Multi-messenger Astronomy

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Outline

1. Gravitational Waves, Photons, and Neutrinos
2. Other LSC and Virgo Multi-Messenger Talks at Moriond
3. High and Low Energy Neutrinos
Gravitational Waves, Photons, and Neutrinos

- Initial LIGO has ended, Advanced LIGO will arrive in 2014
- There may be a Virgo - GEO science run in summer of 2011
- Advanced Virgo in 2014; LCGT in 2015
- Numerous photon detectors now and in future (radio, optical, x-ray, gamma)
- High energy neutrinos (ANTARES, Ice Cube)
The Global Network of Gravitational Wave Detectors

- GEO600
  - Germany
- VIRGO
  - Italy
- LIGO
  - Livingston
  - Hanford
- LIGO
  - Australia
- LCGT
  - Japan
Sensitivity of Advanced LIGO

Circular Inspirals: 
\(~20 / \text{year} \) (Kalogera et al. 2006)

Eccentric Encounters: 
\(~\text{several} / \text{year?} \) (O'Leary, Kocsis, Loeb 2008)
**Advanced LIGO**

- Major upgrade of LIGO interferometers
- A factor of $> \times 10$ improvement in strain sensitivity: $> \times 10^3$ in detectable volume
- $<1$ day of AdvLIGO observation $\approx 1$ year of current LIGO observation
- Detect gravitational waves regularly... hope so!
- Installation: planned to start in Oct 2010, Observation: planned to start in 2014

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180 W laser

Seismic isolation

Mirror Suspensions

1/4 1/2
NPRO EOM FI
front-end

high-power
Foraday isolator

output

GR BP

high-power oscillator

PZT HR Mirror

Data Acquisition / Timing
Large Cryogenic Gravitational-wave Telescope

- 3 km
- 400 kW
- 20 K
- 30 kg

Detection Range with SNR=8

for binary inspiral
- Detuned RSE
- Broadband RSE

for BH QNM ringdown
- Detuned RSE
- Broadband RSE

Note: The range is defined for SNR=8, sources at optimal direction.
Open Questions for Multimessenger Observations

- What is the speed of gravitational waves? (subluminal or superluminal?)
- Can gravitational wave detectors provide an early warning to electromagnetic observers? (to allow the detection of early light curves?)
- What is the precise origin of SGR flares? (what is the mechanism for GW and EM emission and how are they correlated?)
- What happens in a core collapse supernova before the light and neutrinos escape?
- Are there electromagnetically hidden populations of GRBs?
- What GRB progenitor models can we confirm or reject?
- Is it possible to construct a competitive Hubble diagram based on gravitational wave standard sirens?
“Multi-messenger astrophysics”: connecting different kinds of observations of the same astrophysical event or system

“Looc-Up” strategy:

GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

“ExtTrig” strategy:

Telescopes, Satellites or other external entities → Flow of trigger information → GW Search
Transient 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 ⇒ Higher sensitivity to GW signals.
✓ More information about the source/engine.
✓ Measurements made possible through coincident detection.
Soft Gamma Repeaters (SGRs)

Highly magnetized ($10^{15}$G) neutron-stars...! Emitting flares sporadically...

Why search for GW?

- Time and direction is known...
- Close-by sources!
- Observed QPOs...
- Some models predict strong GW emission...
- GW sensitivity in $40^{44} - 10^{48}$ erg range...

Exciting Models:

- Highly magnetized neutron-stars
- Emission flares sporadically
- Observed QPOs
- Some models predict strong GW emission
- GW sensitivity in $40^{44} - 10^{48}$ erg range

[2] Corsi & Owen, LIGO-T0900242
  VIR-NOT-ROM-028A-09
Long-lived quasiperiodic GWs after giant flare?
December 2004 giant flare of SGR 1806–20
Searched for GW signals associated with X-ray QPOs
GW energy limits are comparable to total EM energy emission

Are there GW bursts at times of SGR flares?
2004 giant flare plus 188 other flares from SGR 1806–20 and SGR 1900+14 during first calendar year of LIGO S5 run (First search for neutron star $f$-modes ringing down ($\sim$1.5–3 kHz, 100ms), also for arbitrary lower-frequency transients...) For certain assumed waveforms, GW energy limits are as low as $3 \times 10^{45}$ erg, comparable to EM energy emitted in giant flares

Are repeated GW bursts associated with multiple flares?
“Storm” of flares from SGR 1900+14 on 29 March 2006
“Stack” GW signal power around each EM flare. Gives per-burst energy limits an order of magnitude lower than the individual flare analysis for the storm events

Can we see gravitational waves from newly discovered close-by SGRs?
SGR 0501+4516 and SGR 0418+5729 are 5-10x closer than SGR 1806–20 and SGR 1900+14... our GW energy scales as distance$^2$... stay tuned!

