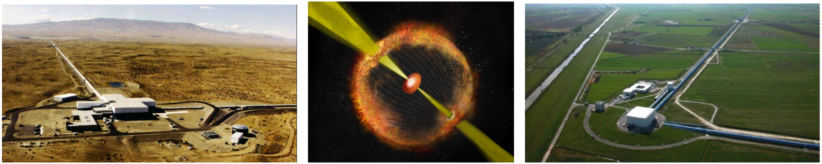
Synergies between radio and gravitational wave observations

Michał Wąs
for the LIGO Scientific Collaboration and the Virgo collaboration

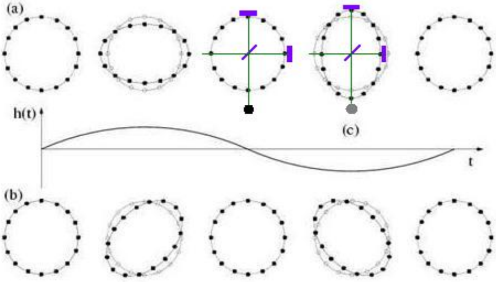
Journées radio SKA-LOFAR

Laboratoire d'Annecy-le-Vieux de Physique des Particules

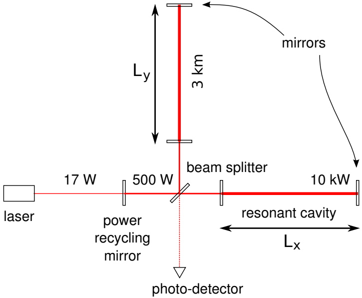


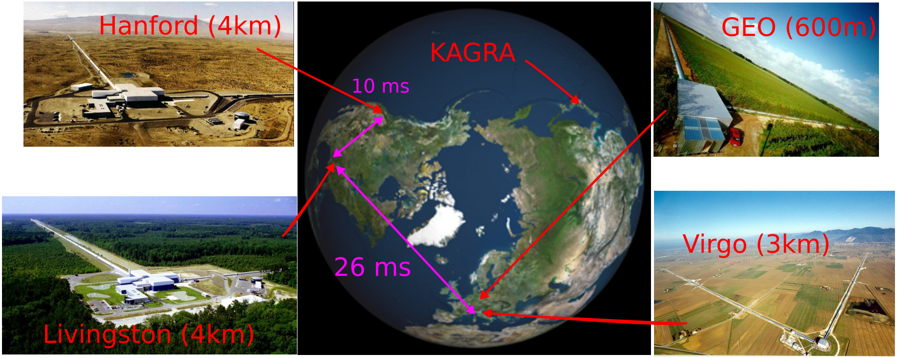
Gravitational waves

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

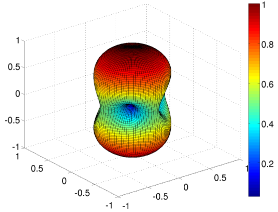


basic optical layout of a GW detector



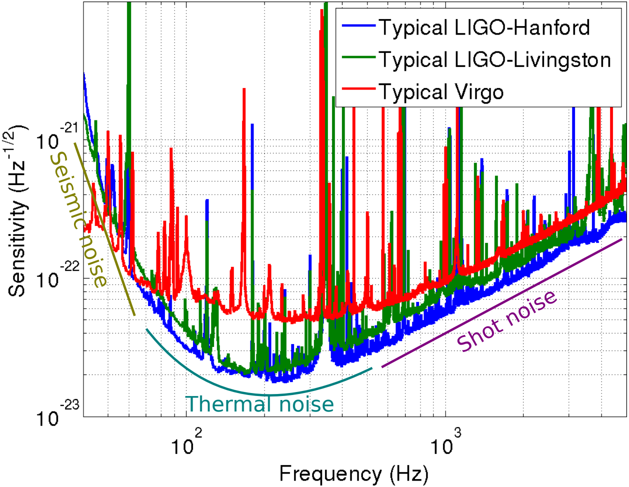


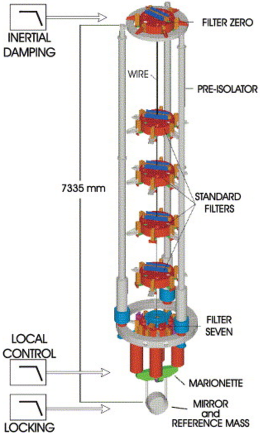
- GW same everywhere but propagation delayed
  ⇒ Reject spurious non-Gaussian glitches
- 3 omnidirectional detectors
  → sky localization by triangulation



antenna response

A network of detectors – 2009/2010





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

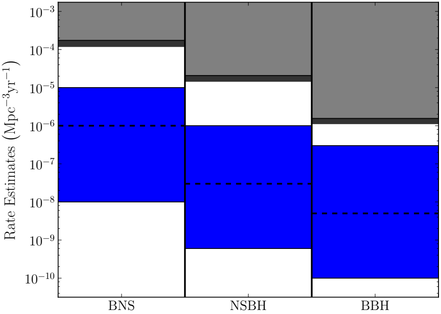
(Abadie et al., 2012b)

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
  → $\times 10^3$ increase in sensitive volume



- $40\,\mathrm{yr}^{-1}$ detections expected (Abadie et al., 2010)
