Overview of NASA's Gravitational-Wave Mission Concept Study

Robin Stebbins, Goddard Space Flight Center

Town Hall Meeting, 219th AAS Meeting, Austin

10 January 2012

Outline

- End of NASA/ESA partnership
- Status in Europe
  - Re-formulation
  - LISA Pathfinder
  - eLISA/NGO
- Status of the NASA Study
- Ned Wright will talk about the Community Science Team work
- Discussion

End of the LISA Partnership

- NASA and ESA Headquarters met in mid-March at a regular bi-lateral meeting
  - ESA had to proceed with the implementation of an L-class mission in 2015.
  - NASA's constrained out-year resources led ESA to conclude that the LISA partnership wasn't feasible within the L1 schedule.
  - ESA ended the partnership
  - ESA initiated a rapid study to define a mission that ESA and its member states could carry out alone.
  - A future minor role for NASA in the ESA-led mission has not been ruled out.
- NASA adjusted its goals to adapt to the end of the partnership.

ESA Concept Re-Formulation

- Activities
  - Small team searched for descopes and alternate designs (April-June).
  - Science community evaluated the science products for a grid of concepts and design parameters (April-October)
  - Concurrent Design Facility at ESTEC carried out a design audit and costing (June-July)
  - Astrium UK and Astrium GmbH carried out an industrial design study (July-October)
  - ESA had a technical and programmatic review (October-November)
- The science case and mission design of eLISA/NGO are described in a new Yellow Book, to be released soon.

ESA Timeline

- The “advisory structure” (i.e., AWG, FPWG, SSAC) will review the science and make recommendations (December - ?)
- The downselect schedule will be reviewed and decided by the Science Programme Council (SPC) at its February meeting.
- A likely outcome is that a downselect to a single mission will be made by June 2012.

U.S. Participation in eLISA/NGO to date

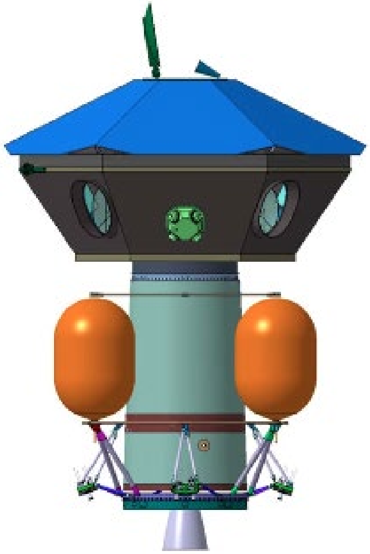
- Goal is to prepare for a minor U.S. role in an ESA-led mission.
- NASA supported the re-formulation through
  - Participation in the small design team
  - A HQ selected scientist (RTS) is a member of the new ESA Science Definition team.
  - That representative will act as conduit for input from and information to the US science community.
- Several other U.S. researchers participated in the science evaluation.
- Members of the LISA Project team carried out some mission design work to support the concept definition in Europe.
  - Orbital and trajectory analysis.
  - Systems assessment

Future U.S. Participation in eLISA/NGO

- Process for selecting NASA participation in L1
  - Current thinking is to fund NASA participation through the Explorer program via a Mission of Opportunity call on a TBD timeframe that will ultimately align with the ESA instrument AO process.
- Possible contributions
  - Technologies where there is US leadership
  - Science data analysis
  - Spacecraft subsystems

Context of the Study – Activities in Europe

- LISA Pathfinder
  - Demonstration of space-based GW technology, in late stages of I&T
- Technology development
  - Inertial sensor electronics, charge control
  - Optical system
  - Laser system
  - Pointing and point-ahead mechanisms
- NGO
  - Candidate for ESA's Cosmic Visions L1, decision in April/May 2012, before the end of the Study!
  - See talk by Karsten Danzmann



LISA Pathfinder: Mission Status

Paul McNamara
LISA Pathfinder Project Scientist

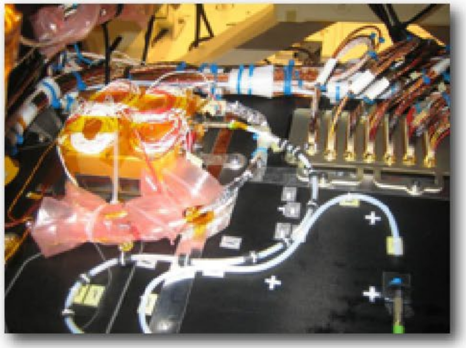
Introduction

- LISA Pathfinder (LPF) is a technology validation mission for NGO[1]
  - LPF was approved by ESA to demonstrate the concept of low frequency gravitational wave detection in space
- LISA Pathfinder will test in flight:
  - Inertial sensors (a.k.a. Gravitational Reference Sensor)
  - Interferometry between free floating test masses
  - Drag Free and Attitude Control System (DFACS)
  - Micro-Newton propulsion technology
- The basic idea of LISA Pathfinder is to squeeze one arm of the NGO constellation from 1 million km to a few tens of cm!
  - Fully tests NGO local interferometry

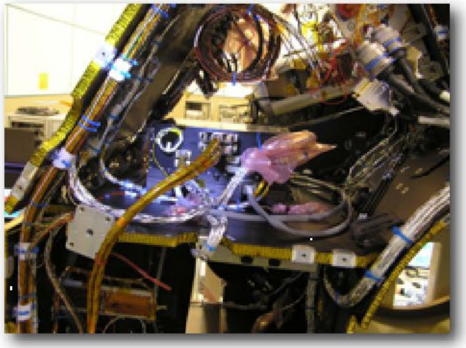
[1] When approved by the Science Programme Committee, LISA Pathfinder was a dedicated technology validation mission for the LISA mission. In the mean time, LISA has been reformulated and renamed NGO

LTP Status

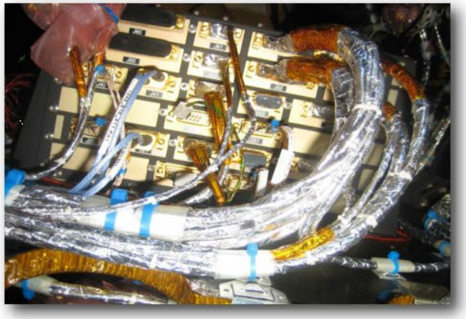
- All electronic units have been delivered and integrated to the spacecraft
  - – Laser, laser modulator, phasemeter, payload computer, UV lamp unit, ISS front-end electronics, diagnostics



