Einstein Telescope

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Wigner VIRGO Group and MGGL

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Content

- 2g gravitational wave detectors
- 3g: Einstein Telescope (ET)
- New physics with ET
- Wigner group activities: site selection +
Ripples in spacetime

- General relativity, connects the curvature of spacetime with the matter content, its motion and properties

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

- Gravitational waves, change of gravitational field, ripples of spacetime, propagating with the speed of light

- Linear approximation, far from the source GWs are described as the perturbation of the flat metric

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

\[ \eta^{\rho\sigma} h_{\mu\nu}^{\rho\sigma} = -16\pi T_{\mu\nu} \]
2g detectors worldwide
Sensitivity of GW detectors

- Sensitivity of first (2009 - 2010) and second (2017) generation detectors

Scientific Runs S1 – S6

Observation Runs O1 – O2
GW observations

- 11 confident detections in O1 and O2, 1 BNS and 10 BBH, 11 marginal triggers
  - Total mass $18.6 - 85.1 \, M_\odot$
  - Distance $40,320 - 2750 \, \text{Mpc}$
  - 1 detection / 15 days of data searched
GW observations

- GW170729 the most massive $80 \, M_\odot$ and distant $1250 \, \text{Mpc}$ GW source
- GW170818 best localized $39 \, \text{sq}^2$ BH source

BH or a hypermassive NS
Observation plan

LIGO-VIRGO Joint Run Planning Committee

**Working schedule for O3**
(Public document G1801056-v4, based on G1800889-v7)

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<th>2018</th>
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- **LIGO H1**
  - Commissioning
  - ER13
  - Commissioning
  - ER14
  - O3: one calendar year long

- **LIGO L1**
  - Commissioning
  - ER13
  - Commissioning
  - ER14
  - O3: one calendar year long

- **VIRGO**
  - Commissioning
  - ER13
  - Commissioning
  - ER14
  - O3: one calendar year long

- **GEO**
  - ~70% observing mode

Legend:
- Detector operational/commissioning mode (small fraction of observing mode time)
- Detector in observing mode for a fraction of the time during Engineering Runs (ERs), possible GW alerts with human vetting
- Detector not producing data (downtime)
- 24/7 observing mode (Observing Run, Open Public Alerts in low-latency)
Observatories in the next 10 years

- Heterogeneous network of observatories
- Obsolescence / limits of the instruments
- Quest for new research infrastructures / more than a new detector

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<th>Detector</th>
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- 3g: Einstein Telescope (ET)
3G / ET

- Scientific relevance in Europe
- 3G new observatory / infrastructure ET
- 10x better sensitivity compared to 2G (1000x more BH observations)
- Wide frequency, special attention to low frequency
- Capable to work alone
  - Localization capability
  - Polarizations
  - High duty cycle / redundancy
- 50 years lifetime

www.et-gw.eu
Evolution of interferometers

- 2\textsuperscript{nd} generation, VIRGO, LIGO
  - Dark fringe operation
  - Power recycling
  - Fabry-Perot arm cavities
  - Input mode cleaning
  - Signal recycling
  - Squeezed light
  - Suspension systems (passive, active)

- 3\textsuperscript{rd} generation, e.g. ET, 10 x sensitivity improvement Design Study 2011
  - Larger laser, 125 W → 500 W
  - Bigger mirrors, 30 kg → 210 kg
  - Longer arm, 3.4 km → 10 km
  - Cooling, 290 K → 20 K
  - Underground operation
Standalone observatory

- Improving at low and high frequencies with a single detector
- LF: cold mirrors ↔ HF: more laser power
- Split the detection band with 2 specialized instruments
Standalone observatory

- Start with a single – xylophone – detector
- Add a second one to resolve polarization
- Add a 3rd one for null stream and redundancy

Einstein Telescope
Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filter cavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF:IFO) of which 12 are cryogenic.

Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linear filter cavities and 54 for triangular filter cavities

Beams per tunnel = 7
ET timeline

ET project roadmap (APPEC):

- 2018-19 formation of ET collaboration (LoI signatures, ...)
- Site selection parameters (Italy, Hungary, The Netherlands)
- Several options xylophone vs. L shape: Cosmic Explorer, LIGO Voyager
- 2022 Site selection (technical and political)
- 2023 Full technical design report. Here the design options are frozen.
- Cost definition
- 2025 Infrastructure realization (excavation, etc..)
- 2030-31 end of infrastructure construction, beginning of installation
- 2032+ installation, comissioning, operation

M. Punturo
- New physics with ET
GW / multi-messenger astronomy

Frequency [Hz]

ELF
- Primordial gravitational waves
- Inflation

VLF
- Supermassive Black Hole Binaries
- Cosmic strings

LF
- Stellar mass compact binaries
- Massive black hole mergers

HF
- Neutron star binaries
- Black hole binaries
Sensitivity improvement

- Mass accuracy
- High mass / high z
- Merger physics localization
- Number of sources
Questions addressed by GWs

