Gravitational-Wave Astronomy

2015-2020: Challenges and Opportunities

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Gravitational Waves

The Einstein field equations of GR have wave solutions:
- Emitted by a rapidly changing configuration of mass
- Travel away from the source at the speed of light
- Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

Looking at a fixed place in space while time moves forward, the waves alternately stretch and shrink the space.

“Plus” polarization

“Cross” polarization

Circular polarization

Rowan: RS 2012
GWs as Astrophysical Probes

• GWs trace the bulk motion of their source
  - non-imaging
  - very weakly scattered / absorbed.

• GW detectors are all-sky, low bandwidth.
  - archival searches: easy.
  - source localization: hard.

• Complementary to properties of photons.
How to Detect Gravitational Waves

Use interferometry to measure time-varying *differential strain* as small as $\sim 10^{-22}$
The Global GW Detector Network in the Recent Past

- LIGO Hanford
  - 4 km
  - +2 km
- GEO600
  - 600 m
- TAMA, CLIO
  - 300 m
  - 100 m
- LIGO Livingston
  - 4 km
- VIRGO
  - 3 km
Science Runs: Past, Present & Future

- LIGO '05 '06 '07 '08 '09 '10 '11 '12 '13 '14 '15 '16
- GEO-HF S7 S8
- Virgo VSR1 VSR2 VSR3 VSR4 VSR5 VSR6
- AstroWatch S6 S6e
- Advanced LIGO
- Advanced Virgo

Most recent joint data-taking run
GW Detectors: 2009-2010

- LIGO’s maximum range for binary coalescences:
  - neutron star – neutron star: 40 Mpc
  - neutron star – black hole: 90 Mpc
  - Virgo: about half that
- Expected detection rates < 1 yr\(^{-1}\).

Abadie et al., arXiv:1111.7314
Abadie et al., arXiv:1003.2480
Types of GW Burst Searches

• All-sky, all-times search
  – Analyze all available data for GW bursts arriving from any direction
    (offline search – can be done with months/year latency)

• Externally triggered searches
  – Analyze GW data more deeply using information from:
    –► Known astrophysical events (GRBs, magnetar flares, pulsar timing glitches…)
    –► Candidate transient signals (high-energy neutrinos, radio bursts, …)

• All-sky GW search with rapid EM follow-up
  – Reconstruct apparent sky positions of GW event candidates
  – Try to catch optical, X-ray, and/or radio transient counterpart
    (‘with-followup’ search is done at low latency (minutes) )
All-Sky Generic GW Burst Search

• Analyzed all LIGO and Virgo data since 2005 when at least 2 detectors were running (plus GEO for investigating event candidates)
  – Total observation time: 636 days
• Sensitive to arbitrary GW signals between 64–5000 Hz
  – Background estimated by analyzing data with artificial time shifts
  – Event selection thresholds set for low false alarm probability
• No event survived all selection cuts
• We set upper limits on burst rate vs. amplitude for representative waveforms
  
  Abadie et al., submitted to PRD, arXiv:1202.2788
Search for Coalescing Compact Binary signals

LIGO-Virgo upper limits
Abadie et al arXiv:1111.7314

Astrophysical Predictions
Abadie et al arXiv:1003.2480
Multi-Messenger Advantages

• If an event has already been detected, then GW searches:
  -► know *when* to look at the data
  -► know *where* in the sky to look
  -► may know *what kind* of GW signal to search for
  -► may know the distance to the source

• As a result,
  -► Background is suppressed, so a weaker GW signal could be confidently detected
  -► The extra information from the combined observations will reveal more about the astrophysics of the source
  -► *Non*-detection of a GW signal can still provide useful information
GRB 070201

- Short, hard gamma-ray burst
  - Leading model for short GRBs: merger involving a neutron star
- Position was consistent with being in M31 (Andromeda galaxy)
- Both LIGO Hanford detectors were operating
  - Searched for inspiral & burst signals
- No plausible GW signal found ➔ very unlikely to be a merger in M31
- Similar analysis done for GRB 051103
  - Abadie et al., arXiv:1201.4413
Prospects for EM (and n) Counterparts

GW sources release a lot of energy

\[ \text{e.g. compact binary merger: } \sim 10^{53} \text{ erg or more} \]

Many ways for some fraction of that energy to go into EM emissions

- [Piran, RMP 76, 1143]
- [Ghisellini et al., MNRAS 406, 2650]
- [Novelletto et al., ApJ 609, 2033]
- [Novelletto et al., ApJ 609, 2033]

Likely to be detectable \textit{if} an appropriate telescope is pointed in the right direction at the right time

Optical and radio surveys only cover part of the sky at any given time

See nice talk yesterday from Stephen Rosswog
EM Follow-ups

Analyze GW data, select candidates

[e.g. see Kanner et al., CQG 25, 184034]

Rowan: RS 2012
• Mostly (but not all) robotic wide-field optical telescopes
  – Many of them used for following up GRBs, surveying for supernovae
  and other optical transients
Binary signal detected in LIGO-Virgo network on 16 Sept 2010

Sky map reconstructed by online processor (>130 sq deg)
The Big Dog: EM Follow-up Regions Imaged by Telescopes

Images taken ASAP, by Partner telescopes pointed at nearby galaxies (<50 Mpc) and on subsequent nights.

