1st August 2017
VIRGO joins LIGO for the “Observation Run 2” (O2) data-taking period
VIRGO joins LIGO for the “Observation Run 2” (O2) data-taking period

Today, Tuesday August 1st 2017, the VIRGO detector based in Europe has officially joined “Observation Run 2” (O2) and is now taking data alongside the American-based twin LIGO detectors. This major step forward for the VIRGO Collaboration is the outcome of a multi-year upgrade program, whose primary goal was to significantly improve the detector performance in terms of sensitivity. “The last months have been spent on commissioning VIRGO, and this went very well. We are eager to start our first science run, joining LIGO at this exciting time for our field” says Jo van den Brand of Nikhef and VU University Amsterdam, the spokesperson of the VIRGO collaboration.

Although the VIRGO sensitivity is, for the time being, at a lower level of those of the LIGO interferometers, it is adequate for confirming a potential detection with LIGO and would allow locating sources of gravitational waves in the sky with greater accuracy. The current VIRGO sensitivity significantly exceeds the previous VIRGO record sensitivity, achieved in 2011 before dismantling the detector to start its upgrade. VIRGO is now a brand new instrument comprising several new components, which have been made work together in less than one year, during the so-called commissioning phase. “It took many years of intense and innovative work to realize the ambitious objectives of the VIRGO upgrade. I wish to recognize the dedication of the members of the VIRGO Collaboration, of the EGO staff and of the participating labs” says Federico Ferrini, the director of the European Gravitational Observatory (EGO).
“Today, for the first time, we have a network of three second generation detectors capable of localizing the source of a gravitational-wave signal. This is a major achievement and the best is yet to come: the sensitivity of the involved detectors will progressively improve and more detectors are expected to join in the next years, opening exciting perspectives for the multimessenger investigation of our universe”, concludes Giovanni Losurdo from INFN Pisa who has been the leader of the “Advanced VIRGO” project.

The VIRGO Collaboration, consists of more than 280 physicists and engineers belonging to 20 different European research groups: six from Centre National de la Recherche Scientifique (CNRS) in France; eight from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; two in The Netherlands with Nikhef; the MTA Wigner RCP in Hungary; the POLGRAW group in Poland; Spain with the University of Valencia; and EGO, the laboratory hosting the VIRGO detector near Pisa in Italy.
From Initial to Advanced GW detectors

- **Initial LIGO, initial Virgo**
  - Active 2002-2011
  - No detections
  - Design sensitivity reached
    - Proof of the technology!

- **Advanced detectors**
  - **O1**: September-December 2015
    Advanced LIGO, limited sensitivity
  - **O2**: 2016-2017
    Advanced LIGO + Advanced Virgo
  - **O3**: 2017-2018
    Advanced LIGO + Advanced Virgo (+ KAGRA?)
  - Design sensitivity: 2019+

<table>
<thead>
<tr>
<th>Network</th>
<th>Source</th>
<th>( N_{\text{low}} ) (yr(^{-1}))</th>
<th>( N_{\text{re}} ) (yr(^{-1}))</th>
<th>( N_{\text{high}} ) (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>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>( 7 \times 10^{-5} )</td>
<td>0.0004</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>( 2 \times 10^{-4} )</td>
<td>0.007</td>
<td>0.5</td>
</tr>
<tr>
<td>Advanced</td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>
GW150914 - the first LIGO gravitational wave detection all together < 200 ms (a chirp signal)
The detection on Sep 14th, 2015
GW150914 – found by both BURST and CBC team

Waited to acquire 16 days background data to estimate properly the significance.

False alarm probability – better than 1 event in 203000 years.
GW150914 - a binary black hole!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4}M</em>{\odot}$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4}M</em>{\odot}$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4}M</em>{\odot}$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180} \text{ Mpc}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>
GW150914 - our firsts:

- Detection of gravitational waves
- Detection of a black hole
- Detection of a black hole binary
- The brightest source ever seen in the sky:

\[ L_{GW} = 200^{+30}_{-20} M_\odot \, s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \text{erg s}^{-1} \]

- Evidence for heavy BHs with masses of 30 and up to 60 solar masses
- Their formation requires an origin from low-metallicity environments
- Such BBH can form both dynamical processes or isolated binaries
LIGO- the first observing run O1 (14.09.2015-19.01.2016). The era of GW astronomy has begun
BBH merger rate:
9 - 240 Gpc$^{-3}$ yr$^{-1}$
From Initial to Advanced GW detectors

- **Initial LIGO, initial Virgo**
  - Active 2002-2011
  - No detections
  - Design sensitivity reached
    - Proof of the technology!

