Observing Massive Black hole binaries with Gravitational Waves

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Cardiff University – 10th june 2013

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Outline

- Introduction to Massive Black Hole Binaries (MBHB)
- Observing MBHB with Pulsar Timing Array
  - Introduction to PTA : EPTA and IPTA,
  - GW signal of MBHB in PTA measurements,
  - Data analysis (MultiSearch Genetic Algorithm, ...),
  - Preliminary results
- Observing MBHB with eLISA
  - Status of the mission (selected as L3 at ESA !) and LISAPathfinder
  - MBHB observation with eLISA
  - Improvement using hybrid waveform
  - Spin direction degeneracies
- Conclusion

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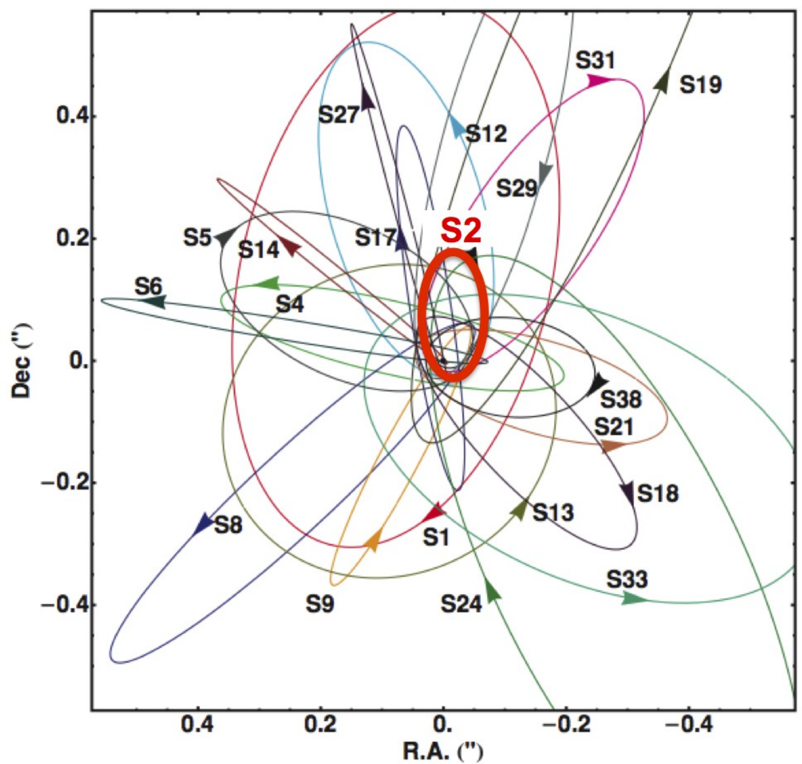
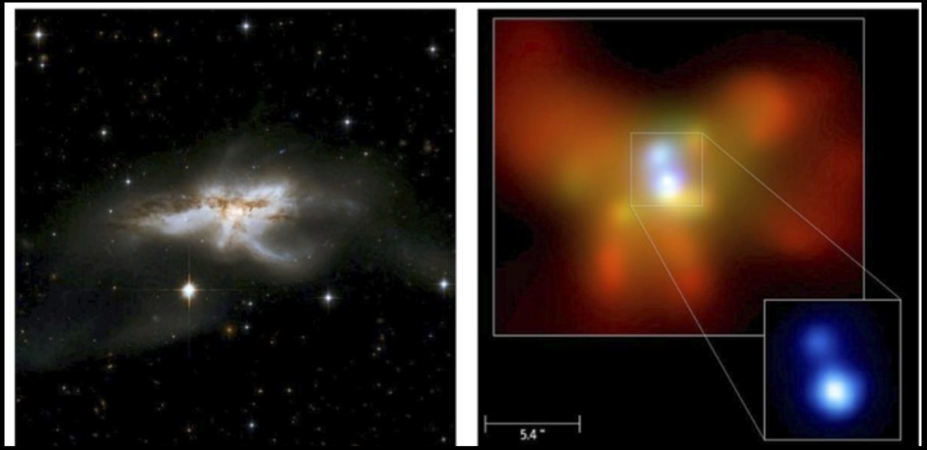
Massive Black Hole

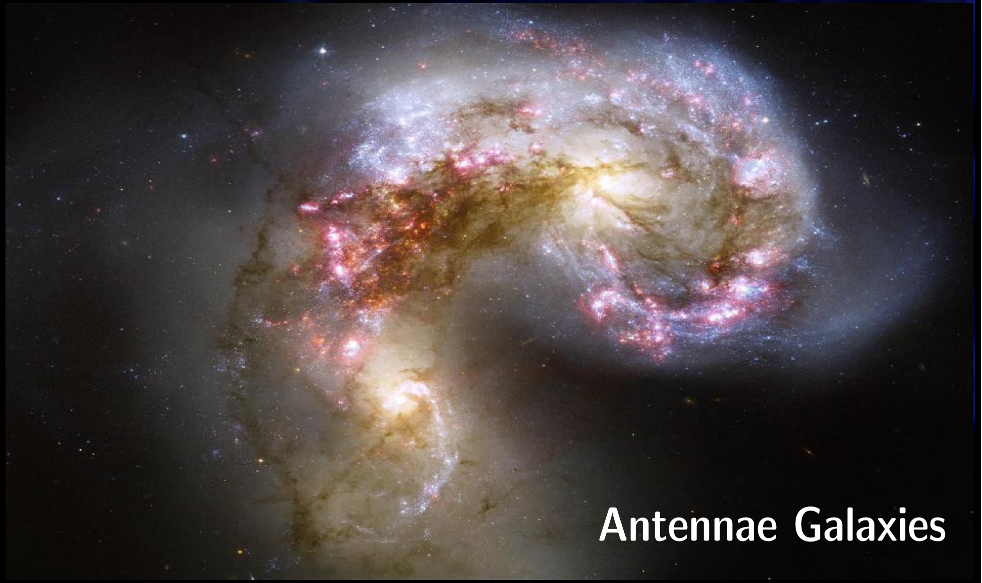
- Observations of Sgr A*, a dark massive object of $4.5x10^{6}$ M_{Sun} at the centre of Milky Way.
- Massive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).
- Observations of galaxies mergers.

  → MBH binaries should exist.
- Observations of double AGN





NGC 6240 (Komossa et al. ApJ 582 L15)

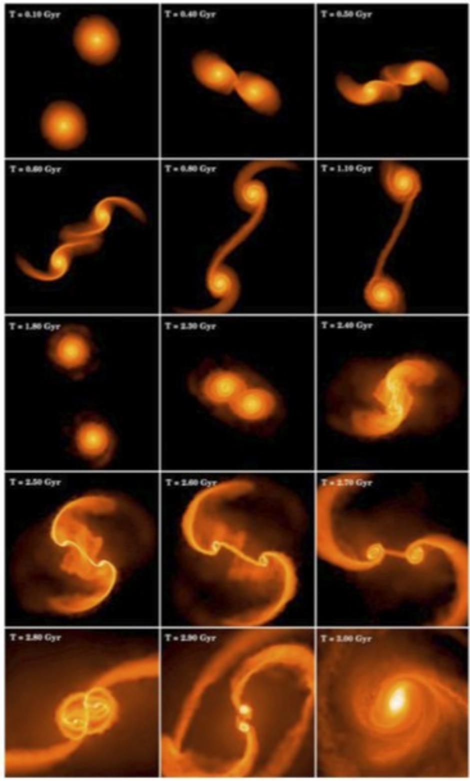


Antennae Galaxies

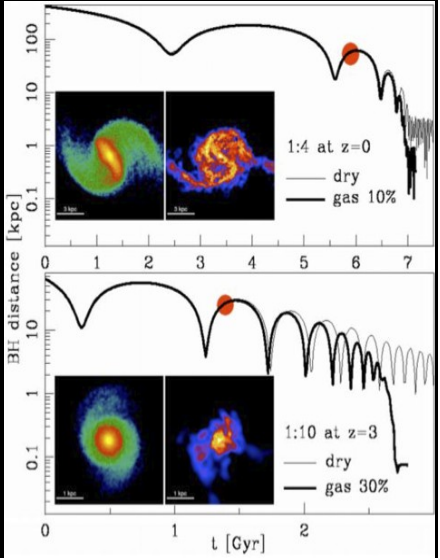
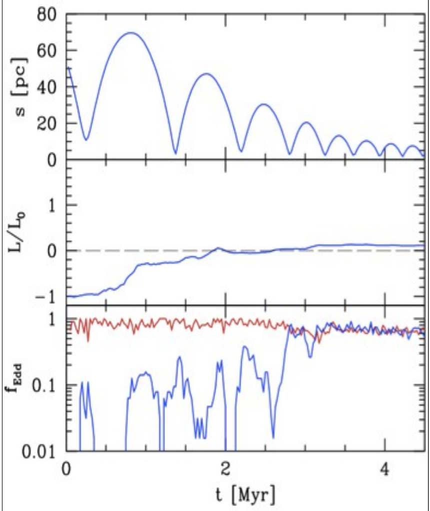
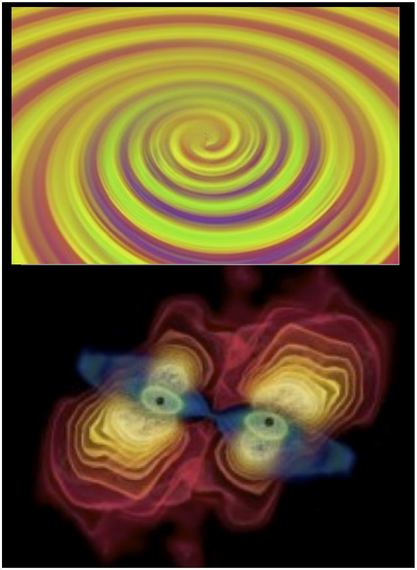
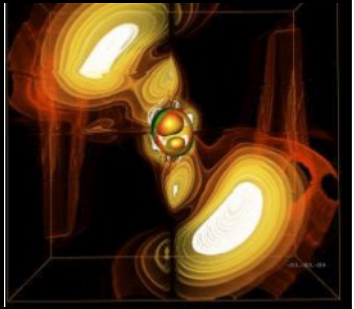
Massive Black Hole

- Formation: several hypothesis (In early Universe baryons need to cool down in order to condense in dense structures and dynamics depends on metallicity)
  - Pop III: light seeds (Madau & Rees 2001, Volonteri Harrdt & Madau 2003),
  - Direct collapse: heavy seeds (Loeb & Rasio 1994, Koushiappas et al. 2004, Begeleman Volonteri & Rees 2006, Dotan Rossi & Shaviv 2011),
  - Mild metal enrichment: light seeds + nuclear cluster (Devecchi & Volonteri 2009, Devecchi et al. 2010)
- Evolution:
  - Accretion: coherent (disc) or chaotic
  - Merger with others MBH

MBH Binaries: formation & evolution

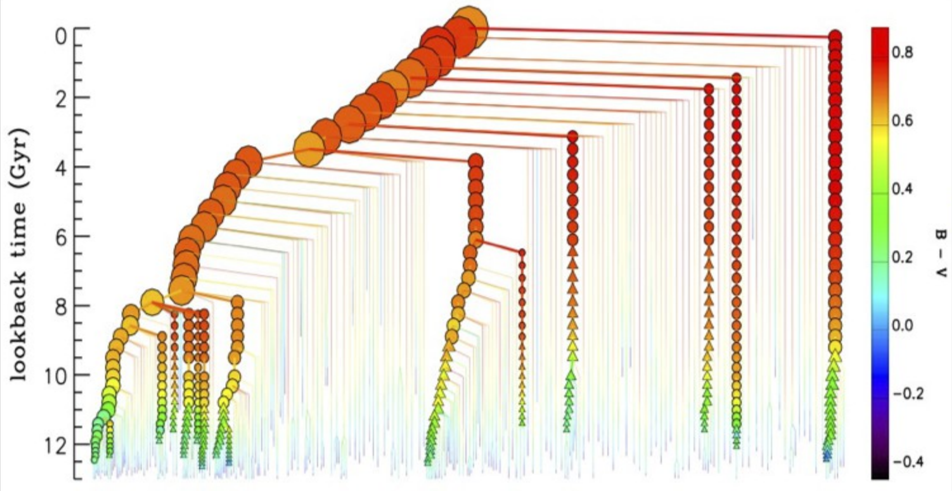


Colpi & Dotti (2009) Review astro-ph 0906.4339

Galaxies mergers	Binary formation	Close binary	Merger
			
100 kpc → 100 pc	100 pc → sub-pc	sub-pc → few M (au)	
few Gyr	few Myr		few days - hours
➢ Dynamical friction ➢ Stellar formation ➢ Tidal shocks ➢ Gas dynamics ➢ Callegari & al. (2009) ApJ 696 L89	➢ Gas-dynamical friction ➢ Circularisation ➢ Orbital angular momentum can flip ➢ 3 bodies interaction ➢Dotti & al. (2009) MNRAS 396-1640	➢ Inspiral of the 2 MBHs due to GW emission	➢ GW burst ➢ Recoil velocities of remnant BH

Model for MBHB event rate

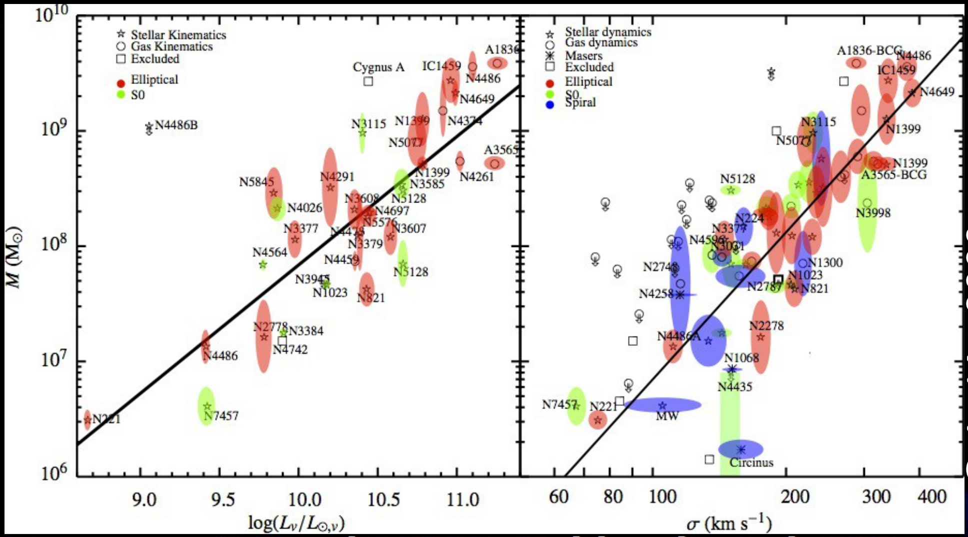
Galaxies merger trees



From De Lucia et al 2006

+

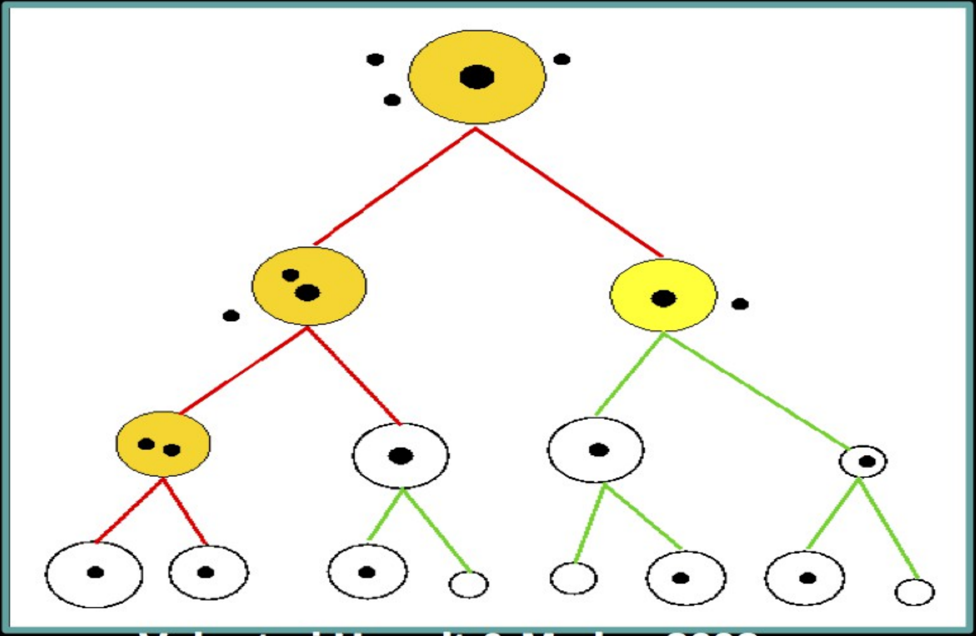
“M - σ relation”: the speed of stars in bulge is linked to the central MBH mass



Gultekin 2009

Ferrarese & Merritt 2000, Gebhardt et al. 2000

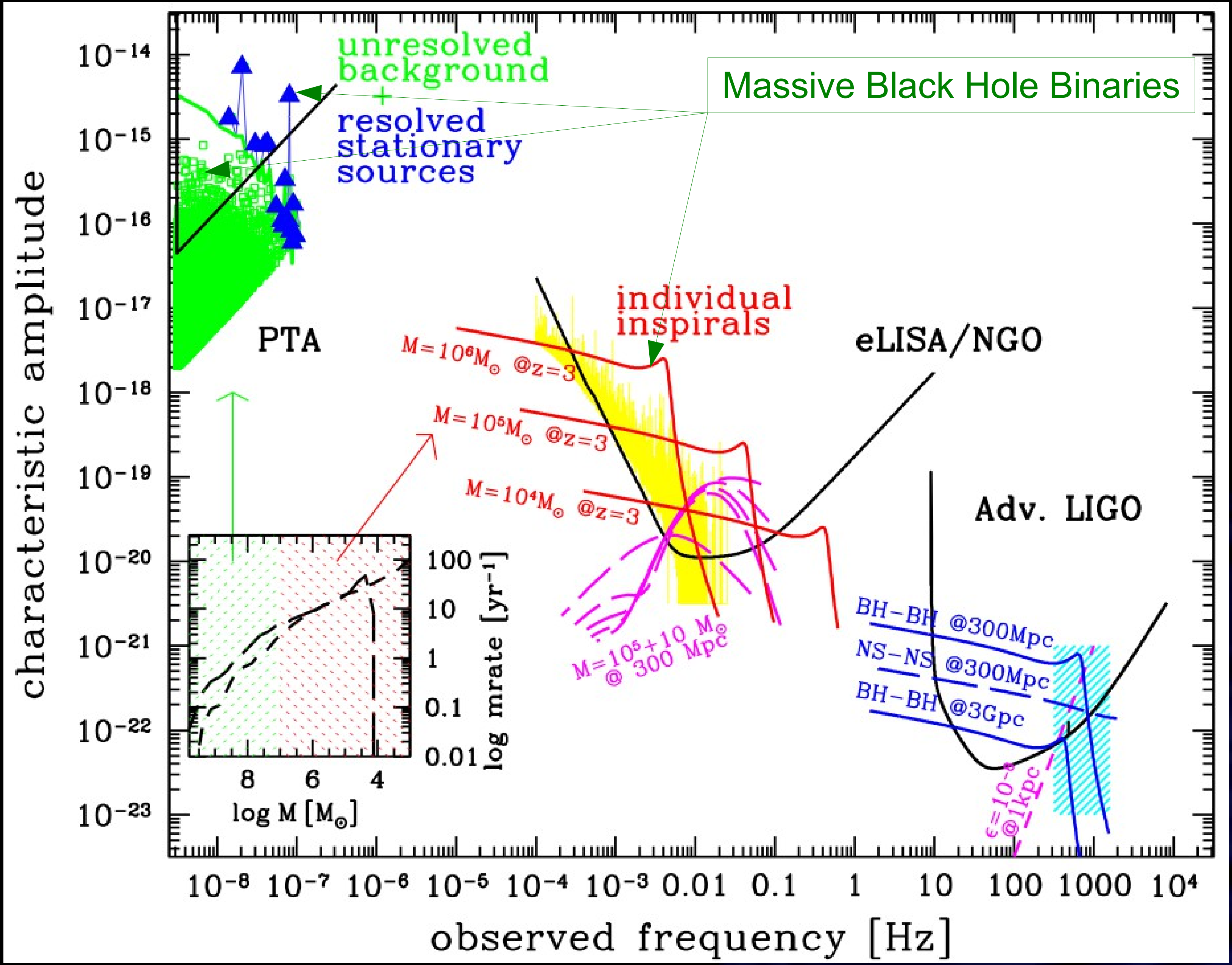
=



Volonteri Haardt & Madau 2003

Codes from A. Sesana & M. Volonteri generates catalogs of potential events: each catalog is a “realization of the Universe” with particular prescription

Gravitational waves

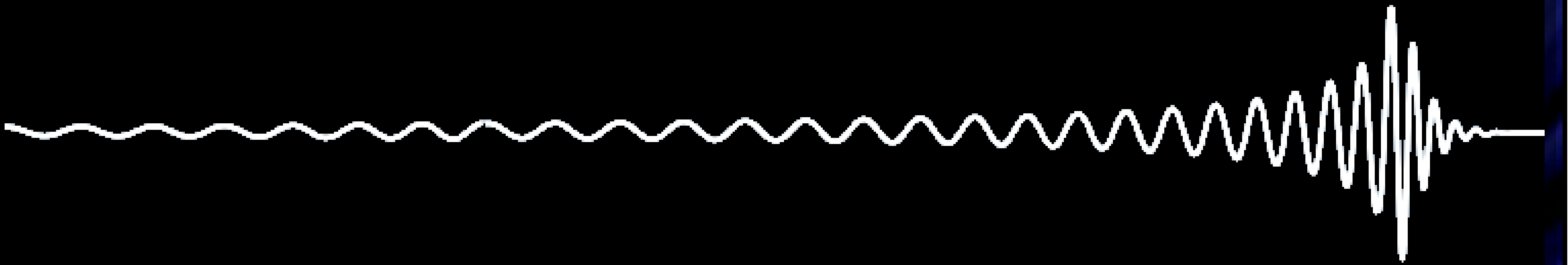


Massive Black Hole Binaries

Sesana astro-ph.CO 1304.0767 (2013)

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 (Damour et al. , Buonnano et al.),
  - ...



