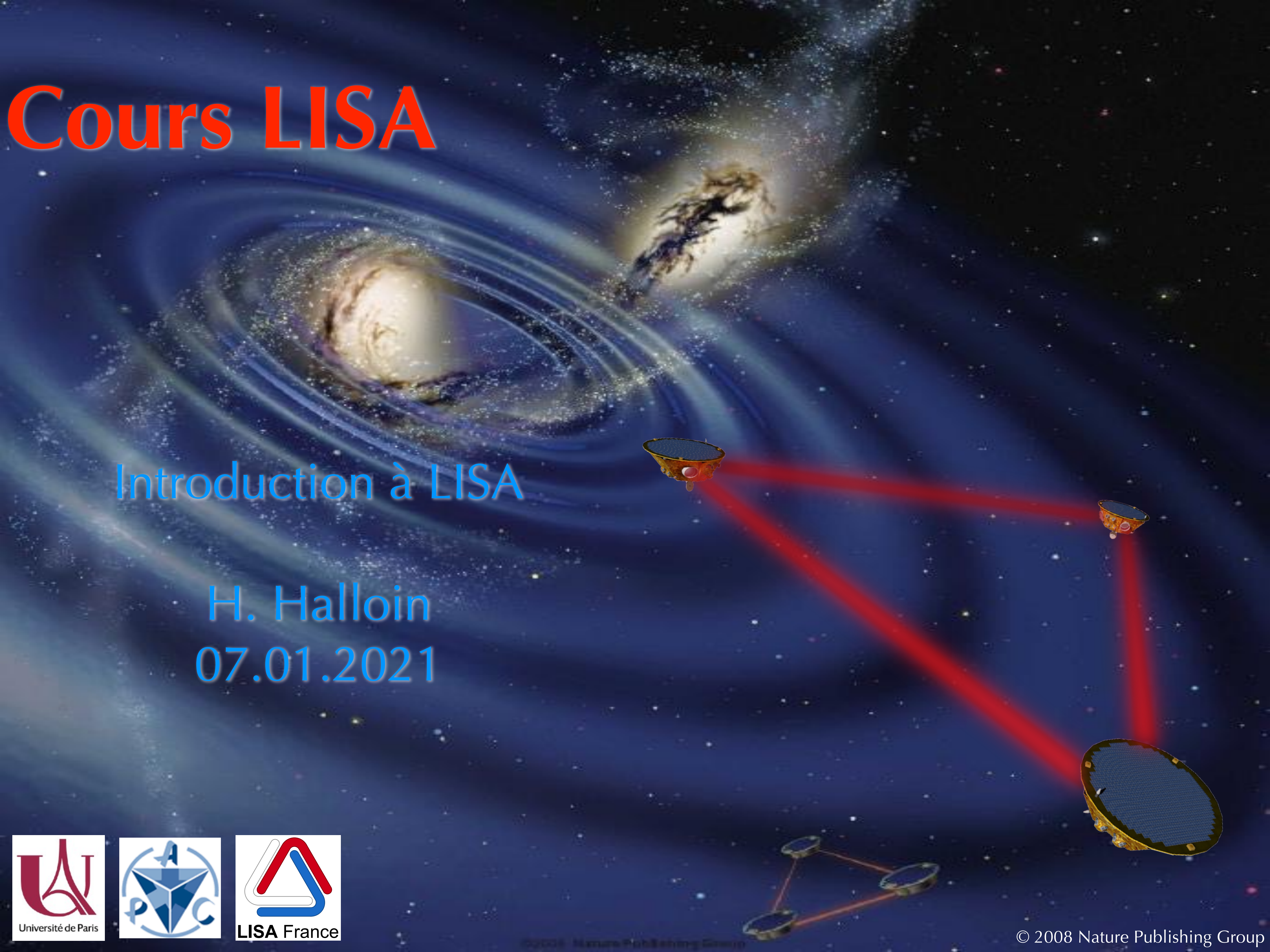
Cours LISA



Introduction à LISA

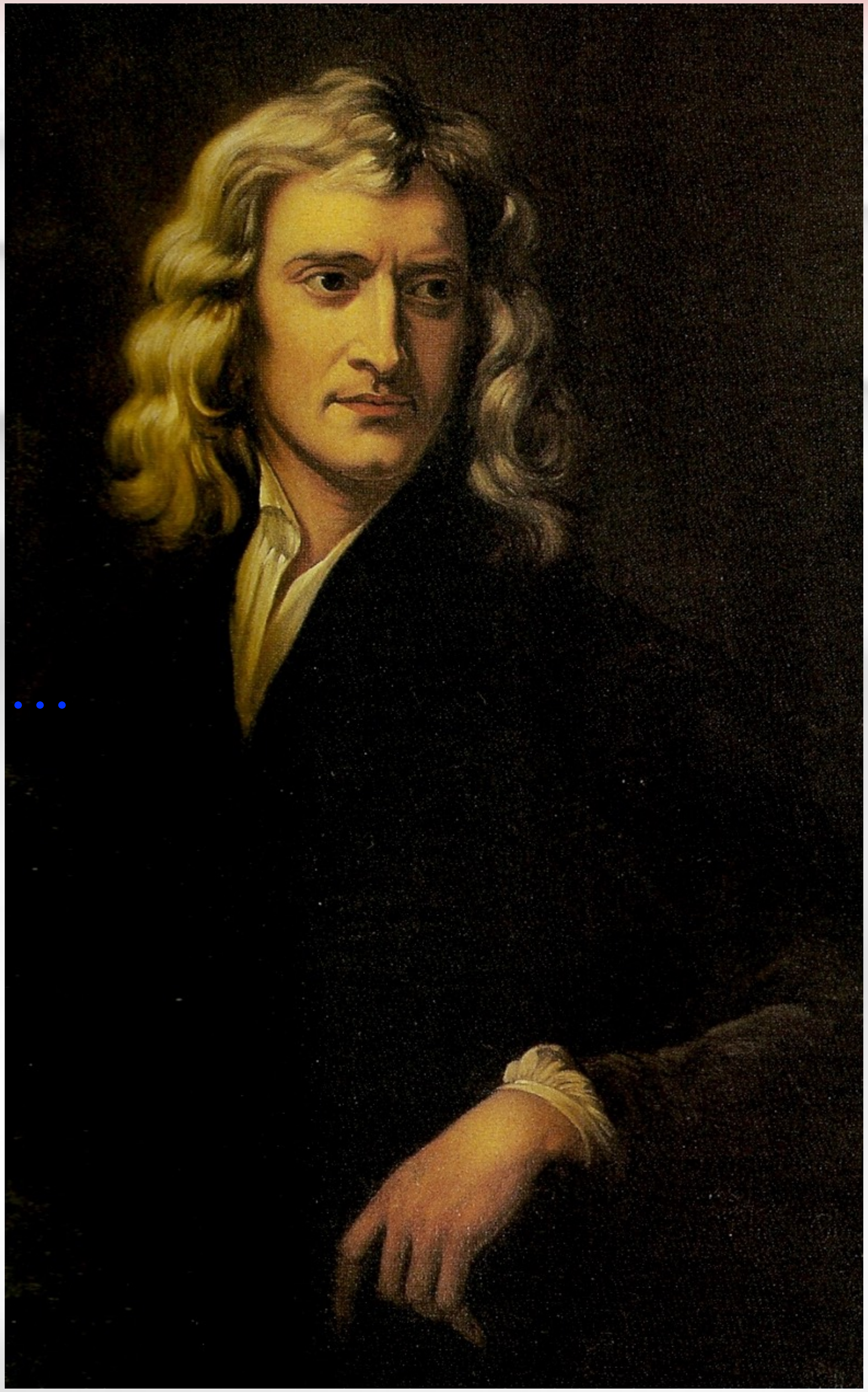
H. Halloin
07.01.2021

Contenu

- Quelques mots sur les OG
- La science de LISA
- LISA Pathfinder
- Profil mission LISA
- Organisation LISA

Quelques mots sur les ondes gravitationnelles

Some history …



- Isaac Newton (1687) : gravity is a instantaneous central force
  - conservation of energy,
  - separation of space and time,
  - orbit = ellipse repeated infinitely,
  - simple but precise theory,
  - idea of instantaneous force is disturbing …

$$\boxed{\nabla^2\phi} = \boxed{4\pi G\rho}$$

Spatial fluctuations of potential

Mass distribution

Some history …

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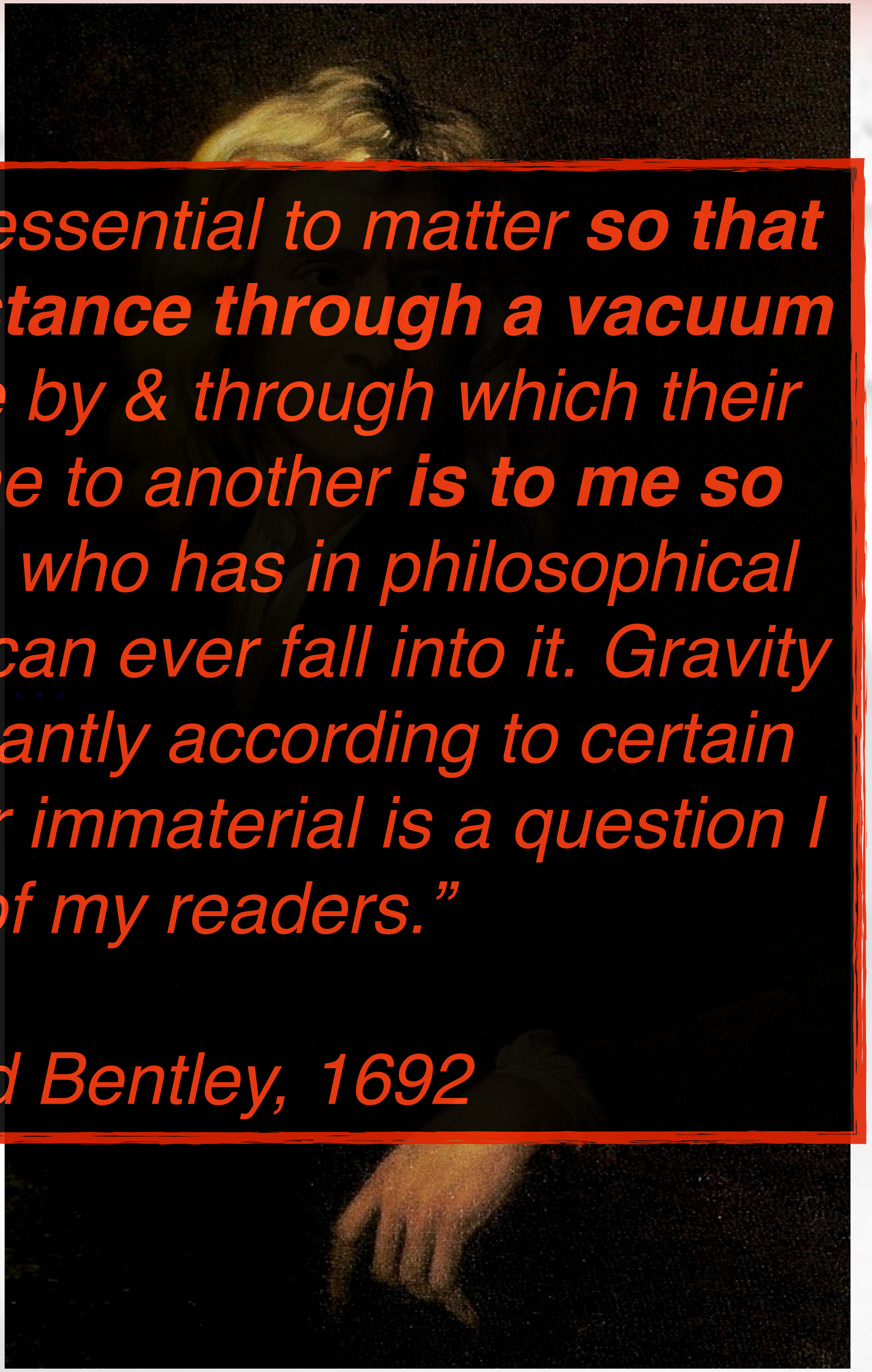
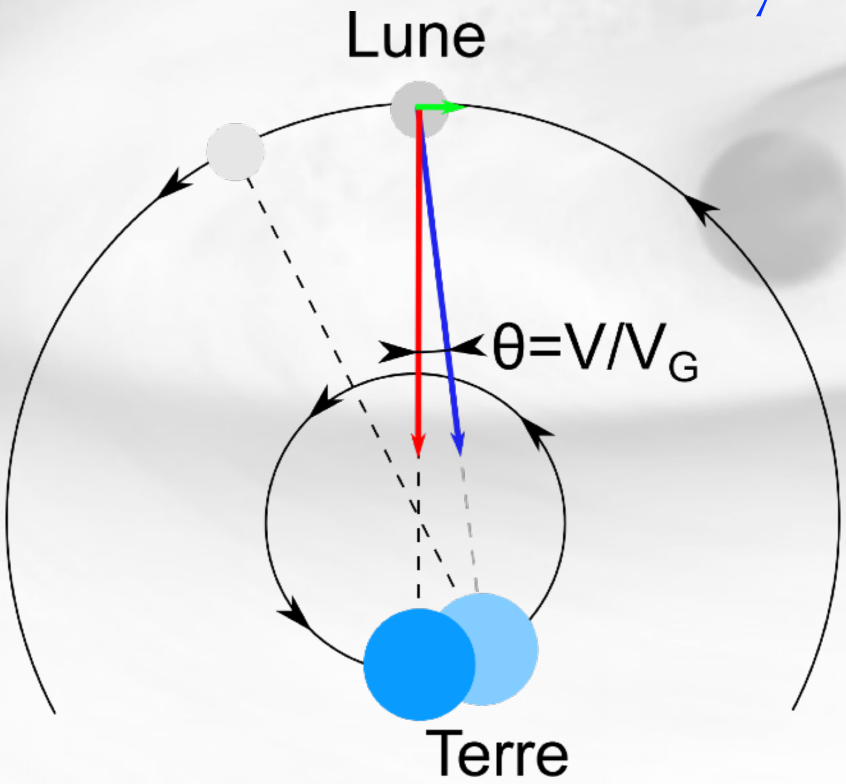


> *“That gravity should be innate inherent & essential to matter* ***so that one body may act upon another at a distance through a vacuum without the mediation of any thing*** *else by & through which their action or force may be conveyed from one to another* ***is to me so great an absurdity*** *that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws, but whether this agent be material or immaterial is a question I have left to the consideration of my readers.”*
>
> *Isaac Newton, Letter to Richard Bentley, 1692*

Some history …

- Pierre Simon de Laplace (1805) : What if gravity is not instantaneous ?
  - dissipation of energy (“friction”)
  - incompatible with observational constraints

  good intuition but bad theory !



$$\boxed{\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2}} = \boxed{4\pi G\rho}$$

Spatial and time fluctuations of potential (waves !)

Some history …

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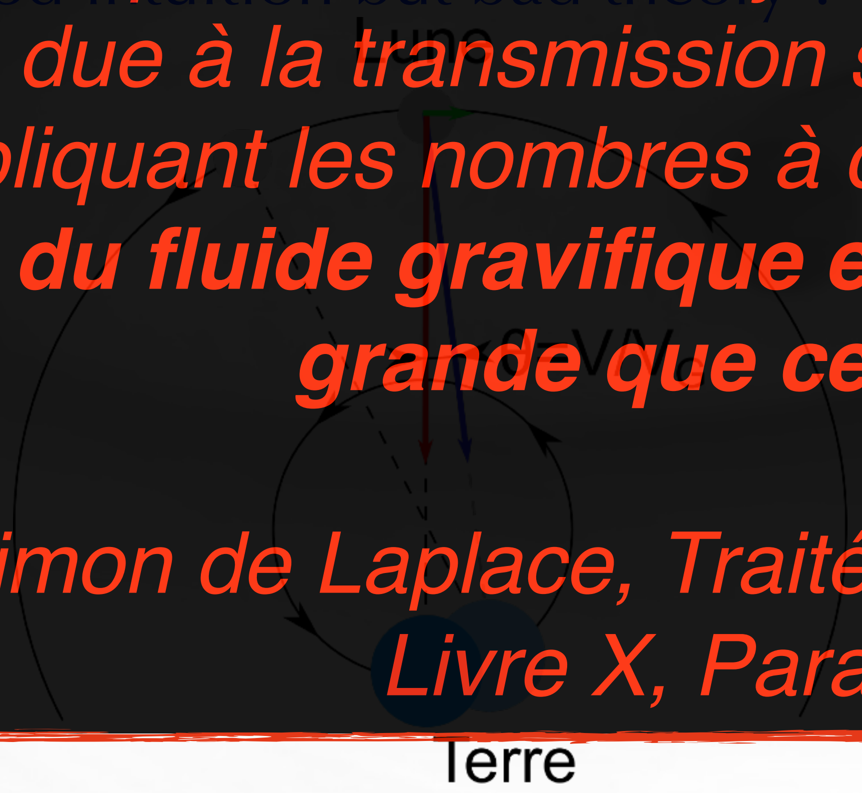
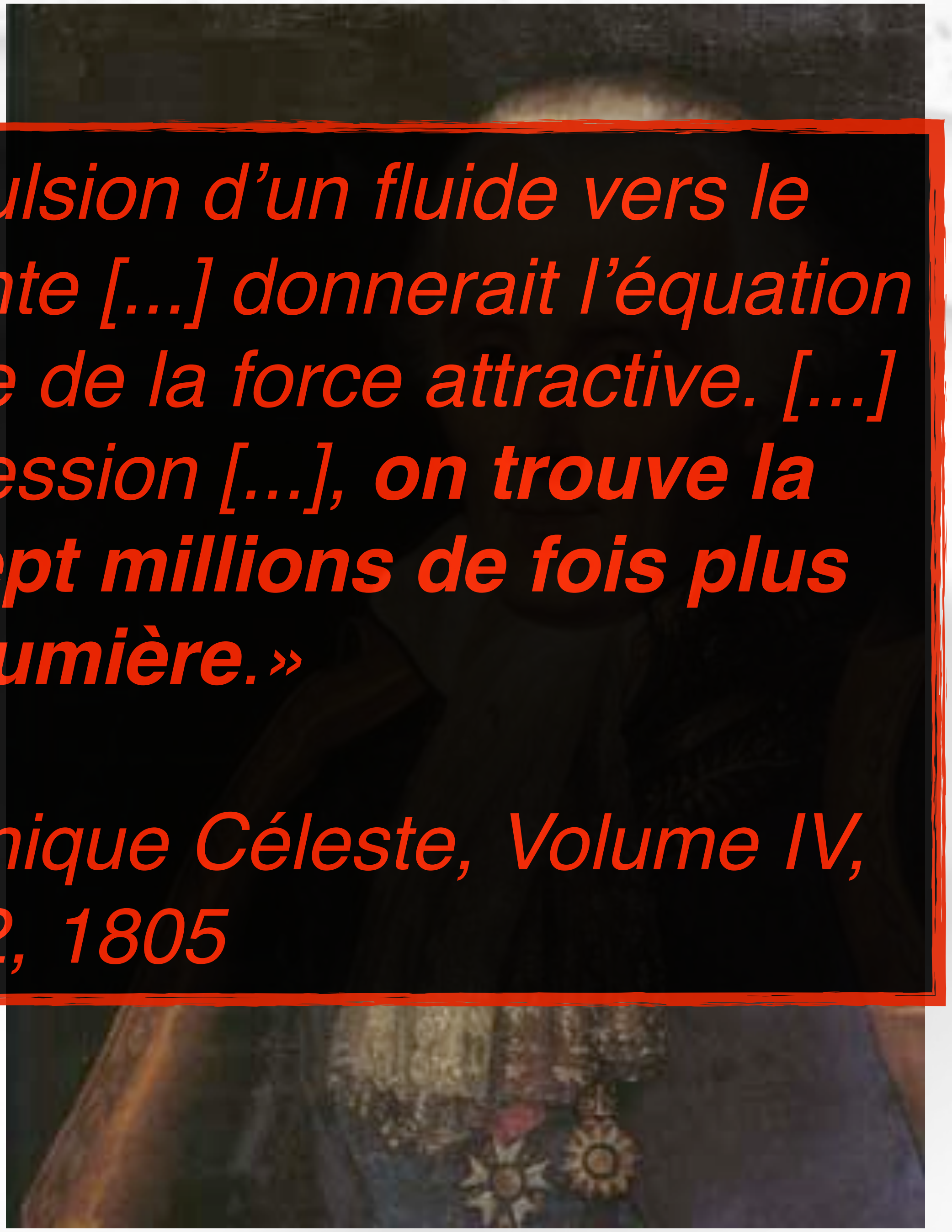




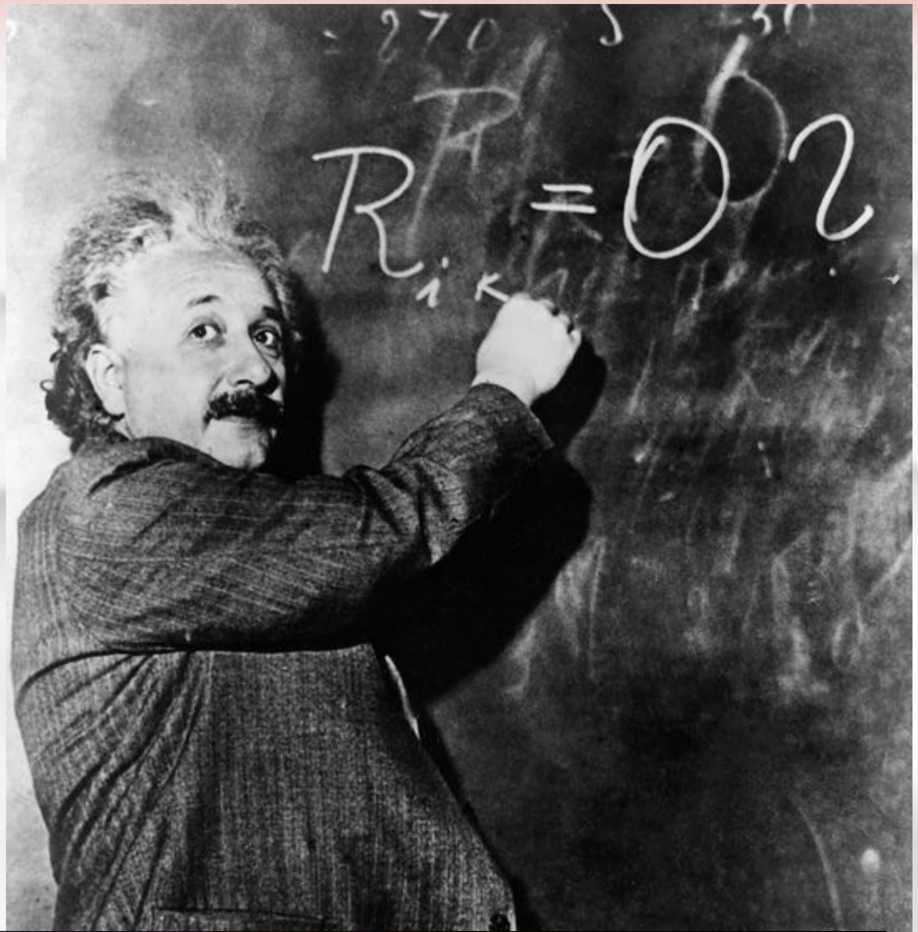
> *«Si la gravitation était produite par l'impulsion d'un fluide vers le centre du corps attirant, l'analyse précédente [...] donnerait l'équation séculaire due à la transmission successive de la force attractive. [...] En appliquant les nombres à cette expression [...],* ***on trouve la vitesse du fluide gravifique environ sept millions de fois plus grande que celle de la lumière.»***
>
> *Pierre Simon de Laplace, Traité de Mécanique Céleste, Volume IV, Livre X, Paragraphe 22, 1805*

$$\boxed{\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2}} = \boxed{4\pi G\rho}$$

Spatial and time fluctuations of potential (waves !)

100 years ago …

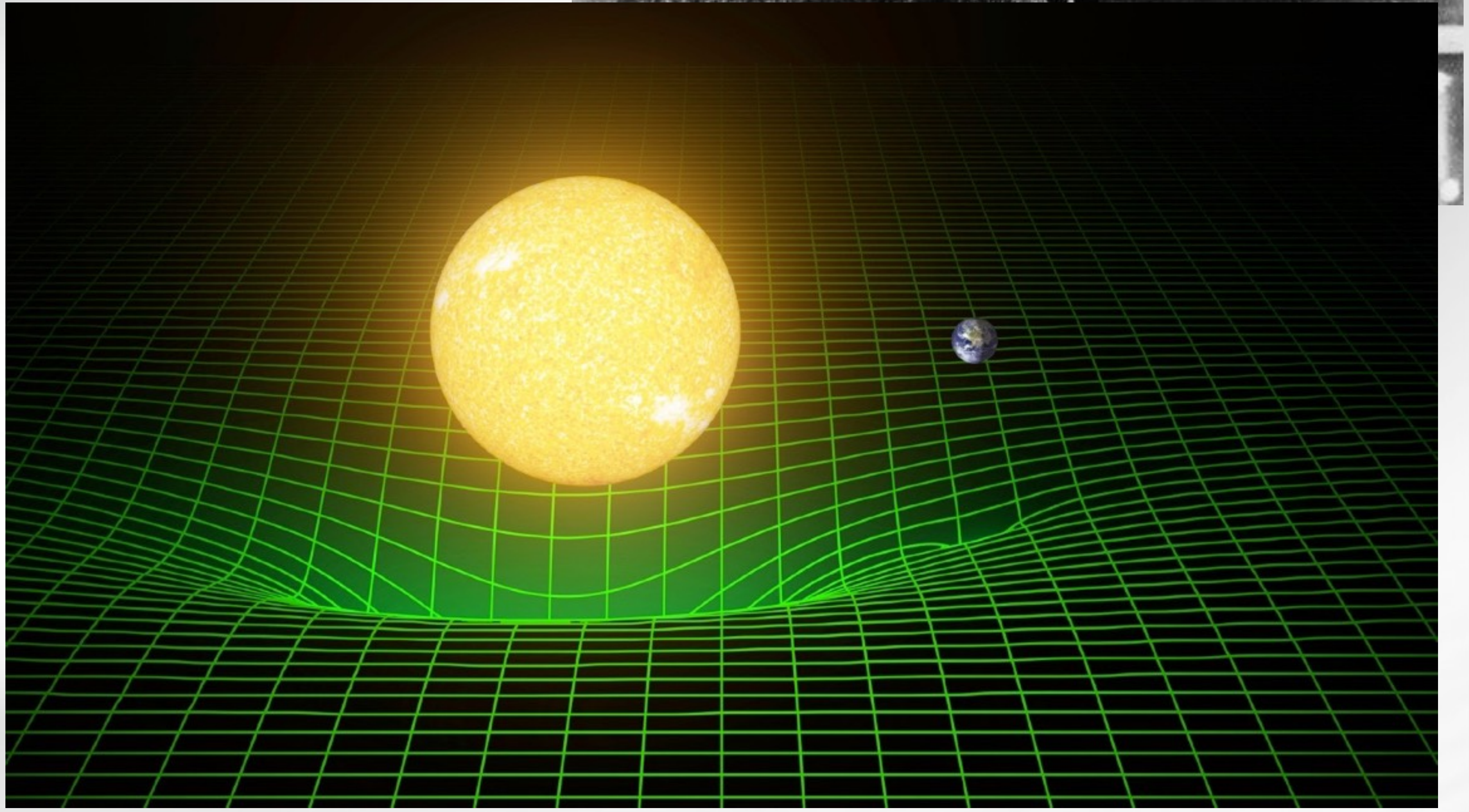
- Albert Einstein (1915) : Gravity is not a force …
  - Mass deforms geometry of space-time.
  - Bodies are moving in a curved space.
  - Gravitational information propagates at the speed of light.
  - Dissipation of energy through deformation of space-time => gravitational waves



$$\boxed{G_{\mu\nu}} = \frac{8\pi G}{c^4}\boxed{T_{\mu\nu}}$$

Geometry
of space-time

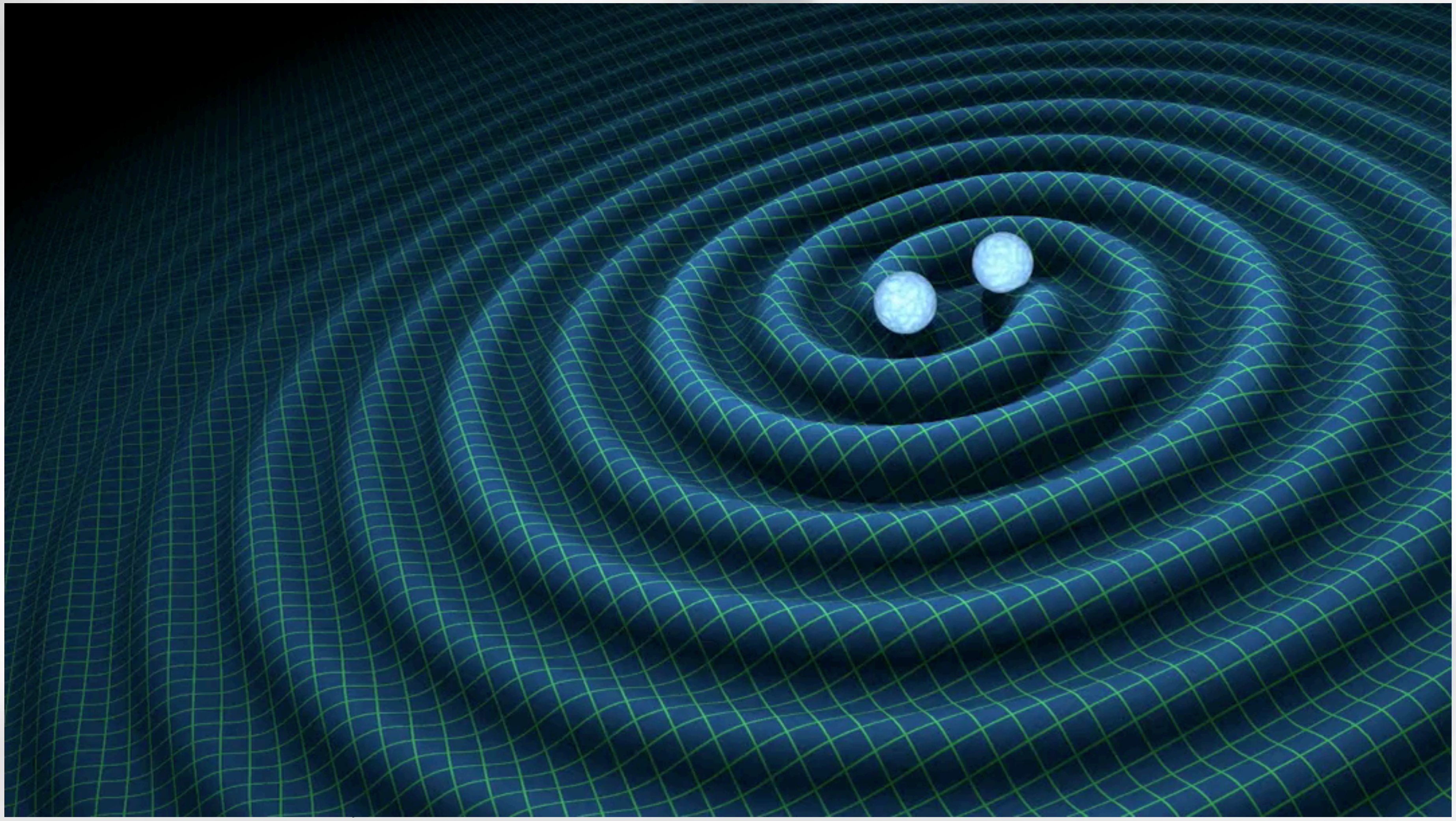
Energy
distribution



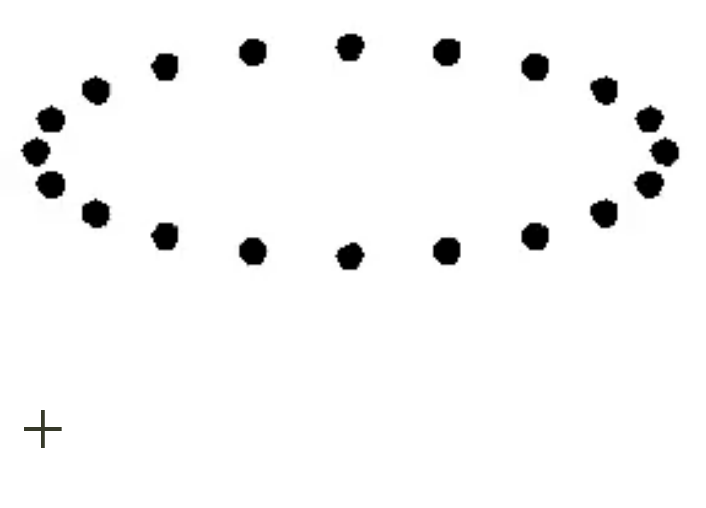
Grauitational waues ?

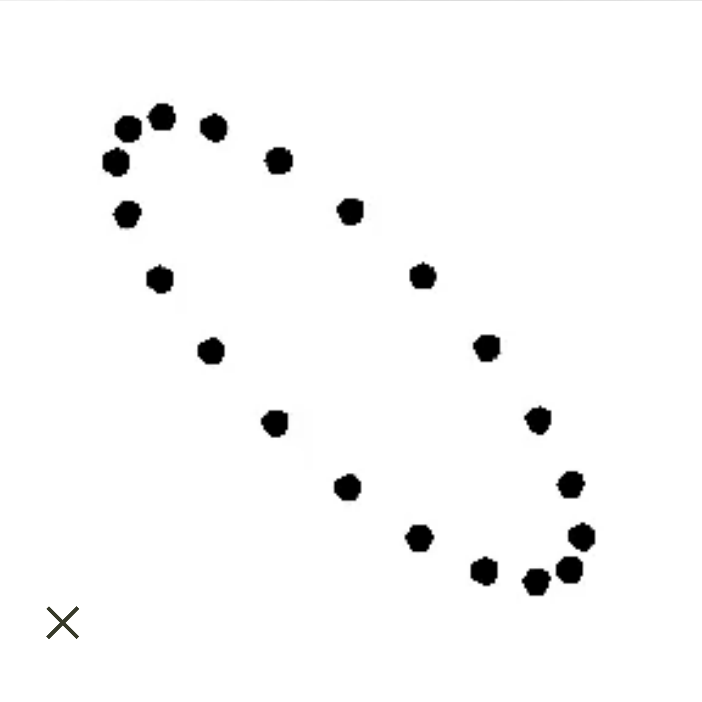
- What are GW ?
  - The GW are elastic deformations of the space-time metric
  - Transverse, quadrupole waves
  - Observational effect : Variation of the light-distance between 2 masses at rest.

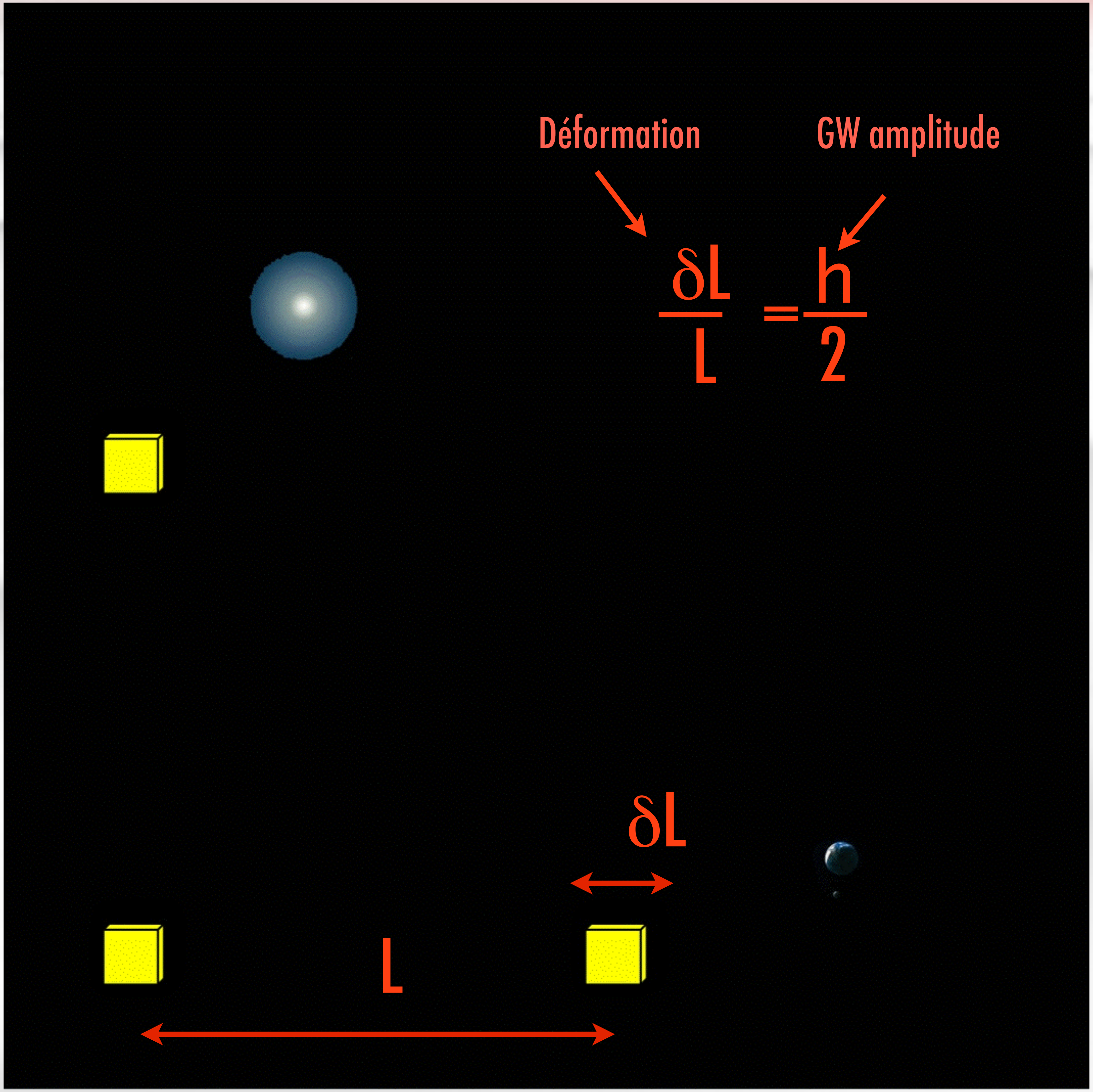
- Requires non spherical acceleration of massive objects
  - No GW emission : isolated bodies, even rotating
  - GW emission : binary systems, asymmetric star explosion /core collapse, etc.



Gravitational waves ?



