



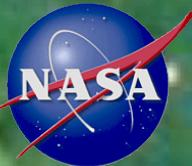
Progress Towards a Space-based Gravitational-Wave Observatory Since 2010

Robin Stebbins, GSFC
Midterm Assessment Committee
Washington, DC, 9 October 2015



Outline

- State of Play in August 2010
- 2010-2015
 - The LISA Project and Subsequent Studies
 - LISA Pathfinder
 - Technology Development
 - ESA's Cosmic Visions Programme
 - Gravitational Wave Science
- The Plan Forward: 2016-2020



STATE OF PLAY IN AUGUST 2010



LISA in August 2010

Laser Interferometer Space Antenna (LISA)

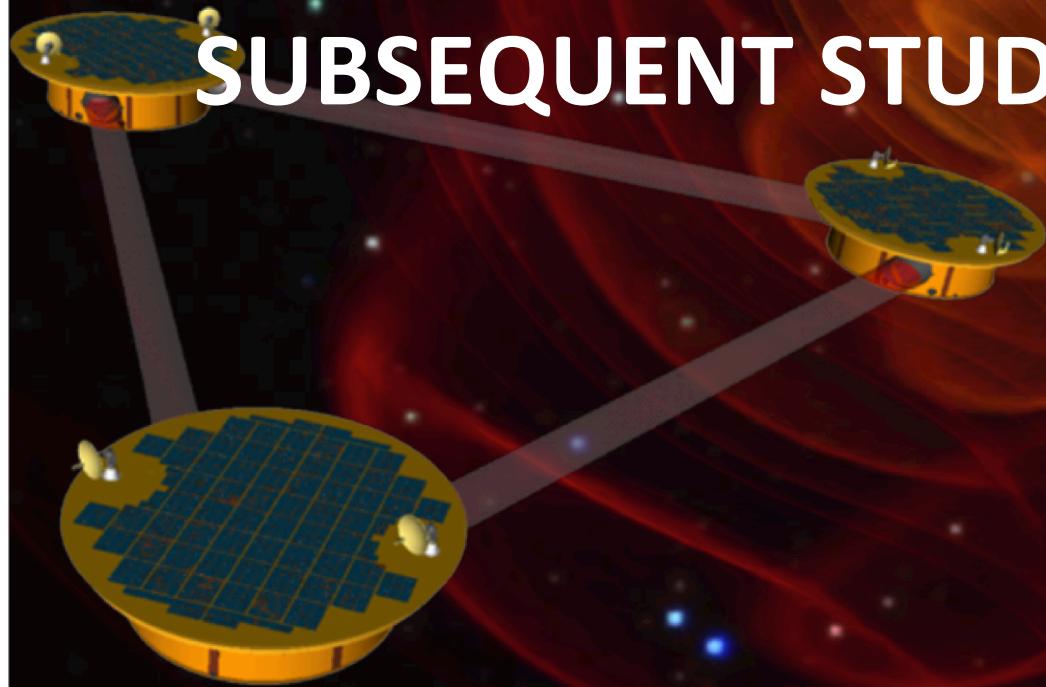
- Focus of all work since 1993
- Unchanged since 1997
- Project in Phase A since 2004
- Extensive formulation work and products
- Reviewed and recommended in many major reviews:
 - AANM (NRC, 2001)
 - TRIP (HQ, 2003)
 - Connecting Cosmos to Quarks (NRC, 2003)
 - AETD (GSFC, 2005)
 - Beyond Einstein Program (NRC, 2007)
 - NWNH (NRC, 2010)
 - Second in 'large' space projects after WFIRST.
 - Recommended for a new start
 - Contingent on Pathfinder success and a roughly 50/50 European partnership.



ST7 in August 2010

- 2001: New Millennium Program selected the “Disturbance Reduction System” as Space Technology 7 (ST7)
- U.S. contribution to ESA’s LISA Pathfinder mission
- Original idea: NASA and ESA payloads, each with
 - 2 Gravitational Reference Sensors (GRSes)
 - Metrology interferometer
 - Microthrusters
 - Drag-free controller
- 2005: Descoped interferometer and GRSes
- 2010: Remaining U.S. hardware nearing completion.

