LISA data analysis activities at L2IT

Sylvain Marsat, Nicola Tamanini, Danny Laghi
(L2IT, Toulouse)

Outline

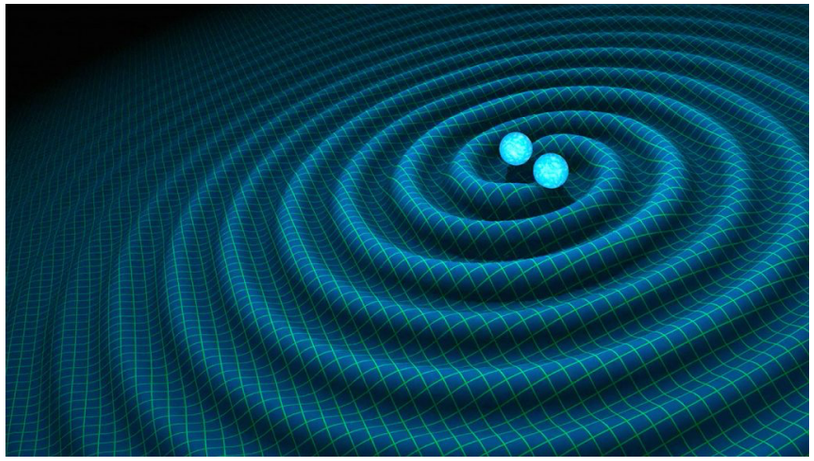
- L2IT, a new IN2P3 laboratory
- LISA group at L2IT
- Overview of LISA activities
- Core data analysis activities
- Other data analysis activities
- LISA-related science

L2IT: a brand-new IN2P3 laboratory

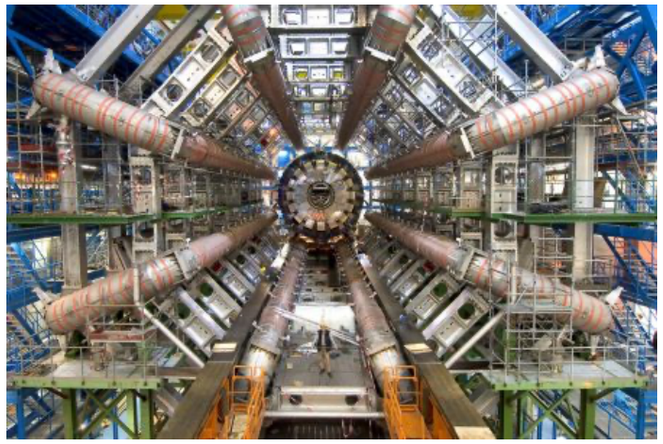
The Laboratoire des 2 infinis - Toulouse (L2IT) was established in 2019 with the objective to pursue fundamental research with innovative numerical and theoretical approaches applied to data collected by large-scale cutting-edge experiments

L2IT: a brand-new IN2P3 laboratory

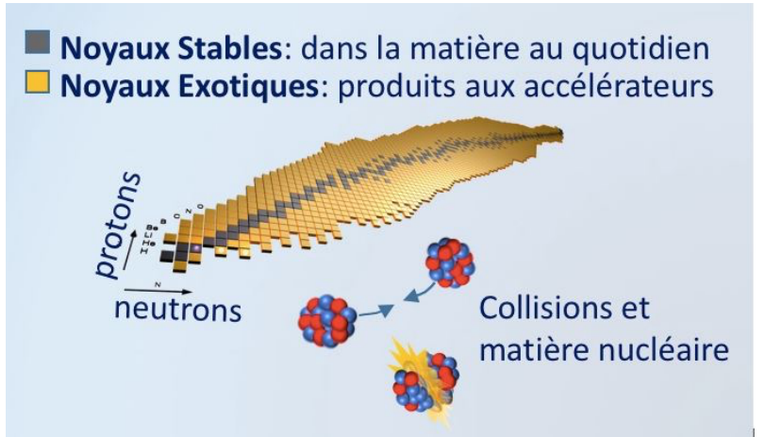
The laboratory has <u>4 main research themes/ groups</u>



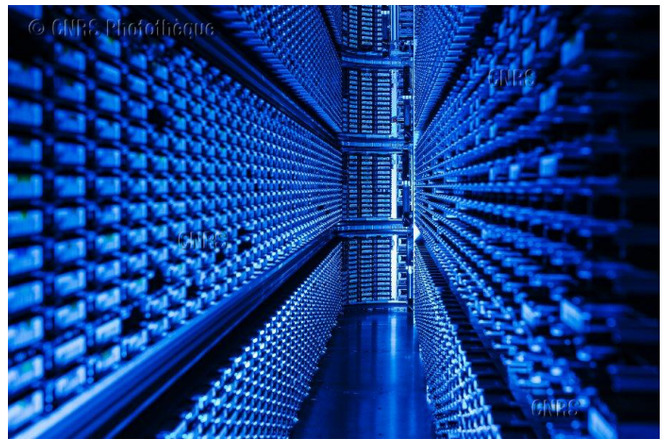
Gravitational waves



Particle physics



Nuclear physics



Computing, algorithms & data

L2IT: a brand-new IN2P3 laboratory

The laboratory has 4 main research themes/ groups, each one associated to large-scale experimental/computing facilities/collaborations

