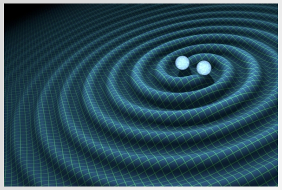
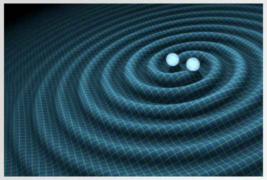


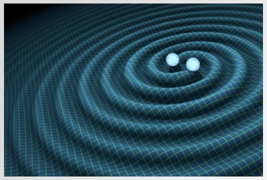
LISA: A spaceborne gravitational wave observatory

David Shoemaker, MIT
NASA L3 Study Team Chair

3 May 2017



- This series has had talks about most pieces of the GW jigsaw puzzle
  - LISA Sources: sure, hoped-for, and speculative
    - Unique access to very massive systems – SMBH
    - Offers uniquely high SNR for GR testing
    - A tiny chance at a view of the Cosmic GW Background
    - And a host of other astrophysics objectives
- Here discussion of the LISA mission
  - Conceptual design
  - Practical challenges
  - Demonstrated solutions; LISA Pathfinder
  - Baseline design
  - Organization of the LISA Project
  - The path forward

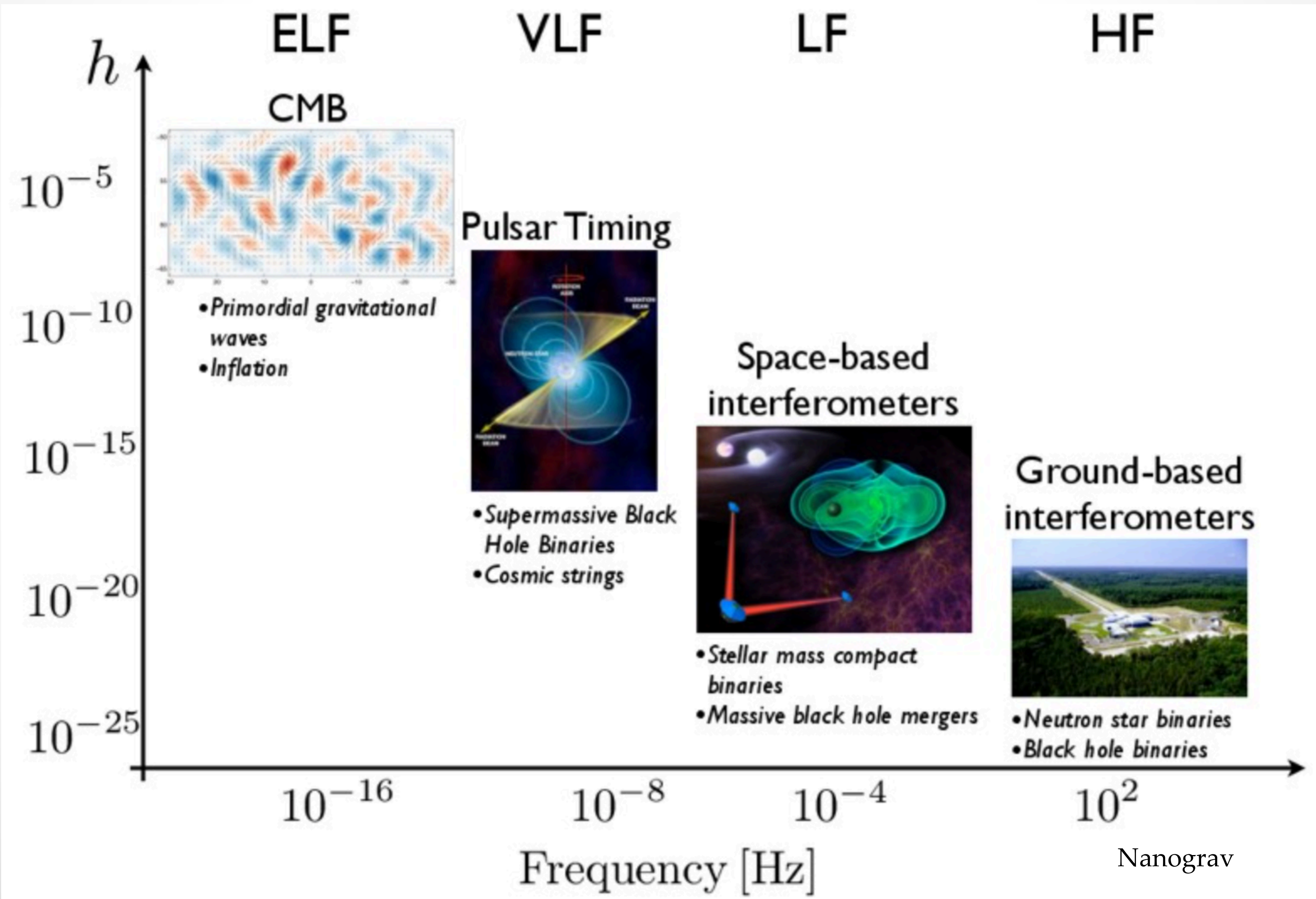


What is LISA?

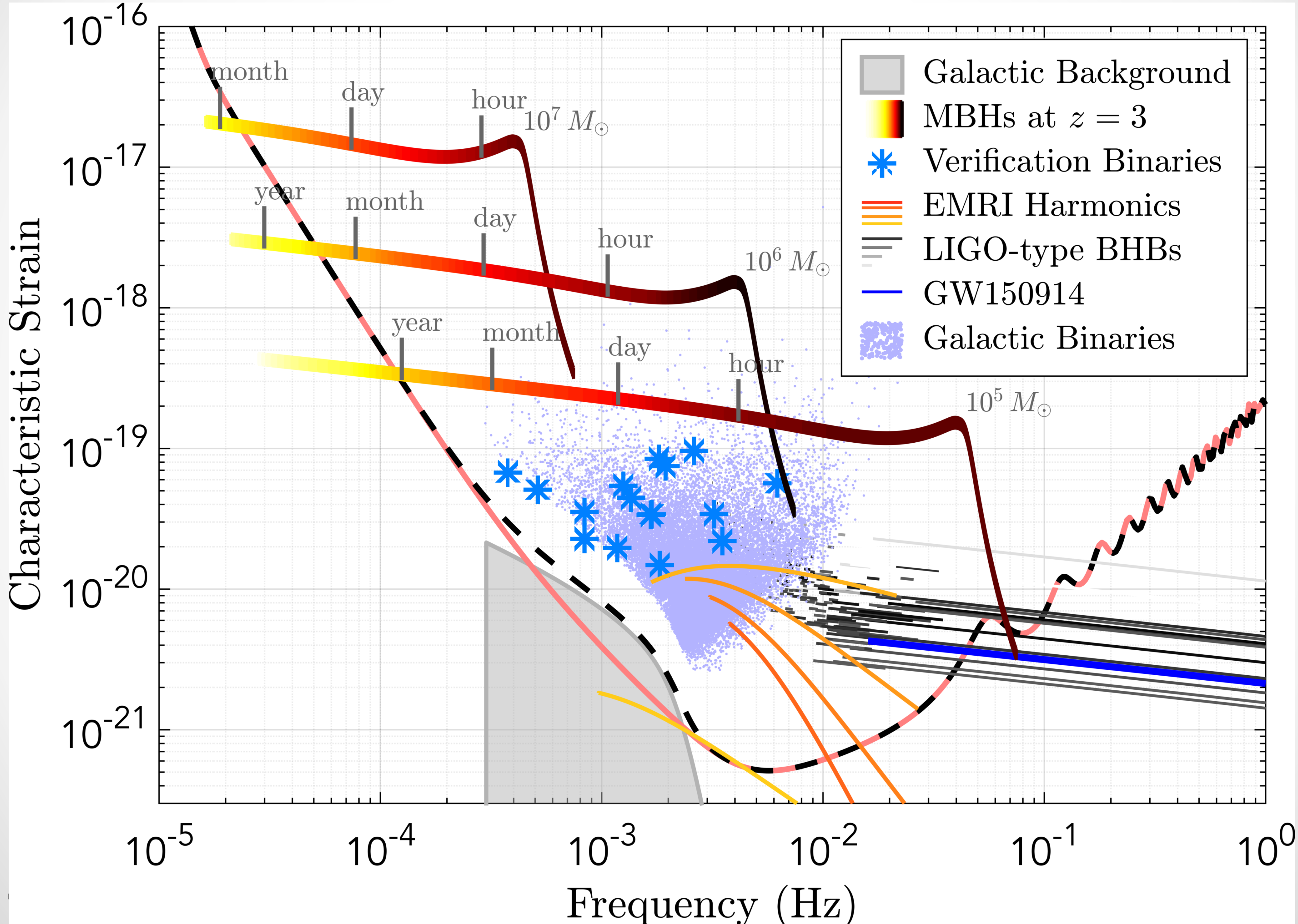
- LISA is the name of the proposed ‘L3’ ESA mission for a space-based gravitational-wave observatory
  - L3 = ESA’s third Large mission (JUICE is L1, Athena is L2)
- Uses laser interferometry to record gravitational-wave amplitude time series
- Studies very massive – up to 10^7 $M_{\odot}$ – astrophysical systems via their gravitational-wave emission
- Launch of 4-year nominal mission in early 2030’s

- NASA L3ST is the Study Team supporting NASA’s role in the ESA-Led mission
- Informing NASA on technical contributions, organizing astrophysics developments supporting the LISA mission

