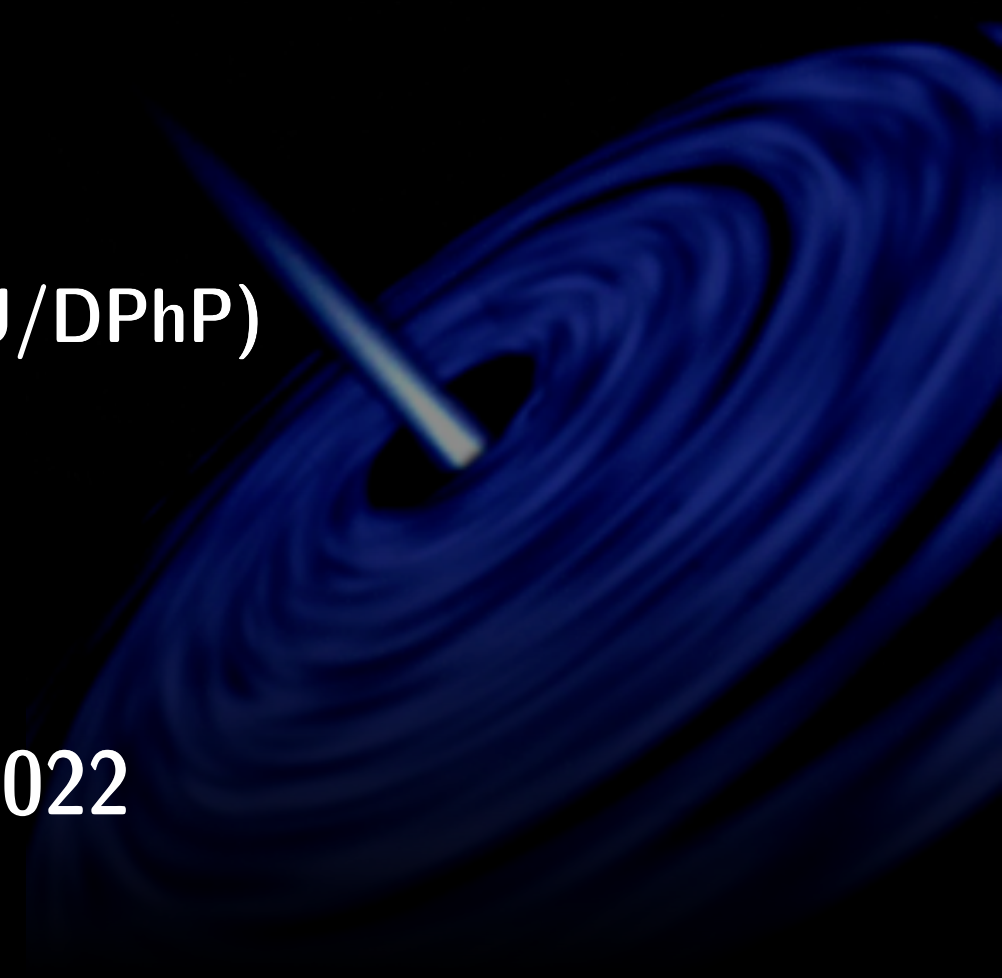
LISA Data Processing

Antoine Petiteau (CEA/IRFU/DPhP)

LISA Greece

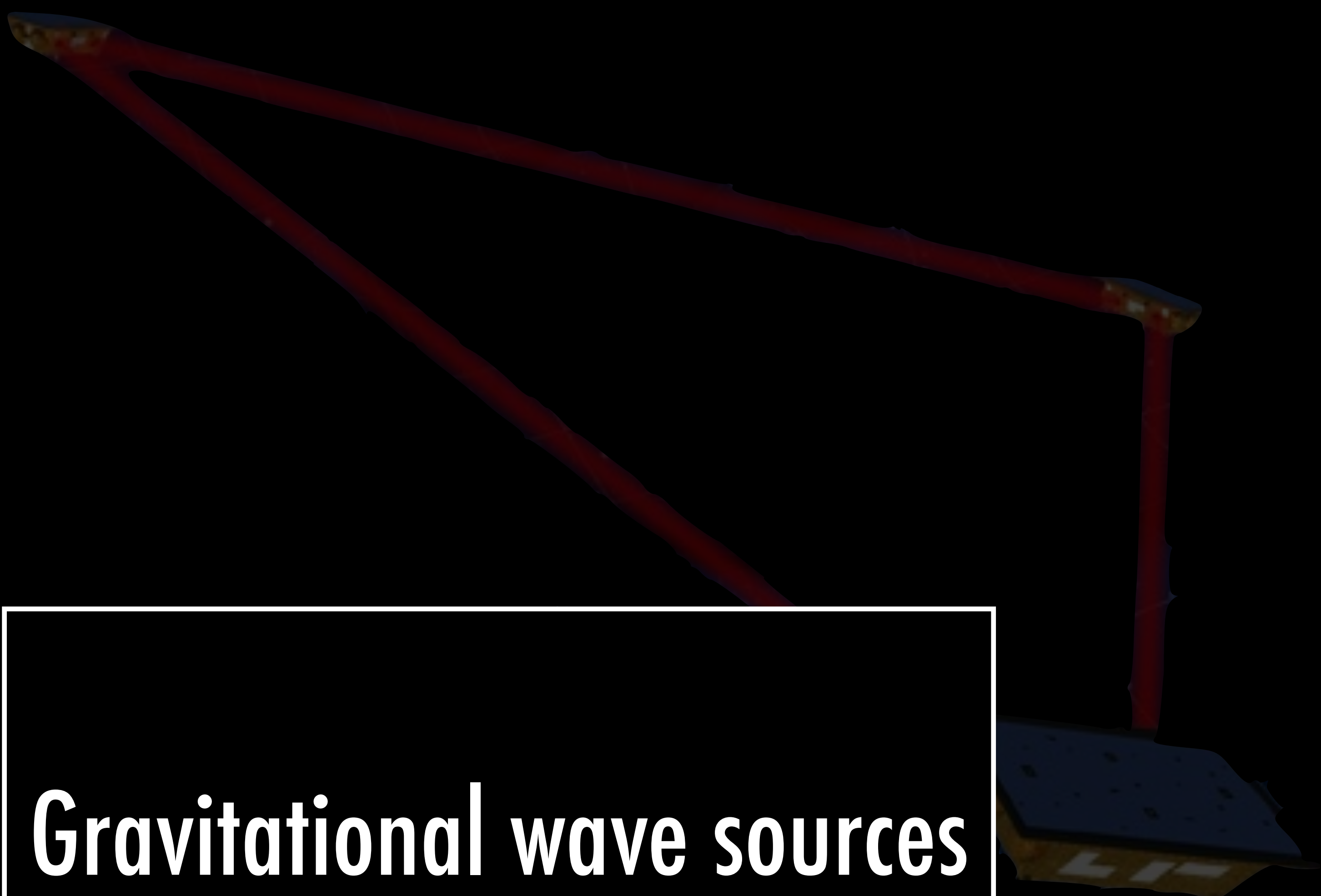
Remote - 23 February 2022



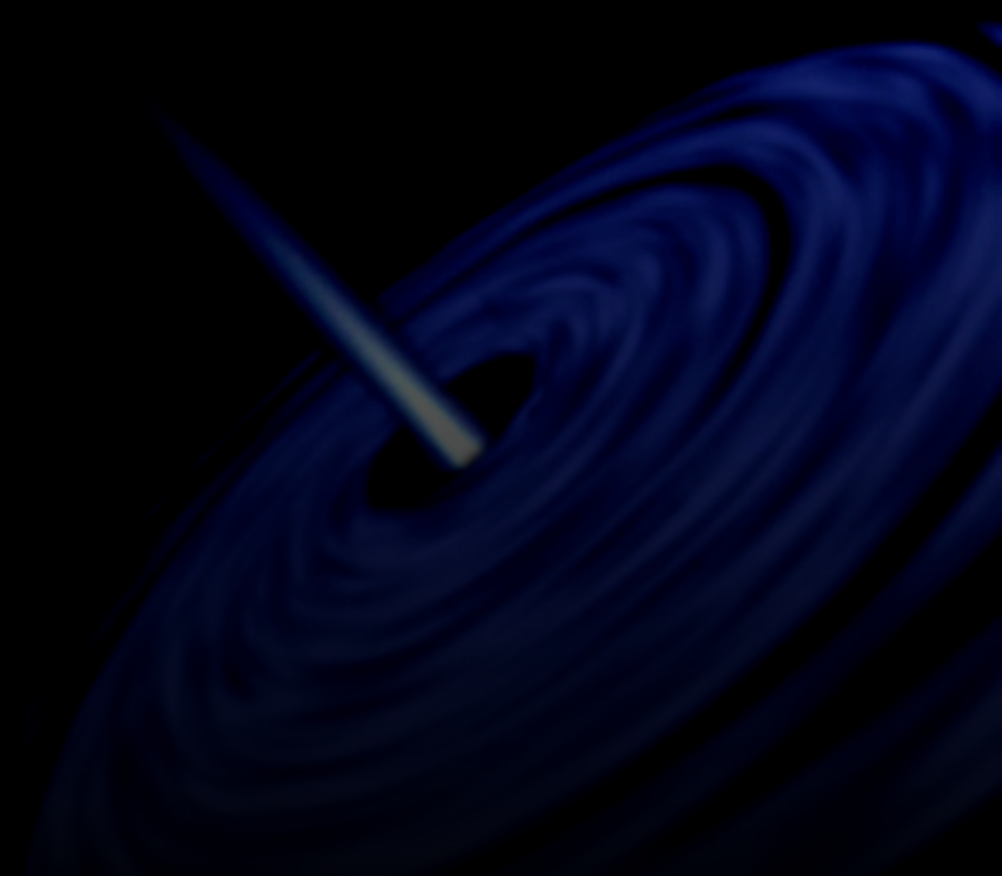
Contents

- Overview of LISA Data
- Data analysis and processing concepts
- Ground segment organisation and development
- On going activities

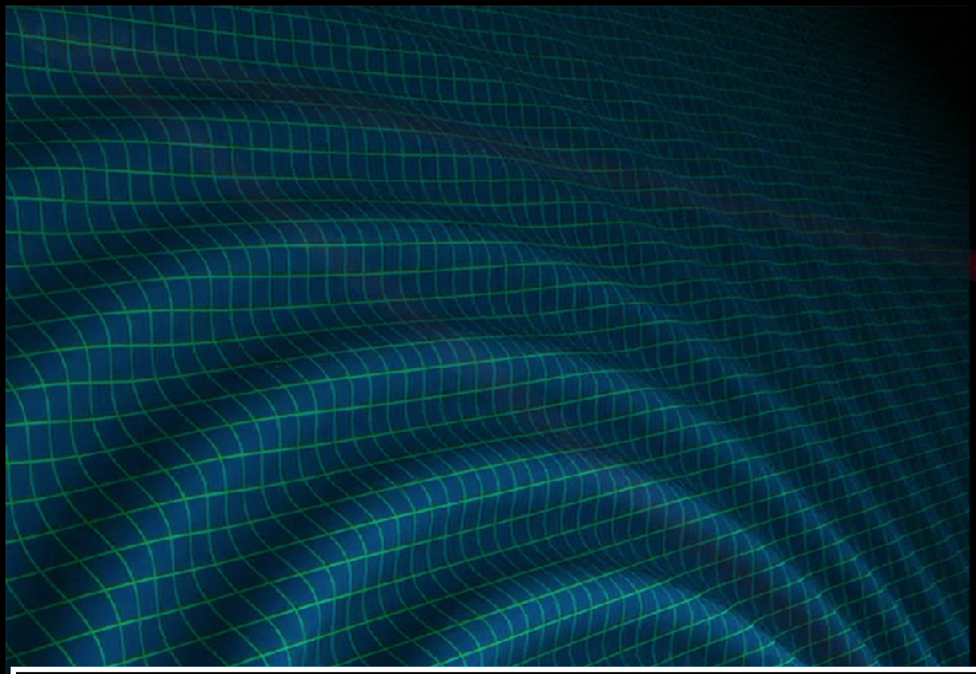
LISA data



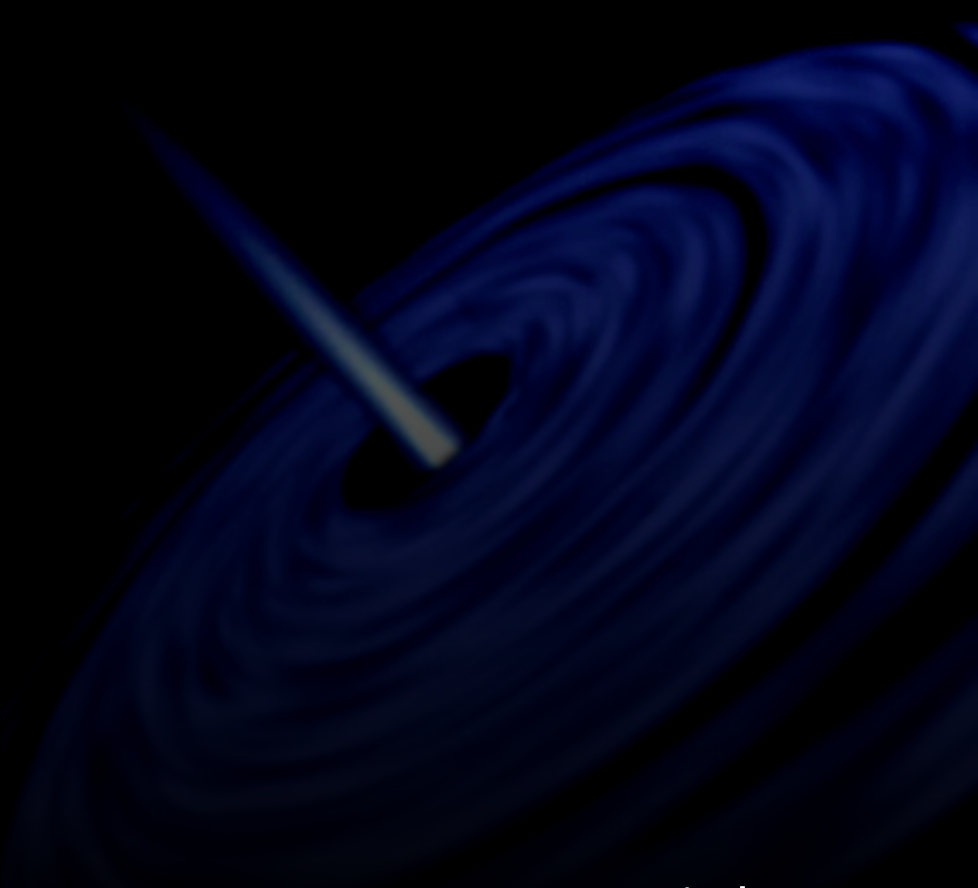
Gravitational wave sources emitting between 0.02mHz and 1 Hz



LISA data

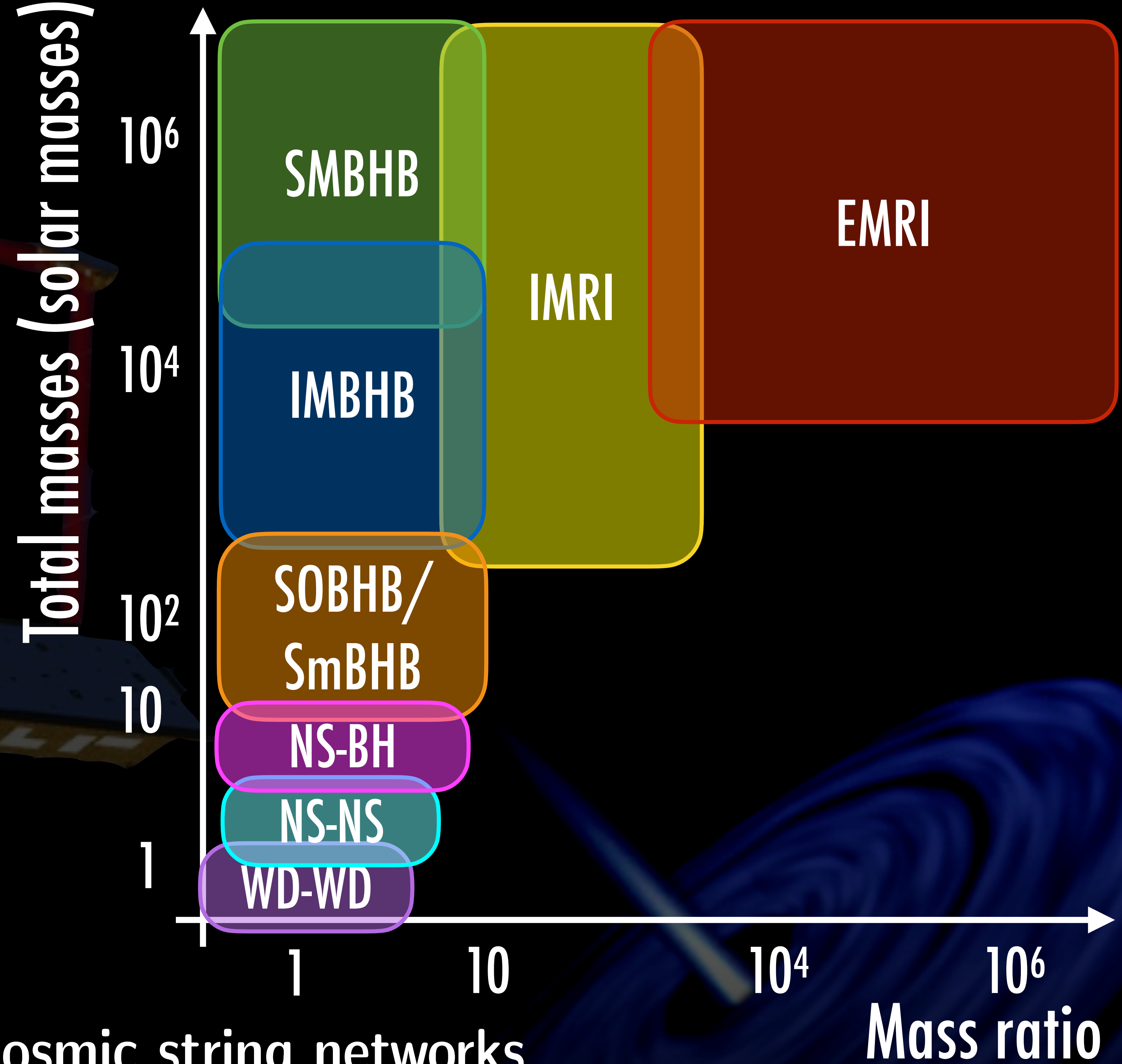


Gravitational wave sources emitting between 0.02mHz and 1 Hz



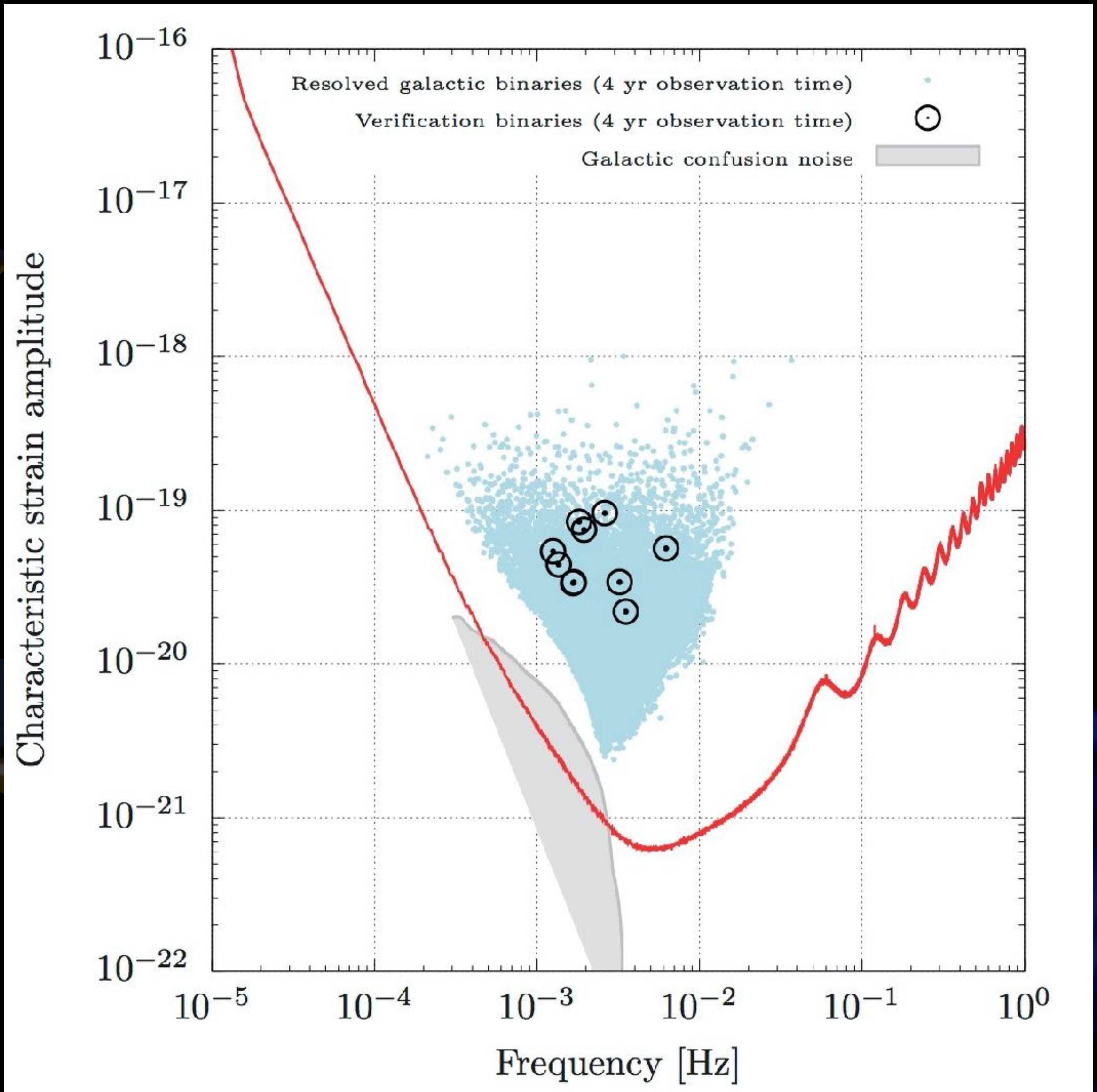
GW sources in the mHz band

- Binaries: large range of masses and mass ratios:
  - SuperMassive BH Binaries
  - Extreme Mass Ratio Inspiral
  - Stellar mass BH Binaries
  - Double White Dwarfs
  - Double Neutron Stars
  - Intermediate Mass Ratio Inspiral
  - Intermediate Mass BH Binaries
- Stochastic backgrounds:
  - First order phase transitions, cosmic string networks, …
- Bursts: cosmic strings, …
- Unknown?



Galactic binaries

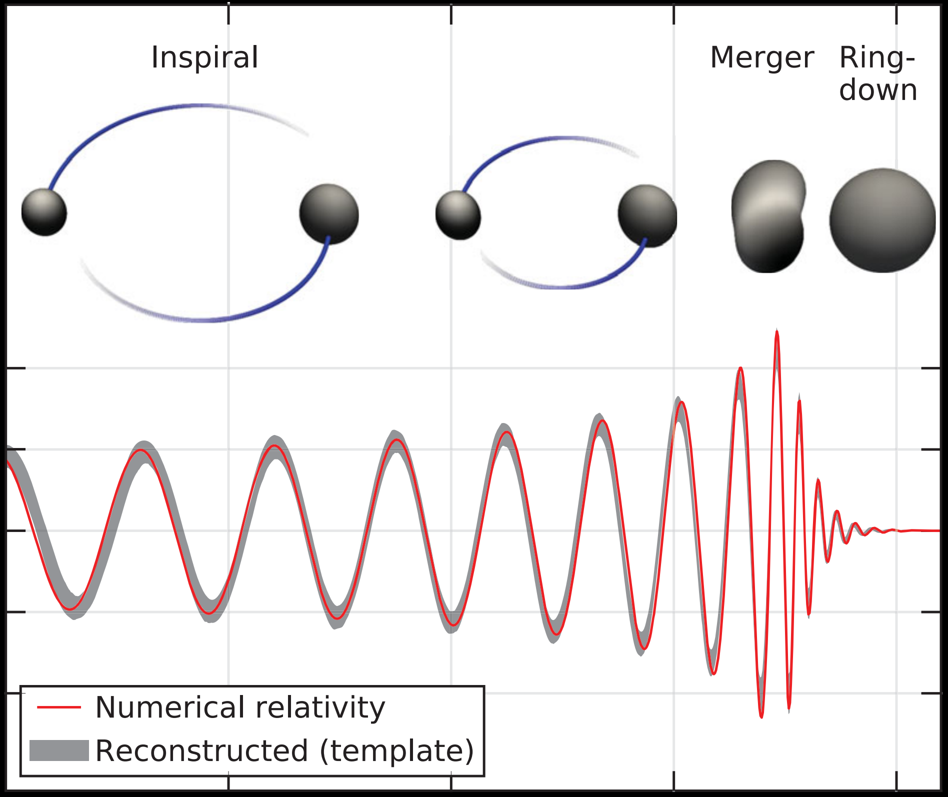
- Binaries with White Dwarfs and Neutrons Stars
- In the Galaxy: 30 millions.
- GW waveform: quasi-monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources

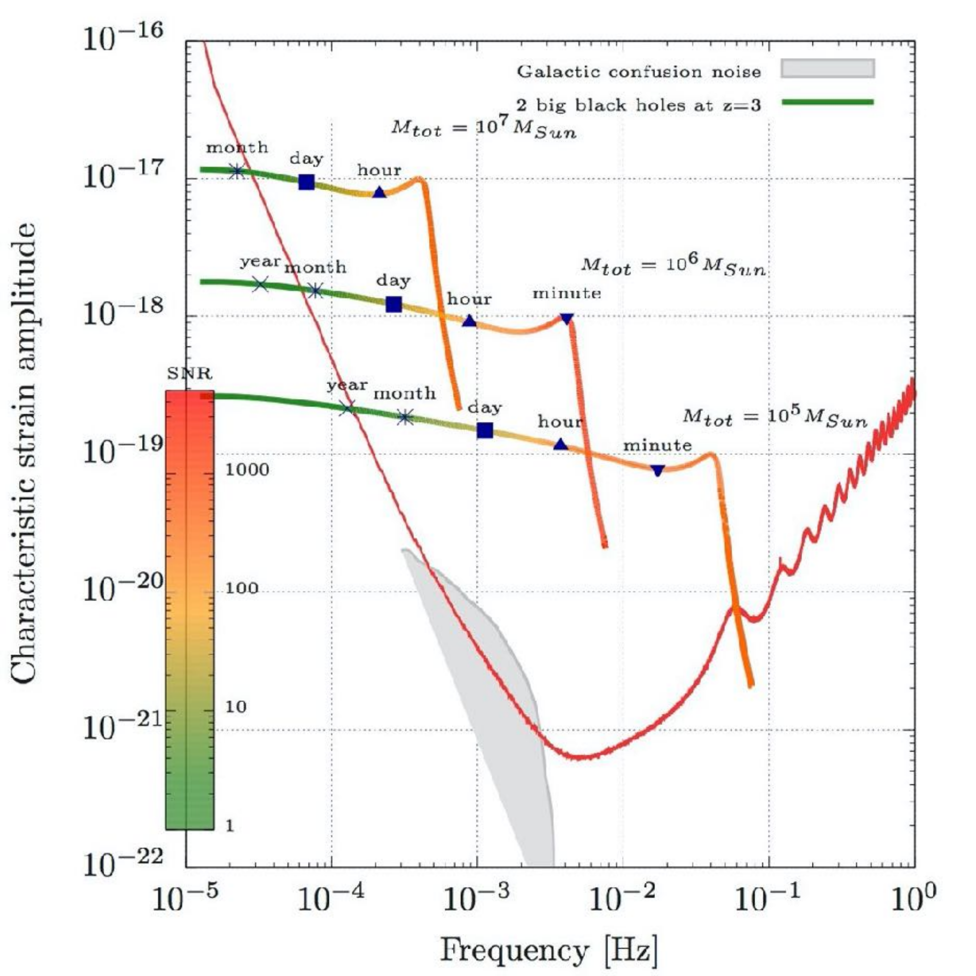


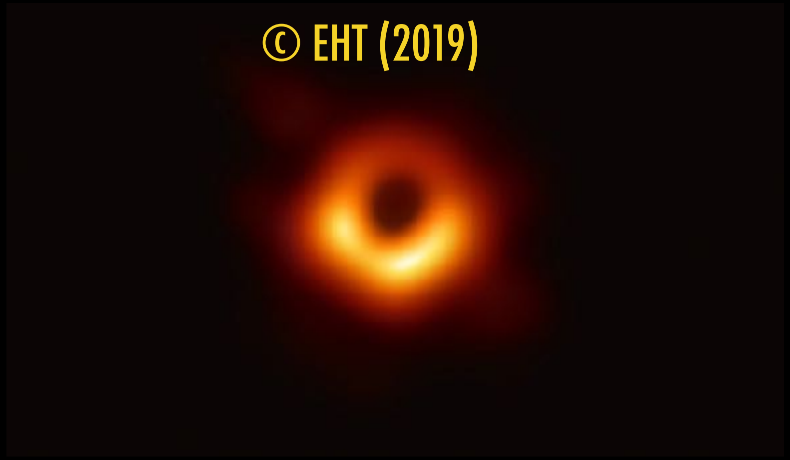
- Event rate:
  - 25 000 detected sources (over 30 millions sources)
  - 17 guarantied sources (verification binaries) now more are expected (GAIA, …)

Super Massive Black Hole Binaries

- Mass $> 10^5\ M_{Sun}$
- GW waveform:
  - Inspiral: Post-Newtonian
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.
- Inspiral at frequency $<$ 10 mHz
- Merger and ringdown around mHz
- 10 - 100 events per year



