LISA science performance in the context of LISAPathfinder first results and simulation for LISA

Antoine Petiteau

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On behalf of the LISAPathfinder collaboration

& the simulation working group

LISASymposium 11 - Zurich

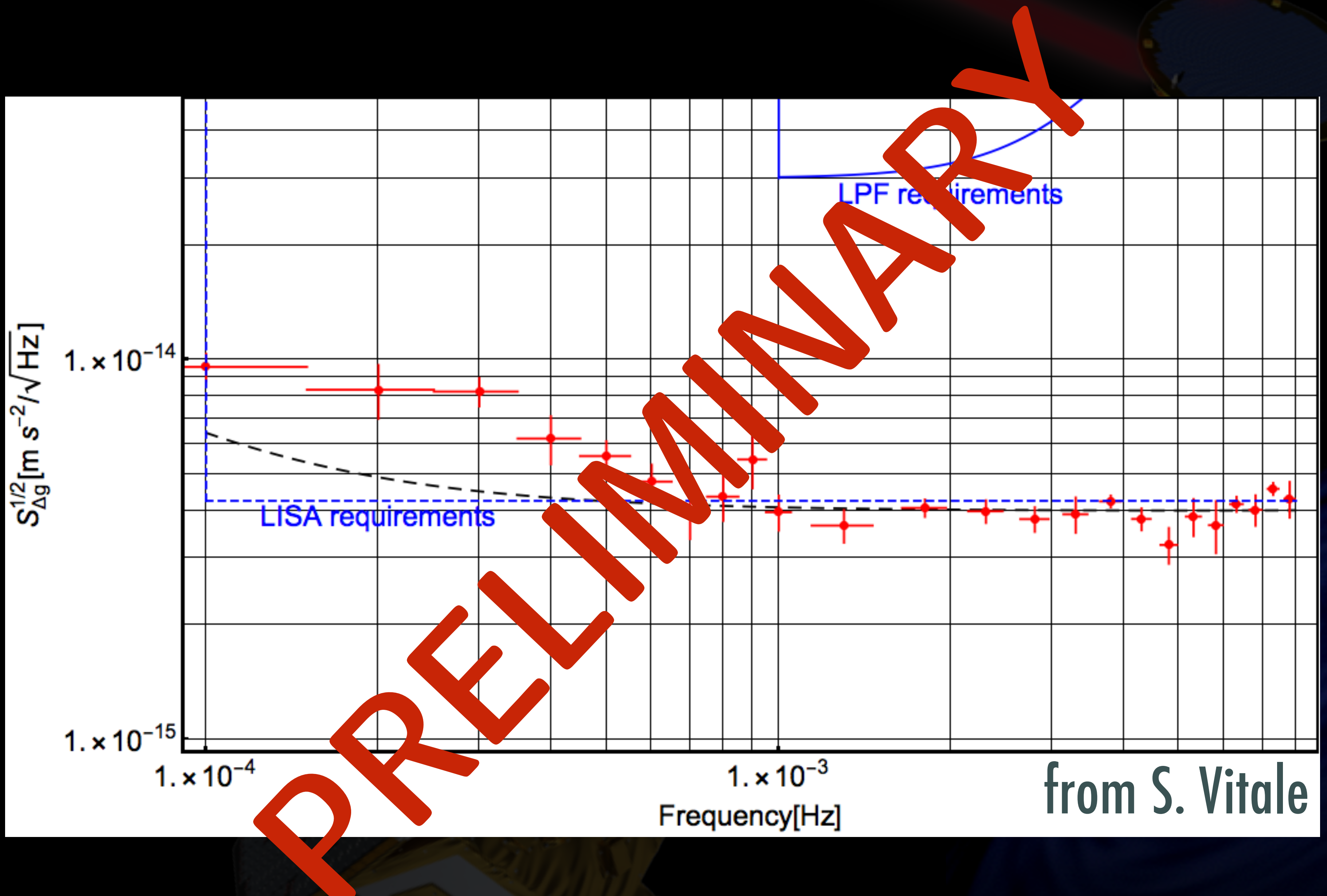
8th September 2016

Outline

- LISAPathfinder results
- LISA sensitivity curve for various configurations
- (Partial) LISA science performances:
  - Verification binaries, Galactic binaries, SMBHBs, EMRIs, BHB, cosmological backgrounds
- The simulation working group
- The Data Processing Center
- Conclusion

LISAPathfinder results

- Best average results from LISAPathfinder adapted to LISA (no actuation, ...) [talk from Stefano Vitale]



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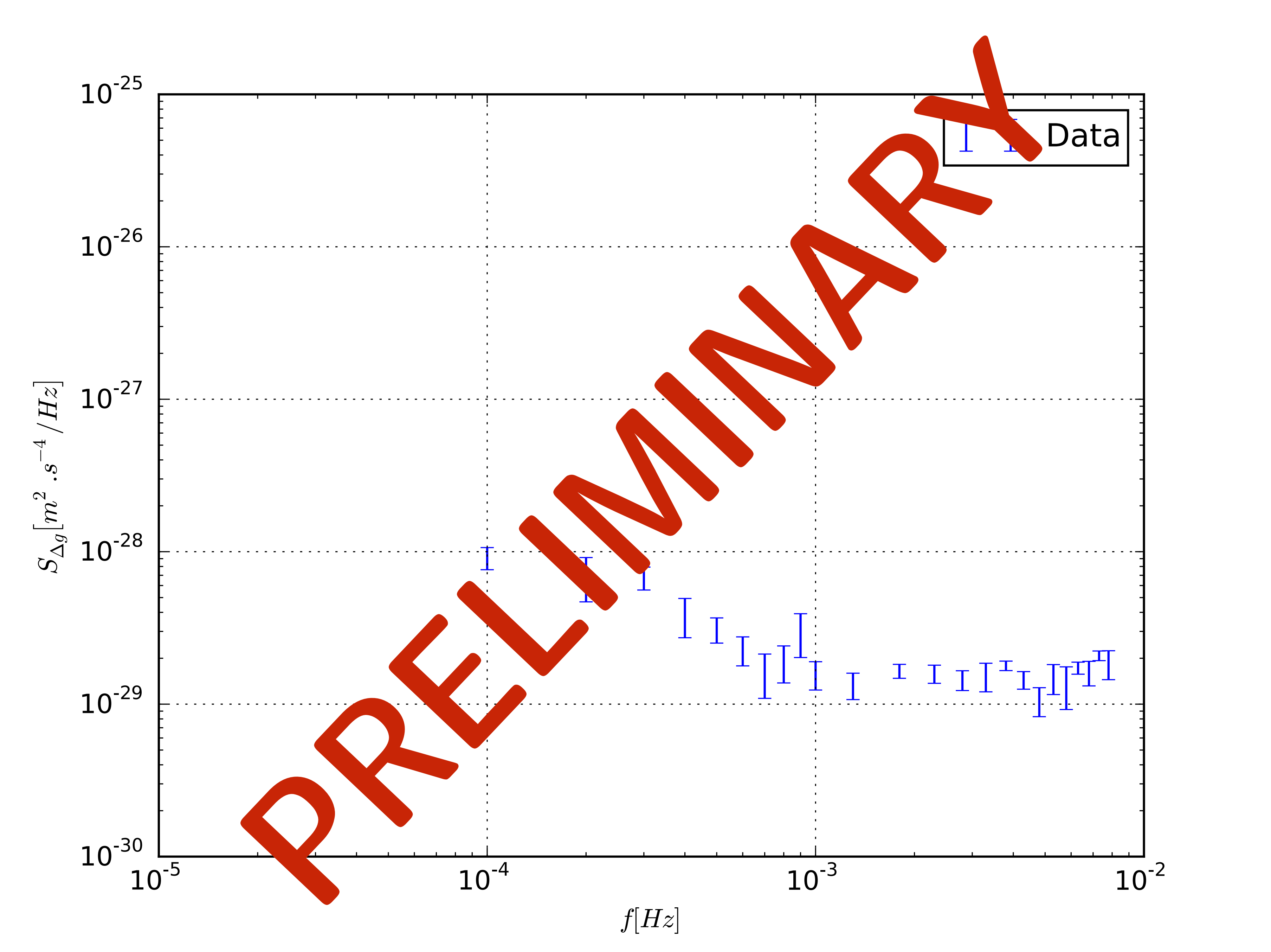
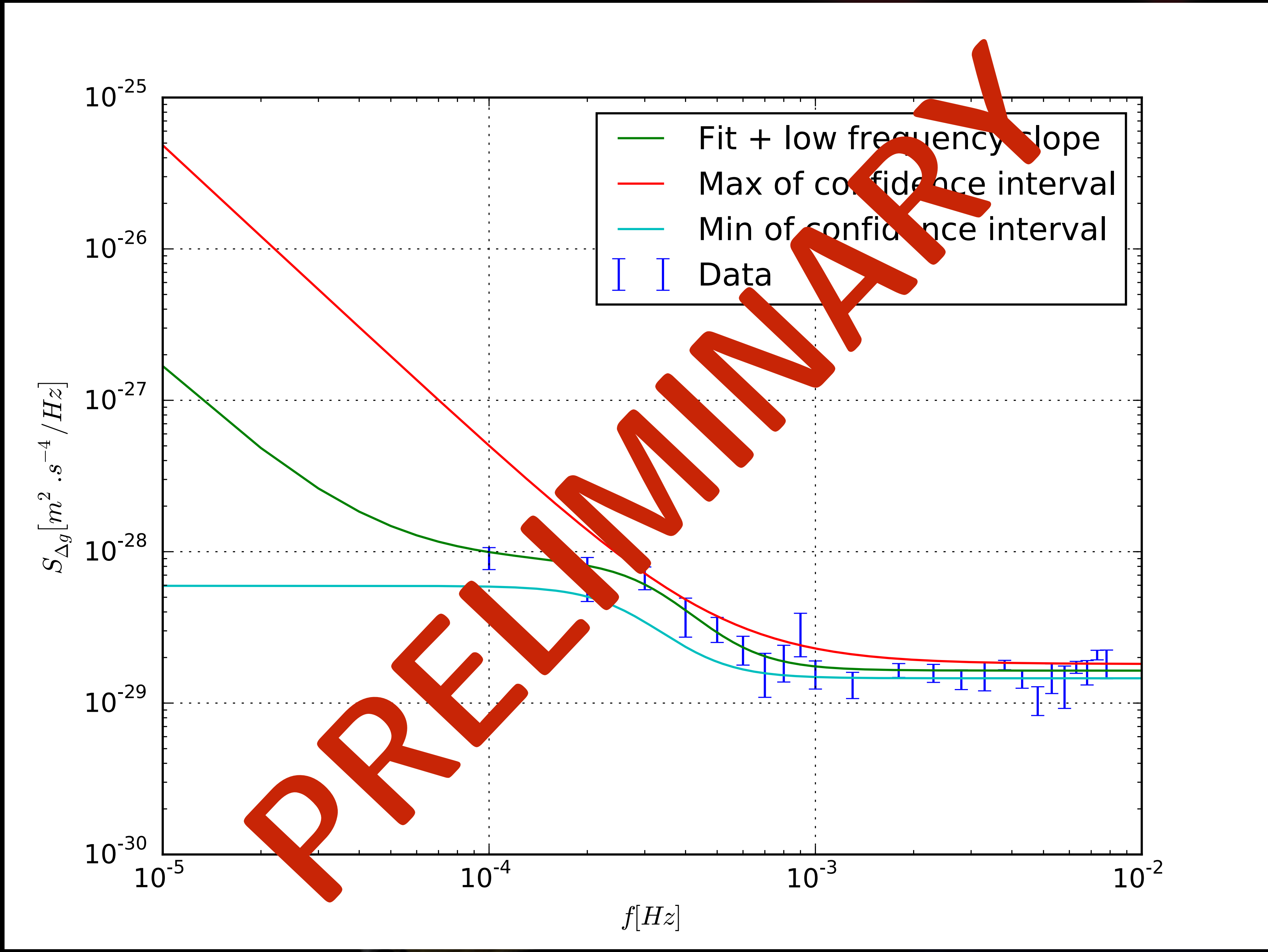


LISAPathfinder results

- Best average results from LISAPathfinder

  + confidence interval (large uncertainty at low frequency)



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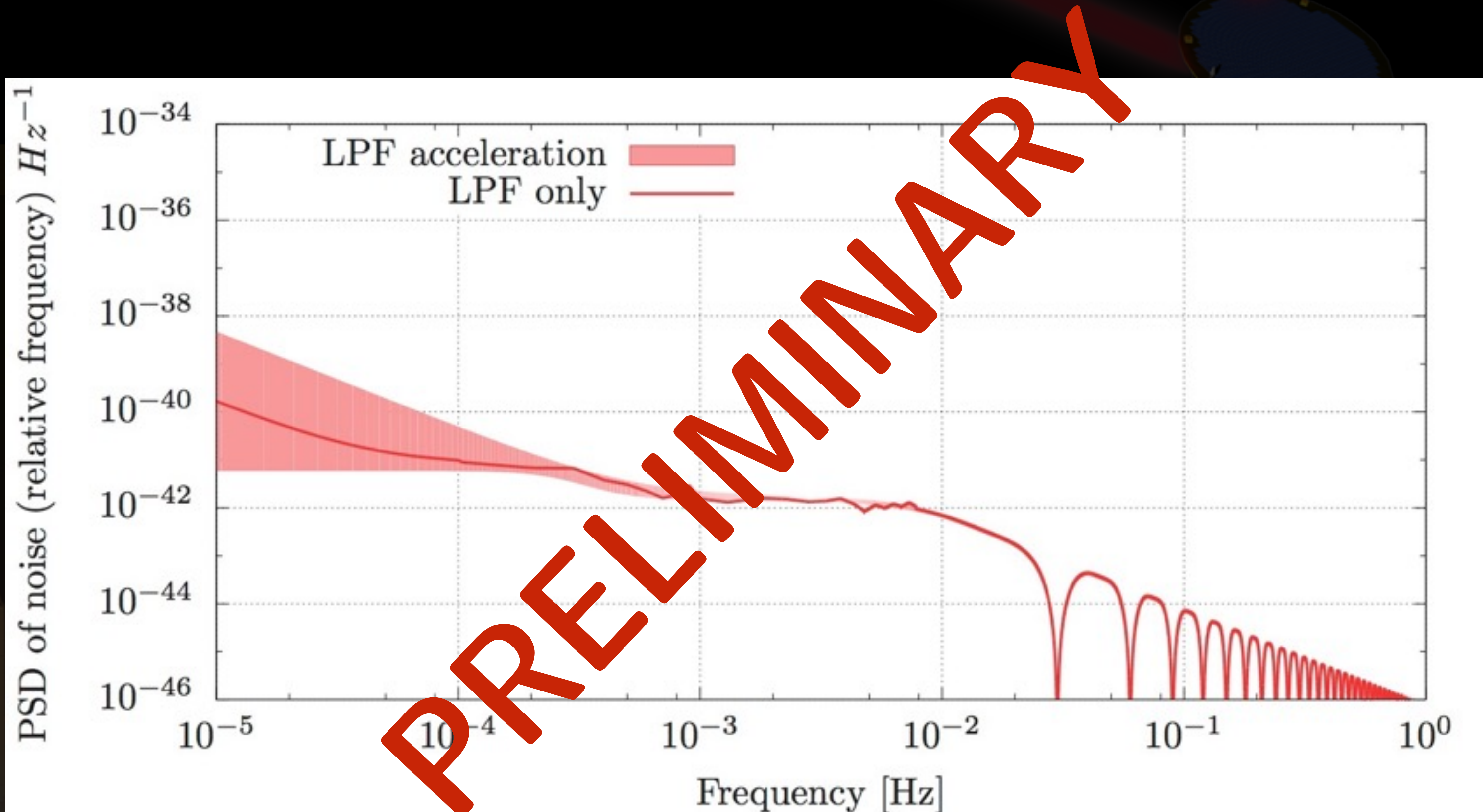

LISA high frequency noise

- 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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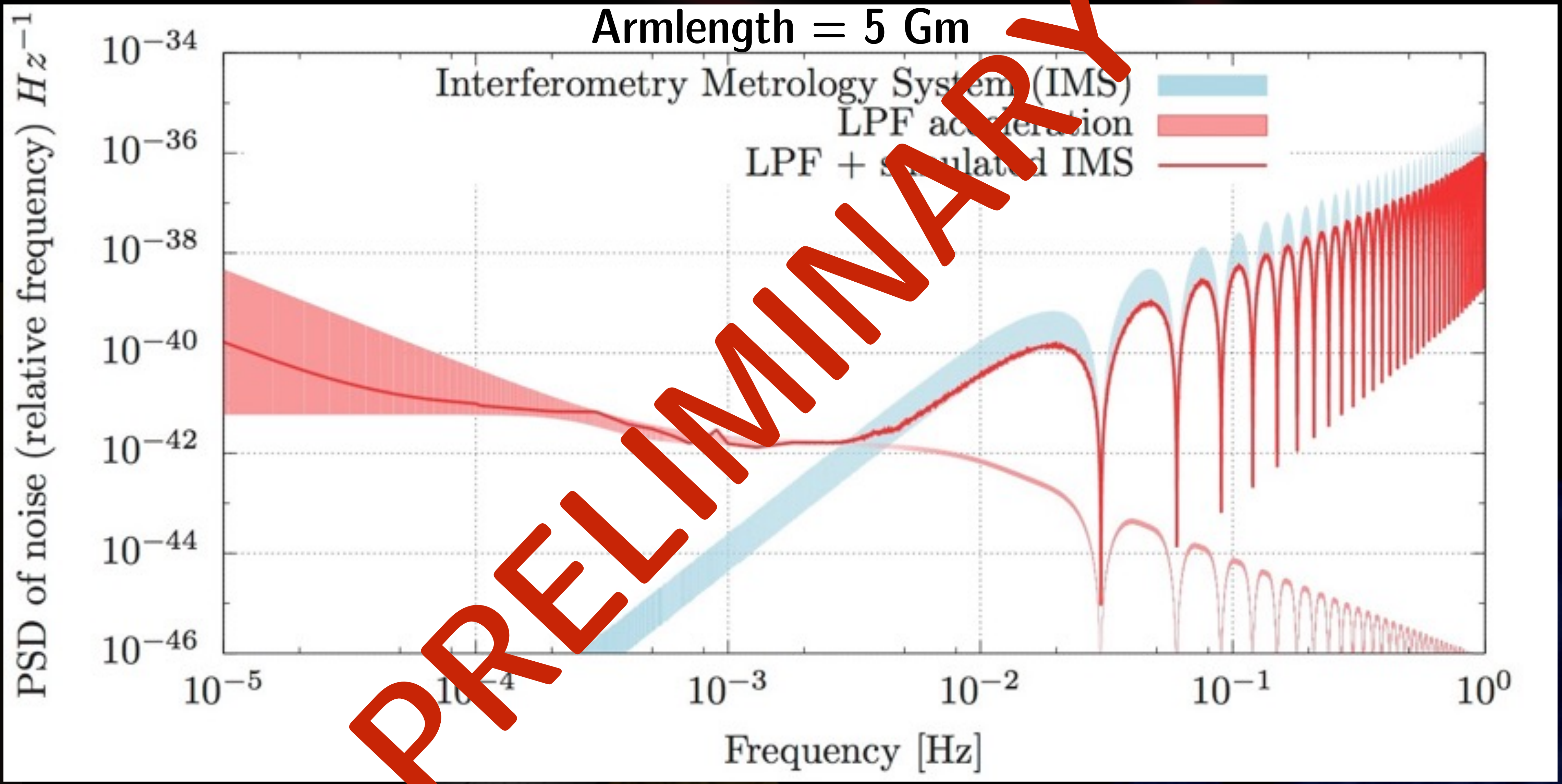

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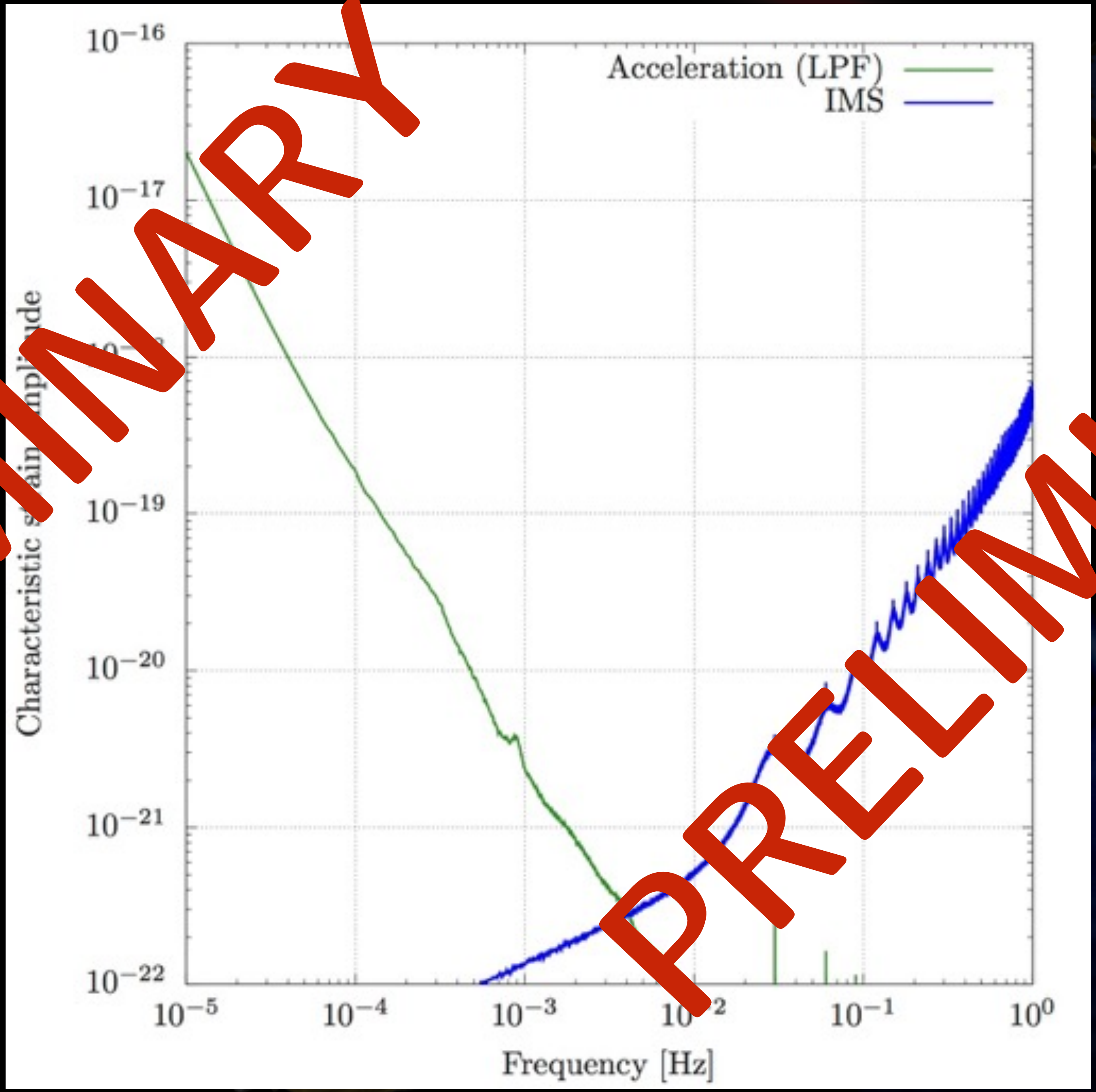
LISA sensitivity with LPF results

- Sensitivity in characteristic strain

L = 5 Gm



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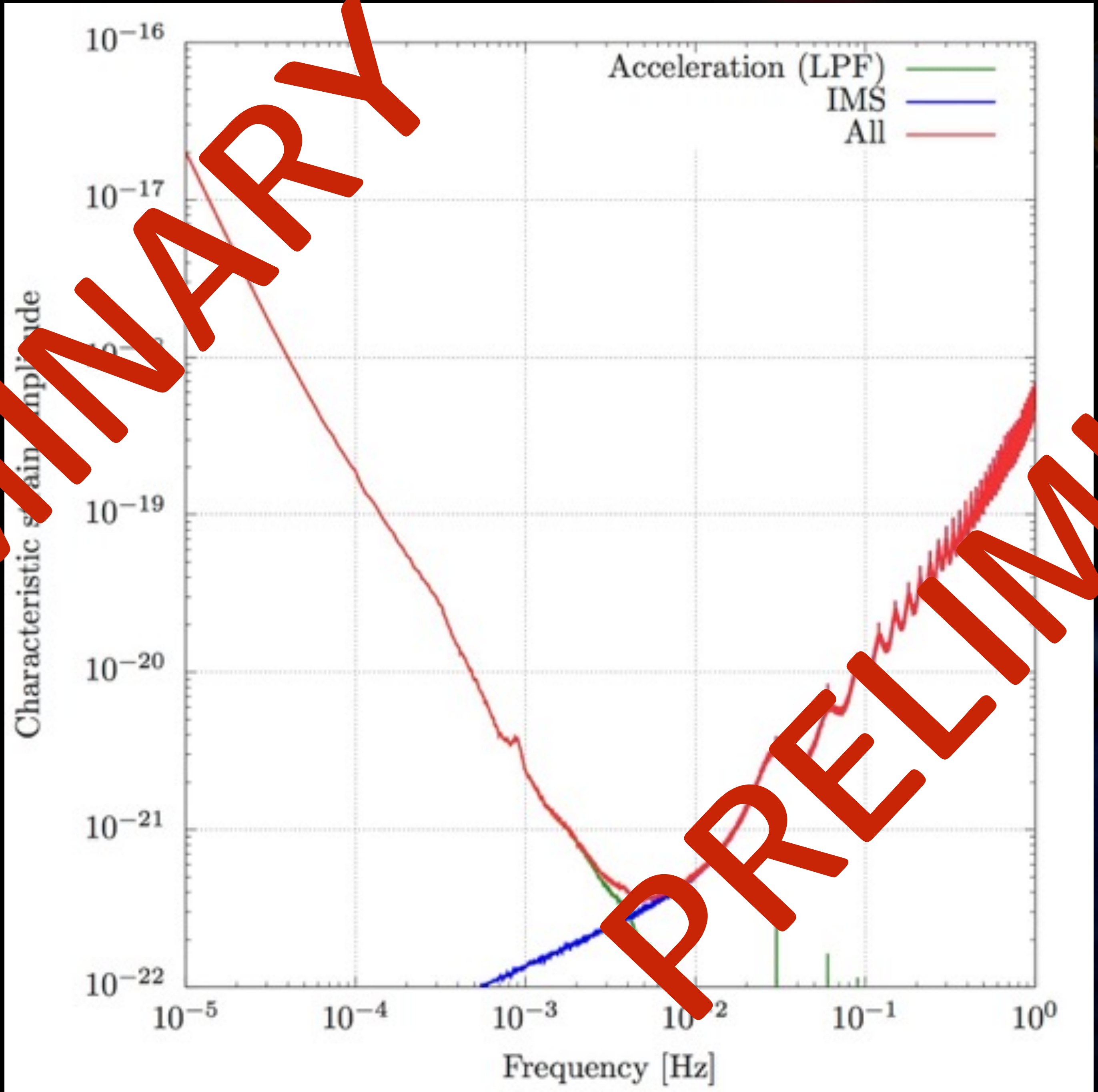

