LISA SCIENCE PERFORMANCE

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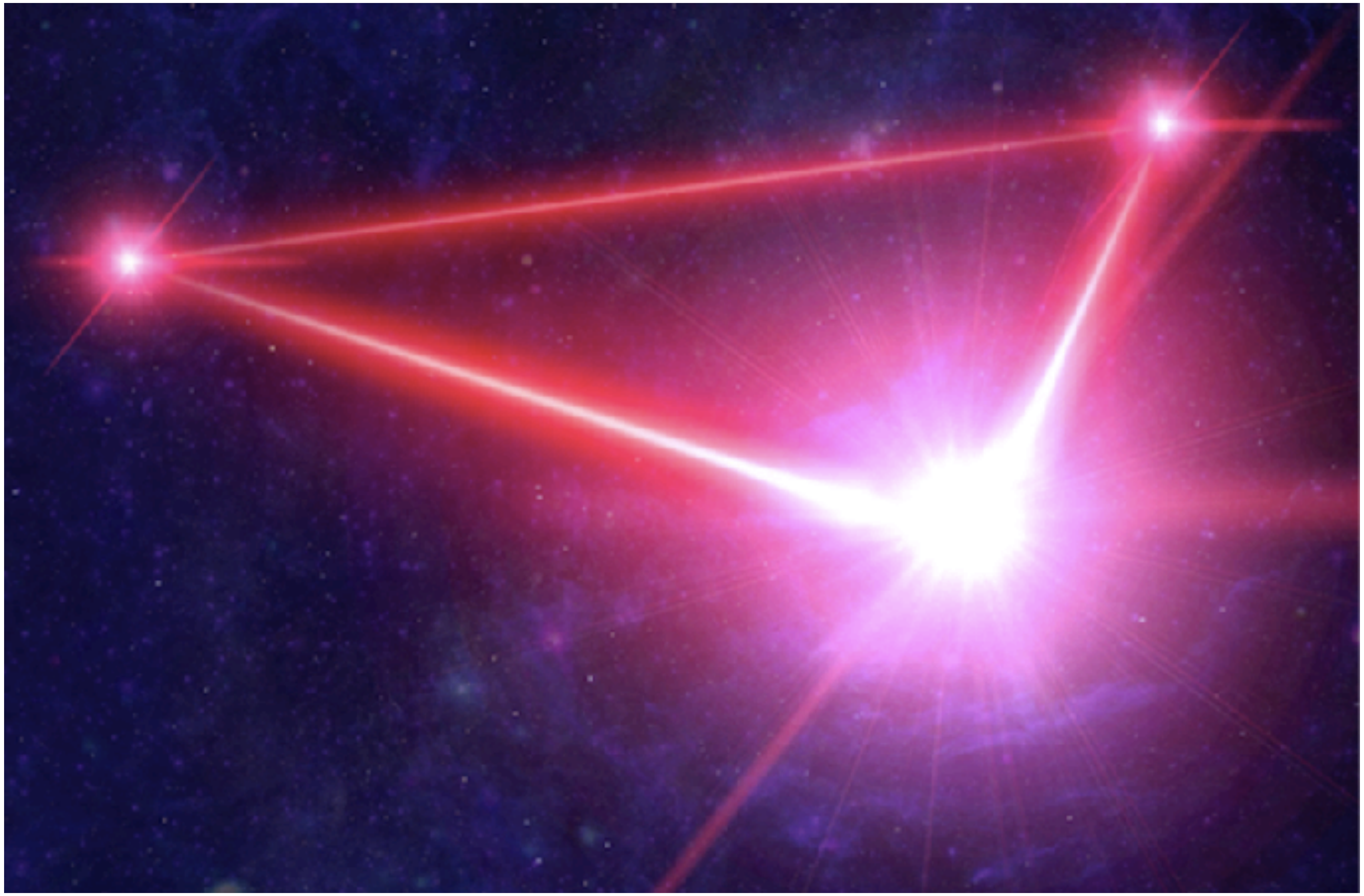
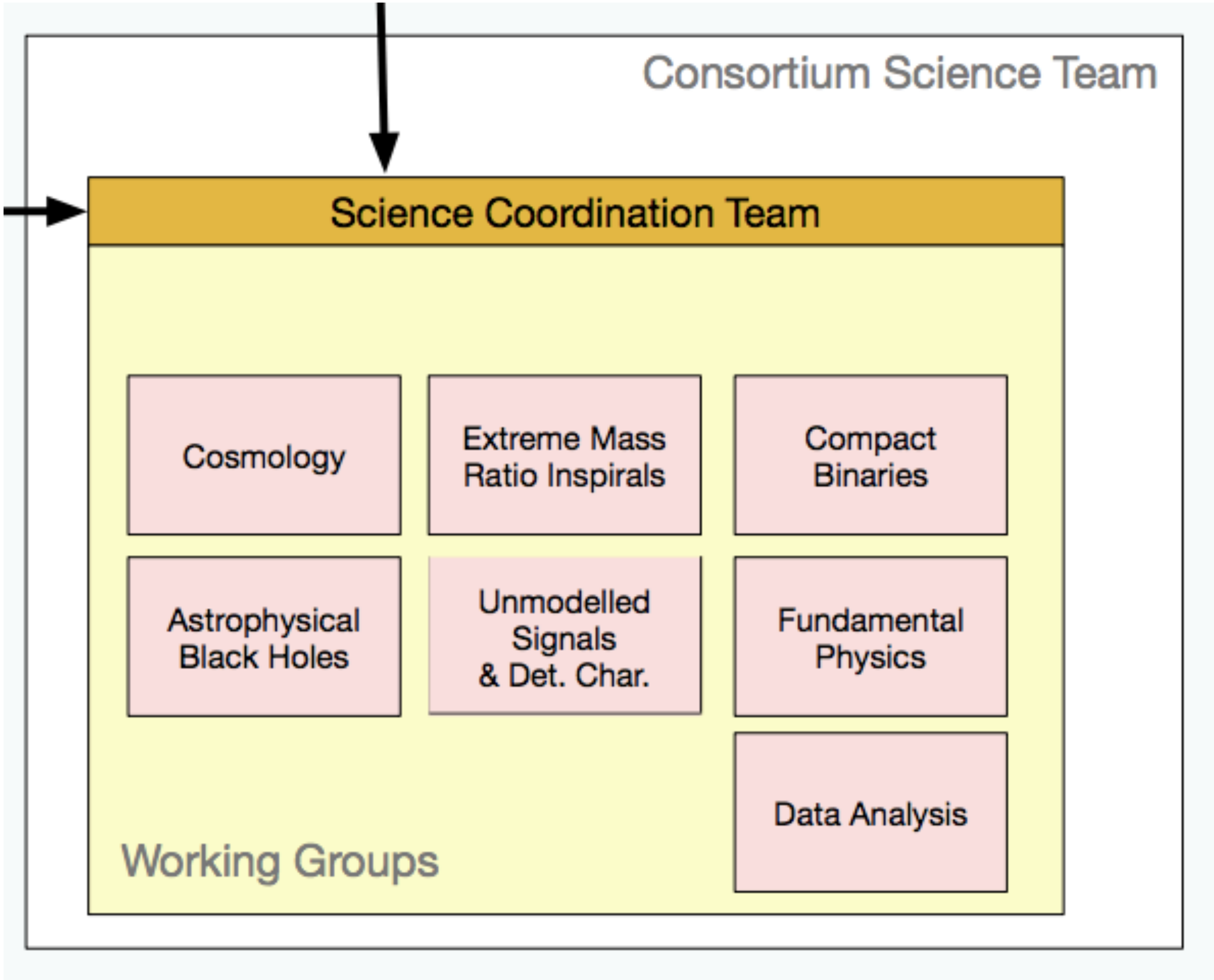


Consortium science team

Consortium Board, ESA…

Ground segment team…



Consortium Science Team

Science Coordination Team

Working Groups

- Cosmology
- Extreme Mass Ratio Inspirals
- Compact Binaries
- Astrophysical Black Holes
- Unmodelled Signals & Det. Char.
- Fundamental Physics
- Data Analysis

Consortium science team

Working groups:

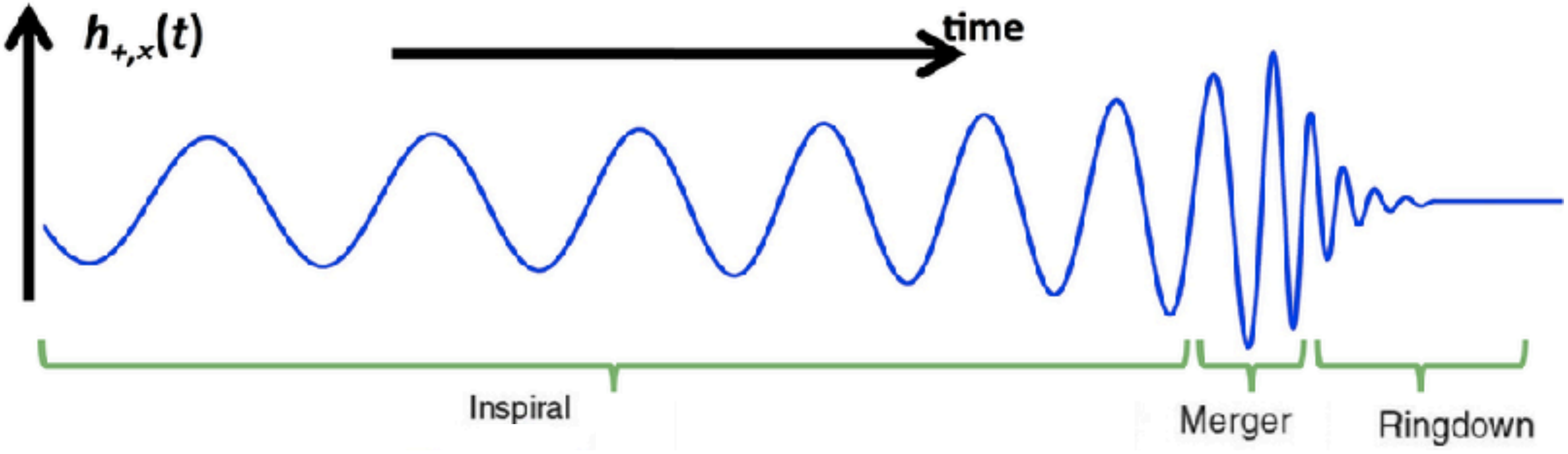
- two coordinators per group
- they unify the scientific community around the scientific themes of the mission
- they provide the manpower for the projects of the SCT and others
- they organise occasions for the community to meat (workshops, teleconferences…)

What LISA measures

1. The gravitational wave strain from the inspiral and merger of compact binaries : it encodes information on the binary parameters

$$h(t) \sim 2\,\frac{\Delta L}{L} \qquad\qquad \mathcal{M}_c,\, d_L,\, t_c,\, \eta,\, \Phi_c,\, \phi$$

LISA target :
- BH binaries, massive (high SNR) and LIGO-like
- galactic binaries
- Extreme Mass Ratio Inspirals



What LISA measures

2. the stochastic background of gravitational waves

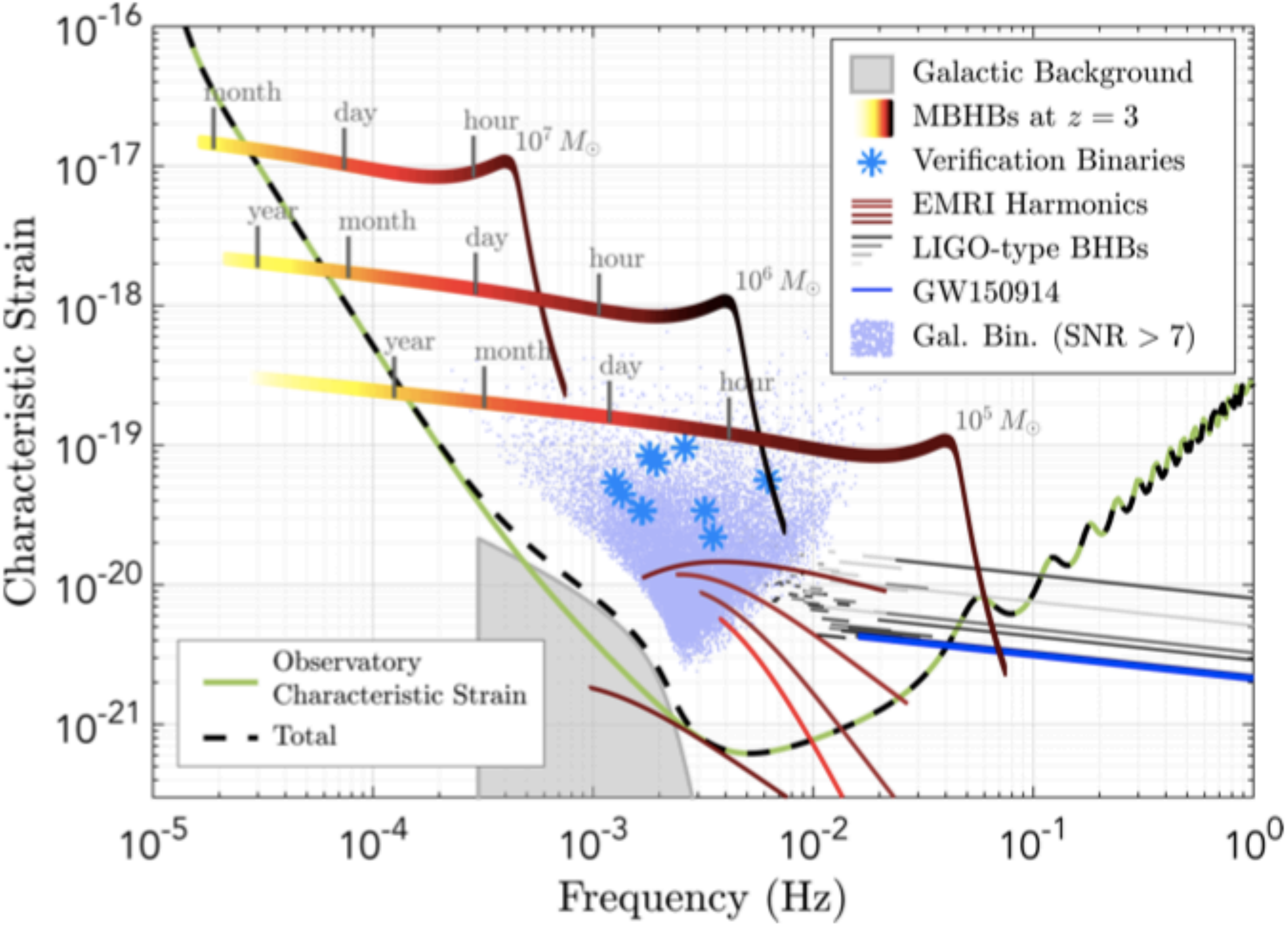
the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale (typically horizon at the time of production) with respect to the detector resolution

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij} \dot{h}_{ij} \rangle}{32\pi G\, \rho_c} = \int \frac{{\rm d}f}{f} \frac{{\rm d}\Omega_{\rm GW}}{{\rm d}\ln f}$$