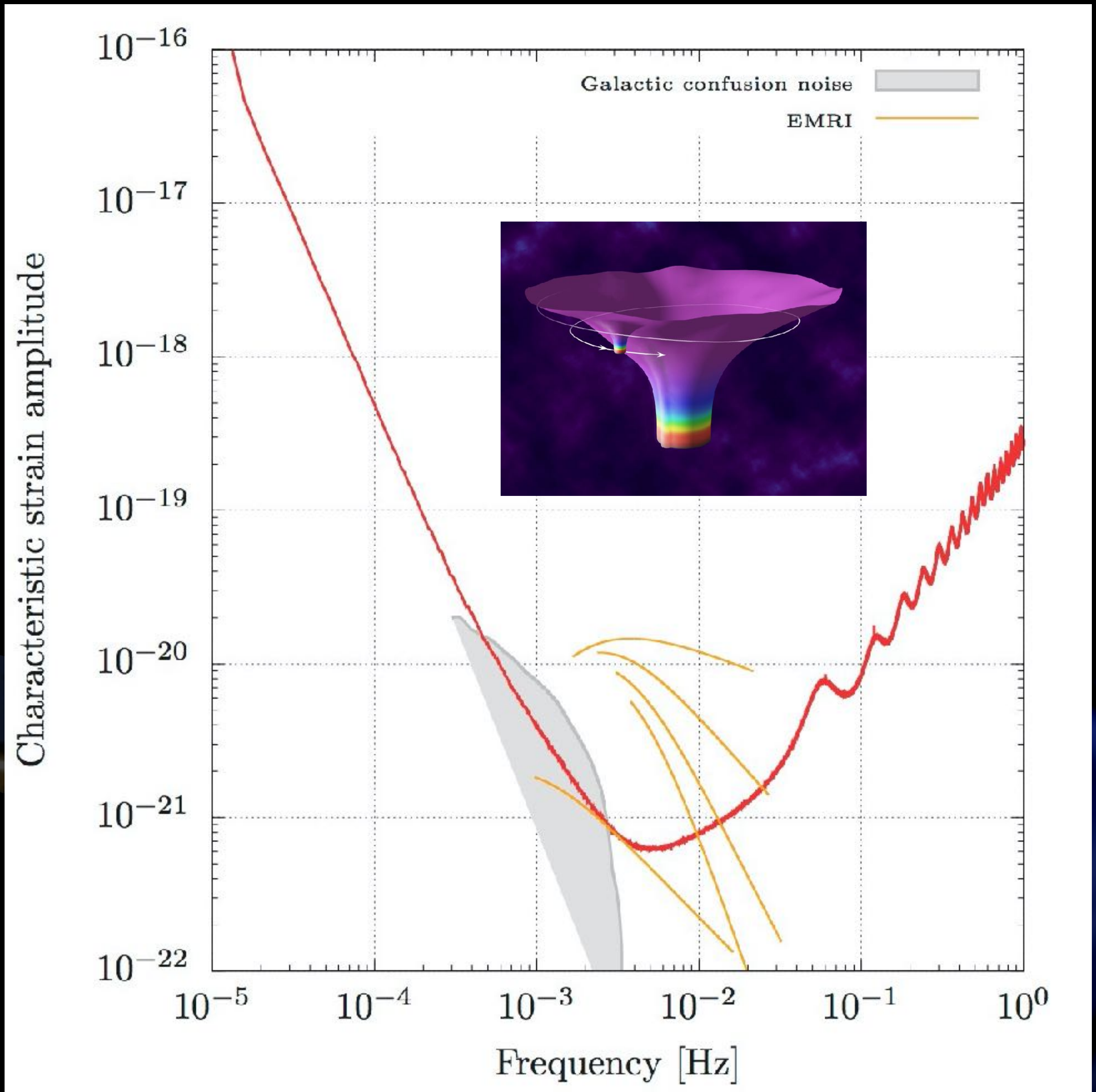



© EHT (2019)


© Vincent, Paumard, Gourgoulhon, Perrin (2011)

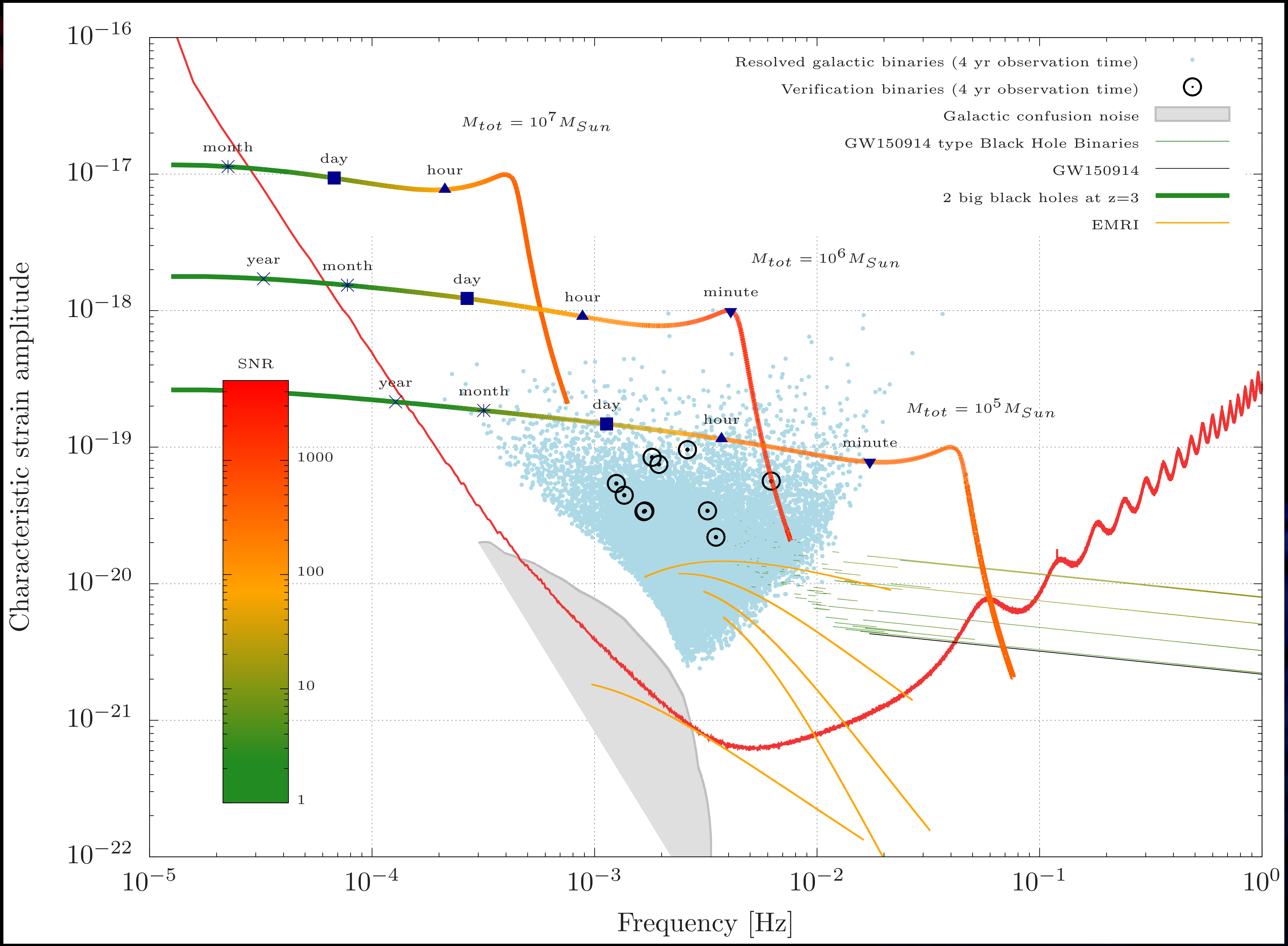
EMRIs

- GW waveform:
  - Very complex waveform
  - Multiple harmonics
  - No long & precise simulation at the moment
- Duration: about 1 year
- Signal to Noise Ratio: from tens to few hundreds



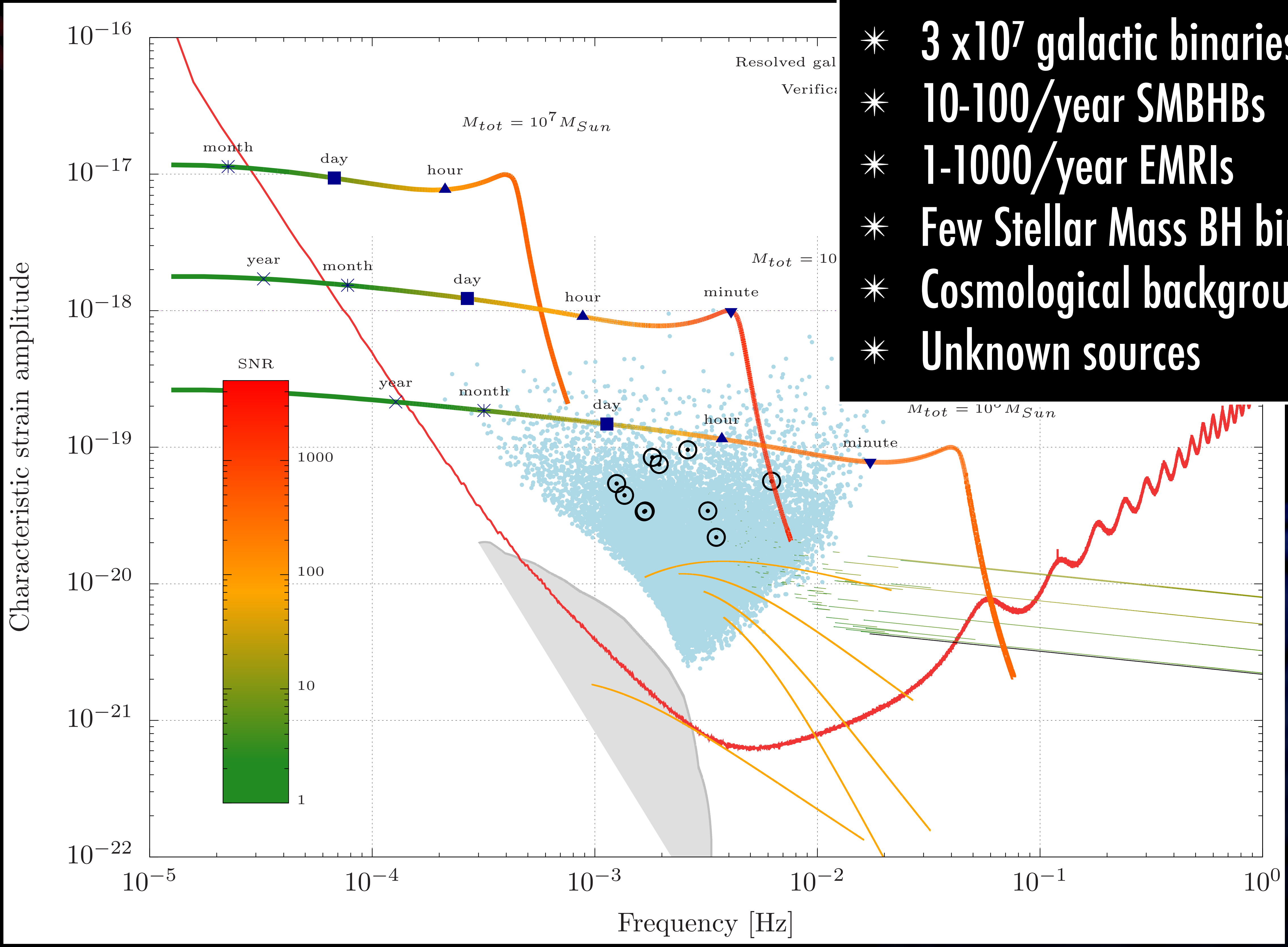
- Event rate: from few events per year to few hundreds

GW sources



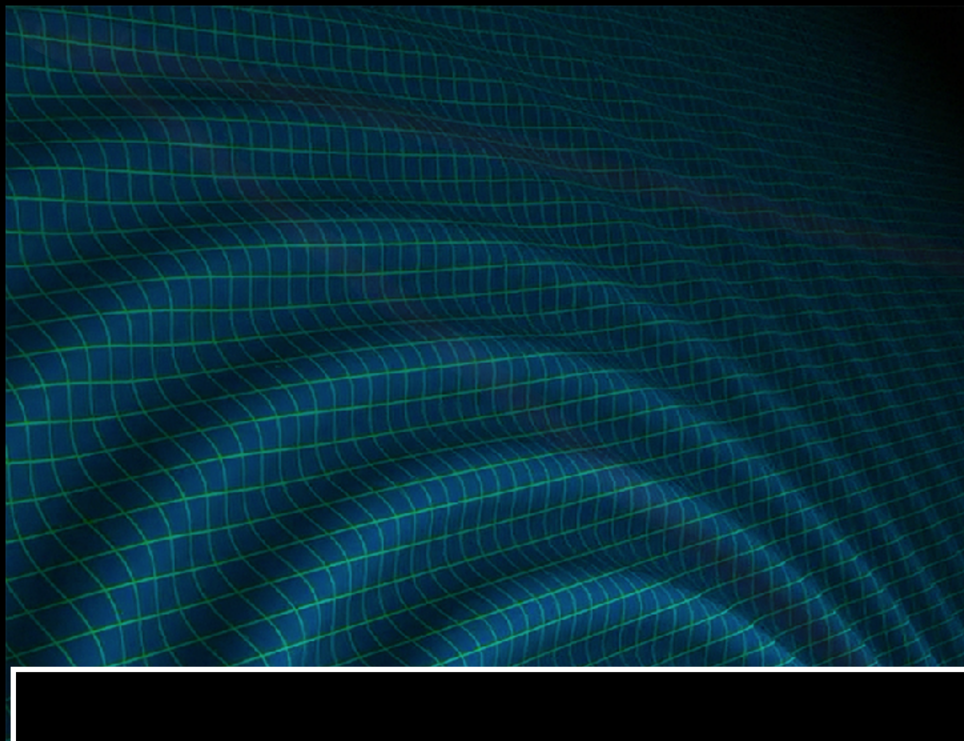
Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole Binaries
GW150914
2 big black holes at z=3
EMRI
$M_{tot} = 10^7 M_{Sun}$
$M_{tot} = 10^6 M_{Sun}$
$M_{tot} = 10^5 M_{Sun}$
month
day
hour
year
minute
SNR
1000
100
10
1
Characteristic strain amplitude
Frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

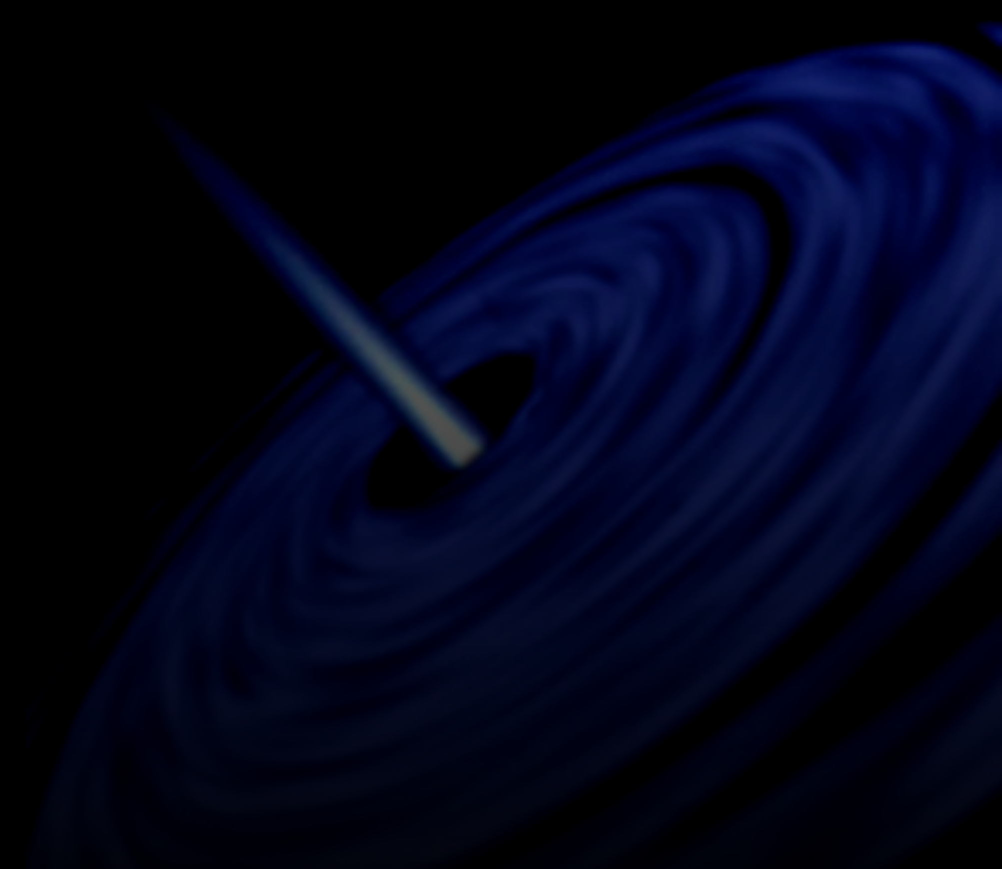
GW sources



- 3 x10⁷ galactic binaries
- 10-100/year SMBHBs
- 1-1000/year EMRIs
- Few Stellar Mass BH binaries
- Cosmological backgrounds
- Unknown sources

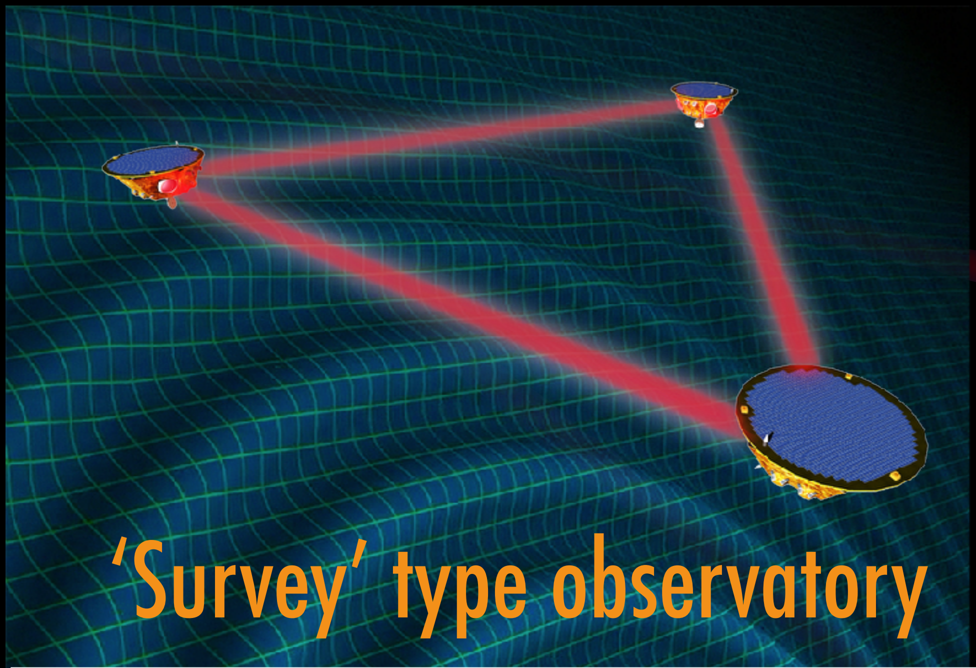
LISA data



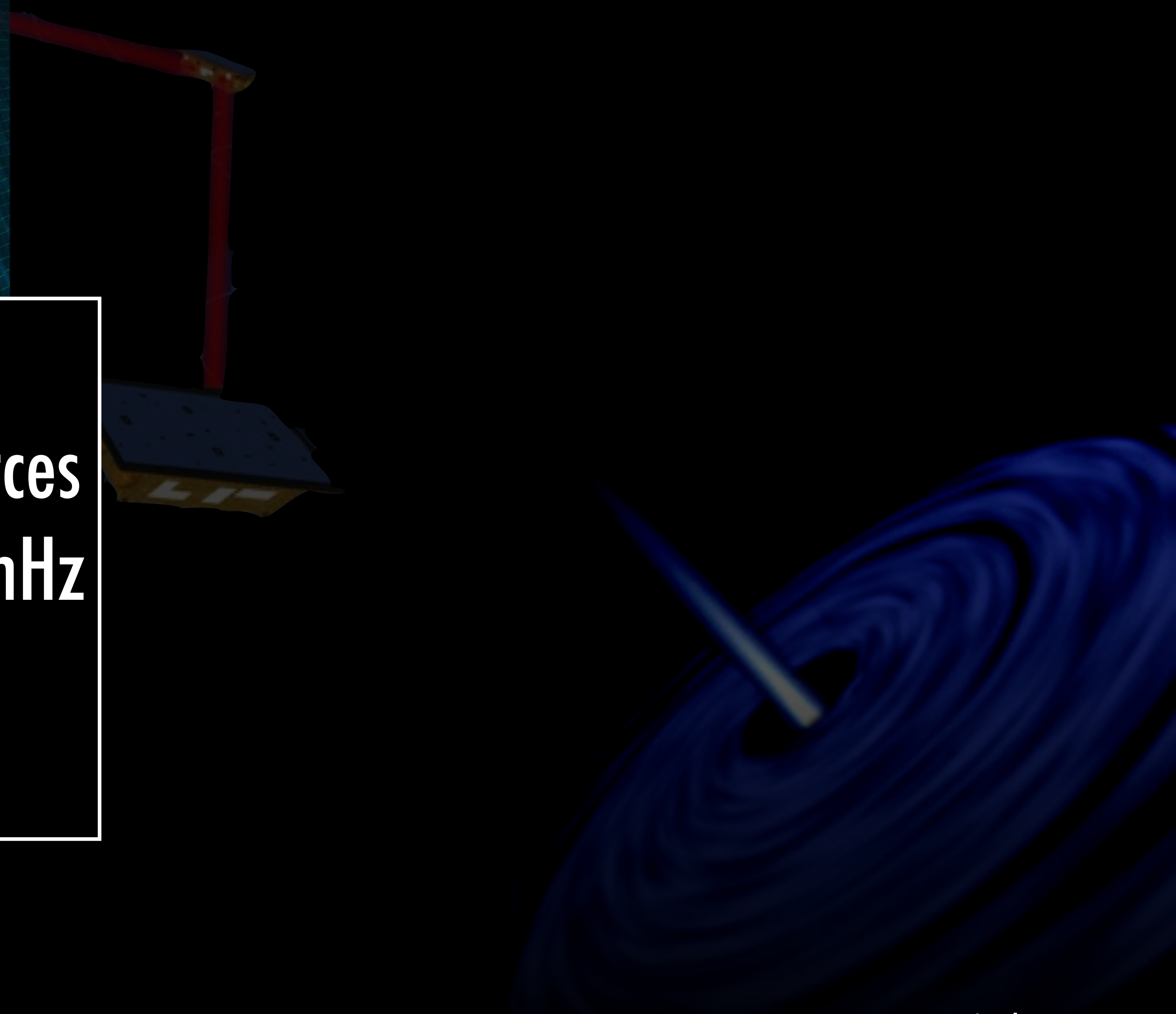


Gravitational wave sources emitting between 0.02mHz and 1 Hz

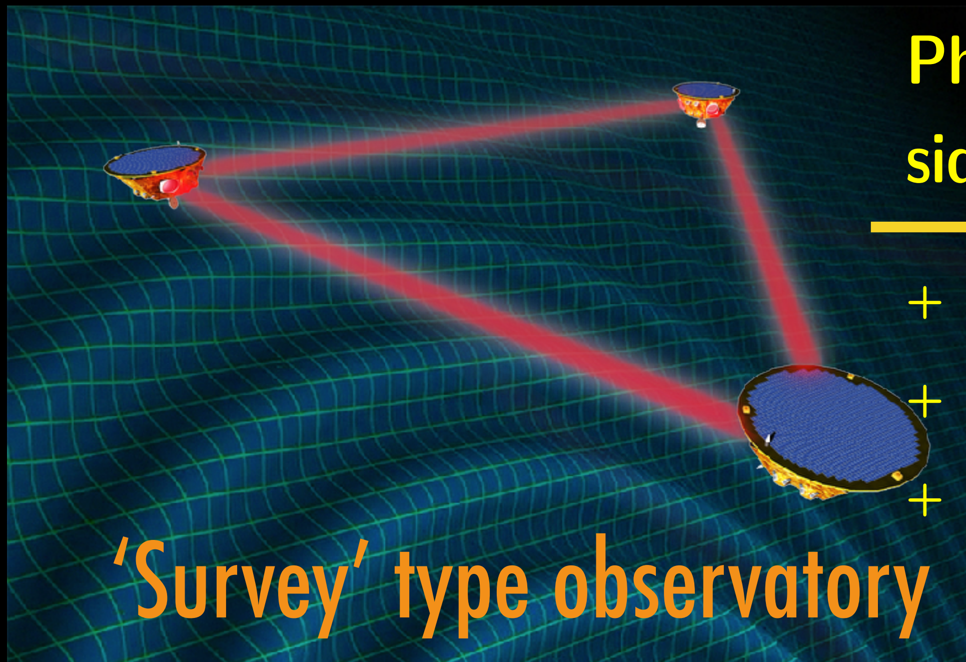
LISA data



Gravitational wave sources emitting between 0.02mHz and 1 Hz



LISA data



Phasemeters (carrier, sidebands, distance)

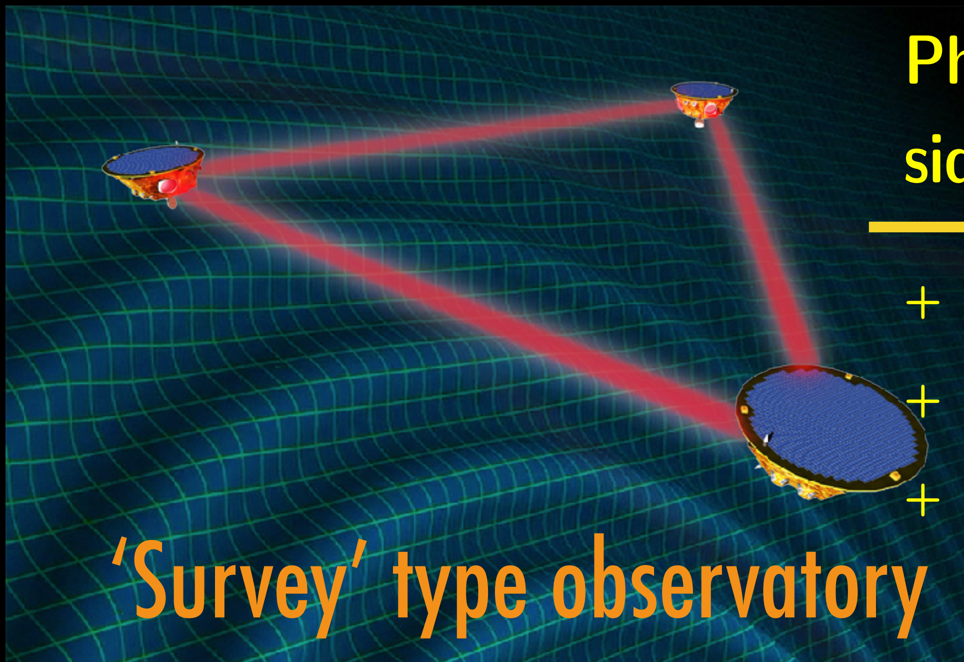
- + DFACS* & CMD**
- + Diagnostics
- + Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

LISA data



Phasemeters (carrier, sidebands, distance)

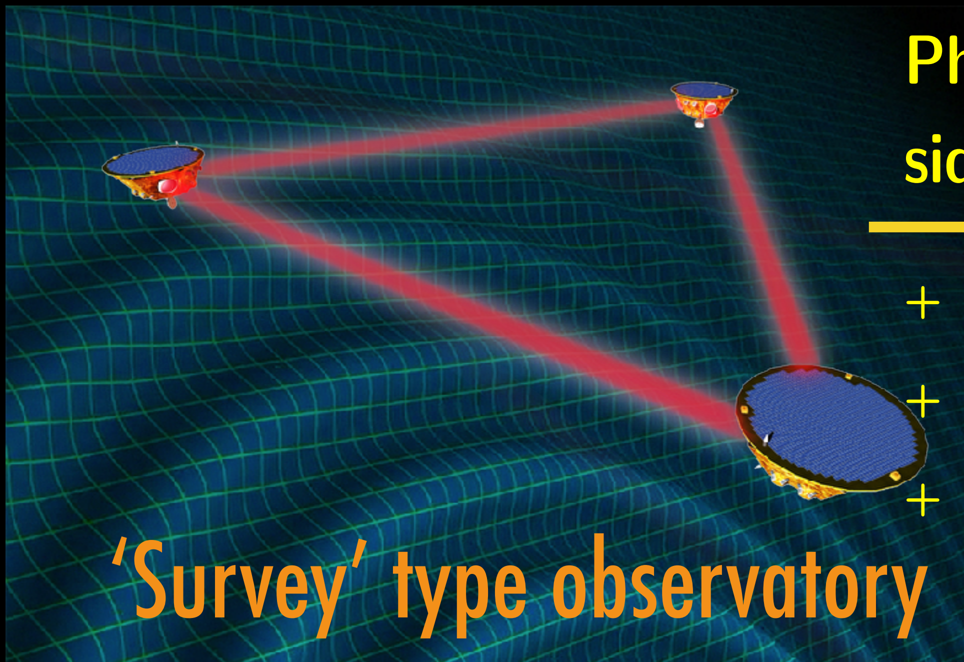
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

LISA data



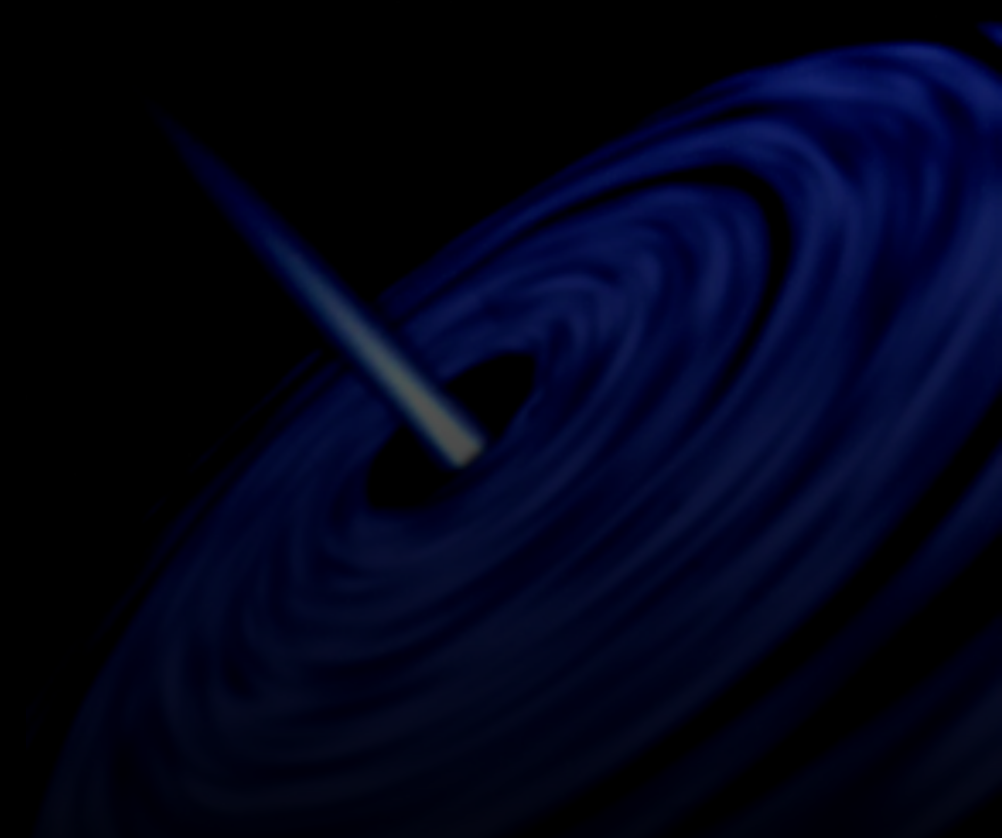
Phasemeters (carrier, sidebands, distance)

L0

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0.5

Gravitational wave sources emitting between 0.02mHz and 1 Hz



* Drag-Free Attitude Control System

** Charge Management Device

LISA data

- Data provided to the Ground Segment:

  Daily a time segment of 24h corrected for transmission error

  + Near real-time raw data stream during communication periods (about 8h per day)

- Content of reformatted telemetered data, L0.5:
  - GW sources: all sources together (overlapping)
  - Dominant noises: laser (8 orders of magnitude higher than GWs), clock noise, Tilt-To-Length, ...
  - Secondary noises
  - Instrument artefacts: gaps, glitches, spectral lines, non-stationarities,...

