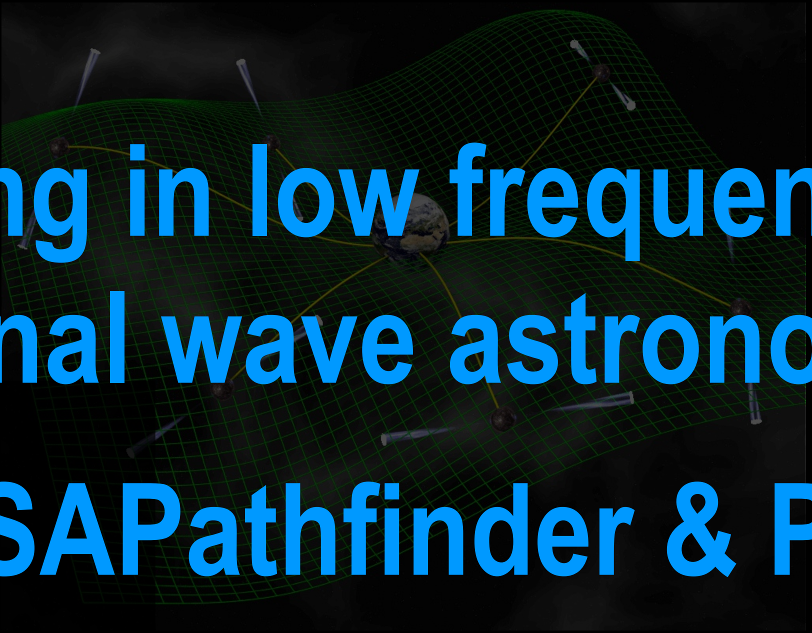


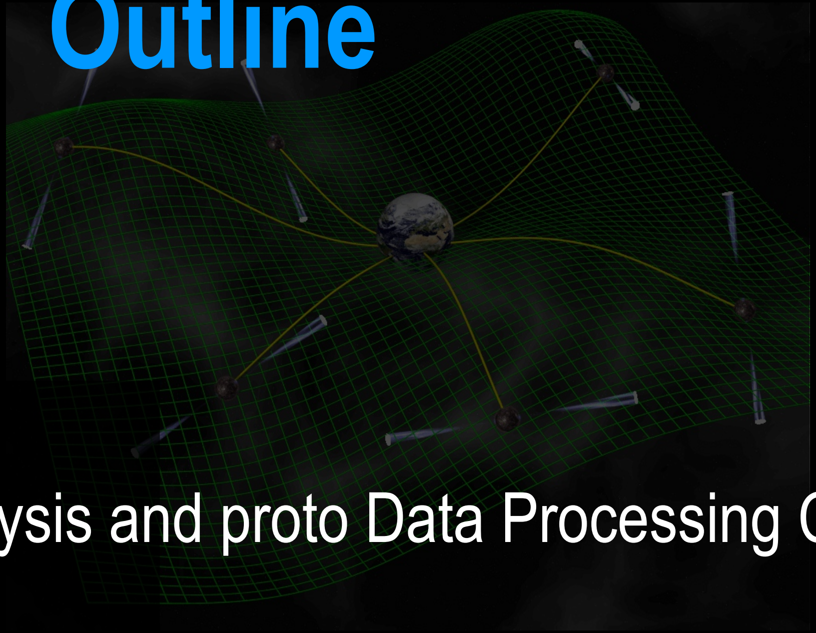
Computing in low frequency gravitational wave astronomy

eLISA, LISAPathfinder & PTA

A. Petiteau (APC – University Paris Diderot)

FACe (Paris) – 8th December 2015
Workshop
Distributed computing in Astrophysic

Outline



- Gravitational waves
- eLISA
  - eLISA mission
  - Preliminary data analysis and proto Data Processing Center
- LISAPathfinder
  - LISAPathfinder mission
  - Data analysis and hybrid cluster
- Pulsar Timing Array
  - Introduction
  - Data analysis
- Conclusion

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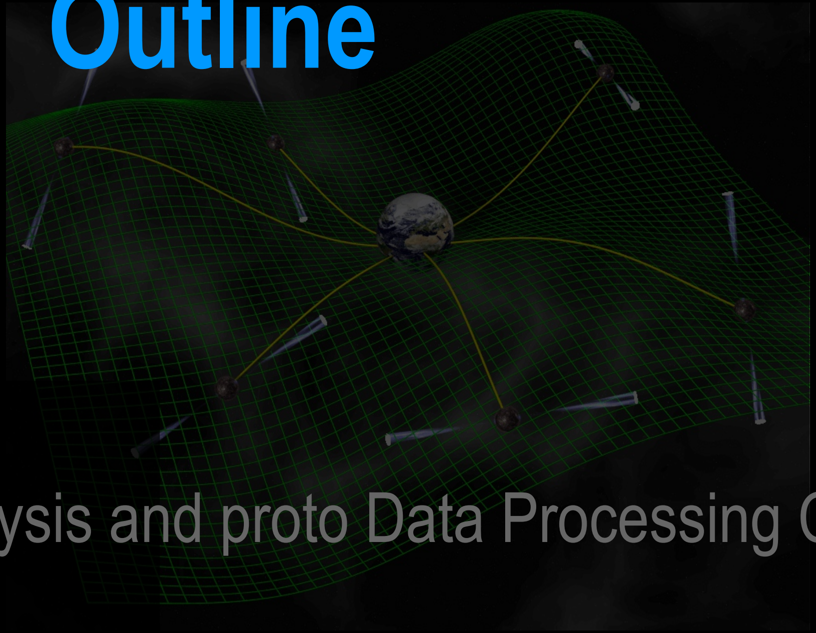

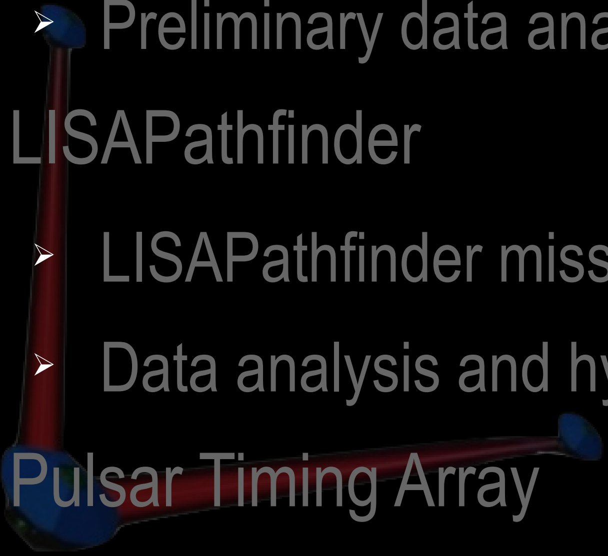

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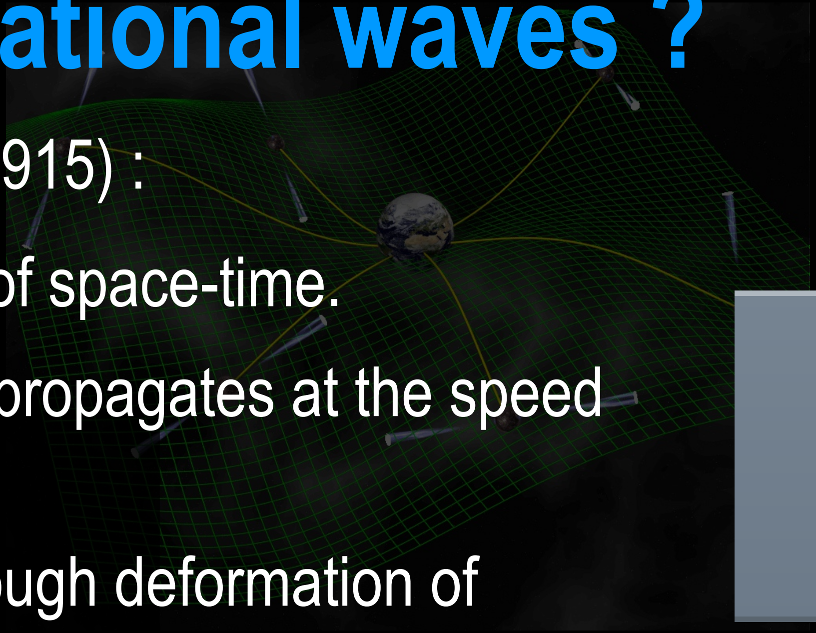
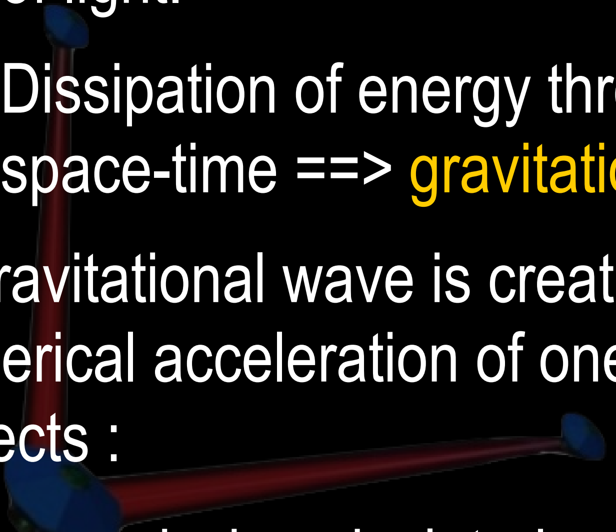
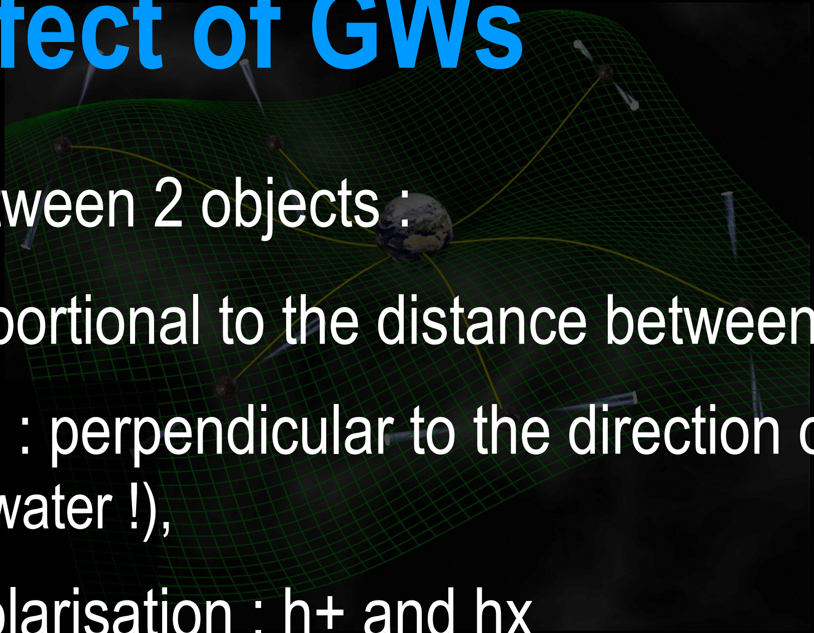
Gravitational waves ?





- General Relativity (Einstein 1915) :
  - Mass deforms geometry of space-time.
  - Gravitational information propagates at the speed of light.
  - Dissipation of energy through deformation of space-time ==> gravitational waves
- A gravitational wave is created during the non-spherical acceleration of one or several massive objects :
  - no emission : isolated, spherical body possibly in rotation
  - emission : asymetric collapse, bodies in orbits or coalescing, ...

Effect of GWs



- Modification of distance between 2 objects :
  - Elastic deformation proportional to the distance between the 2 objects,
  - Transverse deformation : perpendicular to the direction of propagation (different from ripples on water !),
  - Two components of polarisation : h+ and hx

$$\frac{\delta L}{L} = \frac{h}{2}$$

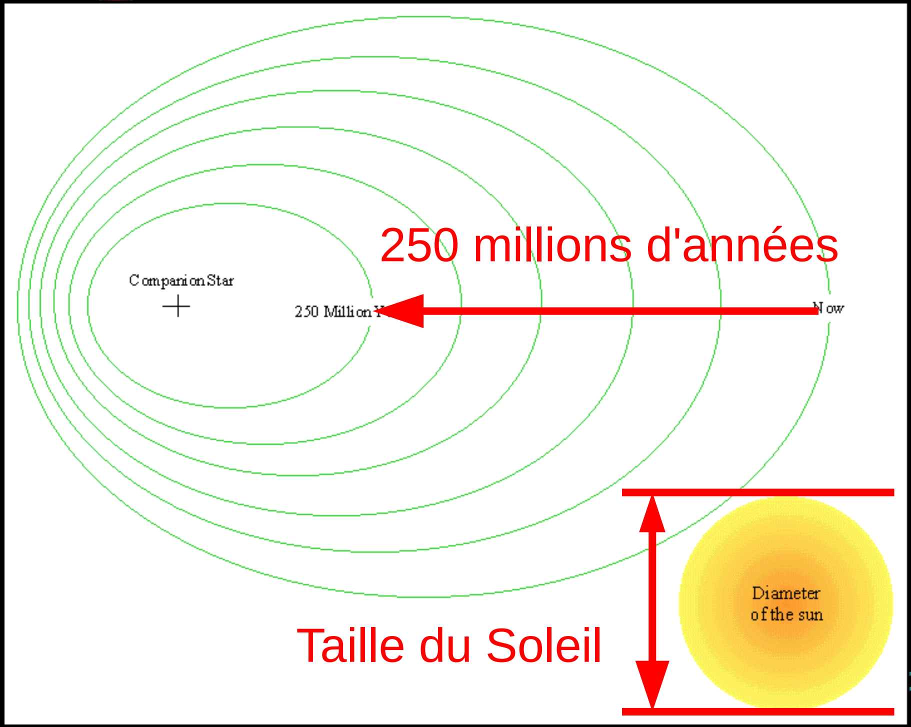
deformation

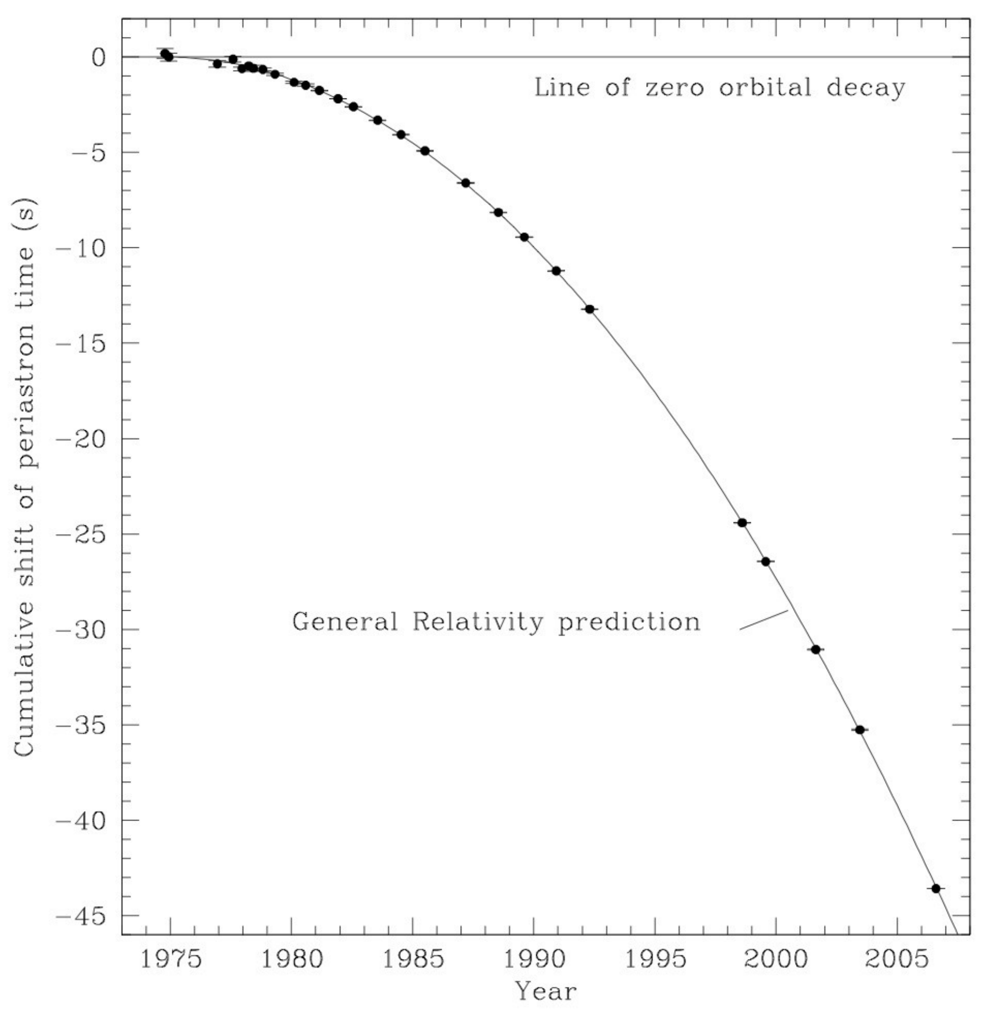
wave amplitude (h)

Effect of GWs

GWs exist !

- Observation of GWs from pulsar in binary system
- Shrinking of the orbit due to the loose energy … by emission of GWs !
- => (indirect proof) : Hulse & Taylor (Nobel Prize 1993)

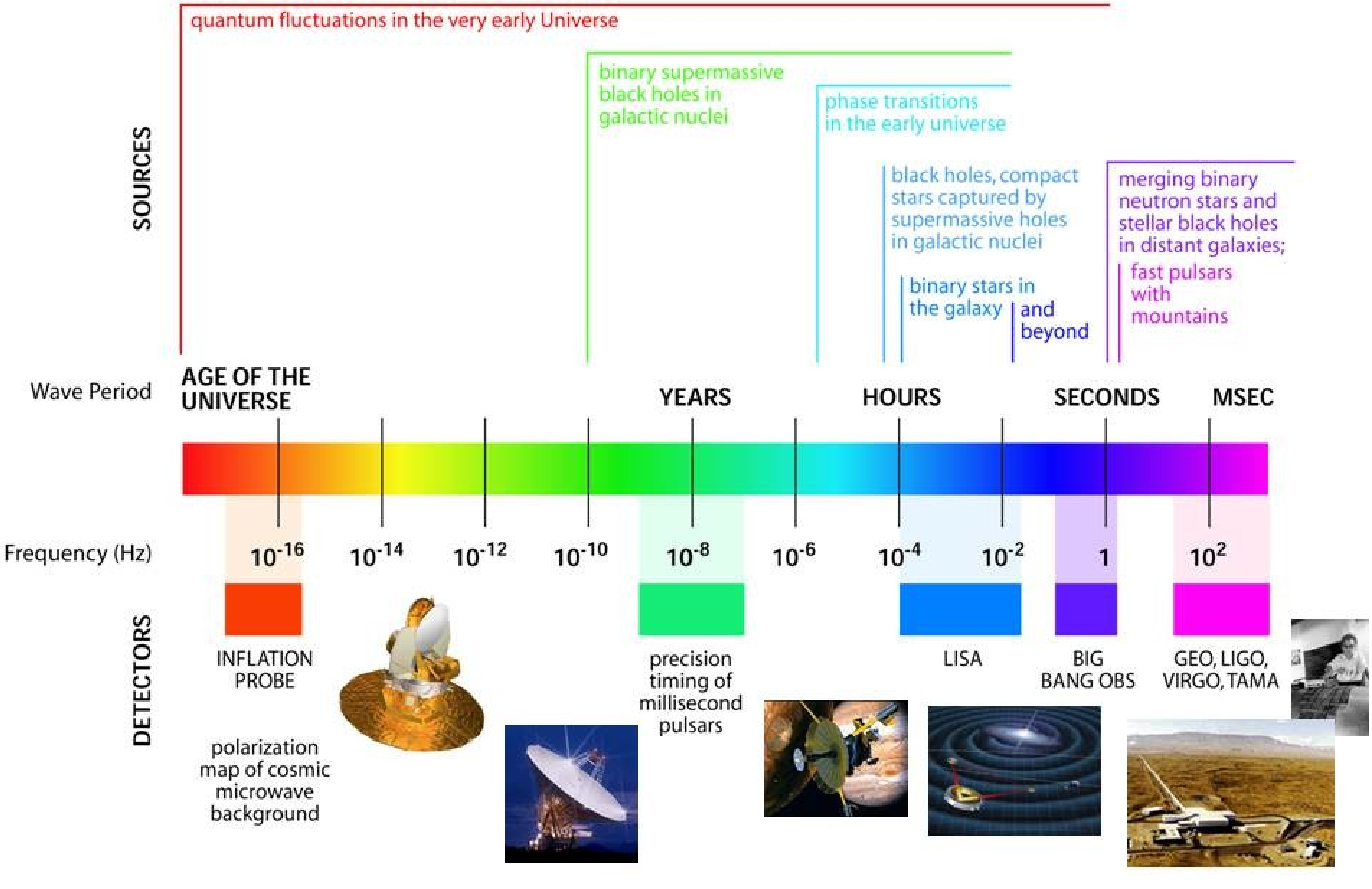




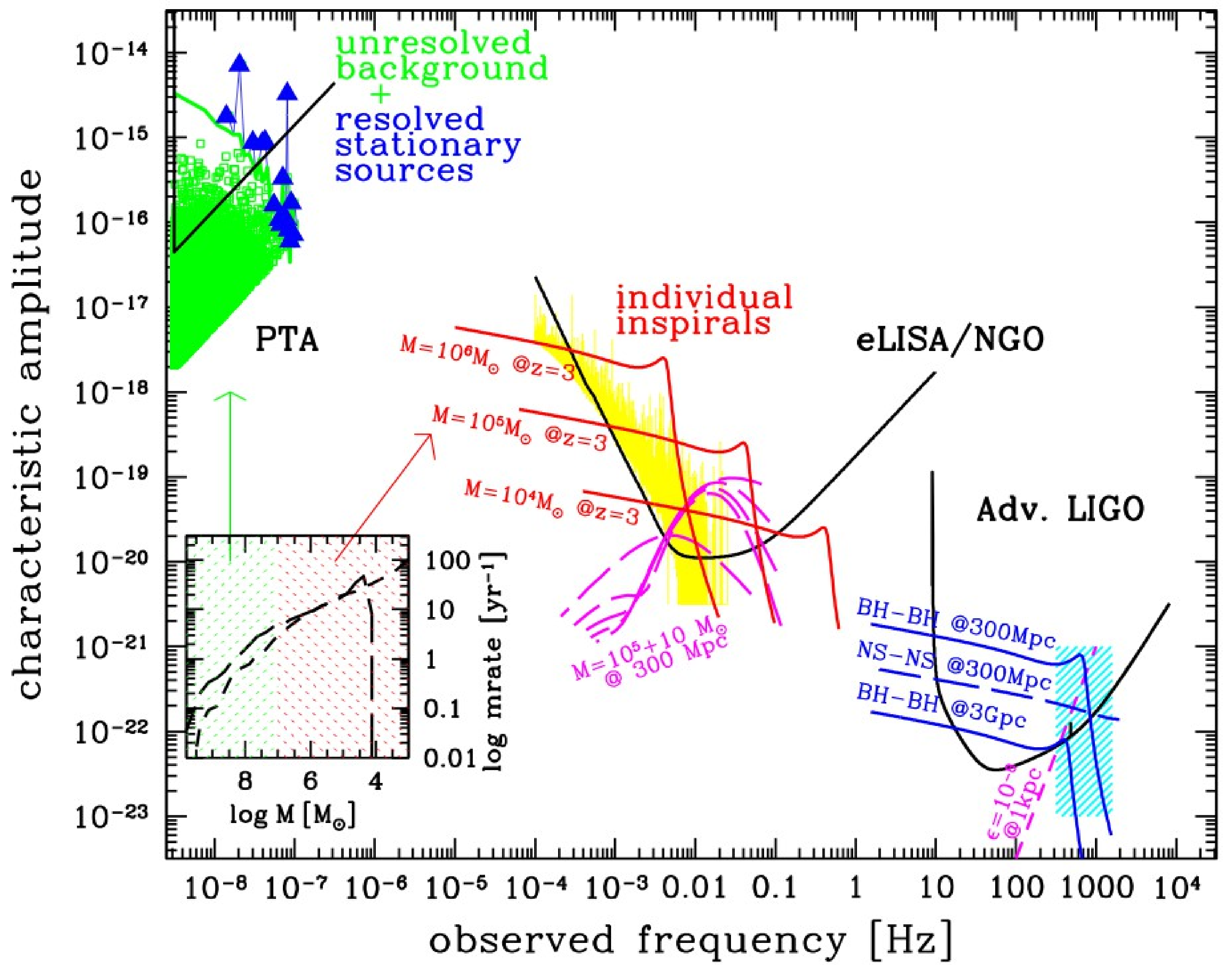
Why observing with GWs ?

- The nature of gravity (testing the basis of general relativity)
- Fundamental nature of black hole : existence of horizon, ...
- Black holes as a source of energy,
- Nonlinear structure formation : seed, hierarchical assembly, accretion,
- Understanding the end of the life of massive stars,
- Dynamic of galactic nuclei,
- The very early Universe : Higgs TeV physics, topological defects, ...
- Constraining cosmological models,
- ...
- ==> Opening a new observational window on the Universe (with all the unexpected …) : looking at dark side of the Universe !

