eLISA
sensitivity and data analysis

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eLISA cosmology working group

CERN – 14th April 2015

Outline

- Introduction on eLISA
- “Cosmological sources” and eLISA
- Keys aspects of the design constraining the sensitivity
- The first set of configurations
- First estimations on the science capabilities for various configurations
- Status of data analysis
- Conclusion

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eLISA as L3 mission at ESA

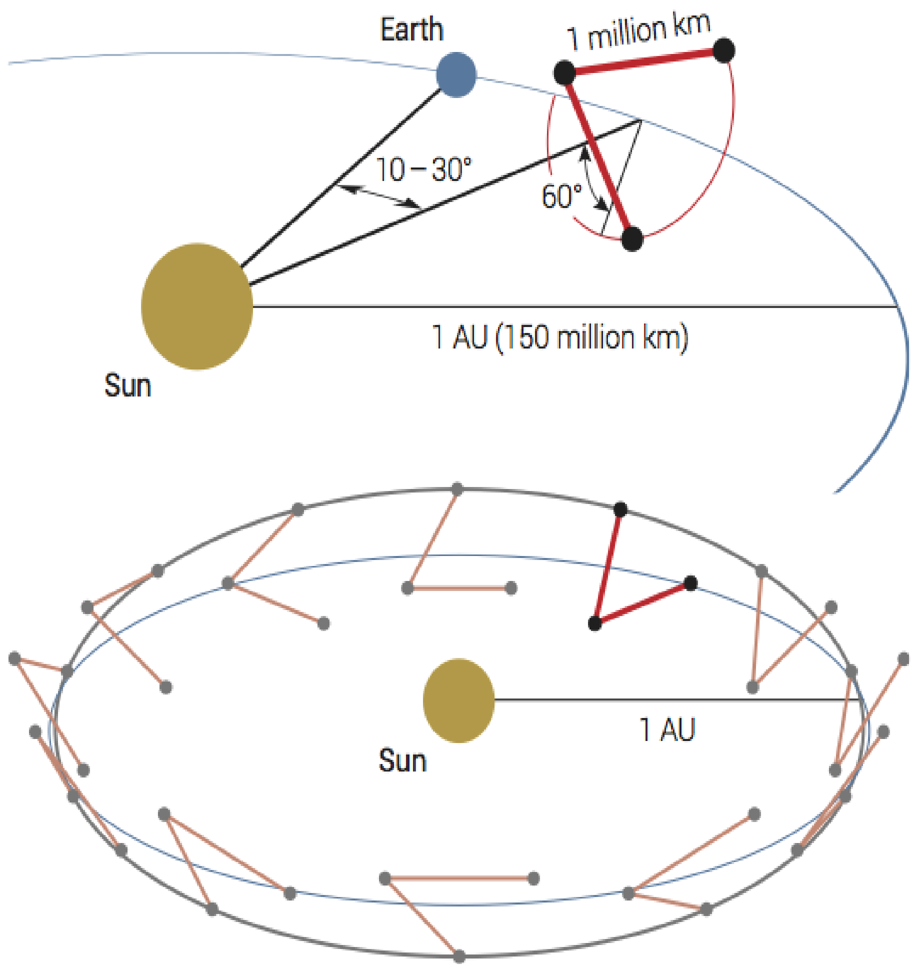
- “Gravitational Universe” theme selected for L3 in Cosmic Vision program at ESA : launch around 2034
- ESA asks to start NOW the study of technological needs,
- Selection of the mission around 2018,
- → If LISAPathfinder (2015) is a success, some chance to have a rearrangement of calendar and a launch before 2034 !

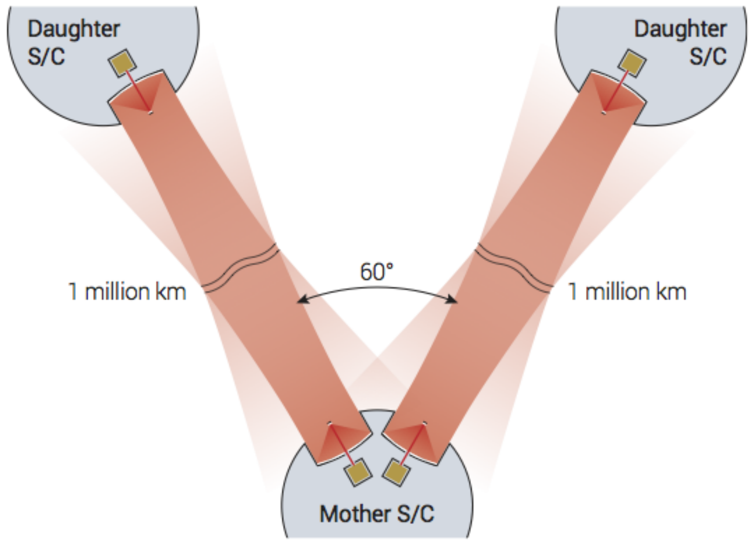
THE GRAVITATIONAL UNIVERSE

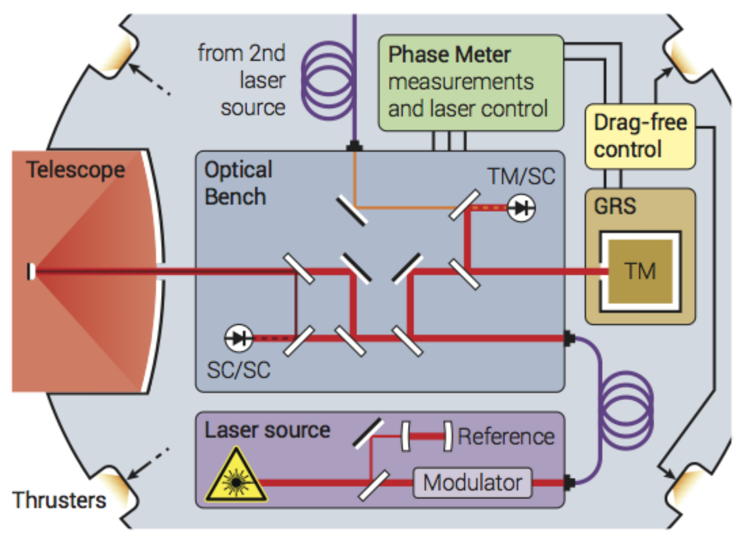
A science theme addressed by the *eLISA* mission observing the entire Universe

eLISA L3 concept

- 3 spacecrafts (SC) forming 2 arms of 1 million kilometres,
- SC always adjusts on a free-falling test mass using micro-thruster,
- Exchange of laser for forming an interferometer and measuring GW deformations

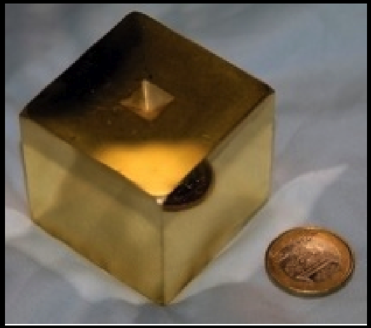


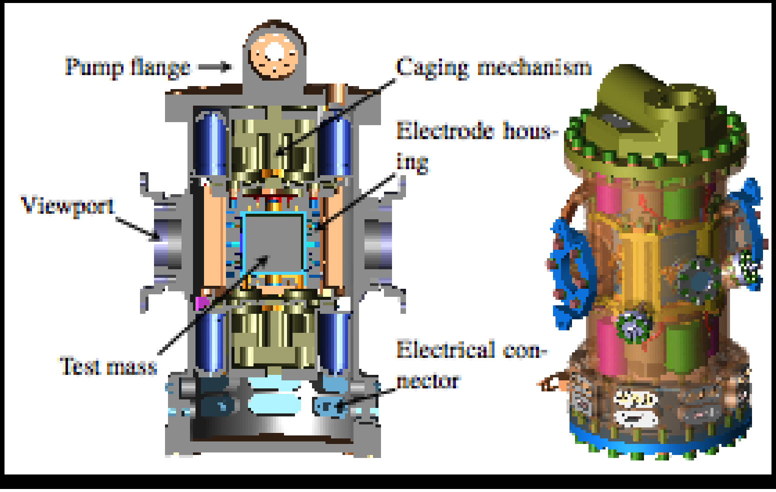


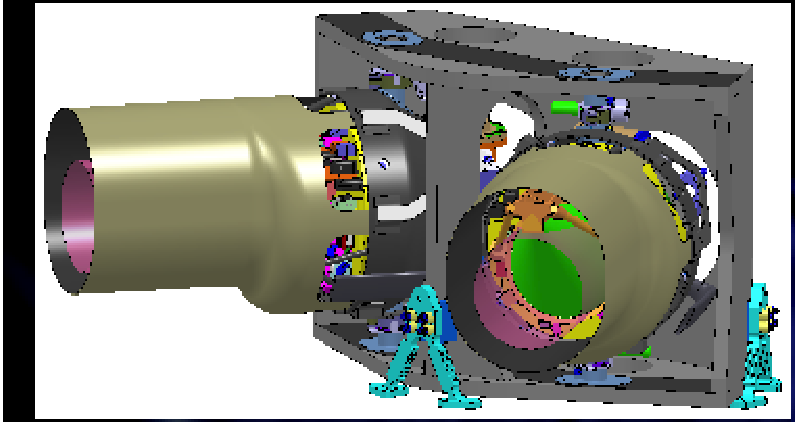


eLISA in next years

- Enlarge scientific community around eLISA: future of GW astronomy,
- Science potential and data analysis has to be studied in details,
- Detailed concept has to be defined : preliminary studies based on eLISA/NGO varying key aspects already start ...



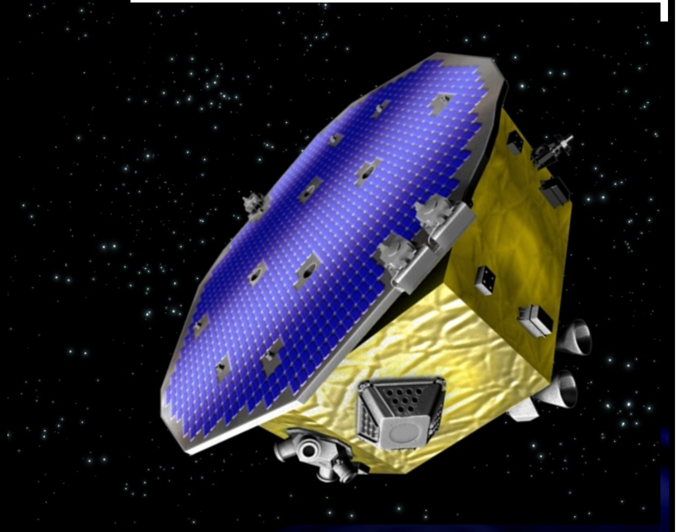


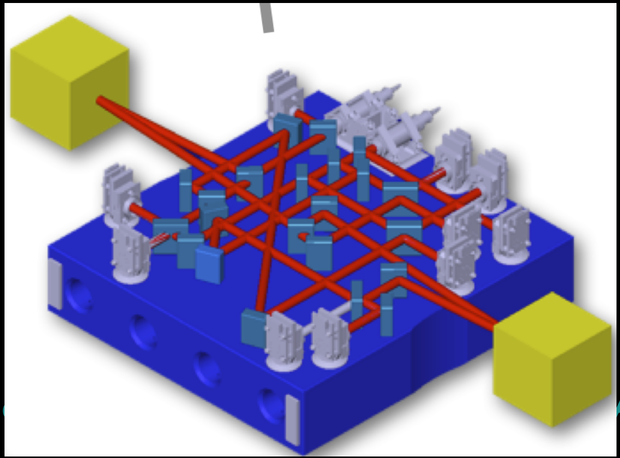


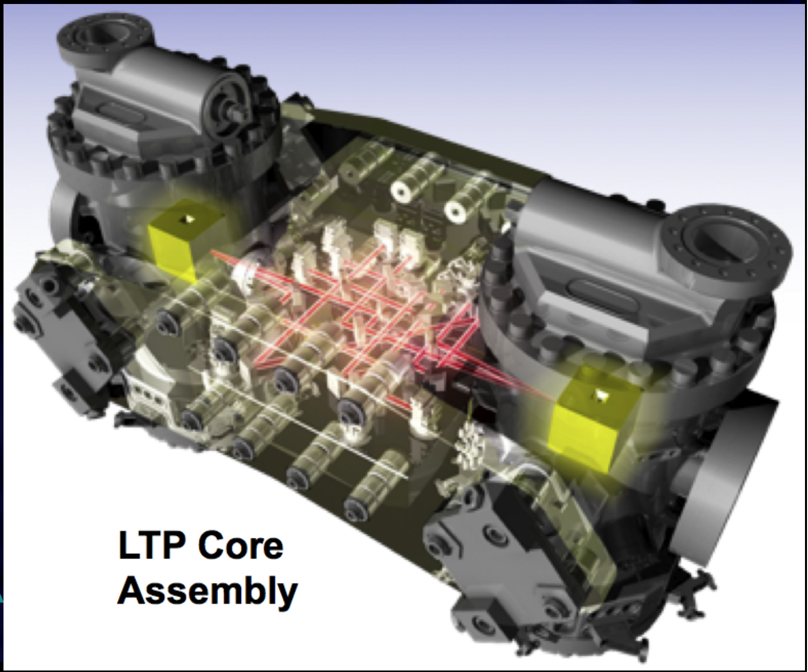
LISAPathfinder

- Basic idea : squeeze one arm of eLISA from one millions km to few tens of cm.
- The LISAPathfinder will test in flight :
  - Inertial sensor,
  - Interferometry between free floating test masses,
  - Drag Free and Attitude Control System
  - Micro-Newton propulsion technology

