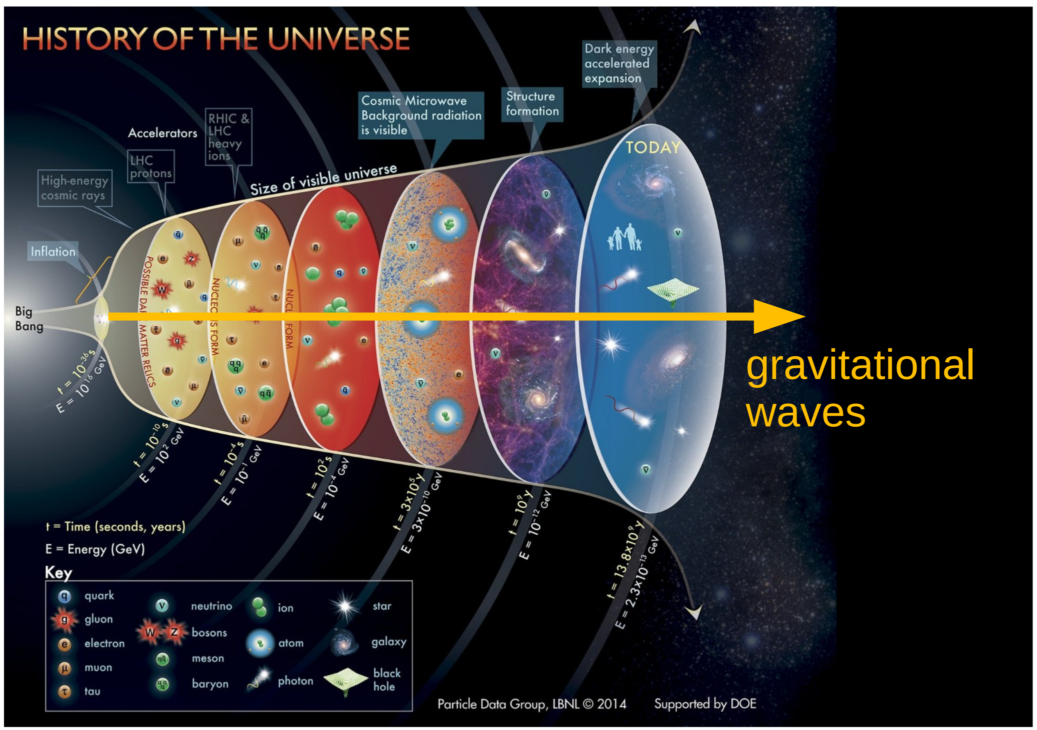
Gravitational wave physics

what we know and what we want to know



Valerie Domcke
CERN

Academic training lectures
April 2024

Outline

1) What we know

- Motivation
- What is a GW?
- LIGO: signal & detection
- LIGO: some highlights

Literature:

- M. Maggiore, GWs, Vol I
- C. Caprini, D. Figueroa, Cosmological backgrounds of GWs, arxiv: 1801.04268

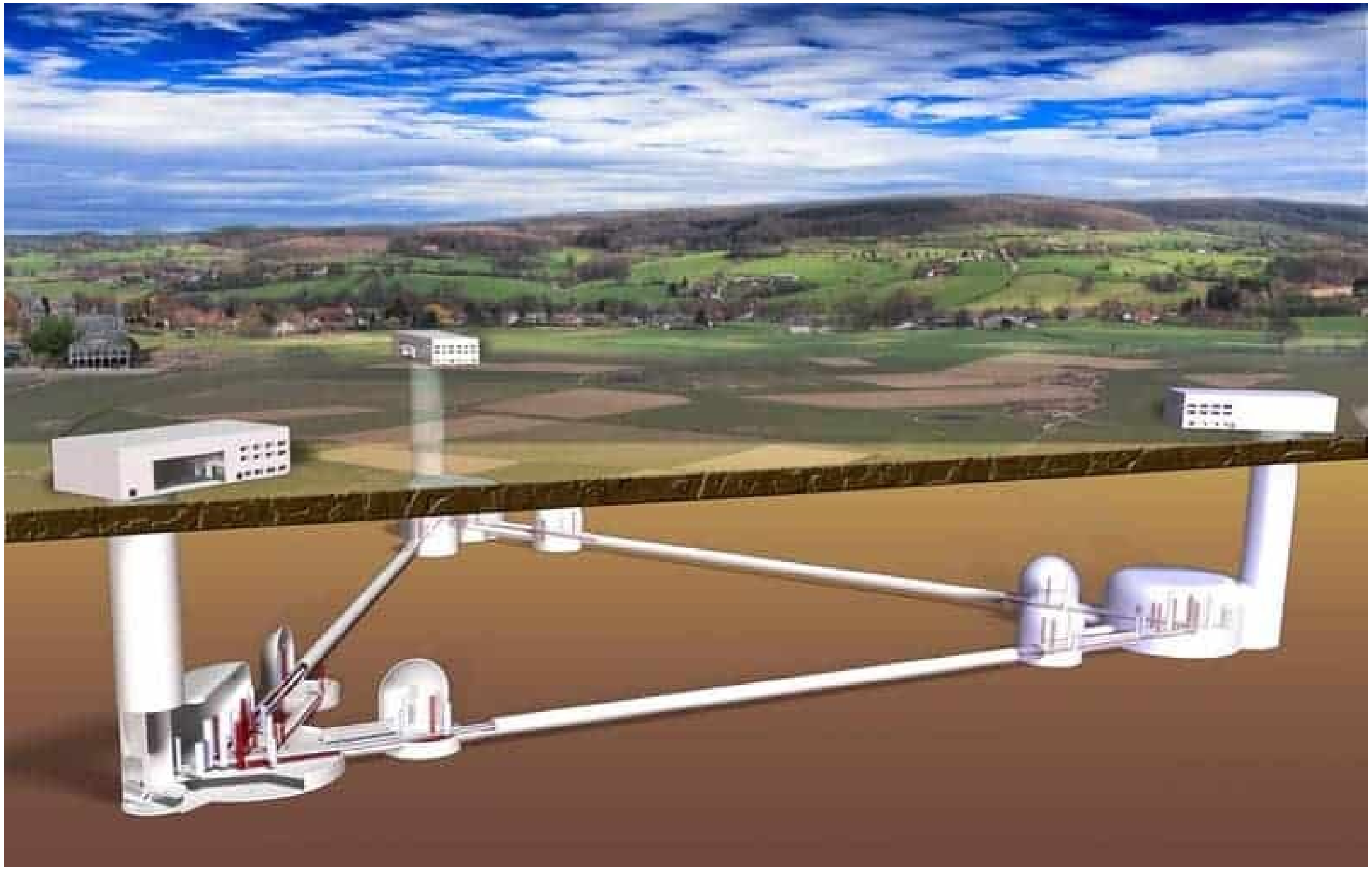
2) Current frontier

- GW background
- Pulsar timing arrays
- BSM searches with GWS

3) What we want to know

- Going to space & underground
- New opportunities at new frequencies

Einstein Telescope (ET)



