Past and Future in the Quest for Gravitational Wave Transients

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Gravitational waves are ripples in the fabric of space-time: perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

- They travel at the speed of light, carrying information from the coherent, relativistic motion of large masses.

- As they pass, they change the distance between neighboring bodies.

Dimensionless strain:

\[ h(t) = \frac{1}{R} \frac{2G}{c^4} \dddot{I}(t) \]

- \( I \) = mass quadrupole moment of the source
- \( R \) = source distance

American Museum of Natural History GW project
Interferometer: Suspended Mirrors as Test Masses

Deformation of a ring of particles due to the + and x polarization

Goal: measure difference in length to one part in $10^{21}$, or $10^{-18}$ meters
An International Network Of Ground-Based Interferometers

LIGO Hanford Observatory
H1: 4km arms
H2: 2km arms

LIGO Livingston Observatory
L1: 4km arms

GEO600
G1: 600m arms

Virgo
V1: 3km arms

AIGO
cornerstation

LCGT
3km arm (future)

world map credit: NASA's Earth Observatory
Strain noise at 150 Hz $[\text{Hz}^{-1/2}]$

- Initial LIGO
- Enhanced LIGO
- Advanced LIGO

$\frac{\text{sqrt(PSD)}}{\text{frequency}} [\text{Hz}^{1/2}]$

$10^{-17}$, $10^{-19}$, $10^{-21}$, $10^{-22}$, $4 \times 10^{-23}$

$\sim 10$ better amplitude sensitivity

$\sim 1000$ more volume
Gravitational Wave Transients

- short (fraction of second to minutes) bursts of gravitational waves from violent astrophysical events
- Plausible sources include mergers of compact binaries, supernova explosions, instabilities in nascent neutron stars, kinks and cusps in cosmic strings....
“Ears Wide Open”

Excess power in time-frequency maps, coherent in multiple detectors
Don’t require prior knowledge of the waveform.

Rate limit per unit volume 90% CL linearly polarized sine-Gaussian with $E_{GW} = 1 \, M_\odot \, c^2$

GW energy in short, monochromatic pulses detectable with 50% probability.
Function of frequency.

Talk by Giovanni Prodi

Based on first 5 months of S5 (Initial LIGO)

$\sim 0.05 \, M_\odot \, c^2$

$\sim 2 \times 10^{-8} \, M_\odot \, c^2$

Virgo cluster

16Mpc

10kpc

Typical Galactic distance

90% Confidence rate [1/year/Mpc$^3$]

PRD 81 (2010) 102001
Adding Models: Core-Collapse Supernovae

- Waveforms not well constrained: variety of morphologies, must use template-less analysis approach
- Core Collapse numerical simulations: $E_{GW}$ up to $10^{-7} M_{\odot}c^2$
- Analytical calculations for extreme models: $E_{GW}$ up to $10^{-2} M_{\odot}c^2$

EXAMPLE

| Model  | $\Delta t$ (ms) | $|h_{+,\text{max}}|$ (10^{-21}) | $h_{\text{char, max}}$ (10^{-21}) | $f(h_{\text{char, max}})$ (Hz) | $E_{GW}$ (10^{-7} M_{\odot}c^2) |
|--------|----------------|-------------------------------|--------------------------------|--------------------------------|---------------------------------|
| s11WW  | 1045           | 1.3                           | 22.8                           | 654                            | 0.16                            |
| s25WW  | 1110           | 50.0                          | 2514.3                         | 937                            | 824.28                          |
| m15b6  | 927.2          | 1.2                           | 19.3                           | 660                            | 0.14                            |

$11 M_{\odot}$ progenitor (s11WW model) $\Rightarrow \sim 0.4$ kpc
$25 M_{\odot}$ progenitor (s25WW model) $\Rightarrow \sim 16$ kpc
Adding Models: Compact Binary Coalescences

- Pairs of black holes, neutron stars, or a black hole and neutron star
- As they orbit one another, they emit gravitational waves causing the objects to get closer, and eventually merge
- Ground-based detectors are sensitive to the last few minutes of inspiral (mass dependent)

*Match filter to templates*

PRD 82 (2010) 102001
PRD 83 (2011) 122005
How Far? How Many?

“Horizon” = Distance at which an optimally oriented inspiral yields SNR=8

Binary coalescence rate in a galaxy follows approximately the star formation rate, or blue light luminosity. \[ L_{10} = 10^{10} L_{\odot,B} \] (Milky Way = 1.7 \[ L_{10} \])

Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1

PRD 82 (2010)102001
Advanced LIGO

Expected Rate of Binaries

Binary neutron star mergers: from ~30 Mpc to ~450 Mpc
Binary black hole mergers: from ~100 Mpc to z=2
Multi-Messenger Astrophysics:
connecting different observations of the same astrophysical event or system

- Gamma-Ray transients (GRBs, SGRs)
- Optical transients
- Neutrino Events
- Radio transients
- X-ray transients
- ...