THE LISA PROJECT AND SUBSEQUENT STUDIES: 2010-2015





The LISA Project

- March 2011: NASA withdrew from ESA's L1 proposals because of increased program demands and decreased budget projections.
- April 2011: Joint NASA/ESA LISA Project ended
- Science team disbanded
 - Working groups stopped working.
 - Mock LISA Data Challenge stopped.
- Project team at GSFC and JPL largely disbanded.
- Technology support transitioned to SAT grants



Probe Mission Concept Study

2011-2012: Study of probe class concepts ($\leq \$1B$)

- Design trade-offs explored for impact on science, risk and cost.
- No viable concepts near or below \$1B
- No technology dramatically reduces cost
- LISA architecture can be scaled down (SGO Mid), still compelling science.
- Science performance decreases far more rapidly than cost. Risk increases to an unacceptable level.

Final report and (many) other documents at

<http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php>

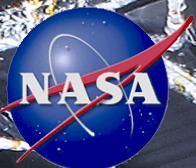


Technology Development Roadmap

2012-2013: prepared 'technology roadmap' for a future GW mission

- The eLISA and SGO Mid concepts require the same technology.
- U.S.-centric plan to develop technologies for a LISA-like mission in the 2030's.
- *Predates the selection of L3.*
- Links to final document and annual program technology reports at

<http://pcos.gsfc.nasa.gov/technology/>



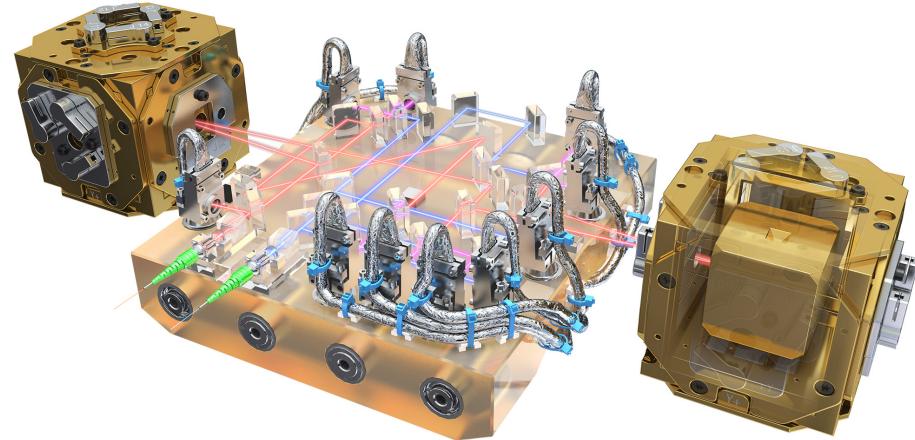
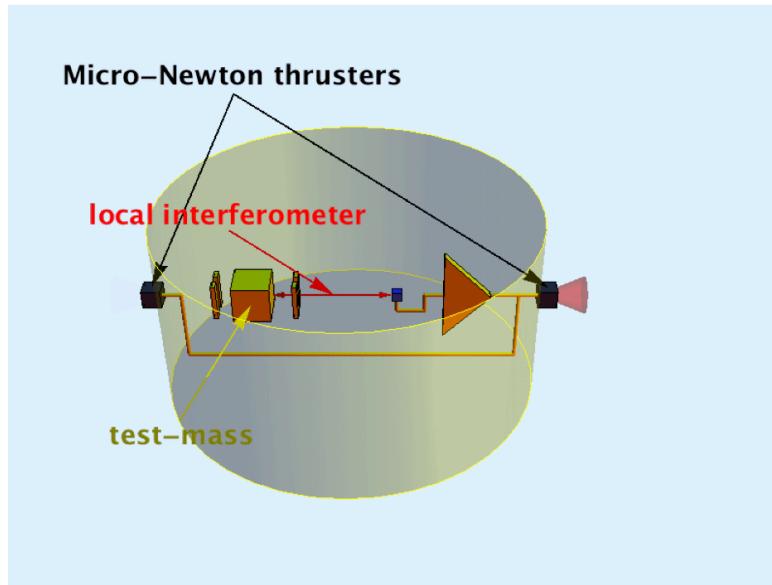
LISA PATHFINDER



LPF Objectives

- Drag-free flight demonstration
 - Residual acceleration on the test mass $<3 \times 10^{-14} \text{ m/sec}^2/\sqrt{\text{Hz}}$ at 1 mHz
 - Multi-degree-of-freedom control system
- Microthruster demonstration
 - Thrust noise
 - Controllability
- Error budget validation
 - Programmable environment disturbances (magnetic, thermal, charging)
 - Measure the transfer function
 - Extrapolate to LISA