- **Advanced detectors**
  - **O1**: September-December 2015
    Advanced LIGO, limited sensitivity
  - **O2**: 2016-2017
    Advanced LIGO + Advanced Virgo
  - **O3**: 2017-2018
    Advanced LIGO + Advanced Virgo (+ KAGRA?)
  - Design sensitivity: 2019+

### Table

<table>
<thead>
<tr>
<th>Network</th>
<th>Source</th>
<th>$N_{\text{low}}$ (yr$^{-1}$)</th>
<th>$N_{\text{re}}$ (yr$^{-1}$)</th>
<th>$N_{\text{high}}$ (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>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.0004</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
</tr>
<tr>
<td>Advanced</td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>
GW170104: the first BBH from O2 LIGO
- the most distant observed BBH, the spin axes in a merging binary system could be misaligned

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass $m_1$</td>
<td>$31.2^{+8.4}<em>{-6.0} M</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass $m_2$</td>
<td>$19.4^{+5.3}<em>{-5.9} M</em>\odot$</td>
</tr>
<tr>
<td>Chirp mass $\mathcal{M}$</td>
<td>$21.1^{+2.4}<em>{-2.7} M</em>\odot$</td>
</tr>
<tr>
<td>Total mass $M$</td>
<td>$50.7^{+5.9}<em>{-5.0} M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass $M_f$</td>
<td>$48.7^{+5.7}<em>{-4.6} M</em>\odot$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}$</td>
<td>$2.0^{+0.6}<em>{-0.7} M</em>\odot c^2$</td>
</tr>
<tr>
<td>Peak luminosity $\ell_{\text{peak}}$</td>
<td>$3.1^{+0.7}_{-1.3} \times 10^{56} \text{erg s}^{-1}$</td>
</tr>
<tr>
<td>Effective inspiral spin parameter $\chi_{\text{eff}}$</td>
<td>$-0.12^{+0.21}_{-0.30}$</td>
</tr>
<tr>
<td>Final black hole spin $a_f$</td>
<td>$0.64^{+0.09}_{-0.20}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L$</td>
<td>$880^{+450}_{-390} \text{ Mpc}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.18^{+0.08}_{-0.07}$</td>
</tr>
</tbody>
</table>
Gravitational waves from coalescing binary black holes
observational runs O1 (12.09.2015-19.01.2016) i
O2 (30.11.2016- mid 2017)
Evidence of existence of heavy masses stellar mass black holes $>20$ solar masses

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1(M_\odot)$</td>
<td>$36.2^{+5.2}_{-3.8}$</td>
<td>$14.2^{+8.3}_{-3.7}$</td>
<td>$23^{+18}_{-6}$</td>
</tr>
<tr>
<td>$m_2(M_\odot)$</td>
<td>$29.1^{+3.7}_{-4.4}$</td>
<td>$7.5^{+2.3}_{-2.3}$</td>
<td>$13^{+4}_{-5}$</td>
</tr>
</tbody>
</table>

Abbott et al. 2016, Phys. Rev. X, 6, 041015

B. P. Abbott et al.*
(LIGO Scientific and Virgo Collaborations)
PRL 118, 221101 (2017)
Where the mergers of two black holes occurred?
with a aVirgo \(~10\times\) better localization

**Luminosity distance**

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Omega \ (\text{deg}^2)$</td>
<td>230</td>
<td>850</td>
<td>1600</td>
</tr>
</tbody>
</table>

**Final sky localization**

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_L \ (\text{Mpc})$</td>
<td>420$^{+150}_{-180}$</td>
<td>440$^{+180}_{-190}$</td>
<td>1000$^{+500}_{-500}$</td>
</tr>
</tbody>
</table>

Abbott et al. 2016, Phys. Rev. X, 6, 041015

Image credit: LIGO/L. Singer/A. Mellinger

GW170104: $880^{+450}_{-390} \ \text{Mpc}$

B. P. Abbott et al.*
(LIGO Scientific and Virgo Collaboration)

PRL 118, 221101 (2017)
**Gravitational waves and EM joint observations**

Two possible scenarios:

- **EM follow-up**: low-latency GW data analysis pipelines promptly identify GW candidates and send GW alerts to trigger prompt EM observations and start archival searches.