Abbott et al., PRD 76, 062003 (2007)
Abbott et al., LIGO-P0900192 TBS(ApJL)
PRD, 80, 042001, 2009
CQG, 24, 659, 2007
GRB 070201 – Sky Location

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

$D_{\text{M31}} \approx 770 \text{ kpc}$

Possible progenitors for short GRBs:

- NS/NS or NS/BH mergers
  Emits strong gravitational waves
- SGR
  May emit GW but weaker

$E_{\text{iso}} \sim 10^{45} \text{ ergs}$
if at M31 distance

IPN 3-sigma error region [Mazets et al., ApJ 680, 545]
These coincidences do happen from time to time… the 070201 result created a new trend…

**GRB 051103**

Sky position error box overlaps with

**M81 group**

~3.6 Mpc

**Discovery of the second extragalactic SGR…?**

(Hurley et al. 2010)

*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.*
Search for Gamma-Ray Bursts during S5/VSR1

Lower Limits on Source distances

Short Transients

Q=8.9, sine-gaussians
f=150Hz, \( E_{GW}L_{0.01} M_A \)

Histogram of lower limits on source distances
- 137 GRBs in the X-Pipeline analysis
- derived from upper limits on GW energy

\[ E_{GW} \approx \frac{\pi^2 C^3}{G} D^2 f^2 h_{\text{rss}}^2 \]

1438, arXiv:0908.3824

PRD, 77, 062004, 2008
PRD, 72, 042002, 2005
CQG, 26, 204017, 2009
CQG, 21, 1831, 2004
CQG, 21, 765, 2004
AIPC, 836, 605, 2006
Electromagnetic Follow-Ups to GW Triggers

- Analyze GW data promptly to identify possible event candidates and reconstruct their apparent sky positions; alert telescopes
  - Try to capture an EM transient that would otherwise have been missed!
  - Pioneering study with Columbia MDM!
  - Full blown observations are underway...

...and many other telescopes...
Other LSC and Virgo Multi-Messenger Talks at Moriond

- Searching for EM counterparts of gravitational-wave transients
  Marica Branchesi

- Searching for gravitational waves associated with gamma-ray bursts using the LIGO/Virgo network
  Michal Was

- Search for long duration gravitational wave transients using STAMP
  Shivaraj Kandhasamy
The first program of EM follow-up to GW candidates has been performed during last LIGO/Virgo observing runs.

Candidate GW triggers have been used in real time to obtain EM observations.

The talk “Searching for Electromagnetic Counterparts of Gravitational-Wave Transients” (M. Branchesi) describes:

- the strategy for the low-latency EM follow-up
- the EM telescopes involved in the project
- the development of image analysis procedures able to identify the EM counterparts in images taken with wide field optical telescope.
Example: GW associated with GRBs
See talk by Michal Was

- Gamma-ray burst detection by satellites, mainly: Swift, Fermi, ...
  - Known position and time
- 2 astrophysical models: 2 complementary searches
  - Short GRBs and binary coalescence
  - Long GRBs and hypernova
- Gain in sensitivity compared to blind search $\sim 2$
- Even null results are astrophysically relevant
Long duration GW transients

- Traditional GW searches look for signals which are either short ($\lesssim$ sec) or persistent long term signals.
- GWs with time scales of $\sim$ secs - weeks left unexplored.
- There are models that predict GWs of these time scales.
  - Protoneutron star (PNS) convection
  - Merger phase highly eccentric binaries
High Energy Neutrino (HEN) Detectors

- IceCube and ANTARES (complementary directional sensitivity)
- Cherenkov detectors observing HENs through secondary muons
- IceCube (22 strings), ANTARES (5 strings) during S5/VSR1
- There is an active GW-HEN working group (>20 person), which is a joint project between the LSC, Virgo, ANTARES, and IceCube.
Some GW+HEN source candidates

**Short GRBs:** HENs can also be emitted during binary mergers (Nakar 2007; Bloom et al. 2007; Lee & Ramirez-Ruiz 2007).

**Low-Luminosity GRBs:** Associated with particularly energetic population of core-collapse supernovae (Murase et al. 2006; Gupta & Zhang 2007; Wang et al. 2007). Local event rate can be significantly larger than that of conventional long GRBs (Liang et al. 2007; Soderberg et al. 2006).

