[
\rho_{\text{GW-HEN}} \lesssim 10^{-3}\text{Mpc}^{-3}\text{yr}^{-1} \left( \frac{E_{\text{GW}}}{10^{-2}M_\odot} \right)^{-3/2}
\]

LIGO/Virgo/ANTARES arXiv:1205.3018
158$\nu$-events (Feb-Sep 2007) from ANTARES (±496sec win.)
External triggered search: magnetars

GW-search in coincidence with 1217 soft GRB’s from 5 Soft Gamma Repeaters and 1 Anomalous X-ray Pulsar associated with magnetars @ 2 < D/kPc < 15 (4 sec win.)

Energy upper limits for 2 magnetars
12 different waveforms

\( L_\odot \approx 4 \cdot 10^{33} \text{erg/s} \)

\( M_\odot \sim 10^{54} \text{erg} \)
Asymmetric rotating neutron star

- Pulsar asymmetry $\epsilon \rightarrow h \sim \epsilon (Rf)^2 M/D$

$$L_{GW} = f^6 M^2 R^4 \epsilon^2 \rightarrow t_{SD} \sim \frac{M(Rf)^2}{L_{GW}} = f^{-1} \left( \frac{M}{R} \right)^{-1} \frac{1}{\epsilon f^3}$$

If all the spin-down is due to GW emission

$$\epsilon \simeq 7 \cdot 10^{-3} \quad \epsilon_{GW} < 1.4 \cdot 10^{-4} \quad \text{Crab}$$

$$\epsilon \simeq 1.2 \cdot 10^{-3} \quad \epsilon_{GW} < 5 \cdot 10^{-4} \quad \text{Vela}$$

Beating the spin-down limit!

- Best upper limit $h_{ul} \sim 10^{-24}$ @ 150Hz

LIGO/Virgo APJ 2010


- Upper limit on GW’s emitted by Vela pulsar glitch

$h_{ul} < 10^{-20} \quad E_{GW} < 10^{45}$ erg

LIGO PRD 2011
Stochastic background

\[ \Omega_{GW} = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \]

\[ S_h(f) = \frac{3H_0^2}{4\pi^2 f^3} \Omega_{GW} \]

\[ \text{SNR}^4 = 2T \int_0^\infty df \gamma^2(f) \frac{S_h^2(f)}{S_{n1}(f)S_{n2}(f)} \]

Bound on stochastic GW’s between 50 and 150 Hz

\[ \Omega_0 = 6.9 \times 10^{-6} \]

LIGO/Virgo Nature 2009
Compact binary coalescences

Inspiral phase
post-Newtonian approximation: $\nu/c$

Merger: fully non-perturbative

Ring-down: Perturbed Kerr Black Hole

Accurate source modeling allows match-filtering
Low mass \(<25M_\odot\) binary (inspiral)
Upper limit from previous runs
improved by the 7/2009-10/2010 run

Combined upper limit from old and new runs compared with astrophysical estimates

LIGO/Virgo PRD 2012
Upper limits for high mass systems

- For high masses $25 < M/M_\odot < 100$ also merger and ring-down are in band and necessary to have complete analytic description of coalescence waveform.
  Observative bound on coalescence rate $R_c < 2 \text{ Mpc}^{-3} \text{ Myr}^{-1}$

  LIGO/Virgo PRD 2011

- For higher masses $100 < M/M_\odot < 500$ signals are burst-like:
  Best upper limit for equal mass system with $M \sim 170M_\odot$:
  Merger Rate $R_m < 0.13 \text{ Mpc}^{-3} \text{ Myr}^{-1}$

  LIGO/Virgo arXiv:1201.5999
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Advanced detectors

Sensitivity vs. signals @ 200Mpc w. optimal orientation
Distance reach for compact binary coalescence

![Graph showing distance reach for compact binary coalescence with Advanced and Initial labels.](image-url)
Observational rate estimates

LIGO/Virgo Advanced Observatories will detect

\[ SNR = 8, \text{ optimal orientation} \]