- **Externally-triggered GW searches**: an EM transient event is detected and GW data are analyzed to look for possible associated GW events.
Multi-messenger astronomy
GW and EM joint observations

80 MoUs* involving 170 instruments (satellites and ground-based telescopes) covering the full spectrum from radio to very high-energy $\gamma$-rays

65 teams of astronomers were ready to observe during O1!

Although no EM emission was expected from stellar mass BBH mergers due to the absence of matter around them, an intensive EM follow-up campaign has been performed to look for a possible EM counterpart to GW150914 and GW151226

Image credit: M. Branchesi
Gravitational wave sources

Requirements: compact M/R, relativistic and highly asymmetric
- $-16 < \log f_{GW} \, [Hz] < 6$
  (sensitivity of terrestrial detectors 10 Hz to 10 kHz)

- unknown sources
- known sources:
  -- rotating and oscillating neutron stars
  -- binaries $S/N \sim M_{chirp}/\text{Distance}$,
  -- $f_{GW} = 2$ for b,
  -- $f_{merger} \sim 2kHz/M_{\text{tot}}$
  -- supernovae
- stochastic background (primordial and originating from cosmic sources)
Astrophysical Sources of GW
10 Hz - 10 kHz

- **Periodic sources**
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries

- **Coalescing compact binaries**
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW waveforms

- **Burst events**
  - e.g. Supernovae with asymmetric collapse

- **Stochastic background**
  - Primordial Big Bang (t = 10^{-22} sec)
  - Continuum of sources — *The Unexpected!*
Supernovae and the core collapse

Core collapse of massive stars

- supernovae:
  - SBO X-rays, UV (minutes, days)
  - optical (week, months)
  - radio (years)

- long GRBs

Isolated neutron stars

- soft $\gamma$-ray repeaters
- radio/X-ray pulsar glitches

Image Credit: Avishay Gal-Yam

Image Credit: NASA, CXC, M. Weiss
The merger of a NS with NS or BH

**NS-NS and NS-BH mergers**

- **Short GRBs:**
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelength *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).

- **Kilonova:** optical and NIR (days-weeks).

- **Late blast wave emission:** radio (≈ months, years).

*Image credit: Metzger & Berger 2012*
Goals of Gravitational Waves Observations

- **Fundamental Physics**
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Is Einstein theory the correct theory of gravity?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?

- **Astrophysics**
  - What is the nature of gravitational collapse?
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?

- **Cosmology**
  - How did massive black holes at galactic nuclei form and evolve?
  - What is dark energy?
  - What phase transitions took place in the early Universe?
  - What were the physical conditions at the big bang?
Gravitational Wave Astronomy

open a new Window on the Universe

test GR and GR instabilities

Solving the enigma of GRBs and resolving their different classes

Measuring the cosmological parameters with GW standard sirens.

Understanding the mass-spectrum of compact stars and their populations – constraints on evolution

Measuring masses, spins,..of compact objects in binaries (constraints on NS EOS)

....
The Gravitational Wave Spectrum

- Quantum fluctuations in early universe
- Binary Supermassive Black Holes in galactic nuclei
- Compact Binaries in our Galaxy & beyond
- Compact objects captured by Supermassive Black Holes
- Rotating NS, Supernovae

**Sources**

- Wave period (years)
- Age of universe (years)
- Hours
- Seconds
- Milliseconds

**Detectors**

- Cosmic microwave background polarization
- Pulsar Timing
- Space Interferometers
- Terrestrial interferometers
So much to look forward in GW astrophysics!

