Where we are
Target sensitivity: \(40-60 \text{ Mpc}\) as horizon for a NSNS 1.4 M at SNR=8

Main benefit from putting back the monolithic suspension

Removing the steel wire thermal noise from noise budget gives a 20 Mpc range increase

Theoretical limit of this configuration: 80 Mpc @13W

*Main criteria applied to choose the new parts to be installed:*  
*just those new elements that they don’t require long commissioning time*
Sensitivity prediction: theoretical and experimental one i.e. intrinsic noise of the detector and technical noises
Pre-installation: commissioning to cure glitches
Monolithic suspensions are back

Done in less than four months

- Arm valves closed on Nov 27, reopen March 19
- Include two weeks of commissioning
- Faster than scheduled
Installation: additional highlights

Squeezing bench provided by AEI – MAX Planck
14 – 15 dB squeezed vacuum
( then when we match to the main interferometer significant loss in the gain are added )

New laser amplifier 70 W ➔ 100 W
New pre-mode cleaner

We can inject in the ITF up to 50 W

Stray light hunting restarted adding extra baffles
Running a Quantum Optics Interferometer

(VIRGO without squeezed vacuum)

(VIRGO with squeezed vacuum)

(2019—04-03 23:05:54 UTC)
The aLIGO detectors

Hanford

Livingstone
LIGO status: major hardware upgrade at both LIGO sites

- High power
- Laser noise
- Squeezing
- Signal recycling mirror change

- Stray light control
- Electric field sensors
- Test mass replacements

*Pre and post installation of the new baffles*
Projection of noise improvements from high power and squeezing: 120 Mpc

Hanford needs to improve low frequency noise in order to reach sensitivity goal for next observing run
KAGRA: a new partner will join soon the network
KAGRA project
Kamioka mine, Japan
3 km, underground, cryogenic detector (20 K)
KAGRA: from Installation to Commissioning - I
KAGRA: from Installation to Commissioning - II
Installation Sequence

- IMC/IFI installed in 2015
- IMMTs installed in 2016
- Type-A installed in 2017
- CRY payload installed at Yend in 2017 (w/spare TM) and at Xend in ‘18 Mar.
- PRMs installed in 2017 (Type-Bp suspension)
- BS installed in 2017 (Type-B suspension)
- Yend in vac ‘18/Jan
- ETMY cooled ‘18 Feb (currently T=18K)
- Center in vac ‘18/Mar
- Xend in vac ‘18/Apr

Credits: KAGRA coll.
Physics Results
Hunting several categories of GW signals emitted in different processes

**TRANSIENT**

- **Chirps** from Coalescent Compact Binaries (CBC)
- **Burst** from Core Collapse Supernovae (CCSN)

**PERSISTENT**

- Quasi monochromatic signals due to Rotation of Asymmetric Neutron Stars
- Stochastic signals due to Gravitational Background

**Matched Filters**

**Unmodeled waveforms**
A Primer on the GW signal

\[ h(t) = F_+ (\theta, \phi, \psi) h_+(t) + F_x (\theta, \phi, \psi) h_x(t) \]

(\theta, \phi) are angles describing the location of the source on the sky

\[ \psi \] polarization angle

\[ h(t) = F(t) \left( \cos \xi h_+ + \sin \xi h_x \right) \quad \rightarrow \quad \text{spacetime strain seen by the interferometer} \]

\[ F^2 = F_+^2 + F_x^2 \quad \text{(independent of the polarization angle } \psi) \]

\[ \tan \ \xi = \frac{F_x}{F_+} \]

Antenna pattern of a single interferometer
The detected GW signals so far are \textit{Chirps}

In the case of with almost equal masses the orbit in the final phase the orbits tend to be circular.

The chirp signal depends on 15 parameters:

- Masses (2), spins (6), sky position (2), orientation (2), coalescence time and phase (2), distance (1)

- Matter effects add 2 more parameters

- At lowest order the signal phase depends on the chirp mass $\mathcal{M}$ (usually \textit{the best measured parameter}), then mass ratio, then spins, then matter effects

\[
\mathcal{M} = \mu^{3/5} M^{2/5} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \approx \frac{c^3}{G} \left( \frac{5}{96 \pi^{8/3}} \right) \nu^{-11} \frac{d\nu}{dt}^{3/5}
\]
Emission during the inspiral phase: the quadrupolar contribution

\[ h_+ = \frac{2M_z^{5/3} [\pi f(t)]^{2/3}}{D_L} \left[ 1 + (\mathbf{L} \cdot \hat{n})^2 \right] \cos[\Phi(t)] \]

\[ h_\times = \frac{4M_z^{5/3} [\pi f(t)]^{2/3} (\mathbf{L} \cdot \hat{n})}{D_L} \sin[\Phi(t)] \]

\[ M_z = (1 + z)(m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5} \]

\[ M = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} = \frac{c^3}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \right]^{3/5} \]