LPF – The Basic Idea

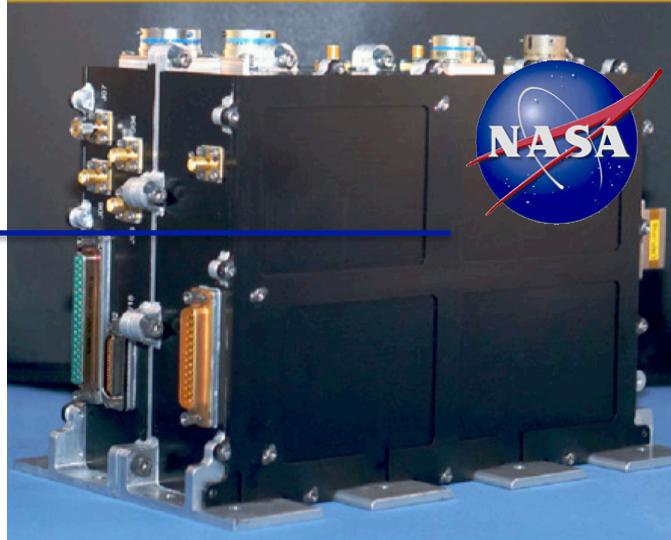
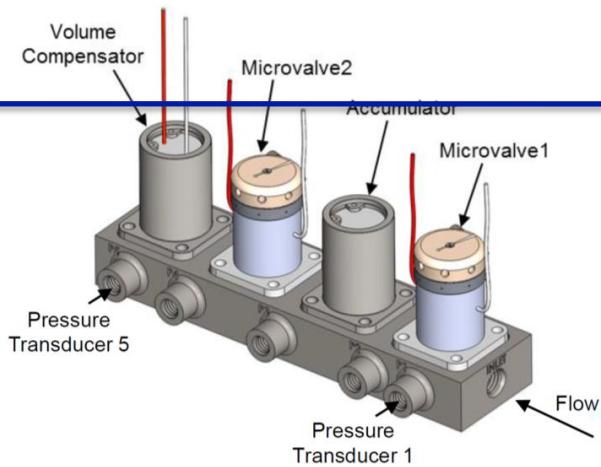
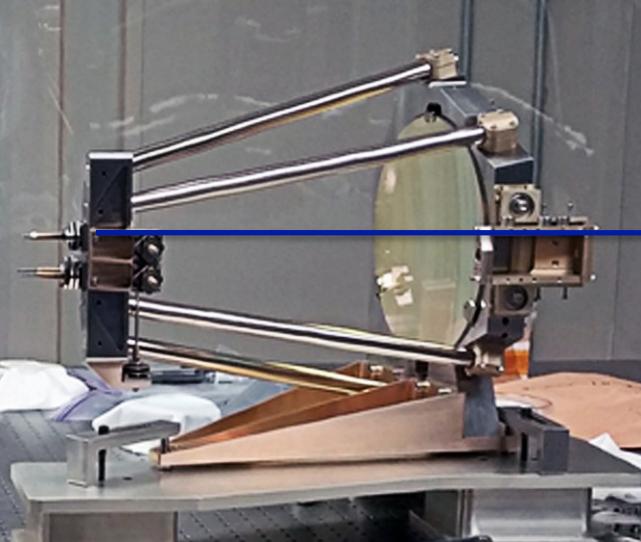


- Drag-free control system
 - One test mass as a sensor
 - Microthruster as a forcer.
 - Controller
- Second test mass as a “witness.”
- Measure the relative motions of the two test masses with picometer interferometer