LISA data

- Data provided to the Ground Segment:

  Daily a time segment of 24h corrected for transmission error

  + Near real-time raw data stream during communication periods (about 8h per day)

- Content of reformatted telemetered data, L0.5:
  - GW sources: all sources together (overlapping)
  - Dominant noises: laser (8 orders of magnitude higher than GWs), clock noise, Tilt-To-Length, ... → To be reduced
  - Secondary noises
  - Instrument artefacts: gaps, glitches, spectral lines, non-stationarities,...

LISA data

- Data provided to the Ground Segment:

  Daily a time segment of 24h corrected for transmission error

  + Near real-time raw data stream during communication periods (about 8h per day)

- Content of reformatted telemetered data, L0.5:
  - GW sources: all sources together (overlapping) → To be separated and extracted
  - Dominant noises: laser (8 orders of magnitude higher than GWs), clock noise, Tilt-To-Length, ... → To be reduced
  - Secondary noises
  - Instrument artefacts: gaps, glitches, spectral lines, non-stationarities,...

LISA data

- Data provided to the Ground Segment:

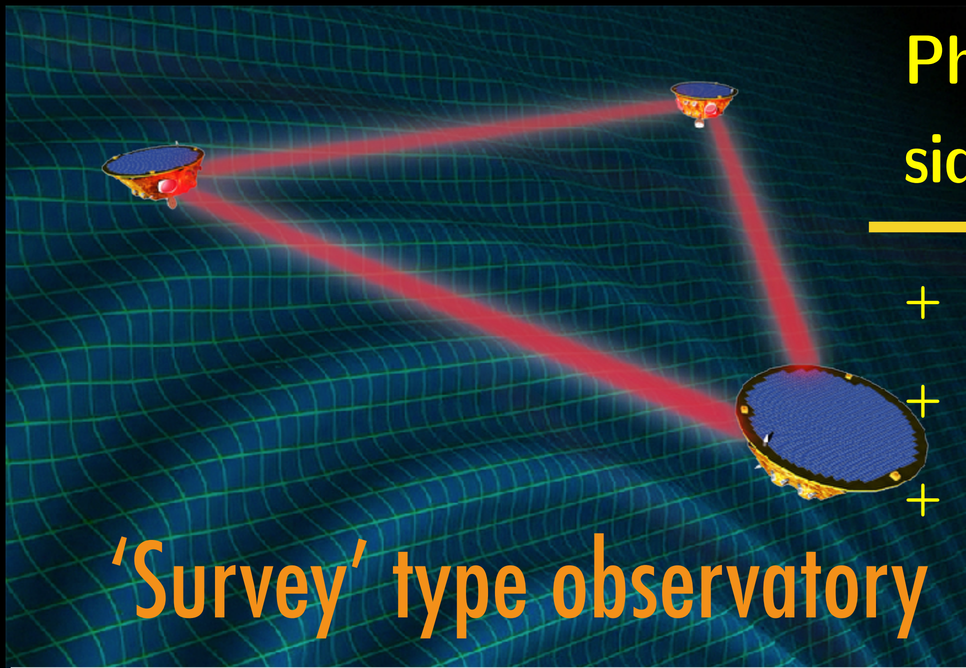
  Daily a time segment of 24h corrected for transmission error

  + Near real-time raw data stream during communication periods (about 8h per day)

- Content of reformatted telemetered data, L0.5:
  - GW sources: all sources together (overlapping) → To be separated and extracted
  - Dominant noises: laser (8 orders of magnitude higher than GWs), clock noise, Tilt-To-Length, ... → To be reduced
  - Secondary noises
  - Instrument artefacts: gaps, glitches, spectral lines, non-stationarities,...

Challenge for data analysis

LISA data



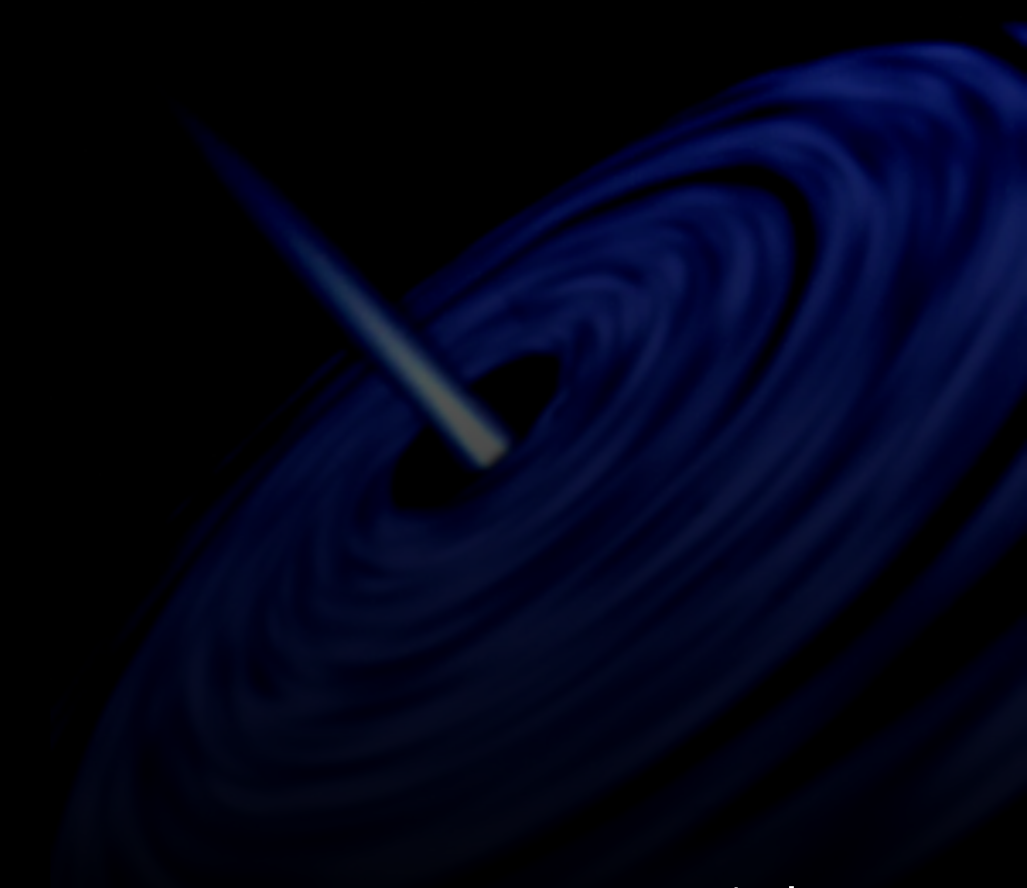
Phasemeters (carrier, sidebands, distance)

L0

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0.5

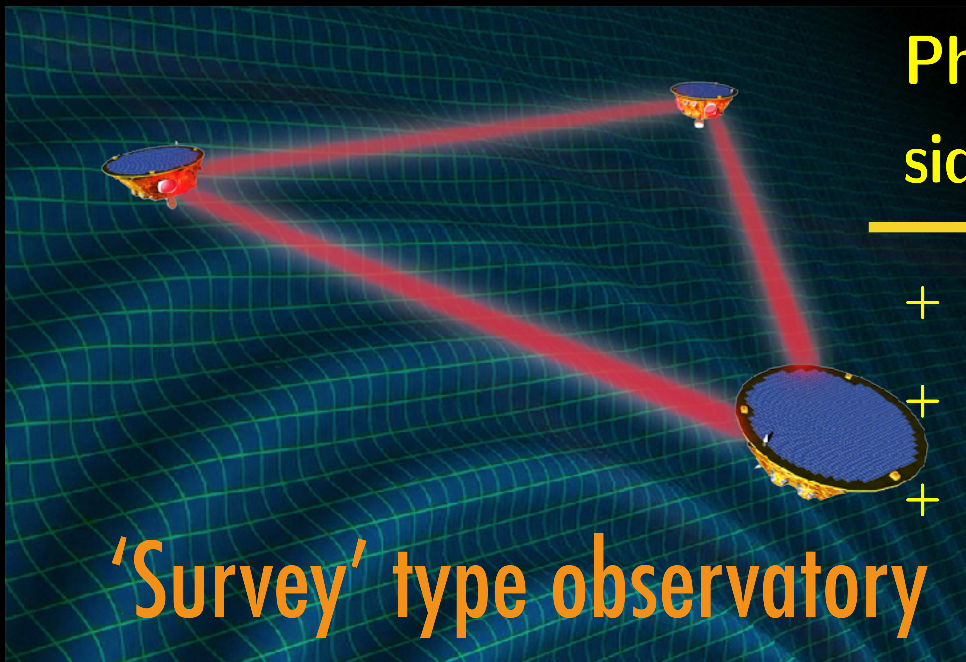
Gravitational wave sources emitting between 0.02mHz and 1 Hz



* Drag-Free Attitude Control System

** Charge Management Device

LISA data



Phasemeters (carrier, sidebands, distance)

L0

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0.5

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

L1

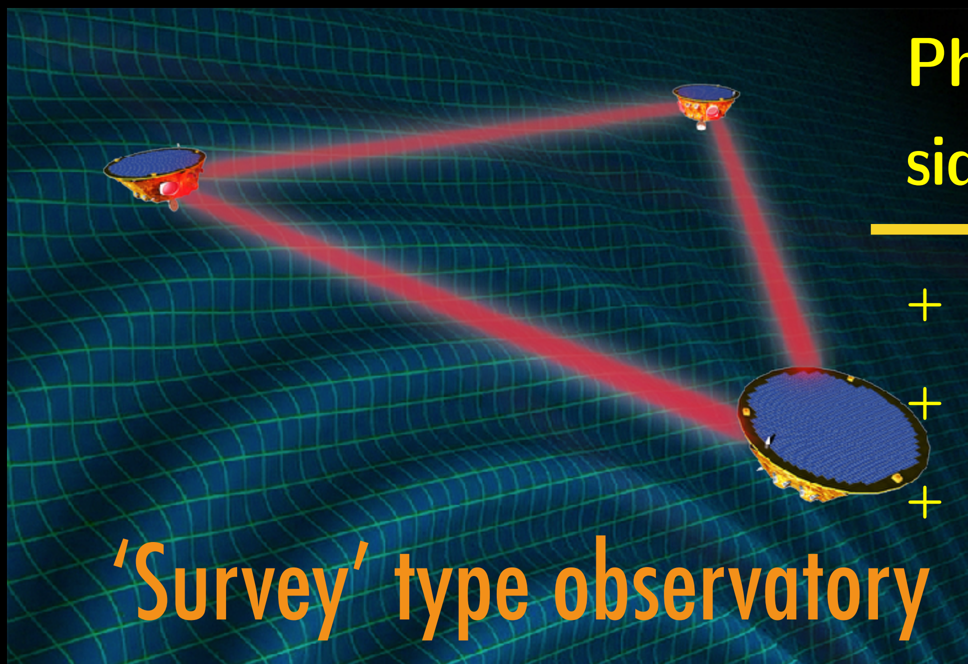
3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

LISA data



‘Survey’ type observatory

Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0

L0.5

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

L1 — 3 TDI channels with 2 “~independents”

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

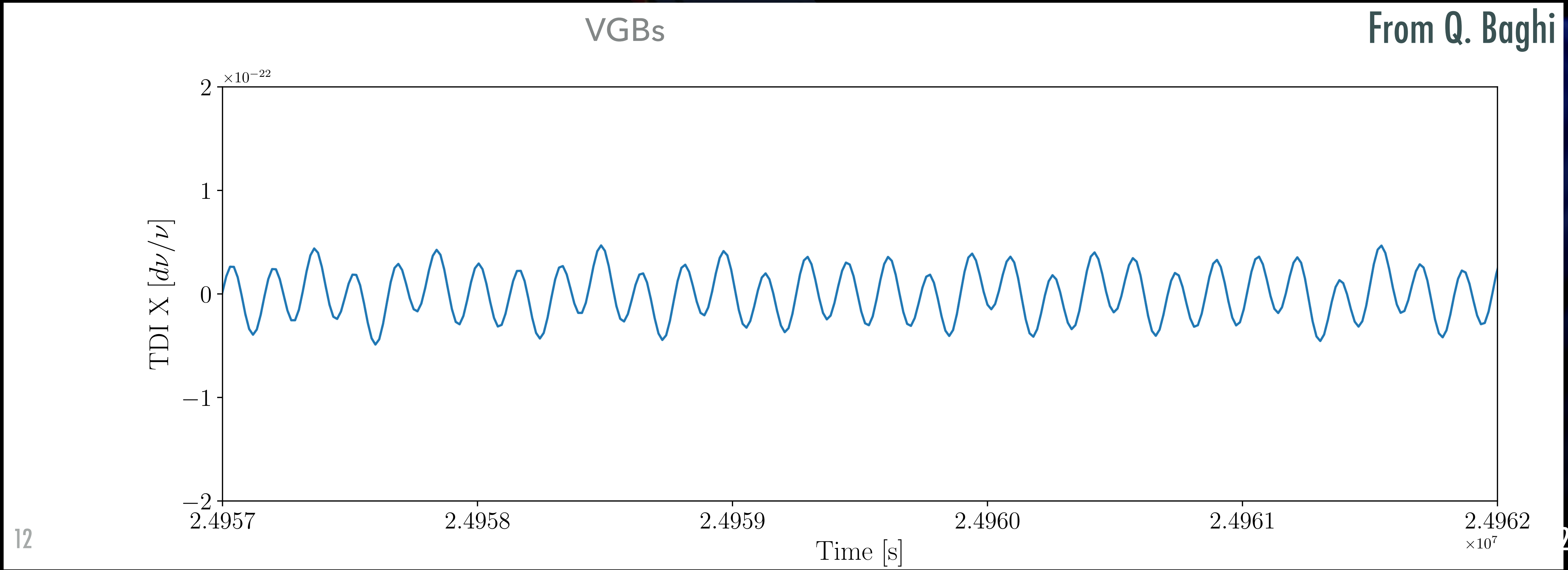
** Charge Management Device

LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)

LISA data

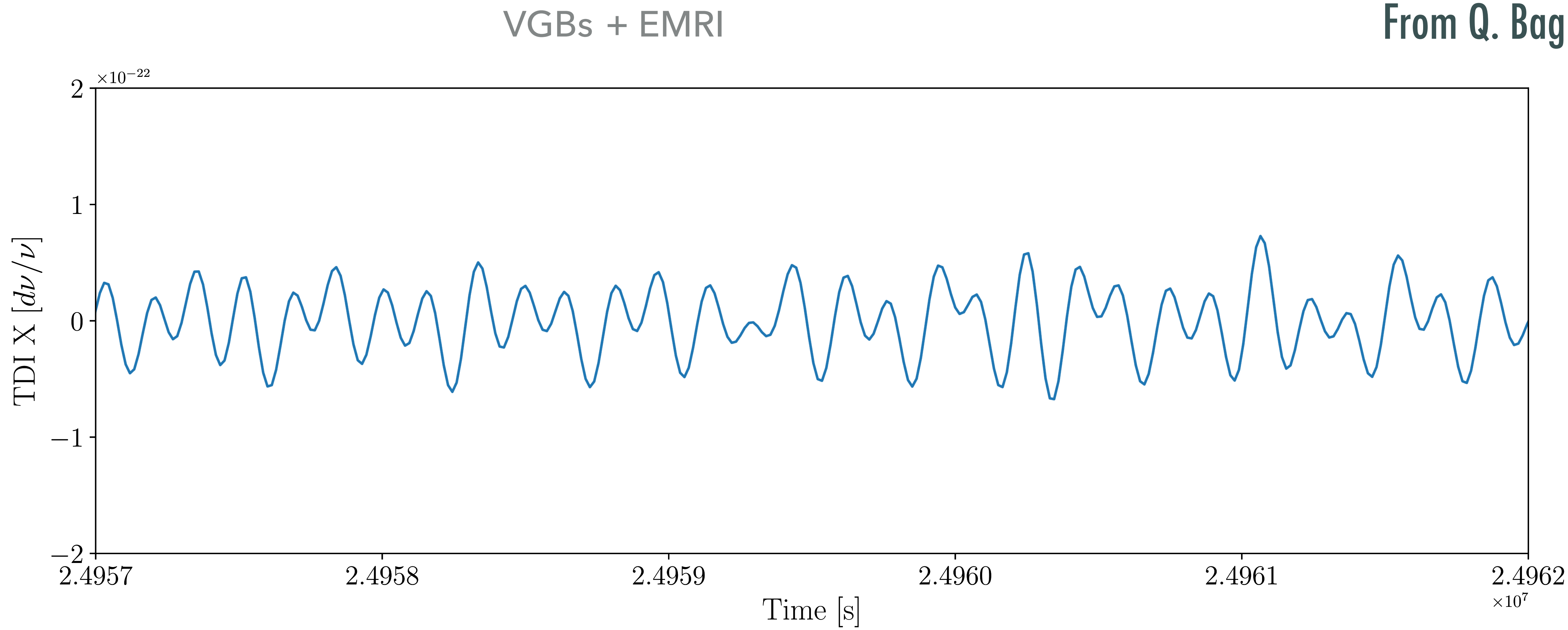
- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)

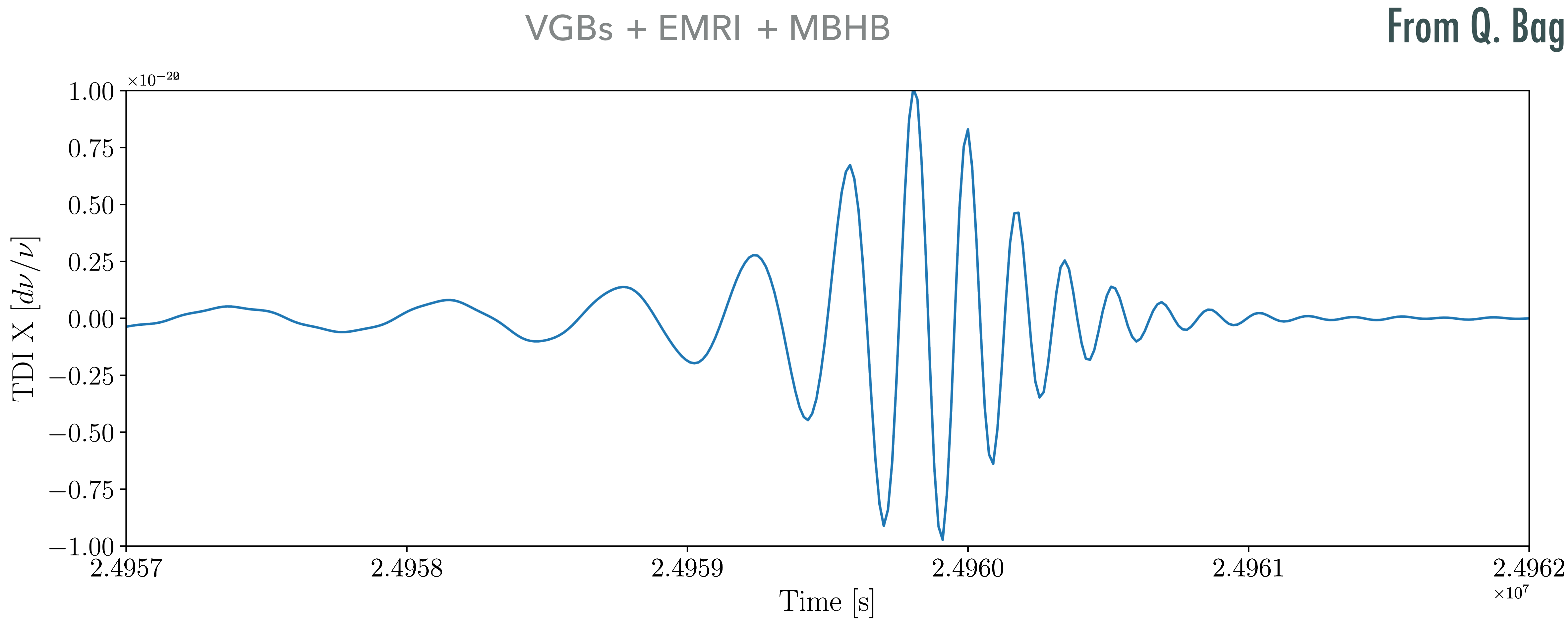
From Q. Baghi



LISA data

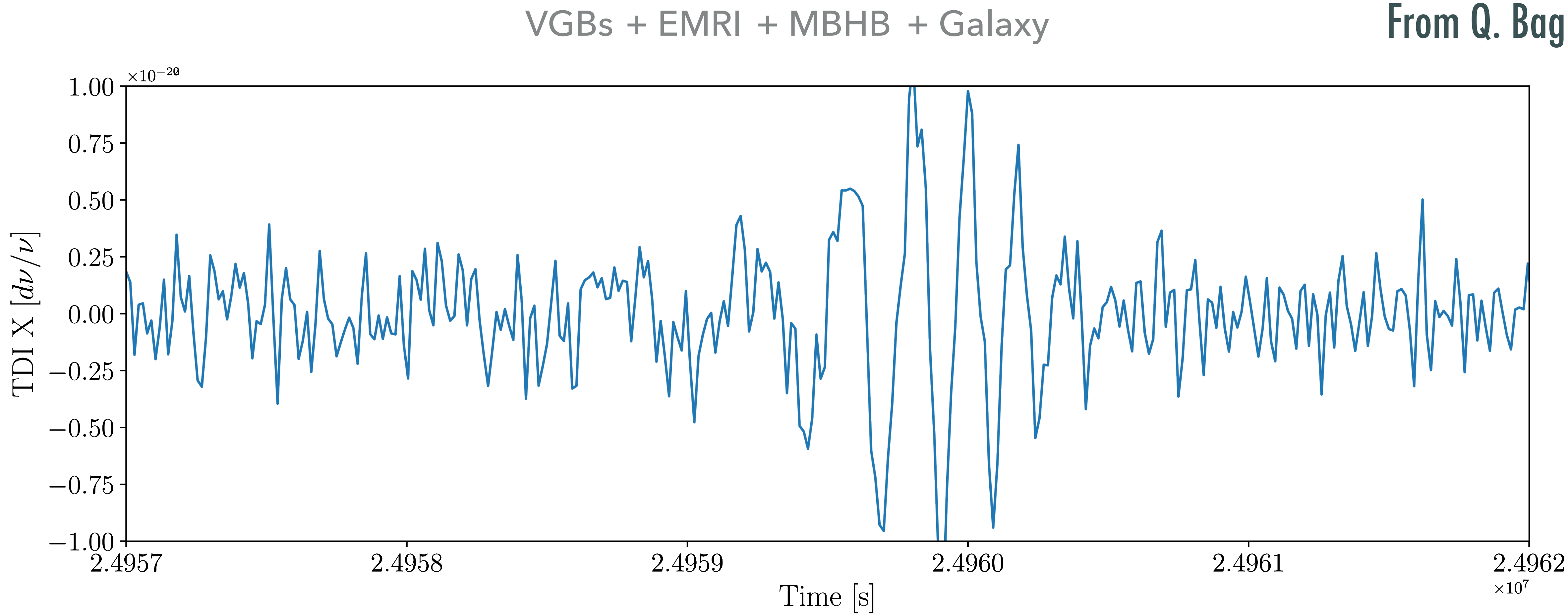
- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)

From Q. Baghi



LISA data

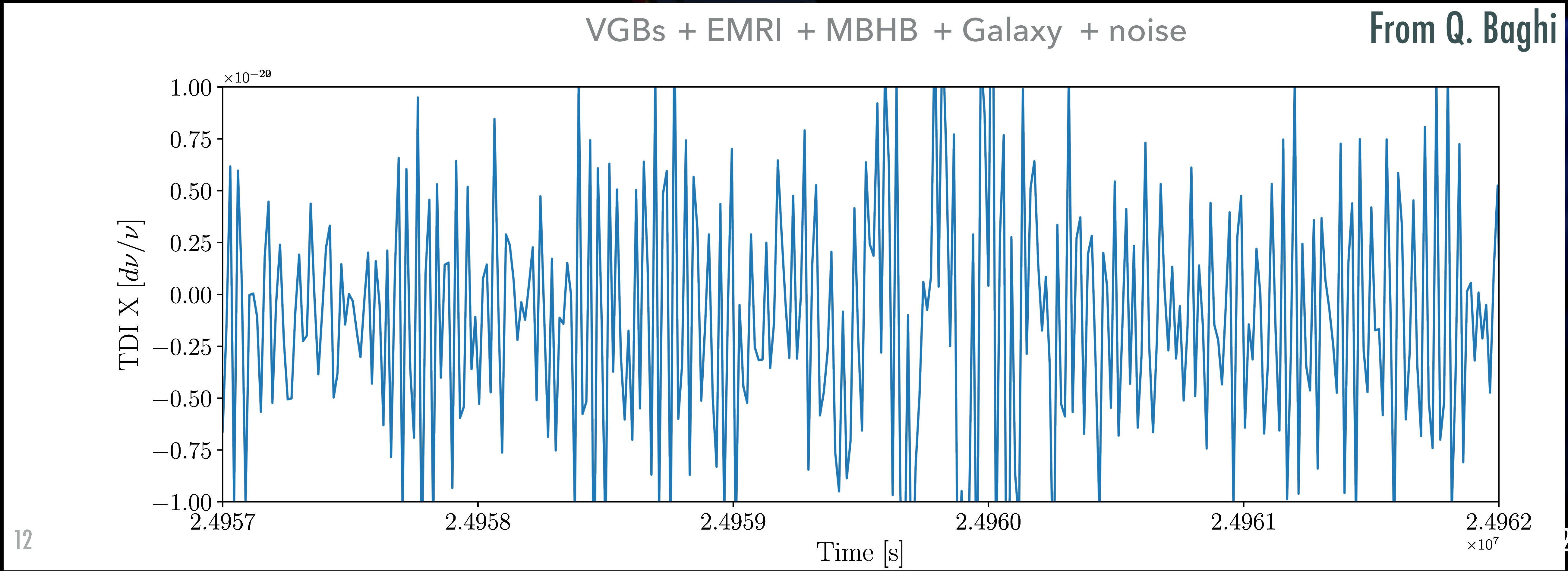
- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



From Q. Baghi

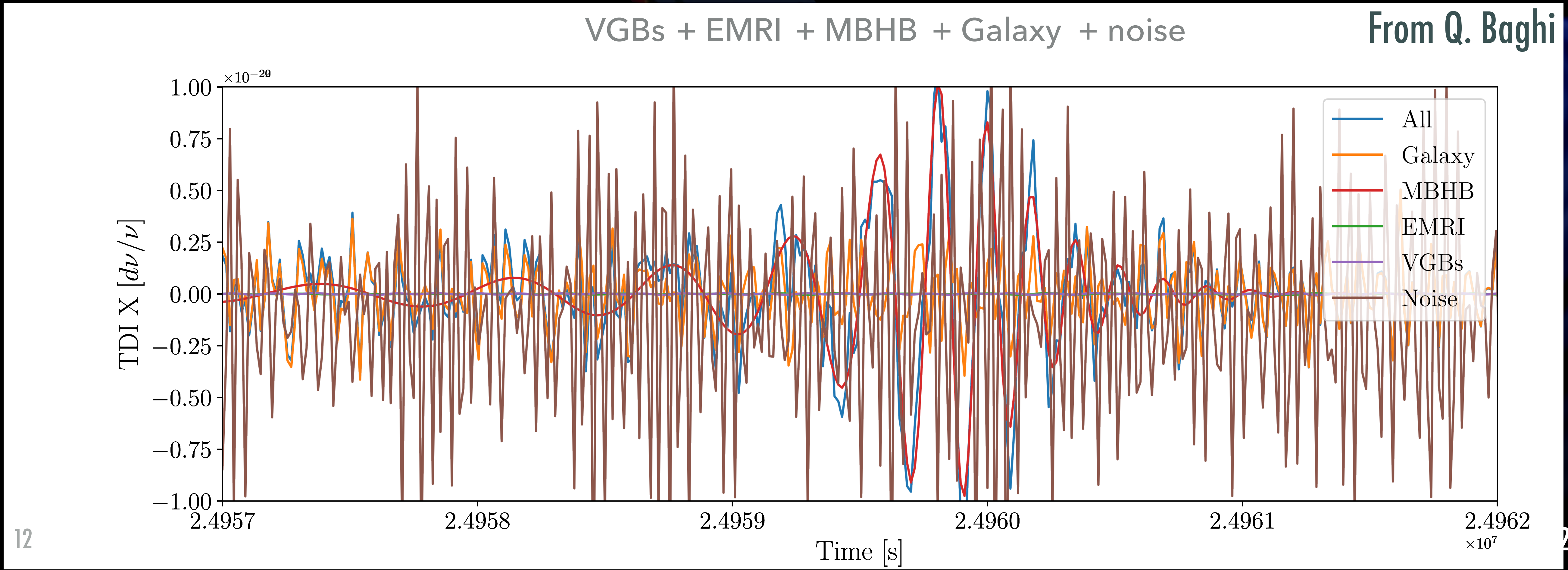
LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



