Electromagnetic Counterparts to LIGO-VIRGO Events
Expanded Very Large Array Observations

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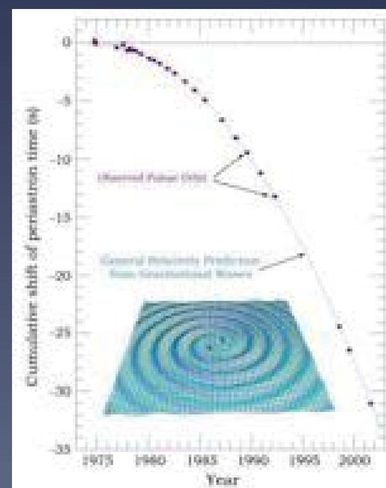
EM (Radio) Counterparts to GW Events

* GW Events: Why radio observations?
* LIGO-VIRGO run and the EVLA
* Results
  … lessons learned and future prospects

Gravitational Wave Astronomy

$g_{\mu\nu} = g_{\mu\nu}^{(B)} + h_{\mu\nu}$

- Probe of strong gravity and “gravitational window” on the Universe
  - Potentially akin to opening a new spectral window in the electromagnetic spectrum
- Existence inferred from radio timing observations of pulsars in neutron star-neutron star binaries
- Direct detection and study recognized as exciting new frontier
  - “Can we observe strong gravity in action?” (European AstroNet)
  - GW Astronomy is a “science frontier discovery area” (U.S. *New Worlds, New Horizons* Decadal Survey)



GW Astronomy and the Time Domain

$L_0 = 2.03 \times 10^5\, c^2\, M_\odot\, s^{-1}$

- Generation of GWs requires large masses, high velocities, or both
- Potential sources include
  - Mergers
    - Neutron star-neutron star, neutron star-black hole, black hole-black hole
  - Supernovae
  - Cosmic strings
  - …

Why EM? Why Radio?

- Electromagnetic counterparts: More complete understanding of GW event
  - Nature of progenitor
  - Environment
  - …
  - Confirmation
- Radio wavelength counterparts
  - Non-thermal (high-energy) particle emission
  - Precision astrometry
  - Unaffected by dust obscuration
  - Observe during daytime

Radio Wavelength Observations

- Explosive Events

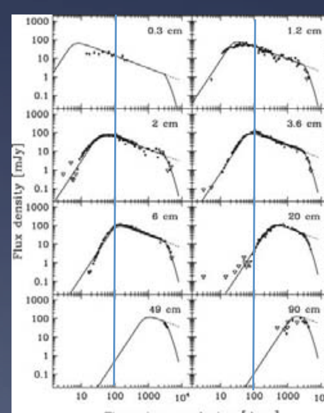
  E.g., expanding synchrotron fireball, radio emission from blast wave impacting surrounding medium and accelerating particles

  - Radio supernovae, gamma-ray bursts, …
  - "Clean" environments likely to be faint? (BH-BH merger?)

- Relativistic Jets

  Magnetically collimated relativistic plasma

  X-ray binaries, AGN, tidal disruption events



(Radio supernovae, Weiler et al.)

Jet from tidally disrupted star, Zauderer et al.)

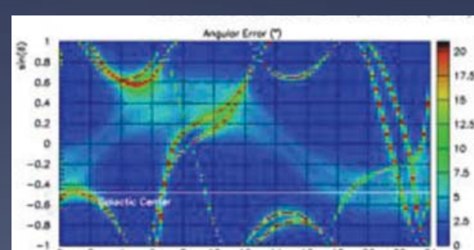
LIGO-Virgo Observations

- LIGO-Virgo joint observations during 2010 Q3 & Q4
  2010 October for this result
- 3-element interferometer
  - LIGO internal ~ 3000 km
  - LIGO-Virgo ~ 8000 km

LIGO-Hanford, WA, USA | LIGO-Livingston, LA, USA | Virgo, Pisa, IT

LIGO-Virgo Analysis

- Time differences of signal arrival between different detectors
  - E.g., 1 ms rms uncertainties in arrival times
  - Median error ~ 1.5°
  - Uncertainty regions ~ 10 deg^2 (90% confidence)
- *A priori* information!
  - 40 Mpc range for reasonable signal-to-noise ratio
  - Assume GW event "close" to a galaxy
  - Fold in star formation rate of galaxies
- ~ 3 galaxies meet all selection criteria