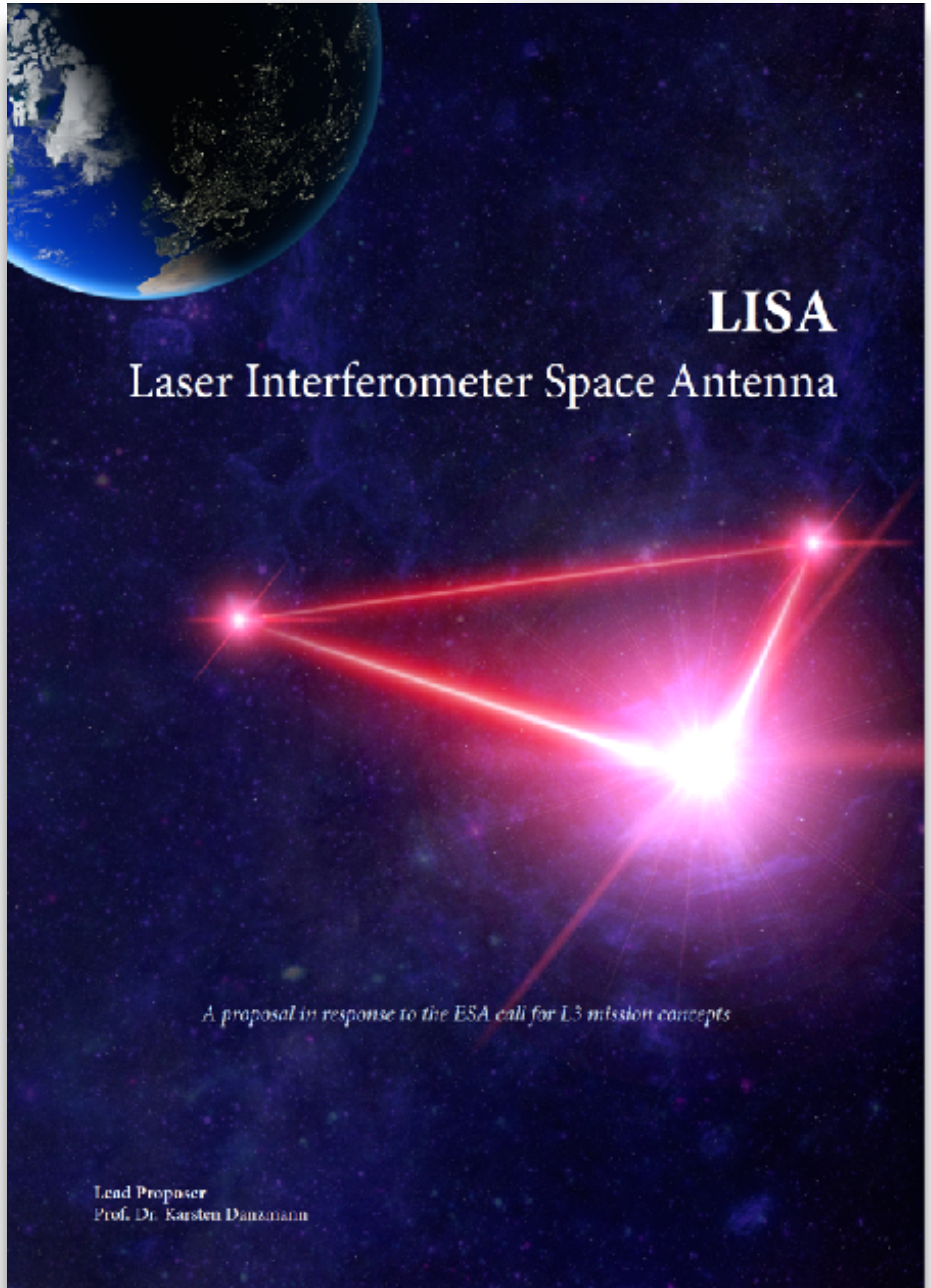
energy density
power spectrum

What LISA measures



LISA proposal

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

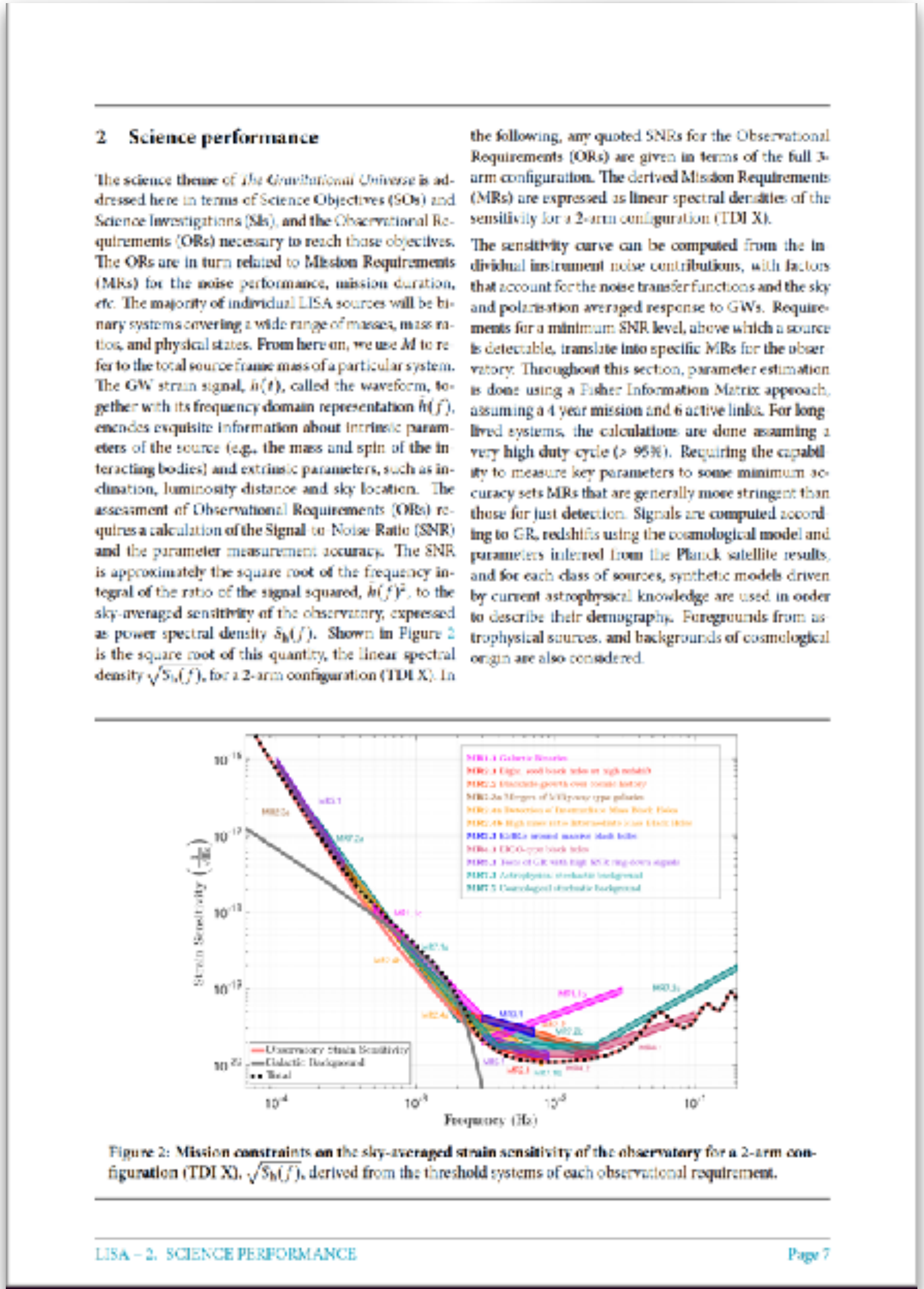


LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann



2 Science performance

The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, mission duration, *etc.* The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states. From here on, we use M to refer to the total source frame mass of a particular system. The GW strain signal, $h(t)$, called the waveform, together with its frequency domain representation $\tilde{h}(f)$, encodes exquisite information about intrinsic parameters of the source (e.g., the mass and spin of the interacting bodies) and extrinsic parameters, such as inclination, luminosity distance and sky location. The assessment of Observational Requirements (ORs) requires a calculation of the Signal to Noise Ratio (SNR) and the parameter measurement accuracy. The SNR is approximately the square root of the frequency integral of the ratio of the signal squared, $\tilde{h}(f)^2$, to the sky-averaged sensitivity of the observatory, expressed as power spectral density $S_h(f)$. Shown in Figure 2 is the square root of this quantity, the linear spectral density $\sqrt{S_h(f)}$, for a 2-arm configuration (TDI X). In the following, any quoted SNRs for the Observational Requirements (ORs) are given in terms of the full 3-arm configuration. The derived Mission Requirements (MRs) are expressed as linear spectral densities of the sensitivity for a 2-arm configuration (TDI X).

The sensitivity curve can be computed from the individual instrument noise contributions, with factors that account for the noise transfer functions and the sky and polarisation averaged response to GWs. Requirements for a minimum SNR level, above which a source is detectable, translate into specific MRs for the observatory. Throughout this section, parameter estimation is done using a Fisher Information Matrix approach, assuming a 4 year mission and 6 active links. For long lived systems, the calculations are done assuming a very high duty cycle (> 95%). Requiring the capability to measure key parameters to some minimum accuracy sets MRs that are generally more stringent than those for just detection. Signals are computed according to GR, redshifts using the cosmological model and parameters inferred from the Planck satellite results, and for each class of sources, synthetic models driven by current astrophysical knowledge are used in order to describe their demography. Foregrounds from astrophysical sources, and backgrounds of cosmological origin are also considered.

Figure 2: **Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X),** $\sqrt{S_h(f)}$, **derived from the threshold systems of each observational requirement.**

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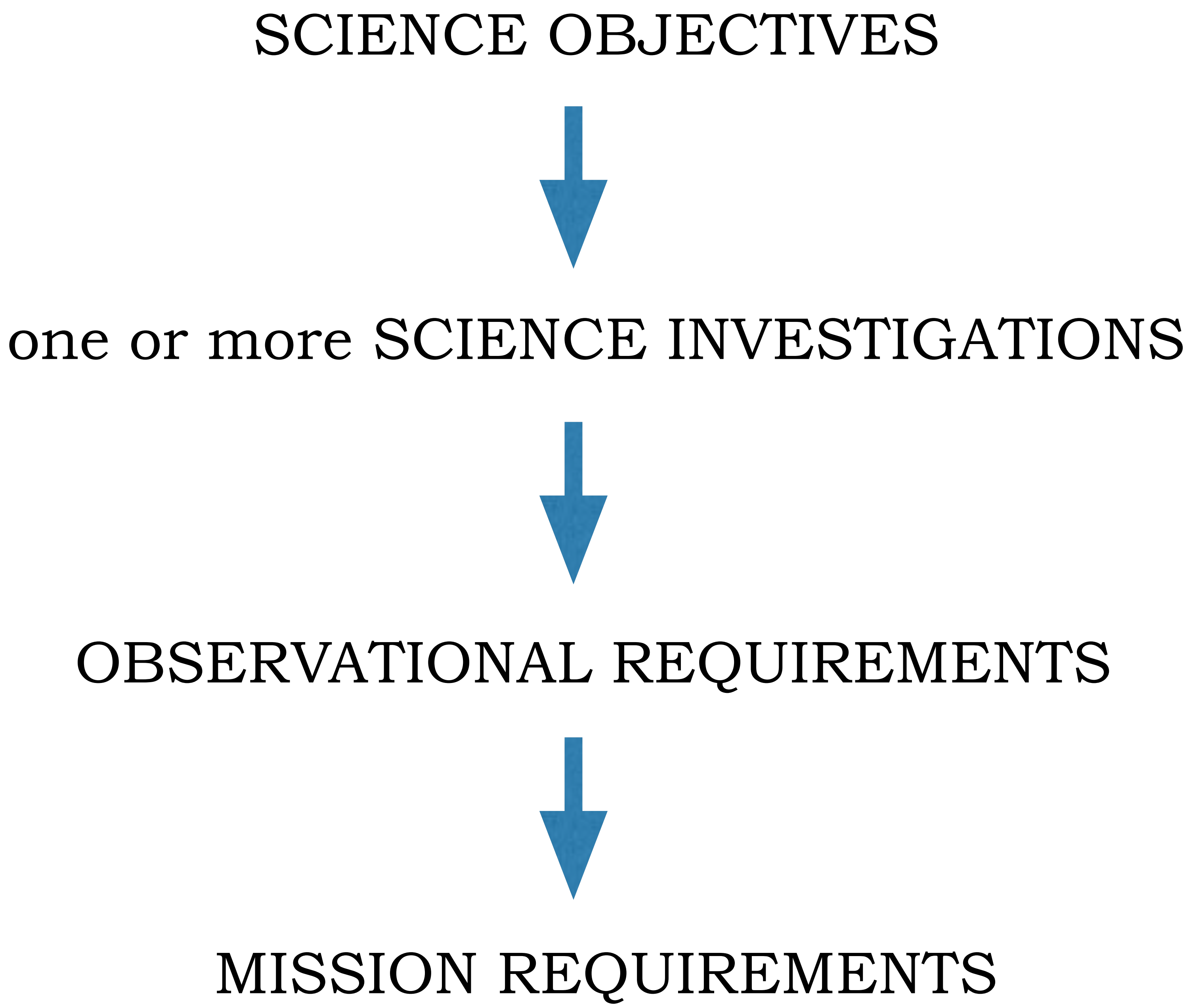
LISA science

<u>what can we learn using these sources?</u>



SCIENCE OBJECTIVES

one or more SCIENCE INVESTIGATIONS

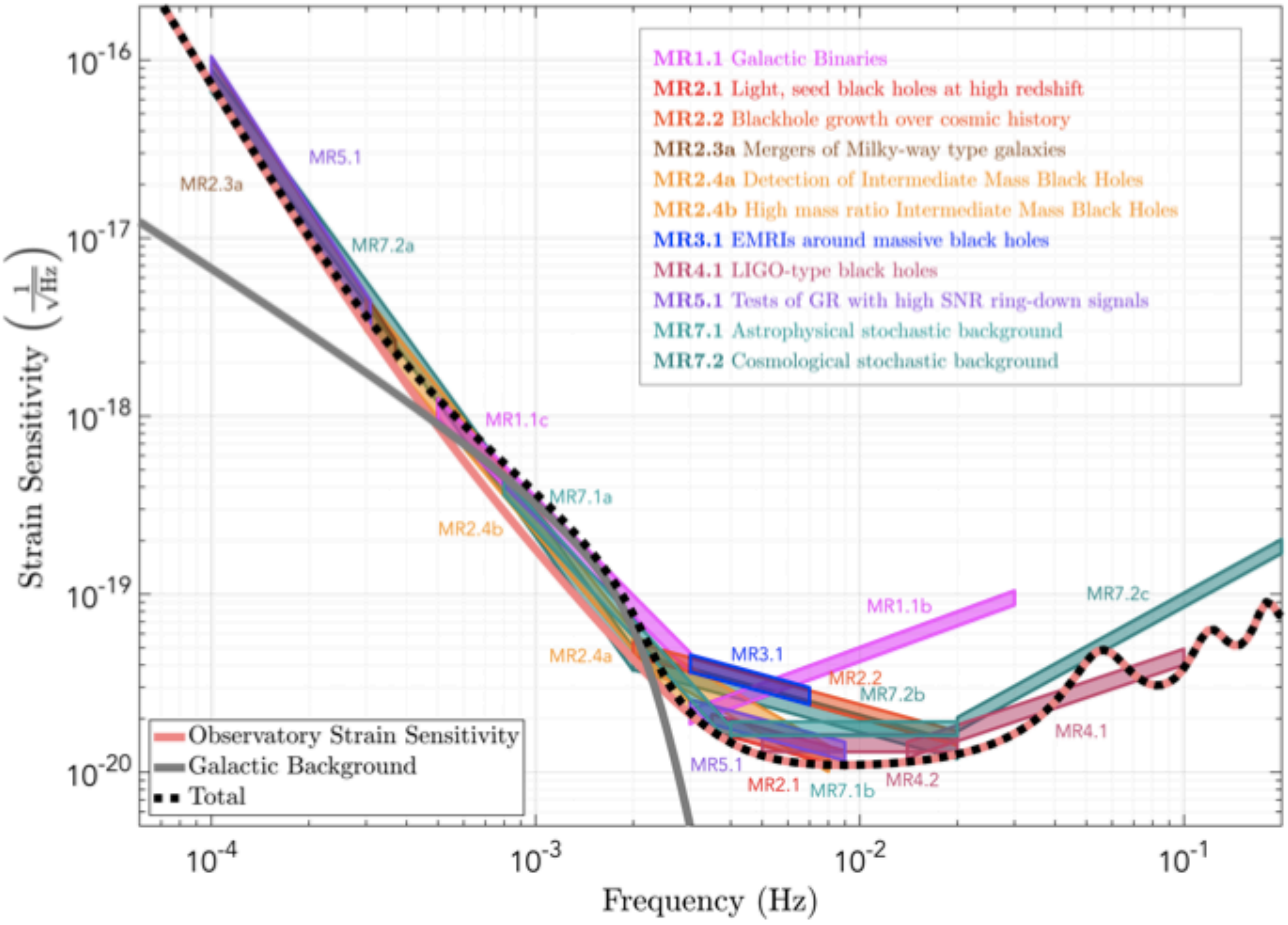
OBSERVATIONAL REQUIREMENTS

MISSION REQUIREMENTS

LISA science

MISSION REQUIREMENTS

define the sensitivity curve and detection strategies



SO1: study formation and evolution of compact binary stars in the galaxy

white dwarfs, neutron stars, stellar origin BH
(including verification ones)

- SI: elucidate the formation and evolution of GBs

- OR: measure period, mass distribution, distance and sky location

$$\frac{\delta P}{P} < 10^{-6} \qquad M > 0.2\,M_\odot \qquad d < 15\,\mathrm{kpc} \qquad f > 3\,\mathrm{mHz}$$

- OR: detect the stochastic background at low frequency

$$0.5 < f < 3\,\mathrm{mHz}$$

- leads to MR on the duration of the mission, not only on the strain sensitivity

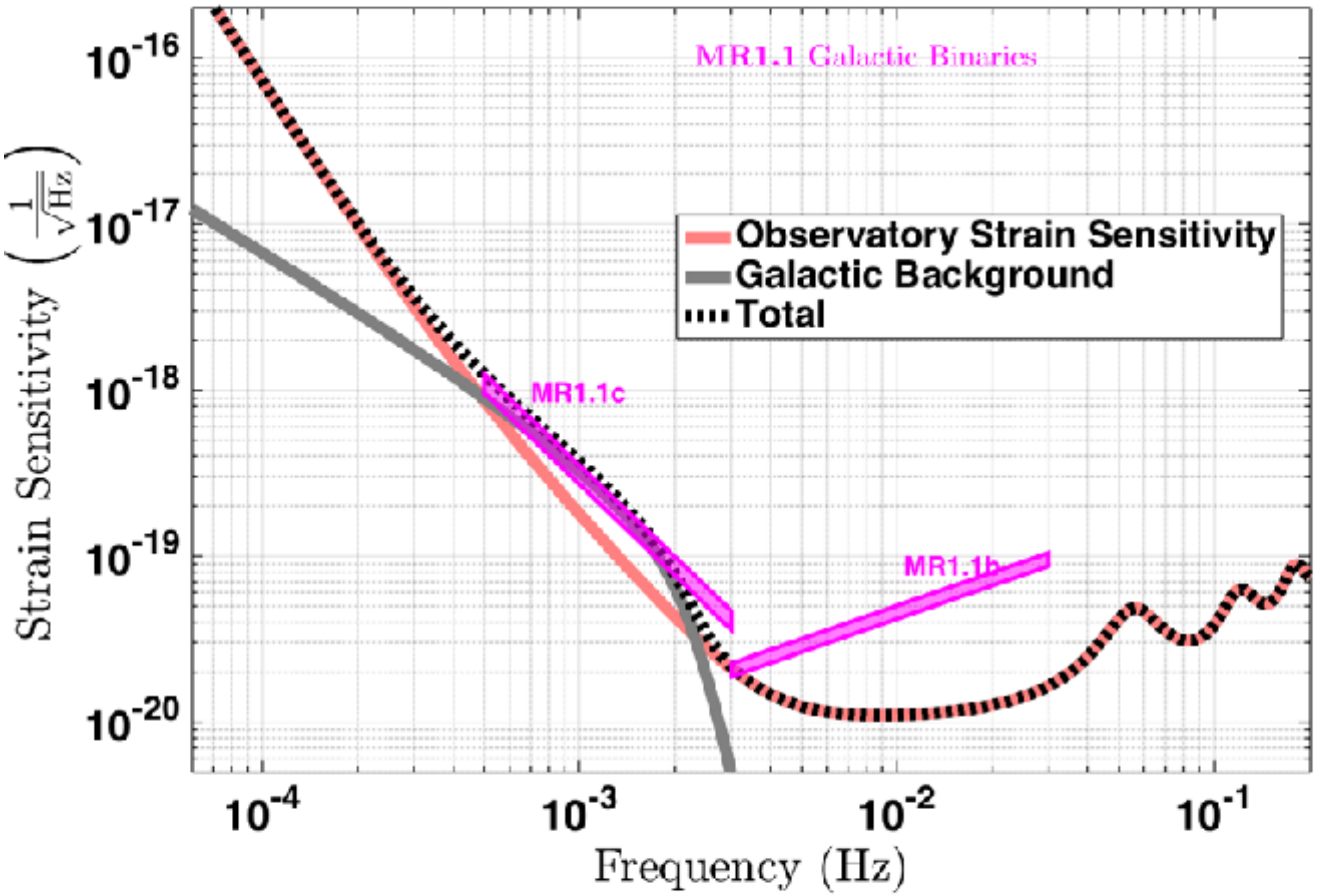
SO1: study formation and evolution of compact binary stars in the galaxy

white dwarfs, neutron stars, stellar origin BH
(including verification ones)

- SI: enable joint gravitational and EM observations
  - OR: be able to detect the verification binaries
  - OR: in order to identify the counterparts, determine sky location of 500 systems within 1 deg^2
  - OR: to perform tests of GR, measure also first derivative of period to 10% for 100 systems

SO1: study formation and evolution of compact binary stars in the galaxy

white dwarfs, neutron stars, stellar origin BH
(including verification ones)

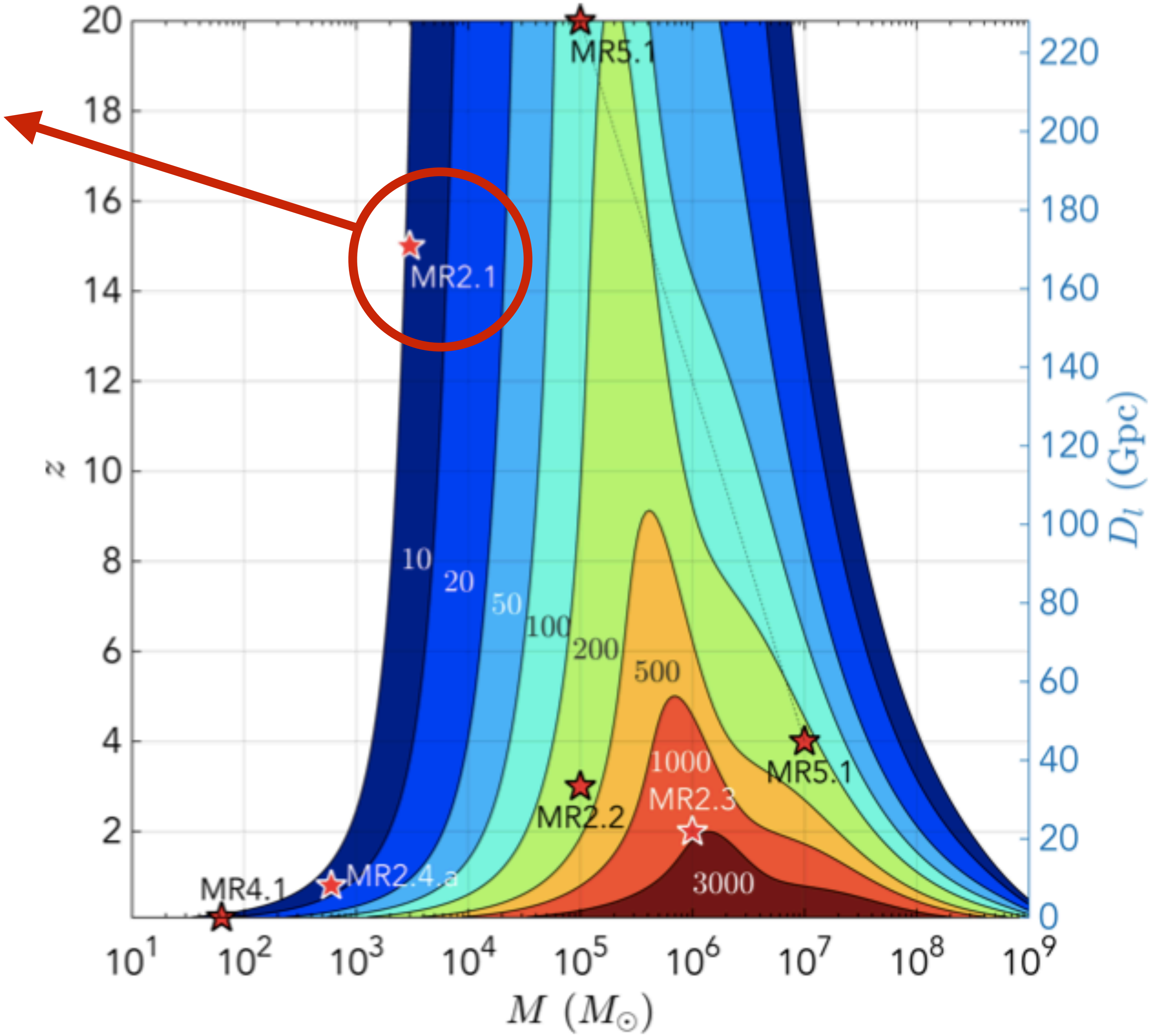


SO2: trace the origin, growth and merger history of massive BHs

most probably the sources with higher SNR
cross all LISA frequency band
the signal lasts from minutes to months prior to merger:
see all phases inspiral, merger, ringdown

- seeds: $10^3 < M < 10^5\, M_\odot$ $\qquad 10 < z < 15$
- accretion and mergers brings them to $M \geq 10^8\, M_\odot$
- participate in the clustering of cosmic structure
- accretion and mergers shape their spins
- measure redshift chirp mass and luminosity distance (from which infer source frame mass) $\mathcal{M}_c = (1+z) M_c$
- population model uncertain: minimum few per year with current sensitivity

SO2: trace the origin, growth and merger history of massive BHs



threshold
systems to
fulfil ORs: they
define the MRs

SO2: trace the origin, growth and merger history of massive BHs

- SI: search for the seeds of MBH
  - OR: for the seeds, be able to measure source frame mass and luminosity distance within 20%

example of threshold: $M = 3000\, M_{\odot} \quad m_1 = 0.2\, m_2 \quad z = 15$

- SI: study their growth
  - OR: be able to measure source frame mass within 5%

$$10^4 < M < 10^6\, M_{\odot} \quad z \leq 9$$

  - OR: be able to measure the spin to 0.1 and spin misalignment with orbital angular momentum within 10 deg

$$10^5 < M < 10^6\, M_{\odot} \quad z < 3$$

SO2: trace the origin, growth and merger history of massive BHs

- SI: observe EM counterparts to unveil the environment around merging BHs

$$10^6 < M < 10^7\, M_\odot \quad z \sim 2$$

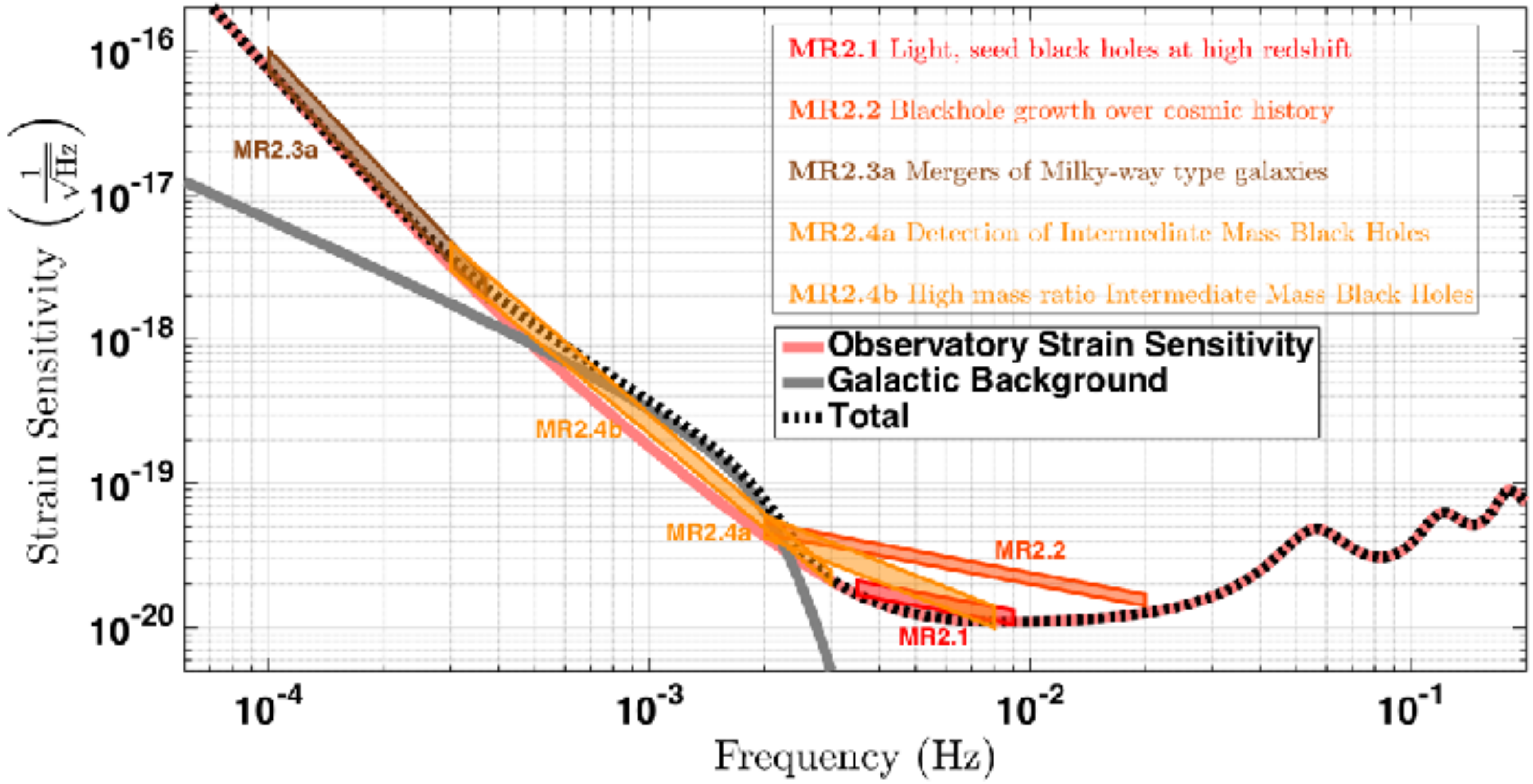
  - OR: allow the issue of alerts to EM observatories: sky localisation better than 100 deg^2 is needed at least one day prior to merger

  - OR: after merger, sky localisation improves: reach 1 deg^2 to allow follow-up EM observations that could witness the formation e.g. of a quasar

- leads to elaborate MR (not only on the strain sensitivity):
  - cadence of the data: should be available on Earth 1 day after measurement on board
  - ability to trigger a protect period (to allow coincident detection)

SO2: trace the origin, growth and merger history of massive BHs

- SI: test the existence of intermediate mass BH binaries
  - OR: nearly equal mass $600 < M < 10^6\, M_\odot$
  - OR: large mass ratios $100 + 10^5\, M_\odot$ $z < 3$



SO3: probe the dynamics of dense nuclear clusters using EMRIs

inspiral and merger of a stellar origin BH into a massive BH

$$m_1 = \ 10 - 60\, M_\odot \qquad m_2 = 10^5 - 10^6\, M_\odot$$

- the signal lasts months to years: 10^3 - 10^5 orbits, very precise determination of the binary parameters
- the orbits are highly relativistic, very complicated: precise mapping of spacetime around the MBH
- the rates are uncertain: fulfilment of OR requires one EMRI per year

SO3: probe the dynamics of dense nuclear clusters using EMRIs

inspiral and merger of a stellar origin BH into a massive BH

- SI: study the environment of Milky Way-like BH at low redshift

  - OR: detect EMRIs around MBH of 10^5 $M_\odot$ to $z \simeq 4$ with accuracies

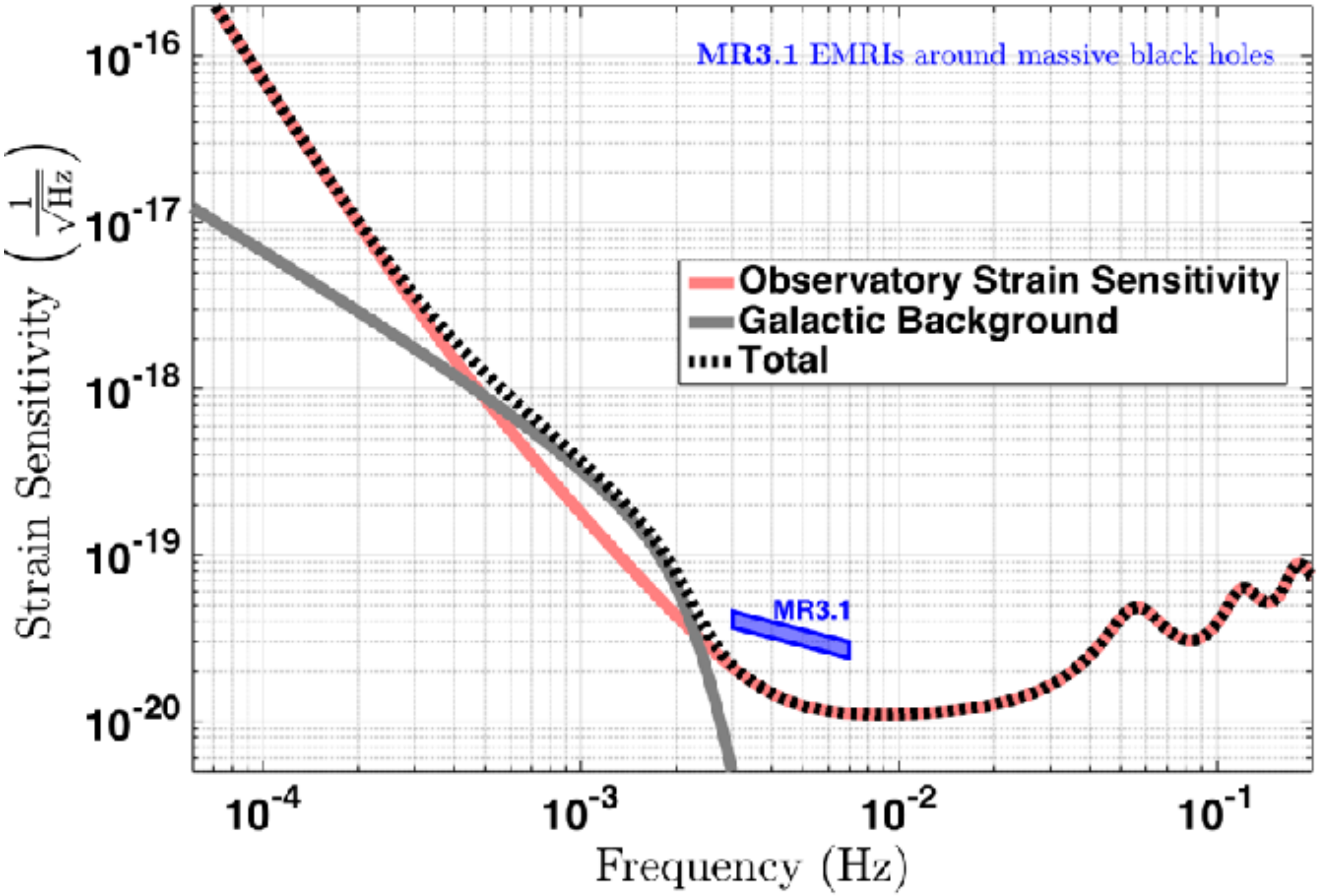
$$\frac{\delta M}{M} < 10^{-4} \quad \frac{\delta m}{m} < 10^{-3}$$

  spin of the MBH and orbit inclination

- leads to elaborate MR (not only on the strain sensitivity):
  - the absence of strong spectral lines from the instrument in the band $2 < f < 20$ mHz
  - ability to trigger a protect period around the plunge time

SO3: probe the dynamics of dense nuclear clusters using EMRIs

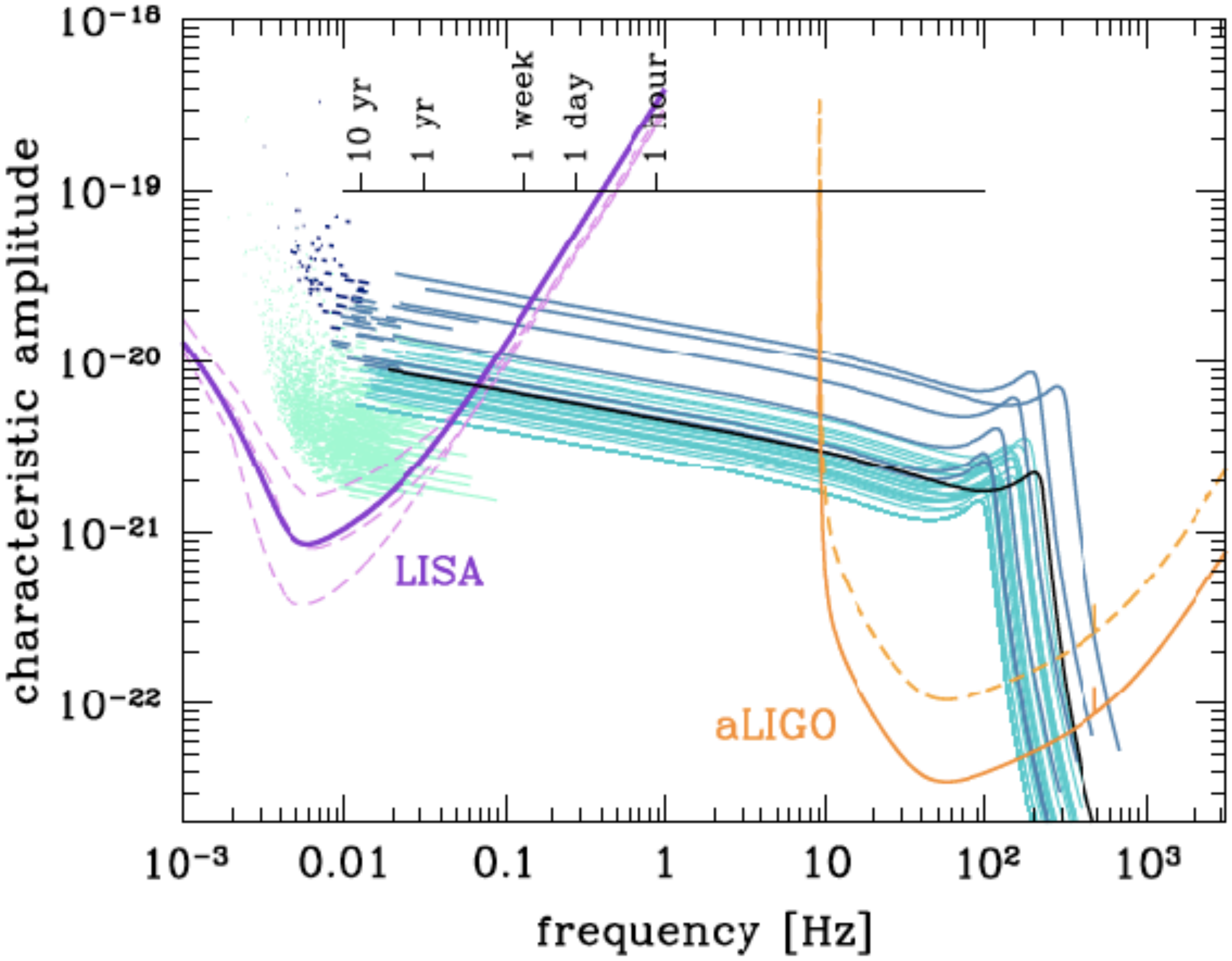
inspiral and merger of a stellar origin BH into a massive BH



SO4: understand the astrophysics of stellar origin BH

new SO following LIGO discovery of stellar origin BH
with 10 - 30 $M_\odot$

minimum 100 binaries based on LIGO rates
some will cross LIGO band when close to merger

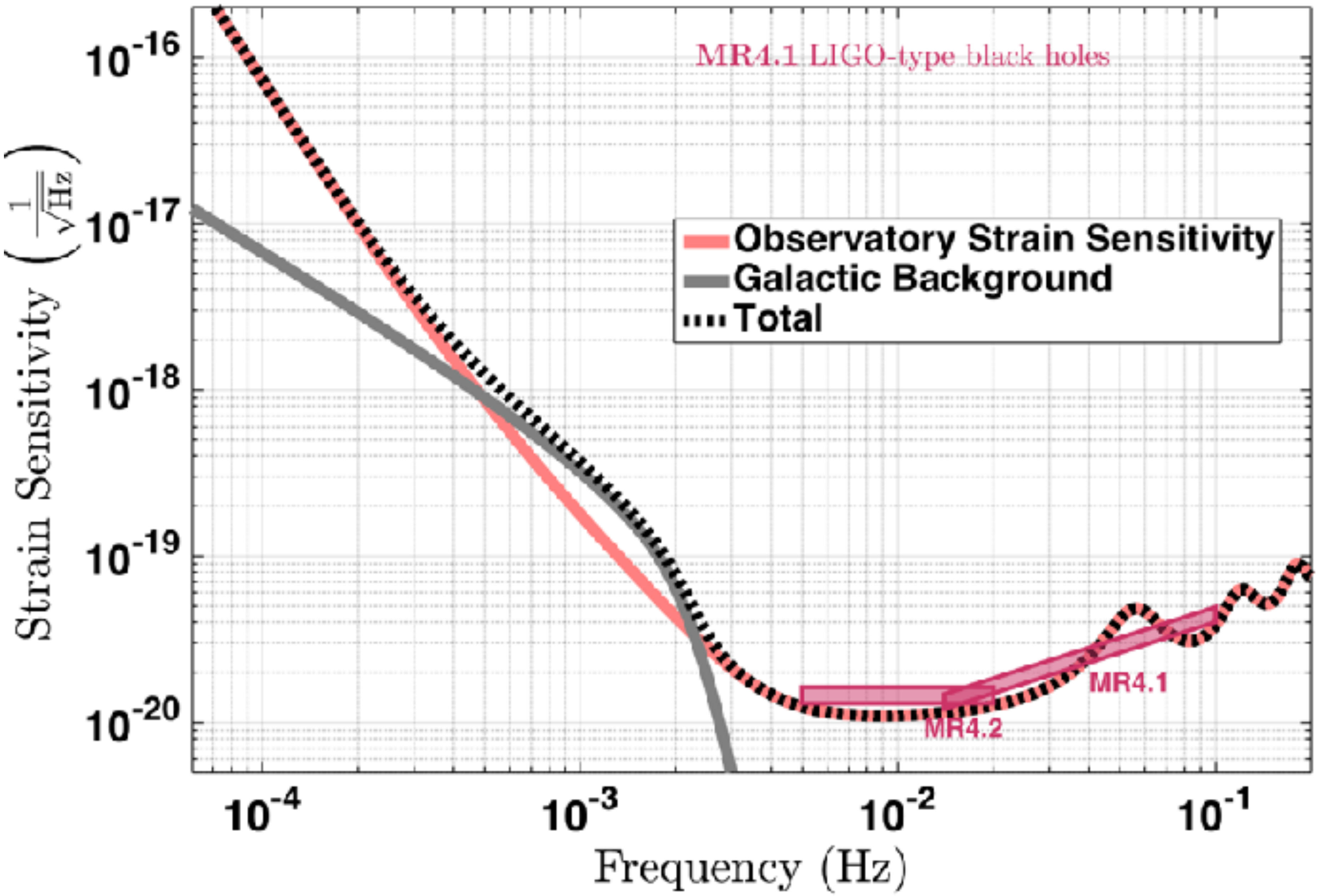


A Sesana
arXiv:1702.04356

SO4: understand the astrophysics of stellar origin BH

- SI: study the environment of stellar mass origin BH binaries with multi-band and multi-messenger observations of coalescences
    - OR: detect the inspiral signal with sky localisation better than 1 deg^2 and time of coalescence better than 1min (alert ground-based and EM observatories)
- SI: disentangle the formation channel
    - OR: detect the inspiral signal with 10^{-2} error on the mass and 10^{-3} on the eccentricity

SO4: understand the astrophysics of stellar origin BH



SO5: Explore the nature of gravity and the fundamental nature of BH

MBHB and EMRIs allow tests of GR in the strong field regime
This can be done using binaries with SNR>100 in the post-merger phase

- SI: use the ring-down phase to test whether the post-merger object is a General Relativity BH
  - OR: have the ability to observe more than 1 ring-down mode to test the no-hair theorem (requires very high SNR>100 in the post-merger phase)

- SI: use EMRIs to explore deviations from Kerr quadrupole moment
  - OR: at least one EMRI with SNR>50, spin>0.9
  - leads to MR on the duration of the mission to improve number of detections

SO5: Explore the nature of gravity and the fundamental nature of BH

MBHB and EMRIs allow tests of GR in the strong field regime
This can be done using binaries with SNR>100 in the post-merger phase

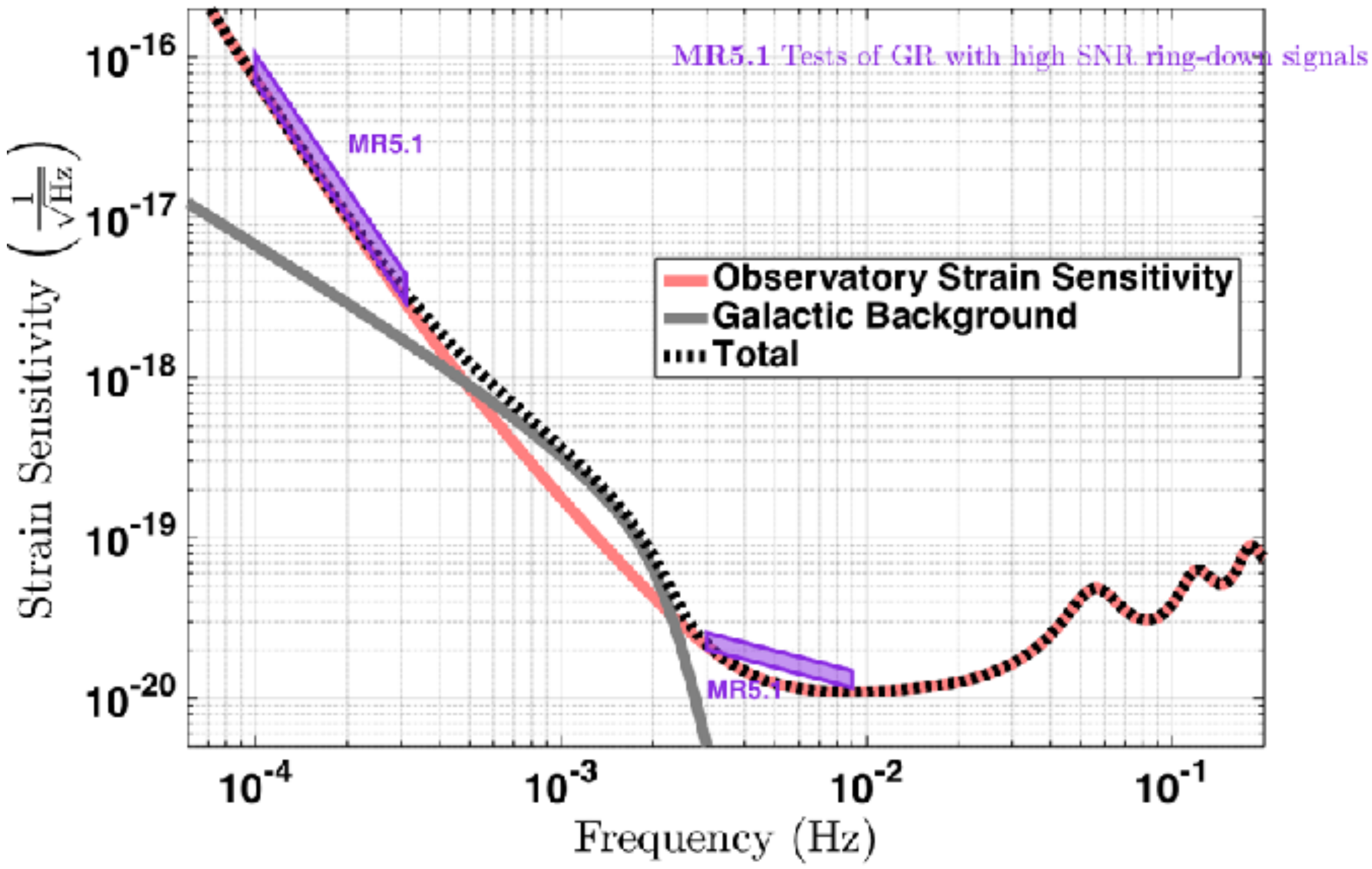
- SI: test beyond GR emission (dipole radiation) with multi-band sources

