# Gravitational Waves: where we are, where we go

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## Talk Outline

Where we are
 Status of the detectors

- Where we go
   Upgrades and new detectors
   Looking for new physics
- Conclusion

#### Status of the Virgo detector





New minimal target sensitivity: **60 Mpc** at horizon for a NSNS 1.4 M at SNR=8

Main benefit should come 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: **100 Mpc** @13W and without squeezing bench

> 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

#### To beat technical noises we need time for commissioning !!!



# Pre-installation: commissioning to cure glitches

V1:Hrec\_hoft\_16384Hz: cluster frequency vs. time



#### 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 )





Stray light hunting restarted adding extra baffles

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

We can inject in the ITF up to 50 W



#### Planning toward O3



#### Status of aLIGO detectors





# 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



 $10^{1}$ 

 $10^{2}$ 

Frequency [Hz]

 $10^{3}$ 

# KAGRA: a new partner will join soon the network

#### KAGRA project Kamioka mine, Japan

3 km, underground, cryogenic detector (20 K) waiting for funding

#### **Installation status**



### KAGRA status and plan



KAGRA collaboration has agreed to somehow accelerate the schedule to join O3 in 2019.

## Masses in the Stellar Graveyard



Credit: Robert Hurt/Aurore Simmonet/Frank Elavsky

- LIGO-Virgo has made first measurements of gravitational wave amplitude and phase
- Merging binary black hole and neutron star systems have been observed for the first time!

'a scientific revolution'

 Plans are underway to improve LIGO and Virgo sensitivity for O3 and beyond



#### ANTIMATTERWEBCOMICS.COM

# Future Upgrades and new detectors



..and UGO India plans to come online in 2024-2025

arXiv:1304.0670 Living Rev Relativ (2016) 19

#### What next?

2.5 G: a set of upgrades capable of enhancing the sensitivities of the current detectors (event rate 5-10x)

•AdV+ in Europe; A+ in USA

- Timeline: ~2024
- Cost: ~20÷30 M€

#### 3 G: new infrastructures/detectors capable of reaching the early universe. One order of magnitude gained in sensitivity wrt 2G –Timeline: ~2030 –Cost > 1 G€

•Einstein Telescope: EU for a nested assembly of co-located interferometers, 10 km long –underground

-bandwidth extended to 1 Hz

-cryogenics

•Cosmic Explorer: US idea for a 40 km interferometer

#### Current discussion in GWIC (Gravitational Wave International Committee) for a strong action coordinated at a global international level

#### Middle term: Advanced Virgo+ (AdV+)

LIGO and Virgo expected upgrade to 2.5 G at mid 2020s with a localization capability of 60% of sources within 10 deg<sup>2</sup> sources



New results expected in

- fundamental physics
- ➤ astrophysics
- ➤ cosmology
- nuclear physics

Upgrades split in two phases: Phase 1: BNS range up to 160 Mpc

- frequency dependent squeezing
- newtonian noise cancellation
- Preparation od Pahse II

Phase 2: BNS range up to 260 (300) Mpc

- new larger mirrors
- factor 3 of coating thermal noise reduction

#### Bridge to future 3G GW - stepping stone to 3G detector technology

#### AdV+ tentative timeline

Five year plan for observational runs, commissioning and upgrades



Note: duration of O4 has not been decided at this moment

## Einstein Telescope

The next gravitational wave observatory Coordinated effort with US

Worldwide for 3G network

#### **Conceptual Design Study**

#### EINSTEIN TELESCOPE



### Our Proposal is to have ET inSARDINIA



ET Symposium, April 20th, 2018

### POPULATION DENSITY



### LOCAL GEOPHYSICS



### SEISMIC MEASUREMENTS



More details are in Naticchioni et al. :

Microseismic studies of an underground site for a new interferometric gravitational wave detector

Class. Quantum Grav. **31** (2014) 105016 (20pp) doi:10.1088/0264-9381/31/10/105016

## ITALY GOVERNMENT SUPPORT

#### 17 MEuros for AdV+, ET R&D and support of the Sos Enattos candidature

#### ONDE GRAVITAZIONALI: MIUR, INFN E UNISS CANDIDANO LA REGIONE SARDEGNA A OSPITARE IL FUTURO OSSERVATORIO INTERNAZIONALE

🛗 Pubblicato: 22 Febbraio 2018



COMUNICATO CONGIUNTO MIUR/INFN/REGIONE SARDEGNA/UNISS\_II Ministero dell'Istruzione, dell'Università e della Ricerca sosterrà la candidatura della Regione Sardegna a ospitare un Centro europeo per l'Osservatorio delle onde gravitazionali nella miniera di Sos Enattos a Lula. Il MIUR, la Regione, l'Istituto Nazionale di Fisica Nucleare e l'Università di Sassari hanno firmato un Protocollo d'intesa finalizzato a mettere in atto ogni iniziativa utile a favorire l'insediamento della infrastruttura