- Relic radiation
- Cosmic Strings
- Extreme Mass Ratio Inspirals
- BH and NS Binaries
- Supernovae
- Spinning NS
- Supermassive BH Binaries
- Binary coalescence

Frequency bands:
- $10^{-16}$ Hz: Inflation Probes
- $10^{-9}$ Hz: Pulsar timing
- $10^{-4}$ Hz: Space detectors
- $10^{0}$ Hz: Ground interferometers
- $10^{3}$ Hz: Laser Interferometer Gravitational Wave Observatory

Slide: Matt Evans (MIT)
Compact binaries- three phases of coalescence

.inspiral” - until marginally stable orbit
“merger” - until the common horizon
“ringdown” - black hole oscillations

\[ M = \frac{c}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5} \]
Advanced LIGO+Virgo 2015-2022

**Advanced LIGO**

- Early (2015, 40 – 80 Mpc)
- Mid (2016–17, 80 – 120 Mpc)
- Late (2017–18, 120 – 170 Mpc)
- Design (2019, 200 Mpc)
- BNS–optimized (215 Mpc)

**Advanced Virgo**

- Early (2016–17, 20 – 60 Mpc)
- Mid (2017–18, 60 – 85 Mpc)
- Late (2018–20, 65 – 115 Mpc)
- Design (2021, 130 Mpc)
- BNS–optimized (145 Mpc)

---

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2}M_{\odot}c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg$^2$</th>
<th>% BNS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>-</td>
<td>0.0004 – 3</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>20 – 40</td>
<td>0.006 – 20</td>
<td>5 – 12</td>
<td>12 – 12</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months (per year)</td>
<td>75 – 90</td>
<td>40 – 80</td>
<td>0.04 – 100</td>
<td>3 – 8</td>
<td>28 – 28</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>80</td>
<td>0.2 – 200</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>2022+</td>
<td>(India)</td>
<td>105</td>
<td>200</td>
<td>0.4 – 400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
How far we can go?
Gravitational Waves

- predicted by A. Einstein in 1916, consequence of GR 1915
- they carry energy (Trautman 1958)
- exact solution for spherical gravitational waves (Robinson & Trautman, 1960)
- GW propagates if concentration of mass (energy) moves/changes shape
- spacetime oscillations that travel at velocity $v = c$
- interact weakly with matter (we can see objects that cannot be seen in any other way)
- new sort of radiation --> new discoveries
- the effect of a wave on 2 test particles $dL \sim h \cdot L$

GW amplitude $h \sim 1/10^{21}$
CBC search

Search targeted at binary coalescence signals: NSNS, BHNS BHBH

Template bank

Background estimate using time shifts
Masses

\begin{itemize}
\item \textit{Overall}
\item \textit{IMRPhenom}
\item \textit{EOBNR}
\end{itemize}
Gravitational Waves

predicted by GR, 1916
spacetime oscillations
new sort of radiation

--> new discoveries
we can see objects
that cannot be seen
in any other way

a new test of GR
Distance and inclination

\[ D_{\text{L}/\text{Mpc}} \]

\[ \theta_{JN} \]

- Overall
- IMRPhenom
- EOBNR

50%
90%
Burst search

- No prior knowledge of the shape of the signal
- Search for coincident bursts
- Signal reconstruction
- Detection statistics based on similarity of waveforms in two (or more) detectors
- Low latency – less than 3 minutes
- Later off line detailed analysis with background estimates
GW150914 - EM Follow-up

All upper limits except potential Fermi GBM gamma-ray burst counterpart?

Flurry of theoretical ideas for how a BBH could produce a GRB:


**Archive data search** → Fermi/GBM → possible sub-threshold candidate?

- a hard event 0.4 s after the GW event, lasted 1 s → rate $10^{-3}$ Hz, no sky-localization

Not detected by INTEGRAL, but not ruled out as a possible counterpart, though unexpected for a BBH!!
GW Science From First Generation (2005-2010)

PRD 85 (2012) 08202
From Initial to Advanced GW detectors

- **Initial LIGO, initial Virgo**
  - Active 2002-2011
  - No detections
  - Design sensitivity reached
    - Proof of the technology!

- **Advanced detectors**
  - **O1**: September-December 2015
    Advanced LIGO, limited sensitivity
  - **O2**: 2016-2017
    Advanced LIGO + Advanced Virgo
  - **O3**: 2017-2018
    Advanced LIGO + Advanced Virgo (+ KAGRA?)
  - Design sensitivity: 2019+

<table>
<thead>
<tr>
<th>Network</th>
<th>Source</th>
<th>$N_{\text{low}}$ (yr$^{-1}$)</th>
<th>$N_{\text{re}}$ (yr$^{-1}$)</th>
<th>$N_{\text{high}}$ (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>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.0004</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
</tr>
<tr>
<td>Advanced</td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>
Gravitational wave astronomy