  - Large uncertainties on astrophysical predictions: $0.4 - 400\,\mathrm{yr}^{-1}$
  - Based on binary pulsars observation / population synthesis

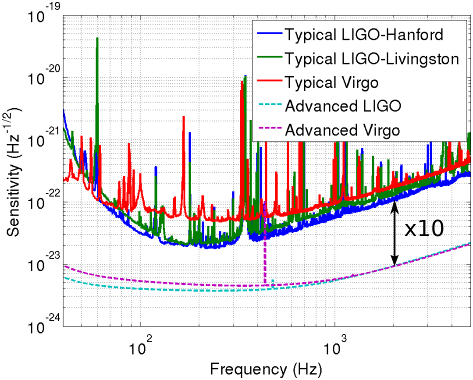
Results - isolated neutron stars

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

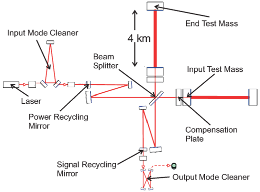
  spin frequency is precisely observed in radio
- The rotation period is decreasing
  $\rightarrow$ loss of rotational energy
- less than 1% of Crab energy loss is due to GW emission (Aasi et al., 2013a)
- less than 10% of Vela energy loss is due to GW emission (Aasi et al., 2013a)
- Without any radio observation the limits on energy loss higher by $\sim 10^2 - 10^3$ (Abadie et al., 2011)

$\Rightarrow$ EM observation enhance GW searches sensitivity

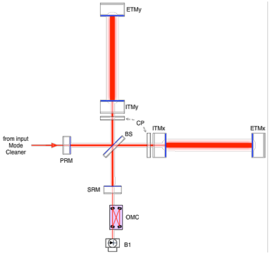
Network of “Advanced” detectors



Advanced LIGO



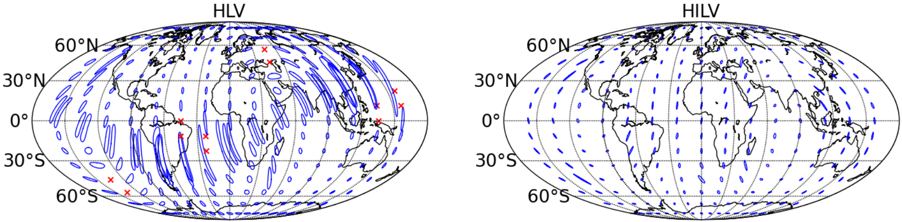
Advanced Virgo



- 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 $\gtrsim$ 2020

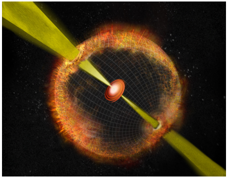
A fourth detector site helps with sky localization



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

(Aasi et al., 2013b)

Why EM counterparts?

