FUTURE PLANS FOR GW DETECTORS

PAOLA PUPPO (INFN – ROMA)
LIGO/VIRGO/KAGRA COLLABORATION

- 10TH INTERNATIONAL CONFERENCE ON NEW FRONTIERS IN PHYSICS (ICNFP 2021)
• CONTEXT AND BACKGROUND
  • GW INTERFEROMETERS: THE CONCEPT
  • THE DATA TAKING RUNS
  • A BRIEF VIEW OF THE MAIN RESULTS (talk of C. Lazzaro for details)

• THE NEXT DATA TAKINGS (O4 AND O5)

• FROM O5 TO THE THIRD GENERATION DETECTORS
Ground-based GW detector

Frequency BW: 10Hz-10kHz
Strain amplitude: $10^{-21}$ from astrophysical sources

→ $10^{-18}$ m displacement on 3-4 km arms

→ Main noise sources:
  → Seismic and Thermal noise, Quantum noise, radiation pressure noise
  → Mirrors suspended, big masses, high laser power

$h = \frac{\delta L}{L}$ : GW STRAIN
**DETECTOR SENSITIVITY**

**MIRRORS**: large mass/diameter, good flatness/roughness, low absorption, good homogeneity, good coating uniformity, high Q

**SUSPENSIONS**: high pendulum Q, monolithic FS suspensions

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**Limitations to sensitivity**

- **Mirror**
  - geometry/flatness may change the optical gain and, thus, the **SHOT NOISE**

- **RADIATION PRESSURE** and **SUSPENSION THERMAL** noises depend on mirror pendulum and mass

- Mid-frequency range dominated by coating **THERMAL NOISE**

- Aberrations depend on coating absorption (thermal lensing) and substrate inhomogeneity

- Scattered light from flatness/roughness
DATA TAKING RUNS

O1: 12 SEP 2015 → 19 JAN 2016
ONLY LIGO DETECTORS

O2: 30 NOV 2016 → 25 AUG 2017
VIRGO JOINED ON 1 AUG 2017

O3A: APR 1 2019 → OCT 1 2019
O3B: NOV 1 2019 → MAY 1 2020
(WITH KAGRA)
TWO GROUND-BREAKING DISCOVERIES
A NEW WINDOW IN THE OBSERVATION OF THE UNIVERSE

GW150914 BBH
Mf~ 60 Solar Masses
1.3 Mly (r=0.09)

GW170817 BNS
Mf~ 2.8 Solar Masses
300 ly (r=0.01)
EM counterpart observed
O3 RESULTS

- SIGNIFICANT IMPROVEMENT OF THE DETECTION RATE!
- MORE DISTANT SOURCES DETECTED ($Z \sim 0.5 \rightarrow \sim 0.8$)
- 6 NEW EXCEPTIONAL EVENTS PUBLISHED
- BH POPULATION STUDIES
- UPPER LIMITS ON SEVERAL SOURCES AND PHYSICAL EFFECTS (I.E. GW BACKGROUND, LENSING, SPECIFIC DARK MATTER CANDIDATES)
GWTC-2 (Second GW Transient Catalog):
STATISTICS, POPULATION STUDIES

- What is the minimum mass of a BH?
- Does the merger rate evolve with $z$?
- Are there structures in the distribution of masses?


Next data takings will give us more useful data:

~ hundreds of events in O4
~ 1000 events for O5
O3 EXCEPTIONAL EVENTS (1)

**GW190412:** first observation of a BBH with unequal masses: 8.3 and 30.1 Solar masses

Biggest Mass asymmetry $\Rightarrow$ observable GW beyond the leading quadrupolar order

[Abbott et al. (LIGO/Virgo Coll.), Phys. Rev. D 102, 043015]

**GW190814:** the most asymmetric mass ratio merger ever observed $(m_1/m_2 = 9)$

The secondary mass of 2.6 Solar Masses lies in the lower ‘mass gap’ either the lightest BH or the heaviest NS ever observed