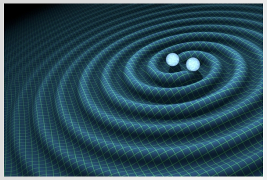
LISA's place in the spectrum



LISA Astrophysics

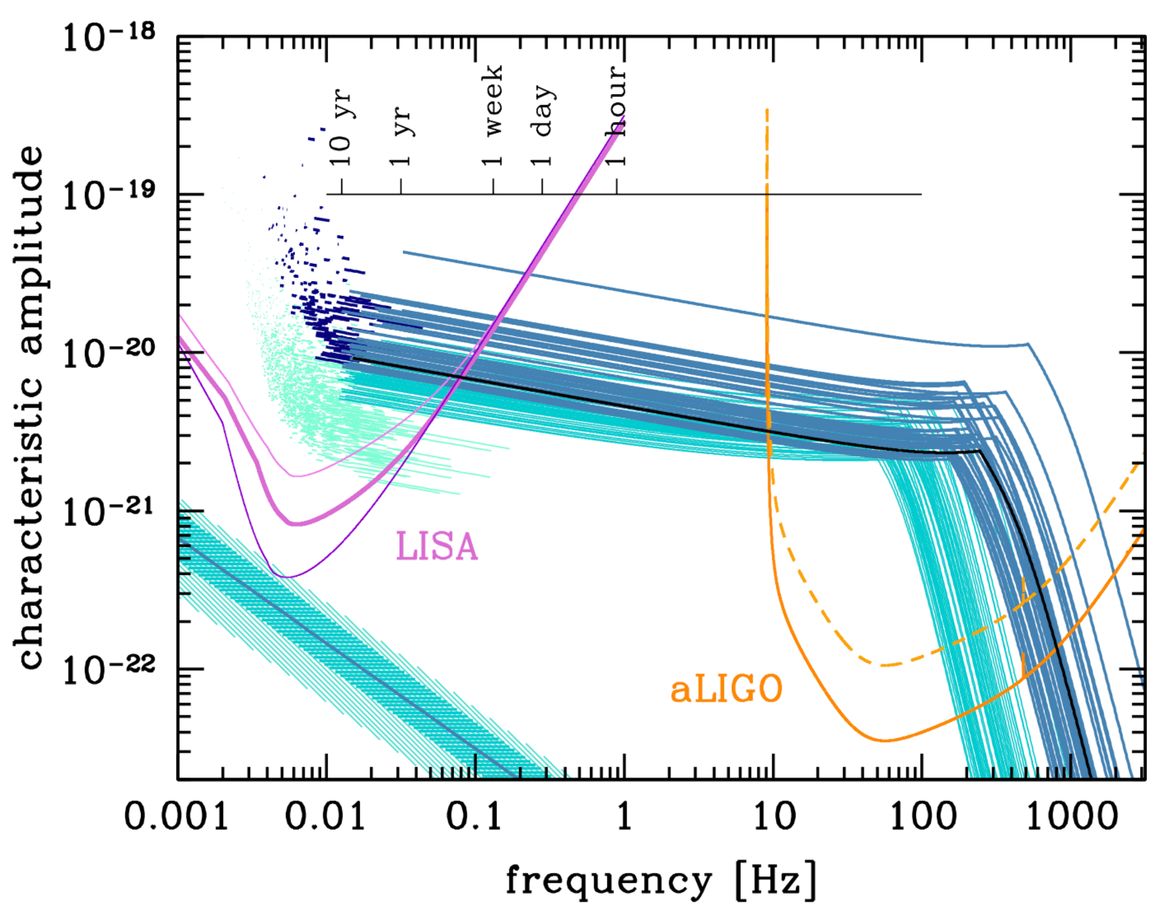


Credit: LISA L3 Mission Concept Proposal



Astrophysics with Binary Black Holes

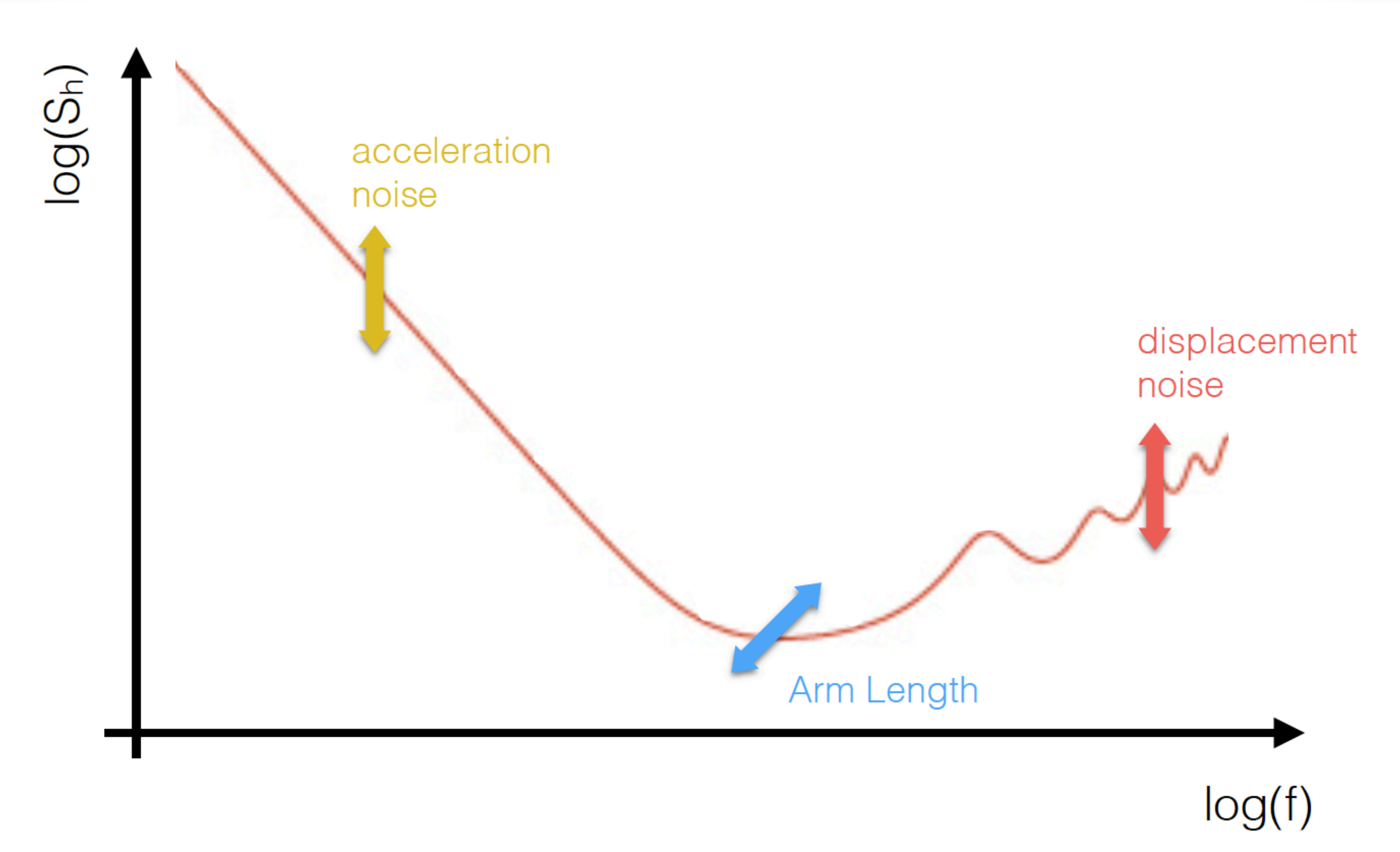
- Joint gravitational and electromagnetic observations
  - Low-latency alerts for EM observation (1 day)
  - High-precision pointing information (1 deg^2)
- Multi-band measurements with LISA and LIGO-like detectors
- (excited about 3G ground detectors in ~2034, but that's a different talk!)



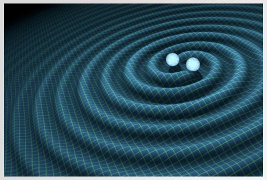
Credit: Sesana PRL 116, 1102

Sensitivity of LISA

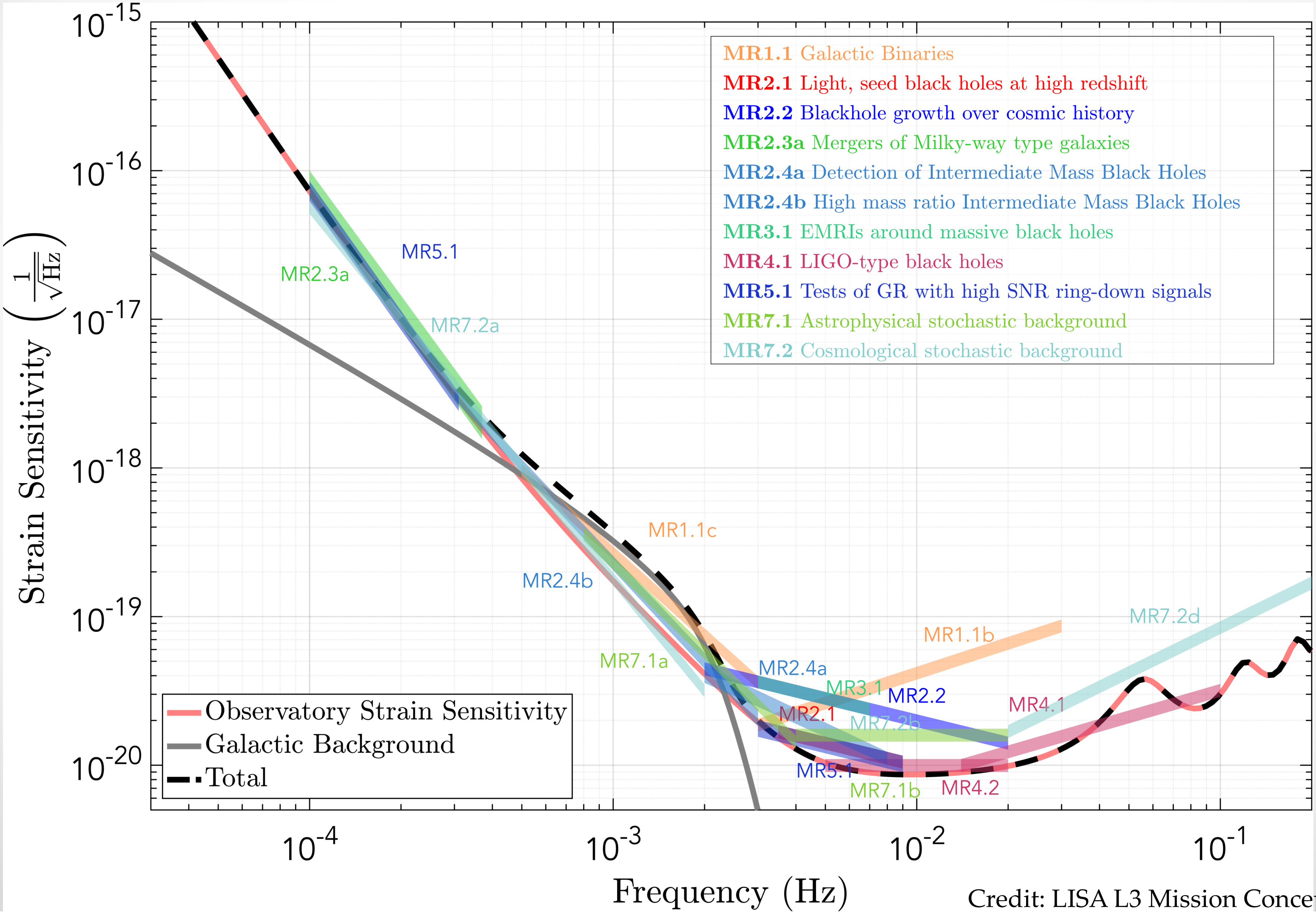
- Interferometric measurement between free masses
  - Light travel time influenced by distortion in space-time from GWs
- Challenges in both the interferometry and the test mass isolation



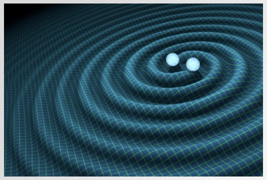
Credit: Ira Thorpe



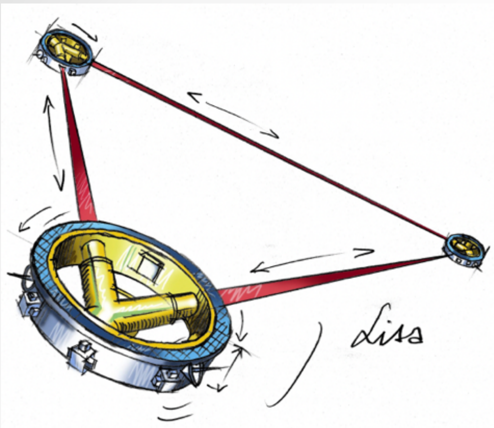
Science-imposed mission performance; 4-year mission

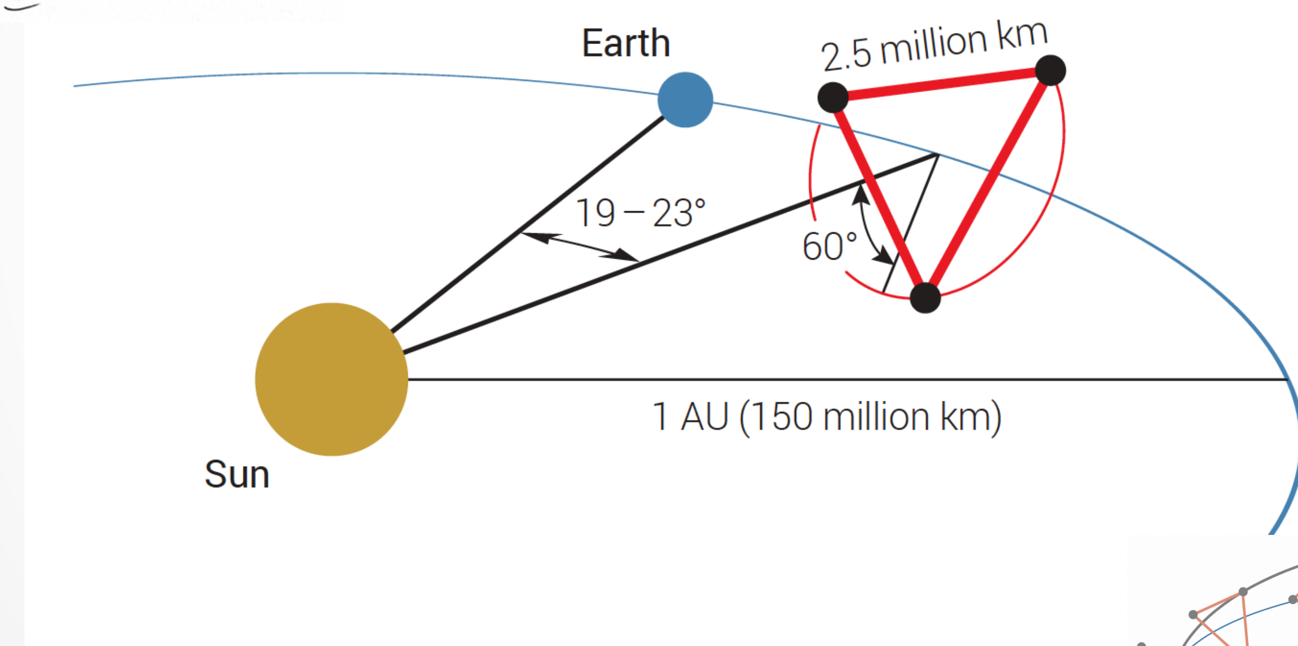


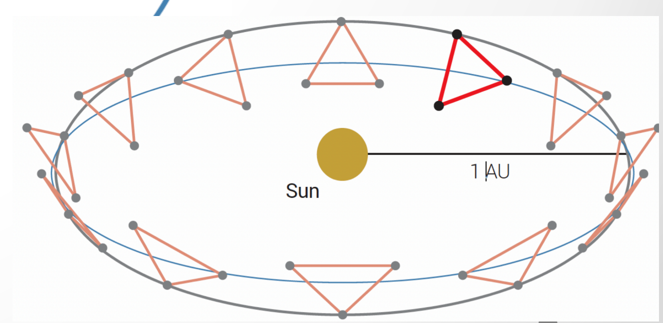
Credit: LISA L3 Mission Concept Proposal