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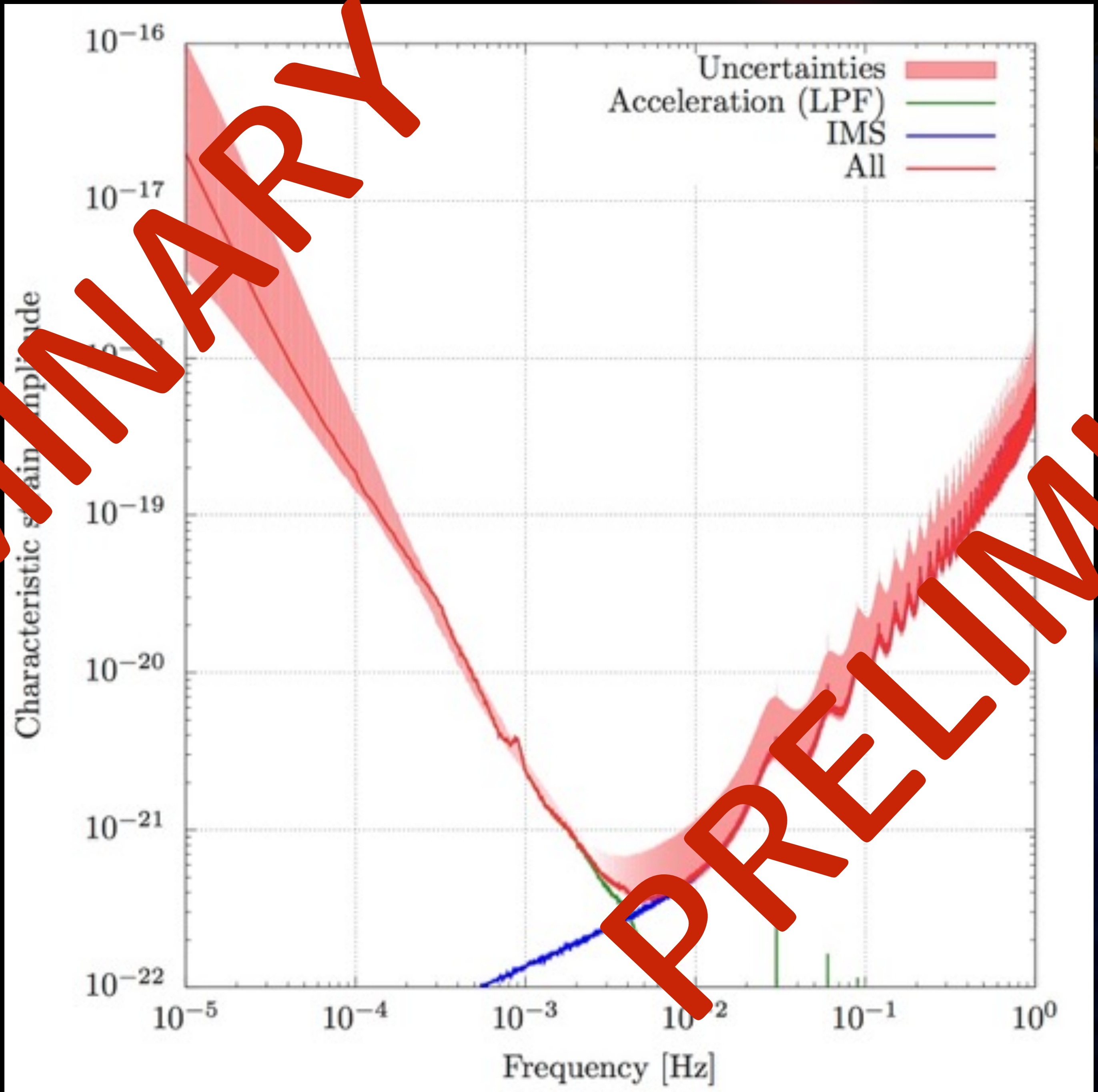

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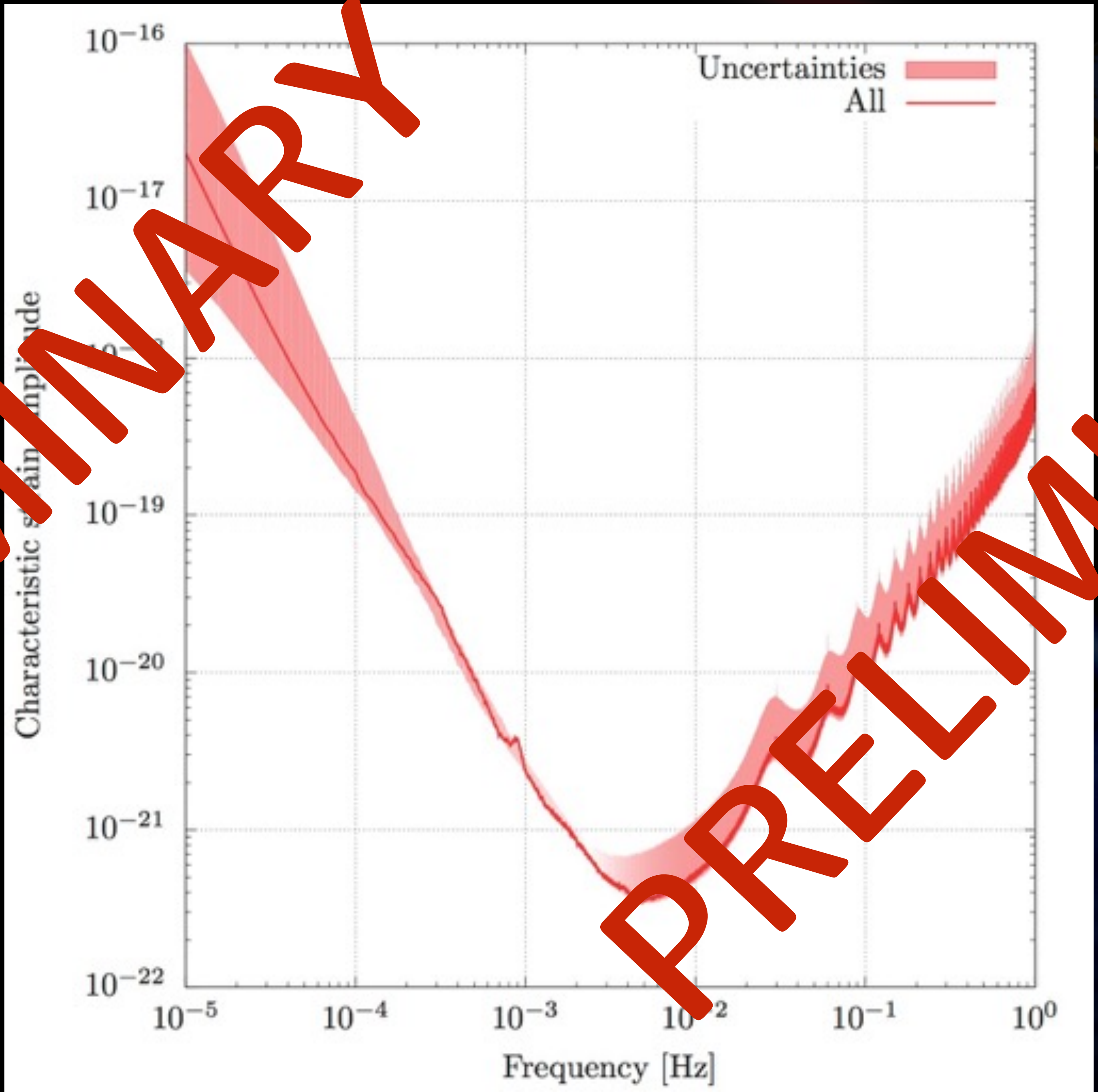

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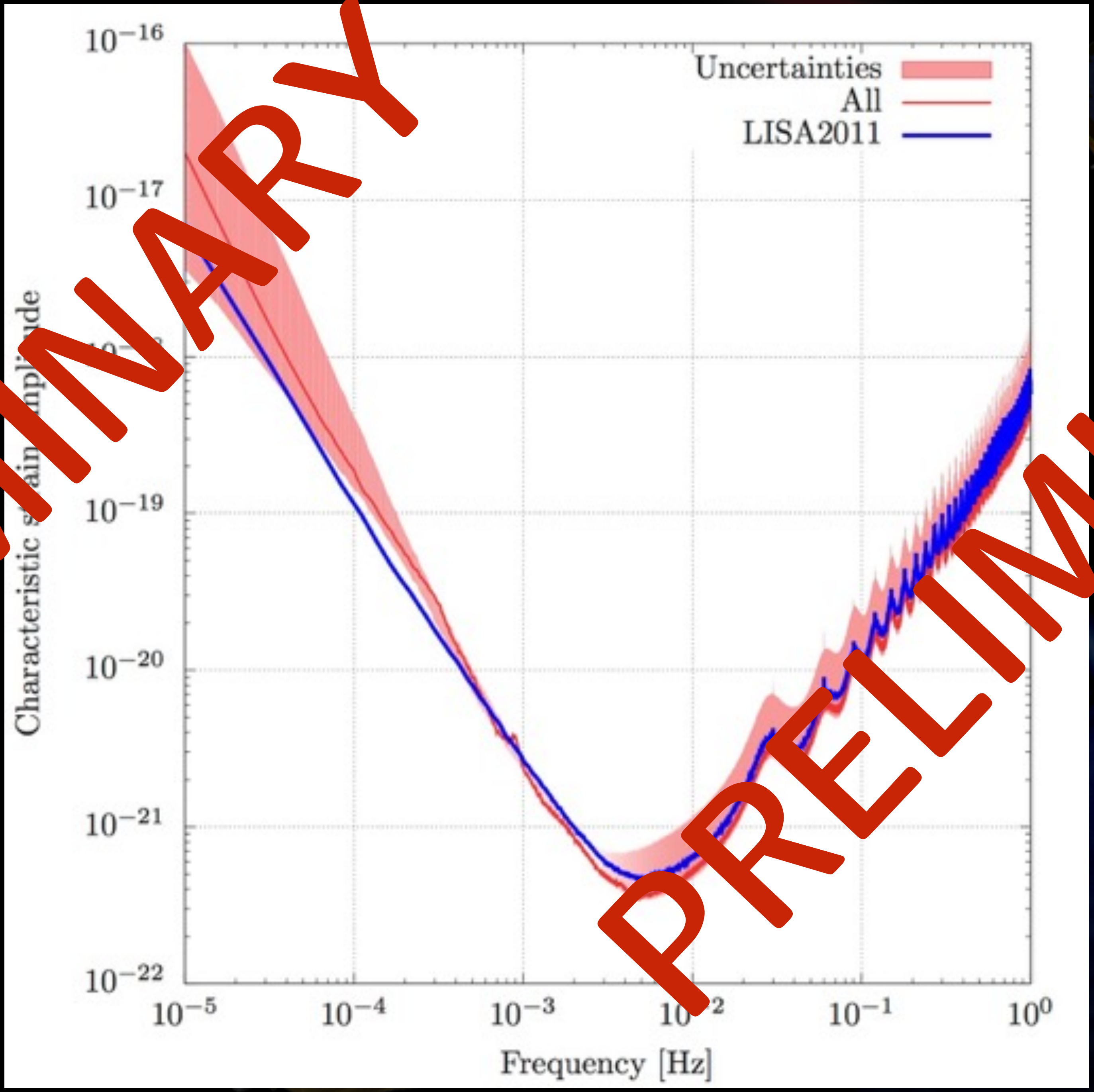

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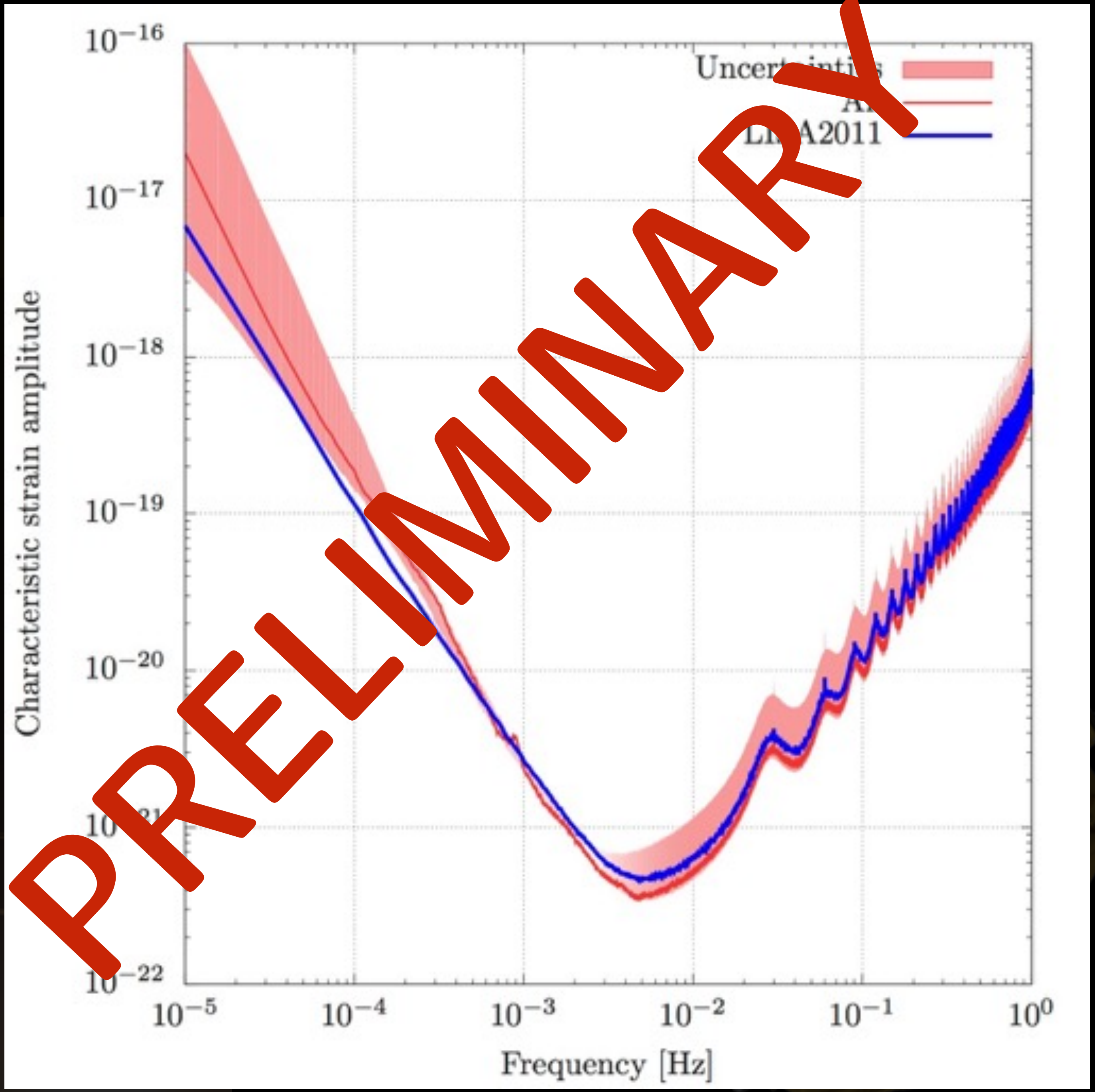
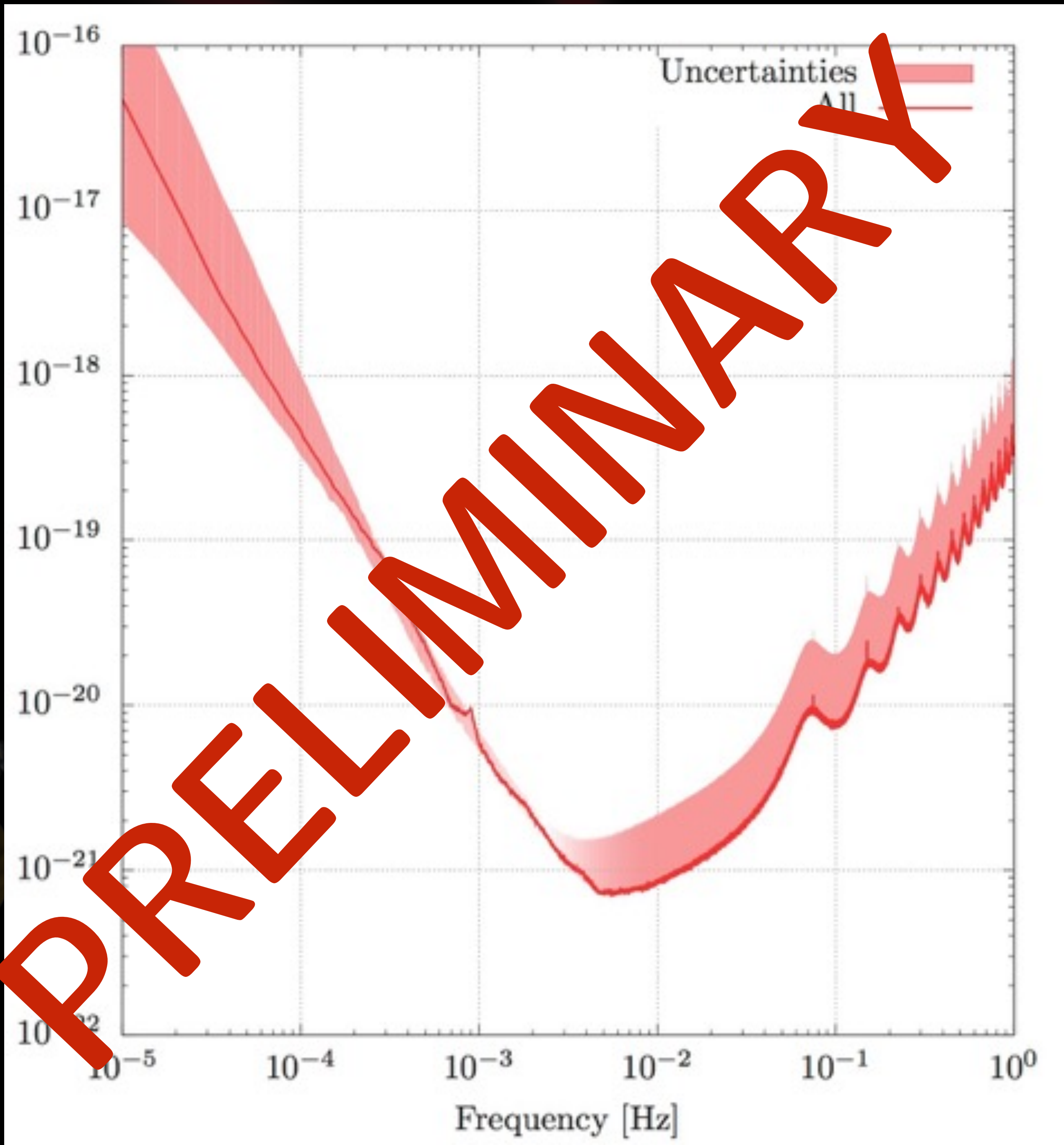


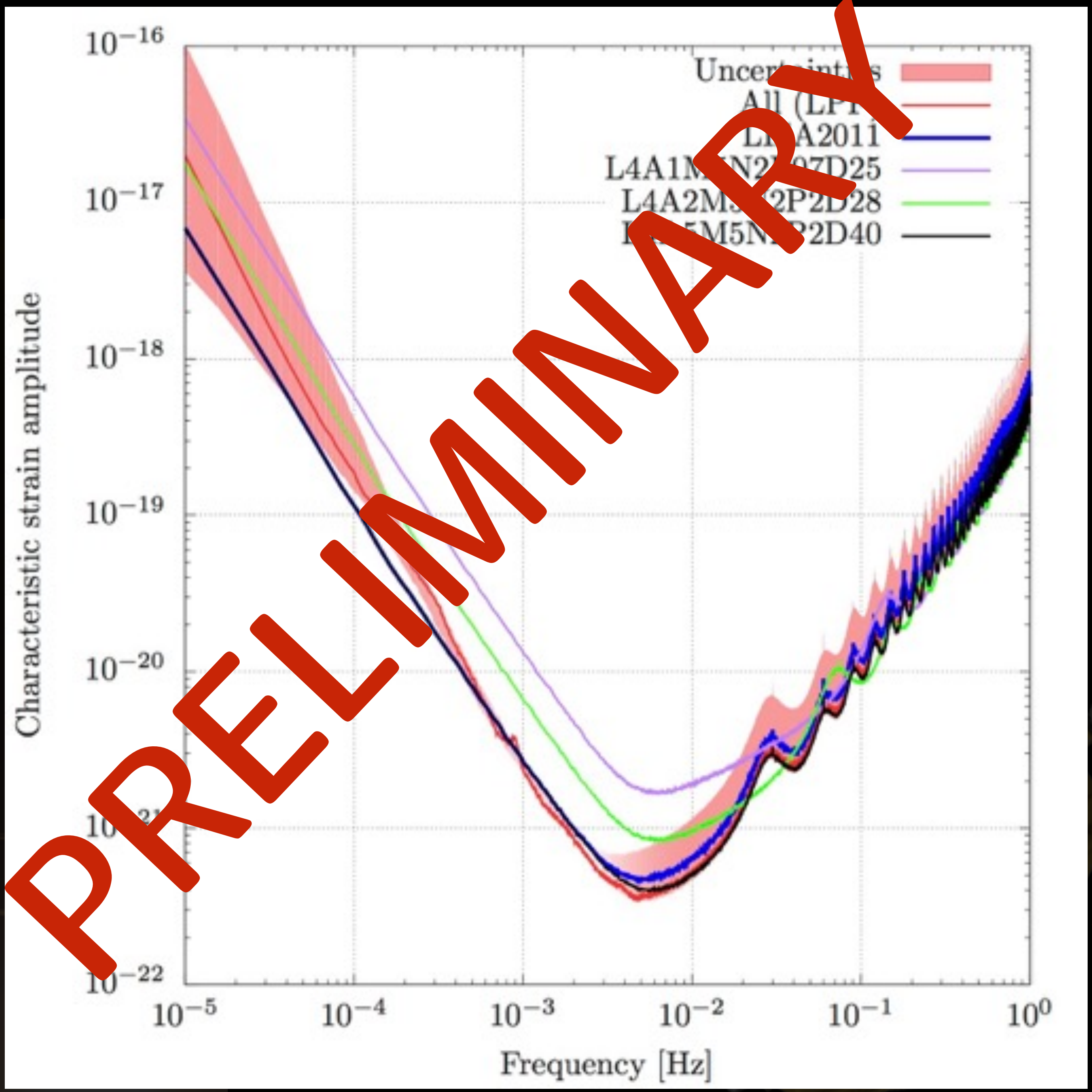
L = 2 Gm



LISA sensitivity with LPF results

- Comparison with GOAT configuration

L = 5 Gm



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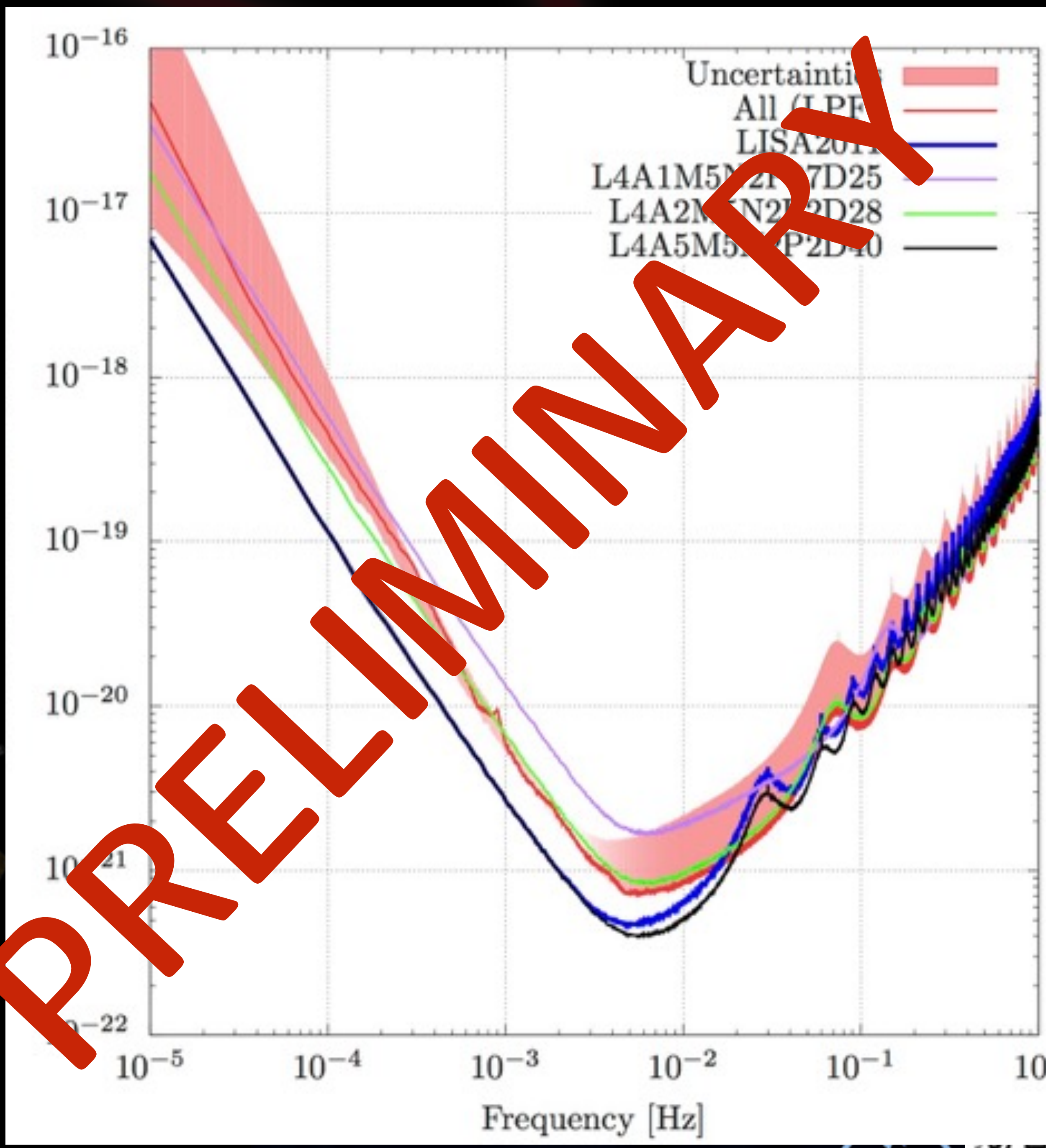

LPF→LISA: Verification binaries

- Few tens of galactic binaries are known from electromagnetic observation => guaranteed sources
- ~ 12 "detected" after 2 years
- More sources from GAIA