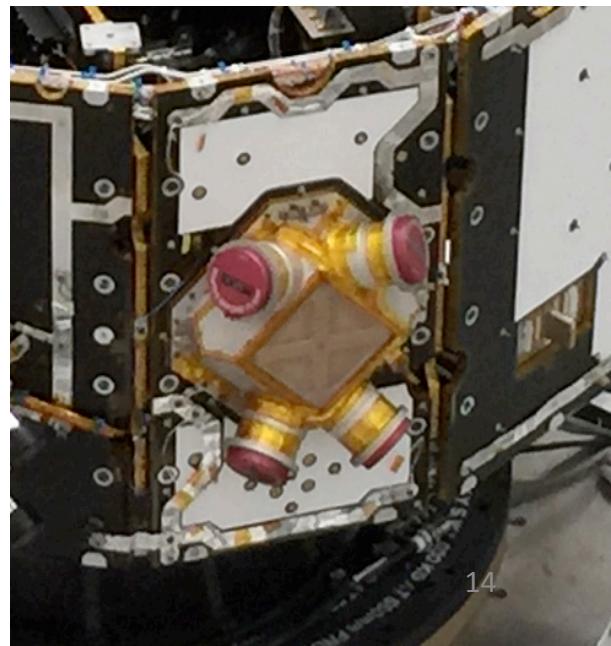
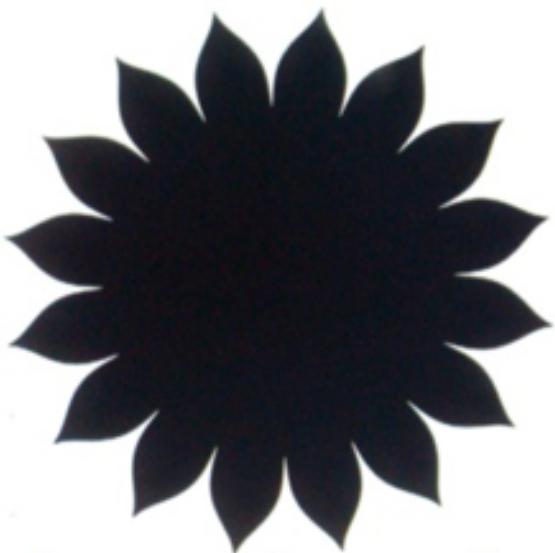
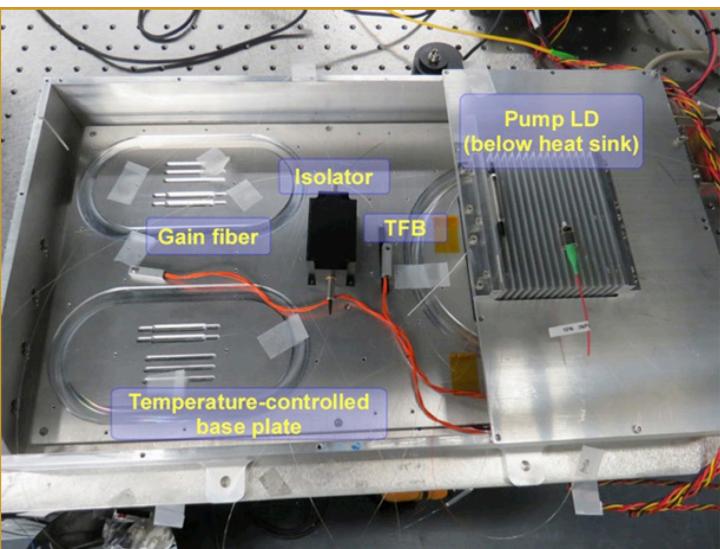


LPF – Status

- 2012: ST7 delivered to ESA, integrated later in the year
- ESA thrusters changed to GAIA cold gas thrusters
- Final ground testing met or exceeded all requirements.
- September 3: spacecraft, propulsion module and launch I&T complete, ready for shipping
- Numerous operations exercises have been carried out.
- October 8: Flown to Kourou.
- December 1, 11:15 pm EST: scheduled launch on Vega 6
- L+74 d: LTP operations start
- L+186 d: ST7 operations start
- L+288 d: Nominal mission ends.
- Extended mission under consideration.



TECHNOLOGY DEVELOPMENT





Technology Development

- Telescope Subsystem – Jeff Livas (GSFC)
 - Demonstrate pathlength stability, stray light and manufacturability
 - SAT renewed FY16
- Phase Measurement System – Bill Klipstein (JPL)
 - Key measurement functions demonstrated
 - Incorporate full flight functionality
 - SAT expired
- Laser Subsystem – Jordan Camp (GSFC)
 - 1064 nm ECL master oscillator
 - Phase noise of fiber power amplifier
 - Demonstrate end-to-end performance in integrated system
 - Lifetime
 - SAT expires May '16
- Micronewton Thrusters – John Ziemer (JPL)
 - Propellant storage and distribution for long duration
 - Improve system robustness
 - Improve manufacturing yield
 - Lifetime
 - SAT expired