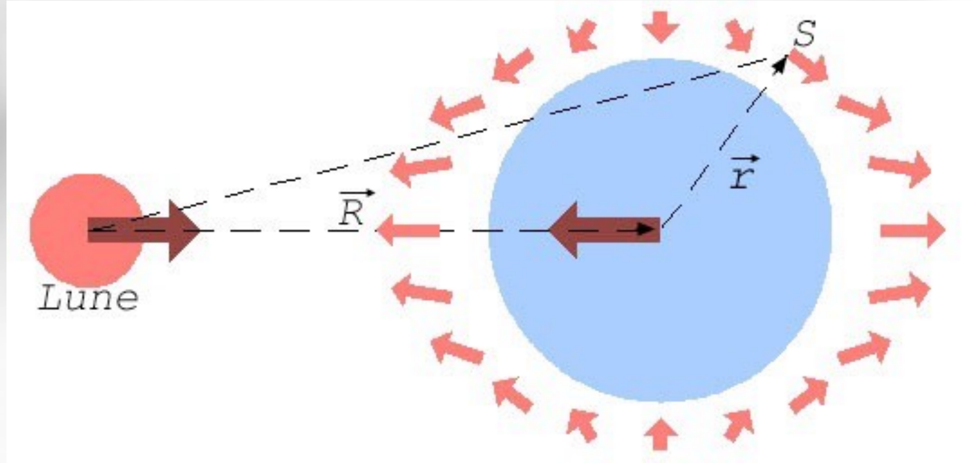


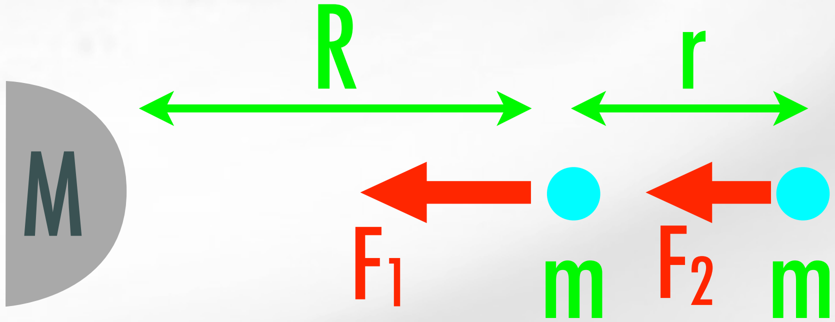


$$\frac{\delta L}{L} = \frac{h}{2}$$

Faux amis…

- Ne pas confondre les ondes gravitationnelles avec :
  - Les forces de marée / gradient de gravité :
    - différence d'attraction gravitationnelle en fonction de la distance à la masse centrale
    - explique les marées, l'aplatissement terrestre, les volcans d'Io et le pointage de certains satellites

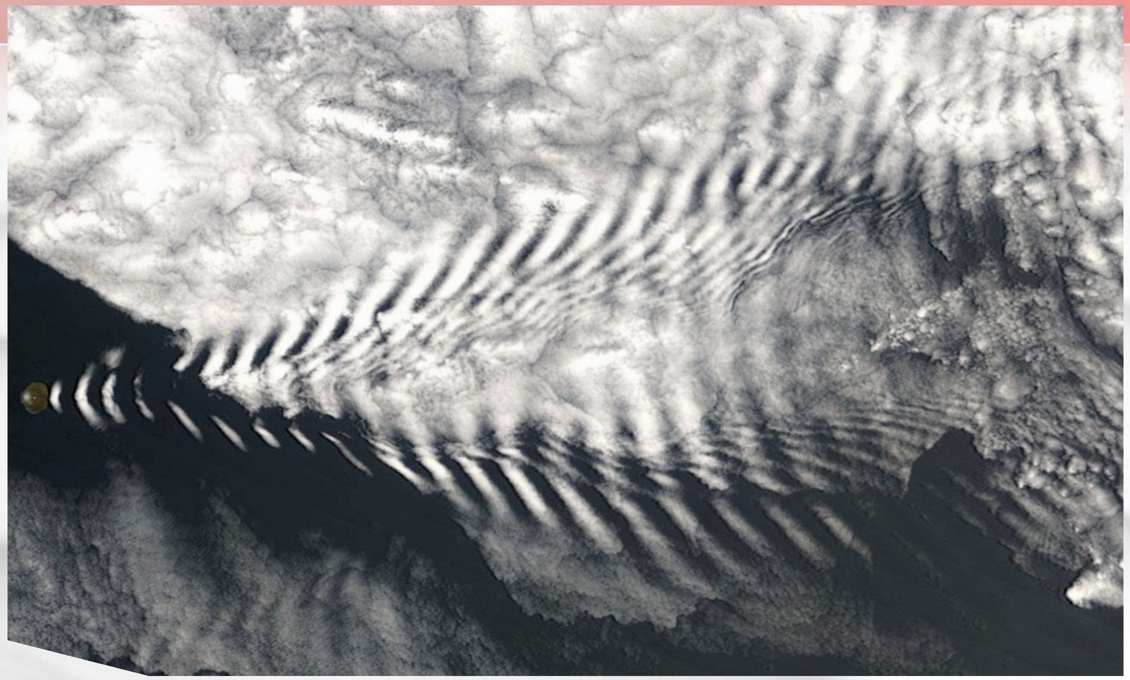


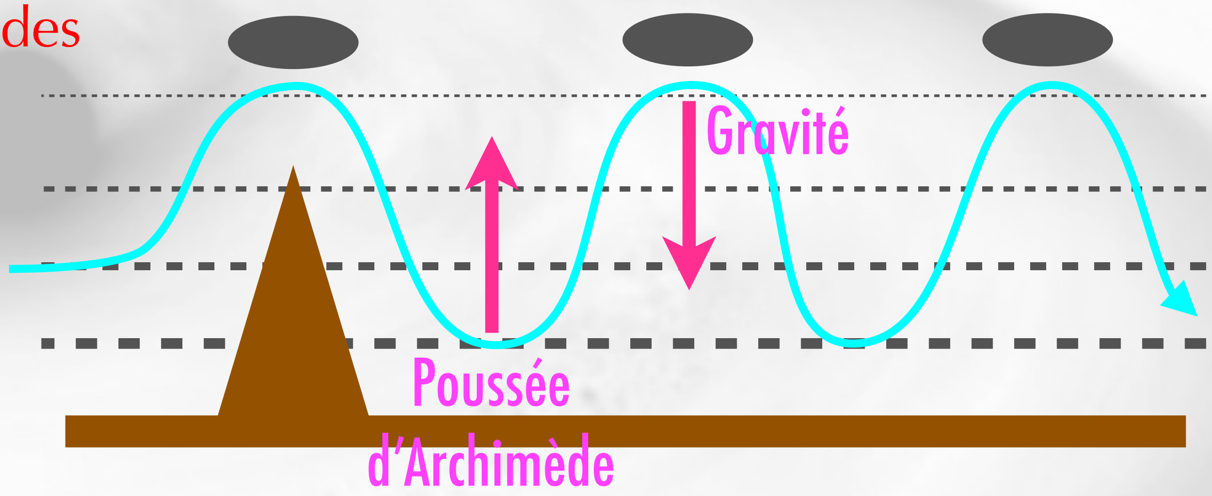


$$\Delta F = F_1 - F_2 \approx GMm\frac{2r}{R^3}$$

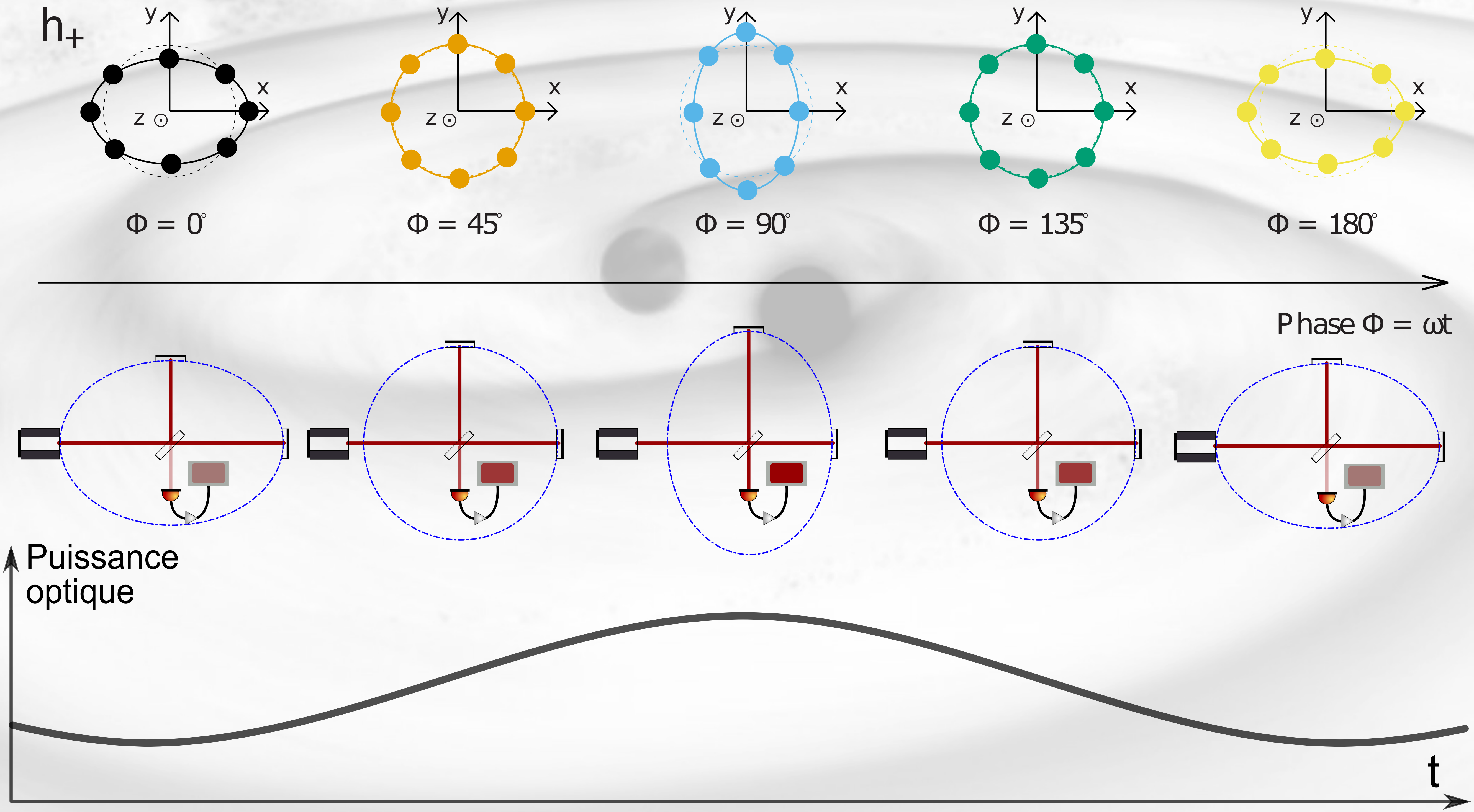
Faux amis…

- Ne pas confondre les ondes gravitationnelles avec :
  - Les ondes de gravité
    - Oscillations périodiques dans (ou à la surface) d’un fluide lorsque la force de rappel est la gravité (analogue au rappel exercé par un ressort)
    - Responsables de la houle, de courants atmosphériques ascendants / descendants et des oscillations de certaines étoiles

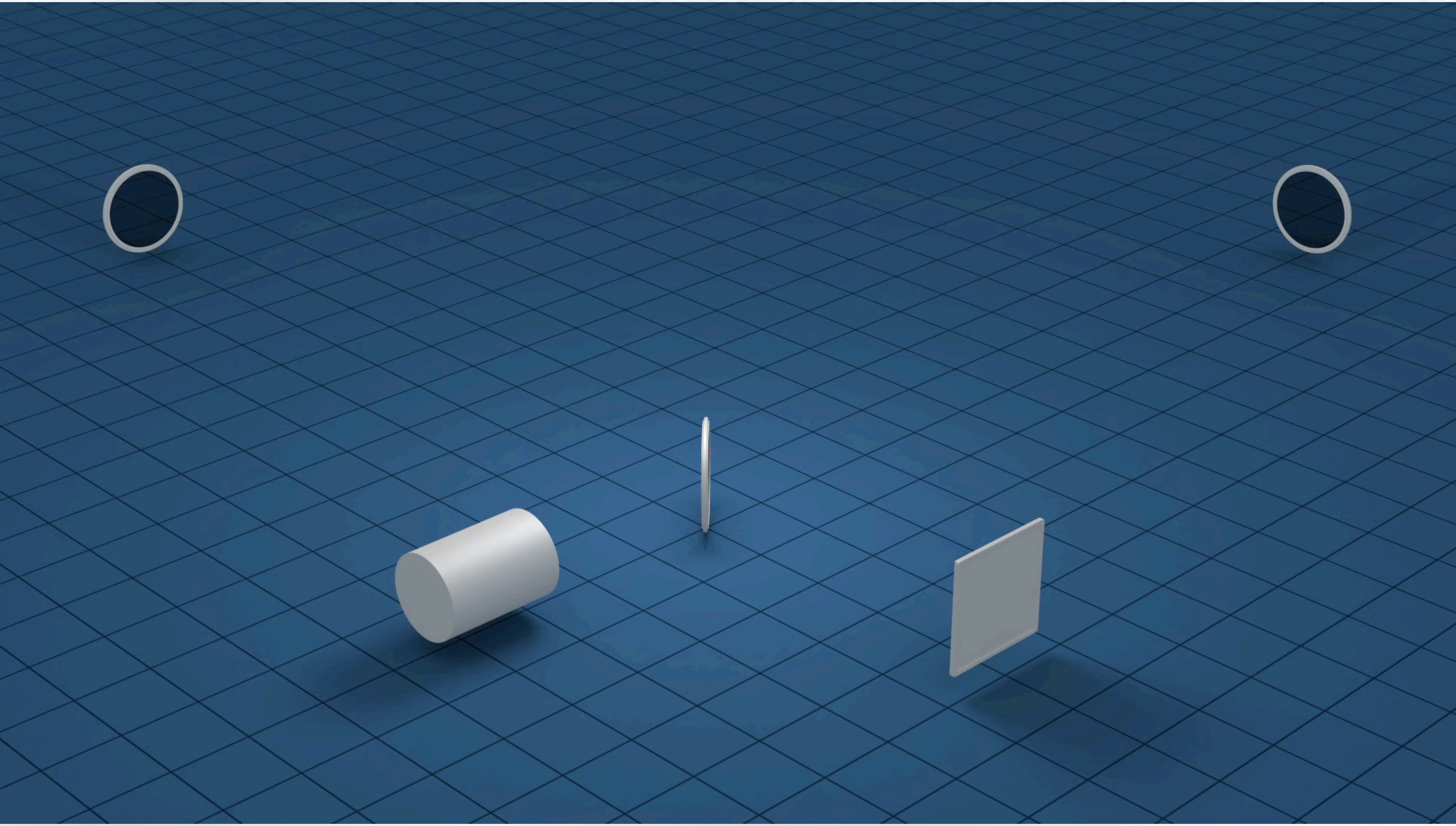




Interferometric detectors

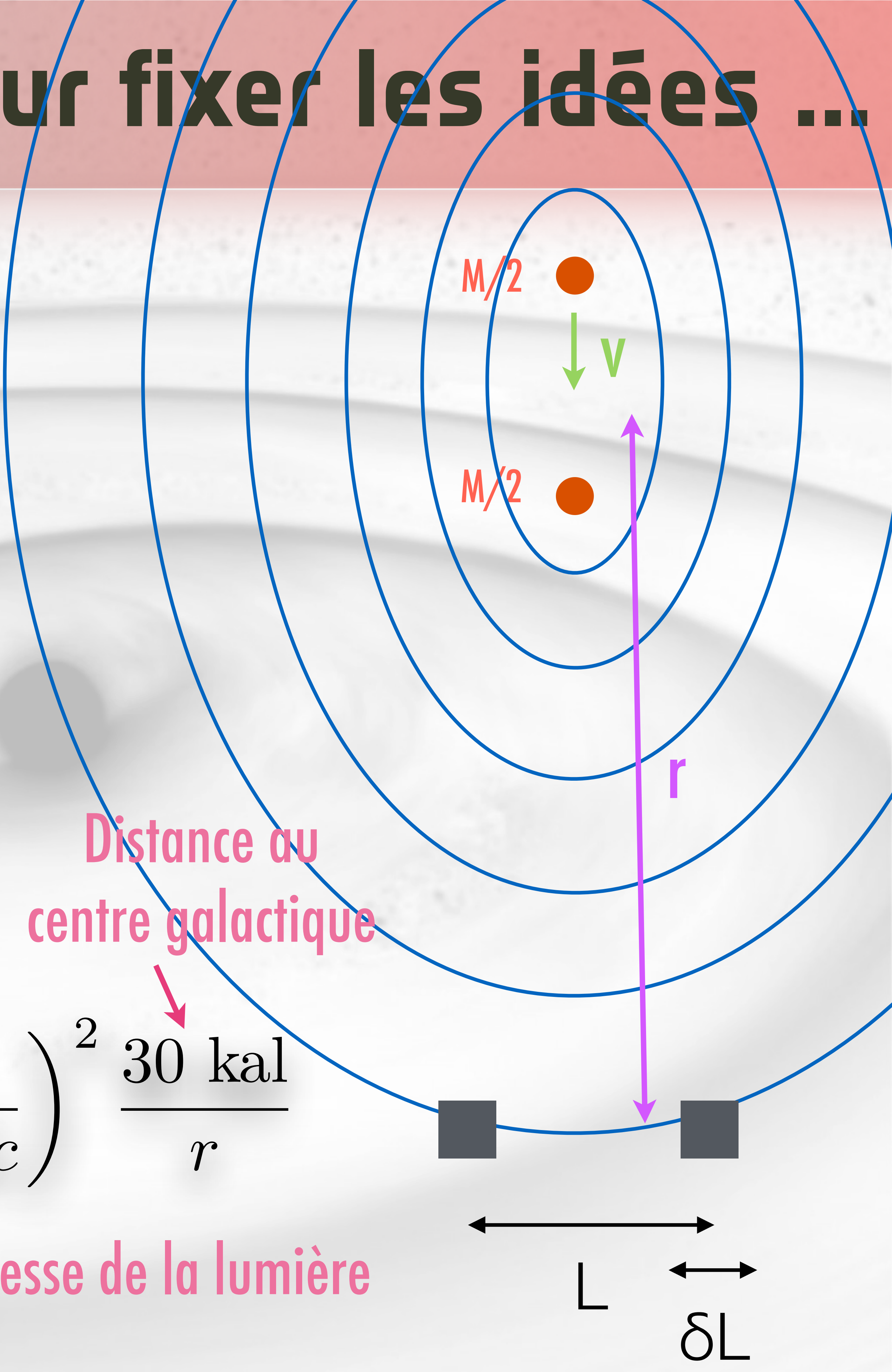


Interferometric detectors



Pour fixer les idées …

- Considérons une source de masse M, soumise à une vitesse v (composante non sphérique), observée à une distance r



amplitude de la déformation observée :

G : constante de gravitation ($\approx 6{,}7.10^{-11}\ m^3.kg^{-1}.s^{-2}$)

c : vitesse de la lumière ($\approx 3.10^8\ m.s^{-1}$)

$$h = 2\frac{\delta L}{L} \approx \frac{2GMv^2}{rc^4}$$

3x distance Terre-Lune

Distance au centre galactique

$$\approx\ 1\ \mathrm{pm/Mkm}\frac{M}{M_{Soleil}}\left(\frac{v}{0,01c}\right)^2\frac{30\ \mathrm{kal}}{r}$$

Diamètre d'un atome / 100

1% vitesse de la lumière

Pour fixer les idées …

- Considérons une source de masse M, soumise à une vitesse v (composante non sphérique), observée à une distance r

Les sources possibles doivent donc être :

- ✓ très rapides (proches de la vitesse de la lumière)
- ✓ très massives (donc denses)
- ✓ proches ?

amplitude de la déformation observée :

G : constante de gravitation (≈ 6,7.10⁻¹¹ m³.kg⁻¹.s⁻²)

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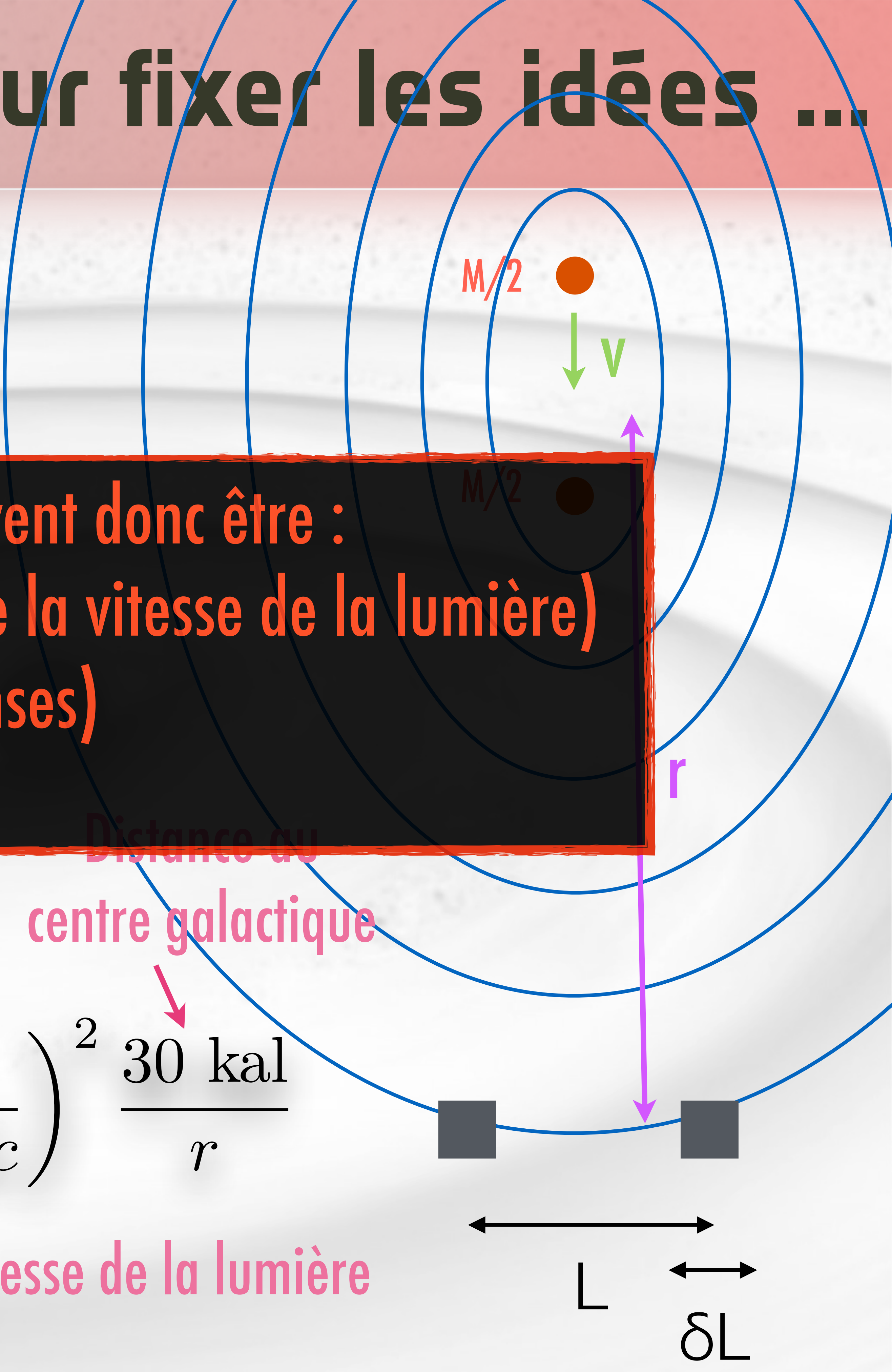
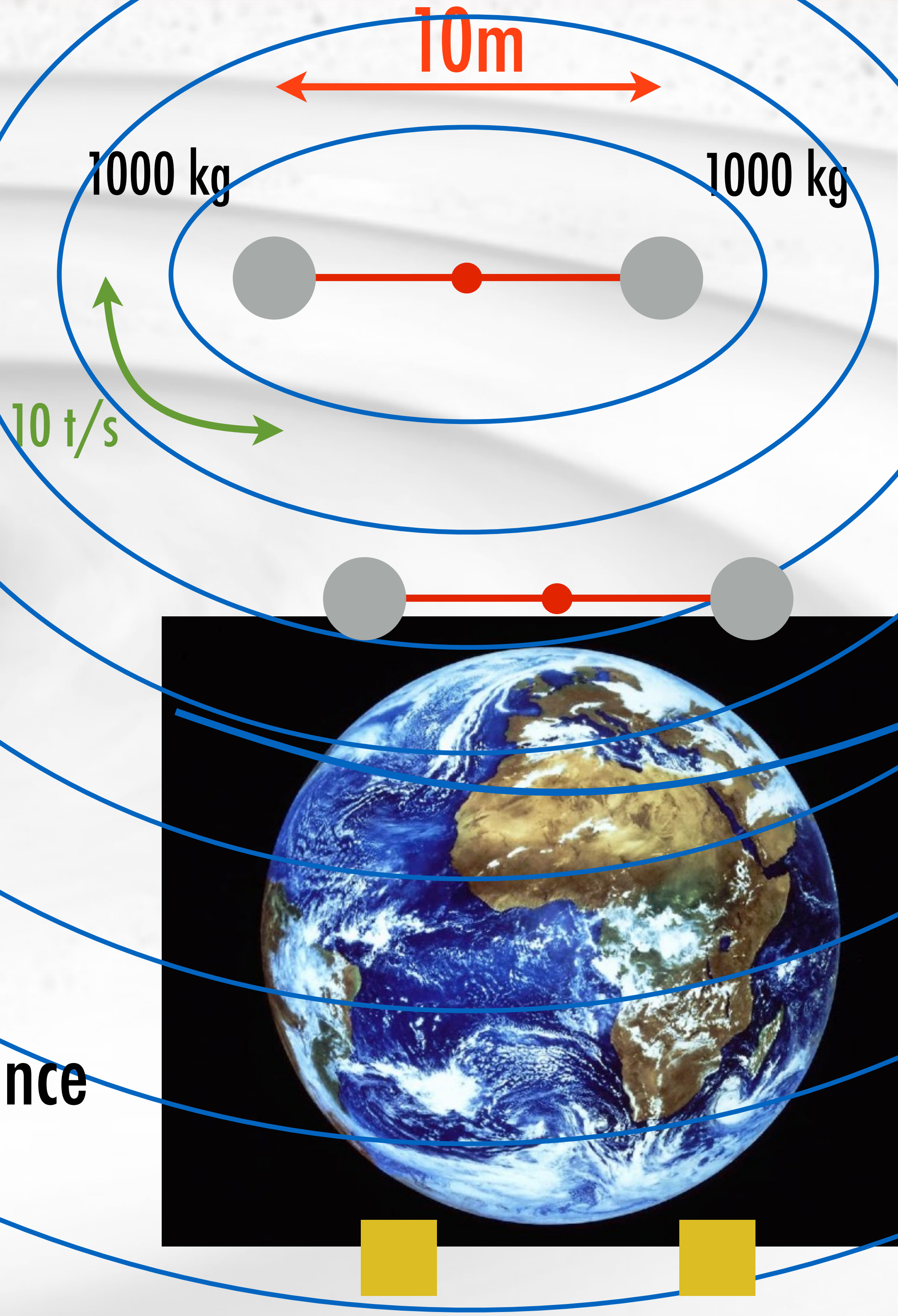


Existe-t-il des sources observables ?

- Des sources artificielles (humaines) détectables sur Terre ?
  - considérons l'expérience (extrême) suivante :
    2 masses de 1t chacune sur un bras de 10m tournant à 10 tours/s.



La période de l'onde gravitationnelle créée est de 0,05 s, soit une longueur d'onde de 15 000 km (~diamètre de la Terre)

Supposons un détecteur de longueur (équivalente) de 1000 km à une distance d'une longueur d'onde (distance minimale)

$$\delta L \approx 5.10^{-37}\ \text{m !}$$

↑

Longueur de Planck / 100

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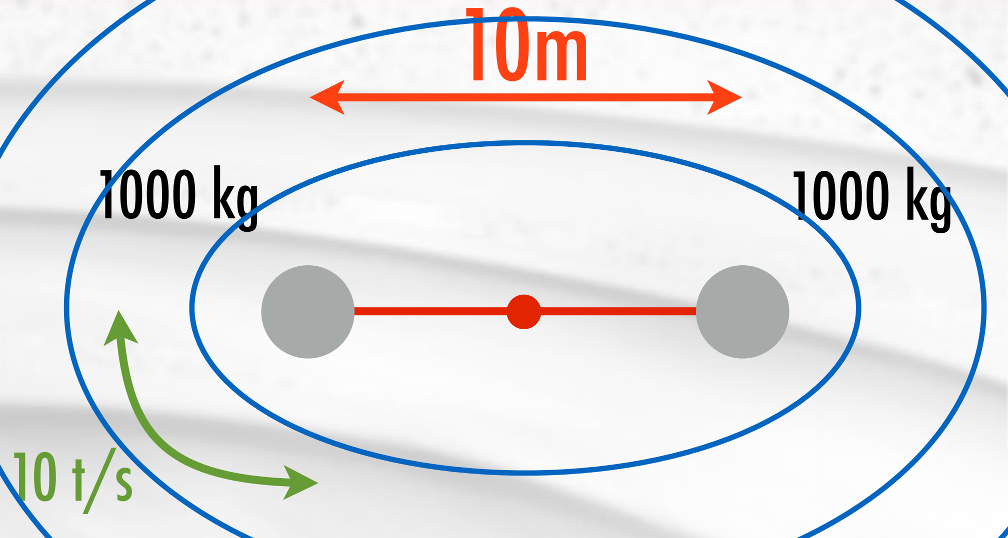

La période de l'onde gravitationnelle créée est de 0,05 s, soit une longueur d'onde de 15 000 km (~diamètre de la Terre)

Aucune activité humaine ne peut créer d'onde gravitationnelle détectable !

Supposons un détecteur de longueur (équivalente) de 1000 km à une distance d'une longueur d'onde (distance minimale)

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↑ Longueur de Planck / 100

Existe-t-il des sources observables ?

- Et des source astrophysiques ?
  - soumise à la gravité un système de taille R atteint une vitesse typique v

$$v \approx \sqrt{\frac{GM}{R}}$$

  - un objet astrophysique est relativiste si sa vitesse est proche de c :

$$v \lesssim c \Leftrightarrow \kappa = \left(\frac{v}{c}\right)^2 = \frac{GM}{Rc^2} \lesssim 1 \qquad \kappa = \text{compacité}$$

  - amplitude et fréquence de l'onde :

$$h \approx 2\kappa\frac{GM}{rc^2} \approx \boxed{10\ \mathrm{pm/Mkm}}\ \frac{M}{M_{Soleil}}\ \frac{30\ \mathrm{kal}}{r}\ \frac{\kappa}{0{,}001}$$

$$f \approx \sqrt{\frac{G\rho}{\pi}} \approx \boxed{2\ \mathrm{Hz}}\ \frac{M_{Soleil}}{M}\left(\frac{\kappa}{0{,}001}\right)^{3/2}$$

$\rho = 3M/(4\pi R^3)$: densité moyenne de la source

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  - soumise à la gravité un système de taille R atteint une vitesse typique v

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✓Les objets astrophysiques sont les seules sources observables d'ondes gravitationnelles

✓Il faut des objets très massifs et très denses (relativistes)

✓Les ondes gravitationnelles permettent «d'entendre» des objets très lointains

✓Les ondes gravitationnelles couvrent un domaine de fréquences très large

(M ~ 1 - 10^9 M_{Soleil}, $\kappa \sim 0 - 1$)

Les effets sont toujours faibles ! !

$$f \approx \sqrt{\frac{G\rho}{\pi}} \approx \boxed{2\ \mathrm{Hz}} \frac{M_{Soleil}}{M} \left(\frac{\kappa}{0{,}001}\right)^{3/2}$$

$\rho = 3M/(4\pi R^3)$: densité moyenne de la source

Energie transportée

- Question difficile en RG : les ondes gravitationnelles transportent-elles effectivement de l'énergie ?
  - réponse définitive dans les années 50 et 60 : oui .. et cette énergie est importante !
- Luminosité pour un système gravitationnel de masse M et taille R :

$$L \lesssim \frac{\pi c^5}{G} \cdot \kappa^5 \approx \boxed{10^{38}\ \mathrm{W}} \left(\frac{\kappa}{0,001}\right)^5$$

  - 10^{38} W ≈ 7 · 10^{11} L_{soleil} ! : un système compact peut perdre énormément d'énergie par émissions d'ondes gravitationnelles
- Flux reçu au niveau de la terre (distance r) :

$$\begin{aligned} F &\lesssim \boxed{0,1\ \mathrm{mW/m^2}} \left(\frac{\kappa}{0,001}\right)^5 \left(\frac{30\ \mathrm{kal}}{r}\right)^2 \\ &\lesssim \boxed{3\ \mathrm{mW/m^2}} \left(\frac{h}{10\ \mathrm{pm/Mkm}}\right)^2 \left(\frac{f}{10\ \mathrm{Hz}}\right)^2 \end{aligned}$$

Energie transportée

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- Luminosité pour un système gravitationnel de masse M et taille R :

✓La dissipation d'énergie par ondes gravitationnelles peut être très efficace et affecte la dynamique du système

✓La coalescence d'un système binaire compact peut être la source la plus «brillante» du ciel (flux reçu de la pleine lune ≈ 3 mW/m², Sirius ≈ 0,1 µW/m²)

✓Il faut une énergie considérable pour une déformation infinitésimale : l'espace-temps est extrêmement rigide ...

- Flux reçu au niveau de la terre (distance r) :

$$F \lesssim 0,1\ \mathrm{mW/m^2} \left(\frac{\kappa}{0,001}\right)^5 \left(\frac{30\ \mathrm{kal}}{r}\right)^2$$

$$\lesssim 3\ \mathrm{mW/m^2} \left(\frac{h}{10\ \mathrm{pm/Mkm}}\right)^2 \left(\frac{f}{10\ \mathrm{Hz}}\right)^2$$

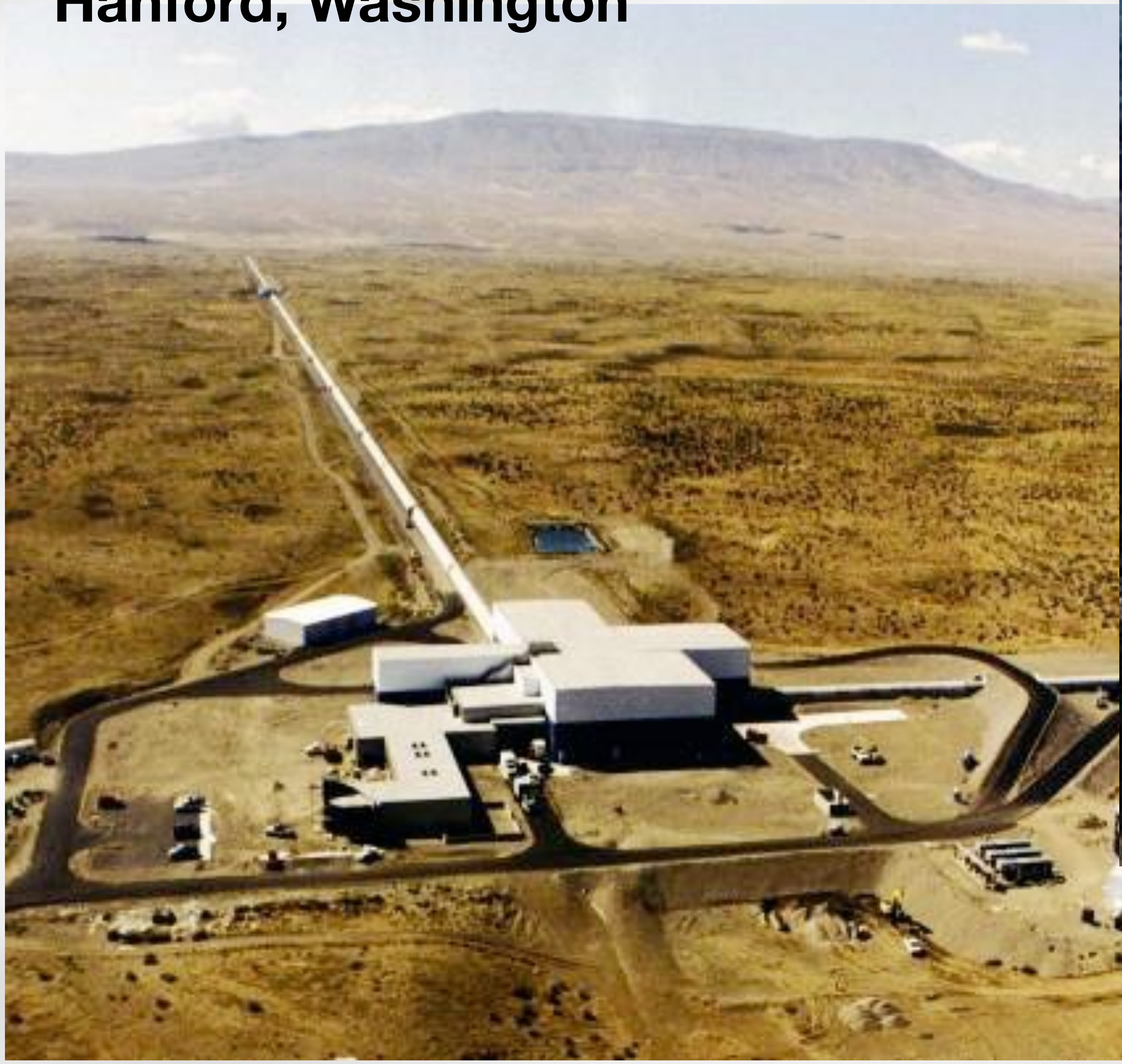
Quelques exemples

Paramètres	Binaire de naines blanches (quasi-monochromatique)	Binaire de naines blanches (à la coalescence)	Binaire d'étoiles à neutrons	Binaire de trous noirs stellaires	Binaire de trous noirs super-massifs
compacité κ [1]	10^{-5}	0,01	0,15	0,5	0,5
Masse M [M_{Soleil}]	0,5	0,5	2,8	20	2.10^6
Distance [Mal]	0,03	0,03	66	3	22 000 ($z \approx 1$)
amplitude h [pm/Mkm]	0,05	50	2	1 000	14 000
fréquence [Hz]	0,004	100	1 200	1 000	0,01
Temps d'évolution	2.10^6 années	1 ms	10 ms	0,5 ms	50 s

Ground based detectors

- LIGO : 4 km long arms

Hanford, Washington

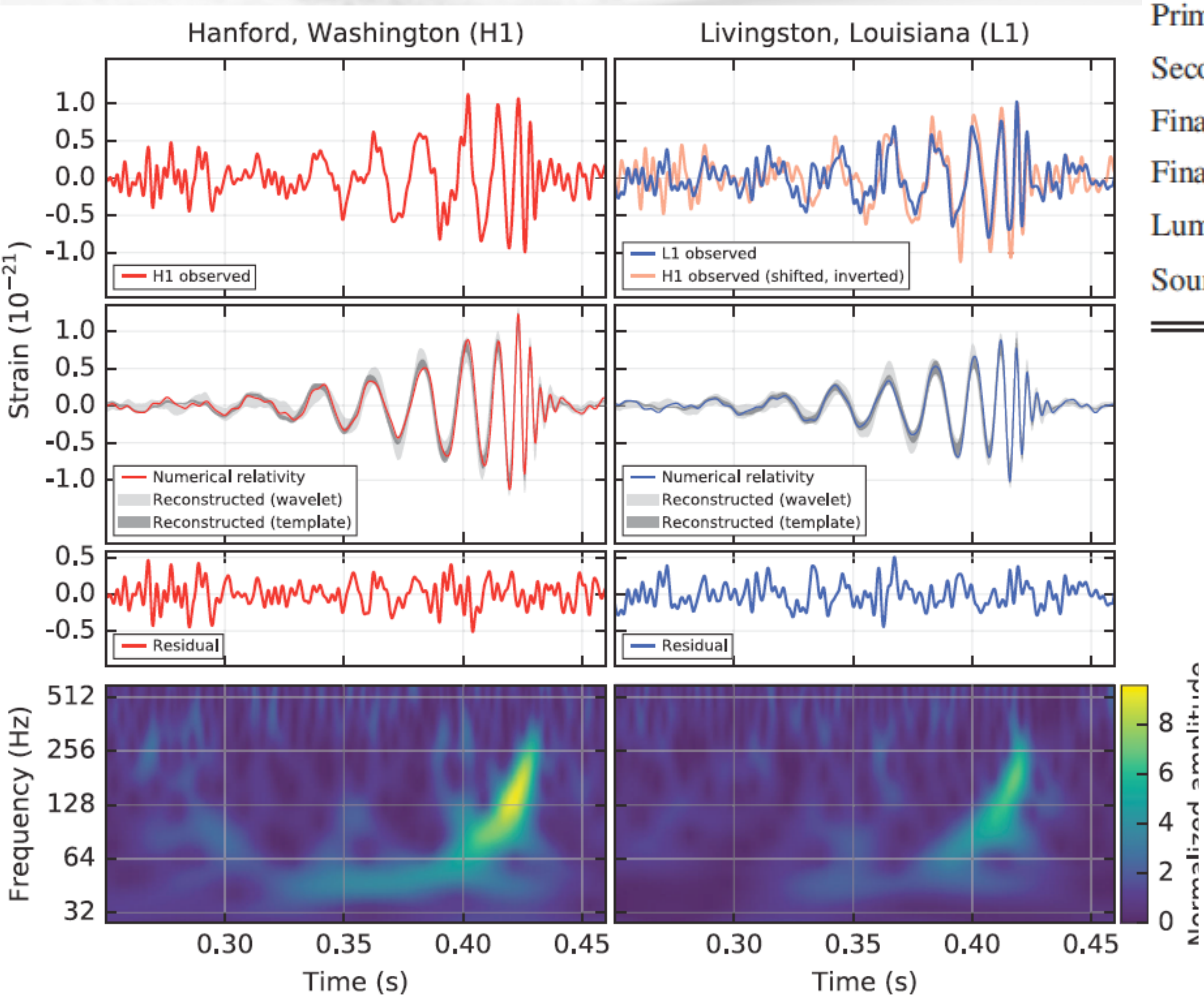


Livingston, Louisiane

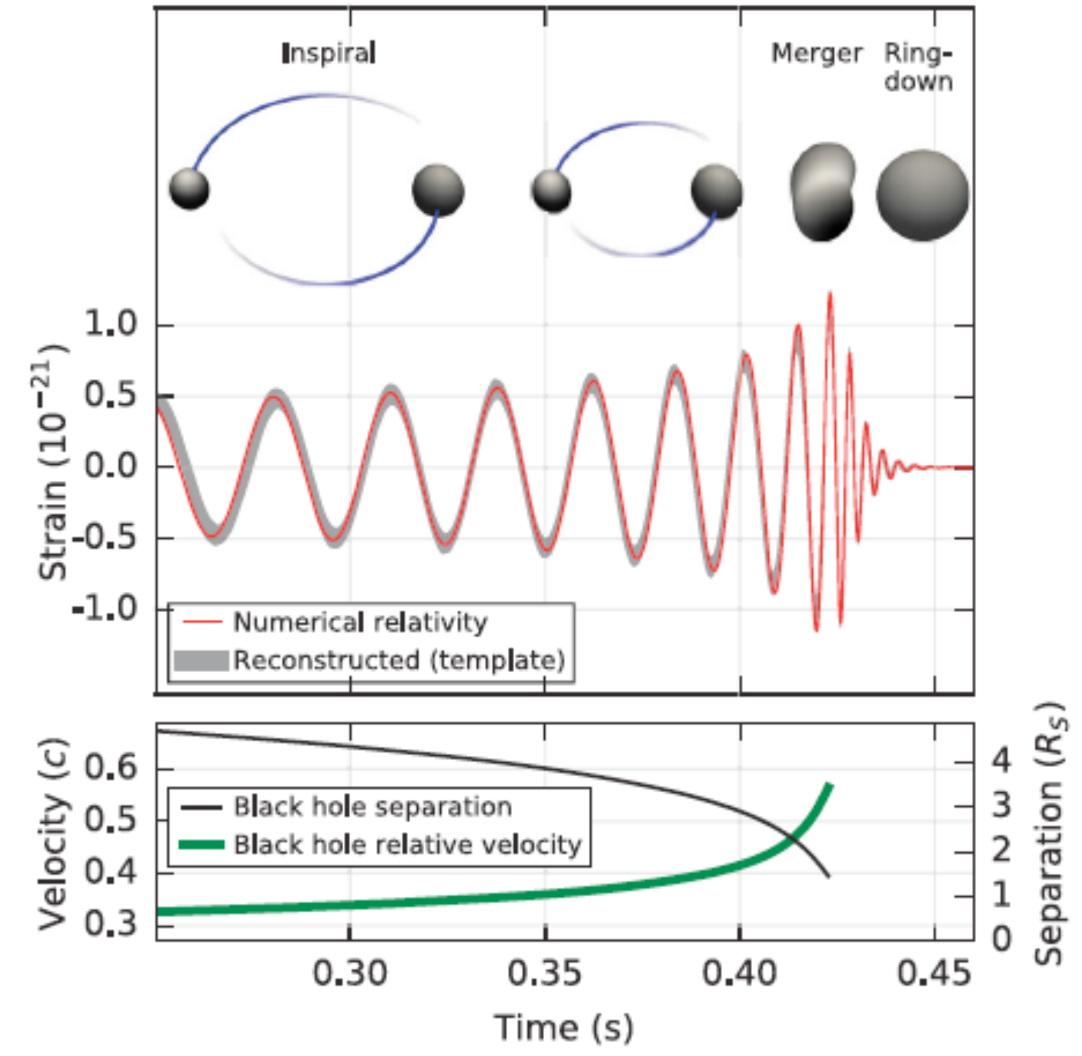
Ground based detectors

- VIRGO : 3-km long arms

Sept. 14th, 2015



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



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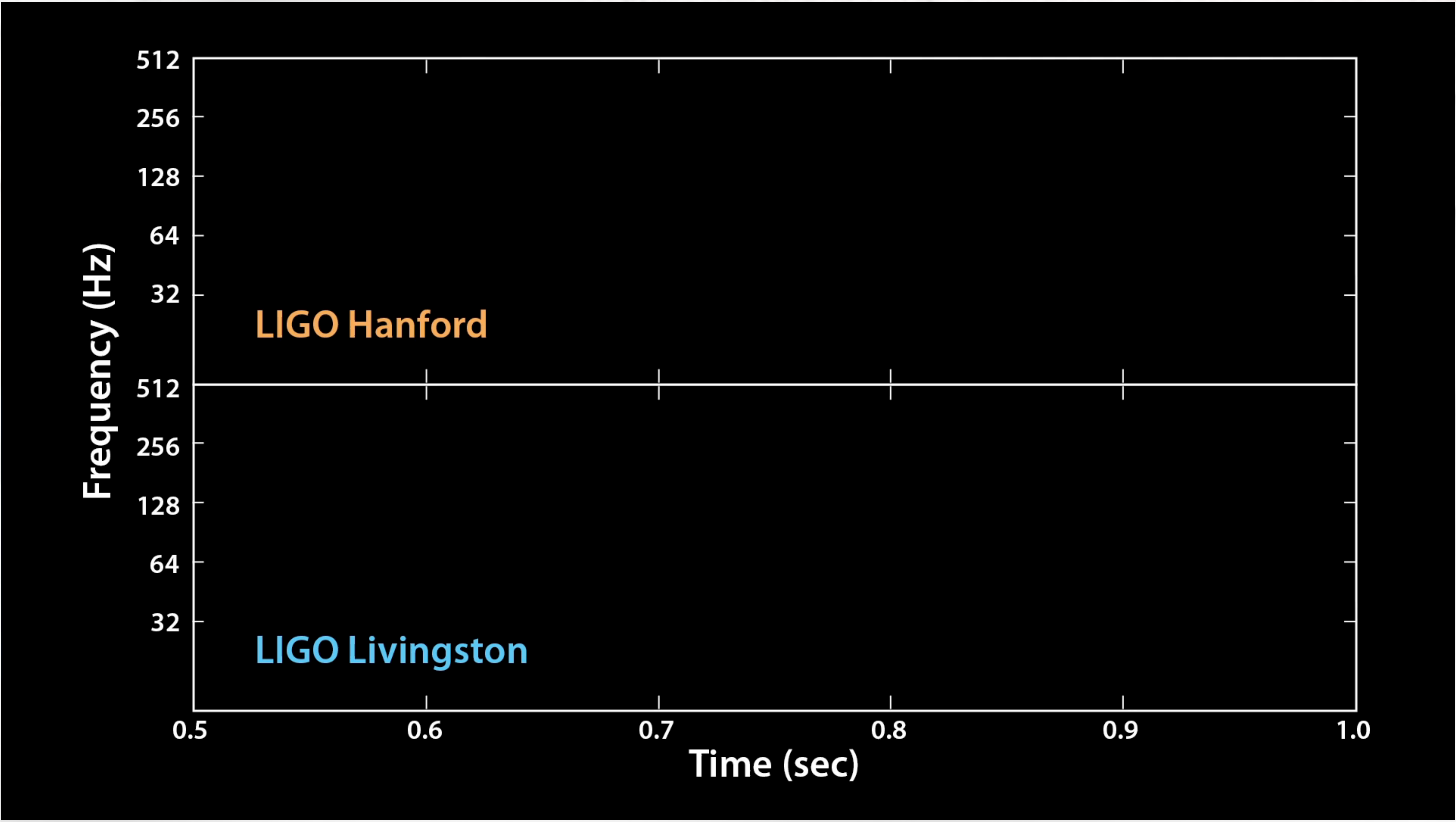
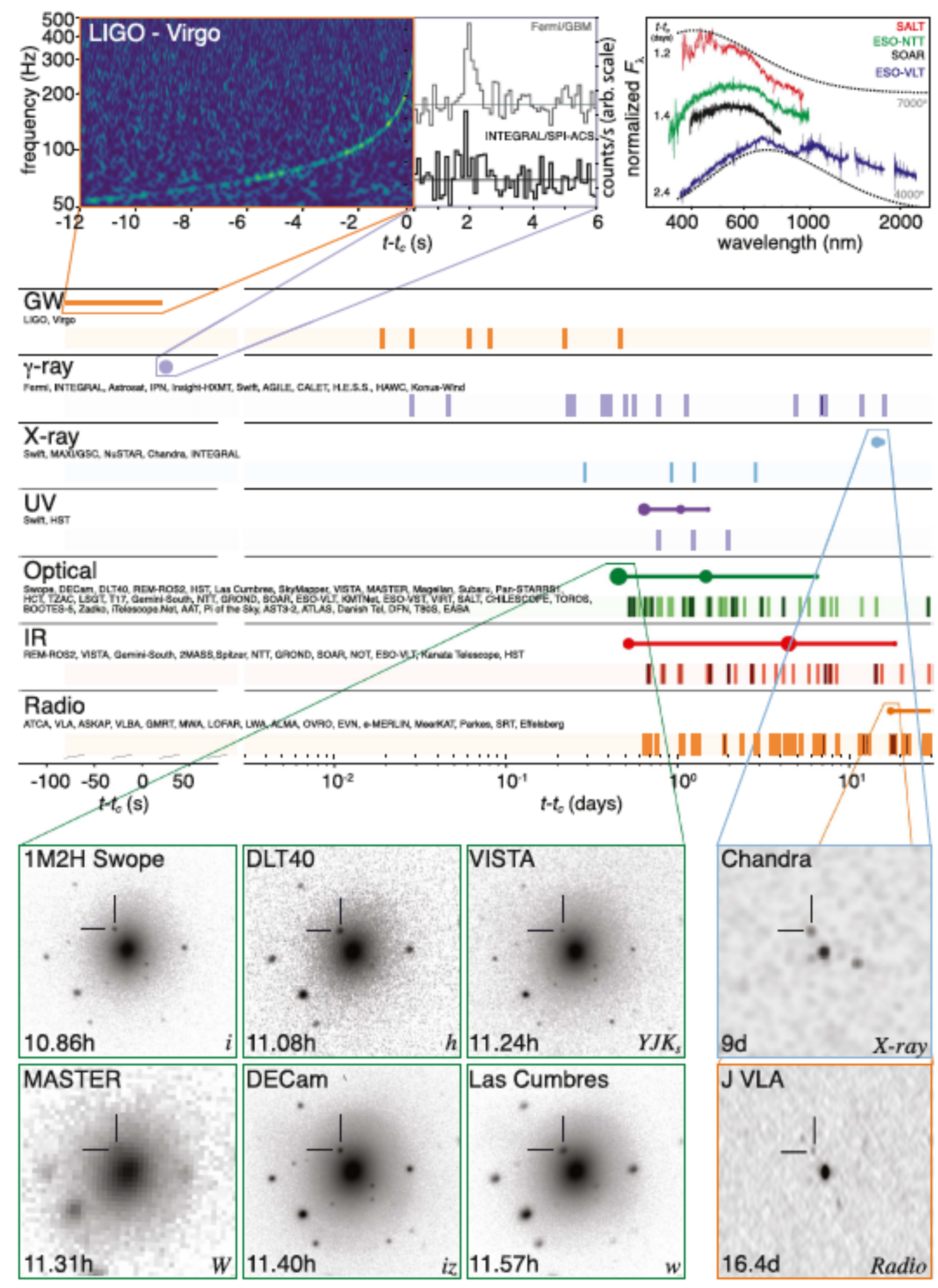


August 17th, 2017 : Kilonova !