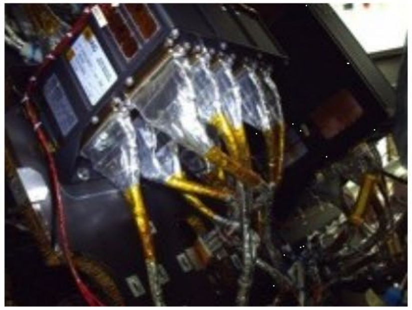
Reference Laser Unit



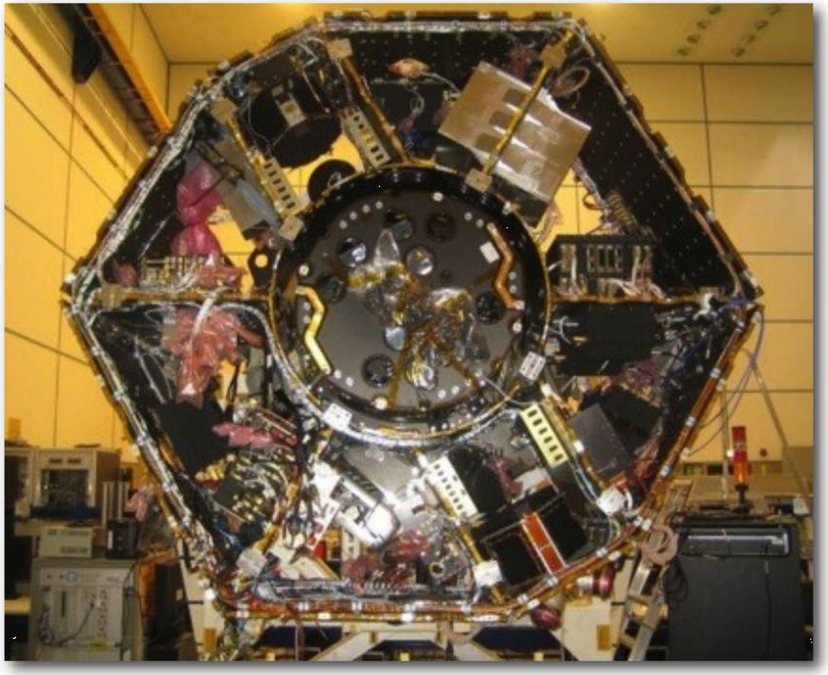
Phasemeter



Payload Computer



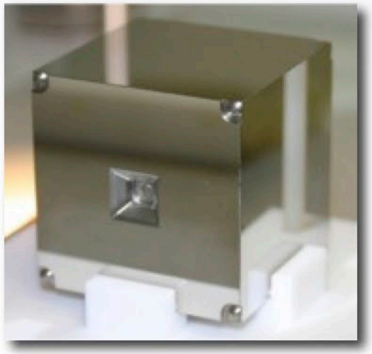
ISS Front-End Electronics



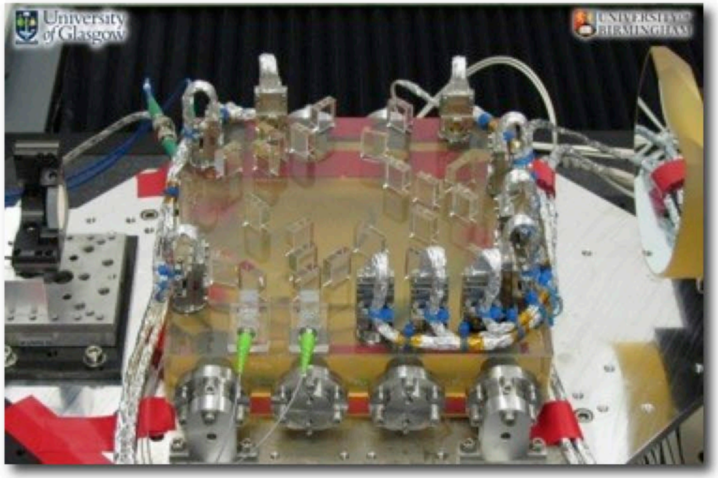
LPF during AIT at Astrium UK

LTP Status

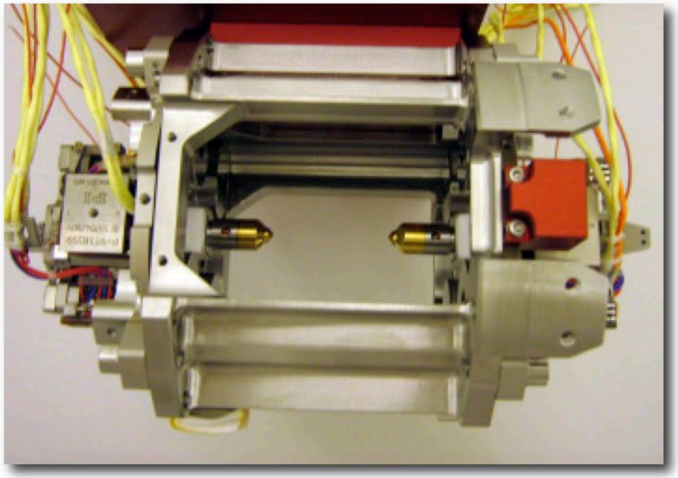
- Most of the components of the LTP Core Assembly are ready, however subsequent integration has been delayed.
  - – Optical bench
  - – Inertial sensor
    - Test Masses
    - Vacuum enclosure
    - Grabbing, positioning and release mechanism



Uncoated Au:Pt Test Mass



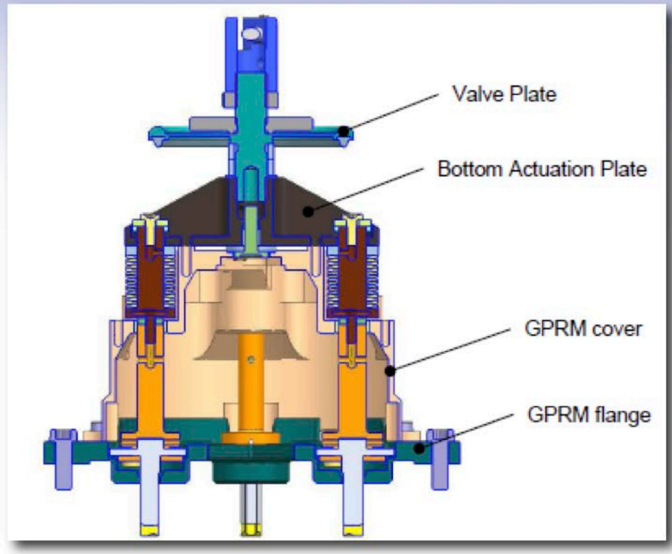
Optical Bench

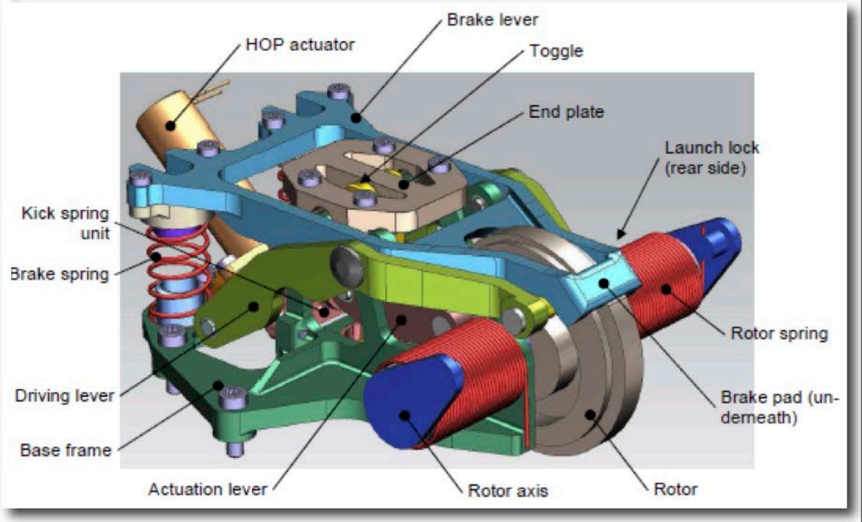


Test Mass Grabbing, positioning and Release Mechanism (GPRM)

LTP Status

- Delays in the integration, and delivery, of the LTP Core Assembly are due to problems with the test mass launch lock
  - Original (hydraulic) launch lock failed during testing
  - A new design has now been selected, and flight units are being manufactured
    - New design is a much simpler, single-shot mechanism utilising a paraffin actuator
    - Delivery of FMs is scheduled for September 2012