The horizon for NS $M_1 = M_2$ at SNR=8

\[ D_L = \frac{1}{8} \left( \frac{5\pi}{24c^3} \right)^{1/2} (GM)^{5/6} \pi^{-7/6} \sqrt{4 \int_{f_{low}}^{f_{high}} \frac{f^{-7/3}}{S_n(f)} df} \]
The Catalogue of the GW signals from BBH

BH merger rate density

\[ R = 53.2^{+58.8}_{-28.8} \text{ Gpc}^{-3} \text{yr}^{-1} \] (90% credibility)  

*arXiv:1811.12940*
Parameter correlations – I

- The amplitude of GWs emitted by compact binaries depends on the *luminosity distance* $D_L$.

- The *luminosity distance* enters both polarizations in combination with the *orbital inclination angle* $\iota$ degeneracies.

- An inclination of $\theta = 90^\circ$ means we are looking at the binary (approximately) edge-on.

\[ h_+ \propto \frac{(\hat{L} \cdot \hat{n} + 1)^2}{2D_L} \]
\[ h_\times \propto \frac{\hat{L} \cdot \hat{n}}{D_L} \]

**Polarization** can be used to break the degeneracy between distance and inclination and for this we need 2 LIGOs + Virgo.
Effect of orientation of binary’s orbital plane

Polarization of gravitational waves depends on the orientation of the orbital plan of the binary system.

Face-on we observe a mixture. While edge-on we observe pure $h$.

$q = m_1/m_2$
• We usually work with dimensionless spins $a_i = c \frac{|\vec{s}_i|}{(G m_i^2)} < 1$ and their components to the respect of the orbital angular momentum:

$0 = \text{no spin}, \pm 1 = \text{maximally spinning (along the same/opposite direction of the orbital angular momentum)}$

• Poor accuracy in measuring the individual spins

(Purrer et al. , PRD93,084042; Vitale et al. PRL 112 251101, PRD 95 064053)
Parameter correlations – I I

In the case of low masses the signal analysis is dominated by the inspiral phase where mass ratio $q = m_1/m_2$ and the component of the total spin along the orbital angular momentum, are correlated