LISA Constellation and Orbit

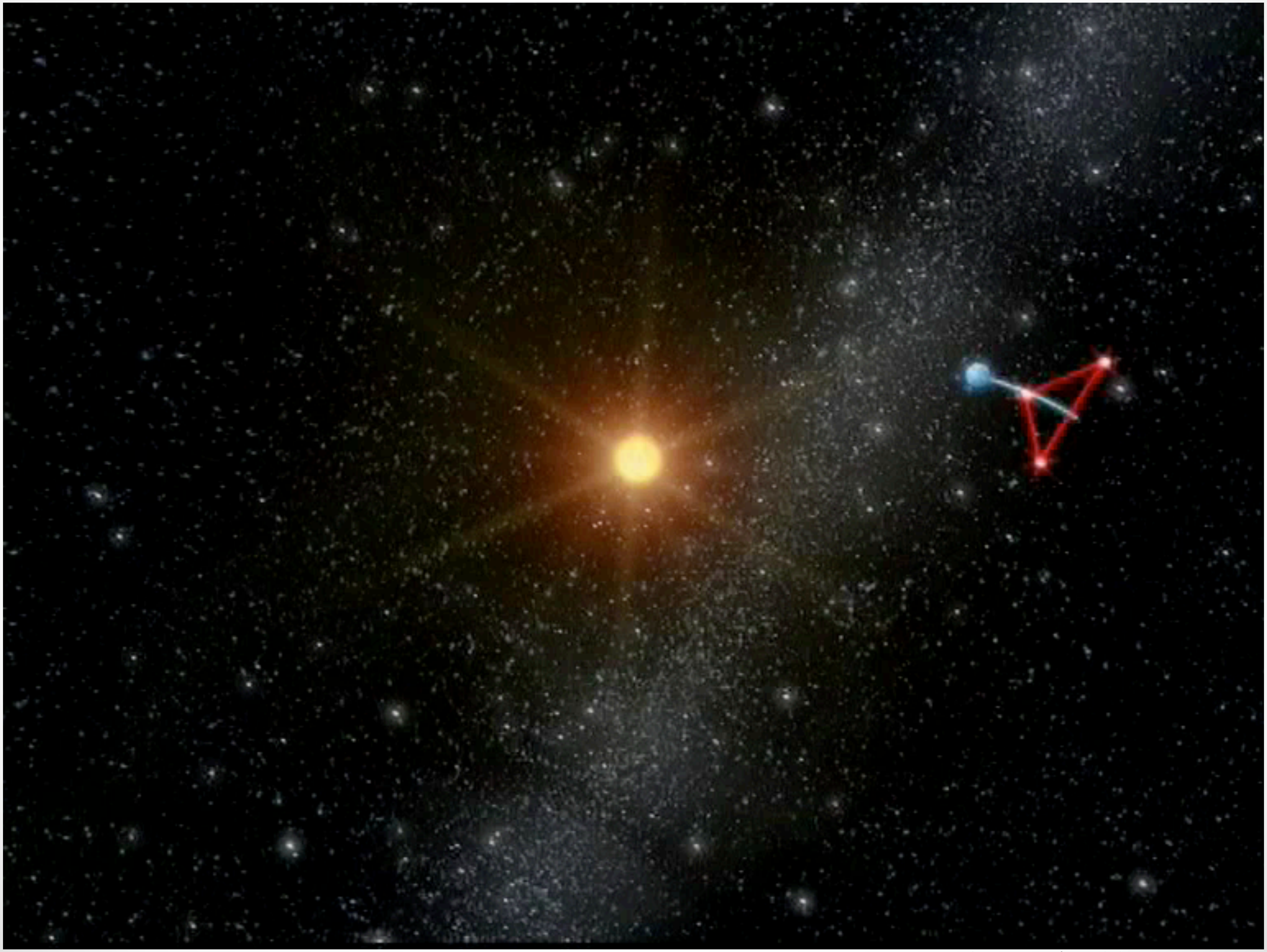




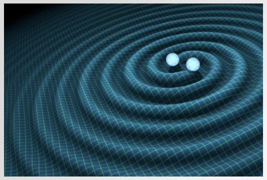


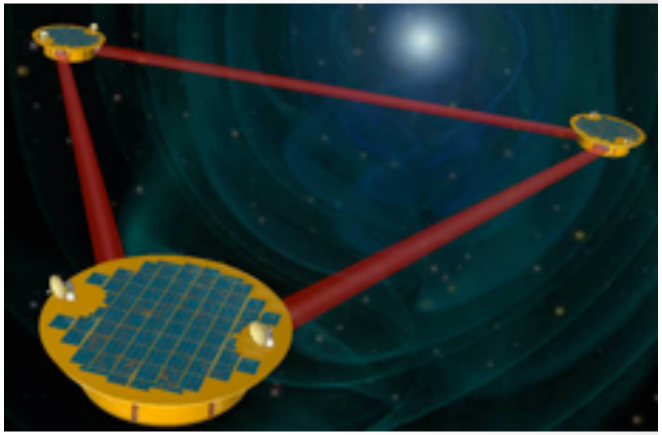
Credit: LISA L3 Mission Concept Proposal

LISA Orbit



Credit: AEI / Milde

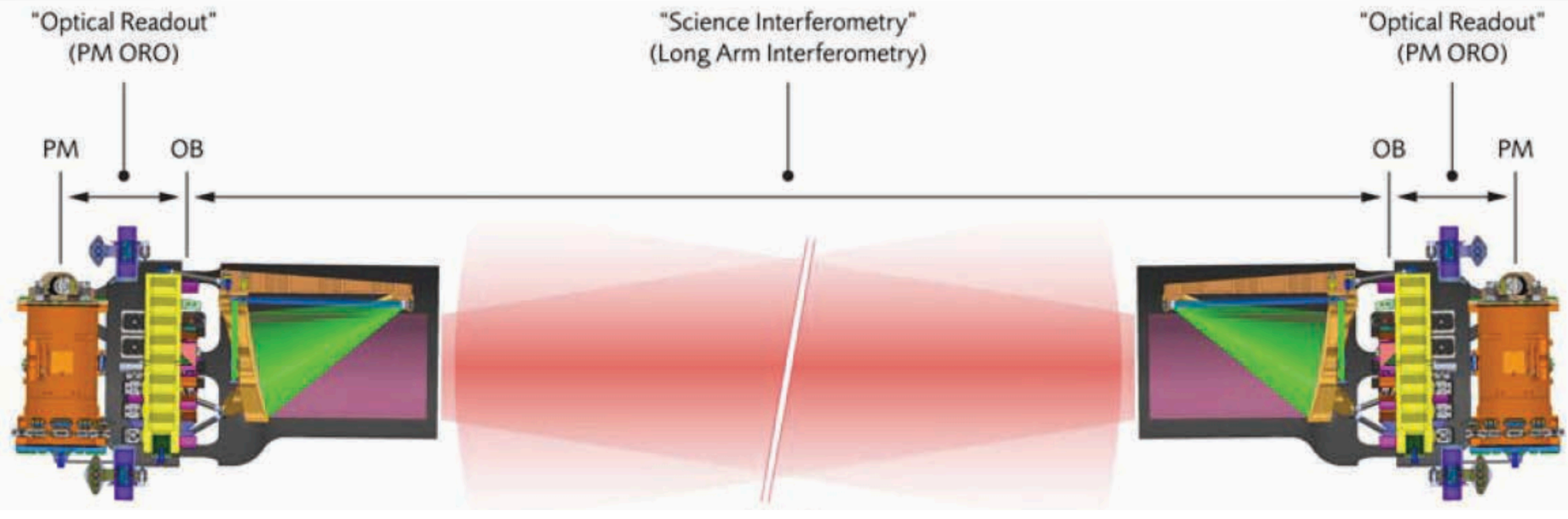


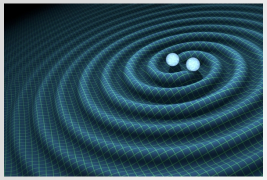


- Build constellation from one-way ‘links’ or arms
  - 6 links total
  - ‘back links’ made at each vertex using an optical fiber.
- Each link measurement contains large noise + small signal
- Combine link measurements on ground to extract signal. Accounts for varying arm-lengths.
- Fundamental sensing limit is shot noise
- Many other ‘technical’ noises. Error budget designed so that shot noise potential can be realized.
- Many options to meet overall system requirement (e.g. trade laser power, telescope diameter, etc.)

View of one arm of constellation

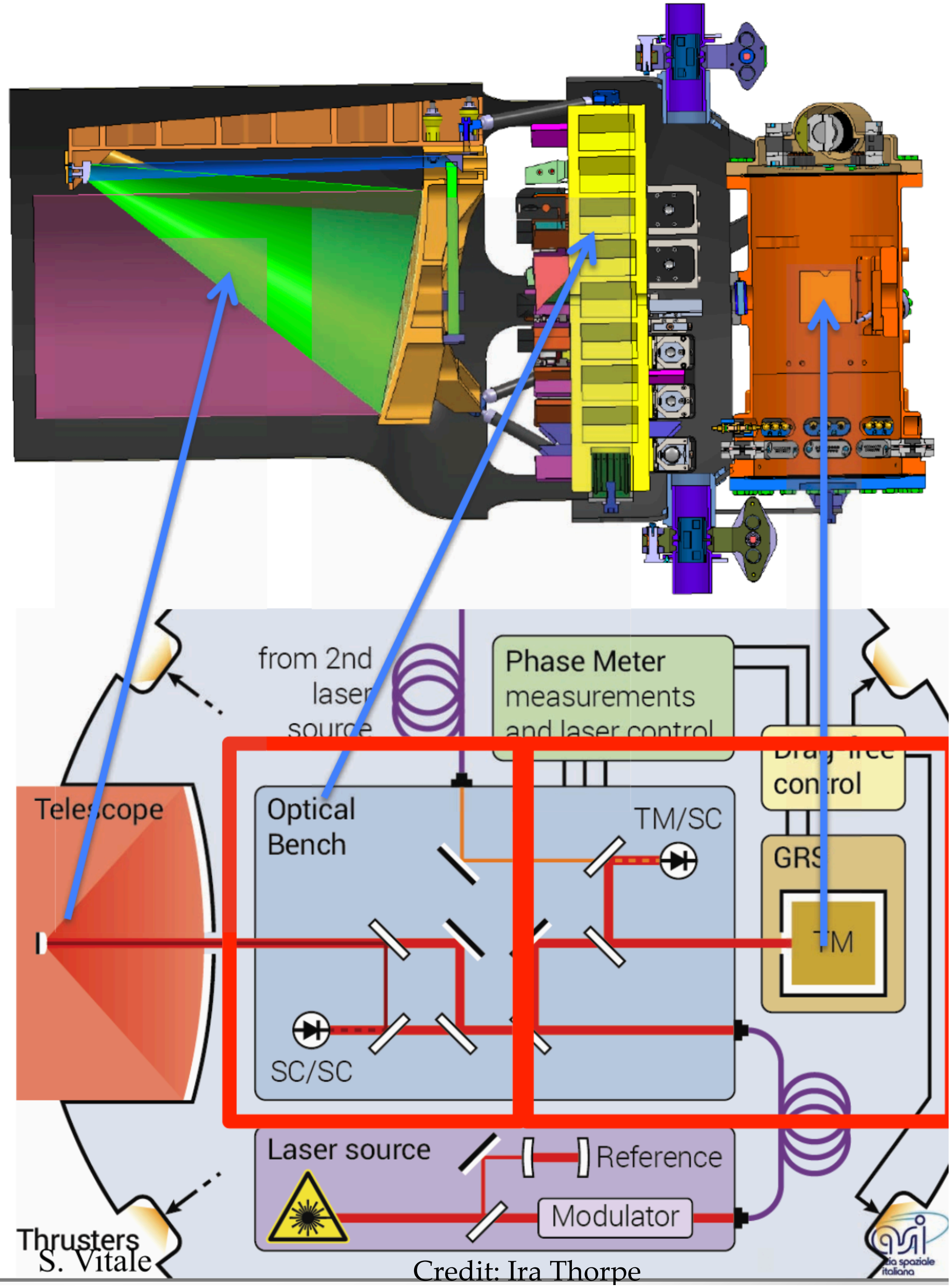
- Long baseline (~2gigameters) and h=**δ**L/L means large **δ**L – 'easy' to measure pico-meter length changes (LIGO does ~20^{-20})
- Constellation *not* 'locked formation flying' even if long-term stable
  - Screaming through fringes at tens of Mhz; phasemeter 'unfolds' fringes
- Forces on test mass must be very strongly filtered
  - Shielding must track test mass very precisely to avoid Newtonian attraction fluctuations