Gravitational waves

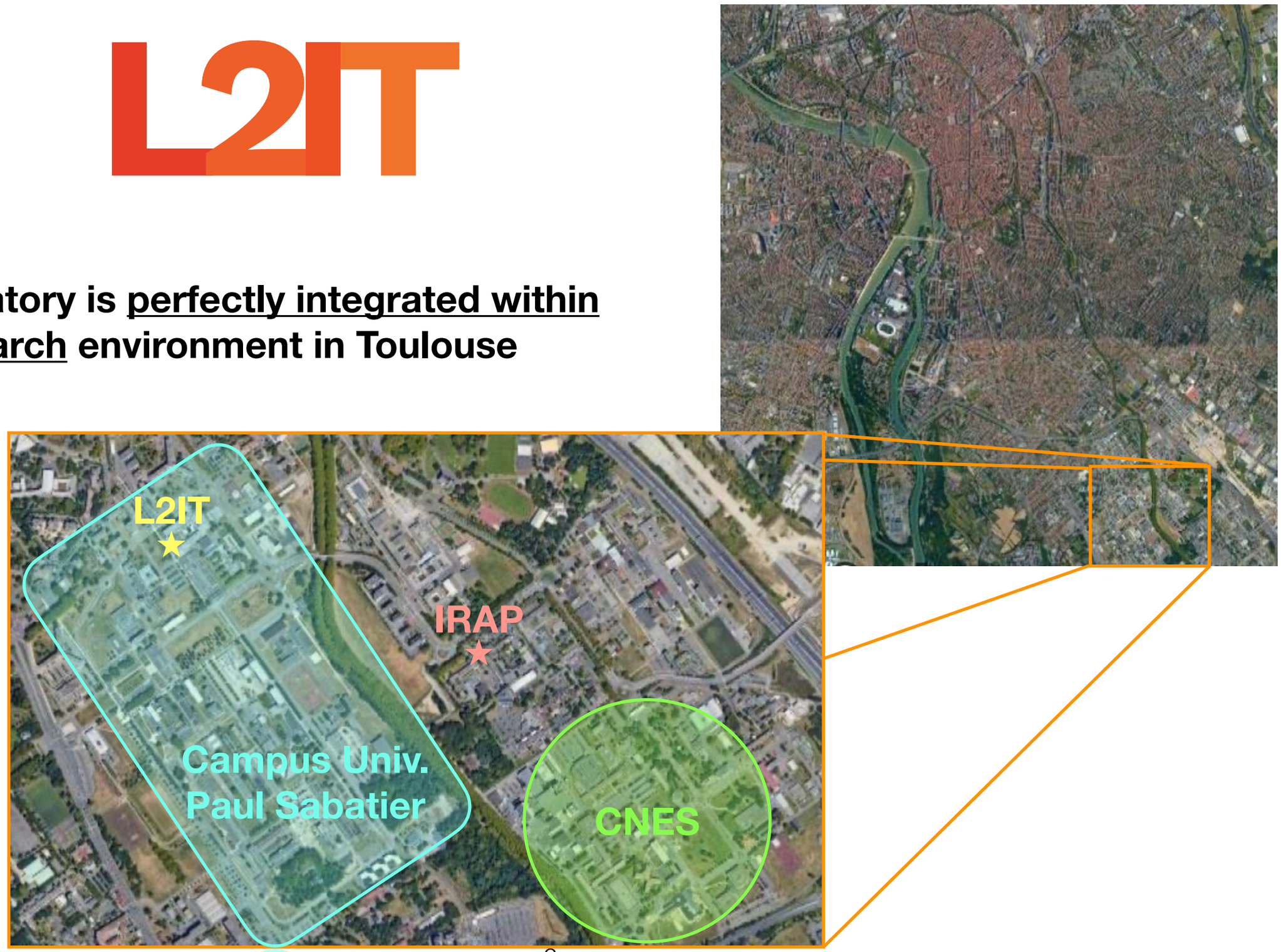
Particle physics

Nuclear physics

Computing, algorithms & data

L2IT: a brand-new IN2P3 laboratory

The laboratory is <u>perfectly integrated within local research</u> environment in Toulouse

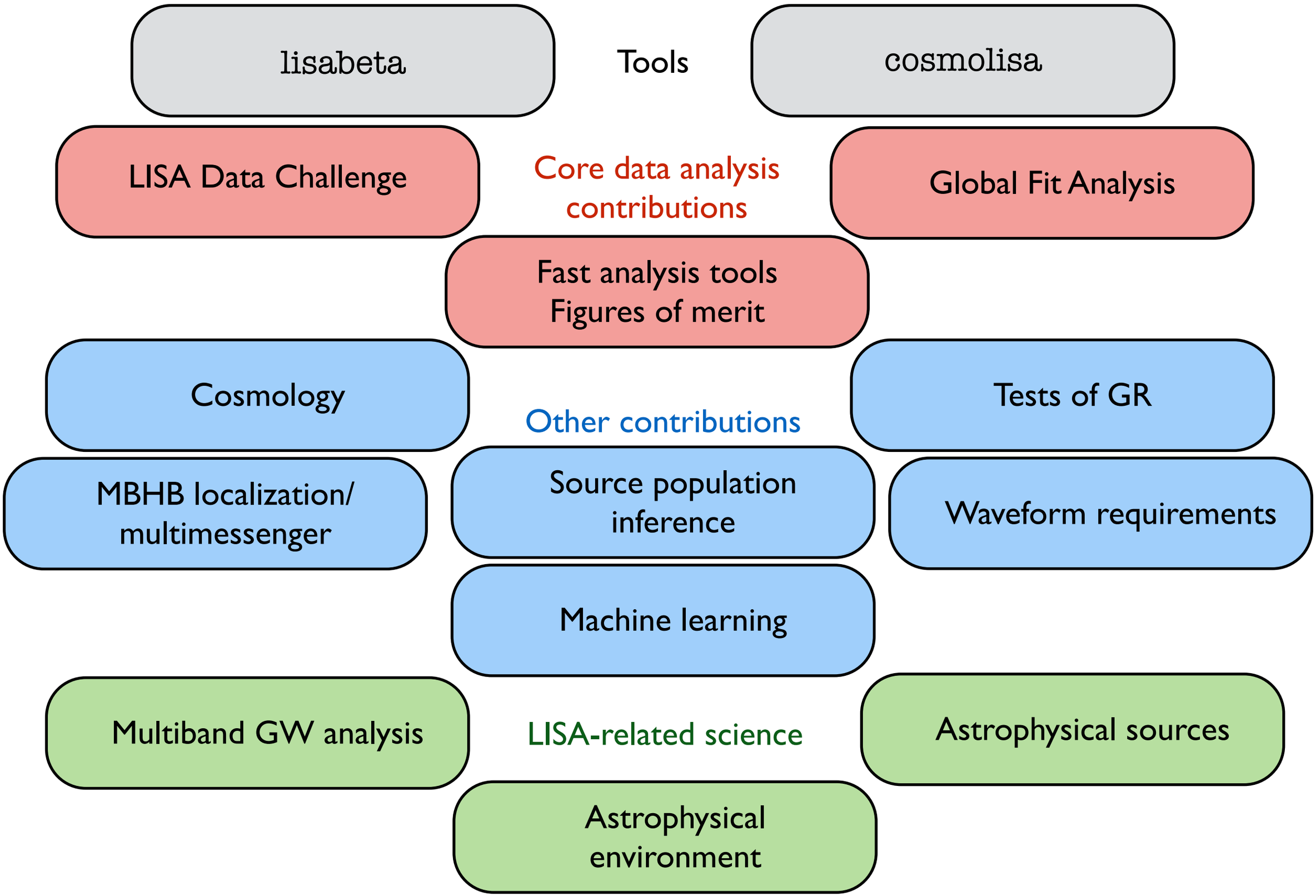


LISA group at L2IT

Name	Status	FTE	LISA Memberships	Areas of work/expertise	Proposed Contribution
Nicola Tamanini	Permanent	0,4	LSG, LDPG, LDC WG Astrophysics WG Cosmology WG chair Fundamental Physics WG LECS	Cosmology, Theory, Tests of GR, Data analysis	Cosmology and data analysis. Co-chair of the LISA Cosmology WG Coordinator of the SIWP sub-working package on the measurement of cosmological parameters.
Christelle Buy	Permanent	0,5	LIG member (AIVT)	Laser Interferometry, Laser Frequency	Instrument and AIVT activities
Rodolphe Clédassou	Permanent	0,1	LIG member (AIVT)	Project management	Instrument and AIVT activities
Catherine Biscarat	Permanent	0,3	LDPG, LDC WG	Project management Scientific computing	Computing support and code development for data anlaysis investigations within the LDC and LDGP
Cayetano Santos	Permanent	0,7	LDPG, LDC WG	Scientific computing	Computing support and code development for data analysis
Sylvain Marsat	Permanent	0,5	LSG, LDPG, LDC WG Waveform WG Cosmology WG	Waveform models, Data analysis, Tests of general relativity	Data analysis and waveform modelling. Coordinator of a Waveform WP: waveforms for SBHB
Martina Toscani	Postdoc	0,5	LSG, Astrophysics WG LECS	Tidal disruption, multimessenger astronomy, hydro simulations	Tidal disruption events and GWs, MBH physics and population
Danny Laghi	Postdoc	0,55	LSG, LDPG, LDC WG Cosmology WG	Cosmology, Data analysis Tests of General Relativity	Cosmology and data analysis techniques for the inference of cosmological parameters
Vivienne Langen	PhD	0,6	LSG, LDPG, LDC WG Astrophysics WG LECS	Data analysis, astrophysical interpretations	MBHB population modelling and inference
		4,2			

- + Niccoló Muttoni, recently left (PhD at Geneva)
- + Arrival of a new postdoc (2 years) : LISA data analysis and global fit
- + Interns : 2 master 2, 1 license 3

LISA Data analysis at L2IT: overview



Status of lisabeta

Objectives and scope

- Science prospective
- Prototyping real analysis (LDC)
- Source types: MBHBs, SBHBs for now — GBs soon
- Consortium-available (full members, public soon)

https://gitlab.in2p3.fr/marsat/lisabeta
https://gitlab.in2p3.fr/marsat/lisabeta_release

Levels of approximation

MBHBs:

- Fisher: for high SNR limit (depends on signal !) ✓
- Set noise realization to 0 ✓
- Initialize MCMC from Fisher ✓
- Full run with initialization from priors ✓
- Full run with noise ✓ (refactoring)
- Superposition of sources, unknown noise, noise artifacts… ✗

(SBHBs less advanced)

Tools implemented

- SNR computations
- MCMC: ensemble sampler with parallel tempering (`ptemcee`)
- Nested sampling: `pymultinest`
- Informed proposals to deal with sky degeneracies
- Fast likelihoods
- Waveforms: PhenomD, PhenomHM

