Detecting Gravitational Waves with Advanced Interferometric Detectors

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On behalf of the Virgo Collaboration and the LIGO Scientific Collaboration
Outline

• Gravitational wave sources and properties

• Gravitational wave detection
  ▪ Interferometric detectors

• Results of the first generation of interferometric detectors

• Advanced interferometric detectors
  ▪ From Virgo to Advanced Virgo

• Outlook
Gravitational Waves and their detection
Gravitational waves in a nutshell

- Gravitational waves (GW) are ripples in the curvature of the spacetime, emitted by accelerated masses and which propagate at the speed of light
  - Time-varying quadrupolar moment of the mass distribution required
    → No emission if spherical or cylindrical symmetry

- One of the first predictions of General Relativity (GR) – Einstein 1916

- GW characterized by its dimensionless strain $h$
  - $h \propto 1 / \text{(distance from the source)}$

- GW are transverse with two polarizations: « + » and « × »
  - Effect on a ring of (free-falling) test masses: length variations in $\perp$ directions

\[
h(t) = \frac{2 \Delta L(t)}{L}
\]
Gravitational waves in a nutshell

- GW are extremely weak
  - No man-made source detectable

- Only astrophysical sources can potentially be observed
  - Distant, rare (cataclysmic) events

- Power radiated by GW
  \[ P = \frac{c^5}{G} \epsilon^2 \left( \frac{v}{c} \right)^6 \left( \frac{R_s}{R} \right)^2 \]

- Requirements to emit GW
  - Deviation from axisymmetry
  - Relativistic motion
  - Compact mass distribution
  \[ \rightarrow \text{Radius close to } R_s \]

- Numerical application: \( h \sim 10^{-22} - 10^{-21} \) at best
  - Type-II supernova (few M\(\odot\)) in the Milky Way (\(\sim 10 \text{ kpc away}\))
  - Coalescence of a compact binary system in the Virgo cluster (\(\sim 16 \text{ Mpc}\))

- \( R_s \): Schwartzschild radius
  - 3 km for the Sun

\[ R_s = \frac{2GM}{c^2} \]
Sources of gravitational waves

- Many potential GW sources
- Span the whole frequency range
  - From the \((\text{age of the Universe})^{-1}\) until the kHz
- Several possible detectors
  - Each relevant in a given frequency band

\[ \rightarrow \text{Focus on the frequency range accessible by ground-based detectors: above a few Hz} \]

- More later about the potential GW sources for ground-based interferometric detectors
Gravitational wave interferometric detectors

- **Instructions to build a GW detector**
  - Use free test masses
  - Locate them far apart
  - Measure their relative displacement
  - Make sure their motion is not perturbated by any external source

- **Solution: a Michelson interferometer**
  - Suspended mirrors
  - 3-4 km away
  - Interference pattern
  - Active control + noise mitigation

- **Incident GW**
  - Optical path changes
  - Output power variation

- **Best sensitivity around the dark fringe**
Improving the interferometer sensitivity

- Interferometer (IFO) sensitivity \( \propto \frac{1}{(\text{Arm length}) \times \sqrt{\text{Light power}}} \)

→ Use high power laser, power- and frequency-stabilized
  - Tens to hundreds of watts
→ Add Fabry-Perot cavities in the kilometric arms
  - Light path length increased by a factor of at least 50
→ Add recycling mirror between the input laser and the beam splitter
  - IFO set to the dark fringe: all power reflected back to the laser
→ Minimize transmission and losses for all mirrors
  - Define the gains of the interferometer cavities

- Sensitivity characterized by the IFO power spectrum density (PSD)
  - Unit: \( 1 / \sqrt{\text{Hz}} \)
  - Dominant noise depends on frequency range

Noise in the frequency band \([f_{\text{min}}, f_{\text{max}}]\) = \(\sqrt{\int_{f_{\text{min}}}^{f_{\text{max}}} \text{PSD}^2(f) \, df}\)

→ More details later
The Virgo detector scheme
A network of interferometric detectors

- A single interferometer is not enough to detect GW
  - Difficult to separate a signal from noise confidently
  - There have been unconfirmed claims of GW detection in the past...