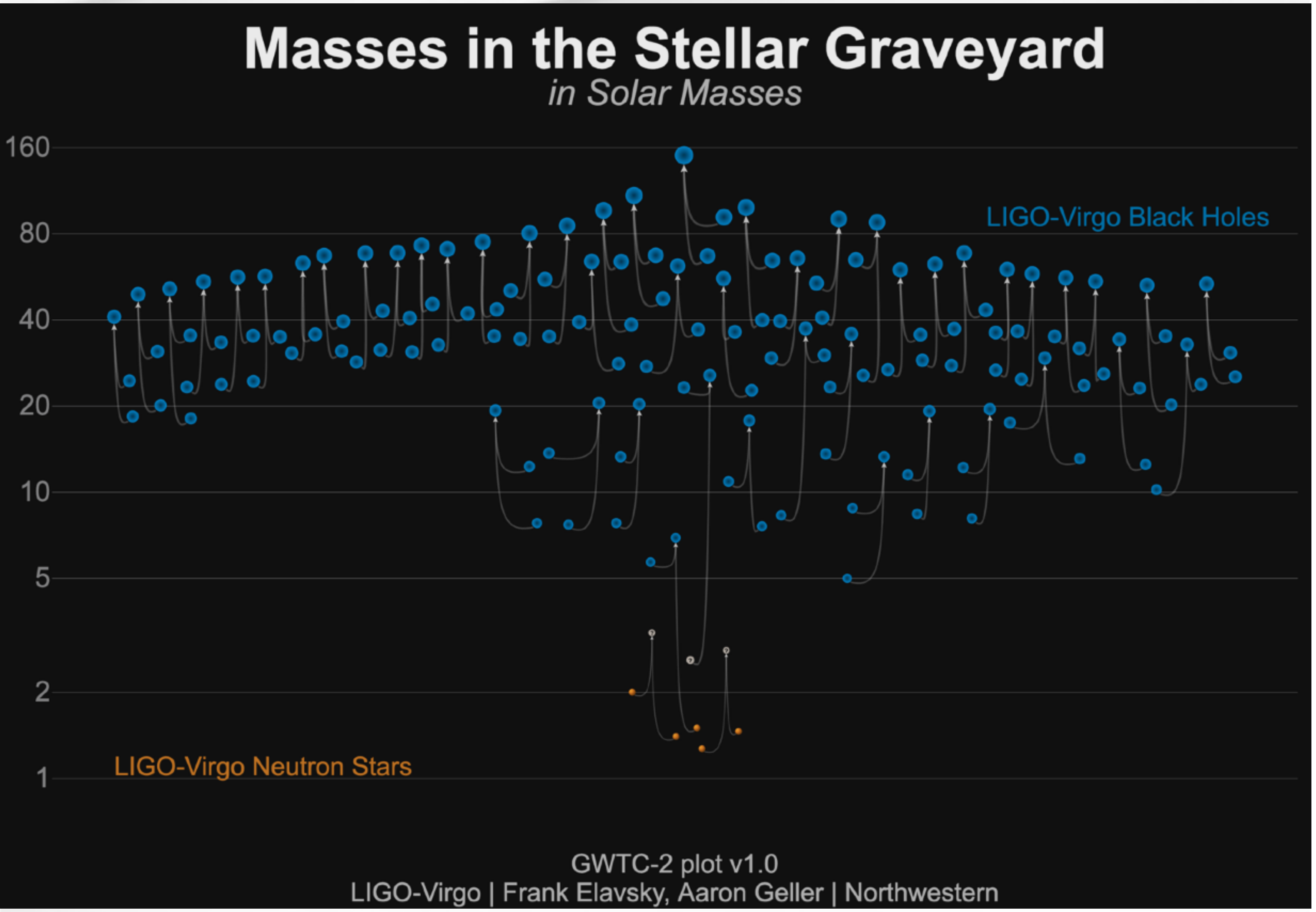
onoua !



LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

Detections LIGO/VIRGO

- >50 détections confirmées depuis 2015
  - ~1 évènement / semaine en O3



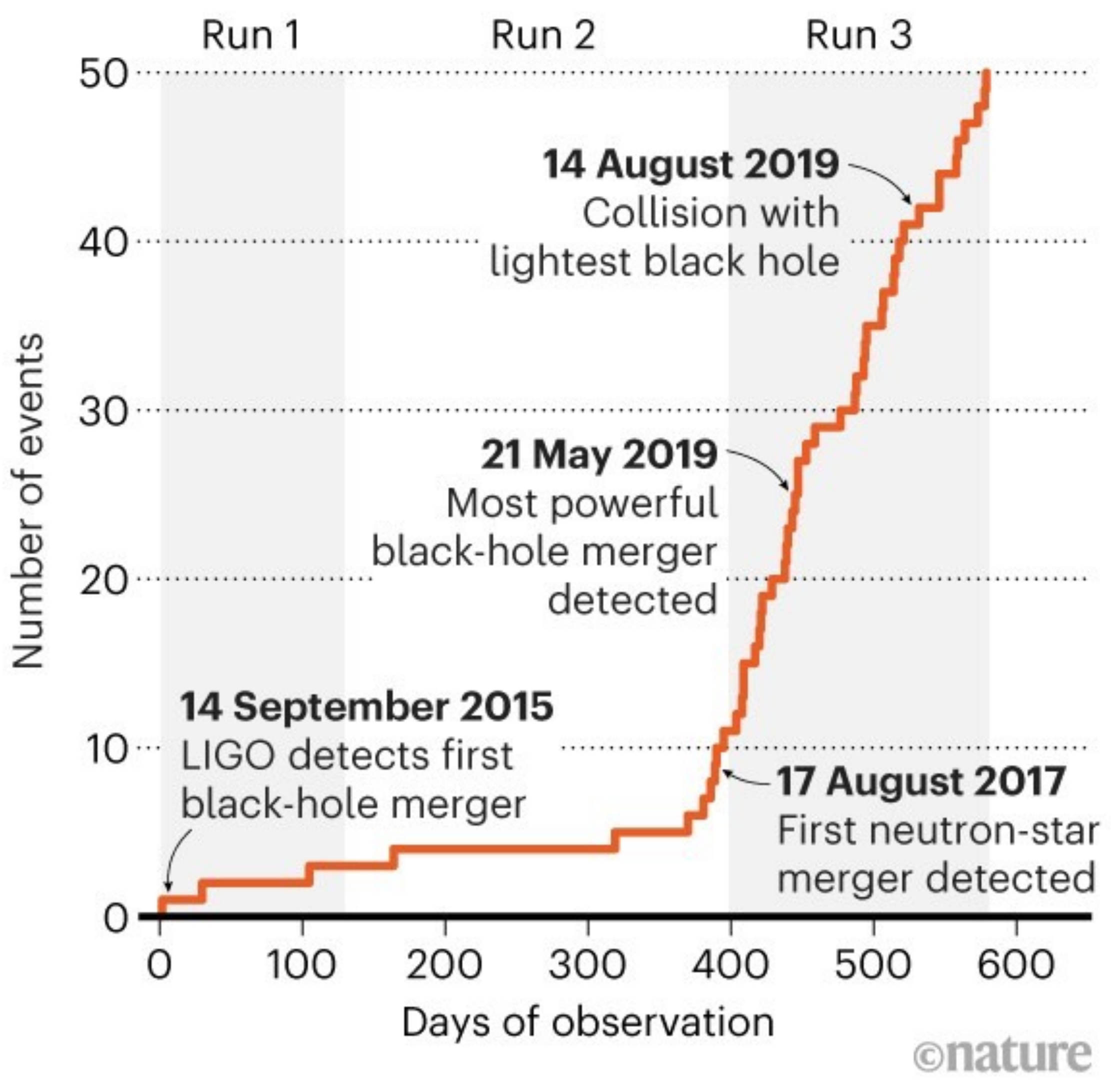
Masses in the Stellar Graveyard

in Solar Masses

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

COSMIC CLASHES

Gravitational-wave detectors have identified 50 collisions between black holes and other cosmic objects in the distant Universe. The US-based detector LIGO made the first discovery after a major upgrade in 2015; Italy-based Virgo joined the hunt in 2017.



14 August 2019
Collision with lightest black hole

21 May 2019
Most powerful black-hole merger detected

14 September 2015
LIGO detects first black-hole merger

17 August 2017
First neutron-star merger detected

©nature

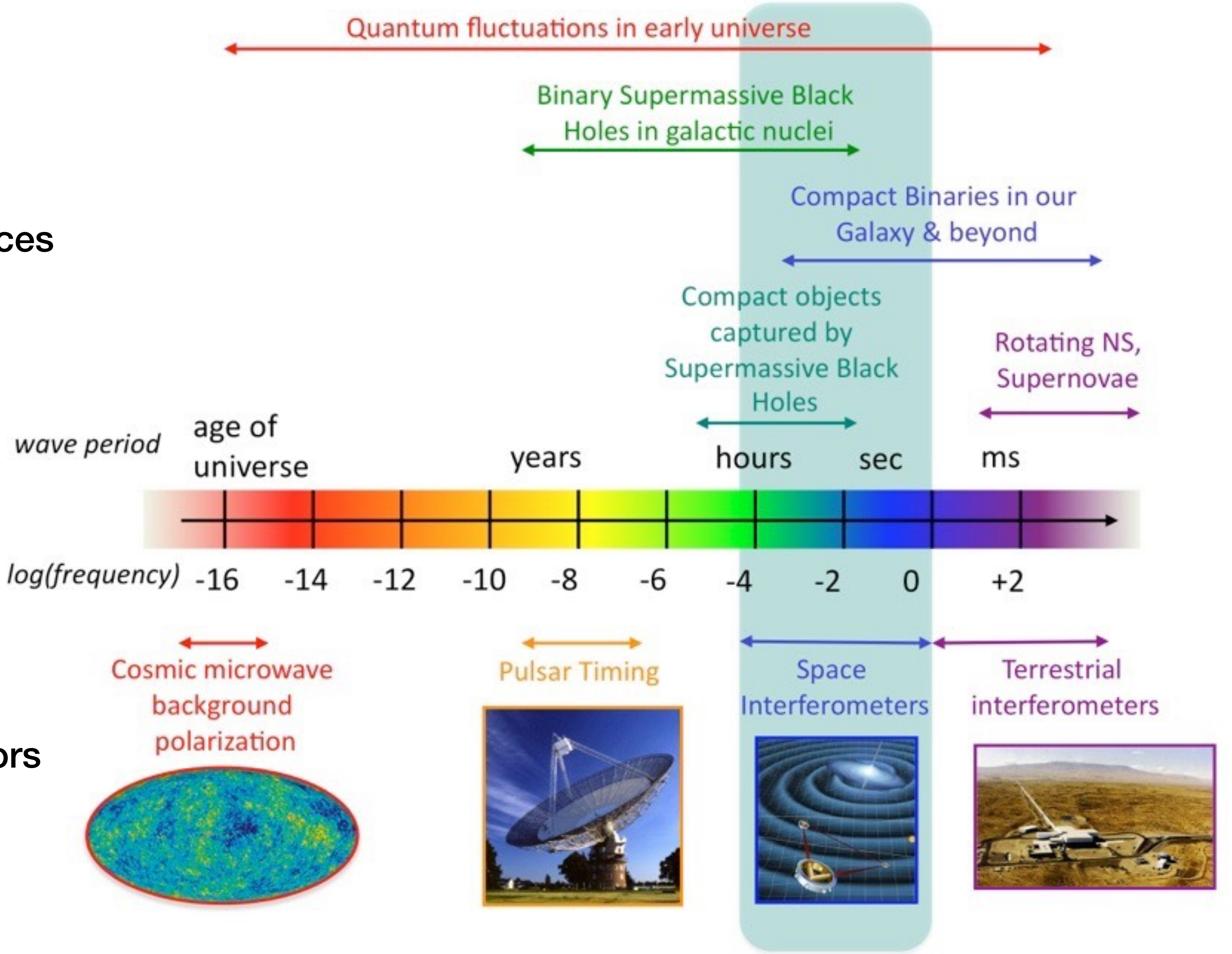
La science de LISA

LISA France

The GW spectrum

Sources

Detectors



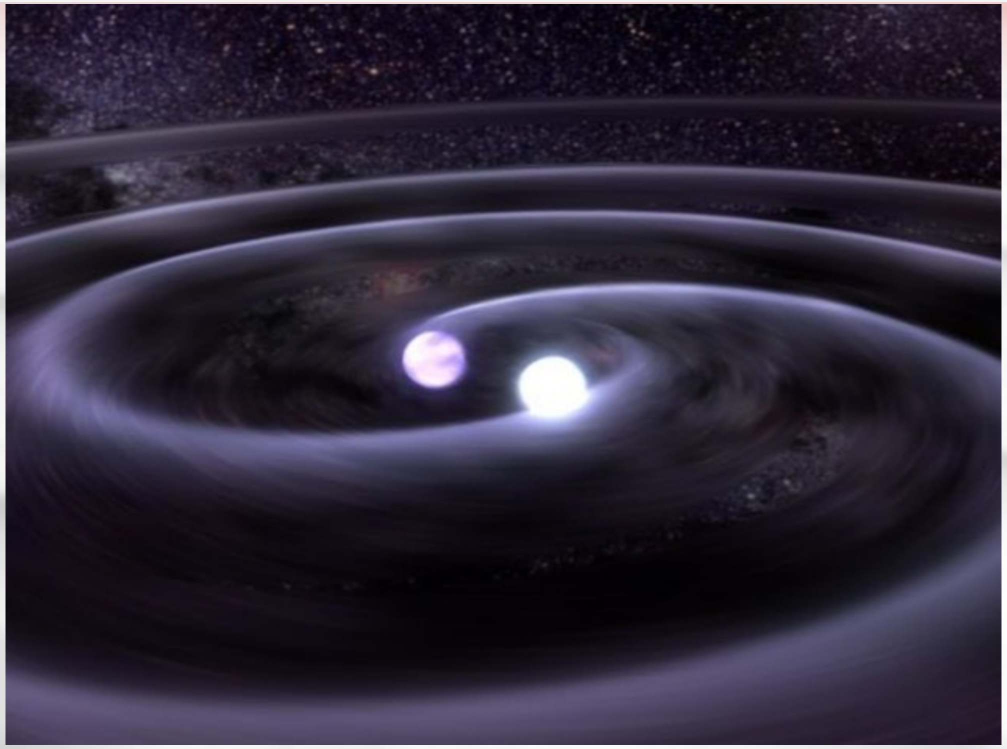
Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

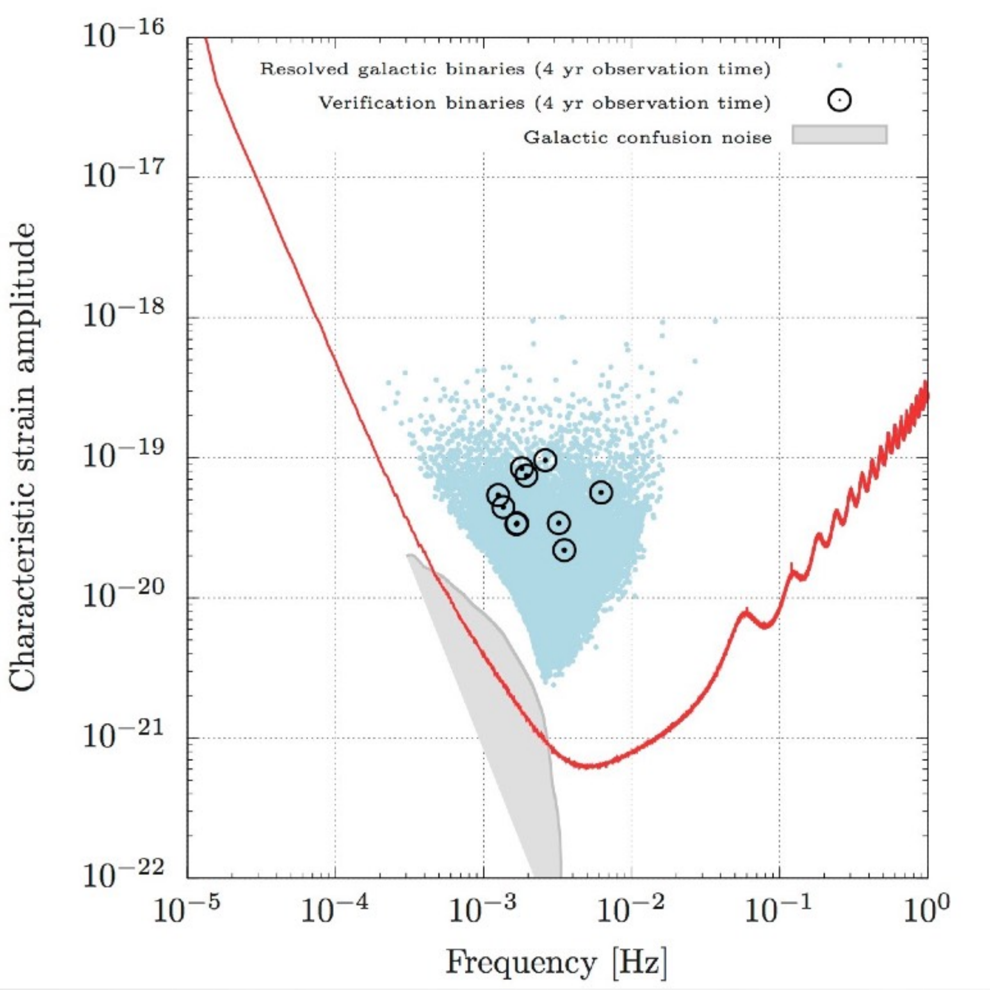
- Large number of stars are in binary systems

- Evolution in white dwarf (WD) and neutron stars (NS).
  - Existence of WD-WD NS-WD and NS-NS binaries
  - Estimated population for the Galaxy : $\sim 10^7$.

- Monochromatic sources for LISA (far from coalescence)

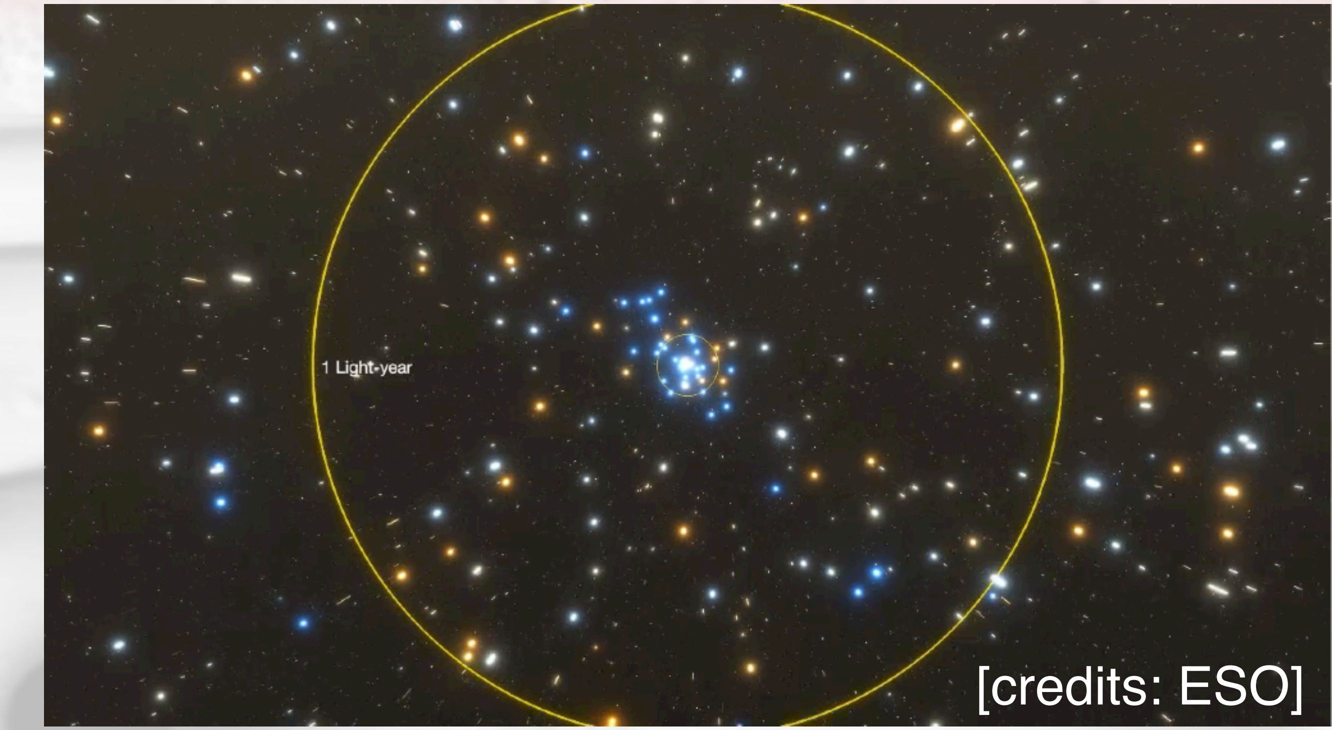
- Three categories
  - Joint EM - GW sources (Gaia, LSST)
    - Already ~10 known verification binaries in the LISA band
  - Individually detected : $\sim 10^4$
  - Stochastic GW signal
    - foreground 'noise'



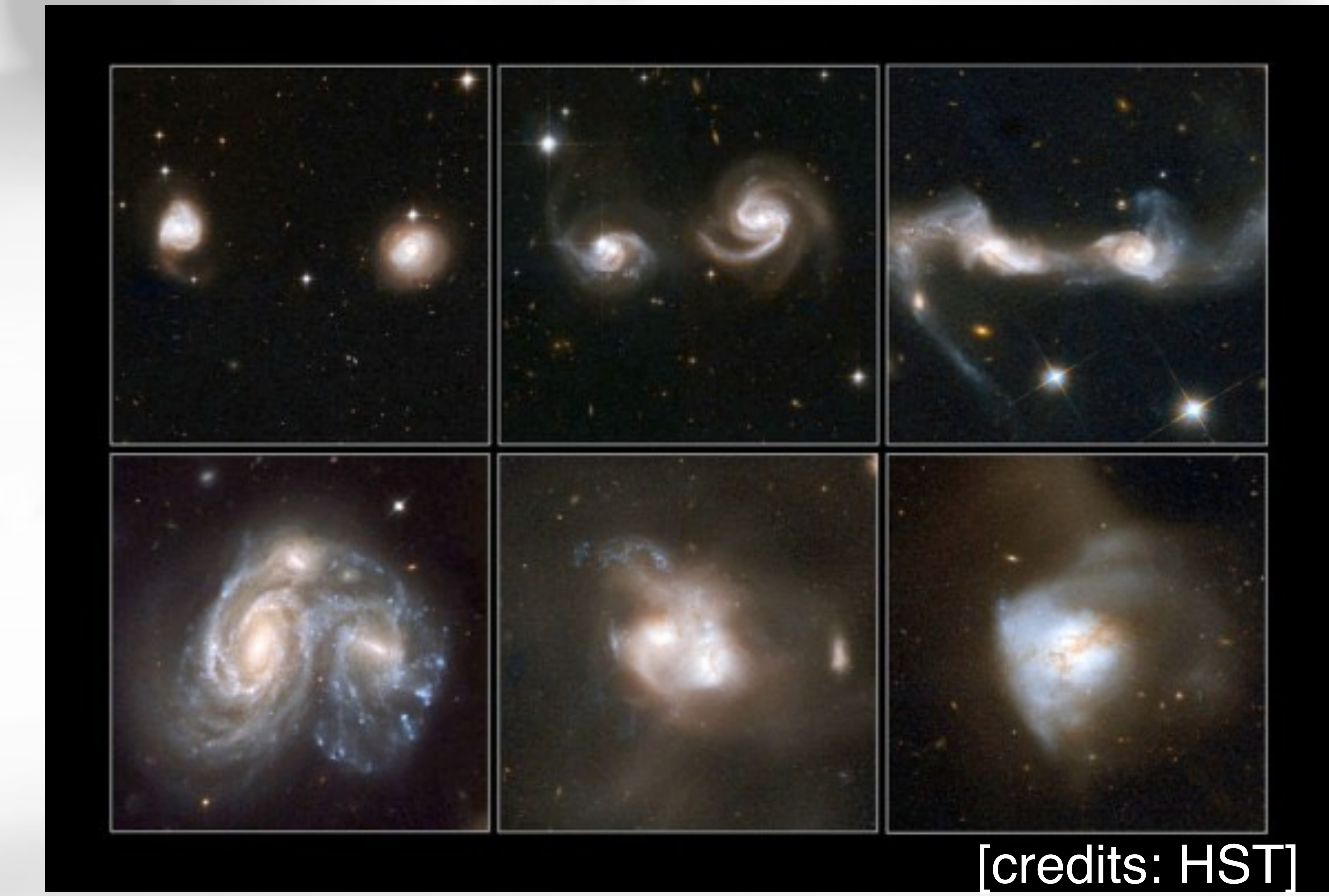


Massive BH binaries

- Massive BHs in the nucleus of every Galaxy
  - $4\ 10^6\ M_{sun}$ at the center of the Milky Way
- MBHs accumulate mass
  - gas accretion
  - merging with other BHs
- Galaxies merge
  - observed…
  - may result in a MBH binary which could merge in a reasonable time
    - Stars and/or gas required to dissipate orbital momentum and bring it in GW driven regime

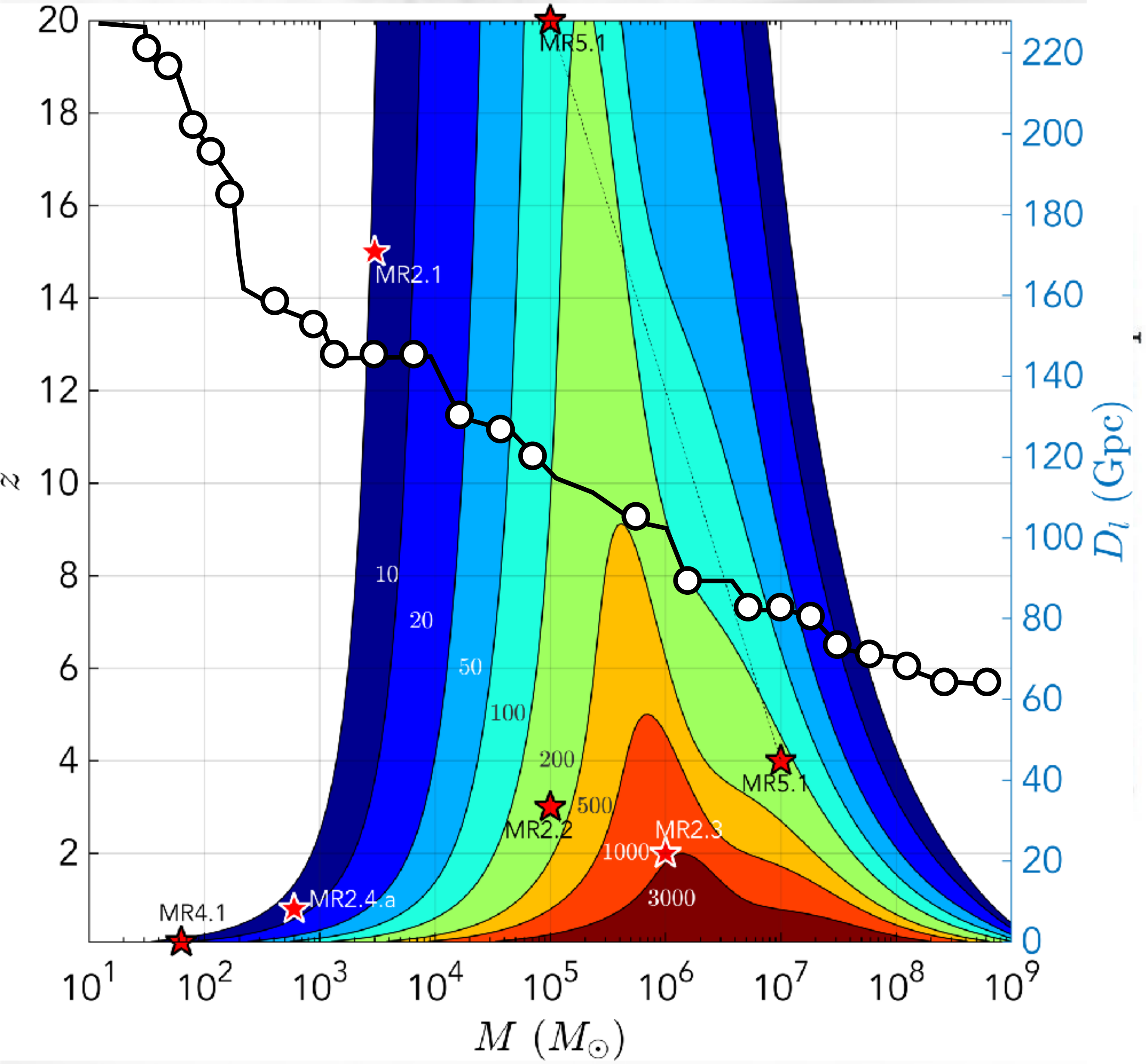


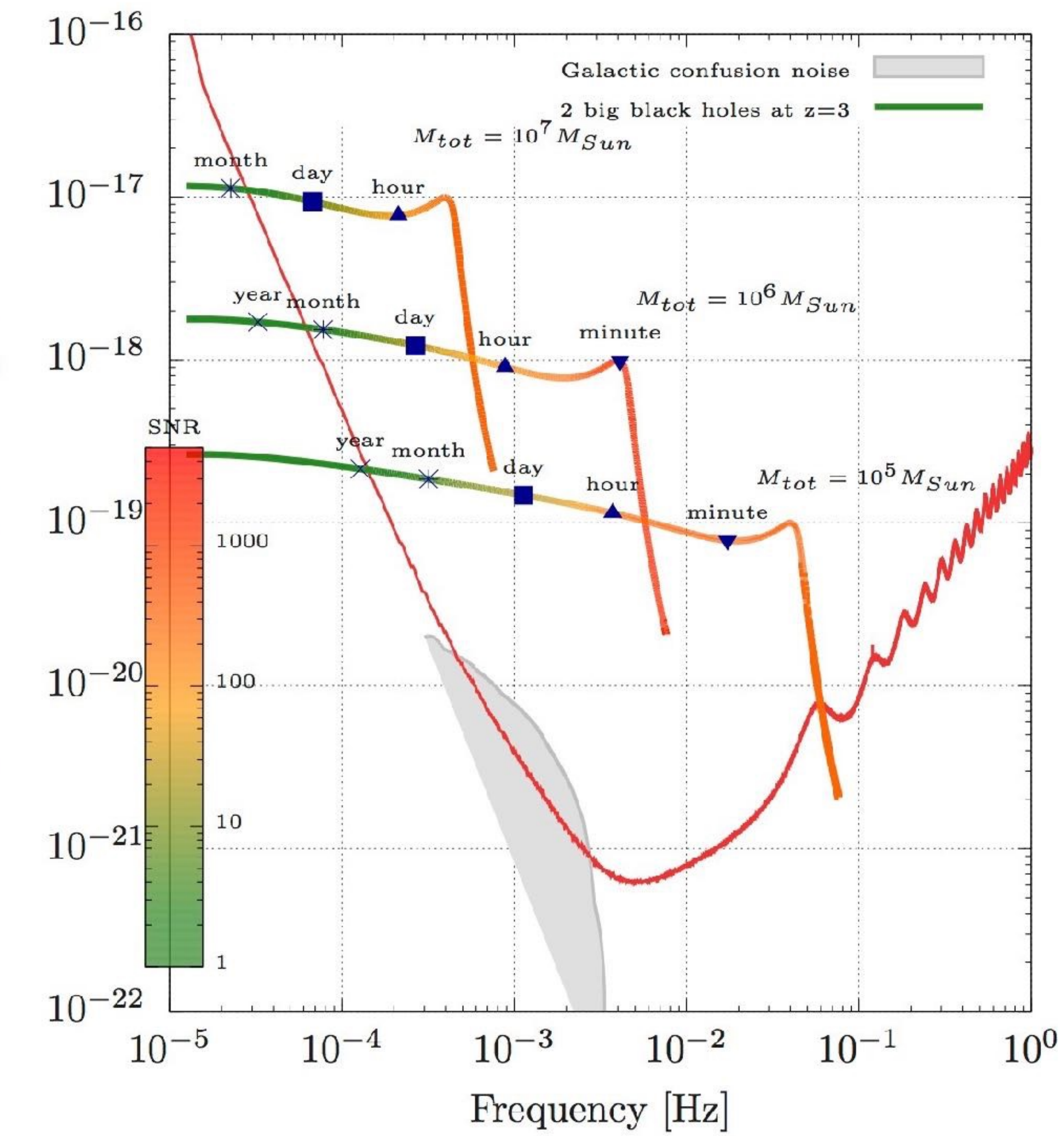
[credits: ESO]



[credits: HST]

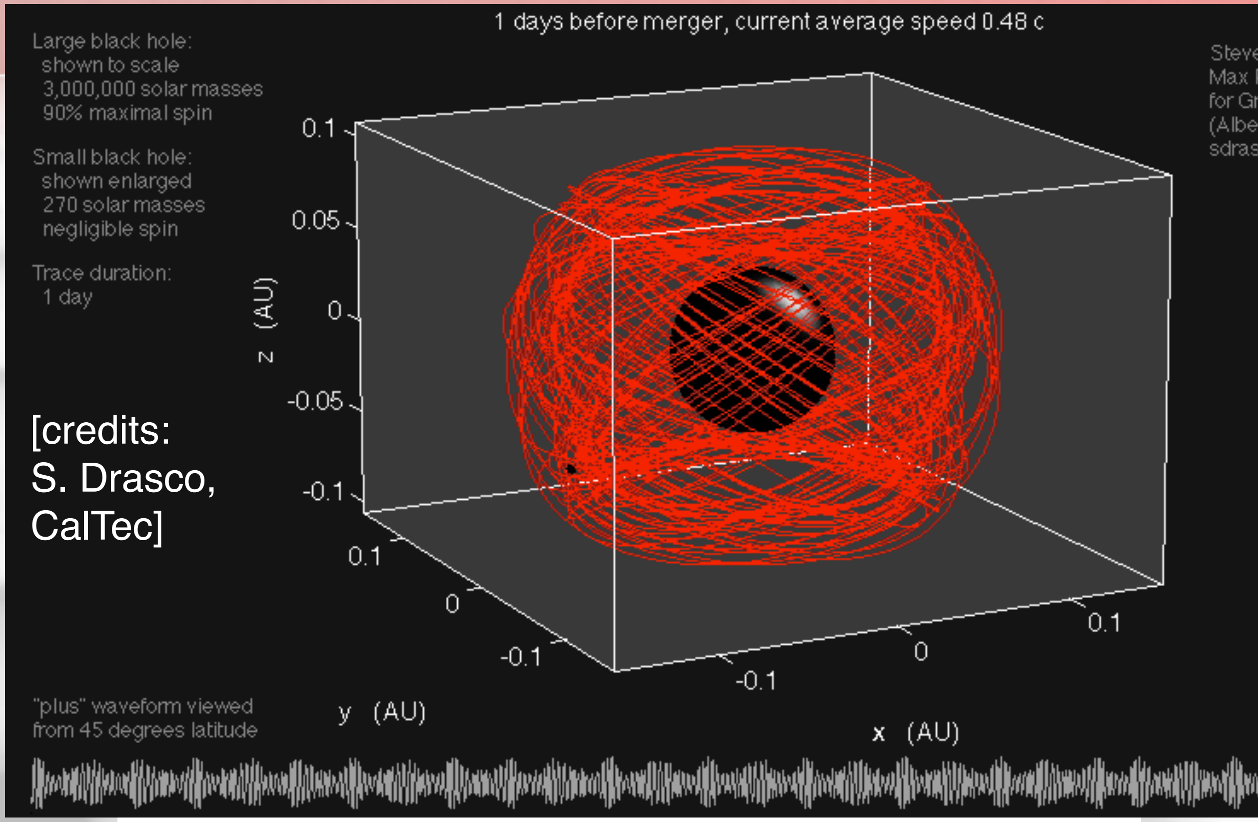
Origin, growth and merger history of massive black holes across cosmic ages



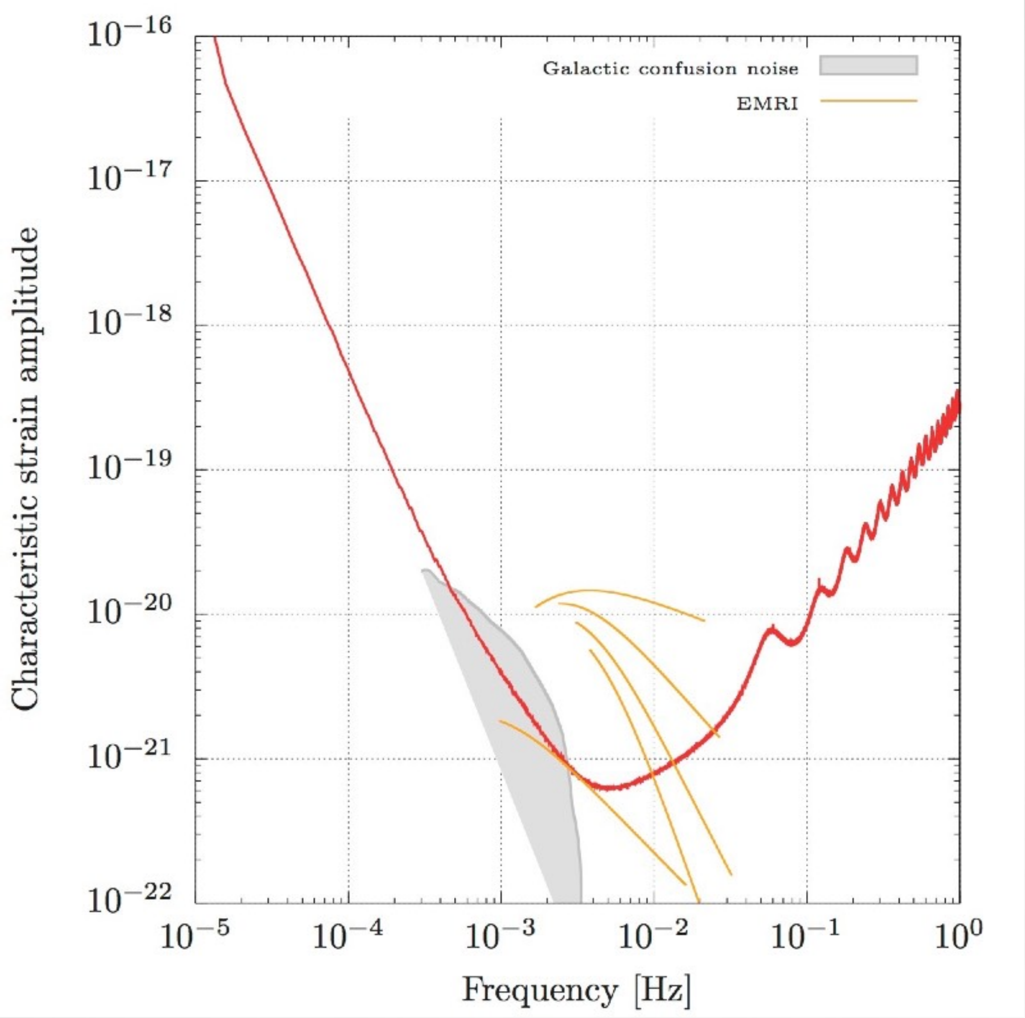


EMRIs (extreme mass ratio inspirals)