Costs

- SNR: few ms
- Fisher: <100ms at high-M, worse at low-M
- Likelihood: MBHB 2-3ms, SBHB 3-5ms
- Inference with Fisher init. (best case): ~1CPUh
- Inference of complicated posterior, with noise: 100-200 CPUh

Status of cosmo lisa

Objectives

- Bayesian inference of cosmological parameters with LISA (and 3G detectors)
- **Statistical method** (cross-matching with galaxy catalog) or assuming **EM counterpart**
- Sources: EMRIs, MBHB, …
- Maintainers: Walter Del Pozzo, Danny Laghi
- The code is **public**: https://github.com/wdpozzo/cosmolisa

Data

d_L (from GW)

z (from galaxy catalogs/ direct observation)

Inference

$p(\{H_0, \Omega_m, \dots\} \mid \text{Data, Model})$

Tools implemented

- Modules written in **cython** (likelihood, libraries from LALCosmology) to speed up the inference
- **Nested sampling** algorithm (CPNest) optimised for multithreading

Levels of approximation

- GW likelihood in the high-SNR approximation
- Selection effects & joint inference of cosmo + source population parameters (to be implemented)

LISA Data Challenge

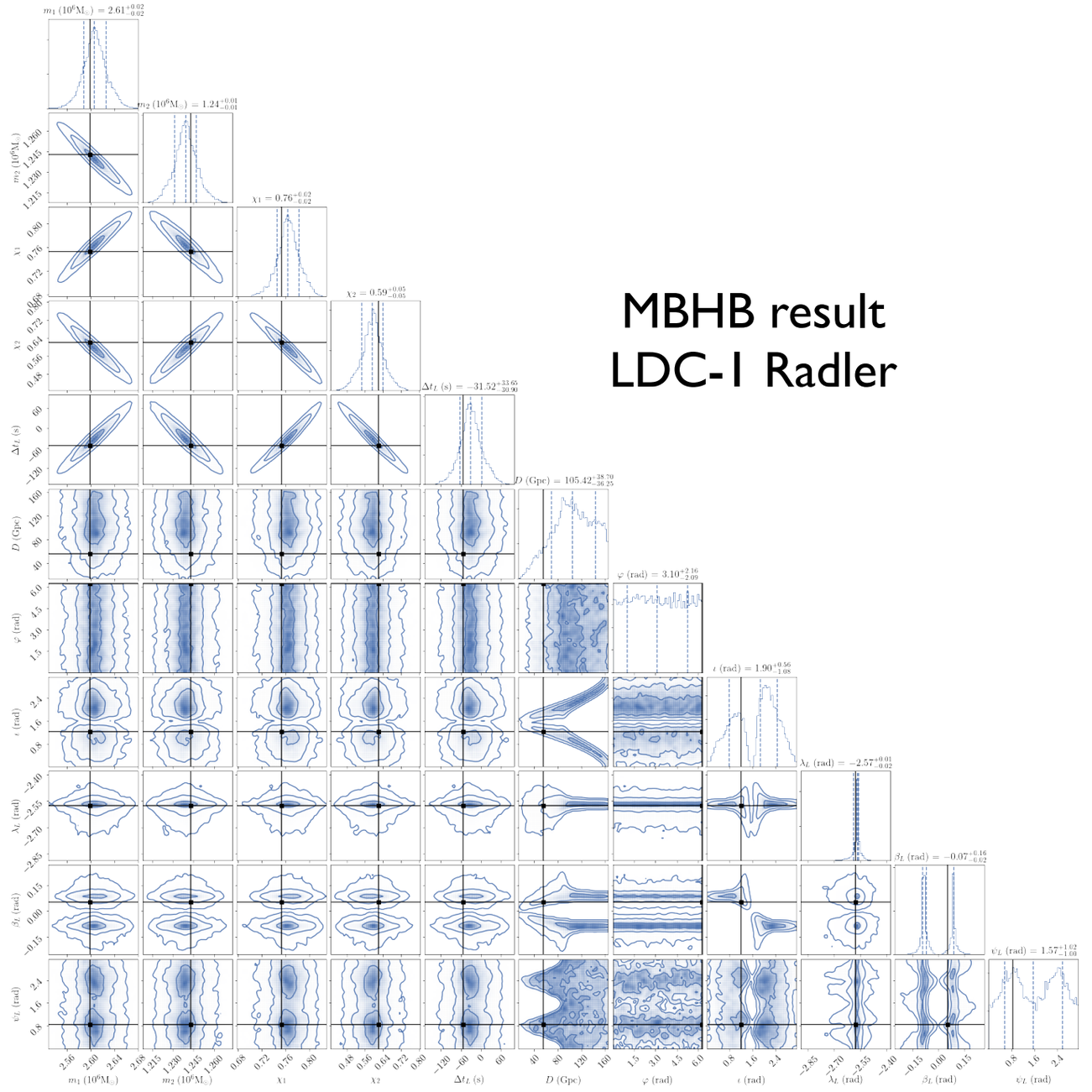
Sylvain Marsat

Past & current activities

- Participated (with J. Baker) in LDC-1 MBHB challenge
- Contributed to the infrastructure of LDC

Future prospects

- **MBHB analysis in LDC-2, part of Sangria, in collaboration with APC**
- (Possibly) accelerating GB signal generation and GB inference
- Extend our methods for SBHBs



MBHB result
LDC-1 Radler

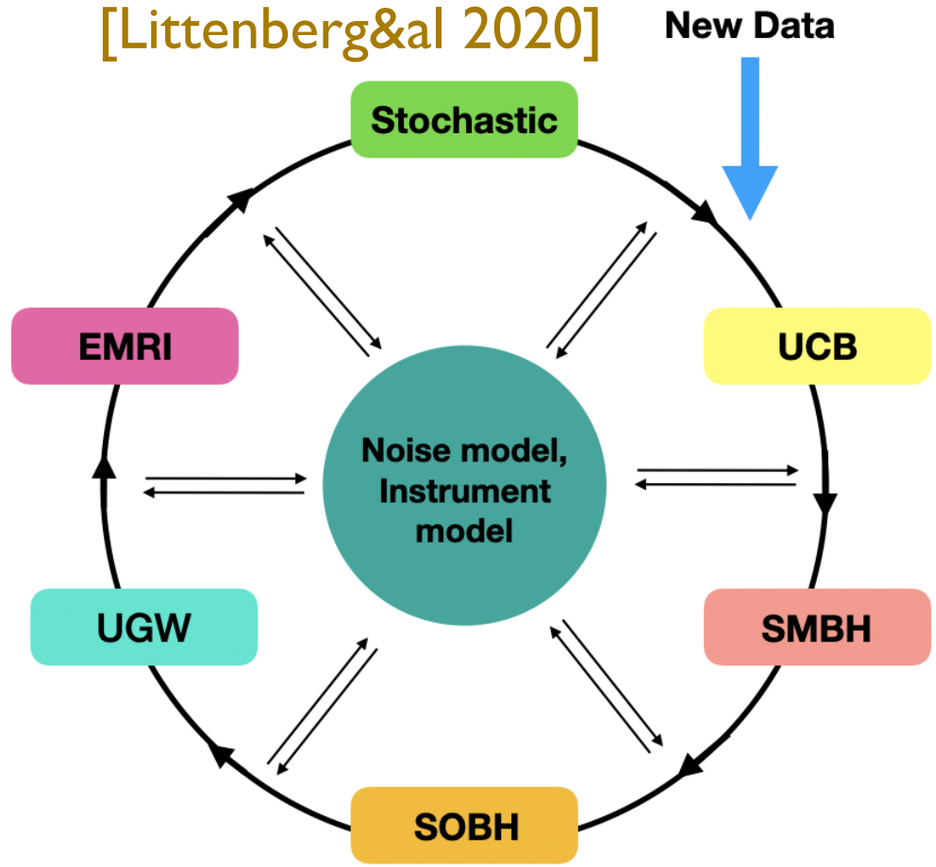
Global fit analysis

New post-doc
Sylvain Marsat

Past & current activities

- Collaborating with APC (GB analysis) for global fit : modular MBHB+GB

[Littenberg&al 2020]