THE GRAVITATIONAL WAVE SPECTRUM

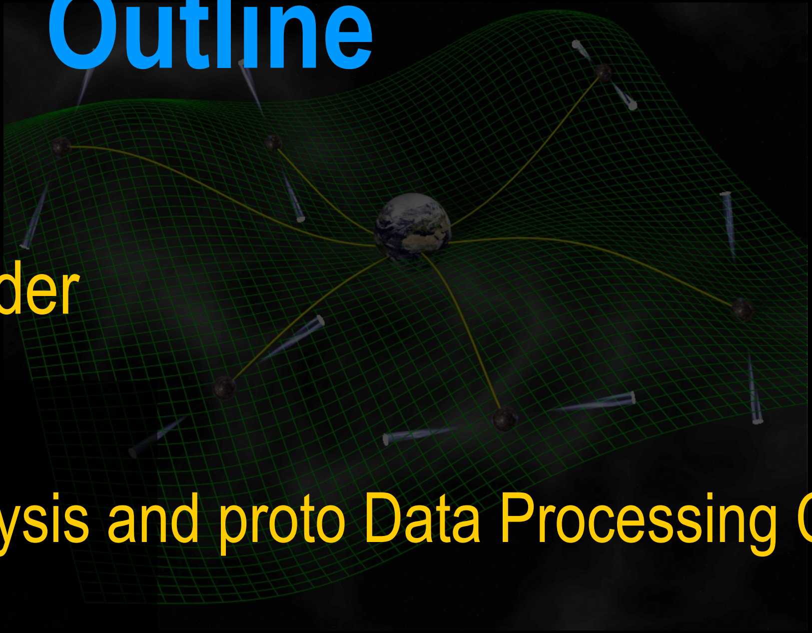


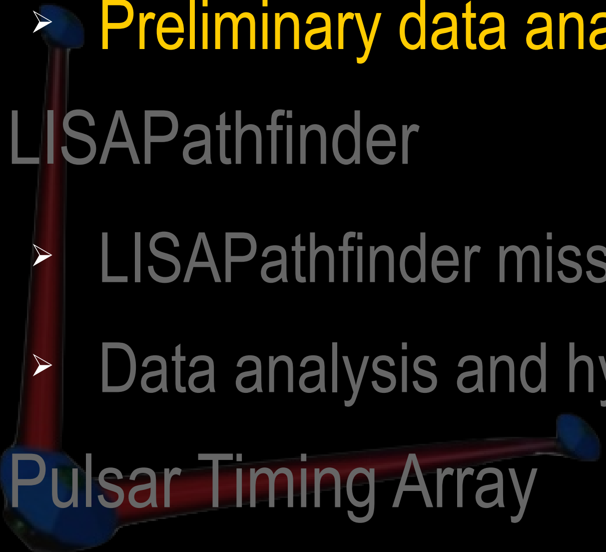
Gravitational waves



Sesana astro-ph.CO 1304.0767 (2013)

Outline





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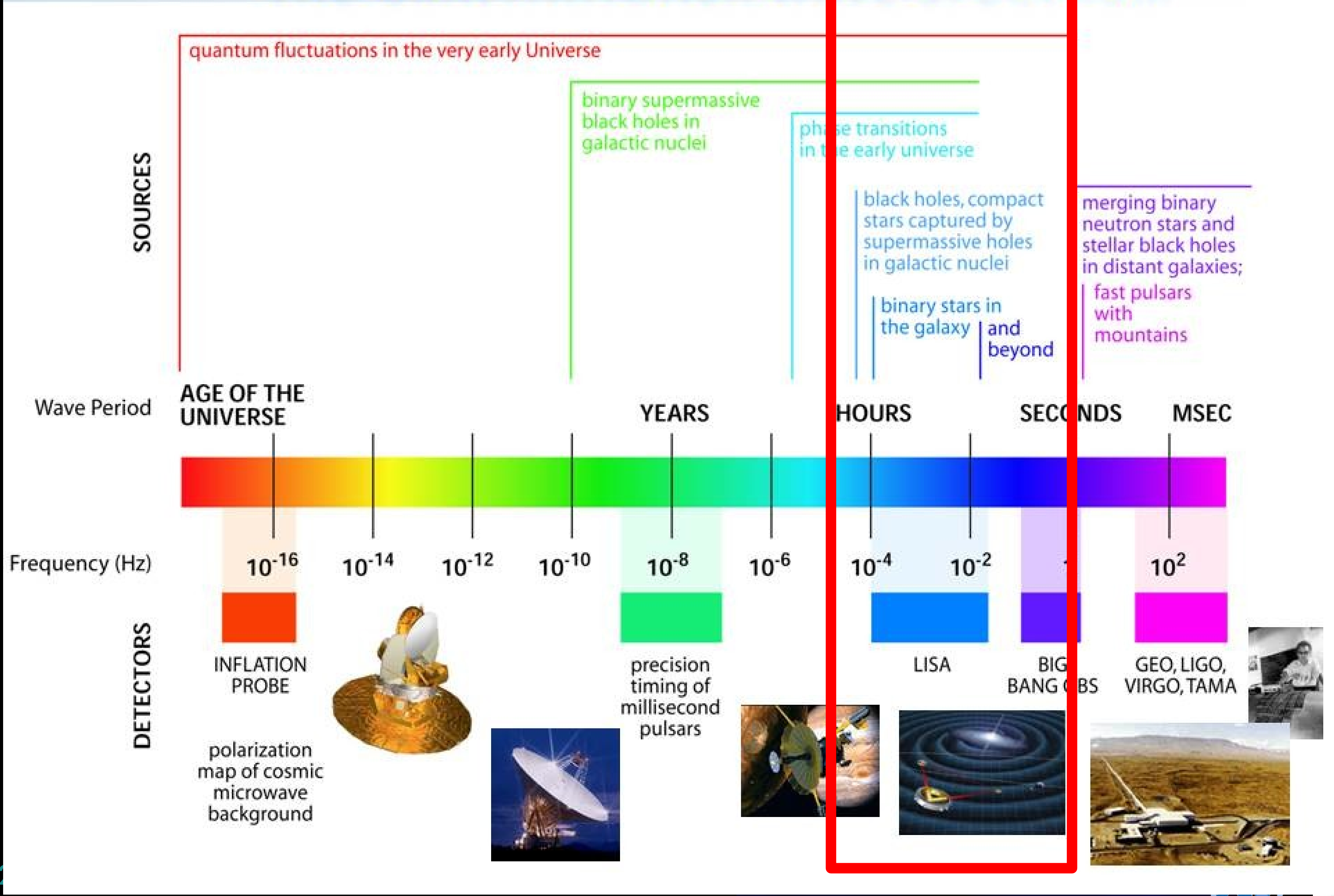
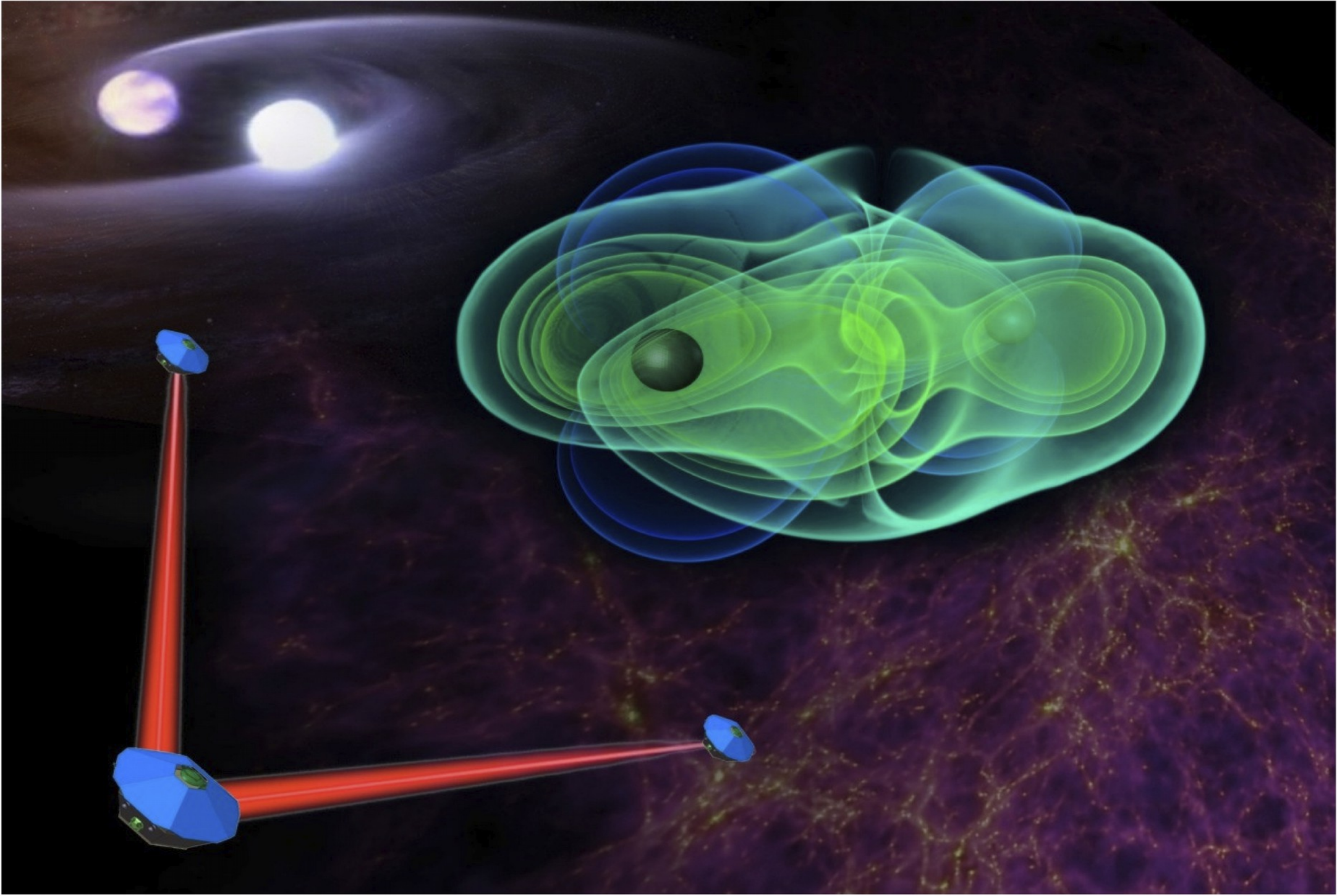


eLISA: space based GW observatory

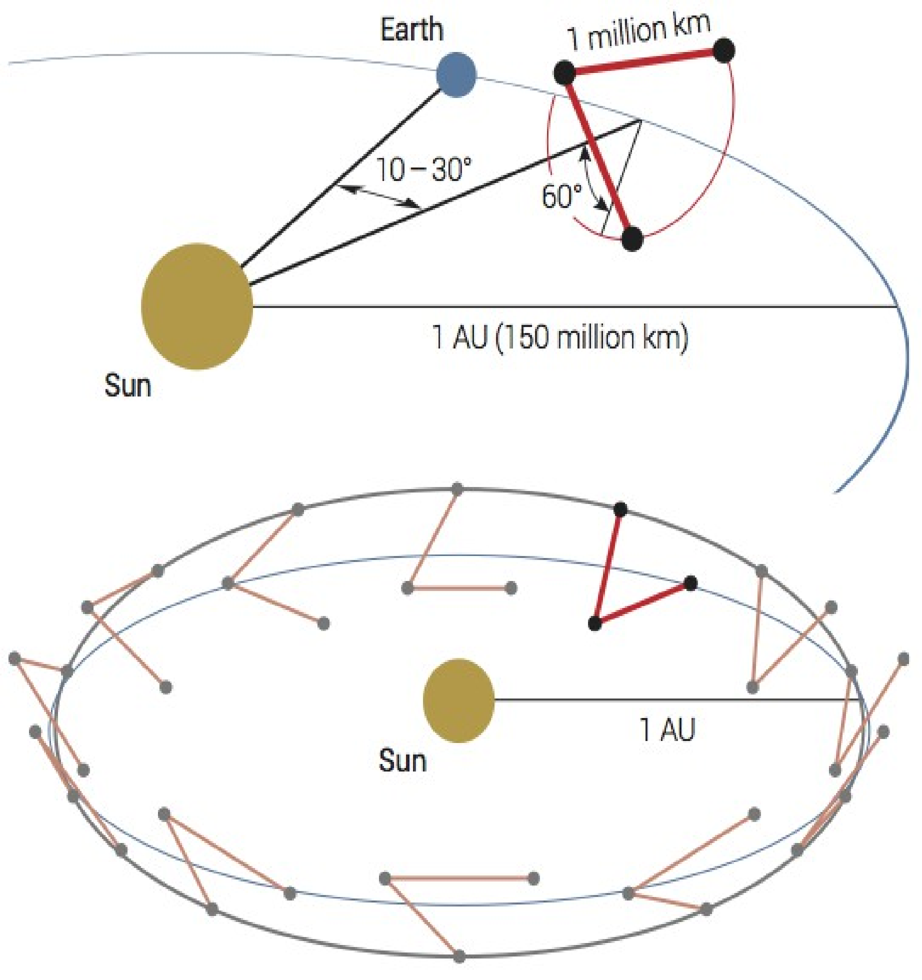
- A large number of sources expected in the frequency range 0.01 mHz to 1 Hz : we need larger armlength, no seismic noise …
- Going to space !

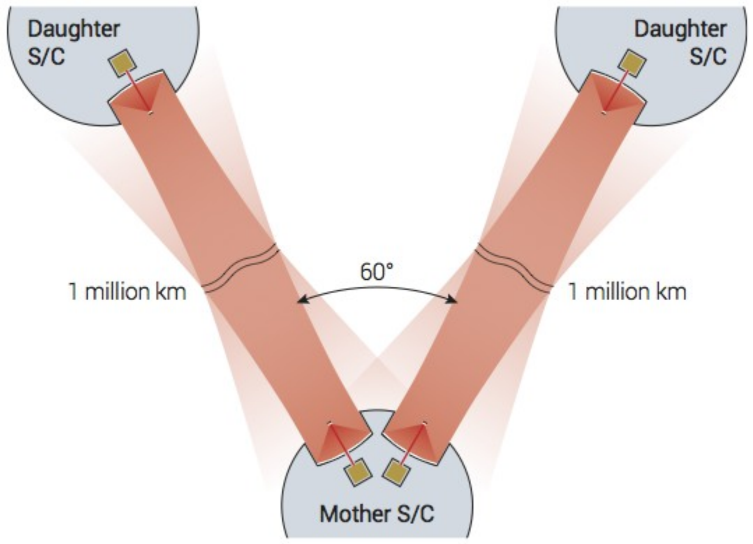
==> eLISA : evolved Laser Interferometer Space Antenna

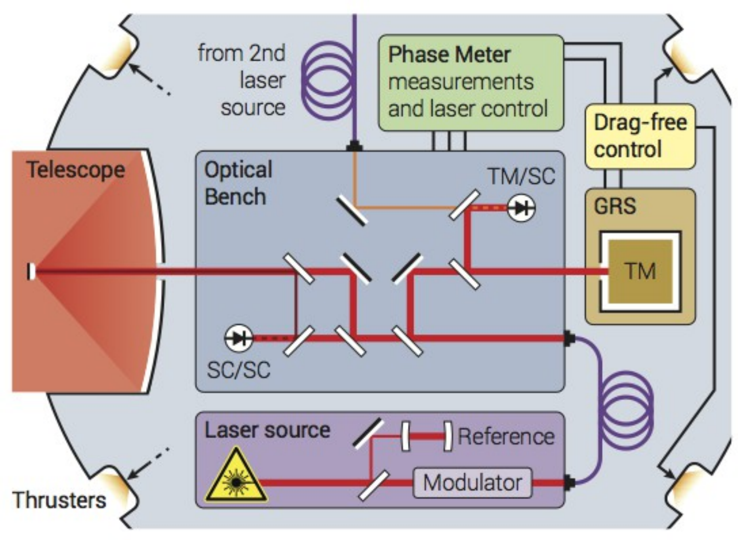


eLISA current concept

- 3 spacecrafts 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

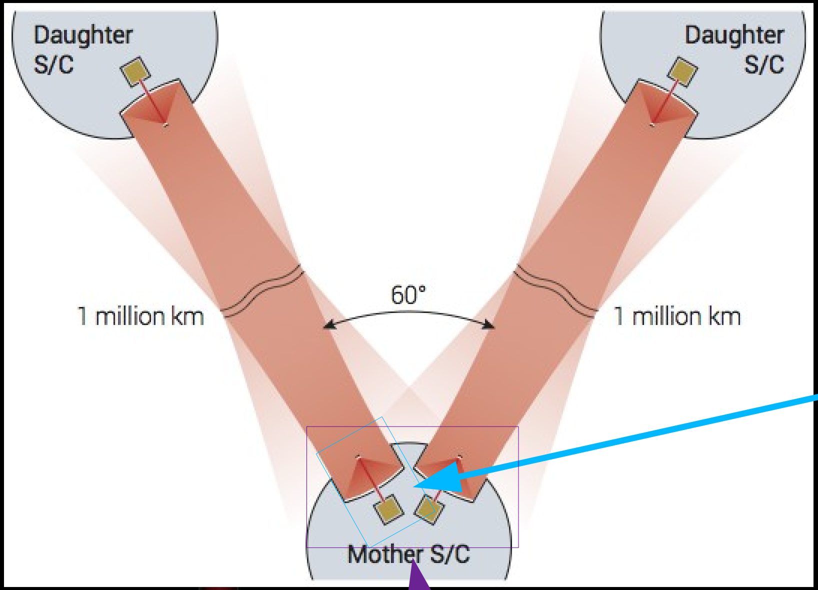


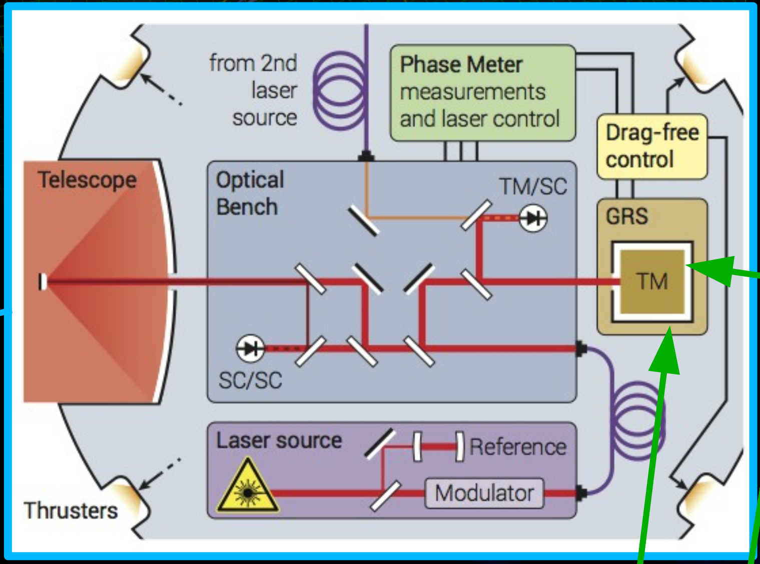


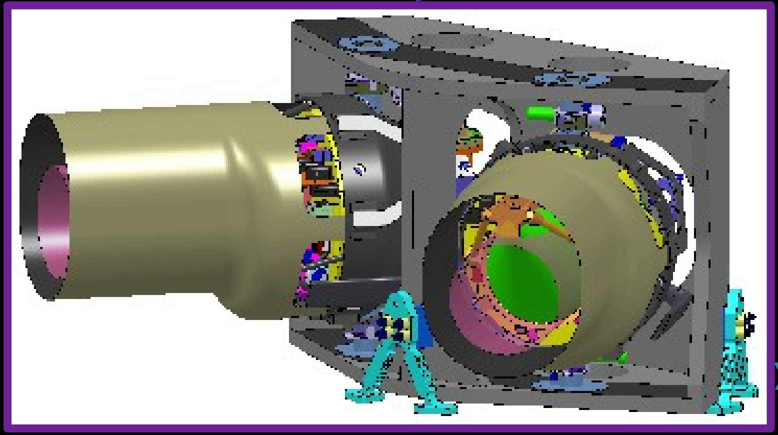


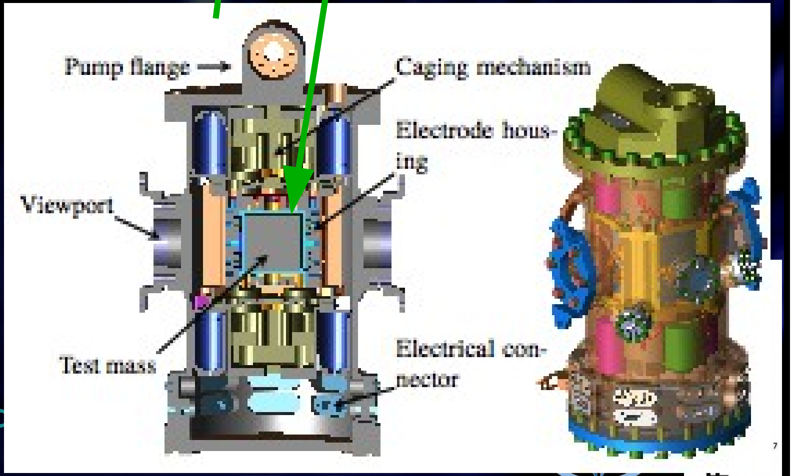
eLISA

- Few key points on the actual design :