10 km arms, 250 – 300 m underground, cyrogenic cooling, squeezed light, xylophone,...

possible locations: NL/BE/DE, IT, DE + Cosmic Explorer in the US

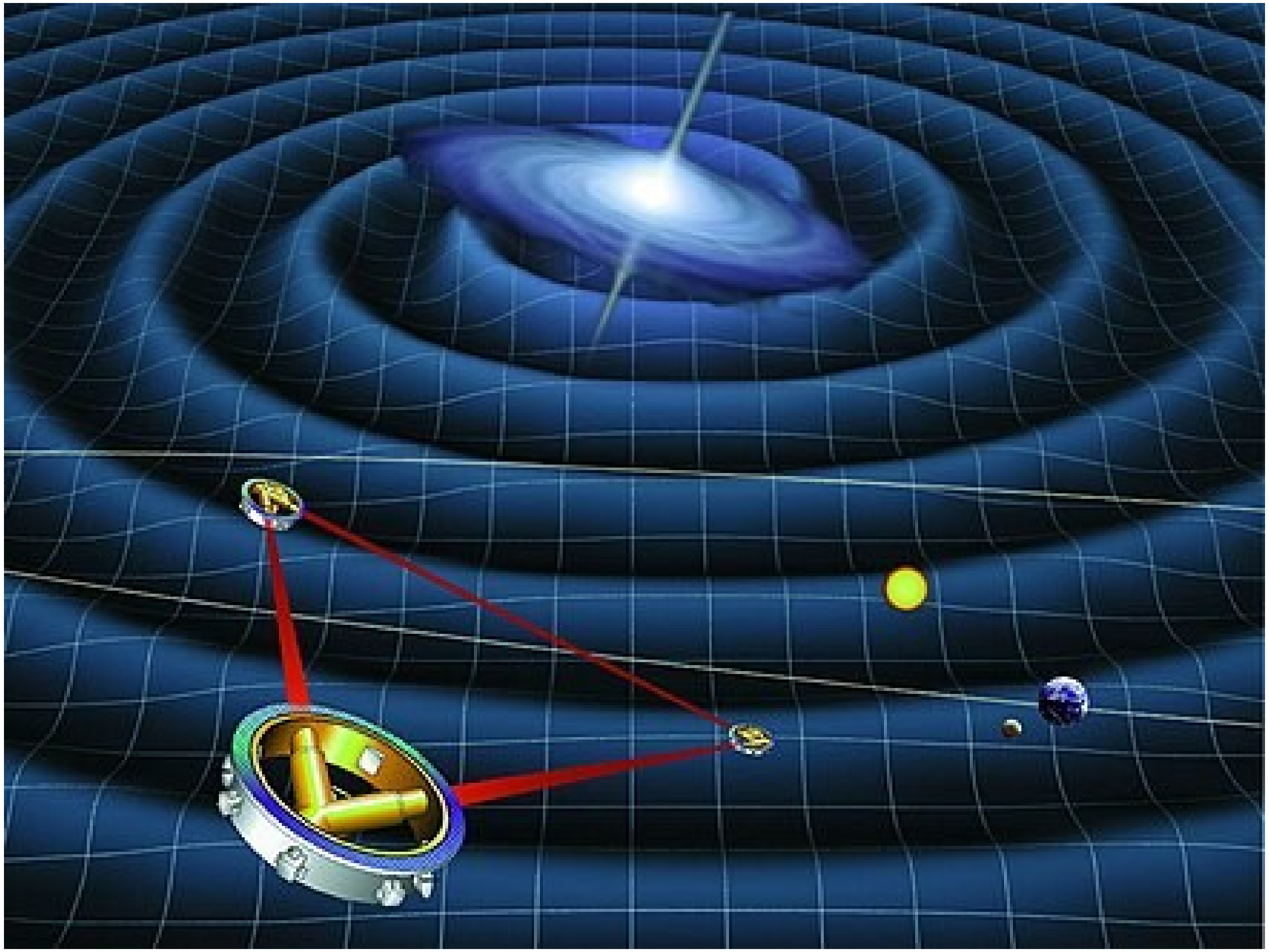
Einstein Telescope (ET)

Some science highlights:

- Detect all stellar origin black hole binaries in the observable universe (red shift reach beyond star formation)
- Detect ~ 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: supernovea, single neutron stars, ...

CERN involvement in civil engineering, technology development, theory,..