Why observing MBHB ?

- Astrophysics:
  - Understand the formation of the first BH,
  - Evolution of MBH with galactic nuclei due to accretion and merger,
  - Role of MBH in galaxy formation,
  - …
- Cosmology:
  - Constrain cosmological parameter (Van Der Brook et al. 2010, Petiteau Babak Sesana 2011)
  - Test model of hierarchical structure formation,
  - …
- Fundamental physics:
  - Test General Relativity,
  - Massive Graviton (Berti Gair Sesana 2011, …)
  - Is GWs travel at speed of light ?
  - Test BH no-hair theorem
  - …

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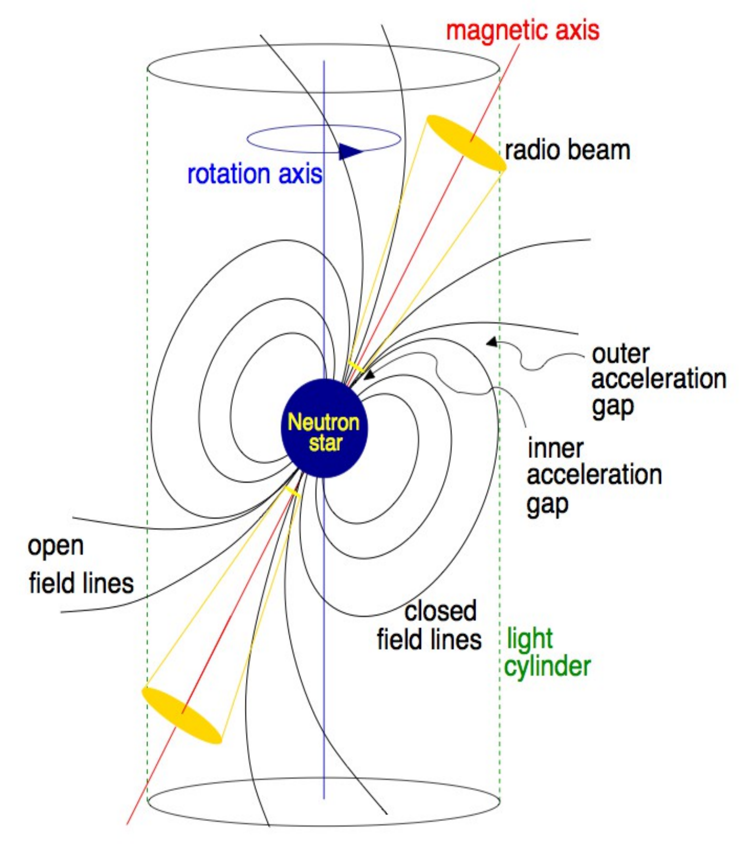
Pulsar Timing

- Pulsar is rotating neutron star emitting very regular burst of radiation (radio, gamma ray, etc)
- 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 :

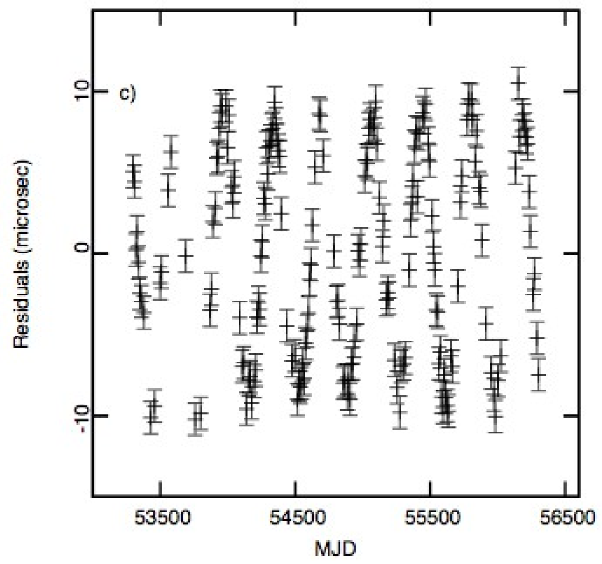
$$R = TOA - TOA_{model}$$

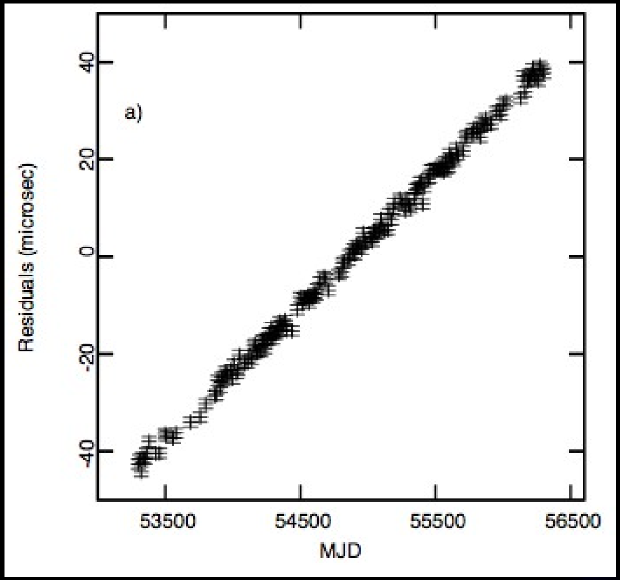
it contains all the unmodelled physics including gravitational waves passing between the pulsar and the receiver on Earth.

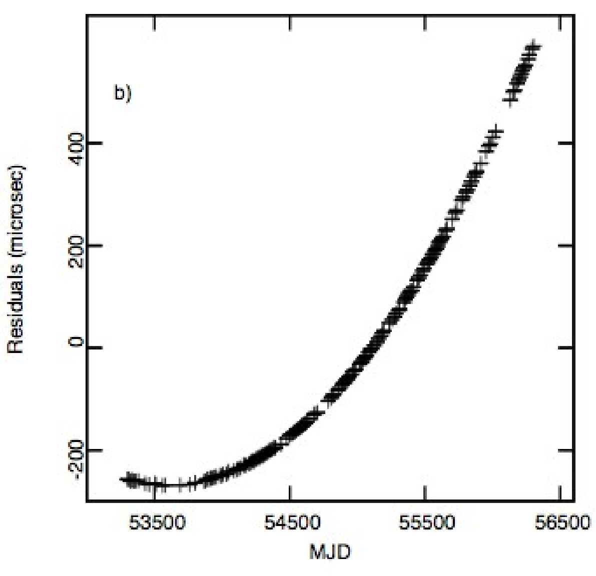


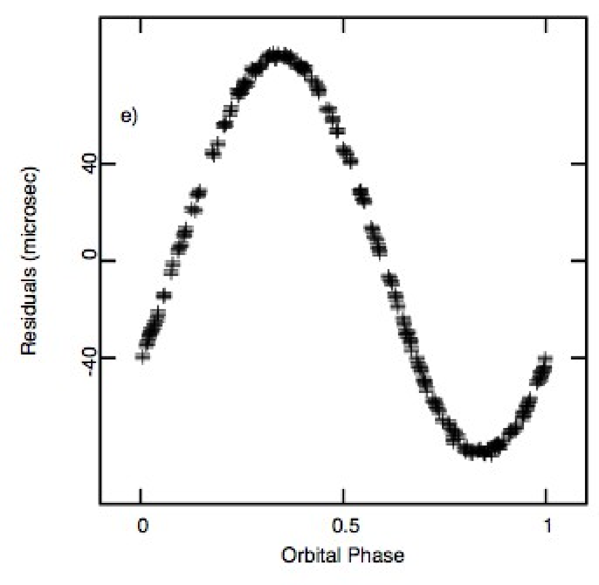
Pulsar Timing

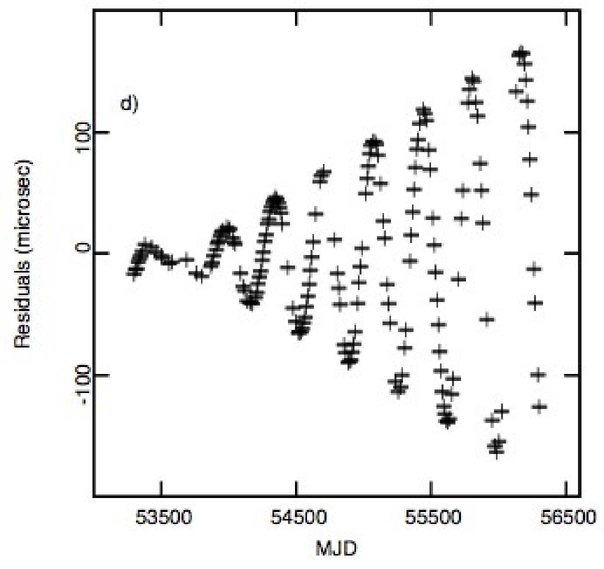
- Example of errors in timing, i.e. error in model parameters (from A. Lassus):

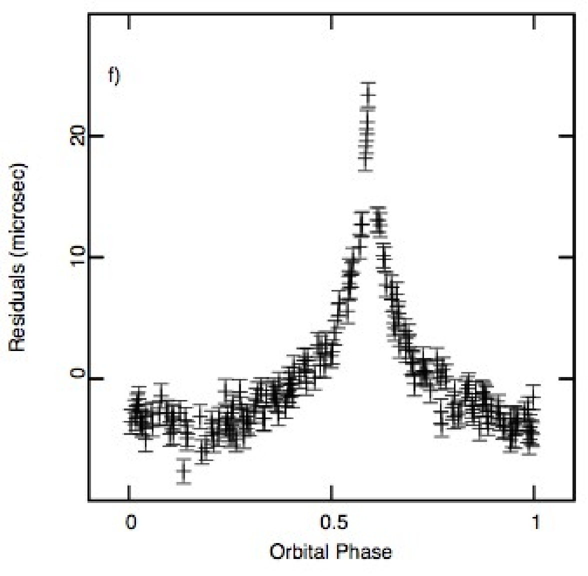

Error in position: annual effect


Error in period


Error in period derivative

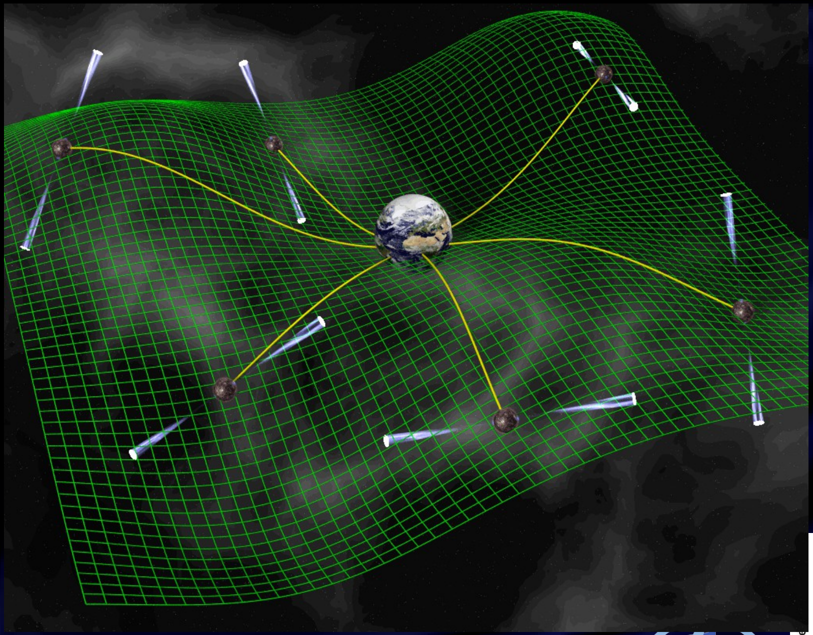

Error in orbital period


Error in proper motion


Without correction of Shapiro effect

Pulsar Timing 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, ...



Pulsar Timing Arrays

- Member of **EPTA (European PTA)** :
  - Nancay RT (FR),
  - Effelsberg RT (G),
  - Jodrell Bank Obs. (UK),
  - Westerbork Synthesis RT(NL),
  - Sardinia RT (I).


J.-P. Letourneur, CRDP Orléans

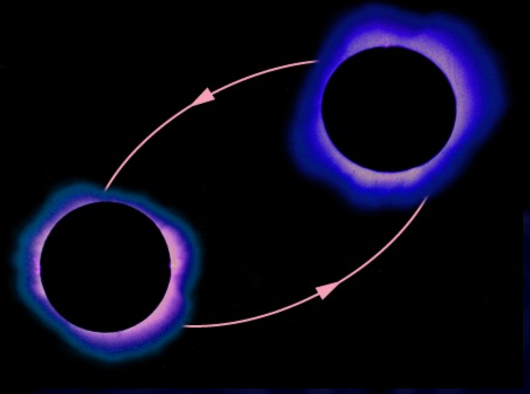
Nancay(FR)

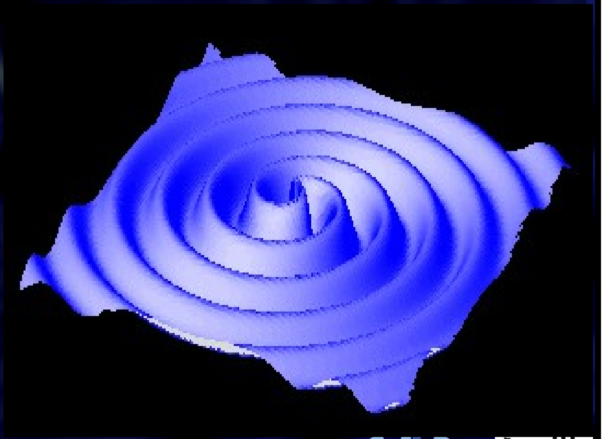

Effelsberg (Bonn)

- Other PTA :
  - PPTA (Parkes PTA – Australia)
  - NanoGrav (US) : Arecibo - Green Bank Tel.
- Collaboration of all PTA within the **IPTA** (International PTA)

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 wave signal

- GW signal to pulsar residual :

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

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

- 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.

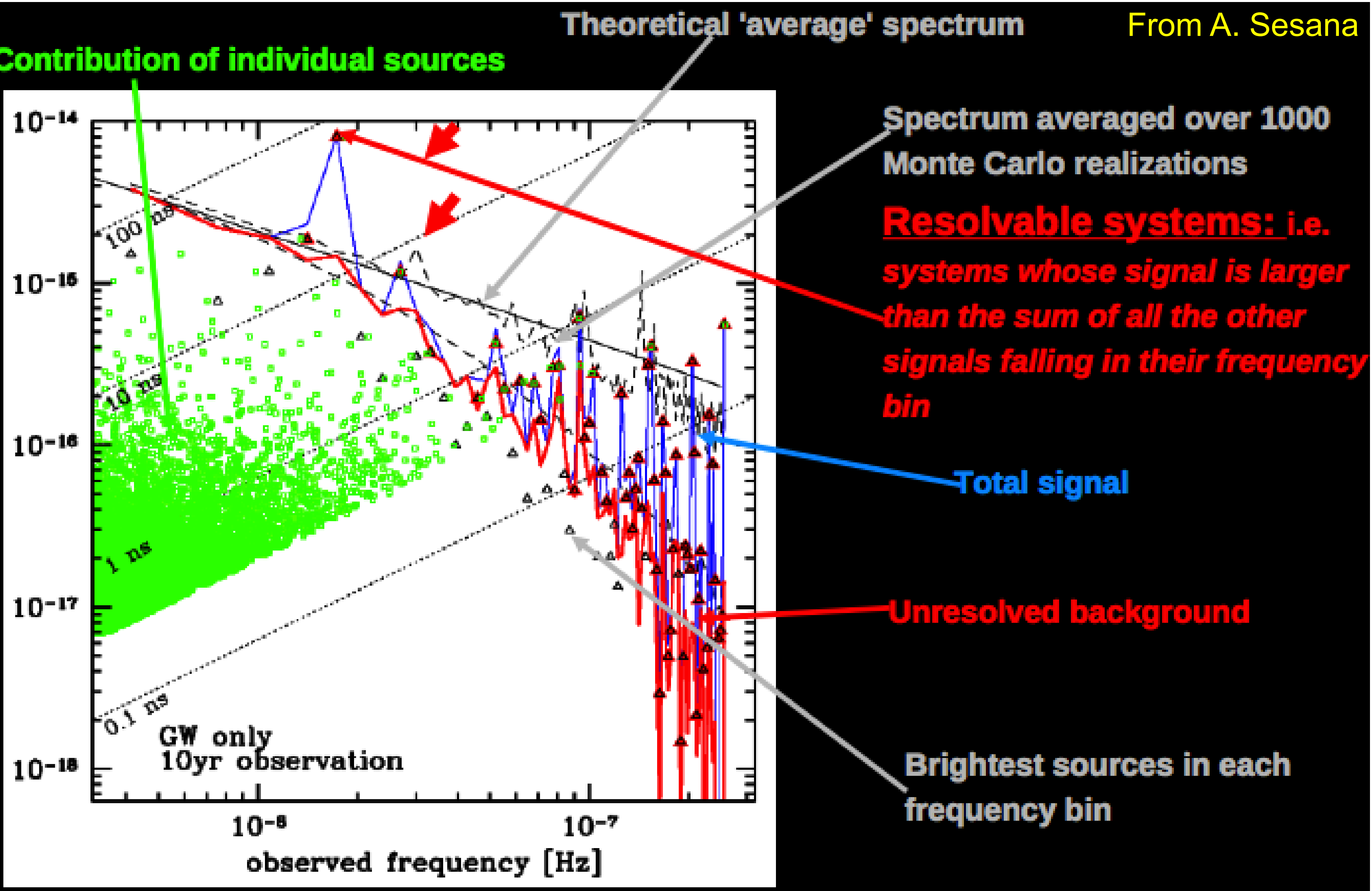
- Residual can be separated in 2 terms: Earth term and pulsar term

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

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

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

Typical signal from MBHB



From A. Sesana

Contribution of individual sources

Theoretical 'average' spectrum

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

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

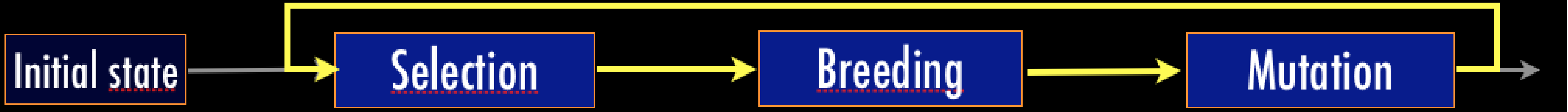
DA ind. sources: Genetic Algorithm

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

Evolution : organism ⟷ template described by a set of genes



Selection : Selection of parents for the breeding

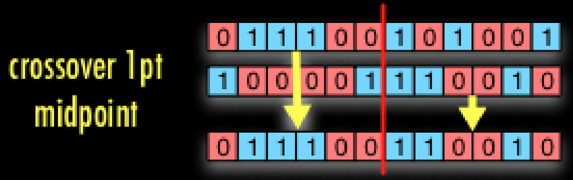
Probability of selecting one organism depend on Quality.