• Initial GW detectors - no detection but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot, et al. 2009, 2010)

• Advanced GW – GW150914 - first direct detections, Robust data analysis techniques are in place, 4 working groups: Burst, Stochastic Backgrounds, Coalescing Binaries, Continuous Waves

• Detector development:

  - 2015-2022: 2nd: Adv LIGO/VIRGO + KAGRA + India LIGO ~10 times more sensitive (10^3 times more events/yr), NS-NS (200 Mpc), NS-BH (1Gpc), BH-BH (2Gpc); 10Hz-10kHz

  - 2030 ?: 3rd: ET ~ 100 (10^6 events/yr), 1 Hz-10 kHz

  - 2034 ?: space detectors: eLISA/NGO (0.003-0.01 Hz), DECIGO (0.1-1Hz)
**sensitivity (h~dL/L)**
- 10 km arms instead of 3-4 km

**sensitivity below**
- 10 Hz
  (seismic noise)
- 150 m underground

**> 1 kHz thermal noise**
- cryogenic mirrors cooled down to 10 K
LISA - cosmic mission

3 detectors - 5 mln km
--->1 detector, 1 mln km

$f_{GW} \sim 0.001 - 0.01$ Hz
Interferometers: initial
1st generation - summary

- no detection :(
- obtained required S/N :)
- common scientific runs :

S5-VSR1 (4 months, 2007),
S6-VSR2/ VSR3 (6/2 months, 2009/2010:)
- blind injection test – Big Dog event, NS-BH :)
The principle of detection

Two polarizations: $h^+$, $h_x$, 45 degree, quadrupole transverse wave, interaction with matter:

\[
h \approx \frac{R_g v^2}{D \frac{c^2}{c^2}} \approx 2 \times 10^{-21}
\]

\[
M = 60 M_\odot \quad D = 400 Mpc \quad v = 0.2c
\]
1\textsuperscript{st} detectors: LIGO, VIRGO, GEO600, TAMA \( f_{GW} \sim 10\text{Hz-1kHz} \)
Detection principle
Order of magnitude estimates

\[ \Delta L \approx 10^{-18} m \]

500 round trips, expected delay:

\[ \Delta L_{eff} = 500 \times 10^{-18} m \approx 5 \times 10^{-16} m \]

The laser wavelength is 1064nm. Expected phase amplitude:

\[ \Delta \phi \approx 5 \times 10^{-16} / 10^{-6} = 5 \times 10^{-10} \]

With 100kW power the Poisson noise fluctuations are

\[ \delta \phi = N^{-1/2} = \sqrt{\frac{hc}{\lambda P \Delta T}} = \sqrt{\frac{10^{-19} J}{10^5 W 10^{-2} s}} \approx 10^{-11} \]
Astrophysical sources for LISA

- Galactic Binaries
- Galaxy mergers
- Capture orbits
GW Astronomy

**ELF** log $f = -16$ to $-10$, **VLF** log $f = -10$ to $-6$, **LF** log $f = -6$ to $0$, **HF** log $f = 0$ to $6$
Polish participation in GW searches

Konsorcjum **VIRGO (POLGRAW)** - 1	extsuperscript{st} i 2	extsuperscript{nd} generacji detektory fal grawitacyjnych (od 2008), lider - A. Królak

Instytut Matematyki PAN (IMPAN), Uniwersytet Zielonogórski (UZ)
Uniwersytet Warszawski (UW), Uniwersytet Białostocki (UwB), Narodowe Centrum Badań Jądrowych (NCBJ), Uniwersytet M. Kopernika (UMK)
Instytut Matematyki PAN (IMPAN), Centrum Astronomiczne PAN

Kontrybucje: Analiza danych, Budowa części detektora Advanced VIRGO, Badania teoretyczne, Symulacje numeryczne sygnału z astrofizycznych źródeł (MNiSW, FNP)

Konsorcjum **EINSTEIN TELESCOPE** - 3	extsuperscript{rd} generacji (od 2013), lider - T. Bulik UZ, UW, PW, UwB, IMPAN, CAMK

Kontrybucje: Badania teoretyczne astrofizycznych źródeł, poszukiwanie miejsca na budowę ET (budowa sejsmometrów) (NCN, EU „Aspera”)