Technology Development

- Arm-locking Demonstration – Kirk McKenzie (JPL)
 - Studying a demonstration of laser frequency stabilization with GRACE Follow-On
 - Expiring APRA
- Torsion Pendulum – John Conklin (UF)
 - Develop U.S. capability with GRS and torsion pendulum test bed
 - Nancy Grace Roman Fellowship FY15-16
- Multi-axis Heterodyne Interferometry – Ira Thorpe (GSFC)
 - Investigate test mass/optical bench interface
 - APRA starting FY16
- UV LEDs – John Conklin+ (UF)
 - Flight qualify UV LEDs to replace mercury lamps in discharging system
 - Non-NASA support
- Optical Bench – Guido Mueller (UF)
 - Investigate alternate designs and fabrication processes to ease manufacturability
 - APRA starting FY16

LISA researchers at JPL are leading the Laser Ranging Interferometer instrument on the GRACE Follow-On mission.



ESA'S COSMIC VISION PROGRAMME 2015-2025



Cosmic Visions 2015-2025

- Next “planning horizon” for ESA science
- NASA withdrew from initial L1 competition in 2011.
- Next Gravitational Observatory (NGO) concept proposed to second L1 competition in 2012.
 - Descoped LISA-like mission to meet ESA cost cap without US participation
 - *Two arms, 1 million Km baselines, 2 year science operations, 2 launches, mother-daughter configuration.*
 - JUICE selected
- “Gravitational Universe” proposed for L2/L3 Competition in 2013
 - NGO the “notional” mission concept.
 - Senior Selection Committee selected Athena for L2 and the Gravitational Universe as the “science theme” for L3, on account that LPF had not yet flown.



