Many thanks to the experimenters building the detectors!

Gravitational Waves and Gamma-Ray Bursts in Multimessenger Astrophysics

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Indirect evidence of gravitational radiation

Matching the theoretical prediction
(Nobel Prize in Physics, 1993)

Typical strain at Earth: $h \sim 10^{-21}$

~ diameter of a hydrogen atom!
Gravitational Wave Sources

- Transients
- Repeaters
- Continuous

**Searches for Sources**

<table>
<thead>
<tr>
<th>Modeled</th>
<th>UnModeled</th>
</tr>
</thead>
<tbody>
<tr>
<td>short GRB</td>
<td>SGR</td>
</tr>
<tr>
<td>pulsar</td>
<td>supernovae</td>
</tr>
<tr>
<td>circular inspiral</td>
<td>stochastic bkg.</td>
</tr>
<tr>
<td>eccentric encounter</td>
<td>BH-BH merger</td>
</tr>
</tbody>
</table>

**Triggered**

- All-Sky/Time

**E.g., S5 Publications:**


The Global Network of Gravitational Wave Detectors

- GEO600, Germany
- VIRGO, Italy
- LIGO, Livingston
- LIGO, Hanford
- TAMA, Japan
Multimessenger Astrophysics with GWs

- Gamma-ray transients (GRBs, SGRs)
- Optical transients
- Neutrino events
- Radio transients
- X-ray transients

... 

- Correlation in time
- Correlation in direction
- Information on the source properties, host galaxy, distance

... 

- Confident detection of GWs.
- Better background rejection $\Rightarrow$ Higher sensitivity to GW signals.
- More information about the source/engine.
- Measurements made possible through coincident detection.

Graphics courtesy of Zsuzsa Marka
“Multi-messenger astrophysics”: connecting different kinds of observations of the same astrophysical event or system

“Looc-Up” strategy:

GW $\rightarrow$ Flow of trigger information $\rightarrow$ Telescopes, Satellites or other external entities

“ExtTrig” strategy:

Telescopes, Satellites or other external entities $\rightarrow$ Flow of trigger information $\rightarrow$ GW
Pulsars Spinning Down (5th Science Run)

• The Crab Pulsar  [see Abbott et al., ApJL 683, L45 for details]
  » Null search result implies that < ~2% of the spin-down energy is going into GW emission (beat spin-down amplitude limit by a factor of ~7)

• Other known pulsars  [see e.g., Abbott et al., PRD 76, 042001 for pulsar list]
  » PSR J1603–7202: \( h_0 < 2.3 \times 10^{-26} \)
  » PSR J2124-3358: \( \varepsilon < 7 \times 10^{-8} \)

• Theoretical context
  » Normal crystalline crust can have \( \varepsilon \) to be up to \( \sim 4 \times 10^{-6} \)  [see e.g., Horowitz & Kadau, PRL 102, 191102]
  » Exotic forms of crystalline quark matter could sustain \( \varepsilon \) up to \( \sim 10^{-4} \)  [see e.g., Owen 2005; Lin 2007; Haskell et al 2007; Knippel & Sedrakian 2009]

Slide inspired by P.Shawhan’s, M.Pitkin’s Amaldi8 talk
S5y1 Individual SGR Burst Search

- First search sensitive to NS f-modes
- LIGO S5 + Astrowatch
- 191 SGR events including:
  - largest giant flare (SGR 1806-20)
  - SGR 1900+14 storm
- Ioka MNRAS 327, 639 (2001)
- Most quantitative, detailed model
- $E_{GW} \approx 10^{48}$ erg not unreasonable

Isotropic GW emission upper limits at 10kpc
Circles: Giant Flare
Diamonds: GRB 060806
GRB 070201 – Sky Location

R.A. = 11.089 deg,
Dec = 42.308 deg

$D_{M31} \approx 770$ kpc

Possible progenitors for short GRBs:

- NS/NS or NS/BH mergers
  Emits strong gravitational waves

- SGR
  May emit GW but weaker

$E_{\text{iso}} \sim 10^{45}$ ergs

if at M31 distance

(more similar to SGR than GRB energy)
Exercise matched filtering techniques for inspiral waveform search

No plausible gravitational waves identified

Exclude compact binary progenitor with masses

$1 \, M_\odot < m_1 < 3 \, M_\odot$ and $1 \, M_\odot < m_2 < 40 \, M_\odot$ with $D < 3.5 \, \text{Mpc}$ at 90% CL

Exclude any compact binary progenitor in our simulation space

at the distance of M31 at $> 99\%$ confidence level

These do happen from time to time…

**GRB 051103**

Sky position error box overlaps with M81 group ~3.6 Mpc

(Frederiks et al 2006)

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Fig. 4.— The 21 cm HI emission map of the central region of the M81 group of interacting galaxies. M81 at the center; M82 ~ 35′ to the north; and NGC 3077 ~ 40′ to the east and ~ 20′ to the south. X-ray sources (crosses) observed by Chandra, and IPN box of GRB 051103 are superimposed.
Some GW+HEN source candidates

**Long GRBs:** In the prompt and afterglow phases, high-energy neutrinos ($10^5$-$10^{10}$ GeV) are expected to be produced by accelerated protons in relativistic shocks (e.g., *Waxman & Bahcall 1997; Vietri 1998; Waxman 2000*). Good prospects for detection in GW too.