L = 5 Gm

Name	6 months 6 links	1 year 6 links	2 years 6 links	5 years 6 links
RXJ0806	191	245	347	549
V407Vul	39	58	82	130
V407Vul.	40	59	84	132
ESCet	57	78	110	173
AMCVn	73	113	160	253
HPLib	108	147	209	330
CRBoo	39	52	73	116
KLDra	1.9	3.4	4.8	7.6
V803Cen	56	69	98	155
SDSSJ0926	5.9	8.1	11	18
CPEri	2.1	3.2	4.5	7.1
2003aw	1.6	1.9	2.7	4.3
SDSSJ1240	0.80	0.93	1.3	2.1
SDSSJ0804	0.62	0.81	1.1	1.8
SDSSJ1411	0.34	0.69	0.98	1.5
GPCom	2.4	3.3	4.6	7.3
SDSSJ0902	0.37	0.52	0.73	1.2
SDSSJ1552	0.15	0.28	0.40	0.64
CE315	0.94	1.1	1.5	2.4
SDSSJ0106	1.2	1.5	2.2	3.5
SDSSJ1053	0.67	1.1	1.5	2.4
SDSSJ0923	3.7	4.8	6.8	11
SDSS_J1436	0.99	2.1	3.0	4.8
WD0957	2.8	4.4	6.3	[illegible]
SDSSJ0755	0.19	0.28	0.40	[illegible]
SDSSJ0849	0.25	0.31	0.44	[illegible]
SDSSJ0022	0.16	0.19	0.27	[illegible]
SDSSJ0849	0.16	0.19	0.27	[illegible]
SDSSJ2119	0.08	0.10	[illegible]	0.22
SDSSJ1234	0.05	0.05	[illegible]	[illegible]
4U1820	12	17	[illegible]	37
4U0513	1.2	2.4	[illegible]	5.4
2S0918	6.8	10	14	22
4U1543	3.4	5.1	7.2	11
4U1850	1.2	1.7	2.4	3.9
M15X	0.96	1.1	1.6	2.5
PSRJ0737	0.42	0.62	0.88	1.4

L = 2 Gm

Name	6 months 6 links	1 year 6 links	2 years 6 links	5 years 6 links
RXJ0806	96	124	175	277
V407Vul	17	25	35	56
V407Vul.	17	25	36	57
ESCet	24	33	[illegible]	74
AMCVn	30	46	[illegible]	102
HPLib	44	60	[illegible]	133
CRBoo	16	[illegible]	29	47
KLDra	0.77	[illegible]	1.9	3.1
V803Cen	23	[illegible]	[illegible]	62
SDSSJ0926	2.4	3.2	4.6	7.3
CPEri	0.85	[illegible]	1.8	2.9
2003aw	0.65	[illegible]	1.1	1.7
SDSSJ1240	[illegible]	0.37	0.53	0.83
SDSSJ0804	[illegible]	0.32	0.46	0.73
SDSSJ1411	[illegible]	0.28	0.39	0.62
GPCom	[illegible]	1.3	1.8	2.9
SDSSJ0902	0.15	0.21	0.29	0.46
SDSSJ1552	0.06	0.11	0.16	0.26
CE315	0.38	0.44	0.62	0.98
SDSSJ0106	0.49	0.62	0.88	1.4
SDSSJ1053	0.27	0.44	0.62	0.97
SDSSJ0923	1.5	1.9	2.7	4.3
SDSS_J1436	0.40	0.86	1.2	1.9
WD0957	1.1	1.8	2.5	4.0
SDSSJ0755	0.08	0.11	0.16	0.25
SDSSJ0849	0.10	0.13	0.18	0.28
SDSSJ0022	0.06	0.08	0.11	0.17
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M15X	0.39	0.45	0.64	1.0
PSRJ0737	0.17	0.25	0.35	0.56

PRELIMINARY

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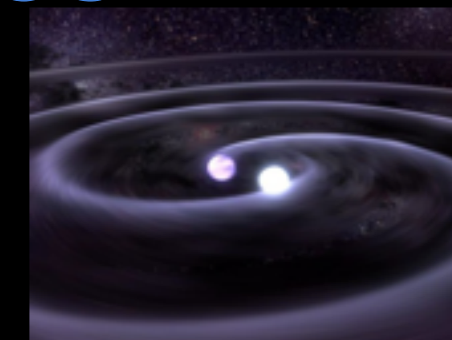
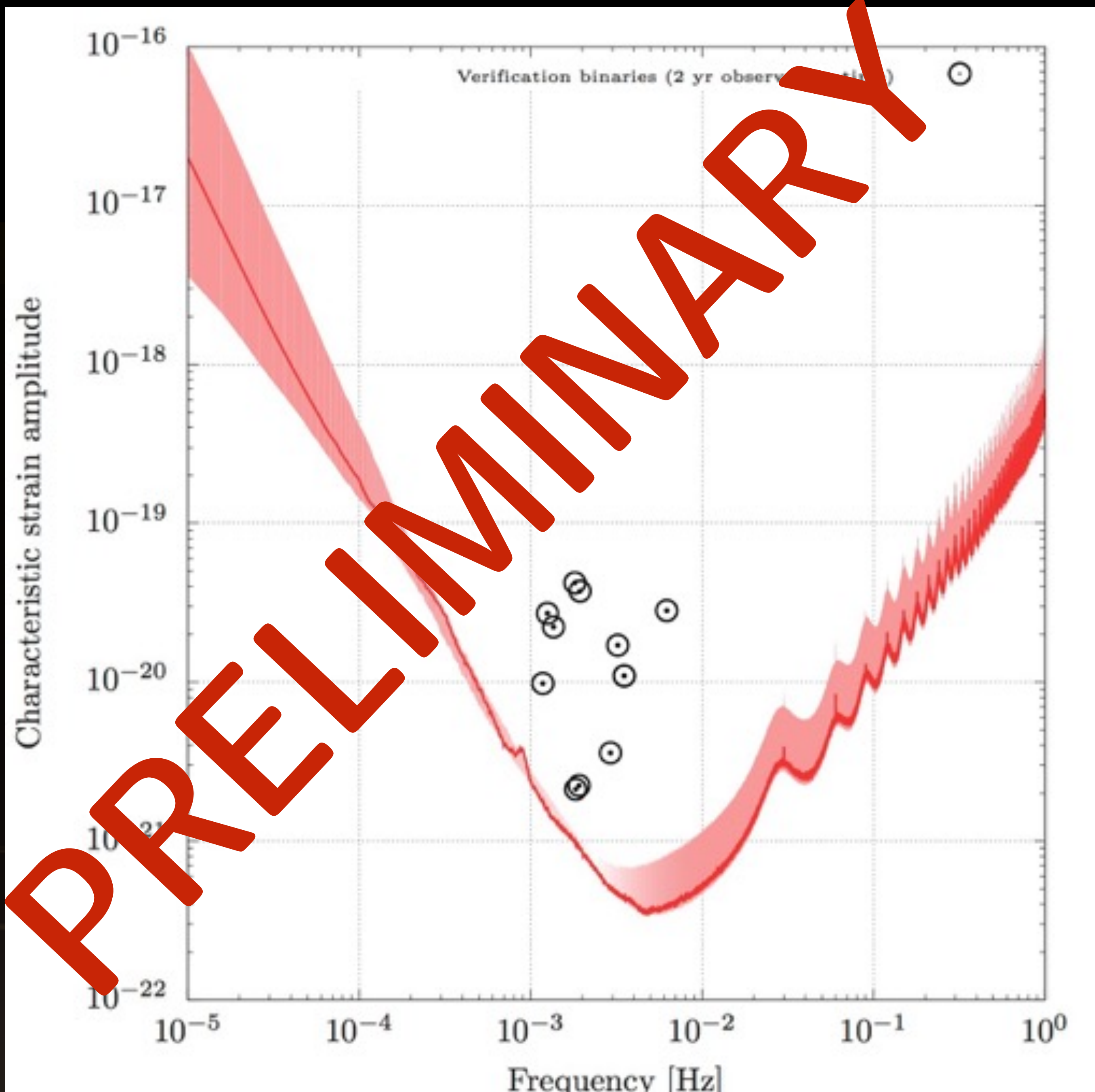
LPF→LISA: Galactic binaries

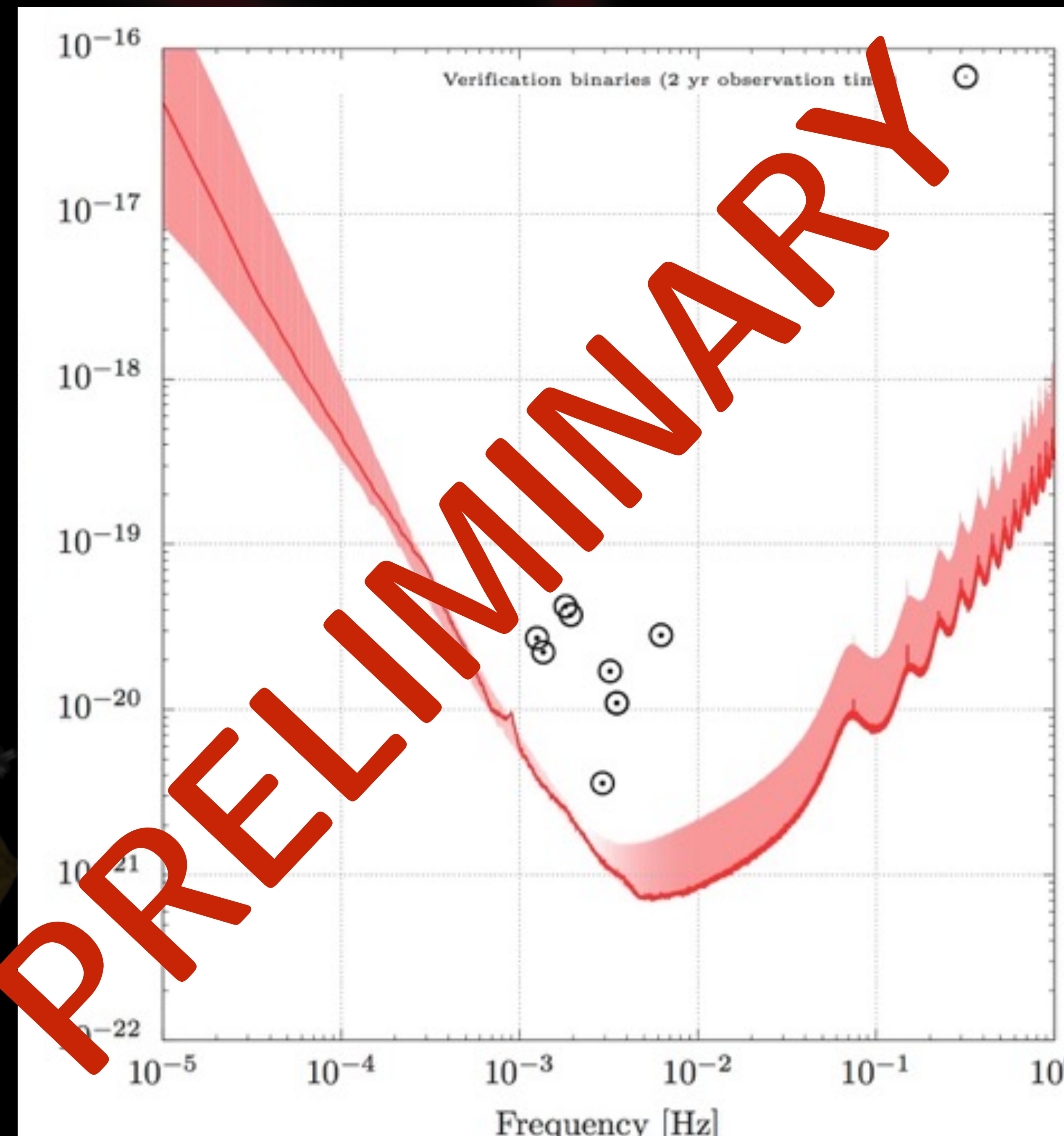
- Verification binaries



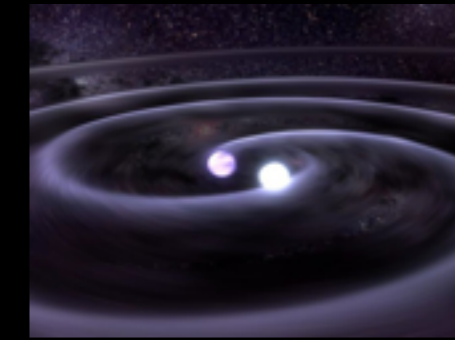
L = 5 Gm



L = 2 Gm



LPF→LISA: Galactic Binaries



- About 60 millions of binaries in the Galaxy (White Dwarfs, Neutron stars)
- With LISAPathfinder-LISA, we can

	5 Gm	2 Gm
detect	~22600	~15700
have a 2D localization	~9400	~5000
have a 3D localization	~2170	~1400
measure the first frequency derivative (at 20%)	~4100	~3000
measure the second frequency derivative (at 20%)	few	few

LPF→LISA: Galactic binaries

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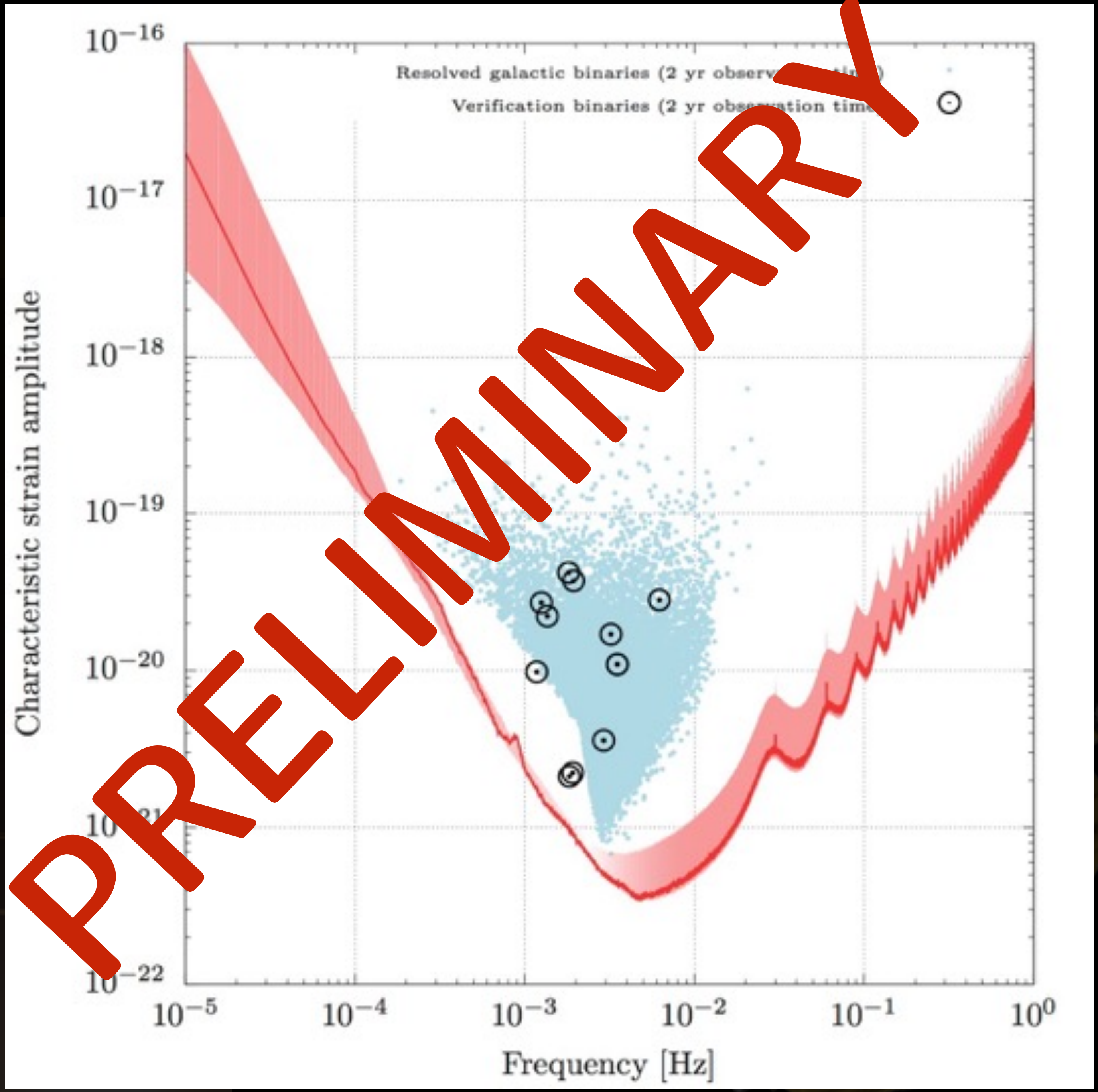

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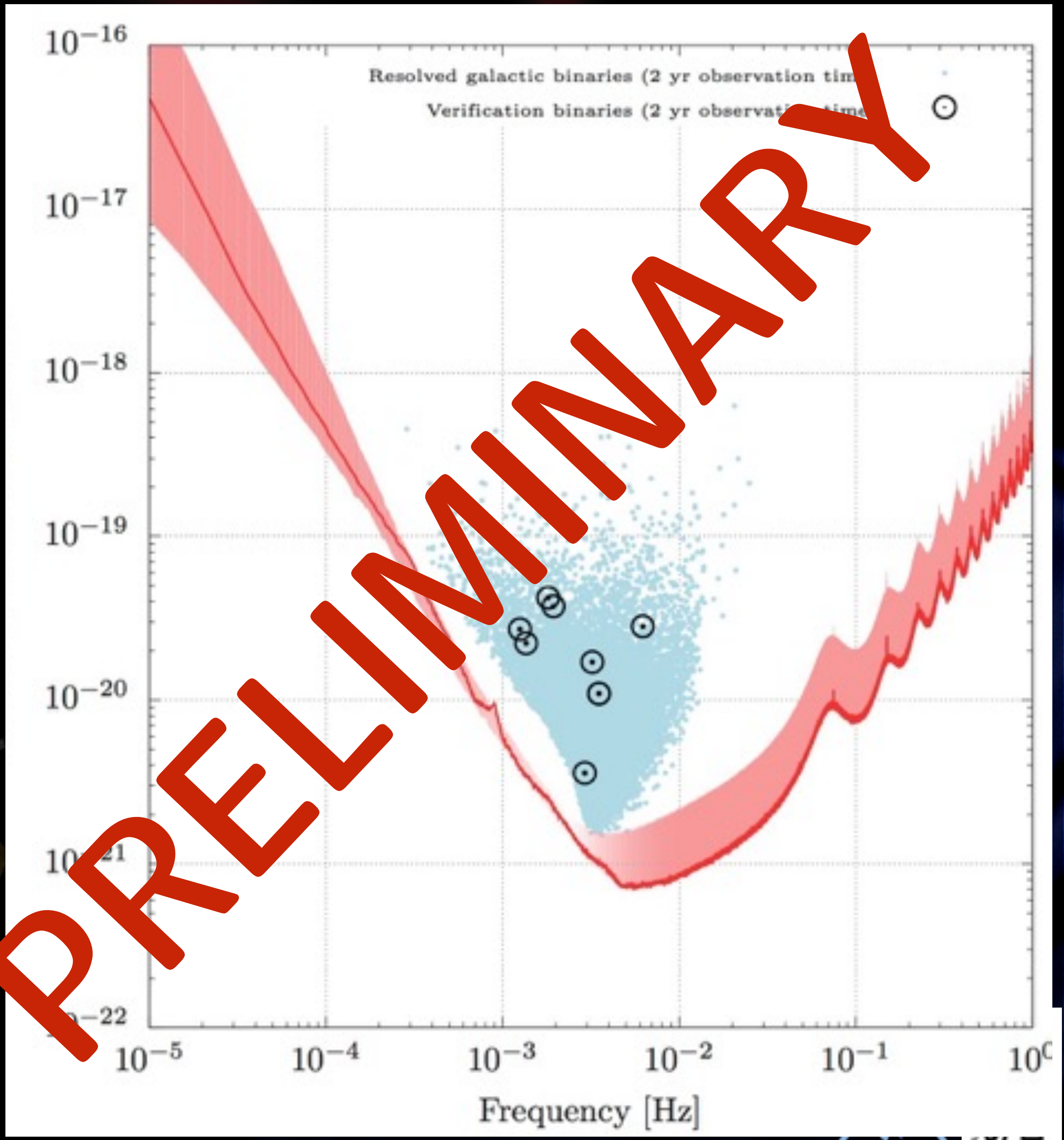

LPF→LISA: Galactic binaries

- Confusion noise from unresolved sources

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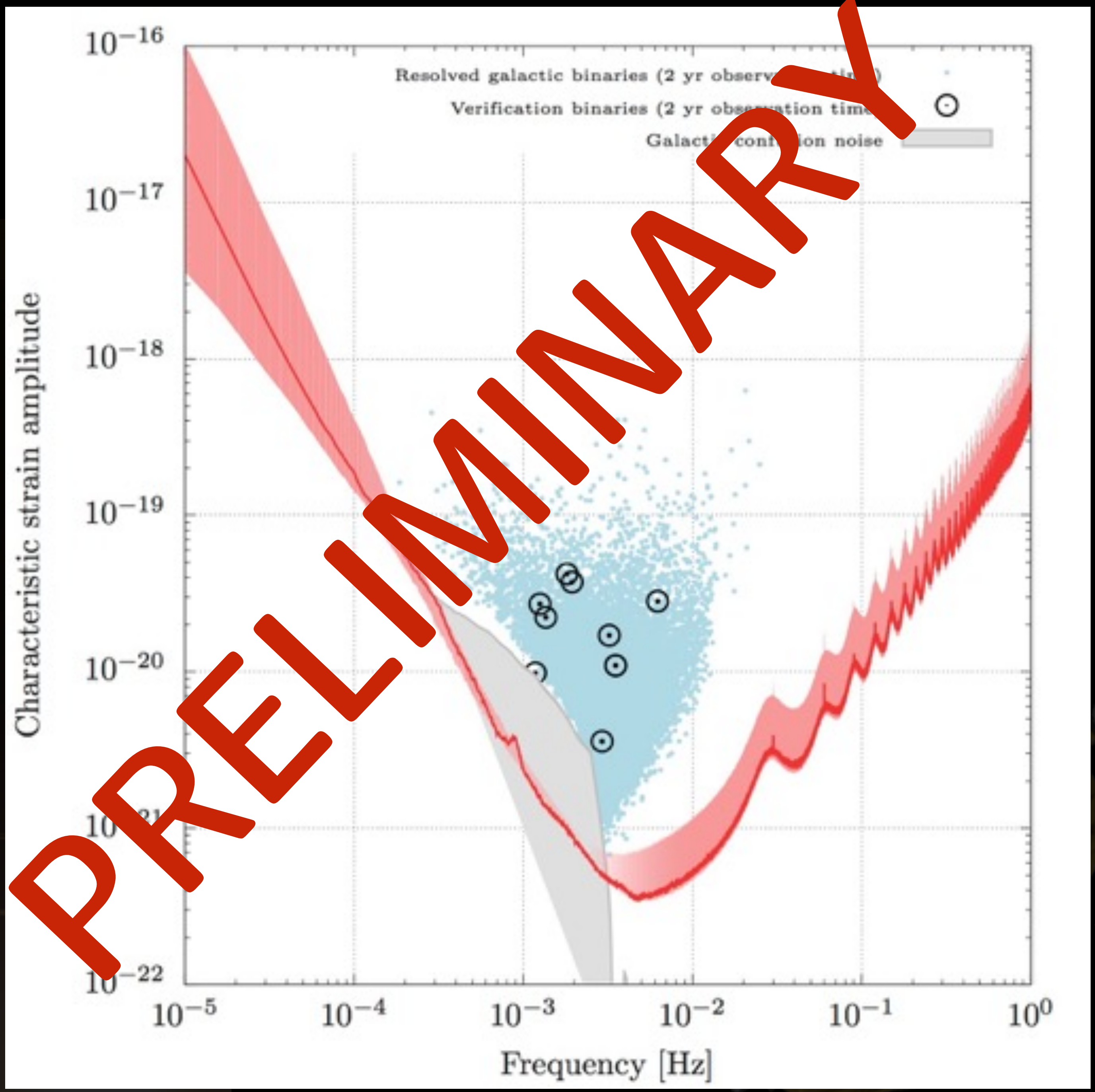

