Gravitational Wave Detectors

Abstract:

Sarà presentato lo stato della ricerca sperimentale delle onde gravitazionali, con particolare riferimento ai risultati scientifici ottenuti dal network di antenne interferometriche Virgo, LIGO e GEO ed alle prospettive del run in corso da parte dei rivelatori Virgo e GEO. Si discuteranno quindi, in sintesi, le prospettive future dei rivelatori avanzati in fase di costruzione.
Talk outline

- Gravitational Waves (GW)
- GW sources
- Gravitational Interferometers (introduction)
- Development and status of current interferometer technology
- GW search results: continuous waves, transient signals, stochastic background
- The path to Advanced Detectors
- Conclusions
The Gravitational Waves (GW)

- Basic ingredients: General Relativity
  
  - Einstein equations in free space and in weak gravitational field (far from big masses) admit wave solutions

- Gravitational waves in General Relativity are:
  
  - propagating at the speed of light
  - transverse, 2 independent polarizations
  - generated by mass quadrupole acceleration

- WEAK!
  
  - Order of magnitude: \( h \approx \delta L/L = 10^{-21} \)
    (coalescence of 1.4 Msun mass neutron stars at 15 Mpc)
  
  - Not reproducible in lab

\[
g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad |h_{\mu\nu}| \ll 1
\]

\[
\Rightarrow \left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0
\]

\[
h(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\]

\[
h_{\mu\nu} = \frac{2G}{c^4} \frac{1}{r} \dot{Q}_{\mu\nu}
\]
Sources of Gravitational Waves

- Supernovae (SN)
- Coalescing Compact binary systems
  - Each member either a Neutron Star (NS) or a Black Hole (BH)
- Spinning asymmetric Neutron Stars (NS)
- Stochastic signals
  - Cosmological GW background
  - Unresolved sum of astrophysical sources
    - Binary systems, pulsars, etc
Interferometers

- Interferometers (ITF) are nowadays the most promising GW detectors
Network is the detector

Benefits of a network of detectors:
- Confidence in detection
- Sky coverage
- Duty cycle
- Sky position localization

2007: agreement between Virgo and LIGO scientific collaboration (LSC) for
- full data exchange
- joint data analysis
- publication policy
ITF noise: “ideal”…

- Seismic
- Thermal
- Shot
2007: 1\textsuperscript{st} Virgo science run (VSR1)
- 5 months duration

2009: 2\textsuperscript{nd} Virgo science run (VSR2)
- 6 months
- New less noisy read-out and control electronics
- New laser amplifier to increase laser power
- Thermal Compensation System (TCS) to reduce the thermal effects at the input mirrors

2010: 3\textsuperscript{rd} Virgo science run (VSR3)
- 3 months
- New mirror suspensions made of silica fibers (Monolithic Suspensions, MS)
- High reflectivity mirrors on the Fabry-Perot cavities. Defects in the end mirrors’ radius of curvature (RoC), polishing and coating affected sensitivity

2011: 4\textsuperscript{th} Virgo science run (VSR4)
- 3 months
- End mirrors’ RoC corrected
- Best performance at low frequency
The network sensitivity

[Graph showing the strain sensitivity (sqrt[1/Hz]) vs. frequency (Hz) for different designs and years.]

- Virgo design
- LIGO design
- GEO600 design
- Virgo 2011
- LIGO L 2010
- LIGO H 2010
- GEO 2006

Yearly progress:
- 2007: Virgo, LIGO S5
- 2008: VIRGO1
- 2009: VIRGO2
- 2010: VIRGO3
- 2011: VIRGO4
- 2012: VIRGO5
Noise monitoring & hunting

Many “non intrinsic” noise sources affect ITF sensitivity:
- vibrations due to engines, fans, etc.
- magnetic glitches due to power line instabilities
- environment noise from airplanes, cars, etc.

Great efforts have been made to understand and possibly reduce their effect on the science data.

ITFs are equipped with several environment sensors (seismometers, microphones, cameras, etc.), whose data can be correlated to the gravitational channel to study the “noise coupling paths”.

Many tools have been developed to monitor the data quality on-line during the science runs and help noise hunting, or to discard “bad” data in the off-line analysis.

Examples from Virgo:
- Omega, WDF for transient noise
- NoEMi for continuous noise (“noise lines”)
GW search results: continuous waves

- **Source:** non-axisymmetric rotating neutron stars
  - GW amplitude proportional to star ellipticity factor $\varepsilon$, maximum value ranging from $10^{-6}$ from “standard” Equation of State (EOF) models to $10^{-4}$ for exotic models

- Quasi-monochromatic signal ($f_{GW} = 2 \cdot f_{rot}$)

- GW signal at the detector modulated by Doppler and relativistic effects ($\Delta f/f \approx 10^{-4}$)

- EM observation reveal rotation frequency slows down ($df/dt \approx 10^{-10}$ Hz/s)

- Part of the energy emitted as GW?