Future prospects

- Arrival of a new postdoc on LISA data analysis and global fit
- **Delivering a global fit pipeline prototype for the end of phase B1**
- EMRI data analysis (new postdoc) + SBHBs
- More realistic MBHB waveforms

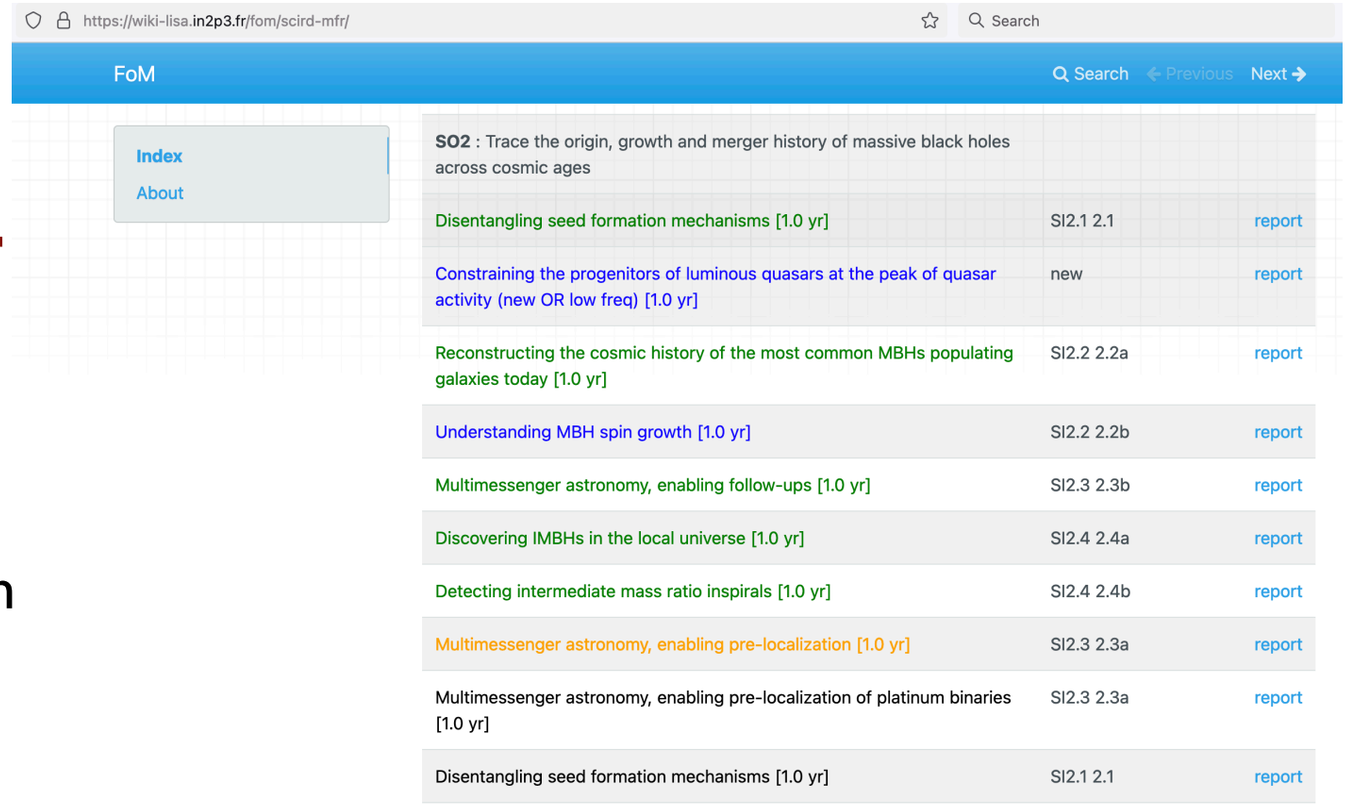
Fast analysis tools / Figures of Merit

Sylvain Marsat
Cayetano Santos

Past & current activities

- lisabeta used in present FOM

- Comparison of Fisher matrix tools in lisabeta and Etienne Savalle's code (ongoing)



Future prospects

- **Develop and maintain lisabeta as a tool to assess easily parameter recovery**

- Expand the scope of FOM to include parameter estimation : approximate or full

- Contribute other FOM: EM couterparts, cosmology, TGR, …

LISA MBHB localisation / multimessenger

Sylvain Marsat

Past & current activities

- LISA-Athena synergy : advance localisation

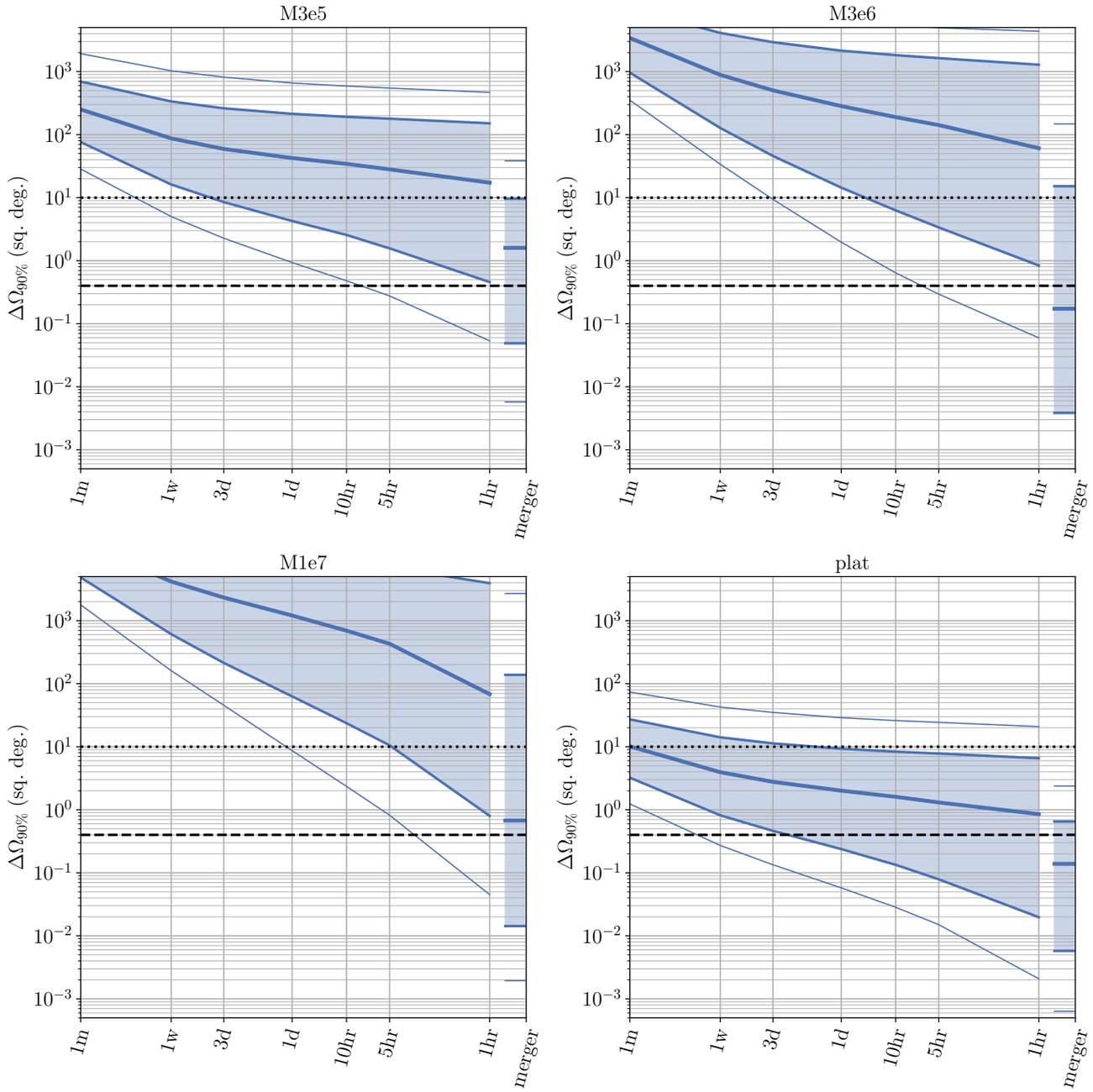
- Exploring LISA PE for MBHB in the FOM range (R. Cotesta, J. Hopkins)