- **Fundamental questions in Gravity:**
  - New/further tests of GR
  - Exploration of possible alternative theories of Gravity
  - How to disprove that Nature black holes are black holes in GR (e.g. non-tensorial radiation, quasi normal modes inconsistency, absence of horizon, echoes, tidal deformability, spin/induced multipoles)

- **Fundamental questions in particle physics**
  - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population characteristics, of Bhs, Nss

- **EOS of neutron stars**

- **GW models in alternative theories of gravitation**

- **Te population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs?**

- **Explosion mechanisms in Supernovae?**

- **History of supermassive black holes?**

- **GW stochastic background? Probing the big bang?**

- **Multimessenger astronomy in 3G?**
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- Multimessenger astronomy in 3G?
Neutron Stars

- Neutron stars are extreme labs for nuclear physics
- EOS and tidal deformability / Love number
Binary coalescences

- Well defined waveform templates for the early and late stages
Low frequency - multi-messenger astronomy

- GWs are the only messengers to bring information before coalescence
- Early warning of EM observatories
- Low frequency sensitivity is a key factor
- Wigner group activities:
  wave forms, pn calculations
  site selection
  Newtonian noise, material models
  Eötvös balance
Low frequencies: seismic and Newtonian noise

Active damping for newtonian noise and for seismic below 4 Hz
Maximum passive damping: 10 Hz, $10^{15}x$
ET site selection

- European effort, 3 candidates based on original studies
- Long-term measurements: Mátra Gravitational and Geophysical Laboratory
Optimal noise level

- Left: Baker et.al. (2015), short term, Right: Somlai et.al. (2018), 2 weeks
- Plotted: Acceleration ASD, 10 – 90 percentiles (stripe), and the mode (line)
- Cumulative characteristics, $rms_{2Hz}$
  - Beker et.al. (2011): 0.082 nm (5 days)
  - Somlai et.al. (2018): 0.083 nm (2 weeks)
Newtonian noise

What is a rock?
What is a rock?
Jánossy Underground Physical Laboratory
Eötvös balance measurements

- MTA Wigner RCP and BME
- Aim: Eötvös year, weak equivalence principle, *Newtonian noise*
„…..still we are very much aware that the observations presented here were not made under the most favorable conditions, also, they are not the best that we believe are achievable with our instrument. But: „Ars longa vita brevis” - we have to content ourselves with having made a step forward.”

Handwritten draft of Roland Eötvös, 1909. (to be published)
Thank you for your attention!
Waveforms

- Numerical evolution
e.g. LORENE, KADATH

- GR and hydrodynamics
e.g. Rezzola and Takami, 2016
Waveforms

- **Stationary Phase Approximation**

\[ \tilde{h}_T(f) = A f^{-7/6} e^{i \Psi_T(f)} \]

- **GW phase**

\[ \Psi_T(f) = \phi_c + 2\pi ft_c + \frac{3}{128\eta v_5^5} \left( \Delta \Psi_{3.5\text{PN}}^{pp} + \Delta \Psi_{3\text{PN}}^{\text{spin}} + \Delta \Psi_{2\text{PN}}^{\text{ecc.}} + \Delta \Psi_{6\text{PN}}^{\text{tidal}} + \Delta \Psi_{6\text{PN}}^{\text{tm}} \right) \]

- **NS tidal love number:** \( \sim \text{few hundred} \)
  
  for black holes: \( 0 \)

\[ \Delta \Psi_{6\text{PN}}^{\text{tidal}} = -\frac{39}{2} \tilde{\Lambda} v^{10} + v^{12} \left( \frac{6595}{364} \delta \tilde{\Lambda} - \frac{3115}{64} \tilde{\Lambda} \right) \]
First BNS merger – GW170817

- The tidal field of the companion induces a mass-quadrupole moment

- Tidal deformability
  \( \Lambda \sim \text{quadrupole moment} / \text{external tidal field} \)

- Measurements disfavor EOS that predict less compact stars

\[ \Lambda = \left( \frac{2}{3} \right) k_2 \left[ \left( \frac{c^2}{G} \right) \left( \frac{R}{m} \right) \right]^5 \]
Observations with such delicate instruments should be made in a vibration-free environment which is also protected from temperature variations, and especially from the effects from unilateral irradiation. Windowless chambers in basements would fit those conditions best. Unfortunately, no such chambers were available for us. Time was pressing so we had to be content with an observation room located at the second floor. Of the laboratory available to us and had two windows looking South. However, buildings on the opposite side cast their shadow on these windows during most of the day, also, they were obstructed by rolling curtains, this the room was kept dark all the time. For even more complete protection even within the room a separate housing was built for each instrument, whose walls consisted of canvas sheets stretched on double frames, and the space between was filled with fine sawdust and sewn stitched blankets.

Since the room where we made our observations was away from street traffic initially we had no reason to be worried about stronger vibrations, but unfortunately the circumstances deteriorated when a new construction was started in close vicinity during the observations.

Although the results of observations show no significant influence of these circumstances, still we are very much aware that the observations presented here were not made under the most favorable conditions, also, they are not the best that we believe are achievable with our instrument. But: „Ars longa vita brevis“ — we have to content ourselves with having made a step forward.