- Spin-down limit equation (constrains maximum energy emitted as GW):

\[
h_{sd} = 8 \cdot 10^{-25} \sqrt{\frac{|f|}{10^{-10} \text{ Hz/s}}} \left(\frac{f}{100 \text{ Hz}}\right)^{-1} \left(\frac{d}{1 \text{ Kpc}}\right)^{-1}
\]

- Search parameters: sky coordinates, $f$, $df/dt$, spin axis and polarization angles, phase
  - Some parameters can be constrained by EM observations

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Coherent (targeted) vs. Incoherent (blind) search
Crab and Vela pulsars

Spin-down limit beaten for two pulsars so far, using coherent search methods (source parameters known):

- **Crab** \((f_{GW}=59.4 \text{ Hz})\) with Ligo S5 data
  - Spin-down limit beaten by a factor 7, limiting the power radiated as GW to less than 2%, and the star ellipticity to \(10^{-4}\)

- **Vela** \((f_{GW}=22.4 \text{ Hz})\) with Virgo VSR2 data
  - Fraction of spin-down energy due to GW constrained to \(\sim 35\%\), limit on ellipticity: \(\sim 10^{-3}\)

Compatible upper limit values obtained with various analysis methods and statistical approaches.

Spin-down upper limits on Vela will be likely improved with Virgo VSR4 data, due to its better sensitivity at low frequency.

Possibility to improve results also for Crab, joining VSR2 and VSR4 data.

Instrumental disturbance worsened sensitivity at the Vela frequency during VSR2. Not detected during data taking as the monitoring tools were not yet developed.

Expected gain in sensitivity (preliminary!):

\[
\frac{\sigma_{VSR2}}{\sqrt{T_{VSR2}}} / \frac{\sigma_{VSR4}}{\sqrt{T_{VSR4}}} \approx \frac{2.9}{\sqrt{2.75}} \approx 1.76
\]
Other continuous GW search methods

Various analysis pipelines are under development for the search of continuous GW when one or more source parameters (sky position, frequency, etc) are unknown.

- **all-sky searches**: search over a portion of the source parameter space as large as possible. Computationally bound (need large computing resources). Based on incoherent methods or on the alternation of coherent and incoherent steps (hierarchical searches).

- **Directed searches**: 'intermediate' between targeted and all-sky. For sources of known position frequency, position within relatively small region,...

- **Search for accreting NS**: short coherence time due to stochastic nature of the accretion process. Target for Advanced Detectors.

- **Transient searches**: short lived CW signals; possibly very high spin-down objects (e.g. young magnetars).

No credible GW signal found. Upper limits put on the source amplitude, as a function of distance and frequency, have been put according to the current detector sensitivities and integration time.

**FIG. 4.** Estimated sensitivity of the Einstein@Home search for isolated periodic GW sources in the early S5 LIGO data. The set of three curves shows the source strain amplitudes $h_0$ at which 10% (bottom), 50% (middle) and 90% (top) of simulated sources would be confidently detected (i.e., would produce at least 20 coincidences out of 28 possible) in this Einstein@Home search.
Compact Binary Coalescence (CBC) are among the most promising GW sources.

- Evolution goes through 3 phases: "Inspiral", "Merger" and "Ringdown".
  - Inspiral phase waveforms can be modelled → matched filter.
  - Merger phase should emit EM radiation (Gamma Ray Burst, GRB) → triggered search.
- Detection with ITF network provide accurate source localization.
- Problem: very rare events.
  - with current detectors: << 1 event / year.
CBC search example: “GRB070201” event

- Intense, short (0.15 s) GRB seen by 5 satellites on 1st February 2007
  - Estimated position M31 (0.8 Mpc)
  - Only LIGO detectors online
  - GW signal searched 3 minutes around trigger

- No signal found
  - Exclude (conf. > 99%) a compact binary at d < 3.5 Mpc to be at the origin of the GRB
  - Other possible sources: Soft Gamma Repeater (SGR) in M31 or CBC behind it
Another CBC example: “Big Dog” event

- “Blind Hardware Injection”
- Realistic CBC signal injected in the ITF by automatic procedure
- Date: 2010-09-16, during Virgo VSR3 and LIGO S6
- Source parameters: 24.8 $M_\odot$ BH / 1.7 $M_\odot$ NS pair, 4.4 Mpc distance, in the Big Dog constellation
- Discovered in real time by the online analysis pipelines (obviously no GRB trigger!)
- Event followed up with an offline analysis, which reconstructed the source parameters
- Results in agreement with the injection parameters
- Role of Virgo data important for source localization

Big Dog event confirmed the detection and reconstruction capabilities of the ITF network!
Transient GW signal search: results overview

(Partial) overview of transient signal search results with LIGO–Virgo network

Soft gamma-ray repeaters (SGR’s) and some high-mass neutron stars (HMNS) are among the more unusual and exciting results of the LIGO–Virgo transients search. Although no signals from either of these two classes have been confirmed in the LIGO–Virgo data, the search continues.

Novel search algorithms and optimized data processing have led to the detection of two events with uncertain astrophysical interpretations.

One of these events, SGR 1806–20, is associated with the SGR 1806–20 neutron star and the other is associated with a neutron star in the globular cluster 47 Tucanae.