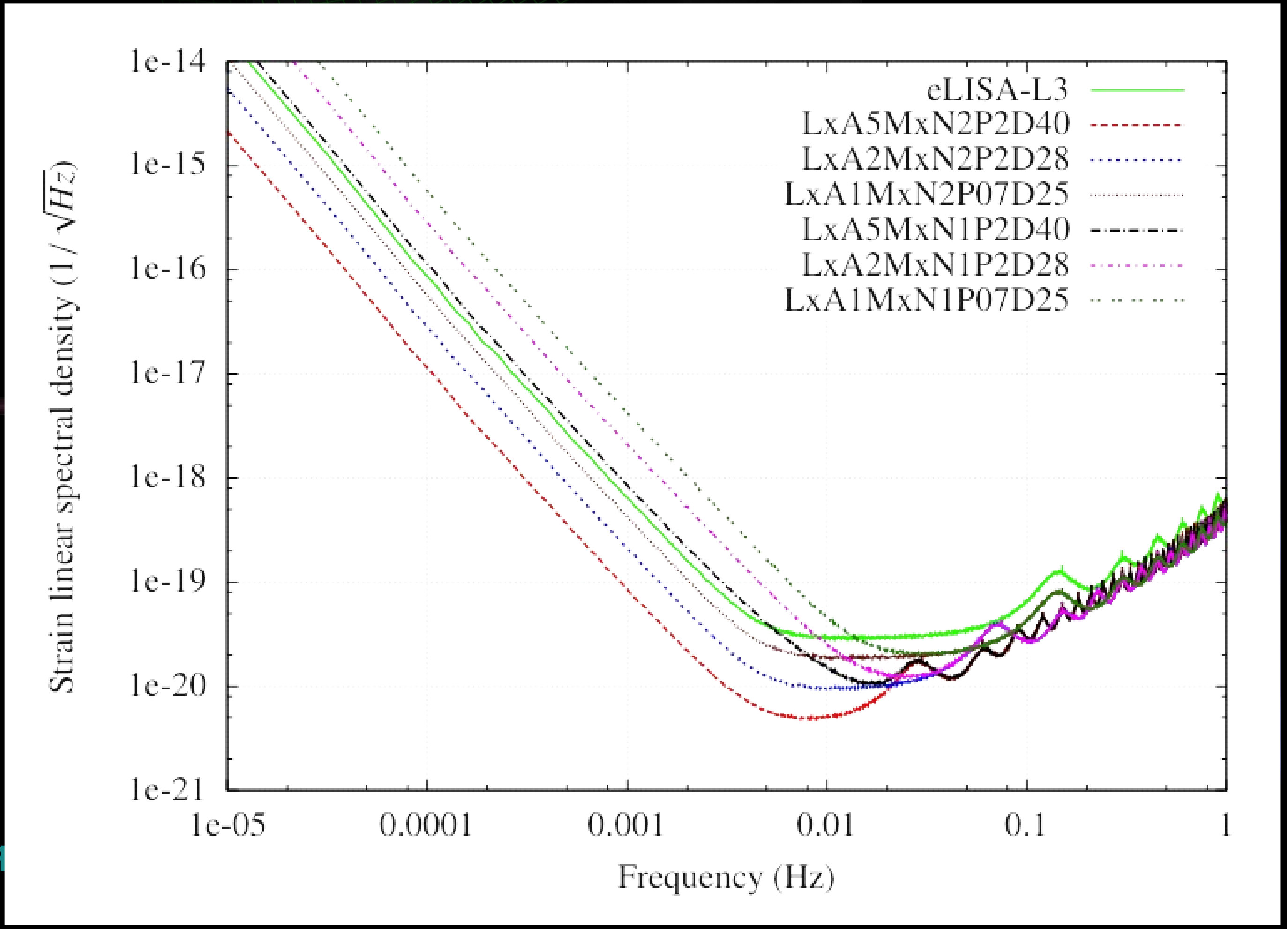






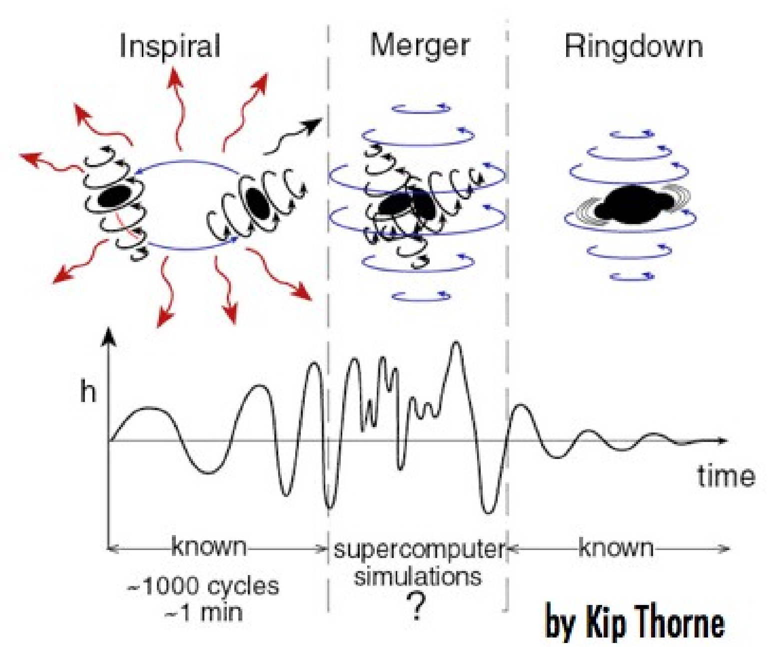
eLISA sensitivity

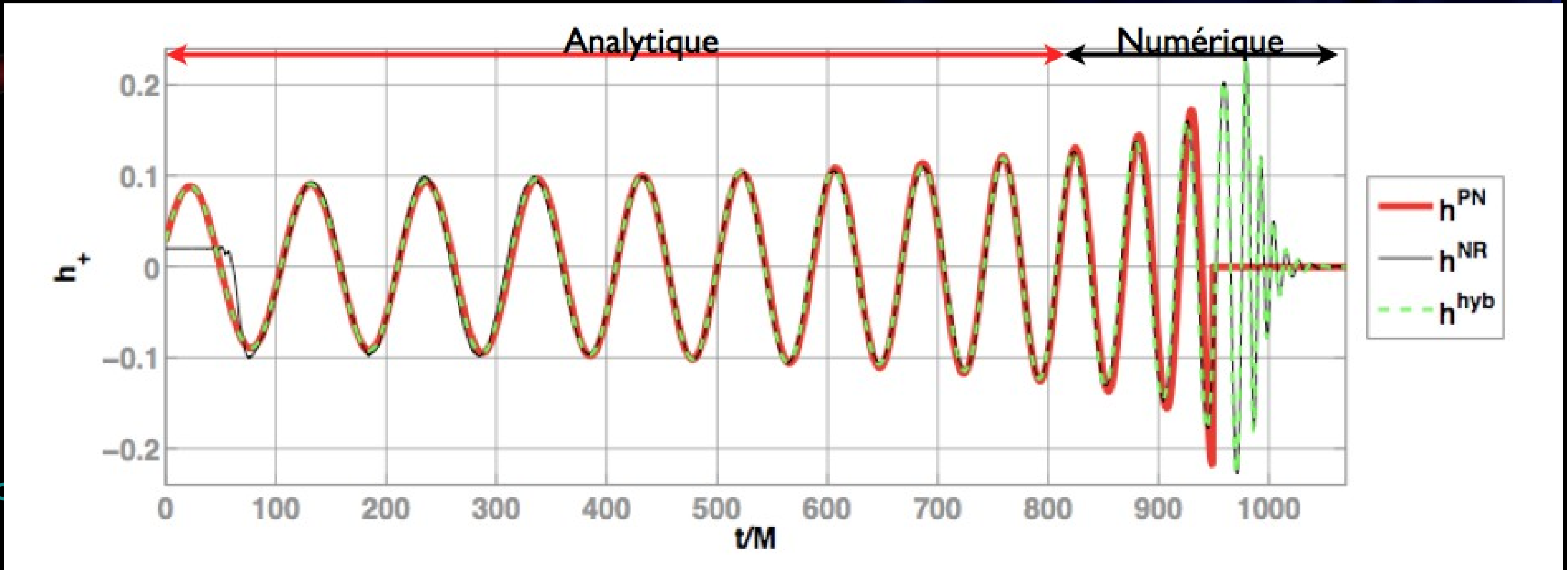
- Call for design around 2017-2020 for a launch around 2034
- Current concept : 2 arms of one million kilometres
- BUT several concepts are studied to optimize the detector, varying :
  - Armlength
  - Number of links
  - Mission duration
  - Acceleration noise



Massive Black Hole Binaries

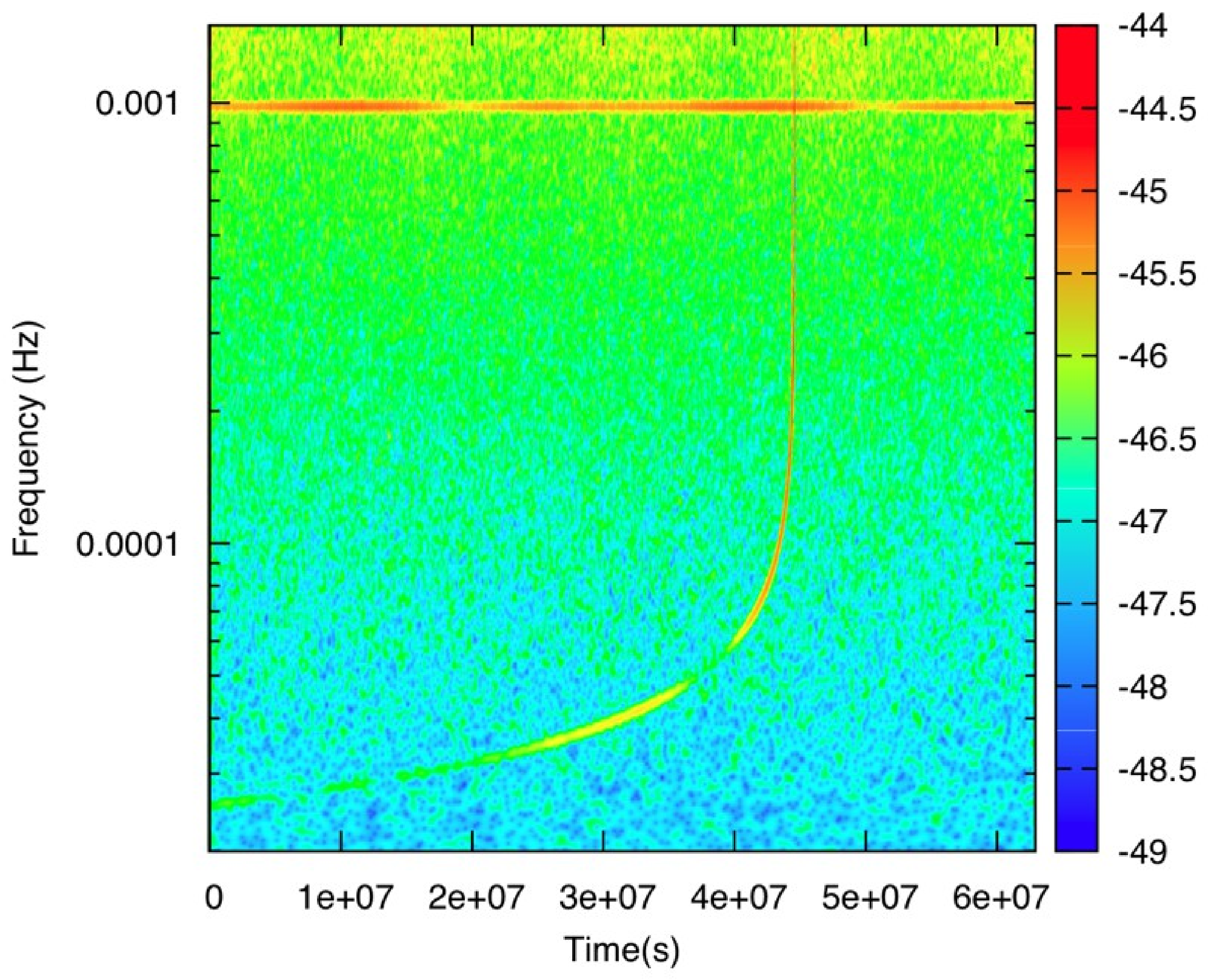
- GW emission: 3 phases:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.
- No full waveform but several approximations exist :
  - Phenomenological waveform (Ohme et al.)
  - Effective One Body
  - ...





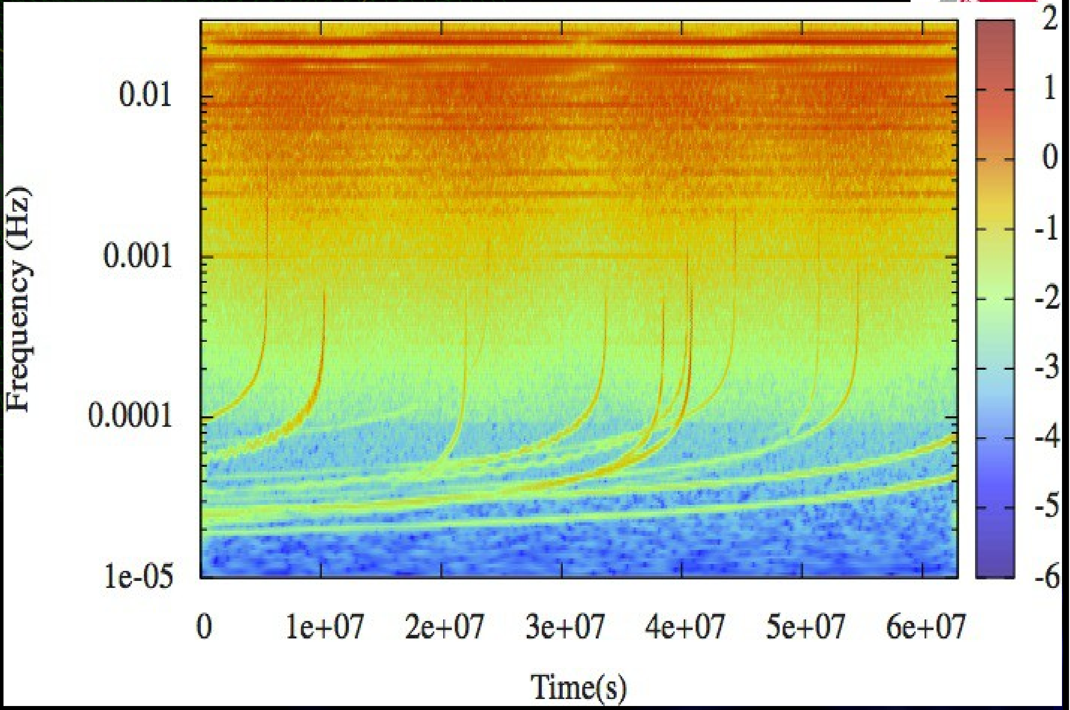
Massive Black Hole Binaries

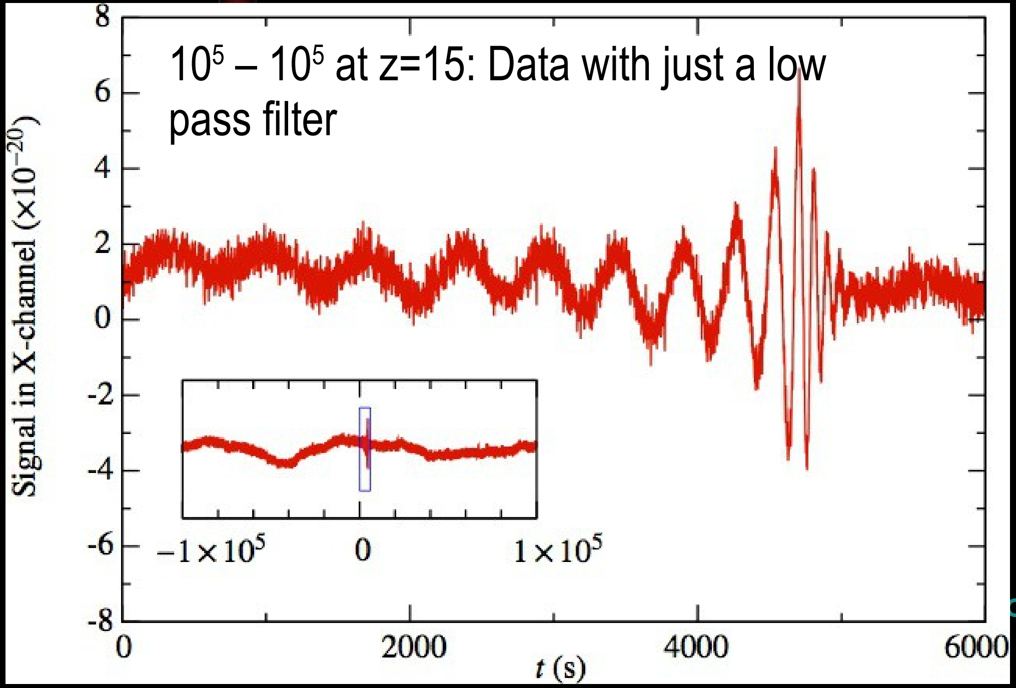
- High signal to noise ratio ==> clear detection in the data

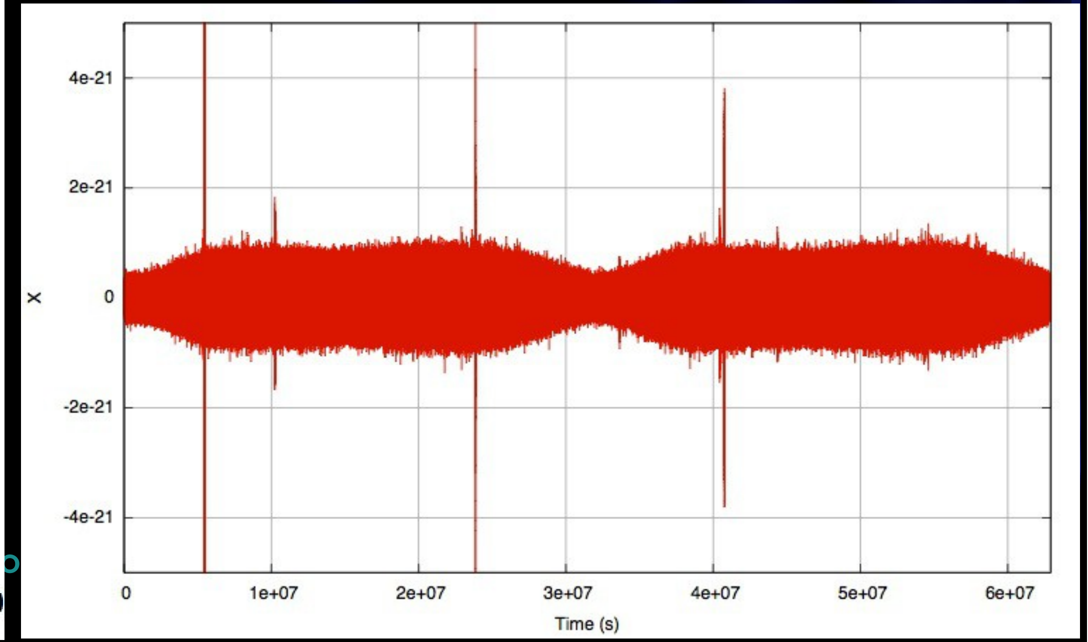


MBH binaries observed by eLISA

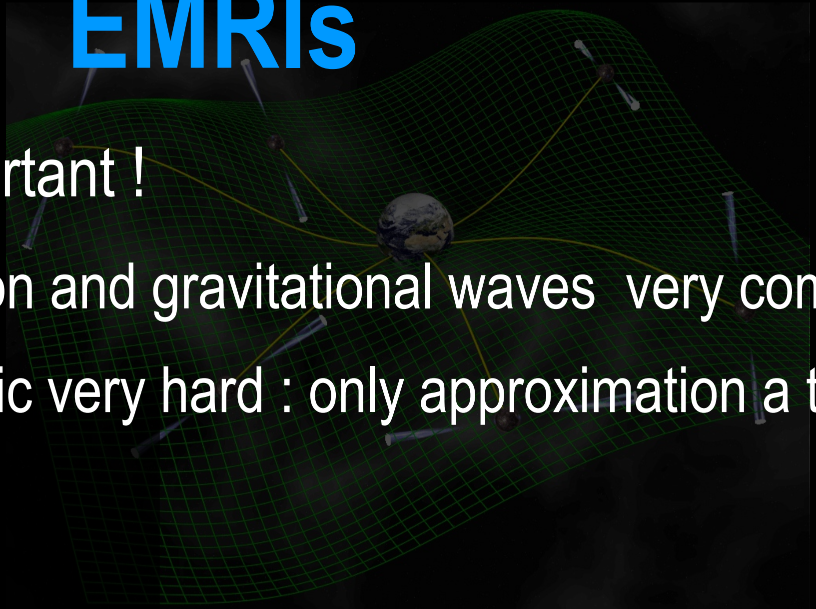
- MBHB can almost be seen “by eyes” in the data.
- Merger for high SNR events appears directly in time data
- Chirps visible time – frequency plan



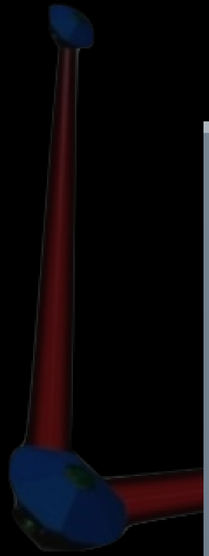

$10^5 – 10^5$ at z=15: Data with just a low pass filter



EMRIs

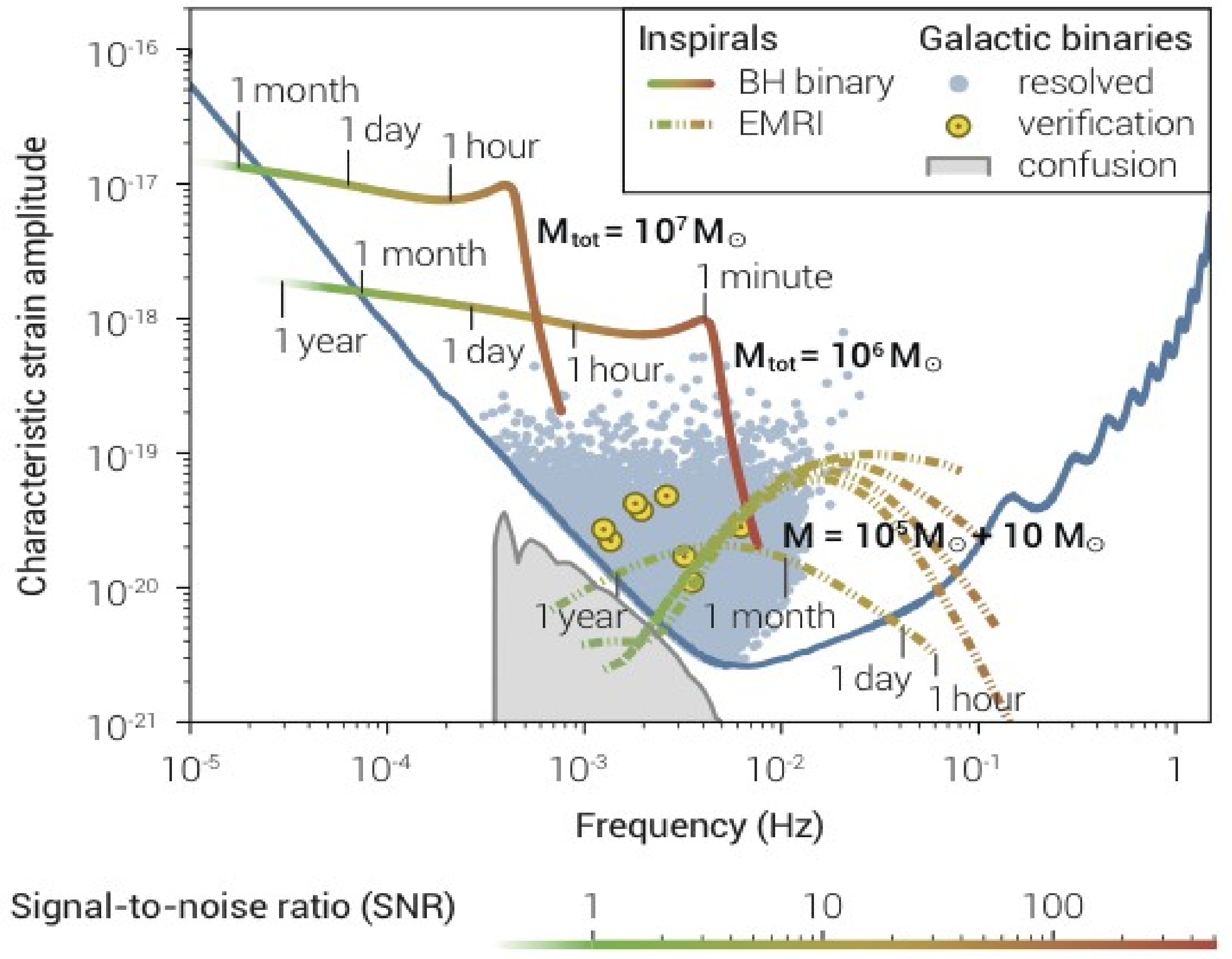


- Relativistic effect very important !
  - trajectory of the companion and gravitational waves very complex.
  - simulation analytic/numeric very hard : only approximation a the moment ...



eLISA sources

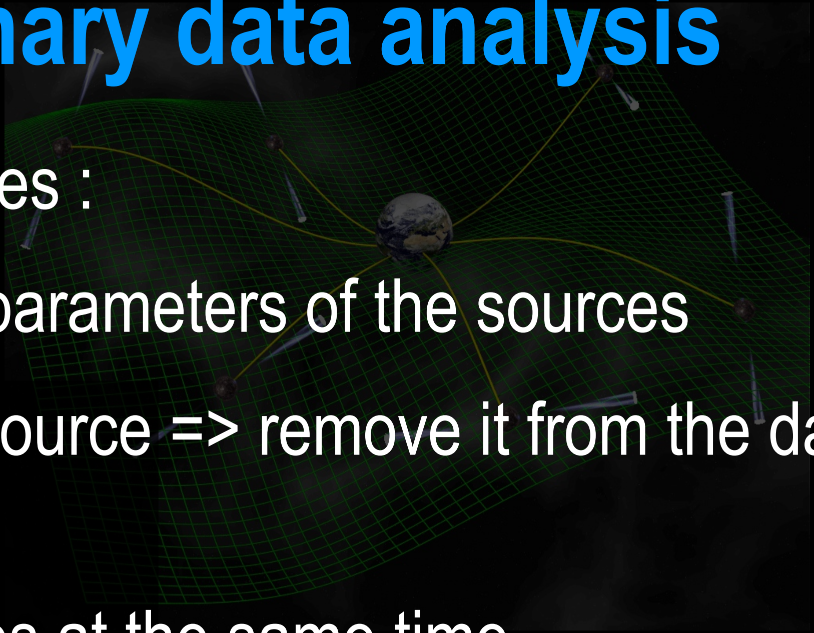
- Galactic binaries : few tens millions in Galaxy and about 3000 resolvable including verification binaries, i.e. sources already observed (about ten more are coming with Gaia) → guaranteed sources
- MBHB
- Extreme Mass Ratio Inspirals
- Bursts : cosmic string cusps, …
- Cosmological background,
- All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



Computing challenges for eLISA

- Simulation :
  - GW MBHB : numerical relativity : solving Einstein equation on a grid
  - GW EMRI : highly relativistic system : self-force computation
  - Instrument : noise simulation, future end-to-end simulator,
  - GW+Instrument (no payload/platform : the set of 3 spacecrafts is the detector) : LISACode, optimisation of the detector ...
- Data analysis :
  - Few detector outputs / large number of sources.
  - First space mission of that kind : unexpected sources and noises.
  - For expected type of sources, some preliminary methods are developed : time-frequency, matched filtering, iterative…
  - For the unexpected sources … ?

Preliminary data analysis



For known types of sources :

- matched filtering : fit the parameters of the sources
- Iterative method : find a source => remove it from the data => find the next one, …
- Search for several sources at the same time
- PROBLEM : large number of parameters

=> stochastic methods possibly running on multiple cores :

parallel MCMC, MCMC Hammer, genetic algorithm, MultiNest, Particle Swarm Optimisation, ..

- New approaches ?

Example: Genetic Algorithm

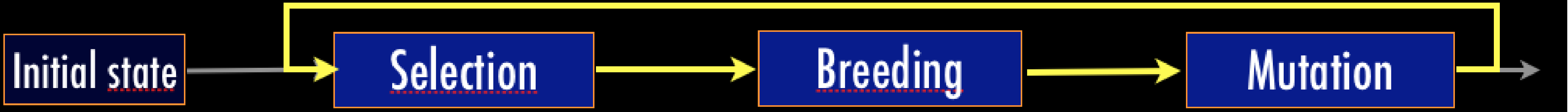
Petiteau et al., PRD 81, 104016 (2010) & Petiteau et al., PRD 87,064036 (2013)

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

parameter value ⟷

0	1	1	1	0	0	1	0	1	0	0	1

Evolution : organism ⟷ template described by a set of genes



Selection : Selection of parents for the breeding

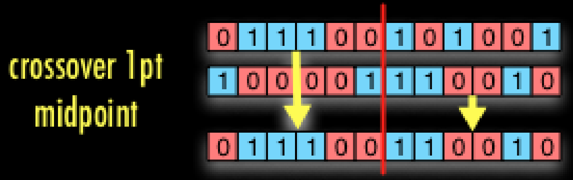
Probability of selecting one organism depend on Quality.