**“Choked” GRBs:** Plausibly from baryon-rich jets. Optically thick, can be hidden from conventional astronomy, neutrinos and GWs might be able to reveal their properties (Ando & Beacom 2005), Razzaque et al. 2004; Horiuchi & Ando 2008).

**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).
Event candidate position reconstruction example: LIGO+Virgo vs. IceCube

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

LIGO + Virgo + IceCube:
- IceCube-Virgo-LIGO MoU
  May 5, 2010

\[ \text{False Alarm Rate} = \frac{1}{600} \left( \frac{p}{1\%} \right) \left( \frac{T_w}{1\text{sec}} \right) \left( \frac{R_{gw}}{1/\text{day}} \right) \left( \frac{R_{\nu}}{20/\text{day}} \right) \text{per year} \]
ANALYSIS PIPELINE READY (ICECUBE)

**GALAXY CATALOG**

Distribution weighted with signal probability (BL/r^2)

**NEUTRINO**

Energy, directional uncertainty PDF ≤ 1°

**GRAVITATIONAL WAVE**

Skymap and Significance

**JOINT TEST STATISTIC**

Joint test statistic
Status and Next Steps for IceCube Study

- Data received from IceCube (1000’s of neutrinos, but time scrambled)
- Full data when ready for a full *un-blind* study
- Monte Carlo simulation results are encouraging
- Observation paper by the end of 2011 (interesting science!)
X-Pipeline search (ANTARES)

- Same procedure as bursts GRB search:
  - Each neutrino trigger is processed independently of the others.
  - The data is divided on-source ([−496, +496] s around each neutrino trigger) and off-source (all other data within +/- 1.5 hr of the neutrino + time slides) [arXiv:1101.4669].
  - The on-source data is searched coherently for large-energy events.
  - Event significance estimated by comparing to the off-source data.
  - Detection / upper limit for each neutrino trigger.

GW detector data

- Time of neutrino
  - On-source time searched for GW from neutrino
  - Off-source time used to estimate noise background

https://trac.ligo.caltech.edu/xpipeline/wiki/Documentation
Status and Next Steps for the Joint Study with ANTARES

- A list of neutrino candidates produced for the S5/VSR1–5 line data set including time, direction and uncertainties
- This list is being processed with the same analysis procedure used for GRB searches
- Sanity checks are being performed, and final results to come in 2011.
Low Energy Neutrinos and Gravitational Waves

- A multi-messenger partner to GWs for core collapse supernovae
- LSC and Virgo are developing search methods especially for the advanced detectors
- For a range of 5 Mpc the supernovae rate becomes about 1/year
- 5 Mpc is on the outside edge of the aLIGO and Super-K ranges, but a weak coincident signal in both may be convincing (especially if there were also an optical signal)
- For a galactic supernova, the neutrino signal will be large, and one would do a standard external trigger search (GRB search) with a tight coincidence window
Core-collapse supernovae

- **Classic multi-messenger astronomical events:**
  - Neutrinos (prompt, 10s of MeV, 3 flavors)
  - Electromagnetic (delayed)
  - Gravitational Waves (prompt)

- **Optical (EM) signature:**
  - may be obscured (e.g., SN 2008iz in M82 missed in optical)
  - unable to determine time of bounce to better than \( \sim \) day

- **Only neutrinos and GWs directly probe physics of core collapse**
  - Signatures separated by \(<\) seconds
  - A tight coincidence window can be used to establish a correlation
  - Sensitivity range of current GW and neutrino detectors similar

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Low-energy neutrinos from CC SNe

- CCSN produces 10-20 MeV neutrinos (all flavors) over a few 10s of seconds
  - The onset can be determined to < 1 s
- Super-K would detect \( \sim 10^4 \) neutrinos at the galactic center
  - \( \sim 1 \) at distance of Andromeda
- Direction determined by \( \nu + e \rightarrow \nu + e \)
  - Few % of total rate
  - Direction from galactic SN determined by Super-K
## Summary of supernova neutrino detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kton)</th>
<th>Location</th>
<th>Events at 8.5 kpc</th>
<th>Status</th>
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<tr>
<td>Super-K</td>
<td>Water</td>
<td>32</td>
<td>Japan</td>
<td>7000</td>
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<td>Scintillator</td>
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<td>AMANDA/IceCube</td>
<td>Long string</td>
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<td>CLEAN</td>
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<td>Canada, USA?</td>
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<tr>
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</table>
Summary

- There is an active effort by LIGO and Virgo to find gravitational waves in coincidence with electromagnetic or neutrino counterparts.
- Advanced Virgo, aLIGO, and GEO-HF are coming soon.
- LCGT has received substantial funding.
- The fruitful era of multimessenger astronomy is upon us!