Gravitational Waves and Connections with Fermi

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Sixth International Fermi Symposium
Washington, DC — November 9, 2015

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)
Fermi image: NASA/Sonoma State University/Aurore Simonnet
The Einstein field equations have wave solutions!

- Sourced by changing mass quadrupole (or higher) moment
- Waves travel away from the source at the speed of light
- Are variations in the spacetime metric — i.e., the effective distance between locally inertial points

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

“Plus” polarization

“Cross” polarization

Circular polarization
# The Wide Spectrum of Gravitational Waves

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Likely Sources</th>
<th>Detection Method</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 10^{17} \text{ Hz} )</td>
<td>Primordial GWs from inflation</td>
<td>B-mode polarization patterns in cosmic microwave background</td>
<td>Planck, BICEP/Keck, ABS, POLARBEAR, SPTpol, SPIDER, …</td>
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<tr>
<td>(\sim 10^{8} \text{ Hz} )</td>
<td>Grav. radiation driven Binary Inspiral + Merger</td>
<td>Pulsar Timing Array (PTA) campaigns</td>
<td>NANOGrav, European PTA, Parkes PTA</td>
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<tr>
<td>(\sim 10^{-2} \text{ Hz} )</td>
<td>Ultra-compact Galactic binaries</td>
<td>Interferometry between spacecraft</td>
<td>eLISA, DECIGO</td>
</tr>
<tr>
<td>(\sim 100 \text{ Hz} )</td>
<td>Spinning NSs</td>
<td>Ground-based interferometry</td>
<td>LIGO, GEO 600, Virgo, KAGRA</td>
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</table>
Fermi AGN studies can shed light on accretion and the environments around supermassive black holes

Relevant for understanding dynamics which can bring a pair of BHs close enough to inspiral by GW emission – the “final parsec problem”

[e.g. Shannon et al., Science 349, 1522]

May also impact the population of stellar-mass compact objects available to spiral into the BH [Merritt et al., PRD 84, 044024]

**Fermi observations of X-ray binaries contribute to the census of black holes**

Population, spin history of black holes
HMXB system evolution → future compact binary merger?
LMXB could be continuous GW source
Compact binary mergers are thought to cause most short GRBs

Strong evidence from host galaxy types and typical offsets
Could be NS-NS or NS-BH, with post-merger accretion producing a jet

Beamed gamma-ray emission $\rightarrow$ many more mergers than GRBs

Some opening angles measured, e.g. $16\pm10^\circ$ [Fong et al., arXiv:1509.02922]
Also may get detectable isotropic emission from nearby GRBs, such as infrared “kilonova” peak after several days, [e.g. Barnes & Kasen, ApJ 775, 18] seen for GRB 130603B? [Berger et al., ApJ 765, 121; Tanvir et al., Nature 500, 547]
Possible to detect X-ray afterglow from a somewhat off-axis nearby GRB?

Exciting possibility to confirm the merger-GRB association!
The rate of binary mergers and the beaming angle are uncertain, but the rate of observed SGRBs is known rather well.

Suggests we might detect a handful of joint GW-GRB events per year when LIGO runs at design sensitivity [Pelassa et al. poster at 4th Fermi Symp]

**GW emission is stronger along the axis than in the plane of binary**

By a factor of 2 in amplitude

⇒ Most favorable for detection when we’re in the cone of gamma-ray emission

If SGRBs are produced by NS-BH mergers, those are detectable out to greater distances than NS-NS

**Relative arrival time of GW versus gamma rays can test GR**

Do GWs travel at exactly the speed of light, or slightly different?
Additional millisecond pulsars provide more good clocks for Pulsar Timing Array observations

Gain the most from stable pulsars with well-defined pulses

Short-period binary pulsar systems provide information about the population of compact binaries which merge via GW emission

GW emissions are only weakly beamed, and GW detectors are only weakly directional

- Monitor the whole sky for sources with all inclinations
- Not dependent on being within the cone of a jet

GWs come directly from the central engine

- Not obscured or scattered by material
- Complements photon diagnostics of photosphere, outflows, circumburst medium, etc.