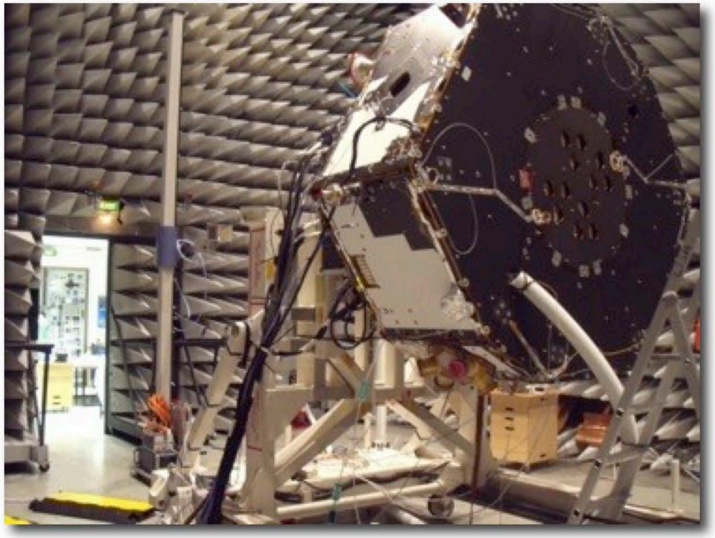




System Test Campaigns

Sine Vibration

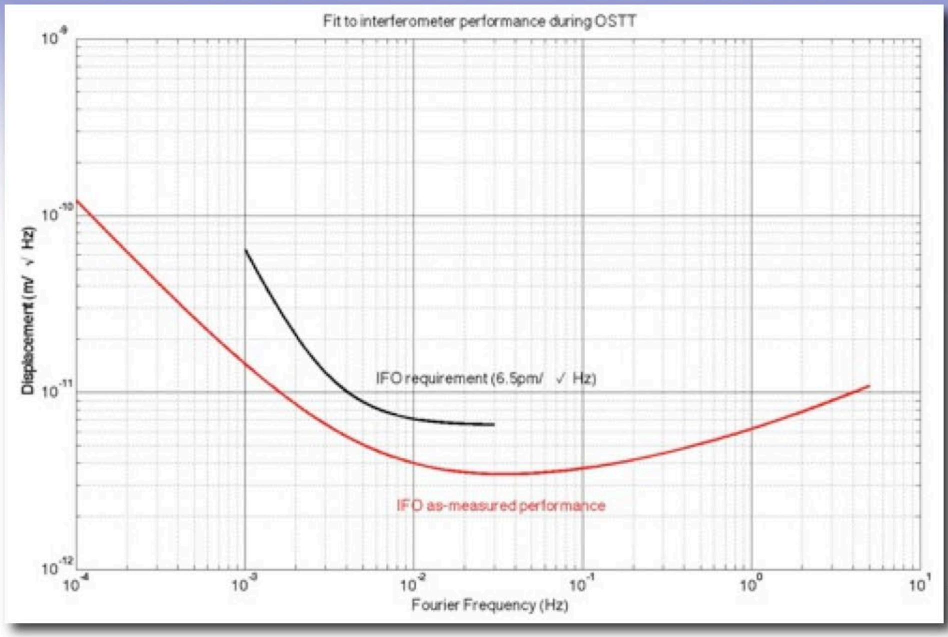
Transfer Orbit Thermal Test

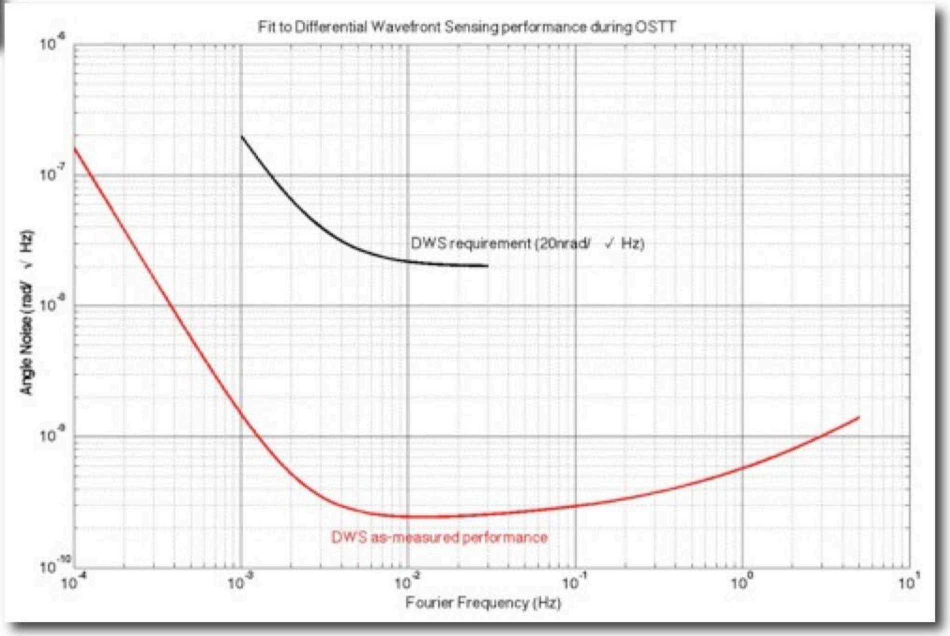


EMC

On-Station Thermal Test

Fit to OSTT Performance



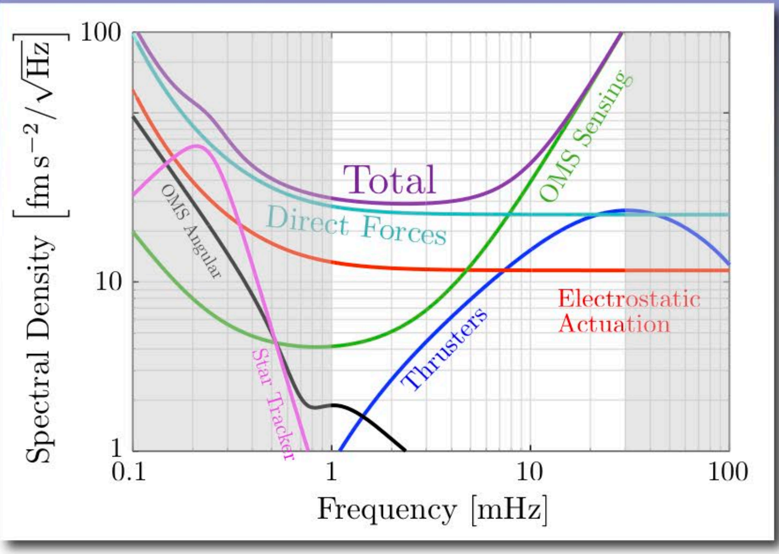


Micro-Thrusters

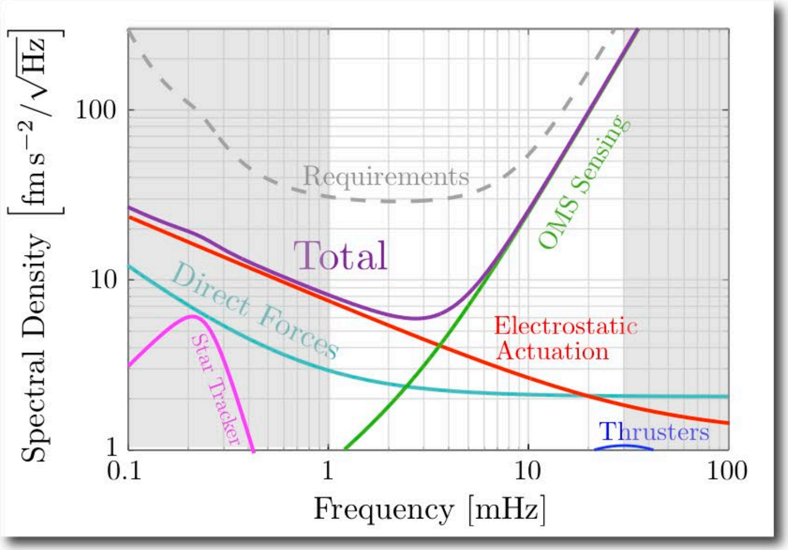
- Review Board requested that the FEEP tests continue into next year
  - Culminating in two thruster assembly endurance tests, both of which must demonstrate the full LPF total impulse requirements.
- After thorough investigation, the FEEP thruster head has been redesigned to limit caesium leakage from the emitter slit
  - Achieved in part by narrowing the slit width from 1.3μm to 0.7μm
- Ongoing thruster unit validation test is demonstrating that the new design of thruster is working perfectly!!
- Downselect on which thruster to take to flight will be made in June 2012.

LPF Performance

- Extensive performance noise model has been developed by both the PI and industry
- The main goal of LPF is to validate this noise model
- Model is updated as ground test results become available
- Current Best Estimate of LPF is now approaching the NGO requirements!



Requirements noise projection



Current Best Estimate

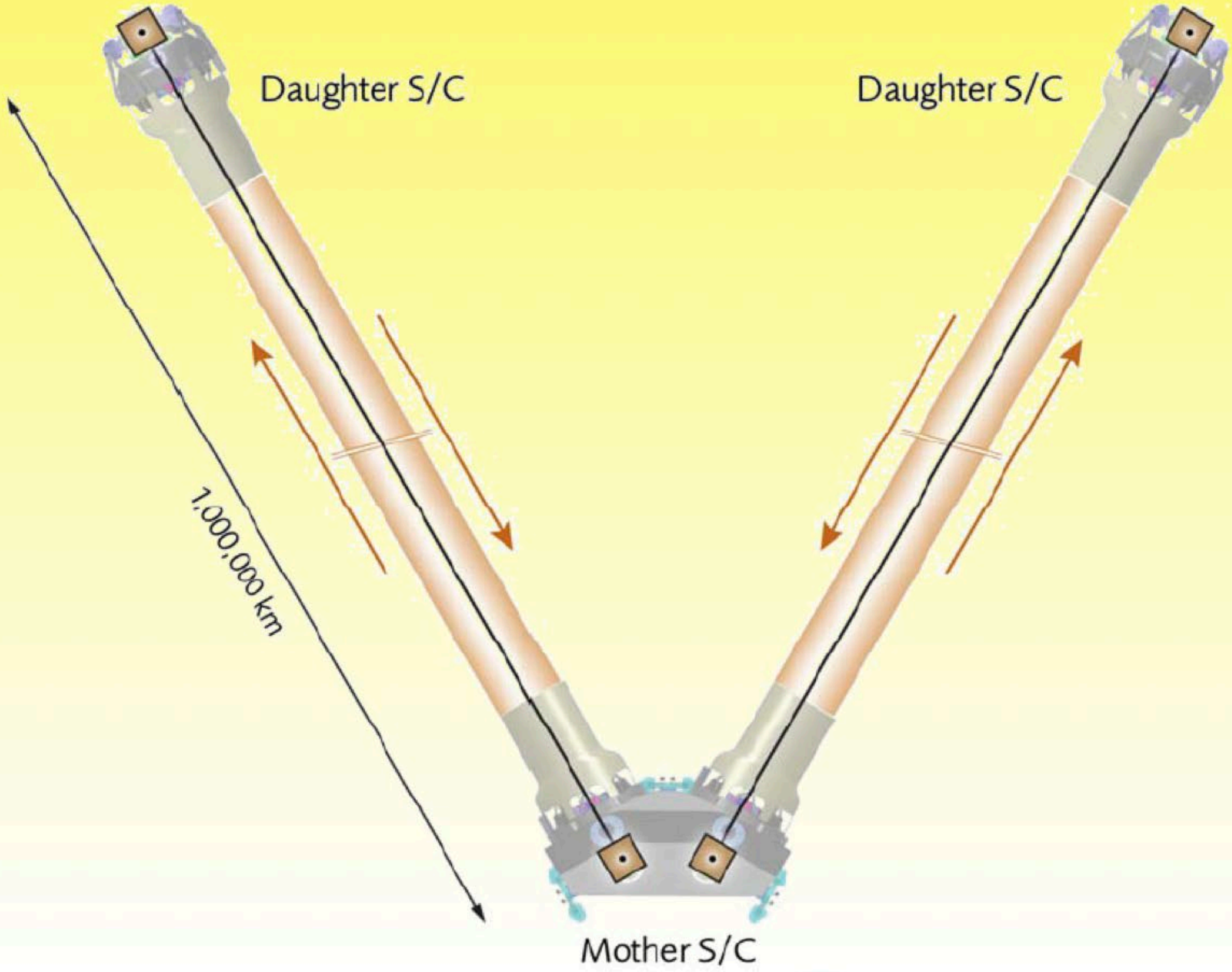
In Summary

- All environmental tests complete
- The caging mechanism launch lock drives the critical path
- Results from OSTT (TOQM) demonstrate performance better than requirements
- Cold Gas thrusters are a viable alternative to the FEEPs.
- The project will enter hibernation at the beginning of next year
  - Hibernation is scheduled to last ~15months
- Launch is scheduled for June 2014.

