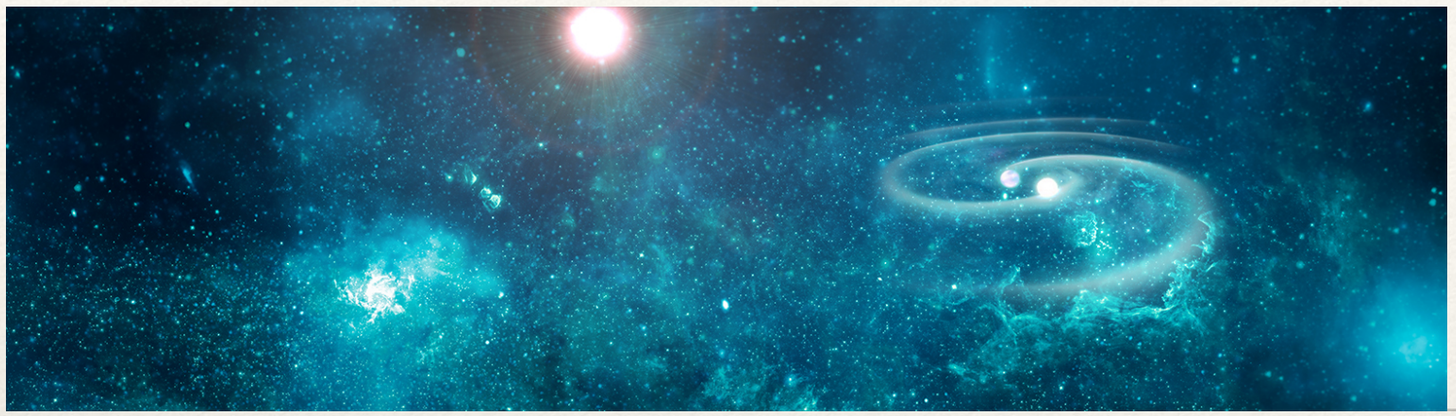
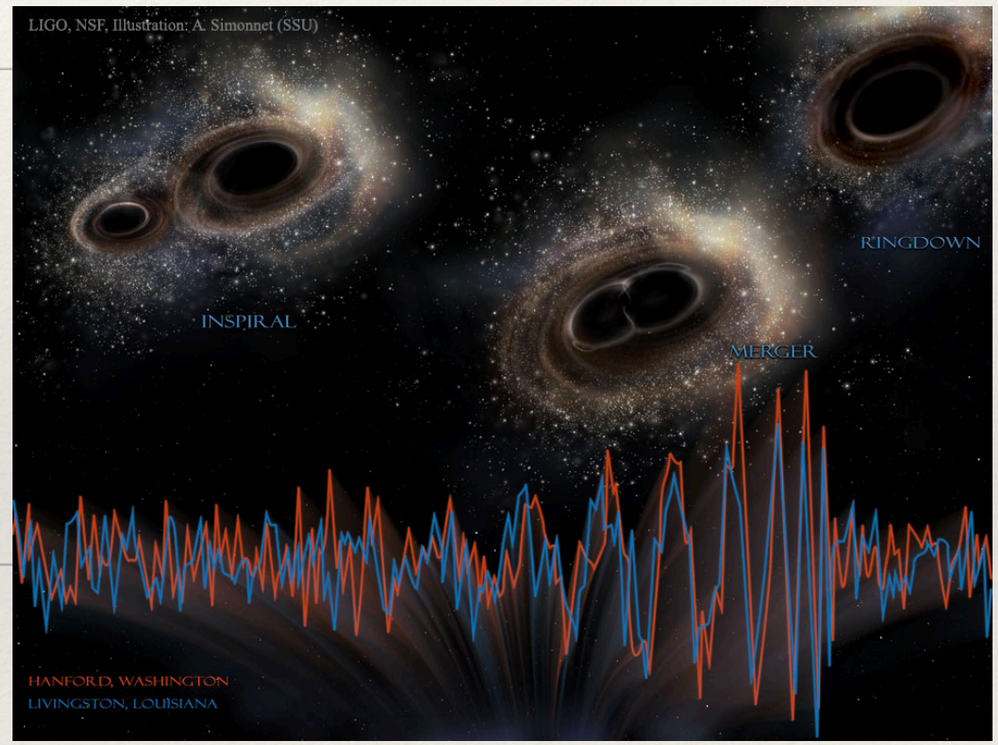




Gravitation group @APC

Biennale 2022

Stas Babak

1-3 June 2022

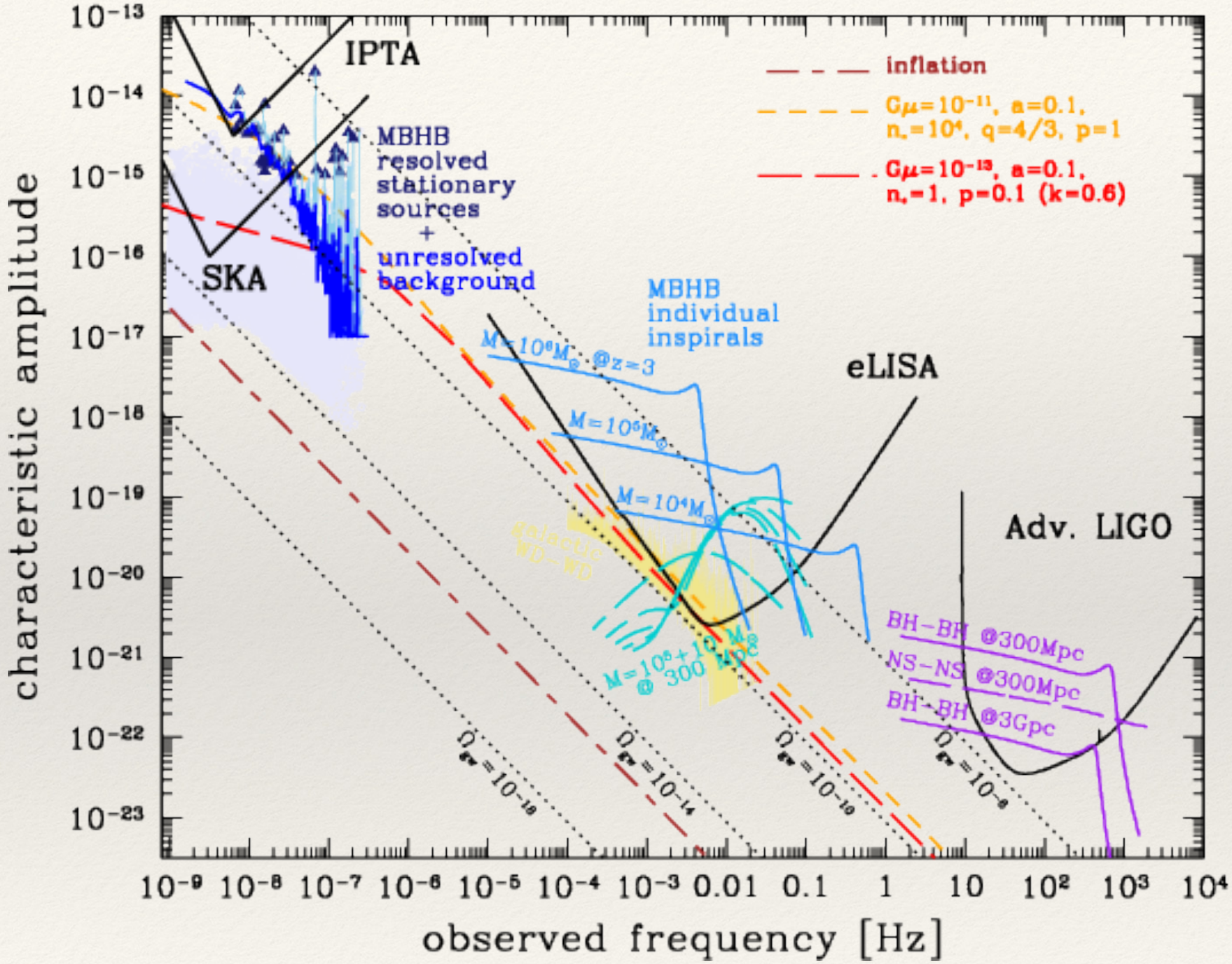
Gravitation group

Permanent (7+1)	Position	Project
BABAK Stanislav	DR2	LISA, VIRGO, PTA
BARSUGLIA Matteo	DR1	VIRGO, ET
CHASSANDE-MOTTIN Eric	DR1	VIRGO
PLAGNOL Eric	Emeritus	LISA
PORTER Edward	DR2	VIRGO, ET
HALLOIN Hubert	MCF	LISA
CAPOCASA Eleonora	MCF	VIRGO, ET
PETITEAU Antoine	20 %	CEA/IRFU

Post docs (2.5+1)	Duration	Project
HAEGEL Leila (PRfP)	2020/2023	VIRGO CNRS position
GARCIA-QUIROS Cecilio (ext)	2022/2024	LISA/VIRGO/ET
MANGIAGLI Alberto (PRfP)	2023/2025	LISA
BAYLE Jean-Baptiste (ext)	2022/2023	LISA
FRANCHINI Nicola (*) (Pierre Binetruy C.)	2022/2024	VIRGO/ET

PhD (3.5)	Start	Project
LEYDE Konstantin (Theory)	2020/2023	VIRGO
DAM Quang Nam	2019/2022	LISA
FALXA Mikel	2019/2022	PTA, LISA
VIDAL Leon	2019/2022	LISA

Gravitational Waves across frequency



[Credits A. Sesana}

VIRGO(+) and ground-based GW astronomy

Responsible (APC): Eric Chassande-Motin

5 Permanent members:

- Matteo Barsuglia (optical design, R&D squeezing)
- Edward Porter (astrophysical inference)
- Stanislav Babak (testing GR, waveform modelling)
- Eric Chassande-Mottin (chef de groupe, search for transient, cosmology)
- Eleonora Capocasa (design optique, R&D squeezing, commissioning, telescope)

Associate

- Danièle Steer (cosmologie, cordes cosmiques)
- Sylvain Chaty (AIM) (populations et outreach)
- Benoit Revenu (Subatech) (cosmologie)
- Nicola Tamanini (L2IT) (cosmologie, lensing, test RG)
- Irina Dvorkin (IAP) (fond stochastique)
- Nicolas Lebihan (Gipsa-lab) (methodes d'analyse)

VIRGO(+) and ground-based GW astronomy

Responsible (APC): Eric Chassande-Motin

2 post docs

- Leila Haegel (testing GR waveform modelling)
- Ceilio Garcia-Quiros (waveform modelling)

Associate

- Federico Garcia (populations)

New ANR grant
"Ricochet"