$q = m_1/m_2$
System Parameters derived from the O1/O2 detected signals

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<tr>
<th>Event</th>
<th>$m_1/M_\odot$</th>
<th>$m_2/M_\odot$</th>
<th>$M/M_\odot$</th>
<th>$\chi_{\text{eff}}$</th>
<th>$M_f/M_\odot$</th>
<th>$a_f$</th>
<th>$E_{\text{rad}}/(M_\odot c^2)$</th>
<th>$\ell_{\text{peak}}/(\text{erg s}^{-1})$</th>
<th>$d_L/\text{Mpc}$</th>
<th>$z$</th>
<th>$\Delta\Omega/\text{deg}^2$</th>
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<td>30.6$^{+3.0}_{-4.4}$</td>
<td>28.6$^{+1.6}_{-1.5}$</td>
<td>-0.01$^{+0.12}_{-0.13}$</td>
<td>63.1$^{+3.3}_{-3.0}$</td>
<td>0.69$^{+0.05}_{-0.04}$</td>
<td>3.1$^{+0.4}_{-0.4}$</td>
<td>3.6$^{+0.4}_{-0.4} \times 10^{56}$</td>
<td>430$^{+150}_{-170}$</td>
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<td>23.3$^{+14.0}_{-5.5}$</td>
<td>13.6$^{+4.1}_{-4.8}$</td>
<td>15.2$^{+2.0}_{-1.1}$</td>
<td>0.04$^{+0.28}_{-0.19}$</td>
<td>35.7$^{+9.9}_{-3.8}$</td>
<td>0.67$^{+0.13}_{-0.11}$</td>
<td>1.5$^{+0.5}_{-0.5}$</td>
<td>3.2$^{+0.8}_{-1.7} \times 10^{56}$</td>
<td>1060$^{+540}_{-480}$</td>
<td>0.21$^{+0.09}_{-0.09}$</td>
<td>1555</td>
</tr>
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<td>GW151226</td>
<td>13.7$^{+8.8}_{-3.2}$</td>
<td>7.7$^{+2.2}_{-2.6}$</td>
<td>8.9$^{+0.3}_{-0.3}$</td>
<td>0.18$^{+0.20}_{-0.12}$</td>
<td>20.5$^{+6.4}_{-1.5}$</td>
<td>0.74$^{+0.07}_{-0.05}$</td>
<td>1.0$^{+0.1}_{-0.2}$</td>
<td>3.4$^{+0.7}_{-1.7} \times 10^{56}$</td>
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<td>-0.04$^{+0.17}_{-0.20}$</td>
<td>49.1$^{+5.2}_{-3.9}$</td>
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<td>2.2$^{+0.5}_{-0.5}$</td>
<td>3.3$^{+0.6}_{-0.9} \times 10^{56}$</td>
<td>960$^{+430}_{-410}$</td>
<td>0.19$^{+0.07}_{-0.08}$</td>
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<td>7.9$^{+0.2}_{-0.2}$</td>
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<td>56.4$^{+5.2}_{-3.7}$</td>
<td>0.70$^{+0.08}_{-0.09}$</td>
<td>2.7$^{+0.6}_{-0.6}$</td>
<td>3.5$^{+0.6}_{-0.9} \times 10^{56}$</td>
<td>990$^{+320}_{-380}$</td>
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<td>25.3$^{+2.9}_{-4.1}$</td>
<td>24.2$^{+1.4}_{-1.1}$</td>
<td>0.07$^{+0.12}_{-0.11}$</td>
<td>53.4$^{+3.2}_{-2.4}$</td>
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<td>2.7$^{+0.4}_{-0.3}$</td>
<td>3.7$^{+0.4}_{-0.5} \times 10^{56}$</td>
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<tr>
<td>GW170817</td>
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<td>1.27$^{+0.09}_{-0.09}$</td>
<td>1.186$^{+0.001}_{-0.001}$</td>
<td>0.00$^{+0.02}_{-0.01}$</td>
<td>$\leq 2.8$</td>
<td>$\leq 0.89$</td>
<td>$\geq 0.04$</td>
<td>$\geq 0.1 \times 10^{56}$</td>
<td>40$^{+10}_{-10}$</td>
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<td>59.8$^{+4.8}_{-3.8}$</td>
<td>0.67$^{+0.07}_{-0.08}$</td>
<td>2.7$^{+0.5}_{-0.5}$</td>
<td>3.4$^{+0.5}_{-0.7} \times 10^{56}$</td>
<td>1020$^{+430}_{-360}$</td>
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<td>0.71$^{+0.08}_{-0.10}$</td>
<td>3.3$^{+0.9}_{-0.8}$</td>
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<td>1850$^{+840}_{-840}$</td>
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<td>1651</td>
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</tbody>
</table>

LVC, Arxiv:1811.12907
The BH Individual masses
LVC, Arxiv:1811.12907

\[ q = \frac{m_1}{m_2} \quad (\text{assumption } \Rightarrow m_1 > m_2) \]

\[ M_f \Rightarrow \text{Mass of the final BH} \]

\[ a_f = \frac{c \cdot |S_f|}{(GM_f^2)} \Rightarrow \text{normalized spin of the final BH} \]
Mass ratio and Spin correlation

The mass ratio is not usually measured well due to correlation with the effective spin parameter (Baird et al., Arxiv:1211.0546), which for low-mass events introduces characteristic skewness.
SPIN probability distribution based on all detected BH

On the base of the Spin distribution we can disentangle between the two formation channels of BBH

- Dynamical capture $\rightarrow$ random spins
- Galactic fields $\rightarrow$ Spins more aligned with the orbital angular momentum

- Apparently it seems that we are detecting BHs with small spins, but........

- At present no significant constraints on spin population or their characteristics

- We will do better with more BBH detections

More results in LVC, Arxiv 1811.12940
The outcome of the NS-NS signal GW170817

• The binary neutron star GW170817 was detected both in the GW and electromagnetic (EM) band
  – Proved BNS are progenitors of short gamma ray bursts
  – Proved BNS produce kilonovae emission, and heavy metals
  – Stringent limits on $c_{GW} \rightarrow$ Graviton Mass

$m_g < 7.7 \times 10^{-23}$ eV

Formation of Cesium $^{55}$Cs and Tellurium $^{52}$Te is difficult to explain in supernova explosions

Evidence of spectral lines broaded by Doppler effect
Neutron Stars as Nuclear Physics Laboratories

Leading tidal contribution to GW phase appears at 5 PN:

\[ \tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5} \]

Densities \( \sim 4 \times 10^{17} \text{ kg/m}^3 \)
GW170817 and NS equation of state