Konsorcjum **KAGRA** - współpraca z Japonią, UZ, PW, UW (od 2014)
Virgo-POLGRAW

- prof. dr hab. Andrzej Królak (IM PAN), lider grupy
- dr hab. Michał Bejger (CAMK PAN)
- prof. dr hab. Krzysztof Belczyński (OAUW)
- dr Arkadiusz Blaut (IFT UWr)
- dr Kazimierz Borkowski (CA UMK)
- prof. dr hab. Tomasz Bulik (OAUW)
- dr Paweł Ciecieląg (CAMK PAN)
- dr Orest Dorosh (NCBJ)
- prof. dr hab. Piotr Jaranowski (WF UwB)
- dr Izabela Kowalska-Leszczynska (OAUW)
- mgr inż. Adam Kutynia (WE PWr)
- dr Maciej Piętka (kiedyś WF UwB)
- dr hab. Dorota Rosińska (IA UZ)
- mgr Magdalena Sieniawska (CAMK PAN)
- dr Adam Zadrożny (NCBJ)

Virgo-POLGRAW: 15 członków grupy (9 na liście autorów).
Współpraca Virgo: 250.
LIGO Scientific Collaboration: >1000.
GW150914: parametry

- $M_1 = 36^{+5}_{-4} \, M_{\odot}$, $M_2 = 29^{+4}_{-4} \, M_{\odot}$,
- Parametry finalnej czarnej dziury:
  - masa $M_f = 62^{+4}_{-4} \, M_{\odot}$,
  - spin $a_f = 0.67^{+0.05}_{-0.07}$,
- Odległość: $410^{+160}_{-180} \, \text{Mpc}$ (1 miliard 300 milionów lat świetlnych, przesunięcie ku czerwieni $Z = 0.09^{+0.03}_{-0.04}$).
- Czas trwania zdarzenia: 0.12 s,
- Końcowa prędkość orbitalna: 0.5 c,
- Energia wyemitowana w falach: $3 \, M_{\odot}c^2$,
- W momencie największej „jasności”: $3.6 \times 10^{49} \, \text{W}$ ($200 \, M_{\odot}c^2/s$),
  → 100 razy więcej mocy niż cały wszechświat!
GW150914: najjaśniejsze kosmiczne wydarzenie kiedykolwiek zaobserwowane

- Pierwsza bezpośrednia detekcja fal grawitacyjnych
- Pierwsza detekcja dynamicznie zmiennego horyzontu
- Nowy sposób pomiaru masy i tempa rotacji (spinu) czarnych dziur
- Pierwsza obserwacja układu podwójnego czarnych dziur
- Najbardziej energetyczne zjawisko obserwowane w historii
- Nowe ograniczenie na masę grawitonu
- Nowe Okno na Wszechświat
Gravitational wave astronomy

1st: Virgo/Ligo - no detection yet, but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot, et al. 2009, 2010) required S/N, common runs: S5-VSR1 (4 months, 2007), S6-VSR2/VSR3 (6/2 months, 2009/2010), blind injection

Detector development:

- 2015: 2nd: Adv LIGO/VIRGO (10Hz-10kHz) ~10 x more sensitive (10^3 times more events/yr),
- NS-NS (450 Mpc), NS-BH (1Gpc), BH-BH (2Gpc),
- 2030?: 3rd: ET (1 Hz-10 kHz) ~ 100 (10^6 events/yr)

<table>
<thead>
<tr>
<th></th>
<th>BNS</th>
<th>NS-BH</th>
<th>BBH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial LIGO</td>
<td>0.02</td>
<td>0.006</td>
<td>0.01</td>
</tr>
<tr>
<td>(2002-06)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adv. LIGO</td>
<td>40</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>(2014+)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ET</td>
<td>Millions</td>
<td>100,000</td>
<td>Millions</td>
</tr>
</tbody>
</table>
Advanced LIGO

- **Funded by NSF in April 2008**
- **Cost of the upgrade:** $205M (NSF) and $30M from partners in Germany (Max Planck Albert Einstein Institute), UK (STFC), and Australia (ARC)
  - Cost comparison: 1 Advanced LIGO = 0.03 Large Hadron Colliders
- **Design goals:**
  - Complete upgrade of three LIGO interferometers
  - Sensitivity to binary neutron star inspirals to 200 MPc*
    - 10X the range of initial LIGO, 1000X the volume (and event rate)
- **Planned 7 year construction phase scheduled for completion in March 2015**
- **Current Status:** **Advanced LIGO Project FINISHED as of March 31!**
  - *LIGO Livingston interferometer*: completed installation in April 2014, first lock in May, currently being commissioned
  - *LIGO Hanford interferometer*: completed installation in September 2014, first lock in December, currently being commissioned
  - *Third interferometer*: components assembled and in storage for future installation in LIGO-India
What Might the First Direct GW Detection Look Like?

