Gravitational wave
Recent results

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2018 LHC days in Split
What are Gravitational waves?

- Solution from General Relativity derived by A. Einstein in 1916
- Far from sources they can be seen as a perturbation of the metrics i.e.:
  - They are ripples of space-time produced by rapidly accelerating mass distributions
  - Provide info on mass displacement
  - Weakly coupled – access to very dense part of objects
- Main properties:
  - Propagate at speed of light
  - Emission is quadrupolar at lowest order
  - Two polarizations ‘+’ and ‘x’
  - Produce a differential effect on metric
GW network

aLIGO Hanford, 4 km
9/2015

GEO, Hannover, 600 m

aLIGO Livingston, 4 km

8/2017

AdV, Cascina, 3 km

~2019

~2024
Detectors evolution

- O1
- O2

Graph showing the evolution of detectors from 2005 to 2019 with different colors representing different detectors (V1, L1, H1) and years (2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019).
GW detections

Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

LIGO-Virgo | Frank Elavsky | Northwestern
Coalescing binaries

- Searching for objects containing black holes (BH) and neutron stars (NS)
- Possible electromagnetic emission if one object is a NS
- Known waveforms from analytical model or numerical relativity simulations
- Waveform allow to retrieve:
  - Masses: ratio and total mass
  - Spins: initials and final object(s)
  - Geometry of the system
  - Distance
  - Total energy dissipated
- Can be used to test GR
Detecting black holes

- Detected Binary Black Holes in the mass range: $5 - 50 \, M_\odot$
- Detection range up to $\sim$Gpc, mostly $\sim$450 Mpc
- Rate: $R = 12 - 213 \, \text{Gpc}^{-3} \, \text{yr}^{-1}$
- A large fraction of energy in GW: 1 to 3 $M_\odot$
- No large constraint on spins

Abbott et al, PRX 6 041015 (2016)
Sky error regions

Sky map reconstructed with time of flight technic
Large improvement since Virgo joined data taking
Testing General relativity in a new regime

- We have for the first time test under highly relativistic and non linear conditions
- Different tests can be performed:
  - Remove waveform and see any deviation from noise in the data: possible deviations less than 4%
  - Check the consistency of the waveform if:
    - Look only the pre merger phase
    - Use the remaining time serie

Abbott et al. PRL 116, 221101

Abbott et al. PRL 118, 221101
Constraining parametrization deviations

- We can test any non linear deviation to GR
- Using the complete waveform it then possible to test any deviation in the different orders of the post-Newtonian development of the waveforms with phase evolution

Abbott et al, PRX 6 041015 (2016)
Can we say something on graviton?

- If we postulate a massive graviton we need to take into account Yukawa type correction to Newtonian potential.
- This will induce a dispersion depending on the frequency and can be tested with 1 PN order.

\[
\frac{v_g^2}{c^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}
\]

\[
\lambda_g = \frac{h}{m_g c}
\]

\[\lambda_g > 10^{13} \text{ km}\]

\[m_g < 10^{-22} \text{ eV}\]
Polarization in GR

- Generic theories predict up to 6 polarizations states
- With a third detector (non aligned) : test new types of polarizations

**Only ones expected with GR**

**Allowed by other gravitation theories**

**Tensor modes**

**Vector modes**

**Scalar modes**

**Antenna pattern**

Favor pure tensor vs pure vector or scalar

Cannot conclude on mixed version

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott et al., PRL 119, 141101
GW170817: First binary neutron star

- SNR ~ 32.4,
- FAR < 1 $10^{-4}$ /year
- Long event (~100 secs)
  - light masses system!
- Probability to have at least one neutron star is important
- Possible electromagnetic counterpart!

$$M_{\text{Chirp}} = \frac{(m_1m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_{\odot}$$

Known BNS
- $|\chi_z| < 0.05$
- $|\chi_z| < 0.89$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Abbott et al., PRL 119, 161101
A first electromagnetic counterpart

- Association to a gamma-ray burst (> 5.3 $\sigma$) within 1.7s and same sky region
- Including the 3 interferometers -> 28 deg$^2$
- Radio to X-rays counterpart found (latency hours to days)
- Found in NGC4993, distance determined between EM and GW compatible
- Kilonova emission
Equation of state of nuclear matter

- Among the most densest objects in the Universe
- Large uncertainties on their structure
  - Structure of the crust
  - Neutron superfluid in outer core
  - Deep core composition?
  - Magnetic fields

- GW information complementary to the LHC
- Equation of state influence:
  - Pressure as function of density
  - Mass as function of radius
  - Tidal deformability
  - Impact on post merger
Properties of the binary neutron star merger GW170817, Abbott et al, submitted to PRX

- Tidal effects when stars are close
- Affect the GW waveform
- Compact stars are favored
- Consistent with radius below 14 km
- 10s of detections to distinguish between the models
- First detections of pulsars will also add constraints
Hubble constant measurement

- For closed-by source: $v = H_0 D$
- EM counterpart found in NGC4993, can then measure redshift
- GW: Distance and orientation are correlated
- 10s of common detections to reach few % precision

\[ H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

\[ h(t) \propto \frac{M_{\text{chirp}}^{5/6}}{D} f(\cos i) \]
Common GW-GRB analysis
Test for fundamental physics using time delay and source distance

- **Speed of gravity:**
  \[-3 \times 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7 \times 10^{-16}\]

- **Equivalent principle (Shapiro effect):**
  \[-2.6 \times 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \times 10^{-6}\]
  Deviation to Einstein-Maxwell

- **Lorentz Invariance violation:**
  Improve between a factor 2 and $10^{10}$ previous constraints
  Falsify most of models predicting a difference with $c$

Common GW-GRB analysis
Astrophysical impact

- Binary neutron star can be central engine of short GRBs
- Short timescale: fireball model with internal shocks
- 2 energy components
- Softer component could come from photosphere of the fireball
- Time delay could then be due to:
  - Propagation of the shells in the jets
  - Time needed for the fireball to become optically thin to gamma-rays

Kilonova

- During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
- Quasi isotropic emission, heated by radioactivity, emission expected to shift from blue to red during cooling
Kilonova – spectral observations

- Spectrum favor a relativistic ejecta
- Rule out supernova hypothesis
- 11000 K at day 1, 5000 K a day later, 1400 K 10 days later
- Spectrum show contributions from heavy elements
Conclusions

- **O2 run analysis close to be finished**
- **6 detections up to now**
  - Black holes with large masses
  - First binary neutron star merger, observed in coincidence with a short gamma-ray burst
  - Test on GR passed
  - First H0 measurement
- **New run in 2019 (O3) for one calendar year**
  - 3 detectors at beginning
  - KAGRA may join before the end of the data taking
Backup
Advanced generation detectors

Michelson interferometer
Goal: \((L_x - L_y)/L_x = 10^{-23}\)

Feedback loops from few Hz to few kHz

High power laser

High quality optics – 40 kg
Surface RMS ~nm

Fabry-Perot cavities

Full system under vacuum \(\sim 10^{-12}\) atm

Suspended Optics

Attenuation \(10^{14} \text{ @ } 10\text{ Hz}\)