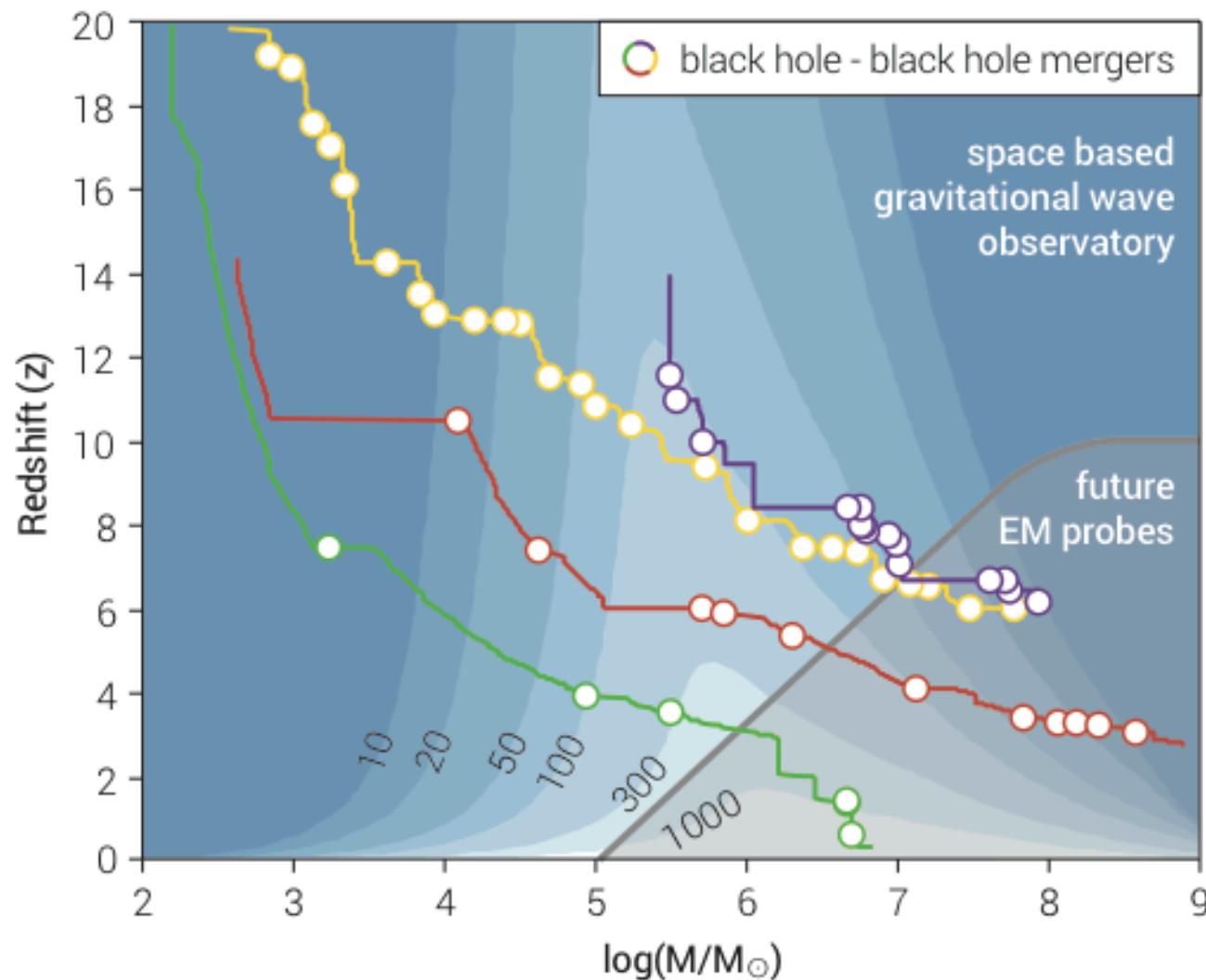
ESA's L3 Mission

- Only 'science theme' selected, not a mission concept
- Planned launch date is 2034.
- Cost cap is 1B€ to ESA.
- Member states typically contribute an additional 30-35%.
- International partners limited to 20% of total European contribution (about \$300M).
- NASA interested at the \$100-150M level
- ESA included three U.S. members and one NASA observer on the Gravitational Observatory Advisory Team (GOAT)



GRAVITATIONAL WAVE SCIENCE

LISA and Cosmological Structure Formation





Advances in LISA Science

- Improvements in MBHB parameter estimation
 - Added merger and ring-down phases to waveforms
 - Added higher harmonics to waveforms
 - Improved understanding of sky localization, especially from merger phase
 - Orbital eccentricity explored
 - Improved understanding of the interaction between SMBHs and their host galaxies, including effects of eccentricity and spin alignments
 - Kicks explored
 - Improved cosmological modeling of structure formation
 - Better understanding of final parsec problem and its resolution
- Emerging methods for quantifying GR tests
- Science performance calculations
 - ~50 mission concept variants analyzed

2010s – The GW Decade



Advanced LIGO/Virgo/KAGRA begin operations

- O1 observing run began September 18th for 3 months
- Reach 70 Mpc for NS-NS mergers, 3 times previous LIGO distance (27 times volume)
- Progressive sensitivity improvement in next few years
- First GW observations expected by ~2019

Pulsar Timing Arrays (PTAs)

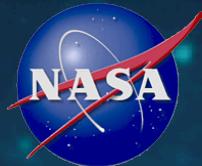
- Several PTA efforts have published upper-limits on stochastic GW backgrounds from SMBH binary mergers (NANOGrav, EPTA, PPTA)
- A key astrophysical uncertainty is in the strength of SMBH binary interactions with their environments
- Recent (2015) results from Parkes (PPTA) are in conflict with models that assume modest rates of evolution passing through the nHz band.
- Models less sensitive to environmental effects at higher frequencies