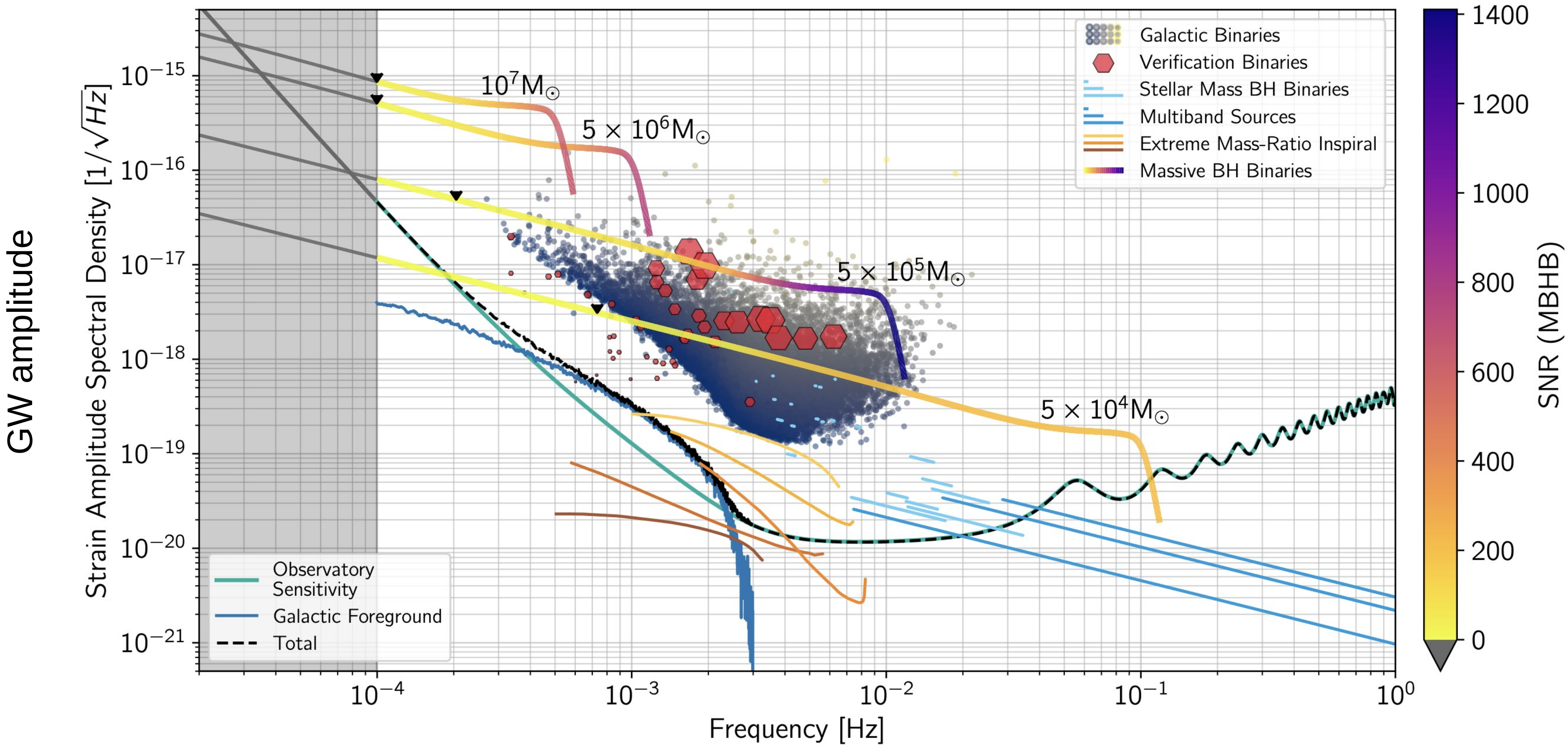
Laser Interferometer Space Antenna (LISA)



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



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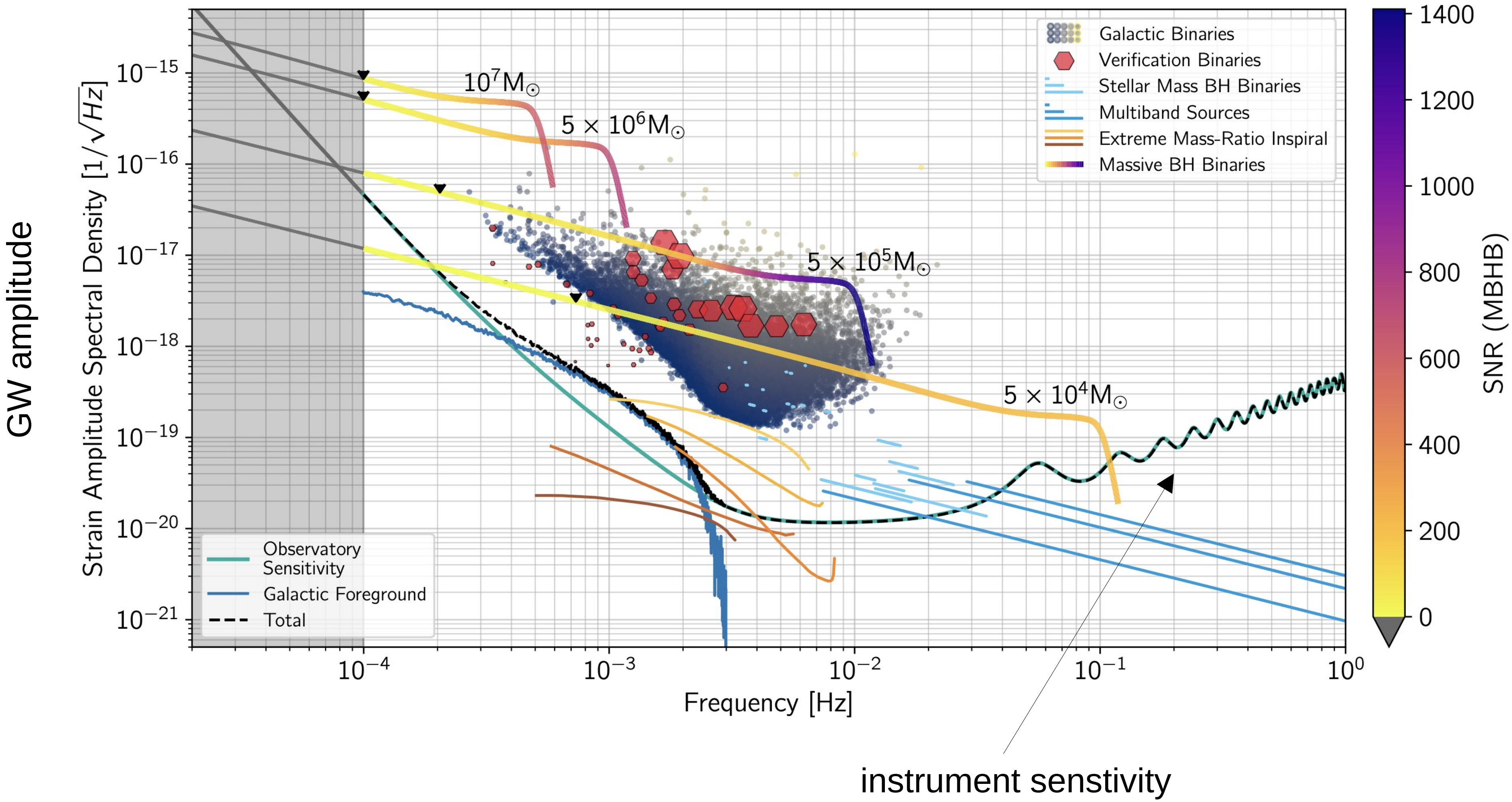