$3,4! ^Gd` '6)++)1*'T$+)M*'

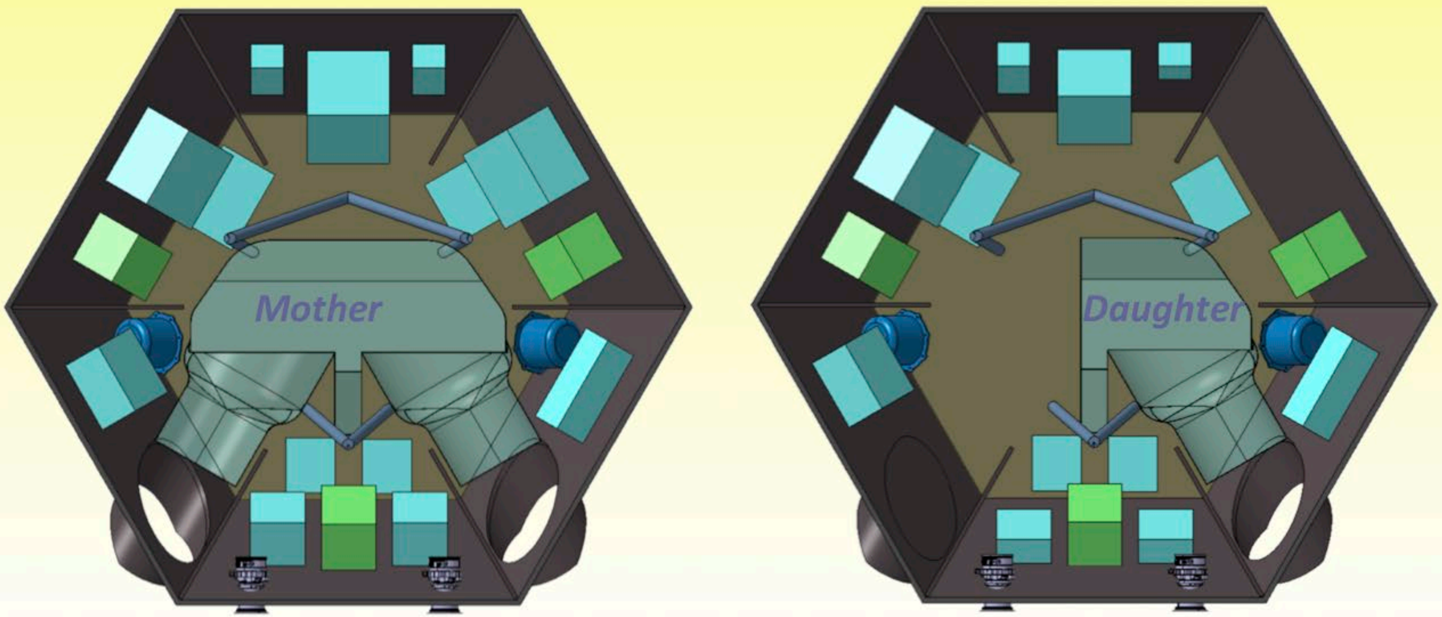
- ! %H "$*M&K'>'6)"")1*'bH B'S'0%H +'
- ,=$*- 80"6 1&K$%FT0. MK&$%4F7B#0+$='1*'3,4! 'J 0&K<*=$%
- C'+908$8%0; ')*'0'Z^81*<M %0- 1*'B*1H)*0"0*M$'i AjB'
  H 0] 'T199'$%k>AH F+''
- 6)*)H)h$'1. &^1D9'0*$'91)*- *M20%)0- 1*'&1'=%19'91)*&^
  0K$0=^08& 0&1%1*'` 9- 80"V$*8K'
- / $")18$*&)8'+"1X '=%); ^0X 0N1%#)&B(0%&K^"$0=)*M1%&0)")*MB
  +&0% *M>AjBi Aj')*8")*0- 1*'X %&$8")9- 8B%0*M$'&1'(0%&K'*1&
  $] 8$$=)*MI A'6 bH '0; $%E'N$0%+'0*='i I '6 bH '0; $%i 'N$0%+I'
- 30. *8K'&1'+. #^d L` B+$90%0- 1*'D%1H '3ZB$+809$'0*='
  &0*+D$%&1'<*0"1%#)&#N'Y$m+1*0#'$'9%19. "+)1*'H 1=. '$'
- LX 1'41N. h^PWd ''0. *8K$+'[1%+K0%$='! %)0*$'Z''0. *8K\'
- 6)++)1*'")D$- H $5#0+$")*$'S'N$0%+'e'S'e'S'
- T1X *")*b'8090#)")&N'D%1H '$08K'4F7B1*$^0])+'/ d ! 'e'3d ! +'

eLISA-NGO Layout

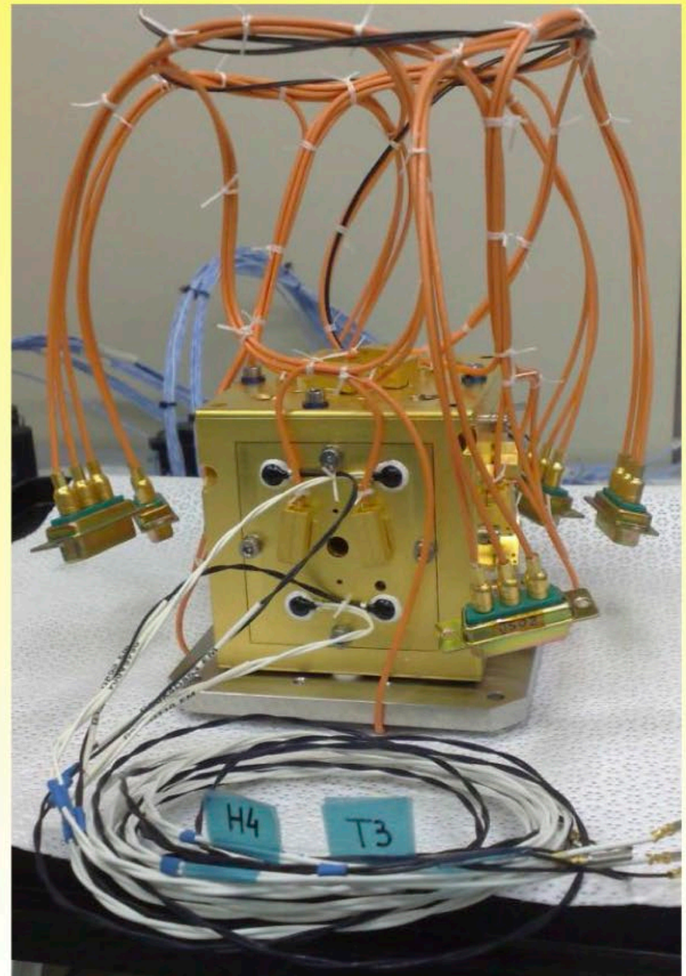


M & Ds S/C configuration

- Optimized accommodation to minimize impact of removal of telescope and FEE between Mother and Daughter



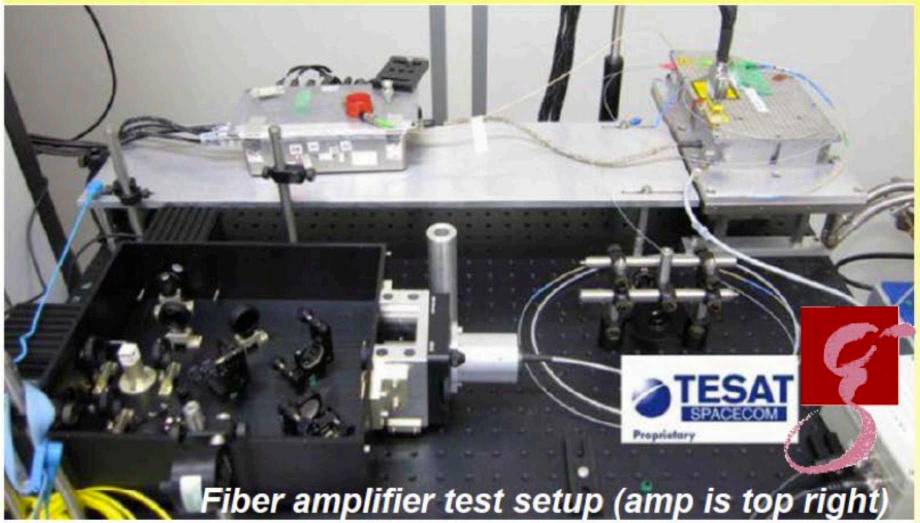
The eLISA GRS Head and Integration: Identical to LISA Pathfinder