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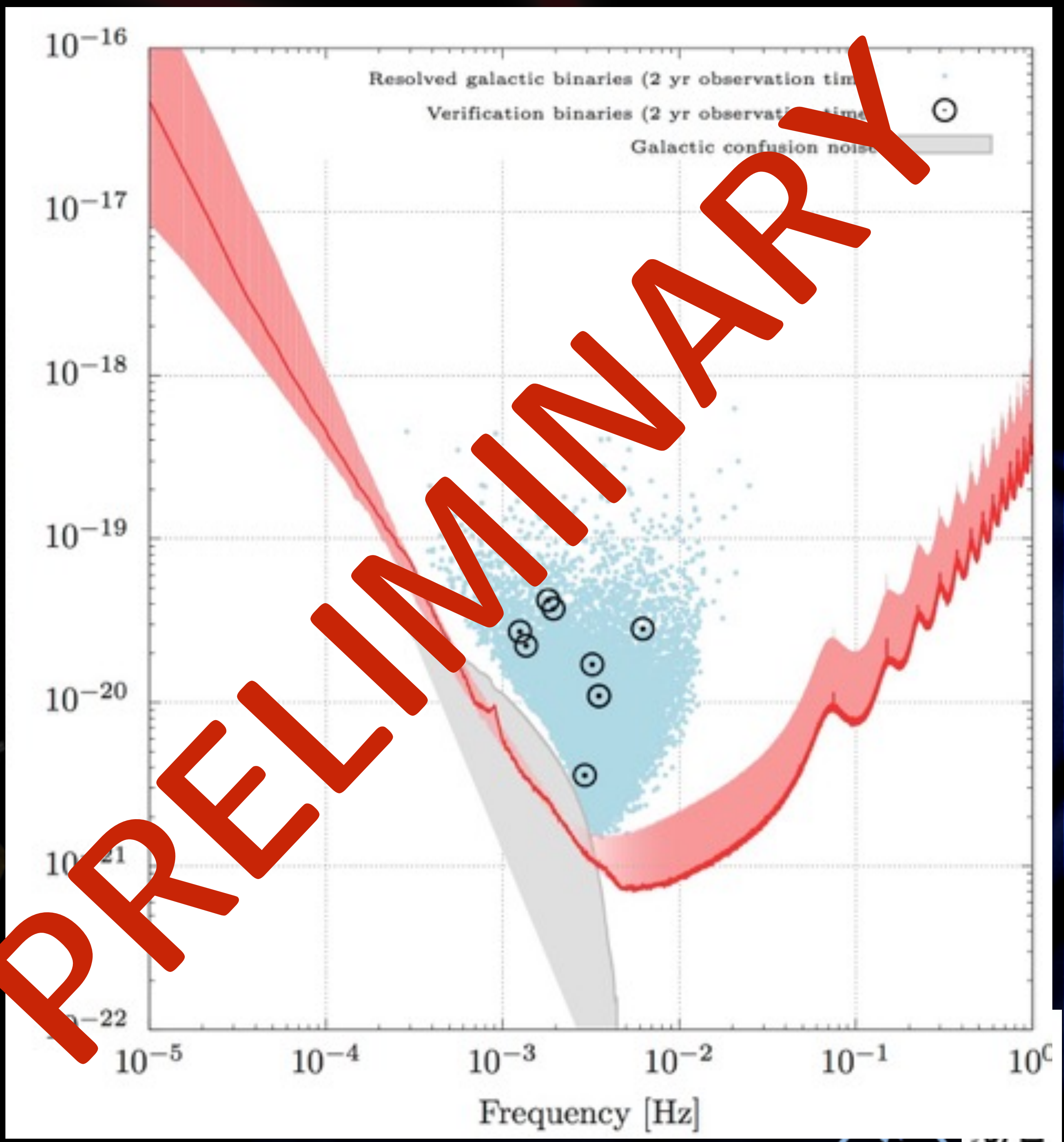
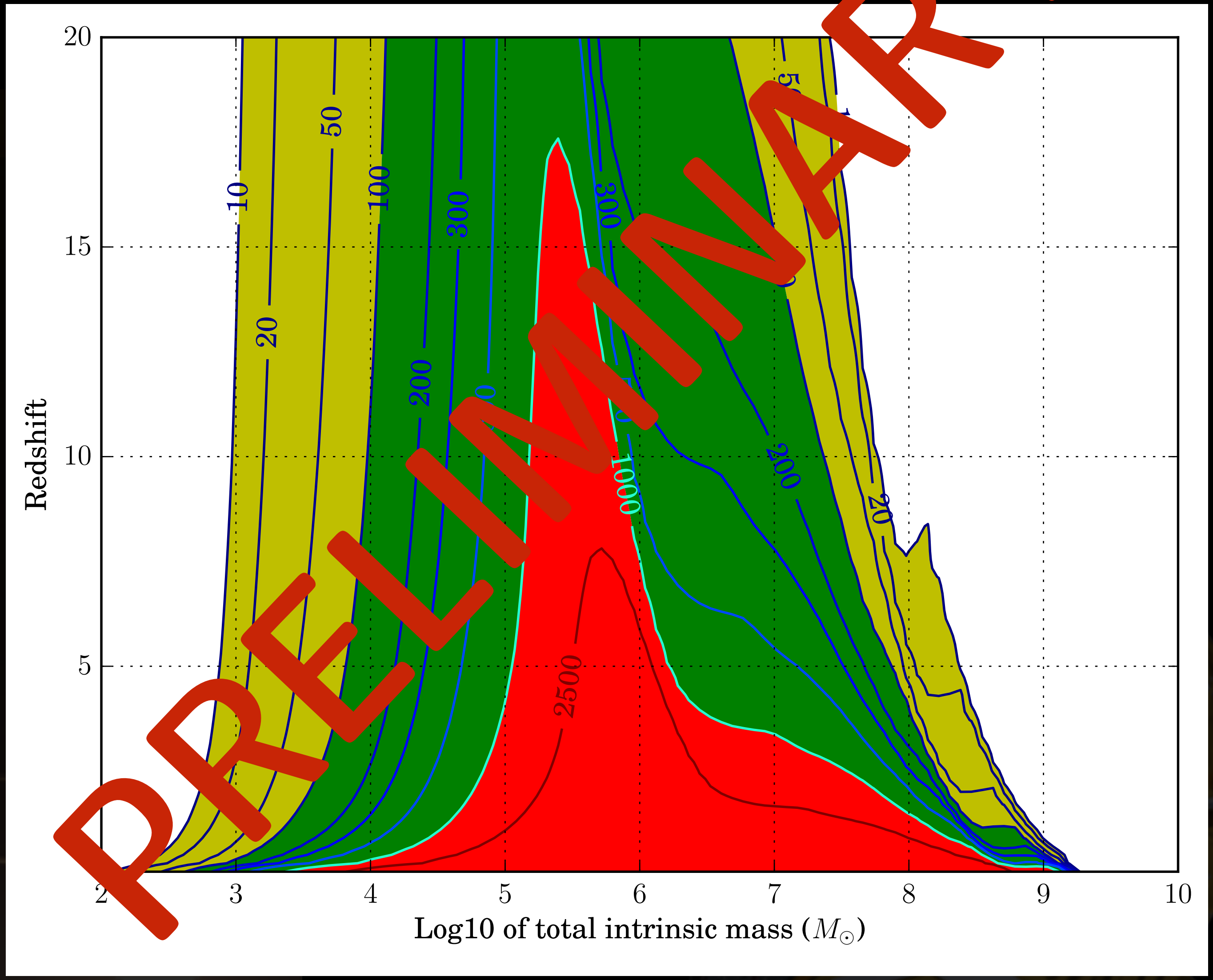


LPF→LISA: SMBHBs

- With LPF-LISA, we observe :
  - SMBH binaries at very high redshift (z > 15)
  - nearby SMBH binaries with very high redshift (> 1000)



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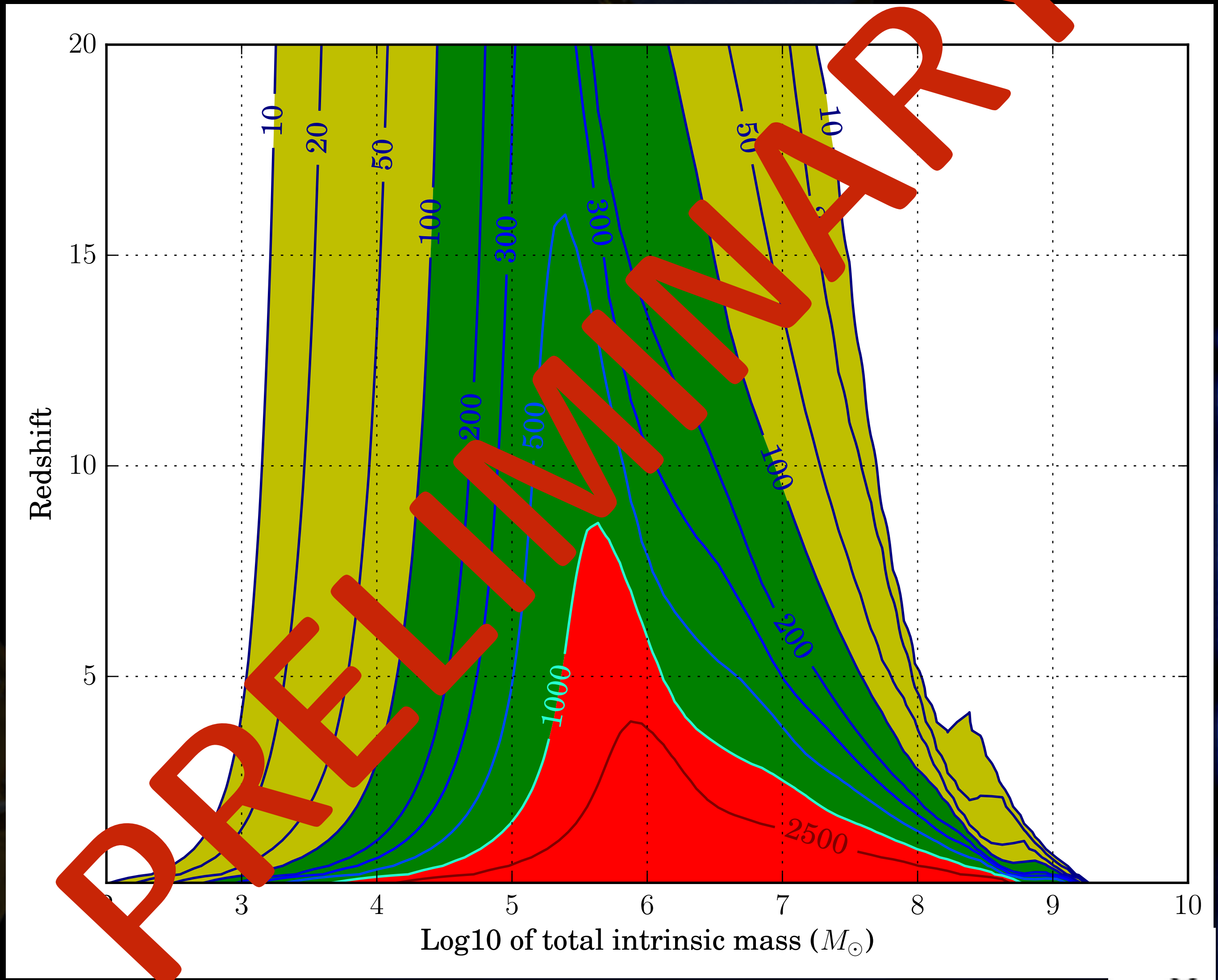

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LPF→LISA: SMBHBs

- With LPF-LISA, we observe :
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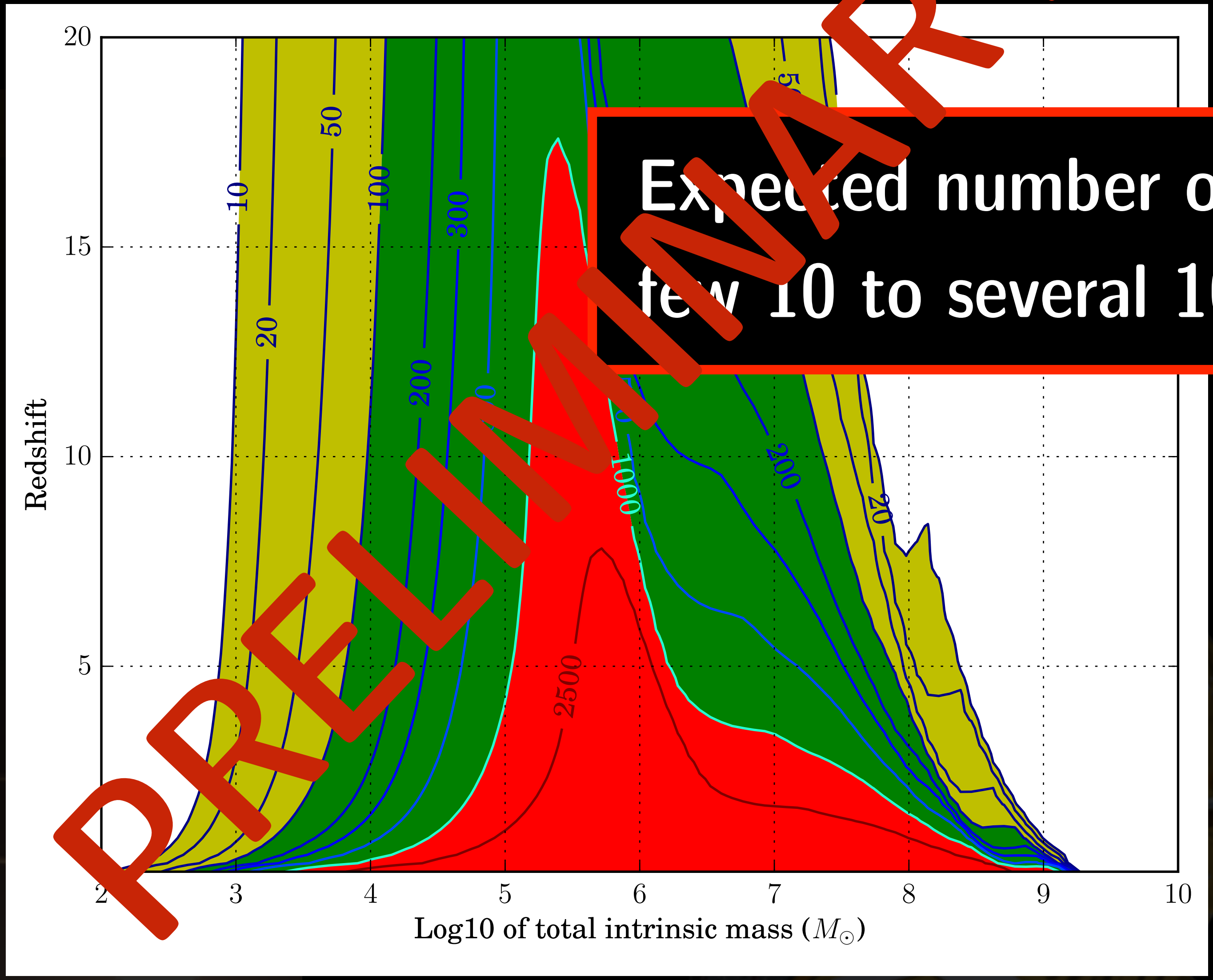
Expected number of sources per year:
few 10 to several 100 sources



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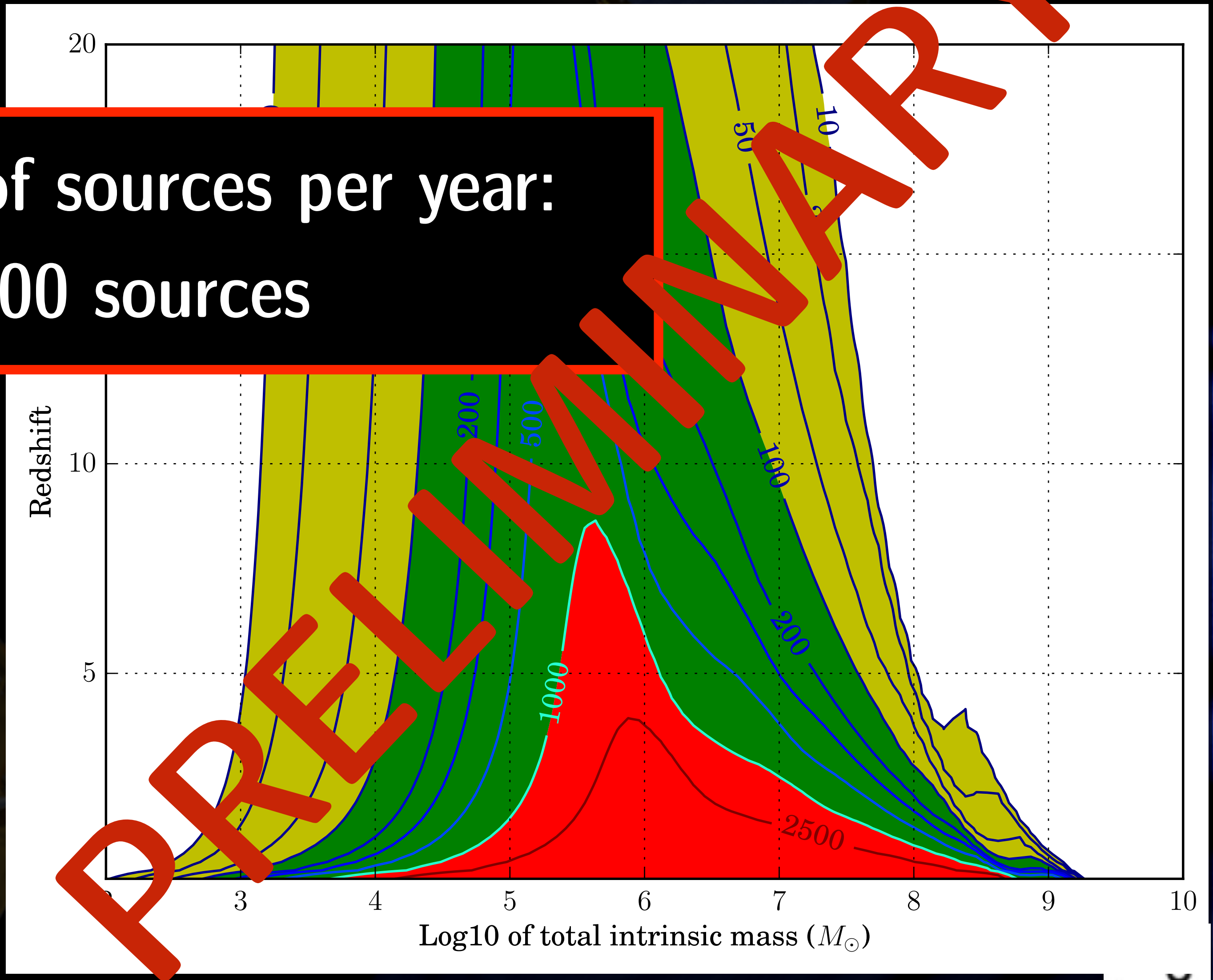

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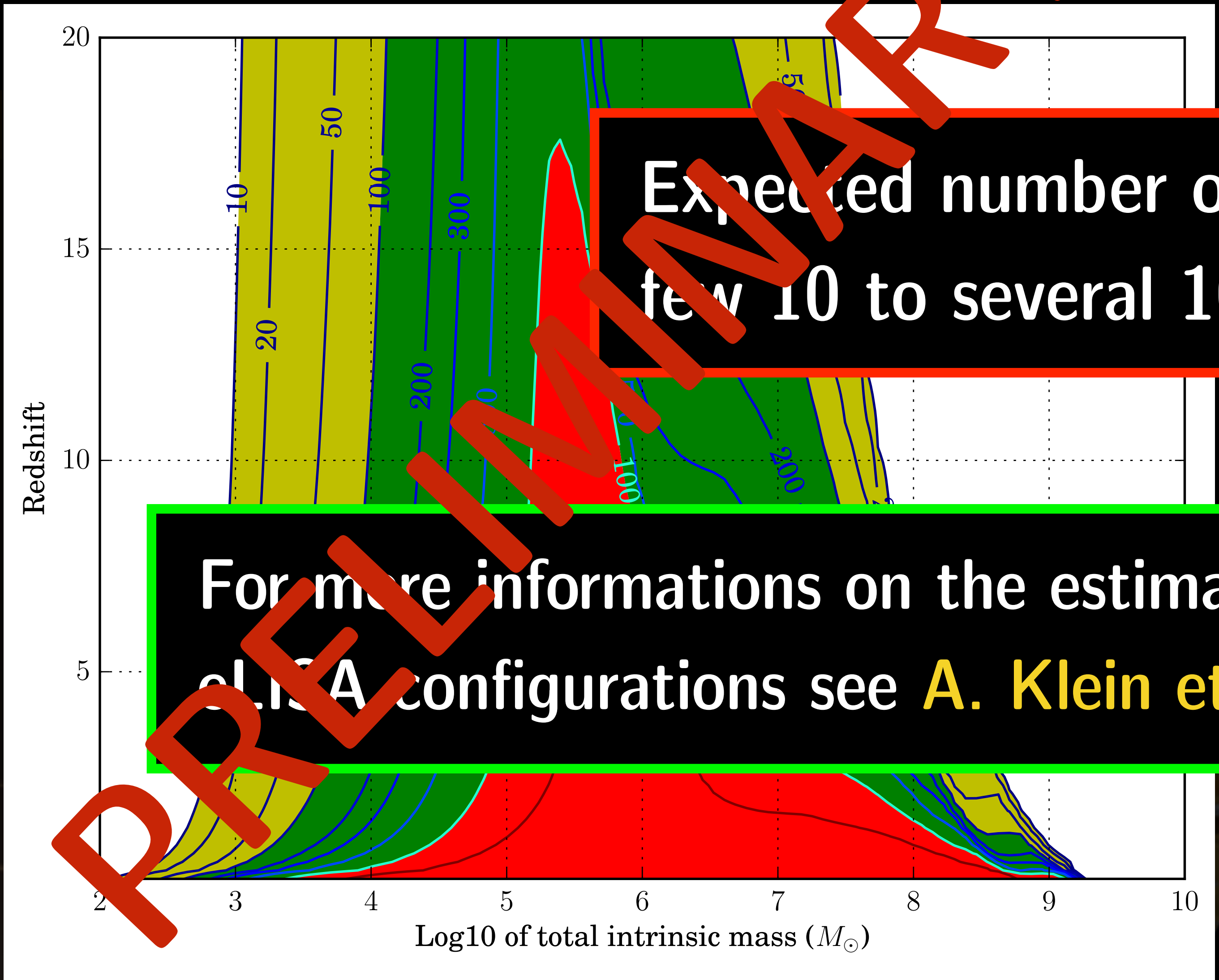

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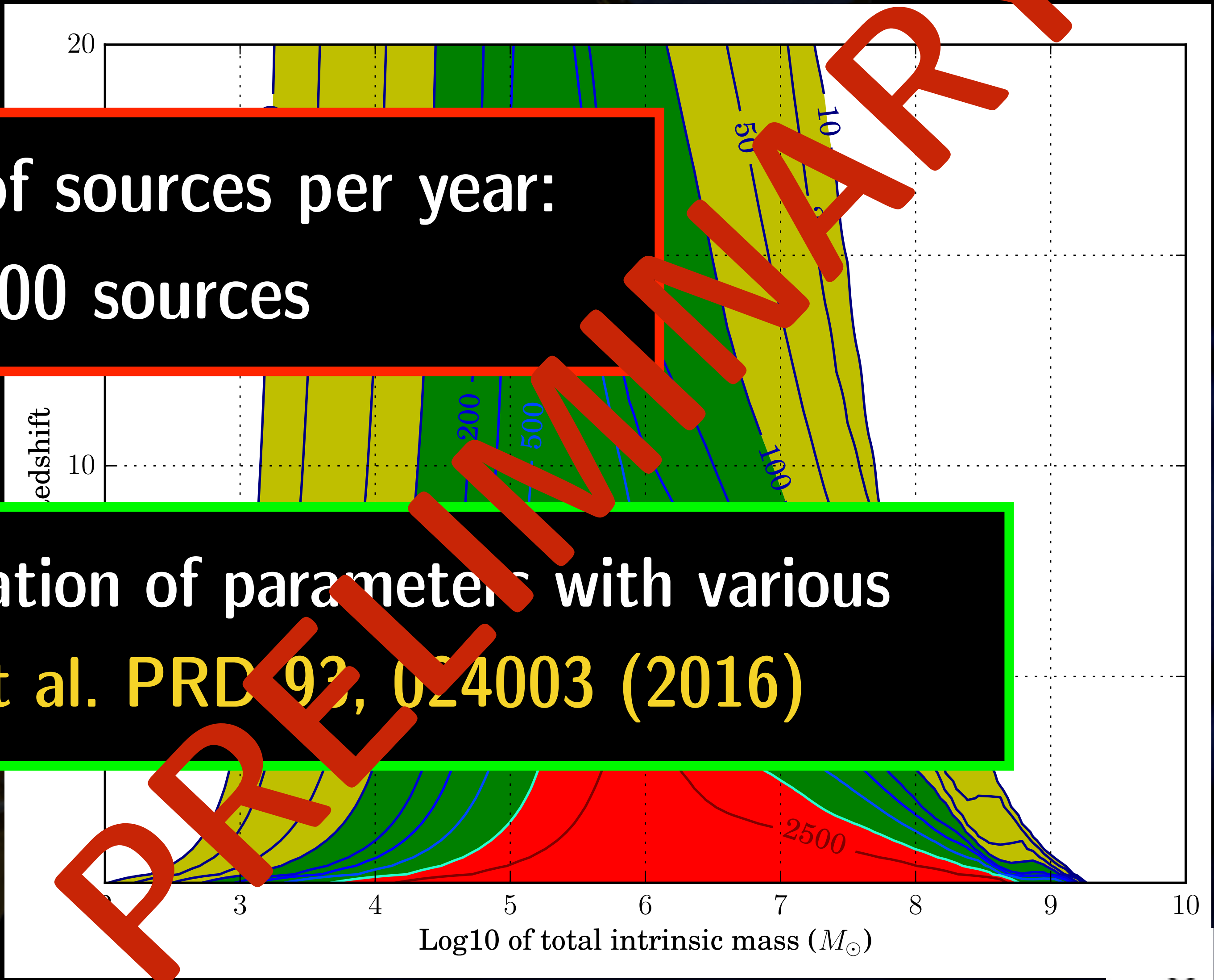

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For more informations on the estimation of parameters with various eLISA configurations see A. Klein et al. PRD 93, 024003 (2016)

LPF→LISA: SMBHBs

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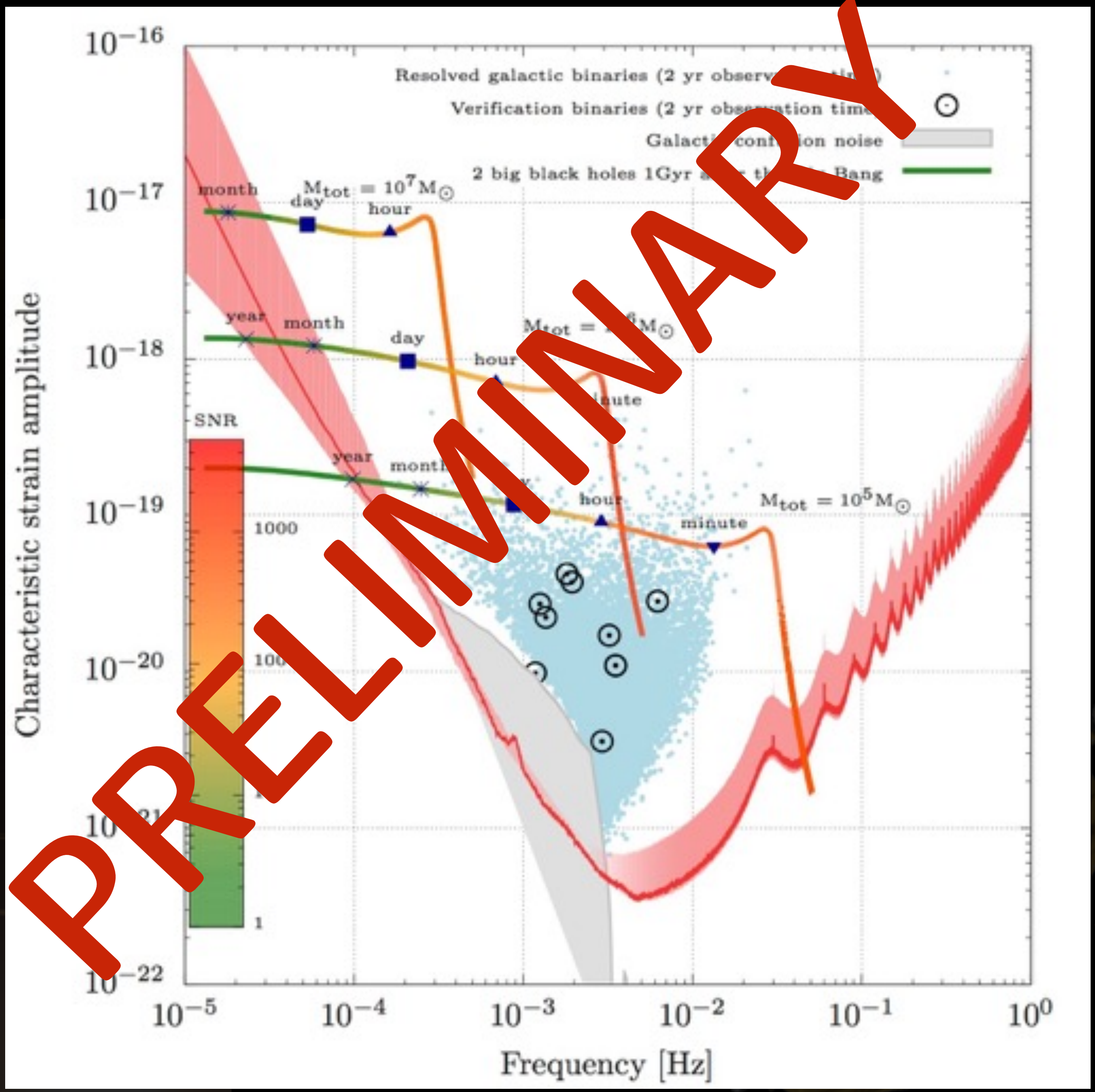