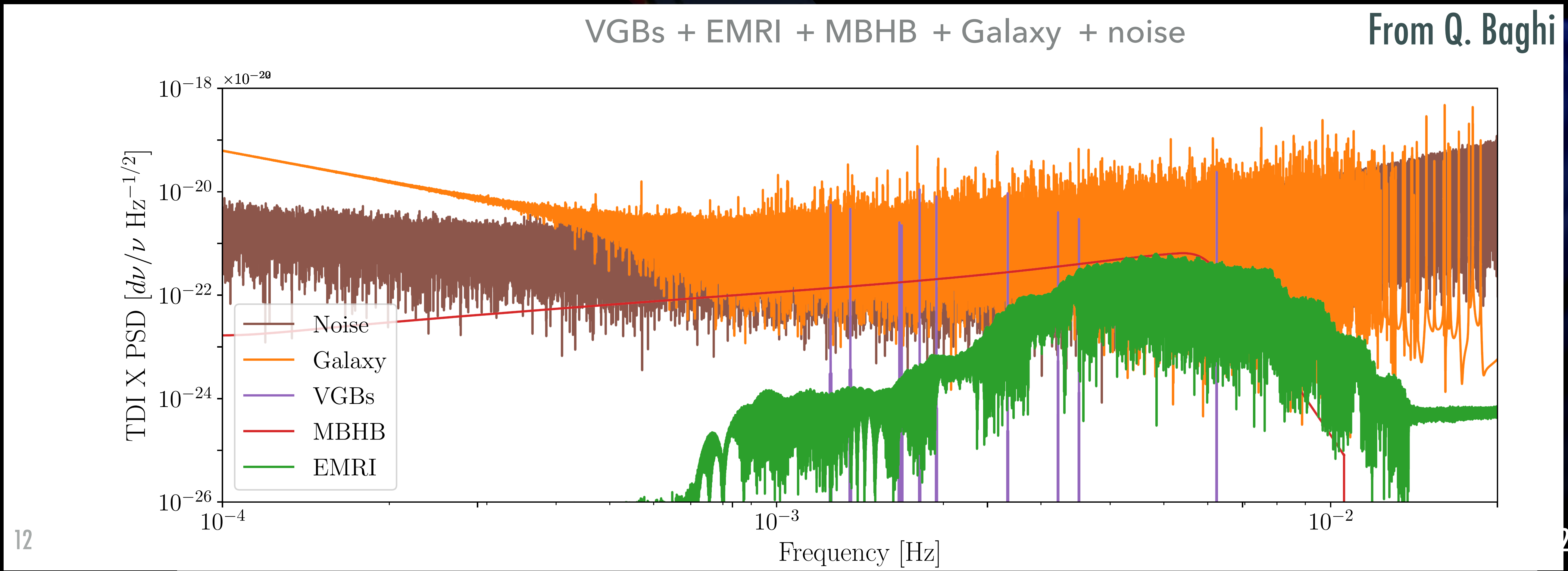
LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



LISA data

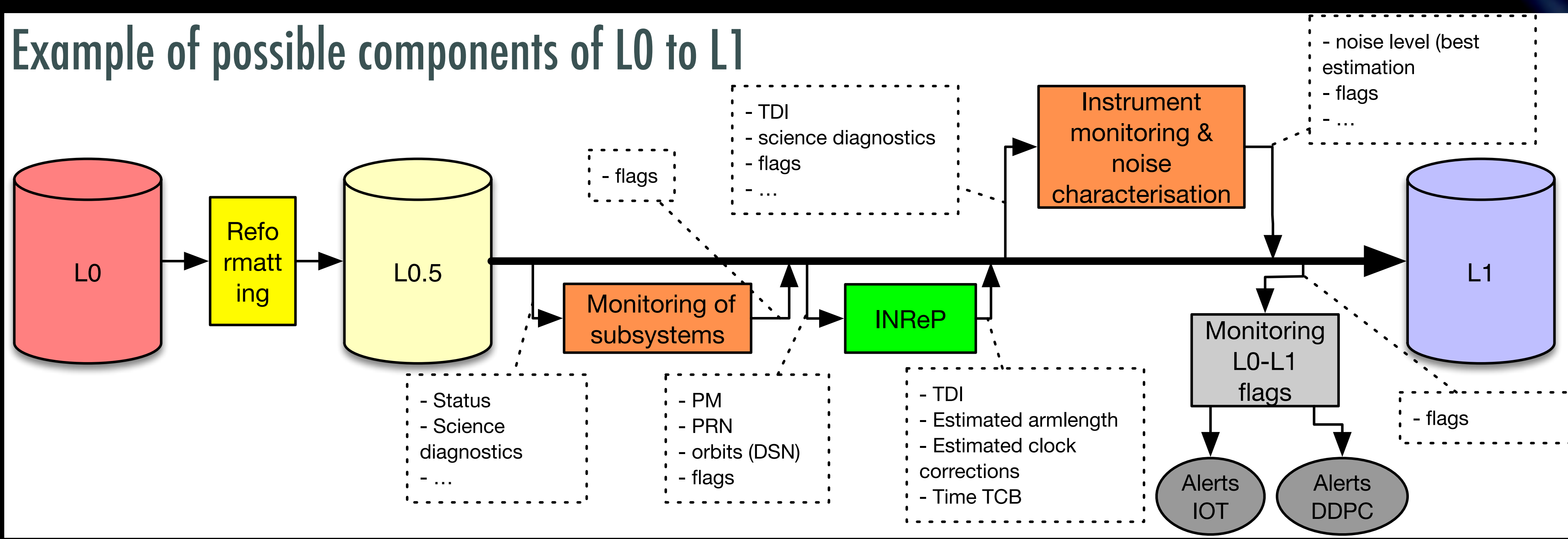
- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



LISA data analysis logic

- Analysis of all signals and noises together => global analysis
- Flexibility: first data of this kind => novel analysis challenge
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production (devOps)
- Multiple steps approach with iterations between steps because data products are very interconnected:
  1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data (TDI data)
  2. GW sources extraction + better understanding of noises and instrument with multiple pipelines => L2 data
  3. Cross-check, combination, merging of L2 data to produce catalogs + associated scientific products => L3 data
- All levels requires continuous scientific interactions: collaboration all over the mission
- Science exploitation, mainly on L3 data: Consortium is expecting to do science as well as the world wide community

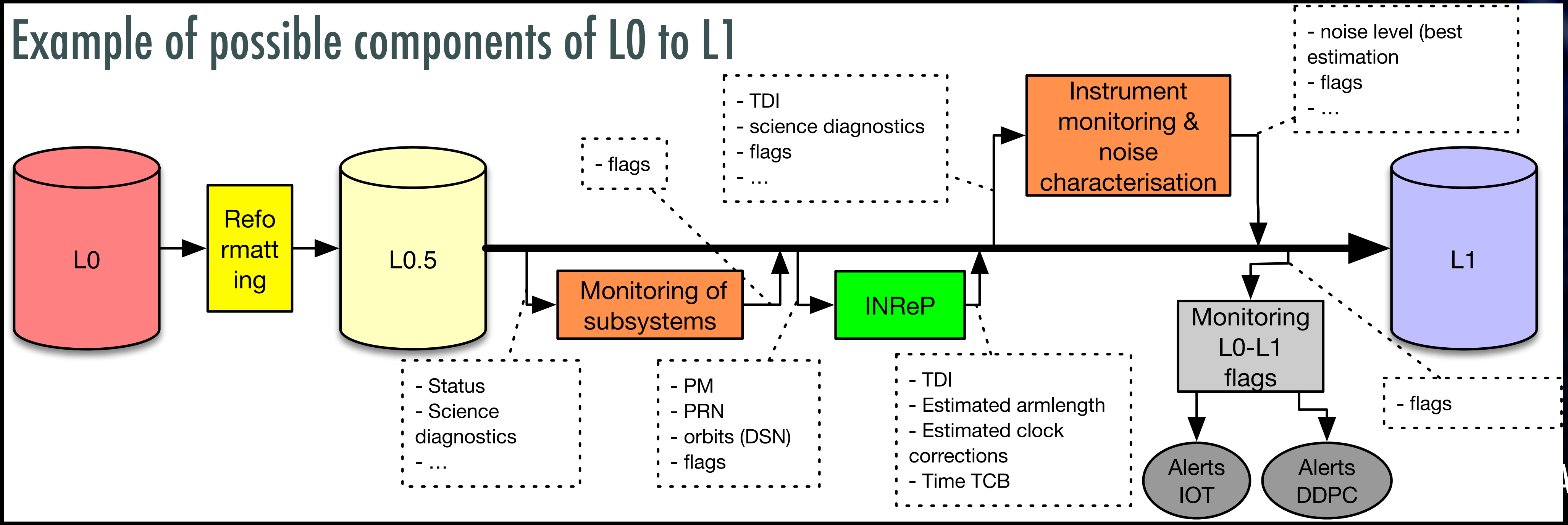
L0 to L1



Example of possible components of L0 to L1
L0
Refo rmatt ing
L0.5
Monitoring of subsystems
- Status
- Science diagnostics
- …
- flags
INReP
- PM
- PRN
- orbits (DSN)
- flags
- TDI
- science diagnostics
- flags
- …
- TDI
- Estimated armlength
- Estimated clock corrections
- Time TCB
Instrument monitoring & noise characterisation
- noise level (best estimation
- flags
- …
Monitoring L0-L1 flags
Alerts IOT
Alerts DDPC
- flags
L1

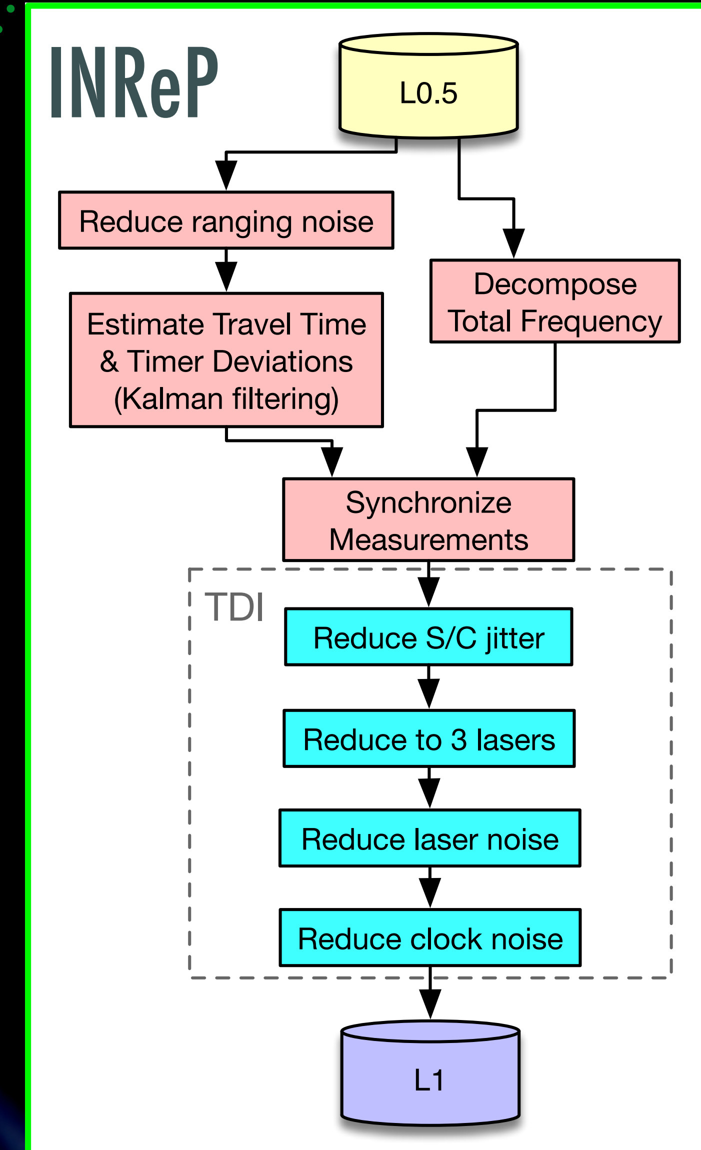
L0 to L1

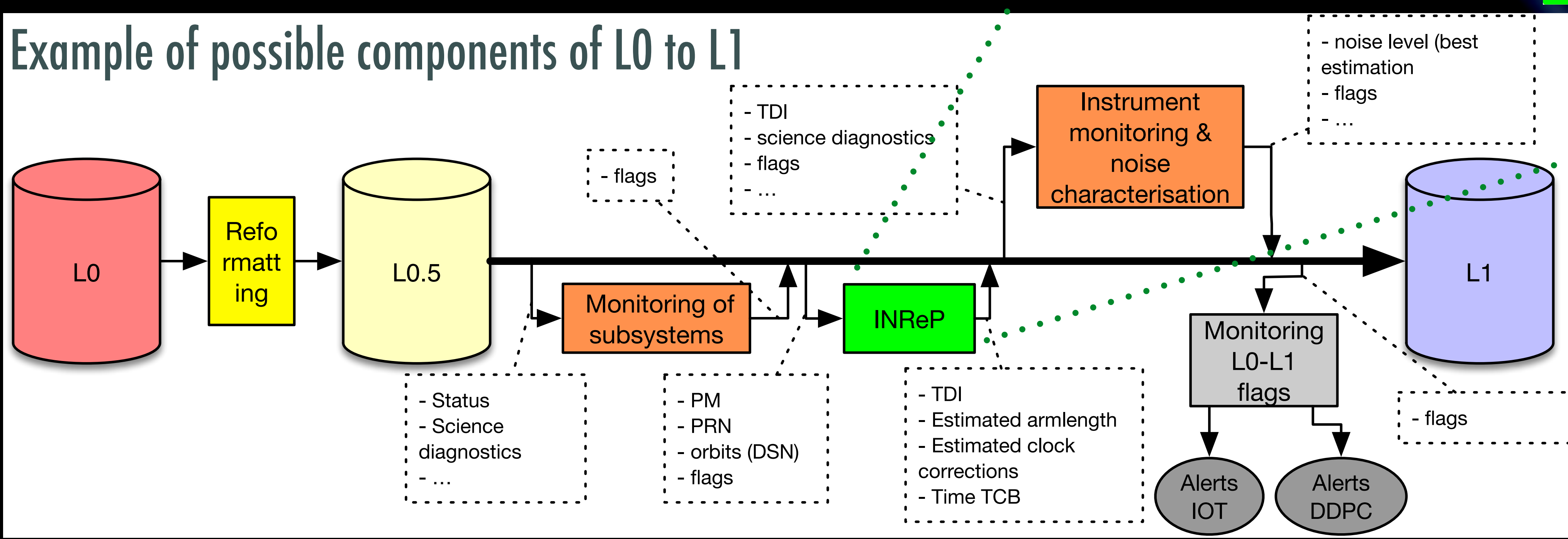
- Data levels:
  - L0.5: L0 reformatted: engineering/physical values
  - L1: All requested data for GW extraction



L0 to L1

- Data levels:
  - L0.5: L0 reformatted: engineering/physical values
  - L1: All requested data for GW extraction
- Core part of L0 to L1: Initial Noise Reduction Pipeline (INReP):
  - TDI+: Suppress laser noise, clock noises, spacecraft jitter noise
  - Data synchronisation
  - Reduce Tilt-To-Length noise

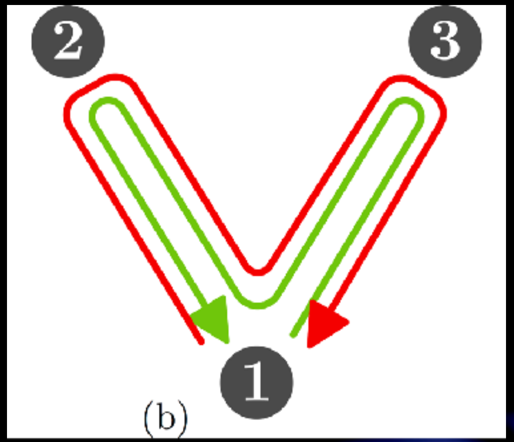




TDI for reducing laser noise

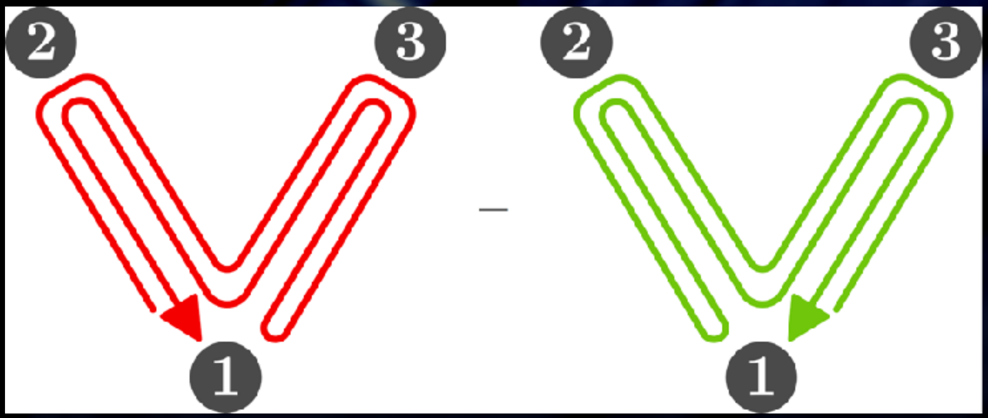
- Combine measurements to reduce laser noise by 8 order of magnitude
- Several complex combinations
- Can be seen as virtual interferometer
- TDI generation 1.5 takes into account the unequal arms

$$X_1 = \eta_{1'} + \mathcal{D}_{2'}\eta_3 + \mathcal{D}_{2'2}\eta_1 + \mathcal{D}_{2'23}\eta_{2'} - \eta_1 - \mathcal{D}_3\eta_{2'} - \mathcal{D}_{33'}\eta_{1'} - \mathcal{D}_{33'2'}\eta_3$$



- TDI generation 2 takes into account first order time evolution of arm length

$$\begin{aligned} X_2 = \eta_{1'} &+ \mathcal{D}_{2'}\eta_3 + \mathcal{D}_{2'2}\eta_1 - \mathcal{D}_{2'23}\eta_{2'} + \mathcal{D}_{2'233'}\eta_1 \\ &+ \mathcal{D}_{2'233'3}\eta_{2'} + \mathcal{D}_{2'233'33'}\eta_{1'} + \mathcal{D}_{2'233'33'2'}\eta_3 \\ &- \eta_1 - \mathcal{D}_3\eta_{2'} - \mathcal{D}_{33'}\eta_{1'} - \mathcal{D}_{33'2'}\eta_3 - \mathcal{D}_{33'2'2}\eta_{1'} \\ &- \mathcal{D}_{33'2'22'}\eta_3 - \mathcal{D}_{33'2'22'2}\eta_1 - \mathcal{D}_{33'2'22'23}\eta_{2'} . \end{aligned}$$



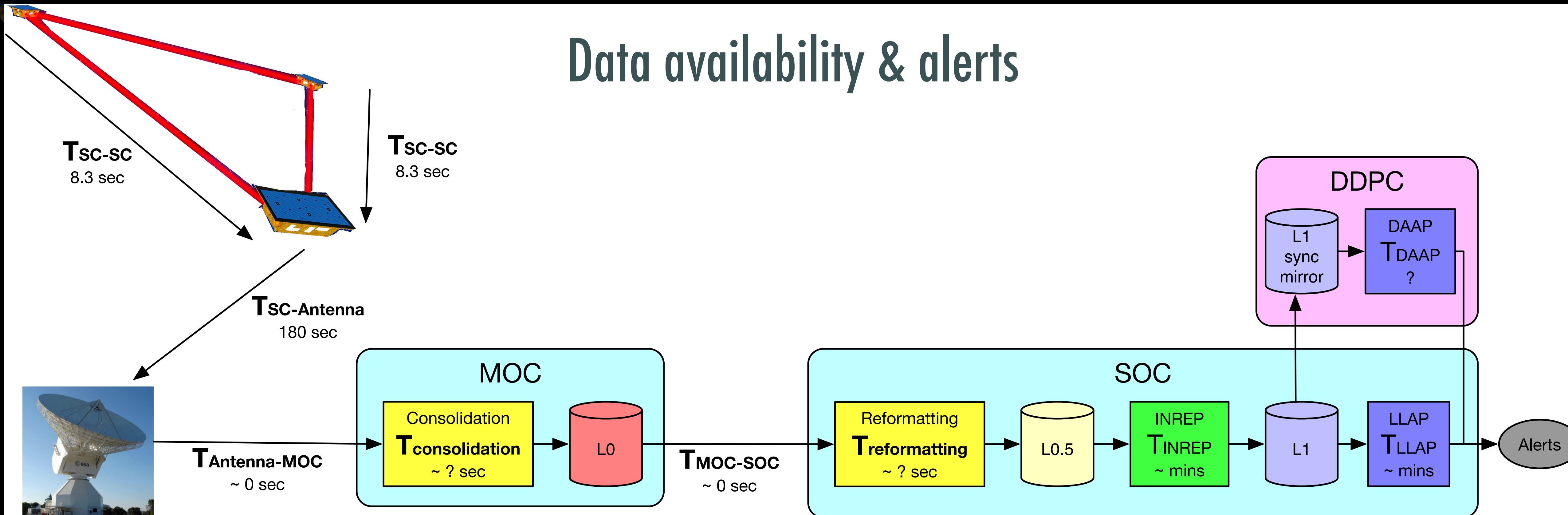
L1 to L2

- « Global fits »
- Multiple pipelines with multiple approaches
- Different steps in each pipeline
- Flexibility
- Two main aspects
  - Alerts (as quick as possible => less than 1 hour):
    - Low Latency Alerts
    - Deep Alert Analysis
  - Full analysis (long term) for extracting the best knowledge of observed GW sources + the best understanding of instrument

L1 to L2: alerts

- Two types of near-real time analysis for alerts:
  - Detect new events
  - Improve of parameters estimation for already detected events (ex: sky)
- Near-real time when communication: current plan 8h/24h but scientific benefits in increasing this duration
- Two steps:
  - Low Latency Alerts Pipeline: automatic near-real time analysis to release an alert as fast as possible
  - Deep Analysis Alerts Pipeline: when an alert has been detected, analysis to:
    - Confirm the nature of the events
    - Refine the parameters

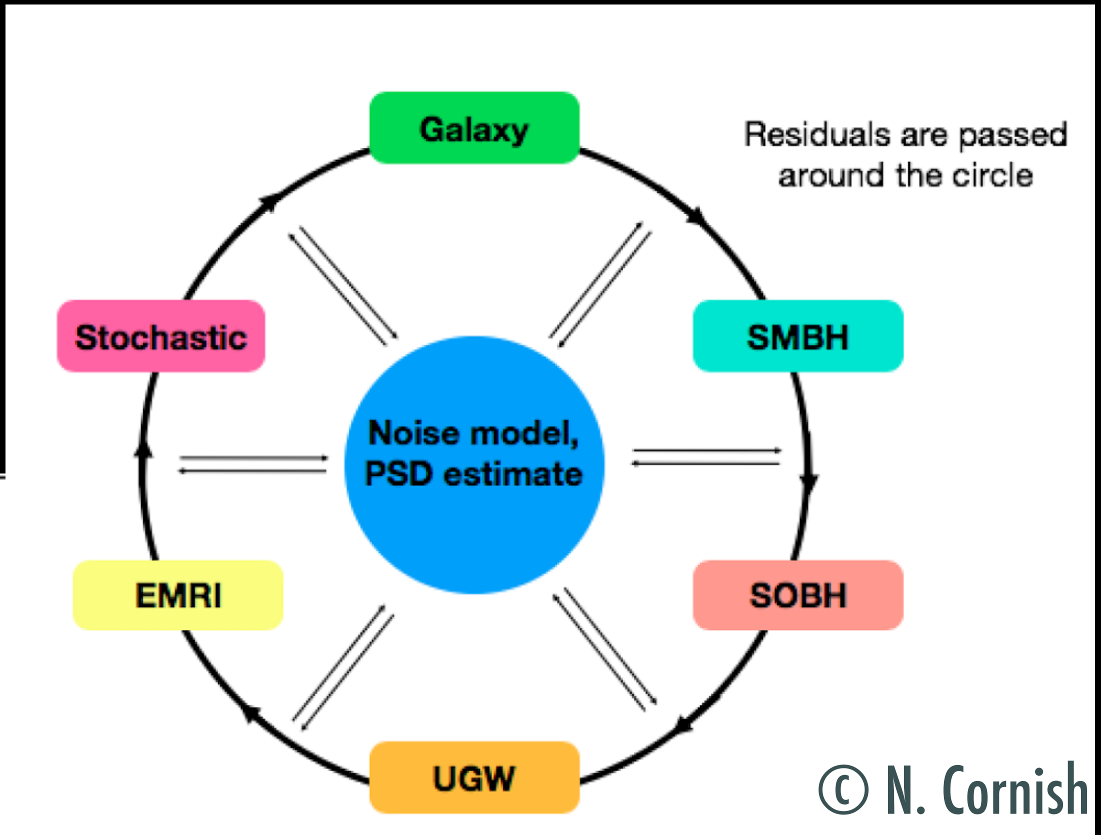
L1 to L2: alerts

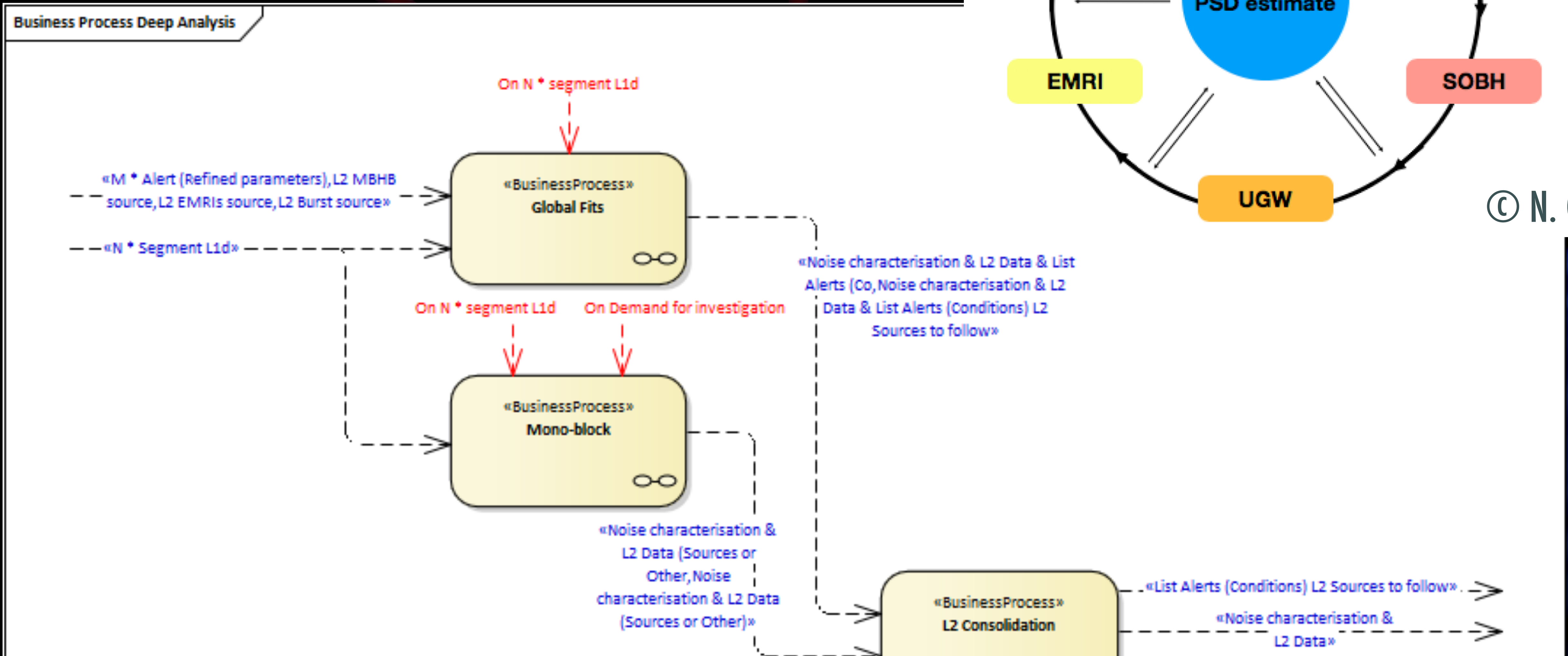


- Two steps:
  - Low Latency Alerts Pipeline: automatic near-real time analysis to release an alert as fast as possible
  - Deep Analysis Alerts Pipeline: when an alert has been detected, analysis to:
    - Confirm the nature of the events
    - Refine the parameters

L1 to L2: Deep Analysis

- Extract GW sources
- Global fits
- Sources investigations, ...





From "LISA-LCST-SGS-AD-001 SGS Data and Information Flow Analysis and Architecture Assumptions"

L1 to L2: Deep Analysis

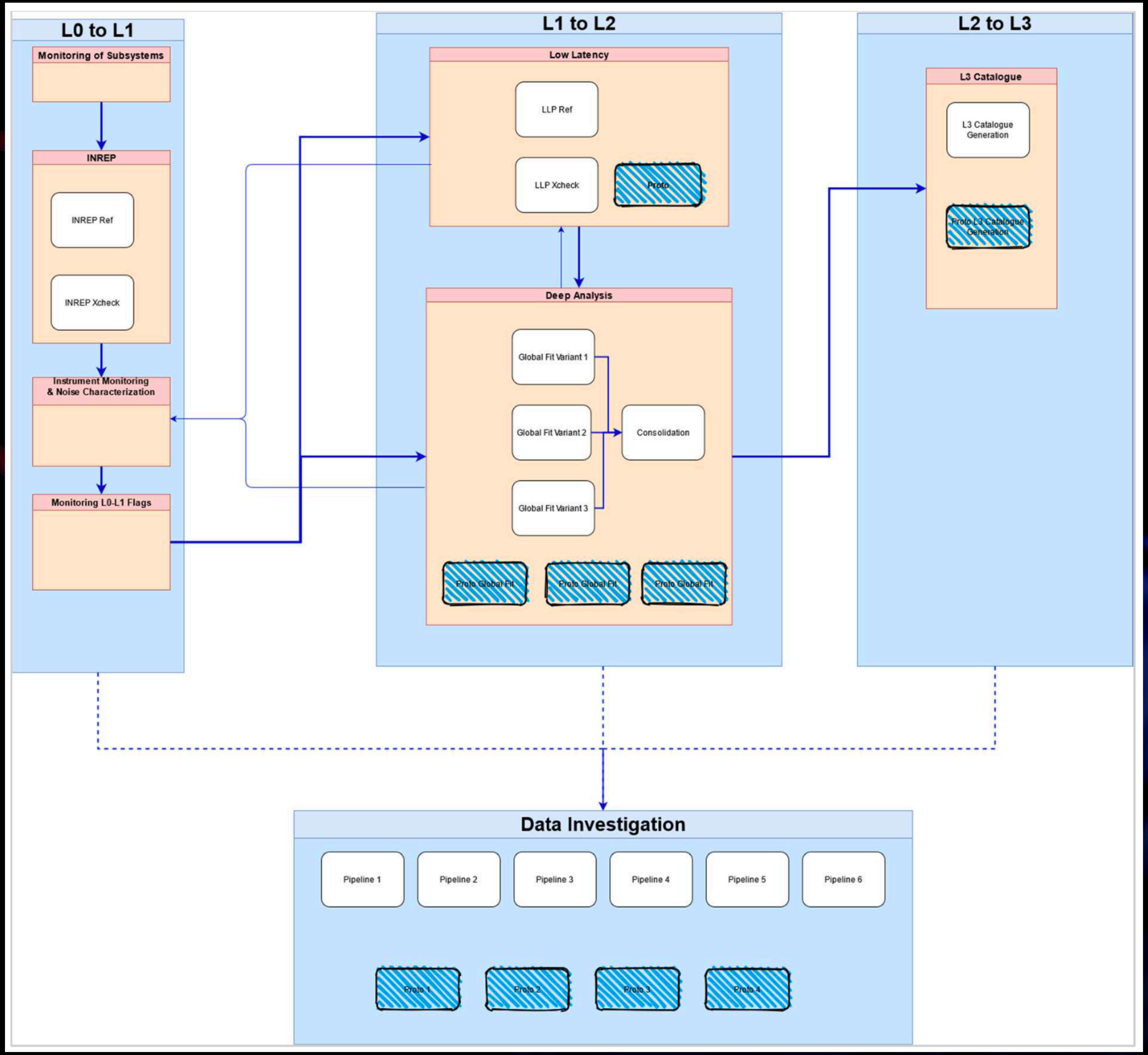
- Complex problem: Multiple approaches and Flexibility
- Large computing ressources required:
  - Estimation per year extrapolated from the first LISA Data Challenge (2021 CPU -hours) BUT possible factor 10 to 100:

Per year of data	CPU-hours	Scratch volume	Informative volume
#1 With SBBH	30M	500TB	160GB
#1 without SBBH	17M	225TB	160GB
#2 with SBBH	(14.5-52.5)M	500TB	160GB
#2 without	(7.5-15)M	225TB	160GB
Low-latency	550K	52TB	6GB

=> Distributed Data Processing Center sharing computation load (production and development) on multiple computing centres in Europe and USA.