- Exploring MBHB localisation with lisabeta

Future prospects

- Make lisabeta tools accessible to the astro. community (fits)

- Extend the analysis to more realistic waveforms



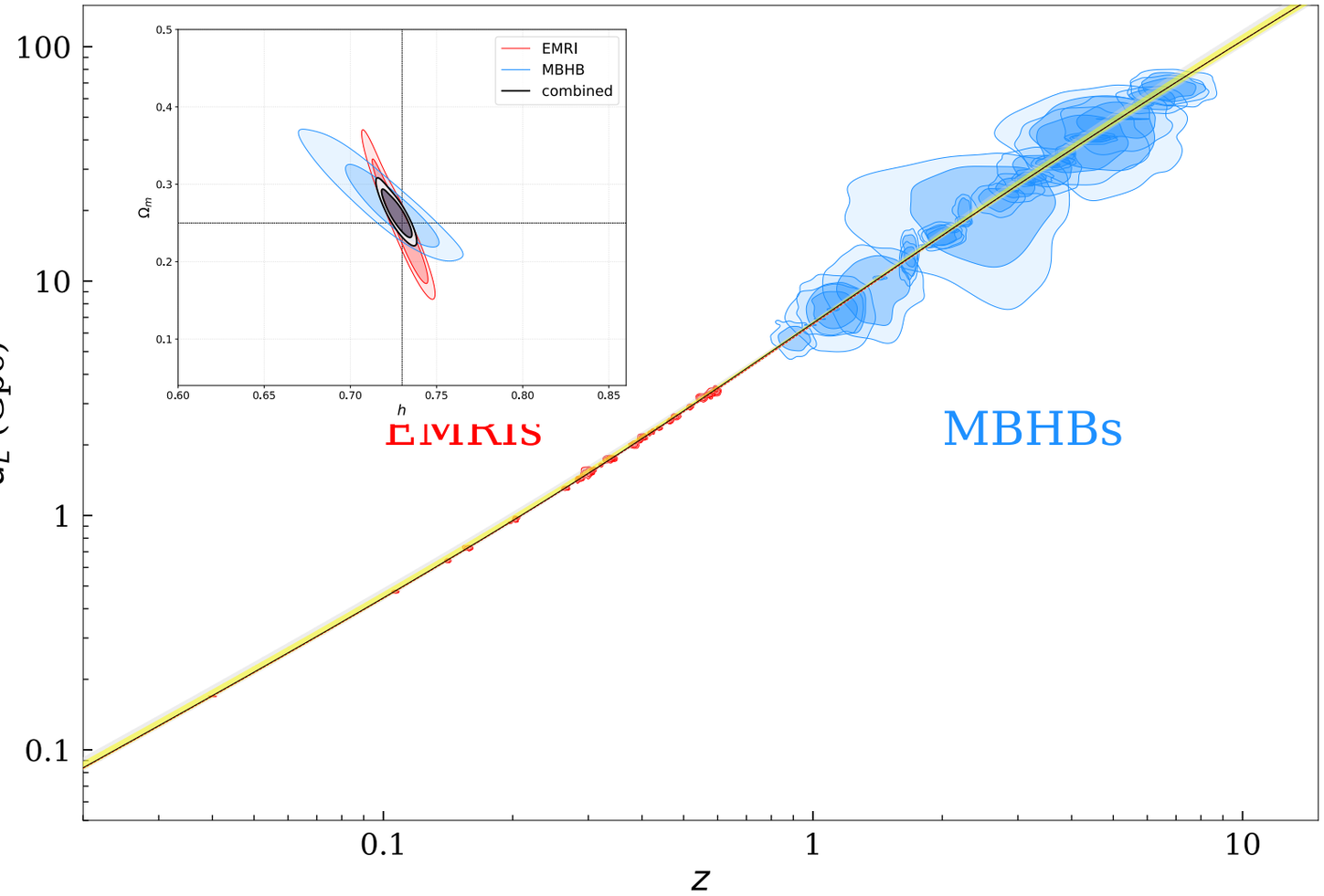
[Piro&al, in prep.]

Cosmology with LISA

Nicola Tamanini
Danny Laghi
Sylvain Marsat

Past & current activities

- cosmolisa: EMRI as dark sirens
- MBHB standard sirens: EM counterparts and cosmological inference (A. Mangiagli)



[Laghi&al 2022, in prep]

Future prospects

- Combining EMRI dark sirens with MBHB bright sirens in cosmological inference
- Build a pipeline for cosmological inference with LISA
- FOM for cosmology

Tests of GR with LISA

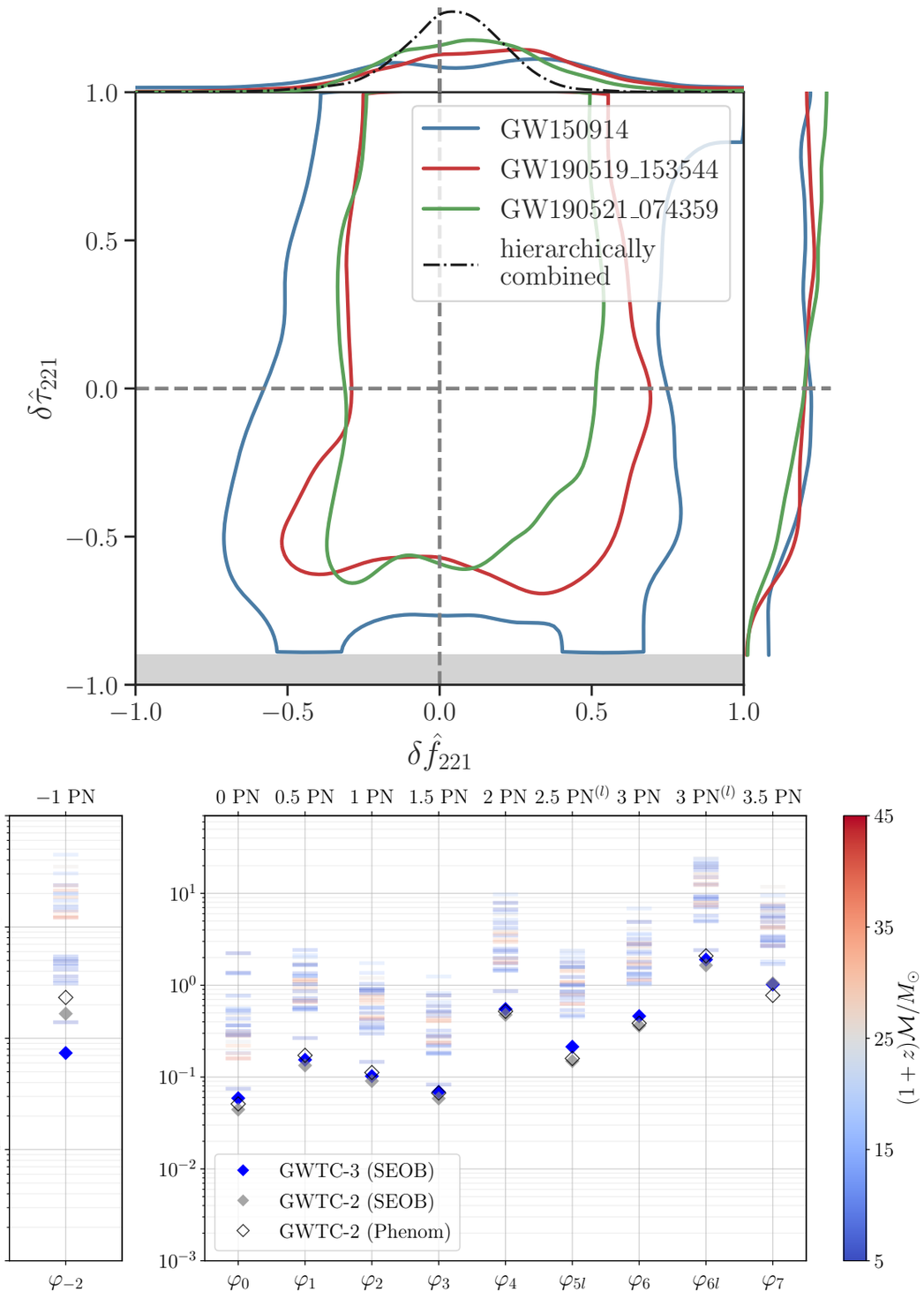
Danny Laghi
Sylvain Marsat

Past & current activities

- Ringdown tests for ground-based detectors (pyRing)
- Review activity for LVK TGR
- Ringdown tests for MBHBs (CEA, Johns Hopkins)