This source: Binary NS-NS system

Embedded in this noise stream:

Produces this waveform:

$h(t)$

$\text{SNR} (t)$

Normalized Tile Energy
### Astrophysical sources of GW

- **ELF** \( \log f = -16 \) to \(-10\), **VLF** \( \log f = -10 \) to \(-6\), **LF** \( \log f = -6 \) to \(0\), **HF** \( \log f = 0 \) to \(6\)

<table>
<thead>
<tr>
<th>(f) (Hz)</th>
<th>wavelength</th>
<th>method</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 10^{-16})</td>
<td>(\sim 10^{9}) ly</td>
<td>anisotropy of microwave background</td>
<td>primordial</td>
</tr>
<tr>
<td>(\sim 10^{-9})</td>
<td>(\sim 10) ly</td>
<td>timing of millisecond pulsars</td>
<td>primordial, cosmic strings</td>
</tr>
<tr>
<td>(\sim 10^{-4}) to (10^{-1})</td>
<td>(\sim 0.01) AU to (10) AU</td>
<td>Doppler tracking of spacecraft, laser interferometer in space (LISA)</td>
<td>binary stars, supermassive black holes</td>
</tr>
<tr>
<td>(\sim 10) to (10^{3})</td>
<td>(\sim 300) km to (30,000) km</td>
<td>laser interferometers on earth (LIGO, VIRGO, GEO, TAMA)</td>
<td>inspirals: NS+NS, BH+BH, NS+BH</td>
</tr>
<tr>
<td>(\sim 10^{3})</td>
<td>(\sim 300) km</td>
<td>Cryogenic resonant bar detectors</td>
<td>supernovae, spinning neutron stars</td>
</tr>
</tbody>
</table>
Detection rate

Future evolution: stable mass transfer
Formation of BBH

May already be detected in current LIGO/VIRGO data!
GW150914: układ podwójny czarnych dziur
14 września 2015 r. oba detektory LIGO (Livingston i Hanford) zarejestrowały, z przesunięciem 7 ms, ten sam sygnał:

Parametry źródła sygnału i odległość zostały obliczone metodami statystycznymi (*metoda filtru dopasowanego*).
Gravitational waves are transverse
Two polarisations: EM 90 deg; GW 45 deg

Gravitational wave polarisations

<table>
<thead>
<tr>
<th>$h_+$</th>
<th>$h_\times$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>phase</th>
<th>0</th>
<th>$\frac{\pi}{2}$</th>
<th>$\pi$</th>
<th>$\frac{3\pi}{2}$</th>
<th>$2\pi$</th>
</tr>
</thead>
</table>
Estimate of the amplitude

- Source: mass M, size L, variability P
- Quadrupole moment $ML^2$
  - $h = \left( \frac{G}{c^4} \right) \left( \frac{ML^2}{P^2} \right) / r$
- $h \sim$ second derivative of quadrupole moment
- Higher moments – factors $(\nu/c)$
- Maximally:
  $$ h \approx \frac{rg}{r} \left( \frac{\nu}{c} \right)^2 $$
laser → detektor → No signal
\[ dL = h \cdot L \]
4km Beam Tubes

- Light must travel in an excellent vacuum
  - Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters’ bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth’s curved surface
laser

detektor

Gravitational wave

SIGNAL!
Rotating Neutron Stars

- GW if NS non-axisymmetric frequency depends on a mechanism:
  - $r$-modes $\sim \frac{4}{3} f_{\text{rot}}$
  - spin precession $\sim f_{\text{rot}}$
  - bar shape $\sim 2 f_{\text{rot}}$