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 :



- Others possibilities ...

Mutation : Change few bits in gene

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

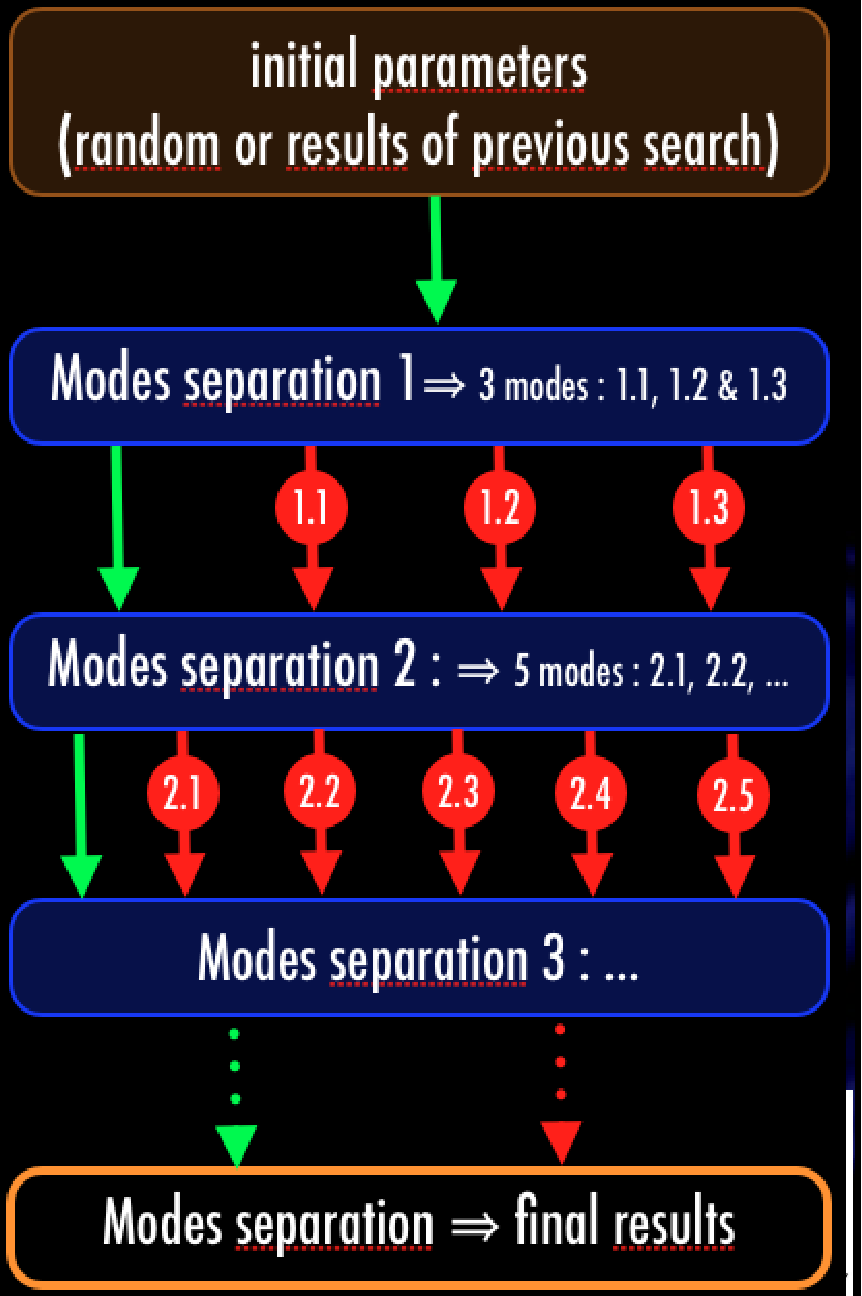
Several types of mutation :

- 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, ...

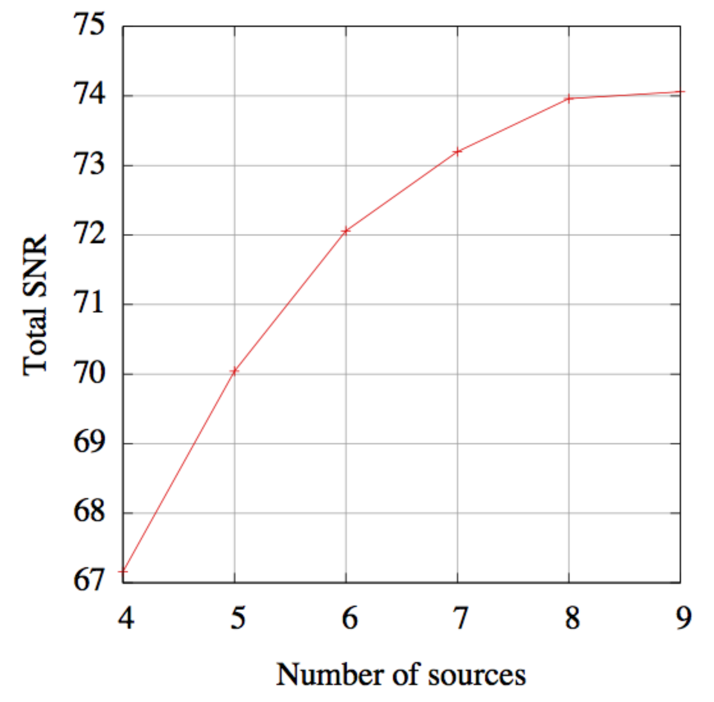
Modes separation 3 : ...

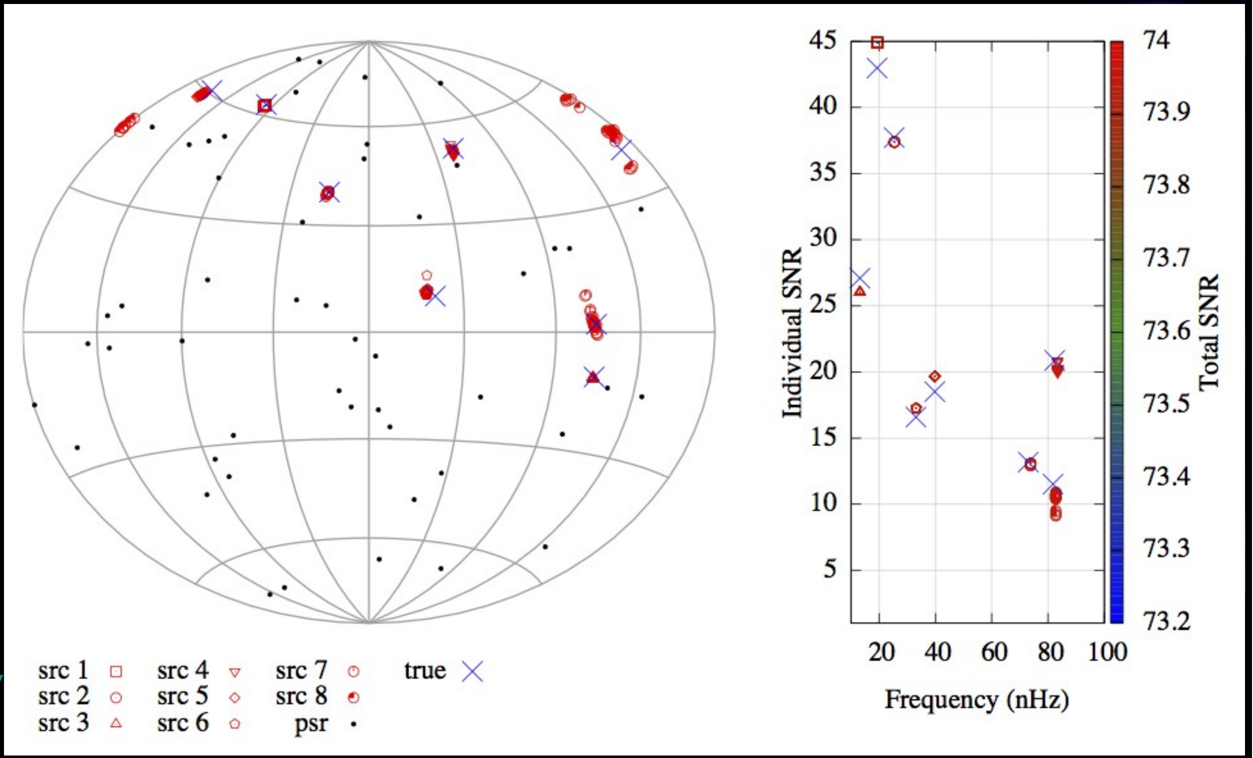
Modes separation ⇒ final results

DA individual sources: MSGA

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

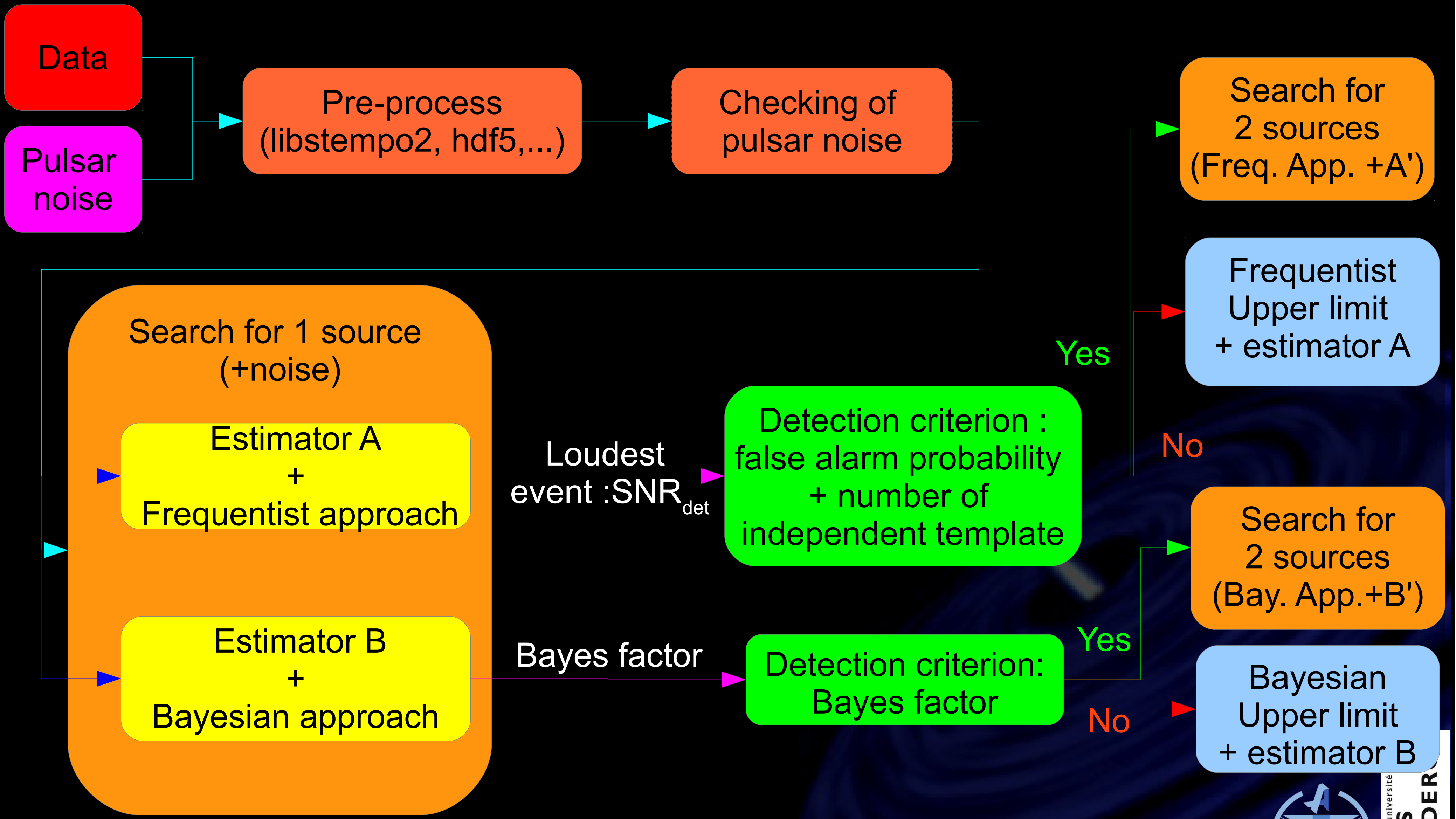
- Results on simulated data:
  - Data: 30-50 pulsars, simplified pulsar model, white noise at 30-200 ns, 3-8 sources at SNR>10.
  - MS-GA successfully identified all injected sources in all datasets.
  - MS-GA found all source parameters : sky position offset by less than few degrees and frequencies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

Bayes factor

Detection criterion : false alarm probability + number of independent template

Detection criterion: Bayes factor

Yes

No

Yes

No

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

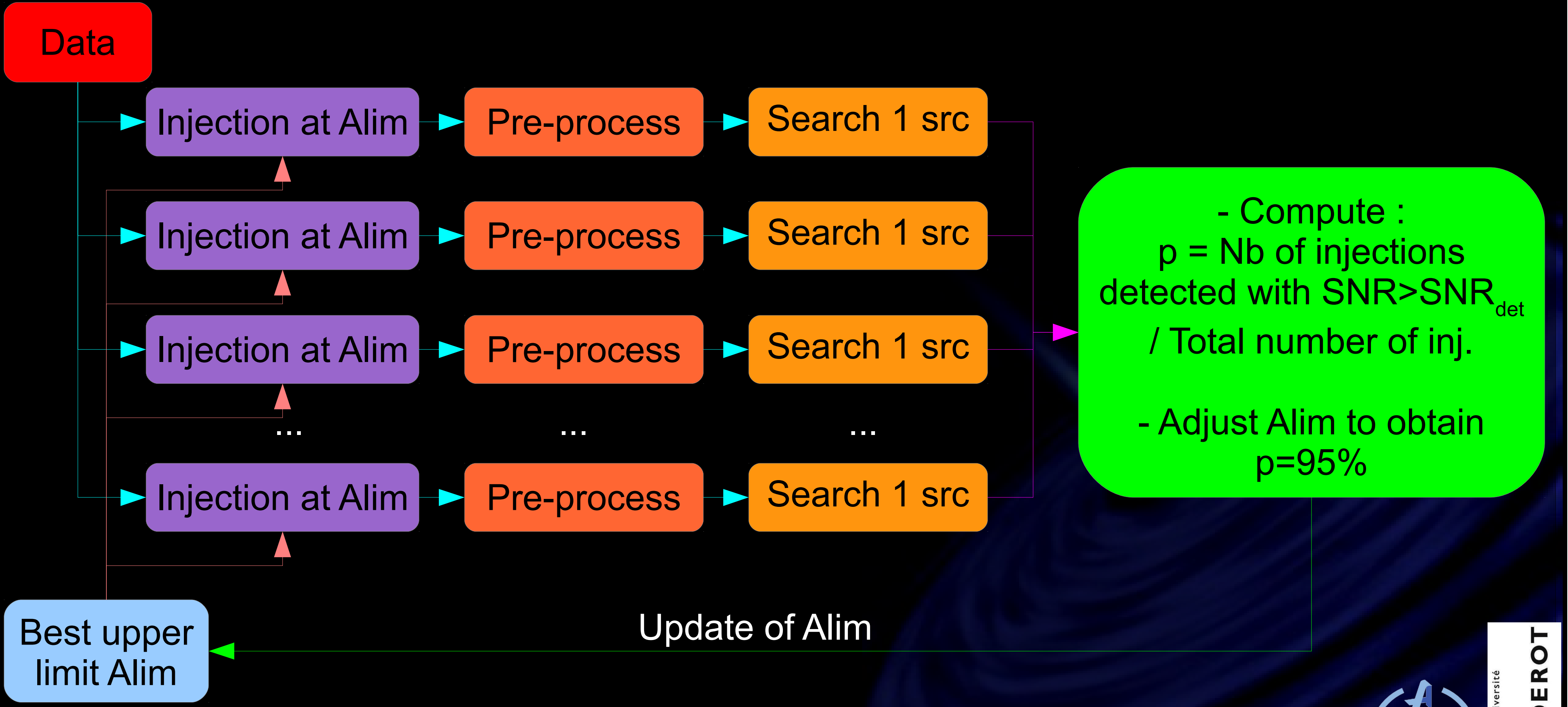
Frequentist Upper limit + estimator A

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.



Data

Injection at Alim → Pre-process → Search 1 src

Injection at Alim → Pre-process → Search 1 src

Injection at Alim → Pre-process → Search 1 src

… … …

Injection at Alim → Pre-process → Search 1 src

- Compute :
p = Nb of injections detected with SNR>SNR_{det} / Total number of inj.