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 :



0	1	1	1	0	0	1	0	1	0	0	1
1	0	0	0	0	1	1	1	0	0	1	0
0	1	1	1	0	0	1	1	0	0	1	0

- Others possibilities …

Mutation : Change few bits in gene

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

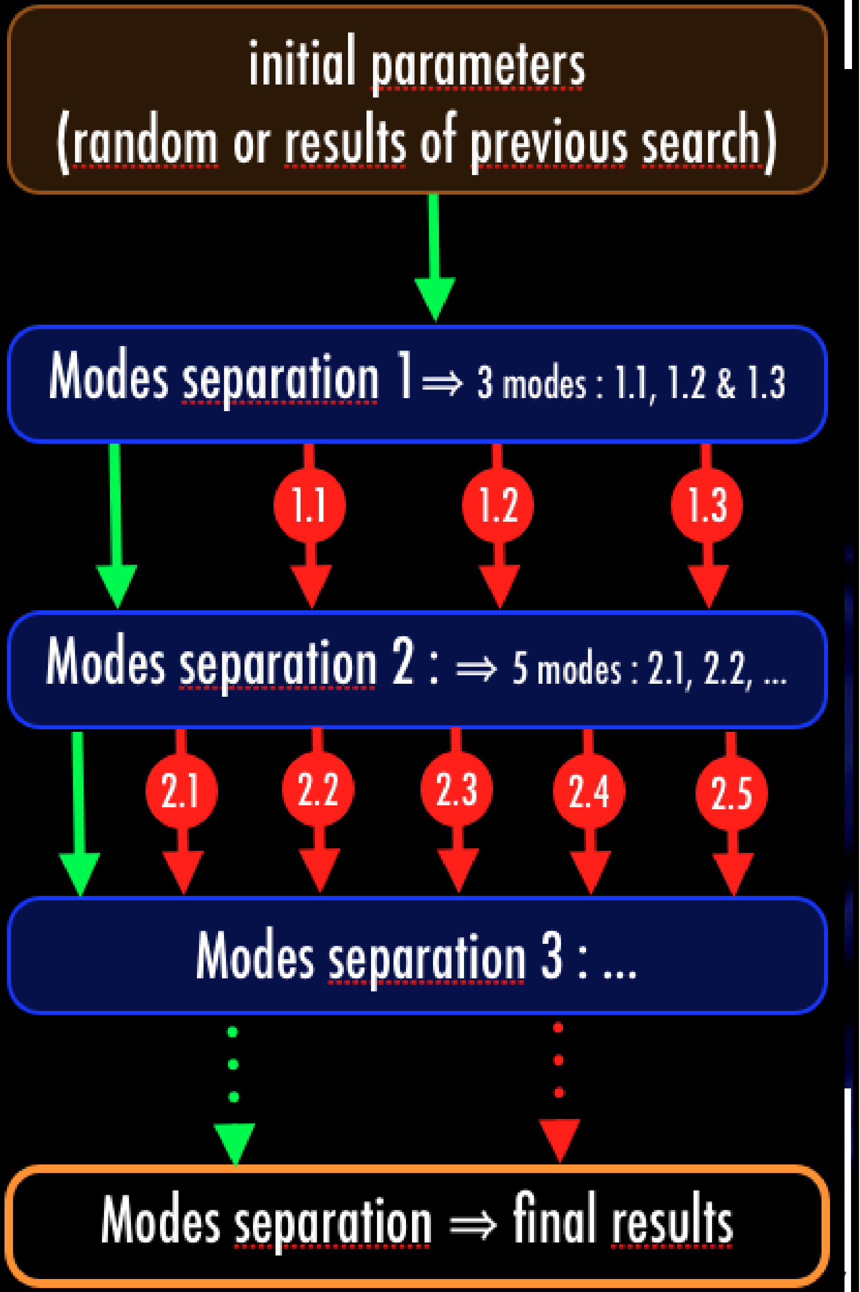
Several types of mutation :

- 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, ...

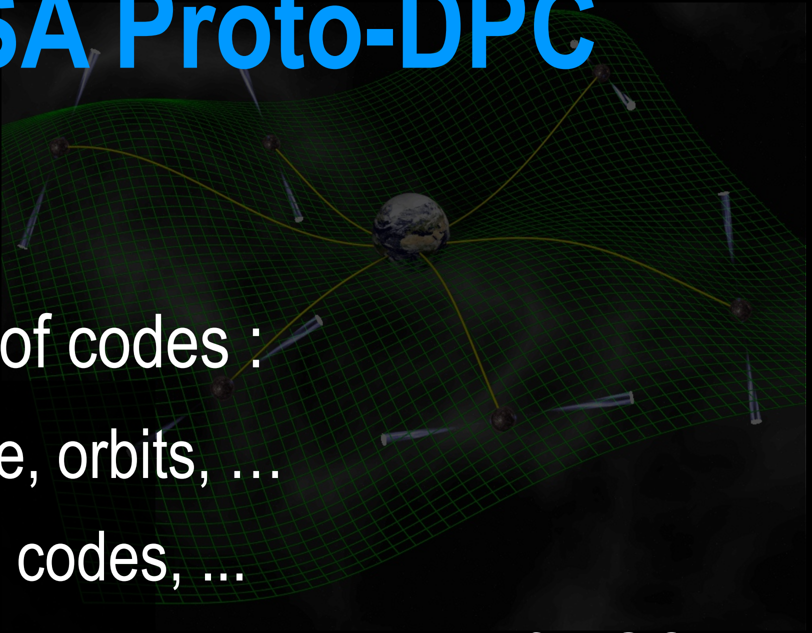
Modes separation 3 : ...

Modes separation ⇒ final results

Data Processing Center

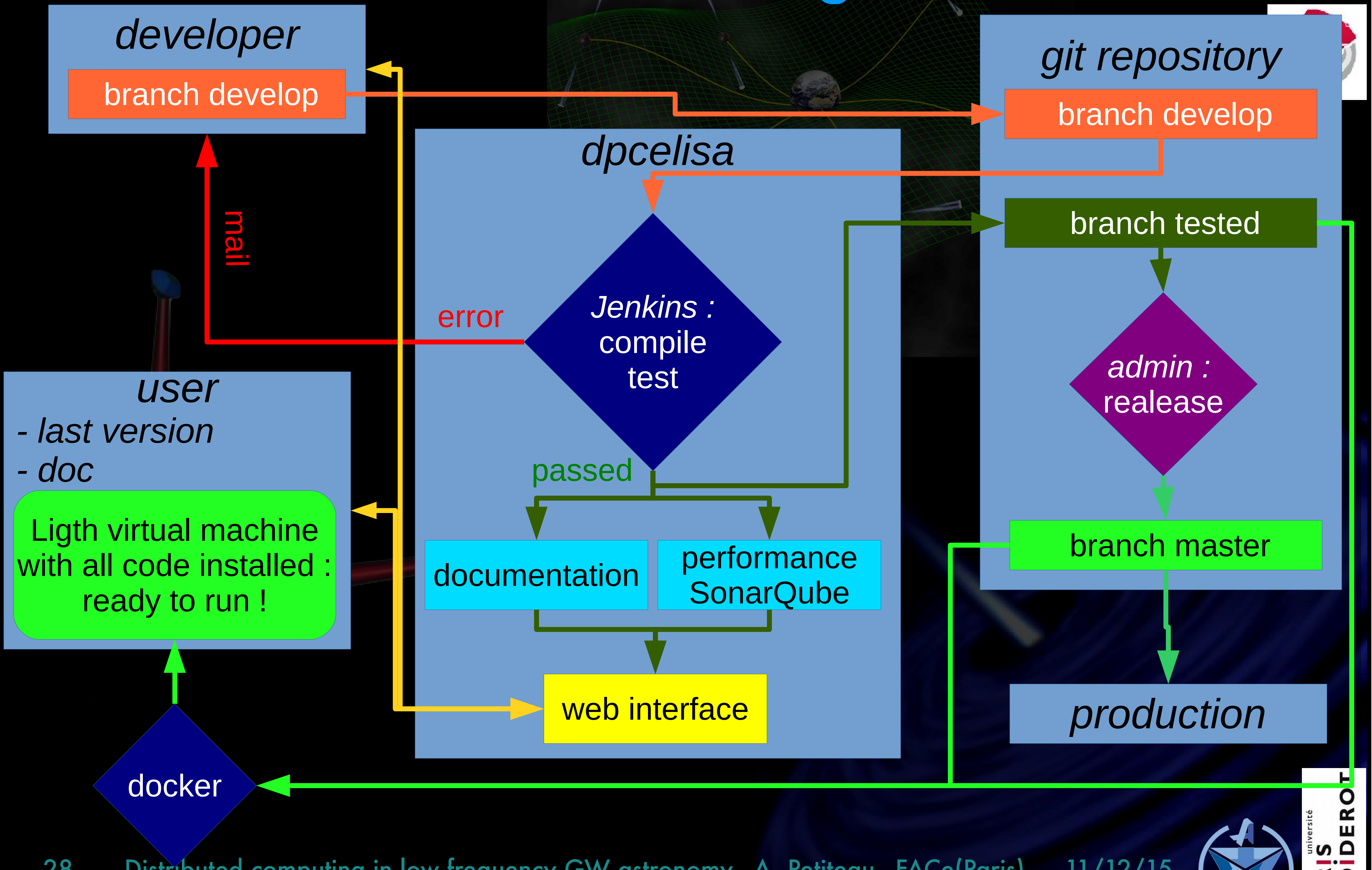
- In the current plan within the consortium, France is in charge of the eLISA Data Processing Centre.
- CNES did a phase-0 study :
  - doable within the budget
  - technological ideas flexibility : mixed infrastructure based on regular cluster + cloud to absorb variation of needs with time
- CNES + APC started development of a proto-DPC
  - IT : Maude Lejeune (project manager), Gabriele Mainetit (full time), Suyan Dong (support) and Cecile Cavet (support)
  - Scientists/developers : Antoine Petiteau, Eric Plagnol, Hubert Halloin, … + open to everybody … you are welcome !

eLISA Proto-DPC



- Guidelines and goals :
  - Continuous integration of codes :
    - simulators : LISACode, orbits, …
    - data analysis : MLDC codes, ...
    - science case evaluation tools : tools used for GOAT science case studies
  - Take care of compilation and libraries compatibility (cmake, …)
    - Simplify the development
    - Simplify the use for any user (virtual machine via docker)
  - Manage documentation
  - ...

Continuous integration



developer

branch develop

git repository

branch develop

dpcelisa

Jenkins : compile test

error

mail

passed

branch tested

admin : realease

branch master

user

- *last version*
- *doc*

Ligth virtual machine with all code installed : ready to run !

documentation

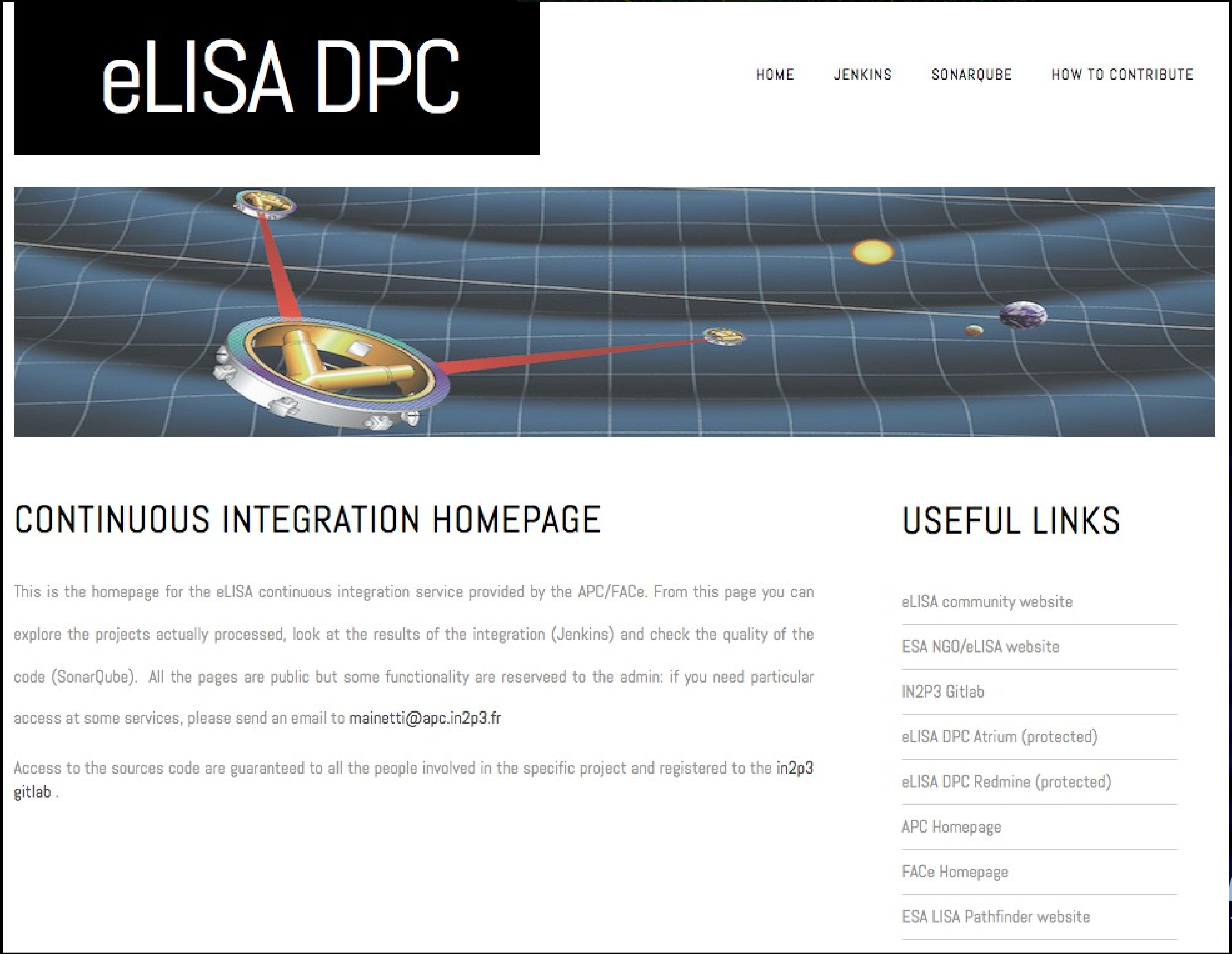
performance SonarQube

web interface

production

docker

Proto-DPC web interface



CONTINUOUS INTEGRATION HOMEPAGE

This is the homepage for the eLISA continuous integration service provided by the APC/FACe. From this page you can explore the projects actually processed, look at the results of the integration (Jenkins) and check the quality of the code (SonarQube). All the pages are public but some functionality are reserveed to the admin: if you need particular access at some services, please send an email to mainetti@apc.in2p3.fr

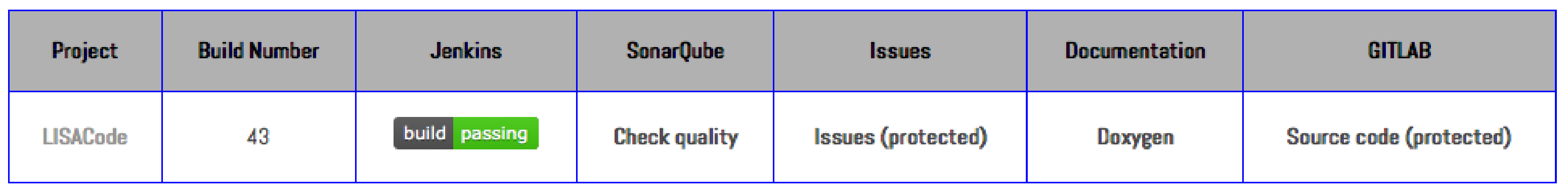
Access to the sources code are guaranteed to all the people involved in the specific project and registered to the in2p3 gitlab .

USEFUL LINKS

- eLISA community website
- ESA NGO/eLISA website
- IN2P3 Gitlab
- eLISA DPC Atrium (protected)
- eLISA DPC Redmine (protected)
- APC Homepage
- FACe Homepage
- ESA LISA Pathfinder website

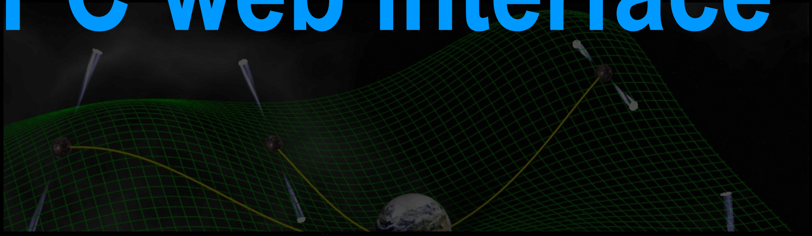
Proto-DPC web interface

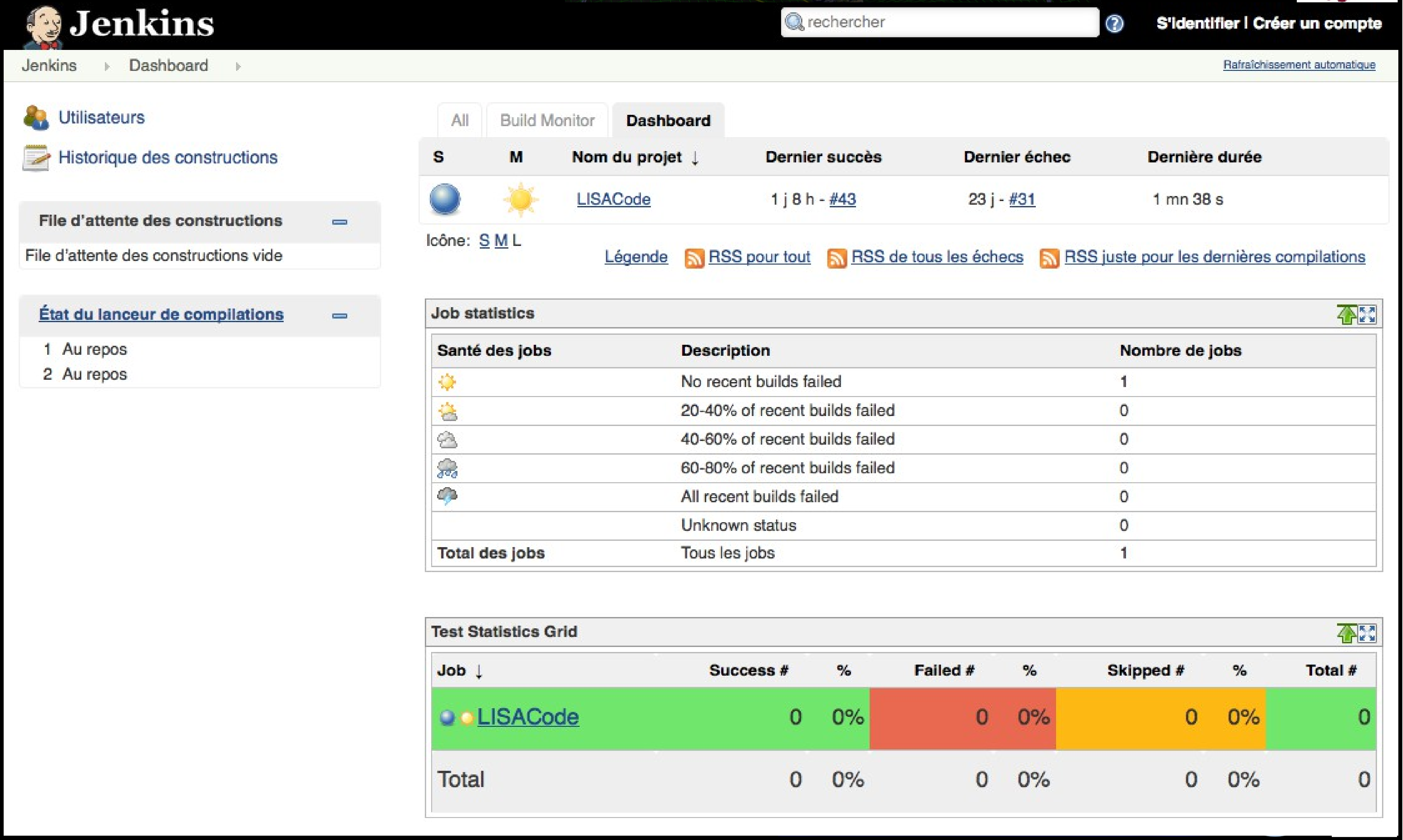
- Project status bar : at the moment only LISACode



Project	Build Number	Jenkins	SonarQube	Issues	Documentation	GITLAB
LISACode	43	build passing	Check quality	Issues (protected)	Doxygen	Source code (protected)

Proto-DPC web interface





File d'attente des constructions

File d'attente des constructions vide

État du lanceur de compilations

1 Au repos
2 Au repos

S	M	Nom du projet ↓	Dernier succès	Dernier échec	Dernière durée
●	☀	LISACode	1 j 8 h - #43	23 j - #31	1 mn 38 s

Icône: S M L

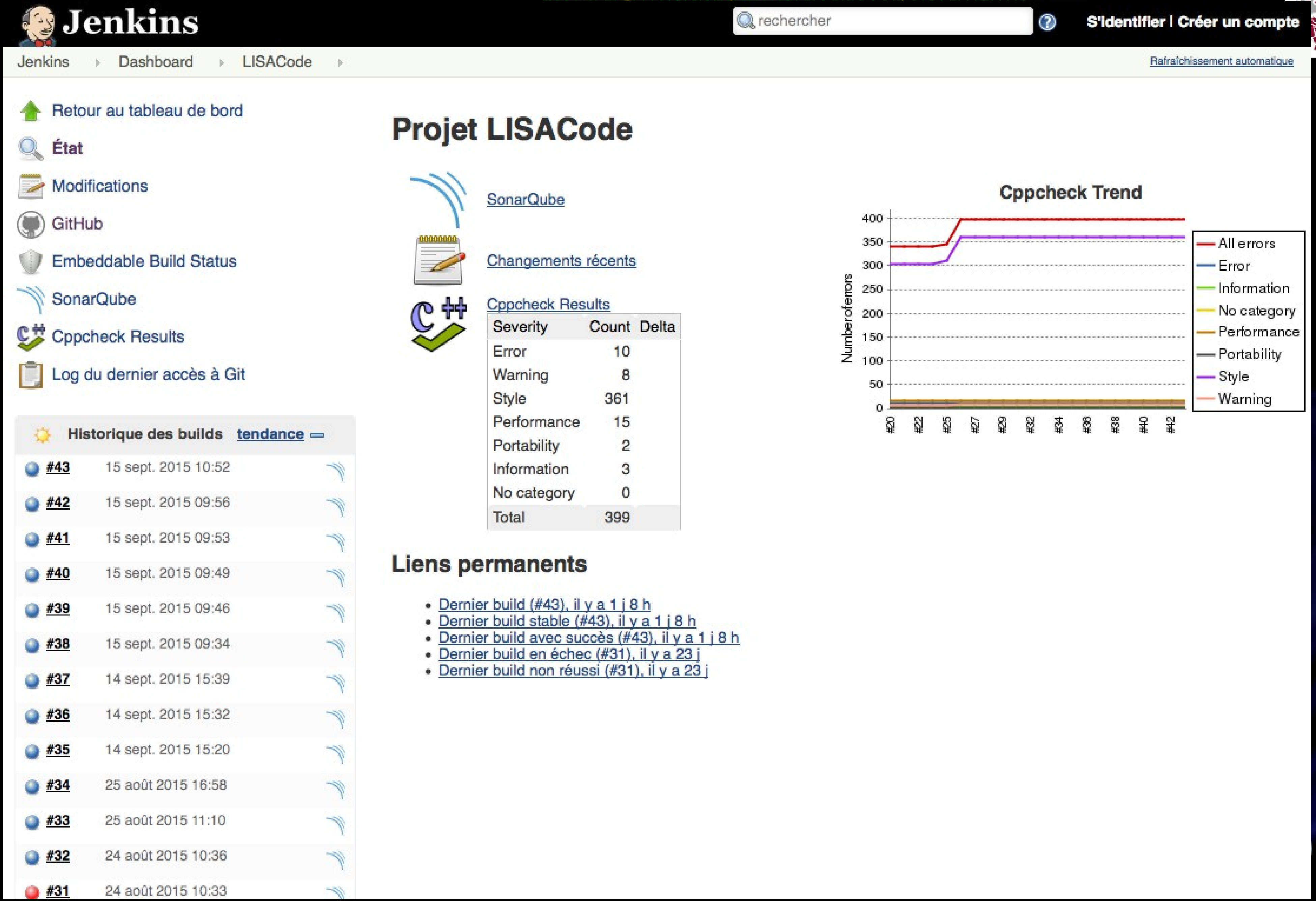
Job statistics

Santé des jobs	Description	Nombre de jobs
☀	No recent builds failed	1
⛅	20-40% of recent builds failed	0
☁	40-60% of recent builds failed	0
🌧	60-80% of recent builds failed	0
⛈	All recent builds failed	0
	Unknown status	0
Total des jobs	Tous les jobs	1

Test Statistics Grid

Job ↓	Success #	%	Failed #	%	Skipped #	%	Total #
● ● LISACode	0	0%	0	0%	0	0%	0
Total	0	0%	0	0%	0	0%	0

Proto-DPC web interface



Projet LISACode

SonarQube

Changements récents

Cppcheck Results

Severity	Count	Delta
Error	10	
Warning	8	
Style	361	
Performance	15	
Portability	2	
Information	3	
No category	0	
Total	399	

Historique des builds tendance

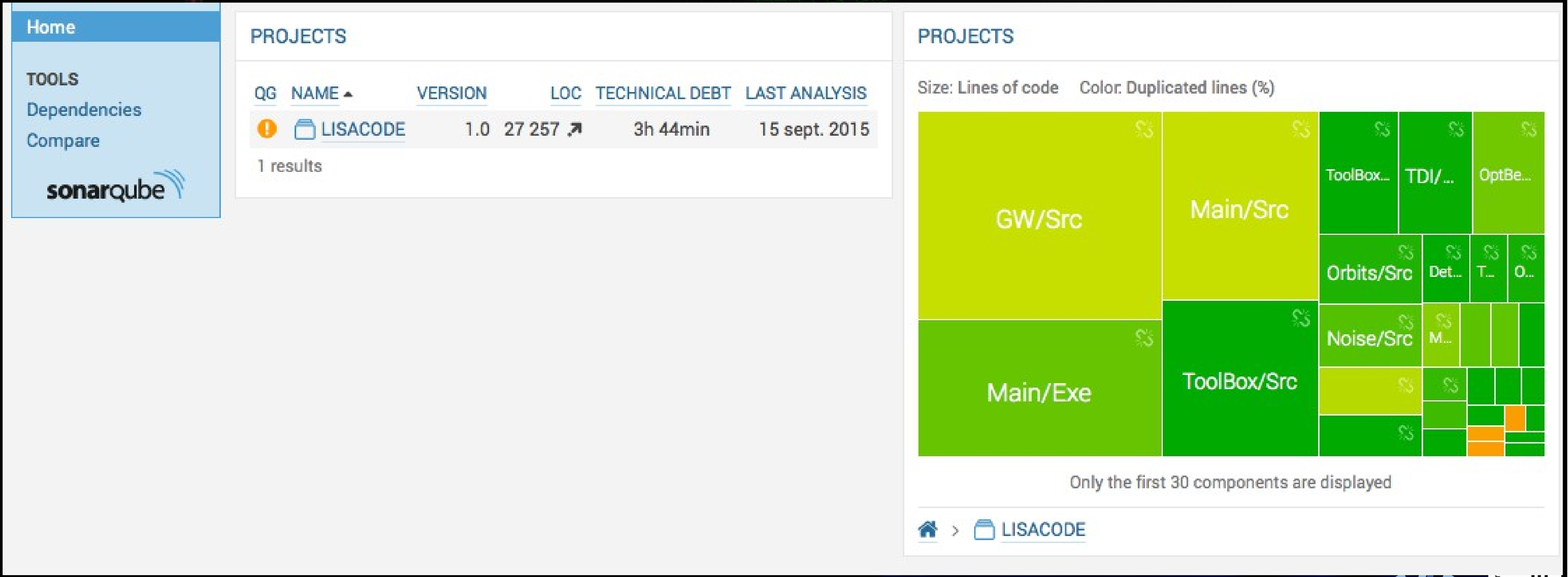
#43	15 sept. 2015 10:52
#42	15 sept. 2015 09:56
#41	15 sept. 2015 09:53
#40	15 sept. 2015 09:49
#39	15 sept. 2015 09:46
#38	15 sept. 2015 09:34
#37	14 sept. 2015 15:39
#36	14 sept. 2015 15:32
#35	14 sept. 2015 15:20
#34	25 août 2015 16:58
#33	25 août 2015 11:10
#32	24 août 2015 10:36
#31	24 août 2015 10:33

Liens permanents

- Dernier build (#43), il y a 1 j 8 h
- Dernier build stable (#43), il y a 1 j 8 h
- Dernier build avec succès (#43), il y a 1 j 8 h
- Dernier build en échec (#31), il y a 23 j
- Dernier build non réussi (#31), il y a 23 j

Proto-DPC web interface

- Analysis of code quality : SonarQube
- Using configurable rules, check if the code is “well written”, i.e. if it's easy for another developer to understand it and improve it.