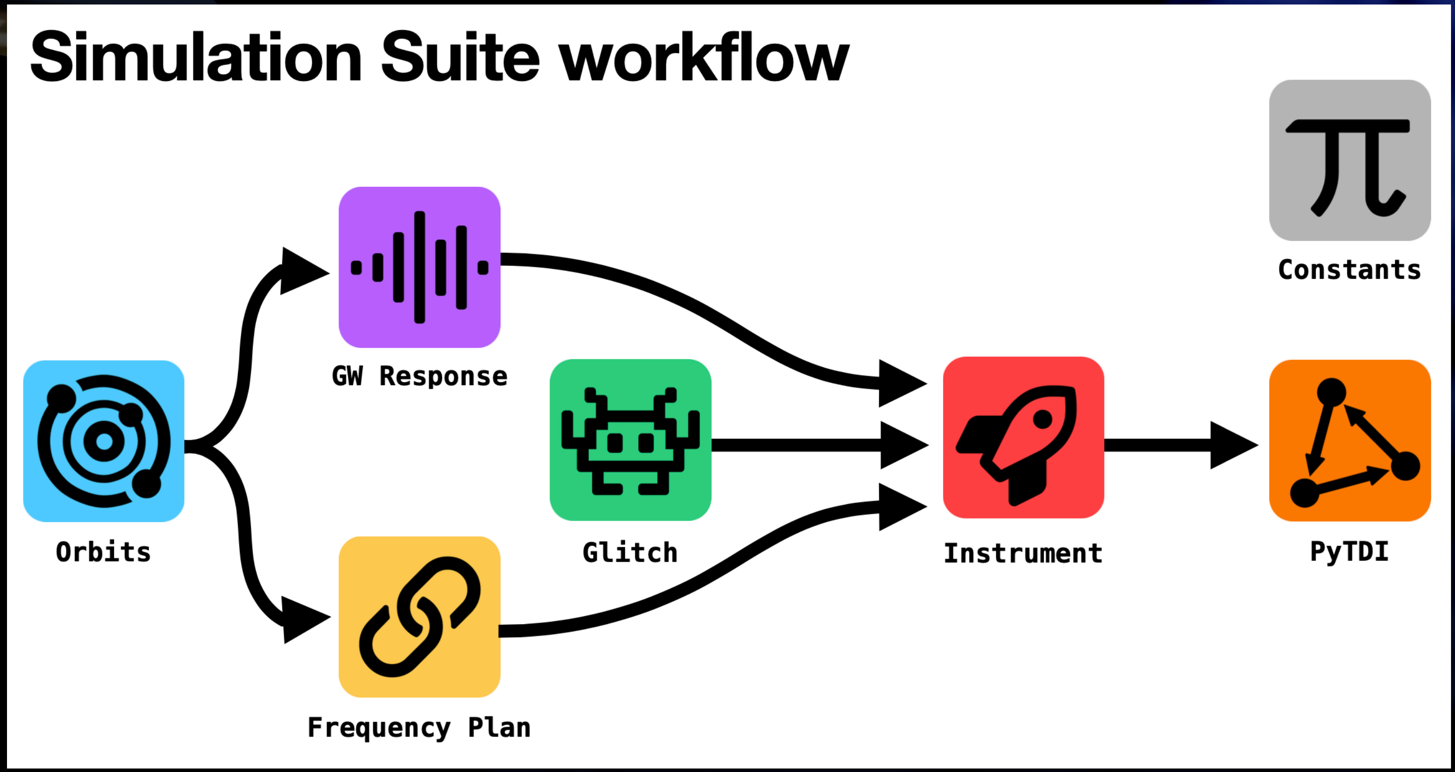
Multiple analysis

- Multiple independent analysis/pipelines is already part of the SGS plan:
  - Mechanism of multiple analysis part of the construction of the SGS organisation
  - Independent intellectually, not by flags



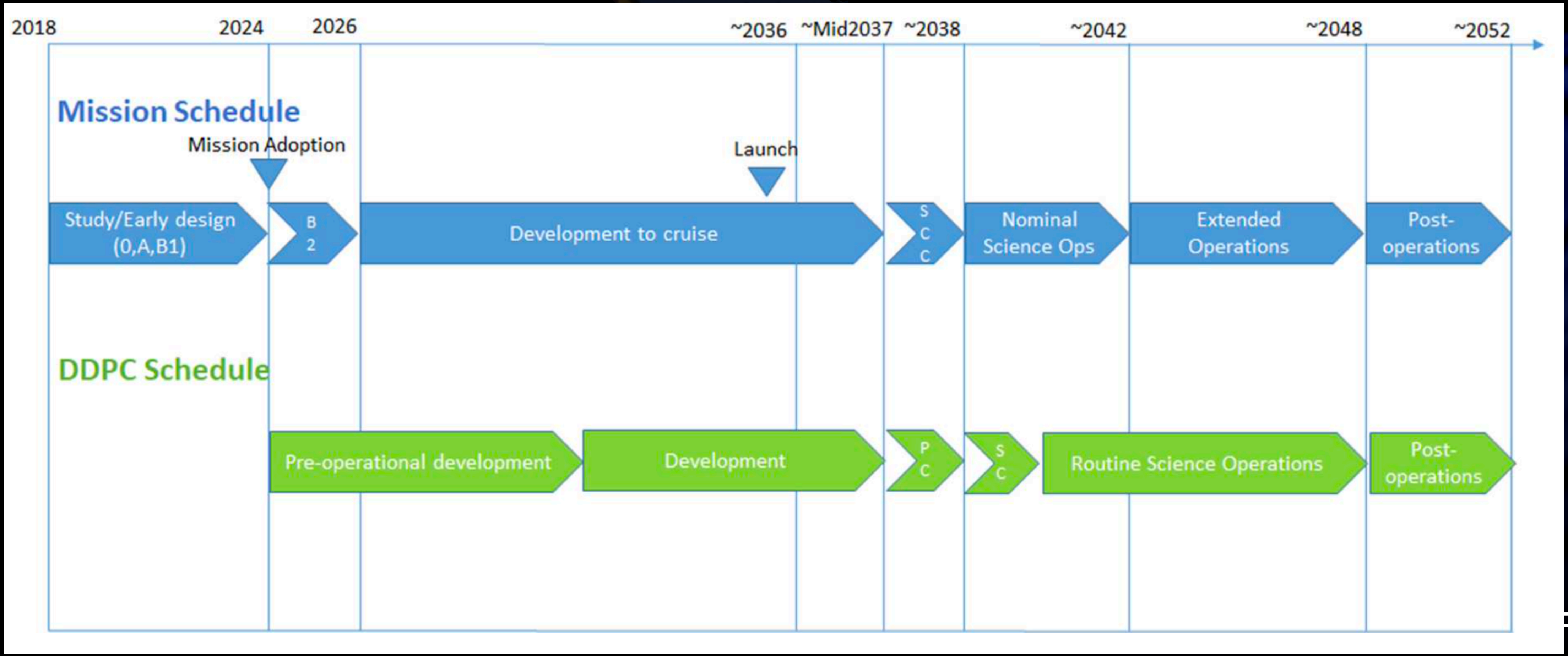
Simulation

- Given the complexity of the data and the sensitivity of LISA to any perturbations, simulations are at the core of the development for data analysis and instrument:
  - Validation performance model and instrument design
  - Generation of realistic data
- Global simulation (GW+instrument): LISA Data Challenge infrastructure
- Simulation of the instrument:
  - LISANode (official)
  - LISA SimScape
  - LISASim

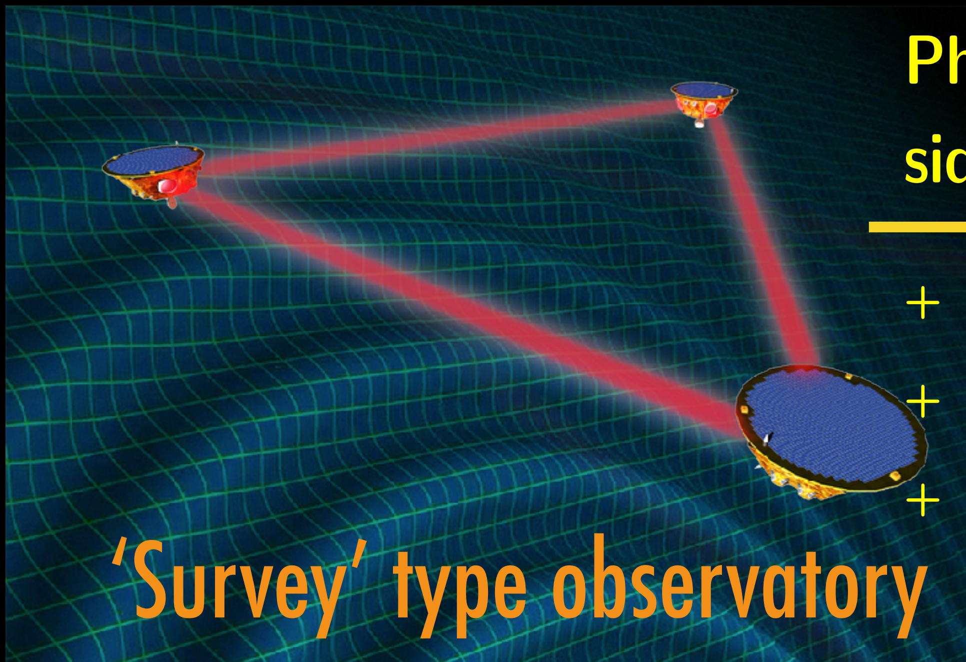


Development of the SGS

- Commissioning: 2 phases:
  - Primary commissioning (PC): sub-systems, instrument, prime
  - Science commissioning (SC): initial part science operations, tapering as milestones are reached
- "Routine" operations: main pipelines operated routinely with in parallel prototyping and updates



LISA data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0

L0.5

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

LISA data

Mission Operation Center (ESA)

Science Operation Center (ESA)

DDPC: Distributed Data Processing Center (Consortium)

Phasemeters (carrier, ...ds, distance)

...CS* & CMD**

+ Diagnostics

+ Auxiliary channels

'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz

* Drag-Free Attitude Control System

** Charge Management Device

L0

L0.5

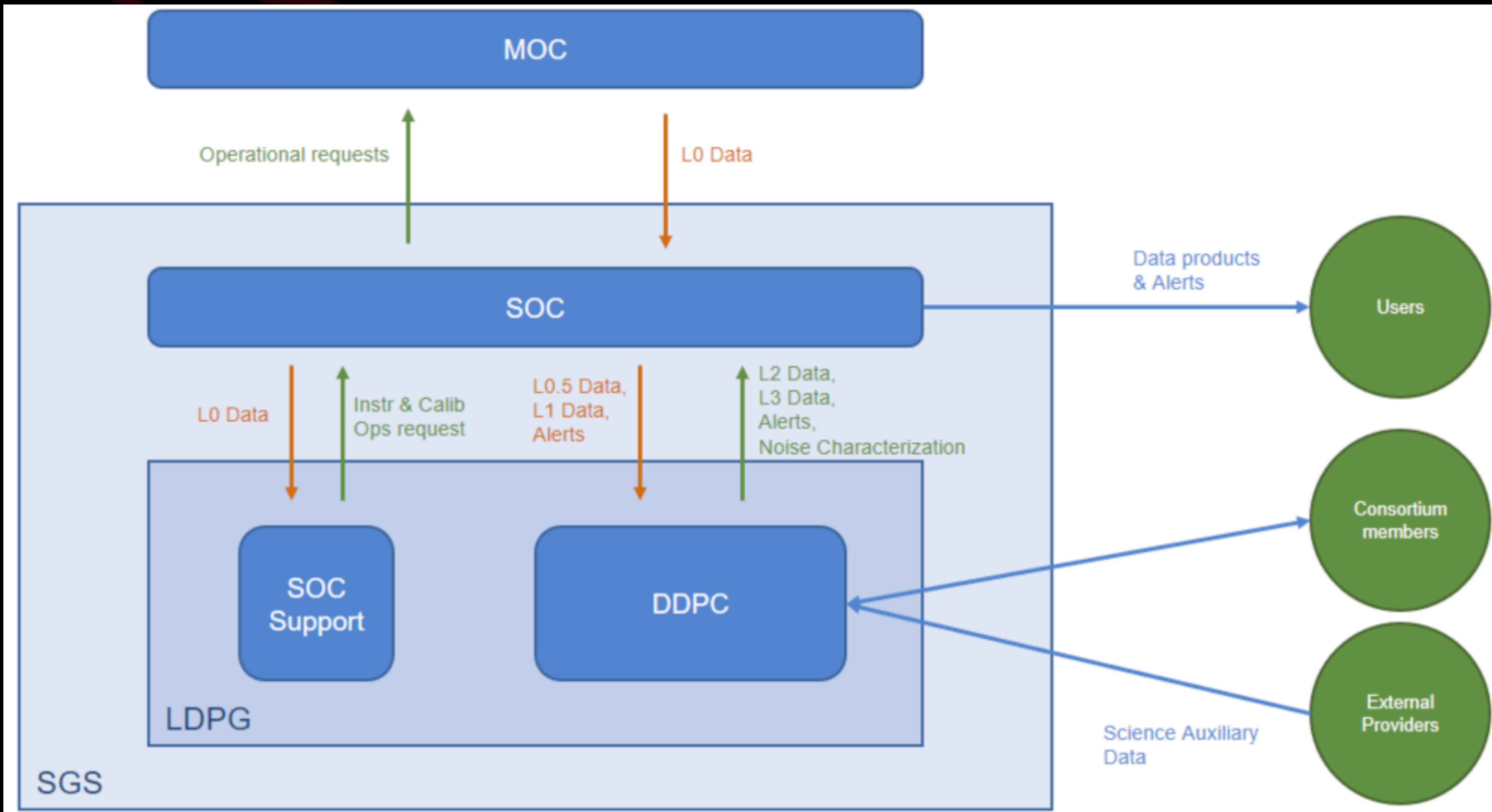
Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Organisation of the SGS



Organisation of the SGS

- Context:
  - ESA:
    - In charge of operational decisions
    - Build the hardware and responsible for the performance
    - Manage archive
    - Interact with public (alerts, data releases)
  - Consortium:
    - Has the expertise in science
    - Develop data analysis pipelines
    - Provide the core hardware
  - NASA/US: delivering to ESA but also in the Consortium?

Organisation of the SGS

- Share of responsibilities between ESA and Consortium:
  - ESA:
    - Operates L0 to L1: Noise reduction subsystem monitoring, global instrument characterisation
    - Run Low Latency Alerts Pipelines (LLAP)
    - Diffusion of data (releases and alerts)
  - Consortium:
    - Develops and operates L1 to L2
    - Develops and operates L2 to L3
    - Delivers to ESA products L2, L3 and feedback for the L0 to L1
  - Shared developments Consortium/ESA/NASA for L0 to L1 pipelines and LLAP (ex: Consortium prototypes and delivers first version; ESA finalises implementation and operates)

Collaborative approach

- Main vision in the Consortium:

  LISA data are complex with large number of sources of different kinds and instrumental artefacts simultaneously present in the data

  + First data of this kind

  => To best analyse the data and maximise the scientific return, it is necessary to collaborate within the Consortium while maintaining multiple approaches

- DDPC: French lead + many contributors

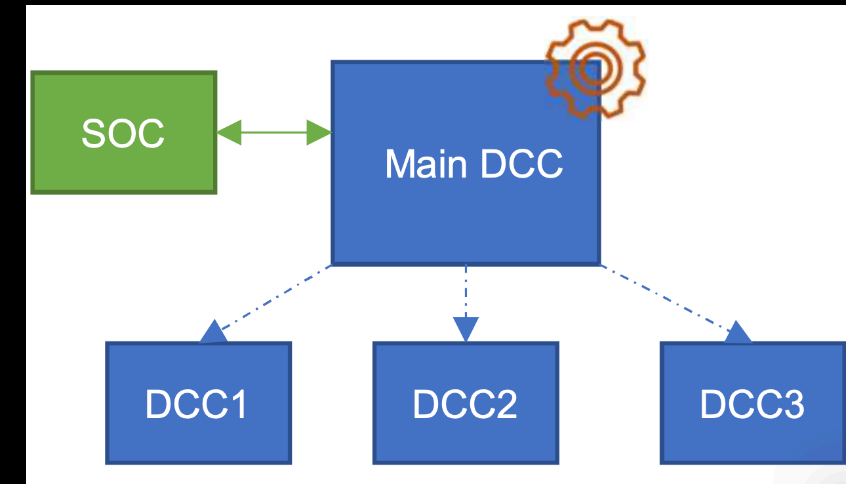
- Work Breakdown Structure & Development Plan: Work in progress (to be ready for adoption):
  - Product tree, functional tree, ...

On going activities for B1

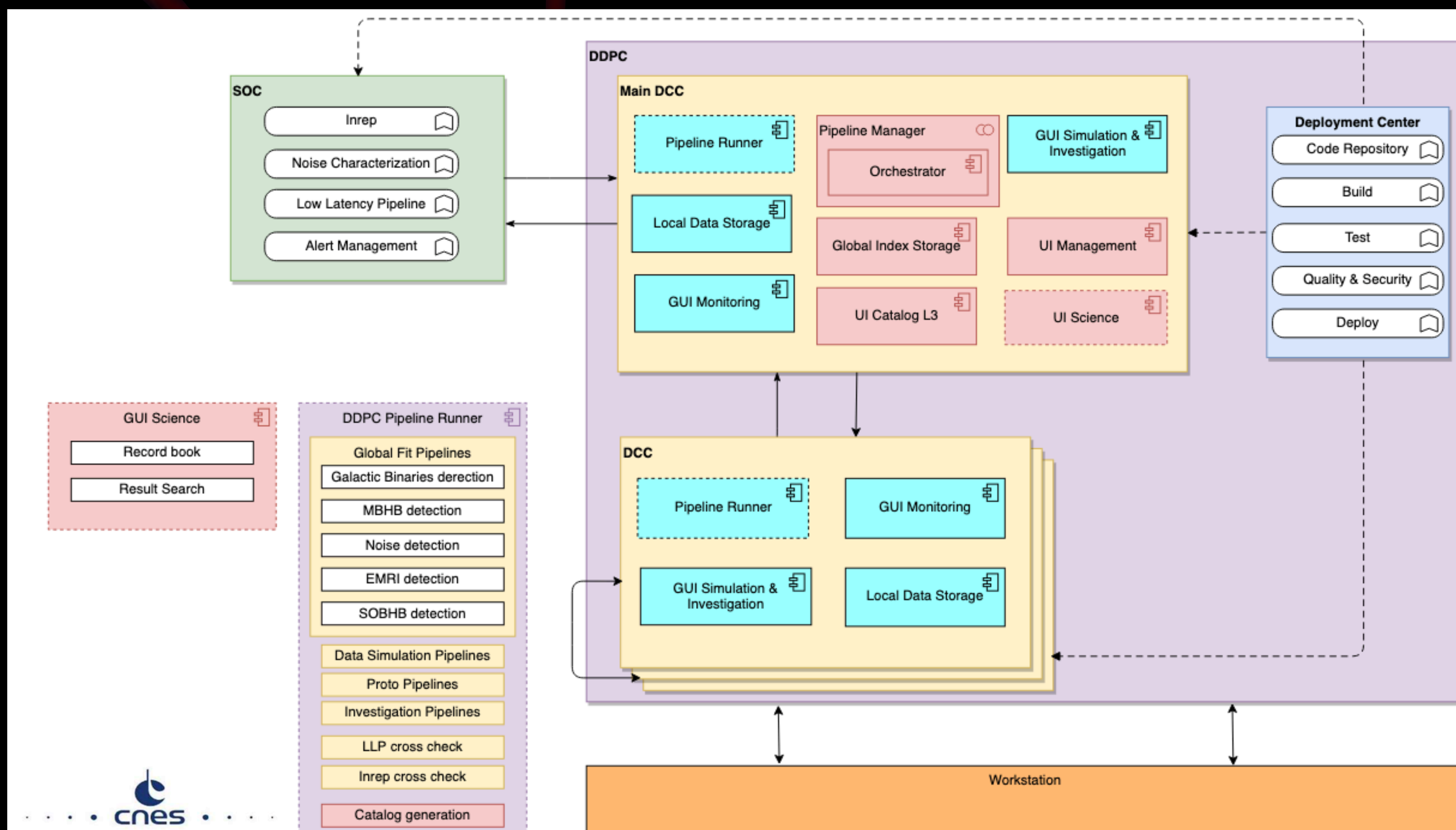
- Detailed definition of the Ground Segment in particular the DDPC
- Mapping of responsibilities on the DDPC
- Demonstrating the feasibility of LISA Science regarding data analysis: prototyping and dedicated studies:
  - Initial Noise Reduction Pipeline (L0.5 to L1)
  - LISA Data Challenge (L1 to L2/L3)

Detailed definition

- Infrastructure with multiple Data Computing Centres (CPU and storage)

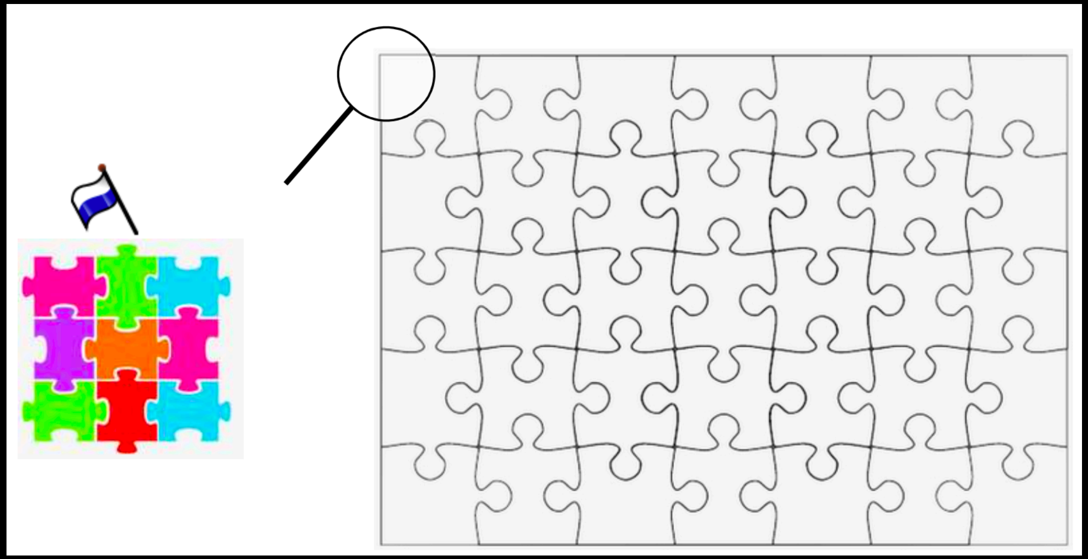


- Example of possible architecture:



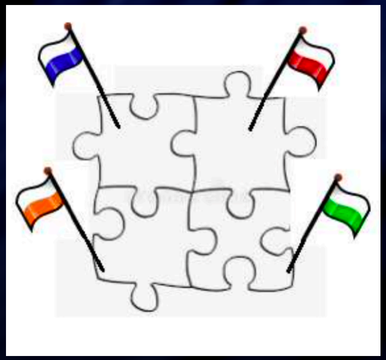
Mapping of responsibilities

- For adoption, we have to identify who is responsible or contribute to which DDPC products and sub-products
  => Science Implementation Plan and Multi-Lateral Agreements



- Main support: the current product tree

- Multiple iterations, starting for the first one with
  - At each country level :
    - To identify the wishes of each institute of the country
    - to gather all the wishes
  - At Ground segment level:
    - To gather all the wishes of all countries
    - To present the overlaps and holes



Product tree (preliminary)

LISA CONSORTIUM

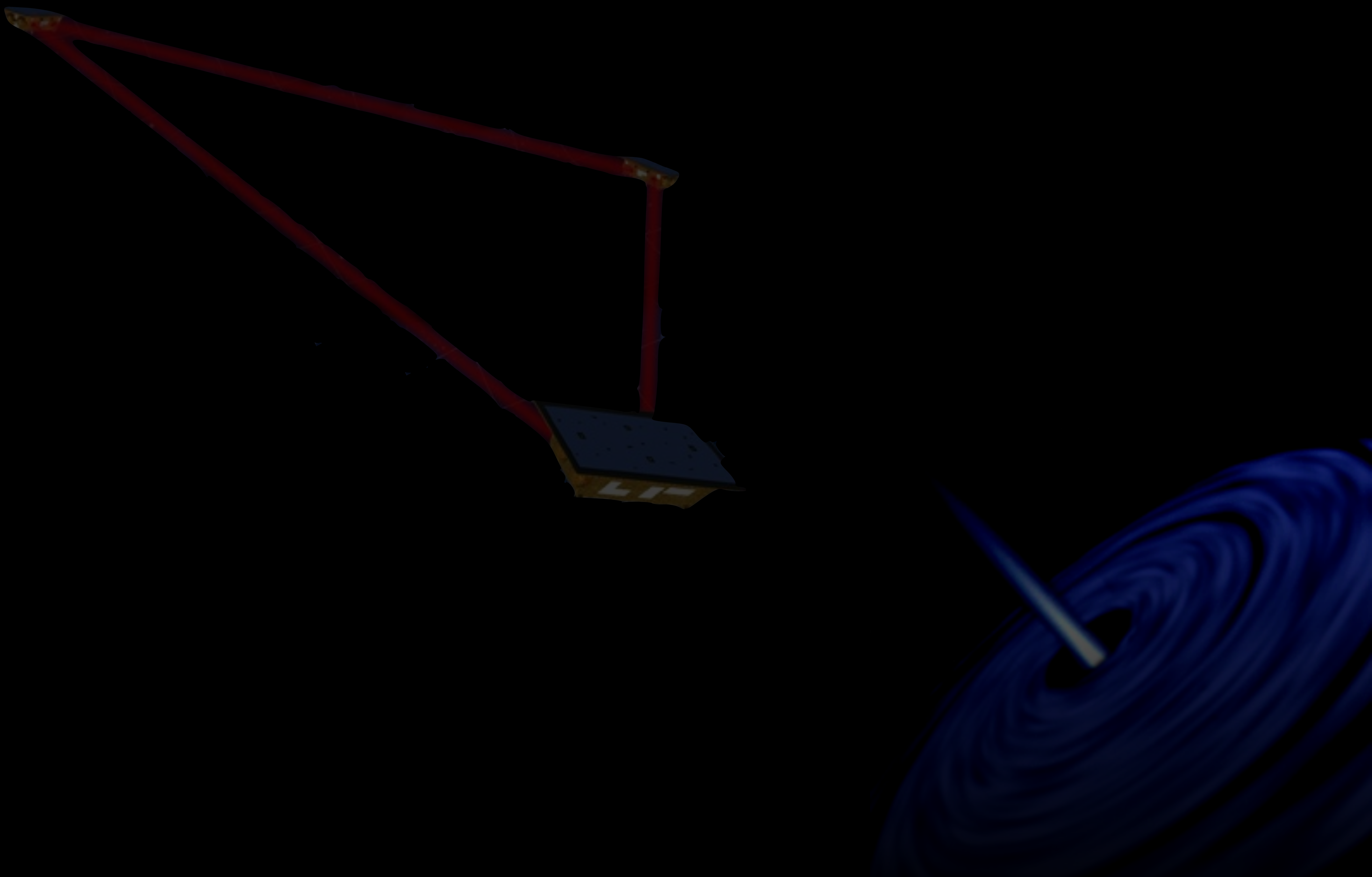
- Science Softwares
  - L0->L1 SW
    - INREP 1
    - INREP 2
    - ?
  - L1->L2 Alerts SW
    - Low Latency Alert Pipeline 1
    - Low Latency Alert Pipeline 2
    - Deep Analysis Alert Pipeline
  - L1->L2 Deep Analysis
    - Global Fit 1 pipeline
    - Global Fit 2 pipeline
    - Global Fit 3 pipeline
  - L1->L2 Mono-Blocks
    - MBHB
      - MBHB 1
      - MBHB 2
    - EMRIs
      - EMRIs 1
      - EMRIs 2
    - SOBBH
      - SOBBH 1
      - SOBBH 2
    - Galactic Binaries
      - Galactic Binaries 1
      - Galactic Binaries 2
    - Unmodelled Sources
      - Unmodelled Sources 1
      - Unmodelled Sources 2
    - Stochastic Background
      - Stochastic Background 1
      - Stochastic Background 2
    - Instrumental Noise Cleaning
      - Instrumental Noise Cleaning 1
      - Instrumental Noise Cleaning 2
  - L2->L3 SW
    - Catalogue facilities
  - Simulation
    - **Simulateur Instrumental**
    - **Simulation GW Sources**
    - **Simulation L0.5 data**
    - **Simulation L1 data**
    - **Simulation L2 data**
    - **Instrumental effects (Fast Approximate and High fidelity)**
      - Instrumental effect / Dynamic
      - Instrumental effect / Phasemeter
      - Instrumental effect / Thermal Noise
      - ...