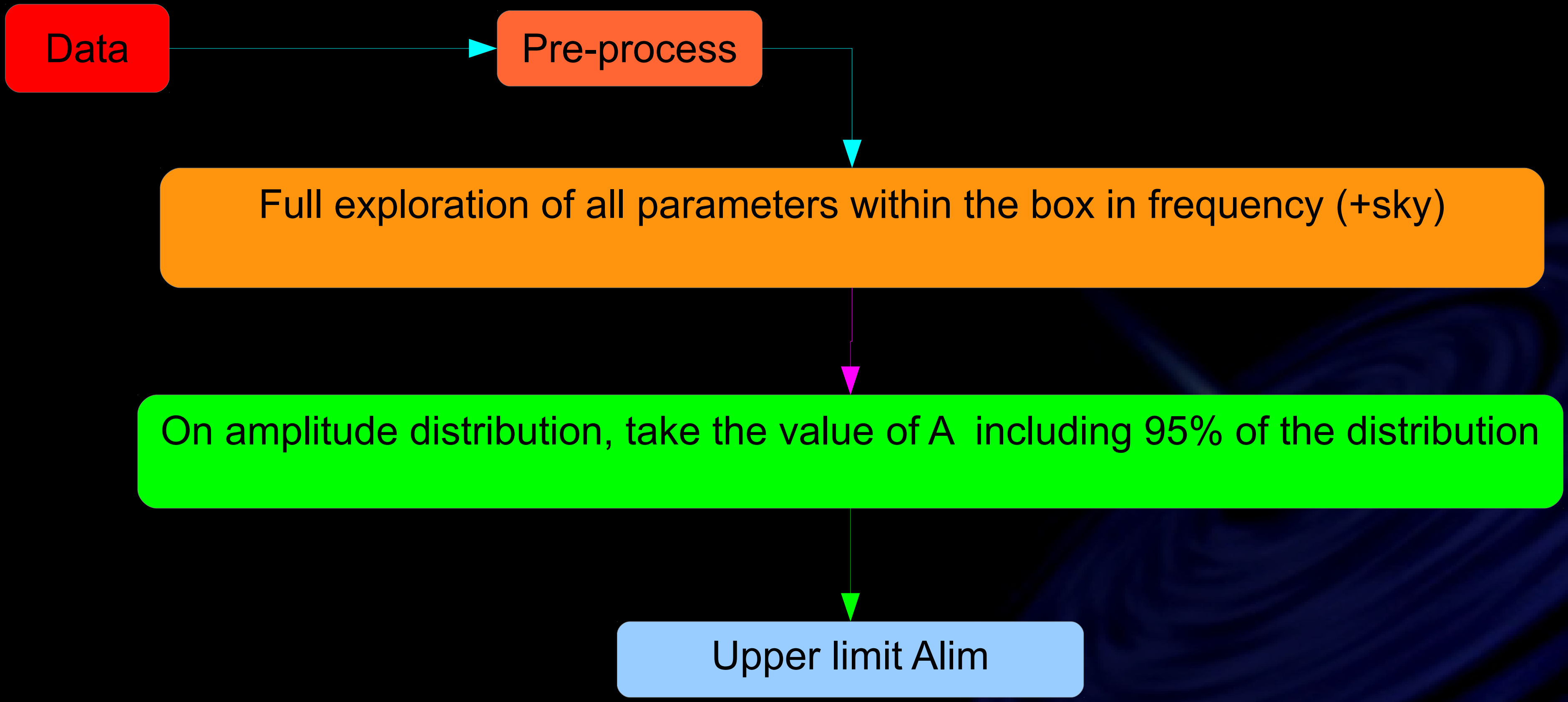
- Adjust Alim to obtain p=95%

Update of Alim

Best upper limit Alim

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

Estimators used in EPTA DA

	Description	Term	Npar	Search	Maximized
Le	Standard likelihood / model with Earth term only	Earth	7	sky, fe, A, i, ψ & Φe	-
Lp1	Standard likelihood / model with Earth and Pulsar terms (frequency & phase for each pulsar).	Earth + Pulsar	7 + 2 Npsr	sky, fe, A, i, ψ,Φe, fp, Φp,	-
Lp2	Standard likelihood / model with Earth and Pulsar terms (search for distance of each pulsar).Source's evolution is approximately known.	Earth + Pulsar	7+ Npsr	sky, fe, A, i, ψ,Φe & dpsr	-
Fe	Fstatistic / with Earth term only: analytic maximization of likelihodd over 4 parameters	Earth	3	sky & fe	A, i, ψ, Φe
Fp	Non-coherent search for monochromatic signal (most profits if earth and pulsar terms fall in the same frequency bin)	Earth + Pulsar (fe=fp)	1	fe	sky, A, i, ψ,Φe & Φp
Mp	Analytic/numerical marginalisation of likelihood over pulsar phase parameters (see Taylor's talk)	Earth + Pulsar	7/8	sky, fe, A, i, ψ, Φe,	Φp

sky: sky position (2 parameters),
fe: frequency of Earth term,
A: amplitude,

i: inclination,
ψ: polarisation,
Φe: initial phase of Earth term,

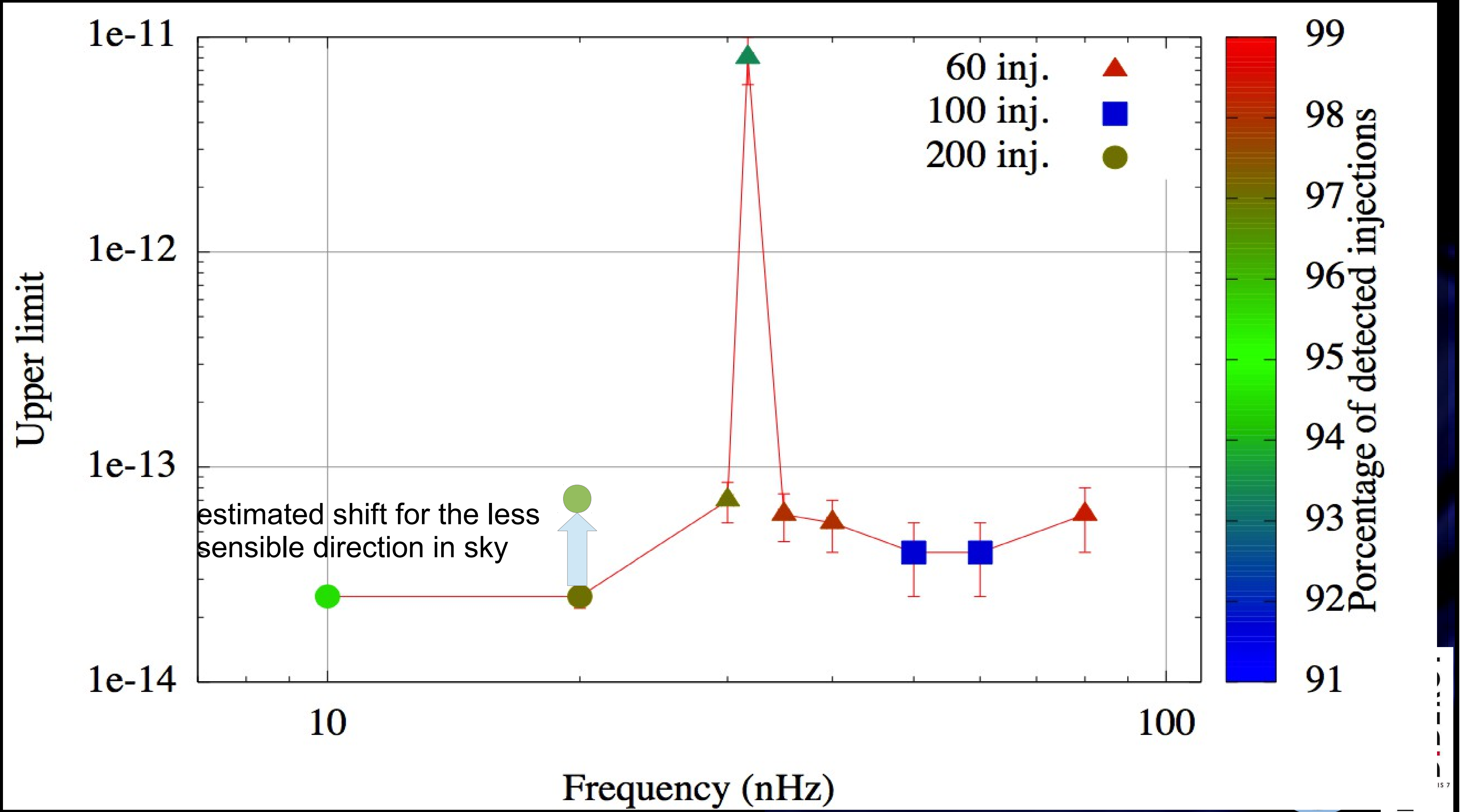
fp: frequency of Pulsar term
Φp: initial phase of Pulsar term
dpsr: pulsar distance

Steps of project: minimal plan

i	Goal	Approach	Estim.	Method	Status code	Status method
1	detect	Frequent	Fe	MultiSearch Genetic Algorithm & Stochastic Bank	ready (for fixed noise) ; in dev	MSGA done Bank in dev.
2	Alim	Frequent	Fe	Stochastic Bank	ready	-
3	detect	Frequent	Fp	Frequency scan	?	?
4	Alim	Frequent	Fp	Frequency scan	?	?
5	detect	Bayesian	Le	Parallel tempering MCMC	ready	in dev.
6	Alim	Bayesian	Le	MCMC	ready	in dev.
7	detect	Bayesian	Mp	Fixed noise (multinest); vary noise (PTMCMC)	Fixed noise (ready); vary noise (in dev.)	in develop
8	Alim	Bayesian	Mp	Fixed noise (multinest); vary noise (PTMCMC)	Fixed noise (ready); vary noise (in dev.)	?
9	Compare and cross-check results					

Preliminary results on upper limit

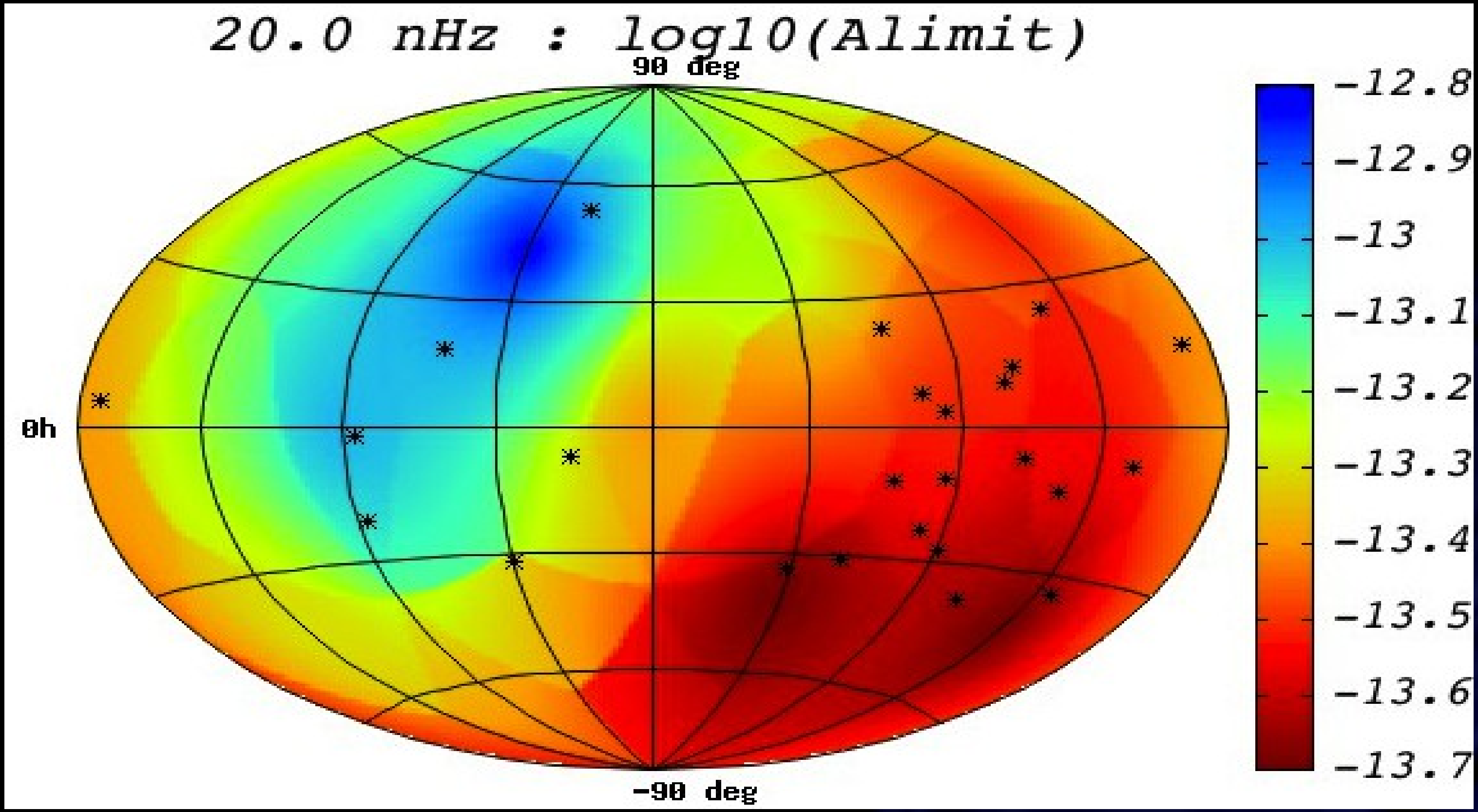
- 25 pulsars : upper limit on amplitude vs frequency for the direction in sky where the sensitivity is the best : PRELIMINARY results : 60 to 200 injections, problem with noises model



estimated shift for the less sensible direction in sky

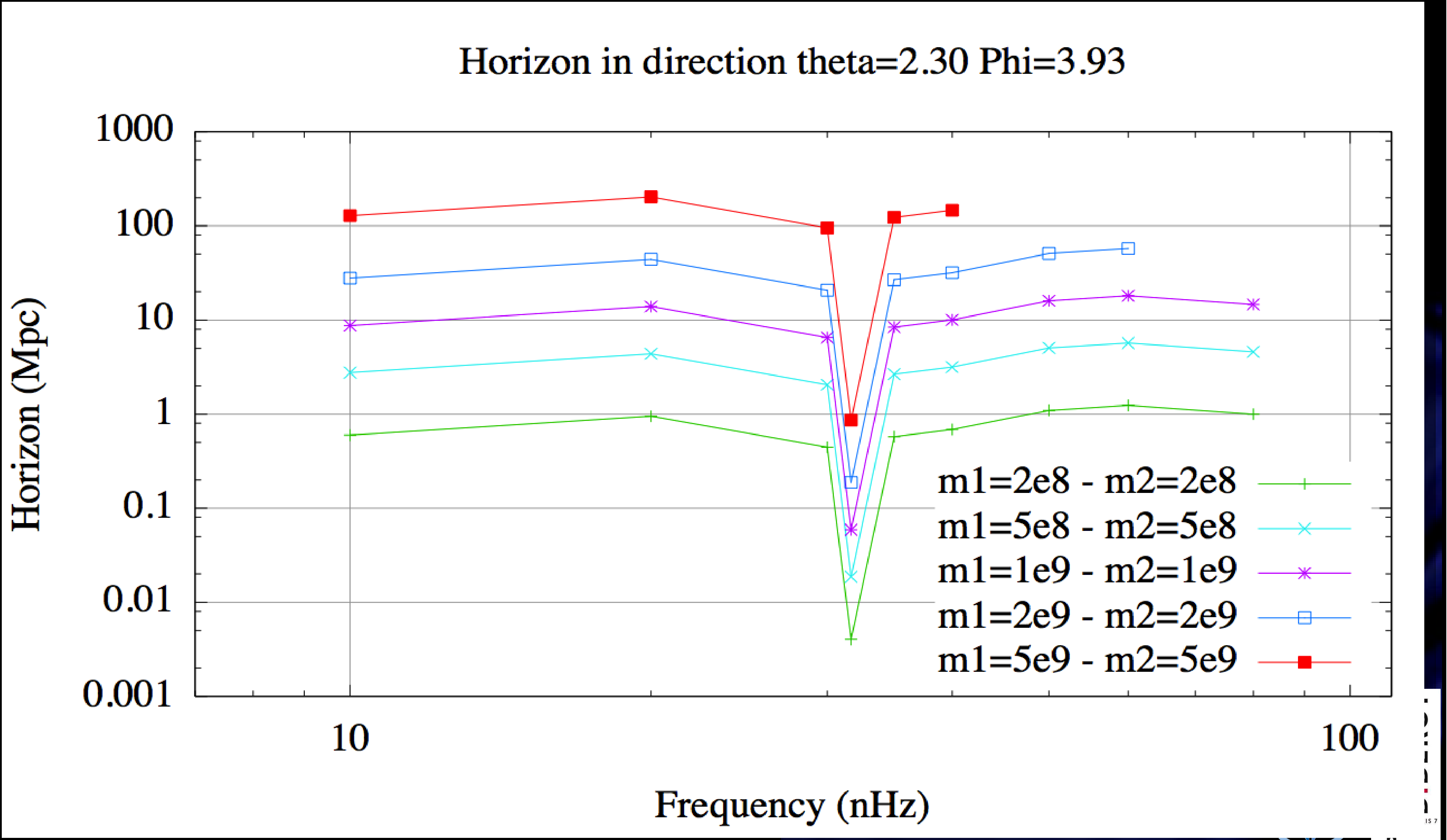
Preliminary results on upper limit

- Sky map of upper limit on amplitude at 20 nHz : preliminary result
  - only 12 directions (interpolations for rest of the map)
  - low statistic (60 to 200 injections)



Horizon of MBH binaries with EPTA

- From the upper limit, it is possible to set horizon for a given chirp mass below which one the presence of binaries can be excluded with 95% confidence level - PRELIMINARY

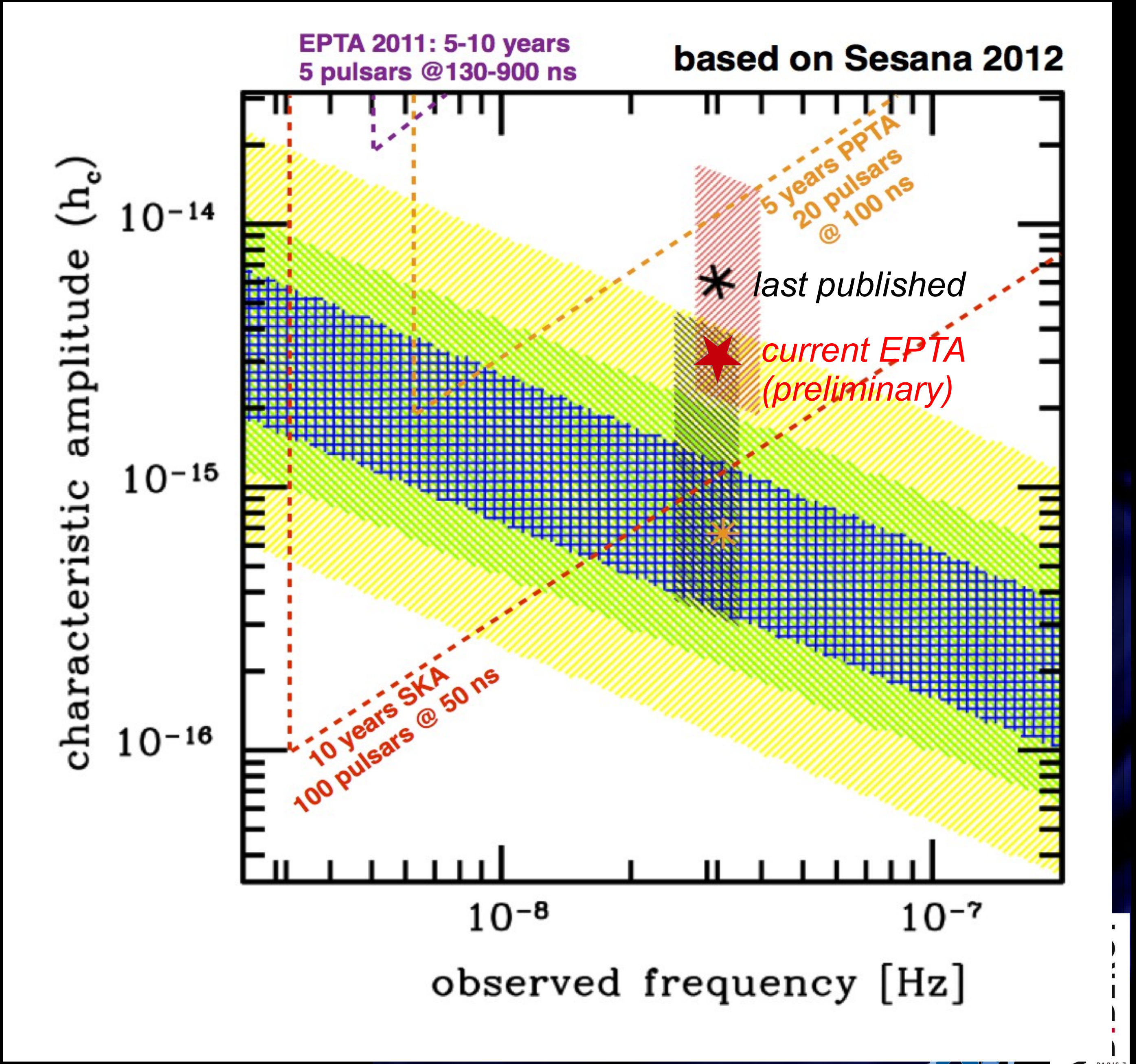


Status of EPTA DA of individual sources of MBHB

- Done:
  - General pipeline.
  - Test on simulated data using Earth term
- In progress:
  - Making and characterising a “correct” data sets (41 pulsars): check data from each observatory (interaction with timing group and observers) and better estimation of noises parameters for each pulsars ($4+2xN_{obs}$ param. / psr)
  - Construct proper detection criterion,
  - Problem of pulsar term : interference with Earth term ; pulsars term add 2 x N_{psr} x N_{GW} parameters if we want to include it in the search
  - In general problem managing search with big matrices (30 000 x 30 000) and large number of parameters : new estimators, new or improved search methods
  - Eccentricity in MBHB modelling,
  - …

Sensitivity of PTA and future

- Detection expected with current PTA : probably the background & few individual sources with low precision parameter estimation.
- SKA (around 2026 = 2021+5) : Real observations of sources with GWs expected (precise parameter estimation).