lisa pathfinder







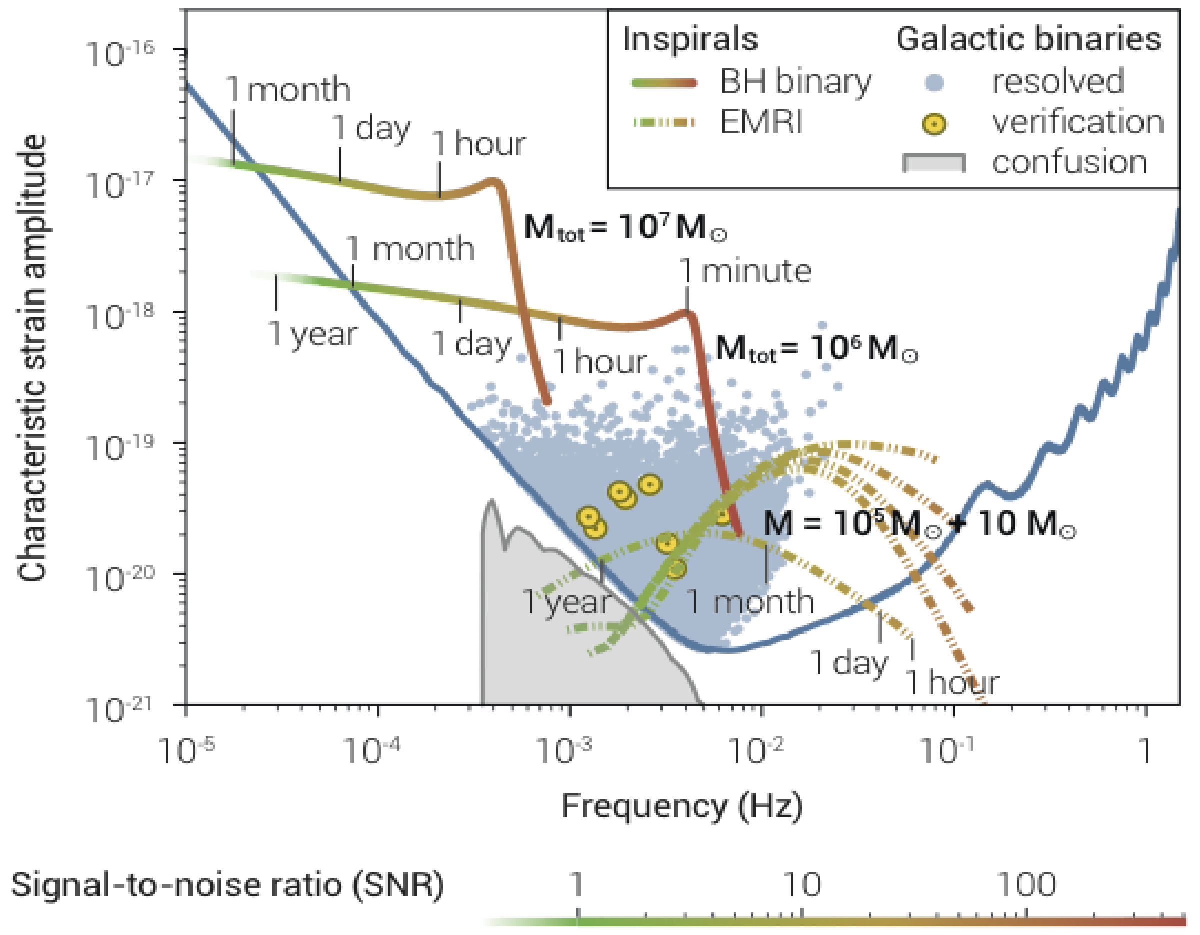
LISAPathfinder

- Ready to be launch on September 2015.

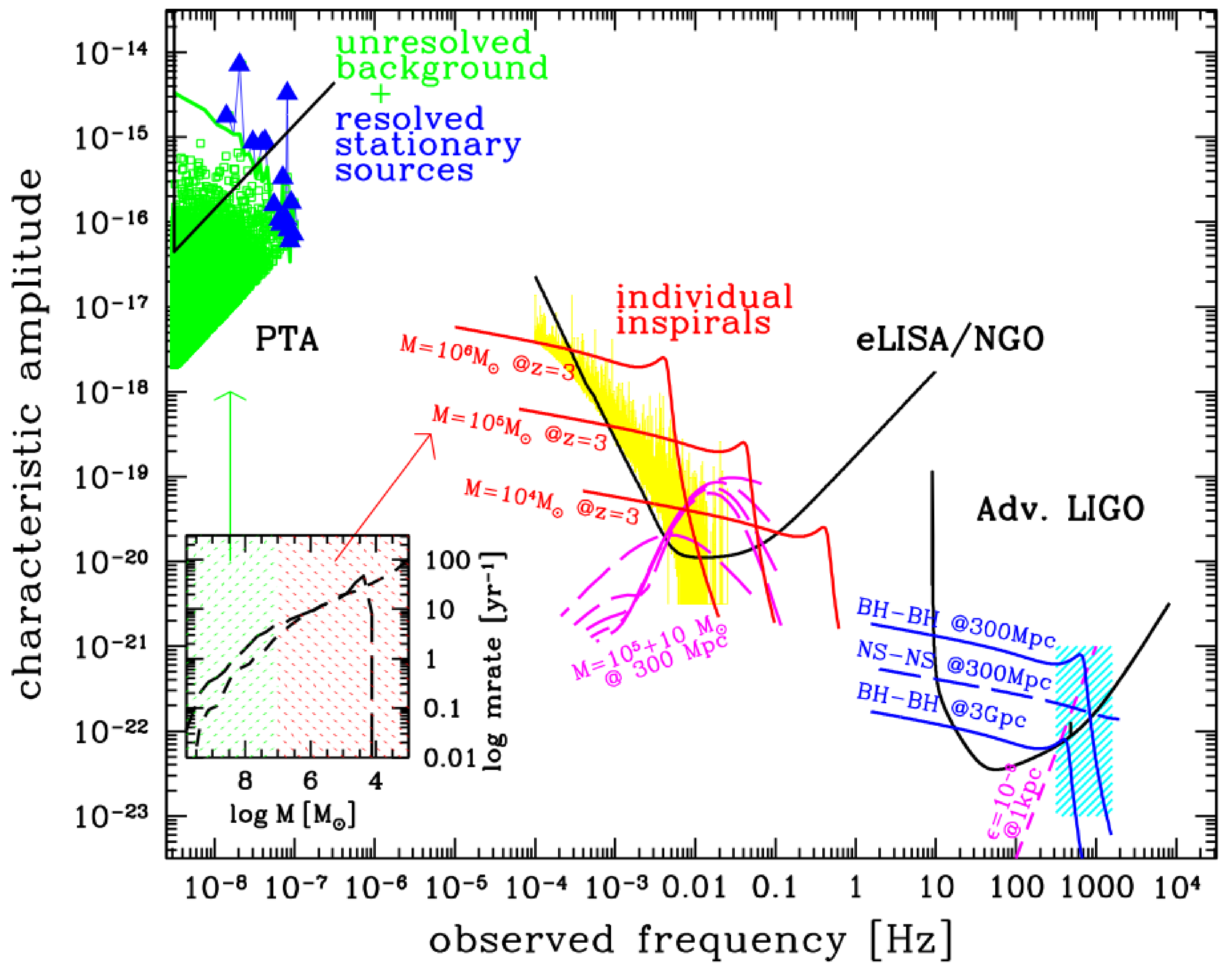
See Martin's Talk

eLISA sources

- Galactic binaries : few tens millions in Galaxy and about 3000 resolvable including verification binaries, i.e. sources already observed (about ten more are coming with Gaia) → guaranteed sources
- Massive Black Hole Binaries,
- Extreme Mass Ratio Inspirals
- Bursts : cosmic string cusps, ...
- Cosmological backgrounds,
- All the unknown sources !



Complementarity between detectors: binary sources



Sesana astro-ph.CO 1304.0767 (2013)

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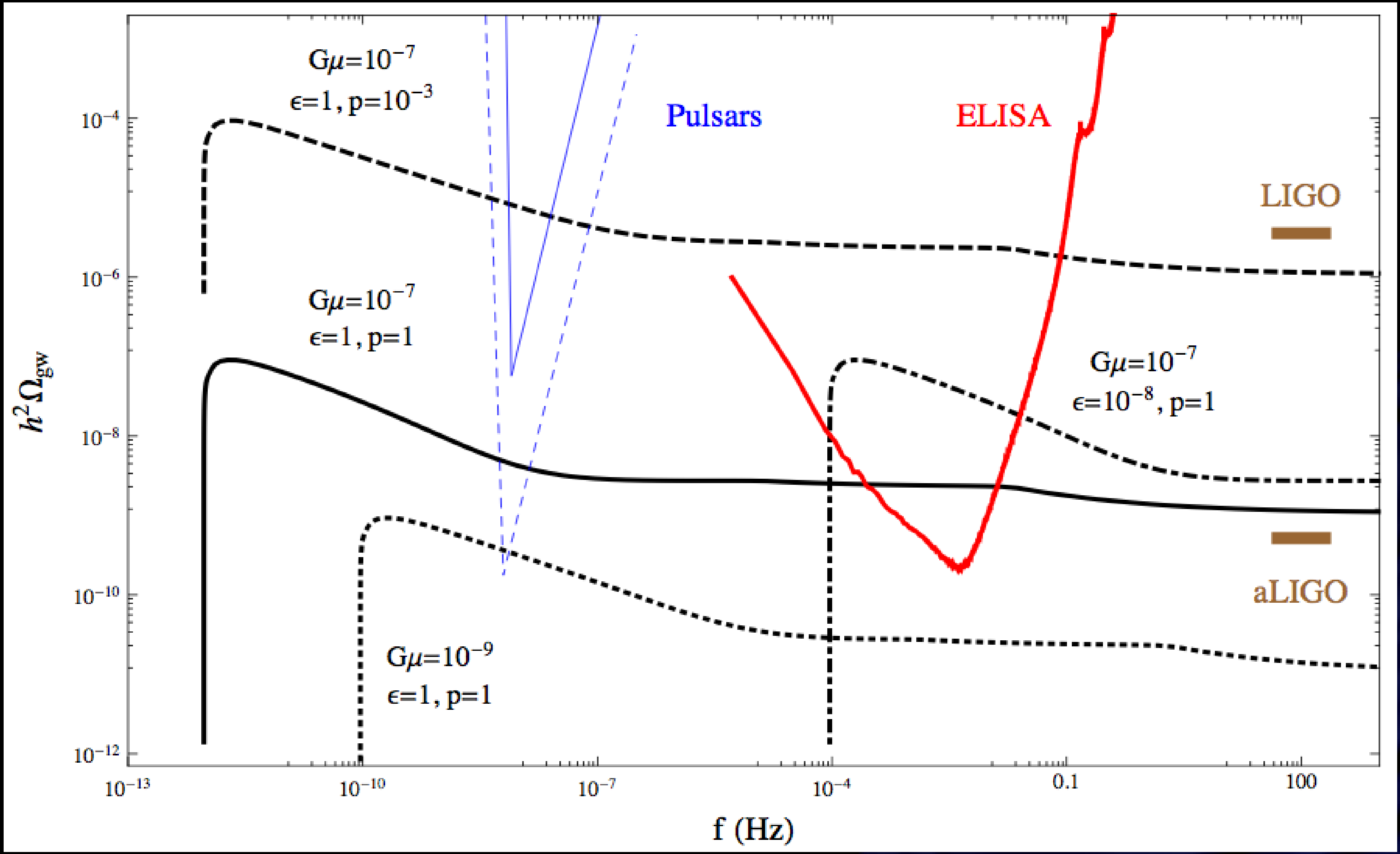
“Cosmological sources” and eLISA

- At least 2 possible types of signals :
  - Stochastic background : example : first order phase transitions in the early Universe, cosmic string background, ...
  - Bursts : cosmic string cusps and/or kinks, ... (?)
- Important to study them now in order to evaluate the characteristic of a realistic signal and the possible impact on the design :
  - How to detect this kind of signal ?
  - How to separate them from instrumental noise ?
  - How can it influence observation of others sources ?
  - Which calibration procedures are need (and have to be consider in the design) to be able to identified noises and background ?
  - ...