Einstein Telescope nell'Isola, anche con lo scopo di entrare nella lista delle infrastrutture di ricerca riconosciute a livello europeo. Il progetto era stato presentato lo scorso 7 febbraio a Roma alla ministra Valeria Fedeli dal presidente della Regione Francesco Pigliaru e dall'assessore della Programmazione

Ministero dell'Istruzione dell'Università e della Ricerca



REGIONE AUTÒNOMA DE SARDIGNA REGIONE AUTONOMA DELLA SARDEGNA



Istituto Nazionale di Fisica Nucleare



## LOCATION - TRIANGLE



## GEOLOGICAL SECTIONS

#### Intrusive complex



Granodiorites and monzogranites

Metamorphic basement

Orthogneiss





vertical exaggeration 10x

## LOCATION - L



## A robust R&D program for ET

An R&D program, focused on some crucial technologies, will pave the way for the realization of the next generation of instruments:

- the improvement of the VIRGO seismic attenuation system, to improve the low frequency sensitivity and to maintain the INFN historic leadership in this field
- the design, construction and test of a cryogenic payload
- the development of innovative frequency dependent squeezing techniques, to reduce quantum noise;
- the improvement of the (optical and mechanical) losses of the mirrors' coatings, to reduce thermal noise

#### New Physics with the 3G detectors

### New Physics with the New Detector

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
## **Extreme Physics**



#### Credits Aaron Zimmerman

## **BBH** population study

The detected signals confirmed the existence of black holes with masses larger than 20  $\rm M_{\odot}$ 

- 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.

## BBH population study: from 2G to 3G

Under a simplified hypothesis of a uniform distribution of BBH creation on the universe history

With a 3G detector we expect

- 10<sup>5</sup> y<sup>-1</sup> BBH
- SNR ~ 10<sup>4</sup> for rare events
- Population study biased in function of the achievable SNR

**GW signal amplitude** depends on  $\mathcal{M}^{5/2}$  $\mathcal{M} = chirp \ mass = (m_1 \ m_2)^{3/5} / (m_1 + m_2)^{1/5}$ Higher  $\mathcal{M} \rightarrow$  easier detection **GW signal duration** decreases with  $M_{tot} = m_1 + m_2$ 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)

Salvatore Vitale, Phys. Rev. D 94, 121501 (2016)



FIG. 2. The redshift distribution of detectable events with a 2-detector network of advanced detectors at design (2G) or CE-like (3G). Note that the two curves use different y scales to improve clarity.



FIG. 3. The source-frame total mass distribution of detectable events with a 2 interferometers network of advanced detectors at design (2G) or CE-like (3G).



#### Testing GR via Polarization

#### 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

## Ringdown of a Kerr Black hole





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



Berti, Cardoso, Starinets (2009)

#### BH spectroscopy with the future detectors

- 3G 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



Brito, Buonanno, Raymond arXiv:1805.00293

## QNM to Probe Wormhole Spacetime



A point particle plunges radially and emerges in another "universe". When the particle crosses each of the light rings curves, it excites <u>QNM characteristic modes</u> 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

## **Echos Searches**

- Exotic compact objects (ECOs): resemble BHs
- But are not perfectly absorbing
- Parametrize by reflecting barrier
- Initially ringdown normally
- Waves going into the horizon become "echoes"

Abedi, Dykaar, Afshordi 1701.03475 Conklin, Holdom, Ren 1712.06517

Abedi, Afshordi 1803.10454



Westerwick et al.1712.09966

Ashton et al. 1612.05625

Tsang et al. 1804.04877

Time delay between the echoes is related to the ECO compactness while the decay and shape of each pulse encodes the reflective properties of the ECO

## BH and particle physics

With a stellar mass BH we have a new precision tool that may diagnose the presence of new light (10<sup>-20</sup> 10<sup>-10</sup> eV) and weakly interacting bosonic particles

When such a particle's Compton wavelength is comparable to the horizon size of a rotating BH,

$$\lambda_{\rm C} \gtrsim R_s$$

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

 $\mu_a = 10^{-10} - 10^{-14} \,\mathrm{eV} \longrightarrow \lambda_c = 10 - 10^5 \,\mathrm{km}$ 



Population inferences

**Direct searches** 

Arvanitaki et al., Phys. Rev. D 95, 043001 (2017)