- Massive BHs could be embedded in stellar cusps
  - high density stellar environment
- Massive BH could capture a compact object
  - companion : NS, stellar mass BH
  - very eccentric orbit shrinking under GW radiation
- EMRI: Binary system with an extreme mass ratio: 10^{-7} - 10^{-5}
  - ~10^6 orbits of the compact object close to the MBH before the plunge
- Companion as 'test particle'
  - Strong relativistic effects
  - Complex (and very informative…) waveforms

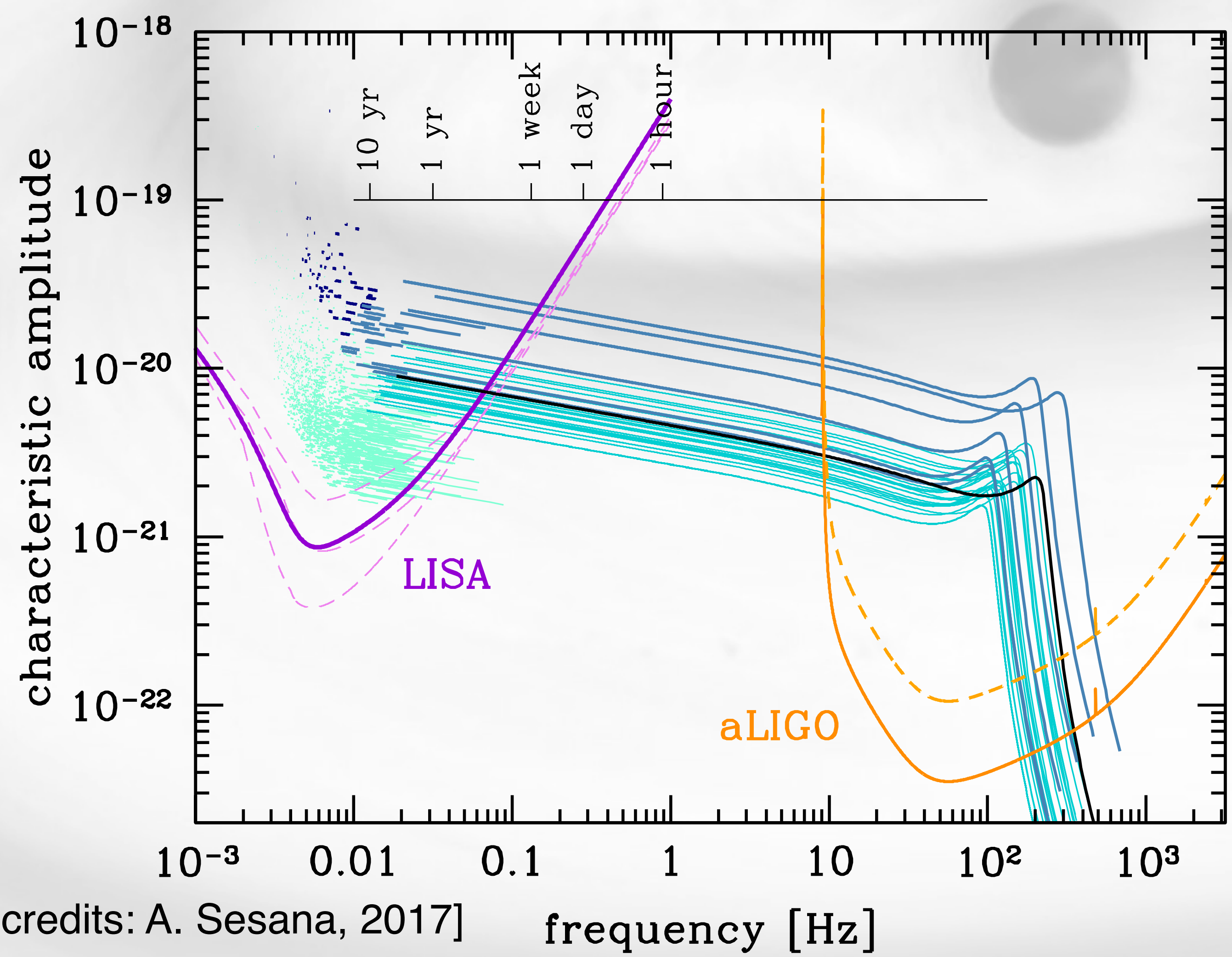


[credits: S. Drasco, CalTec]

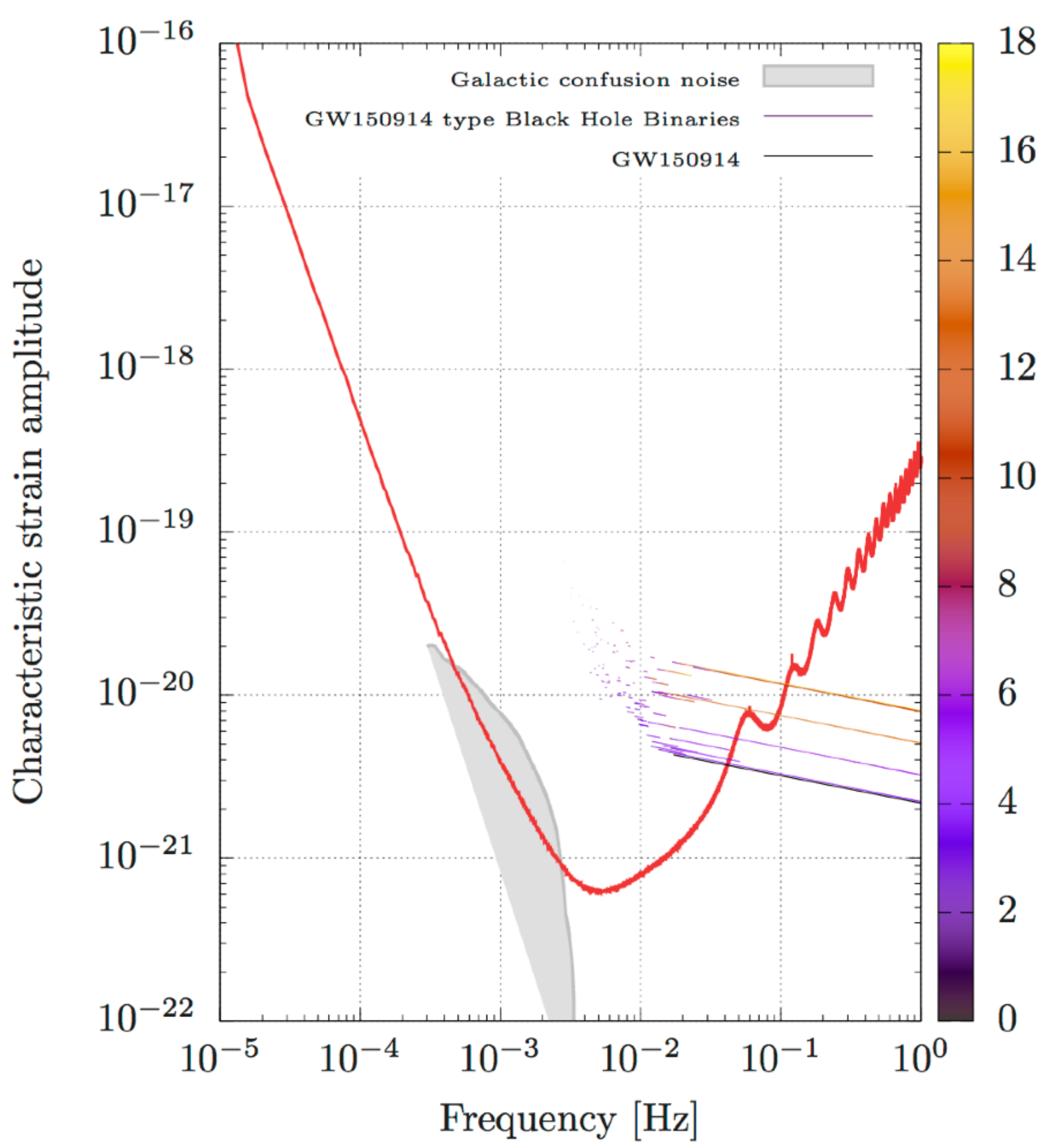


Multiband GW astronomy

- Stellar BH may be detectable by LISA prior coalescing in the ground based detectors band
  - Observed for ~years in LISA until ~days before merger
- Possible pre-warning
  - Time of coalescence at ~10s accuracy
  - Sky localisation : 0.1 - 1 deg²

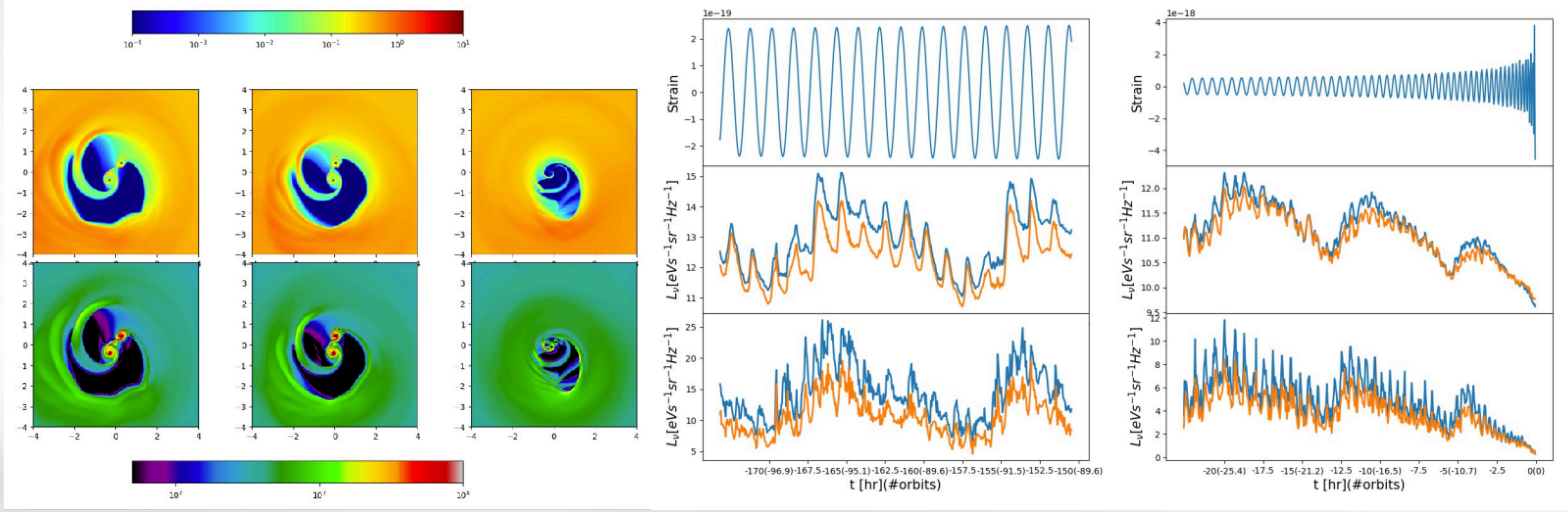


[credits: A. Sesana, 2017]



Possible e/m counterparts

- Possible X-ray emission during the late stages of the SMBH inspiral (days to hours before final merger) comes from:
  - Circumbinary disc:
    - X-ray emission in soft x-rays (≤1keV)
  - Mini-discs around black holes
    - Hard x-ray emission (≥10keV) from accretion of minidiscs individually onto each black hole
  - Interaction of circumbinary and mini discs:
    - Accretion of circumbinary disc onto mini-discs via optically thick streams
    - Thermal radiation dominated by the inner edge of the circumbinary disc, producing soft x-rays (~2keV)
  - X-ray emission shows clear modulation on timescales as short as a few hours



Y. Tang+, MNRAS 2018

Fundamental physics with LISA

- Using emitted GW to map the spacetime structure

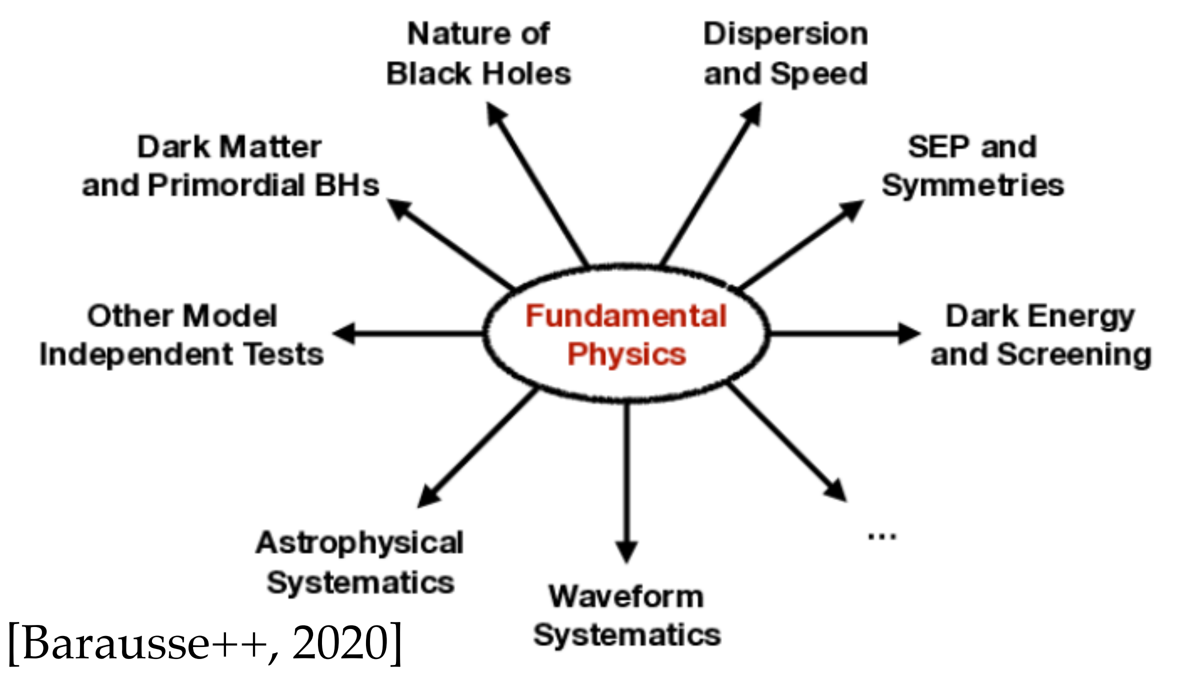
- Tests of GR
  - Fundamental principles and symmetries of GR
  - Testing GR with compact objects

- Tests of the Nature of Black Holes

- Dark matter and Primordial Black Holes

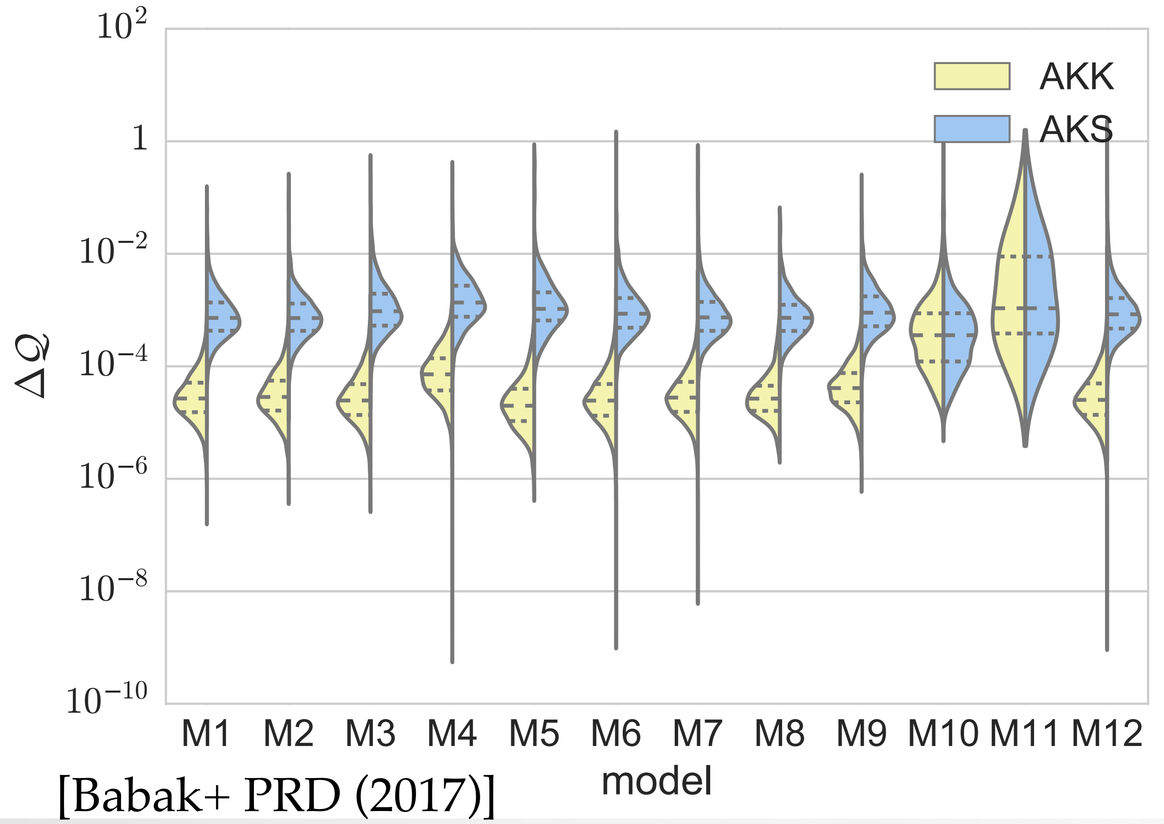
- Model-independent tests
  - Consistency of GR vs constraining Modified Gravity
  - Parameterised tests
  - Other tests including: Polarisation, GW propagation, Stochastic GW Background

- Astrophysical and Waveform systematics



[Barausse++, 2020]

Deviation in quadrupole moment from Kerr value (no hair theorem):

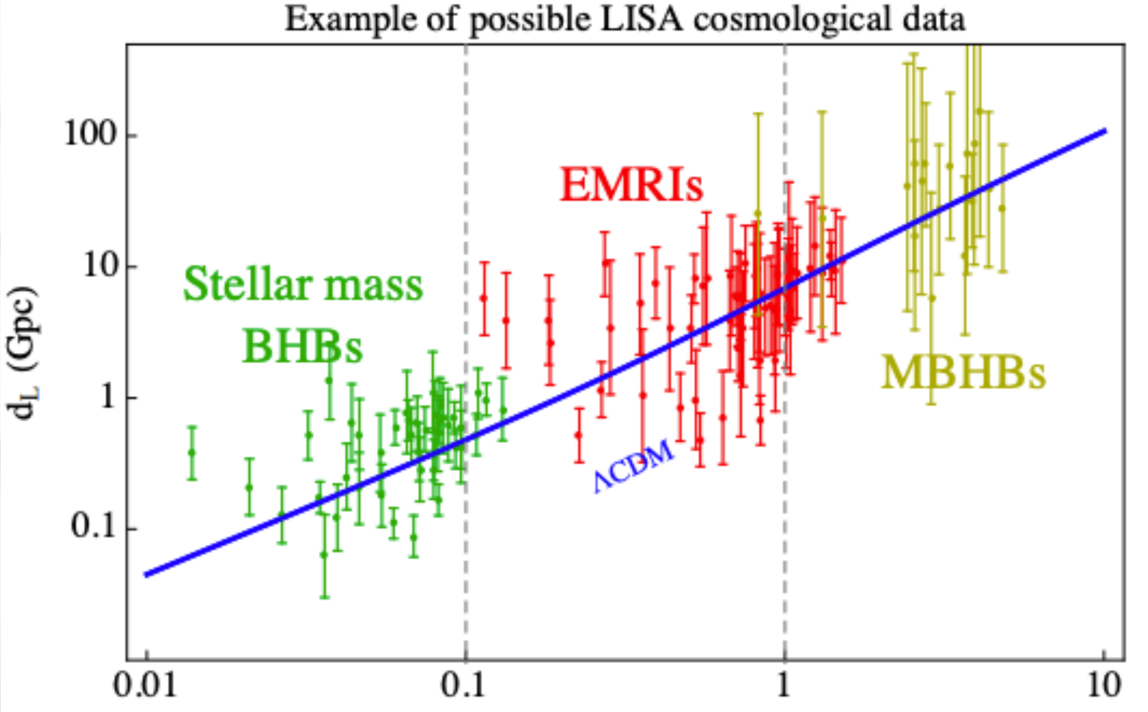


[Babak+ PRD (2017)]

Cosmography with LISA

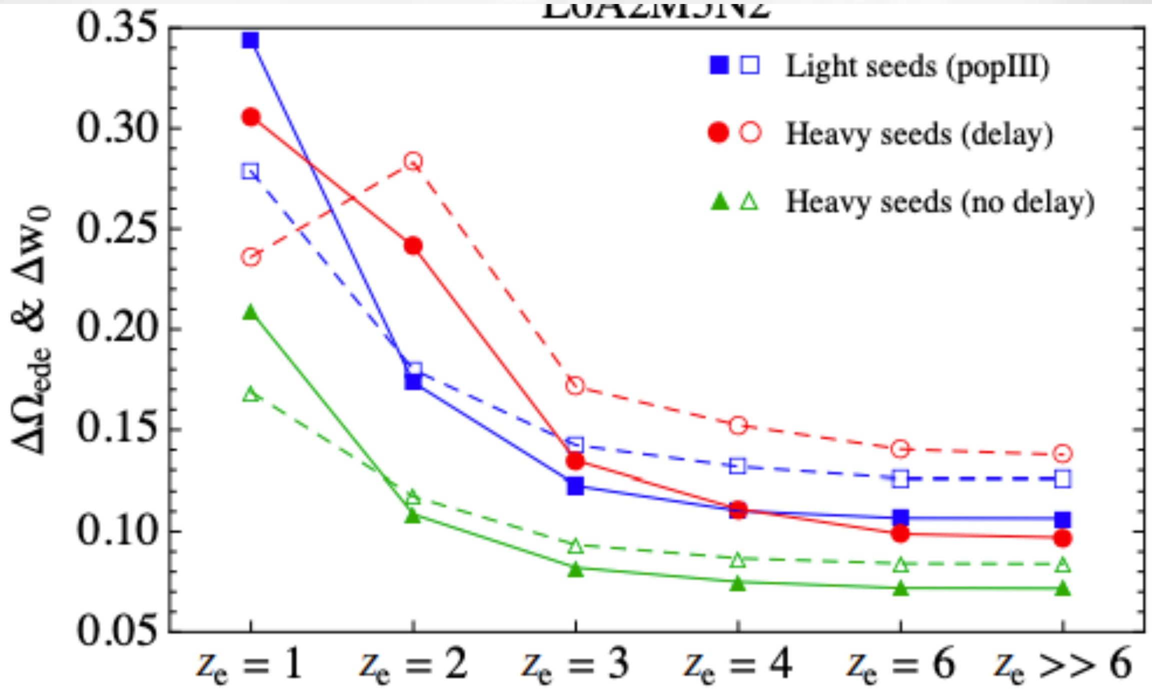
- LISA may help on many cosmological problems
  - Expansion rate of the Universe : late acceleration ?
    - CMB : $H_0 = 66.93 \pm 0.62$ km.s^{-1}.Mpc^{-1}
    - SN Ia : $H_0 = 73.5 \pm 1.4$ km.s^{-1}.Mpc^{-1}
  - Dark energy
    - Cosmological constant ?
    - Early dark energy: DE evolves with redshift and contributes to rate of expansion at z>1
  - Modification of GR on large scale
- LISA can probe the Universe at different scales
  - Use BHBs merger events as standard sirens
  - Requires the knowledge of the redshift
    - from e/m counterpart of the host galaxy
    - or from statistical inference

Universe expansion rate from GW events :



N. Tamanini J. Phys. CF 2016

Universe DE content:



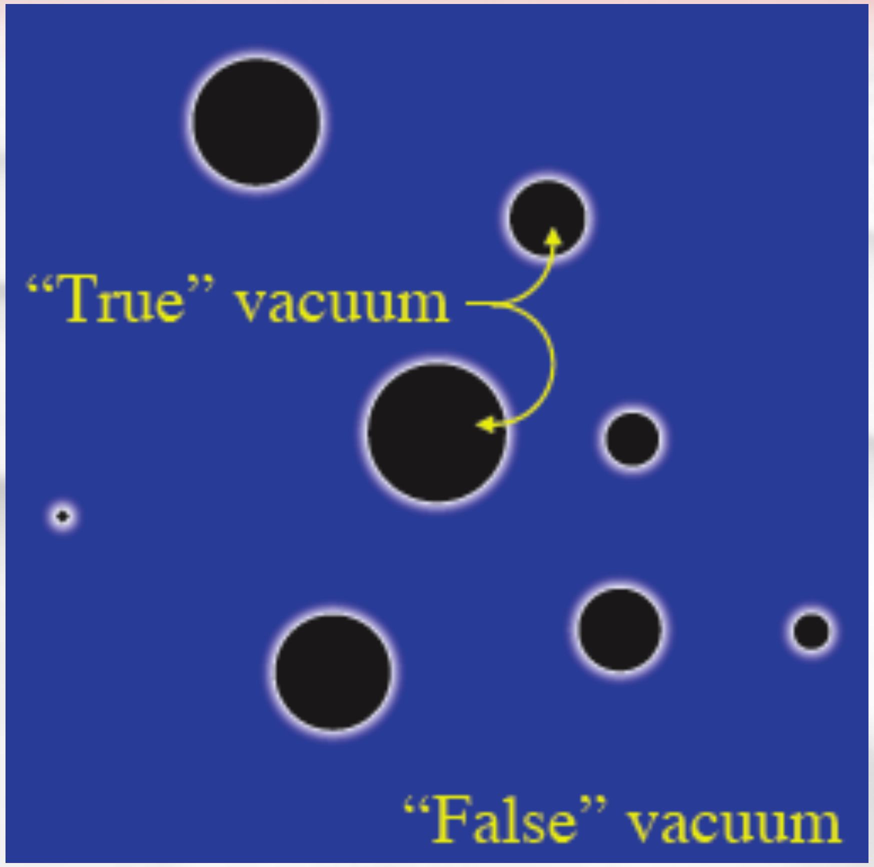
Ch. Caprini, N. Tamanini JCAP 2016

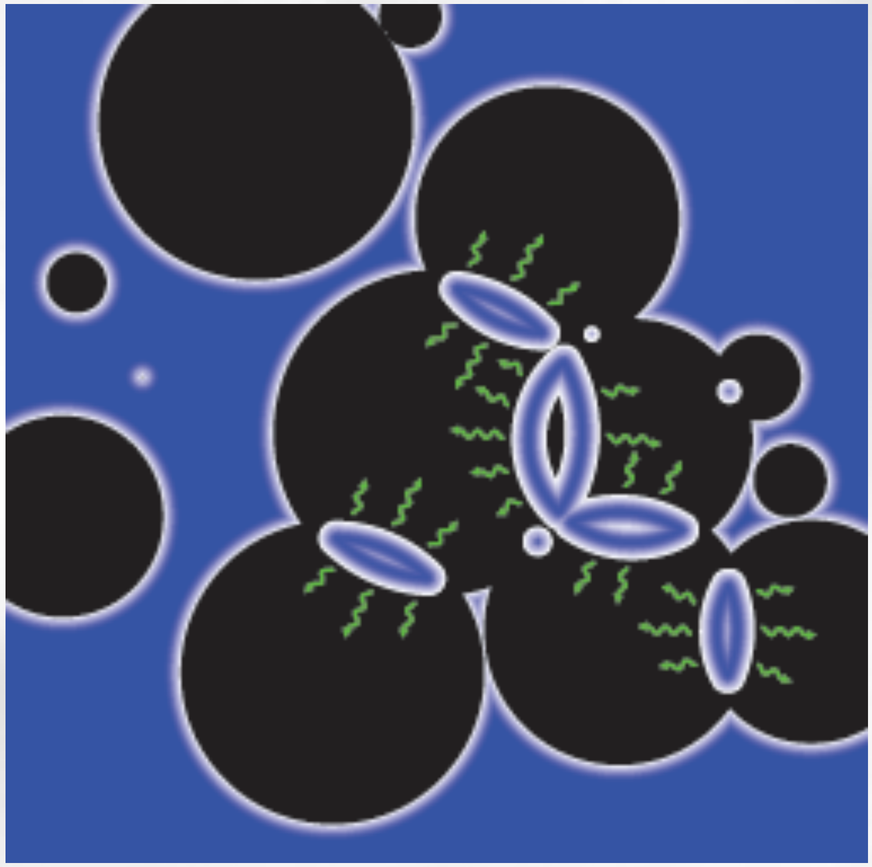
Early Universe in GWs

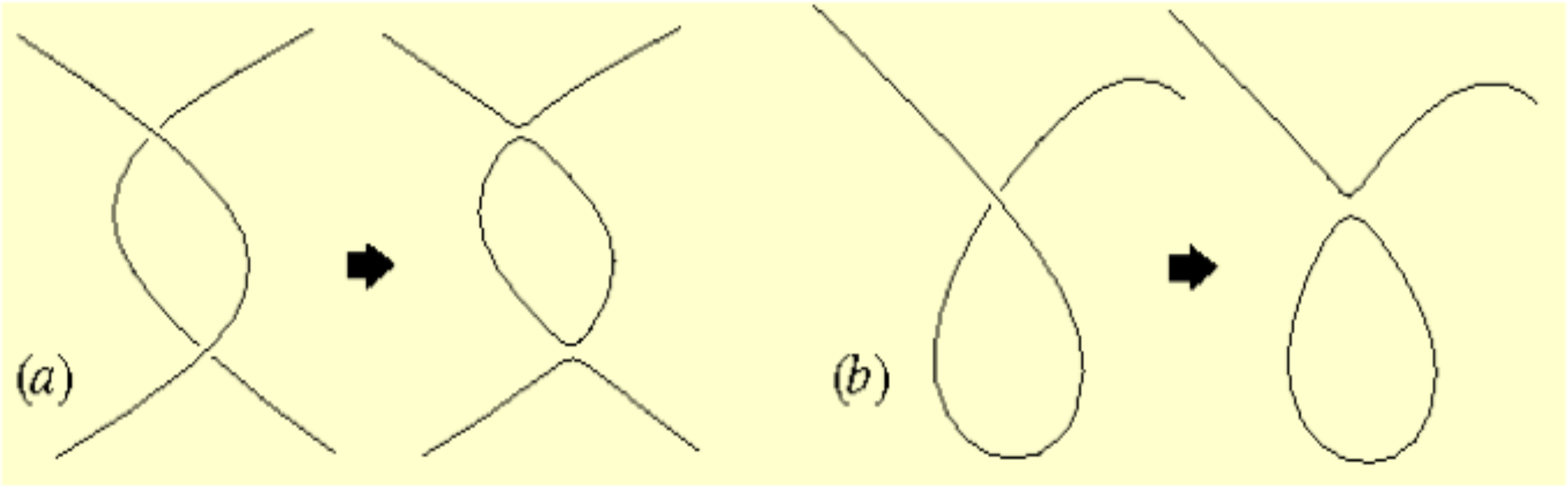
- Violent processes in the early Universe may produce stochastic GW background (SGWB)

- First order phase transition
  - Collision of true vacuum bubbles and conversion to the symmetry-broken phase accompanied with anisotropic stresses.
  - The LISA band (10^{-4} - 0.1 Hz) corresponds to the energy scale of the EW (electroweak) phase transition (up to 10^4 TeV).
  - Formation of sound wave, shocks and turbulence in the plasma

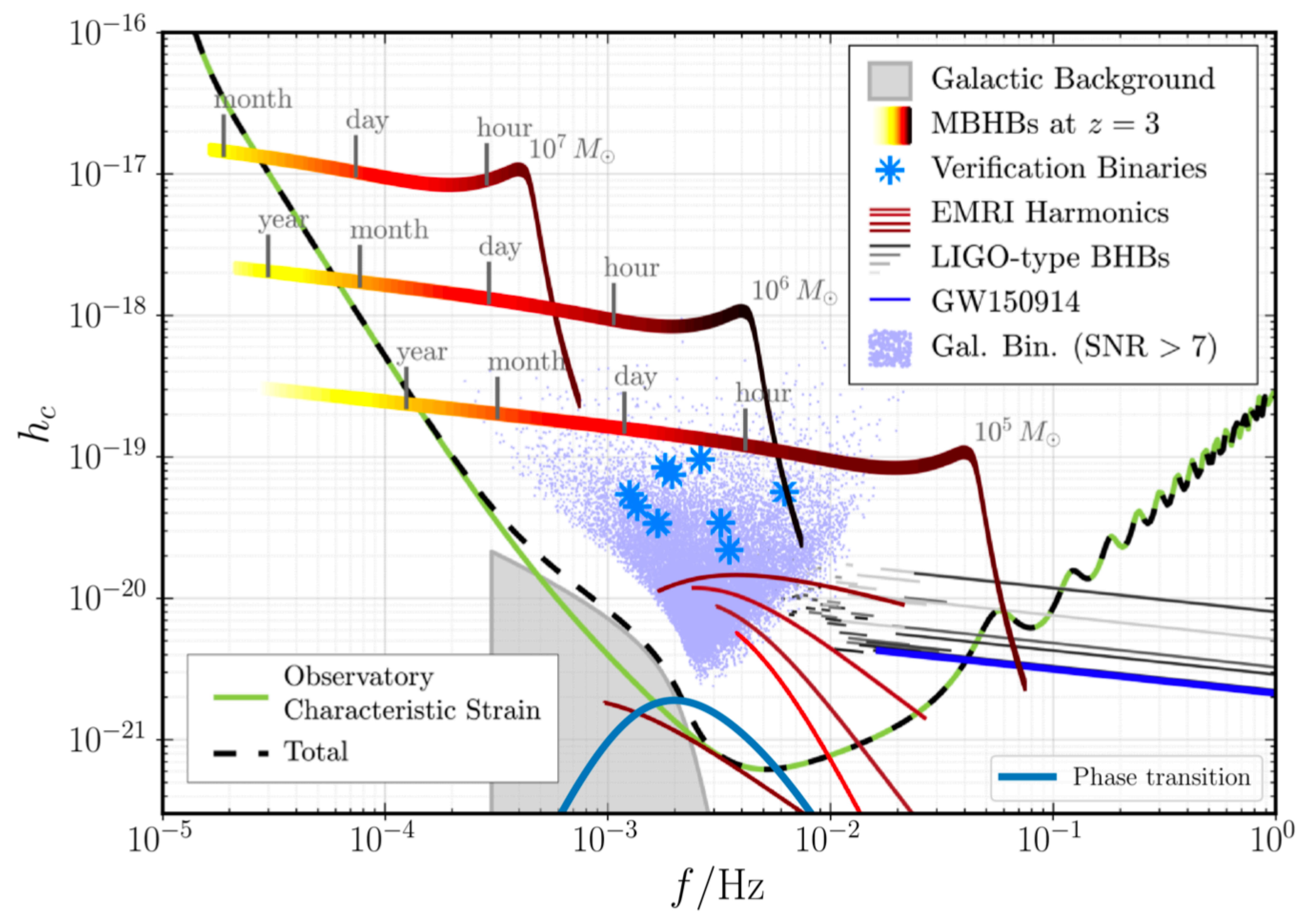
- Cosmic strings:
  - A network of strings formed in the early Universe generates SGWB (as superposition of many uncorrelated sources) and (possibly) individual bursts







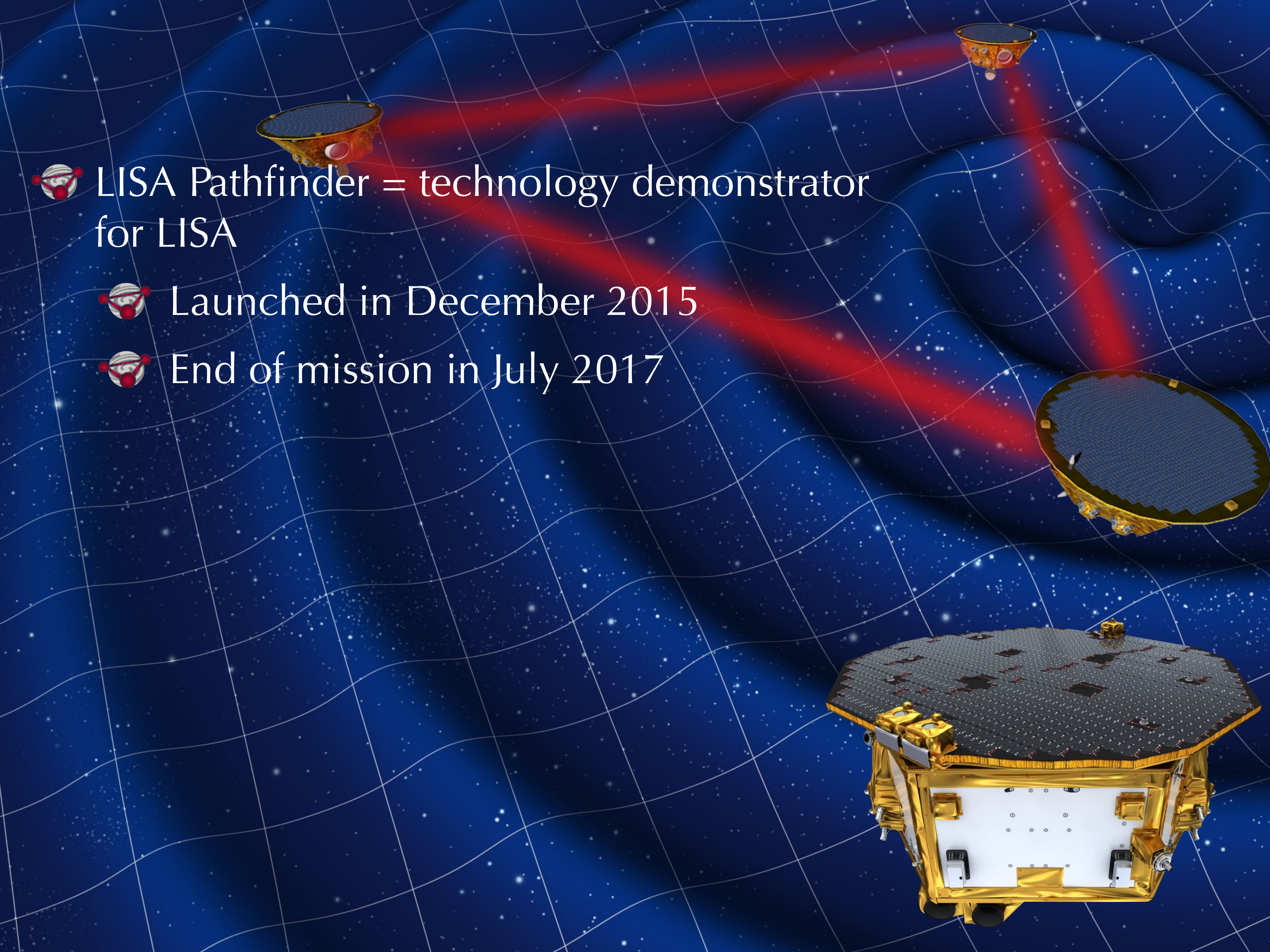
Potential sources for LISA: summary



Université de Paris

LISA France

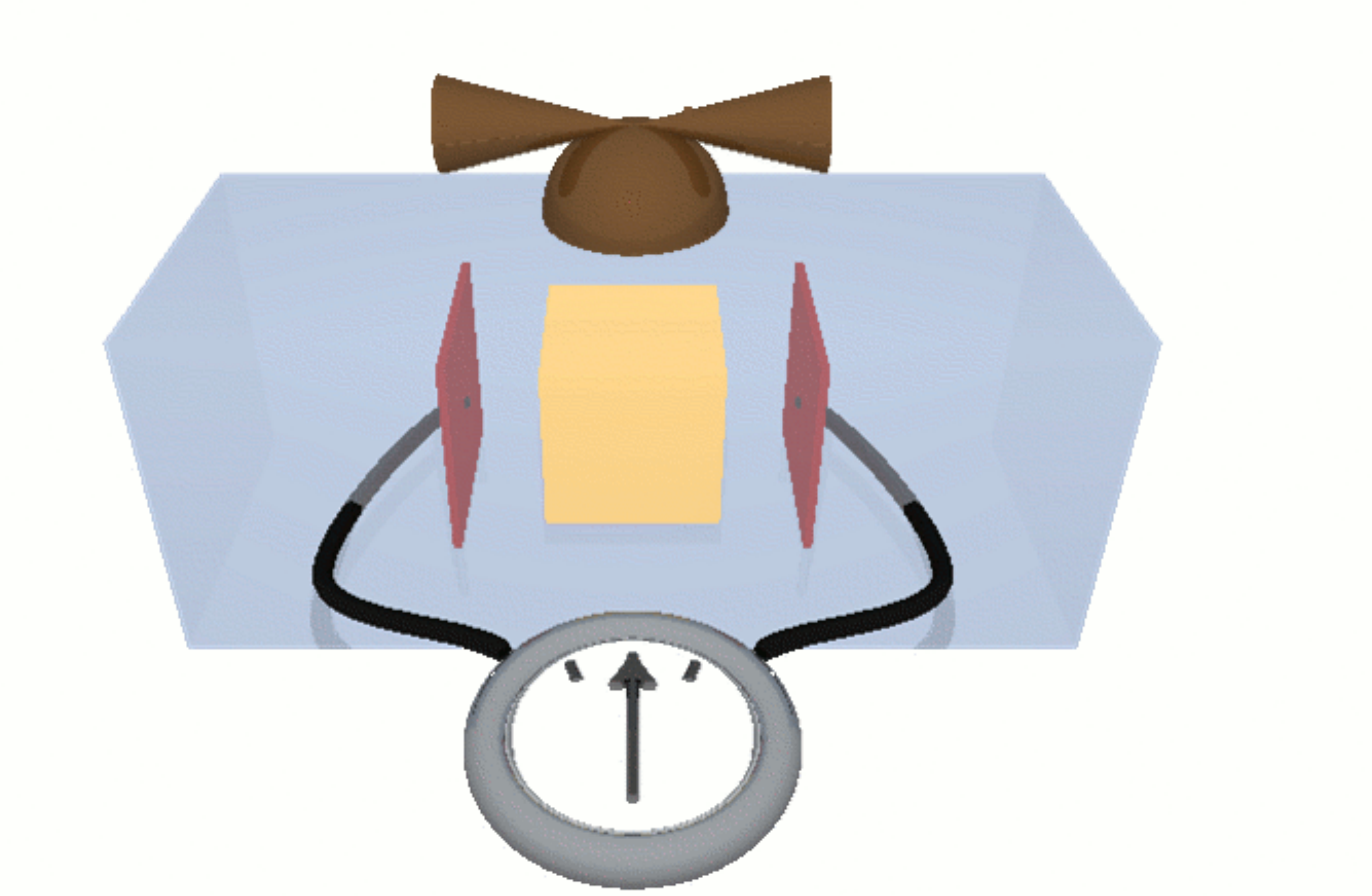
LISA Pathfinder



- LISA Pathfinder = technology demonstrator for LISA
  - Launched in December 2015
  - End of mission in July 2017

Drag-free flying ?