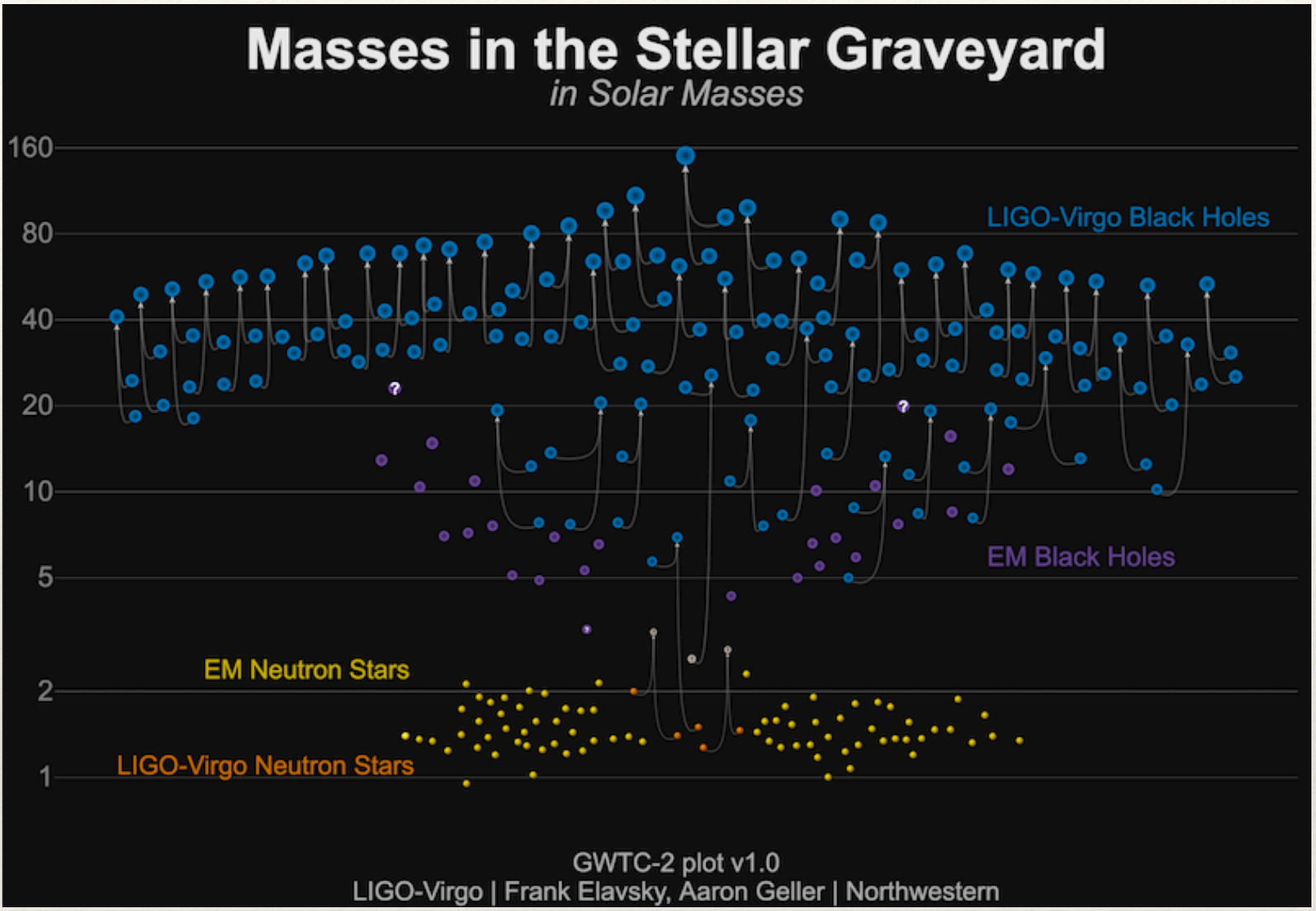
1 PhD

- Konstantin Leyde, (cosmologie)•

Associate

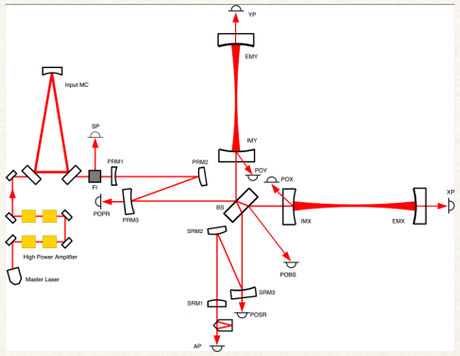
- Cyril Cano, (methodes d'analyse)
- Julien Marchioro, (BBH progenitors)

Results from O3 runs



- **The catalogue of 90 GW mergers:**
  - **Mostly GW signals from black hole binaries and**
  - **1 binary neutron star merger**
  - **5 NS-BH (?) mergers**

Ground based GW astronomy



AdVirgo+: Optical design, system design, operation optimization, frequency dependent squeezing

ET: squeezing , optical/system design, quantum nondemolition, Computing

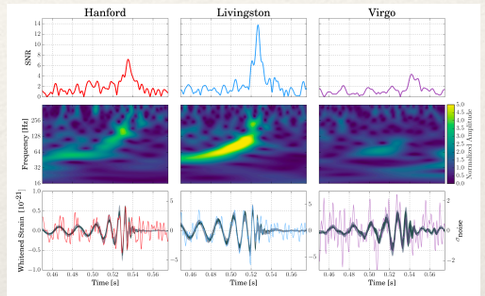
(E. Capocasa, M. Barsuglia, E. Porter)

Data analysis and signal reconstruction:

- Bayesian parameter inference, testing GR,

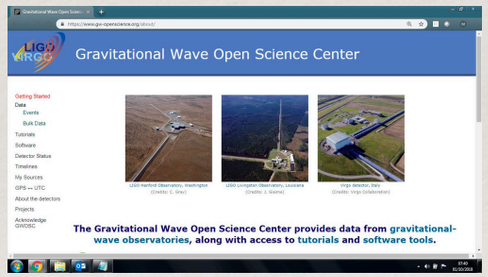
(L. Haegel, E. Porter, E. Chassande-Mottin, S. Babak)

- Cosmology using standard sirens (K. Leyde, E. Chassande-Mottin, L. Haegel)
- Machine learning techniques (L. Haegel, C. Cano, E. Chassande-Mottin)



Open data science:

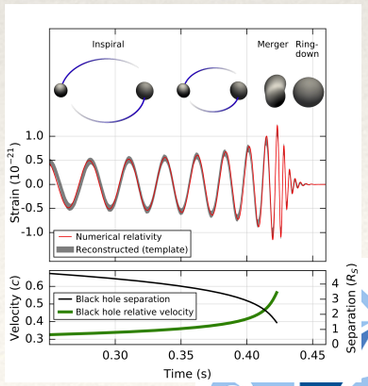
Preparation, validation and release LVC data (E. Chassande-Mottin)



Waveform modelling:

Modelling GW signal from merging black hole binaries

(C. Garcia-Quiros, L. Haegel, C. Cano, S. Babak, E. Porter)

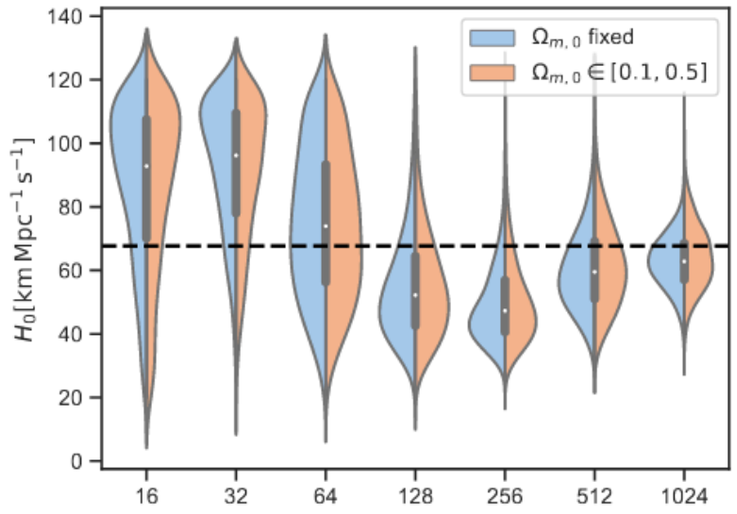


Ground-based GW Astronomy (selected topics)

Research areas overlapping Virgo-ET & LISA

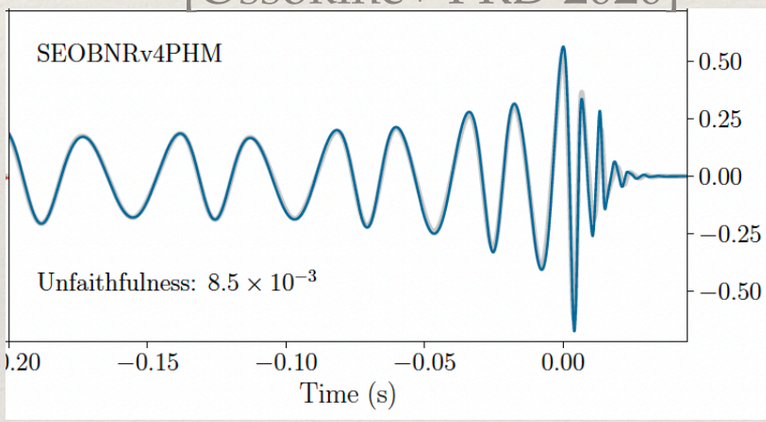
- Inferring parameters of expanding Universe using GW observations.

[Mastrogiovanni+ PRD 2021]



- Modelling GW signals from merging BHs.
  - Analytic (based on numerical simulations)
  - speed-up using machine learning
  - systematic errors in the waveform modelling

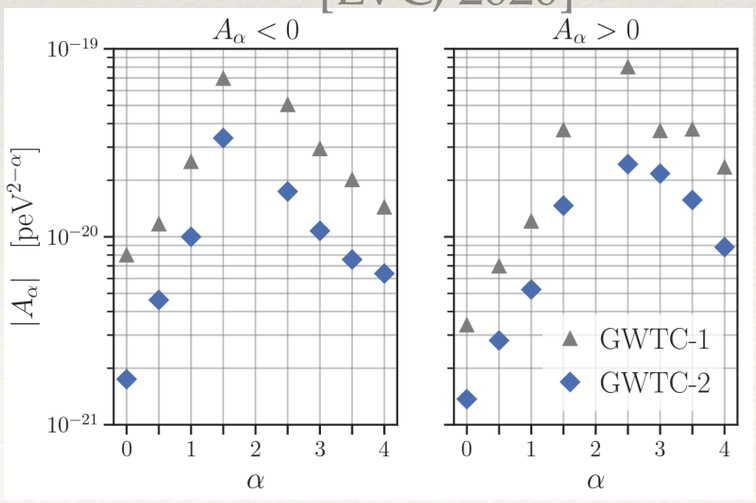
[Ossokine+ PRD 2020]



Testing GR (breaking symmetries):

- propagation test

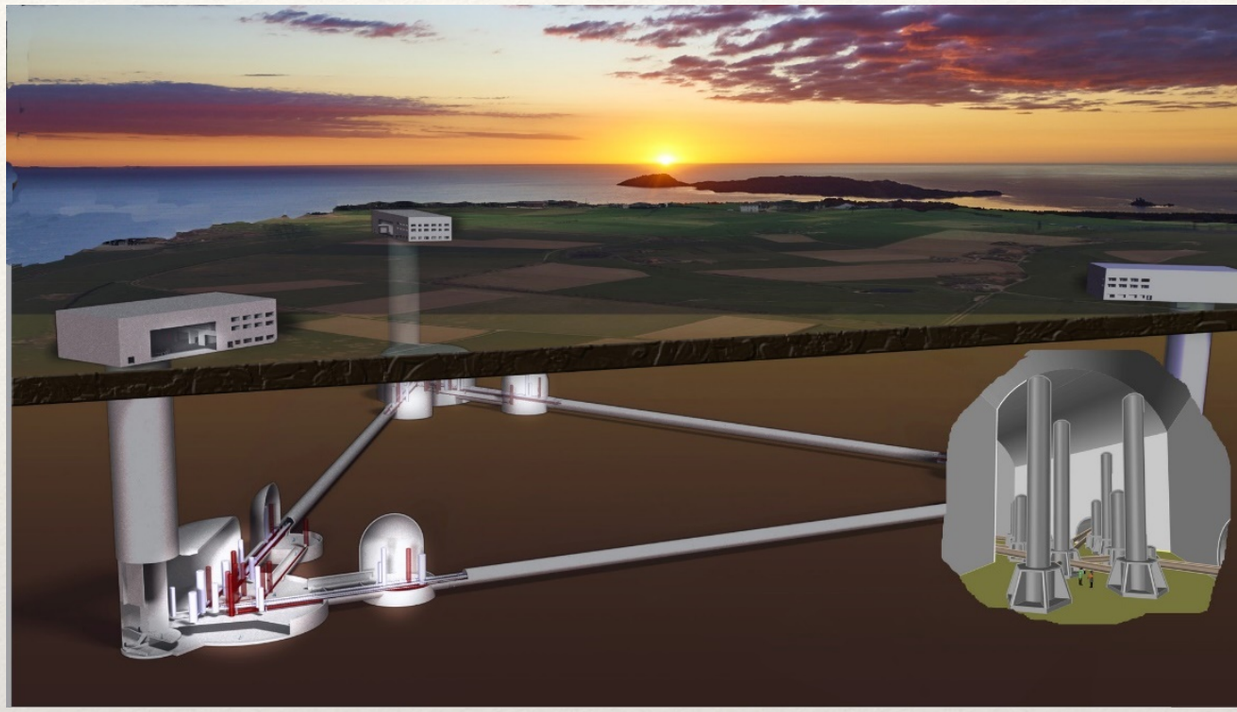
[LVC, 2020]