→ Need to use a network of interferometers
  - 2 LIGO detectors (USA)
  - Virgo (Italy)
  - GEO600 (Germany)
  + later KAGRA (Japan)
  and then LIGO-India

- Agreements (MoUs) between the different projects
  - Share data, run common analysis, publish together

- IFO: non-directional detectors; non-uniform response in the sky

- Threefold detection: reconstruct source location in the sky
Exploiting multi-messenger information

- Transient GW events are energetic
  - Only (a small) part of the released energy is converted into GW
    → Other types of radiation released: electromagnetic waves and neutrinos

- Astrophysical alerts ⇒ tailored GW searches
  - Time and source location known
  - Possibly the waveform – depending on the event model
    → Example: gamma-ray burst – GW coincidences
      - Long $\gamma$-ray burst $\leftrightarrow$ core collapse of massive rapidly spinning stars
      - Short $\gamma$-ray burst $\leftrightarrow$ coalescing compact binaries

- Offline coincidences as well

- GW detectors will also release alerts to a worldwide network of telescopes
  - Agreements signed with 75 groups – 150 instruments, 10 space observatories
  - Policy enabled after the first four detections of a GW signal
    → Software infrastructure being tested
The Virgo experiment
Sensitivity of an interferometric detector

- Several *fundamental* noises limit the sensitivity in the different frequency bands
  - Contrary to *technical* noises (e.g. due to a noisy pump) which have to be mitigated

- Example of the design Virgo sensitivity curve
Sensitivity of an interferometric detector

- **Seismic noise**
- Defines the low frequency limit of the sensitivity
- Mitigated by the Superattenuators
Sensitivity of an interferometric detector

- Quantum noises: **shot noise** and radiation pressure noise

- Fluctuations of the number of photons

- Dominant at high frequencies, above a few hundred Hz
  - Fabry-Perot cavities act as low-pass filters

- Scales like $1/\sqrt{P}$
  - The higher the laser power, the lower the shot noise
Sensitivity of an interferometric detector

- Quantum noises: shot noise and radiation pressure noise

- Fluctuations of the radiation pressure due to photons hitting the mirrors
  - Scales like $\sqrt{P}$
    - Opposite to the shot noise

- Not limiting Virgo but important for Advanced Virgo
Sensitivity of an interferometric detector

- **Thermal noise**: several contributions

- **Mirror pendulum mode**
  - Frequency: 0.6 Hz
    → Below the Virgo range
  - Very large Q
    → Long tail dominating the noise up to few tens of Hz
Sensitivity of an interferometric detector

- Thermal noise: several contributions

- Vertical resonance converted into horizontal motion
  - Couplings

- Substrate resonance
  - High Q again
Sensitivity of an interferometric detector

- Thermal noise: several contributions

- Mirror violin modes
  - Fundamental + harmonics
Data quality & noise hunting

- 1000+ auxiliary channels to monitor the IFO behaviour
  - Correlations with the *(single)* dark fringe signal containing the GW information
  - Main tool: time-frequency online maps

- Flag and remove noisy periods from the physics dataset
  - A few percent deadtime at most
  - Such vetos can be analysis-dependent

- A catalog of identified noise sources: electronic noise in a crate, acoustic noise on an optical bench (on air for Virgo), magnetic noise on a coil used to act on a mirror, air conditioning system, airplane, wind, tide, etc.

- Frequency line studies
  - 50 (60) Hz and its harmonics

- Not all noise sources / mechanisms identified
  - An always ongoing activity

- Yet, a key work to control the false alarm rate of the data analysis pipelines
Results from initial detectors
• Improving the instrument sensitivity is a long-term job
  ▪ Example of Virgo (2003-2011)
Performance of the first generation detectors

- Both LIGO 4-km detectors exceeded their design sensitivity
Gravitational wave searches

- A wealth of potential GW sources
  - Coalescing binaries (neutron stars, NS, or black holes, BH)
  - « Burst » (transient) events: supernovae, cosmic strings, etc.
  - Continuous GW from fast-spinning neutron stars
  - Stochastic background (cosmological or astrophysical origin)

- They all have different characteristics
  - Known/unknown waveform
  - Frequency band
  → Robust data analysis methods to search for these signals

- The GW signal seen by an IFO is a linear combination of the two polarisations of the incident GW
  \[ h(t) = F_+ h_+(t) + F_\times h_\times(t) \]
  - \( F_+ \) and \( F_\times \) are the beam pattern functions which depend on the source direction in the sky w.r.t. the IFO plane
  → Maximal for GW \( \perp \) to the IFO
  → Blind spots along the arm bisector
Compact coalescing binaries