- Test masses must be protected from external perturbations (mainly solar wind)
- Technology demonstrator : LISA Pathfinder

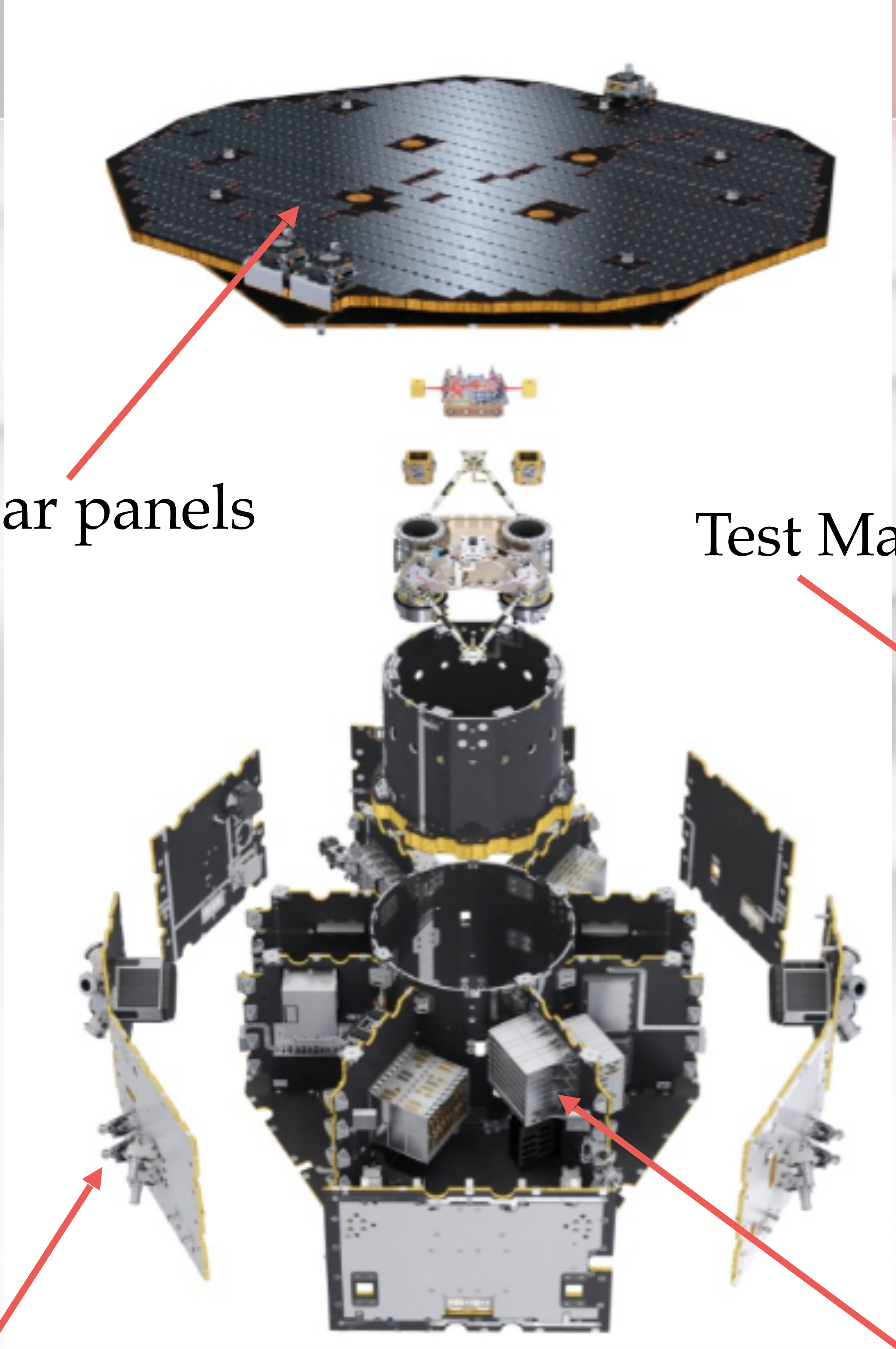


LISA Pathfinder

- **Main goal**: demonstrate the possibility of "Free Fall" in space at the level of ≈ 10^{-14} m.s$^{-2}/\sqrt{\text{Hz}}$, around 1 mHz

- A number of effects have to be minimized:
  - The static gravitational potential between the TMs and the SC,
  - Residual links of the TMs w.r.t the SC via the residual vacuum,
  - Cross talk between various electrostatic actuators,
  - TM charging by cosmic rays that is eliminated by UV illumination,
  - Temperature fluctuations ,
  - Magnetic field fluctuations,
  - …

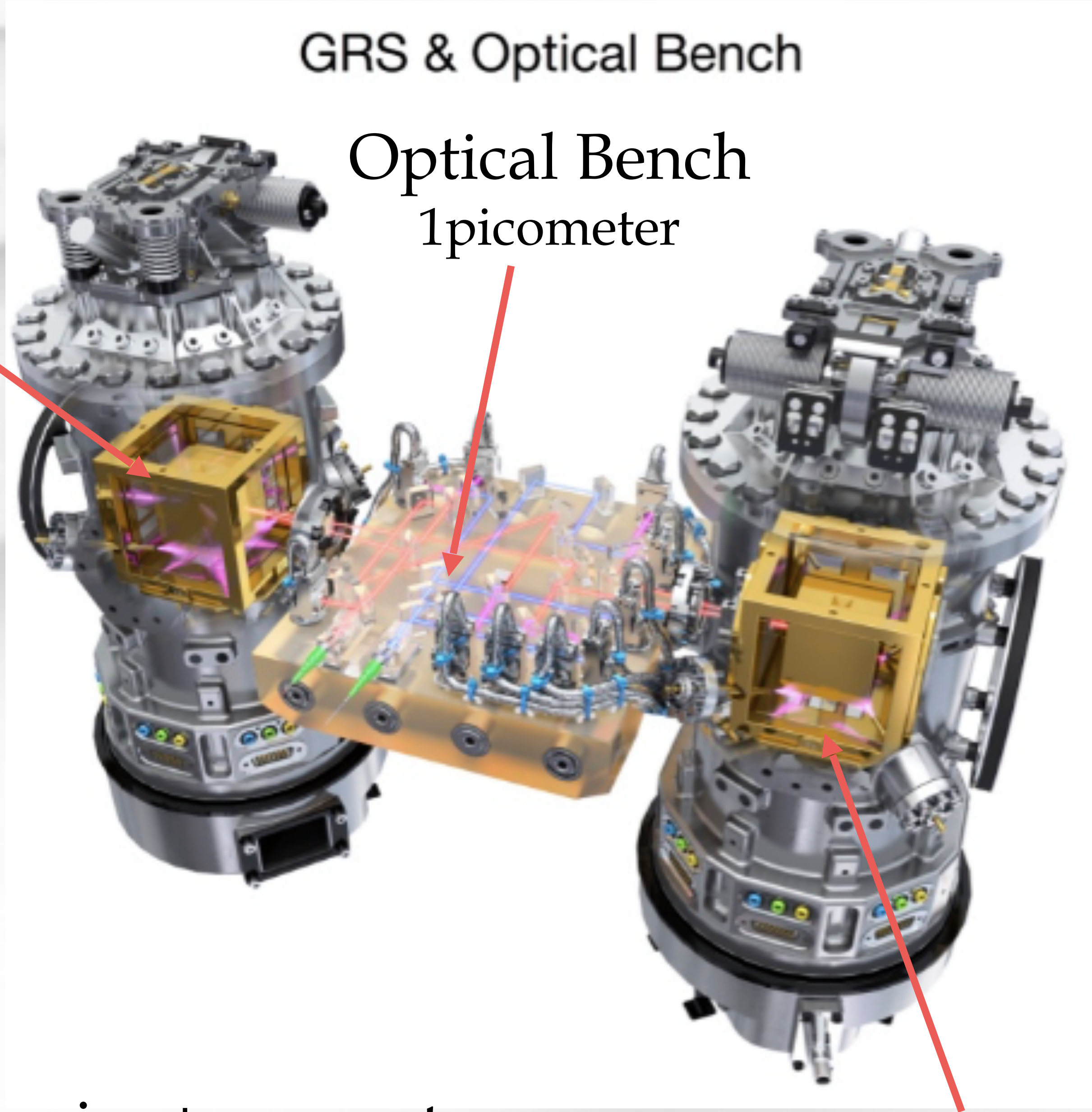
LisaPathfinder : A technology demonstrator



Solar panels

The micro-thrusters
Cold Gas (μ-Newton)

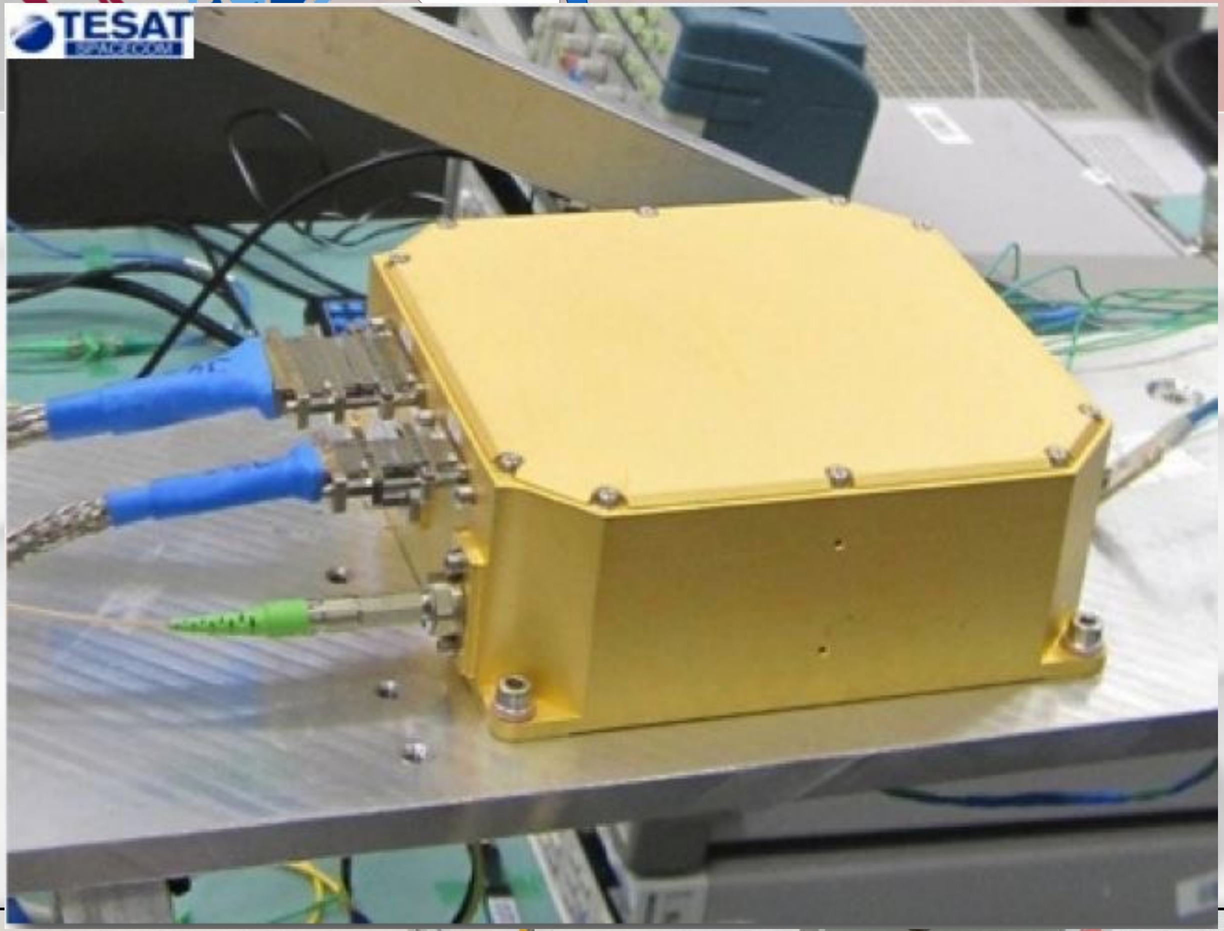
Electronics + computers

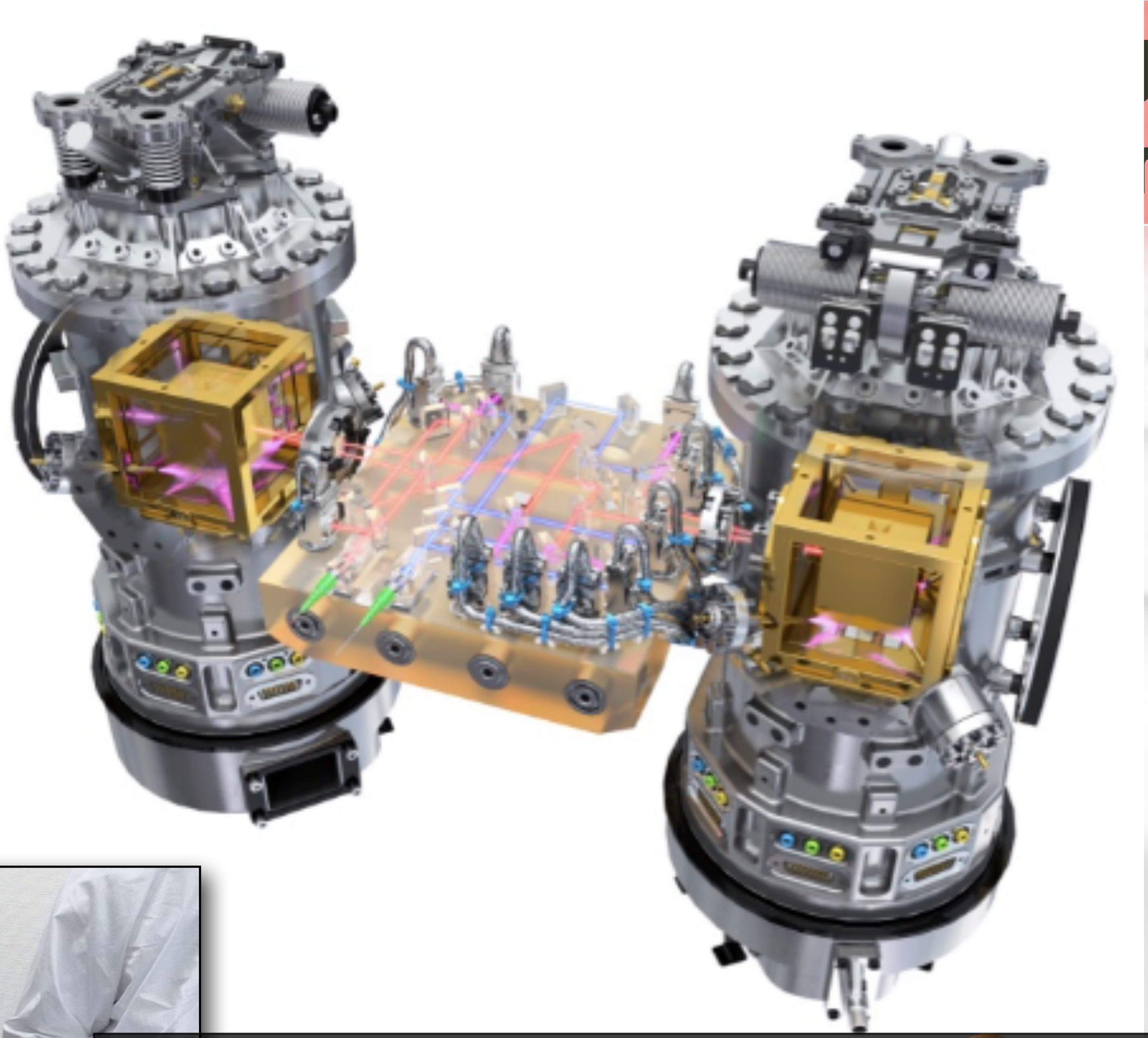


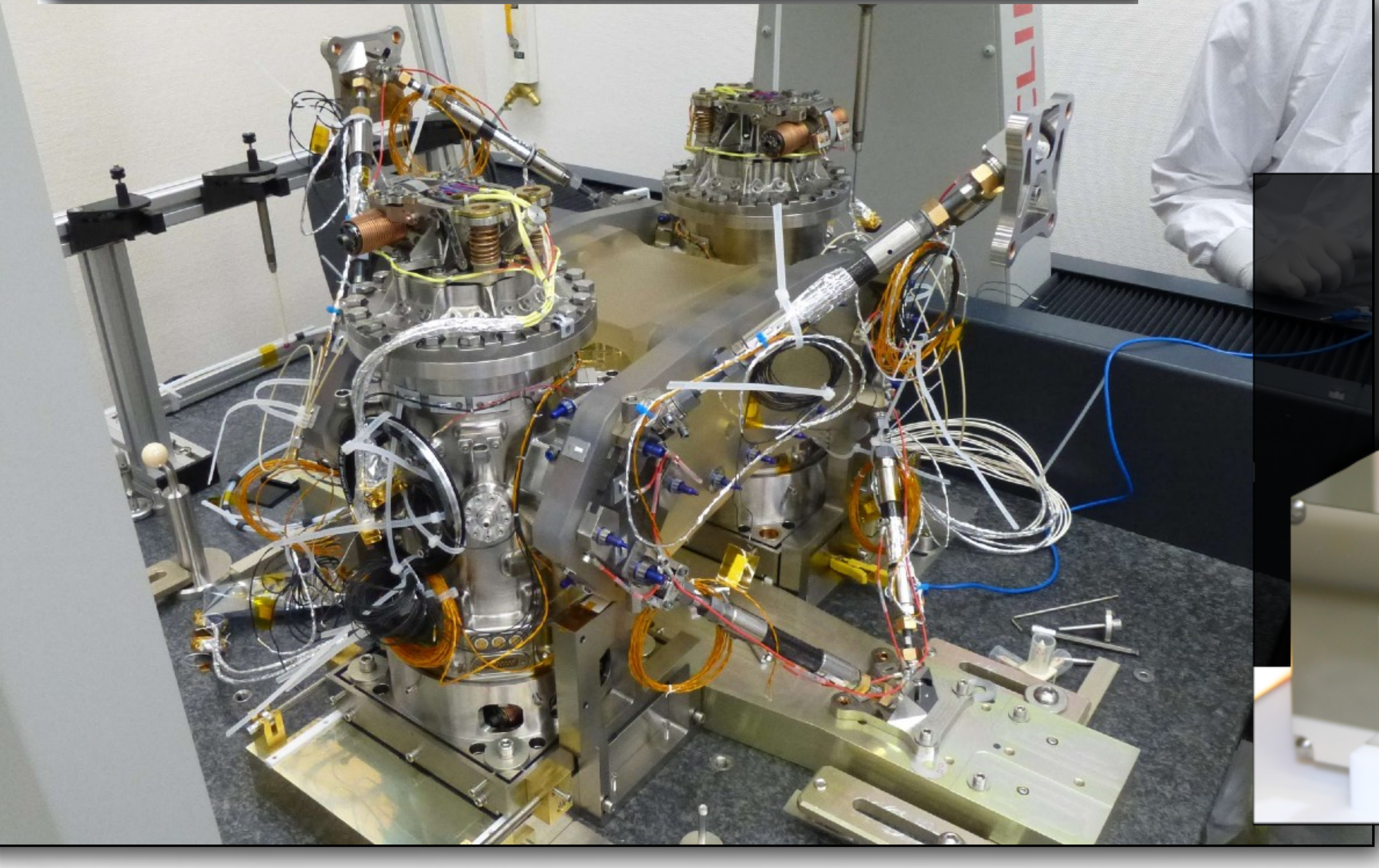
Test Mass

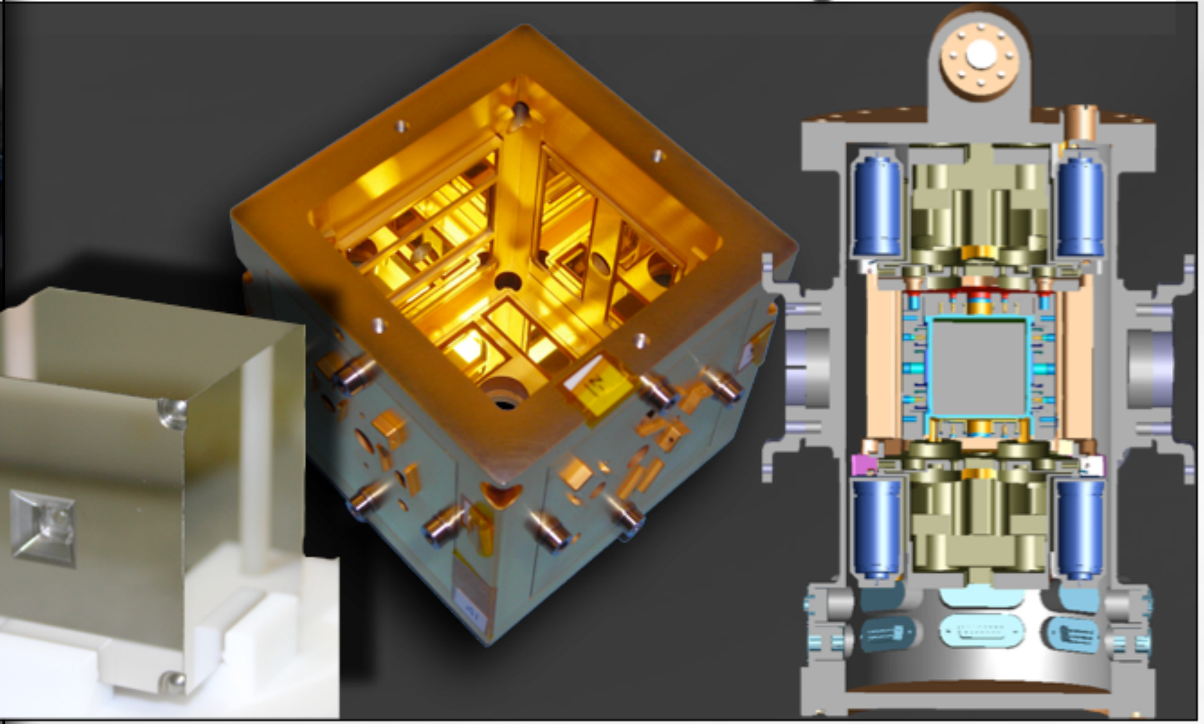
Optical Bench
1picometer

UV illumination



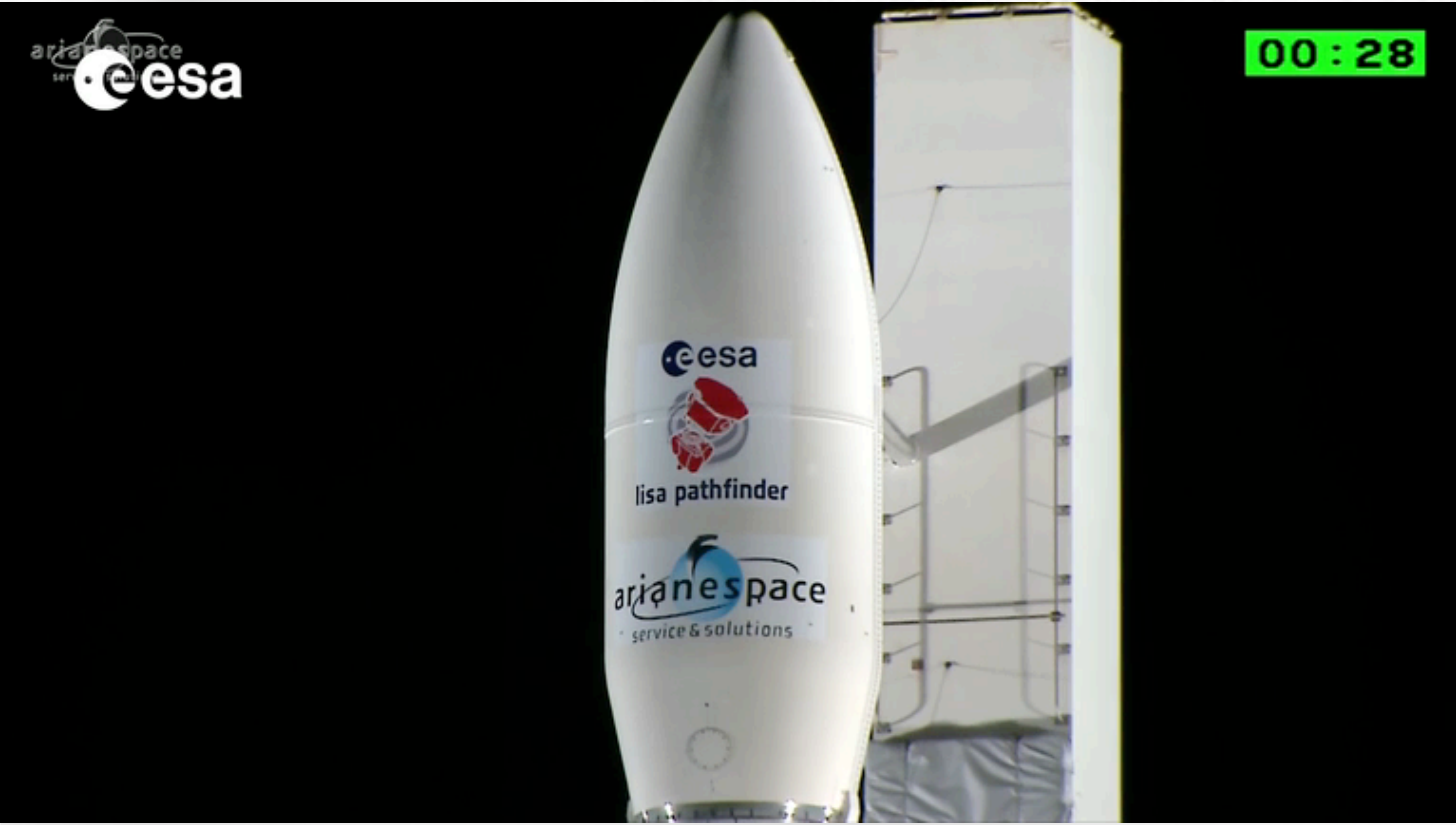






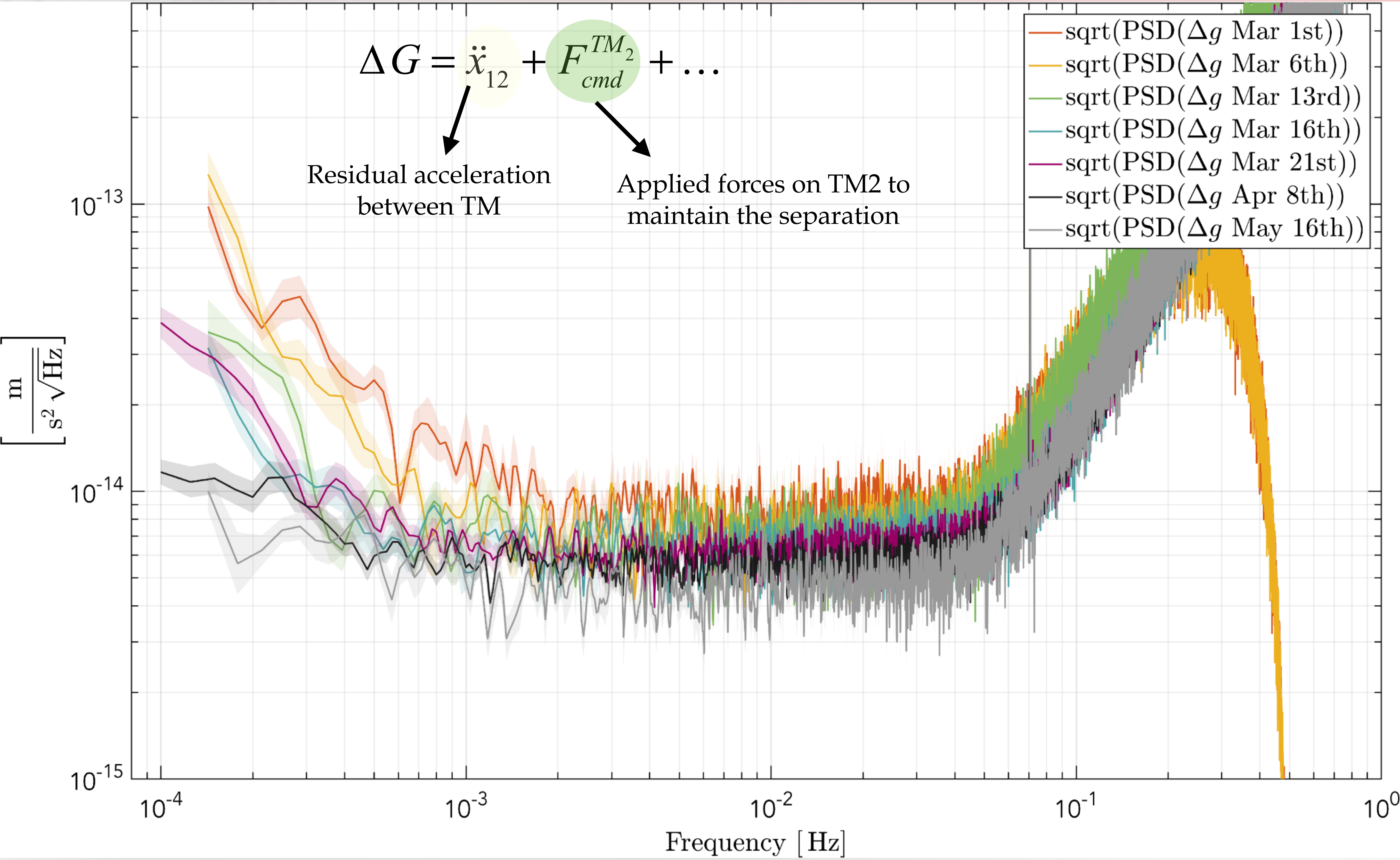

IABG

LISA Pathfinder - 03/12/15



LISA Pathfinder

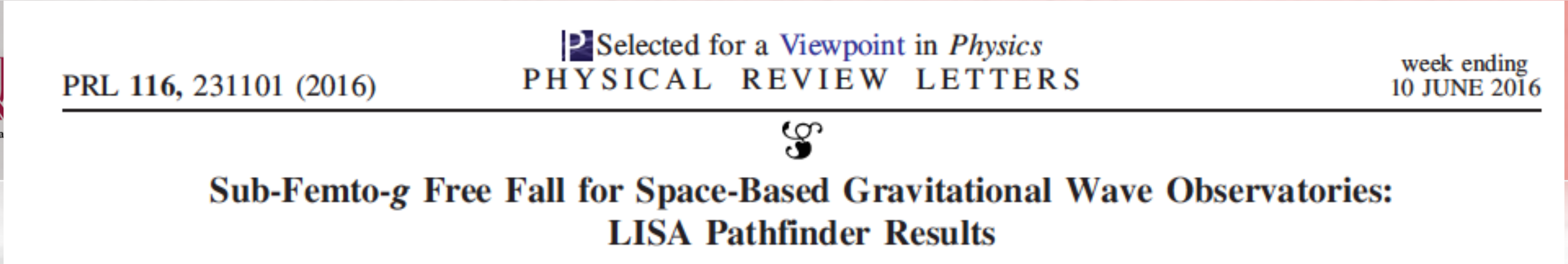
In-flight performance evolution



$$\Delta G = \ddot{x}_{12} + F^{TM_2}_{cmd} + \dots$$

Residual acceleration between TM

Applied forces on TM2 to maintain the separation



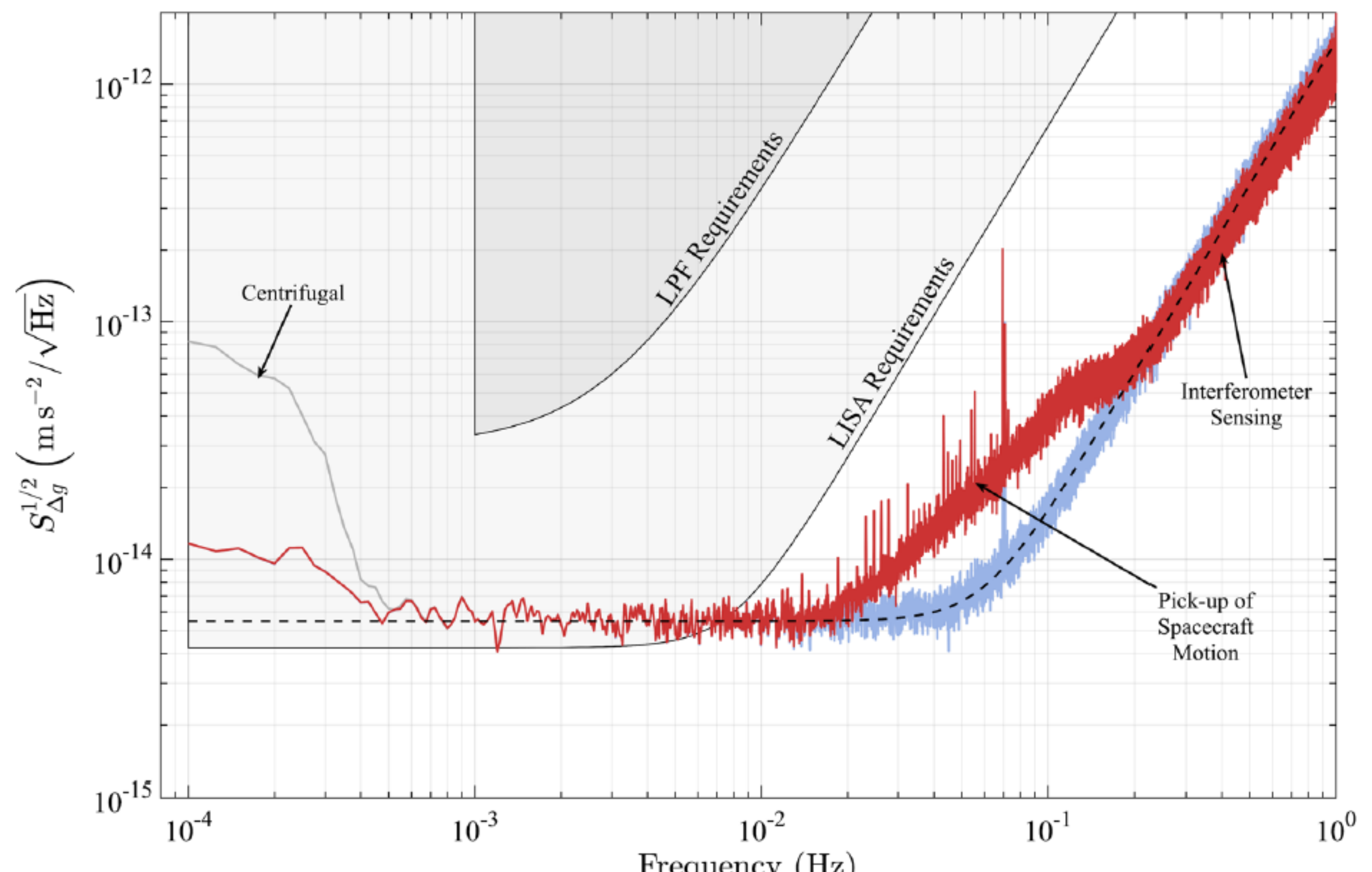
PRL 116, 231101 (2016)

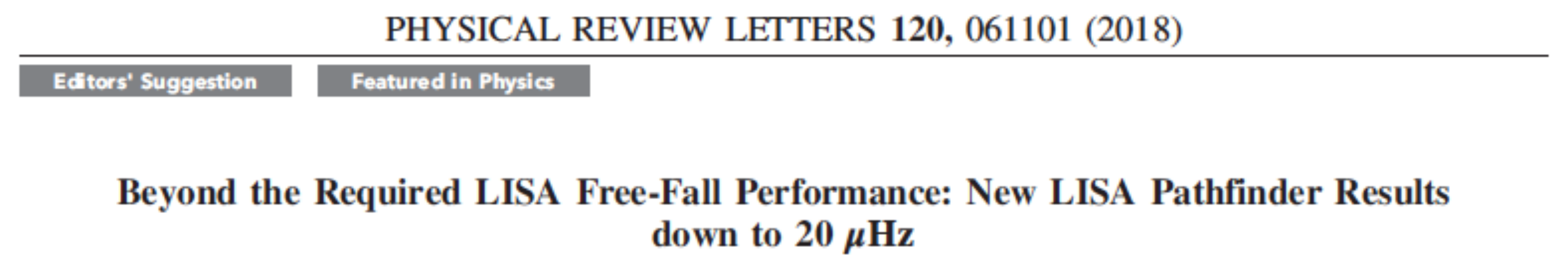
Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
10 JUNE 2016

Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results



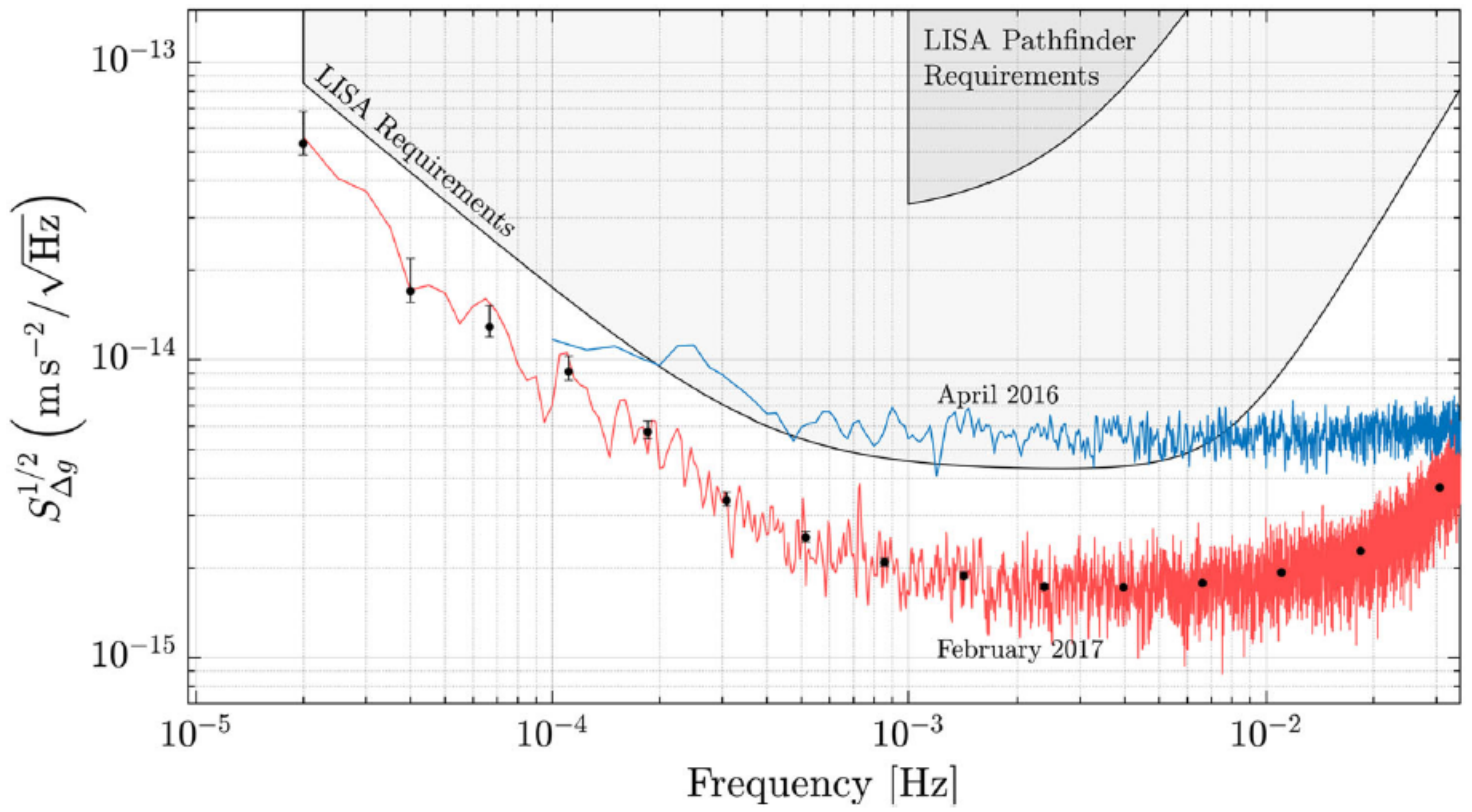


PHYSICAL REVIEW LETTERS 120, 061101 (2018)

Editors' Suggestion

Featured in Physics

Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz

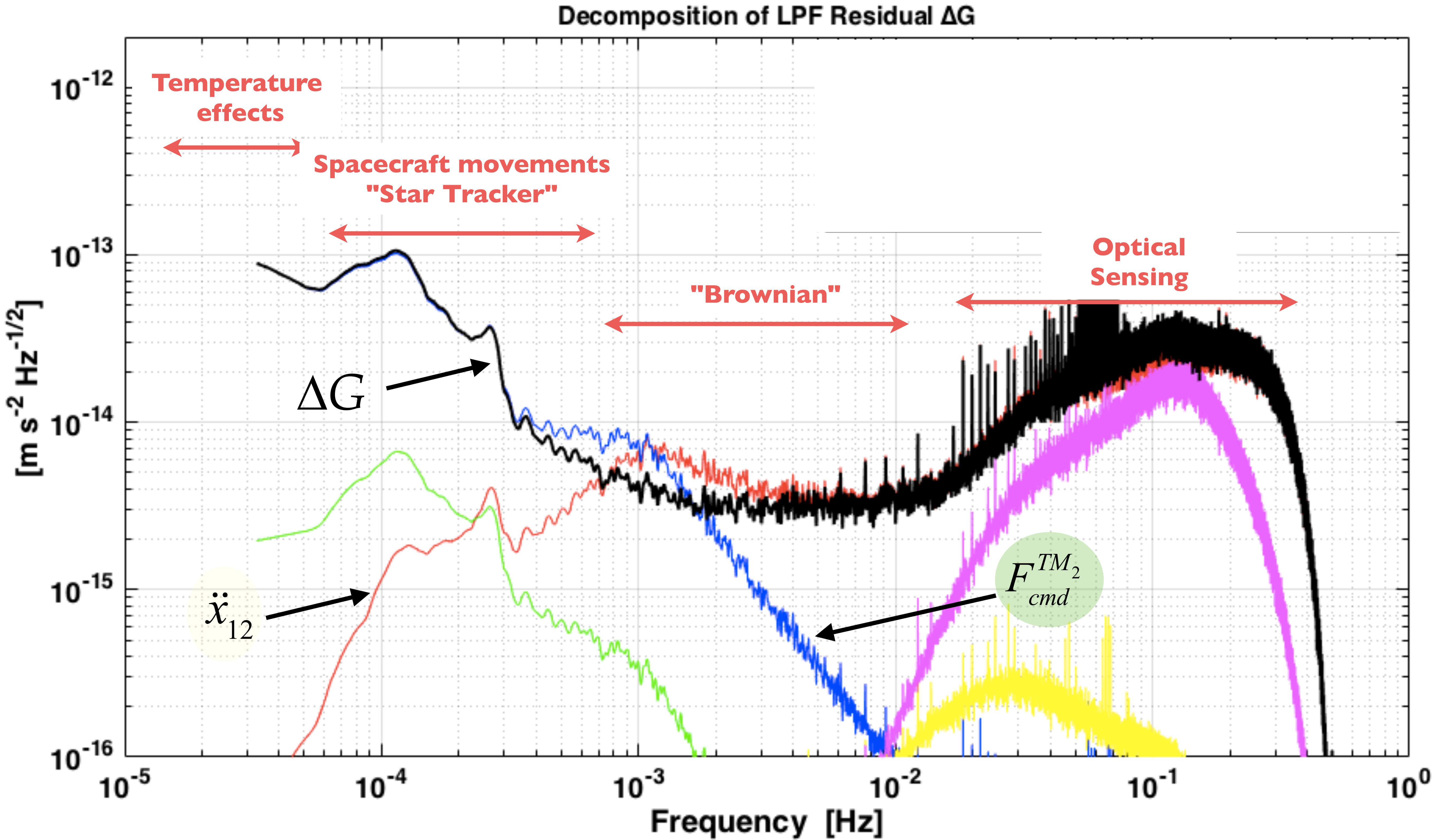


The Different Frequency Ranges

$$\Delta G = \ddot{x}_{12} + F^{TM_2}_{cmd} + \ldots$$

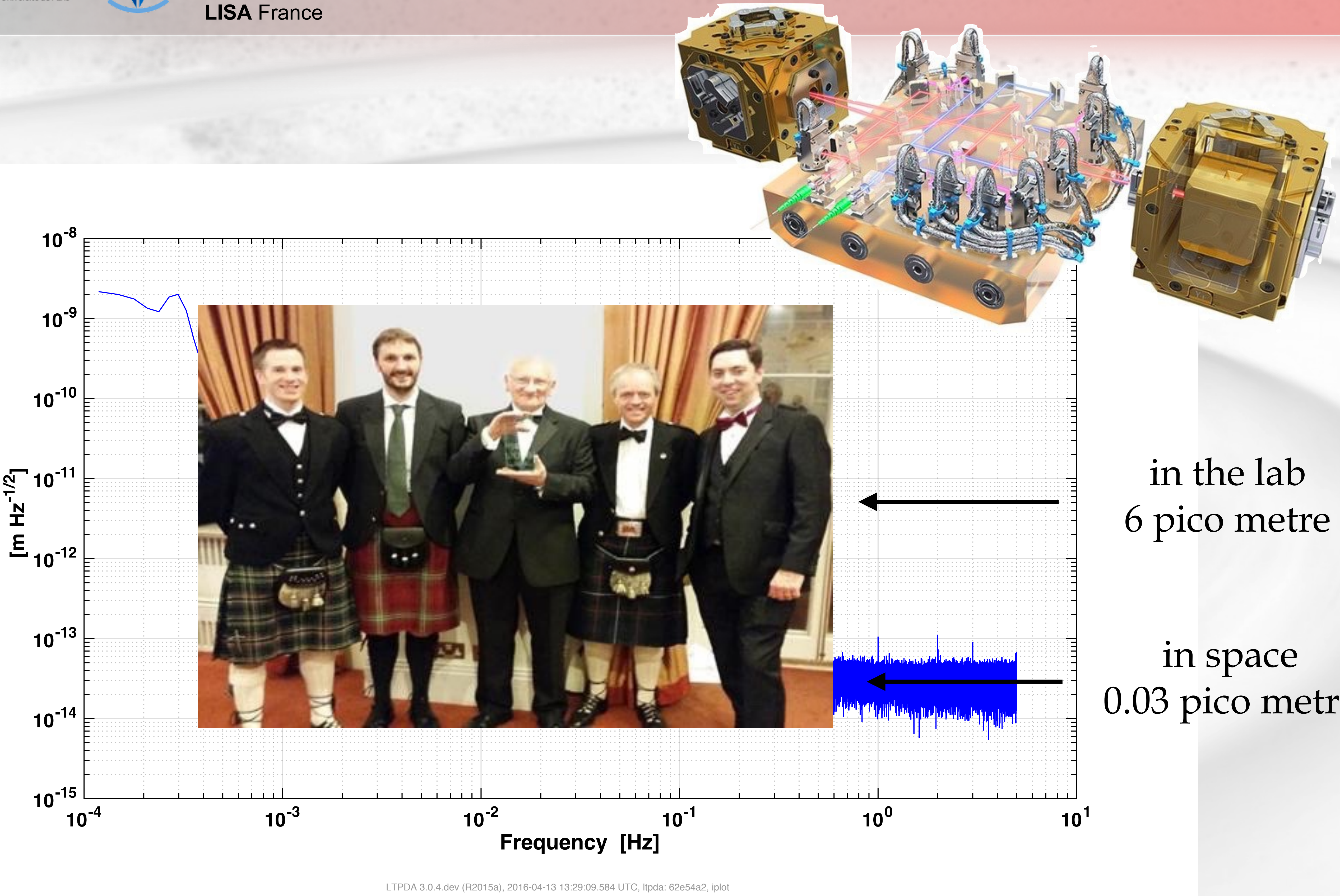
x_{12} is measured
by the optical bench

Obtained by "on board" telemetry
and precisely calibrated.