<table>
<thead>
<tr>
<th>Event</th>
<th>Distance (Mpc)</th>
<th>Rates MWEY^{-1}Myear^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS</td>
<td>450Mpc</td>
<td>1/10^3</td>
</tr>
<tr>
<td>10 M⊙ BH-BH</td>
<td>1Gpc</td>
<td>4 · 10^{-2} / 100</td>
</tr>
</tbody>
</table>

\[ N = 0.011 \times \frac{4}{3} \pi \left( \frac{D_H/\text{Mpc}}{2.26} \right)^3 \text{MWEY} \]

Realistic case:

\[ R_{NS-NS} \sim 40\text{yr}^{-1} \quad R_{BH-BH} \sim 10^2\text{yr}^{-1} \]

for LIGO/Virgo at design sensitivity
Advanced LIGO/Virgo goals

- Make first “direct” detection of GW’s from neutron stars and/or black holes
- Probe $1 \div$ few $100 M_\odot$ black holes
- Measure rate of binary coalescences
- Measure pulsar parameters
- Possible probe of neutron star interior/nuclear matter at high density
- Verify association between short GRB’s and GW’s
- Combine EM and GW detection
- Make strong tests of GR
- Use coalescing binaries as standard sirens for cosmology
Detector number and location affects source sky position reconstruction. Sky fraction of reconstructed source position vs. error region size.

Burst-like injections excess noise analysis. Klimenko et al. PRD 2012

Inspiral waveform injections and analysis. $5 < SNR < 35$. Veitch et al. arXiv:1201.1195
More detectors help

- Larger baseline improves localization
- Positions orthogonal to the detectors’ plane are better recovered
- Large (future) survey telescopes like LSST can scan a $10^\circ \times 10^\circ$ sky patch in 30 minutes
- A fourth detector with giving a longer base-line improves drastically the localization

Possibility of an additional detector in INDIA
Fundamental Gravity

- Black hole ring-down modes depend on mass and spin: test of the no-hair theorem are hard with AdvLIGO/Virgo

source @ 1Gpc, Kamaretsos et al. PRD 2011
Fundamental Gravity

- Strong field test of gravity: present observations constrain conservative gravity at first post-Newtonian (PN) order and dissipative effects at leading order in binary pulsar where $v/c \sim 10^{-3}$

GW detectors’ output is sensitive to phase $\phi(t)$ and its PN corrections

$$\phi(t) = \phi_N \left( 1 + \#v^2(t) + \ldots + \#v^6(t) + \ldots \right)$$

In principle at least 3PN order is necessary for match-filtering

See Salvatore Vitale poster and N. Yunes talk on Friday

- Learn about neutrino mass by coincidence with EM events
Astrophysics goals

- **Direct** detection of pulsars, binary neutron stars and black holes
- **Rate** of coalescences in the mass range $< \text{few} 100 M_\odot$
- Ellipticity of neutron stars
- Learning about **magnetars** and pulsar glitches
- Neutron stars and **nuclear matter** and high density
- Supernovae (not granted)
Periodic signals in the Advanced detectors

Minimum detectable ellipticity for known pulsars

Distance reach
Target: galactic sources

C. Palomba
Integrated sensitivity ($T_{\text{obs}}=1\text{yr}$) for known pulsars vs. spin-down limit

C. Palomba
Probing neutron star interior

Glitches (magnetars) may cause oscillations of the core → GW

Normal modes freq. vs. Mass for various eq.'s of state

Benhar, Ferrari and Gualtieri, 2004
Measuring the Hubble constant $H_0$

Coalescing binary systems are standard sirens:

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

In cosmological settings source and observer clocks tick differently:

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

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

Schutz, Nature ’86
Determining $H_0 \equiv h H_{100}$

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 localized $(\alpha, \delta)$
- GW sources are in the galaxy catalog with known red-shift

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

$m_1, m_2 \subset (1, 15)M_\odot$

$D_L < 450$ Mpc

$(z \lesssim 0.1)$

W. Del Pozzo, arXiv:1108.1317
No compelling case for stochastic GW detection, unless some exotic sources jumps in
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Outlook

- A new class of astrophysical objects will become visible:
  - detection of solar mass black holes
  - neutron star interiors
  - origin of GRB’s
  - combined electromagnetic and gravitational detections

- Fundamental physics:
  - test GR in the genuinely strong regime
  - eq. of state of supra-nuclear matter
  - independent constraint/measurement of neutrino mass

- Cosmology:
  - Hubble law (equation of state of dark energy)
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- unknown unknowns...