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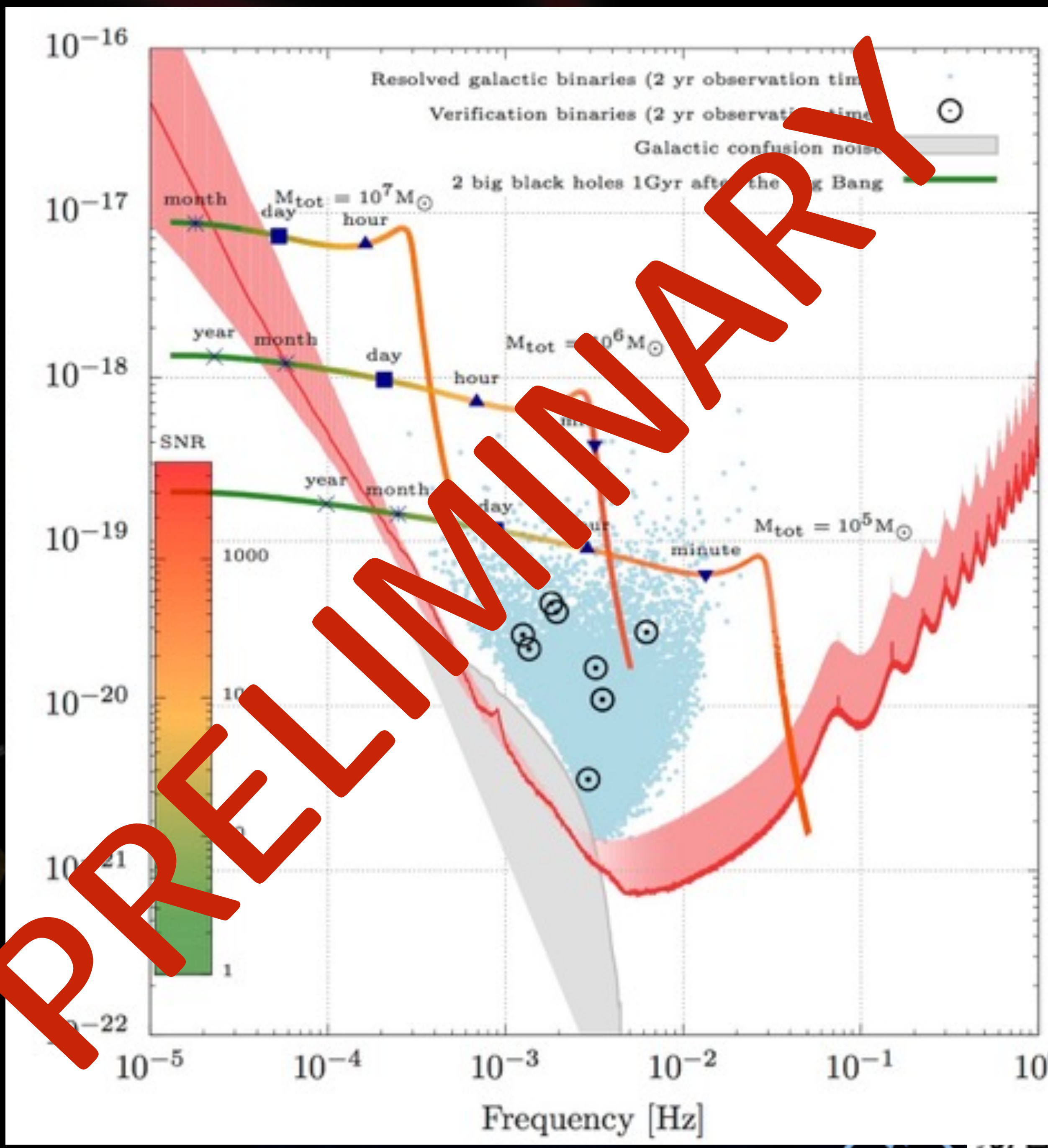
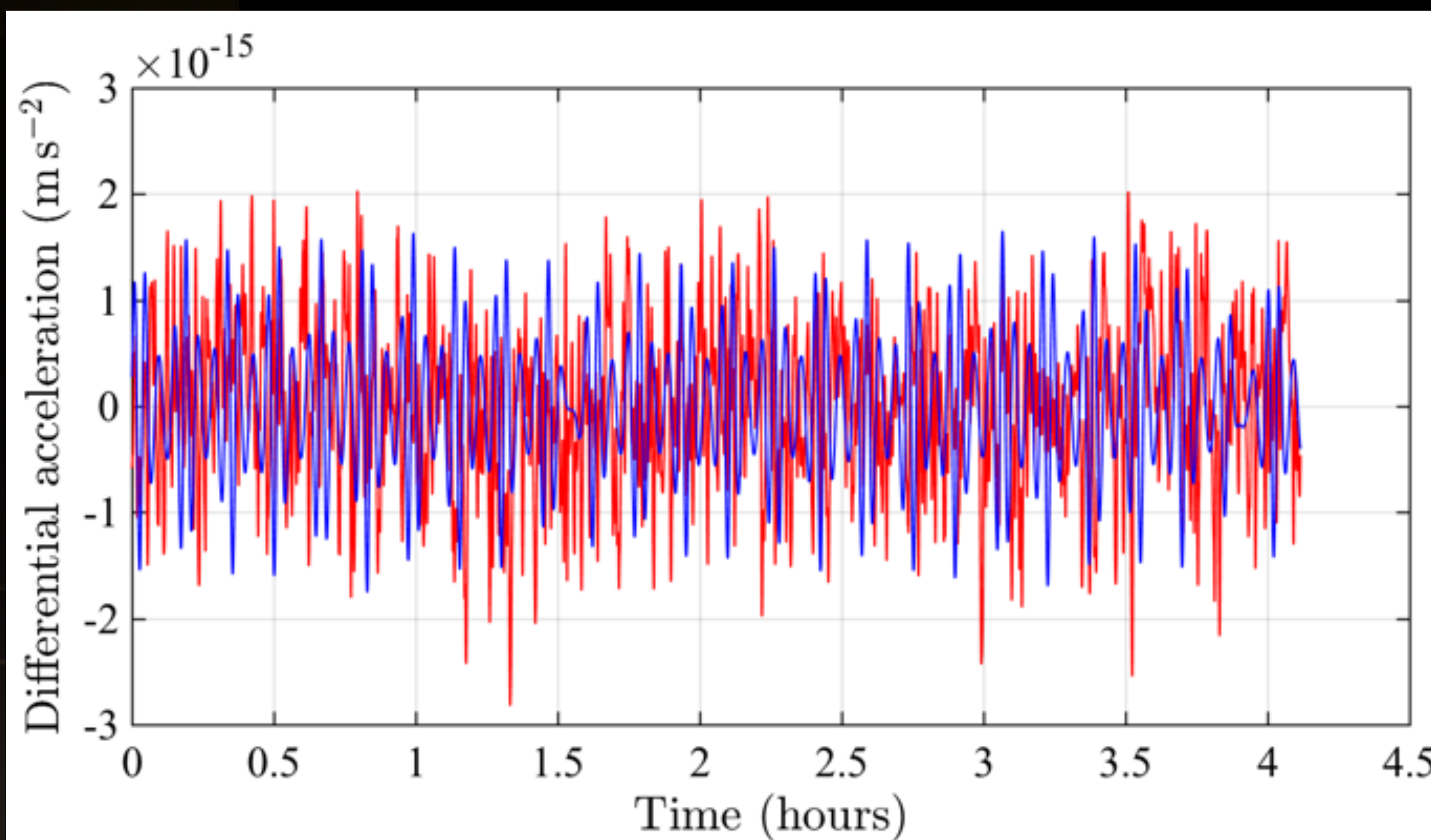
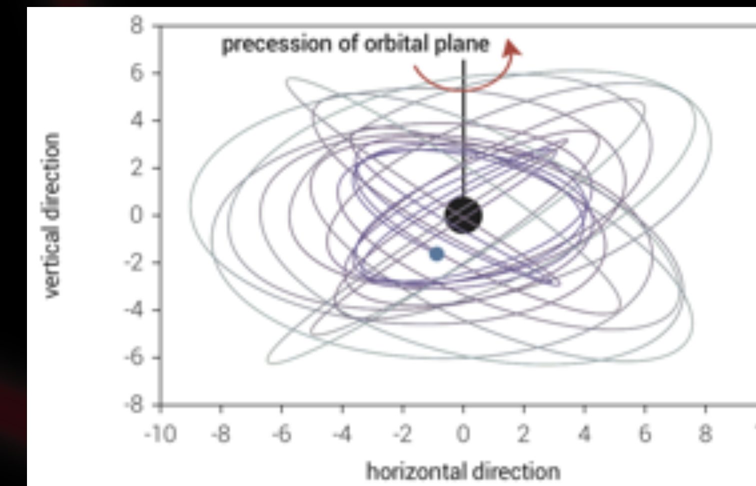


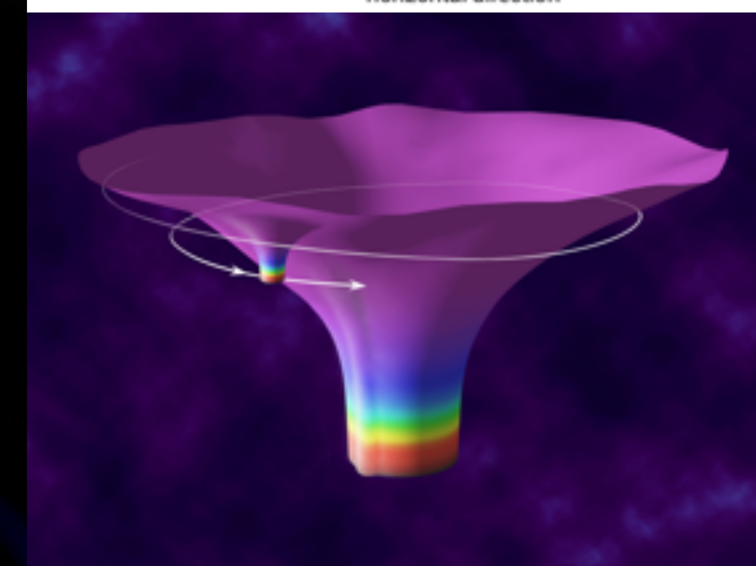
LPF→LISA: EMRIs

- 10^6 – 10 M_{Sun} at 1 Gpc (generated by C. Sopuerta): signal for one LISA arm on top of LISAPathfinder noise

- Coherent signal over a year



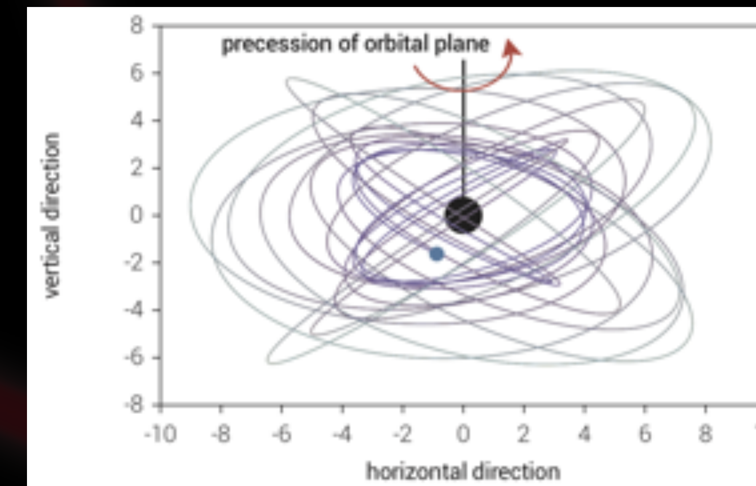


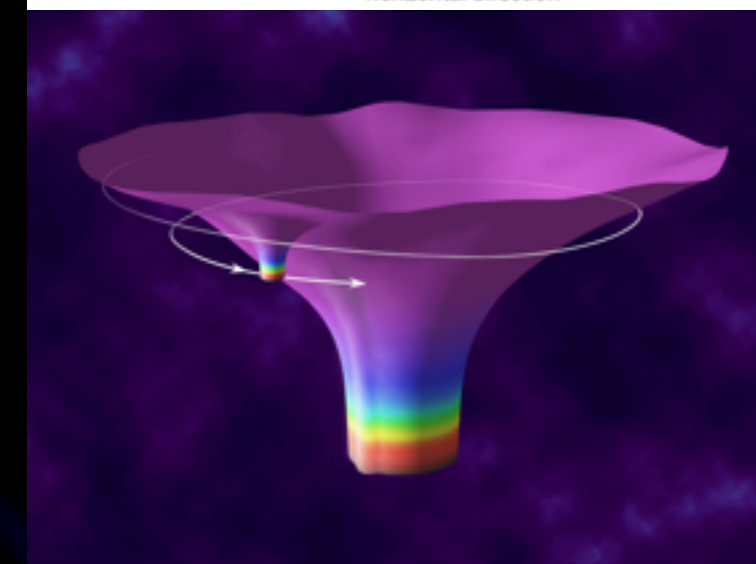


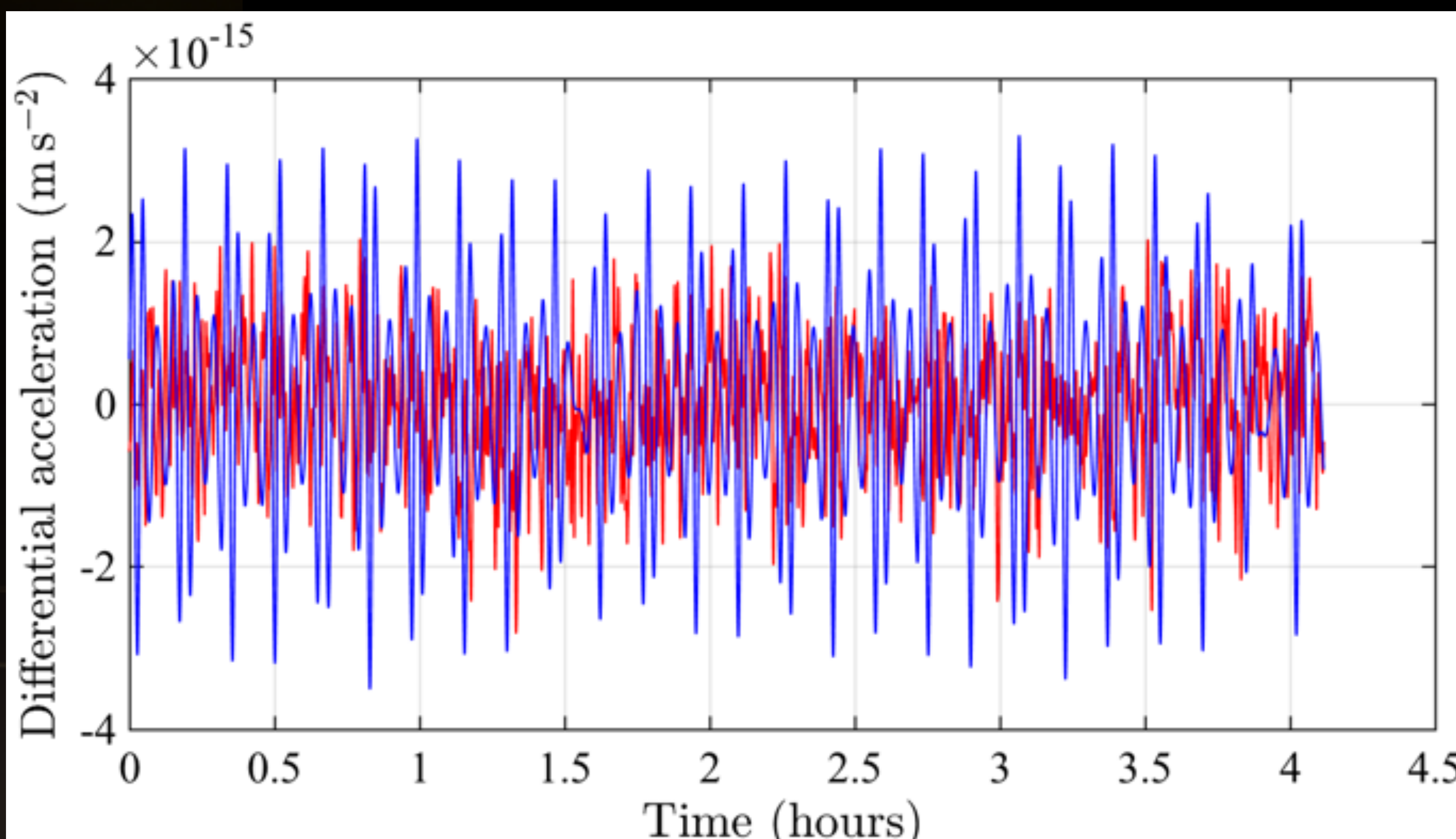
Work in progress by the EMRI WG on the event rates, etc

LPF→LISA: EMRIs

- 10^6 – 10 M_{Sun} at 500 Mpc (generated by C. Sopuerta): signal for one LISA arm on top of LISAPathfinder noise
- Coherent signal over a year







Work in progress by the EMRI WG on the event rates, etc

LPF→LISA: EMRIs

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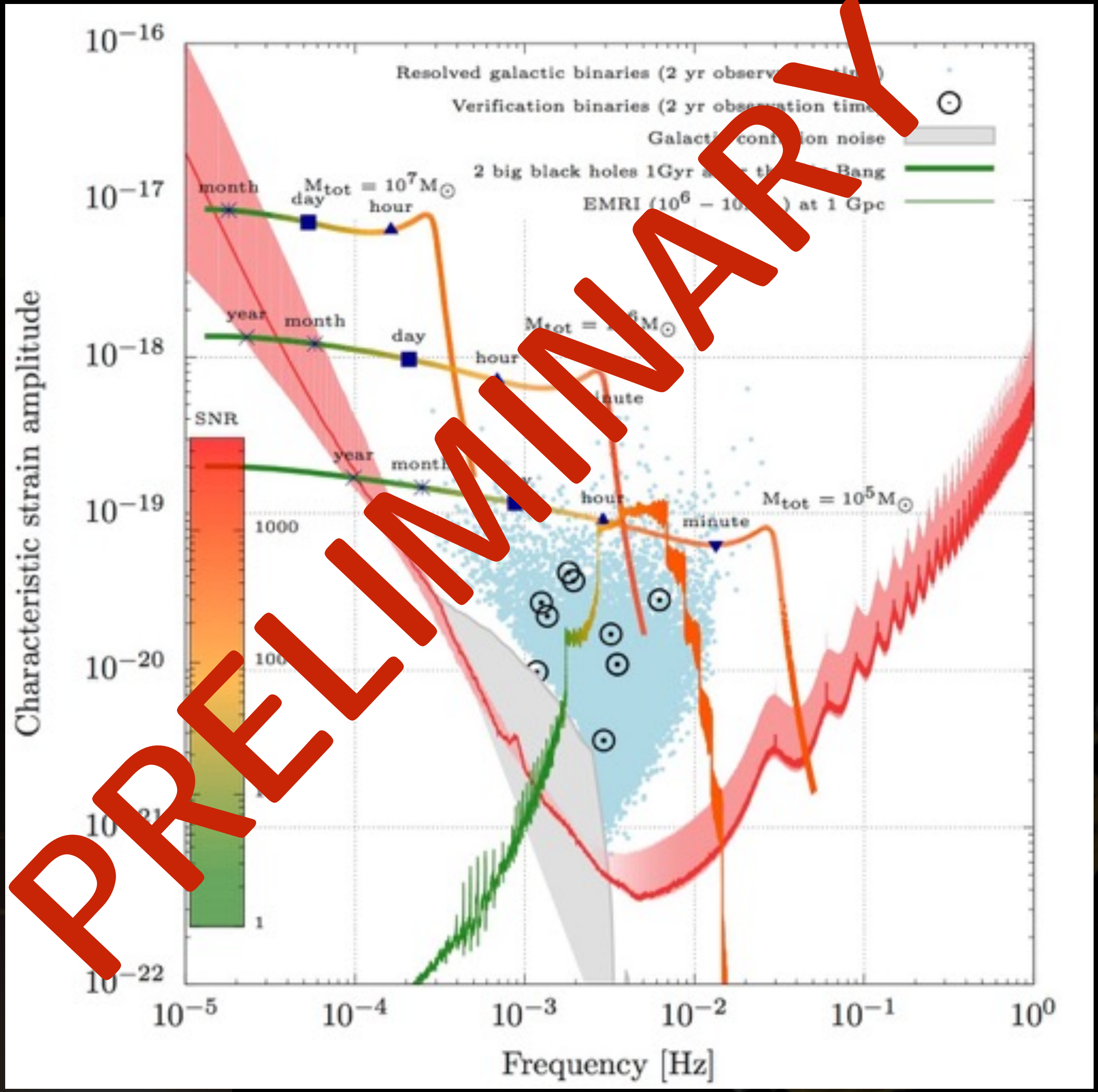

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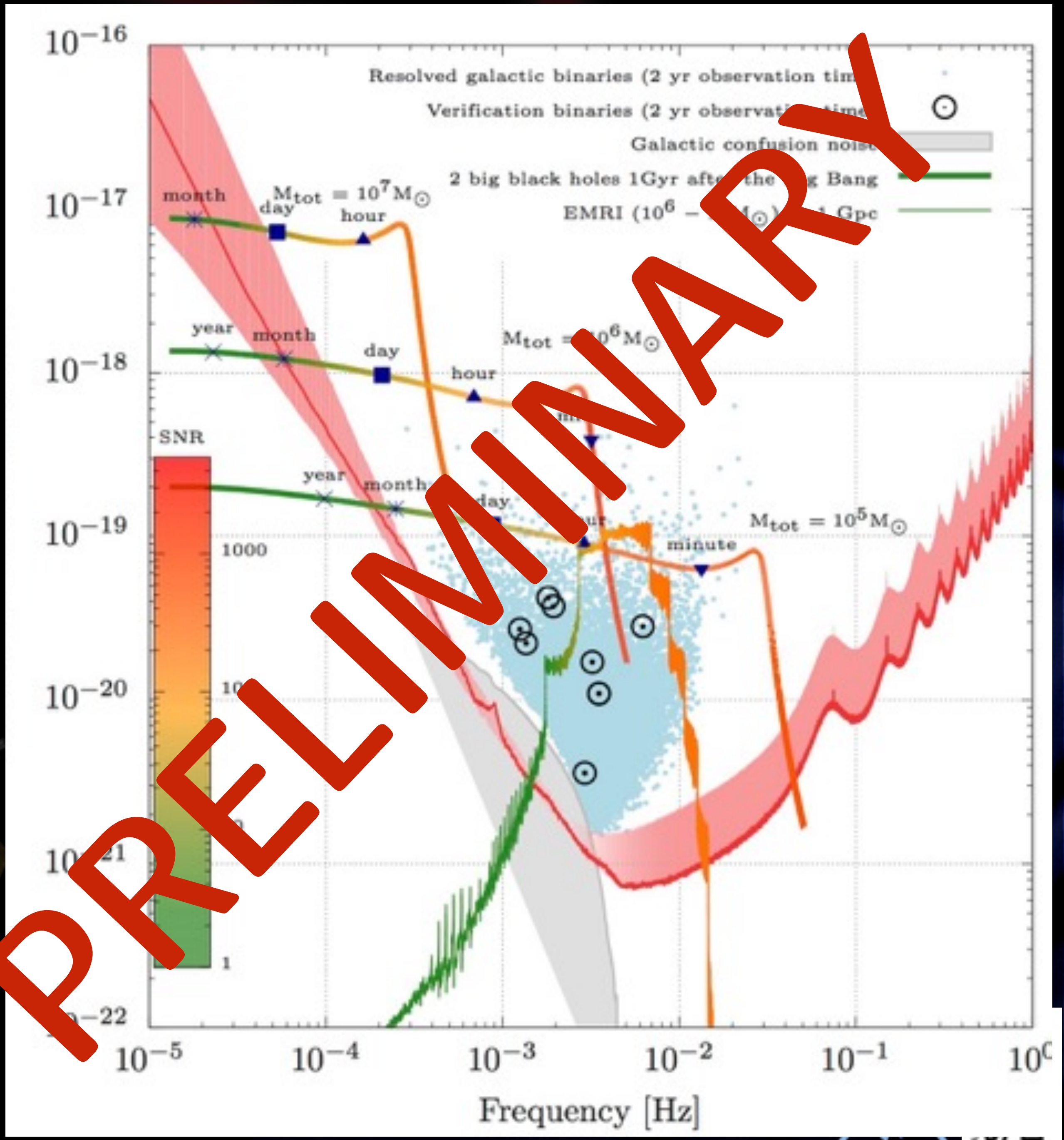
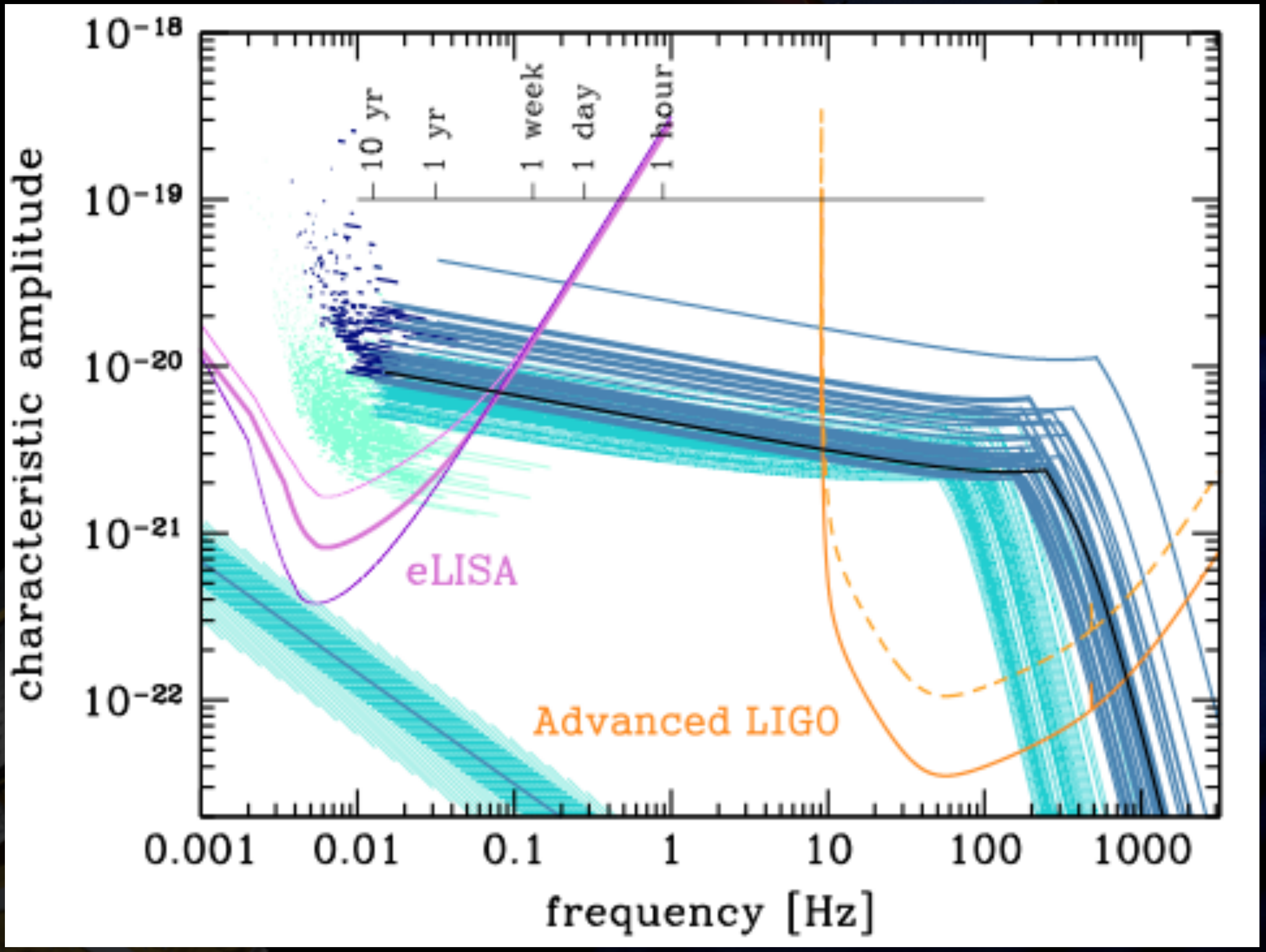


Black Hole Binaries

- Black hole binaries of few tens solar masses (as GW150914)
- With LPF-LISA : work in progress ...