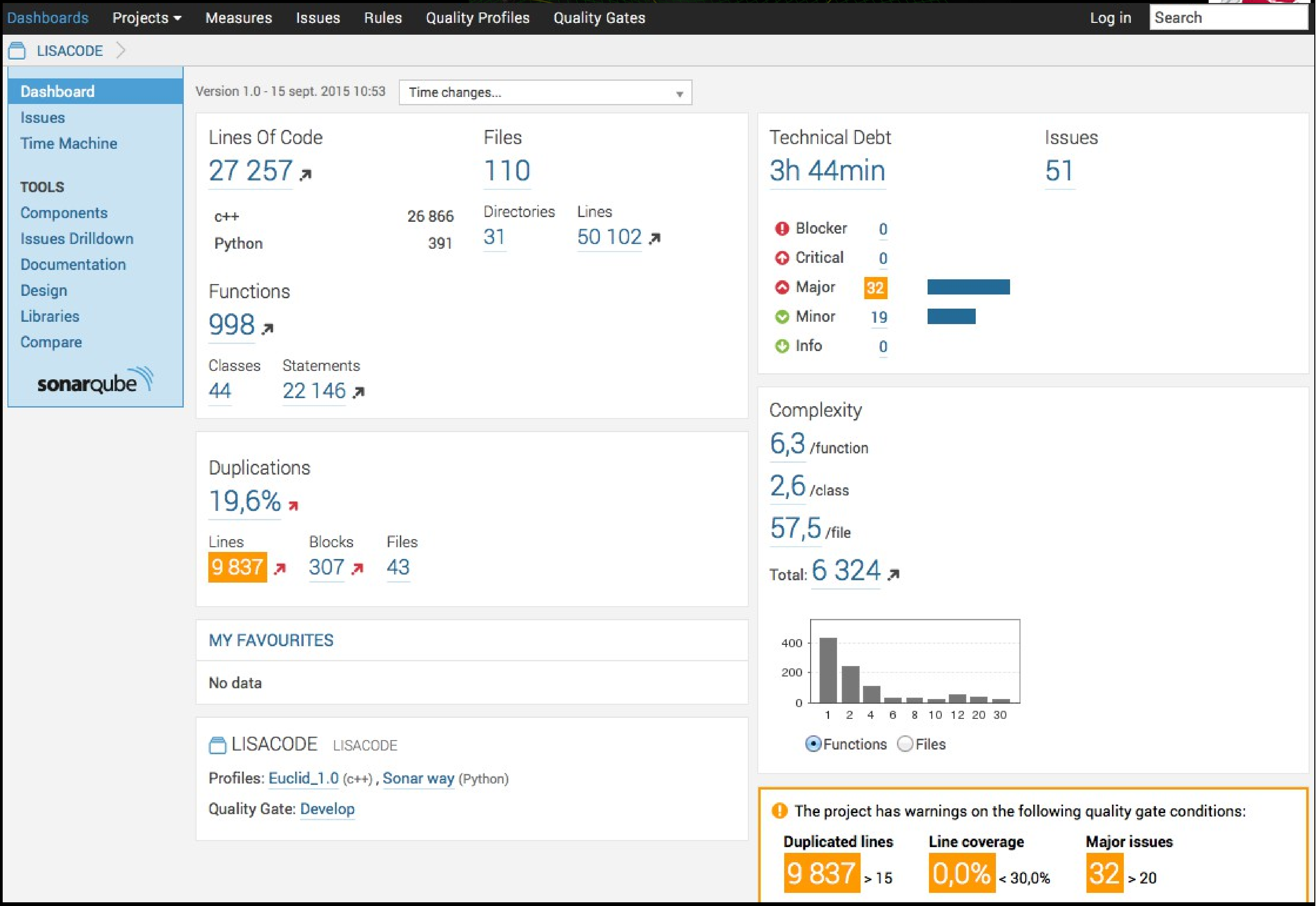
PROJECTS

QG	NAME ▲	VERSION	LOC	TECHNICAL DEBT	LAST ANALYSIS
!	LISACODE	1.0	27 257 ↗	3h 44min	15 sept. 2015

1 results

Only the first 30 components are displayed

Proto-DPC web interface



Dashboard
Issues
Time Machine

TOOLS
Components
Issues Drilldown
Documentation
Design
Libraries
Compare

sonarqube

Version 1.0 - 15 sept. 2015 10:53 | Time changes... ▾

Lines Of Code
27 257 ↗

c++	26 866
Python	391

Files
110

Directories: 31
Lines: 50 102 ↗

Functions
998 ↗

Classes: 44
Statements: 22 146 ↗

Duplications
19,6% ↗

Lines: 9 837 ↗
Blocks: 307 ↗
Files: 43

MY FAVOURITES

No data

LISACODE LISACODE

Profiles: Euclid_1.0 (c++) , Sonar way (Python)

Quality Gate: Develop

Technical Debt
3h 44min

Issues
51

Blocker	0
Critical	0
Major	32
Minor	19
Info	0

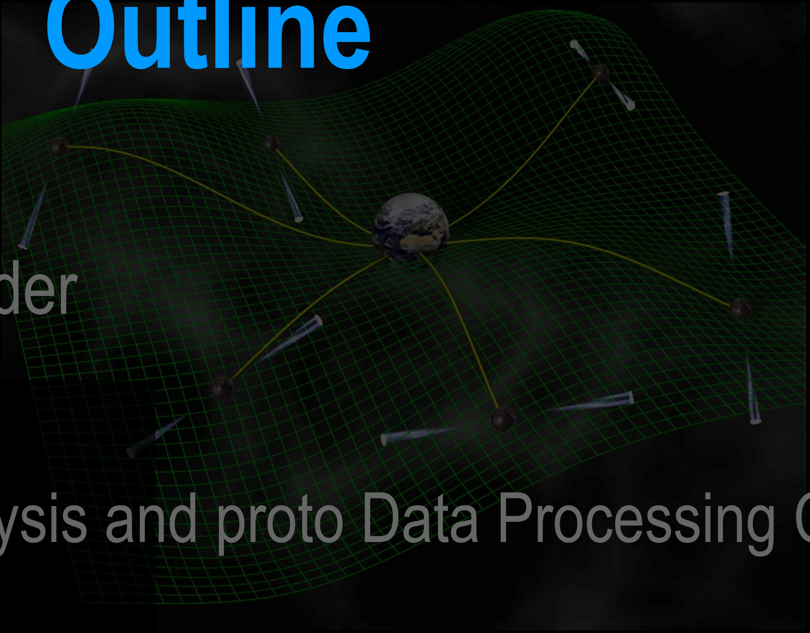
Complexity
6,3 /function
2,6 /class
57,5 /file
Total: 6 324 ↗

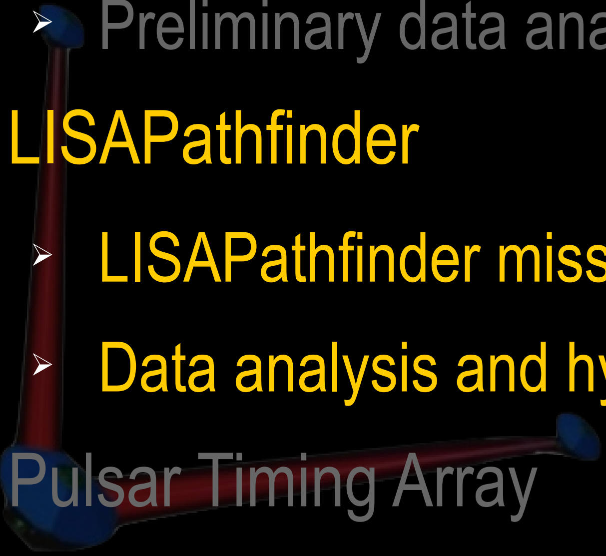
● Functions ○ Files

The project has warnings on the following quality gate conditions:

Duplicated lines	Line coverage	Major issues
9 837 > 15	0,0% < 30,0%	32 > 20

Outline

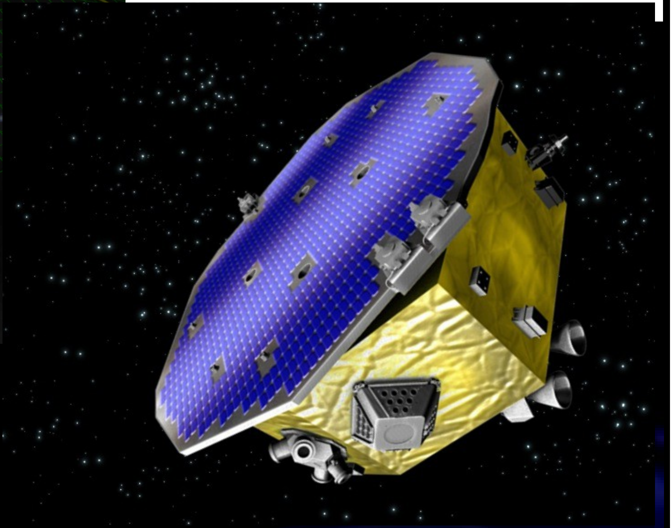


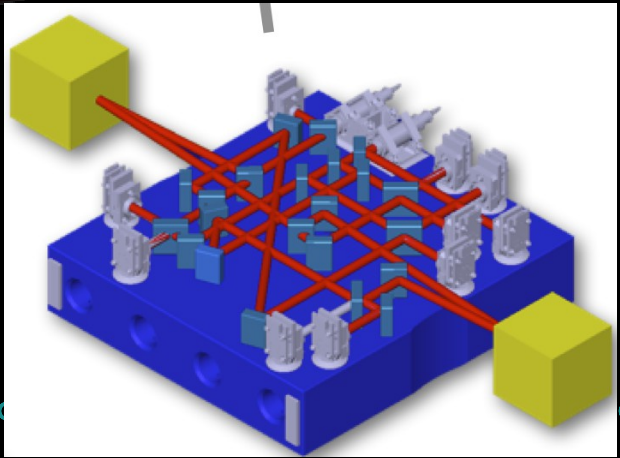


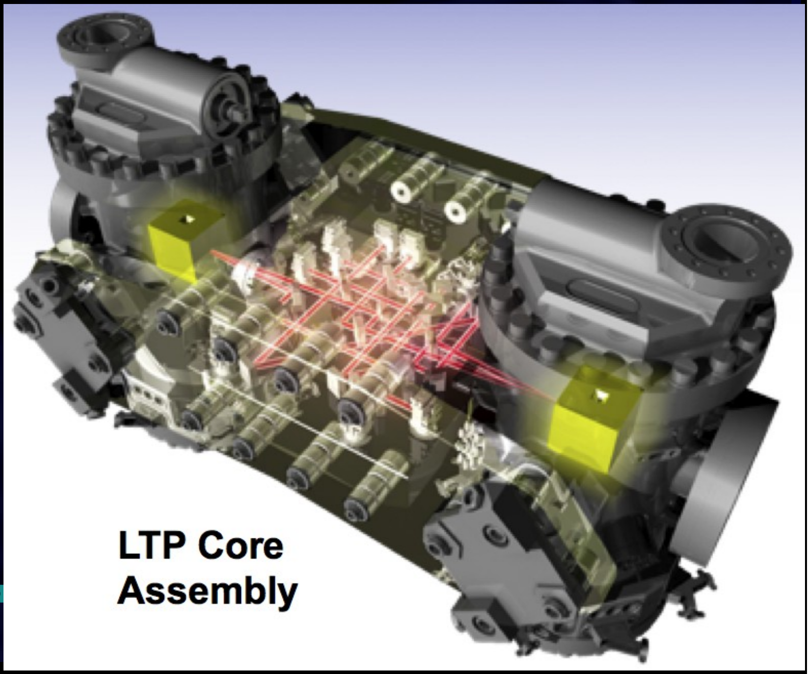
- Gravitational waves
- eLISA and LISAPathfinder
  - eLISA mission
  - Preliminary data analysis and proto Data Processing Center
- LISAPathfinder
  - LISAPathfinder mission
  - Data analysis and hybrid cluster
- Pulsar Timing Array
  - Introduction
  - Data analysis
- Conclusion

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

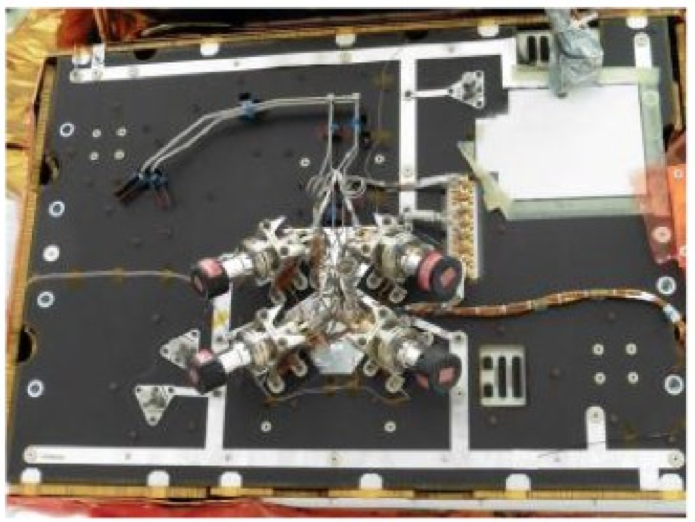






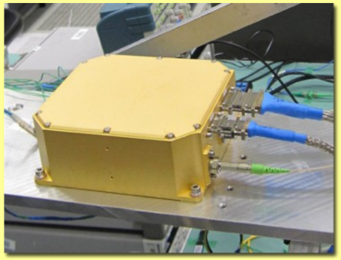
Drag free system

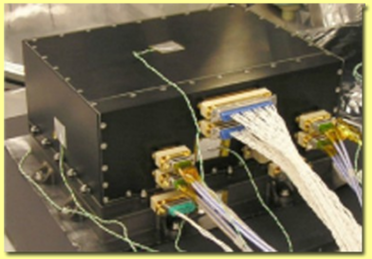
- Spacecraft protect the proof mass in the centre of its housing using microthrusters

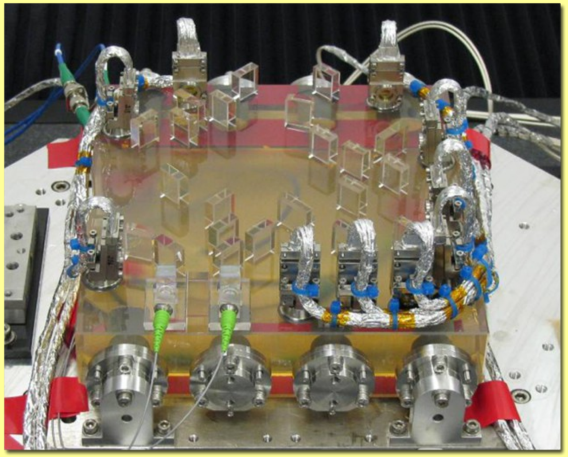


Thrusters on S/C (Feb 2015)

Core of LISAPathfinder : LISA Technology Package

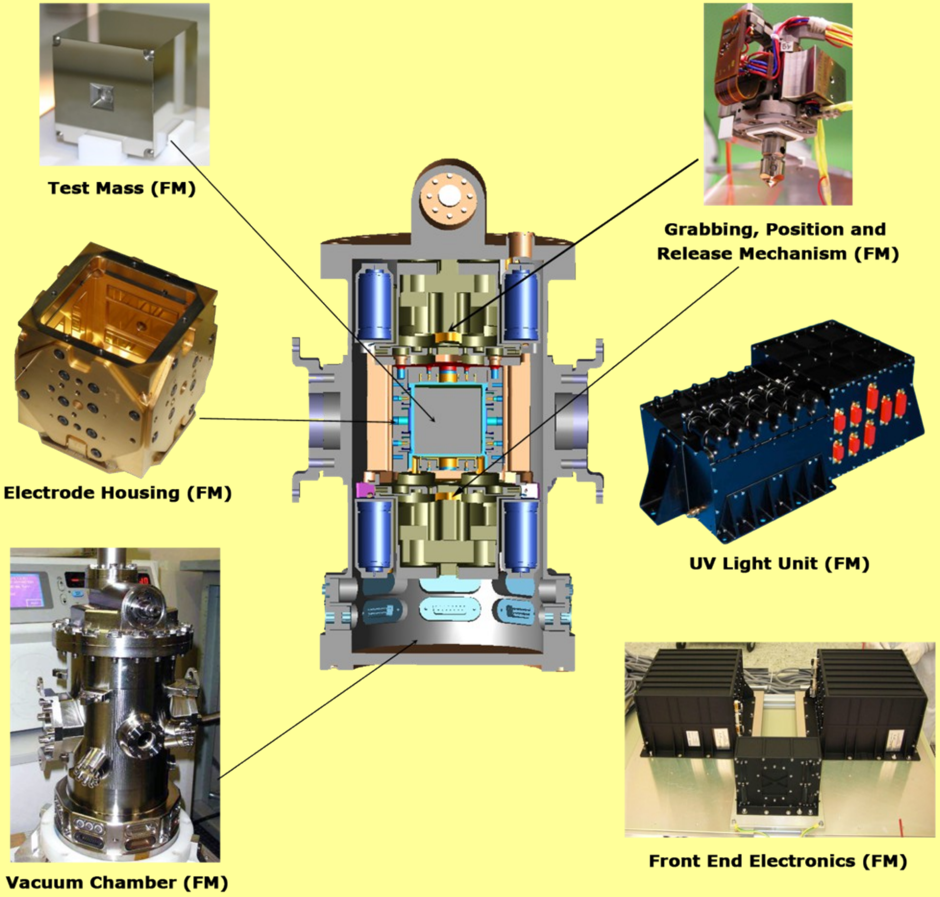

Reference Laser Unit


Phasemeter


Optical Bench Interferometer

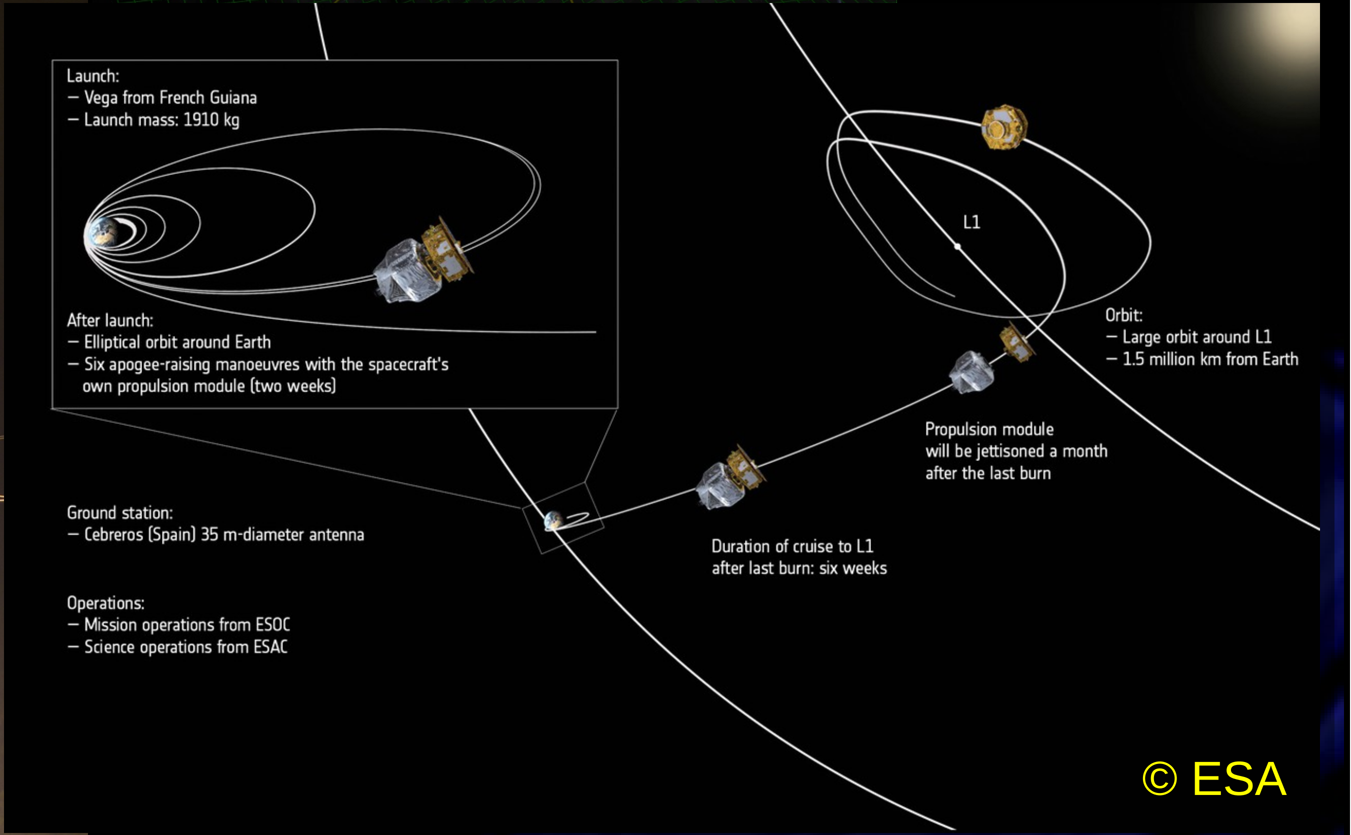

Laser Modulator


Data Management Unit



LISAPathfinder

- … and launched on the 3rd December 2015 at 1:04 am : success !



