Synergies between radio and gravitational wave observations

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Gravitational waves

- Gravitational waves
  - Simple consequence of General Relativity
  - Transverse space time perturbations
  - Travel at speed of light
  - Produced by accelerated mass

![Basic optical layout of a GW detector](image_url)

- Laser: $17 \text{ W}$
- Power recycling mirror: $500 \text{ W}$
- Resonant cavity: $10 \text{ kW}$
- Beam splitter 3 km
- Photo detector
- Mirrors $L_x$ $L_y$

Michał Wąs (G1400114)
GW same everywhere but propagation delayed
⇒ Reject spurious non-Gaussian glitches
3 omnidirectional detectors
→ sky localization by triangulation
A network of detectors – 2009/2010

Most sensitive for GW in [50, 500] Hz band

(Abadie et al., 2012b)
What have we not seen?

two examples
Results - binary coalescence

- Search for coalescence of binary neutron star and/or black hole (Abadie et al., 2012a)
- 2005-2010 upper limits 2 orders of magnitude above expectation
- advanced detectors $\rightarrow \times 10^3$ increase in sensitive volume
- $40 \text{yr}^{-1}$ detections expected (Abadie et al., 2010)
  - Large uncertainties on astrophysical predictions: $0.4 - 400 \text{yr}^{-1}$
  - Based on binary pulsars observation / population synthesis
Results - isolated neutron stars

- Young pulsars (neutron stars)
  - Crab (SN 1054)
  - Vela (SN $\sim 10^4$ yr ago)
  - ...

spin frequency is precisely observed in radio

- The rotation period is decreasing
  $\rightarrow$ loss of rotational energy

- less than 1% of Crab energy loss is due to GW emission (Aasi et al., 2013a)

- less than 10% of Vela energy loss is due to GW emission (Aasi et al., 2013a)

- Without any radio observation the limits on energy loss higher by $\sim 10^2 - 10^3$ (Abadie et al., 2011)

$\Rightarrow$ EM observation enhance GW searches sensitivity
Network of “Advanced” detectors

- 3 Advanced LIGO / Advanced Virgo → 2015
- factor $\sim 10$ improvement in sensitivity
- factor $\sim 10^3$ improvement in volume within reach
- Reaching design sensitivity will take a few years
- KAGRA construction underway → 5 detectors $\sim 2020$
A fourth detector site helps with sky localization

- Sky localization error regions: hundreds of deg$^2 \rightarrow$ tens of deg$^2$
- Third Advanced LIGO detector planned in India 2020-2022

(Aasi et al., 2013b)
Why EM counterparts?

- Observe lower amplitude GW events
- Additional information on astrophysical event
- **Requirement for transients:**
  - EM counterpart false alarm rate needs to be low
  - $\Delta T$ – coincidence time window
  - $100 \text{ deg}^2$ – GW sky localization error

\[
\text{rate} \times \Delta T \times \frac{100 \text{ deg}^2}{40000 \text{ deg}^2} < 1
\]

⇒ Probability that there is one false transient per GW trigger
Main case scenario: neutron star merger

- Expected progenitor of short hard gamma ray bursts
- Involves a relativistic jet
- Advanced detectors range: \( \sim 200 \text{ Mpc} \)
- Three potential radio counterparts:
  - Prompt signal, seconds–minutes
  - On-axis afterglow, \( \sim \) day, jet pointing at Earth
  - Off-axis afterglow, \( \sim \) year, jet becomes non-relativistic

(From Metzger and Berger, 2012)
Prompt signal, seconds–minutes

- Several highly speculative scenarios (merger at 200 Mpc):
  - Gravitationally excited MHD waves (Moortgat and Kuijpers, 2005)
    - 50 MJy at 30 MHz
  - Rotational energy of post-merger object (Pschirkov and Postnov, 2010)
    - 10 kJy at 100 MHz
  - Emission from PSR-like magnetosphere (Hansen and Lyutikov, 2001)
    - 1 mJy at 400 MHz
  - Order of magnitude: $10^{-6}$ of short GRB flux
    - $10^{-6}$ erg cm$^{-2}$ for 0.1 s $\rightarrow$ 1 kJy at 1 GHz

- Radio delayed by propagation:
  - DM=$10^3$ pc cm$^{-3}$ $\rightarrow$ 13 min at 75 MHz
  - GW trigger could be available with $\sim$ 1 minute latency
    $\rightarrow$ pointing information for LOFAR

- Background
  - Fast Radio Bursts (Thornton, 2013), rate = $0.2$ day$^{-1}$ deg$^{-2}$ at 3 Jy and 1.4 GHz
  - If $\Delta T = 13$ min, limiting coincidence rate is $1$ day$^{-1}$ deg$^{-2}$
    $\Rightarrow$ need lower $\Delta T$ or higher radio flux threshold
  - What is the transient sky at 100 MHz?
On-axis afterglow, $\sim$ day

- Observed for at least two short GRBs (050721 and 051221)
- correspond to 10 mJy at 1-10 GHz
- $\sim$ 1 day delay and transient duration
- $\Delta T = 1$ day $\rightarrow$ limiting rate $\sim 3$ yr$^{-1}$deg$^{-2}$ $\Rightarrow$ problematic
Off-axis afterglow, \( \sim \) year

- Delay of \( \sim 1 \) year, produce by jet after slow-down to sub-relativistic
  - 0.3 mJy at 1 GHz \( \Rightarrow \) \( \sim \) same as background from SFR
- lower flux, larger time window than on-axis
  - require better sky localization of source by other EM observations?
  - Can afterglows be distinguished from other transients (AGN, ...)?

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{(Metzger and Berger, 2012)}
\end{figure}
Practical aspects: GW trigger dissemination

- Initially
  - GW triggers shared with LIGO/Virgo partners (few minutes latency)
  - Open call for MOU agreements with LIGO and Virgo for EM follow up
  - Relevant for observations in 2015-2017
  - Deadline: February 16 (repeats every year)

- After 4 published GW detections
  - GW triggers available publicly with low-latency (GCN style)
Case scenario 2: pulsar discoveries

- Candidates for GW detection (continuous emission or glitches)
  - Vela, Crab, ...
- Millisecond pulsars
  - clocks for observation of very low frequency (nHz) GWs
  - pulsar timing arrays
Conclusion

- Advanced LIGO/Virgo expect to observe dozens of neutron star mergers per year, in (2015) 2020
- There is potential bright radio prompt emission
  - LOFAR could be pointed to catch the rise time
- GW detector have poor $\left(10 - 100 \text{ deg}^2\right)$ sky localization for transients
  - Prompt and afterglow observation limited by other transients in error region
  - Off-axis afterglow observation unlikely
- A detailed study of the prospects is needed
- Pulsar detection/observation, both GW sources and parts of detector
References


Abadie, J. et al. (2010). Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors. Class. Quantum Grav., 27:173001.