**GW190425:** BNS merger of total mass of $\sim$3.4 Solar Masses: 2 and 1.4 Solar Masses

Significantly larger than any other known BNS system, no EM counterpart

O3 EXCEPTIONAL EVENTS

- Biggest Mass asymmetry (GW190412)
- BH in Mass Gap (GW190814)
- BNS system: (GW190425)

Credit: Chris North (Cardiff University). See http://catalog.cardiffgravity.org/
GW190521: BBH with component masses ~66 and 85 Solar masses
First observation of an intermediate mass BH (IMBH) formation (Mf ~ 142 Solar Masses). Farthest source so far (z ~ 0.8)

GW200105-GW200115: 1st certified detection of NSBH (2 events)
O3 EXCEPTIONAL EVENTS

Biggest Masses (GW190521) (IMBH) $M_p > 140$ Ms

Credit: Chris North (Cardiff University). See http://catalog.cardiffgravity.org/
O3 : LIGO/VIRGO PERFORMANCES

April 2019 → March 2020 (1 month before the expected date because of the COVID pandemic)

- **L1**: 120-140 Mpc
- **H1**: 110-120 Mpc
- **Virgo**: 50 to 60 Mpc

**Duty cycle**

47% of the time 3 detectors
83% of the time at least 2 detectors
SQUEEZING IN VIRGO AND LIGO DURING O3

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

OPEN DATA  WWW.GW-OPENS CiENCE.ORG

GW200105 and GW200115 event data available!
New Event Portal Query Page!
O3 IMBH marginal event data available!
O3a data available!

Begin with a Learning Path
Download data
Join the email list
Open Data Workshops

1-hour time-series data around each event
Also contains:
• Pointers to analysis software tools;
• Materials from Open Data Workshops;
• Online tutorials
KAGRA has joined the network in O3b
Ligo/Virgo are being upgraded (A+/AdV+)
Ligo India will join the network in ~202?
Virgo has a phased plan to increase its sensitivity: AdV+

- Phase 1: BNS range from 60 Mpc (O3) to 90-120 Mpc (O4)
- Phase 2: BNS range 150-260 Mpc (O5)

Similar upgrade for Advanced Ligo (A+).
PHASE 1

QUANTUM NOISE REDUCTION:

• LASER POWER INCREASE
  25 W $\rightarrow$ 40 W (already on O3b)

• SIGNAL RECYCLING

• FREQUENCY DEPENDENT SQUEEZING
PHASE 2 (O5)

QUANTUM NOISE REDUCTION:
• LASER POWER INCREASE

40 W → 80 W

THERMAL NOISE REDUCTION LARGE END MASSES (ETM 40→100 kg)
• BIGGER BEAM SIZE ON ETM (5→10 cm)
• IMPROVEMENT OF COATING MECHANICAL AND OPTICAL LOSSES OF ALL THE TM (R&D)
KAGRA
- Sapphire mirrors (23 kg)
- 20 K
- Hosted in the Kamioka mine, Gifu prefecture

Kagra+
- Large Sapphire masses (100 kg)
- FD Squeezing (5 dB)
- High power (3.5 kW on BS)

Y. Michimura et al.,
*PRD 102, 022008 (2020)*
PLANS FOR THE FUTURE

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- **3G detectors**
- **POST-O5**

- **O1**
- **O2**
- **O3**
- **O4**
- **O5**

- **LIGO**
  - 2015: 80 Mpc
  - 2016: 100 Mpc
  - 2017: 110-130 Mpc
  - 2018: 160-190 Mpc
  - 2019: Target 330 Mpc

- **Virgo**
  - 2015: 30 Mpc
  - 2016: 50 Mpc
  - 2017: 90-120 Mpc
  - 2018: 150-260 Mpc

- **KAGRA**
  - 2015: 1 Mpc
  - 2016: 25-130 Mpc
  - 2017: 130+ Mpc
  - 2018: Target 330 Mpc

- **LIGO-India**
  - 2015: 1 Mpc
  - 2016: 25-130 Mpc
  - 2017: 130+ Mpc
  - 2018: Target 330 Mpc
GWIC

