Science with the Einstein Telescope

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11th ET Symposium
Advanced LIGO/Virgo have truly opened a new window on the Universe

GW150914: first detection of a BH-BH coalescence, September 14, 2015

GW170817: birth of multi-messenger astronomy
• LIGO/Virgo detections in O1/O2/O3a during O3, detections have become a routine (1/week) +NS-NS, NS-BH
What we have learned? Some highlights:

**Astrophysics**

- GW170817 solved the long-standing problem of the origin of (at least some) short GRBs
- NS-NS mergers are a site for the formation of some of the heaviest elements through r-process nucleosynthesis
- BH-BH binaries exist and merge within the age of the Universe
- Discovered a new population of stellar-mass BHs, much heavier than those detected through X-ray binaries
Cosmology/fundamental physics

• speed of GWs equal to speed of light \((1:10^{15})\)

• first measurement of the Hubble constant with GWs

• the tail of the waveform of GW150914 consistent with the prediction from General Relativity for the quasi-normal modes of the final BH

• deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded
Still, 2G detectors lack the sensitivity to make really stringent tests of fundamental physics/cosmology.

2G detectors have opened a new window:
3G detectors ground-based detectors (ET, CE) will look deeply into this window.

We will focus on the science that can be done with ET based on
MM et al “Science Case for the Einstein Telescope”, JCAP, 1912.02622 see also 3G Science Book, in preparation

More details in the session of Tue. (15h00 CEST)
- BBH to $z \approx 20$
  $10^6$ BBH/yr
  masses up to $10^3 \, M_\odot$
- BNS to $z \approx 2 \times 10^5$ BNS/yr
  (possibly O(10yr) with counterpart)
- high SNR

Evans and Hall 2019

courtesy Colpi and Mangiagli
The combination of
• distances and masses explored
• number of detections
• detections with very high SNR

will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics
A summary of the Science of ET

Astrophysics

• Black hole properties
  – origin (stellar vs. primordial)
  – evolution, demography

• Neutron star properties
  – interior structure (QCD at ultra-high densities, exotic states of matter)
  – demography

• Multi-messenger astronomy
  – joint GW/EM observations (GRB, kilonova,...)
  – multiband GW detection (LISA)
  – neutrinos

• Detection of new astrophysical sources
  – core collapse supernovae
  – isolated neutron stars
  – stochastic background of astrophysical origin.
Fundamental physics and cosmology

- The nature of compact objects
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects

- Tests of General Relativity
  - post-Newtonian expansion
  - strong field regime

- Dark matter
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
• Dark energy and modifications of gravity on cosmological scales
  – DE equation of state
  – modified GW propagation

• Stochastic backgrounds of cosmological origin and connections with high-energy physics
  – inflation
  – phase transitions
  – cosmic strings
  – ...

... and we should not forget that ET will be a `discovery machine’

Expect the unexpected!
Astrophysics with BBH

ET will uncover the full population of coalescing stellar BBH since the end of the cosmological dark ages

(a single BBH has a peak luminosity higher than the integrated em luminosity of the observable Universe!)

• contribute to uncover the star-formation history of the Universe
• disentangle stellar origin from primordial BH
  – compare redshift dependence with SFR determined electromagnetically
  – PBH should trace the distribution of DM rather than of baryons
    the large number of detections will allow cross-correlations
  – any stellar-mass BBH at $z > 10$ will be primordial
  – predictions for spin, mass distribution,...
• discover seed BHs with $M=O(10^3) \, M_\odot$

see talk by A. Lamberts
QCD with neutron stars

BNS merger @100 Mpc
(adapted from J. Read)