Einstein Telescope

- Order of magnitude improvement in sensitivity: 10^3 in events

- Vast improvement at low freq. (down to 2Hz)
- Underground (seismic noise reduction)
- 10- km long arms (signal increase)
- “Xylophone” (two combined detectors)
- Cryogenics (20 K) (thermal noise reduction)



New Physics

Nature of dark eneregy

- Inferring cosmological parameters: observing mergers to high redshift
- Test of modified gravity theories with new observables

Nature of matter at the smaller scales

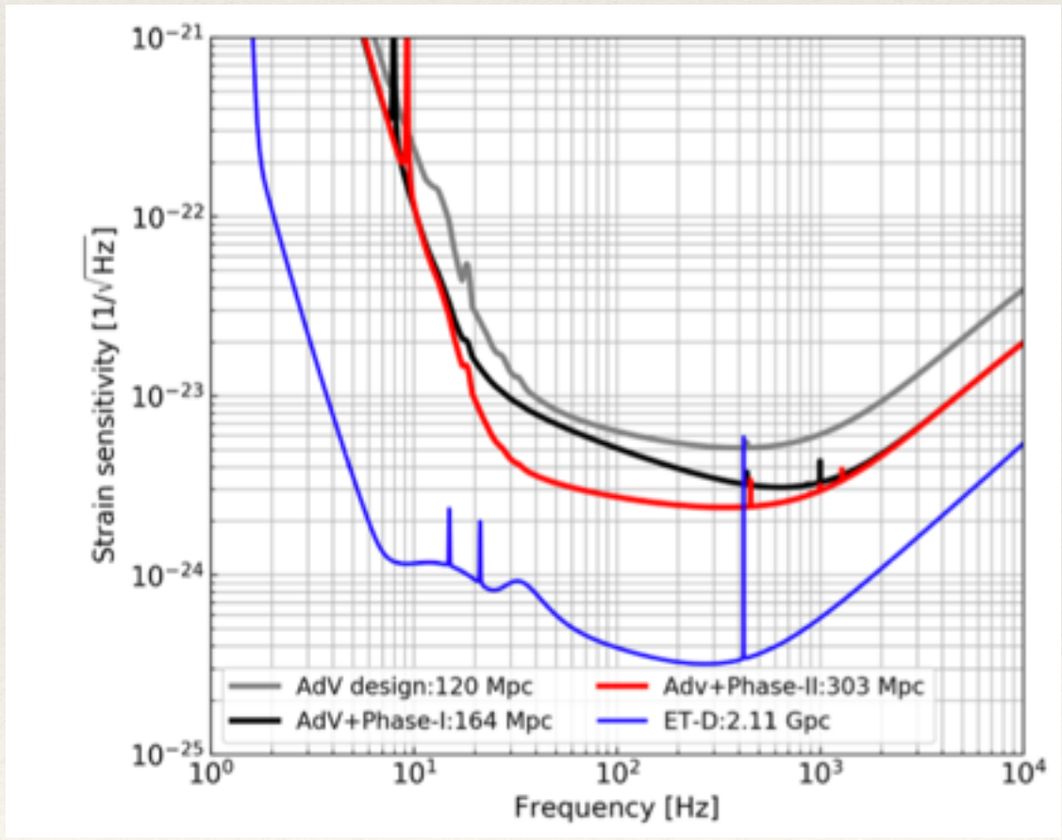
- Study of nuclear matter from merging NSs not possible on Earth

Possible contribution of APC to ET

- 3 person from France in the ET steering committee (APC, LAPP-Annecy, Artemis-Nice)
- E.Porter is co-chair of ET Observational Board.
- System and optical design
- Auxiliary optics (mode-matching telescopes)
- Squeezing, quantum noise reduction
- Cosmology (Standard sirens, dark sector, modified gravity theories)
- Inference of properties, formation and evolution of population of GW sources.
- Multi-messenger astrophysics

UPDATE IT

2011 conceptual design report
2019 ET collaboration formation
2020 submission to the ESFRI roadmap
2021 end design
2026 end preparation phase
2035 end construction
2033-2080 Science !



LISA project

Responsible: S. Babak (Theory), H. Halloin (Instrumental)

7 Permanent:

- Antoine Petiteau (LISA Board, LISA PI-France, LISA Distributed Data Processing Centre lead)
- Hubert Halloin (LISA AIVT lead, LISA System Engineering Office)
- Chiara Caprini (LISA Cosmology working group lead)
- Eric Plagnol (LISA PathFinder data analysis)
- Edward Porter (LISA data analysis, waveform validation lead)
- Stanislav Babak (LISA data challenge lead, LISA data pipeline lead, LISA data analysis tools lead)

Associate

- Daniele Steer (Modelling stochastic GW signal)
- Sylvain Chaty (populations et outreach)

2 postdocs.

- Alberto Mangiagli (LISA data analysis, Cosmology with standard sirens)
- Cecilio Garcia-Quiros (waveform modelling)

LISA' time line

lisa

June 2017: Selection of LISA as L3 with anticipated launch at 2034

May 2018: Phase A kick-off

2018 - 2021 Mission Phase A (formulation)

Dec. 2021: Formulation review (end of Phase A)

> 2022 Mission Phase B1

>**Dec. 2023: Mission Adoption**

> 2024: Mission Implementation (Phase B2/C/D)

< **2034: Launch**

> Launch: 4-5 years of operation (with potential extension to 10yrs)

LISA @APC

LISA data analysis:

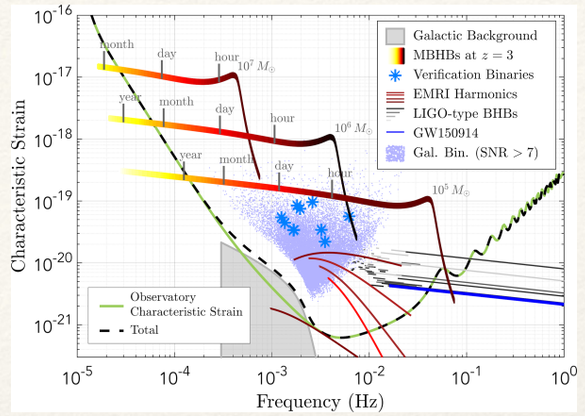
Detection methods, Bayesian parameter estimation, testing GR

A. Mangiagli, M. Falxa, S. Babak, A. Petiteau, E. Plagnol, M. LeJeune

LISA simulator (software and hardware):

Development of LISA simulator with the accent on TDI, LISA performance study

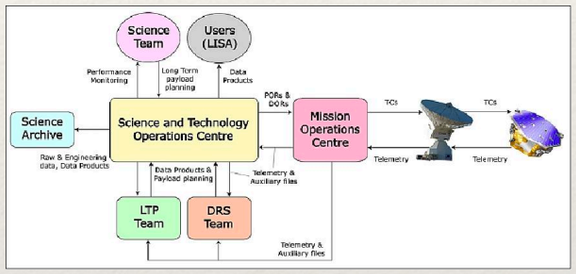
Dam Nam, L. Vidal, J. Martino, A. Petiteau, H. Halloin



Building Distributed Data Processing Center:

Analysis pipeline development, Simulating of LISA data, assessment of data analysis methods, prototyping catalogues creation, …

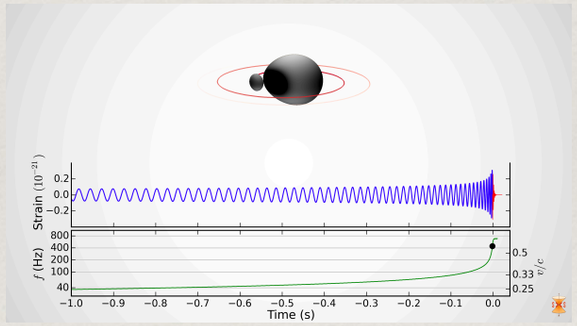
Dam Nam, M. Lejeune, C. Cavet, A. Boucaud, A. Petiteau, S. Babak, Ph. Bacon, M. Souchal



Waveform Modelling:

Modelling merging MBHBs, Extreme mass ratio inspiral, stochastic signal.

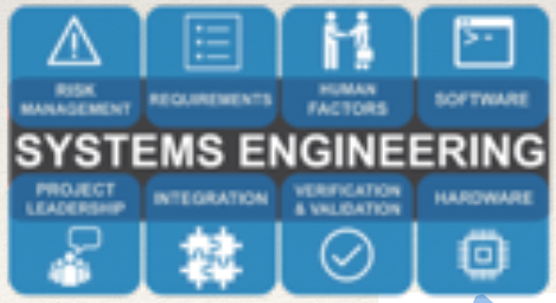
S. Babak, C. Garcia-Quiros, E. Porter, D. Steer



Assembly Instrument, Verification and Testing (AIVT):

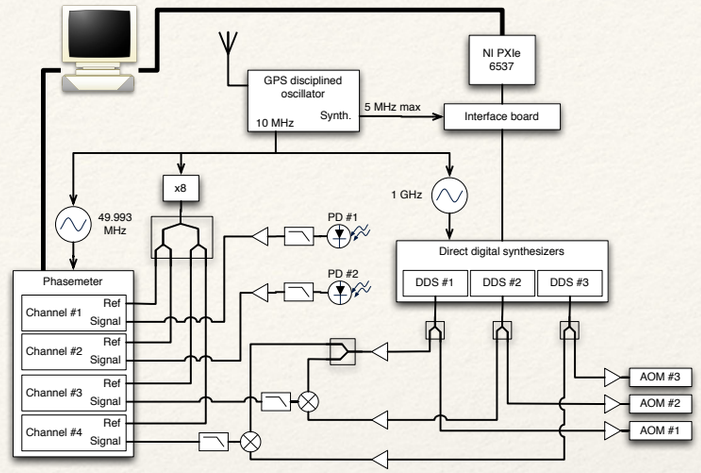
Prototyping AIVT optical test benches and designing the optical ground support equipments

H. Halloin, T. Zerguerras, J. Martino, St. Dheilly, P. Prat, G. Monier, F. Cortavarria, W. Bertoli, C. Juffroy, M. Laporte, J. Lesrel, F. Cortavarria