GWIC Mission: facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide

https://gwic.ligo.org

Subcommittee to look at the 3G in a coordinated way

- D Reitze, M Punturo co-chairs

6 study groups

» 3G Science Case
» R&D Coordination
» Community Networking
» Agency Interfacing
» Investigation of Governance Structures
» Computing (added September 2018)

The GW community is engaged in a coherent effort to develop 3G
Technology Readiness Roadmap

- Infrastructure & Facilities
- Core Optics
- Cryogenics
- Newtonian Noise
- Light Sources
- Quantum Enhancements
- SAS & SUS
- Auxiliary Optics
- Simulation & Control
- Calibration

Required maturity level:
- ML1: Conceptual
- ML2: Technical
- ML3: Prototype demo
- ML4: Ready for Installation

Relative R&D Investment:
- Low
- Mid
- High

D. Reize, talk on GWIC at 2nd EPS Meeting on Gravitation
POST-O5 STUDY GROUPS IN LIGO AND VIRGO

CHAIRS: PETER FRITSCHEL (MIT) FOR LIGO, VIVIANA FAFONE (ROME 2) AND SAMAYA NISSLANKE (UVA) FOR VIRGO

• DELIVERABLES:
  • Report assessing the scenarios and makes recommendations that can form the basis for proposing an upgrade project to be implemented after A+/ADV+
  • Report to be shared with the funding agencies

• TIMELINE & PROCESS
  • The group engages widely the LSC/VIRGO groups
  • Workshop by the end of 2022

• REQUESTS TO ASSES:
  • Implementations of design choices and technologies to improve sensitivity
  • Technical readiness of the options and needed R&D’s
  • Balance of the observing time against improved sensitivity
Options for upgrades for A+/AdV+

- Improvements to **seismic isolation and mirror suspensions upgrades**: to improve the low frequency sensitivity
- Continued improvements to **squeezed light** injection → 10 dB (also for 3G)
  - Ligo-Voyager designs call for 10 dB
- Interferometer modifications for **better high frequency** sensitivity
  - Increment of input power
- **Larger test masses** (>100 kg): reduce radiation pressure noise below 40 hz
- **AlGaAs crystalline coatings**: another factor 2 lower thermal noise
A COORDINATED WORK

**Virgo**
Virgo has not been considered a Voyager-like upgrade
- Similar situation as LIGO in terms of the detector possibilities: upgrades to the existing 1um room temperature
  - Fused silica ITF
- Study of the possibility to include Stable recycling cavities (already in Ligo)

**LIGO**
- Ligo is considering a Voyager-like upgrade

**LIGO India**
- Timeline already uncertain...

**KAGRA**
• CONCEPT FOR A NEW DETECTOR IN THE CURRENT FACILITIES;
• DESIGNED TO MAXIMIZE THE OBSERVATIONAL REACH OF THE INFRASTRUCTURE AND DEMONSTRATE THE KEY TECHNOLOGIES TO BE USED FOR 3G OBSERVATORIES IN NEW INFRASTRUCTURES.
• USE HEAVY (CA. 200 KG) CRYOGENIC MIRRORS WITH IMPROVED COATINGS AND UPGRADED SUSPENSIONS MADE OF ULTRA-PURE SILICON AT A TEMPERATURE OF 123 K
• USE THE EXISTING VACUUM ENVELOPE
• A LASER WAVELENGTH OF VOYAGER ~ 1.5um – 2um

• A FURTHER FACTOR OF 3 INCREASE IN BNS RANGE (TO 1100 MPC) IS ENVISIONED ALONG WITH A REDUCTION OF THE LOW FREQUENCY CUTOFF.

LIGO-T1400316–v4
• RECENTLY THE NEMO HAS BEEN PROPOSED BY AUSTRALIAN GROUPS

• IT MAY USE ASPECTS OF VOYAGER TECHNOLOGY, BUT IT IS OPTIMIZED FOR THE KHZ BAND IN ORDER TO MEASURE THE NEUTRON STAR STATE EQUATION OF STATE.