- The NS composition and properties determine the equation of state (EOS) and constrains how large can be a neutron star $\Rightarrow$ NS radius limits

- Gravitational waves carry information on the tidal deformability $\Lambda$ of the coalescing bodies, which were then translated to constraints on neutron star radii

$[R_1 = 10.8 (+2, -1.7) \text{ km}, R_2 = 10.7 (+2.1, -1.5) \text{ km}] (90\%)$

Assuming that masses can be even higher than $1.97 M_{\odot}$

$[R_1 = 11.9 \pm 1.4 \text{ km}, R_2 = 11.9 \pm 1.4 \text{ km}] (90\%)$

Green, blue, and orange areas $\Rightarrow$ equal EOS of two body, no mass limit, independent EOSs

Pressure at

$P = 3.5 (+2.7, -1.7) \times 10^{34} \text{ dyne cm}^{-2}$

inner density twice the nuclear saturation one

$(2.8 \times 10^{14} \text{ g cm}^{-3})$

GW170817 seems to support EOS that produce NS with smaller radius (soft EOS). Will do better with more sources.
GW170817: first result on cosmology

Measurement of the local Hubble parameter:
-- Distance from GW signal
-- Redshift from EM counterpart (galaxy NGC 4993)

• LVC measurement $\Rightarrow$ 14% (1σ) uncertainty

\[ \approx 11\% \text{ GW luminosity distance} \]
\[ \approx 3\% \text{ peculiar velocity of the galaxy} \]

5-σ discrepancy between CMB and SHOES
The New Data Taking -- O3
The network in action

- USA - 4 km
- USA - 4 km
- ITALY - 3 km
- GERMANY - 600 m

![Map showing network locations](image)
New Installation in the time window between O2 to O3

LIGO
- Higher laser power
- Replaced 5 of 8 test masses (better optical quality)
- Added squeezed light injection systems
- New baffles to mitigate scattered light
- Improvements to various controls systems (seismic, alignment, etc)

Virgo
- New (more powerful) laser
- Replaced the suspensions of the last stage to reduce the thermal noise (monolithic fibers)
- Added squeezed light injection systems
- New faraday isolator and photodiodes
- Improvements to various controls systems (seismic, alignment, etc)
Improved sensitivities
O3 RUN – Started April 1\textsuperscript{st}, 2019

GEO-LIGO-Virgo gravitational-wave strain

Network status on May 30\textsuperscript{th}, 2019
O3 and Instruments Status

O3 started in time on Mon Apr. 1st 2019 and it will last for almost 1 year

Better sensitivity than O2 for all 3 instruments.

As planned, shorter than usual commissioning time at all three sites for the first week.

Coordination between the sites to maximize 3-IFO operation.

At least one instrument tries to remain online at any given time.

Very good triple coincidence: so far more than 40%.

At least two interferometers 80% of the time.

Only 1.1% with no interferometer in observation mode.
Run status on June 4th, 2019
How many event do we expect?

**BBH** mass distribution models: 
- **Model A** \( m_{\text{min}} = 5 \, M_\odot \), \( \beta_q = 0 \) and fit on \( \alpha, m_{\text{max}} \);
- **Model B** fit all 4 parameters \( m_{\text{min}}, m_{\text{max}}, \alpha, \beta_q \).

\[
p(m_1, m_2|m_{\text{min}}, m_{\text{max}}, \alpha, \beta_q) \propto \begin{cases} 
C(m_1)m_1^{-\alpha}q^\beta & \text{if } m_{\text{min}} \leq m_2 \leq m_1 \leq m_{\text{max}} \\
0 & \text{otherwise}
\end{cases}
\]

where \( C(m_i) \) is chosen so that the marginal distribution is a power law in \( m \): 
\[
p(m_1|m_{\text{min}}, m_{\text{max}}, \alpha, \beta_q) = m_1^{-\alpha}
\]

\[
R = 64.9^{+75.5}_{-33.6} \, \text{Gpc}^{-3} \, \text{yr}^{-1} \quad \text{for Model A}
\]
\[
R = 53.2^{+58.5}_{-28.8} \, \text{Gpc}^{-3} \, \text{yr}^{-1} \quad \text{for Models B}
\]

*Since we are able to observe BBH coalescence in a volume of the order of \( \sim 1 \, \text{Gpc}^3 \), \( R V \sim 1 \, \text{week}^{-1} \)*

**NS-NS** rate based on just one observed event

PDF based on the output two search algorithms GstLAL and PyCBC.

---

uniform mass distribution

---

Gaussian mass distribution.

Vertical lines \( \Rightarrow \) symmetric 90% confidence intervals.