- SI: test propagation properties (dispersion relation, mass of the graviton, Lorentz invariance violations) with both MBHB and EMRIs

- SI: test the presence of massive fields around BH (e.g. scalar dark matter candidates…)

SO5: Explore the nature of gravity and the fundamental nature of BH

MBHB and EMRIs allow tests of GR in the strong field regime
This can be done using binaries with SNR>100 in the post-merger phase



SO6: Probe the rate of expansion of the universe

GW binaries can be used as standard sirens since they provide a neat measurement of the luminosity distance
several populations at different redshift :
SOBHBs ($z<0.2$), EMRIs ($z<1.5$), MBHB ($z<8$)

- SI: measure Hubble factor using GW observations only
  - OR: observe SOBHBs with $M_{tot}>50\ M_\odot$ and $z < 0.1$ with sky location constrained to better than 1 deg^2
  - OR: localise EMRIs with $M=10^5\ M_\odot$ and $m=10\ M_\odot$ at $z < 1.5$ with sky location constrained to better than 1 deg^2
    - leads to MR on the duration of the mission:
      - 4 yr mission allows to constrain h better than 0.02

SO6: Probe the rate of expansion of the universe

GW binaries can be used as standard sirens since they provide a neat measurement of the luminosity distance
several populations at different redshift :
SOBHBs ($z<0.2$), EMRIs ($z<1.5$), MBHB ($z<8$)

- SI: constrain cosmological parameters through joint GW and EM observations

  - OR: observe MBHBs with $10^4\,M_\odot < M < 10^5\,M_\odot$ and $z < 5$ with sky location constrained to better than 10 deg^2 in order to allow EM follow ups

- leads to MR on the duration of the mission:
  - 4 yr mission allows to constrain h better than 0.01 and w_0 better than 0.1
  - a mission extension to 10 yr yields an improvement of a factor of 2 on the errors

SO7: Understand stochastic gravitational wave backgrounds

measuring a stochastic background of cosmological origin provides information on new physics in the early universe
determine the shape of the signal indicates its origin, while an upper bound constraints beyond-standard models

- SI: characterise the astrophysical background
  - OR: measure the background in the range predicted by LIGO rates and verify the spectral shape in at least two frequency bins
- SI: measure the spectral shape or set upper limits on the cosmological background
  - OR: probe a broken power law as predicted e.g. by a first order phase transition

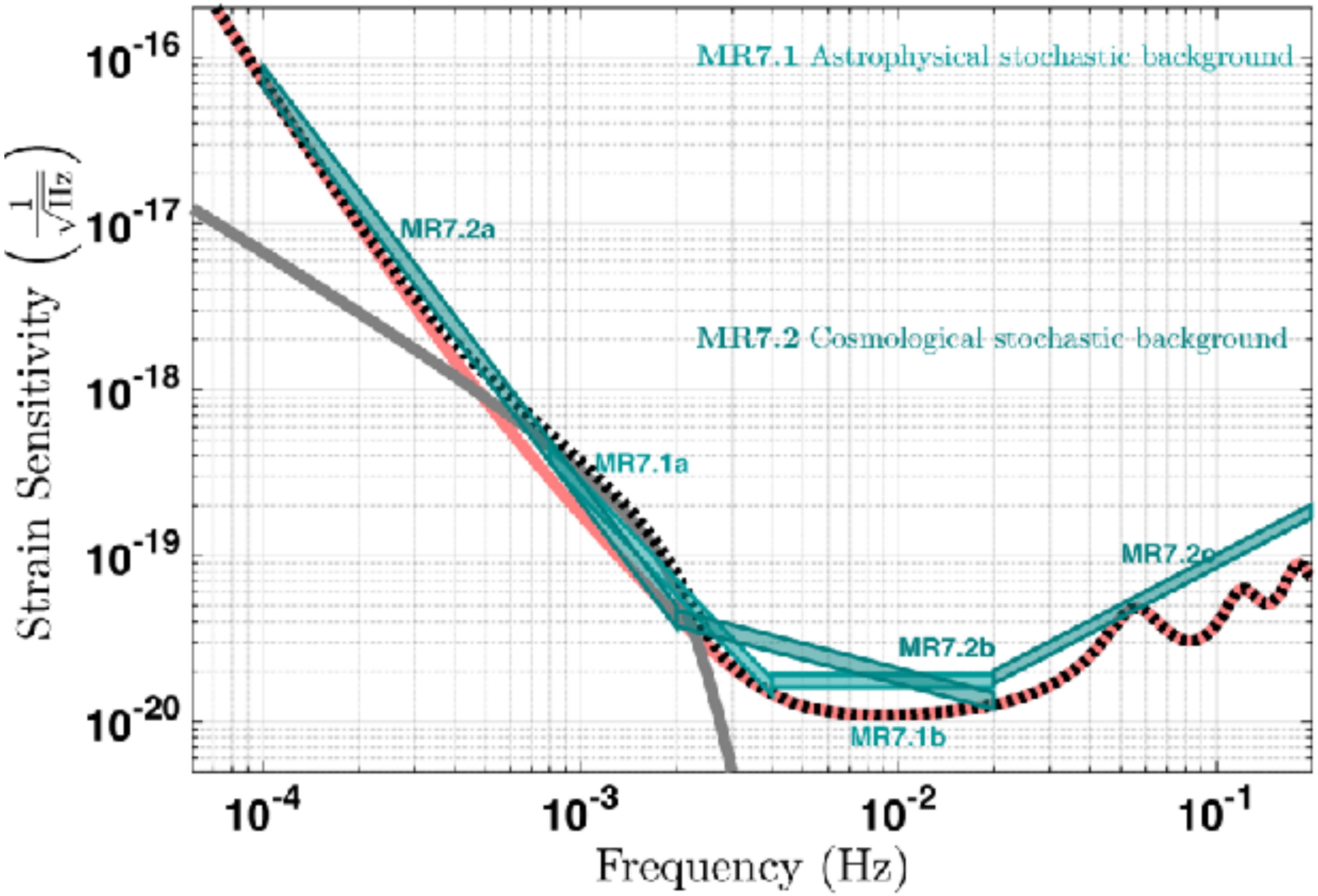
SO7: Understand stochastic gravitational wave backgrounds

measuring a stochastic background of cosmological origin provides information on new physics in the early universe
determine the shape of the signal indicates its origin, while an upper bound constraints beyond-standard models

- leads to elaborate MR (not only on the strain sensitivity):
  - three arms (Sagnac TDI channel, polarisation)
  - limiting the number of instrumental glitches (non-gaussianity)
  - (probe the anisotropy?)

SO7: Understand stochastic gravitational wave backgrounds

measuring a stochastic background of cosmological origin provides information on new physics in the early universe
determine the shape of the signal indicates its origin, while an upper bound constraints beyond-standard models



SO8: Search for GW bursts and unforeseen sources

there is the potential for new discoveries
unforeseen, unmodelled sources should ideally be distinguishable from instrumental artefacts

- SI: search for bursts from cosmic strings
- SI: search for unmodelled sources
  - MR : three arms to understand and characterise the noise; reduce the presence of glitches

SUMMARY

- LISA is a discovery mission that will enlarge our knowledge of the Universe

- it has the ability to test fundamental physics (tests of GR, constrain models of the very early universe and universe expansion…)

- some of the science it will do depends on models (astrophysical populations, existence of early universe sources…) - the aim is to constrain those models

- the chosen baseline is technically feasible and performant to achieve the scientific goals, given present knowledge of population models

- extension that would improve science return are envisageables: 10yr, extended low frequency sensitivity…