Gravitational wave physics
what we know and what we want to know

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Academic training lectures
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Outline

1) What we know
   - Motivation
   - What is a GW?
   - LIGO: signal & detection
   - LIGO: some highlights

2) Current frontier
   - GW background
   - Pulsar timing arrays
   - BSM searches with GWS

3) What we want to know
   - Going to space & underground
   - New opportunities at new frequencies

Literature:
- M. Maggiore, GWs, Vol I
- C. Caprini, D. Figueroa, Cosmological backgrounds of GWs, arxiv: 1801.04268
10 km arms, 250 – 300 m underground, cyrogenic cooling, squeezed light, xylophone,...
possible locations: NL/BE/DE, IT, DE + Cosmic Explorer in the US
Einstein Telescope (ET)

Some science highlights:

- Detect all stellar origin black hole binaries in the observable universe (red shift reach beyond star formation)

- Detect $\sim 10^4$ neutron star mergers per year (→ H0 measurement, QCD equation of state, ...)

- Test of general relativity to sub-permille level

- Detect astrophysical background from black hole binaries and search for cosmological backgrounds

- New astrophysical sources: supernovae, single neutron stars, ...

CERN involvement in civil engineering, technology development, theory,..
Laser Interferometer Space Antenna (LISA)

3 satellites trailing earth in orbit around sun, 2.5 million km arms, laser links
ESA adopted mission with NASA participation, 2030s.
LISA: Sources

LISA red book: 2402.07571
LISA : Sources

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GW amplitude

Strain Amplitude Spectral Density [\mu]\text{m}/\sqrt{\text{Hz}}

10^{-15}

10^{-16}

10^{-17}

10^{-18}

10^{-19}

10^{-20}

10^{-21}

Frequency [Hz]

10^{-4}

10^{-3}

10^{-2}

10^{-1}

10^0

SNR (MBHB)

1400

1200

1000

800

600

400

200

0

Galactic Binaries
Verification Binaries
Stellar Mass BH Binaries
Multiband Sources
 Extreme Mass-Ratio Inspiral
Massive BH Binaries

Observatory Sensitivity
Galactic Foreground
Total

instrument sensitivity
LISA: Sources

LISA red book: 2402.07571

GW amplitude

Strain Amplitude Spectral Density [\mu{\text{A}}/\text{Hz}]

Frequency [Hz]

Observatory Sensitivity
Galactic Foreground
Total

10^7 M_\odot
5 \times 10^6 M_\odot
5 \times 10^5 M_\odot

SNR (MBHB)

instrument sensitivity
LIGO – like BHs

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LISA: Sources

massive black hole binaries

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GW amplitude

Strain Amplitude Spectral Density [μ/m/sqrtHz]

Frequency [Hz]

10^-21
10^-20
10^-19
10^-18
10^-17
10^-16
10^-15

10^-4
10^-3
10^-2
10^-1
10^0

10^7 M☉
5 x 10^6 M☉
5 x 10^5 M☉
5 x 10^4 M☉

Observatory Sensitivity
Galactic Foreground
Total

SNR (MBHB)

0
200
400
600
800
1000
1200
1400

Galactic Binaries
Verification Binaries
Stellar Mass BH Binaries
Multiband Sources
Extreme Mass-Ratio Inspirals
Massive BH Binaries

instrument sensitivity

LIGO – like BHs
LISA : Sources

massive black hole binaries

white dwarfs

stochastic background from galactic binaries

LISA red book: 2402.07571

GW amplitude

Strain Amplitude Spectral Density $[\text{d}^{2} / \sqrt{\text{Hz}}]$}

LIGO – like BHs

instrument sensitivity

LIGO – like BHs

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LISA: Sources

- Massive black hole binaries
- White dwarfs
- Stochastic background from galactic binaries
- EMRIs
- Instrument sensitivity
- LIGO-like BHs

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LISA: Sources

- Massive black hole binaries
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+ Search for cosmological stochastic background

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LISA : science objectives

● Study structure of Milky Way galaxy through binary stars
● Origin, growth and merger history of massive black holes
● Study environment of BHs through EMRIIs and IMRIIs
● Tests of general relativity in strong gravity regime
● Massive black hole binaries as standard sirens: test of ΛCDM
● Search for cosmological stochastic backrounds
● Search for the unexpected
Data analysis challenge of next generation detectors

signal vs background discrimination is very challenging!

- ‘GW orchestra’ : thousands of overlapping signals
- signal cannot be shielded, noise models have uncertainties
- cosmological and astrophysical contributions superimposed
- cosmological SGWB shape is model and parameter dependent

possible avenues

- parameter estimation and subtraction of loudest (transient) signal, iterate
- simultaneous ‘global’ fit of all parameters (MCMC based)
- machine learning approaches
- ...

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Landscape of GW detectors

GW amplitude $\Omega_{GW}$

- PTAs
- extra radiation bound
- interferometers
- new ideas needed

- LISA
- LIGO
- ET

- BH mergers (astro background)
- First order EW phase transition
- GUT scale phase transition
- axion inflation
- cosmic strings

Frequency

nHz Hz GHz
The challenge of high frequency GWs

Theorists are joyful people

Experimentalists live on a slippery slope

CMB/BBN bound constrains energy

experiments measure displacement

\[ \Omega_{GW} \propto f^2 h_c^2 \]
The challenge of high frequency GWs

Theorists are joyful people

CMB/BBN bound constrains energy

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UHF GW initiative:
https://www.ctc.cam.ac.uk/activities/UHF-GW.php
synergies with axion searches: CAST

- Helioscope: search for axions / GWs at x-ray frequency. To be succeeded by IAXO

- Sensitivity to single gravitons (though we cannot think of a source that would produce them in any significant number)
Conclusions

A century after the prediction of GWs, observatories across the world in different frequency ranges are seeing `first light’

These observations have already provided new insights in astrophysics, gravity, and particle physics

This is only the beginning of GW astronomy: new GW telescopes will reach far into unexplored ranges in frequency, BH mass, distance and cosmic history

This comes with many challenges: technological, engineering, data analysis, theory,.. 

Good coverage of the GW sky calls for exploration of new ideas and technologies to expand the frequency reach
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„such detectors [laser interferometers] have so low sensitivity that they are of little experimental interest“ [Misner, Thorne, Wheeler 1974]

nobel prize 2016 for detection of GWs with LIGO