Complementarity between detectors: cosmological backgrounds

Example of cosmic string background :



Binetruy et al. (2012)

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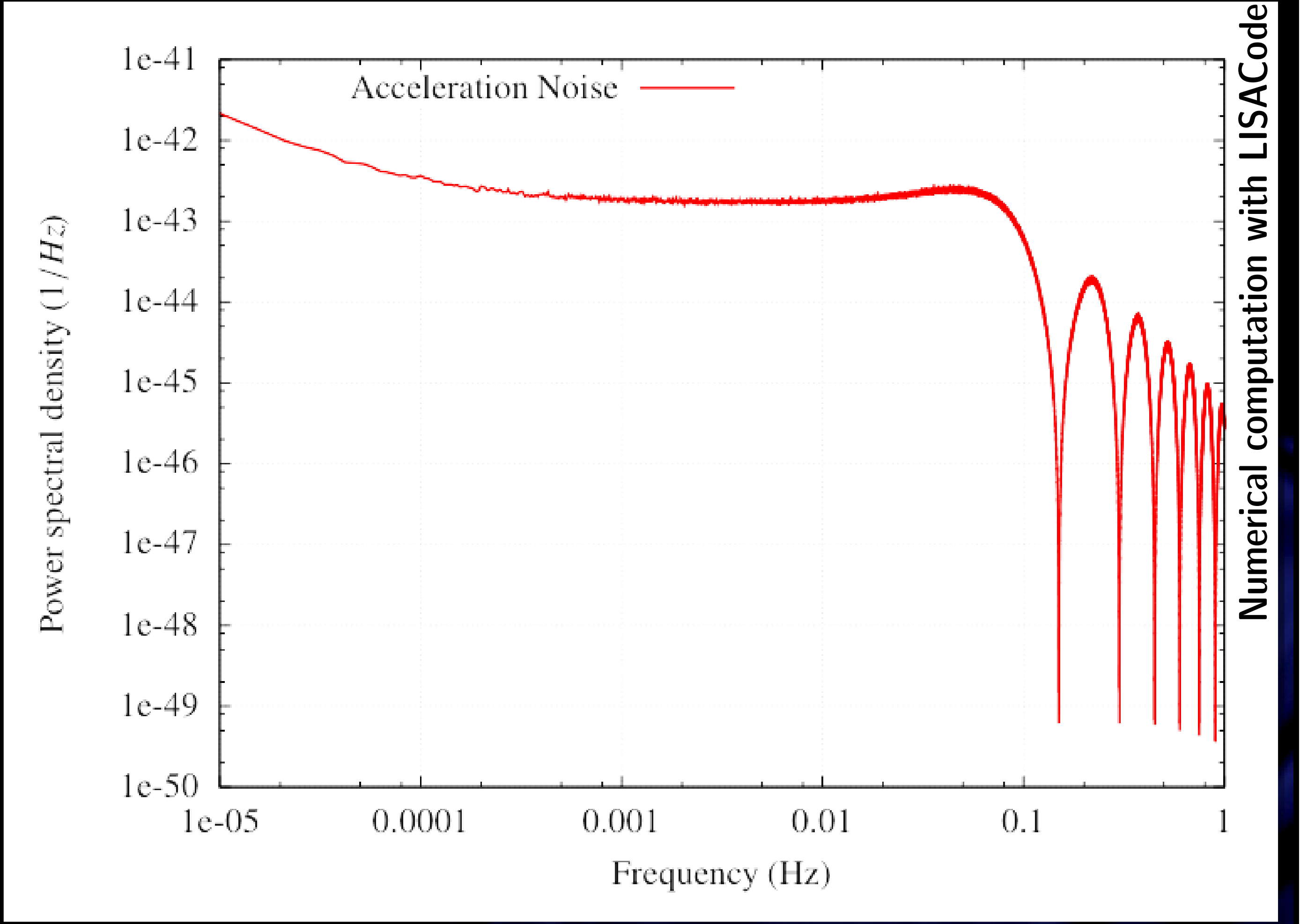
Main noises sources in the simplified eLISA-L3

- Acceleration noise :
  - Ability to keep a mass in free fall
  - Will be measured by LISAPathfinder
  - For eLISA-L3 : Margin x 3×10^{-15} $m.s^{-2}.Hz^{-1/2}$

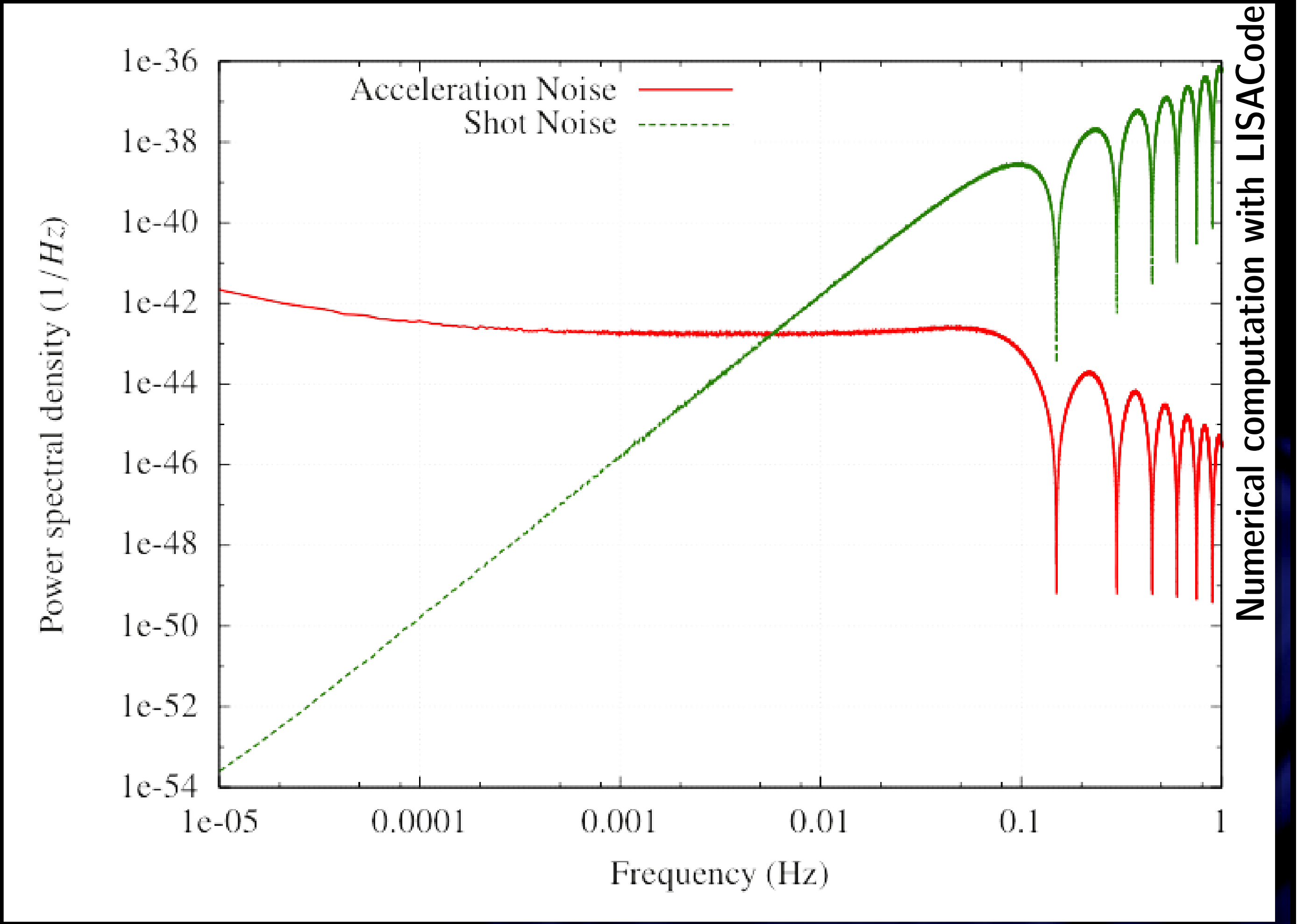


Numerical computation with LISACode

ESA Margin = 1/0.65

Main noises sources in the simplified eLISA-L3

- Shot noise :
  - Due to the very weak power received on photodiode after the inter-spacecraft travelling.
  - Depend on armlength and telescope diameter
  - For eLISA-L3 : Margin x 4.7×10^{-12} m.Hz^{-1}

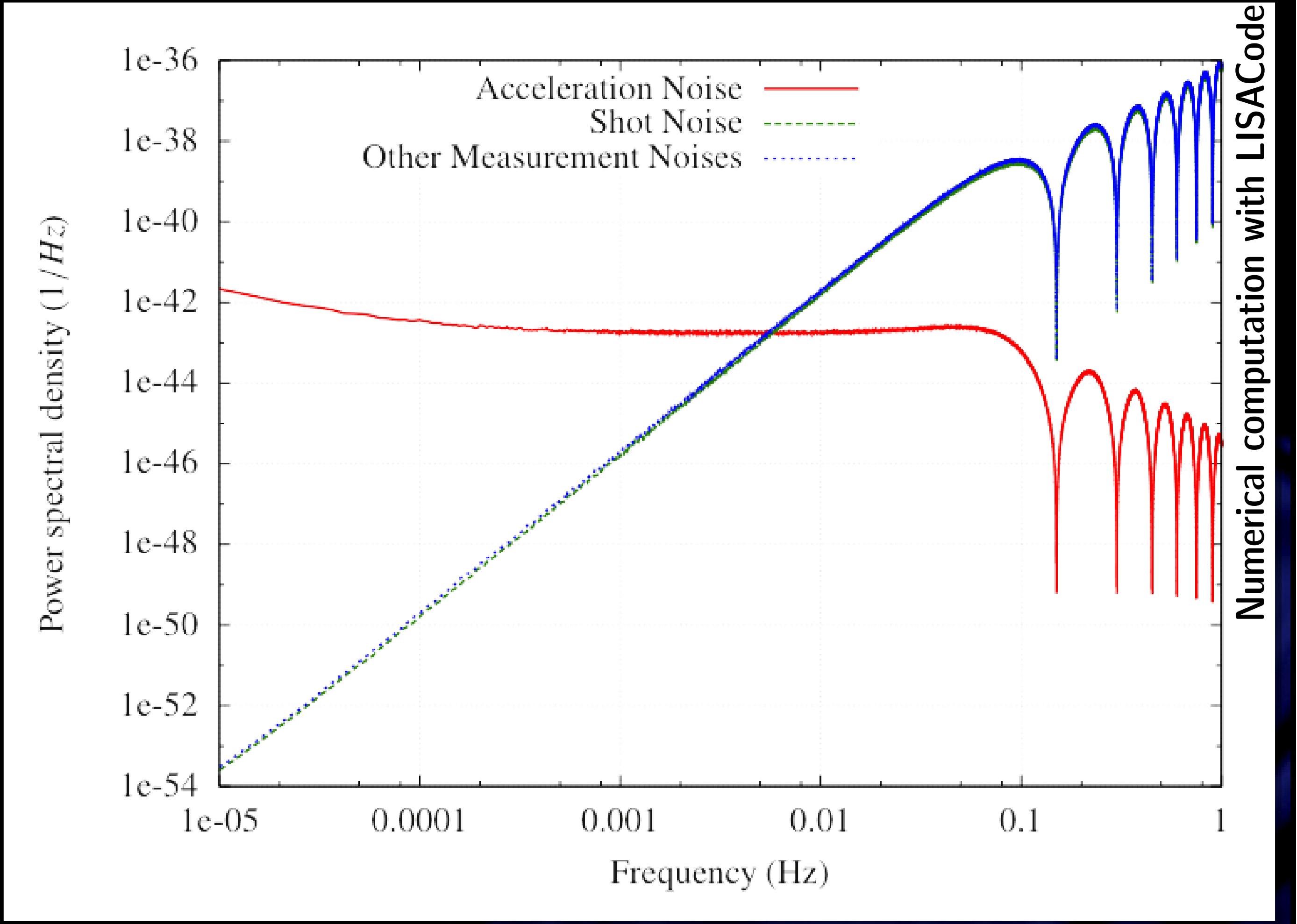


Numerical computation with LISACode

ESA Margin = 1/0.65

Main noises sources in the simplified eLISA-L3

- Other Measurement Noises :
  - All unknown noise.
  - Very approximative in the simplified version.
  - For eLISA-L3 : Margin x 5.15×10^{-12} $m.Hz^{-1}$