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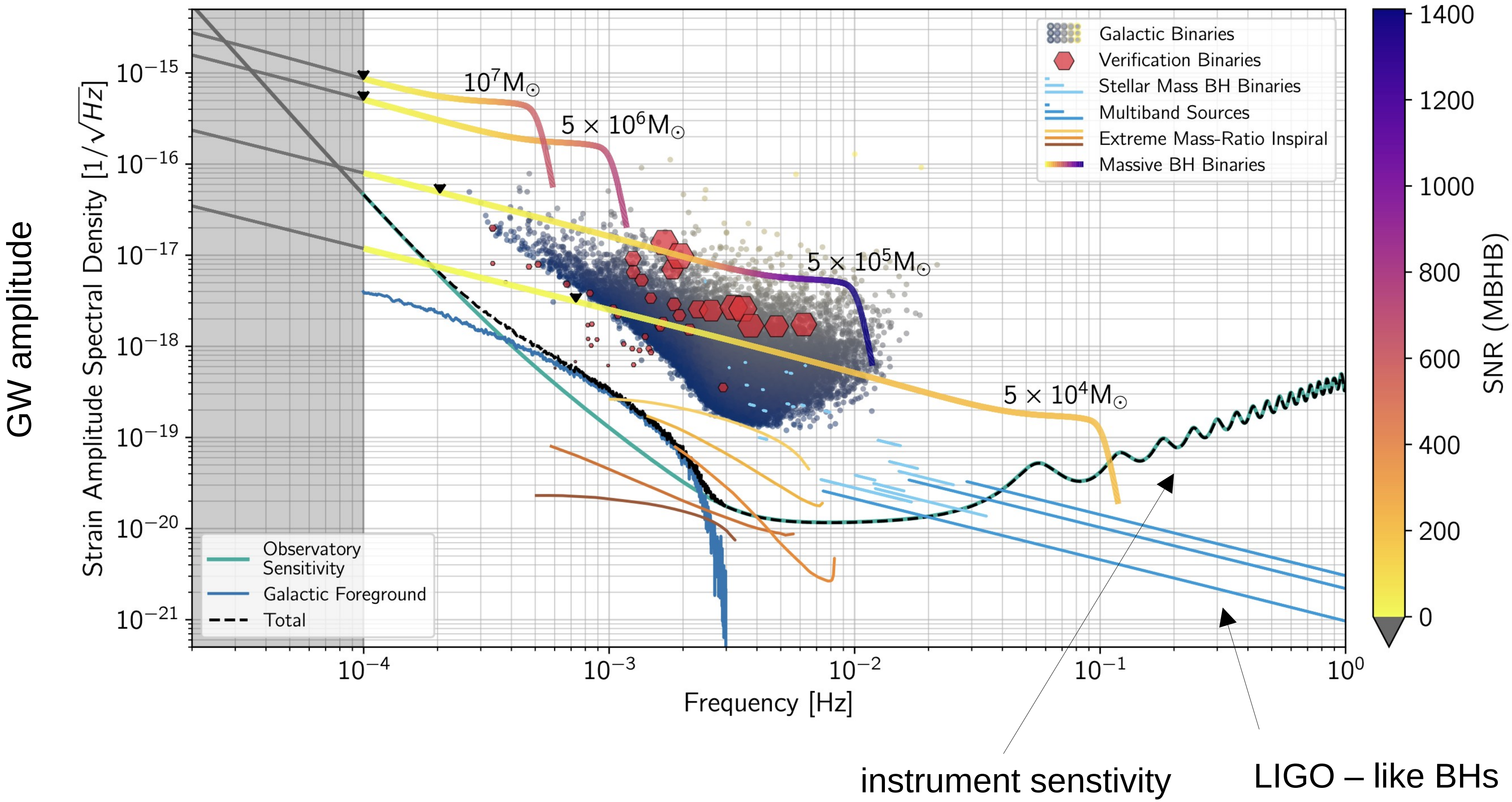
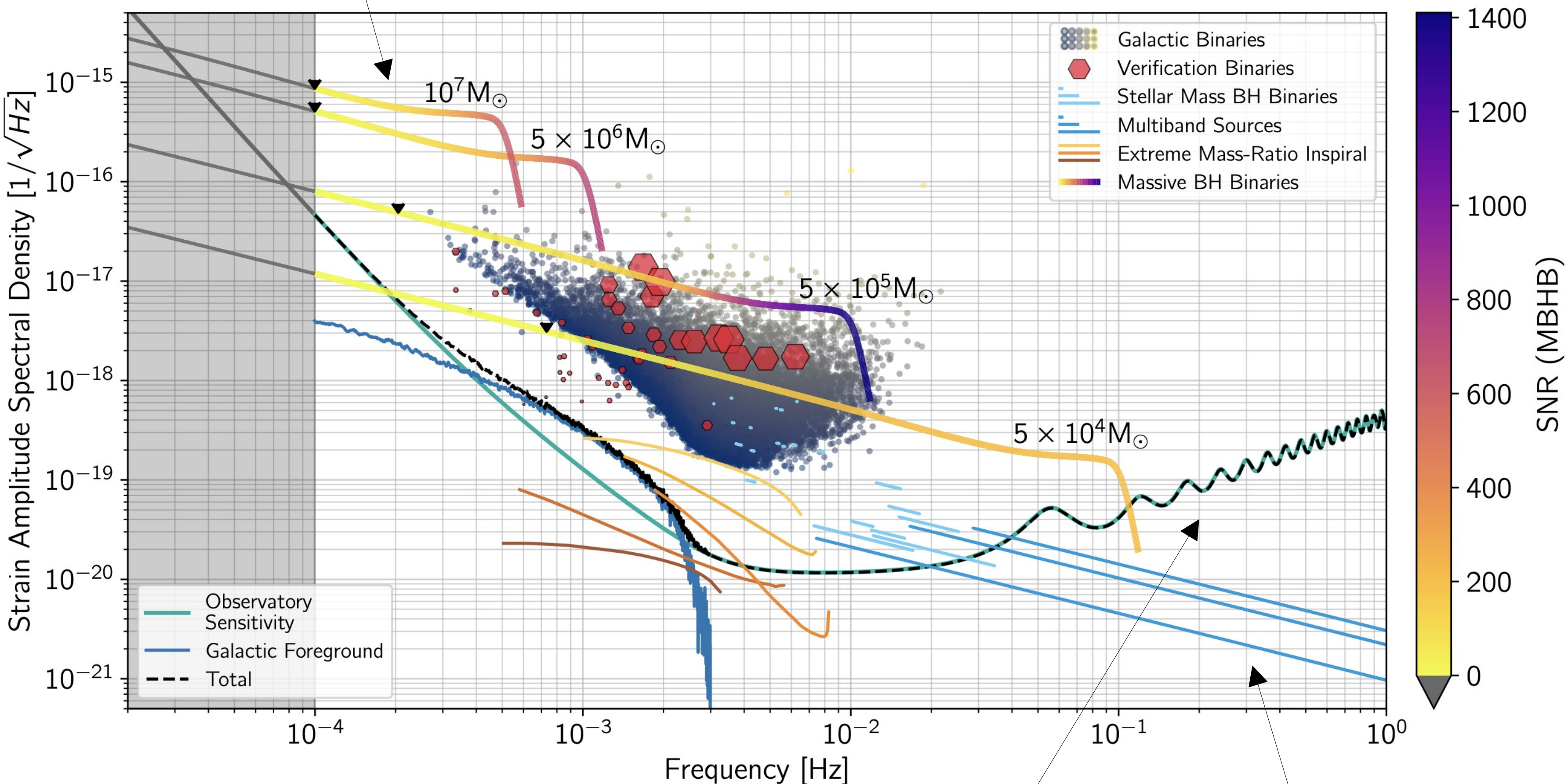