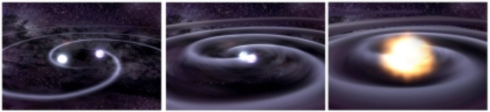


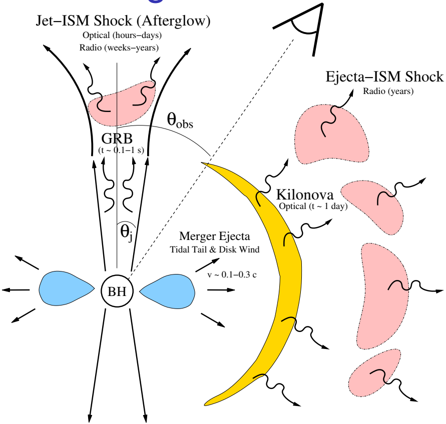
- Observe lower amplitude GW events
- Additional information on astrophysical event
- Requirement for transients:
  - EM counterpart false alarm rate needs to be low
  - ΔT – coincidence time window
  - $100\,\mathrm{deg}^2$ – GW sky localization error

$$\text{rate} \times \Delta T \times \frac{100\,\mathrm{deg}^2}{40000\,\mathrm{deg}^2} < 1$$

$\Rightarrow$ Probability that there is one false transient per GW trigger

Main case scenario: neutron star merger





(Metzger and Berger, 2012)

- Expected progenitor of short hard gamma ray bursts
- Involves a relativistic jet
- Advanced detectors range: $\sim 200\,\mathrm{Mpc}$
- 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

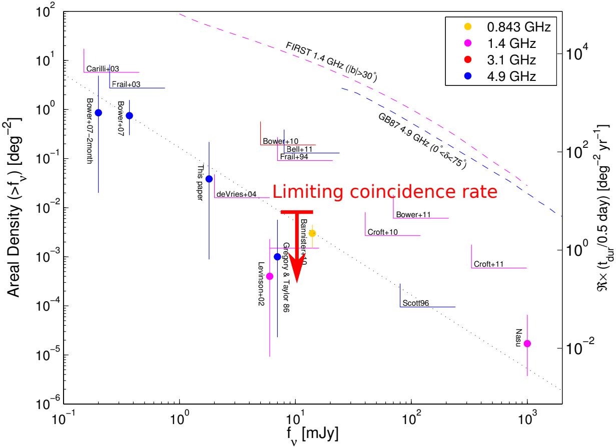
Prompt signal, seconds–minutes

- 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 → 1 kJy at 1 GHz
- Radio delayed by propagation:
  - DM=10^3 pc cm^{-3} → 13 min at 75 MHz
  - GW trigger could be available with ∼ 1 minute latency → 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}

  ⇒ need lower ΔT 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 $\sim 3\,\mathrm{yr}^{-1}\mathrm{deg}^{-2}$ $\Rightarrow$ problematic



Off-axis afterglow, ∼ year

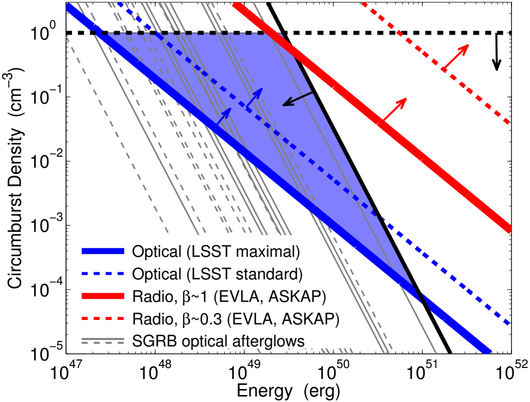
- Delay of ∼ 1 year, produce by jet after slow-down to sub-relativistic

→ 0.3 mJy at 1 GHz ⇒ ∼ 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, ...)?