*Since we are able to observe NS-NS coalescence in a volume of the order of \( \sim 4 \times 10^{-3} \, \text{Gpc}^3 \), \( R V \sim \text{few year}^{-1} \) at the PDF peak*

(arXiv:1811.12907)

(arXiv:1811.12940)
## GraceDB — Gravitational Wave Candidate Event Database

### Latest — as of 4 June 2019 17:57:50 UTC

Test and MDC events and superevents are not included in the search results by default; see the [query help](https://gracedb.ligo.org/latest/) for information on how to search for events and superevents in those categories.

### Search for: Superevent

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Example of a couple of SUPEVENTs: S190412m and S190408an

\[
\text{FAR} = 1.683 \times 10^{-27} \text{ Hz} \Rightarrow \text{1 per } 1.883 \times 10^{19} \text{ years}
\]

\[
\text{FAR} = 2.81 \times 10^{-18} \text{ Hz} \Rightarrow \text{1 per } 1.1273 \times 10^{10} \text{ years}
\]
O3 and future plans

![Graph showing O3 and future plans for LIGO, Virgo, KAGRA, and LIGO-India across different years and distance ranges.](image-url)
The network in the final part of O3
**O2 localization:** the smaller uncertainties when we have the 3 detectors: GW170814, GW170817, GW170818

Credits: S. Fairhurst
Moving forward the new 3G detectors: the Einstein Telescope case

- The GW detection and the beginning of the multimessenger astronomy stimulated a worldwide acceleration toward 3G GW observatories.
- In Europe, we are going toward the formation of a ET collaboration, a competition between ~3 sites, candidate to host the infrastructure, the submission of an ET project proposal to the ESFRI roadmap.
- In US, the idea of a giant 40km detector, named Cosmic Explorer, is now born and supported, as Conceptual Design Study, by NSF.
- We set up a global coordination committee (GWIC-3G) that is attempting to harmonise the efforts and to find synergies.
Motivations for New Detectors

- Expand the exploration to the entire Universe
- Black holes through cosmic history
  - Formation, evolution and growth of black holes and their properties
- Understanding extremes of physics
  - Structure and dynamics of neutron stars
  - Physics of extreme gravity
- Probing the transient Universe
  - Gamma ray bursts, gravitational collapse and Supernovae
- Beyond GR looking for new Physics: gravastars, wormholes, new particles and fields
Why a new infrastructure

• Increase the arm length to gain in sensitivity

• Implementation of new technological plants requiring more space (cryogenics system)

• Reduce the seismic impact of the sensitivity (Underground detector)

• Permit longer data taking runs of the 2G detectors by relaxing the needs to implement new technologies on 2G

• Prepare the transition from obsolete to new infrastructures

The target should be to realize a 3G-infrastructure in the next decay choosing sites that must have specific features that can enhance the planned investments.
The 3rd GENERATION: site basic requirements

- lower seismic motion, meteorologically generated seismic noise, anthropogenic activity (local infrastructure, population density, etc.);

- lower Newtonian noise originates from fluctuations in the surrounding geologic and atmospheric density, causing a variation in the Newtonian gravitational field.

The Einstein Telescope (ET) case

The Einstein Telescope will be located underground at a depth of about 100 m to 200 m and, in the complete configuration, will consist of three nested detectors each in turn composed of two interferometers.
ET collaboration: Letter of Intent

• Addressed to all the scientists and engineers interested to the 3G GW science and technology

• The signatories (606 persons, the 24th of August) probably will become the future members of the ET collaboration


Credits: M. Punturo
ET site(s)

- In the Design Study we investigated several EU sites
  - The same instruments and methods have been used to roughly compare the sites
  - Three are survived per quality and/or interest

Data collected from these sites
3rd party data obtained and analyzed from these sites

Thanks to:
- Dr. Kazuaki Kuroda
- Dr. Uchiyama Takashi
- Dr. Osamu Miyakawa
- Dr. Shinji Miyoki
3 site candidates

- Belgium-Germany-Netherlands
- Hungary (Matra Mountain)
- Italy (Sardinia-Sos Enattos)
Sites studies already started

• G-B-N Site, in the Meuse-Rhine region between Netherland, Belgium and Germany
• Mátra Mountain Site, in the northern of Hungary, (first cancelled and now revived?)
• Lula Site, in the Sardinia - Italy.
Sardinia, Italy

• Site identified:
  • Sos Enattos, Sardinia

• Site qualification: well advanced
  • Excellent seismic and geological properties
  • Small underground lab under construction funded (1M€) by local region and INFN

• Few M€ support assured by Italian government for the early phase

• International involvement to be structured

Dichiarazione di Intenti
SARDEGNA – CORSICA

Les Exécutifs corse et sarde échangent sur les thèmes majeurs de la coopération entre les deux îles

Lundi 14 Mars 2016
The Sos Enattos mine (Lula – SARDINIA)

We (**) have studied the placement of the ET detector in the SOS ENATTOS area. We tried to fulfill the following requirements:

- Vertexes placed in solid rock
- Access to caverns through tunnels

(**) A. Paoli, G. Losurdo, G. Oggiano, D. D’Urso, IGEA and SWS company et al.