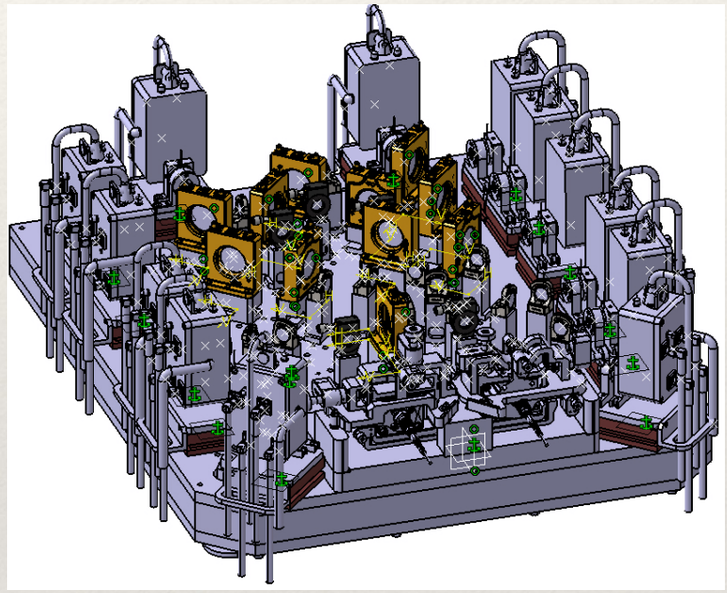


LISA@APC: instrumentation

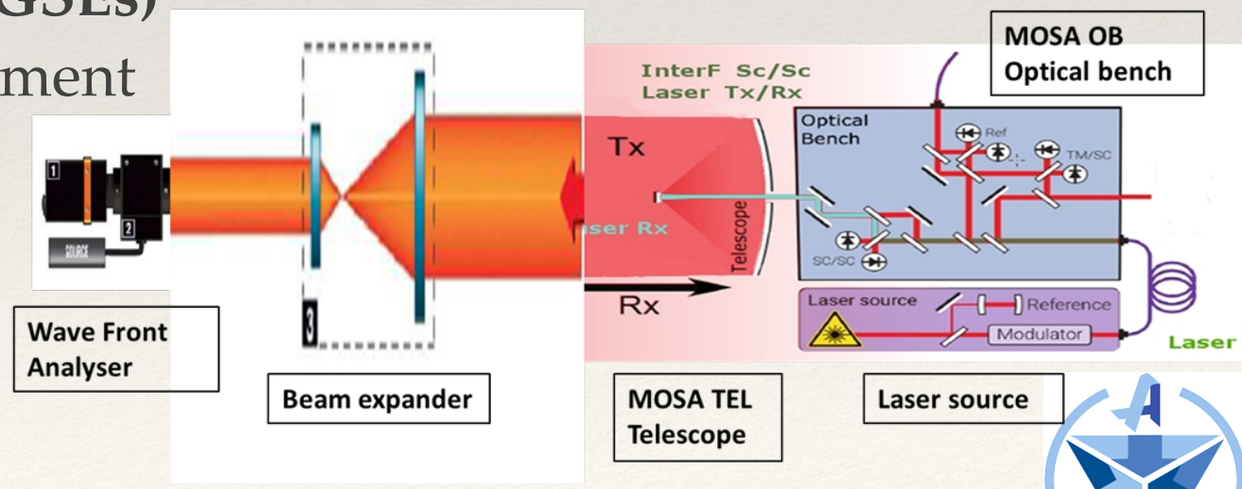
LISA On Table (LOT) experiment
generating LISA-representative photodiode signals (e.g. for TDI testing) (*L. Vidal, P. Prat, H. Halloin*)



Metallic and Zerodur Interferometers (MIFO/ZIFO)
Prototyping optical benches and methods for LISA instrument integration (*Th. Zerguerras, P. Prat, G. Monier, J. Martino, C. Juffroy, W. Bertoli, F. Cortavarria, S. Dheilly, H. Halloin*)

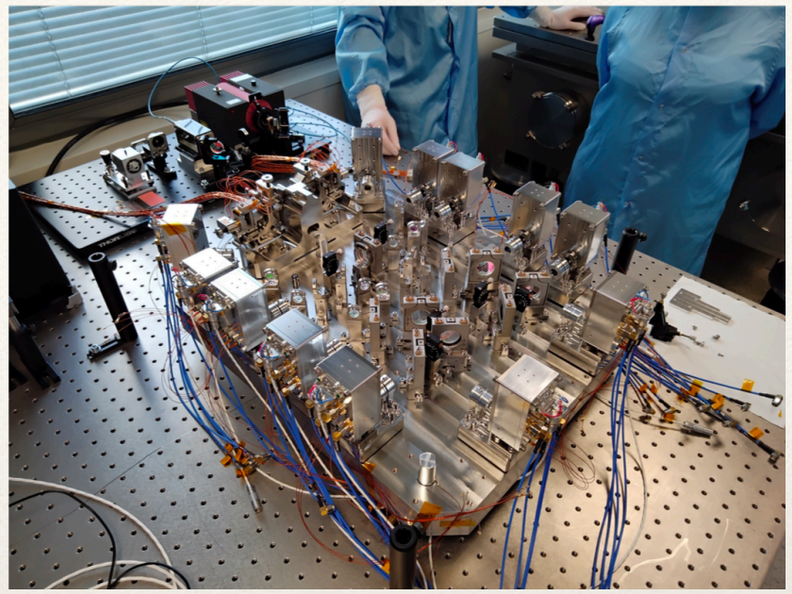


LISA Optical Ground Support Equipments (OGSEs)
Designing and sizing the OGSEs for LISA Instrument tests (starting in 2025).
(*Th. Zerguerras, H. Halloin*)

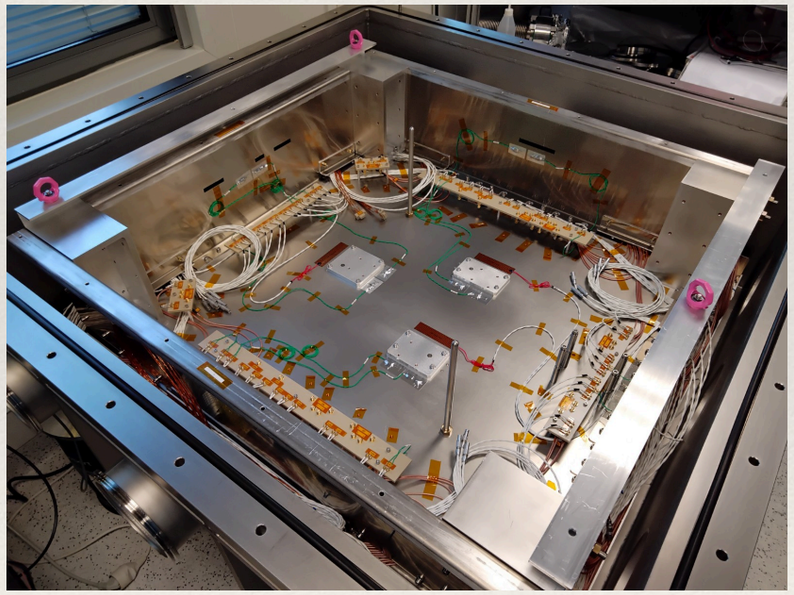


Current status

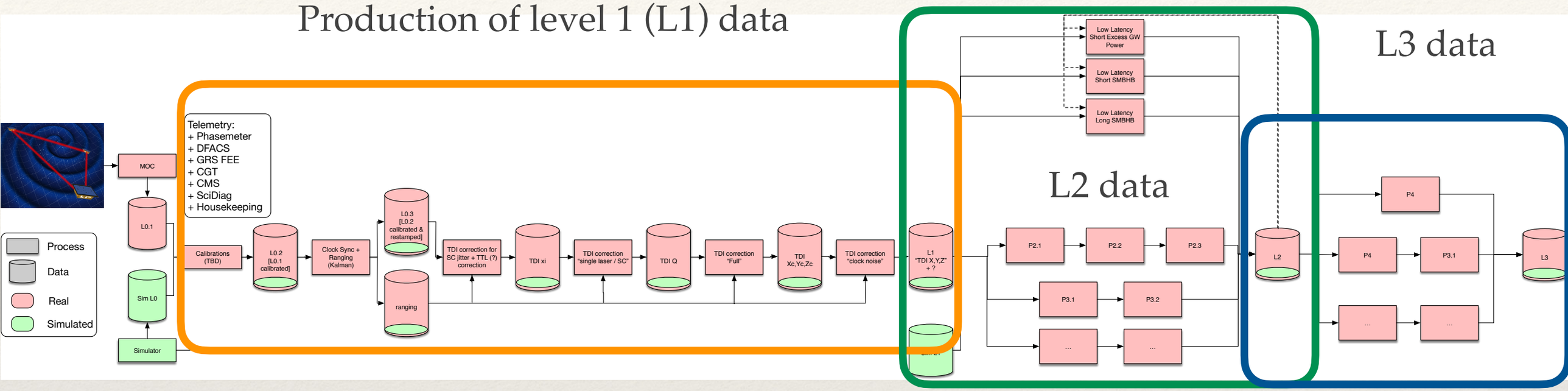
Metallic interferometer: optical bench



Thermal shielding
installed in the vacuum tank



LISA@APC: data processing

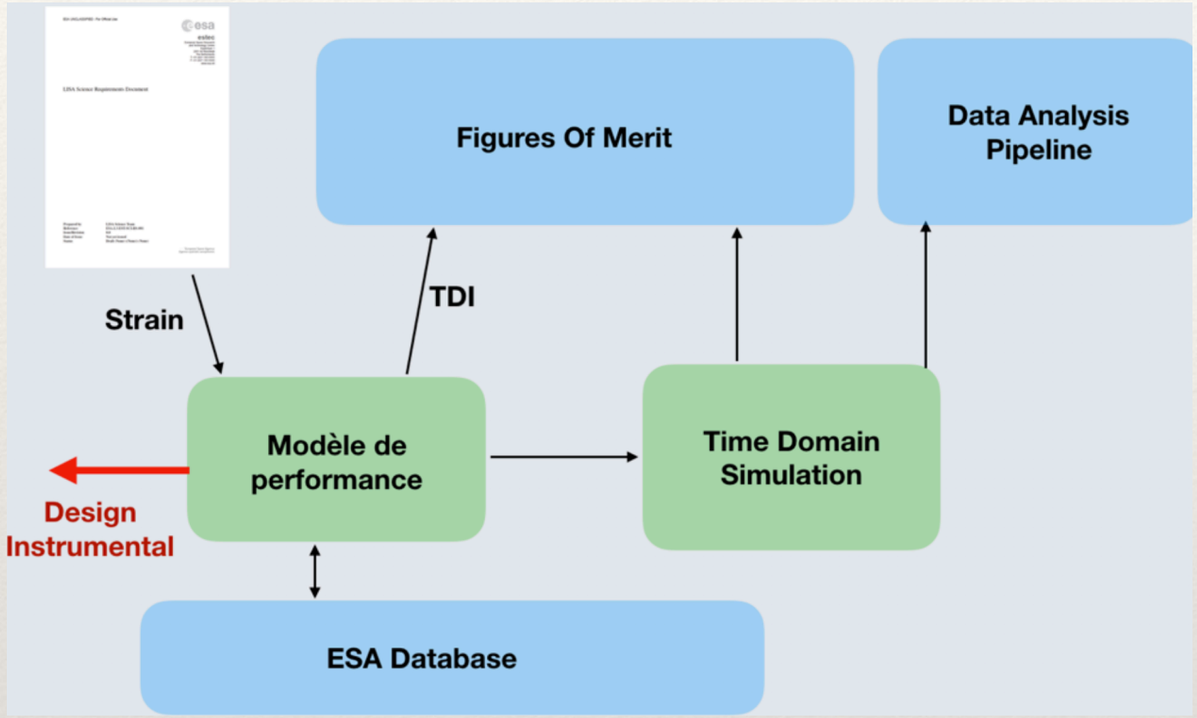


Calibration, laser & clock noise reduction
(*H. Inchauspe, Dam Nam, J.Martino, e. Savalle, A. Petiteau*)

Extraction of GW signals, noise modelling
(*H. Inchauspe , Dam Nam, M. Lejeune, C. Cavet, S. Marsat, N. Karnesis, A. Petiteau, S. Babak*)

Catalogues and science interpretation of the data
(S. Marsat, N. Karnesis, A. Petiteau, S. Babak)

Figures of merit



Testing scientific performance during design study (Phase A)