Outline

- Introduction to Massive Black Hole Binaries (MBHB)
- Observing MBHB with Pulsar Timing Array
  - Introduction to PTA : EPTA and IPTA,
  - GW signal of MBHB in PTA measurements,
  - Data analysis (MultiSearch Genetic Algorithm, ...),
  - Preliminary results
- Observing MBHB with eLISA
  - Status of the mission (selected as L3 at ESA !) and LISAPathfinder
  - MBHB observation with eLISA
  - Improvement using hybrid waveform
  - Spin direction degeneracies
- Conclusion

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

eLISA selected as L3 mission

- One of the main reason is the launch of LISAPathfinder in 2015,
- ESA asks to start NOW the study of technological needs,
- LISAPathfinder in 2015 : problem : how to keep expertise during 20 years ...

→ If LISAPathfinder is a success, good 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

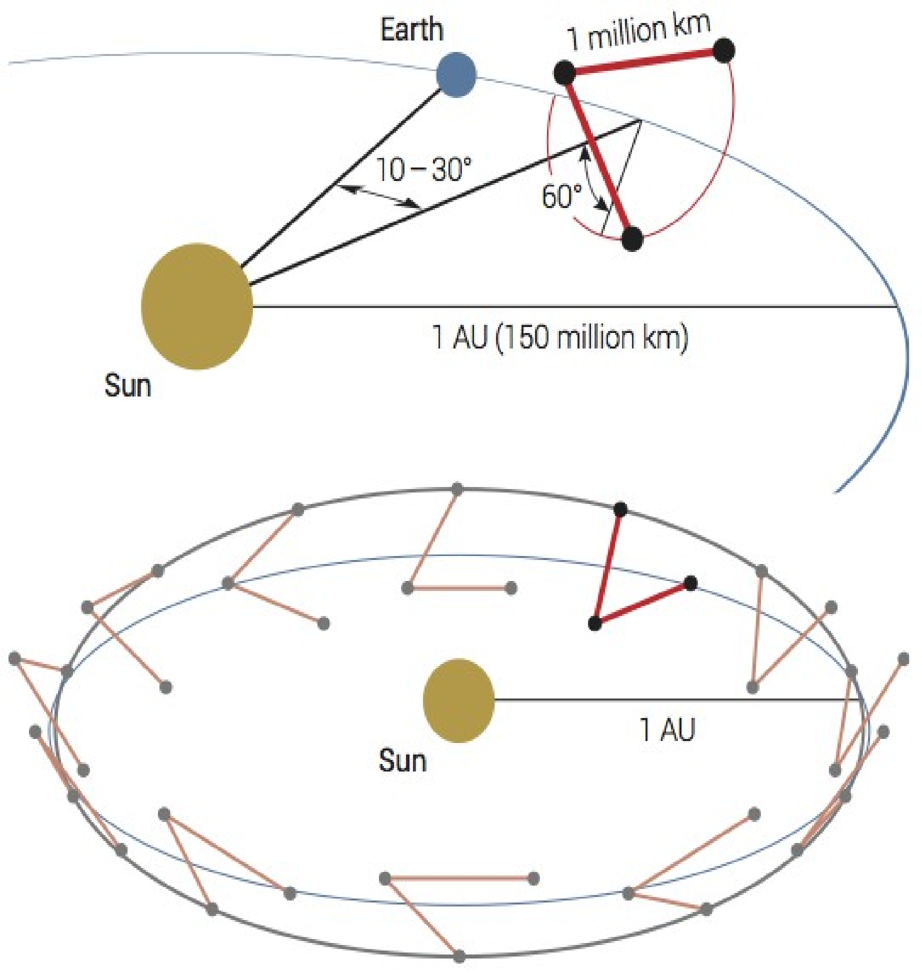
eLISA selected as L3 mission

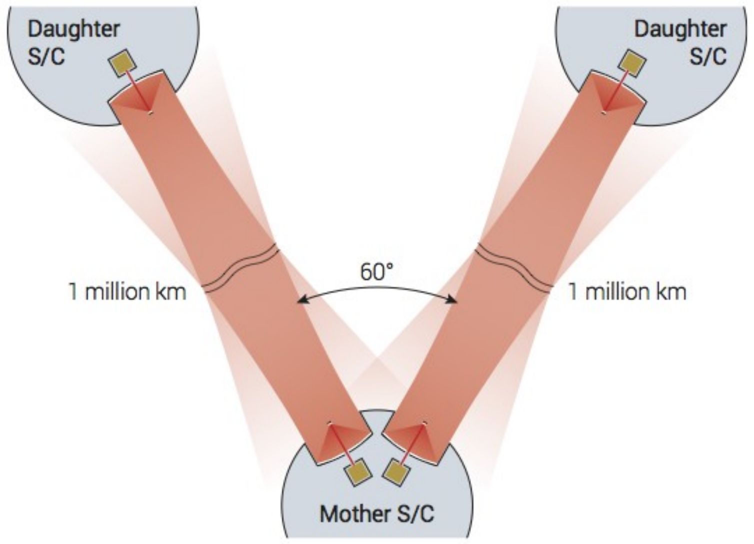
Among the, roughly, 1000 scientific supporters of the Gravitational Universe science theme, are

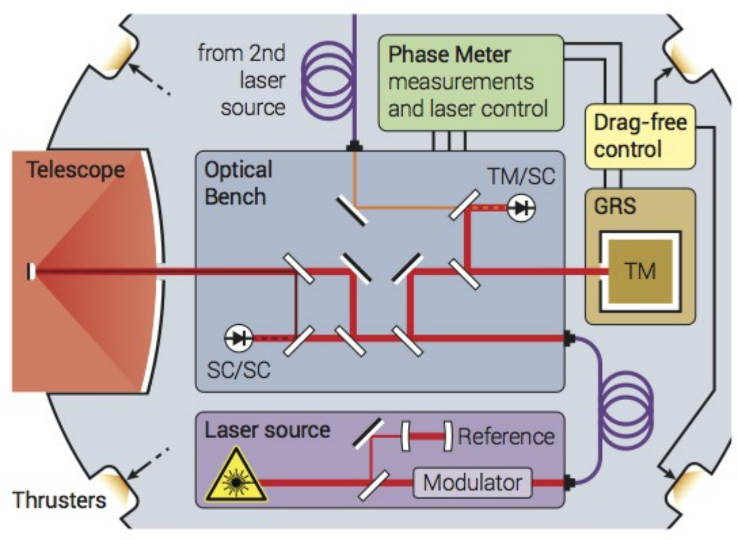
Gerardus 't Hooft *Utrecht University (Netherlands)*, **Barry Barish** *Caltech (United States)*, **Claude Cohen-Tannoudji** *College de France (France)*, **Neil Gehrels** *NASA Goddard Space Flight Center (United States)*, **Gabriela Gonzalez** *LIGO Scientific Collaboration Spokesperson, LSU (United States)*, **Douglas Gough** *Institute of Astronomy, University of Cambridge (United Kingdom)*, **Stephen Hawking** *University of Cambridge, DAMTP (United Kingdom)*, **Steven Kahn** *Stanford University/SLAC National Accelerator Laboratory (United States)*, **Mark Kasevich** *Stanford University, Physics Dept. (United States)*, **Michael Kramer** *Max-Planck-Institut fuer Radioastronomie (Germany)*, **Abraham Loeb** *Harvard University (United States)*, **Piero Madau** *University of California, Santa Cruz (United States)*, **Luciano Maiani** *Università di Roma La Sapienza (Italy)*, **John Mather** *NASA Goddard Space Flight Center (United States)*, **David Merritt** *Rochester Institute of Technology (United States)*, **Viatcheslav Mukhanov** *LMU München (Germany)*, **Giorgio Parisi** *Universita di Roma la Sapienza (Italy)*, **Stuart Shapiro** *University of Illinois at Urbana-Champaign (United States)*, **George Smoot** *Universite Paris Diderot (France)*, **Saul Teukolsky** *Cornell University (United States)*, **Kip Thorne** *California Institute of Technology (United States)*, **Gabriele Veneziano** *Collège de (France)* (France), **Jean-Yves Vinet** *Virgo Collaboration Spokesperson, OCA Nice (France)*, **Rainer Weiss** *MIT (United States)*, **Clifford Will** *University of Florida (United States)*, **Edward Witten** *Institute for Advanced Study, Princeton (United States)*, **Arnold Wolfendale** *Durham University (United Kingdom)*, and **Shing-Tung Yau** *Harvard University (United States)*.

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

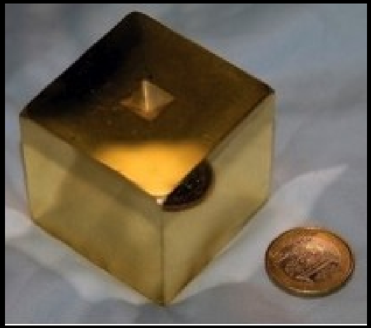


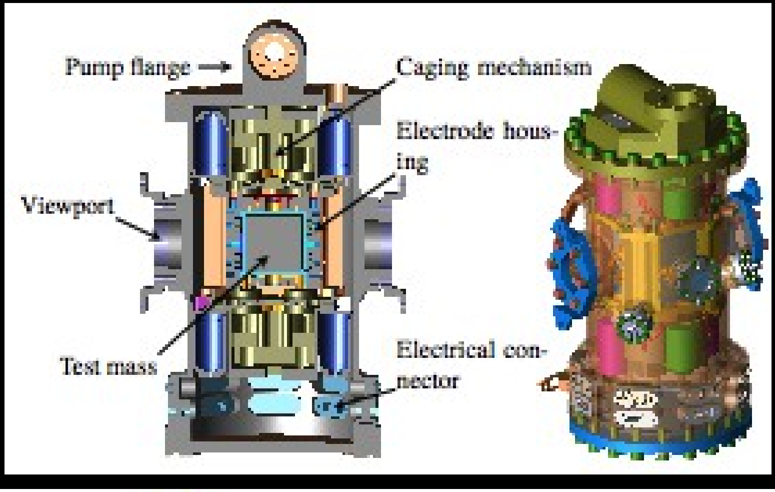


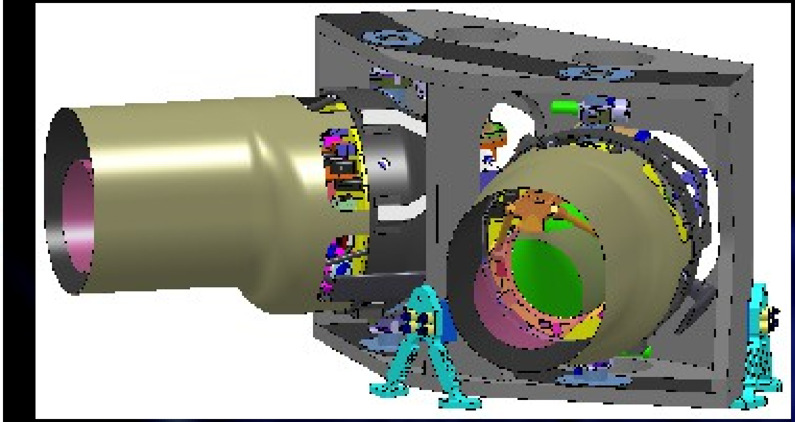


eLISA in next years

- 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 …

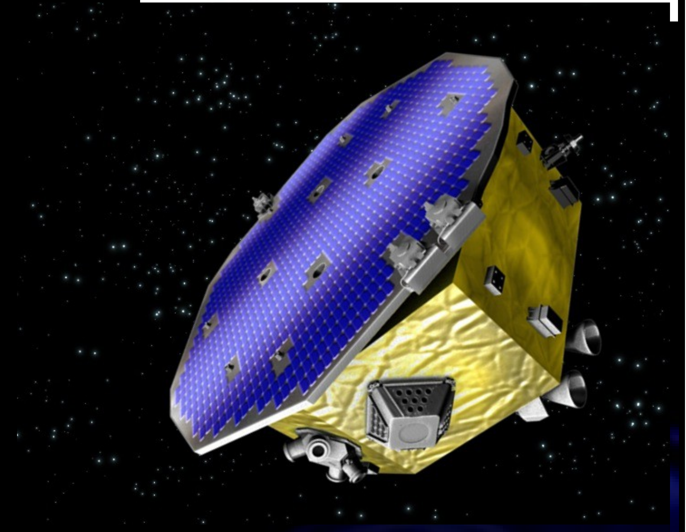


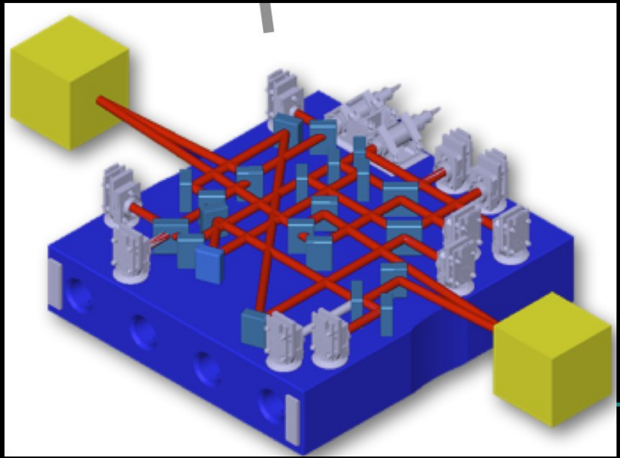


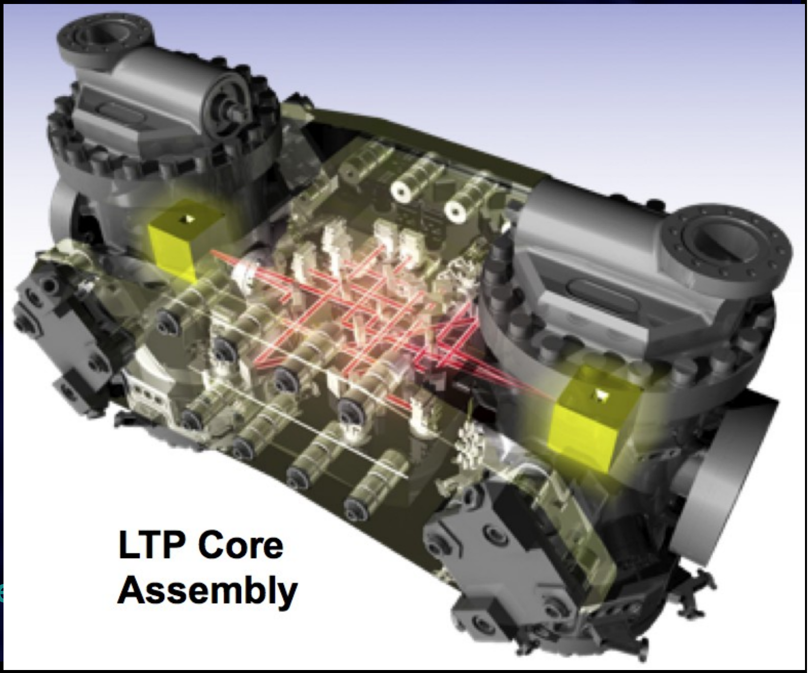


LISAPathfinder

- 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







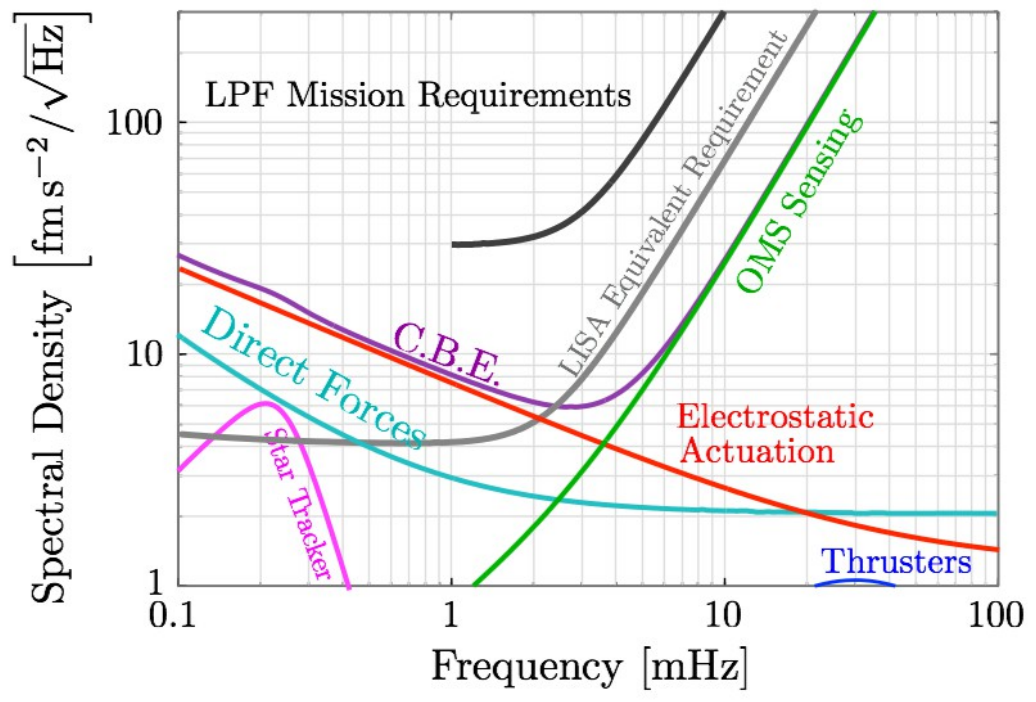
LISAPathfinder : in-fligth activities

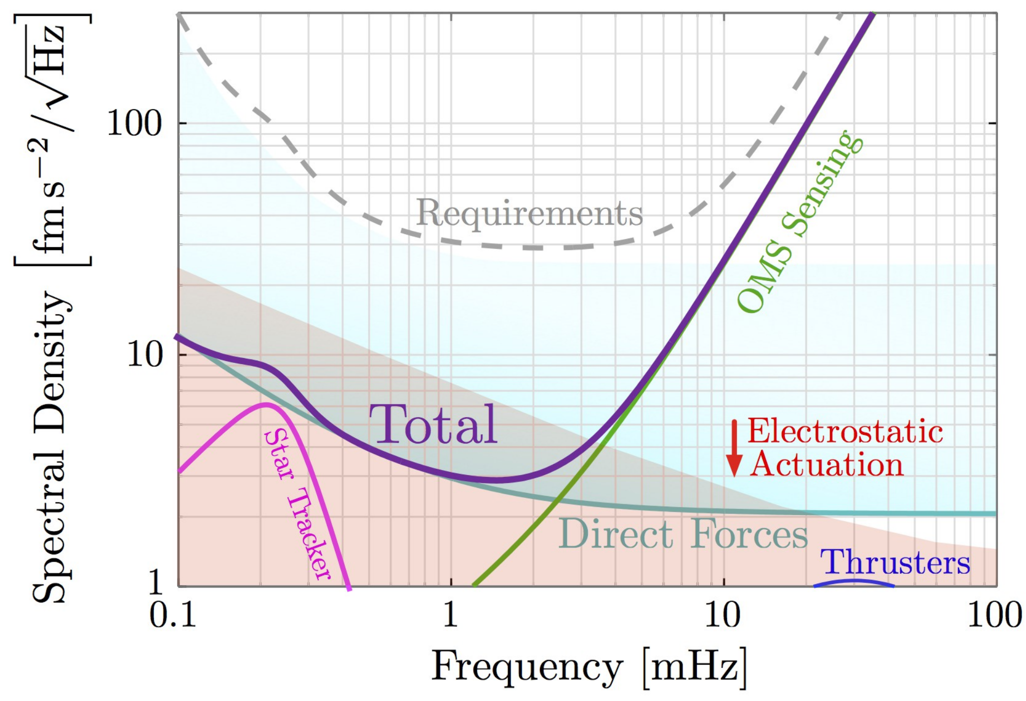
- Goal understand the noise performance we observe
- Optimise the system to reach the best noise performance
- Pick from a menu of available pre-designed experiments to characterise and optimise the system
- Rough scheme:
  1. long noise measurement
  2. identify limiting noise source
  3. measure/assess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

