LISA

Pre-riunione preventivi 2024 TIFPA

Rita Dolesi
Responsabile Nazionale LISA
Università di Trento/INFN

Why bother to continue to investigate gravity?

It is a fundamental interaction of nature

General Relativity with its empirical succes is considered
the foundation of our understanding of the gravitational interaction.

But all attempts in quantize gravity and to unify it with other forces suggest that
the standard GR of Einstein may not be the last word

→ Very active and challenging field with many experimental and theoretical possibilities

Experimental tests must give the empirical bound to the new theories

The possibility to find discrepancies between GR/other theories and the experimental test
is continuously driving new experiments
enabled by the development of advanced technology as well as access to space.

Gravity probed by different experiment

Experimental gravitation plays a central role in the search for new physics beyond Einstein in many different regimes

TEST OF GR FOUNDATIONS : EQUIVALENCE PRINCIPLE

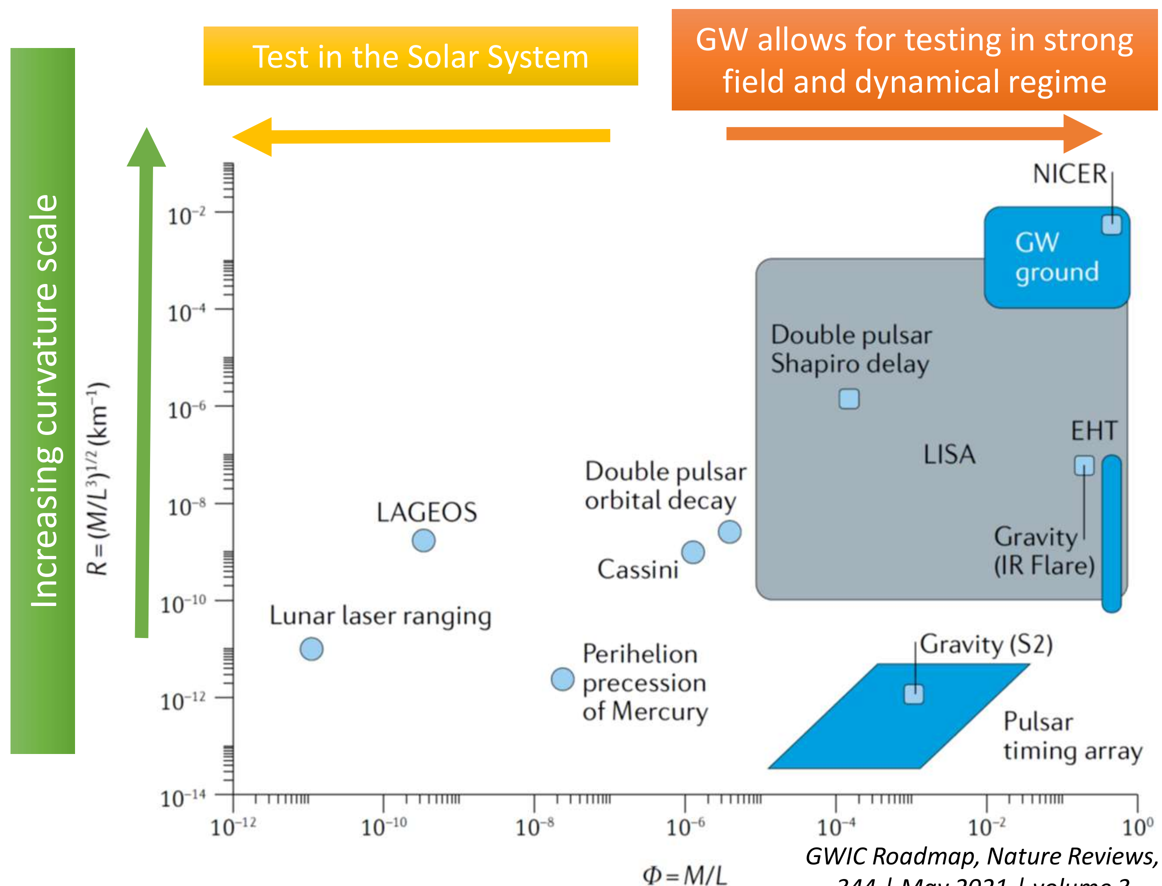
TEST OF THE CONSEQUENCES OF GR / ALTERNATIVE THEORIES OF GRAVITY

Strong field regime and weak field regime

Small scale → Cosmological scale

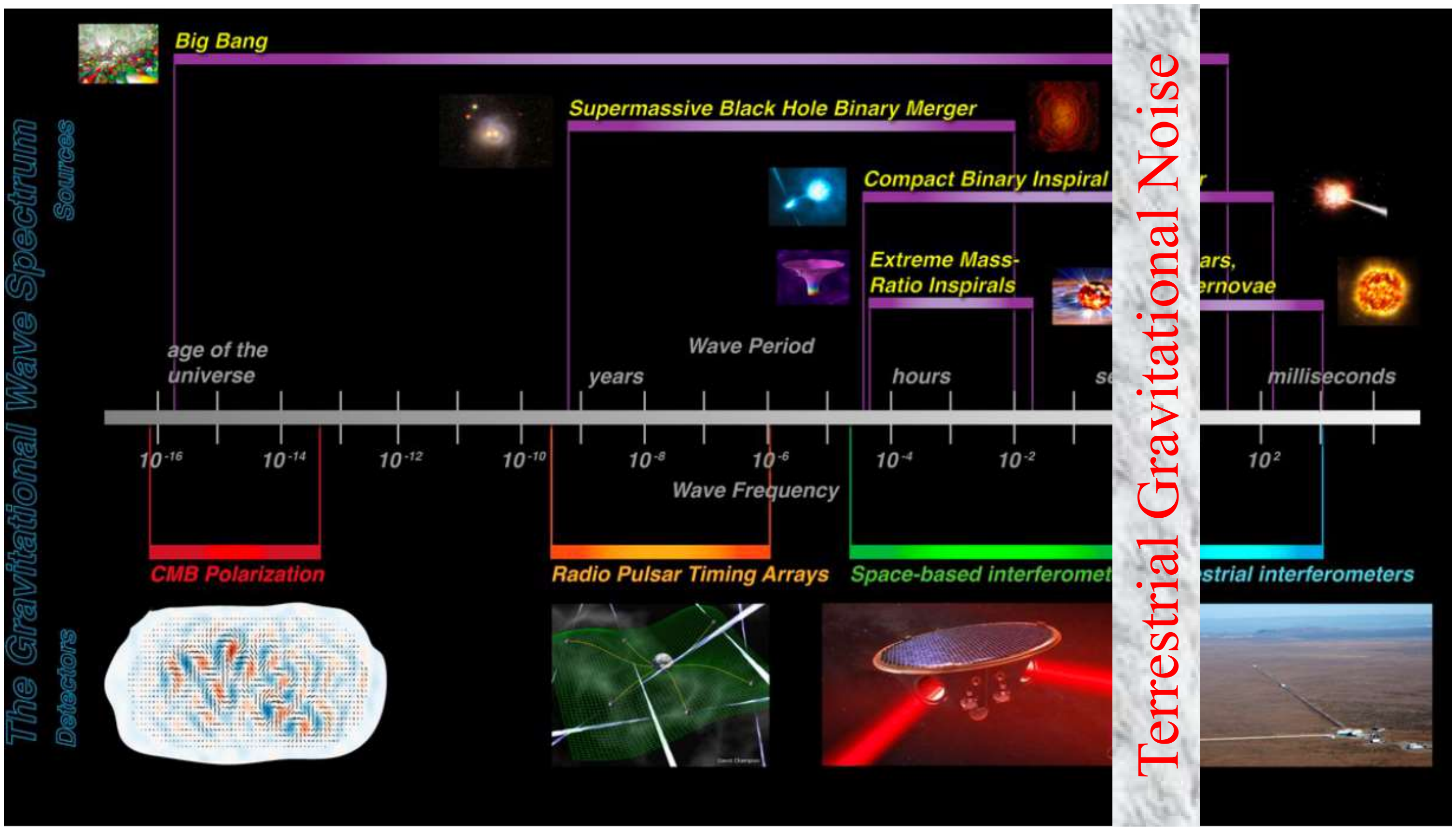
Static regime and Dynamical gravity

In a wide range
of field intensity (compactness)
and spacetime curvature



GWIC Roadmap, Nature Reviews, 344 | May 2021 | volume 3

Space-based detector



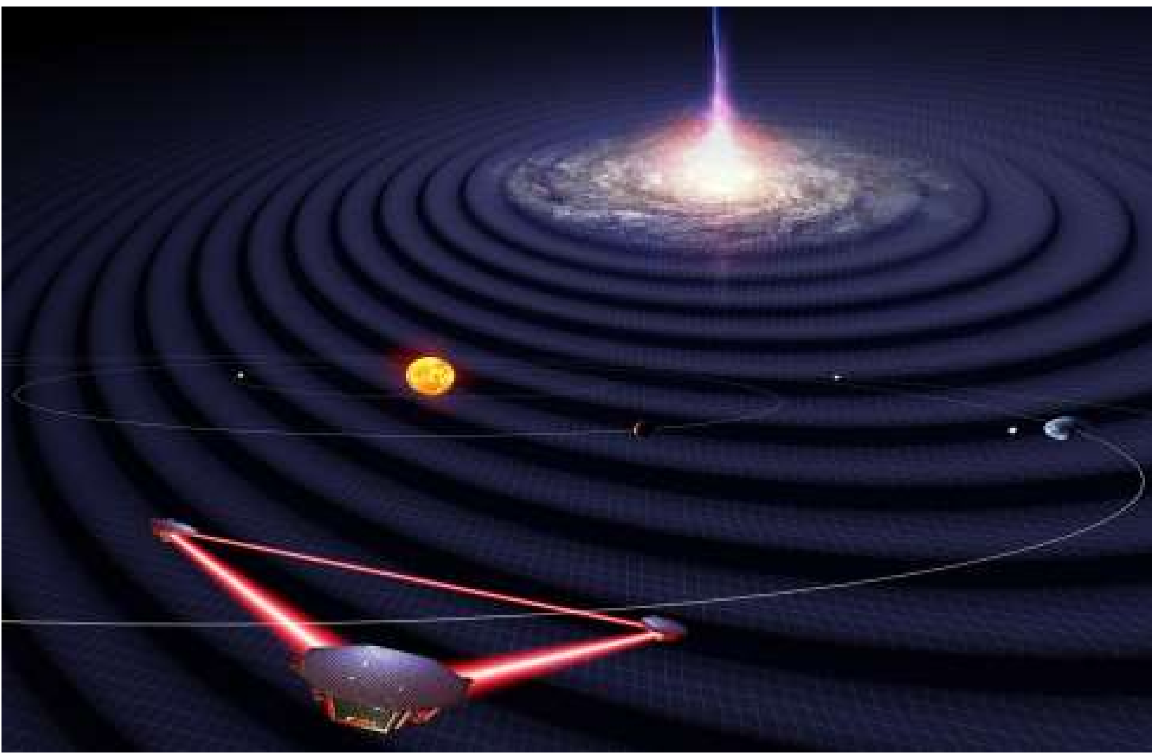
(credit: K. Jani)

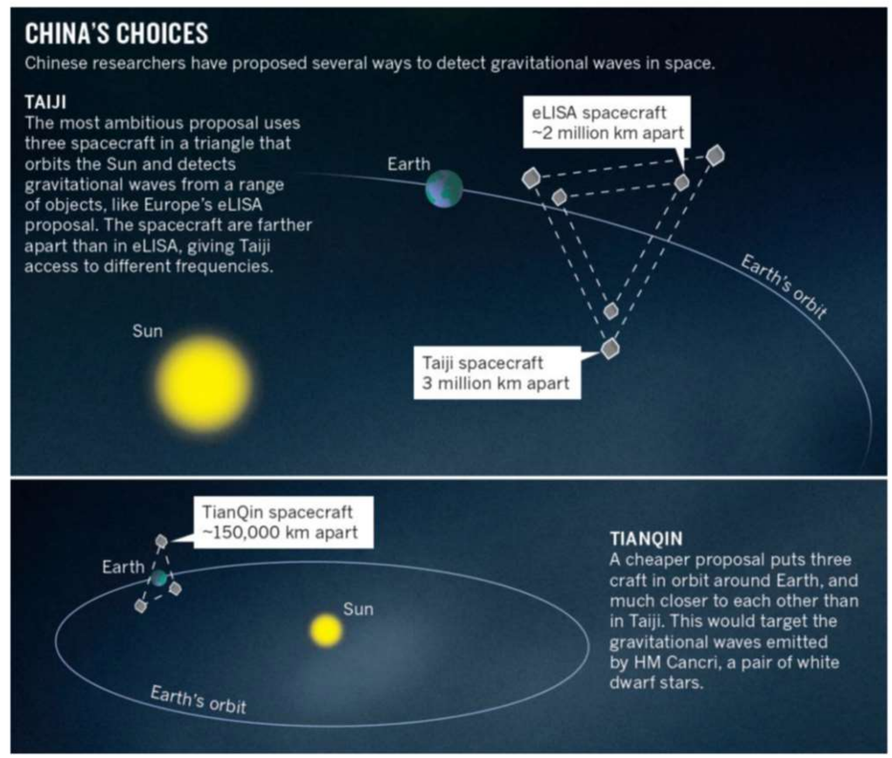
First generation space-based detector

LISA: planned launch date 2035

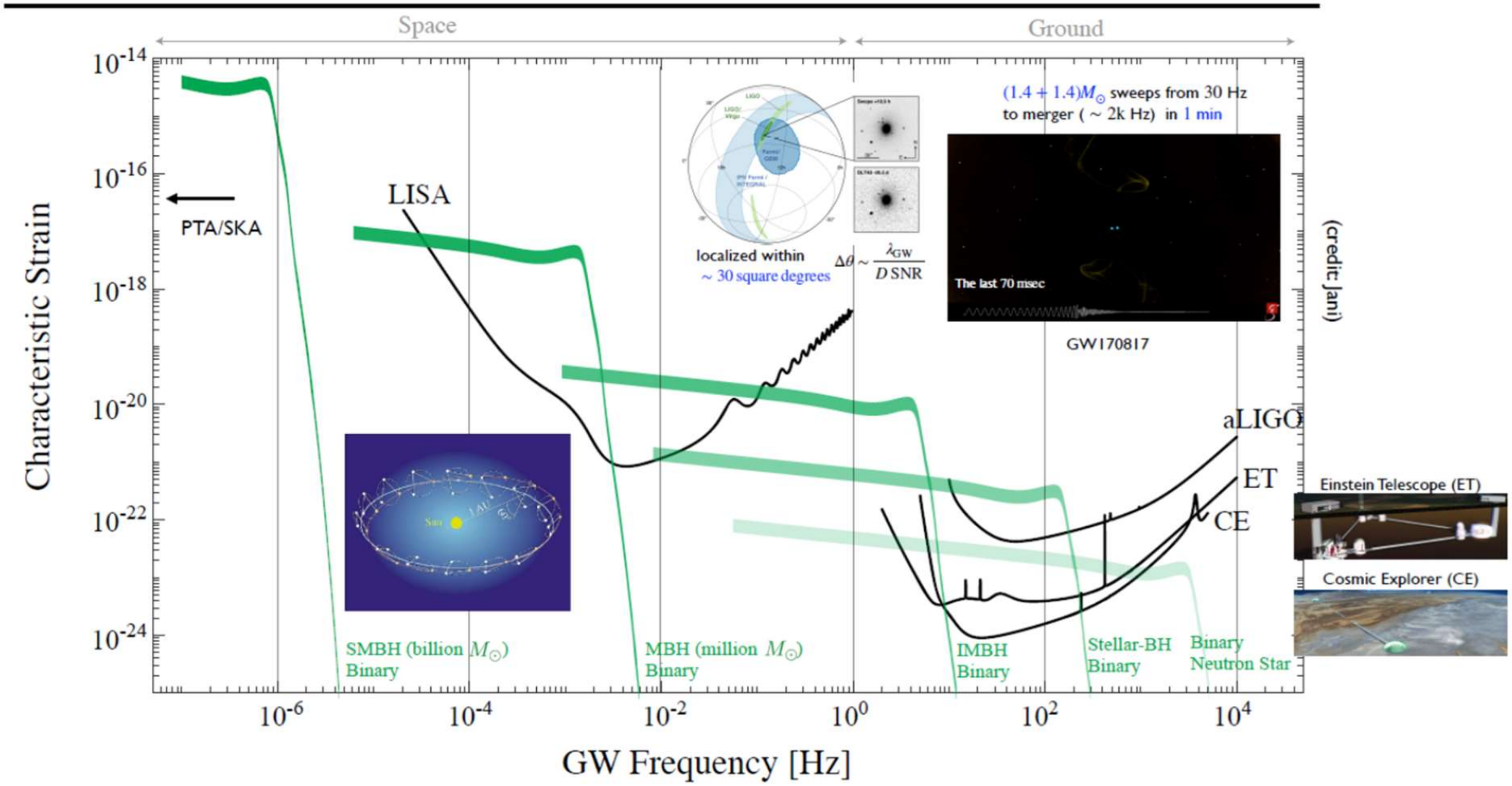
Two competing projects in China:

- "Taiji" (Chinese Academy of Sciences)
- "Tianqin" (Sun-Yat-Sen University)
- Both aim to build LISA-like missions in the LISA timeframe.
- Both launched single-satellite pathfinders and plan to launch missions with two satellites (GRACE Follow-On like)

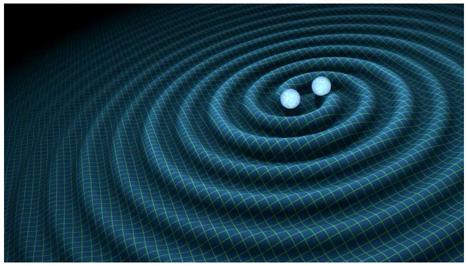




First generation space-based detector



Low frequency GW astronomy



- Binaries are nearly Keplerian,

$$f_{GW} = \frac{1}{\pi}\sqrt{\frac{\mathcal{G}(M_1+M_2)}{r^3}}$$

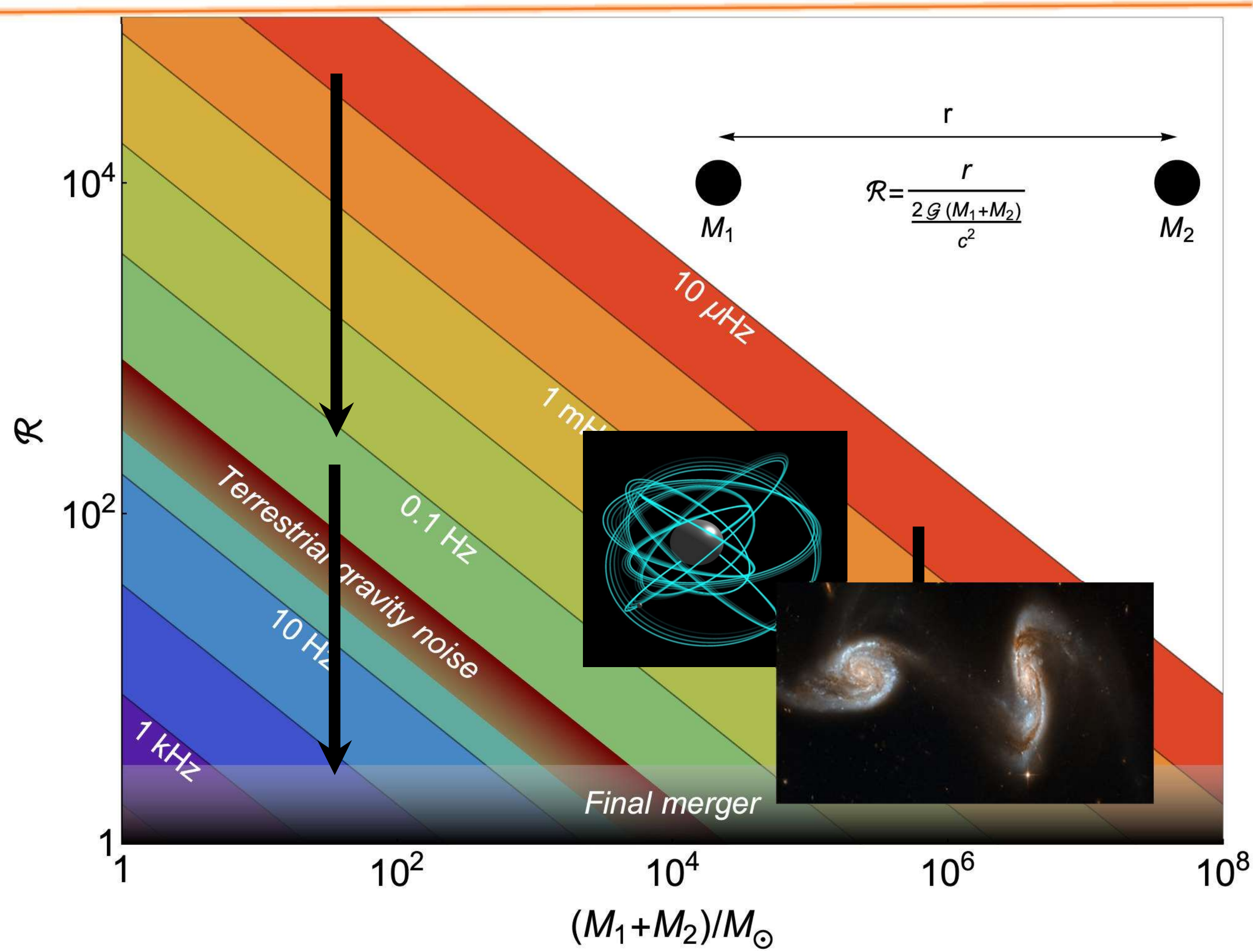
- Separation normalized to Schwarzschild radii:

$$\mathcal{R} = \frac{r}{\left(\frac{2\mathcal{G}(M_1+M_2)}{c^2}\right)}$$

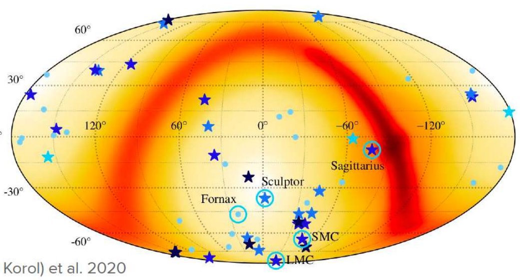
- Frequency decreases with both mass and $\mathcal{R}$

$$f_{GW} = \frac{c}{\pi\sqrt{2}\,R_\odot}\left(\frac{M_1+M_2}{M_\odot}\right)^{-1}\mathcal{R}^{-\frac{3}{2}}$$

($\mathcal{R} \to 1 \simeq$ final merger max f_{GW})

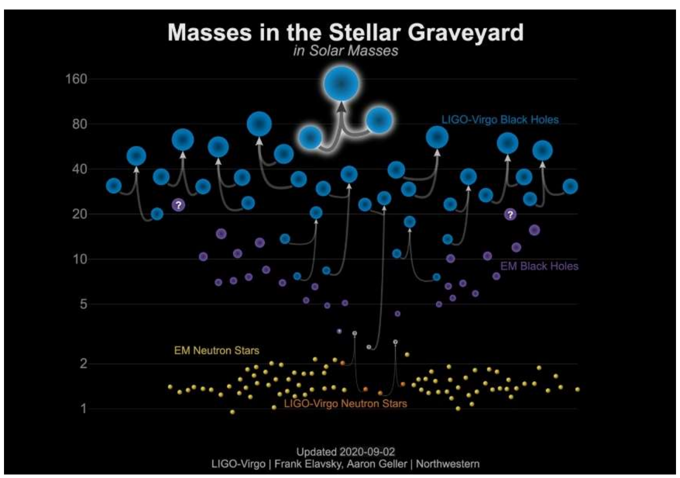


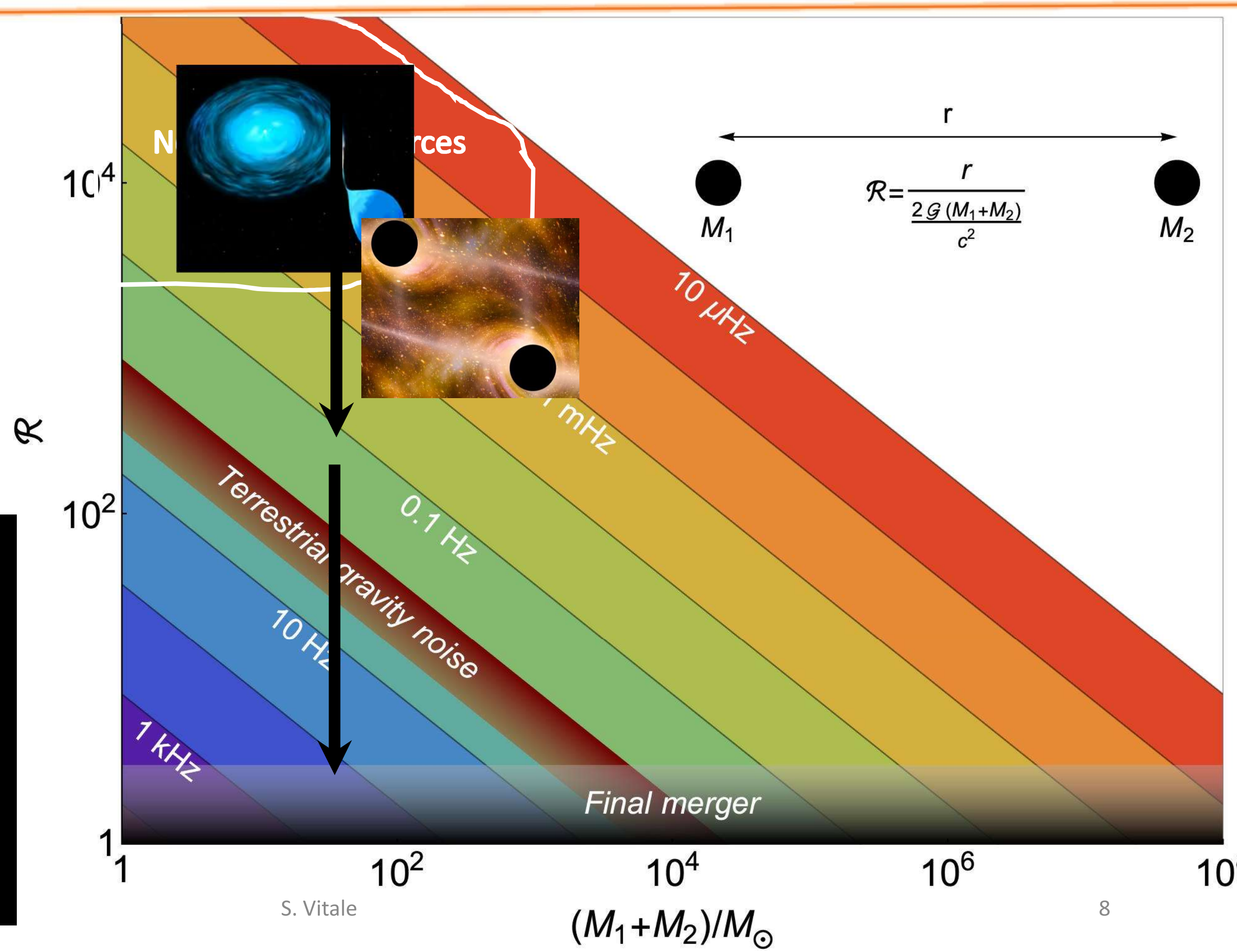
Non-transient GW astronomy



Roebber (incl. Korol) et al. 2020

- GW-binary astronomy of local group
- BH multi-band astronomy





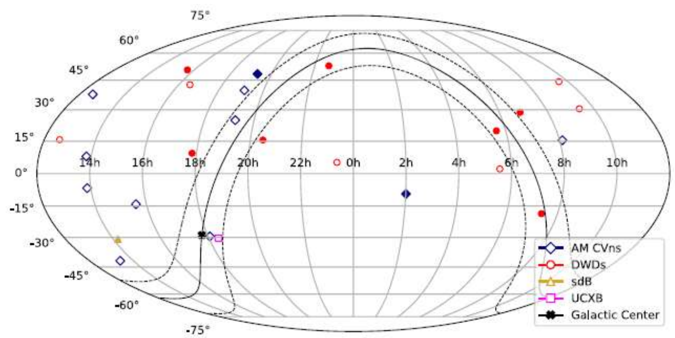
LISA science case is still growing

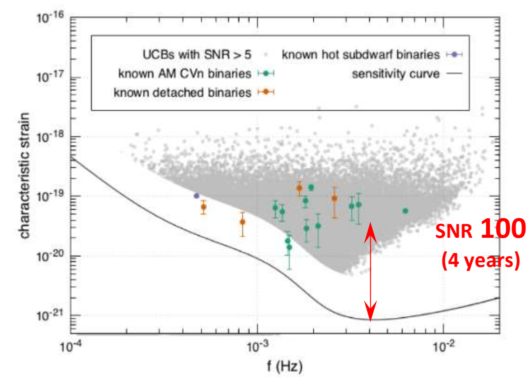
summarized in upcoming science team “LISA Redbook” for Adoption Review
recent review papers:

- “Astrophysics with LISA”, Living Reviews GR, March 2023
- “New Horizons for Fundamental Physics with LISA”, [gr-qc] 2205.01597 (May 2022)

growing catalog of Milky Way “verification binaries”

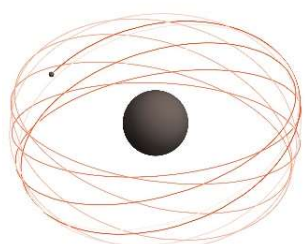
- GAIA, Zwicky, Rubin, JWST ...
- known sources “tip of iceberg”
- expect >10000 resolvable



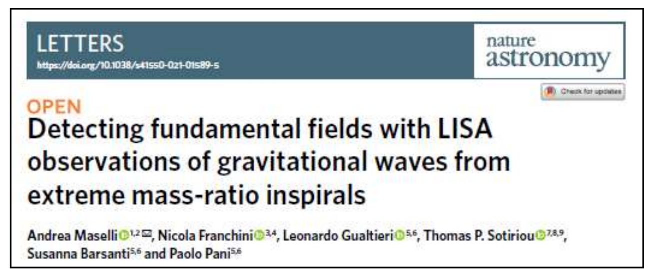


growing spectrum of tests of GR and new physics
exploiting unique LISA:

- high SNR
- deep universe
- large mass range
- long observation time

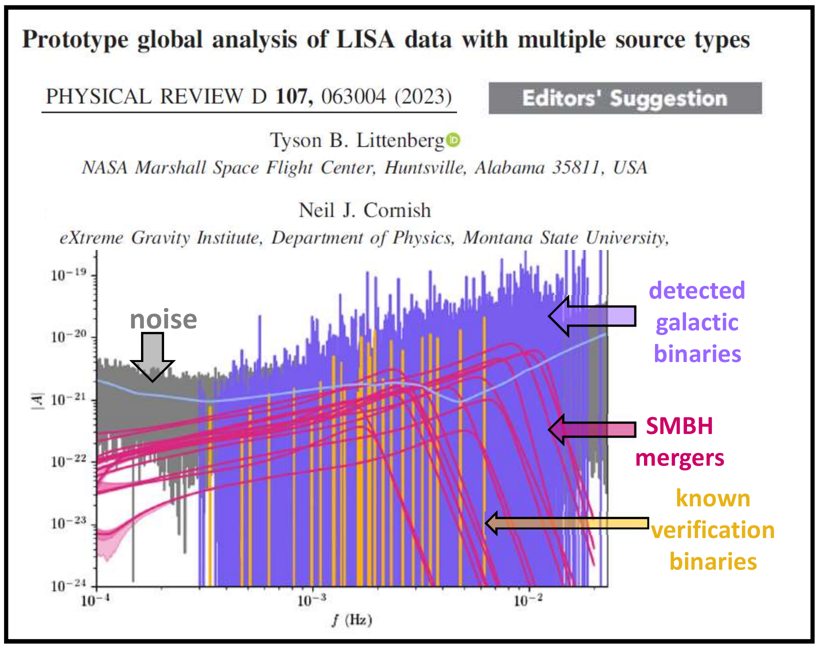


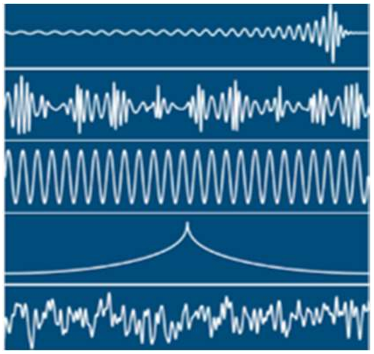
Example: “extreme mass ratio inspirals”


LETTERS
https://doi.org/10.1038/s41550-021-01589-5
nature astronomy
OPEN
Detecting fundamental fields with LISA observations of gravitational waves from extreme mass-ratio inspirals
Andrea Maselli[1,2], Nicola Franchini[3,4], Leonardo Gualtieri[5,6], Thomas P. Sotiriou[7,8,9], Susanna Barsanti[5,6] and Paolo Pani[5,6]

LISA data analysis

- ***LISA hardware*** has mature design and national agency commitments
- ***LISA data analysis*** is young, actively growing and still open to new groups
  - possible solutions for extracting thousands of sources exist, but research rapidly expanding, from “TDI” initial data analysis to “global fit” to science interpretation





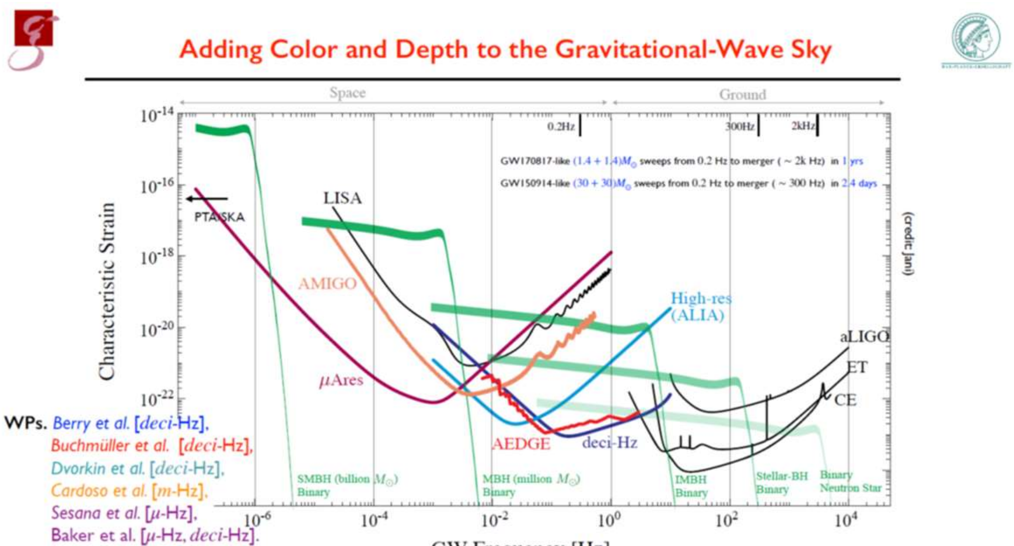
«LISA data challenge»
https://lisa-ldc.lal.in2p3.fr/

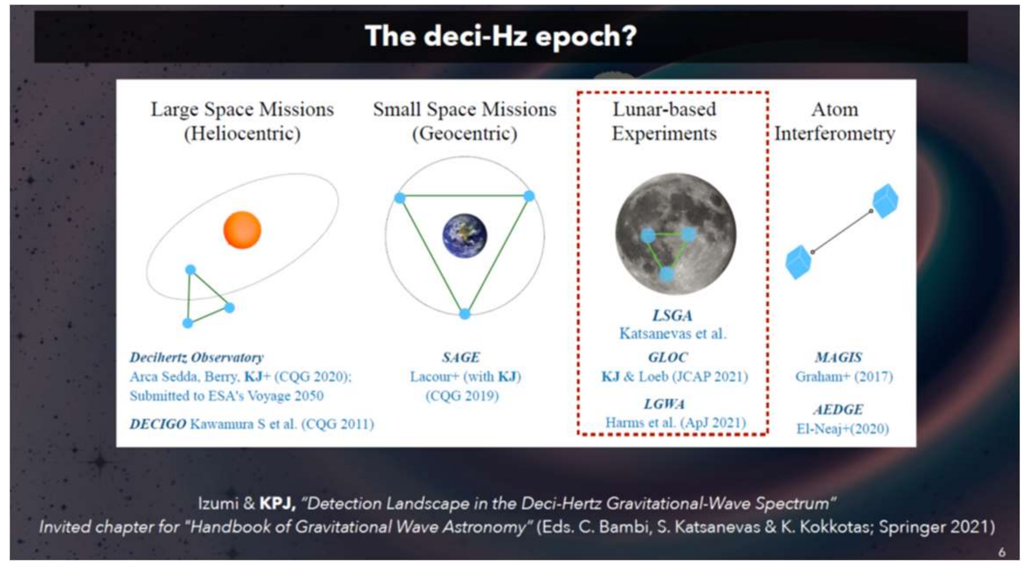
ASI commitment to provide data center (HW + eng support), plus pipeline development

- “bottom up” opportunities for new groups to emerge
- requires Institute / Agency level resources

Beyond First generation space-based detector (a not exhaustive glance….)

Alessandra Buonanno, ***Max Planck Inst for Grav Physics, “Voyage 2050 and Beyond “; LISA Cons Meet Jan 2022***





With Laser Ranging of the Moon and artificial satellites

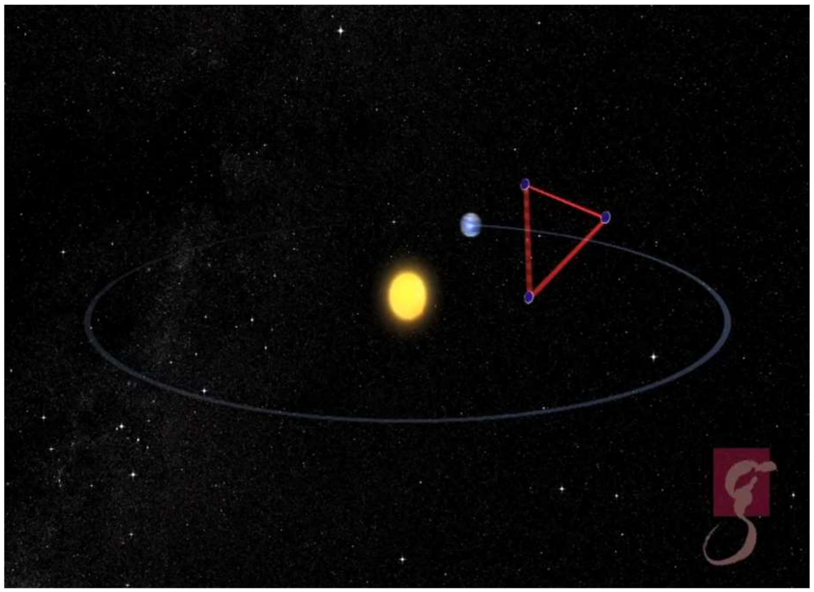
PHYSICAL REVIEW LETTERS **128,** 101103 (2022)

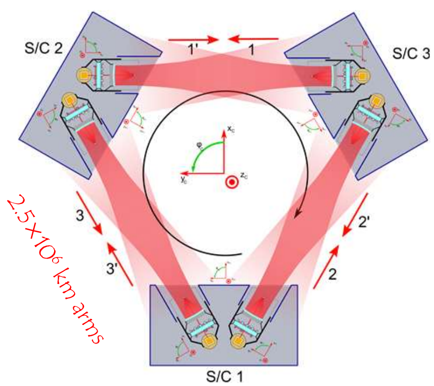
Featured in Physics

Bridging the μHz Gap in the Gravitational-Wave Landscape with Binary Resonances

Diego Blas[1,2,3] and Alexander C. Jenkins[3,*]

LISA fundamental challenging features



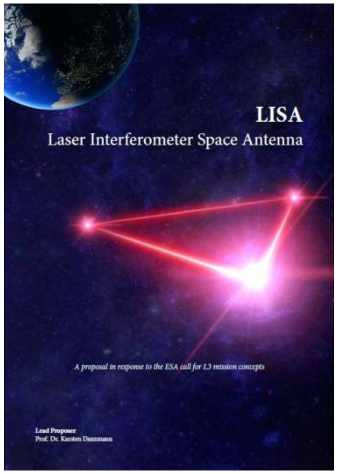


LISA CONFIGURATION

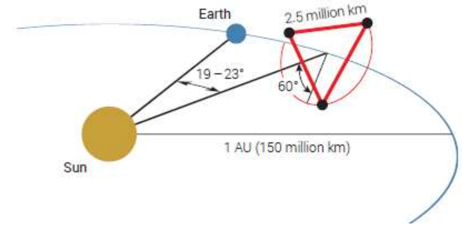
- 3 identical spacecraft
- 3 arms of 2.5 Million km
- 30 cm telescopes, 2W lasers, 100 pW at receiver, 1064 nm:
- LISA constellation quasi rigid, quasi equilateral rotating configuration: 1 AU , 20-degree trailing Earth orbit

LISA IMPLEMENTATION REQUIREMENTS

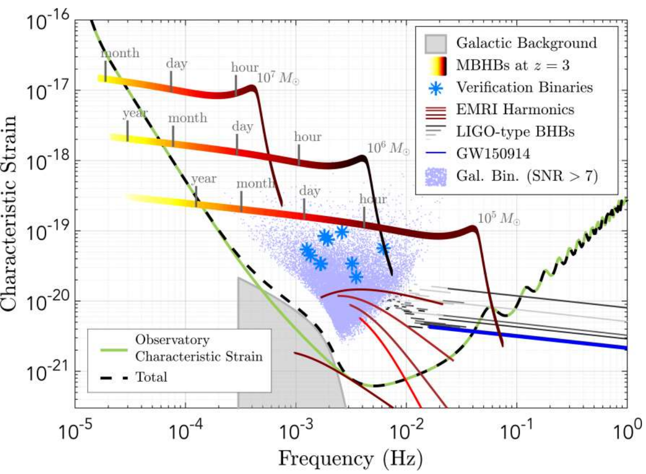
- Inter satellite heterodyne laser interferometry in transponder mode 10 pm/√Hz,
- Time Delay Interferometry to suppress laser frequency noise
- Test masses in sub-femto-g free fall 3 fm/s²/√Hz



LISA:Laser Interferometer Space Antenna



- under study for 2035 launch:
  - to follow JUICE as next ESA Cosmic Vision «Large Mission»
- mission adoption under preparation now (complete by end 2023 / begin 2024)
  - instrument review starts May 2023 (includes ASI «gravitational reference system»)
  - mission-level review Summer-Fall 2023 (end of competitive industrial study)



Adoption: ESA – NASA – national agency commitment to implement LISA with:

- science requirements and baseline design
  - 100 μHz – 1 Hz band (LPF demonstrated down to 20 μHz)
  - 4.5 year nominal science (but combustible + orbits for 10 years)
- cost and schedule
- provision scheme for hardware (+ operations and analysis)
- data policy (analysis plans, data access + release)
  - under definition between agencies and community / LISA Consortium

LISA CONSORTIUM

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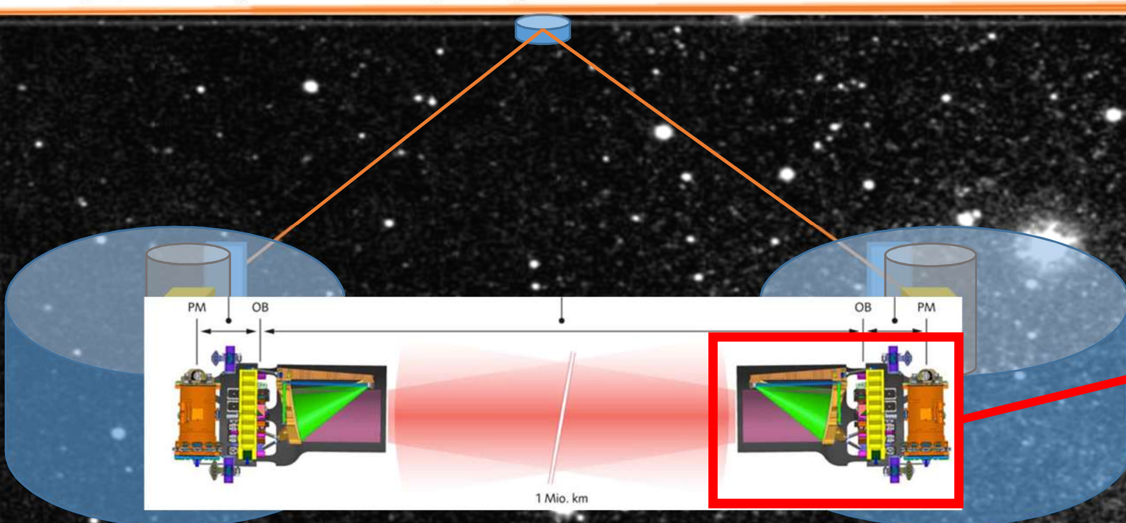
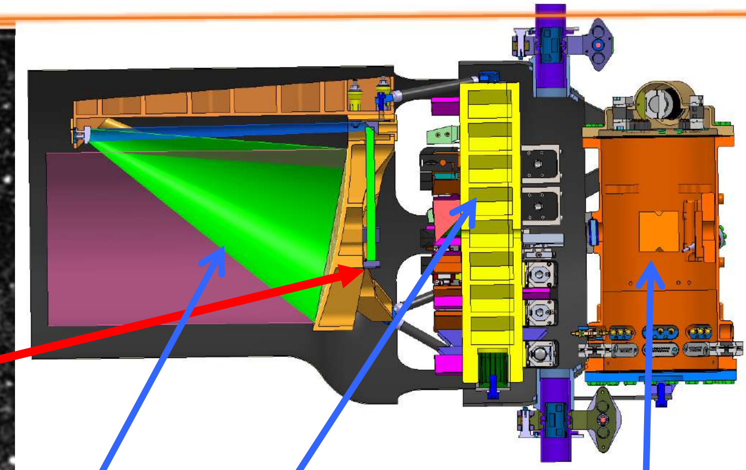
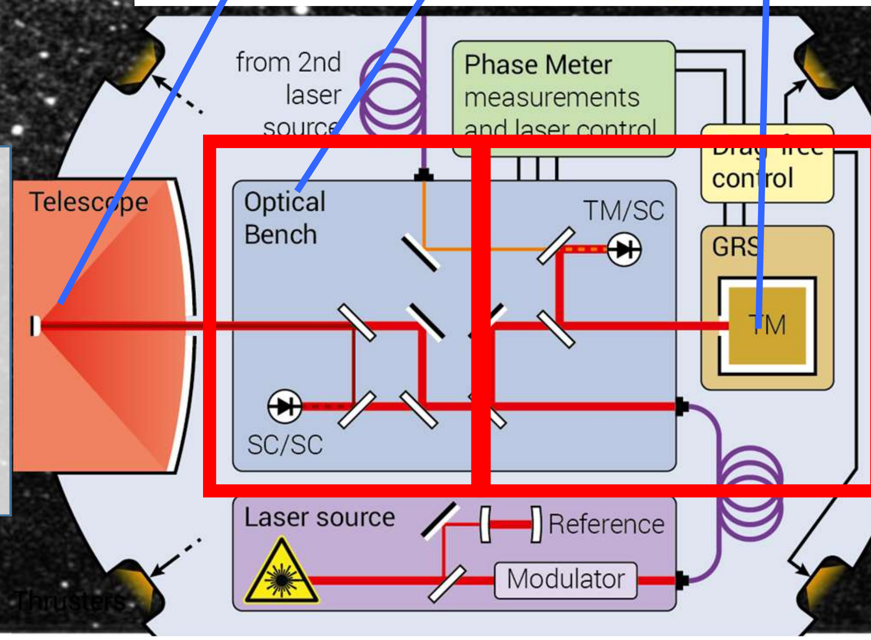
LISA instrument







The Gravitational Reference Sensor with the test-mass

The Optical Bench with:

Local interferometer

Spacecraft to spacecraft interferometer

Telescope for the spacecraft to spacecraft interferometer

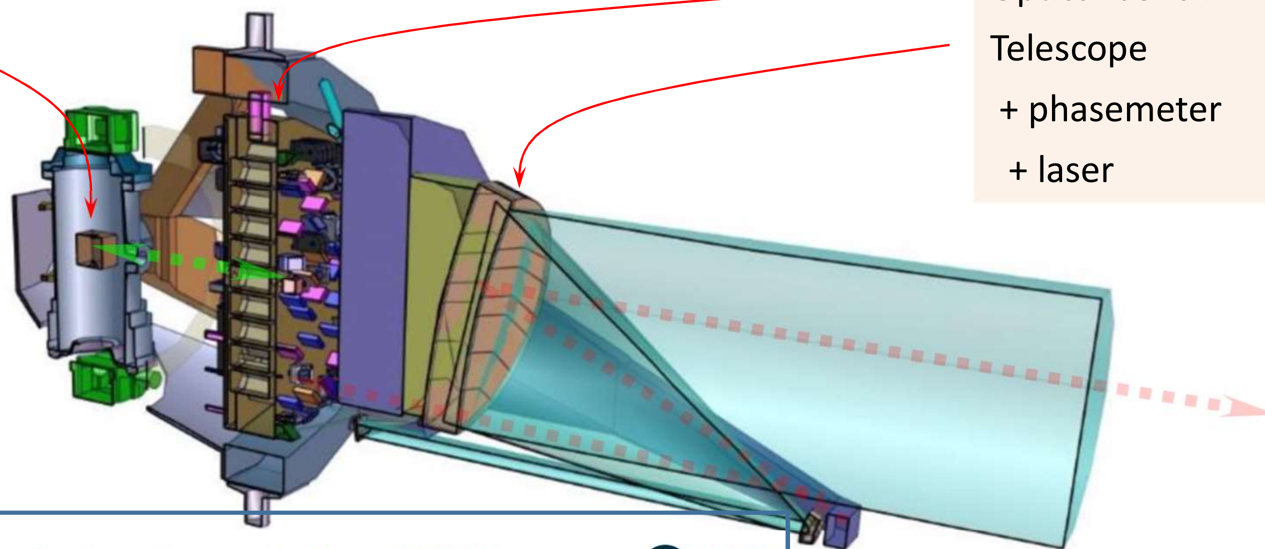
LISA instrument for measuring GW tidal acceleration at 2.5 million km

Gravitational reference system (GRS)

- GRS head
- + electronics
- + UV light source

Optical metrology system

- Optical bench
- Telescope
- + phasemeter
- + laser



Nationally Provided Items in Implementation (TBC)

esa

Gravitational Reference Subsystem	Interferometric Detection Subsystem	Optical Test Systems - GSE	Science Diagnostics Subsystem
▪ GRS Head (IT) ▪ GRS FEE (CH) ▪ GRS MCU (IT) ▪ CMD (ESA/NASA)	▪ Optical Bench (UK) ▪ ePMS (DE) ▪ IDS AIVT (FR) ▪ Multiple units on OB (BE,		

9

→ THE EUROPEAN SPACE AGENCY

2 major LISA instrument systems:

- free-falling test mass (GRS): Italy (ASI)
- interferometery detection (IDS): Germany (DLR)

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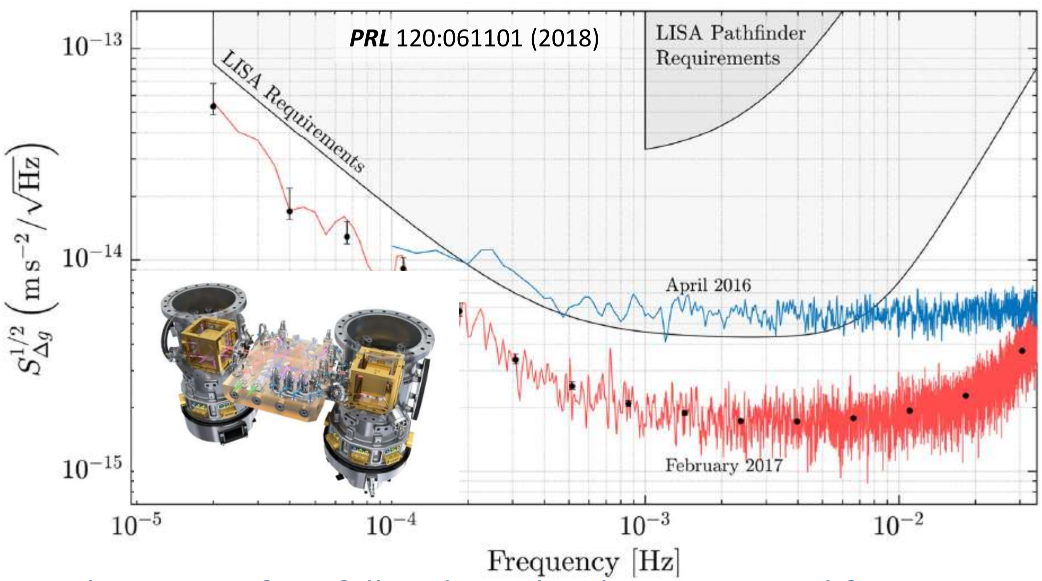
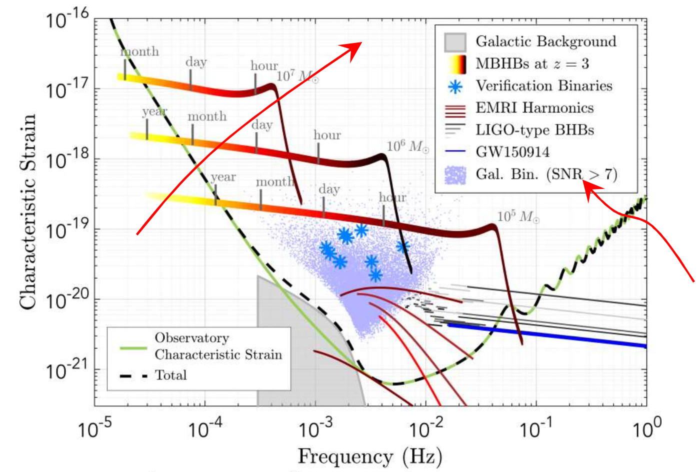
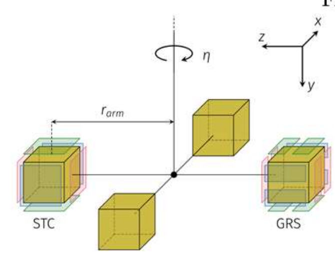
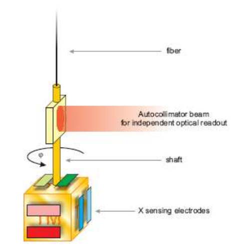
LISA Pathfinder + torsion pendulum testing on ground anchors LISA low frequency performance and super massive black hole science



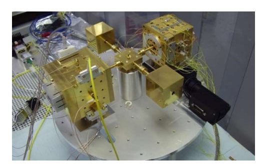


LPF heritage – free-fall and GRS hardware – critical for LISA maturity





- ground testing and INFN R&D (LPF and LISA) essential to this!
- 2023-2026 key for LISA ground testing
  - includes "engineering model" testing in Trento (INFN)
  - ground verification, consolidate LPF
  - mitigate remaining challenges



Ruolo INFN in LISA

CSN2 supporta autonomamente altre attività, monitorando ulteriori opportunità di estensione del coinvolgimento in altre attività collegate a LISA

LISA a INFN/Tor Vergata: elettronica di controllo per la scarica delle masse di test (TM) di LISA mediante luce UV. Interesse di ASI ed ESA, che considerano strategico uno sviluppo di tale componente in Europa. Roma Tor Vergata/INFN fa parte del Charge Management Device Working Group, insieme ad ESA, NASA e ai gruppi di UFL,ETHZ, e Trento che contribuiscono al GRS per LISA.

LISA Firenze Urbino: studio e simulazione del processo di carica delle masse di prova per l'interazione con i raggi cosmici. E' il gruppo di riferimento del campo, tanto che nel dicembre 2020 ESA ha finanziato con 400k€ la proposta presentata dai gruppi di Urbino/Firenze e Trento, insieme a OHB-Italia, in risposta ad un ITT ESA "Test mass Charging toolkit and LISA Pathfinder (LPF) Lessons Learned".

Siglato accordo di collaborazione con il CERN su questioni legate all'outgassing.

Trasferimento tecnologia del LISA GRS alla geodesia: contributo al PNRR PE-15 (Space) per GEO-GRS development study

Ancora non assegnata GRS FEE SCOE: sofisticata elettronica di test che simula il comportamento elettrico della massa di prova e del sensore capacitivo connesso alla GRS Front End Electronic. Per test del software e dei comandi al sistema di controllo dei satelliti LISA, sia a terra che durante la missione. ESA l'ha inserito formalmente tra i Ground Support Equipment per il GRS, e guarda quindi all'Italia come naturale candidato a fornirlo.

LISA Trento group activities

- Contribution to the LISA design/ project

- Contribution to the simulator of the LISA space observatory

- Gravitational Reference Sensor development: supported the key analysis and key documentation, including the crucial definition of requirements, and reviews in collaboration with OHB Italia, ASI, ESA and the two Primes.

- Development of an alternative technique for calculating TDI combinations, and involvement in the activities of the INREP (Initial Noise Reduction Pipeline) group, in particular in the development of an independent verification pipeline for the construction of TDI

- Contribution to a catalog of instrumental artifacts (the "glitches" in the accelerating signal seen by LISA Pathfinder) that can be interfaced with the LISA simulator and to an algorithm for inserting these artifacts into the phase signals of the simulator.

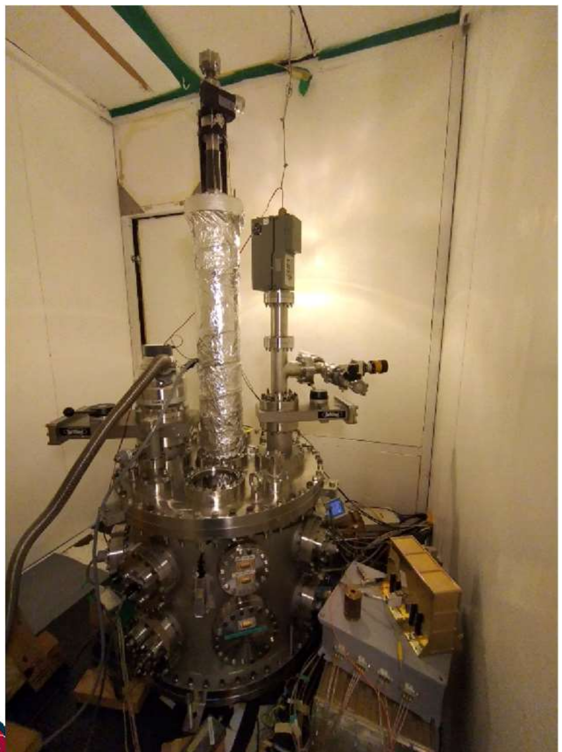
- Consolidation of LISA Pathfinder results for in-flight TM release LISA PF: an ASI contract to OHB Italia started an engineering evaluation of the LPF GPRM system and possible design modifications. The UTN team is participating in this study, based on LPF experience and ground-testing heritage.

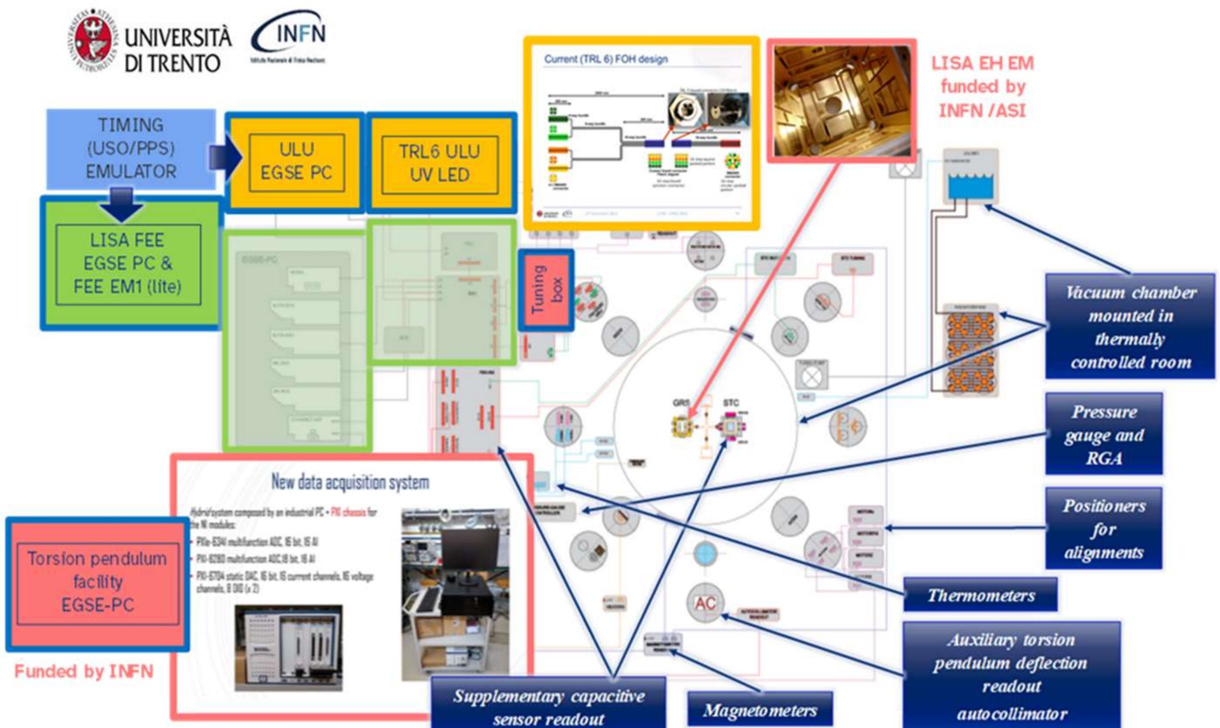
- Torsion pendulum facilities in Trento: the experimental investigation of the discharge system based on synchronized pulsed UV LED light continued by investigating the charge noise introduced by the basic continuous discharge scheme envisaged for LISA, with the aim of verifying the proposed noise model. The planning of upgrading interventions for the 4-mass pendulum/1-mass pendulum continued in view of the test campaign envisaged in the LISA GRS verification plan.

- Development of a model for the tracking of the UV light and of the photoelectrons, and of capacitive sensor electrostatic model

LISA Trento group activities: torsion pendulum testing

- Firts release of Testing Plan @ ISRR (May 2023)
- Definition of the detailed testing facilities configurations, planning of the maintenance/upgrading activities within 2023 (with a second release of Testing Plan)
- Completion preparation/maintenance/upgrades of testing facilities for GRS EM level testing for GRS EM level testing TRR @ Q4 2024.
- Deliver final Testing Plan, Integration Procedure, Testing Procedure for GRS EM level testing TRR @ Q4 2024
- GRS EM level testing campaign KO @ Q1 2025, with core testing results provided @ GRS PDR and for the QM GRSH phase.





Richieste Trento per testing con i pendoli di torsione del EM EH+TM Release facility

Capitolo	Descrizione	NOTE	Parziali (K-EUR)
interno	Meeting di collaborazione: 1 incontro con i referees non a Trento (4 persone 2K), 1 meeting di collaborazione non a Trento 4 persone (2k)		4,00
interno	1 conferenza internazionale per persona in presenza (2 k a persona x 14 persone) 28 k	Inseriti per riferimento nella discussione delle missioni su dotazioni	28,00
apparati	copia del sensore capacitivo di volo di LISA destinato alla campagna di test con i pendoli di torsione di Trento, Costi stimato provvisorio, contrattazione con OHB ed ASI in corso	Per la campagna di test con il pendolo 4TM facente parte del percorso di verifica a terra del GRS	500,00
apparati	Test Mass superfici rappresentative delle masse di LISA, più grande	Per indagini molto sensibili con il pendolo a 1TM, la test mass è più grande di quella di LISA in modo da ridurre i gap con gli elettrodi del sensore capacitivo amplificando le interazioni stray superficiali,	20,00
apparati	3 x Multipin electrical high vacuum electrical feedthrough	4TM: sostituire quelli vetusti non più affidabili	2,00
consumo	Materiali da costruzione, colle, componentistica elettronica e ottica per piccoli interventi di upgrade/manutenzione degli apparati	Per tutte le facility	6,00
inventario	posizionatori motor linear stage high vacuum compatible	Per sostituire quella non pù funzionanet del 4TM	4,50
inventario	multimetro Keithley per la lettura dei termometri (Keitley 2700/E, Farnell, 1800)	Per il monitoraggio della temepratura del pendolo 1TM	2,00
inventario	Pompa turbo Hipace 700 DN 160 CF-F	Pendolo 1TM	12,00
inventario	Due Lock-in Stanford SR830	1TM:messa in funzione readout/actuation nuovo (basta uno!)	15,00
inventario	Rigol DG1062Z 2 canali	1TM:messa in funzione readout/actuation nuovo	1,00
inventario	alimentatore DC (Rigol DP832A tripla uscita)	1TM:messa in funzione readout/actuation nuovo	0,50
manutenzione	Manutenzione dispositivi per sistemi da vuoto e bagni termici con sistema di termalizzazione, autocollimatore	per tutte le facility	8,00
		TOTALE	603,00

Condivisione costi tra ASI e INFN. Per INFN: 350 kEUR IVA incl.

Nel 2023 ASSEGNATI 370 k€
Nel 2024 richieste dell'ordine di 100 k€

Gruppo di Trento

- 15 ricercatori/tecnologi, circa 14 FTE

Cognome	Nome
Bortoluzzi	Daniele
Cavalleri	Antonella
Chiavegato	Vittorio
Dal Bosco	Davide
Dalla Ricca	Edoardo
Dimiccoli	Francesco
Dolesi	Rita
Ferroni	Valerio
Mezzena	Renato
Sala	Lorenzo
Vetrugno	Daniele
Vignotto	Davide
Weber	William
Zanoni	Carlo

+ nuovo assegnista da settembre 2023
Stefano Vitale associazione senior

Pubblicazioni recenti

"Sensor noise in LISA Pathfinder: An extensive in-flight review of the angular and longitudinal interferometric measurement system", M. Armano *et al* (LISA Pathfinder Collaboration), *Phys. Rev. D* 106:082001 (2022) [1]

"Transient acceleration events in LISA Pathfinder: properties and possible physical origin", M. Armano *et al* (LISA Pathfinder Collaboration), *Phys. Rev. D* 106:062001 (2022) [2]

"The role of low-energy electrons in the charging process of LISA test masses", S. Taioli *et al*, *Class. Quantum Grav.*, 40:075001 (2023) [29]

"Charging of free-falling test masses in orbit due to cosmic rays: Results from LISA Pathfinder", M. Armano *et al* (LISA Pathfinder Collaboration), *Phys. Rev. D* 107:062007 (2023) [3]

"Effectiveness of null time-delay interferometry channels as instrument noise monitors in LISA", M. Muratore *et al*, *Phys. Rev. D*, 107:082004 (2023)[25]

Note tecniche recenti

Documenti consegnati dal gruppo di Trento per la I-SRR:

1. Management plan for the GRS (LISA-UTN-INST-PL-001) [33]
2. GRS EM test plan at the University of Trento / INFN TIFPA (LISA-UTN-INST-TP-001)[7]
3. GRS Operations Concept Analysis (LISA-UTN-INST-TN-024)[30]
4. GRS TM UV discharge model (LISA-UTN-INST-TN-021)[8]
5. GRS EH TM electrostatic capacitance model (LISA-UTN-INST-TN-020) [9]
6. GRS Electromagnetic shield effect of the EH (LISA-UTN-INST-TN-022)[10]
7. Model of the plunger-to-TM gap for the GPRM (LISA-UTN-INST-TN-025)[4]

Altri documenti di progetto per il GRS, fornita per la I-SRR, consegnata da OHB con un contributo importante UTN:

1. GRS system engineering plan (LISA-OHB-INST-PL-001 Iss. 4) [19]
2. GRS system risk assessment report (LISA-OHB-INST-RP-001 Iss. 2) [21]
3. GRS system requirements specification (LISA-OHB-INST-RS-002 Iss. 4) [20]
4. GRS head requirements specification (LISA-OHB-INST-RS-001 Iss. 3) [18]
5. GRS design description and justification (LISA-OHB-INST-DD-001 Iss. 4) [23]

Documenti del Consortium (FMT) consegnati per la I-SRR che includono un contributo importante del gruppo:

1. LISA Performance Model and Error Budget (LISA-LCST-INST-TN-003 v2.3) []
2. Consortium Performance Model Inputs Parameters and Noises (LISA-LCST-INST-RP-006 Iss. 1.1)
3. LISA Performance Model MBE and Allocations (LISA-LCST-INST-RP-006 Iss. 1)

Documenti di progetto ESA, soprattutto documenti di requisiti, prodotti in collaborazione con il gruppo di UTN per il GRS e con il FMT:

1. LISA Mission Requirements Document (ESA-L3-EST-MIS-RS-001 Iss. 2.1)
2. LISA Space Segment Requirements Document (ESA-L3-EST-MIS-RS-001 (Iss. 0.2 draft)
3. LISA GRS system and interface requirements document (ESA–LISA–EST–PL–RS–005, update per I-SRR)
4. LISA CMD system and interface requirements document (ESA–LISA–EST–PL–RS–010, update per I-SRR)

In fine una tesi di dottorato focalizzata sullo studio sperimentale del sistema di scarica UV:

- *Torsion Pendulum Testing of the LISA Charge Management System*, Davide Dal Bosco (aprile 2023, Università di Trento)