- Search for NS-NS, NS-BH and BH-BH systems
- Three phases
  - **Inspiral**: analytical waveforms
  - **Plunge and merger**: numerical relativity
  - **Ringdown**: BH quasi-normal modes known
    → BH formation: direct test of General Relativity
- **Matched filtering** techniques: integrate a given waveform against the data
  - External parameters (source location, distance) absorbed in overall amplitude
  - Correlation takes into account the noise PSD
  - Output: signal-to-noise ratio (SNR)
- Do this in parallel for a large number of parameter choices
  - Set of « templates » tiling the parameter space
  - Local density of templates depends on how quickly the waveform changes when its parameters are varie
Compact coalescing binaries

- No detection by initial detectors → Upper limits on the rates
- Detections expected for advanced detectors

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

\( ^a \) Realistic estimates

- Compact coalescing binaries are « standard candles » for GW searches
  - Horizon detection: figure of merit for the IFO sensitivity → Distance up to which a coalescing binary system is « detected » (SNR threshold)

PRD 85 (2012) 082002
Bursts

- All other transient sources
  - Supernovae
  - Cosmic strings
  - Long gamma-ray bursts
  - NS instabilities
  - Accretion disk instabilities
  - …

- Most signals poorly-modeled
  - Cannot use matched filtering
  - Search « coherent » signals
    → Seen in multiple detectors
    → Shapes consistent with the different detector responses
  - Look for excess power in time-frequency maps
    → Pattern recognition algorithms to track signals

- Main challenge: keep the background under control
  - Rely heavily on data quality, noise hunting and data segment vetoes
Bursts

- Supernovae: upper limits on the amount of energy released as GW vs. frequency

- Constraints on the cosmic string parameter space

- Constraints on the gamma ray burst population

PRD 85 (2012) 122007
PRL 112 (2014) 131101
Periodic gravitational wave signals

- Strain sensitivity upper limits for 195 pulsars – red and yellow stars

- Spin-down limit (*) broken for
  - Crab (<1%)
  - Vela (<10%)

- Spin-down limit within reach for dozens of pulsars with advanced detectors – see black curve

(*) Assumes that all energy radiated by the pulsar is emitted as GW

Stochastic background

- Constraints on $\Omega_{GW}$ from LIGO-Virgo
  - Isotropic search

- Upper limits on strain$^2$ Hz$^{-1}$ from directional searches

- 4 orders of magnitude improvement expected for advanced detectors
  $\rightarrow$ 2 from sensitivity, 2 from bandwidth
Advanced detectors
Advanced interferometric detectors

- Goal: a factor 10 improvement in sensitivity
  → A factor 10 increase in the radius of the searched Universe volume
  → A factor 1,000 increase in source rates, assuming a uniform distribution of sources in volume

- Makes the first detection of GW likely within a few years (months) of data taking
Advanced Virgo

- **Design**

- Quantum noise dominant at low (radiation pressure) & high (shot noise) frequencies
- Coating thermal noise dominant in between

- **Corresponding sensitivity curve**

CQG 32 (2015) 024001
Installation status

- As of July 2015

**Commissioning of the IMC cavity**

- Upgrade the superattenuators,
- Install new mirrors

**Preparation/installation of some suspended optical benches**

**Installation of the TCS**

**Commissioning of the optical bench suspension system**
A few pictures

- Beam splitter integrated and hooked to its superattenuator
  - Now under vacuum
- First long cavity mirror installed

(foto: M. Perciballi)
A few pictures

- The overcrowded (both sides used) suspended input optical bench
- A cryotrap
- The detection bench
Status of the advanced LIGO detectors

- Quick and successful commissioning on both IFOs: Hanford & Livingston
- Sensitivity of the initial detectors surpassed
  - Horizon 3 times larger
- Successful test runs
- First science run to start in September

*T0=06/06/2015 04:12:40
*BW=0.187493
Advanced detectors data taking

- Fall 2015: first advanced LIGO science run
  - Sensitivity significantly better than for the initial detectors
- 2016: Virgo will join LIGO for the second science run
- Over the next few years
  - Sensitivities ramp up
  - KAGRA and then LIGO-India join the network

http://arxiv.org/abs/1304.0670
In the past decade, the first generation of GW interferometric detectors have achieved their design sensitivity over a wide frequency range, ranging from a few tens of Hz to a few kHz.

Advanced Virgo and Advanced LIGO detectors are being built and commissioned:
- First Advanced LIGO science run scheduled to start in September
- More detectors will join the existing network in the coming years

With a factor 10 improvement in sensitivity with respect to the initial detectors, a first direct detection of GW is likely to happen within the next few years.

This would open a new window onto the Universe: GW astronomy.

→ See talk by C. Van den Broeck during the ECFA/EPS session on Saturday afternoon