No significant optical transient found in telescope images.

Event a simulated GW added to the data as a detection test.

Advanced GW detector era - opportunities for joint observations
GW Detectors: 2015-2020

- LIGO’s maximum sensitive ranges:
  - NS-NS: 450 Mpc
  - NS-BH: 930 Mpc

- Expected detection rates:
  - NS-NS: 0.4 - 400 yr\(^{-1}\)
  - NS-BH: 0.2 – 300 yr\(^{-1}\)

Abadie et al., arXiv:1003.2480
What will advanced detectors tell us?

- A characteristic “chirp” GW coincident with short GRB:

  J Read / YITP

- Smoking gun for a binary progenitor

Finn & Chernoff, PRD 47, 2198 (1993)

GWs + GRBs = cosmology

- Binaries are “standard sirens” (candles)
  - GW amplitude gives luminosity distance (≈10%) if GRB observed.
- Side-step cosmological distance ladder.
  - Measure $H_0$ with to 13% (5%) with 4 (15) GW-GRB detections.

Joint EM – GW – v Sources...

**Core-collapse Supernovae:** Galactic SN: \((10^{-2} \text{ yr}^{-1})\)
- Optical emission beginning hours after collapse, prompt neutrino emission
- GWs probe collapse physics

**GRBs & High-Energy Neutrinos:**
- Choked GRBs
- Long GRBs: precursor, prompt, afterglow phases.

**Soft Gamma Repeaters & Anomalous X-ray Pulsars**
- Magnetars – GWs from crust-cracking? Magnetic rearrangement?

**Cosmic string cusps:** ????
- Photon, high-energy neutrinos.

*Want to stay open to the unexpected.*
Source localization from timing-based triangulation. Near threshold:

$$\Delta \Theta \sim 1^\circ \left( \frac{100 \text{ Hz}}{\Delta f} \right) \left( \frac{10 \text{ ms}}{d} \right)$$
March 2012: The LSC & LIGO Lab have endorsed transferring one of the three Advanced LIGO instruments to India

Needs approval from NSF (US) & formal announcement of funding (India); hopefully by May/June 2012
Sky localization with 3 sites ...

Typical 90% error box areas for NS-NS binaries

- median > 20 sq deg

Fairhurst, CQG 28 105021 (2011)
... and with 5 sites

Fairhurst (2011)
Challenges

• Low-latency GW analysis to identify significant events, send alerts (sec-min).
• Better models of expected EM emission to find the right needle in the haystack of transients.
• Strategies for scanning large error boxes to find transients of a priori unknown type.
  – Automated EM transient identification, spectral follow-ups.
  – Rely on high-cadence surveys (Pan-STARRS, LSST, LOFAR)?
  – Coordinated follow-ups by MOU?
  – Public trigger release after first detections?
• Impetus to talk to EM astronomy community NOW to be ready for 2015.

(Draft) LSC–Virgo Policy on GW Trigger Release

• Before first published detections: trigger release by MoU.
  – "Both Collaborations ... will partner with astronomers to carry out an inclusive observing campaign for potentially interesting GW triggers, with MoUs to ensure coordination and confidentiality of the information. They are open to all requests from interested astronomers or astronomy projects which want to become partners through signing an MoU."
• After first published detections:
  – public: high-quality triggers (false alarm rate < 1 / 100 years).
  – by MoU: lower threshold triggers, possibly lower latency.

Proposal: policy not yet approved by all relevant agencies.
Concluding Remarks

• Multi-messenger observations will enable us to extract the most physics from the advanced GW detectors.
  – probe source engines
  – galaxy hosts, redshifts
  – binaries: luminosity distance, measure cosmological parameters

• Full exploitation of GW data presents many challenges.
  – low latency GW analysis
  – better GW, EM emission models
  – strategies & partnerships for electromagnetic follow-up of GW events
Various aspects of gravitational wave astronomy will be discussed, including:

- Waveform modelling
- Source populations
- Source dynamics
- EM counterparts (GRBs, radio, neutrinos, optical...)

Bringing together astronomers, numerical relativists and gravitational wave data analysts to work towards gravitational wave astronomy

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END