Universe observation through gravitational waves

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the detection of gravitational waves.
Plan of the talk

1. GW research motivations
2. Sources
3. Principles of interferometric detection
4. What is Virgo
5. LIGO-Virgo joint observation
6. The discovery
7. The start of the GW astronomy
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Linearized Einstein eqs. (far from big masses) admit wave solutions (perturbations to the background geometry) admit wave solutions (perturbations to the background geometry)

GW: transverse space-time distortions

Dynamical part of gravity, filling the space

Ripples in the Cosmic Sea

\[ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & +\eta - \frac{\partial}{\partial z} & 0 \\ 0 & \frac{\partial}{\partial t} & +\eta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \]

2 independent polarization propagating at the speed of light,

\[ \frac{\mathcal{C}}{8\pi G} = \frac{c^4}{8\pi G} \]

\( \mathcal{C} \) transverse space-time distortions

With \( \eta + \xi = \delta \)

\( \xi = \eta \)
Coupling constants

In SN collapse with stand 10^3 interactions before leaving the star,
GW leave the core undisturbed
GW emission: very energetic events but almost no interaction

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Weak</th>
<th>e.m.</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-3}</td>
<td>10^{-5}</td>
<td>1/137</td>
<td>0.1</td>
</tr>
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</table>

Ideal information carrier, Universe transparent to GW all the way back to the Big Bang!!

Decoupling after Big Bang

\( \nu \approx 10^{-4} \text{ s} \quad (T \approx 10^{19} \text{ GeV}) \)
\( \nu \approx 1 \text{ s} \quad (T \approx 1 \text{ MeV}) \)
\( e.m. \approx 10^{12} \text{ s} \quad (T \approx 0.2 \text{ eV}) \)
Luminosity: \( \text{Amplitude:} \)

GW detectors are sensitive to amplitude \( h \) : \( 1/r \) attenuation!

Efficient sources of GW must be "compact" and "fast".

Compactness \( C \)

- 10.4 for WD
- 0.3 for NS
- 1 for BH

Target GW amplitude

- Amplitude: 10.59 erg/s
- Luminosity: 10.59 erg/s

Target amplitude:

\( r \sim 10 \text{ Mpc} \)

Coalescing NS/NS in the Virgo cluster
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Compact stars (NS/NS, NS/BH, BH/BH)

- Inspiral signal accurately predictable
  - Newtonian dynamics
  - Post-Newtonian corrections (3PN, $v/c^{11/2}$) [L. Blanchet et al., 1996]

Recent big progress in merger 3D simulation [Baker et al, 2006, Preposterous 2006]

Chirp

Inspiral signal accurately predictable (NS/NS, NS/BH, BH/BH)
Supernovae

Collapse dynamics and waveform badly predictable

Estimated rate: several /yr in the VIRGO cluster, but the efficiency of GW emission is strongly model dependent

Simulations suggest $E_{\text{GW}} \sim 10^6 M_{\odot} c^2$, but NS kick velocities suggest possible strong asymmetries

GW emitted

Explosive section of envelope

Interaction of shock with collapsing envelope

Pre-supernova star

Collapse of the core

Neutrinos emitted

Light emitted

Star brightens by 10^6 times

[Zwerger, Muller]
Relic Stochastic Background

- Correlation of two interferometers needed for detection
- Imprinting of the early expansion of the universe

Relic neutrinos

CMBR

Relic gravitons

Modern Universe

First Galaxies

Parting Company

Big Freeze Out

Quark Soup

Inflation

Big Bang

Radius of the Visible Universe

10^{-3}\text{sec.}

1\text{Second}

300,000\text{Years}

15\text{Billions Years}

12-15\text{Billions Years}
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Great challenge for experimentalists!