**Short GRBs:** HENs can also be emitted during binary mergers (*Nakar 2007; Bloom et al. 2007; Lee & Ramirez-Ruiz 2007*). The $\nu$ flux is expected to be large enough for the current generation of detectors. Prospects for detection in GW too.

**Low-Luminosity GRBs:** Associated with particularly energetic population of core-collapse supernovae. Might also be strong neutrino emitters (*Murase et al. 2006; Gupta & Zhang 2007; Wang et al. 2007*). Expected event rate in the local volume is more than an order of magnitude larger than that of conventional long GRBs (*Liang et al. 2007; Soderberg et al. 2006*).

”Failed” GRBs: Associated with plausible baryon-rich jets. Optically thick, can be hidden from conventional astronomy, neutrinos and GWs might to be able to reveal their properties. *Ando & Beacom (2005), Razzaque et al. 2004; Horiuchi & Ando 2008.*
Likelihood Function for Spatial Overlap: LIGO + Virgo

LIGO + Virgo:
- Triple coincidence
- Improved “point” spread function
- Reduced coincident noise trigger rate

Y. Aso et al. APS'08 and CQG 25, 114039, 2008

Pradier arXiv:0807.2567v1 and

False Alarm Rate = \frac{1}{600} \left( \frac{p}{1\%} \right) \left( \frac{T_w}{1\text{sec}} \right) \left( \frac{R_{gw}}{1/\text{day}} \right) \left( \frac{R_{\nu}}{20/\text{day}} \right) \text{ per year}
Astronomical Reach

x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 year of Initial LIGO < 1 day of Advanced LIGO

Circular Inspirals: ~20 / year (Kalogera et al. 2006)

Eccentric Encounters: ~ several / year (O’Leary, Kocsis, Loeb 2008)
Far-Future Detectors – Rule of Thumb?

Data is courtesy of VIRGO and the LIGO Scientific Collaboration.

\[ D_L \simeq \sqrt{\frac{3G (1 + z) E_{GW}}{\pi^2 c^3 S(f)}} \frac{F_{\text{rms}}}{\rho_{\text{det}} f} \]

Einstein Telescope Gravitational Wave observatory (planned)

\[ \sim \times 10 \at \sim 100 \text{ Hz} \]
Far-Future Detectors – Rule of Thumb?

\[ D_L \simeq \sqrt{\frac{3G (1 + z) E_{GW}}{\pi^2 c^3 S(f)}} \frac{F_{\text{rms}}}{\rho_{\text{det}} f} \]

\[ y \lesssim 5 \text{Gpc} (1 + z)^{1/2} \frac{10}{\rho_{\text{det}}} \frac{100 \text{Hz}}{f} \left( \frac{E_{GW}}{10^{-2} M_\odot c^2} \right)^{1/2} \frac{2.5 \times 10^{-25} / \sqrt{\text{Hz}}}{S(f)^{1/2}} F_{\text{rms}} \]
Unmodelled GW burst (rough) examples

Soft Gamma Repeater

$E_{GWiso} \sim 10^{46}$ erg
SGR giant flares

$E_{GW} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{rss}^2$

Based on Gareth Jones’ ILIAS slide.
ET Reach for SGRs

Minimum energy in gravitational waves detectable by ET as a function of frequency for an SGR source. This limit assumes isotropic and narrowband GW emission.

10^{-7}!
Unmodelled GW burst (rough) examples

0.05 Msol of energy released in GW

\[E_{\text{GWiso}} \approx O(9 \times 10^{52}) \text{ erg}\]

Merger phase of compact body coalescence

Based on Gareth Jones’ ILIAS slide.
Image courtesy of U. of Florida, LIGO, LSC
This is great exploratory science!

- There is a bold effort underway to get a new view of the universe

- Initial LIGO has reached its design sensitivity
  - Several astrophysically interesting results are out from S5
    - SGR1806-20
    - GRB070201
    - Crab-spindown
    - and others to come…

- Active data sharing collaboration with VIRGO

- Enhanced LIGO is here
- Advanced LIGO is around the corner… the excitement is high!