Start	End	Sim Time (s)	Sim Time (H)	Duration (H)	Description
13-Nov-13 8:00	13-Nov-13 14:00	0	0	6.0	Decage and transition to Acc3
13-Nov-13 14:00	13-Nov-13 20:00	21600	6	6.0	Acc3
13-Nov-13 20:00	14-Nov-13 8:00	43200	12	12.0	Nom2
14-Nov-13 8:00	15-Nov-13 8:00	86400	24	24.0	Science 1.2
15-Nov-13 8:00	15-Nov-13 14:00	172800	48	6.0	DC bias estimate TM1 (Q step, lamps)
15-Nov-13 14:00	15-Nov-13 20:00	194400	54	6.0	DC bias estimate TM1 (Q step, lamps) with changed dc biases
15-Nov-13 20:00	16-Nov-13 2:00	216000	60	6.0	DC bias estimate TM1 (Q step, lamps) with changed dc biases
16-Nov-13 2:00	16-Nov-13 8:00	237600	66	6.0	Acceleration noise run
16-Nov-13 8:00	16-Nov-13 12:00	259200	72	4.0	Guidance phi1
16-Nov-13 12:00	16-Nov-13 16:00	273600	76	4.0	Guidance phi2
16-Nov-13 16:00	16-Nov-13 20:00	288000	80	4.0	Guidance y1
16-Nov-13 20:00	17-Nov-13 0:00	302400	84	4.0	Guidance y2
17-Nov-13 0:00	17-Nov-13 4:00	316800	88	4.0	Guidance Phi
17-Nov-13 4:00	17-Nov-13 6:00	331200	92	2.0	Acceleration noise run
17-Nov-13 6:00	17-Nov-13 7:00	338400	94	1.0	Fast Discharge TM1
17-Nov-13 7:00	17-Nov-13 8:00	342000	95	1.0	Fast Discharge TM2
17-Nov-13 8:00	18-Nov-13 8:00	345600	96	24.0	OSTT / Station Keeping
18-Nov-13 8:00	18-Nov-13 9:00	432000	120	1.0	Fast Discharge TM1
18-Nov-13 9:00	18-Nov-13 10:00	435600	121	1.0	Fast Discharge TM2
18-Nov-13 10:00	18-Nov-13 17:00	439200	122	7.0	Magnetics Coil 1
18-Nov-13 17:00	19-Nov-13 0:00	464400	129	7.0	Magnetics Coil 2
19-Nov-13 0:00	20-Nov-13 8:00	489600	136	32.0	Thermal
20-Nov-13 8:00	20-Nov-13 9:00	604800	168	1.0	Fast Discharge TM1
20-Nov-13 9:00	20-Nov-13 10:00	608400	169	1.0	Fast Discharge TM2
20-Nov-13 10:00	21-Nov-13 5:00	612000	170	19.0	Long Q estimate TM2
21-Nov-13 5:00	21-Nov-13 8:00	680400	189	3.0	DC bias estimate TM1 (Q step, lamps) - shorter
21-Nov-13 8:00	21-Nov-13 12:00	691200	192	4.0	SC X guidance
21-Nov-13 12:00	21-Nov-13 16:00	705600	196	4.0	TM sus x guidance
21-Nov-13 16:00	21-Nov-13 20:00	720000	200	4.0	SC X guidance
21-Nov-13 20:00	22-Nov-13 0:00	734400.0	204.0	4.0	TM sus x guidance
22-Nov-13 0:00	22-Nov-13 4:00	748800.0	208.0	4.0	Fool SC X, TM1 X
22-Nov-13 4:00	22-Nov-13 8:00	763200.0	212.0	4.0	Fool SC X, TM1 X, TM2 X

LISAPathfinder

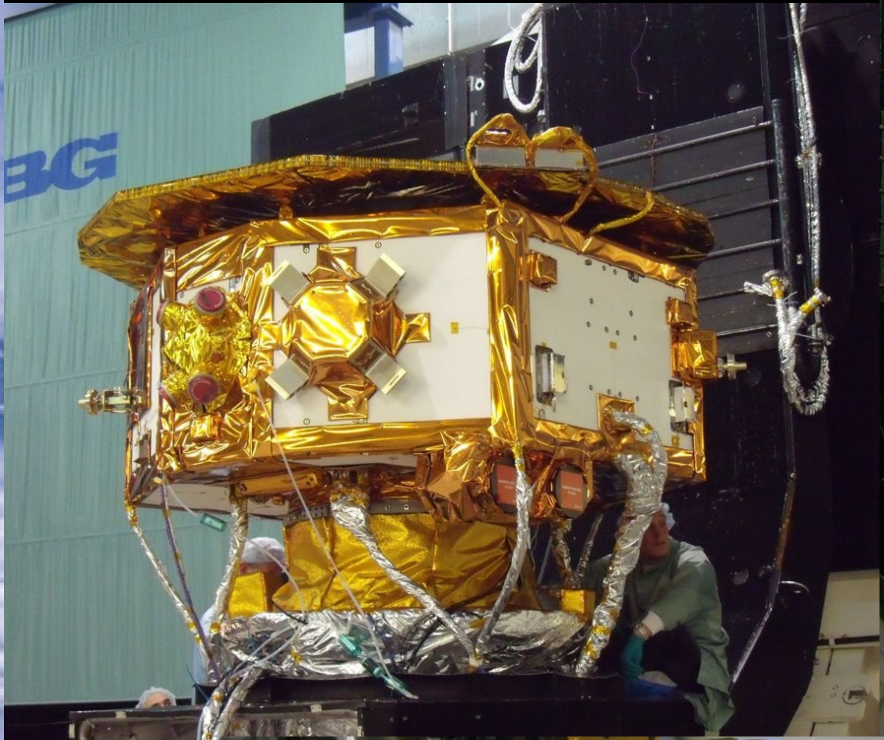
- Data analysis :
  - Fitting model to estimate parameters of the system: few hundred parameters but usually only few parameters are relevant,
  - Methods : Linear Fit, MCMC, EMCEE (MCMC on running on FACe/APC cluster : for quick analysis and large number of parameters)
- **Sensitivity:** expected performance from ground measurements largely beats requirements

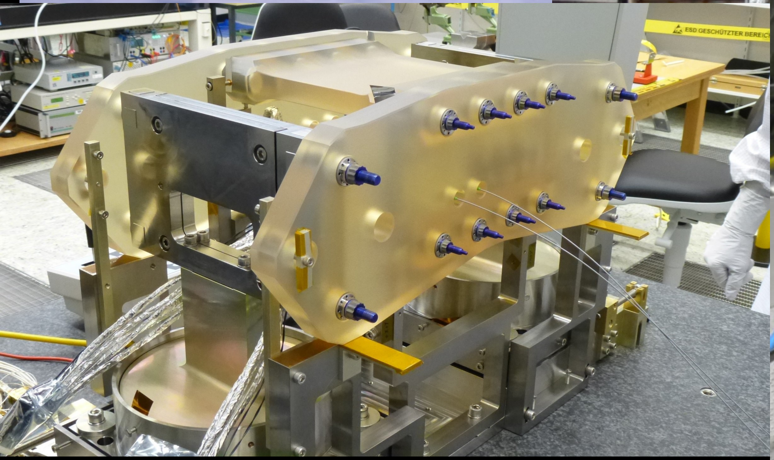


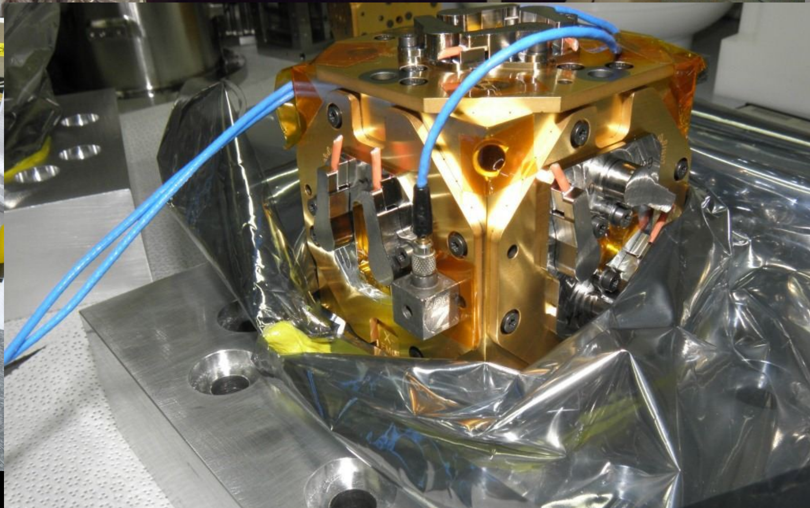


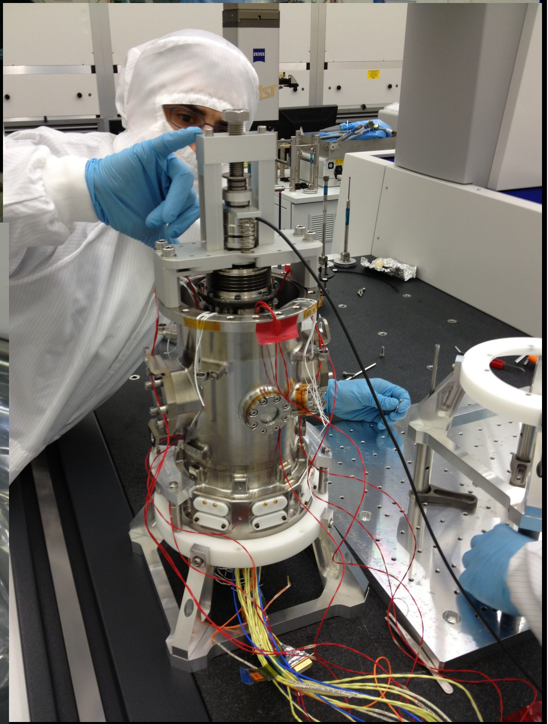
LISAPathfinder

- Ready to be launch on July 2015.



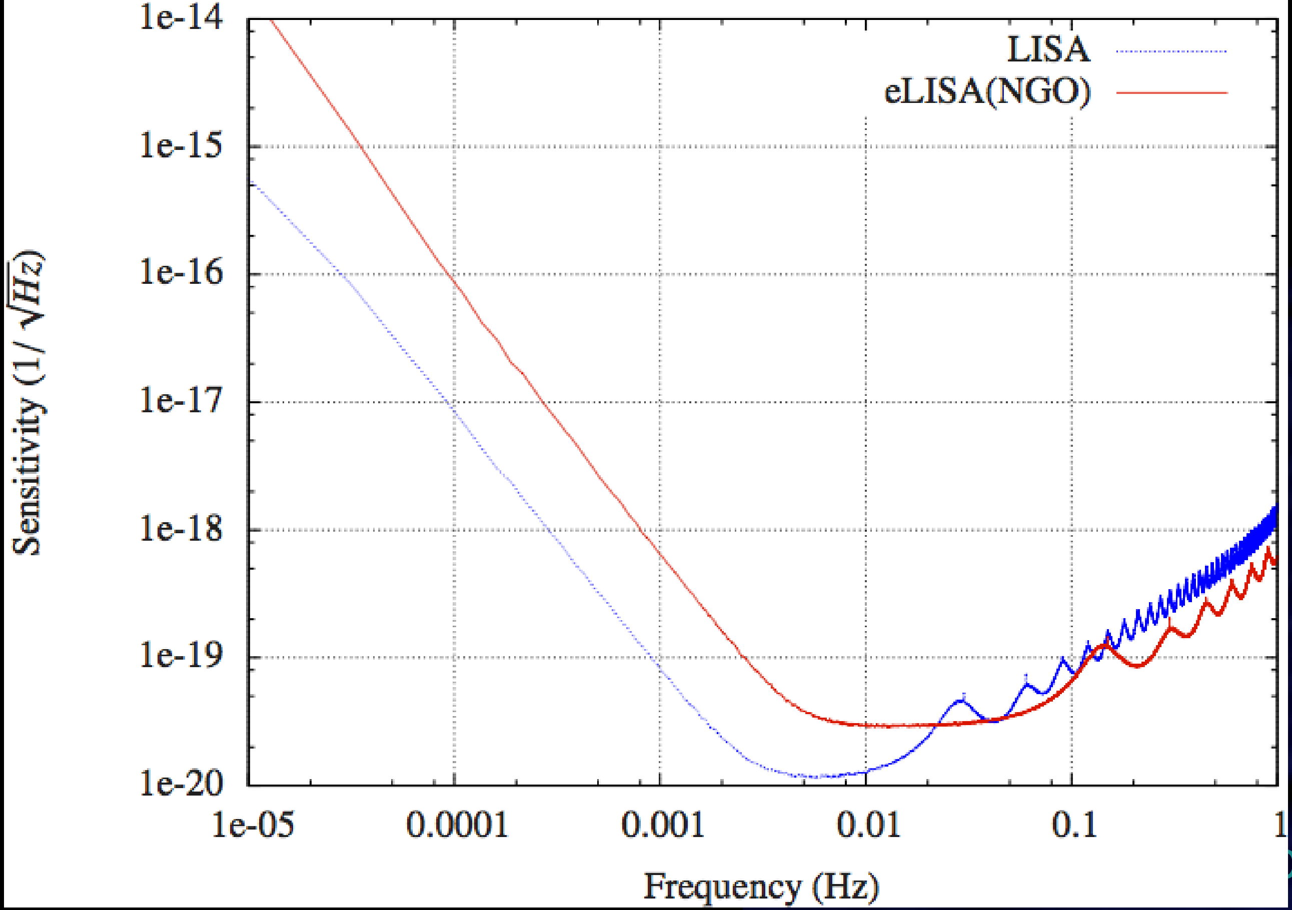






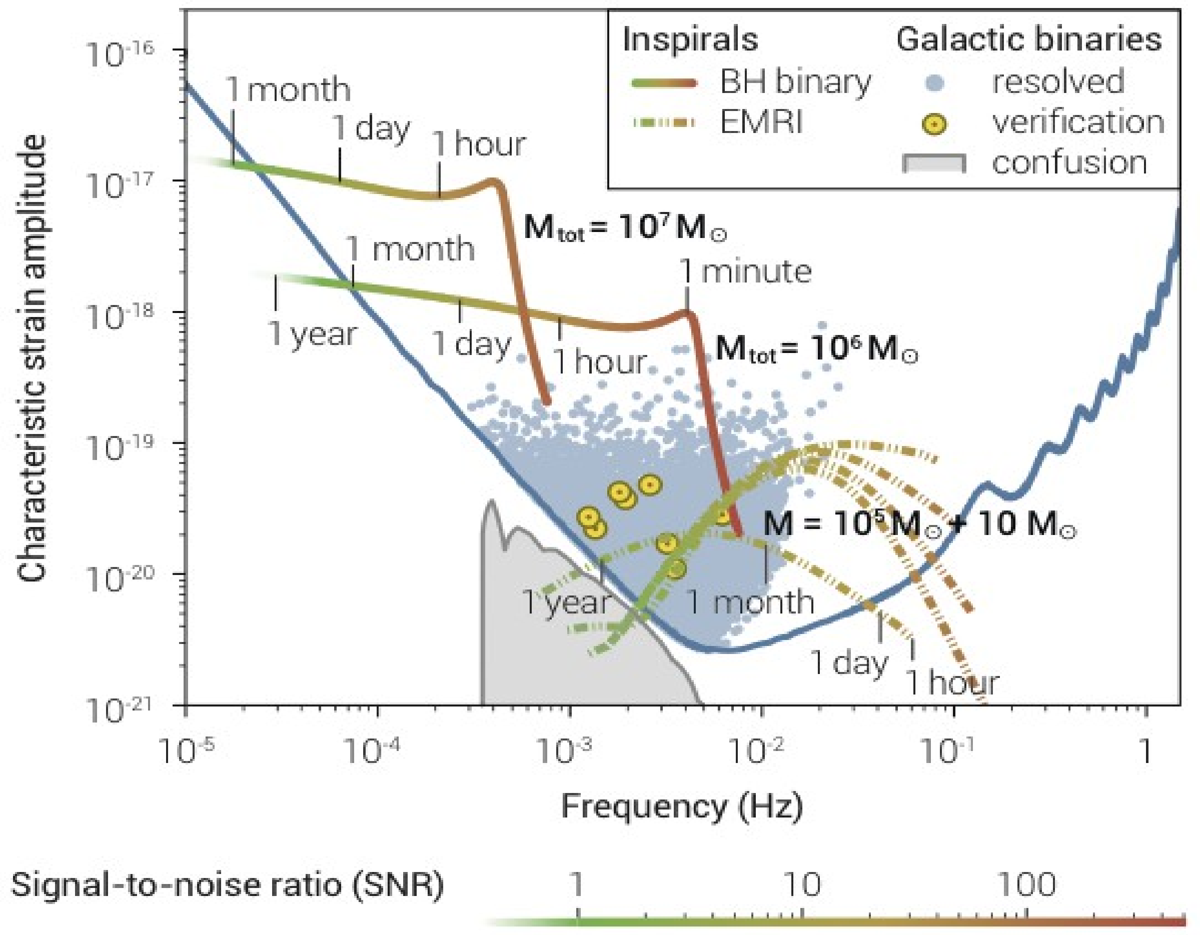
eLISA sensitivity

- Call for design in 2020 but probably earlier (after LISAPathfinder results)
- Current concept : 2 arms of one million kilometres
- Sensitivity computed by LISACode



eLISA sources

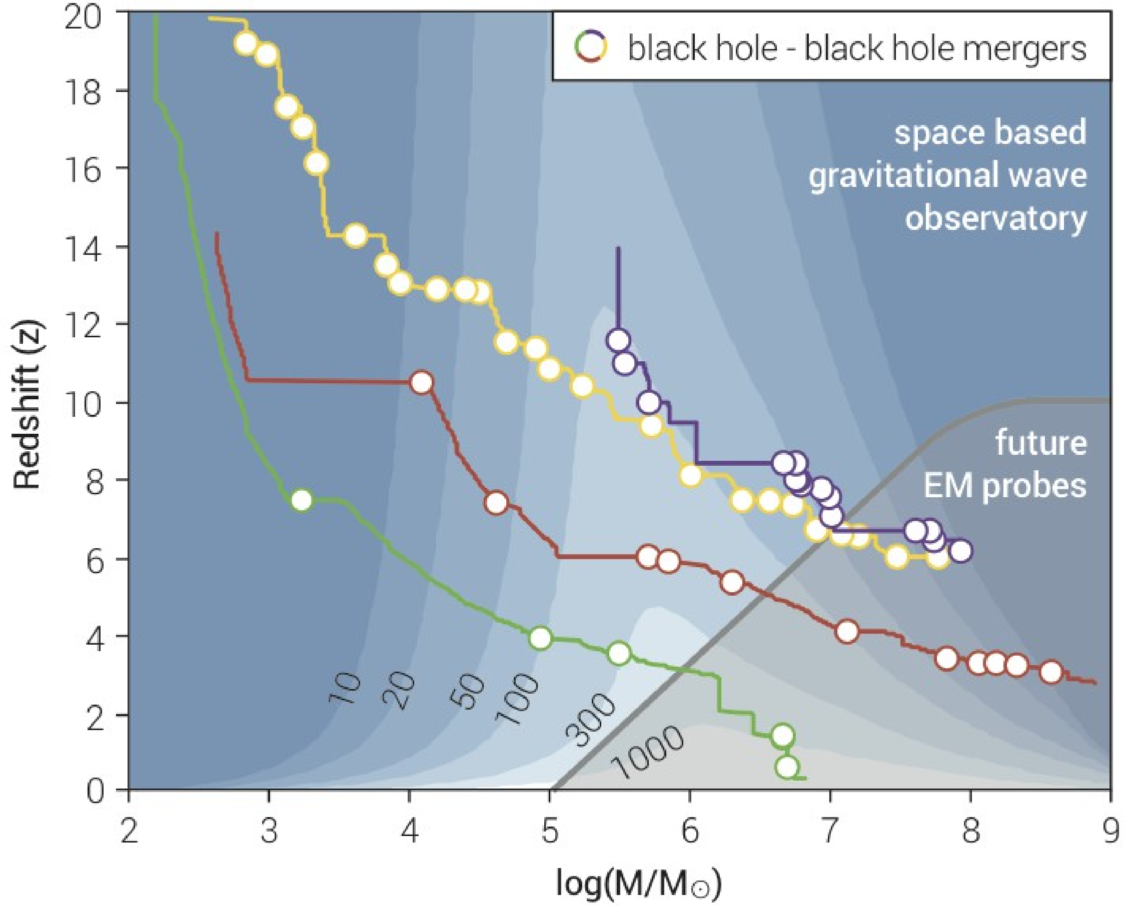
- Galactic binaries : few tens millions in Galaxy and about 3000 resolvable including verification binaries, i.e. sources already observed (about ten more are coming with Gaia) → guaranteed sources



- MBHB
- Extreme Mass Ratio Inspirals
- Bursts : cosmic string cusps, …
- Cosmological background,
- All the unknown sources !