- Common SW and Tools
  - **Comparison Methods**
    - Comparison Method 1
    - Comparison Method 2
    - Comparison Method 3
  - **Wave Form generator (Fast Approximate and High fidelity)**
    - WFG - MBHB
      - WFG - MBHB - FA
      - WFG - MBHB - HF
    - WFG - Galaxy
      - WFG - Galaxy -FA
      - WFG - Galaxy - HF
    - WFG - EMRIs
      - WFG - EMRIs - FA
      - WFG - EMRIs - HF
    - WFG - SOBBH
      - WFG - SOBBH - FA
      - WFG - SOBBH - HF
    - WFG - Stochastic Background
  - **Time series Management tool**
    - Plotting
    - Transform Frequenncy domain
    - Time frequency representation
    - Power Spectral Density
    - ...
  - **AI model**
  - **Generic Research Methods**
- External Preparatory Data
  - Gaia data
  - Other mission data
- Data Quality Monitoring
  - Tools
  - Science validation in operations
  - Science validation in development

- System Softwares
  - DDPC Development Facilities and Deployment
    - Software Development kit
    - CI/CD
    - DCCs Installation and configuration
      - All the DCCs are identical. They can run any defined pro DCC. For example, there will be only one DCC with the
  - Prototyping Framework _ Lisacollab
  - Expertise Lab Framework
    - Platform allowing the scientist to prototype new algorithms
    - Expertise Logs: Managing & Searching facility
      - This component is dedicated to register "science" logs, l
  - Data Management
    - This product includes the data model, database schema, a
    - Data Model Definition
      - Science Data Model
      - Engineering Interfaces
      - Metadata (science/technical)
    - Data Storage
    - Data Access library
    - Data Access tools
    - Data exchange facility
      - The data exchange facility enables internal (between the
  - DDPC Operations Facilities
    - Tools for Operations
      - It gathers all the tools needed for operators during the
    - System Supervisor (monitoring)
  - Pipeline Management
    - Pipelines builder
      - This component ease the integration/chaining of the diffe MBHB, EMRIs, etcâ€¦
    - Workflow Manager/DCC
      - The workflow manager is located in each DCC. It will ch manager monitor their resources. It is also in charge of p
    - DDPC System Orchestrator
      - The orchestration tool dispatches the work to perform or
  - DDPC security facility
    - Implement the authentication, privacy, authorization and s

- Infrastructure
  - DCC Main
  - DCC 1
  - DCC 2
  - DCC 3
  - DCC 4
  - DCC N
  - Notes

LISA Data Challenge



LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:

LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:

Design specific challenges

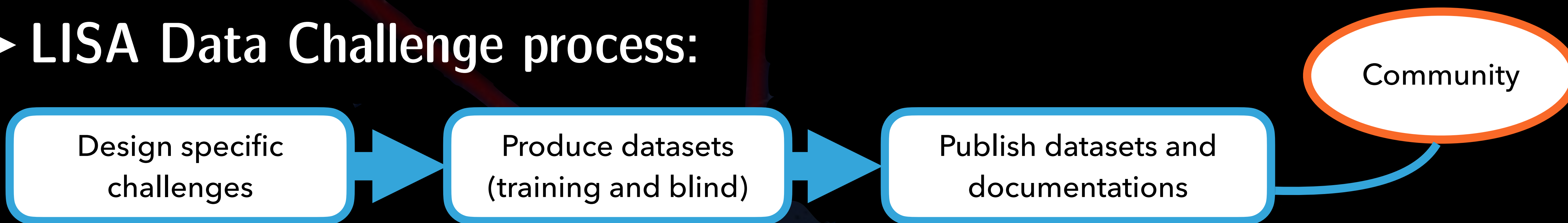
LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:

Design specific challenges → Produce datasets (training and blind)

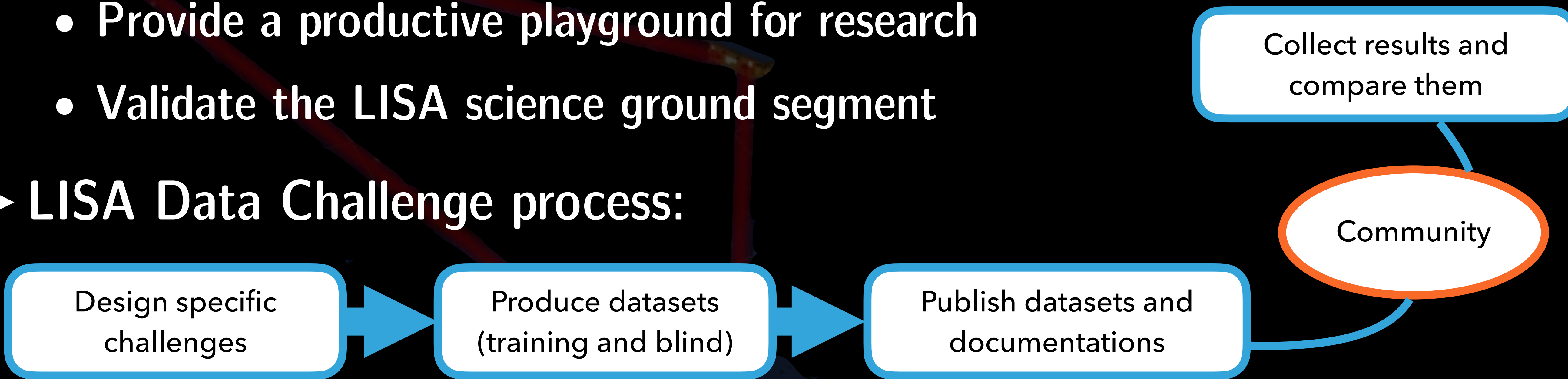
LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:



LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:



LISA Data Challenge

- Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- LISA Data Challenge process:

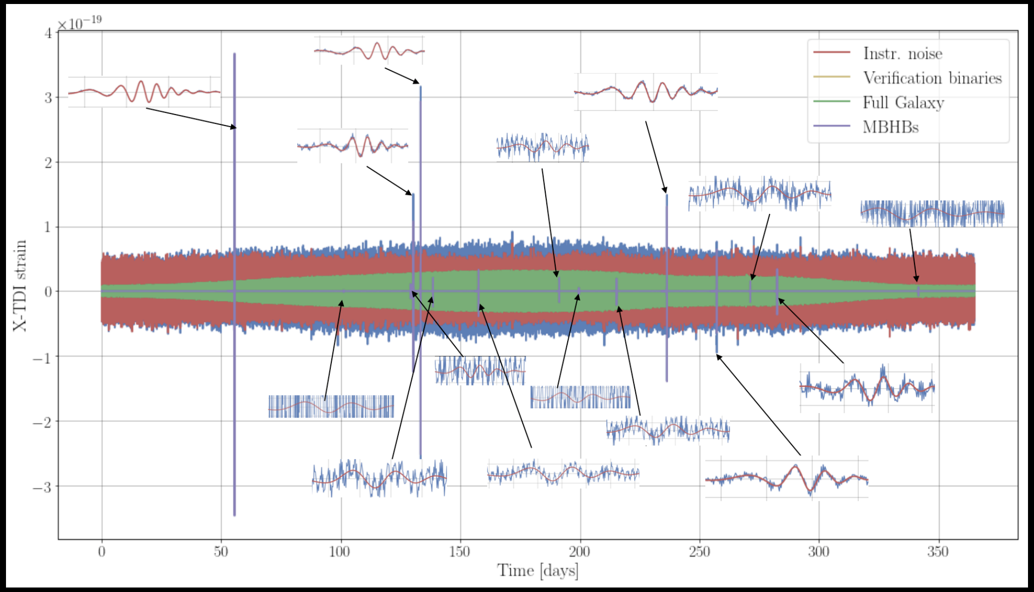
Design specific challenges → Produce datasets (training and blind) → Publish datasets and documentations

Community

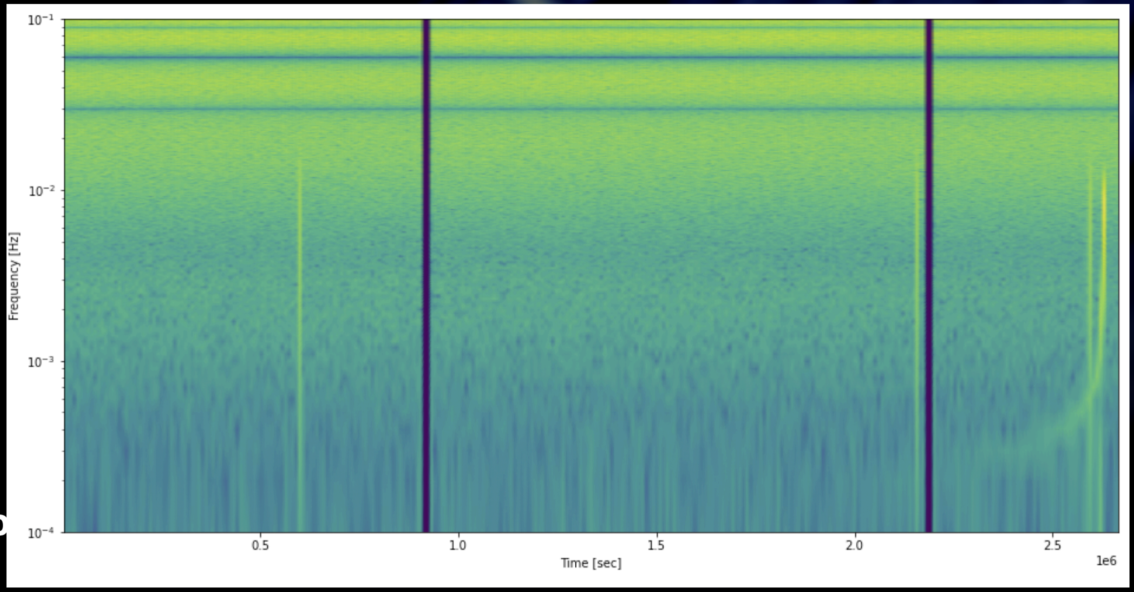
Collect results and compare them

- On going challenges:

SMBHBs + Galactic binaries



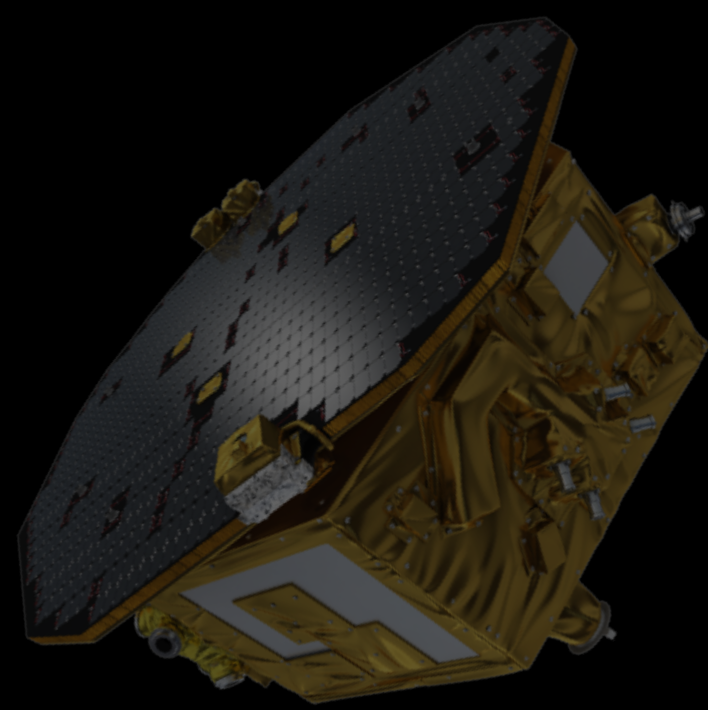
One SMBHB + gaps + glitches

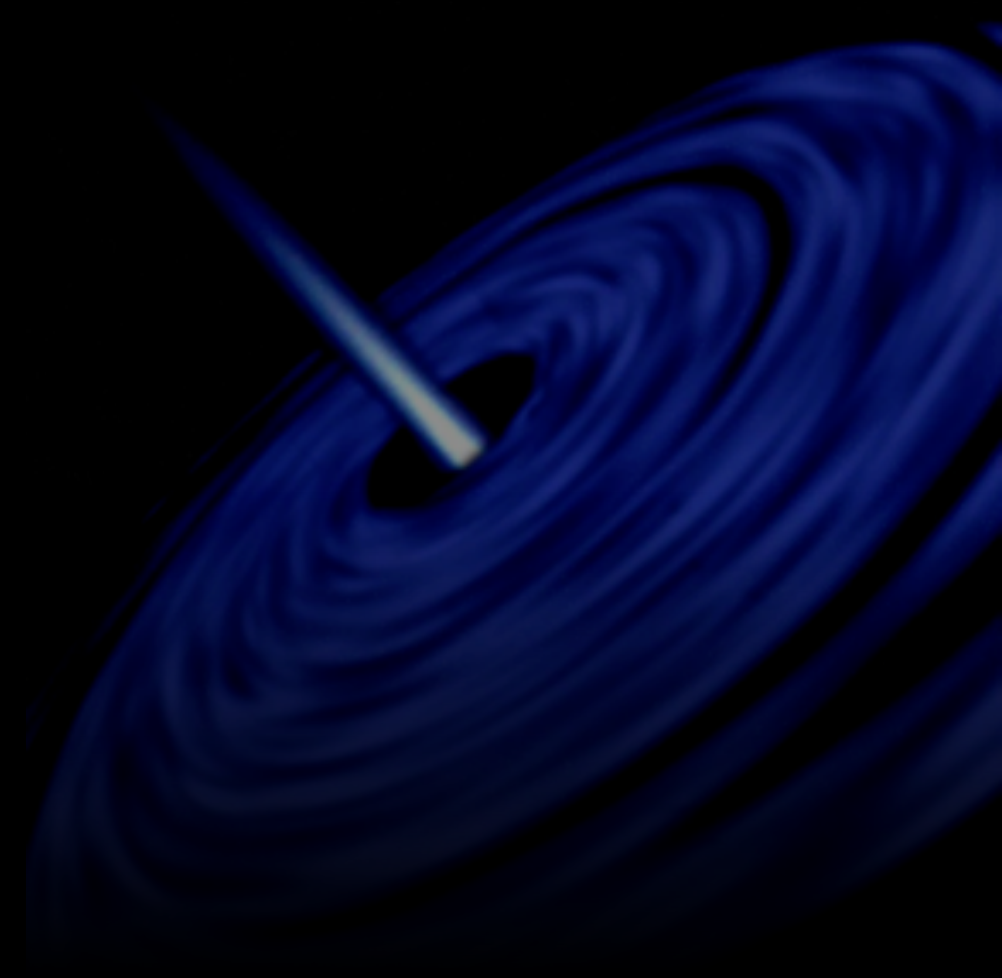


Conclusion

- LISA raw data: small volume but complex :
  - Large number of overlapping GW sources to extract
  - Multiples noises to reduce
- Challenge for data analysis:
  - First data of this kind => flexibility + multiple approaches
  - Ongoing research and prototyping (LDC)
  - Large computing ressources needed
- Organisation: collaborative approach
  - ESA: communication, instrument monitoring, noise reduction, alerts, public releases
  - Consortium: extraction of GWs, support to alerts and instrument monitoring
- Consortium contribution: Distributed Data Processing Center: collaborative approach with multiple contributors for software and for infrastructure (Data Computing Center) => open for more contribution

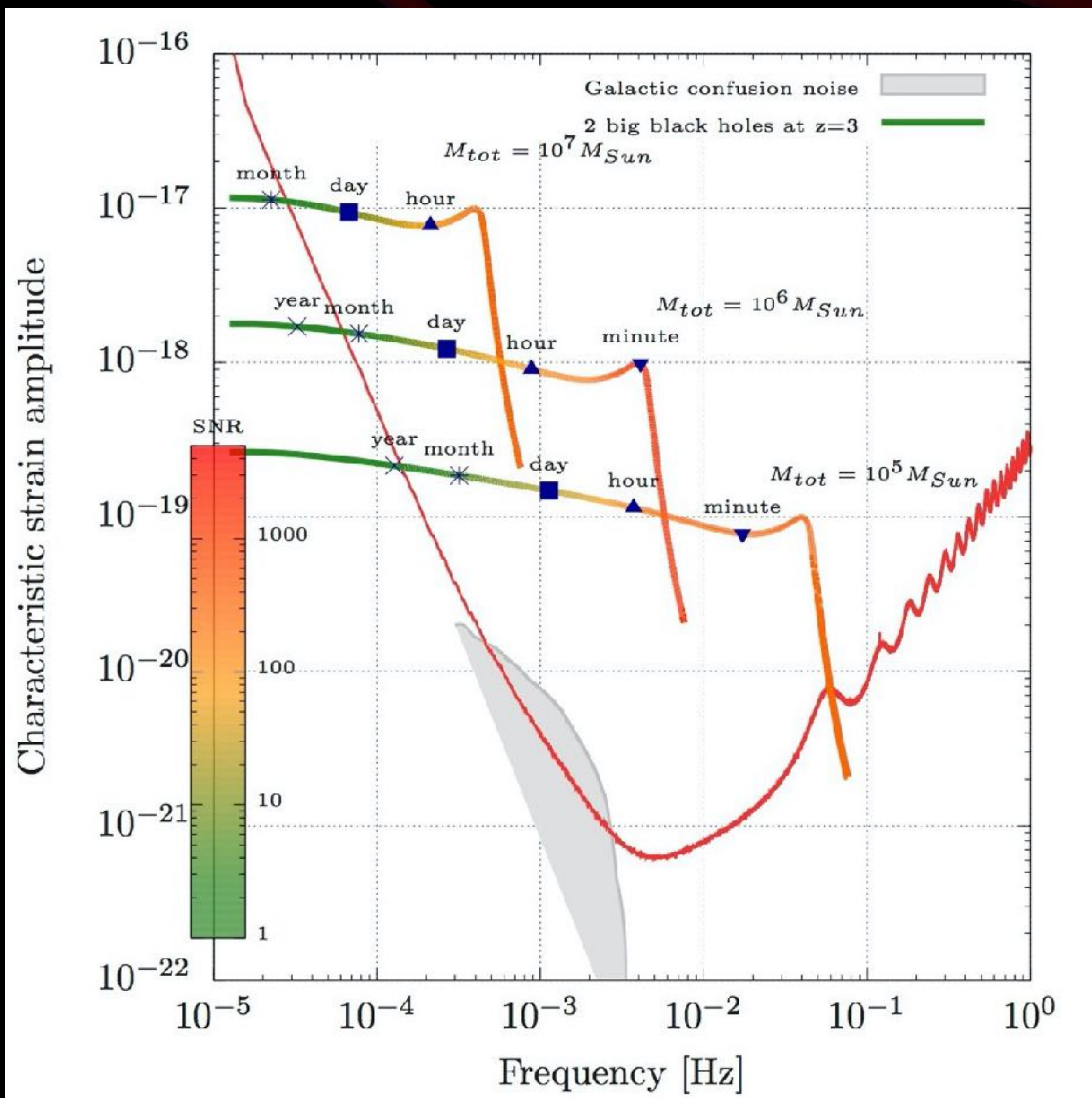
Thank you!

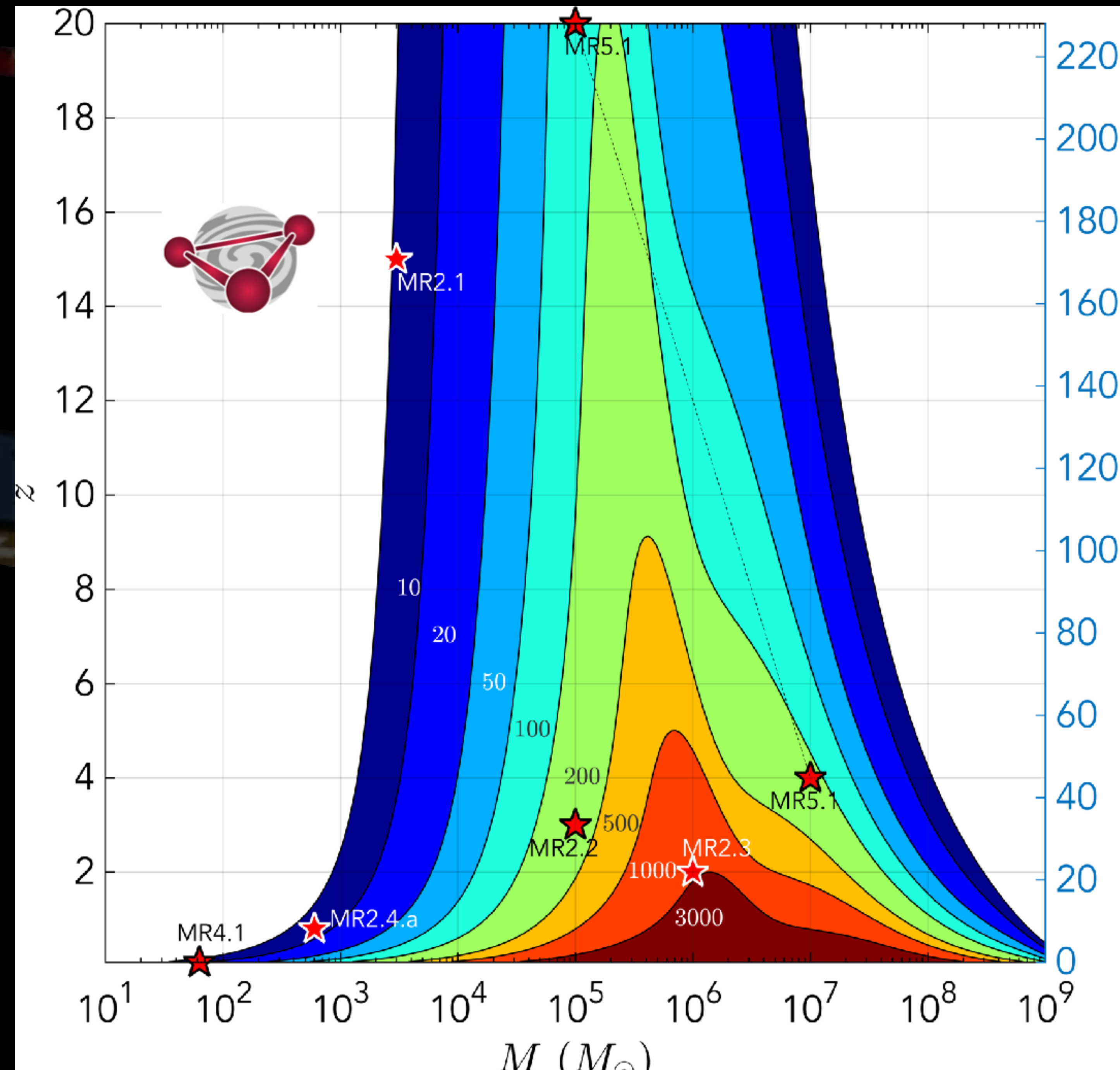




Super Massive Black Hole Binaries

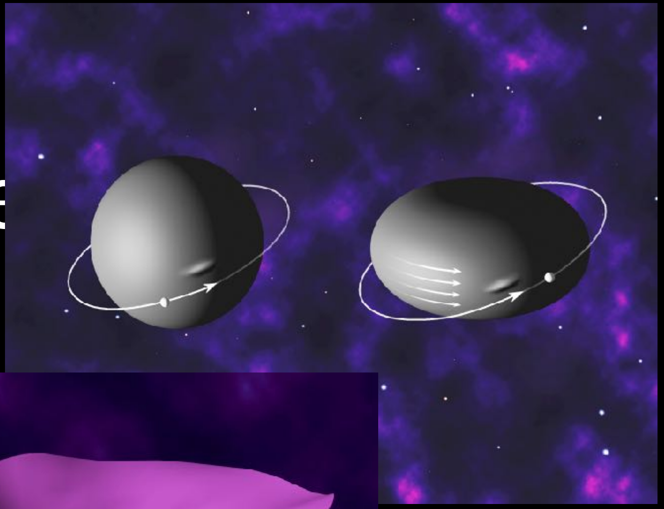
- **LISA: SMBHB from 10^4 à 10^7 solar masses in "all" Universe**

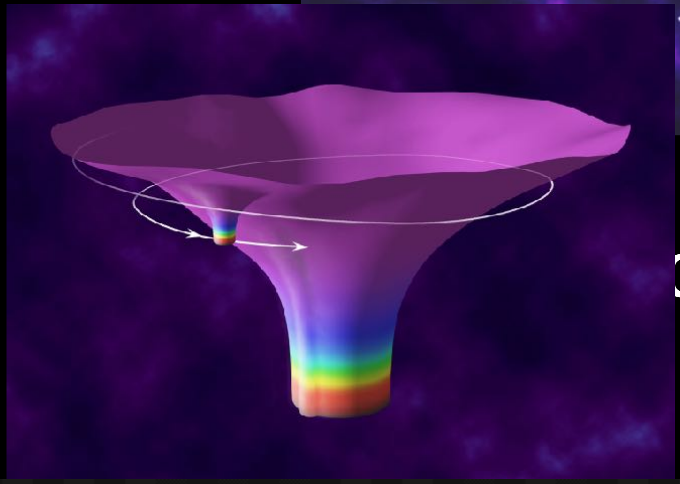


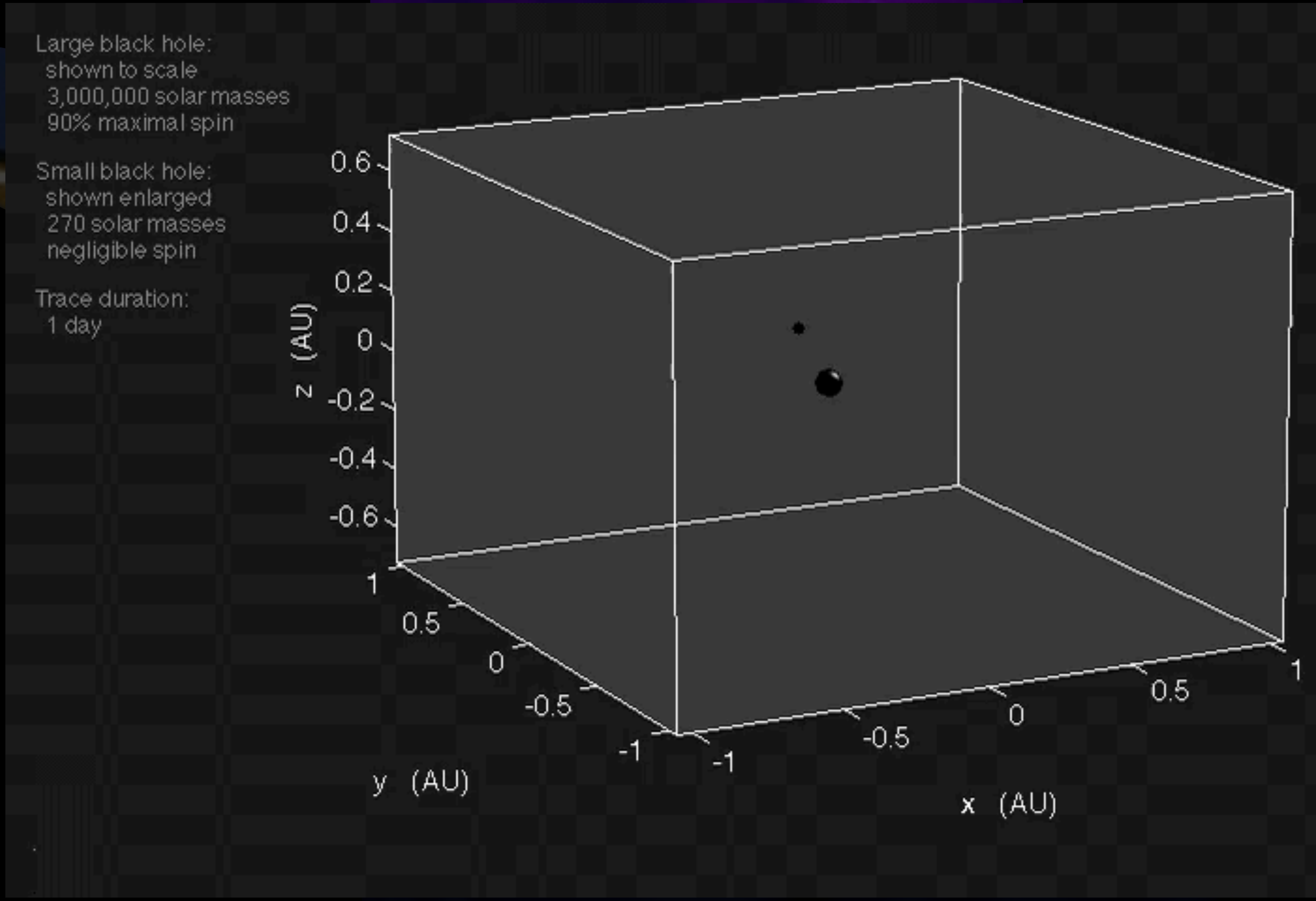


EMRIs

- Capture of a "small" object by massive black hole
  M_{Sun}): Extreme Mass Ratio Inspiral
  - Mass ratio > 1000
  - GW gives information on the geometry ound the black hole.
  - Test General Relativity in field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could observed by LISA