A. Sesana,
PRL 116,
231102 (2016)



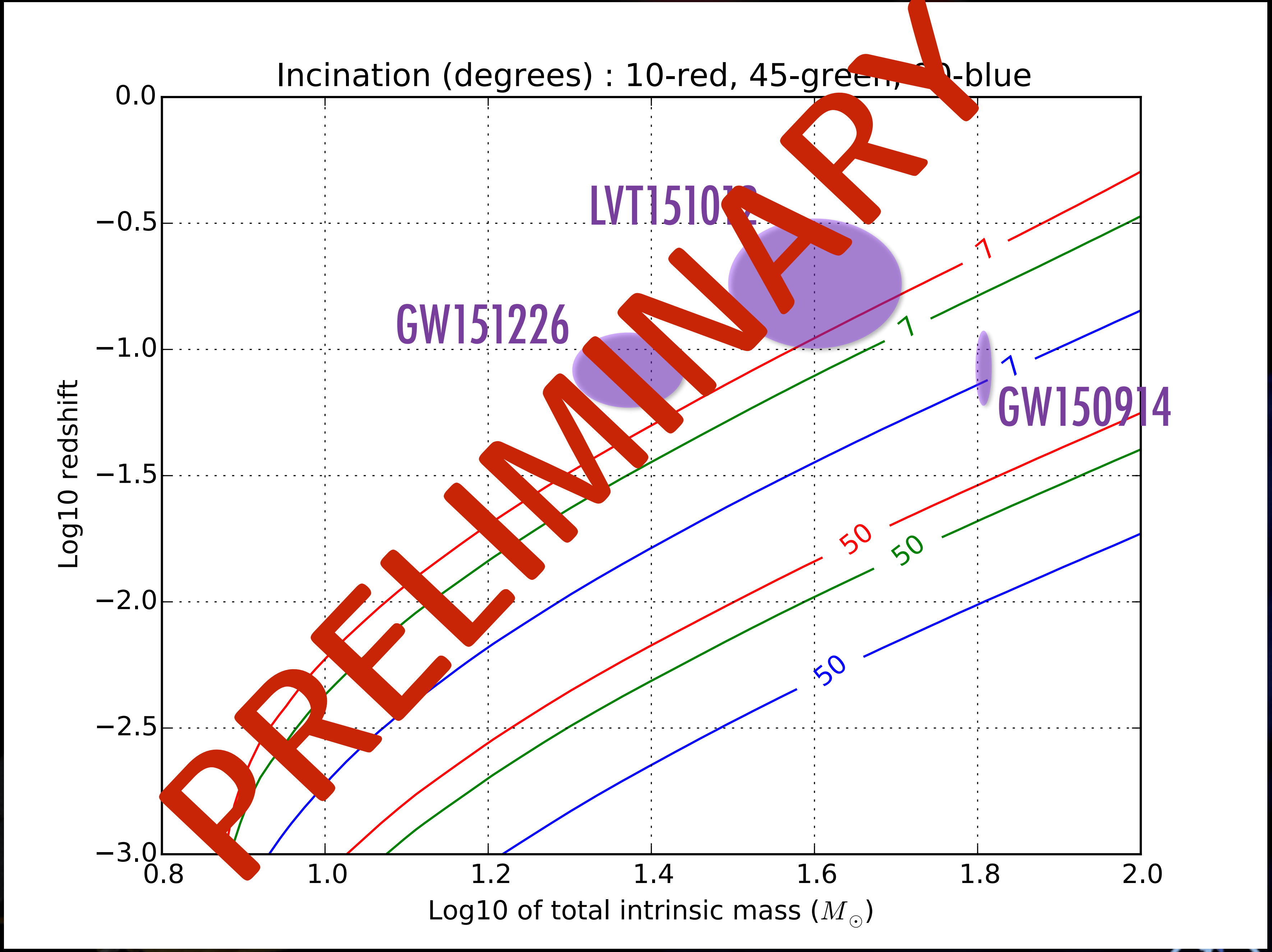
Talk from
Alberto Sesana

Black Hole Binaries

- Performance of LISA for BHB (model independent) : PRELIMINARY result : SNR contour plot

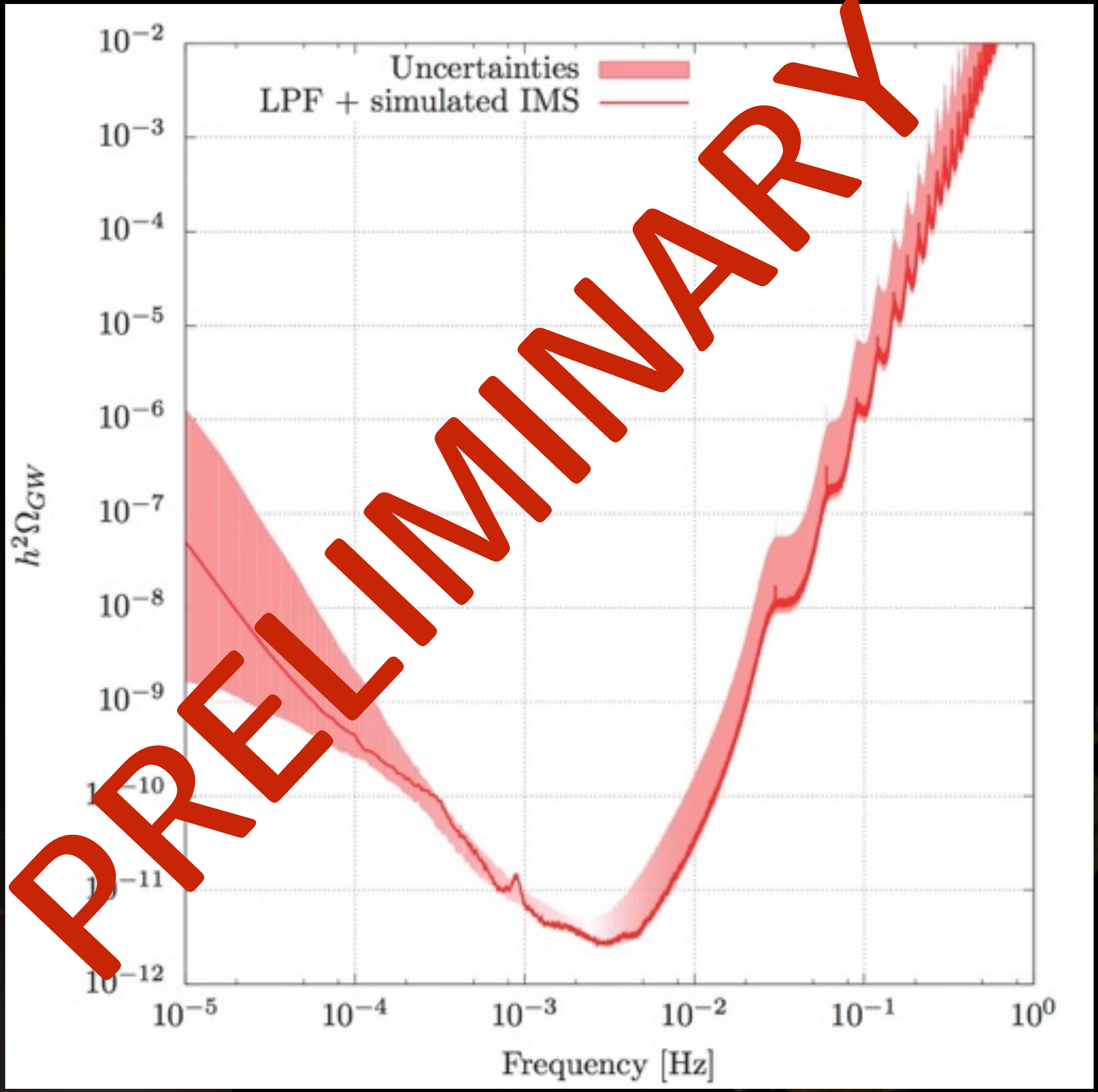
Configuration:
GOAT version
of
L6A2M5N2P2D28:
L = 2 Gm,
5 years

Need to be updated for LPF-LISA

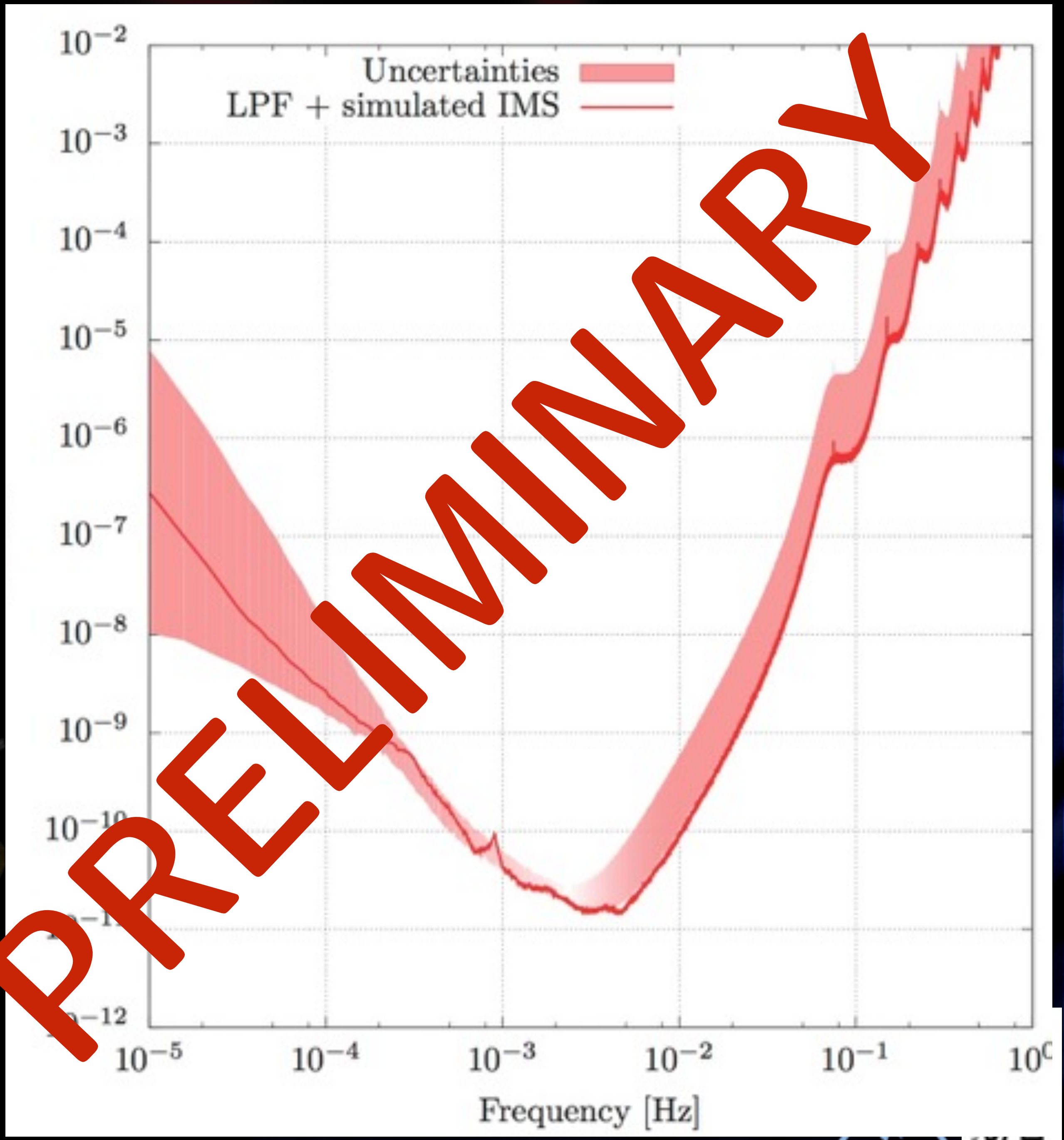


LPF→LISA: Cosmological backgrounds

L = 5 Gm



L = 2 Gm



LPF→LISA: Cosmological backgrounds

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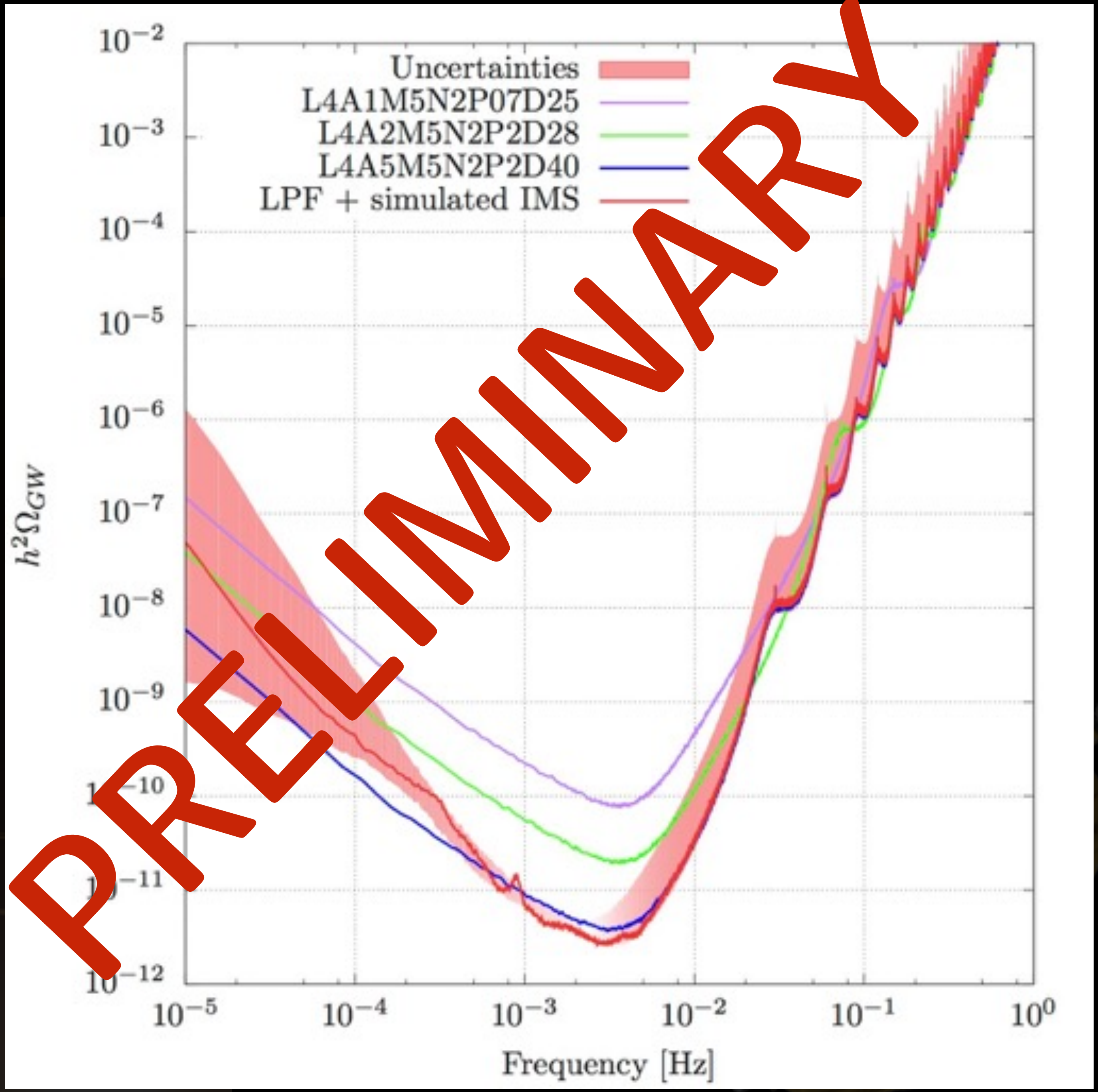

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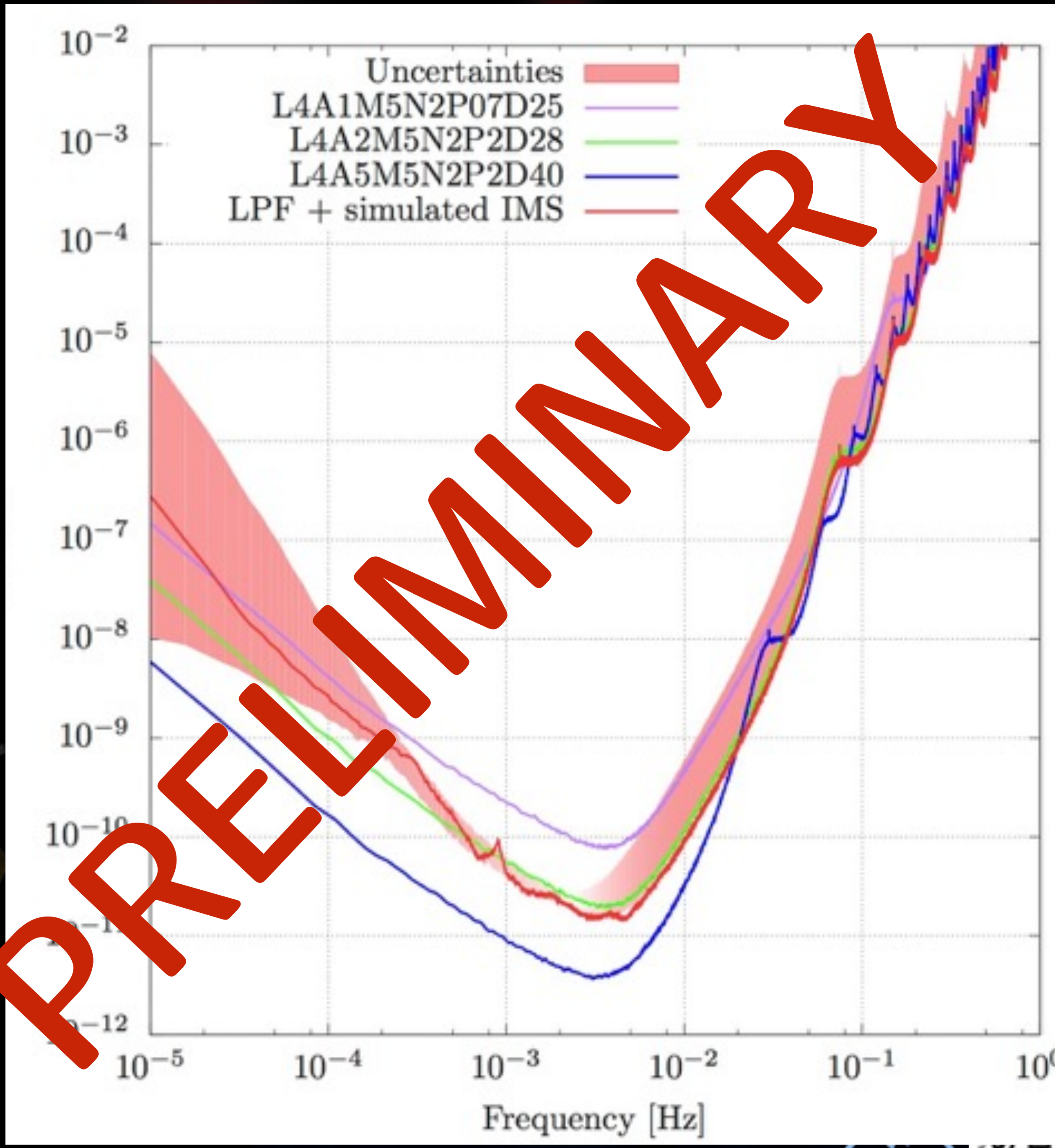

LPF→LISA: Cosmological backgrounds

- Power Law Sensitivity introduced by Thrane & Romano 2013

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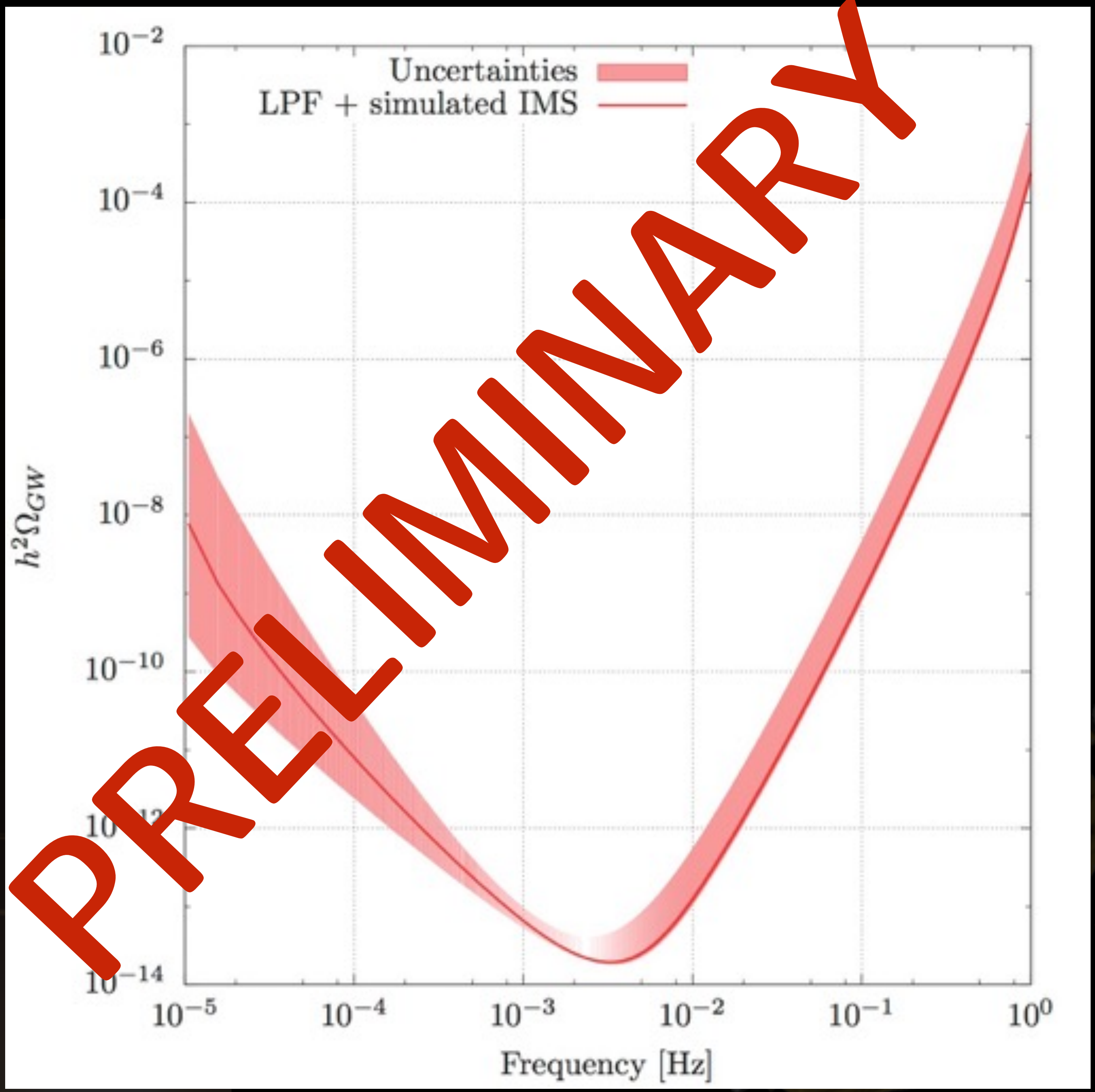