Future prospects

- Transpose TGR tools and experience to LISA
- TGR FOMs and pipelines



[LVK 2021]

LISA MBHB population inference

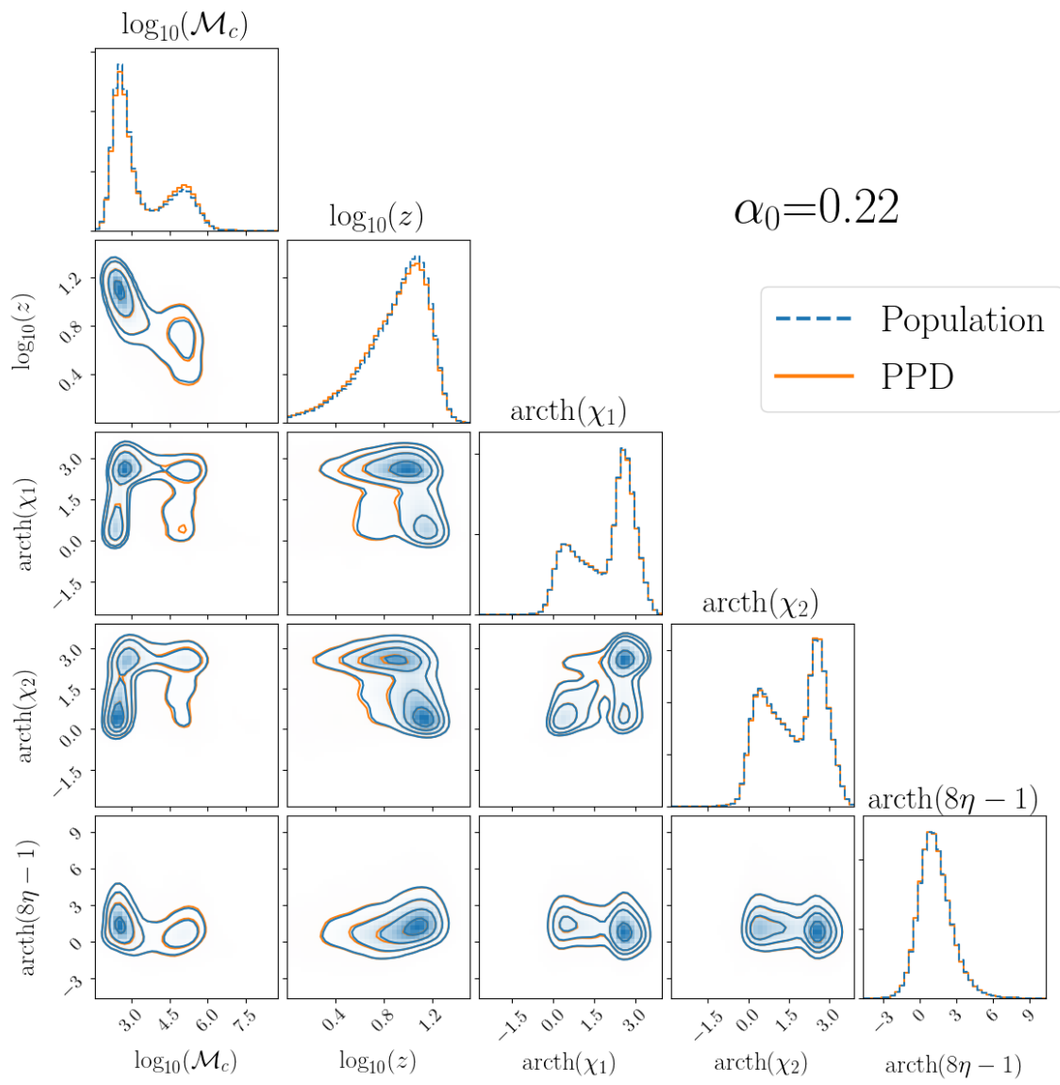
Vivienne Langen

Past & current activities

- Estimating the number of merging galaxies in deep MUSE fields, deduce the number of MBHB mergers (assumptions !)

Future prospects

- Hierarchical Bayesian analysis for an analytical parametrization of MBHB population
- FOM for MBHB population inference



(b)Mid-range case.

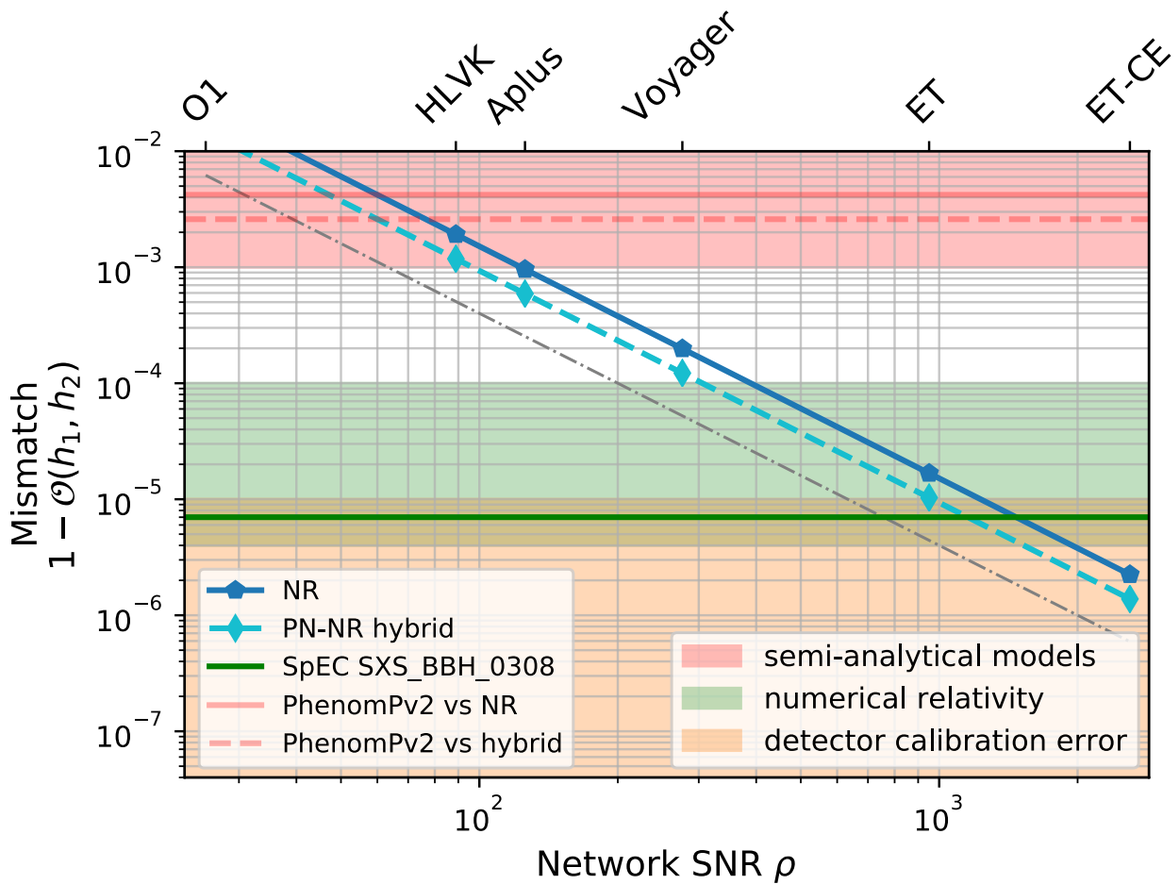
[Toubiana&al 2020]

LISA Waveform requirements

Sylvain Marsat

Past & current activities

- Understanding the map between the SNR and the waveform requirement in terms of mismatch, for LISA MBHBs (with J. Hopkins, AEI)



[Pürrer-Haster 2019]

Future prospects

- More realistic waveform models : precession, eccentricity

- Waveform requirements for MBHBs, SBHBs, EMRIs …

Machine Learning applications

All ?