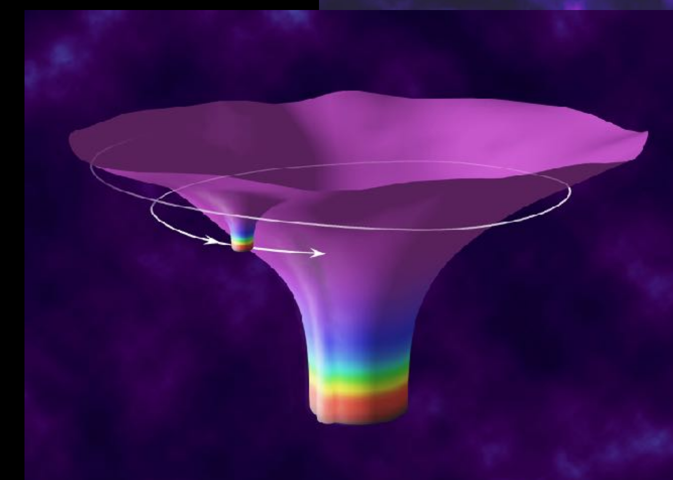


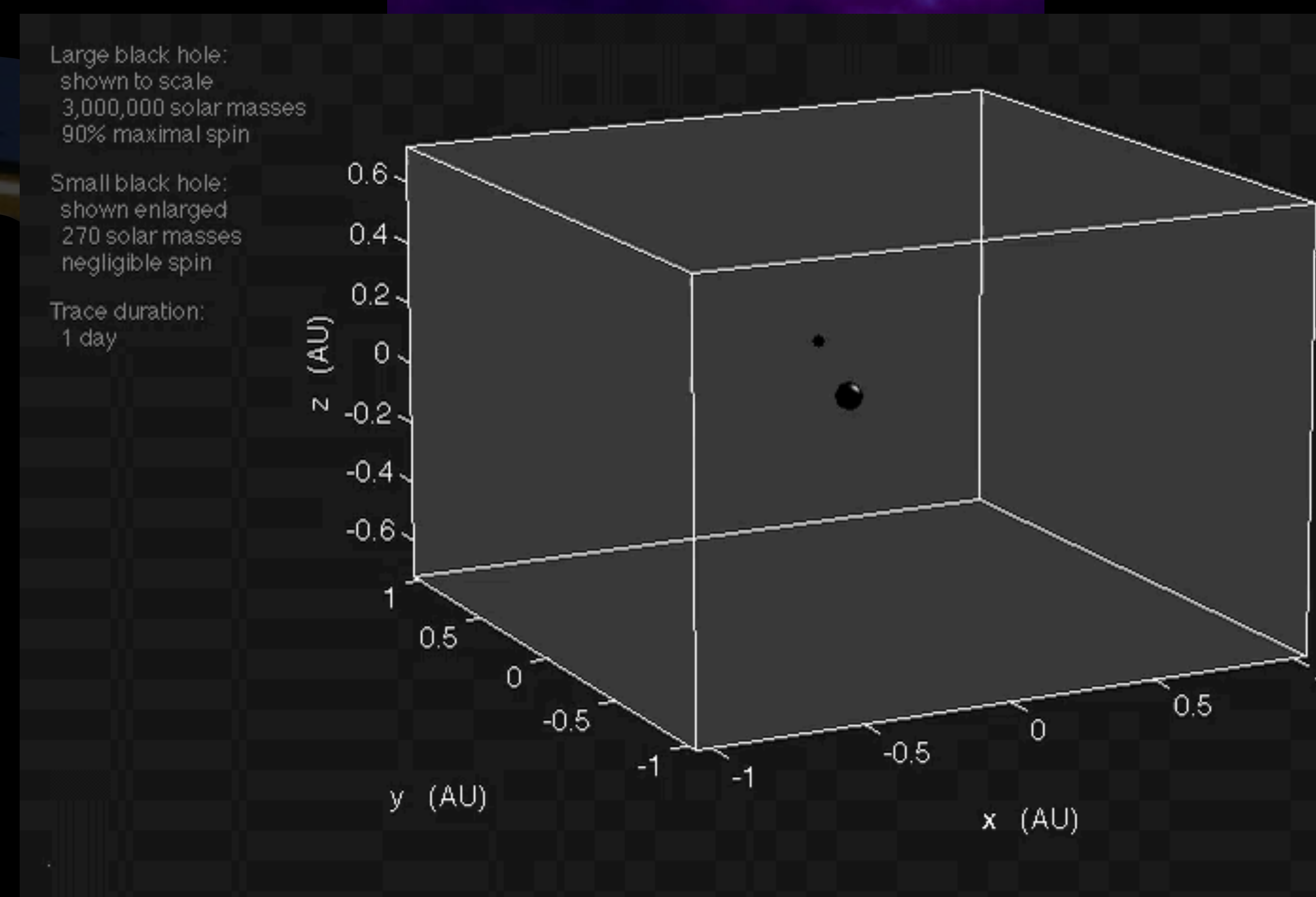




EMRIs

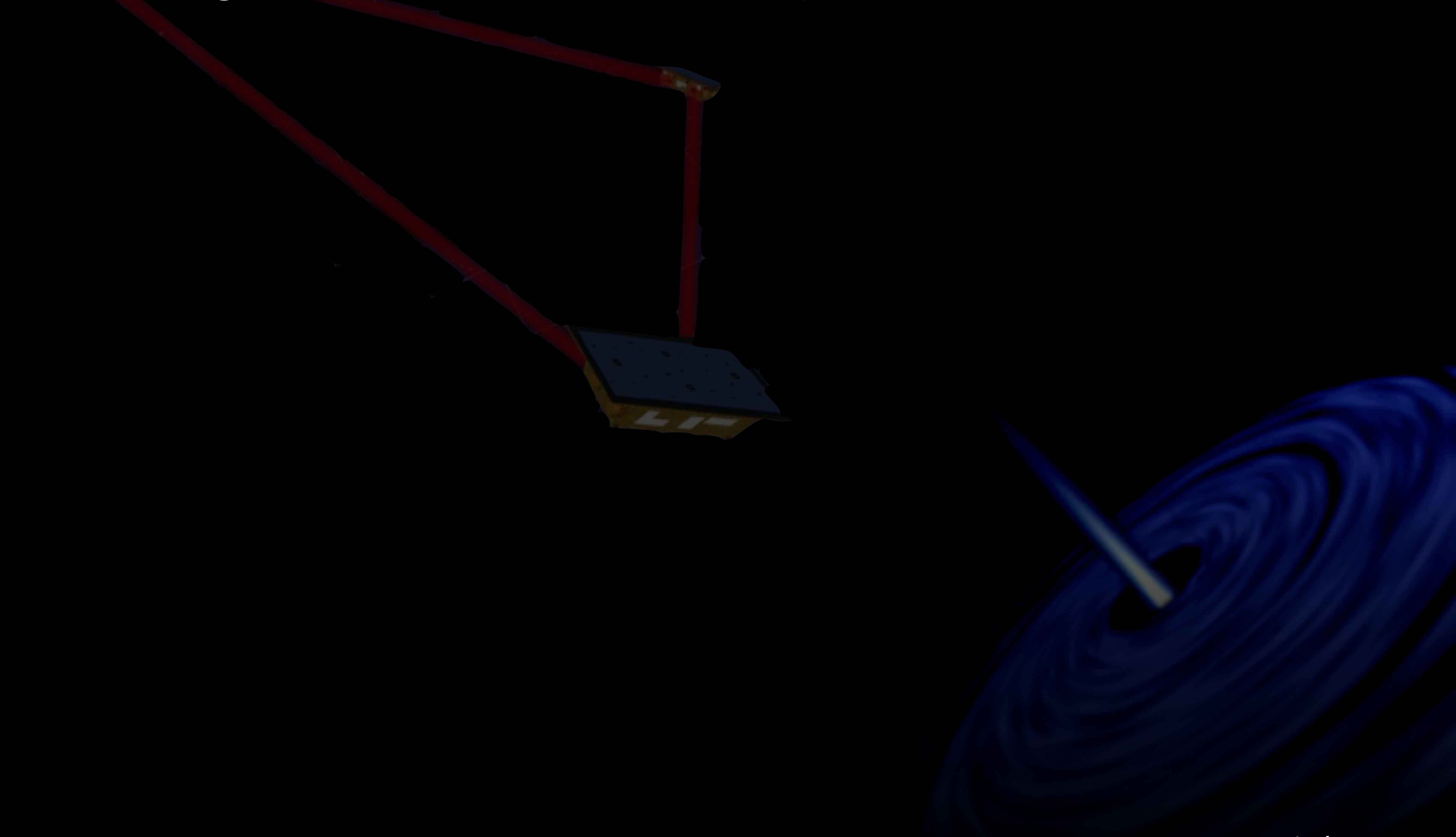
- Capture of a "small" object by massive black hole M_{Sun}): Extreme Mass Ratio Inspiral
  - Mass ratio > 1000
  - GW gives information on the geometry ound the black hole.
  - Test General Relativity in field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could observed by LISA





LISA Data Challenge

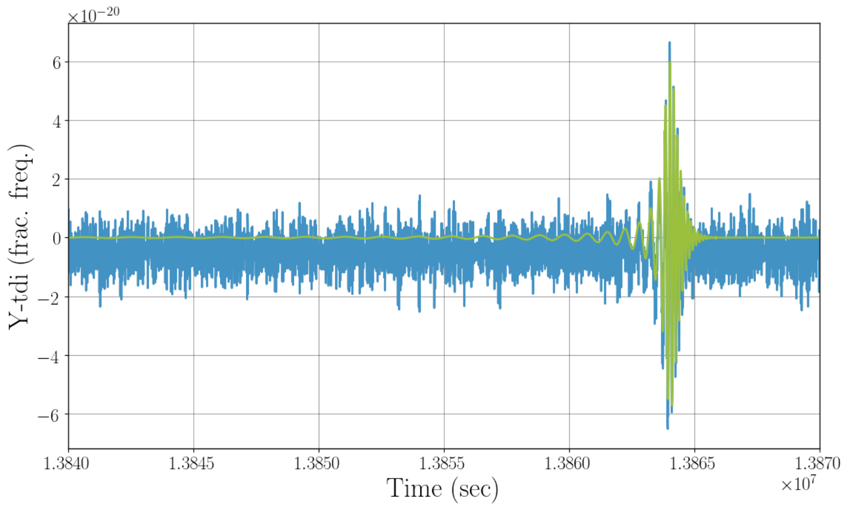
- Challenge 1: Radler - one source type per dataset



LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

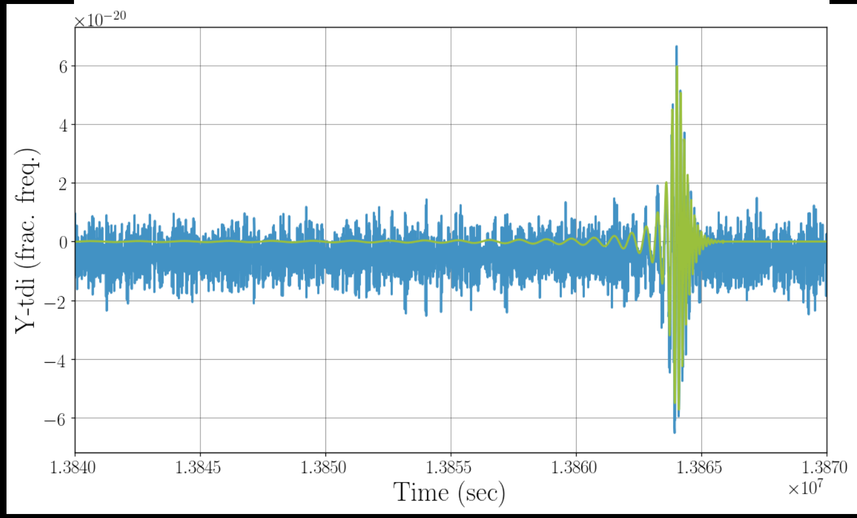
Merging MBHB



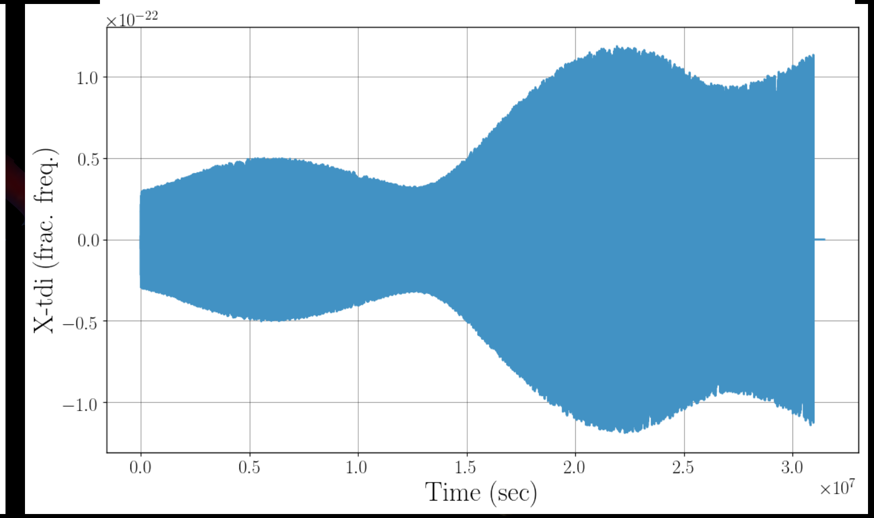
LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

Merging MBHB



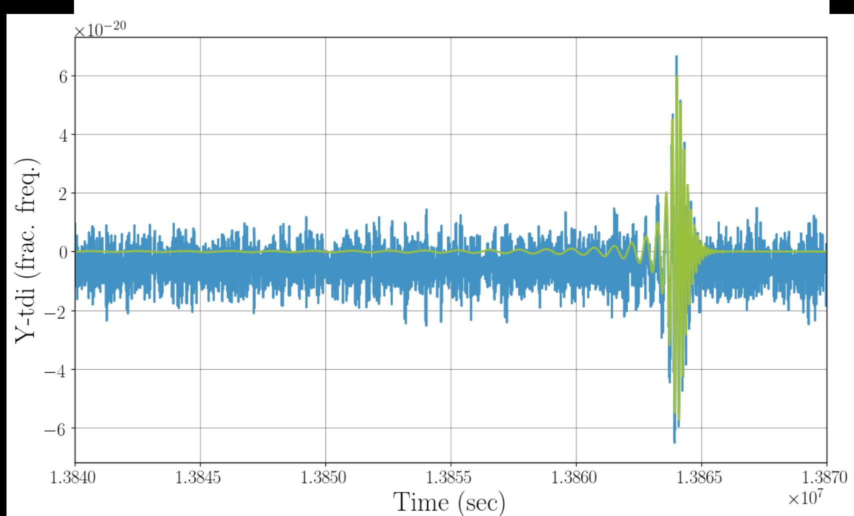
EMRI



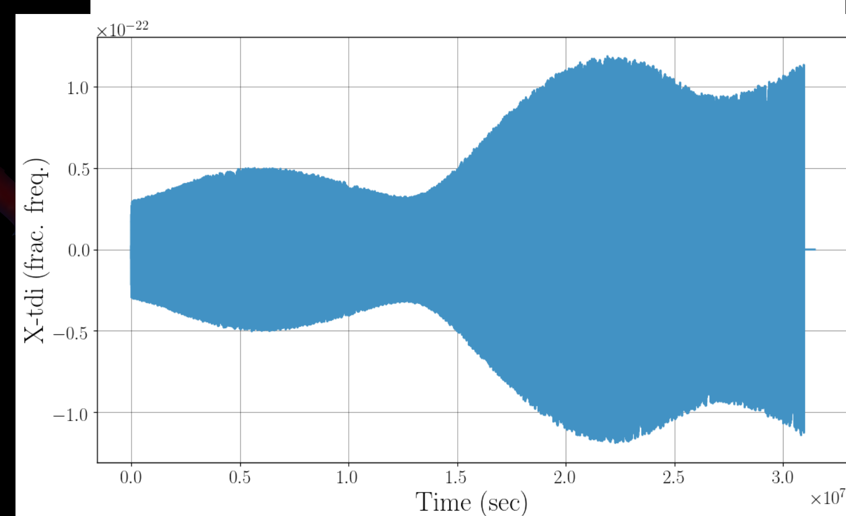
LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

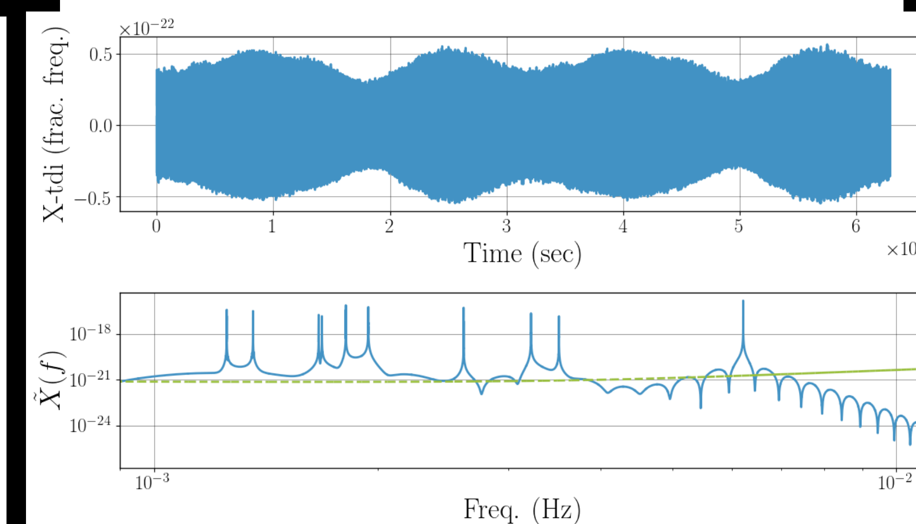
Merging MBHB



EMRI



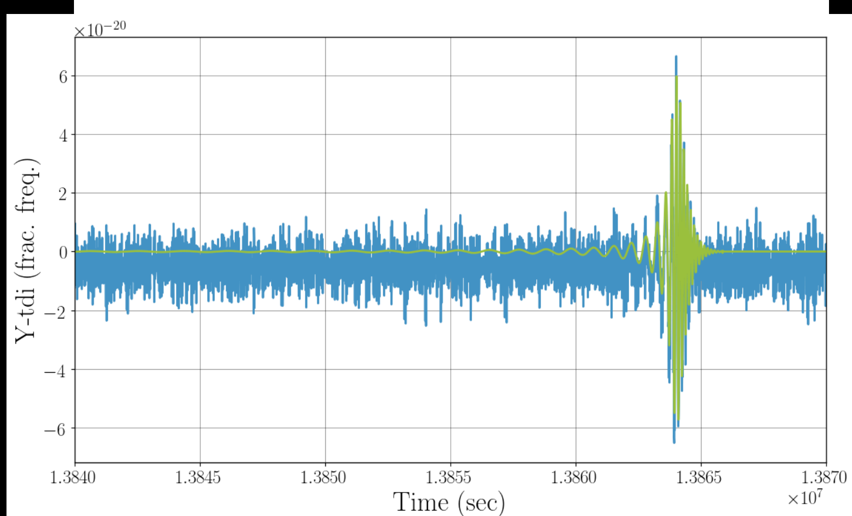
Verification Galactic binaries



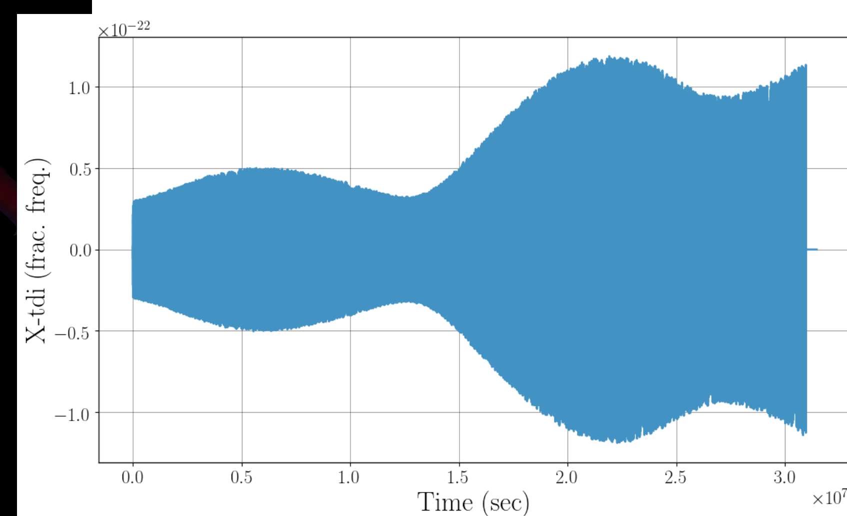
LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

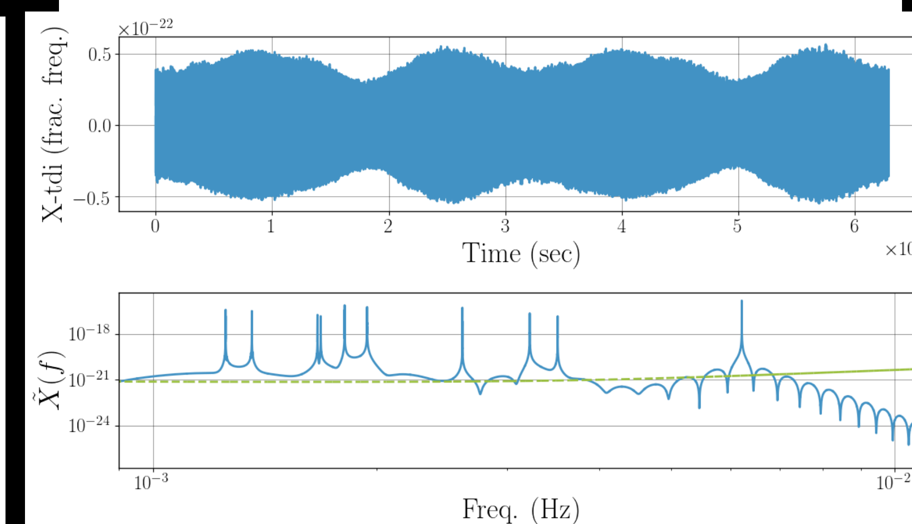
Merging MBHB



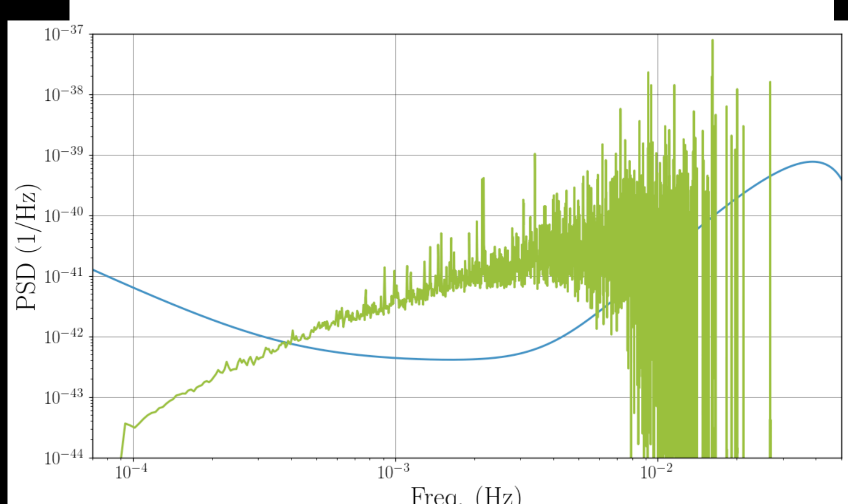
EMRI



Verification Galactic binaries



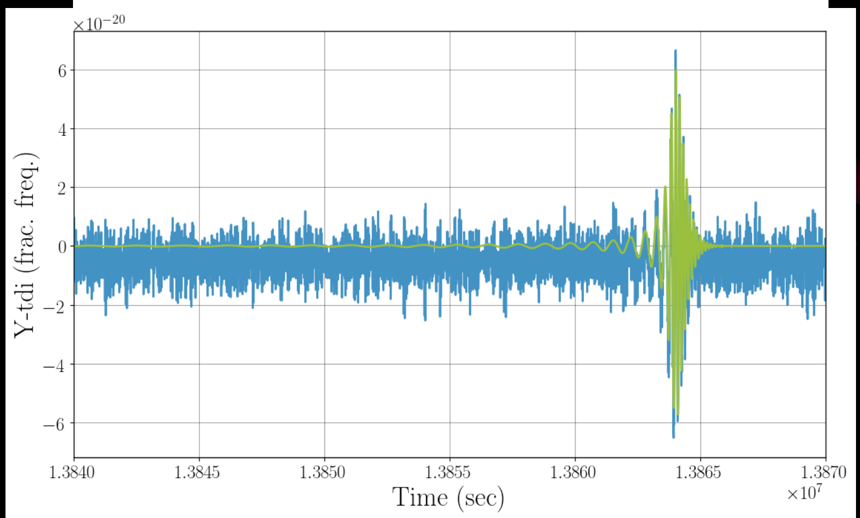
Full galaxy (WD binaries)



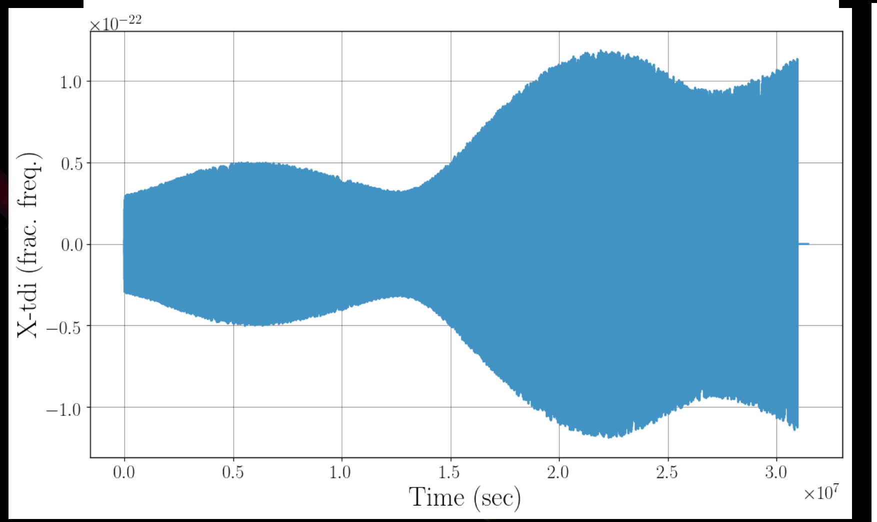
LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

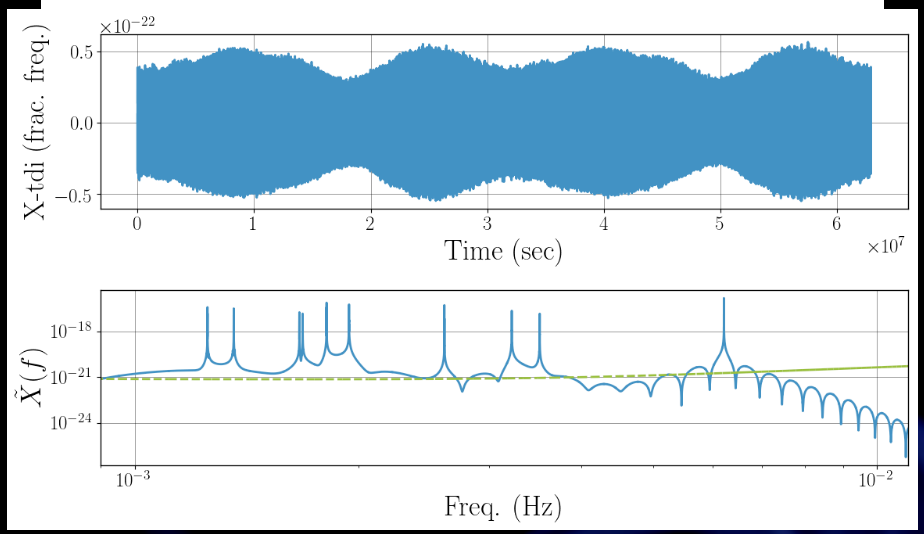
Merging MBHB



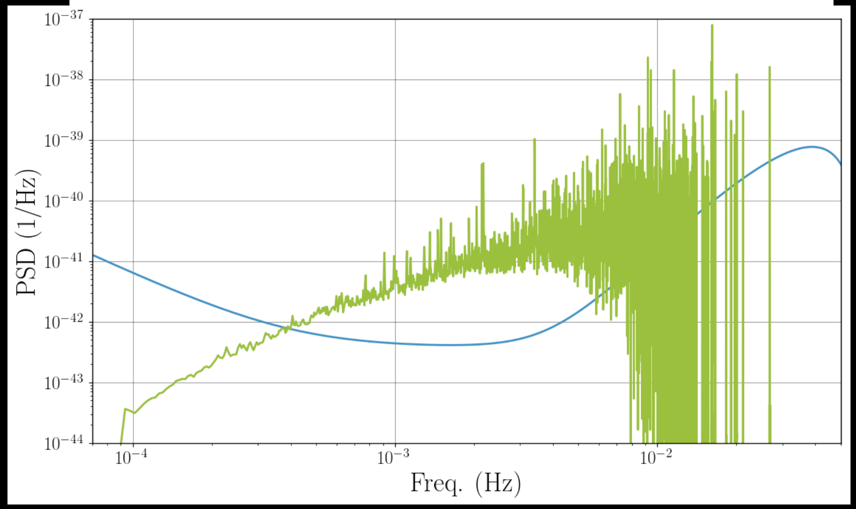
EMRI



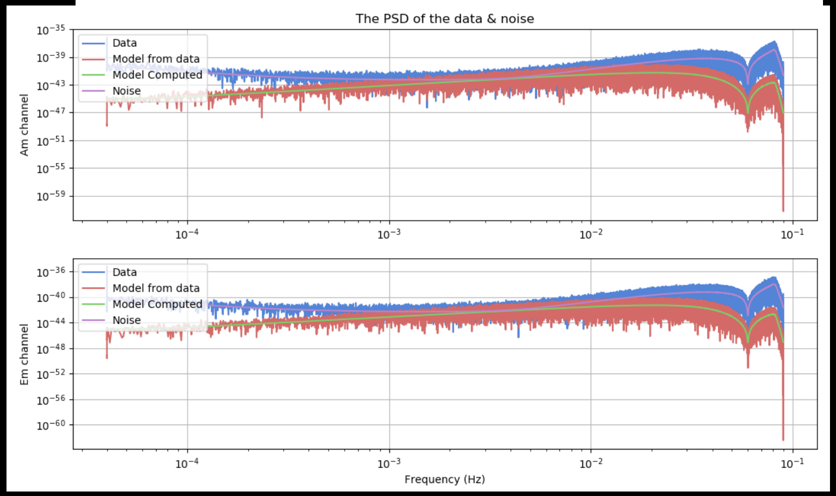
Verification Galactic binaries



Full galaxy (WD binaries)



