What advanced detectors will be able to do

Moriond 2015

Andrea Viceré

Università degli Studi di Urbino "Carlo Bo" & INFN Firenze

On behalf of LSC and Virgo Collaborations

LIGO-G1500392  VIR-0124A-15
ADVANCED DETECTORS

- Starting the GW astronomy requires increasing dramatically the number of observable galaxies
- We have the technology to expand substantially the observable universe. A “second generation” network is being realized
- Aim: tenfold sensitivity increase
- Target: $\sim 10^5$ galaxies
SENSITIVITY GOAL(s)

- Advanced detectors are tuneable for different sources
- Typical benchmarks include BNS and 10+10 BBH
**Reasonable guess, on the basis of current detectors’ status**

- Note that Virgo lags behind LIGO by about 1.5 – 2 yrs

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NETWORK

LIGO – WA (2015)

GEO600 - D

KAGRA – J (2018)


Virgo – I (2016)

LIGO – India (> 2020)
# Plausible run schedule

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>( E_{GW} = 10^{-2}M_\odot c^2 )</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg (^2)</th>
<th>20 deg (^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Burst Range (Mpc)</td>
<td>LIGO</td>
<td>Virgo</td>
<td>LIGO</td>
<td>Virgo</td>
</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>–</td>
<td></td>
<td>40 – 80</td>
<td>–</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>20 – 40</td>
<td></td>
<td>80 – 120</td>
<td>20 – 60</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>40 – 50</td>
<td></td>
<td>120 – 170</td>
<td>60 – 85</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>40 – 80</td>
<td></td>
<td>200</td>
<td>65 – 130</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>80</td>
<td></td>
<td>200</td>
<td>130</td>
</tr>
</tbody>
</table>

  *Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories*

- Official information about prospective observation schedules and associated sensitivities

- A live document: to be updated as our understanding progresses
Will we make it? Good progress so far

https://LIGO-G1401390/publicdcc.ligo.org
AdV and aLIGO science in one slide

- Range for BNS or BBH expanded by 10 → rate by 1000
- Amplitude sensitivity improved by 10 → same factor improvement of UL (or detection) of signals from galactic distorted NS: allow to probe ellipticities down to ~ 10^{-9}
- Detection of impulsive events in our Galaxy with energies as small as 10^{-9} M_\odot c^2 → possible detection of next supernova
- Limits on stochastic background, for instance on \Omega_{GW}, improved by a factor ~ 10^4
- Localization of BNS events improved as sensitivity progresses and all detectors come on line: from only 2% of the events localized within 5 deg^2, up to about 20% (and about 50% within 20 deg^2)
- But it will take time: please be patient!
BNS: distance scale

- Phasing of the signal $\rightarrow$ (red-shifted) masses, spins $\rightarrow$ expected amplitude, as a function of distance $D$
- Reconstruction of the signal from a detectors’ network $\rightarrow$ measured amplitude
- **Direct measurement of distance $D$** [standard sirens]
Independent measurement of Hubble constant

Possible even without EM counterpart, by catalogue based host galaxy identification

W. Del Pozzo, JPCS 484 (2012) 012030
BNS: NS equation of state

- “Soft” EOS: prompt collapse to a black hole

- “Hard” EOS: unstable bar mode, eventually black hole

W. Del Pozzo et al, PRL 111 (2013) 071101
Lackey and Wade, PRD 91 (2015) 043002

Interesting info already from 2° generation detectors
The BNS - GRB connection

- Short GRB result from coalescences?
- If yes, tight coincidences of GW and EM signals should be found

Short gamma-ray burst (<2 seconds’ duration)

- Eventually colliding.
- The resulting torus has at its center a powerful black hole.
- Possibly neutron stars.

As BH is formed: direct GR test

- The BH resulting from a coalescence is in an excited state, ringing at its Quasi Normal Modes.

- The resulting signal is a superposition of damped sinusoids.

- In GR, frequency and damping time of the modes are related, as a consequence of BH uniqueness: mass and spin uniquely determine BH dynamics.

- Allow direct check of GR consistency.
Statistics? **Realistic** BNS rates

- Initial detectors: 20 Mpc inspiral range. One event/50 years
- Advanced detectors: 200 Mpc range (aLIGO at its best). **40 ev/yr!**

### Table 5. Detection rates for compact binary coalescence sources.

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source</th>
<th>$\dot{N}_{\text{low}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{re}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{high}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{max}}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>NS–NS</td>
<td>$2 \times 10^{-4}$</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>NS–BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>&lt;0.001$^b$</td>
<td></td>
<td>0.01$^e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMBH–IMBH</td>
<td>$10^{-4}$</td>
<td></td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>NS–NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>NS–BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>0.4</td>
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<td>$10^b$</td>
<td></td>
<td>300$^e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMBH–IMBH</td>
<td>0.1$^d$</td>
<td></td>
<td></td>
<td>1$^e$</td>
</tr>
</tbody>
</table>
Supernovae