- Correlation in time and direction, targeted analysis
- Information on source properties
- Increased confidence in detection of gravitational waves

Increasing importance as way to the future...
Electromagnetic Followup of GW Transient Candidates

A detectable GW source must be an extremely energetic event and/or be located relatively close. Expect radiation in EM channels too (optical, X)
Use GW information to point telescopes, SWIFT
Tested in the 2010 run

See: Kanner et al. CQG 25 (2008) 184034 [0803.0312]
The GRB-GW Connection

GRBs are the result of catastrophic events; expect gravitational wave emission from the immediate neighborhood of the GRB central engine.

GW-GRB Probe

- Direct evidence of engine mechanism
- Measure component masses and spins in NS-NS/NS-BH
- Constrain NS equations of state
- Test general relativity in the strong-field regime
- Calibration-free luminosity distance (Hubble expansion, dark energy)

Questions

- Which GW waveform
- Timing of GW burst emission
If Fermi sky coverage and Enhanced LIGO sensitivity $E_{GW} = 0.01 \ M_\odot$, $f_0 = 150$ Hz

$<N_{\text{short}}>$ \approx 1 \times 10^{-4}$ /year

$<N_{\text{long}}>$ \approx 7 \times 10^{-6}$ /year

$<N_{\text{local}}>$ \approx 7 \times 10^{-3}$ /year

Advanced Detectors will be 10 times more sensitive, probe 1000 times larger volume: good probability to observe GRB-GW coincidence.
Absence of a GW signal in LIGO: exclude compact binary coalescence progenitor in M31 with more than 99%CL

Most likely an SGR giant flare in Andromeda

Mazets et al., ApJ 680, 545
Ofek et al., ApJ 681, 1464
Neutron Star Physics

Soft gamma repeater (SGR) flares


Crustal cracking in neutron stars may excite quasi-normal modes which can emit gravitational waves

SGR 1806-20, SGR 1900+14: for certain assumed waveforms, gravitational wave energy limits are as low as few \( \times 10^{45} \) erg, comparable to EM energy in giant flares

Long-lived quasiperiodic GWs after giant flare?

[ PRD 76 (2007) 062003]

SGR 1806-20 hyperflare of December 27, 2004: GW energy limits are comparable to total EM energy emission

Mechanism for pulsar time glitches?

[ PRD 83 (2011) 042001]

Search for ringdown around the August 2006 timing glitch of the Vela pulsar for model selection, limits a few \( \times 10^{45} \) erg
High Energy Neutrinos
\((10^5 - 10^{10} \text{ GeV})\)

No absorption/diffusion: travel cosmological distances
(as opposed to photons - dust, gas, microwave or IR background)

No deflection by magnetic fields: trace back
(as opposed to charged cosmic rays)

weakly interacting: escape from dense objects

Long GRBs, Short GRBs, “Failed GRBs”

Talk by Irene di Palma

Ongoing collaboration with Antares, IceCube

CQG 25, 114039, 2008
arXiv:0807.2567
arXiv:0908.2454
arXiv:1101.4669
Low Energy Neutrinos (1-100 MeV)

Core-collapse supernovae

Joint search would bring greater detection confidence and improved sensitivity

Advanced detectors: could constrain models in galactic neighborhood, most extreme models to Andromeda.

At proposal stage  
arXiv:1002.1511
1. Can numerical relativity help improve how we search for gravitational waves?
2. Once we have a detection, what can we say about the source?

Most progress incorporating models in the analysis so far: Binary Black Hole Coalescences, vacuum solutions - ongoing collaboration with Numerical Relativity community.

CQG 26 (2009) 165008
Matter Effects

- Wide set of phenomena: (NS-NS, NS-BH, SNe, single NS, GRB engine, etc.). Examples of current interests:
  - post-merger oscillation from neutron star coalescences (NS equation of state, tidal disruption effects)
  - EM counterparts to black hole binaries
  - core-collapse supernovae (mechanism, 3D models, numerical vs analytical)

Talk by Alan Weinstein

Circularity of the problem: relativistic astrophysics needs observations to constrain models. Some examples:
Conclusions

1. Initial Detector Era: GW transient searches have placed meaningful constraints on individual objects and events, source populations, total energy density in gravitational waves.

2. Preparing for detection: increasing confidence, increased interaction with modeling and astrophysics community, to maximize science output.

The Advanced Detector era is around the corner!