LISA : Sources

massive black hole binaries

LISA red book: 2402.07571

GW amplitude



instrument senstivity

LIGO – like BHs

LISA : Sources

massive black hole binaries

white dwarfs

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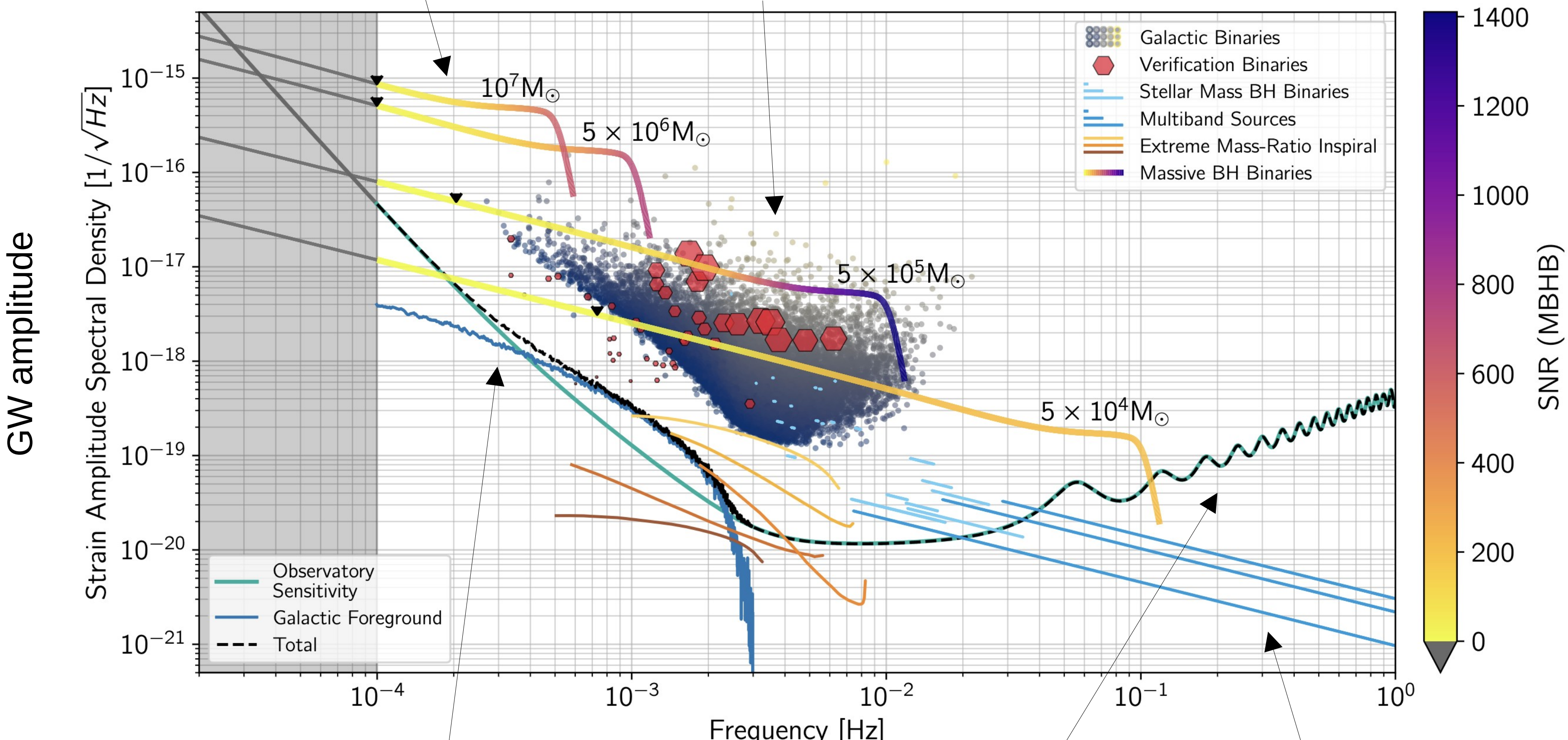