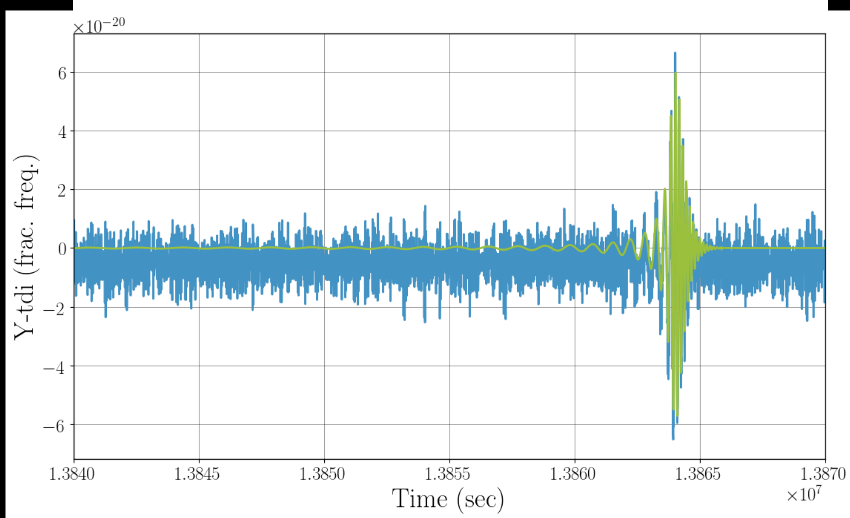
Stochastic GW background



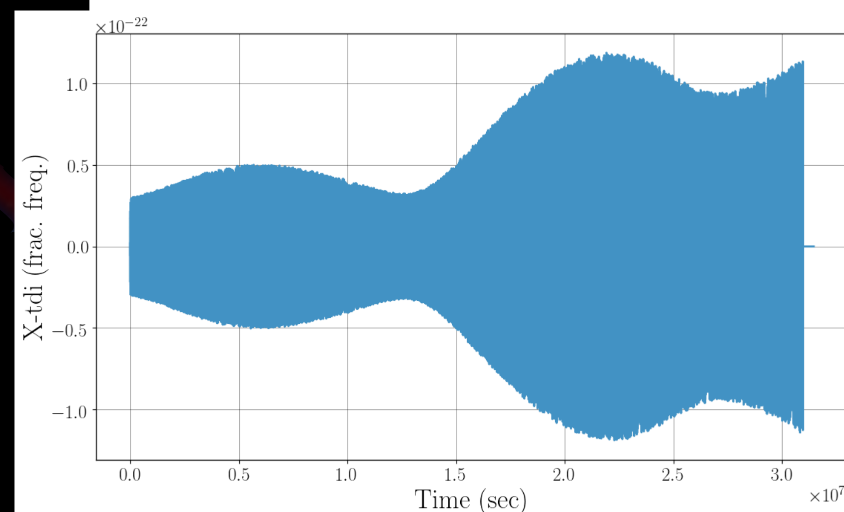
LISA Data Challenge

- Challenge 1: Radler - one source type per dataset

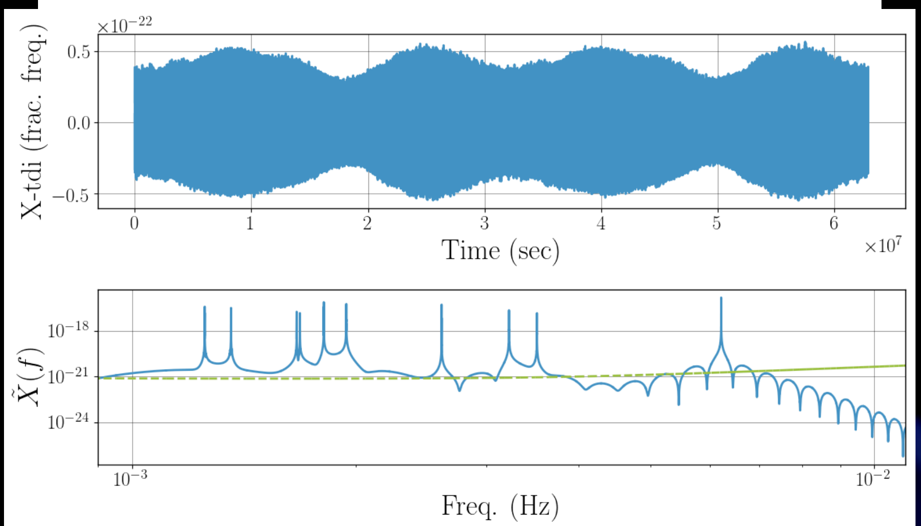
Merging MBHB



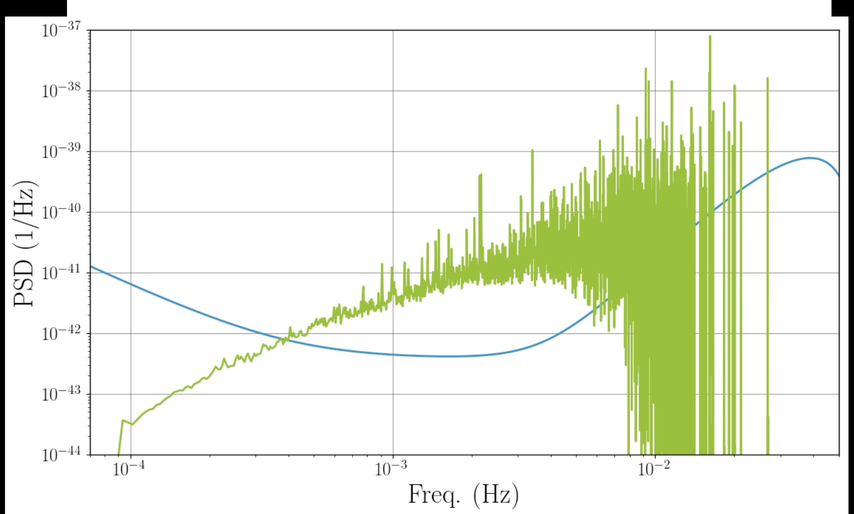
EMRI



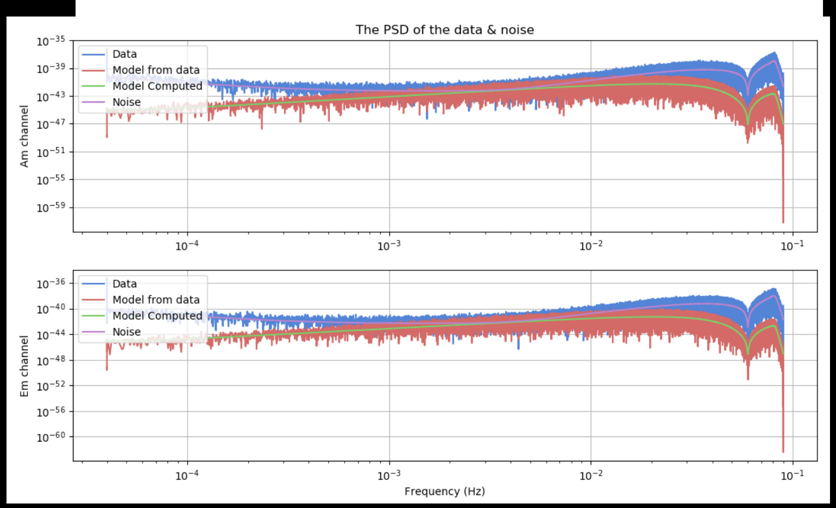
Verification Galactic binaries



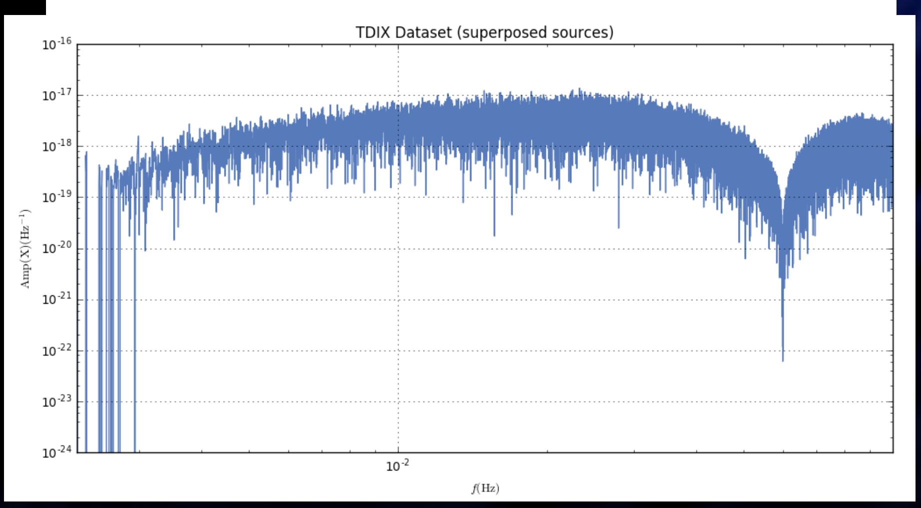
Full galaxy (WD binaries)



Stochastic GW background

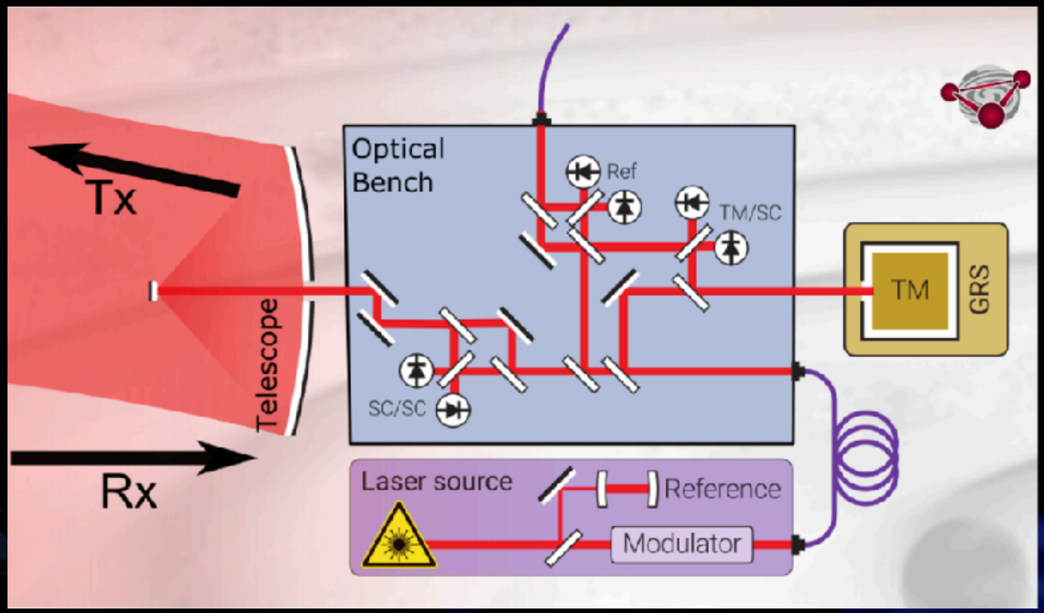


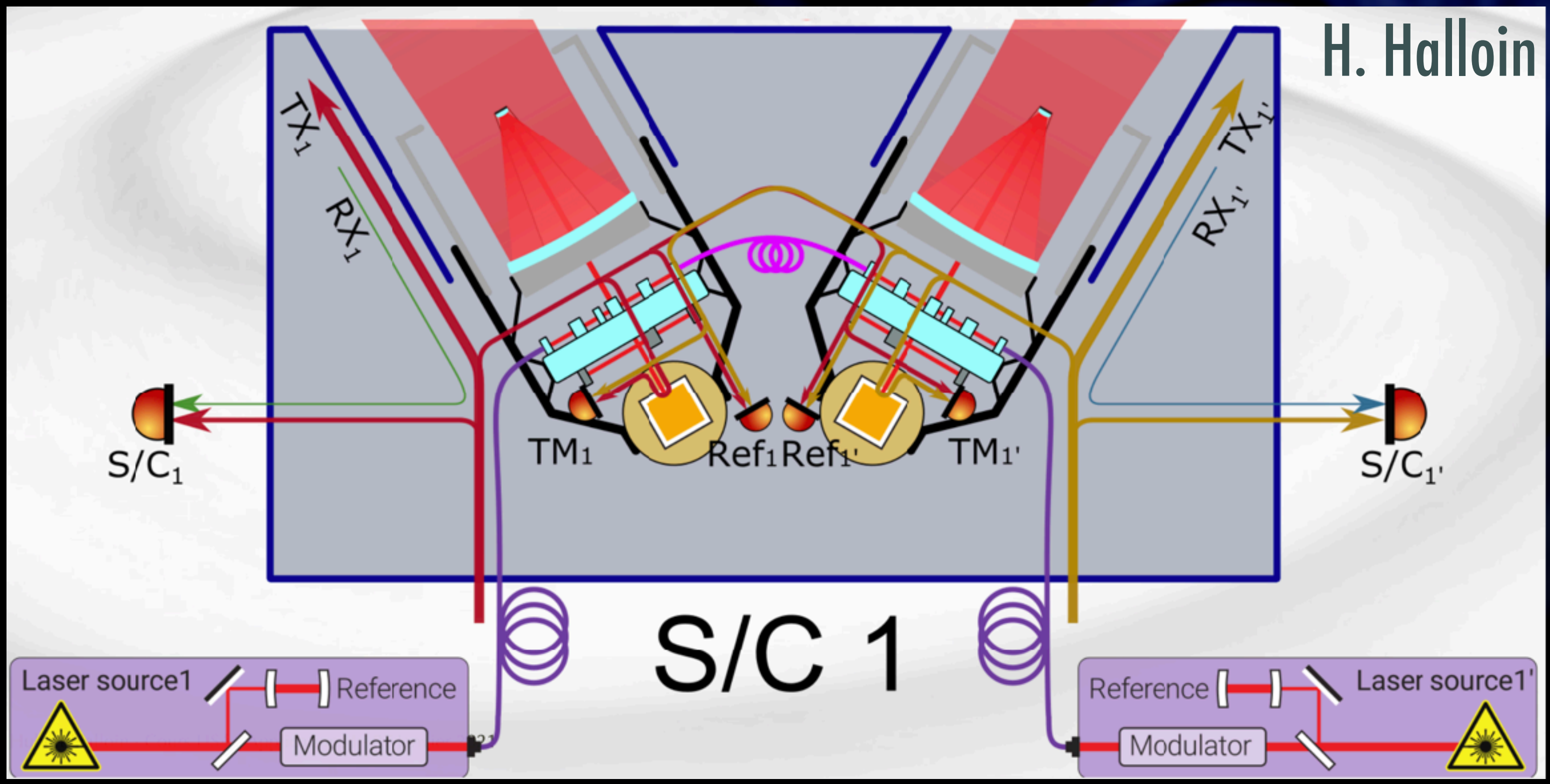
Stellar mass BH binaries



Interferometric measurements

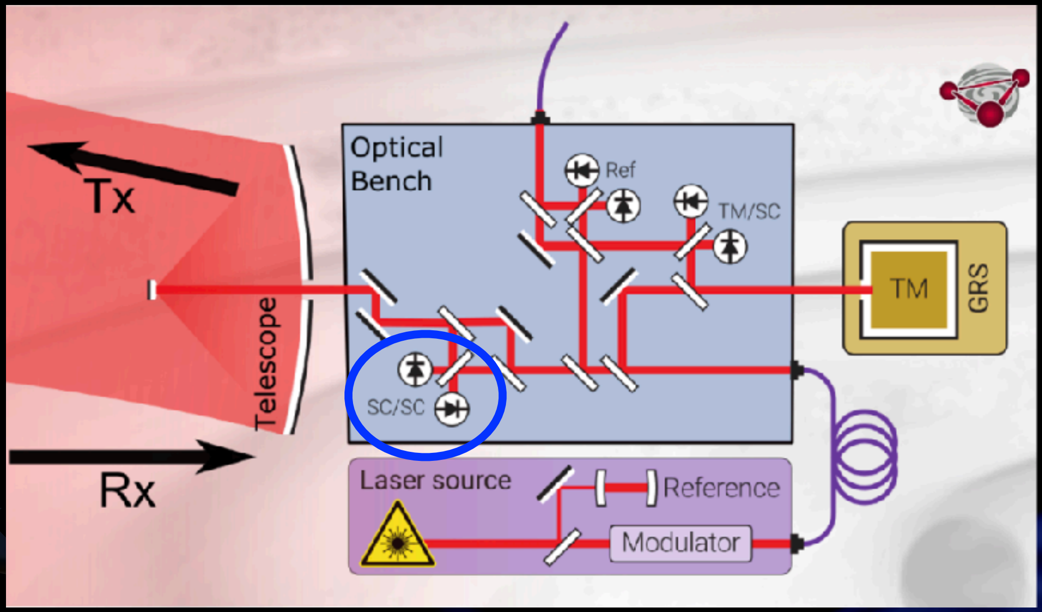
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

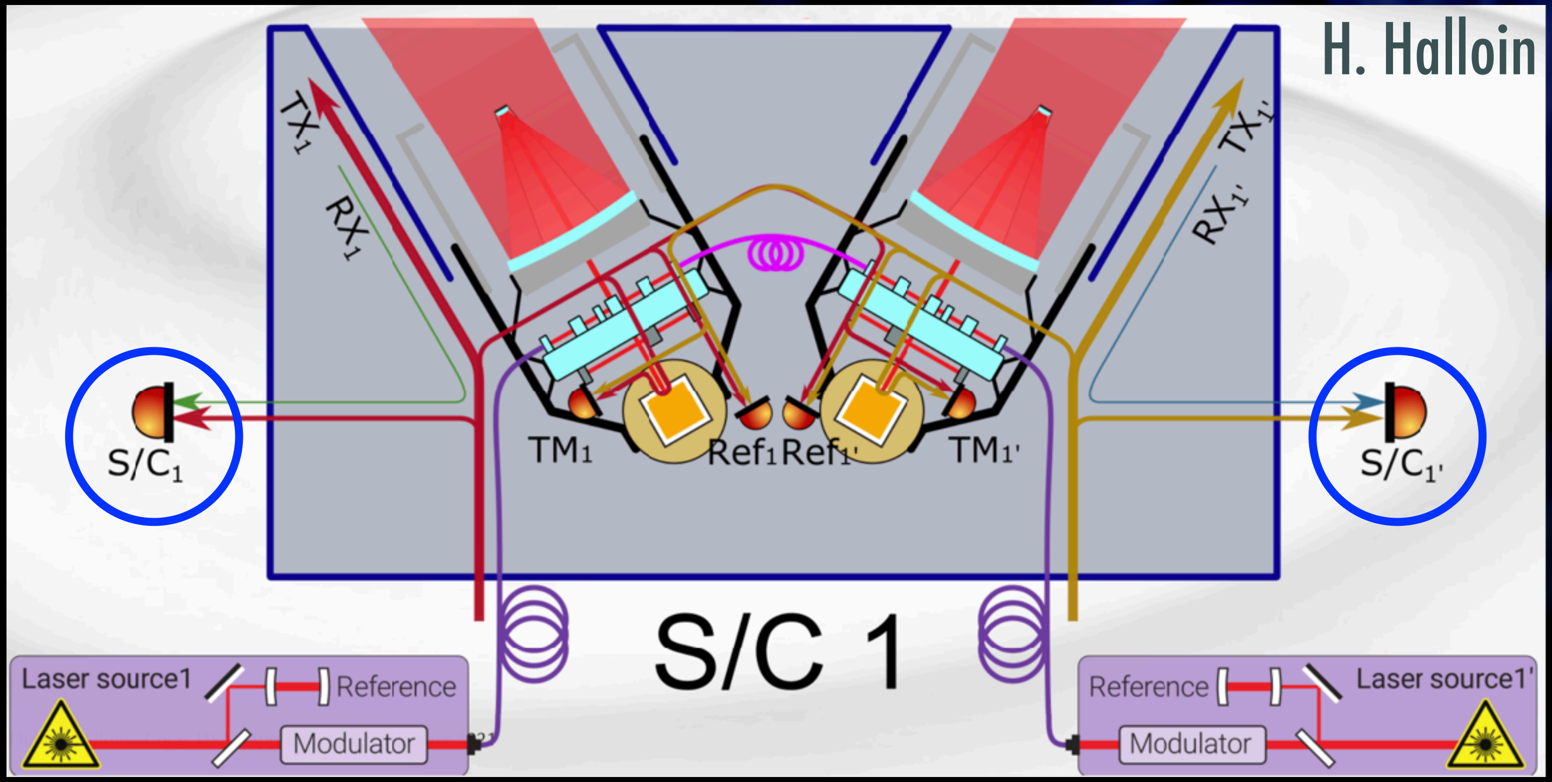




Interferometric measurements

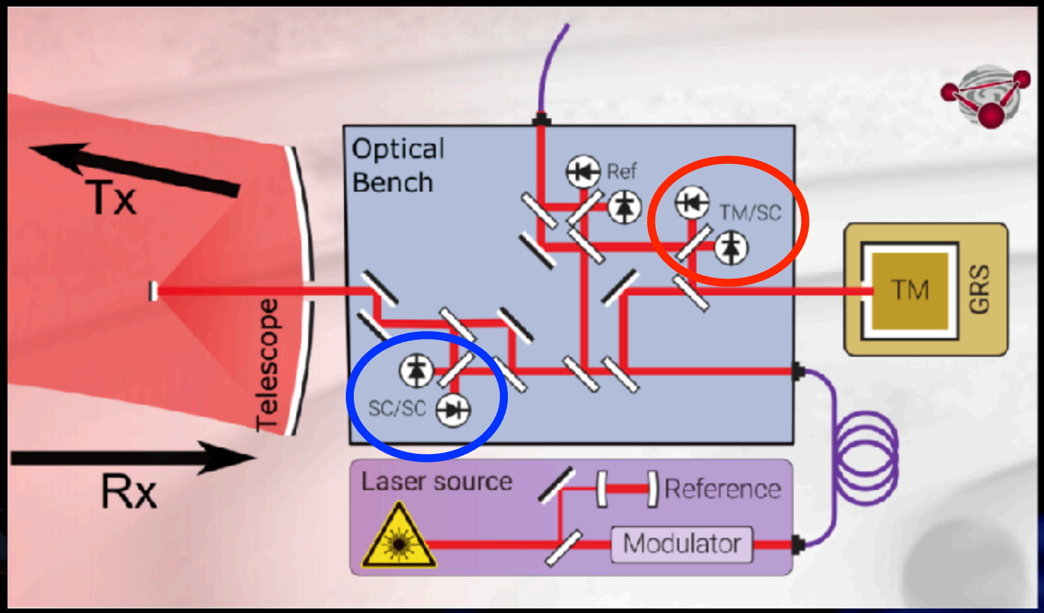
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

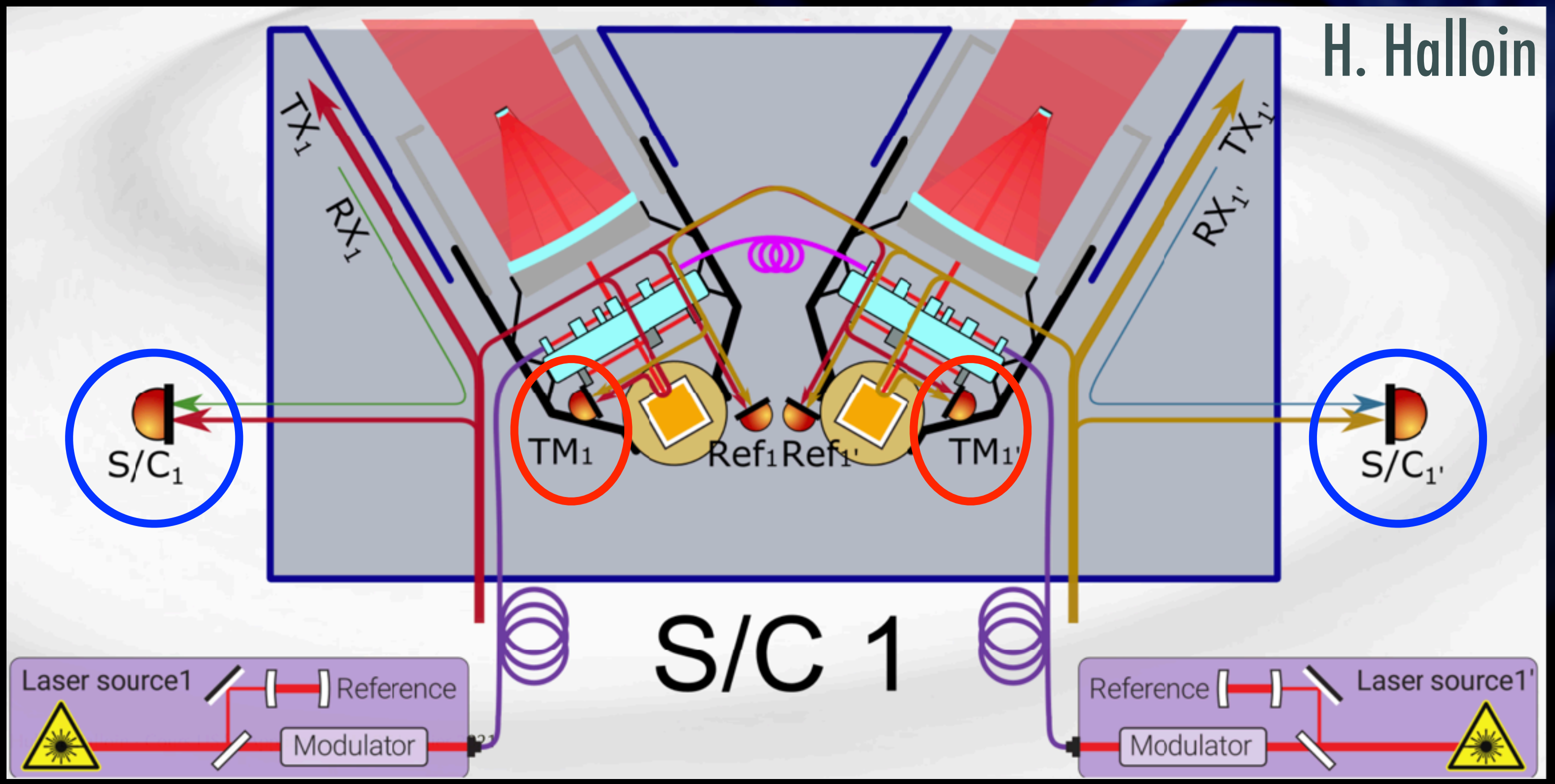




Interferometric measurements

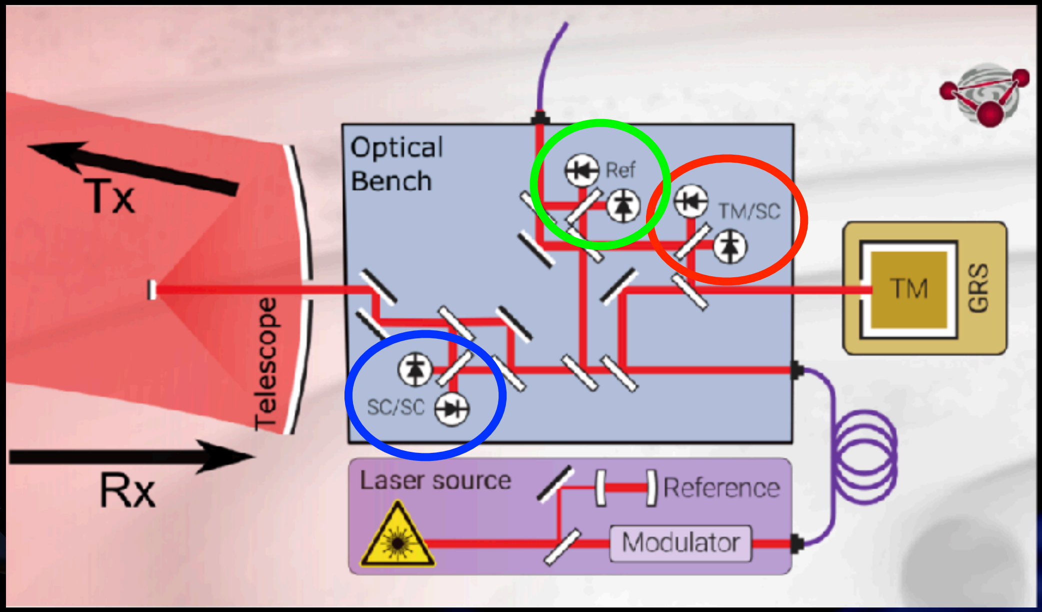
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

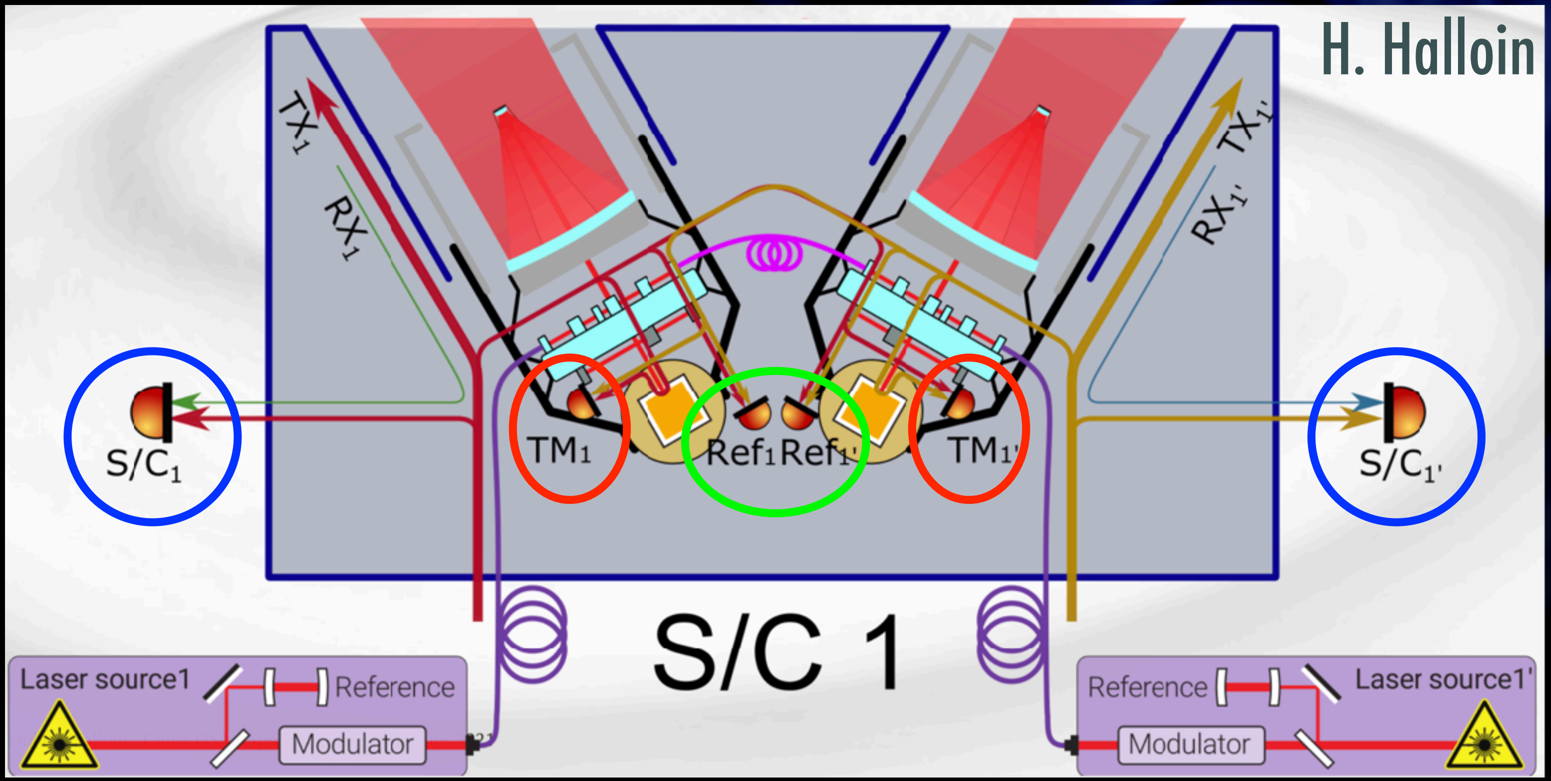




Interferometric measurements

- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts





Interferometric measurements

- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement => GWs
  - Sideband for transferring amplified clock jitter => correction of additional clock jitter
  - Pseudo-Random Noise => ranging (measure arm length)
  - Laser locking

See talk from Olaf Hartwig