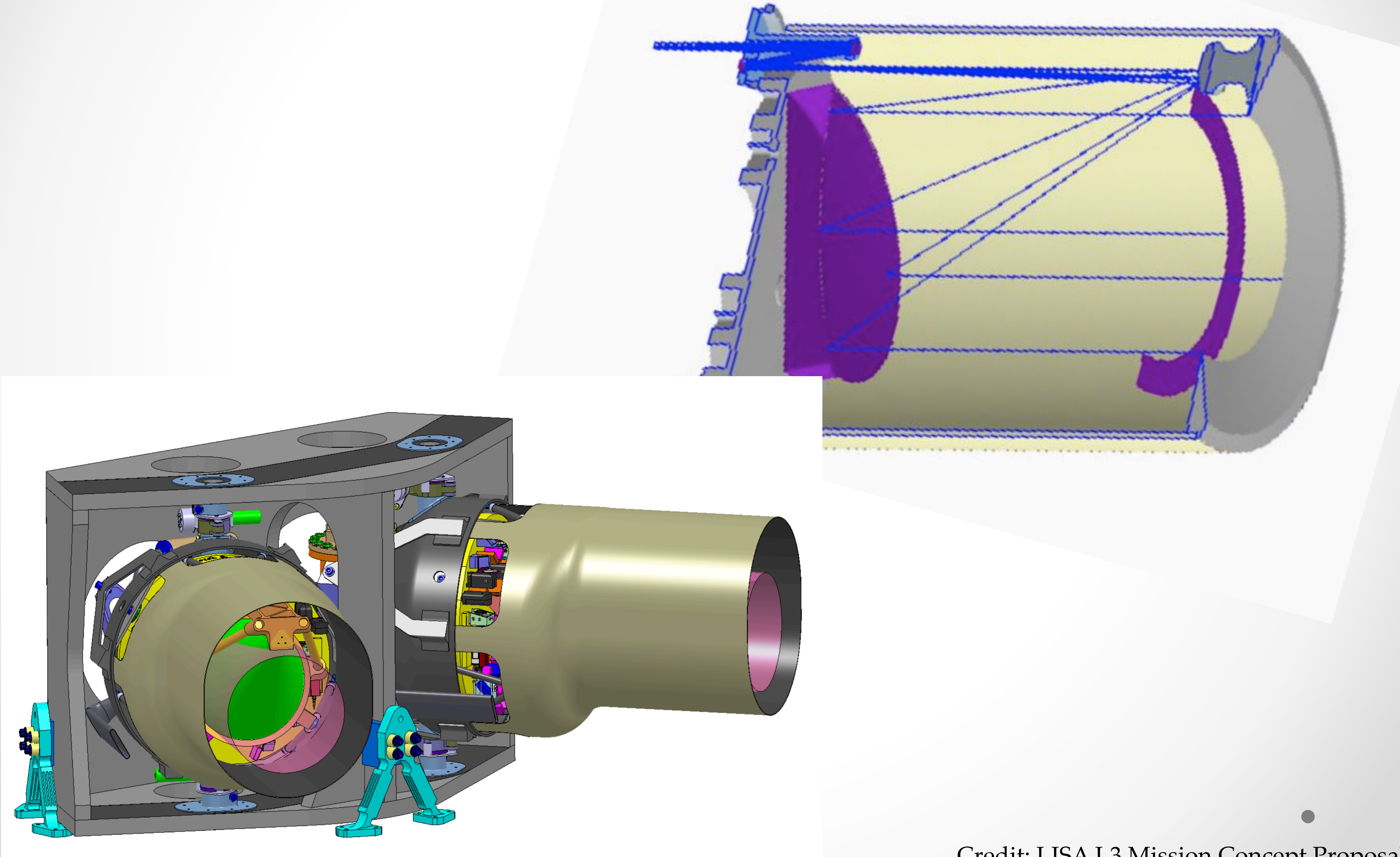


’End station’

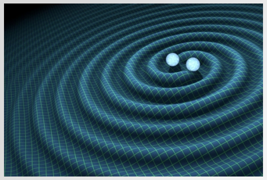
- Coupling telescope, optical bench, and test mass/cage
- Picometer mechanical stability required over tens of hours
- Send out ~2W; receive back ~100 picowatts
  - 1μ light; diffraction from 30cm telescope
  - Scatter from outgoing beam mixing with incoming beam