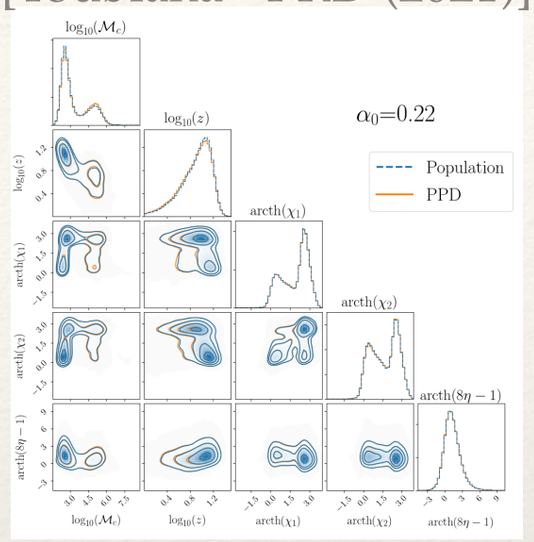
(*H. Inchauspe , Dam Nam, M. Lejeune, C. Cavet, S. Marsat, N. Karnesis, A. Petiteau, S. Babak*)

LISA: observing GW in space

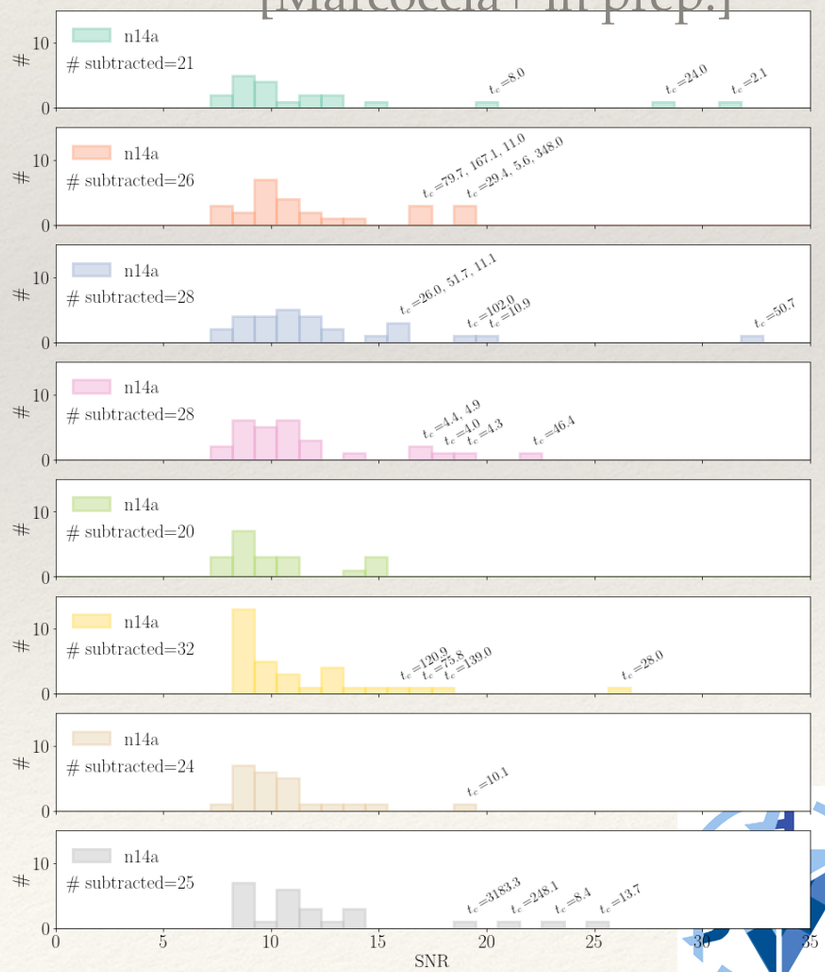
Science overlapping with the ground-based GW observatories (VIRGO & ET)

- Inferring astrophysical models of formation and evolution of the population of GW sources
- Cosmology at high redshift
- Modelling stochastic GW signal from unresolved astro. population
- **Multiband observation of stellar-mass black hole binaries**

[Toubiana+ PRD (2021)]



[Marcoccia+ in prep.]



PTA: pulsar timing array

Responsible: A. Petiteau/S. Babak

PTA-France

2 Permanent:

- Antoine Petiteau (PTA data analysis)
- Stanislav Babak (PTA data analysis)

1PhD

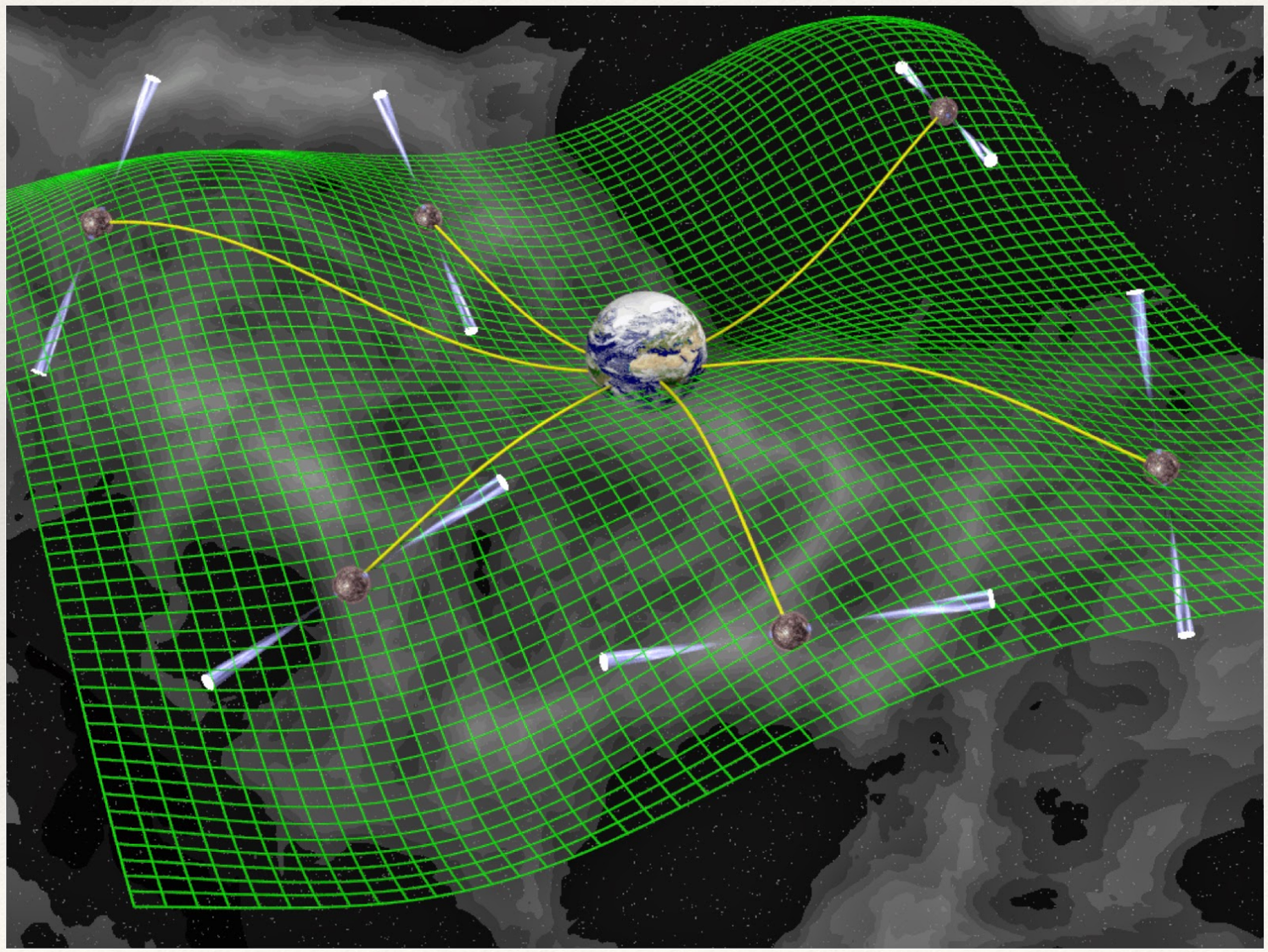
- Mikel Falxa (PTA data analysis: search for a population of supermassive black hole binaries)

On INSU side (Orleans/Nançay):

- Gilles Theureau (1CL) (Coordination)
- Ismaël Cognard (DR2) (Instrument, Observation)
- Lucas Guillemot (Astron. Adjoint) (Observation, data reduction)
- Siyuan Chen (CDD) (PTA data analysis, astrophysics)
- 2x PhD students (data reduction, data analysis)

Pulsar Timing Array: PTA

The main idea behind pulsar timing array (PTA) is to use ultra-stable millisecond pulsars as beacons for detecting GW in the nano-Hz range 10^{-9} - 10^{-7} Hz

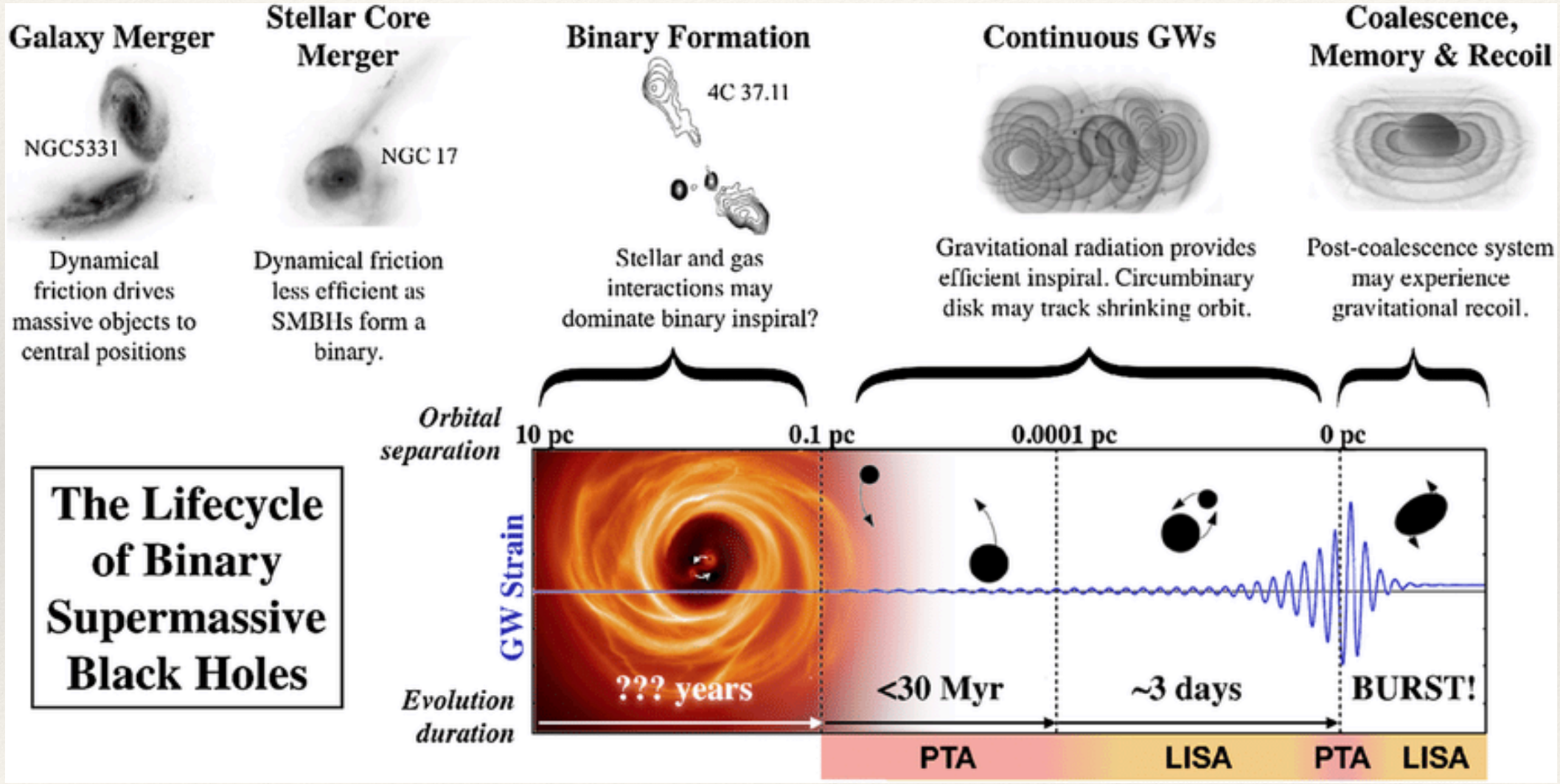


Credits: D. Champion

Population of Supermassive Black Hole Binaries

Superposition of multiple (overlapping) signals:

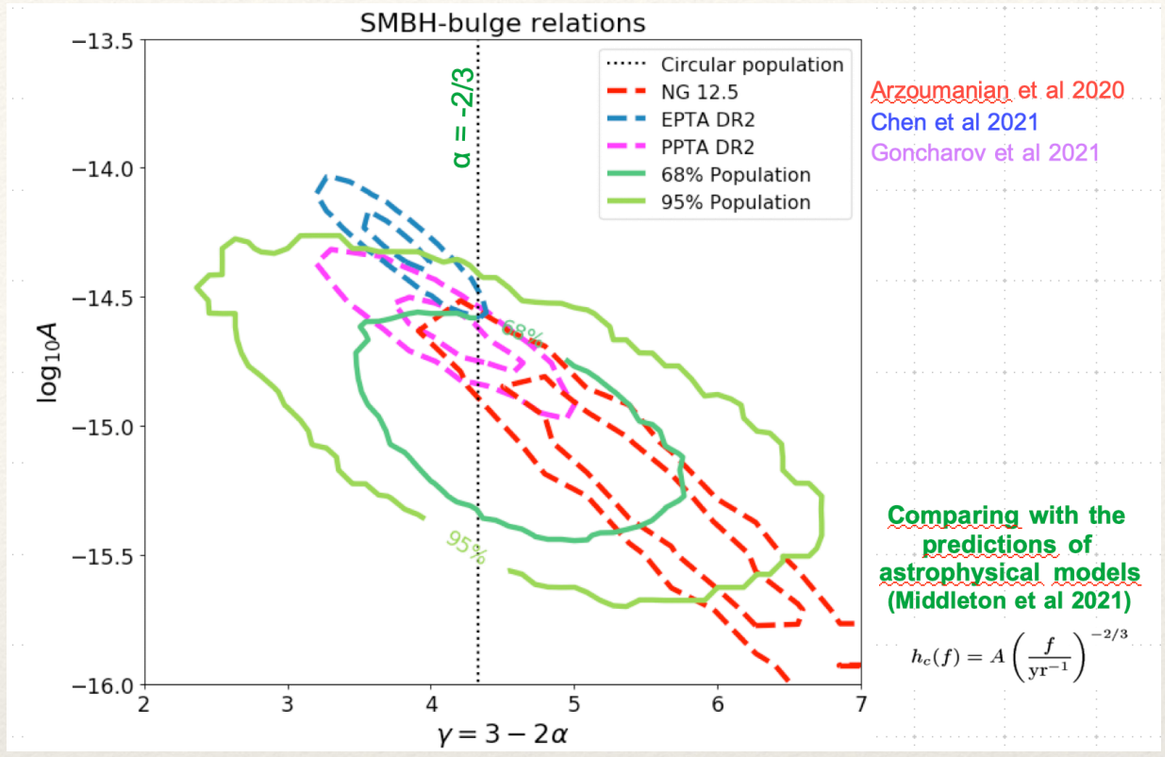
- Stochastic (possibly) anysotropic signal
- Individually resolvable (possibly) multiple signals
- Orbits could be eccentric

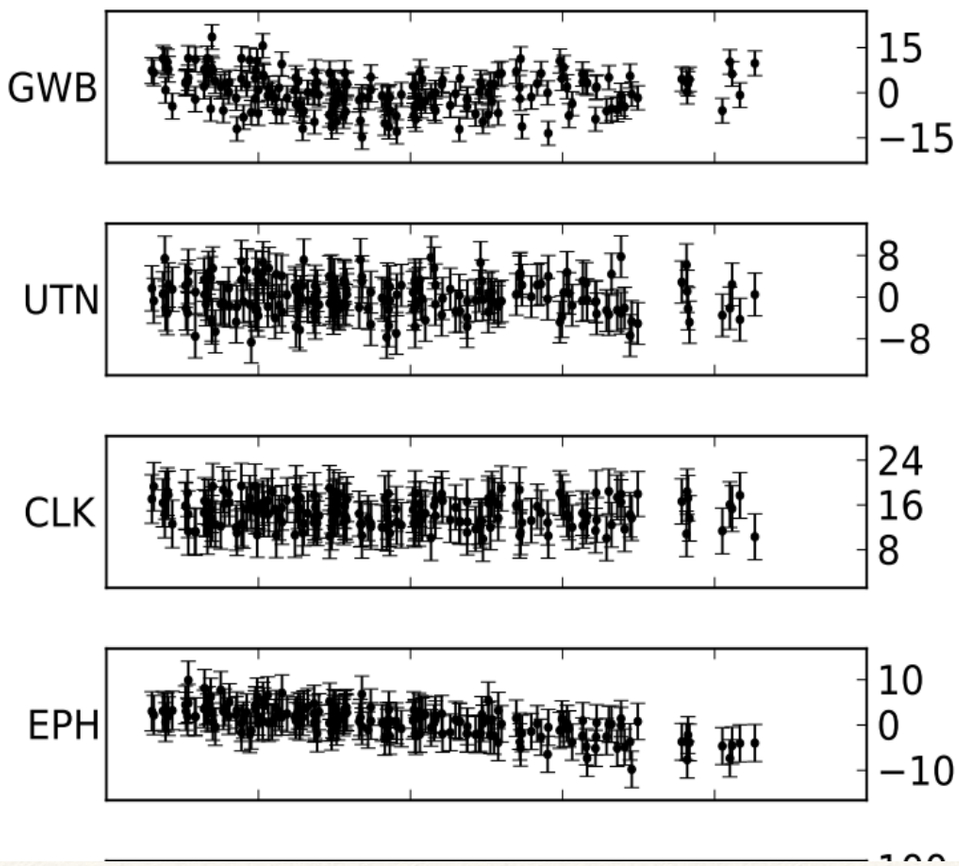


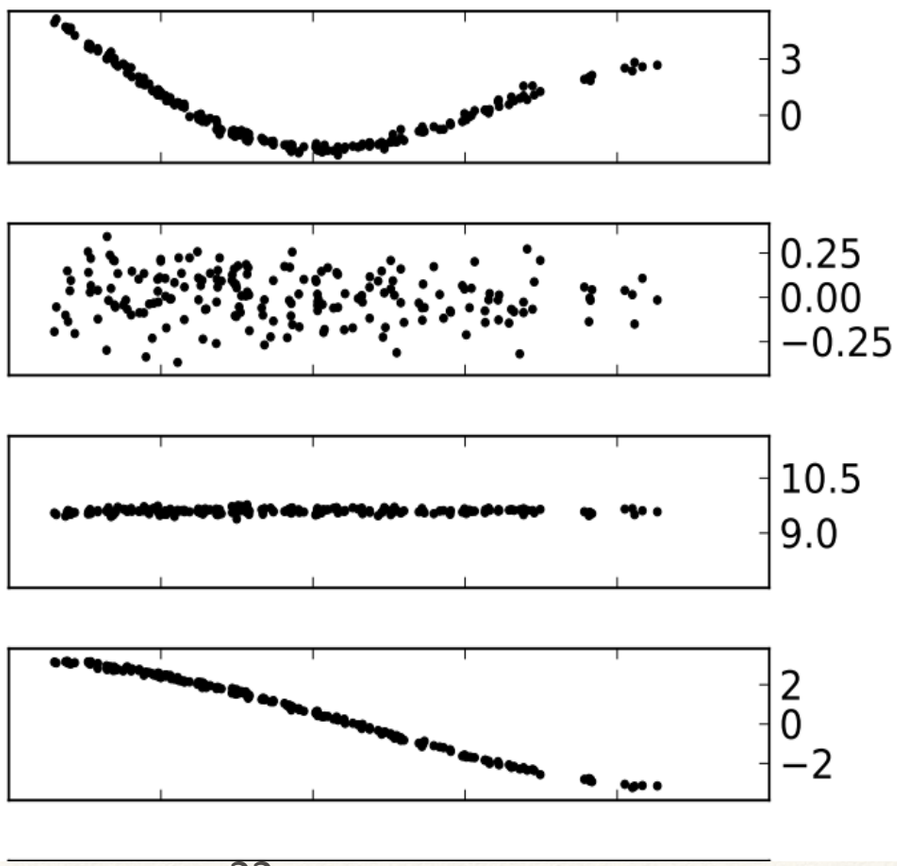
[S. Burke-Splolaor A&A review (2019)]

Recent results

- Discovery of the stochastic signal common to all pulsars (necessary condition for GWB)
- No evidence for or against spacial correlations expected for GWB (sufficient condition)







GWB

Uncorrelated RN

Clock error

Ephemeris

TOAs,

Correlation, angular

Summary

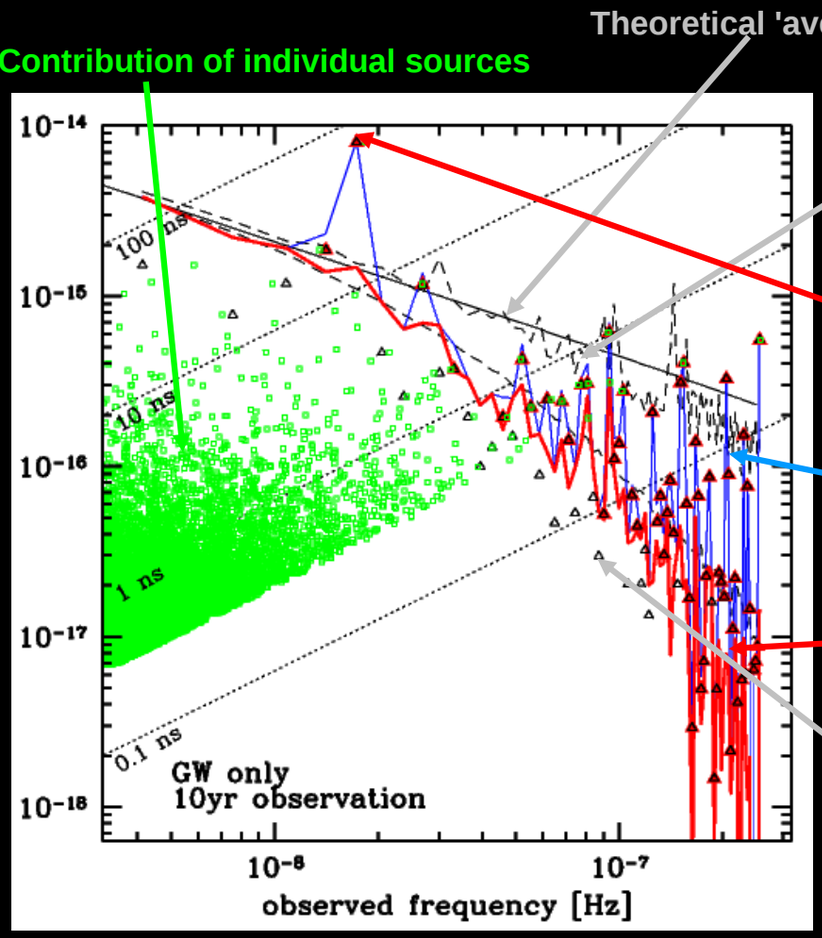
- Les ondes gravitationnelles sont cool. Vraiment! Très cool ! Et l'avenir est très lumineux pour les OG
- Plus de sources pendant le prochain run O4 avec LIGO-VIRGO (détecteurs au sol) : fin 2022-début 2023.
  - Avec un peu de chance, nous verrons d'autres événements multimessagers : fusion d'étoiles à neutrons, fusion de trous noirs dans un environnement gazeux.
- Télescope Einstein : 3ème génération de détecteurs GW (2033+)
  - Nouvelle technologie : cryogénique, souterraine, grande taille (10 km).
  - Une science nouvelle et très riche, notamment en matière de physique nucléaire.
- LISA ! Observation des ondes gravitationnelles dans l'espace (2034+)
  - Bande de fréquence inexplorée (mili-Hz): pleine de sources + pleine de surprises
- Très riche en physique unique(!): test de la théorie de la relativité générale, formation des trous noirs massifs, régions centrales des galaxies quiescentes, structure de notre Galaxie, cosmologie, observation multiband et multimessager, …..
- Pulsar Timing Array : Première observation d'ondes gravitationnelles dans la bande nano-Hz : dans quelques années.
  - Nouvelle physique, nouvelles sources, nouveaux défis