Decomposition of LPF Residual ΔG

Looking in depth: Optical Sensing Noise



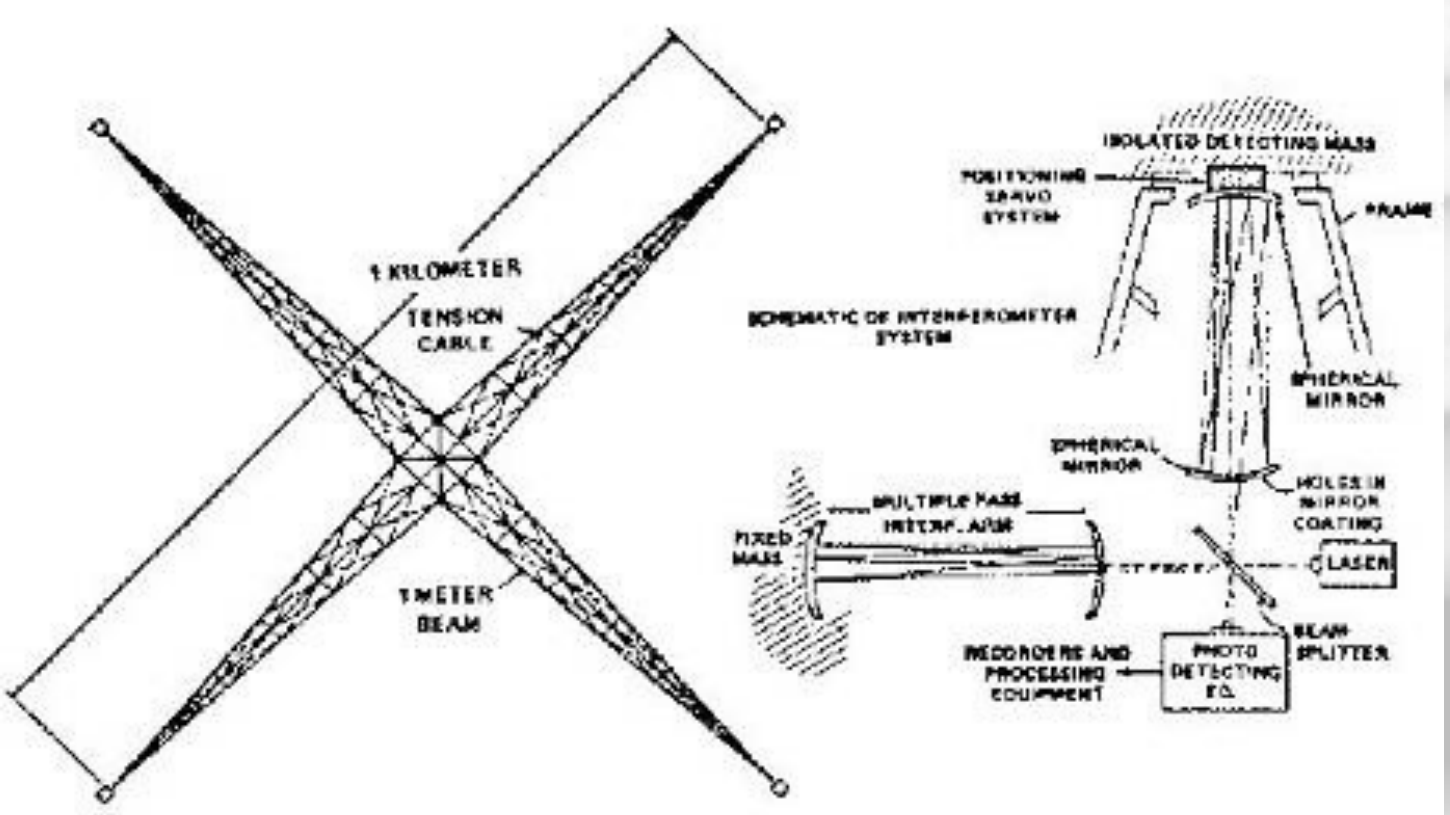
in the lab
6 pico metre

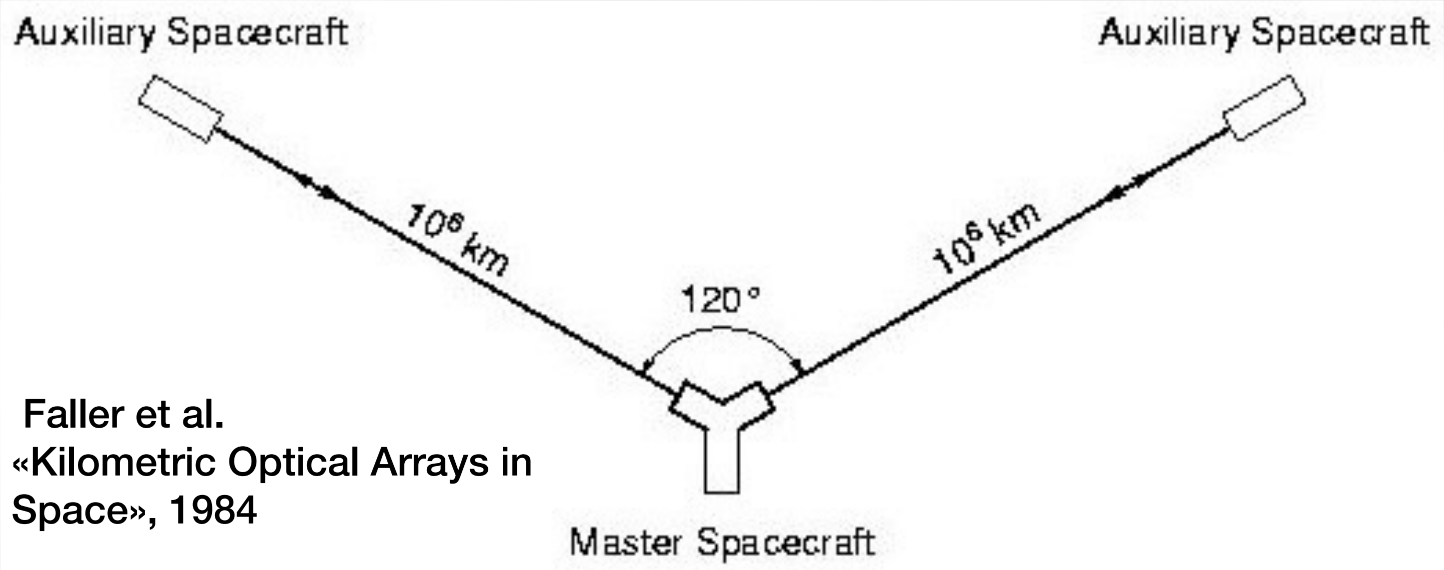
in space
0.03 pico metre

Profil mission LISA

LISA : genèse d'une mission spatiale

LISA France



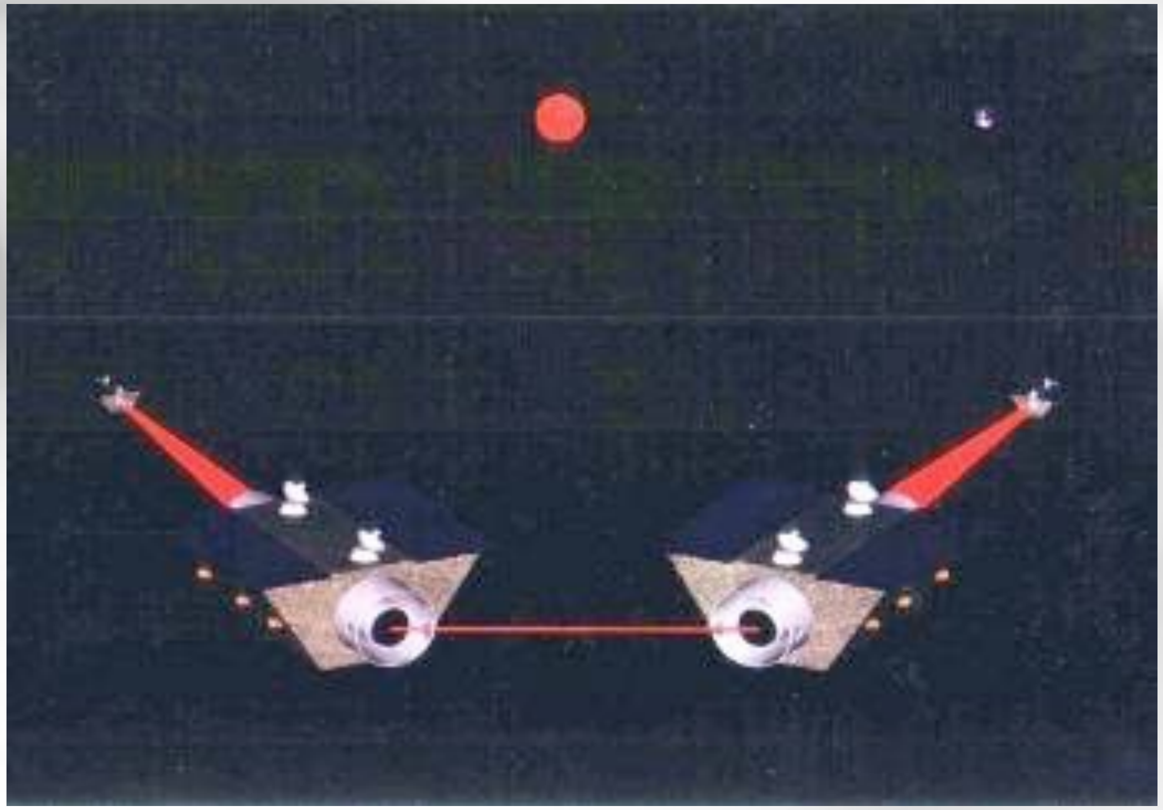


Faller et al.
«Kilometric Optical Arrays in Space», 1984

- Premières études NASA
  - Based on laser experiments from Apollo missions…
  - structure rigide 1x1 km (1978)
  - 3 satellites en vol libre (années 80), bras d'1 Mkm

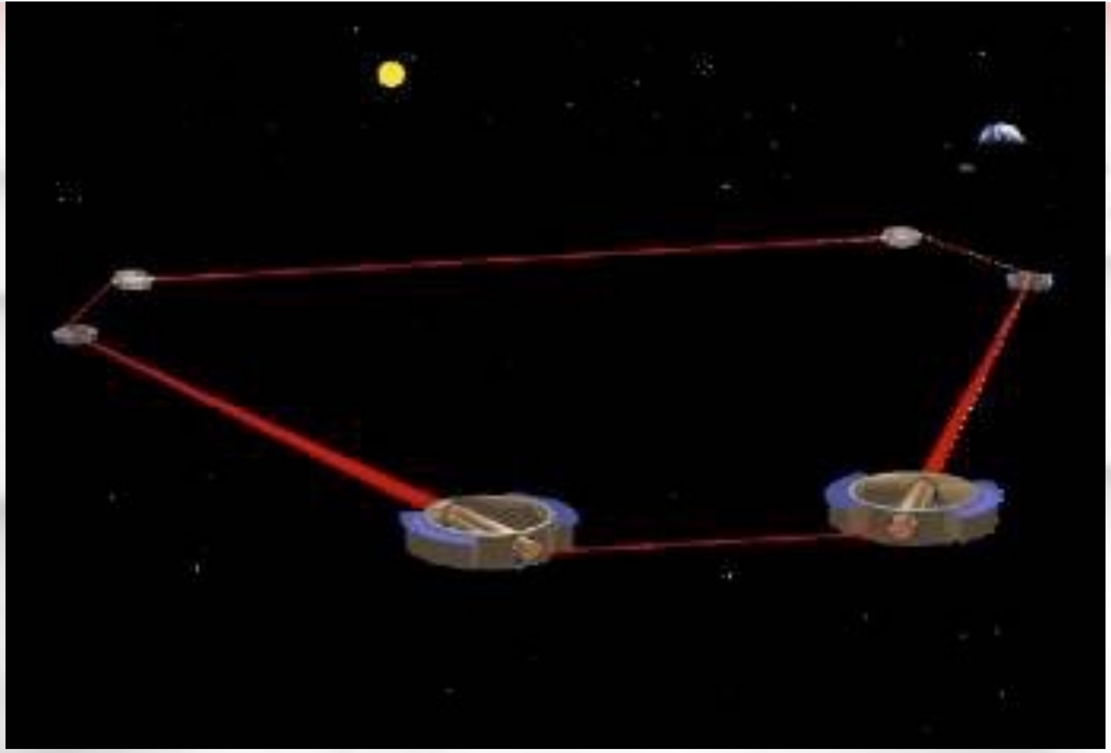
LISA : genèse d'une mission spatiale

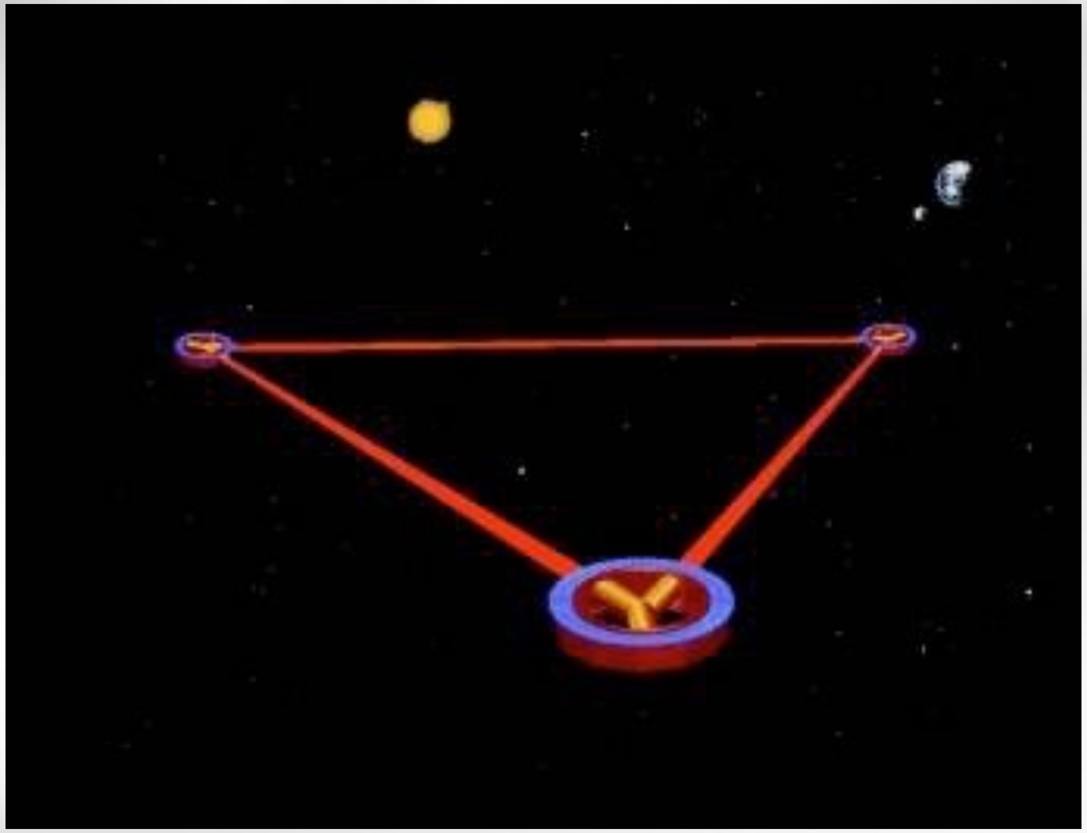
- Proposition conjointe ESA/NASA en 1993 (4 satellites)
  - Apparition du nom LISA
  - Sélection pour étude de faisabilité par l'ESA
- Compromis entre orbite héliocentrique et géocentrique :
  - Gradients de gravité et thermiques importants en orbite géocentrique
  - Longueurs des bras limités en orbite basse



LISA : genèse d'une mission spatiale

- Proposition en 1993/94 :
  - 6 satellites en orbite héliocentrique
  - Sélectionnée comme projet « pierre angulaire » par l'ESA
- 1997 : réduction à 3 satellites :
  - en collaboration avec la NASA
  - configuration finale ...
- Jusqu'en 2011, mission conjointe ESA-NASA :
  - mission L du programme Cosmic Vision à l'ESA
  - en concurrence avec IXO et Laplace
- En 2011, proposition de mission sous responsabilité ESA :
  - conséquence de l'absence de priorité NASA sur les missions conjointes et du manque de financement US au-delà du JWST
  - réduction du coût de la mission (plus de participation NASA)
  - redéfinition du projet ...





LISA : genèse d'une mission spatiale

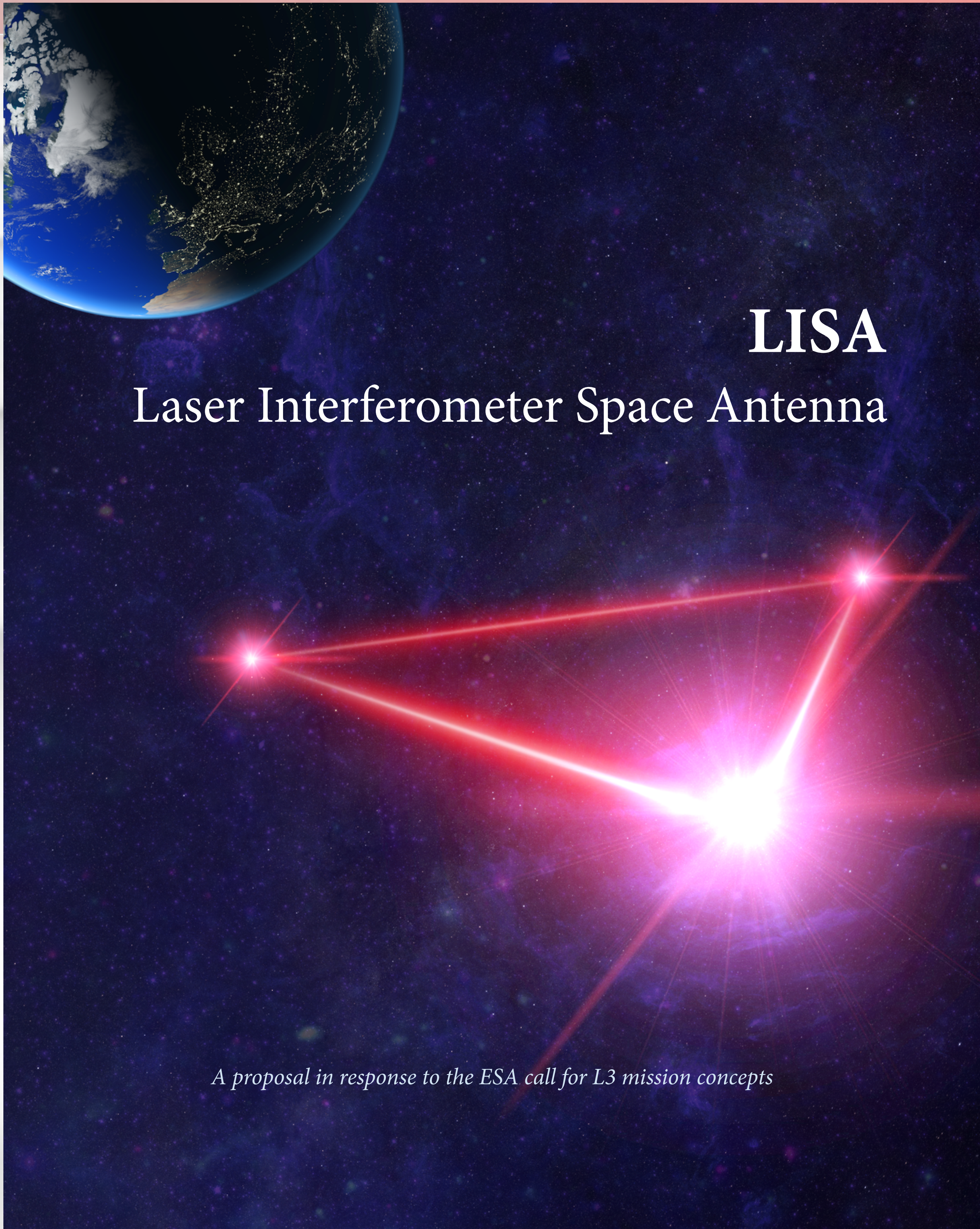
- Processus de sélection des 3 missions ‘Large’ de l’ESA
  - Décembre 2011 : appel à mission pour la mission L1
  - Mai 2012 : sélection de JUICE (JUpiter ICy Moons Explorer), départ en 2022, arrivée en 2030.
  - Mai 2013 : appel à ‘thèmes scientifiques’ pour les missions L2 et L3
    - ≈40 propositions reçues à l’ESA
  - Sélection en Novembre 2013 :
    - L2 (départ 2028) : ‘L’Univers Chaud’ (astronomie X) ⇒mission Athena+
    - L3 (départ 2034) : ‘L’Univers Gravitationel’

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

LISA : genèse d'une mission spatiale

- October 2016 : call for proposal for the L3 mission slot
  - LISA submitted in january 2017
- LISA selected as L3 mission in spring 2017
  - Launch expected in 2034/2035
- Proposal :
  - https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf



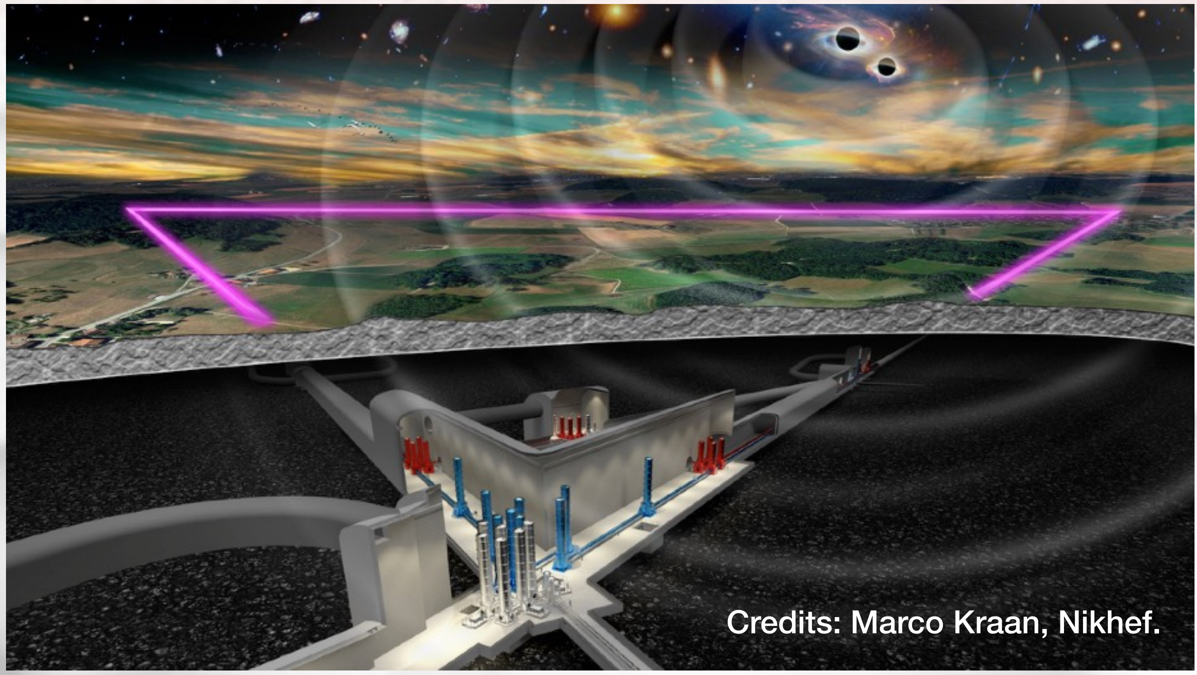
LISA

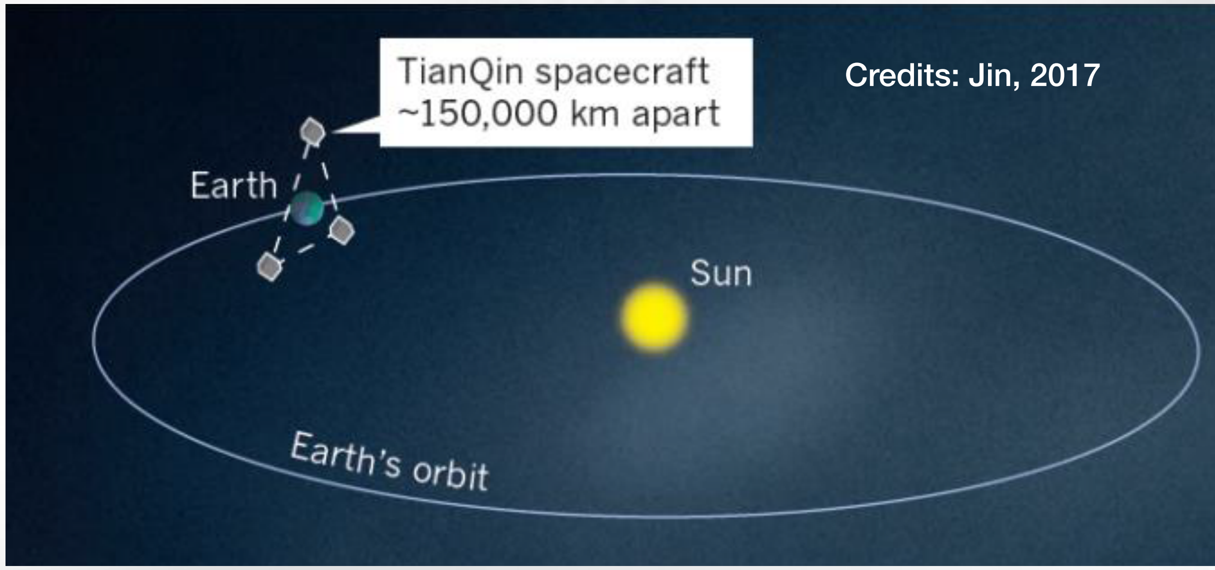
Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Science context in 2035

- LISA will be complementary of other operational instruments in 2035 - 2045
    - 3rd generation of interferometric GW ground-based detectors (Einstein Telescope, Cosmic Explorer) and Pulsar Timing Array
        - Broad simultaneous coverage of the GW spectrum from nHz to kHz
        - LISA as early (years in advance…) detection system for some binary sources coalescing in the ET/CE band
        - Detection or constraints on the GW backgrounds from the early Universe (at 10^{10} GeV)
    - Multimessenger astronomy
        - With ATHENA for observing the X-ray emission emitted by discs around coalescing massive black holes.
        - With wide field telescopes (e.g. LSST, SKA) for identifying e/m counterparts and host galaxies
        - With large telescopes on ground (ELT, TMT, GMT) and in space (JWST) for the measurement of redshifts at cosmological distances
    - Particle physics
        - LISA may be complementary to future colliders to identify physical processes at the TeV scale: constraints on cosmic strings, inflation, …
- No equivalent mission with the same objectives in the same time frame
    - Active development of the TianQin mission by the Chinese Academy of Science
        - Rapidly progressing but still a lot of technologies to master
        - Launch of TianQin in the same timeframe as LISA difficult to assess

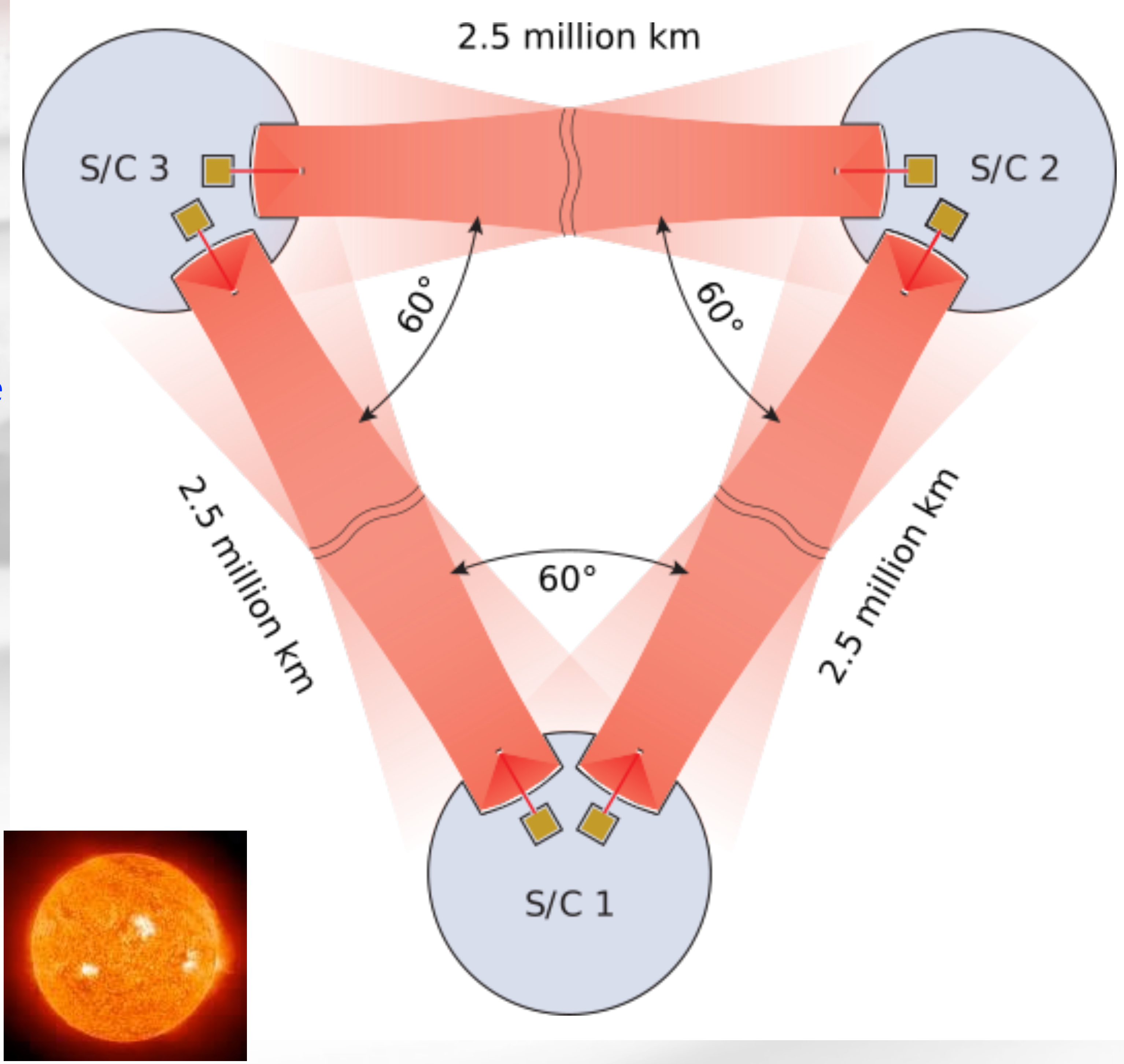

Credits: Marco Kraan, Nikhef.

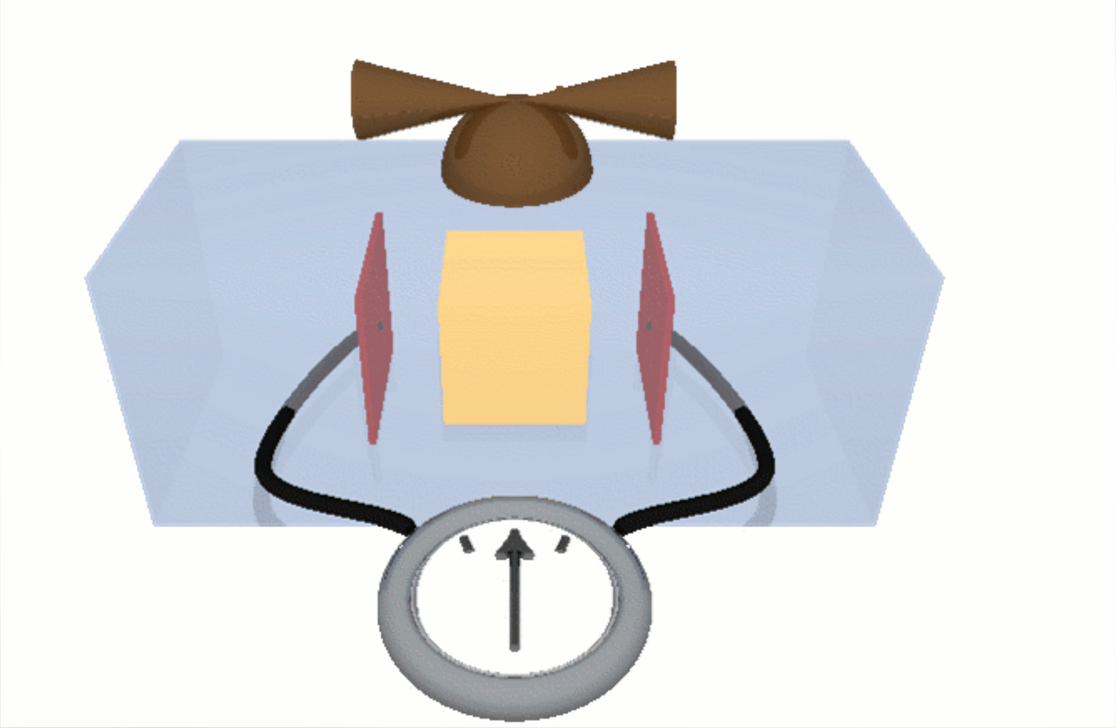


Credits: Jin, 2017

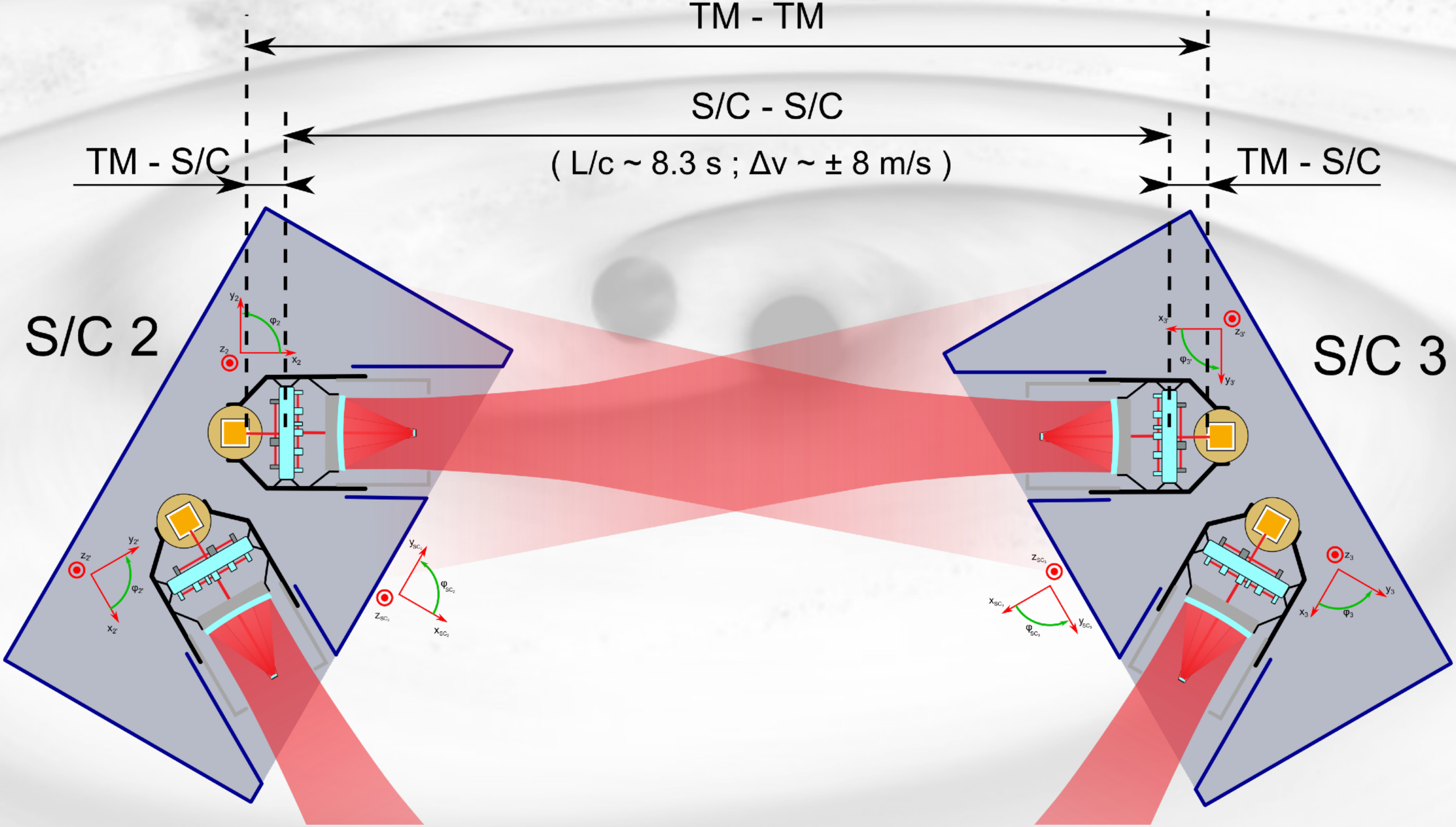
LISA Interferometer

- Equilateral configuration
  - 3 arms / 6 links ; 2,5 Mkm
- Inertial test masses
  - Direct heritage from LISA Pathfinder
  - 2 TM / satellites
  - 2 steerable optical benches / satellite
- Typical metrology requirement : **~10 pm/√Hz @ 1 mHz**





Measurement principle



TM - TM

S/C - S/C

(L/c ~ 8.3 s ; Δv ~ ± 8 m/s)