MBH binaries observed by eLISA

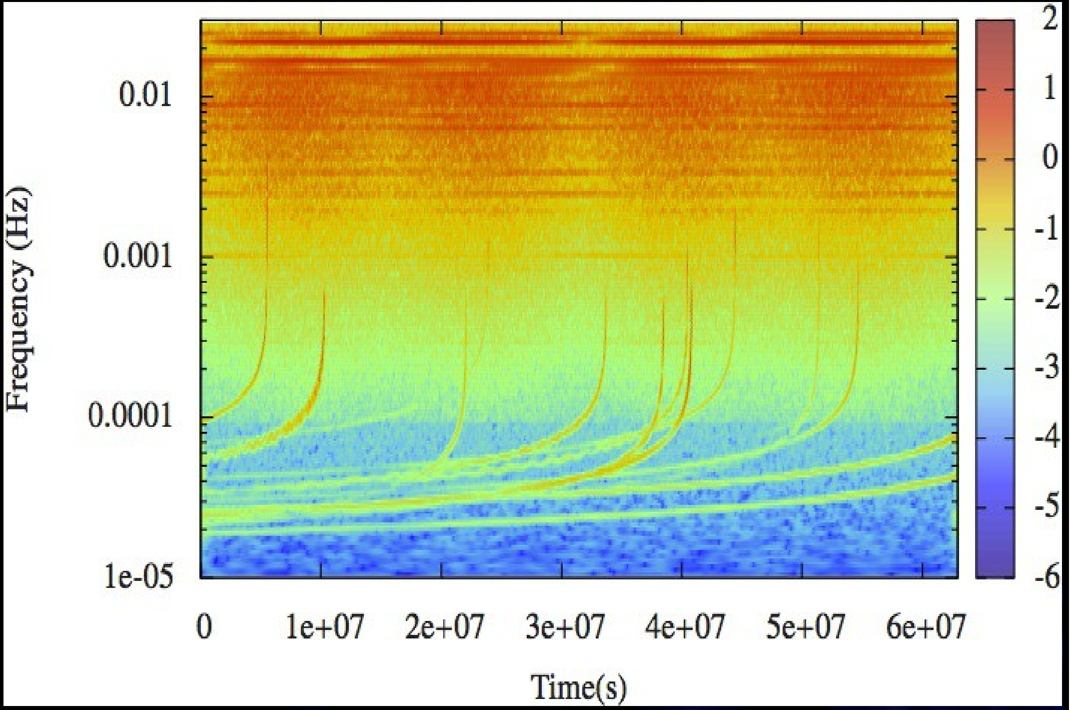
- From study of A. Sesana et al.
- $10^4 < M < 10^7\ M_{Sun}$
- Until $z = 10 - 20$ depending on the masse.
- Typically from 10 to 100 events per years depending on the model : light / heavy seed and coherent / chaotic accretion

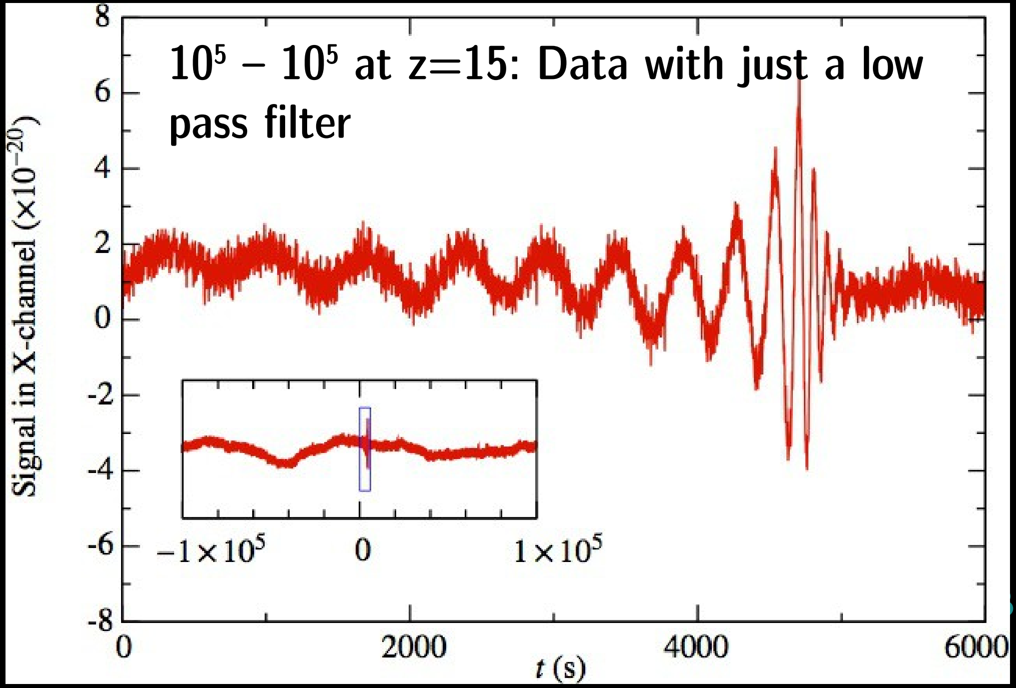


- SNR from 10 to few thousands in the band during days to month
- Observation of inspiral, merger and ringdown

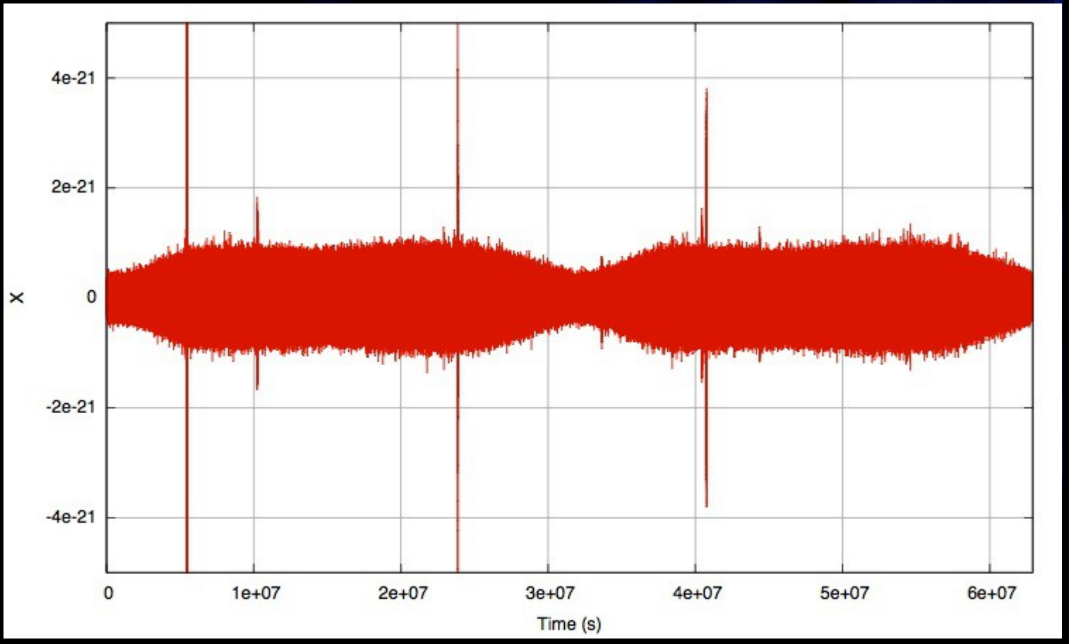
MBH binaries observed by eLISA

- 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



Measure masses and spins

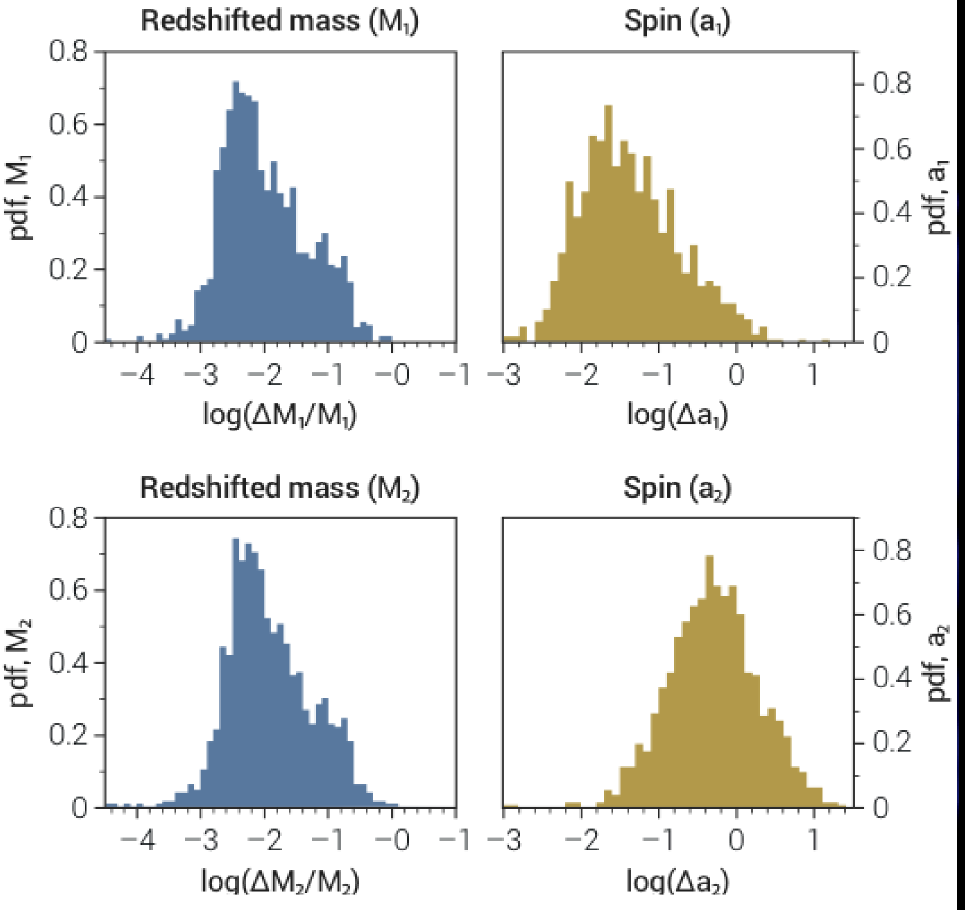
- Parameters estimation study for eLISA:
  - Sources: 10 realisations of 4 types of catalogs (about 6000 sources)
  - Several waveforms used trying to mix Post-Newtonian inspiral, higher harmonics and phenomenological waveforms.
  - Estimate errors using Fisher matrix

- Relative error on the 2 masses :

  0.1 to few percents

- Absolute error on spins :

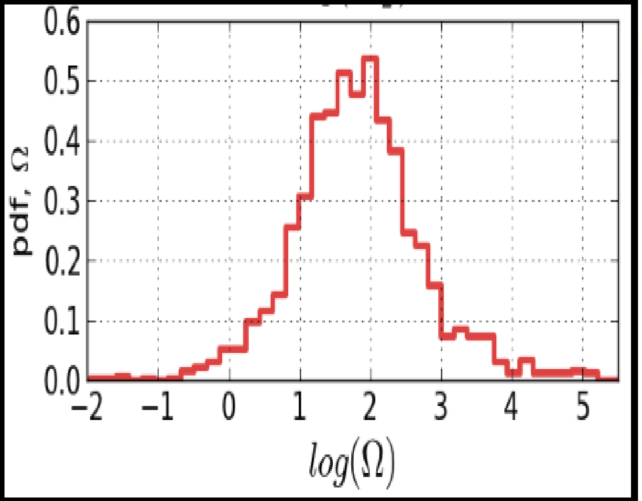
  0.02 to 1 : depend on :
  - SNR
  - If the merger clearly visible or not

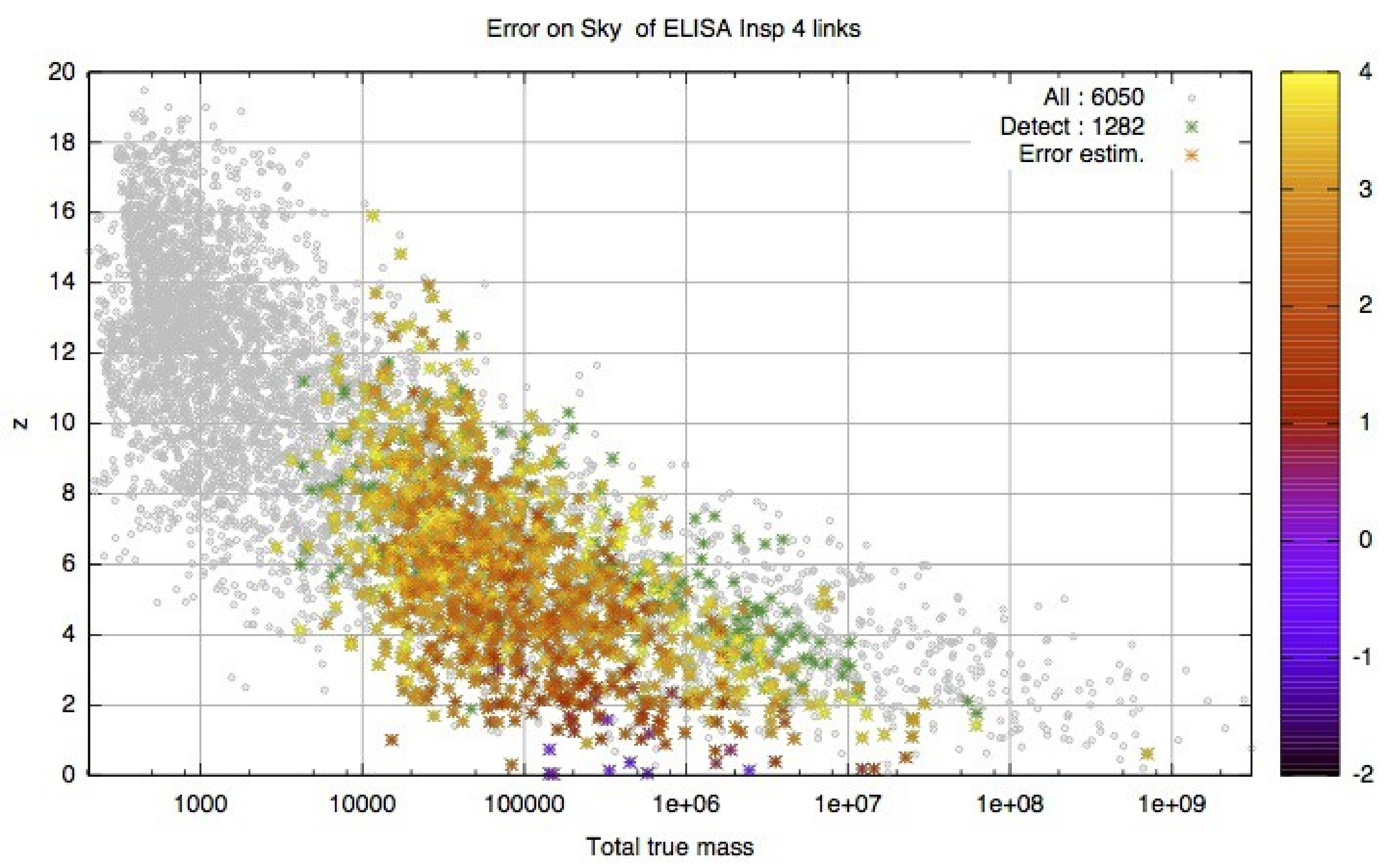


Mix FIM from inspiral + phenomenological

Measure sky position

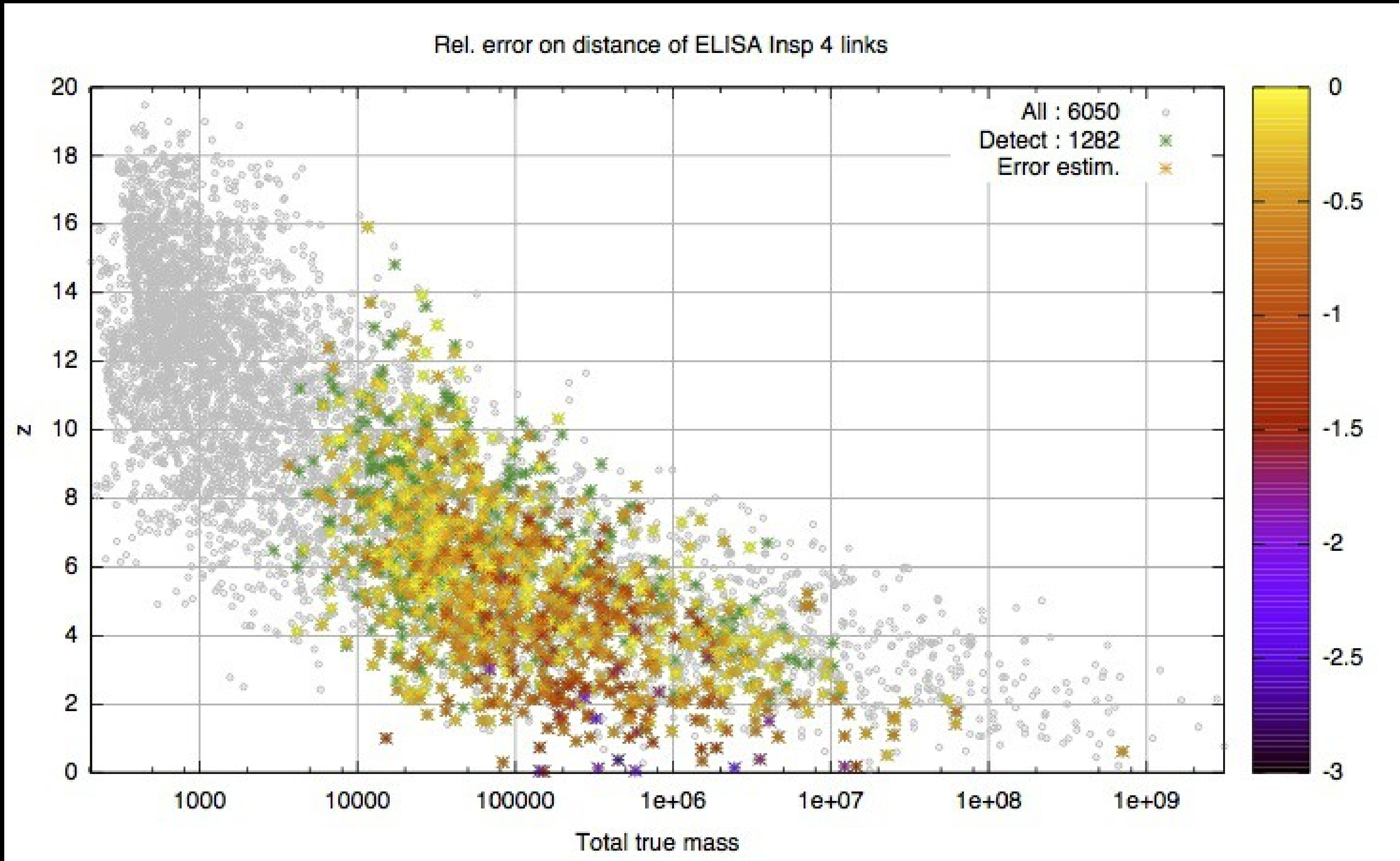
- Typical error : < 100 deg^2 at $z < 6$ and < 10 deg^2 at $z<2$
- Conservative results :
  - using inspiral only with higher harmonics → very conservative because adding merger will improve distance measurement,
  - For some sources, no estimation because of Fisher Matrix limitation