(Metzger and Berger, 2012)

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
  - http://www.ligo.org/science/GWEMalerts.php
  - Deadline: February 16 (repeats every year)

IDENTIFICATION AND FOLLOW UP OF ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE CANDIDATE EVENTS

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration currently plan to start taking data in 2015, and we expect the sensitivity of the network to improve over time. Gravitational-wave transient candidates will be identified promptly upon acquisition of the data; we aim for distributing information with an initial latency of a few tens of minutes initially, possibly improving later. The LSC and the Virgo Collaboration (LVC) wish to enable multi-messenger observations of astrophysical events by GW detectors along with a wide range of telescopes and instruments of mainstream astronomy.

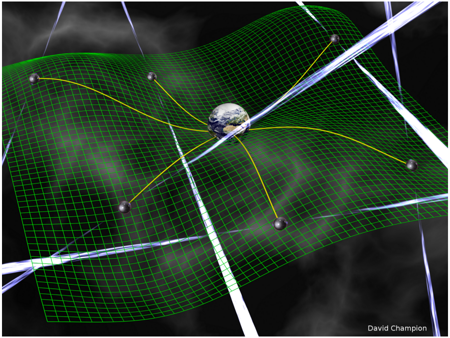
In 2012, the LVC approved a statement (LSC, Virgo) that broadly outlines LVC policy on releasing GW triggers (partially-validated event candidates). Initially, triggers will be shared promptly only with astronomy partners who have signed an Memorandum of Understanding (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting. After four GW events have been published, further event candidates with high confidence will be shared immediately with the entire astronomy community (and the public), while lower-significance candidates will continue to be shared promptly only with partners who have signed a MoU.

Devour thy Neighbor: An artist's illustration of two neutron stars close to merger look misshaped, becoming more oblong the closer they get to one another. A black hole is then formed and gamma rays shoot out as a GRB. (Credit: NASA/Swift)

- After 4 published GW detections
  - GW triggers available publicly with low-latency (GCN style)

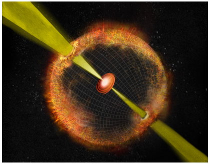
Case scenario 2: pulsar discoveries

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


David Champion

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 ($10 - 100\,\mathrm{deg}^2$) 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

Aasi, J. et al. (2013a). Gravitational waves from known pulsars: results from the initial detector era. arXiv:1309.4027.

Aasi, J. et al. (2013b). Prospects for localization of gravitational wave transients by the Advanced LIGO and Advanced Virgo observatories. arXiv:1304.0670.

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.

Abadie, J. et al. (2011). All-sky search for periodic gravitational waves in the full S5 LIGO data. *Astrophys. J.*, 737:93.

Abadie, J. et al. (2012a). Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3. *Phys. Rev. D*, 85:082002.

Abadie, J. et al. (2012b). Sensitivity achieved by the LIGO and Virgo gravitational wave detectors during LIGO's sixth and Virgo's second and third science runs. LIGO-T1100338. arXiv:1203.2674.

Hansen, B. M. S. and Lyutikov, M. (2001). Radio and x-ray signatures of merging neutron stars. *Mon. Not. Roy. Astron. Soc.*, page 695.

Metzger, B. D. and Berger, E. (2012). What is the most promising electromagnetic counterpart of a neutron star binary merger? *Astrophys. J.*, 746:48.

Moortgat, J. and Kuijpers, J. (2005). Indirect visibility of gravitational waves in magnetohydrodynamic plasmas. In Chen, P., Bloom, E., Madejski, G., and Patrosian, V., editors, *Proceedings of the 22nd Texas Symposium on Relativistic Astrophysics*, page 326.

Pschirkov, M. S. and Postnov, K. A. (2010). Radio precursors to neutron star binary mergings. *Astrophys. Space Sci.*, 330:13.

Thornton, D. (2013). A population of fast radio bursts at cosmological distances. *Science*, 341:53.