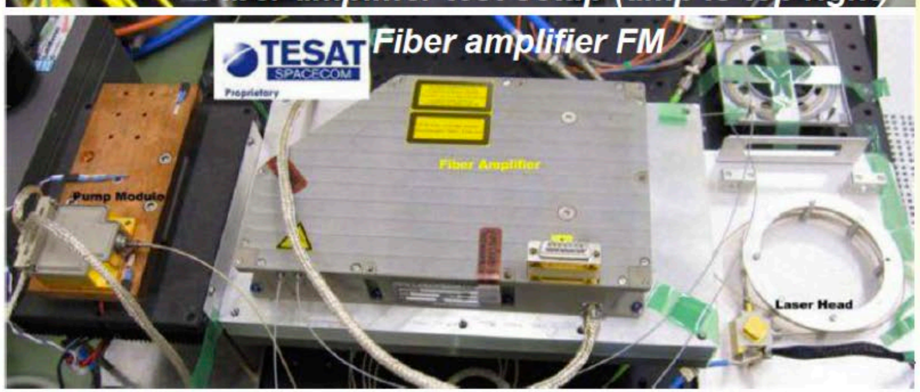


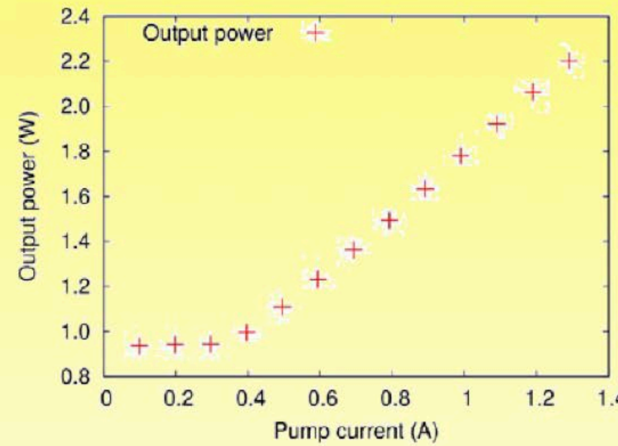
High Power Laser

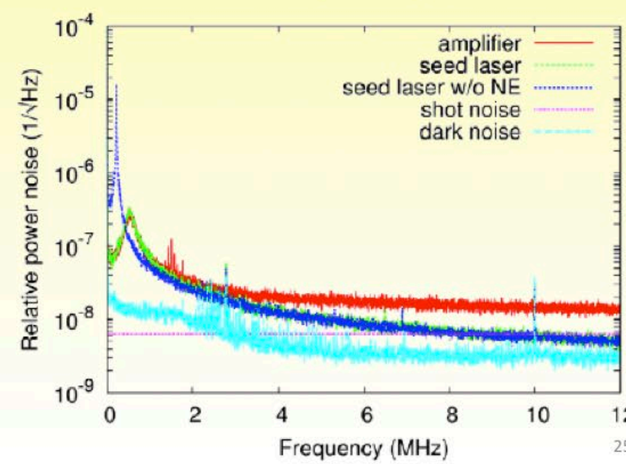
→Re-use LISA Pathfinder master and ERDS fiber amplifier

- Tests: Stable low-noise operation up to 2.2 W



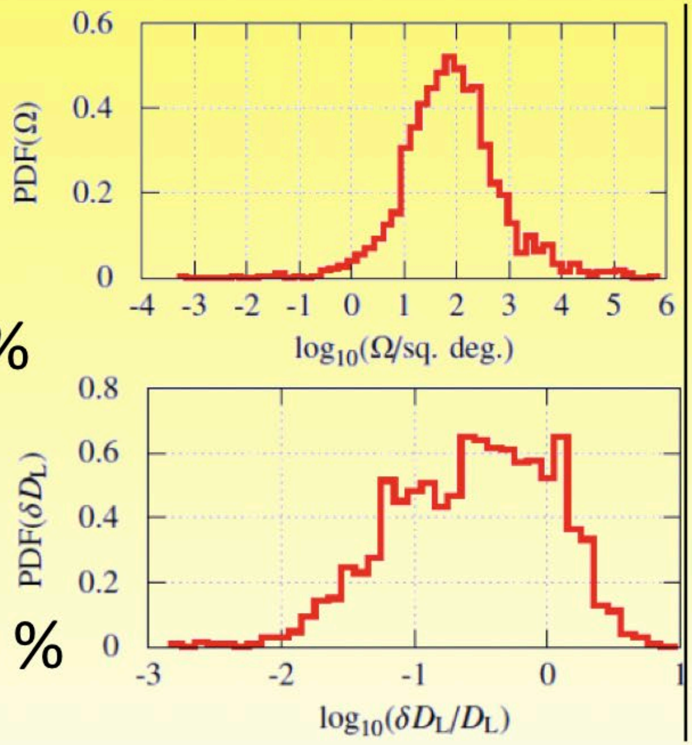






eLISA Black Hole Physics at high SNR

- BBH rest mass $10^4 - 10^7$
- Out to redshift $z \approx 7$
- Redshifted mass to 0.1%-1%
- Absolute spin to 0.01-0.1
- Luminosity distance 1 – 50 %
- Sky location 3° - 10 °



Extreme Mass Ratio Inspirals

- SNR 20 up to $z \approx 0.7$ for 10^5-10^6 $M_\odot$
- Dozens of events
- Mass, spin to 0.1% – 0.01 %
- Quadrupole moment to < 0.001 $M_\odot^3 G^2/c^4$

Summary of NASA's Mission Concept Study

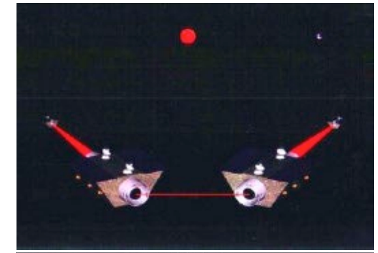
- Goals of the Study
- Context
- Elements of the Study
- RFI responses
- Core Team work
- Science task force work
- Workshop
- Ned Wright will talk about the Community Science Team work

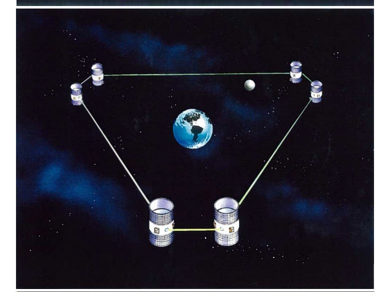
Goals of the Study

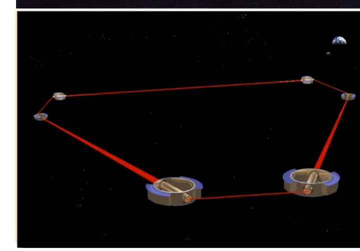
- Develop mission concepts that will accomplish some or all of the LISA science objectives at lower cost points.
- Explore alternative mission architectures and technical solutions (e.g., instrument concepts, enabling technologies).
- Assess the technical readiness and risk of the mission concepts, instruments and technologies.
- Report the options for science return at multiple cost points .

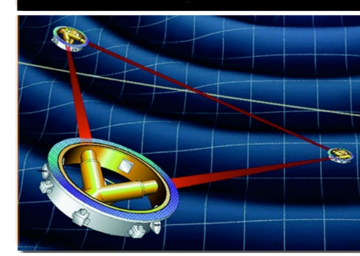
Context of the Study – A Brief History of LISA

- 1972 - A dinner conversation: Weiss, Bender, Misner and Pound
- 1985 – LAGOS Concept (Faller, Bender, Hall, Hils and Vincent)
- 1993 – LISAG - ESA M3 study: six S/C LISA & Sagittarius
- 1997 - JPL Team-X Study: 3 S/C LISA
- 2001-2015 - LISA Pathfinder and ST-7 DRS
- 2001 – NASA/ESA project began
- 2003 – TRIP Review
- 2005 – GSFC AETD Review
- 2007 – NRC BEPAC Review
- 2009 – Astro2010 Review
- 2011 – NASA/ESA partnership ended
- 2011 – Next Generation Gravitational-Wave Observatory (NGO) started









Context of the Study – Decadals and NRC Reviews

- 2000 – Astronomy and Astrophysics for the New Millennium
  - LISA ranked as the next new start after GLAST/Fermi in the Moderate Initiatives
- 2003 – Connecting Quarks with Cosmos
  - LISA recommended for "exploring the basic laws of physics"
- 2007 – Beyond Einstein Program Assessment Review
  - LISA "should be the flagship mission of a long-term program addressing Beyond Einstein goals"
- 2010 – New Worlds, New Horizons
  - LISA ranked behind WFIRST and Explorer Augmentation in the Large category
- 2020 – Astro2020

Elements of the Study – 1/3

- Request for Information (RFI)
  - Mission concepts, instrument concepts and technologies
  - 10 page whitepapers, due November 10
- Core Team
  - Technical expertise in GW science, mission design, relevant technologies
  - Scientists and engineers, mostly from LISA Project Team, at Goddard and JPL
- Science task force
  - Expertise in the science performance analysis of gravitational-wave detectors.
  - Volunteers from the LISA research community

Elements of the Study – 2/3

- Community Science Team (CST)
  - Responsible for evaluating the RFI responses for the degree to which they fulfill the LISA science objectives and for their degree of technical readiness.
  - 10 researchers selected from respondents to an invitation
- Open Workshop
  - Presentation and discussion of RFI responses, open to public
  - Maritime Institute, 20-21 December 2011, Linthicum, MD
- Rapid concurrent engineering studies by Team-X
  - ~3 mission concept studies
  - 1-2 instrument studies
  - March-April 2012

Elements of the Study – 3/3

- Final Report to NASA Headquarters
  - Survey the choices of mission architectures and technologies
  - Summarize the impact of architectural choices on science return
  - Three Team-X studies with costing
  - Evaluate the cost and science trade-offs
- Presentation to the Committee on Astronomy and Astrophysics (CAA) of the National Research Council (NRC)

RFI Responses

- 17 responses total
  - 12 for mission concepts
  - 3 for instrument concepts
  - 2 for technologies
- Four natural groups
  - Non-drag-free concepts (2)
  - Geocentric orbits (4)
  - LISA-like (5)
  - Other (2)