(Cavalier et al. 2006)

Expanded Very Large Array

- Major upgrade of the world's most flexible, sensitive, and capable synthesis array
  - Significant leveraging of an existing (a.k.a. "paid for") and operating telescope
- Top-level goal: Order-of-magnitude improvements in all observational capabilities, except resolution
  - Complete frequency coverage from 1 to 50 GHz (0.7 to 30 cm)
  - 1-hour, rms continuum point-source sensitivity of 3 μJy
  - New correlator of unprecedented flexibility to enable matching resources to scientific goals
- Status
  - All antennas modified
  - Four receiver bands fully available: C, K, Ka, Q; remaining four bands (L, S, X, Ku) completed by late 2012
  - Correlator fully installed, still undergoing commissioning
  - Science programs now well established
    - Started March 2010, with turning on of new correlator
- 2011 September 20 ApJL Special Edition
  - 37 early science papers
    - Largest in ApJL history

Radio Observations of GW Events Considerations

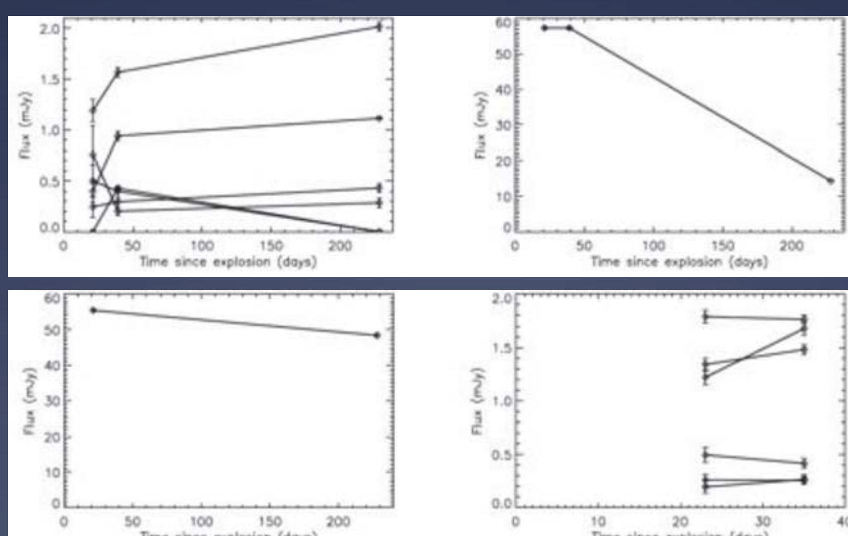
- Field of View
  - Ideal: Size of LIGO-Virgo uncertainty region
  - Minimum: Size of typical galaxy target (10 kpc @ 40 Mpc ~ 1′)
- Angular resolution/localization
  - Sub-arcsecond (< 1 kpc @ 40 Mpc)
- Wavelength/Frequency
  - Short wavelength/high frequency
    - \+ Better localization, better tuned to physics(?)
    - − Smaller FoV
  - Long wavelength/lower frequency
    - \+ Larger FoV
    - − Poorer localization, not well-matched to physics(?)

EVLA FoV, detected sources on DSS image

EVLA Followup of LIGO-Virgo GW Events

- 2010 October observations
- EVLA C configuration
- 5 GHz / λ 6cm
  - ~ 4" angular resolution, ~ 0.4" localization for s-to-n ratio of 5
- 2 LIGO-Virgo triggers observed
  - 6 galaxies initially, later trimmed to 5 as one target galaxy found to be more distant than 40 Mpc

EVLA Light Curves



Future Prospects

- Radio wavelengths integral part of GW followup and study, but …
- New approach likely needed
  - Advanced LIGO sensitivity means more distant galaxies, *large* number of targets
  - Larger field of view radio telescopes, but at lower frequencies / longer wavelengths
  - FoV ~ 10 deg^2 at 10 GHz / 3 cm would be useful