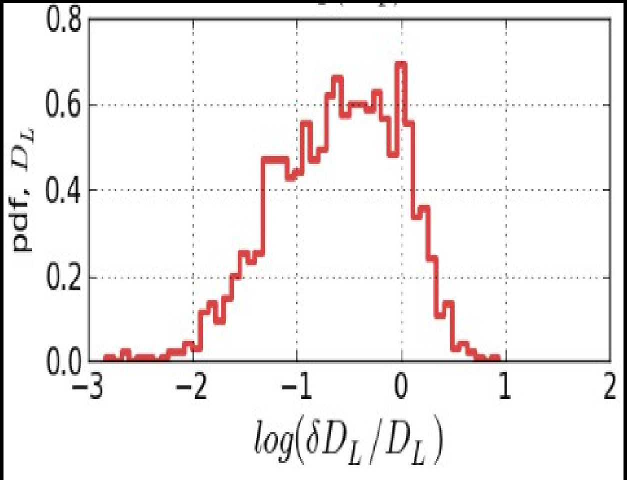




Measure distance

- Typical error : 1 to few 10 % for source at $z < 6$
- Conservative results :
  - using inspiral only with higher harmonics → very conservative because adding merger will improve distance measurement,
  - For some sources, no estimation because of Fisher Matrix limitation

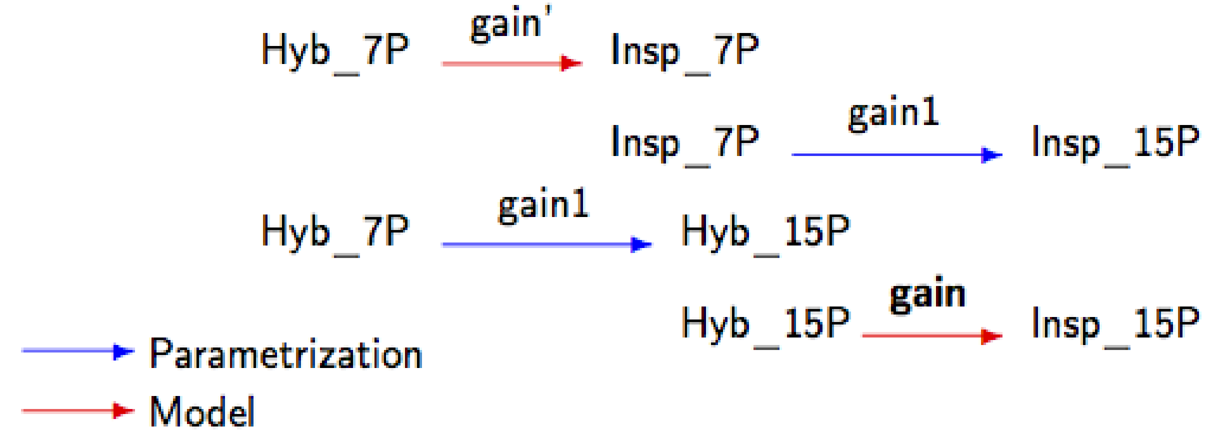




Improvement using full waveform

Aoudia, Babak, Hinder, Petiteau, Ohme, Sesana, Wardell, in preparation

- How to estimate improvement due to merger & ringdown ? Use hybrid waveforms (F. Ohme et al.) based on numerical relativity simulations.
- Two families of waveform: pure inspiral (PN+taper) & hybrid (PN+NR)
- BUT hybrid only 7 free parameters.
- Procedure: estimate error using Fisher for same source with both waveform and measure gain on distribution



Hyb_7P → gain' → Insp_7P

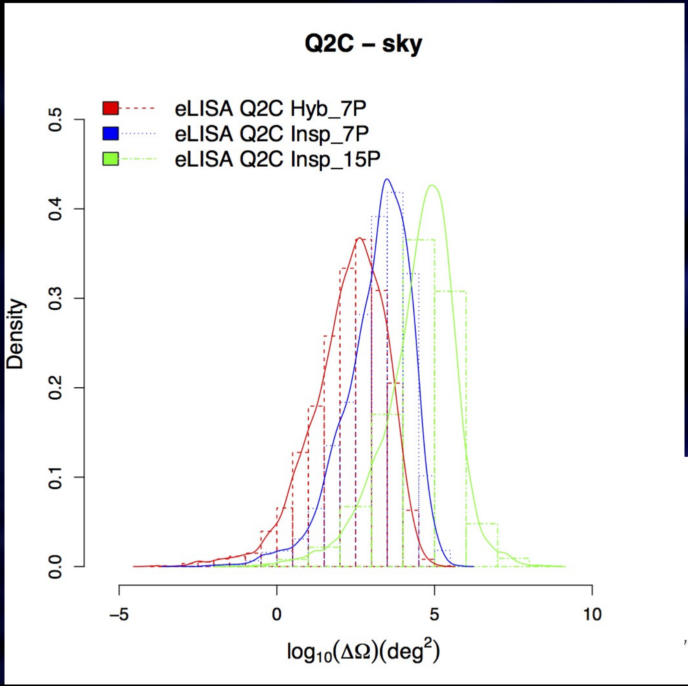
Insp_7P → gain1 → Insp_15P

Hyb_7P → gain1 → Hyb_15P

Hyb_15P → gain → Insp_15P

→ Parametrization

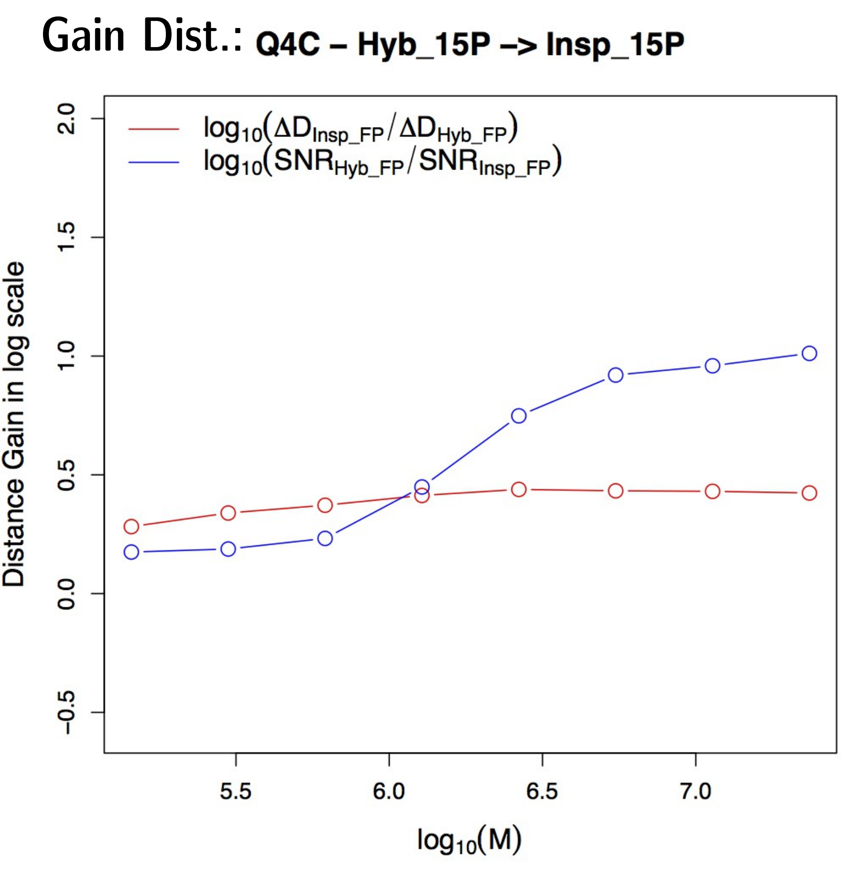
→ Model



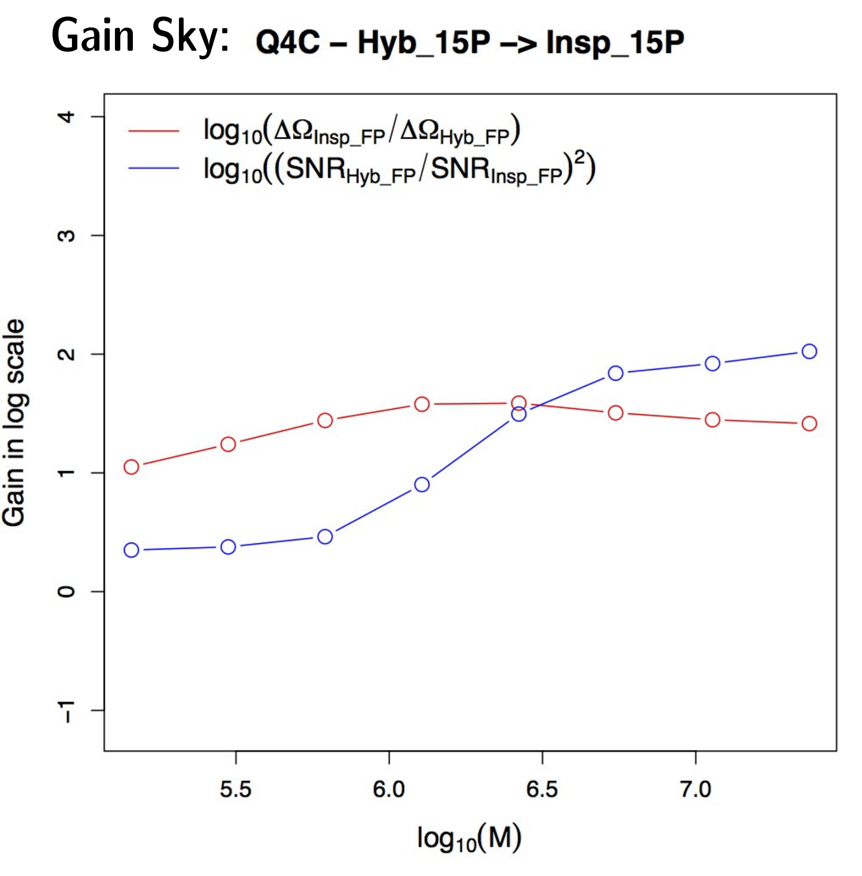
Improvement using full waveform

Aoudia, Babak, Hinder, Petiteau, Ohme, Sesana, Wardell, in preparation

- Typical results : ex. for mass ratio = 4
  - Sky : gain of factor few tens
  - Distance : gain of few tens percent



Gain Dist.: **Q4C – Hyb_15P –> Insp_15P**



Gain Sky: **Q4C – Hyb_15P –> Insp_15P**

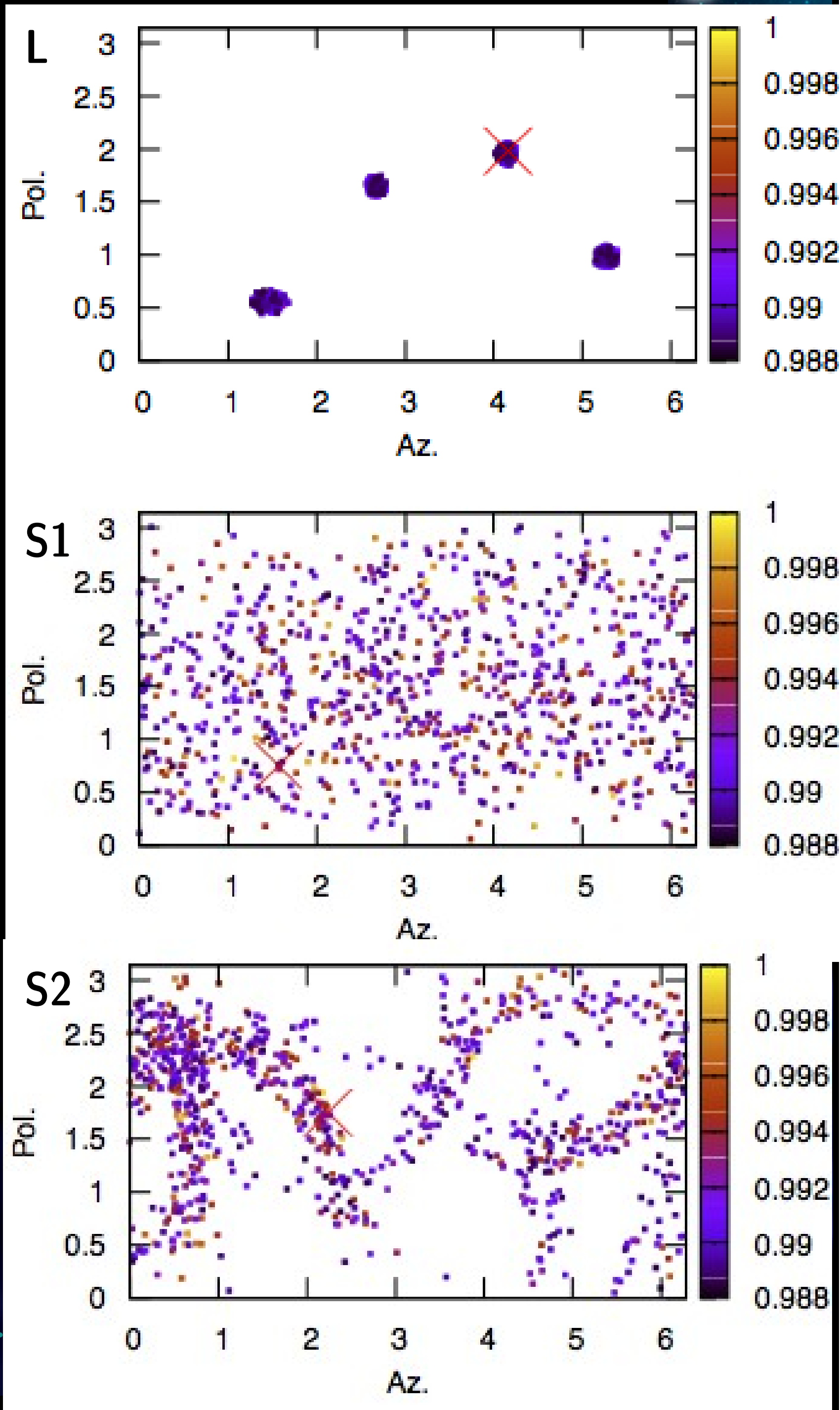
Heritage from LISA studies

- 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 !

Spin direction degeneracies

Petiteau & Babak in preparation

- During MLDC3, it appears that there were a problem for obtaining spin direction : number of solutions have likelihood F close to the best.
- Example: All points in the following figures correspond to $F \,/\, F_{\text{Best}} > 0.99$ (less than 10 of SNR difference over total SNR at 1778)



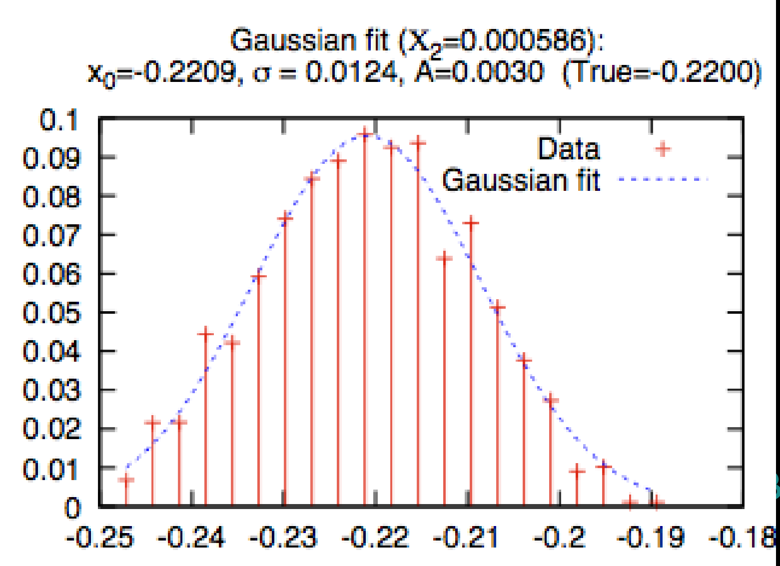
Spin direction degeneracies

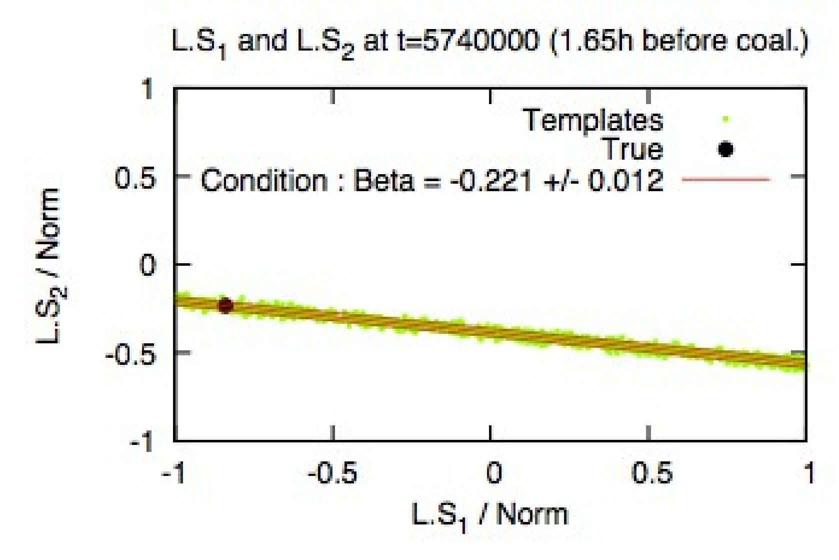
- Attempt to solve the problem :

Petiteau & Babak in preparation

  - Effect of spin more important close to the merger → Reference time for initial condition on precession (L, S1 & S2 directions) choose close to the merger.
  - What is common between all this waveform ? → study of phase term → try to identify new parameters :
    - parameter based on spin-orbit coupling :

$$\beta(t) = \frac{1}{12} \sum_{i=1,2} \left[\chi_i \left(\hat{L}(t) \cdot \hat{S}_i(t) \right) \left(113 \frac{m_i^2}{M^2} + 75\eta \right) \right]$$





Spin direction degeneracies

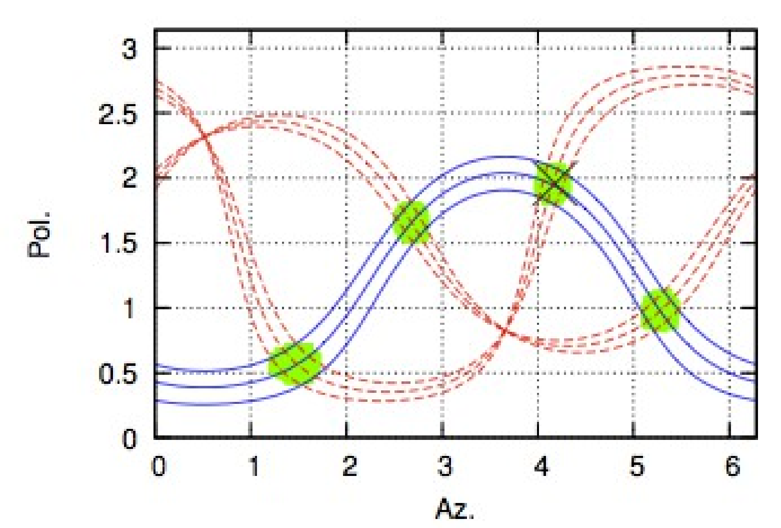
- Another constrain come from LISA phase and precession :
  - We have approximately :

$$\hat{L}.\hat{n} = constant$$
$$\tan(2\Psi) = constant$$

  - which gives :

$$\cos(\phi_L - \lambda) = \frac{\hat{L}.\hat{n} - \cos\theta_L \sin\beta}{\cos\beta \sin\theta_L},$$
$$\tan(\theta_L) = \frac{\cos\beta}{\sin\beta\cos(\lambda - \phi_L) + \sin(\lambda - \phi_L)\frac{1\pm\sqrt{1+\tan^2(2\psi)}}{\tan(2\psi)}}.$$

→ constrain on angular momentum L :



- Preliminary results fixing sky position
- The study has to be extended

→ Working in progress (slowly) ...

Conclusion

- Observation of MBHB with GW will help us to understand important scientific questions about astrophysics (black holes and galaxies), cosmology and fundamental physic.
- Pulsar Timing Array :
  - probably detection in next few years
  - real “observations” will probably need the SKA
- eLISA : mission selected as L3 in Cosmic Vision Program at ESA (in ESA budget) :
  - Observation with a very good precision of MBHB,
  - Still a lot of work to do … everybody is welcome !

Thank you.