- Upper limits: spin down luminosity

- Magnetic mountains

- Wobbling Neutron Star

- $\sim 10^9$ NS in the Galaxy $f_{\text{GW}}$

- $\sim 10^3$ identified

- R-modes in accreting stars
Supernovae

Asymmetry

Graviational wave amplitude

Detectability

Galactic rate
First detection- BBH

Belczynski et al 2010
Compact binaries - three phases of coalescence

“inspiral” - until marginally stable orbit
“merger” - until the common horizon
“ringdown” - black hole oscillations
Coalescing BBH

- $10M_\odot + 10 M_\odot$
  - BH/BH binary
- Event rates based on population synthesis,
- mostly globular cluster binaries.
- Totally quiet!!
Coalescing BH-NS

NS-BH Event rates
Based on Population Synthesis

Initial interferometers
- Range: 43 Mpc
- 1/1000 yrs to 1 per yr

Advanced interferometers
- Range: 650 Mpc
- 2 per yr to several per day
Coalescing BNS

**NS-NS coalescence event rates**

- **Initial interferometers**
  - Range: 20 Mpc
  - 1 per 40 yrs to 1 per 2 yrs
- **Advanced interferometers**
  - Range: 300 Mpc
  - few per yr to several per day
- The discovery of a new binary pulsar have increased the rate upwards by an order of magnitude

**Signal shape very well known**

![Signal waveform and frequency vs. time graph](image)
Strain $h(f)$ ($1/\sqrt{\text{Hz}}$)

- LHO-4km (18 Mar 2007)
- LH0-2km (14 May 2007)
- LLO-4km (07 Aug 2007)
- GEO-600m (06 Jun 2006)
- Virgo-3km (29 Aug 2007)
- LIGO-4km design
- Virgo design
Detection of gravitational waves

• Test masses
• A network of detectors needed: to confirm detections independently and open a new window on the Universe
• narrow bandwidth: resonance detectors (~1 kHz)
• large bandwidth: laser interferometers (~10Hz-1kHz)
• Measurement of distances between them using light beams
  • $dL \sim hL$
Pulsar timing

- PPTA, EPTA, NanoGrav
- Sensitivity: wave amplitude – $10^{-13}$, $10^{-14}$
- Frequency range: below $10^{-7}$ Hz
- Directional sensitivity – important to monitor many pulsars
- Timescale for detection
- vs. frequency range
Coalescing compact binaries

But Bulik et al. 2011, IC10 X-1/NGC300 X-1: THE VERY IMMEDIATE PROGENITORS OF BH-BH BINARIES (BH-WR) will form BH-BH system with Mtot~40 Msol in < 0.3 Myr, d< 2 Mpc => 1-3 events/yr for Initial VIRGO/LIGO
Coalescing compact binaries

- Bulik et al. 2011, IC1613-NGC500 X-1: THE VERY IMMEDIATE PROGENITORS OF BH-BH BINARIES (BH-WR) will form BH-BH system with $M_{\text{tot}} \sim 40$ M$_{\odot}$ in $< 0.3$ Myr, $d < 2$ Mpc => 1-3 events/yr for Initial VIRGO/LIGO
2\textsuperscript{nd} generation: Adv Virgo/LIGO

- The upgrade to the advanced phase (2\textsuperscript{nd} generation) is just started (LIGO) or will start within this year (Virgo). The detectors should be back in commissioning in 2014.
- Advanced are promising roughly a factor 10 in sensitivity improvement.
Observational proof – PSR 1913+16

Nobel 1993 - Hulse & Taylor

<-- observed decay of $P = 7 \text{ h } 45 \text{ min}$ (75 microsekund/yr) due to gravitational radiation --- $\rightarrow$ merger in 140 Myr

$P_{\text{obs}}/P_{\text{teo}} = 1.0025 +/- 0.0022$
Gravitational wave polarisations

Gravitational waves are transverse
Two polarisations: EM 90 deg; GW 45 deg

$h_+$

$h_x$

phase  0  $\pi/2$  $\pi$  $3\pi/2$  $2\pi$

Curricular
Within a tiny fraction of a second, the big bang inflated the universe. Compression waves created a pattern in the afterglow of the expansion, known as the cosmic microwave background, which scientists have studied and mapped since the 1960s. In the 1990s, physicists theorized that rapid inflation during the big bang would also generate gravity waves, which would leave their mark by polarizing light in the cosmic afterglow. Extremely sensitive telescopes at the South Pole have detected such skewed light waves, but scientists have spent almost a decade ensuring that the phenomenon was not the result of other factors.
Detection principle