Launch:
– Vega from French Guiana
– Launch mass: 1910 kg

After launch:
– Elliptical orbit around Earth
– Six apogee-raising manoeuvres with the spacecraft's own propulsion module (two weeks)

Ground station:
– Cebreros (Spain) 35 m-diameter antenna

Operations:
– Mission operations from ESOC
– Science operations from ESAC

Duration of cruise to L1 after last burn: six weeks

Propulsion module will be jettisoned a month after the last burn

Orbit:
– Large orbit around L1
– 1.5 million km from Earth

© ESA

LISAPathfinder : operations

Goal :

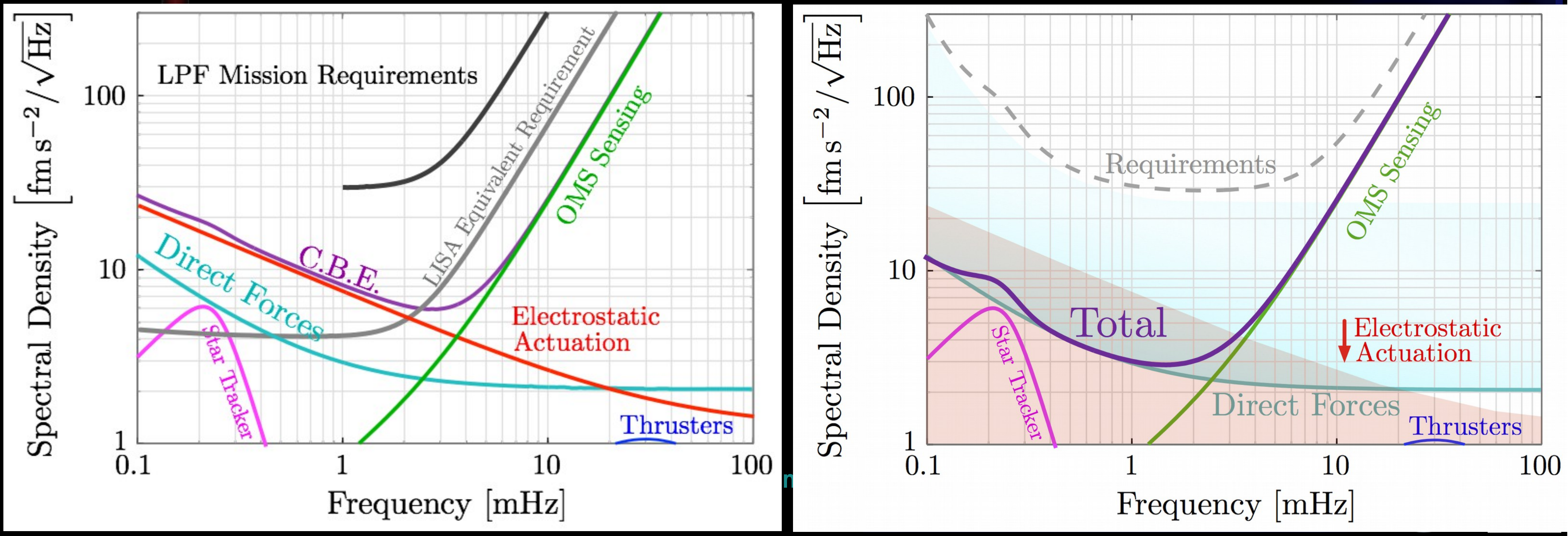
- Understanding the noise performance we observe
- Optimise the system to reach the best noise performance
- Pick from a menu of available pre-designed experiments to characterise and optimise the system
- Rough scheme:
  1. long noise measurement
  2. identify limiting noise source
  3. measure/assess the coupling and/or key parameters
  4. minimise noise and/or coupling
  5. goto 1

LISAPathfinder : operations

Noise	Sources	Parameters
OMS sensing	Shot noise, readout electronics, phase meter distortions, frequency noise, etc	Temperature, laser power, alignment, etc
Electrostatic actuation	Suspension loops on certain degrees of freedom, voltage stability, cross-talk coefficients	Actuation authority, temperature, component lifetime, alignment and working points of TMs
Gas damping	Residual gas around TM	Temperature, pressure
Magnetic	Interplanetary, SC fields, gradient fluctuations	TM susceptibility, power switching around SC
Laser radiation pressure	Momentum transfer to TM	TM reflectivity, laser power stability at mHz at TM
thermal	Radiometer, thermal radiation, outgassing	Pressure, temperature, temperature stability, etc

LISAPathfinder data analysis

- Data analysis :
  - Fitting model to estimate parameters of the system: few hundred parameters but usually only few parameters are relevant,
  - Methods : Linear Fit, MCMC, EMCEE ...
- Sensitivity: expected performance from ground measurements largely beats requirements

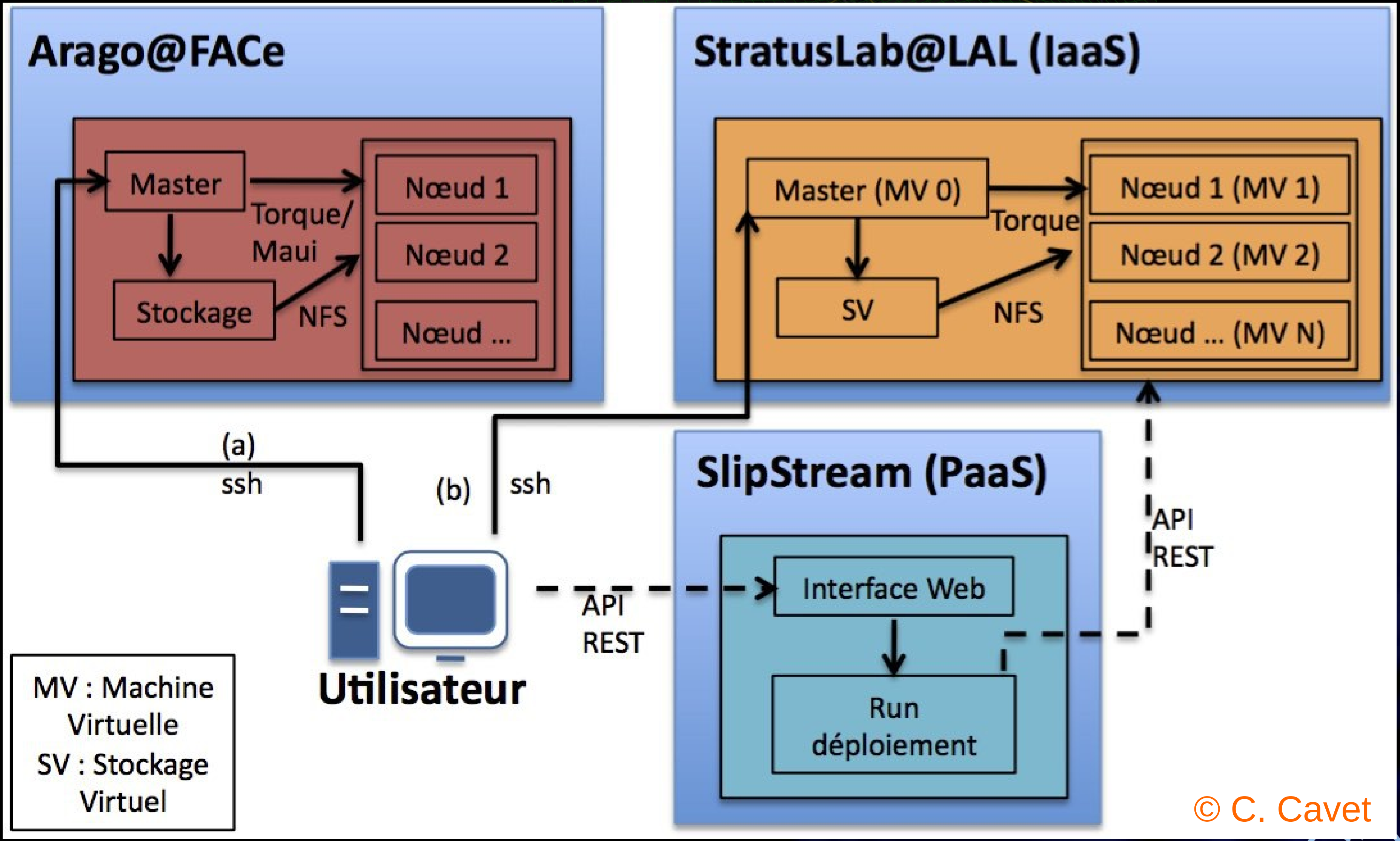


LISAPathfinder data analysis

- EMCEE (MCMC Hammer) : parallelized version of MCMC
  - Code : C++, parallel, libraries (MPI, LAPACK, BLAS, ATLAS)
- Quick analysis with large number of parameters : offline deep analysis
- Running on ARAGO cluster (FACe/APC)
- Cecile Cavet putted in place a system for transferring charge from ARAGO to a virtual cluster on stratuslab :
  - Very quick and easy to set-up (based on Slipstream)
  - Allocation of resources on demand : larg number of CPUs and memory (> 8 CPUs, >16 GB de RAM), multi-users (study of LDAP).
- Test case for future eLISA hybrid system.
- Test bench for a R&D study with CNES.

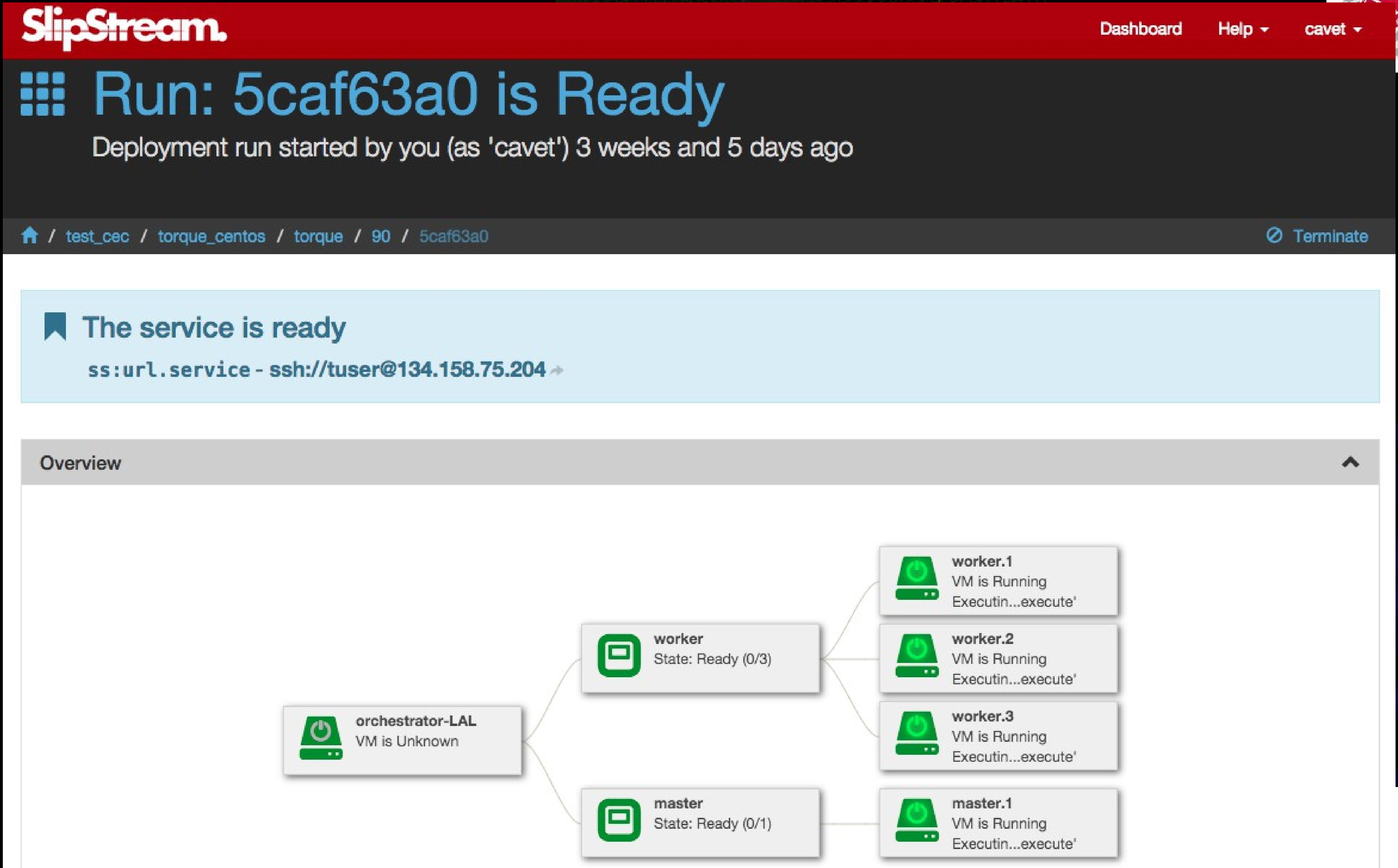
LPF DA on hybrids clusters

- Workflow



© C. Cavet

LPF DA on hybrids clusters



Run: 5caf63a0 is Ready

Deployment run started by you (as 'cavet') 3 weeks and 5 days ago

The service is ready

`ss:url.service` - ssh://tuser@134.158.75.204

orchestrator-LAL
VM is Unknown

worker
State: Ready (0/3)

master
State: Ready (0/1)

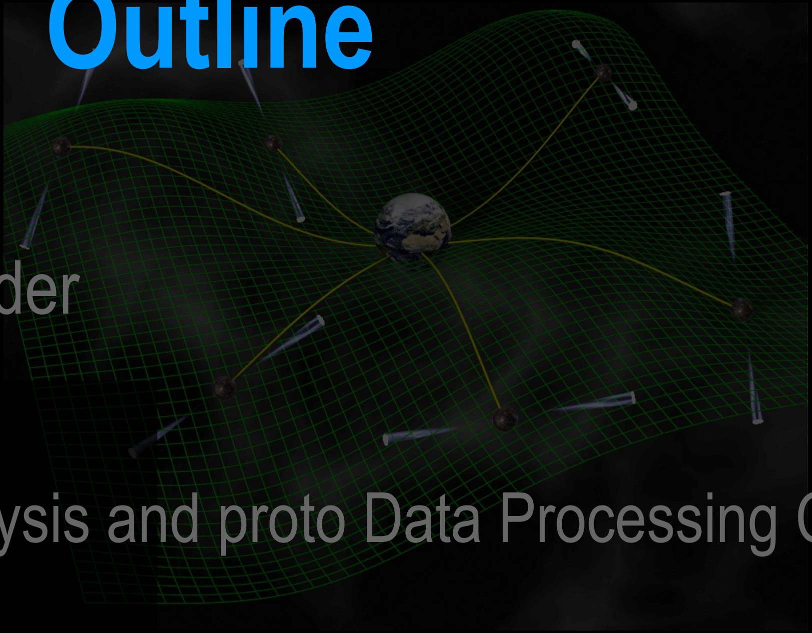
worker.1
VM is Running
Executin...execute'

worker.2
VM is Running
Executin...execute'

worker.3
VM is Running
Executin...execute'

master.1
VM is Running
Executin...execute'

Outline



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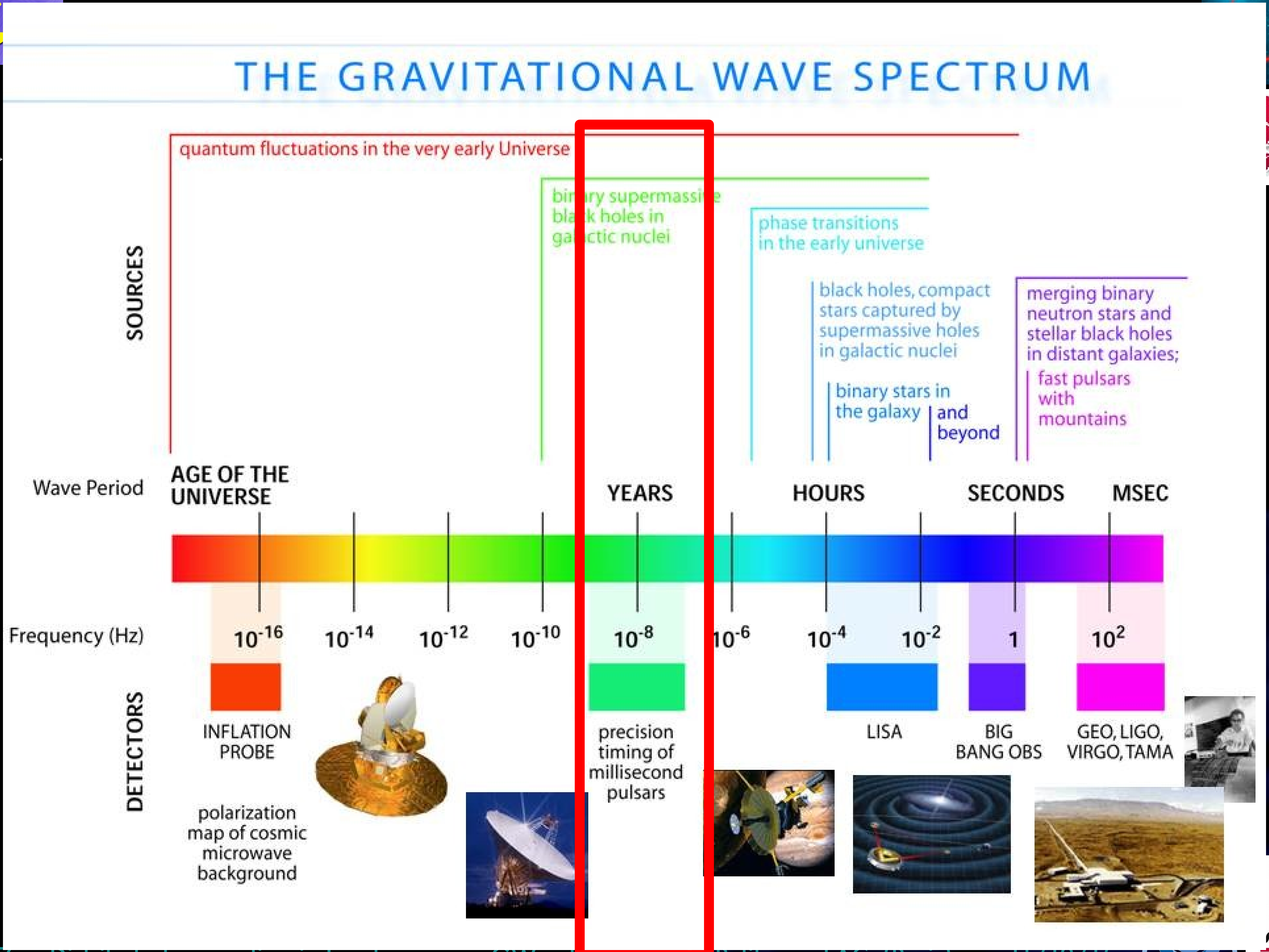
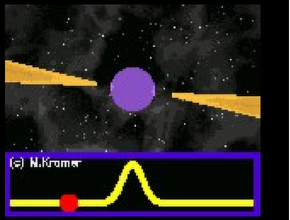

THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
bi ry supermassi e
bla k holes in
ga ctic nuclei
phase transitions
in the early universe
black holes, compact
stars captured by
supermassive holes
in galactic nuclei
binary stars in
the galaxy
and
beyond
merging binary
neutron stars and
stellar black holes
in distant galaxies;
fast pulsars
with
mountains
Wave Period
AGE OF THE
UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
INFLATION
PROBE
polarization
map of cosmic
microwave
background
precision
timing of
millisecond
pulsars
LISA
BIG
BANG OBS
GEO, LIGO,
VIRGO, TAMA

Pulsar Timing

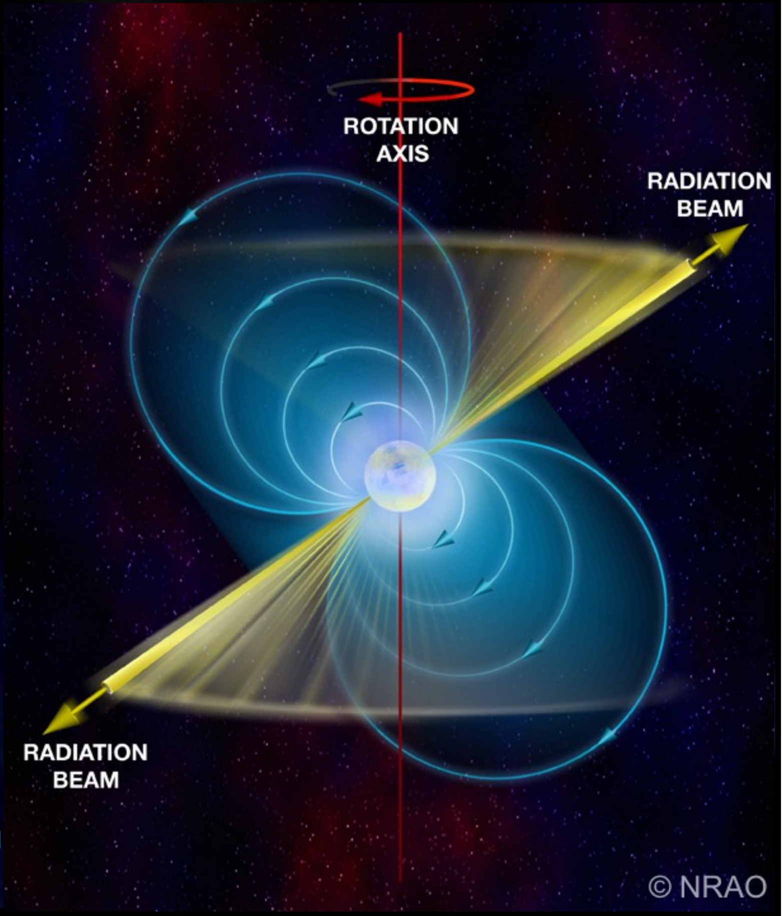
- Pulsar is rotating neutron star emitting very regular burst of radiation (radio, gamma ray, etc) ; emission : few MHz to few GHz.
- Pulsar timing is the process of measuring time of arrival (TOA) of individual pulse and subtracting off the expected TOA given a physical model for the system :



1. Observe a pulsar and measure TOA of each pulse,
2. Determine the model which best fits the TOAs : coordinate transformations, GR effects (Shapiro delay, PN binary dynamics, …), propagation uncertainties (atmospheric delays, InterStellar Medium, …)
3. Calculate the timing residual :

$$R = TOA - TOA_{\text{model}}$$

it contains all the unmodelled physics including gravitational waves passing between the pulsar and the receiver on Earth.