TM - S/C

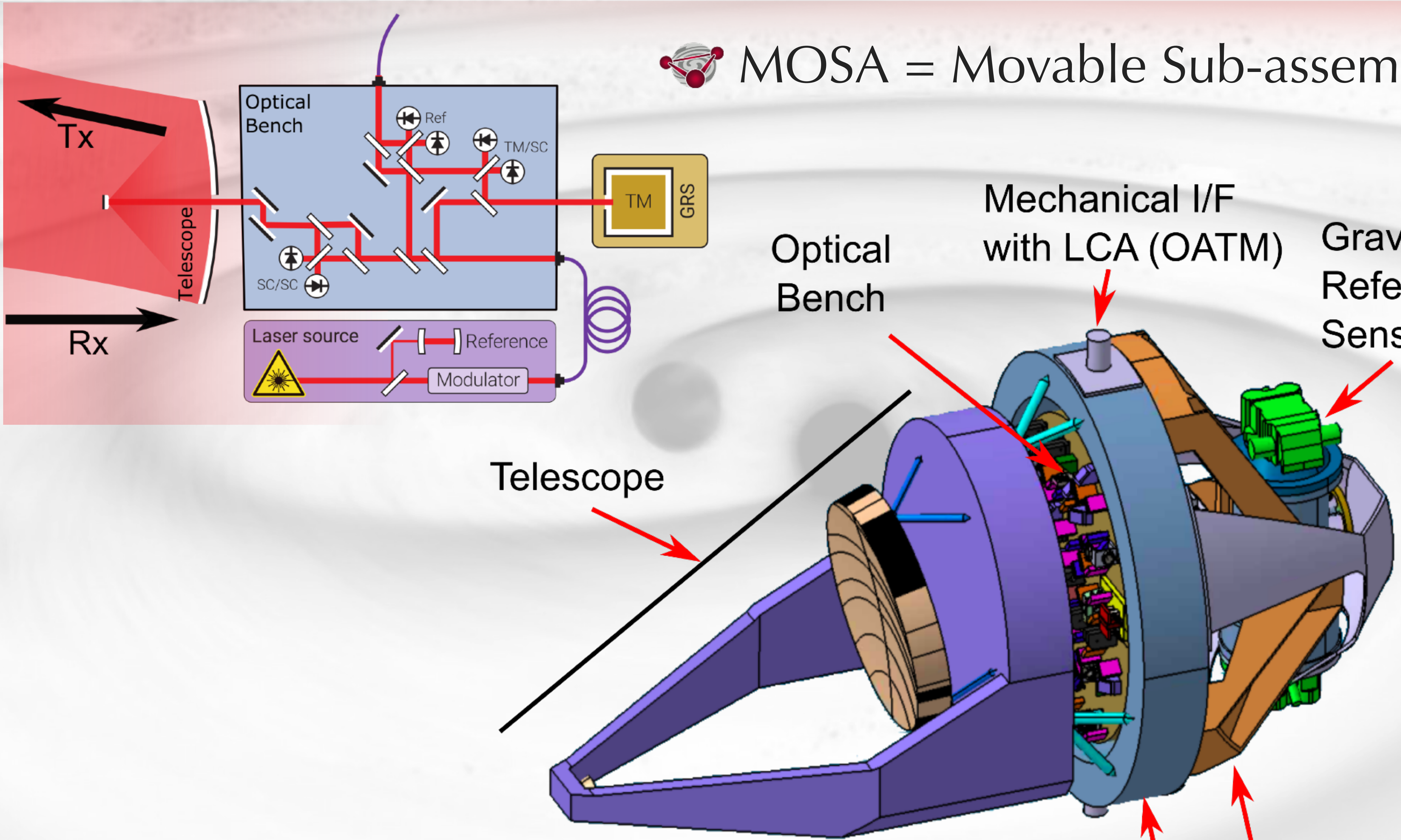
TM - S/C

S/C 2

S/C 3

Scheme of a instrument

- MOSA = Movable Sub-assembly



Optical Bench

Mechanical I/F with LCA (OATM)

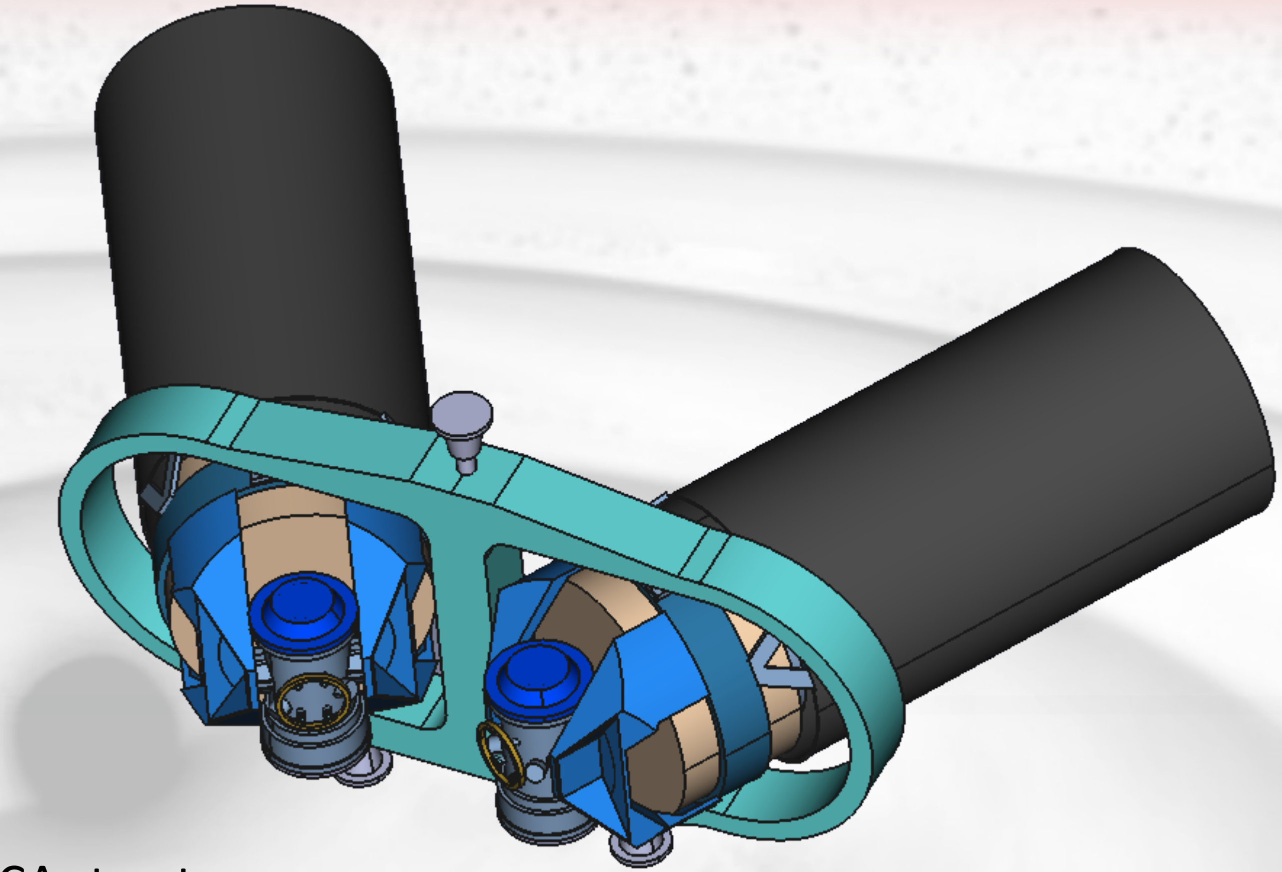
Gravitational Reference Sensor

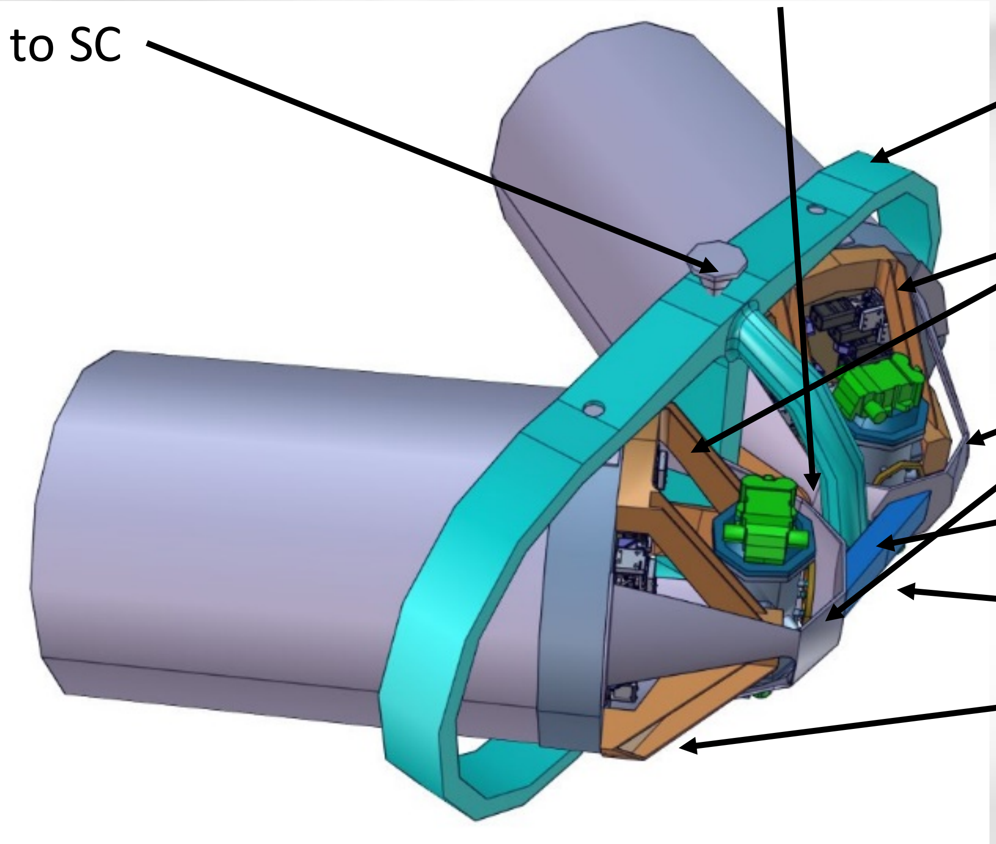
Telescope

MOSA support structure

Two MOSAs form an LCA …

- LCA = LISA Core Assembly





OATM

Interface to SC

LCA structure

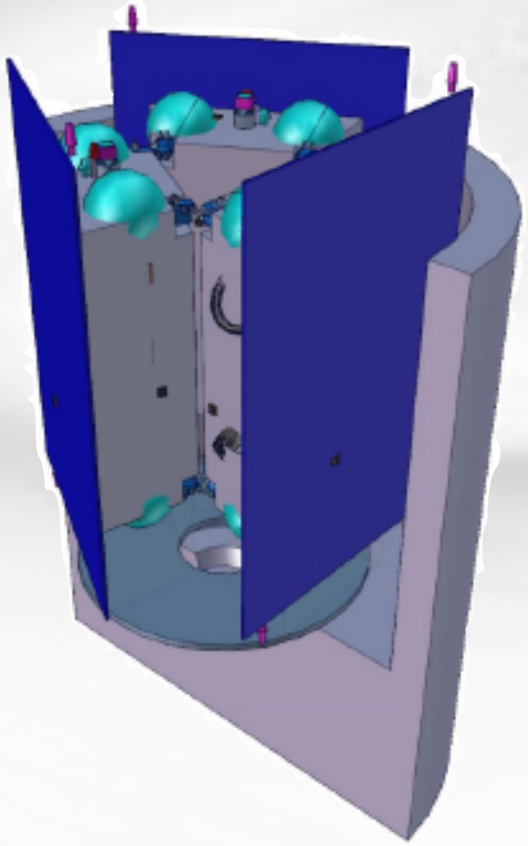
GRS supporting structure

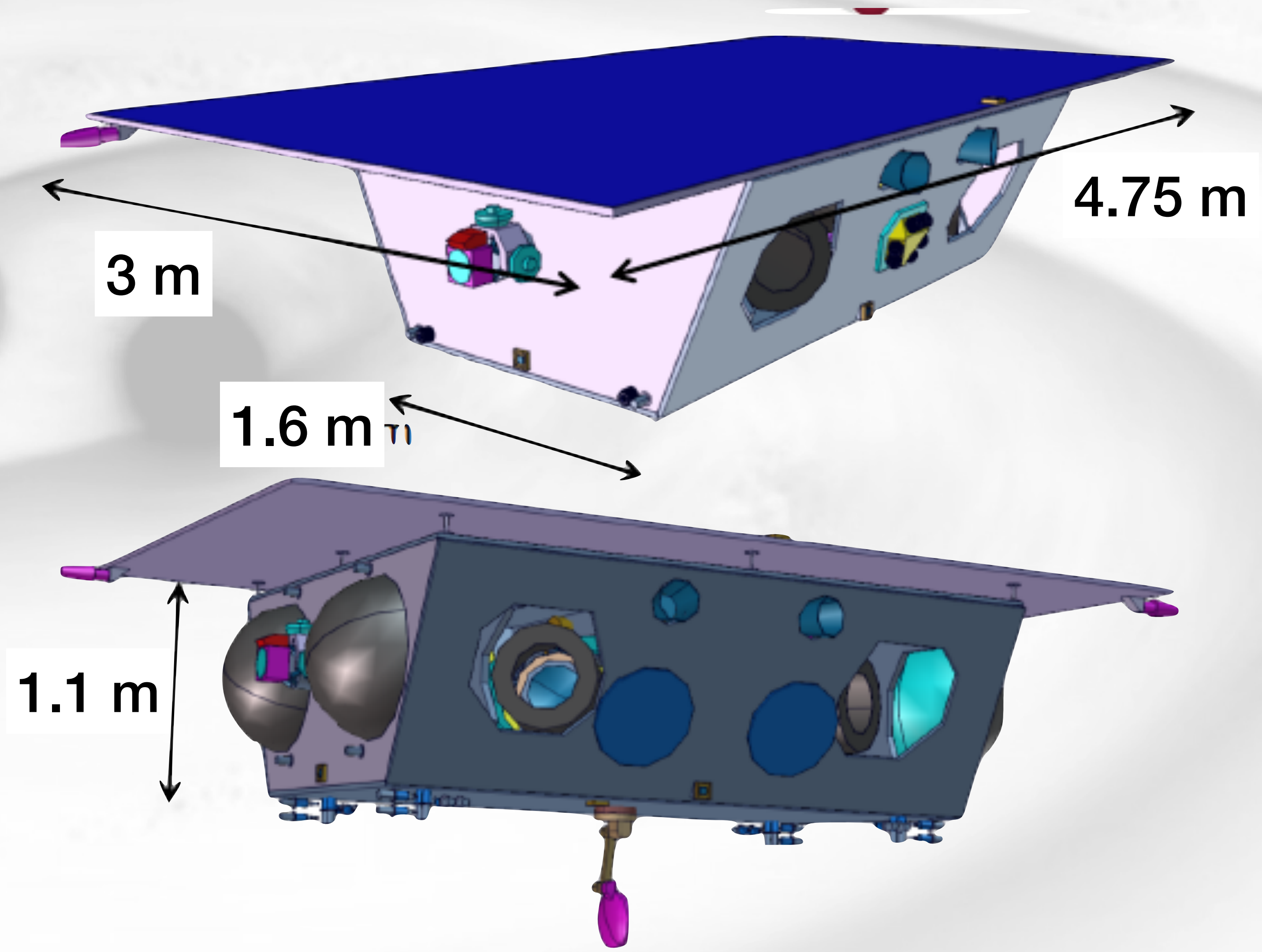
OATM and Launch Lock structure

Launch Lock

Interface to SC

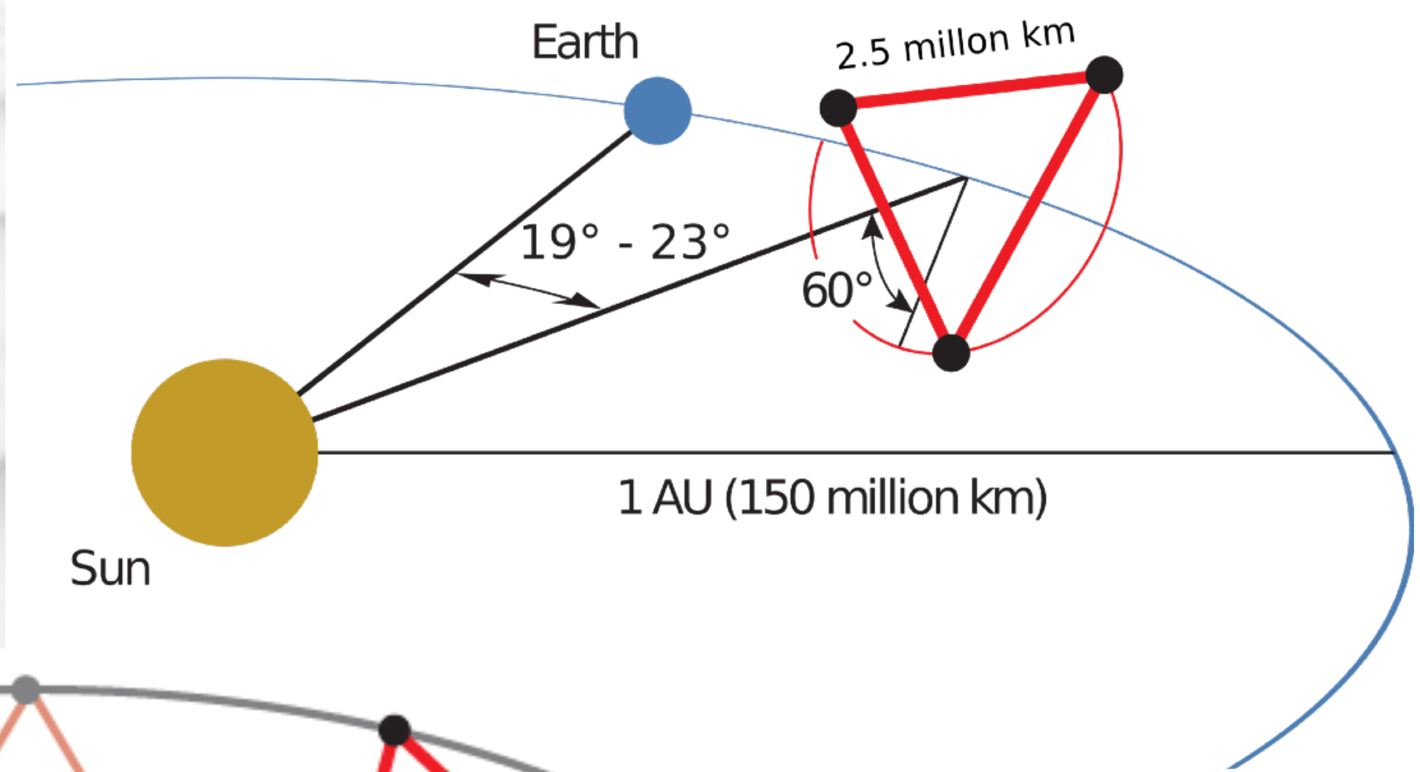
Three S/C fit into an Ariane 6.4

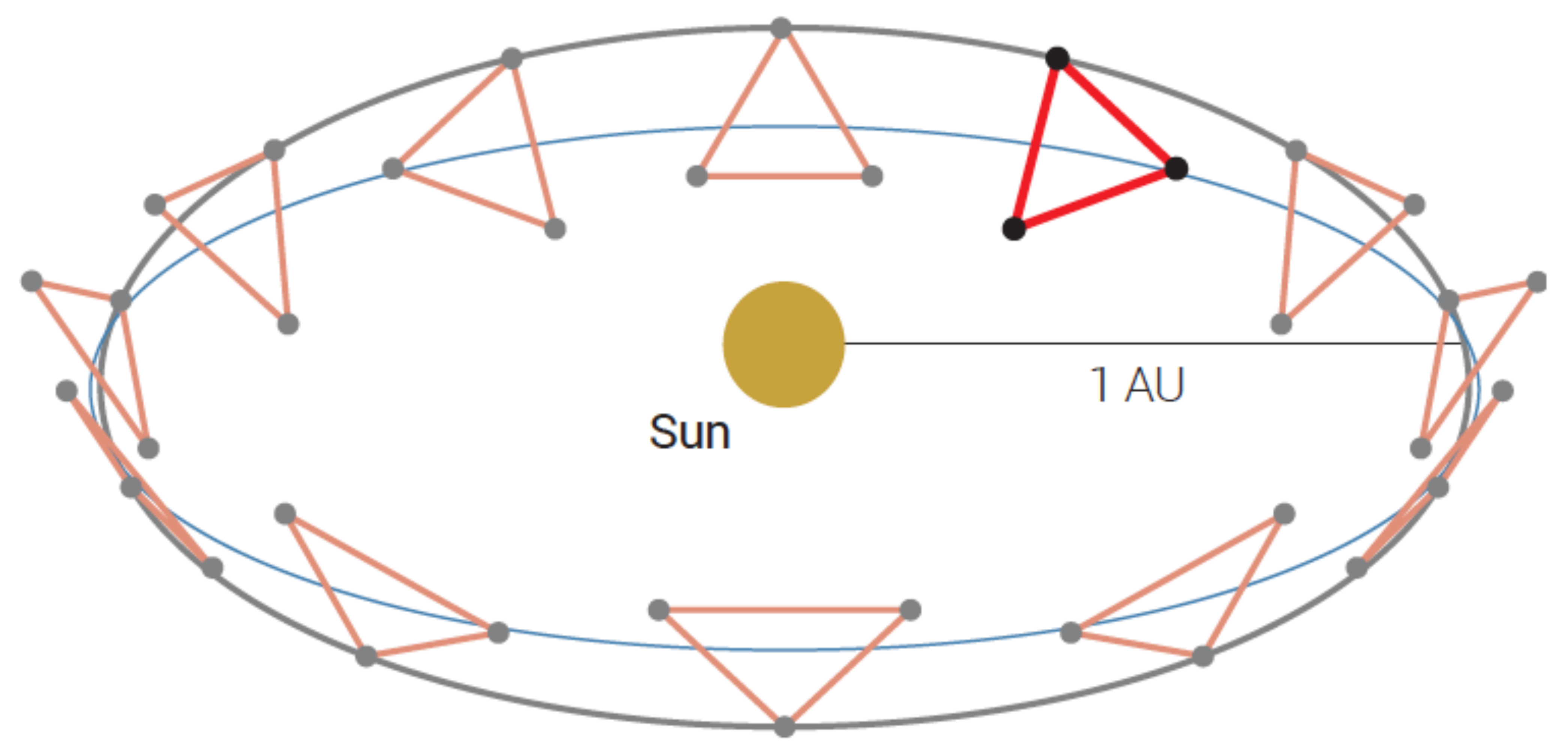




Configuration orbitale

- Orbites terrestres
  - 19° à 23° derrière la Terre
  - Durée de mission :
    - 6 ans nominal (>4 ans effectif)
    - consommables pour 10 ans

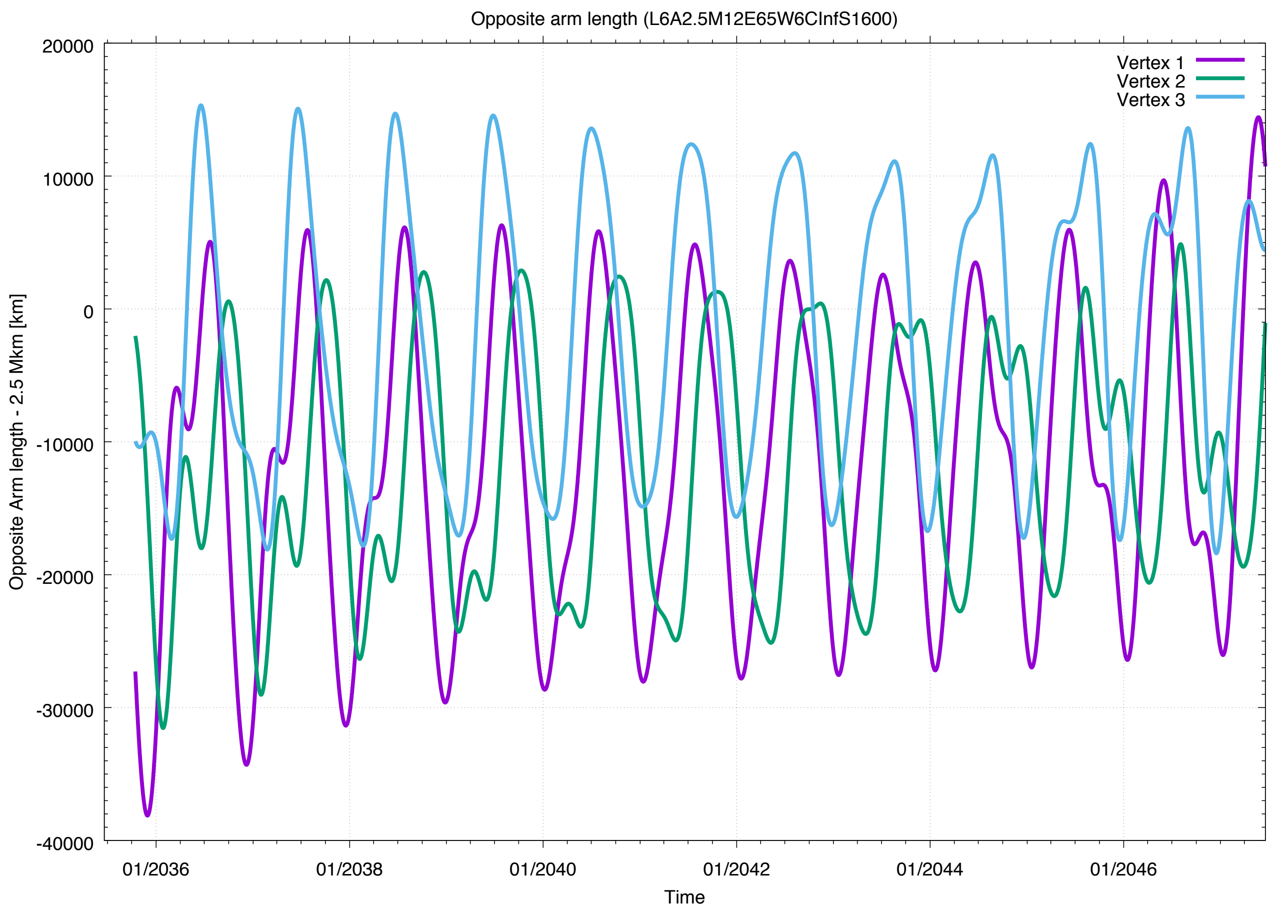


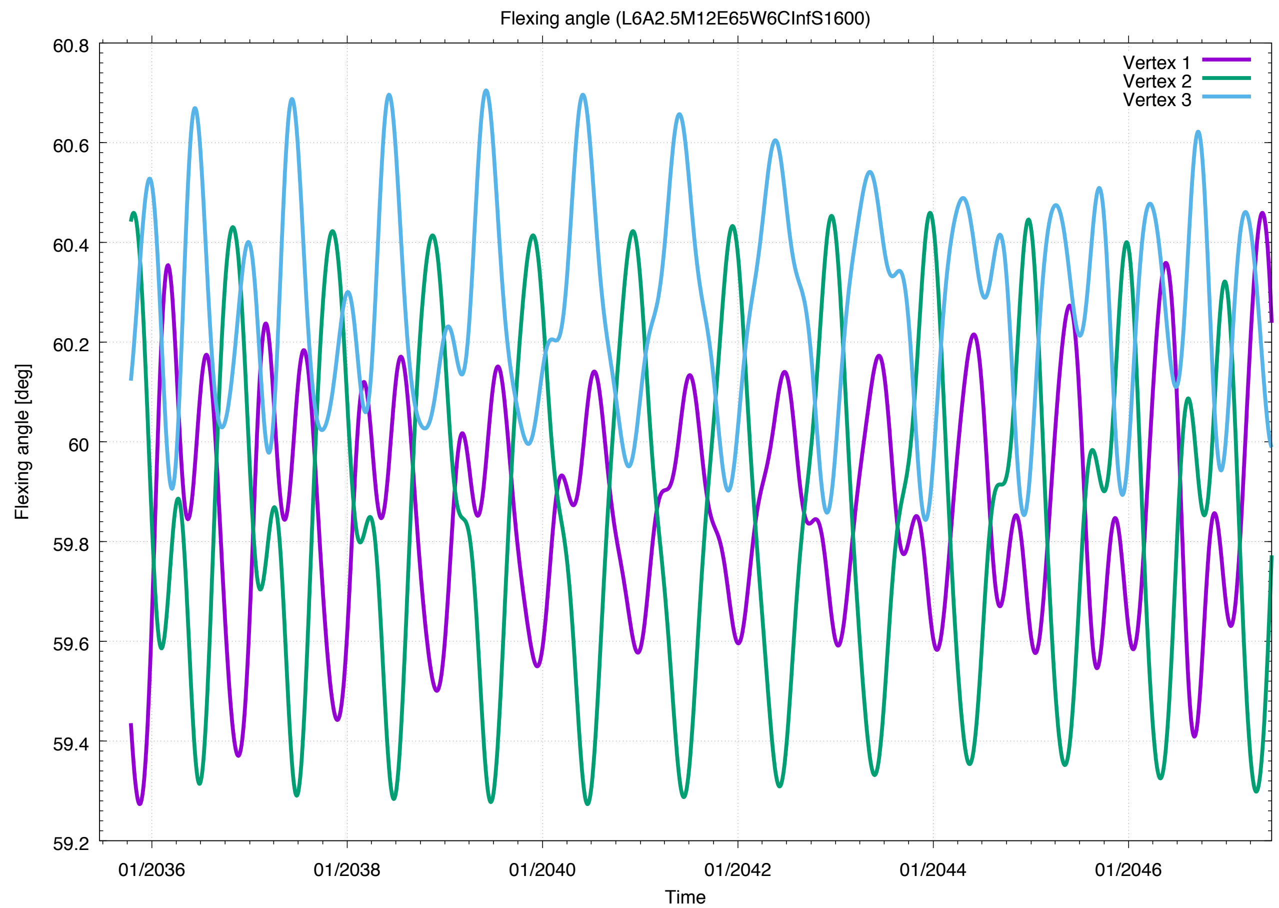


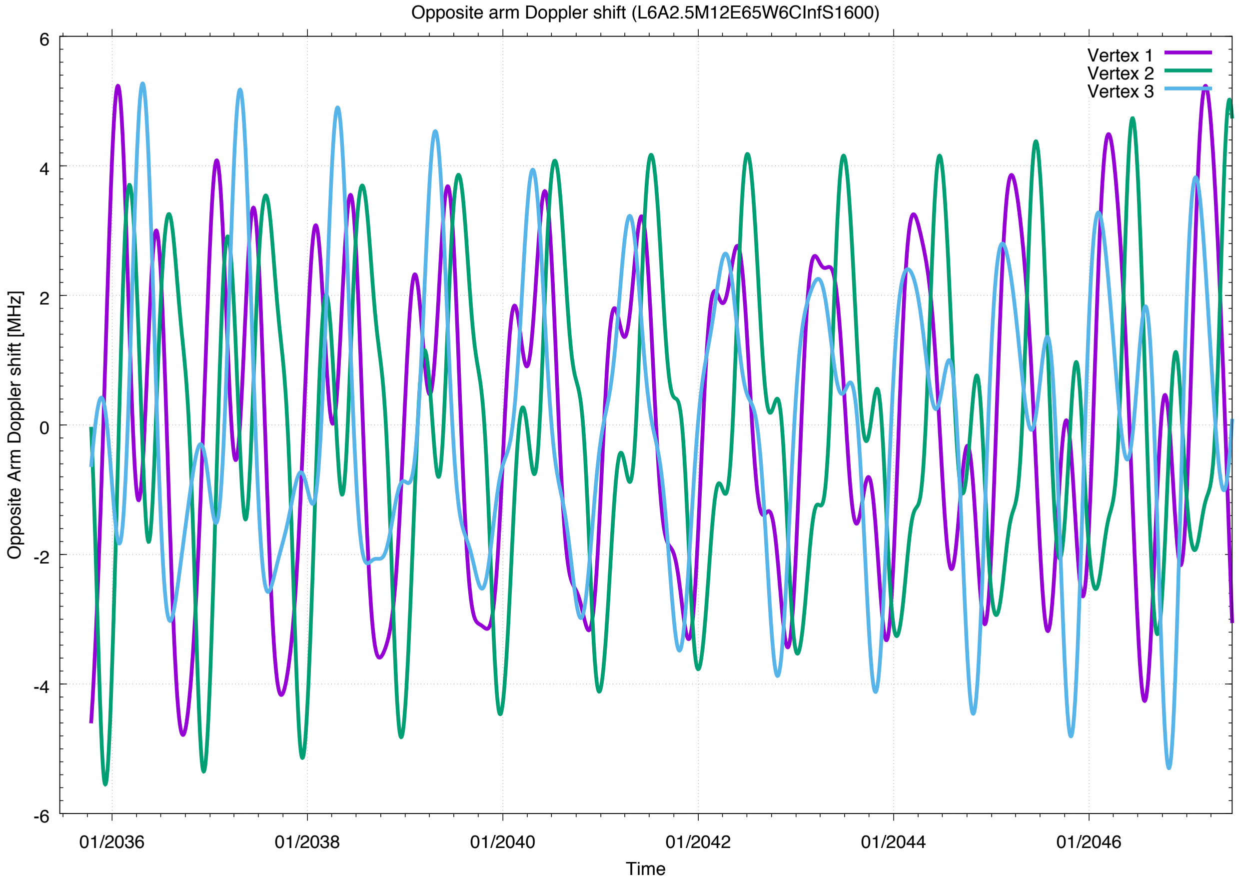
Orbites et mise à poste

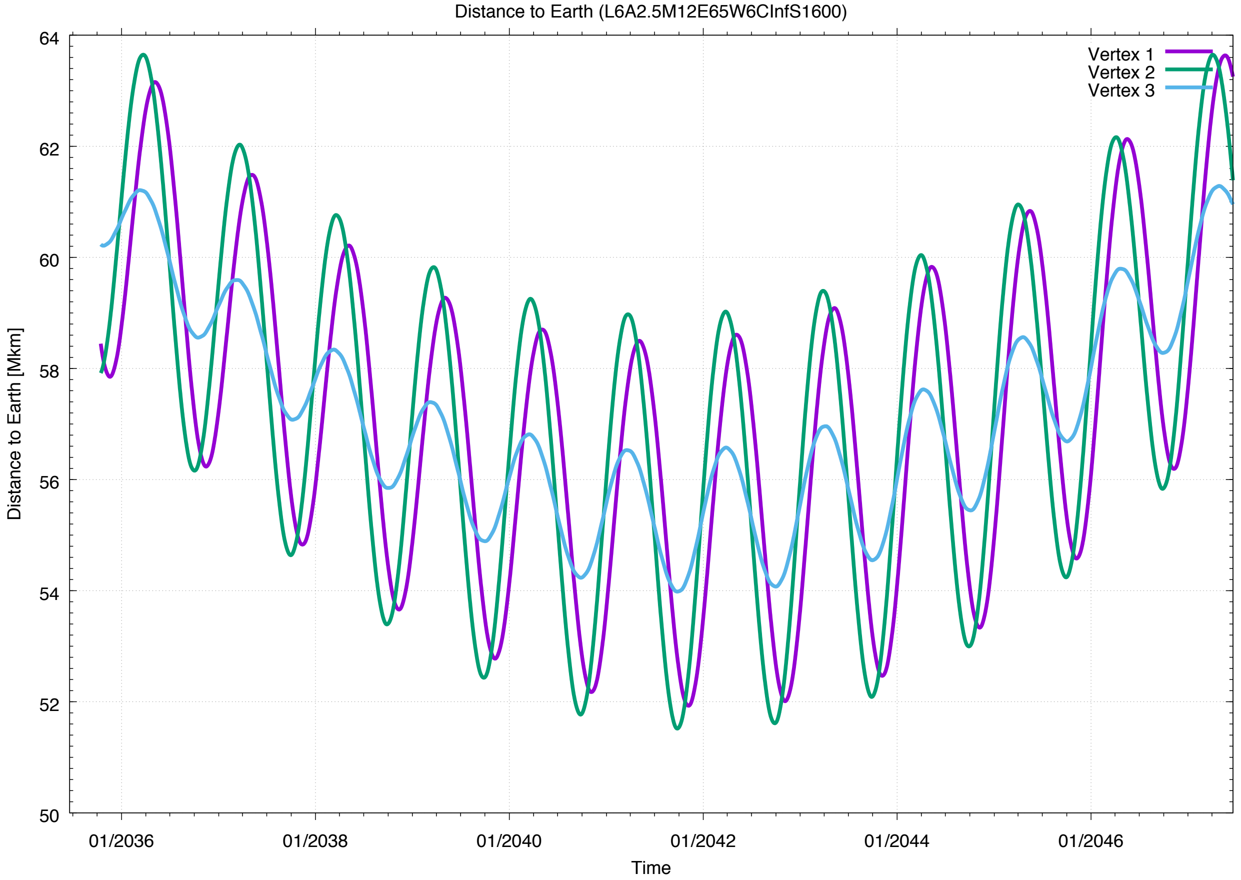
- On veut, pour une durée de 10 ans :
  - Minimiser la déformation du triangle due aux perturbations gravitationnelles de la Terre (flexing / Doppler)
  - Maintenir un débit de communication suffisant avec la Terre (donc pas trop loin…)
  - Avoir une masse au décollage compatible avec un lancement Ariane 6.4 (donc pas trop de carburant pour aller à poste)
- Résultats :
  - Lancement avec échappement direct
    - Les satellites ne sont plus liés à l'attraction terrestre après le lancement
  - Propulsion électrique
    - Impulsion spécifique importante, consommation faible (mais poussée limitée, ~80 mN)
  - Transfert en 540 jours max
    - Plus long qu'en propulsion chimique mais moins de masse de carburant
    - 4 poussées par satellite
  - Trajectoire 'balistique' : LISA se rapproche de la Terre puis s'éloigne
  - Flexing : ±0.7 deg
  - Doppler : ±6 MHz

Orbites et mise à poste









Paramètres dimensionnant

- Number of arms / laser links:
  - 2 or 3 arms (i.e. 4 or 6 laser links)
  - 3 arms Pros :
    - Allow forming 2 (noise) independent interferometers.
      - more robust to the noise rejection and increased sensitivity
    - Allow to better determine the GW polarization
      - hence the aspect angle and distance of the source)
    - More robust to the loss of a laser link
  - 3 arms Cons :
    - Increasing the number of laser links implies additional ‘instruments’ (telescope + optical bench + GRS + phasemeter +…)
      - hence a mass, volume and (some) cost increase.
- Armlength:
  - 1 to 5 Mkm
  - The armlength changes the antenna frequency response
    - an interferometer with arms of equal length L is sensitive up to a wave cut-off frequency of c/(2L) (=150 mHz for L=1 Mkm)
    - The low frequency cut-off is due to the residual acceleration noise, independent of L
  - Increasing the armlength has also major impacts on the instrument design and noise performance:
    - Larger shot noise (due to free space losses) for a given emitted laser power
    - Larger relative S/C velocities, hence deeper Doppler modulation, which will require more complex frequency planning (laser frequencies jumps) to fit within the phase measurement system bandwidth
    - Larger point ahead angle (PAA): a point ahead angle mechanism (PAAM) is required if the PAA is greater than the instantaneous FOV.