Caltech/MIT/LIGO Lab



Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

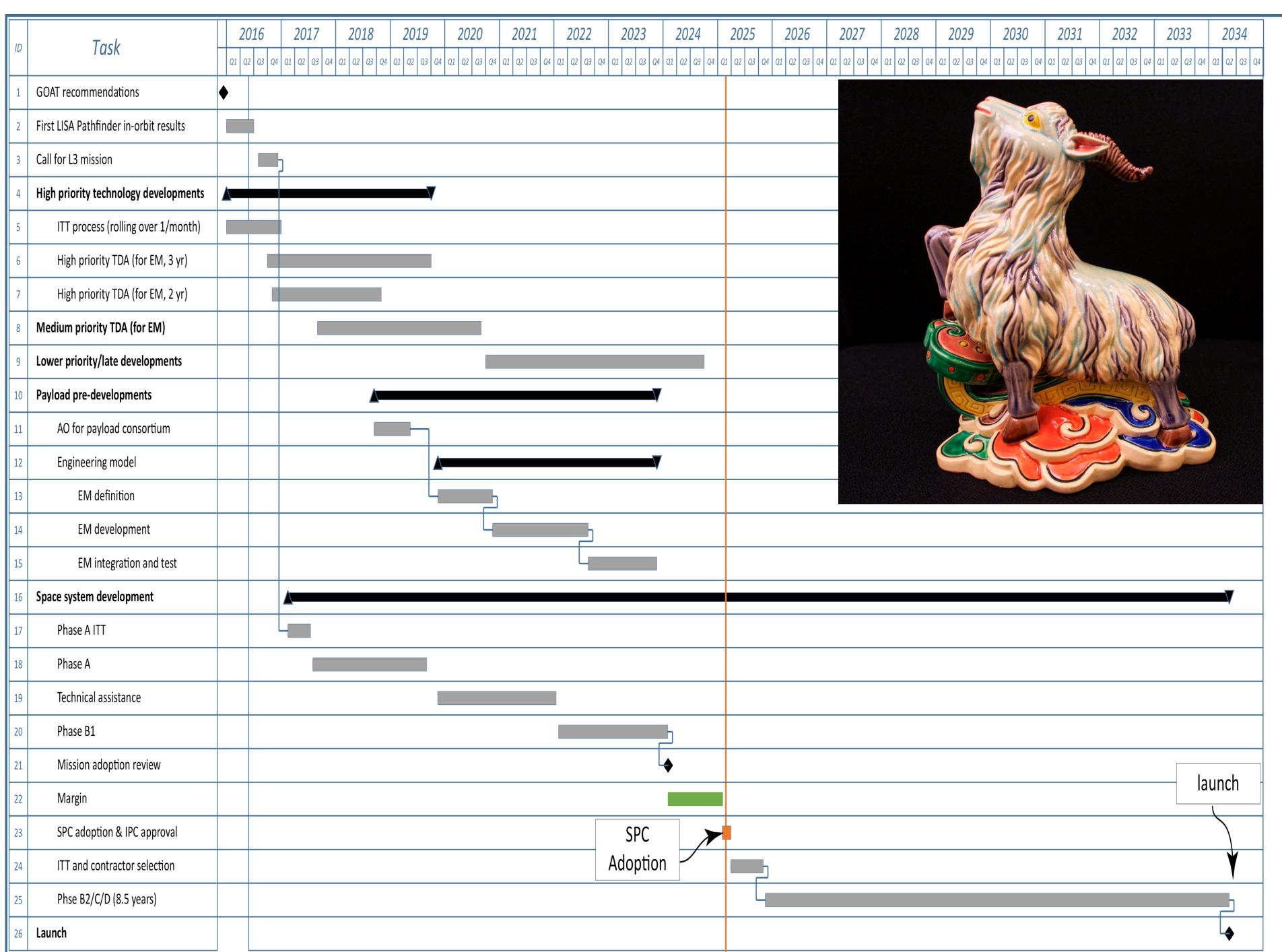


THE PATH FORWARD: 2016-2020



Gravitational Observatory Advisory Team (GOAT)

- GOAT: an ad-hoc ESA advisory committee initiated in September 2014:
“To evaluate and recommend on possible scientific and technical approaches for a gravitational wave observatory envisaged for a planned launch date in 2034.”
- 3 US members and 1 NASA observer out of 12 total, very active in the internal studies and debates
- Topics: technical feasibility, science goals, data analysis, system view, technology, partners, cost and schedule
- **GOAT has been asked to assess LPF success, with addition of European and US experts. (cf. NWNH)**
- GOAT Intermediate Report and other material at:
<http://www.cosmos.esa.int/web/goat/home>





Pre-decadal Study

- NASA participation in L3 needs a strong recommendation from Astro2020 to go forward.
- NASA needs to define its role, and understand the options
 - Starting point: \$100-150M contribution
 - ESA's limit: 20% of European contribution (~\$300M)
 - Contributions: elements of the flight system
 - U.S. activities: science team, data analysis, data center, guest observer program
 - Cost and schedule estimates for collaboration, technology development, flight system contributions and U.S. activities
- Produce the basis for a proposal to Astro2020 by late 2018.