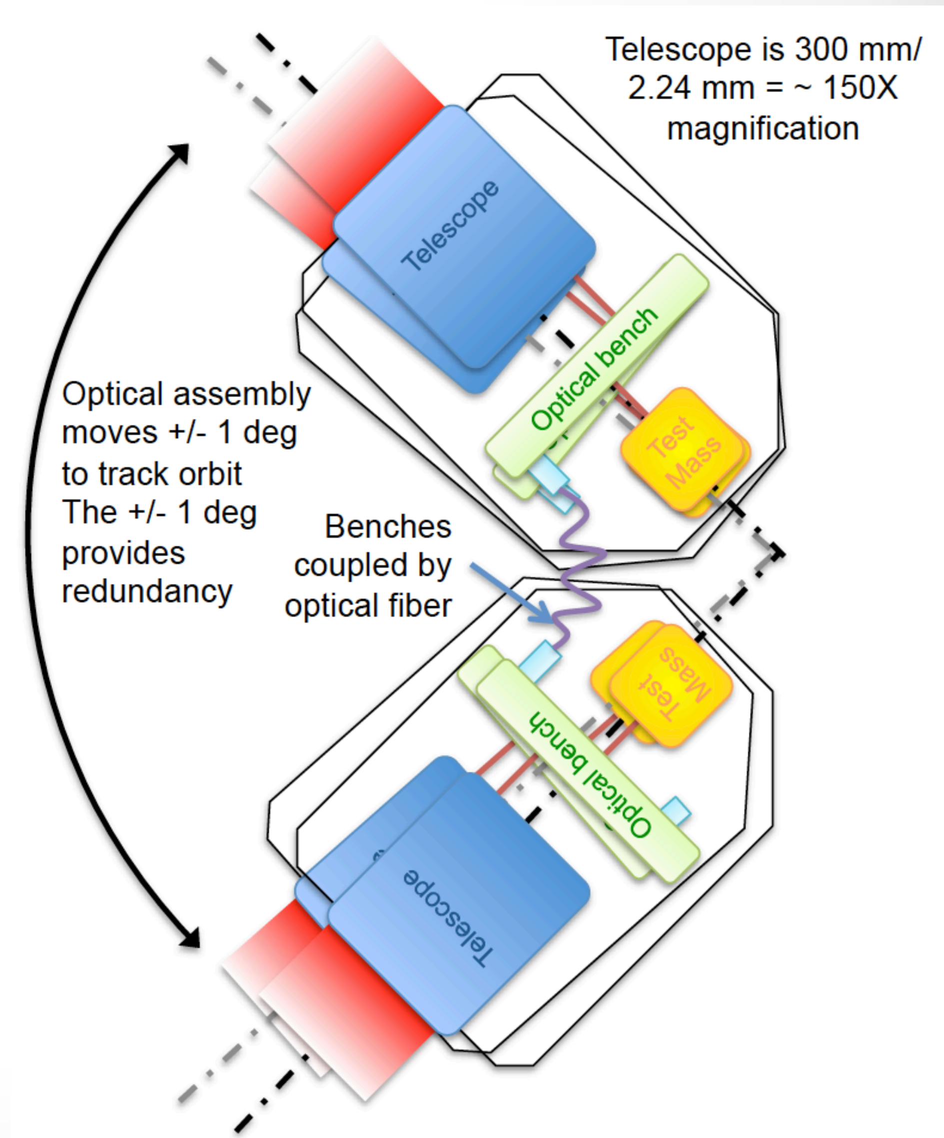
Send/Receive Telescopes



Credit: LISA L3 Mission Concept Proposal

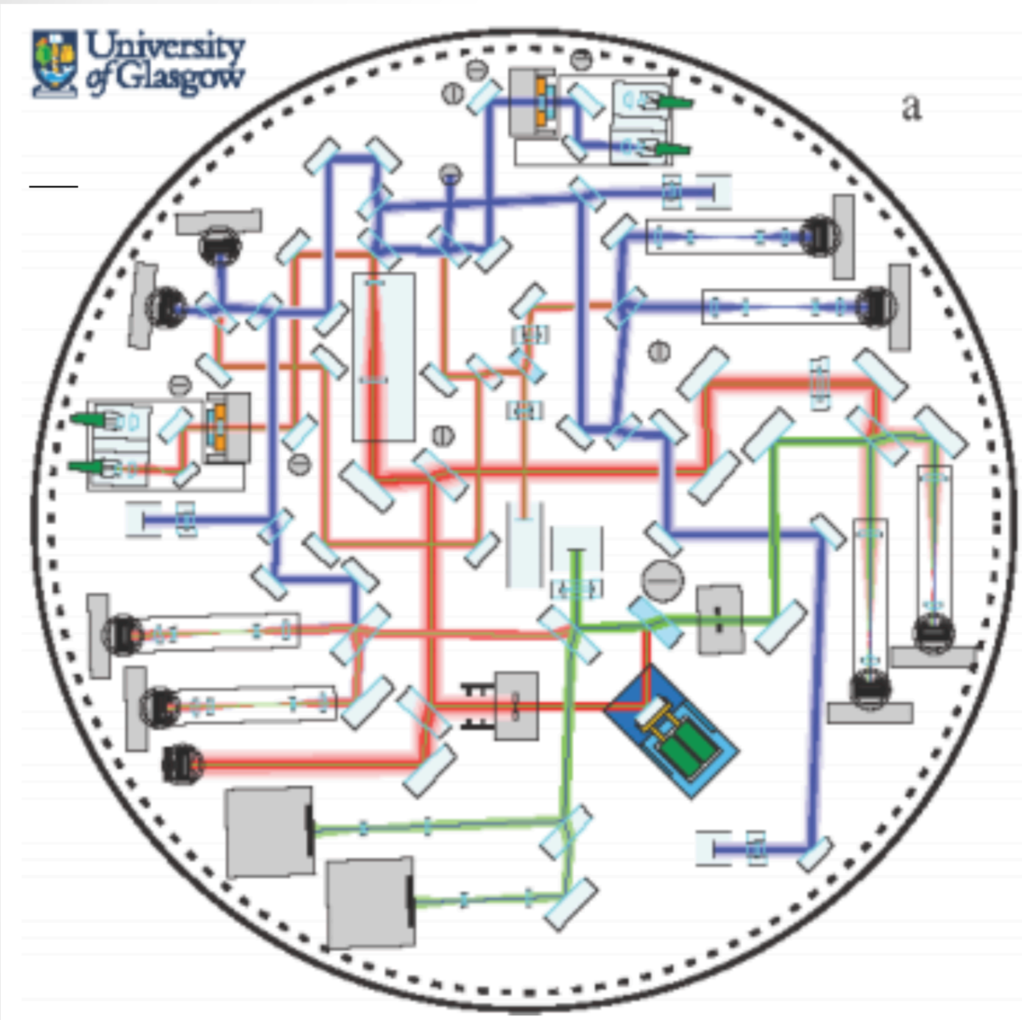


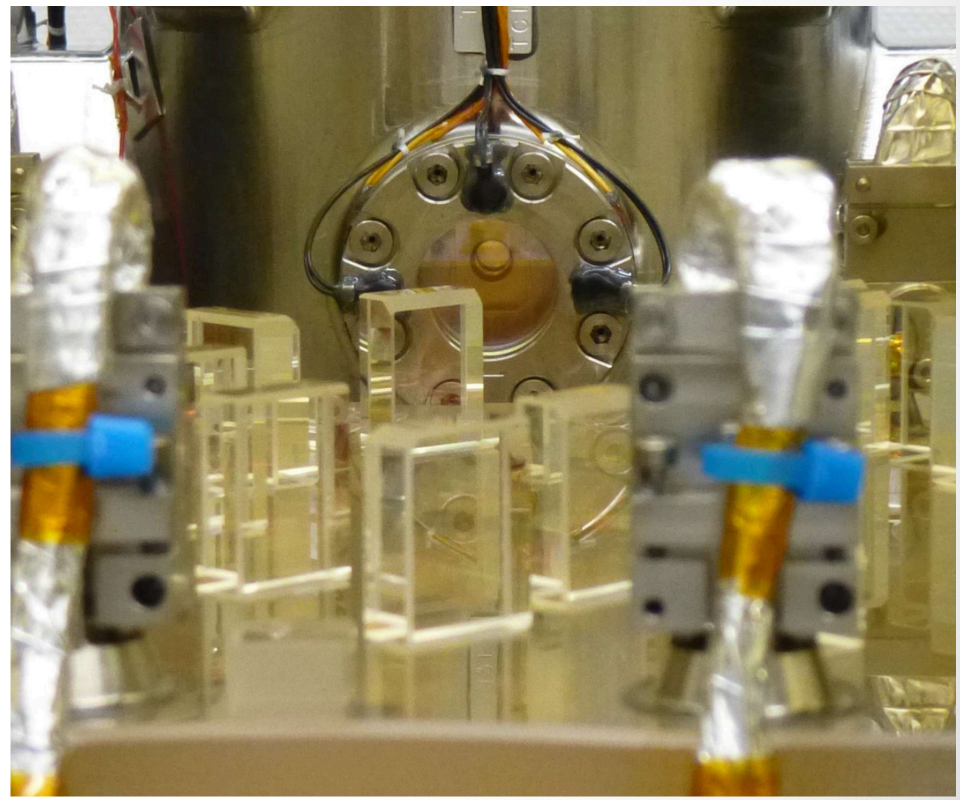
- Constellation *not* 'locked formation flying'
- Need to do pointing actively in telescope or as a unit
- Linking the two units is one of the leading remaining technologies
- May instead use 'in-field guiding', but adds complication, changing scatter, etc.



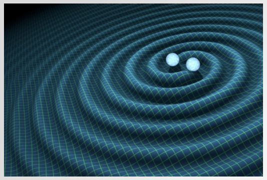
Credit: Ira Thorpe

More realistic optical bench



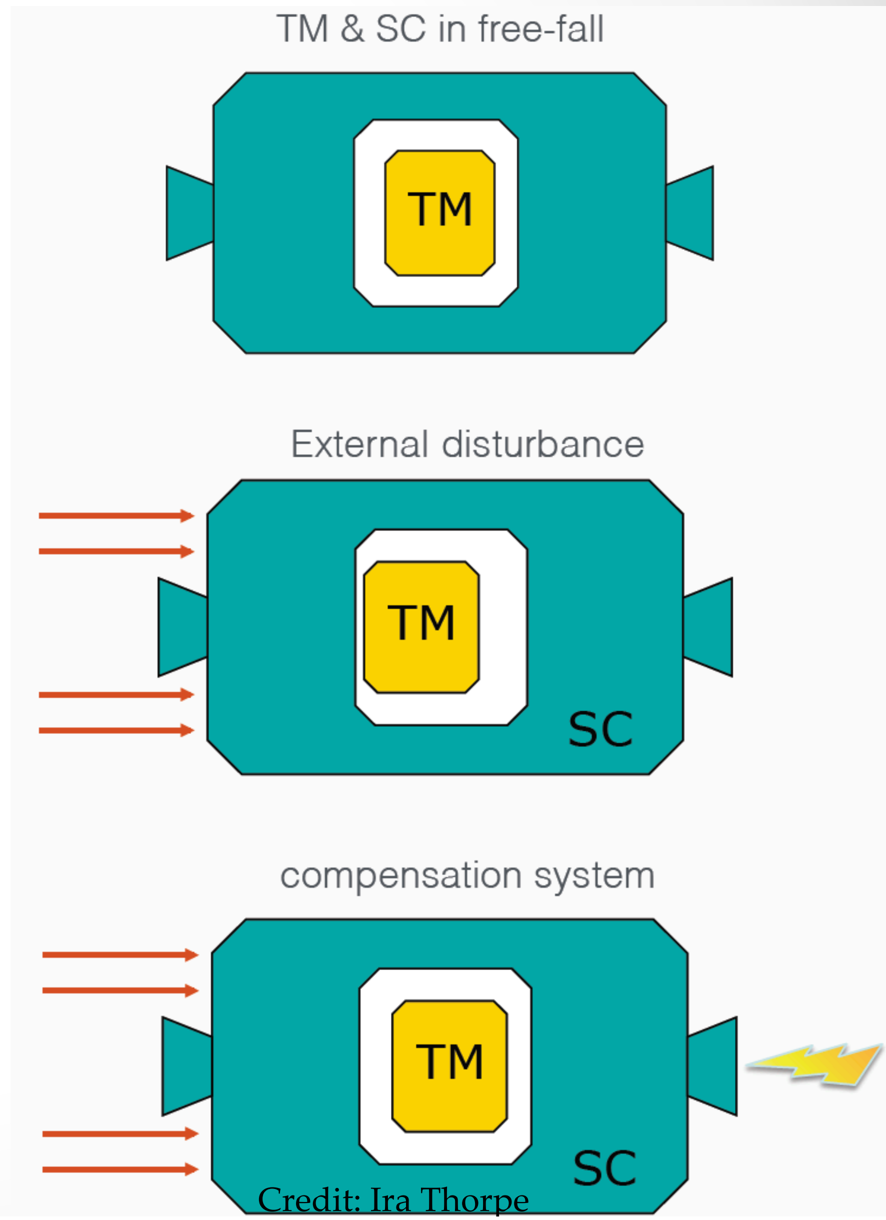


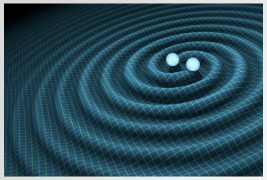
Credit: Harry Ward



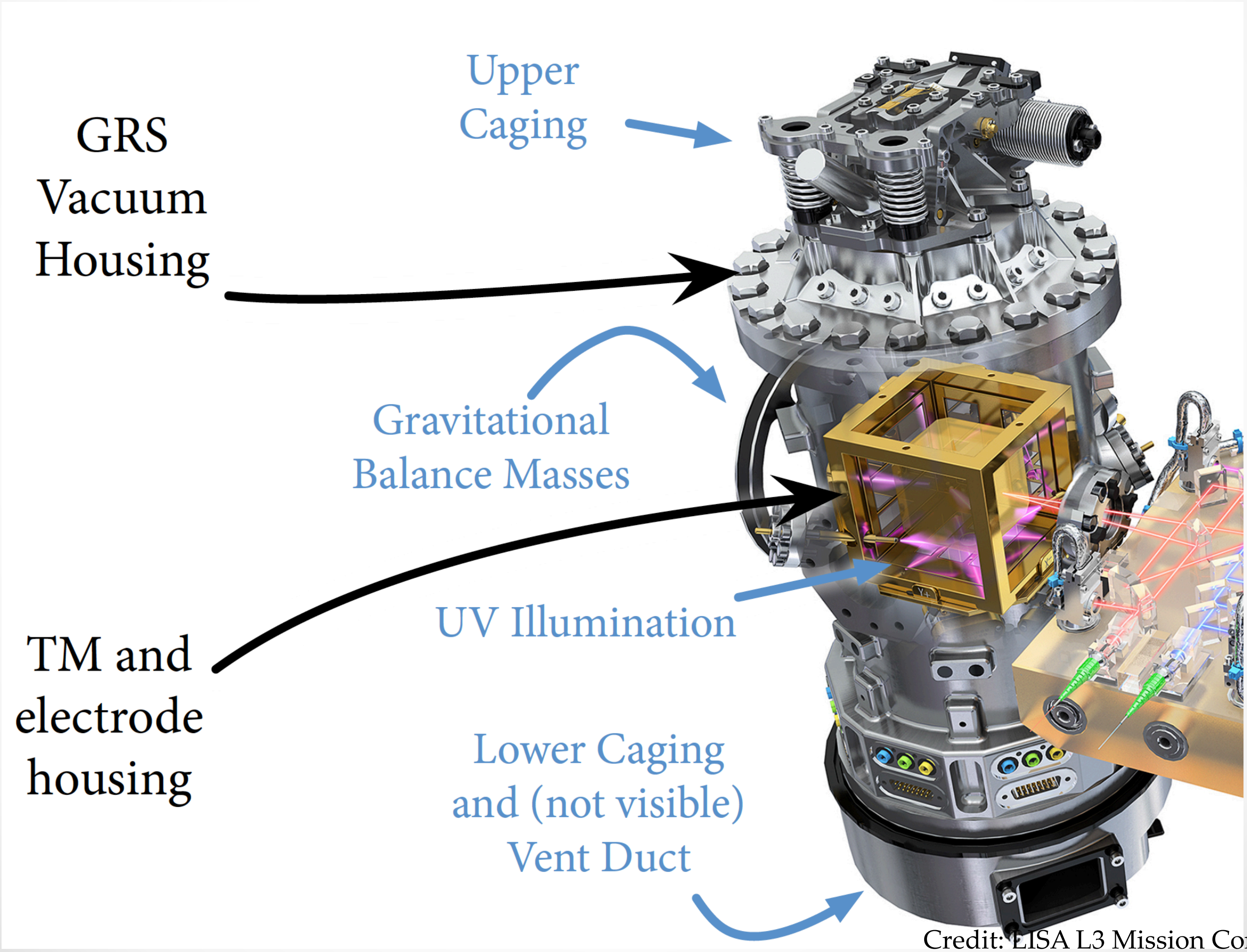
Drag-free control

- All degrees of freedom under servocontrol
- Key: avoid Forces on test mass
- Static: initial balance must be excellent
  - Cable tie ends must be weighed
- Dynamic:
  - Internal mass distribution must remain constant
  - Shielding must track test mass very precisely
  - Charging must be limited to prevent coupling to spacecraft
  - Thermal deformations of spacecraft must be controlled
  - Thermal noise from residual gas to be limited
-



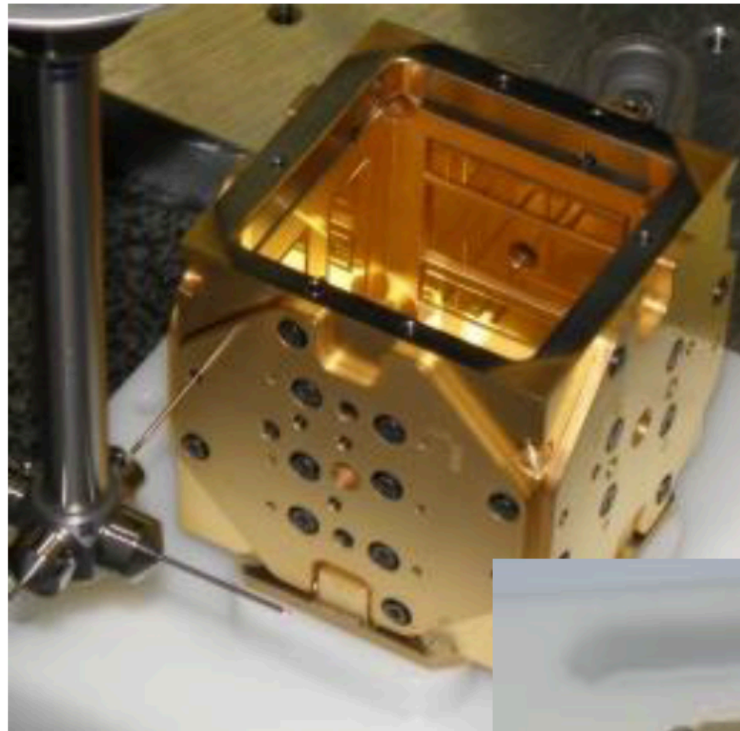


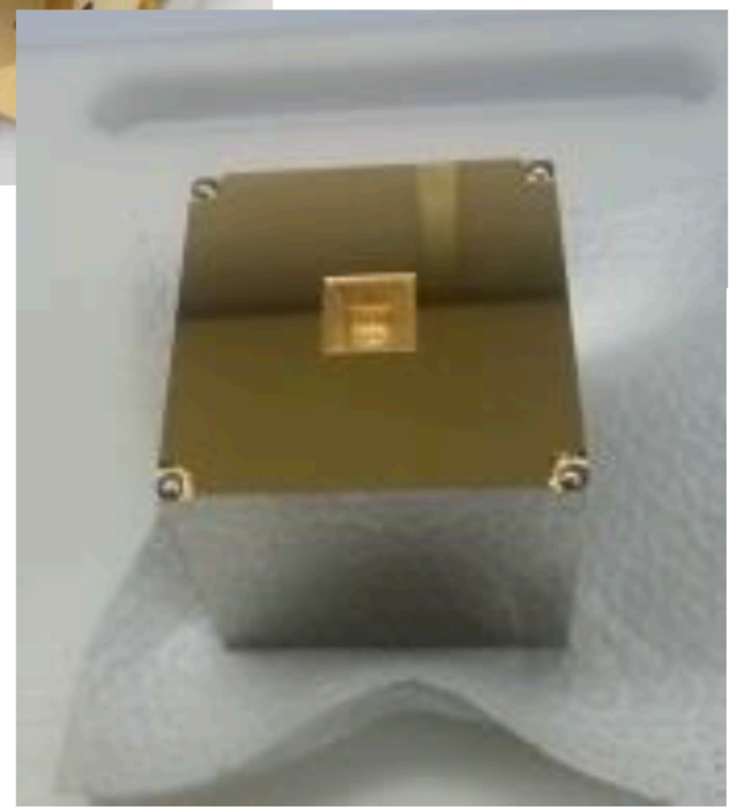
Gravitational Sensor (as flown on LISA Pathfinder)