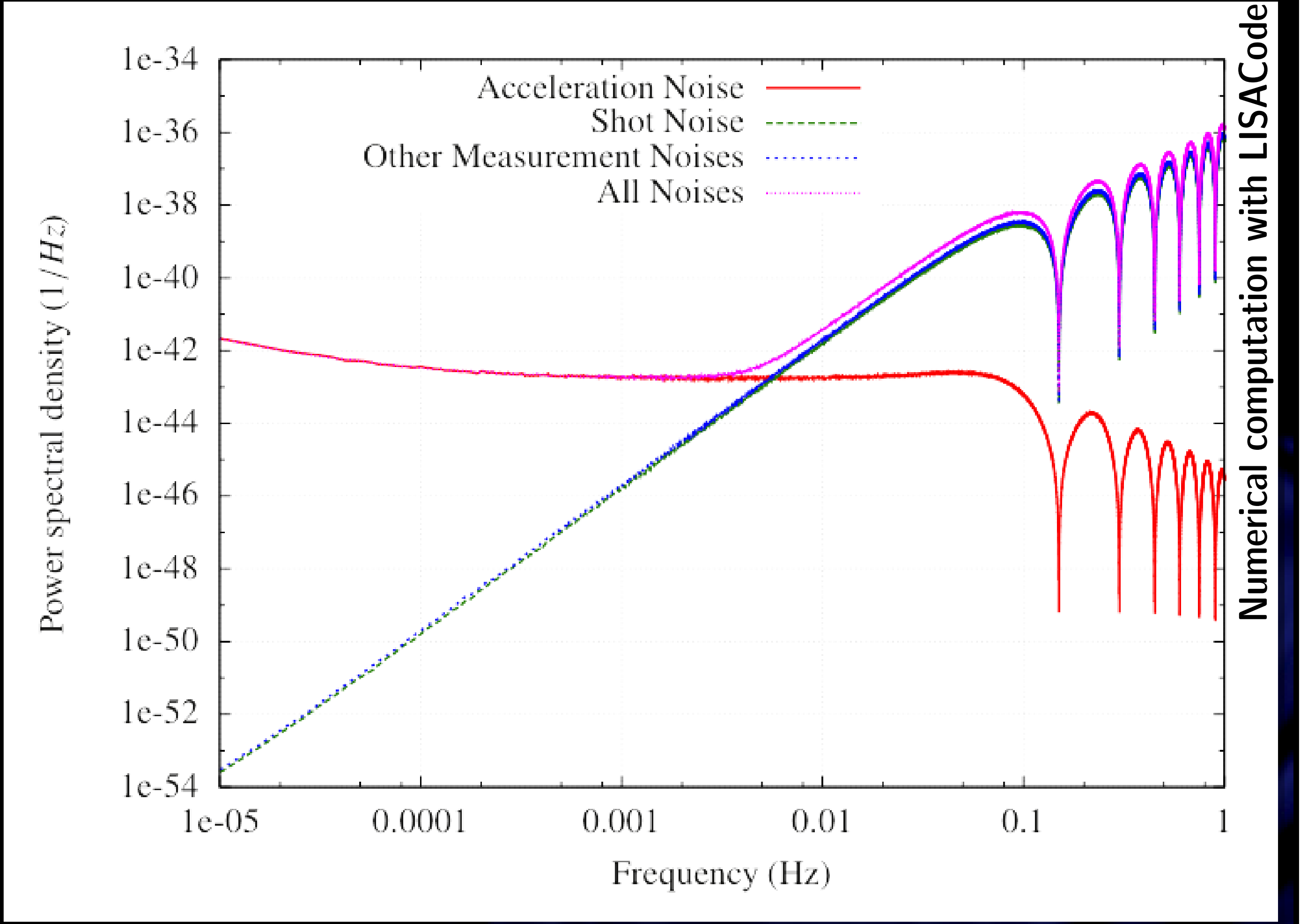


Numerical computation with LISACode

ESA Margin = 1/0.65

Main noises sources in the simplified eLISA-L3

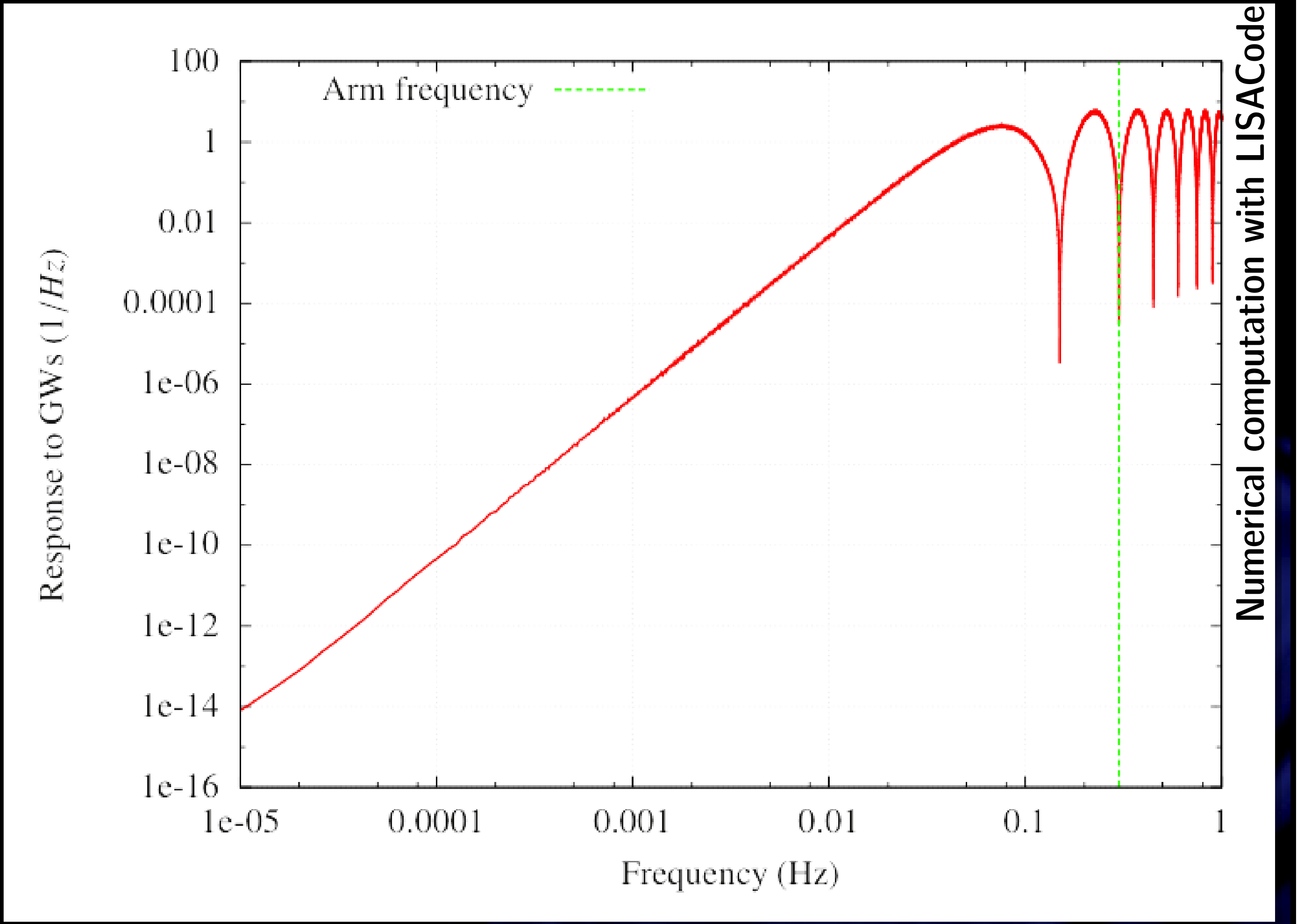
- All Noises :
  - Low frequency dominated by Acceleration Noise.
  - High frequency dominated by Shot Noise and Other Measurement Noise



Numerical computation with LISACode

Response to Gws for eLISA-L3

- Response to GWs :
  - Depending on orbits (armlength)
  - Frequency dependance partially due to Time Delay Interferometry (recombination of phasemeter measurements to remove the laser noise)

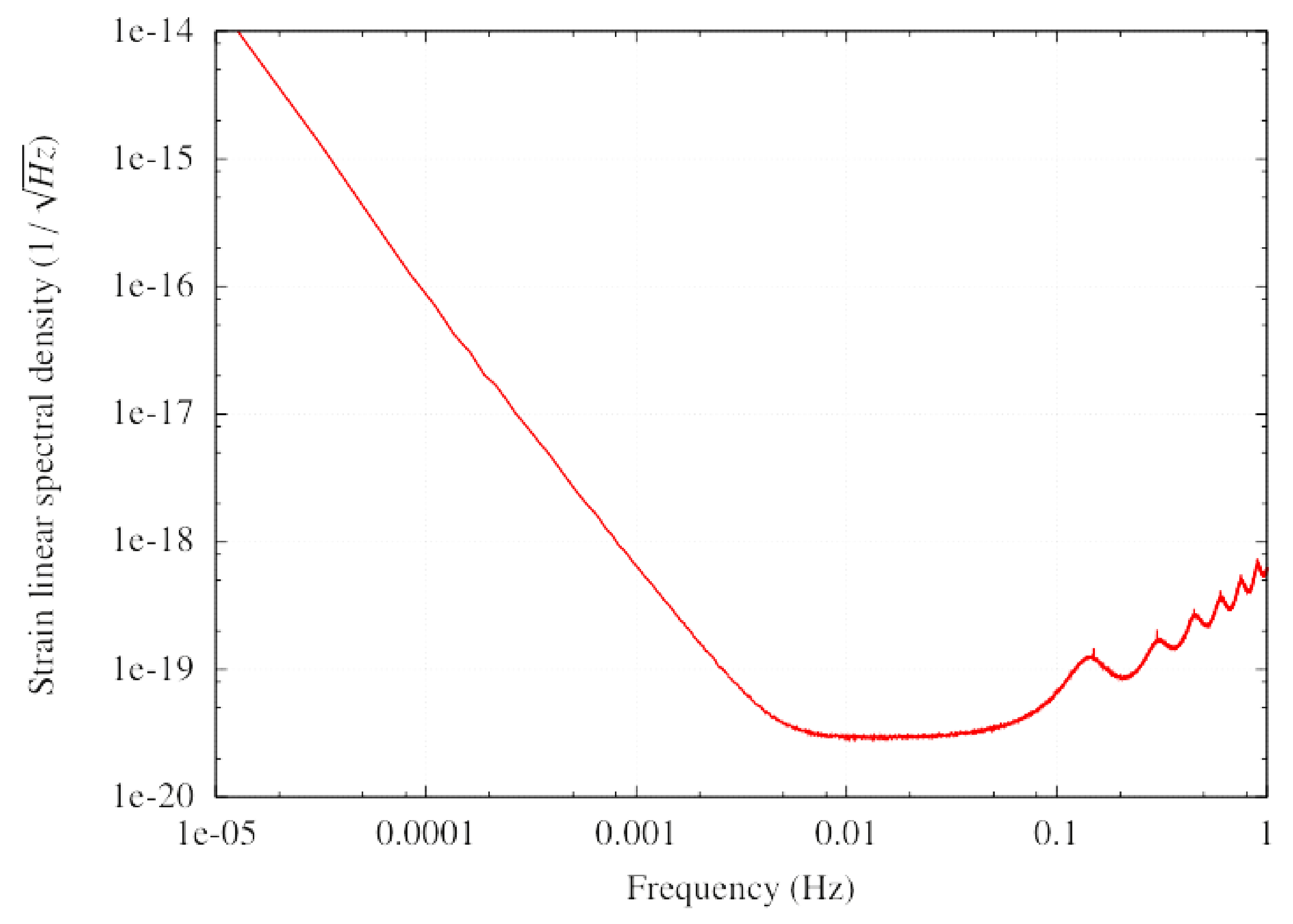


Numerical computation with LISACode

- Computation: PSD of TDI X with as input 192 white stochastic GWs isotropically distributed on sky

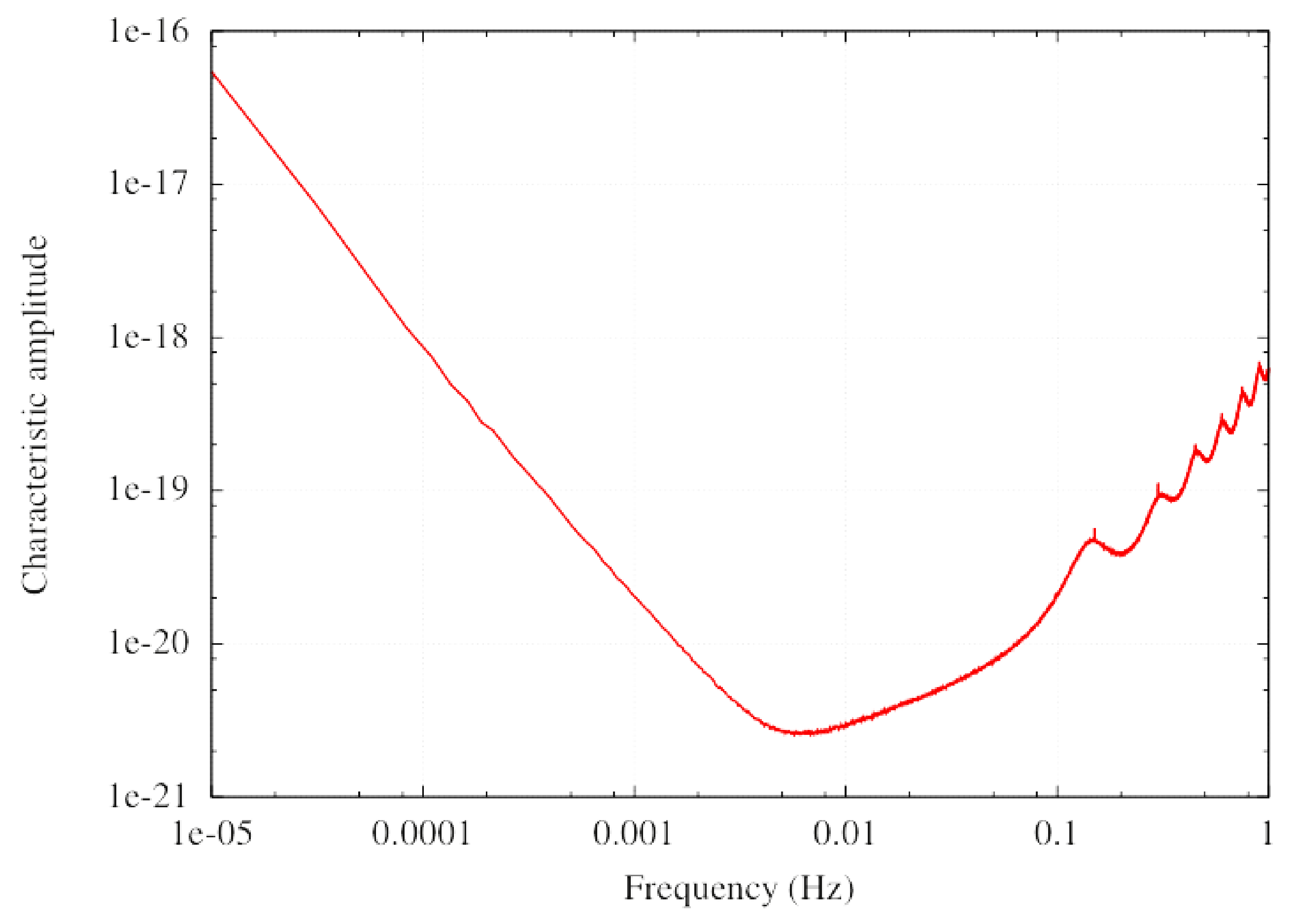
Standard sensitivity

- S^2 = Response to Noises / Response to GWs = PSD_{Noises} / PSD_{GWs}
- Also called "Strain linear spectral density"
- In $Hz^{-1/2}$