stochastic background from galactic binaries

instrument senstivity

LIGO – like BHs

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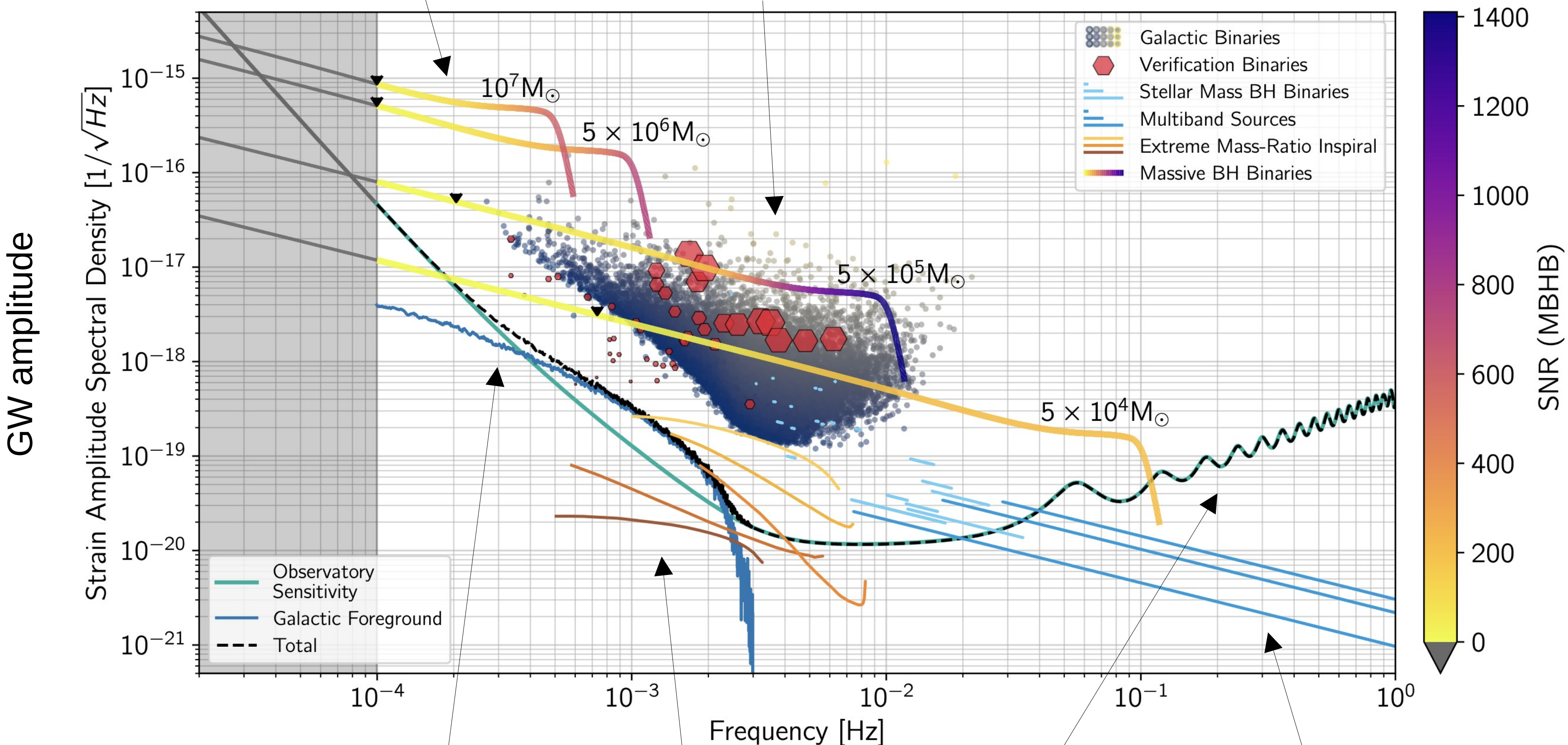

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EMRIs

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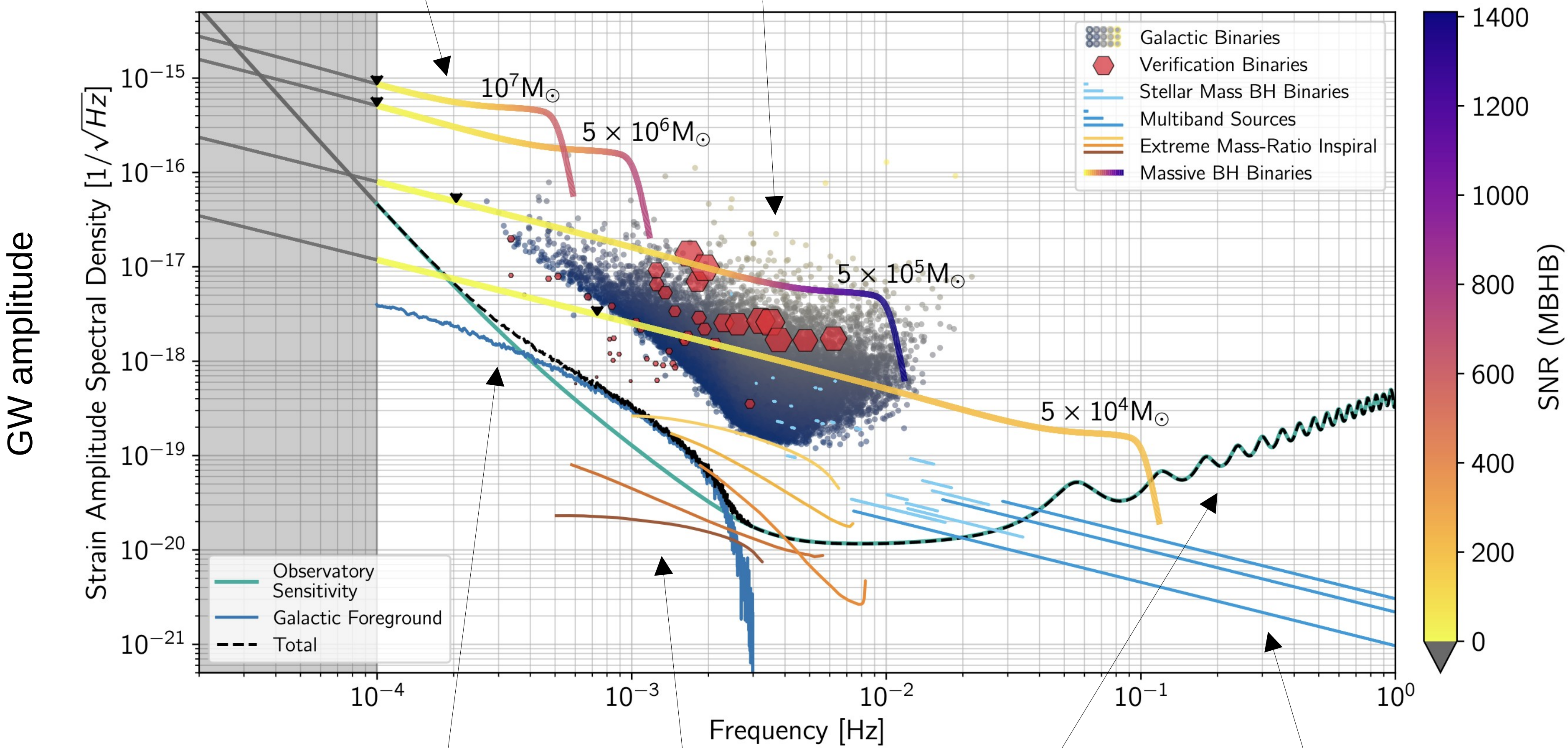