Need to measure: $\Delta L \sim 10^{-18}$ m

Feasible: $L \sim 10^3$ m

Target $h \sim 10^{-21}$

Measuring space-time deformation

GW induce space-time strains using light

$\frac{2}{\sqrt{r}} \approx \mathcal{A}$

Detection
Pout depends also on Pin, ρ, L.

\[ \eta \cdot I \frac{\gamma}{\nu r^4} = \omega \phi \]

\[ (\omega \phi + \phi_0) \cos \frac{\nu}{\gamma} \frac{u^1}{d} = \frac{u_0}{d} \]

A simple detector
Increasing the optical path

Effective length:

\[ \frac{\pi}{4H} \cdot L = L' \]

Fabry-Perot cavities: amplify the length-to-phase transduction

Higher finesse \( \leftrightarrow \) higher \( df/dL \)

Drawback: works only at resonance

Resonance
Power fluctuations limit the phase sensitivity. Ultimate power fluctuations associated to the quantum nature of light.

Lengthen the detector to 100 km.

HOW?

Increase the light power more than 1 kW.

Lengthen the detector to 100 km.

\[ L = 100 \text{ km, } P = 1 \text{ kW} \]

Optical Readout Noise

\[ \frac{d I}{\gamma c h} \approx 10^{-21} \text{ Hz}^{1/2} \]

\[ \approx 10^{-21} \text{ Hz}^{1/2} \]

\[ \approx 10^{-21} \text{ Hz}^{1/2} \]

\[ \approx 3 \cdot 10^{-23} \text{ Hz}^{1/2} \]

Shot noise (assuming P, λ stable):

\[ \frac{d I}{\gamma c h} \approx 10^{-21} \text{ Hz}^{1/2} \]

Footnotes:

Fluctuations associated to the quantum nature of light.

Power fluctuations limit the phase sensitivity. Ultimate power
Interferometer Ecology: recycle the wasted light!

\[ P_{\text{eff}} = \text{Recycling factor} \cdot P_{\text{in}} \]

\[ 50 \times 20 \text{ W} = 1 \text{ kW} \]

Shot noise reduced by a factor ~ 7

One more cavity to be controlled!
A real detector scheme

Laser 20 W

Output Mode Cleaner

3 km long Fabry-Perot cavities:

to lengthen the optical path to 100 km

Power recycling mirror:
to increase the light power to 1 kW

Input Mode Cleaner
Free falling test masses
ACTIVE CONTROLS NEEDED!

Keep the arm length constant within 10 - 12 m

Maximize the phase response –

Minimize the shot noise –

Keep the PR cavity in resonance –

Maximize the phase response –

Keep the FP cavities in resonance –

Fluctuations –
Reduce the dependence on power –

Keep the output on the "dark fringe" –

ACTIVE CONTROLS NEEDED!
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Participated by scientists from Italy and France (former founders of Virgo), The Virgo Collaboration:

6 European countries

Total number 350 members

68% Physicists and Engineers
16% Consultants
16% PhD Students and PhD Students

Netherlands, Poland, Hungary and Spain

20 labs
6 European countries

COLLABORATION:
The VIRGO
Ad Virgo in a nutshell

- Heavier mirrors (42 kg)
- Fused silica suspensions
- Heavier mirrors
- New IP
- New payload
- Large central vacuum links
- Large cryotrap
- High finesse
- Larger beam waist
- DC detection
- Signal recycling
- New IP control
- Master laser
- High power SSL (200 W)
- High power amplifier
- Large central vacuum links

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Larger central vacuum links
Surface uniformity < 10^{-9} m
Homogeneity < 5 \times 10^{-7}

Beam Splitter: 50 cm diameter, 10 cm thick

Mirror: 42 kg, 35 cm diameter, 20 cm thick

Substrate: SiO₂
The payload

The central area
Seismic noise attenuation

The vacuum to reduce the diffusion of the light
Electronic control of the super attenuator

Superattenuator

Sensors

Coil

Drivers

Motors

Acc. Sens: -10^-9 m/s^2
-0 – 100Hz
-f.s. 1g

Drivers

Sensors

F.S. 1g
-0 – 100Hz
-10^-9 m/s^2

Acc. Sens:

Super attenuator

Electronic control of the

VIRGC
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The “single machine” MOU to be signed between LIGO Scientific Collaboration and Virgo:

- Full exchange of data, joint analysis
- Joint publications
- Coordinate science runs, commissioning and shutdowns

4 detectors to operate as a single machine with Great scientific value added
Triangulation allows to pinpoint the source

The network allows to deconvolve detector response and signal waveform to measure signal parameters.