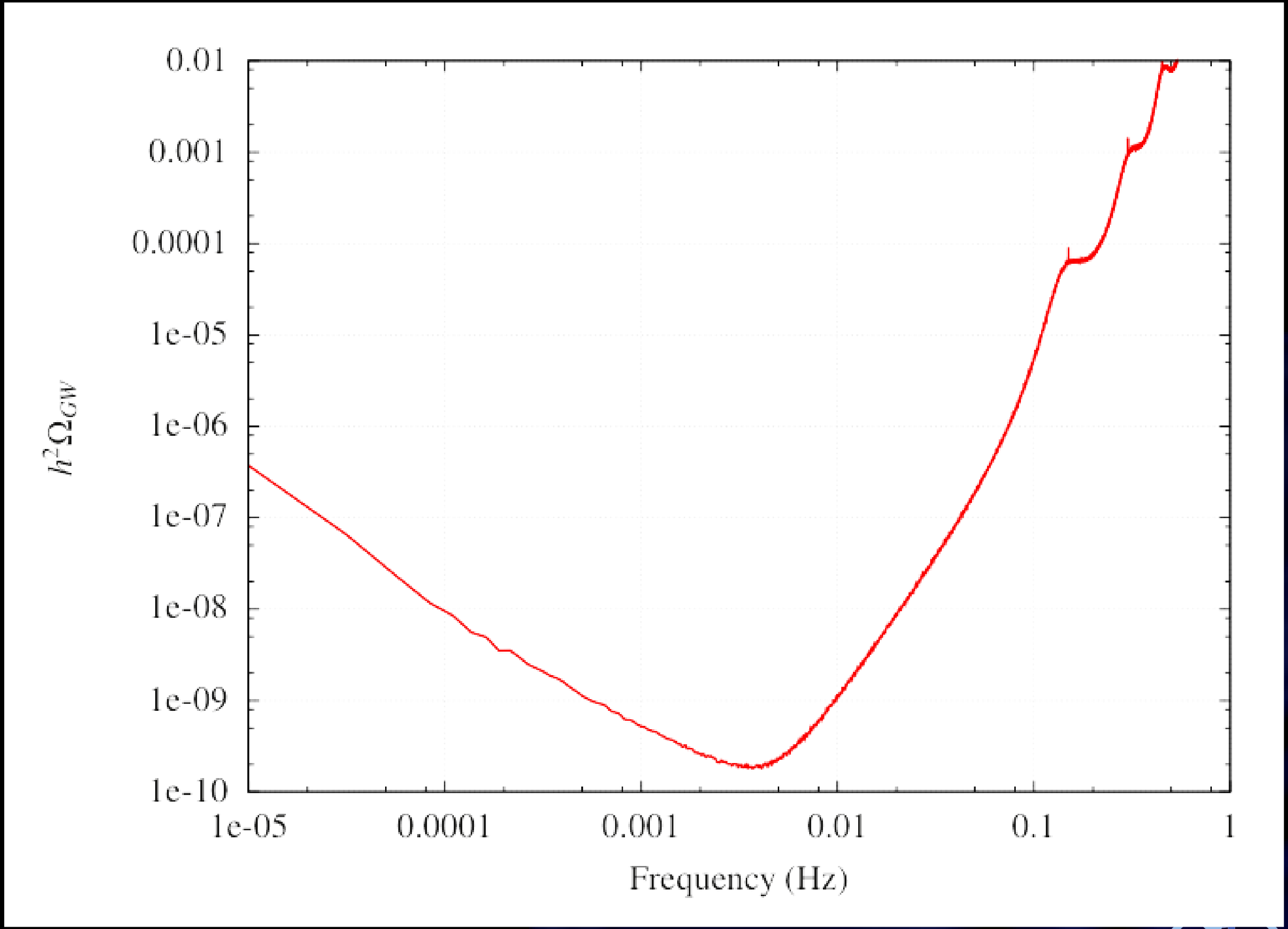
Sensitivity in characteristic amplitude

- $S_h^2 = f\ S^2$
- Dimensionless



Sensitivity in GW energy density

- $h^2\,\Omega_{GW} = 4\,\pi^2\,f^3\,S^2\,/(3\,H_0^{\,2})$
- Typical representation used in cosmology and more generally in theoretical physics (cosmic strings, etc)



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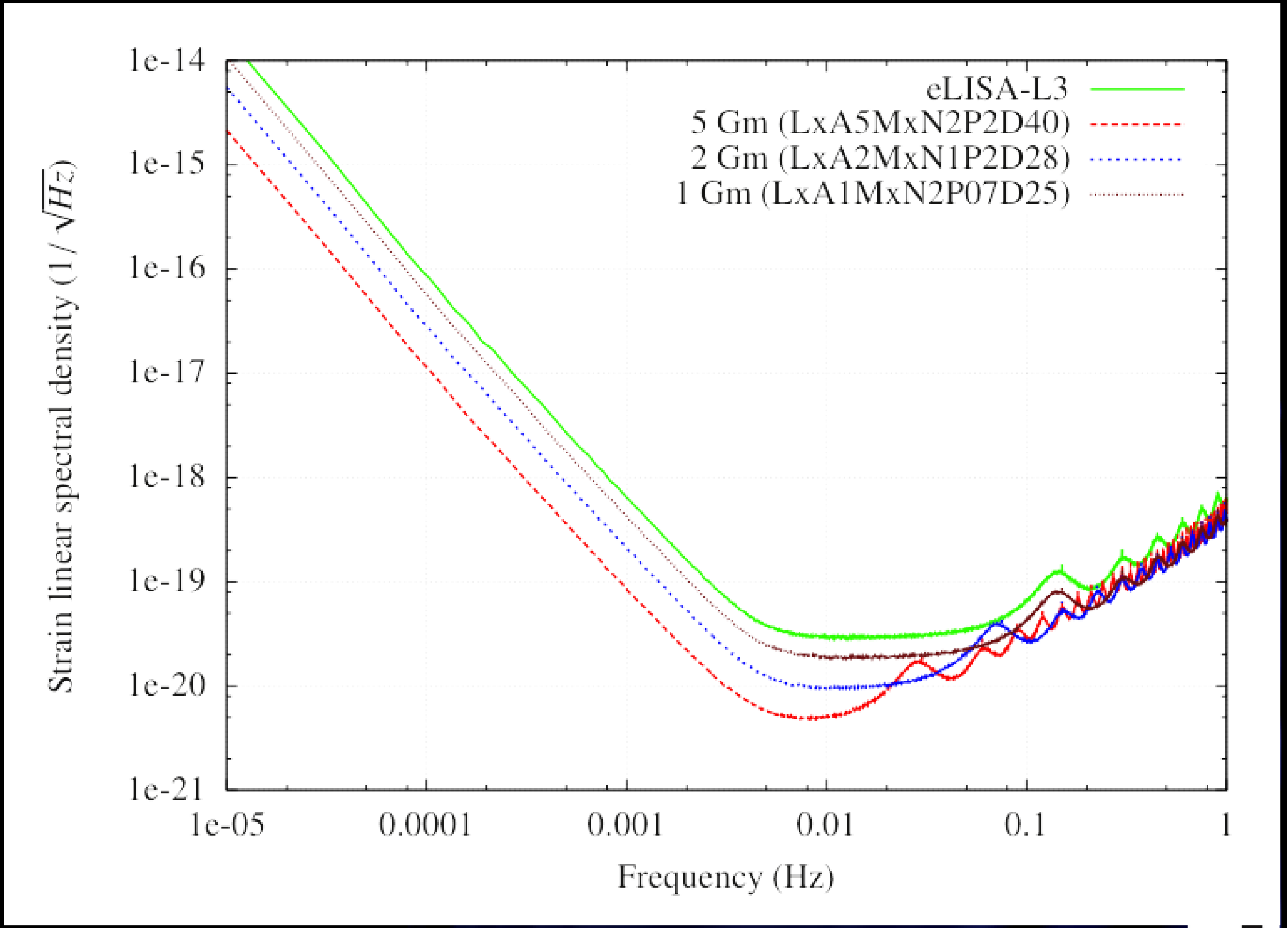
Context

- Need a “detailed” configuration for the selection in 2017-2018.
- We have some time now :
  - to study the technical possibilities for the instrument,
  - and in parallel doing science studies as exhaustive as possible.
- Step 1 : study science with simplified configurations covering a wide range of possibilities in coordination with the GOAT.

  → understand the relations between design and science returns.
- Step 2 : (in parallel) define detailed configurations.
- Step 3 : do science case for few detailed configurations.
- …

Varying armlength

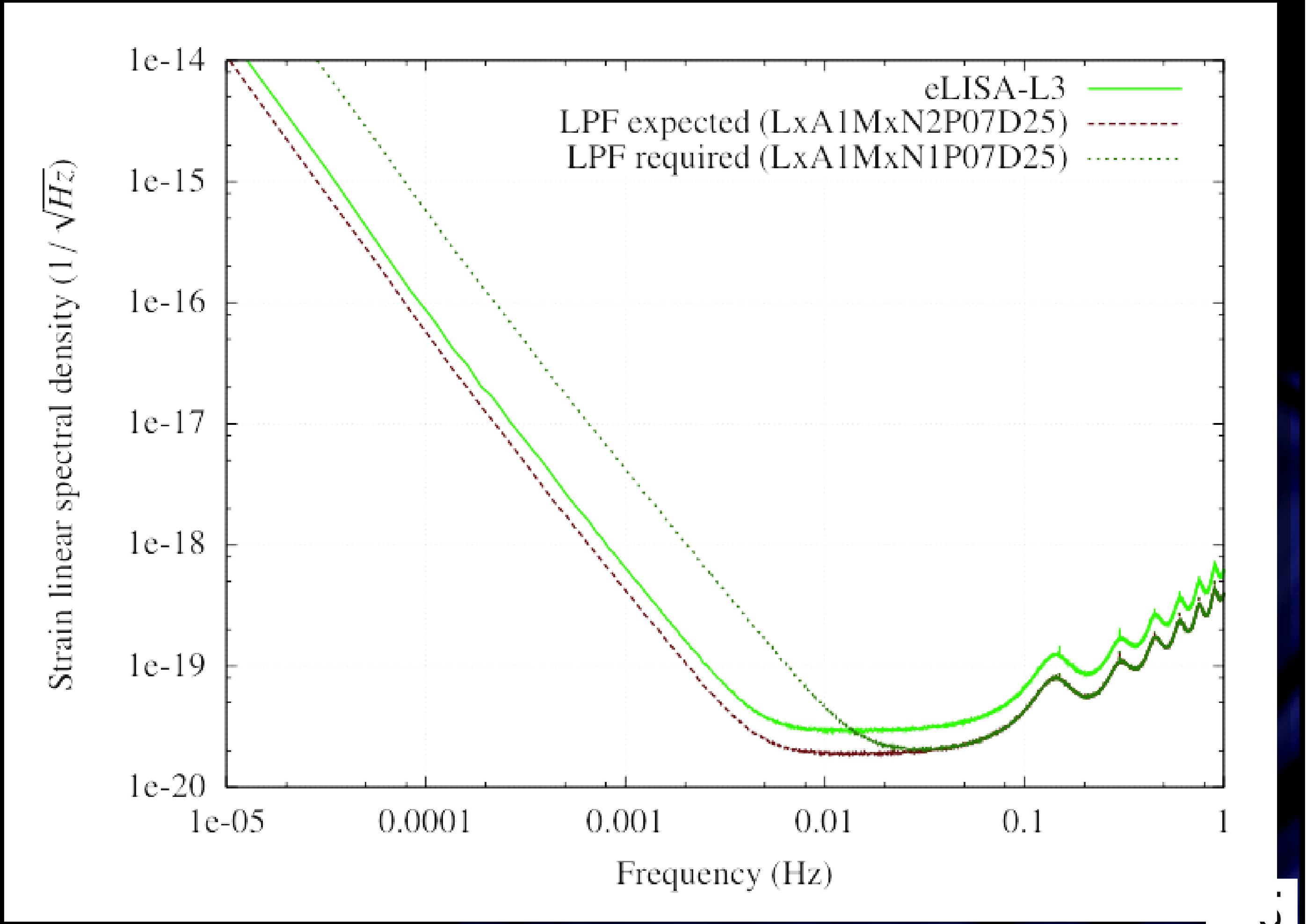
- 3 armlength values djusting telescope diameter D & laser power Pto have shot noise just below other measurement noises :
  - A1: 1 Gm (eLISA) :
    P = 0.7 W
    D = 25 cm
  - A2: 2 Gm :
    P = 2 W
    D = 28 cm
  - A5 : 5 Gm (old LISA)
    P = 2 W
    D = 40 cm



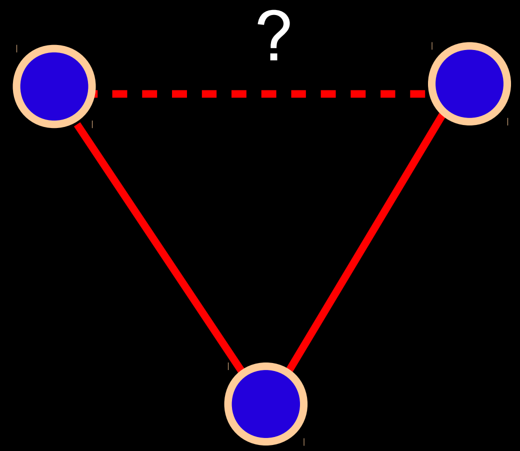
- Note : no margin

Varying acceleration noise

- 2 choices for the acceleration noise :
  - N1 : LISAPathfinder required : very pessimistic : 3×10^{-14} m.s^{-2}.Hz$^{-1/2}$
  - N2 : LISAPathfinder expected : optimistic : 3×10^{-15} m.s^{-2}.Hz$^{-1/2}$



2 or 3 arms (4 or 6 links)



- 2 arms :
    - one interferometer
    - cheaper (?)
- 3 arms :
    - 2 independent interferometers noise independent :
        - possible to measure the polarisation
        - detect correlation between the 2 interferometer ... stochastic background
        - Increase of SNR by square root of 2