Concept Characteristics – Group 1

Group	Group 1 (No drag-free)	
Proposal Number	**3**	**16**
Lead Author	**Folkner**	**McKenzie**
Acronym		**LAGRANGE**
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction
Proposal Type	Concept	Concept
Number of Alternates	2	2
Arm length (km)	2.6×10^{8}	2.09×10^{7}
Spacecraft/Constellation	3/equilateral triangle //4/square	3/isosceles triangle
Orbit	Heliocentric	Heliocentric/ Earth-Sun L2
Trajectory	Not specified beyond HEO parking, double lunar assist. Solar electric propulsion mentioned.	Direct escape to L2, "drift" of SC1/3 to 8° leading/trailing
Inertial Reference	None	GOCE accelerometer
Displacement Measurement	3 arms, 6 links	2 arms, 4 links
Launch vehicle		Falcon 9 Block 3
Baseline/Extended Mission Duration	3 arms, 6 links	2
Telescope Diameter (cm)	30	20/40
Laser power out of telescope, EOL (W)	1	1.2
Sensitivity curve	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)	1.0×10^{-13}	4.4×10^{-14} (0.001/f)^0.75
Displacement sensitivity ($m/Hz^{1/2}$)	550×10^{-12}	150×10^{-12}

Concept Characteristics – Group 2

Group	Group 2 (Geocentric)			
Proposal Number	**4**	**17**	**7**	**10**
Lead Author	**Tinto**	**McWilliams**	**Hellings**	**Conklin**
Acronym	**GEOGRAWI**	**GADFLI**	**OMEGA**	**LAGRANGE**
Novel Idea	Geocentric orbit, single spherical TM	Smaller telescope and laser, smaller satellites	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating
Proposal Type	Concept	Concept	Concept	Concept
Number of Alternates	3	3	1	1
Arm length (km)	7.3×10^4	7.3×10^4	1.04×10^6	6.7×10^5
Spacecraft/Constellation	3/equilateral triangle	3/equilateral triangle	6/triangle	3/equilateral triangle
Orbit	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5
Trajectory	Not specified	Direct launch together to geostationary, re-phase 2 S/C	Butterfly trajectories to Weak Stability Boundary, 384 days total	Either: direct to WSB, return and lunar fly-by; direct to Trans Lunar Injection, return and lunar fly-by
Inertial Reference	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical
Displacement Measurement	3 arms, 6 links	3 arms, 6 links		
Launch vehicle		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9
Baseline/Extended Mission Duration		2	3	5
Telescope Diameter (cm)	Same as LISA	15	30	20
Laser power out of telescope, EOL (W)	Same as LISA	0.7	0.7	1
Sensitivity curve	Yes	Yes	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
Displacement sensitivity ($m/Hz^{1/2}$)	7×10^{-12}	8×10^{-12}	5×10^{-12}	5×10^{-12}

Concept Characteristics – Group 3

Group	Group 3 (LISA-like)				
Proposal Number	11	14	15	12	13
Lead Author	Shao	Stebbins	Livas	Thorpe	Baker
Acronym		SGO High	SGO Mid	SGO Low	SGO Lowest
Novel Idea	Formation-flying payload, torsion suspension for test mass	LISA with all known cost savings	Smallest LISA-like design with 6 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links
Proposal Type	Instrument	Concept	Concept	Concept	Concept
Number of Alternates	1	1	1	1	1
Arm length (km)	5.0×10^6	5.0×10^6	1.0×10^6	1.0×10^6	2.0×10^6
Spacecraft/Constellation	3+3/triangle	3/equilateral triangle	3/equilateral triangle	4/triangle (60-deg Vee)	3/In-line: Folded SyZyGy
Orbit	LISA-like	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away
Trajectory		Direct injection to escape with recircularization and out-of-plane boost, 14 months	Direct injection to escape with out-of-plane boost, 21 months	Direct injection to drift away, with out-of-plane boosts, 21 months	Direct injection to escape, with small delta-v for S/C separation, 18 months
Inertial Reference	Single, torsion pendulum	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular
Displacement Measurement		3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links
Launch vehicle	Falcon 9	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2
Baseline/Extended Mission Duration	5	5/3.5	2/2	2/2	2/0
Telescope Diameter (cm)		40	25	25	25
Laser power out of telescope, EOL (W)		1.2	0.7	0.7	0.7
Sensitivity curve	No	Yes	Yes	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)		3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
Displacement sensitivity ($m/Hz^{1/2}$)		8×10^{-12}	8×10^{-12}	8×10^{-12}	8×10^{-12}

Concept Characteristics – Group 4

Group	Group 4 (Other)			Instrument Concepts/Technologies
Proposal Number	**5**	**8**	**9**	**6**
Lead Author	**Saif**	**Yu**	**Gulian**	**de Vine**
Acronym	**InSpRL**			
Novel Idea	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor	Replace optical bench with photonic integrated circuit
Proposal Type	Concept	Instrument	Concept	Instrument
Number of Alternates	2			
Arm length (km)	0.5/500			
Spacecraft/Constellation	1//2/in-line		1	
Orbit	1200 km above geostationary	LISA-like	Not specified.	Comparable to LISA
Trajectory	Not specified	LISA-like	Not specified	
Inertial Reference	Atom interferometers			
Displacement Measurement				
Launch vehicle	Falcon			
Baseline/Extended Mission Duration				
Telescope Diameter (cm)				
Laser power out of telescope, EOL (W)	10-20			
Sensitivity curve	Yes			Comparable to LISA
Residual acceleration ($m/s^2/Hz^{1/2}$)				
Displacement sensitivity ($m/Hz^{1/2}$)				5×10^{-12}

Core Team Work

- Prior to the Workshop,
  - Assessed Concept Characteristics
    - Summary presentations at PCOS website
  - Re-evaluated several aspects, e.g.,
    - Sensitivity curves
    - Orbit and trajectories
- Since the Workshop
  - Preparing Team-X materials for recommended concepts
    - Introductory material
    - Orbit and trajectory descriptions
    - Block diagram (aka, The FID)
    - Master Equipment List

Analysis of Concepts – 1/2

Mission Element	Factors
Concept	Do we understand it? Novel ideas Proposal type, number of concepts
Science	Sensitivity curve (claimed & estimated) Horizons for MBH binaries, EMRIs, compact binaries Number of events of each type Parameter estimation for MBH binaries Error budget Robustness
Payload	Instrument requirements Master Equipment List Mass and power
Spacecraft	How many different ones? Subsystem requirements Master Equipment List Mass and power

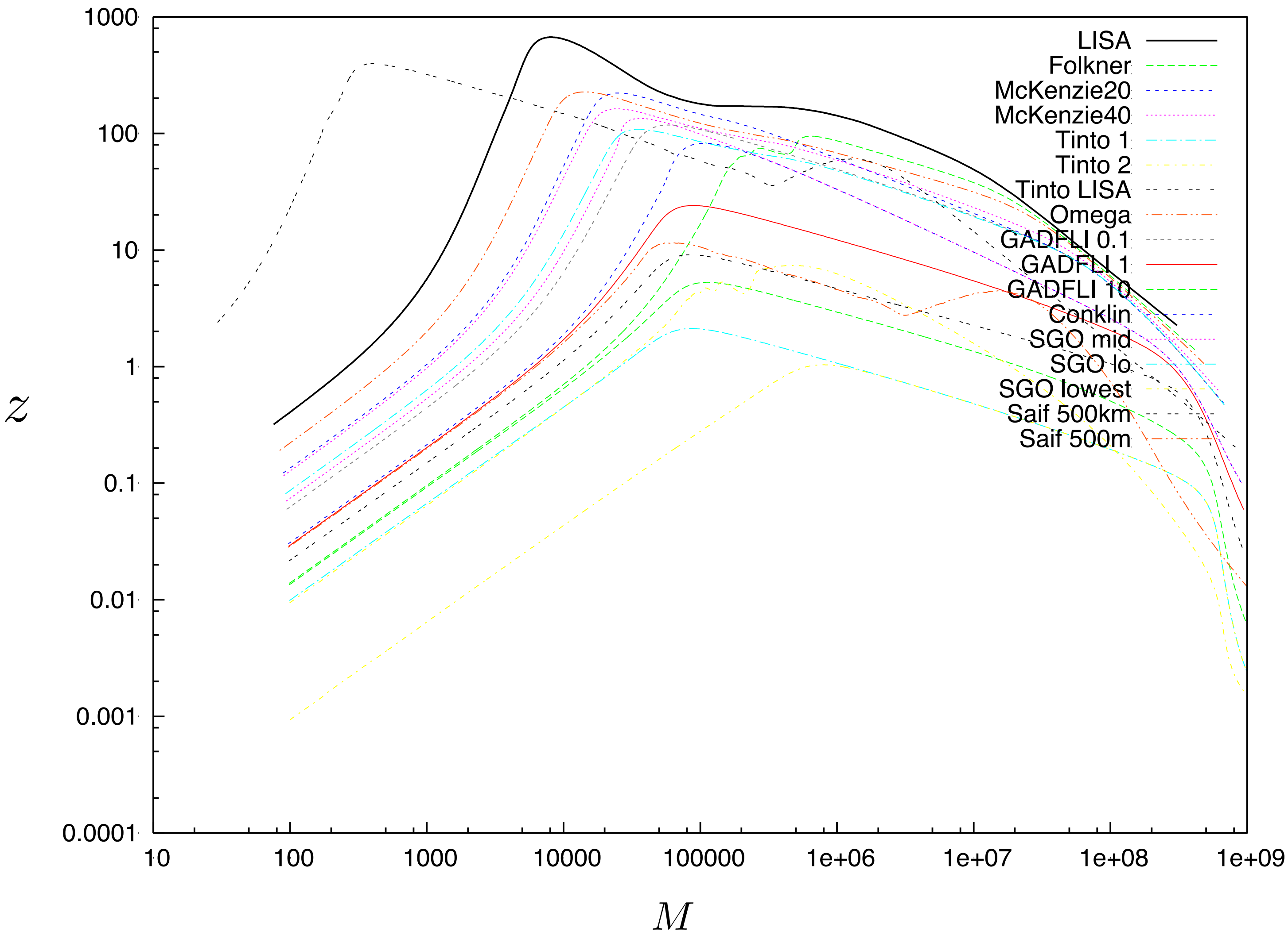
Analysis of Concepts – 2/2

Mission Element	Factors
Mission design	Orbits: interior angles of constellation, doppler rates, etc Trajectories: delta-v, cruise time Launch vehicle
Operations	Length of science operations Comm strategy, assets and schedule Downlink budget Science ops, GI program, data analysis, archiving, distribution
Technical readiness	TRLs Technology development
Risk	Science risk Technical development risk Redundancy Programmatic (cost and schedule)
Cost and schedule	Contingency 70% probability of success