Paramètres dimensionnant

- Telescope diameter:
  - 20 to 40 cm
  - The telescope diameter defines the divergence of the beam as well as the collection area. It has a major impact on shot noise.
  - For the same reason, it defines the instantaneous field-of-view of the instrument and is therefore linked to the need of a PAAM.
  - Increasing the size of the telescopes also increases the mass and volume of the instrument and is more difficult to manufacture at the required surface accuracy.
- Mission duration:
  - 2 to 10 years
  - In the present context, the mission duration is the time over which the stability of the constellation is optimized (flexing, armlength, distance to Earth, total wet mass, etc).
  - Increasing the mission duration requires a slow drift away velocity
    - therefore, a larger gravitational influence of the Earth and a degraded stability (higher Doppler shifts, flexing, etc)
  - The mission duration has also an impact on the required tank capacity for station keeping (hence on the S/C mass).
    - Gold gas propellant required for counter acting the solar wind pressure

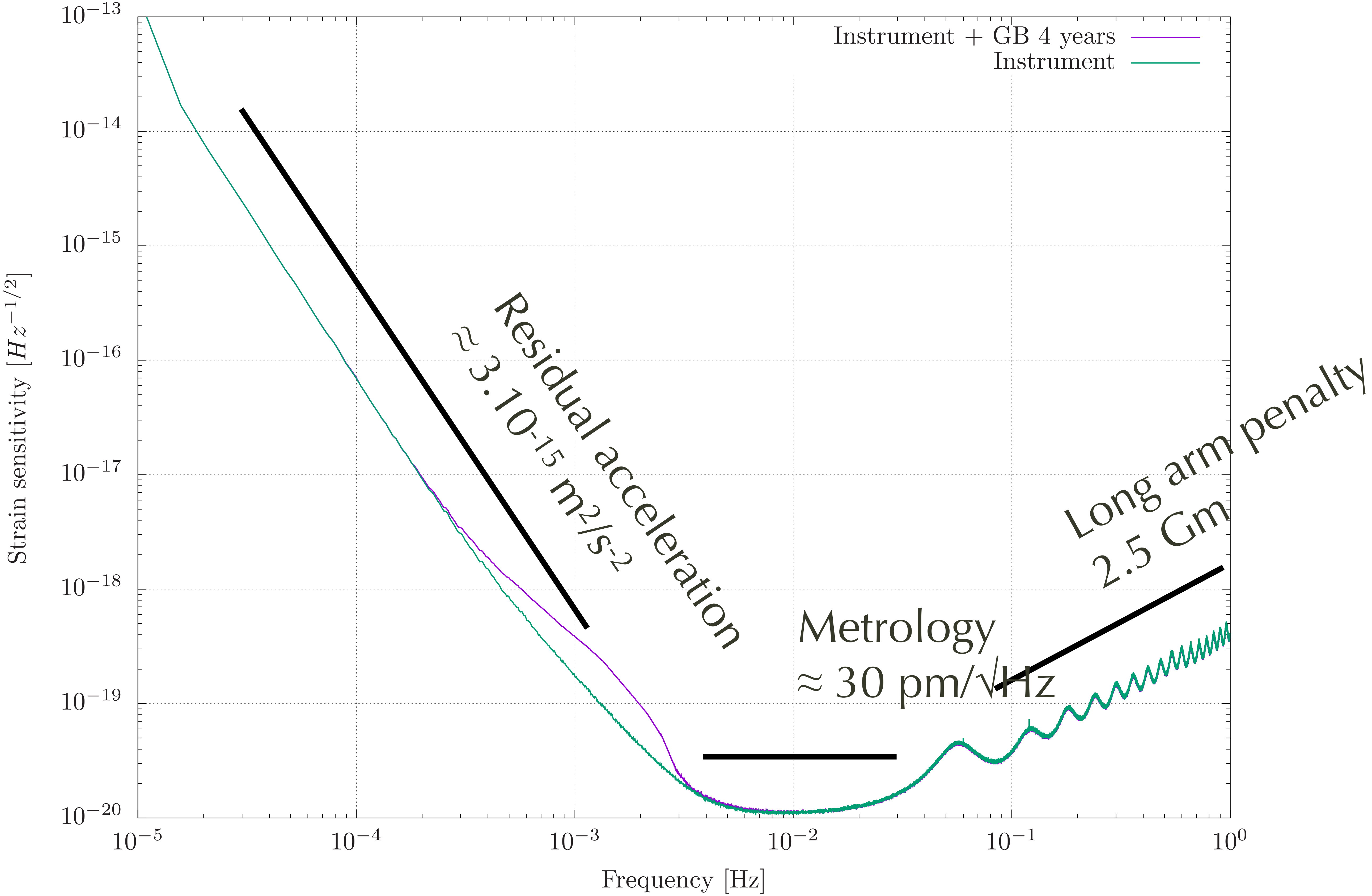
Modèles phénoménologiques

Mission Duration [Years]	Parameter	Linear trend
2	Armlength breathing (km, peak-to-peak)	5 000 $\times L_{arm}$[Mkm] km
	Maximum Doppler shift (MHz)	$1\times L_{arm}$[Mkm] MHz
	Flexing angle (deg, peak-to-peak)	$0.18\times L_{arm}$[Mkm] deg
5	Armlength breathing (km, peak-to-peak)	7 000 $\times L_{arm}$[Mkm] km
	Maximum Doppler shift (MHz)	$2\times L_{arm}$[Mkm] MHz
	Flexing angle (deg, peak-to-peak)	$0.33\times L_{arm}$[Mkm]deg
10	Armlength breathing (km, peak-to-peak)	10 000 $\times L_{arm}$[Mkm] km
	Maximum Doppler shift (MHz)	$4\times L_{arm}$[Mkm]
	Flexing angle (deg, peak-to-peak)	$0.65\times L_{arm}$[Mkm] deg

Trade-offs

	L6A1M2D20	L6A1M2D30	L6A1M2D40	L6A1M5D20	L6A1M5D30	L6A1M5D40	L6A1M10D20	L6A1M10D30	L6A1M10D40	L6A2,5M2D20	L6A2,5M2D30	L6A2,5M2D40	L6A2,5M5D20	L6A2,5M5D30	L6A2,5M5D40	L6A2,5M10D20	L6A2,5M10D30	L6A2,5M10D40	L6A3M2D20	L6A3M2D30	L6A3M2D40	L6A3M5D20	L6A3M5D30	L6A3M5D40	L6A3M10D20	L6A3M10D30	L6A3M10D40	L6A5M2D20	L6A5M2D30	L6A5M2D40	L6A5M5D20	L6A5M5D30	L6A5M5D40	L6A5M10D20	L6A5M10D30	L6A5M10D40
Max distance to Earth [Mkm]	65																																			
Number of laser links (4/6)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Target armlength [Mkm]	1	1	1	1	1	1	1	1	1	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	3	3	3	3	3	3	3	3	3	5	5	5	5	5	5	5	5	5
Mission Duration [Years]	2	2	2	5	5	5	10	10	10	2	2	2	5	5	5	10	10	10	2	2	2	5	5	5	10	10	10	2	2	2	5	5	5	10	10	10
Telescope diameter [cm]	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40
Minimum laser power (W) - Constant metrology	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	10,27	2,03	0,64	10,27	2,03	0,64	10,27	2,03	0,64	14,80	2,92	0,92	14,80	2,92	0,92	14,80	2,92	0,92	41,10	8,12	2,57	41,10	8,12	2,57	41,10	8,12	2,57
Minimum laser power (W) - Constant strain	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10	1,64	0,32	0,10
Maximum Doppler shift (MHz)	1,0	1,0	1,0	2,0	2,0	2,0	4,0	4,0	4,0	2,5	2,5	2,5	5,0	5,0	5,0	10,0	10,0	10,0	3,0	3,0	3,0	6,0	6,0	6,0	12,0	12,0	12,0	5,0	5,0	5,0	10,0	10,0	10,0	20,0	20,0	20,0
PAA Laser power (W) - Constant Metrology	1,7	0,3	0,1	1,7	0,3	0,1	1,7	0,3	0,1	12,1	2,9	1,2	12,1	2,9	1,2	12,1	2,9	1,2	18,6	4,9	2,3	18,6	4,9	2,3	18,6	4,9	2,3	78,0	34,3	33,3	78,0	34,3	33,3	78,0	34,3	33,3
PAA Laser power (W) - Constant strain	1,7	0,3	0,1	1,7	0,3	0,1	1,7	0,3	0,1	1,9	0,5	0,2	1,9	0,5	0,2	1,9	0,5	0,2	2,1	0,5	0,3	2,1	0,5	0,3	2,1	0,5	0,3	3,1	1,4	1,3	3,1	1,4	1,3	3,1	1,4	1,3

LISA Global Performance

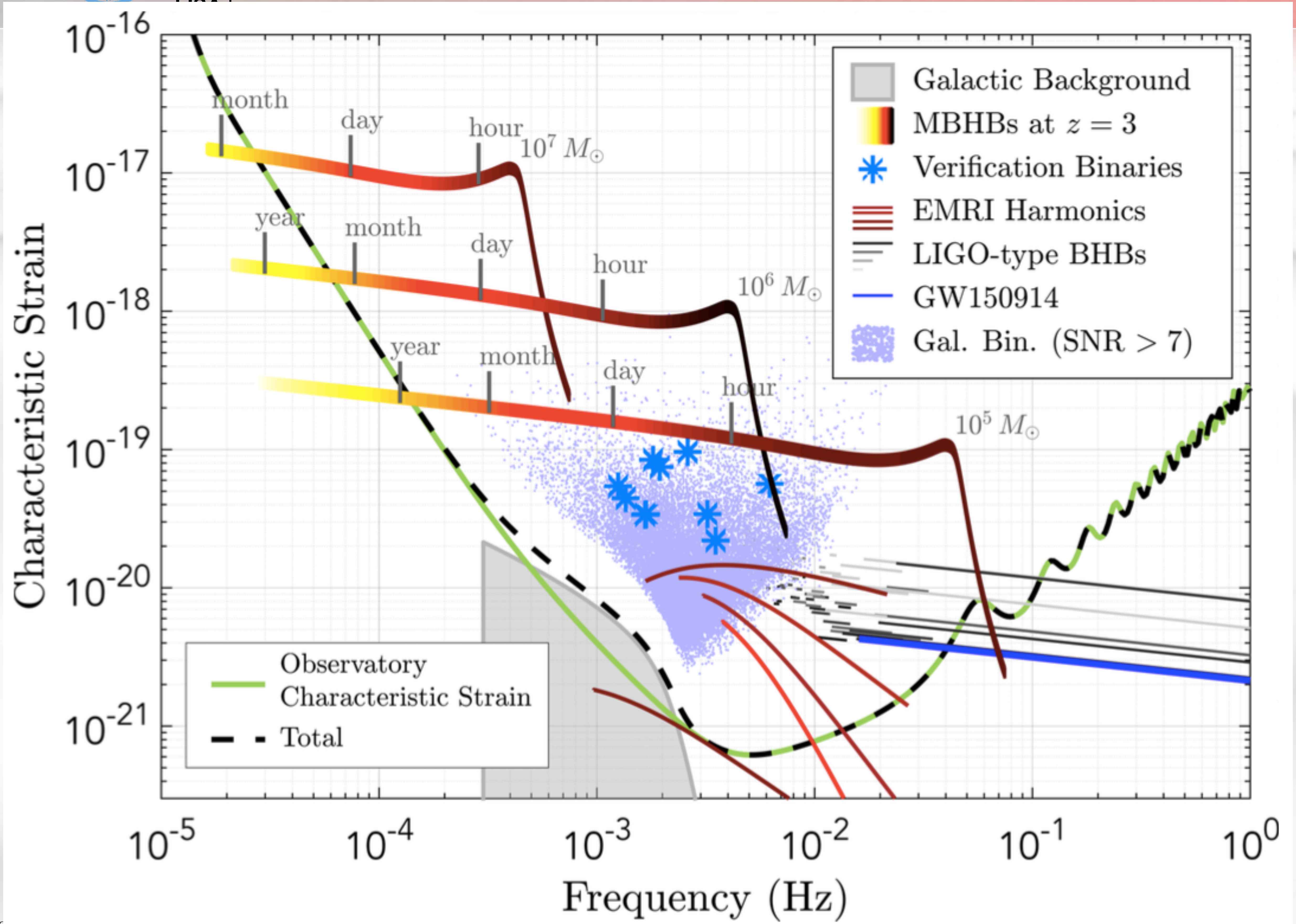


Residual acceleration $\approx 3.10^{-15}$ m^2/s^{-2}

Metrology ≈ 30 pm/√Hz

Long arm penalty 2.5 Gm

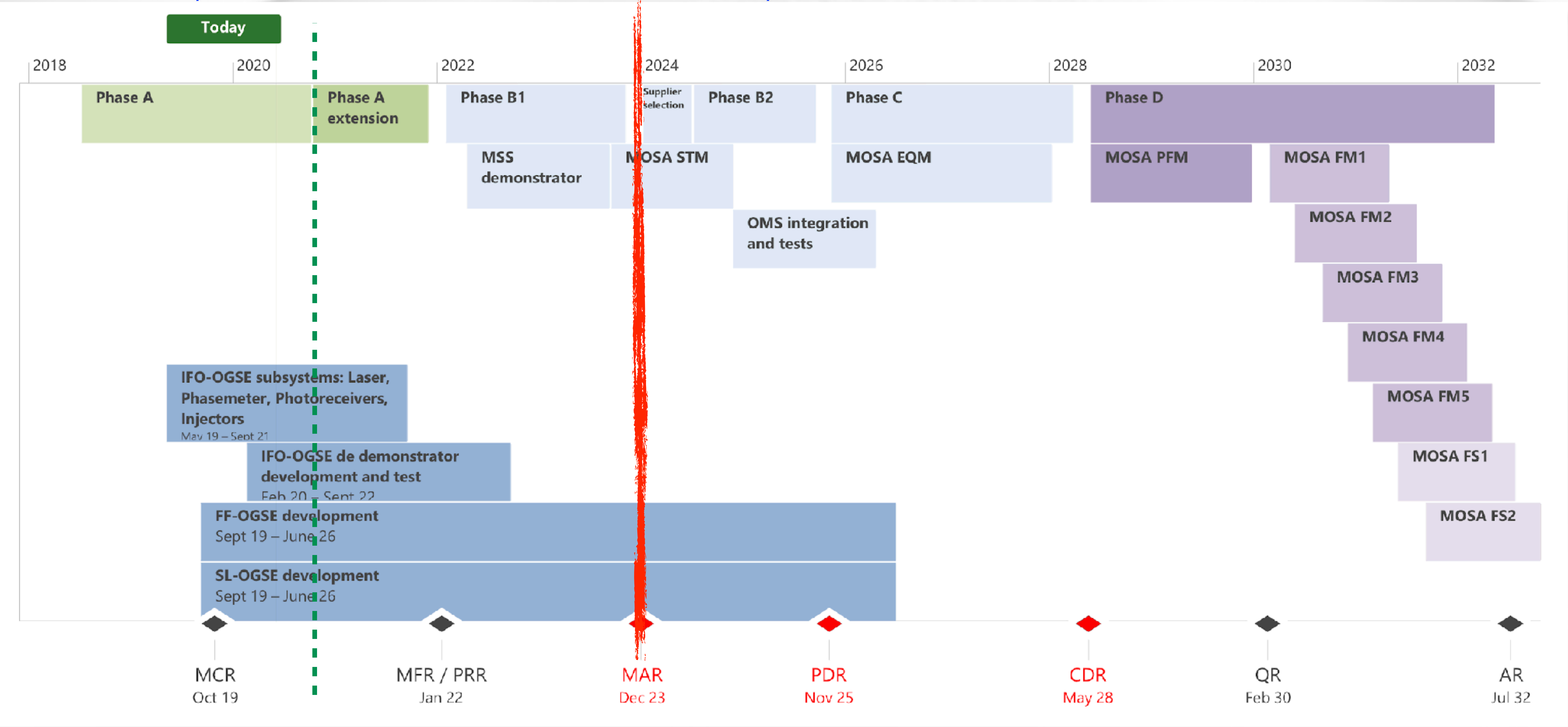
LISA Strain Sensitivity



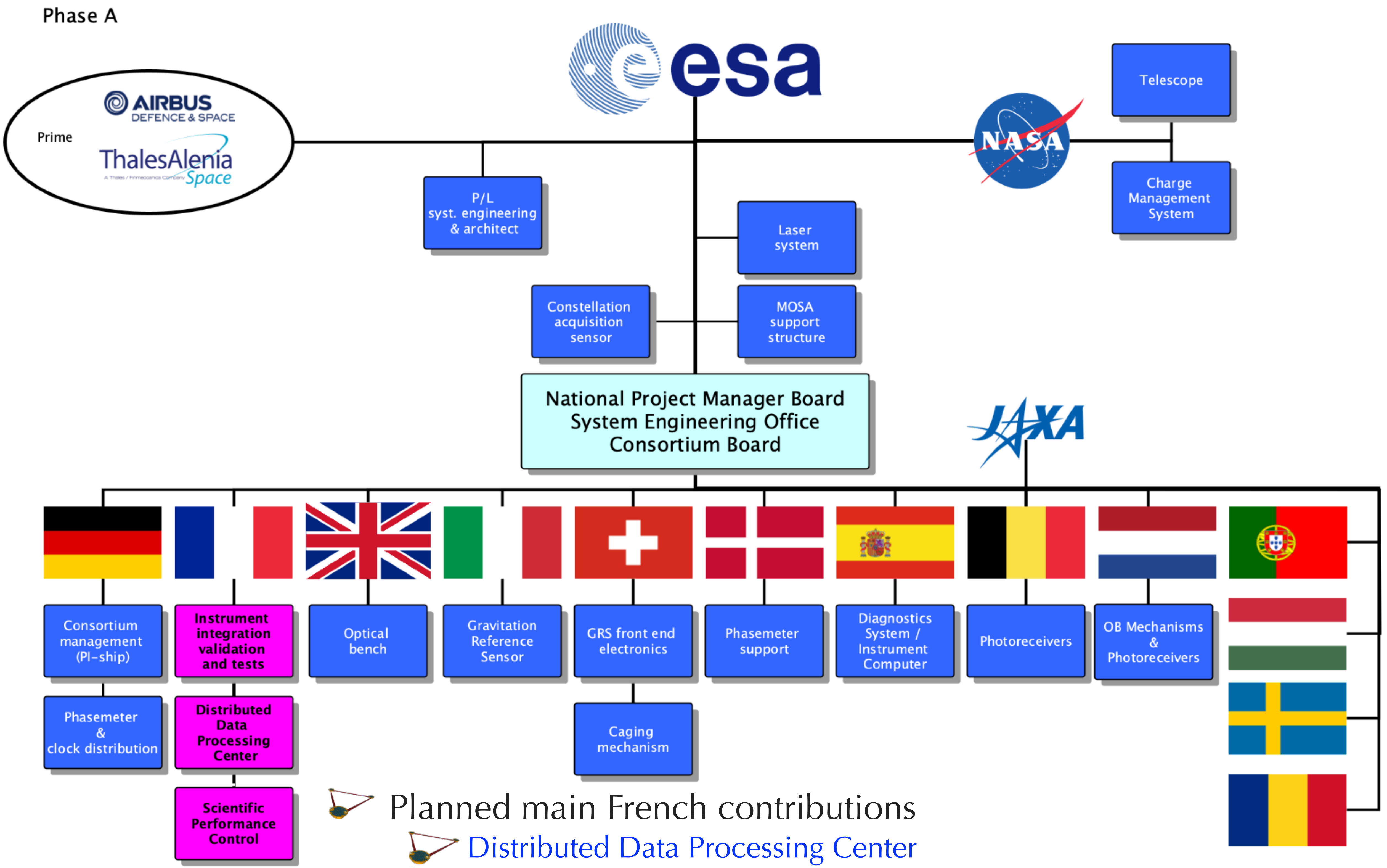
L'organisation LISA

LISA development schedule

- Major milestone : adoption end 2023 / early 2024
- Launch : 2034/2035
- In-flight operations : up to 12.5 years
  - 2.5 years cruise + commissioning
  - 6 years science mission, extendable to 10 years



What contribution for France ?



Phase A

Prime

P/L syst. engineering & architect

Laser system

Constellation acquisition sensor

MOSA support structure

Telescope

Charge Management System

National Project Manager Board
System Engineering Office
Consortium Board

Consortium management (PI-ship)

Phasemeter & clock distribution

Instrument integration validation and tests

Distributed Data Processing Center

Scientific Performance Control

Optical bench

Gravitation Reference Sensor

GRS front end electronics

Caging mechanism

Phasemeter support

Diagnostics System / Instrument Computer

Photoreceivers

OB Mechanisms & Photoreceivers

- Planned main French contributions
  - Distributed Data Processing Center
  - MOSA AIVT & Perf. Control

LISA France research institutes

- Presently 19 laboratories / research institutes participate to the LISA France collaboration
  - @IN2P3 : APC, CPPM, L2IT, LPCC, LMA/IP2I, CC-IN2P3
  - @INSU : LAM, IAP, LPC2E
  - @INSIS : Institut Fresnel
  - @Obs de Paris / INSU : SYRTE, LUTh
  - @Obs. de la Côte d'Azur / INSIS : ARTEMIS
  - @CEA : IRFU (DEDIP, DIS, DPhN, DPhP, DAP), IPhT
  - @Obs Midi Pyrénées / INSU : IRAP

- CNES is managing and supporting the project activities with engineers and financial ressources (incl. short-term contracts).

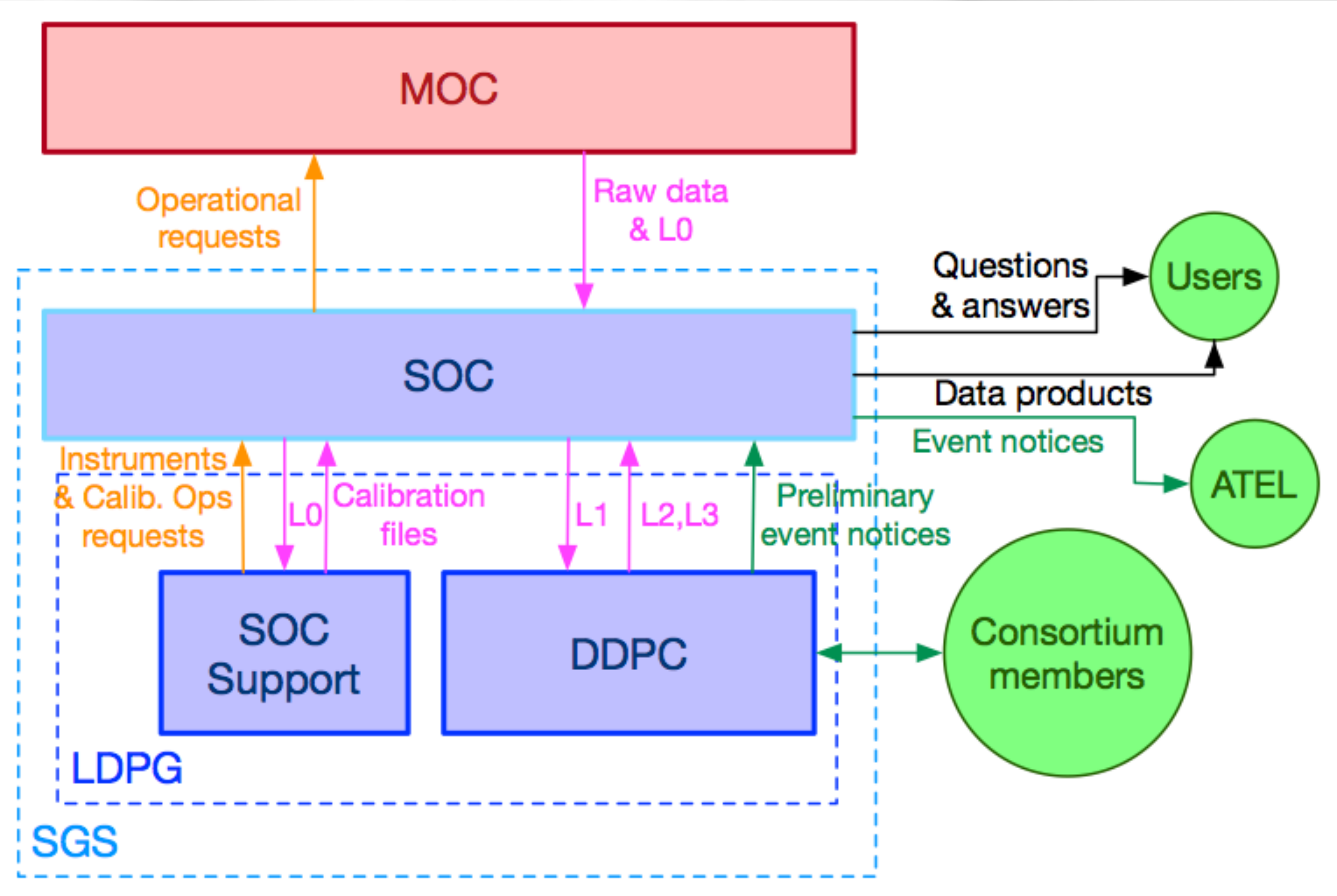
- Members from French institutes in the LISA Consortium (
  - 130 Full members
    - 63 FTEs
    - 1358 members in the LISA Consortium
  - 68 Associates

Université de Paris

LISA France

Distributed Data Processing Center

- Development of a Distributed Data Processing Center for LISA
  - Produces scientific L2&L3 data and supports ESA on L0 to L1 software
  - Will implement, maintain and operate simulations and data analysis
  - Supports the LISA community for SW and collaborative tools
  - Prototype architecture based on virtualisation and continuous integration



MOC

Operational requests

Raw data & L0

Questions & answers

Users

SOC

Data products

Event notices

ATEL

Instruments & Calib. Ops requests

L0

Calibration files

L1

L2,L3

Preliminary event notices

SOC Support

DDPC

Consortium members

LDPG

SGS

docker

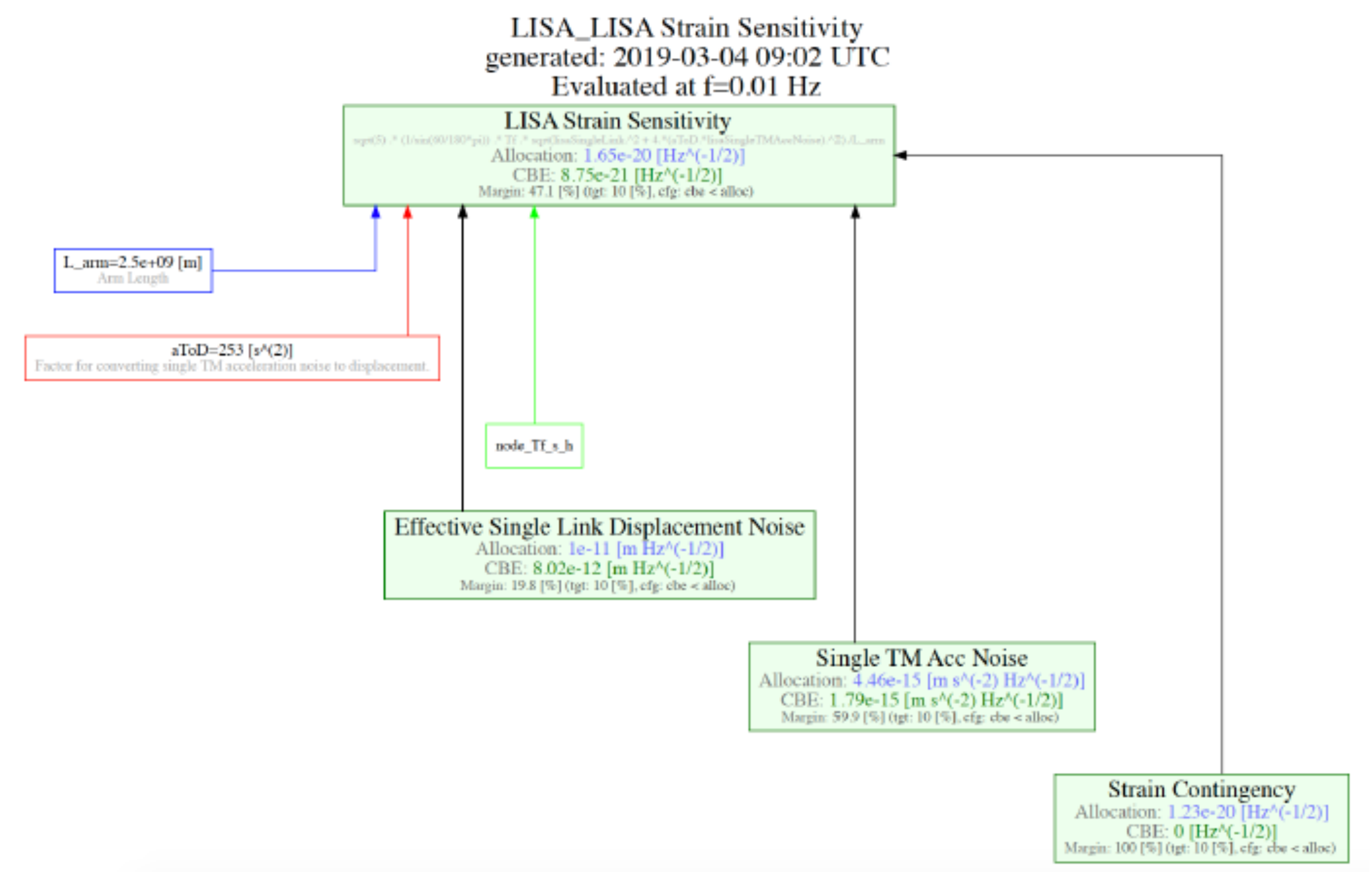
GitLab

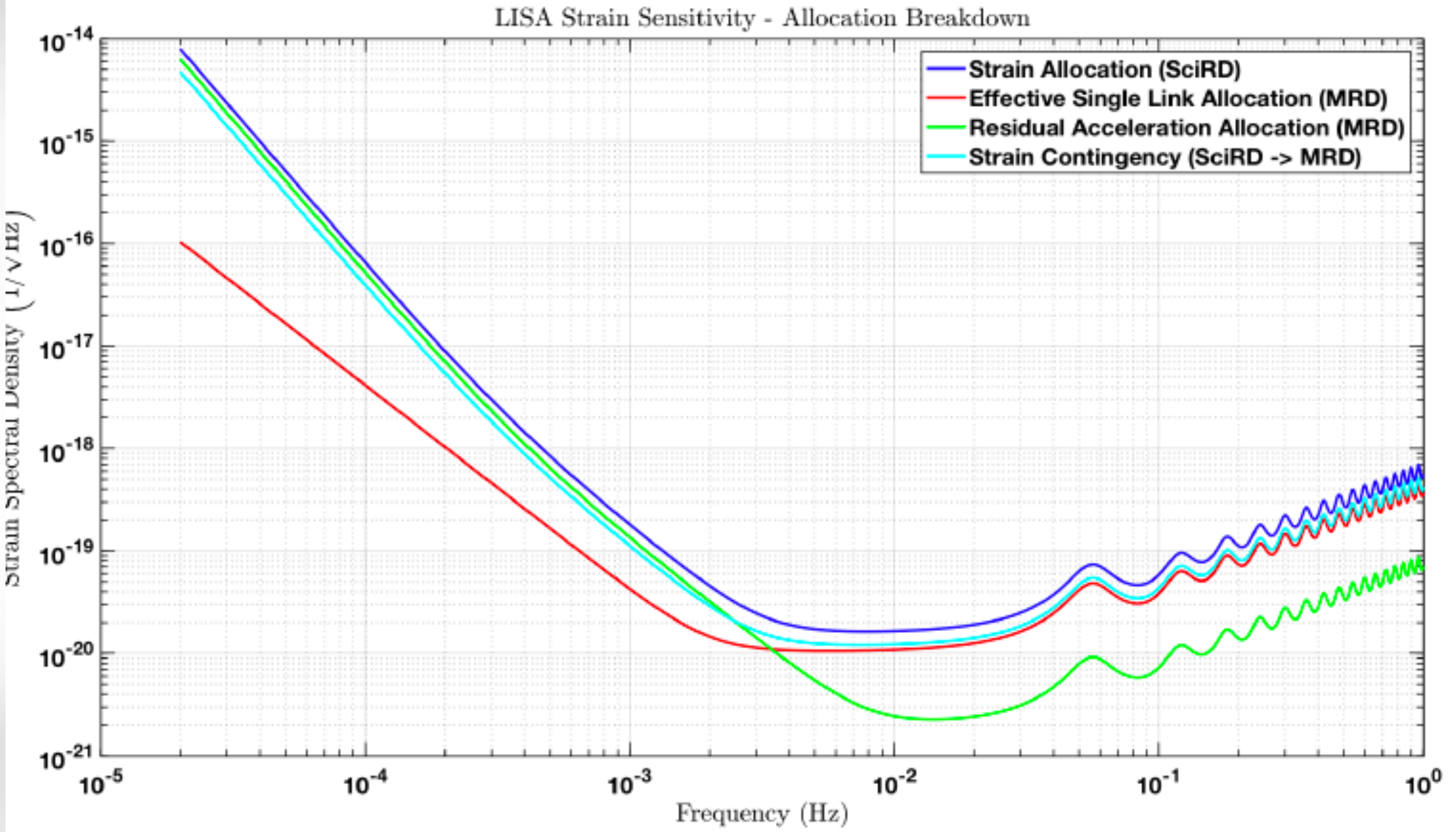
jupyter

Scientific Performance Budget

- Objective : build a ‘simplified’, system-level, performance model
  - Identify critical items
  - Unified view of the system performance from science requirement to sub-systems level.
  - Support the allocation breakdown for each sub-system
  - Sensitivity analysis to support design trade-off
- Different sources of information
  - Specific or ‘end-to-end’ simulations
  - Mathematical & physical models
  - Lab experiments

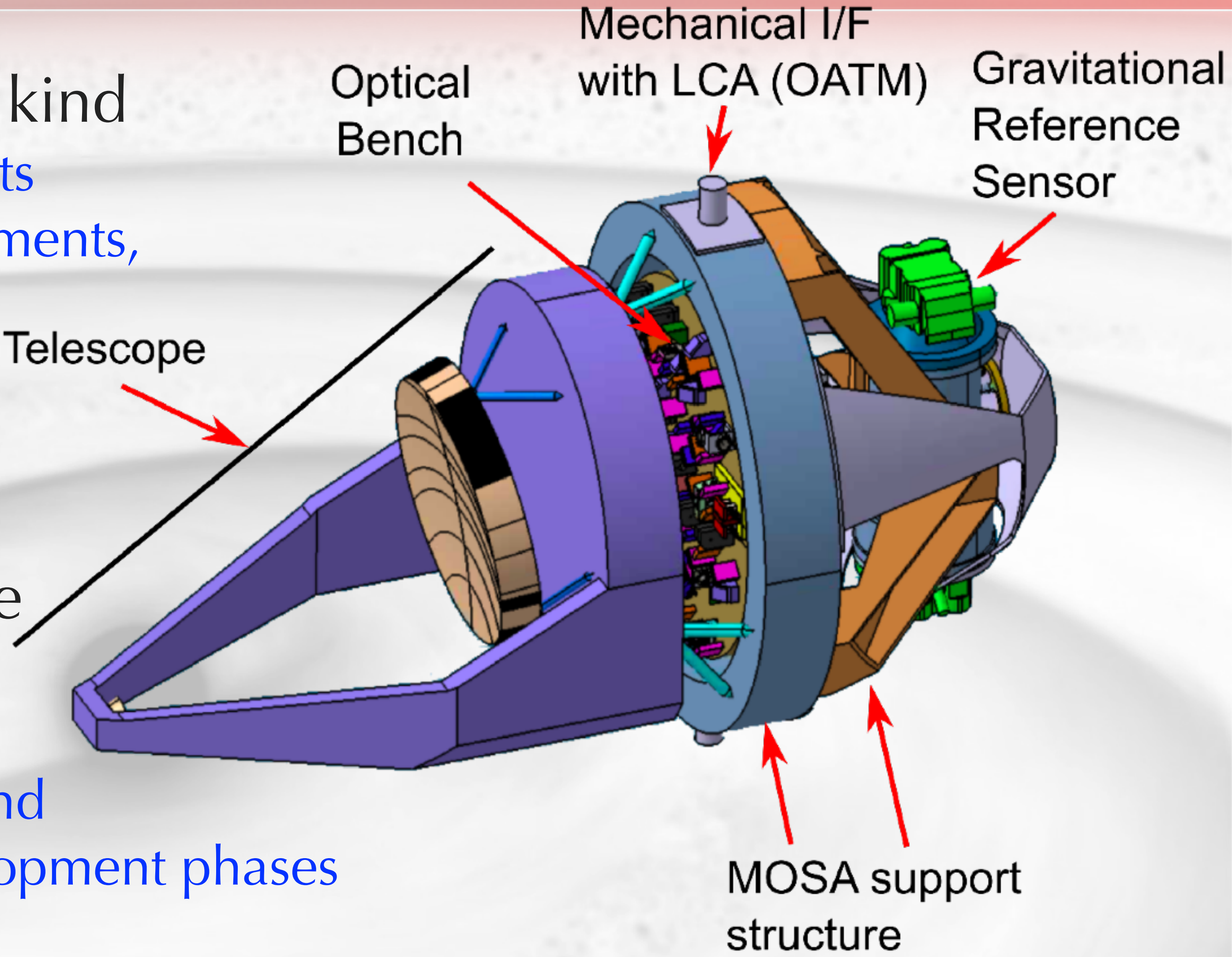
Interface with all stakeholders – Consortium, Agencies, Industry.





MOSA AIVT
Assembly, Integration, Validation and Tests

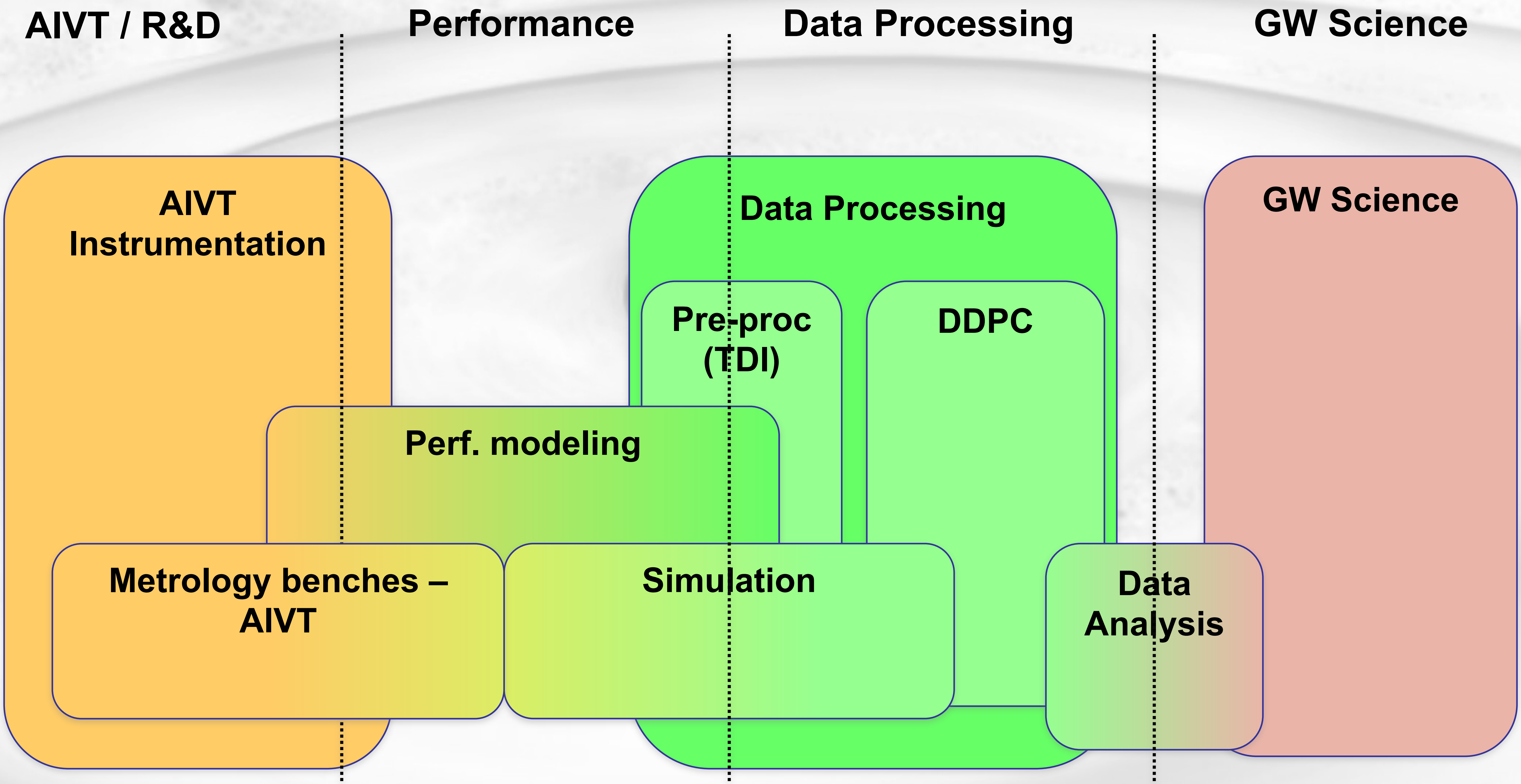
- LISA will be the first instrument of its kind
  - Not a collection of separate instruments
  - Combination of finely designed equipments, forming a Mkm-scale instrument
- LISA science return depends on the in-depth performance characterisation of the metrology core
  - Importance of the AIVT and scientific performance modelling
  - Crucial activity giving high visibility and involvement in early instrument development phases



- Integration and tests in close collaboration with industries
  - 10 MOSAs to integrate and validate (1 STM, 1 EQM, 1 PFM, 5 FMs, 2 spares)
  - Research institutes : development of optical metrology test benches and strong involvement in the EQM characterisation
    - Experience on MOSA testing transferred to industry with PFM
  - Industries : integration procedures and semi-serialisation of FMs & spares AIVT
    - The research institutes still follow the process and interpret the measurements

French LISA activities landscape

- Broad and continuous coverage, from instrument to GW science



AIVT / R&D

Performance

Data Processing

GW Science

AIVT Instrumentation

Data Processing

Pre-proc (TDI)

DDPC

GW Science

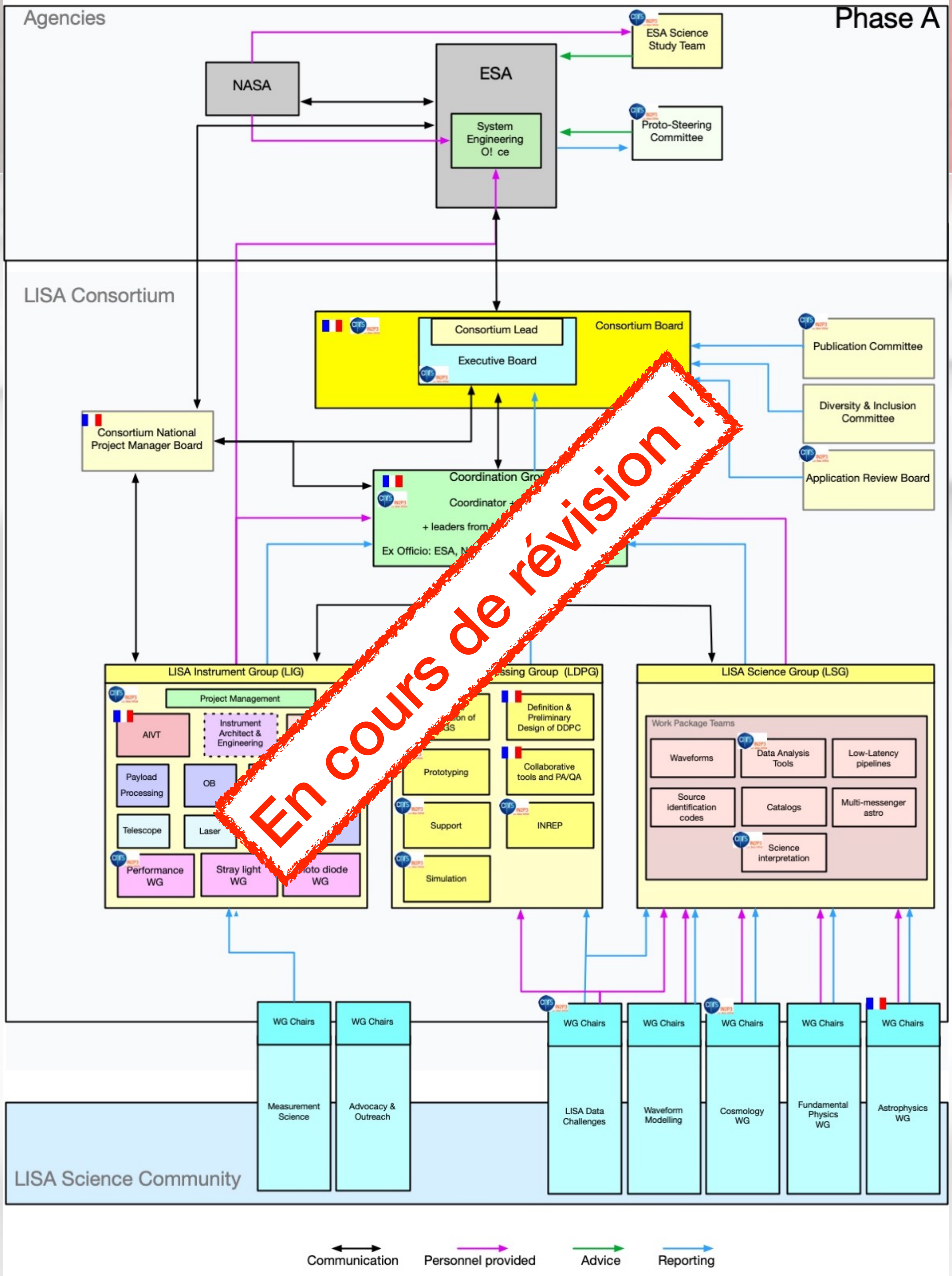
Perf. modeling

Metrology benches – AIVT

Simulation

Data Analysis

Organisation of the LISA Consortium



Agencies

Phase A

ESA Science Study Team

NASA

ESA

System Engineering Office

Proto-Steering Committee

LISA Consortium

Consortium Lead

Executive Board

Consortium Board

Publication Committee

Diversity & Inclusion Committee

Application Review Board

Consortium National Project Manager Board

Coordination Gro

Coordinator +

+ leaders from

Ex Officio: ESA, N

En cours de révision !

LISA Instrument Group (LIG)

Project Management

AIVT

Instrument Architect & Engineering

Payload Processing

OB

Telescope

Laser

Performance WG

Stray light WG

oto diode WG

ssing Group (LDPG)

on of GS

Definition & Preliminary Design of DDPC

Prototyping

Collaborative tools and PA/QA

Support

INREP

Simulation

LISA Science Group (LSG)

Work Package Teams

Waveforms

Data Analysis Tools

Low-Latency pipelines

Source identification codes

Catalogs

Multi-messenger astro

Science interpretation

WG Chairs

Measurement Science

WG Chairs

Advocacy & Outreach

WG Chairs

LISA Data Challenges

WG Chairs

Waveform Modelling

WG Chairs

Cosmology WG

WG Chairs

Fundamental Physics WG

WG Chairs

Astrophysics WG

LISA Science Community

Communication

Personnel provided

Advice

Reporting