Varying mission duration

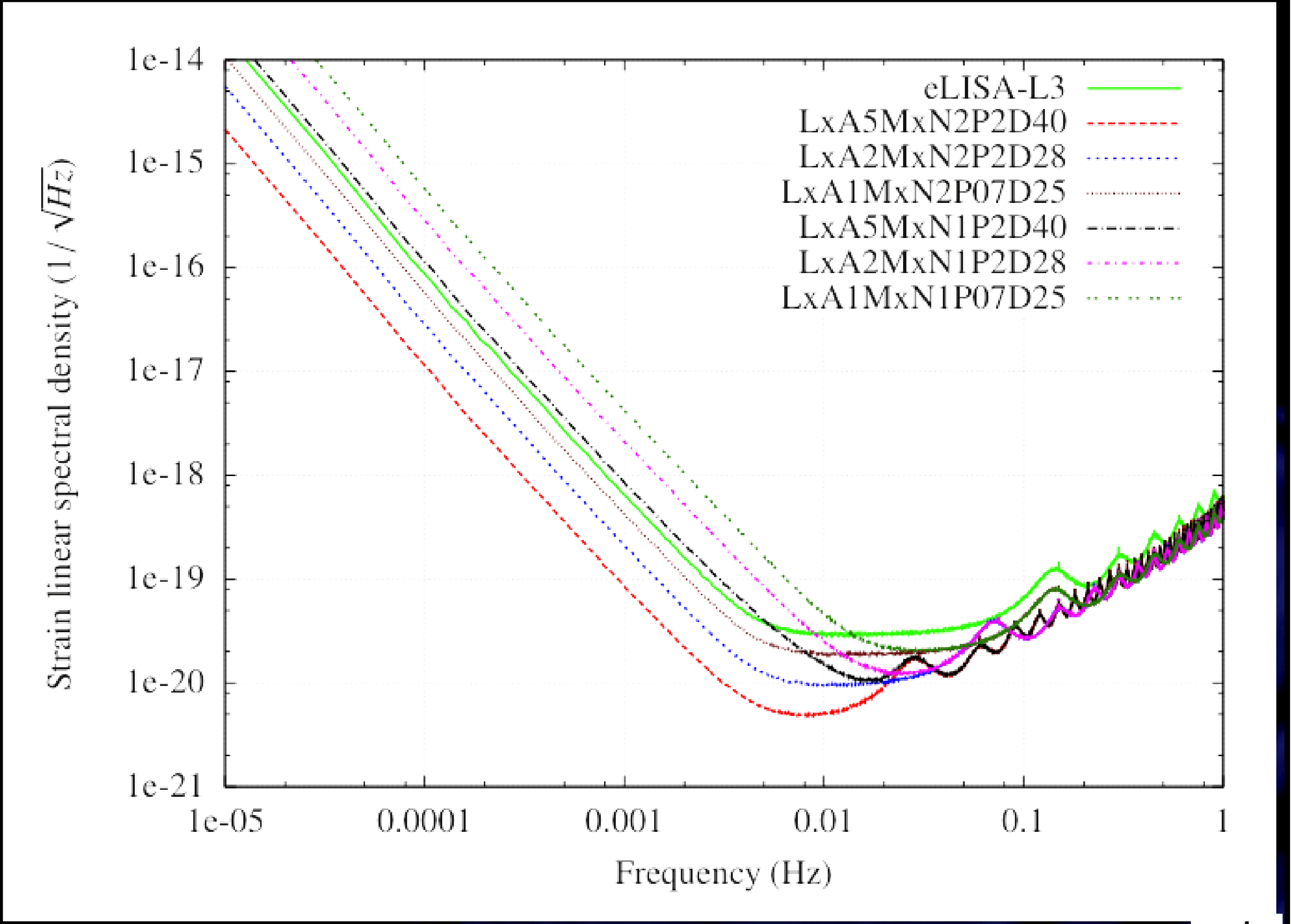
- eLISA-L3 : 2 years
- 2 values : 2 or 5 years
- Science impact on :
  - SNR of “permanent” sources
  - Mathematical increases (in probability) of the number of transients (MBHB, EMRIs, Bursts).
- Technological impacts :
  - requirement and redundancy about the subsystem
  - orbits

6 basic configurations, 24 in total

- Main difference at low frequency : from best to worth :
  - LxA1N1, LxA2N1, LxA5N1, LxA1N2, LxA2N2, LxA5N2

    Main impact from acceleration noise

- For each of this 6 basic configurations :
  - 2 or 5 years
  - 4 or 6 links
- 24 in total



6 basic configurations, 24 in total

- Main difference at low frequency : from best to worth :
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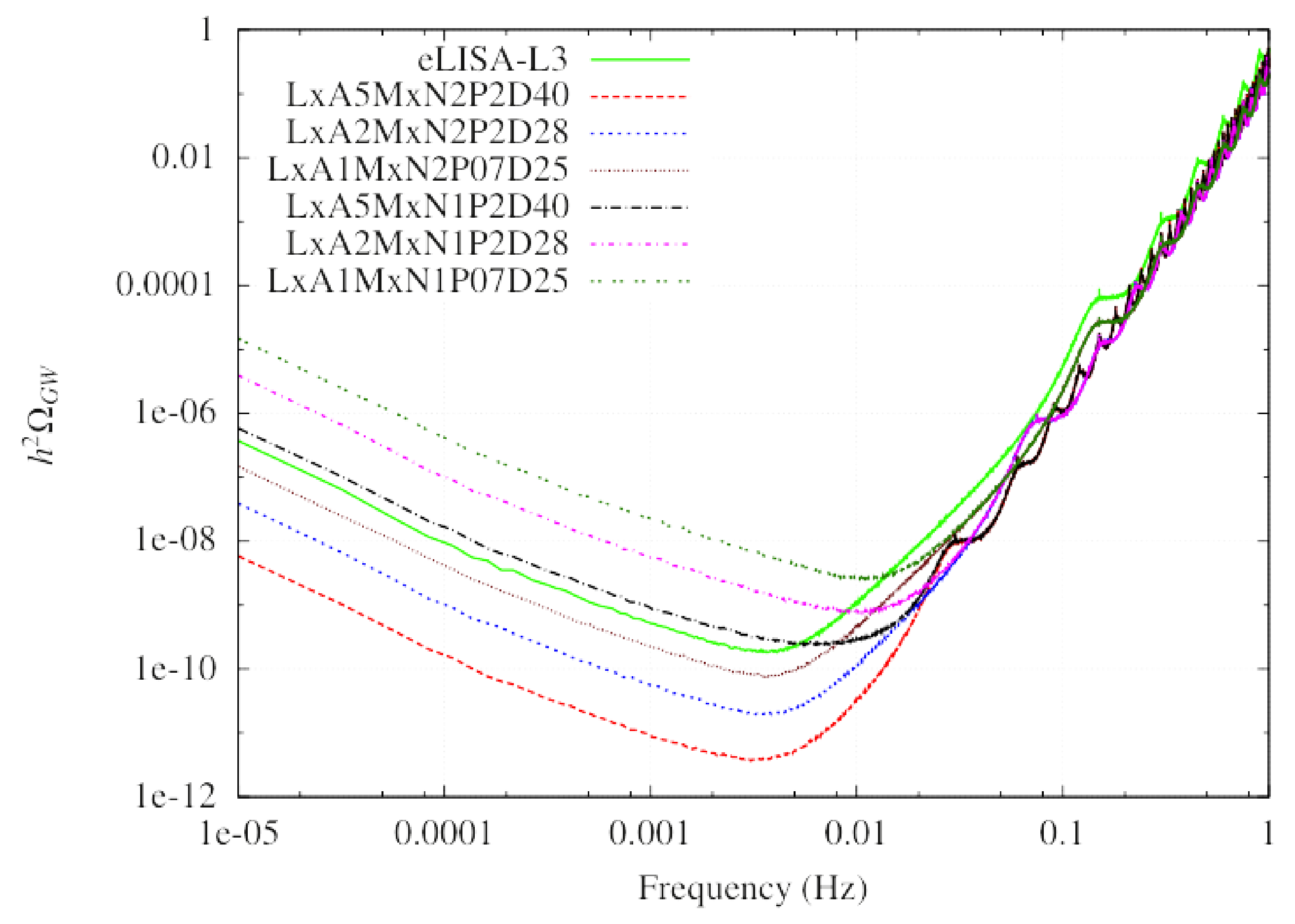

Next steps in the design : detailed configurations

- Replace shot noise + other measurement noises by a decomposition of all effects :
  - thermal, electric, optical, read-out, ...
- Optimize orbits taking into account influence of the Earth
- Realistic acceleration : eLISAnoise simulator (SSM model) + LISAPathfinder
- ...

Work in progress within the simulation working group with major contribution from APC and AEI : new “detailled” simulator (extended LISACode ?)

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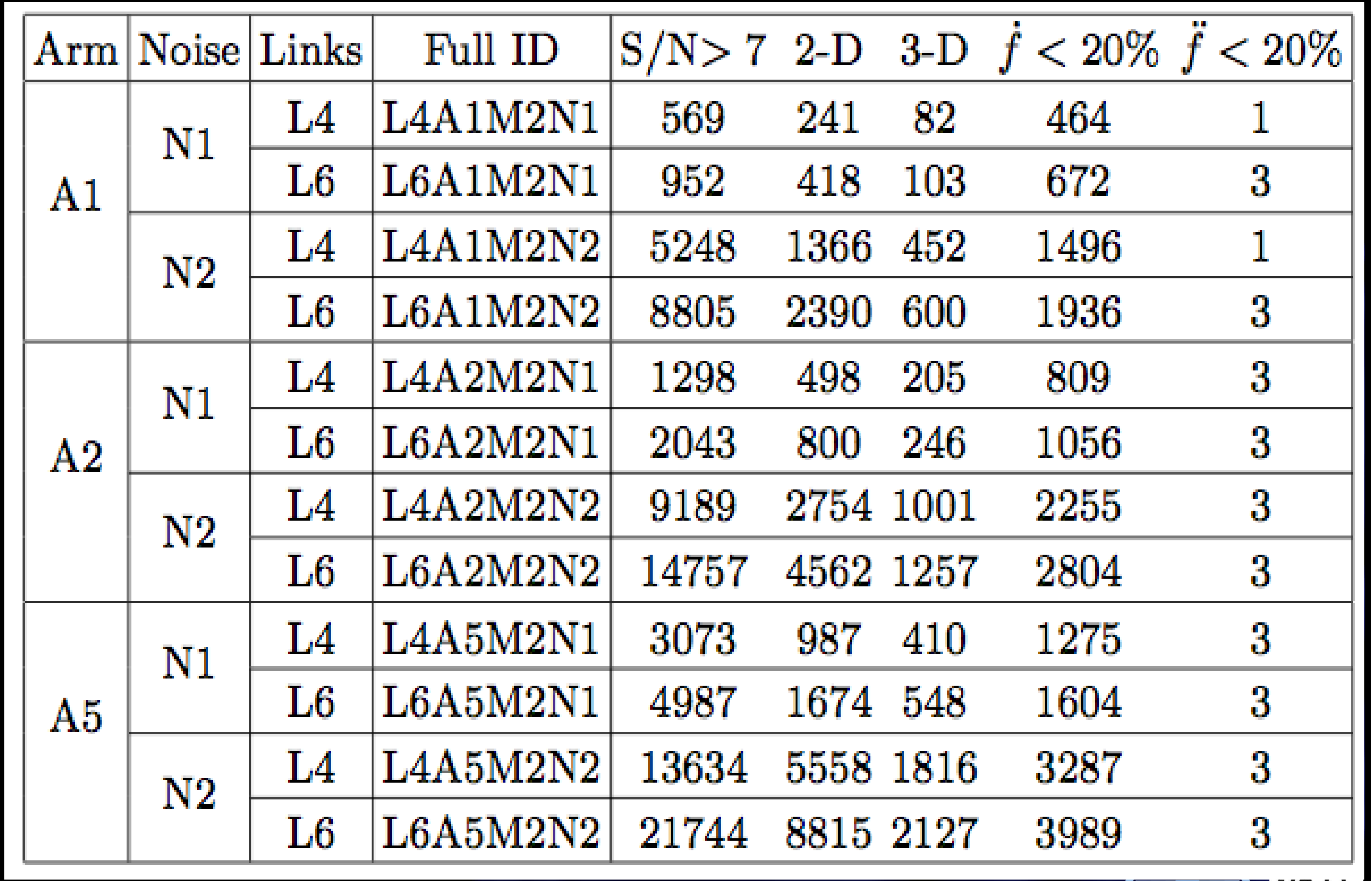
Preliminary estimations for galactic binaries