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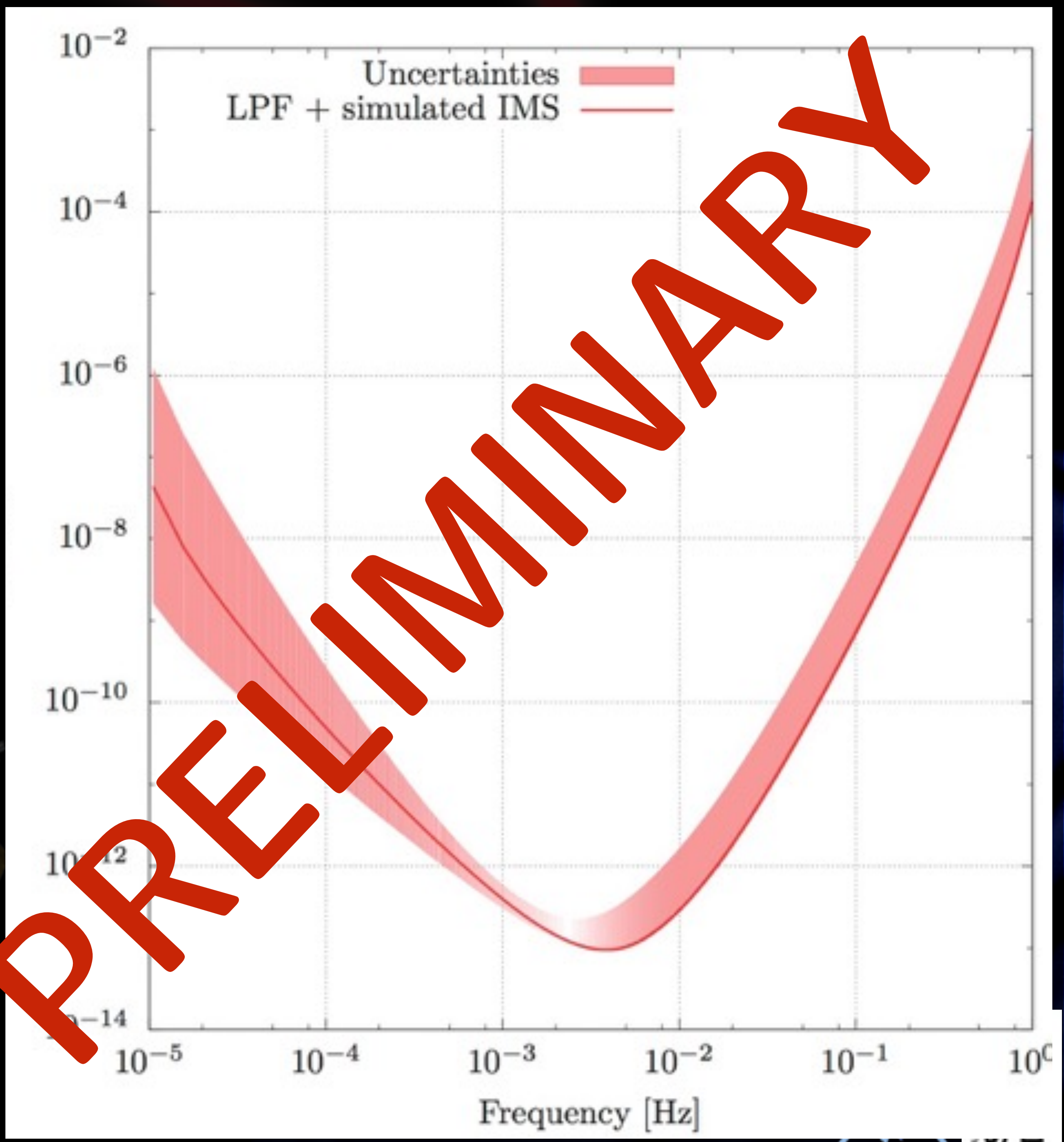

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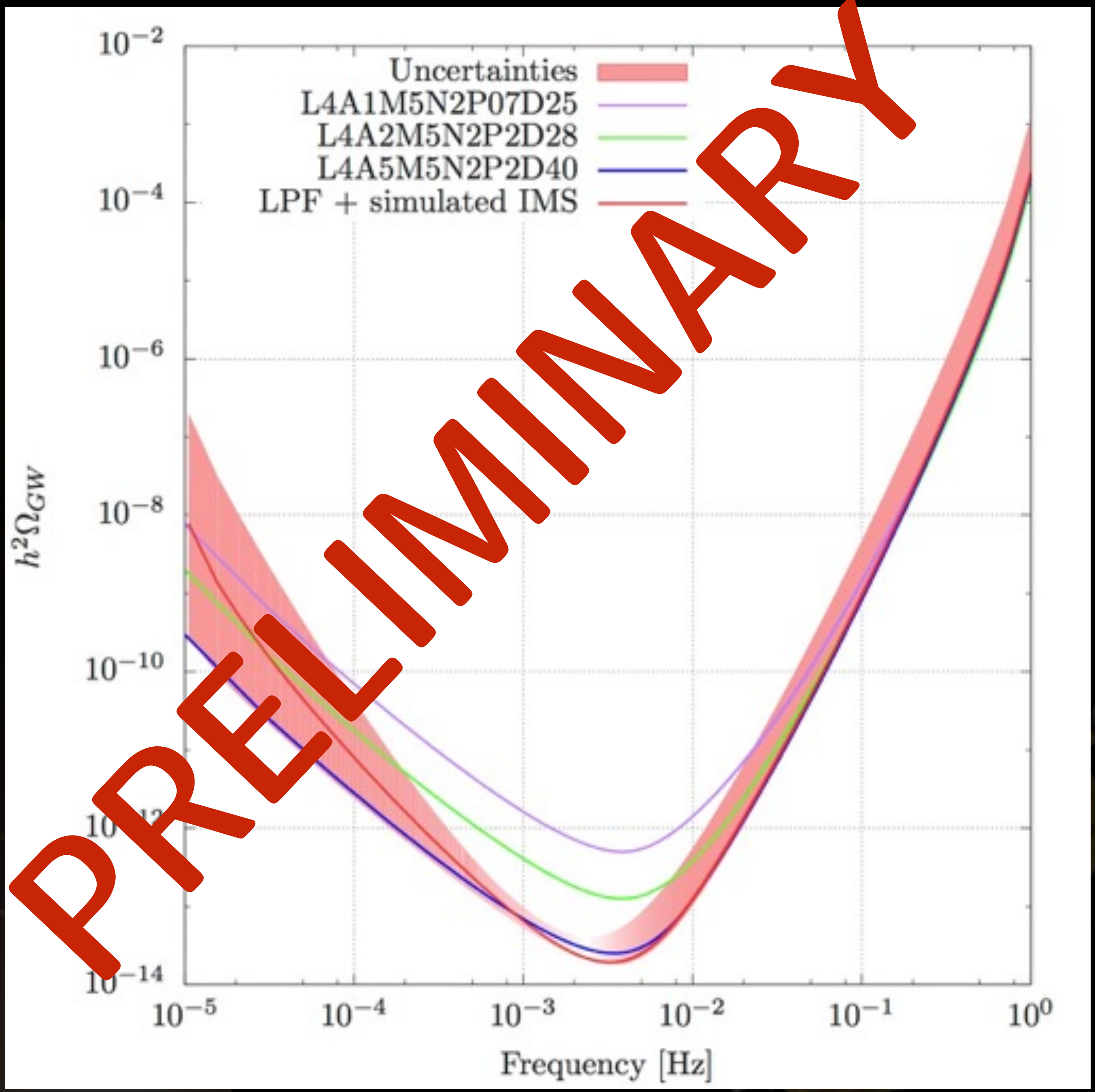

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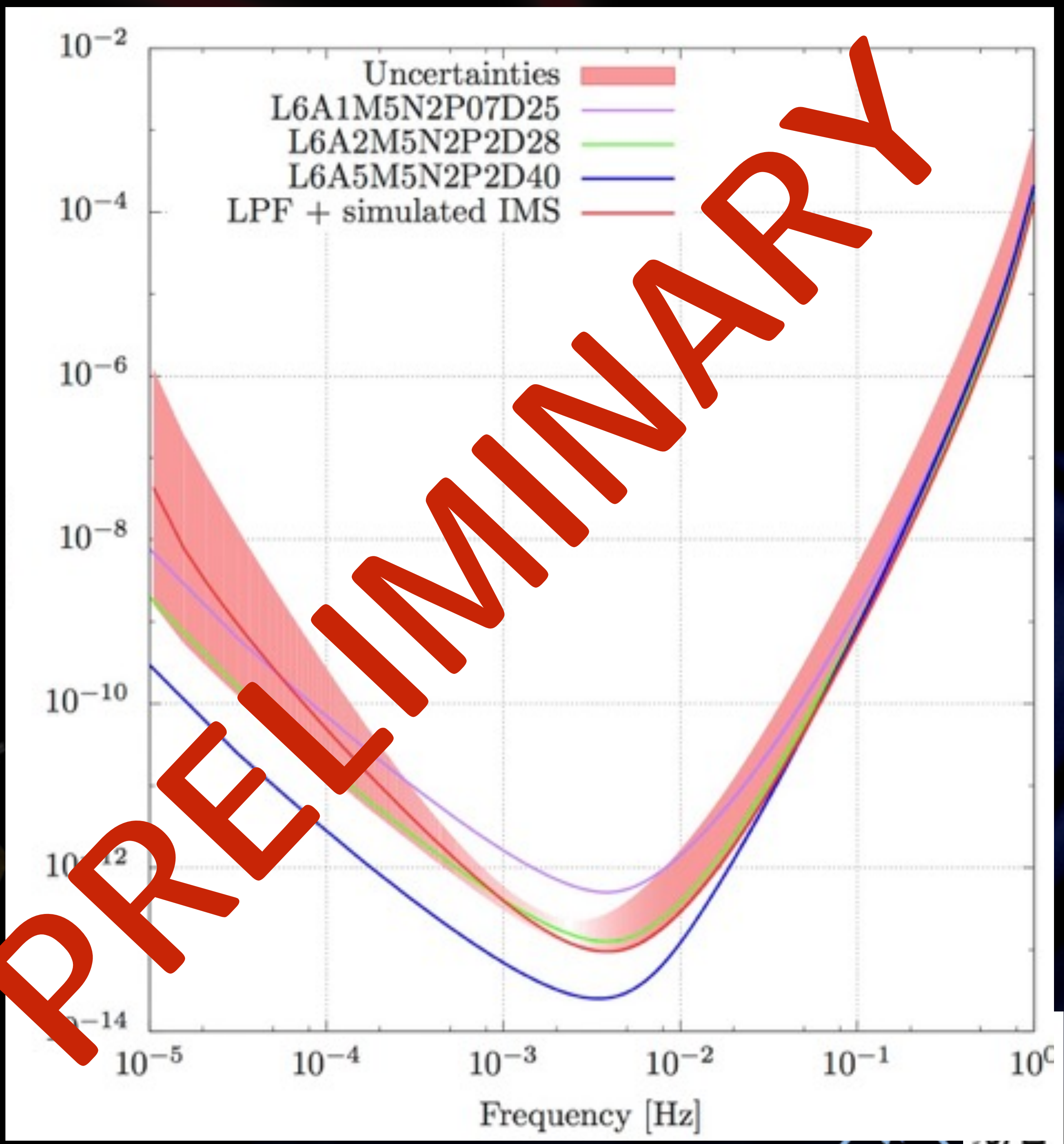
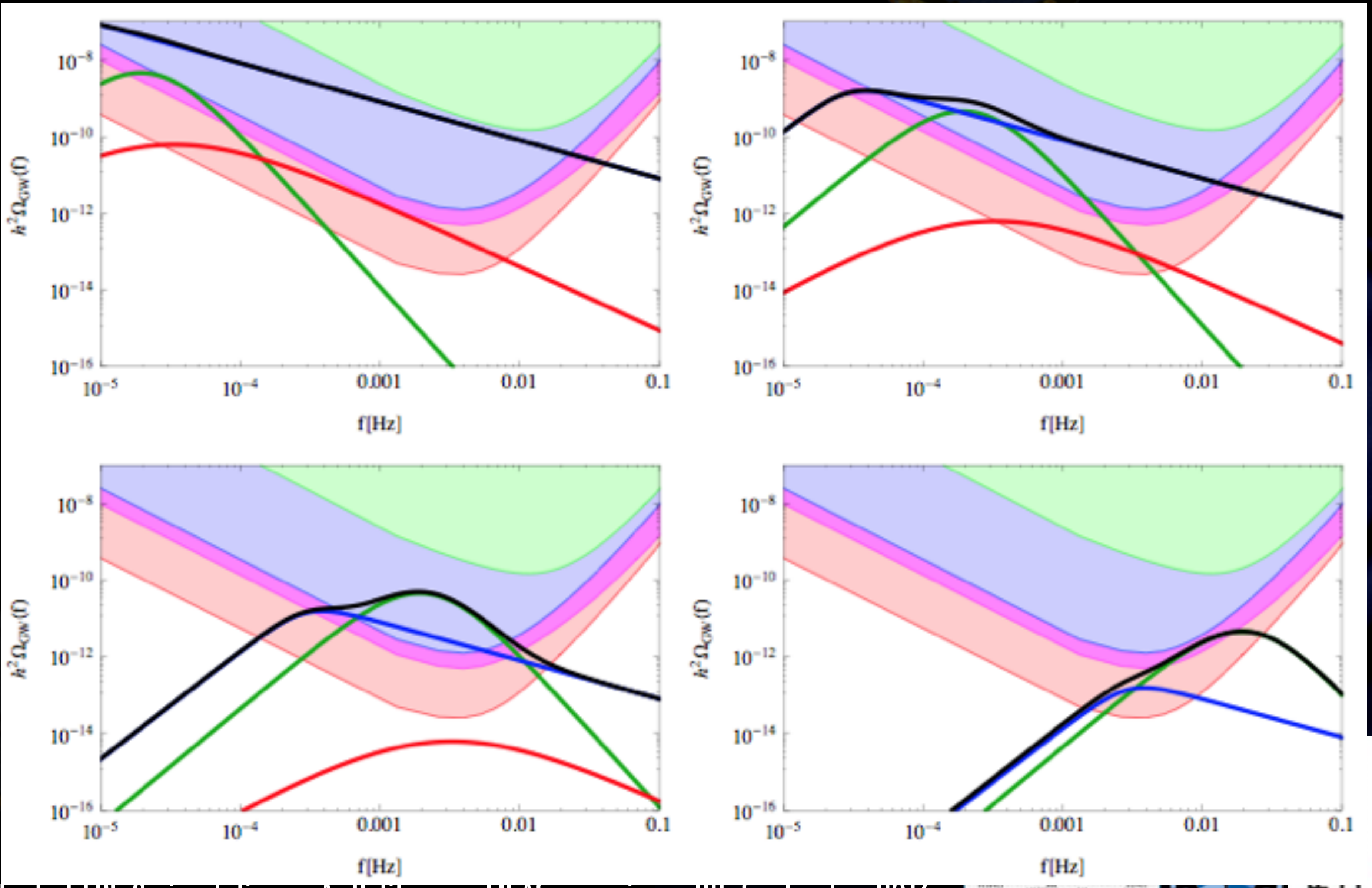


Cosmological backgrounds

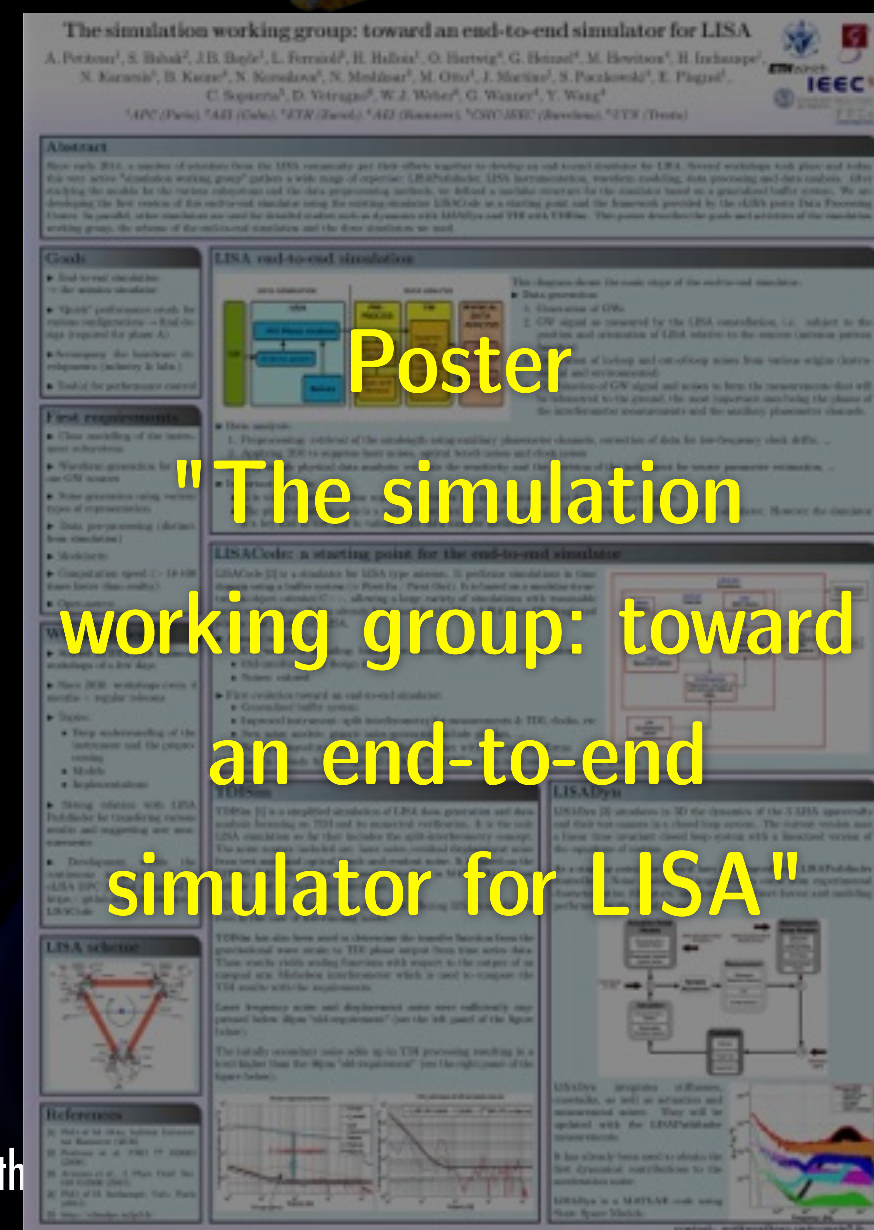
- The Cosmology Working Group already did studies in the context of eLISA (GOAT configuration):
  - Ex: first order phase transition in the very early Universe
    Caprini et al. JCAP 04, 001 (2016)
  - Cosmic strings network
  - ...



Next step

- Complete this update of science case
- Transfer LISAPathfinder noise budget to LISA
- Improve the modeling of the high frequency noise: use
  - split TDI interferometry (M. Otto's PhD)
  - last noise modes
- Complex simulations (dynamics, ...)
- Implement more precise waveforms
- ...

Activities of the Simulation Working Group



Poster "The simulation working group: toward an end-to-end simulator for LISA"

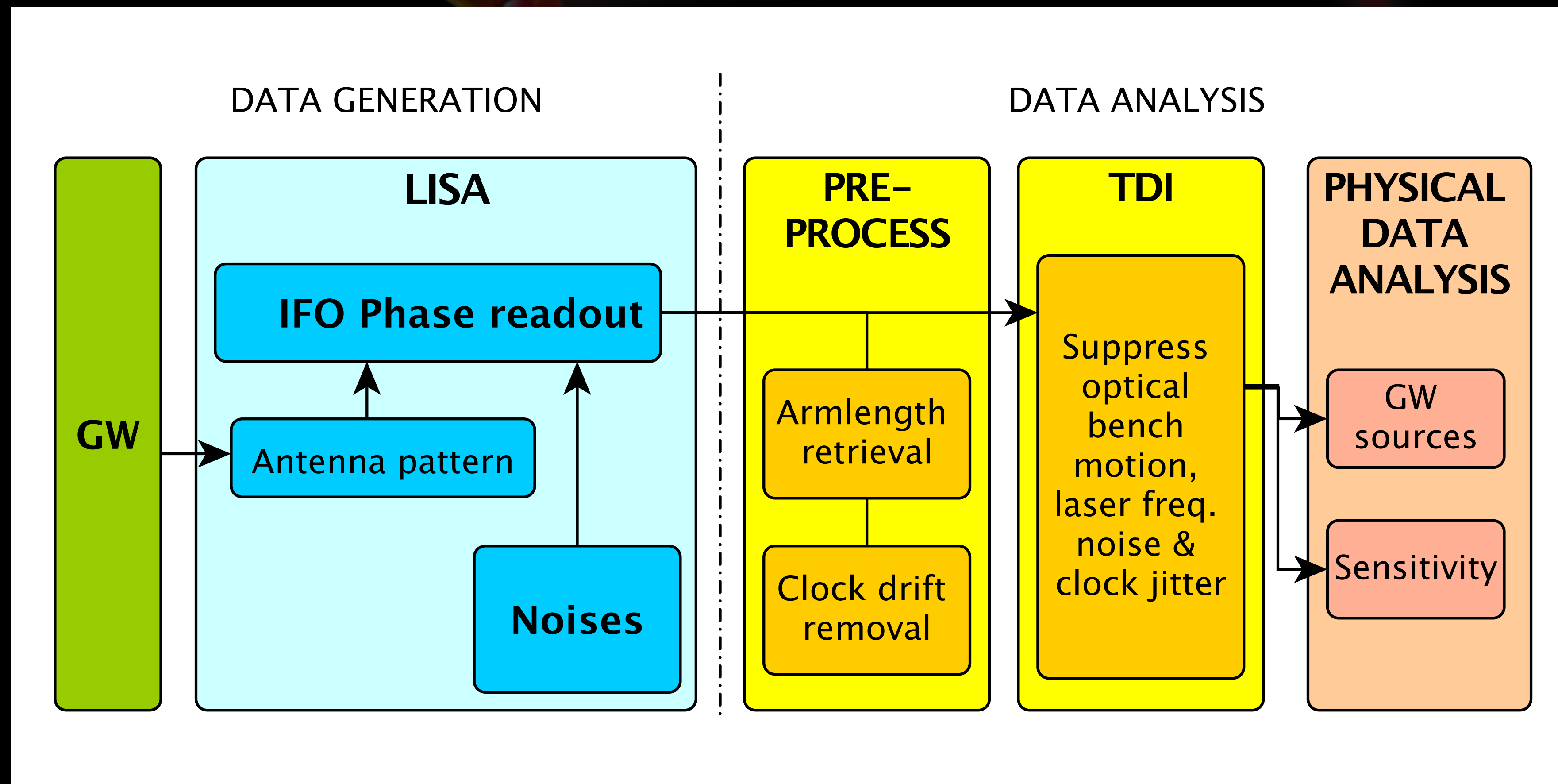
The Simulation Working Group

- 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 !