Credit: LISA L3 Mission Concept Proposal

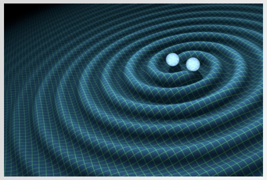
Test Mass and cage





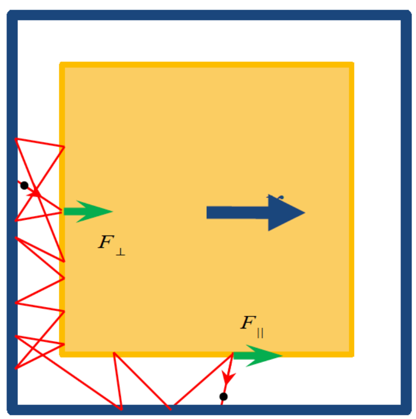
- Heavy TM, 2 kg Au-Pt
- 3-4 mm gaps
- no contacts (no discharge wire)
- AC-carrier force actuation
- Vent to space (< 10 mPa)

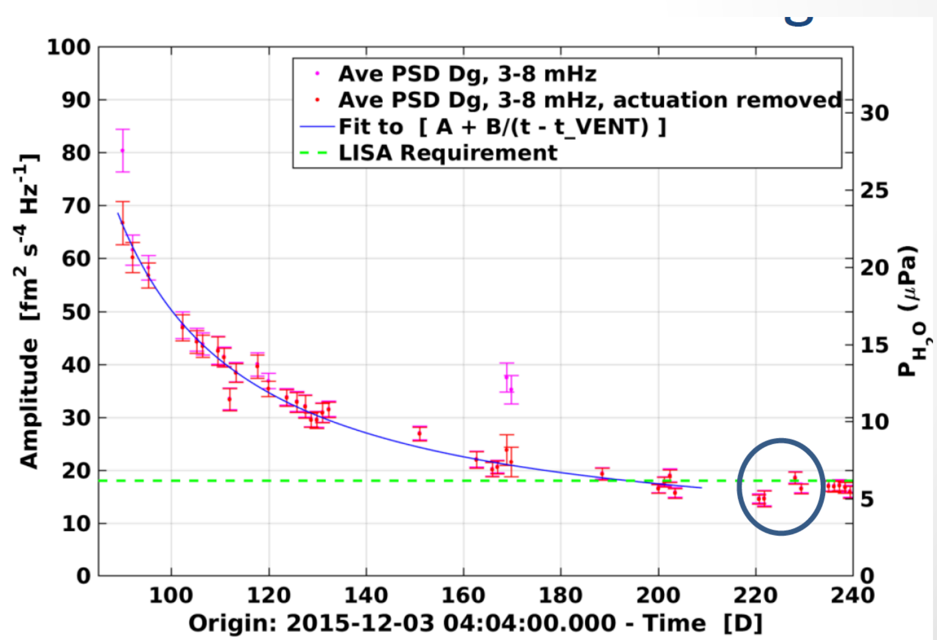
Credit: Bill Weber



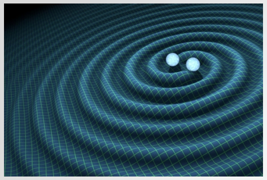
Thermal noise from residual gas

- Thermal noise from ‘squeeze film damping’
- But also stray electrostatic forces, thermal gradients making differential work functions…

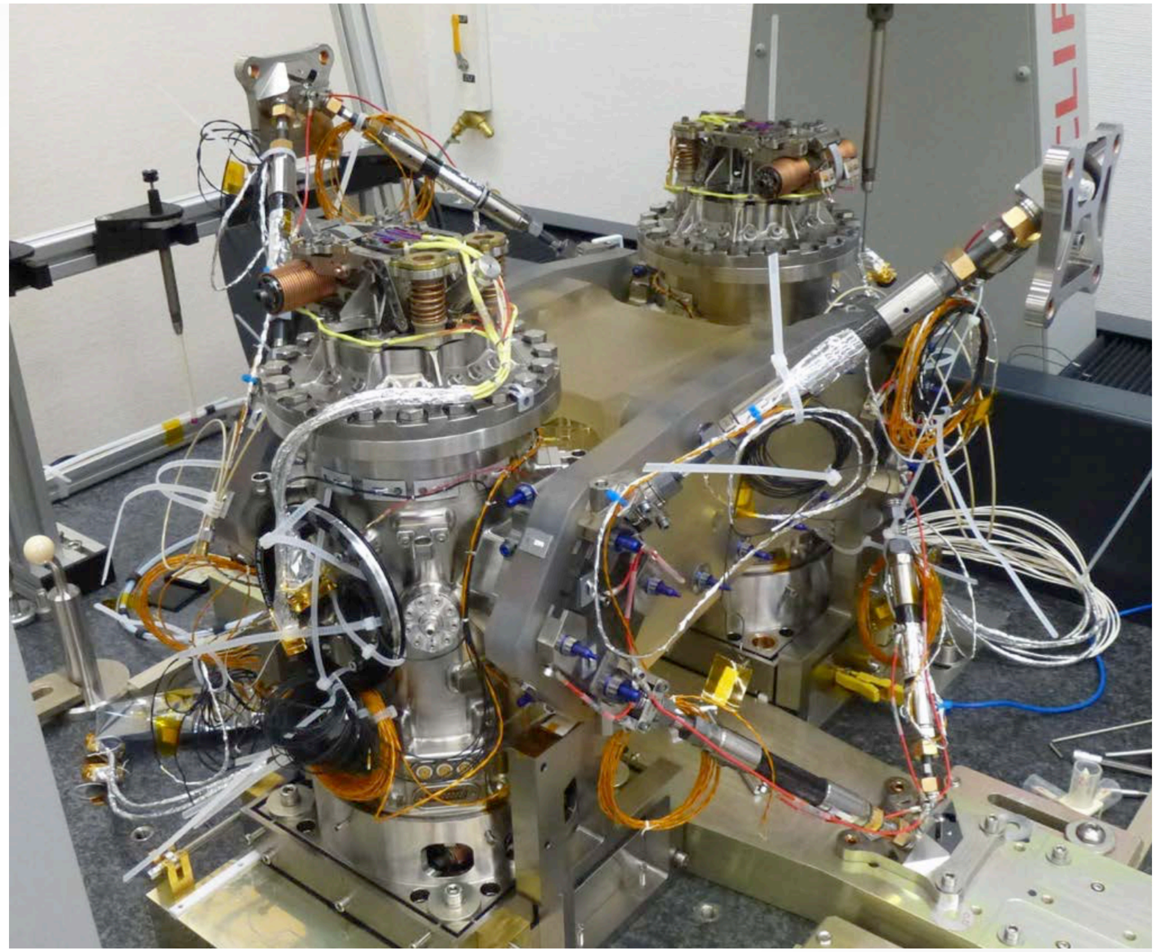




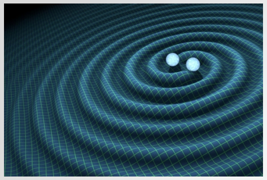
Credit: Bill Weber



LISA Pathfinder

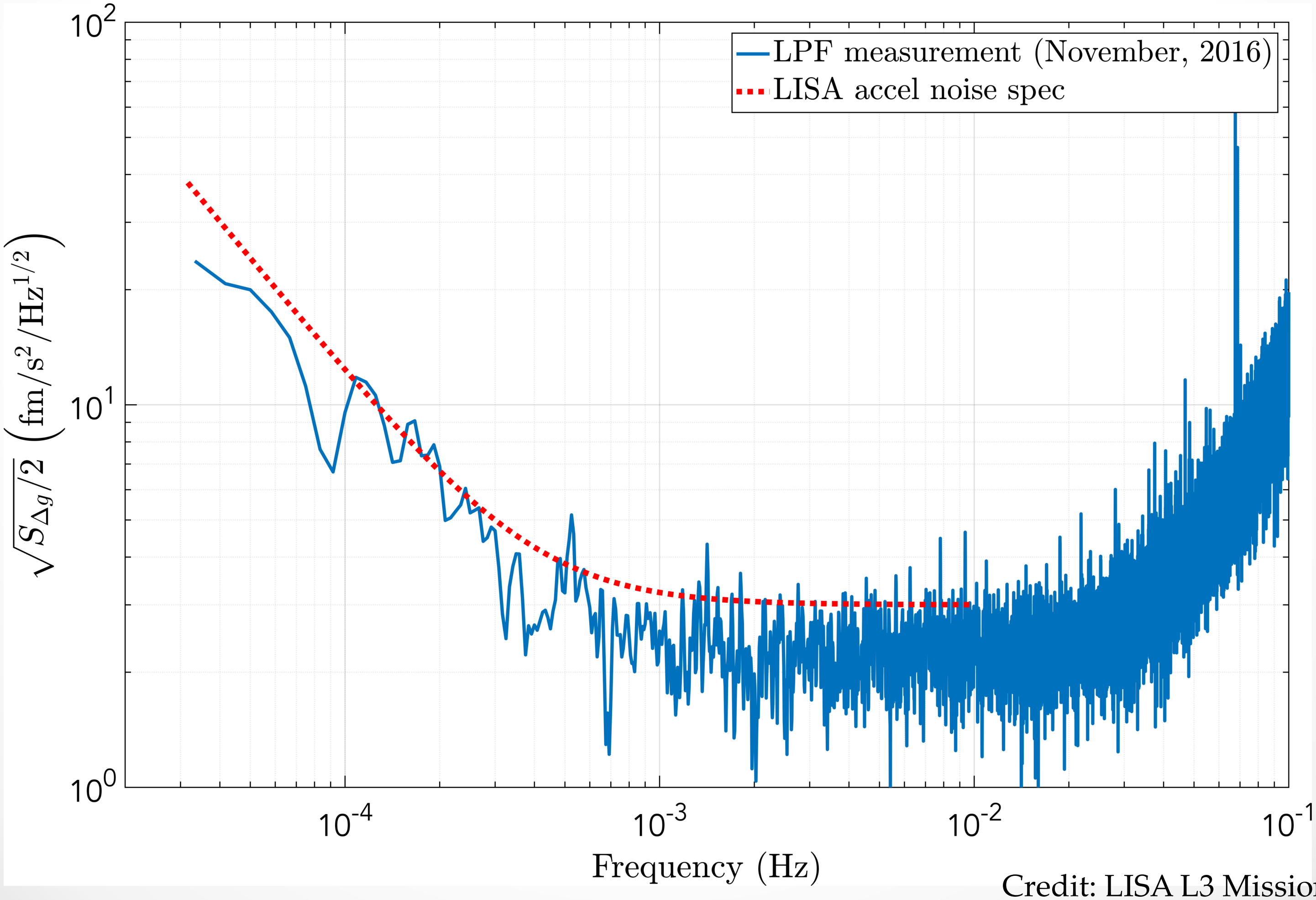


- **LISA Test Mission**
- A test of most of the local measurement (95 % of noise)
- A verification step in the development of LISA using same hardware/processes to carry them at TRL 8-9
- In-orbit consolidation test for our physical model of free fall
- One LISA link inside a single spacecraft (armlength of tens of cm instead of ~2 million km)
- 2 test masses, and LISA-class interferometer to measure relative motion
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics
- Launched Dec ‘15; now wrapping up -- another few months of testing