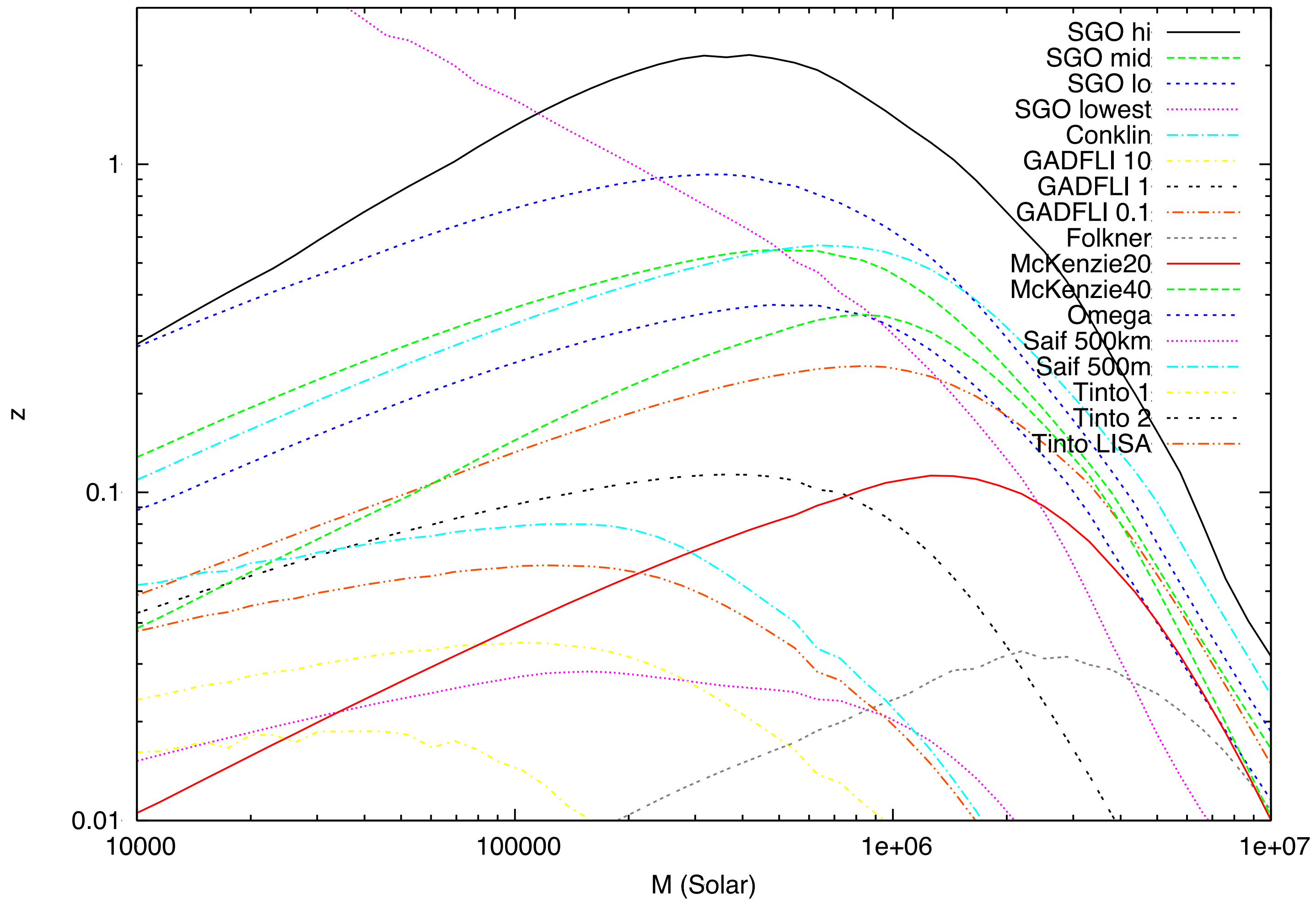
Science Task Force

- Prior to the Workshop
  - Performed a first-cut analysis of science performance based on sensitivity curves provided, some of which could not be reproduced.
  - See Cornish's presentations at PCOS website
- Since the Workshop
  - Parameter estimation for non-drag-free systems
  - Resolution of sensitivity curve issues
- Planned work
  - Independent derivation of sensitivity curves
  - Full science performance analysis of all concepts, all options, including parameter estimation

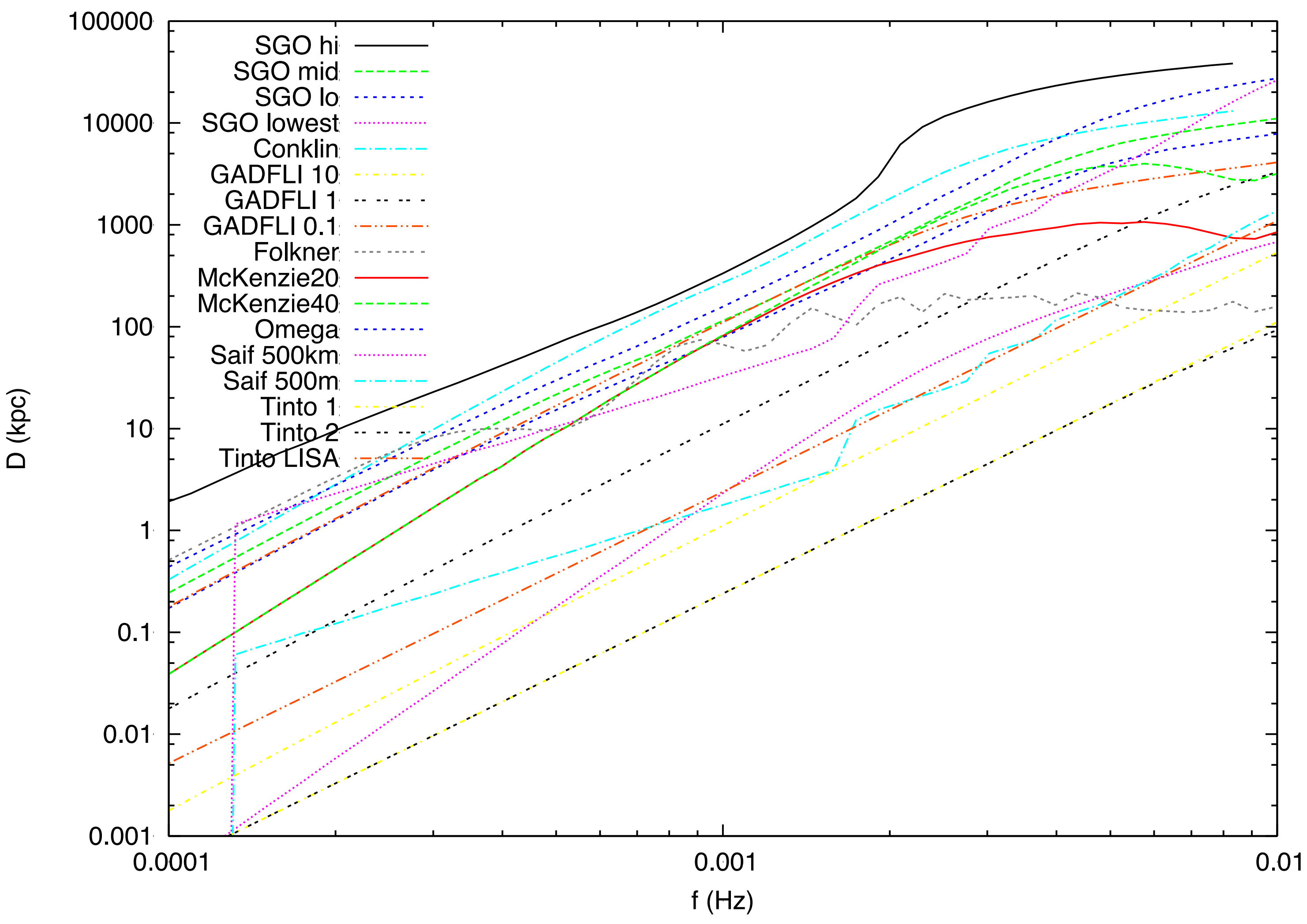
Massive Black Hole Binary Horizons



EMRI Horizons



CWDB Horizons



Workshop

- Maritime Institute, Linthicum, MD, 20-21 December 2012
- Participation
  - Open to anyone
  - ~90 registered, ~50 showed up
- Presentations (see PCOS web site for downloads)
  - LISA Pathfinder
  - NGO
  - Science Task Force
  - Mission and instrumentation concept respondents
  - Core team assessments by Groups