NEMO current design choices

• Test mass weight = 74.1 kg
• Test mass coating : AlGaAs/GaAs*
• ITM = 150 K, ETM = 123 K
• ROC_{ITM} = 1800 m; ROC_{ETM} = 2500 m
• Suspension material : steel*
• Test mass cooling method : radiative

Picture modified from: J. V. van Heijningen, NEMO paper
RECENTLY THE NEMO HAS BEEN PROPOSED BY AUSTRALIAN GROUPS

IT MAY USE ASPECTS OF VOYAGER TECHNOLOGY, BUT IT IS OPTIMIZED FOR THE KHZ BAND IN ORDER TO MEASURE THE NEUTRON STAR STATE EQUATION OF STATE.
G3 DETECTORS SCIENCE

Factor 10 better (X1000 Volume) than 2G detectors
LF sensitivity improvement (1 Hz target)

- Black-holes formation/ population studies
- Fundamental physics / nature of gravitation
- Cosmology / nature of dark energy
- Nuclear physics / ultra-dense matter
- Physics of Supernovae
- Multimessenger astrophysics
- Complementarity and synergies with LISA

ET science case
Extreme matter
Extreme universe
Extreme gravity
EINSTEIN TELESCOPE
ET DESIGN FEATURES

- Widen the bandwidth:
  - Underground (seismic noise reduction)
  - 10 km long arms (signal increase)
  - Triangle configuration
  - "Xylophone" (two combined detectors)
    - hot (ET-HF) and cooled mirrors (ET-LF)
  - Site qualification is ongoing (Italy, Hungary and Netherlands)

- **ET is in ESFRI**
  - Italy (Lead country)
  - Netherlands
  - Belgium
  - Spain
  - Poland

http://www.et-gw.eu/
Extrapolation of current or planned technologies for Virgo and LIGO
- Squeezing (non classical states of light)
- High-power lasers
- Large mirrors
- New mirror’s coatings
- Thermal compensation techniques
- Suspension systems

Technologies not yet tested in Virgo and LIGO
- some of them being tested in KAGRA
- Cryogenics
- New cryogenic materials
- New laser wavelengths (1.5 or 2 microns)
- L-shaped, two detectors
- above-ground observatory
- 20 km and 40 km arm-length
- possible site location in the US (3 candidate sites, New Mexico, Utah, Nevada).
**CE1: initial phase will employ scaled-up Advanced LIGO technology**
- High mass fused silica test masses
- 1.5 MW of optical power
- Frequency-dependent squeezing

**CE2: A major upgrade (R&D technologies)**
- New facility
- Either using Voyager technology such as silicon test masses and amorphous silicon coatings operating at 123 K
- 1.5/2 µm laser light
- 3 MW of optical power in its arm cavities
Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity
Evan D. Hall et al, Phys. Rev. D 103, 122004 (2021)
TO SUMMARIZE

• ADVANCED DETECTORS ARE BEING UPDATES (PLUS DETECTORS) FOR O4 AND O5
  • A+
  • ADV+
  • KAGRA+

• FILLING THE GAP BETWEEN O5 AND G3
  • POST-O5 TECHNOLOGIES
    • INCREMENTAL UPGRADES: POWER, COATINGS, VARIOUS TECHNICAL NOISES, REACHING THE SENSITIVITY AT LOW FREQUENCY
    • IMPORTANT TO MOVE TOWARDS 3G INTERFEROMETERS BUT TRY TO KEEP THE DATA TAKING ON AS MUCH AS POSSIBLE
  • PROJECTS FOR 3G TECHNOLOGIES AND TO PUSH THE CURRENT INTERFEROMETER AT THEIR LIMIT
    • POST-O5 LIGO AND VIRGO
    • VOYAGER
    • NEMO

• G3 DETECTORS
  • ET, GREAT SCIENTIFIC POTENTIAL, ET IN THE ESFRI ROADMAP!

• THE FIRST VERSION OF THE COSMIC EXPLORER HORIZON STUDY HAS BEEN RELEASED: