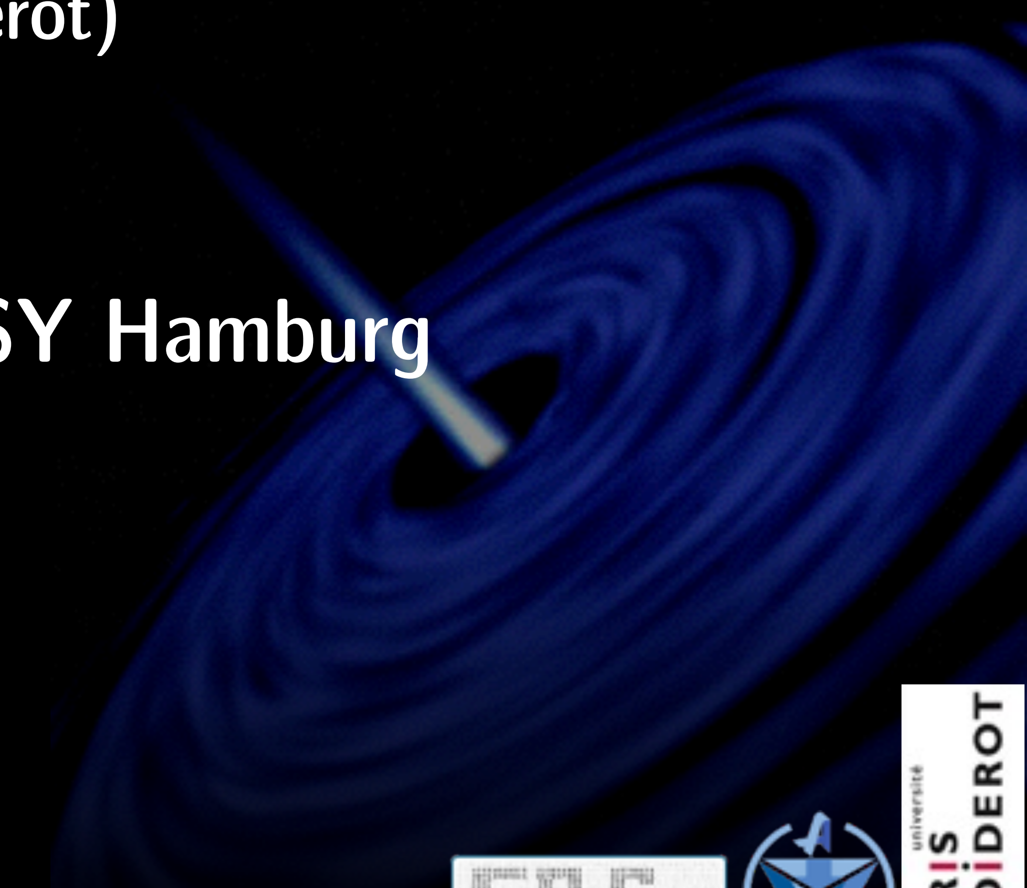
Stochastic Background detection in the context of LISAPathfinder first results and LISA simulation

Antoine Petiteau

(APC – Université Paris-Diderot)

eLISA cosmology workshop - DESY Hamburg

20th October 2016

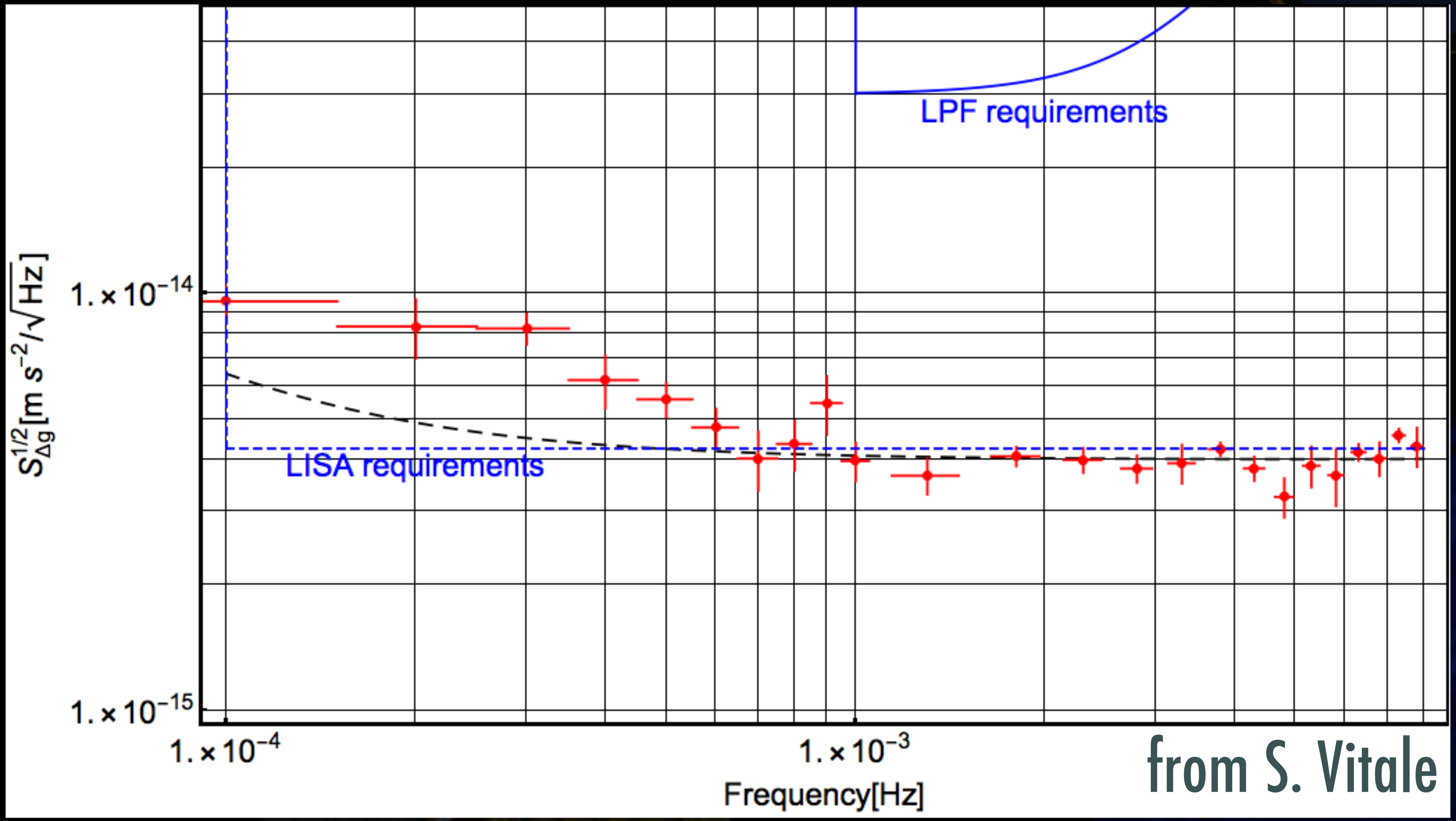


Outline

- LISAPathfinder results and LISA sensitivity
- Foregrounds
- Estimation of detectability of stochastic backgrounds
  - Power Law Sensitivity
  - Calibration of SNR and detectability
- LISA (proto-) Data Processing Center: tools available
- Next steps:
  - Simulation & data analysis
- Conclusion

LISAPathfinder results

- Best average results from LISAPathfinder adapted to LISA (no actuation, …) [talk from Martin Hewitson]



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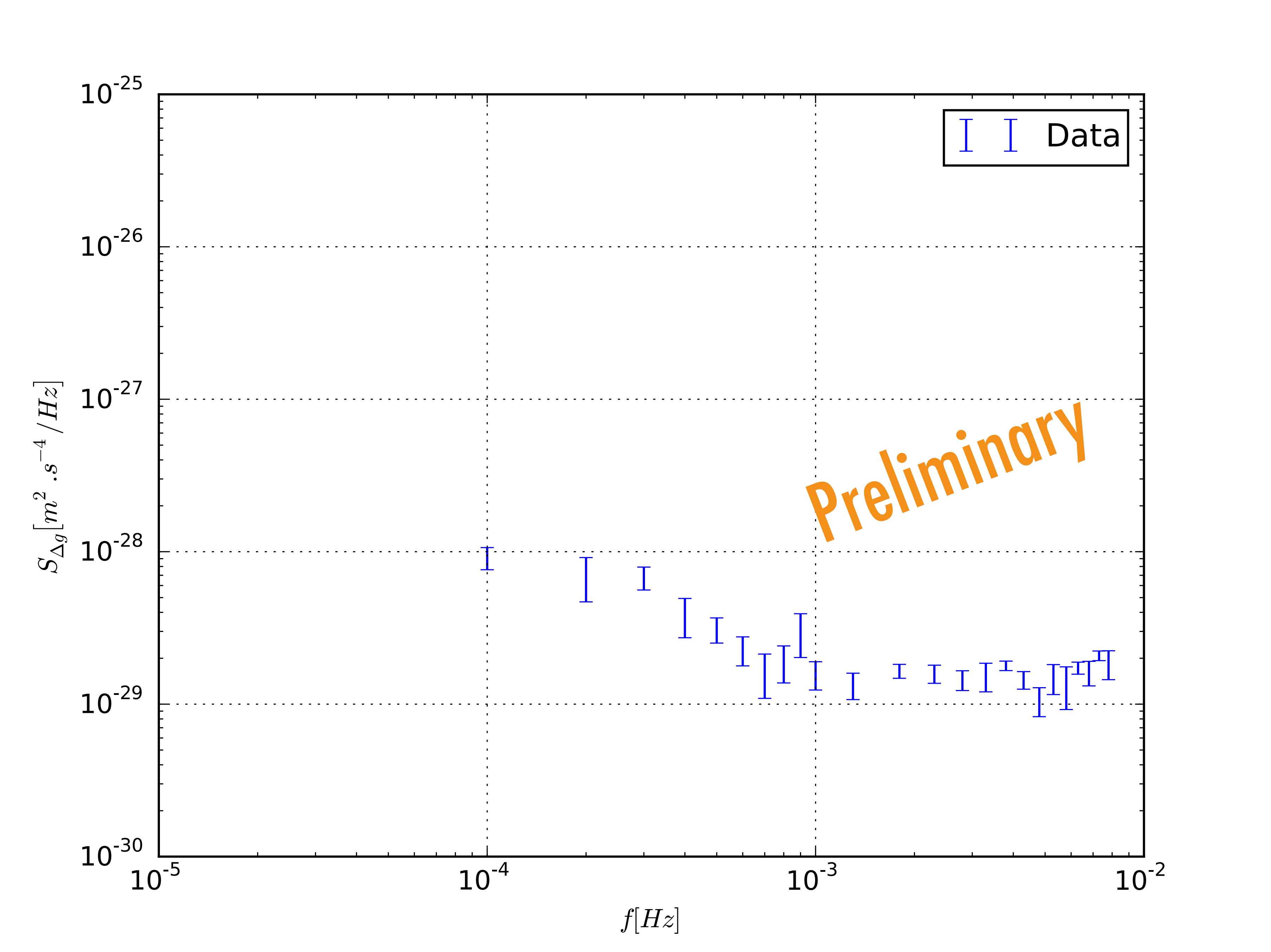
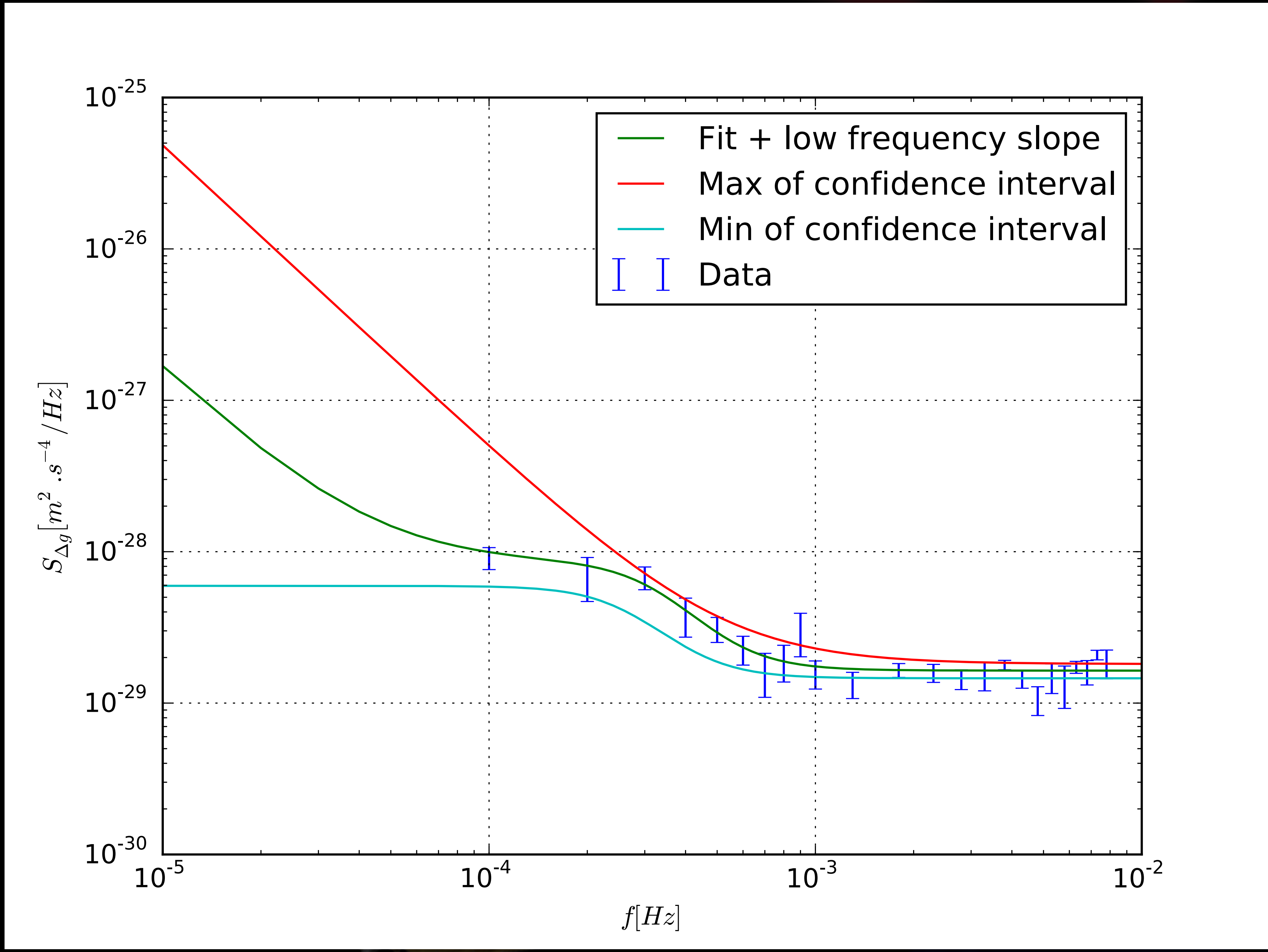


LISAPathfinder results

- Best average results from LISAPathfinder
  + confidence interval (large uncertainty at low frequency)



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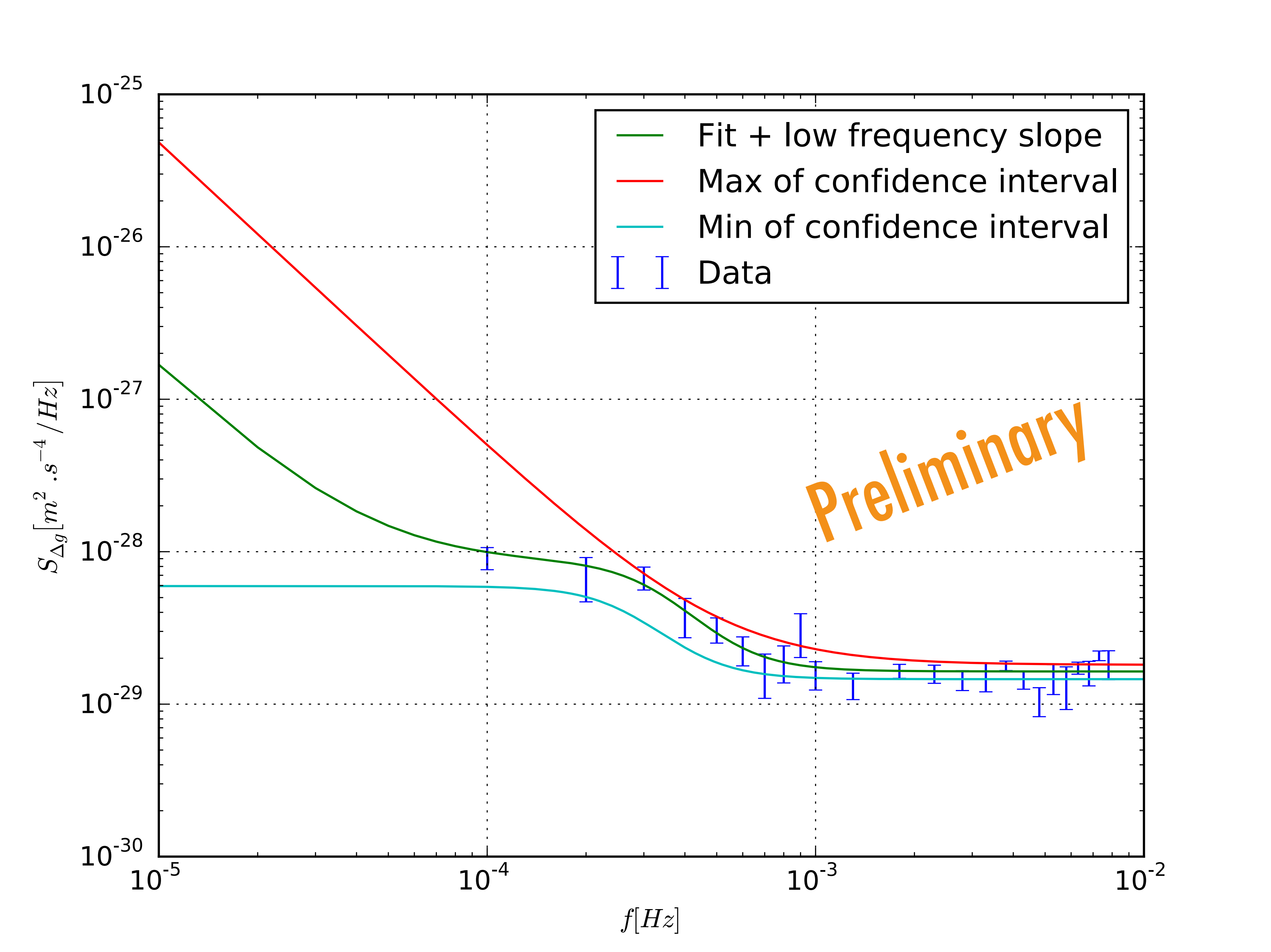

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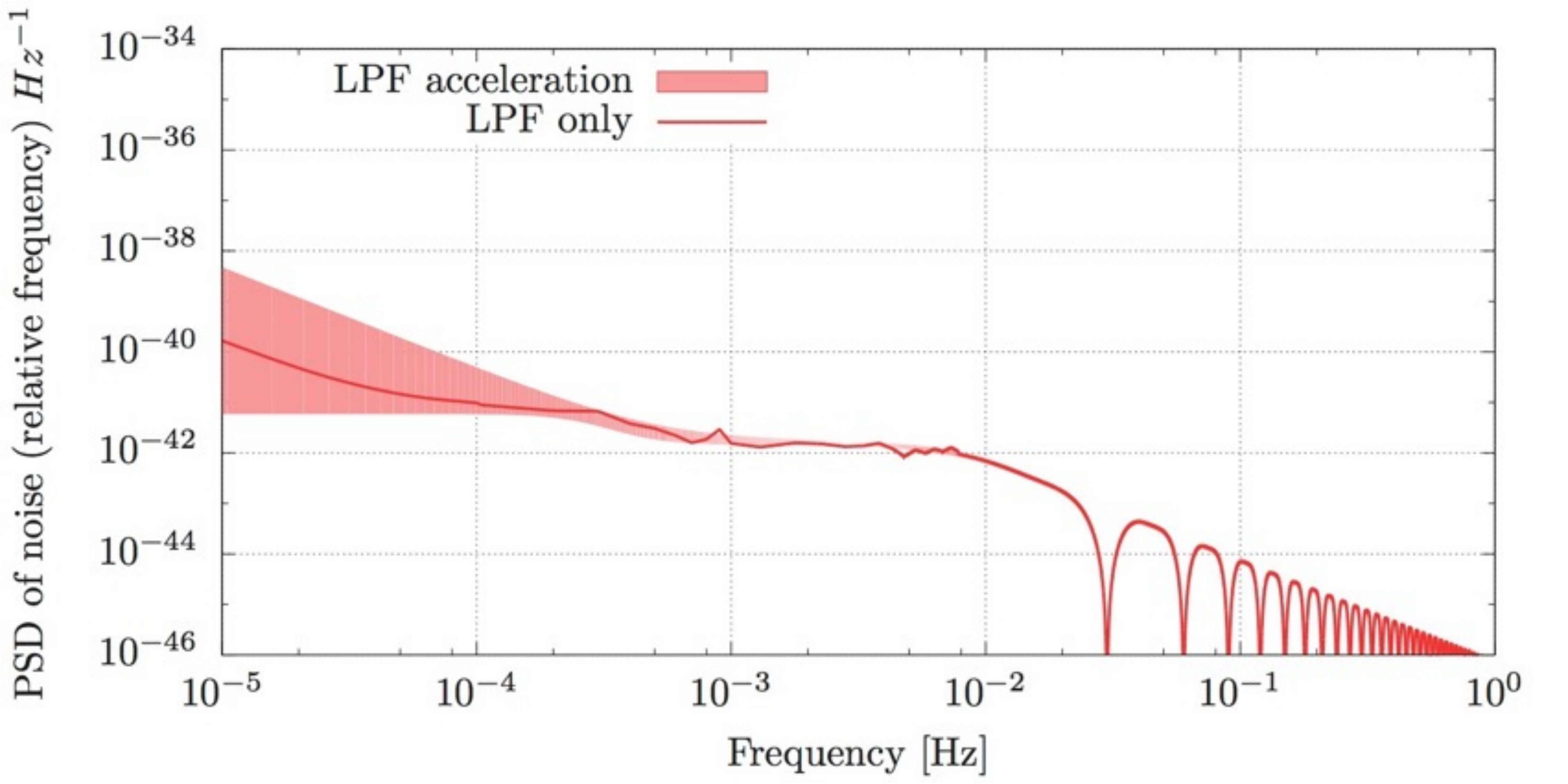

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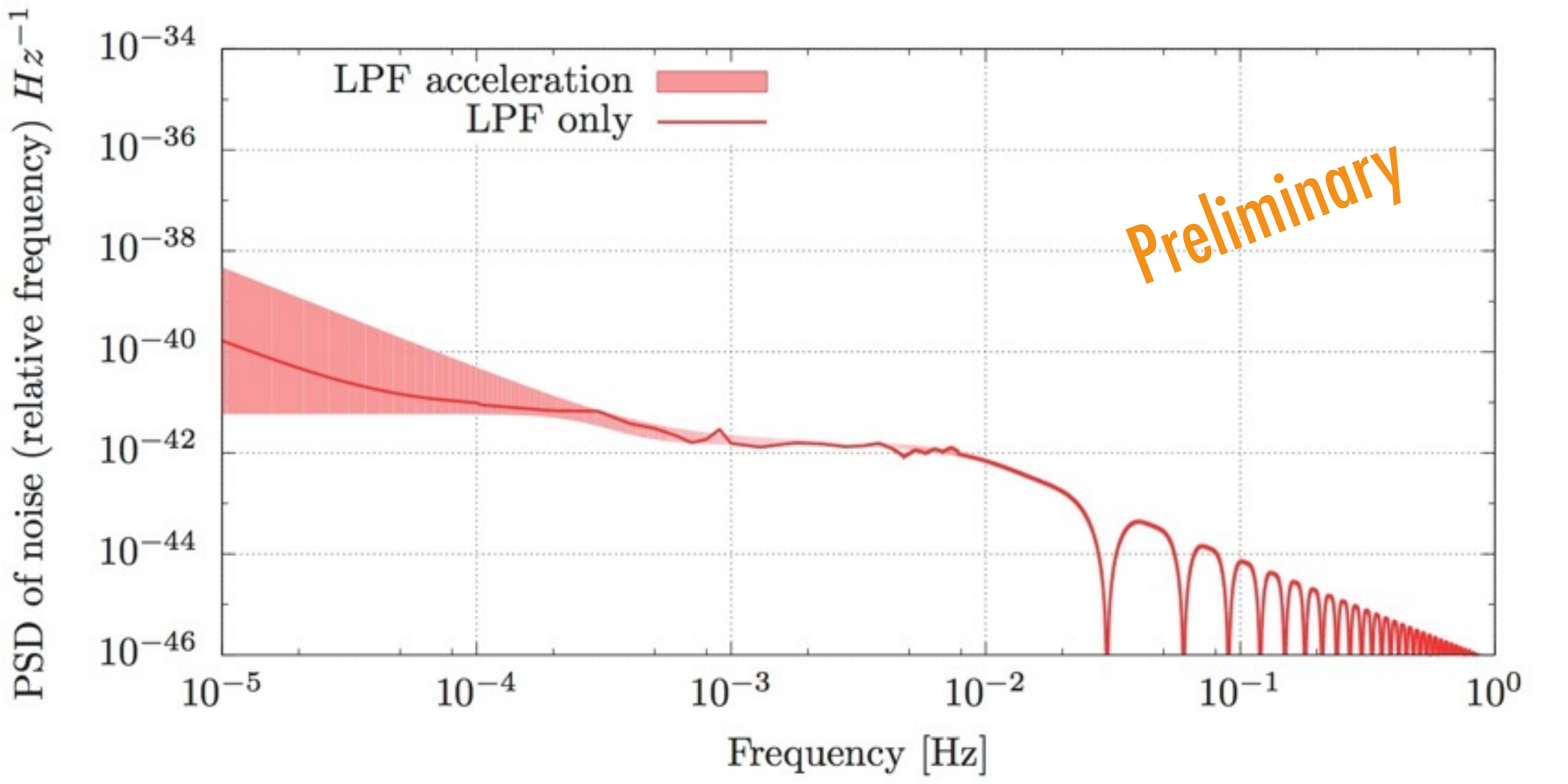

LISA high frequency noise

- Several versions ...

Configuration Model	Units	LISA2011M YB2011M	LISA2011 YB2011	LxA5MxNxP2D40 GOAT	LxA5MxNxP2D40 AEI2015 [4]	LxA2MxNxP2D30 AEI2015 [4]
Armlength	$\times 10^9$m	5	5	5	5	2
Telescope diameter	cm	38	38	40	40	30
Shot noise	pm/$\sqrt{\text{Hz}}$	7.7	7.7	7.49	6.38	4.54
Relative Intensity Noise	pm/$\sqrt{\text{Hz}}$	1	1		3.03	2.16
Electrical noise	pm/$\sqrt{\text{Hz}}$	1	1		3.03	2.16
Optical path noise	pm/$\sqrt{\text{Hz}}$	7	7		1.00	1.00
Metrology noise	pm/$\sqrt{\text{Hz}}$	5.2	5.2		1.02	1.02
Pilot tone noise	pm/$\sqrt{\text{Hz}}$	0	0		2.57	2.57
$\sqrt{S_{OMS,m}}$	pm/$\sqrt{\text{Hz}}$			5.15		
Margin		1/0.65	1	1	1	1
$\sqrt{\mathrm{S_{IMS,m}}}$	pm/$\sqrt{\text{Hz}}$	**18.0**	**11.7**	**7.49**	**8.20**	**6.19**

[4] Barkes et al. 2015

- Work in progress to improve the "high frequency" noise budget within the Simulation Working Group

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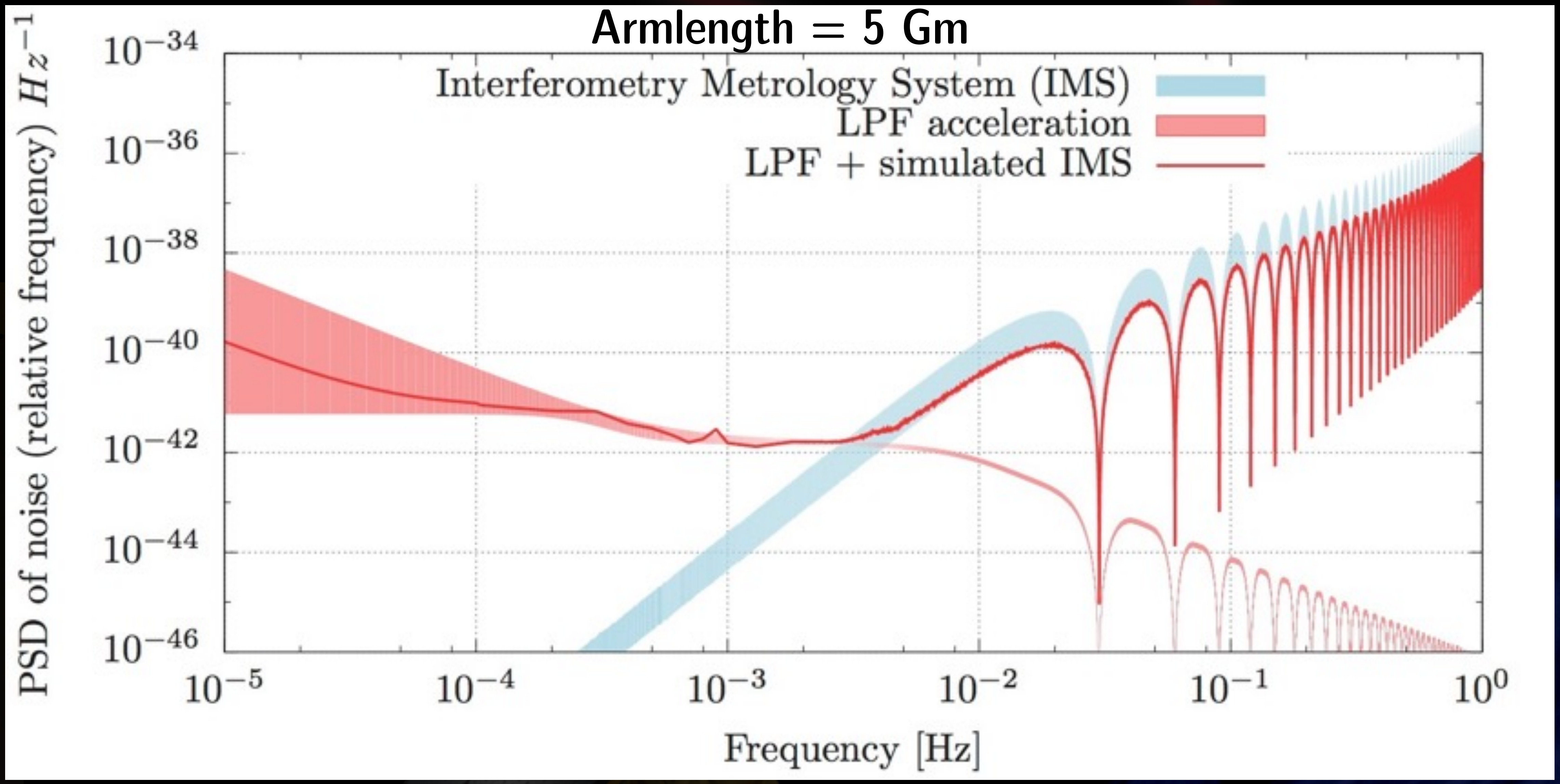

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LISA high frequency noise

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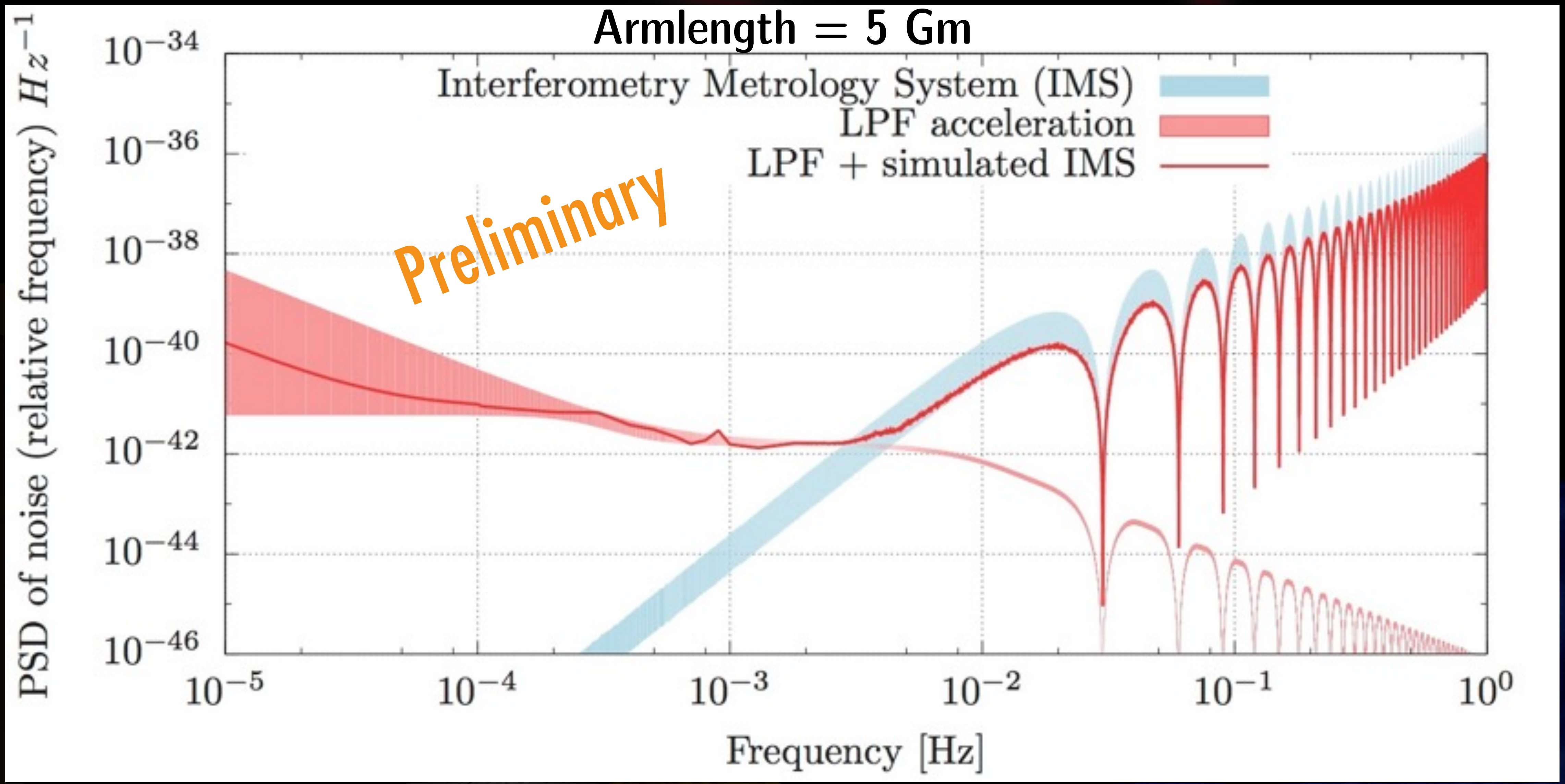

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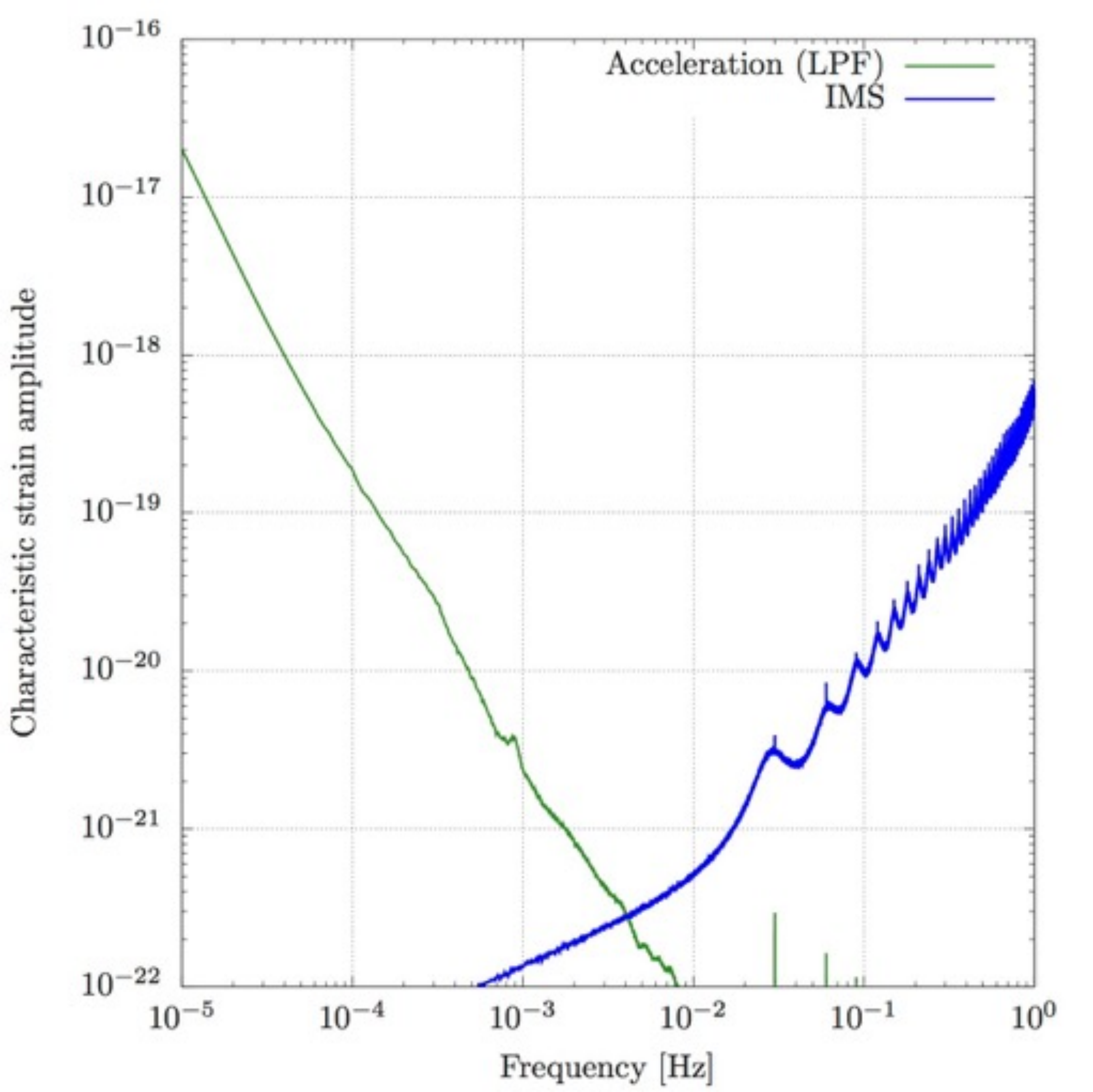
LISA sensitivity with LPF results

- Sensitivity in characteristic strain

L = 5 Gm



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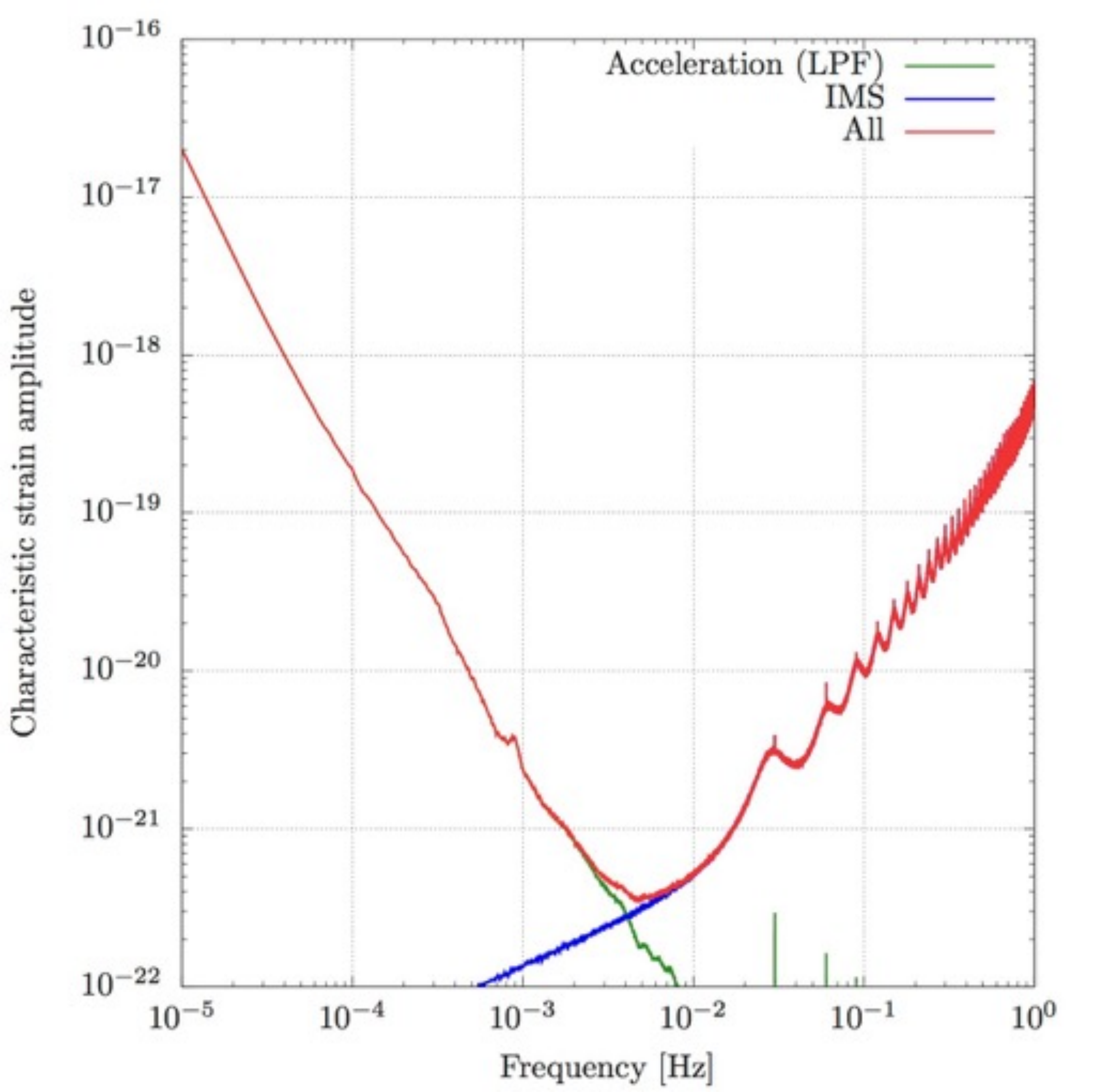

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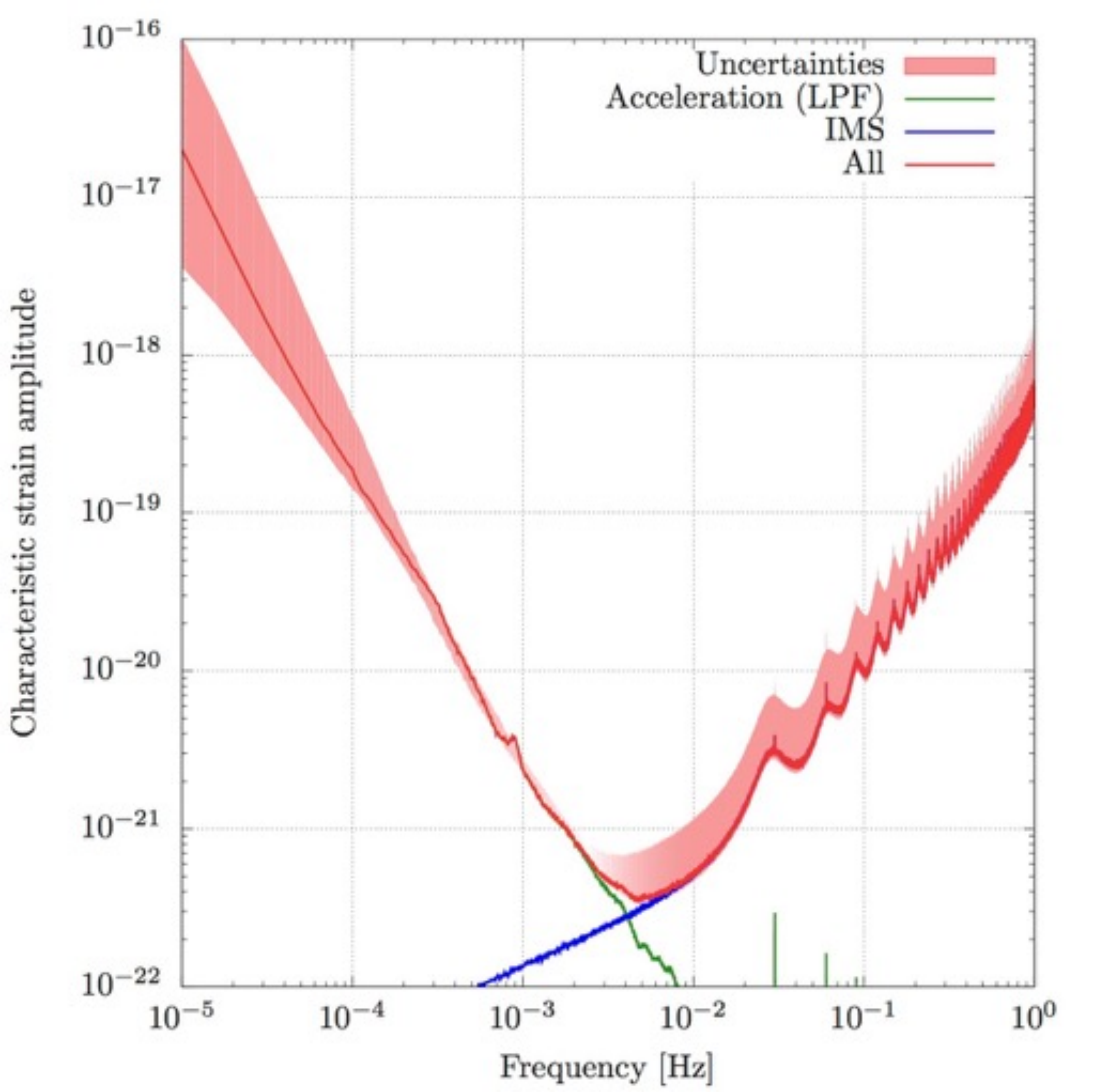

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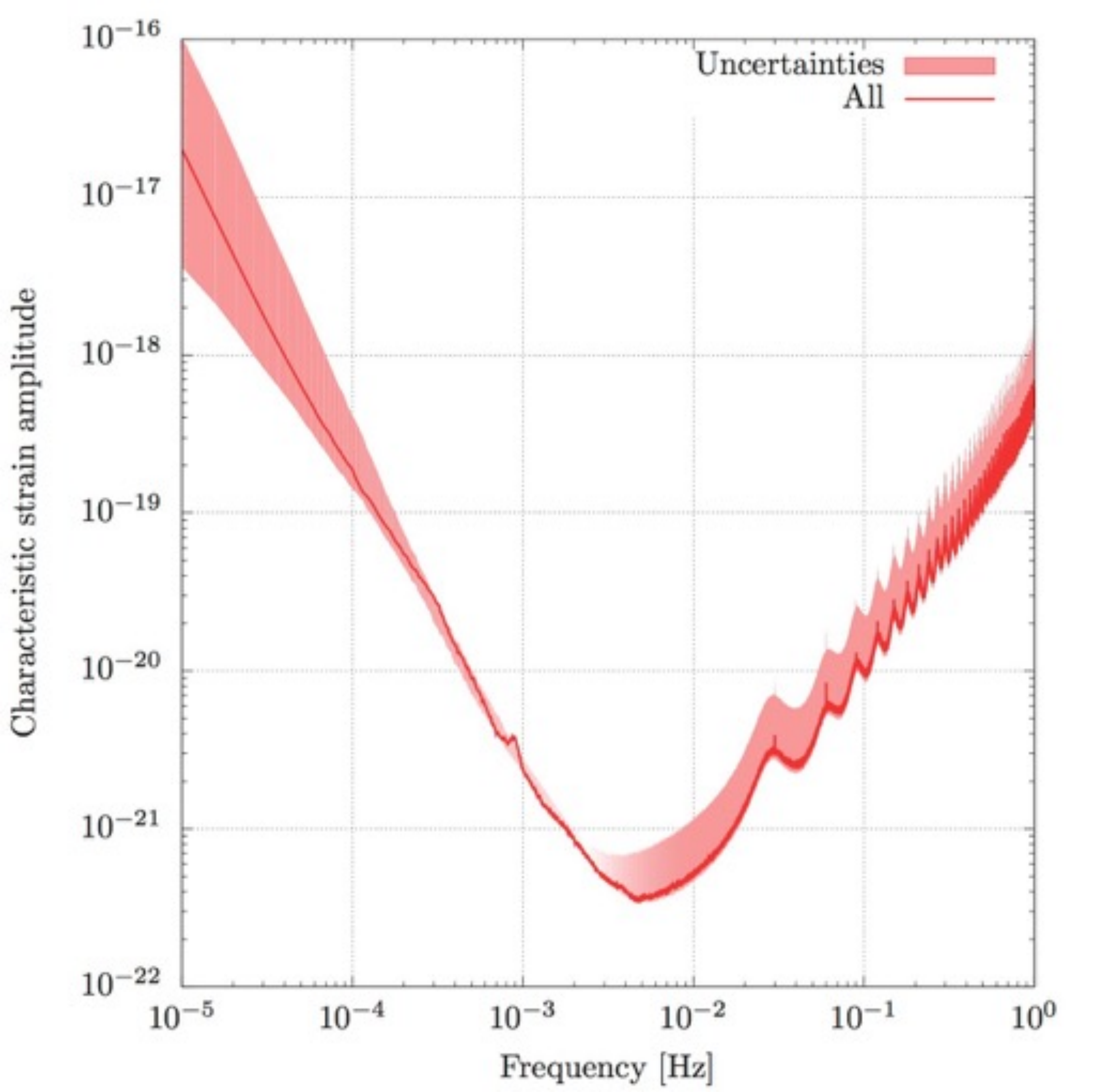

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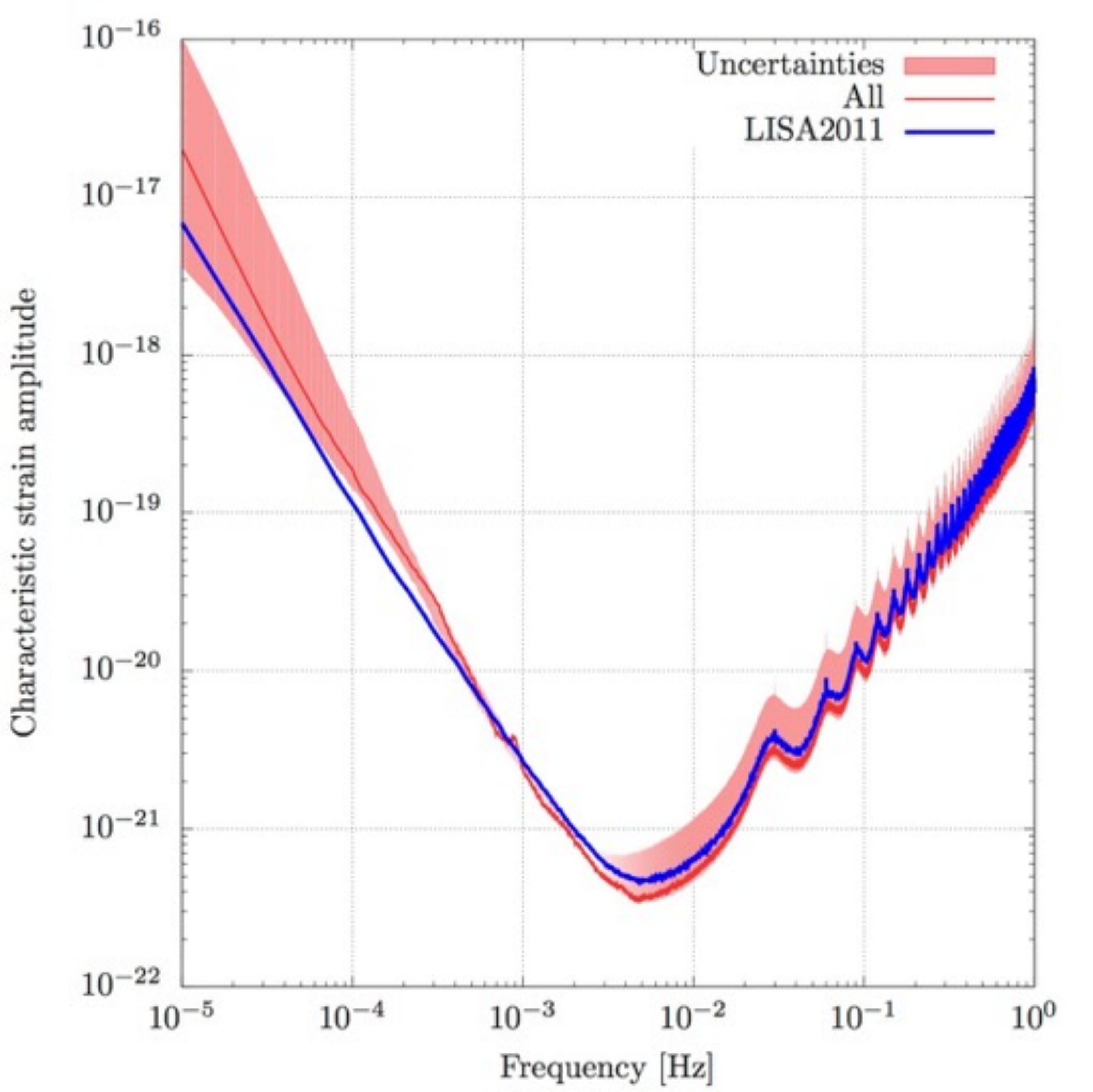

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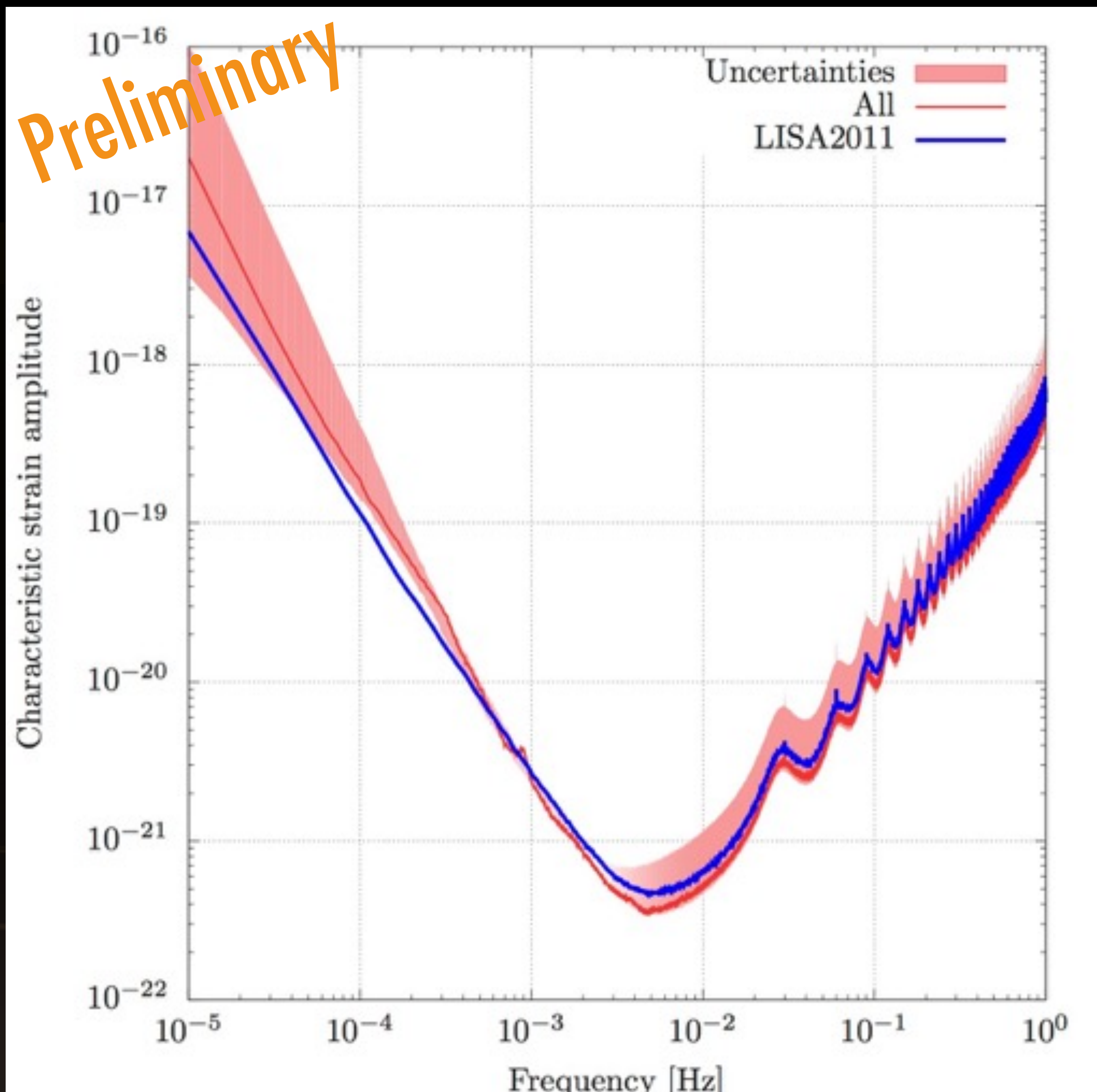

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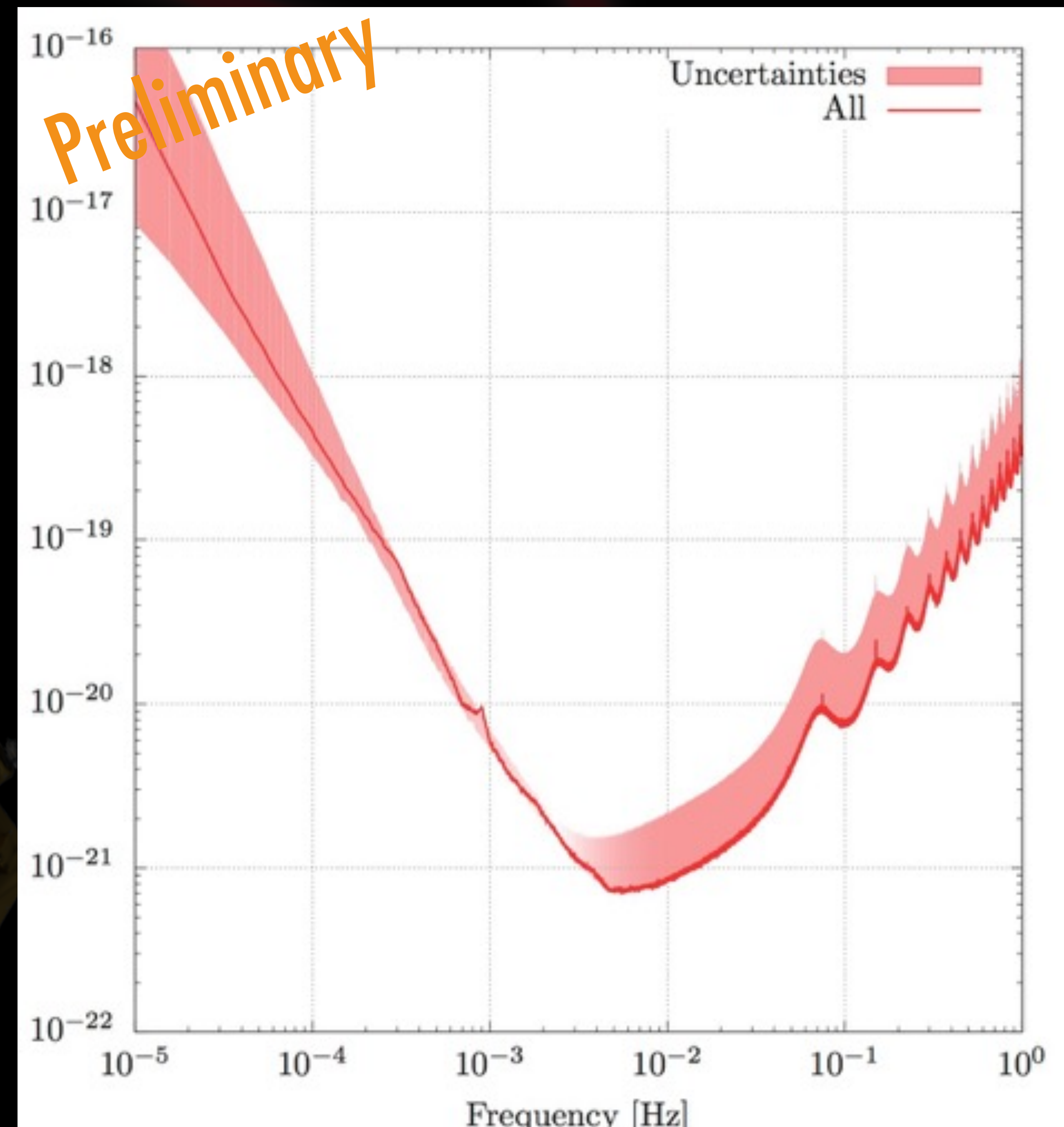
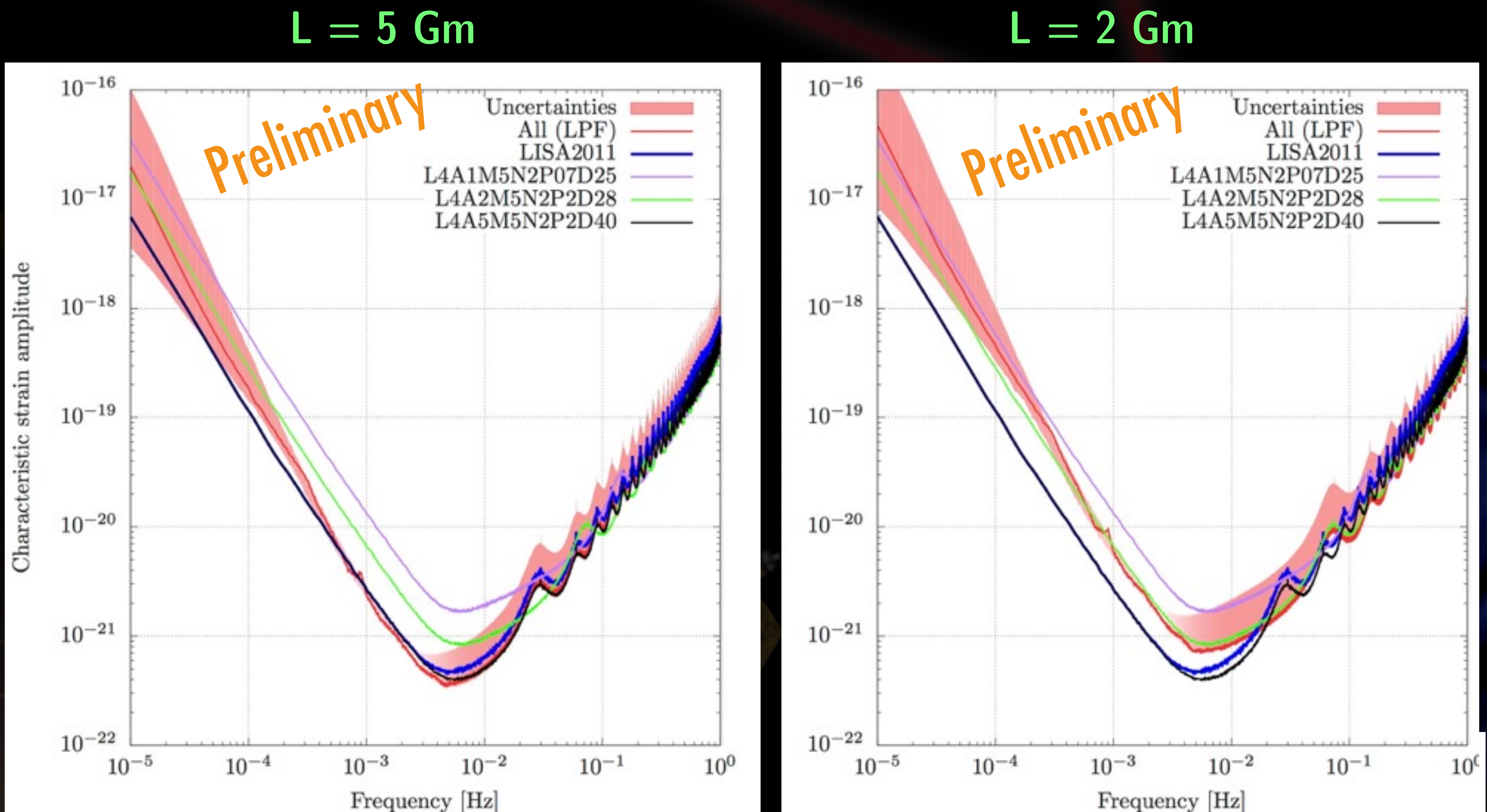


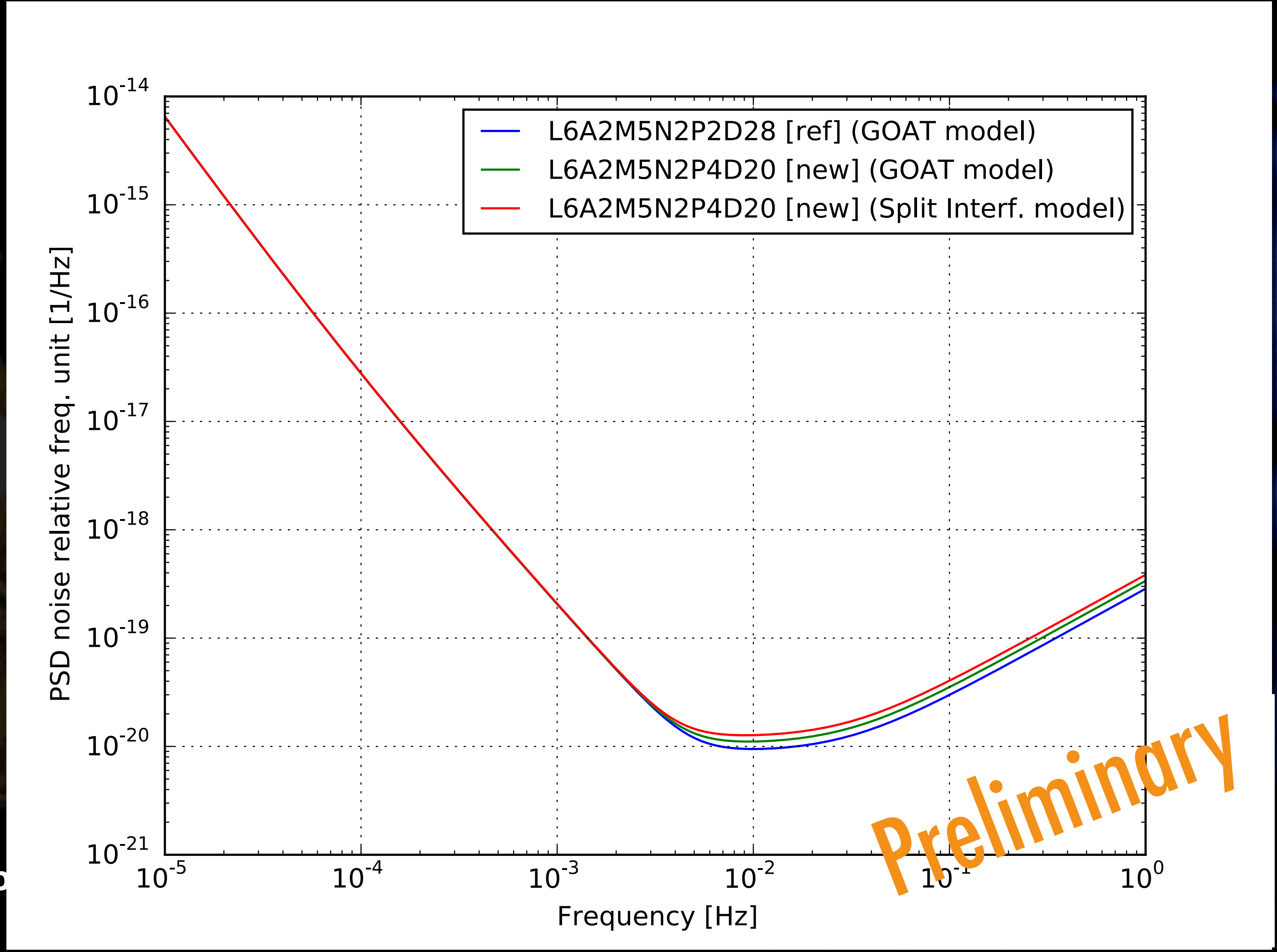
LISA sensitivity with LPF results

- Comparison with GOAT configuration



LISA sensitivity with LPF results

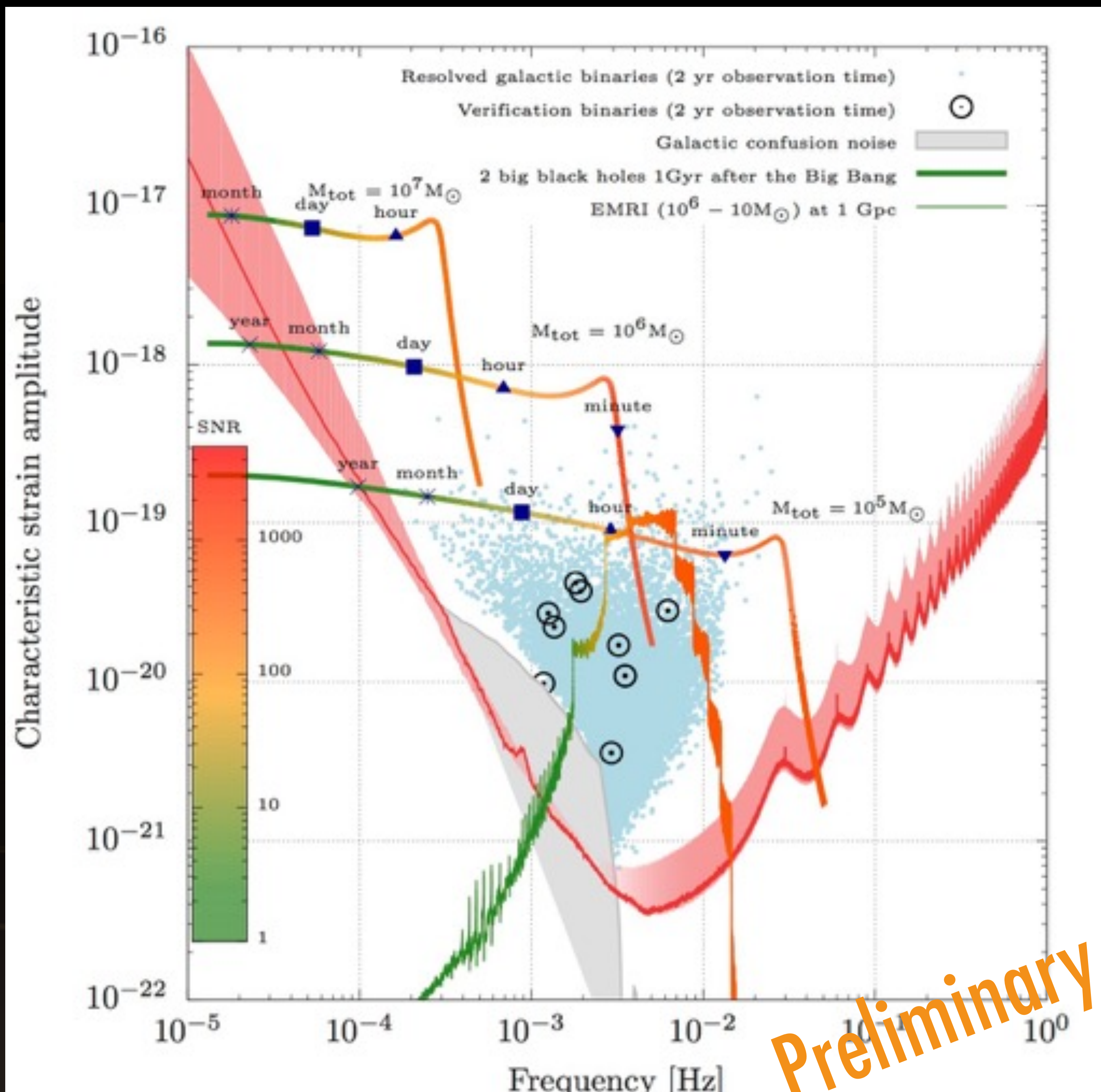
- Configurations in discussion for the response to ESA call (reasonable starting point ?):
  - Telescope: 20 cm, 25 cm, 30 cm, … ?
  - Laser power: 2 W, 3 W, 4 W, … ?
  - Armlength: 2 Gm, 3Gm, … ?
- Maximize the « science » but be sure you can build each item for reasonable cost …



LPF→LISA & usual sources

- Confusion noise from unresolved sources

L = 5 Gm



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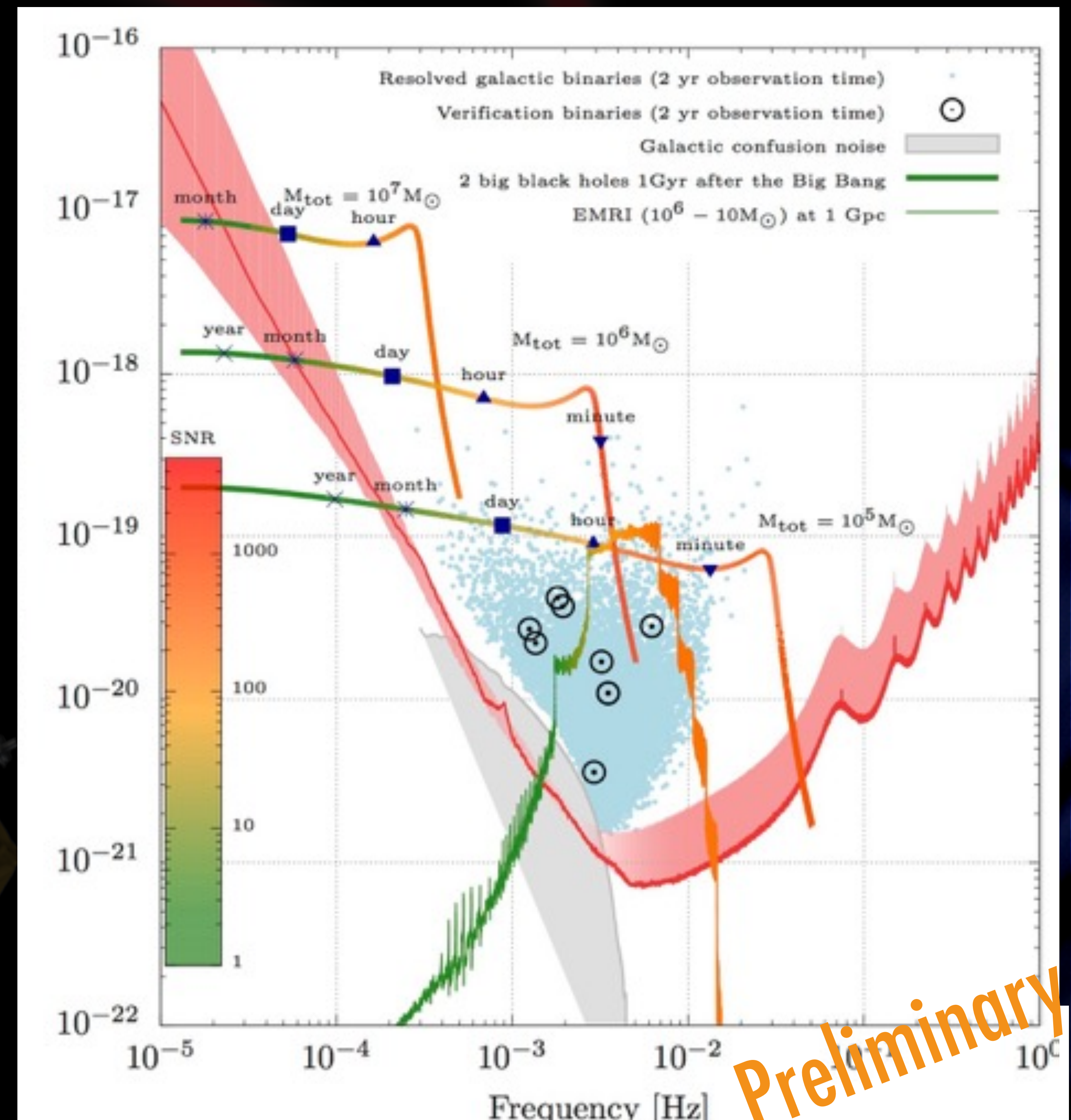
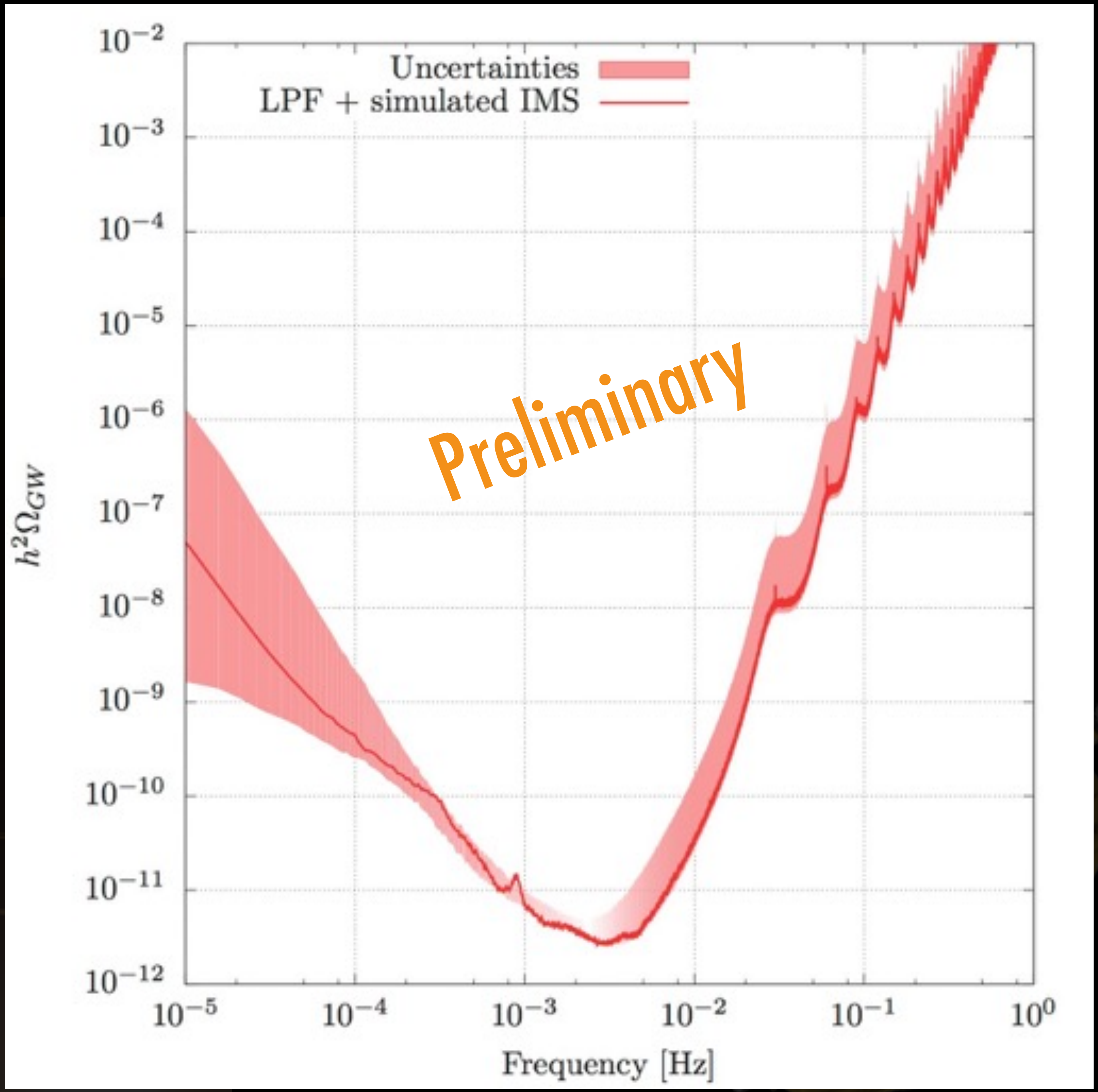


LPF→LISA: Sensitivity

- Sensitivity in energy density LPF-LISA

L = 5 Gm



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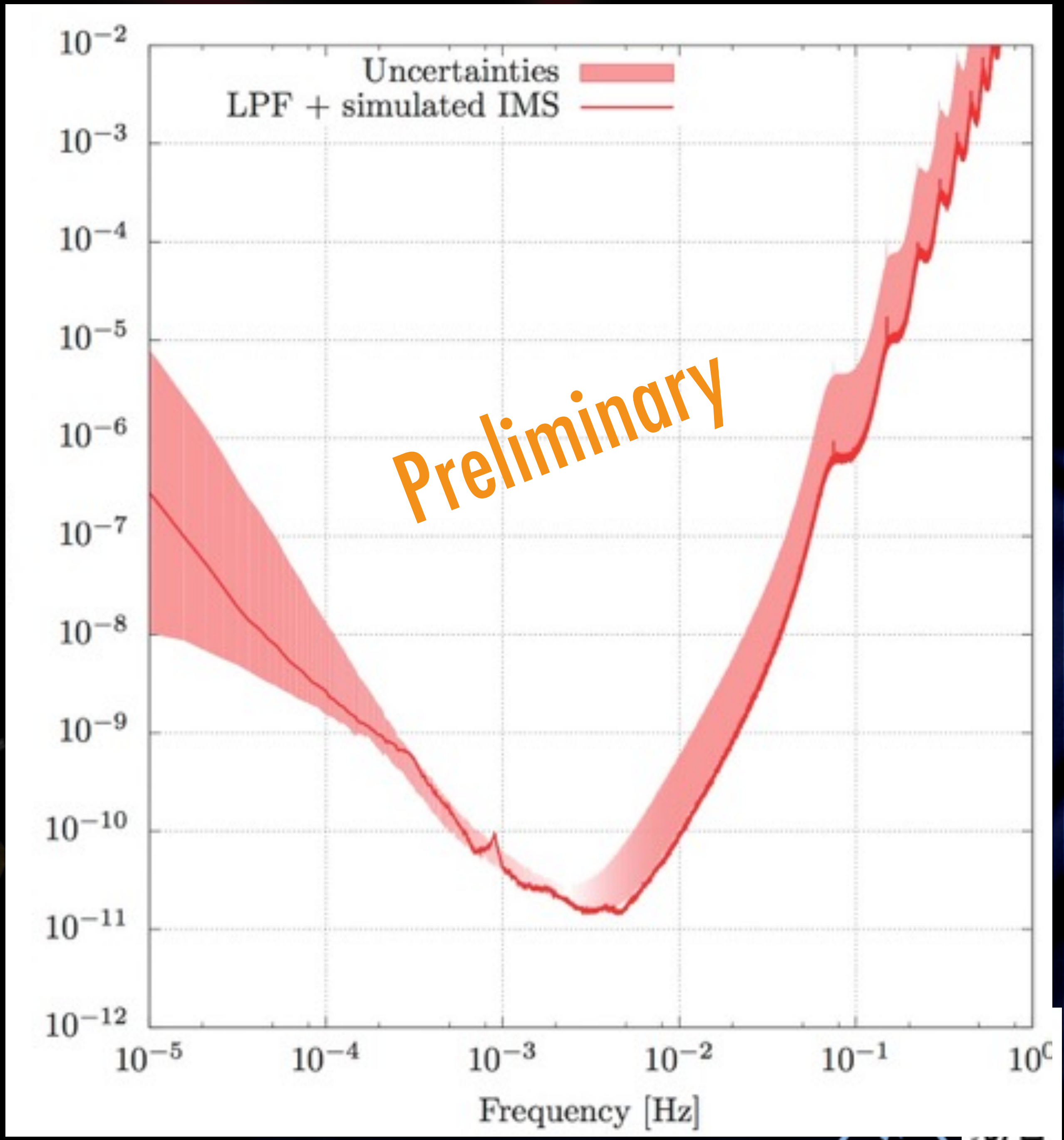

LPF→LISA: Sensitivity

- Sensitivity in energy density LPF-LISA vs GOAT

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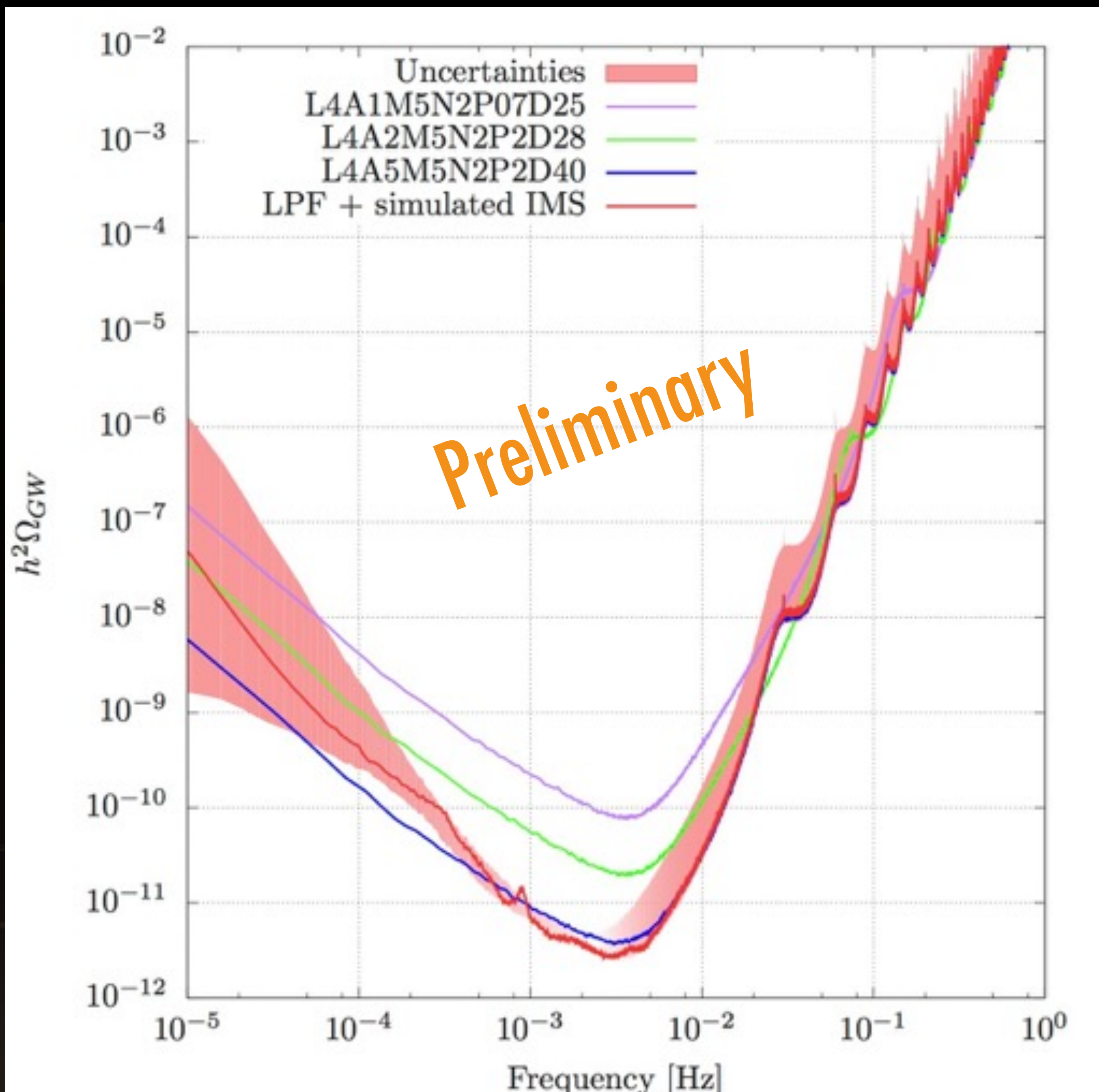

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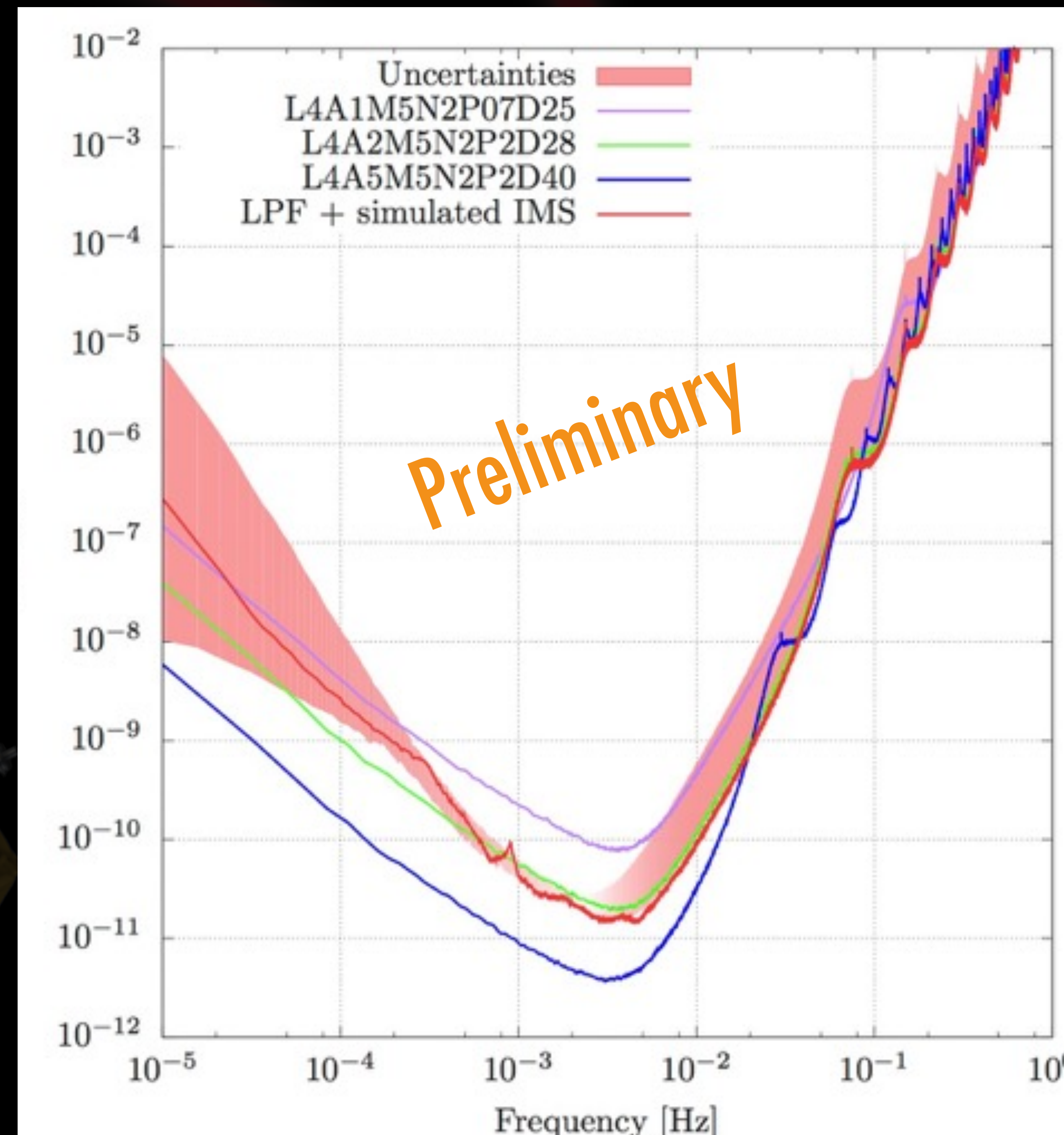
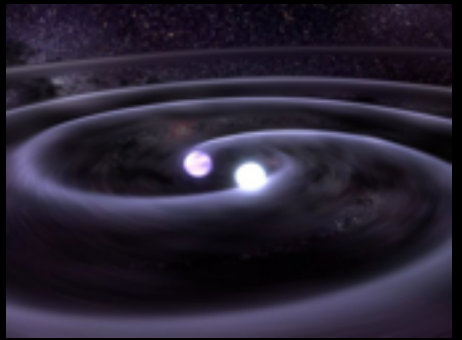


Foregrounds: Galactic binaries

- 60 millions of galactic binaries in the Galaxy:
  - white dwarfs, neutron stars and stellar mass black holes
- About 1000 to 20 000 sources can be detected depending on the LISA configuration.
- The sum of all the unresolved ones for a confusion noise
- Can be partially « removed » because of the particular spatial distribution of the sources (Adams & Cornish 2014)

Foregrounds: Galactic binaries

- Confusion noise from unresolved sources



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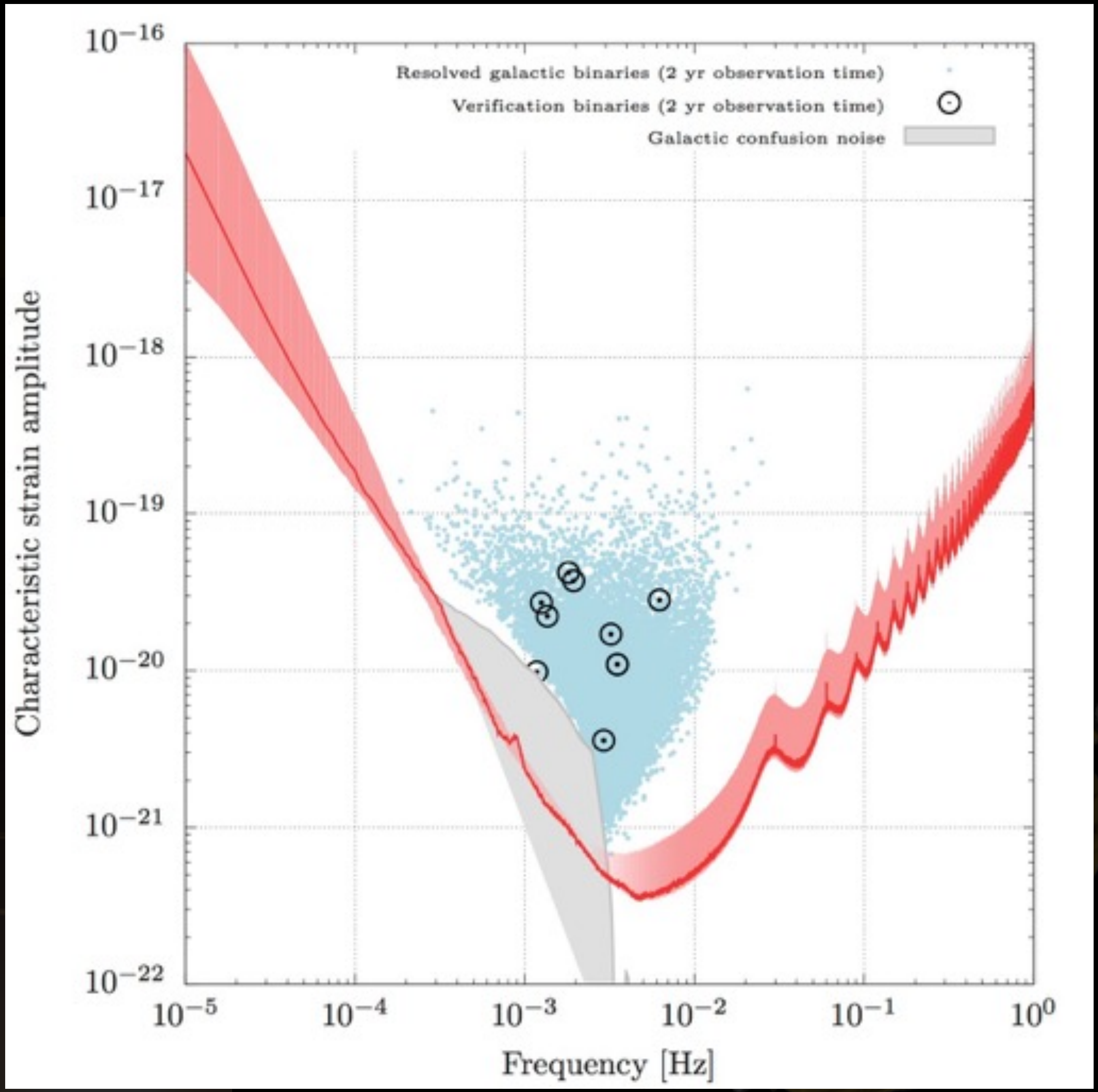

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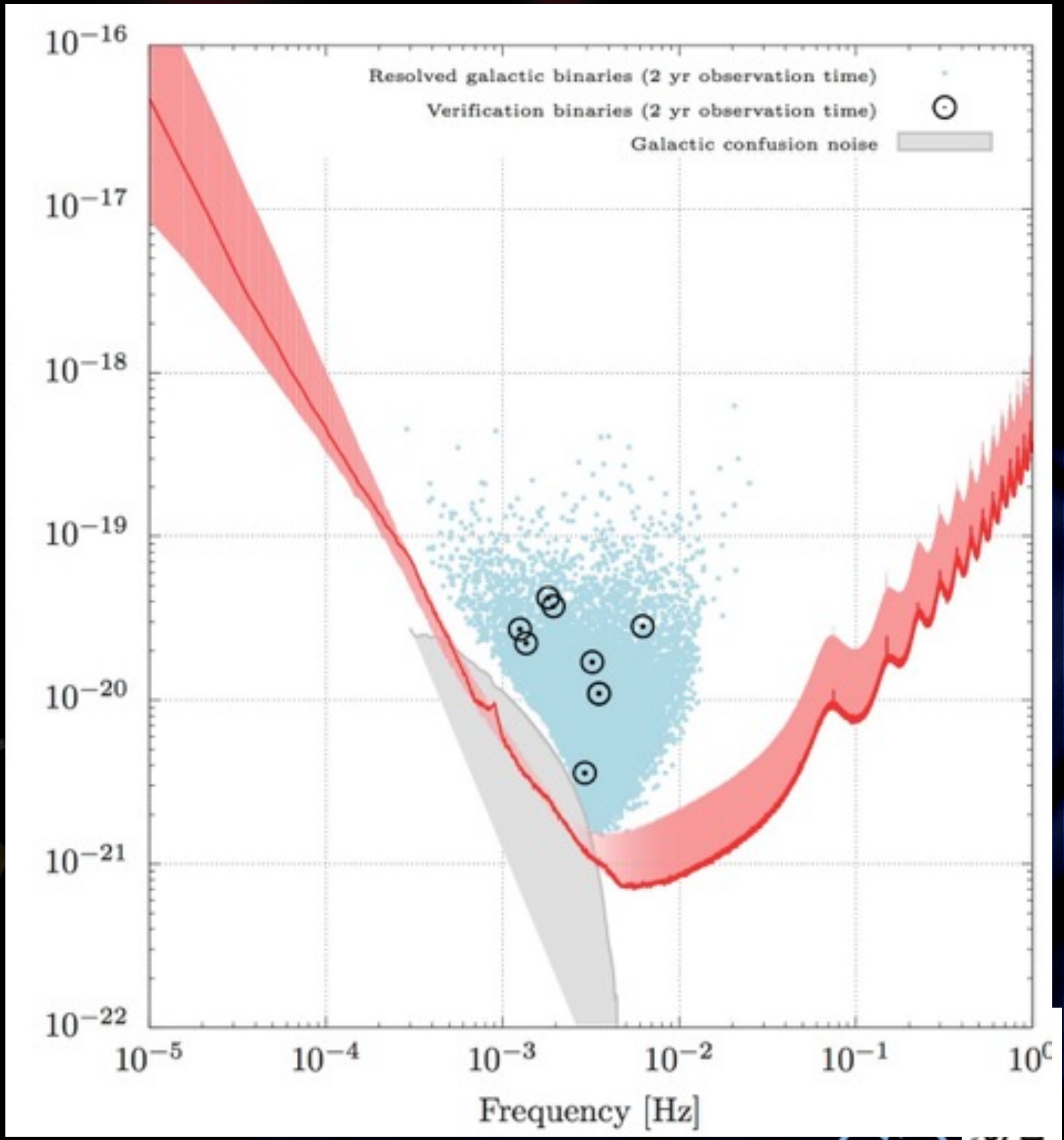
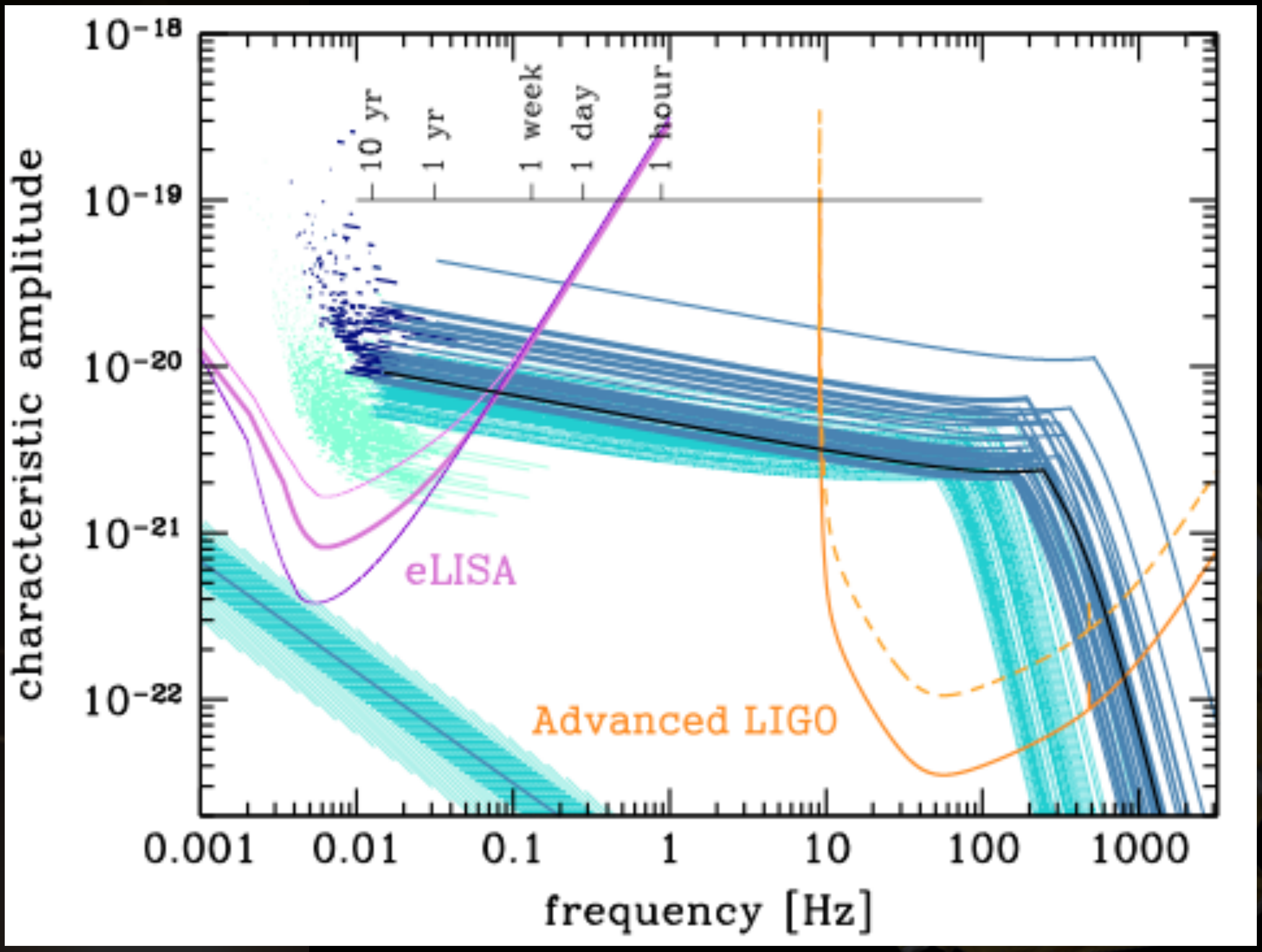
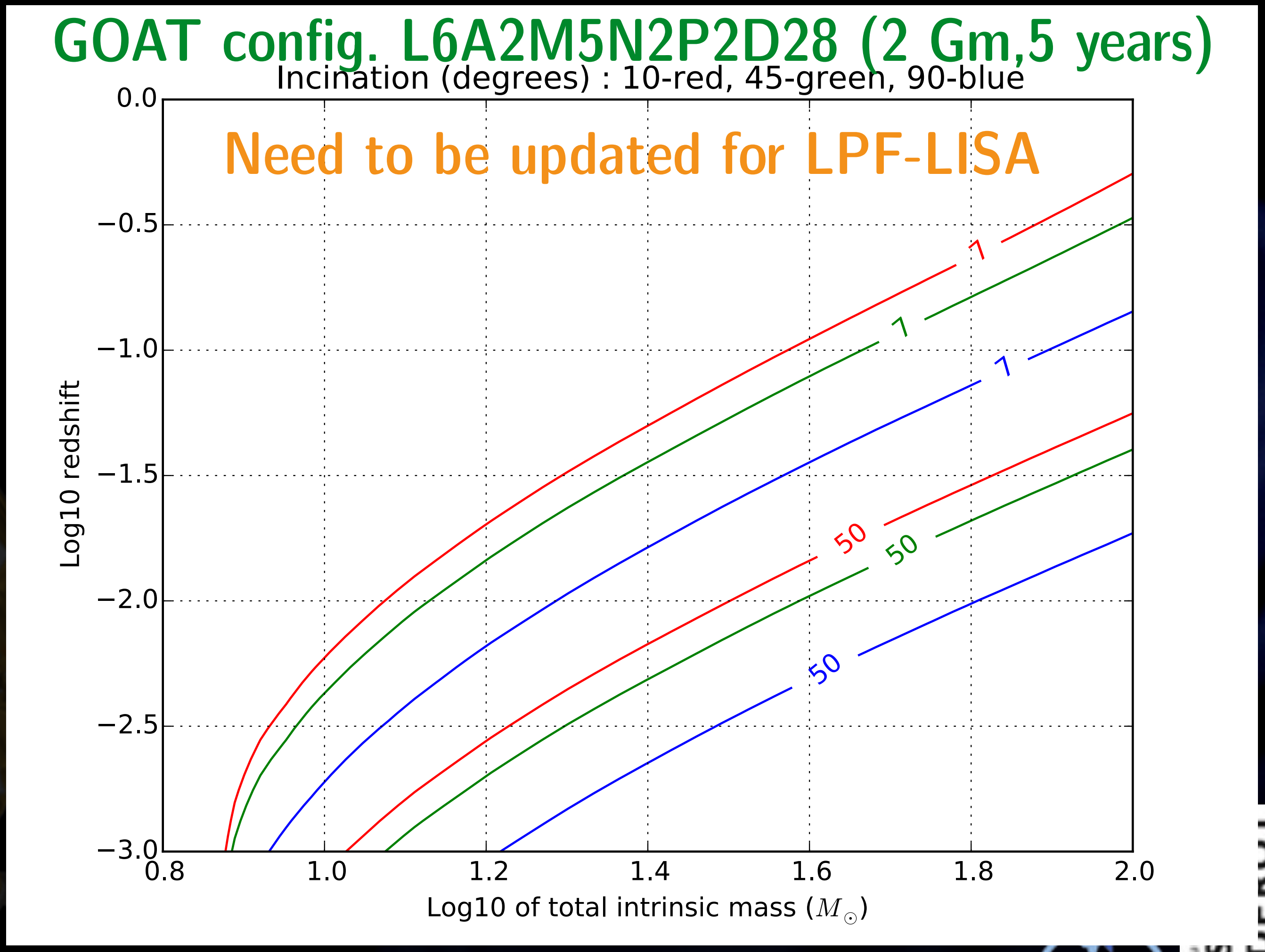


Foregrounds: Black Hole Binaries

- Black hole binaries of few tens solar masses (as GW150914) [Sesana 2016]
- The sum of the unresolved sources could form an isotropic foreground for stochastic background





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Detectability of Stochastic Background

- How to evaluate if a particular stochastic background can be detected ?
- The standard sensitivity not very well adapted because it does not take into account the integration over frequencies and observation time
- One possible estimator: Signal to Noise Ratio (SNR):

$$SNR = \sqrt{T \int_{f_{min}}^{f_{max}} df \frac{(h^2\Omega_{GW}(f))^2}{(h^2\Omega_{Sens}(f))^2}}$$

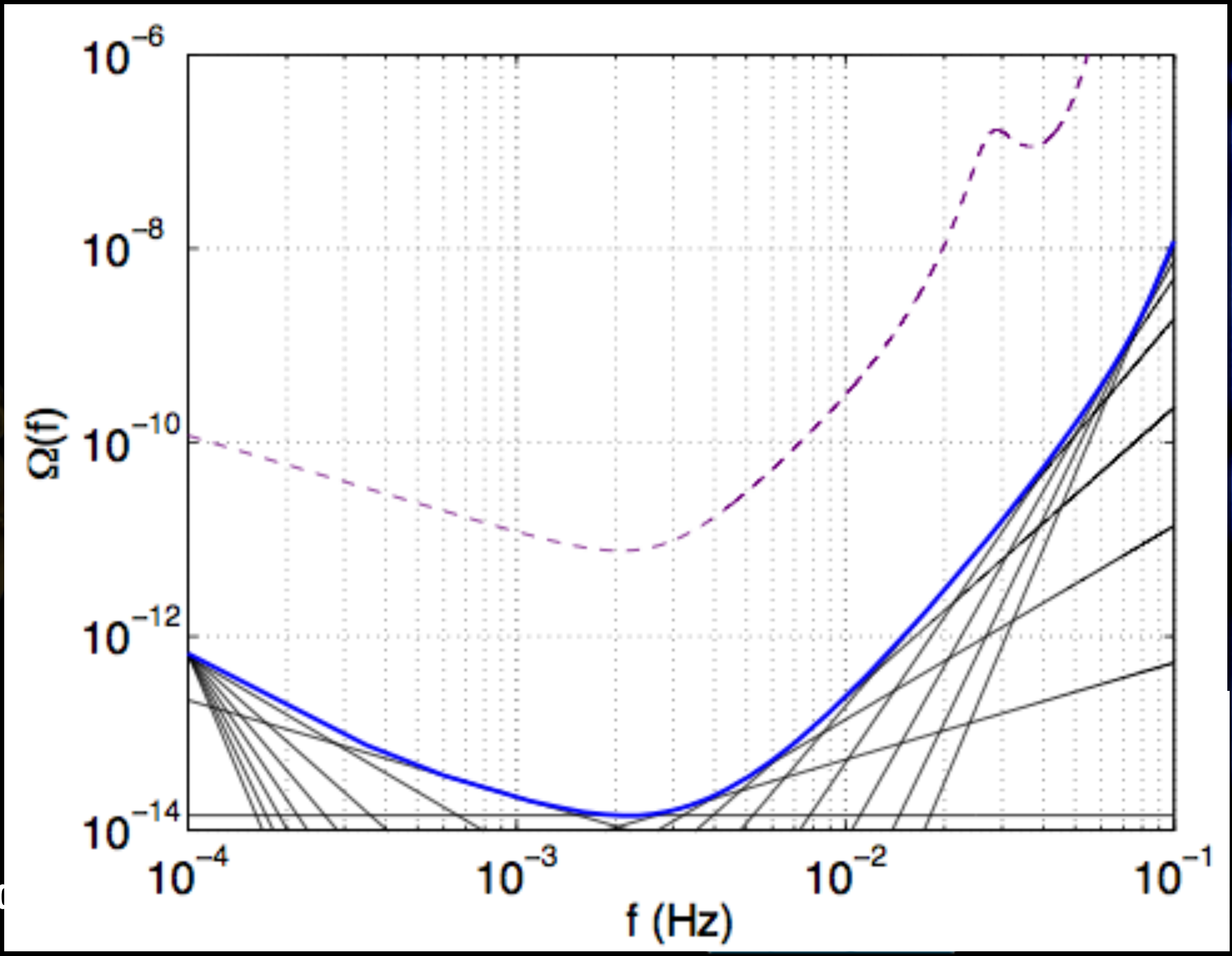
  - If SNR > $SNR_{threshold}$ => detection
  - $SNR_{threshold}$?

Power Law Sensitivity (PLS)

- For an isotropic unpolarized Gaussian stationary stochastic background described by a power law :

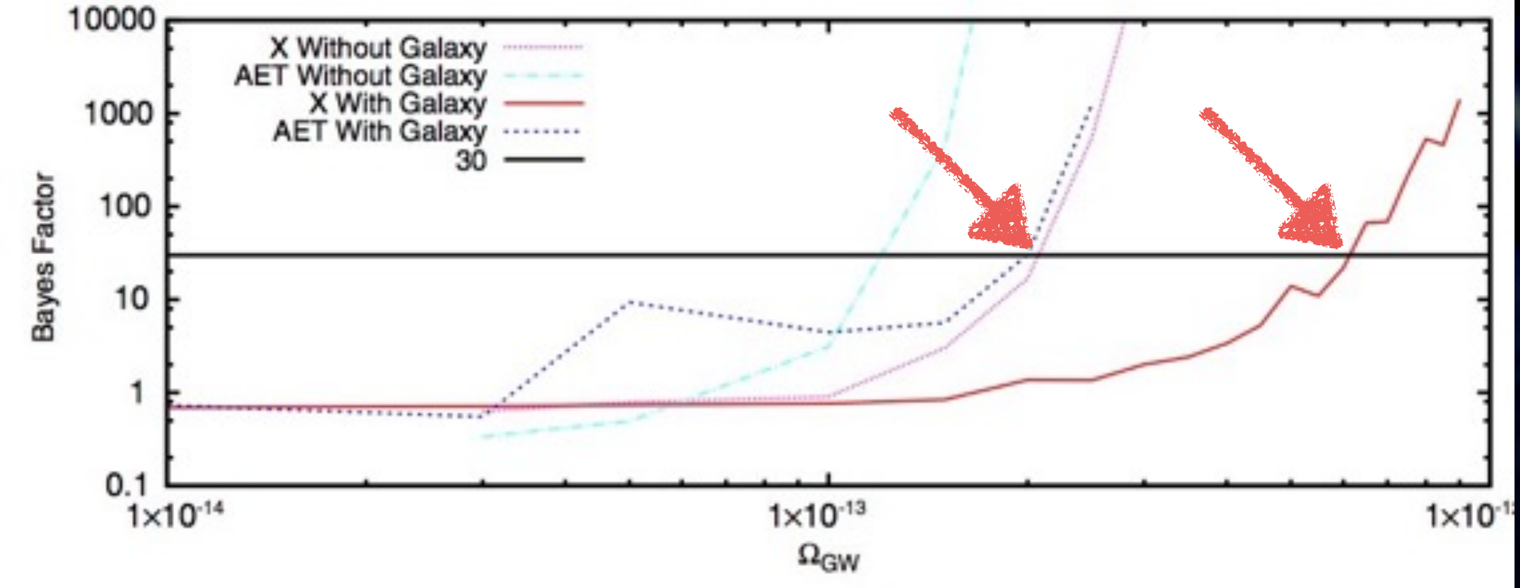
$$h^2\Omega_{GW}(f) = \Omega_\beta \left(\frac{f}{f_{ref}}\right)^\beta$$

- PLS = sensitivity for a given integration time and SNR
- Computed via a scanning of all slopes, finding for each ones the amplitude corresponding to the SNR
- Ex: LISA2011Margin, 1 year
- See Thrane & Romano 2013 for more details



SNR threshold

- How to calibrate the SNR threshold ?
- Results from Adams & Cornish 2014 [see Neil's talk]:
  - Detection of a stochastic background on simulated data taking into account the galactic confusion noise (Bayes factor>30)
  - Minimal detected amplitude:
    - $\Omega_{GW} > 2 \times 10^{-13}$ with 6 links, LISA2011M and 1 year
    - $\Omega_{GW} > 7 \times 10^{-13}$ with 4 links, LISA2011M and 1 year



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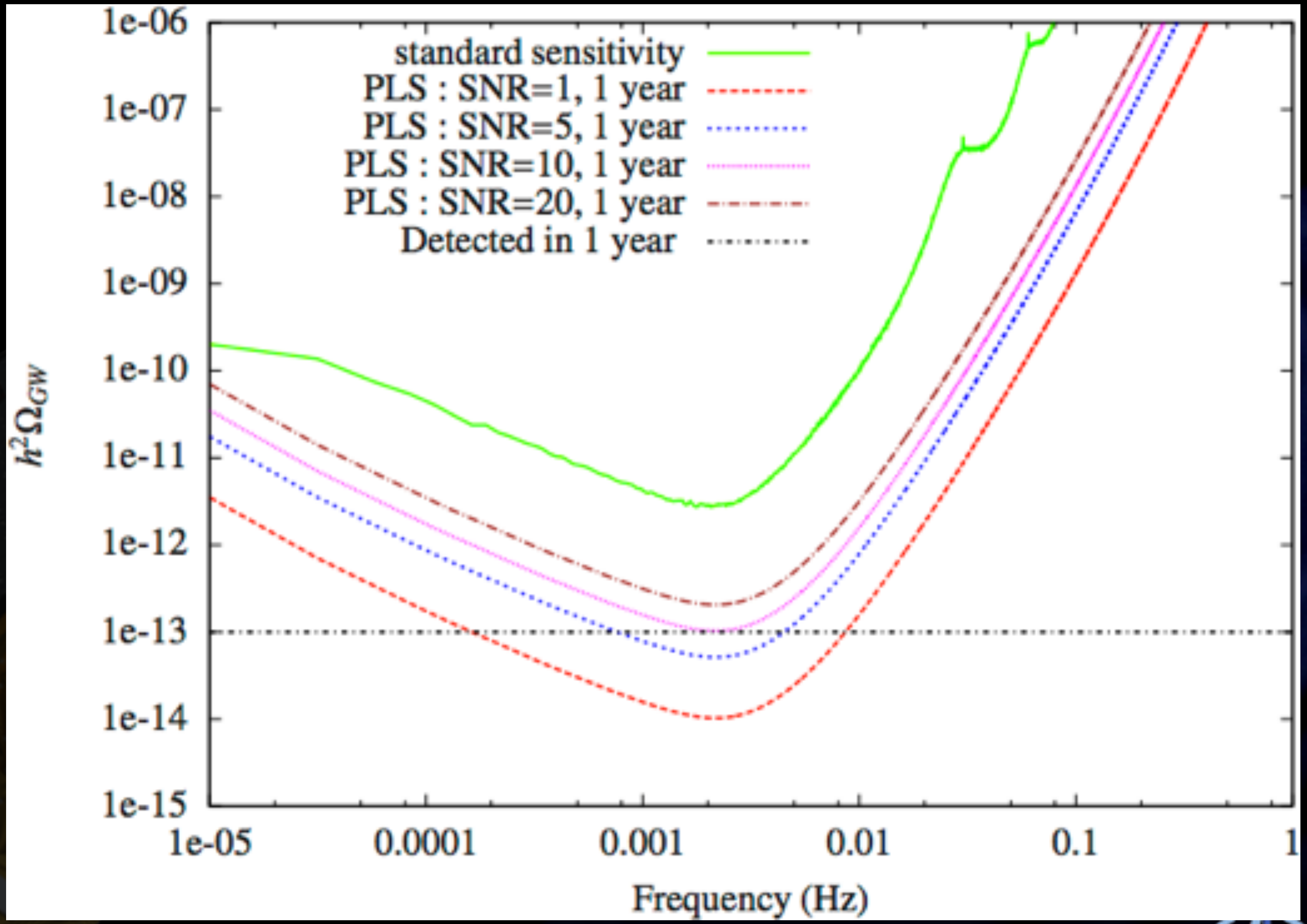
Sensitivity & SNR: 6 links

- Adams & Cornish: with LISA in one year detection of $\Omega_{GW} > 2 \times 10^{-13} \Rightarrow h^2 \Omega_{GW} > 1 \times 10^{-13}$
- Seems to be a safe results because with 3 arms we can "have" spectral shape informations using cross-correlation
- Power Law Sensitivity:

$SNR_{threshold} = 10$



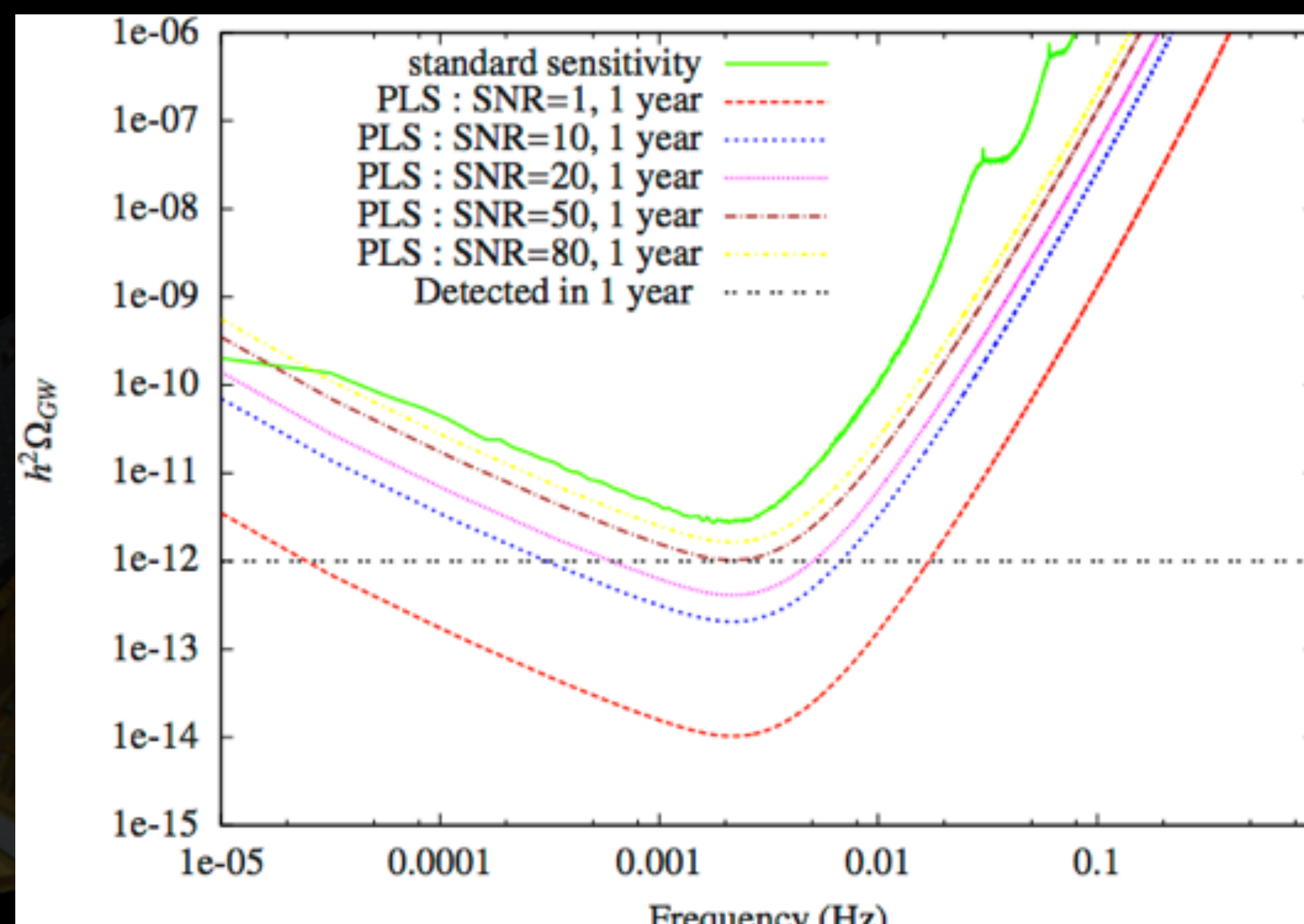
Sensitivity & SNR: 4 links

- Adams & Cornish: with LISA in one year detection of $\Omega_{GW} > 7 \times 10^{-13} \Rightarrow h^2\,\Omega_{GW} > 3.5 \times 10^{-13}$
- BUT we need some spectral informations !
- Raw estimation: more degrees of freedom in the fit:
  - GW bkgd: x 2
  - Noises: x $\sqrt{2}$

  => raw estimation:

  $h^2\,\Omega_{GW} > 10^{-12}$

$SNR_{threshold} = 50$



Power Law Sensitivity (PLS)

- For LPF→LISA

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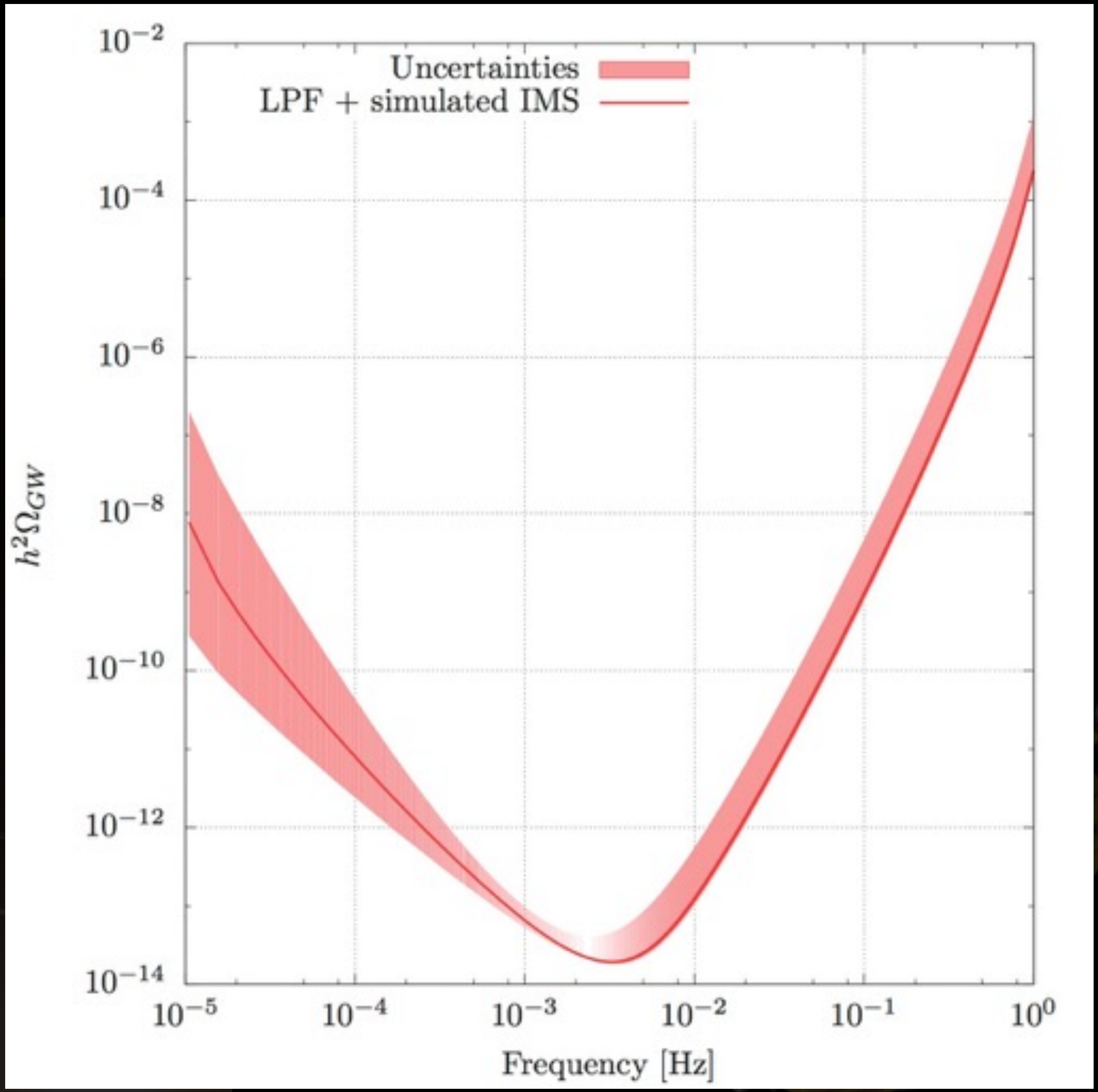

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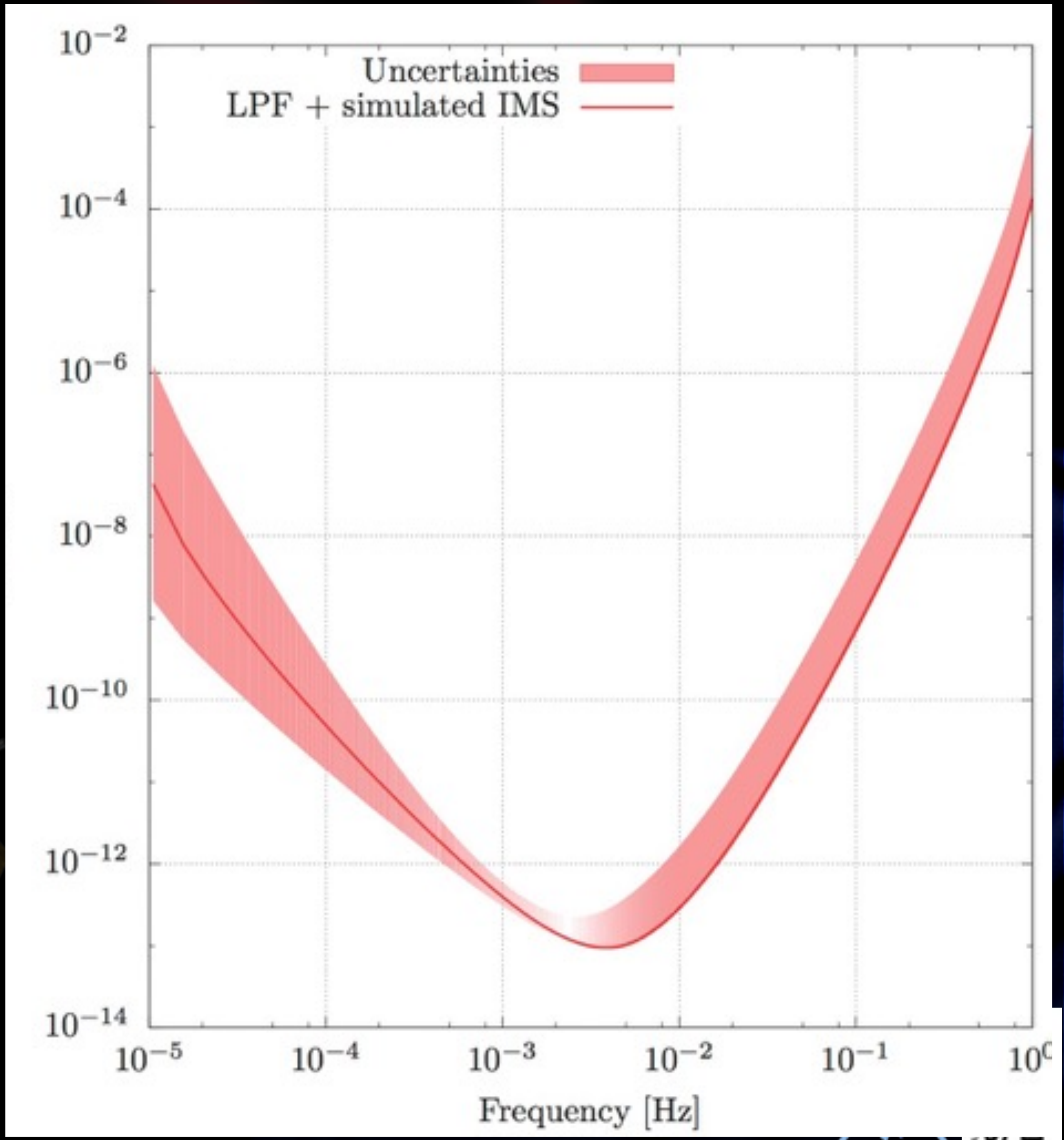

Power Law Sensitivity (PLS)

- For LPF→LISA and GOAT configurations

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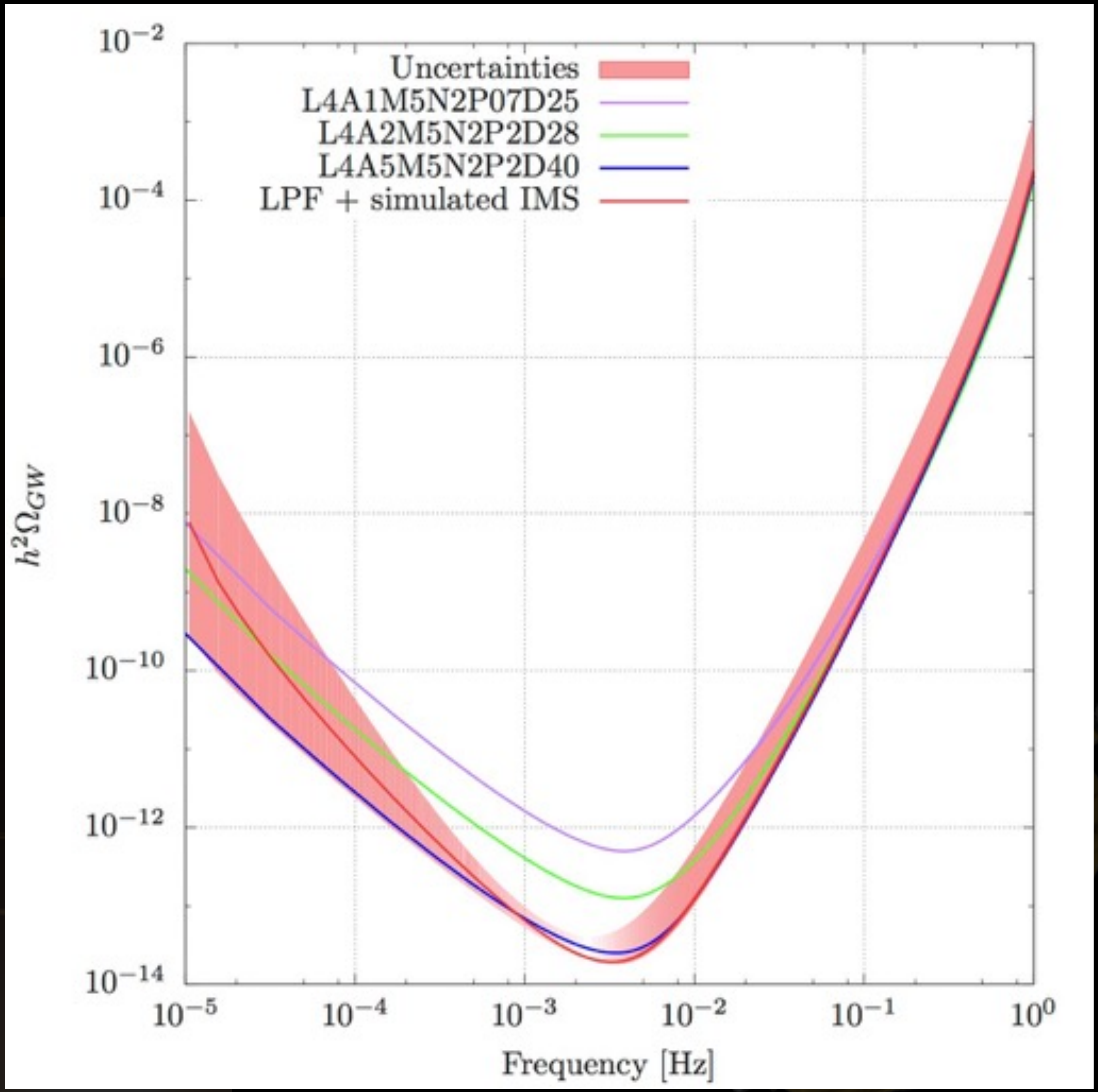

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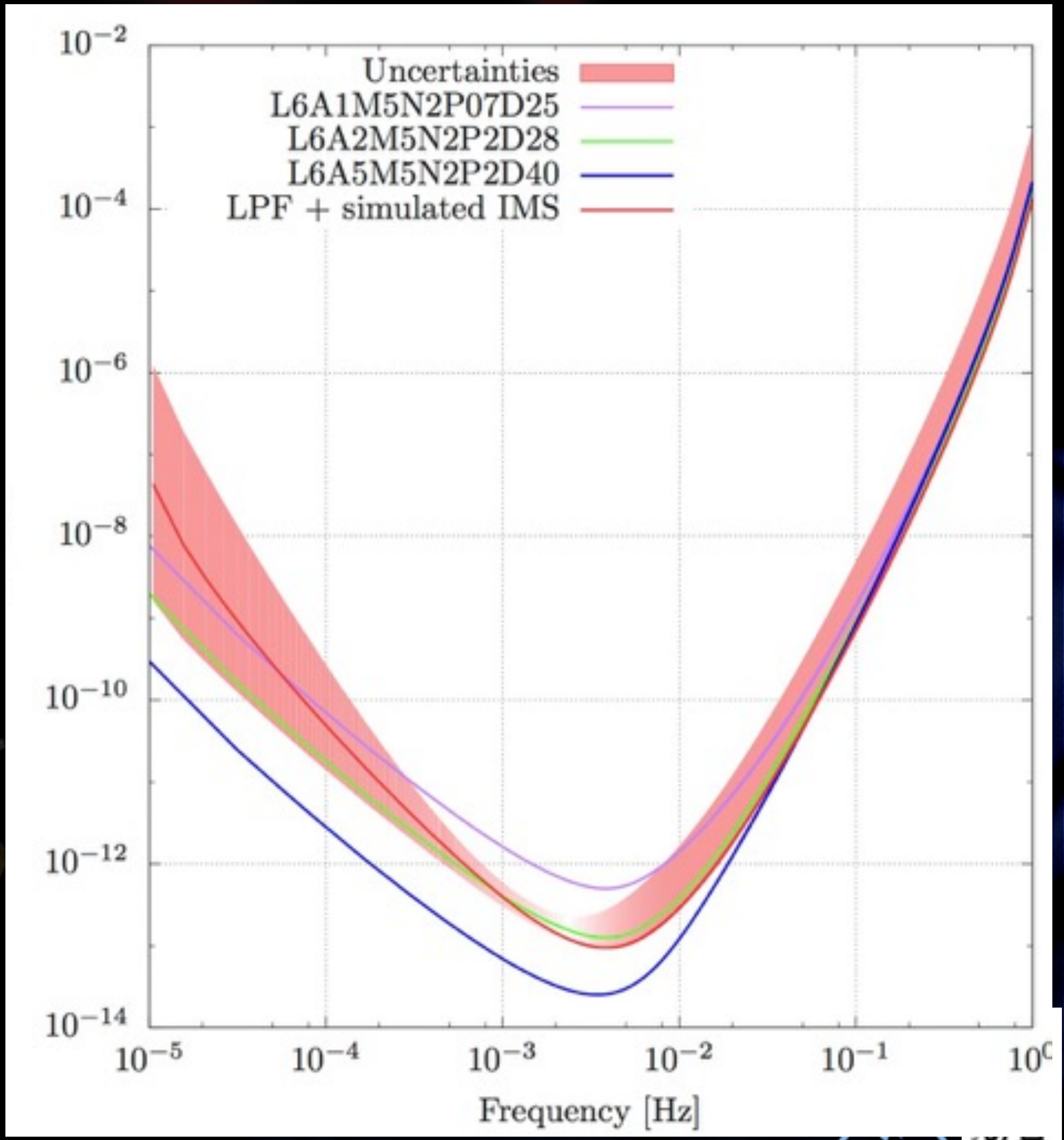
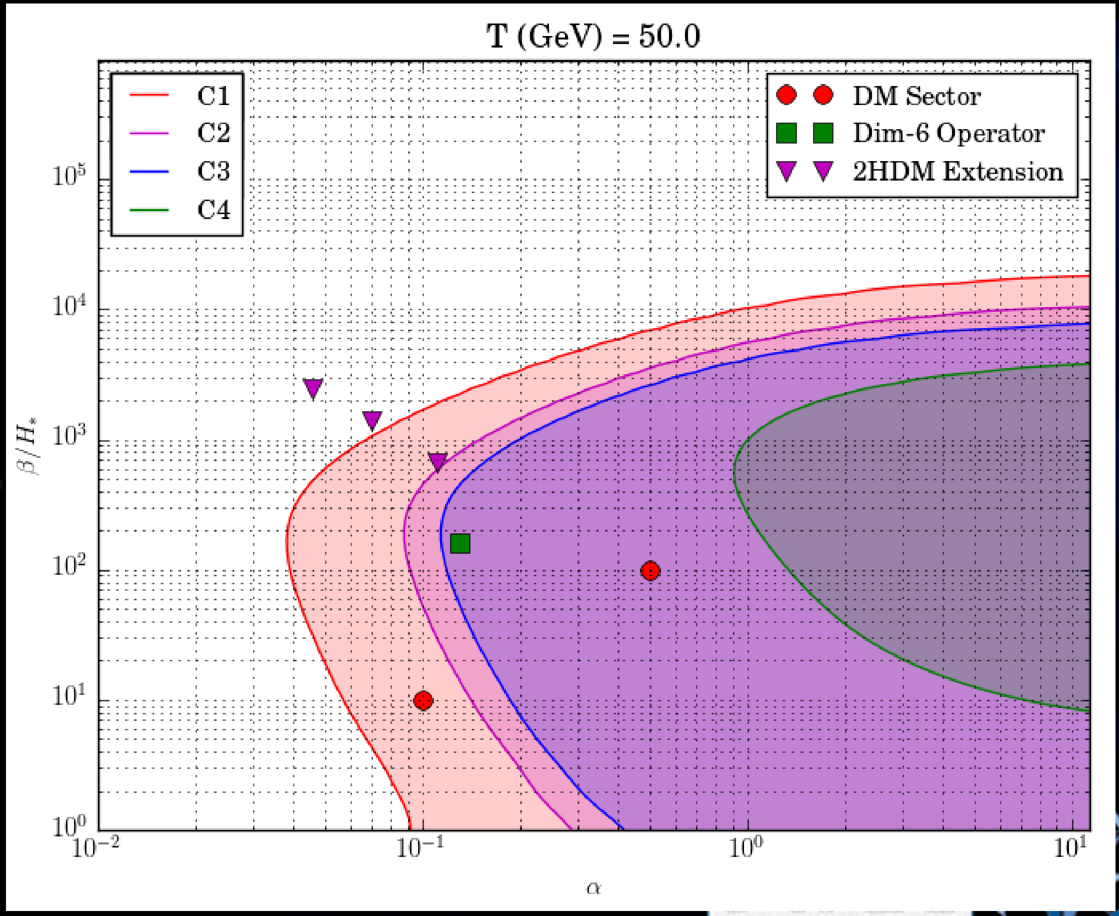


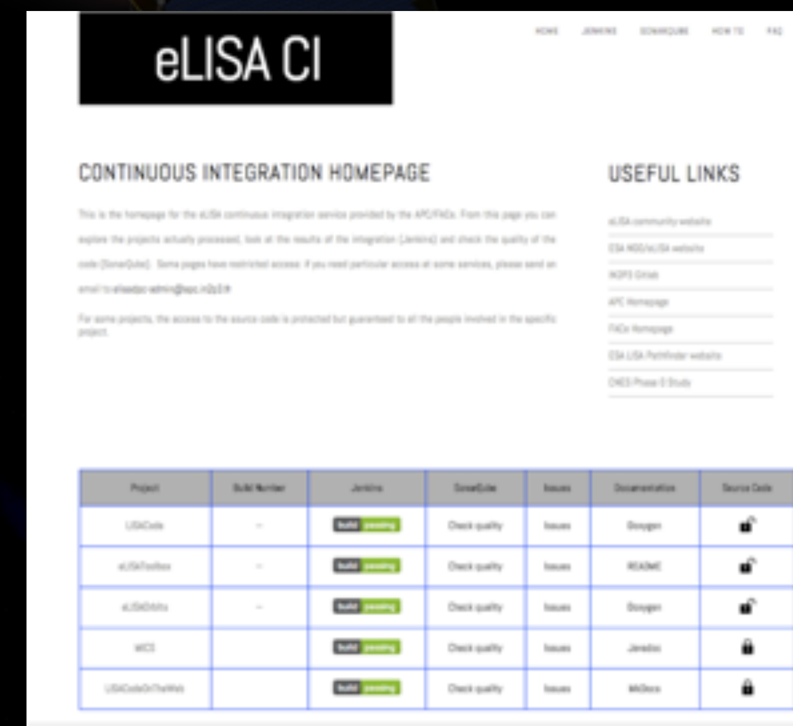
Estimation of detectability

- Given a stochastic background depending on parameters $\Omega_{GW}(f, p_0, p_1, p_2, \ldots)$,
- We compute the SNR for a given configuration & observation time
- The part of the parameter with SNR>SNRthreshold can be detected.
- Already used in Caprini et al. JCAP 04, 001 (2016)

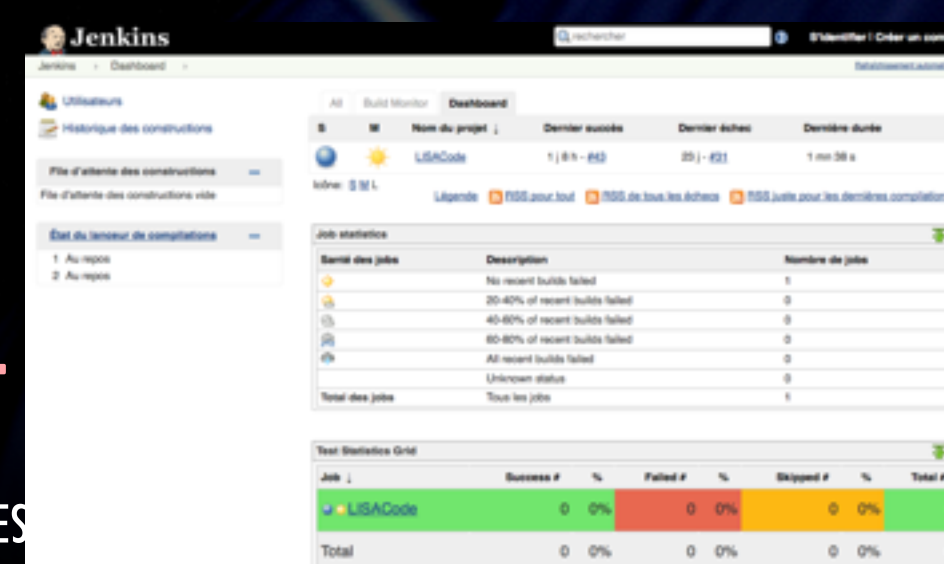


The proto Data Processing Center

- Development started after a CNES phase 0 study
- Tool for the consortium
- DPC: https://elisadpc.in2p3.fr/home/index.php
  - Continuous integration: compilation, quality evaluation, doc., virtual machine for user, …
  - Hybrid infrastructure (regular cluster + cloud) to absorb fluctuations of computation charge.
  - Database
  - Documentation ? Web-service ?



- The proto-DPC is the framework for eLISA simulations & for future MLDC …



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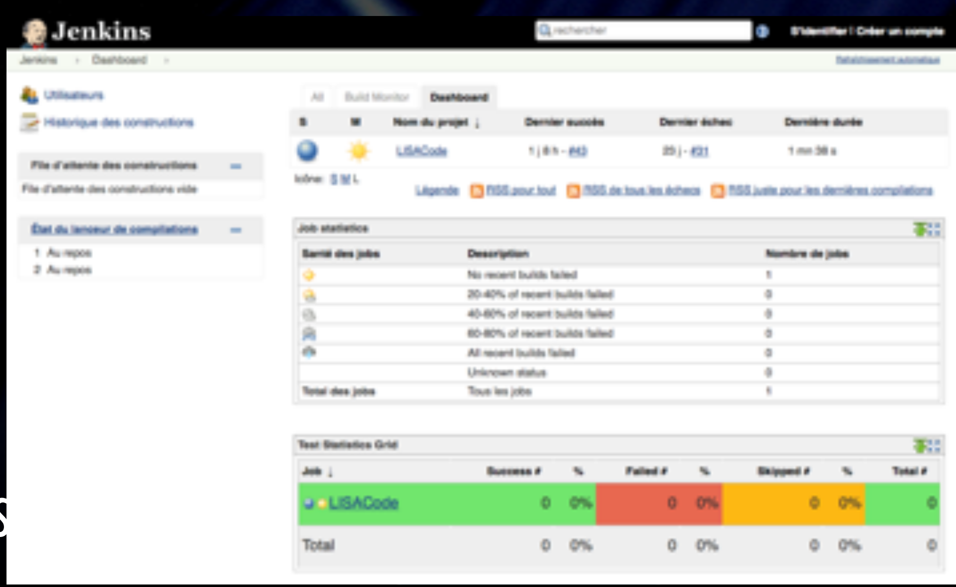


Tools in the LISA DPC

- Several project managed by a continuous integration system:
  - eLISAToolBox:
    - Compute LISA noise budget [LISANoise.py]
    - SNR and plot for a given stochastic background (file) [SNRStochBackground.py]
    - Make contour plot for parametrized stochastic background [PlotContour.py]
    - ...
  - Simulator ...
  - Others tools:
    - LISACommon, LISAOrbits, docker for LISA, ...

Next steps

- Stochastic backgrounds:
  - Polarized background ? Anisotropic background ? Non-gaussian background ?
- Simulation: more realistic data ...

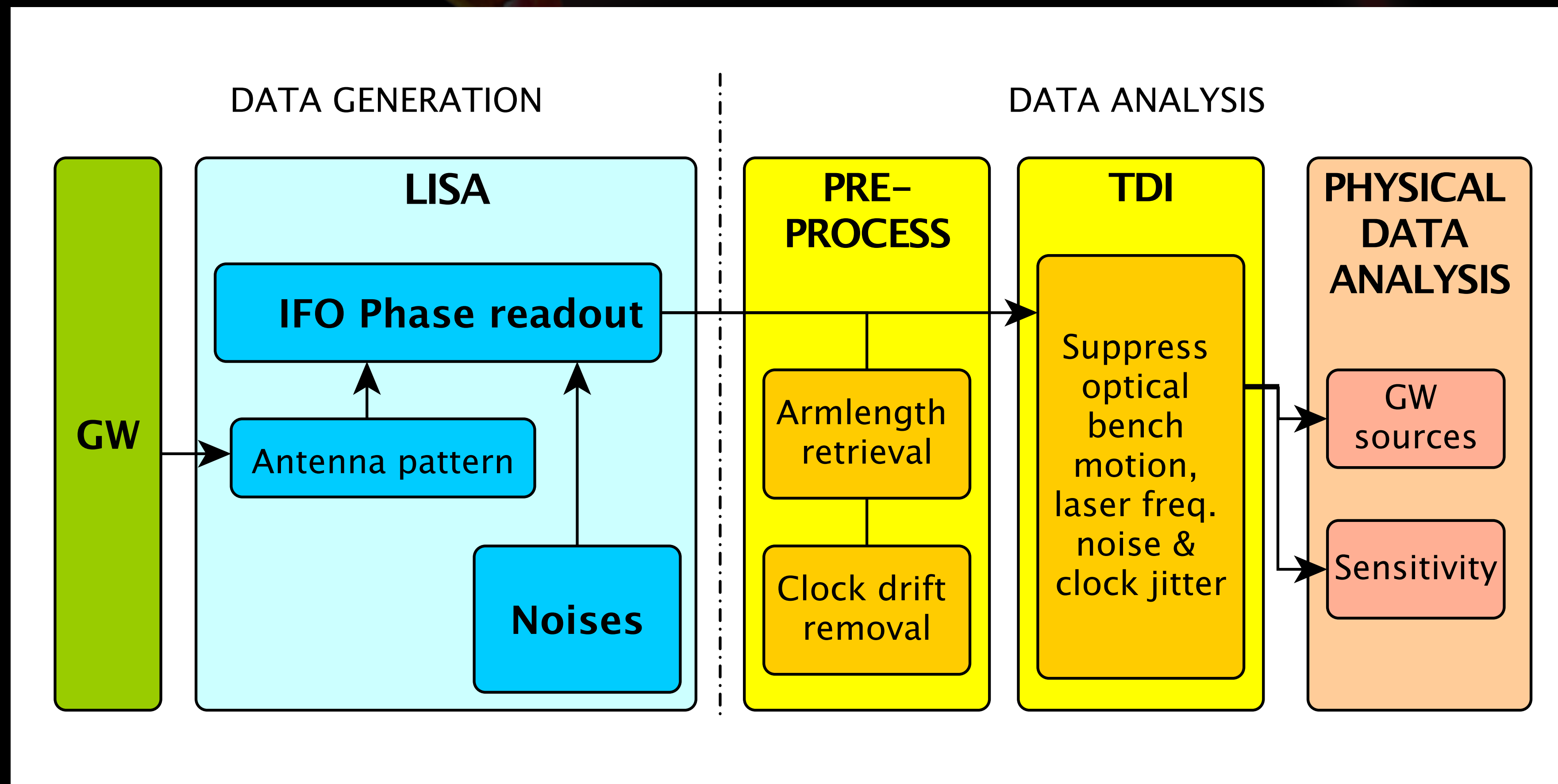
The Simulation Working Group

- About 20 scientists from various European laboratories
- Diversity of expertises:
  - LISAPathfinder
  - LISA instrumentation
  - GW waveform modeling
  - Data analysis
  - Astrophysics
- Led by APC (Paris) and AEI (Hannover)
- Start using LISACode as a basis
- Very active group. You are welcome to join !

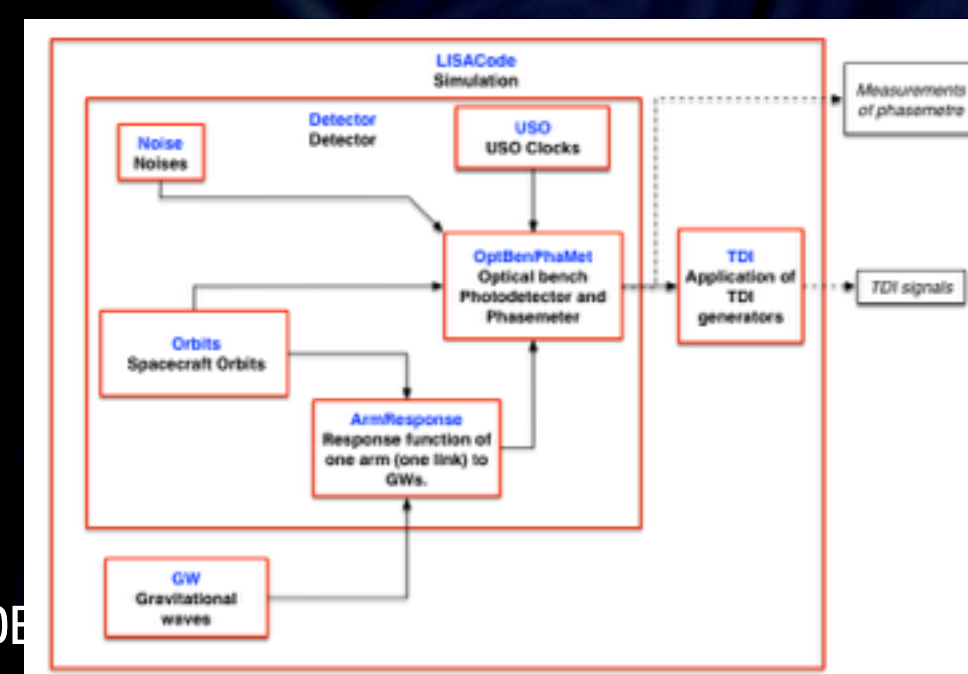
The Simulation Working Group

- **Goals**:
  - End-to-end simulation → the mission simulator
  - "Quick performance" study for various configurations → final design (required for phase A)
  - Accompany the hardware developments (industries & labs.)
  - Tool(s) for performance controls
- **First requirements**:
  - Close modeling of the instrument subsystems
  - Waveform generation for various GW sources
  - Noise generation using various types of representation
  - Data pre-processing (distinct from simulation)
  - Modularity
  - Computation speed (> 10-100 times faster than reality)
  - Open-source

LISA Simulation



- LISACode is the starting point of the end to end simulator
- 2 complementary simulators:
  - TDISim (check TDI)
  - LISADyn (3D dynamic)



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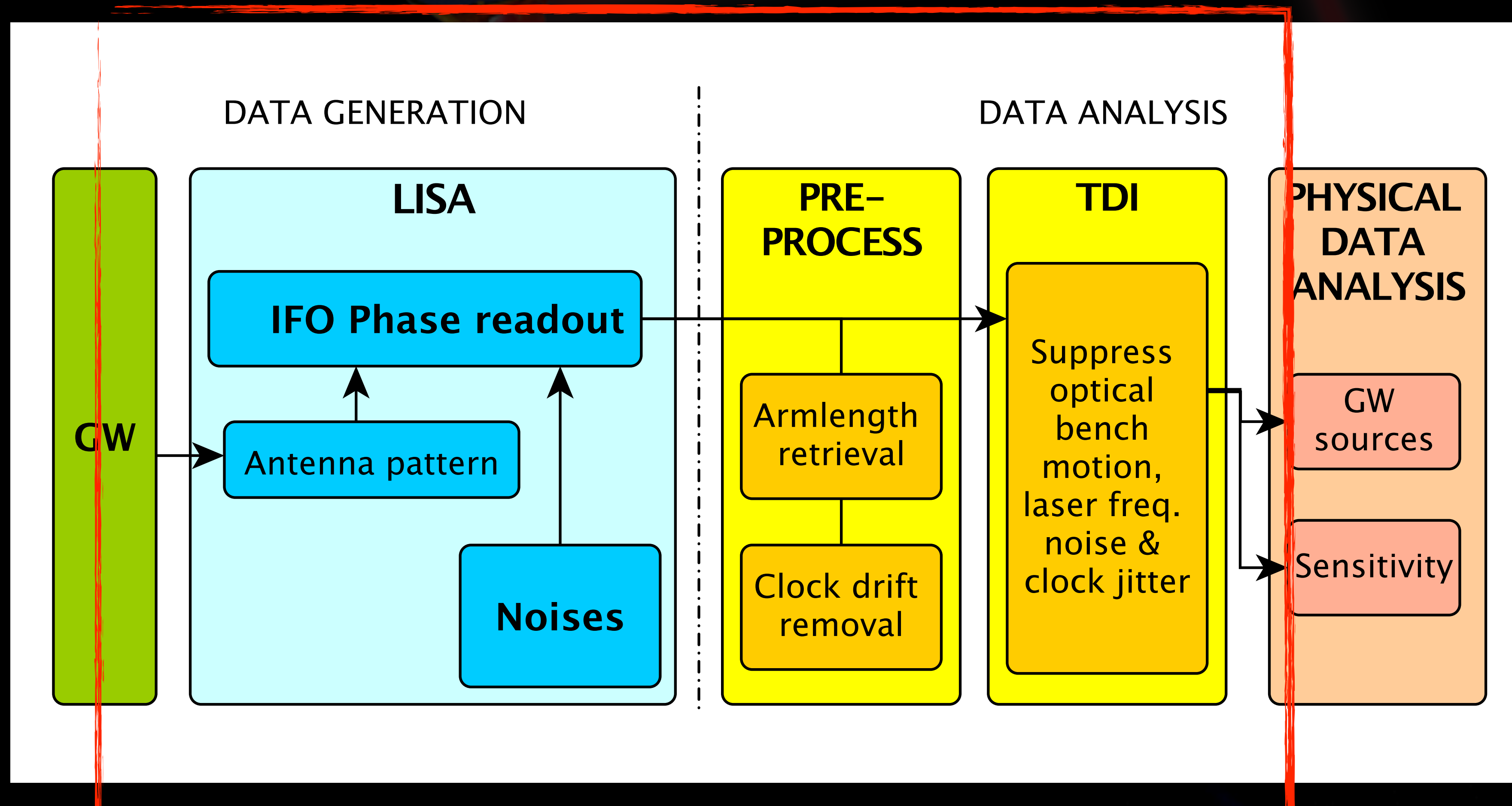

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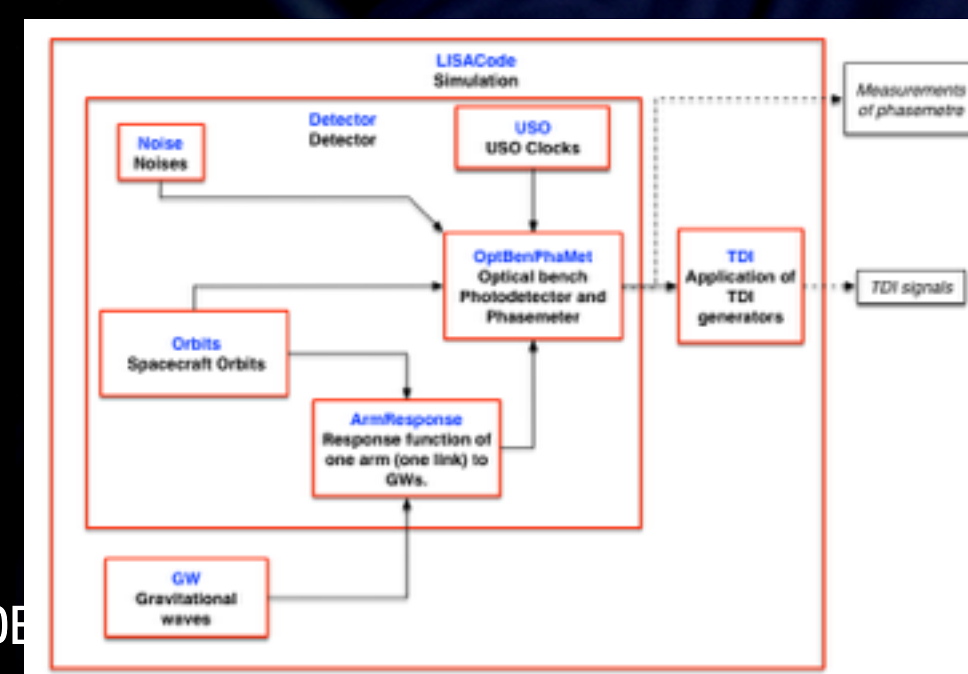
  - TDISim (check TDI)
  - LISADyn (3D dynamic)



Next steps

- **Stochastic backgrounds**:
  - Polarized background ? Anisotropic background ? Non-gaussian background ?
- **Simulation**: more realistic data ...
  - Instrument simulation: work in progress ...
  - Simulation of stochastic background: current implementation similar to the MLDC one: 192 sources of GW noise distributed on sky. Implement new type of stochastic background ?
  - Better modeling of foregrounds:
    - Improved/updated Galactic binaries confusion noise
    - « Confusion noise » from few tens solar masses binaries

Next steps

- **Data analysis:**
  - Restart MLDCs making use of the LISA DPC framework:
    - More realistic sources all together + simplified noises
    - More realistic instrument modeling + simplified sources
  - Implement (or re-implement or just collect) data analysis pipelines for stochastic background
  - Make the exercices of applying them on simulated data

  => Improve or understanding of background detectability

  => Provide easy-to-use tools for estimating the detectability of any stochastic background

Thank you