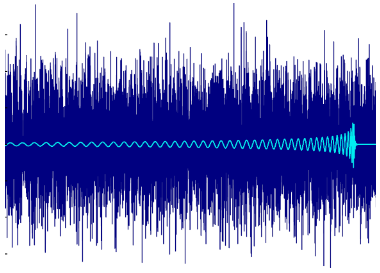
stochastic background from galactic binaries　　EMRIs　　instrument senstivity　　LIGO – like BHs

+ search for cosmological stochastic background

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 EMRIs and IMRIs
- Tests of general relativity in strong gravity regime
- Massive black hole binaries as standard sirens: test of ΛCDM
- Search for cosmological stochastic backroungs
- Search for the unexpected

Data analysis challenge of next generation detectors



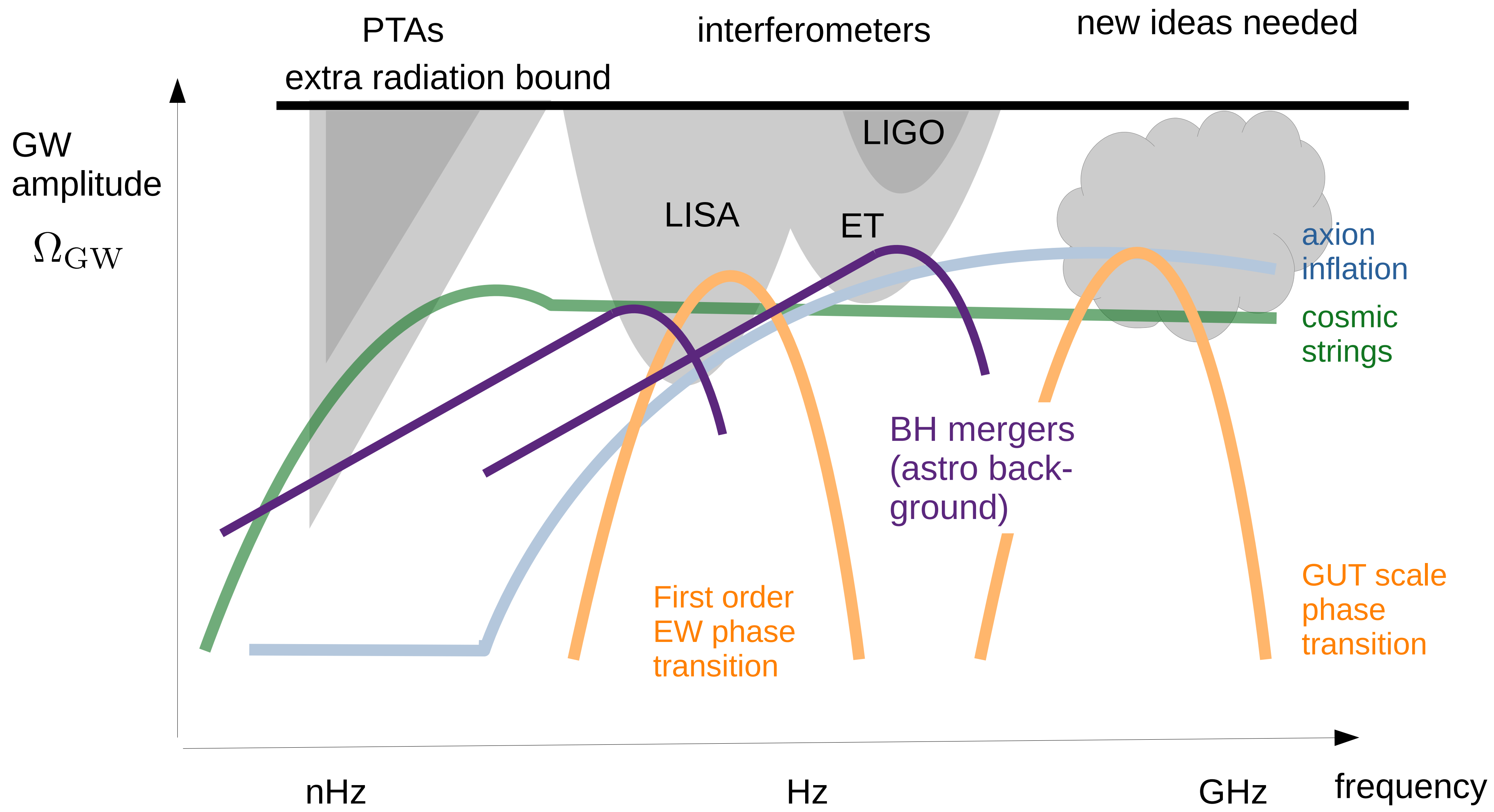
signal vs background discrimination is very challenging!