Ancient rocks, European continental landmass: seismically quiet. Since 16 Million Years, and after the opening of the south Thyrrhenian basin, Sardinia has been excluded from the active dynamics affecting Italy along with Dinarides and Hellenides.

**Granodiorite**
- UCS: 72.1 MPa

**Orthogneiss**
- UCS: 92.6/60.8 MPa

**Micaschist/Paragneiss/Quartzite**
- UCS: 8.8/68 MPa
Extreme Physics with the 3G detectors

Credits: Fermi National Lab

Credits: Aaron Zimmerman
The supernova puzzle

Type II Supernovae unsolved problem: how the neutrino burst transfers its energy to the rest of the star producing the shock wave which causes the star to explode?

- For Type II supernovae, the collapse should be halted by short-range repulsive neutron-neutron interactions, mediated by the strong force, as well as by the degeneracy pressure of neutrons, at a density comparable to that of an atomic nucleus.

- Through a process that is not clearly understood, about 1%, of $10^{44}$ J of the energy released in the form of neutrinos is reabsorbed by the stalled shock, producing the supernova explosion. How does it occur this 1% energy transfer?

- Theoretical models has to include a hydrodynamical instability for re-energizing the stalled shock: Standing Accretion Shock Instability (SASI) are consequence of non-spherical oscillating perturbations, exciting the protoneutron star formed with the collapse

- This implies that we should find characteristic features in the GW signals
Hunting GWs: from Supernovae

- Collapse dynamics and waveform badly predictable (giant numerical effort)
- Estimated rate: several /yr in the VIRGO cluster, but the efficiency of GW emission is strongly model dependent
- Simulations suggest $E_{GW} \sim 10^{-6} - 10^{-9} \ M_\odot c^2$, but NS kick velocities suggest possible strong asymmetries
The driving idea is to identify a set of $N$ features in the data chunks, which are the outcomes of the CCSNe 3D simulations.

The waveforms represent the typical features observed in numerical simulations of neutrino-driven CCSNe. Their origin is well understood (g-modes in the proto-neutron star). These features are not expected to disappear in more detailed, numerical simulations, although the parameter space of possible values for the waveform may change in the future.
The detected signals confirmed the existence of black holes with masses larger than 20 M$_\odot$

- How many black holes? Which size? How are they formed?

- How metallicity environment influence the formation? (stellar wind depends on metallicity)

Two models for the binary black hole formation:
- Two object formed and exploded at the same time from two stars similar spins with the same orientation
- Black holes in a stellar cluster sink to the center of the cluster and pair up spin randomly oriented

- Do it exist miniature black holes?
  They may have formed immediately after the Big Bang. Rapidly expanding space may have squeezed some regions into tiny, dense black holes less massive than the sun.
Under a simplified hypothesis of a uniform distribution of BBH creation on the universe history
With a 3G detector we expect

- $10^5 \text{yr}^{-1}$ BBH
- $\text{SNR} \sim 10^4$ for rare events

Population study biased in function of the achievable SNR

**GW signal amplitude** depends on $\mathcal{M}^{5/2}$

$\mathcal{M} = \text{chirp mass} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$

Higher $\mathcal{M} \Rightarrow$ easier detection

**GW signal duration** decreases with $M_{\text{tot}} = m_1 + m_2$

Too massive systems $\Rightarrow$ GW signals at frequency out of the detector bandwidth

In addition the signals detected depend on the redshifted masses $M (1 + z)$

Testing GR: example via Post Parametrized Expansion

Phenom consistency test

\[ h(f) = A(f, \vec{\theta}) e^{i\Psi(f, \vec{\theta})} \]

\[ \Psi = f^{-5/3} \sum_{i=0}^{7} p_i(\vec{\theta}) f^{i/3} + (\text{log terms}) \]

\[ p_i \rightarrow p_i (1 + \delta p_i) \]
GW170814 result

Bayes factors:
- 1:200, i.e. purely vector disfavoured vs purely tensor
- 1:1000 i.e. purely scalar disfavoured vs purely tensor mode

Test significance will improve a lot when it will be carried on with the extended network

Hanford-Livingston-KAGRA-Virgo
Looking ahead for tests of GR

• Precision era ahead: modeling challenges
  • Part in $10^{-4} - 10^{-5}$ waveform accuracy
  • Predictions from non-GR mergers

More work on mapping constraints to theory
• Beyond leading order PPE
• New ideas/new events lead to dramatic constraints
• Target measurements to rule out classes of non-GR theories
The spectrum of Quasi Normal Modes (QNM) is characterized only by the BH mass and angular momentum.