#### Measuring the EOS of dense nuclear matter



#### **Binary Neutron Star Merger**



#### The waveform

s,



Tidal field \$\varepsilon\$ of one companion induces a quadrupole moment Q in the other
 In the adiabatic approximation \$Q\_{ii} = -\lambda (m) \varepsilon\_{ii}\$ \$\lambda (m) = 2/3 k(m) R^5(m)\$

 $\lambda(m) \rightarrow$  tidal deformability, (size of the quadrupole deformation/strength of external field),  $k_2(m) \rightarrow$  Love number,  $R \rightarrow NS$  radius

#### 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 Credits: Sebastiano Bernuzzi

complex physics of the merger remnant, multi-messenger source, signature of neutron star EoS

#### Hard NS EOS



 $f(H_{7})$ 

#### Soft NS EOS



1 1 1->

#### GW170817: first result on cosmology

~11% GW luminosity distance

•LVC measurement  $\rightarrow$  14% (1 $\sigma$ ) uncertainty

• ~3% peculiar velocity of the galaxy



#### Cosmology

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

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

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

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

Usually, GWs provide the distance How do we get the redshift?

#### How to get the redshift information

#### If the CBC produces an EM counterpart (e.g. GRB) (Sathyaprakash+

CQG 27 215006, Nissanke+ 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)

#### Neutron stars mass distribution

- Neutron star masses are expected to lie in a narrow range
- If one knew the shape of mass distribution could compare measured (redshifted) masses with expected ones, and infer the redshift



## Conclusion

- The installation phase of the new parts is ended in Virgo and (almost) in LIGO
- We are back in the commissioning phase to prepare he new run that we plan to start at the beginning of 2019
- We prepared already plans for future upgrades a+ and AdV+ paving the way for the construction of the new 3 G detectors
- New GW detectors will open a new era in Astronomy and fundamental physics

#### Thanks for the attention

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

## Extra Slides

# **Gravitational Wave Periods**









# Echoes from compact objects

- Exotic compact objects (ECOs): resemble BHs
- But are not perfectly absorbing
- Parametrize by reflecting barrier
- Initially ringdown normally
- Then it contains a train of decaying echo pulses

Cardoso, Franzin, Pani, PRL 116, 171101 (2016) Mark, Zimmerman, Du, Chen, PRD 96, 084002 (2017)



Time delay between the echoes is related to the ECO compactness while the decay and shape of each pulse encodes the reflective properties of the ECO Echoes from compact objects Event horizon 
the heart of the BH information paradox BH in a quantum theory of gravity 
an open question

Horizonless alternatives to BH: gravastars, boson stars, wormholes,.....



- Initially ringdown normally
- Waves going into the horizon become "echoes"

Cardoso, Franzin, Pani, PRL 116, 171101 (2016) Mark, Zimmerman, Du, Chen, PRD 96, 084002 (2017)

#### Waveform: Tidal term +..... A contribution at 5 PN → (v/c)<sup>5</sup>

$$\begin{split} \Psi(v) &= \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v), \\ \Psi_{\rm tidal}(v) &= \frac{3}{128\eta} v^{-5} \sum_{A=1}^{2} \frac{\lambda_A}{M^5 X_A} \left[ -24 \left( 12 - 11 X_A \right) v^{10} \right. \\ &\quad + \frac{5}{28} \left( 3179 - 919 X_A - 2286 X_A^2 + 260 X_A^3 \right) v^{12} \\ &\quad + 24\pi (12 - 11 X_A) v^{13} \\ &\quad - 24 \left( \frac{39927845}{508032} - \frac{480043345}{9144576} X_A + \frac{9860575}{127008} X_A^2 \right. \\ &\quad - \frac{421821905}{2286144} X_A^3 + \frac{4359700}{35721} X_A^4 - \frac{10578445}{285768} X_A^5 \right) v^{14} \\ &\quad + \frac{\pi}{28} \left( 27719 - 22127 X_A + 7022 X_A^2 - 10232 X_A^3 \right) v^{15} \right] \\ X_A &= m_A/M, \ A = 1, 2, \ \text{and} \ \lambda_A &= \lambda(m_A) \\ X_A &= m_A/M, \ A = 1, 2, \ \text{and} \ \lambda_A &= \lambda(m_A) \end{split}$$

#### .....Quadrupolar Term



Testing GR: example via Post Parametrized Expansion Phenom consistency test  $h(f) = A(f, \vec{\theta})e^{i\Psi(f, \vec{\theta})}$ 

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

 $p_i \to p_i (1 + \delta \hat{p}_i)$ 


## Looking ahead for tests of GR

- Precision era ahead: modeling challenges
  - Part in 10<sup>-4</sup> 10<sup>-5</sup> 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