But, challenging to detect

- Strain amplitude is inversely proportional to distance from source
- Have to be able to detect weak signals to search a large volume of space

Typical strain at Earth: $h \sim 10^{-21}$ or even smaller!
Advanced GW Detector Network: Under Construction → Operating

3 separate collaborations working together
Advanced LIGO Optical Layout

Improvements

- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and more …

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system

Advanced Virgo and KAGRA have similar designs

Goal: $10 \times$ lower noise $\Rightarrow 1000 \times$ more volume of space searched
Installation went pretty smoothly at both LIGO observatories

Achieved full interferometer lock in 2014, first at LIGO Livingston, then at LIGO Hanford

Commissioning: lots of work, lots of progress
In August, switched from commissioning work to focus on establishing stable running conditions

Calibration studies completed in early September

Observing run “O1” officially began on September 18, and is scheduled to end on January 12

   Both LIGO detectors are observing together ~half of the time

Operational snapshot available at
https://ldas-jobs.ligo.caltech.edu/~gwistat/gwsnap.html
Current GW Strain Sensitivity

$10^{-23}$ amplitude spectral density!

Current range ~ 70 Mpc for NS-NS inspiral, averaged over orbital inclination & sky position (~100 Mpc for face-on NS-NS mergers)
Projection made in 2013 (arXiv:1304.0670) still seems on target

Was based on guesses at how fast commissioning would progress

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2}M_\odot c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
<td>LIGO</td>
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<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>–</td>
<td>40 – 80</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>20 – 40</td>
<td>80 – 120</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>40 – 50</td>
<td>120 – 170</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>40 – 70</td>
<td>200</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>80</td>
<td>200</td>
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Planning for Virgo to join late next year, then KAGRA in a few years

Still very uncertain when we’ll detect the first GW signal(s)

Wide range of estimates from observed binary pulsars and population synthesis simulations – begs for observational truth!
Searches for GW Transient Sources

Compact Binary Coalescence (CBC)
Known waveform ➔ Matched filtering
Templates for a range of component masses
(spin affects waveforms too, but not so important for initial detection)

Unmodelled GW Burst  (< ~1 sec duration)
e.g. from stellar core collapse
Arbitrary waveform ➔ Excess power
Require coherent signals in detectors,
using direction-dependent antenna response

Low-latency searches run continuously as data is collected
Whenever two or more detectors are operating normally
With coherent analysis, identify event candidates and generate
preliminary sky position probability maps within a few minutes
Goals for Multi-Messenger Science

**Identify GW event candidates as quickly as possible**

With basic event parameters and an estimate of confidence

**Provide rapid alerts to other observers**

Allow correlation with other transient survey events or candidates *

Trigger follow-up observations (prompt and/or delayed)

**What this can enable:**

Pick out interesting (initially marginal) events from GW and other surveys

Prioritize follow-up observing resources

Maybe catch a counterpart that would have been missed, or detected only later

Identify host galaxy ➔ provide astronomical context

Obtain multi-wavelength (and multi-messenger) data for remarkable events

* LIGO/Virgo also monitor GCN and consider other significant transient events, and do deeper GW analysis for notable reported events
Generating and Distributing Prompt Alerts

Challenge: GW reconstructed sky regions are large!
With just the two LIGO detectors: typically a few hundred square degrees
LIGO+Virgo: typically several tens of square degrees
Will improve with KAGRA and LIGO-India
Partnerships for Follow-up Observing

There’s a lot to be gained from finding counterparts

But confident detection of first few GW signals will require time and care—need to avoid misinformation / rumors / media circus

➡️ Established a standard MOU framework to share information promptly while maintaining confidentiality for event candidates

LIGO/Virgo will need to carefully validate the first few detections, at least

Once GW detections become routine (≥4 published), there will be prompt public alerts of high-confidence detections

LIGO & Virgo have signed MOUs with ~70 groups so far!

Broad spectrum of transient astronomy researchers and instruments

Optical, Radio, X-ray, gamma-ray, VHE – including a team from Fermi

Special LVC GCN Notices and Circulars with distribution limited to partners

Encourage free communication among all “inside the bubble” for multiwavelength follow-up
Summary

Gravitational waves are being sought in various frequency bands
  Direct detection will be a major milestone
  Will enable astronomical investigations as well as fundamental physics

There are multiple connections between Fermi and GW science
  Black holes, compact binary mergers → SGRBs (we think), pulsars

Advanced LIGO is observing now!
  With good sensitivity – more than 3 times the distance reach of initial LIGO

Ready for multi-messenger astronomy
  GW signature complements photon diagnostics
    of outflows, circumburst medium, astronomical context
  Low-latency event candidates are now being identified and shared with partner groups,
    including Fermi project team