The detection of a few modes from the ringdown signal can allow for precision measurements of the BH mass and spin.

In addition the detection of higher multipole moments can be used to perform null-hypothesis tests of the no-hair theorems of general relativity.
Black hole spectroscopy

$M(\omega)_{lmn} = \frac{\omega}{\Omega}$

$Q(\omega \tau)_{lmn} = \frac{\omega \tau}{2}$

$a = J/M \rightarrow$ Kerr rotation parameter

$(\omega, \tau) \rightarrow (M, \chi)$

Berti, Cardoso, Starinets (2009)
BH spectroscopy with the future detectors

• ET and LISA detectors ideal for ringdown

• High-SNR events will give individual tests

• Combine many events: both 2G and 3G provide stronger constraints on GR

Practical in active development

\[ f_{lmn} = f_{lmn}^{GR} (1 + bf_{lmn}) \]

Brito, Buonanno, Raymond arXiv:1805.00293
Beyond GR:
New Macro Systems, Fields and Particles
Primordial Black Holes as Dark Matter Objects

*The new detectors would settle the question if LIGO-Virgo black holes constitute dark matter and are primordial in origin*

- sub-solar black holes cannot form by stellar evolution
- must be primordial in origin
- The new detectors can probe existence of light black holes
Extremely Compact Objects
Exploring particle physics theories

The new detectors could discover extremely compact objects such as Boson stars, strange stars, gravastars, worm holes, ...

- Axions, ultra-light bosons, consequence of new interactions on two-body dynamics and population characteristics
- Objects made of new matter
  - fundamental strings, boson stars, strange stars, gravastars

Credits: Paolo Pani
A point particle plunges radially and emerges in another “universe”. When the particle crosses each of the light rings curves, it excites QNM characteristic modes trapped between the light-ring potential wells.
Comparison of the GW waveform between the BH and wormhole case

- Particle plunging into a Schwarzschild BH with the energy $E$ compared to the particle crossing a traversable wormhole

GW waveforms comparison for different values of $E$.

The BH waveform was shifted in time to account for the dephasing due to the light travel time from the throat to the light ring.
BH and particle physics

- With a stellar mass BH we have a new precision tool that may diagnose the presence of new light (10^{-20} \text{ to } 10^{-10} \text{ eV}) and weakly interacting bosonic particles.

- When such a particle’s Compton wavelength is comparable to the horizon size of a rotating BH,
  \[ \lambda_c > R_s \]
  the super radiance effect spins down the BH, populating bound orbits around the BH with an exponentially large number of particles.

- The BH already detected by LIGO/Virgo can act as attractors of QCD axions of the upper end of a mass range, which covers the parameter space for the QCD axion.
GW interferometer as detector of new elementary particles

In this proposed scenario black holes develop clouds of axions

The axion cloud will emit ~monocromatic GWs

Depending on the mechanism, these might be visible to tens of Mpc (Arvanitaki+ 1604.03958)

We can follow-up newly formed BHs and look for this signal.

Source-frame frequency depends on the mass of the axion

(Detected frequency will be redshifted)
Searching for ultra-light particles

\[ \mu_a = 10^{-10} - 10^{-14} \text{ eV} \quad \rightarrow \quad \lambda_c = 10 - 10^5 \text{ km} \]

Population inferences

Direct searches

Arvanitaki et al.,
PHYSICAL EFFECTS IN BINARY NEUTRON STAR COALESCENCE WAVEFORMS

- dominated by gravitational radiation back reaction - masses and spins
- tidal effects appear at high PN order, dynamical tides might be important
- complex physics of the merger remnant, multi-messenger source, signature of neutron star EoS