These limits on the rate of such events are consistent with theoretical predictions for the number of SGR’s and HMNS in our galaxy and in nearby globular clusters.

For more information, please refer to the original research papers and articles referenced in the slides.
GW search results: stochastic signals

- **Cosmological GW background**
  - Due to processes taking place at very early stages of the Universe evolution (amplification of vacuum fluctuations, phase transitions, decay of cosmic strings,...)
  - Expected to be stationary, gaussian, unpolarized, isotropic

- **Astrophysical GW background**
  - Due to the superposition of many unresolved sources (CBC, supernovae, pulsars)
  - Expected to be not isotropic and could be also not continuous (shot or popcorn noise)

- Characterized by the dimensionless parameter: \[
\Omega_{GW}(f_0) = \frac{1}{\rho_c} \frac{d\rho_{GW}}{d \ln f_0}
\]

- Where \( \rho_{GW} \) gravitational energy density; \( f_0 \) frequency in the observer frame; \( \rho_c \) critical energy density to make today’s Universe flat

- Setting limits to \( \Omega_{GW} \) constrains Universe evolution models

- ITF network fundamental for stochastic GW search

  - Analysis consists in cross-correlating the data from multiple detectors.
GW search results: stochastic signals

- The full S5 dataset from LIGO detectors has been used to set an upper limit on the stochastic background in the band 41 – 170 Hz (95% confidence; for a flat gravitational wave spectrum):

\[ \Omega_{GW}(f) < 6.9 \cdot 10^{-6} \]

- This limit beats the indirect limits provided by BigBang nucleosynthesis and cosmic microwave background observations (Nature Lett. 460, 990, 2009).
- It also rules out models of cosmic super-string with small string tension.
- Search for non-isotropic background is under development.
The path to Advanced detectors

- With Virgo VSR4 and LIGO S6 runs the “first generation” detectors completed their working cycle
- Next step: Advanced detector era
- Aim: gain a factor 10 in sensitivity
  - Dual recycling
  - Heavier mirrors, larger beams
  - High laser power (200 W)
  - Thermal compensation
  - DC readout
  - Monolithic suspensions
  - Vacuum improvement
- “Advanced” technologies already developed and tested in the “enhanced” phase of 1st generation ITF (e.g. Virgo+)

Advanced Virgo schedule
Looking farther

Some numbers:

- Factor 10 in sensitivity $\rightarrow$ factor 1000 on event rate!
- Rate of detectable binary neutron stars coalescences from $\sim 1/100$ years to 10/year
- Detectable system distance up to 200 Mpc
- Signals from pulsars detectable for ellipticities as low as $10^{-8}$

<table>
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<th>IFO</th>
<th>Source</th>
<th>$N_{\text{low}}$ yr$^{-1}$</th>
<th>$N_{\text{rec}}$ yr$^{-1}$</th>
<th>$N_{\text{high}}$ yr$^{-1}$</th>
<th>$N_{\text{max}}$ yr$^{-1}$</th>
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<td></td>
<td>BH–BH</td>
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<td>IMBH-IMBH</td>
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Notes:
- $b$: $10^b$
- $c$: $300^c$
- $d$: $0.1^d$
- $e$: $1^e$
Conclusions

- The first generation of gravitational interferometers has just come to its end
- “Robust” detectors (> 80% duty cycle during the science runs) design sensitivity reached and maintained
- First physics results ("beating upper limits era")
- Most “cutting edge” technology for Advanced detectors already developed and tested
- Advanced detectors will set the path for the first GW detection and for the start of GW astronomy!
BACKUP
Sources of Gravitational Waves

- **Transient signals**
  - Supernovae (SN)
    - GW from non spherical collapse
    - Search can be triggered by EM bursts
    - Waveform difficult to model
  - Coalescing Compact binary systems
    - Each member either a Neutron Star (NS) or a Black Hole (BH)
    - Waveforms can be (partially) modeled
    - Search can be triggered by EM bursts
  - Spinning asymmetric Neutron Stars (NS)
    - Waveform can be modeled
      - Help from electro-magnetic (EM) observation (pulsars)
    - Amplitude unknown, depend on star asymmetry
    - SNR increases with observation time

- **Continuous signals**
  - Stochastic signals
    - Cosmological GW background
      - Predicted by standard inflation and by some string models
    - Unresolved sum of astrophysical sources
      - Binary systems, pulsars, etc
Other transient GW sources: Supernovae

- GW emission in case of non-axisymmetric core collapse supernovae
- Associated to “long” (> 2s) GRBs → triggered search
- GW waveform difficult to model
  - Noise glitches may mimic GW bursts → data cleaning tools crucial!
- Estimated signal strength at 10 Kpc (galactic centre): \( \sim 10^{-20} \)
- Same problem as for CBC: event rate
  - O(1/100 \, y^{-1}) in the Milky Way
  - O(10 \, y^{-1}) in the Virgo cluster
Advanced detectors – Expectations for pulsars

- Spin-down limit will be beaten for ~ 40 known pulsars