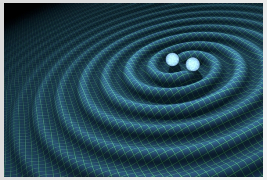


LISA Pathfinder compared to LISA Mission requirements

- Noise performance about a factor of 10 better than Pathfinder requirements, and **meets LISA requirements** in most of the LISA band
  - High-frequency end – telescopes etc. – to be separately tested

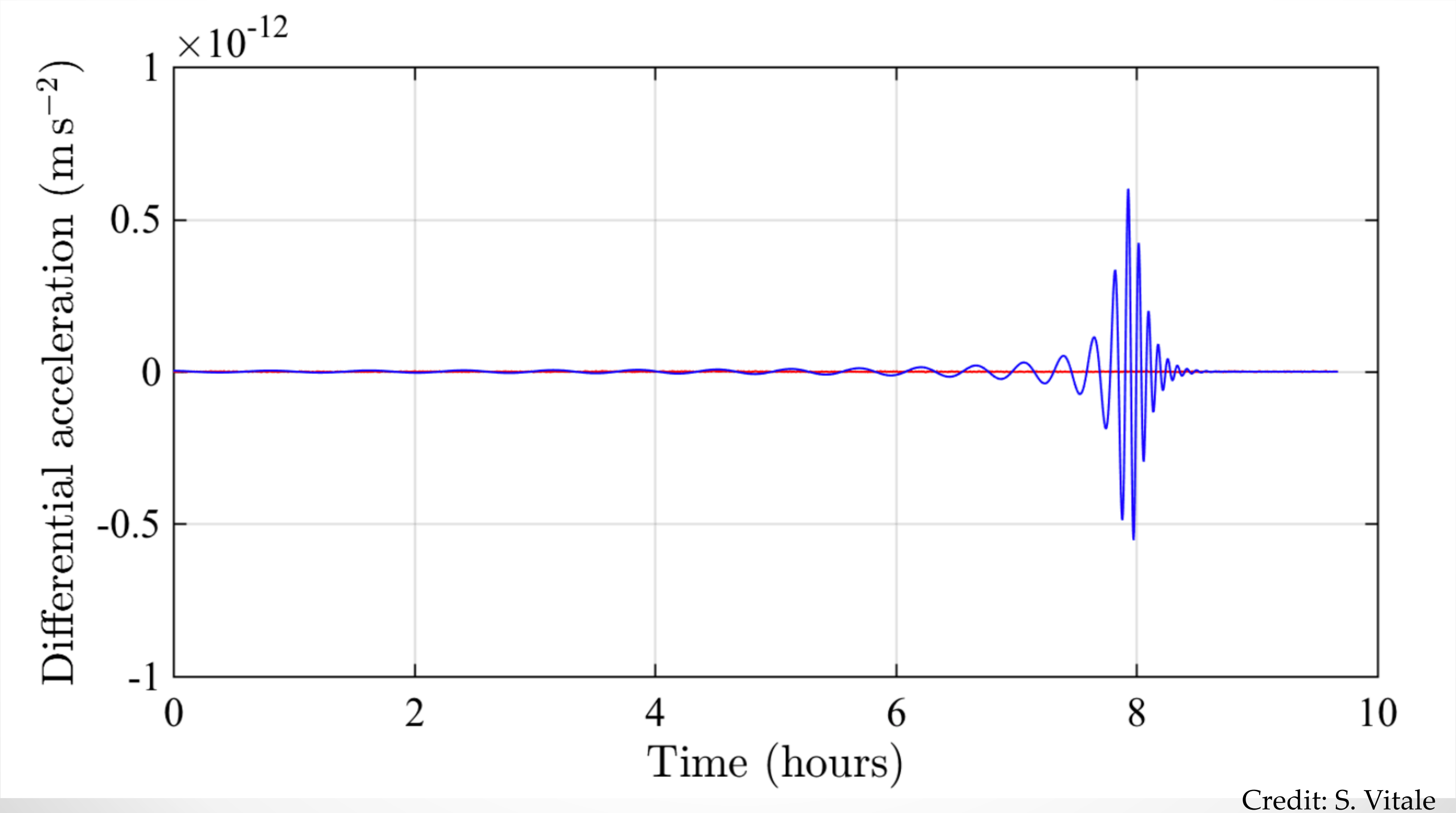


Credit: LISA L3 Mission Concept Proposal



LISA performance, LPF results

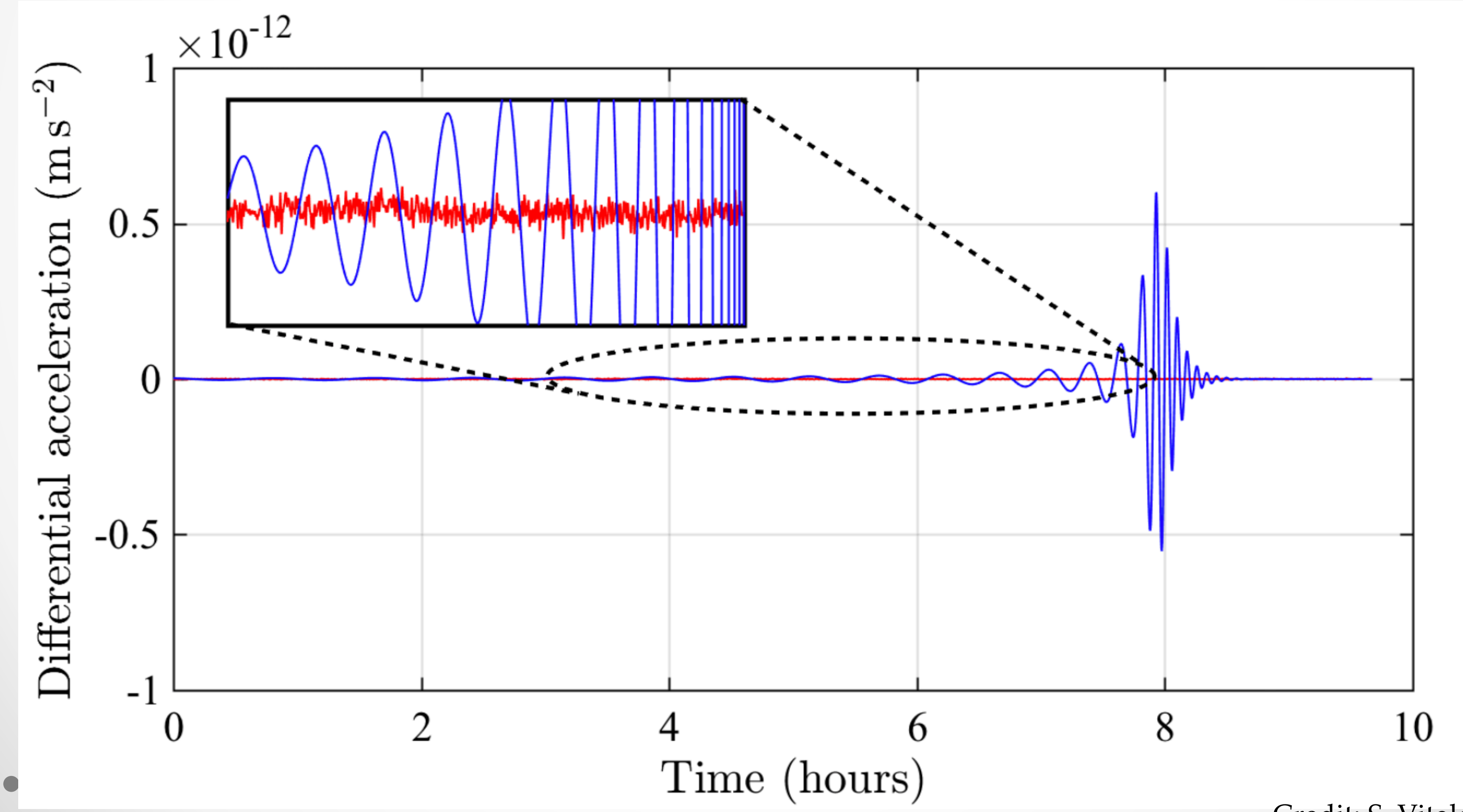
- Simulated LISA equivalent acceleration signal for two $5x10^5$ M black holes with their galaxies merging at z=5
- LISA Pathfinder acceleration data



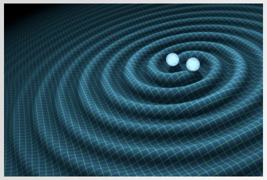
Credit: S. Vitale

LISA performance, LPF results

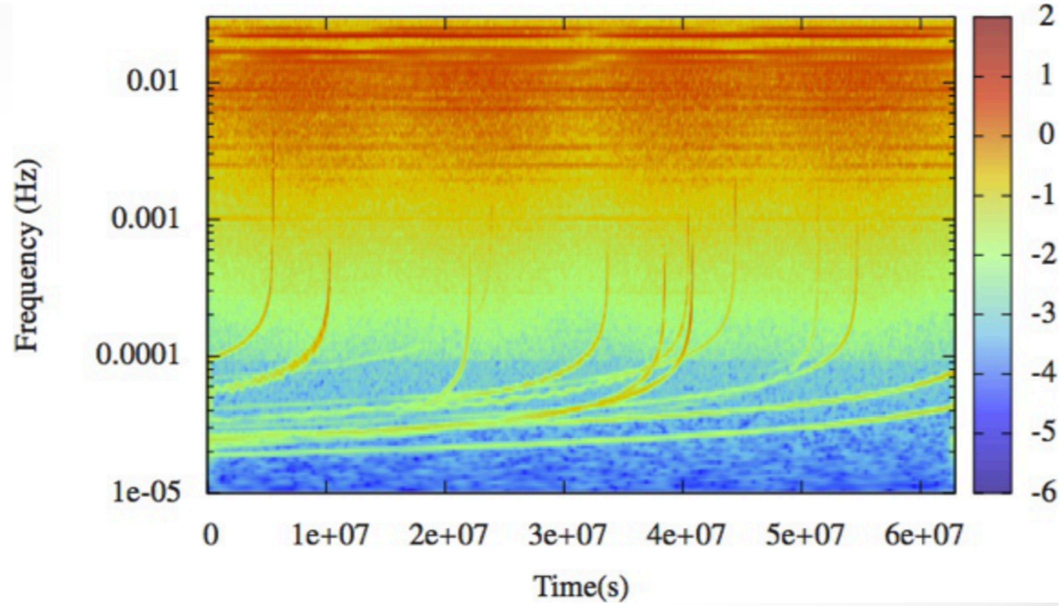
- Simulated LISA acceleration signal for two 5#105 M black-holes with their galaxies merging at z=5
- LISA Pathfinder acceleration data



Credit: S. Vitale

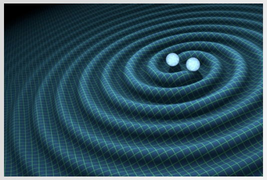


Data



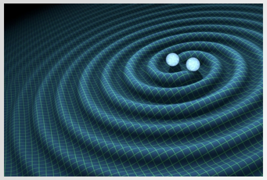
Simulation of ~100 SMBH

- First instrument of its kind
  - Some similarities to e.g., LIGO
  - But signal pile-up quite new
- LISA data are 24/7, and no ‘pointing’
  - ~6 GB/day rate; ‘modest’ in 2034
- Significant post-processing needed to assemble h(t)
  - Synthesis of arms, suppression of technical noise
  - Re-transmission, reconstruction of lost data
  - Removal of instrumental ‘glitches’
- Need to regress out $O(10^4)$ white-dwarf binaries to uncover lower-SNR signals
- Multi-year SMBH observations
- Will also have ‘short’ (hour) transients at coalescence, rapid pointing info
- US and Europe to have data centers, full access to all data



Science Analysis Development

- Pursue new ideas in Science
  - Identify ‘Science Gaps’ – where do we know we don’t know things?
  - Talk with larger observational and theory community to identify common projects, joint observations, theories to confirm
- Raise the ‘TRL’ (technical readiness level) of the simulation and analysis tools
  - Develop a common LISA analysis environment
  - Make complete instrument and data simulators
  - Carry out detailed Mock LISA Data Challenges (MLDC)
  - Develop data quality tools from LPF, LIGO etc., EM experience
  - Where possible, share effort with other domains in GW and EM astronomy
- Support the Phase A iterations on the mission requirements
- Support the Technology Development as needed