Credits: Sebastiano Bernuzzi
QCD Phase Diagram and Neutron Stars

Credits: Sanjay Reddy
Hard NS EOS
Soft NS EOS
Cosmology

To measure the cosmology one needs luminosity distance and redshift of the source

\[ D_L(z) = \begin{cases} 
\frac{(1+z)}{\sqrt{\Omega_k}} \sinh\left[\sqrt{\Omega_k} \int_0^z \frac{dz'}{H(z')}\right] & \text{for } \Omega_k > 0 \\
(1 + z) \int_0^z \frac{dz'}{H(z')} & \text{for } \Omega_k = 0 \\
\frac{(1+z)}{\sqrt{|\Omega_k|}} \sin\left[\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')}\right] & \text{for } \Omega_k < 0
\end{cases} \]

\[ H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_\Lambda E(z, w(z))} \]

\[ E(z, w(z)) = (1 + z)^3(1+w_0+w_1)e^{-3w_1 z/(1+z)} \]

Usually, GWs provide the distance
How do we get the redshift?
Cosmological corrections to CBC Signal

• If the source is at a cosmological distance with redshift $z$, then
  • distance $\rightarrow$ luminosity distance $D_L$,
  • Frequency is the observed one $f$ red-shifted by $(1+z)$ to the respect of the source frequency,
  • Each mass $m \rightarrow (1+z)m$.

$\langle h \rangle \propto (\mu M^{2/3} f^{2/3} / D_L) \Rightarrow \text{r.m.s. mean value of } h(t), \text{ averaged over the orientations of the source and the detector, referred to their joining direction.}$

$\tau = f / f' \propto \mu^{-1} M^{-2/3} f^{-8/3}$

$\langle h \rangle \tau$ is independent of the objects masses to the leading order
  • $D_L \rightarrow 1/ (\langle h \rangle \tau^3 f^2)$

$D_L \rightarrow z$ assuming $\Lambda$CDM cosmology with $H_0 = 67.9 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $\Omega_m = 0.306$
Building a new ladder up to cosmological distance

- CCB gravitational wave source is a "standard siren"
- Amplitude and phase of the GW due to CCB depend strongly on the chirp mass of the system, a parameter well measured. Thus, we can use the signal to infer the luminosity distance $d$
- At cosmological distances, the waves will depend on and reveal the redshifted masses $(1+z)\mu$ and $(1+z)\mathcal{M}$
- When the collision can be observed optically as well, the Doppler shift can be measured and the Hubble constant computed.

\[
h_y(t) = h_o(t) \begin{pmatrix} \cos \Phi(t) & \sin \Phi(t) & 0 \\ \sin \Phi(t) & -\cos \Phi(t) & 0 \\ 0 & 0 & 0 \end{pmatrix}
\]
\[
\Phi(t) = \int 2\omega(t) \, dt = -2\left[ \frac{c^3 (\tau_{\text{coal}} - t)}{5GM} \right]^{5/8} + \Phi_{\text{in}}
\]
\[
h_o(t) = \frac{4\pi^{2/3} \mu \mathcal{M}^{-5/3}}{d \, c^4} G^{5/3} v_{\text{GW}}(t)
\]
\[
\tau_{\text{coal}} = \frac{5}{256} \frac{c^5}{G^3} \frac{r_0^4}{\mu M^2}
\]
\[
\mathcal{M} = \mu^{3/5} M^{2/5} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \quad \mathcal{M} = \frac{c^3}{G} \left( \frac{5}{96} \frac{1}{\pi^{8/3}} \nu^{-11} \frac{d\nu}{dt} \right)^{3/5}
\]
How to get the redshift information

- If the CBC produces an EM counterpart (e.g. GRB) (Sathyaprakash+
  CQG 27 215006, Nissance + 1307.2638)

- If one knows the neutron star (NS) equation of state
  (Read & Messenger PRL 108 091101; Del Pozzo+ 1506.06590)
  *GW phase encodes the equation of state of neutron stars and it
  depends on the source-frame masses. If the EOS is known through other means (EM) one can measure both source-frame
  and redshifted masses, hence get the redshift*

- If the post-merger signal is observed (Messenger+ PRX 4, 041004)
  *Compare the measured redshifted frequency of the post merger
  phase with expected frequency gives redshift.*

- If the shape of NS mass distribution is known (Taylor+ PRD 85
  023535; Taylor & Gair PRD 86, 023502)

- Even if no EM is found, but there is a reliable galaxy catalog
  (Schutz, Nature 1986, Del Pozzo PRD 86 043011)
Conclusion

• The new run O3 with LIGO and Virgo is started on April 1st

• New GW signal have been collected already

• KAGRA in Japan will join the network before the end of the O3 run

• We are preparing plans for future upgrades a+ and AdV+ paving the way for the construction of the new 3 G detectors
Thanks for the attention

The future will be rich of new surprises and conundrums to be solved