Past & current activities

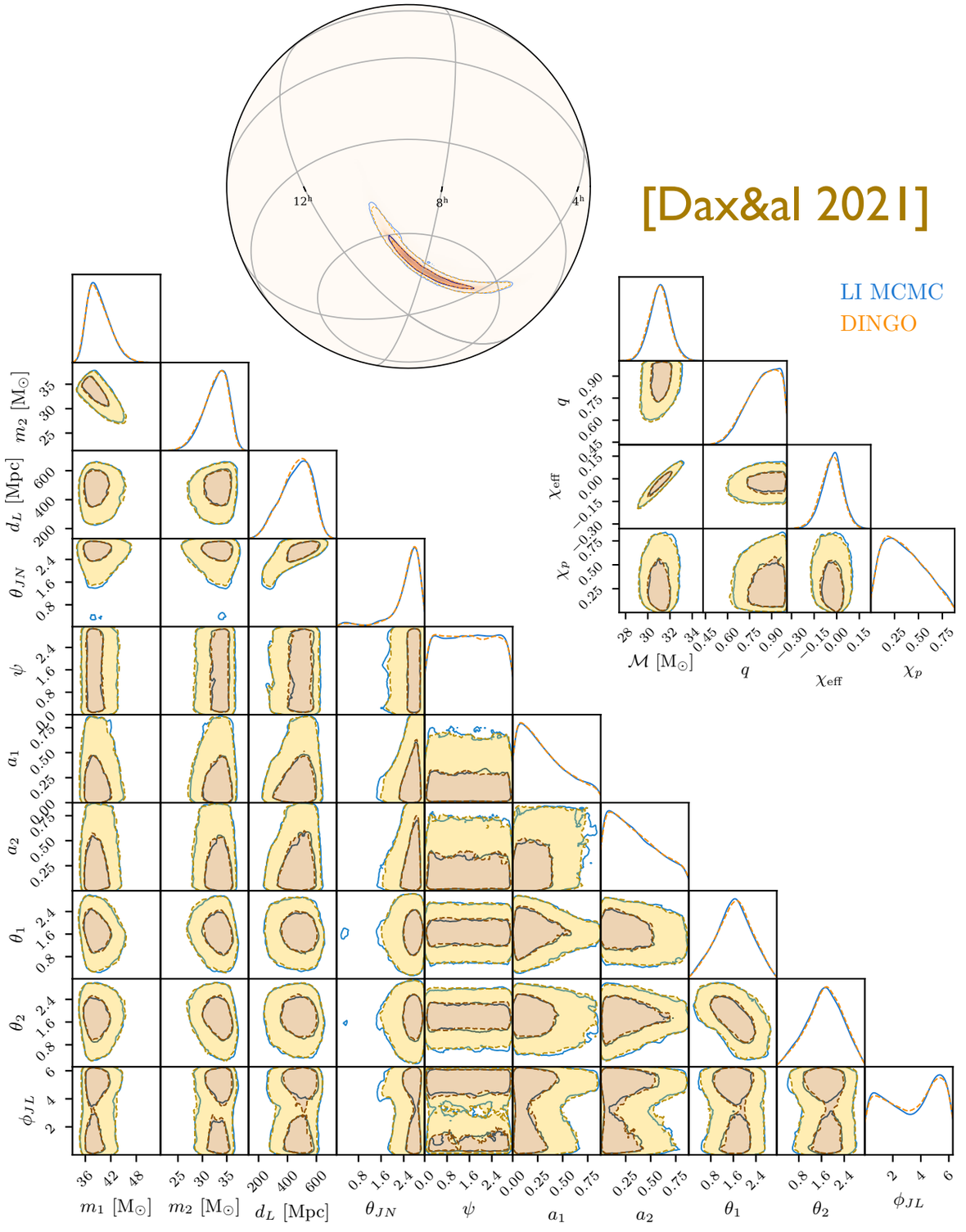
- Learning !

- Local expertise (particle physics) : graph neural networks for LHC data analysis (Sylvain Caillou, Catherine Biscarat, Charline Rougier, Jan Stark)

Future prospects

- Bayesian parameter estimation with machine learning methods

- Incorporate physics into network architecture : parameter maps for multimodality ?



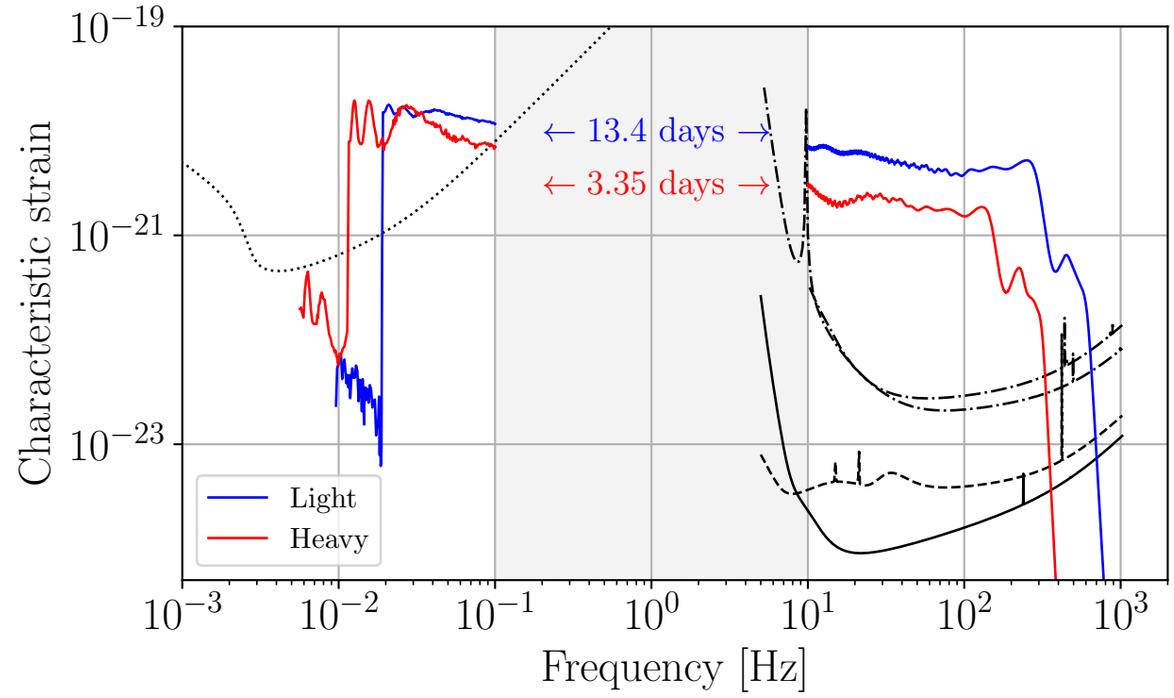
[Dax&al 2021]

Multiband GW observations

Sylvain Marsat
Danny Laghi

Past & current activities

- Bayesian PE for SBHB of GWTC-3
- Tools for multiband analysis in lisabeta (ongoing)



[Klein&al 2022]

Future prospects

- More realistic waveforms
- Acceleration techniques
- SBHB detection and archival searches
- Low-SNR contribution from LISA