The benefits of a network include:
- Better sky coverage:
- Longer observation time;
- False alarm rejection;
- Requires coincidence;
- Longer observation time, better sky coverage.

The network allows to triangulate event location.
The LIGO Observatories

LIGO Hanford Observatory (LHO)
H1: 4 km arms
H2: 2 km arms
H1: 4 km arms

LIGO Livingston Observatory (LLO)
L1: 4 km arms

Credit: P. Shawan
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The Advanced LIGO dedication ceremony was held at Hanford on May 19, 2015. VIRGO will end its upgrade in 2016.
strain amplitude evolution in time and frequency

Residual noise after waveform subtraction

35–350 Hz bandpassed strain time series
Combined SNR = 23.6, FAR = 1/203,000 years.
One of the most energetic astronomical events ever observed:

Energy emitted \( \sim 10^{49} \text{ J} \)

Power emitted \( \sim 200 \text{ M} \odot \text{ s}^{-1} \)

50 times brighter than the entire visible universe

Source redshift, \( z = 0.09^{+0.03}_{-0.04} \)

Luminosity distance \( 410^{+160}_{-180} \text{ Mpc} \)

Final black hole spin \( 0.67^{+0.05}_{-0.07} \)

Final black hole mass \( 62^{+4}_{-4} \text{ M}_\odot \)

Secondary black hole mass \( 29^{+4}_{-4} \text{ M}_\odot \)

Primary black hole mass \( 36^{+5}_{-4} \text{ M}_\odot \)

Parameter Estimation
How the signal might look like.

This source: Binary system

Produces this waveform:

Embedded in this noise stream:

matched filtering or excess power

Time to coalescence

SNR (t)

Signal (t)

Binary system
Assuming that the signal is CBC like:
matched filter search
Compact Binary Coalescence:

\[ s_{1z}^{'} = 0.99, s_{2z}^{'} = -0.99 \]

\[ m_1 = m_2 = 10 M \]

Waveforms
LIGO's first observing run

September 12, 2015 - January 19, 2016

September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED
While we are not so confident to tag this as a detection, it is more likely to be a gravitational wave signal than not.

GW150914: Signal/Noise = 13

GW151012: Signal/Noise = 9.7

GW151226: Signal/Noise = 13

GW150914: Signal/Noise = 24
Final mass 62 times that of the sun

Final mass 35 times that of the sun

Final mass 21 times that of the sun
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Sky Locations of Gravitational-wave Events

GW150914, GW151226 and Candidate LVT151012

Sky localizations

90% credible areas of about

1000 deg² GW151226
1600 deg² LVT15012
620 deg² GW150914

Sky localizations of Gravitational-Wave Events
Simulated Sky Locations of O1 Events and Candidate Including the Virgo Interferometer

90% credible areas of about

GW150914: 10-20 deg²
LVT15012: 600 deg²
GW151226: 1000 deg²

Sky localizations of about 90% credible areas of about

GW150914 + VIRGO
GW151226 + VIRGO
LVT15012 + VIRGO
Source Localization of the Network

Credit: S. Fairhurst
How to improve the sensitivity

Where and how can we reduce further the detector noise?

- Seismic
- Thermal
- Shot
- New optical configuration
- Better optics
- High power laser
- QND techniques
- New materials
- Cryogenic interferometers
- Underground detectors
- New optical configuration
- Better optics
- High power laser
- QND techniques
- New materials
- Cryogenic interferometers
- Underground detectors
GW will probe the status of the matter in the extreme condition. The clue of a super unification phenomenon can be the deviation from the prediction of the classical physics. GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly for the first time by GW, predicted by A. Einstein 100 years ago, have been detected directly.