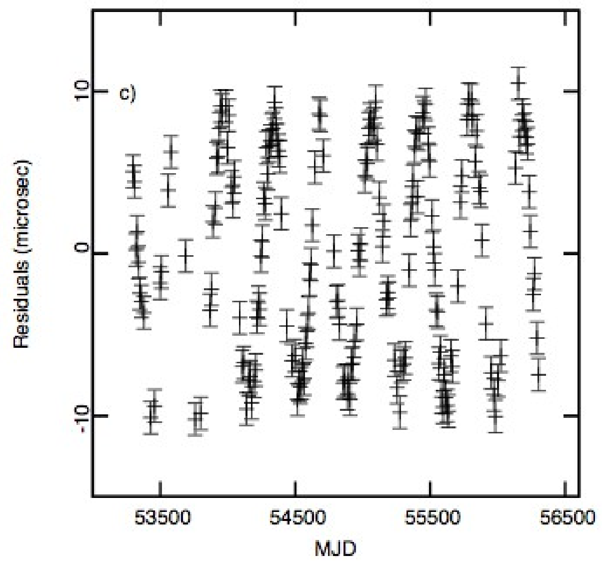


© NRAO

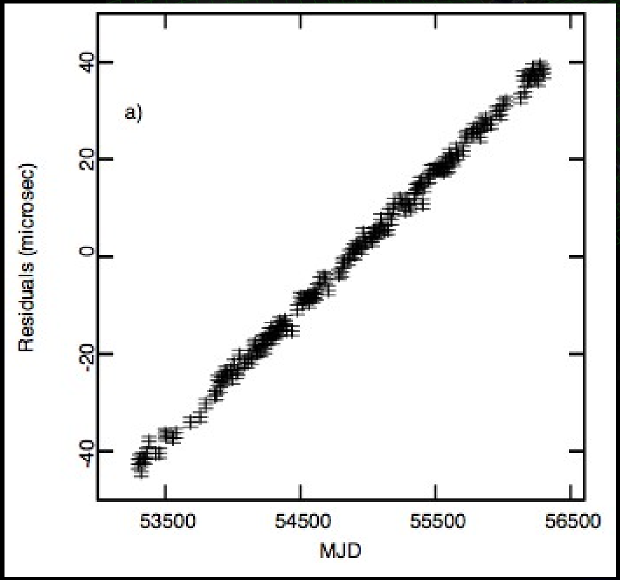
Pulsar Timing

- Example of errors in timing, i.e. error in model parameters (from A. Lassus):

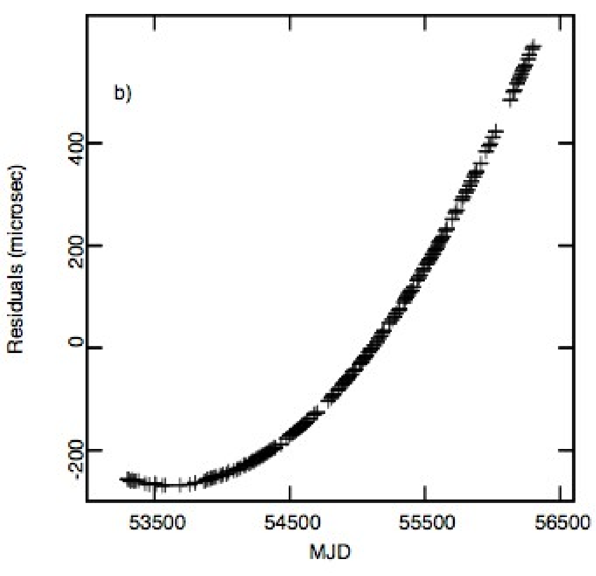
Error in position: annual effect



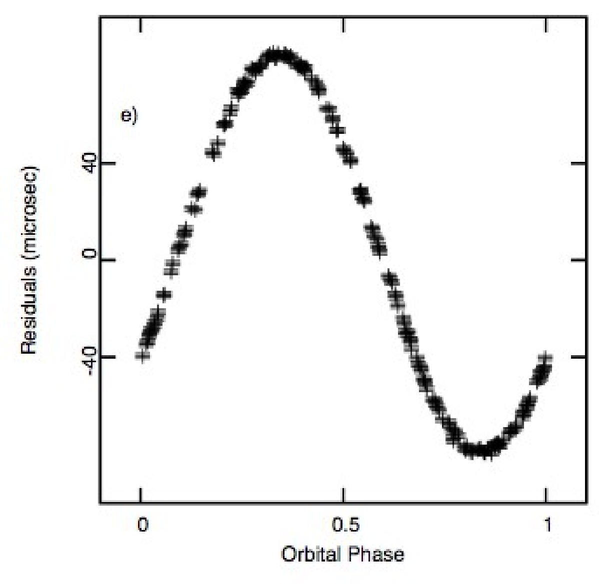
Error in period



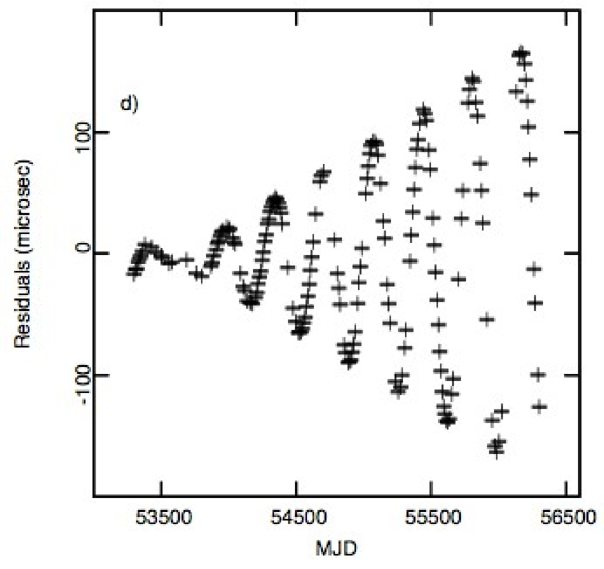
Error in period derivative



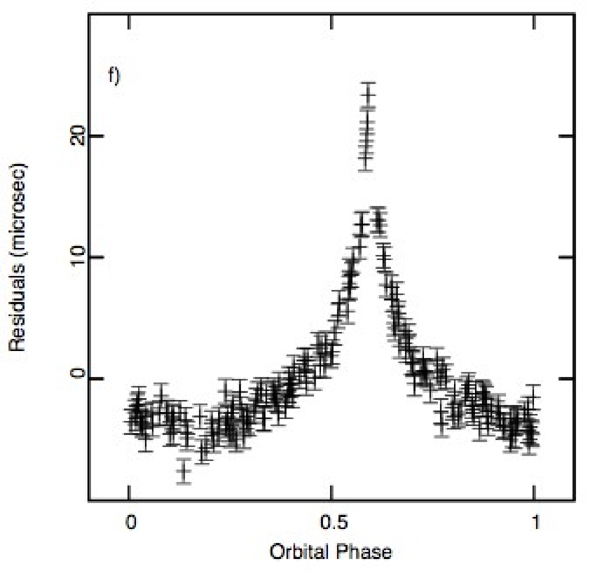
Error in orbital period



Error in proper motion



Without correction of Shapiro effect

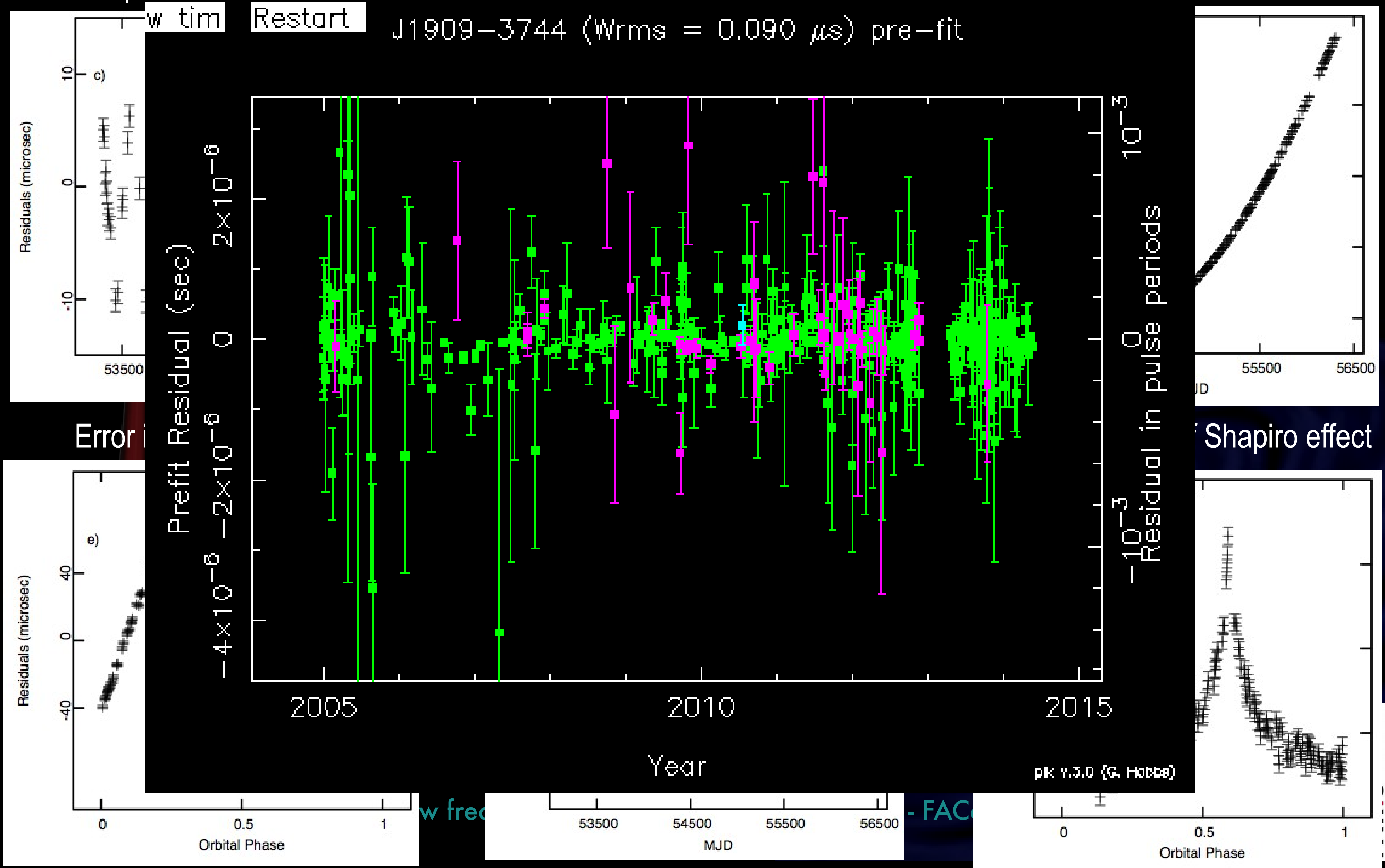


Pulsar Timing

- Example of errors in timing, i.e. error in model parameters (from A. Lassus):

Error in pc

derivative

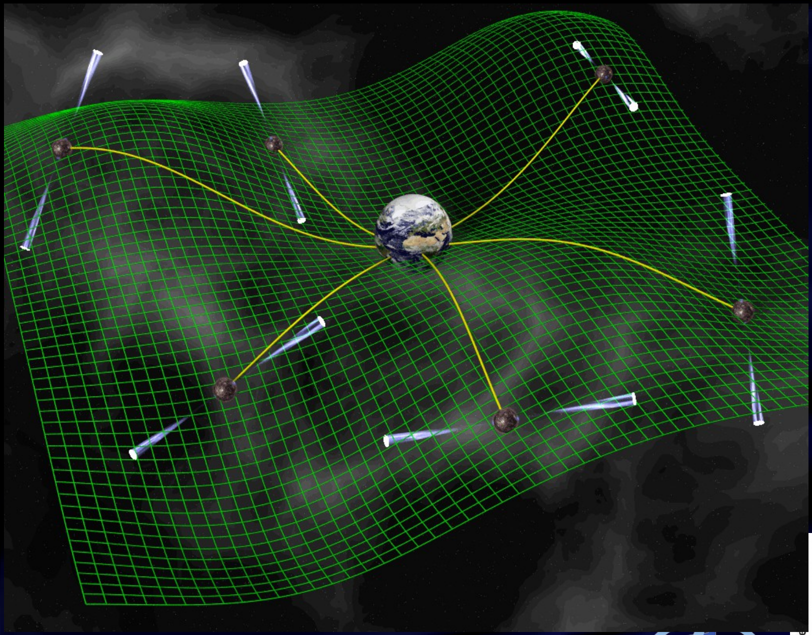


Error i

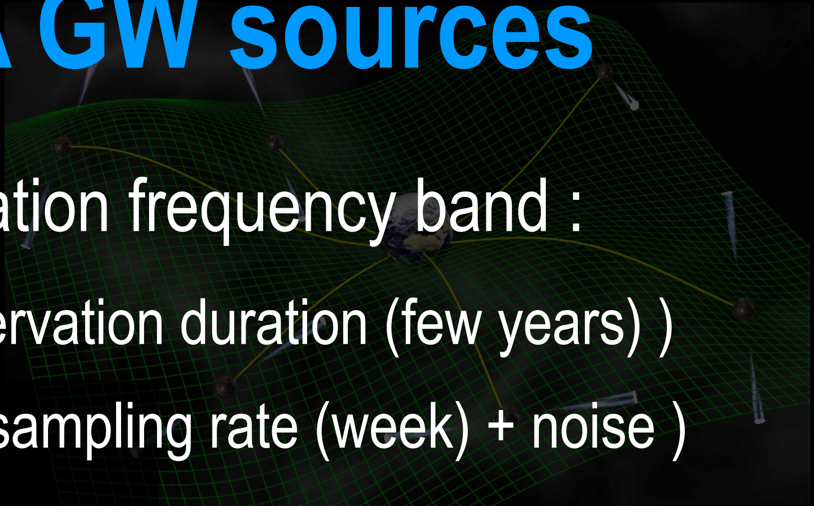
Shapiro effect

Pulsar Timing Array

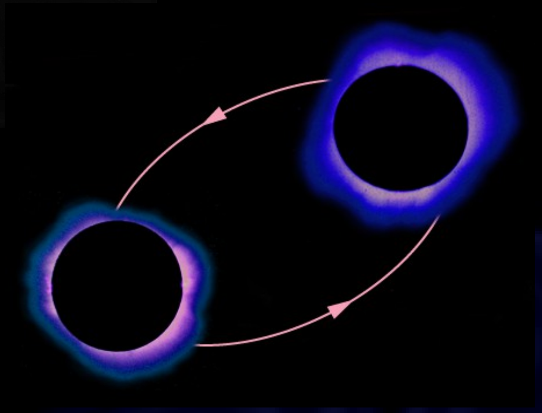
- For detecting GW, we need very stable pulsars : millisecond pulsars (MSP
- The effect of GW is very weak, it cannot be observed on a single pulsar residual. The GW signal can also be partially absorbed in some of the model parameters.
- But the GW signal is coherent on all pulsars → by analysing all residuals of MSPs together it can be detected.
- In addition there are noises parameters for each pulsar due to the pulsar itself, the propagation of beam and from the receiver.
- The ideal method would be to search for pulsar model, pulsar noise and GWs ; but hard because to many parameters, ...

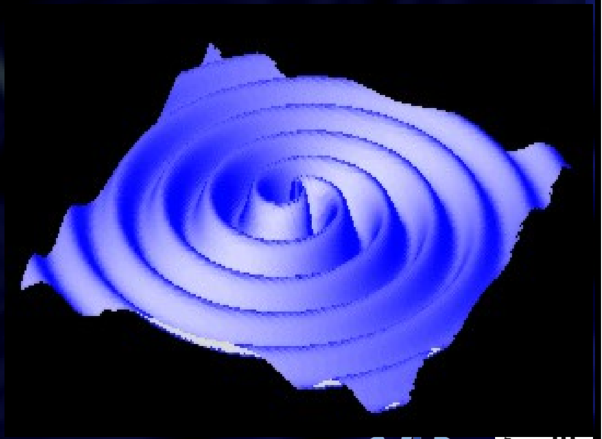


PTA GW sources

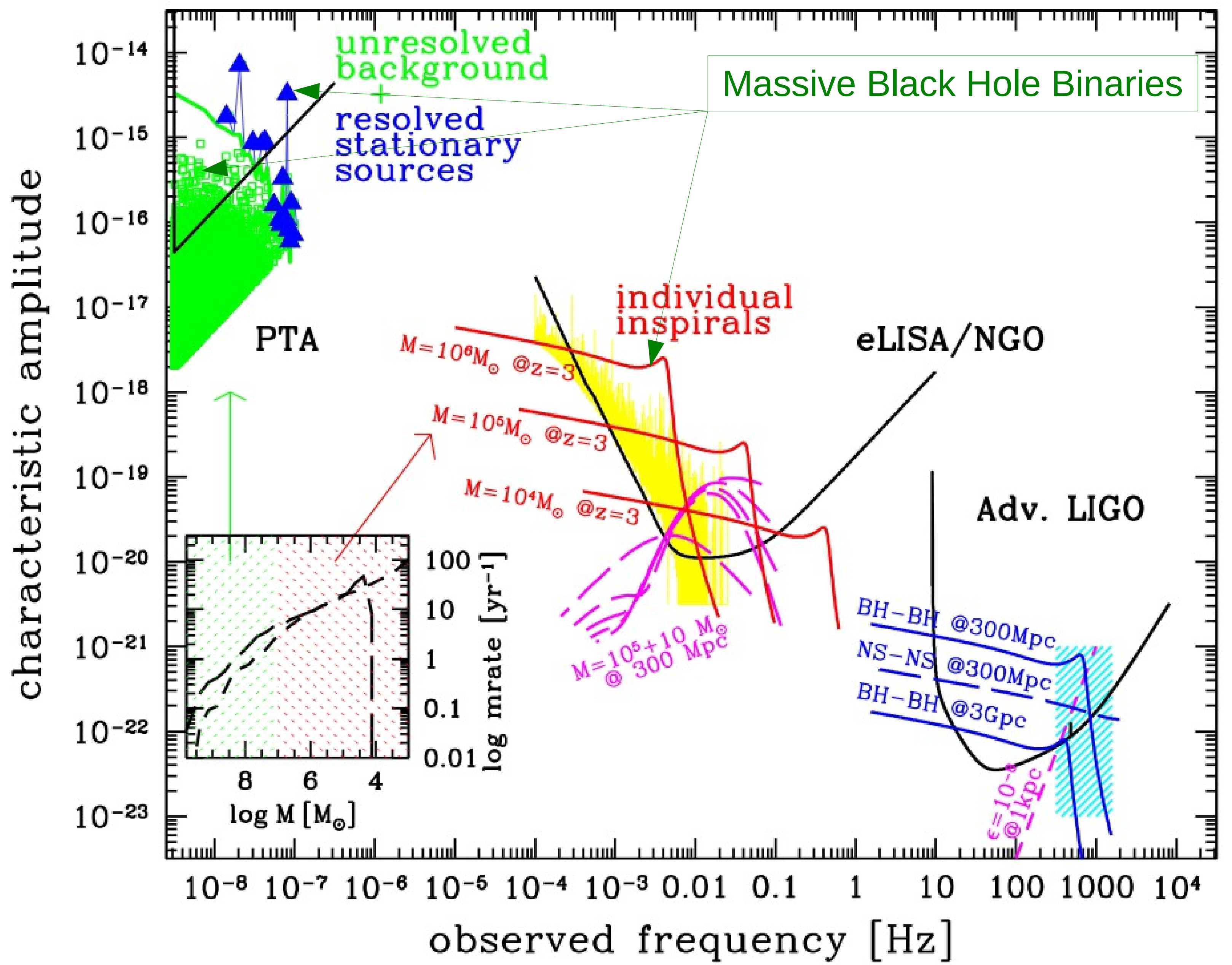


- Gravitational wave observation frequency band :
  - Low-limit : few nHz (1/observation duration (few years))
  - Upper-limit : few 100 nHz (sampling rate (week) + noise)
- Massive black hole binaries :
  - heavy: mass > 10^7 M_{Sun} ,
  - close: distance z<2,
  - far before the merger: quasi-monochromatic,
  - Background + Individual sources.
- Cosmological background (cosmic strings, …)
- Bursts (memory burst of MBHB, ...)





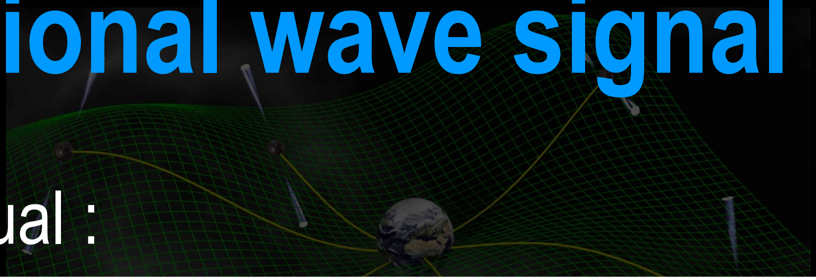
Gravitational waves



Massive Black Hole Binaries

Sesana astro-ph.CO 1304.0767 (2013)

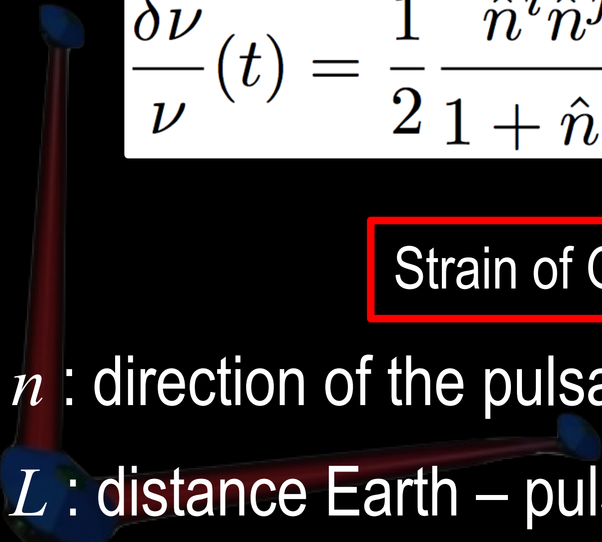
Gravitational wave signal



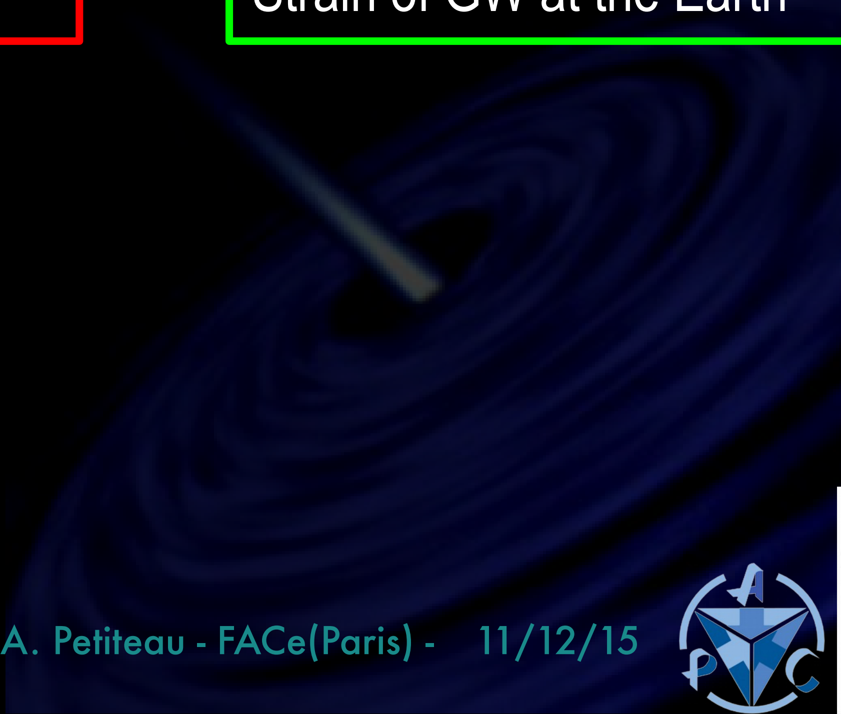
- GW signal to pulsar residual :

$$r(t) = \int_0^t \frac{\delta\nu}{\nu}(t')dt'$$

$$\frac{\delta\nu}{\nu}(t) = \frac{1}{2}\frac{\hat{n}^i\hat{n}^j}{1+\hat{n}.\hat{k}}\left(\underbrace{h_{ij}(t-L(1+\hat{k}.\hat{n}))}_{\boxed{\text{Strain of GW at the pulsar}}} - \underbrace{h_{ij}(t)}_{\boxed{\text{Strain of GW at the Earth}}}\right)$$



- n : direction of the pulsar
- L : distance Earth – pulsar
- k : direction of the GW propagation
- h_{ij} : GW strain



GW signal of MBHB in PTA

- GW strain :

$$h_+(t) = \mathcal{A}(1+\cos^2 i)\cos(\Phi(t)+\Phi_0)$$
$$h_\times(t) = -2\mathcal{A}\cos i \sin(\Phi(t)+\Phi_0)$$

$$\mathcal{A} = 2\frac{\mathcal{M}_c^{5/3}}{D_L}(\pi f)^{2/3}$$

  - i inclination, $f=2\pi\omega$ frequency of GW, M_c chirp mass, D_L distance to GW source, Φ phase, Ψ GW phase shift in pulsar term, $(p\ ,\ q)$ vector of GW polarisation.

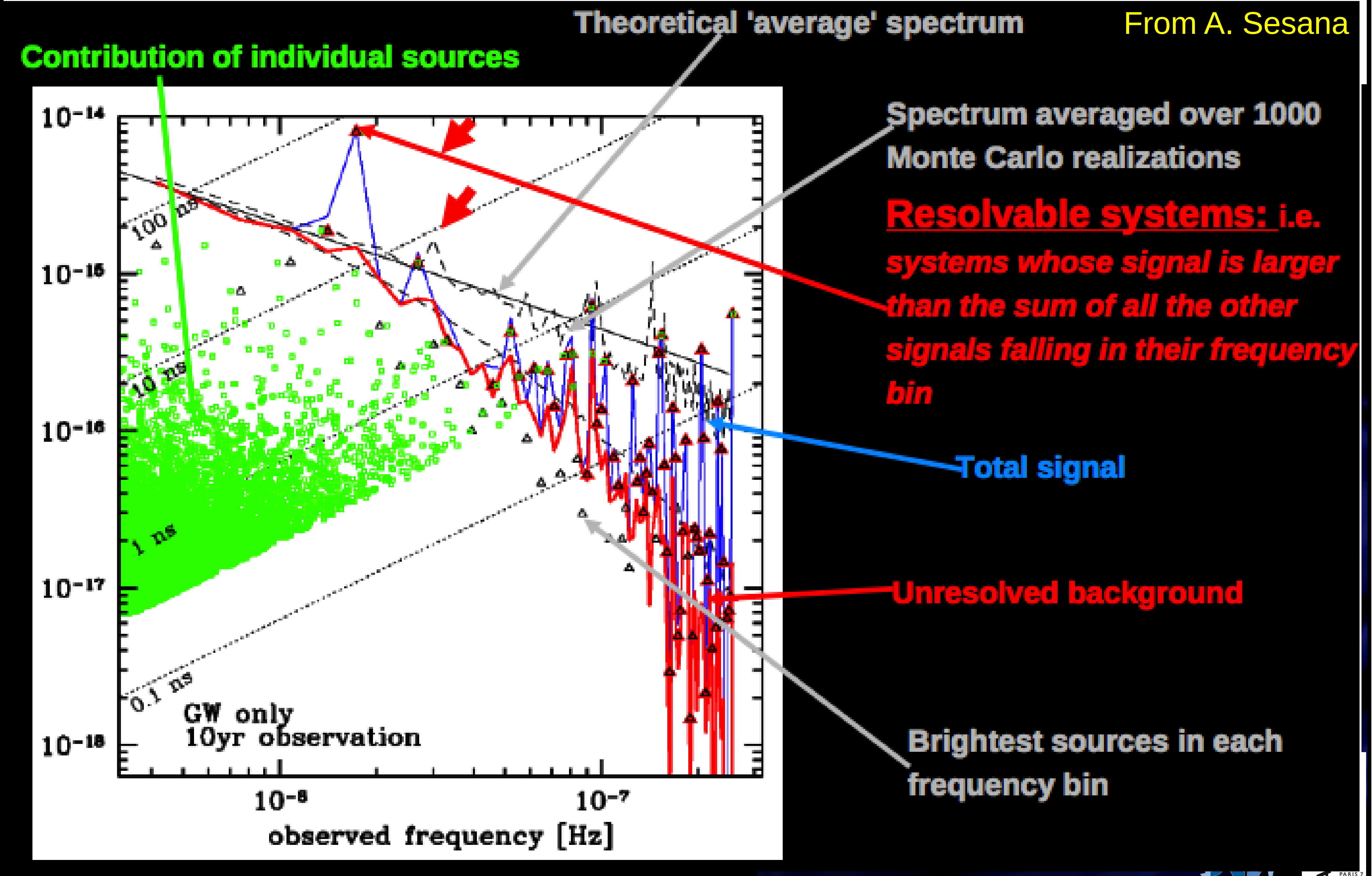
- Residual can be separated in 2 terms: Earth term and pulsar term

$$r^e_\alpha(t) = \frac{\mathcal{A}}{2\pi f}\left\{(1+\cos^2\iota)F^+_\alpha\left[\sin(\omega t+\Phi_0)-\sin\Phi_0\right]+ 2\cos\iota F^\times_\alpha\left[\cos(\omega t+\Phi_0)-\cos\Phi_0\right]\right\},$$

$$r^p_\alpha(t) = \frac{\mathcal{A}_\alpha}{2\pi f_\alpha}\left\{(1+\cos^2\iota)F^+_\alpha\left[\sin(\omega_\alpha t+\Psi_\alpha+\Phi_0)- \sin(\Psi_\alpha+\Phi_0)\right]+2\cos\iota F^\times_\alpha\left[\cos(\omega_\alpha t+\Psi_\alpha+\Phi_0)- \cos(\Psi_\alpha+\Phi_0)\right]\right\},$$

$$F^+_\alpha = \frac{1}{2}\frac{(\hat{n}^\alpha.\vec{p})^2-(\hat{n}^\alpha.\vec{q})^2}{1+\hat{n}^\alpha.\hat{k}}$$
$$F^\times_\alpha = \frac{(\hat{n}^\alpha.\vec{p})(\hat{n}^\alpha.\vec{q})}{1+\hat{n}^\alpha.\hat{k}}$$

Typical signal from MBHB



From A. Sesana

Theoretical 'average' spectrum

Contribution of individual sources

Spectrum averaged over 1000 Monte Carlo realizations

Resolvable systems: i.e. *systems whose signal is larger than the sum of all the other signals falling in their frequency bin*

Total signal

Unresolved background

Brightest sources in each frequency bin

Data analysis

- Likelihood based correlation between all measurements of all pulsars (van Haasteren et al. 2009) with mariginalisation over pulsar parameters :

$$P(\vec{\delta t}, \vec{\theta}) = \frac{1}{\sqrt{(2\pi)^{n-m} det(G^T C G)}} \exp\left(-\frac{1}{2}(\vec{\delta t} - \vec{r})^T G (G^T C G)^{-1} G^T (\vec{\delta t} - \vec{r})\right)$$

  - δt : data (residual),
  - r : model (residual) : GW signal for continuous wave search,
  - C : variance-covariance matrix : pulsar noises + GW background,
  - G : matrix derived from design matrix (linearisation of pulsar model for pulsar parameters),
  - n : number of data,
  - m : number of pulsar model parameters.
- GW signal in C and/or r .