GW Community Science Team

• Peter Bender	JILA
• Joan Centrella	GSFC
• Neil Cornish	Montana St. U.
• Jens Gundlach	U. Washington
• Ronald Hellings	Montana St. U.
• Guido Mueller	U. Florida
• Holger Mueller	Berkeley
• Thomas Prince	CalTech
• Rainer Weiss (chair)	MIT
• Ned Wright (co-chair)	UCLA

GW CST Activities

- Telecons
- Workshop Dec 20-21, 2011 which heard from all the responders to the RFI
- Recommended three mission concepts for study by Team X at JPL, chosen to be “completely different”:
  - Folkner: 260 Gm armlength Δ, not drag-free
  - SGO(mid): LISA-like with 1 Gm armlength Δ
  - OMEGA: 6 identical S/C, 1 Gm armlength Δ in a retrograde geocentric orbit, “Explorer” risk/cost approach
- Future Plans:
  - Further telecons

Summary

- Studying architecture choices and science and cost consequences to find lower alternate mission concepts.
- In the context of
  - The long history of LISA
  - The activities taking place today in Europe and the U.S., notably LISA Pathfinder
  - Decadals, NRC studies and reviews, past and future
  - The near term funding prospects
- The Core Team, Science task force, CST and Team-X are analyzing candidate mission concepts.
- Time for discussion.

BACKUP

Astro2010 Endorsed LISA Science

- Measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies.
- Detection of signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes would provide exquisitely precise tests of Einstein's theory of gravity.
- Potential for discovery of waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings.

Panel on Particle Astrophysics and Gravitation

Table 1. Science Questions and Gravitational Wave Measurements

Science Questions	Measurements Addressing the Questions
How do cosmic structures form and evolve?	Tracing galaxy-merger events by detecting and recording the gravitational-wave signatures
How do black holes grow, radiate, and influence their surroundings?	Using gravitational-wave inspiral waveforms to map the gravitational fields of black holes.
What were the first objects to light up the universe, and when did they do it?	Identifying the first generation of star formation through gravitational waves from core-collapse events.
What are the progenitors of Type Ia supernovae and how do they explode?	Detecting and recording the gravitational wave signatures of massive-star supernovae, of the spindown of binary systems of compact objects, and of the spins of neutron stars.
How do the lives of massive stars end?	
What controls the mass, radius, and spin of compact stellar remnants?	
How did the universe begin?	Detecting and studying very-low-frequency gravitational waves that originated during the inflationary era.
Why is the universe accelerating?	Testing of general relativity—a deviation from general relativity could masquerade as an apparent acceleration—by studying strong-field gravity using gravitational waves in black hole systems, and by conducting space-based experiments that directly test general relativity

Adapted from Panel Reports, New Worlds, New Horizons (NRC 2010, http://www.nap.edu/catalog/12982.html, p. 385)

LISA Science Objectives and Investigations - 1/2

Science Objectives	Science Investigations
Understand the formation and growth of massive black holes	Search for a population of seed black holes at early epochs
	Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs
Trace the growth and merger history of massive black holes and their host galaxies	Determine the relative importance of different black hole growth mechanisms as a function of redshift
	Determine the merger history of 1×10^4 to 3×10^5 $M_\odot$ black holes from the era of the earliest known quasars ($z \sim 6$)
	Determine the merger history of 3×10^5 to 1×10^7 $M_\odot$ black holes at later epochs ($z<6$)
Explore stellar populations and dynamics in galactic nuclei	Characterize the immediate environment of MBHs in $z<1$ galactic nuclei from EMRI capture signals
	Study intermediate-mass black holes from their capture signals
	Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations

LISA Science Objectives and Investigations - 2/2

Science Objectives	Science Investigations
Survey compact stellar-mass binaries and study the morphology of the Galaxy	Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground
	Determine the spatial distribution of stellar mass binaries in the Milky Way and environs
	Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations
Confront General Relativity with observations	Detect gravitational waves directly and measure their properties precisely
	Test whether the central massive objects in galactic nuclei are the black holes of General Relativity
	Make precision tests of dynamical strong-field gravity
Probe new physics and cosmology with gravitational waves	Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured
	Measure the spectrum of, or set bounds on, cosmological backgrounds
Search for unforeseen sources of gravitational waves	

Analysis of Concepts

Group	Group 1 (No drag-free)		Group 2 (Geocentric)				Group 3 (LISA-like)					Group 4 (Other)			Instrument Concepts/Technologies		
Proposal Number	3	16	4	17	7	10	11	14	15	12	13	5	8	9	6	1	2
Lead Author	Folkner	McKenzie	Tinto	McWilliams	Hellings	Conklin	Shao	Stebbins	Livas	Thorpe	Baker	Saif	Yu	Gulian	de Vine	Fritz	McIntyre
Acronym		LAGRANGE	GEOGRAWI	GADFLI	OMEGA	LAGRANGE		SGO High	SGO Mid	SGO Low	SGO Lowest	InSpRL					
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction	Geocentric orbit, single spherical TM	Smaller telescope and laser, smaller satellites	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating	Formation-flying payload, torsion suspension for test mass	LISA with all known cost savings	Smallest LISA-like design with 6 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor	Replace optical bench with photonic integrated circuit		
Proposal Type	Concept	Concept	Concept	Concept	Concept	Concept	Instrument	Concept	Concept	Concept	Concept	Concept	Instrument	Concept	Instrument	Technology	Technology
Cost Estimate (FY12$M)	$924	$1,120	$1,122	$1,200	$300	$950	$990	$1,660	$1,440	$1,410	$1,190	$444/$678			N/A	N/A	N/A
Number of Alternates	2	2	3	3	1	1	1	1	1	1	1	2					
Arm length (km)	2.6×10^8	2.09×10^7	7.3×10^4	7.3×10^4	1.04×10^6	6.7×10^5	5.0×10^6	5.0×10^6	1.0×10^6	1.0×10^6	2.0×10^6	0.5/500					
Spacecraft/Constellation	3/equilateral triangle //4/square	3/isosceles triangle	3/equilateral triangle	3/equilateral triangle	6/triangle	3/equilateral triangle	3+3/triangle	3/equilateral triangle	3/equilateral triangle	4/triangle (60-deg Vee)	3/In-line: Folded SyZyGy	1//2/in-line		1			
Orbit	Heliocentric	Heliocentric/ Earth-Sun L2	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5	LISA-like	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away	1200 km above geostationary	LISA-like	Not specified.	Comparable to LISA		
Trajectory	Not specified beyond HEO parking, double lunar assist. Solar electric propulsion mentioned.	Direct escape to L2, "drift" of SC1/3 to 8° leading/trailing	Not specified	Direct launch together to geostationary, re-phase 2 S/C	Butterfly trajectories to Weak Stability Boundary, 384 days total	Either: direct to WSB, return and lunar fly-by; direct to Trans Lunar Injection, return and lunar fly-by		Direct injection to escape with recircularization and out-of-plane boost, 14 months	Direct injection to escape with out-of-plane boost, 21 months	Direct injection to drift away, with out-of-plane boosts, 21 months	Direct injection to escape, with small delta-v for S/C separation, 18 months	Not specified	LISA-like	Not specified			
Inertial Reference	None	GOCE accelerometer	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical	Single, torsion pendulum	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular	Atom interferometers					
Displacement Measurement	3 arms, 6 links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links				3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links						
Launch vehicle		Falcon 9 Block 3		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9	Falcon 9	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2	Falcon					
Baseline/Extended Mission Duration	3 arms, 6 links	2		2	3	5	5	5/3.5	2/2	2/2	2/0						
Telescope Diameter (cm)	30	20/40	Same as LISA	15	30	20		40	25	25	25						
Laser power out of telescope, EOL (W)	1	1.2	Same as LISA	0.7	0.7	1		1.2	0.7	0.7	0.7	10-20					
Sensitivity curve	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes			Comparable to LISA		
Residual acceleration ($m/s^2/Hz^{1/2}$)	1.0×10^{-13}	4.4×10^{-14} (0.001/f)^0.75	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}		3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}						
Displacement sensitivity ($m/Hz^{1/2}$)	550×10^{-12}	150×10^{-12}	7×10^{-12}	8×10^{-12}	5×10^{-12}	5×10^{-12}		8×10^{-12}	8×10^{-12}	8×10^{-12}	8×10^{-12}				5×10^{-12}		

Team-X

- A cross-functional multidisciplinary team of engineers utilizes concurrent engineering methodologies to complete rapid design, analysis and evaluation of mission concept designs.
- Experienced flight-project engineers are co-located in the Project Design Center to perform architecture, mission, and instrument design studies in real time.
- The Project Design Center is a state-of-the-art facility consisting of networked workstations, a supporting data management infrastructure, large interactive graphic displays, computer modeling and simulation tools, historical data repositories and a shared project model that the design team updates.