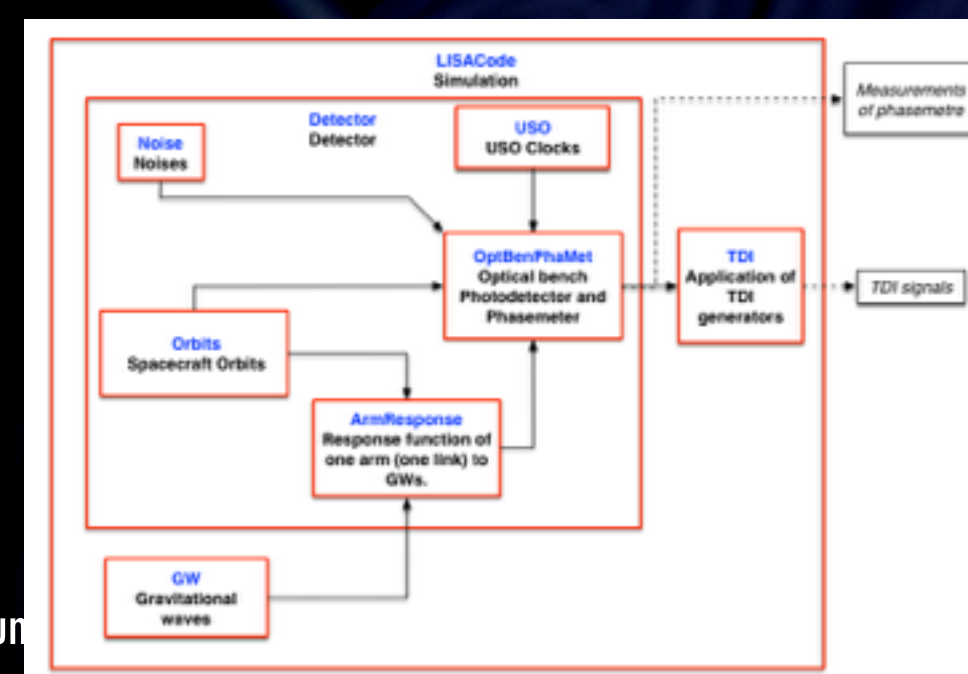
The Simulation Working Group

- **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

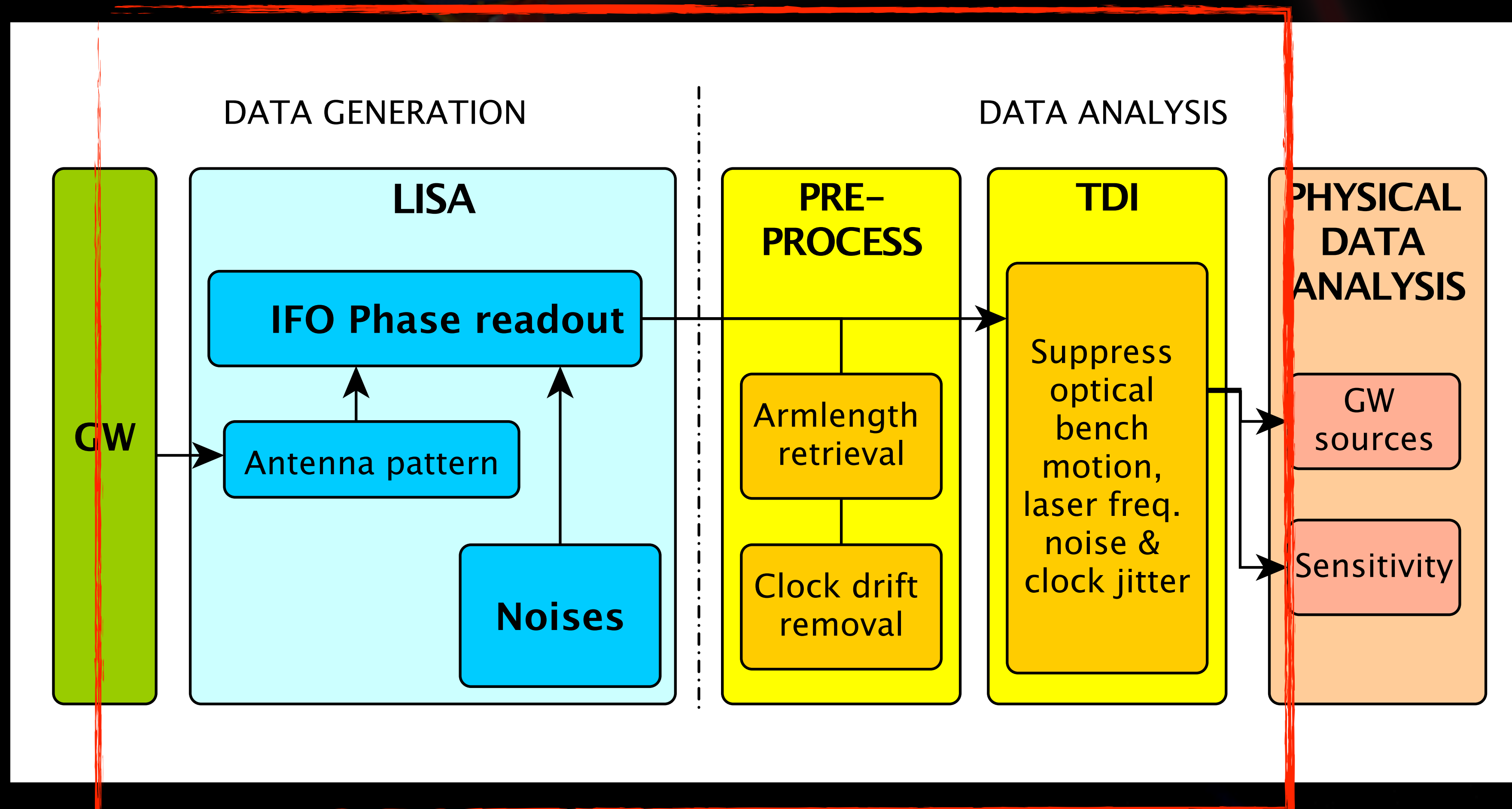
The Simulation Working Group



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



The Simulation Working Group



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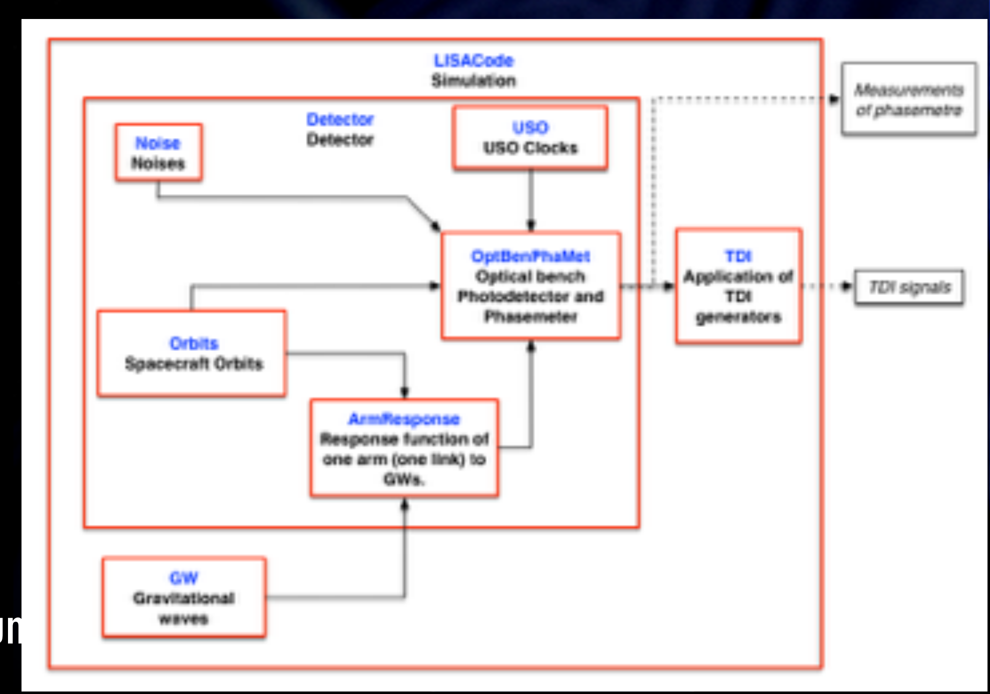
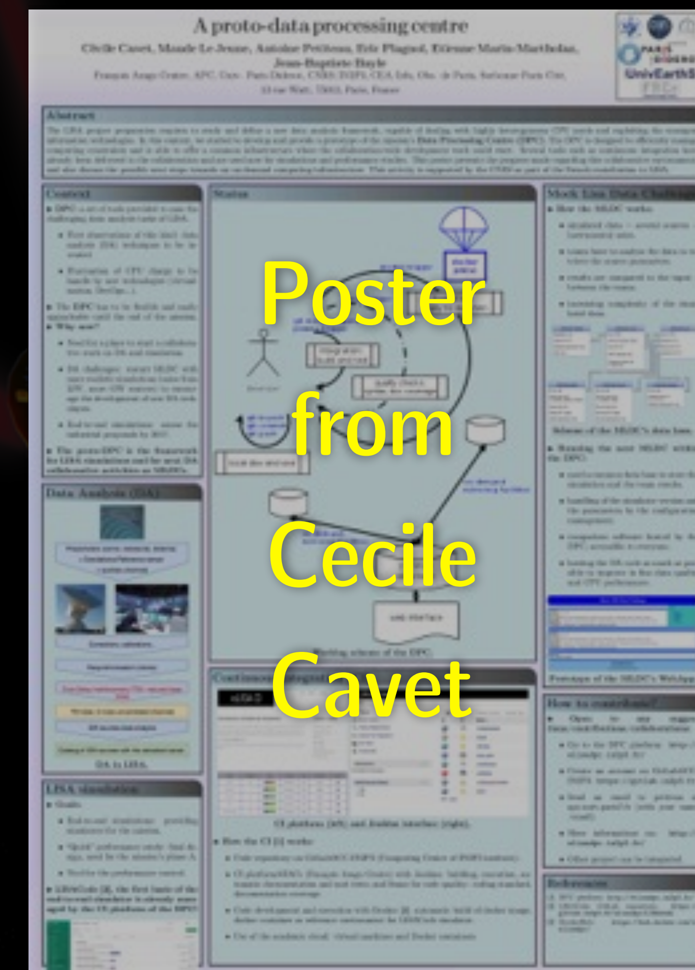


The proto Data Processing Center

- Development started after a CNES phase 0 study
- Tool for the consortium
- DPC:
  - 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 and for future MLDC



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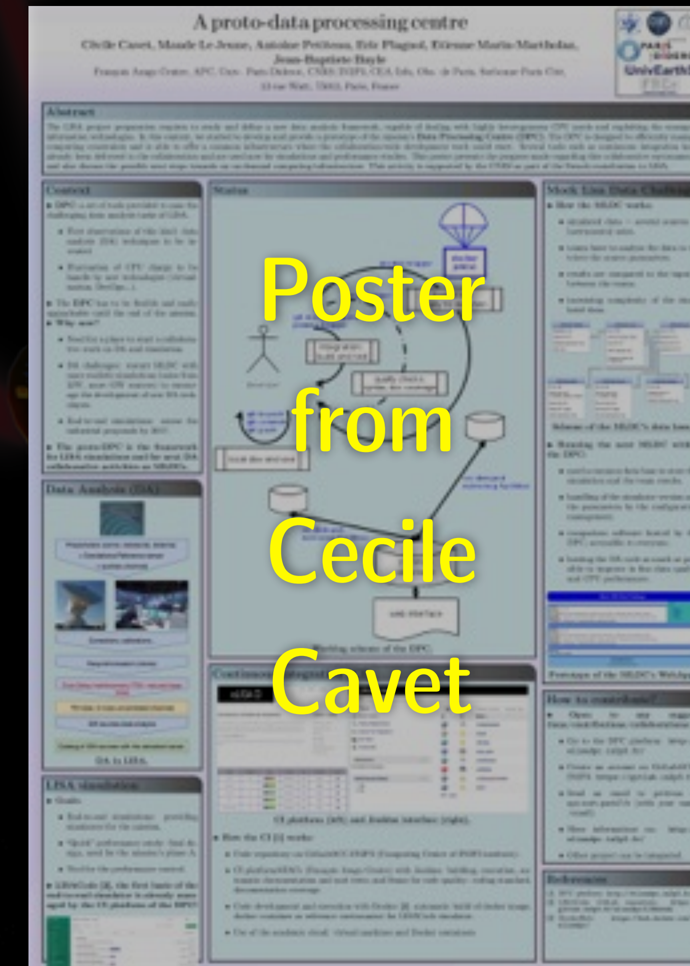
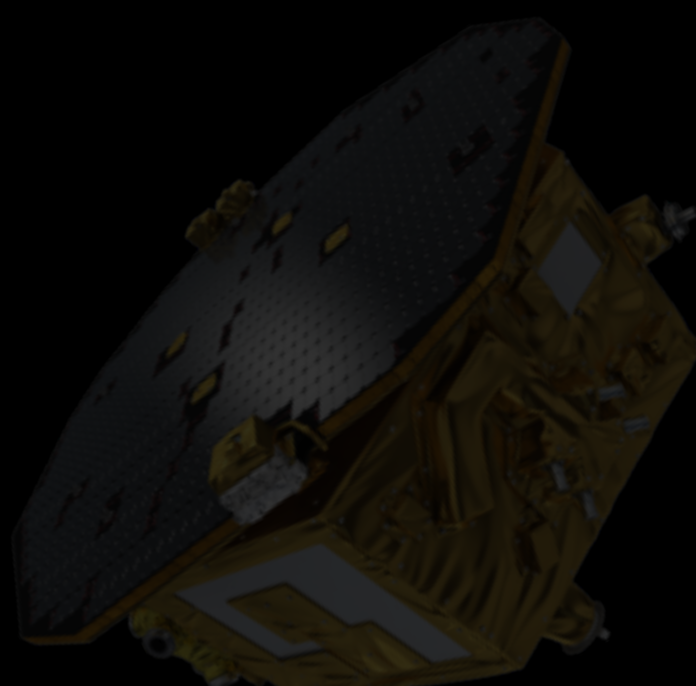
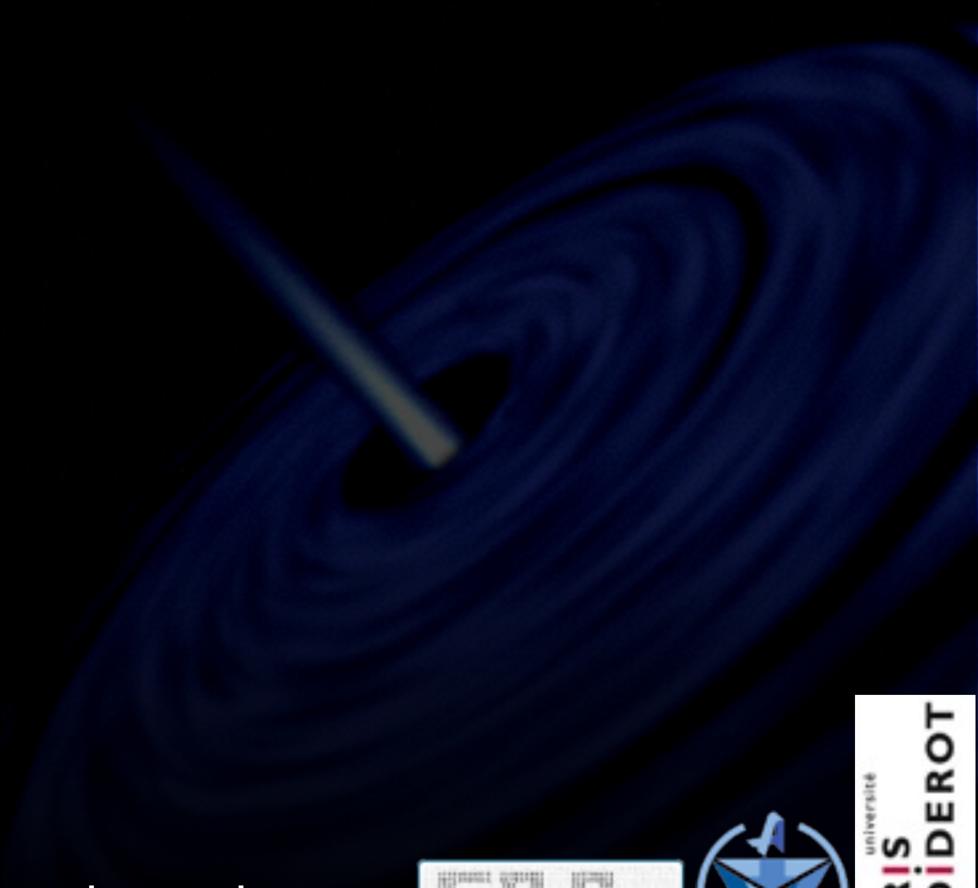


Conclusion

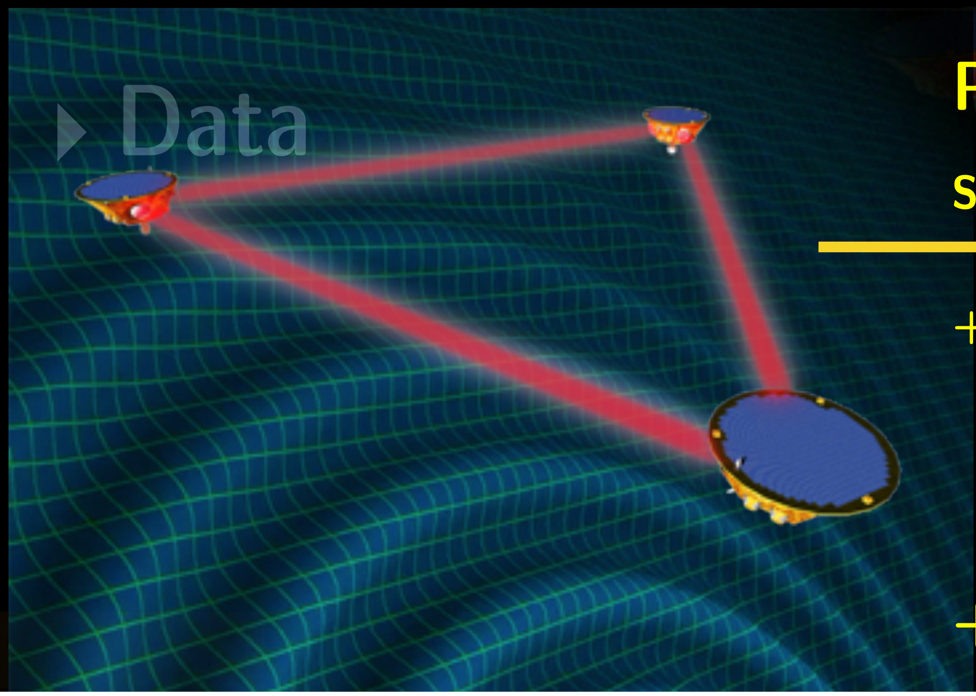
- The excellent LISAPathfinder results enable good performance of LISA for most of the sources => large science case
- Next steps:
  - Consolidate the noise budget:
    - LPF performances at low frequency
    - Improve the simulation of the instrument according to the recent developments
  - Update sources: waveforms + populations [Talk from Stas Babak]
  - Add more parameters estimations
- The simulation/data analysis WG is working on these aspects with the support of the proto-DPC.

Thank you





LISA data processing



Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor
+ Auxiliary channels

Corrections, calibrations

Resynchronisation (clocks)

Time-Delay Interferometry laser noise reduction

TDI data : 2 uncorrelated channels

GW data analysis

Catalog of GW sources with extracted waveforms

GW sources

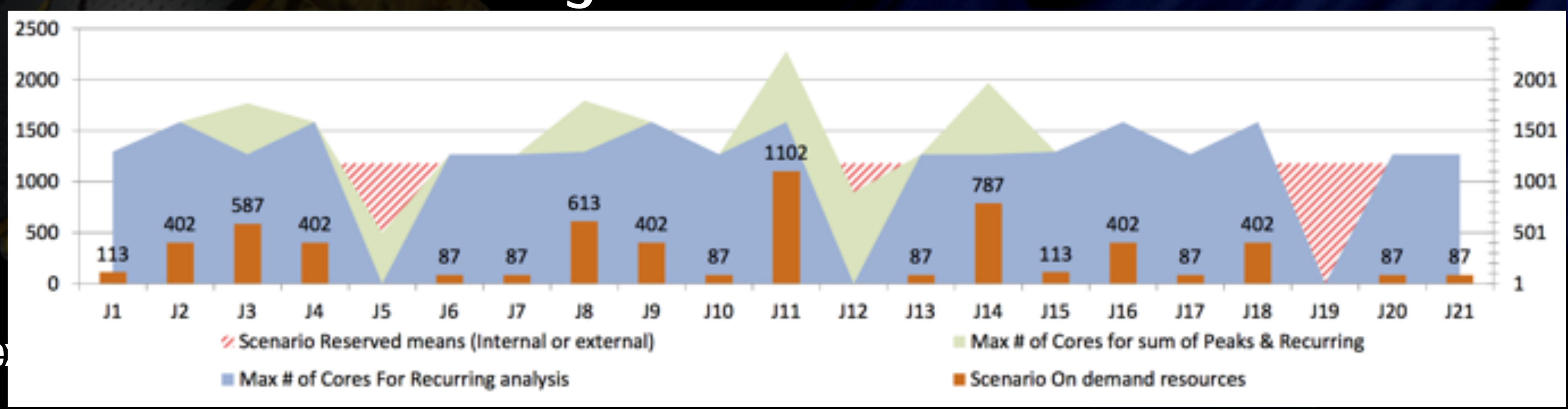
- 10-100/yr SMBHBs
- 10-1000/yr EMRIs
- 60 millions Galactic binaries
- Large number of Black Hole binaries
- Cosmological backgrounds
- Unknown sources

= ? =

DPC CNES Phase 0

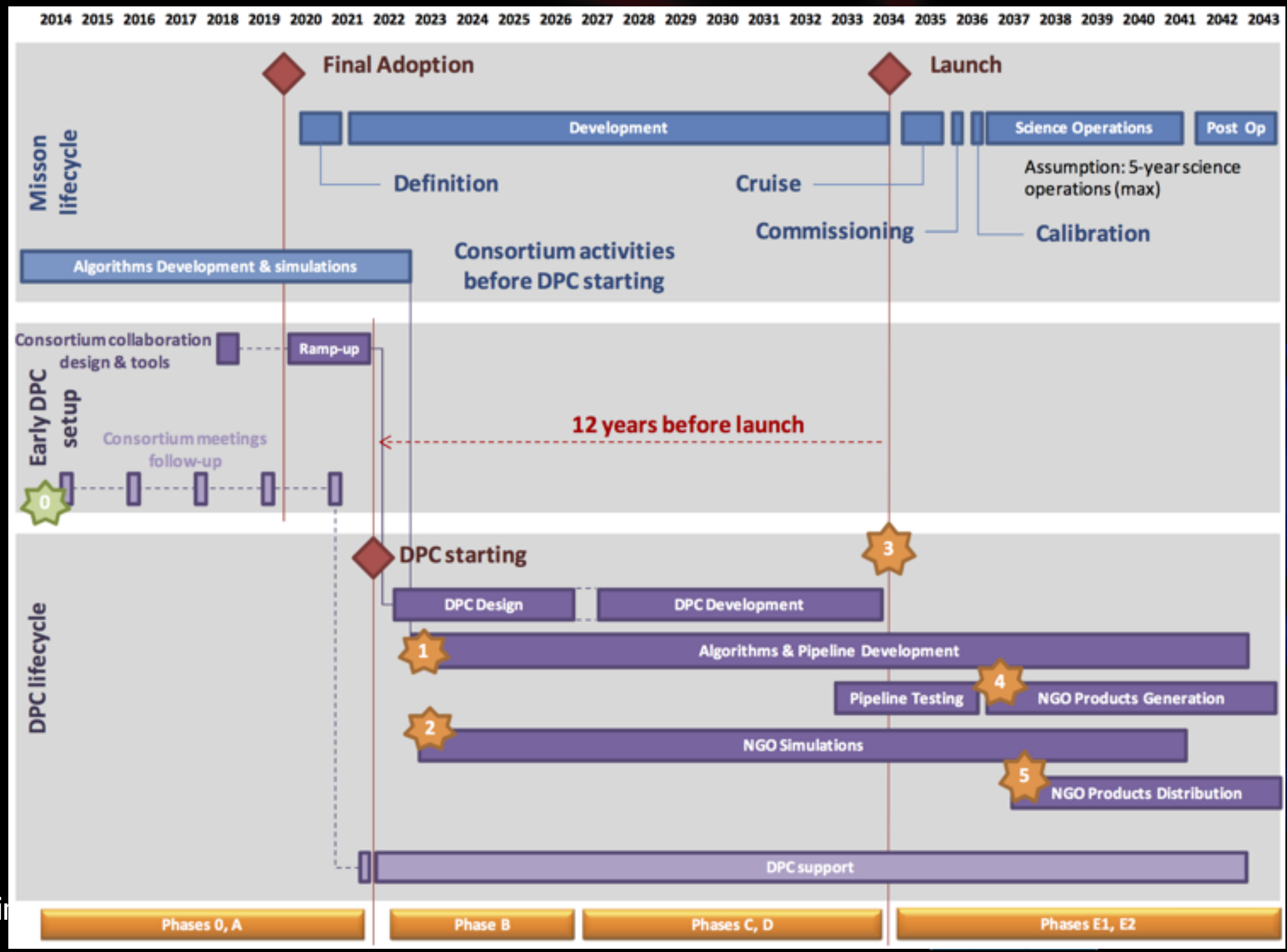
- In 2013-2014, CNES did a phase-0 with APC & CapGemini
- Results of this Phase-0 :
  - Doable within a reasonable budget (~ 22 millions euros)
  - Developments & pipelines: First analysis of this kind + potential unknown sources ➡ Keep flexibility + continuous evolution
  - Infrastructure : fluctuations of the computational charge : permanent sources + transient sources + continuous evolution of codes (full reprocessing phase)

➡ mixed infrastructure based on regular cluster + cloud to absorb variation of needs with



DPC CNES Phase 0

- Planning for a launch in 2034: pre-start in 2019 & start in 2021
- If advanced launch date, we have to start the DPC almost NOW !

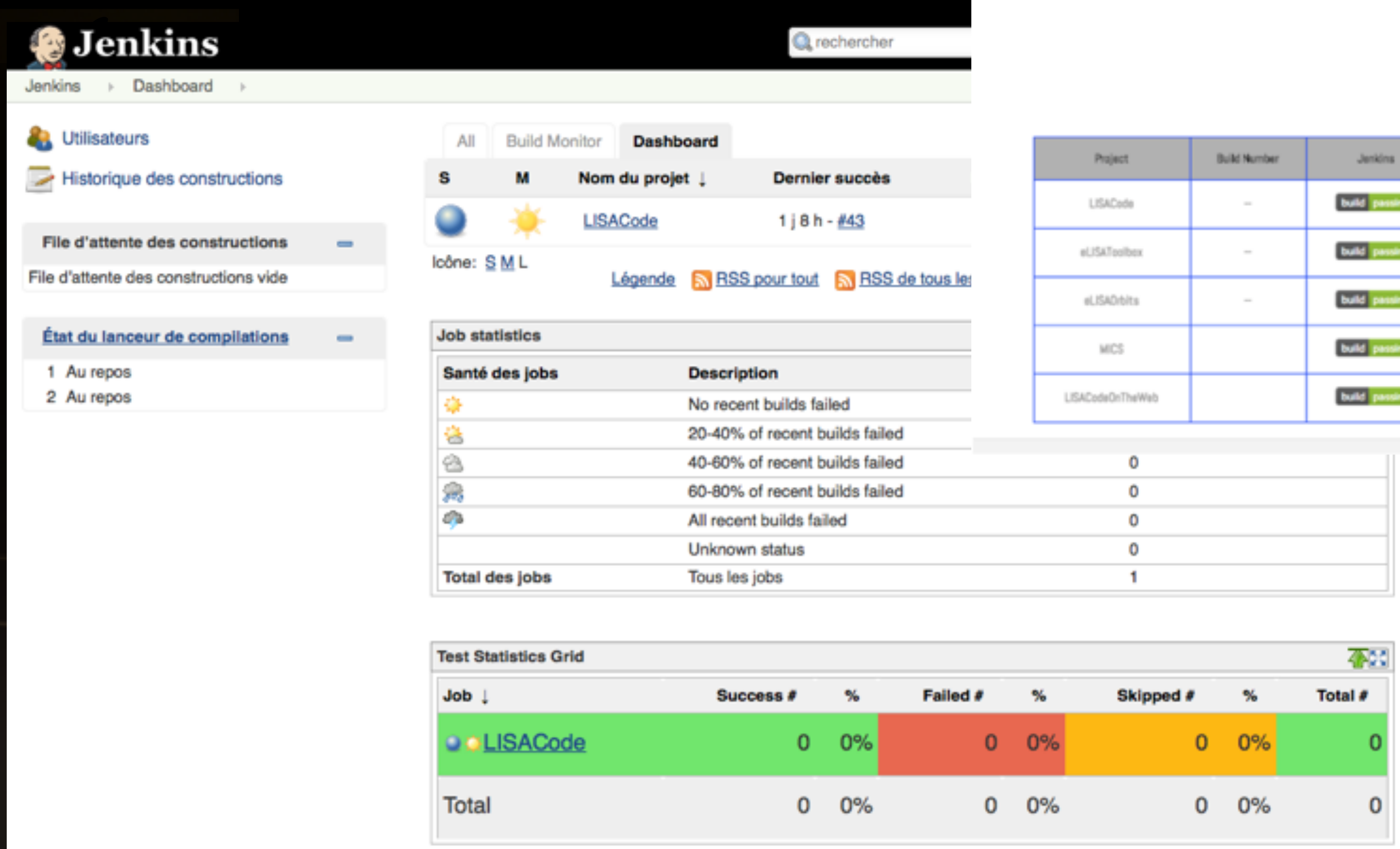


eLISA proto-DPC

- In 2015, CNES + APC started development of a proto-DPC
  - IT: Maude Le Jeune (project manager), Cecile Cavet, Etienne Marin-Matholaz, Gabriele Mainetti (full time for 1 year) & Suyan Dong (support)
  - Scientists/developers : Antoine Petiteau, Jean-Baptiste Bayle, Hubert Halloin, Eric Plagnol, Henri Inchauspé + eLISA simulation WG.
- We started by concentrating on :
  - Providing an environment for development with :
    - Common repository (git), wiki, web interfaces
    - Continuous integration (Jenkins & SonarQube)
    - Providing access to reference environment (docker)
  - Preliminary study on hybrid infrastructure

eLISA proto-DPC

- https://elisadpc.in2p3.fr/



Hybrid infrastructure

- Study of a “new solution” : docker
- “Container” (i.e. virtual machine) including everything : compiled codes + environment + light OS.
- Provide :
  - An easy to use way for user to run tools hosted at DPC
  - A reference machine for developers
  - Potential solution for hybrid system (standard cluster + cloud) : test case for a technological watch of CNES in collaboration with ATOS

eLISA proto-DPC: next

- Simulation:
  - eLISA simulation working group :
    - Diversity of expertises: LPF, LISA instrumentation, waveform modeling, astrophysics, ... (about 20 scientists now)
    - APC lead in collaboration with AEI (Hannover)
  - LISACode simulator: basis of end-to-end simulator & fully integrated to the proto-DPC (test bench)
  - Next/goals :
    - End-to-end simulations → mission simulator
    - "Quick" performance study → final design, need for the phase A
    - Tool for the performance control

eLISA proto-DPC: next

- Data analysis:
  - Challenge of LISA data analysis: identified large number of sources
  - 2005-2011: series of Mock LISA Data Challenges (progressive increase in complexity):
    - trigger development of DA methods
    - LISA analysis is doable: number of sources can be identified but the number of sources in the data was very limited ...
  - Next: new MLD(C)s: identified maximum number of sources in
    - Full enchilada (large number of sources)
    - Realistic noises (LISAPathfinder, ...)

(e)LISA consortium