Summary

- Gravitational waves are cool. Seriously! Very cool! And future is very bright in GWs
- More sources during upcoming O4 run with LIGO-VIRGO (ground based detectors): end 2022-beg 2023
  - Hopefully we will se other multimessanger events: merging neutron stars, merging black holes in gaseous environment
- Einstein Telescope: 3rd generation of GW detectors (2033+)
  - New technologoy: crygenic, underground, large size
  - New very rich physics.
- LISA! Observation of gravitational waves in space (2034+)
  - Unexplored frequency band: full of sources + full of surprises
  - Very rich in unique(!) physics: testing GR, formation massive black holes, central rgions of quiet galaxies, structure of Milky Way, cosmology, multiband and multimessenger observation, ….
- Pulsar Timing Array: we are almost there
  - First observation of GW in nano-Hz band: coming in few years
  - New physics, new sources, new challenges

Population of Supermassive Black Hole Binaries

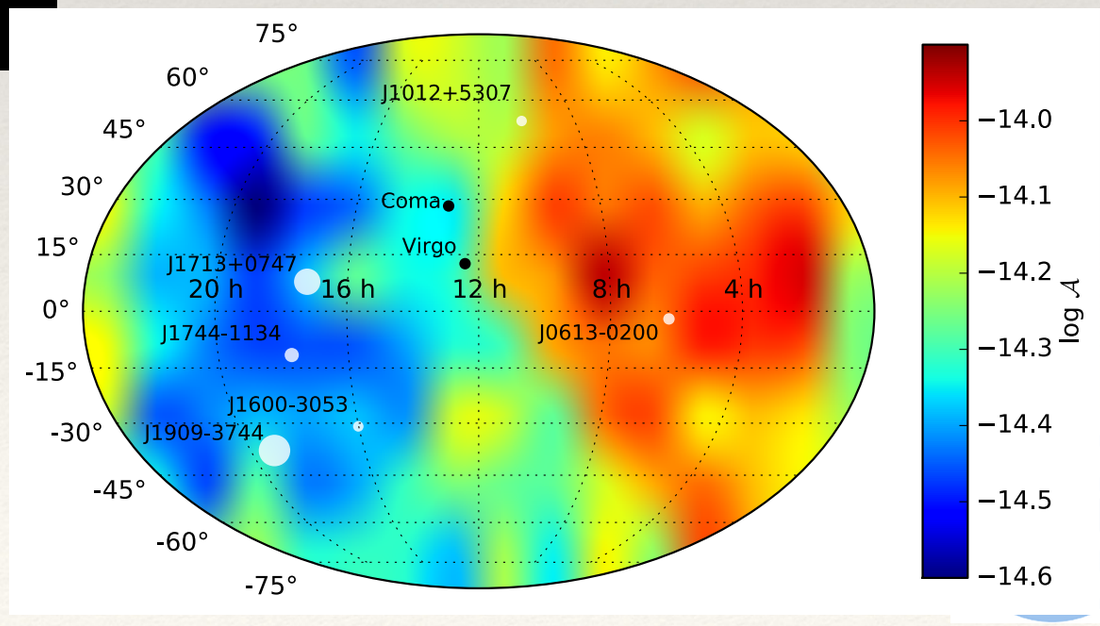
Signal from a MBHB population



Superposition of multiple (overlapping) signals:

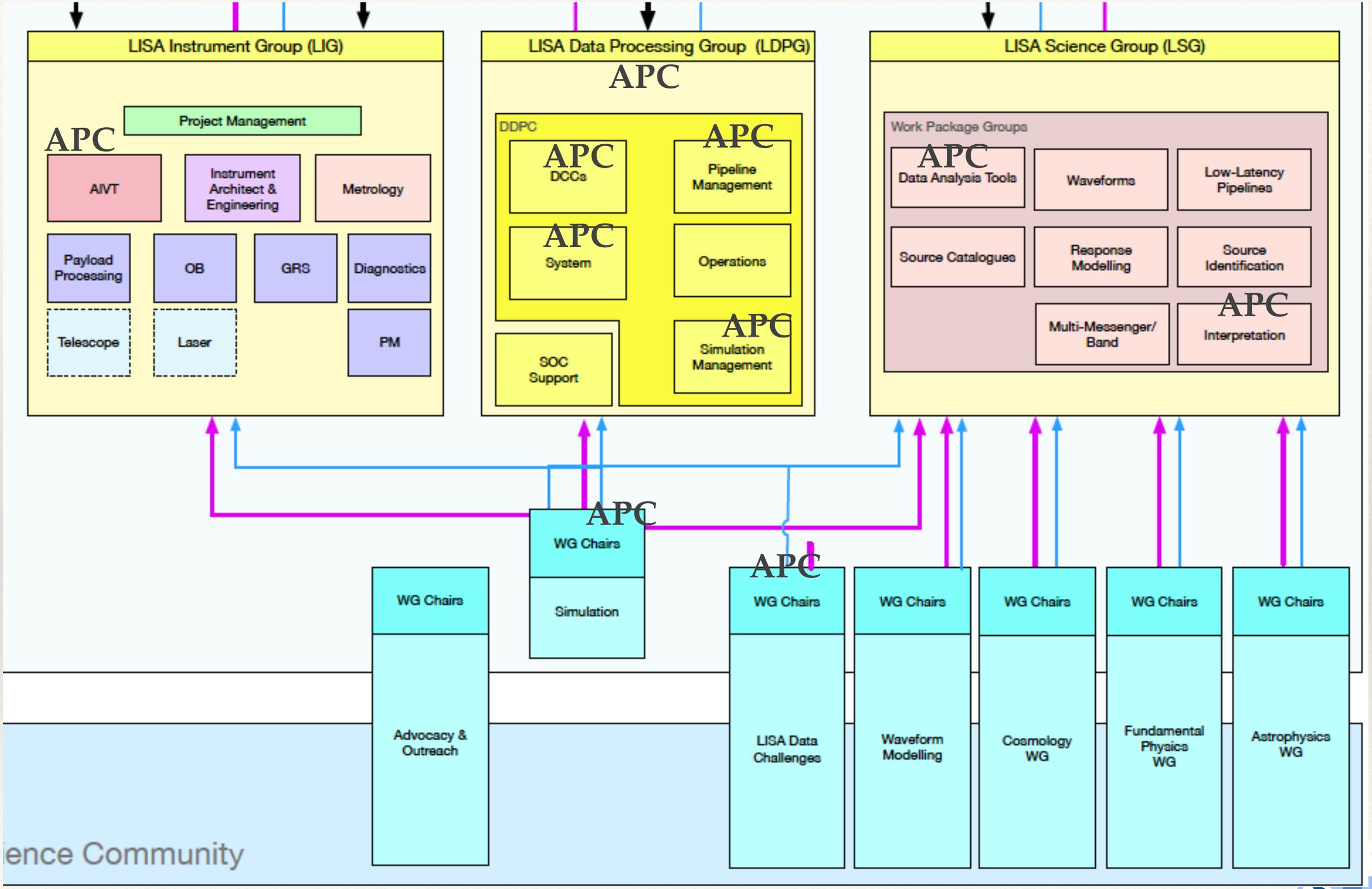
- Stochastic (possibly) anysotropic signal
- Individually resolvable (possibly) multiple signals
- Orbits could be eccentric