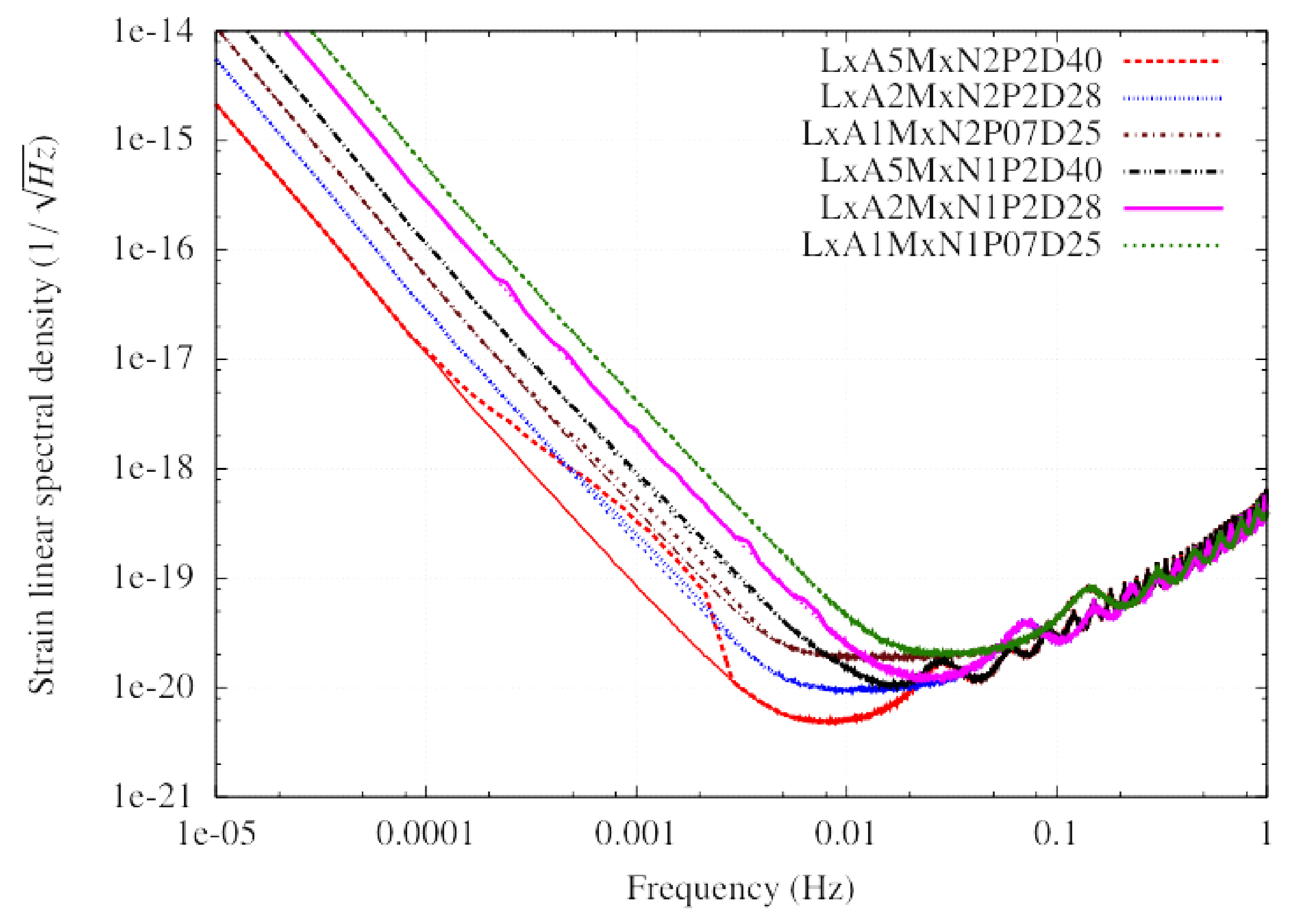
- PRELIMINARY ESTIMATION
- Over 60 millions sources
- Detected
- Localized :
  - 2D
  - 3D
- Type of mass transfer



Arm	Noise	Links	Full ID	S/N> 7	2-D	3-D	$\dot{f} < 20\%$	$\ddot{f} < 20\%$
A1	N1	L4	L4A1M2N1	569	241	82	464	1
		L6	L6A1M2N1	952	418	103	672	3
	N2	L4	L4A1M2N2	5248	1366	452	1496	1
		L6	L6A1M2N2	8805	2390	600	1936	3
A2	N1	L4	L4A2M2N1	1298	498	205	809	3
		L6	L6A2M2N1	2043	800	246	1056	3
	N2	L4	L4A2M2N2	9189	2754	1001	2255	3
		L6	L6A2M2N2	14757	4562	1257	2804	3
A5	N1	L4	L4A5M2N1	3073	987	410	1275	3
		L6	L6A5M2N1	4987	1674	548	1604	3
	N2	L4	L4A5M2N2	13634	5558	1816	3287	3
		L6	L6A5M2N2	21744	8815	2127	3989	3

Preliminary estimations for galactic binaries

- PRELIMINARY ESTIMATION
- Confusion noise : sum of all unresolved galactic binaries
- Needed for at least for configuration with LPF expected acceleration noise



Preliminary estimations for Massive Black Hole Binaries

- PRELIMINARY ESTIMATION : Optimal waveform not available … pessimistic estimations, ..
- 1Gm – 2 years – LPF required :
  - 5-40 detected in total but very few with a decent parameters estimation.
- 1 Gm – 2 years – LPF expected :
  - 10-100 detected in total with few high redshift ($z>10$) but still poor parameters estimation.
- 5 Gm – 2 years – LPF expected :
  - 15 – 250 detected in total ; 0-80 @ $z>10$ and few tens with good parameter estimations

Preliminary estimations : Cosmological sources

- To be done !
- Should be easy to over plot model on sensitivity curve
- It could be very interesting to use more realistic data using for example catalog of event for cosmic strings : working in progress at APC (student J.-B. Jolly) ...

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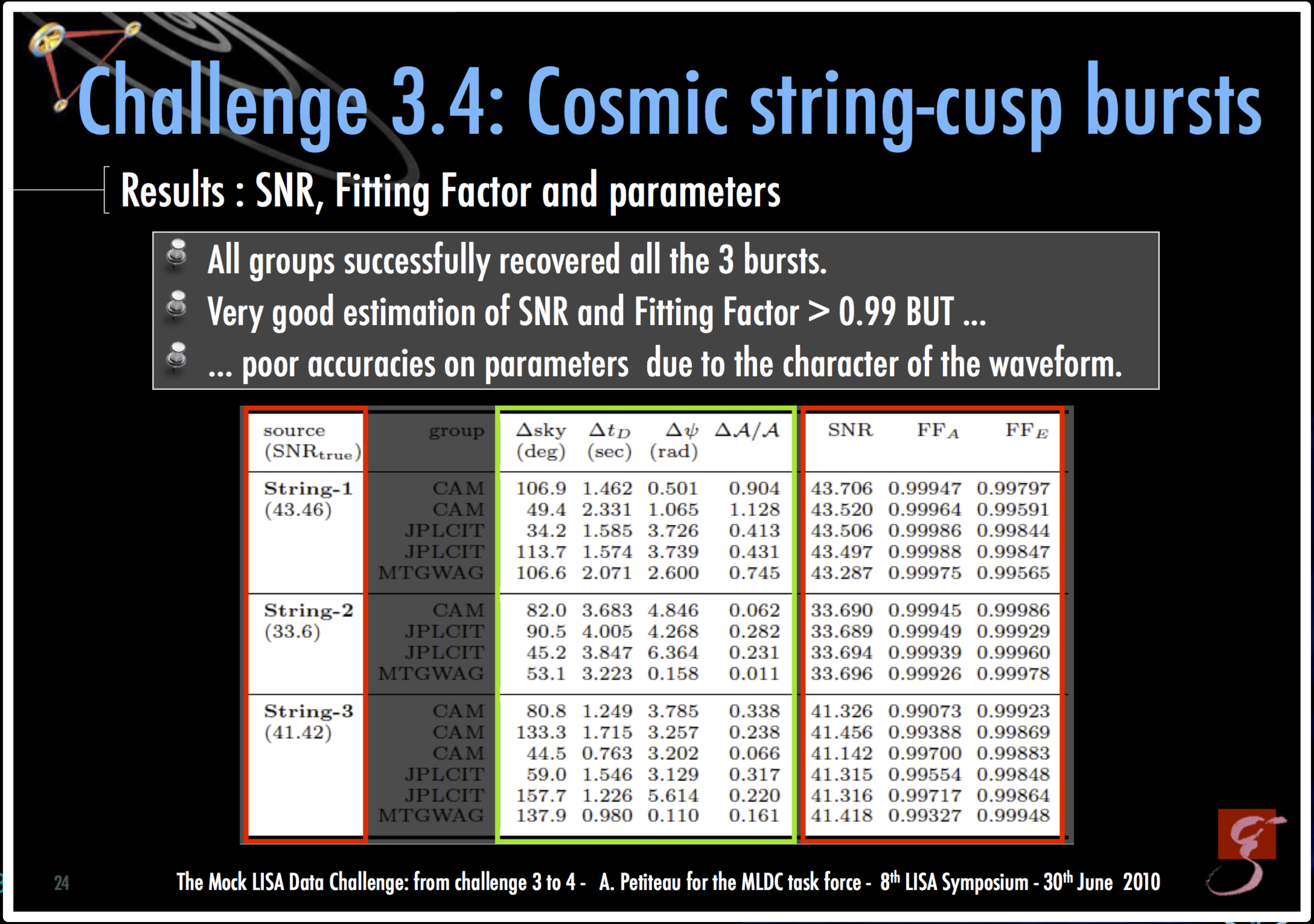
Data analysis for bursts

- Heritage from Mock LISA data Challenge : cosmic string bursts were included in the MLDC3 (Babak et al. CQG27:084009,2010) [5Gm – 3 arms - 2 years – LPF expected] :
  - Methods :
    - Matched filtering with search algorithm to find the best parameters : MultiNest, MCMC parallel tempering
    - Time-frequency
  - Results :
    - Detection : OK
    - Problem to recover the direction of the burst because the waveform is short : very difficult for 3 arms so almost impossible with 2 arms

Data analysis for bursts



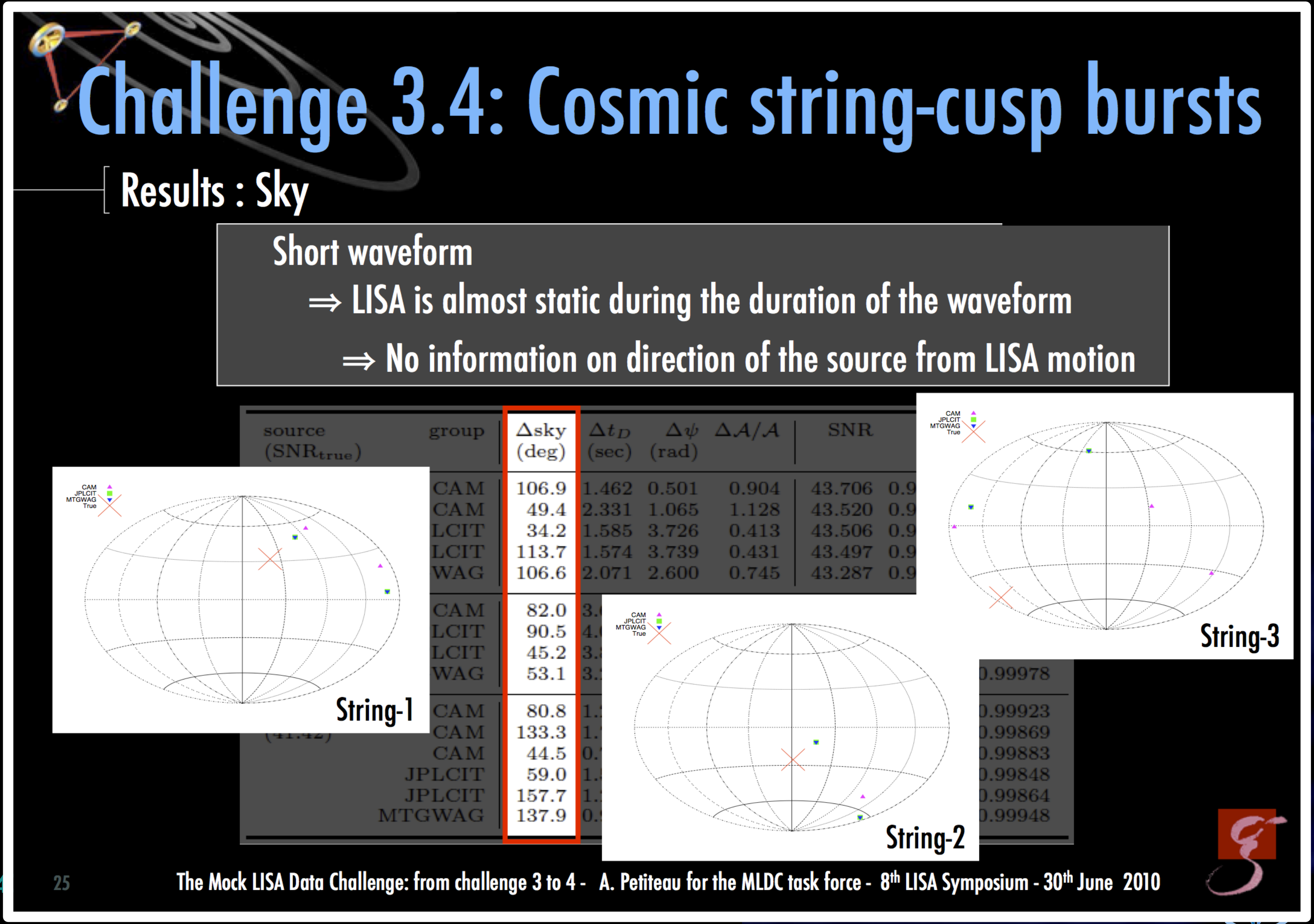
Challenge 3.4: Cosmic string-cusp bursts

Results : SNR, Fitting Factor and parameters

- All groups successfully recovered all the 3 bursts.
- Very good estimation of SNR and Fitting Factor > 0.99 BUT ...
- ... poor accuracies on parameters due to the character of the waveform.

source (SNR_{true})	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR	FF_A	FF_E
String-1 (43.46)	CAM	106.9	1.462	0.501	0.904	43.706	0.99947	0.99797
	CAM	49.4	2.331	1.065	1.128	43.520	0.99964	0.99591
	JPLCIT	34.2	1.585	3.726	0.413	43.506	0.99986	0.99844
	JPLCIT	113.7	1.574	3.739	0.431	43.497	0.99988	0.99847
	MTGWAG	106.6	2.071	2.600	0.745	43.287	0.99975	0.99565
String-2 (33.6)	CAM	82.0	3.683	4.846	0.062	33.690	0.99945	0.99986
	JPLCIT	90.5	4.005	4.268	0.282	33.689	0.99949	0.99929
	JPLCIT	45.2	3.847	6.364	0.231	33.694	0.99939	0.99960
	MTGWAG	53.1	3.223	0.158	0.011	33.696	0.99926	0.99978
String-3 (41.42)	CAM	80.8	1.249	3.785	0.338	41.326	0.99073	0.99923
	CAM	133.3	1.715	3.257	0.238	41.456	0.99388	0.99869
	CAM	44.5	0.763	3.202	0.066	41.142	0.99700	0.99883
	JPLCIT	59.0	1.546	3.129	0.317	41.315	0.99554	0.99848
	JPLCIT	157.7	1.226	5.614	0.220	41.316	0.99717	0.99864
	MTGWAG	137.9	0.980	0.110	0.161	41.418	0.99327	0.99948