LISA SBHB environment

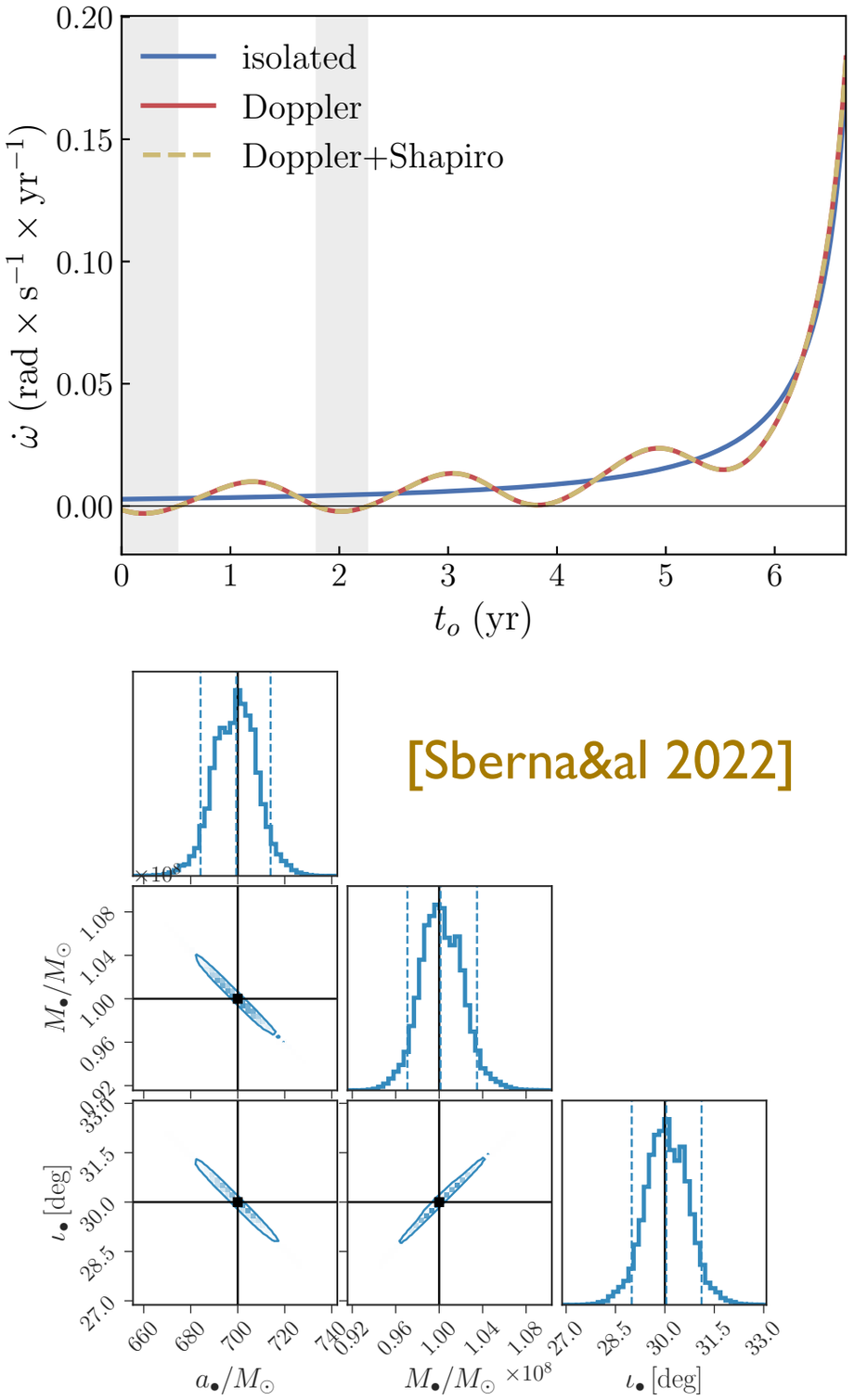
Sylvain Marsat
Nicola Tamanini

Past & current activities

- Environmental effects on GW from a SBHB in orbit around an AGN
- Doppler delay, Shapiro delay + lensing and amplitude modulations

Future prospects

- Understanding these systems as laboratories for fundamental physics : collection of relativistic effects
- Make data analysis robust with respect to these effects



[Sberna&al 2022]

LISA: TDE and other astrophysical sources

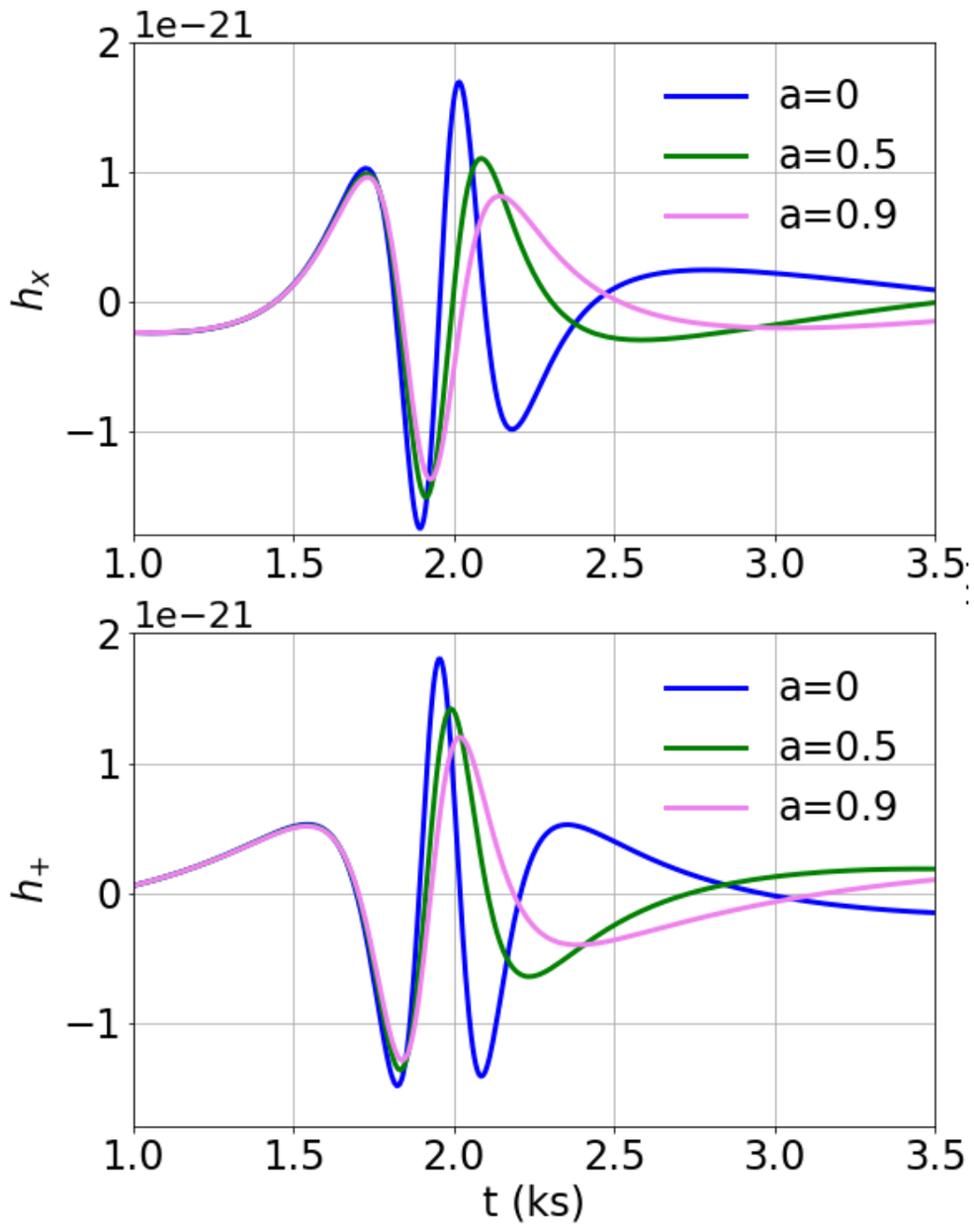
Martina Toscani

Past & current activities

- SPH numerical simulations (Phantom) for TDEs and associated GWs

Future prospects

- TDEs, lensing of GW signals



[Toscani&al 2021]