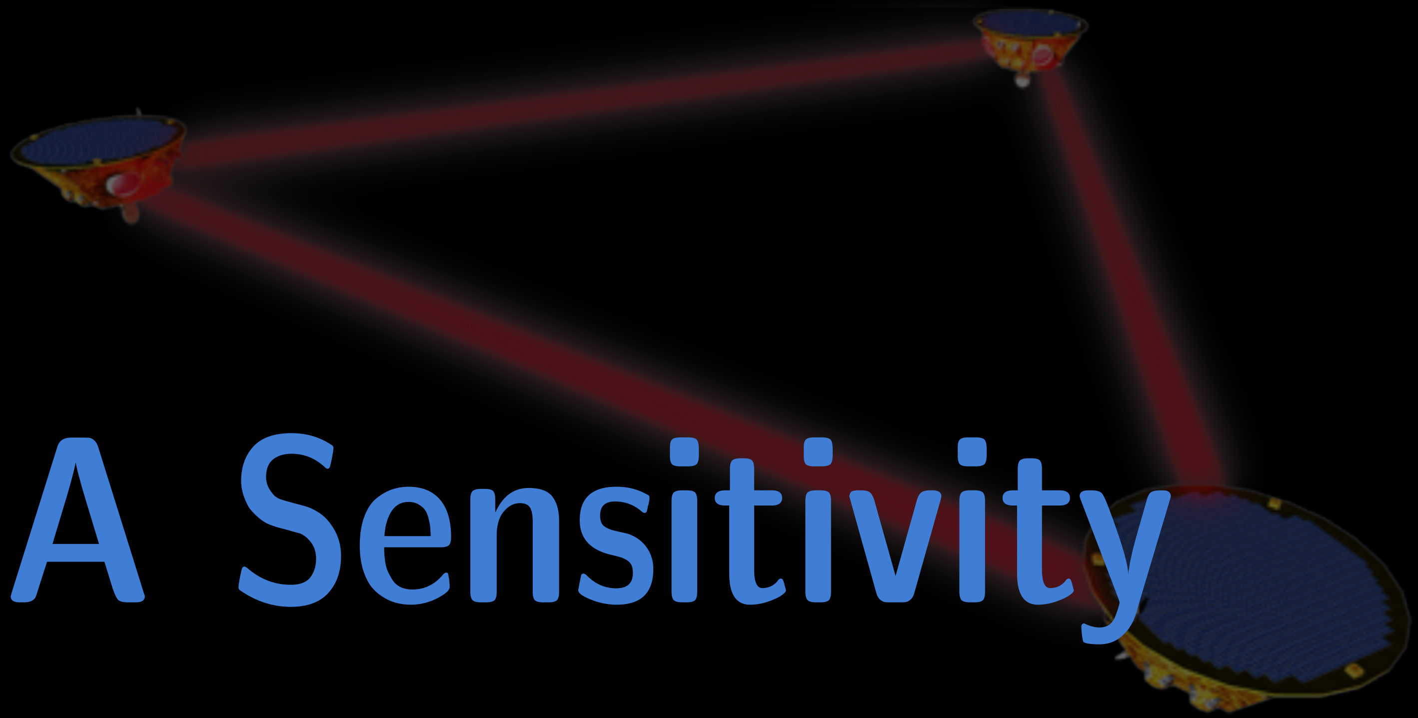


LISA Sensitivity

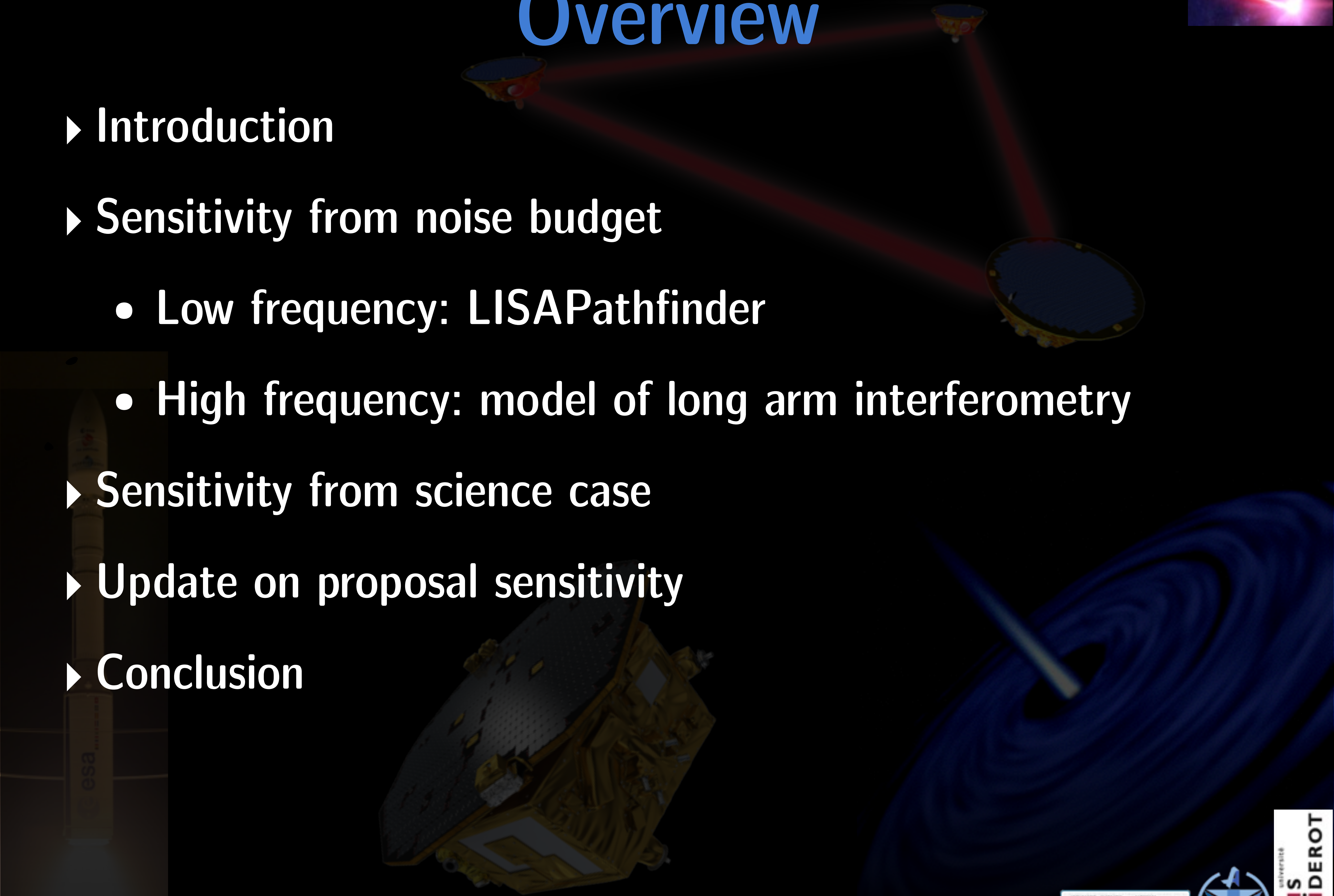
Antoine Petiteau

(APC – Université Paris-Diderot/CNRS)

LISA Cosmology Working Group workshop
MITP - Mainz

16th October 2017

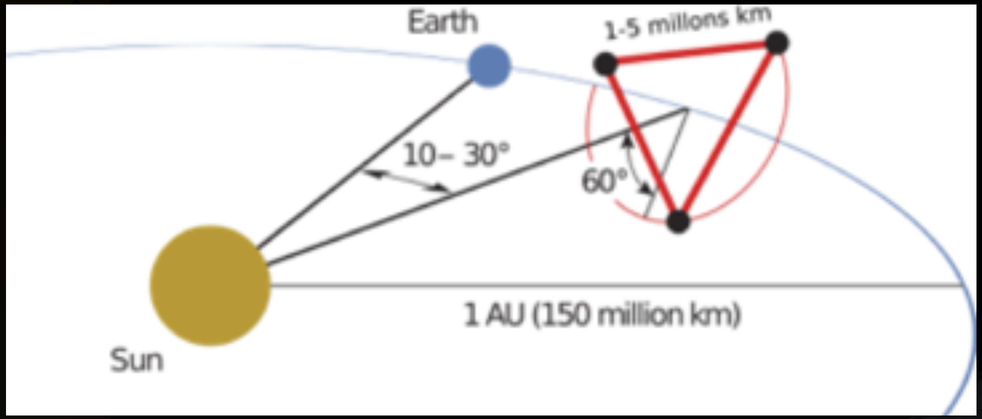
Overview

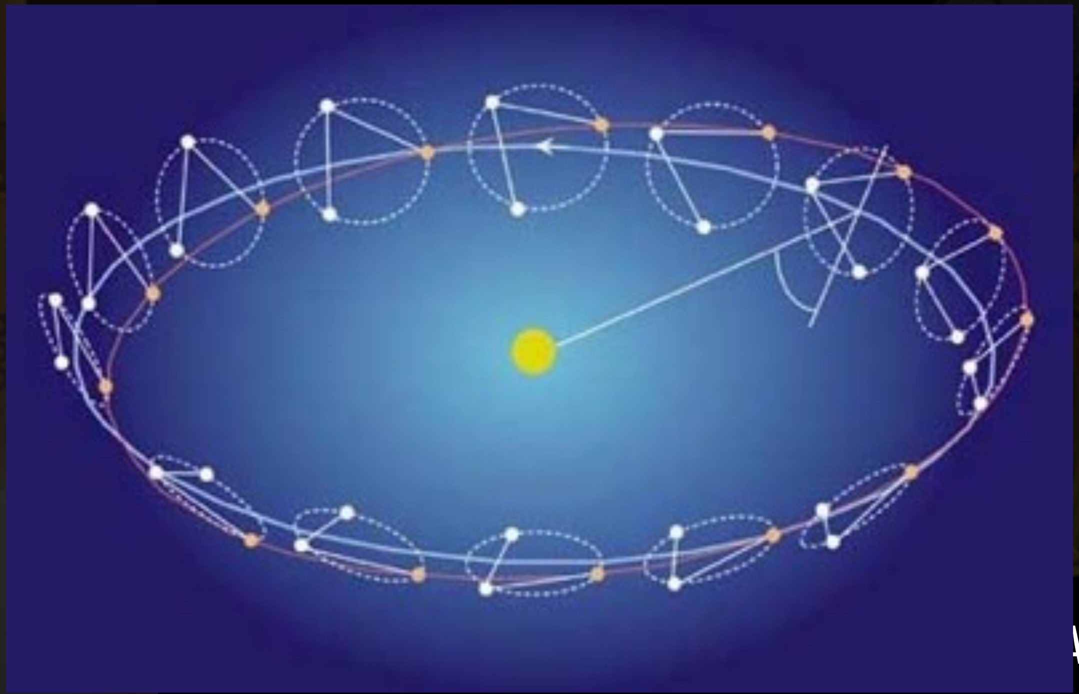


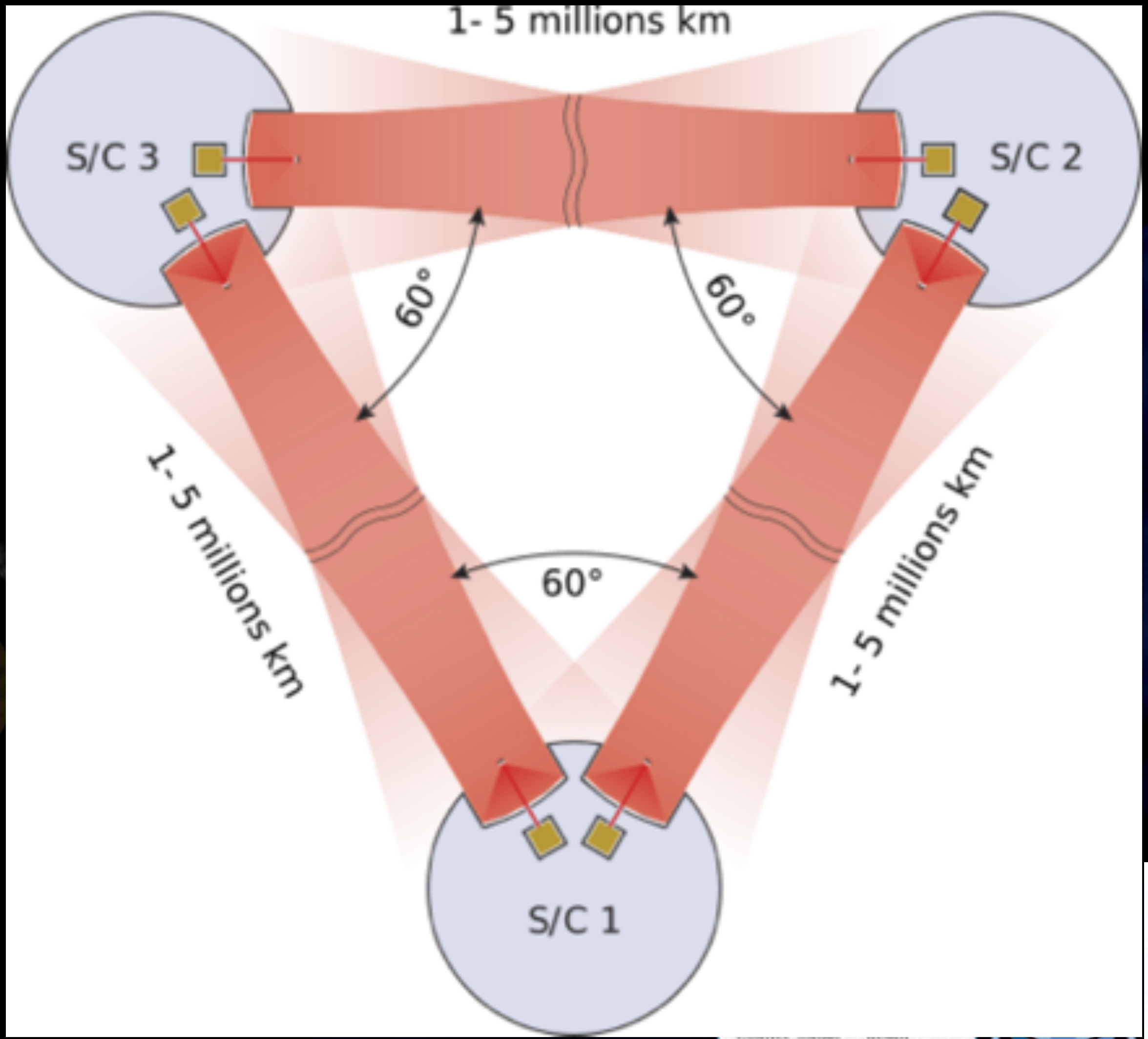
- Introduction
- Sensitivity from noise budget
  - Low frequency: LISAPathfinder
  - High frequency: model of long arm interferometry
- Sensitivity from science case
- Update on proposal sensitivity
- Conclusion

LISA

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from few millions kilometers (2.5 millions km in the proposal L3)
- Goal: detect relative distance changes of 10^{-21}: few picometers

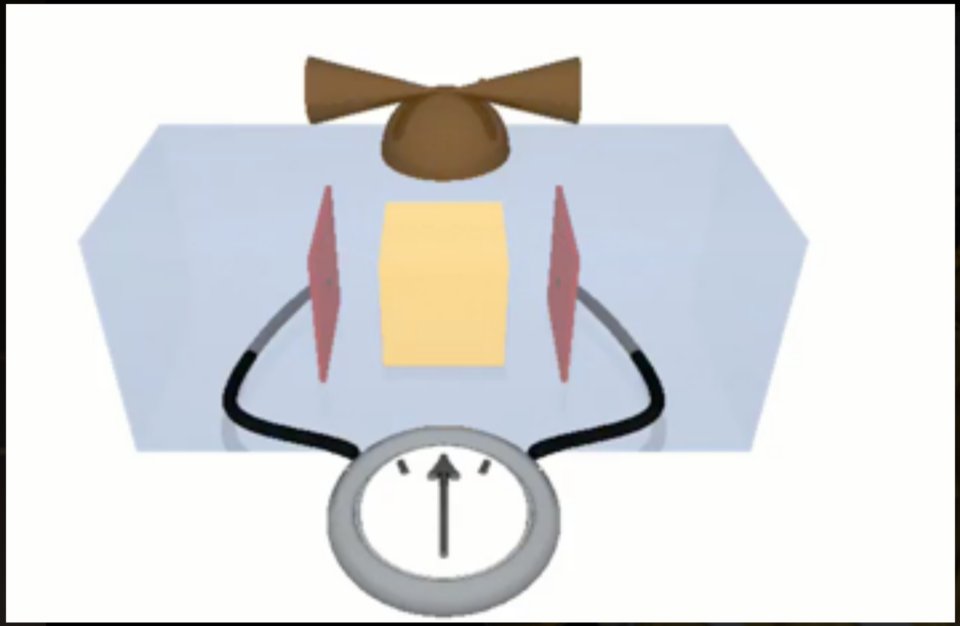


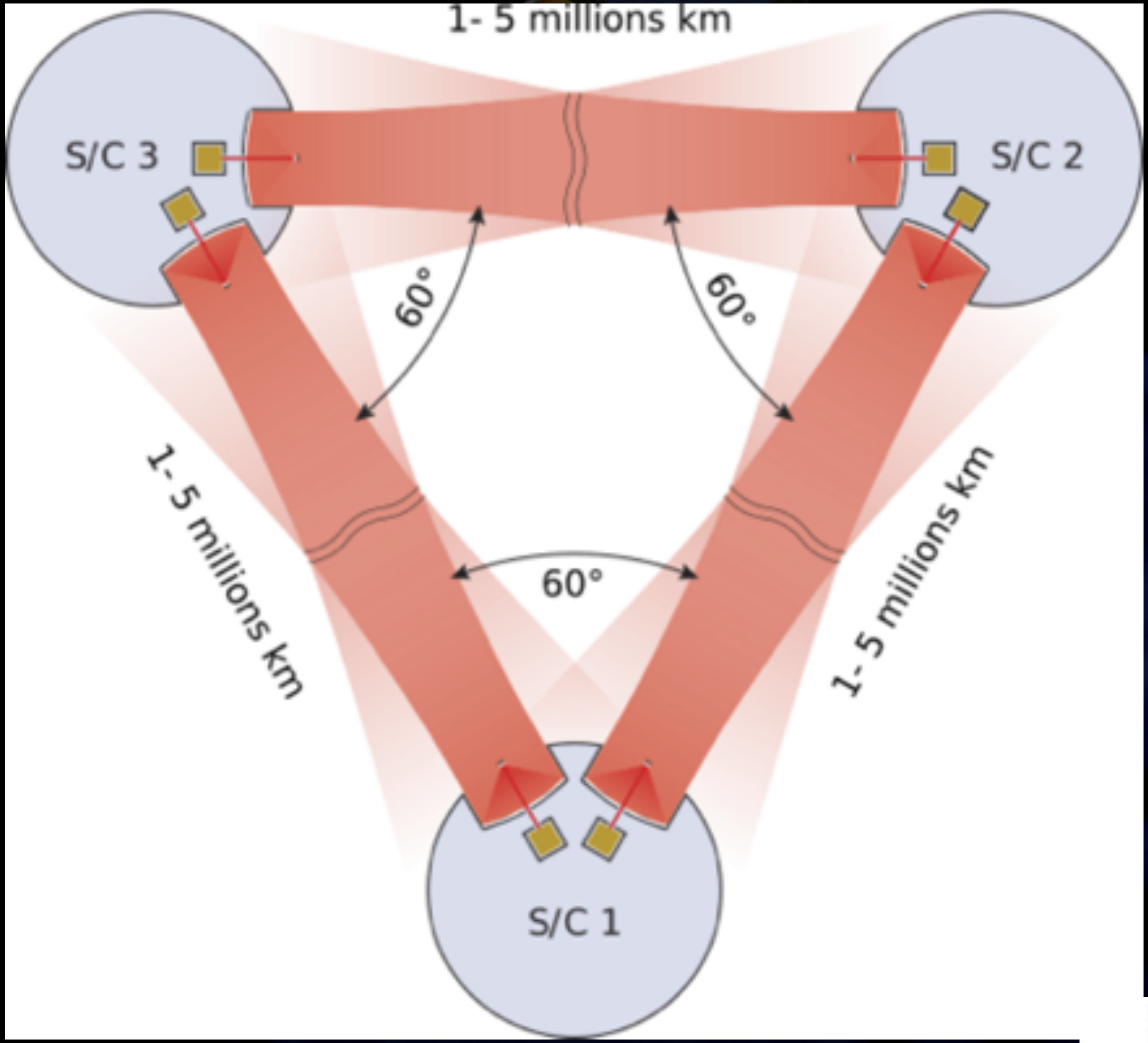




LISA

- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing





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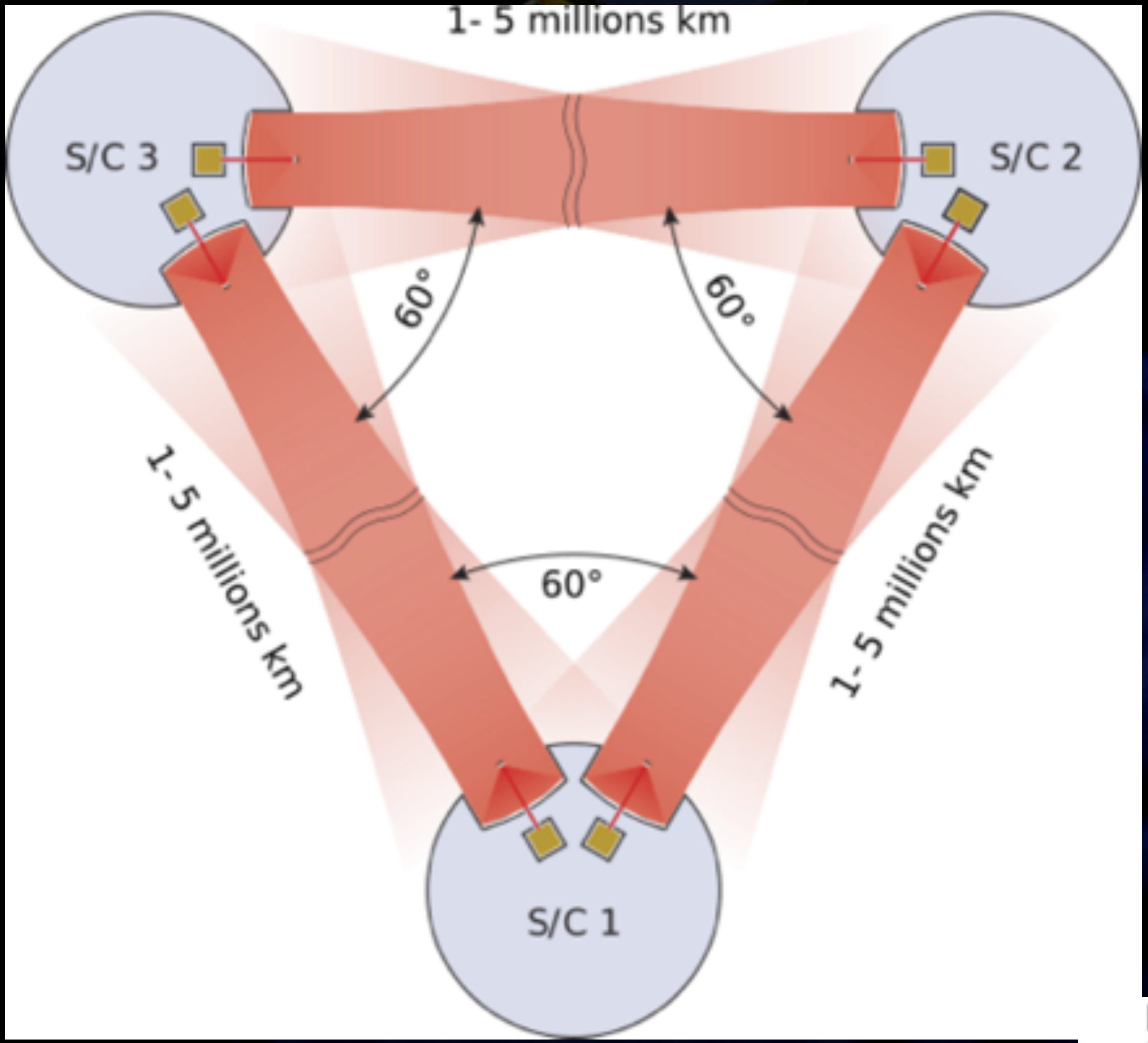
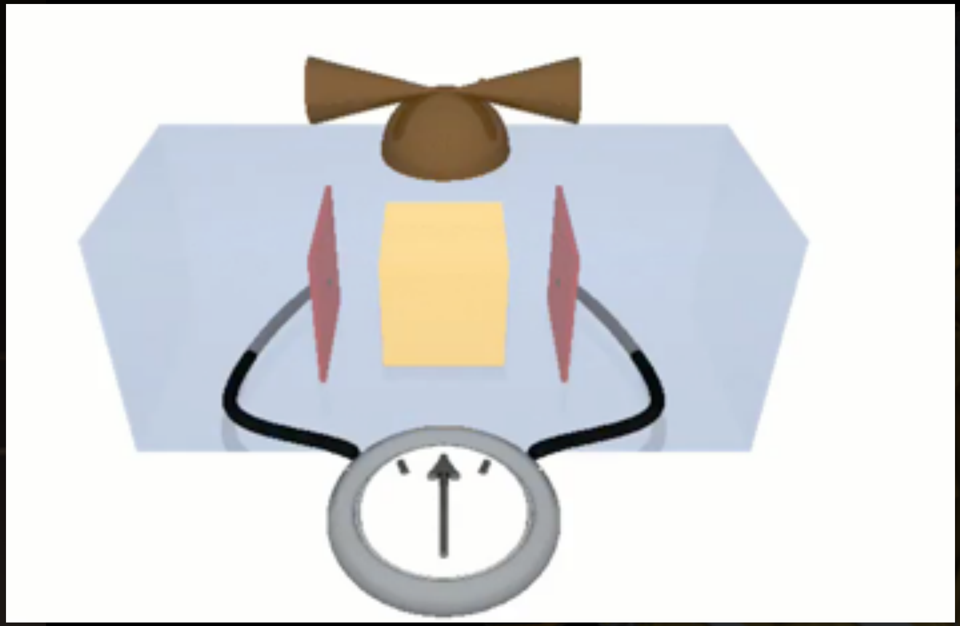
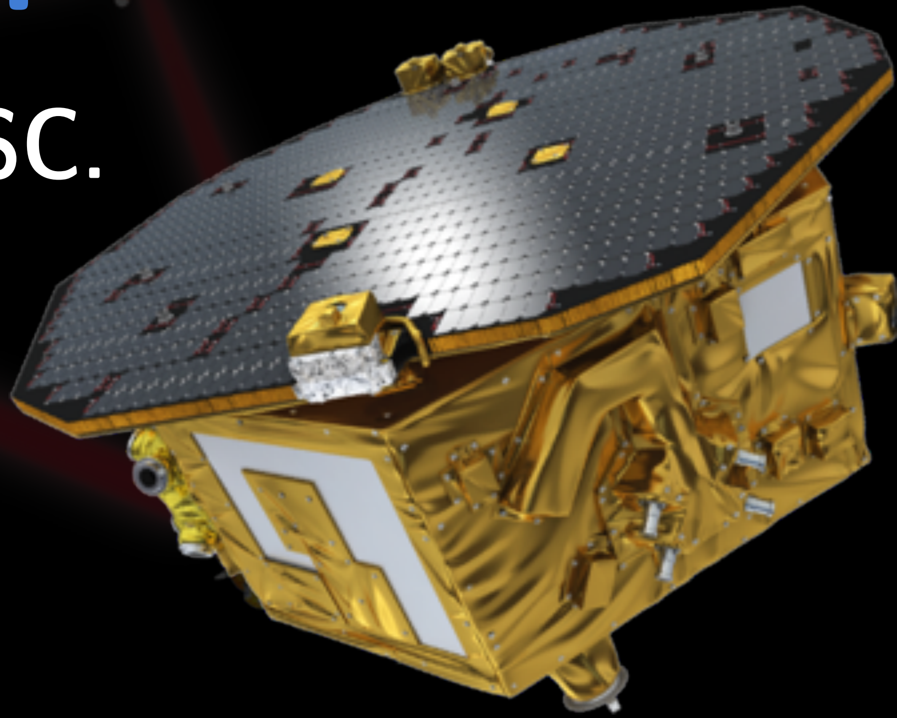
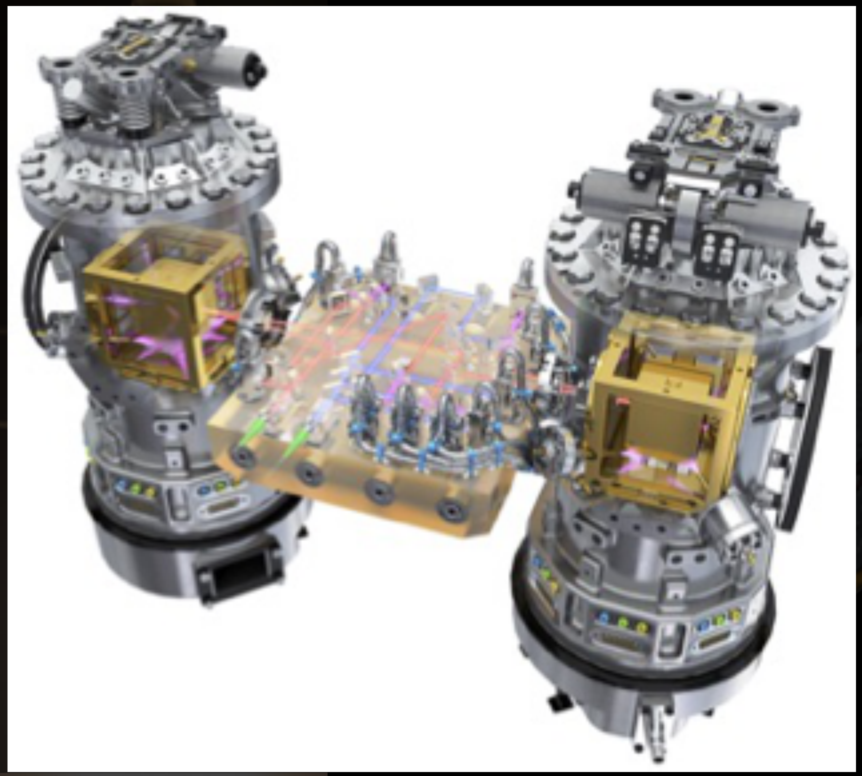


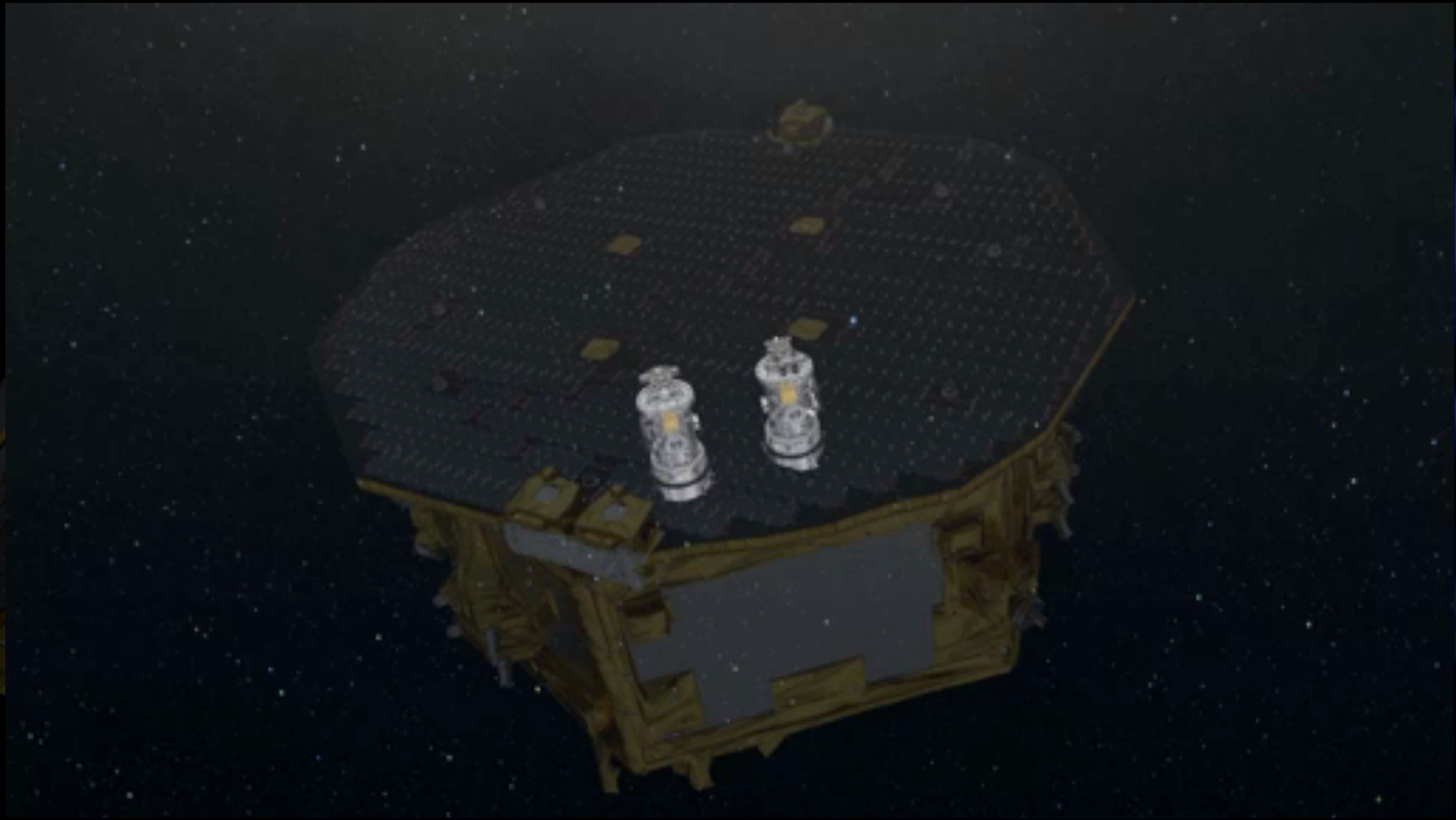


LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing :
    - Inertial sensor,
    - Drag-free and attitude control system
    - Interferometric measurement between 2 free-falling test-masses,
    - Micro-thrusters







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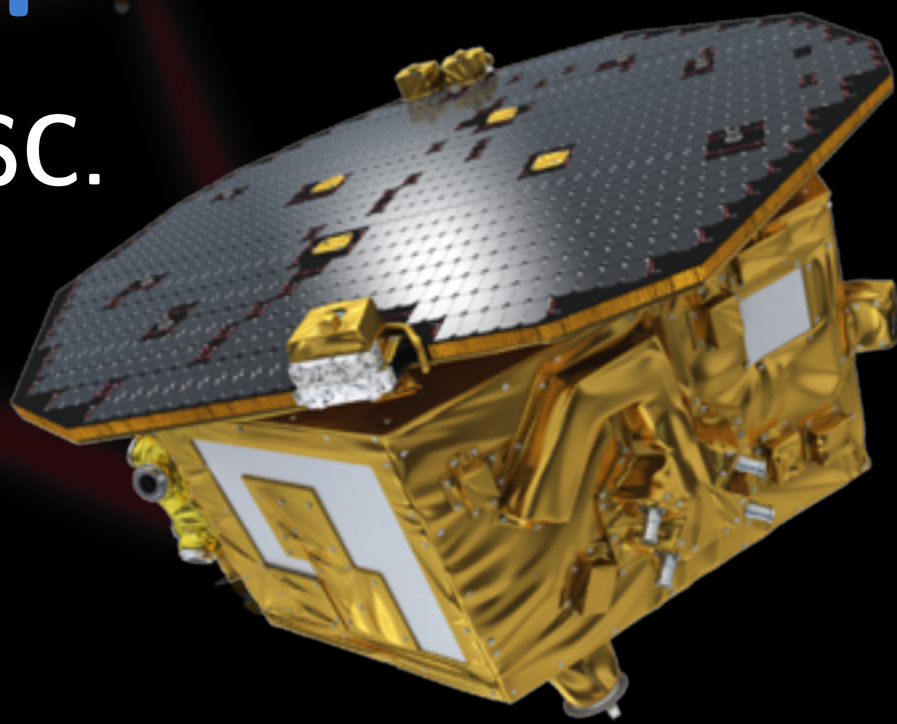
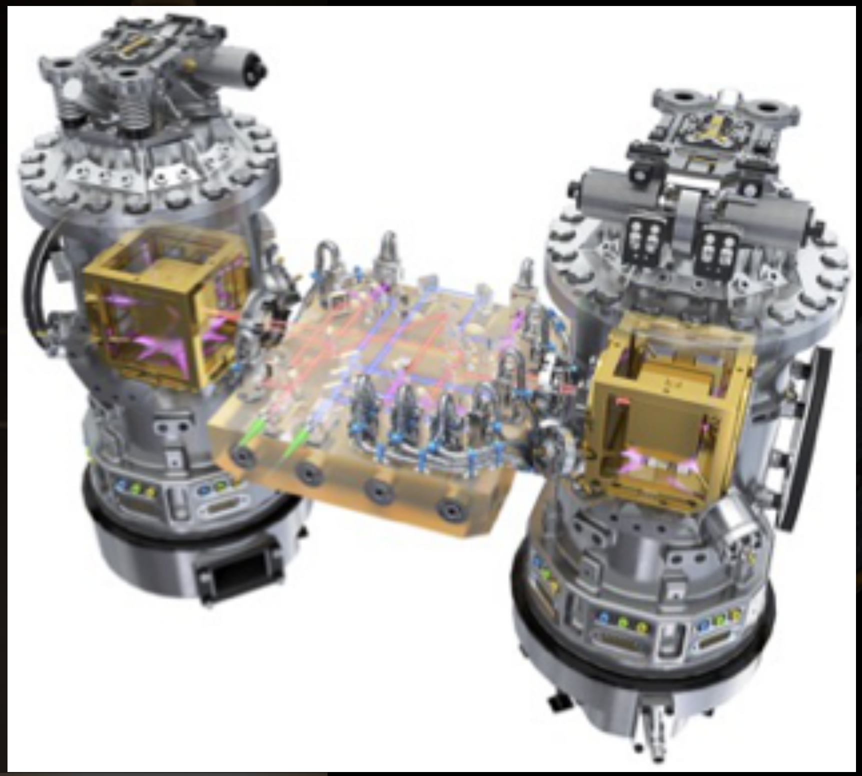
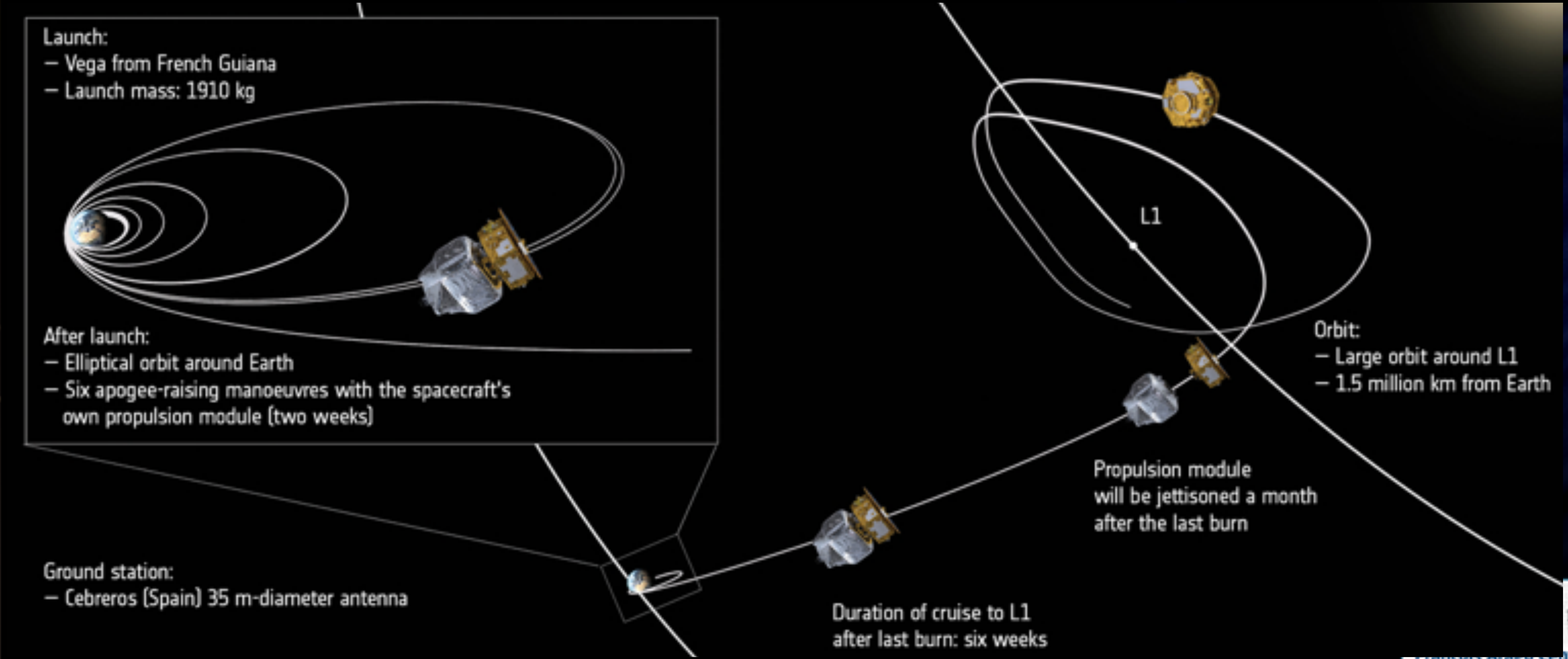




LISAPathfinder timeline

- 3/12/2015: Launch from Kourou
- 22/01/2016: arrived on final orbit & separation of propulsion module
- 17/12/2015 → 01/03/2016: commissioning
- 01/03/2016 → 27/06/2016: LTP operations (Europe)
- 27/06/2016 → 11/2016: DRS operations (US) + few LTP weeks
- 01/12/2016 → 31/06/2017: extension of LTP operations



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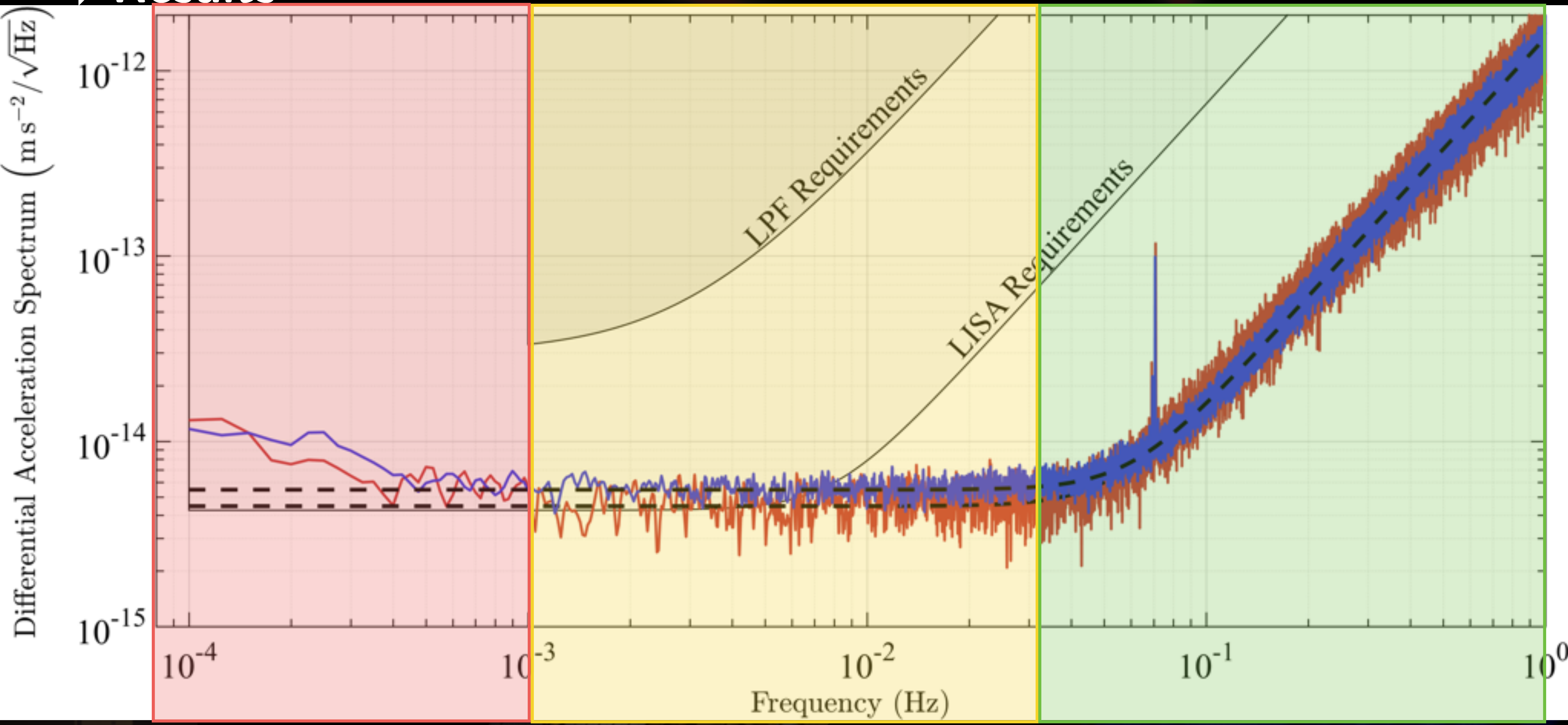
First results

M. Armano et al. PRL 116, 231101 (2016)

- Results



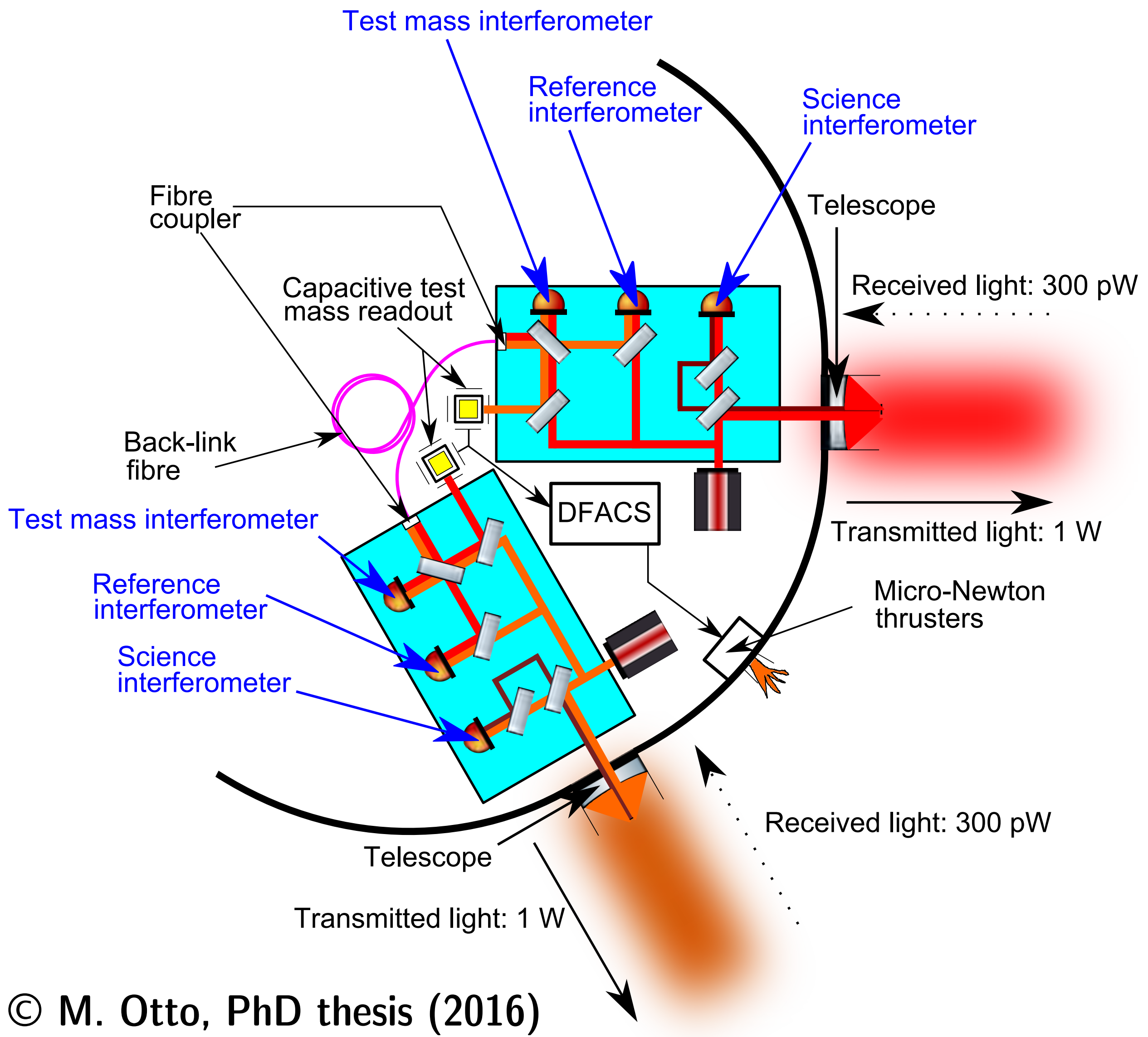
Low frequency noise: actuation noie + ...

Brownian noise
Molecules within the noise
hit test-masses

Interferometric noise
Not real test-mass motion

LISA

- Exchange of laser beam to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises



© M. Otto, PhD thesis (2016)

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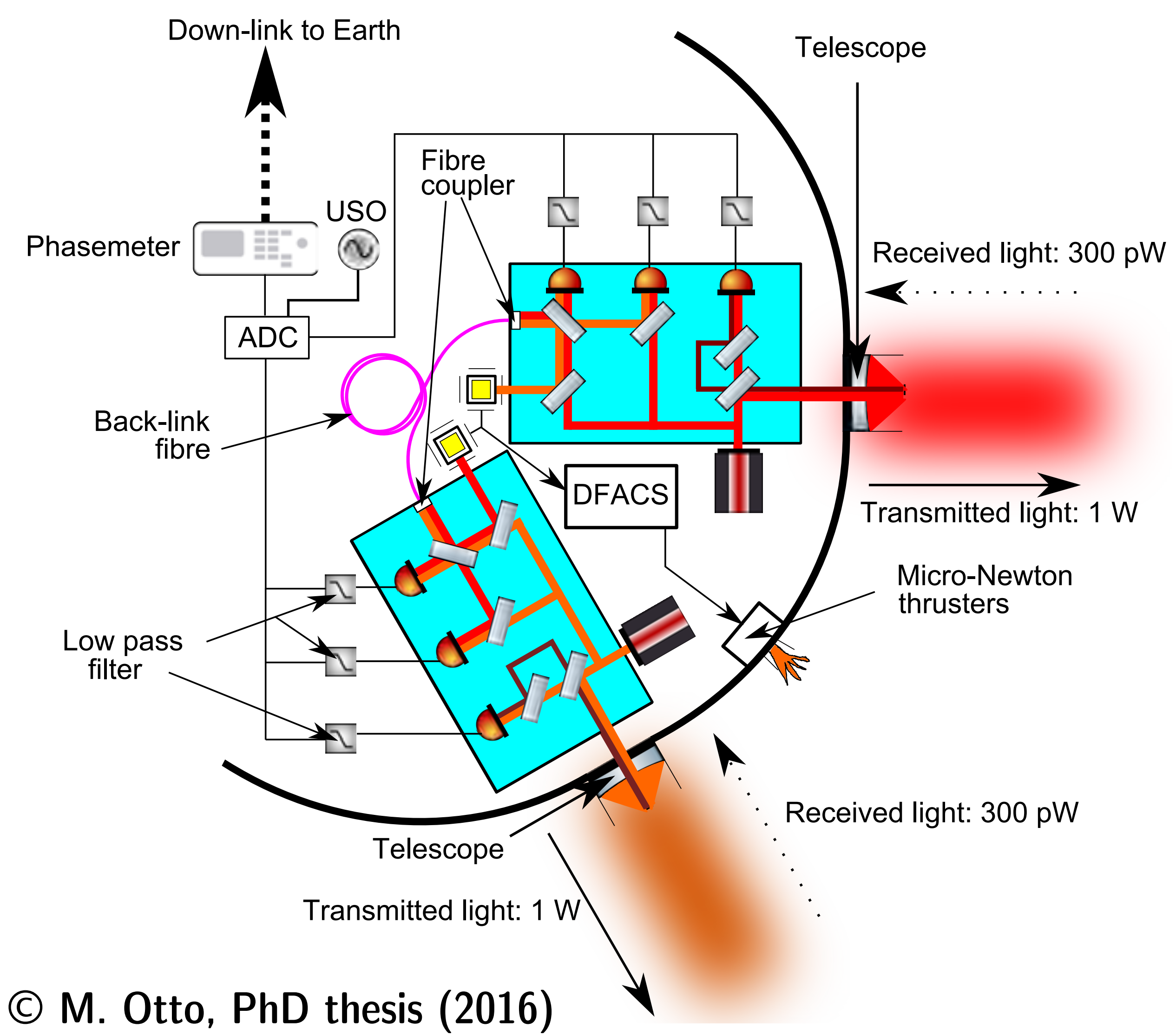

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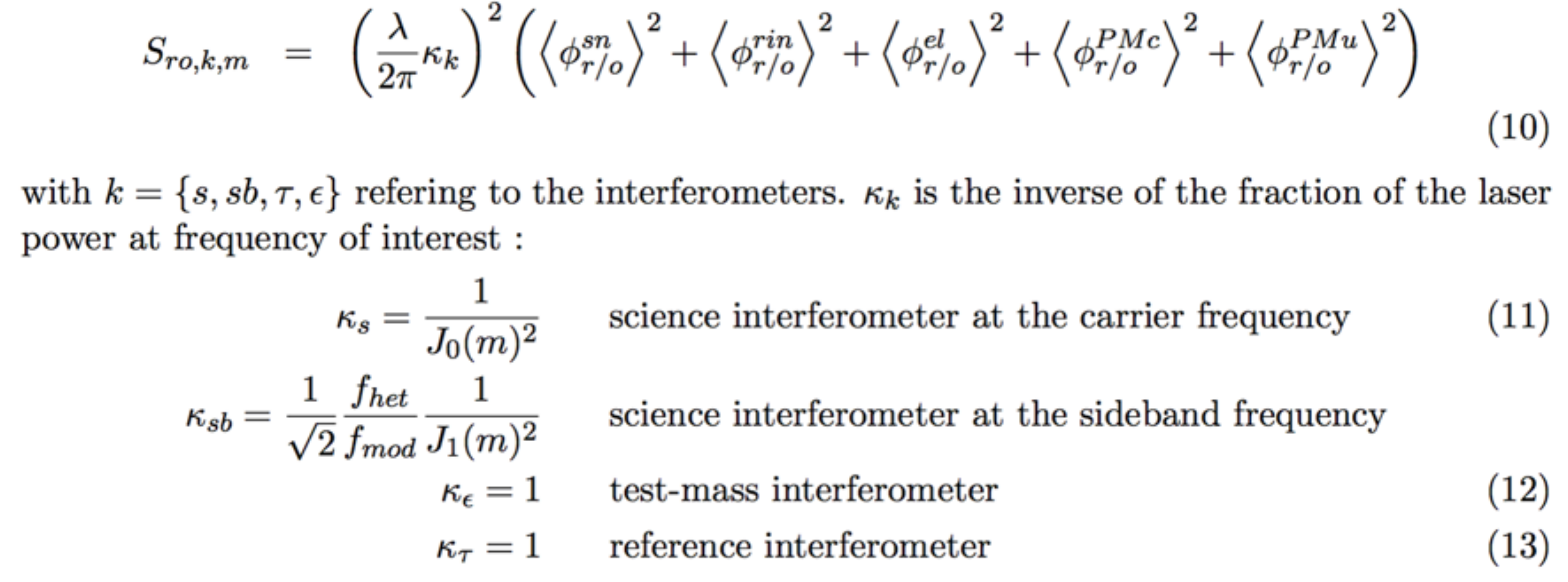
- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises

Readout noise

- Composition of a number of effects:



$$S_{ro,k,m} = \left(\frac{\lambda}{2\pi}\kappa_k\right)^2 \left(\left\langle\phi^{sn}_{r/o}\right\rangle^2 + \left\langle\phi^{rin}_{r/o}\right\rangle^2 + \left\langle\phi^{el}_{r/o}\right\rangle^2 + \left\langle\phi^{PMc}_{r/o}\right\rangle^2 + \left\langle\phi^{PMu}_{r/o}\right\rangle^2\right) \tag{10}$$

with $k = \{s, sb, \tau, \epsilon\}$ refering to the interferometers. κ_k is the inverse of the fraction of the laser power at frequency of interest :

$$\kappa_s = \frac{1}{J_0(m)^2} \quad \text{science interferometer at the carrier frequency} \tag{11}$$

$$\kappa_{sb} = \frac{1}{\sqrt{2}}\frac{f_{het}}{f_{mod}}\frac{1}{J_1(m)^2} \quad \text{science interferometer at the sideband frequency}$$

$$\kappa_\epsilon = 1 \quad \text{test-mass interferometer} \tag{12}$$

$$\kappa_\tau = 1 \quad \text{reference interferometer} \tag{13}$$

- If $k = s$ or sb $=>$ $P_1 = P_{rec}$ and $P_2 = P_{local,1}$
- If $k = \tau$ or ε $=>$ $P_2 = P_{local,1}$ and $P_2 = P_{local,2}$

Readout: shot noise

- Due to the small number of photons in the incoming beam
  - Emitted laser power: $P_{tel} = \eta_{TX} P_{laser}$
  - Received laser intensity:

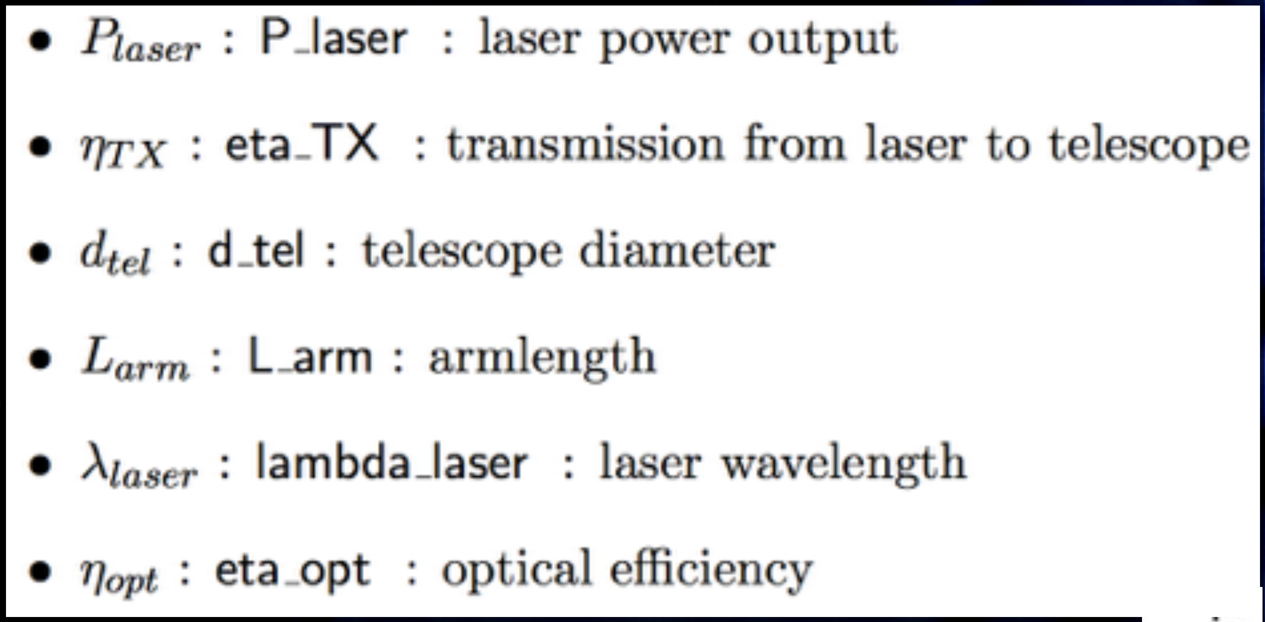
$$I_{red} = \frac{\pi\ P_{tel}\ d_{tel}^2}{2\ L_{arm}^2 \lambda_{laser}^2} \times \alpha^2 e^{-\frac{2}{\alpha^2}} \left(e^{\frac{1}{\alpha^2}} - 1\right)^2$$

  - Received laser power on the optical bench:

$$P_{red} = \pi \left(\frac{d_{tel}}{2}\right)^2 \eta_{opt} I_{rec}$$

  - Shot noise:

$$\left\langle \phi^{sn}_{r/o} \right\rangle = M_{IMS}(f) \sqrt{\frac{q_e \left(P_1 + P_2\right)}{R_{pd}\ \eta_{het}\ P_1\ P_2}}$$



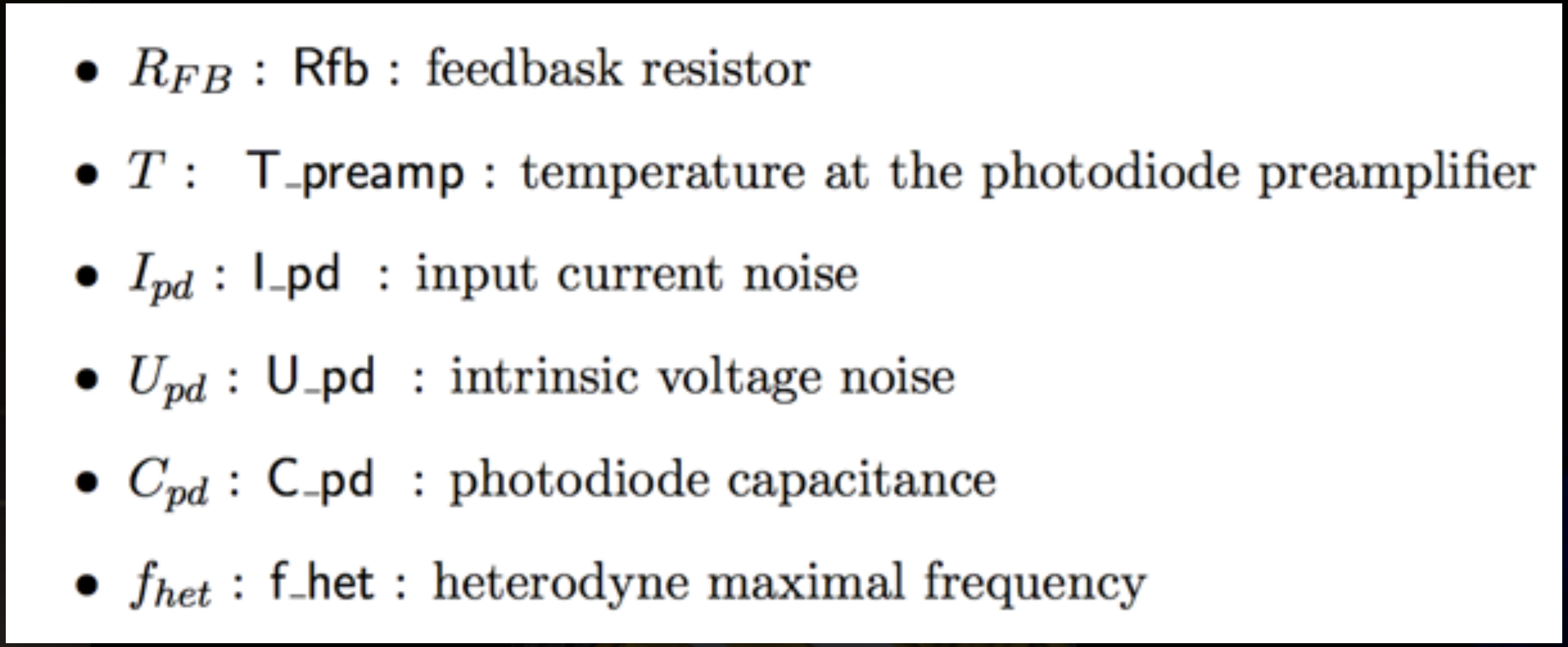
- P_{laser} : P_laser : laser power output
- η_{TX} : eta_TX : transmission from laser to telescope
- d_{tel} : d_tel : telescope diameter
- L_{arm} : L_arm : armlength
- λ_{laser} : lambda_laser : laser wavelength
- η_{opt} : eta_opt : optical efficiency

Readout: electronic noise

- Electronic noise associated to the photodiode

$$\left\langle \phi^{el}_{r/o} \right\rangle = M_{IMS}(f) \frac{\sqrt{N_{seg} N_{pd}}}{R_{pd}\sqrt{2}} \sqrt{\frac{\frac{4k_B T}{R_{FB}} + I_{pd}^2 + \left(\frac{U_{pd}}{Z_{pd}}\right)^2}{\eta_{het}\, P_2\, P_1}}$$

$$Z_{pd} = \frac{1}{2\pi C_{pd} f_{het}}$$



- R_{FB} : Rfb : feedbask resistor
- T : T_preamp : temperature at the photodiode preamplifier
- I_{pd} : I_pd : input current noise
- U_{pd} : U_pd : intrinsic voltage noise
- C_{pd} : C_pd : photodiode capacitance
- f_{het} : f_het : heterodyne maximal frequency

Readout: RIN & phase meter

- RIN: Relative Intensity Noise:
  - For a balanced detection, the phase noise contribution from RIN is

$$\left\langle \phi^{rin}_{r/o} \right\rangle = \phi^{rin}_{r/o} = M_{IMS}(f) \frac{RIN_{laser}}{\sqrt{2}} \frac{\sqrt{1+(P_1/P_2)^2}}{1+P_1/P_2}$$

- Phasemeter measurement noise:
  - Correlated term: $\left\langle \phi^{PMc}_{r/o} \right\rangle = M_{IMS}(f)\, \phi^{PMc}_{r/o}$
  - Uncorrelated term: $\left\langle \phi^{PMu}_{r/o} \right\rangle = M_{IMS}(f) \frac{\phi^{PMu}_{r/o}}{\sqrt{N_{pd} N_{seg}}}$

Optical Path Noises

- Noises on the optical path:

$$S_{opt,k,m}(f) = \left(M(f)x_{opn}^{tel}\right)^2 \cdots\cdots\blacktriangleright$$ telescope

$$+ \left(M(f)x_{opn}^{pointing}\right)^2 \cdots\blacktriangleright$$ pointing (tilt to length)

$$+ \left(M(f)x_{opn}^{align}\right)^2 \cdots\cdots\blacktriangleright$$ line of sight alignement (OB/TM)

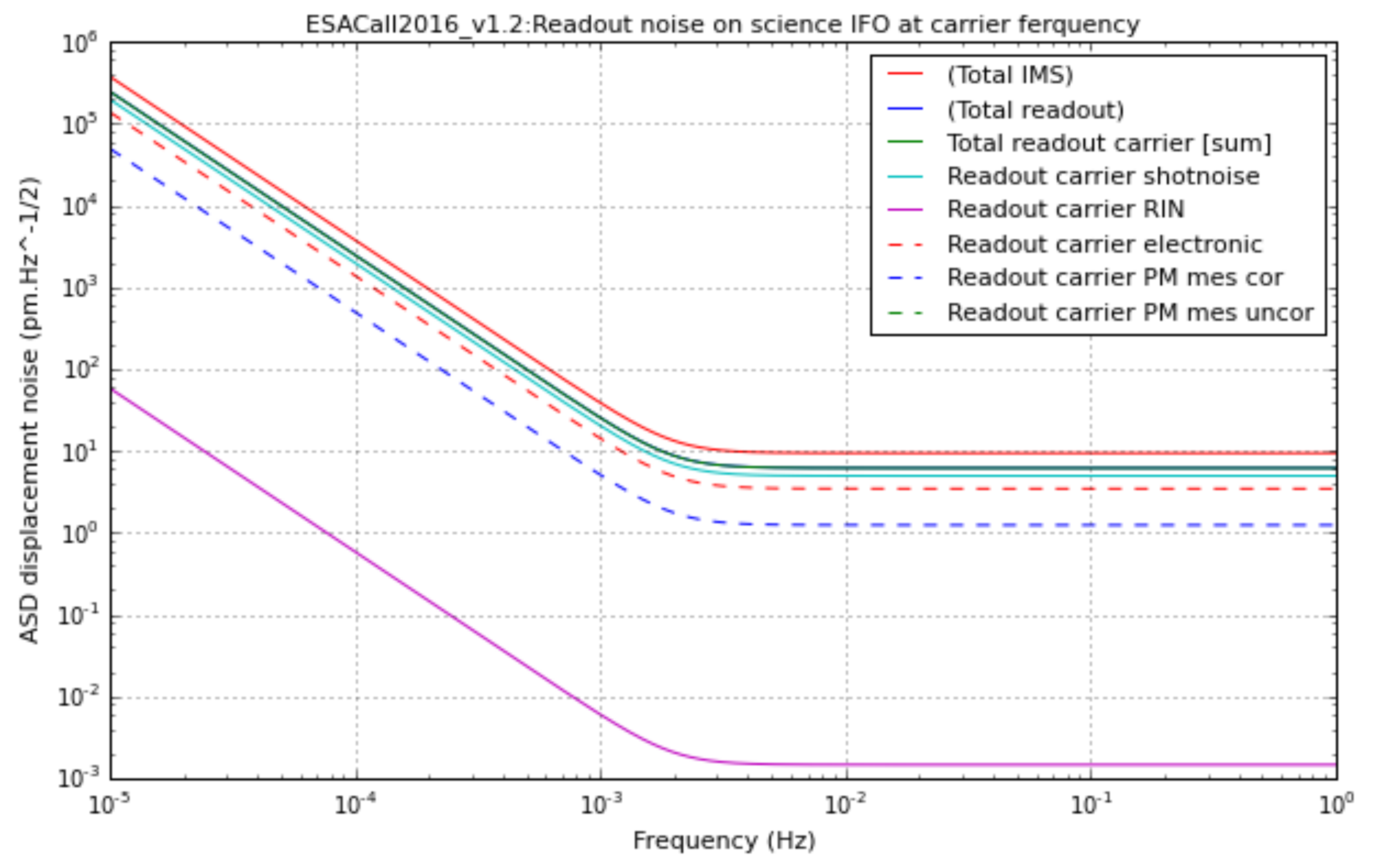
$$+ \left(M(f)x_{opn}^{SLs}\right)^2 \cdots\cdots\blacktriangleright$$ stray light science interferometer

$$+ \left(M(f)x_{opn}^{PAAM}\right)^2 \cdots\blacktriangleright$$ PAAM

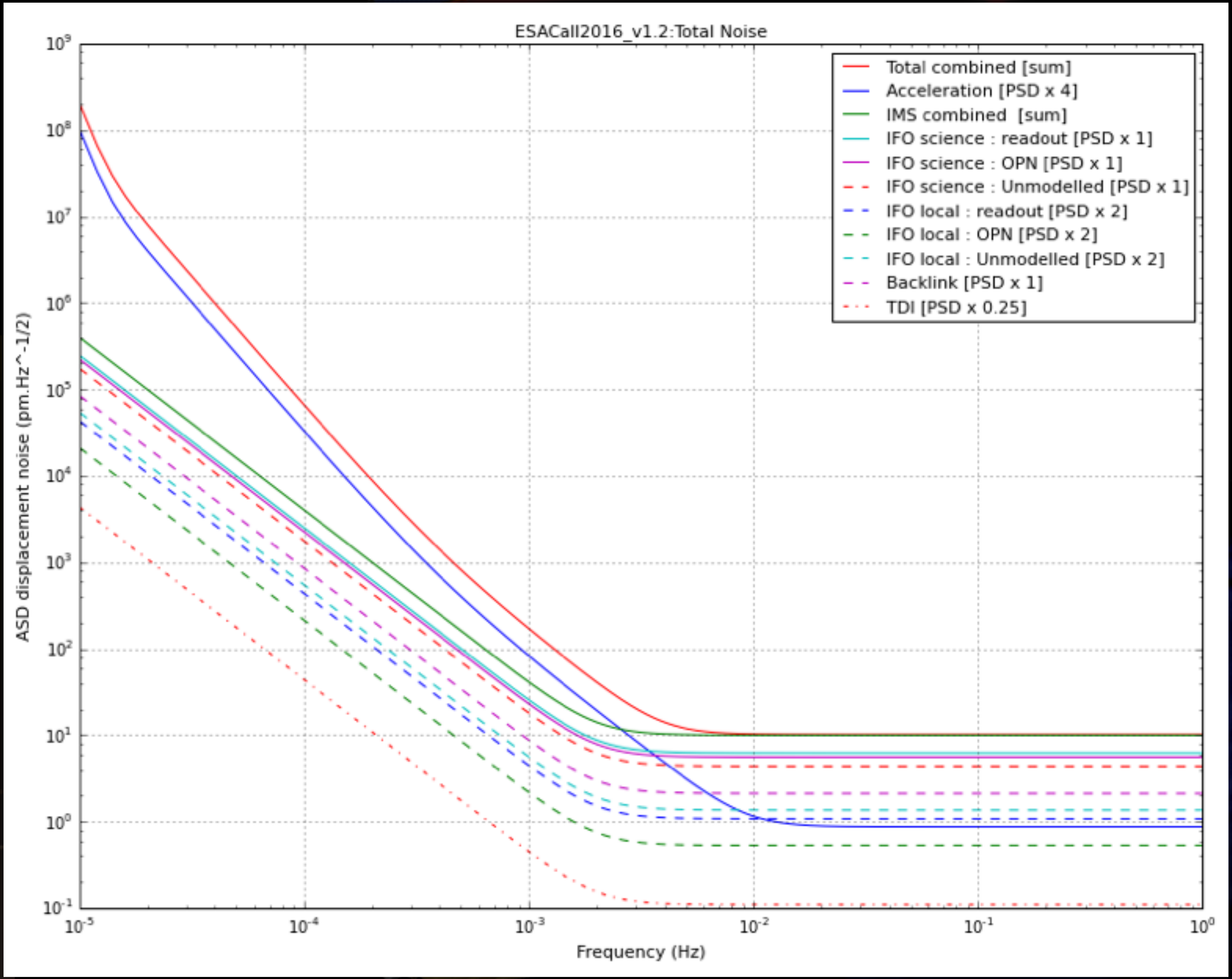
Other noises

- Unmodelled interferometer noise
- Backlink noise
- Residual laser noise after TDI

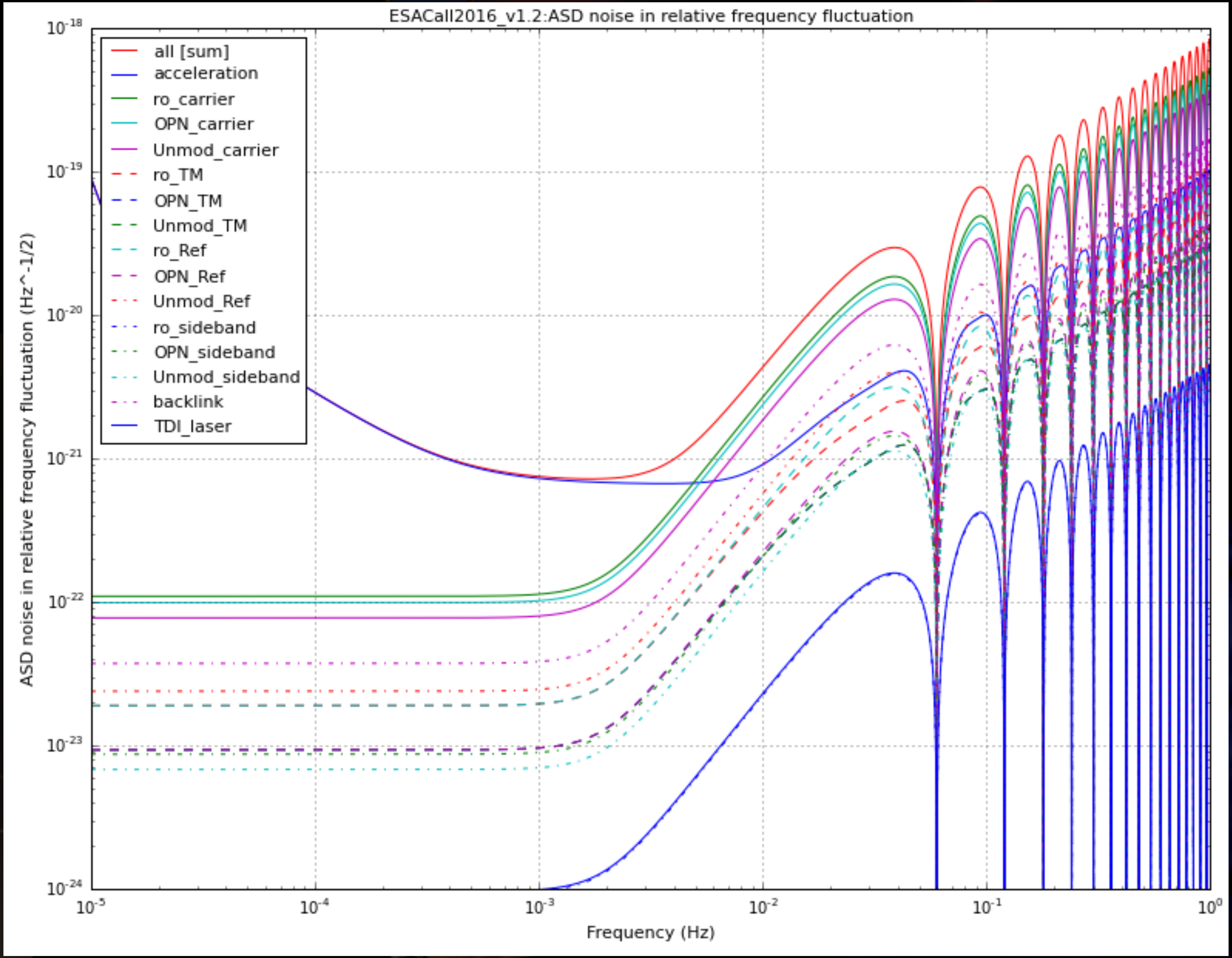
Readout noise budget



Combined on half round trip

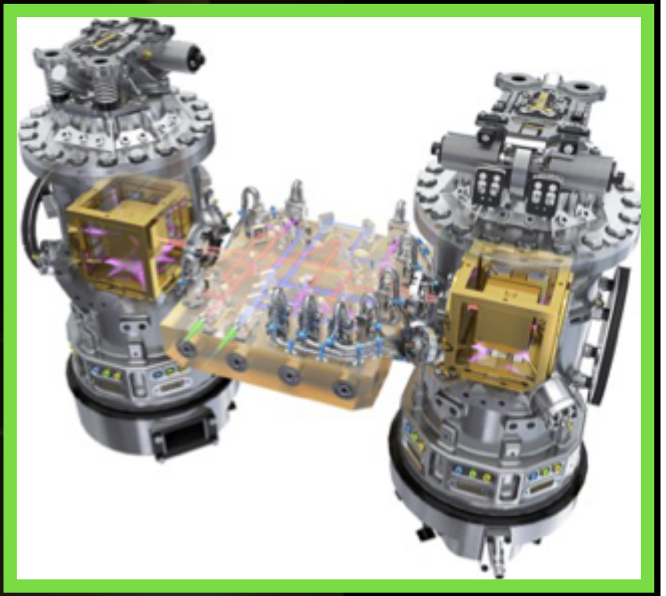


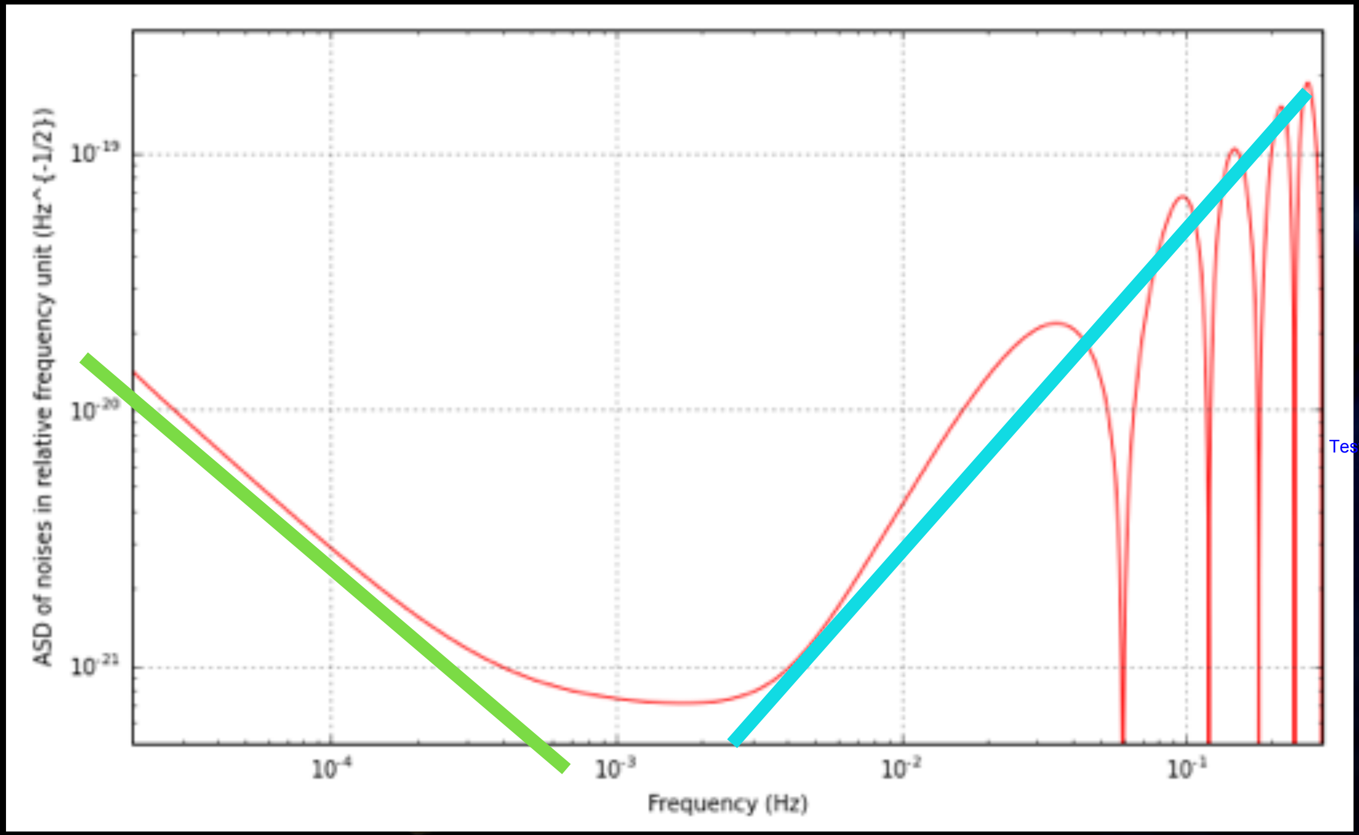
Noise budget in TDI

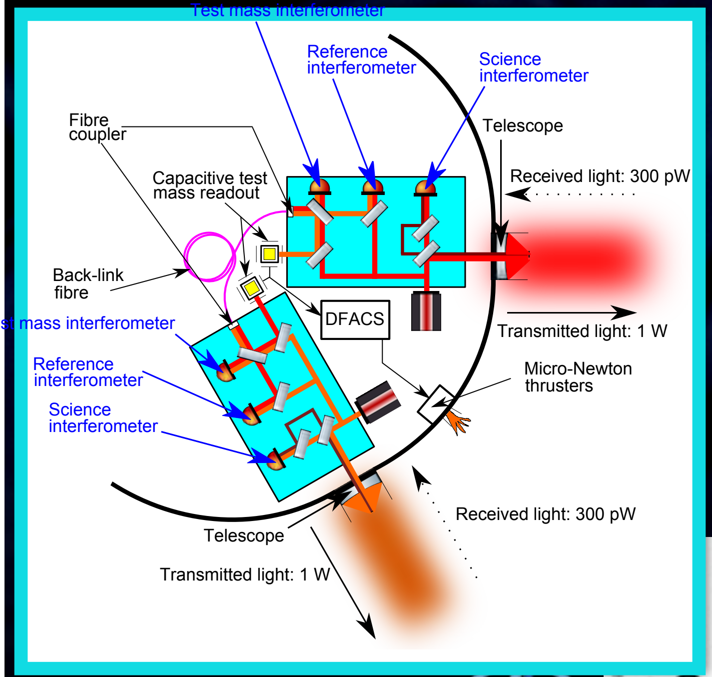


Sensitivity

- Noise budget in 3 points:
  - Low frequencies: acceleration noise (unperfect free-falling of the test)
  - High frequency: interferometric measurements noise
  - Pre-processing pour réduire une partie des bruits (TDI)







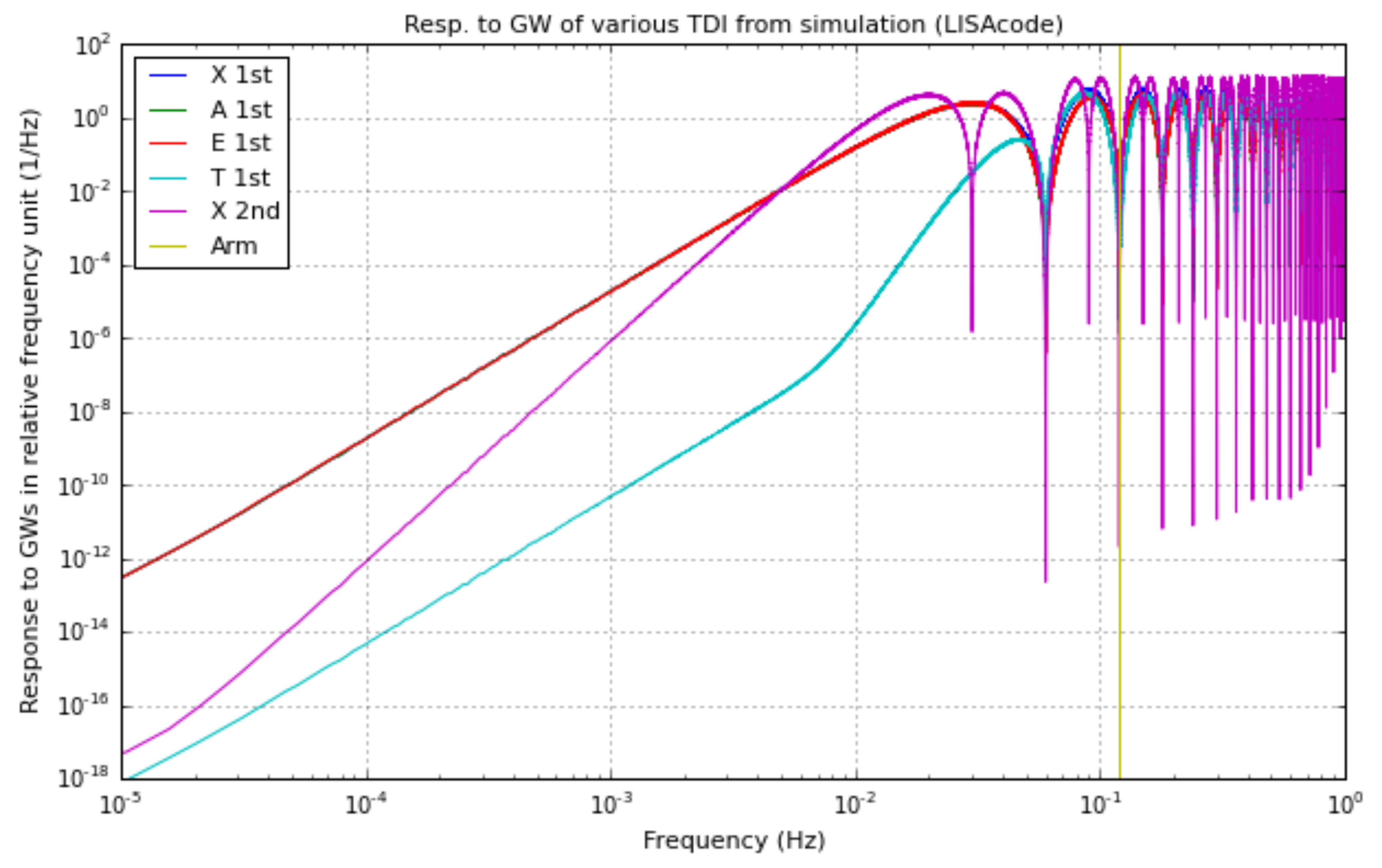
Sensitivity

- Standard sensitivity, so called "strain sensitivity" or "strain linear spectral density" is

$$S(f) = \frac{Resp_{Noise}}{Resp_{GW}} = \frac{PSD_{Noise}}{PSD_{average\ GW}}$$

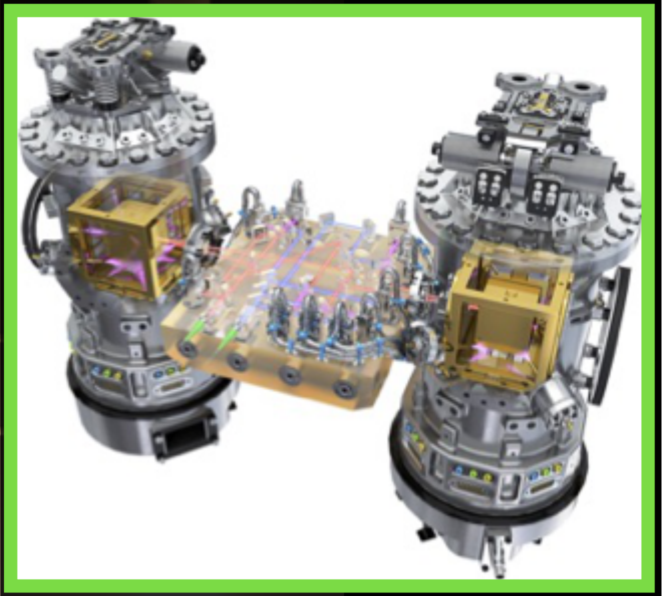
- **Response to GW**:
  - Depends on orbits (see later)
  - Depends on frequency partially due to TDI
  - Computation:
    - Analytic approximation
    - Using simulators: PSD of TDI X with as input 192 white stochastic GWs isotropically distributed on sky

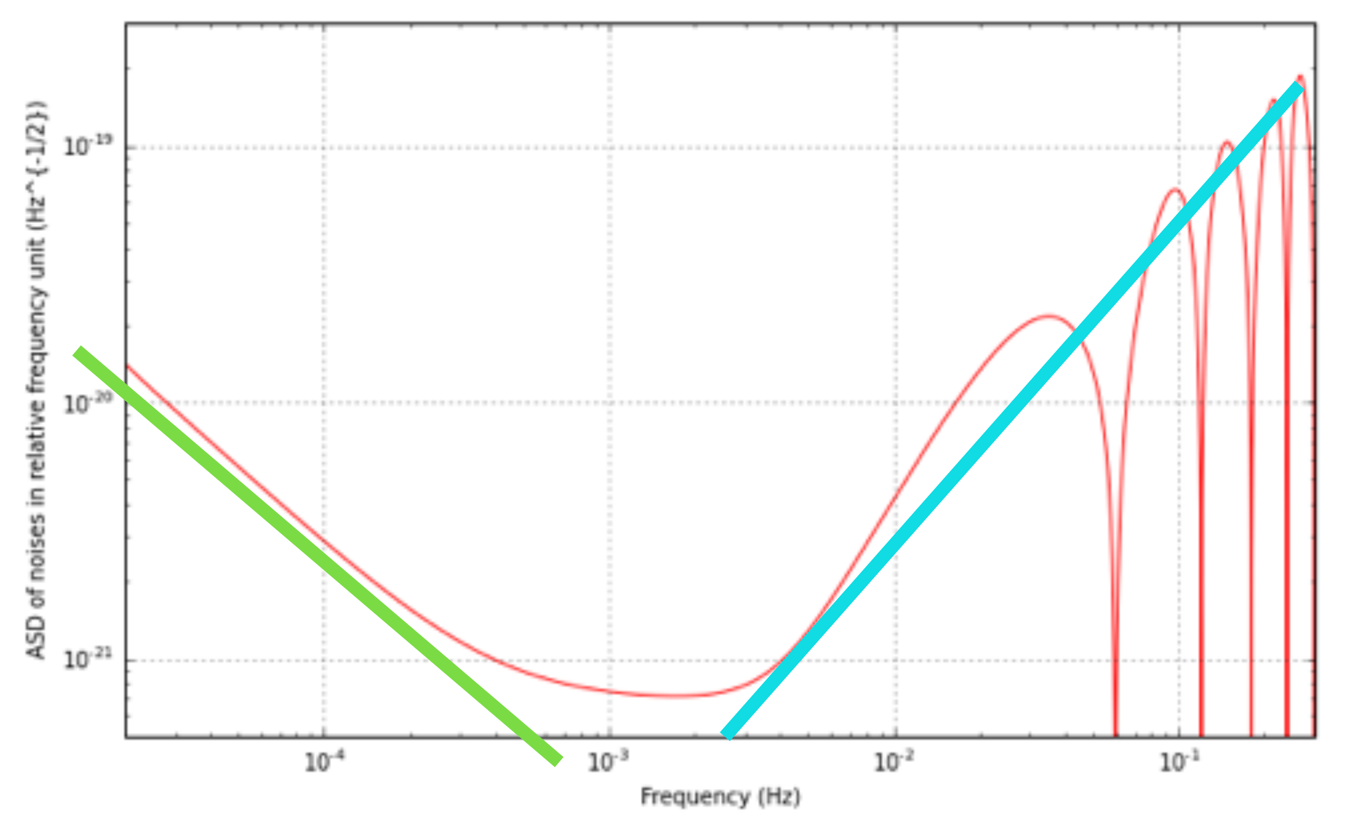
Response to GWs

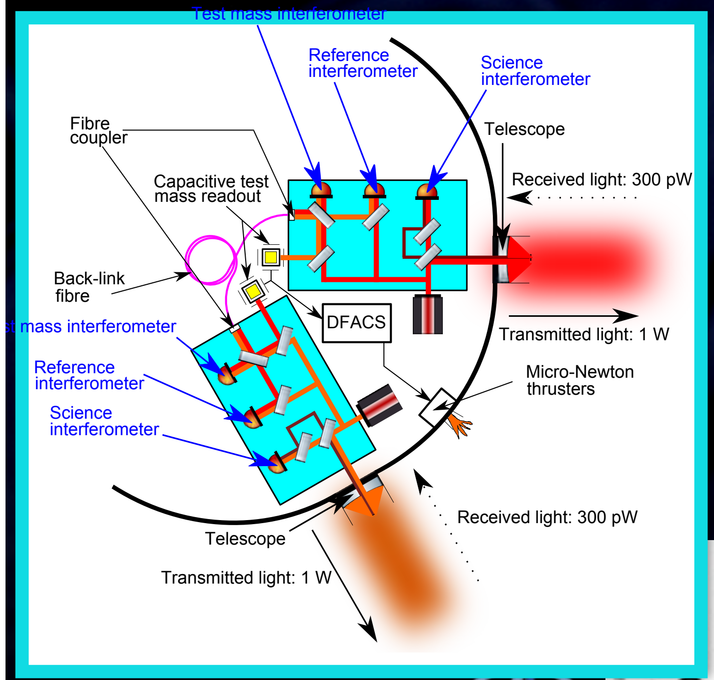


Sensitivity

Noises







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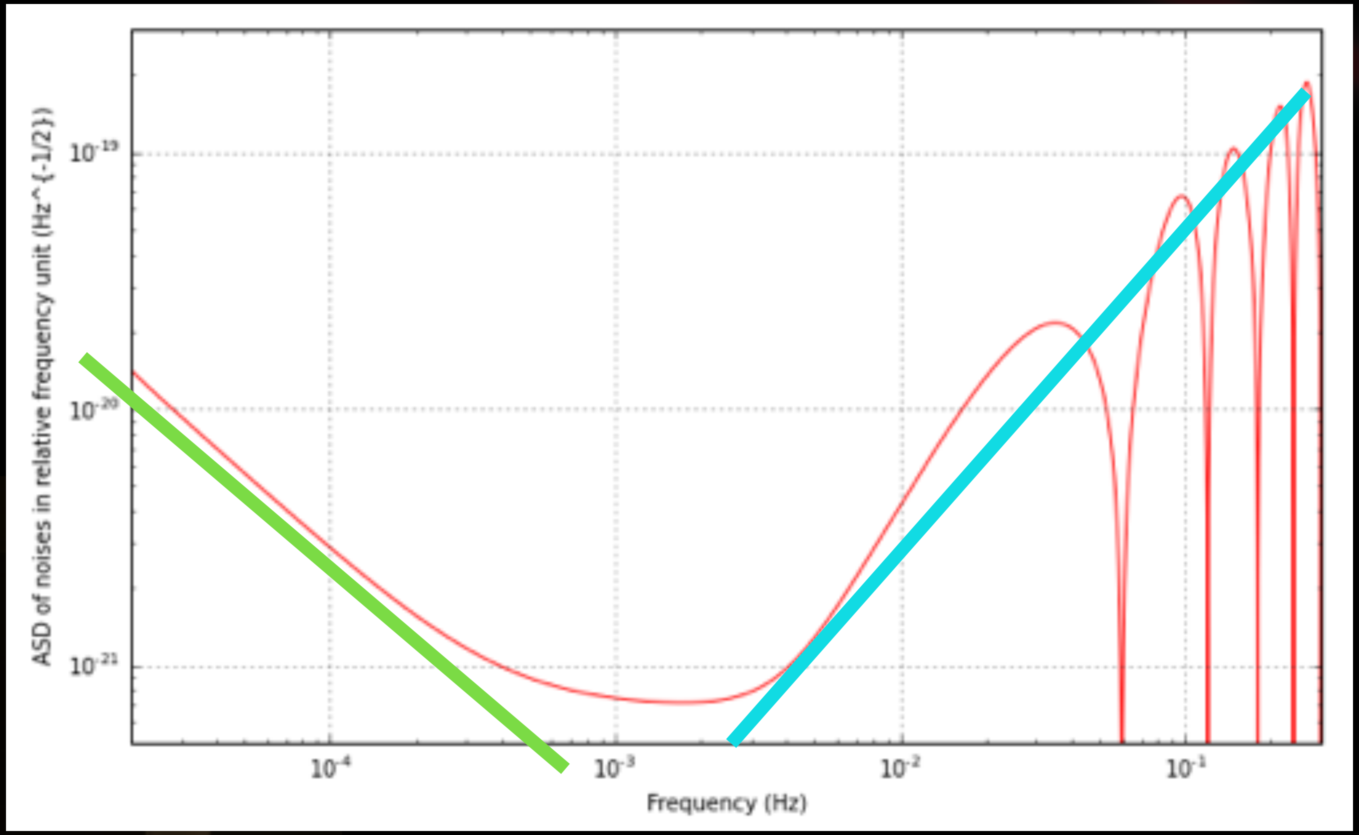
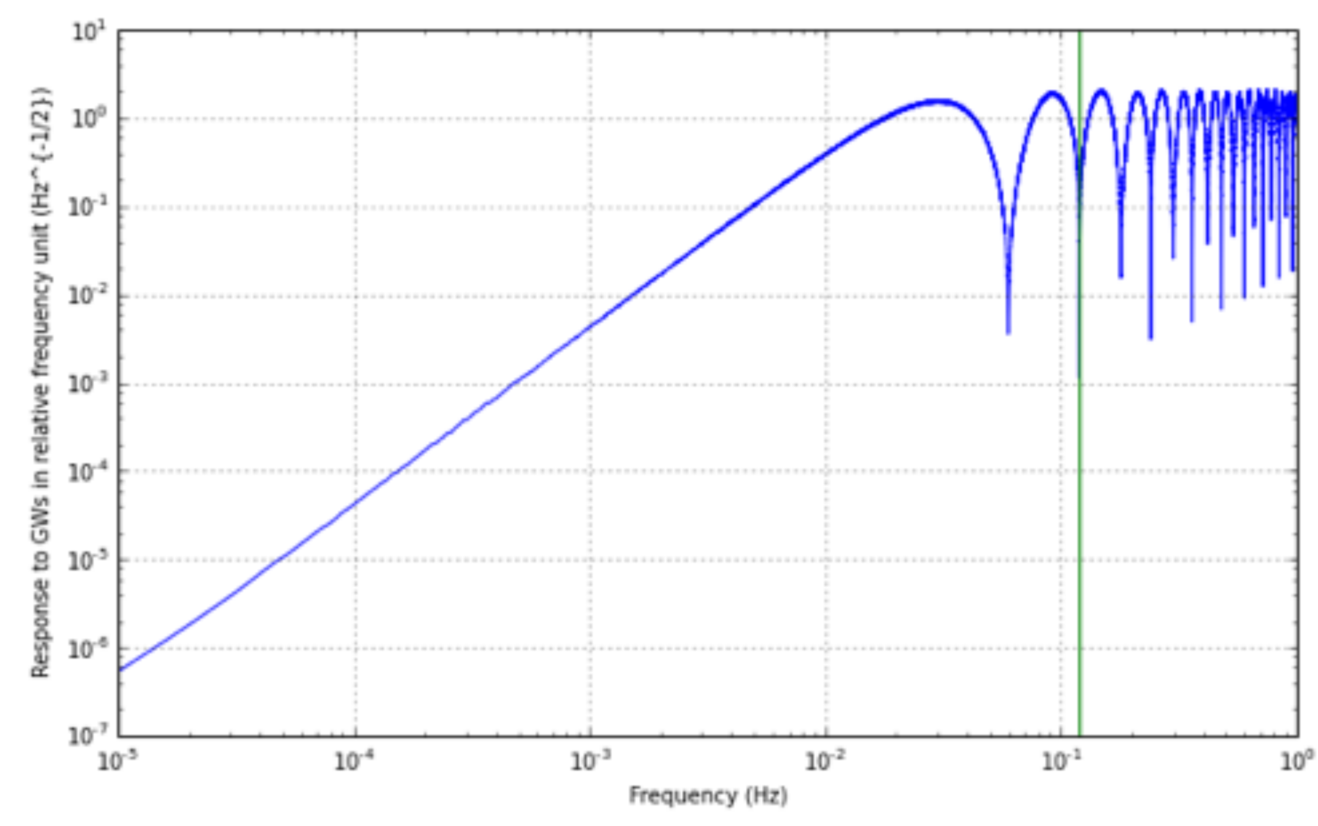
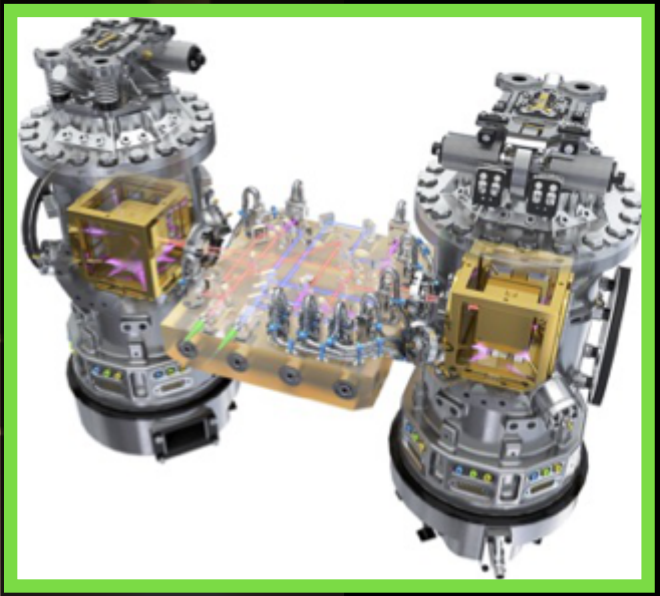
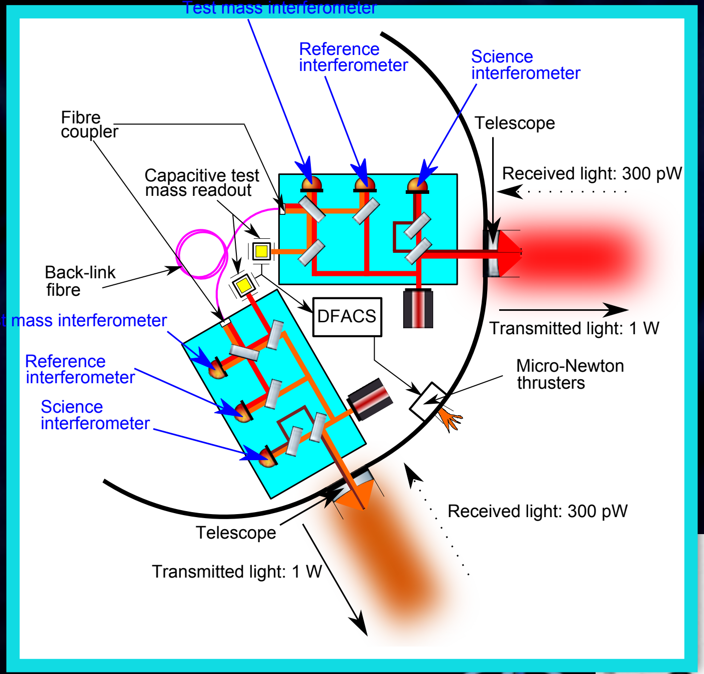


Response of the detector to GWs







Sensitivity

Noises

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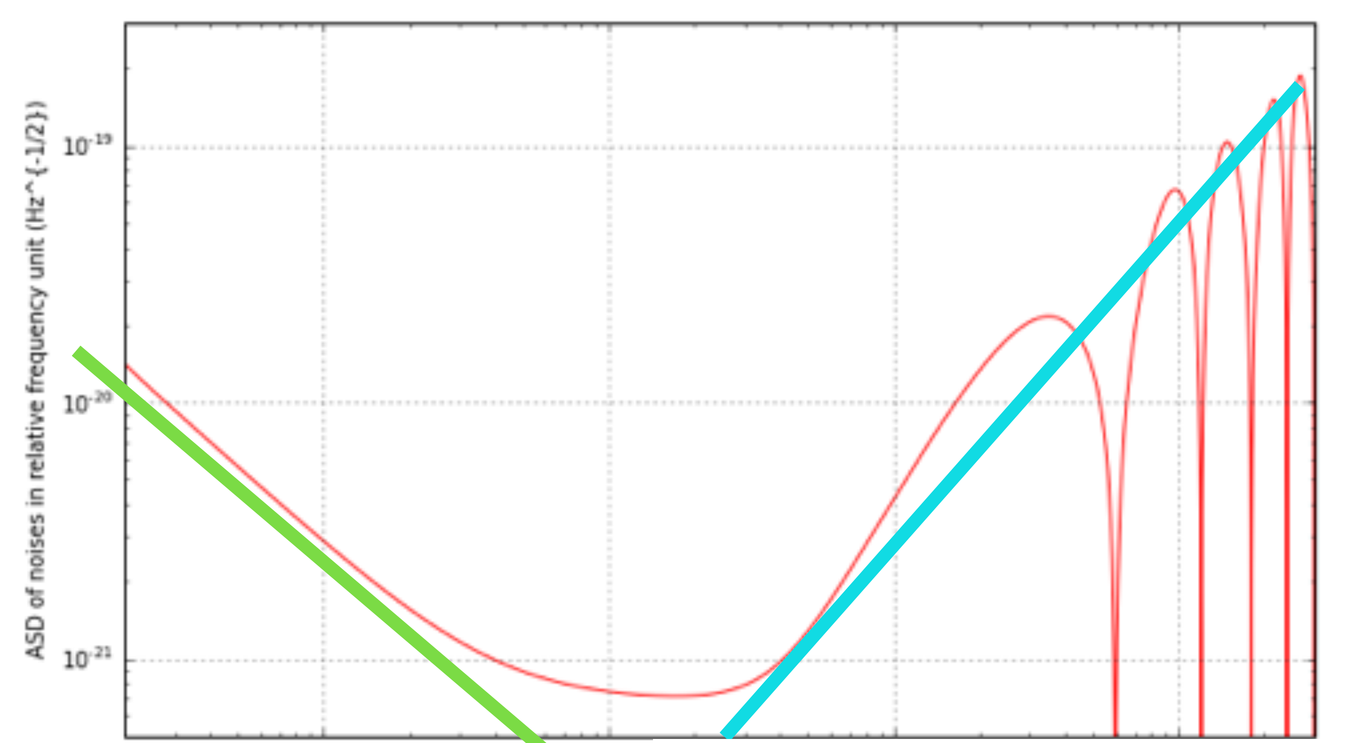
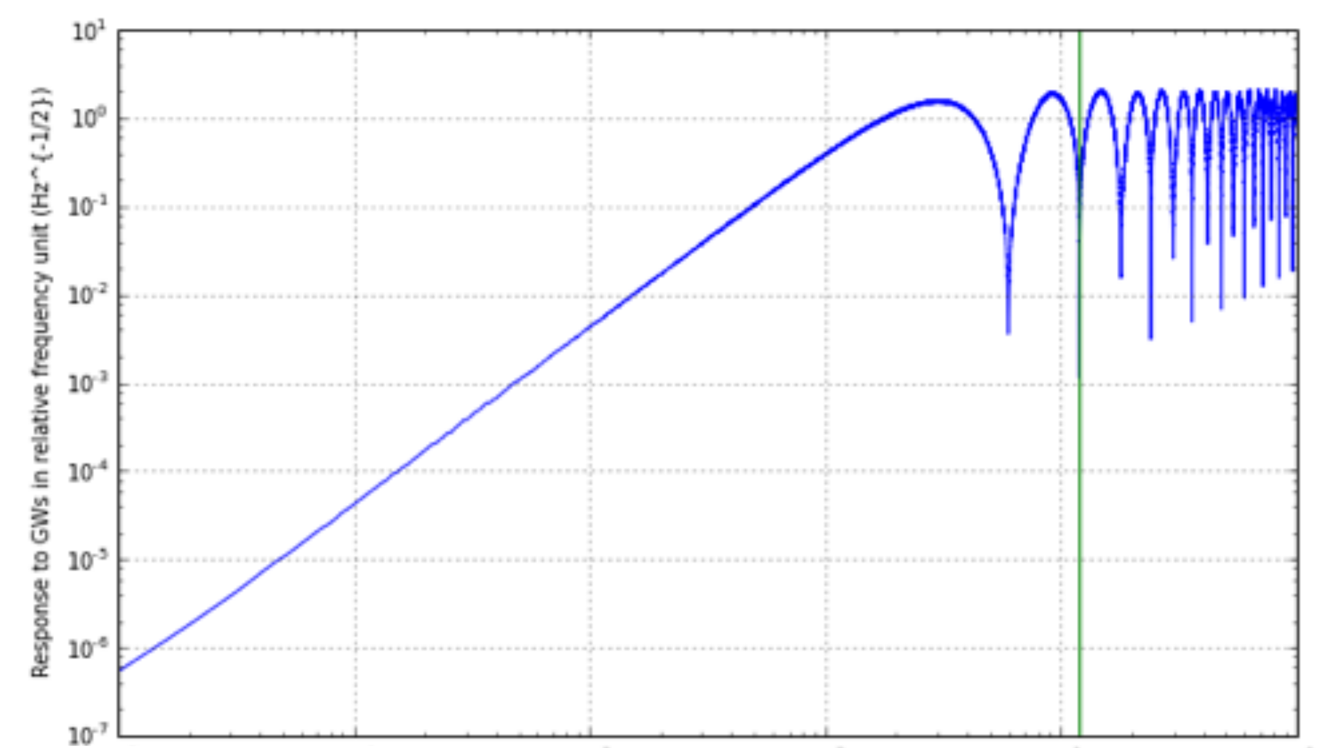
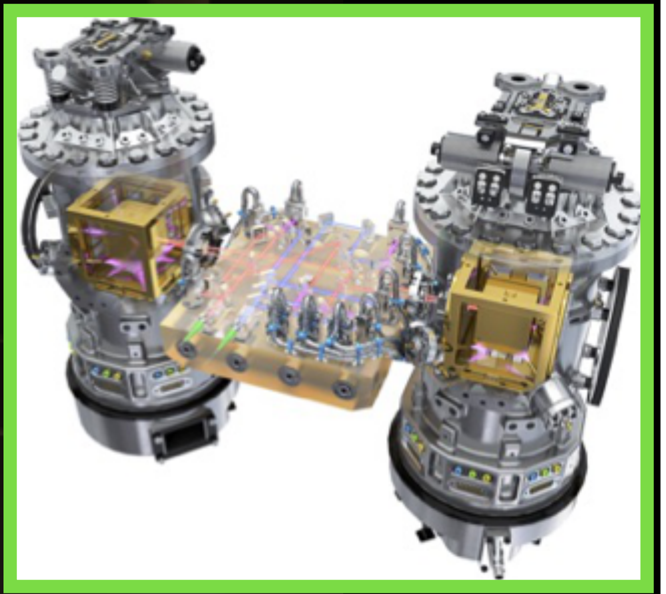
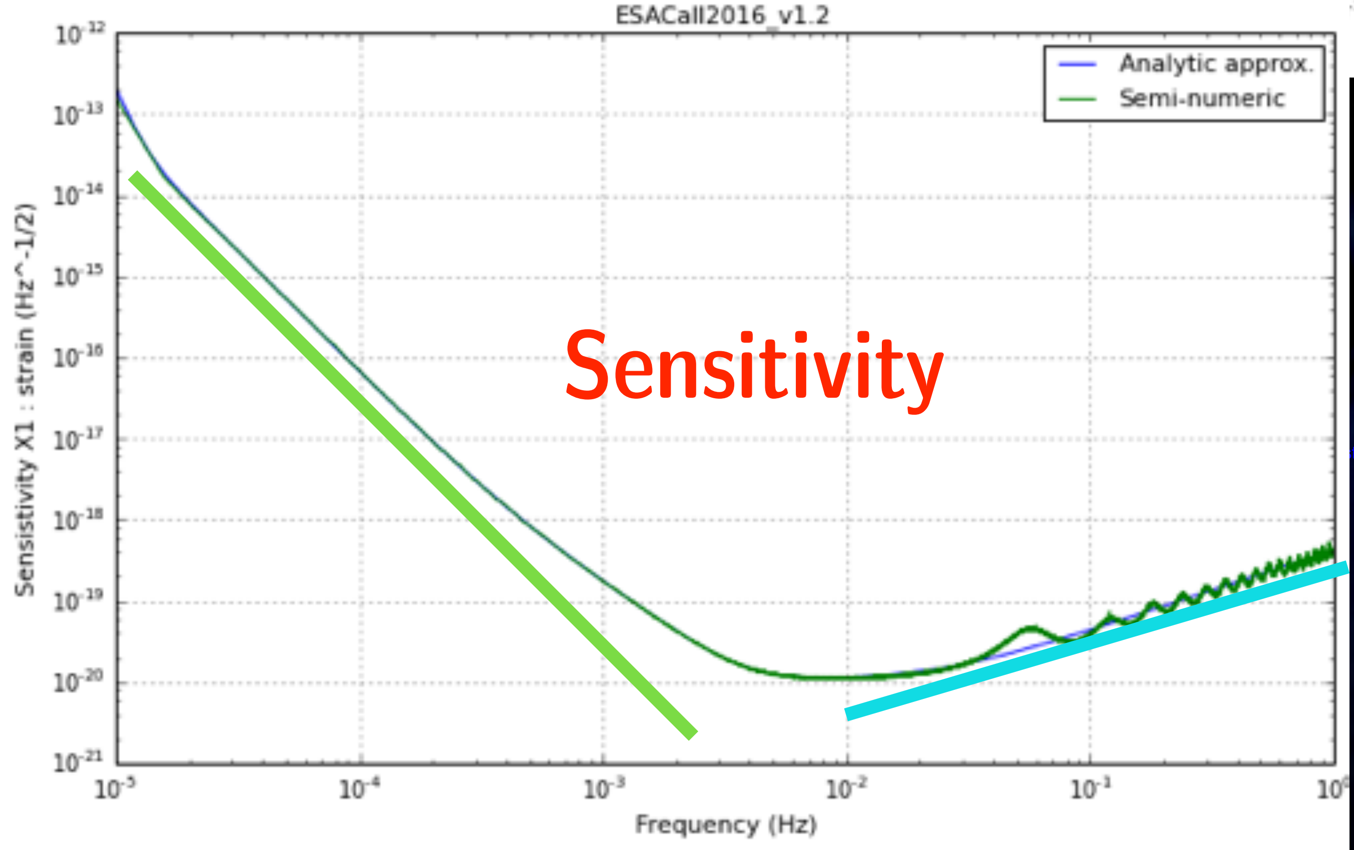
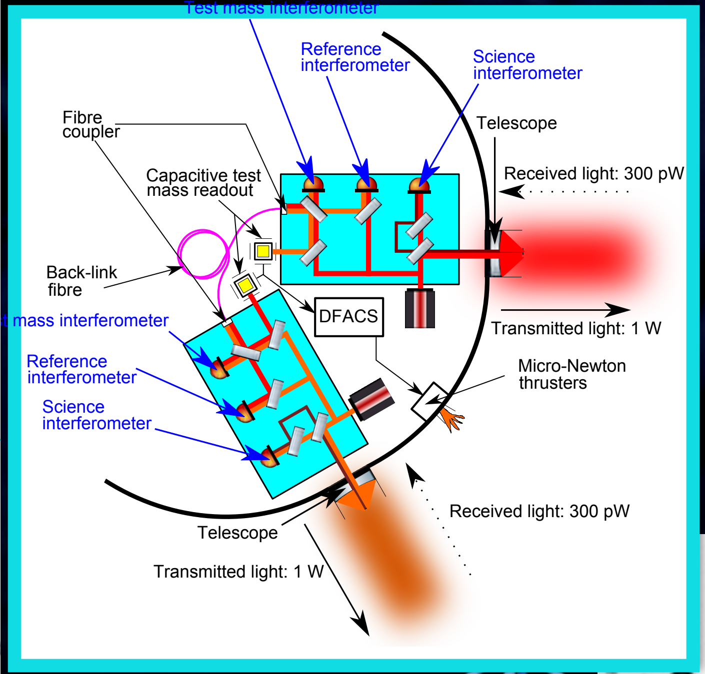






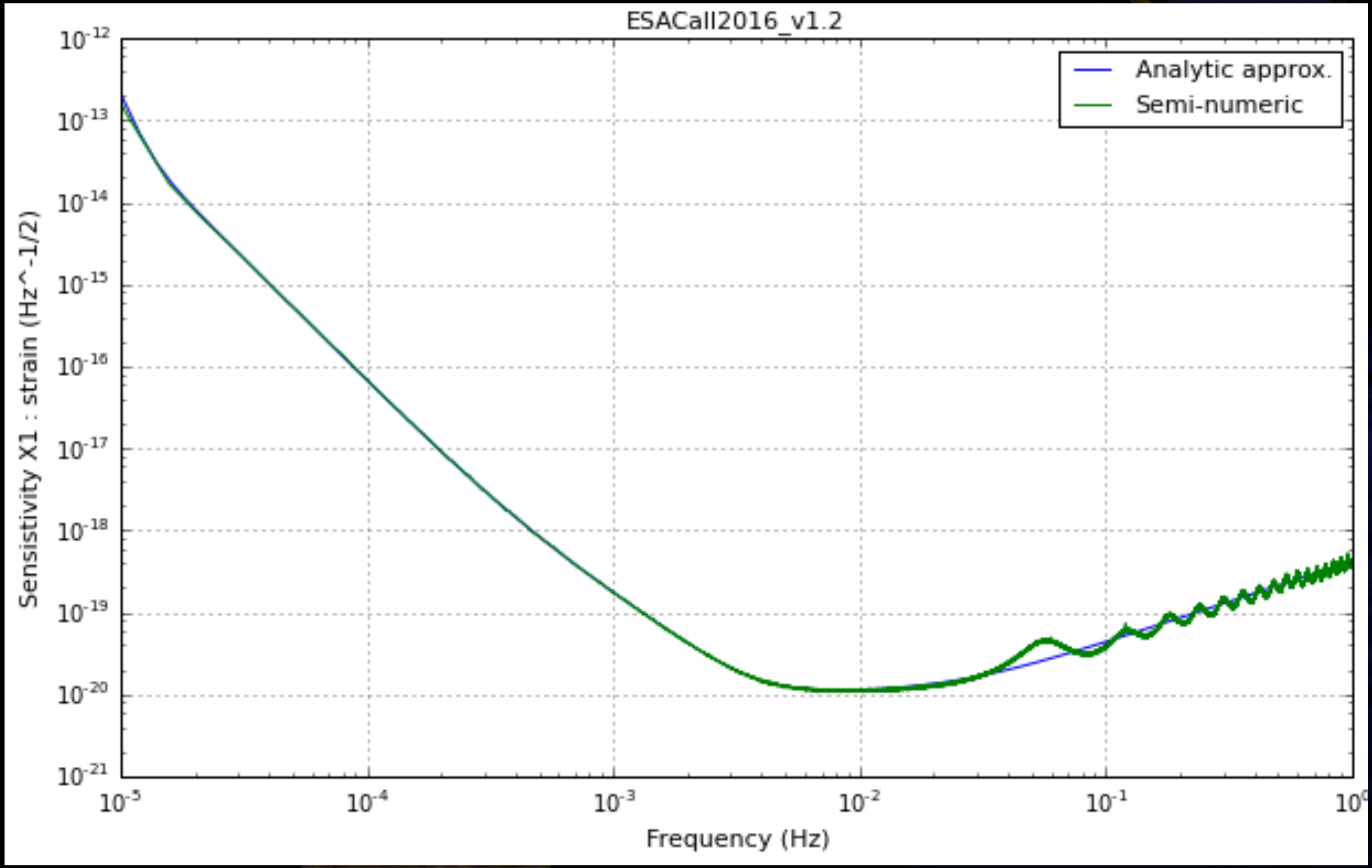




Sensitivity

- Analytic approximation

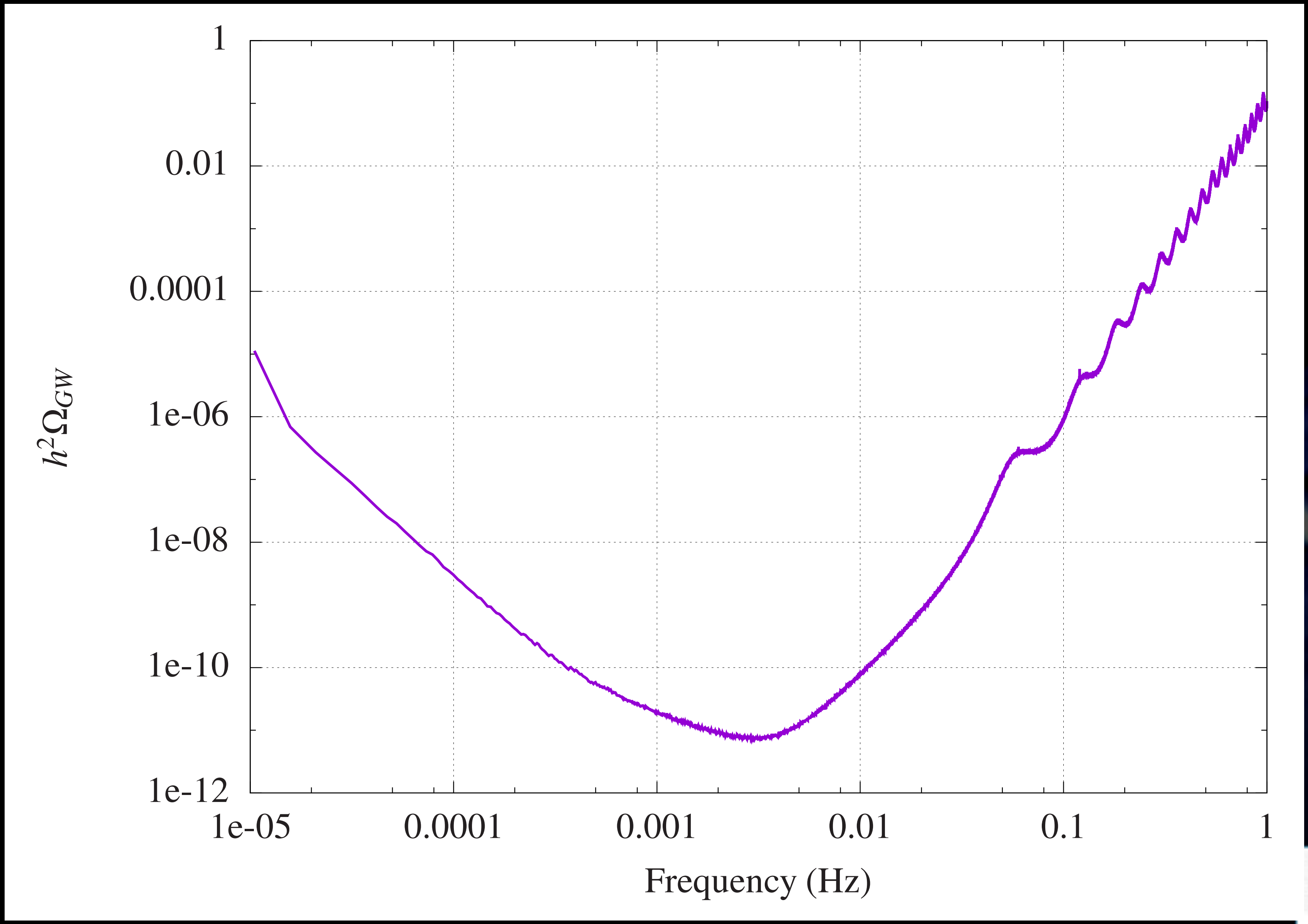
$$\sqrt{S^X(f)} = \sqrt{\frac{20}{3}\left(1+\left(\frac{f}{0.41\left(\frac{c}{2L}\right)}\right)^2\right)\frac{4S_{acc,m}+S_{IMS,m}}{L^2}}$$



Energy density sensitivity

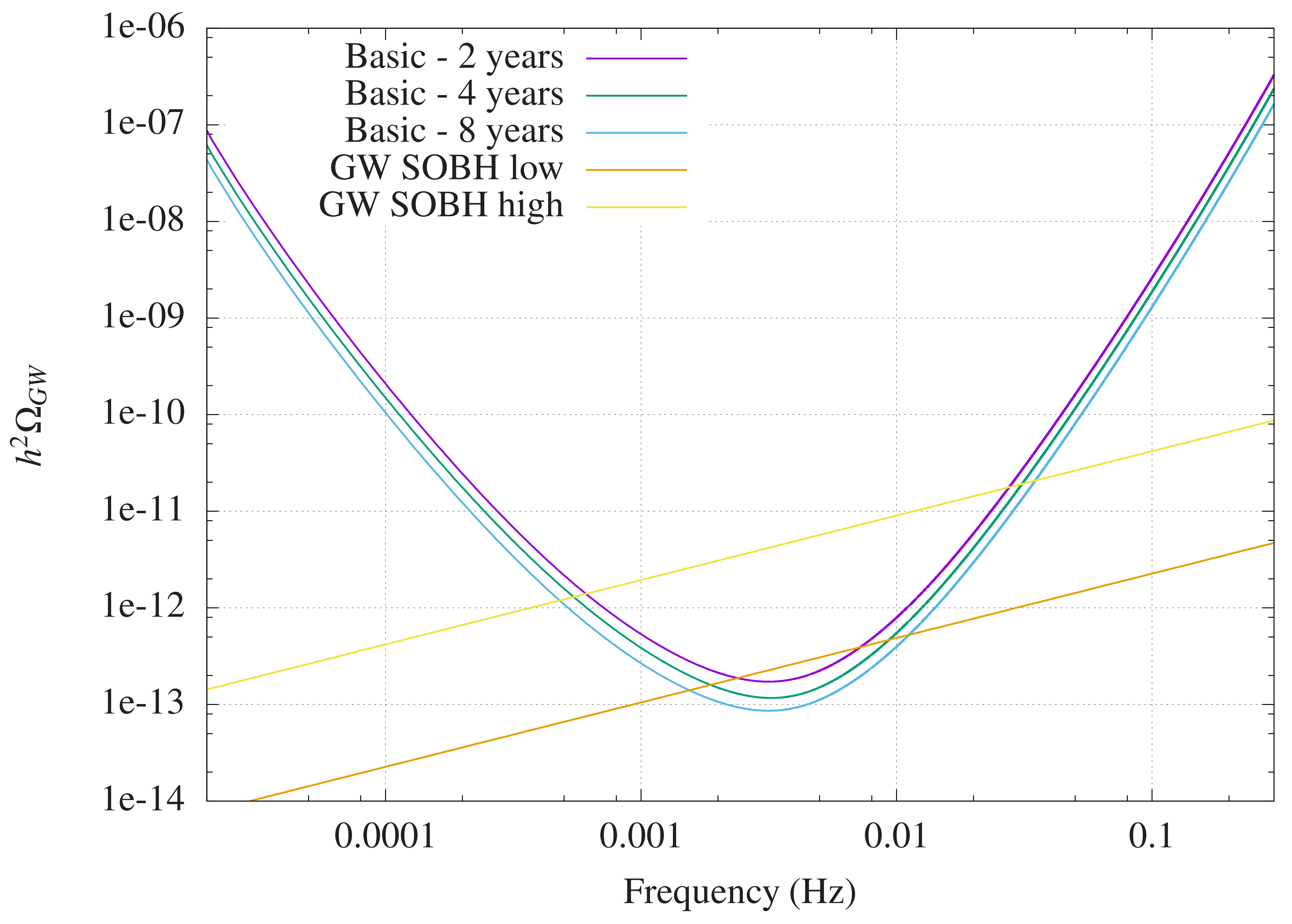
$$h^2\Omega_{GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 S(f)$$

with $H_0 = h\ h_0$ with $h_0 = 100\ \mathrm{km.s^{-1}.Mpc^{-1}} = 3.24 \times 10^{-18}\mathrm{Hz}.$



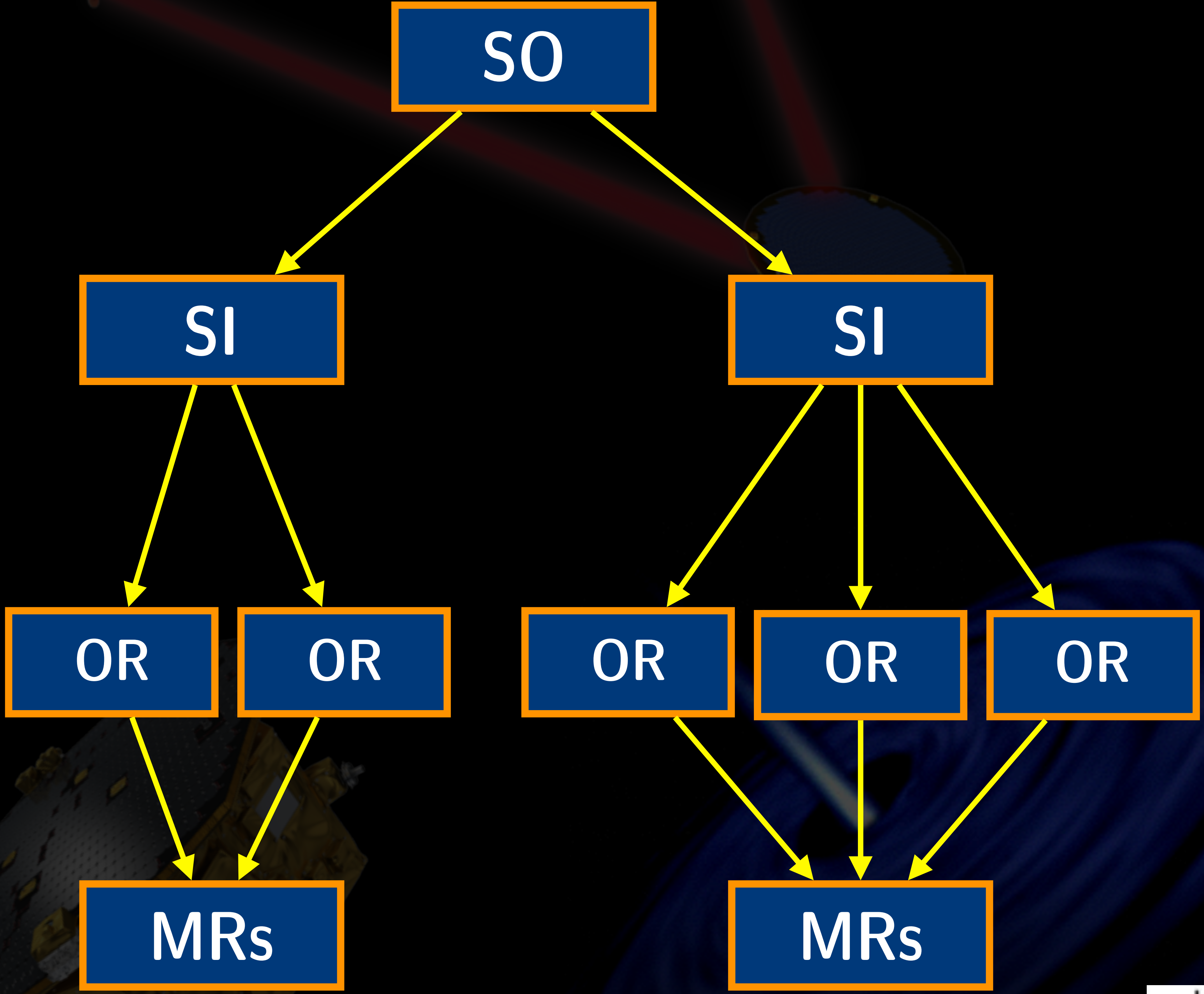
Power Law Sensitivity

- For LISA

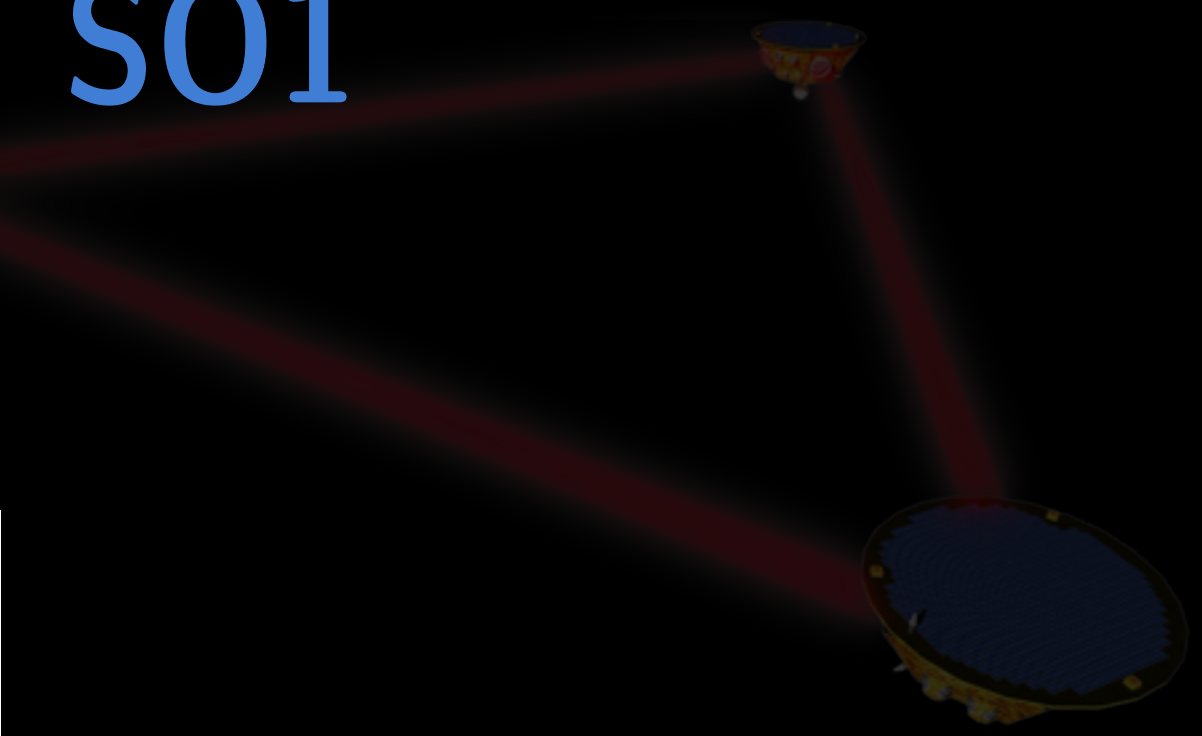


Science performance logic

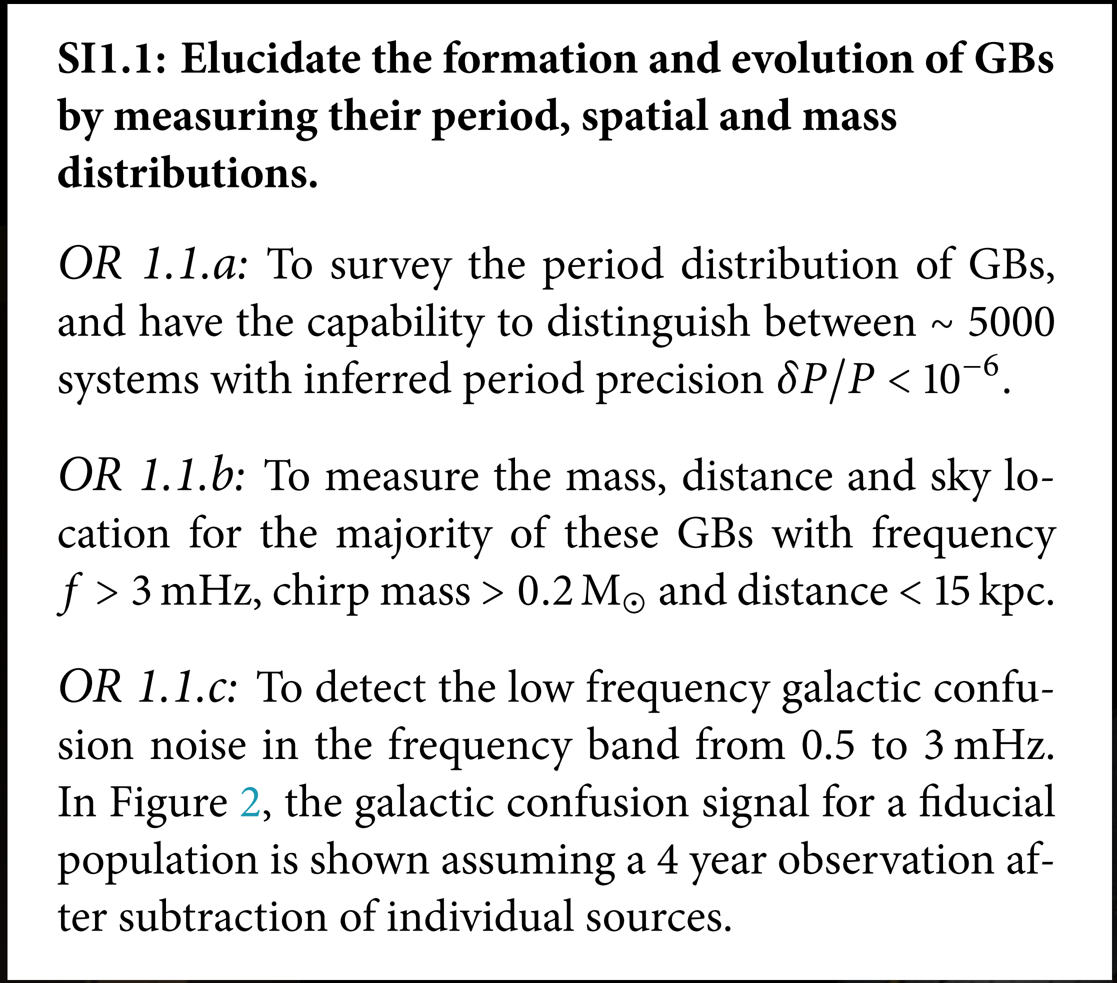
- Science objectives
- Science investigations
- Observation requirements
- Mission requirements



SO1



- Sensitivity
- Mission duration



SI1.1: Elucidate the formation and evolution of GBs by measuring their period, spatial and mass distributions.

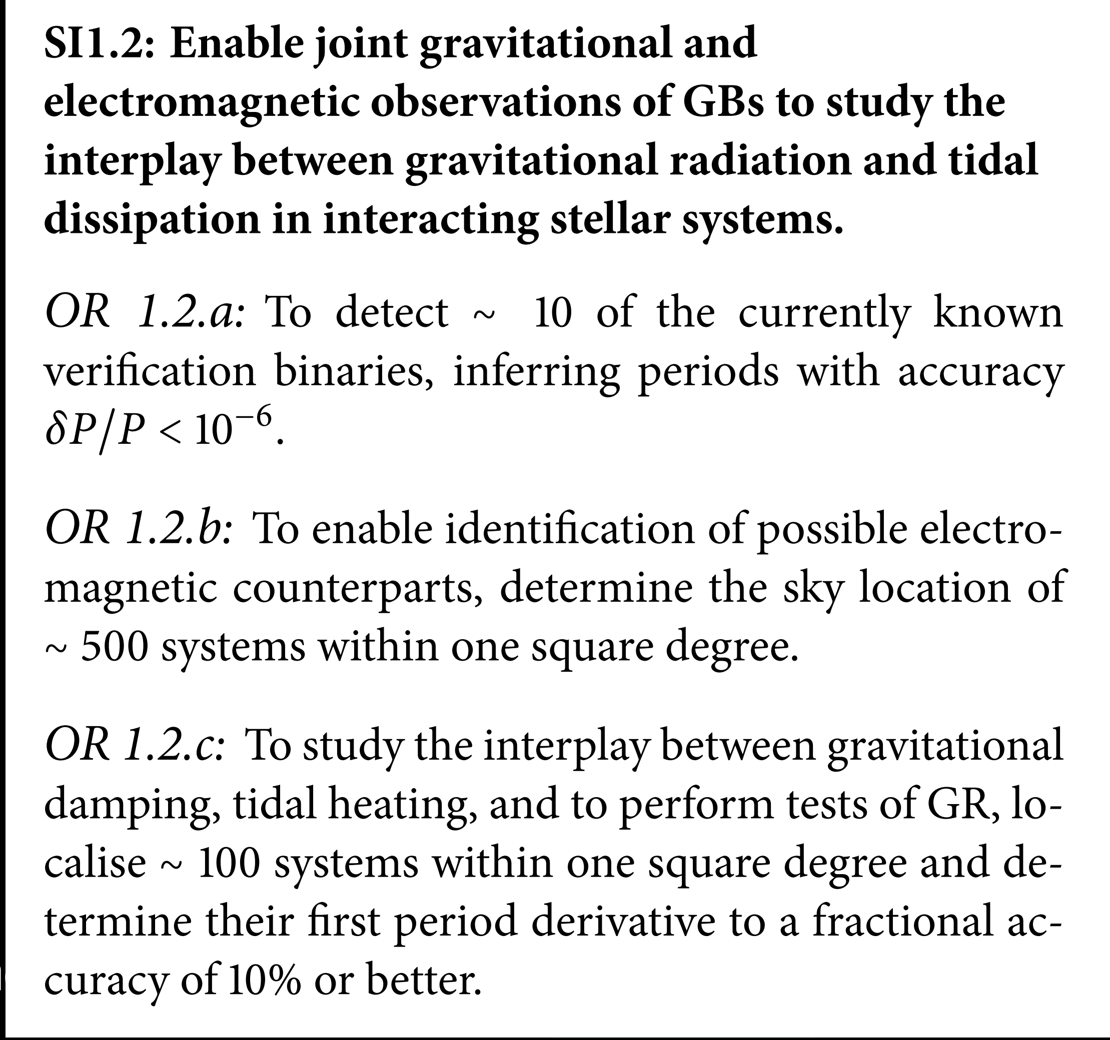
OR 1.1.a: To survey the period distribution of GBs, and have the capability to distinguish between ~ 5000 systems with inferred period precision $\delta P/P < 10^{-6}$.

→ 22106

OR 1.1.b: To measure the mass, distance and sky location for the majority of these GBs with frequency $f > 3\,\mathrm{mHz}$, chirp mass $> 0.2\,\mathrm{M}_\odot$ and distance $< 15\,\mathrm{kpc}$.

→ 268/549

OR 1.1.c: To detect the low frequency galactic confusion noise in the frequency band from 0.5 to 3 mHz. In Figure 2, the galactic confusion signal for a fiducial population is shown assuming a 4 year observation after subtraction of individual sources.



SI1.2: Enable joint gravitational and electromagnetic observations of GBs to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems.

OR 1.2.a: To detect ~ 10 of the currently known verification binaries, inferring periods with accuracy $\delta P/P < 10^{-6}$.

10 ←

OR 1.2.b: To enable identification of possible electromagnetic counterparts, determine the sky location of ~ 500 systems within one square degree.

11209 ←

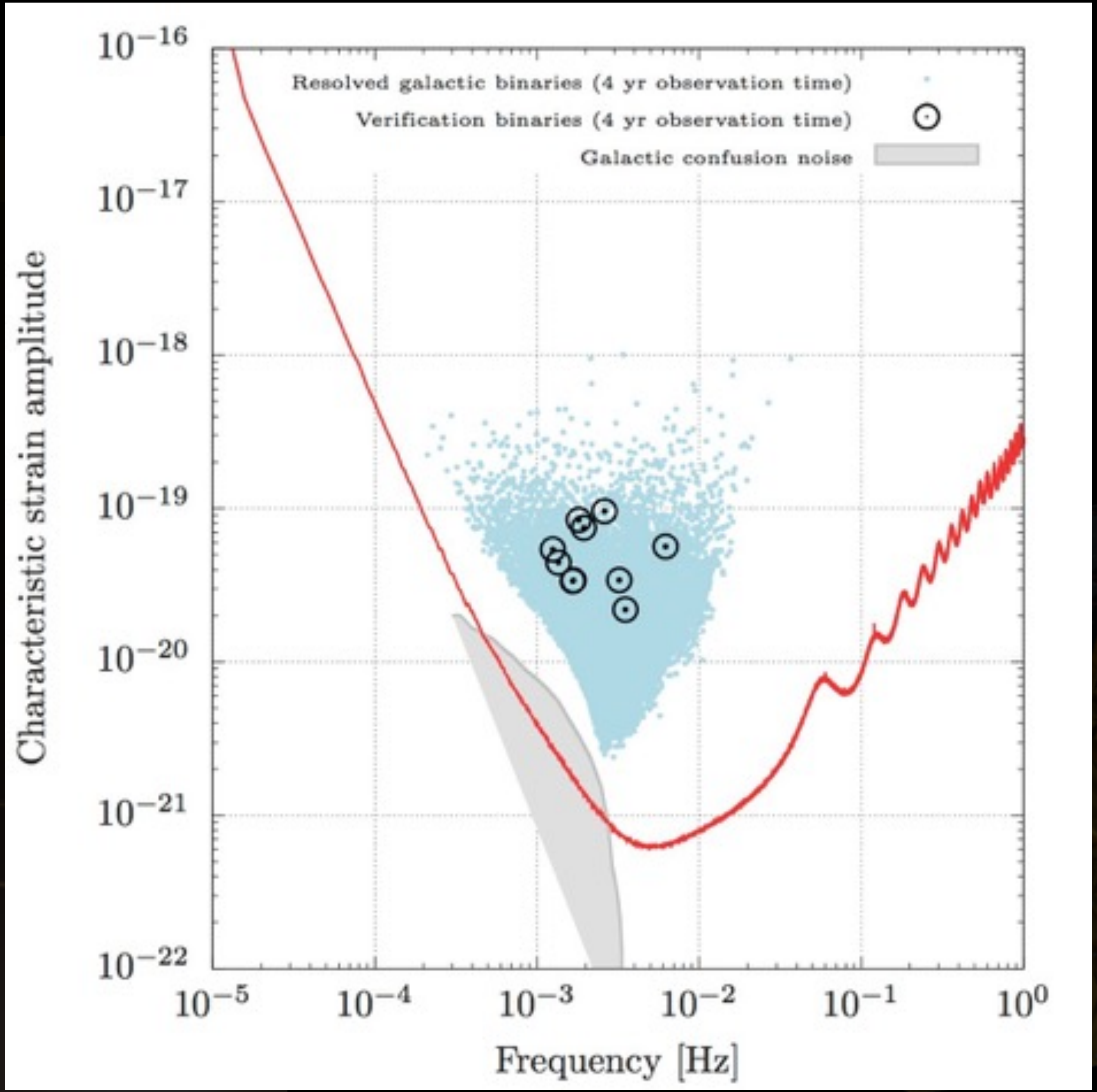
OR 1.2.c: To study the interplay between gravitational damping, tidal heating, and to perform tests of GR, localise ~ 100 systems within one square degree and determine their first period derivative to a fractional accuracy of 10% or better.

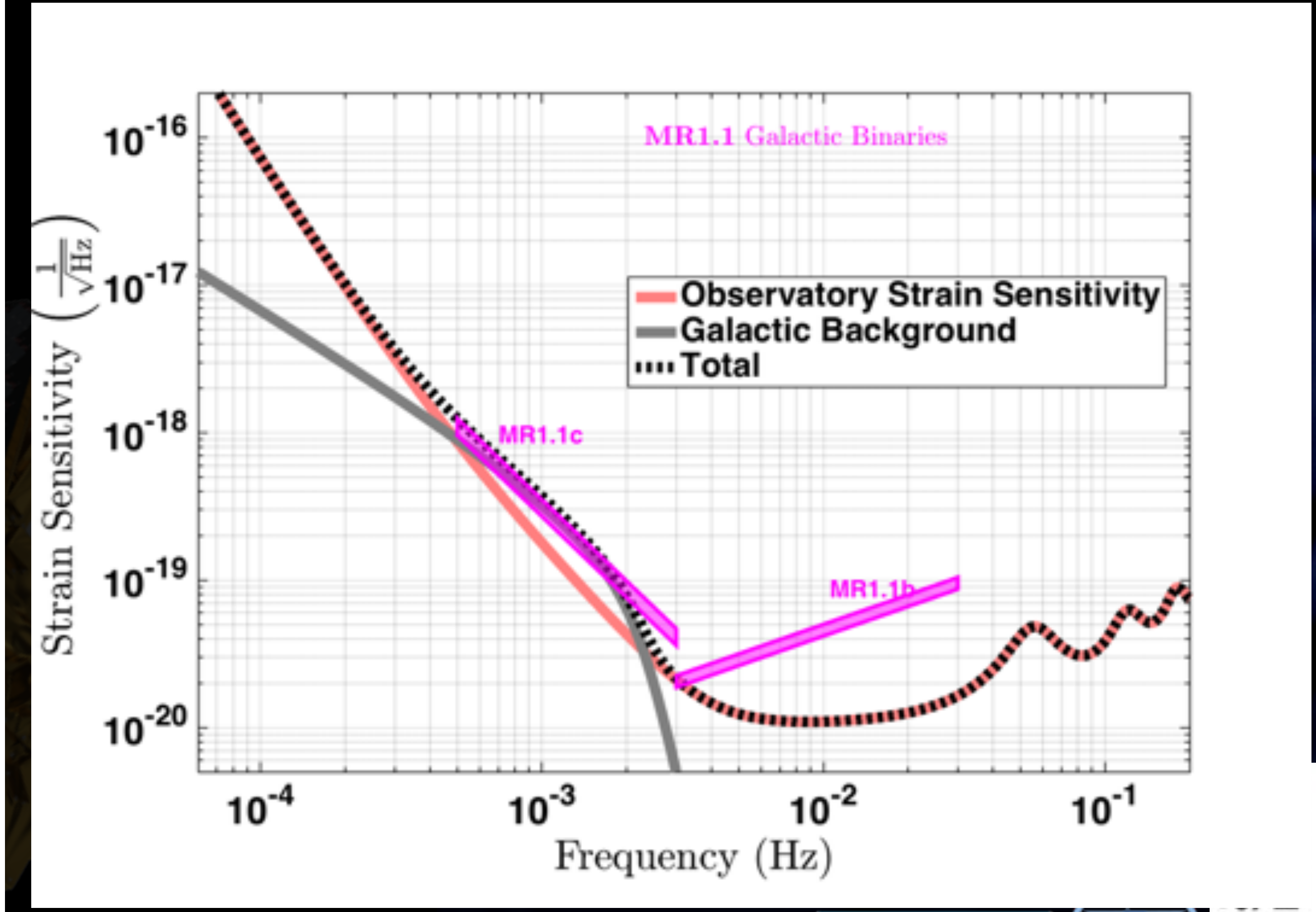
5779 ←

SO1

- Sensitivity
- Mission duration

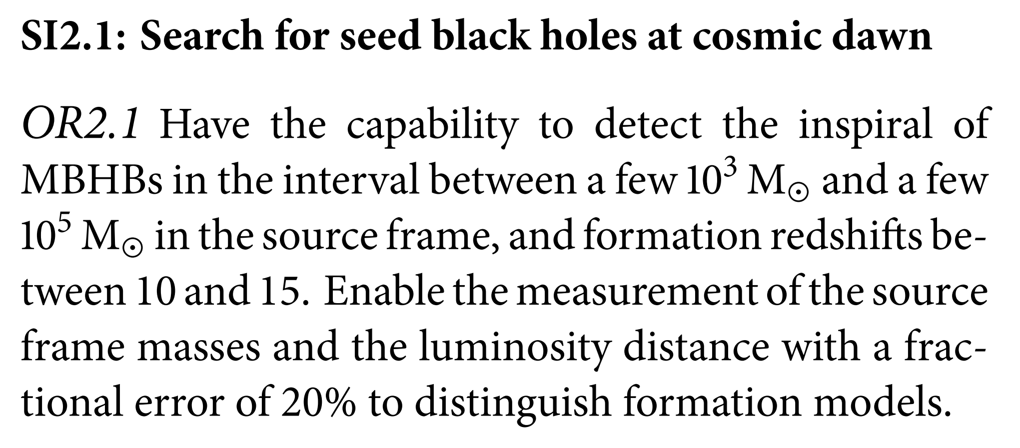
MRs:





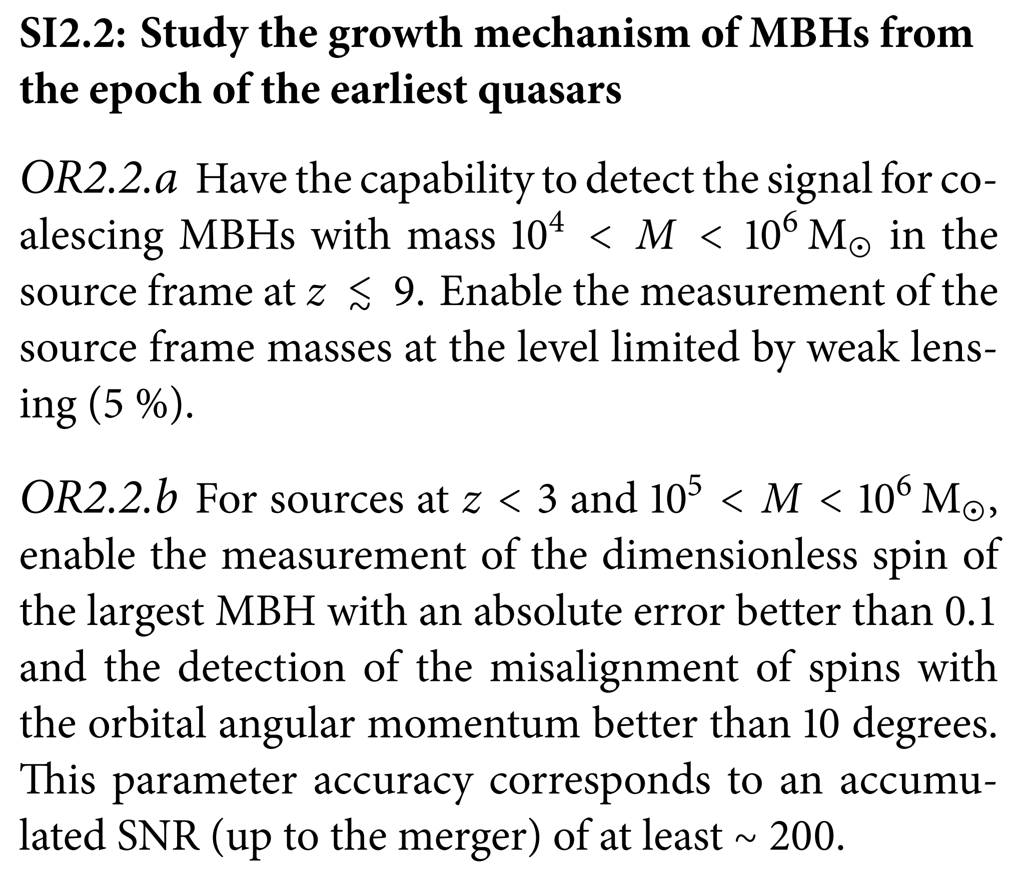
SO2

- Sensitivity
- Mission duration



SI2.1: Search for seed black holes at cosmic dawn

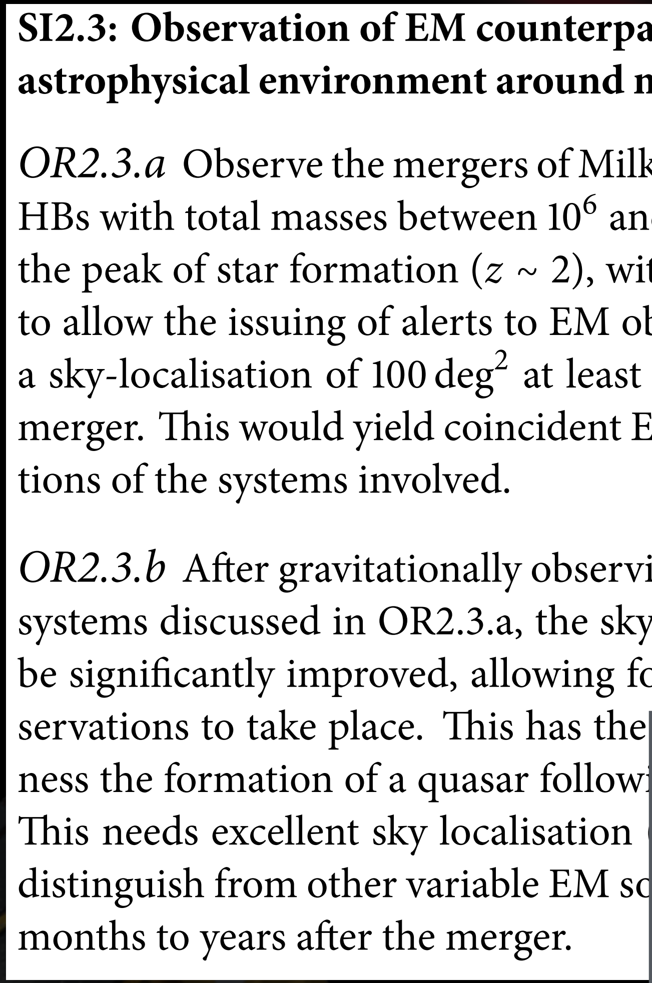
OR2.1 Have the capability to detect the inspiral of MBHBs in the interval between a few $10^3\,M_\odot$ and a few $10^5\,M_\odot$ in the source frame, and formation redshifts between 10 and 15. Enable the measurement of the source frame masses and the luminosity distance with a fractional error of 20% to distinguish formation models.



SI2.2: Study the growth mechanism of MBHs from the epoch of the earliest quasars

OR2.2.a Have the capability to detect the signal for coalescing MBHs with mass $10^4 < M < 10^6\,M_\odot$ in the source frame at $z \lesssim 9$. Enable the measurement of the source frame masses at the level limited by weak lensing (5 %).

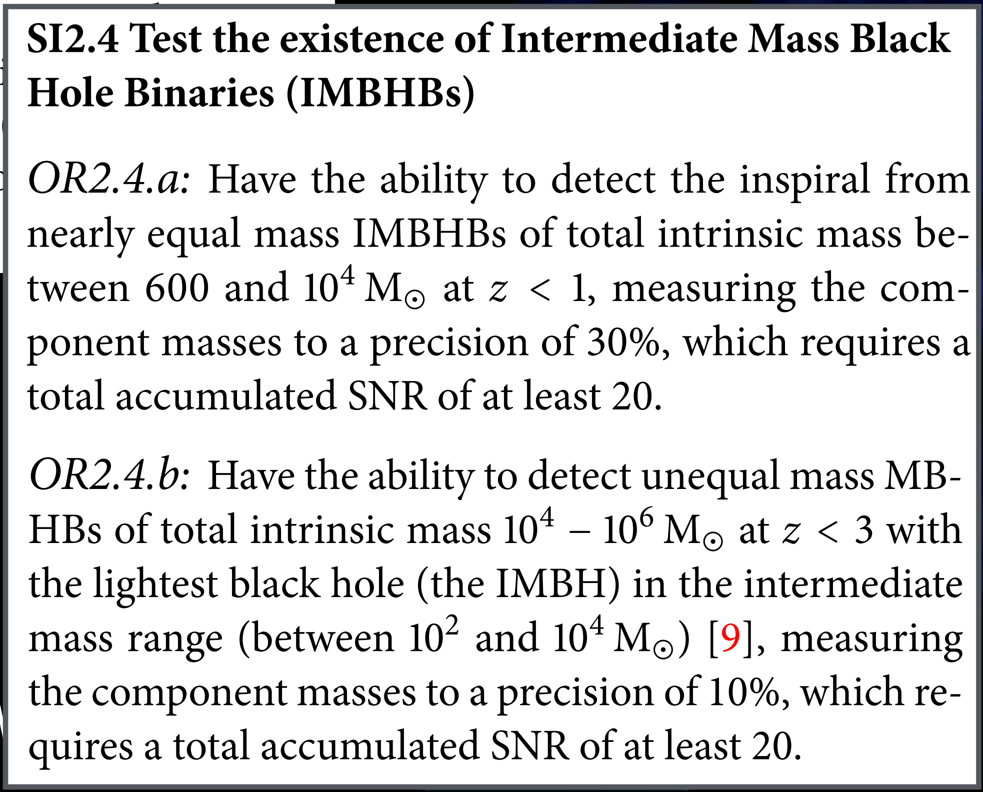
OR2.2.b For sources at $z < 3$ and $10^5 < M < 10^6\,M_\odot$, enable the measurement of the dimensionless spin of the largest MBH with an absolute error better than 0.1 and the detection of the misalignment of spins with the orbital angular momentum better than 10 degrees. This parameter accuracy corresponds to an accumulated SNR (up to the merger) of at least ~ 200.



SI2.3: Observation of EM counterparts to unveil the astrophysical environment around merging binaries

OR2.3.a Observe the mergers of Milky-Way type MBHBs with total masses between 10^6 and $10^7\,M_\odot$ around the peak of star formation ($z \sim 2$), with sufficient SNR to allow the issuing of alerts to EM observatories with a sky-localisation of 100 deg^2 at least one day prior to merger. This would yield coincident EM/GW observations of the systems involved.

OR2.3.b After gravitationally observing the merger of systems discussed in OR2.3.a, the sky localisation will be significantly improved, allowing follow-up EM observations to take place. This has the
ness the formation of a quasar followi
This needs excellent sky localisation
distinguish from other variable EM so
months to years after the merger.



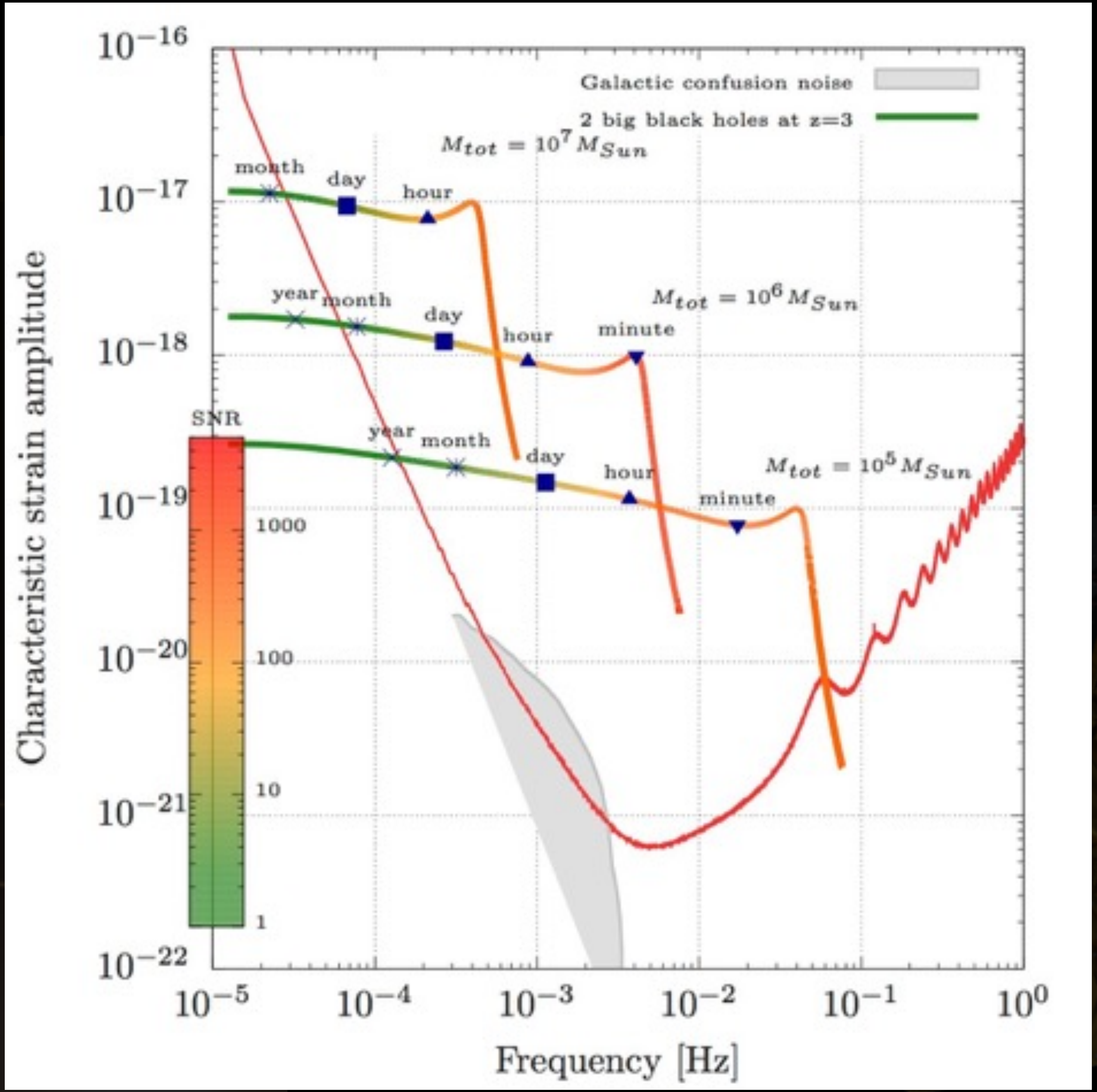
SI2.4 Test the existence of Intermediate Mass Black Hole Binaries (IMBHBs)

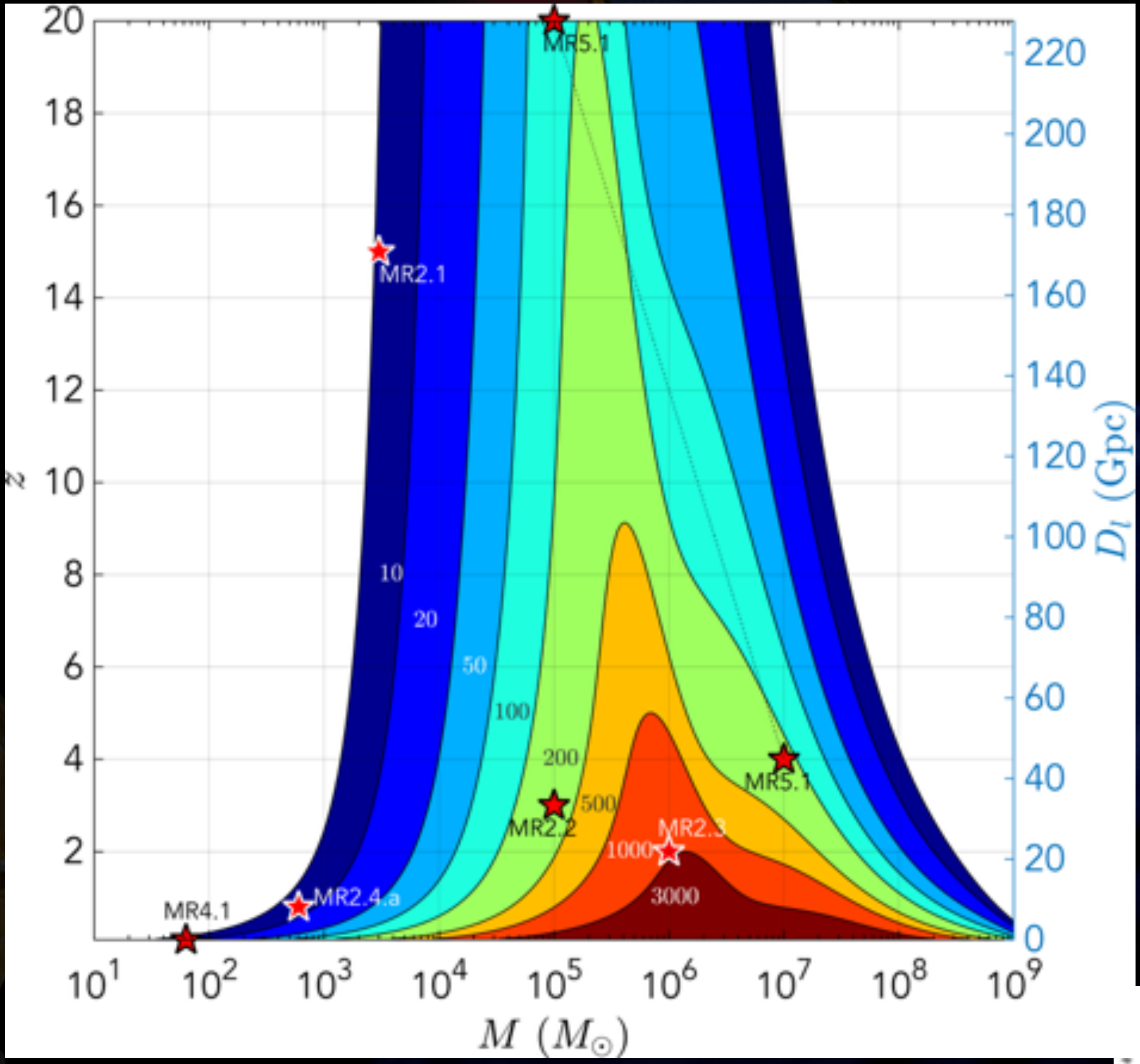
OR2.4.a: Have the ability to detect the inspiral from nearly equal mass IMBHBs of total intrinsic mass between 600 and $10^4\,M_\odot$ at $z < 1$, measuring the component masses to a precision of 30%, which requires a total accumulated SNR of at least 20.

OR2.4.b: Have the ability to detect unequal mass MBHBs of total intrinsic mass $10^4 - 10^6\,M_\odot$ at $z < 3$ with the lightest black hole (the IMBH) in the intermediate mass range (between 10^2 and $10^4\,M_\odot$) [9], measuring the component masses to a precision of 10%, which requires a total accumulated SNR of at least 20.

SO2

- Sensitivity
- Mission duration



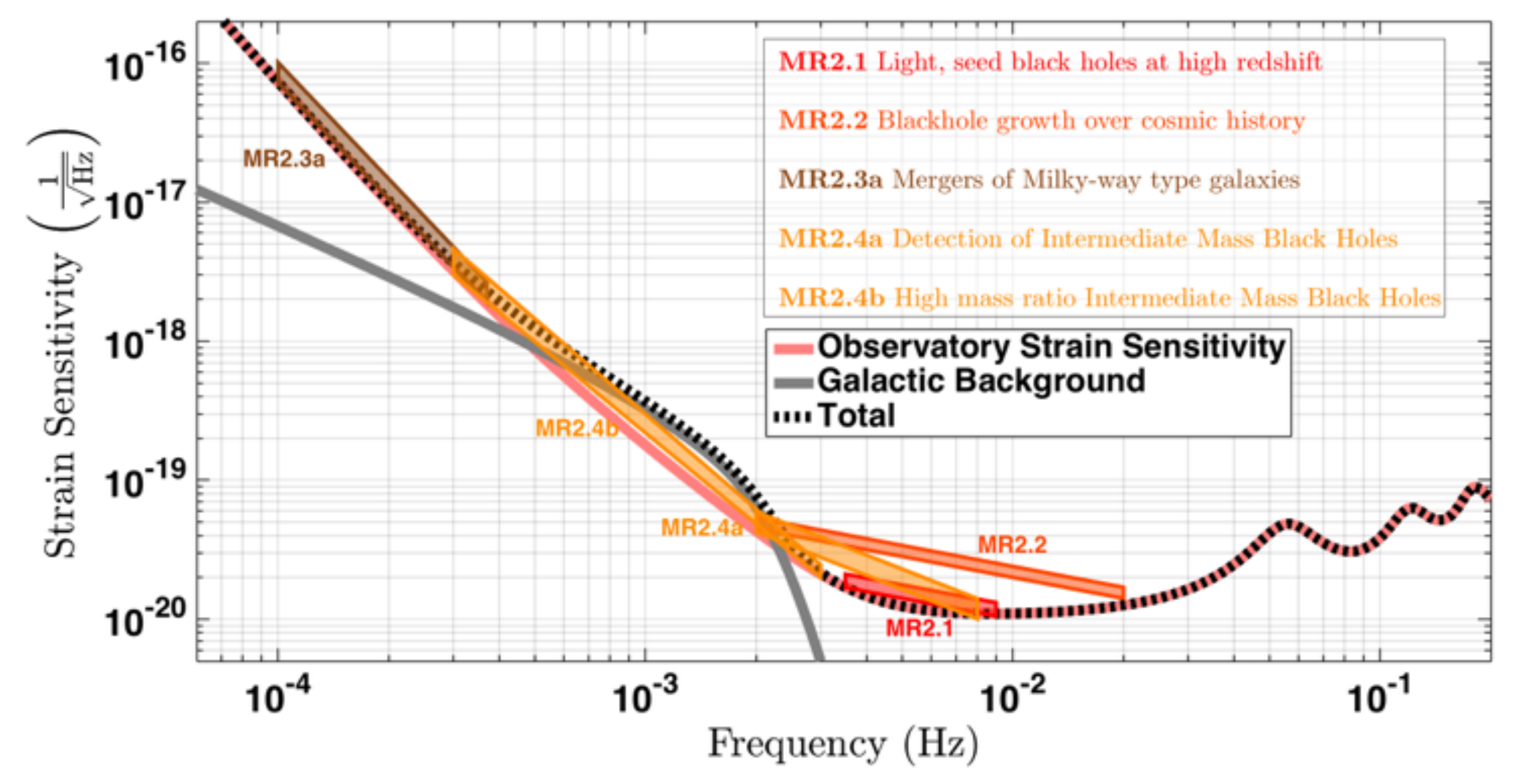


SO2

- Sensitivity
- Cadence for downloading data

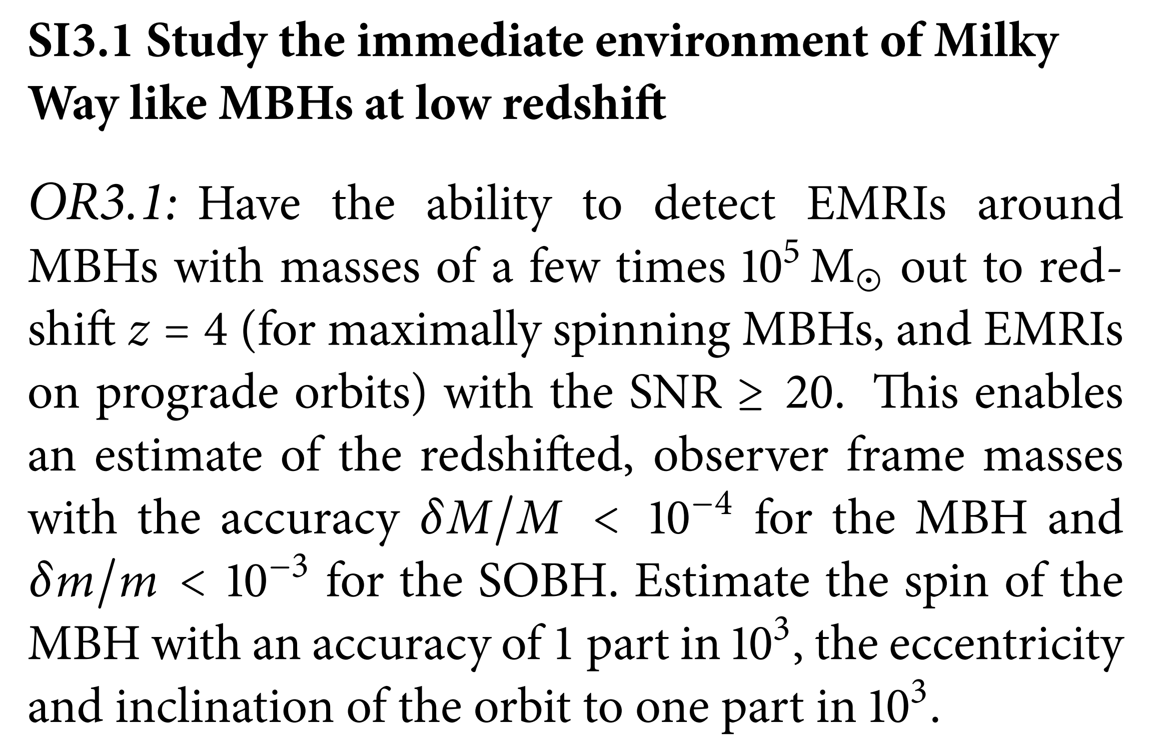
MRs:

- Protected period



SO3

- Sensitivity
- Protected period



SI3.1 Study the immediate environment of Milky Way like MBHs at low redshift

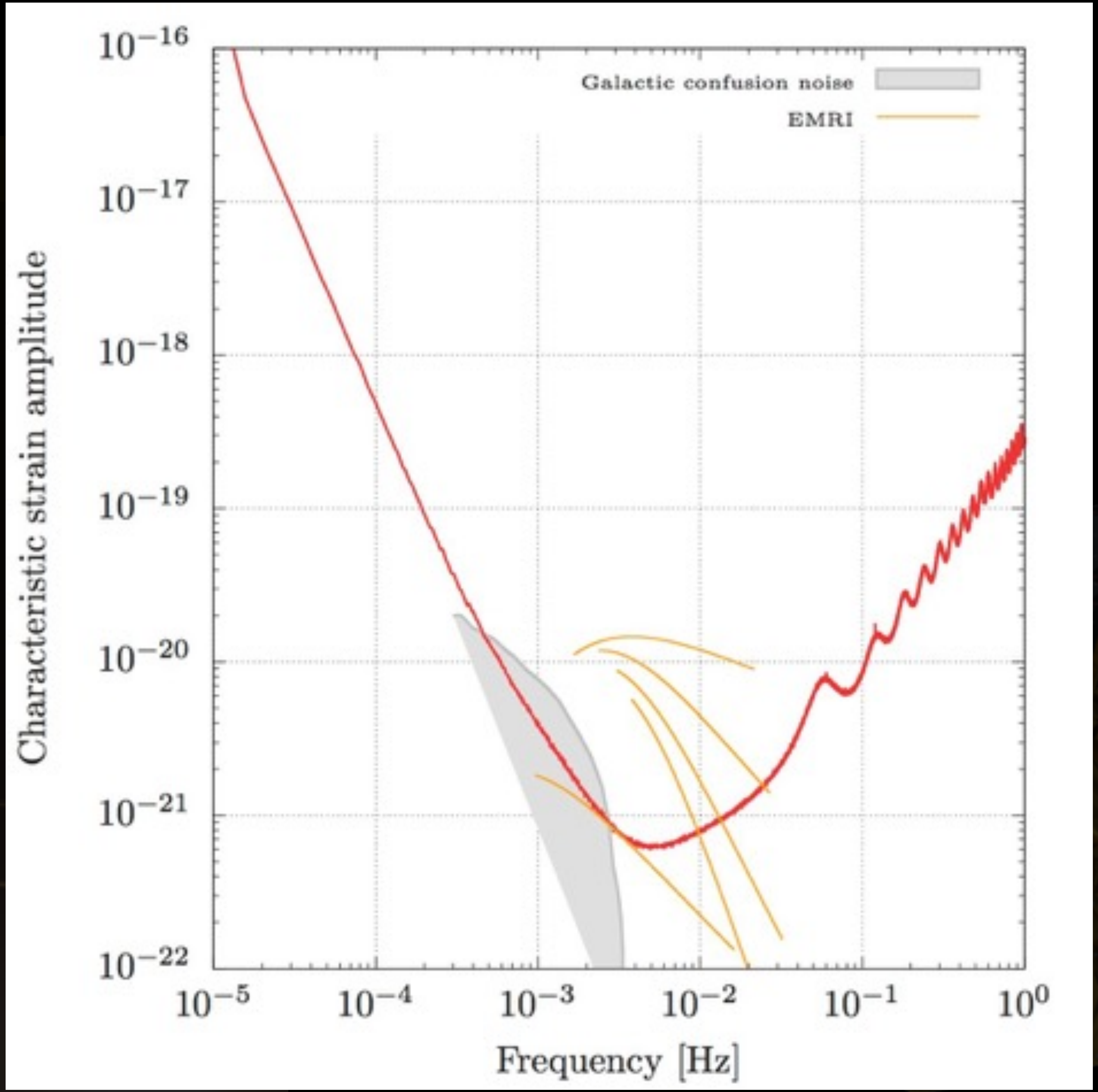
OR3.1: Have the ability to detect EMRIs around MBHs with masses of a few times $10^5\,M_\odot$ out to redshift $z = 4$ (for maximally spinning MBHs, and EMRIs on prograde orbits) with the SNR ≥ 20. This enables an estimate of the redshifted, observer frame masses with the accuracy $\delta M/M < 10^{-4}$ for the MBH and $\delta m/m < 10^{-3}$ for the SOBH. Estimate the spin of the MBH with an accuracy of 1 part in 10^3, the eccentricity and inclination of the orbit to one part in 10^3.

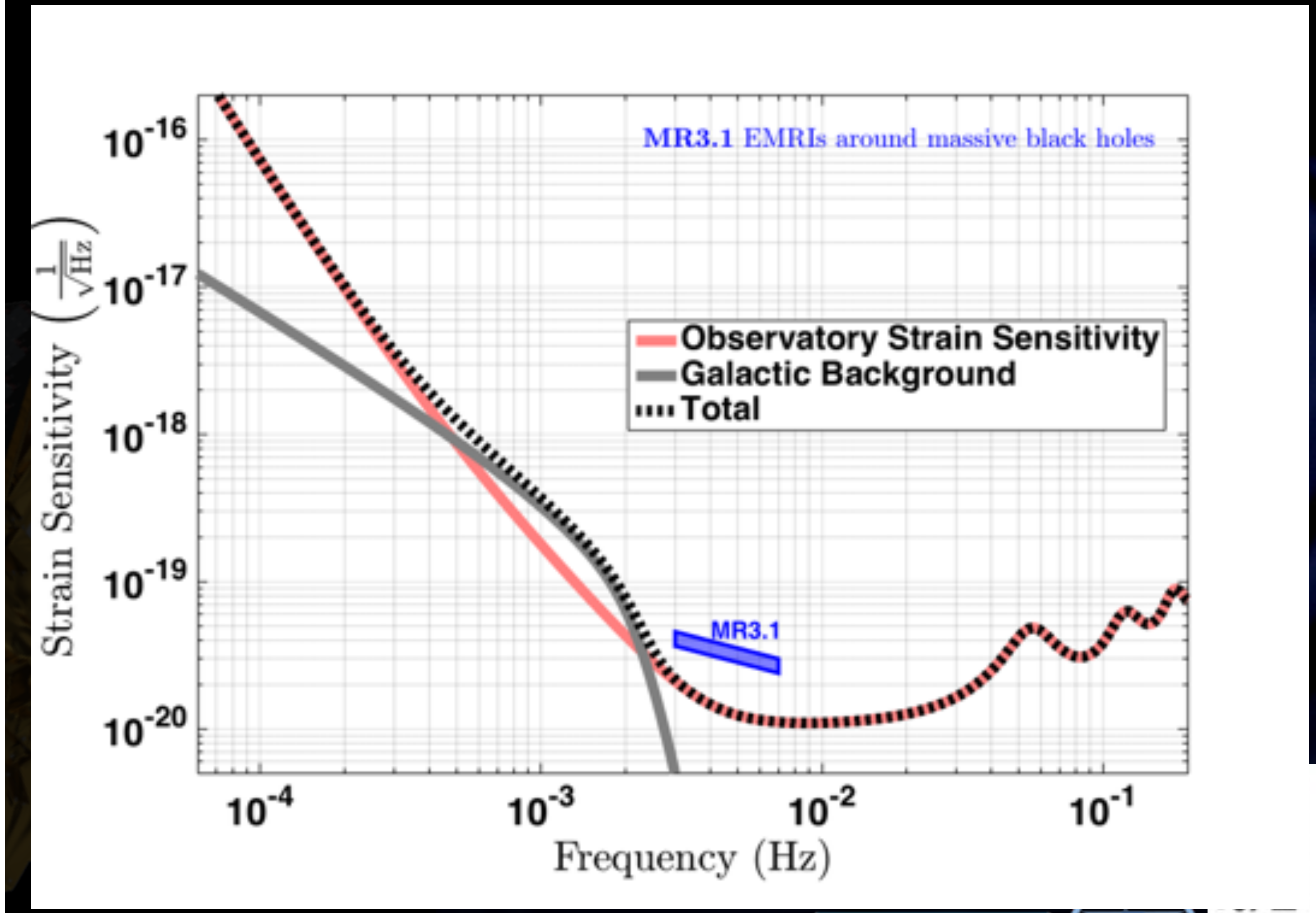
MRs:

SO3

- Sensitivity
- Protected period

MRs:





SO4

- Sensitivity

SI4.1 Study the close environment of SOBHs by enabling multi-band and multi-messenger observations at the time of coalescence

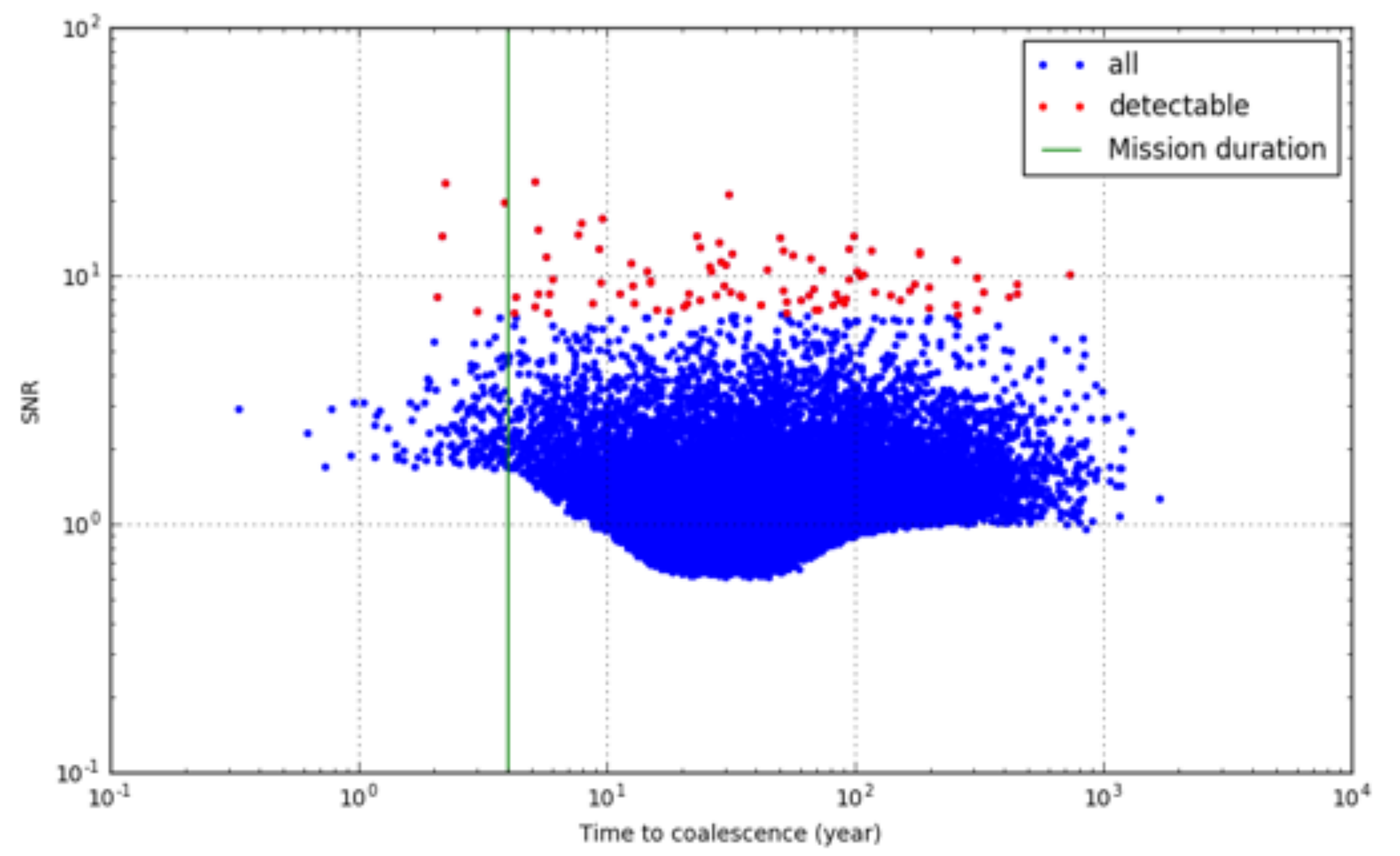
OR4.1: Have the ability to detect the inspiral signal from GW150914-like events with SNR > 7 after 4 years of observation and estimate the sky localisation with $< 1\,\mathrm{deg}^2$ and the time of coalescence in ground-based detectors to within one minute. This will allow the triggering of alerts to ground-based detectors and to pre-point EM probes at the SOBH coalescence.

SI4.2 Disentangle SOBH binary formation channels

OR4.2: Have the ability to observe SOBH binaries with total mass in excess of $50\,M_\odot$ out to redshift 0.1, with an SNR higher than 7 and a typical fractional error on the mass of 1 part in 100 and eccentricity with an absolute error of 1 part in 10^3.

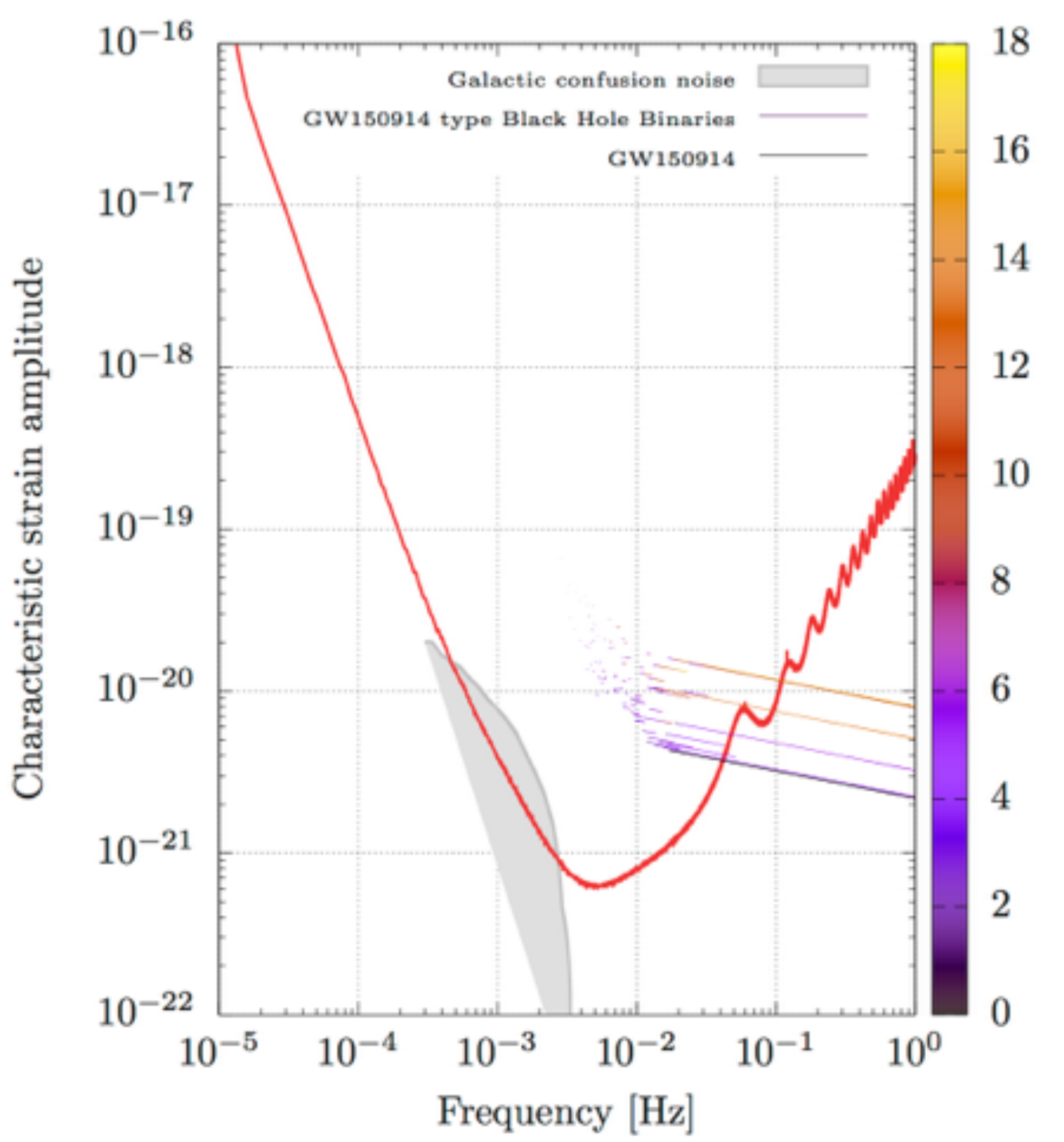
MRs:

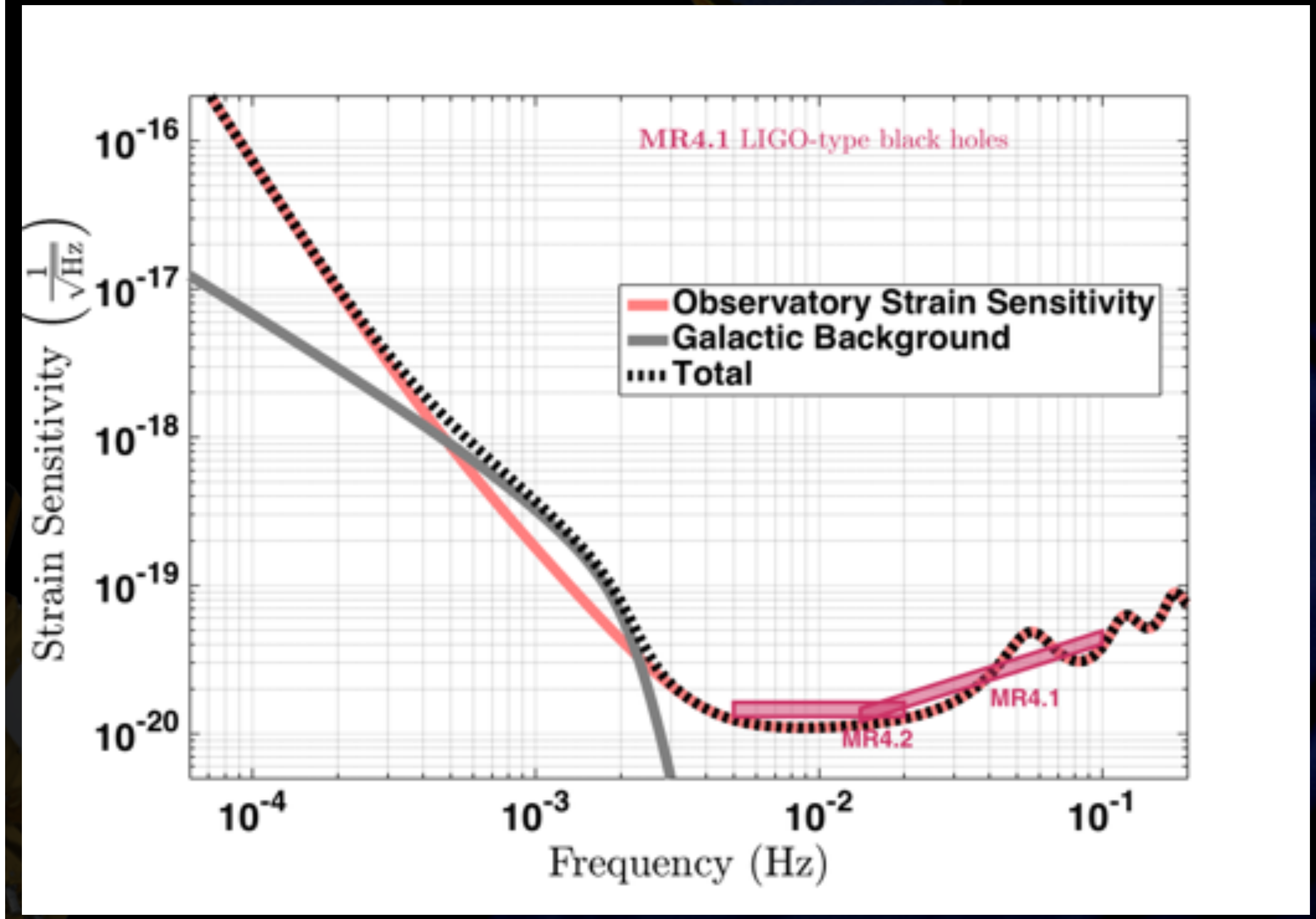
96 detected over a catalog of 17337



SO4

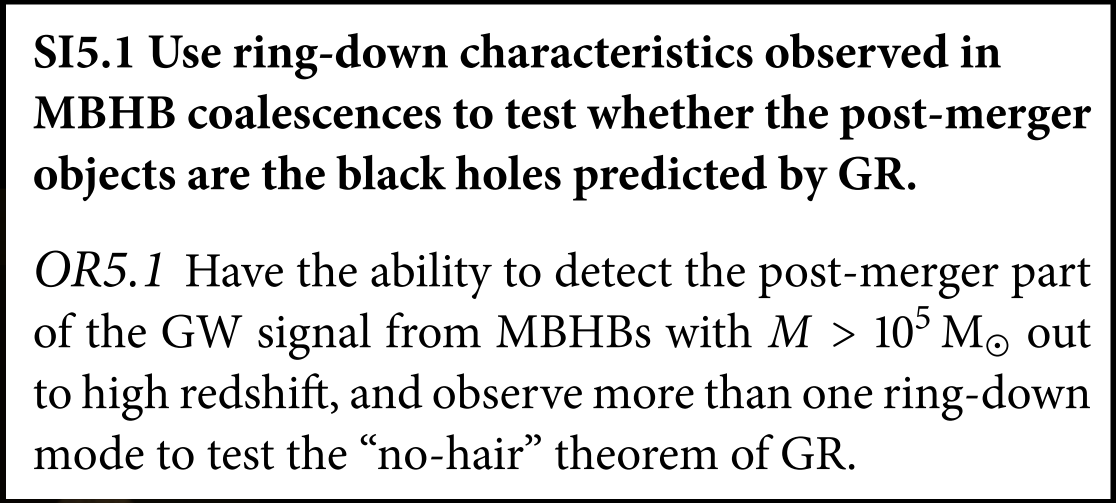
- Sensitivity





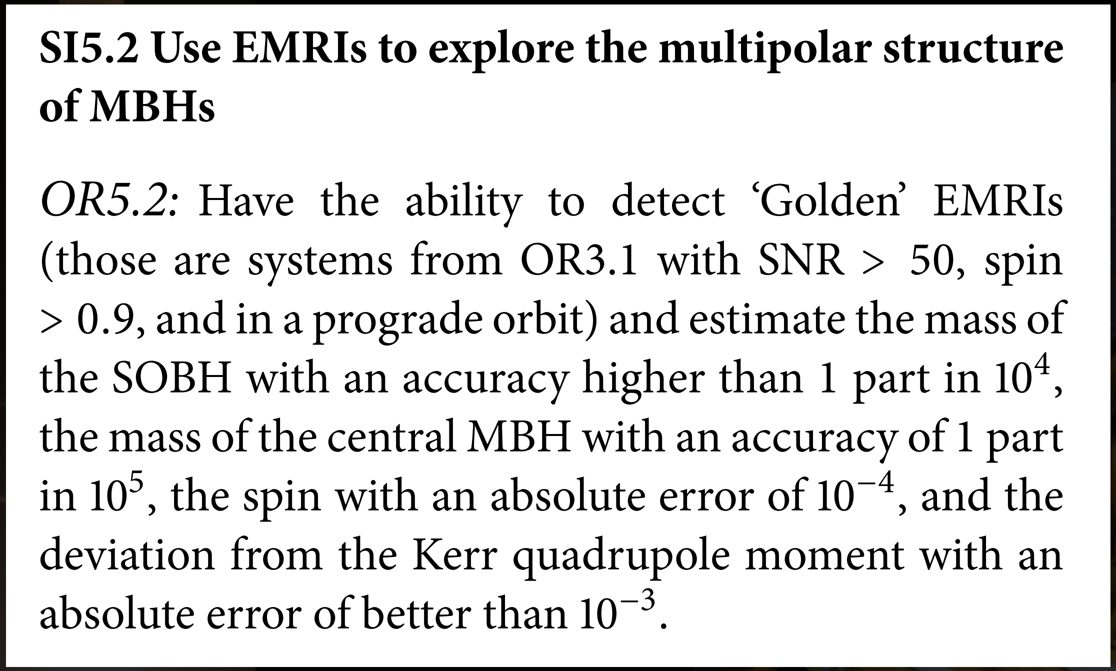
SO5

- Sensitivity



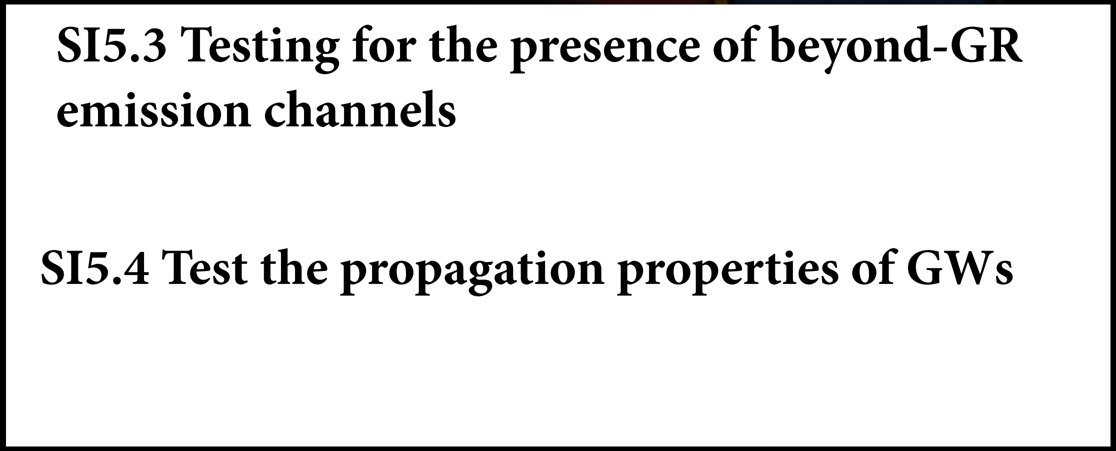
SI5.1 Use ring-down characteristics observed in MBHB coalescences to test whether the post-merger objects are the black holes predicted by GR.

OR5.1 Have the ability to detect the post-merger part of the GW signal from MBHBs with $M > 10^5\,M_\odot$ out to high redshift, and observe more than one ring-down mode to test the "no-hair" theorem of GR.



SI5.2 Use EMRIs to explore the multipolar structure of MBHs

OR5.2: Have the ability to detect 'Golden' EMRIs (those are systems from OR3.1 with SNR > 50, spin > 0.9, and in a prograde orbit) and estimate the mass of the SOBH with an accuracy higher than 1 part in 10^4, the mass of the central MBH with an accuracy of 1 part in 10^5, the spin with an absolute error of 10^{-4}, and the deviation from the Kerr quadrupole moment with an absolute error of better than 10^{-3}.



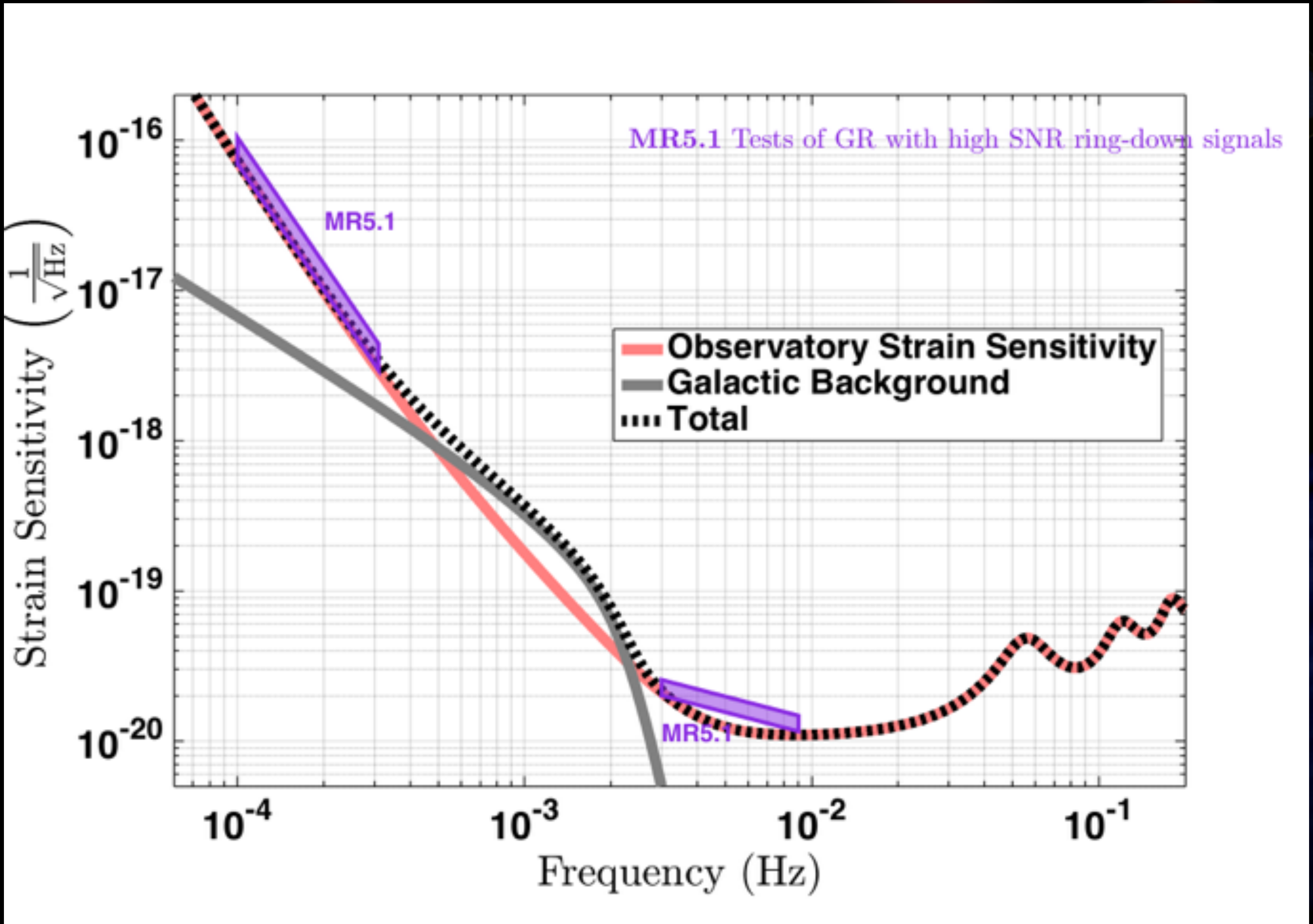
SI5.3 Testing for the presence of beyond-GR emission channels

SI5.4 Test the propagation properties of GWs

MRs:

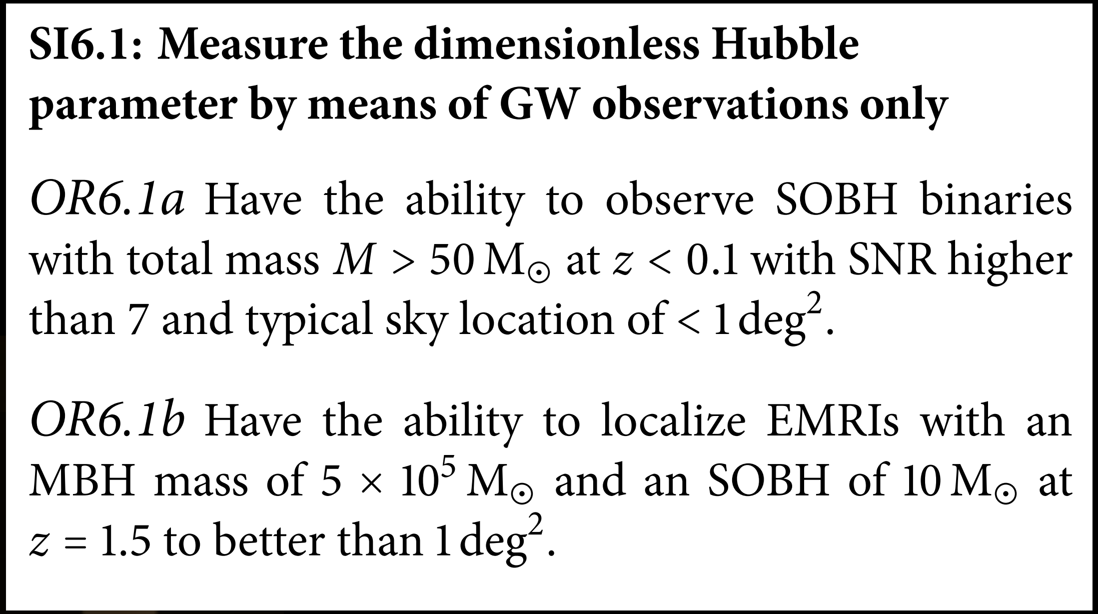
SO5

- Sensitivity



SO6

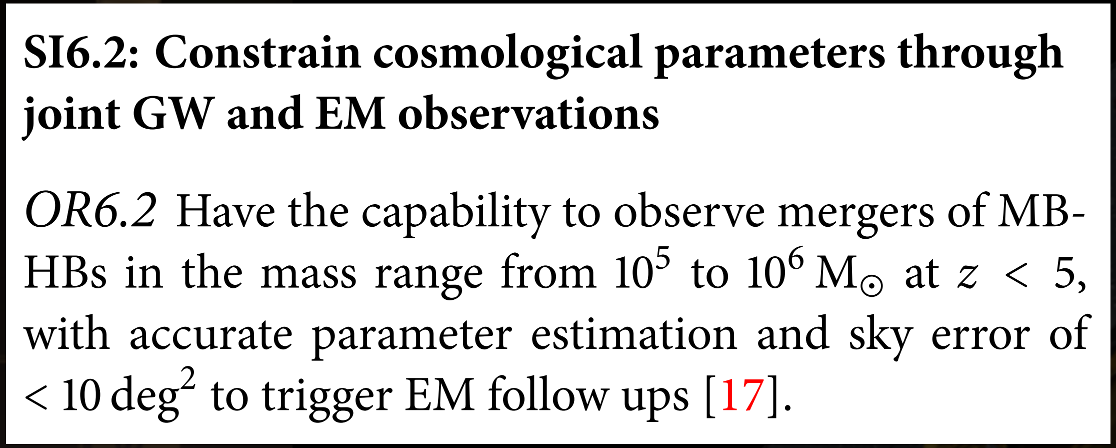
- Sensitivity



SI6.1: Measure the dimensionless Hubble parameter by means of GW observations only

OR6.1a Have the ability to observe SOBH binaries with total mass $M > 50\,\mathrm{M}_\odot$ at $z < 0.1$ with SNR higher than 7 and typical sky location of $< 1\,\mathrm{deg}^2$.

OR6.1b Have the ability to localize EMRIs with an MBH mass of $5 \times 10^5\,\mathrm{M}_\odot$ and an SOBH of $10\,\mathrm{M}_\odot$ at $z = 1.5$ to better than $1\,\mathrm{deg}^2$.



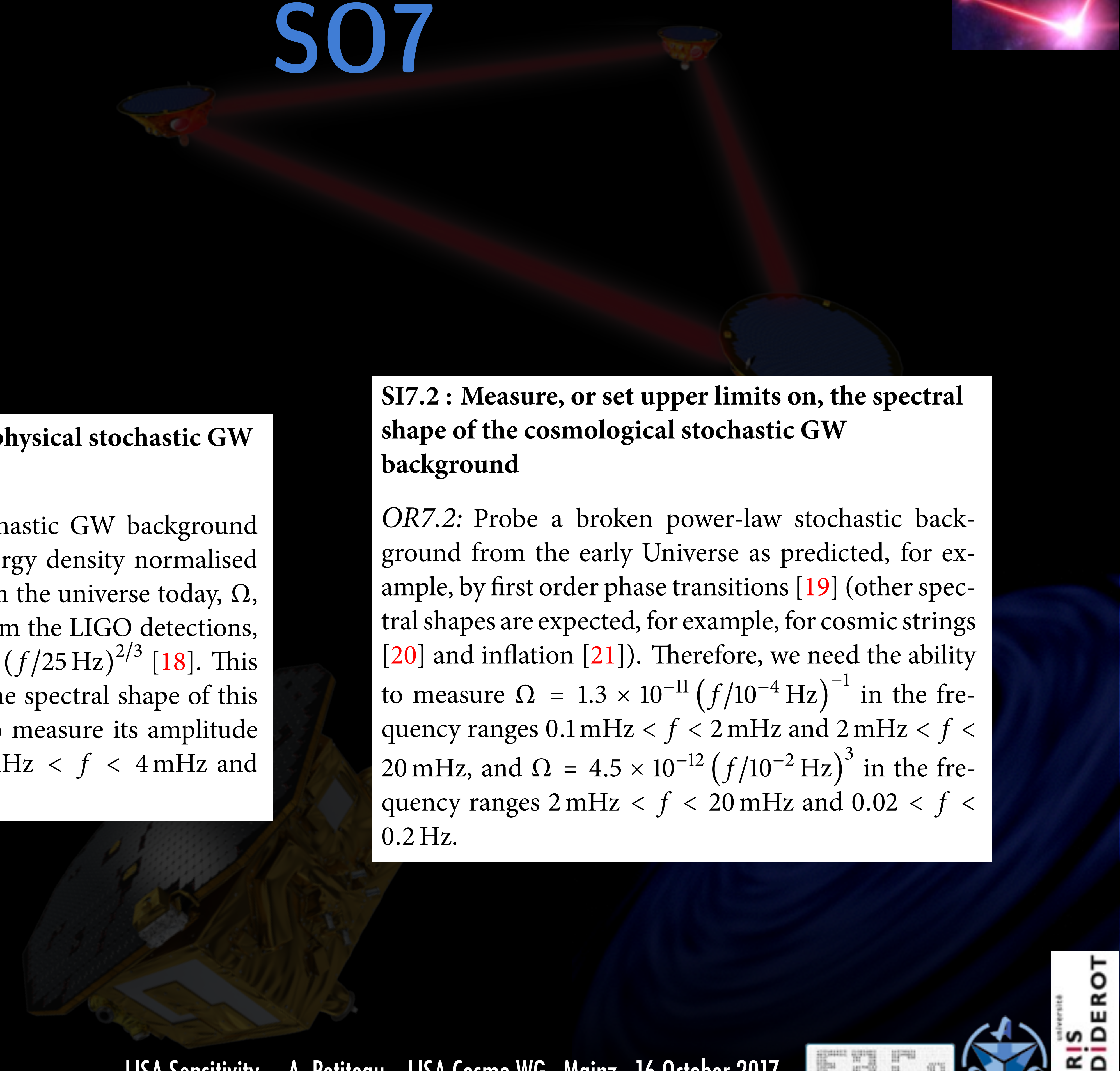
SI6.2: Constrain cosmological parameters through joint GW and EM observations

OR6.2 Have the capability to observe mergers of MBHBs in the mass range from 10^5 to $10^6\,\mathrm{M}_\odot$ at $z < 5$, with accurate parameter estimation and sky error of $< 10\,\mathrm{deg}^2$ to trigger EM follow ups [17].

MRs:

SO7

- Sensitivity



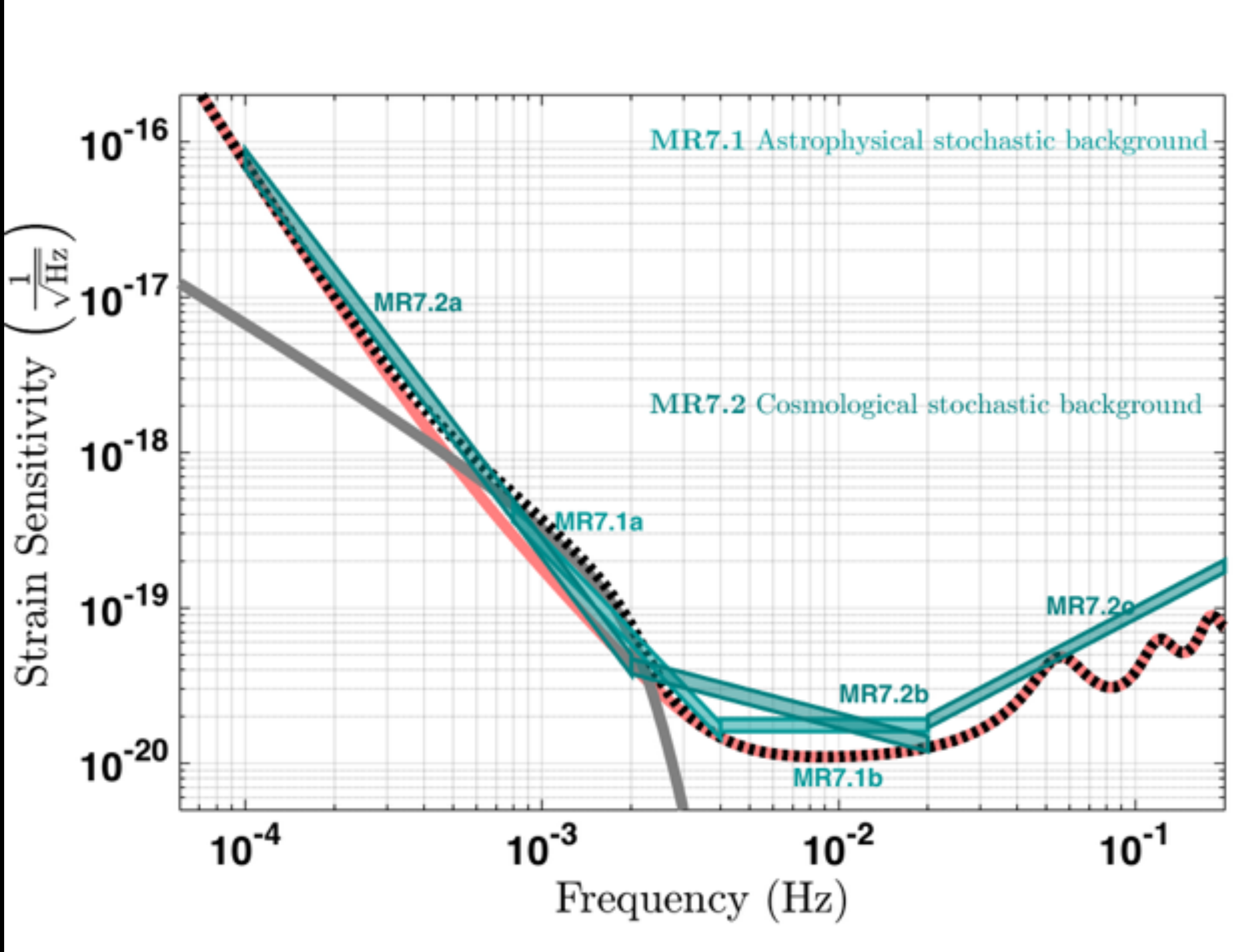
SI7.1: Characterise the astrophysical stochastic GW background

OR7.1: Characterise the stochastic GW background from SOBH binaries with energy density normalised to the critical energy density in the universe today, Ω, based on the inferred rates from the LIGO detections, i.e., at the lowest $\Omega = 2 \times 10^{-10} \left(f/25\,\mathrm{Hz}\right)^{2/3}$ [18]. This requires the ability to verify the spectral shape of this stochastic background, and to measure its amplitude in the frequency ranges $0.8\,\mathrm{mHz} < f < 4\,\mathrm{mHz}$ and $4\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$.

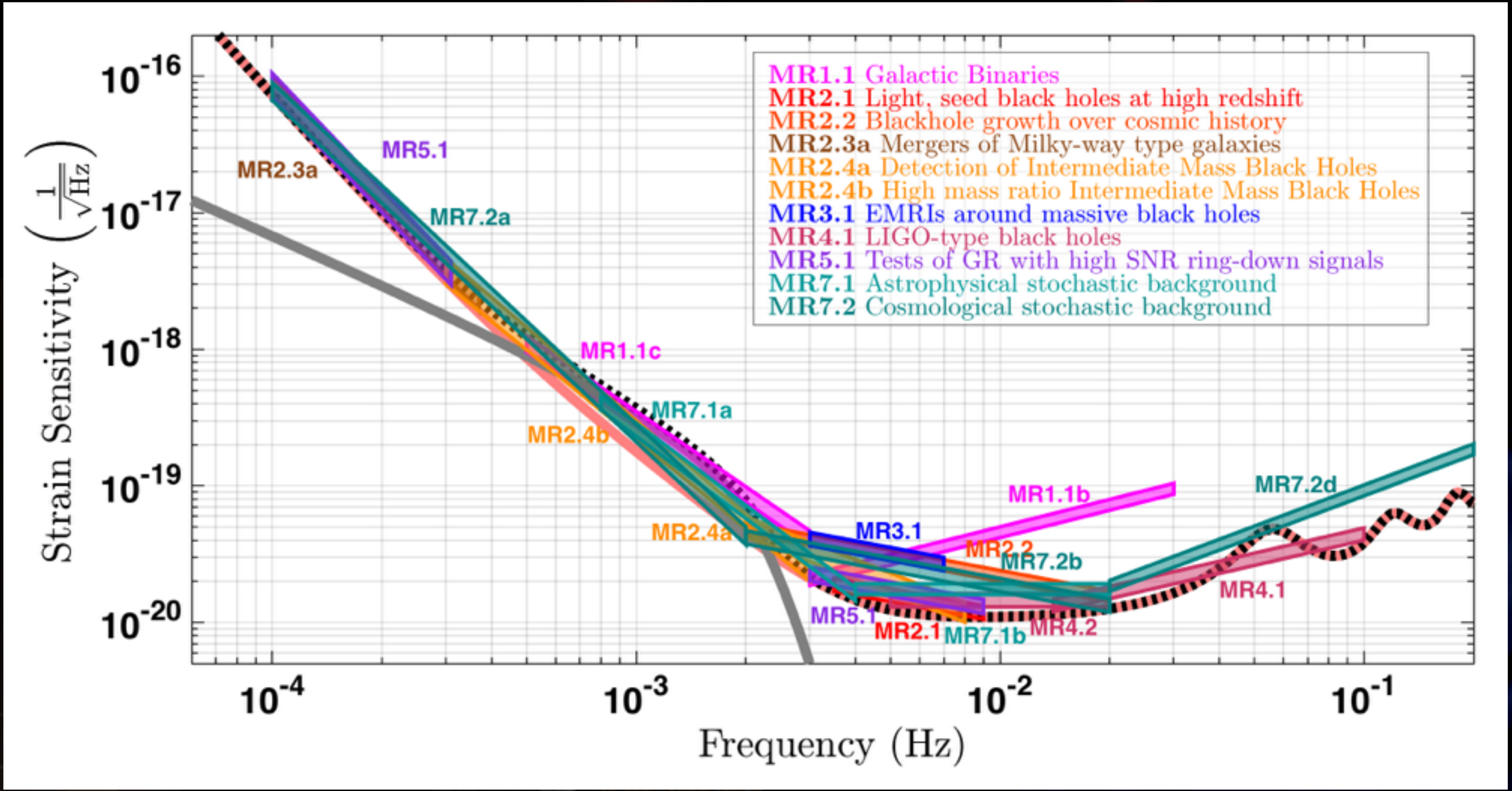
SI7.2 : Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

OR7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions [19] (other spectral shapes are expected, for example, for cosmic strings [20] and inflation [21]). Therefore, we need the ability to measure $\Omega = 1.3 \times 10^{-11} \left(f/10^{-4}\,\mathrm{Hz}\right)^{-1}$ in the frequency ranges $0.1\,\mathrm{mHz} < f < 2\,\mathrm{mHz}$ and $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$, and $\Omega = 4.5 \times 10^{-12} \left(f/10^{-2}\,\mathrm{Hz}\right)^{3}$ in the frequency ranges $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$ and $0.02 < f < 0.2\,\mathrm{Hz}$.

SO7


MR7.1 Astrophysical stochastic background
MR7.2 Cosmological stochastic background
MR7.2a
MR7.1a
MR7.2c
MR7.2b
MR7.1b
Strain Sensitivity $\left(\frac{1}{\sqrt{\mathrm{Hz}}}\right)$
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

All


MR1.1 Galactic Binaries
MR2.1 Light, seed black holes at high redshift
MR2.2 Blackhole growth over cosmic history
MR2.3a Mergers of Milky-way type galaxies
MR2.4a Detection of Intermediate Mass Black Holes
MR2.4b High mass ratio Intermediate Mass Black Holes
MR3.1 EMRIs around massive black holes
MR4.1 LIGO-type black holes
MR5.1 Tests of GR with high SNR ring-down signals
MR7.1 Astrophysical stochastic background
MR7.2 Cosmological stochastic background
MR2.3a
MR5.1
MR7.2a
MR1.1c
MR7.1a
MR2.4b
MR2.4a
MR3.1
MR1.1b
MR7.2d
MR2.2
MR7.2b
MR4.1
MR5.1
MR2.1
MR7.1b
MR4.2
Strain Sensitivity $\left(\frac{1}{\sqrt{\text{Hz}}}\right)$
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

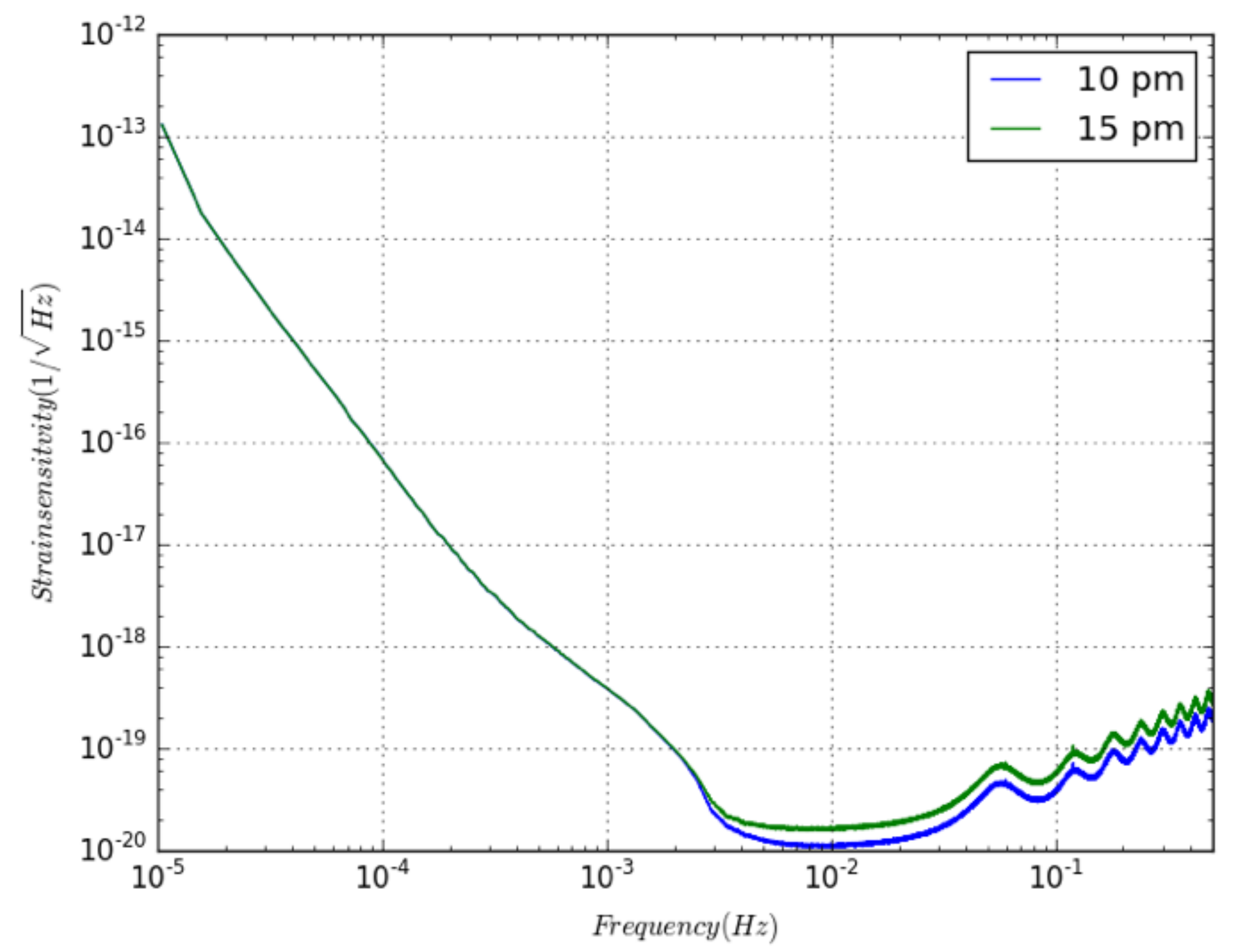
Update for the SRD

- The ESA LISA Science Study Team is preparing the Science Requirement Document based on the science
- Effective duration: 90% duty cycle on LISAPathfinder => 70% on LISA => 3 years of science data ? (pessimistic)
- Limitations on the Interferometric Metrology System noise model used in the proposal:
  - Optimistic for noise sources with large uncertainties
  - No residual laser noise

  => relaxation of the IMS from 10 pm/√Hz to 15 pm/√Hz
    - Impact on middle and high-frequency ...

Update for the SRD

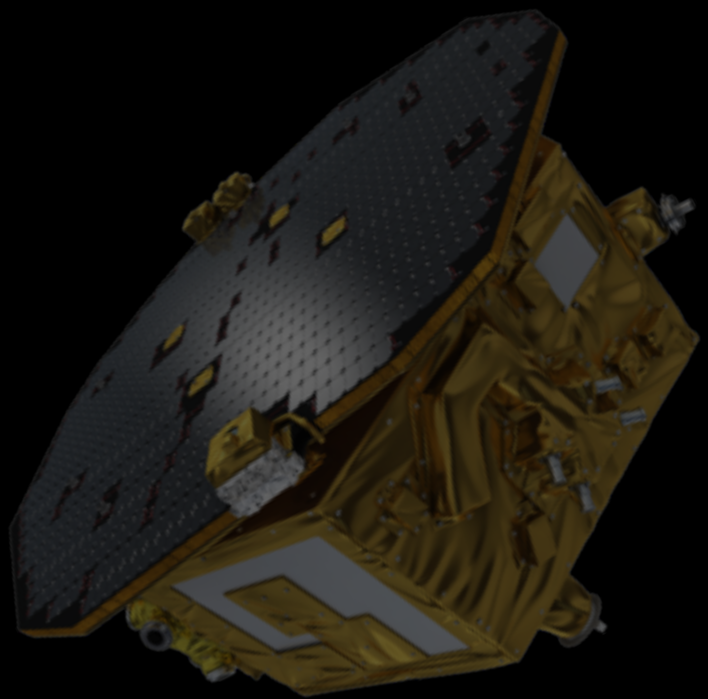
- Impacted Science Objectives:
  - SO4: SOBHBs (96 → 42)
  - SO7: stochastic background …



Conclusion

- The LISA sensitivity used in the LISA proposal is the results of the adjustment of 2 approaches:
  - from noises budget
  - from science requirement
- It enables a large science case
- It will be adjusted and relaxed in the coming month to avoid hard border line constrain on the technologies.
  - Only a small reduction in the science case
- More studies of science performances needed

Thank you



Power Law Sensitivity

- Introduce by Thrane & Romano 2013
- For isotropic unpolarised Gaussian stationary background described by a simple power law $$h^2\Omega_{GW}(f) = \Omega_\beta \left(\frac{f}{f_{ref}}\right)^\beta$$
- Sensitivity for a given SNR and observation time.
- Done by scanning all slopes and finding for each slope the amplitude corresponding to the SNR.
- Example : old-LISA, 1 year