Data analysis for bursts



Challenge 3.4: Cosmic string-cusp bursts

Results : Sky

Short waveform

⇒ LISA is almost static during the duration of the waveform

⇒ No information on direction of the source from LISA motion

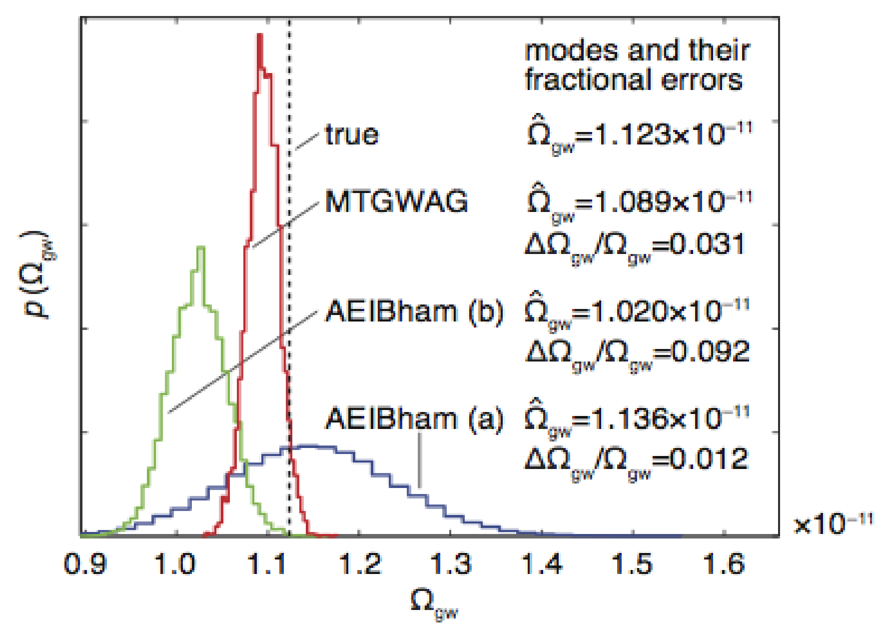
source (SNR$_{\rm true}$)	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR		
	CAM	106.9	1.462	0.501	0.904	43.706	0.9	
	CAM	49.4	2.331	1.065	1.128	43.520	0.9	
	LCIT	34.2	1.585	3.726	0.413	43.506	0.9	
	LCIT	113.7	1.574	3.739	0.431	43.497	0.9	
	WAG	106.6	2.071	2.600	0.745	43.287	0.9	
	CAM	82.0	3.					
	LCIT	90.5	4.					
	LCIT	45.2	3.					
	WAG	53.1	3.					0.99978
	CAM	80.8	1.					0.99923
(41.42)	CAM	133.3	1.					0.99869
	CAM	44.5	0.					0.99883
	JPLCIT	59.0	1.					0.99848
	JPLCIT	157.7	1.					0.99864
	MTGWAG	137.9	0.					0.99948

Data analysis for bursts

- New tests have to be done :
  - with more realistic noises, in particular in the presence of glitches,
  - with more bursts at lower amplitude : confusion limit,
  - with realistic burst population.
- Recover/reimplement old data analysis and develop new ones
- Working in progress at APC ...

Data analysis for stochastic background

- Heritage from Mock LISA data Challenge : cosmic string bursts were included in the MLDC3 (Babak et al. CQG27:084009,2010) [5Gm – 3 arms - 2 years – LPF expected] :
  - Method :
    - Used the noise uncorrelated virtual interferometer A & E or A, E and T : need 3 arms
    - MCMC to estimate parameters
  - Results :
    - Partial recovery.
    - Limitations in data simulation



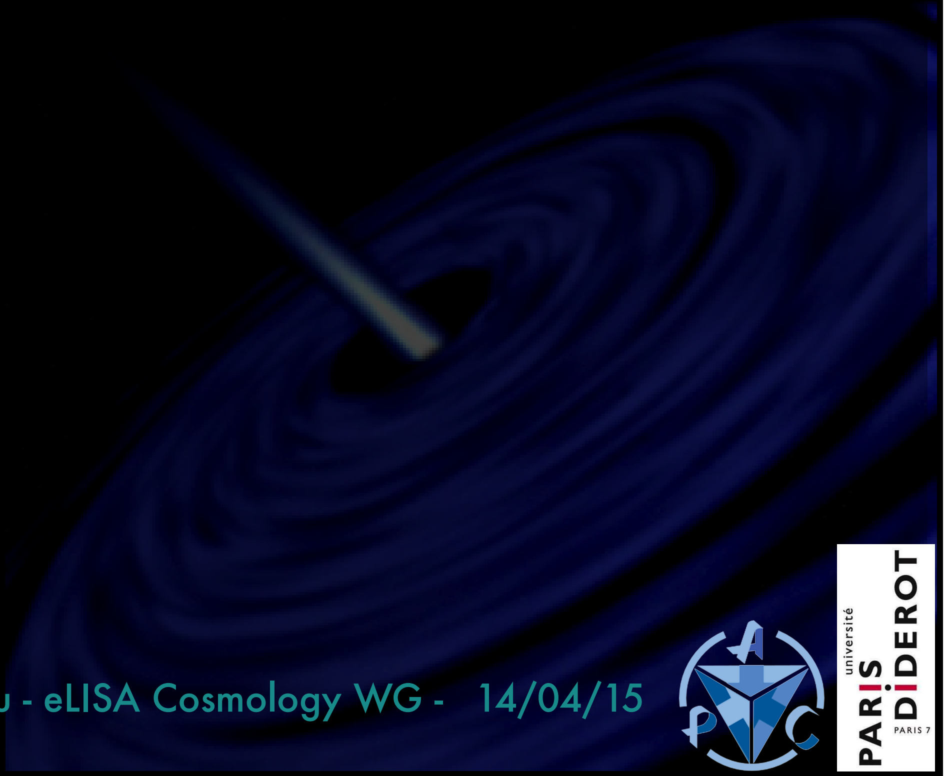
Data analysis for stochastic background

- With 2 arms some ideas using the spectral shape (Cornish et al.) ...
- NEED more work to :
  - Investigate feasibility,
  - Develop new methods,
  - Generate more realistic background.
- Can we characterize each type of background ? Can we do realistic simulation for each of them ?
- Use anisotropy if there is some ?
- Possibly related to the design and the calibration procedure.
- Working in progress ... everybody is welcome !

Conclusion

- Need studies now : the 2–3 next years, before selection in 2018, are the right time to do a “complete” coherent study for eLISA.
- Working in progress on the design of the detector and the key technological aspects.
- Study in progress with a first set of 24 configurations :
    - 3 armlength : 1, 2 or 5 Gm,
    - 2 acceleration noises : LISAPathfinder required or expected
    - 2 durations : 2 or 5 years
    - 2 or 3 arms
- Data analysis : heritage from MLDC but a lot of work has still to be done in particular for the backfround.
- Cosmological sources also have a potential implication on design : calibration procedures, ...

Thank you.



DA ind. sources: Genetic Algorithm

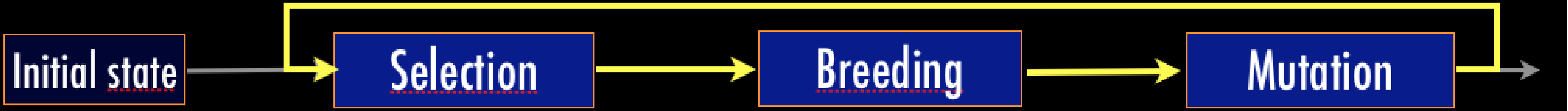
Petiteau et al., PRD 81, 104016 (2010) & Petiteau et al., PRD 87,064036 (2013)

Description : gene ↔ parameter : binary representation (binary or Grey code):

parameter value ↔ 0 1 1 1 0 0 1 0 1 0 0 1

organism ↔ template described by a set of genes

Evolution :



Initial state → Selection → Breeding → Mutation

Selection : Selection of parents for the breeding

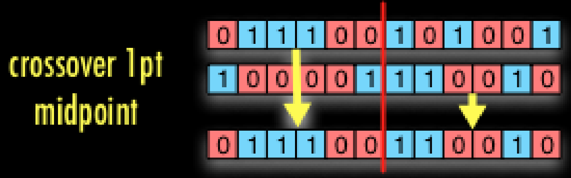
Probability of selecting one organism depend on Quality.

1. Quality $Q_i = Maximized\ Likelihood$,
2. Sort organisms by decreasing normalized quality
3. Roulette selection : Select one organism with probability equal to $Q_{Ni} / \Sigma_j{}^N Q_{Nj}$

Breeding : Making 1 child from the 2 selected parents

Mixing parts of corresponding parental genes. Several types of breeding :

- Crossover one point randomly chosen. Example :



- Others possibilities ...

Mutation : Change few bits in gene

Probability of change described by the 'Probability Mutation Rate' (PMR) ∈[0,1].

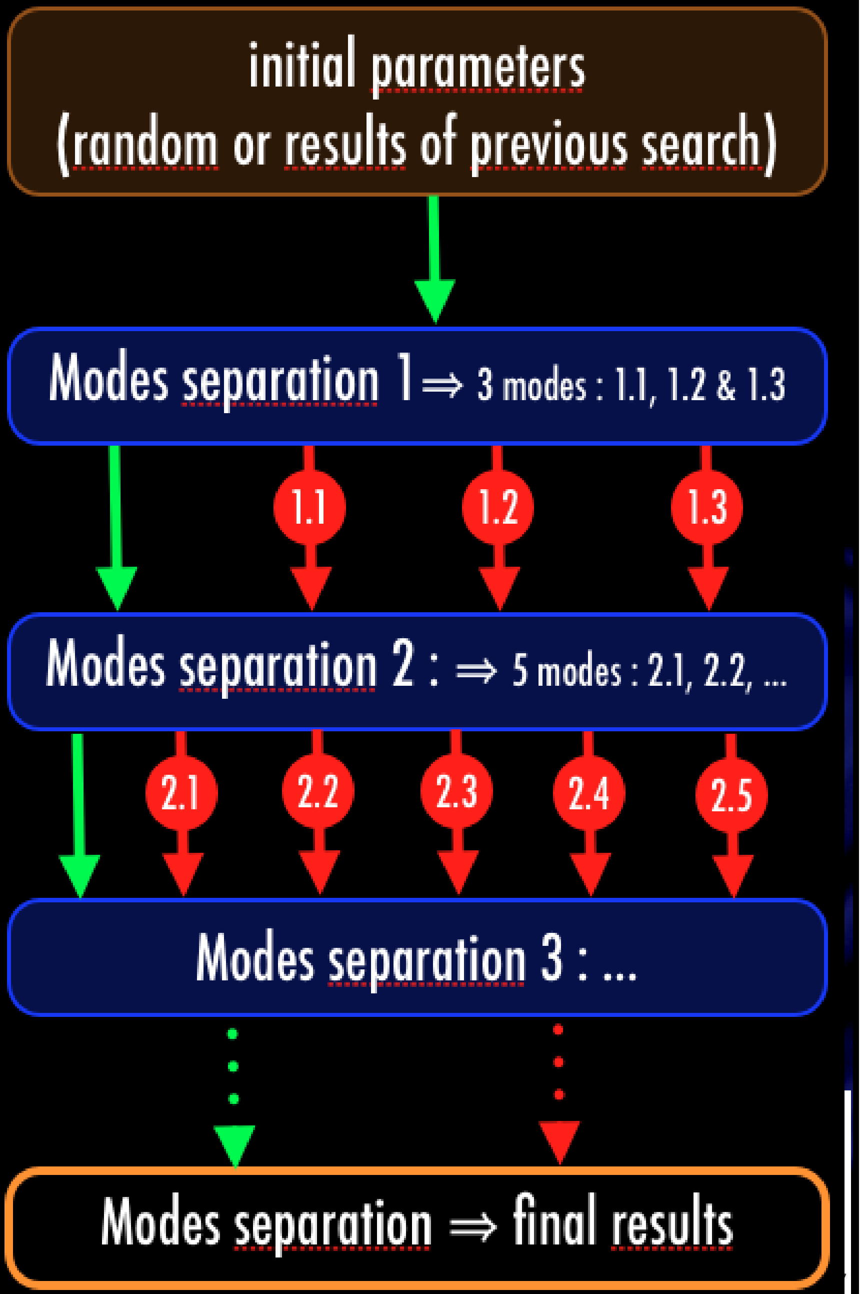
Several types of mutation :

- Mutate all the gene : If a random value α $\alpha<PMR$, mutate the gene. Several types :
  - Choose randomly N bits and flip them.
  - Complete random value
- Mutate bits independently : for each bit compare PMR to a random value α. If $\alpha<PMR$, flip bit (0→1 or 1→0).

DA individual sources: MSGA

Petiteau et al., PRD 87,064036 (2013)

- Framework to run in parallel several dedicated search methods :
  - → "Global searches" looks for new good candidates avoiding the ones already found.
  - → "Local searches" explores in details the best candidates found at the previous step.
  - "Modes separation" : the results are combined to find a new set of best candidates using some criterions (high SNR and not to close to the others).
  - Each search is done by a GA with a special tuning.



initial parameters
(random or results of previous search)

Modes separation 1 ⇒ 3 modes : 1.1, 1.2 & 1.3

Modes separation 2 : ⇒ 5 modes : 2.1, 2.2, ...

Modes separation 3 : ...

Modes separation ⇒ final results