Application to IPTA, DR2- data set



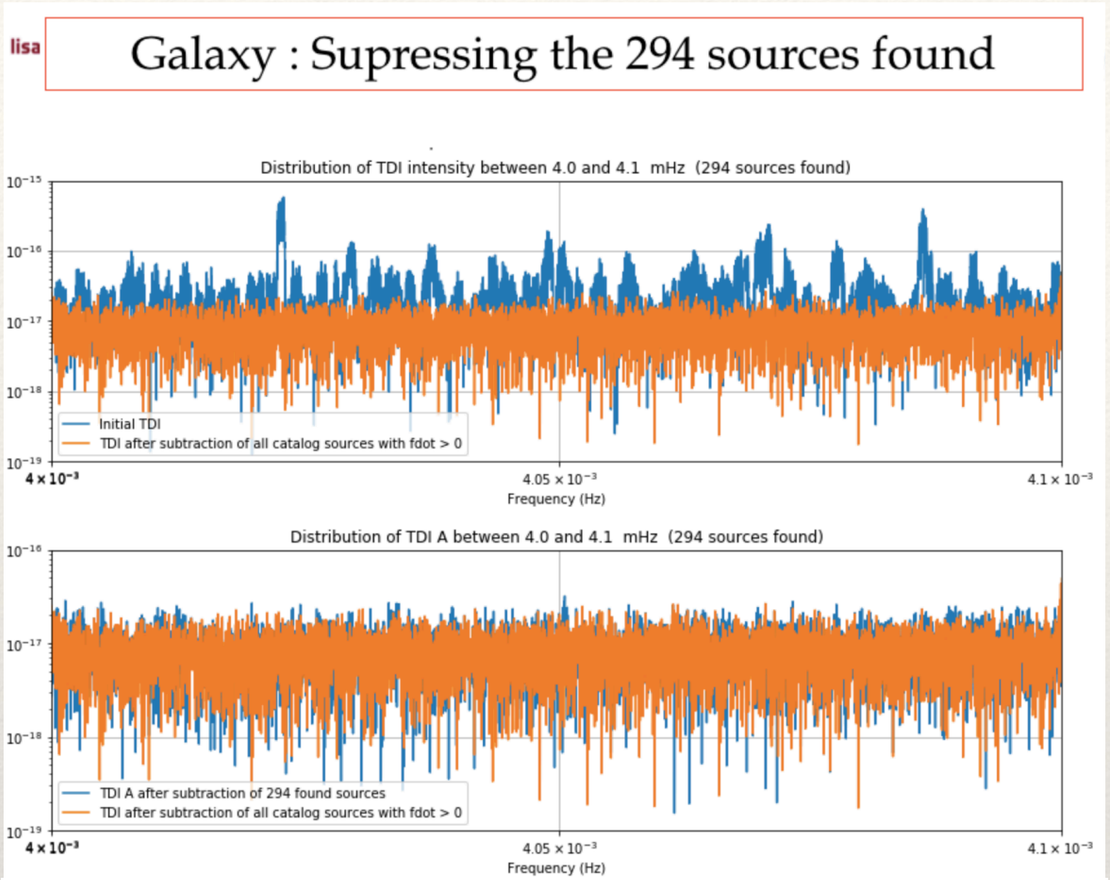
backup

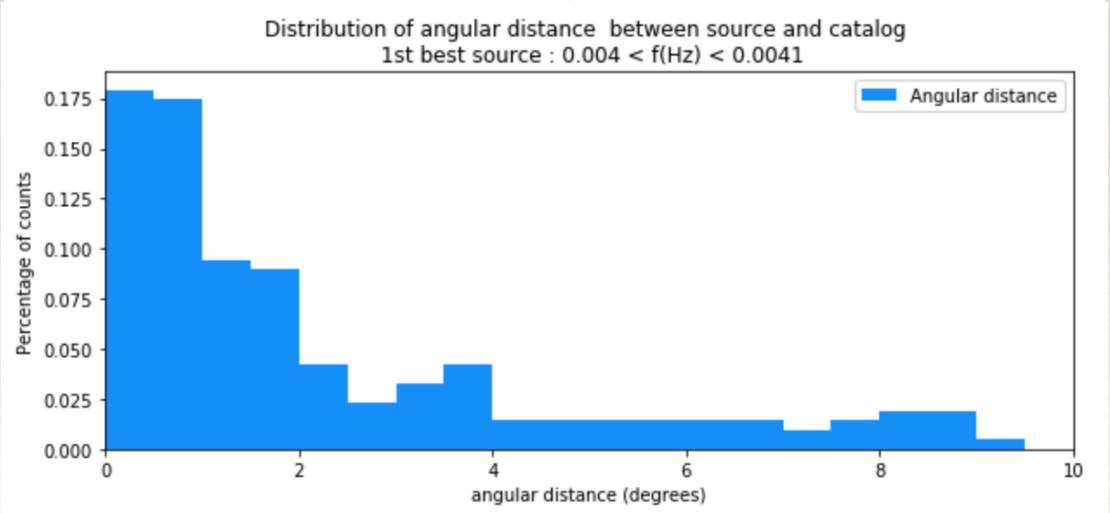
APC role in LISA project

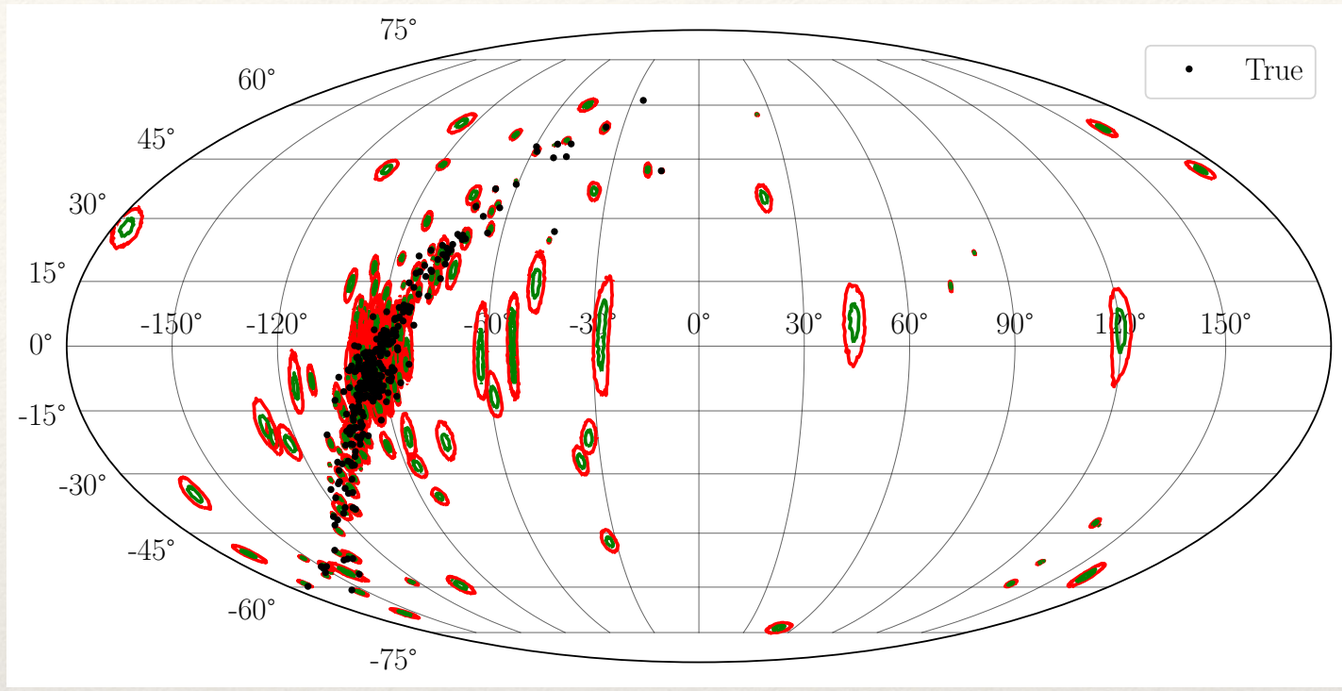


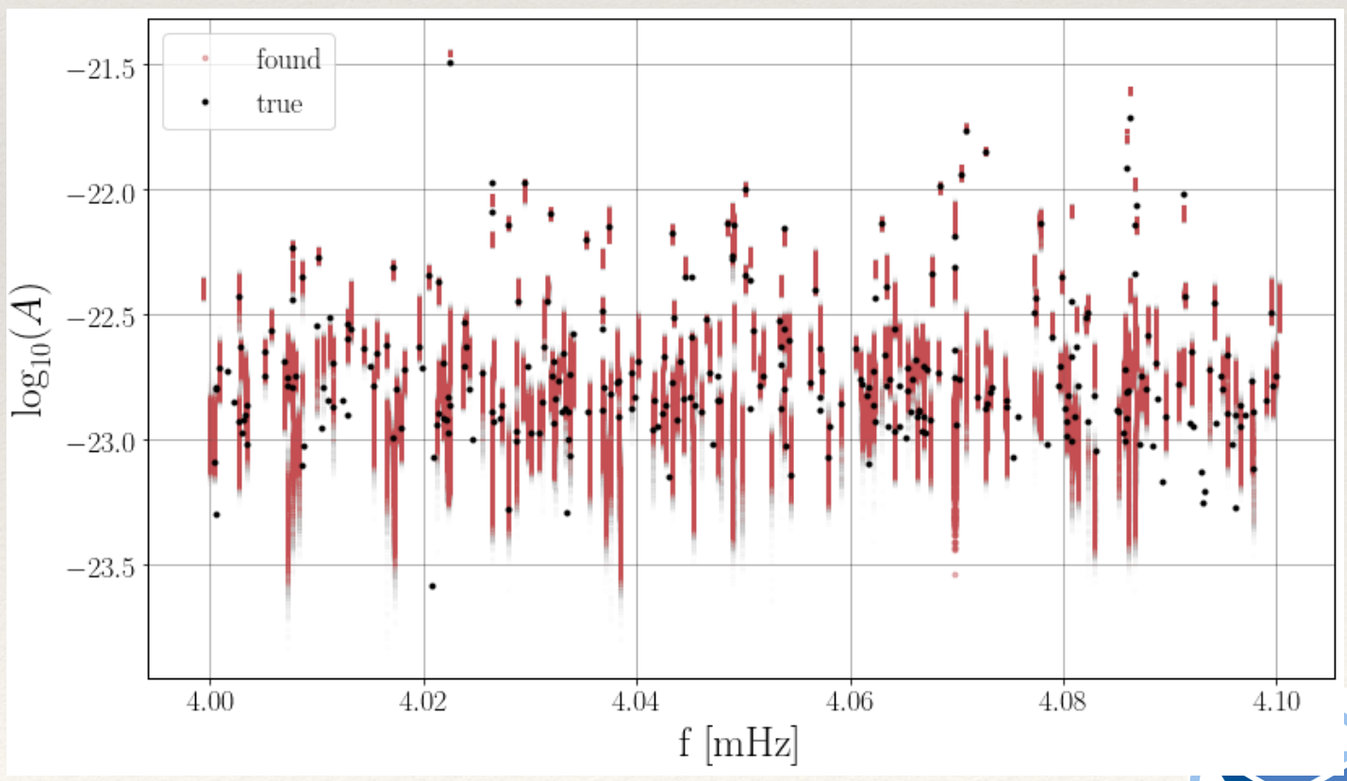
LISA: observing GW in space

Recovery of Galactic Binaries: 4-4.1 mHz band (*E. Plagnol*)



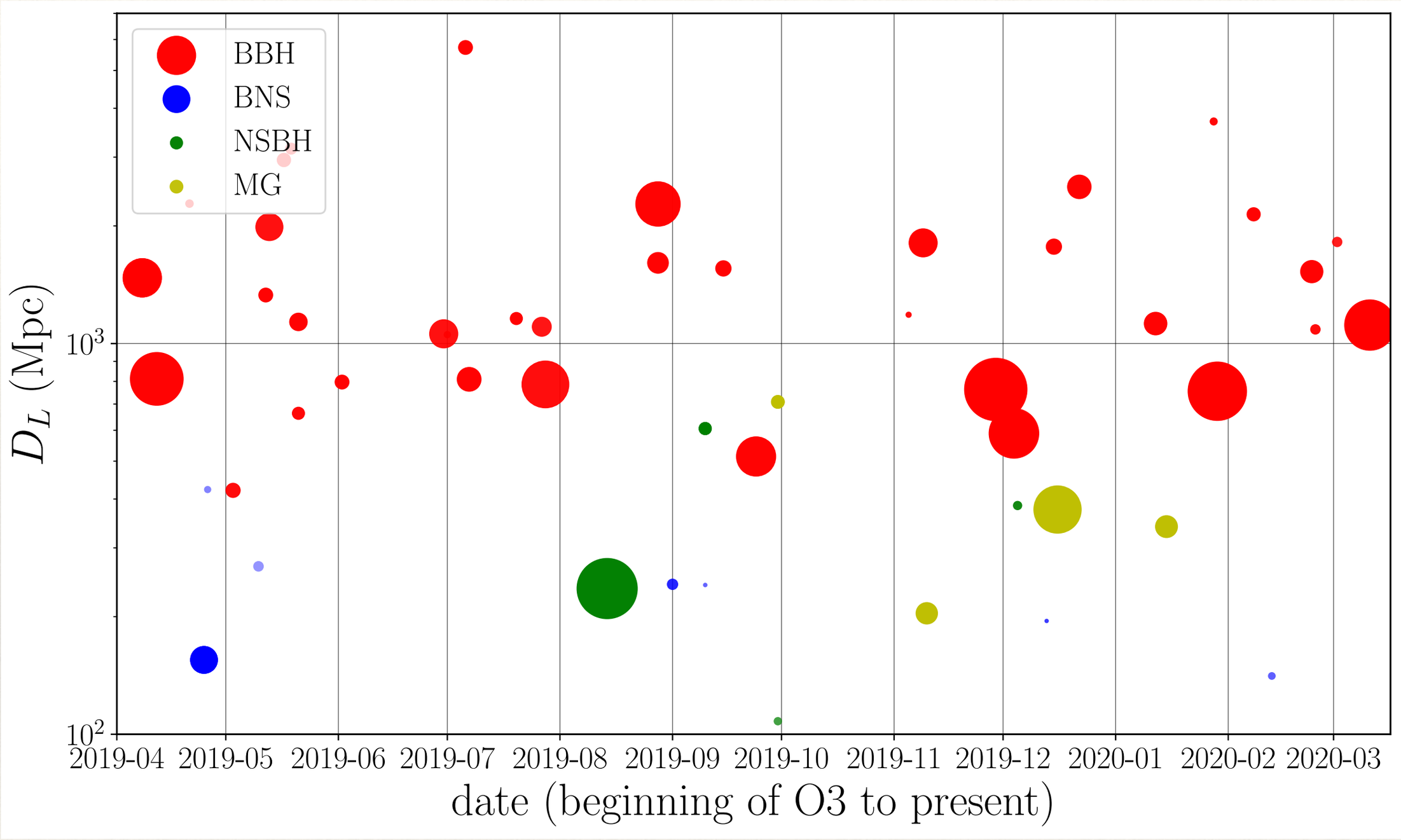






O3: curent status

BBH: 36
BNS: 7
NSBH: 4
Mass Gap: 4



Size corresponds to statistical significance
Transparency corresponds to classification confidence