- ‘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

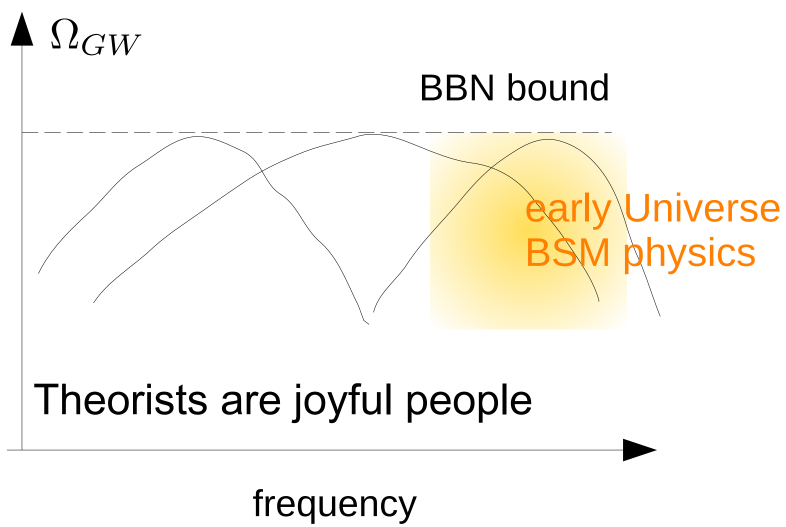
possible avenues

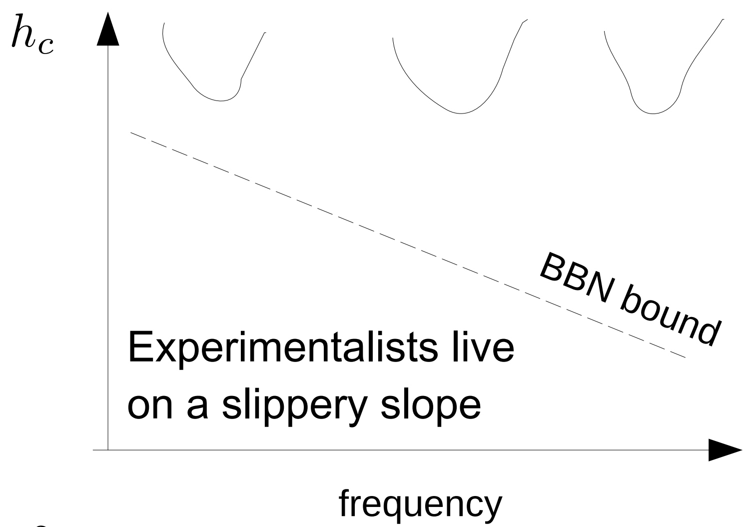
- parameter estimation and subtraction of loudest (transient) signal, iterate
- simultaneous ‘global’ fit of all parameters (MCMC based)
- machine learning approaches
- ...

Landscape of GW detectors



The challenge of high frequency GWs





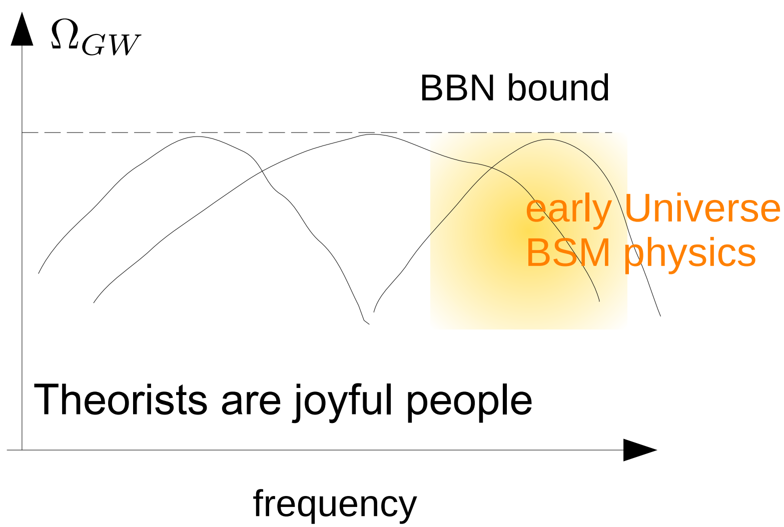
$$\Omega_{GW} \propto f^2 h_c^2$$

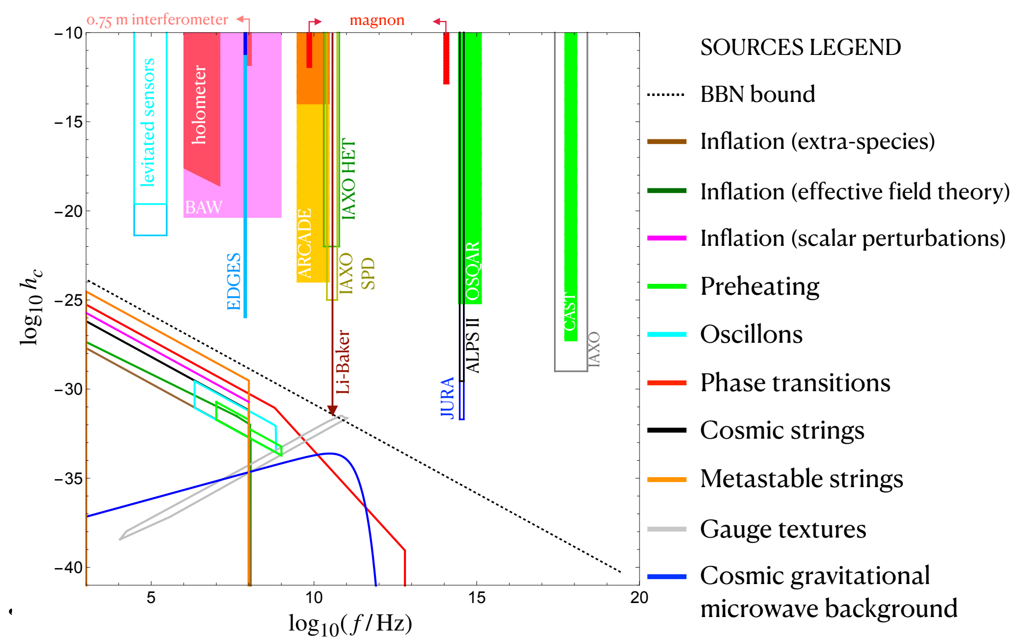
CMB/BBN bound constrains energy

experiments measure displacement

The challenge of high frequency GWs

UHG GW initiative Living Review:
https://arxiv.org/abs/2011.12414





$\Omega_{GW} \propto$

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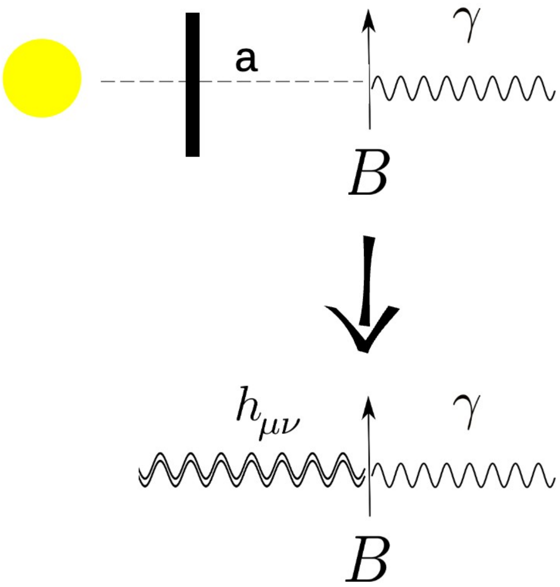
UHF GW initiative:
https://www.ctc.cam.ac.uk/activities/UHF-GW.php

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