Data analysis: background

- Background form by superposition of large number of MBHB looks like a red noise.
- In isotropic approximation (van Haasteren et al. 2009): characterised by 2 parameters : amplitude A and slope γ .

$$C_{GWB} = \zeta_{\alpha\beta} A^2 \left(\frac{1yr^{-1}}{f_L} \right)^{\gamma - 1} \left[\Gamma(1-\gamma) \sin \frac{\pi\gamma}{2} (f_L \tau_{ij})^{\gamma-1} - \sum_{n=0}^{\infty} \frac{(f_L \tau_{ij})^{2n}}{(2n)!(2n+1-\gamma)} \right]$$

$$\zeta_{\alpha\beta} = \frac{3}{2} y \ln y - \frac{1}{4} y + \frac{1}{2} + \frac{1}{2}\delta_{\alpha\beta} \; , \quad y = \frac{1-\cos\theta_{\alpha\beta}}{2} \; , \quad \tau_{ij} = 2\pi |t_i - t_j|$$

  - $\theta_{\alpha\beta}$: angular separation between pulsars
  - τ_{ij} : time shift between 2 measurements
- Search for anisotropic background (Mingarelli et al. 2013)

Data analysis : individual sources

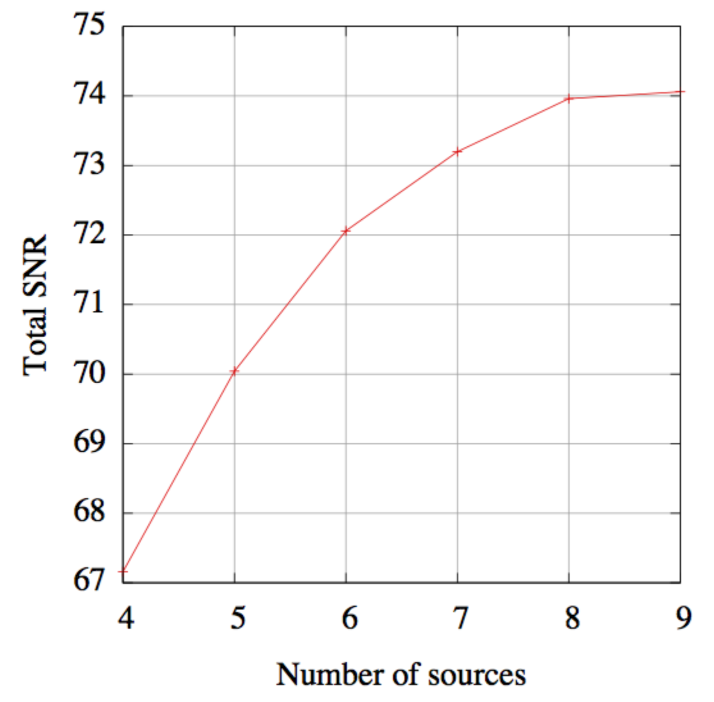
- In theory we need at least 3 N_{GW} + 1 pulsars to resolve N_{GW} GW sources
- At the moment, use Earth term only because GW contributions add up coherently : 7 parameters per source
  - Approximation on source modelling : non-eccentric and fixed frequency,
  - Fstatistic : analytical maximization over 4 parameters
→ search for 3 x N_{GW} parameters
  - Search : Multi-Search Genetic Algorithm (same method as the one used for eLISA and LISAPathfidner)

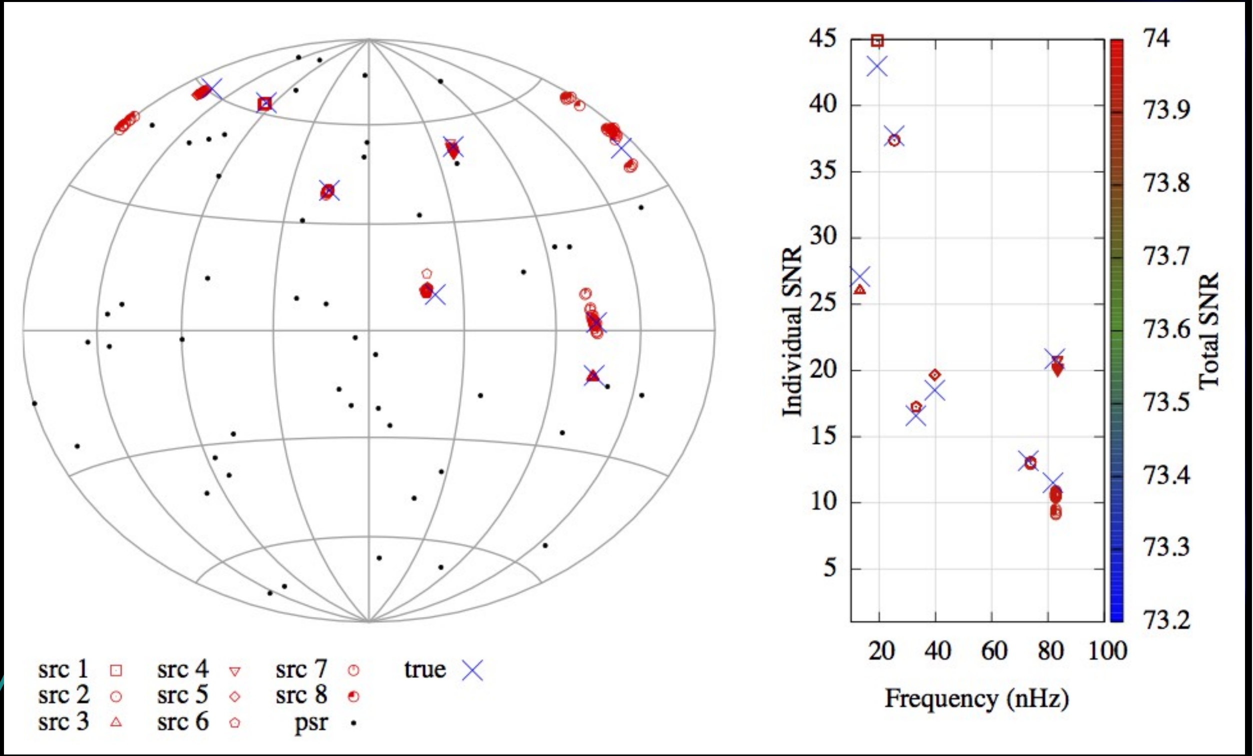
- Petiteau et al., PRD 87,064036 (2013)
- Babak Sesana PRD 85,044034 (2012)
- Ellis et al. (2012)

DA individual sources: MSGA

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

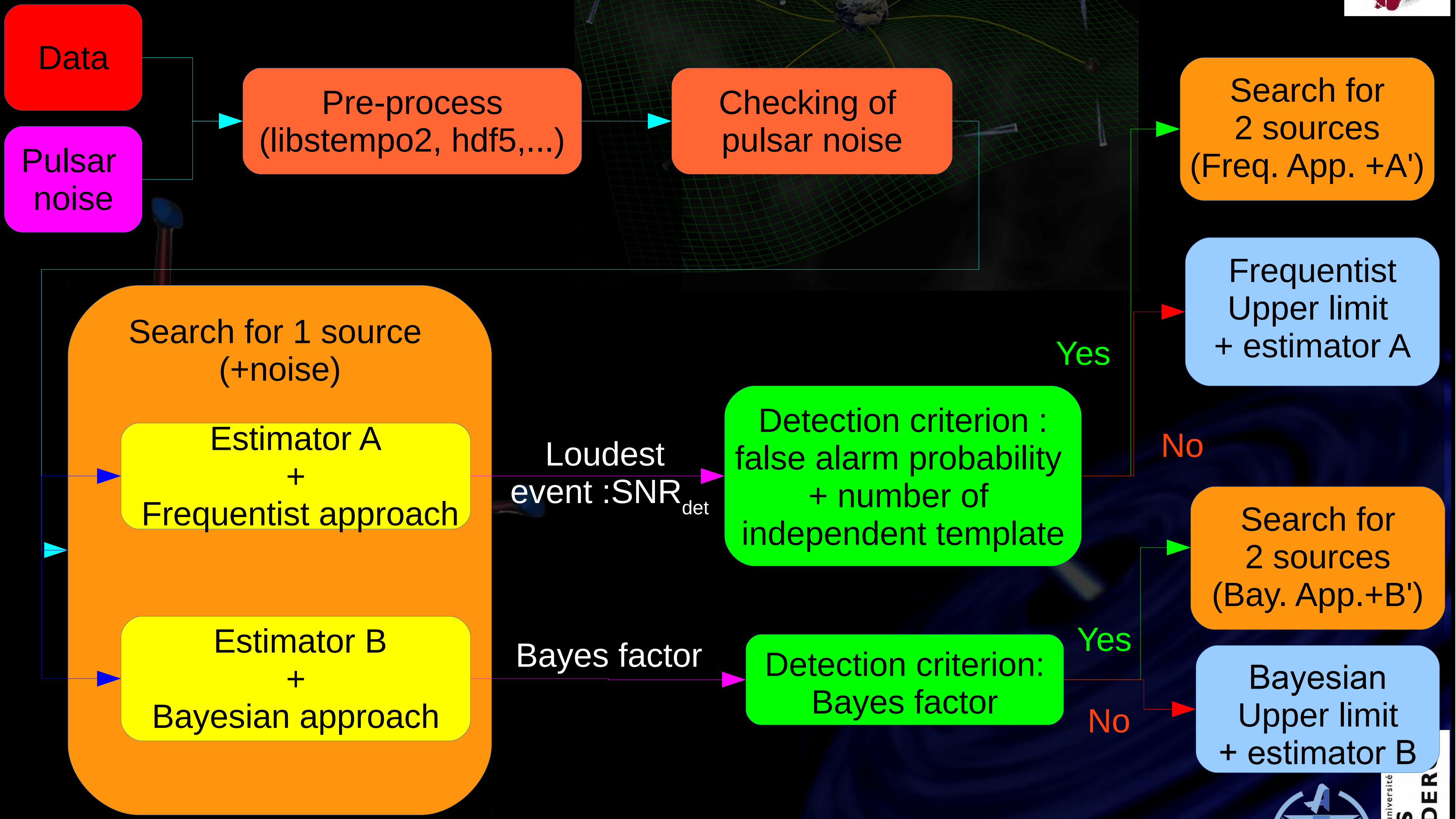
- Results on simulated data:
  - Data: 30-50 pulsars, simplified pulsar model, white noise at 30-200 ns, 3-8 sources at SNR>10.
  - MS-GA successfully identified all injected sources in all datasets.
  - MS-GA found all source parameters : sky position offset by less than few degrees and frequencies found with precision better than 0.1 nHz





Indiv. sources: Detection pipeline

Pipeline for analysis of real data which should take care of pulsar noise



Data

Pulsar noise

Pre-process (libstempo2, hdf5,...)

Checking of pulsar noise

Search for 1 source (+noise)

Estimator A + Frequentist approach

Estimator B + Bayesian approach

Loudest event :SNR$_{det}$

Detection criterion : false alarm probability + number of independent template

Bayes factor

Detection criterion: Bayes factor

Yes

No

Search for 2 sources (Freq. App. +A')

Frequentist Upper limit + estimator A

Yes

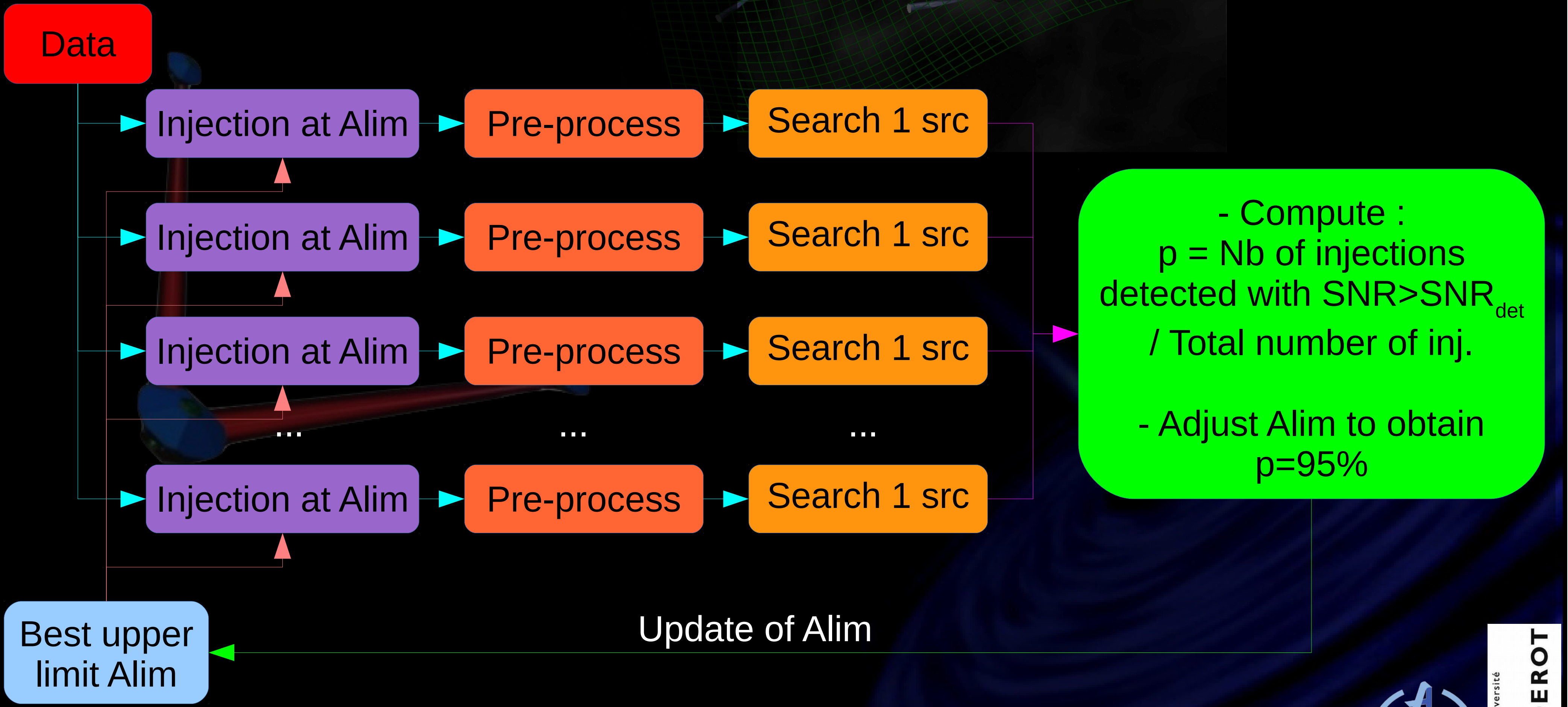
No

Search for 2 sources (Bay. App.+B')

Bayesian Upper limit + estimator B

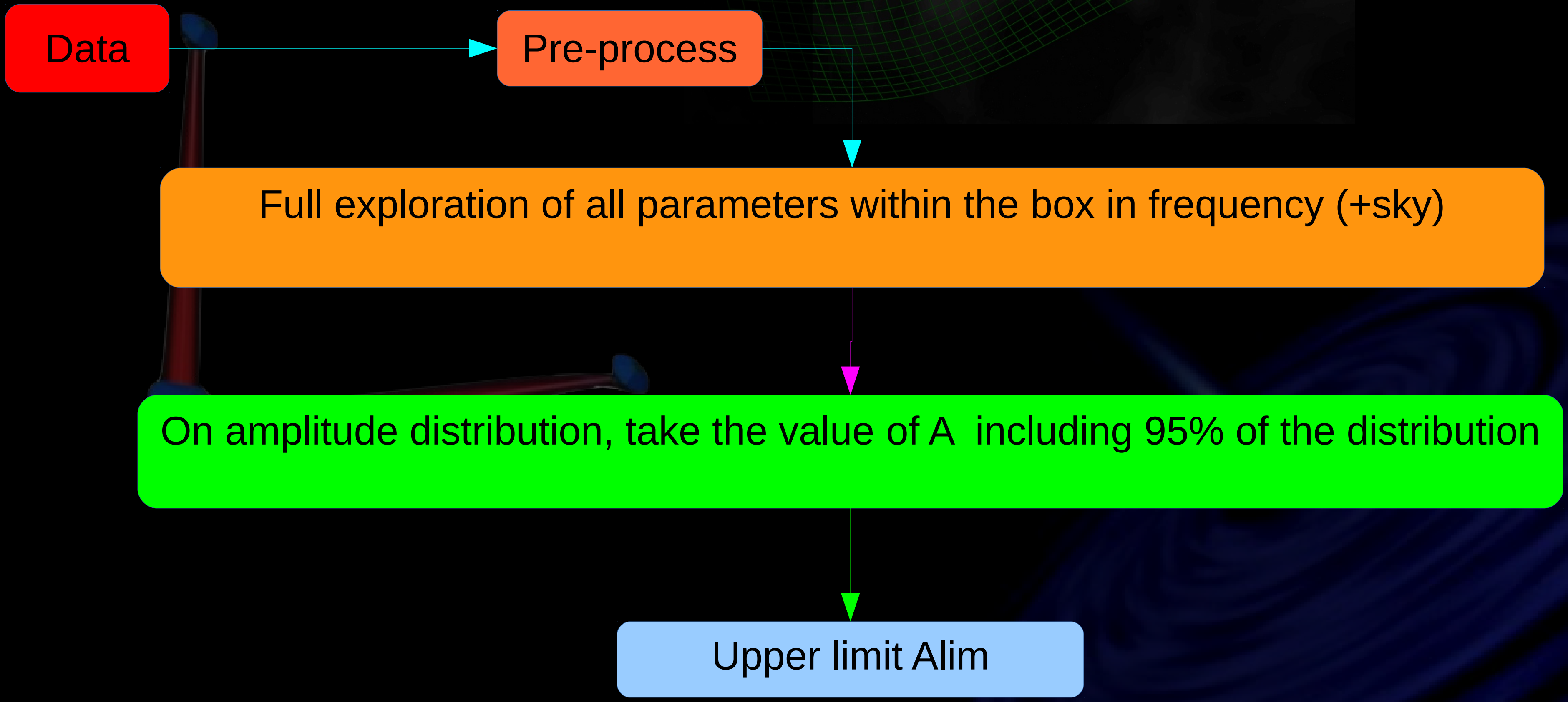
Pipeline to set upper limit frequentist approach

- For each {frequency} or each set of {frequency + sky position}, we can estimate the upper limit on amplitude.



Pipeline to set upper limit Bayesian approach

- For each {frequency} or each set of {frequency + sky position}, set a box and do a full exploration on all parameters.



Data

Pre-process

Full exploration of all parameters within the box in frequency (+sky)

On amplitude distribution, take the value of A including 95% of the distribution

Upper limit Alim

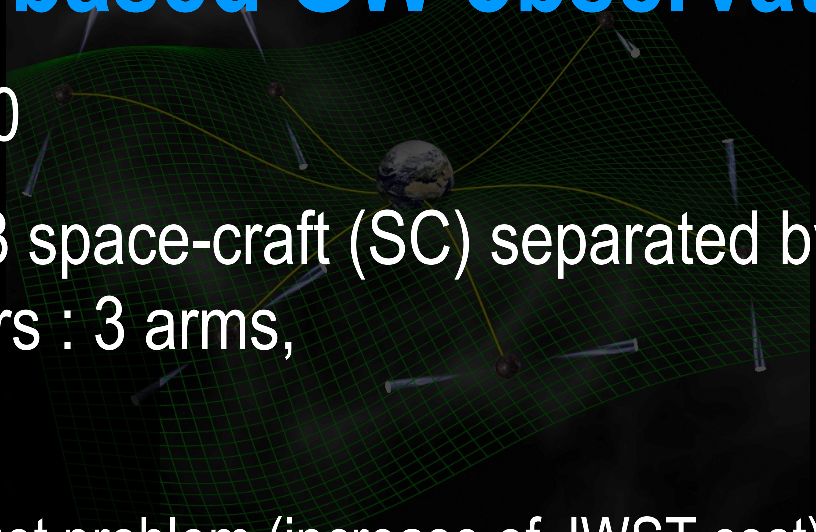
Computing

- Searching for individual source with fixed noise : covariance matrix fixed :
  - The number of parameters to explore can be large => stochastic method for bayesian and frequentist approaches
  - Run on cluster (MPI)
- Searching for noise and/or GW stochastic background : covariance matrix (~ 40000x40000) to be recomputed at each evaluation of likelihood
  - Computation time large due to the inversion of covariance matrix
  - Some code used GPU/CPU cluster (GPU for inversion)
  - Very long run on large number of cores ...

Conclusion

- Gravitational wave are ripples on spacetime emitted by a large number of astrophysical and cosmological sources.
- Soon, **GW astronomy will open a new window on the Universe** :
  - LISAPathfinder results and eLISA in 2034
  - Pulsar Timing Array reaches the sensitivity where there are probable gravitational sources : possible detection in the next years
  - Advanced LIGO is taking data since september 2015
- Computing :
  - Not really big data
  - Big computation with a large number of parameters to estimate
  - Hybrid infrastructure coupling standard cluster and cloud ...

eLISA: space based GW observatory



- First idea around 1970-1980
- ESA+NASA project: LISA : 3 space-craft (SC) separated by 5 millions kilometres exchanging lasers : 3 arms,
- 2011 :
  - NASA stops due to budget problem (increase of JWST cost),
  - ESA decides to do the large mission "alone" : call for L1 mission in Cosmic Vision frameworks to be launched in 2022 : competition between eLISA/NGO, JUICE, Athena,
  - JUICE win but eLISA/NGO was the best science case ...
- 2013 :
  - New call for L2 (launch 2028) and L3 (launch 2034) : 32 candidates
  - November : Athena+ → L2 (acceptation 2018), eLISA → L3

Heritage from LISA studies

- 7 years of Mock LISA Data Challenge from MLDC1 to MLDC4: Challenge of increasing complexity to develop and check data analysis (it get stuck after 2011 due to LISA redefinition).

- During MLDC large development on DA technics for searching MBHB (Babak et al. Report on MLDC 2007, 2008, 2009) :
  - Genetic algorithm (Petiteau et al. 2009 and 2010),
  - Parallel tempering MCMC (Porter & Cornish 2006),
  - MultiNest (Bridges et al. 2009).

- There is still a lot of points to solve for data analysis of eLISA data (realistic noise, more sources, full waveform,...)

- MeLDC will (re)start soon … everybody will be welcome to join !

Continuous integration

- All developers works on a git-clone version of the code on their own machine
- Dedicated machine called dpcelisa is connected to the git and regularly check via Jenkins if there is any change on the git. If so it checks the code :
  - compilation
  - run tests
  - update documentation
  - performance analysis via SonarQube
- If the change is valid save it (in a dedicated git branch).
- Admins or main developers can make realease that, in operation, will replace the version of the code used in production