NASA activities 2015-2017

- Operations and data analysis on Pathfinder and ST7
- GW Science Interest Group/Physics of the Cosmos Program Analysis Group (POCs: John Conklin and Neil Cornish)
- Continued participation in ESA's GOAT
- Participation in early ESA lead-in activities: mission concept proposal/selection, ESA's Phase A starts 2017, ...
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- Rebuild a supporting GW community in the US
- Pre-decadal study in 2017-2018
- Preparations for next decadal



NASA activities 2018-2020

- GW Science Interest Group/Physics of the Cosmos Program Analysis Group
- Participation in early ESA lead-in activities: payload AO, payload engineering model, ...
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- Pre-decadal study in 2017-2018
- Continue rebuilding US research community
- Astro2020 decadal survey, a US role in L3 needs
 - A strong endorsement for science and feasibility.
 - Recommended financial commitment



Wrap-Up

- NASA's strategic plan for a gravitational wave observatory is to participate in ESA's L3 mission
- To carry out that plan, NASA has to
 - Participate in the successful execution of LPF and ST7, baseline and extended missions
 - Successfully negotiate a role with ESA
 - Refine its plan through a pre-decadal study
 - Develop appropriate technology and participate in pre-formulation studies on ESA's schedule
 - Receive an endorsement for L3 participation from the 2020 decadal review



BACKUP



Mission Concept Comparison

Parameter	NGO	SGO Mid	LISA
Measurement arm length	1×10^6 km	1×10^6 km	5×10^6 km
Number & type of spacecraft	1 corner (2 optical assemblies, 2 end (single optical assembly	3 corner (2 optical assemblies)	3 corner (2 optical assemblies)
Number of measurement arms, one-way links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links
Constellation	Vee	Triangle	Triangle
Gravitational-wave polarization measurement	Single instantaneous polarization, second polarization by orbital evolution	Two simultaneous polarizations continuously	Two simultaneous polarizations continuously
Orbit	Heliocentric, earth-trailing, drifting-away 9°- 21°	Heliocentric, earth-trailing, drifting-away 9°- 21°	22° heliocentric, earth-trailing
Trajectory	Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months	Direct injection to escape, 18 months	Direct injection to escape, 14 months
Duration of science observations	2 years	2 years	5 years
Launch vehicle	Two Soyuz-Fregat	Single Medium EELV (e.g., Falcon 9 Block 3)	Single Medium EELV (e.g., Atlas V 551)
Optical bench	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction
Laser	2 W, 1064 nm, frequency and power stabilized	1 W, 1064 nm, frequency and power stabilized	2 W, 1064 nm, frequency and power stabilized
Telescope	20 cm diameter, off-axis	25 cm diameter, on-axis	40 cm diameter, on-axis
Gravitational Reference Sensor	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout



Science Comparison

	NGO	SGO Mid	LISA
MBH Totals	40-47	41-52	108-220
Detected $z > 10$	1-3	1-4	3-57
Both mass errors < 1%	13-30	18-42	67-171
One spin error < 1%	3-10	11-27	49-130
Both spin errors < 1%	<1	<1	1-17
Distance error < 3%	3-5	12-22	81-108
Sky location < 1 deg 2	1-3	14-21	71-112
Sky location < 0.1 deg 2	<1	4-8	22-51
EMRIs	12	35	800
Resolved CWDBs	3,889	7,000	40,000
Interacting	50	100	1,300
Detached	5,000	8,000	40,000
Sky location < 1 deg 2	1,053	2,000	13,000
Sky location < 1 deg 2 , distance error < 10%	533	800	8,000
Stochastic Background	0	0.2	1

Special acknowledgement to Ryan Lang (Univ. of Florida) and Neil Cornish (Montana State Univ.)



What LPF does/doesn't demonstrate

- **Free flying test mass subject to very low parasitic forces:**
 - Drag free control of spacecraft (non-contacting spacecraft)
 - Low noise micro-thruster to implement drag-free
 - Large gaps, heavy masses with caging mechanism
 - High stability electrical actuation on cross degrees of freedom
 - Non contacting discharging of test-masses
 - High thermo-mechanical stability of S/C
 - Gravitational field cancellation
- **Precision interferometric, local ranging of test-mass and spacecraft:**
 - pm resolution ranging, sub-mrad alignments
 - High stability monolithic optical assemblies
- **Precision 1 Mo km spacecraft to spacecraft precision ranging:**
 - High stability telescopes
 - High accuracy phase-meter
 - High accuracy frequency stabilization
 - Constellation acquisition
 - Precision attitude control of S/C