See talk by T. Hinderer
Multi-messenger astronomy

- formation, evolution and multi-messenger emission mechanism of BNS (kilonovae, short GRBs)
- star formation history, chemical evolution of the Universe
- Low z:
  - higher SNR \( \rightarrow \) constrains on EOS (from info progenitors and remnant)
  - Golden sample of detection with localization < 1 deg\(^2\)
  - possibility to detect the kilonova with the second generation instruments of ELT such as MOSAIC
- High-z: benefits in operating with high-energy satellites able to localize GRBs (large sample of detection for cosmology, GRB emission mechanism, jet physics)
  - e.g. THESEUS for short GRB, O(10/yr) on-axis, several tens off-axis
with ET alone: at low $z$, large benefit from operating with 2G

see talks by M. Branchesi, G. Greco, triangle vs 2L, see talk by S. Grimm
BH quasinormal modes and Exotic Compact Objects

BHs have QNM: they represent the elasticity of space-time in a regime of strong gravity. GR predicts their frequency and damping time as a function of mass and spin.

Classic works since the 50s: Regge-Wheeler, Chandrasekhar, Teukolsky...

Several proposals for ECOs (boson stars, stars made of DM particles...) are distinguishable because of the QNM and/or Echoes.

See talk by V. Cardoso.
From GW150914: (LVC)

consistent with GR, but we cannot say much more

at ET:

3G Science Book, elaborating on Brito, Buonanno, Raymond 2018
• on the bold side:

quantum gravity at the BH horizon?

BHs can act as ‘magnifiers’ of quantum gravity effects
e.g. imprints of BH area quantization?

\[ A_n = 8\pi \ell_{P_1}^2 n \]
\[ A = 4\pi (2M)^2 \]
\[ \omega = \frac{\Delta M}{\hbar} = \frac{1}{4M} \]
\[ \Delta A = 8\pi \ell_{P_1}^2 \]
\[ \Delta A = 32\pi M \Delta M \]

of the same order as QNM frequencies!

Agullo, Cardoso, del Rio, MM, Pullin 2020
Cosmology and DE with ET

Observational tensions, in particular early- vs late-Universe probes of $H_0$

maybe already solved by the time of 3G detectors?
although, not really sure with 2G detectors...

$O(50-100)$ standard sirens at 2G
needed to arbitrate the discrepancy

• no counterpart in O3
• dark sirens have complicated systematics
The GW amplitude provides the luminosity distance of the source

\[ d_L(z) = \frac{1 + z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1 + \tilde{z})^3 + \rho_{DE}(\tilde{z})/\rho_0}} \]

\[ \Omega_M = \frac{\rho_M(t_0)}{\rho_0}, \quad \rho_0 = \frac{3H_0^2}{8\pi G} \]

- need an independent determination of \( z \)
  (electromagnetic counterpart, statistical methods)

- low \( z \): Hubble law, \( d_L \approx H_0^{-1}z \)
- moderate \( z \): access \( \Omega_M, \rho_{DE}(z) \)
$p_{DE}(z) = w_{DE}(z) \rho_{DE}(z) \implies \frac{\rho_{DE}(z)}{\rho_0} = \Omega_{DE} \exp \left\{ 3 \int_0^z \frac{dz}{1 + \tilde{z}} [1 + w_{DE}(\tilde{z})] \right\}$

Several studies of forecasts for $w_{DE}$ at ET

Result: not a significant improvement on $w_{DE}$ compared with what we already know from CMB+BAO+SNe

A potentially more interesting observable: modified GW propagation

see talk by E. Belgacem

Belgacem, Dirian, Foffa, MM 1712.08108, 1805.08731
Belgacem, Dirian, Finke, Foffa, MM 1907.02047, 2001.07619
Belgacem et al, LISA CosWG, 1907.01487
Dark matter

Several DM candidates can be studied (only?) by ET

• **primordial BHs**
  – BBH at $z \sim 10-20$,
  – masses down to $(0.1-1) M_\odot$
  – correlation with LSS

• **ultralight axions** (via axion clouds around BHs)

• **DM particles captured in NS/BH**
  – DM core in NS, drag in binary systems
Stochastic backgrounds

vacuum fluctuations from slow-roll inflation too small, but other inflation-related mechanisms can produce detectable signals

- cosmic strings
- 1st order phase transitions at $T \sim 10^7$-$10^{10}$ GeV
- anisotropies, multipole expansion

see talk by G. Cusin
Thank you!