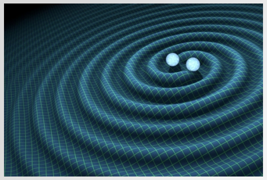


Some LISA requirements, specs

From the LISA L3 Mission Concept Proposal

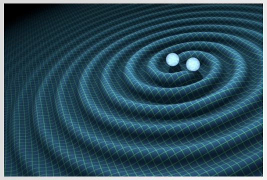
Parameter	Value
Nominal mission duration	4 years
Extended mission duration	10 years
Orbits	3 heliocentric orbits
Transfer time	< 18 months
Range to Earth	50-65 Gm
Arm length	2.5 Gm
Number of Links	6 links/3 arms
Measurement Bandwidth	Req: 100 μHz $\leq f \leq$ 0.1 Hz
	Goal: 20 μHz $\leq f \leq$ 1 Hz
S/C Power Requirements	$\leq$ 760 W
Laser Power	2 W (out of the fiber)
Telescope Diameter	30 cm
System wavefront quality	λ/20 RMS
Data latency	< 1 day
Communication Needs	334 MB/day

Item	Mass [kg]
Ariane 6.4 Launch Capacity	7000.0
Total Launch Mass	**6076.3**
Stack and Launch Adapter	500.0
Wet Stack Mass	5576.3
Total Propellent	2050.0



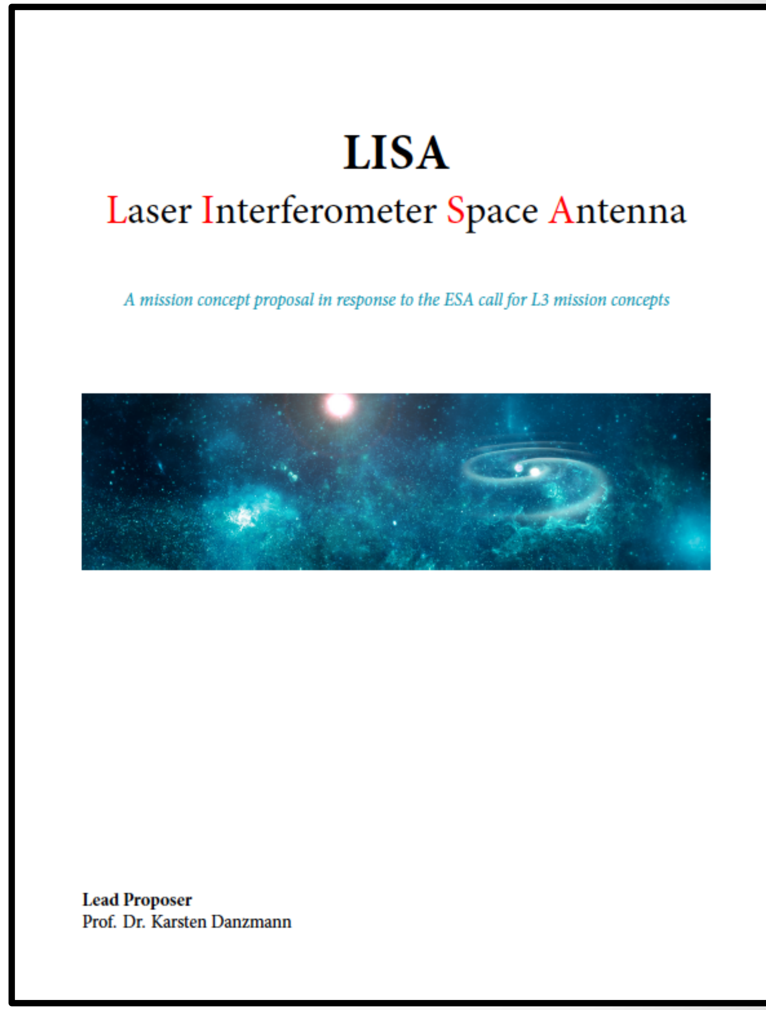
LISA, the Project

- Joint ESA-NASA project
  - ESA the lead, 80%
  - NASA 20% partner
- EU member states contributing much of the "payload"
  - ESA covers most of the "spacecraft"
  - For LISA, the Payload-SpaceCraft separation is nonexistent
- NASA's scope in discussion with ESA at this time; likely elements…:
  - Telescope
  - Laser
  - Micro-thrusters
  - Phasemeter components
  - …and systems engineering/integration/test



ESA Call

- LISA consortium proposed to ESA in Jan ‘17
  - Joint Europe-US proposal
- Mission to fulfill Gravitational Universe science theme
- 1.05B€ ESA cost cap, plus…
- Contributions from EU states, and…
- NASA Planning 20% contribution
- Selection June 2017
- Significant US participation in Consortium leadership and proposal, in both
  - Science
  - Technology/Mission/Requirements
- NASA Study Office starting to support significant effort in technology and astrophysics



LISA

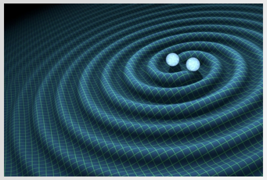
Laser Interferometer Space Antenna

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

Lead Proposer
Prof. Dr. Karsten Danzmann

LISA Consortium website:
http://www.elisascience.org

ESA Mission Concept Call Page:
http://www.cosmos.esa.int/web/2016-l3-mission-call

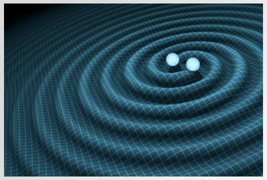


A very welcome nudge from the Decadal Mid-term assessment

- *RECOMMENDATION 4-4: NASA should restore support this decade for gravitational wave research that enables the U.S. community to be a strong technical and scientific partner in the European Space Agency (ESA)-led L3 mission, consistent with the Laser Interferometer Space Antenna's high priority in the 2010 report New Worlds, New Horizons in Astronomy and Astrophysics (NWNH).*

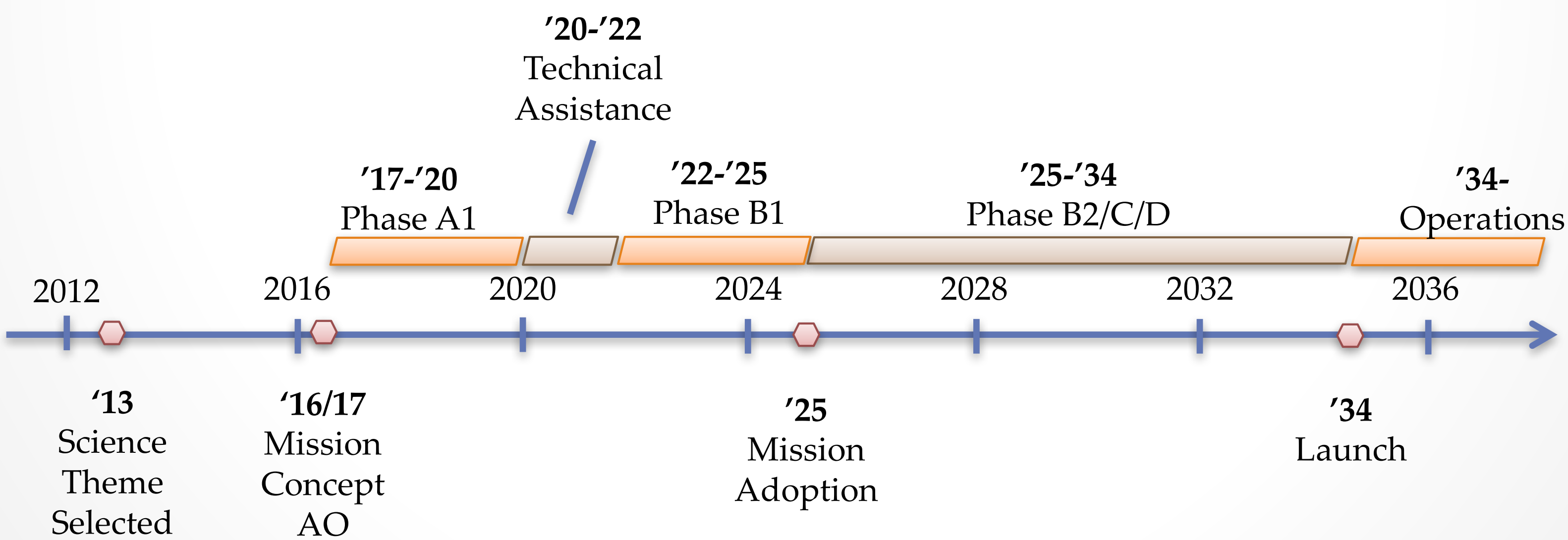
- *One goal of U.S. participation should be the restoration of the full scientific capability of the mission as envisioned by NWNH.*

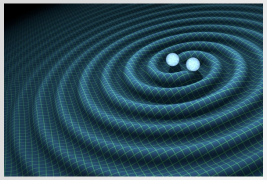
- A near-term US effort is to present LISA to the 2020 Decadal Astro Survey
  - A relatively small cost for a huge science payback
  - Expect arrangements with Europe to be well advanced by that time



What's the Roadmap for LISA?

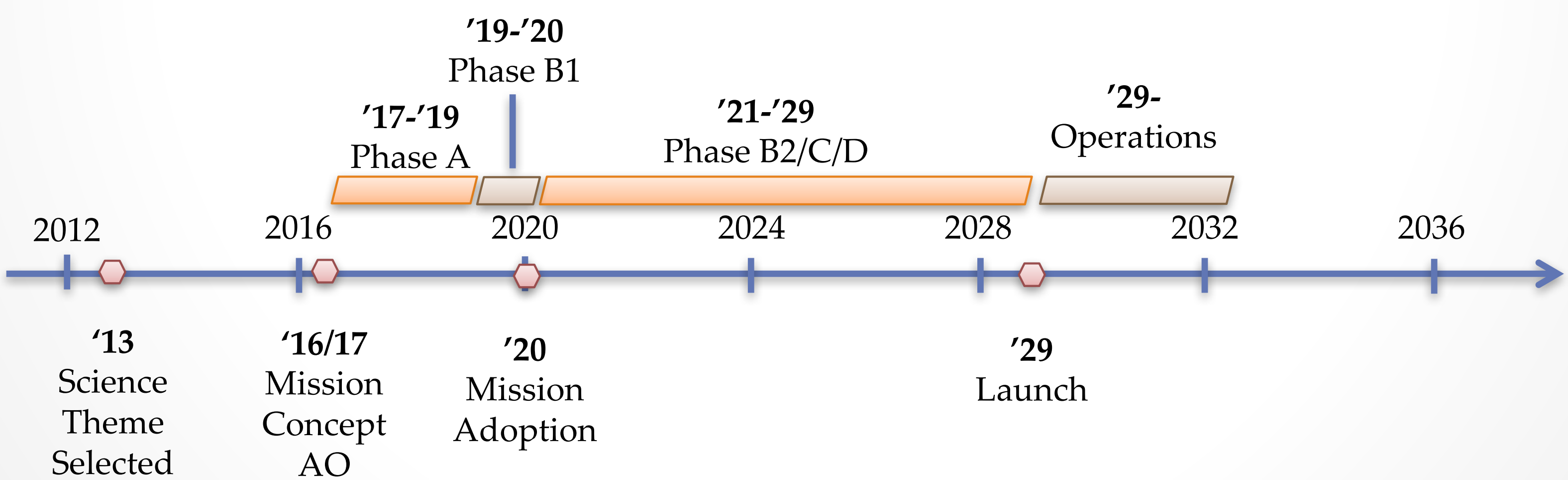
- Nominal timeline, From ESA's Gravitational Observatory Assessment Team (GOAT) Final Report
- http://sci.esa.int/cosmic-vision/57910-goat-final-report-on-the-esa-l3-gravitational-wave-mission/

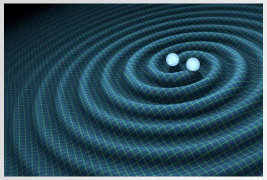




Possible Faster Timeline

- From an unpublished GOAT Special Report, requested by ESA:
- What is the fastest credible schedule from a technical perspective?





The End

- First discussed in ~1975 – Pete Bender of JILA, Rai Weiss of MIT
- A significant gestation period followed…
- LIGO's detection showed unambiguously that we understand GWs and interferometry to detect them
- LISA Pathfinder demonstrated all the parts that are tricky, spectacularly
- ESA and NASA on board for a great science mission
- The entire LISA team is eager to make…

LISA: a completely new tool for the astronomer's and astrophysicist's toolbox