- Core collapse: dynamics, waveform hard to predict
  - Rate: several /yr in Virgo cluster, about 1/century in the Milky Way
  - Efficiency of GW emission strongly model dependent: today, theorists incline towards the range $E_{GW} \sim 10^{-11} - 10^{-7} M_\odot c^2$
Supernovae in ADE

- For unmodeled signals, typical measure of sensitivity is the root mean square signal
  \[ h_{rss} = \sqrt{\int |h_+(t)|^2 + |h_\times(t)|^2 \, dt}. \]

- Advanced detectors will probe \( h_{rss} \sim 10^{-23} \text{ Hz}^{-1/2} \)

- Translating in \( E_{GW} \) is distance and model dependent: if signal close to sweet spot of the detector, \( E_{GW} \sim 10^{-9} M_\odot c^2 \) at 10 kpc

- Advanced detectors should detect the GW signal from the next galactic supernovae, if models aren’t too optimistic, and if detectors are online (yes, we need luck…).

- Will place interesting UL on supernovae in the local group, out to a few Mpc.
Supernovae and $\nu$ mass

- Expect GW and $\nu$ within a few ms delay
- Constrain $m_\nu$ strongly

\[ \delta t_{prop} = 5.2\text{ms} \frac{d}{10\text{kpc}} \left( \frac{m_\nu}{1\text{eV}} \right)^2 \left( \frac{10\text{MeV}}{E_\nu} \right)^2 \]

Arnaud et al., PRD 65 (2002) 033010
The Long GRB connection

- *Hypernova* model proposed for explaining long GRB events

- Again, modeling is difficult; both the scale of \( E_{GW} \) and its frequency distribution are quite uncertain

- For **optimistic** signal models, Advanced detectors will detect GW events coincident with long GRBs out to about 300 Mpc; a distance at which such events are not infrequent (a few / year).

LSC & Virgo, *PRD 88 (2013) 122004*
Cosmological stochastic background...

- In initial LIGO/Virgo
  \[ \Omega_0 < 6.9 \times 10^{-6} \]

- In ADE
  \[ \Omega_0 < 10^{-9} \rightarrow 10^{-10} \]

- Why? In principle
  \( \Omega \) results from a cross-correlation:
  10x lower noise \( \rightarrow \)
  100x better limit

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LIGO–Virgo, PRL 113 (2014) 231101

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... thanks to bandwidth

- Factor $10^2$ from sensitivity improvement
- Further factor 10 – 100 thanks to wider bandwidth
Bumpy or wobbling neutron stars emit periodic signals

GW signal can tell how rigid is a NS $\rightarrow$ EOS, and provide clues on any distortion mechanism (accretion, magnetic field ...)

$h \approx 3 \cdot 10^{-27} \left( \frac{10 \text{ kpc}}{r} \right) \left( \frac{I}{10^{45} \text{ g cm}^2} \right) \left( \frac{f}{200 \text{ Hz}} \right)^2 \left( \frac{\varepsilon}{10^{-6}} \right)$
Known pulsars: what will AD say?

- As far as spin down rate says, tens of known pulsars accessible

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More: cosmic strings, cusps...

- Exotica, like cosmic string cusps
  - Would lead to burst GW events.
  - Some significant limits already set by LIGO and Virgo
  - Improved sensitivity will allow to probe in ADE 1 order of magnitude lower string tensions

- Alternative theories of gravity
  - Affect phasing of CBC signals
  - Do not disrupt detection: signals will just be estimated with wrong parameters
  - Advanced detectors may appreciate few percent deviations from GR in some parameters: limited both by number of events and SNR.
  - ET class instruments will be necessary for more

- ...

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Conclusions

- In the second half of 2015, Advanced LIGO will start the O1 run with a sensitivity significantly better than iLIGO.

- In 2016, Advanced Virgo will join the O2 run.

- Other detectors (LIGO-India, Kagra) joining the network soon.

- Sensitivity will ramp up during the next 4 – 5 years.

- Design sensitivity, 10x better than Virgo and iLIGO, promises to allow starting Gravitational Wave Astronomy.
The end

Thank you for the attention
Sky localization capabilities

- Top left: 2016-17 ; top right: 2017-18
- Bottom left: 2019+ ; Bottom right: 2022 (with India)
Tuneable? How it works

**knob 3**
- Input Light power

**knob 1**
- microscopic position of SRM1 (nm scale)

**knob 2**
- optical transmittance of SRM1

Signal Recycling resonance frequency

- **Optimised for BBH**
- **Example: narrow band**
- **Example: wide band**
- **AdV reference (BNS opt.)**
- **Virgo**

**Signal [1/Hz]**

- **Frequency [Hz]**

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